Application of Plasma Phenomena

Po-Yu Chang

Institute of Space and Plasma Sciences, National Cheng Kung University

Lecture 12

2023 spring semester

Tuesday 9:10-12:00

Materials:

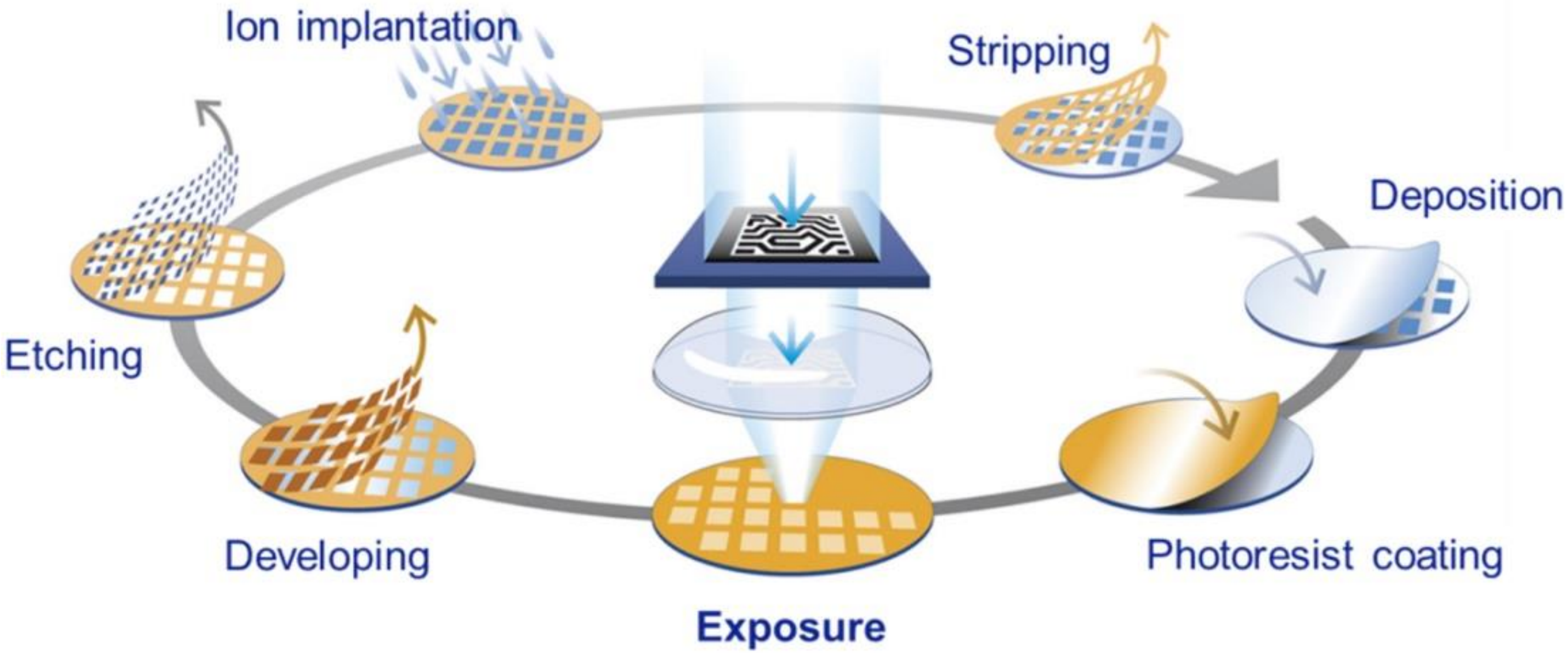
https://capst.ncku.edu.tw/PGS/index.php/teaching/

Online courses:

https://nckucc.webex.com/nckucc/j.php?MTID=m2a52f2d8ea616f434b6ec30 53ef0ebd2

2023/5/23 updated

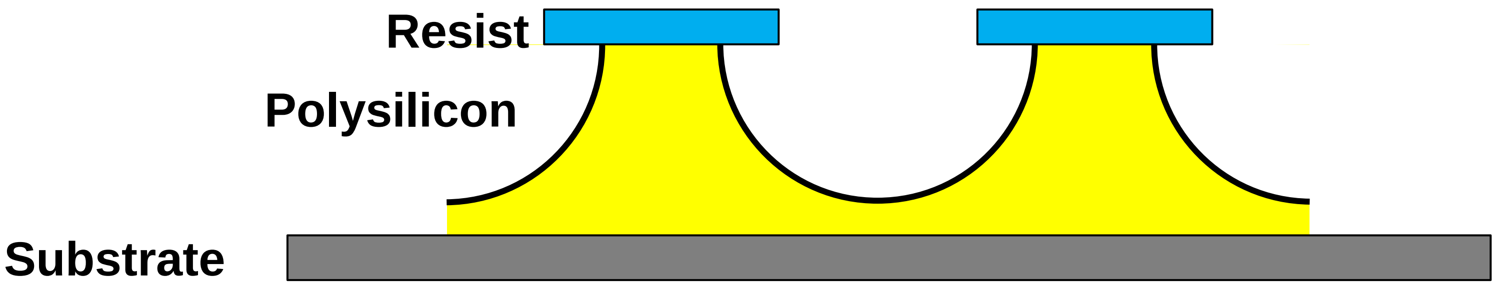
A semiconductor device is fabricated by many repetitive production process



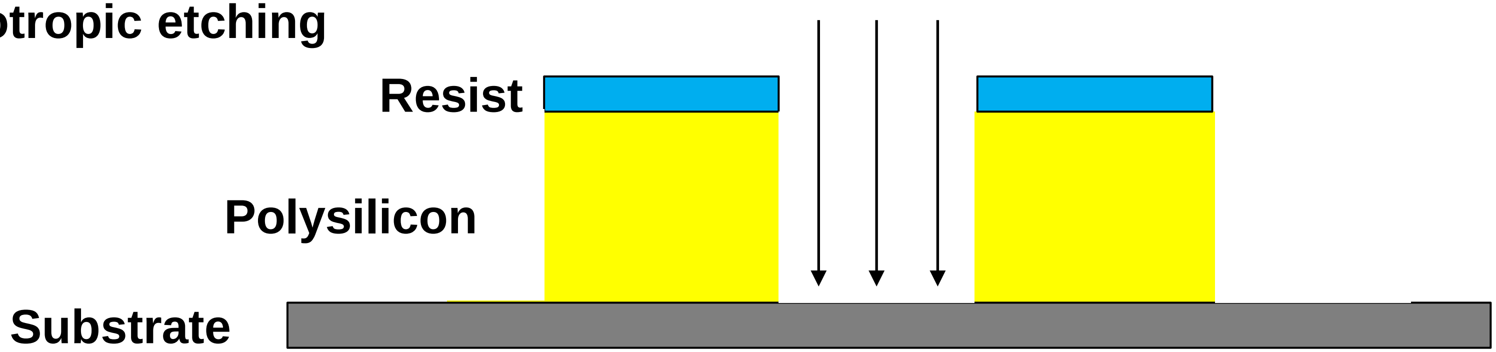
Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

There are two types of etching: isotropic vs anistropic

- **Isotropic etching**

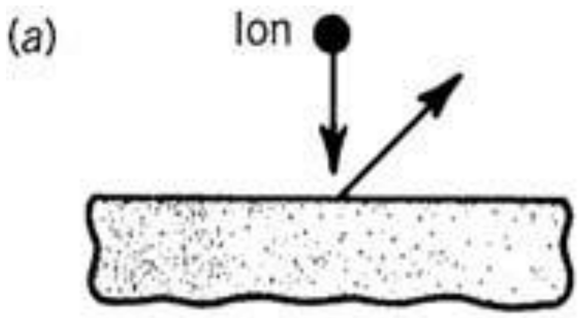


- **Anisotropic etching**

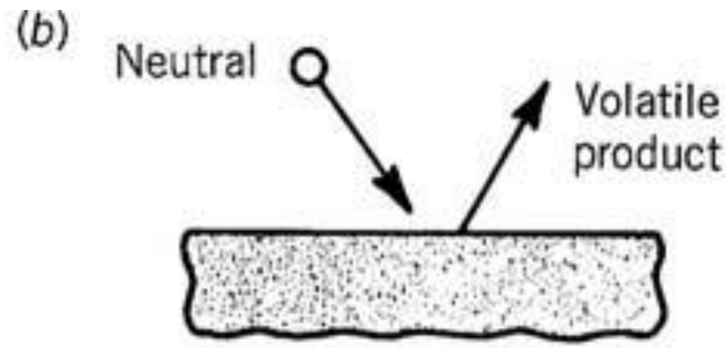


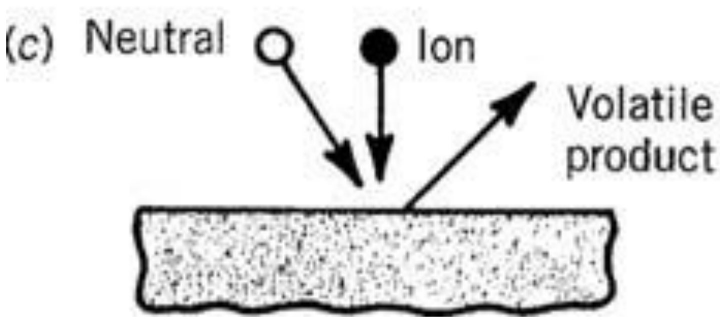
There are four major plasma etching mechanisms

- **Sputtering**

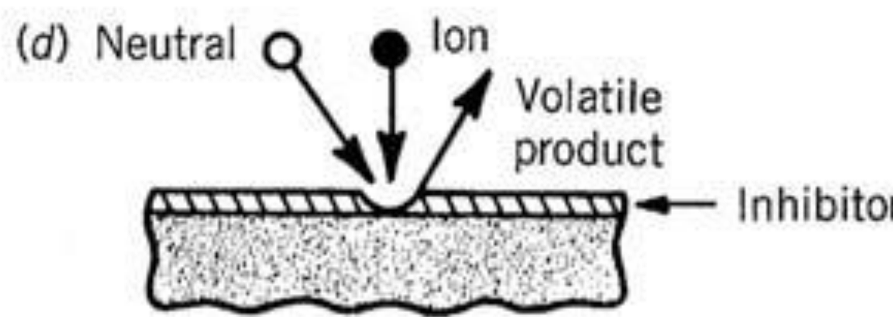


- **Pure chemical etching**





- **Ion energy-driven etching**

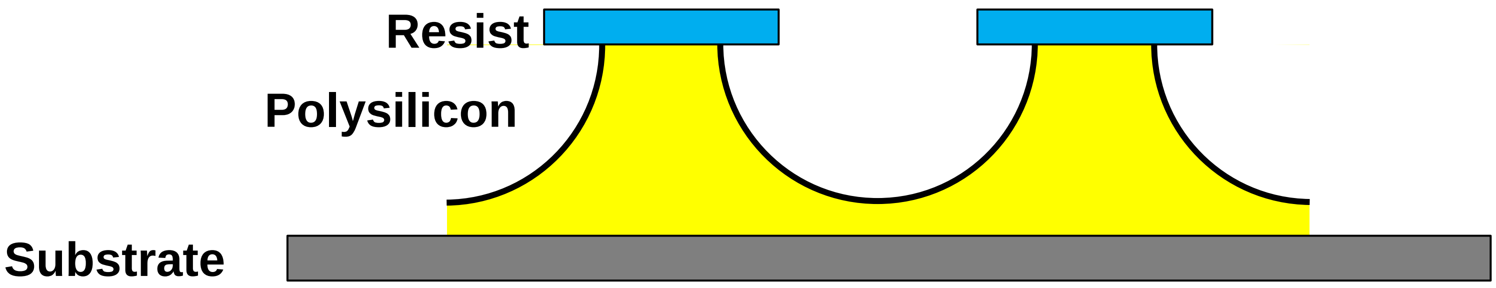


- **Ion-enhanced inhibitor etching**

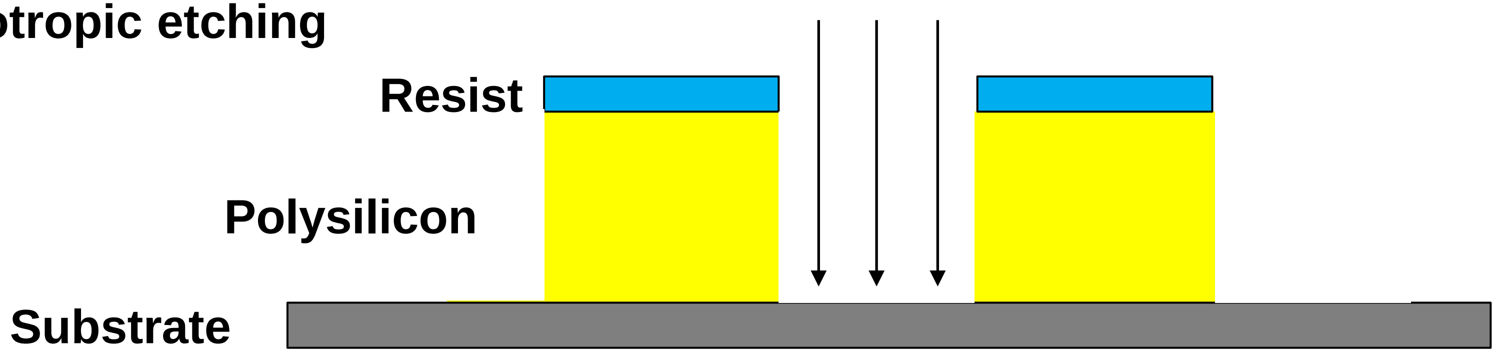
Principles of plasma discharges and materials processing, 2nd edition, by Michael A. Lieberman and Allan J. Lichtenberg

There are two types of etching: isotropic vs anistropic

- Isotropic etching

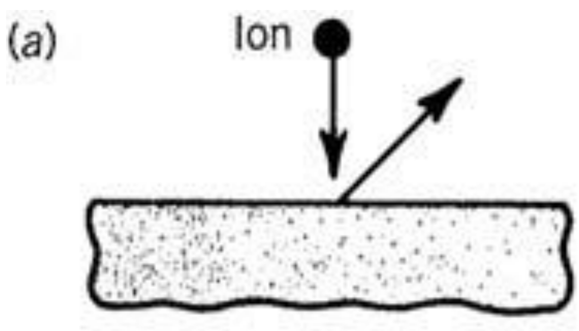


- Anisotropic etching

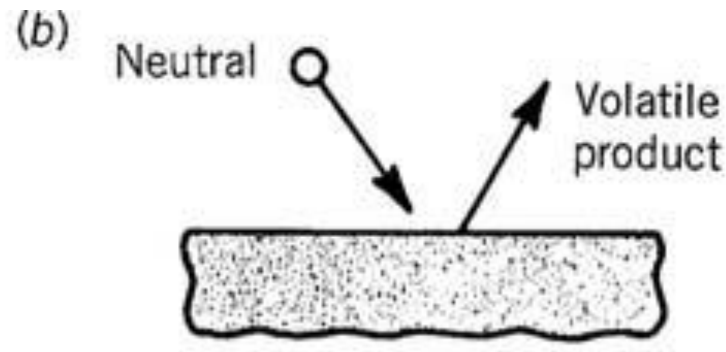


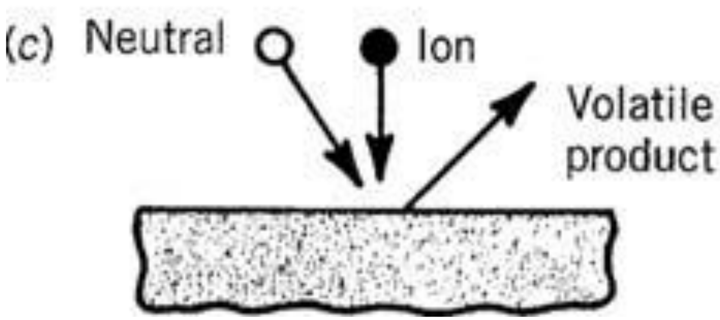
There are four major plasma etching mechanisms

- **Sputtering**

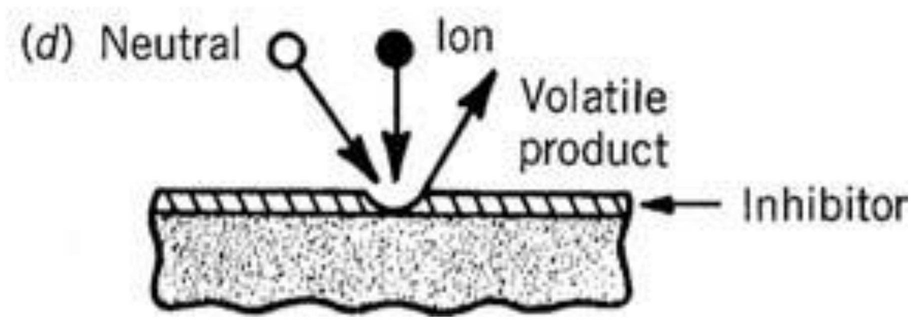


- **Pure chemical etching**





- **Ion energy-driven etching**



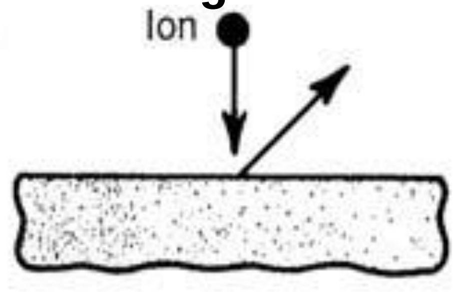
- **Ion-enhanced inhibitor etching**

Principles of plasma discharges and materials processing, 2^{nd} edition, by Michael A. Lieberman and Allan J. Lichtenberg

Sputtering etching

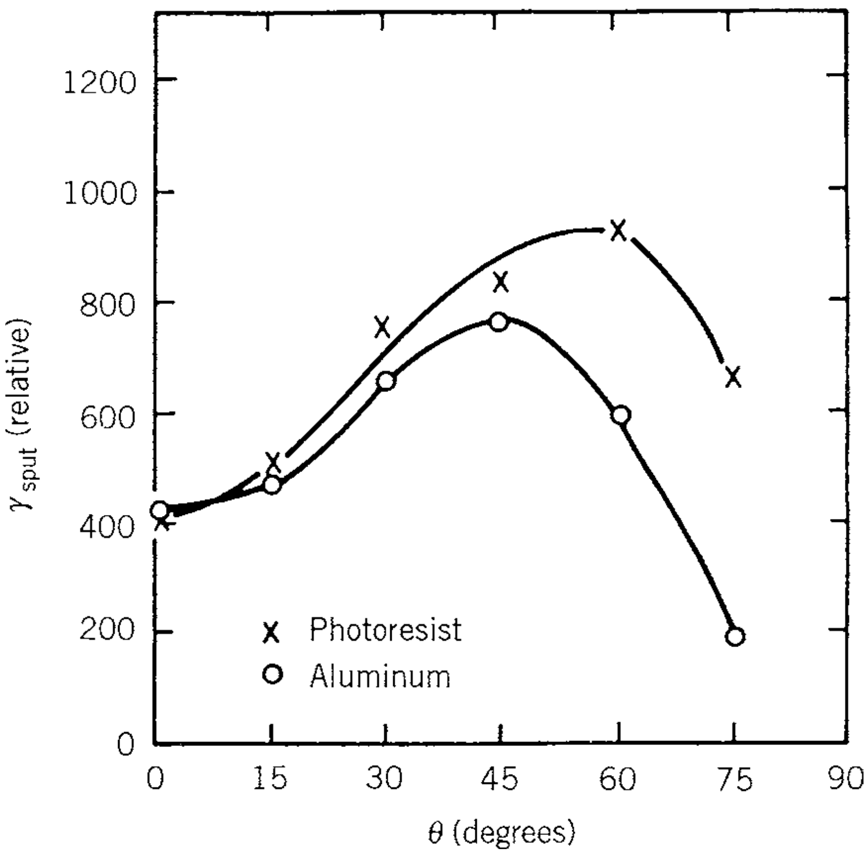
Sputtering is an unselective but anisotropic process

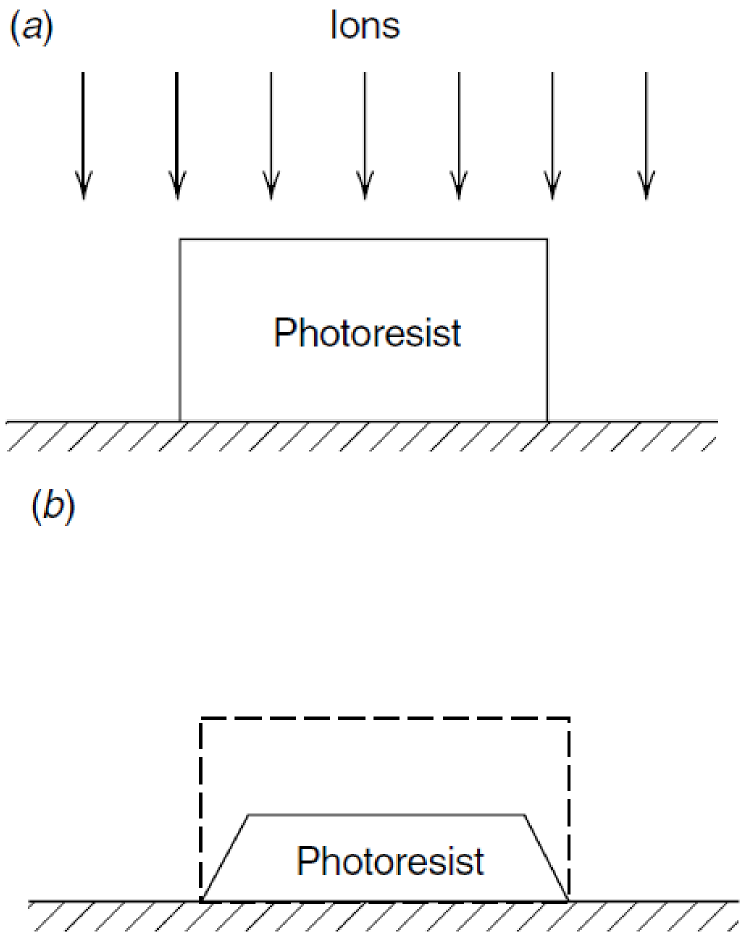
- **Unselective process.**
- **Anisotropic process, strongly sensitive to the angle of incidence of the ion.**
- **Sputtering rates of different materials are roughly the same.**
- **Sputtering rates are generally low because the yield is typically of order one atom per incident ion.**
- **Sputtering is the only one of the four etch processes that can remove nonvolatile products from a surface.**
- **The process is generally under low pressure since the mean free path of the sputtered atoms must be large enough to prevent redeposition on the substrate or target.**



Principles of plasma discharges and materials processing, 2nd edition, by Michael A. Lieberman and Allan J. Lichtenberg

Topographical patterns might not be faithfully transferred during sputter etching





Principles of plasma discharges and materials processing, 2nd edition, by Michael A. Lieberman and Allan J. Lichtenberg

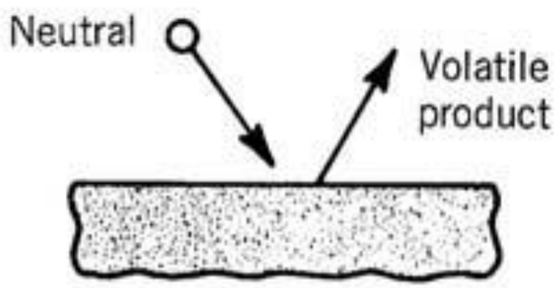
Pure chemical etching

Atoms or molecules chemically react with the surface to form gas-phase products

- **Highly chemically selective, e.g.,**

$$Si(s) + 4F \longrightarrow SiF_4(g)$$

$$\text{photoresist} + O(g) \longrightarrow CO_2(g) + H_2O(g)$$

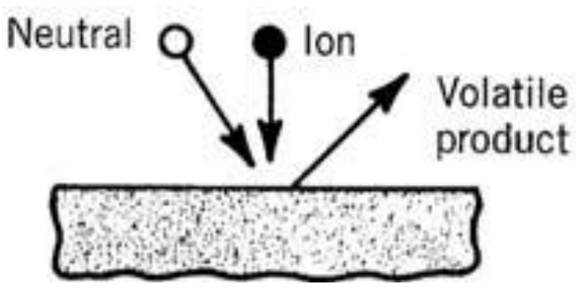


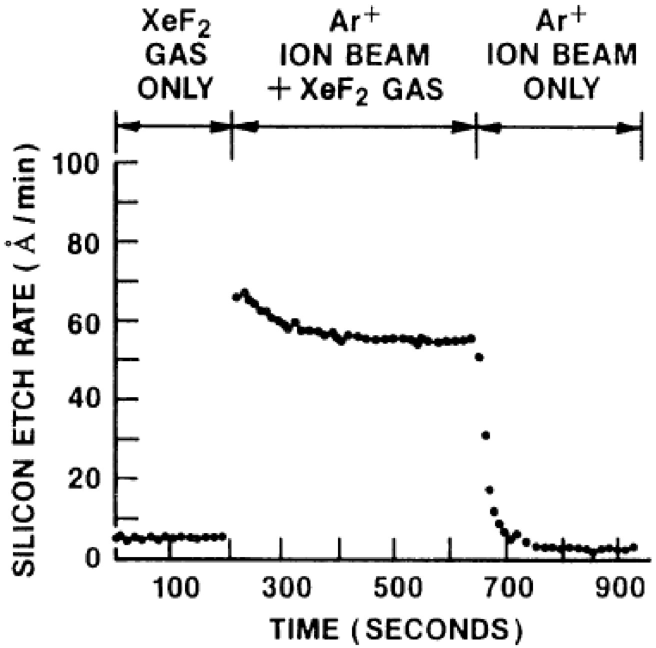
- **Almost invariably isotropic.**
- **Etch products must be volatile.**
- **The etch rate can be quite large.**
- **Etch rate are generally not limited by the rate of arrival of etchant atoms, but by one of a complex set of reactions at the surface leading to formation of etch products.**

Principles of plasma discharges and materials processing, 2nd edition, by Michael A. Lieberman and Allan J. Lichtenberg

Ion-enhanced energy-driven etching

The discharge supplies both etchants and energetic ions to the surface





- **Low chemical etch rate of silicon substrate in XeF2 etchant gas.**
- **Tenfold increase in etch rate with XeF_2 + 500 V argon ions, simulating ion-enhanced plasma etching.**
- **Very low "etch rate" due to the physical sputtering of silicon by ion bombardment alone.**

Plasma etching, by Daniel L. Flamm and G. Kenneth Herb

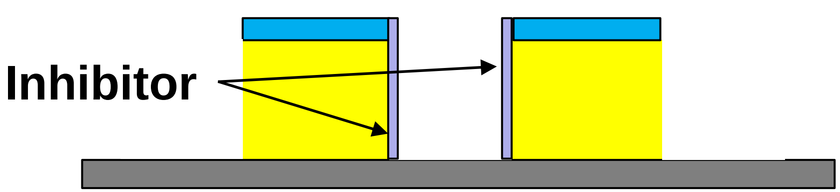
Ion-enhanced energy-driven etching has the characteristic of both sputtering and pure chemical etching

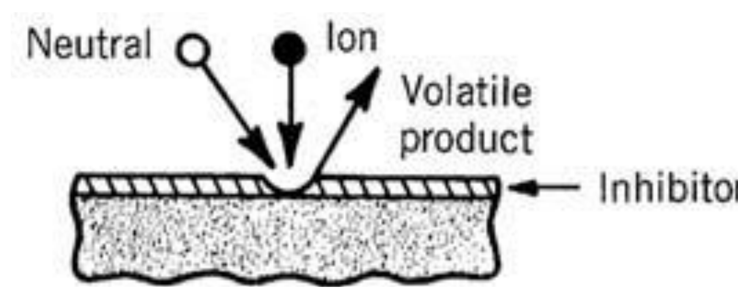
- **Chemical in nature but with a reaction rate determined by the energetic ion bombardment.**
- **Product must be volatile.**
- **Highly anisotropic.**

Ion-enhanced inhibitor etching

An inhibitor species is used

- **Inhibitor precursor molecules that absorb or deposit on the substrate form a protective layer or polymer film.**
- **Etchant is chosen to produce a high chemical etch rate of the substrate in the absence of either ion bombardment or the inhibitor.**
- **Ion bombardment flux prevents the inhibitor layer from forming or clears it as it forms.**
- **Where the ion flux does not fall, the inhibitor protects the surface (side wall) from the etchant.**
- **May not be as selective as pure chemical etching.**
- **A volatile etch product must be formed.**
- **Contamination of the substrate and final removal of the protective inhibitor film are other issues.**





Comparison of different processes

	Sputtering etching	Pure chemical etching	Ion energy-driven etching	Ion-enhanced Inhibitor etching
Selectivity	X	O	O	O
Anisotropic	O	X	O	O
Volatile product	X	O	O	O

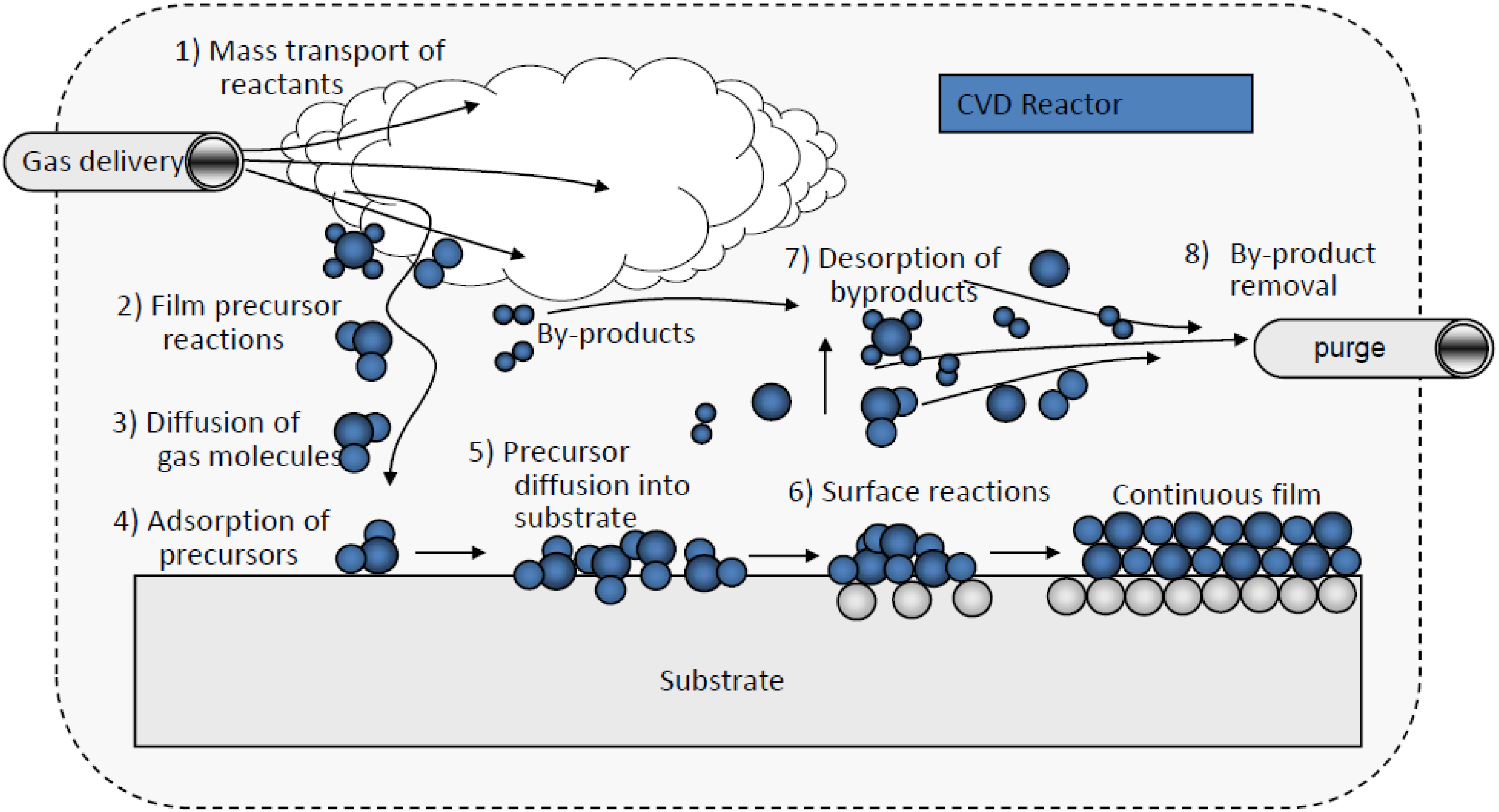
TABLE 15.1. Etch Chemistries Based on Product Volatility

Material	Etchant Atoms
Si, Ge	F, Cl, Br
SiO_2	F, F + C
Si_3N_4, silicides	F
Al	Cl, Br
Cu	Cl ($T > 210°C$)
C, organics	O
W, Ta, Ti, Mo, Nb	F, Cl
Au	Cl
Cr	Cl, Cl + O
GaAs	Cl, Br
InP	Cl, C + H

Deposition and implementation

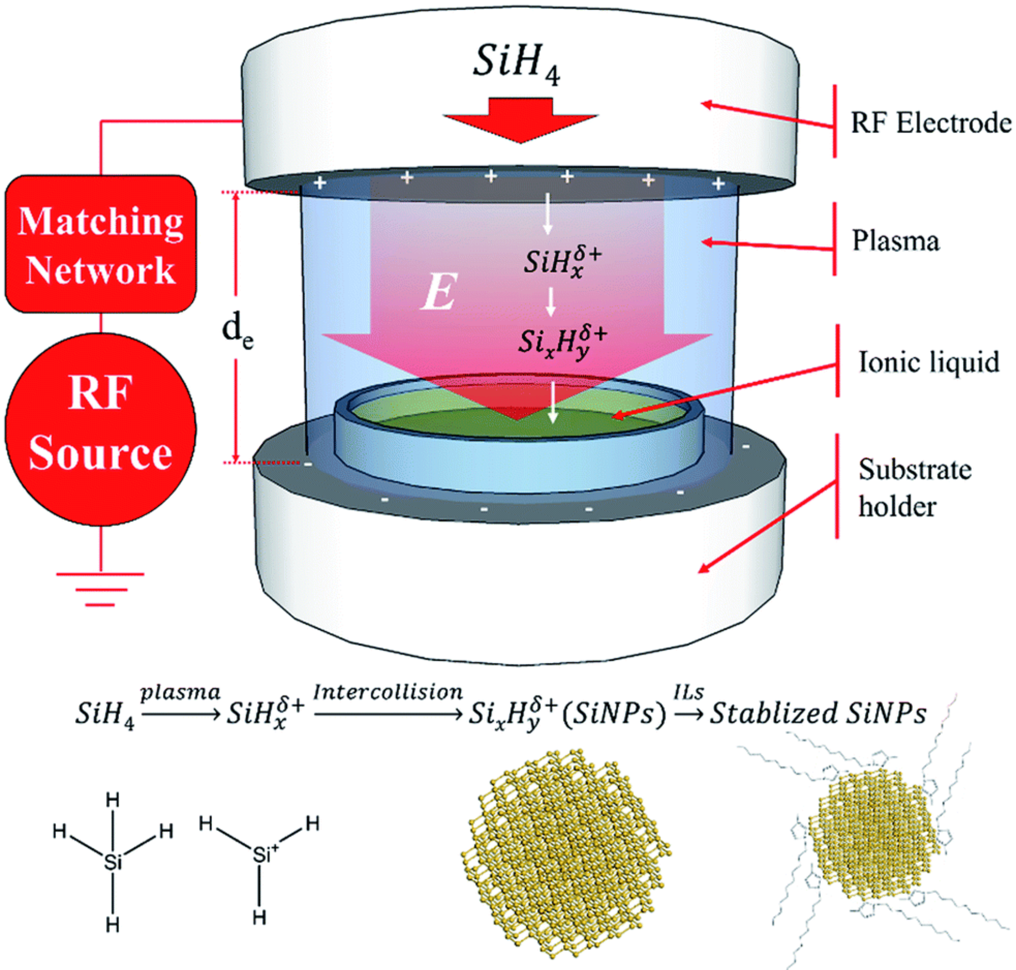
- **Plasma-assisted deposition, implantation, and surface modification are important material processes for producing films on surfaces and modifying their properties**
- **Example processes:**
  - **Plasma-enhanced chemical vapor deposition (PECVD)**
  - **Sputter deposition / physical vapor deposition (PVD)**
  - **Plasma-immersion ion implantation (PIII)**

Chemical Vapor Deposition (CVD)



http://www.ece.uah.edu/courses/material/EE410-Wms/

Plasma-enhanced chemical vapor deposition (PECVD)



Films can be deposited in low temperatures using plasma deposition

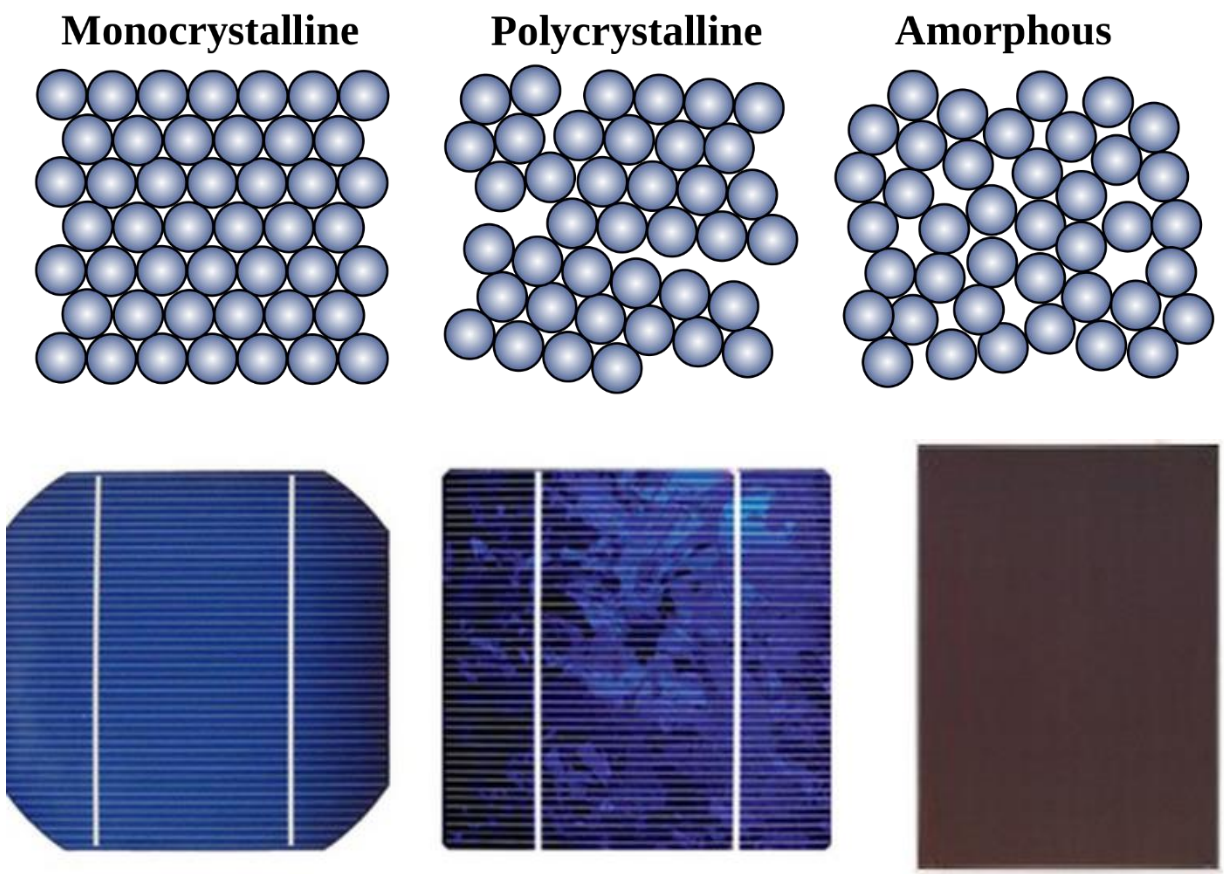
- **Device structures are sensitive to temperature, high-temperature deposition processes cannot be used in many cases.**
- **High-temperature films can be deposited at low temperatures.**
- **Unique films not found in nature can be deposited, e.g., diamond.**

Working temperature is determined by the desired film properties

- CVD – consists of a thermally activated set of gas-phase and surface reactions that produce a solid product at a surface.
- PECVD – gas-phase and the surface reactions are controlled or modified by the plasma properties.
- Te~2-5 eV in PECVD is much greater than the substrate temperature, the temperature in PECVD is much less that CVD.
- Deposition rates are usually not very sensitive to the substrate temperature T.
- Film properties such as composition, stress, and morphology, are functions of T.
- Low-temperature PECVD films are amorphous, not crystalline, which can more easily be achieved with chemical vapor deposition (CVD).

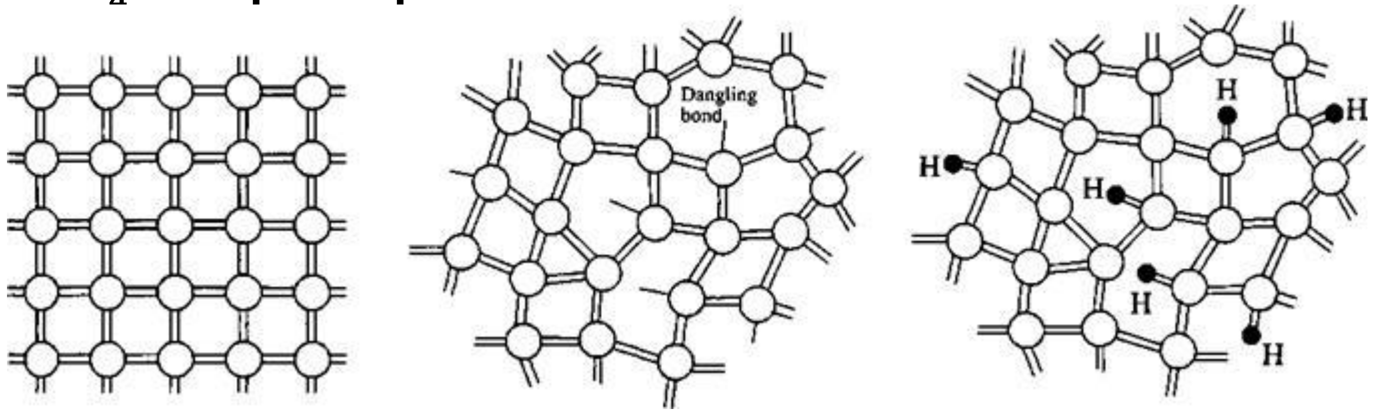
Example of using PECVD – amorphous silicon

- **Amorphous silicon thin films are used in solar cells**



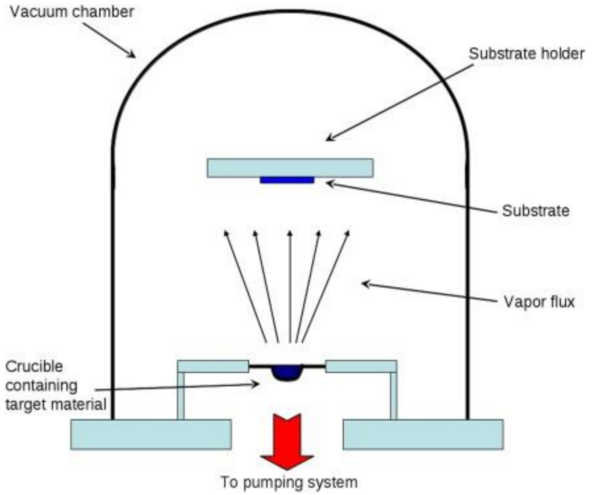
Example of using PECVD – amorphous silicon

- H is required so that SiH_4 is used
  - For the material to be semiconducting.
  - Terminate the dangling bonds.
  - The dangling bonds are created by ion bombardment (SiH_3^+) which also removes hydrogen from the surface.
  - SiH_3 and SiH_2 radicals are important precursors for film growth while SiH_4 also participates in surface reactions.

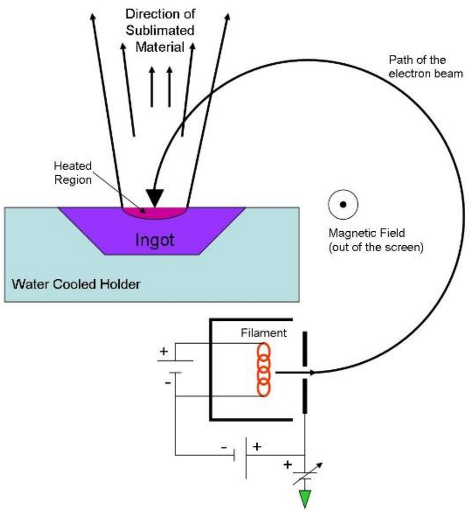


Physical vapor deposition can be achieved by heating the deposited material

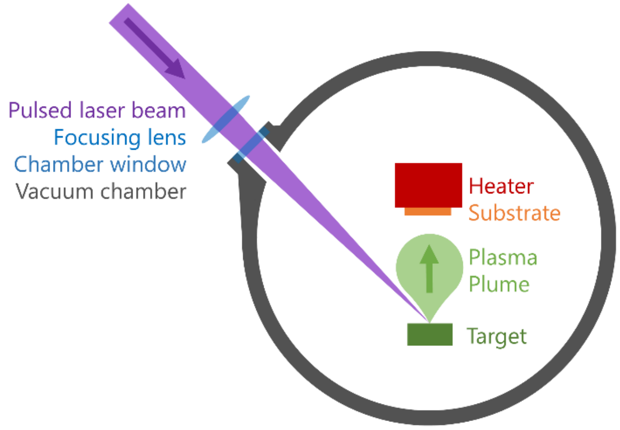
- **Thermal evaporator**



- **Electron-beam evaporator**



- **Pulsed-laser deposition**



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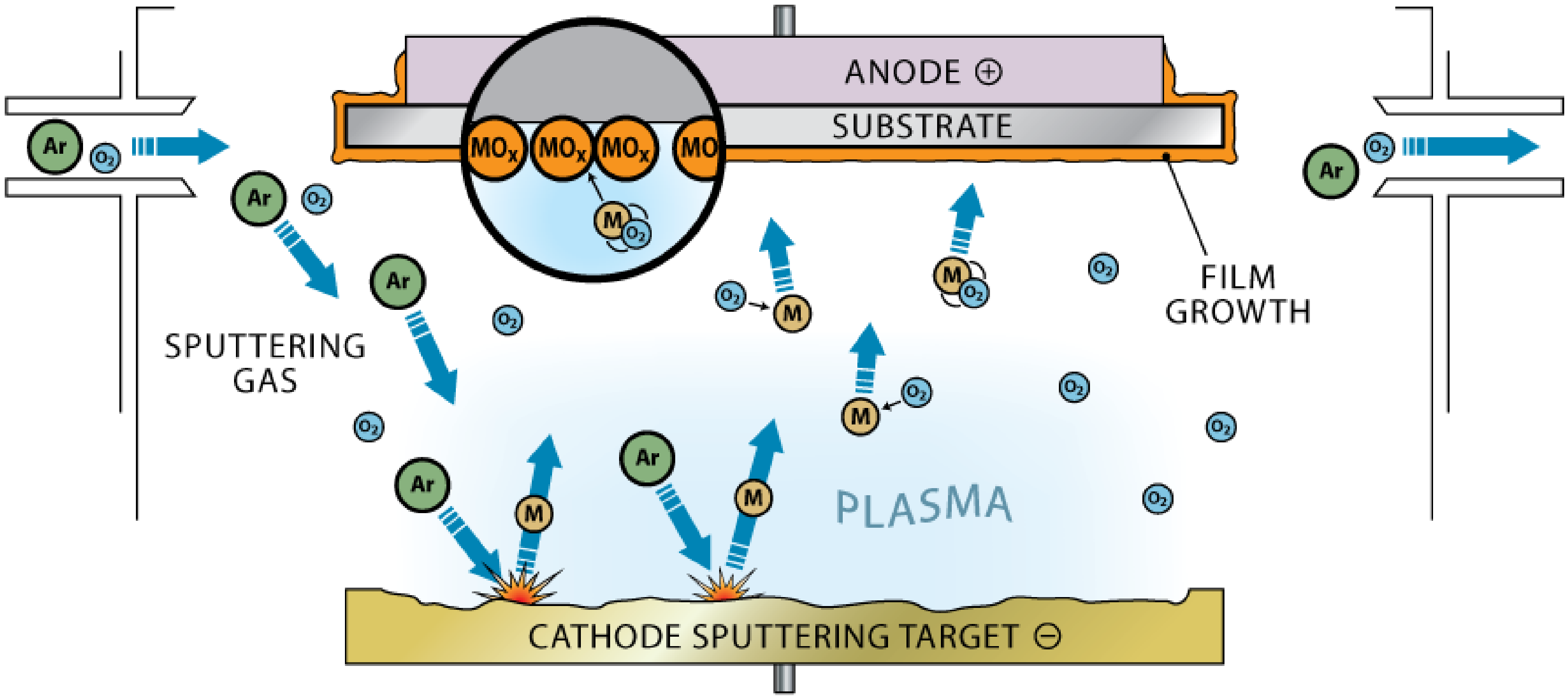
https://en.wikipedia.org/wiki/Pulsed_laser_deposition
Engineered biomimicry by A. Lakhtakia and R. J. Martin-Palma
https://en.wikipedia.org/wiki/Electron-beam_physical_vapor_deposition

Sputtering deposition

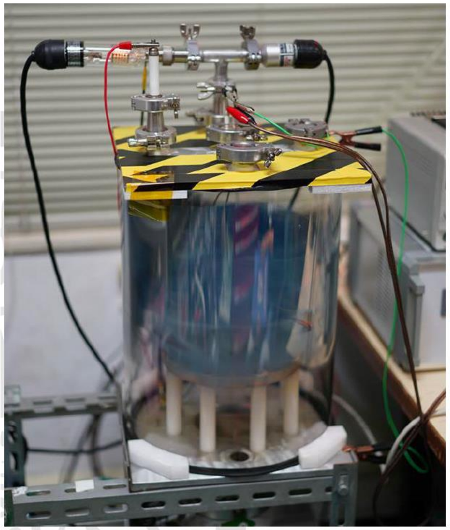


http://lnf-wiki.eecs.umich.edu/wiki/Sputter_deposition

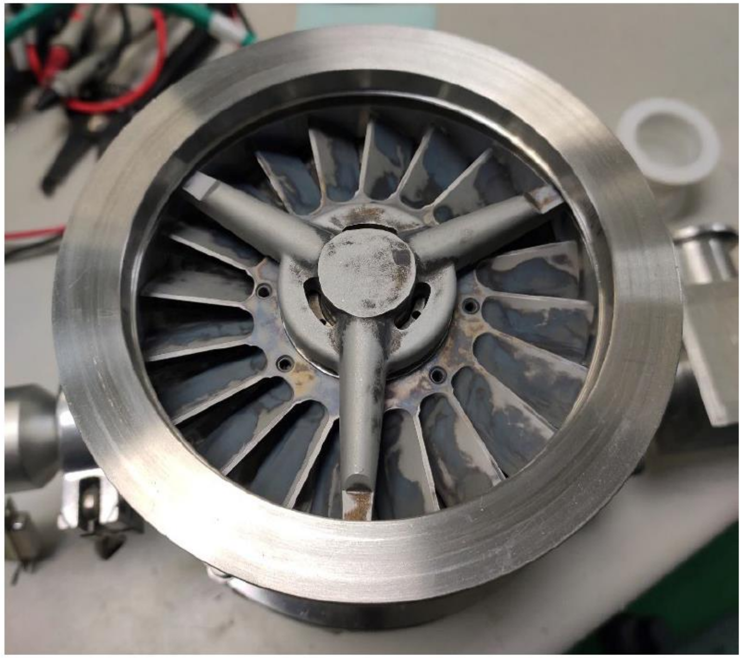
The chamber becomes very dirty after the deposition process

- **Before**

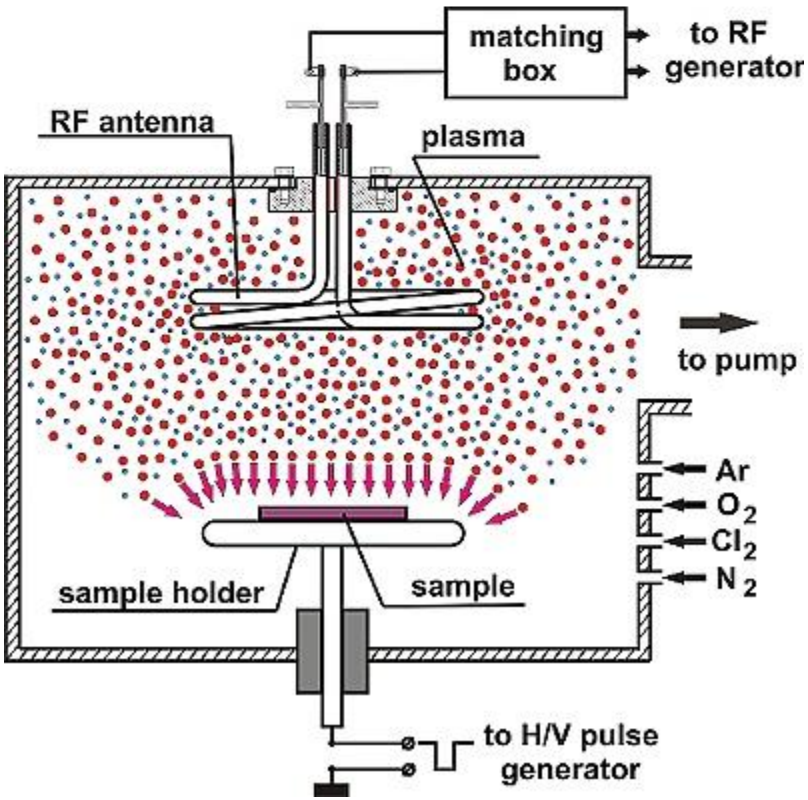
- **After**

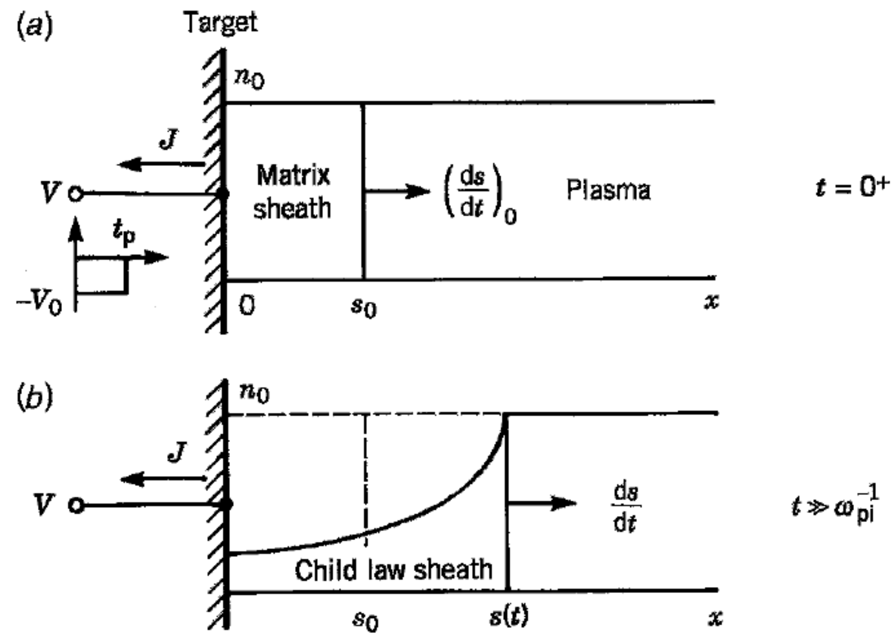


- **The turbomolecular pump is also very dirty after the process.**



Plasma-immersion ion implantation (PIII)

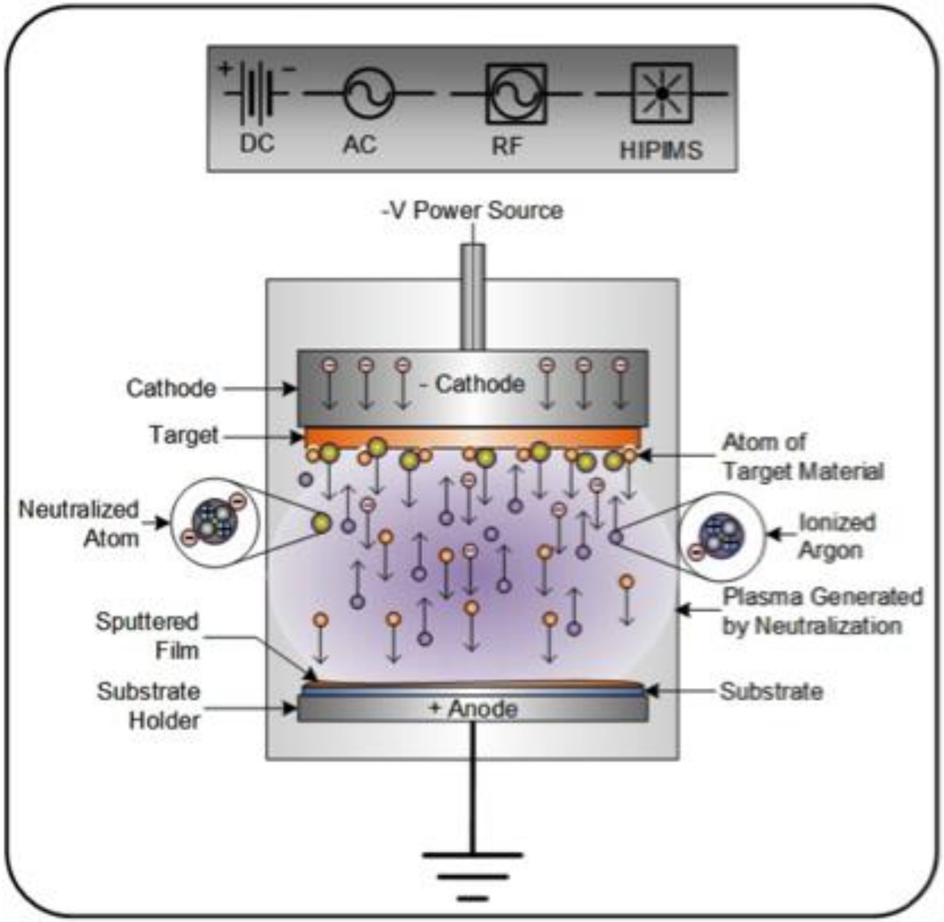


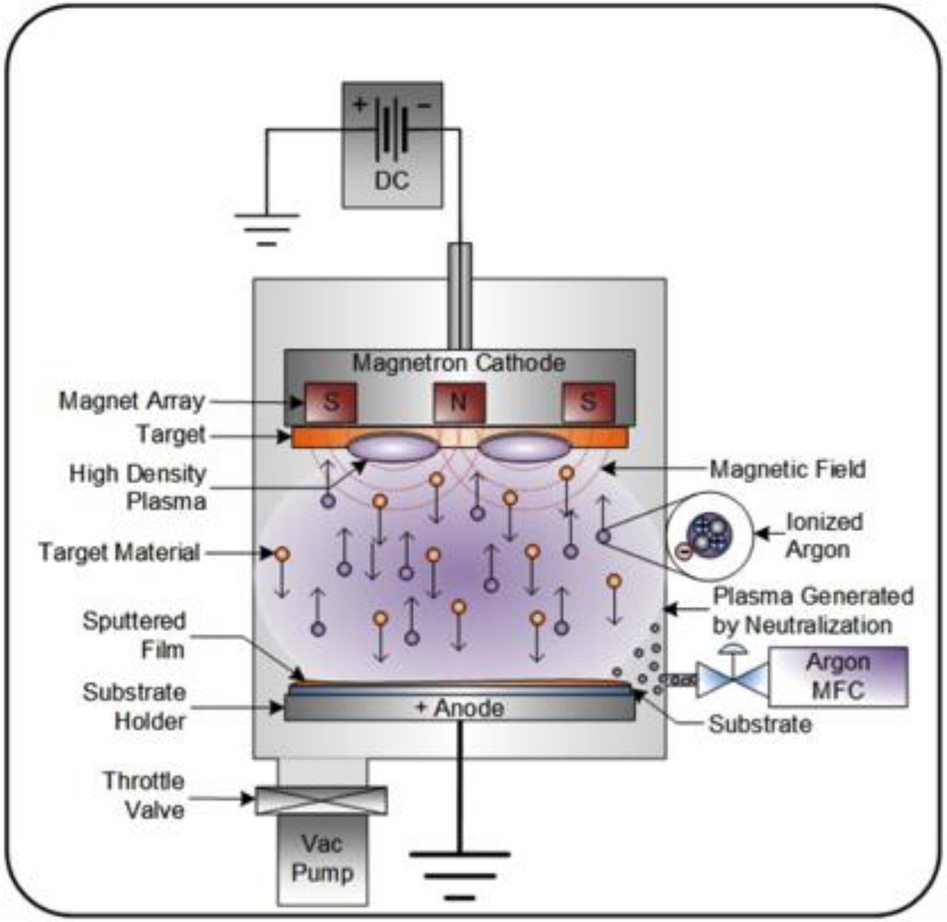


- **Silicon doping – ions such as B, P, As are implanted**
- **Surface hardening of metals – N, C are implanted**

https://www.hzdr.de/db/Cms?pOid=10890&pNid=306

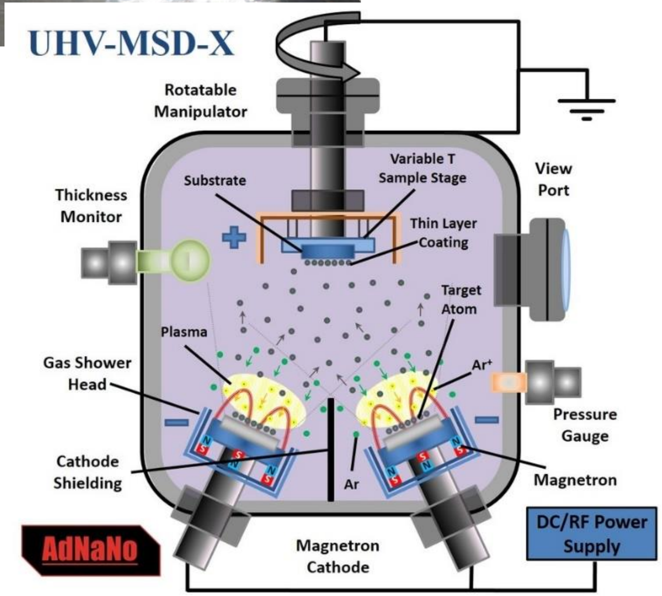
Magnetron sputtering provides higher deposition rates than conventional sputtering





http://www.semicore.com/what-is-sputtering

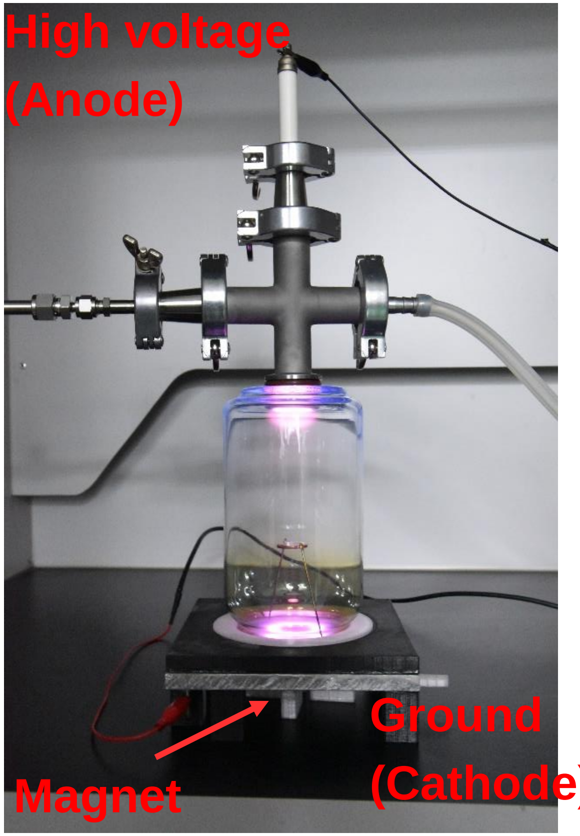
Examples of magnetron sputtering deposition



https://angstromengineering.com/tech/magnetron-sputtering/pulsed-dc/
https://dynavac.com/wp-content/uploads/2017/09/Confocal-Sputtering-2.jpg
https://www.adnano-tek.com/magnetron-sputtering-deposition-msd.html

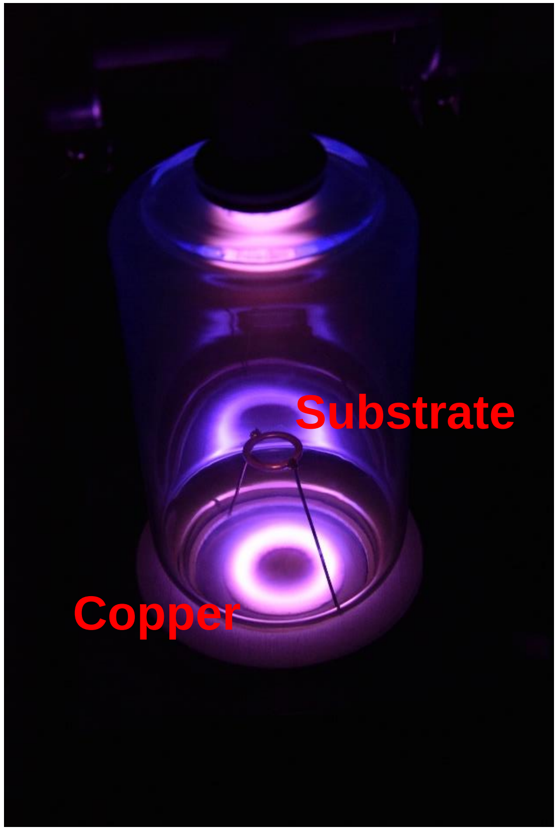
Demonstration experiments – magnetron sputtering

- System

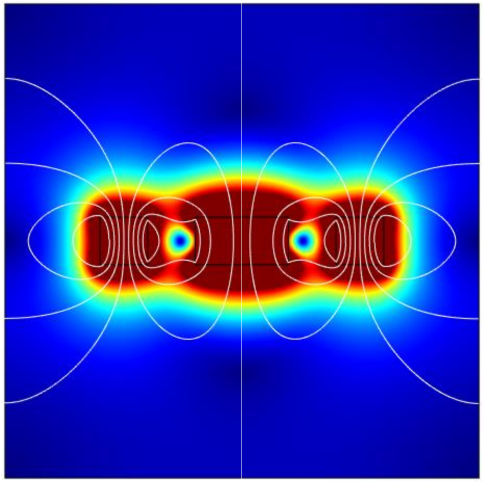


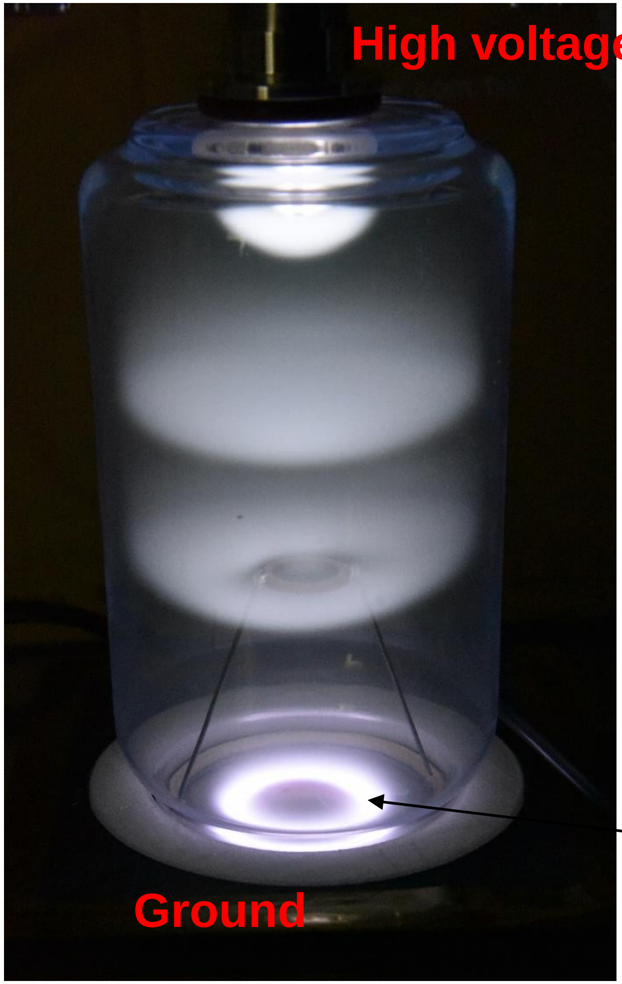
- Without magnet

- With magnet

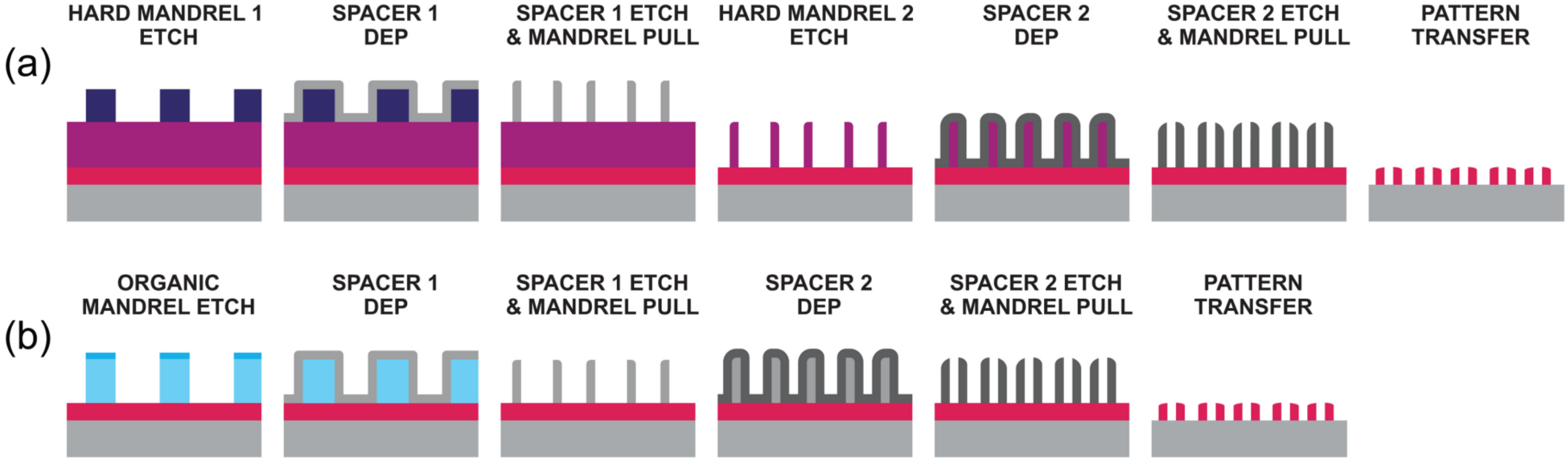


A bright ring occurs when the magnet is inserted into the system





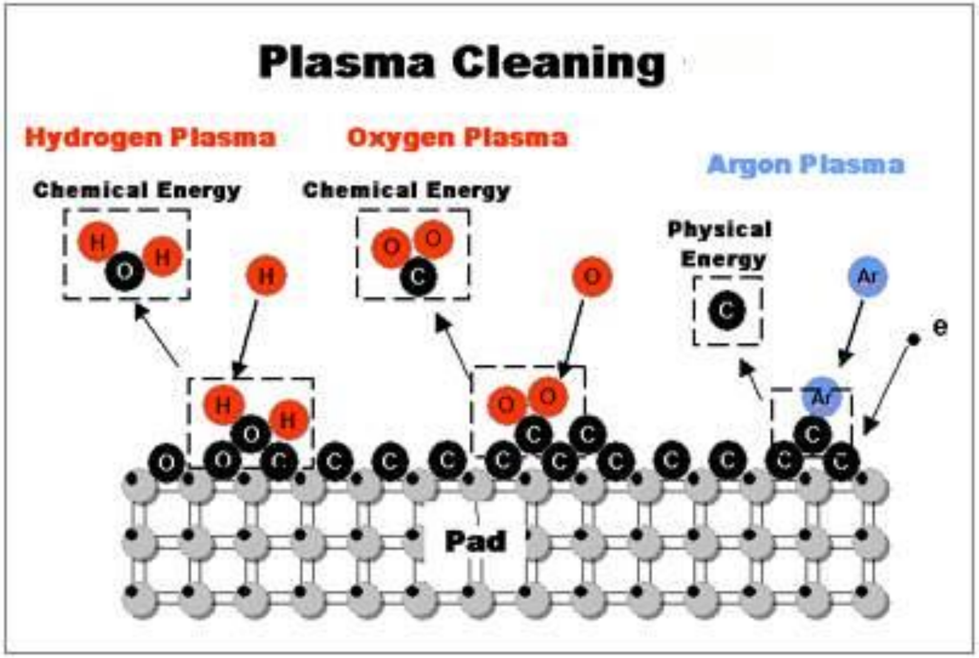
self-aligned quadruple patterning



H. C. M. Knoops *et al.*, J. Vac. Sci. Technol. **A 37**, 030902 (2019)

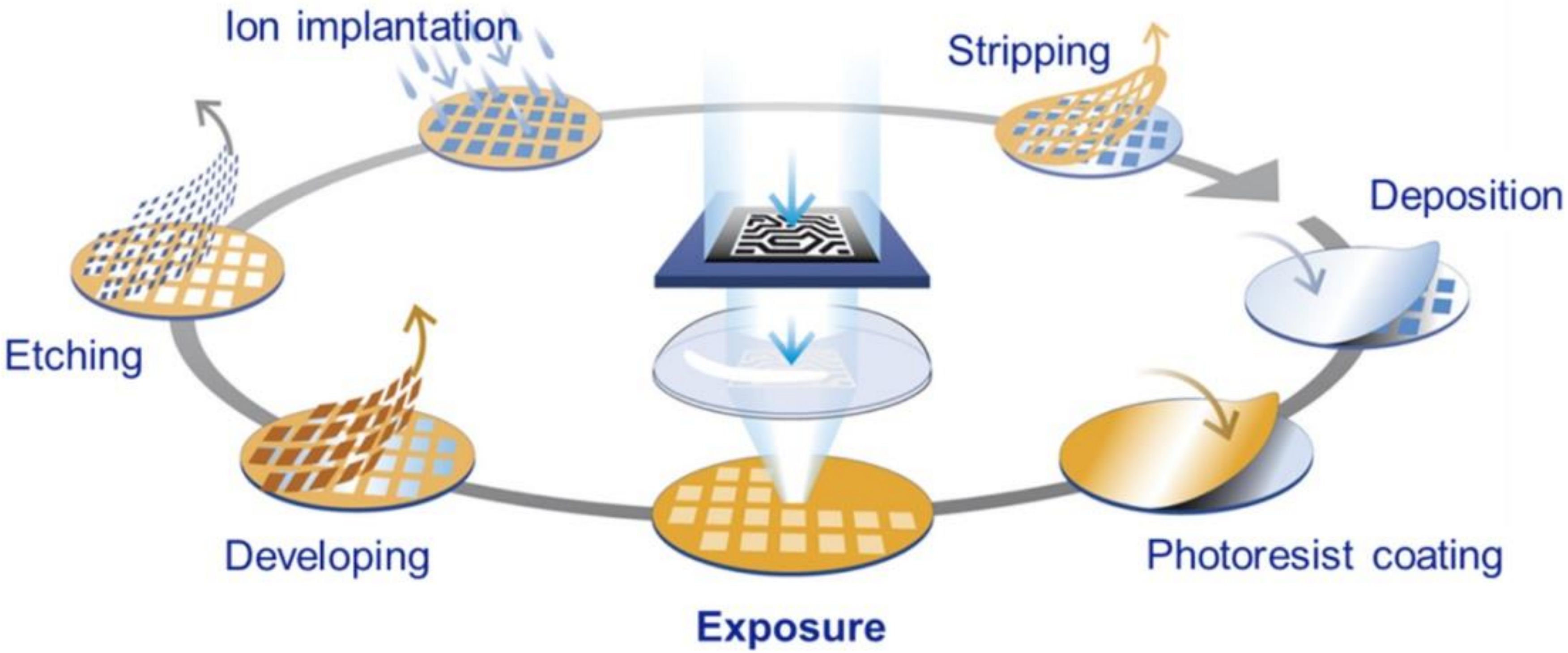
Plasma can be used for cleaning surface

- **Cleaning mechanisms:**
  - **Chemical reactions by free radicals**
  - **Physical sputtering by high energy ions**



搵鼎奈米科技股份有限公司
https://www.ecplaza.net/products/plasma-cleaning_111807

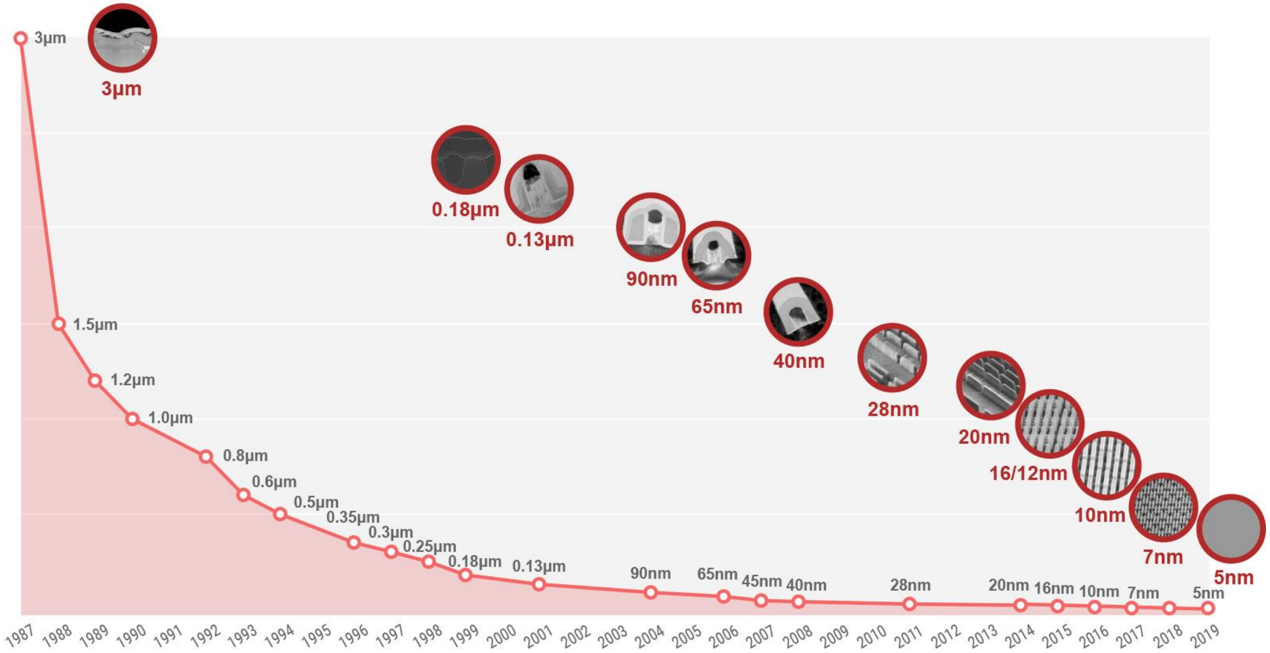
A semiconductor device is fabricated by many repetitive production process



Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

Ultraviolet lithography (EUVL) is one of the key technologies in semiconductor manufacturing nowadays

- **The process technology of Taiwan Semiconductor Manufacturing Company Limited (TSMC):**

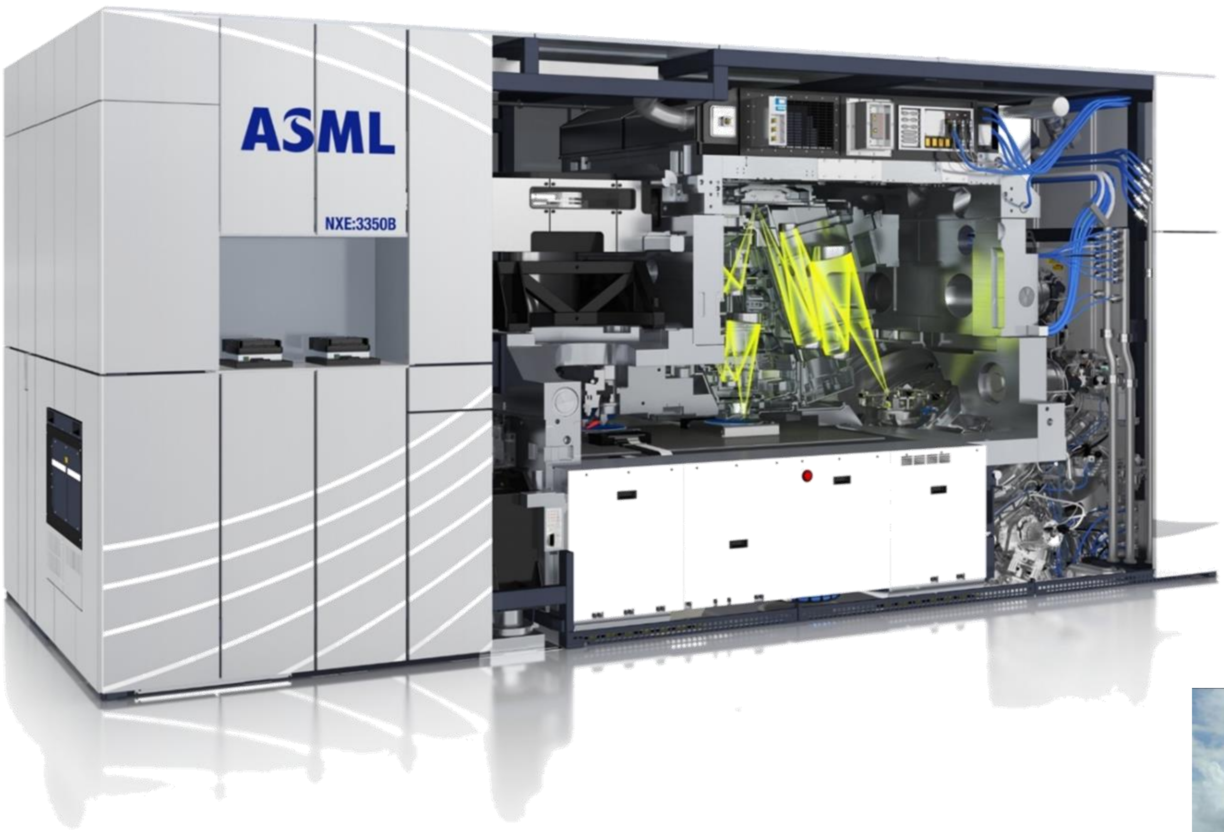


- **Optical diffraction needs to be taken into account.**
- **Shorter wavelength is preferred.**

- **Light source with a center wavelength of 13.5 nm is used.**

https://www.tsmc.com/chinese/dedicatedFoundry/technology/logic.htm

EUV lithography becomes important for semiconductor industry



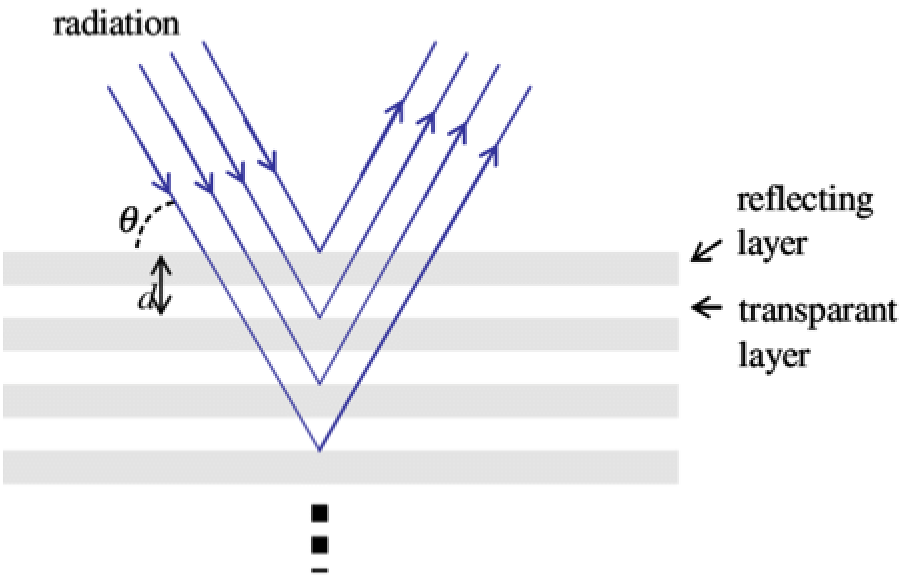
- **0.15 billion USD for each EUV light source.**

https://www.youtube.com/watch?v=NHSR6AHNiDs

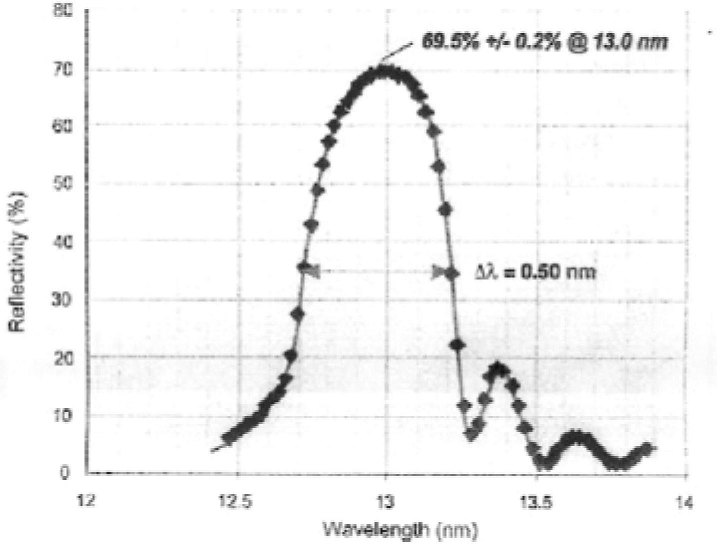
http://finance.technews.tw/2019/01/25/euv-asml-2018/

EUV light can only be reflected using multilayer mirrors

a)

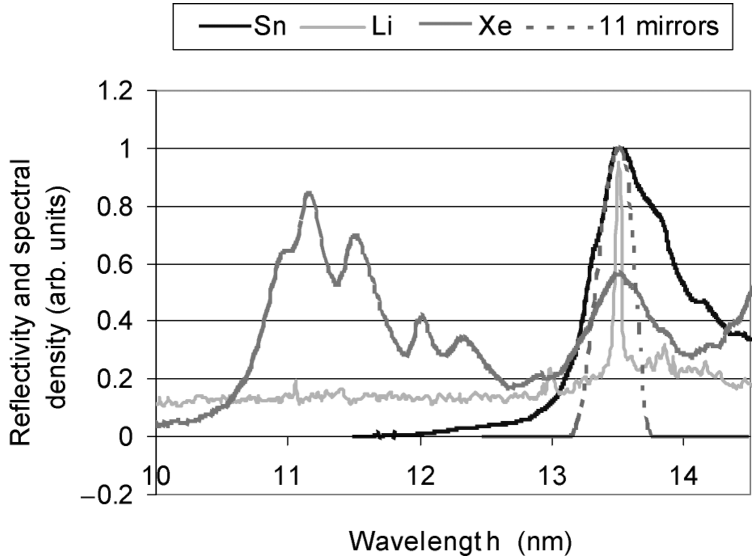


b)



Mo/Si multilayer coating technology for EUVL, coating uniformity and time stability; E. Louis et al.; SPIE 4146-06, Soft X-ray and EUV Imaging Systems, San Diego, 2000.

13.5-nm EUV light is picked for EUV lithography

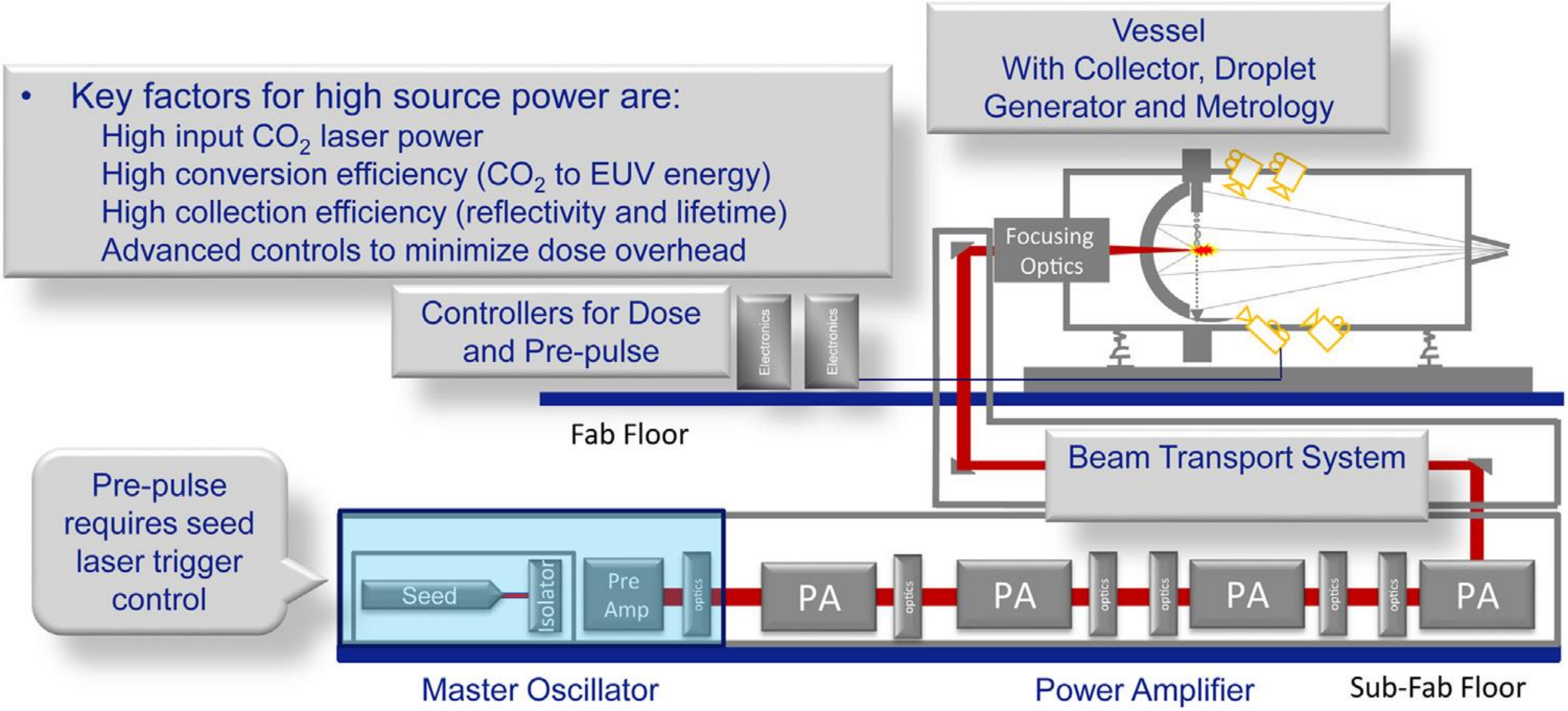


- $\lambda = 13.5\ \mathrm{nm} \pm 1\%$ **is required.**
- **At T=35-40 eV (~450,000 K), in-band emission occurs.**
- **Xenon:**
  - $4p^6 4d^8 \rightarrow 4p^6 4d^7 5p$ **from single ion stage** Xe^{10+}
  - **UTA @ 11 nm**
- **Tin:**
  - $4p^6 4d^N \rightarrow 4p^5 4d^{N+1} + 4p^6 4d^{N-1} 4f$ $(1 \leq N \leq 6)$ **in ions ranging from** Sn^{8+} **to** Sn^{12+}
  - **UTA @ 13.5 nm**
- UTA: unresolved transition array

V. Bakshi, EUV sources for lithography

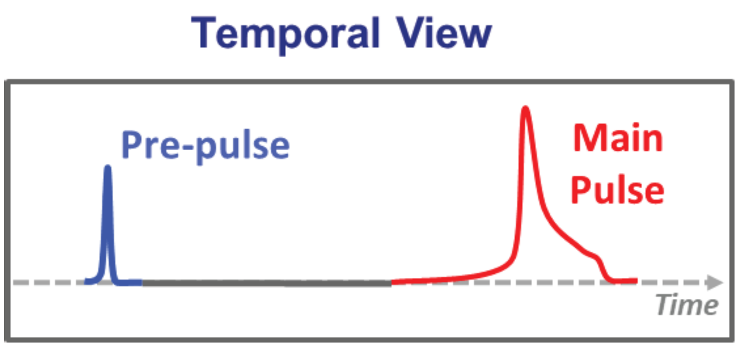
R. S. Abhari, etc., J. Micro/Nanolithography, MEMS, and MOEMS, 11, 021114 (2012)

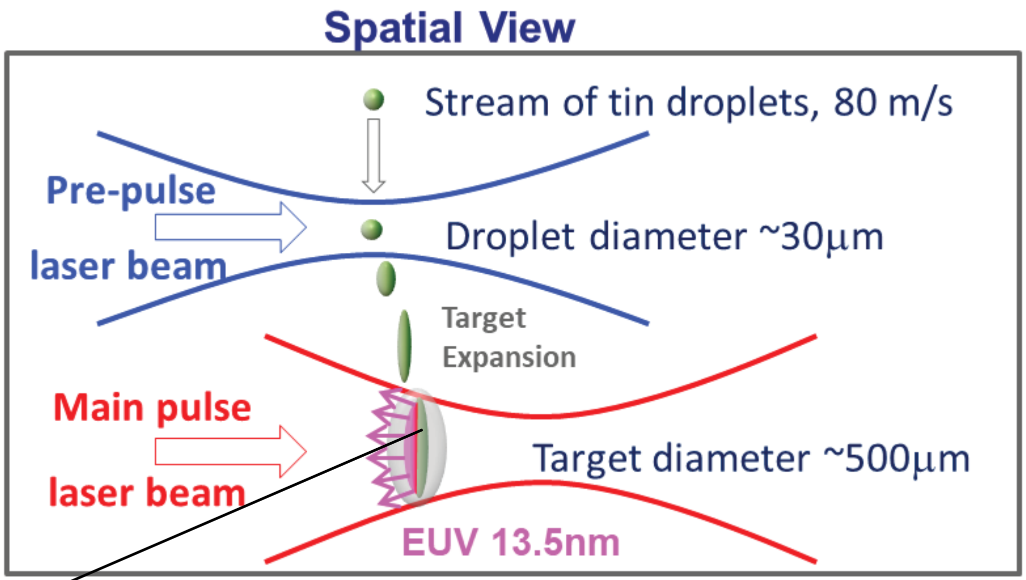
EUV light is generated from laser-produced plasma (LPP)

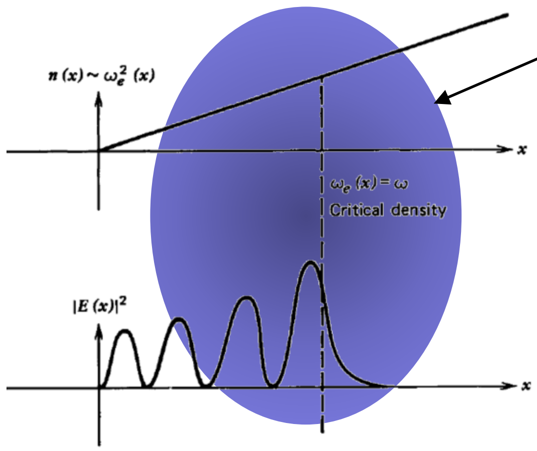


D.-K. Yang, etc., *Chip*, **1**, 100019 (2022)

Two laser pulses are used to heat the plasma

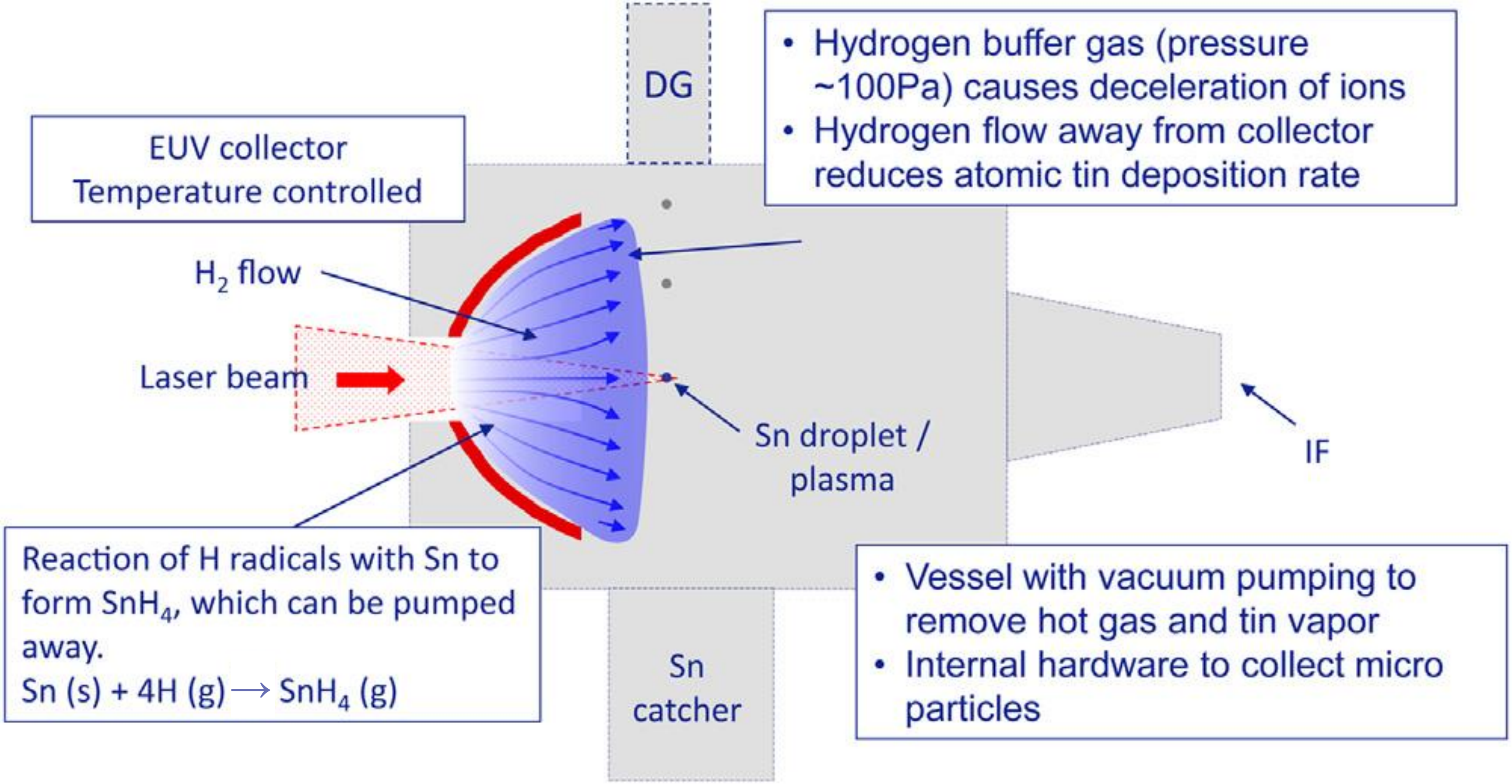






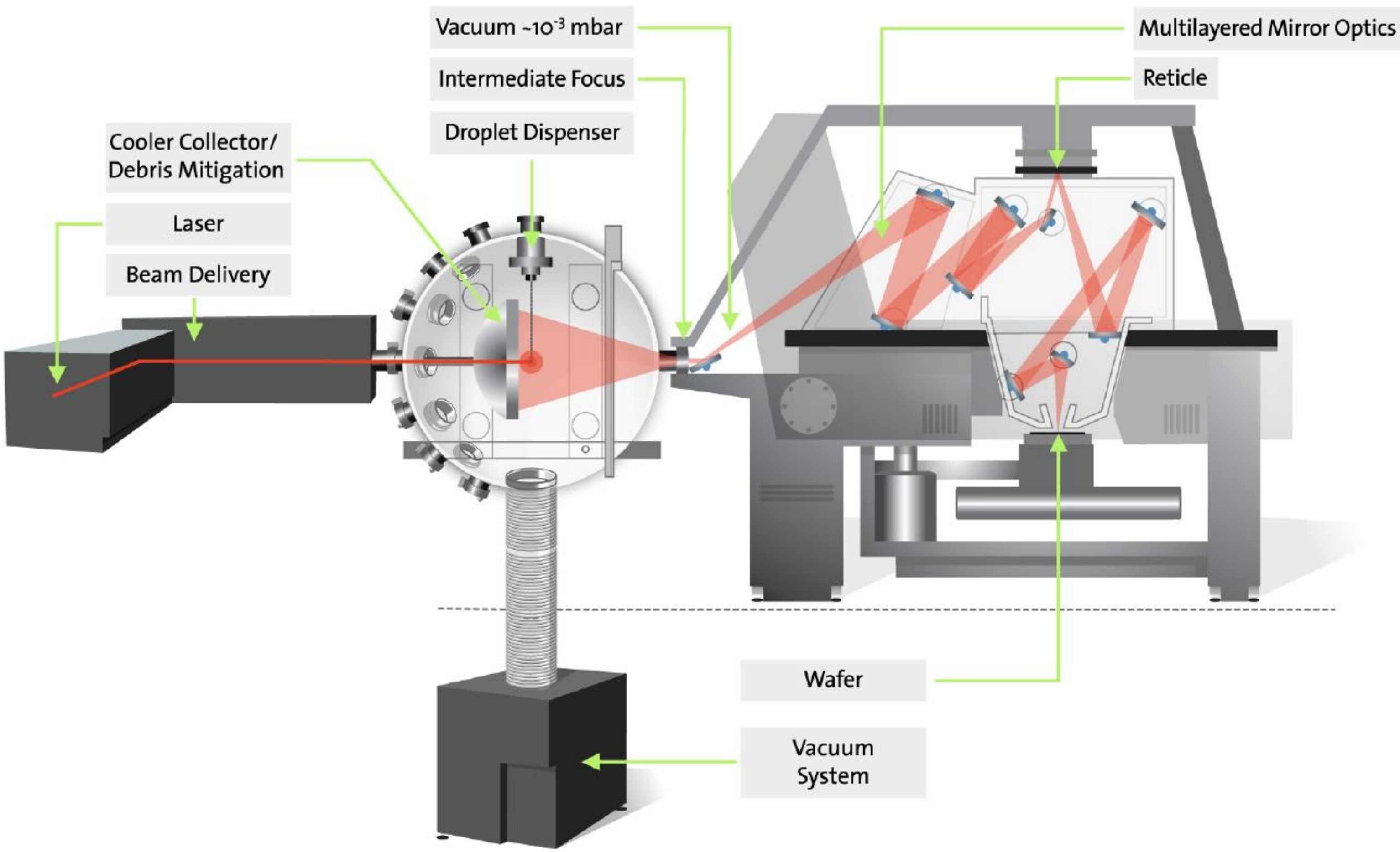
I. Fomenkov, etc., *Synch. Rad. News*, **32**, 3 (2019)

Hydrogen buffer gas with a pressure of ~100 Pa is used to protect the collector mirror



D.-K. Yang, etc., *Chip*, **1**, 100019 (2022)

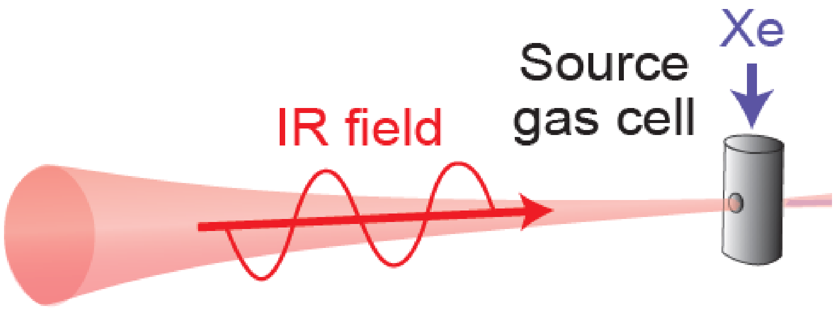
Laser-produced plasma (LPP) is used in the EUV lithography

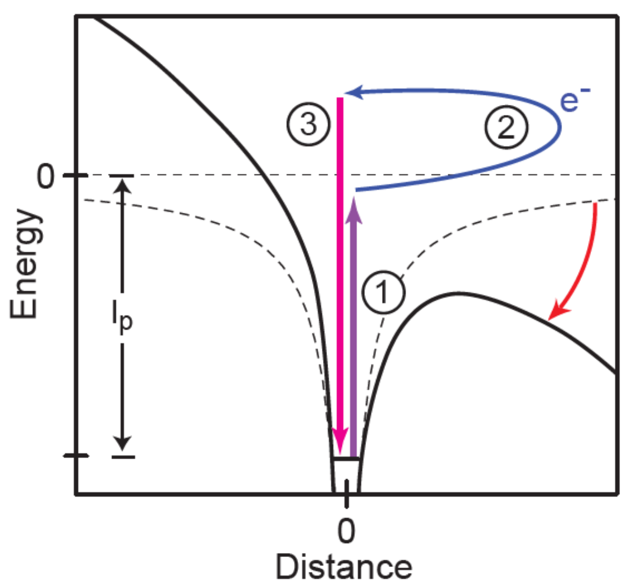


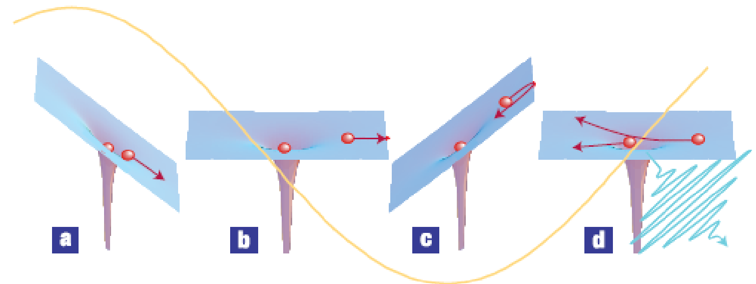
R. S. Abhari, etc., J. Micro/Nanolithography, MEMS, and MOEMS, 11, 021114 (2012)

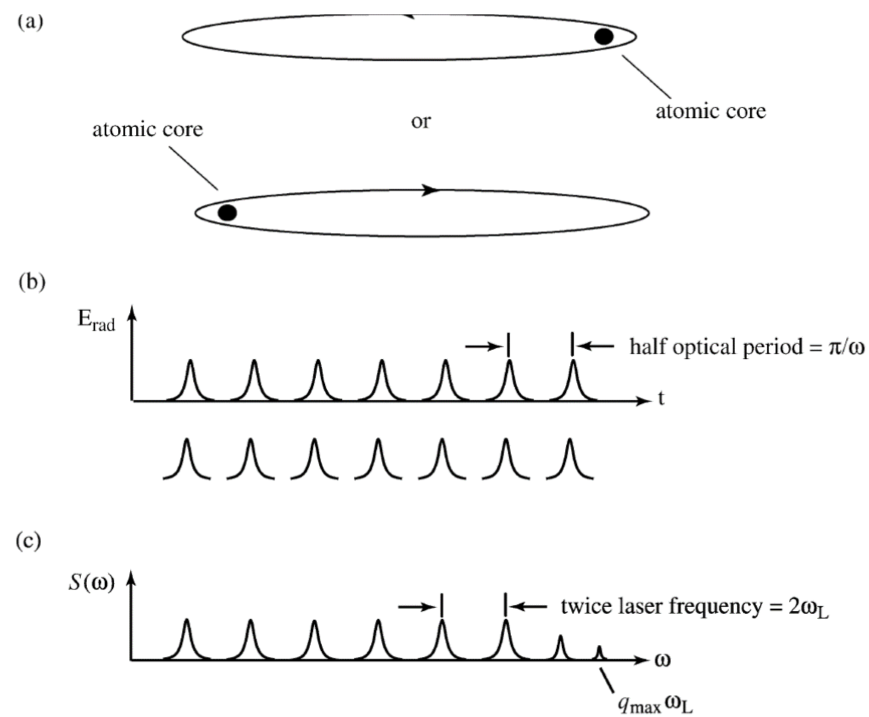
High harmonic generation from high-power laser

- **For I < 10^{18} w/cm^2**



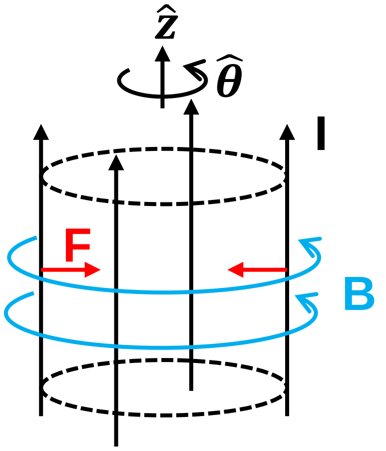






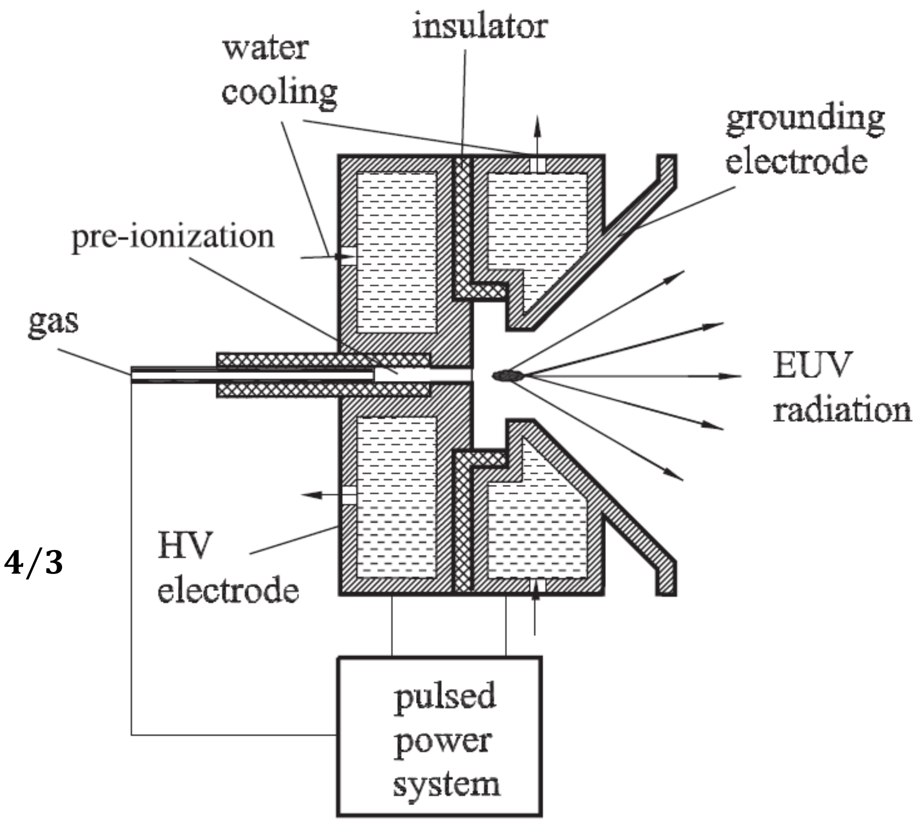
- M. Krüger, etc., Appl. Sci. 9, 378 (2019)
- Nonlinear Optics 3rd edition , by Robert W. Boyd
- P. B. Corkum and F. Krausz, Nature Phys., 3, 381 (2007)

EUV light can be generated using discharged-produced plasma



- **Adiabatic compression:**

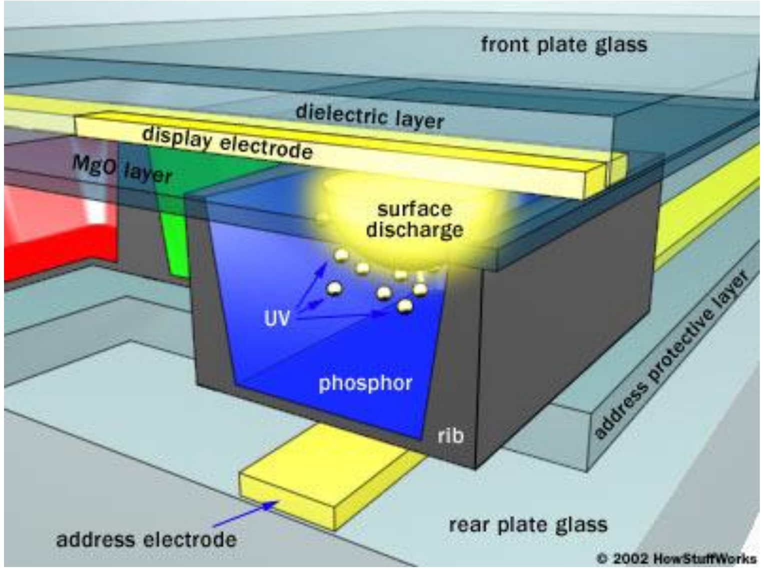
$$TV^{\gamma-1} = \text{const} \quad T_f = T_o\left(\frac{r_o}{r_f}\right)^{4/3}$$



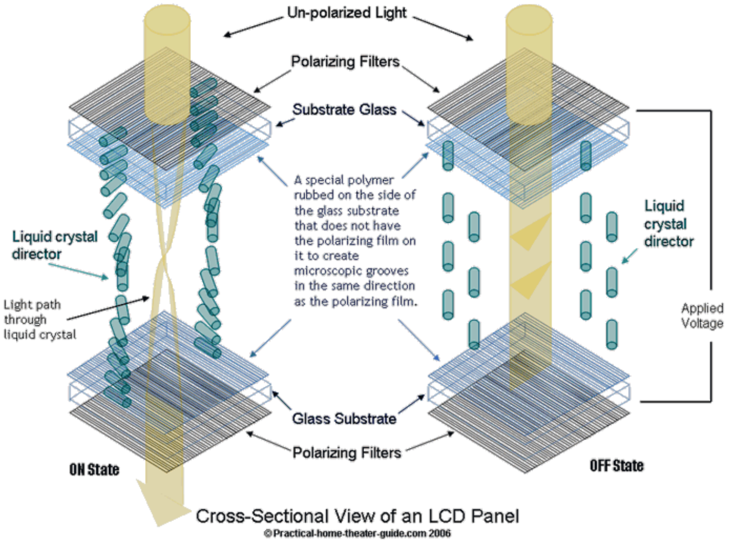
- JPDAP_37_p3254_2004_EUV sources using Xe and Sn discharge plasmas

Light source and display systems

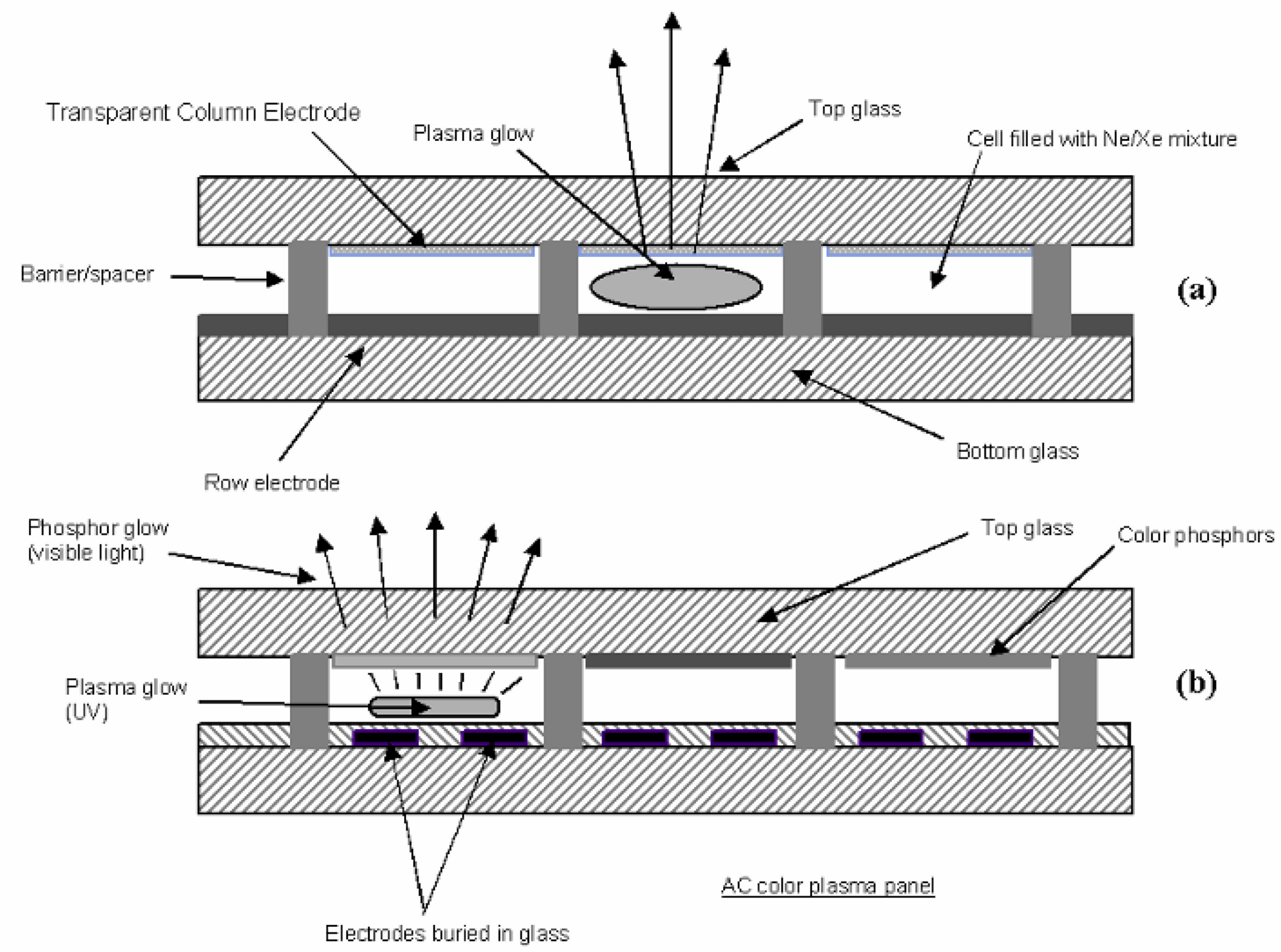
Plasma display panel (PDP)



Liquid crystal display (LCD)

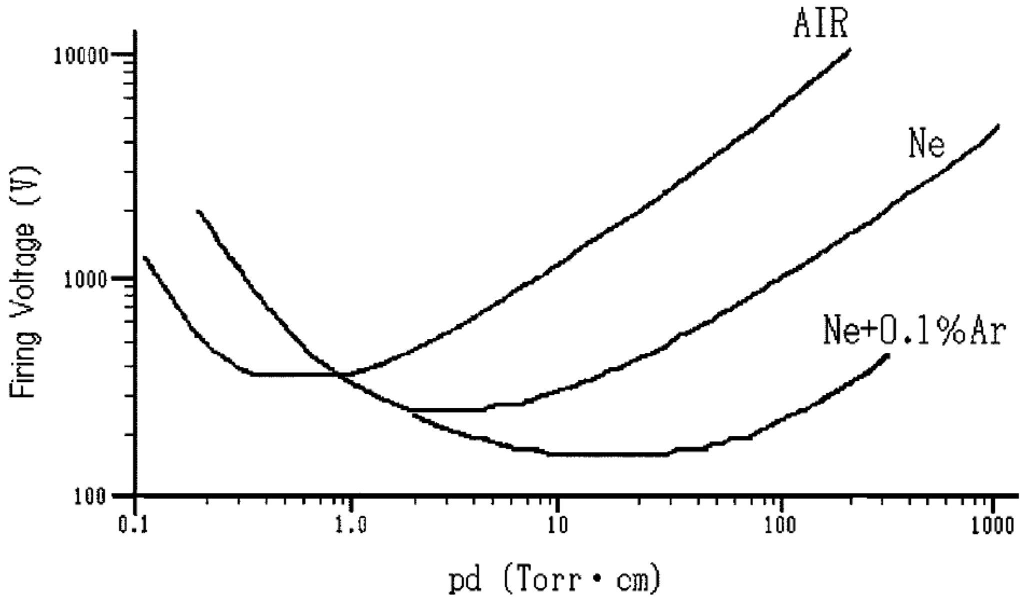


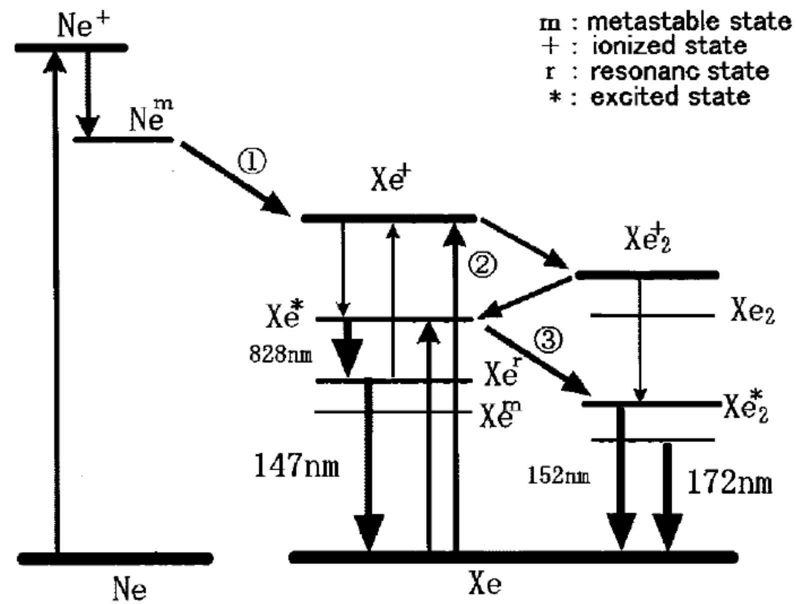
Color PDPs had short display lifetime due to the degradation of color phosphors caused by ion sputtering



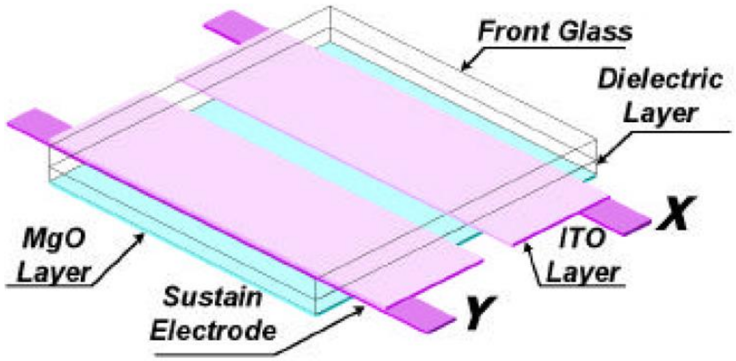
http://what-when-how.com/display-interfaces/display-technologies-and-applications-display-interfaces-part-3/

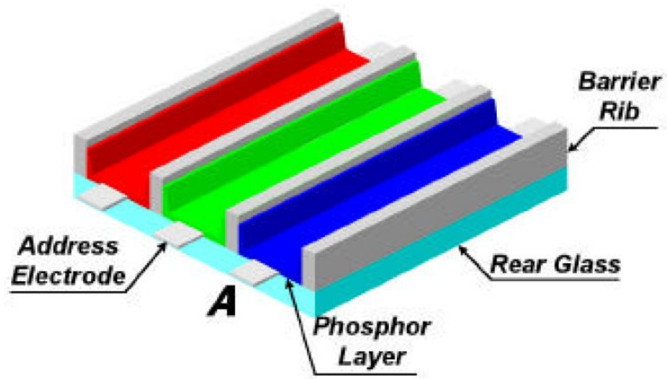
A lower breakdown voltages can be obtained with very small amounts of added gas

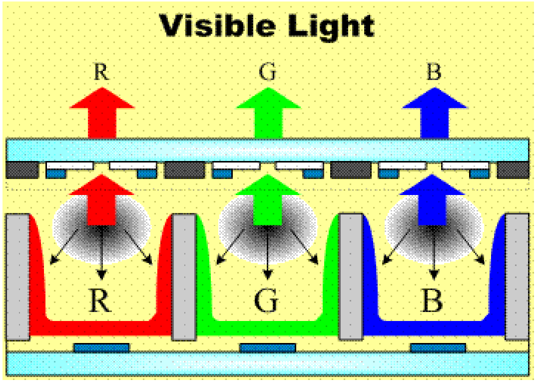




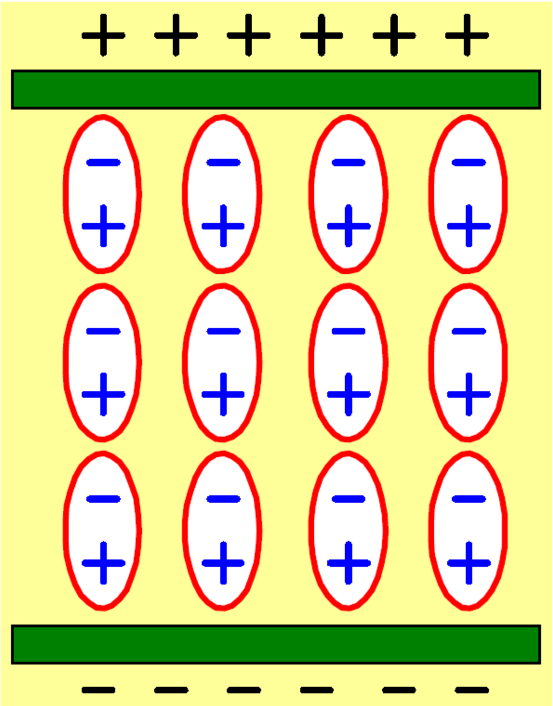
Reflective phosphor geometry is used in most of today's plasma TVs

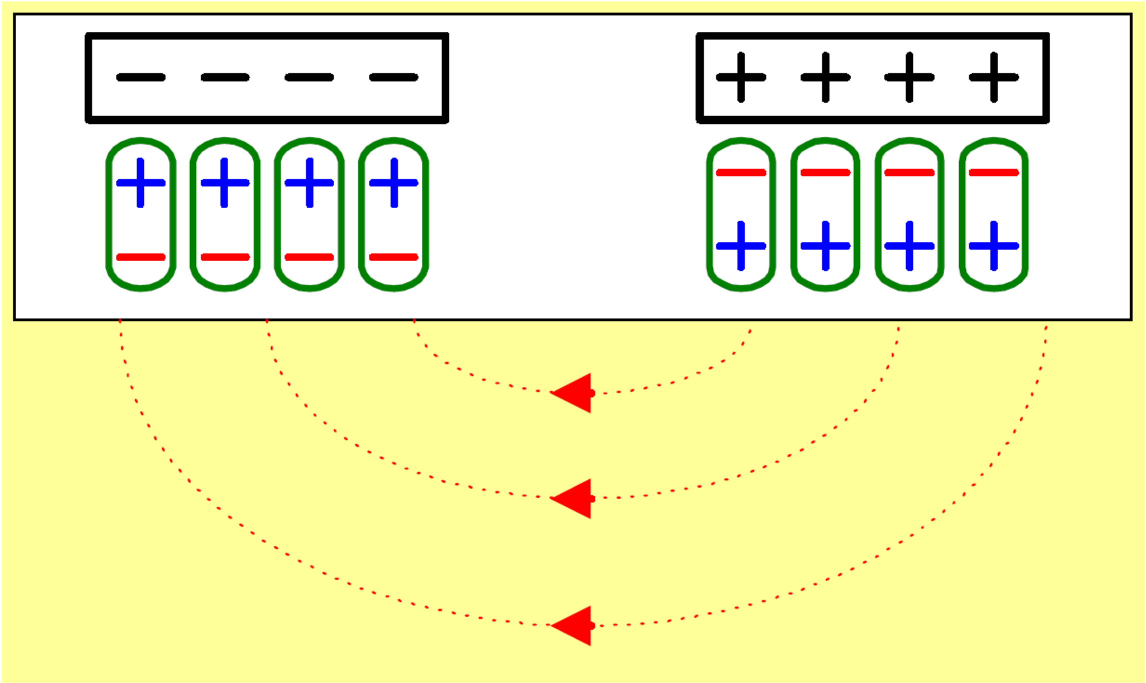






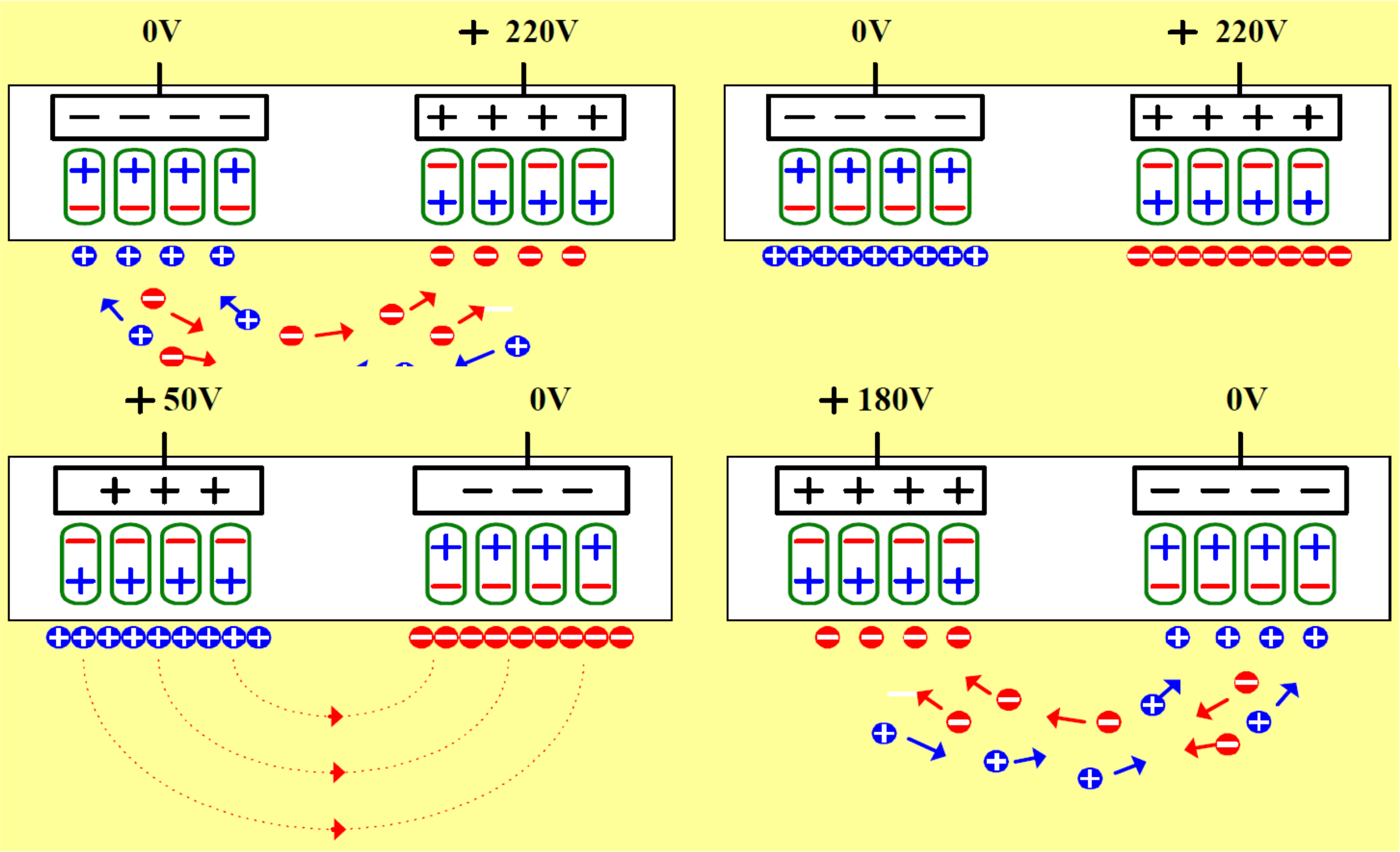
The foundation of AC discharge





Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

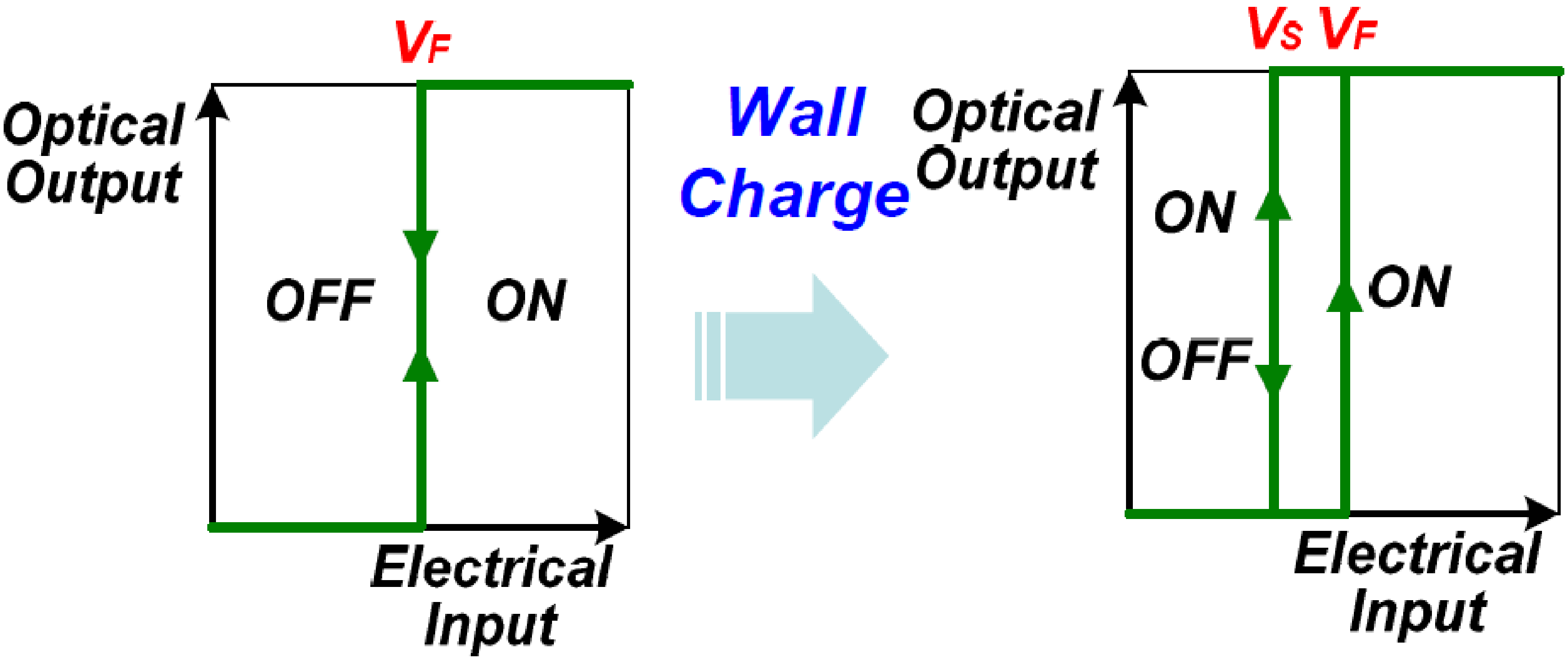
The plasma can be sustained using ac discharged



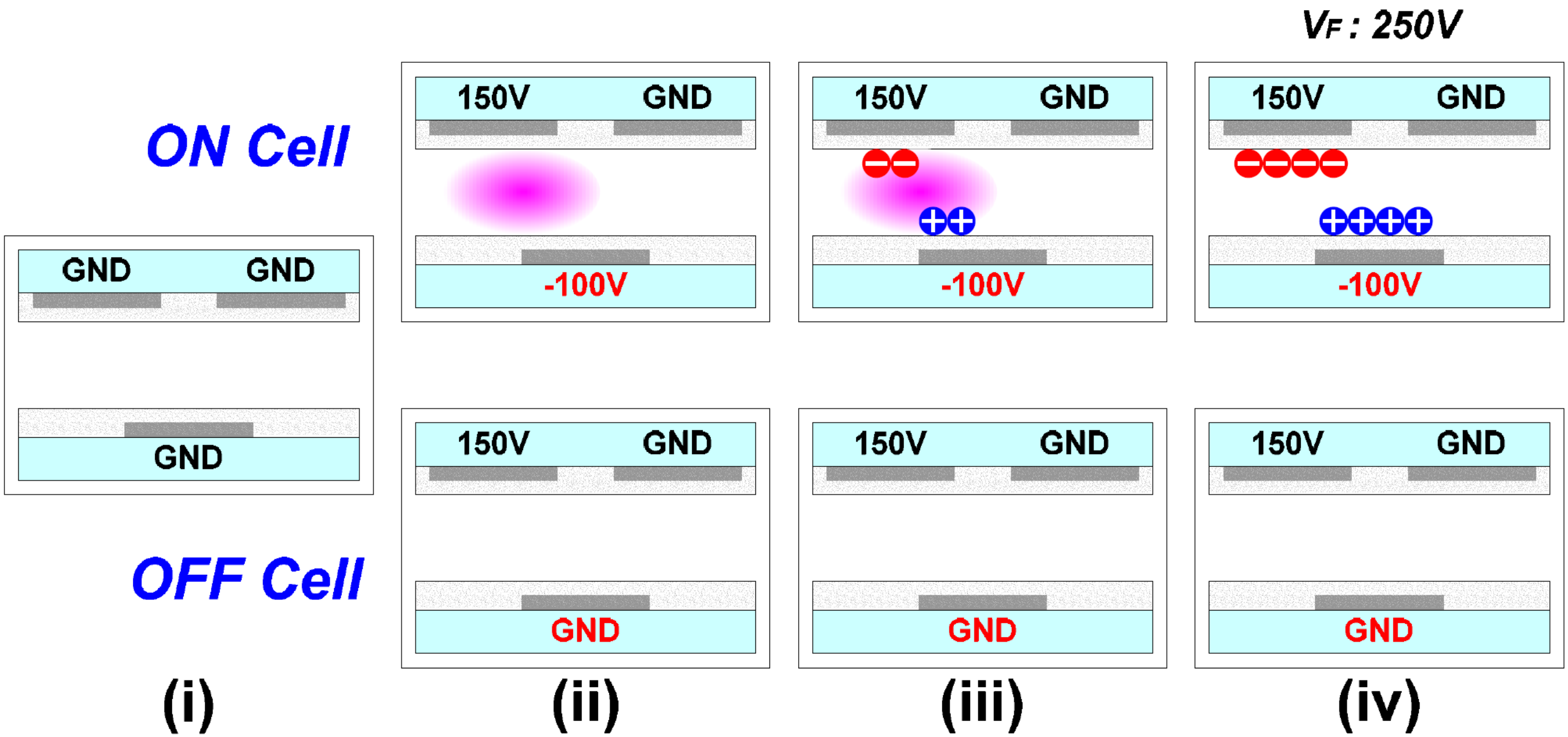
- **Wall discharge reduced the required discharge voltage**

Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

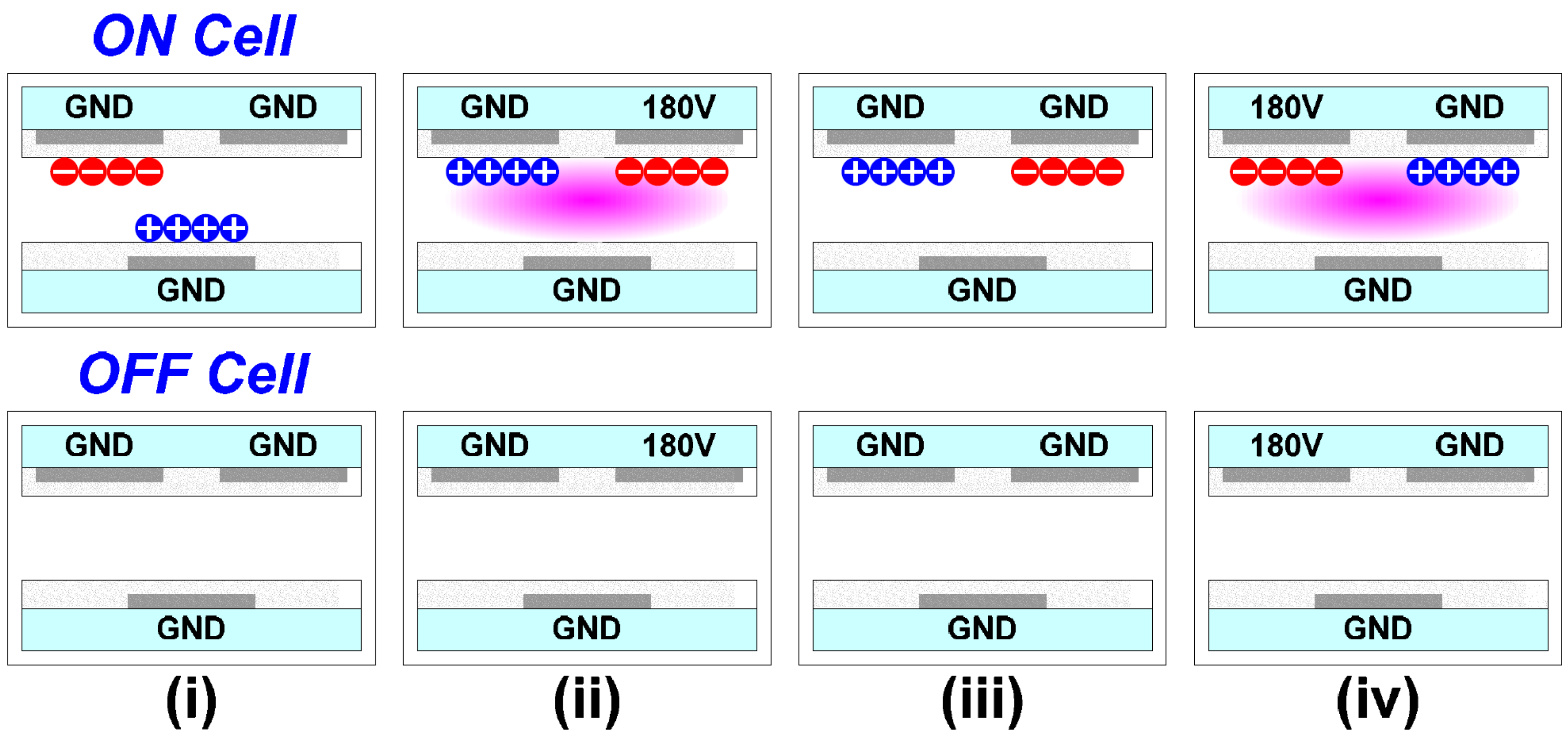
Wall discharge reduced the required discharge voltage



ON/OFF State Selection



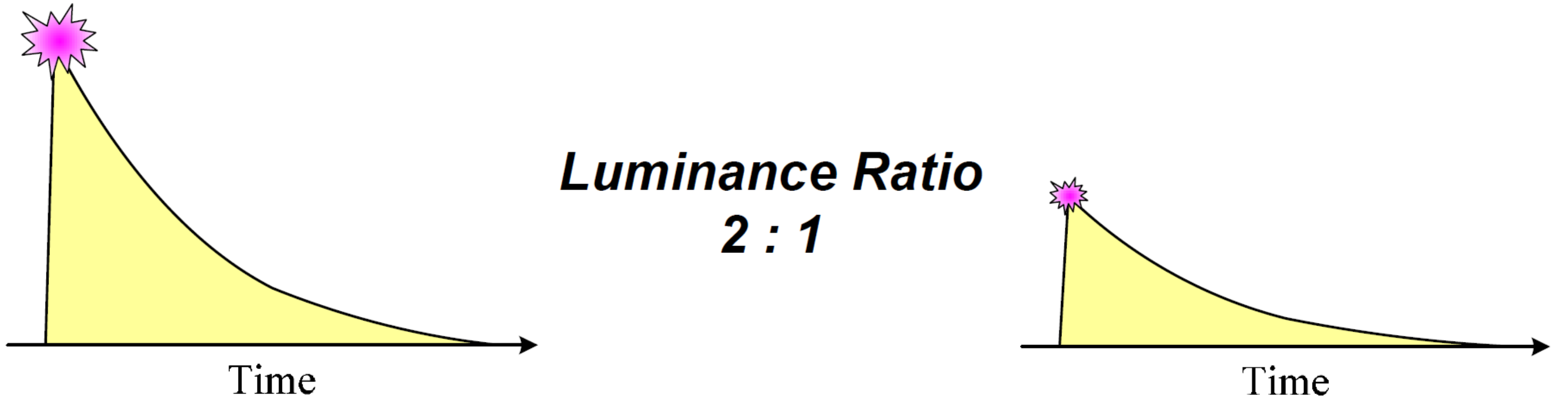
Sustain discharge



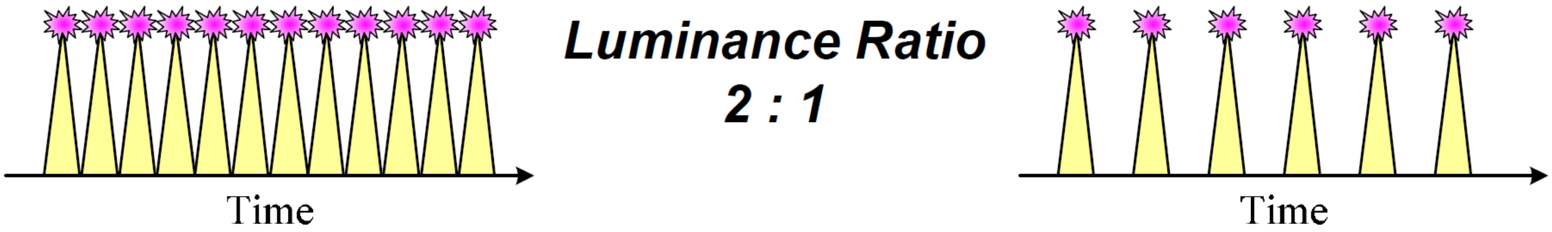
Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

PDP luminance is controlled by using number of light pulses

- CRT : Control the Luminance using Electron Beam Intensity



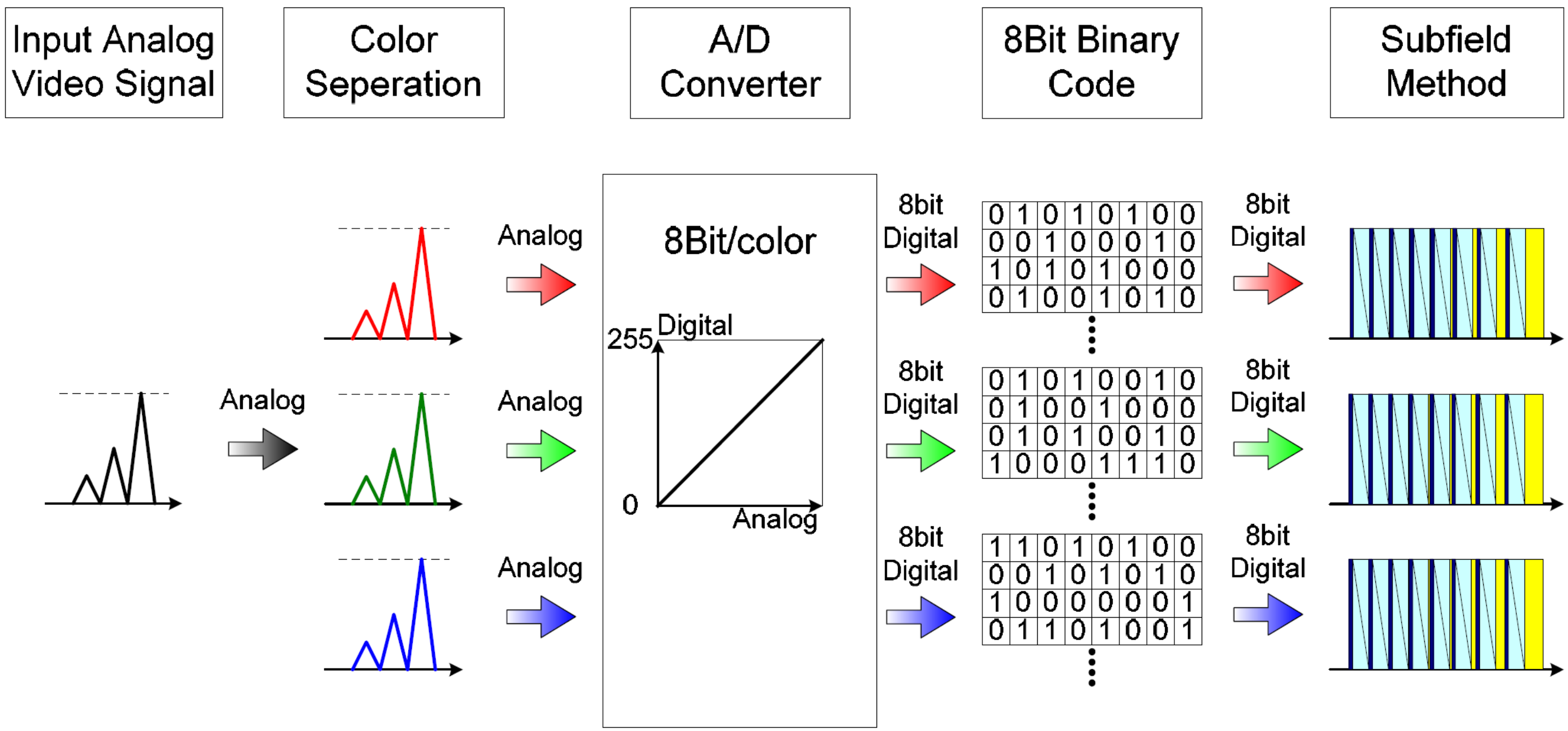
- PDP : Control the Luminance using Number of Light Pulses



Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

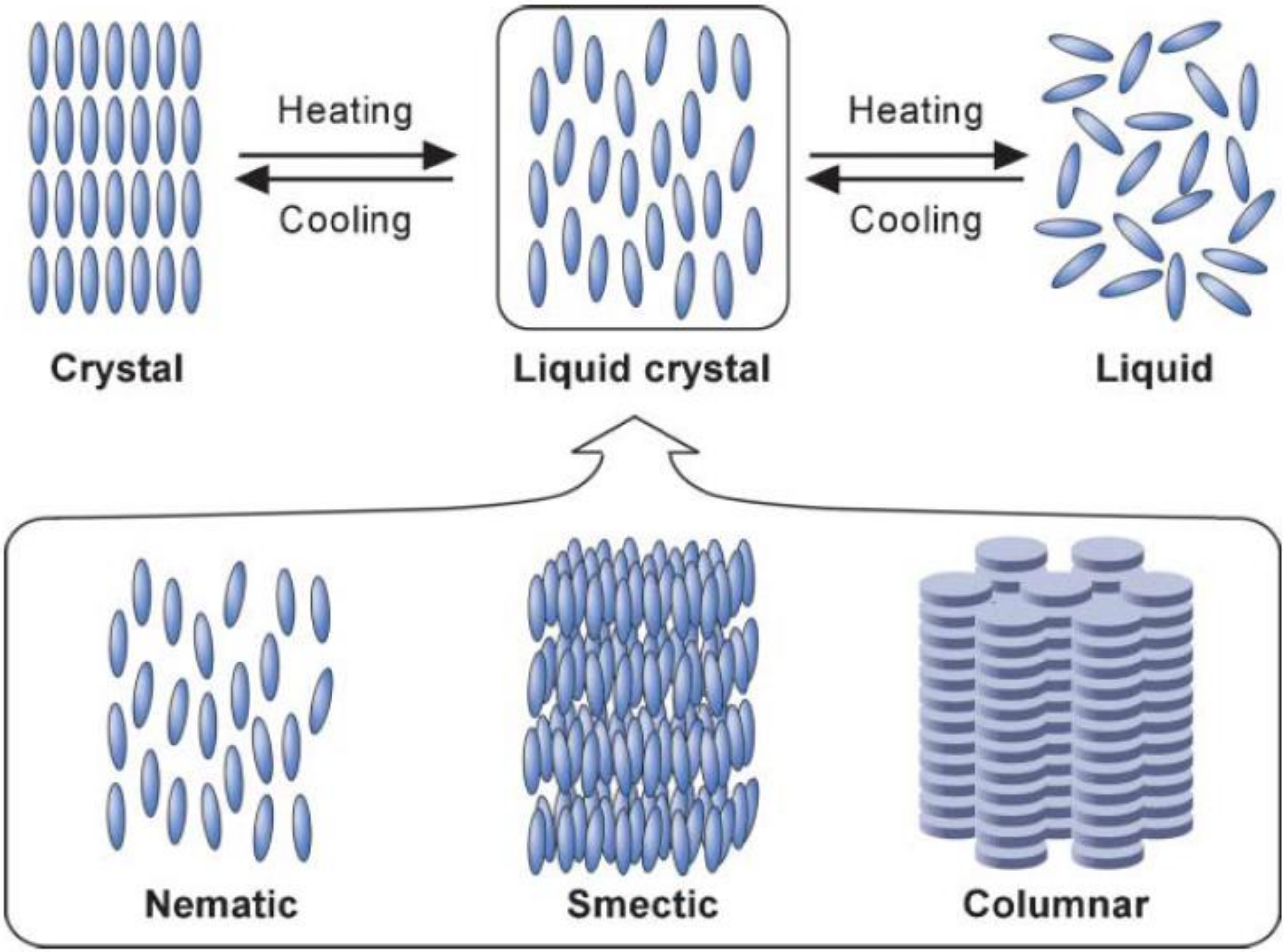
Video signal processing

- Analog Video Signal ⇨ Digital Pulse Signal



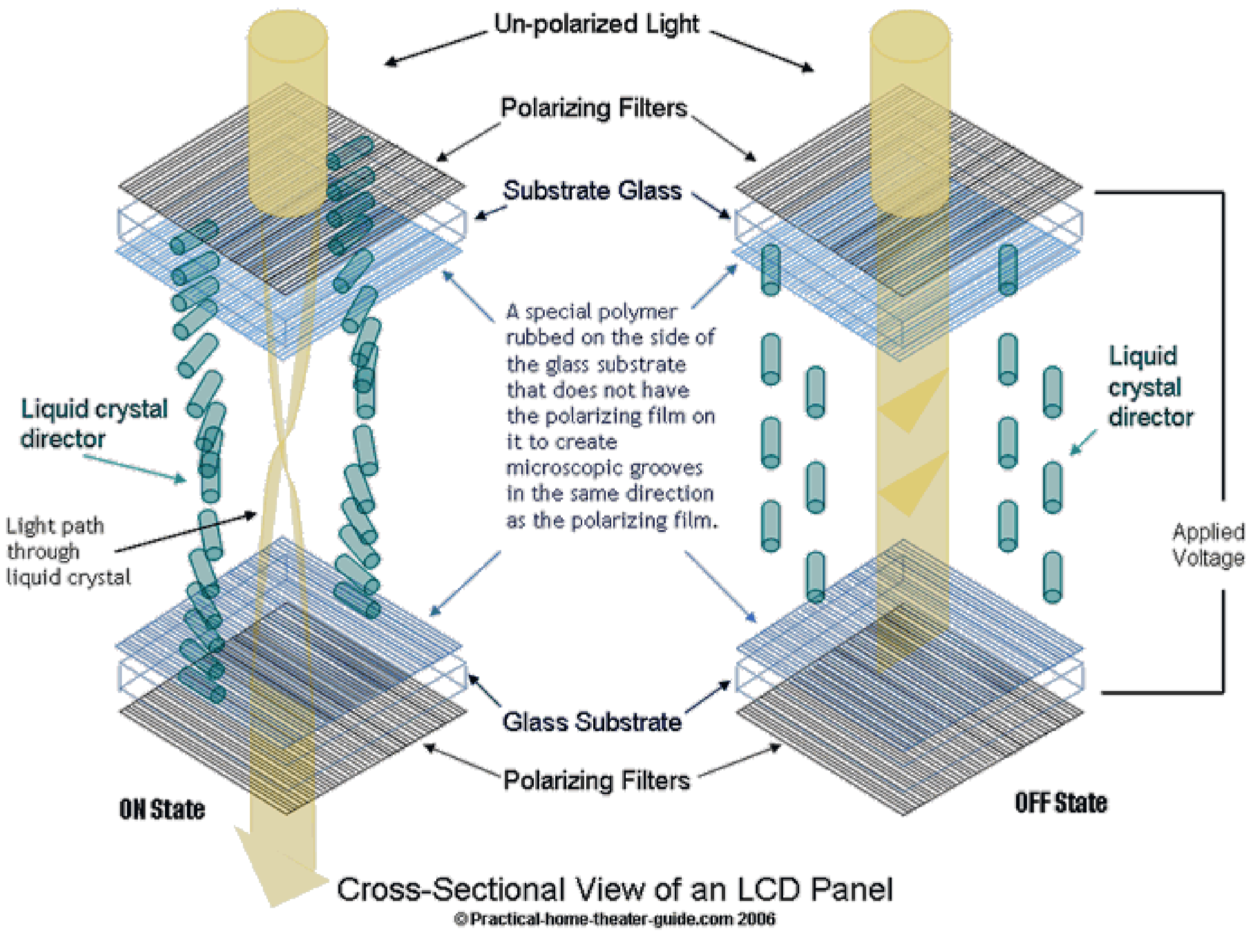
Slides from Prof. Heung-Sik Tae, School of Electronic and Electrical Engineering, Kyungpook National University

Liquid crystal are a special state of matter between liquid and crystal



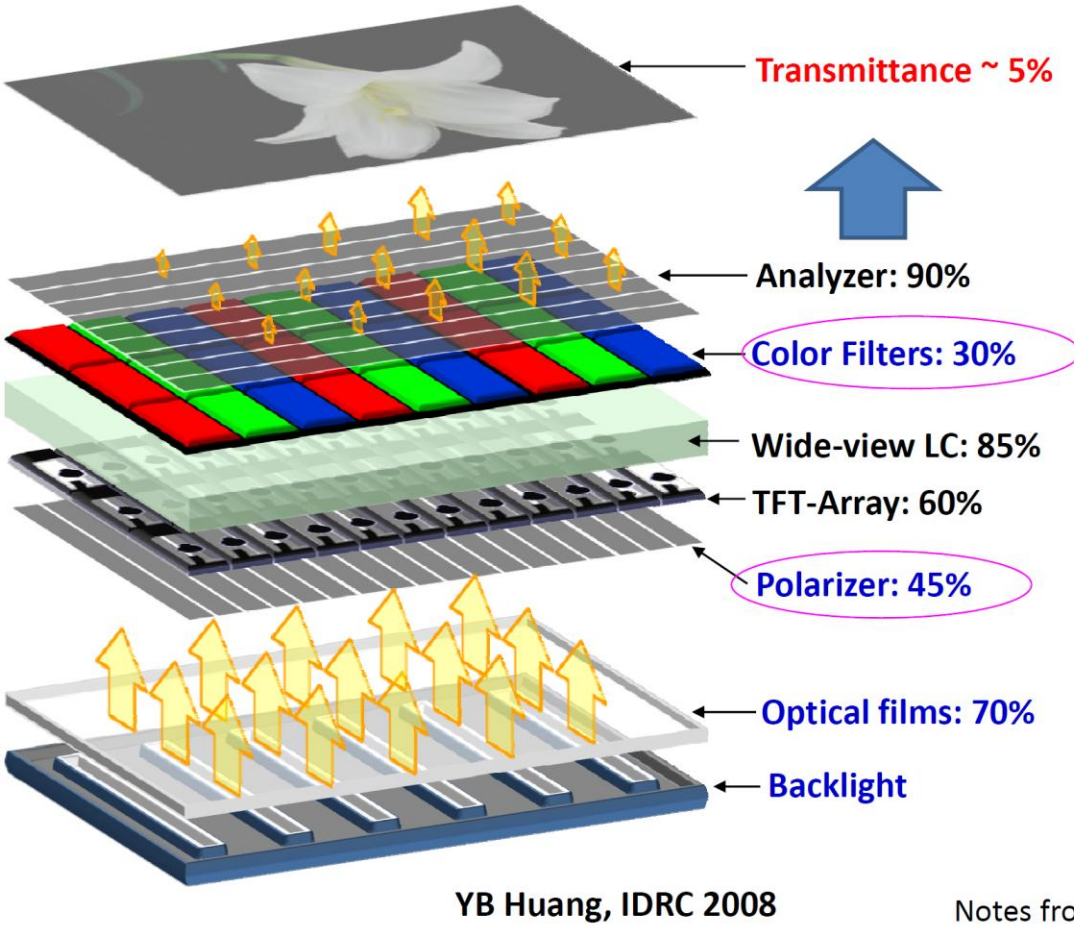
T. Kato, *et. al.*, Chem. Soc. Rev., *36*, 1845, 2007

Linear polarization of a light can be rotated by miss aligned liquid crystal



http://www.practical-home-theater-guide.com/lcd-display.html

Structure of Liquid crystal display (LCD)

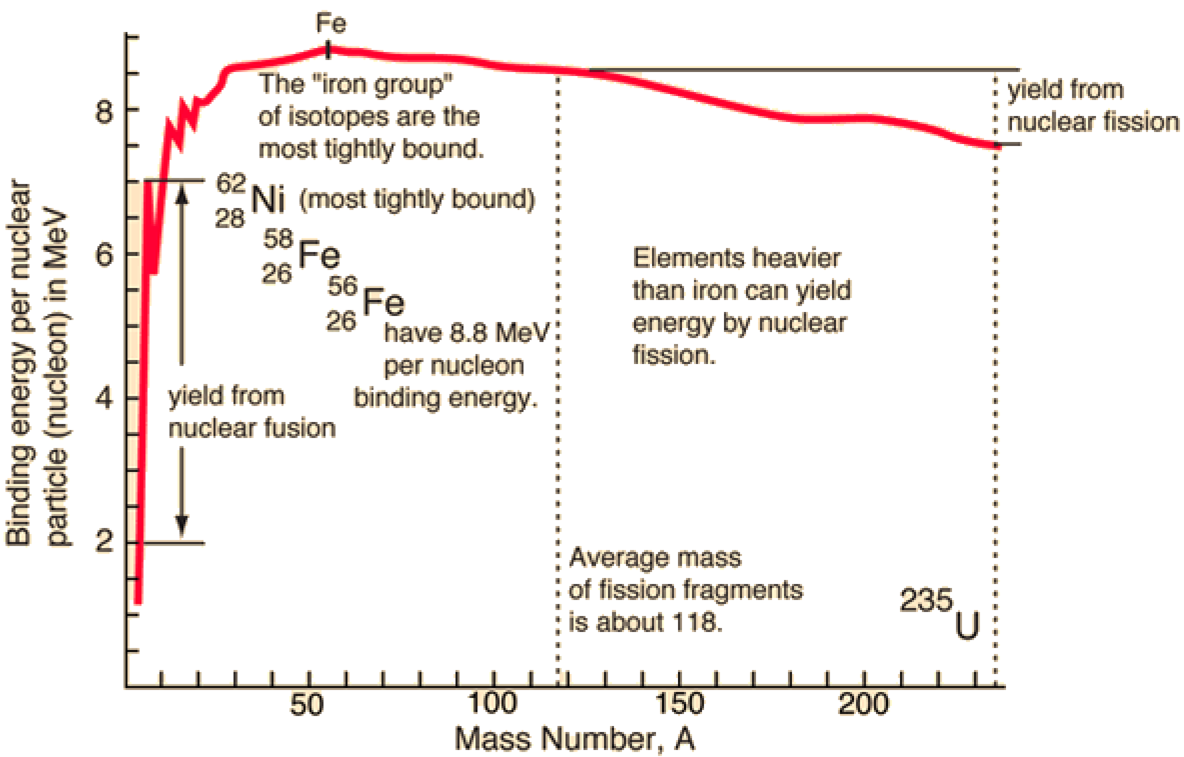


Notes from ST Wu, UCF

http://www6.cityu.edu.hk/cityu25/events/engineering/pdf/proftang.pdf

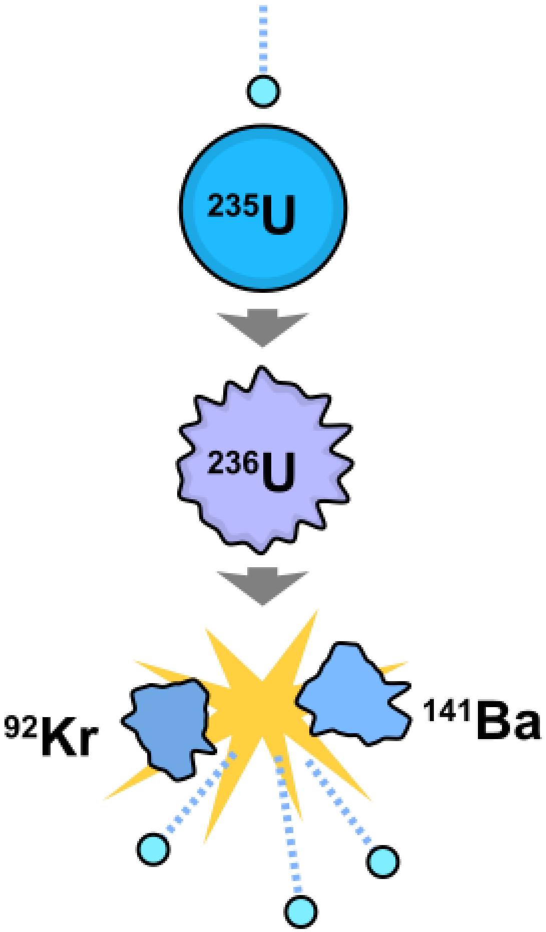
The hydrogen bomb

The "iron group" of isotopes are the most tightly bound



http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html

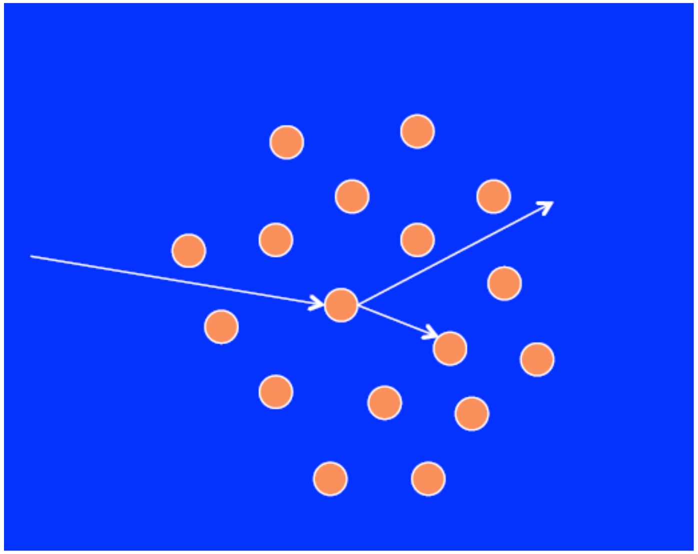
Chain reaction can happen in U^{235} fission reaction



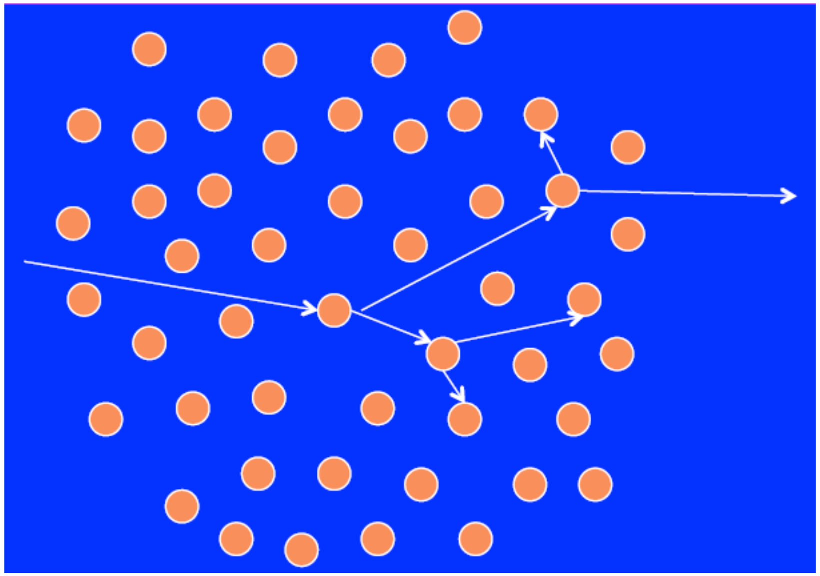
- ~ 200 million electron volts (MeV)/fission, ~million times more than chemical reactions
- Energy for bombs, or for civilian power can generate huge amounts of energy (and toxicity) in a small space with a modest amount of material
- Source of safety, security issues for nuclear power

https://en.wikipedia.org/wiki/Uranium-235
Talk given by Matthew Bunn, IGA-232: Controlling the World's Most Dangerous Weapons, Harvard Kennedy School, 2013

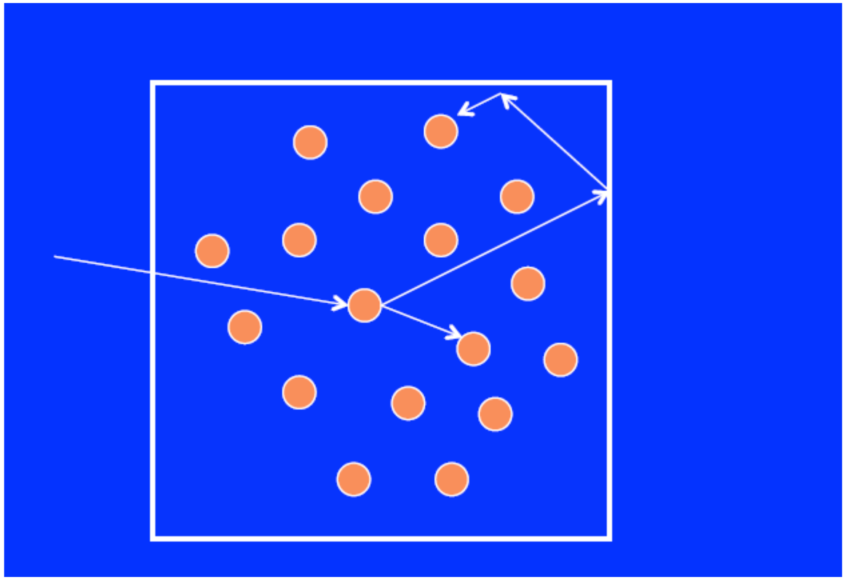
The neutrons are leaking out and stopping the chain reaction in a sub-critical mass



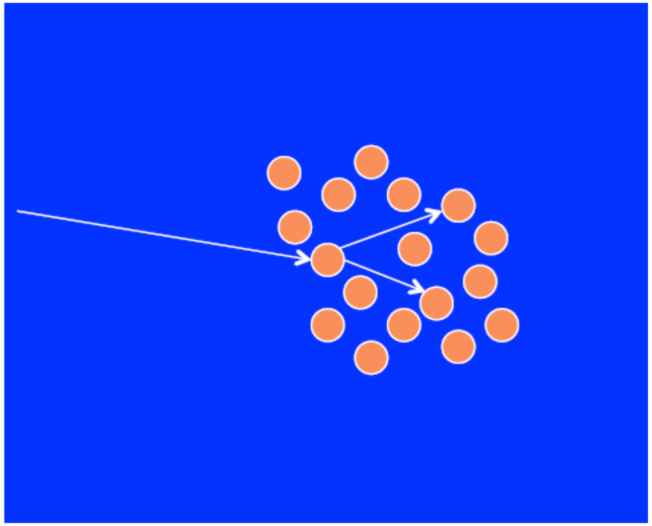
Solution 1: add more material



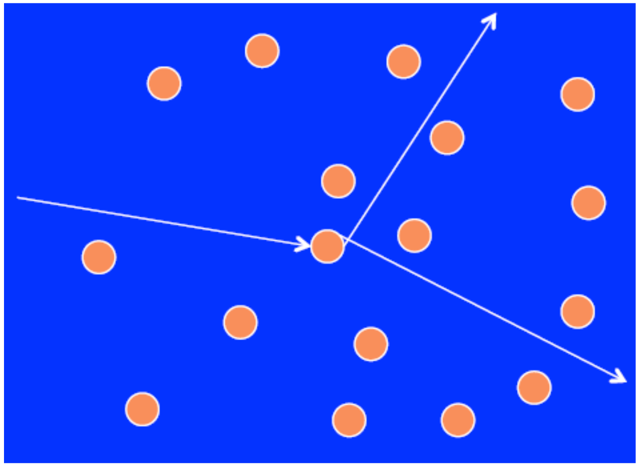
Solution2: reflect the neutron back in



Solution 3: increase the density



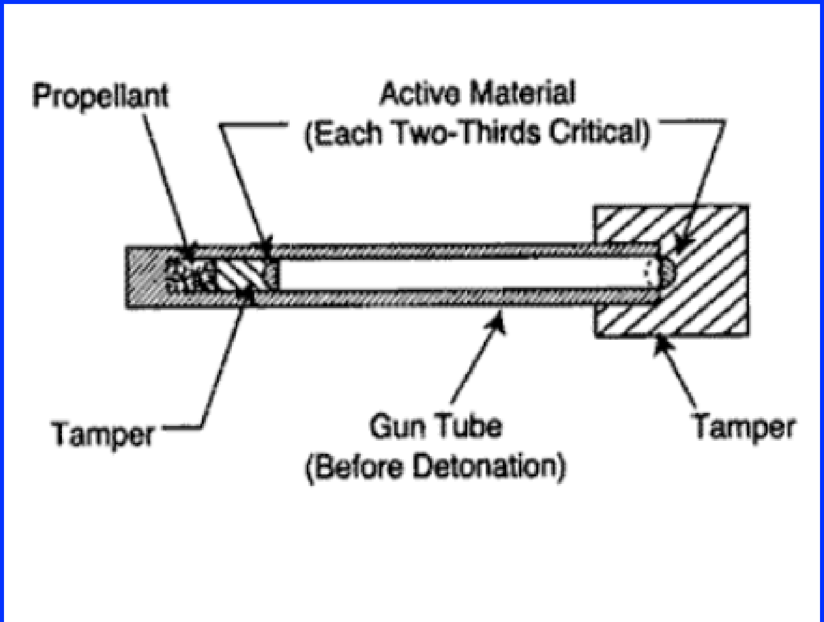
How to get the material together before it blows apart?



- **There are always neutrons around**
- **Once chain reaction starts, material will heat up, expand, stop reaction**
- **How to get enough material together fast enough?**

Gun-type bomb

- **Simple, reliable – can be built without testing**
- **Highly inefficient – require lots of nuclear material (50-60 kg of 90% enriched HEU)**
- **Can only get high yield with HEU, not plutonium**
- **Hiroshima bomb: cannon that fired HEU projectile into HEU target**



Source: NATO

Hiroshima Bomb – “Little Boy”

Gun Type – Easiest to design and build (Hiroshima bomb was never tested)

About 13 kiloton explosive yield

Talk given by Dr. Charles D. Ferguson, President, Federation of American Scientists, Department of Physics, Colloquium, American University, 2012

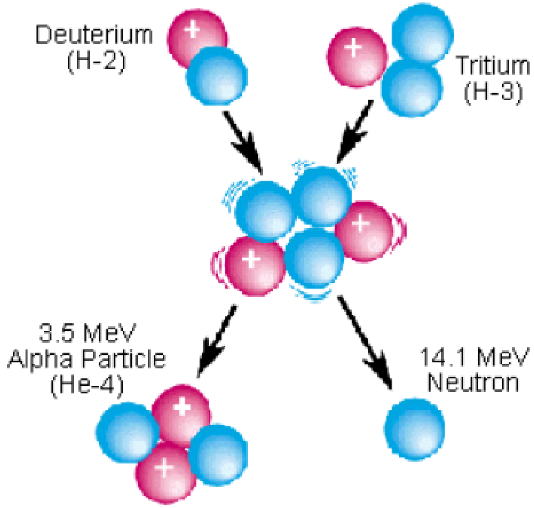
Atomic bomb is very destructive

Hiroshima: August 6, 1945

Nagasaki: August 9, 1945

Talk given by Dr. Charles D. Ferguson, President, Federation of American Scientists, Department of Physics, Colloquium, American University, 2012

The fusion process



Deuterium-Tritium Fusion Reaction

$^{2}H+^{3}H \Rightarrow {}^{4}He+n+Q \equiv 17.6\ MeV$

Energy release Q=17.6 MeV

In comparison

$^{2}H+^{2}H \Rightarrow {}^{1}H+^{3}H +Q \equiv 4.0\ MeV$

$^{2}H+^{2}H \Rightarrow {}^{3}He+n +Q \equiv 3.2\ MeV$

$^{3}H+^{3}H \Rightarrow {}^{4}He+2n+Q \equiv 11.3\ MeV$

$^{235}U+n \Rightarrow X_A+X_B+3n +Q \approx 200\ MeV$

Fusionable Material, deuterium ^{2}H (D) and tritium ^{3}H (t):

Deuterium: natural occurrence (heavy water) (0.015%).

Tritium: natural occurrence in atmosphere through cosmic ray bombardment; radioactive with $T_{1/2}$=12.3 y.

https://isnap.nd.edu/Lectures/phys20061/pdf/10.pdf

“Advantages” of hydrogen bomb

Fusion of $^2H+^3H$: $$\frac{Q}{A}=\frac{17.6\ MeV}{(3+2)\ amu}=3.5\ \frac{MeV}{amu}$$

Fission of ^{235}U: $$\frac{Q}{A}=\frac{200\ MeV}{236\ amu}=0.85\ \frac{MeV}{amu}$$

Fusion is 4 times more powerful than fission
and generates 24 times more neutrons!

Neutron production:

$$^2H+{}^3H:\quad \frac{n}{A}=\frac{1}{5}=0.2$$

$$^{235}U+n:\quad \frac{n}{A}=\frac{2}{236}=0.0085$$

https://isnap.nd.edu/Lectures/phys20061/pdf/10.pdf

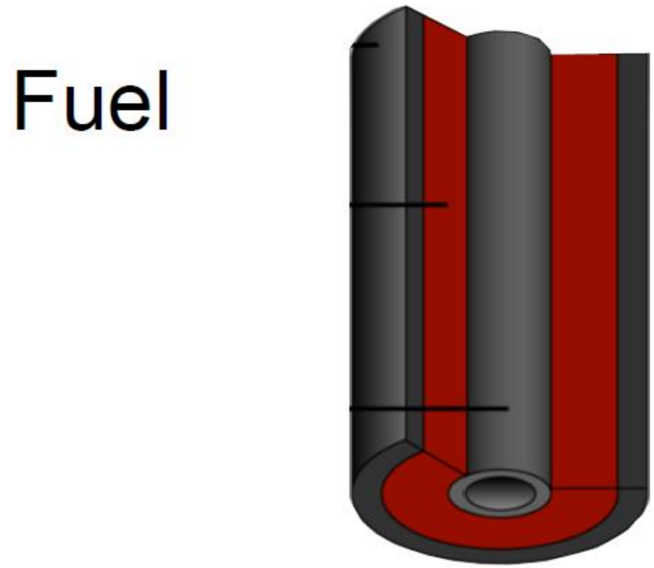
Hydrogen bomb uses a fission bomb to initiate the fusion reaction

Primary Fission Device

Core: ^{239}Pu, ^{235}U,
plus $^{2}H+^{3}H$ booster

Shell: ^{238}U tamper

High explosive lenses



Secondary Fusion Device

Radiation channel

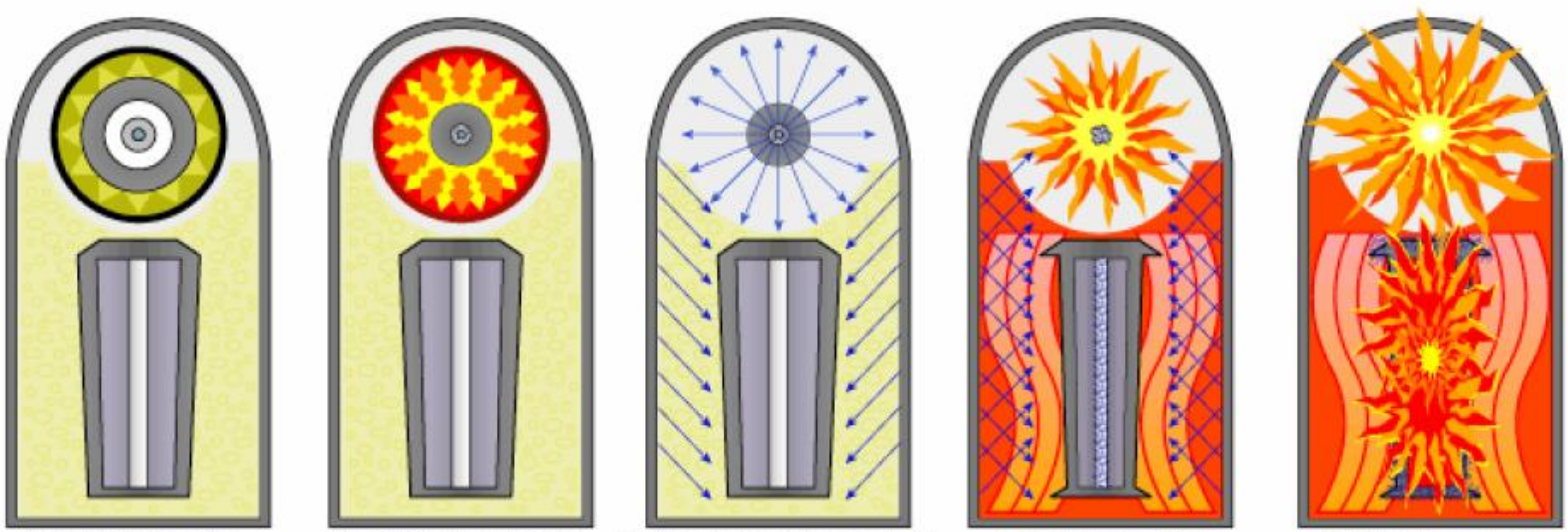
^{239}Pu sparkplug

^{6}Li, ^{2}H, ^{3}H fusion cell

^{238}U tamper

https://isnap.nd.edu/Lectures/phys20061/pdf/10.pdf

Event sequence



1. Warhead before firing; primary (fission bomb) at top, secondary (fusion fuel) at bottom, all suspended in polystyrene foam.

2. HE fires in primary, compressing plutonium core into supercriticality and beginning a fission reaction.

3. Fissioning primary emits X-rays which reflect along the inside of the casing, irradiating the polystyrene foam.

4. Polystyrene foam becomes plasma, compressing secondary, and plutonium sparkplug begins to fission.

5. Compressed and heated, lithium-6 deuteride fuel begins fusion reaction, neutron flux causes tamper to fission. A fireball is starting to form...

Additional pressure from recoil of exploding shell (ablation)!

https://isnap.nd.edu/Lectures/phys20061/pdf/10.pdf

You don't want to build a hydrogen bomb!

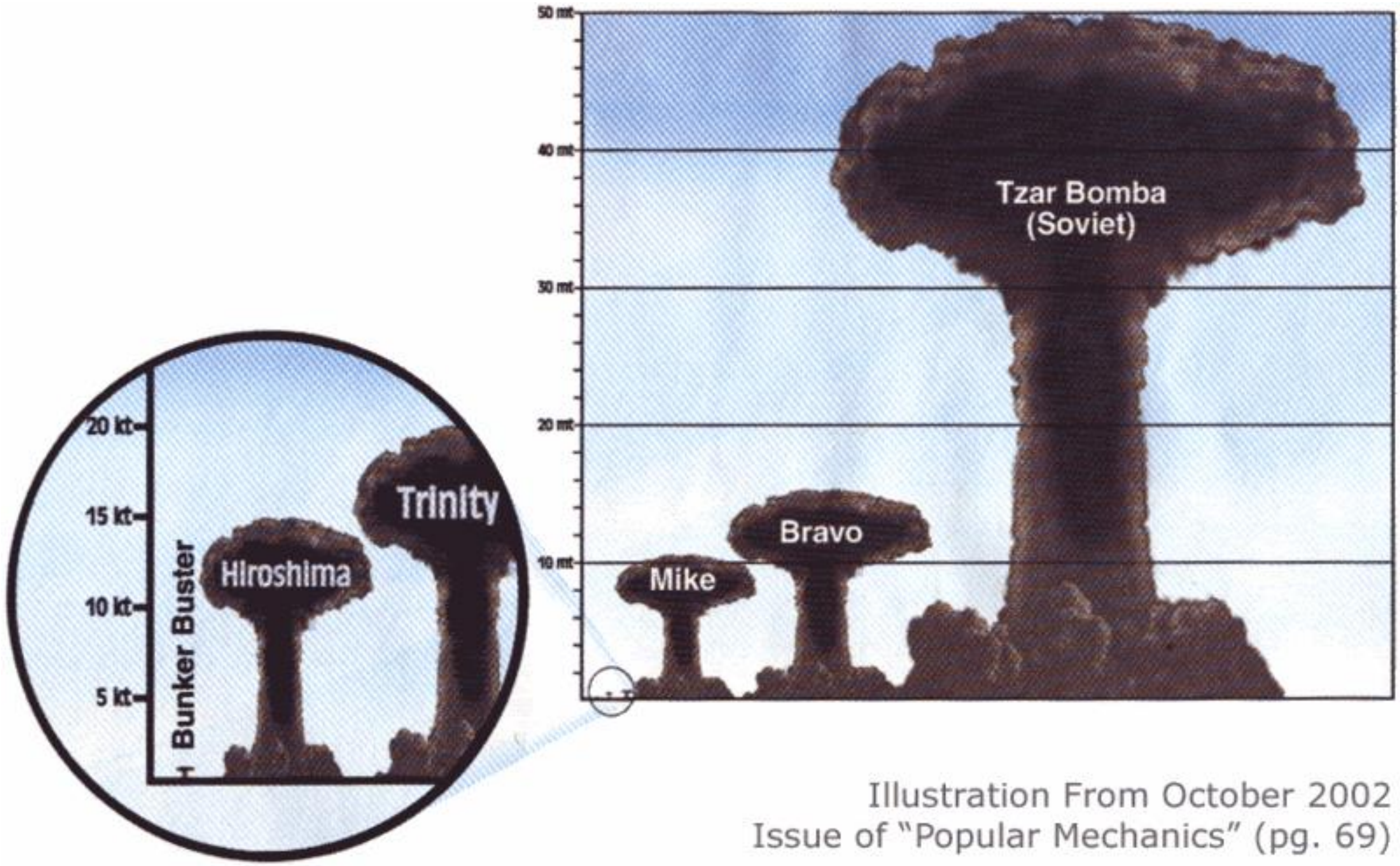
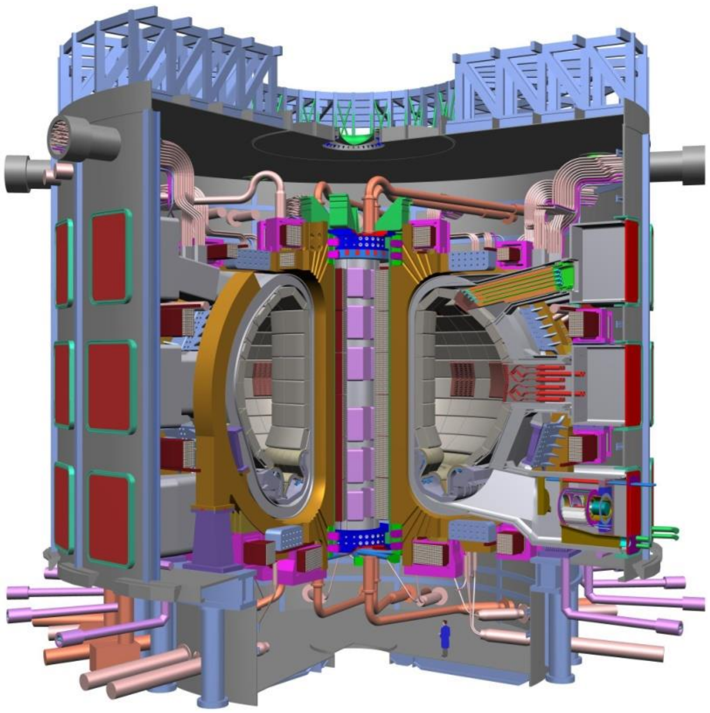
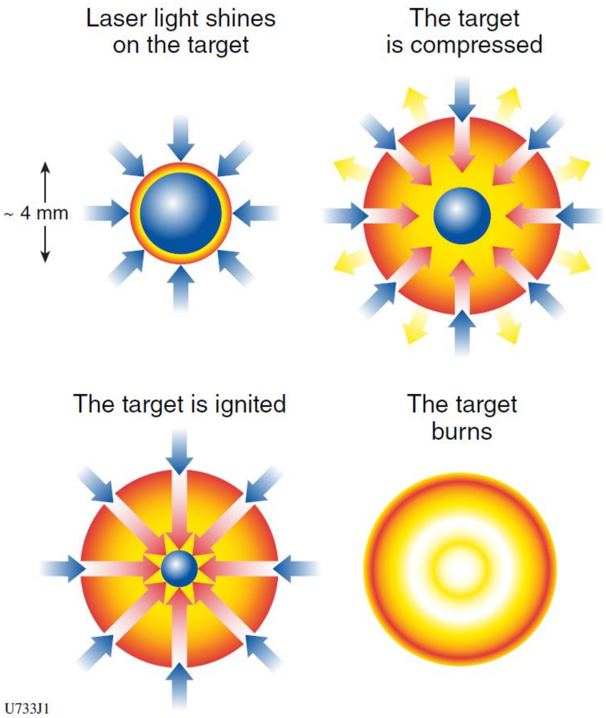


Illustration From October 2002
Issue of "Popular Mechanics" (pg. 69)

To Fuse, or Not to Fuse...





Outline

- Introduction to nuclear fusion
- Magnetic confinement fusion (MCF)
  - Tokamak
  - Stellarator
- Inertial confinement fusion (ICF)
  - Indirection drive ICF
  - Direct drive ICF
- Innovation idea – MCF + ICF
- Plasma in space
- Pulsed-power system at NCKU

Outline

- **Introduction to nuclear fusion**
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  - **Direct drive ICF**
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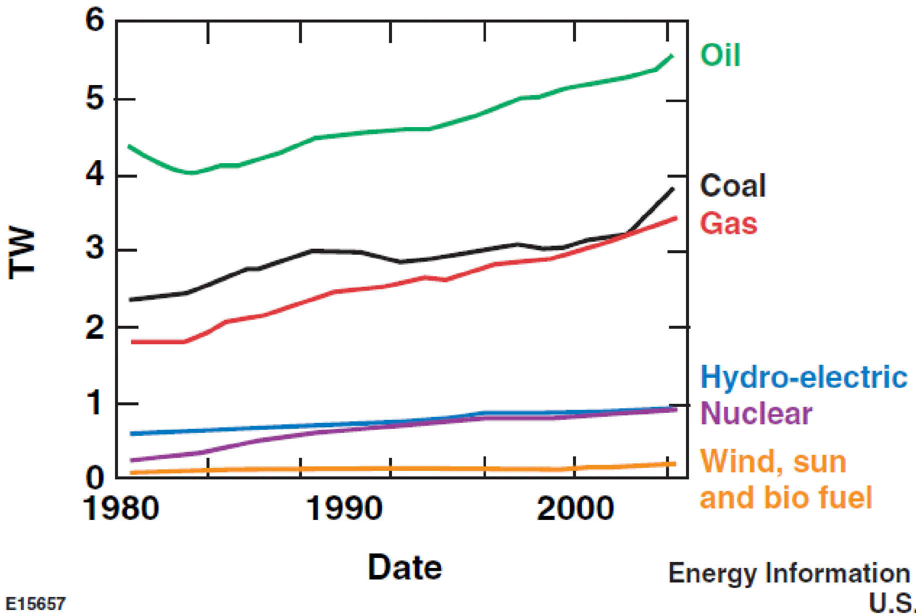
World energy consumption is dominated by the use of dwindling fossil fuels

Fossil fuel	Estimated reserve	(2005 consumption rate) Years remaining
Oil	1,277,702 million barrels	32 years
Natural gas	~6,500,000 billion cubic ft	72 years
Coal	1,081,279 million tons	252 years



While predictions about the exact number of remaining years vary, fossil fuels will run out.

Energy Information Administration (EIA) 2006 Annual Report, U.S. Department of Energy, Washington, D.C.

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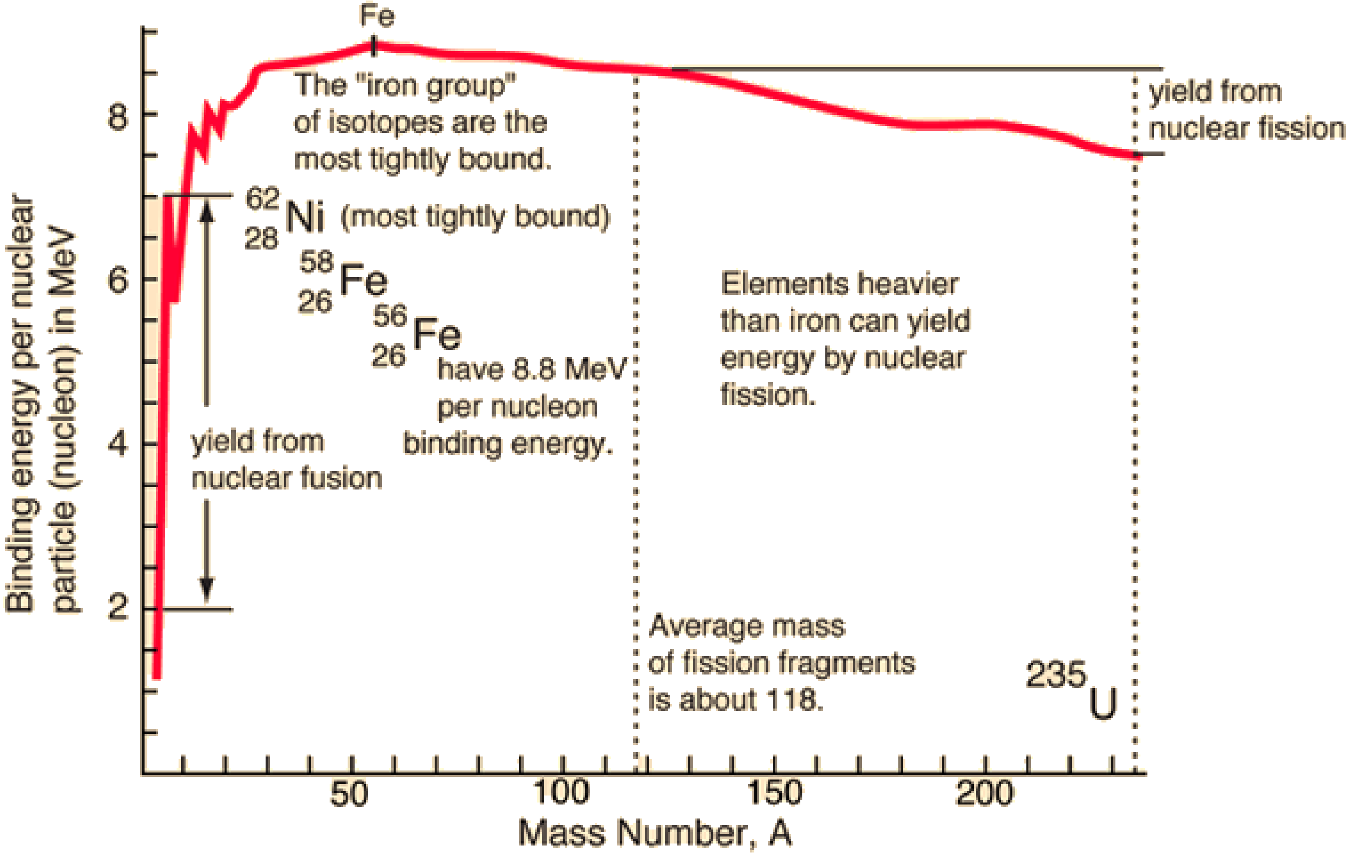
*from Laboratory for Laser Energetics, University of Rochester, Rochester, NY

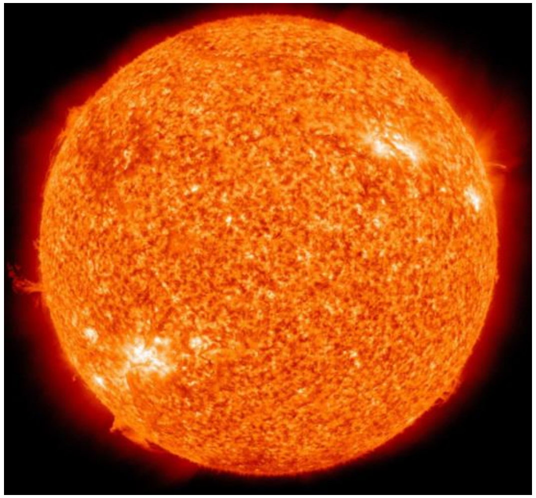
The “iron group” of isotopes are the most tightly bound

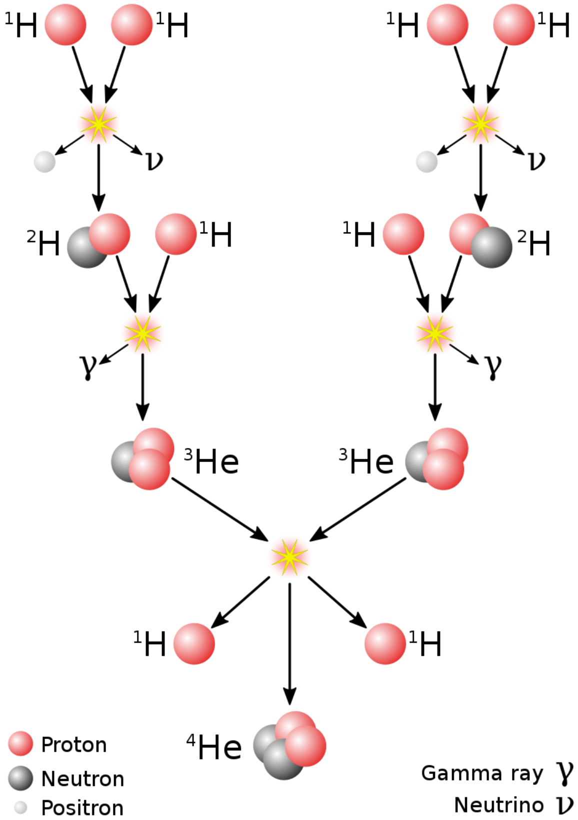


http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html

Fusion in the sun provides the energy

- **Proton-proton chain in sun or smaller**

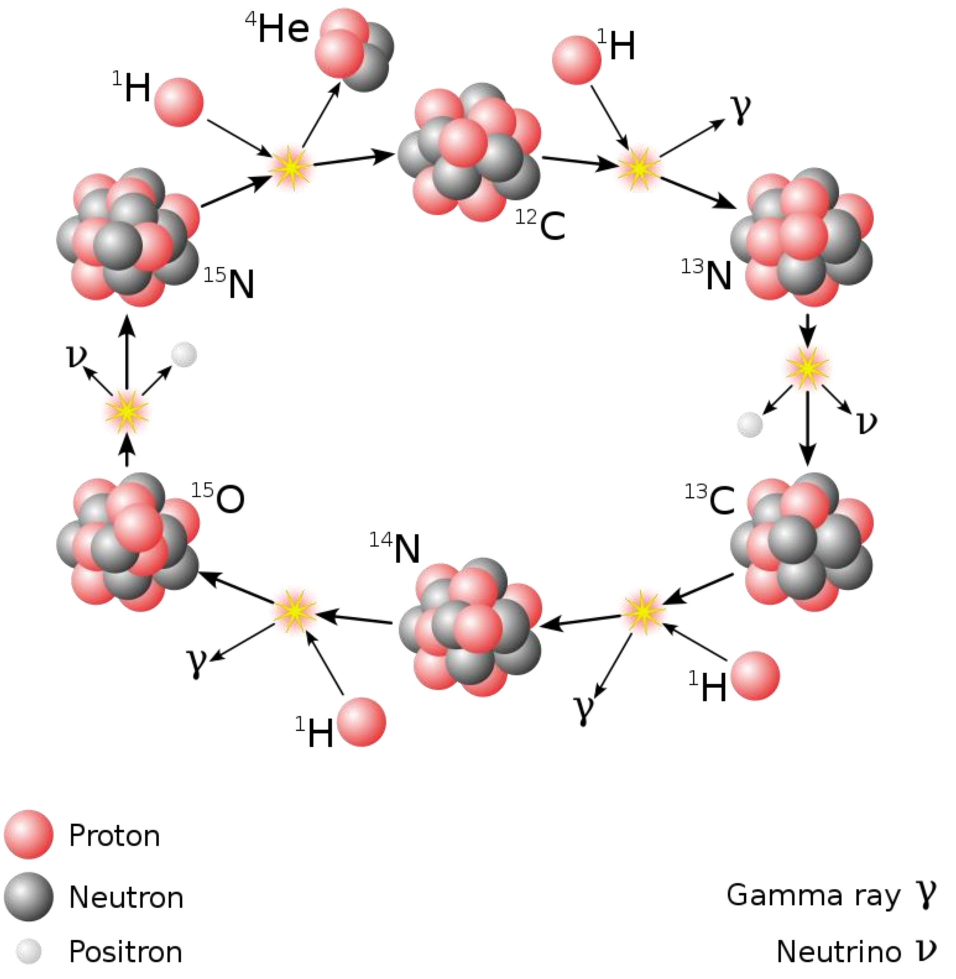




- **Particles are confined by the gravity.**

https://en.wikipedia.org/wiki/Sun
https://en.wikipedia.org/wiki/Nuclear_fusion

In heavy sun, the fusion reaction is the CNO cycle



https://en.wikipedia.org/wiki/Nuclear_fusion

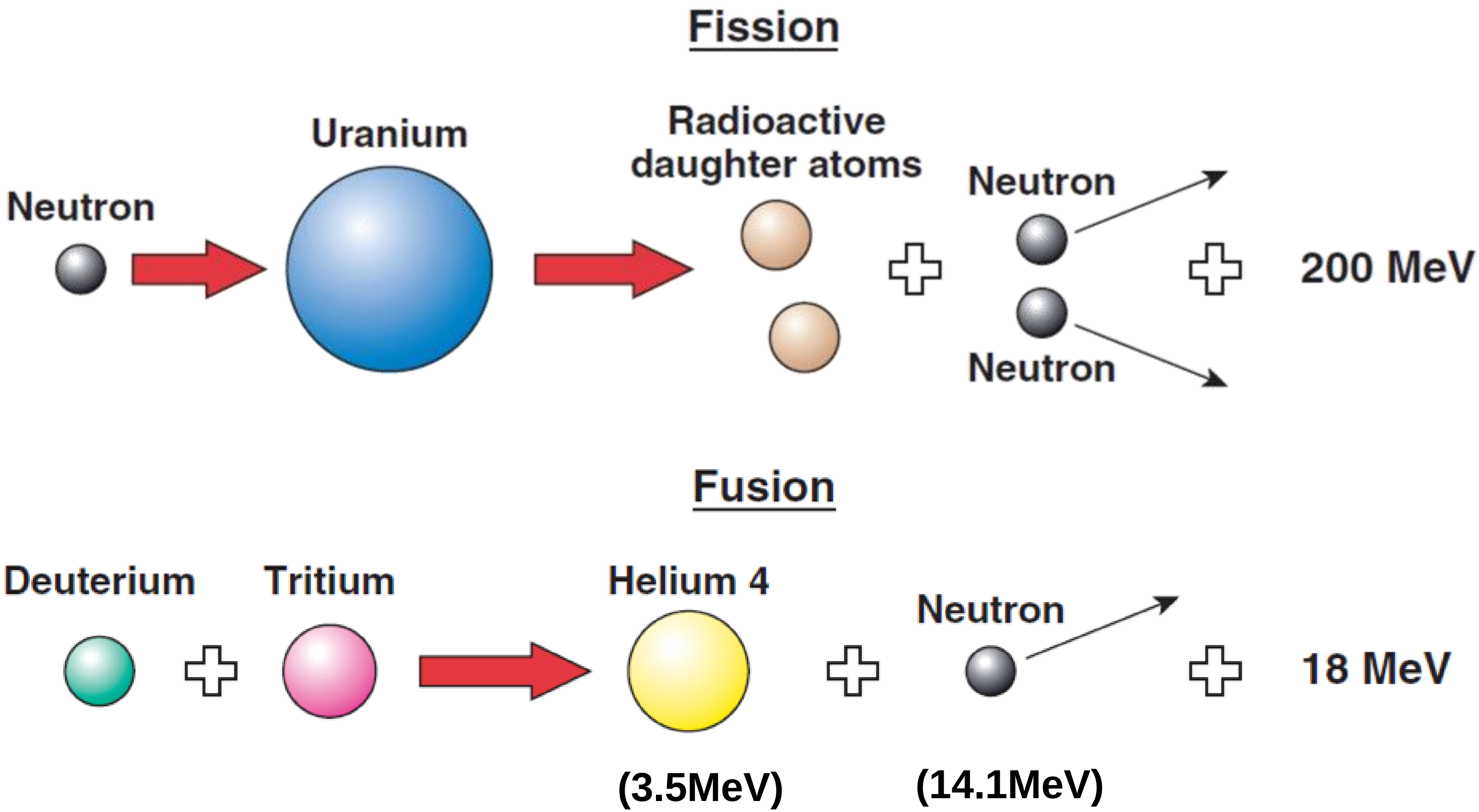
The cross section of proton-proton chain is much smaller than D T fusion

Reaction	$\sigma_{10\ keV}$ (barn)	$\sigma_{100\ keV}$ (barn)	σ_{max} (barn)	ε_{max} (keV)
$D+T\rightarrow\alpha+n$	2.72×10^{-2}	3.43	5.0	64
$D+T\rightarrow T+p$	2.81×10^{-4}	3.3×10^{-2}	0.06	1250
$D+T\rightarrow{}^3He+n$	2.78×10^{-4}	3.7×10^{-2}	0.11	1750
$T+T\rightarrow\alpha+2n$	7.90×10^{-4}	3.4×10^{-2}	0.16	1000
$D+{}^3He\rightarrow\alpha+p$	2.2×10^{-7}	0.1	0.9	250
$p+{}^6Li\rightarrow\alpha+{}^3He$	6×10^{-10}	7×10^{-3}	0.22	1500
$p+{}^{11}B\rightarrow3\alpha$	(4.6×10^{-17})	3×10^{-4}	1.2	550
$p+p\rightarrow D+e^{+}+v$	(3.6×10^{-26})	(4.4×10^{-25})		
$p+{}^{12}C\rightarrow{}^{13}N+\gamma$	(1.9×10^{-26})	2.0×10^{-10}	1.0x10.4	400
${}^{12}C+{}^{12}C$ (all branches)		(5.0×10^{-103})		

- "( )" are theoretical values while others are measured values.

The Physics of Inertial Fusion, by Stefano Atzeni and Jürgen Meyer-Ter-Vehn

Nuclear fusion and fission release energy through energetic neutrons



Nuclear fusion provides more energy per atomic mass unit (amu) than nuclear fission

Fusion of $^{2}H + ^{3}H$: $$\frac{Q}{A} = \frac{17.6\ MeV}{(3+2)\ amu} = 3.5\ \frac{MeV}{amu}$$

Fission of ^{235}U: $$\frac{Q}{A} = \frac{200\ MeV}{236\ amu} = 0.85\ \frac{MeV}{amu}$$

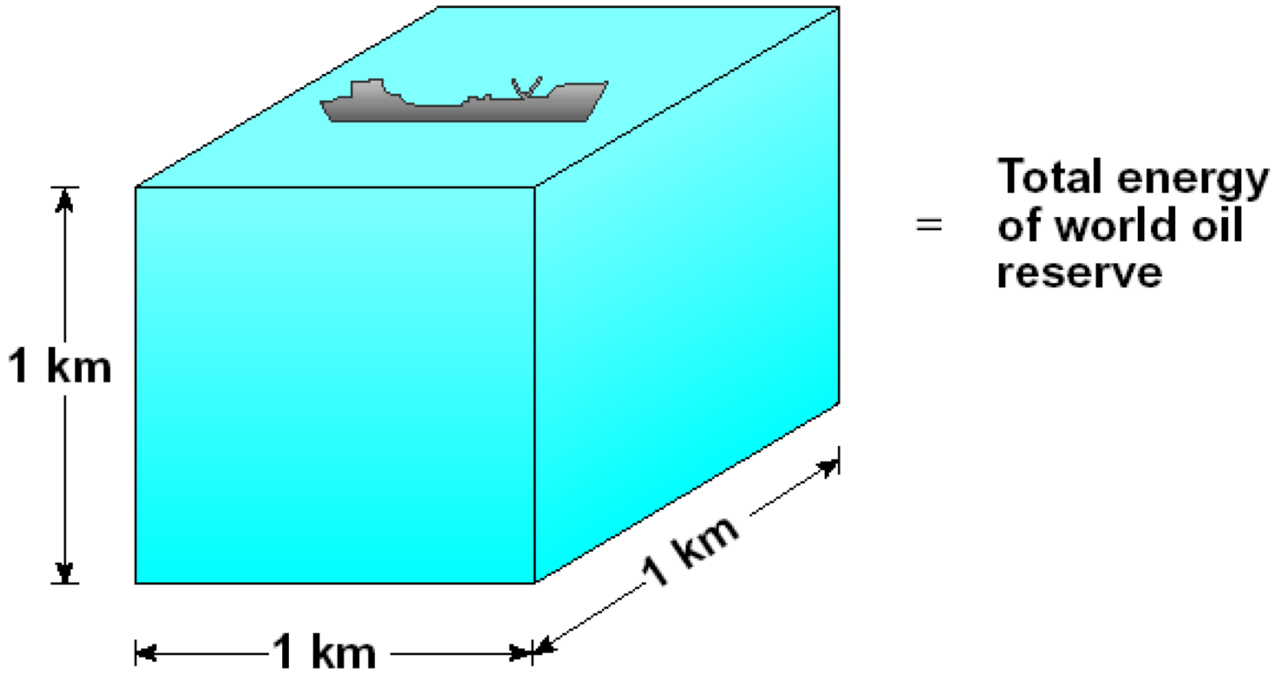
	Half-life (years)
U235	7.04×10^{8}
U238	4.47×10^{9}
…	
Tritium	12.3

What could you do with 1 kg DT?

- 1 kg DT -> 340 Tera joules
  - You can drive your car for ~40,000 km (back and forth between Keelung and Kaoshiung for 50 times).
  - You can keep your furnace running for 8 years.
  - You can blow things up! 1 TJ = 250 tons of TNT.

*R. Betti, HEDSA HEDP Summer School, 2015

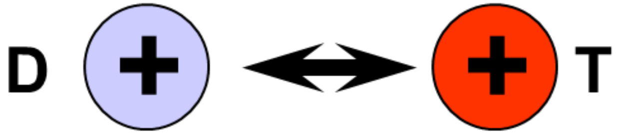
Enormous fusion fuel can be produced from sea water



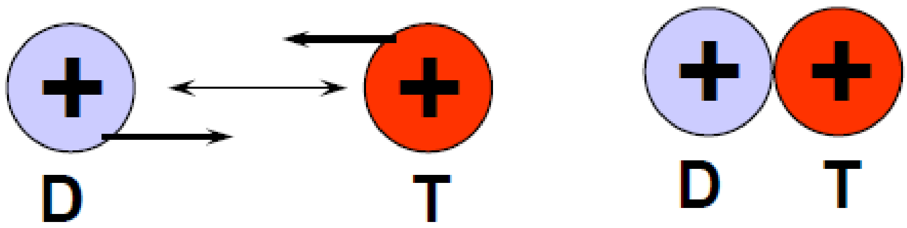
*R. Betti, HEDSA HEDP Summer School, 2015

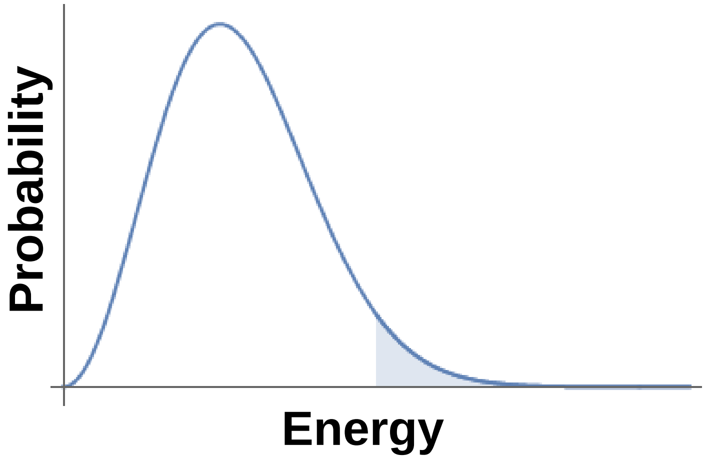
A “hot plasma” at 100M ⁰C is needed

- **Probability for fusion reactions to occur is low at low temperatures due to the coulomb repulsion force.**



- **If the ions are sufficiently hot, i.e., large random velocity, they can collide by overcoming coulomb repulsion**

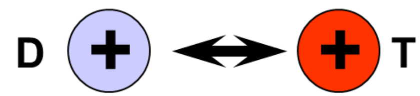


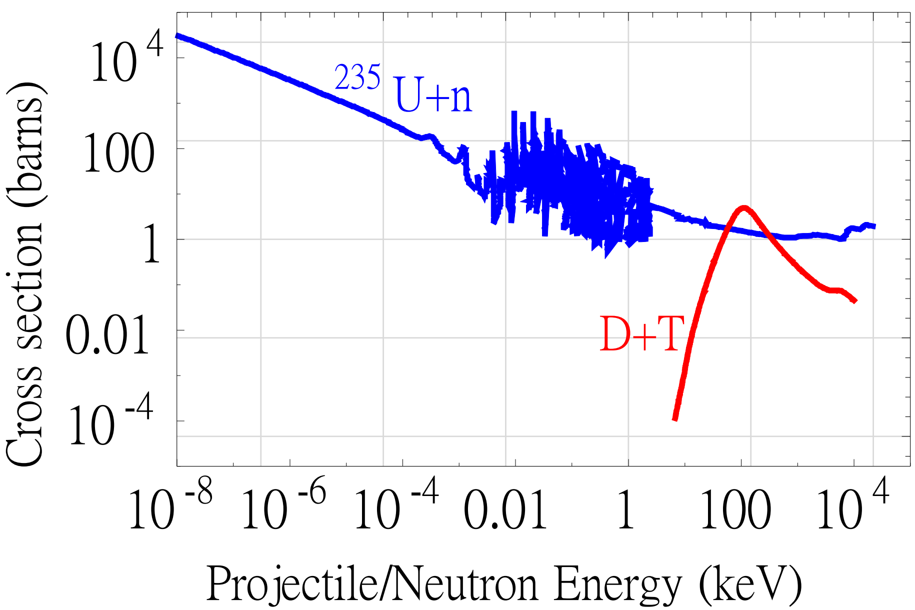


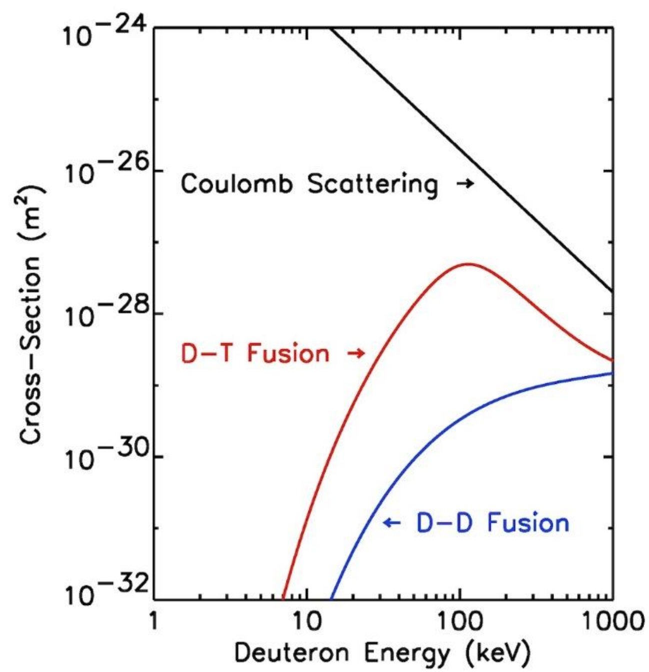
*R. Betti, HEDSA HEDP Summer School, 2015

Fusion is much harder than fission, a "hot plasma" at 100M ºC is needed

- **Fission:** $n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3n + 177\ \mathrm{MeV}$
- **Fusion:** $D + T \rightarrow He^{4}\,(3.5\ \mathrm{MeV}) + n\,(14.1\ \mathrm{MeV})$

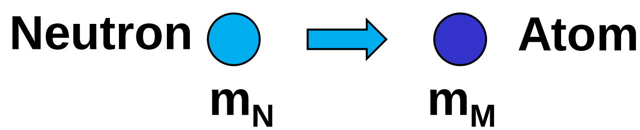






https://www6.lehigh.edu/~eus204/lab/PCL_fusion.php#x1-10096

Fast neutrons are slowed down due to the collisions

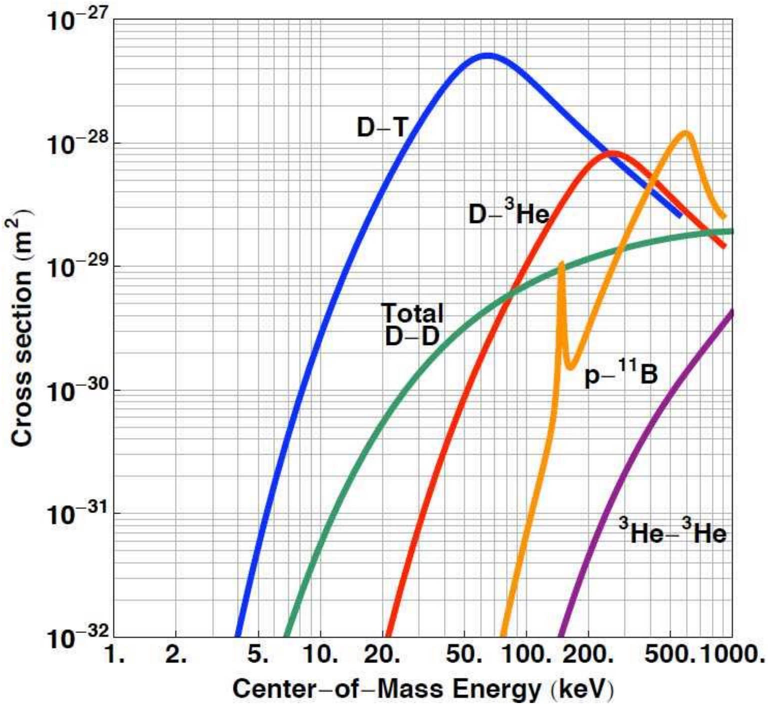


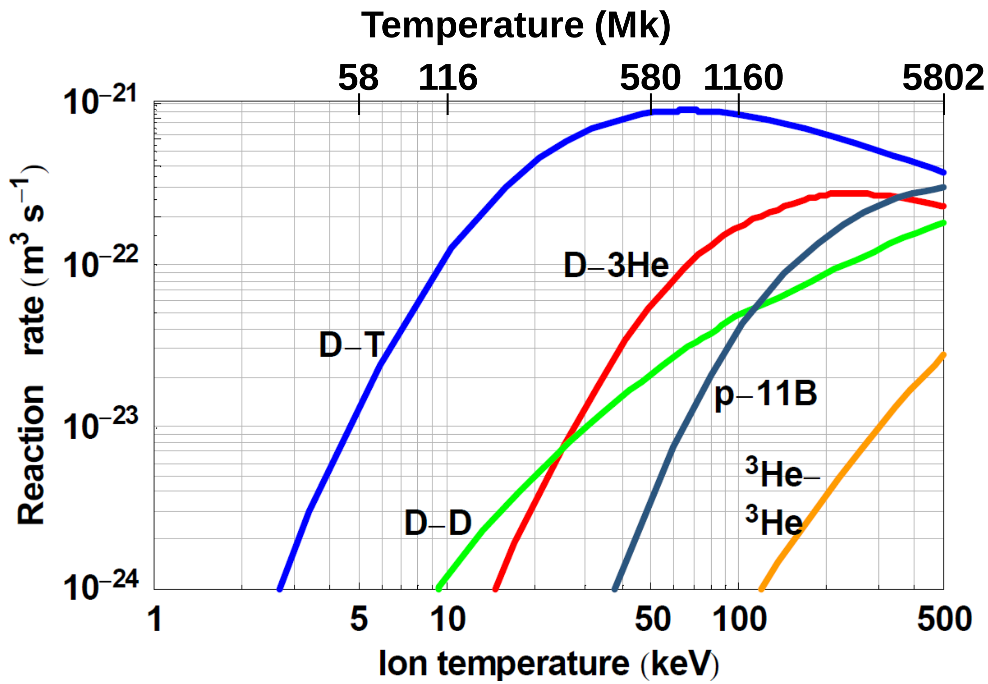
- A moderator is used to slow down fast neutrons but not to absorb neutrons.
- For $m_M \sim m_N$, the energy decrement is higher. Therefore, H slows down neutron most efficiently.
- However, H + n → D, i.e., H absorbs neutrons.
- The best option is the D in the heavy water (D_2O).

	Energy decrement	Neutron scattering cross section (σs) (Barns)	Neutron absorption cross section (σs) (Barns)
H	1	49 (H_2O)	0.66 (H_2O)
D	0.7261	10.6 (D_2O)	0.0013 (D_2O)
C	0.1589	4.7 (Graphite)	0.0035 (Graphite)

https://en.wikipedia.org/wiki/Neutron_moderator#cite_note-Weston-4
https://energyeducation.ca/encyclopedia/Neutron_moderator#cite_note-3

Fusion doesn't come easy





$D + D \rightarrow T + p$

$\rightarrow He^3 + n$

$D + T \rightarrow He^4 + n$

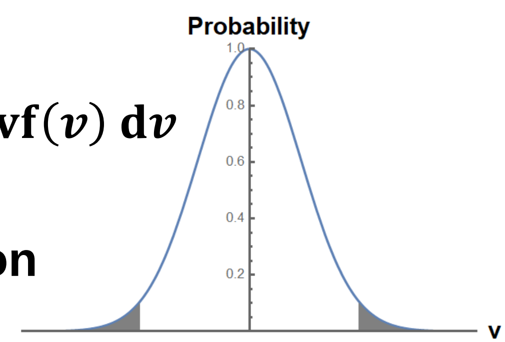
$D + He^3 \rightarrow He^4 + p$

$p + B^{11} \rightarrow 3He^4$

- **Reaction rate:**

$$< \sigma v > = \int \sigma(v) v f(v)\, dv$$

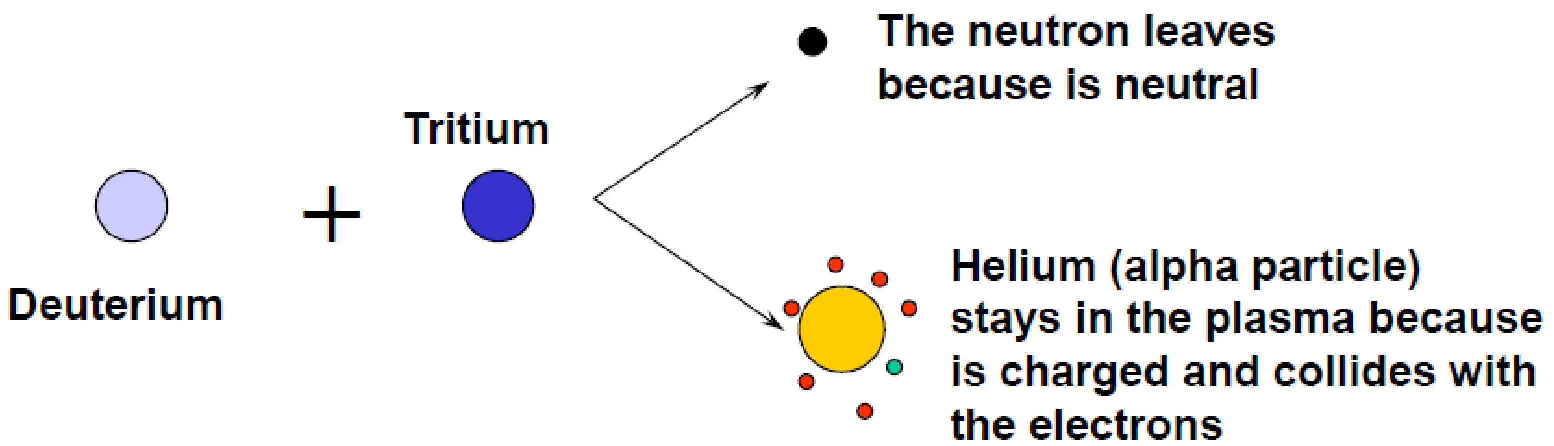
Cross section



https://i.stack.imgur.com/wXQD5.jpg
Santarius, J. F., "Fusion Space Propulsion – A Shorter Time Frame Than You Think", JANNAF, Monterey, 5-8 December 2005.

It takes a lot of energy or power to keep the plasma at 100M ⁰C

- Let the plasma do it itself!



- The α-particles heat the plasma.

*R. Betti, HEDSA HEDP Summer School, 2015

Under what conditions the plasma keeps itself hot?

- **Steady state 0-D power balance:**

  $S_\alpha + S_h = S_B + S_k$

  S_α: α particle heating

  S_h: external heating

  S_B: Bremsstrahlung radiation

  S_k: heat conduction lost

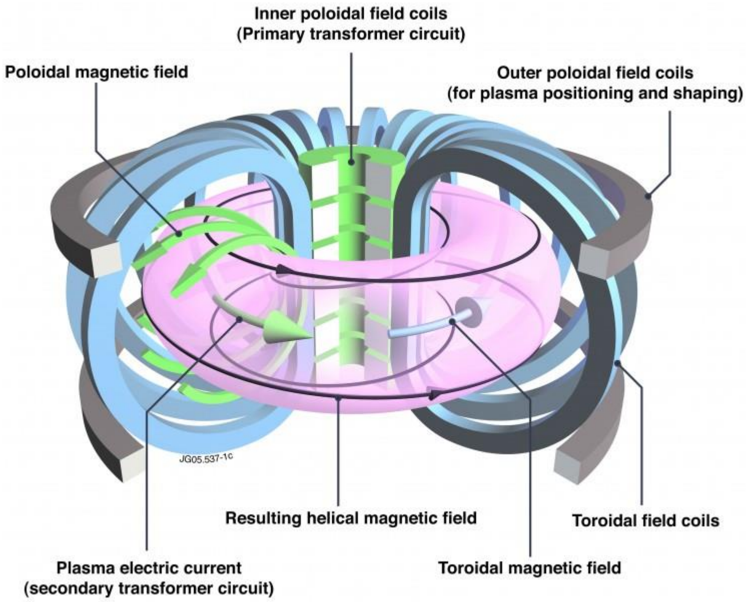
Ignition condition: Pτ > 10 atm-s = 10 Gbar - ns

- **P: pressure, or called energy density**
- **τ is confinement time**

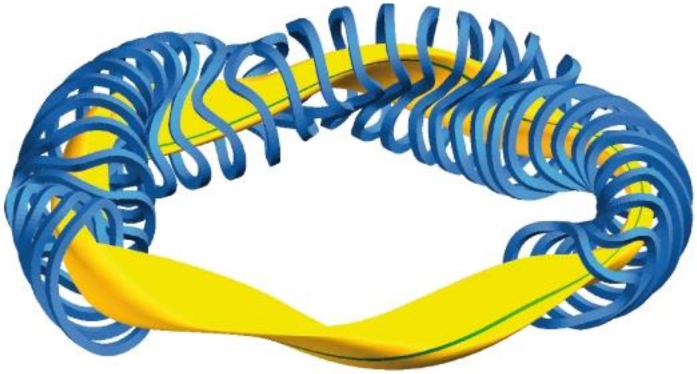
The plasma is too hot to be contained

- **Solution 1: Magnetic confinement fusion (MCF), use a magnetic field to contain it. P~atm, τ~sec, T~10 keV (10^8 ºC)**

Tokamak



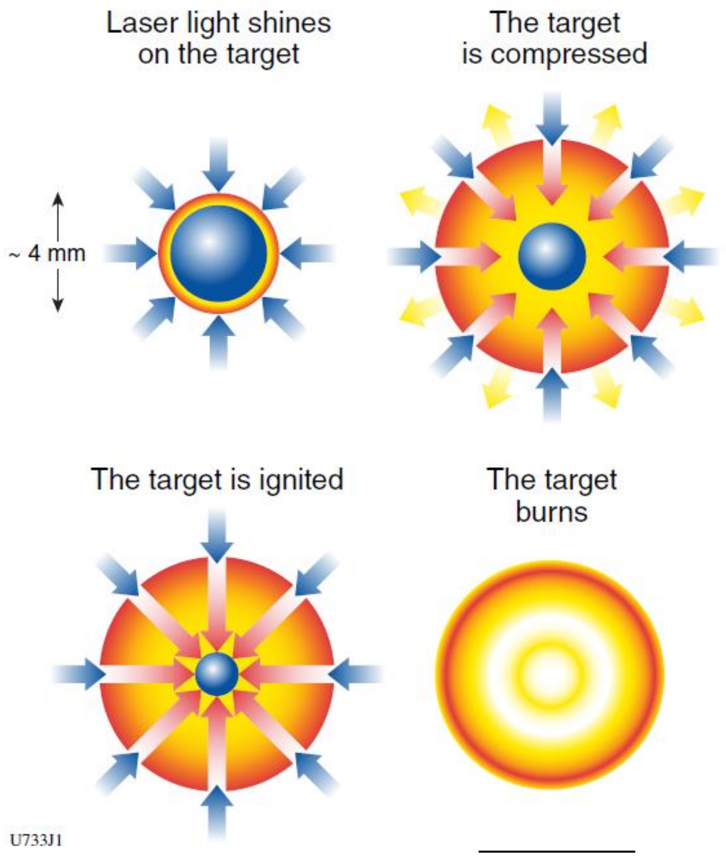
Stellarator



https://www.euro-fusion.org/2011/09/tokamak-principle-2/
https://en.wikipedia.org/wiki/Stellarator

Don’t confine it!

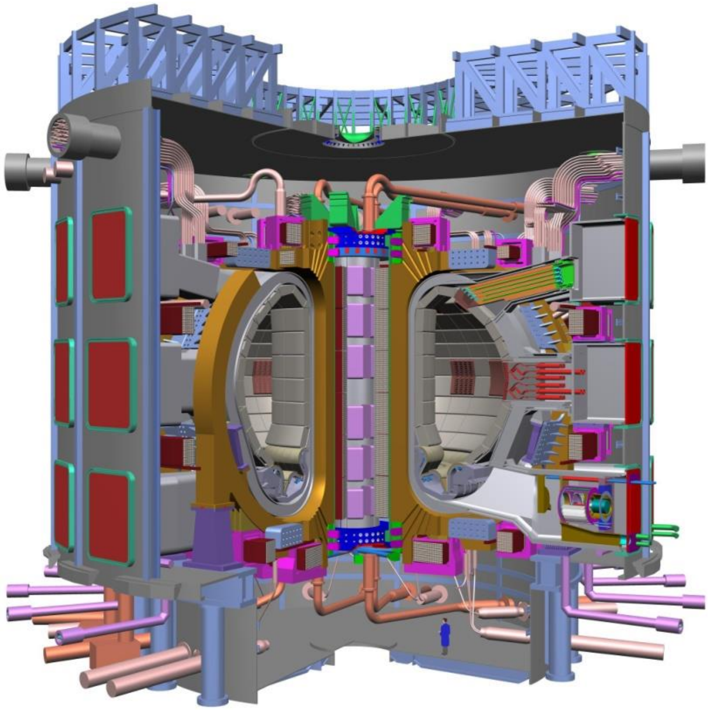
- **Solution 2: Inertial confinement fusion (ICF). Or you can say it is confined by its own inertia: P~Gigabar, τ~nsec, T~10 keV (10^8 ⁰C)**



Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

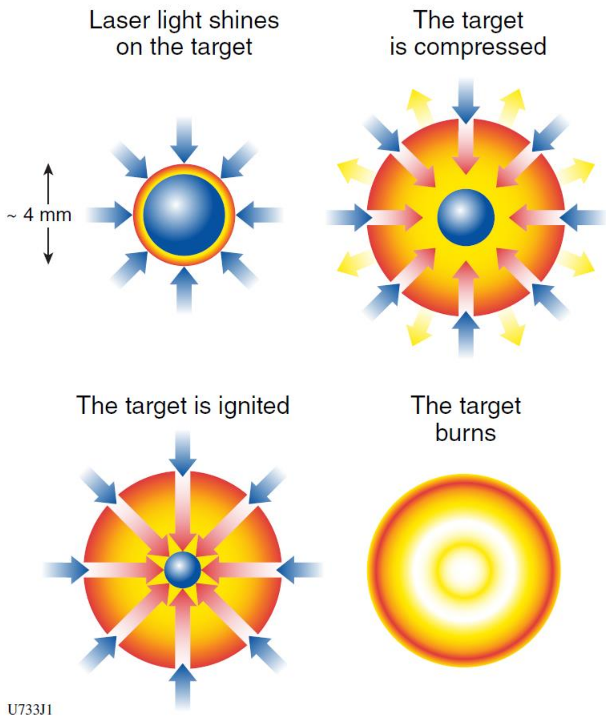
To control? Or not to control?

- Magnetic confinement fusion (MCF)



- Plasma is confined by toroidal magnetic field.

- Inertial confinement fusion (ICF)



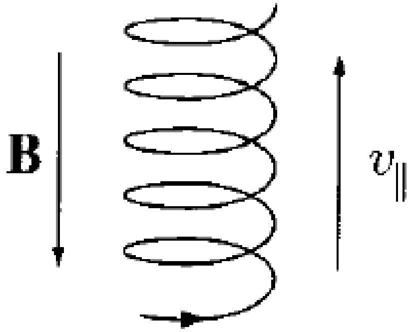
- A DT ice capsule filled with DT gas is imploded by laser.

Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion

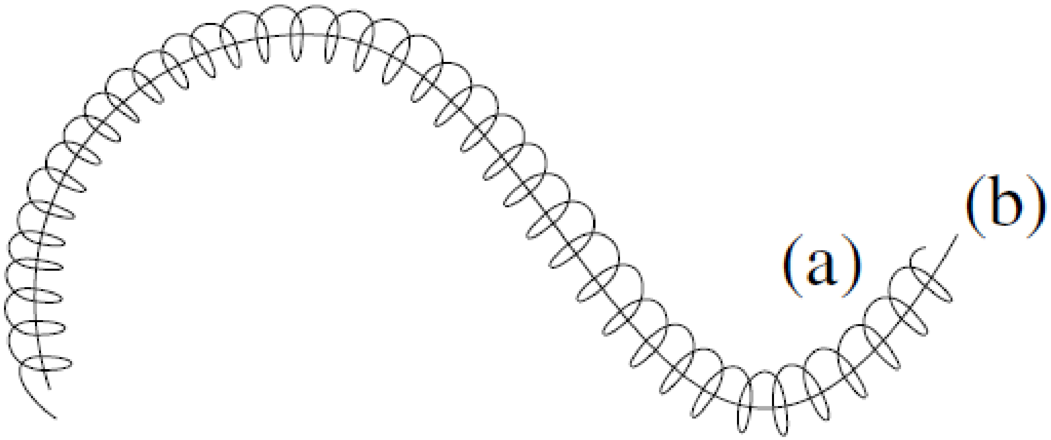
Outline

- Introduction to nuclear fusion
- **Magnetic confinement fusion (MCF)**
  - **Tokamak**
  - **Stellarator**
- Inertial confinement fusion (ICF)
  - Indirection drive ICF
  - Direct drive ICF
- Innovation idea – MCF + ICF
- Plasma in space
- Pulsed-power system at NCKU

Charged particles gyro around the magnetic fields

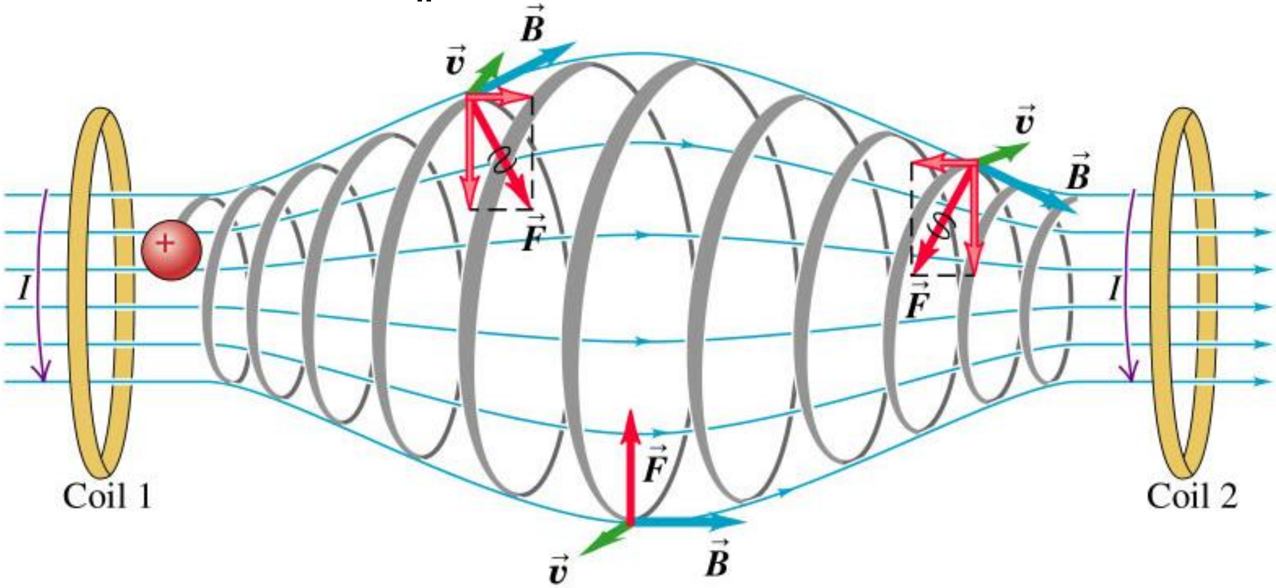


$$r_L = \frac{mv_{\perp}}{|q|B}$$



Charged particles can be partially confined by a magnetic mirror machine

- **Charged particles with small $v_{||}$ eventually stop and are reflected while those with large $v_{||}$ escape.**



$$\frac{1}{2}mv^2 = \frac{1}{2}m{v_{||}}^2 + \frac{1}{2}m{v_{\perp}}^2$$

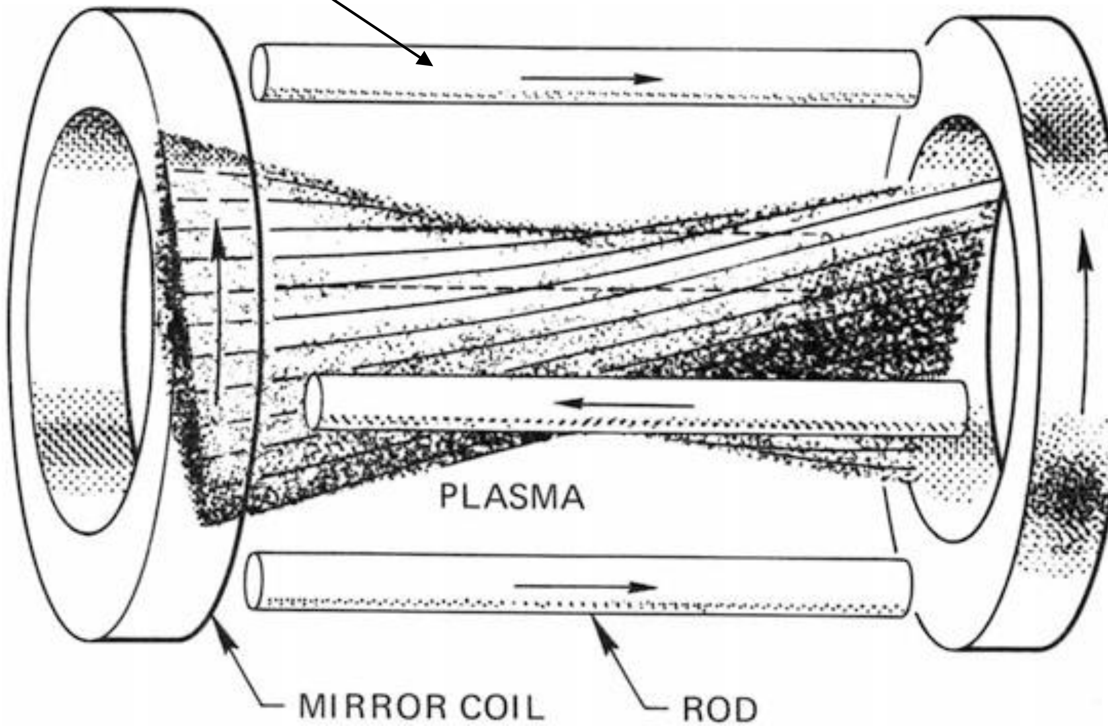
- **Large $v_{||}$ may occur from collisions between particles.**

- **Those confined charged particle are eventually lost due to collisions.**

https://i.stack.imgur.com/GlzGZ.jpg

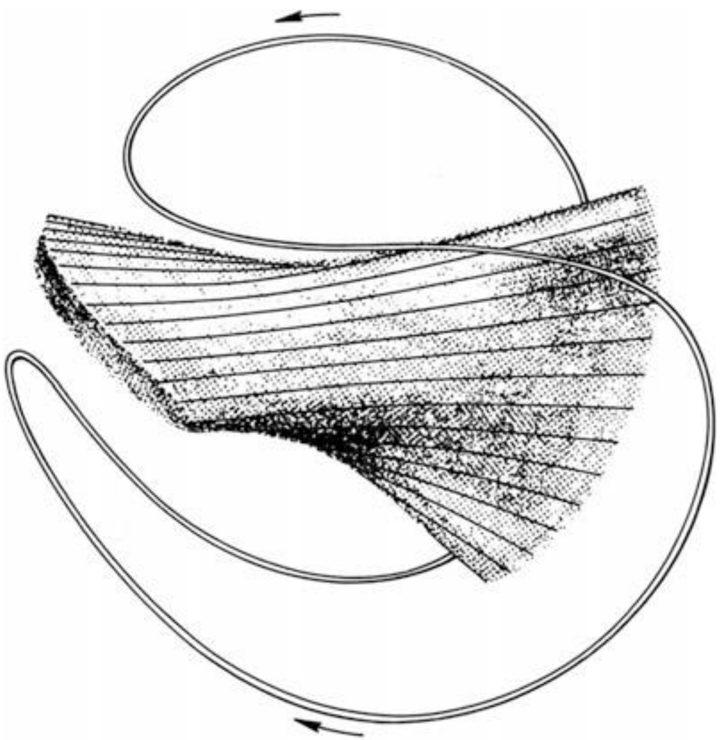
"Ioffe bars" are added to stabilize the Rayleigh-Taylor instabilities at the center of the mirror machine

Ioffe bars



A "baseball coil" is obtained if one links the coils and the bars into a single conductor

- **Baseball coil**

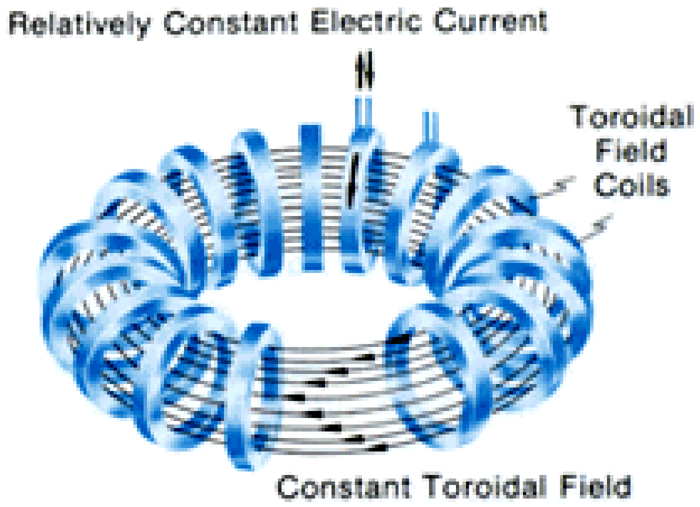


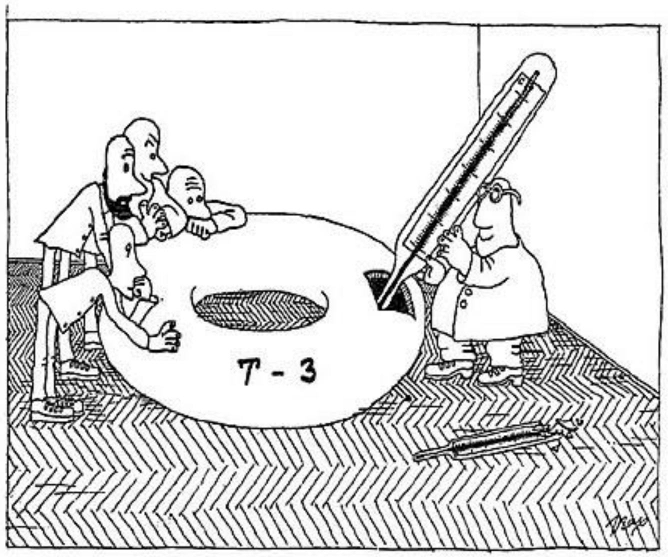
- **MFTF-B mirror machine**

Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

Plasma can be confined in a doughnut-shaped chamber with toroidal magnetic field

- **Tokamak - "toroidal chamber with magnetic coils" (тороидальная камера с магнитными катушками)**

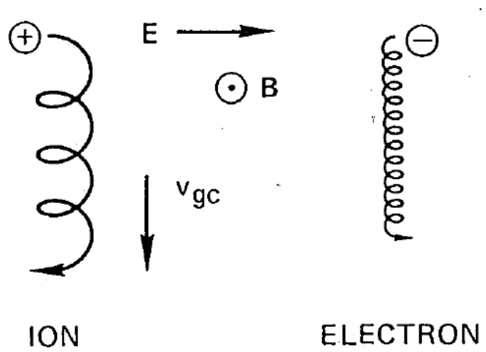




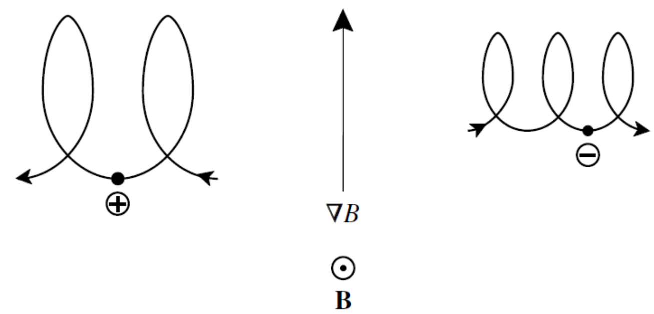
https://www.iter.org/mach/tokamak
https://en.wikipedia.org/wiki/Tokamak#cite_ref-4
Drawing from the talk “Evolution of the Tokamak” given in 1988 by B.B. Kadomtsev at Culham.

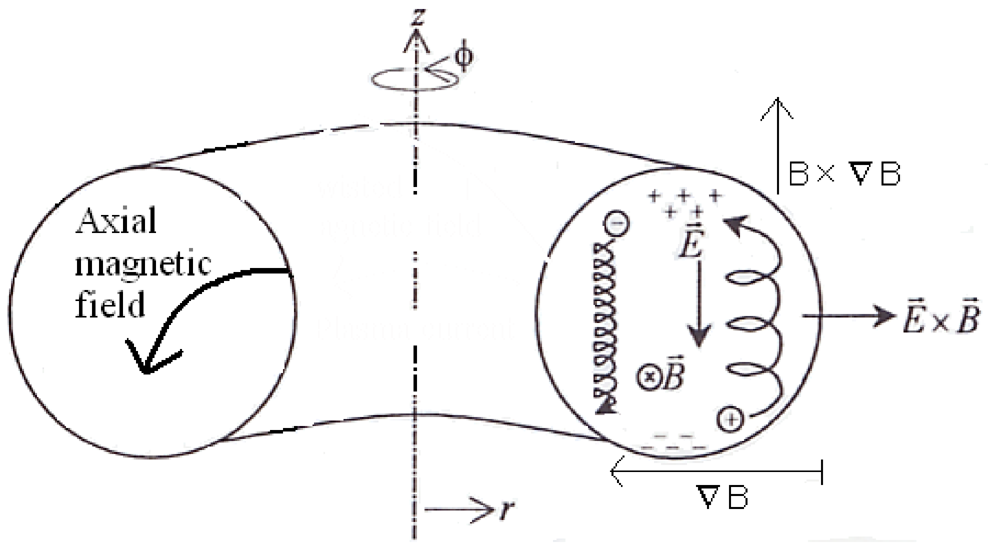
Charged particles drift across field lines

- **ExB drift**



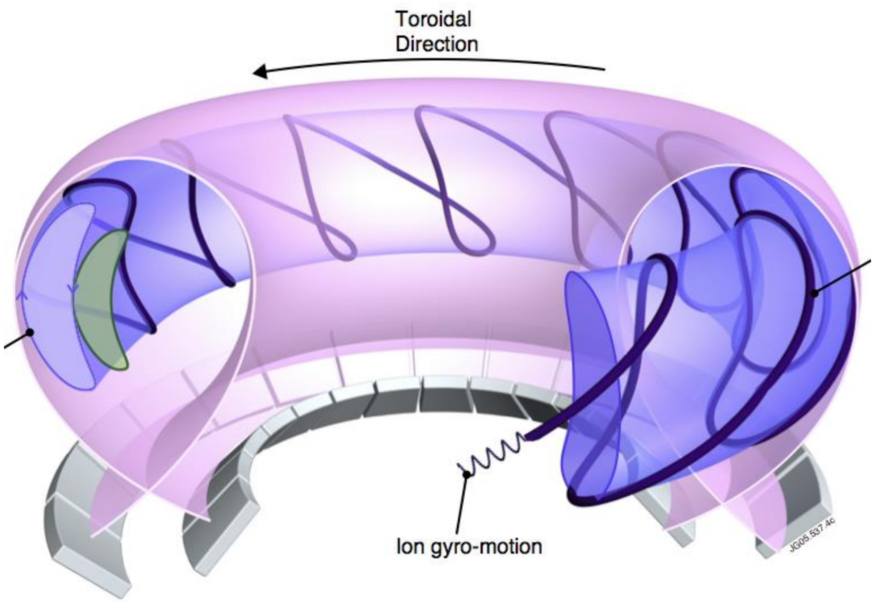
- **Grad-B drift**

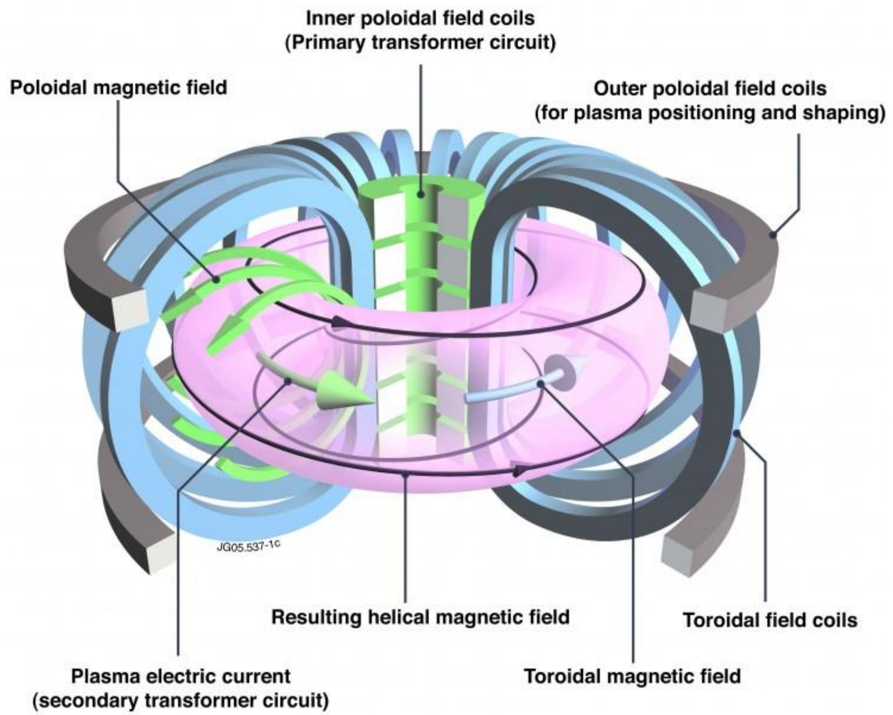




http://www.geocities.jp/tomoyahirata417/fusion/gennkou.htm

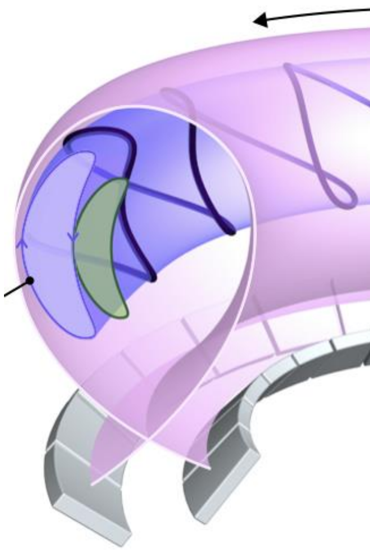
A poloidal magnetic field is required to reduce the drift across field lines

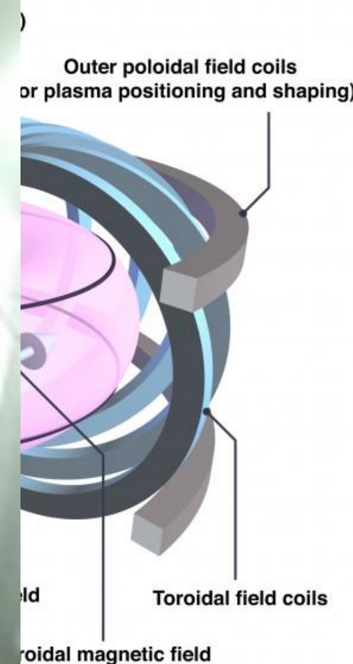




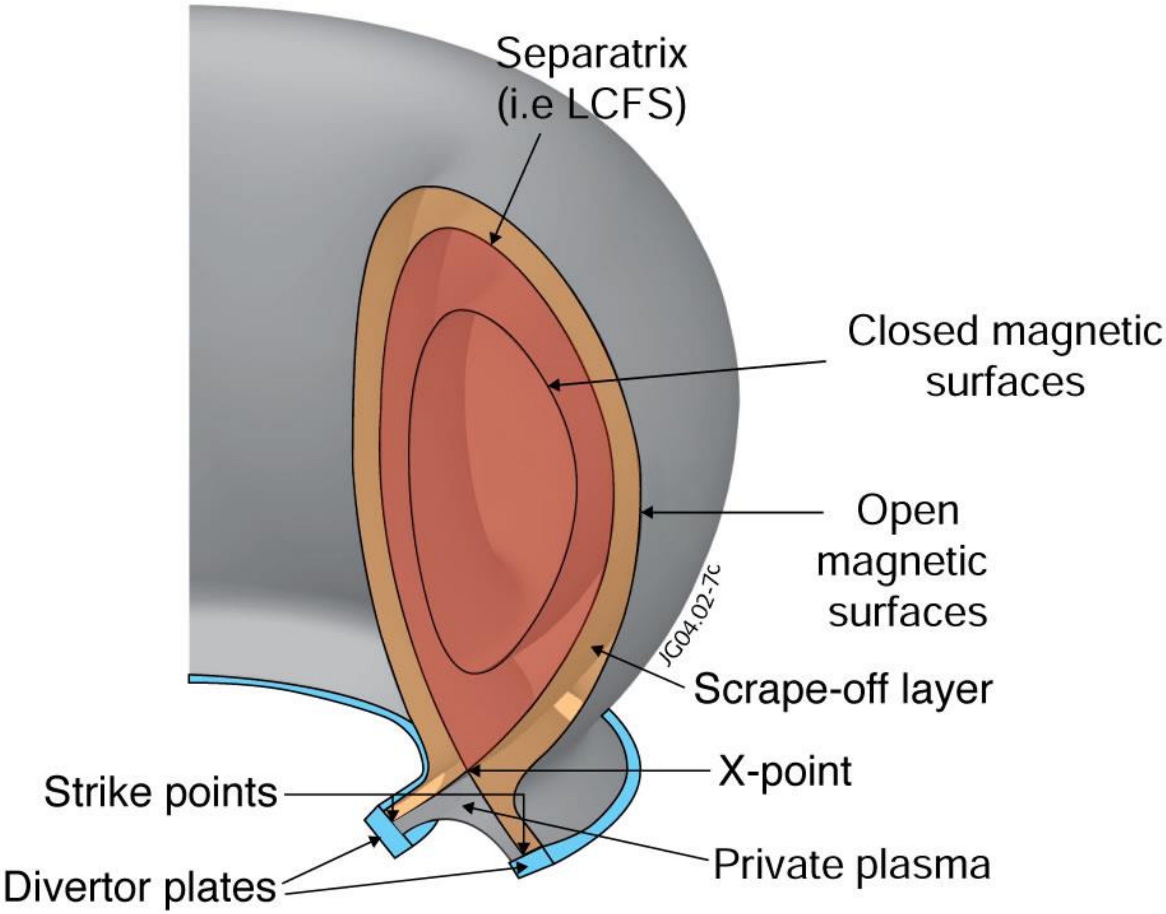
https://www.davidpace.com/keeping-fusion-plasmas-hot/
https://www.euro-fusion.org/2011/09/tokamak-principle-2/

A poloidal magnetic field is required to reduce the drift across field lines



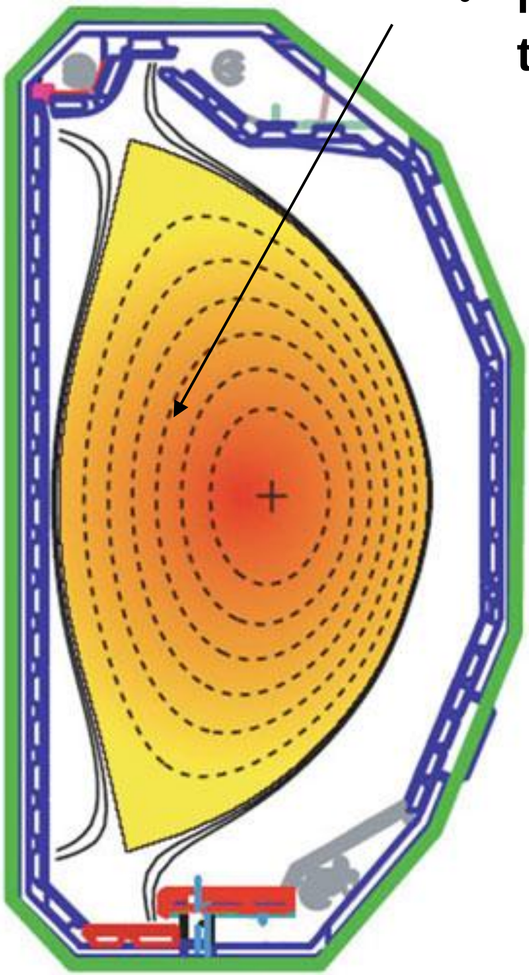


A divertor is needed to remove impurities and the power that escapes from the plasma



https://www.euro-fusion.org/newsletter/divertor-concepts/

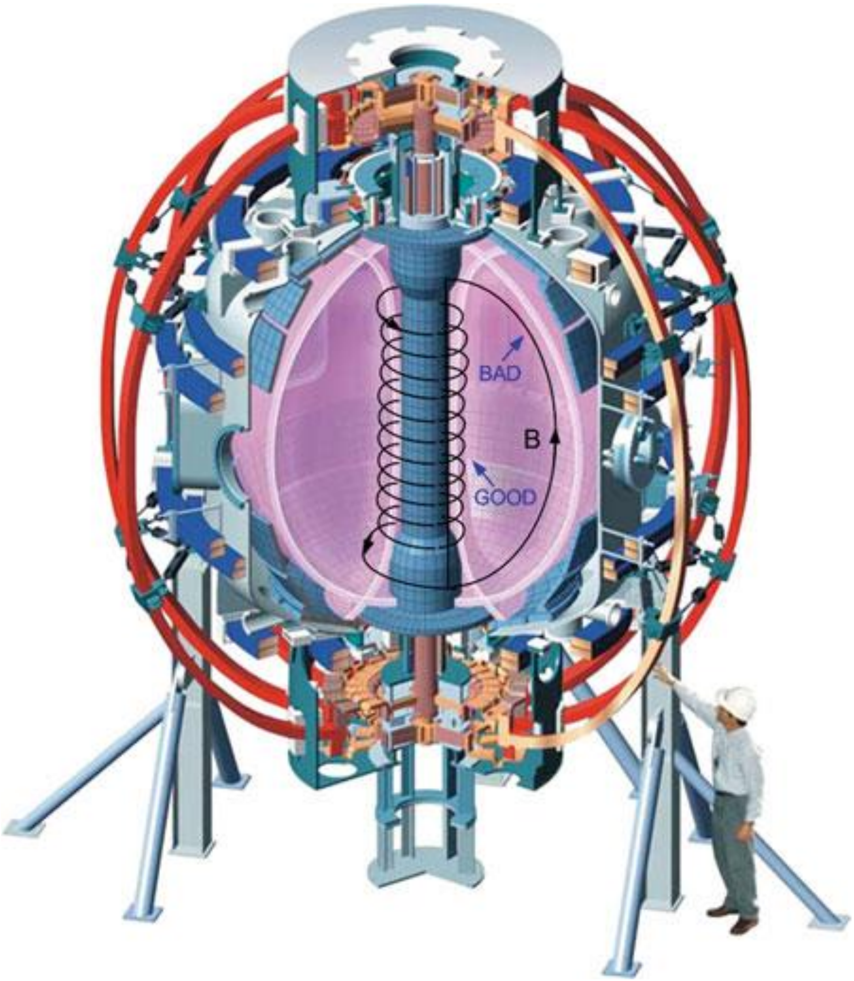
D-shaped tokamak with diverter is more preferred nowadays



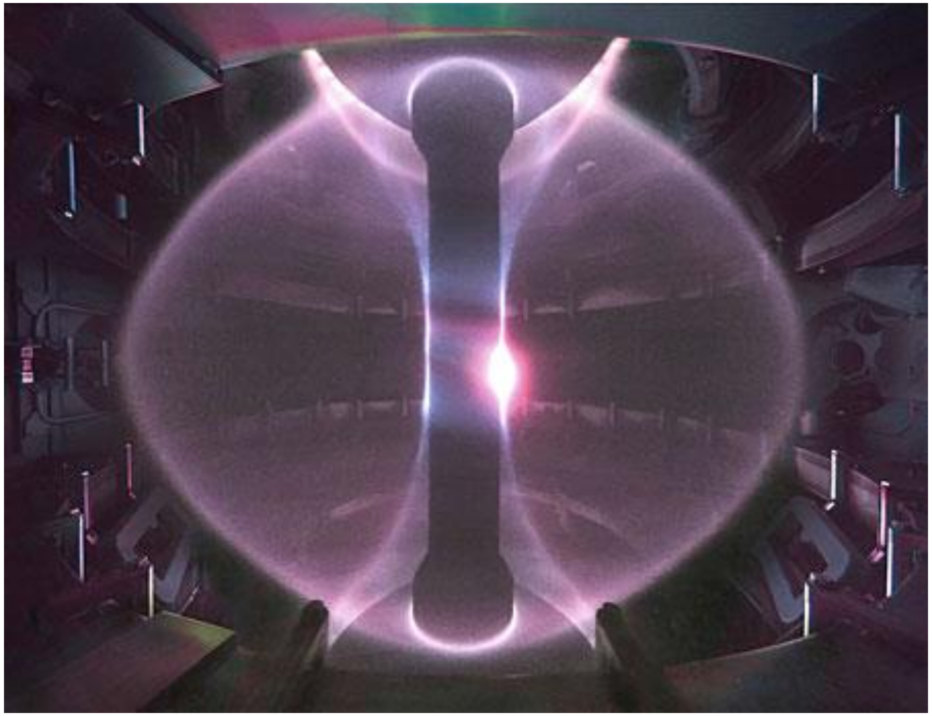
- **Make the plasma closer to the major axis**

Spherical tokamak is formed when the aspect ratio of a tokamak is reduced to the order of unity

- **NSTX @ Princeton**

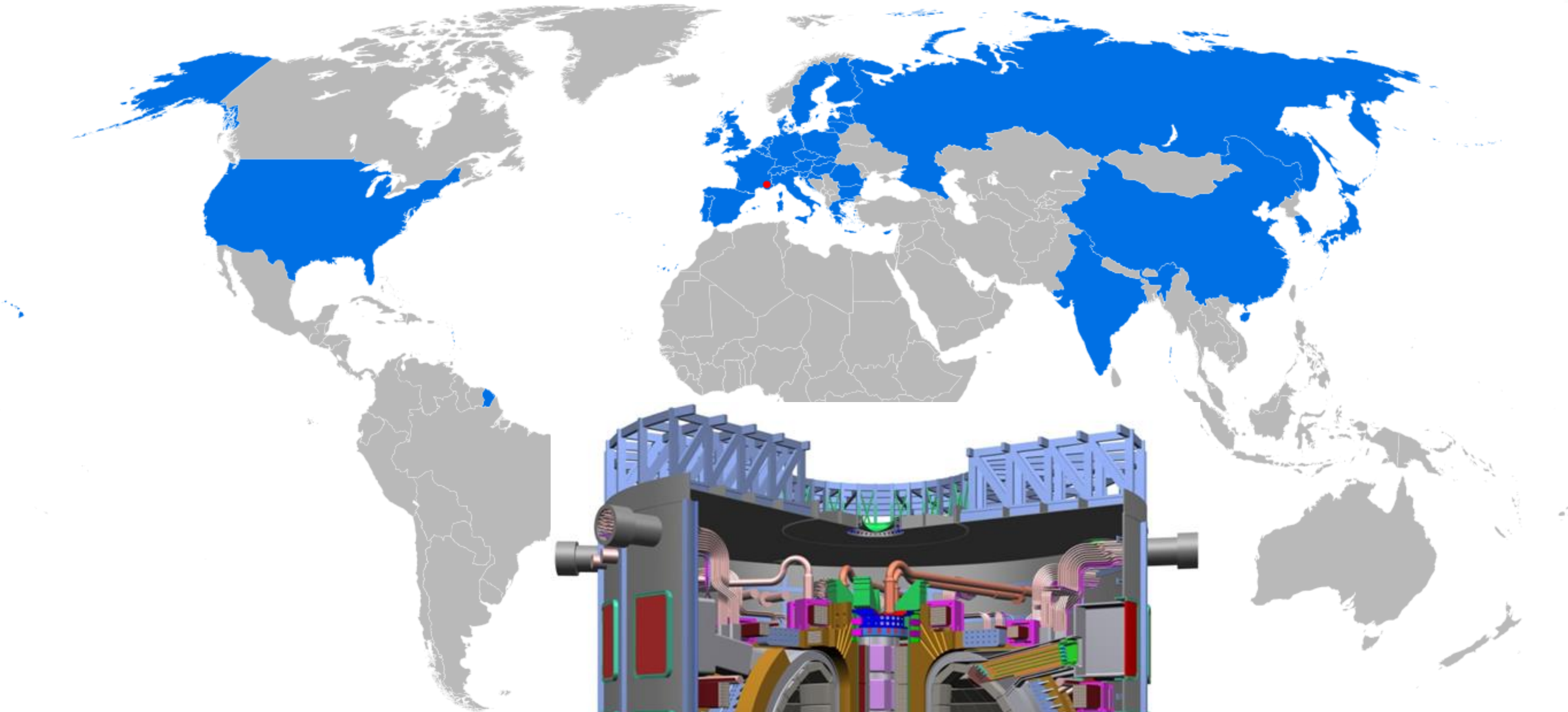


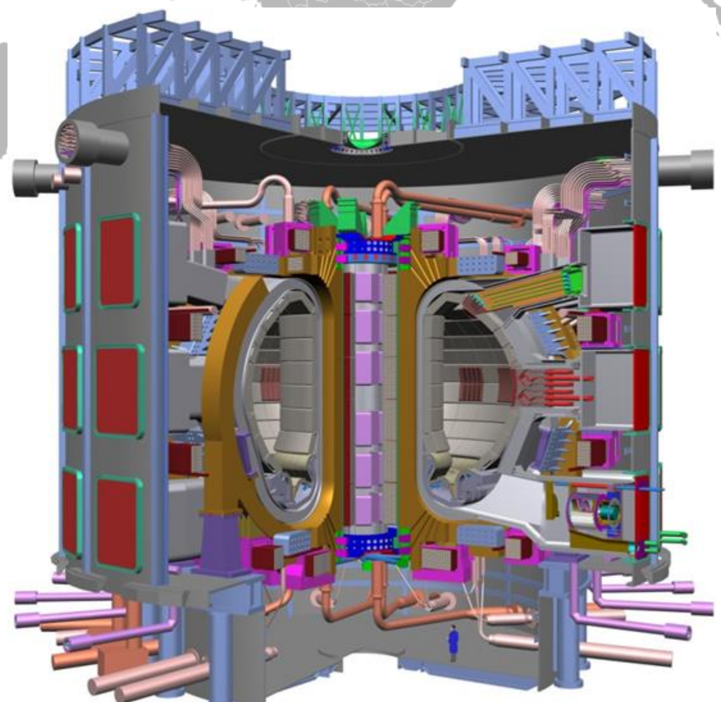
- **MegaAmpere Spherical Tokamak (MAST) @ Culham center for fusion energy, UK**



Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

ITER ("The Way" in Latin) is one of the most ambitious energy projects in the world today

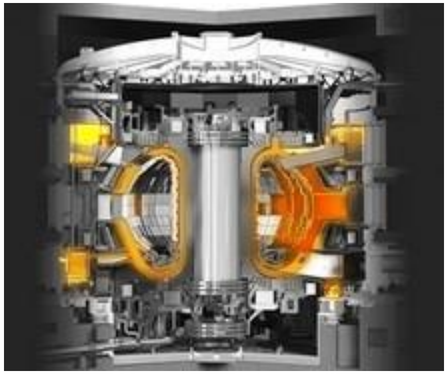




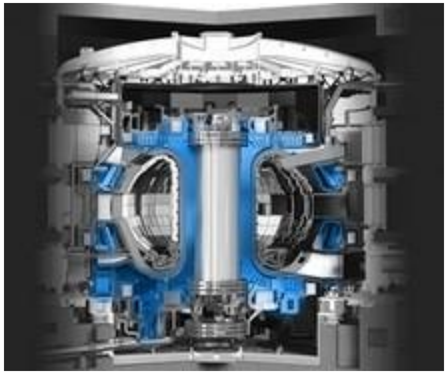
https://www.iter.org

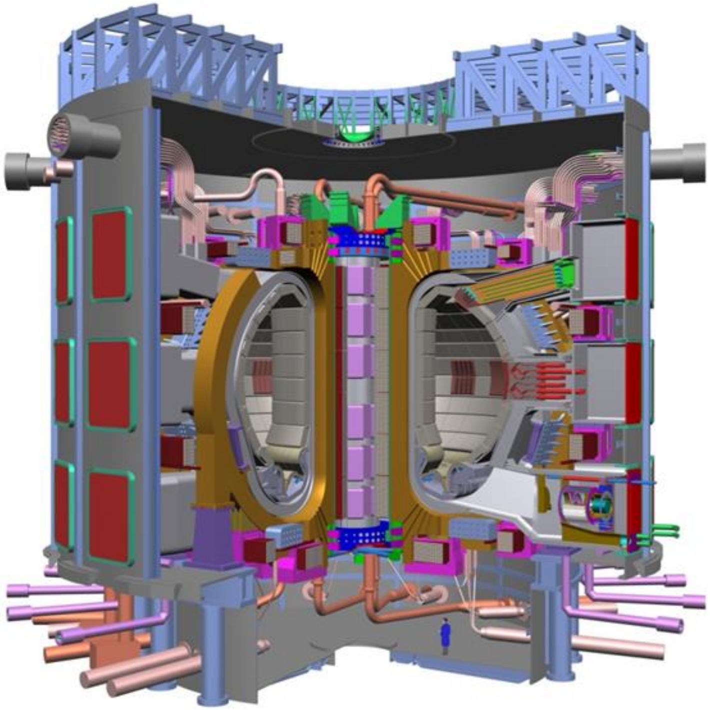
ITER ("The Way" in Latin) is one of the most ambitious energy projects in the world today

- **Vacuum vessel**

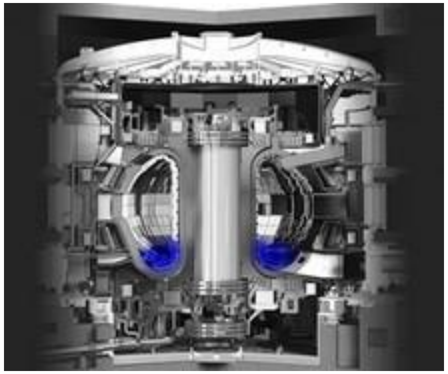


- **Magnets**

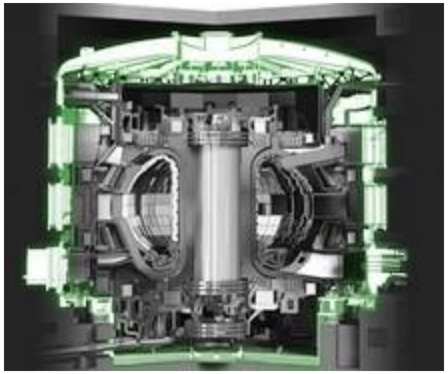




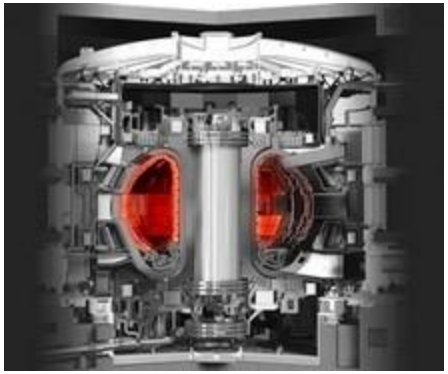
- **Divertor**



- **Cryostat**



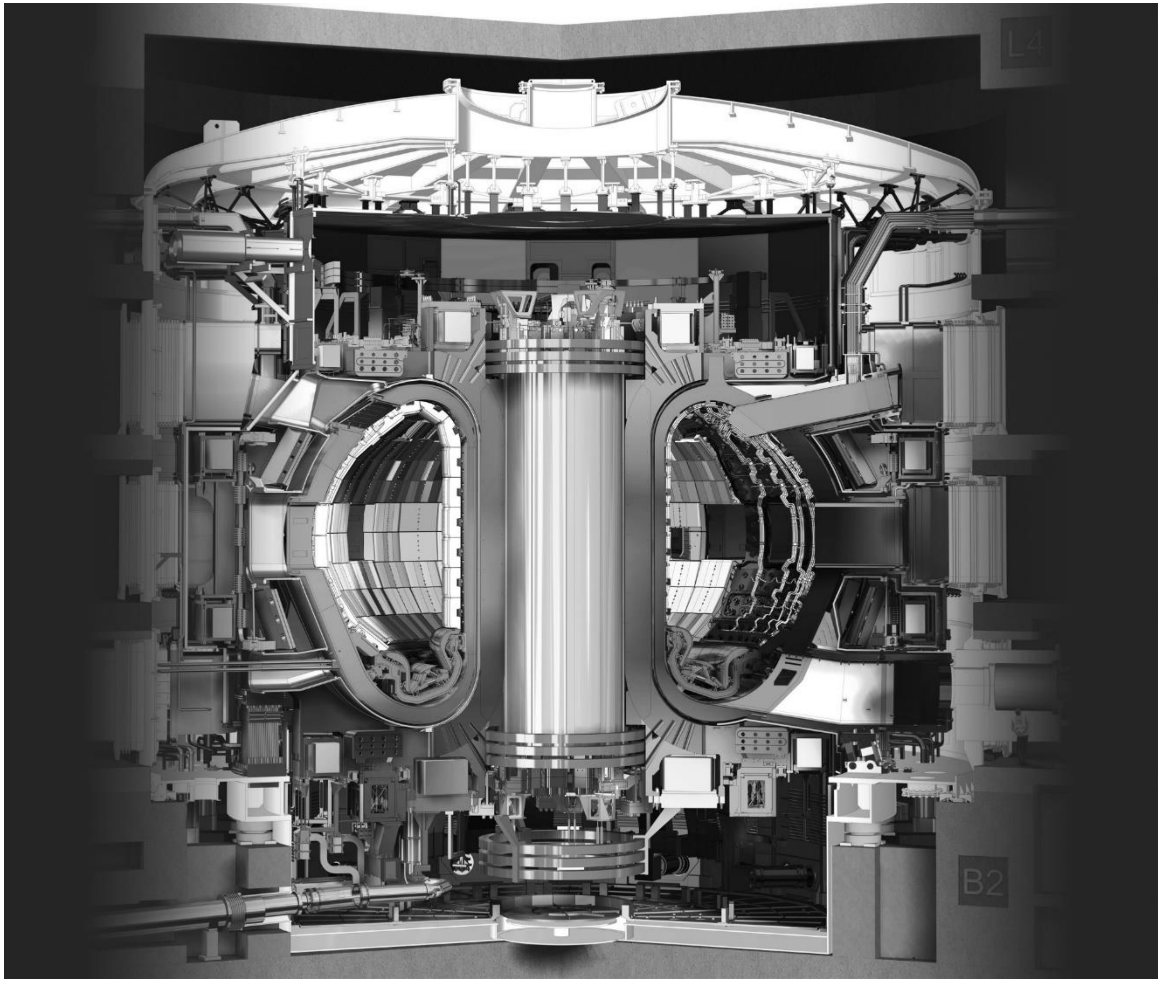
- **Blanket**



https://www.iter.org/

ITER

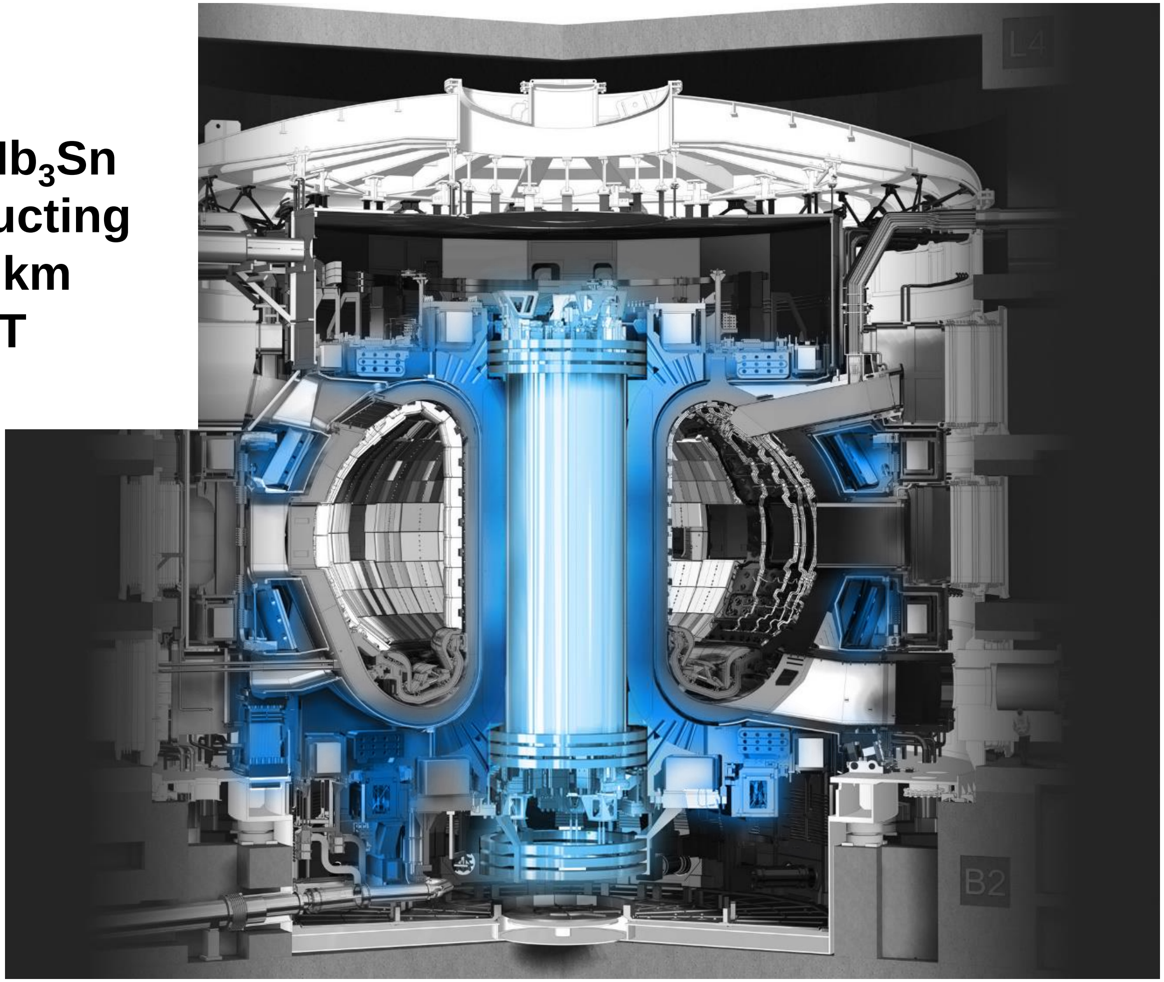
- **T=150M ^{0}C**
- **P=500 MW**



https://www.iter.org

ITER – Magnets

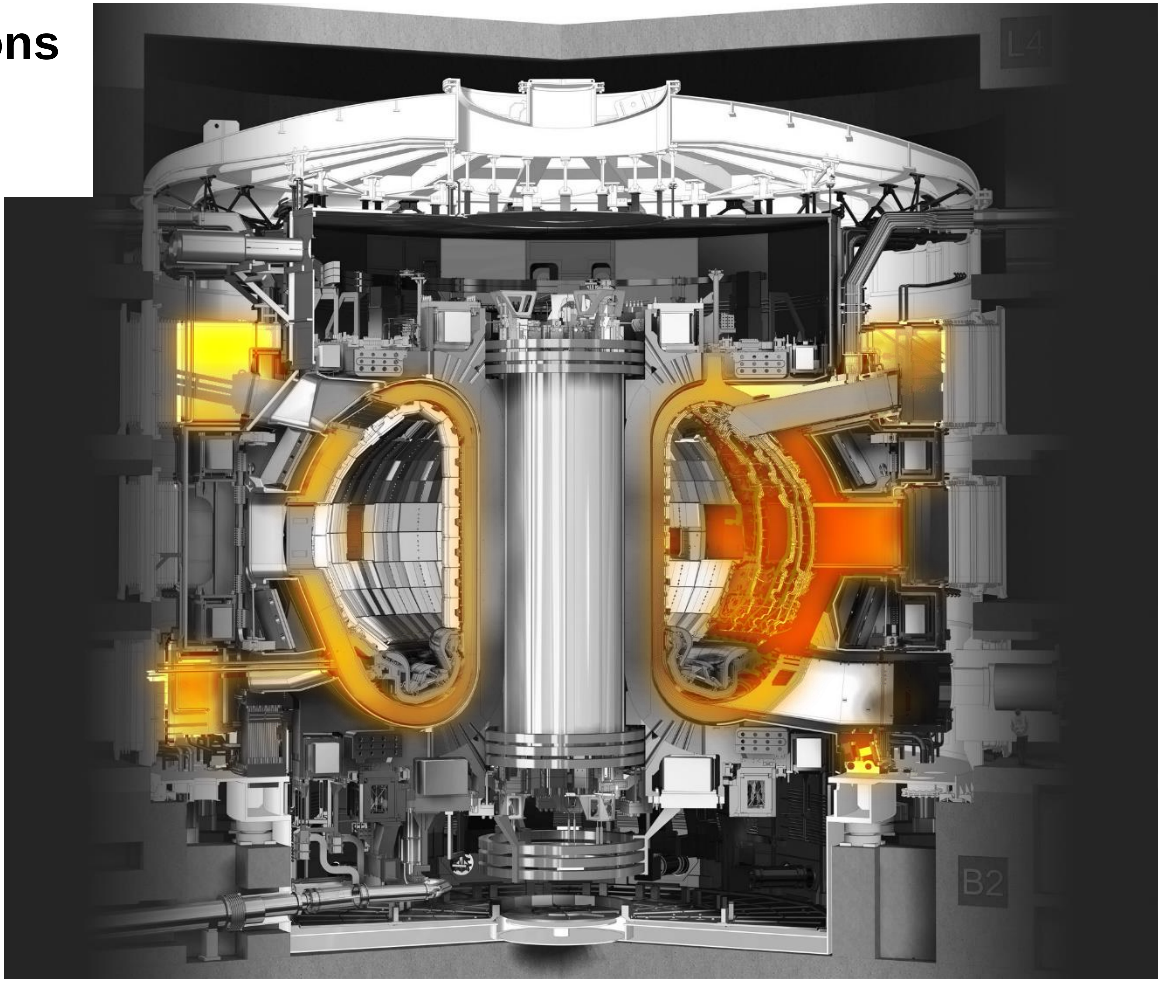
- E_B=51 GJ
- T_B=4 K
- Length of Nb_3Sn superconducting strand: 10^5 km
- $B_{T,max}$=11.8 T
- $B_{P,max}$=6 T



https://www.iter.org

ITER – Vacuum vessel

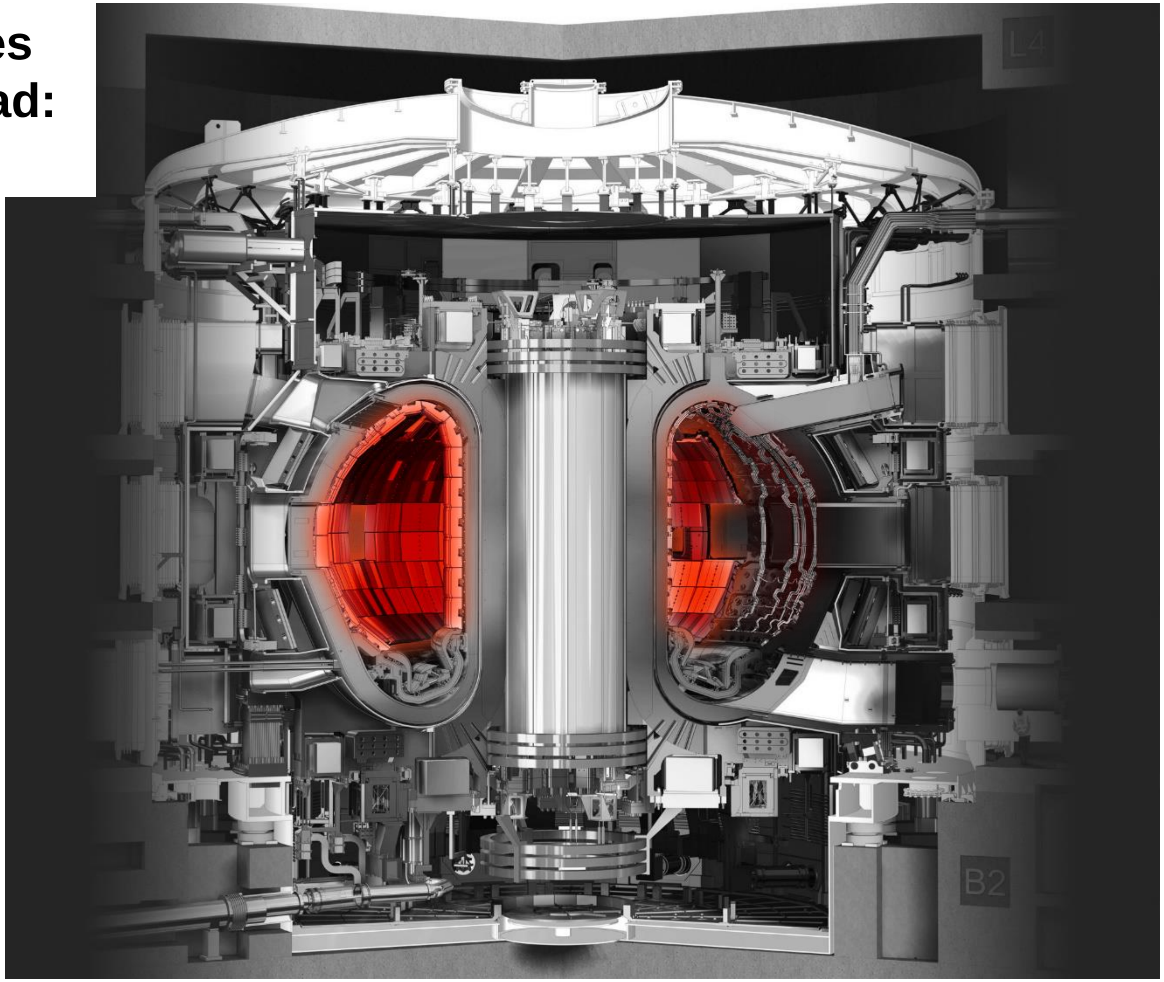
- **W = 8000 tons**
- **V = 840 m^3**
- **R = 6 m**



https://www.iter.org

ITER – Blanket

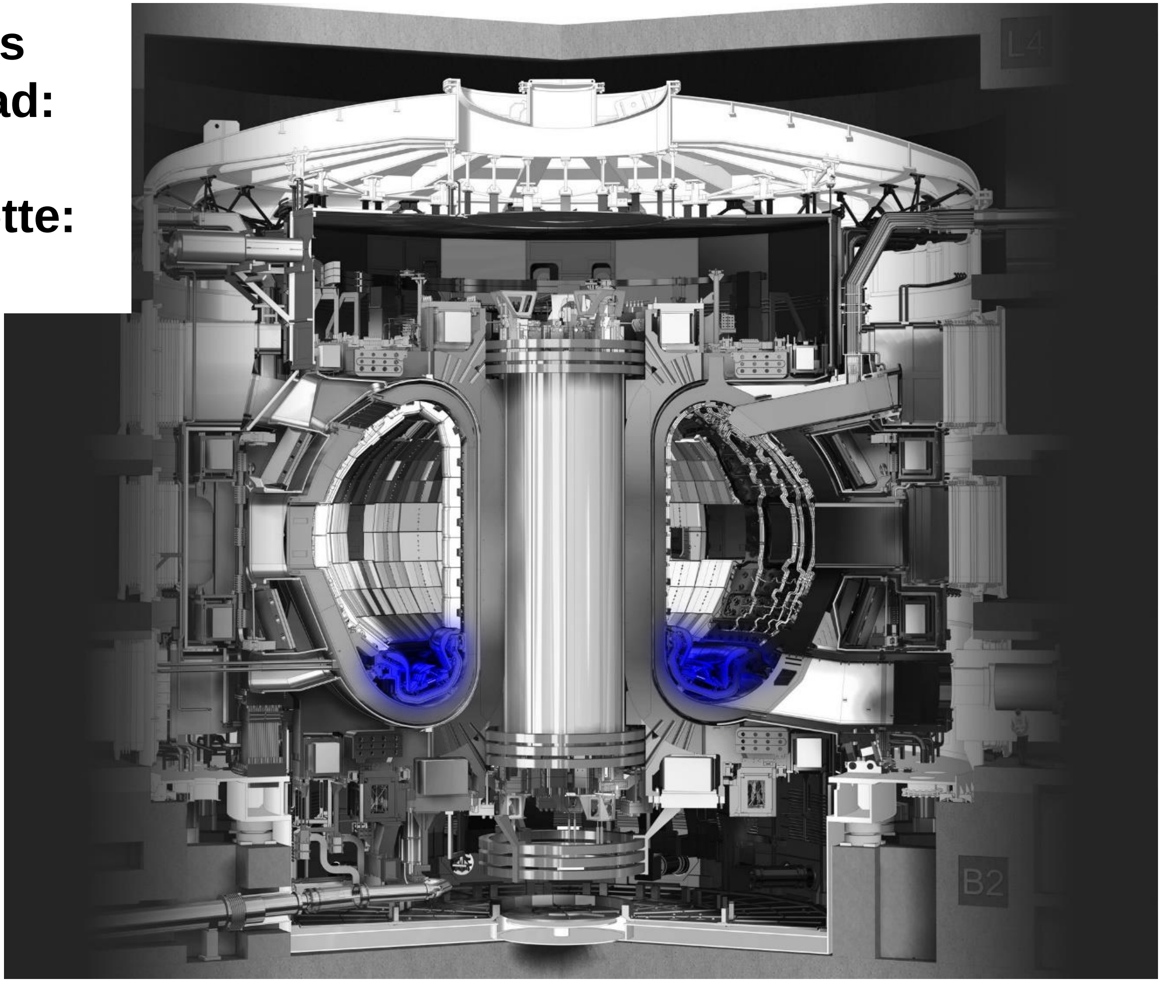
- **440 modules**
- **Thermal load: 736 MW**



https://www.iter.org

ITER – Divertor

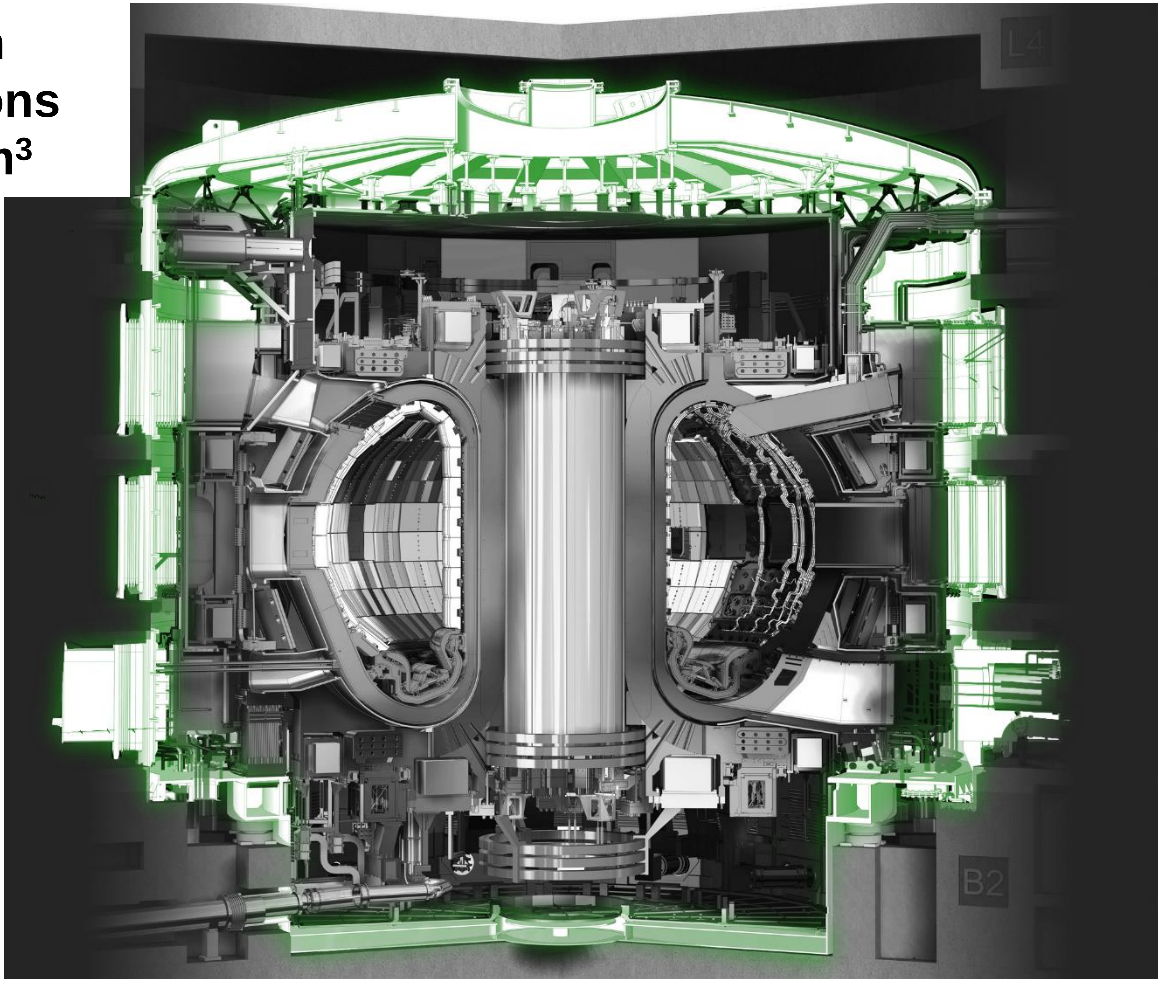
- **54 cassettes**
- **Thermal load: 20 MW/m^2**
- **Each cassette: 10 tons**



https://www.iter.org

ITER – Crystat

- **P = 10^{-6} atm**
- **W = 3800 tons**
- **V = 16000 m^3**

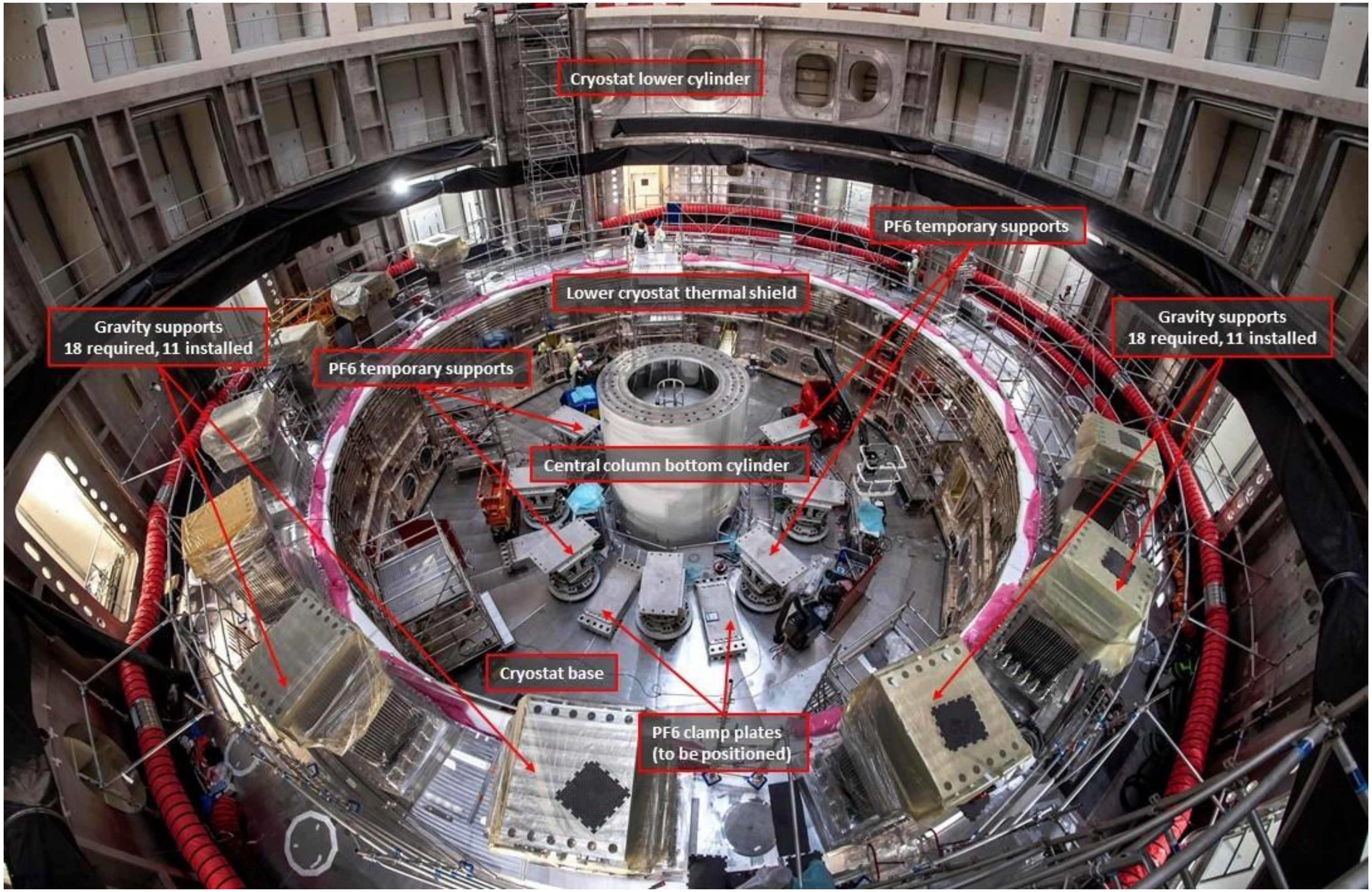


https://www.iter.org

Supporting systems

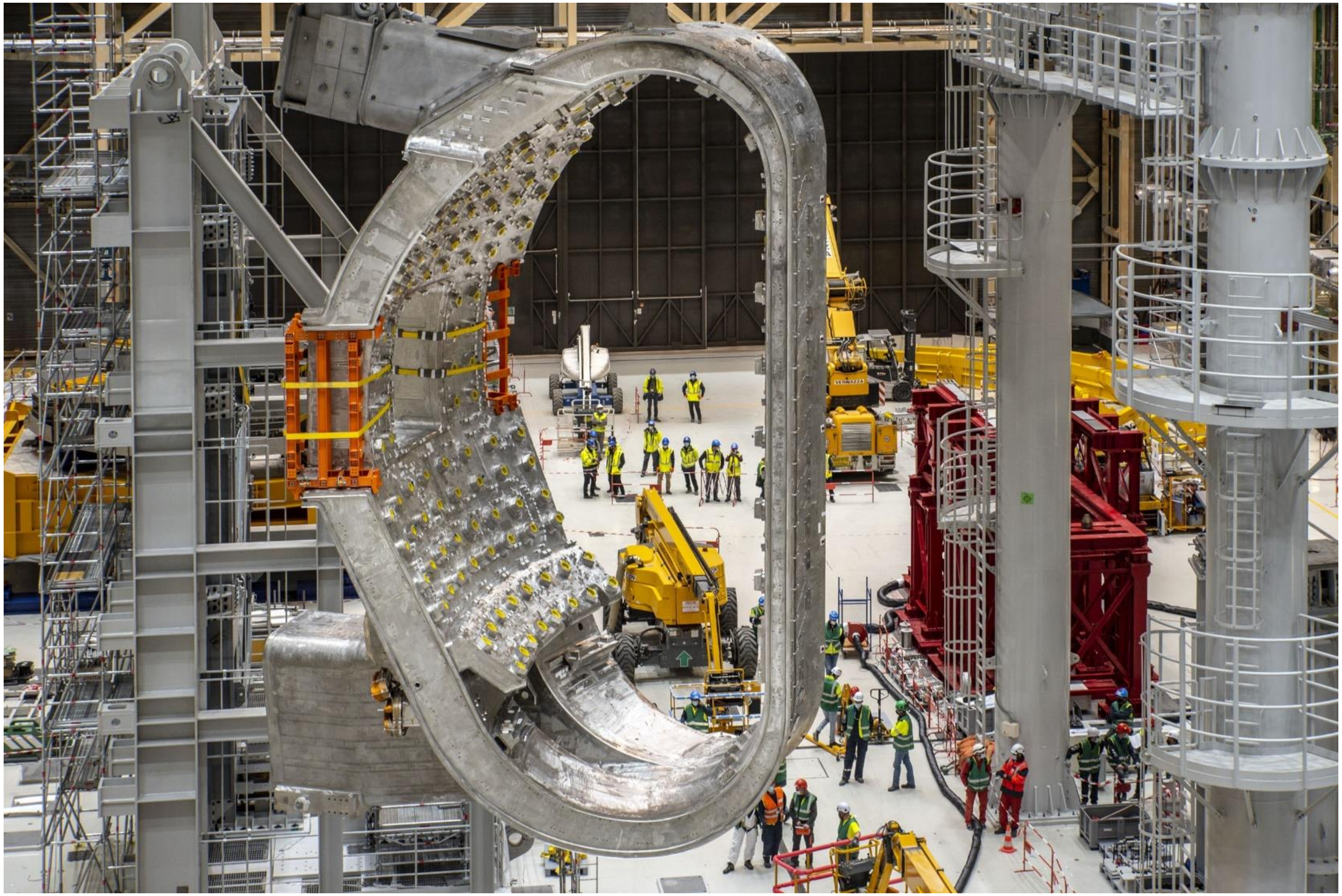
- Tritium breeding
- Control, Data access and Communication (CODAC)
- Cooling water
- Cryogenics
- Diagnostics
- Fuel cycle
- Hot cell - a secure environment for processing, repair or testing, etc., of components that have become activated by neutrons.
- Power supply
- Remote handling
- Heating and current drive
- Vacuum system

ITER is being assembled



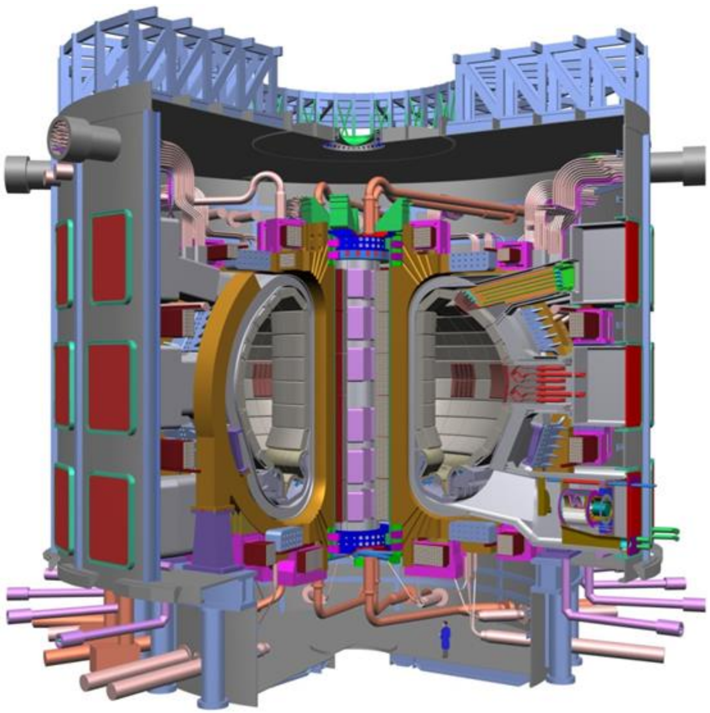
https://www.iter.org

ITER is being assembled



https://www.iter.org

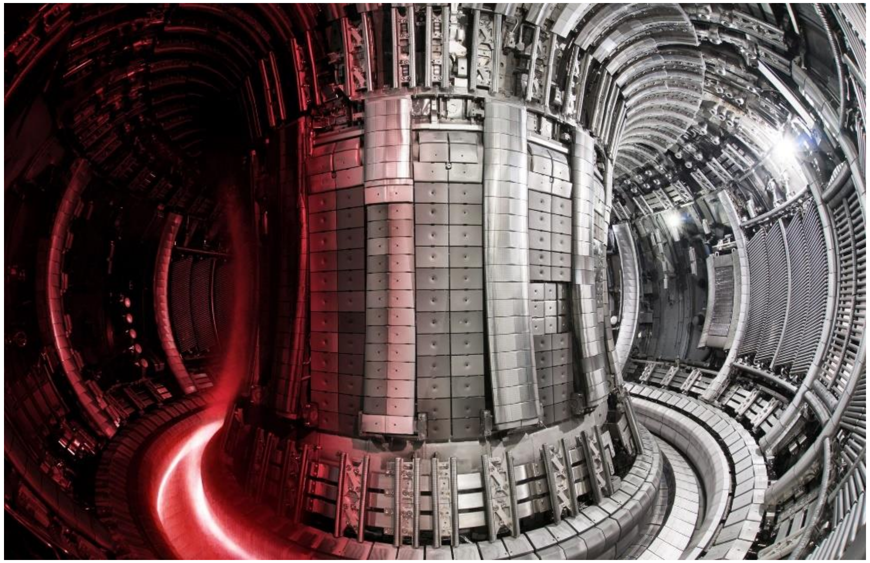
There is a long way to go, but we are on the right path…



- **Dec 2025** **First Plasma**
- **2035** **Deuterium-Tritium Operation begins**

https://www.iter.org

Joint European Torus (JET) facility has a record-breaking 59 megajoules of sustained fusion energy

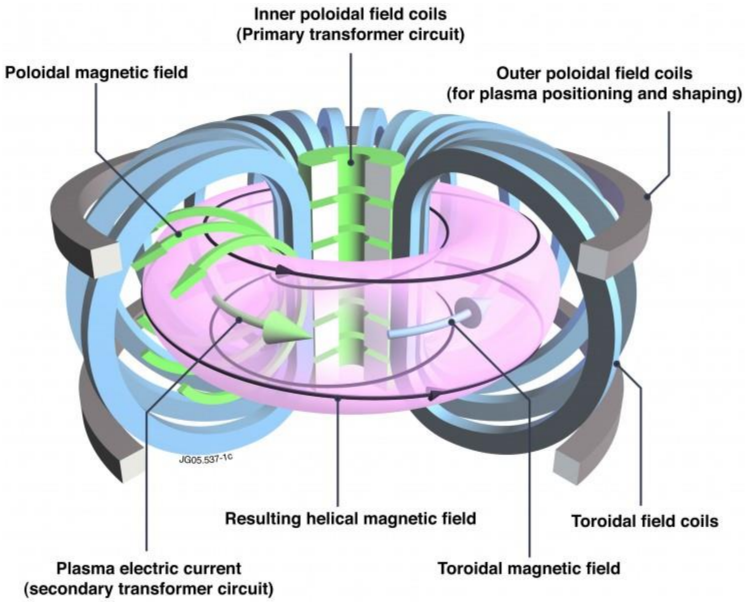


- **Record-breaking 59 megajoules of sustained fusion energy in Joint European Torus (JET) facility in Oxford demonstrates powerplant potential and strengthens case for ITER.**

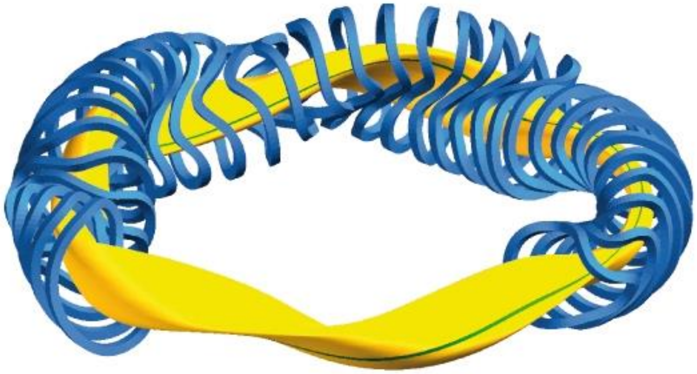
https://ccfe.ukaea.uk/resources/#gallery

Stellarator uses twisted coil to generate poloidal magnetic field

Tokamak

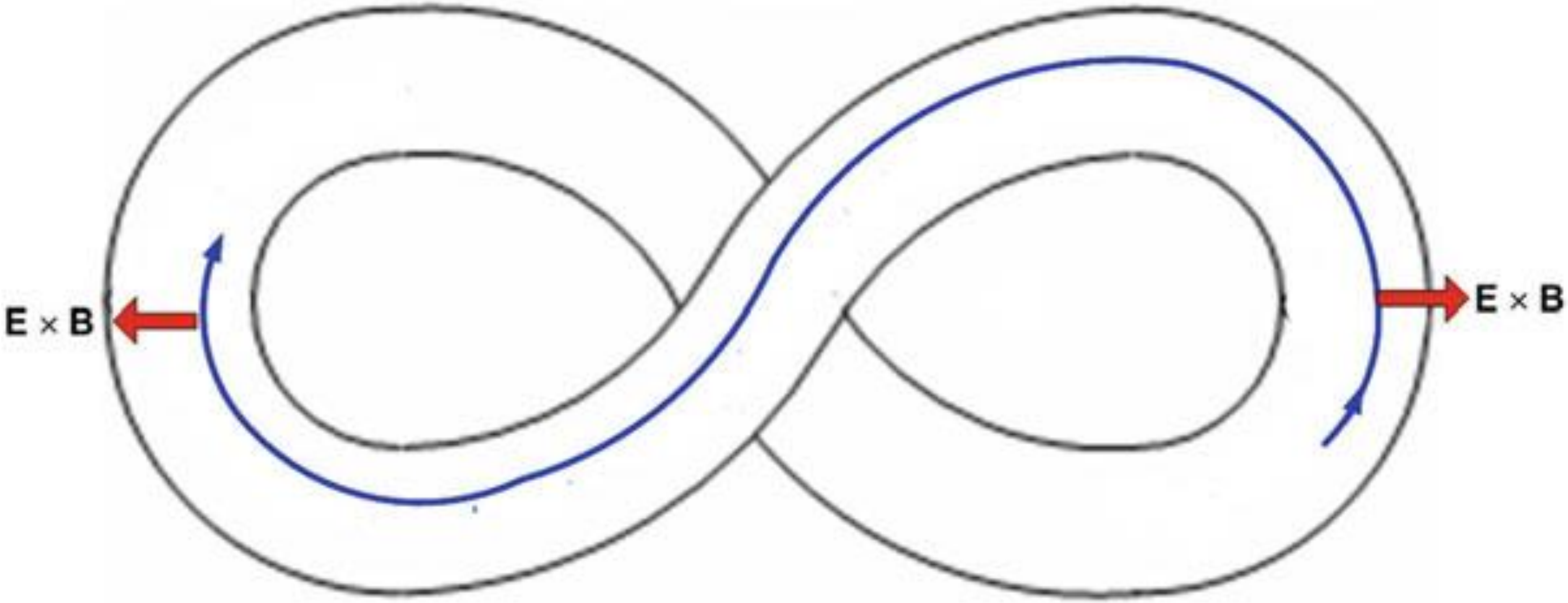


Stellarator



https://www.euro-fusion.org/2011/09/tokamak-principle-2/
https://en.wikipedia.org/wiki/Stellarator

A figure-8 stellarator solved the drift issues

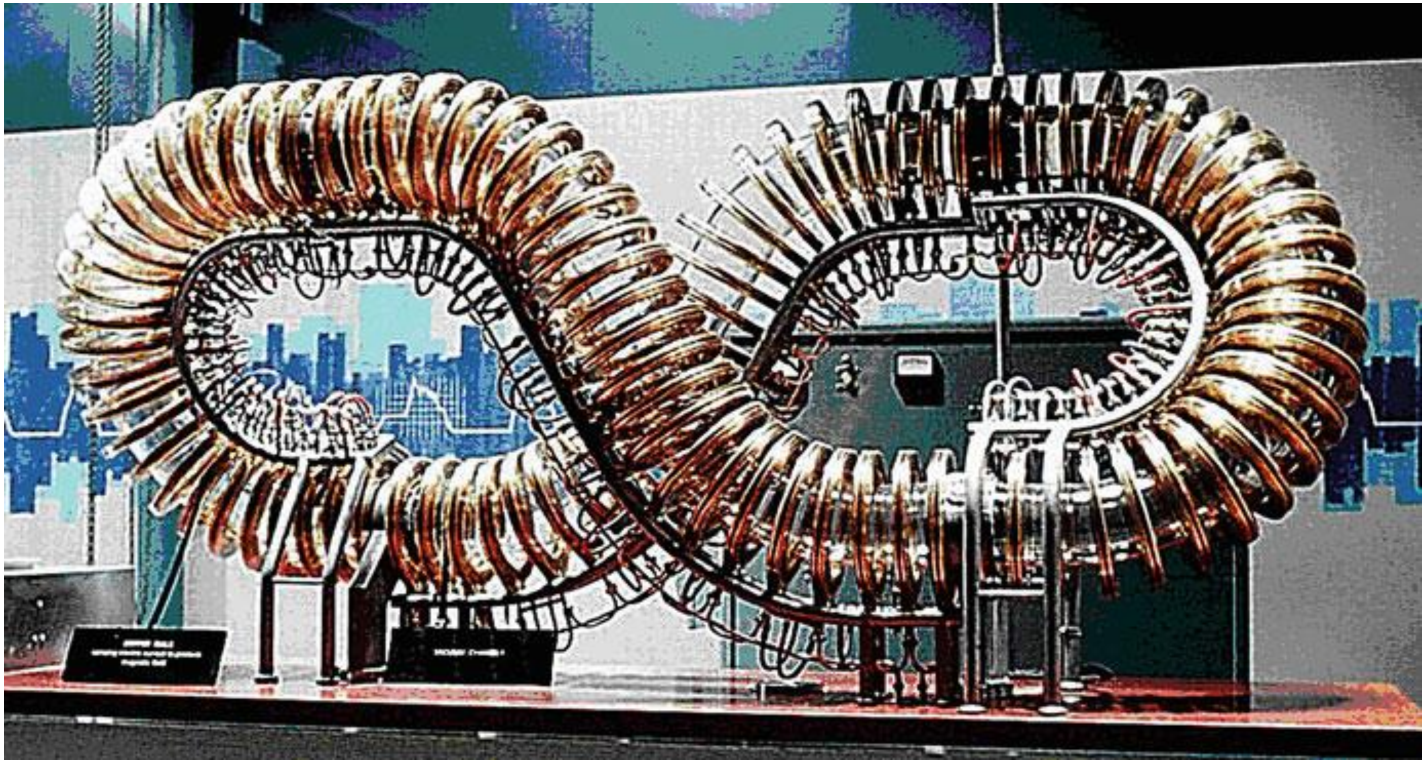


A figure-8 stellarator solved the drift issues

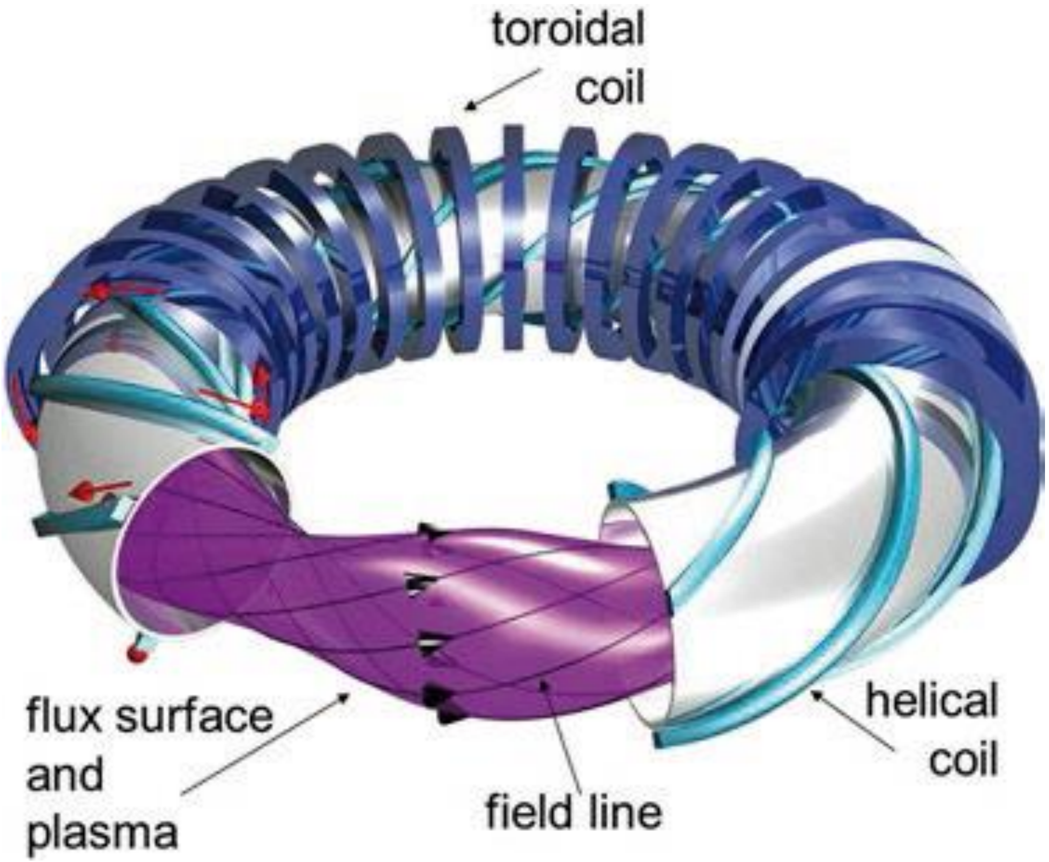
Lyman Spitzer, Jr. came out the idea during a long ride on a ski lift at Garmisch-Partenkirchen

https://www.snowtrex.de/magazin/skigebiete/garmisch-classic-zugspitze/

Exhibit model of a figure-8 stellarator for the Atoms for Peace conference in Geneva in 1958

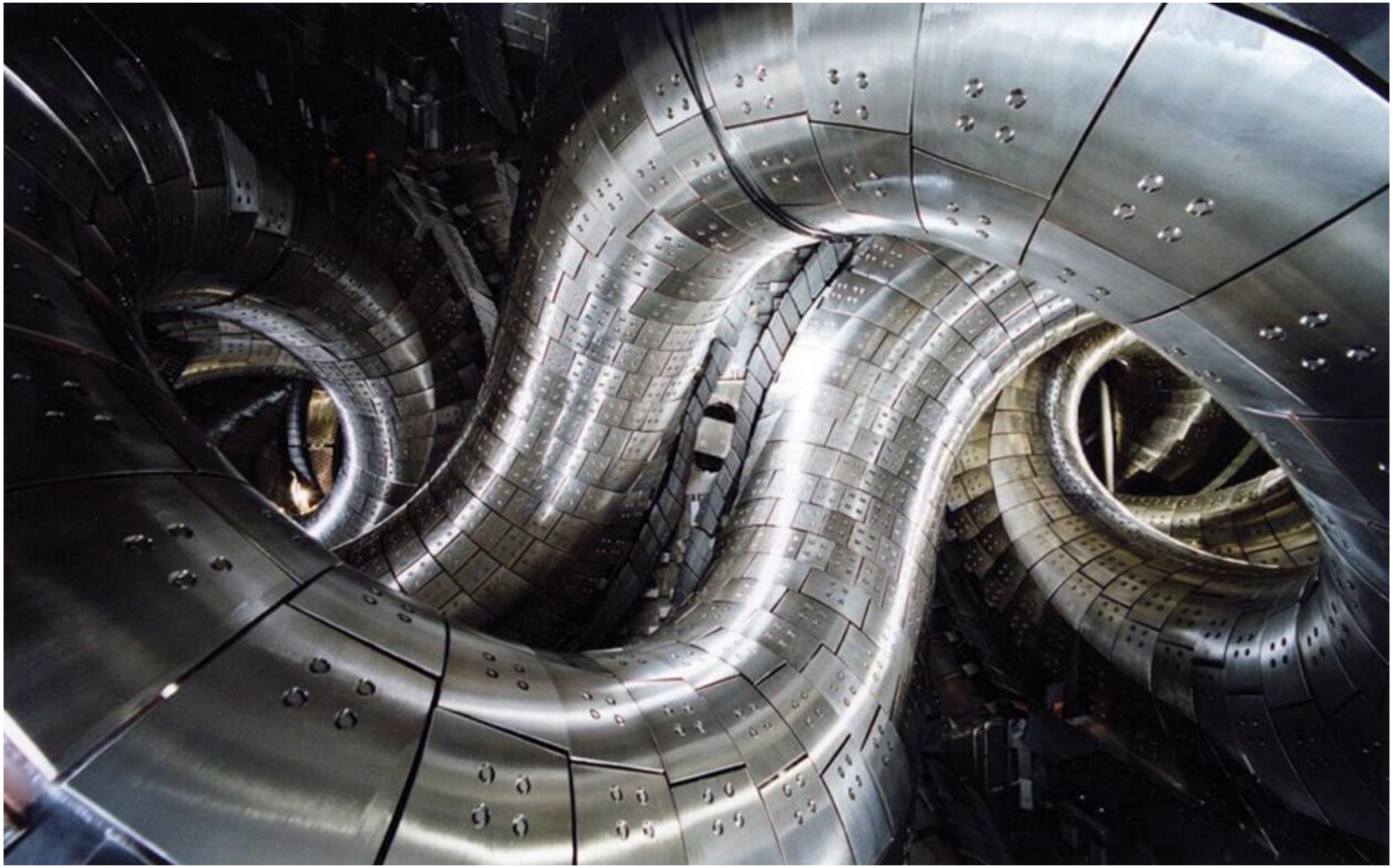


Twisted magnetic field lines can be provided by toroidal coils with helical coils



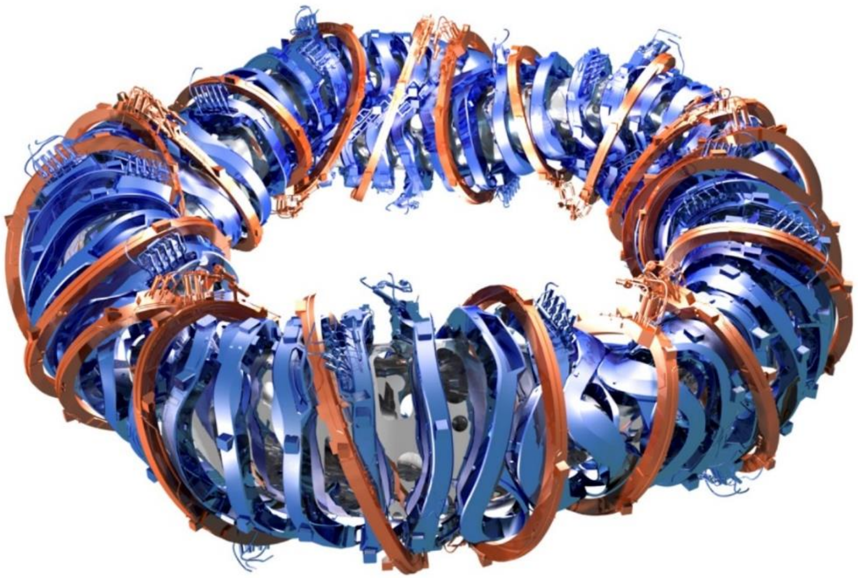
Wagner, F., Fusion energy. MRS Energy & Sustainability, 5, E8 (2018)

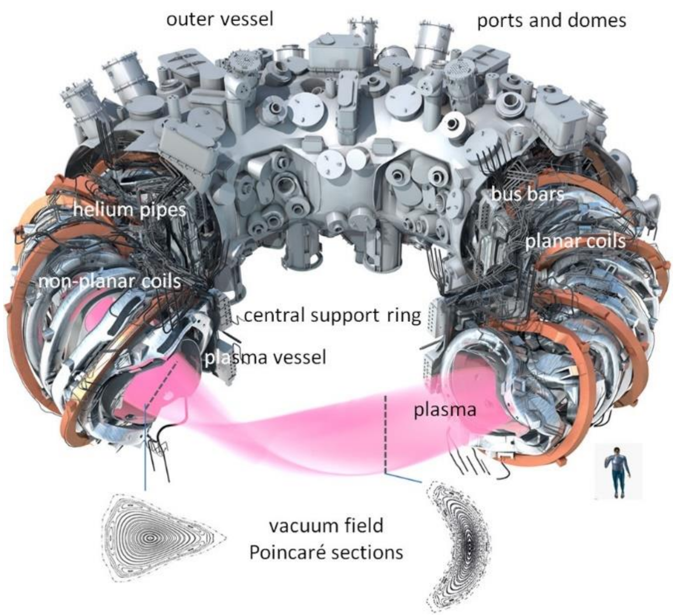
LHD stellarator in Japan



https://en.wikipedia.org/wiki/Large_Helical_Device

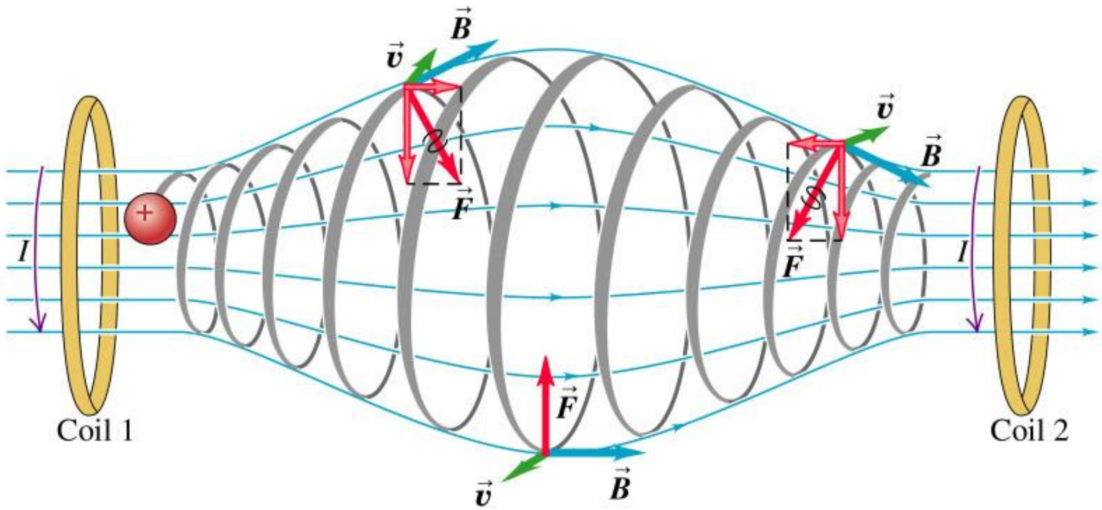
Wendelstein 7-X is a stellarator built by Max Planck Institute for Plasma Physics (IPP)

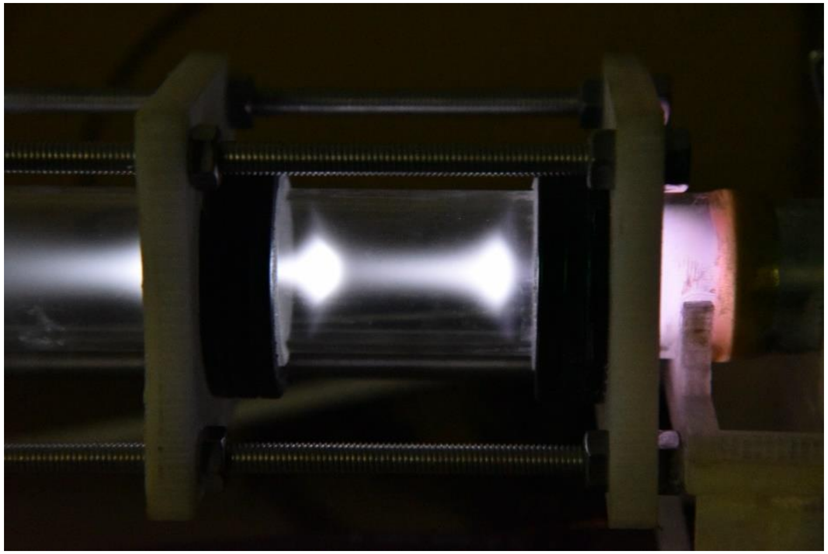




- **Wemdelstein 7-x is now installing new diverters.**

Demonstration of a magnetic mirror machine

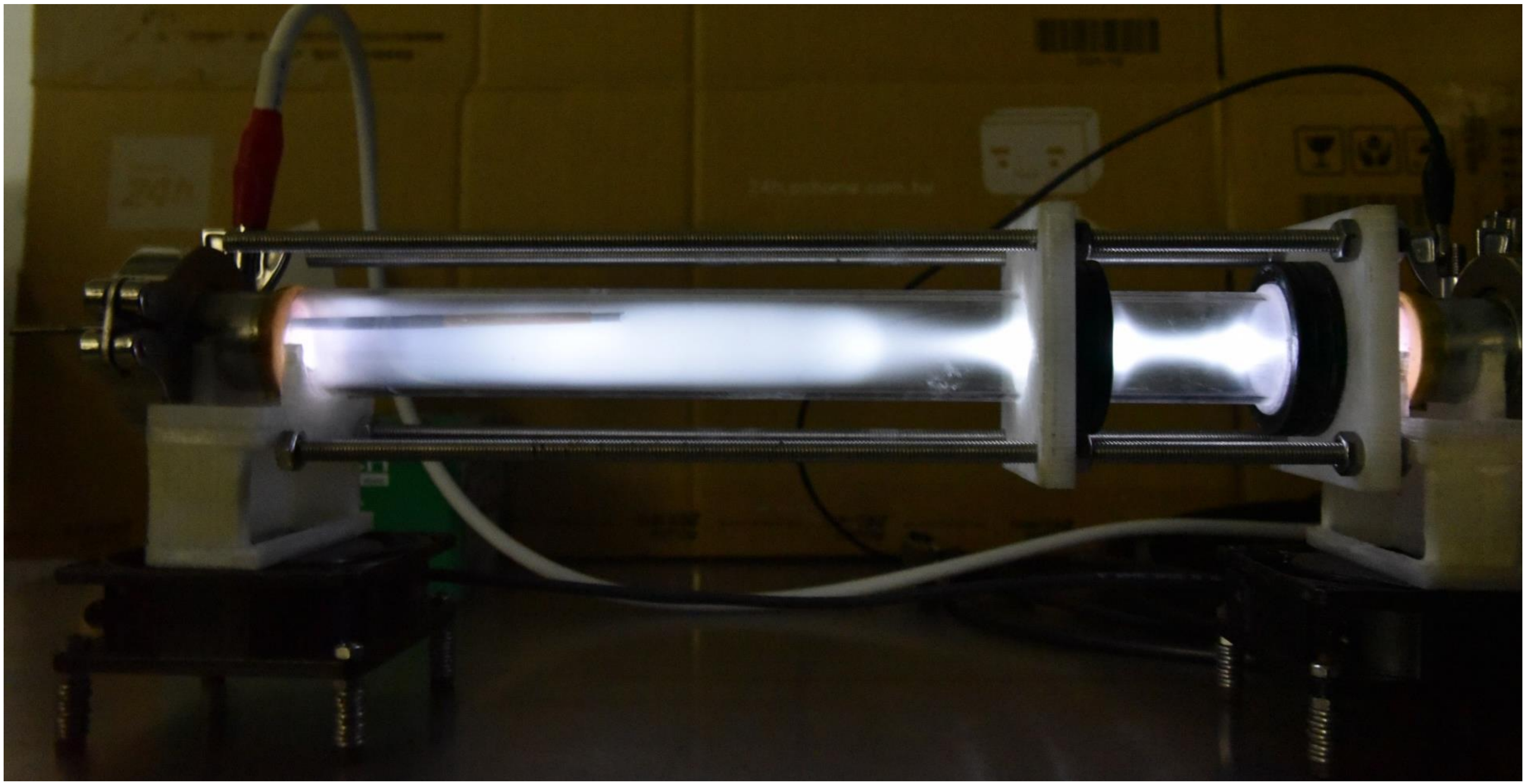




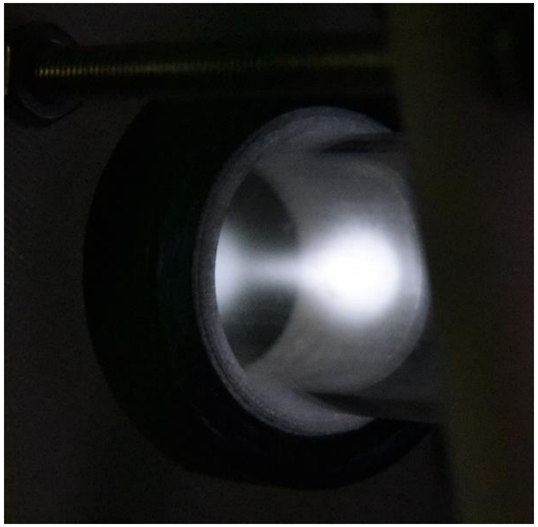
Show video.

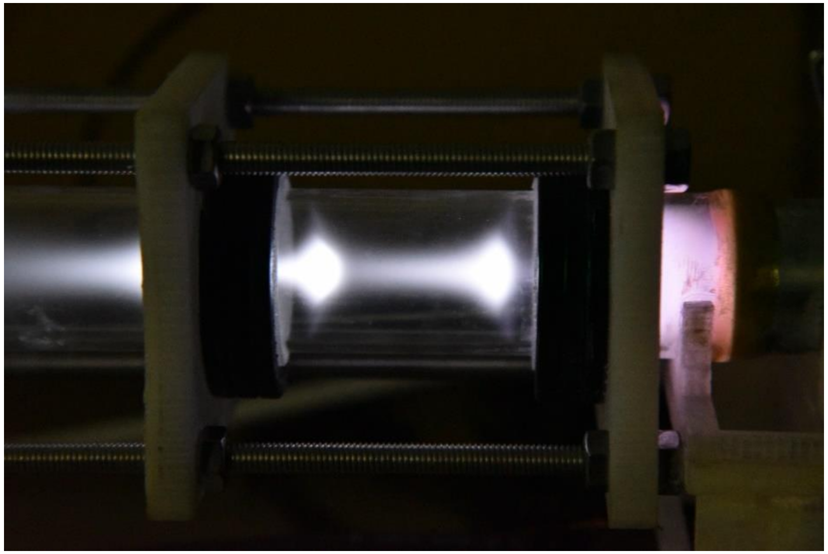
https://i.stack.imgur.com/GlzGZ.jpg

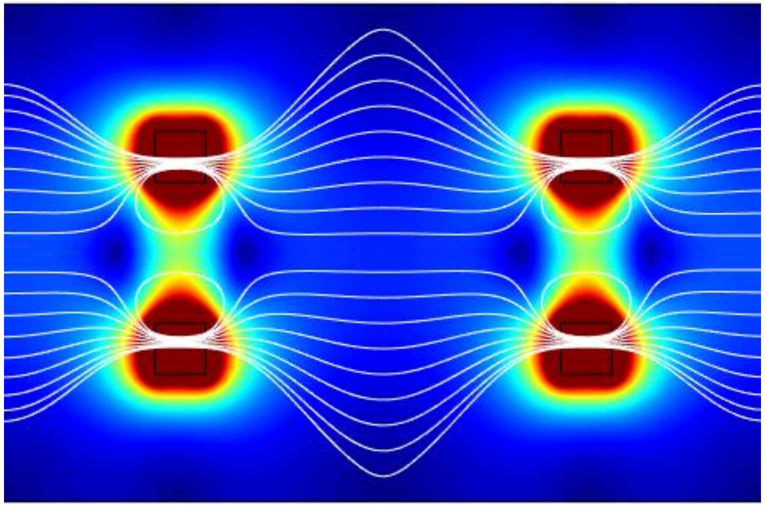
Plasma is partially confined by the magnetic field



Many mirror points are provided by a pair of ring-type magnets



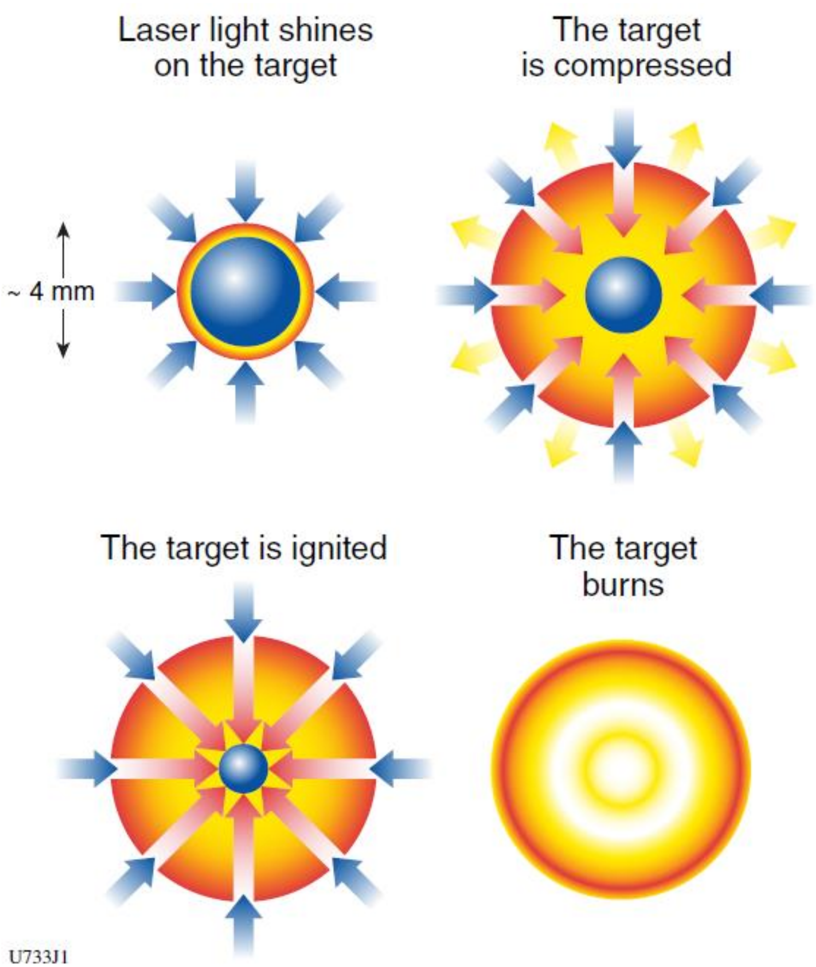


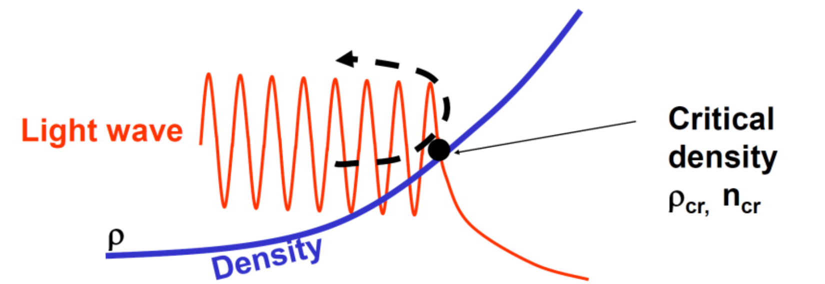


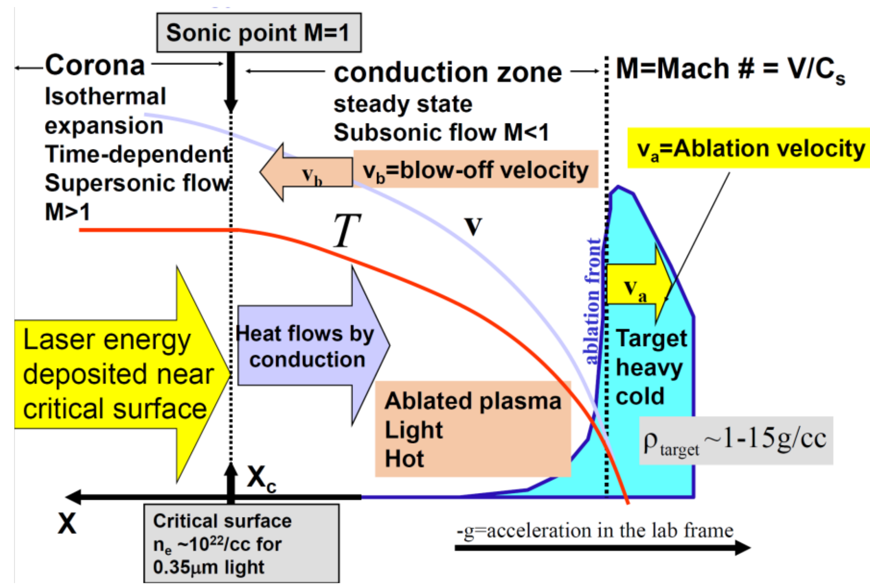
Outline

- Introduction to nuclear fusion
- Magnetic confinement fusion (MCF)
  - Tokamak
  - Stellarator
- **Inertial confinement fusion (ICF)**
  - **Indirection drive ICF**
  - **Direct drive ICF**
- Innovation idea – MCF + ICF
- Plasma in space
- Pulsed-power system at NCKU

Compression happens when outer layer of the target is heated by laser and ablated outward

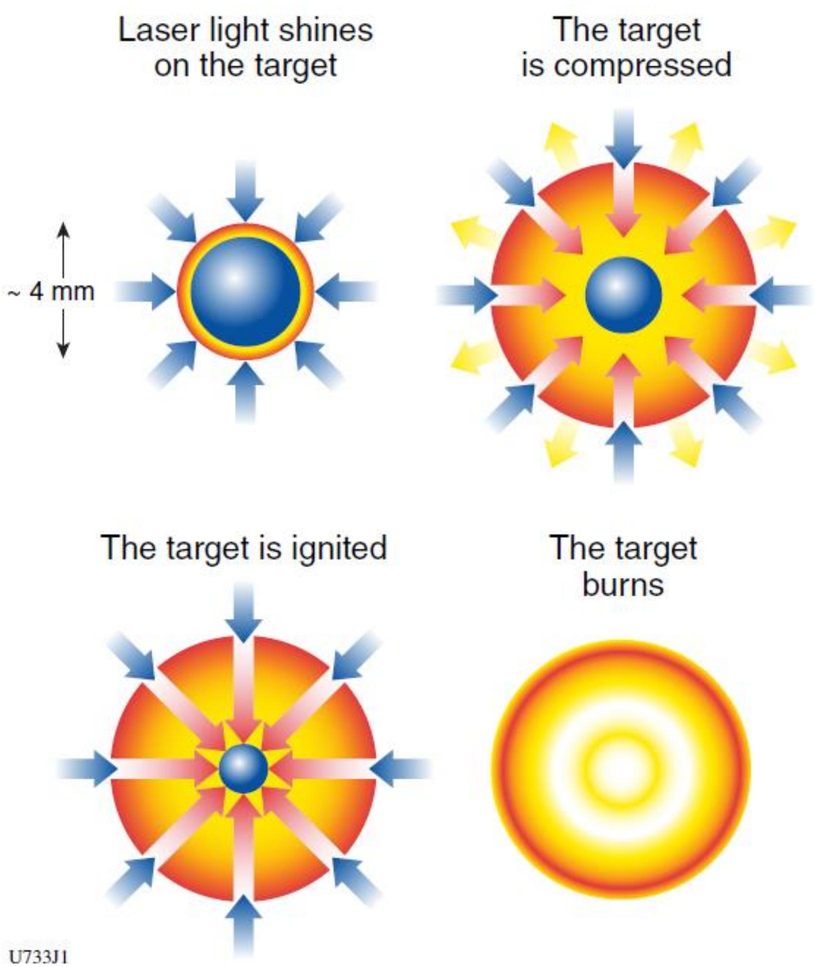




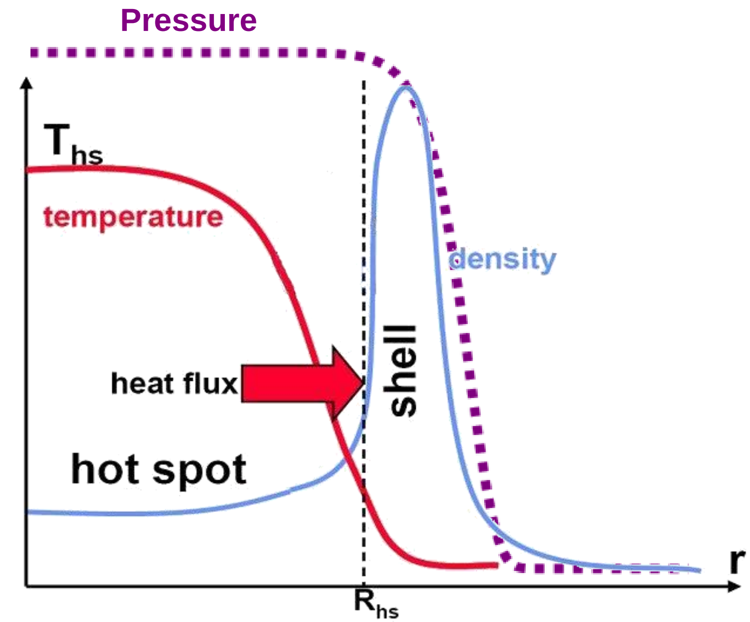


Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester
R. Betti, HEDSA HEDP Summer School, 2015

Plasma is confined by its own inertia in inertial confinement fusion (ICF)



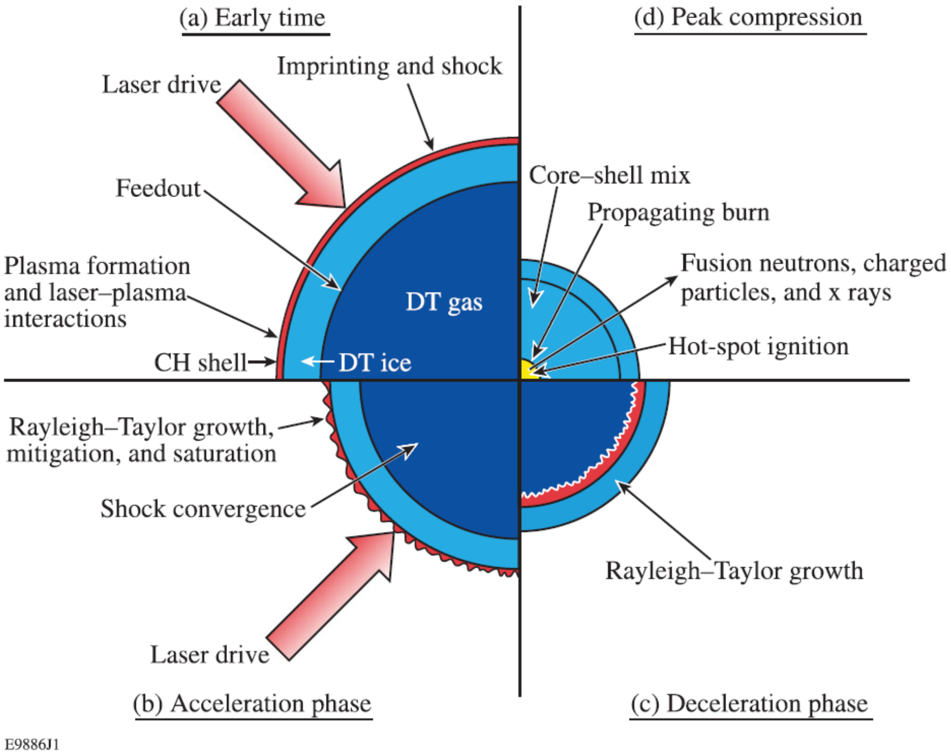
Spatial profile at stagnation



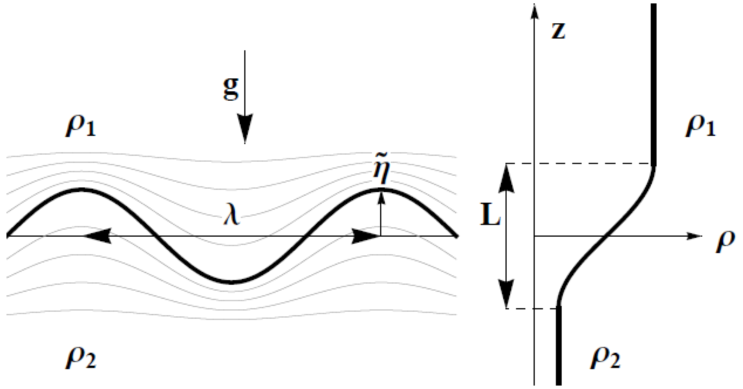
Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

A ball can not be compressed uniformly by being squeezed between several fingers

- **Stages of a target implosion**

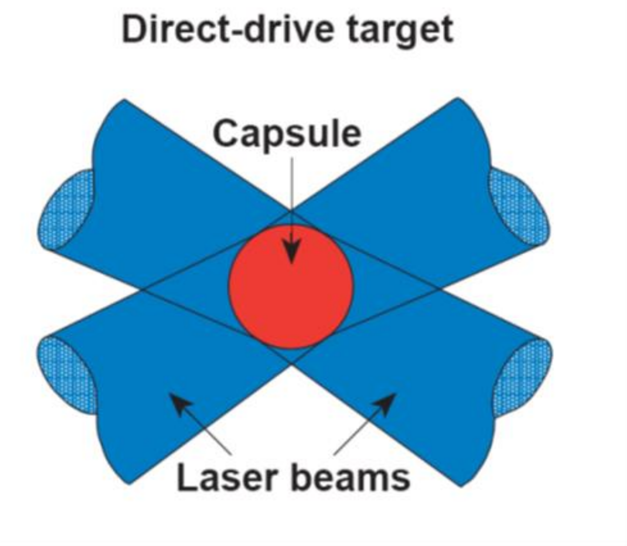


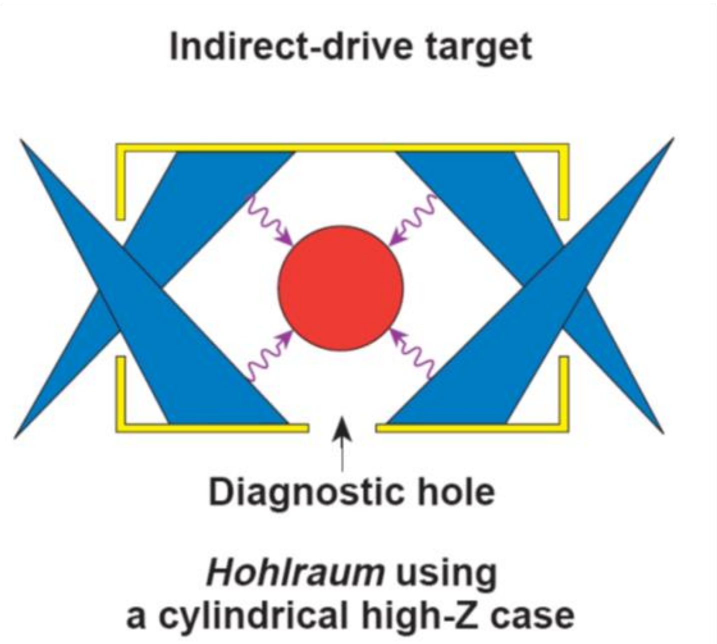
- **Rayleigh-Taylor instability**



P.-Y. Chang, PhD Thesis, U of Rochester (2013)
R. S. Craxton, etc., *Phys. Plasmas* **22**, 110501 (2015)

A spherical capsule can be imploded through directly or indirectly laser illumination



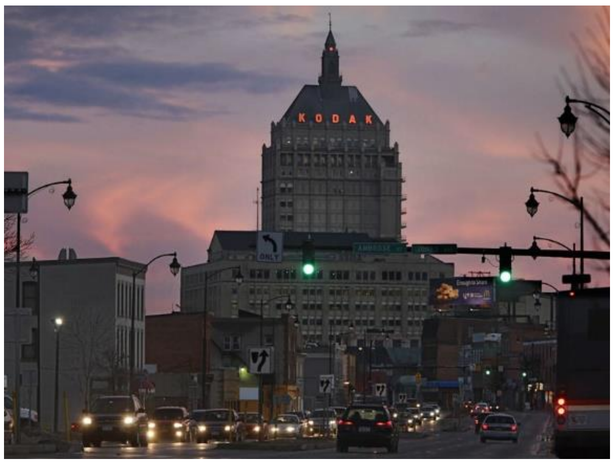


*R. Betti, HEDSA HEDP Summer School, 2015

Rochester is known as “The World's Image Center”

There are many famous optical companies at Rochester

Kodak



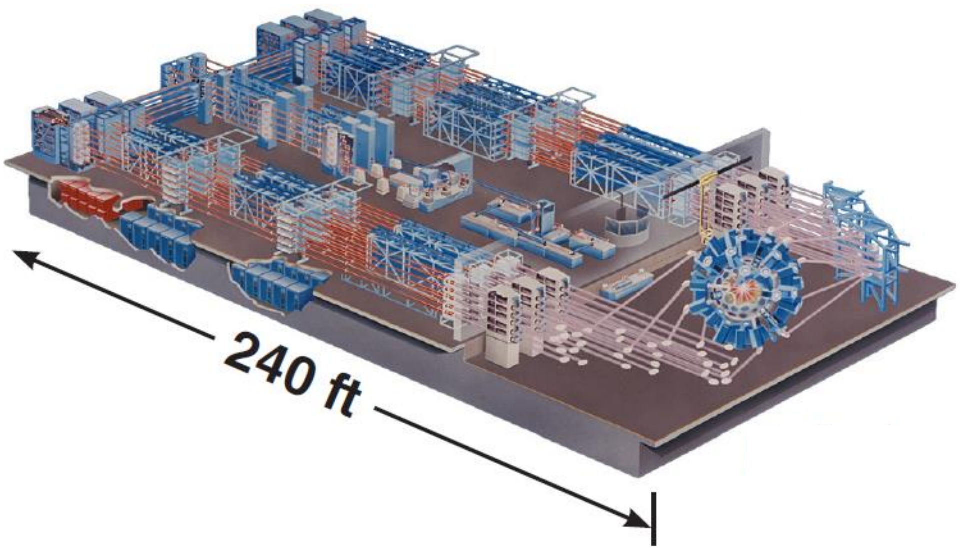
xerox

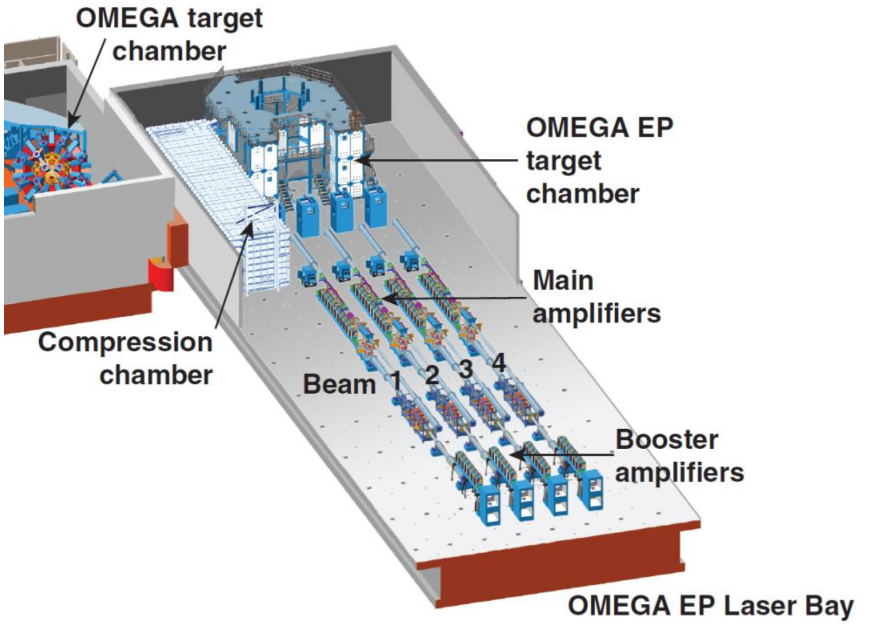
Eastman school of music

BAUSCH + LOMB

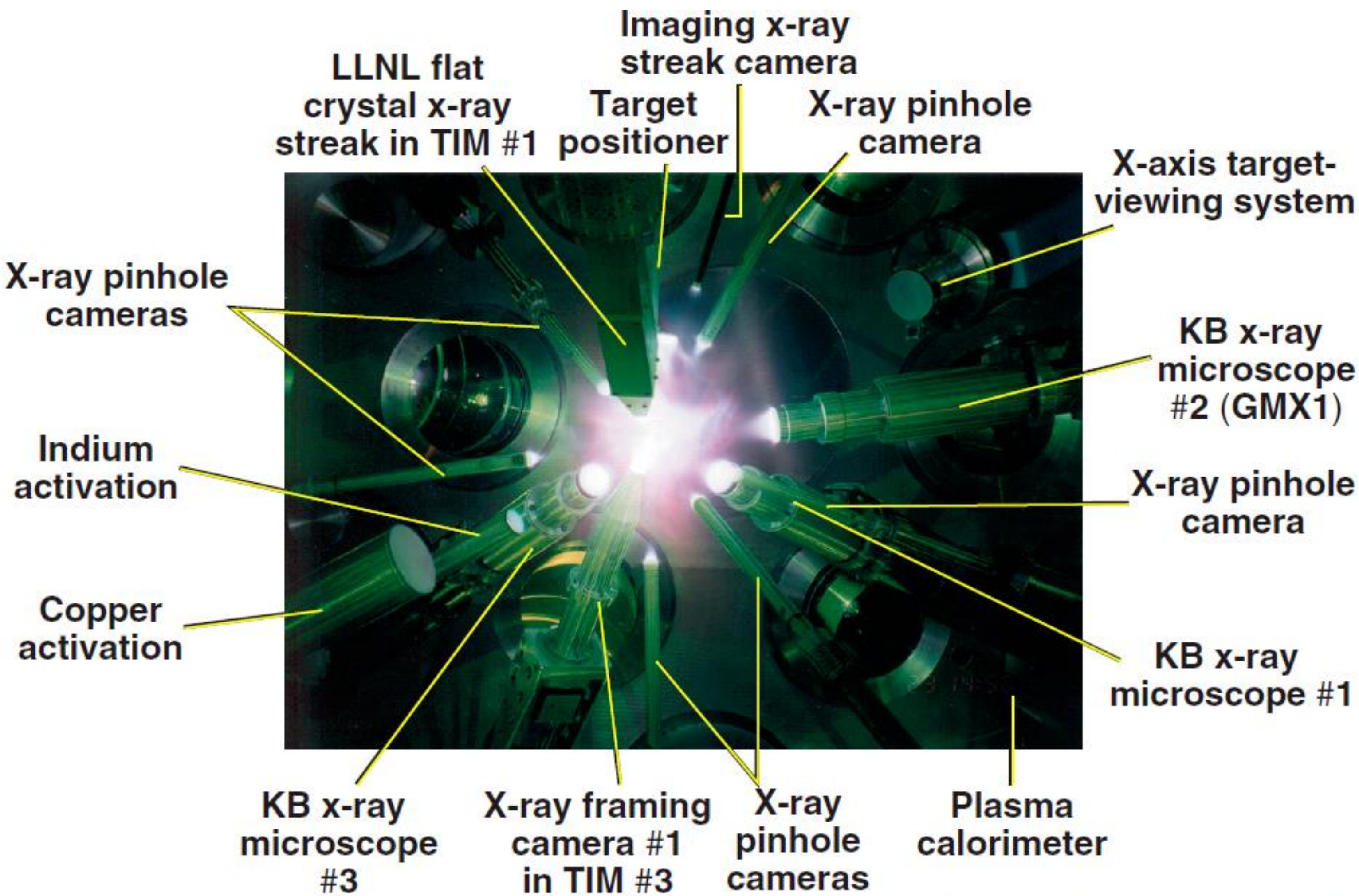
Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion

- **OMEGA Laser System**
  - **60 beams**
  - **>30 kJ UV on target**
  - **1%~2% irradiation nonuniformity**
  - **Flexible pulse shaping**
- **OMEGA EP Laser System**
  - **4 beams; 6.5 kJ UV (10ns)**
  - **Two beams can be high-energy petawatt**
    - **2.6 kJ IR in 10 ps**
    - **Can propagate to the OMEGA or OMEGA EP target chamber**





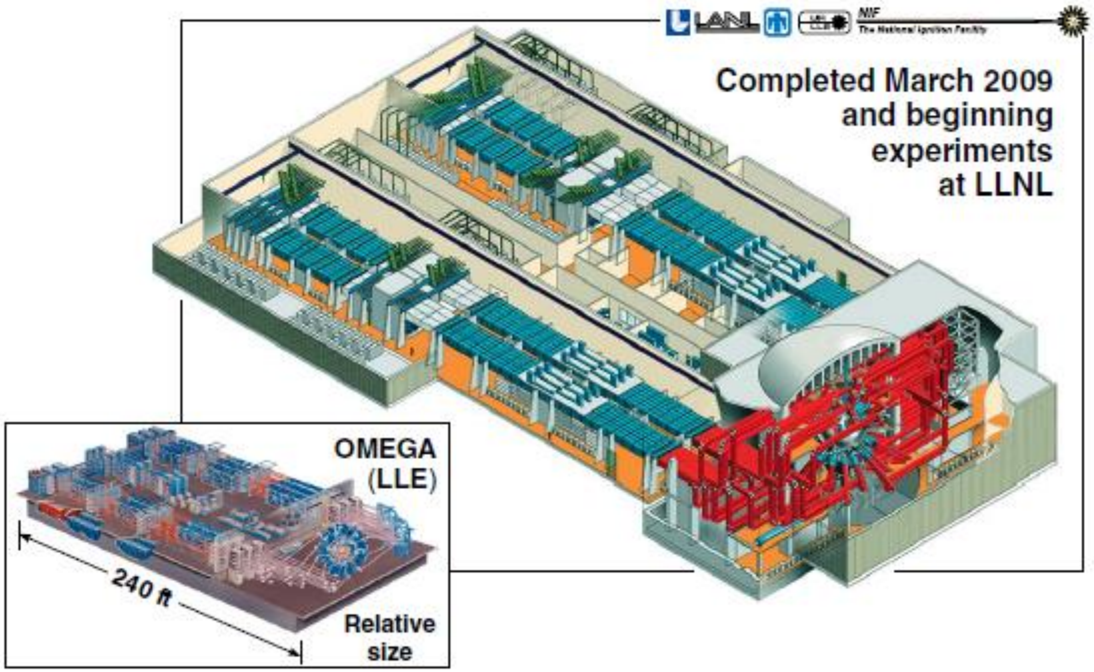
The OMEGA Facility is carrying out ICF experiments using a full suite of target diagnostics



E8012b

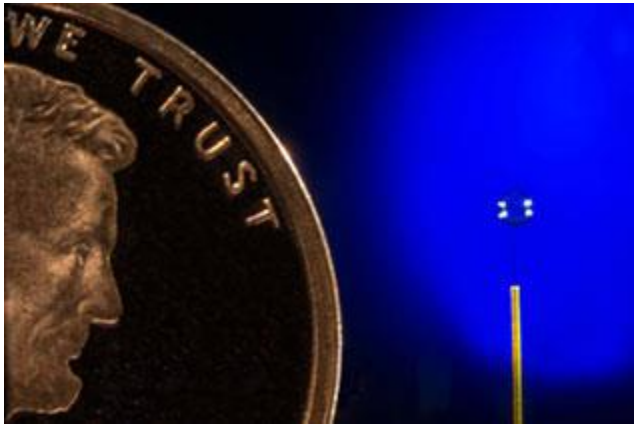
Photo taken from port H11B

The 1.8-MJ National Ignition Facility (NIF) will demonstrate ICF ignition and modest energy gain

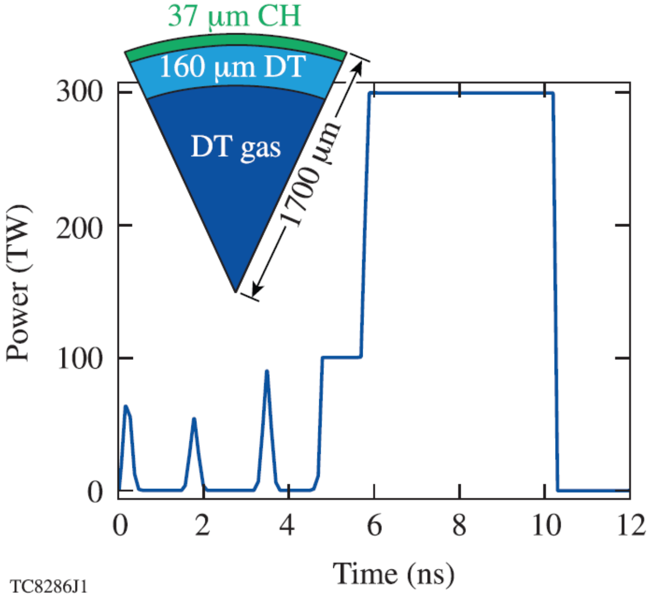


OMEGA experiments are integral to an ignition demonstration on the NIF.

Targets used in ICF



- **Triple-point temperature : 19.79 K**

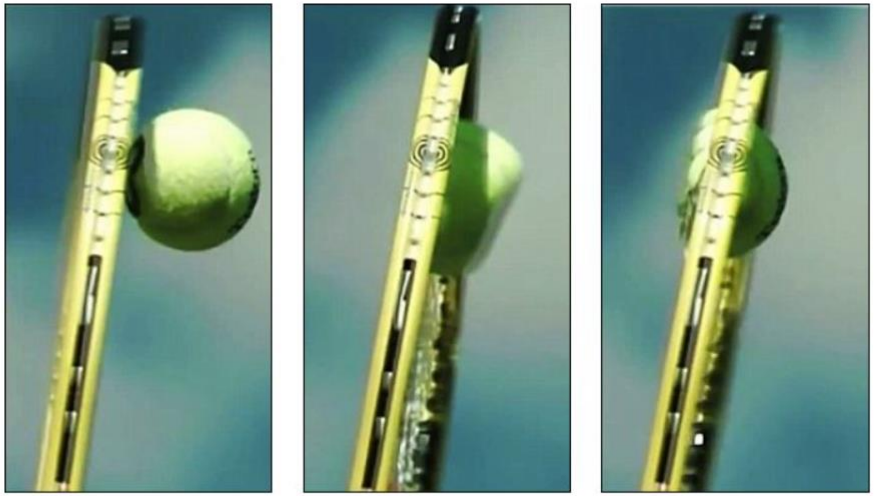


http://www.lle.rochester.ed
https://en.wikipedia.org/wiki/Inertial_confinement_fusion
R. S. Craxton, etc., *Phys. Plasmas* **22**, 110501 (2015)

Softer material can be compressed to higher density

- **Compression of a baseball**

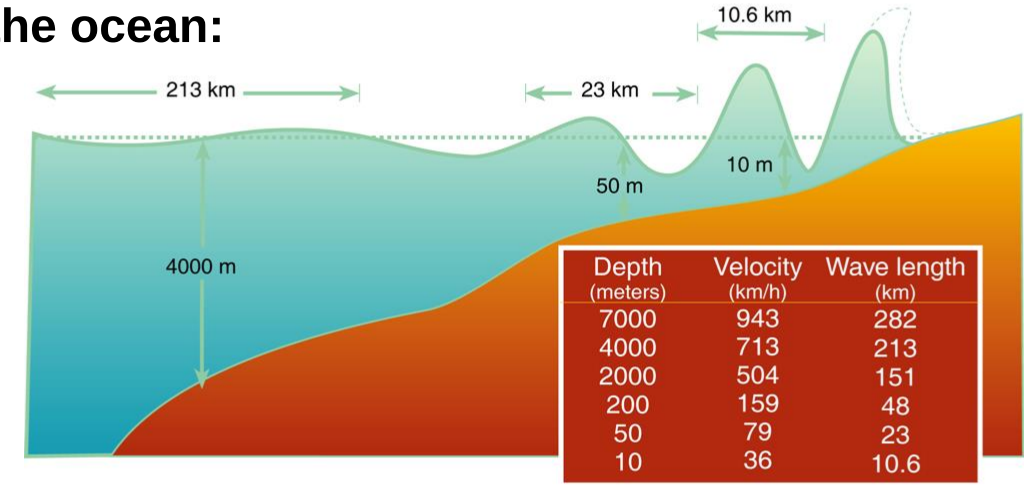
- **Compression of a tennis ball**



https://www.youtube.com/watch?v=uxlIdMoAwbY
https://newsghana.com.gh/wimbledon-slow-motion-video-of-how-a-tennis-ball-turns-to-goo-after-serve/

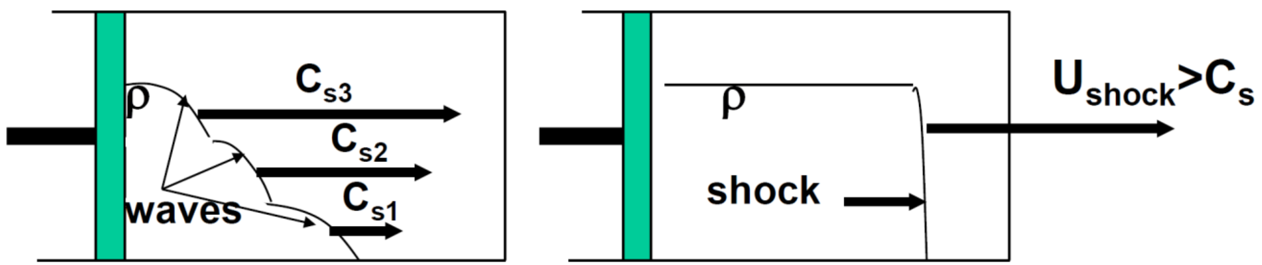
A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **Wave in the ocean:**



Depth (meters)	Velocity (km/h)	Wave length (km)
7000	943	282
4000	713	213
2000	504	151
200	159	48
50	79	23
10	36	10.6

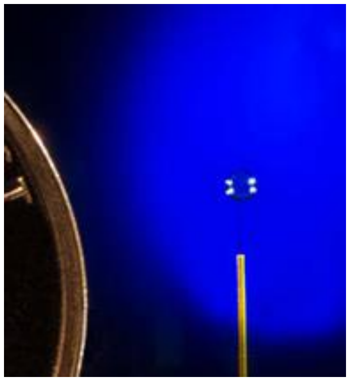
- **Acoustic/compression wave driven by a piston:**



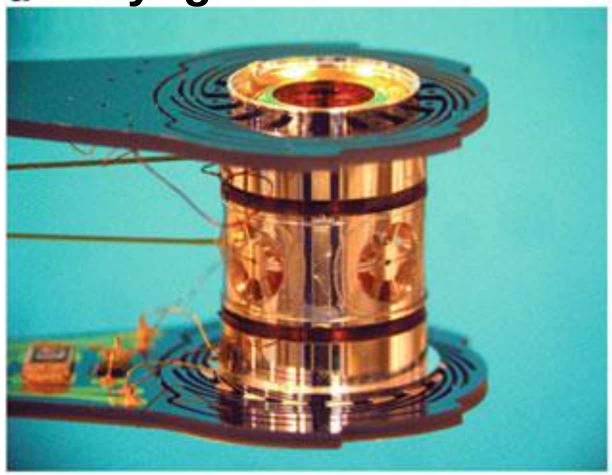
$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha \rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\rho^{1/3}$$

http://neamtic.ioc-unesco.org/tsunami-info/the-cause-of-tsunamis
*R. Betti, HEDSA HEDP Summer School, 2015

Targets used in ICF



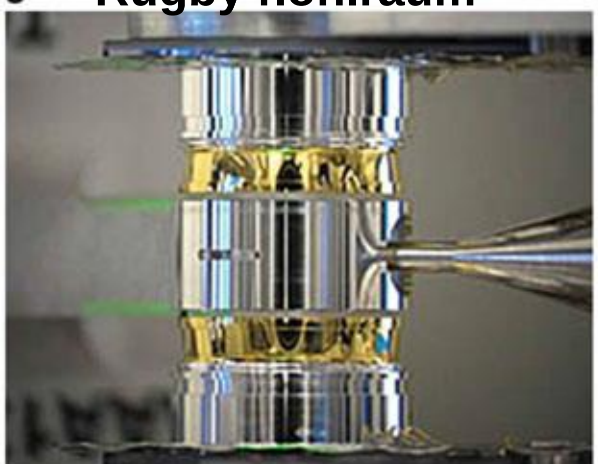
a **Cryogenic hohlraum**



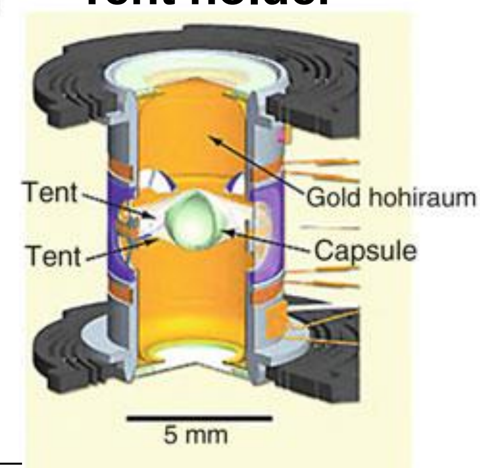
b

Cryogenic shroud

c **Rugby hohlraum**

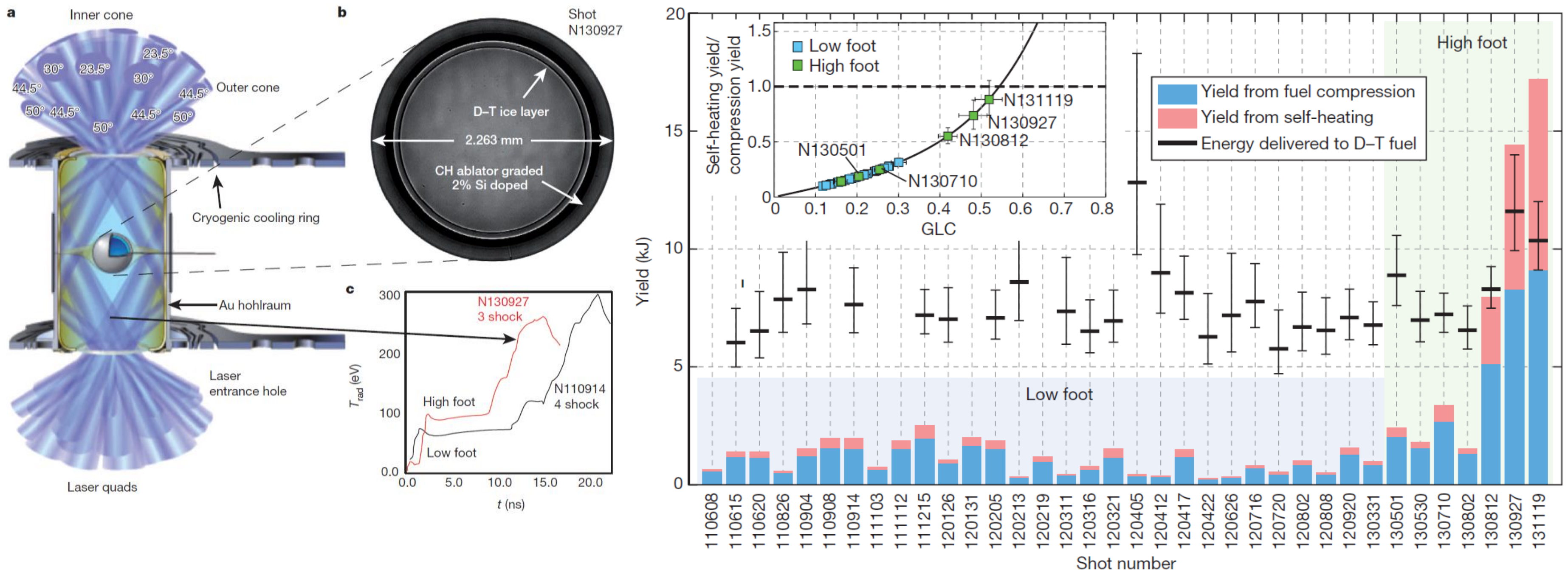


d **Tent holder**



https://www.lle.rochester.edu/index.php/2014/11/10/next-generation-cryo-target/
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen
https://www.llnl.gov/news/nif-shot-lights-way-new-fusion-ignition-phase

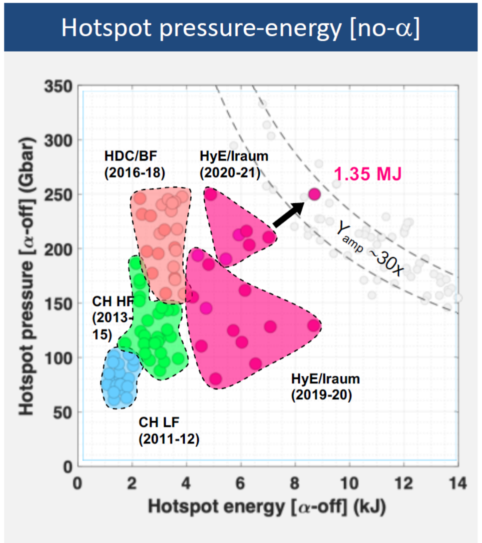
Nature letter "Fuel gain exceeding unity in an inertially confined fusion implosion"

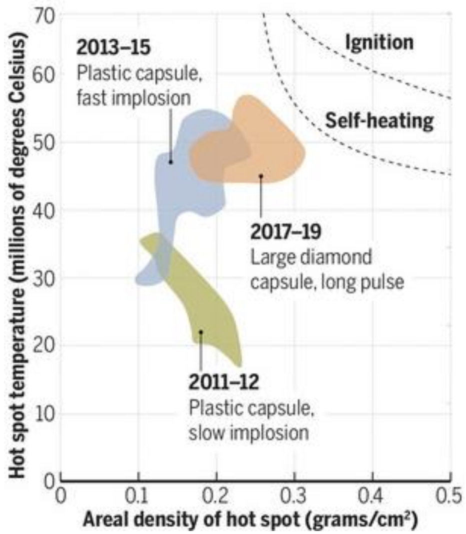


- **Fuel gain exceeding unity was demonstrated for the first time.**

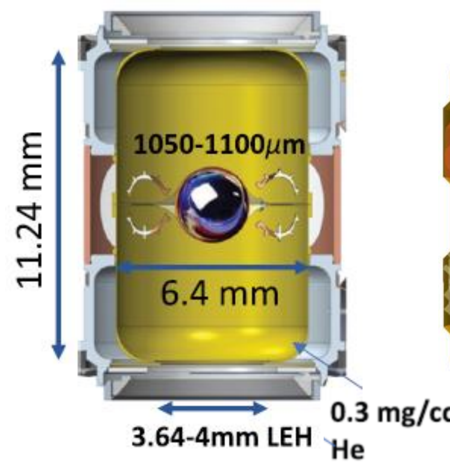
Nature 506, p343, 2014

The hot spot has entered the burning plasma regime

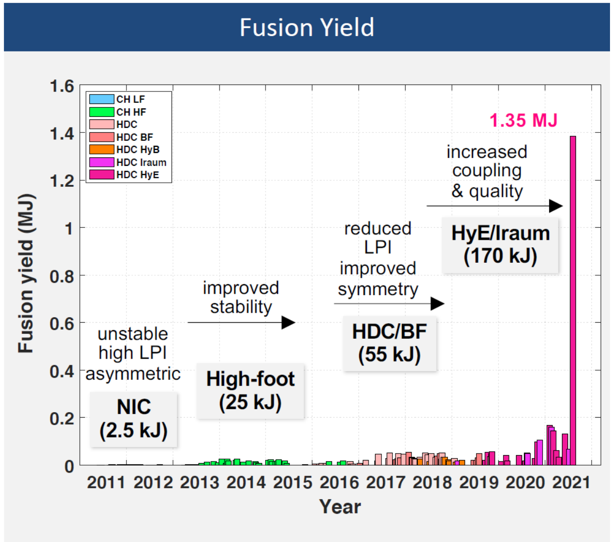




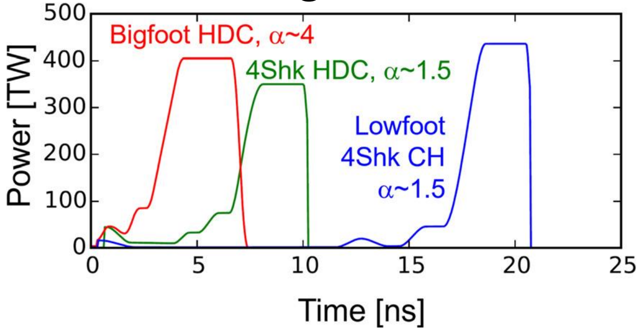
- **Hybrid-E**

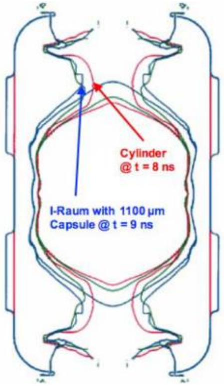


- **I-raum**



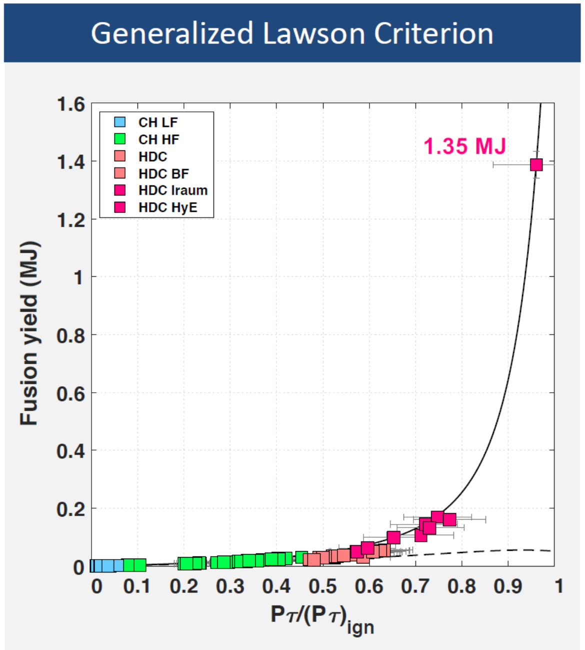
- **Big foot**

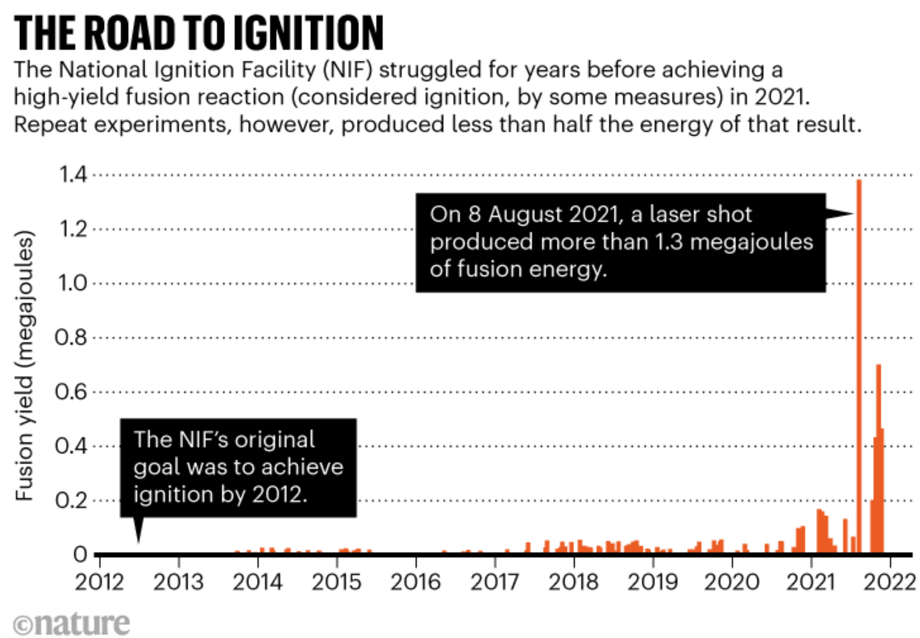




T. Ma, ARPA-E workshop, April 26, 2022
Science 370, p1019, 2020
D. T. Casey, etc., Phys. Plasmas, 25, 056308 (2018)
A. L. Kritcher, etc., Phys. Plasmas, 28, 072706 (2021)
H. F. Robey, etc., Phys. Plasmas, 25, 012711 (2018)

National Ignition Facility (NIF) achieved a yield of more than 1.3 MJ from ~1.9 MJ of laser energy in 2021 (Q~0.7)

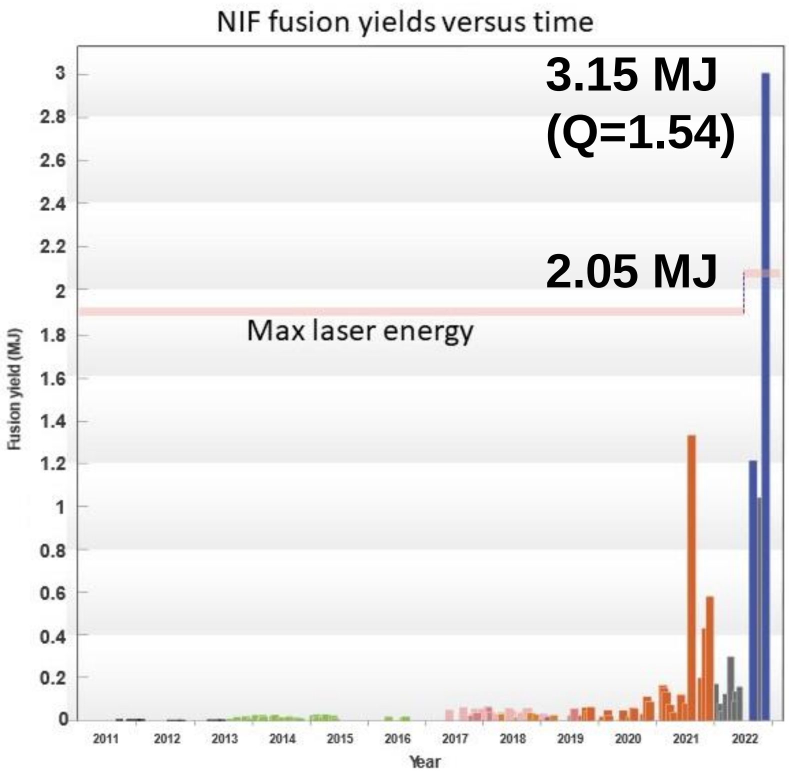


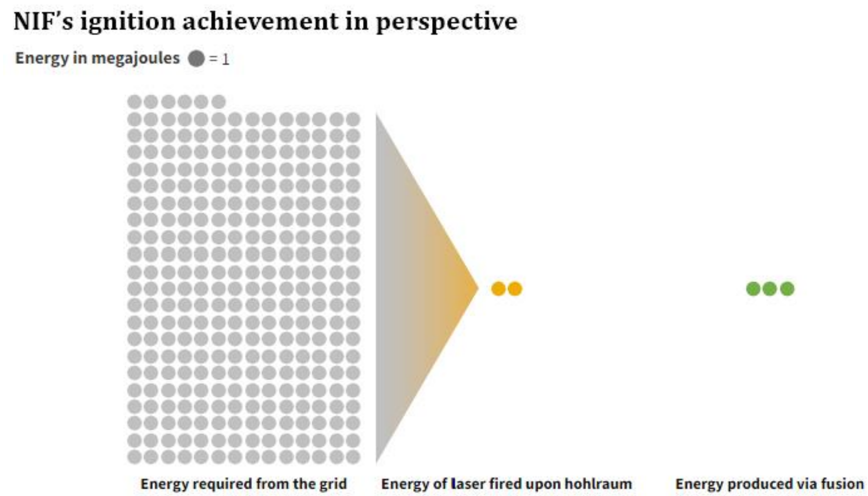


- **National Ignition Facility (NIF) achieved a yield of more than 1.3 MJ (Q~0.7). This advancement puts researchers at the threshold of fusion ignition.**
- **Laser-fusion facility heads back to the drawing board.**

T. Ma, ARPA-E workshop, April 26, 2022
J. Tollefson, Nature (News) 608, 20 (2022)

"Ignition" (target yield larger than one) was achieved in NIF on 2022/12/5

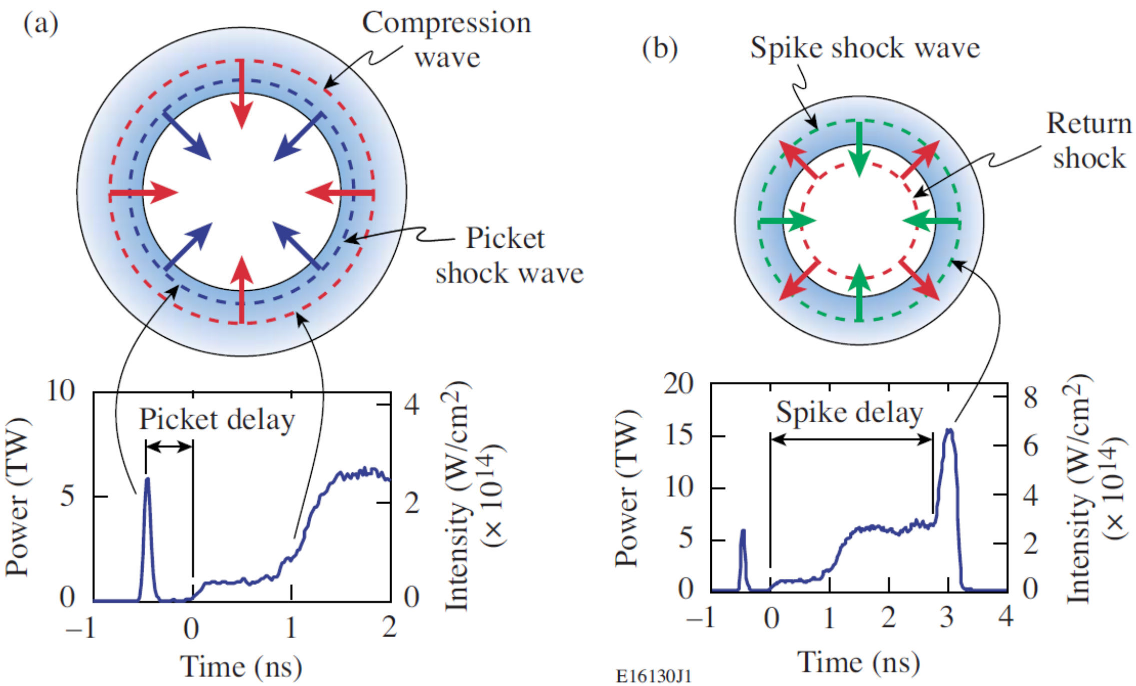




300 MJ   2.05 MJ   3.15 MJ

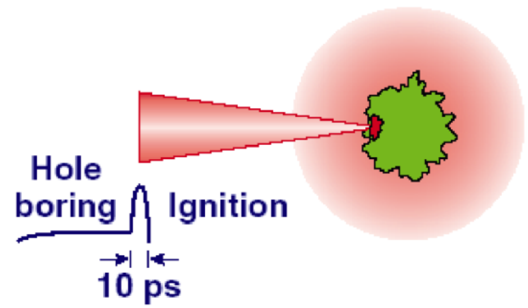
External “spark” can be used for ignition

- **Shock ignition**

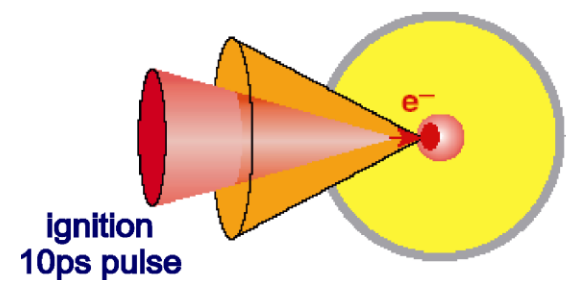


- **Fast ignition**

a) channeling FI concept



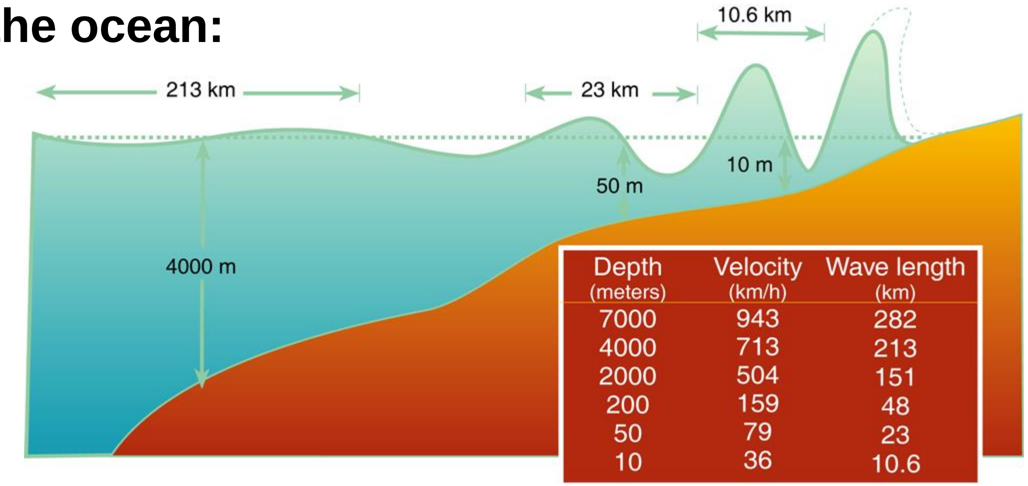
b) cone-in-shell FI concept



J. Badziak, Bull.Polish Acad. Sci. Tech. Sci.Phys. Plasmas 15, 056306 (2008)

A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **Wave in the ocean:**



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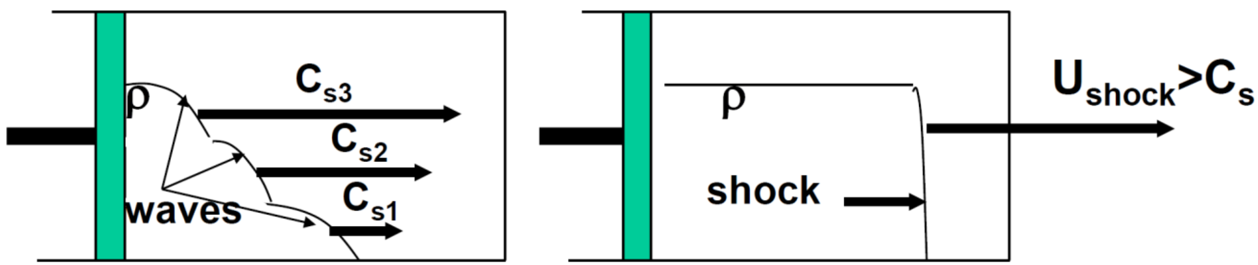
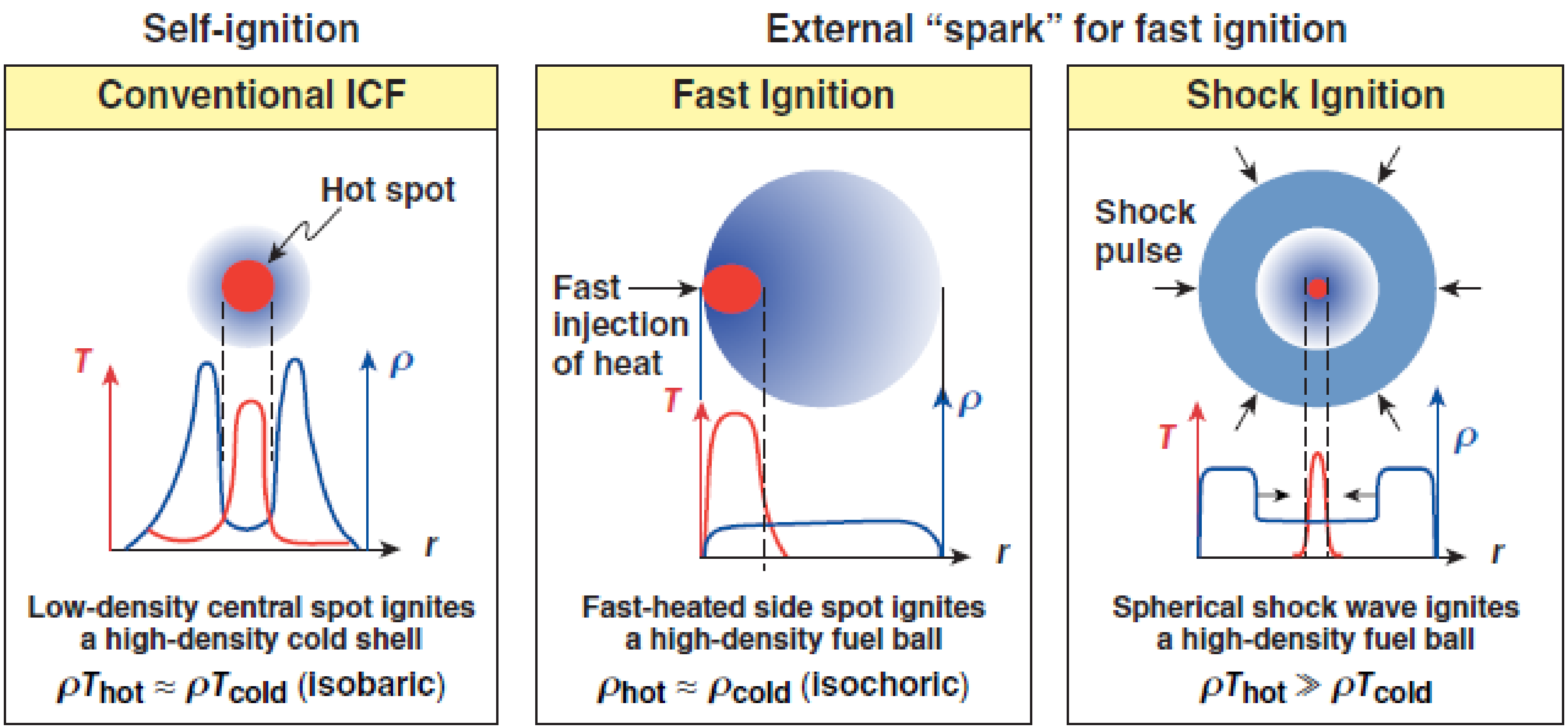
- **Acoustic/compression wave driven by a piston:**



$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha\rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\rho^{1/3}$$

http://neamtic.ioc-unesco.org/tsunami-info/the-cause-of-tsunamis
*R. Betti, HEDSA HEDP Summer School, 2015

Ignition can happen by itself or being triggered externally

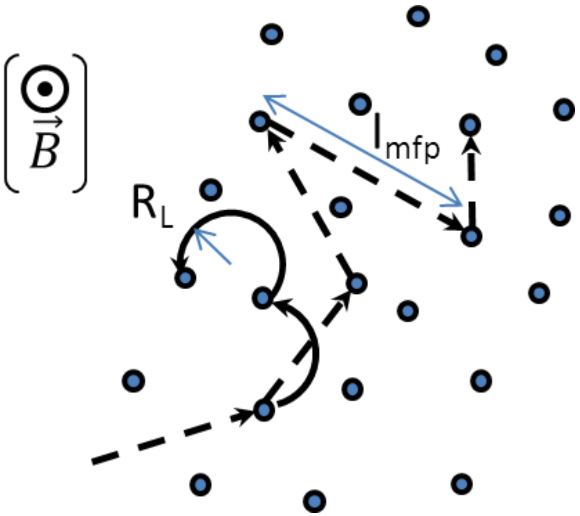


P. B. Radha, Fusion Energy Conference,2018

Outline

- Introduction to nuclear fusion
- Magnetic confinement fusion (MCF)
  - Tokamak
  - Stellarator
- Inertial confinement fusion (ICF)
  - Indirection drive ICF
  - Direct drive ICF
- **Innovation idea – MCF + ICF**
- Plasma in space
- Pulsed-power system at NCKU

A strong magnetic field reduces the heat flux



$$q_T = -\kappa_{||}\nabla_{||}T - \kappa_{\perp}\nabla_{\perp}T$$

$$\kappa_{||} = \kappa_0 T^{5/2}$$

$$\kappa_{\perp} = \frac{\kappa_{||}}{\chi^2} \quad \text{for large Hall parameter } \chi \propto \frac{l_{mfp}}{R_L} >> 1$$

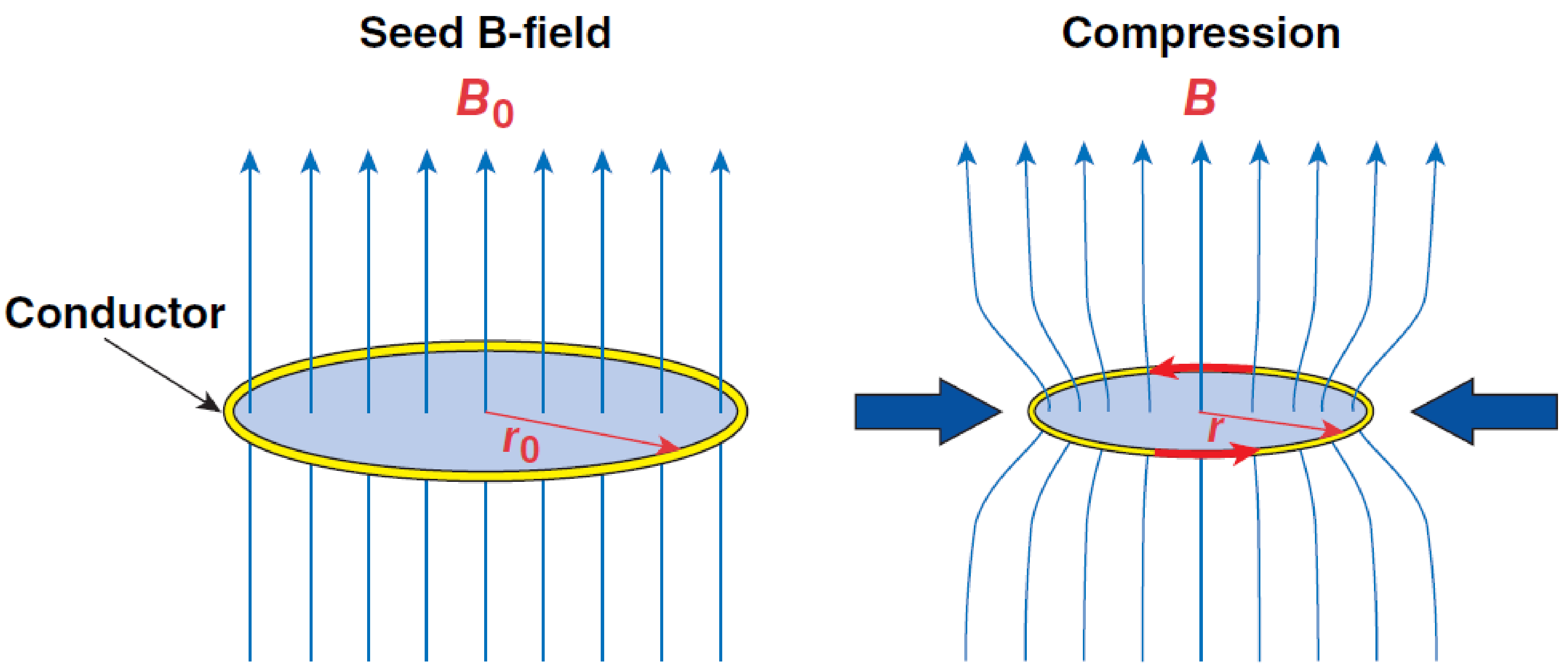
- **Typical hot spot conditions:**

  R_{hs} ~ 40 μm, ρ ~ 20 g/cm^3, T ~ 5 keV:

  $B > 10\,\text{MG}$ **is needed for** $\chi > 1$

Magnetic-flux compression can be used to provide the needed magnetic field.

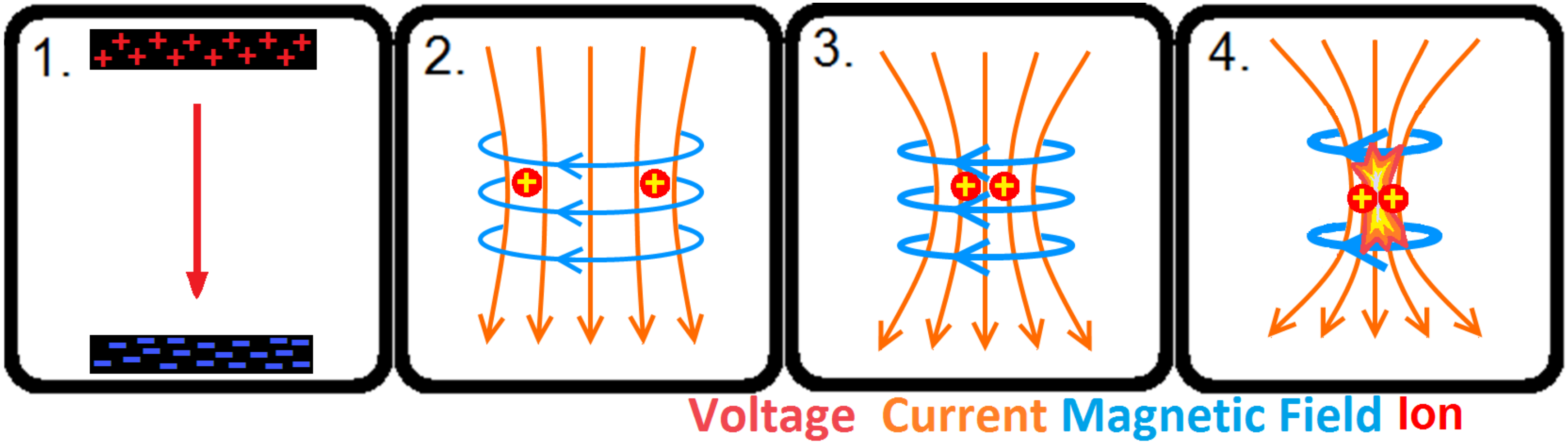
Principle of frozen magnetic flux in a good conductor is used to compress fields



$$\Phi = \pi r_0^2 B_0 = \pi r^2 B$$

M. Hohenberger, P.-Y. Chang, *et al*., Phys. Plasmas 19, 056306 (2012).

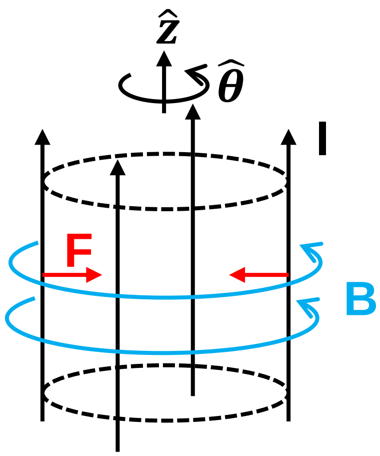
Plasma can be pinched by parallel propagating plasmas



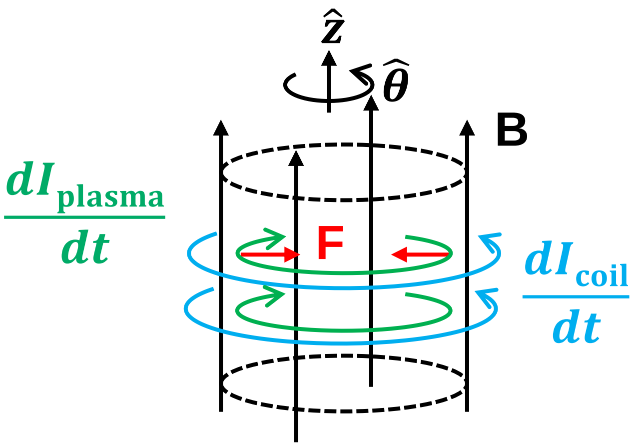
https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

Plasma can be heated via pinches

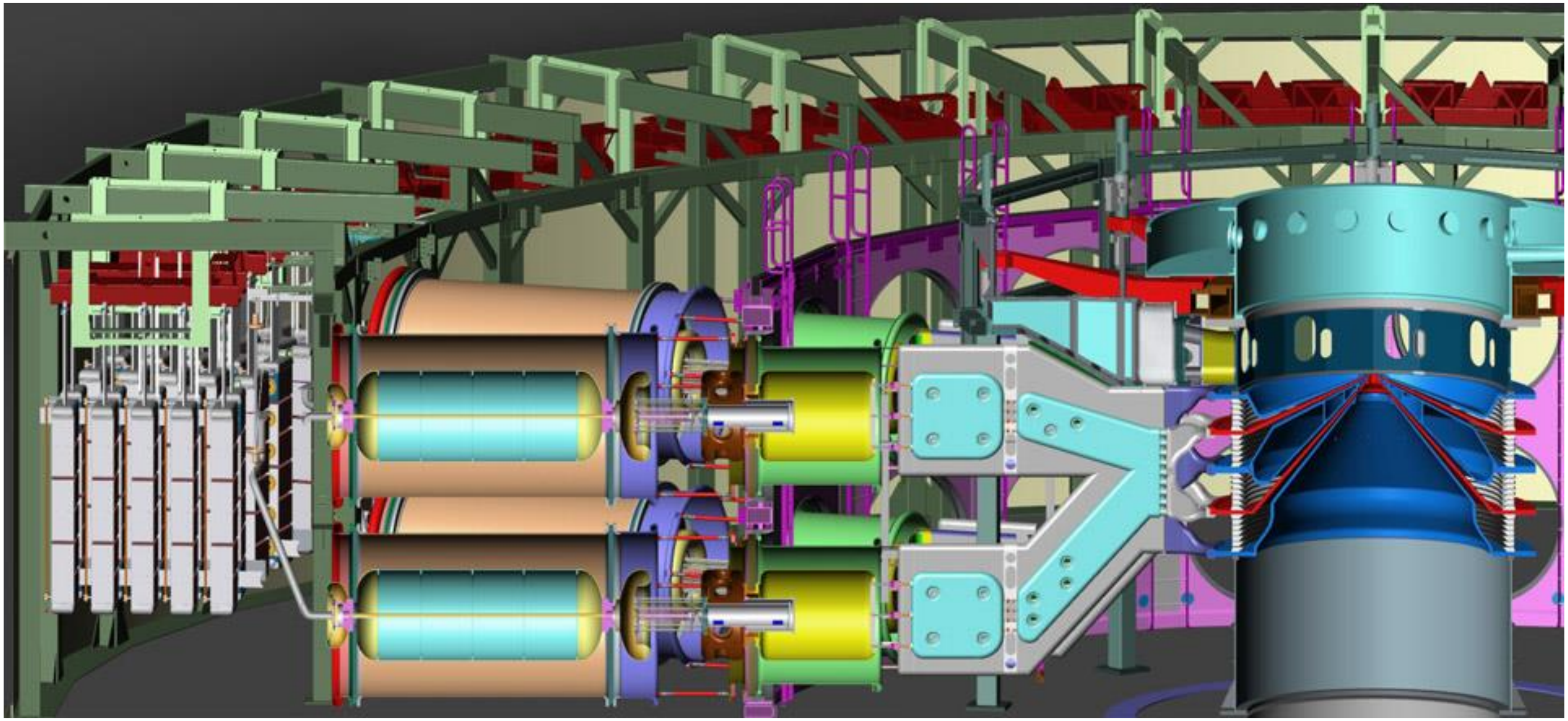
Z pinch



Theta pinch

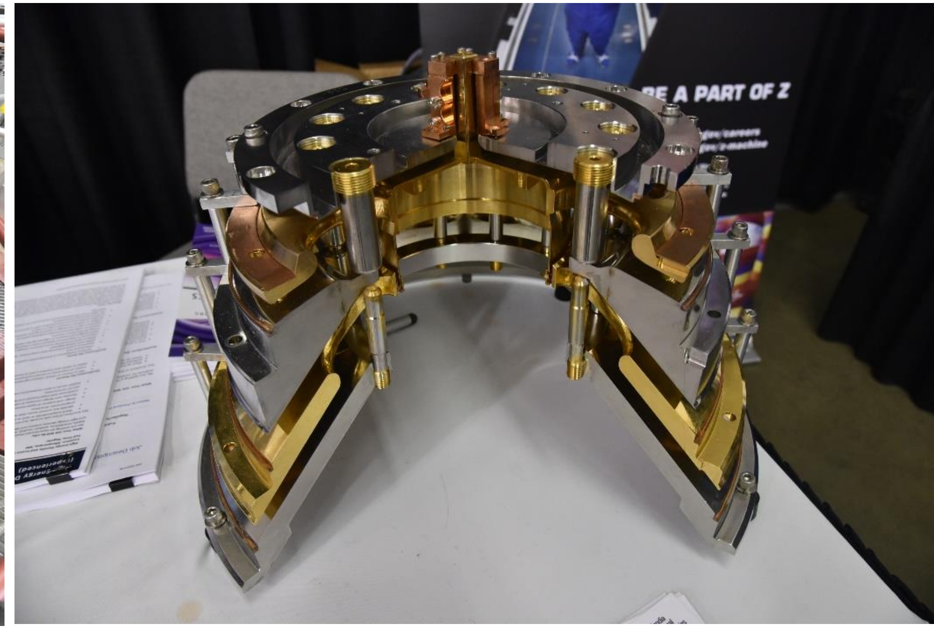


Sandia's Z machine is the world's most powerful and efficient laboratory radiation source

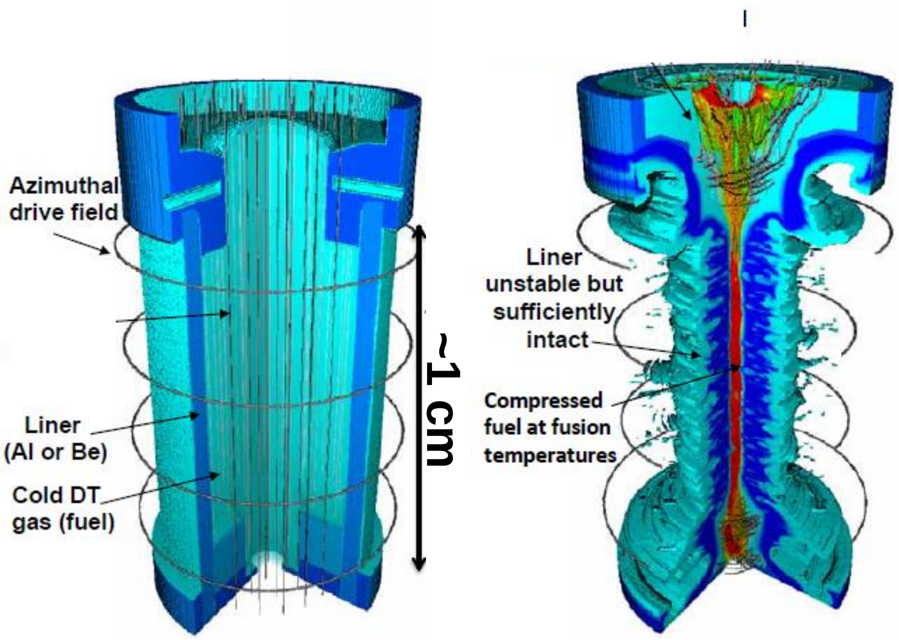


- Stored energy: 20 MJ
- Marx charge voltage: 85 kV
- Peak electrical power: 85 TW
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray emissions: 350 TW
- Peak X-ray output: 2.7 MJ

Z machine

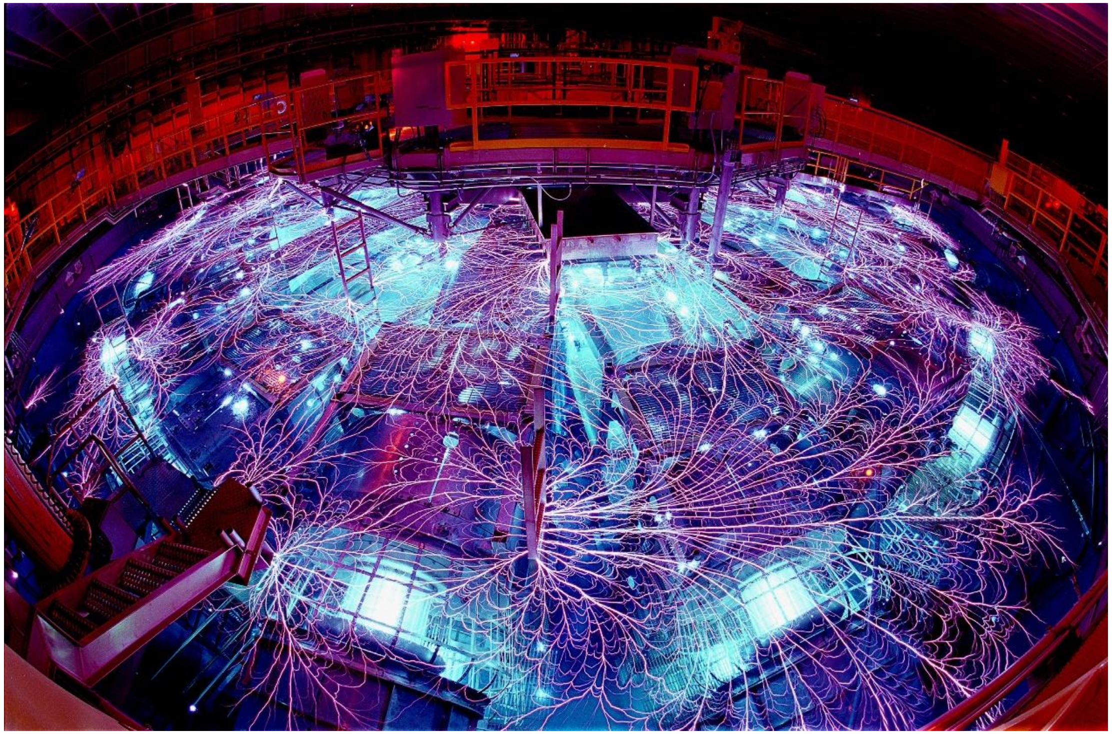


Z machine



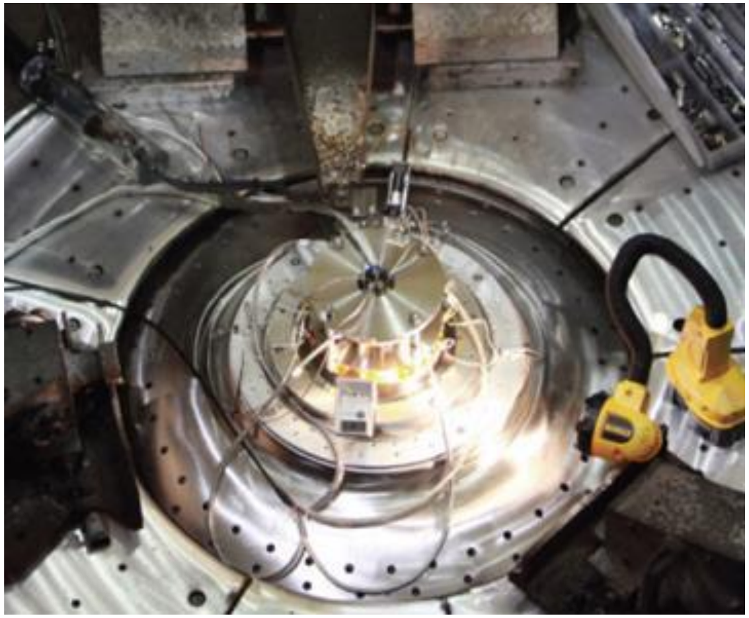
- Stored energy: 20 MJ
- Peak electrical power: 85 TW
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray output: 2.7 MJ

Z machine discharge



Before and after shots

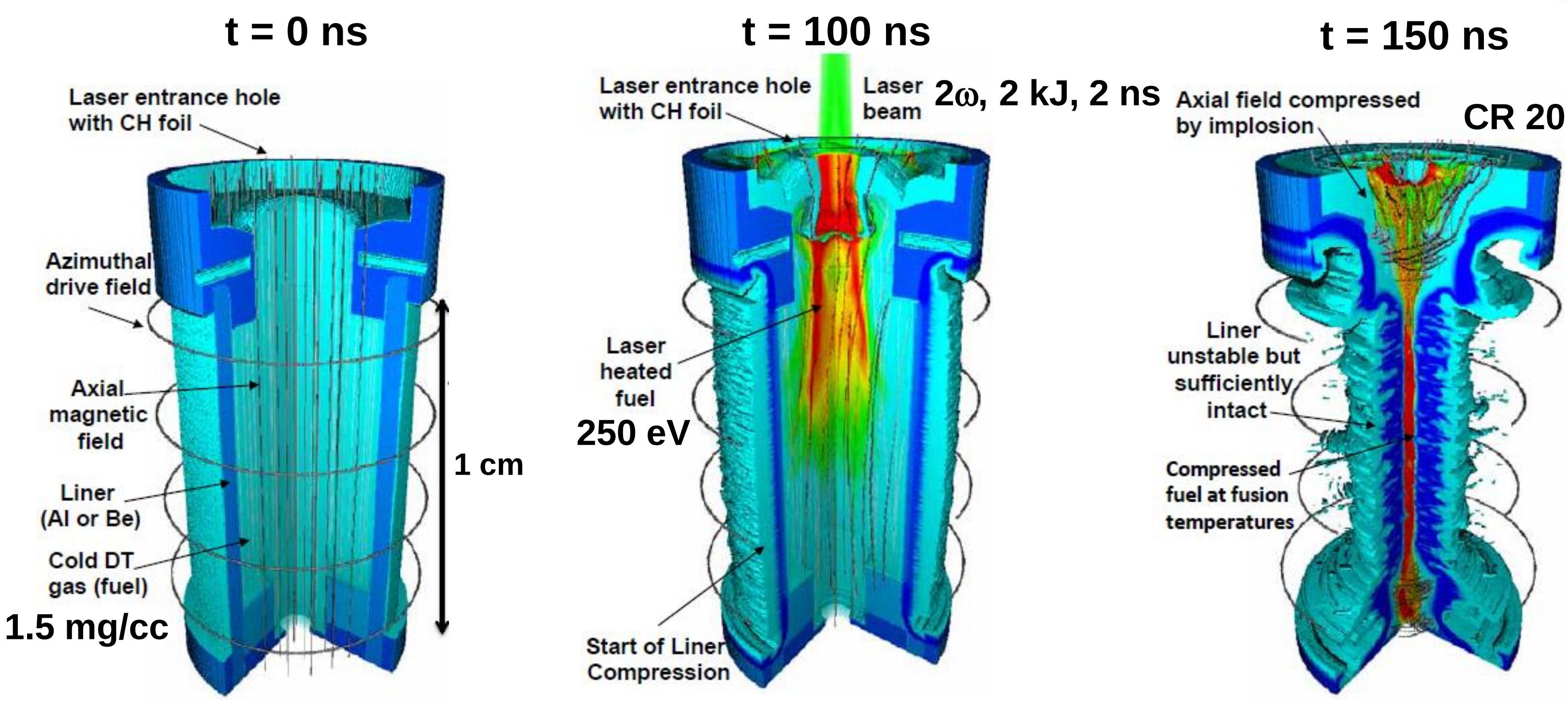
- **Before shots**



- **After shots**

SAND2017-0900PE_The sandia z machine - an overview of the world's most powerful pulsed power facility.pdf

Promising results were shown in MagLIF concept conducted at the Sandia National Laboratories



The stagnation plasma reached fusion-relevant temperatures with a 70 km/s implosion velocity

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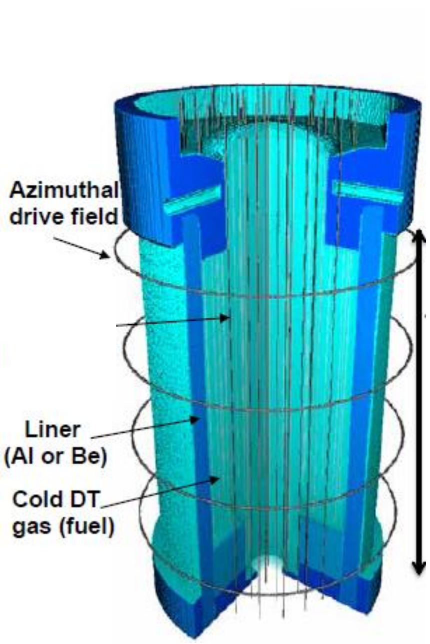
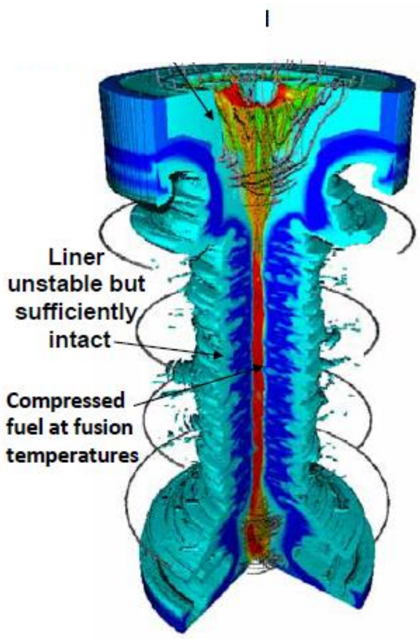
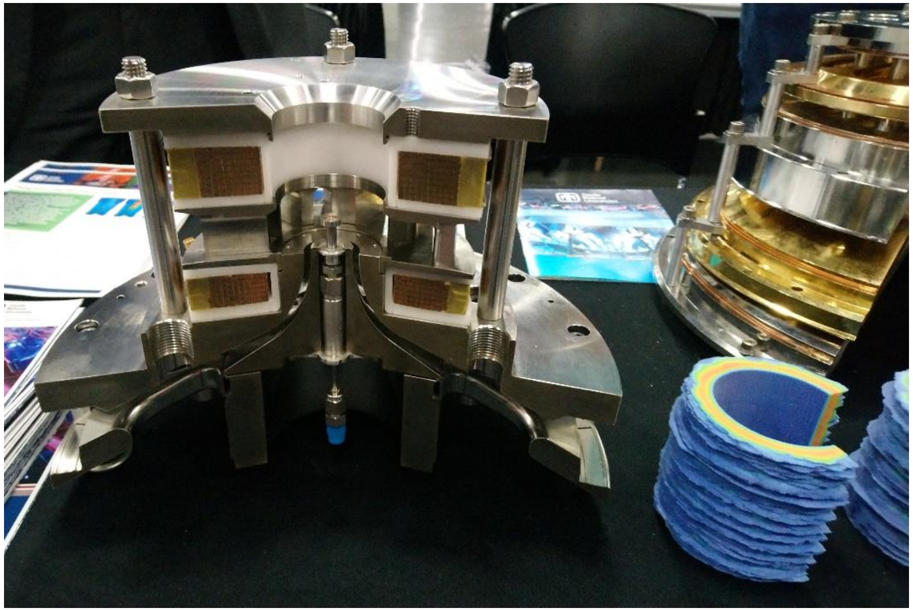
S. A. Slutz *et al* Phys. Plasmas 17 056303 (2010)
M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

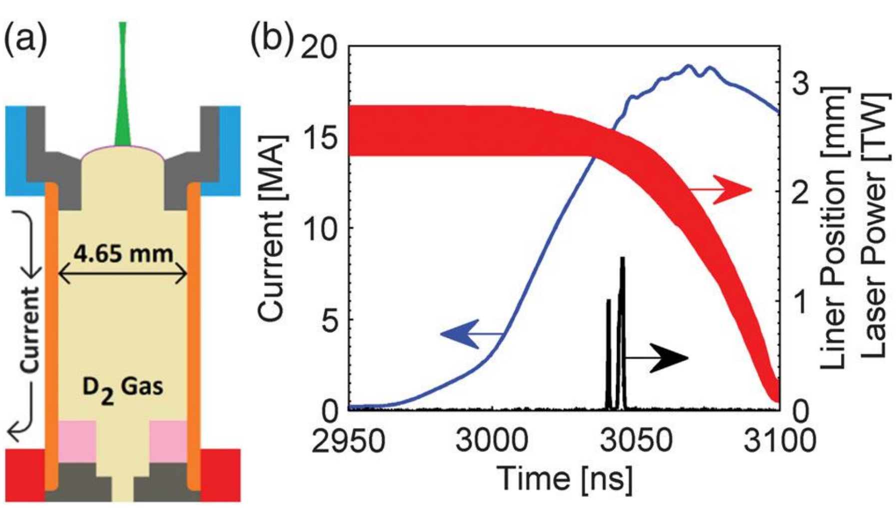
MagLIF target

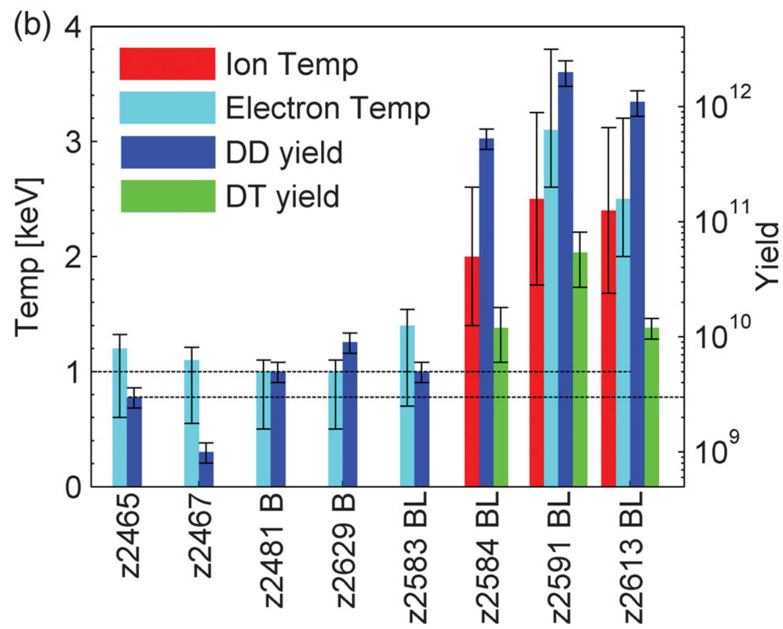






Neutron yield increased by 100x with preheat and external magnetic field.



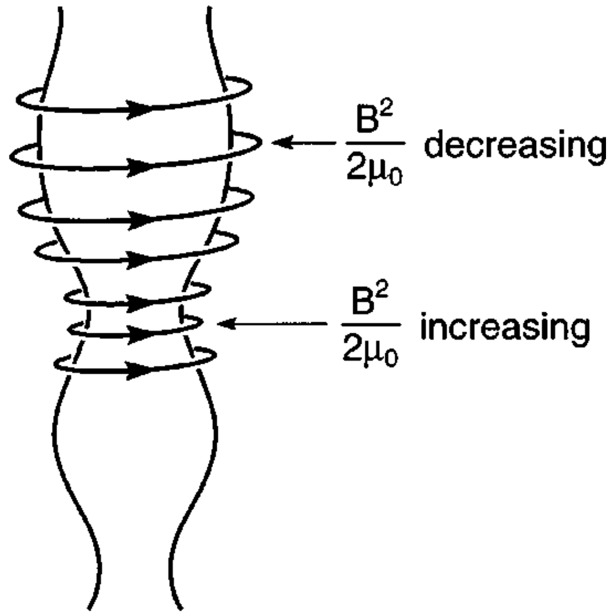


M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

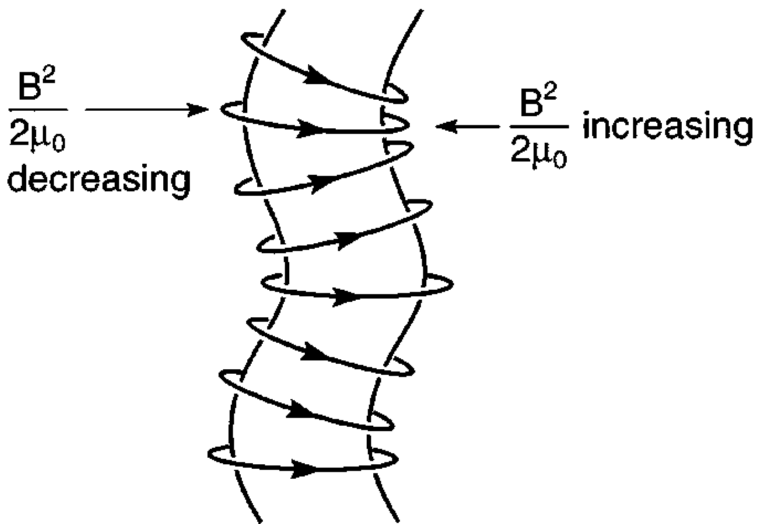
Sheared flow stabilizes MHD instabilities

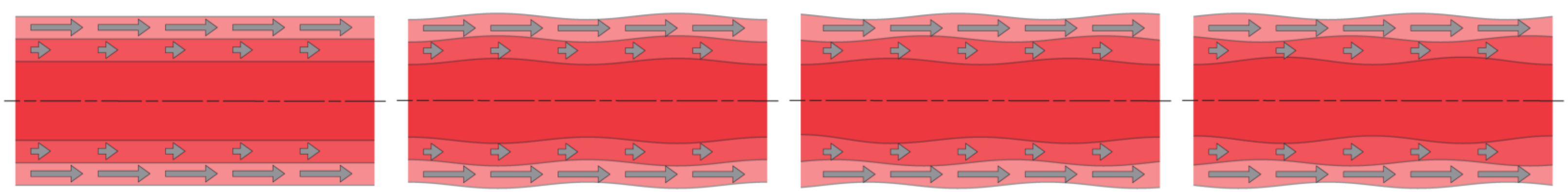
m = 0 (sausage)

Perturbation $\propto e^{(im\theta + ikz + \gamma t)}$



m = 1 (kink)

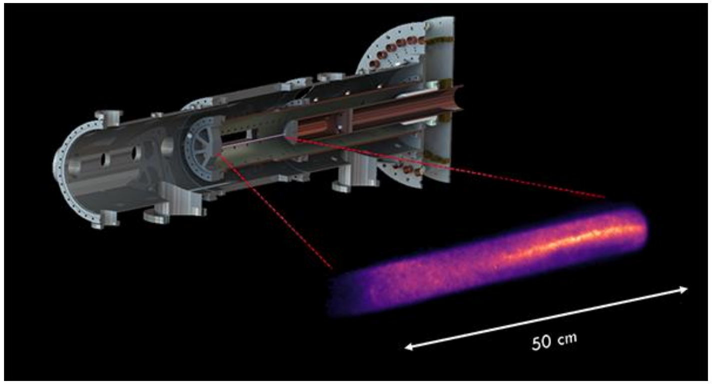




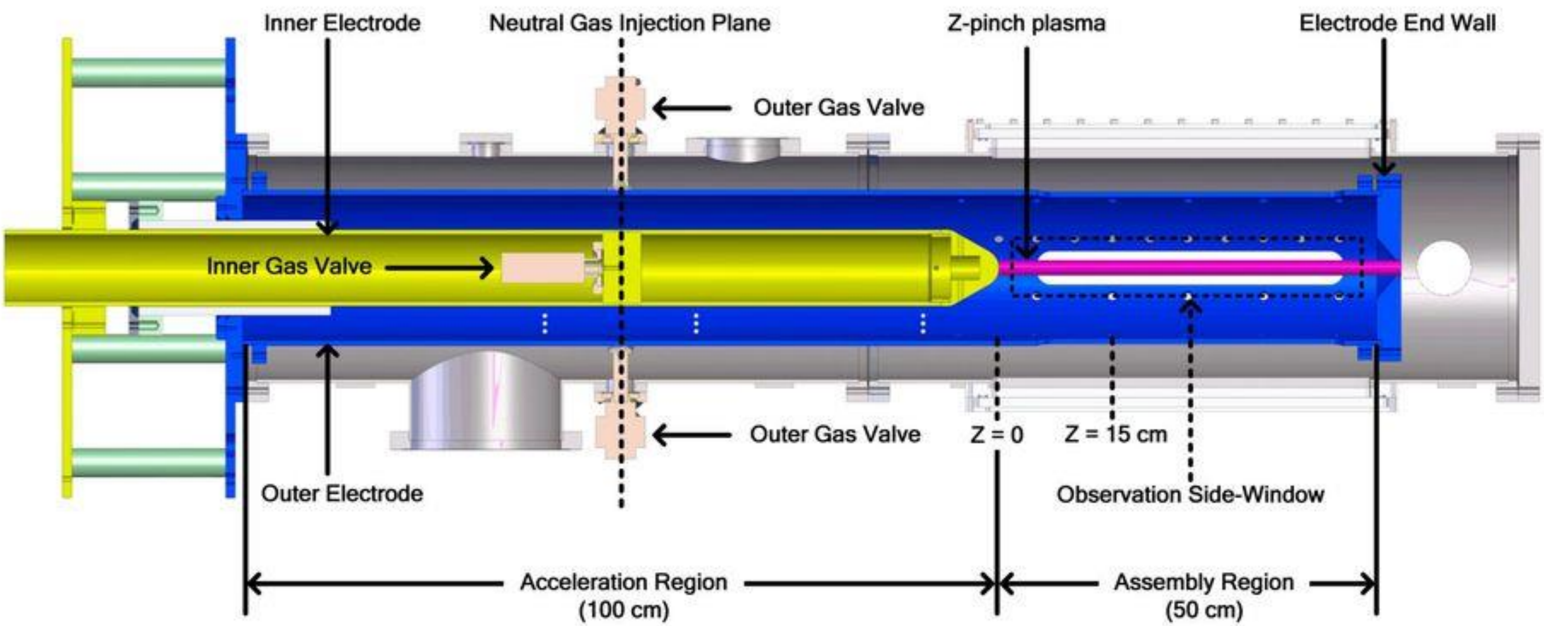
$$\frac{dV_Z}{dr} \neq 0$$

M. G. Haines, etc., Phys. Plasmas 7, 1672 (2000)
U. Shumlak, etc., Physical Rev. Lett. 75, 3285 (1995)
U. Shumlak, etc., ALPHA Annual Review Meeting 2017

A z-pinch plasma can be stabilized by sheared flows

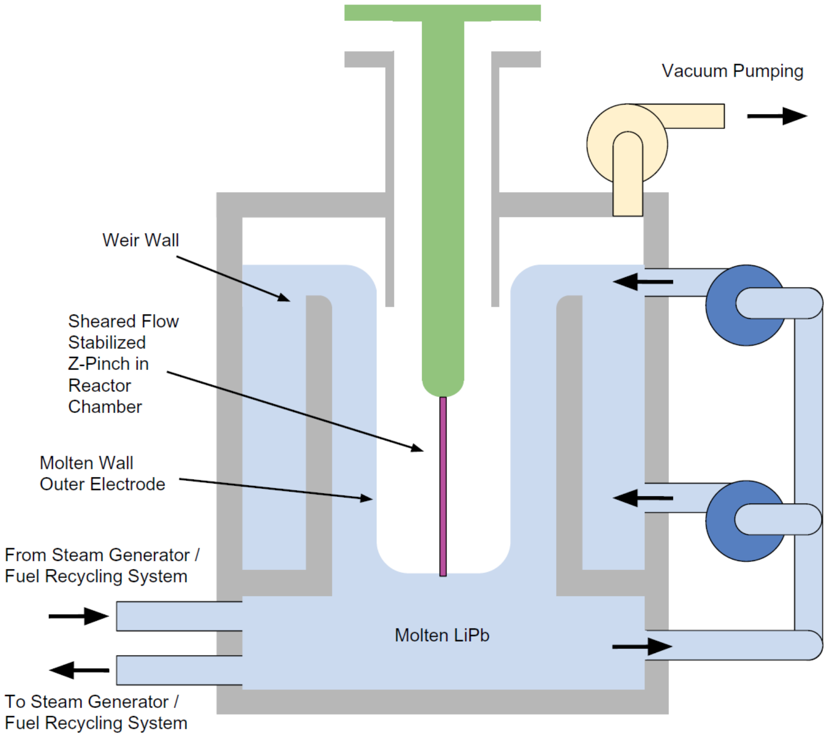


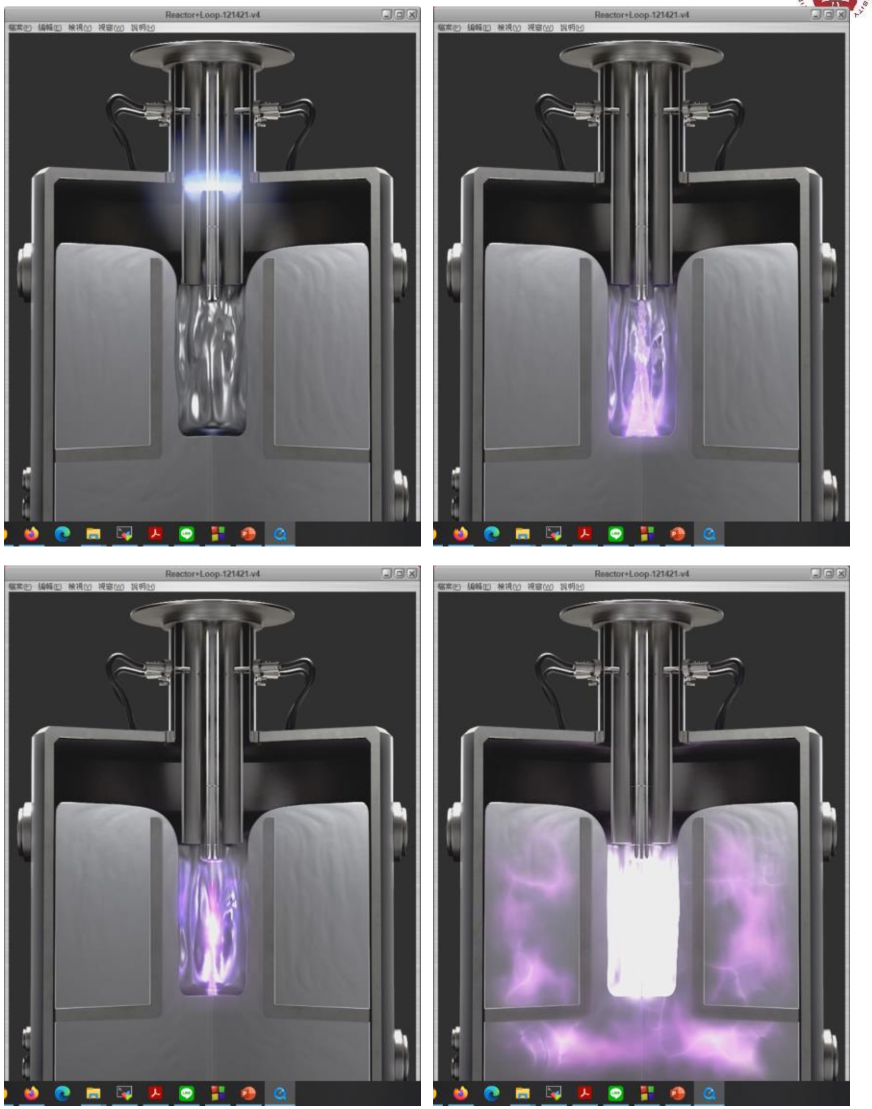
ZAP ENERGY™



https://www.zapenergyinc.com/about
A. D. Stepanov, etc., Phys. Plasmas 27, 112503 (2020)

Fusion reactor concept by ZAP energy

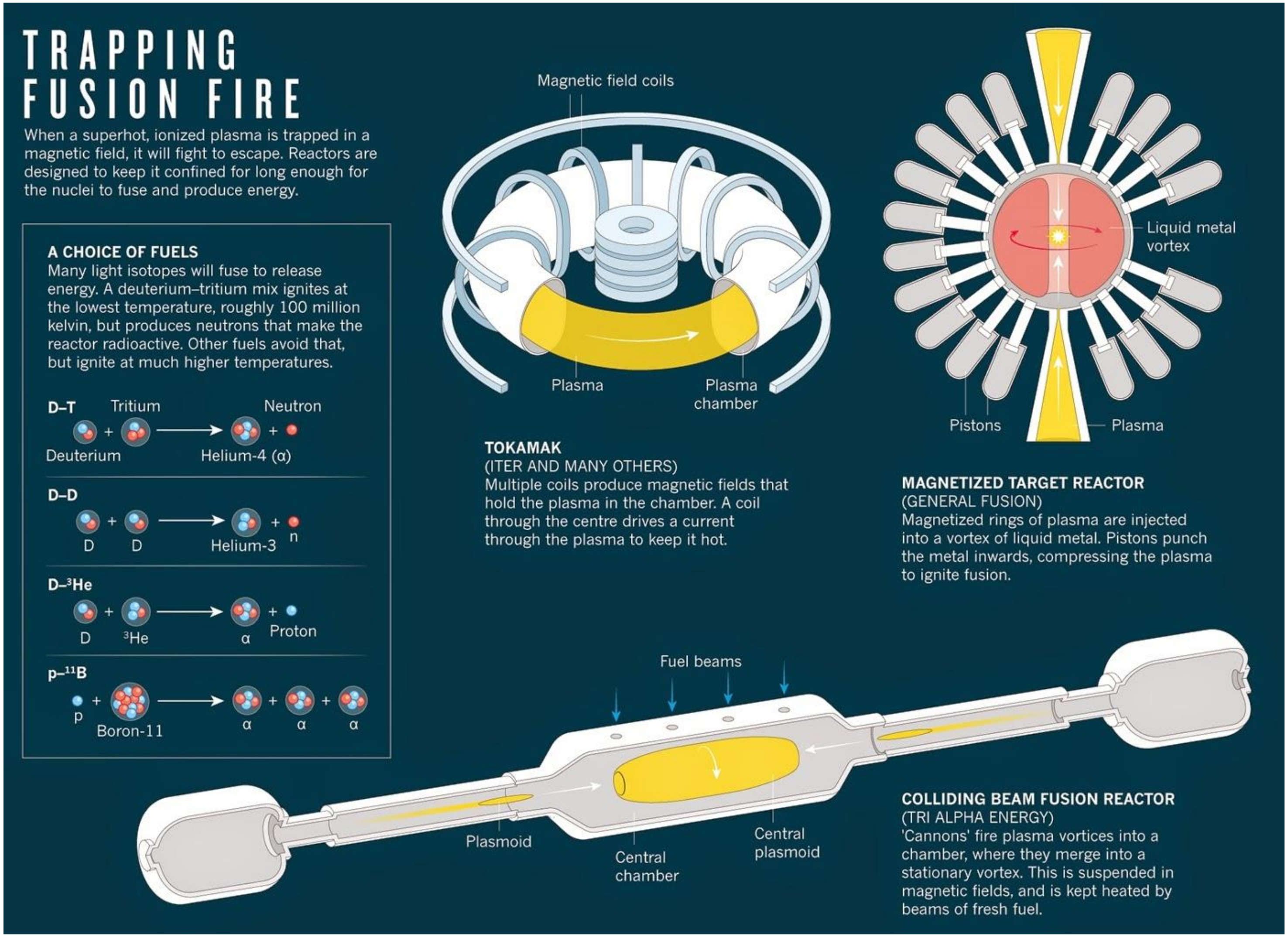




https://www.zapenergyinc.com/about

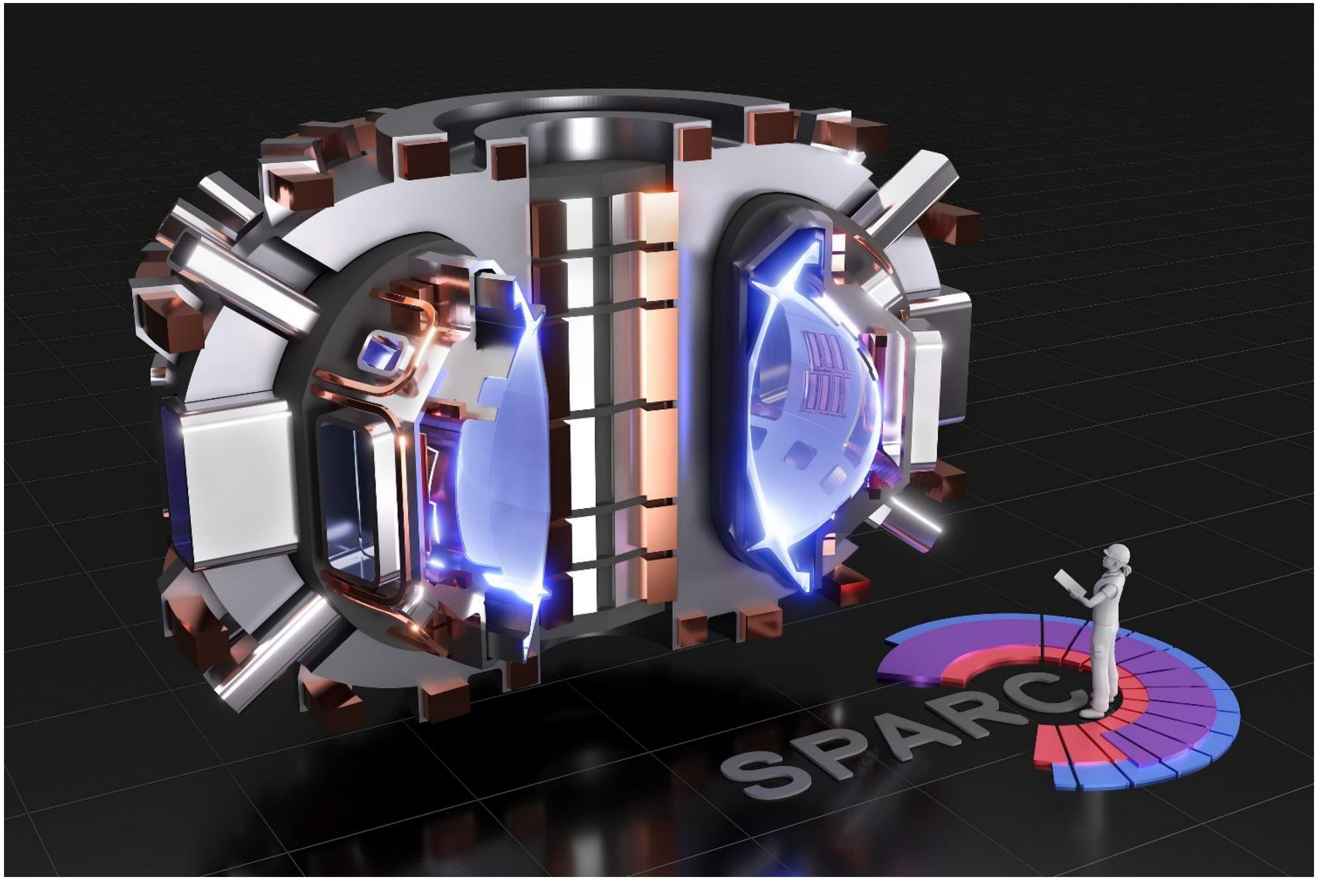
E. G. Forbes, etc., Fusion Sci. Tech. 75, 599 (2019)

There are alternative



http://www.nextbigfuture.com/2016/05/nuclear-fusion-comany-tri-alpha-energy.html

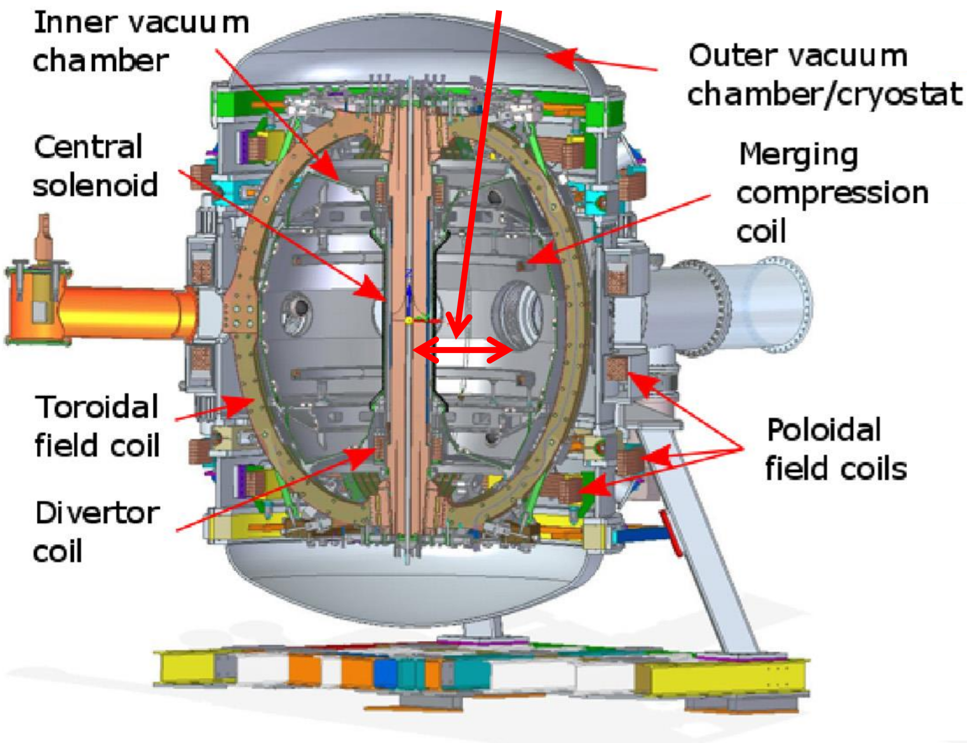
Commonwealth Fusion Systems, a MIT spin-out company, is building a high-magnetic field tokamak



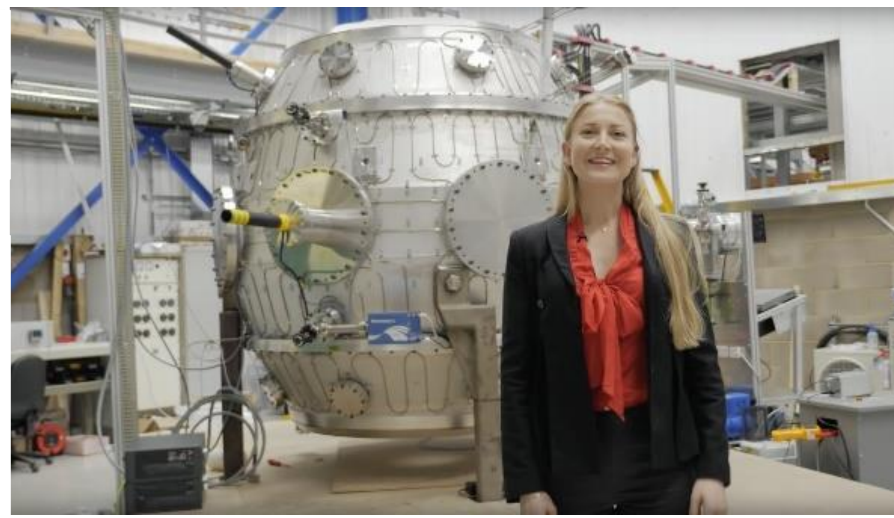
- **Fusion power ∝ B^4.**
- **The fusion gain Q > 2 is expected for SPARC tokamak.**

https://en.wikipedia.org/wiki/SPARC_(tokamak)

Merging compression is used to heat the tokamak at the start-up process in ST40 Tokamak at Tokamak Energy Ltd

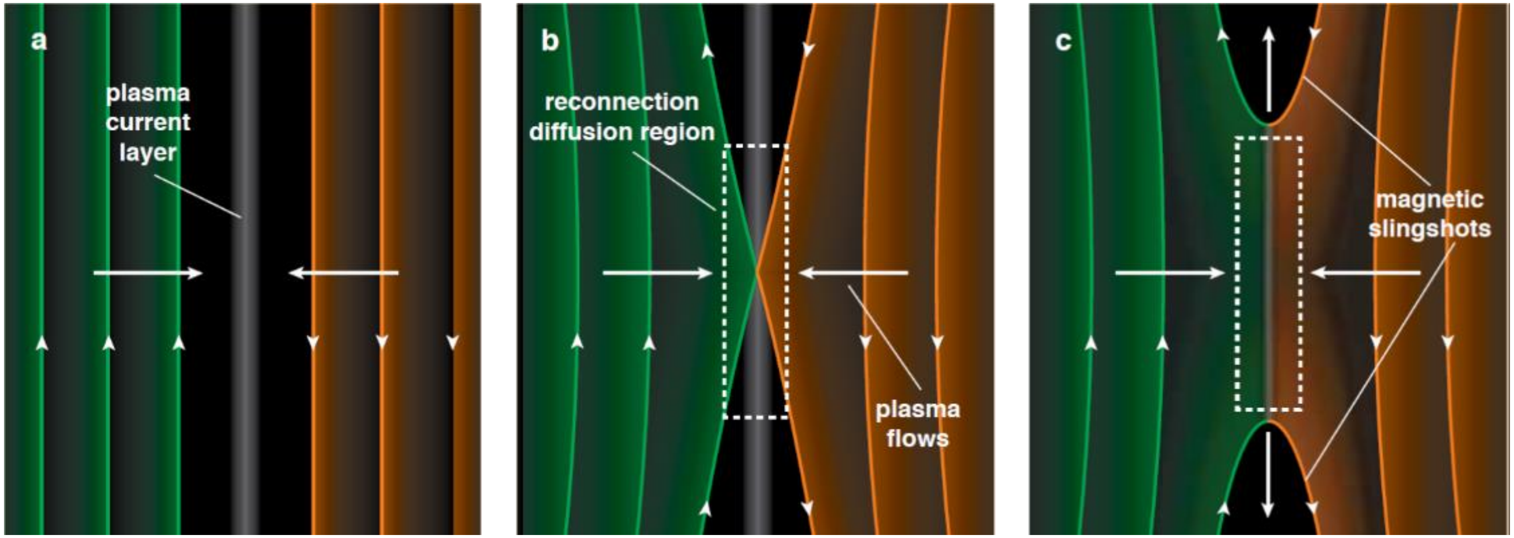


- **High temperature superconductors are used.**
- **B_T ~ 3 T**



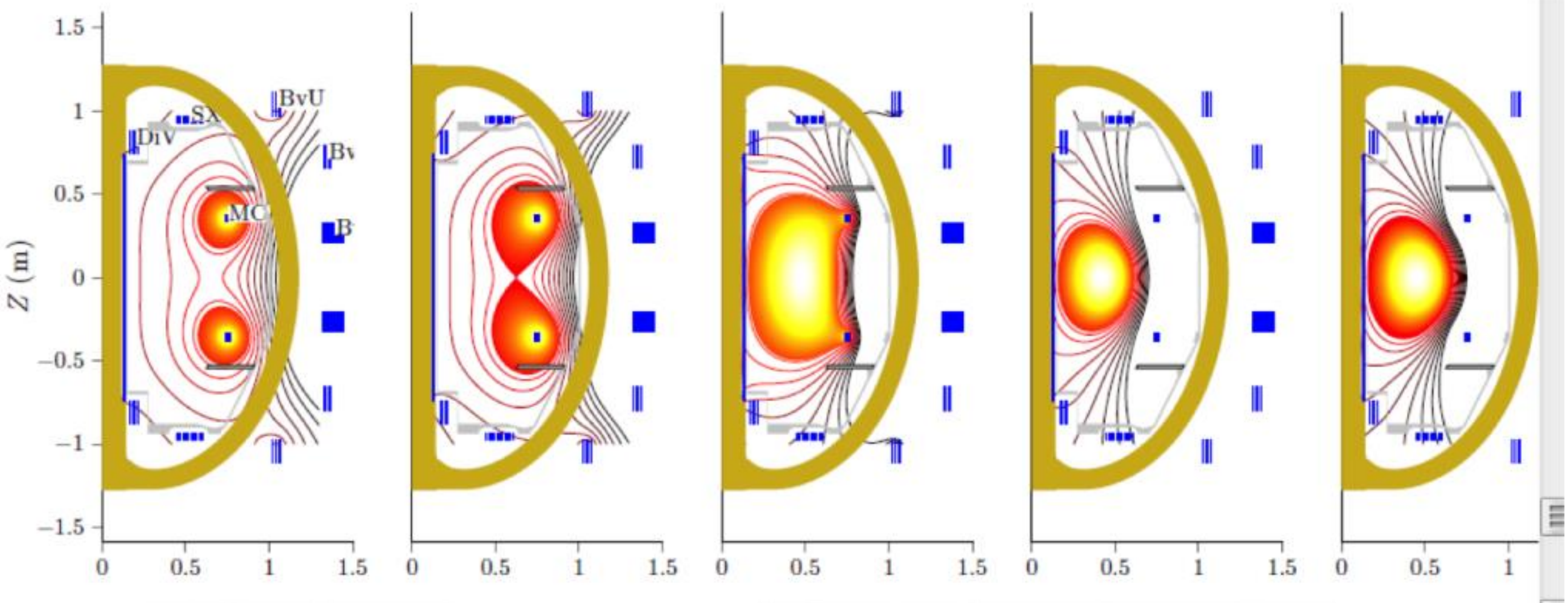
M. Gryaznevich, etc., Fusion Eng. Design, **123**,177 (2017)
https://www.tokamakenergy.co.uk/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

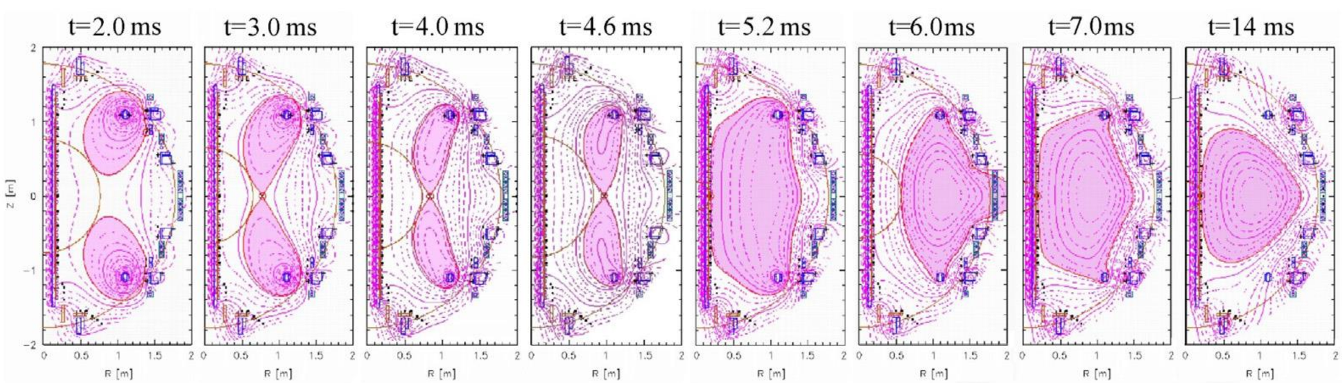
Reconnection



https://www.youtube.com/watch?v=7sS3Lpzh0Zw

Merging compression is used to heat the plasma

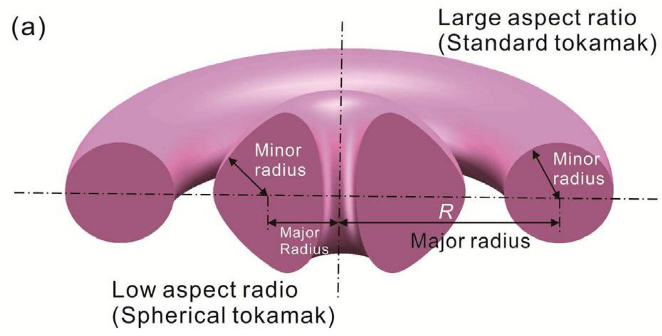




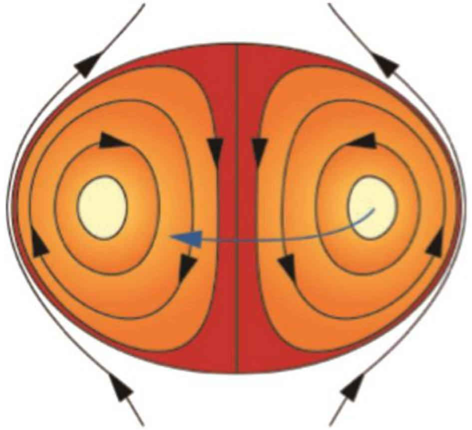
http://www.100milliondegrees.com/merging-compression/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

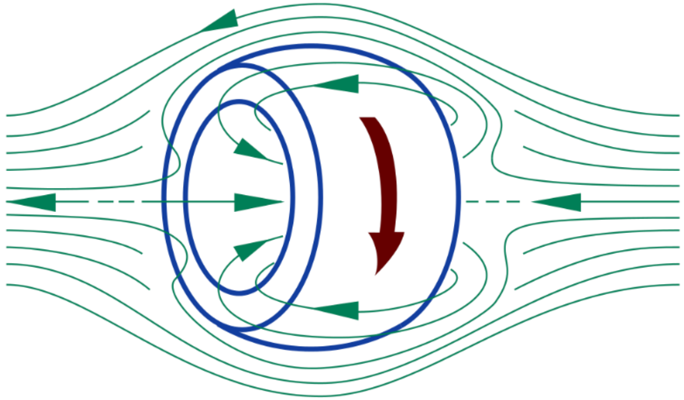
Spherical torus (ST) and compact torus (CT)

- **Spherical torus (ST)**



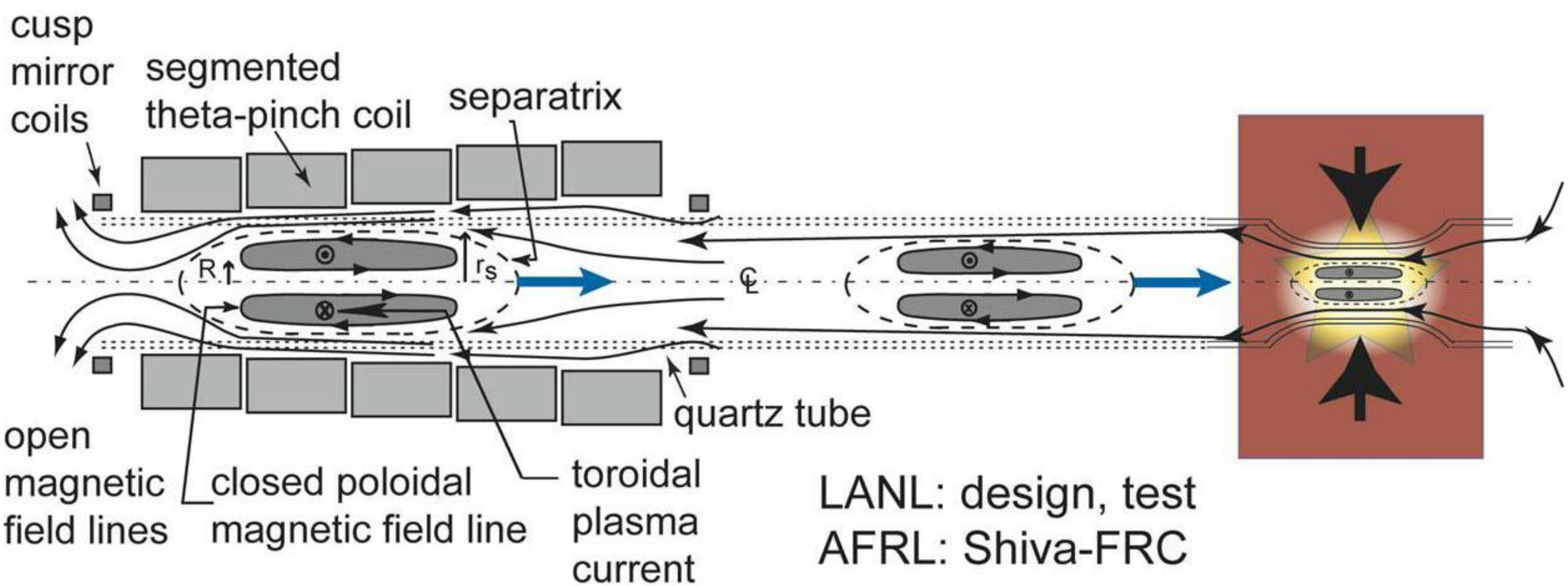
- **Compact torus (CT)**
  - **Spheromak**
  - **Field reversed configuration (FRC)**

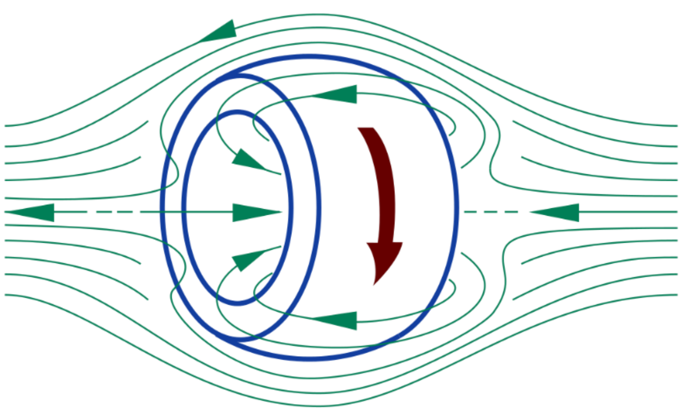




Zhe Gao, Matter Radiat. Extremes **1**, 153 (2016)
https://en.wikipedia.org/wiki/Field-reversed_configuration

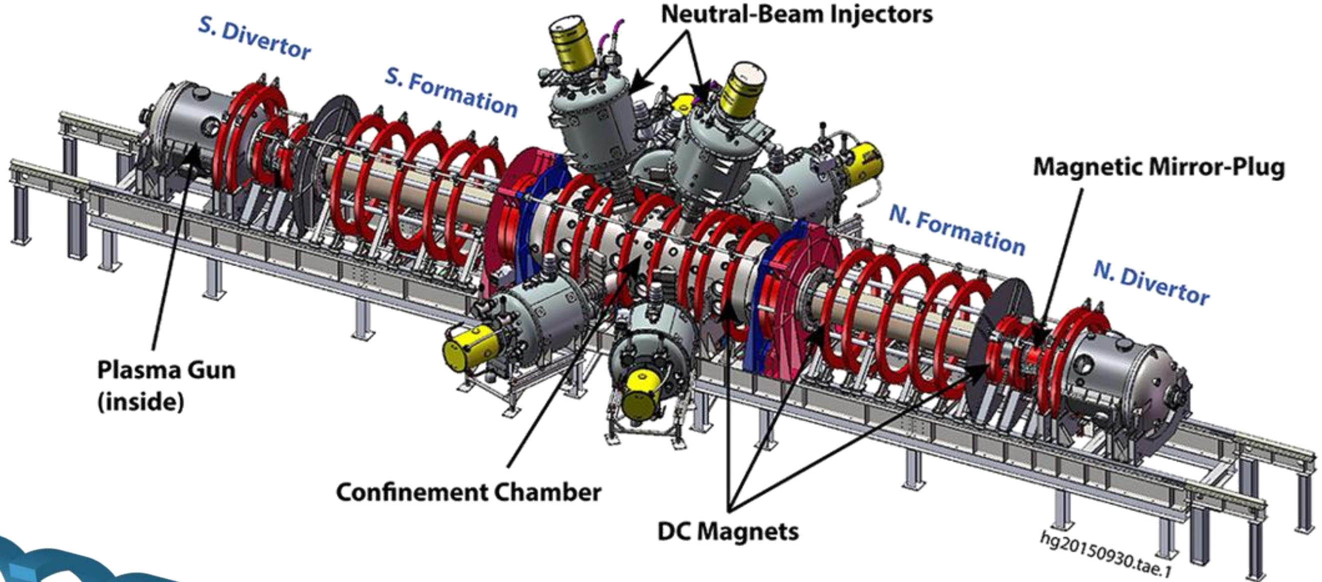
Field reverse configuration is used in Tri-alpha energy

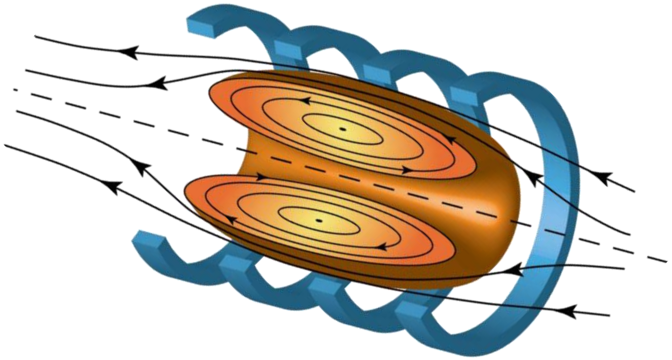




*Magneto-Inertial Fusion& Magnetized HED Physics by Bruno S. Bauer, UNR & Magneto-Inertial Fusion Community
**https://en.wikipedia.org/wiki/Field-reversed_configuration

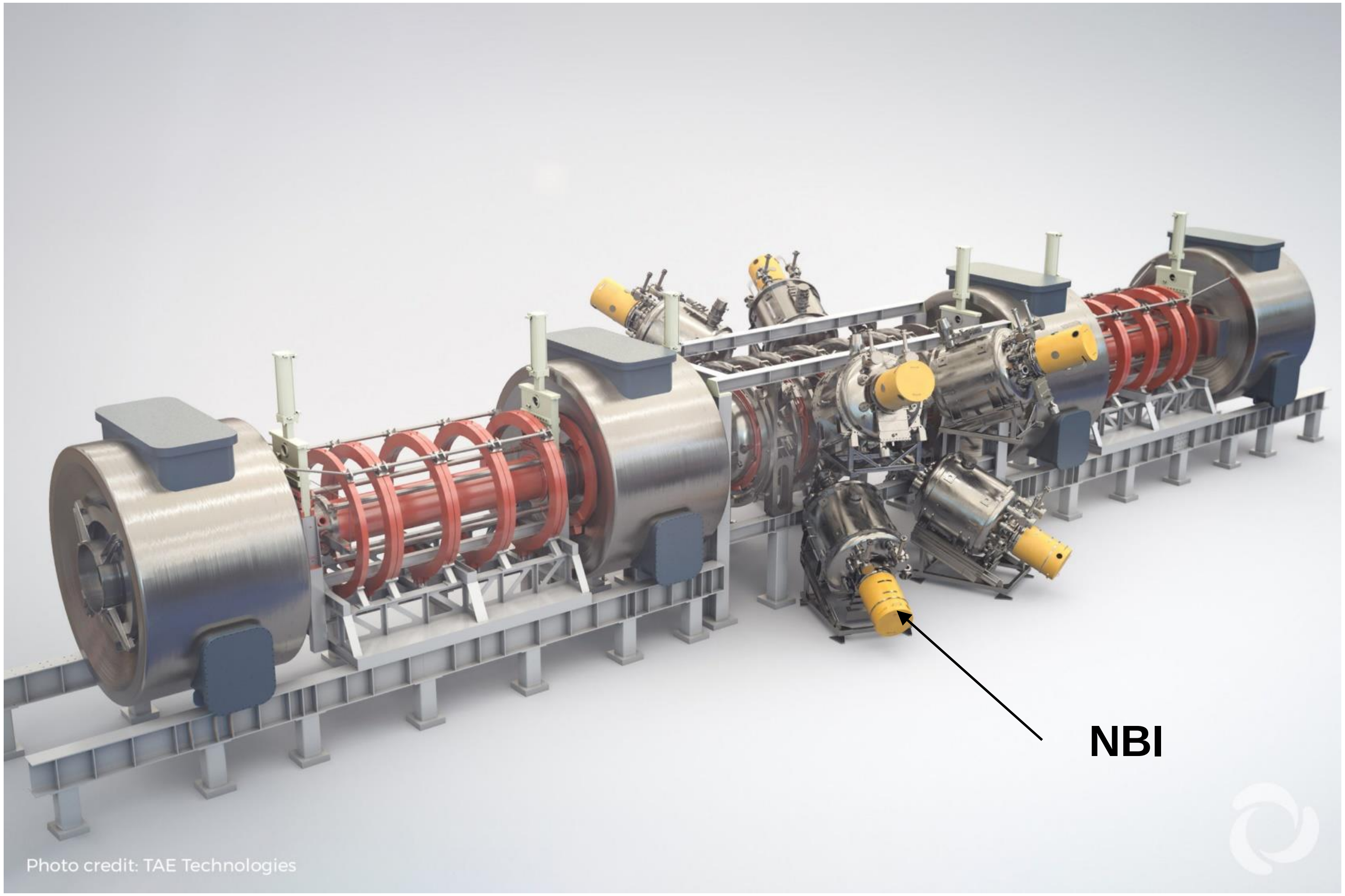
Field reverse configuration is used in Tri-alpha energy





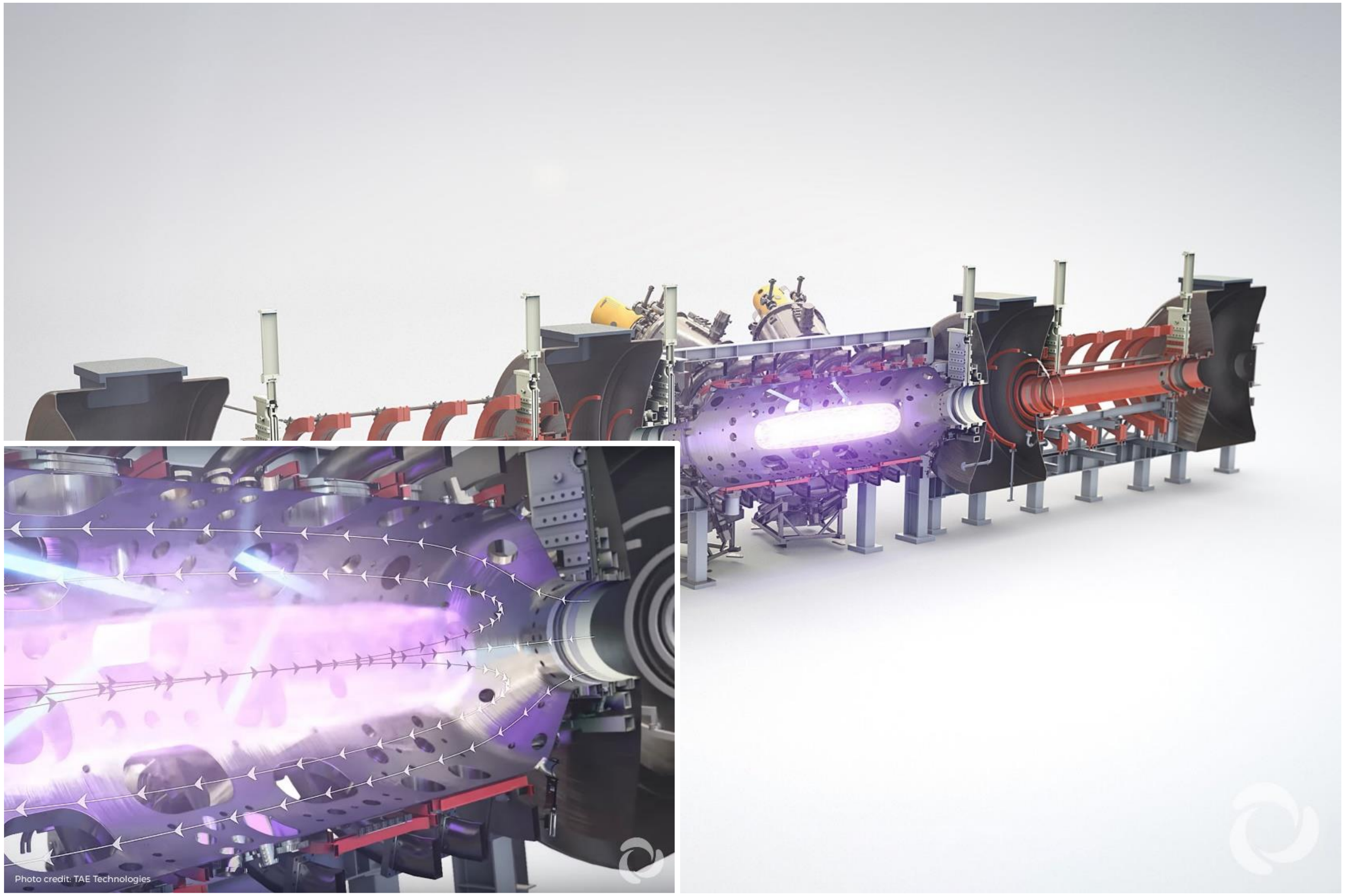
http://trialphaenergy.com/

NBI for Tri-Alpha Energy Technologies



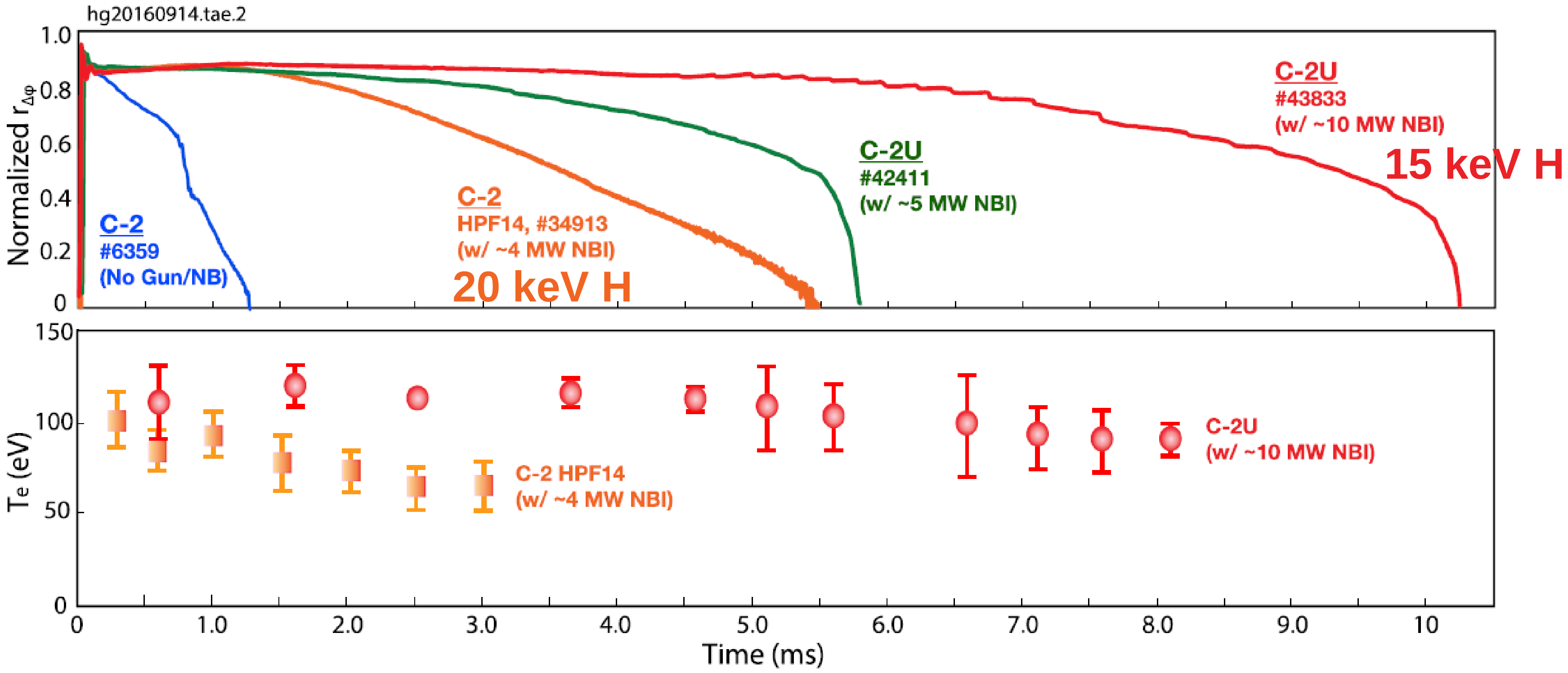
https://tae.com/media/

Neutral beams are injected in to the chamber for spinning the FRC



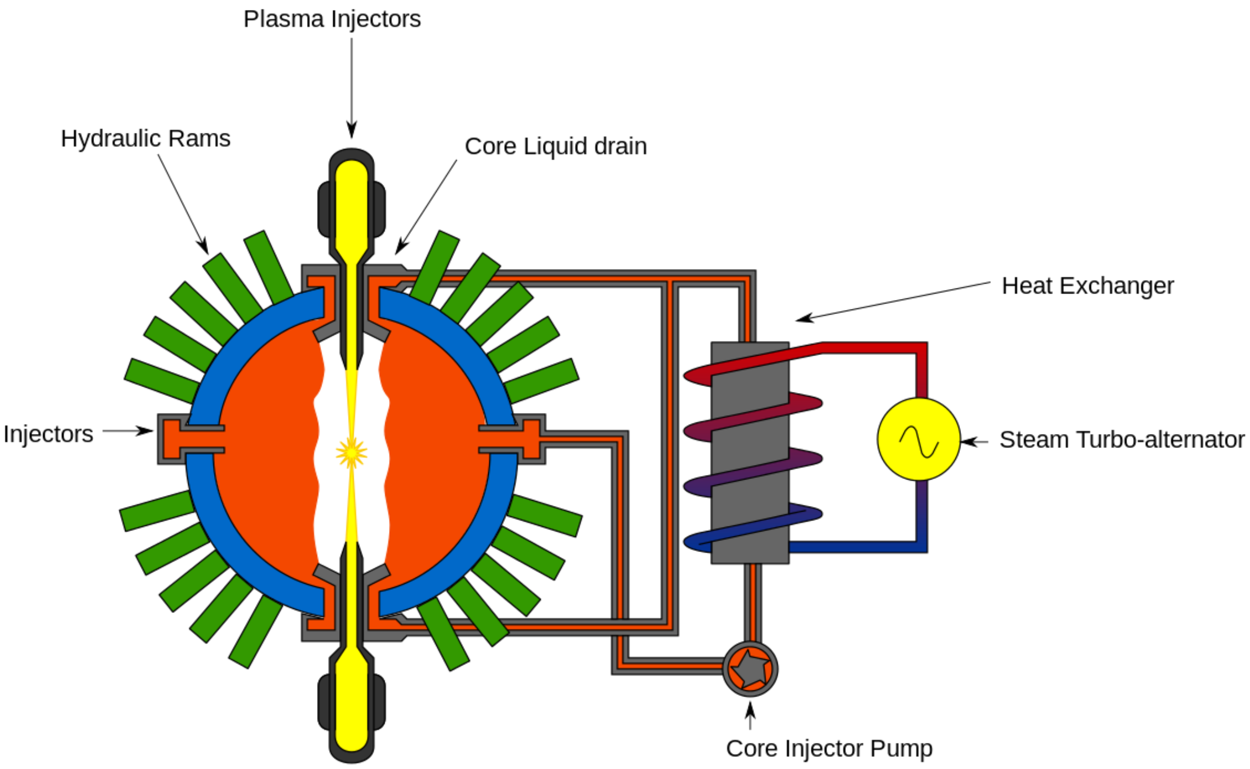
https://tae.com/media/

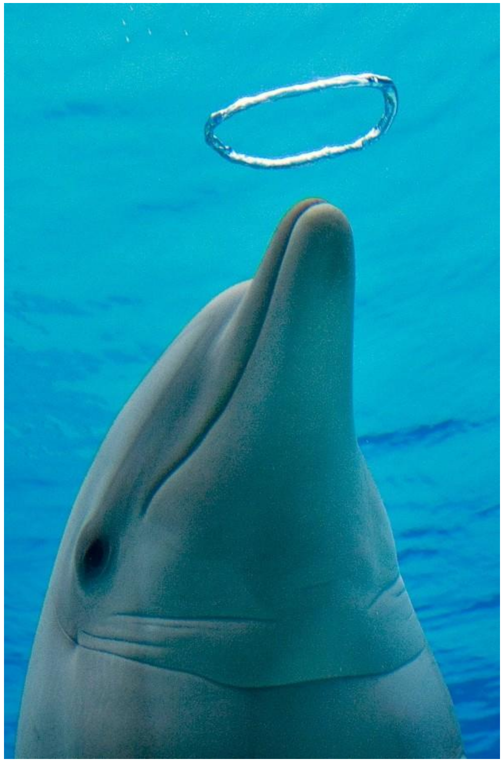
FRC sustain longer with neutral beam injection



H. Gota, *etc.*, Nucl. Fusion **57** (2017) 116021

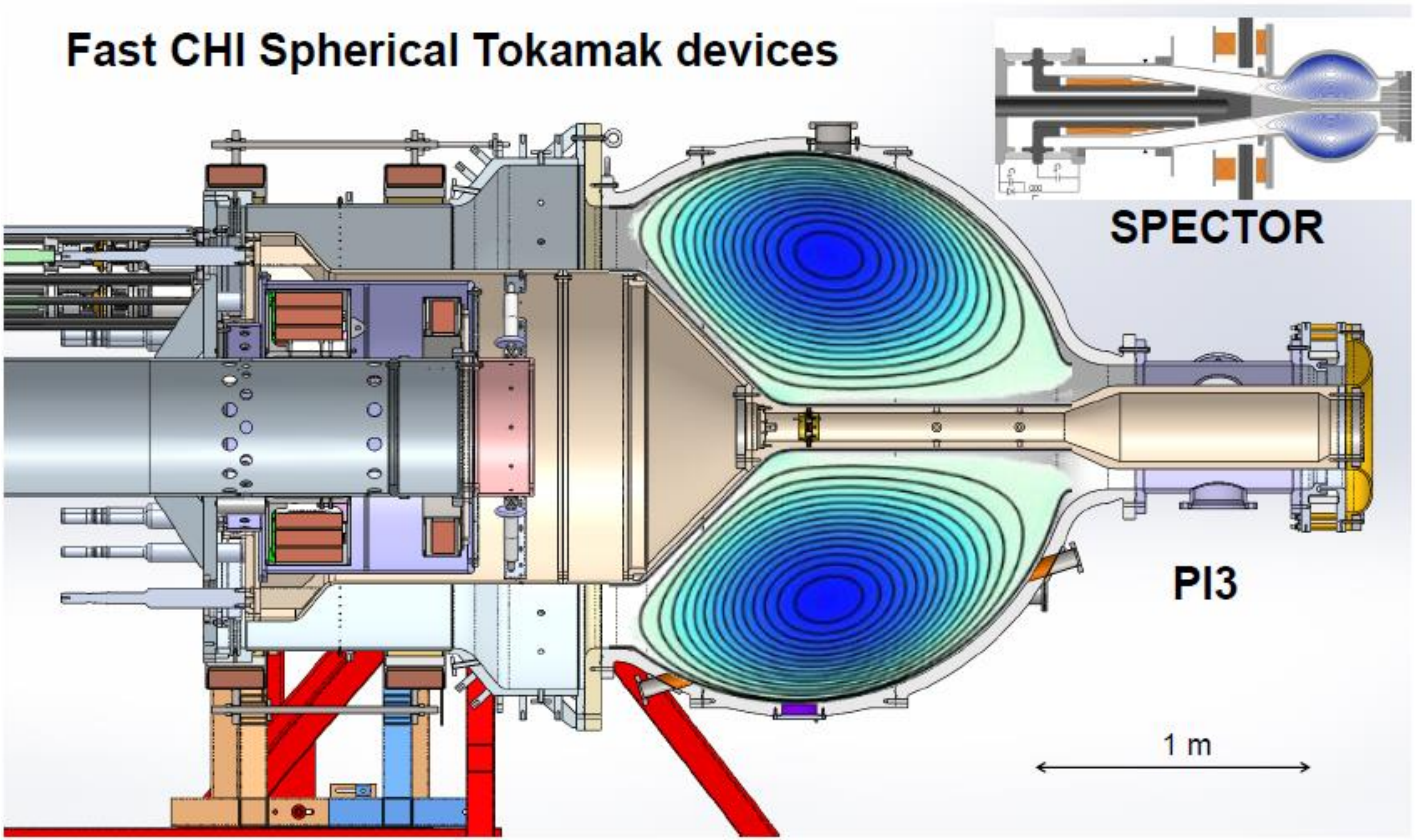
General fusion is a design ready to be migrated to a power plant





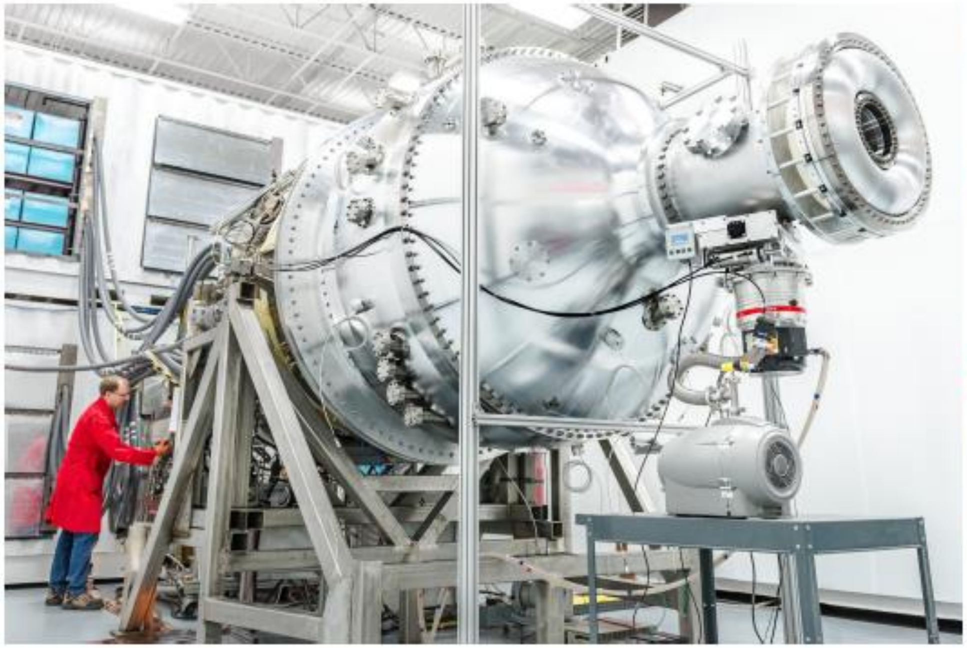
https://en.wikipedia.org/wiki/General_Fusion

A spherical tokamak is first generated



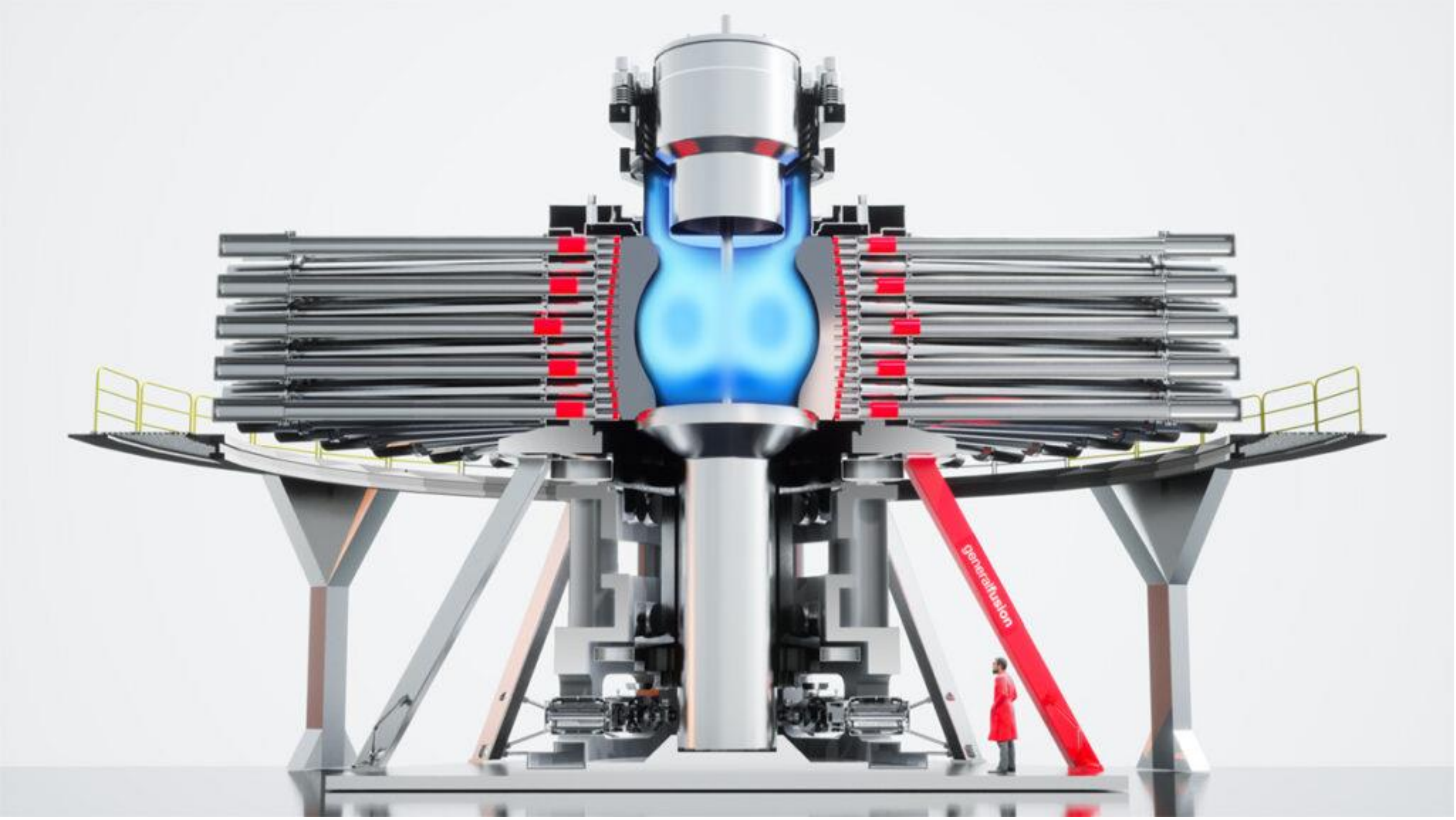
K. EPP, etc., 60th APS-DPP, CP11.00192

Plasma injector for the spherical tokamak

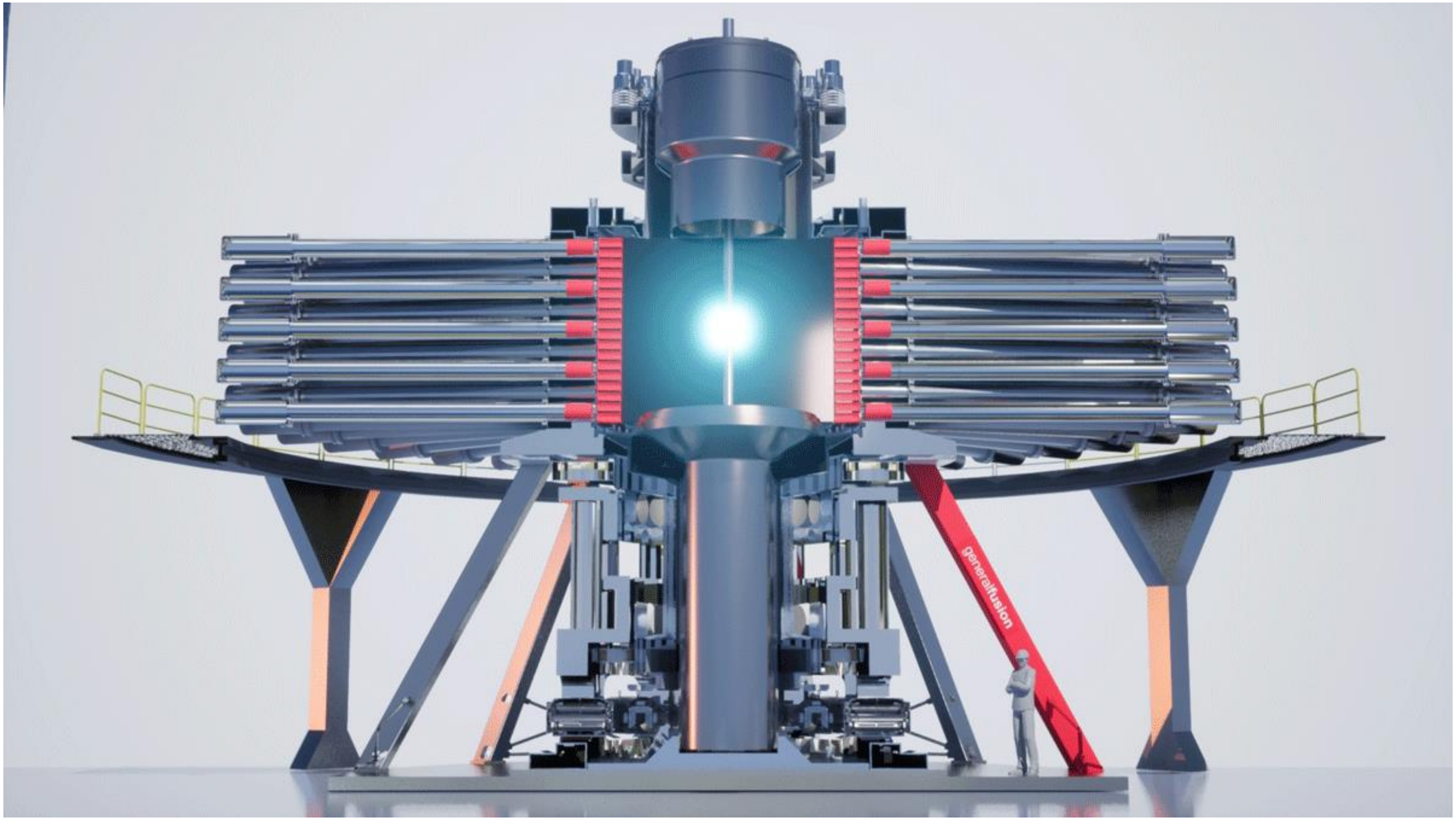


K. EPP, etc., 60th APS-DPP, CP11.00192

A spherical tokamak is generated in a liquid metal vortex



The spherical tokamak is compressed by the pressure provided by the sournding hydraulic pistons



BBC: General Fusion to build its Fusion Demonstration Plant in the UK, at the UKAEA Culham Campus

Nuclear energy: Fusion plant backed by Jeff Bezos to be built in UK

By Matt McGrath
Environment correspondent

17 June

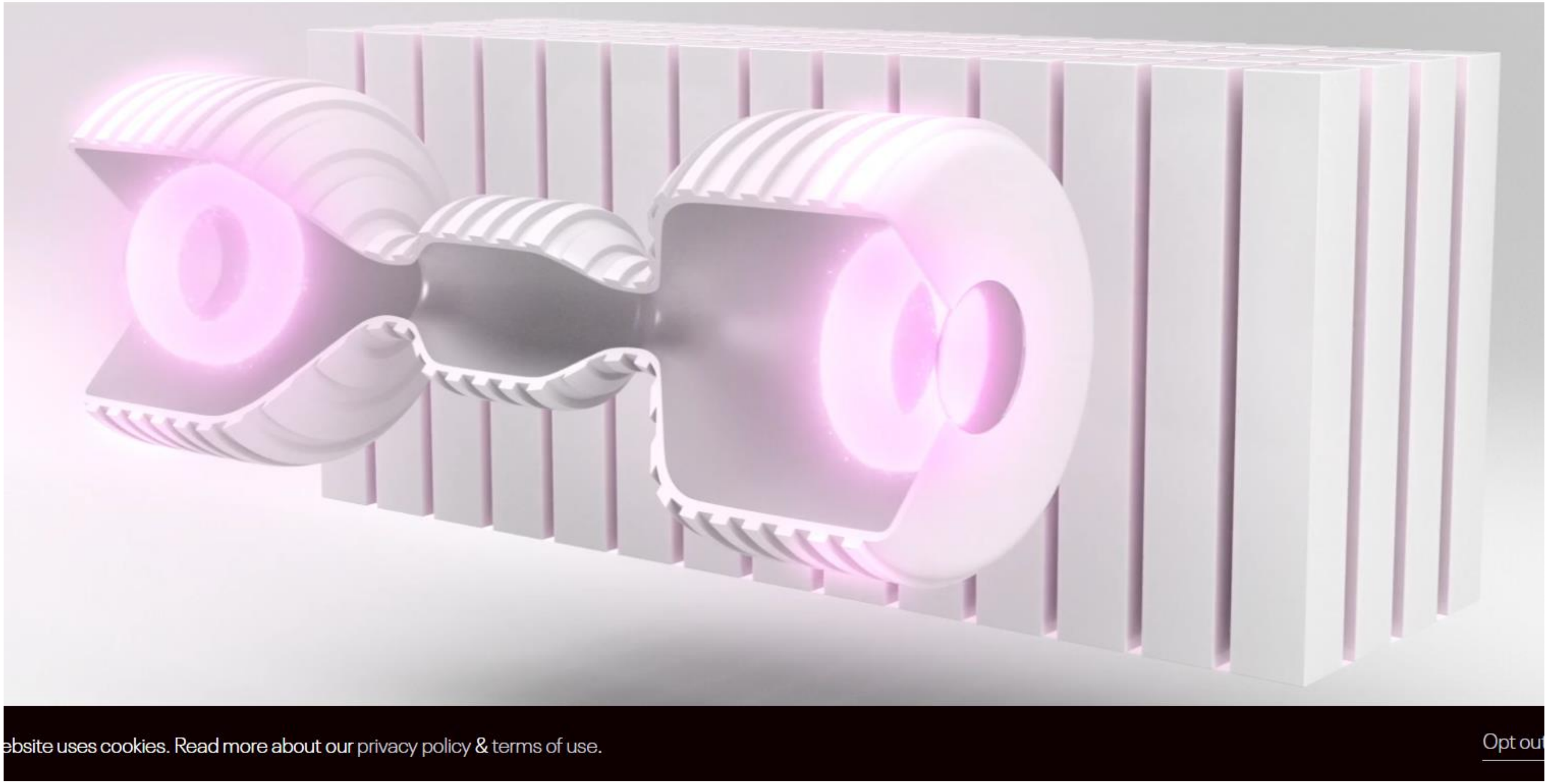
An artist's impression of what the new demonstration plant might look like

A company backed by Amazon's Jeff Bezos is set to build a large-scale nuclear fusion demonstration plant in Oxfordshire.

Canada's **General Fusion** is one of the leading private firms aiming to turn the

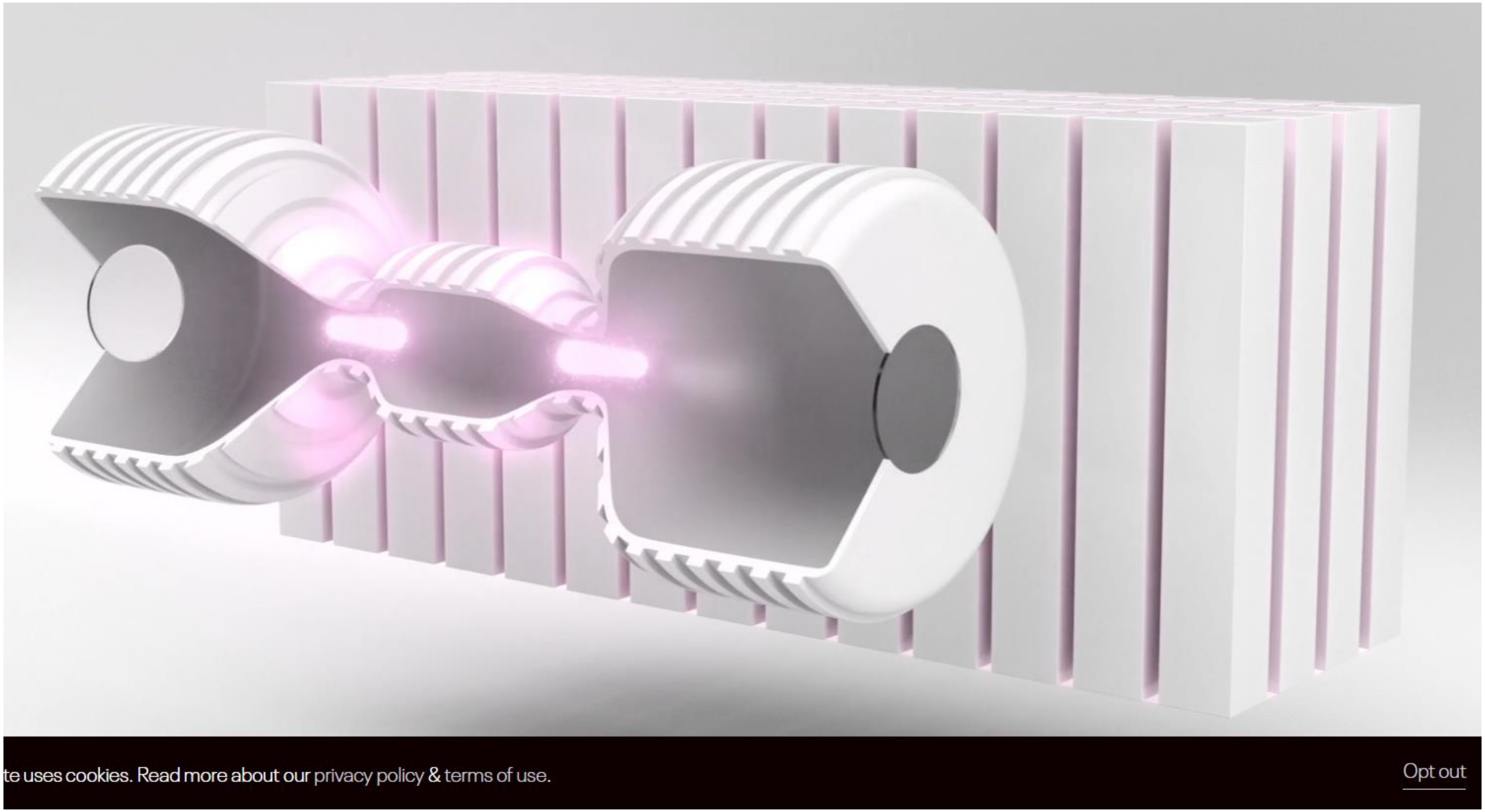
https://www.bbc.com/news/science-environment-57512229

Helion energy is compressing the two merging FRCs



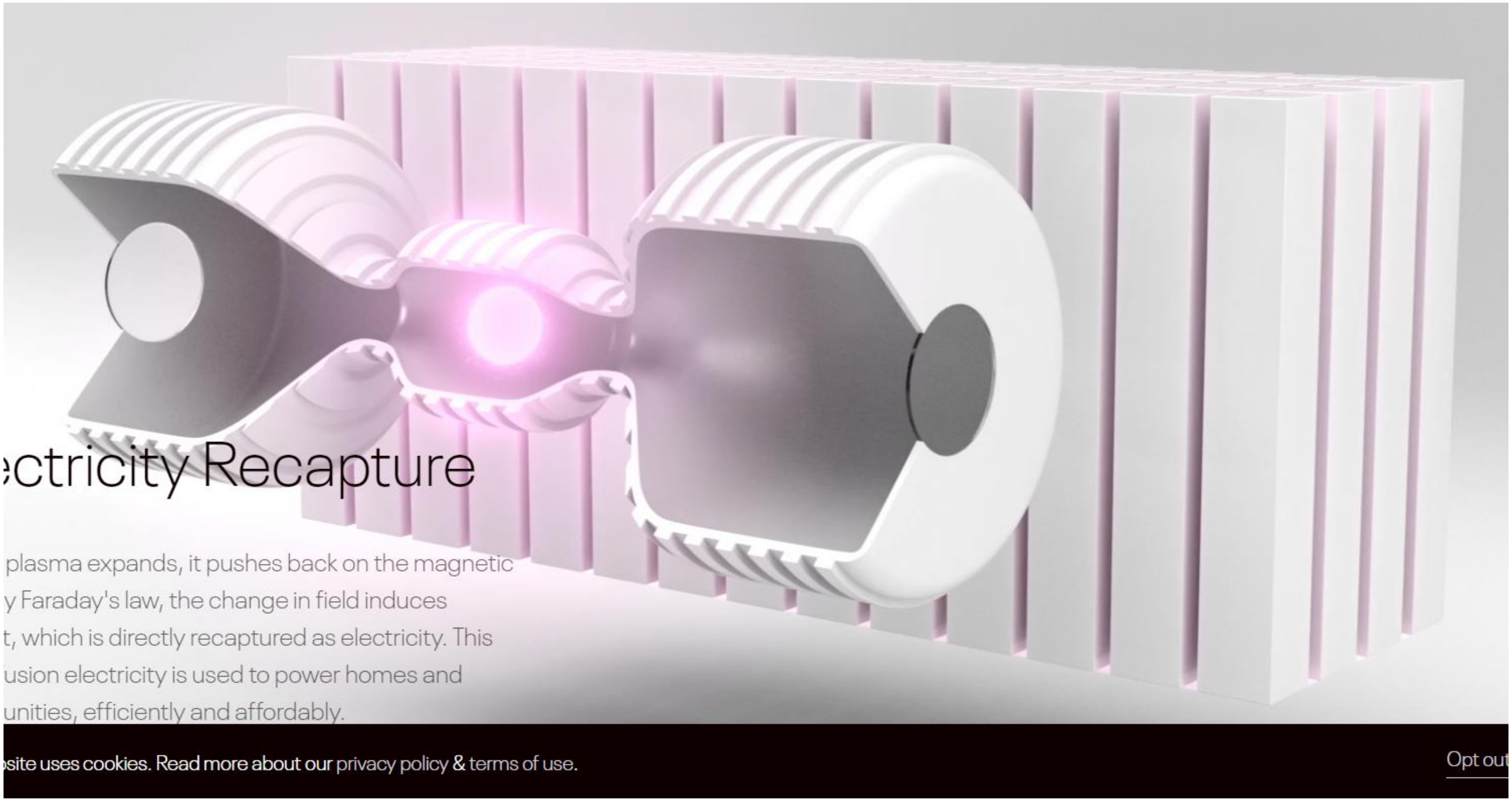
https://www.helionenergy.com/

Two FRCs are accelerated toward each other



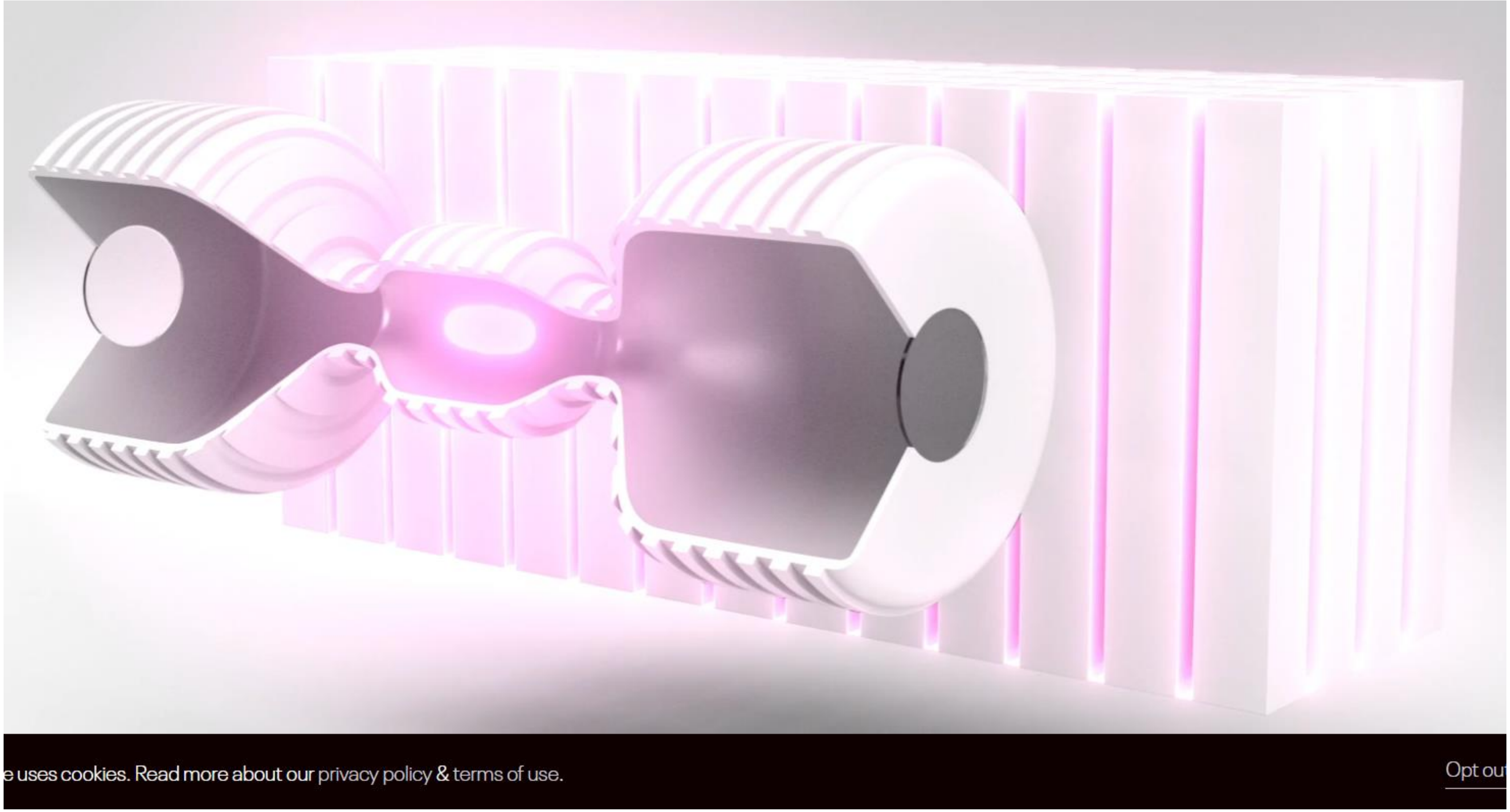
https://www.helionenergy.com/

Two FRCs merge with each other



https://www.helionenergy.com/

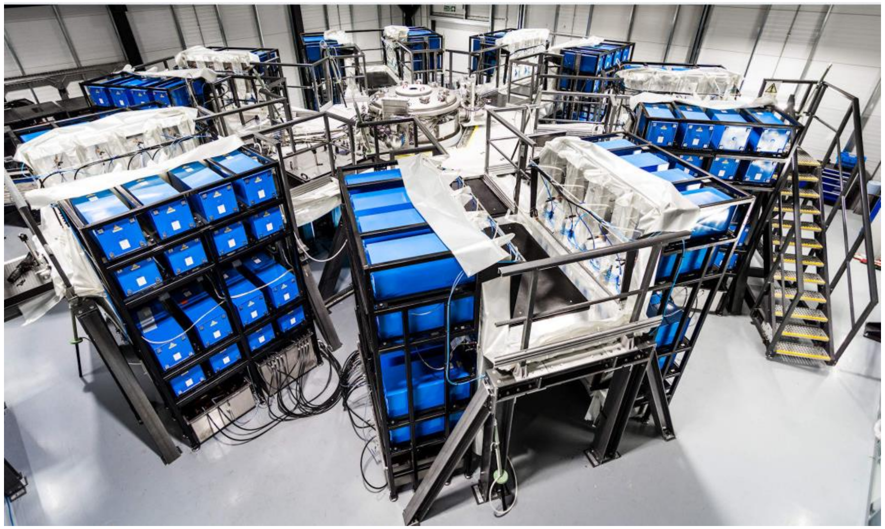
The merged FRC is compressed electrically to high temperature



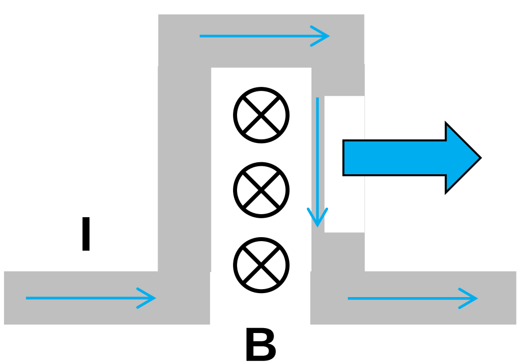
- **Similar concept will be studied in our laboratory.**

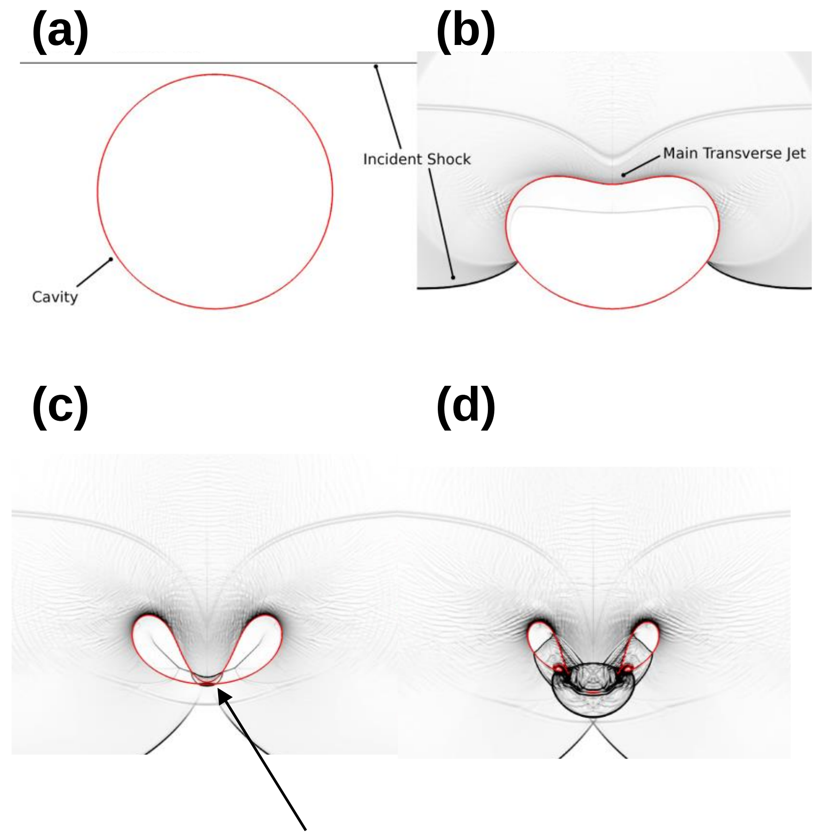
https://www.helionenergy.com/

Projectile Fusion is being established at First Light Fusion Ltd, UK



- **Stored energy: 2.5 MJ @ 200 kV (C_{tot}=125 uF)**
- **I_{peak}=14 MA w/ T_{rise}~2us.**





- **High pressure is generated by the colliding shock.**

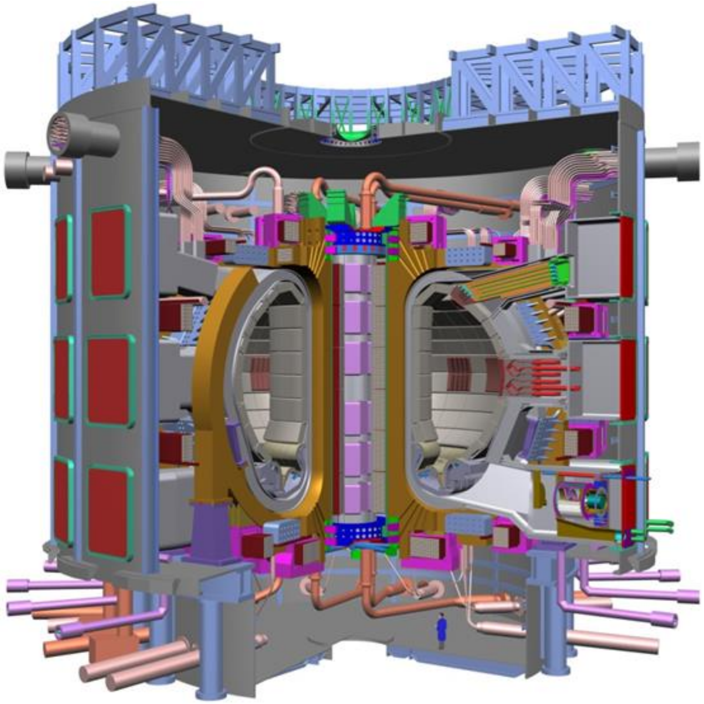
https://firstlightfusion.com/
B. Tully and N. Hawker, Phys. Rev. **E93**, 053105 (2016)

A gas gun is used to eject the projectile

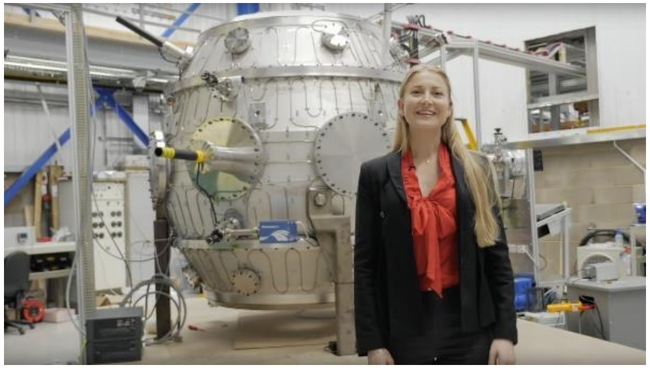
https://www.youtube.com/watch?v=JN7lyxC11n0
https://www.youtube.com/watch?v=aW4eufacf-8

Many groups aim to achieve ignition in the MCF regime in the near future

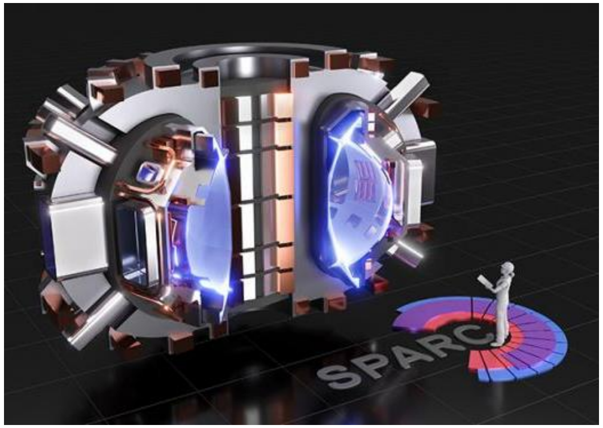
- **ITER – 2025 First Plasma**
  2035 D-T Exps
  2050 DEMO



- **Tokamak energy, UK**
  - **2025 Gain**
  - **2030 to power grid**



- **Commonwealth Fusion Systems, USA – 2025 Gain**



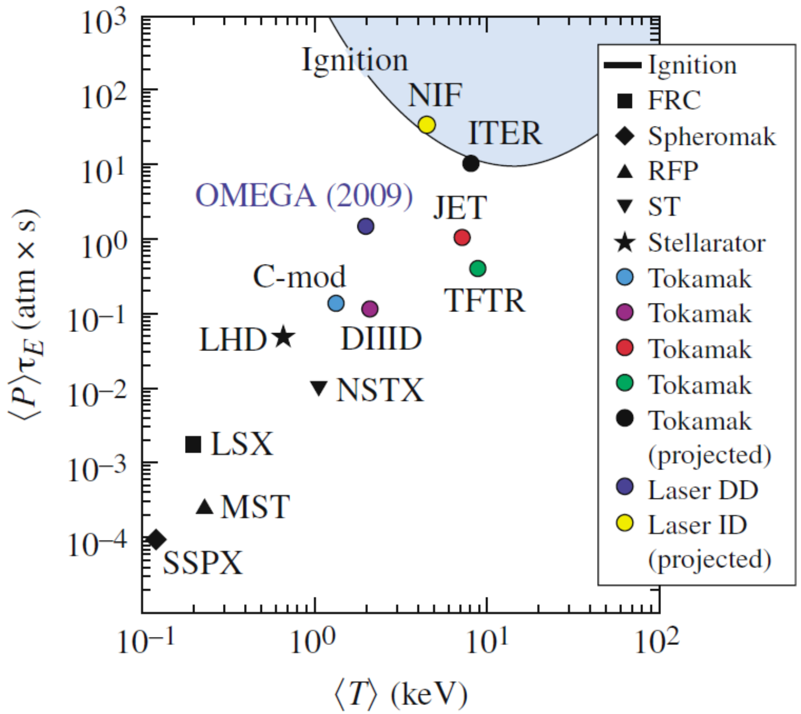
https://www.iter.org
https://www.tokamakenergy.co.uk/
https://www.psfc.mit.edu/sparc

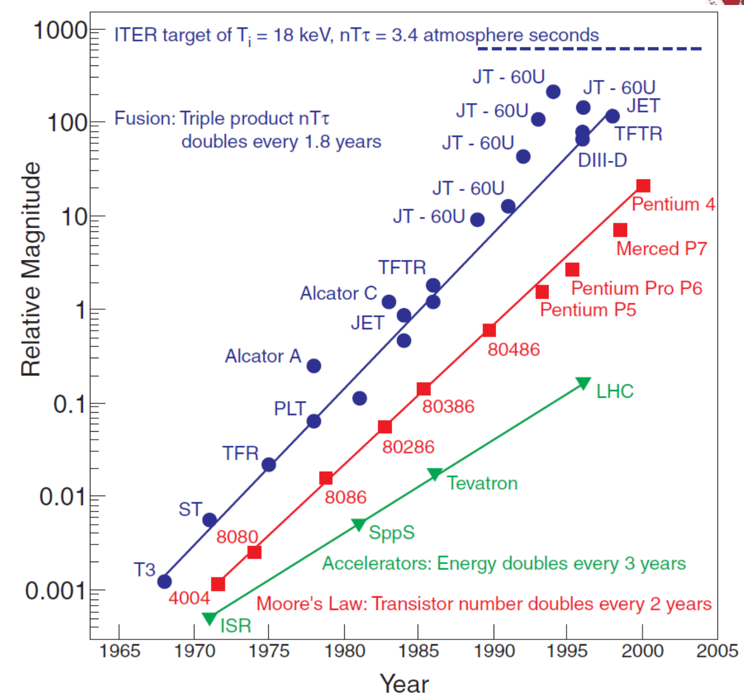
Fusion is blooming

⋮

https://www.fusionindustryassociation.org/members

We are closed to ignition!





- **Other private companies:**

CFS

generalfusion

first light

...

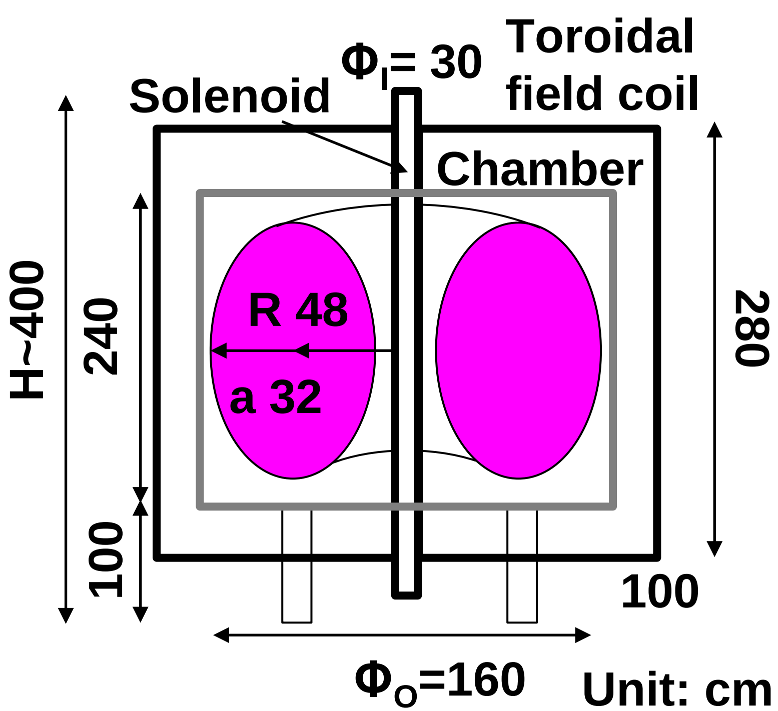
Tokamak **MTF** **ICF**

A. J. Webster, Phys. Educ. **38**, 135 (2003)
R. Betti, etc., Phys. Plasmas, **17**, 058102 (2010)

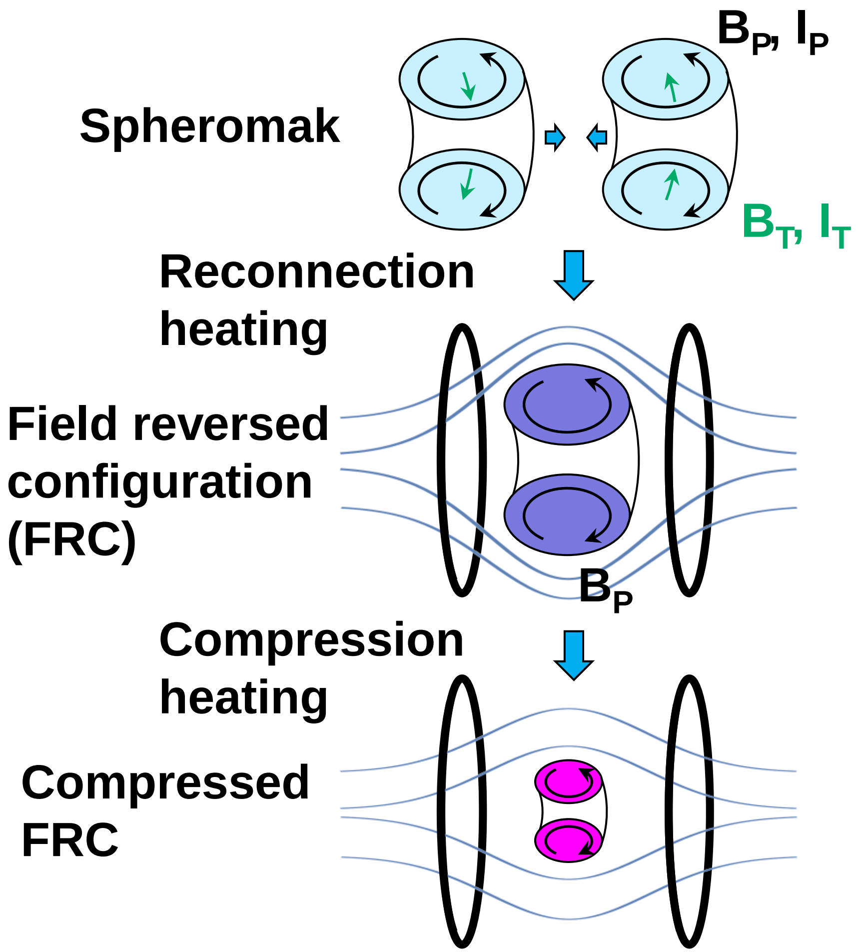
Fusion projects in Inst. Space and Plasma Sciences , National Cheng Kung University

- 國科會計畫 - 磁約束高溫電漿研究

Formosa Integrated Research Spherical Tokamak (FIRST)



- Magneto-inertial fusion (MIF)



- We welcome anyone interested in fusion research to join our team!

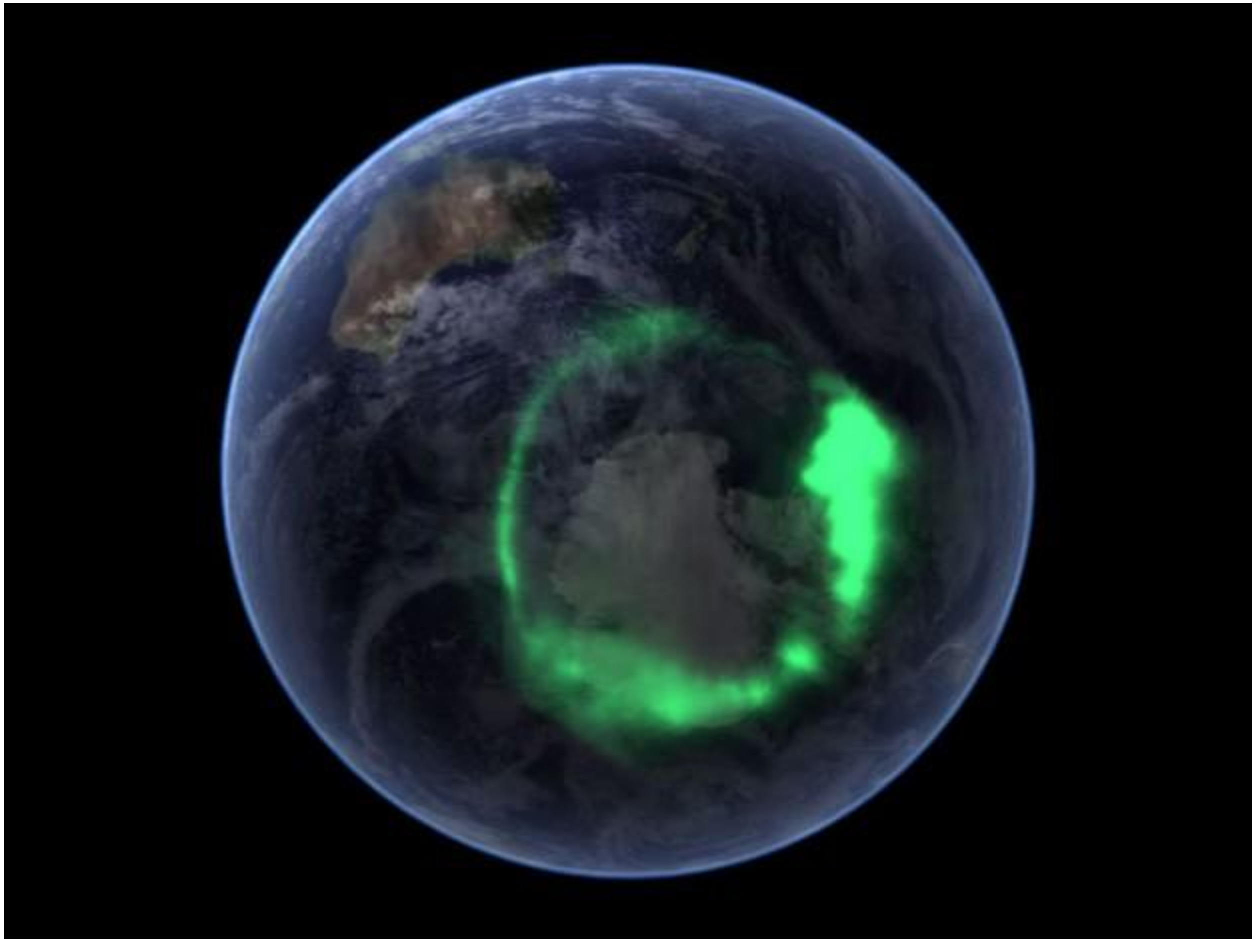
Outline

- Introduction to nuclear fusion
- Magnetic confinement fusion (MCF)
  - Tokamak
  - Stellarator
- Inertial confinement fusion (ICF)
  - Indirection drive ICF
  - Direct drive ICF
- Innovation idea – MCF + ICF
- **Plasma in space**
- Pulsed-power system at NCKU

Aurora

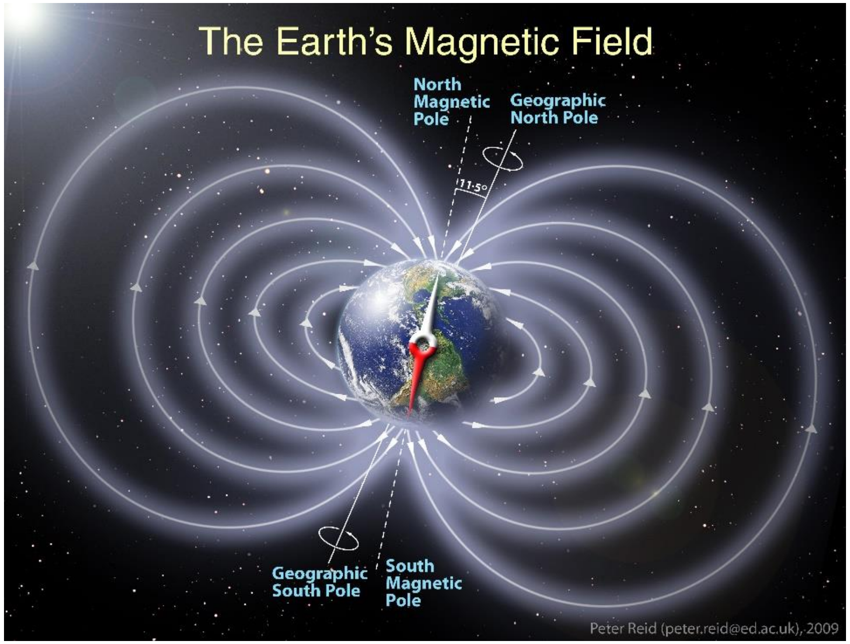
https://en.wiktionary.org/wiki/aurora

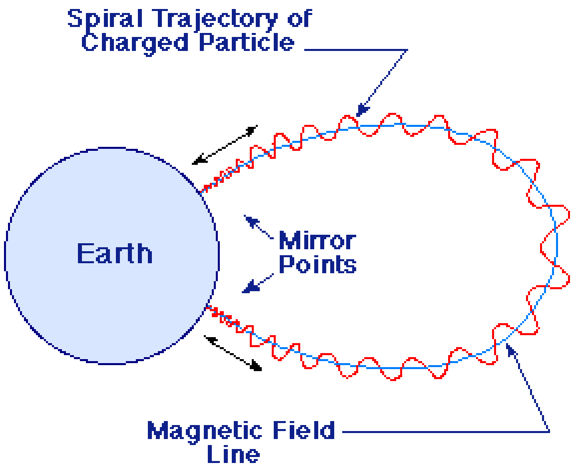
Aurora seen from a satellite



https://flashpack.com/insights/2014/11/20/aurora-australis-forget-the-northern-lights-have-you-heard-about-the-southern-lights/

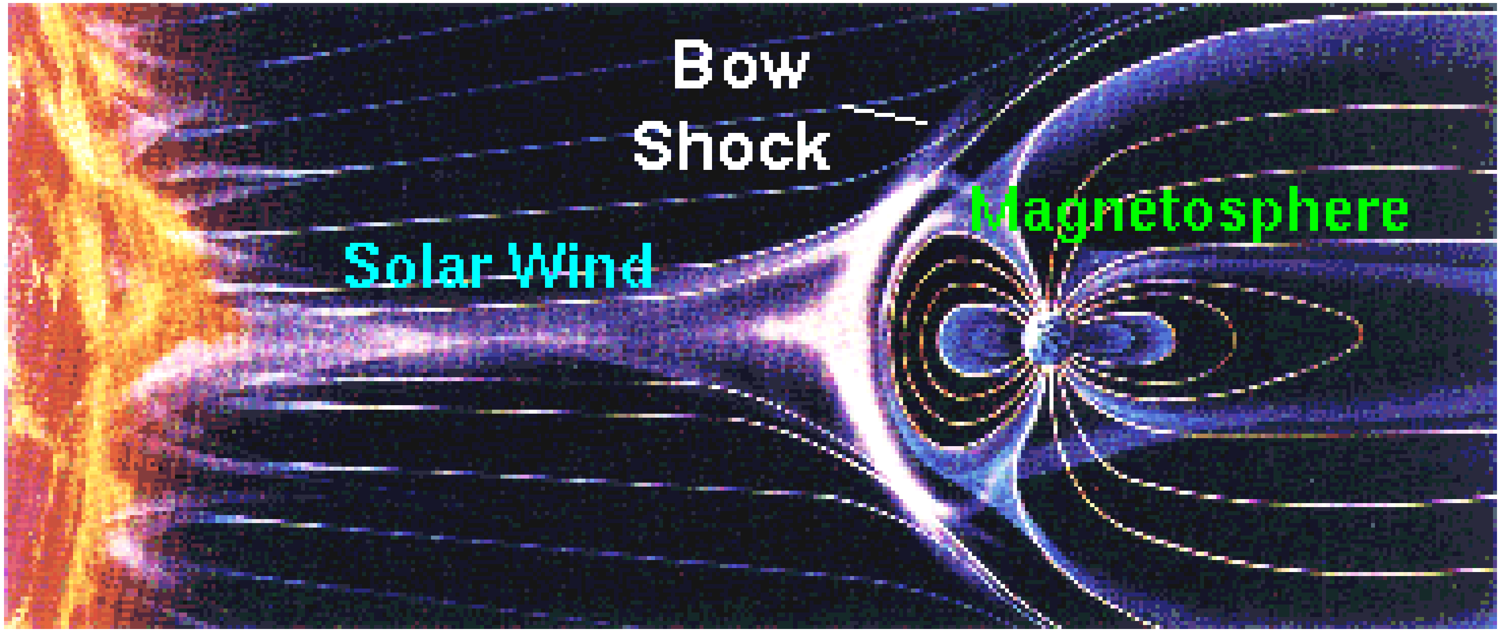
Earth’s magnetic field





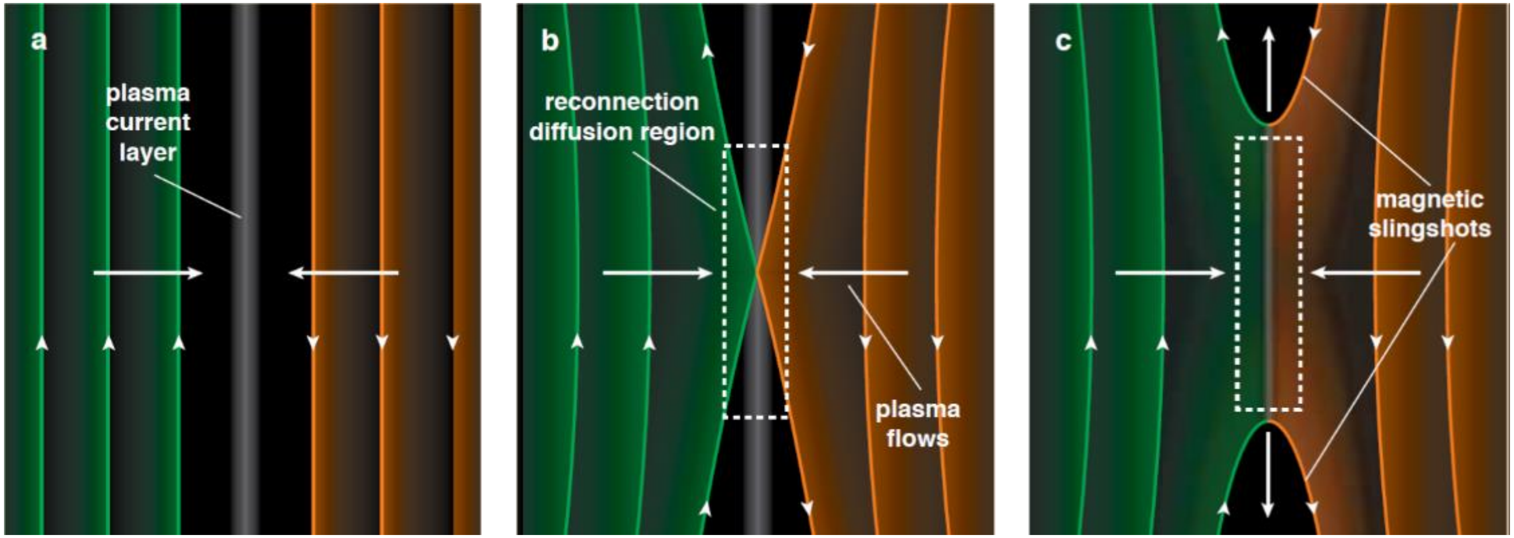
https://www.nasa.gov/mission_pages/sunearth/news/gallery/Earths-magneticfieldlines-dipole.html
http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html

Earth magnetic fields are strongly influenced by solar wind



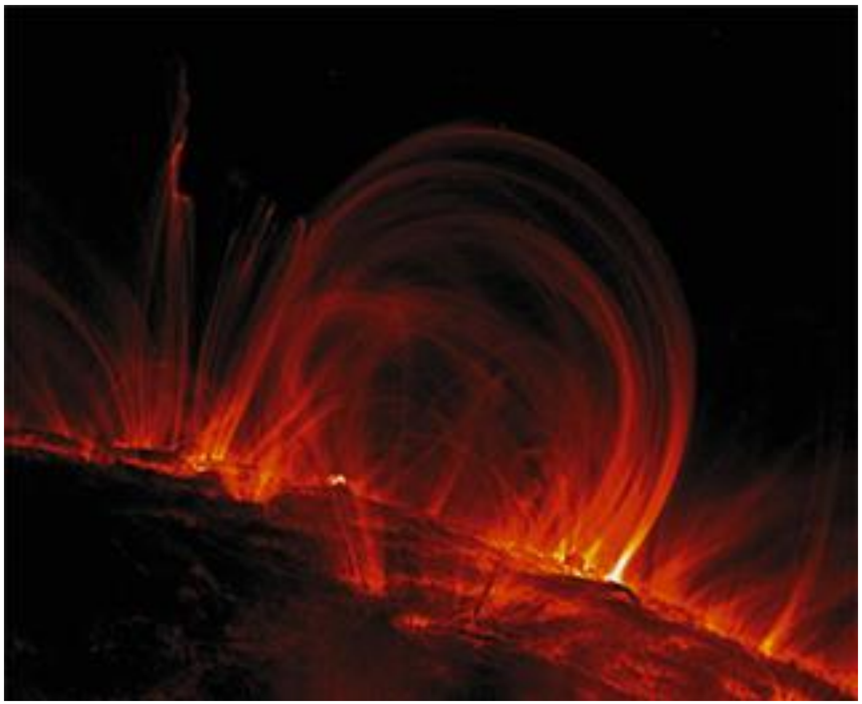
http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html

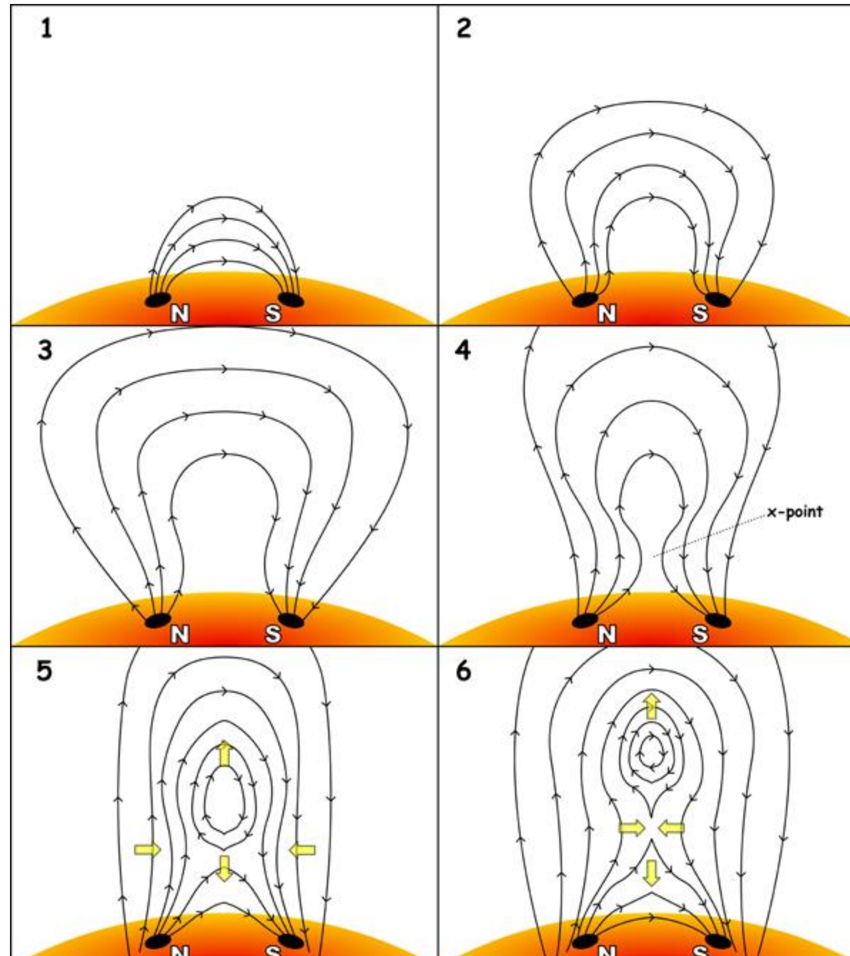
Reconnection



https://www.youtube.com/watch?v=7sS3Lpzh0Zw

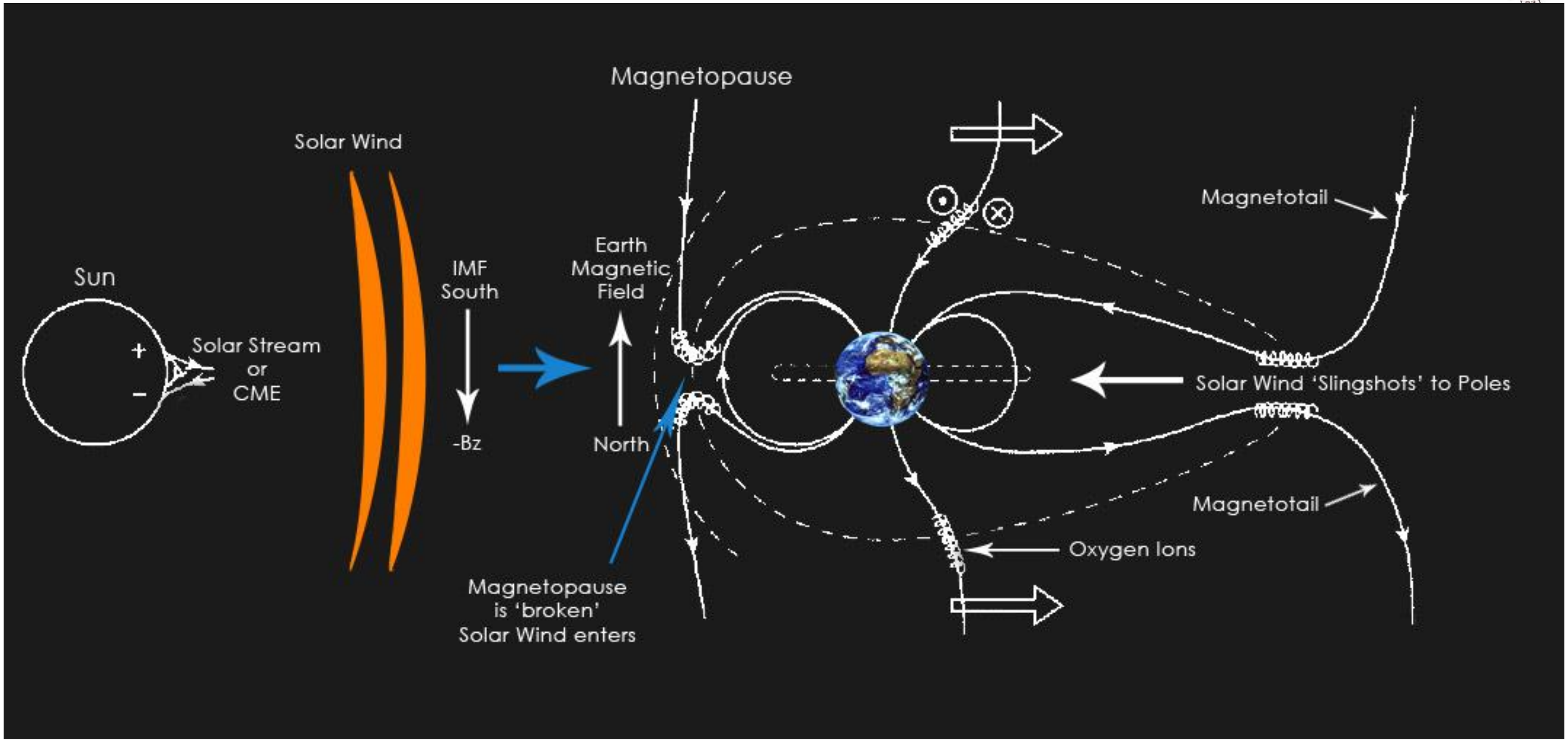
Corona mass ejection (CME)





http://cse.ssl.berkeley.edu/SegwayEd/lessons/exploring_magnetism/in_Solar_Flares/s4.html#sf

Reconnections occur in many locations

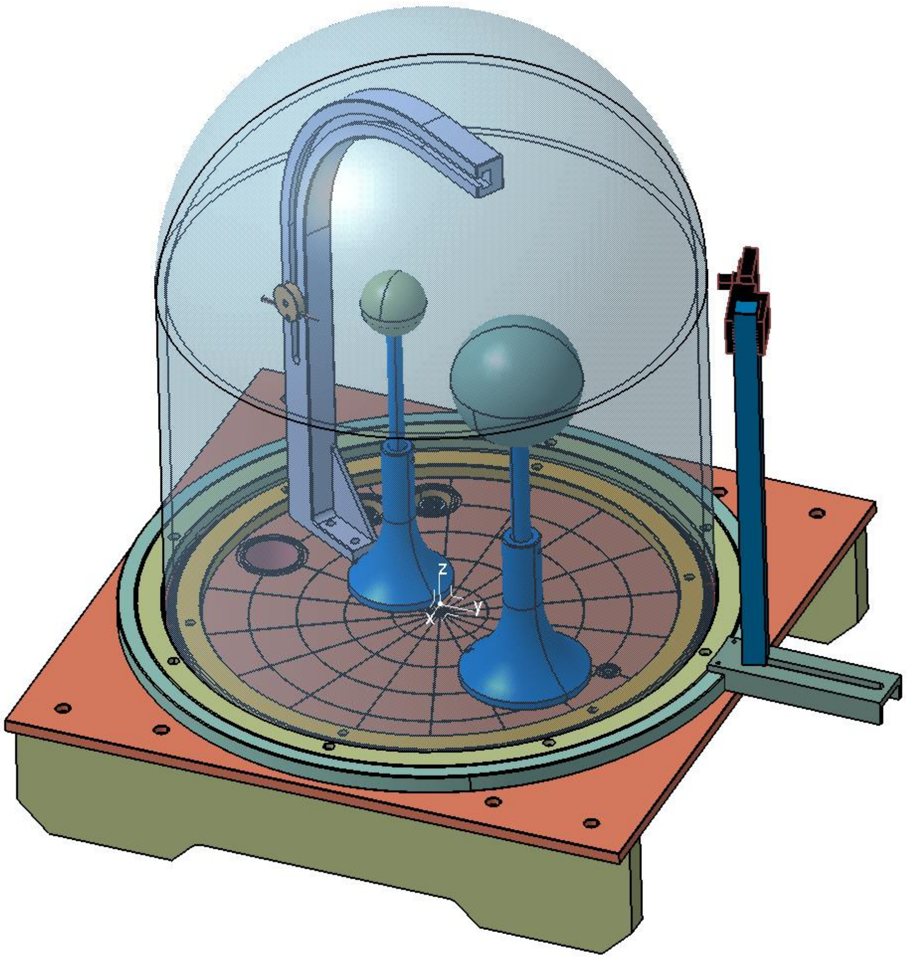


- **The Aurora Borealis:**

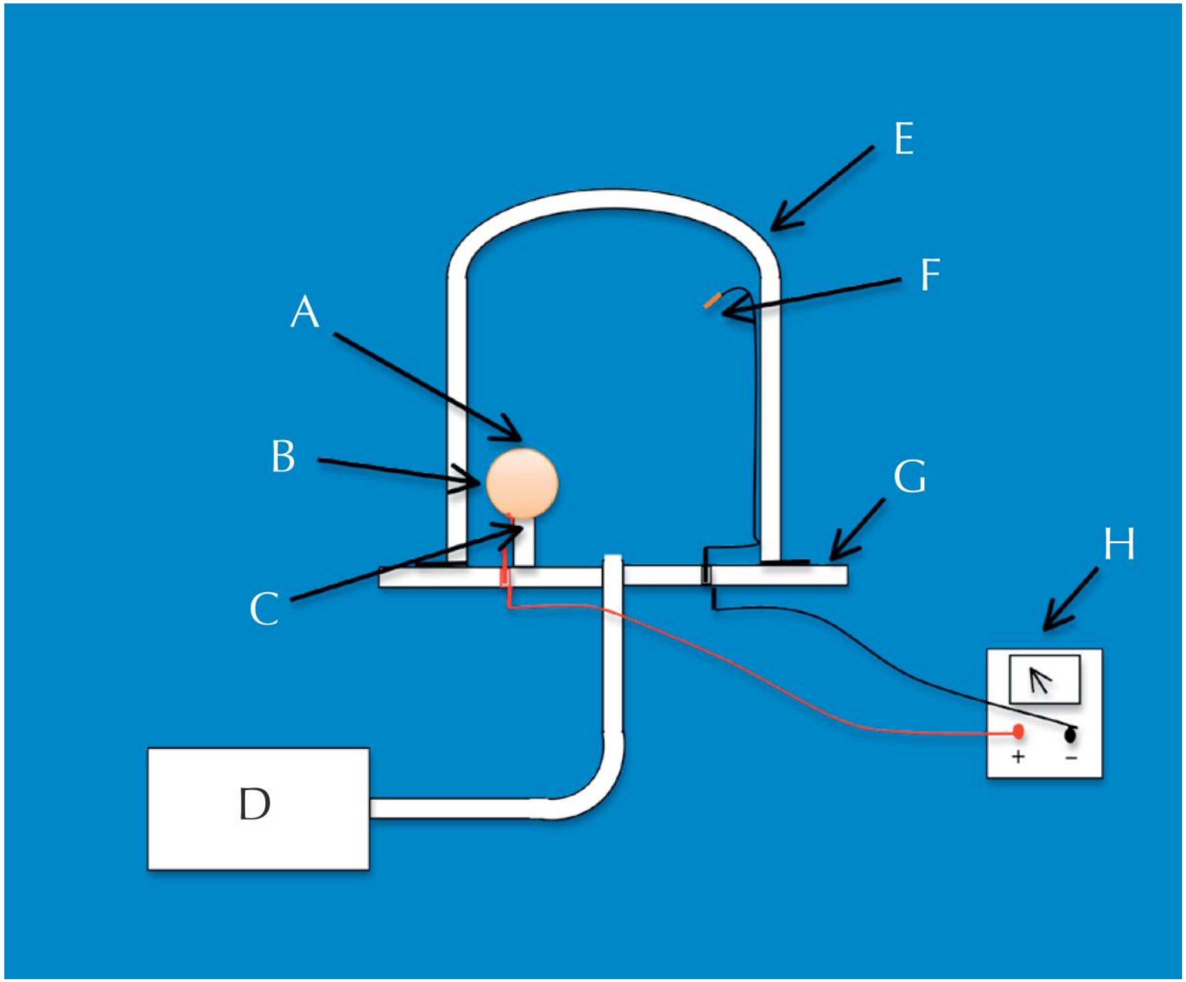
  https://www.youtube.com/watch?v=lT3J6a9p_o8

http://www.natalia-robba.com/myblog/travel/the-aurora-borealis-the-northern-lights-everything-you-need-to-know/

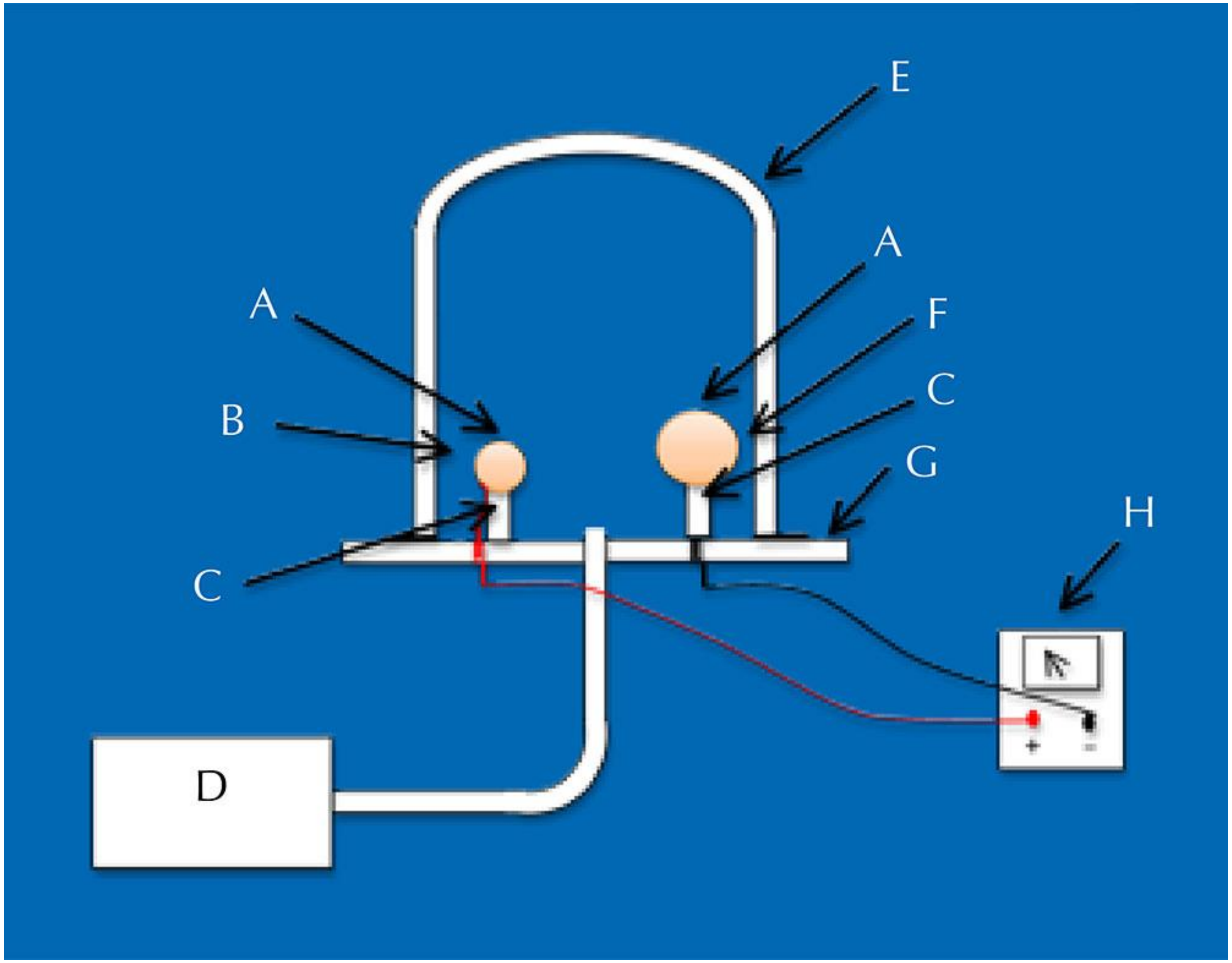
Planeterrella is an aurora simulator



Simple glow discharge is demonstrated

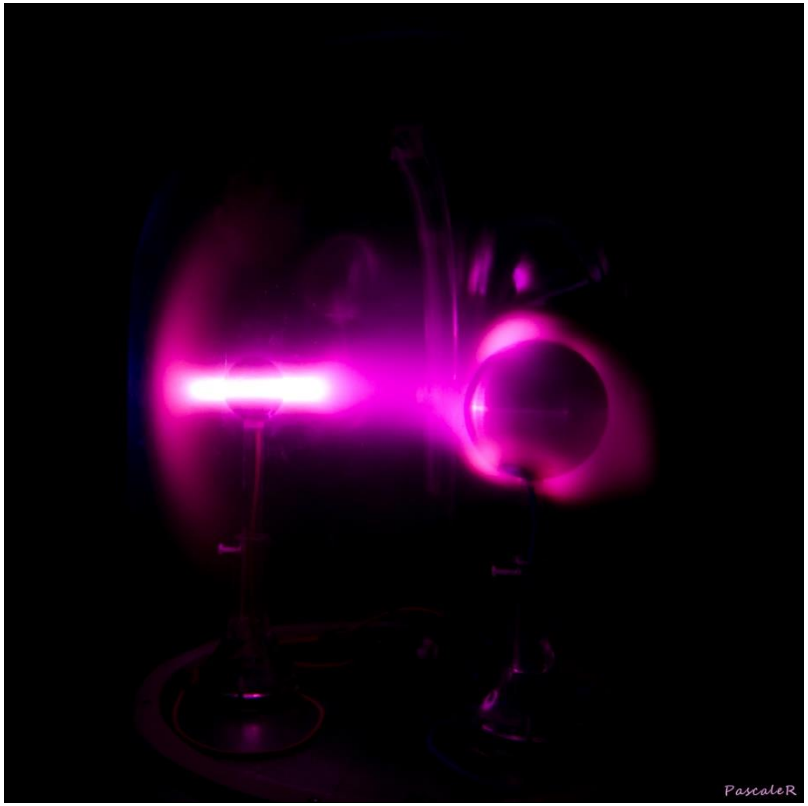


Aurora/ring current are demonstrated



- **B w/ magnet: aurora demonstration**
- **F w/ magnet: ring current**

Aurora and ring current are expected to be seen



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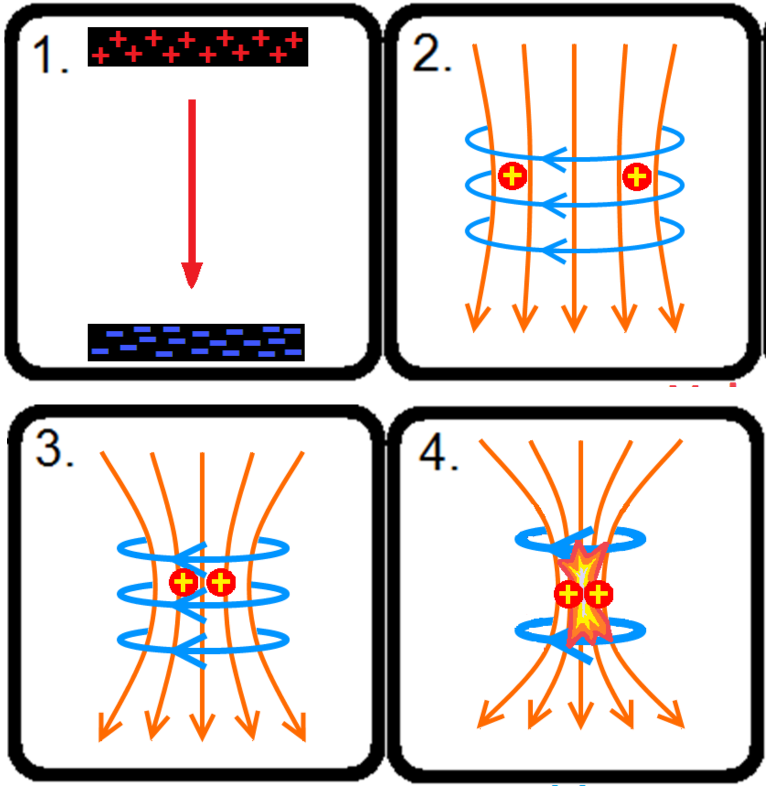
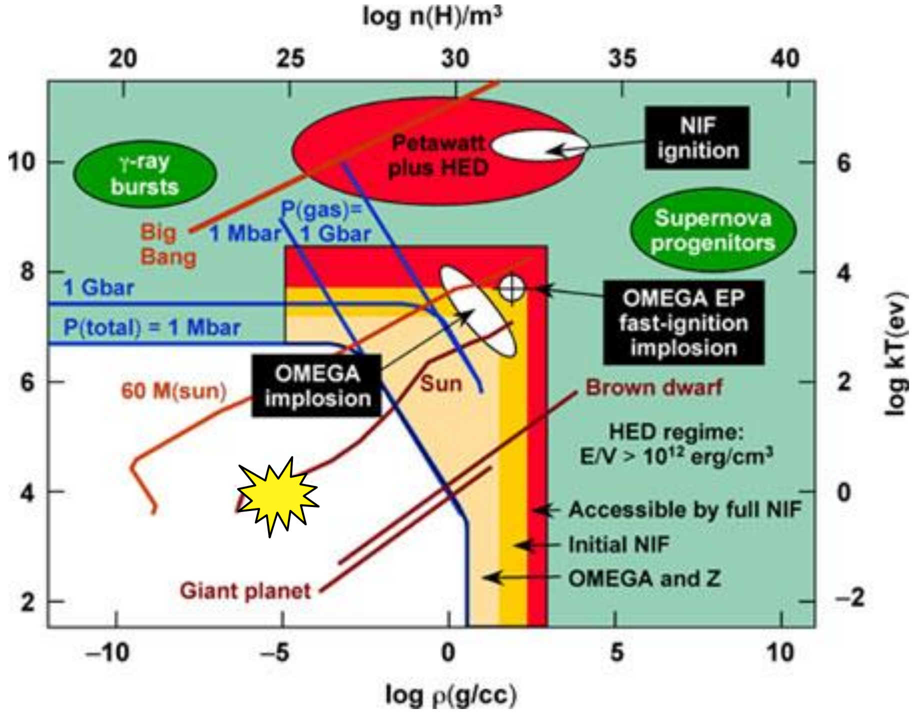
  - Extreme ultraviolet (EUV) light source
  - Studies of the rotational plasma jets

Plasma can be compressed when parallel propagating current occurs





- **High energy density plasma (HEDP) regime: P > 1 Mbar**

---

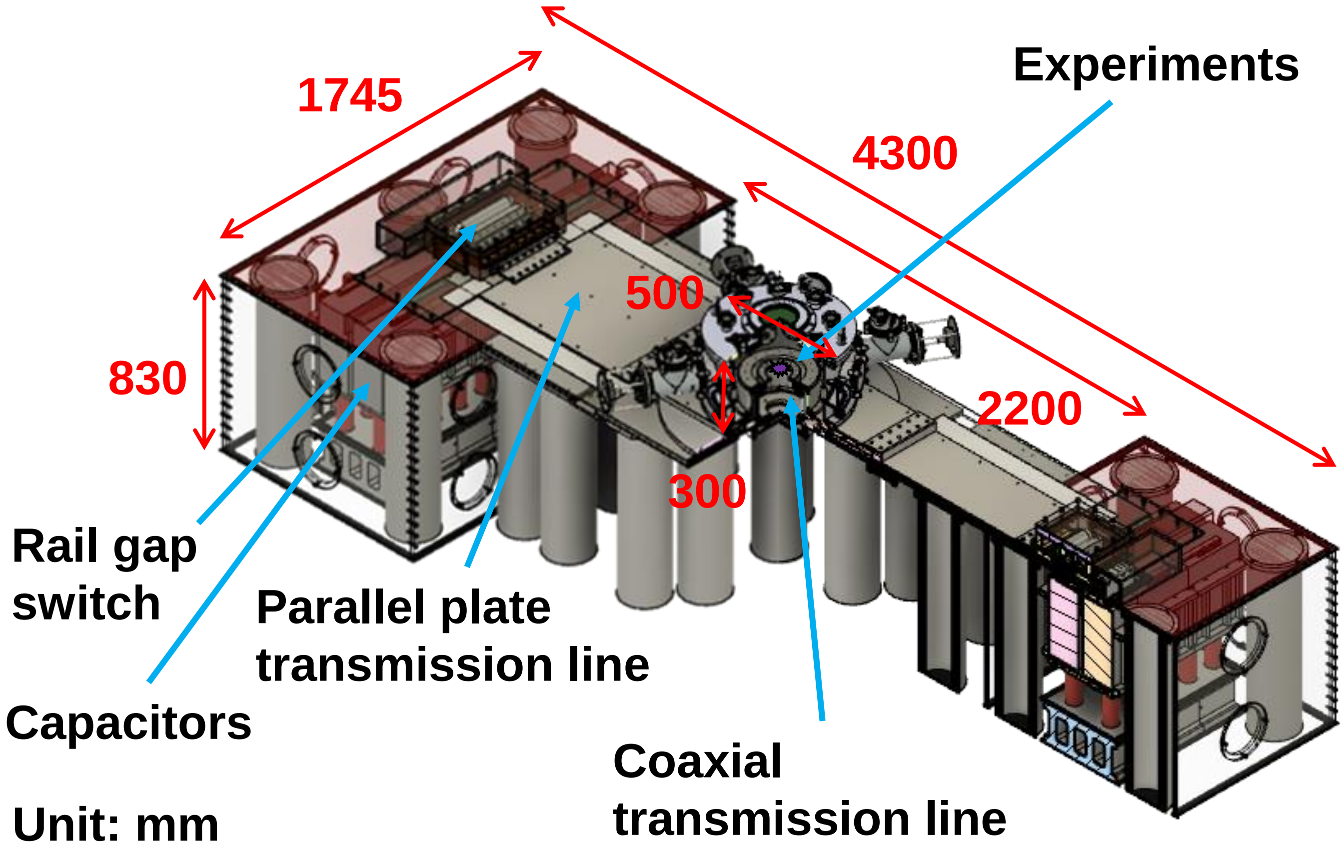
*https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

**Frontiers in High Energy Density Physics: The X-Games of Contemporary Science © (2003) by the National Academy of Sciences, courtesy of the National Academies Press, Washington, D.C.

A pulsed-power system is much cheaper than a laser facility

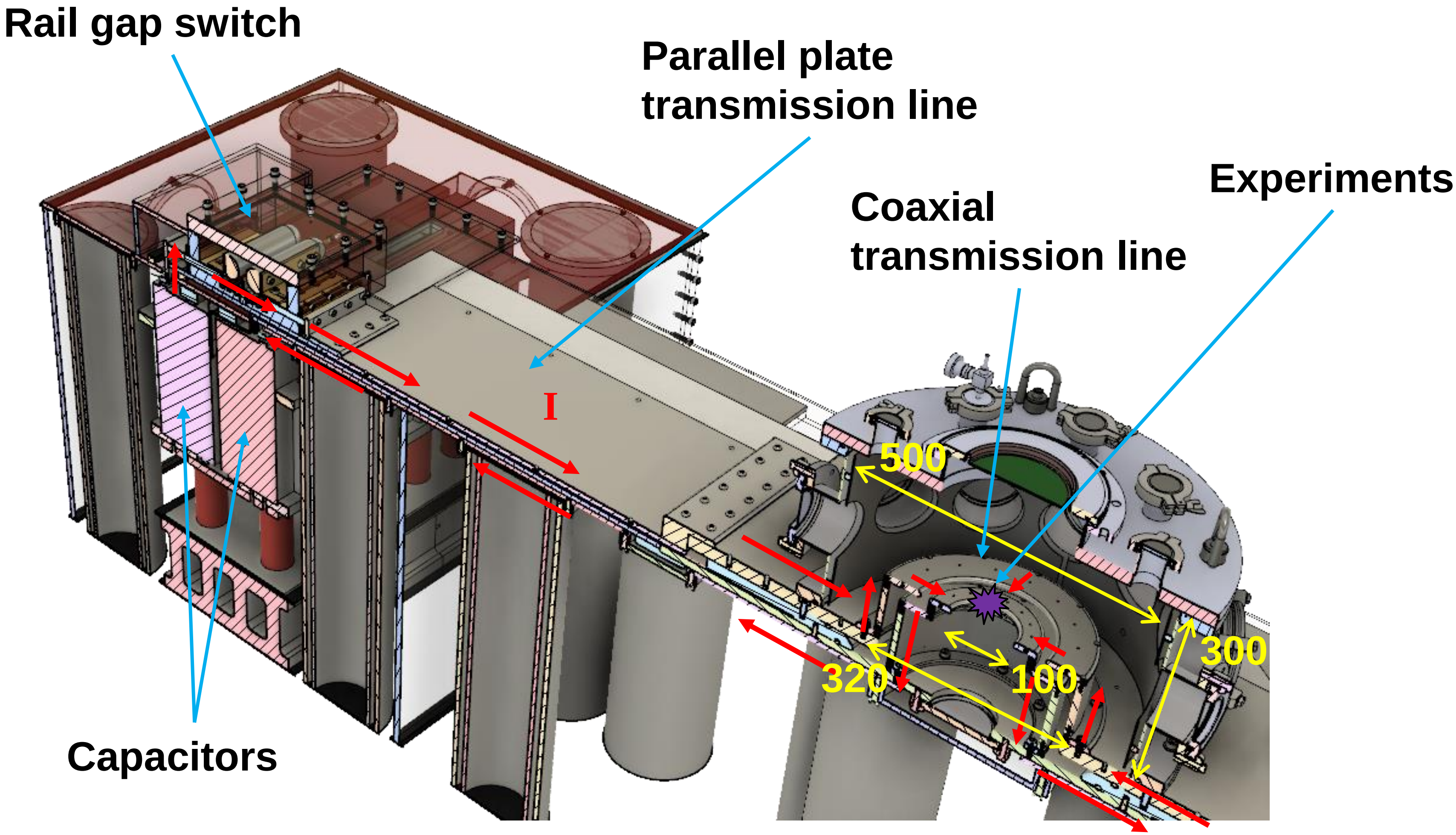
Facility	Budgets (NTD)
OMEGA at University of Rochester	~1.8 billion
National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL)	~100 billion
Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory in Berkeley (LBNL)	~3 billion
Taiwan Photon Source (TPS) at National Synchrotron Radiation Research Center (NSRRC)	~7 billion
Pulsed-power system at ISAPS, NCKU	~0.002 billion (<0.1 %)!!!

The pulsed-power system was built by only students



- **A 1 kJ pulsed-power system at ISAPS, NCKU started being operated since September, 2019.**

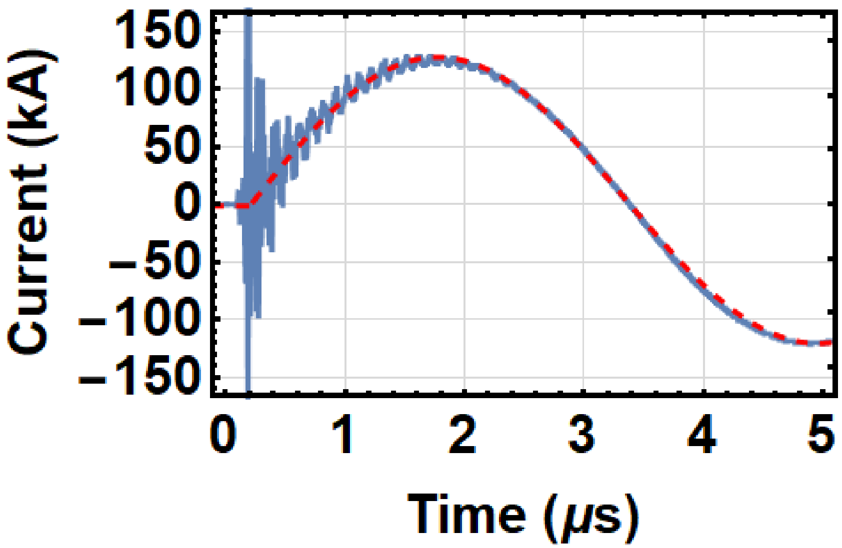
Experiments will be taken placed at the center of the vacuum chamber



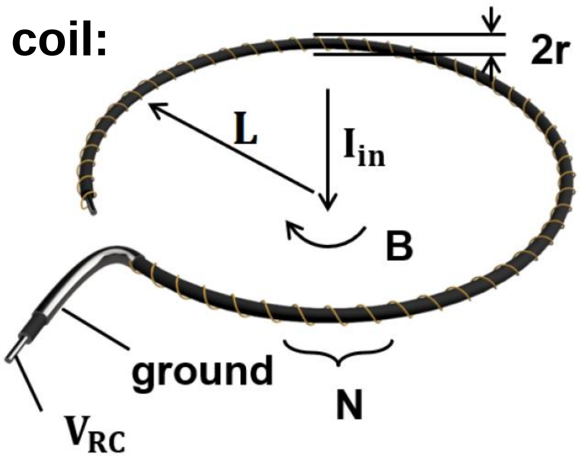
Unit: mm

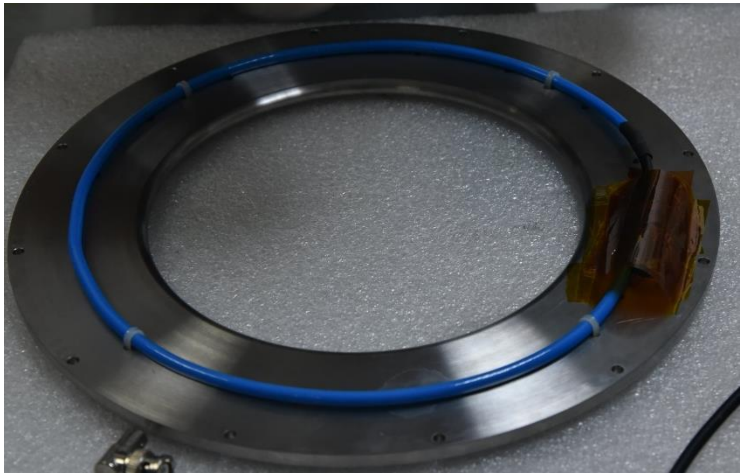
A peak current of 135 kA with a rise time of 1.6 us is provided by the pulsed-power system

Capacitance (μF)	5	
V_{charge} (kV)	20	(50)
Energy (kJ)	1	(6.25)
Inductance (nH)	204 ± 4	
Rise time (quarter period, ns)	1592 ± 3	
I_{peak} (kA)	135 ± 1	(~340)
Peak power (GW)	~0.6	(~4)

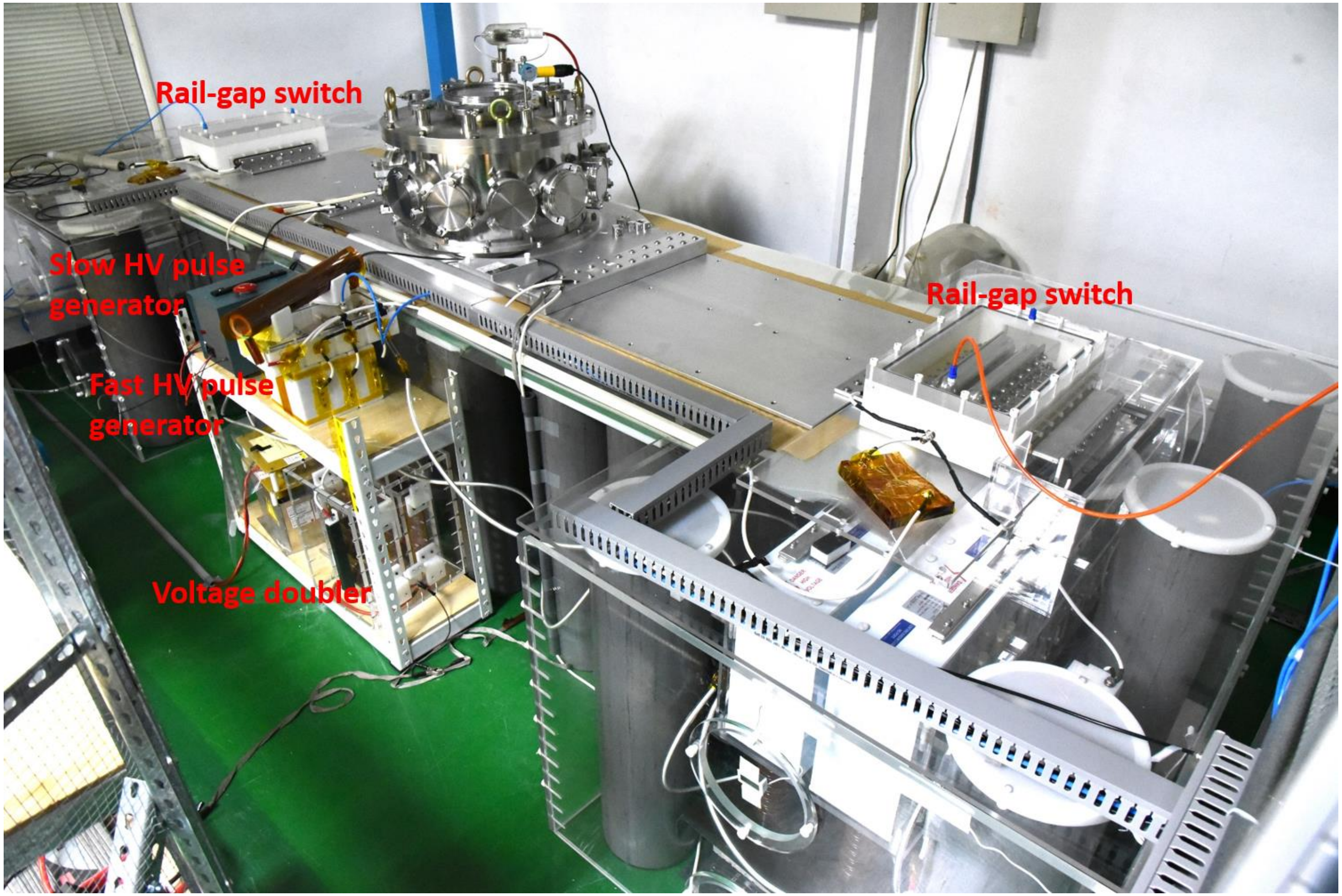


- Rogowski coil:

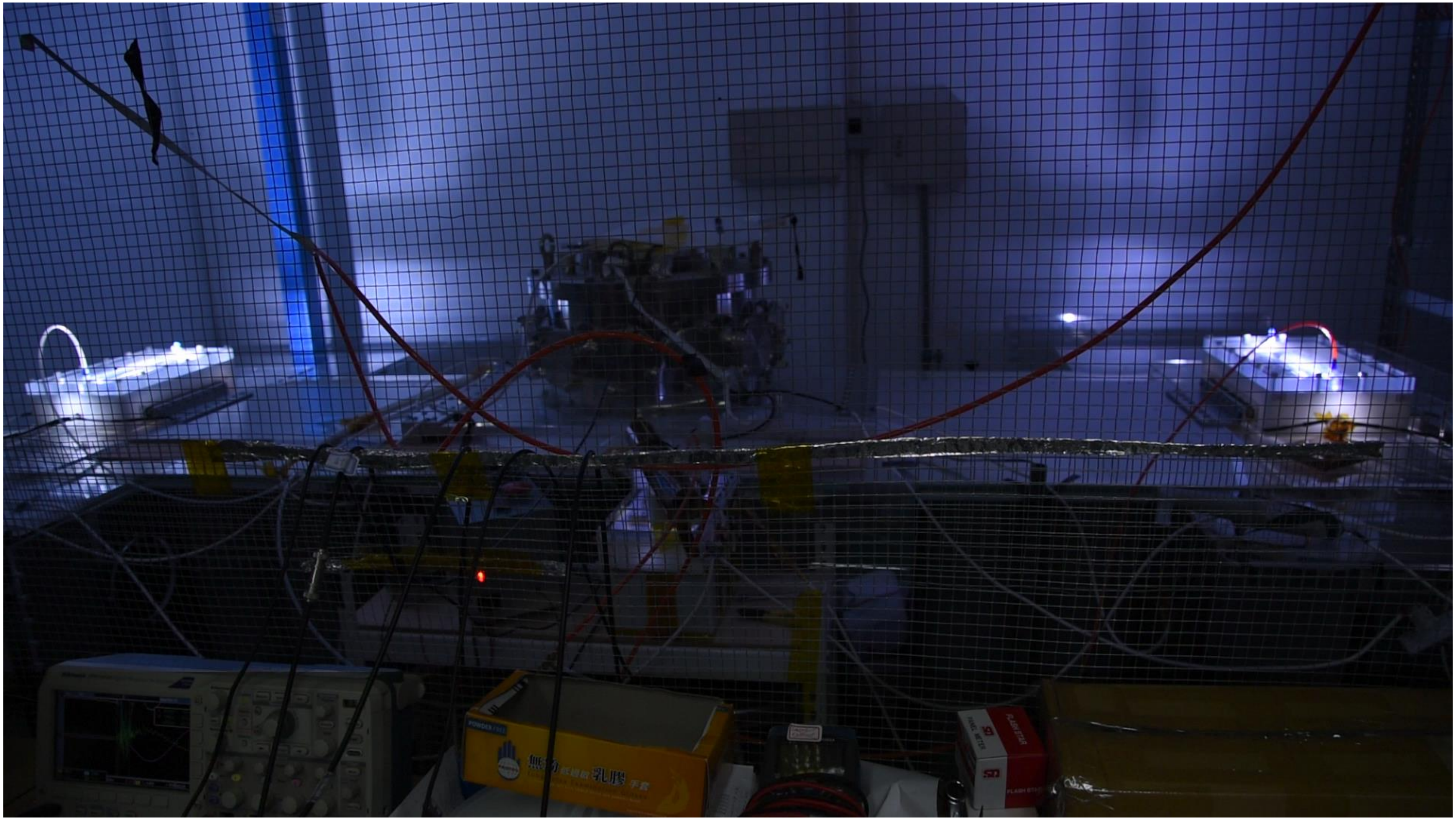




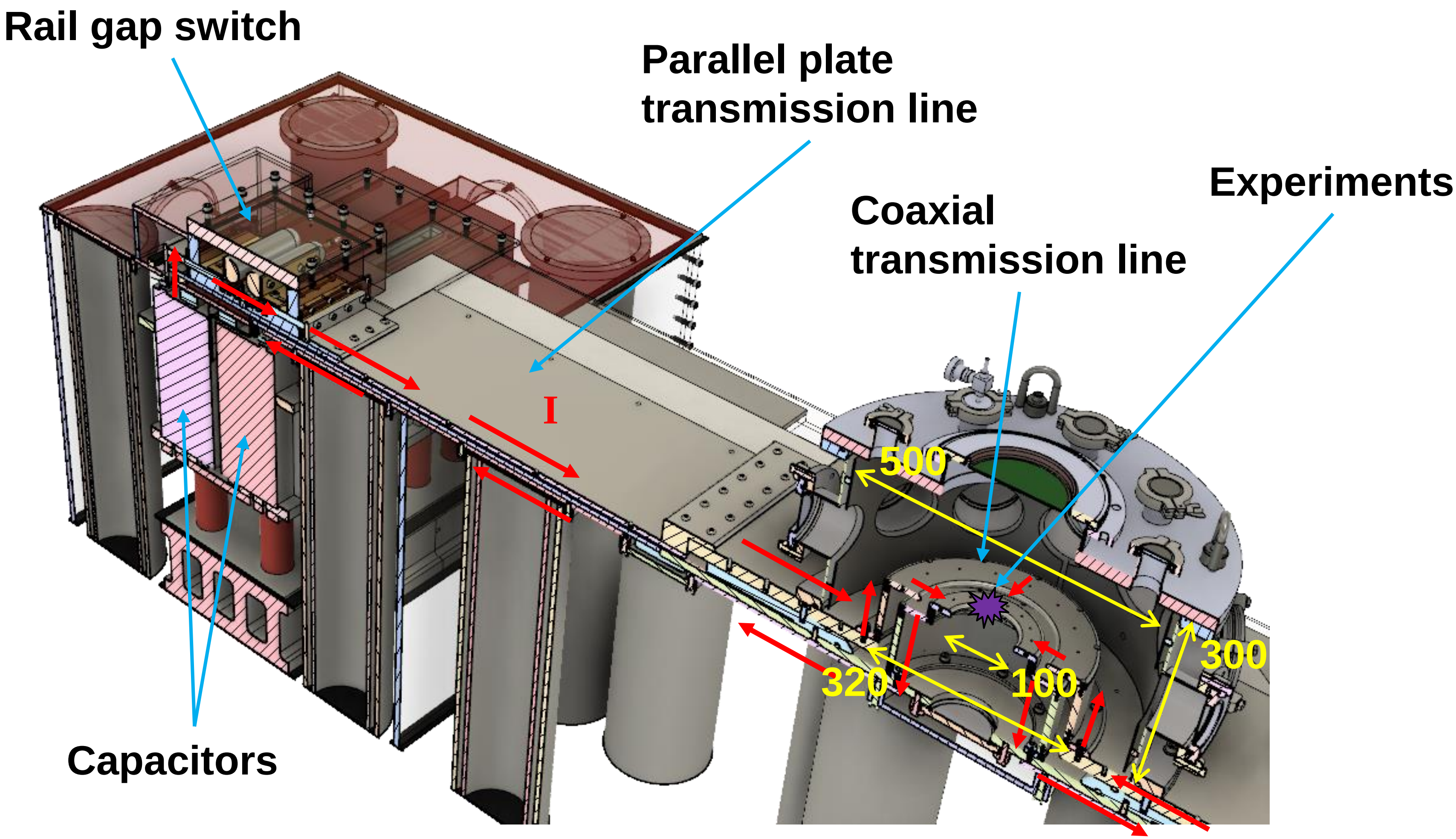
The 1-kJ pulsed-power system



First shot with two synchronized rail-gap switches

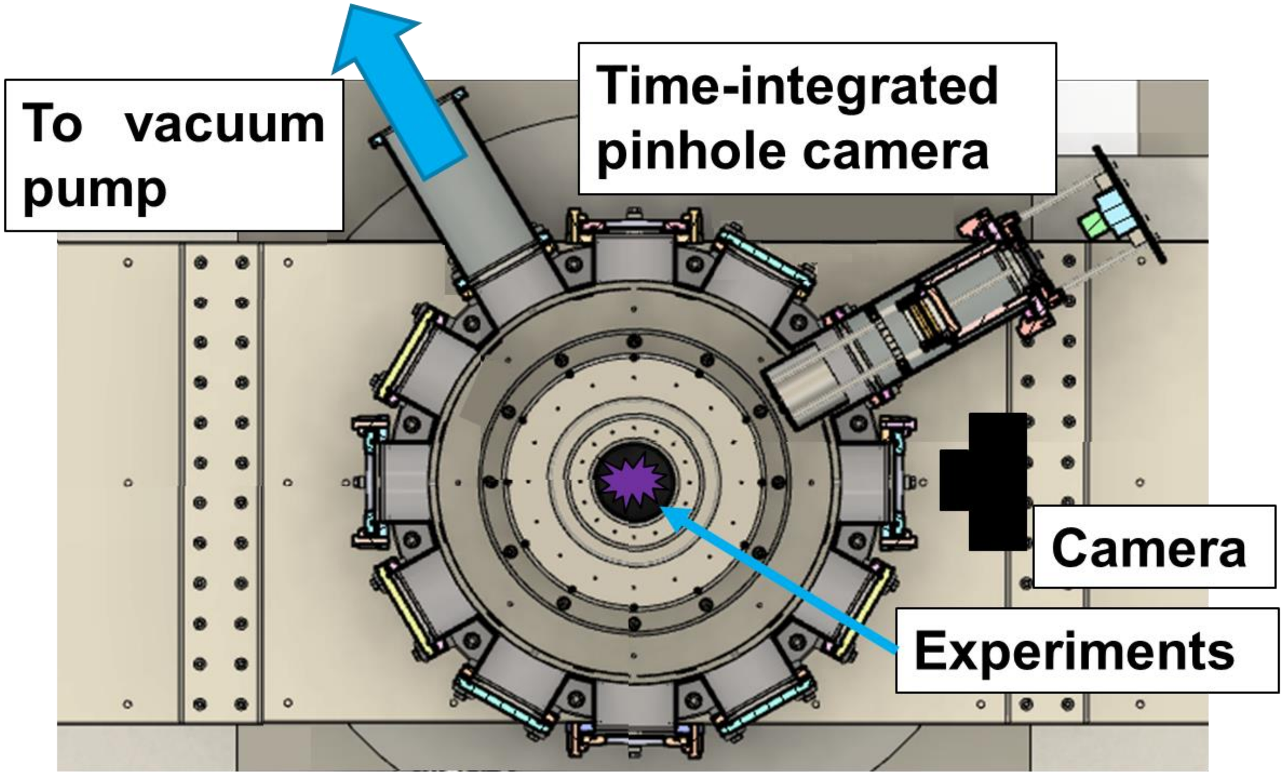


Experiments will take place at the center of the vacuum chamber



Unit: mm

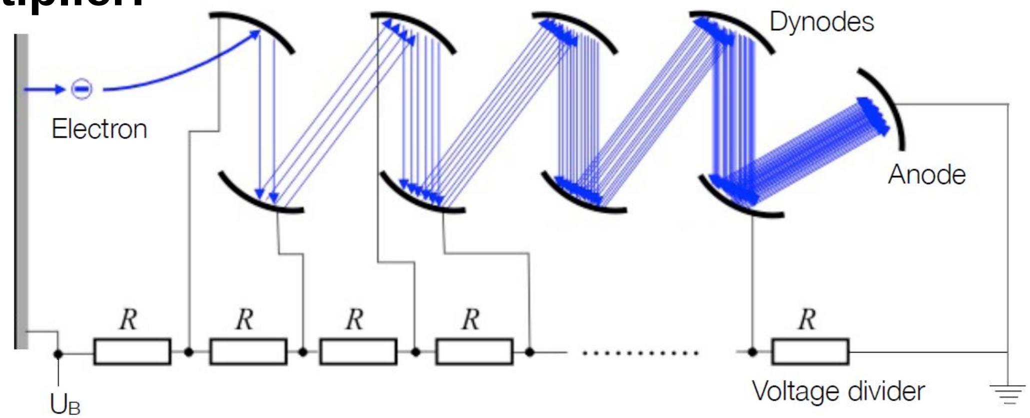
System with current diagnostics



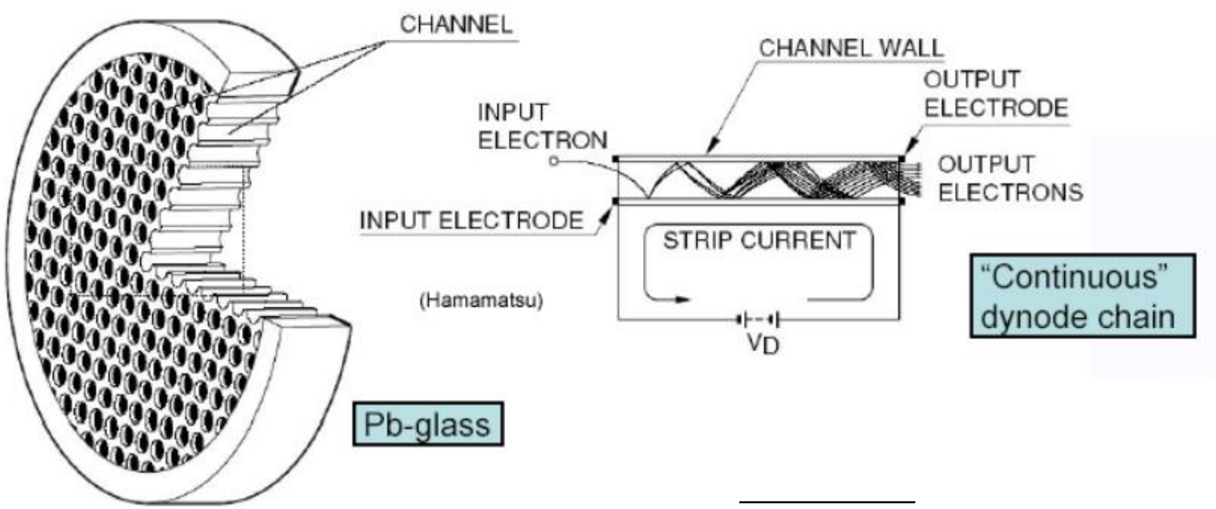
Diagnostic-Camera
- Nikon D750
- f/22
- f = 120 mm
- ISO : L1
- Shutter : 20 s
- Filter : ND100

The number of electrons can be increased through a photomultipliers or a microchannel plate (MCP)

- **Photomultiplier:**

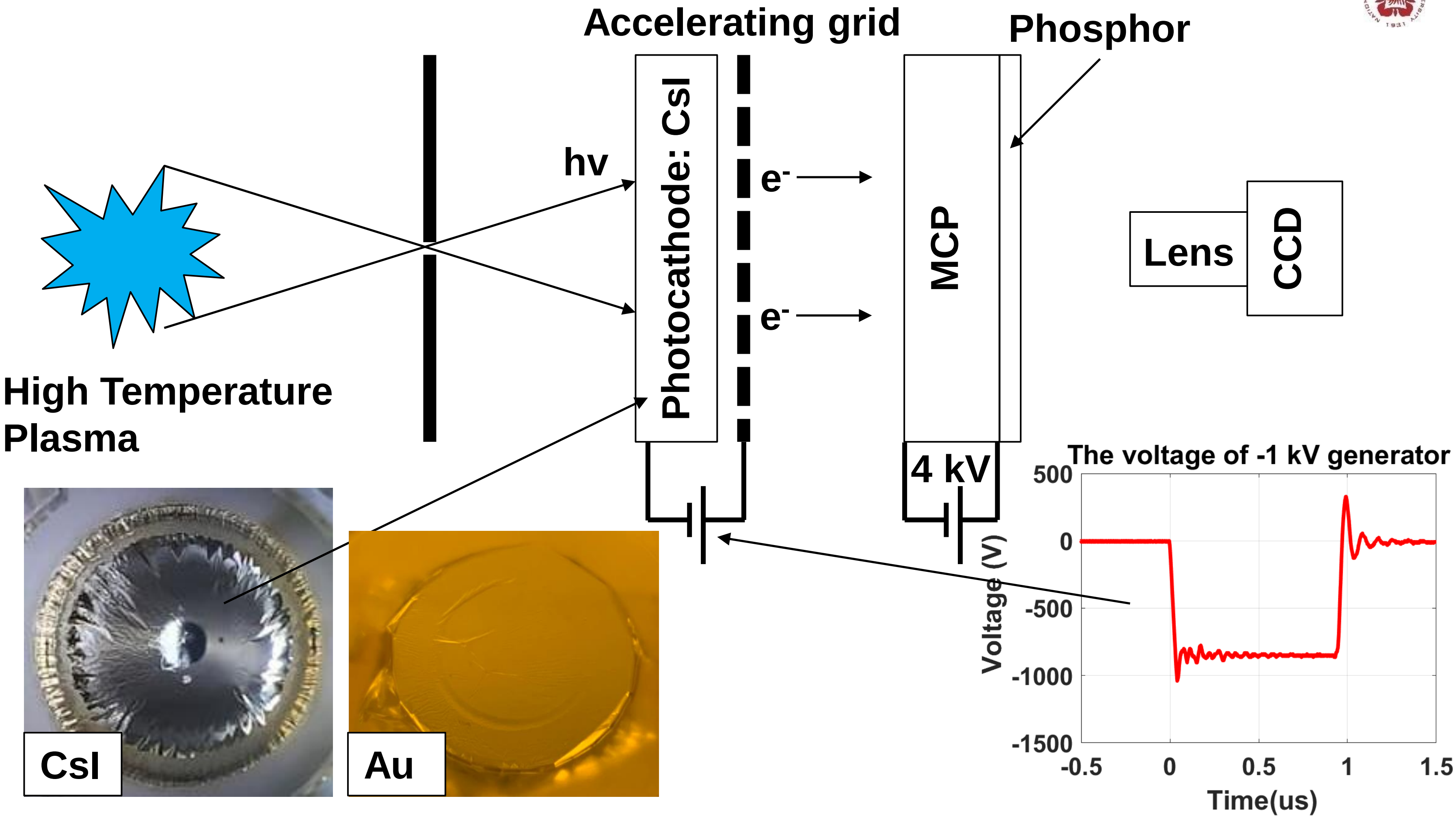


- **MCP:**



http://www.kip.uni-heidelberg.de/~coulon/Lectures/DetectorsSoSe10/
Slides from 2013 HEDP Summer School
(http://hedpschool.lle.rochester.edu/1000_proc2013.php)

X-rays are imaged using photocathode, MCP, phosphor, and CCD

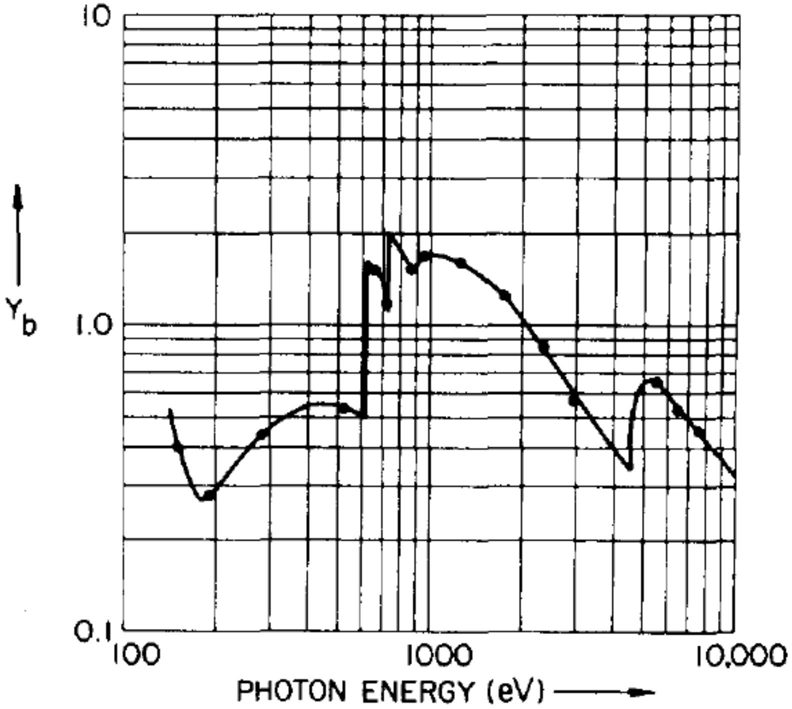


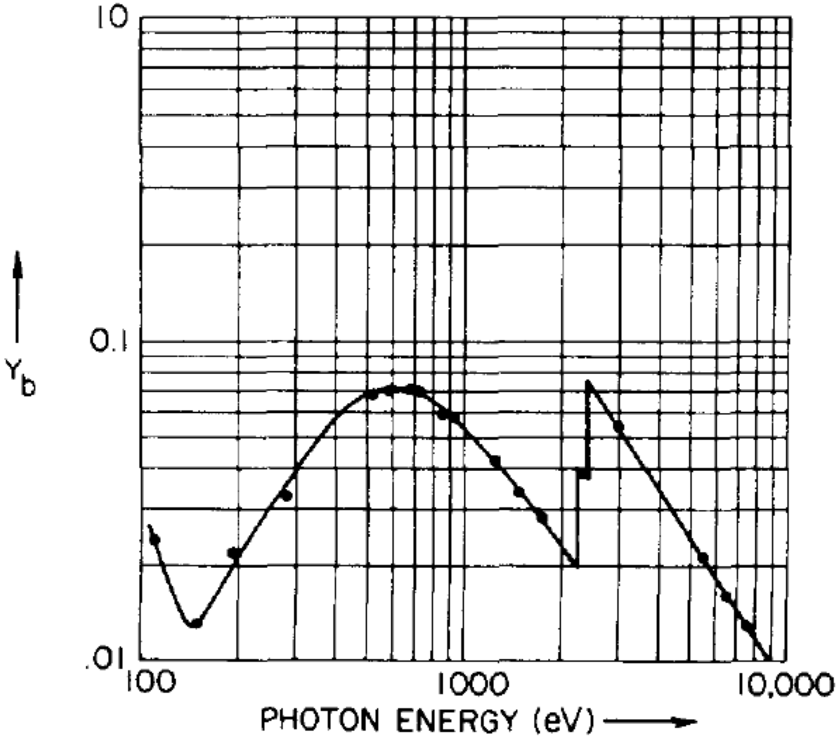
- **Prof. Chou @ Photonics, NCKU is developing 50nm Au foil for us.**

- **Images can be gated using fast high voltage pulses.**

The CsI photocathode is sensitive to photons with energy above 600 eV

- Back-surface secondary electron quantum yield for a 100 nm CsI transmission photocathode.
- Back-surface secondary electron quantum yield for a 23 nm Au transmission photocathode.

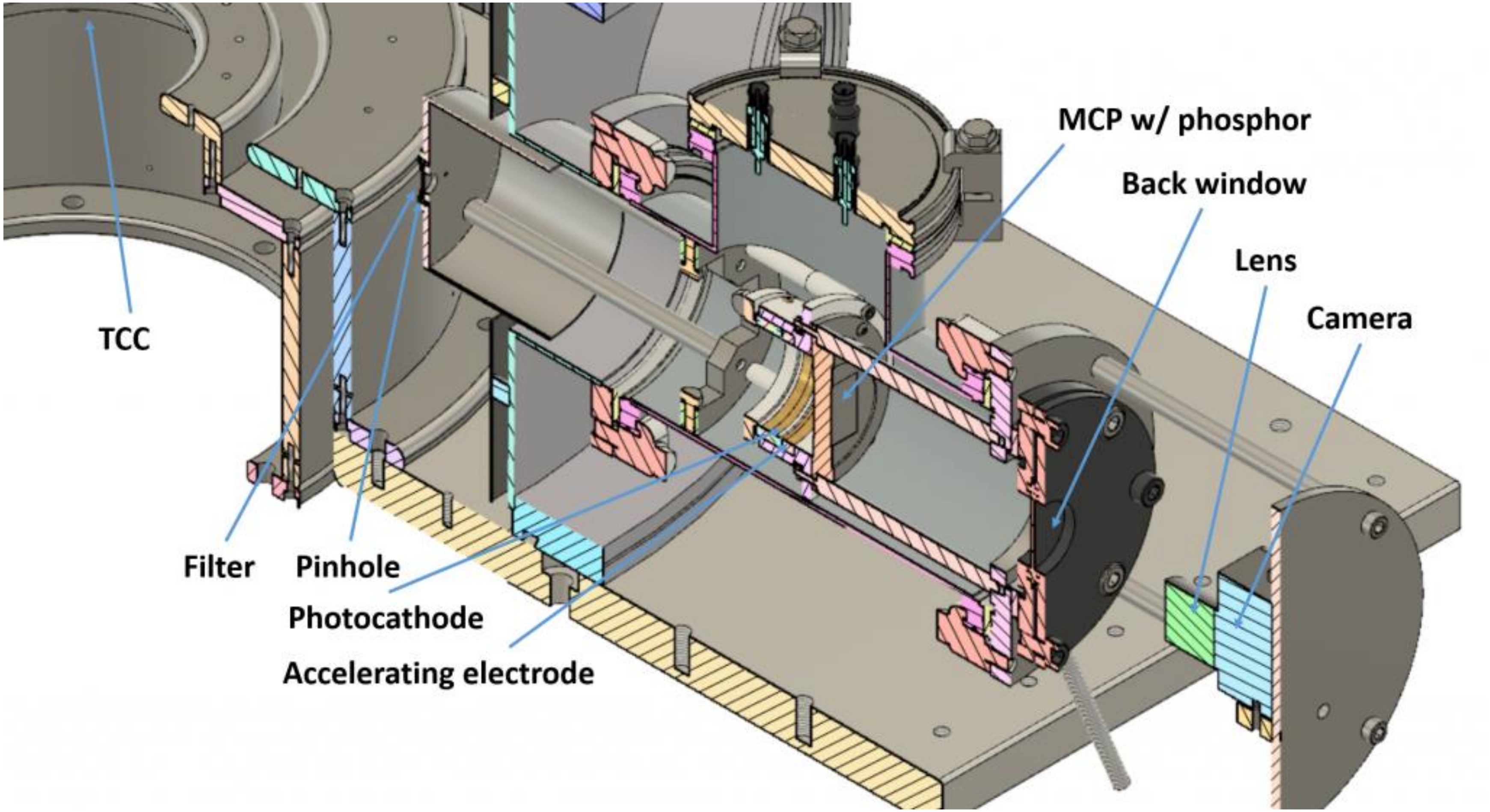




- **Our photocathode: 200nm Lexan / 25nm Al / 120nm CsI.**

B. L. Henke, etc. J. Appl. Phys. 52, 1509 (1981)

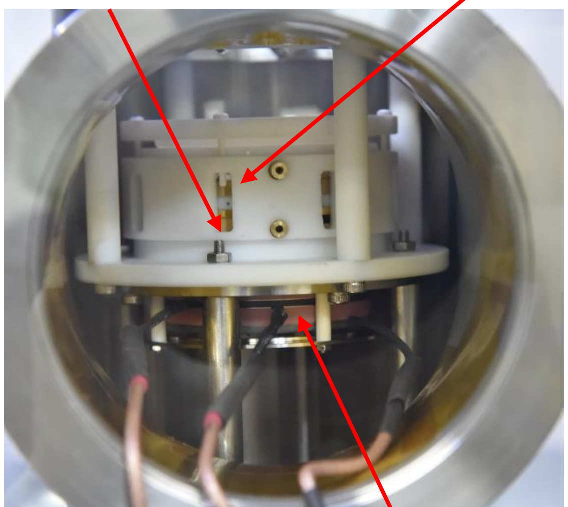
The pinhole camera is attached to one of the flange



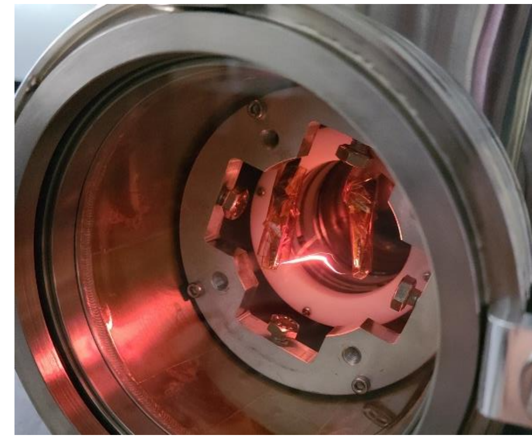
The MCP right was tested

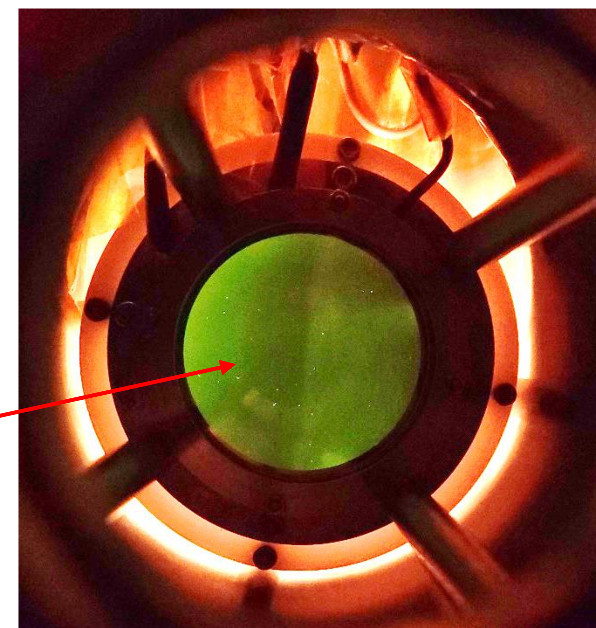
Photocathode

Accelerating grid



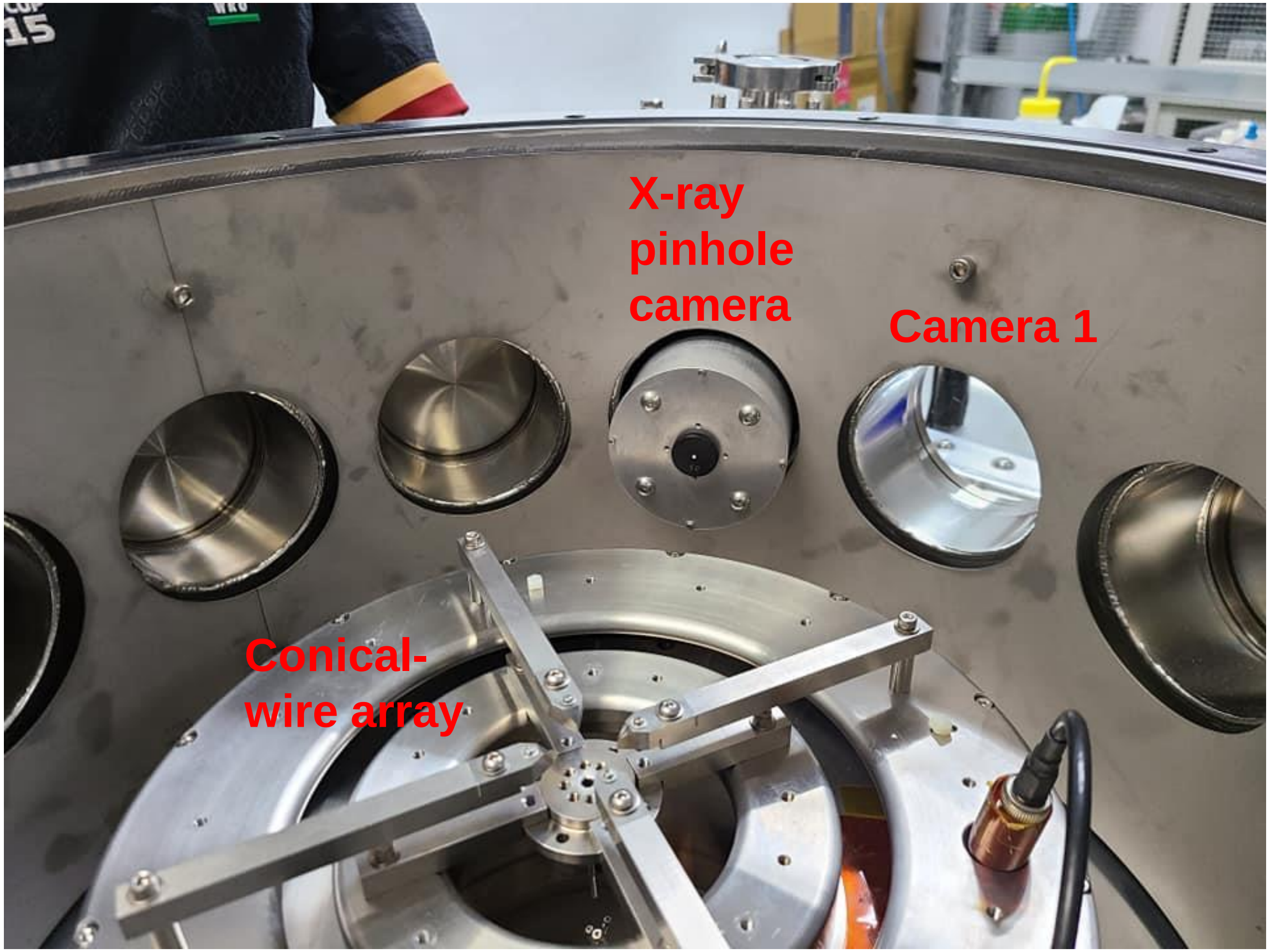
MCP



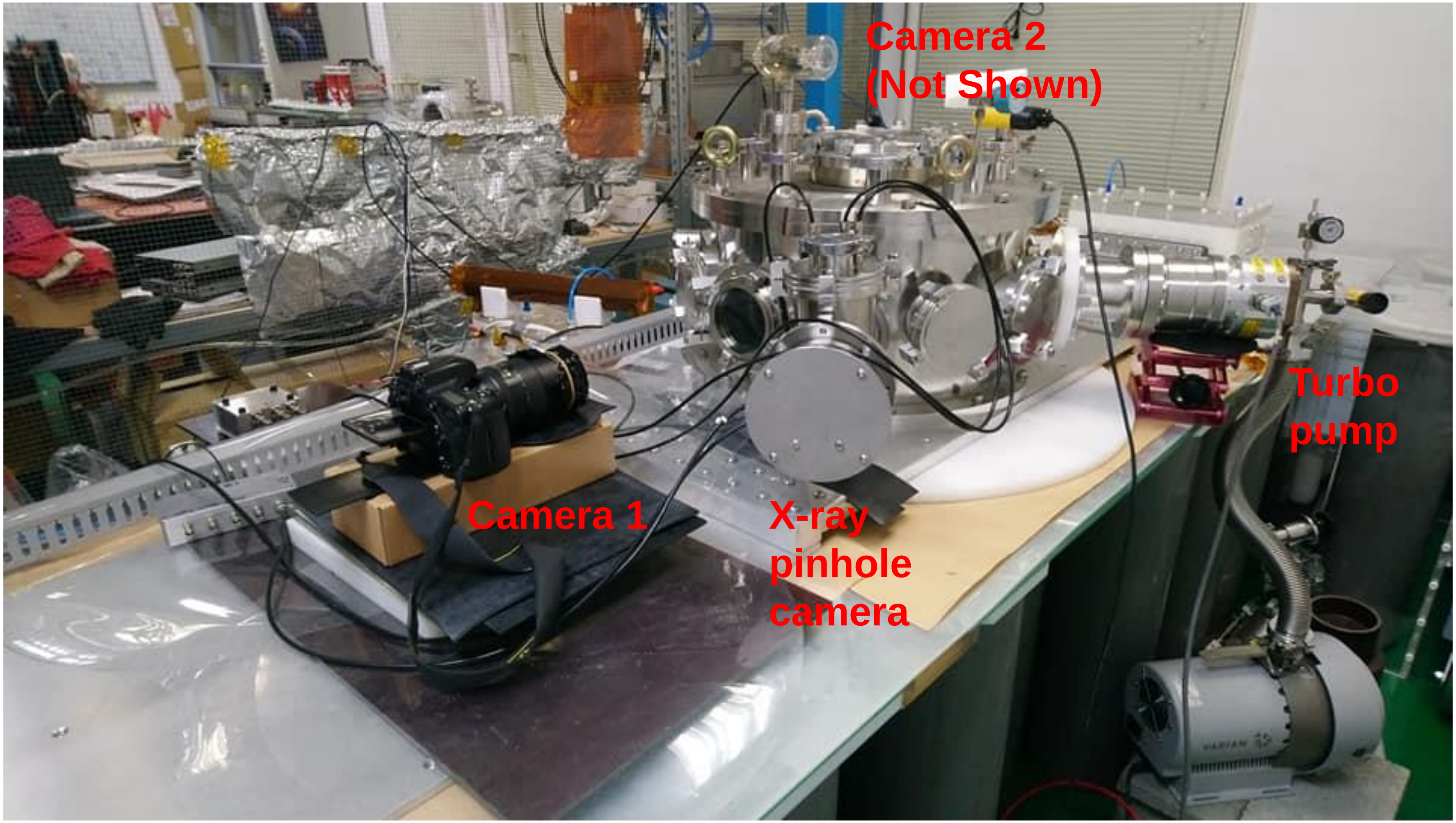


Phosphor

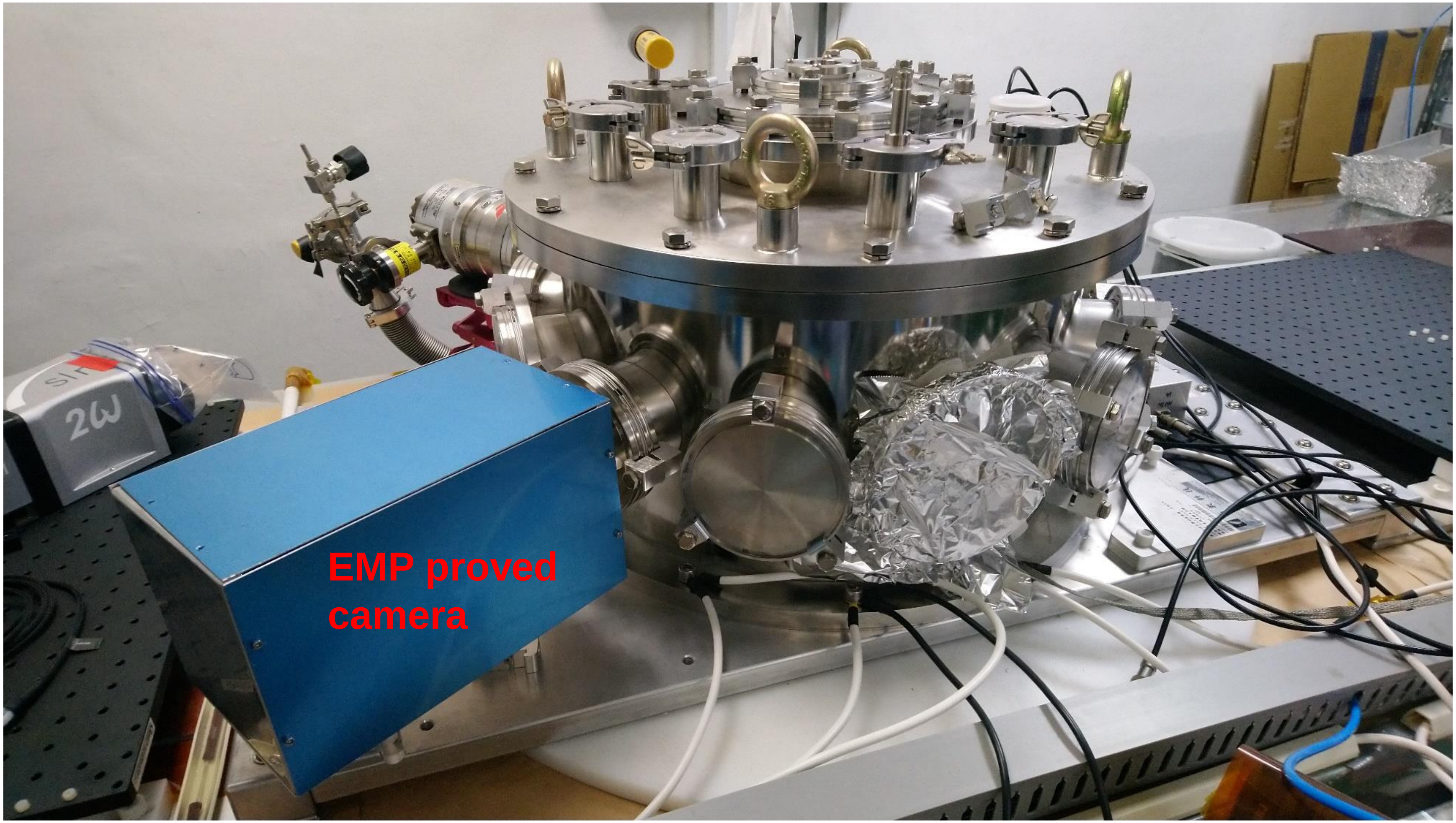
The view inside the vacuum chamber



System with current diagnostics



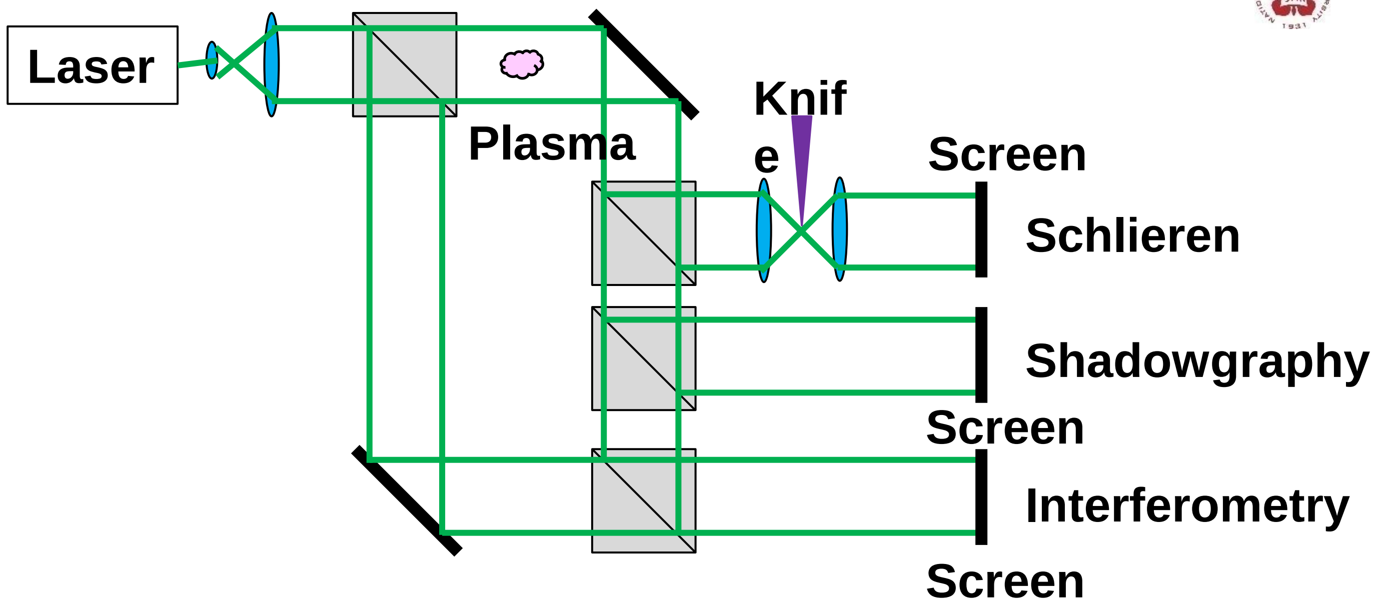
EMP proved camera



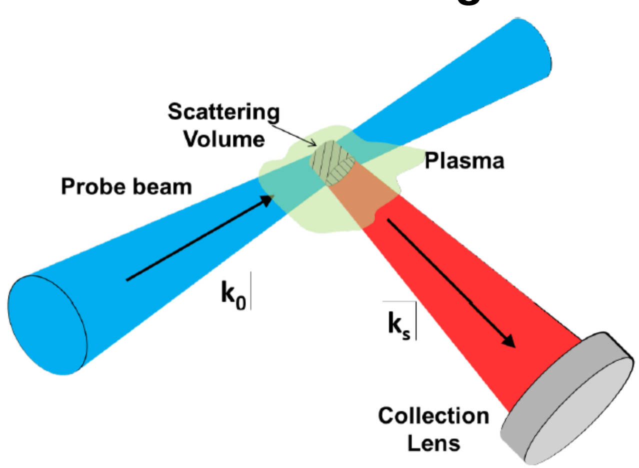
- **The camera is controlled via wifi and powered by batteries.**

Density and temperature can be measured using laser diagnostics

- Imaging



- Thomson scattering



- Ion-acoustic waves:

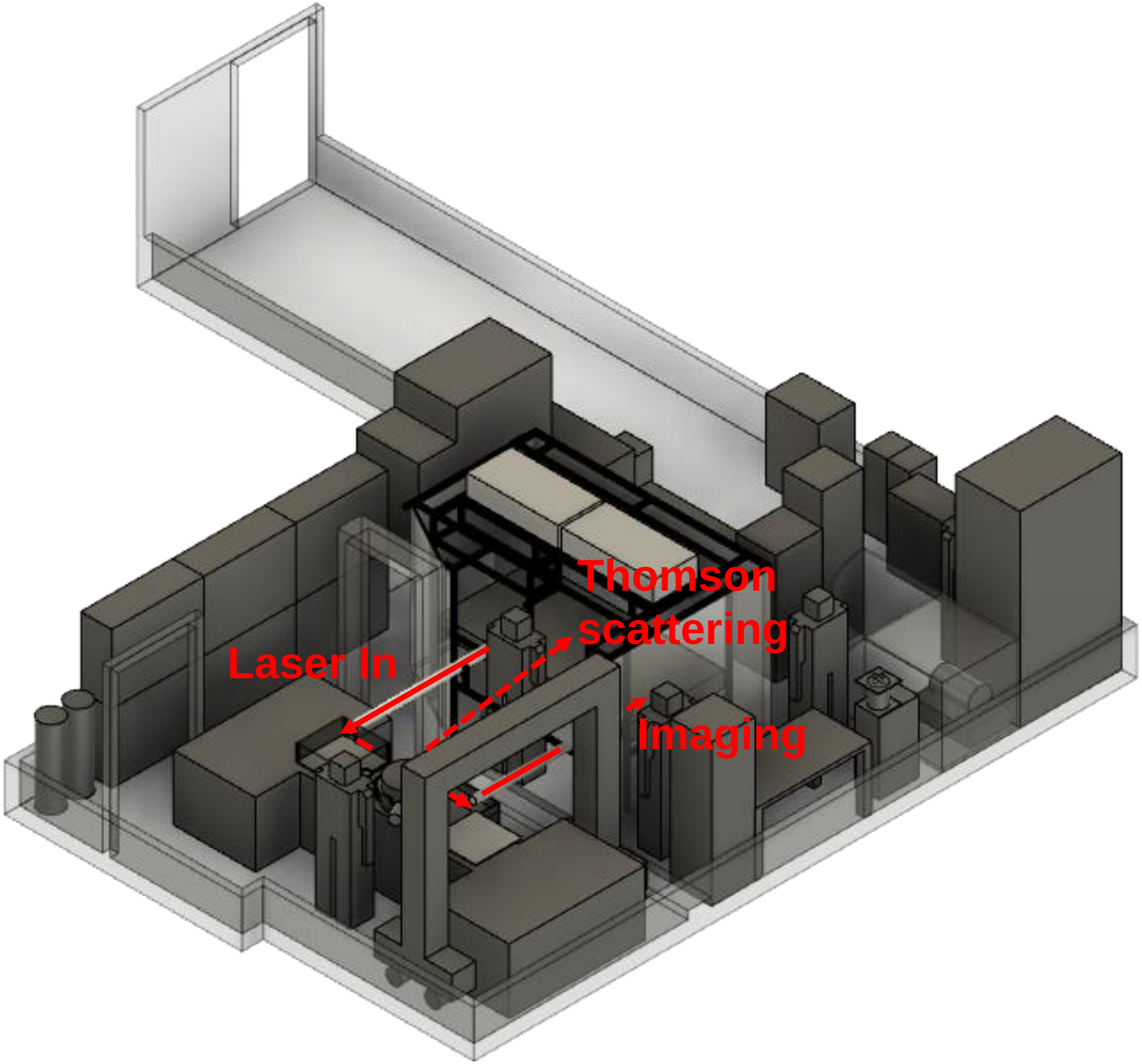
$$\omega^2 \approx k^2 \frac{ZT_e + 3T_i}{M_i}$$

- Electron-acoustic waves:

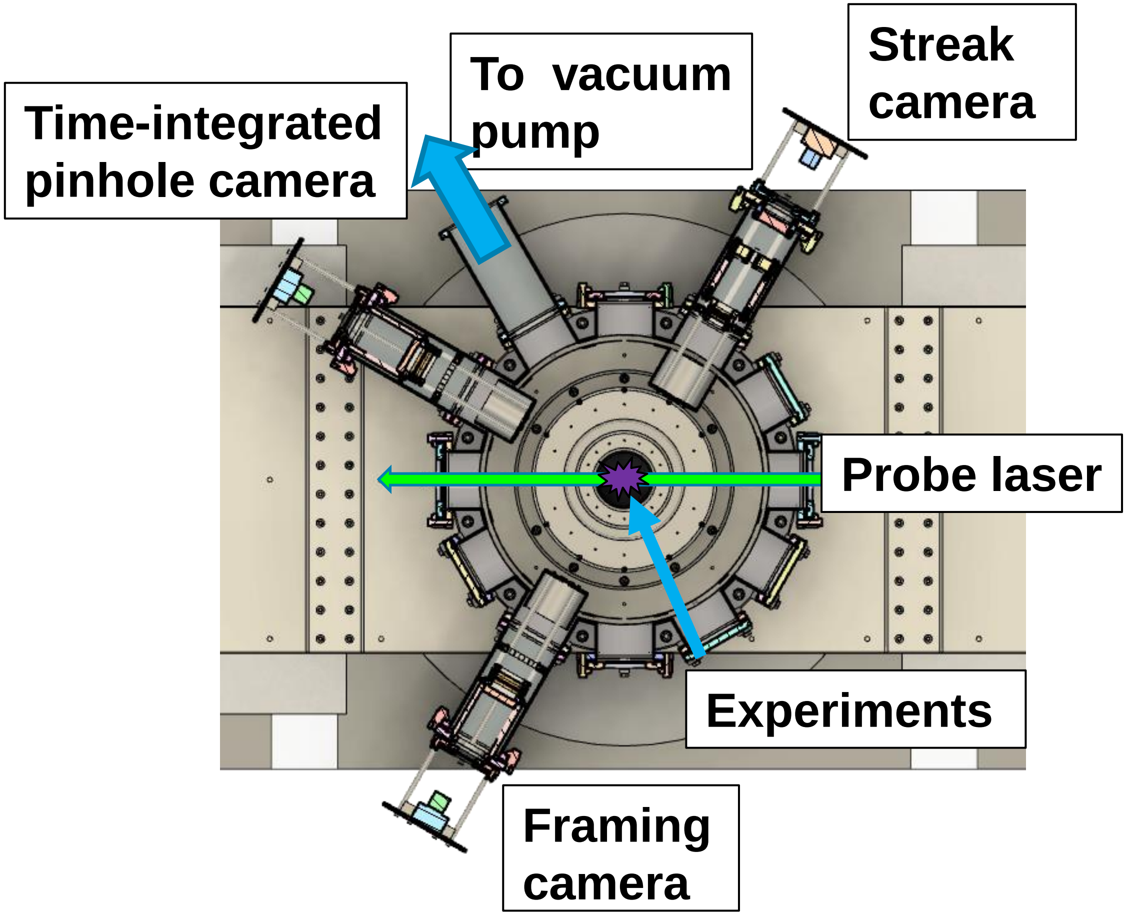
$$\omega^2 = {\omega_{\mathrm{pe}}}^2 + 3k^2 {v_{\mathrm{Te}}}^2$$

J. Sheffield etc., *Plasma Scattering of Electromagnetic Radiation*

Laser alignment on three different optical tables will be challenging but possible



A suit of diagnostics in the range of (soft) x-ray are being built



- CsI are used as the photocathode for all x-ray imaging system.
- Au photocathode may be used in the future.

- **Pinhole camera:**
  - Magnification: 1x
  - Exposure time: 1 us
- **Streak camera:**
  - Magnification: 1x
  - Temporal resolution: 15 ps
- **Framing camera:**
  - Magnification: 0.3x
  - Temporal resolution: ~ns using 4 individual MCPs
- **Laser probing:**
  - For interferometer, schlieren, shadowgraphy, Thomson scattering.
  - Temporal resolution: ~300 ps using stimulated brillouin scattering (SBS) pulse compression in water

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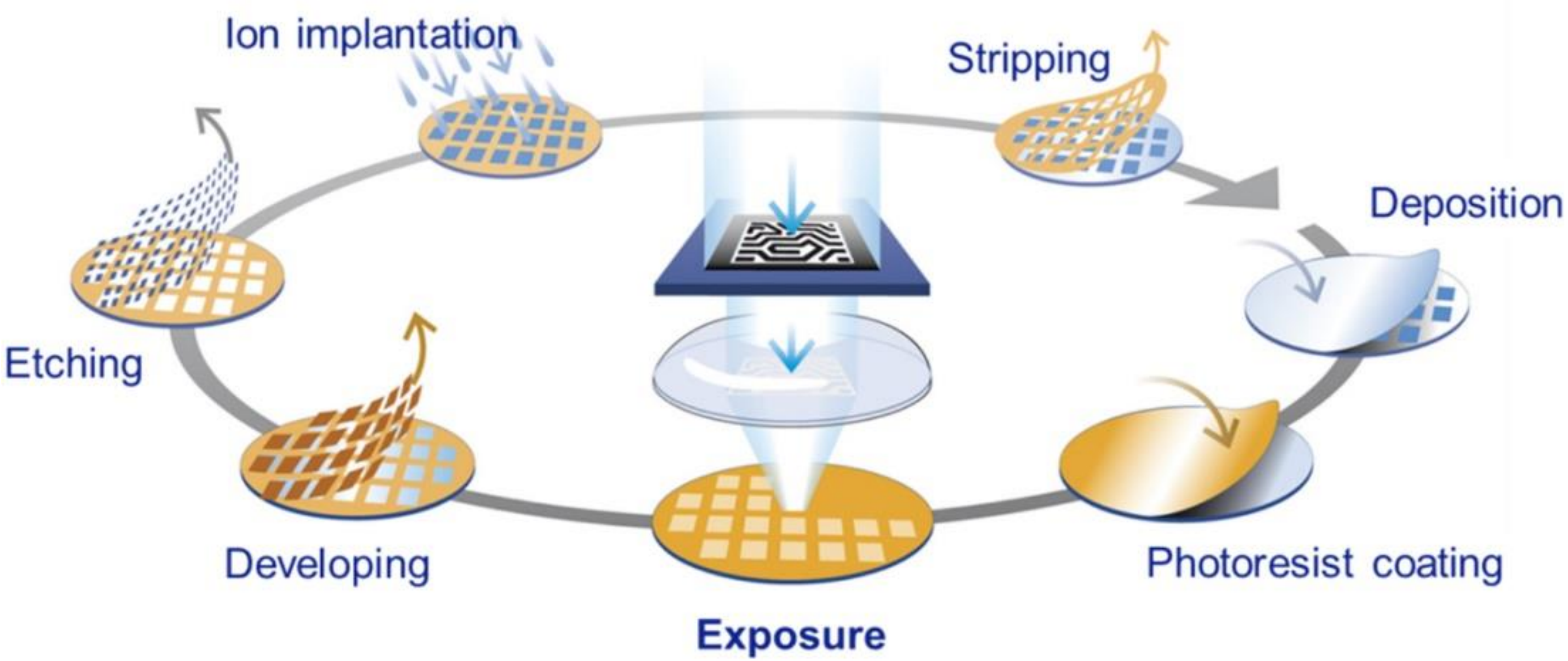
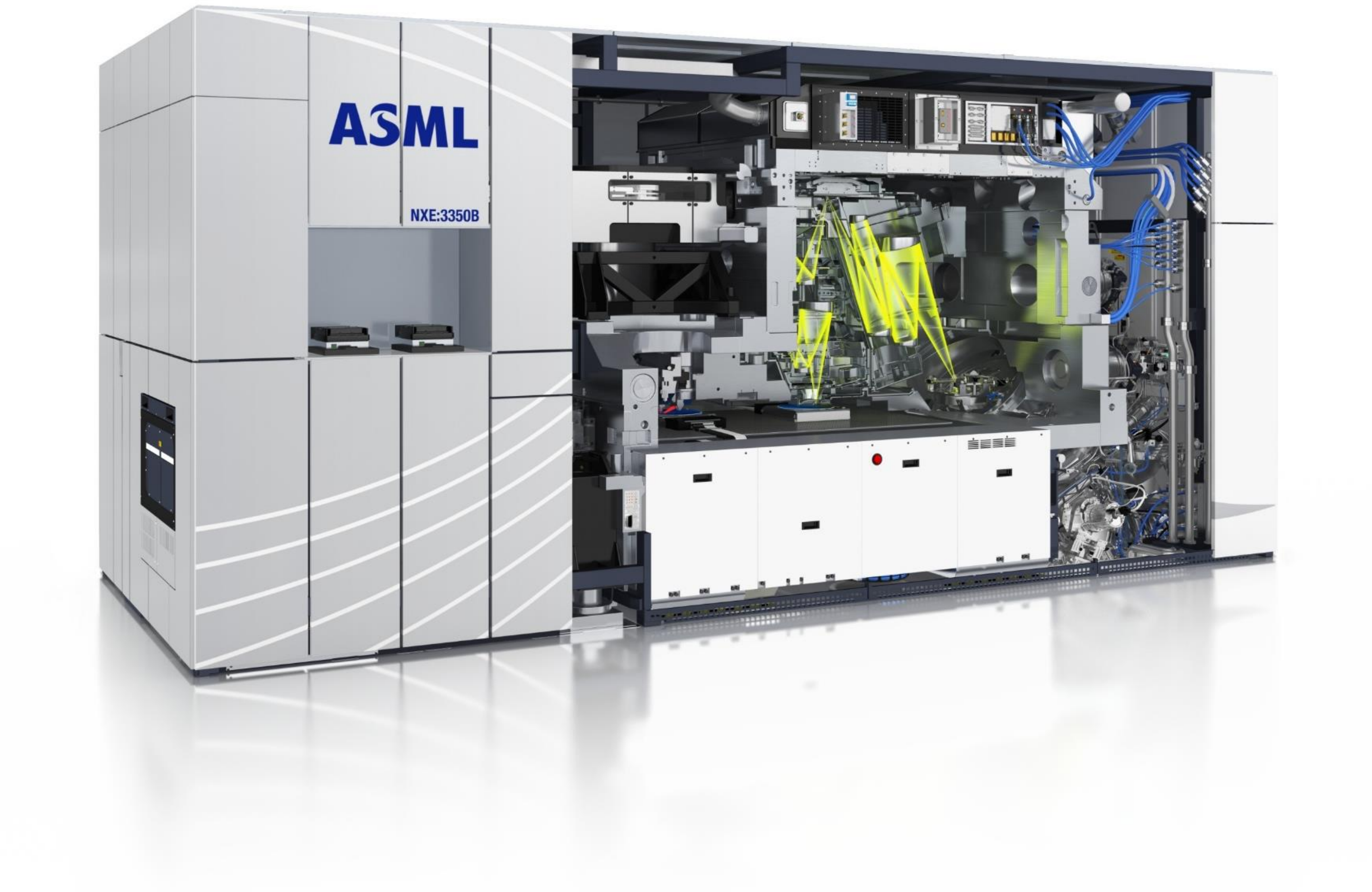
A semiconductor device is fabricated by many repetitive production process



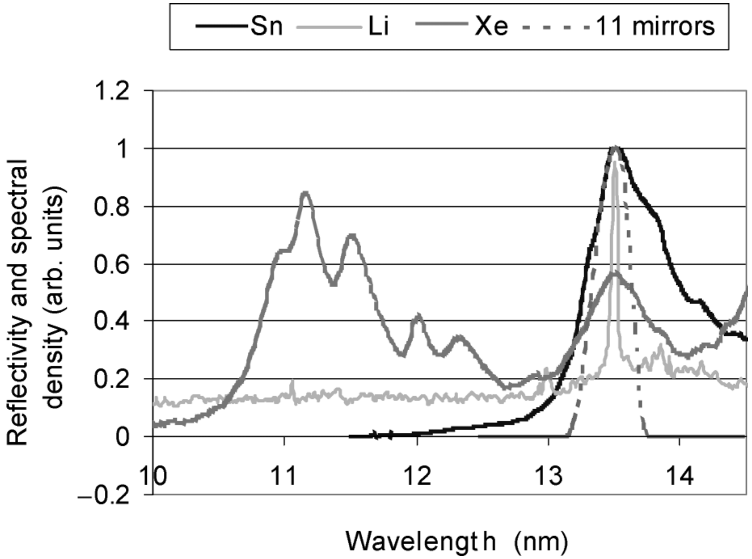
Surf. Topogr.: Metrol. Prop. **4** (2016) 023001

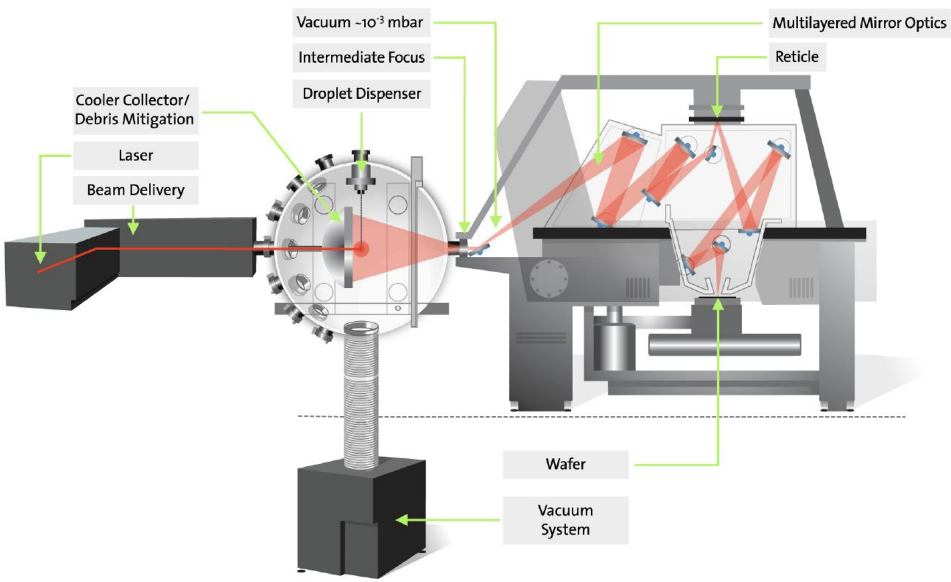
EUV lithography becomes important for semiconductor industry



http://finance.technews.tw/2019/01/25/euv-asml-2018/

EUV light is generated from laser-produced plasma (LPP)

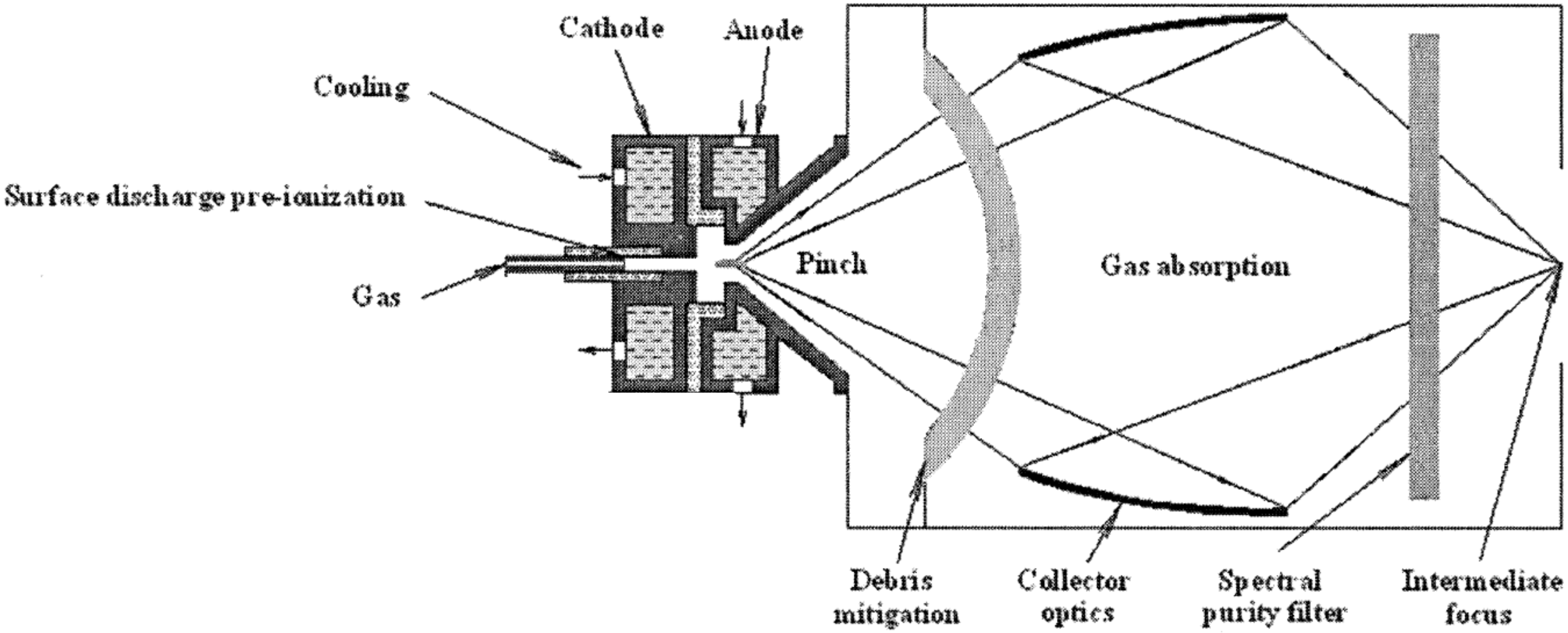




- $\lambda = 13.5\ \mathrm{nm} \pm 1\%$ **is required.**
- **At T=35-40 eV (~450,000 K), in-band emission occurs.**
- **Xenon:**
  - $4p^6 4d^8 \rightarrow 4p^6 4d^7 5p$ **from single ion stage** Xe^{10+}
  - **UTA @ 11 nm**
- **Tin:**
  - $4p^6 4d^N \rightarrow 4p^5 4d^{N+1} + 4p^6 4d^{N-1} 4f$ $(1 \leq N \leq 6)$ **in ions ranging from** Sn^{8+} **to** Sn^{12+}
  - **UTA @ 13.5 nm**
- UTA: unresolved transition array

V. Bakshi, EUV sources for lithography
R. S. Abhari, etc., J. Micro/Nanolithography, MEMS, and MOEMS, 11, 021114 (2012)

Discharge produced plasma (DPP) can generate EUV light for EUV lithography

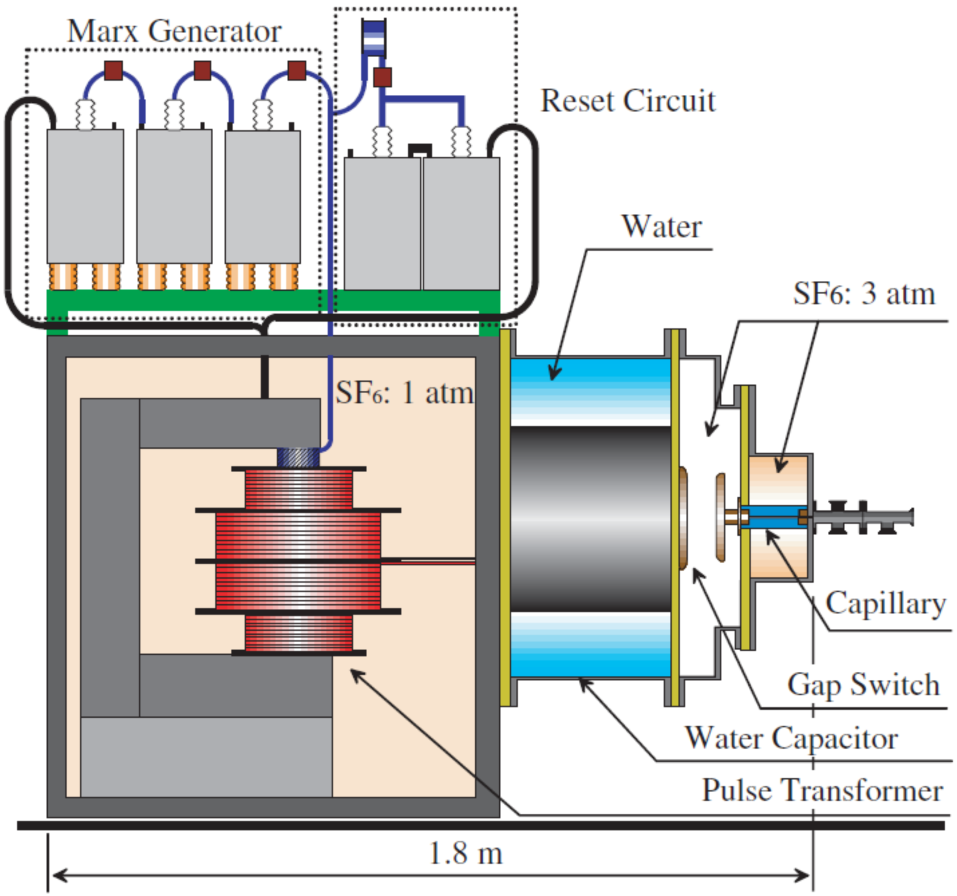


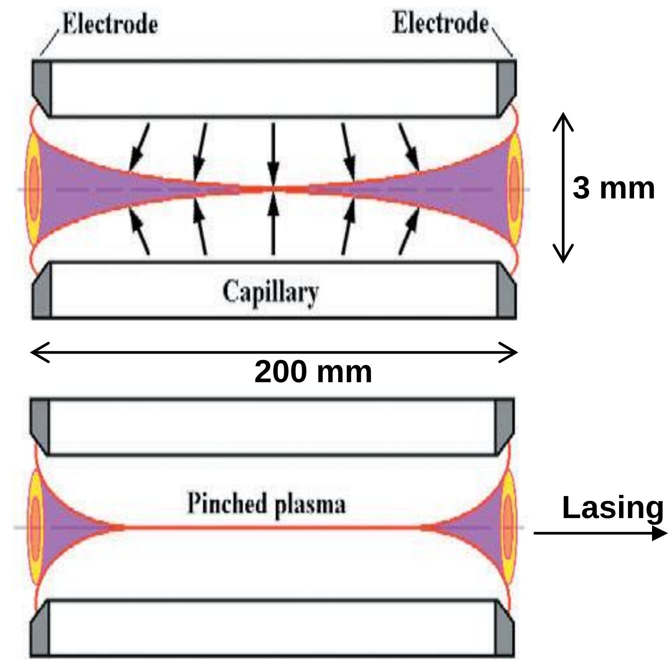
- **Electrodes are damaged significantly due to the heat and sputtering by ions.**

	Laser-produced plasma (LPP)	Discharge-produced plasma (DPP)
Pros	**Commercial system available.**	**High conversion efficiency.**
Cons	**Low conversion efficiency.**	**Short system life time due to electrode erosion.**

V. Borisov, etc., Proc. SPIE 6611, Laser Optics 2006: High-Power Gas Lasers, 66110B (12 April 2007)

Soft x-ray laser can be generated using a capillary z-pinch discharge



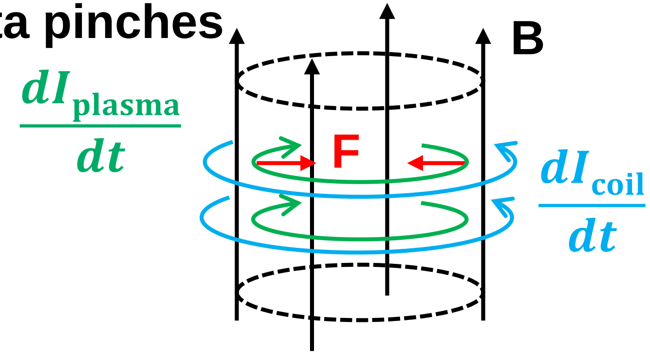


- **If 200～500 mTorr Ar is used as the filled gas, 46.9 nm (26.5 eV) Ne-like Ar laser can be built.**

Y. Hayashi, etc., Plasma Sources Sci. Technol. 13, 675 (2004)

EUV light can be generated using gas-puff theta pinches

- Theta pinches



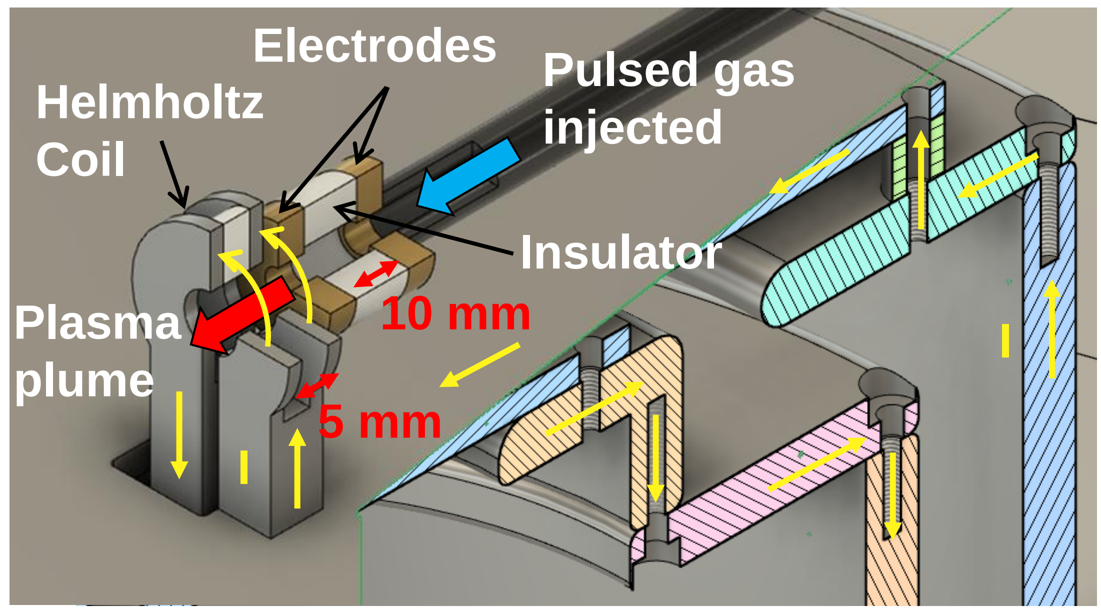
- Adiabatic compression:

$$TV^{\gamma-1} = \text{const} \quad T_f = T_o\left(\frac{r_o}{r_f}\right)^{4/3}$$

$$T_o = 1 \sim 10\ \text{eV} \quad T_f = 40\ \text{eV}$$

Compression ratio: $\frac{r_o}{r_f} = 16 \sim 3$

- Gas-puff Theta pinches
- High voltage is applied between electrodes to generate initial plasma via arc discharge.



- Advantages:
  - Energy is directed used for generating and heating plasma.
  - Electrodes are away from hot plasma.
  - Less current is used to generate plasma.

Simulations show that plasma with temperature higher than 30 eV can be generated on our system

- **Snow plow model is used*:**

$$\frac{d}{dt}\left(M_s\frac{da}{dt}\right) = -2\pi a\left(\frac{B^2}{8\pi} - P_0\left(\frac{a_0}{a}\right)^{2\gamma}\right)$$

$$M_s(t) = \pi m_i N_0\left(a_0{}^2 - a^2\right)\eta(t)$$

- **The magnetic field provided by a Helmholtz coil with both radius and separation equal to 5 mm:**

$$B = B_{max}\sin(\omega t) \text{ where } B_{max} = 9\text{ T}$$

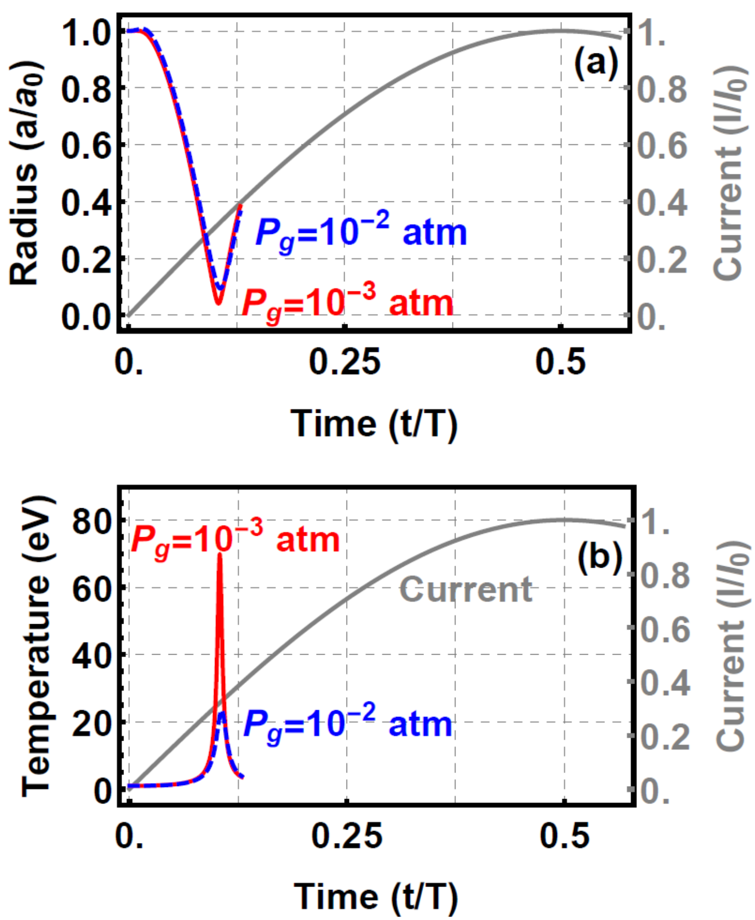
- **Initial conditions:**

$$a_0 = 5\text{mm}$$

$$P_0 = 2P_g\frac{11604}{300}$$

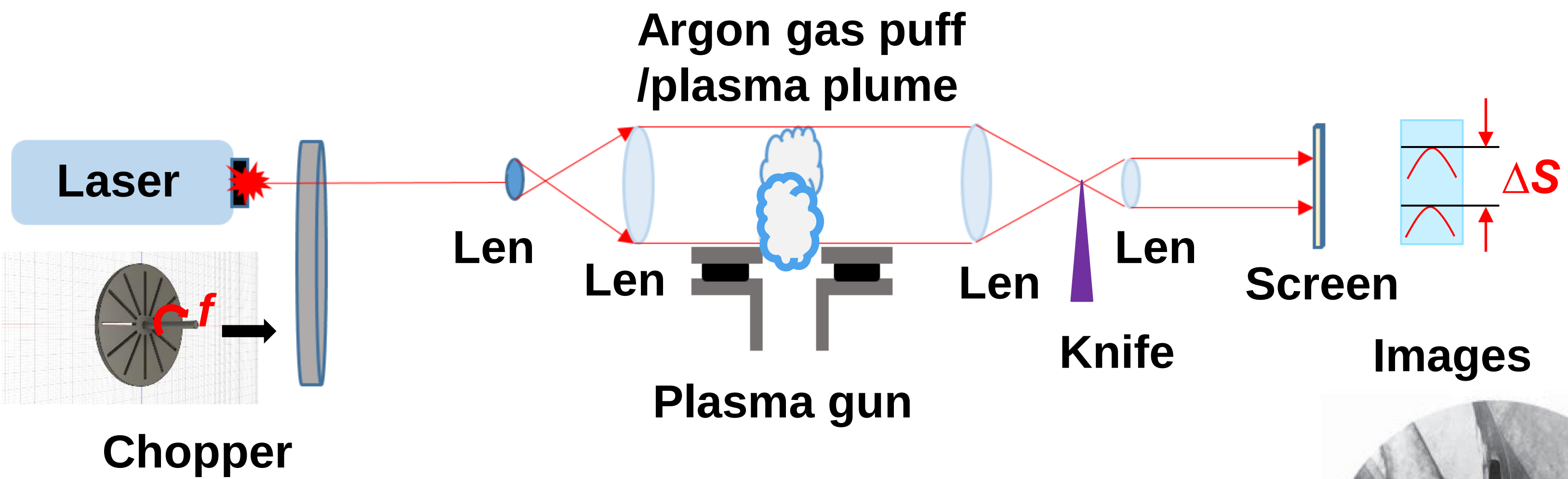
$$N_0 = 2.43\times 10^{19}P_g\text{cm}^{-3}$$

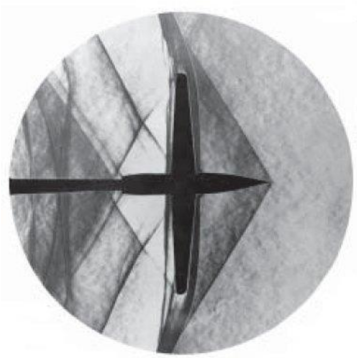
$$m_{i,Ar} = 6.67\times 10^{-23}g$$



*T. Uchida, etc., Nuclear Fusion, **2**, 70, 1962

Flow speed of the Argon gas puff/plasma plume will be measured using time-resolved Schlieren system





- **The flow speed is important for synchronization.**
- **Speed:** $$v = \frac{\Delta S}{\Delta t} = \Delta S f$$
- **Sound speed: 300 m/sec**
  For 50 μs, the traveling distance of the plume is 1.5 cm.
- **An 20-kHz optical chopper provides 50 μs time separate.**

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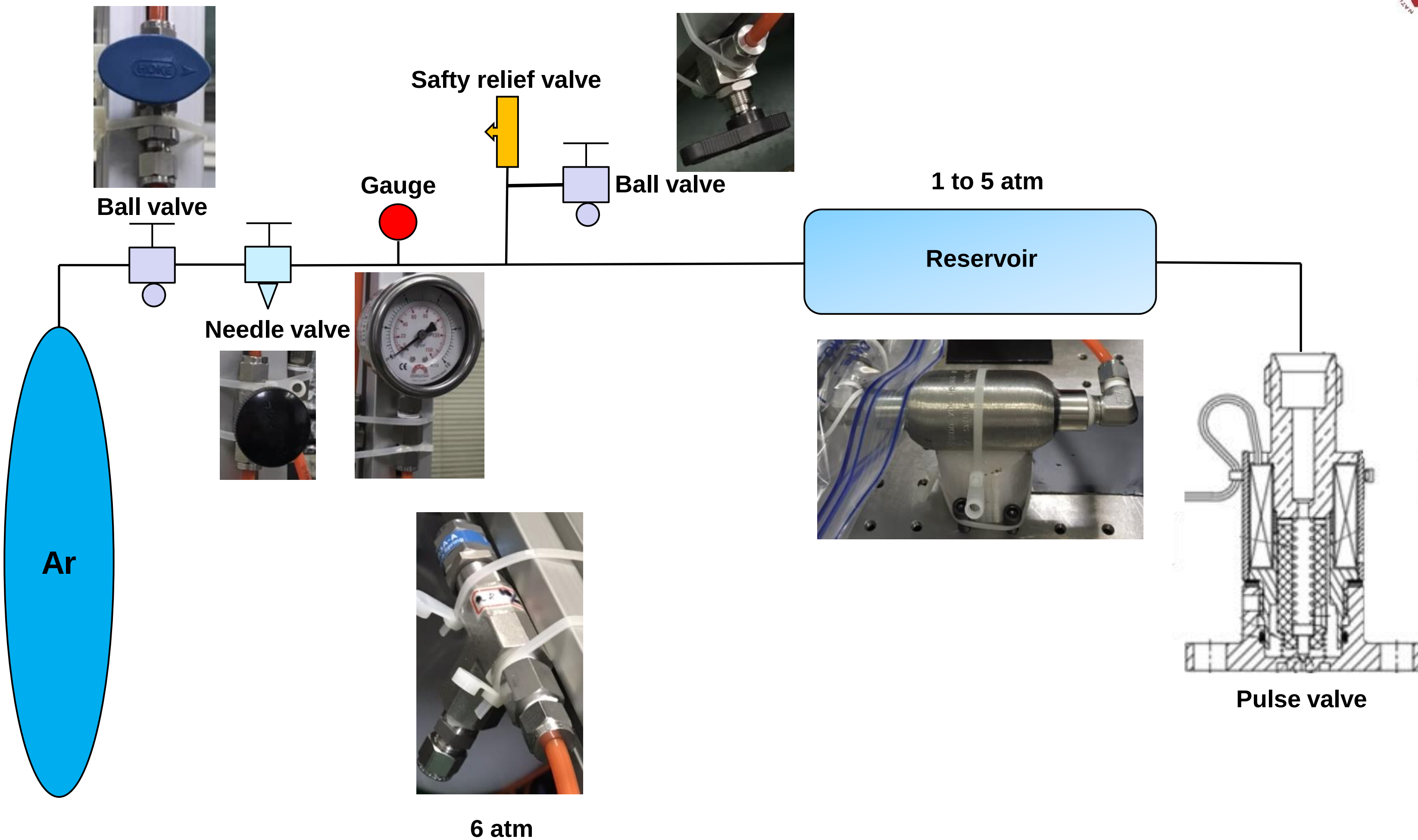
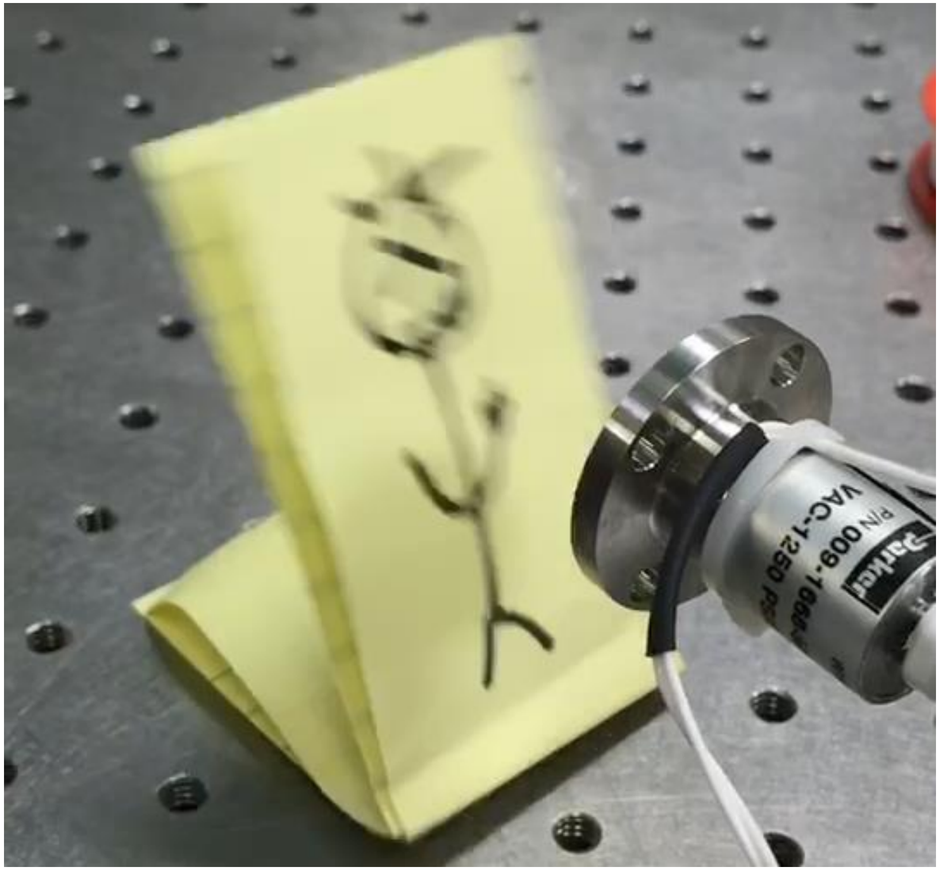
https://en.wikipedia.org/wiki/Schlieren_photography

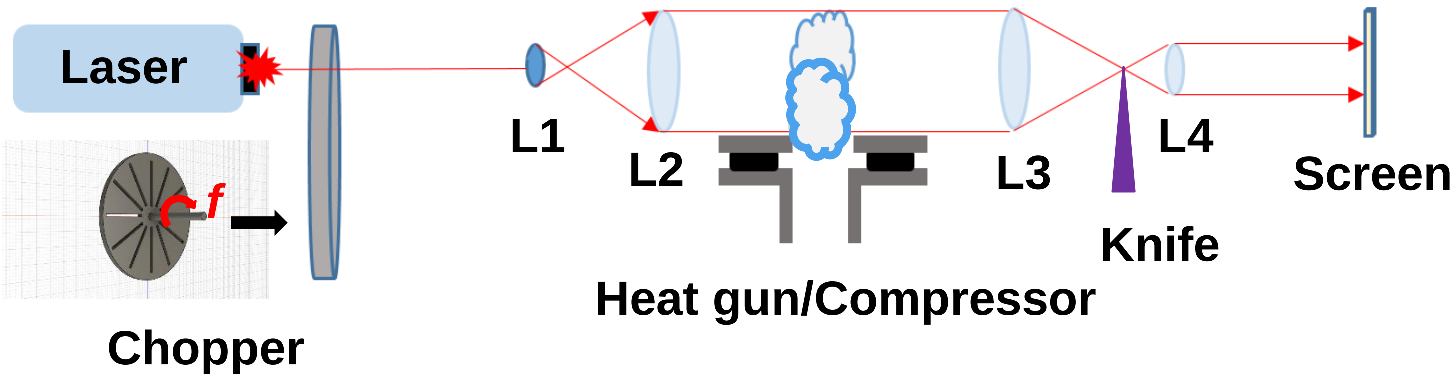
The gas-puff system in atmosphere has been built for testing

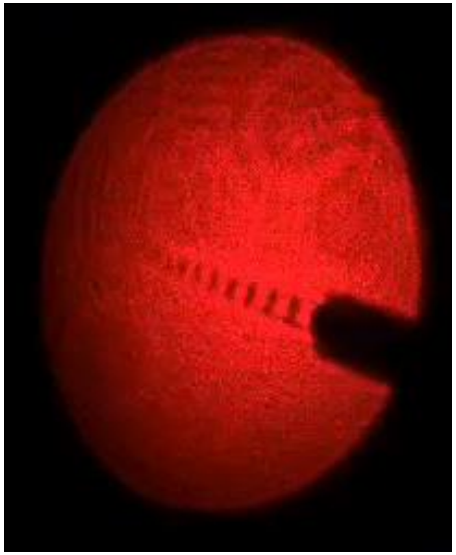


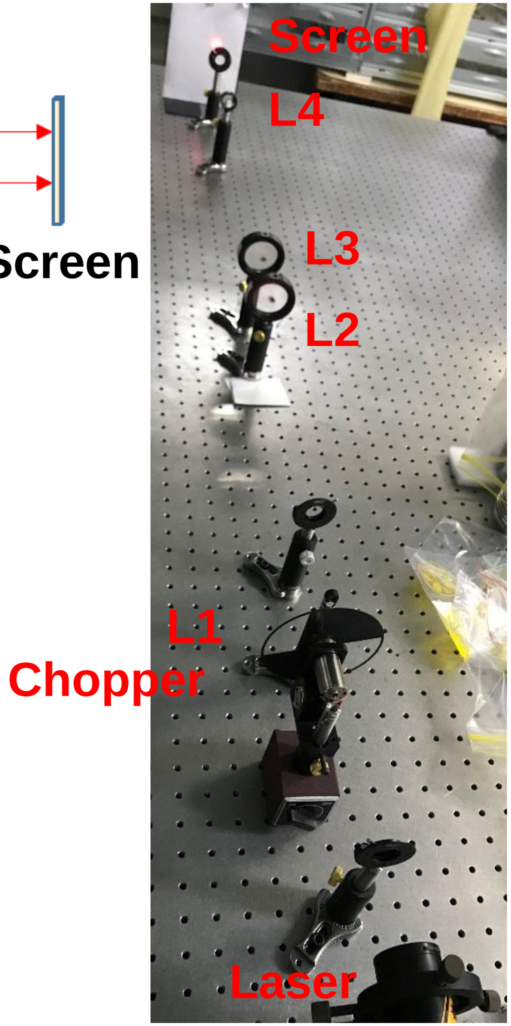
The gas-puff was capable to push two slides of papers



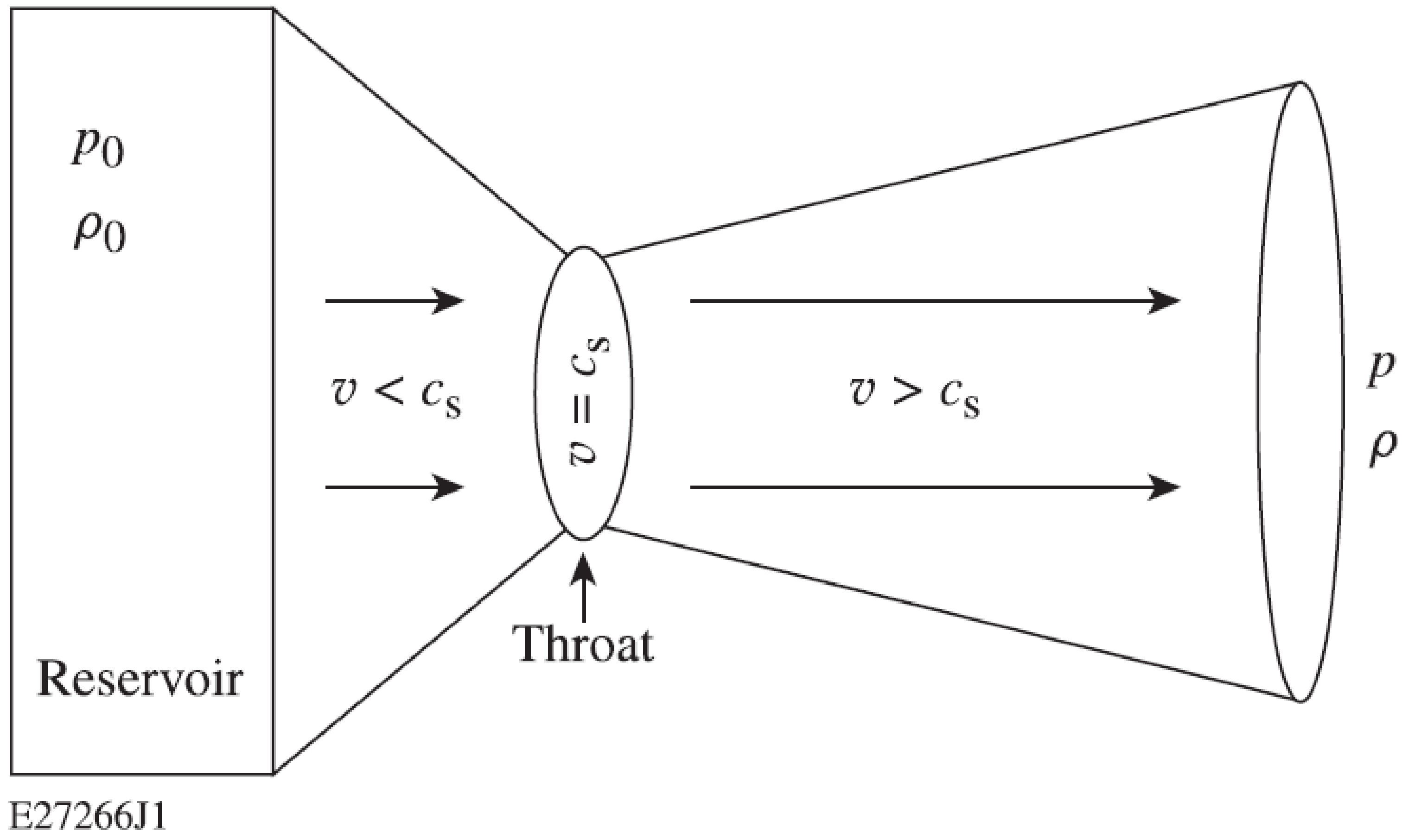
The Schlieren system has been built





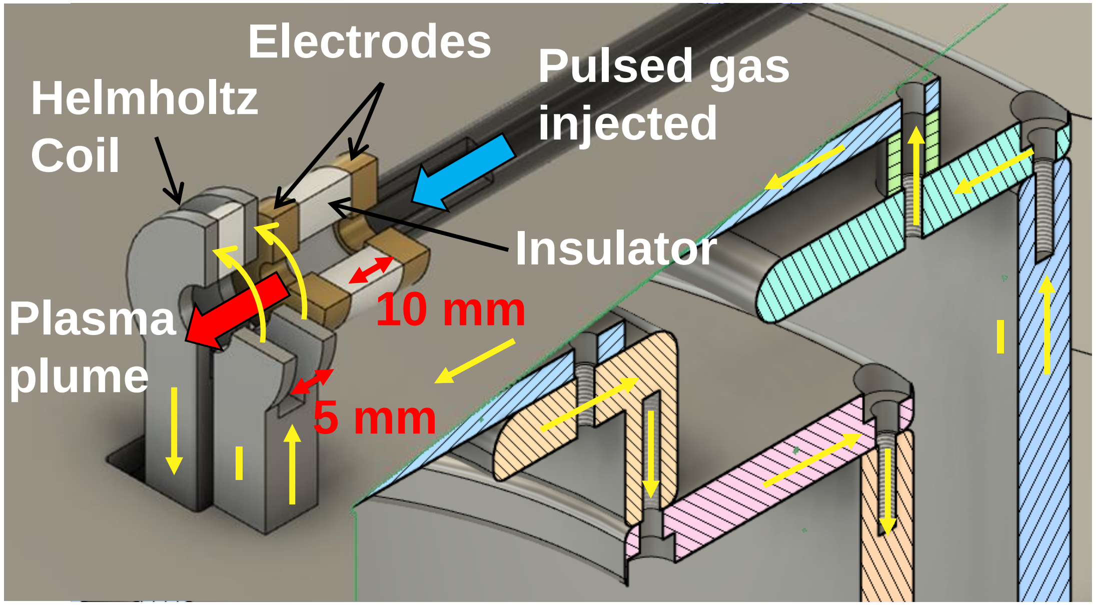


A converging/diverging nozzle is needed to generate a supersonic gas puff



*A. M. Hansen, etc., Rev. Sci. Instrum., **89**, 10C103, 2018

EUV light characteristics will be measured



- Plasma density, temperature before and after compression will be measured.
- EUV light characteristic will be measured.
  - Intensity
  - Pulse width
  - Spectrum
  - Uniformity
  - …….

Outline

- Introduction to nuclear fusion
- Magnetic confinement fusion (MCF)
  - Tokamak
  - Stellarator
- Inertial confinement fusion (ICF)
  - Indirection drive ICF
  - Direct drive ICF
- Innovation idea – MCF + ICF
- Plasma in space
- **Pulsed-power system at NCKU**
  - Extreme ultraviolet (EUV) light source
  - **Studies of the rotational plasma jets**

Hydrodynamic equations can be written in a dimensionless form

- **Dimensional form:**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u}\right) = -\nabla p$$

$$\frac{\partial p}{\partial t} + \vec{u} \cdot \nabla p = -\gamma p \nabla \cdot \vec{u}$$

- **Dimensionless form:**

$$\frac{\partial \tilde{\rho}}{\partial \tilde{t}} + \nabla \cdot \left(\tilde{\rho}\, \tilde{\vec{u}}\right) = 0$$

$$\tilde{\rho}\left(\frac{\partial \tilde{\vec{u}}}{\partial \tilde{t}} + \tilde{\vec{u}} \cdot \nabla \tilde{\vec{u}}\right) = -\nabla \tilde{p}$$

$$\frac{\partial \tilde{p}}{\partial \tilde{t}} + \tilde{\vec{u}} \cdot \nabla \tilde{p} = -\gamma \tilde{p} \nabla \cdot \tilde{\vec{u}}$$

$$\tilde{\vec{r}} = \frac{\vec{r}}{L^*}$$

$$\tilde{t} = \frac{t}{L^*}\sqrt{\frac{p^*}{\rho^*}}$$

$$\tilde{\rho} = \frac{\rho}{\rho^*}$$

$$\tilde{p} = \frac{p}{p^*}$$

$$\tilde{\vec{u}} = \vec{u}\sqrt{\frac{p^*}{\rho^*}}$$

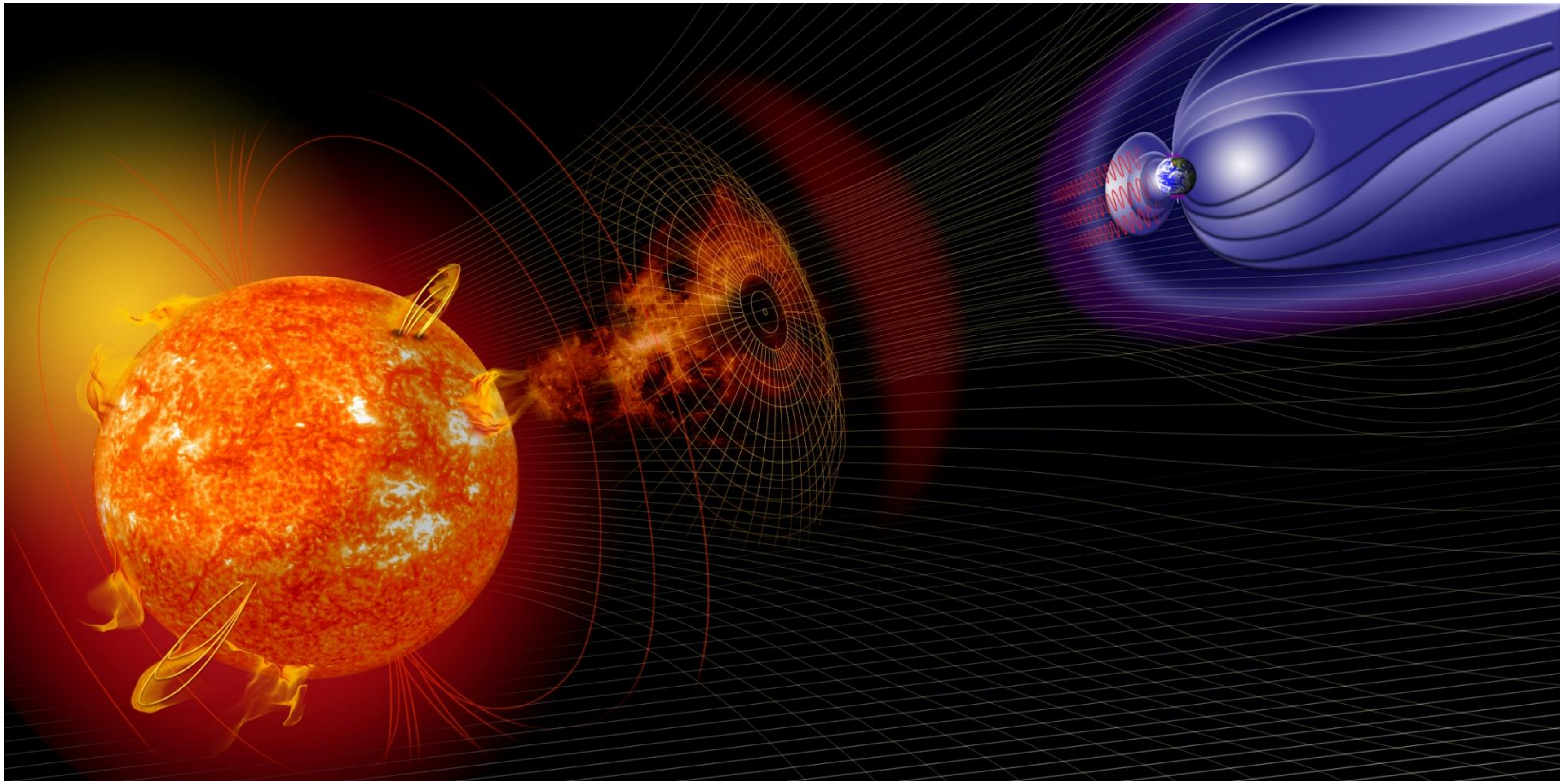
$$\tilde{\rho}_0(\tilde{r}) = f(\tilde{r})$$

$$\tilde{p}_0(\tilde{r}) = g(\tilde{r})$$

$$\tilde{\vec{u}}_0(\tilde{r}) = \sqrt{\frac{p^*}{\rho^*}}\,\vec{h}(\tilde{r})$$

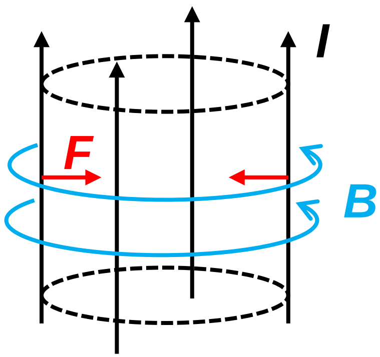
Any two hydrodynamic systems involve identically in a scaled sense if f, g, h, and $u^*(\rho^*/p^*)^{1/2}$ are the same.

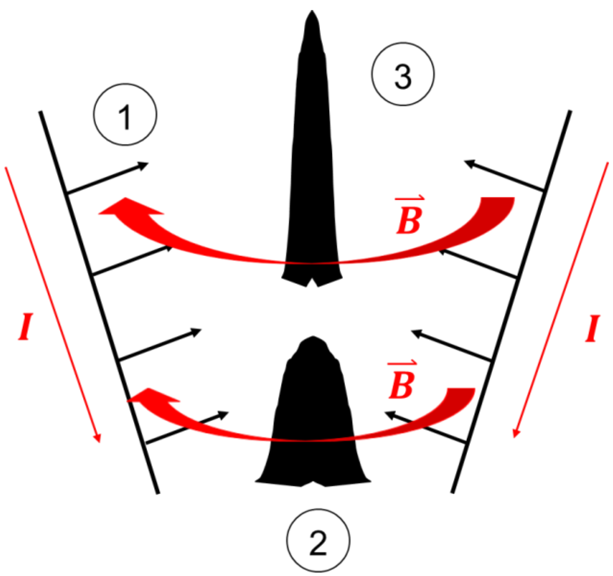
Solar wind is a supersonic plasma plume coming from the sun



https://www.nasa.gov/mission_pages/sunearth/spaceweather/index.html

A plasma jet can be generated by a conical-wire array due to the nonuniform z-pinch effect





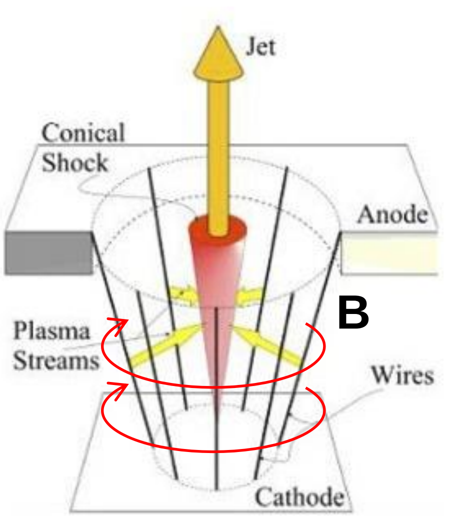
1. Wire ablation : corona plasma is generated by wire ablations.

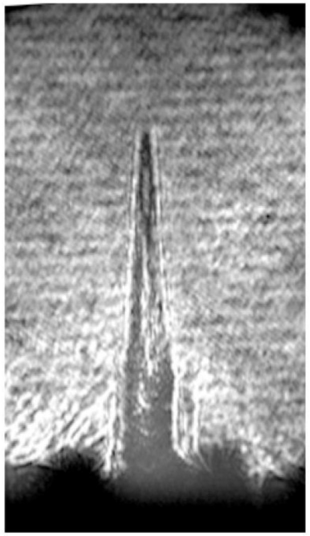
2. Precursor : corona plasma is pushed by the $\vec{J} \times \vec{B}$ force and accumulated on the axis forming a precursor.

3. Plasma jet is formed by the nonuniform z-pinch effect due to the radius difference between the top and the bottom of the array.

D. J. Ampleforda, et al., PHYSICS OF PLASMAS 14, 102704 (2007)

Plasma jets generated by conical-wire arrays can be used to simulate the solar wind





2mm

Driver:

I_{peak}=1 MA

T_{rise}=240 ns

Jet conditions:

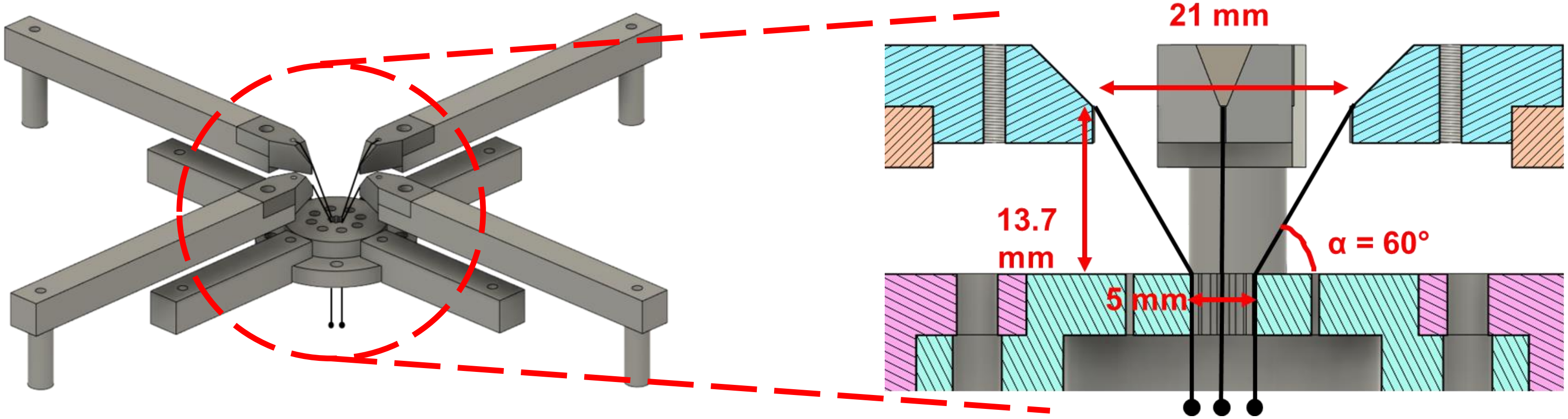
V ~ 200 km/s

n_e ~10^{19} cm^{-3}

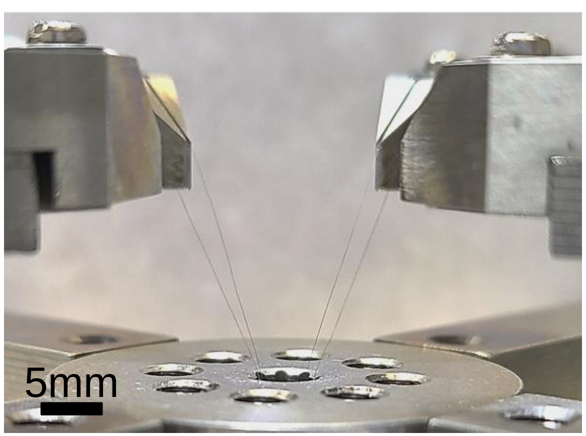
- **A conical-wire array can be used to generate a plasma jet where the flow speed is ~ 200 km/s with Mach number up to 20.**
- **The solar wind is a supersonic plasma flow with Mach number ~ 5-10 and the flow speed ~ 400 km/s.**

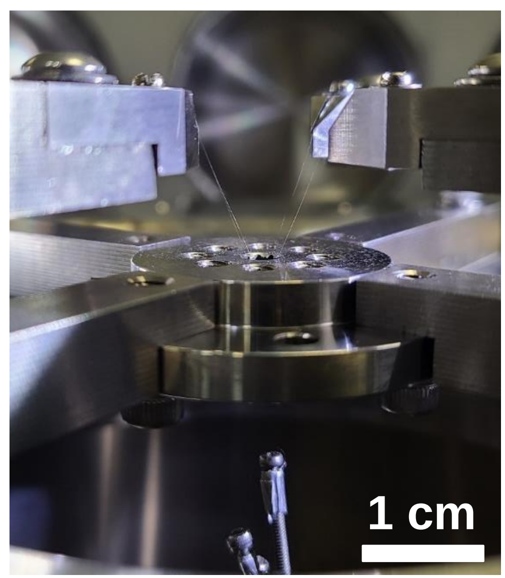
* S. V. Lebedev *et al.* Astrophys. J. 564, 113 (2002)
* George K. Parks, Physics of Space Plasmas: An Introduction (Perseus Books (Sd), 1991).

Our conical-wire array consists of 4 tungsten wires with an inclination angle of 30° with respect to the axis



• Conical-wire array

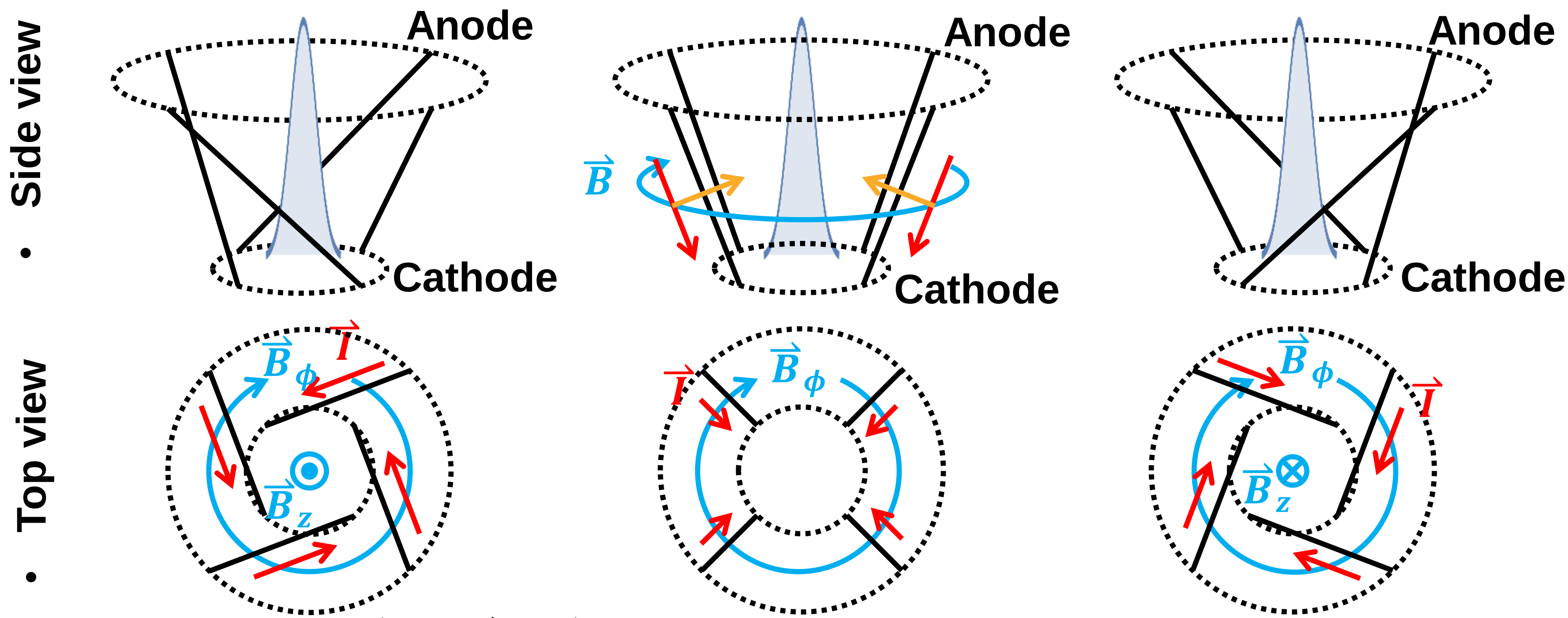




- **Material : Tungsten**
- **Number of wires : 4**
- **Diameter : 0.02 mm**

The rotational plasma jet produced by a twisted-conical-wire array is being studied

- Clockwise
- No rotation
- Counterclockwise



- **No rotation:** $\vec{F}_V = \vec{j} \times \vec{B} = (J_r, 0, J_z) \times (0, B_\phi, 0) = \hat{r}(-J_z B_\phi) + \hat{z}(J_r B_\phi)$
- **With rotation:** $\vec{F}_V = \vec{j} \times \vec{B} = (J_r, J_\phi, J_z) \times (B_r, B_\phi, B_z)$

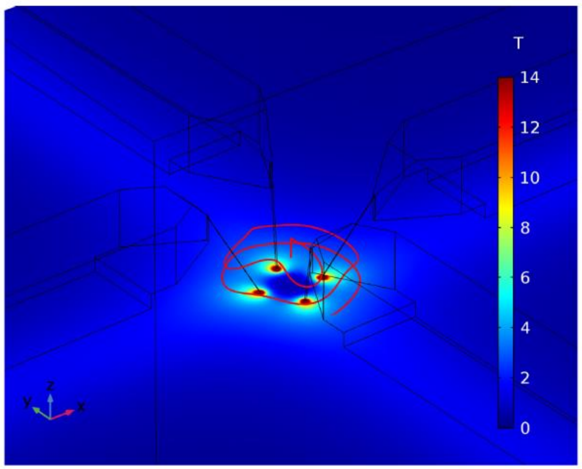
$$= \hat{r}(J_\phi B_z - J_z B_\phi) + \hat{\phi}(J_z B_r - J_r B_z) + \hat{z}(J_r B_\phi - J_\phi B_z)$$

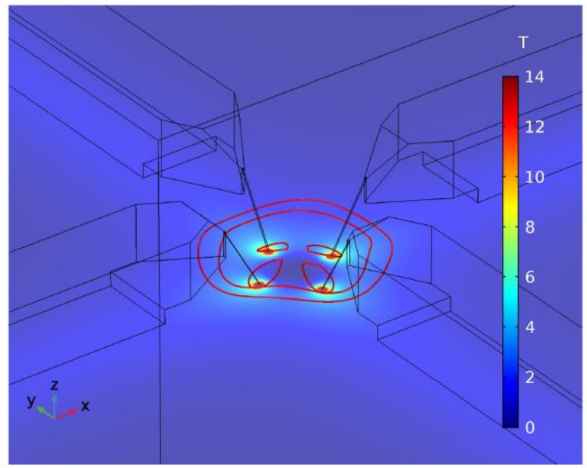
	Compression		Rotation			
• CW:	+ +	- -	- +	- +	- -	+ +
• CCW:	- -	- -	- -	- -	- -	- -

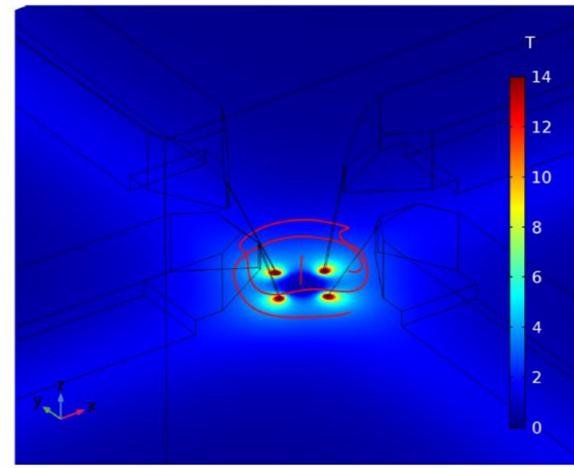
Bz is generated when the coil is twisted

- Clockwise
- No rotation
- Counterclockwise

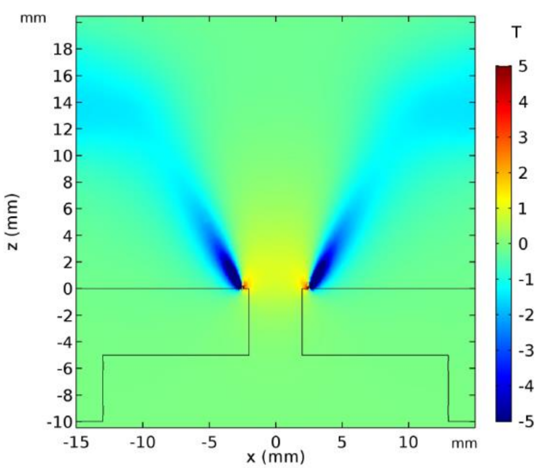
- $\vec{B}$

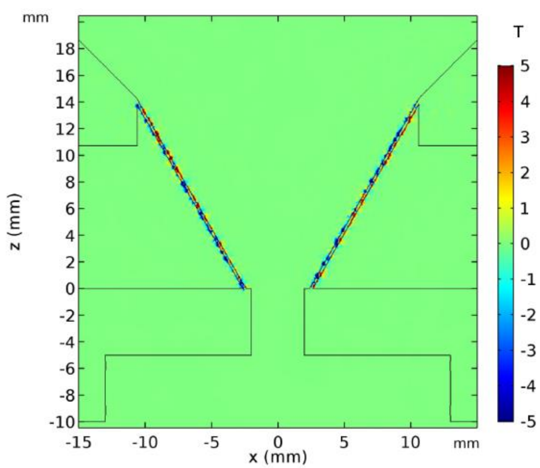


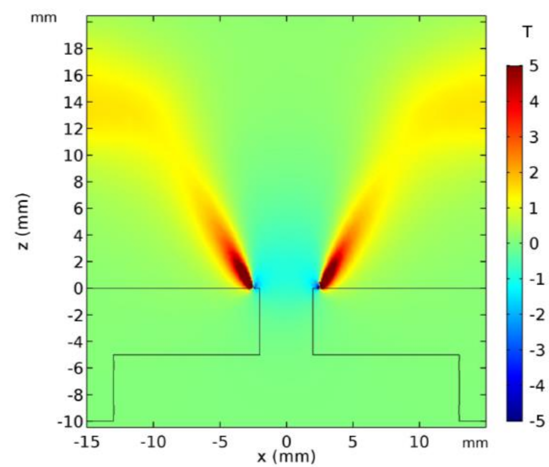




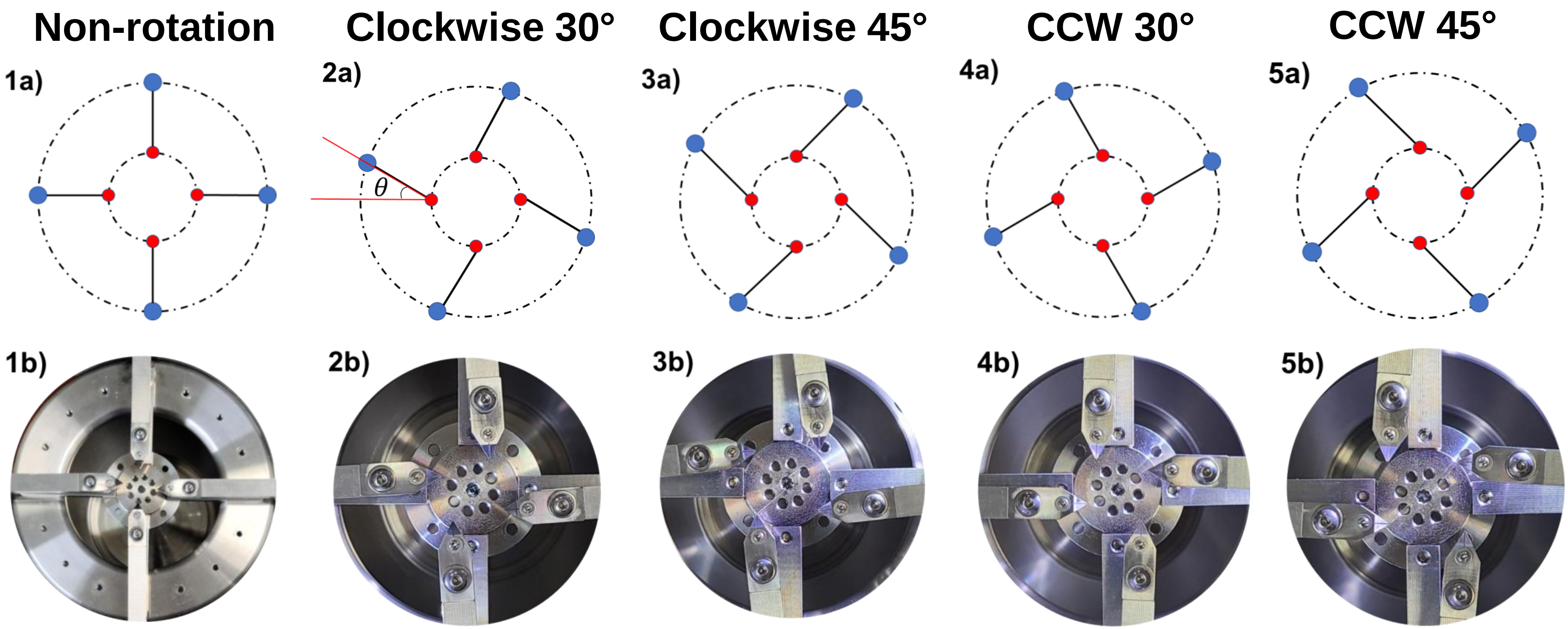
- B_z





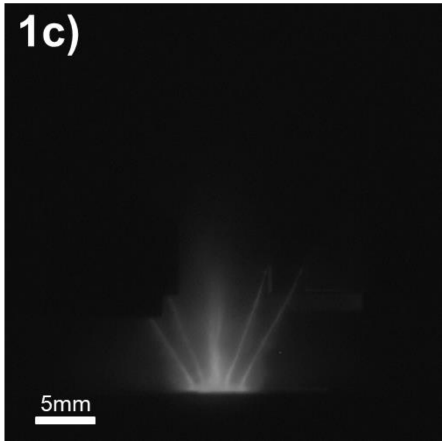


Conical-wire arrays were twisted with different angles and in different directions

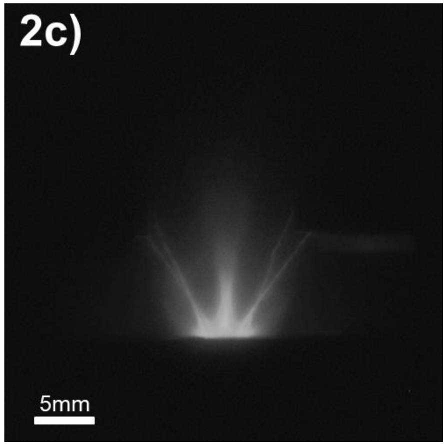


The brightness of the generated plasma jets depend on the twisted angle of the conical-wire array

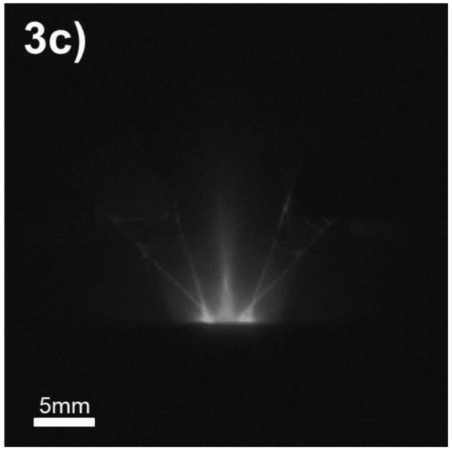
- Non-rotation



- Clockwise 30°

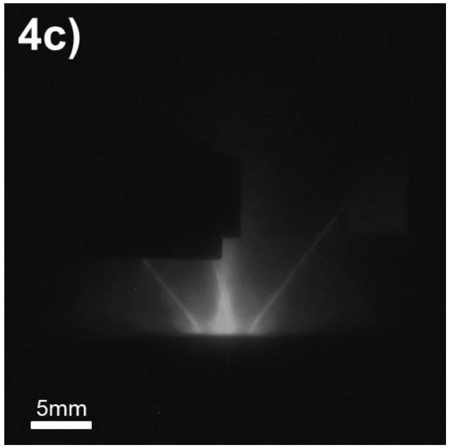


- Clockwise 45°

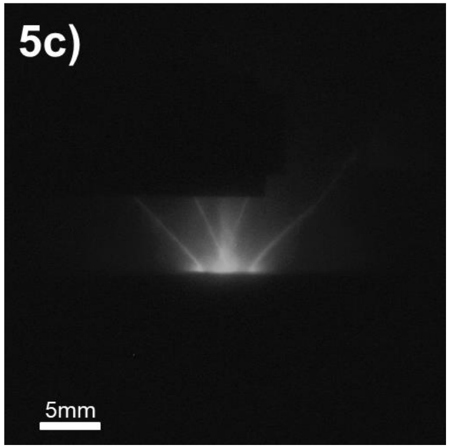


- The view of the plasma jet was blocked

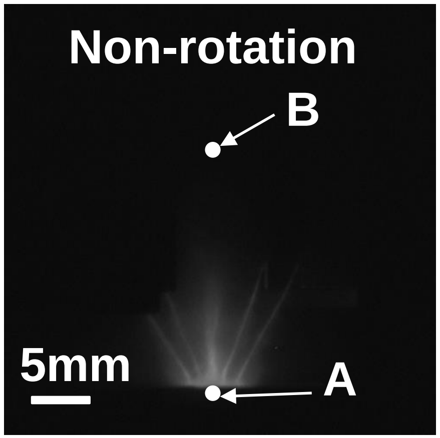
- CCW 30°

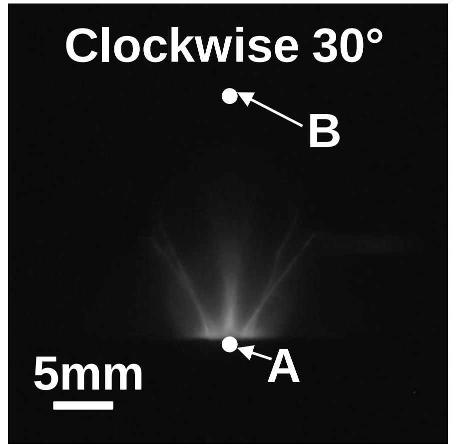


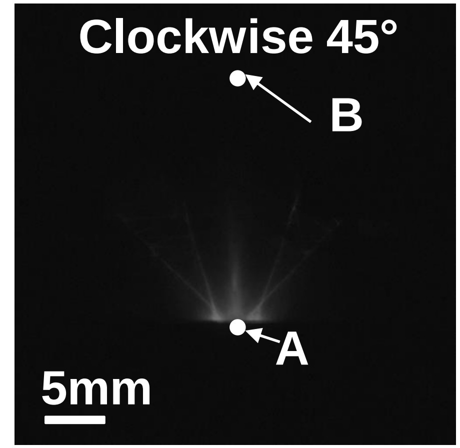
- CCW 45°

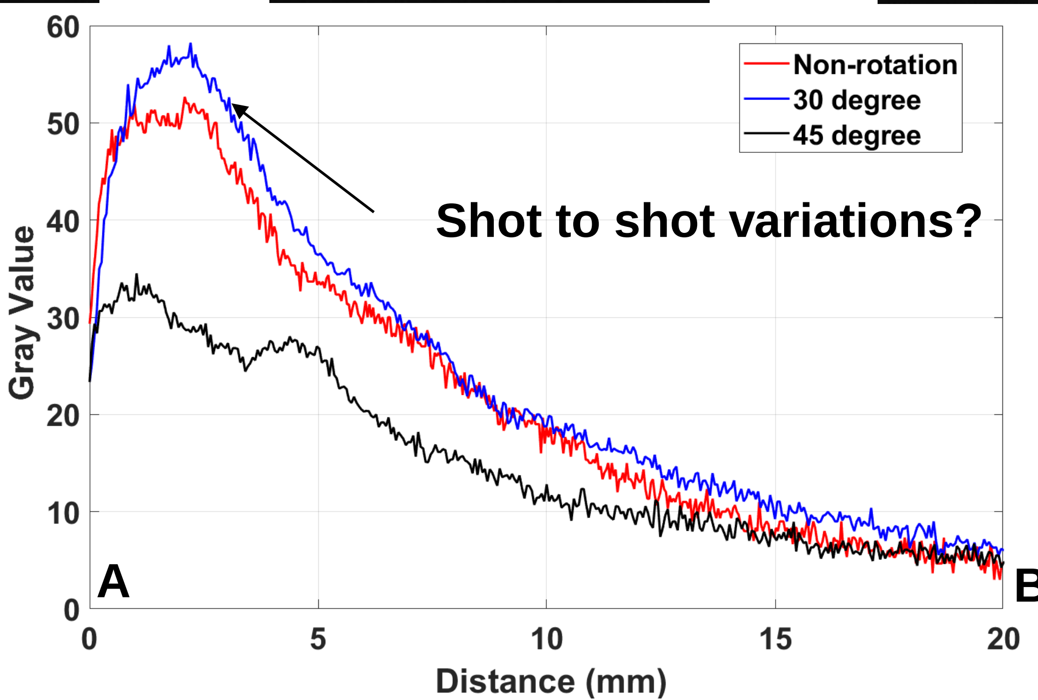


The plasma jet with the twisted angle of 30º was the brightest



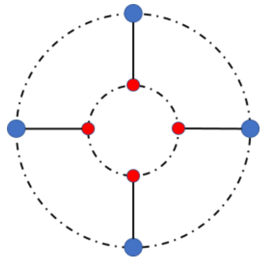


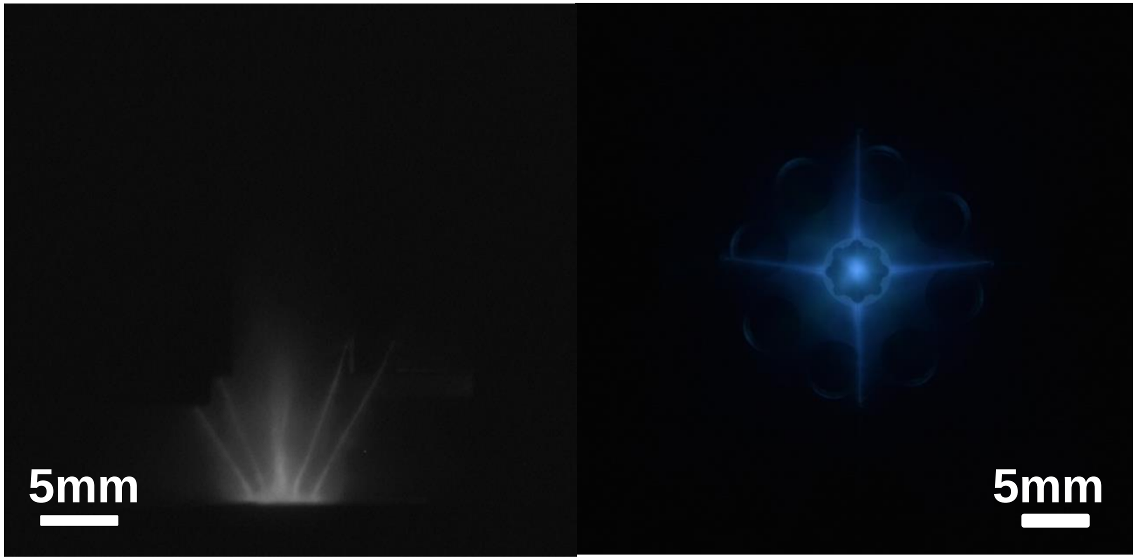




The plasma jet is a bright spot from the top view

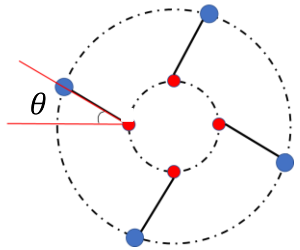
- **Non-rotation**

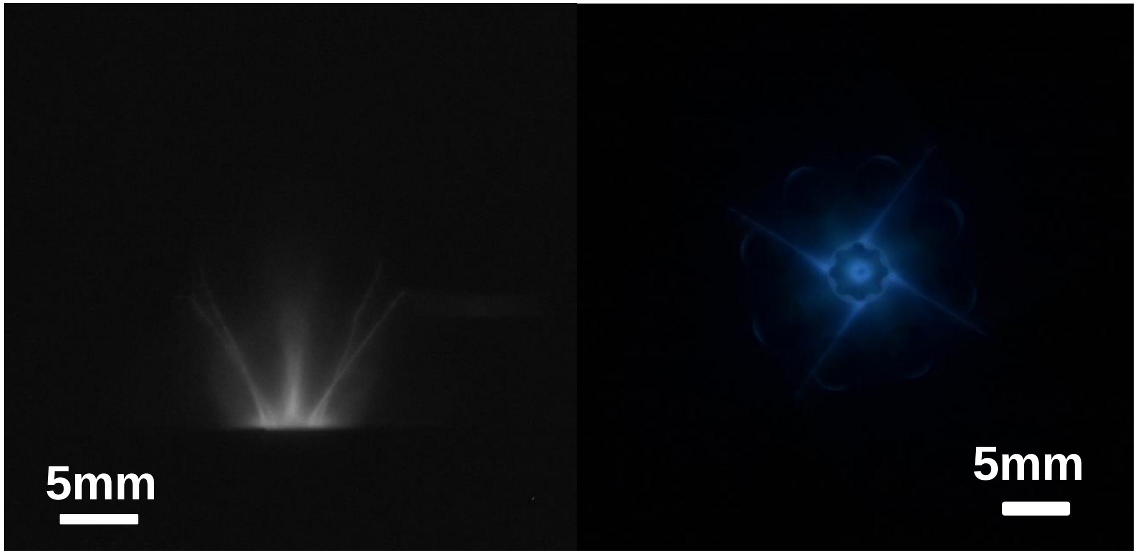




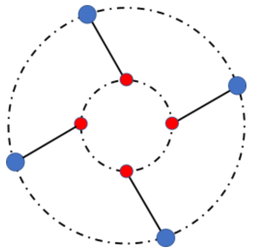
Hollow plasma jets were generated when the conical-wire arrays were twisted

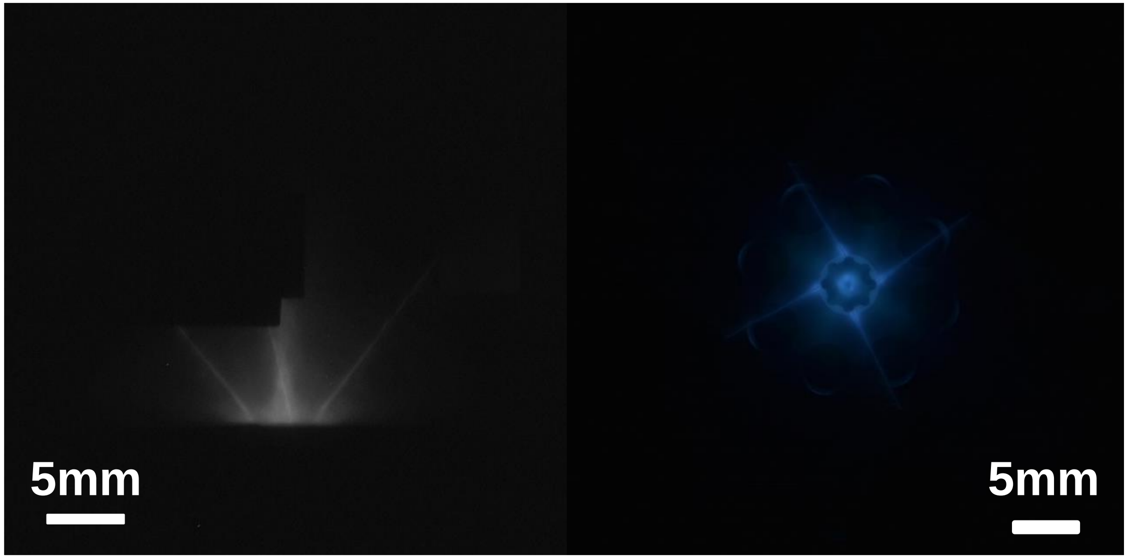
- **Clockwise 30 °**



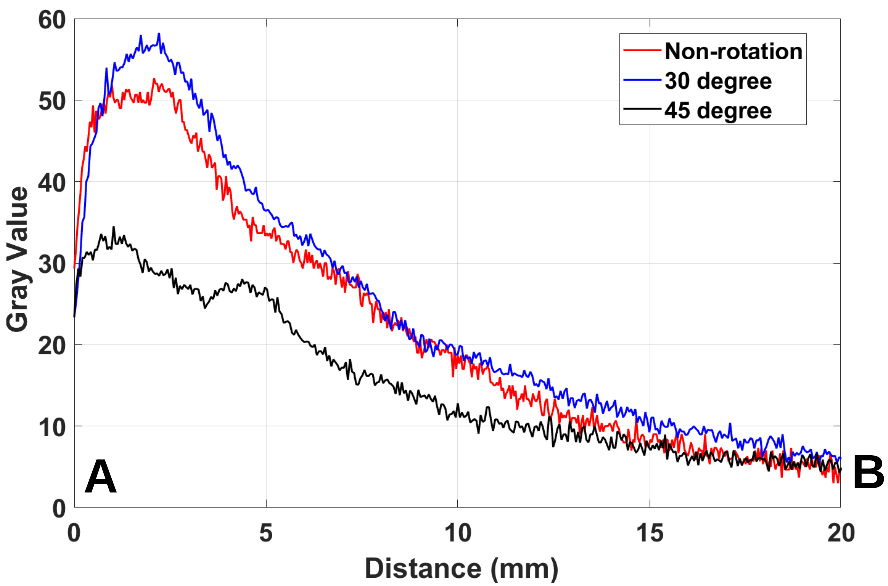


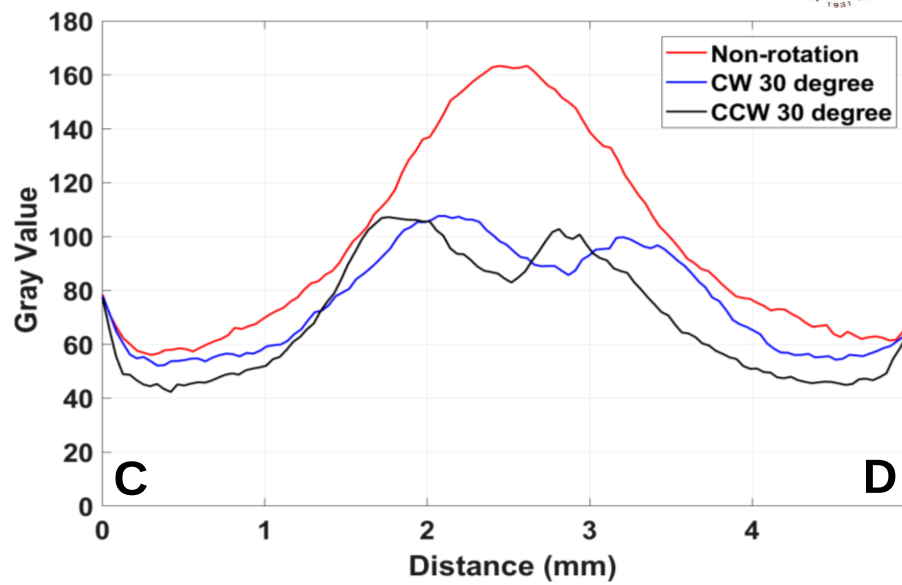
- **Counter clockwise 30 °**

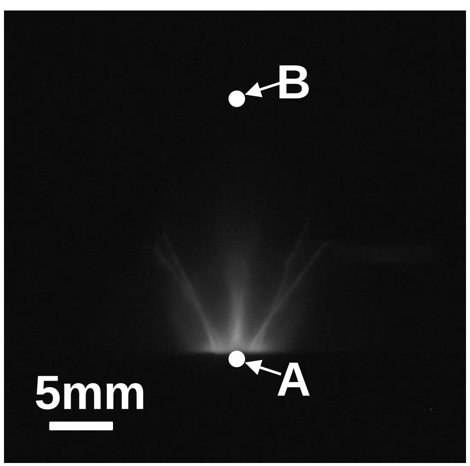




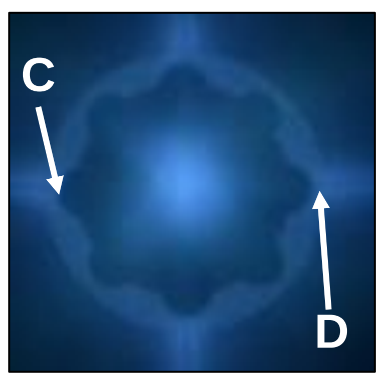
The hollow region at the center was due to angular momentum conservation of the in-coming plasma flow



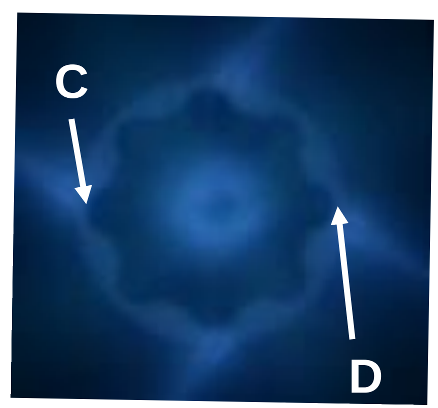




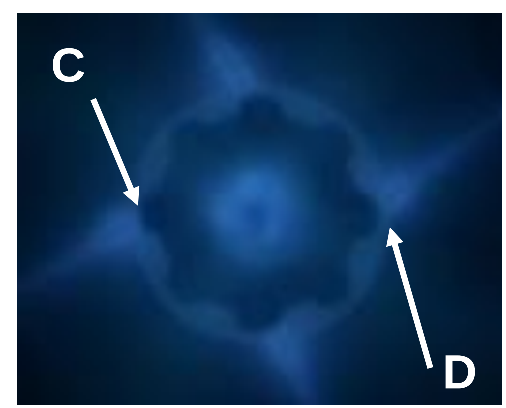
- 0 °



- CW 30 °



- CCW 30 °

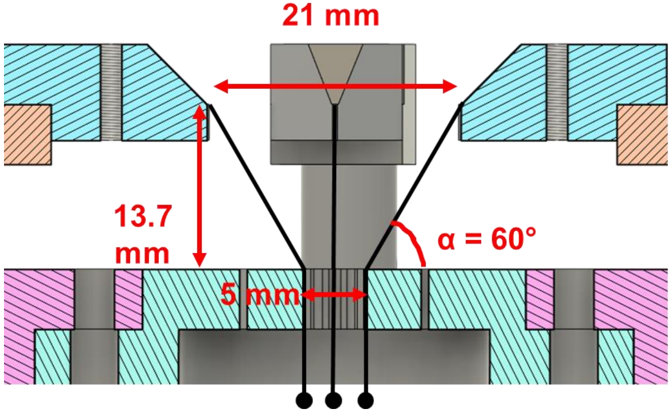


5mm

D. J. Ampleforda, et al., PRL 100, 035001 (2008)

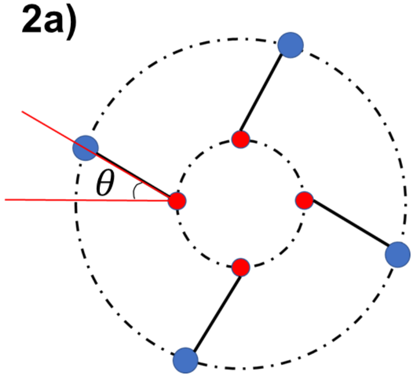
Time-integrated images were not enough to capture the whole stories

- **<u>The angular momentum is conserved:</u> larger initial angular momentum may lead to less compression.**



- **<u>Compression</u>: the magnetic field in the φ direction provides the $\vec{J} \times \vec{B}$ force to compress the plasma jet.**

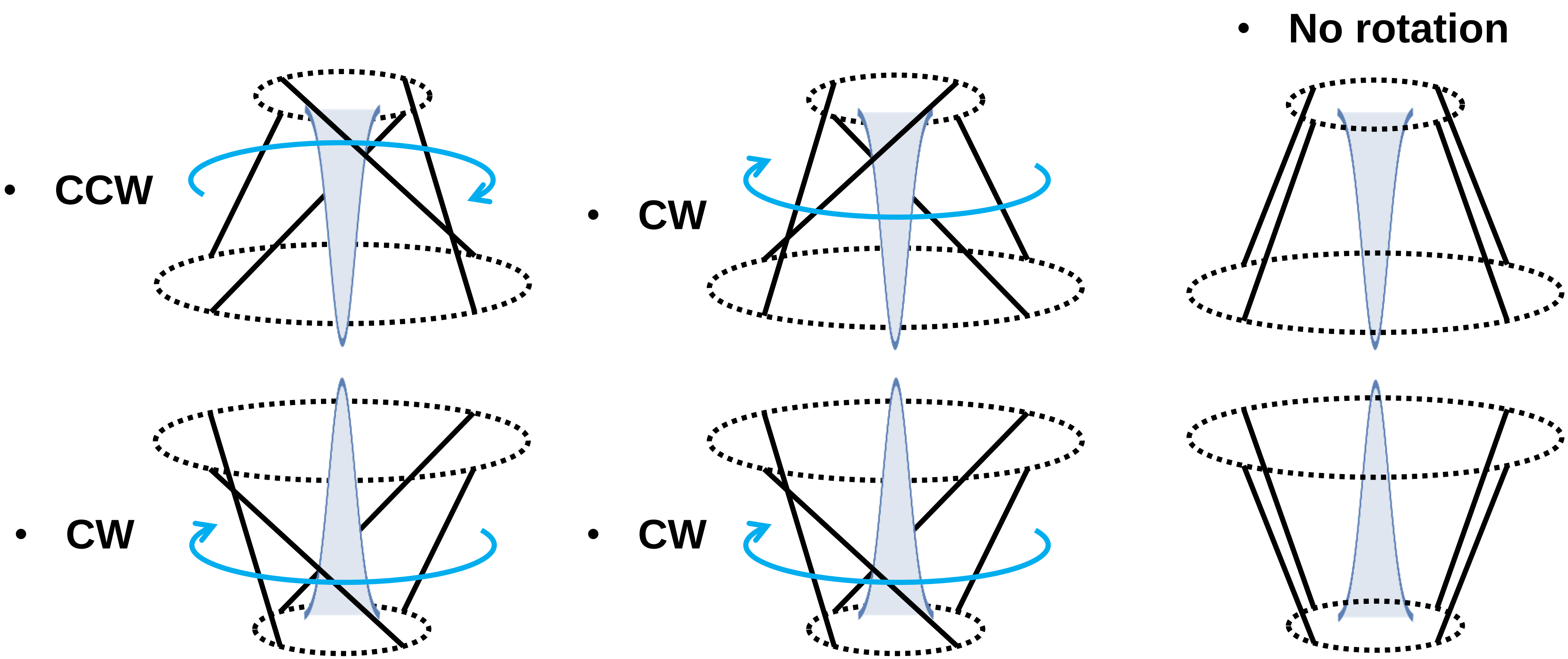
- **<u>Heat conduction suppression</u>: the magnetic field in the z-direction may inhibit the thermal conduction losses. The temperature of the plasma jet may be higher leading to a brighter emission.**



- **<u>Radiation</u>: depends on temperature and density.**

- **The time-resolved densities, temperatures, and magnetic fields of the plasma jets need to be measured.**

Can the angular momentum be cancelled out through collisions?



Neutral beam source

- Neutral beam injection for heating plasma in Tokamak
  - Jure Maglica, Seminar at University in Ljubljana
  - Ian G. Brown, The Physics and Technology of Ion Sources

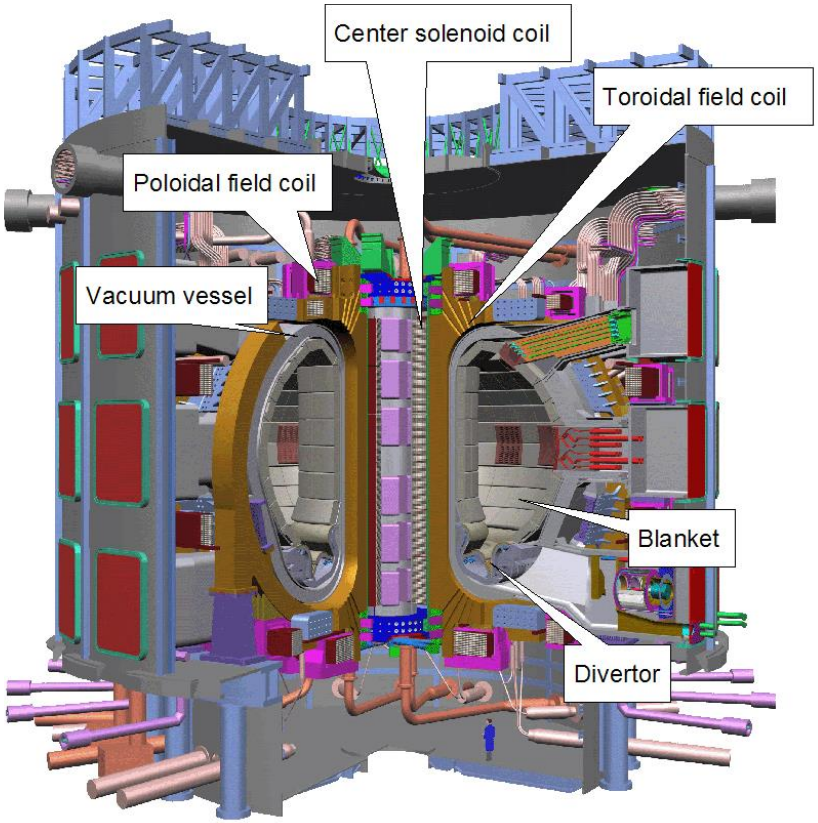
- Electric propulsion (plasma thrusters)
  - D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters

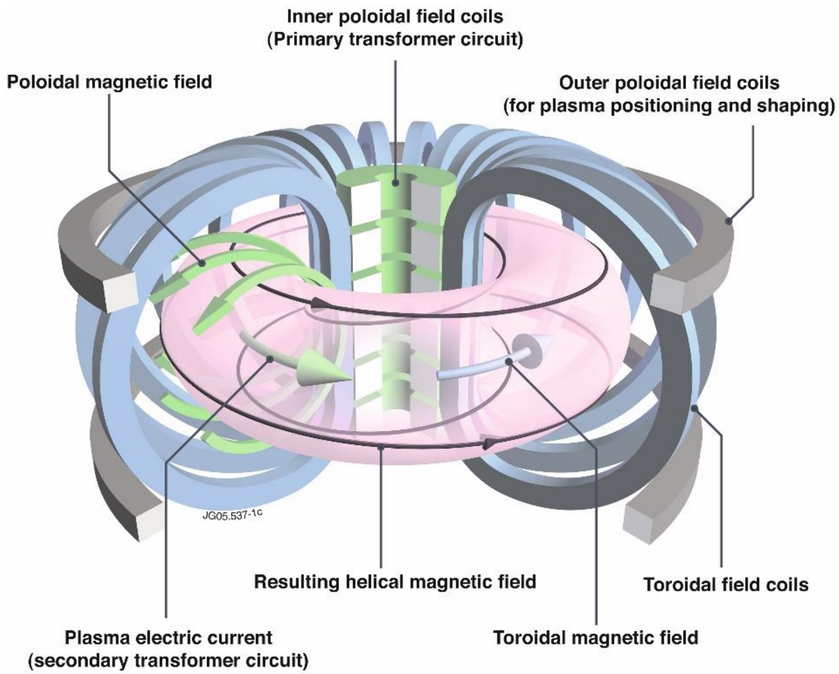
Neutral beam source

- **Neutral beam injection for heating plasma in Tokamak**
  - **Jure Maglica, Seminar at University in Ljubljana**
  - **Ian G. Brown, The Physics and Technology of Ion Sources**

- **Electric propulsion (plasma thrusters)**
  - **D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters**

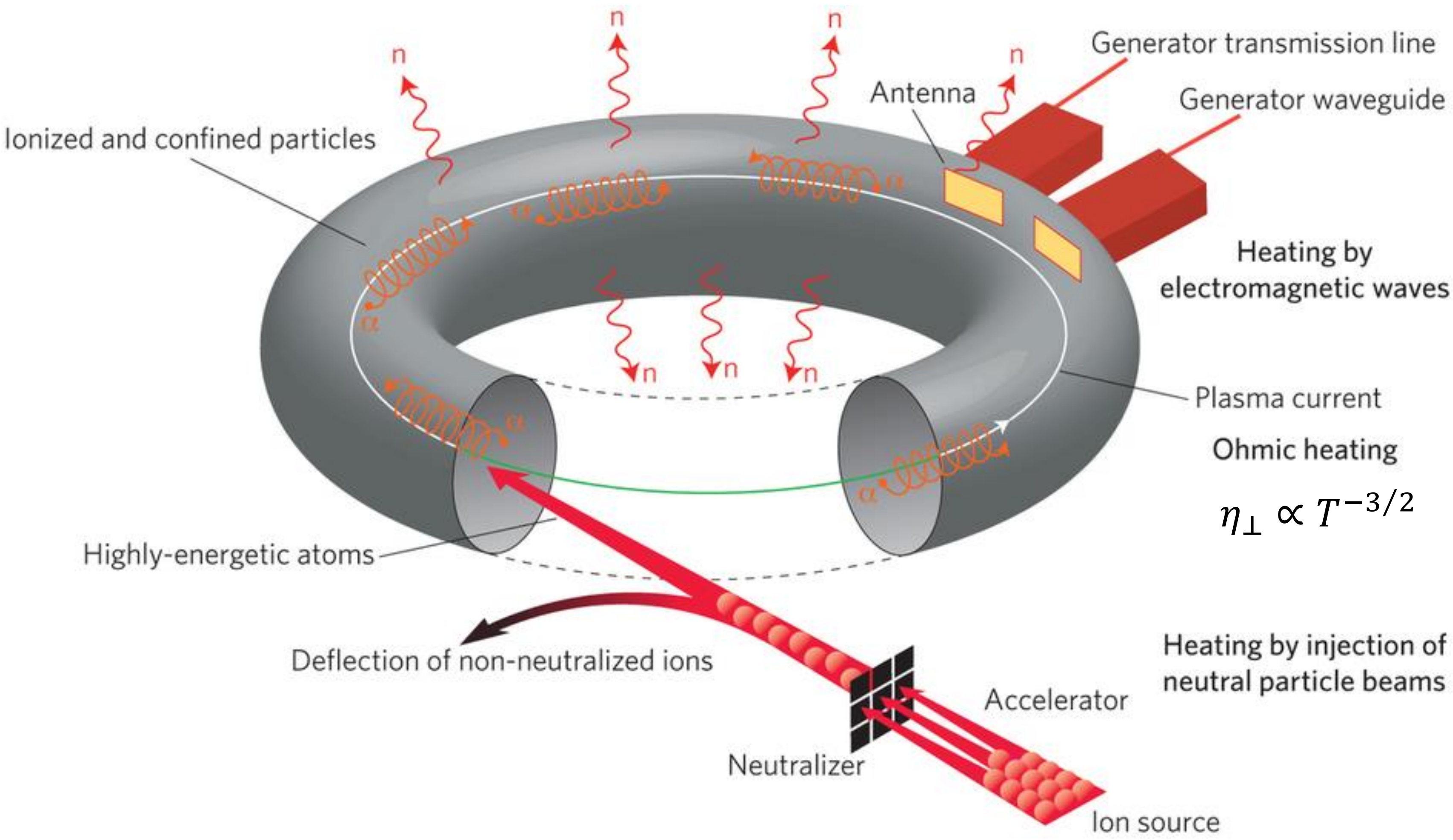
Hot plasma is confined by the magnetic field in magnetic confinement fusion





http://www.dailykos.com/story/2010/5/24/869588/-
https://www.euro-fusion.org/jet/

Neutral beam injector is one of the main heat mechanisms in MCF



$$\eta_{\perp} \propto T^{-3/2}$$

D. Mazon, etc., NATURE PHYSICS, 12, 14, 2016

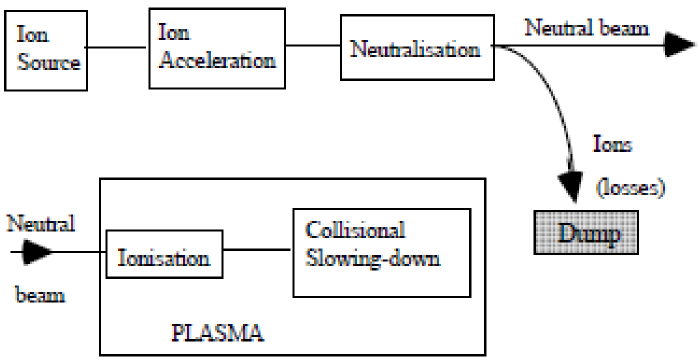
Varies way of heating a MCF device

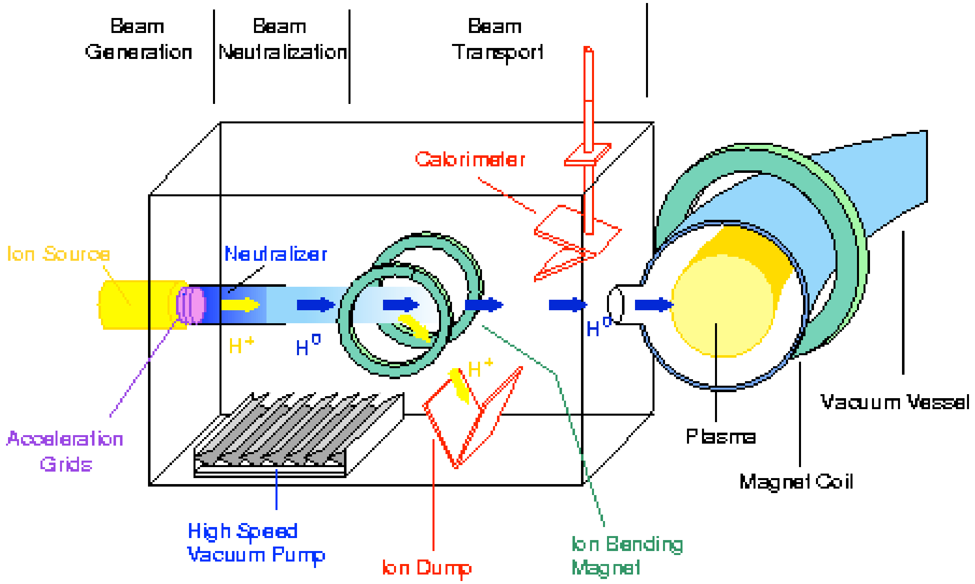
System		Frequency/ energy	Maximum power coupled to plasma	Overall system efficiency	Development/ demonstration required	Remarks
ECRF	Demonstrated in tokamaks	28–157 GHz	2.8 MW, 0.2 s	30–40%	Power sources and windows, off-axis CD	Provides off-axis CD
	ITER needs	150–170 GHz	50 MW, S S			
ICRF	Demonstrated in tokamaks	25–120 MHz	22 MW, 3 s (L-mode); 16.5 MW, 3 s (H-mode)	50–60%	ELM tolerant system	Provides ion heating and smaller ELMs
	ITER needs	40–75 MHz	50 MW, S S			
LHRF	Demonstrated in tokamaks	1.3–8 GHz	2.5 MW, 120 s; 10 MW, 0.5 s	45–55%	Launcher, coupling to H-mode	Provides off-axis CD
	ITER needs	5 GHz	50 MW, S S			
NBI +ve ion	Demonstrated in tokamaks	80–140 keV	40 MW, 2 s; 20 MW, 8 s	35–45%	None	Not applicable
	ITER needs	None	None			
NBI −ve ion	Demonstrated in tokamaks	0.35 MeV	5.2 MW, D^-, 0.8 s (from 2 sources)			
	ITER needs	1 MeV	50 MW, S S	∼37%	System, tests on tokamak, plasma CD	provides rotation

'S S' indicates steady state

Nuclear Fusion, 39, 2495, 1999

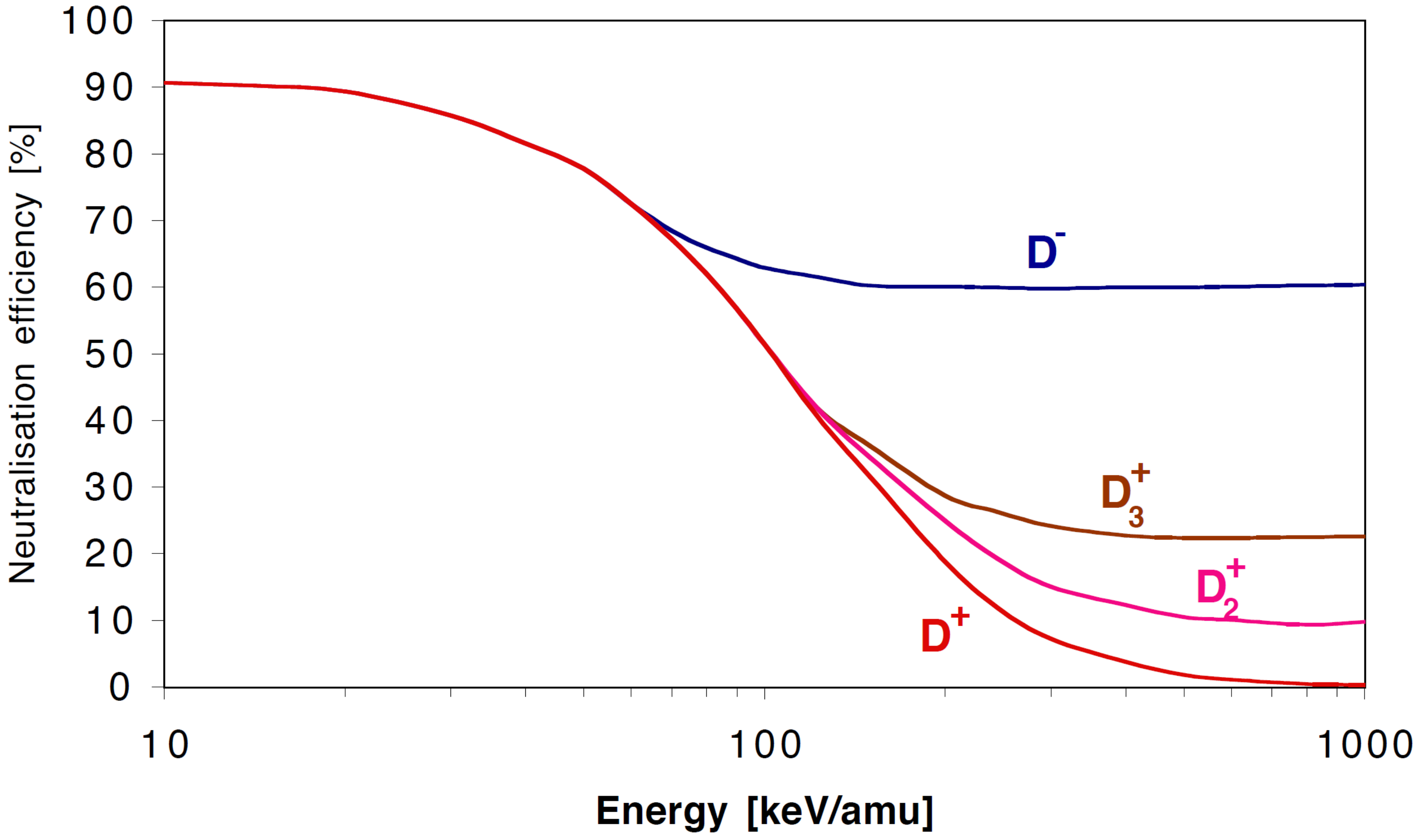
Neutral particles heat the plasma via coulomb collisions





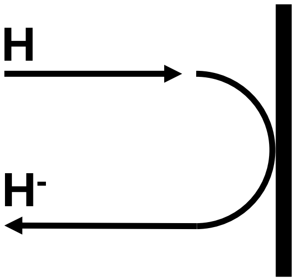
1. create energetic (fast) neutral ions
2. ionize the neutral particles
3. heat the plasma (electrons and ions) via Coulomb collisions

Negative ion source is preferred due to higher neutralization efficiency



There are two ways to make negative ions – surface and volume production

- **Surface production, depends on :**
  - **Work function Φ**
  - **Electron affinity level, 0.75 eV for H⁻**
  - **Perpendicular velocity**
  - **Work function can be reduced by covering the metal surface with cesium**



$$H + e^- \longrightarrow H^-$$

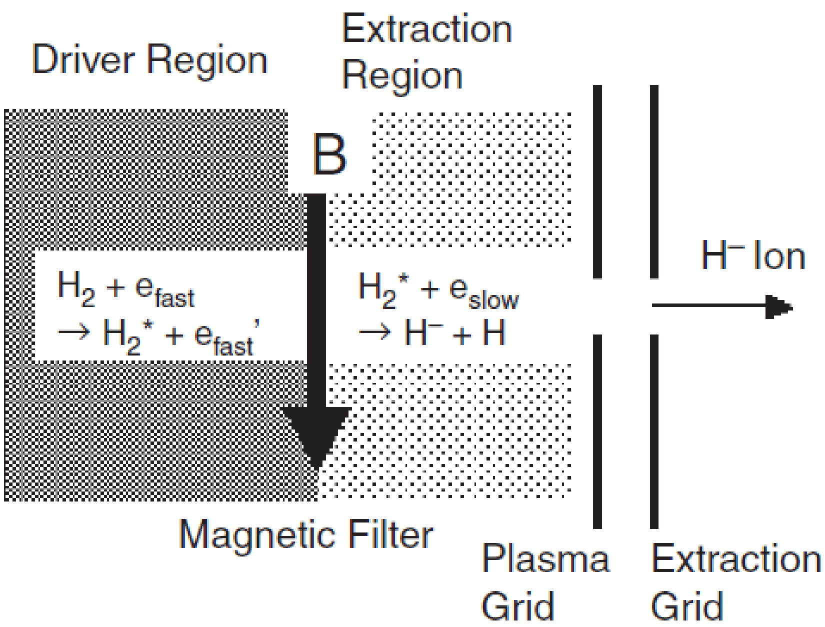
$$H^+ + 2e^- \longrightarrow H^-$$

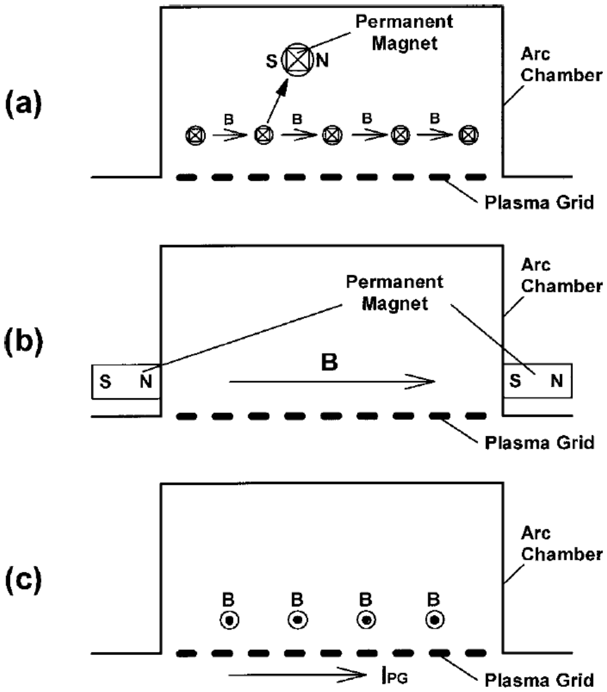
- **Volume production:**

$$H_2 + e_{fast}(>20\ \text{eV}) \rightarrow H_2^*(\text{excited state}) + e_{fast},$$

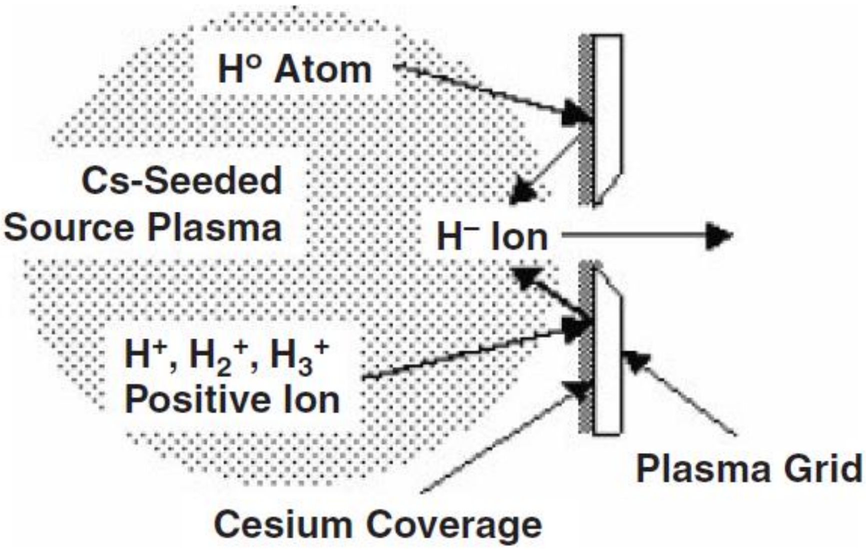
$$H_2^*(\text{excited state}) + e_{slow}(\approx 1\ \text{eV}) \rightarrow H^- + H.$$

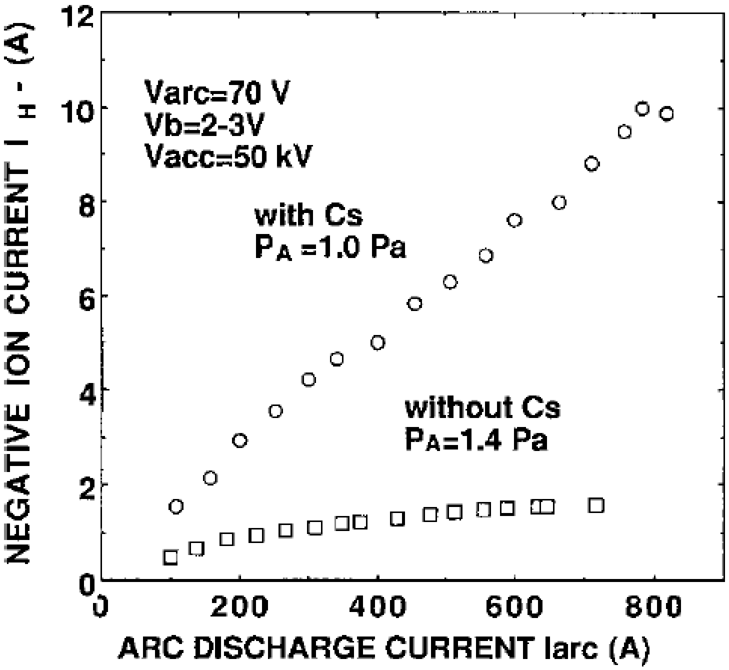
Two-chamber method of negative ions in volume production with a magnetic filter



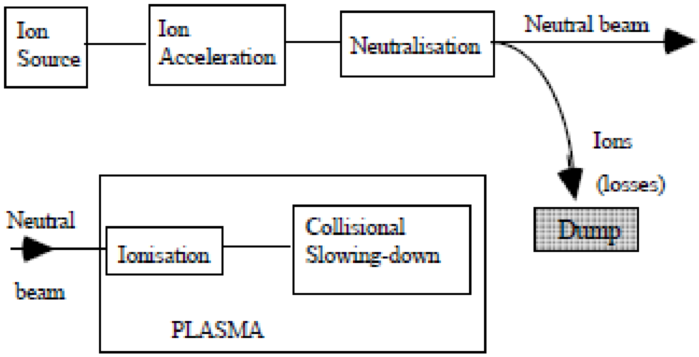


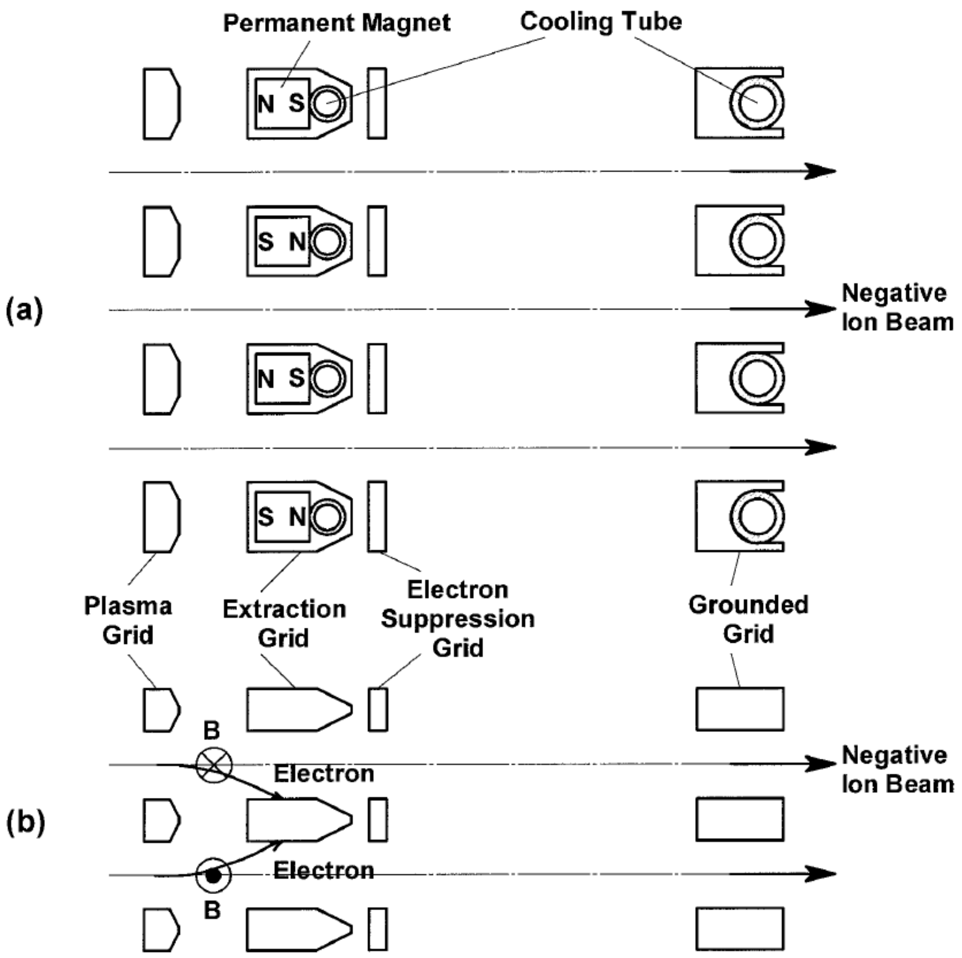
Adding cesium increases negative ion current





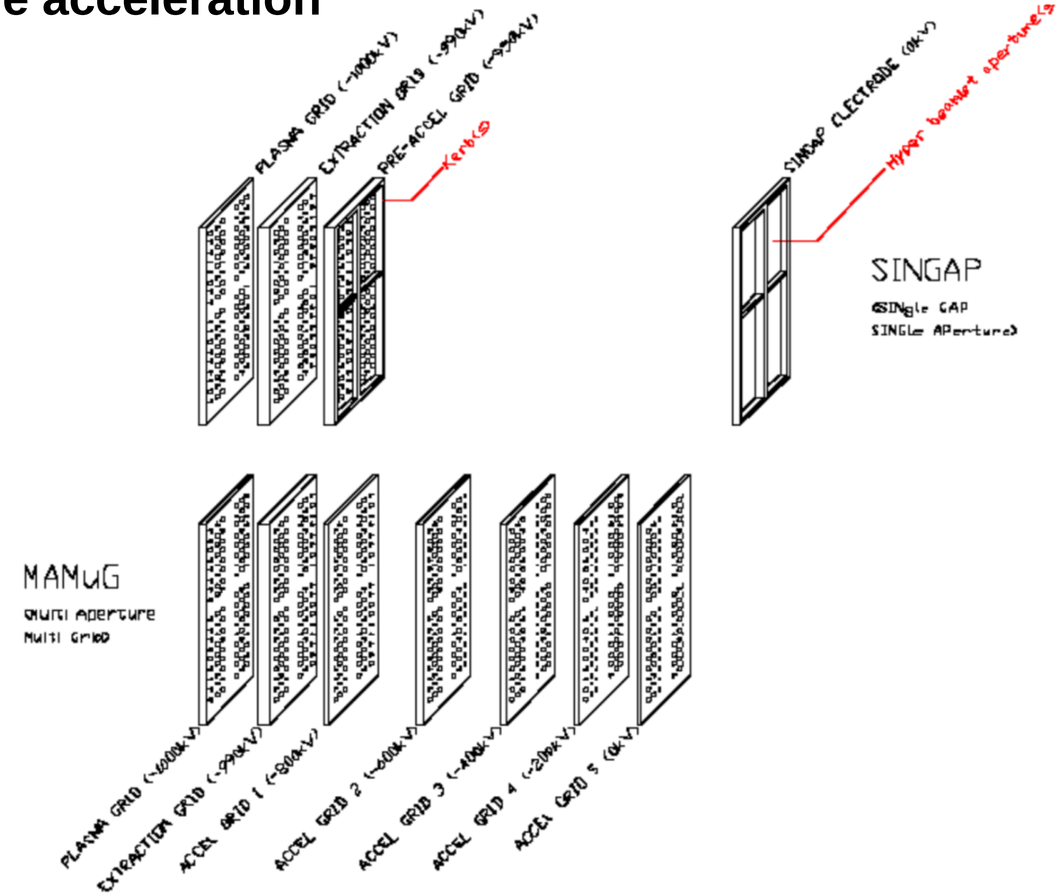
Electrons need to be filtered out since they are extracted together with negative ions





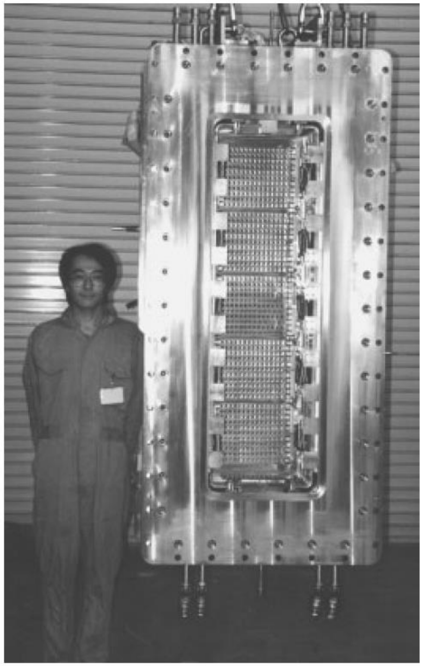
Acceleration

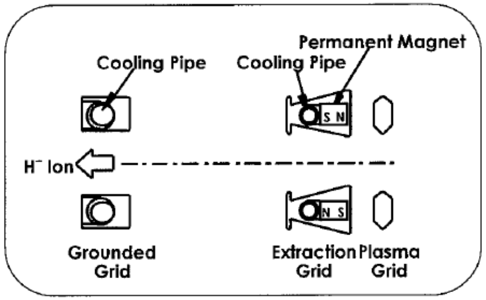
- **Multi-stage acceleration**
- **Single-stage acceleration**



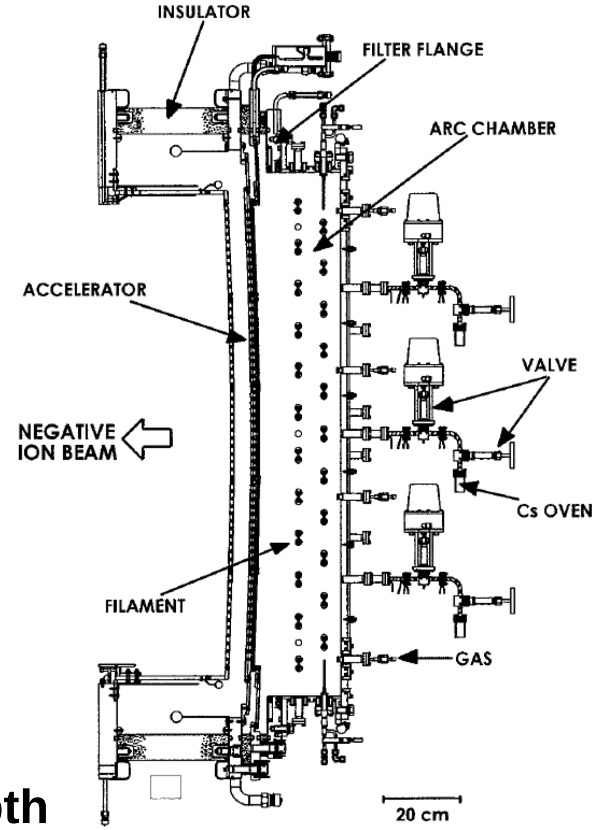
The ITER neutral beam system: status of the project and review of the main technological issues, presented by V. Antoni

NBI system of the LHD fusion machine





Negative Ion Accelerator

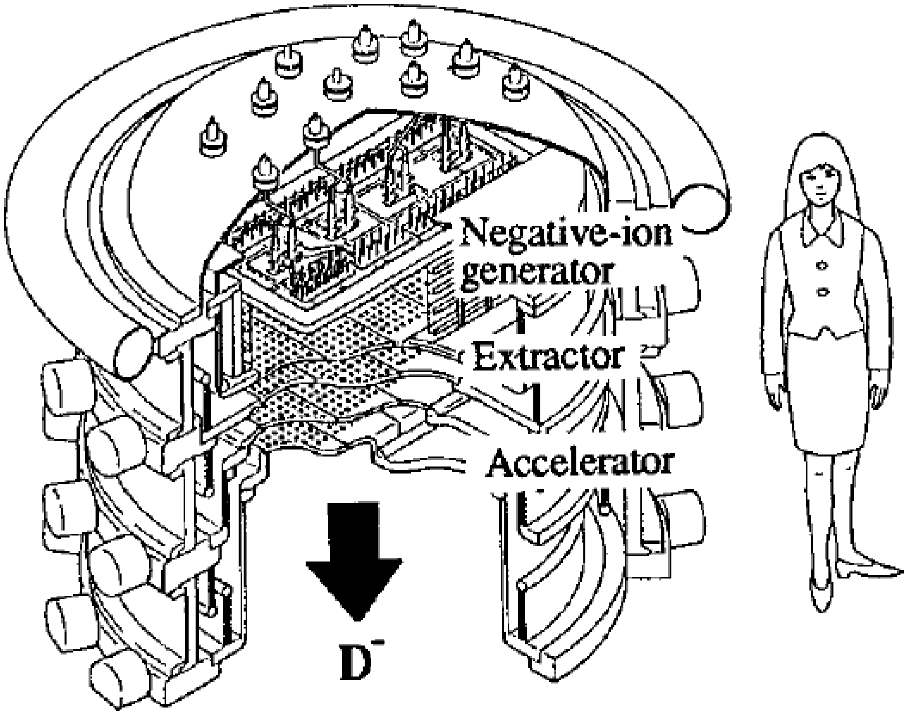


- **180 keV and 30 A**
- **Arc chamber: 35 cm x 145 cm, 21cm in depth**
- **Single stage accelerator**

Y. Takeiri, etc., Nucl. Fusion, 46, S199, 2006

JT60U NBI system

- JT-60 (Japan-Torus) is a tokamak in Japan.
- 550 keV, 22A
- 2m in diameter and 1.7 m in height
- 3-stage accelerator



Neutralization

- **Gas neutralization**
  - **Collisions between fast negative ions and atoms**

$$H^- + H_2 \longrightarrow H + H_2 + e^-$$

  - **Fast ions can lose another electron after neutralized**

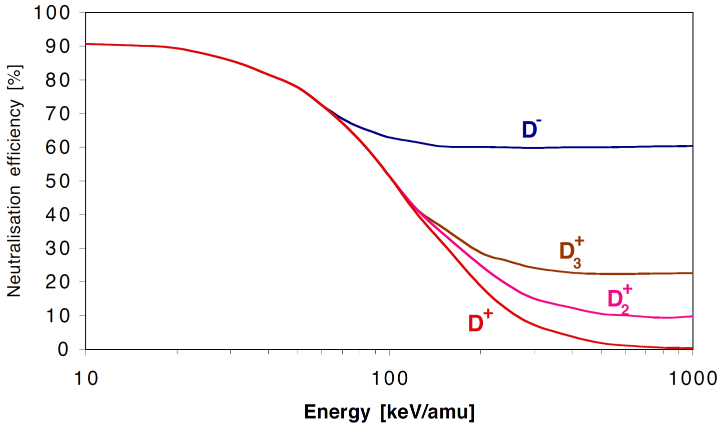
$$H + H_2 \longrightarrow H^+ + H_2 + e^-$$

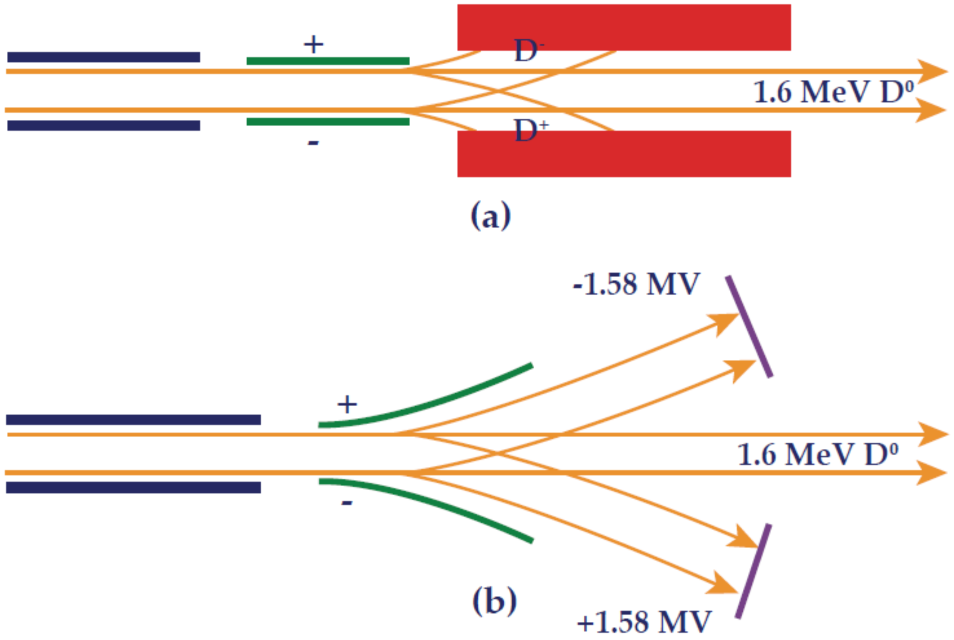
- **Plasma neutralization**
  - **Collisions with charged particles in plasma**

$$H^- + X\left(e, \mathrm{Ar}, H^+, {H_2}^+\right) \longrightarrow H + X + e^-$$

  - **The efficiencies reach up to 85% for fully ionized hydrogen plasma**

Beam dump

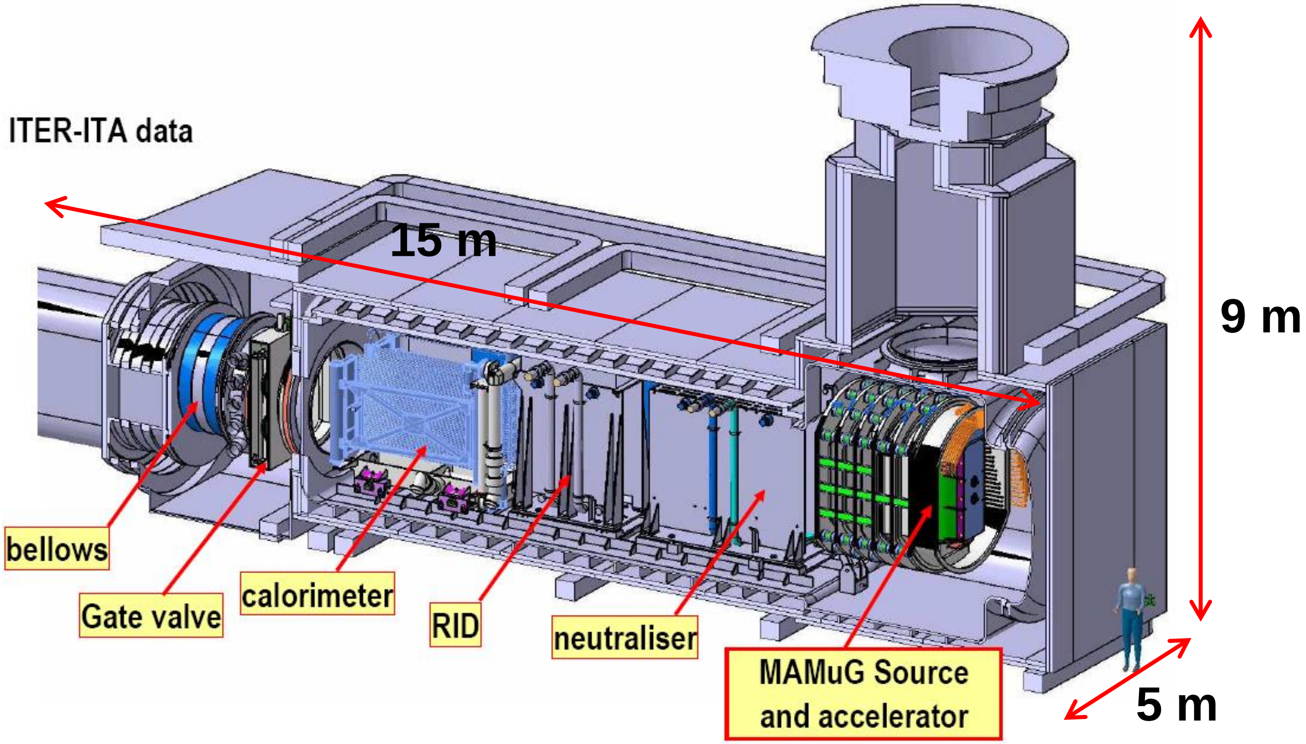




R. W. Moir, Fusion Technology, 25, 129, 1994

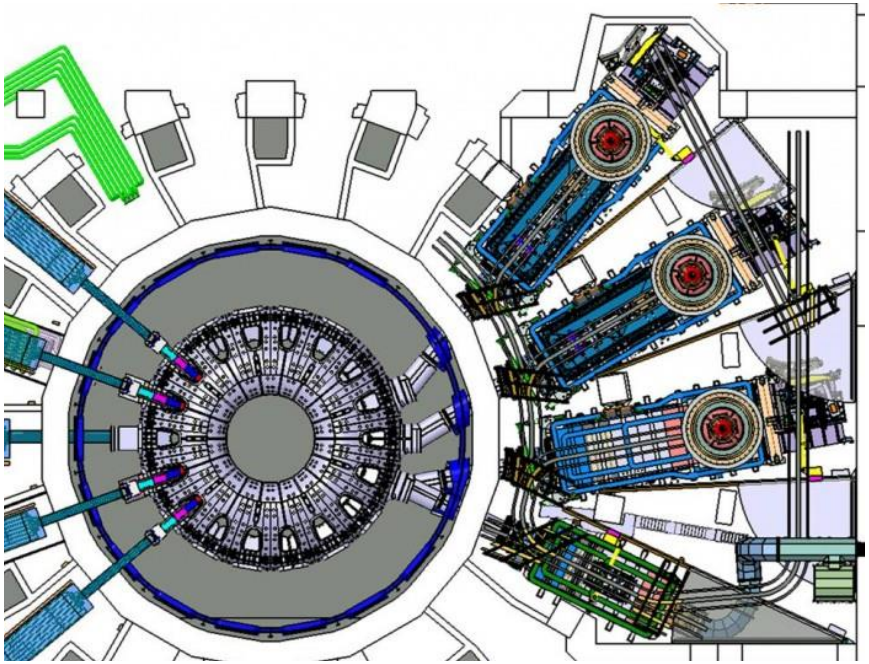
NBI for ITER

- beam components (Ion Source, Accelerator, Neutralizer, Residual Ion Dump and Calorimeter)
- other components (cryo-pump, vessels, fast shutter, duct, magnetic shielding, and residual magnetic field compensating coils)



The ITER neutral beam system: status of the project and review of the main technological issues, presented by V. Antoni

Neutral beam penetration



- **Parallel direction**
  - **Longest path through the densest part of the plasma**
  - **Harder to be built**
- **Perpendicular direction**
  - **Path is short**
  - **Larger perpendicular energies leads to larger losses**
  - **Easier to be built**

https://www.iter.org

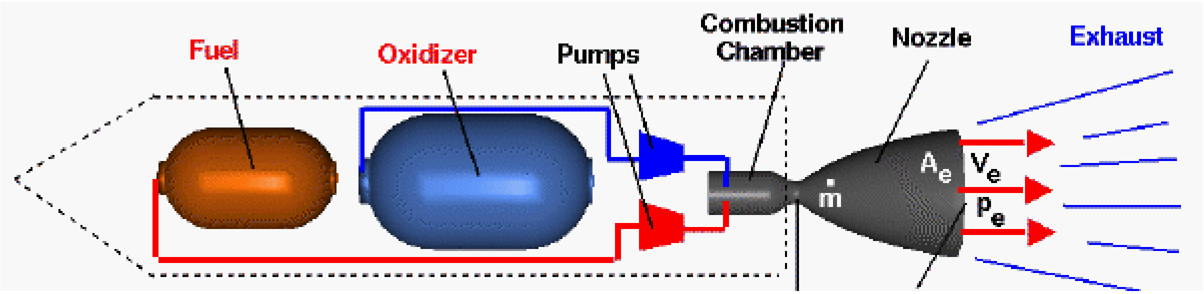
Neutral beam source

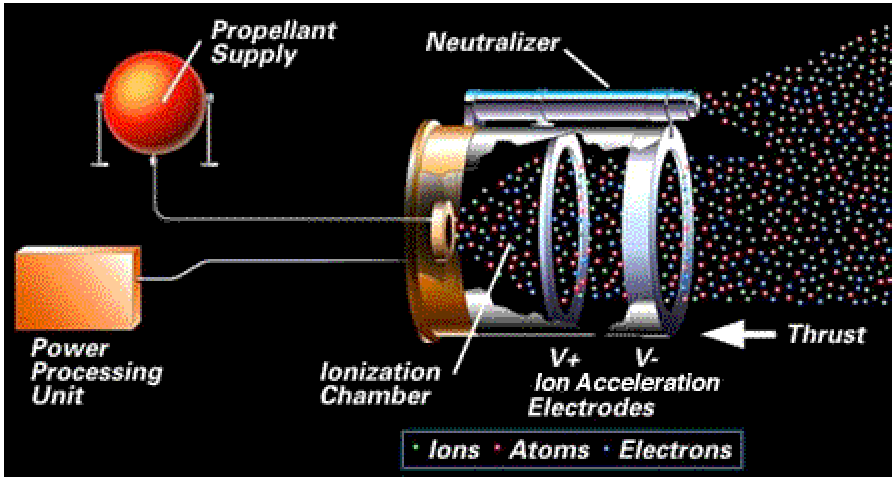
- Neutral beam injection for heating plasma in Tokamak
  - Jure Maglica, Seminar at University in Ljubljana
  - Ian G. Brown, The Physics and Technology of Ion Sources

- **Electric propulsion (plasma thrusters)**
  - **D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters**

Comparison between liquid rockets and ion thrusters

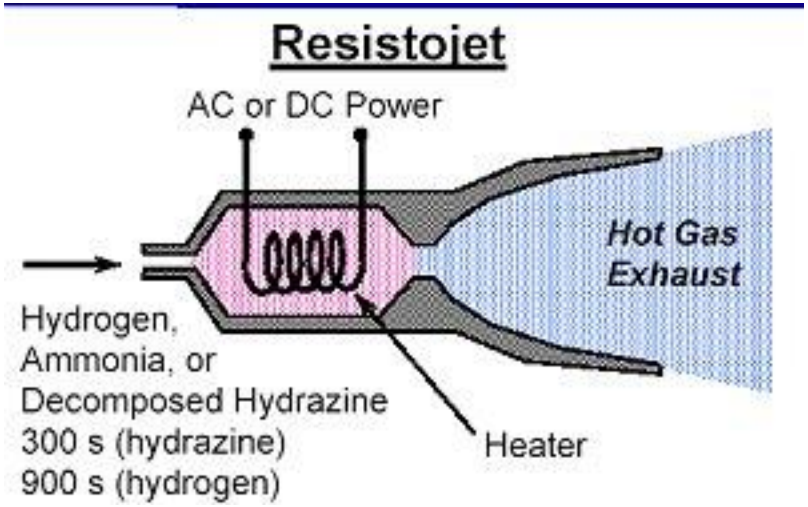
- Liquid rockests
  - u~4500 m/s
  - Isp~450 s
  - Energy ~ 100GJ
  - Power ~ 300MW
  - Thrust ~ 2×10^6 N
- Ion thrusters
  - u~30000 m/s
  - Isp~3000 s
  - Energy ~ 1000GJ
  - Power ~ 1kW
  - Thrust ~ 0.1 N

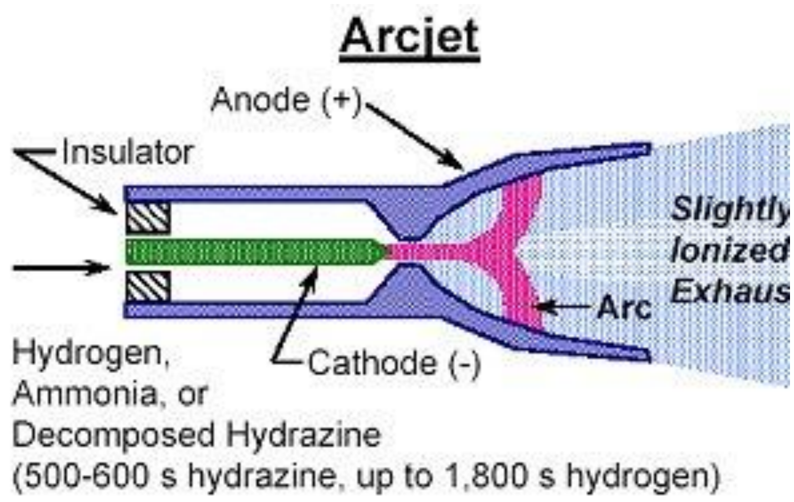




Electric thruster types - electrothermal

- **Resistojet**
- **Arcjet**

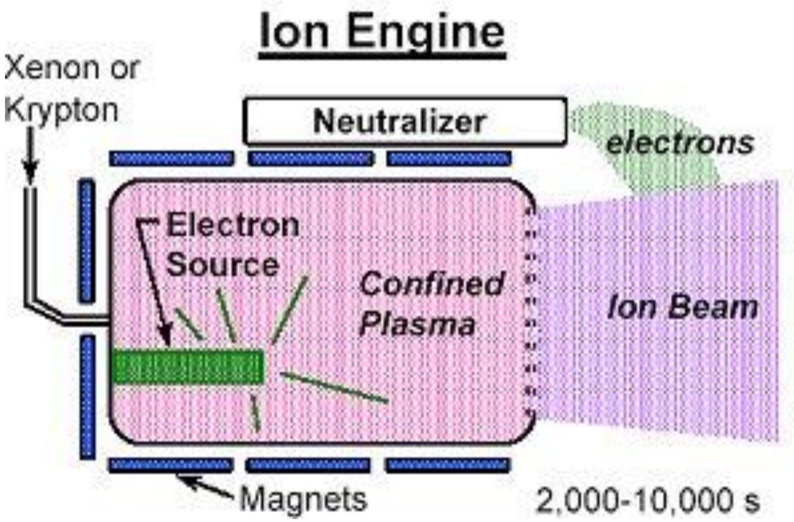




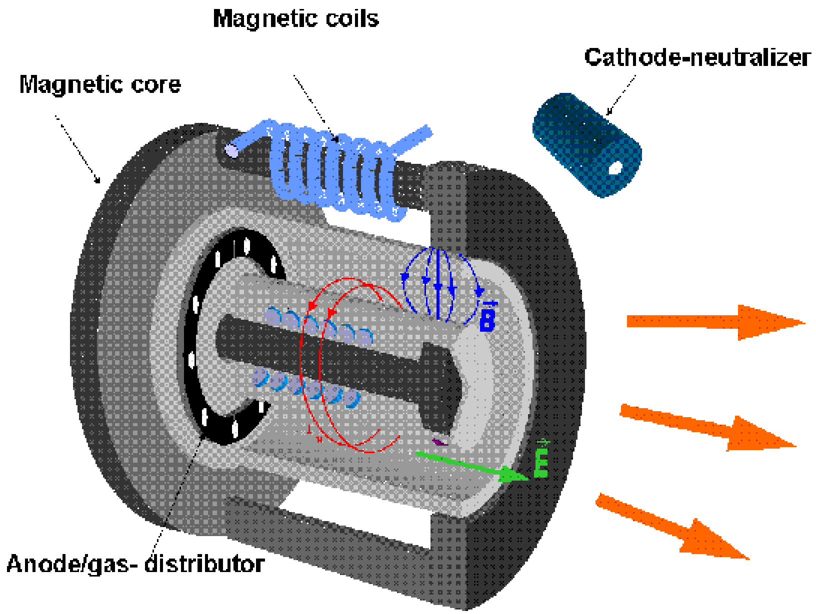
http://pages.erau.edu/~ericksol/courses/sp300/ch5/propul_ch5.html

Electric thruster types - electrostatic

- **Ion thruster**

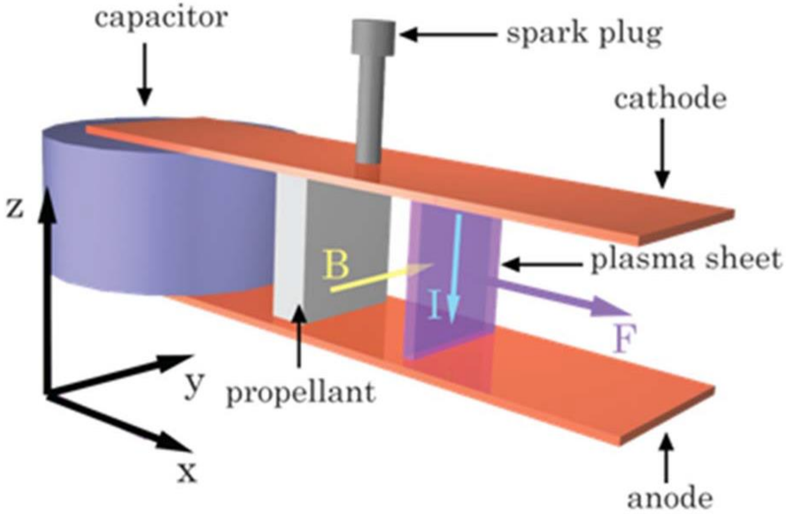


- **Hall thruster**

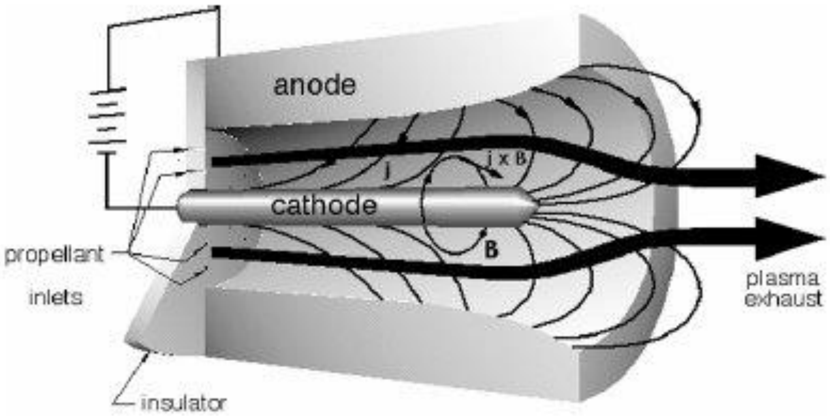


Electric thruster types - Electromagnetic

- **Pulsed plasma thruster**



- **Magnetoplasmadynamic thruster (MPD)**



The thrust in an ion engine is transferred by the electrostatic force between the ions and the two grids

$$\frac{dE(x)}{\mathrm{dx}} = \frac{\rho(x)}{\varepsilon_0} = \frac{\mathrm{qn}_i(x)}{\varepsilon_0}$$

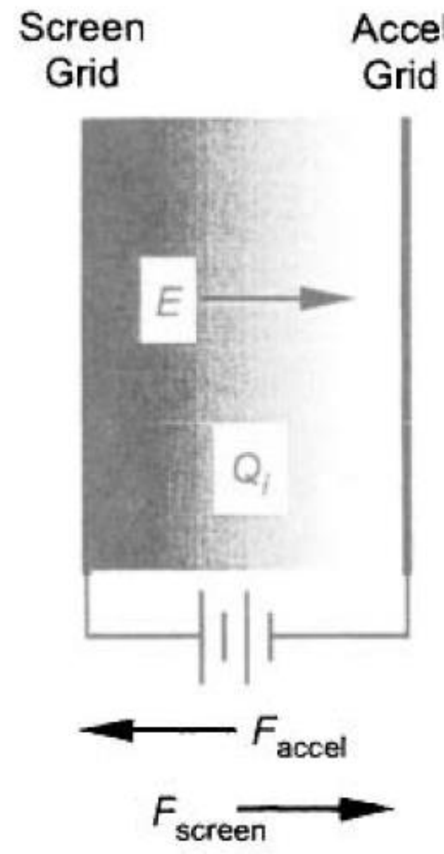
$$E(x) = \frac{q}{\varepsilon_0}\int_0^x n_i(x')\mathrm{dx}' + E_{\mathrm{screen}}$$

Gauss's law: $\sigma = \varepsilon_0 E_{\mathrm{screen}}$

$$F_{\mathrm{screen}} = \sigma\frac{(E_{\mathrm{screen}} + 0)}{2} = \frac{1}{2}\varepsilon_0 E_{\mathrm{screen}}{}^2$$

$$F_{\mathrm{accel}} = -\sigma\frac{(E_{\mathrm{accel}} + 0)}{2} = -\frac{1}{2}\varepsilon_0 E_{\mathrm{accel}}{}^2$$

$$T = F_{\mathrm{screen}} + F_{\mathrm{accel}} = \frac{1}{2}\varepsilon_0(E_{\mathrm{screen}}{}^2 - E_{\mathrm{accel}}{}^2)$$



$$F_{\mathrm{ion}} = q\int_0^d n_i(x)E(x)\mathrm{dx} = \varepsilon_0\int_0^d \frac{dE}{\mathrm{dx}}\mathrm{Edx} == \frac{1}{2}\varepsilon_0(E_{\mathrm{accel}}{}^2 - E_{\mathrm{screen}}{}^2)$$

The rocket equation

$$\text{Force} = T = M\frac{\mathrm{dv}}{\mathrm{dt}}$$

$$T = -\frac{d}{\mathrm{dt}}(m_p v_{\mathrm{ex}}) = -v_{\mathrm{ex}}\frac{\mathrm{dm}_p}{\mathrm{dt}}$$

$$M(t) = m_d + m_p$$

$$\frac{dM}{\mathrm{dt}} = \frac{\mathrm{dm}_p}{\mathrm{dt}}$$

$$M\frac{\mathrm{dv}}{\mathrm{dt}} = -v_{\mathrm{ex}}\frac{\mathrm{dM}}{\mathrm{dt}}$$

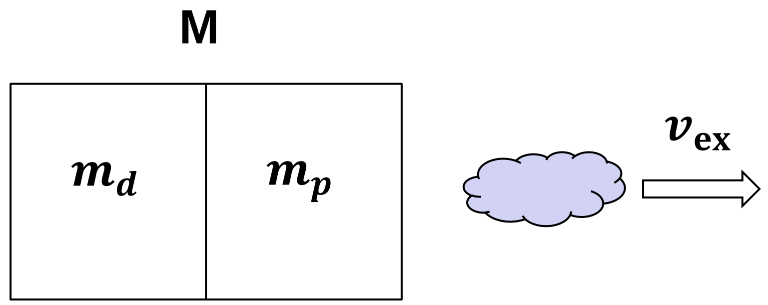
$$\int_{v_i}^{v_f}\mathrm{dv} = -v_{\mathrm{ex}}\int_{m_d+m_p}^{m_d}\frac{\mathrm{dM}}{M}$$

$$v_f - v_i = \Delta\mathrm{v} = -v_{\mathrm{ex}}\ln\left(\frac{m_d}{m_d+m_p}\right)$$

$$m_d = (m_d + m_p)e^{-\Delta\mathrm{v}/v_{\mathrm{ex}}}$$

$$\Delta\mathrm{v} = (\mathrm{Isp}\times g)\ln\left(\frac{m_d+m_p}{m_d}\right)$$

$$\begin{aligned} m_p &= m_d\left[e^{\Delta\mathrm{v}/v_{\mathrm{ex}}} - 1\right] \\ &= m_d\left[e^{\Delta\mathrm{v}/(\mathrm{Isp}\times g)} - 1\right] \end{aligned}$$



Force transfer

$$T = -\frac{d}{\mathrm{dt}}(m_p v_{\mathrm{ex}}) = -v_{\mathrm{ex}}\frac{\mathrm{dm}_p}{\mathrm{dt}} = \dot{m}_p v_{ex}$$

$$\dot{m}_p = \mathrm{QM}$$

$\dot{m}_p$ = propellant mass flow rate in kg/s

Q = propellant particle flow rate in particles/s

M = atomic mass in kg

$$P_{\mathrm{jet}} = \frac{1}{2}\dot{m}_p {v_{\mathrm{ex}}}^2 = \frac{T^2}{2\dot{m}_p}$$

$$T = \frac{\mathrm{dm}_p}{\mathrm{dt}} v_{\mathrm{ex}} \approx \dot{m}_i v_i$$

$\dot{m}_i$ = ion mass flow rate in kg/s

I_b = ion current

$$v_i = \sqrt{\frac{2\mathrm{qV}_b}{M}}$$

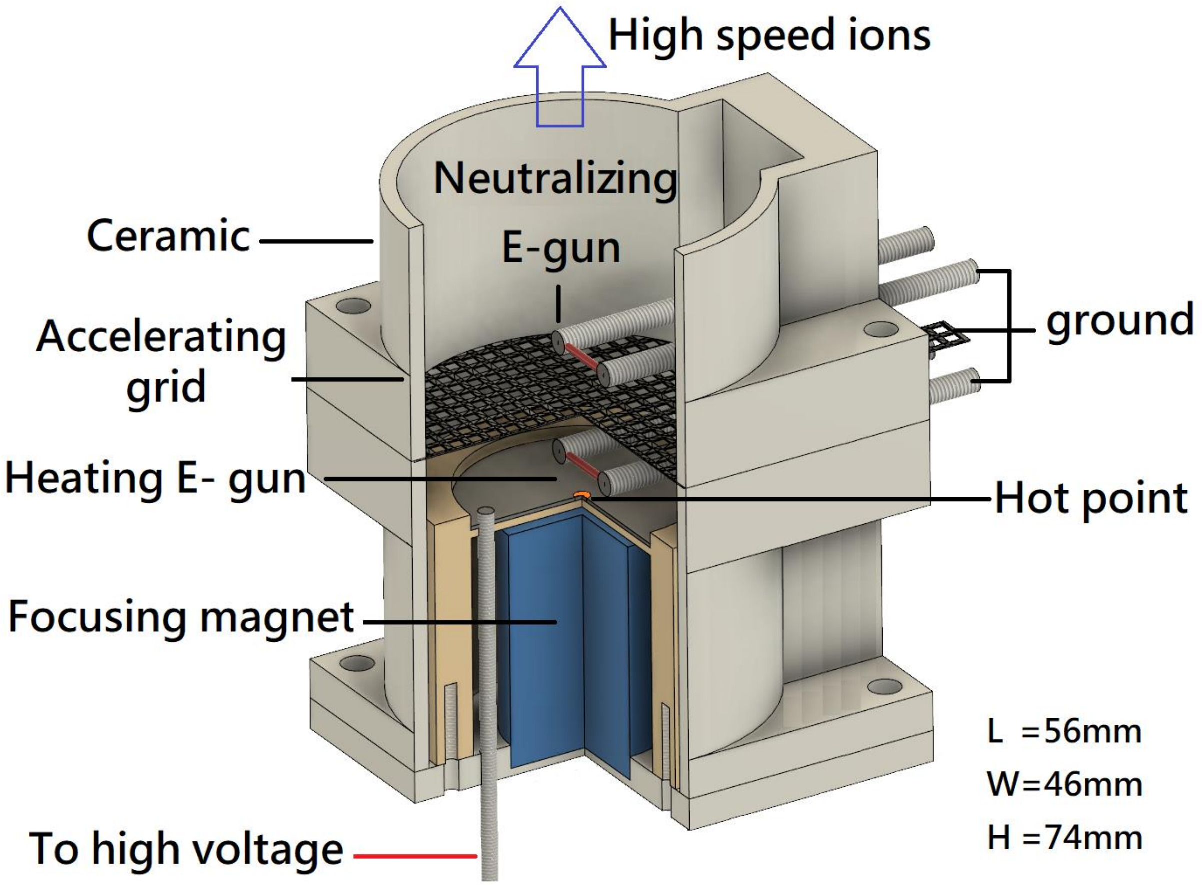
$$\dot{m}_i = \frac{I_b M}{q}$$

$$T = \sqrt{\frac{2M}{e}} I_b \sqrt{V_b}\ (\mathrm{Nt})$$

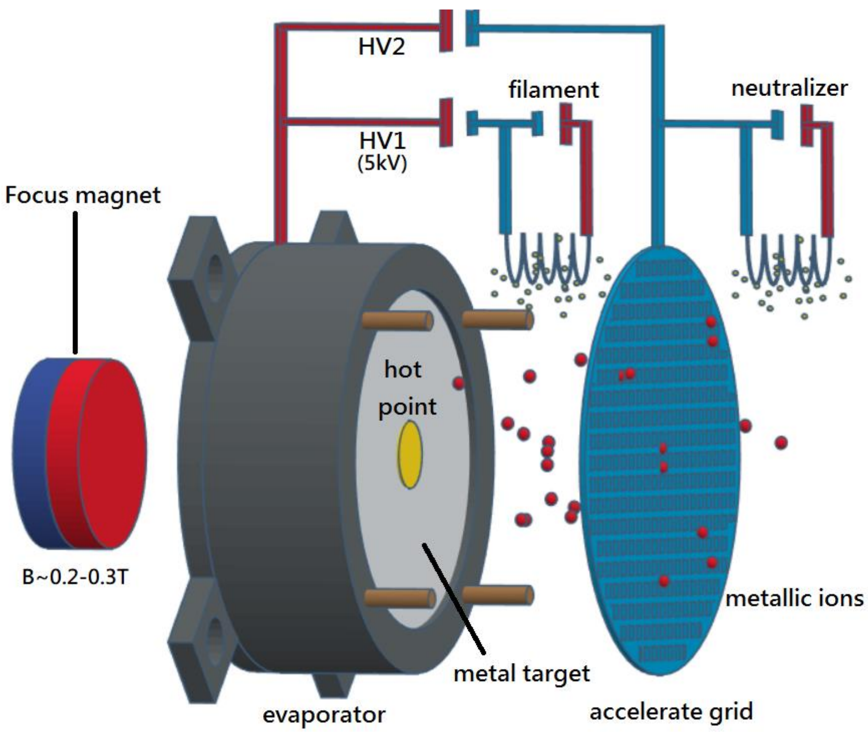
Ion thruster has the highest specific impulse (Isp)

Thruster	Specific Impulse (s)	Input Power (kW)	Efficiency Range (%)	Propellant
Cold gas	50–75	—	—	Various
Chemical (monopropellant)	150–225	—	—	N_2H_4 H_2O_2
Chemical (bipropellant)	300–450	—	—	Various
Resistojet	300	0.5–1	65–90	N_2H_4 monoprop
Arcjet	500–600	0.9–2.2	25–45	N_2H_4 monoprop
Ion thruster	2500–3600	0.4–4.3	40–80	Xenon
Hall thrusters	1500–2000	1.5–4.5	35–60	Xenon
PPTs	850–1200	<0.2	7–13	Teflon

Metallic Ion Thruster Using Magnetron E-Beam Bombardment (MIT-MEB)



Electrons are used to generate metallic gas, metallic plasma and to neutralize ions



heating → filament

filament → Thermal electron → target → vapor → plasma → exhaust

external electric field: Thermal electron → target

evaporated: target → vapor

electron bombardment: vapor → plasma

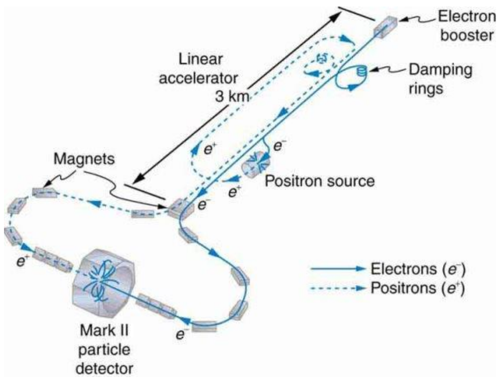
ionized: vapor → plasma

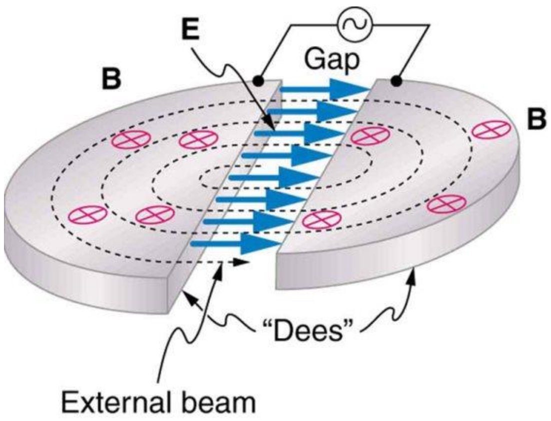
accelerated electric field: plasma → exhaust

neutralizer → exhaust

High energy particle accelerator

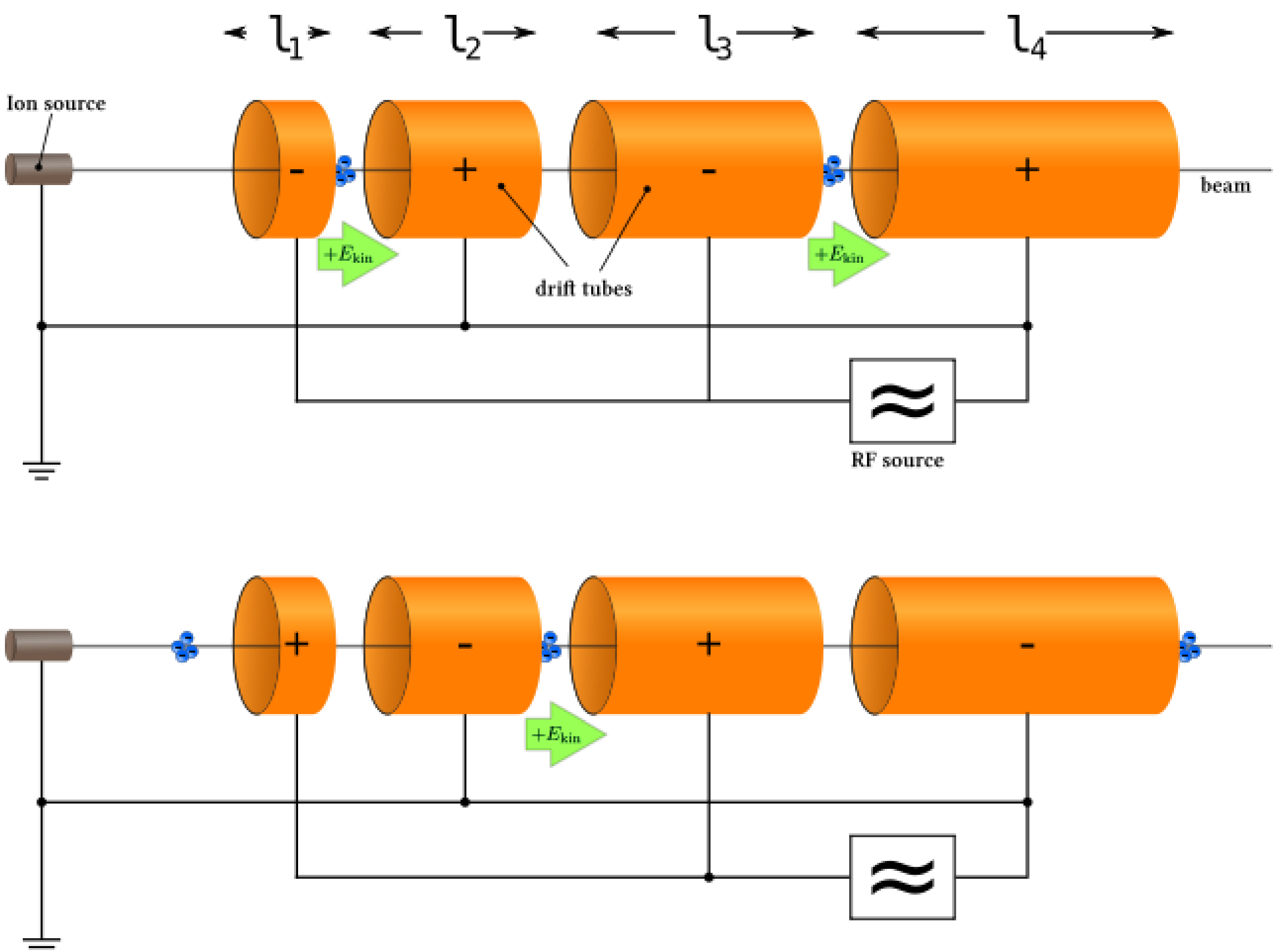
- **linear particle accelerator (Linac)**
- **Cyclotron**
- **Synchrotron**





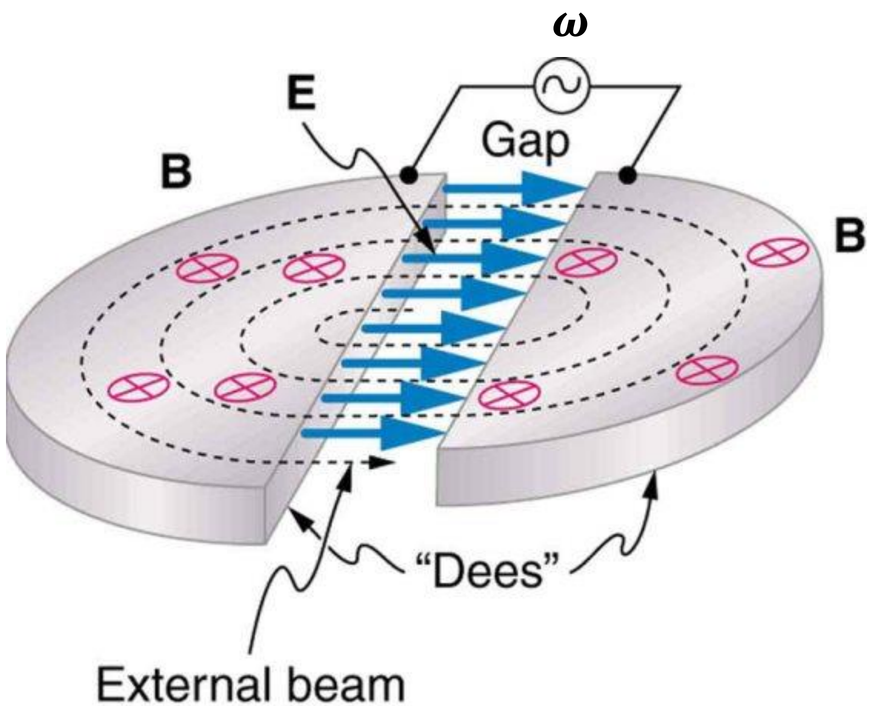
- **Reference: Introduction to plasma phenomena and plasma medicine, Y. Nishida and K.-L. Ou**

A linear particle accelerator (linac) accelerates charged particles using a series of oscillating electric potentials along a linear beamline



https://en.wikipedia.org/wiki/Linear_particle_accelerator

Cyclotrons use a magnetic field to cause particles to move in circular orbits



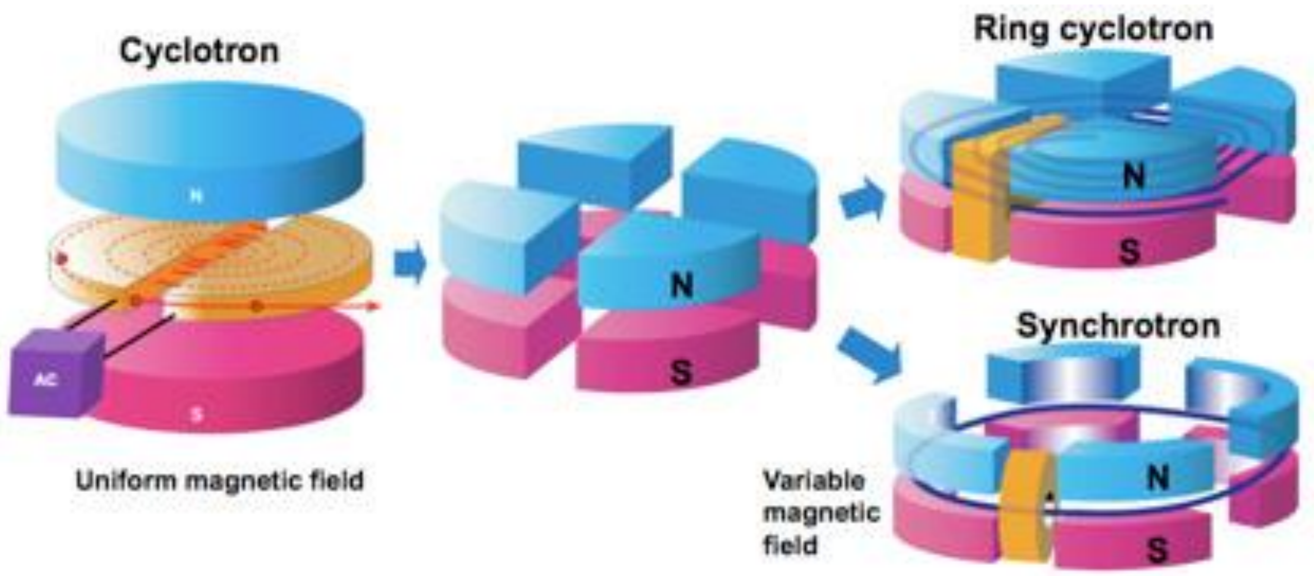
$$\omega_{\mathrm{ce}} = \frac{eB}{m_e c}$$

$$r_e = \frac{v}{\omega_{\mathrm{ce}}} = \frac{m_e c v}{eB}$$

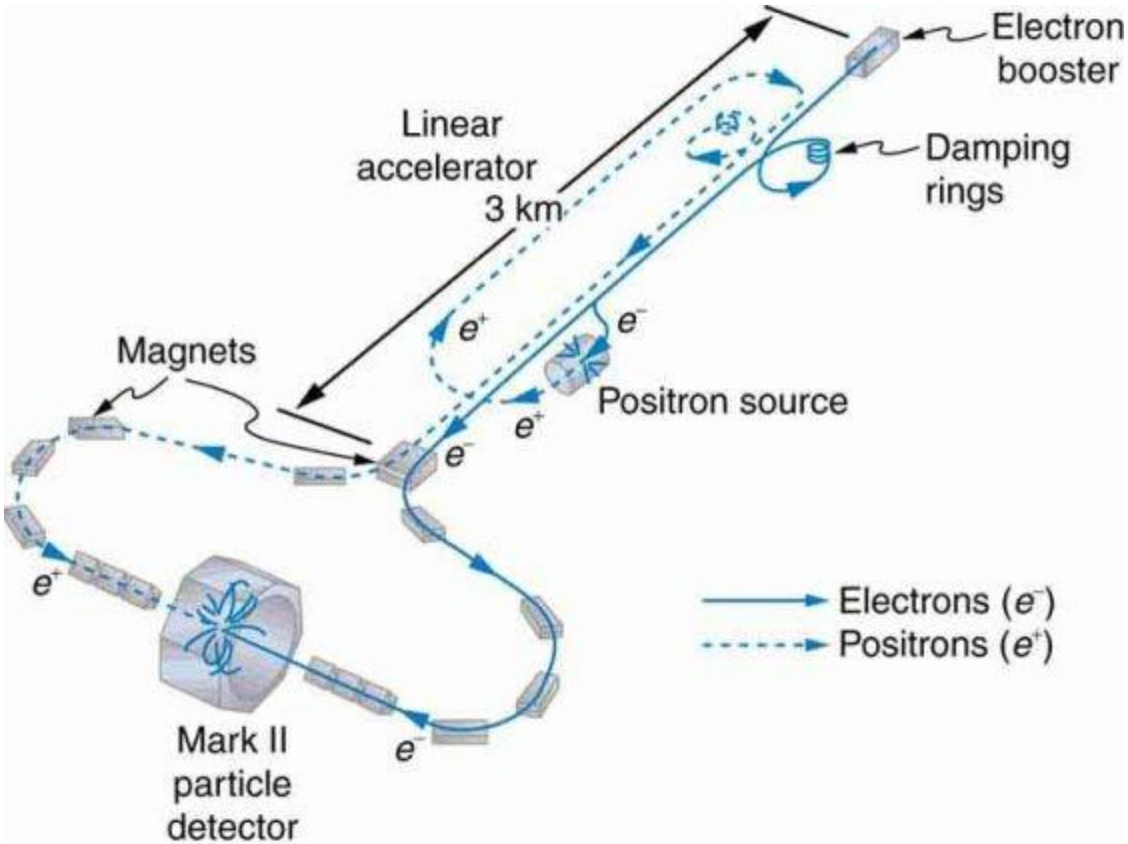
- **Cyclotron was invented by Ernest Lawrence who earned the 1939 Nobel price in physics**

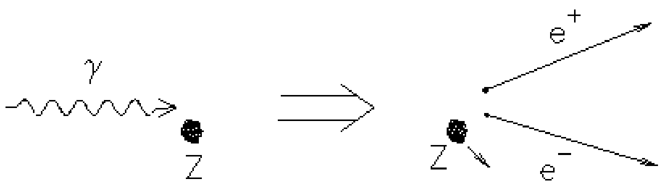
http://math.ubooks.pub/Books/ON/M1/1704/C33S4M004.html

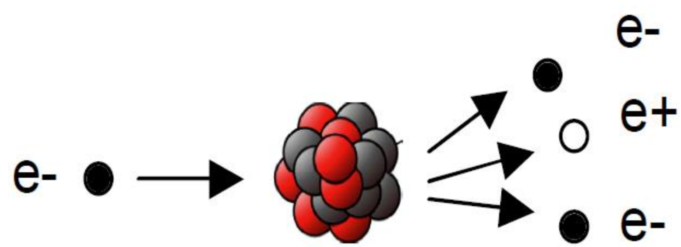
Synchrotron uses time-dependent guiding magnetic field synchronized to a particle beam



Stanford linear accelerator center (SLAC) is a 50 GeV electron / positron accelerator

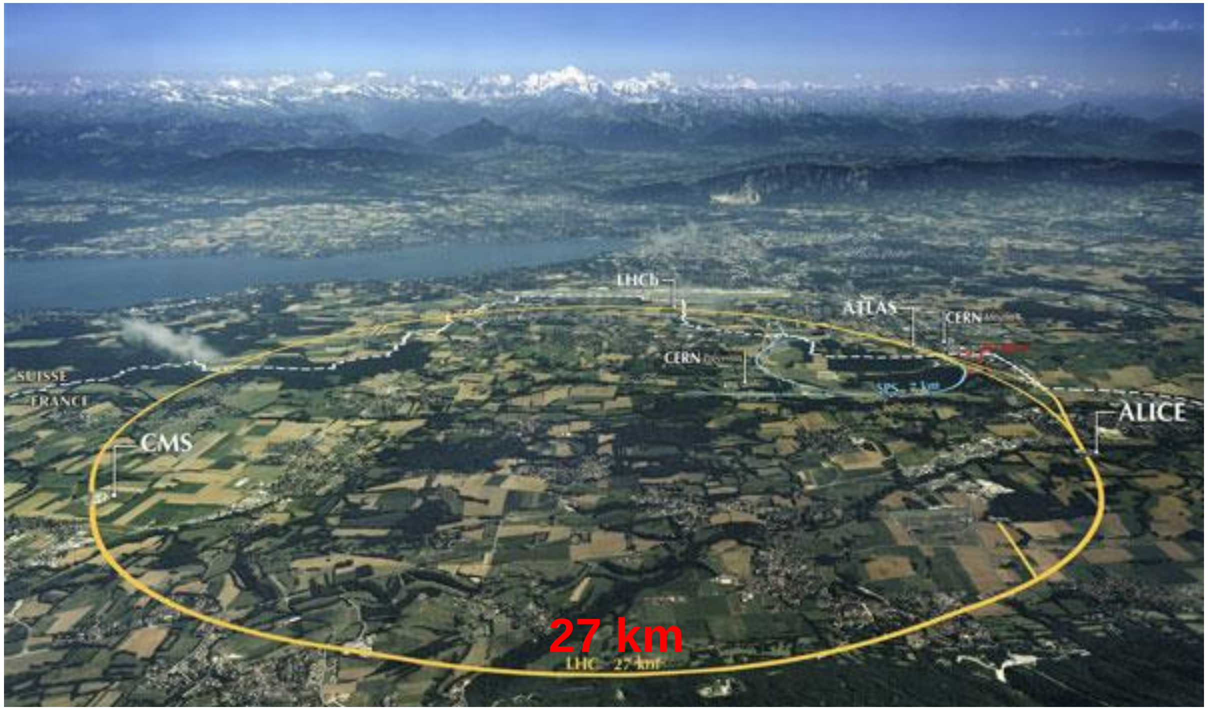






http://cnx.org/contents/aypTUEkP@4/Accelerators-Create-Matter-fro
https://upload.wikimedia.org/wikipedia/commons/6/64/Pair_production_Cartoon.gif

Large Hadron Collider (LHC) is the world's largest and most powerful particle collider providing 13 TeV protons



http://www.coepp.org.au/large-hadron-collider

Plasma based accelerators will become 3 orders smaller than the regular microwave based accelerator

- **Maximum field strength:**
  - **Microwave: 100 MV/m**
  - **Plasma: >10 GV/m, 300 GV/m was achieved using laser wakefield accelerator[1]**

- **Plasma based high energy accelerators:**
  - **V_pxB or surfatron accelerator[2]**
  - **Plasma wakefield accelerator (PWFA)[3]**
  - **Plasma beat wave accelerator (PBWA)[4]**
  - **Laser wakefield accelerator (LWFA)[4]**

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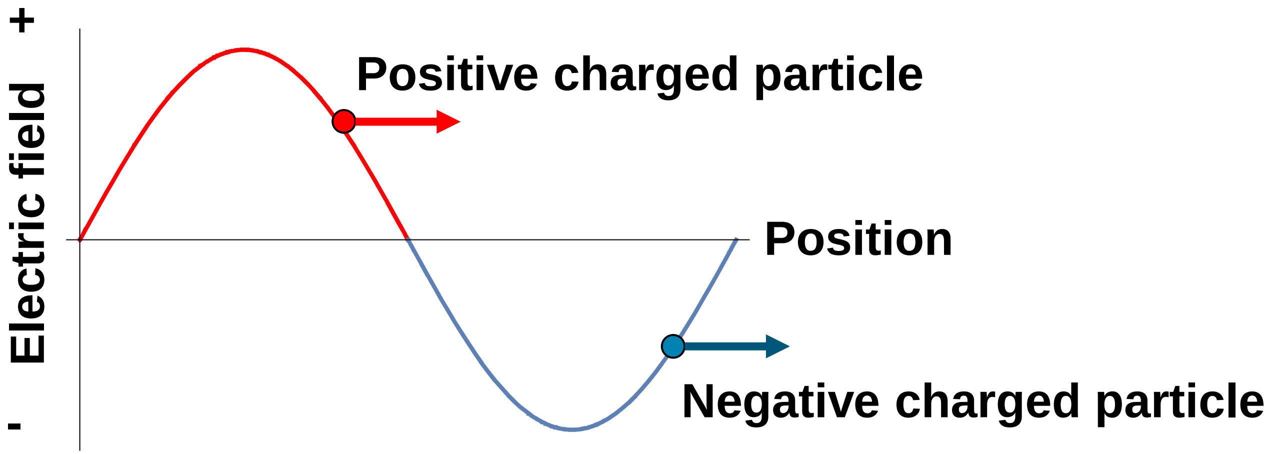
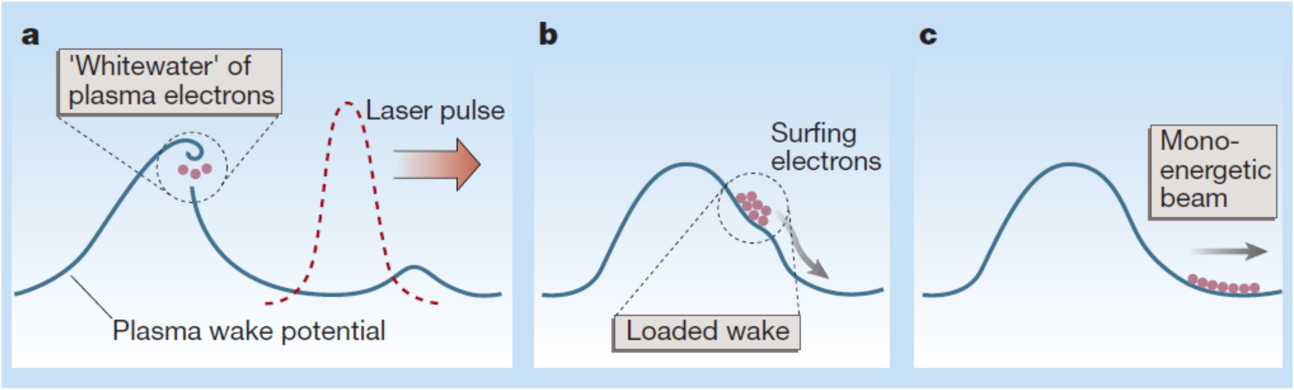
[1] N. A. M. Hafz, *et al.*, Nature Photonics **2**, 571 (2008)
[2] T. Katsouleas and J. Dawson, Phys. Rev. Lett. **51**, 392 (1983)
[3] P. Chen, *et al.*, Phys. Rev. Lett. **54**, 693 (1985)
[4] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979)

Charged particles can be accelerated in the wave electric field





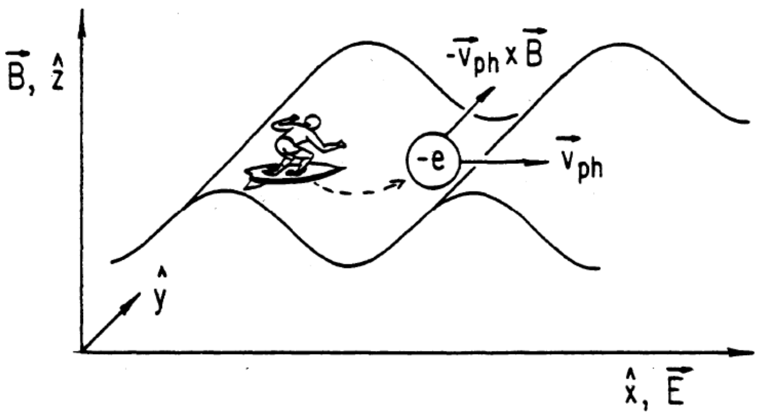
T. Katsouleas, Nature **431**, 515 (2004)

Who will catch the wave?

https://lightsabersandsurfboards.wordpress.com/tag/lake-erie-surfing/

The surfer glides in a direction not parallel to the wave direction to be in phase to the wave propagation

Electrons may be accelerated to speed of light using V_pxB acceleration (Surfatron)



- **Plane wave electric field and uniform magnetic field:**

$$\vec{E} = E_0 \sin(kx - \omega t)\hat{x}$$

$$\vec{B} = B\hat{z}$$

$$\frac{d}{dt}(\gamma v_x) = \frac{qE_0}{m}\sin(kx - \omega t) + \omega_c v_y$$

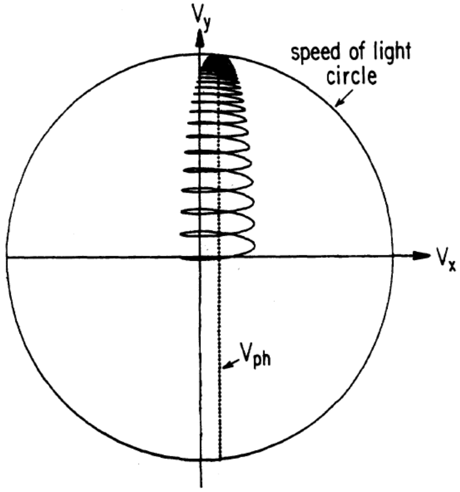
$$\frac{d}{dt}(\gamma v_y) = -\omega_c v_x \qquad \gamma = \frac{1}{\sqrt{1 - \frac{{v_x}^2 + {v_y}^2}{c^2}}}$$

- **On the wave frame and if the particle is trapped in the wave:**

$$x_1 = x - v_{ph}t \qquad \frac{d}{dt}(\gamma v_x) = 0$$

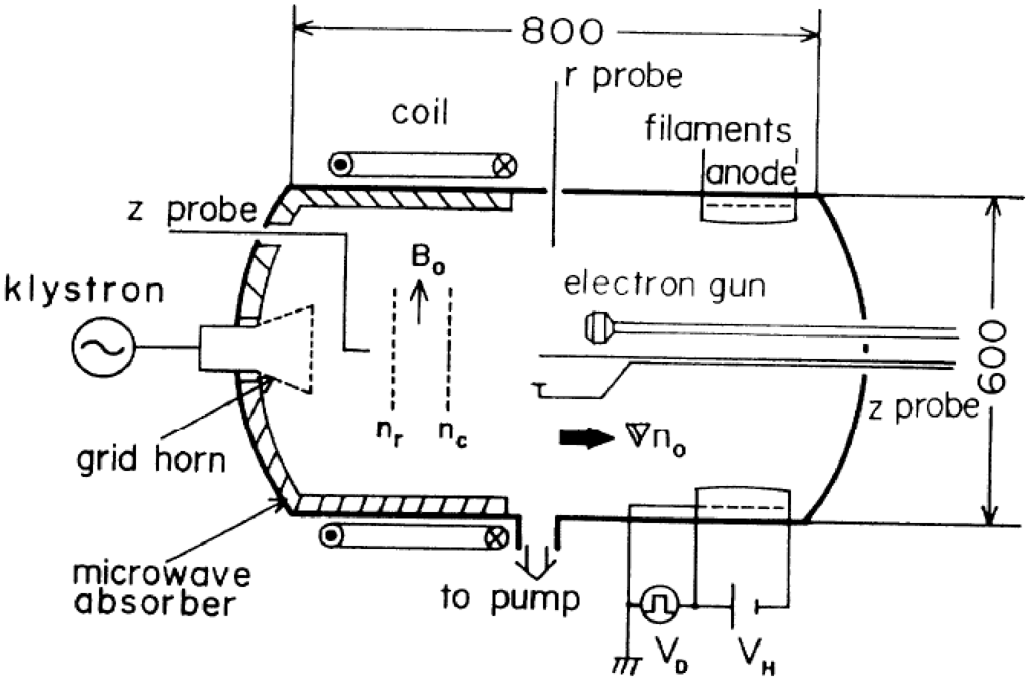
$$v_x \to v_{ph}$$

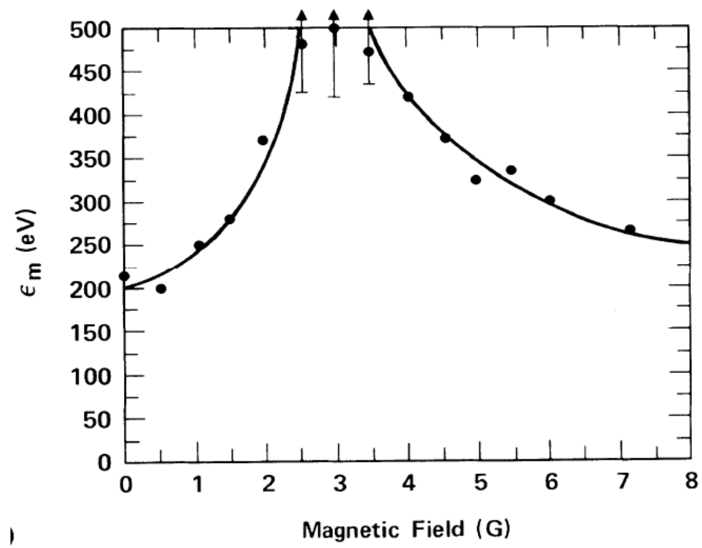
$$v_y = -\frac{\omega_c v_{ph} t}{\gamma_{ph}\sqrt{1 + \frac{{\omega_c}^2 t^2 {v_{ph}}^2}{c^2}}}$$



- T. Katsouleas, *et al.*, PRL **51**, 392 (1983)
- T. Katsouleas, *et al.*, IEEE TNS. **NS-30**, 3241 (1983)
- Y. Nishida, *et al.*, AIP Conf Proc. **737**, 957 (2004)

Experimental results of V_pxB acceleration (Surfatron)

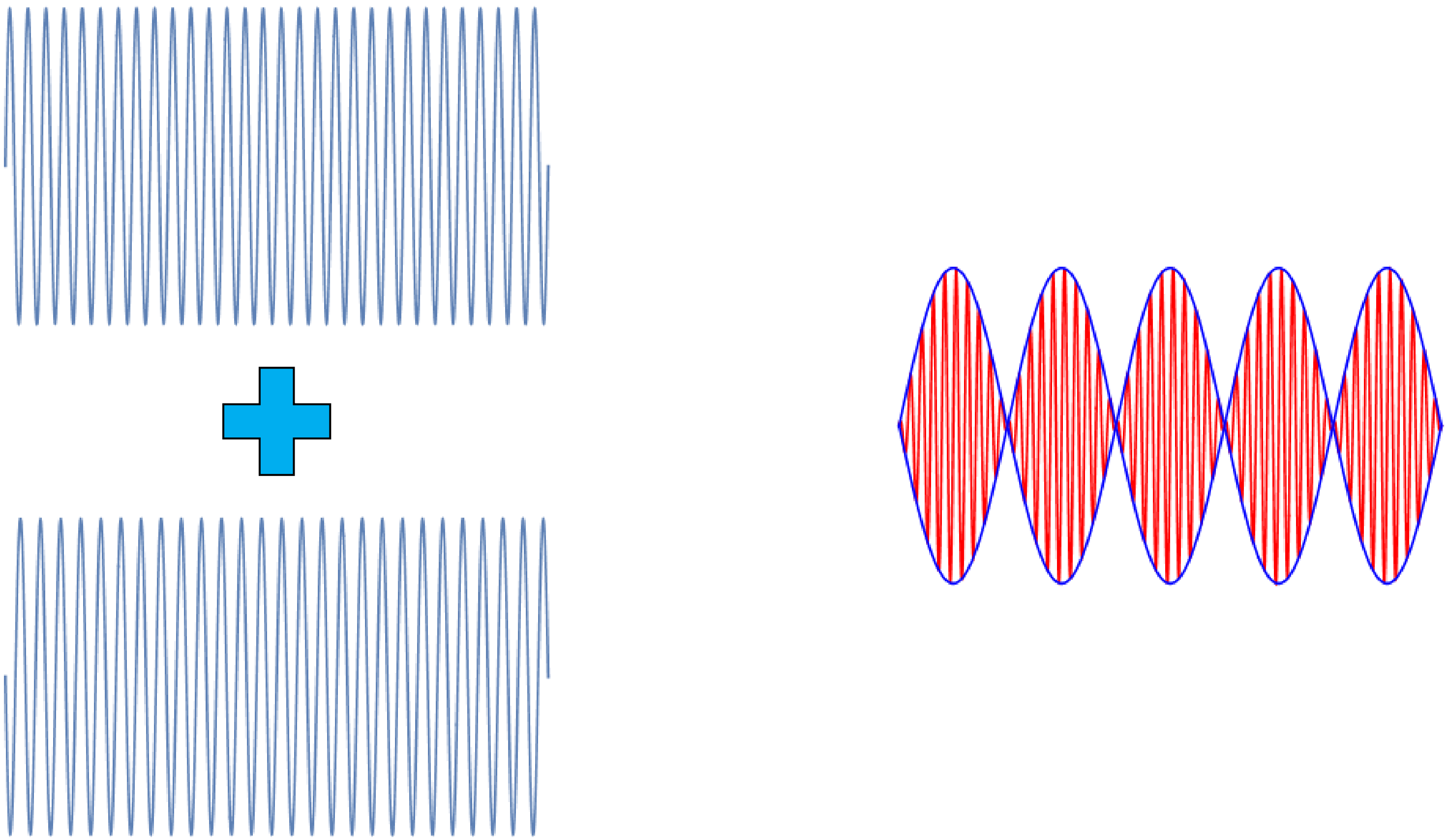




- n_0 ~ 1-30 x 10^{17} m^{-3}
- T_e ~ 2-5 eV
- T_i ~ 0.1-0.2 eV
- Microwave frequency: 3-10 GHz

C. Domier, *et al.*, Phys. Rev. Lett. **63**, 1803 (1989)

Plasma beat wave accelerator



$$sin(x_1) + \sin(x_2) = 2\sin\left(\frac{x_1 + x_2}{2}\right)\cos\left(\frac{x_1 - x_2}{2}\right)$$

A plasma wave is driven by the laser beat wave

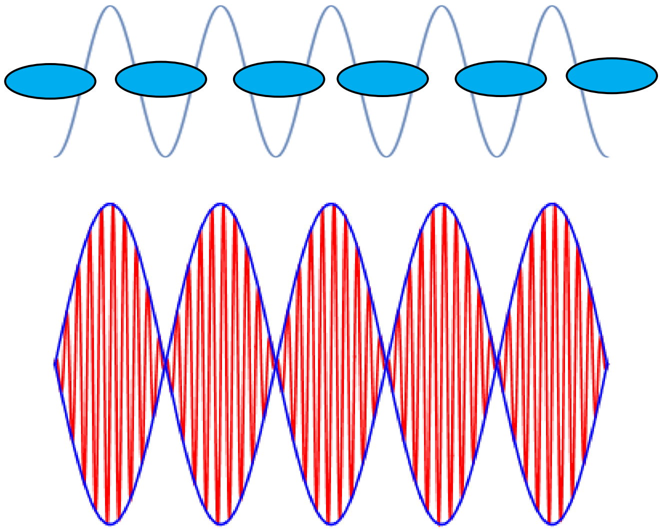
$$\omega_0 = \omega_2 - \omega_1$$

$$k_0 = k_2 - k_1$$

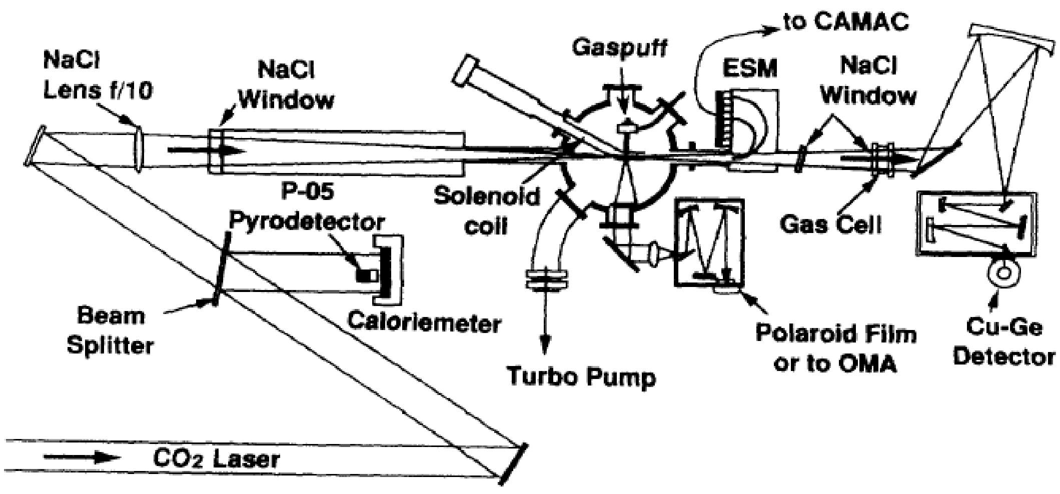
$$v_{\mathrm{ph}} = v_g = c\sqrt{1 - \frac{{\omega_p}^2}{{\omega_0}^2}}$$

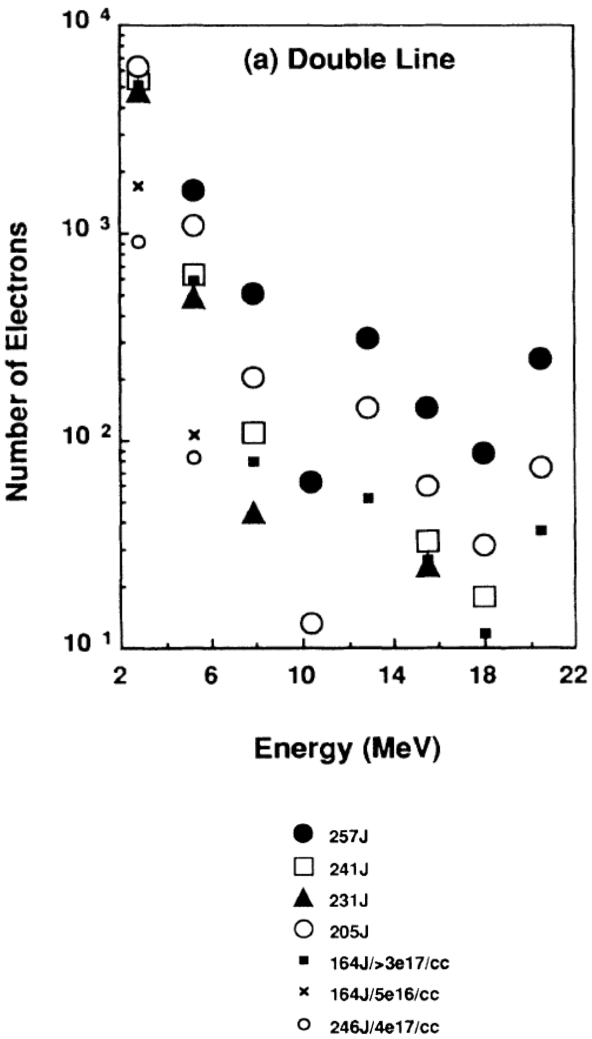
$$F = -e\nabla\phi_p = -\nabla\frac{e^2 E^{(1)} \cdot E^{(2)*}}{\mathrm{m}\omega_1\omega_2}$$

Plasma wave



Electrons were accelerated to over 20 MeV using plasma beat wave accelerator





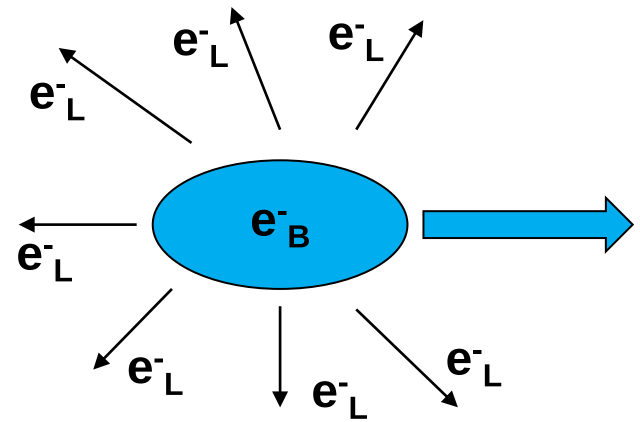
Laser: 10.6 um + 9.57 um
Intensity: $2x10^{13}$ ~ $2x10^{14}$ W/cm^2
Injected E-beam: 0.1~1 MeV
n_0=$3x10^{16}$ ~ $7x10^{17}$ cm^{-3}

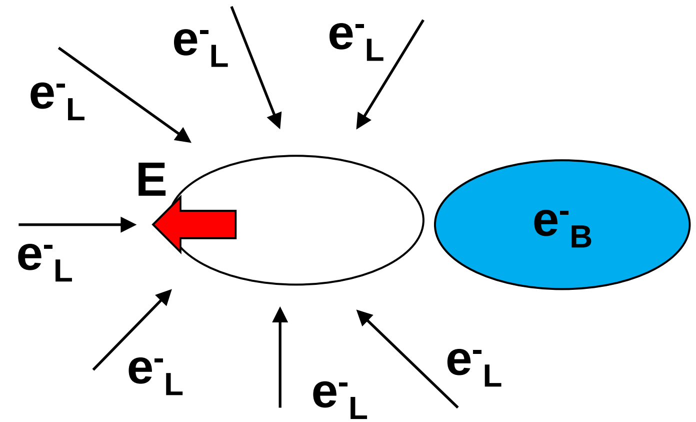
Y. Kitagawa, *et al.*, Phys. Rev. Lett. **68**, 48 (1992)

Plasma wakefield accelerator employs two beams

- When a bunch of electrons enter the plasma, they expel local electrons.
- When the bunch of electrons leave the plasma, the local electrons try to return but oscillate around their original locations and generate a wake field behind the bunch.
- The longitudinal field of the wake can accelerate the particles in the back.

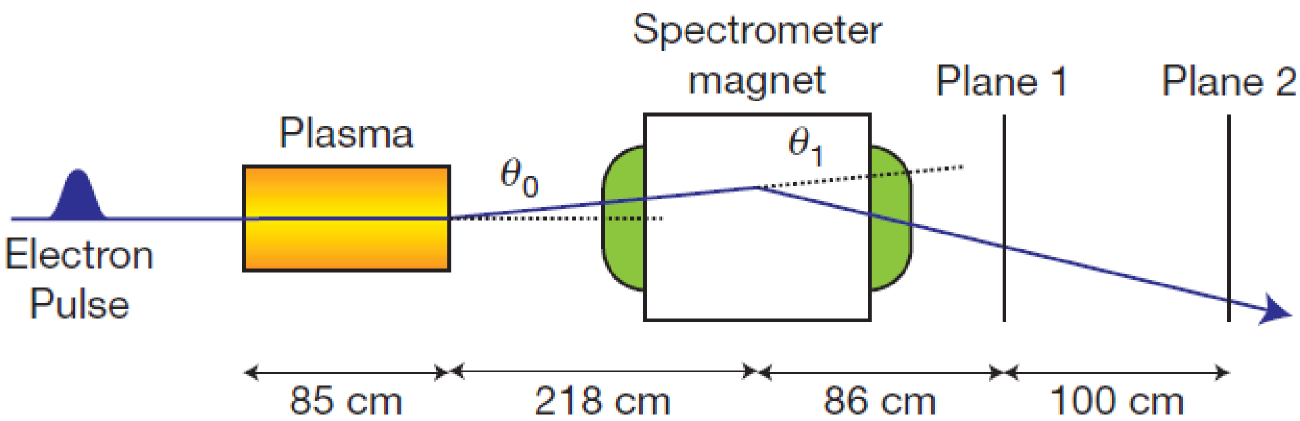
- Key components:
  - Drive bunch: excite wake-field
  - Test bunch: beam that is accelerated to high energy

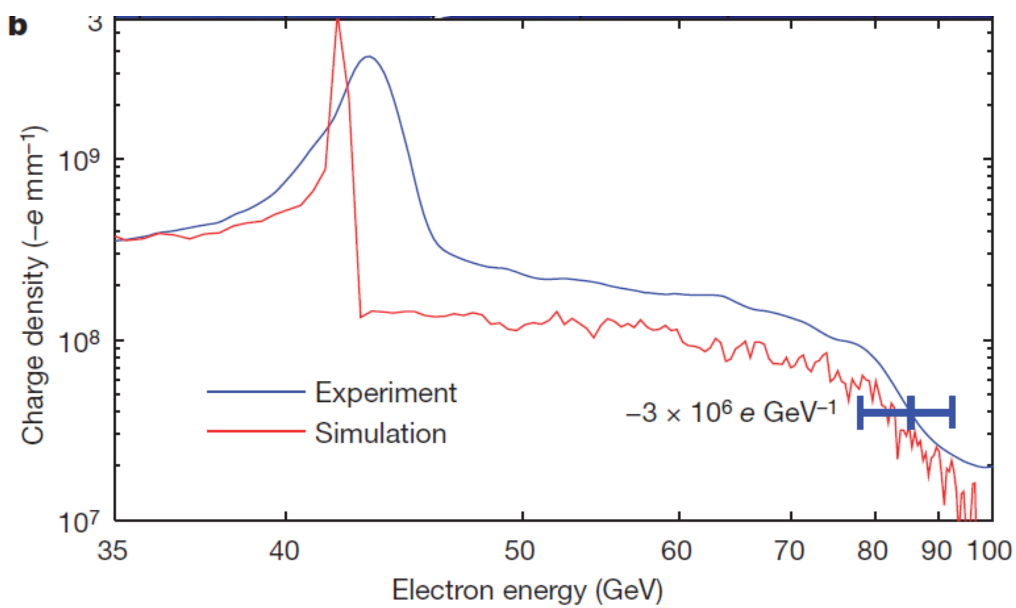




T. Katsouleas, Phys. Rev. A **33**, 2056 (1986)

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator





I. Blumenfeld, *et al.*, Nature **445**, 741 (2007)

Dream beam – the dawn of compact particle accelerators

Front page of nature, 30 Sep., 2004

Ponderomotive force expelled electrons away from the higher electric field region

$$m_s\ddot{x} = q_s E = q_s E_0(x)\cos\omega t$$

$$x = x_0 + x_1 \text{ where } x_0 = \overline{x}$$

$$m_s(\ddot{x}_0 + \ddot{x}_1) = q_s\left(E_0 + x_1\frac{dE_0}{dx}\right)\cos\omega t$$

- Take time average:

$$m_s\ddot{x}_0 = q_s\left.\frac{dE_0}{dx}\right|_{x_0}\overline{x_1\cos\omega t}$$

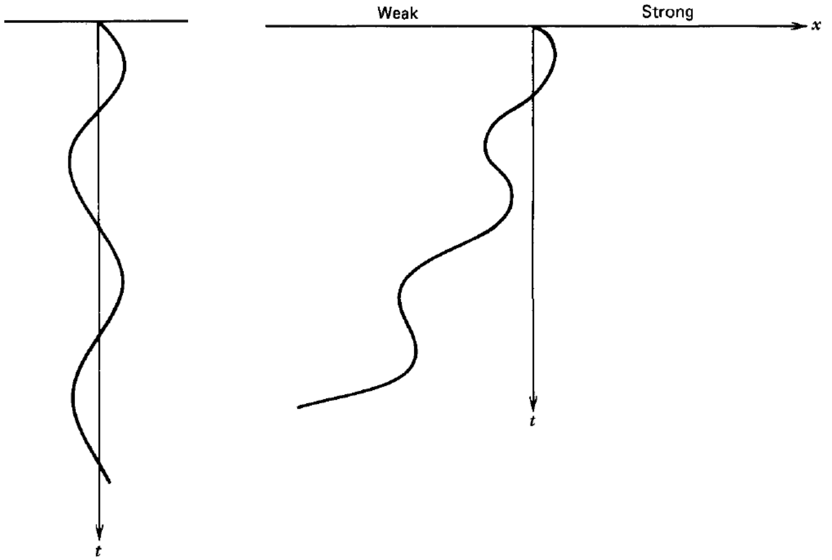
- $\ddot{x}_1 \gg \ddot{x}_0 \quad , \quad E_0 >> x_1\frac{dE_0}{dx}$

$$m_s\ddot{x}_1 = q_s E_0\cos\omega t$$

$$x_1 = -\frac{q_s E_0}{m_s\omega^2}\cos\omega t$$

$$\ddot{x}_0 = -\frac{{q_s}^2 E_0}{2{m_s}^2\omega^2}\frac{dE_0}{dx}$$

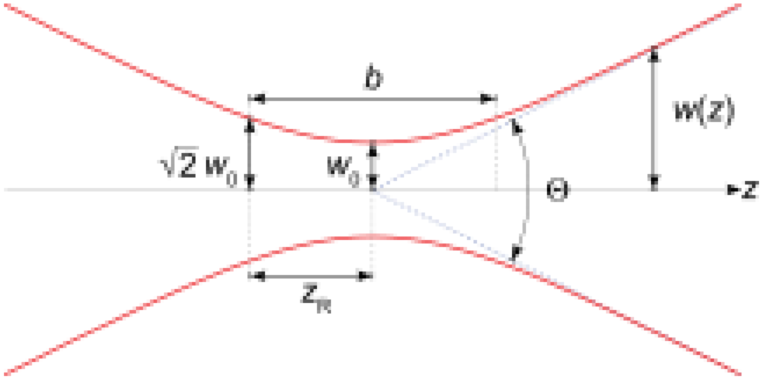
$$\frac{dE_0}{dx} = 0 \qquad\qquad \frac{dE_0}{dx} > 0$$



$$F_p = m_s\ddot{x}_0 = -\frac{{q_s}^2}{4m_s\omega^2}\frac{d}{dx}\left({E_0}^2\right)$$

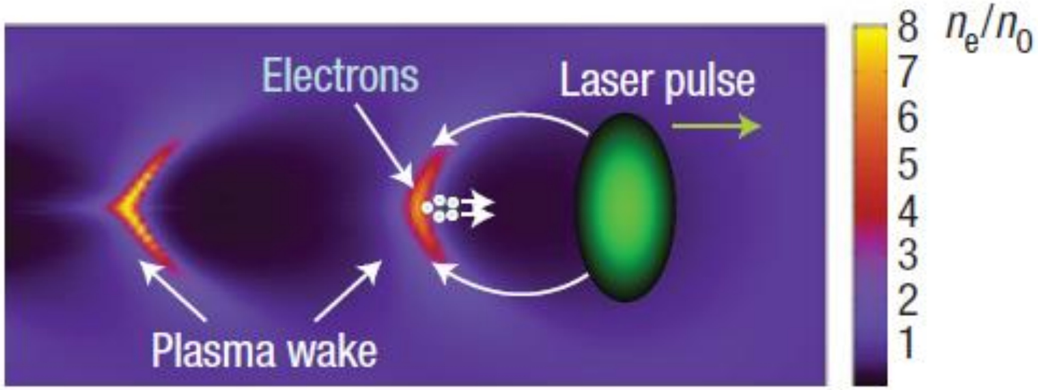
Laser is used to create a bunch in laser wakefield accelerator

$$I(r,z) = \frac{2P}{\pi w^2(z)} \exp\left[-\frac{2r^2}{w^2(z)}\right]$$



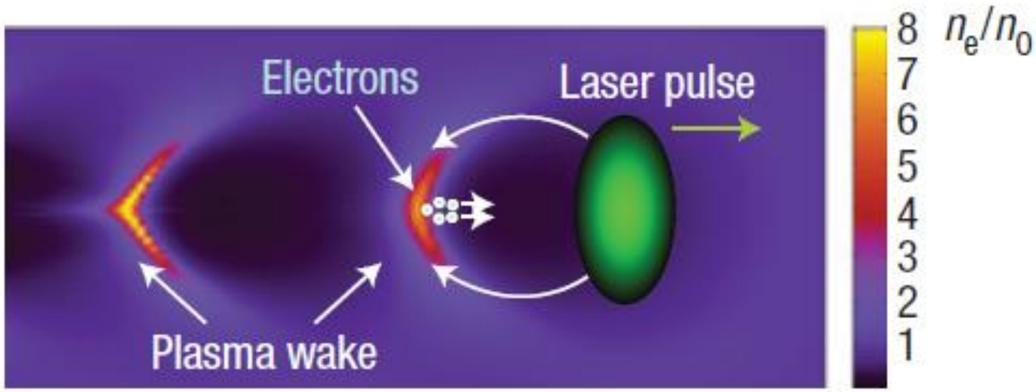
- **Waist:** $w(z) = w_0\sqrt{1+\frac{z^2}{{z_R}^2}}$
- **Rayleigh length:** $z_R = \frac{\pi {w_0}^2}{\lambda_L}$

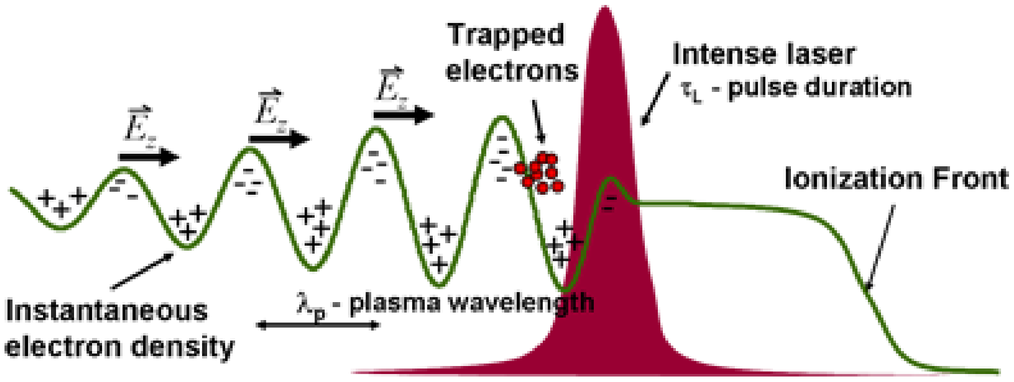
Bubble/blow-out regime



V. Malka, *et al.*, Nature Physics **4**, 447 (2008)

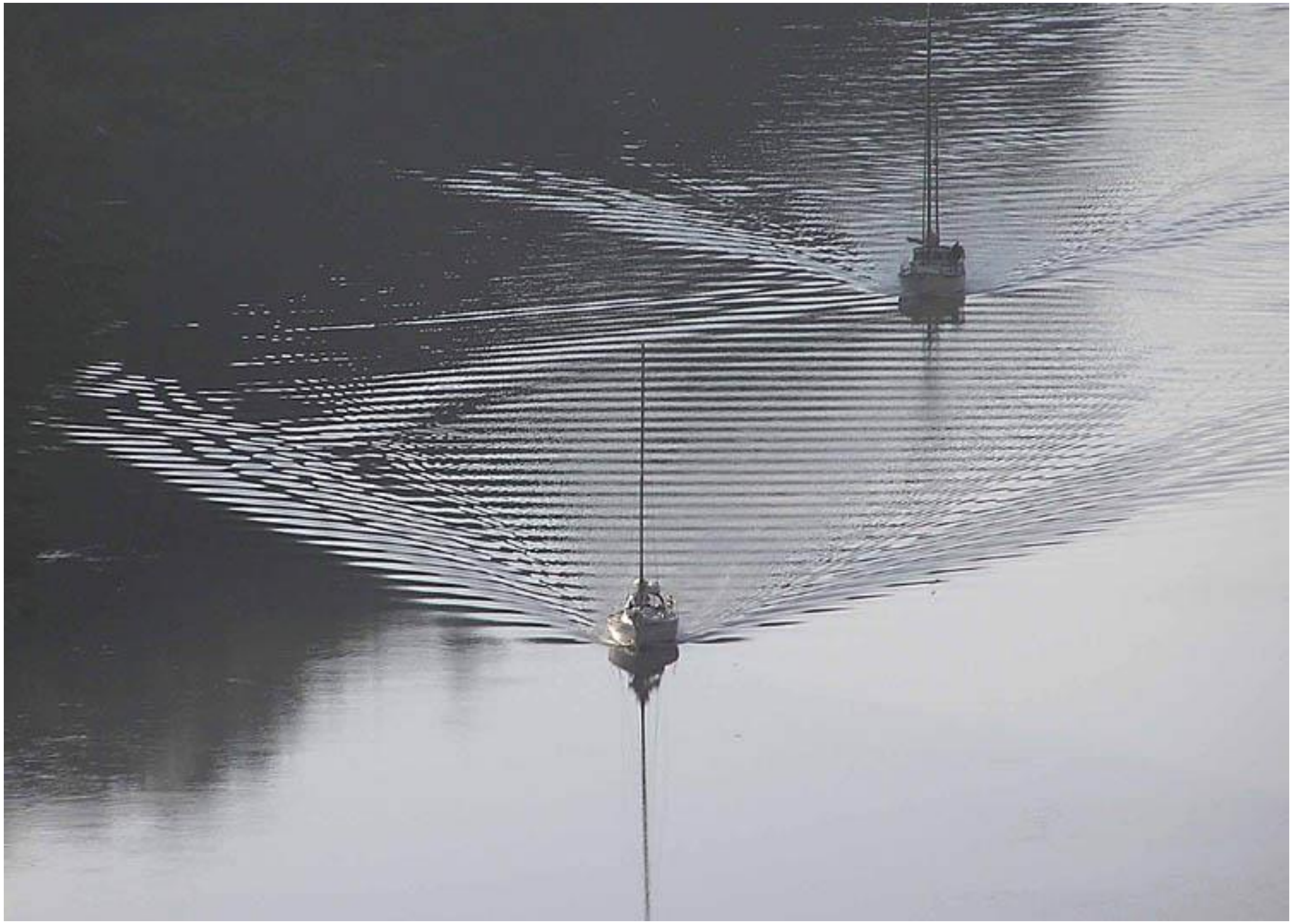
A plasma wake is generated by a short pulse laser





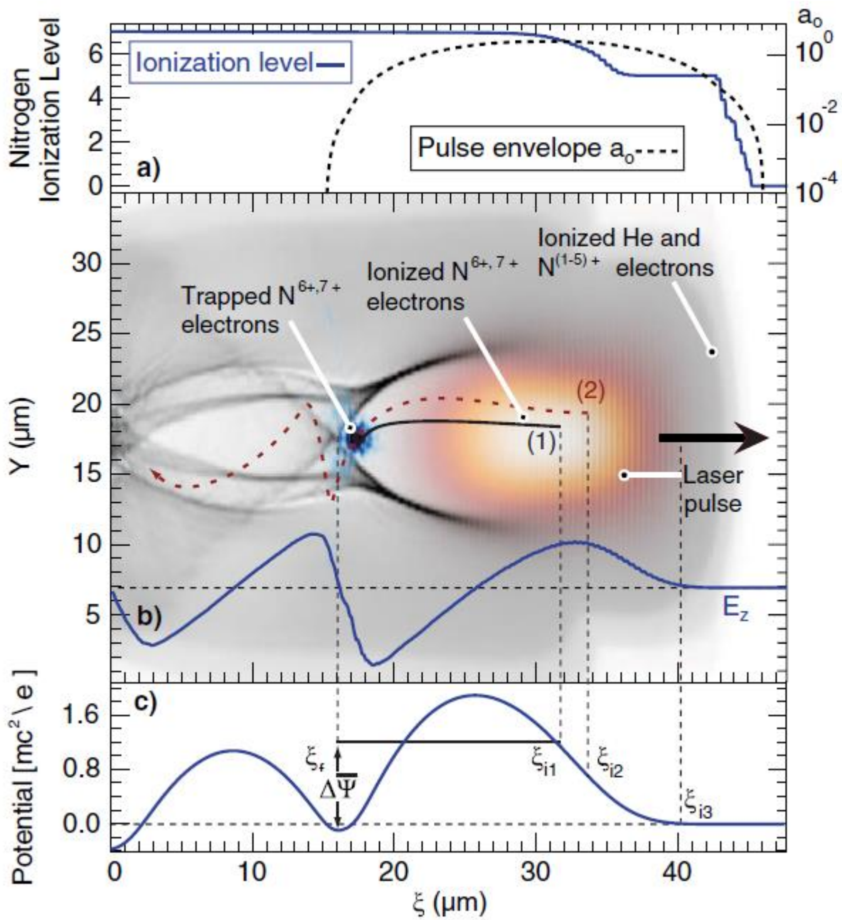
V. Malka, *et al.*, Nature Physics **4**, 447 (2008)
http://cuos.engin.umich.edu/researchgroups/hfs/research/laser-wakefield-acceleration/

The wakefield generated by a short pulse laser is very similar to the wave behind a boat



https://upload.wikimedia.org/wikipedia/commons/4/4f/Wake.avon.gorge.2boats.arp.750pix.jpg

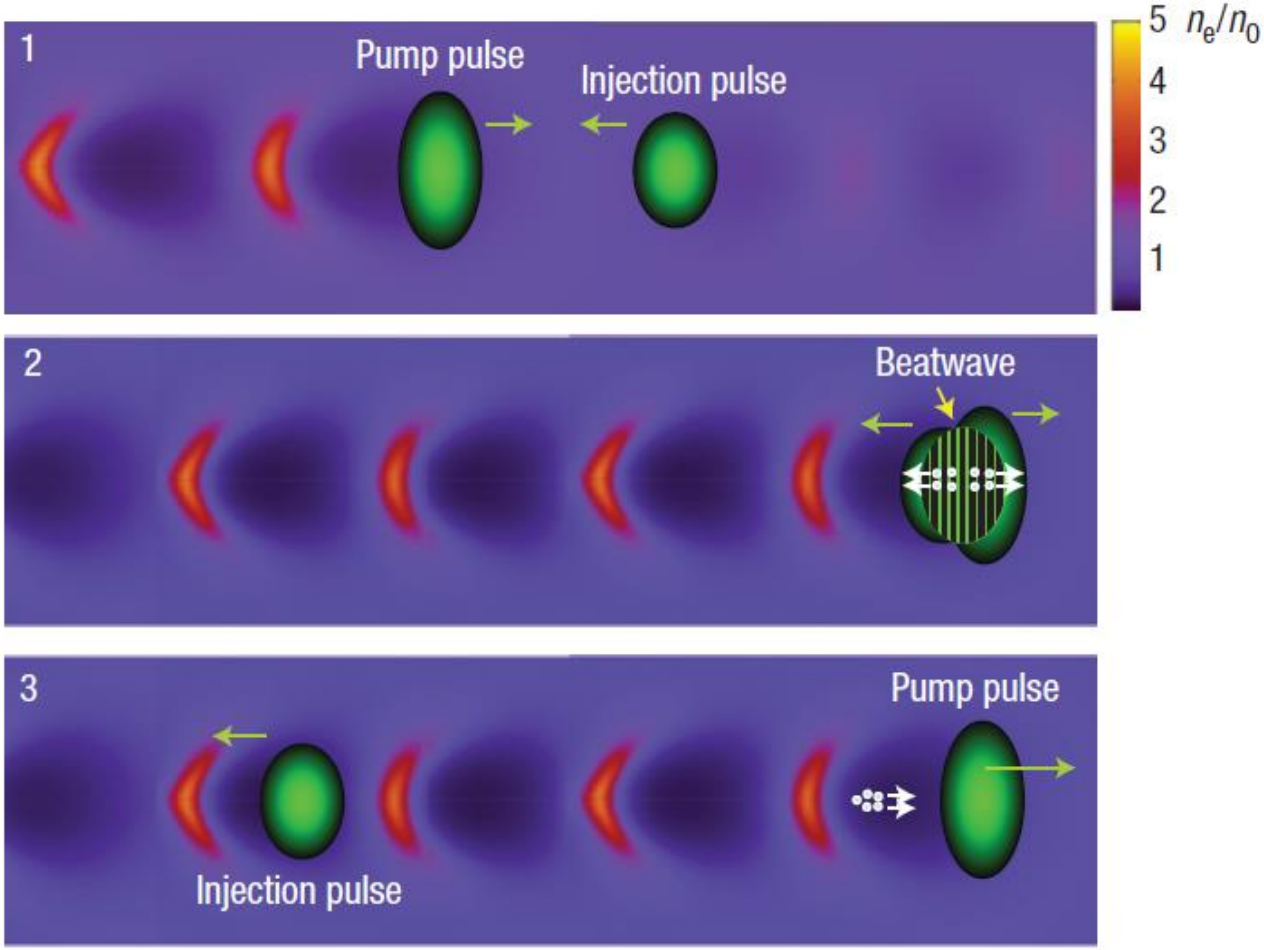
Ionization injection



- **Large relative energy spread**
- **Energy required to trap electrons is reduced so that electron beams with large charge can be produced in a moderate laser energy**

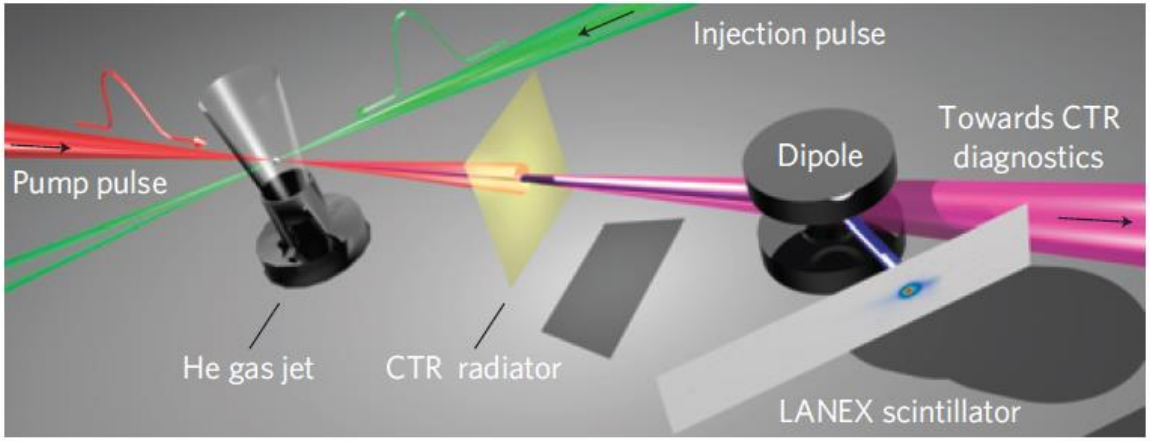
A. Pak, *et al.*, Phys. Rev. Lett. **104**, 025003 (2010)

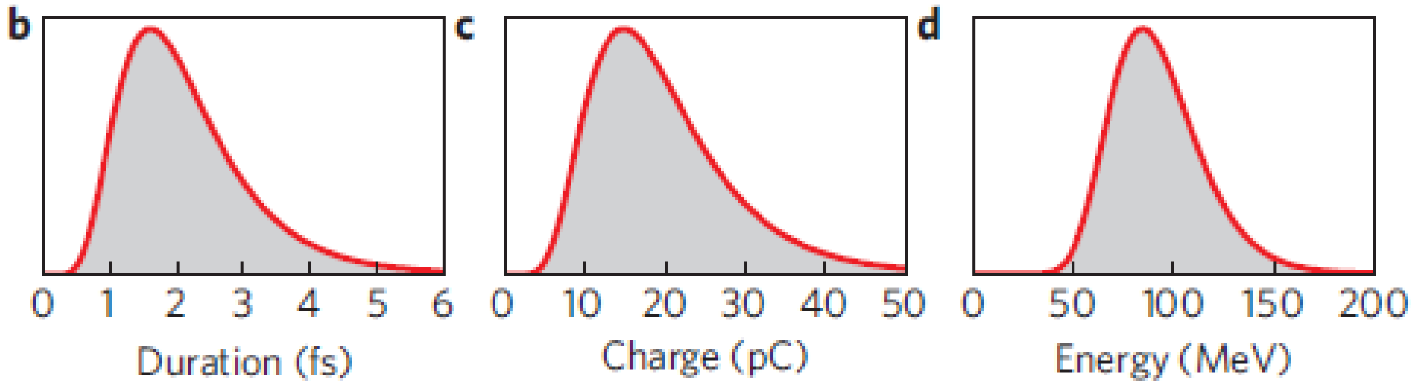
Colliding laser pulses injection



V. Malka, *et al.*, Nature Physics **4**, 447 (2008)

Few femtosecond, few kiloampere electron bunch is produced by a laser–plasma accelerator





O. Lundh, *et al.*, Nature Physics **7**, 219 (2011)