Application of Plasma Phenomena

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Lecture 15

2024 spring semester

Tuesday 9:10-12:00

Materials:

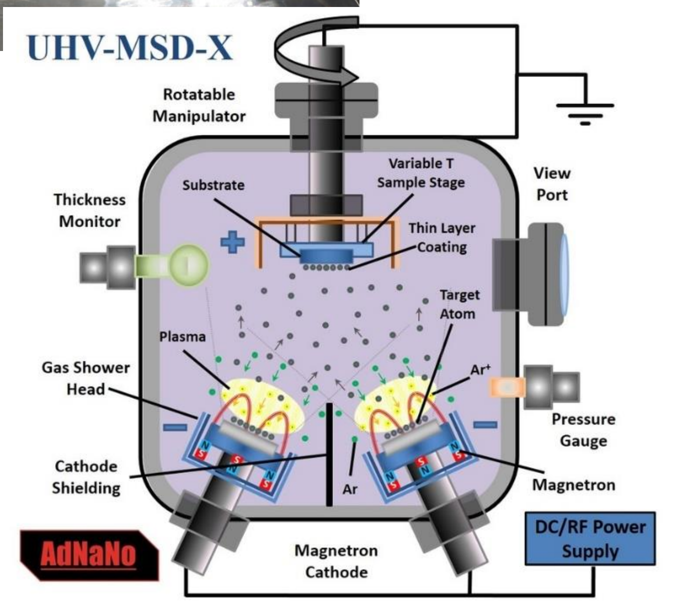
https://capst.ncku.edu.tw/PGS/index.php/teaching/

Online courses:

https://nckucc.webex.com/nckucc/j.php?MTID=m4082f23c59af0571015416f6e58dd803

2024/6/18 updated

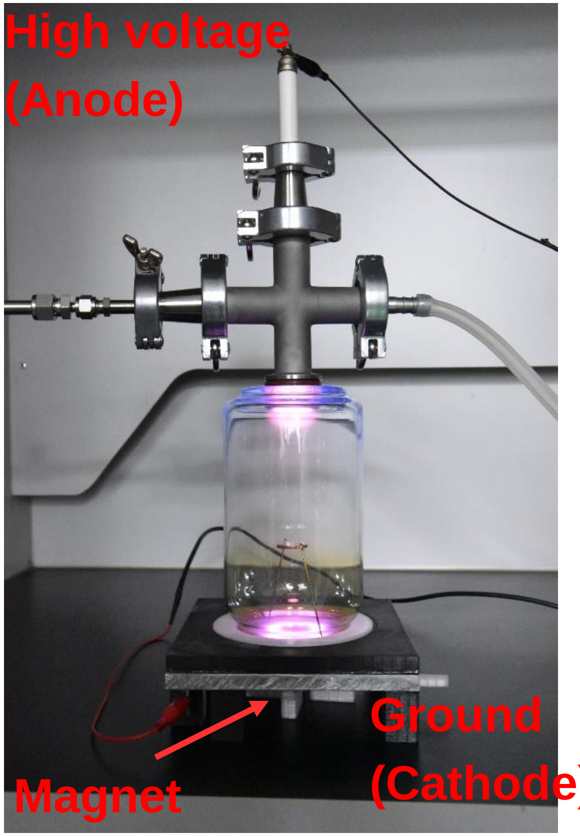
Examples of magnetron sputtering deposition



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

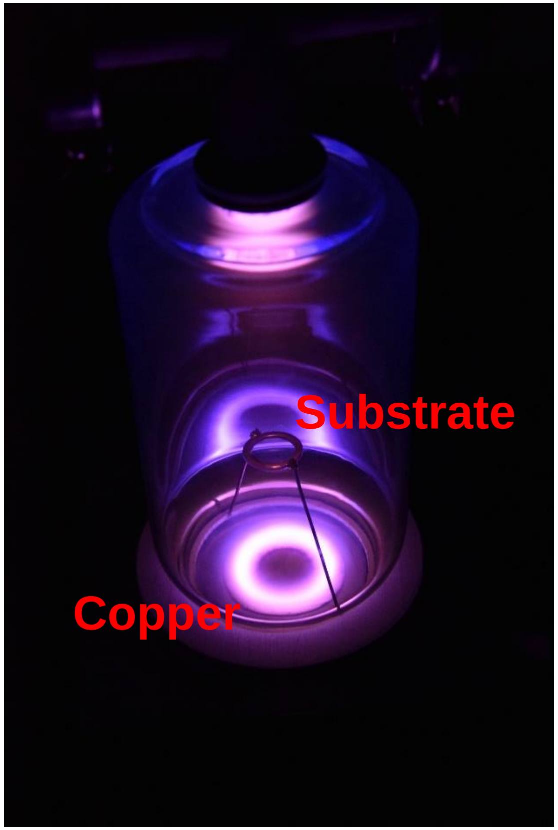
Demonstration experiments – magnetron sputtering

- System

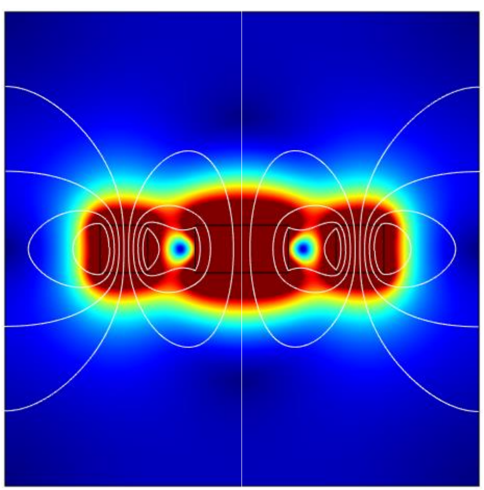


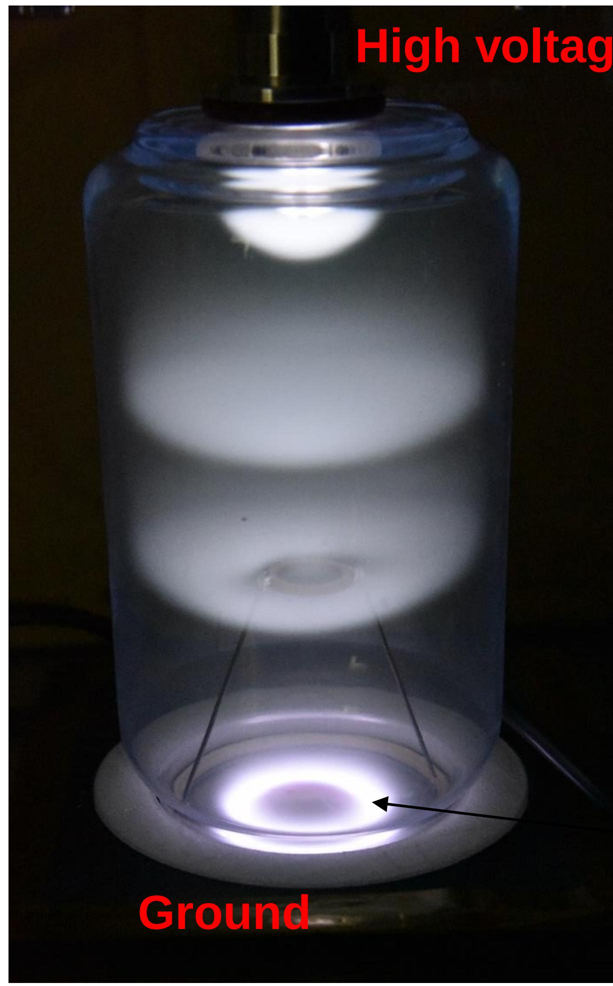
- Without magnet

- With magnet



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



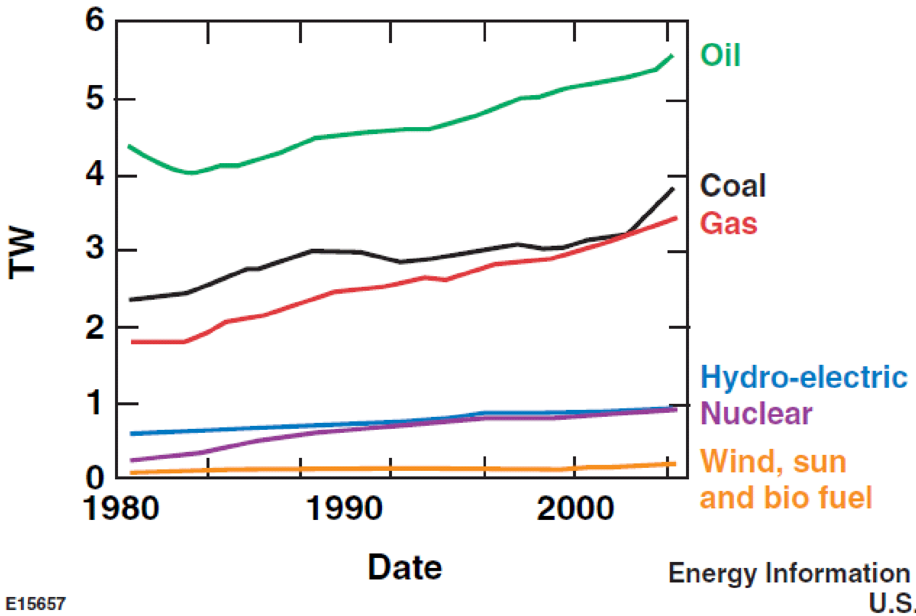


Outline

- 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

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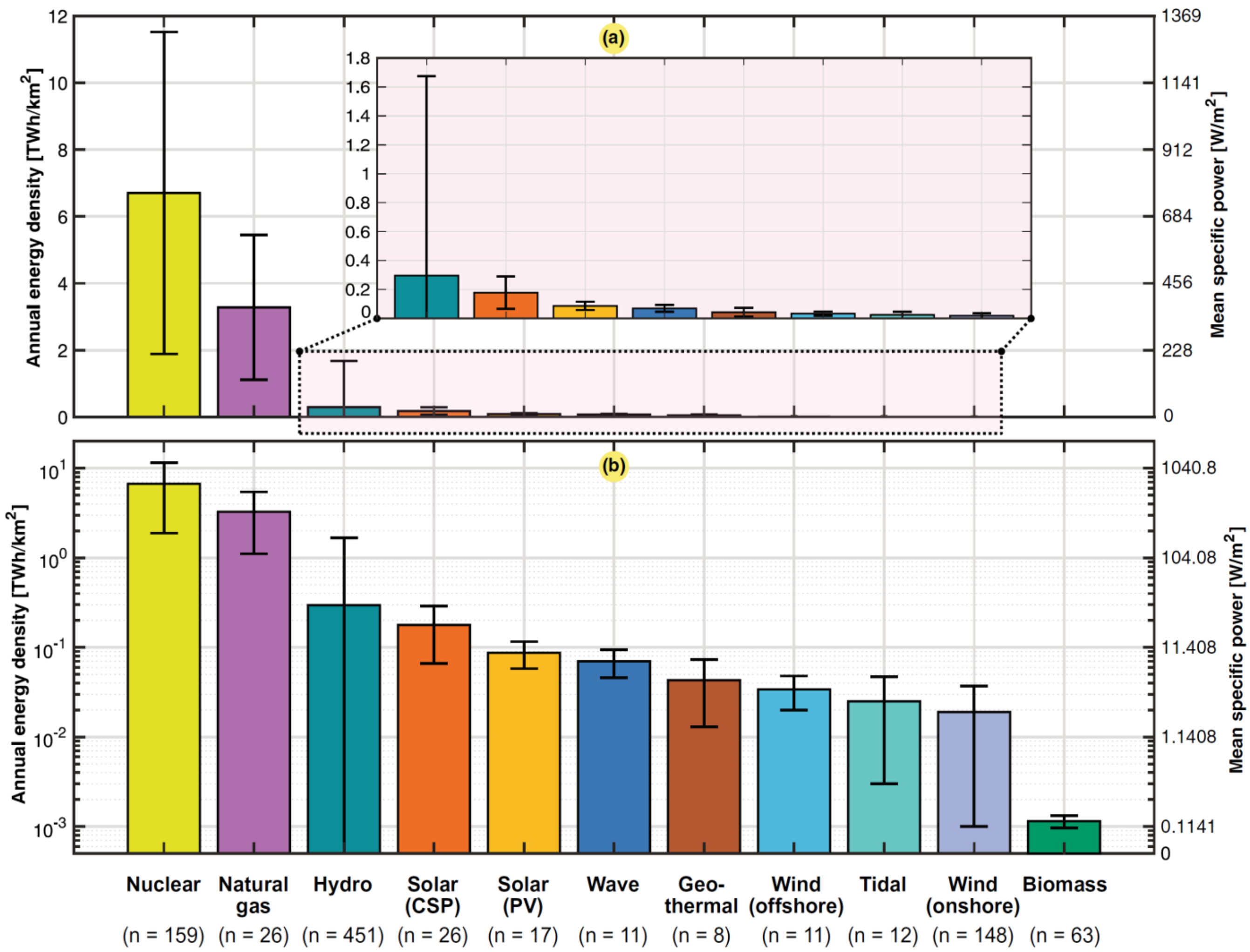
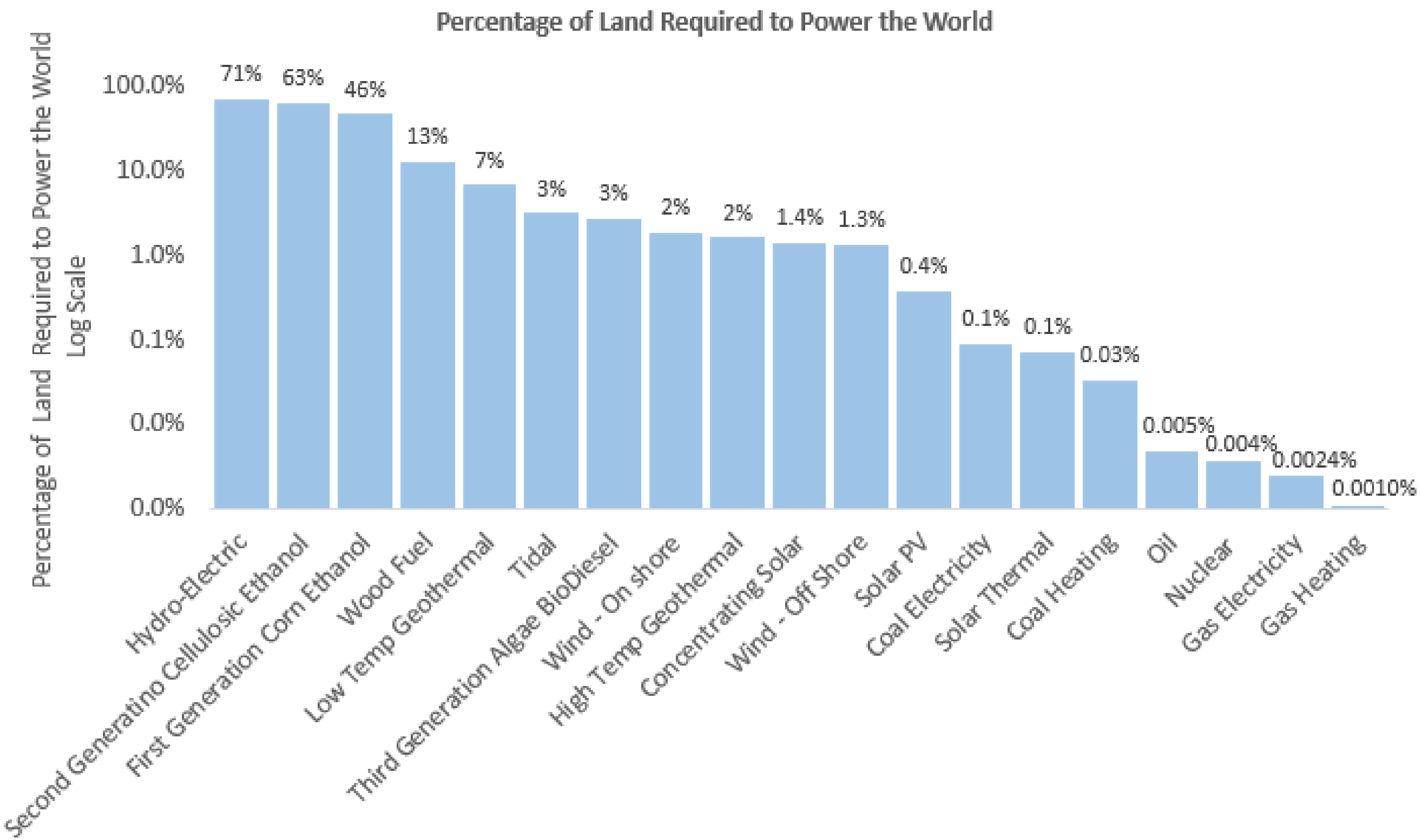
*from Laboratory for Laser Energetics, University of Rochester, Rochester, NY

Nuclear energy has the highest energy density



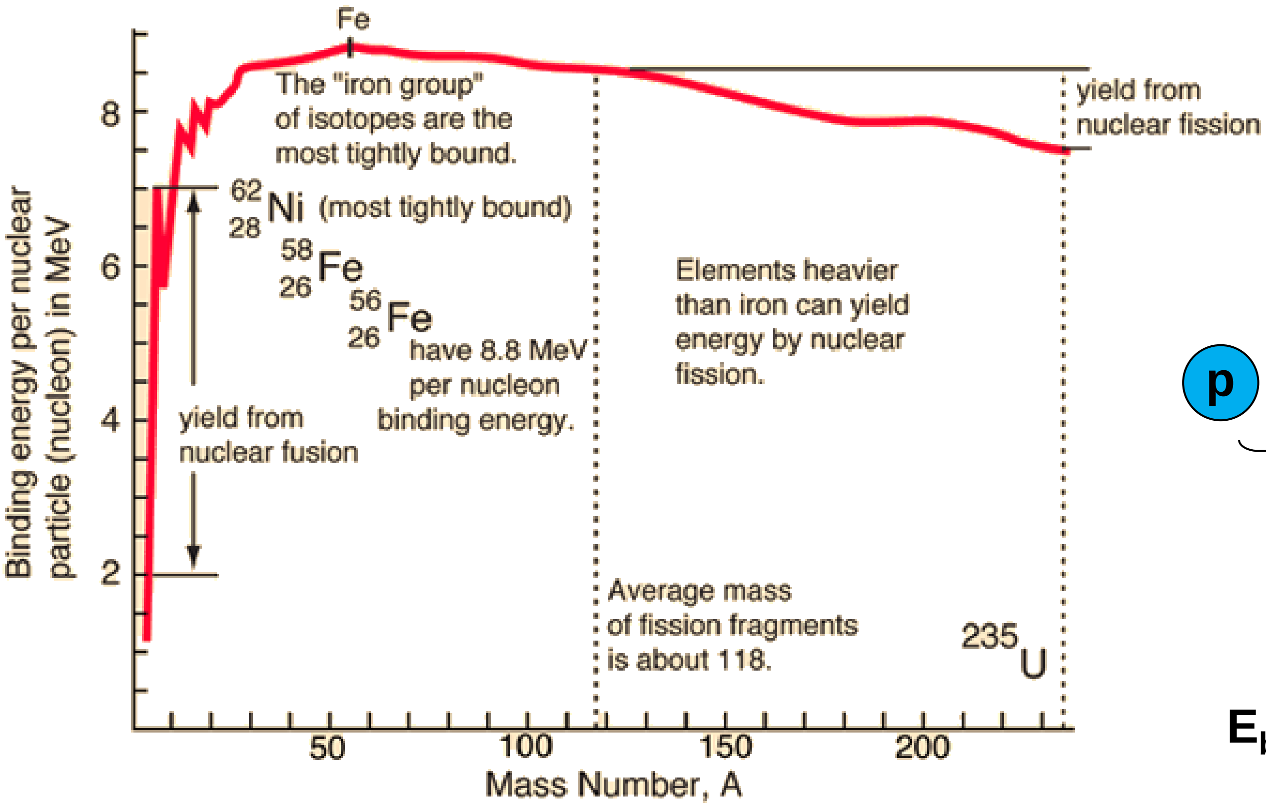
J. K. Noland, etc., Scientific Reports **12**, 21280 (2022)

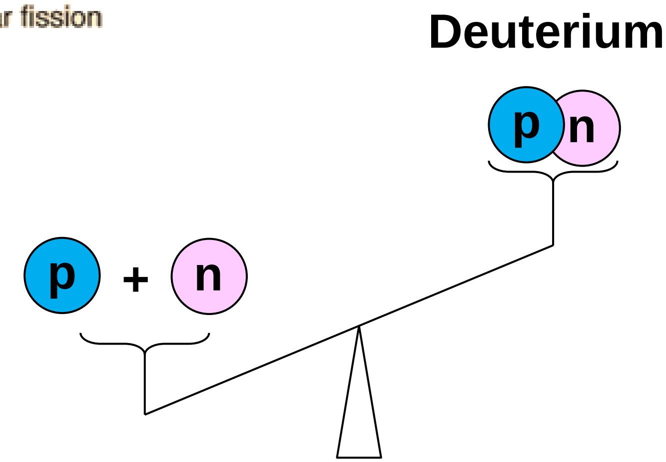
The energy density of an electricity generation needs to be high, or it takes a lot of land for generating electricity



https://net-zero.blog/book-blog/land-use-by-energy-source

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





$m_p + m_n > m_D$

$E_{binding} = [(m_p + m_n) - m_D]c^2$

$$Q = \left(\sum_{\mathrm{i}} m_{\mathrm{i}} - \sum_{\mathrm{f}} m_{\mathrm{f}}\right) c^2$$

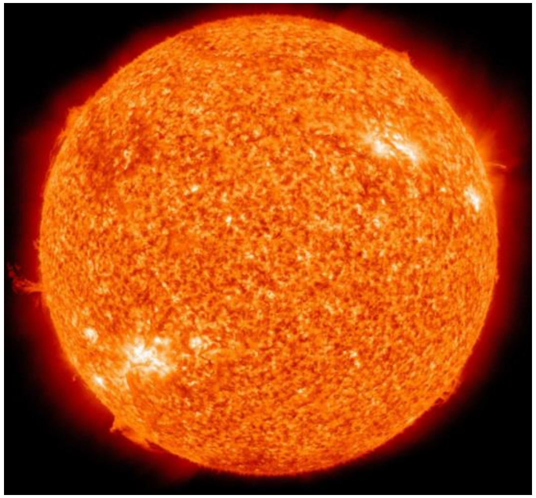
$$\Delta m = z m_{\mathrm{p}} + (A - z) m_{\mathrm{n}} - m$$

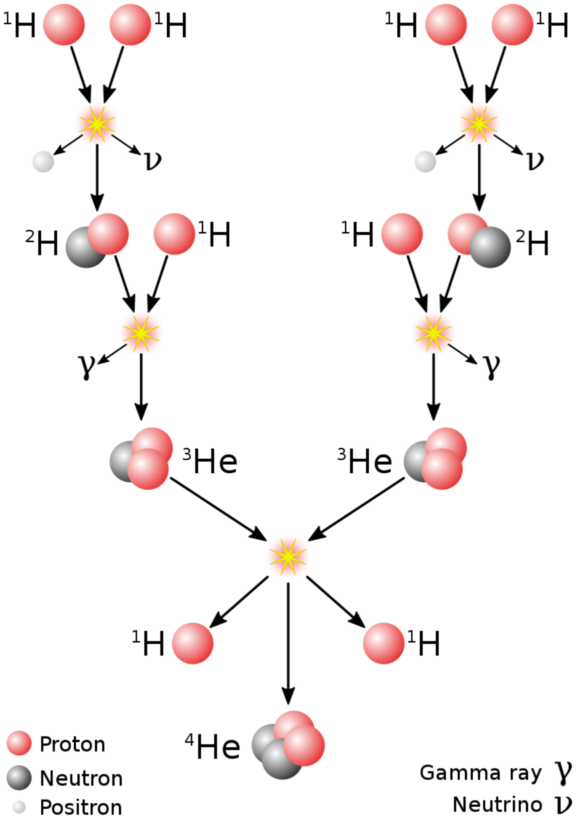
- **Binding energy:** $B = \Delta m c^2$
- **Output energy:** $Q = \sum_{\mathrm{f}} B_{\mathrm{f}} - \sum_{\mathrm{i}} B_{\mathrm{i}}$

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

Fusion in the sun provides the energy

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

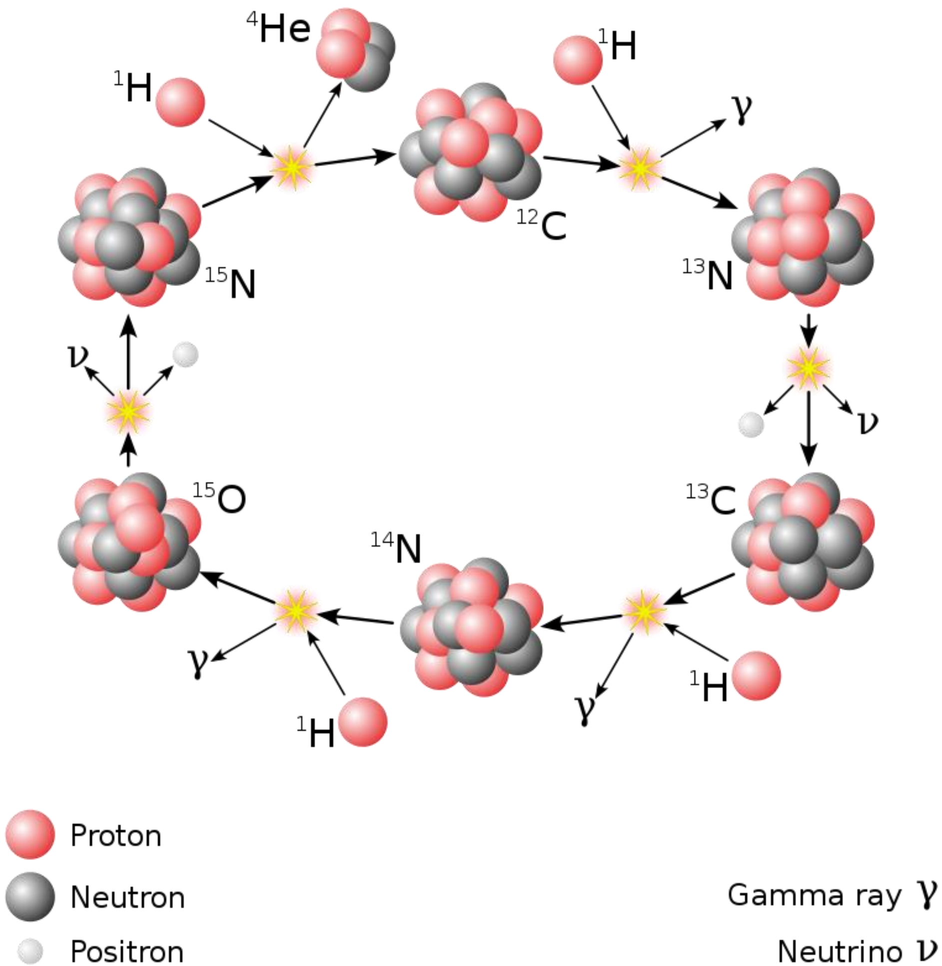




- **Particles are confined by the gravity.**

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

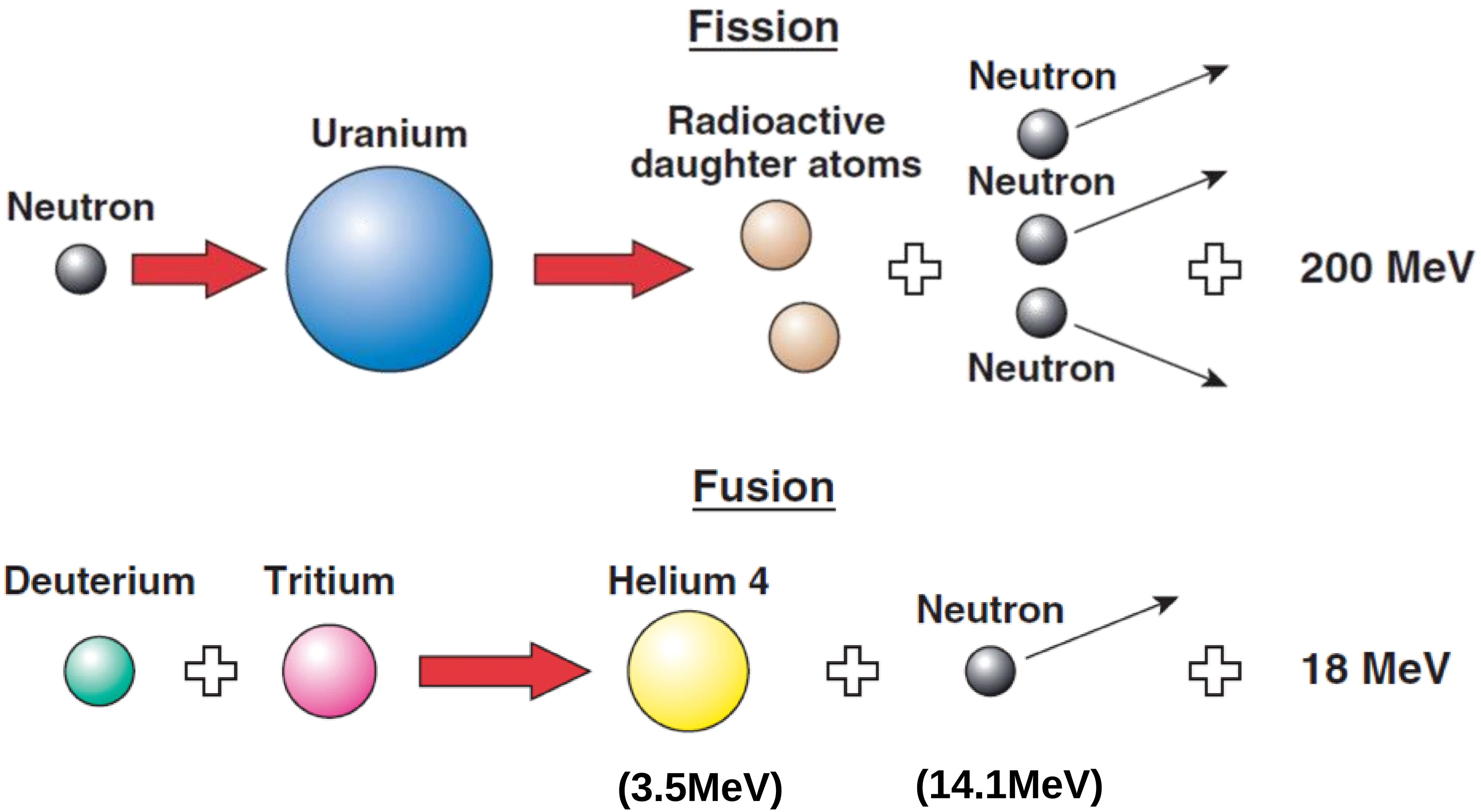
The cross section of proton-proton chain is much smaller than D T fusion

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

- Barn = 10^{-28} m^2. It is the hard sphere cross section of a nucleus with R ≈ 5×10^{-15} m.
- "( )" are theoretical values while others are measured values.

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

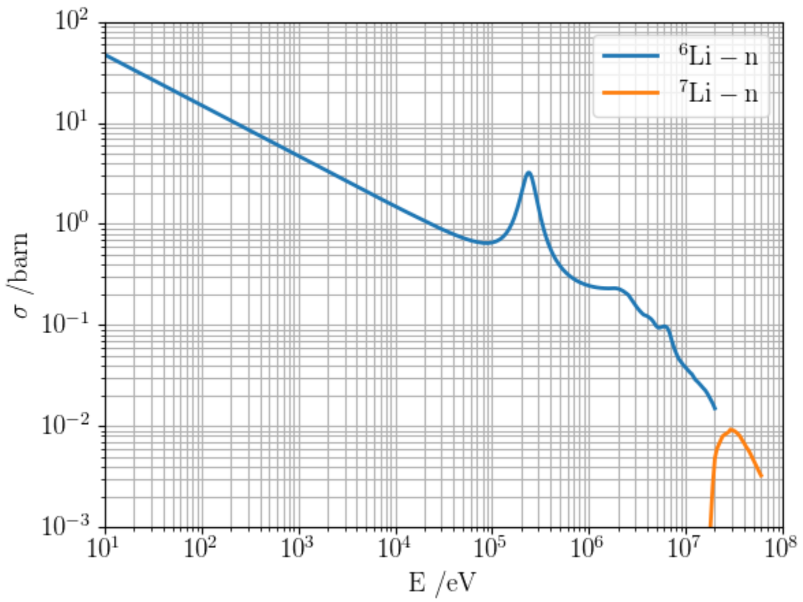
Nuclear fusion and fission release energy through energetic neutrons



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

- **Fission of ^{235}U:** $$\frac{Q}{A} = \frac{200\ \text{MeV}}{(235+1)\text{amu}} = 0.85\ \text{MeV/amu}$$
- **Fusion of D+T:** $$\frac{Q}{A} = \frac{17.6\ \text{MeV}}{(2+3)\text{amu}} = 3.5\ \text{MeV/amu}$$

	Half-life (years)
U235	$7.04\text{x}10^8$
U238	$4.47\text{x}10^9$
…	
Tritium	12.3



- **Tritium breeding:**

n + ^{6}Li → α + T + 4.86 MeV
n + ^{7}Li → α + T + n – 2.87 MeV

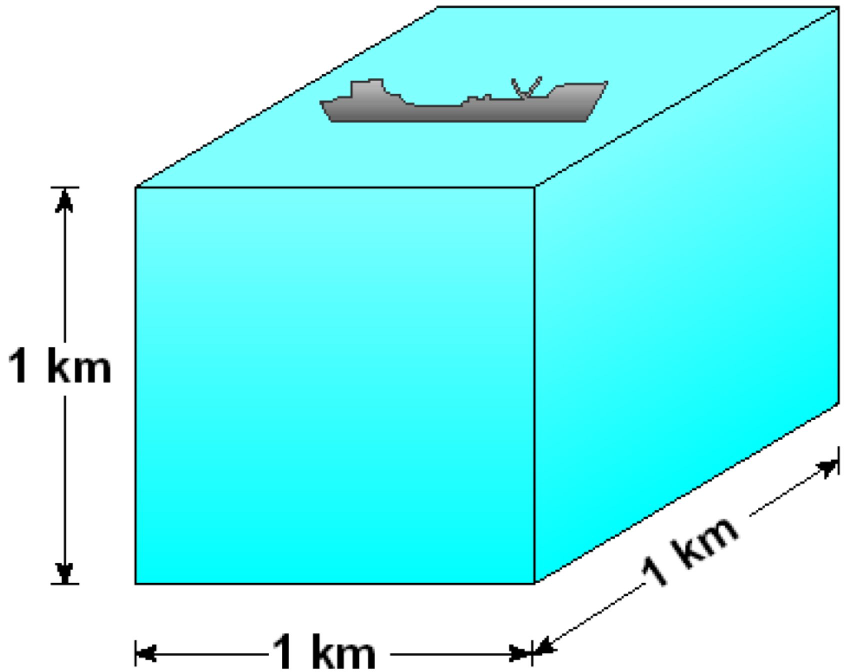
https://scipython.com/blog/breeding-tritium-for-a-fusion-reactor/

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

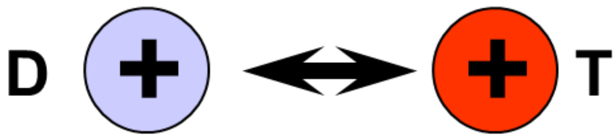


= Total energy of world oil reserve

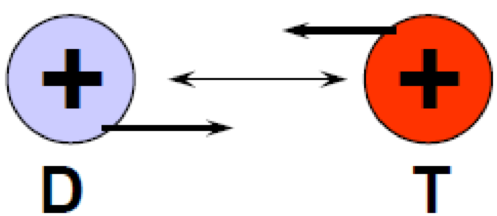
*R. Betti, HEDSA HEDP Summer School, 2015

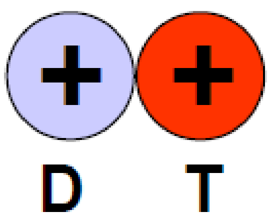
A “hot plasma” at 100M ^{0}C is needed

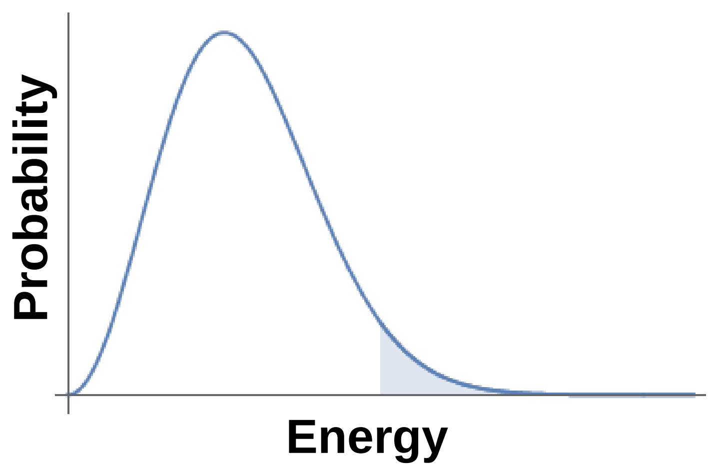
- **Probability for fusion reactions to occur is low at low temperatures due to the coulomb repulsion force.**



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

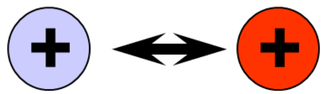


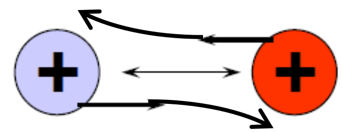


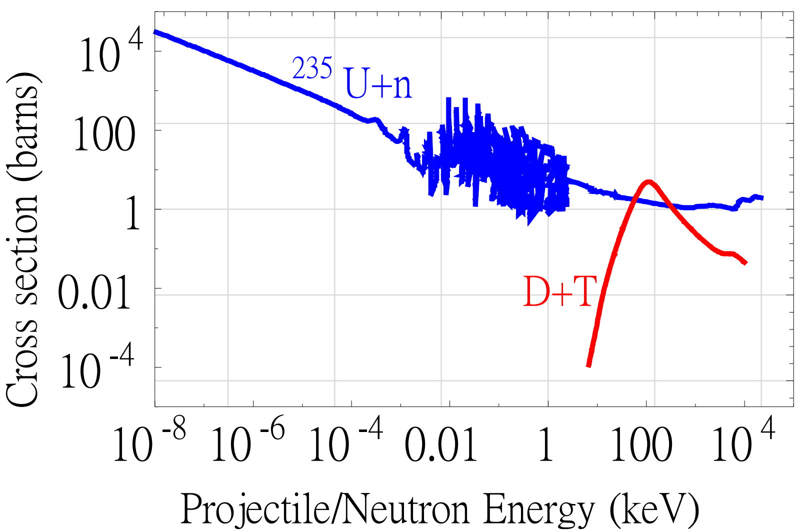


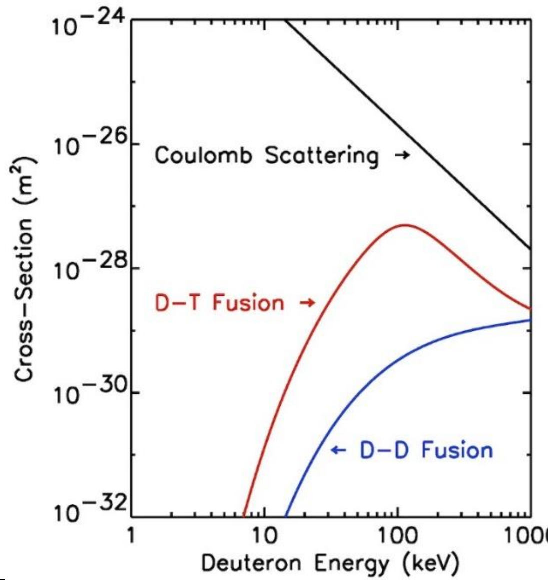
Fusion is much harder than fission

- **Fission:** $n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3n + 177\ \text{MeV}$
- **Fusion:** $D + T \rightarrow {}^{4}_{2}He(3.5\ \text{MeV}) + n(14.1\ \text{MeV})$





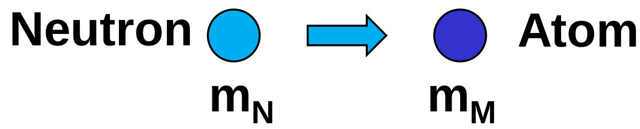




- **Beam particles lose their energy before making a fusion reaction, i.e., they only thermalize the fuel. Therefore, beam fusion does NOT work!**

https://www6.lehigh.edu/~eus204/lab/PCL_fusion.php#x1-10096
https://www.16pic.com/photo/pic_3815585.html

Fast neutrons are slowed down due to the collisions

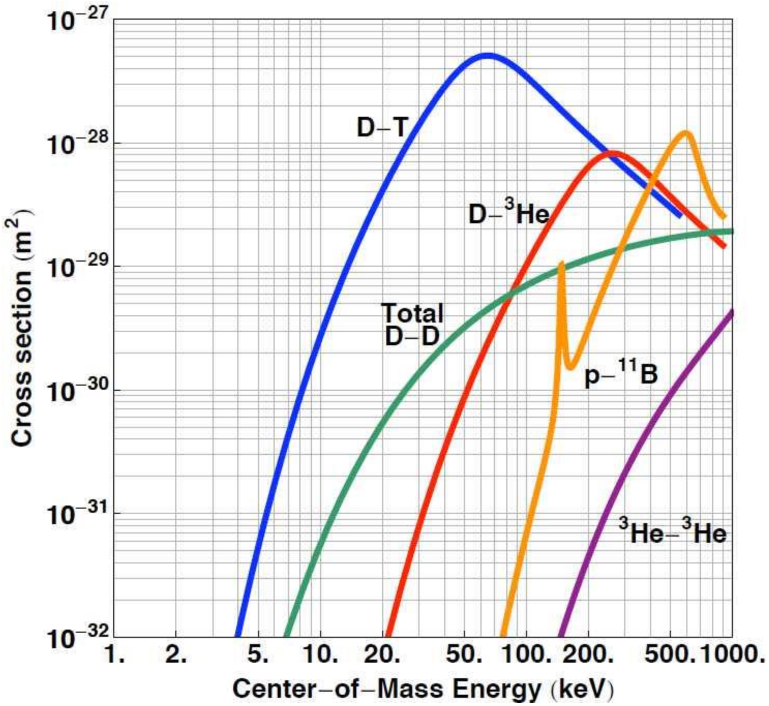


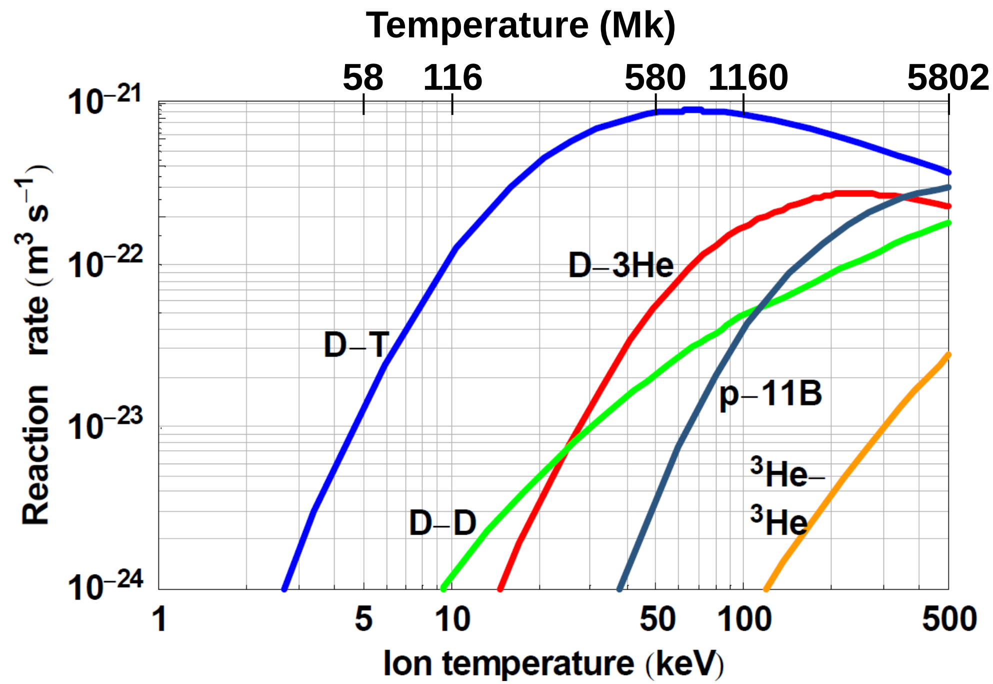
- **A moderator is used to slow down fast neutrons but not to absorb neutrons.**
- **For m_M~m_N, the energy decrement is higher. Therefore, H slows down neutron most efficiently.**
- **However, H + n → D, i.e., H absorbs neutrons.**
- **The best option is the D in the heavy water (D_2O).**

	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





$D + D \rightarrow T + p$

$\rightarrow He^3 + n$

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

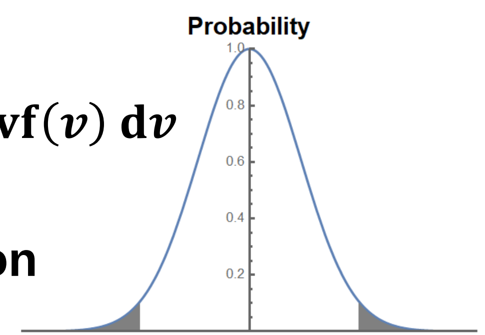
$D + He^3 \rightarrow He^4 + p$

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

- **Reaction rate:**

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

Cross section



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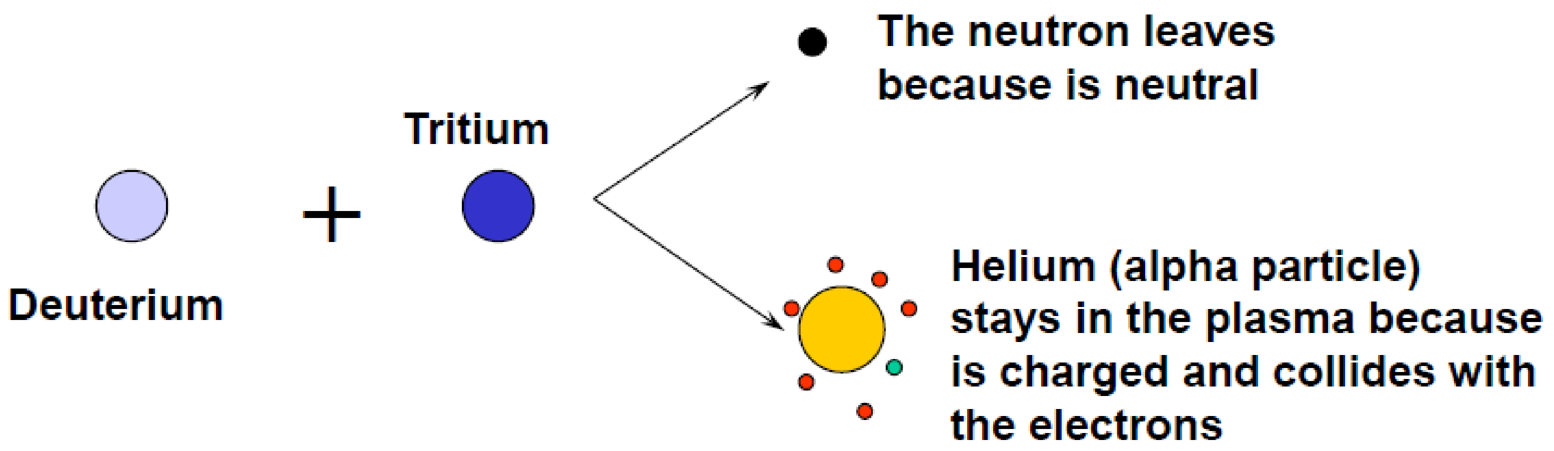
https://i.stack.imgur.com/wXQD5.jpg
Santarius, J. F., "Fusion Space Propulsion – A Shorter Time Frame Than You Think", JANNAF, Monterey, 5-8 December 2005.

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

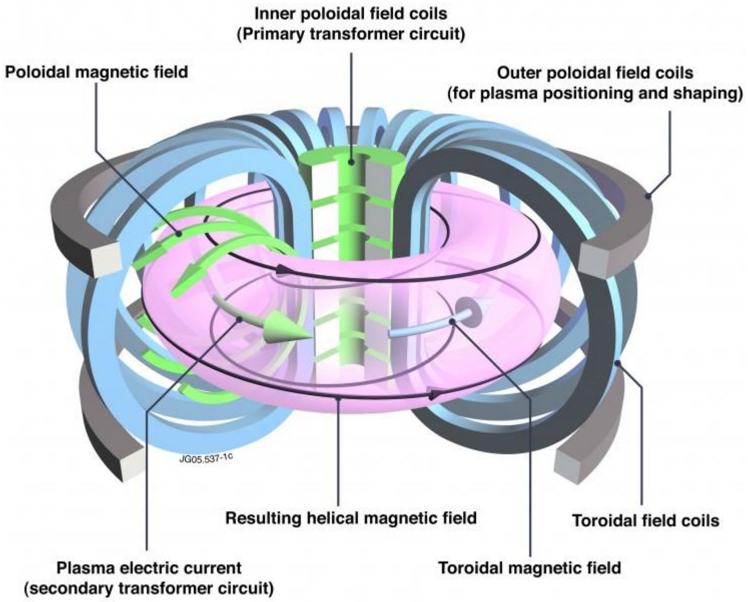
Ignition condition: $P\tau$ > 10 atm-s = 10 Gbar - ns

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

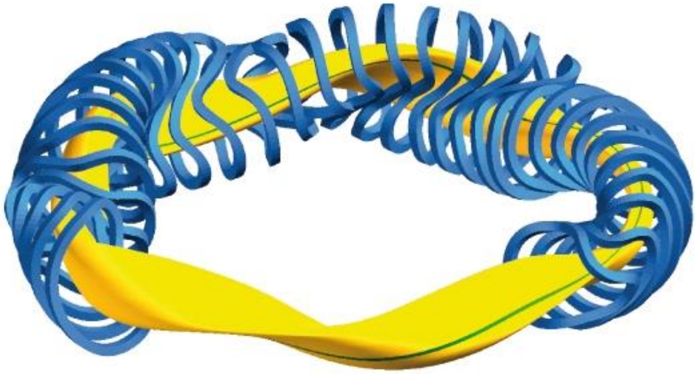
The plasma is too hot to be contained

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

Tokamak



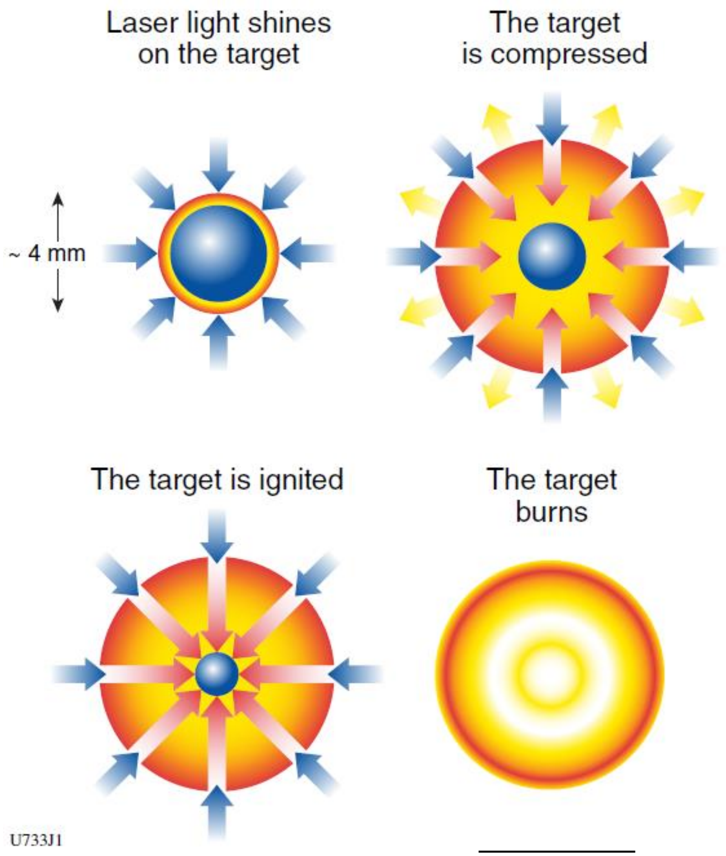
Stellarator



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

Don't confine it!

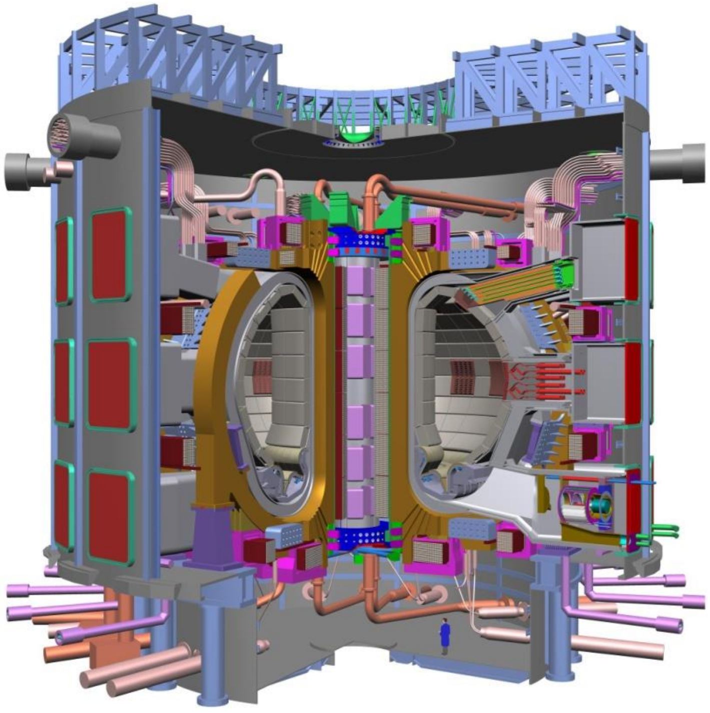
- **Solution 2: Inertial confinement fusion (ICF). Or you can say it is confined by its own inertia: P~Gigabar, τ~nsec, T~10 keV (10^8 ^{0}C)**



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

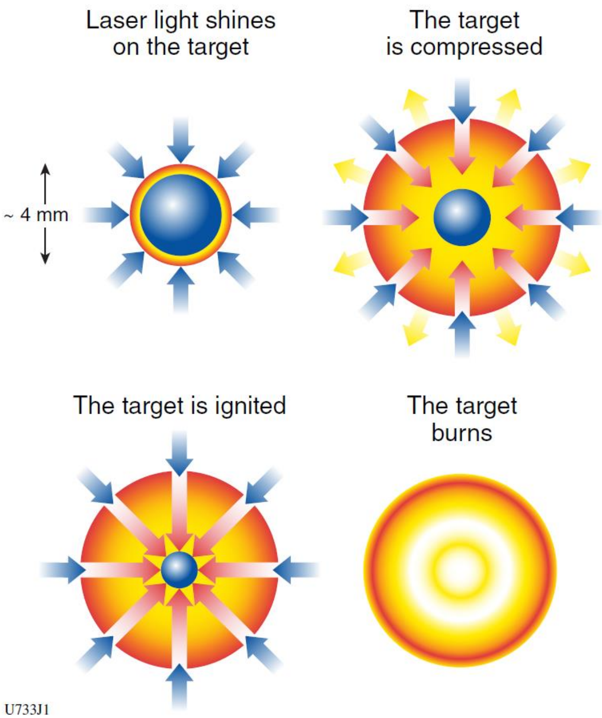
To control? Or not to control?

- **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

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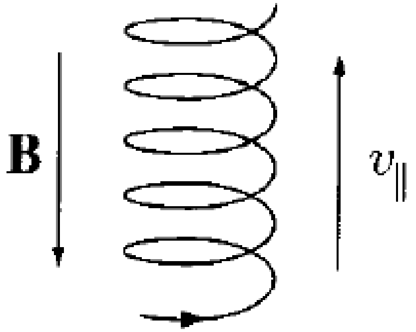
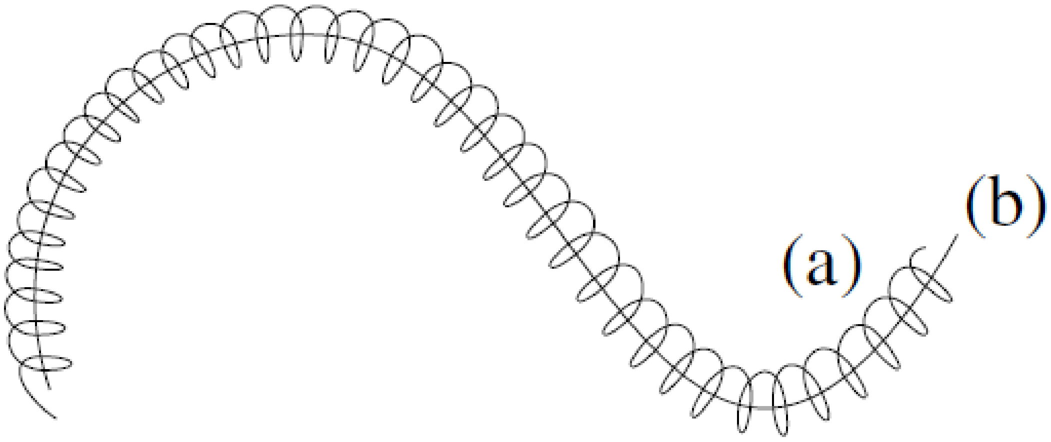
Charged particles gyro around the magnetic fields

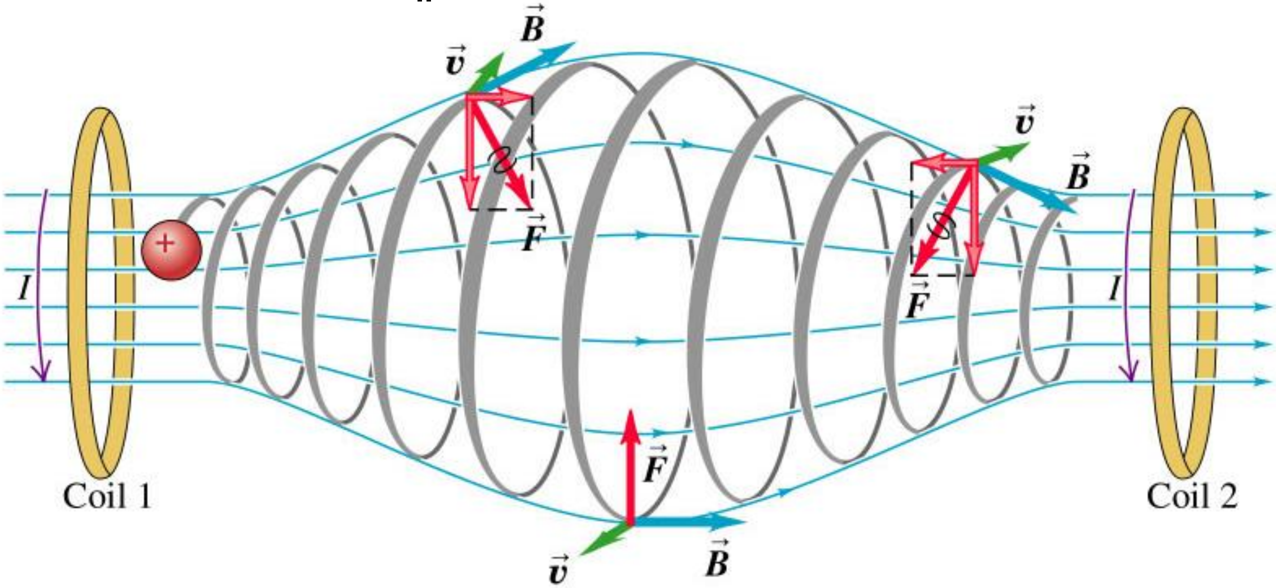


$$r_L = \frac{mv_\perp}{|q|B}$$



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.**



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

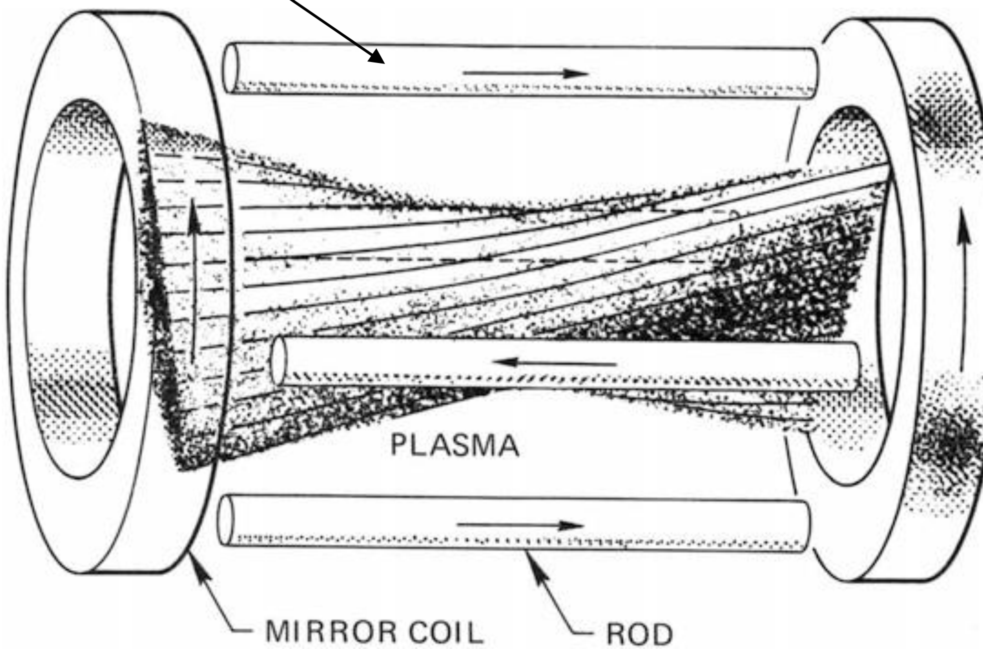
- **Large $v_{||}$ may occur from collisions between particles.**

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

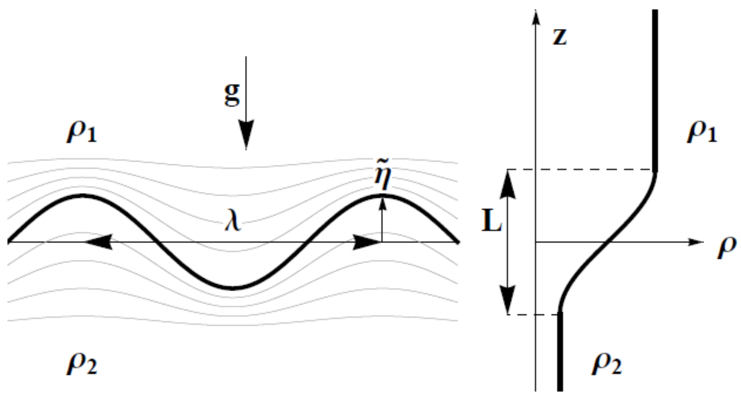
https://i.stack.imgur.com/GlzGZ.jpg

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

Ioffe bars



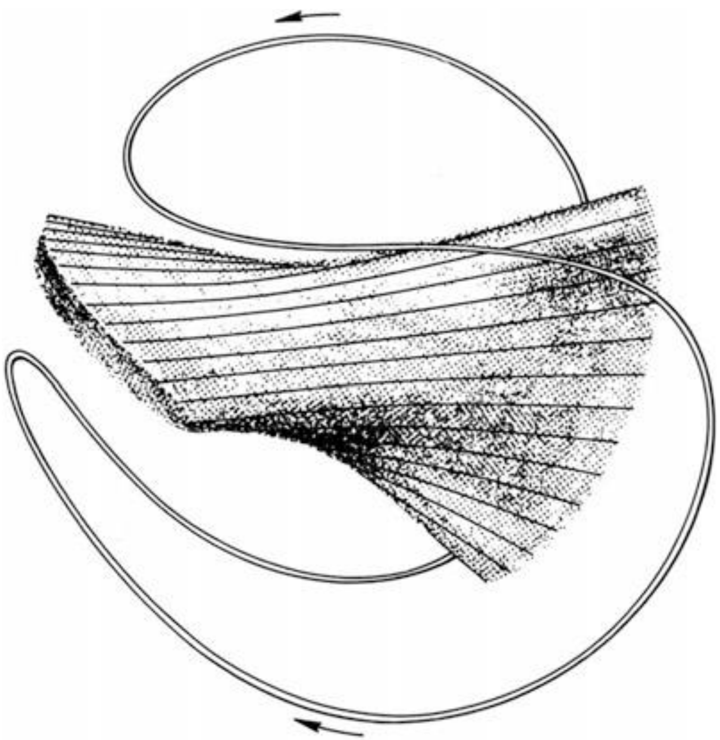
- **Rayleigh-Taylor instability**



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

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

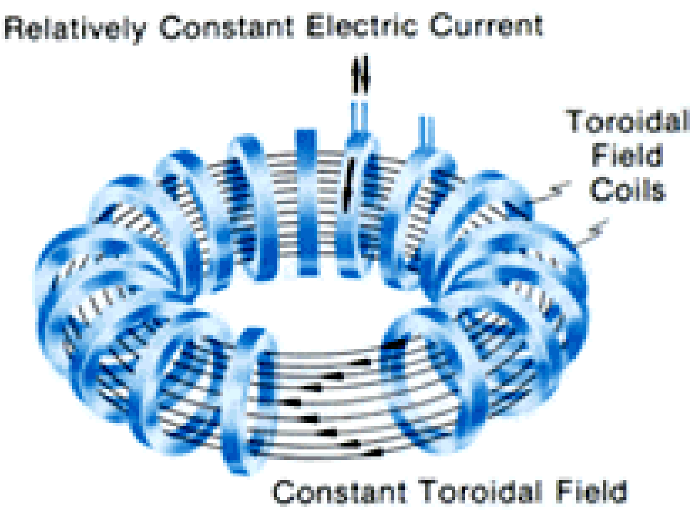
- **Baseball coil**

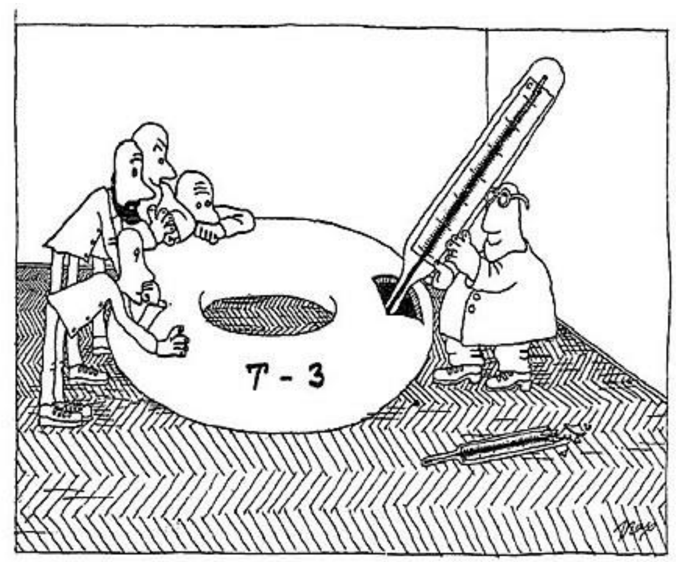


- **MFTF-B mirror machine**

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

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

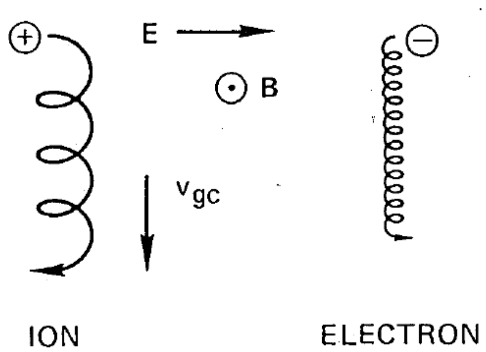




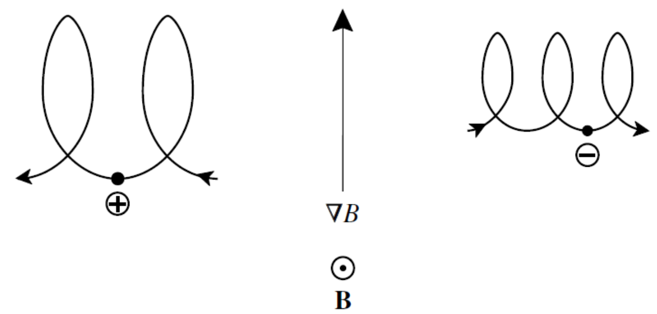
https://www.iter.org/mach/tokamak
https://en.wikipedia.org/wiki/Tokamak#cite_ref-4
Drawing from the talk “Evolution of the Tokamak” given in 1988 by B.B. Kadomtsev at Culham.

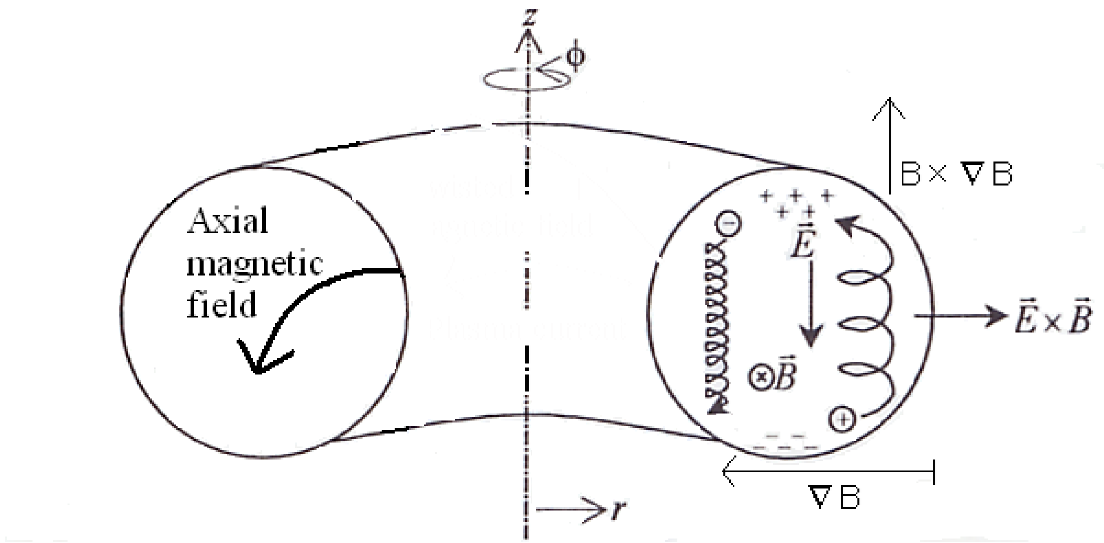
Charged particles drift across field lines

- **ExB drift**



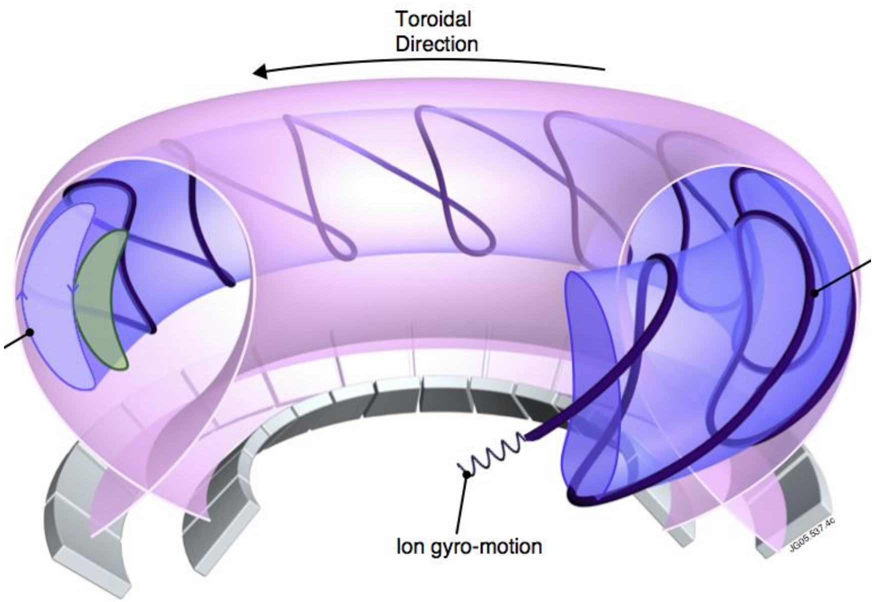
- **Grad-B drift**

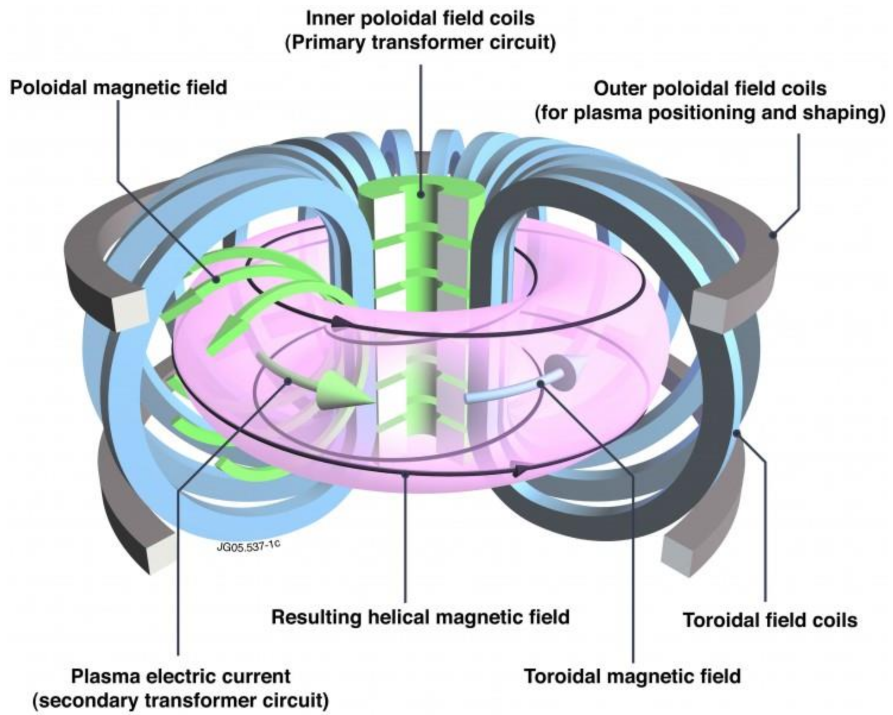




http://www.geocities.jp/tomoyahirata417/fusion/gennkou.htm

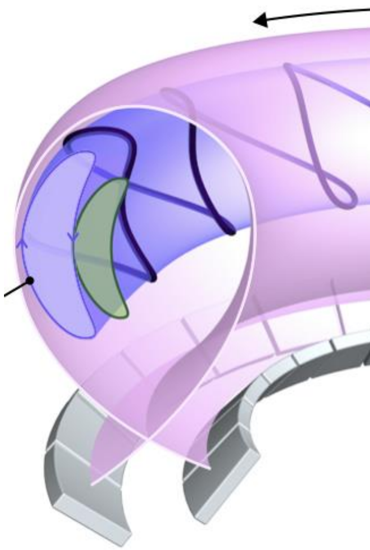
A poloidal magnetic field is required to reduce the drift across field lines

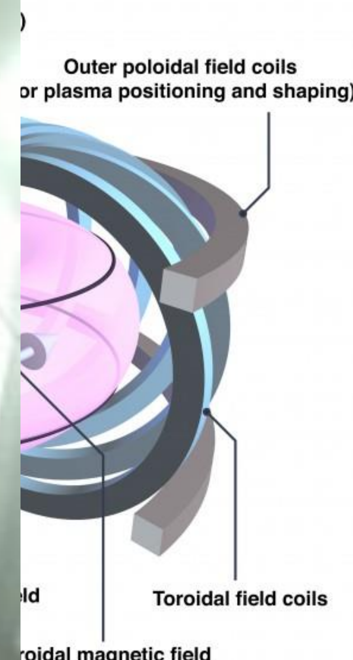




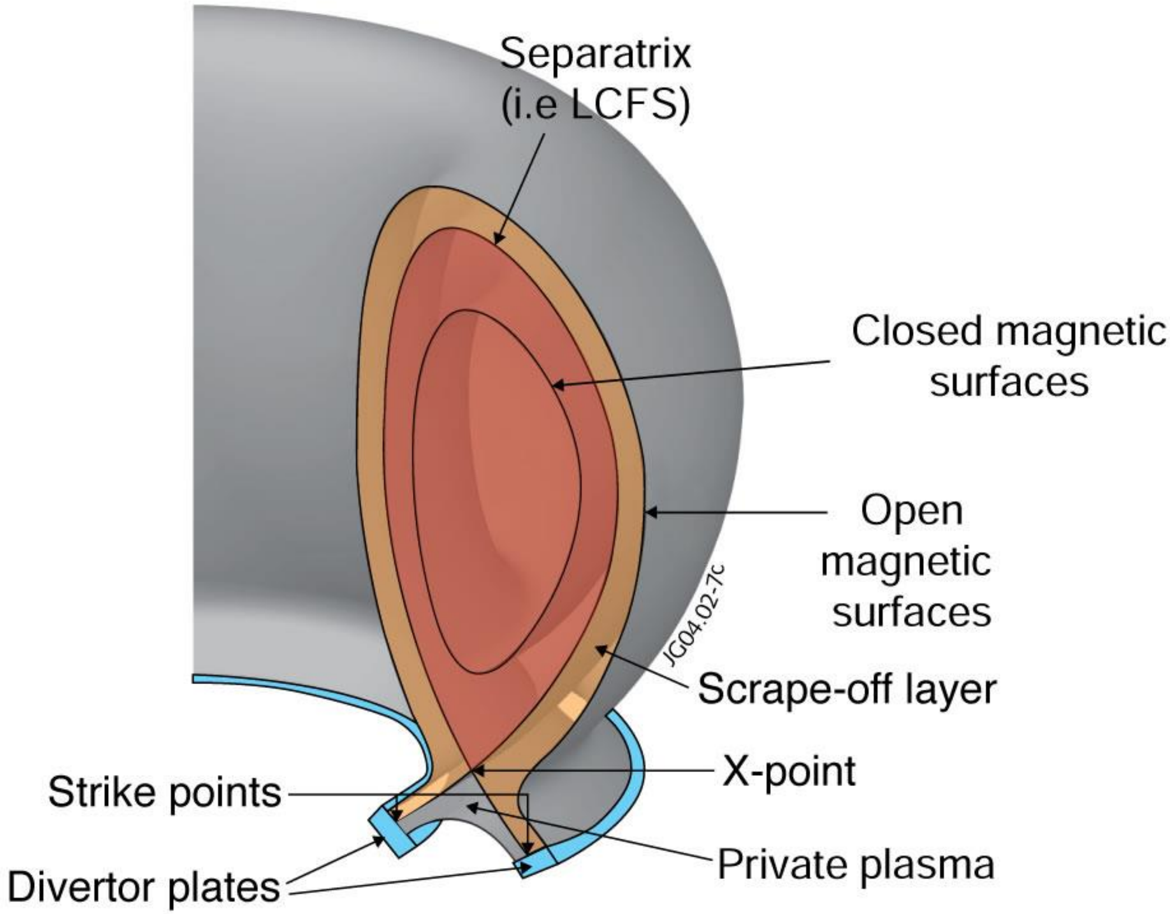
https://www.davidpace.com/keeping-fusion-plasmas-hot/
https://www.euro-fusion.org/2011/09/tokamak-principle-2/

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



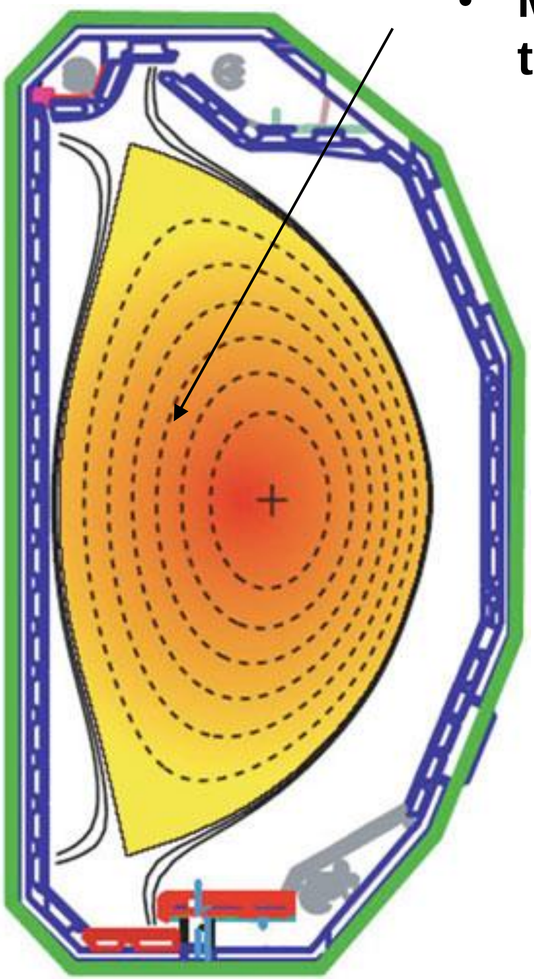


A divertor is needed to remove impurities and the power that escapes from the plasma



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

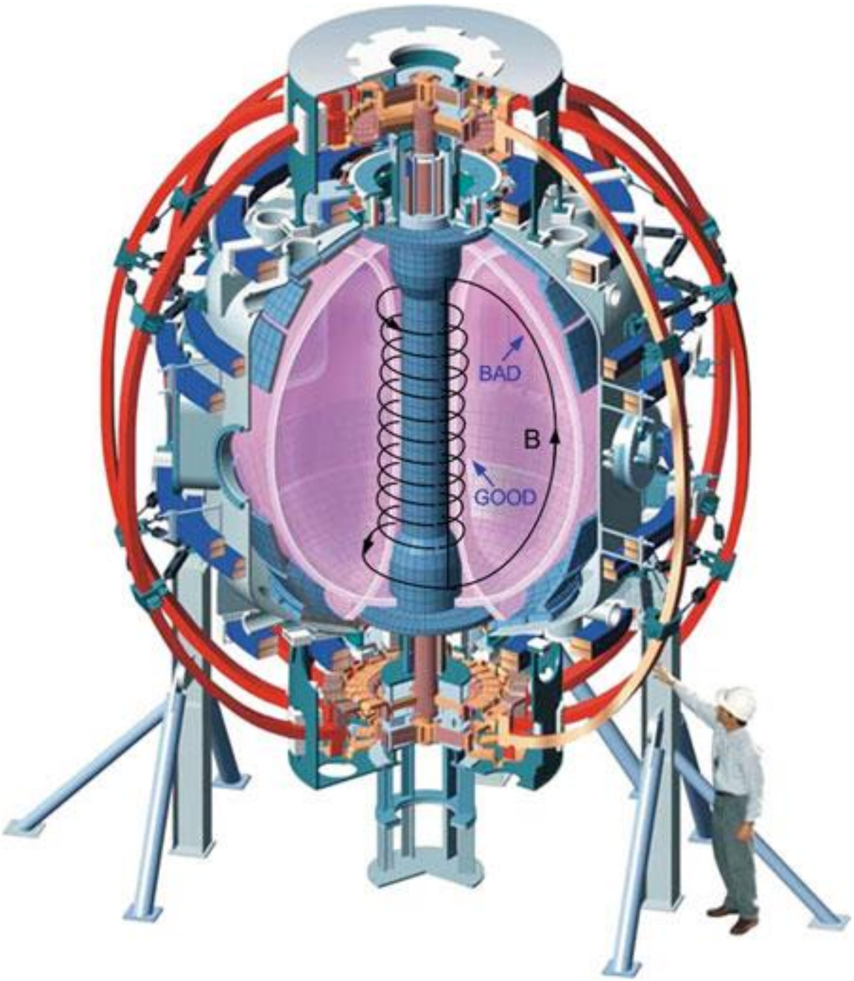
D-shaped tokamak with diverter is more preferred nowadays



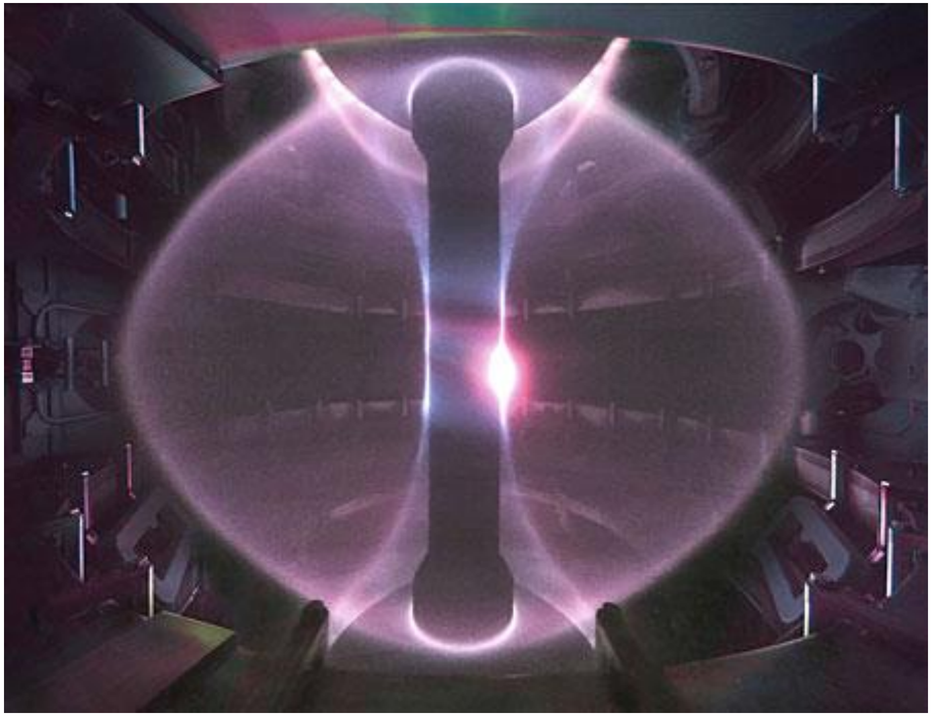
- **Make the plasma closer to the major axis**

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

- **NSTX @ Princeton**

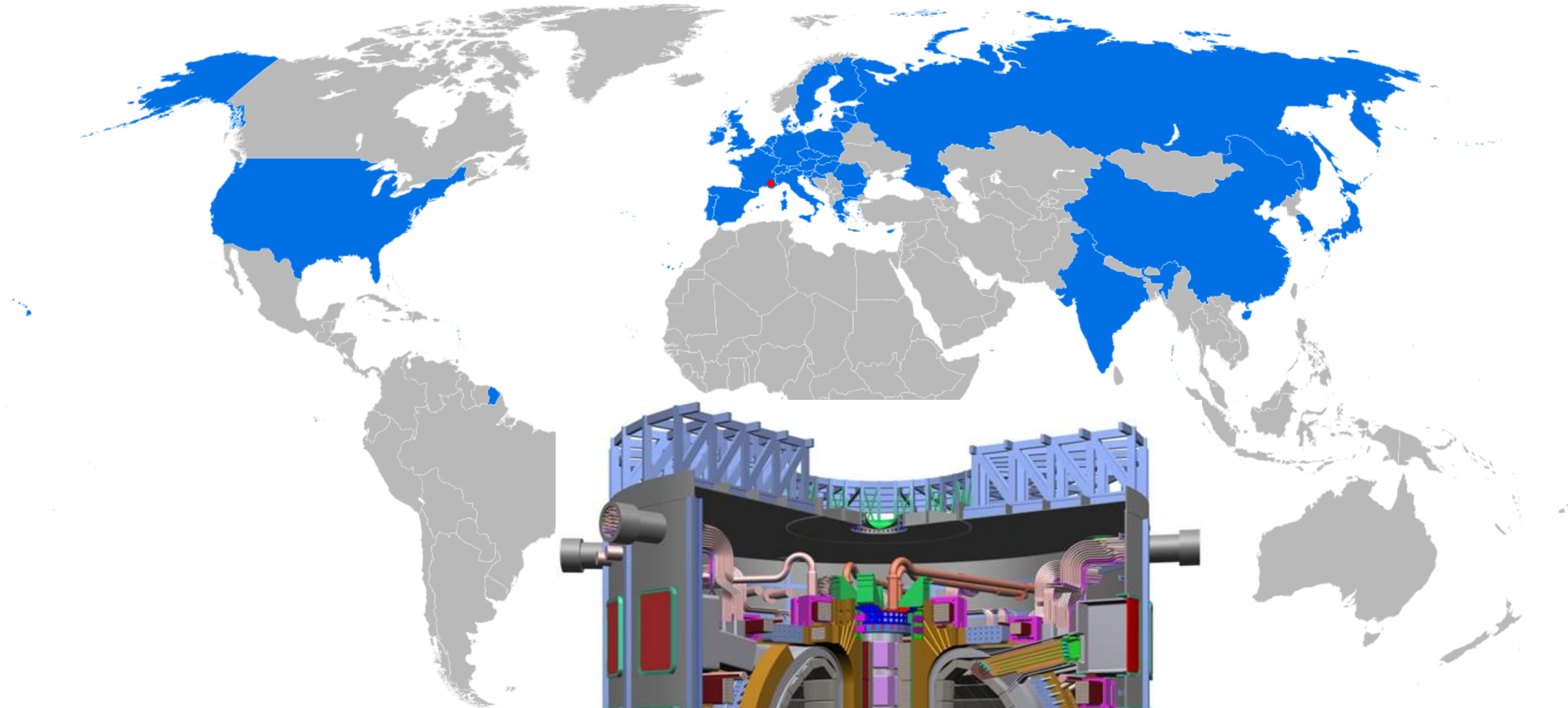


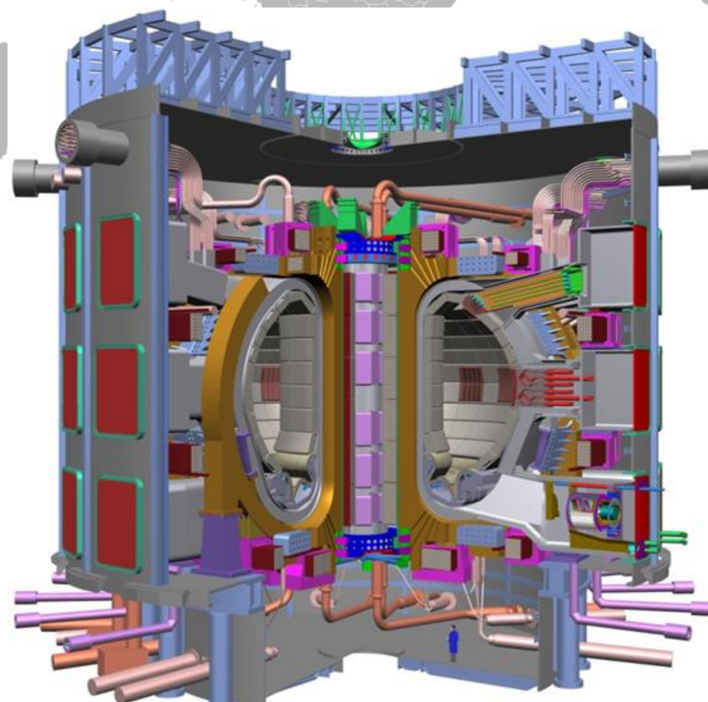
- **MegaAmpere Spherical Tokamak (MAST) @ Culham center for fusion energy, UK**



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

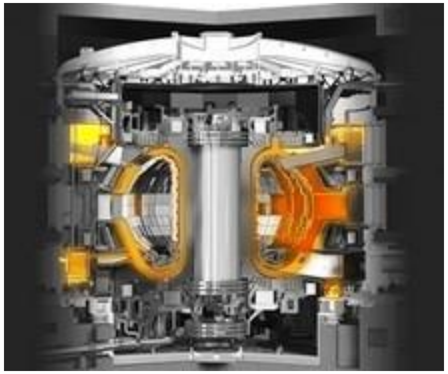




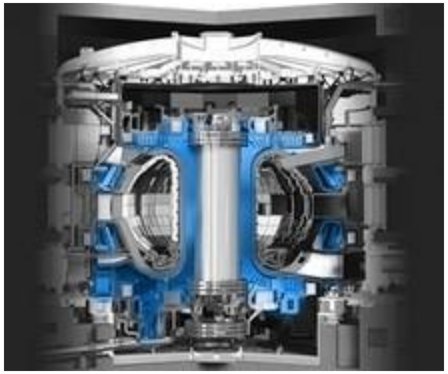
https://www.iter.org

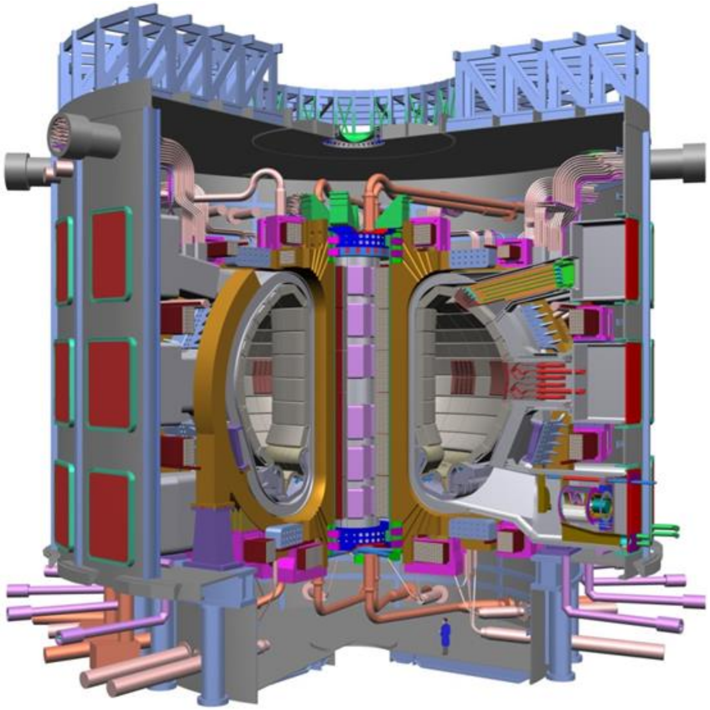
ITER ("The Way" in Latin) is one of the most ambitious energy projects in the world today

- **Vacuum vessel**

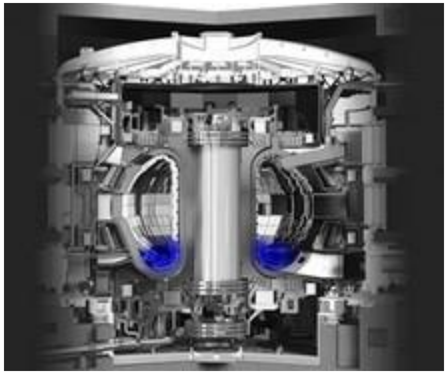


- **Magnets**

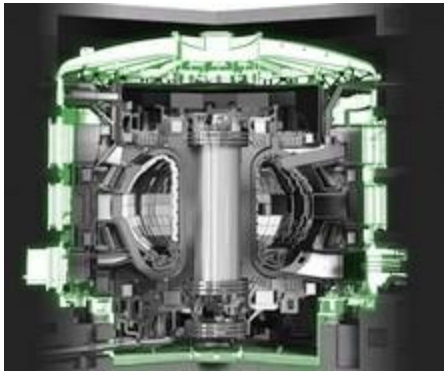




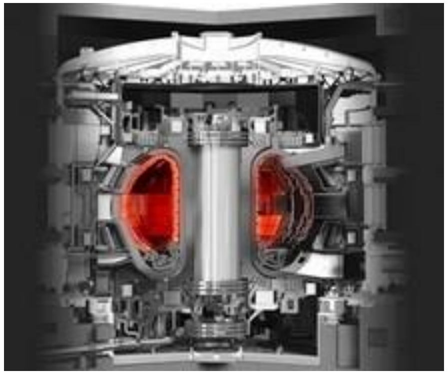
- **Divertor**



- **Cryostat**



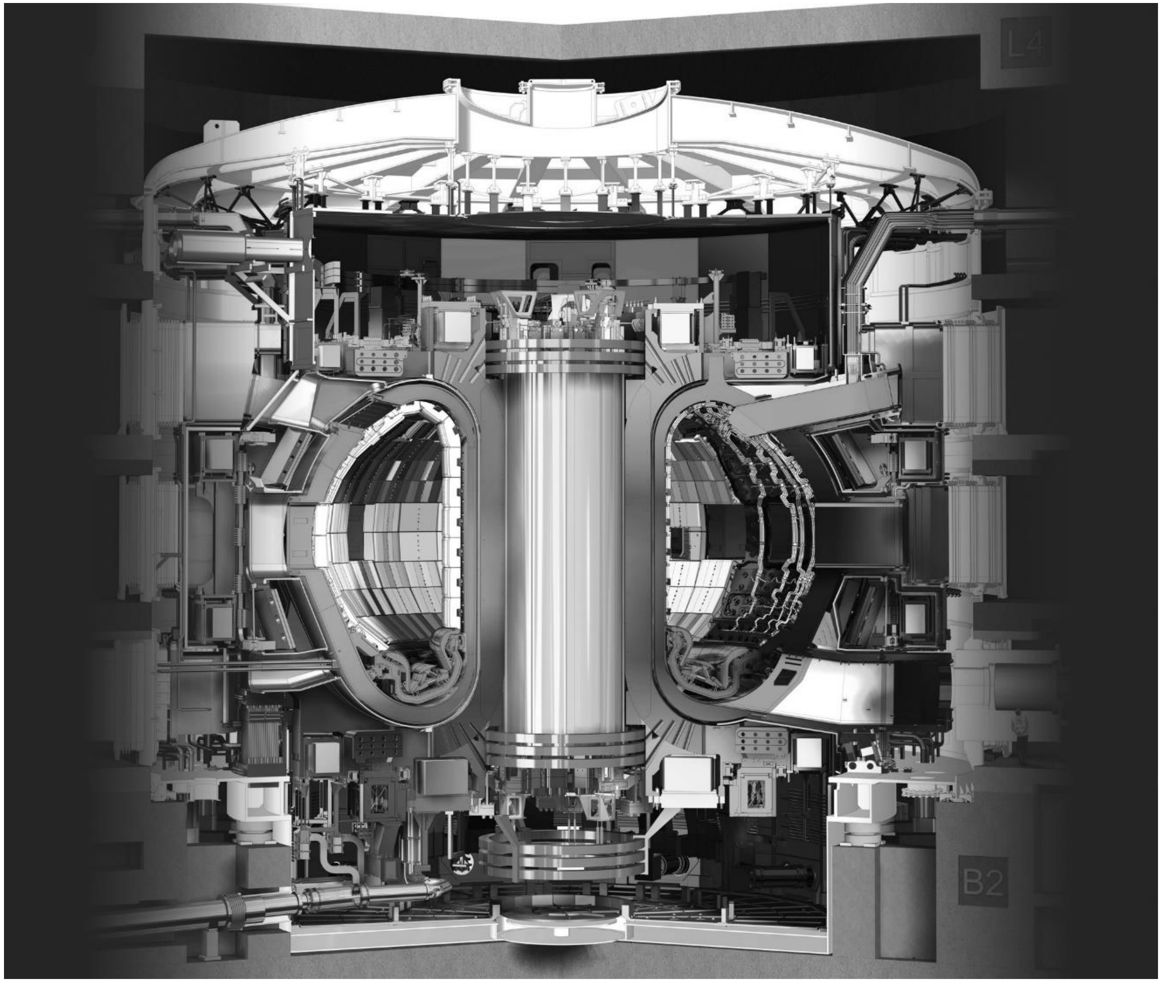
- **Blanket**



https://www.iter.org/

ITER

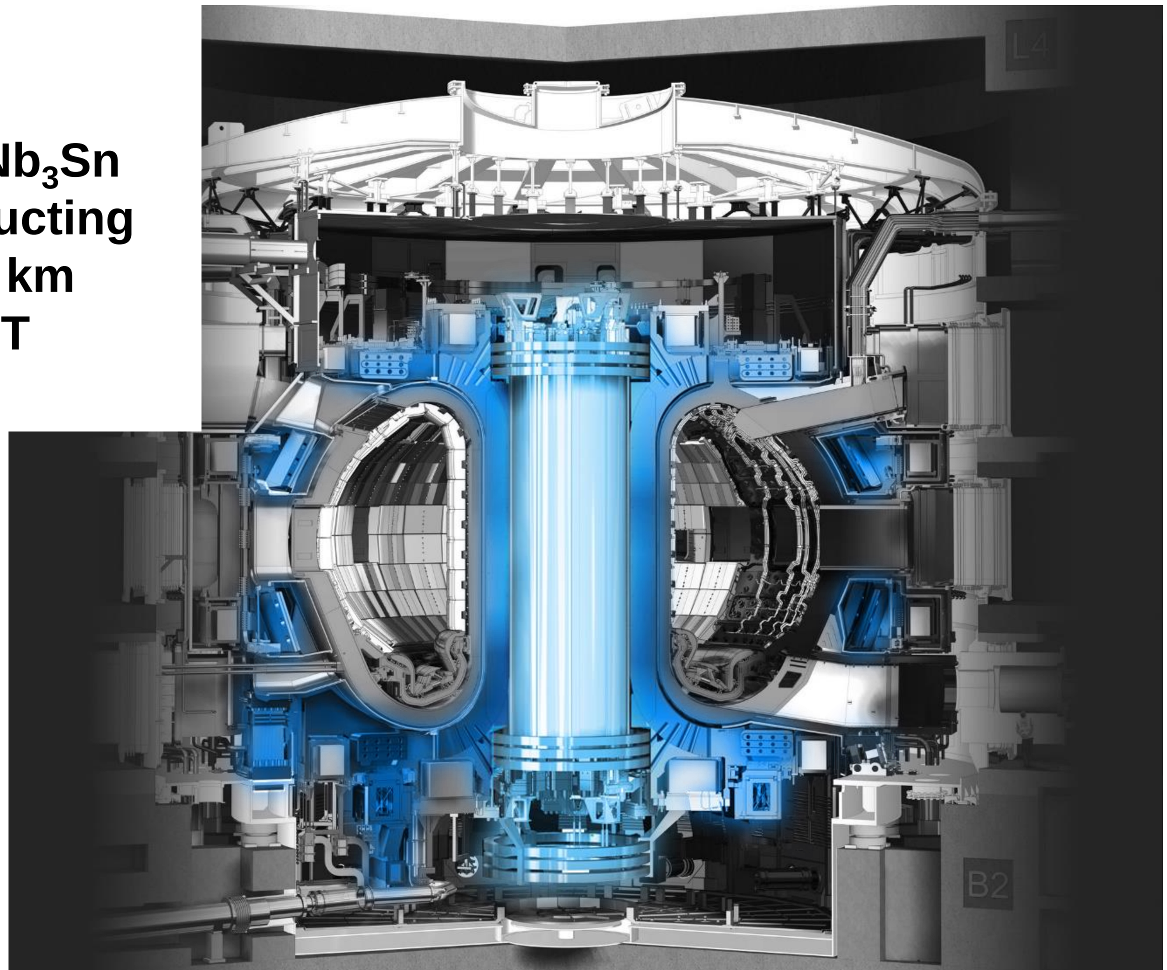
- **T=150M ^{0}C**
- **P=500 MW**



https://www.iter.org

ITER – Magnets

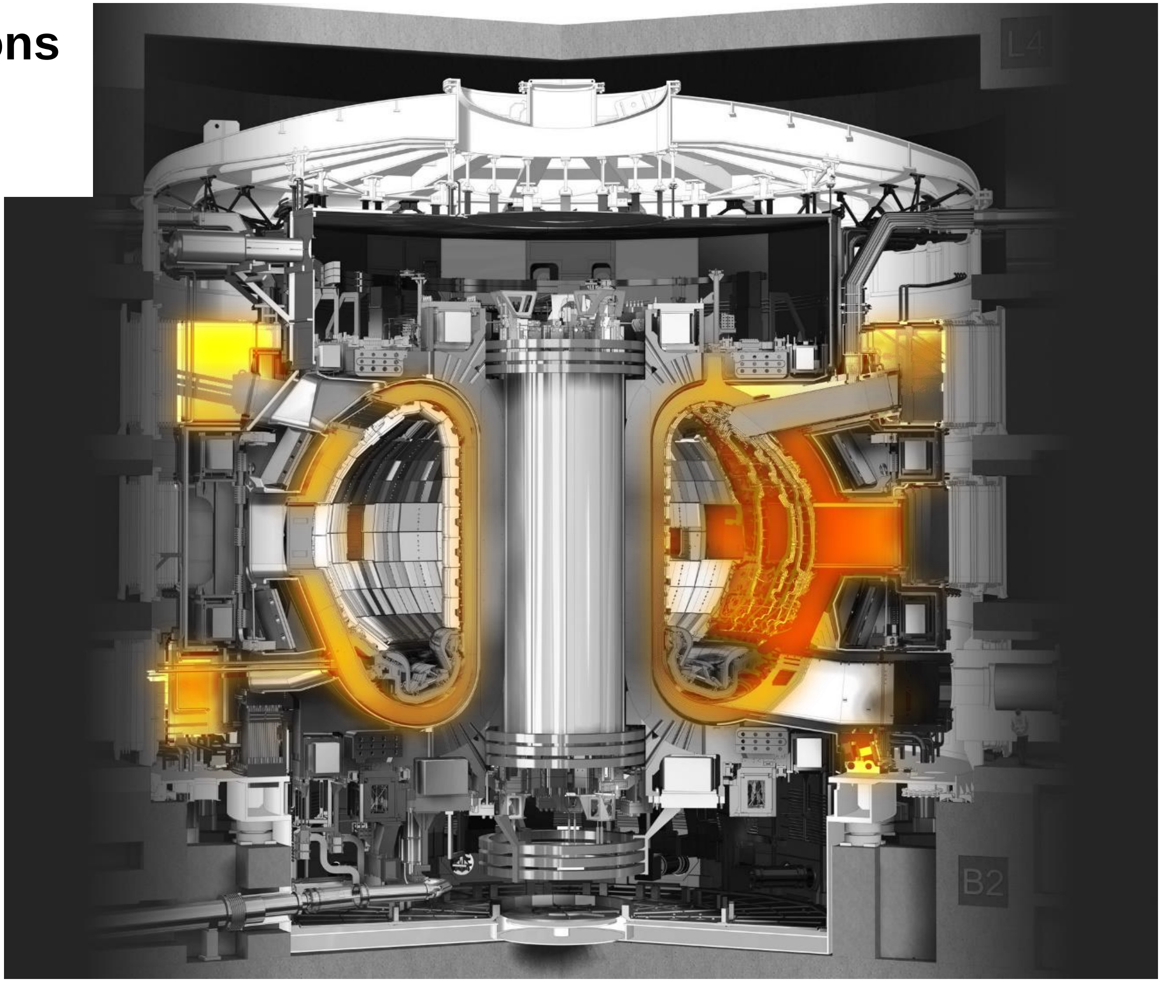
- E_B=51 GJ
- T_B=4 K
- Length of Nb_3Sn superconducting strand: 10^5 km
- $B_{T,max}$=11.8 T
- $B_{P,max}$=6 T



https://www.iter.org

ITER – Vacuum vessel

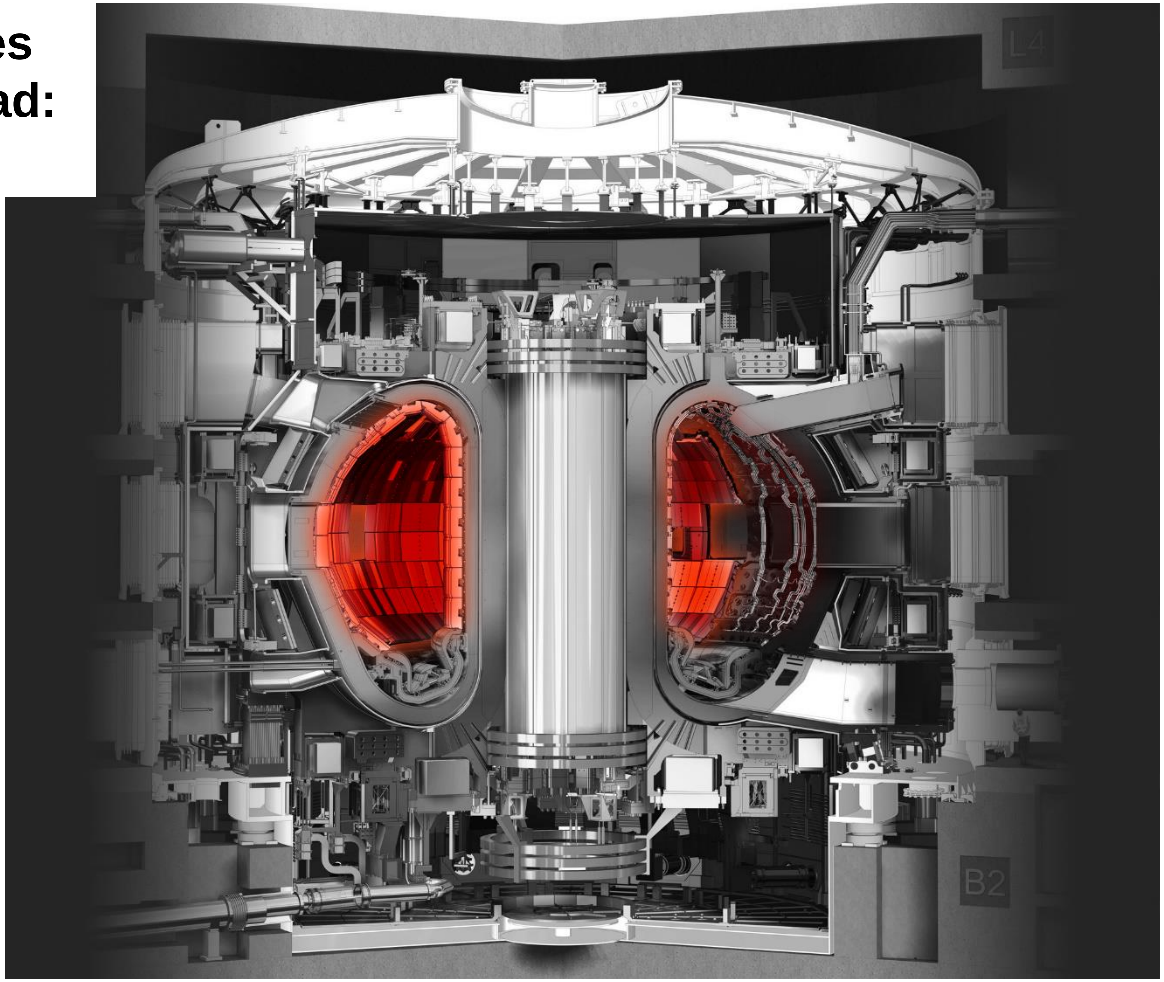
- **W = 8000 tons**
- **V = 840 m^3**
- **R = 6 m**



https://www.iter.org

ITER – Blanket

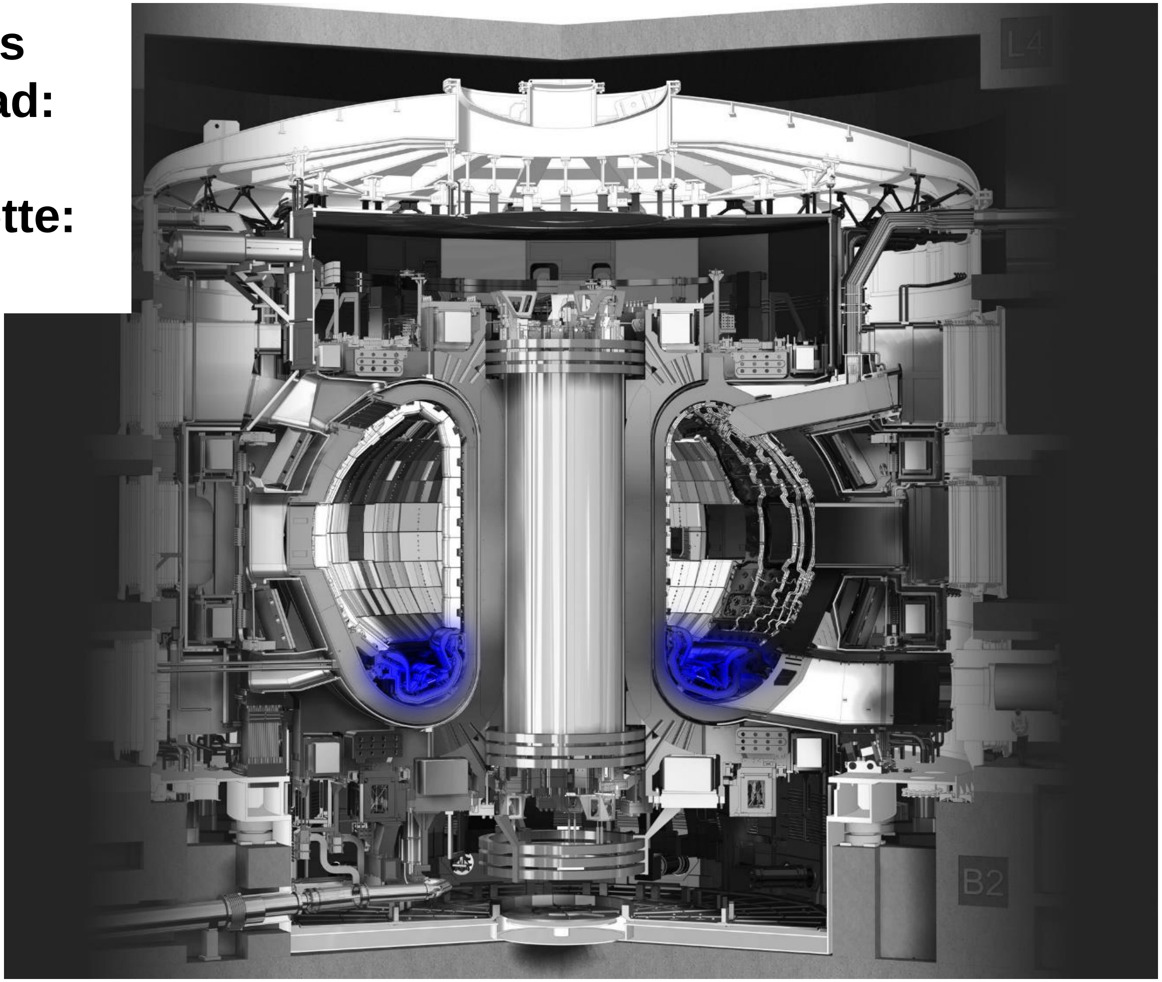
- **440 modules**
- **Thermal load: 736 MW**



https://www.iter.org

ITER – Divertor

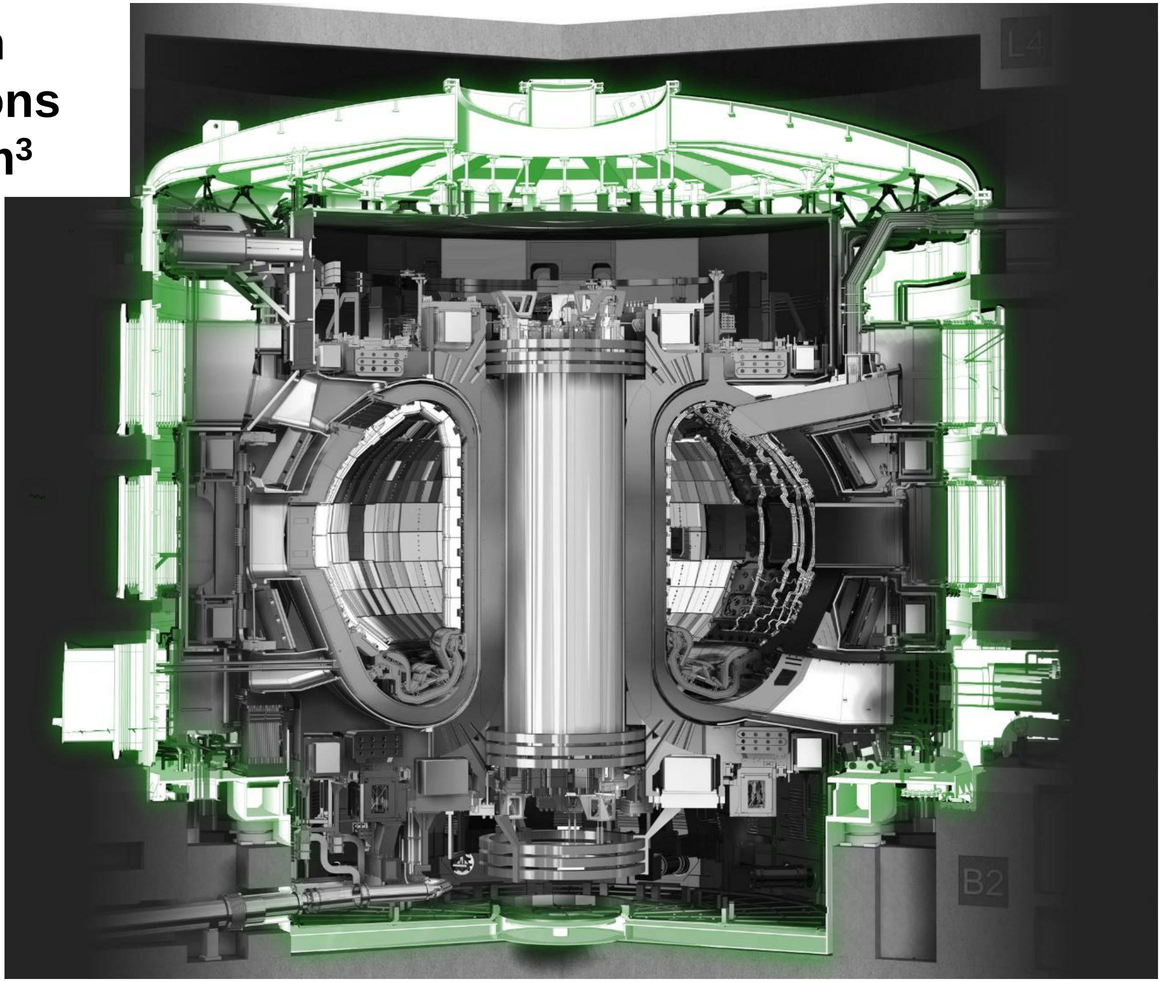
- **54 cassettes**
- **Thermal load: 20 MW/m²**
- **Each cassette: 10 tons**



https://www.iter.org

ITER – Crystat

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

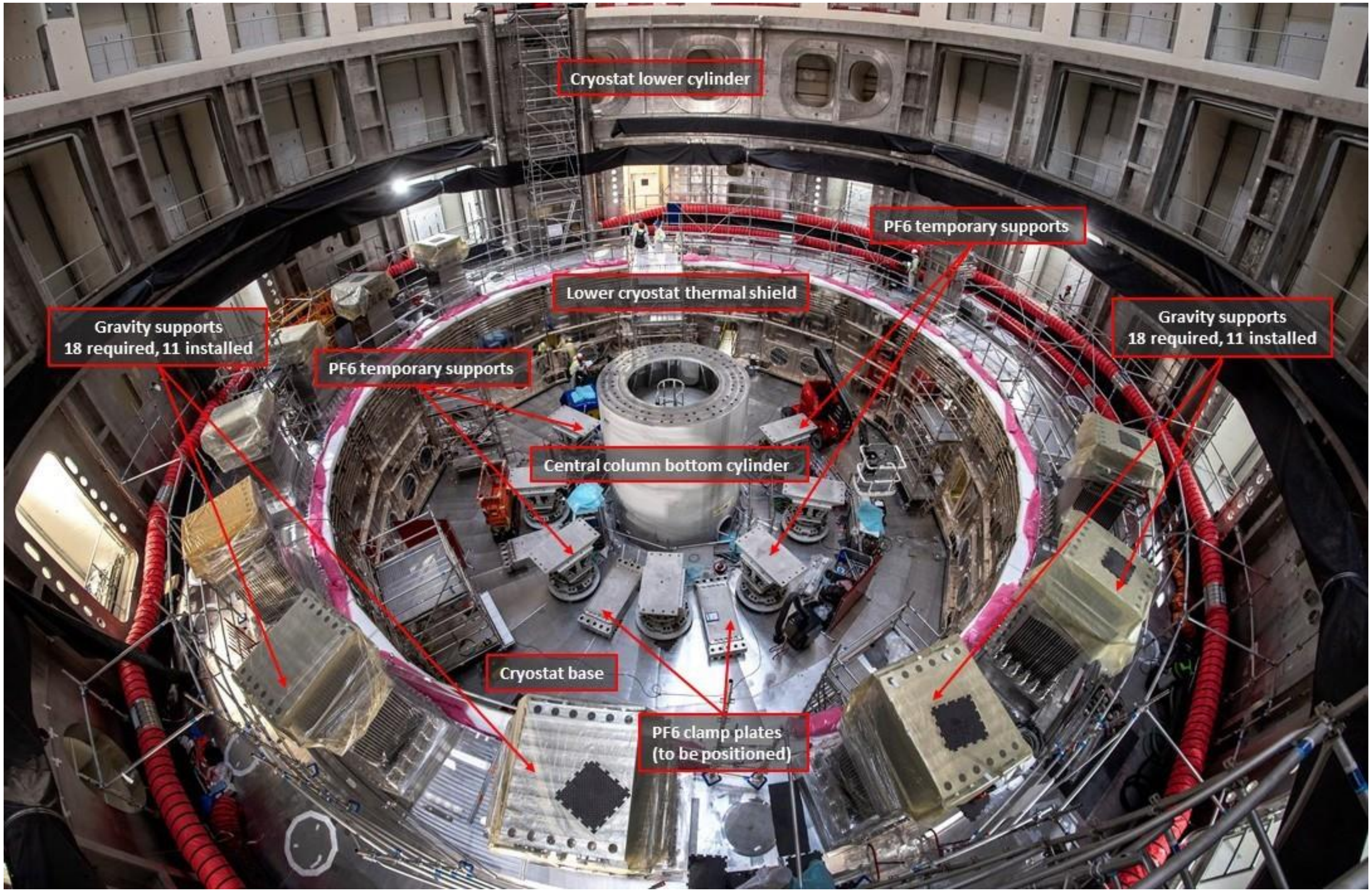


https://www.iter.org

Supporting systems

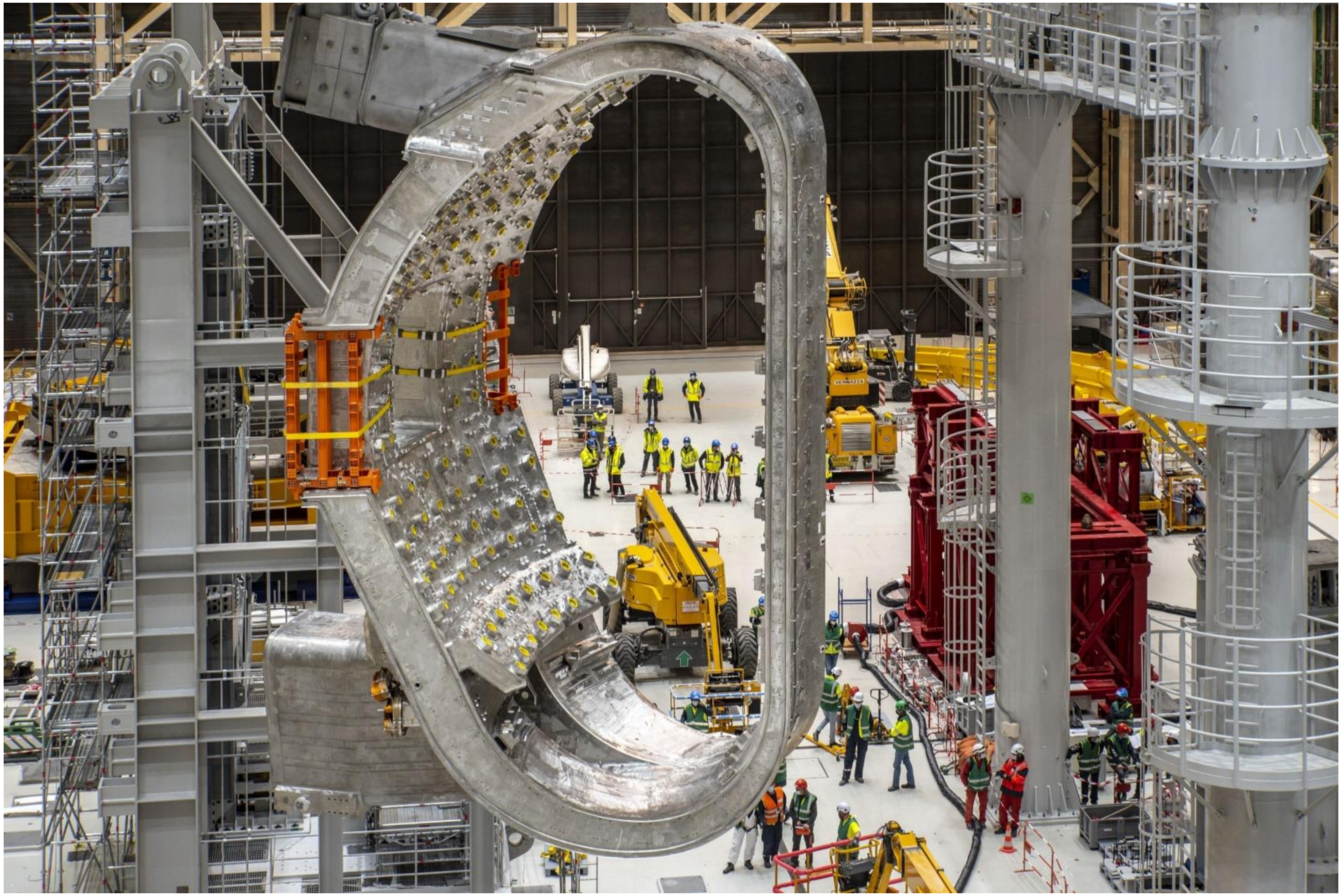
- Tritium breeding
- Control, Data access and Communication (CODAC)
- Cooling water
- Cryogenics
- Diagnostics
- Fuel cycle
- Hot cell - a secure environment for processing, repair or testing, etc., of components that have become activated by neutrons.
- Power supply
- Remote handling
- Heating and current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

ITER is being assembled



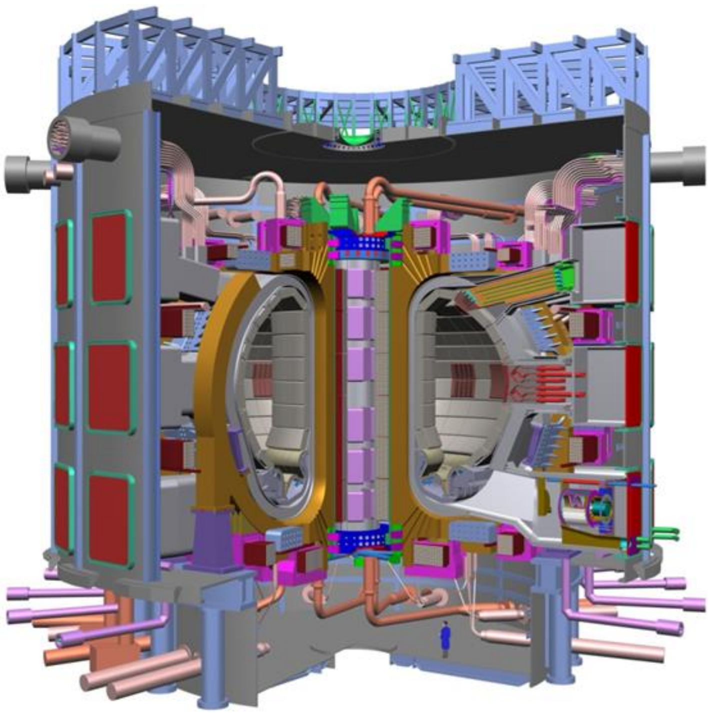
https://www.iter.org

ITER is being assembled



https://www.iter.org

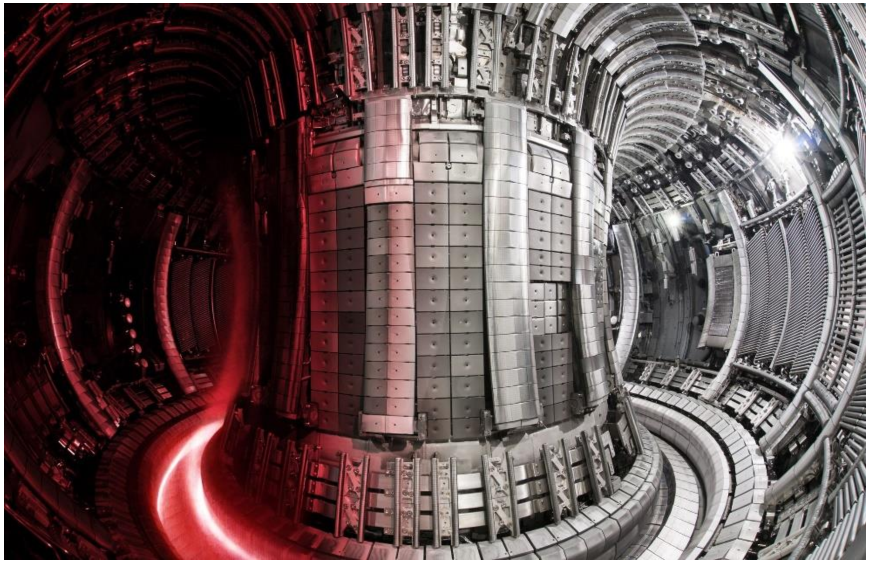
There is a long way to go, but we are on the right path…



•	**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

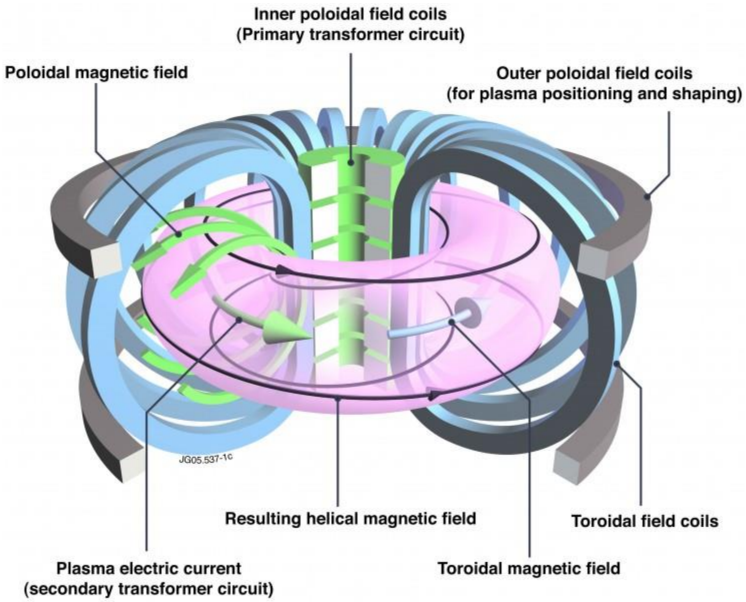


- **Record-breaking 59 megajoules of sustained fusion energy in Joint European Torus (JET) facility in Oxford demonstrates powerplant potential and strengthens case for ITER.**

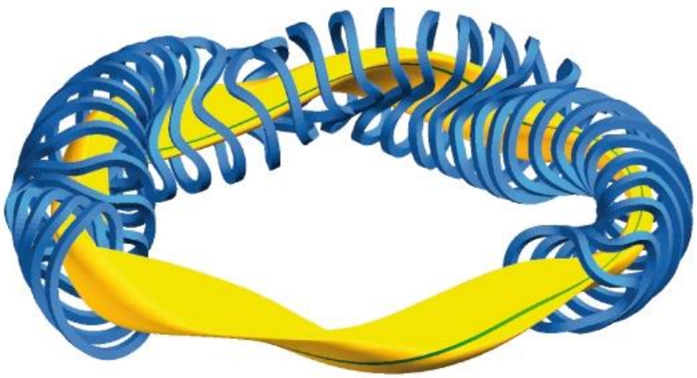
https://ccfe.ukaea.uk/resources/#gallery

Stellarator uses twisted coil to generate poloidal magnetic field

Tokamak

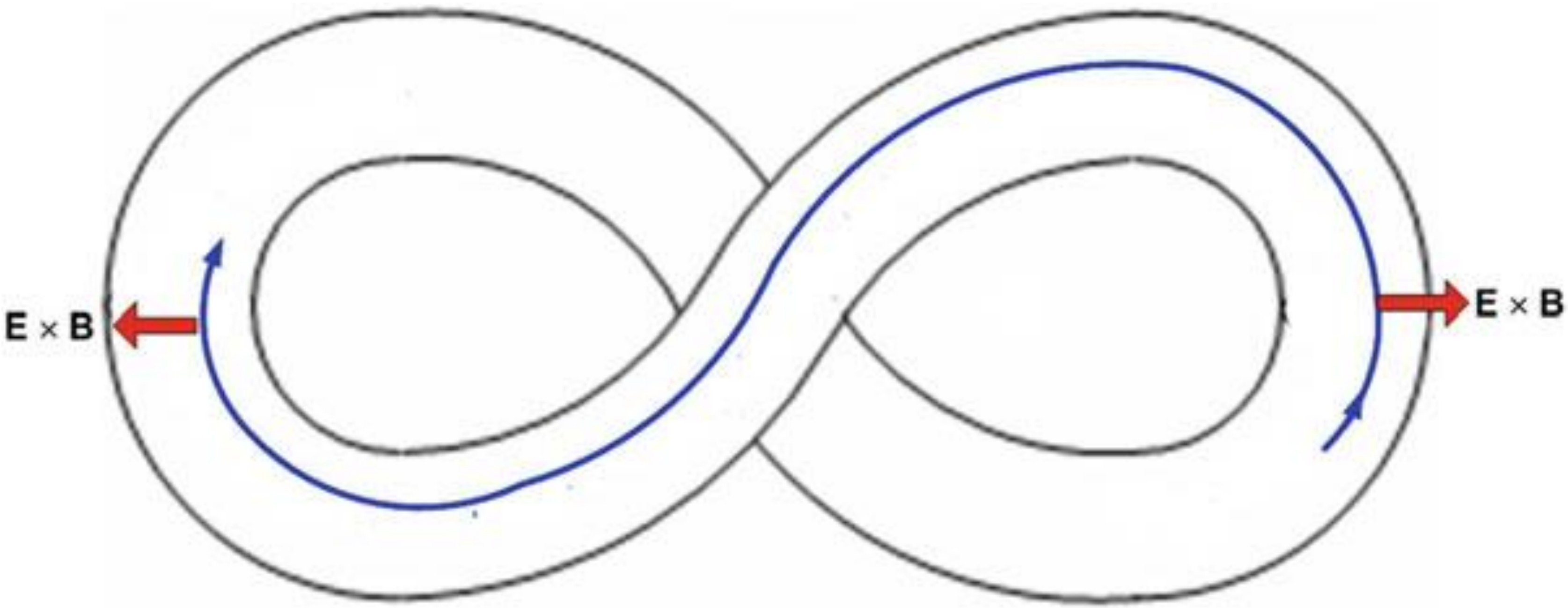


Stellarator



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

A figure-8 stellarator solved the drift issues



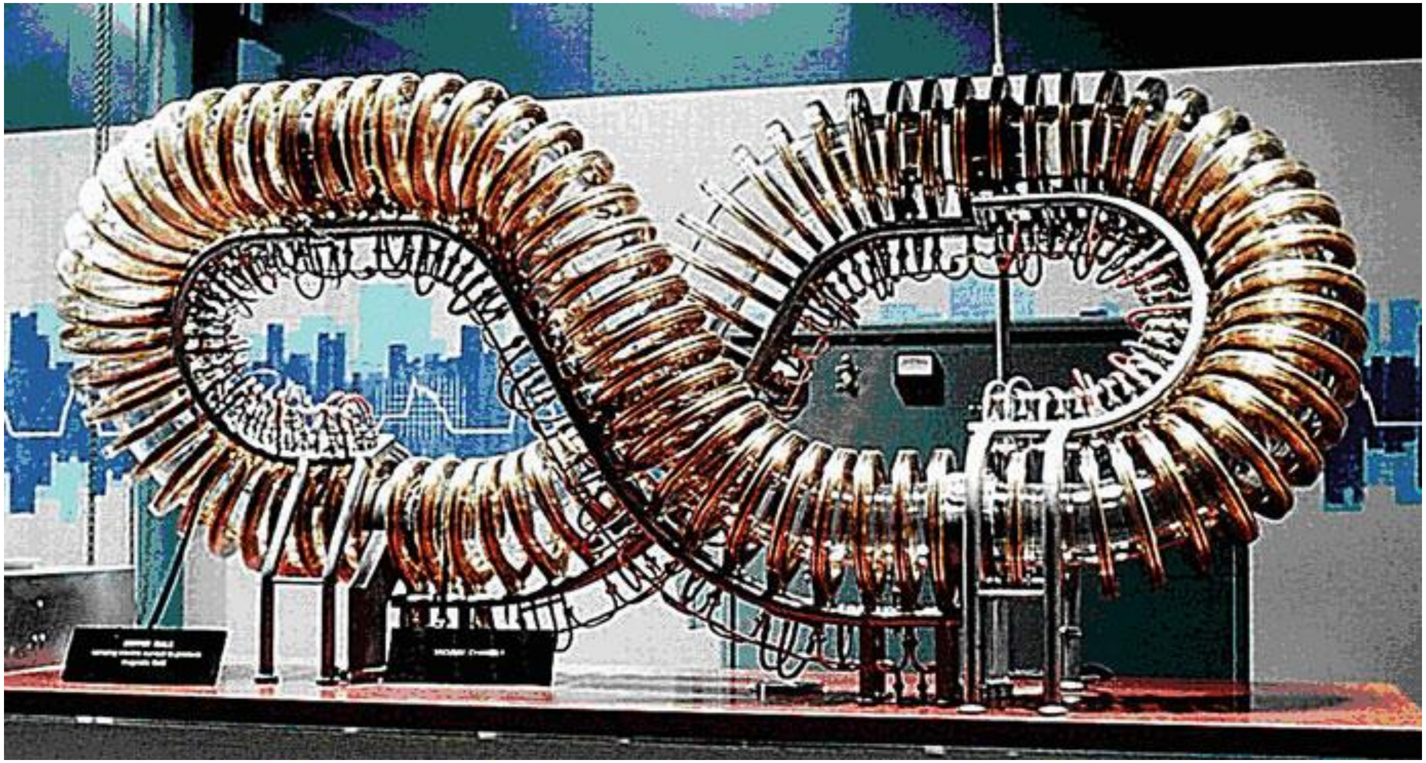
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

A figure-8 stellarator solved the drift issues

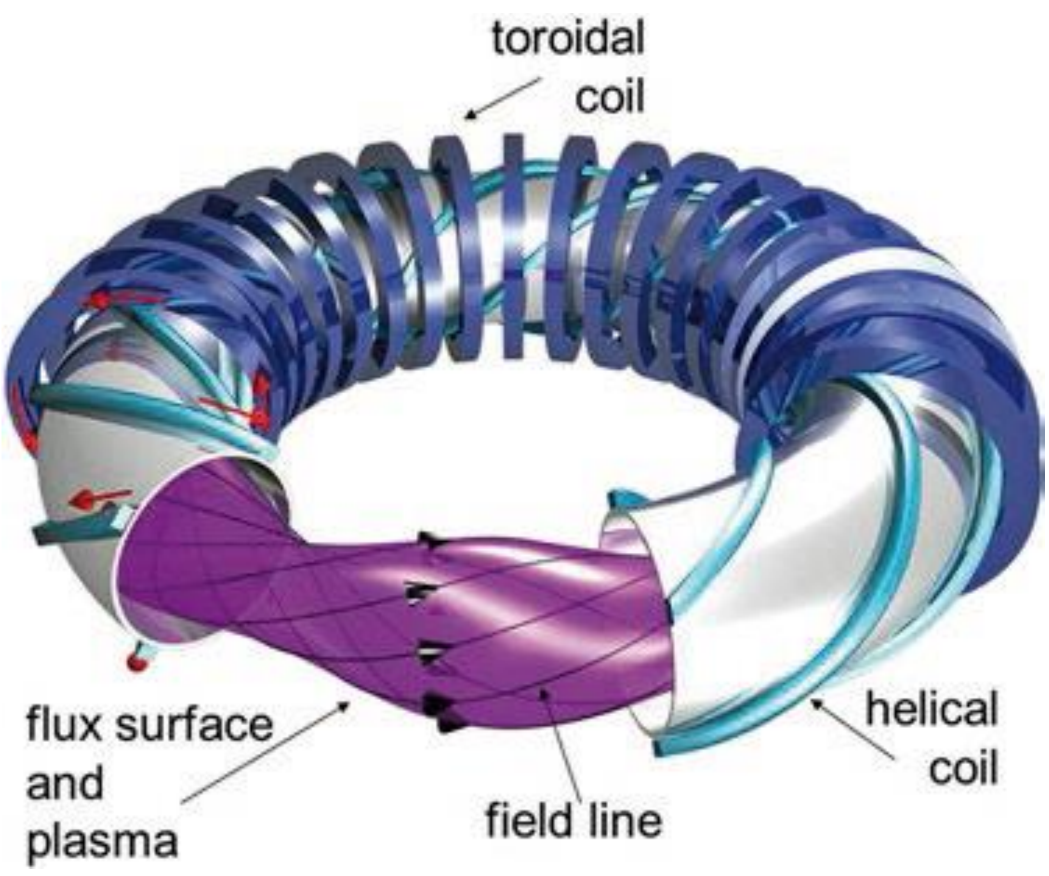
Lyman Spitzer, Jr. came out the idea during a long ride on a ski lift at Garmisch-Partenkirchen

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

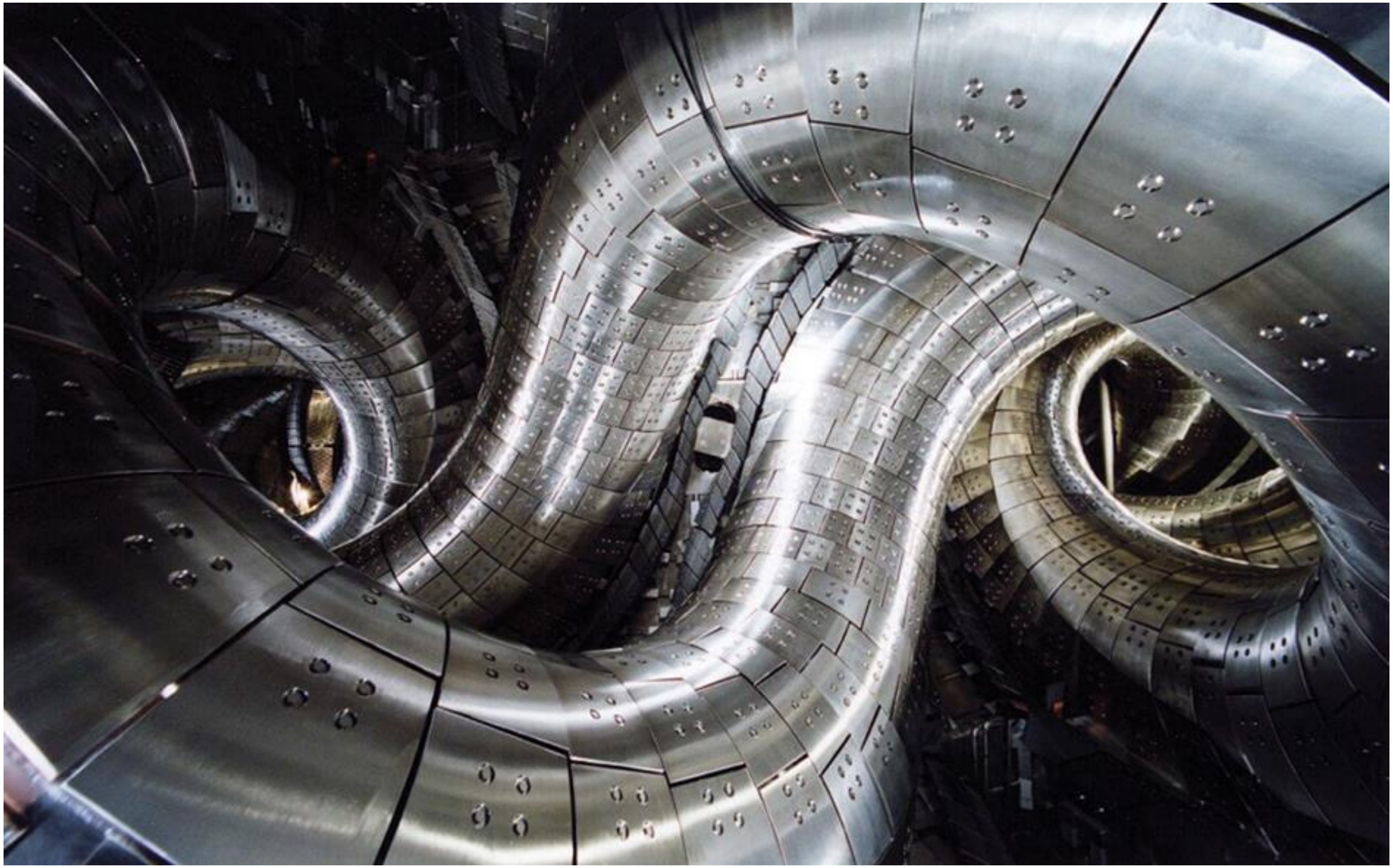


Twisted magnetic field lines can be provided by toroidal coils with helical coils



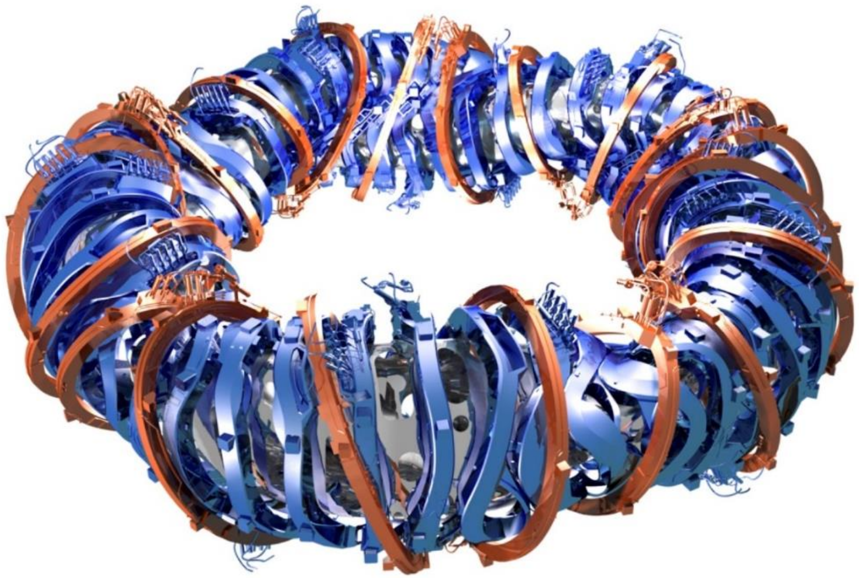
Wagner, F., Fusion energy. MRS Energy & Sustainability, 5, E8 (2018)

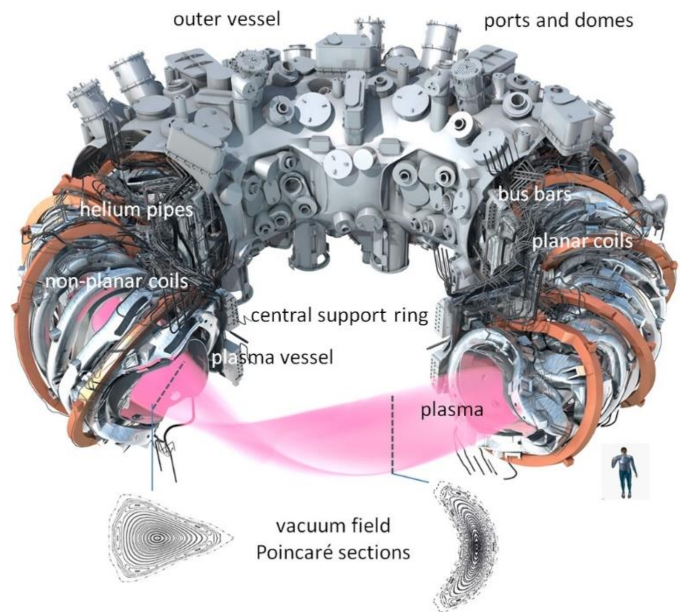
LHD stellarator in Japan



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

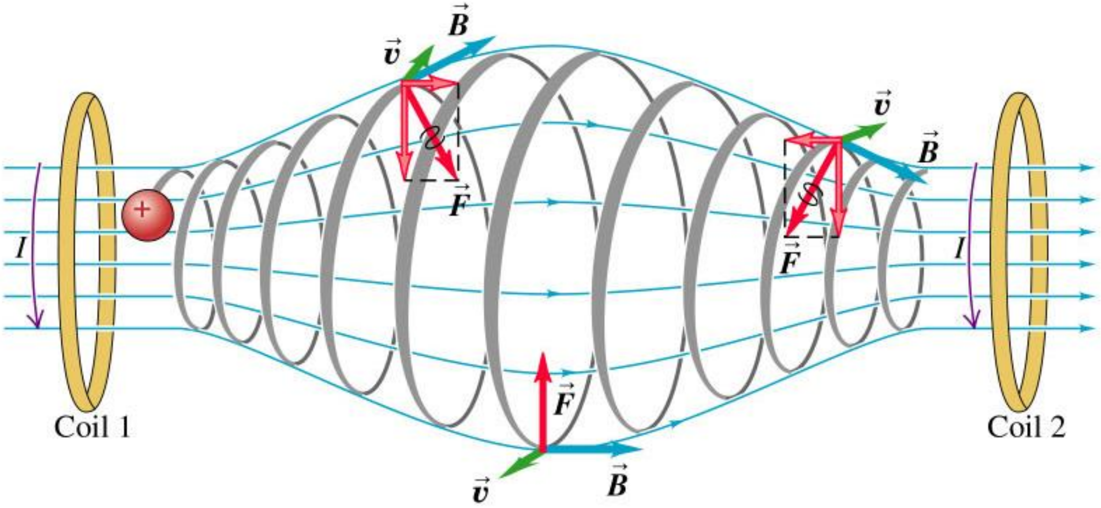
Wendelstein 7-X is a stellarator built by Max Planck Institute for Plasma Physics (IPP)

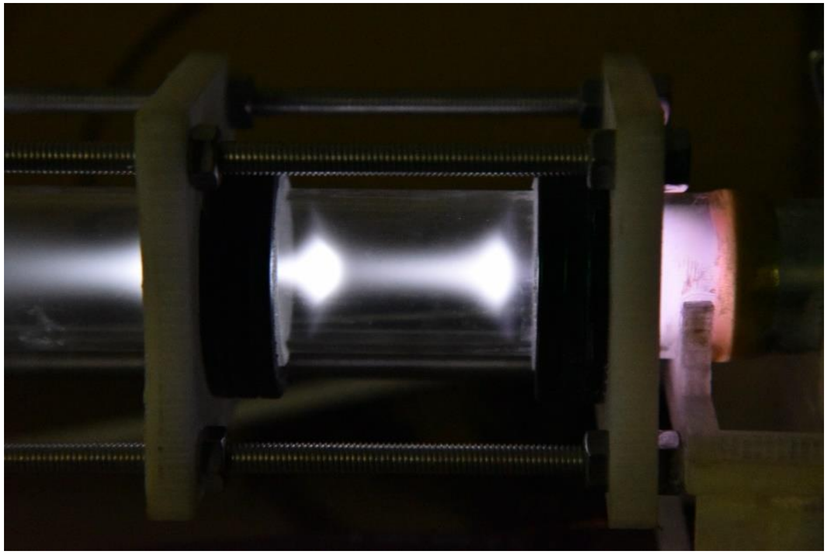




- **Wemdelstein 7-x is now installing new diverters.**

Demonstration of a magnetic mirror machine

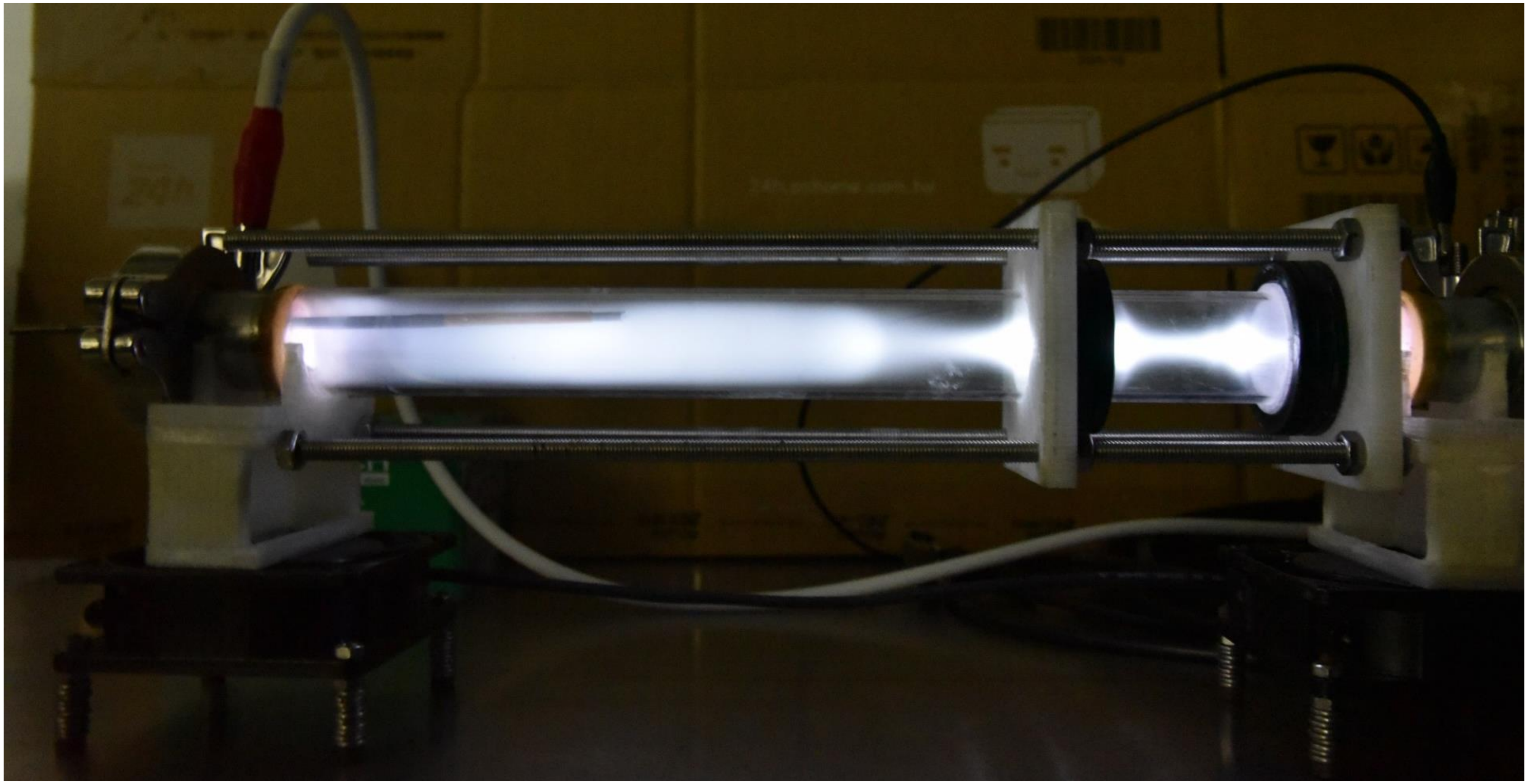




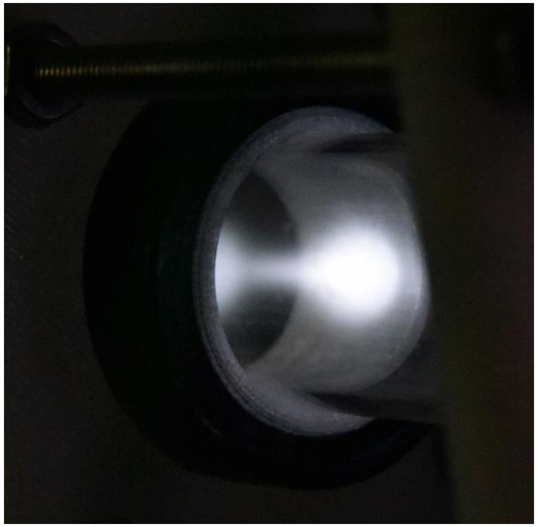
Show video.

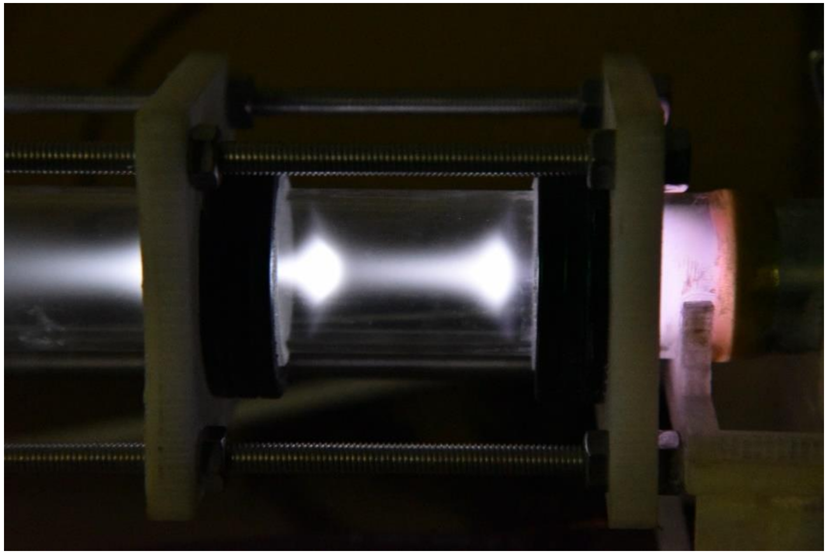
https://i.stack.imgur.com/GlzGZ.jpg

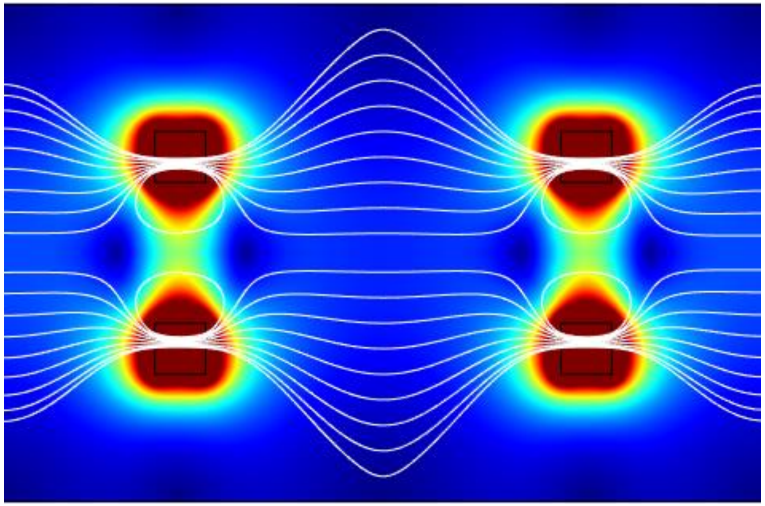
Plasma is partially confined by the magnetic field



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



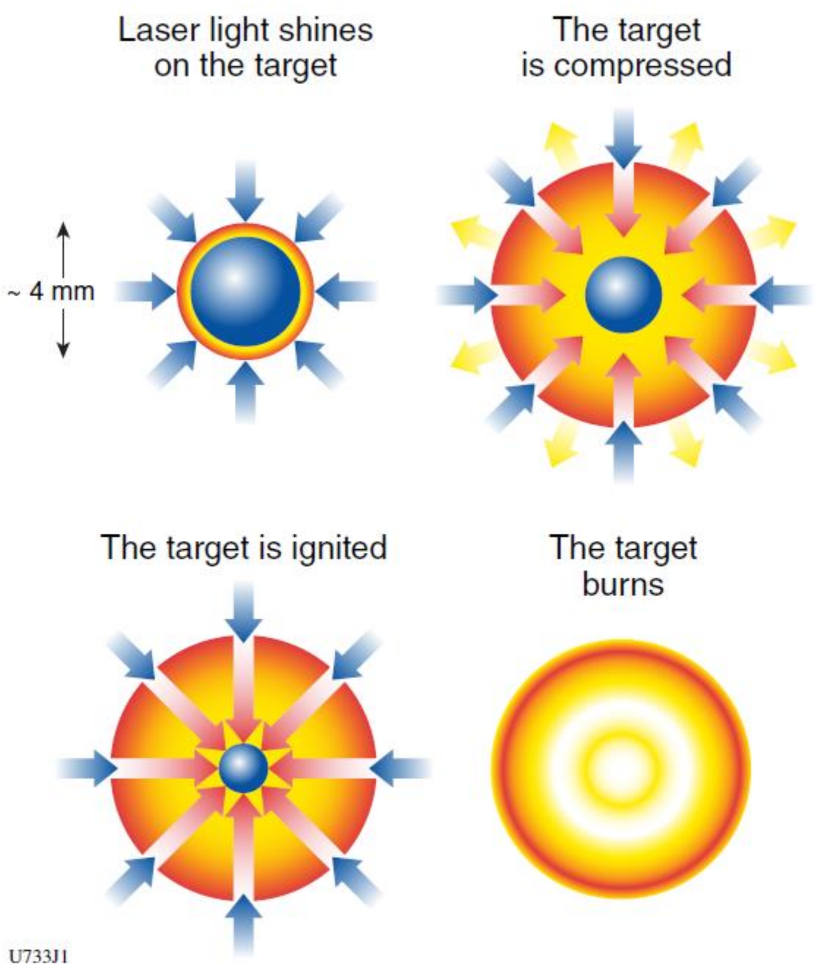


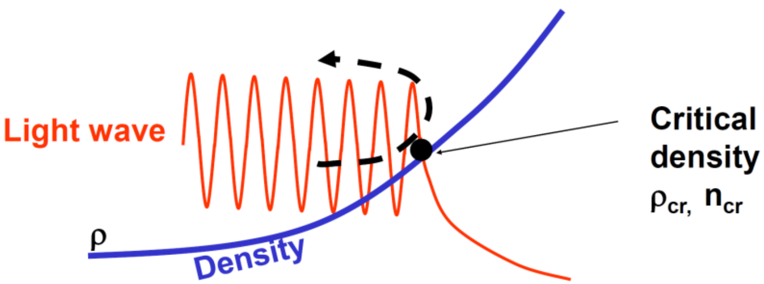


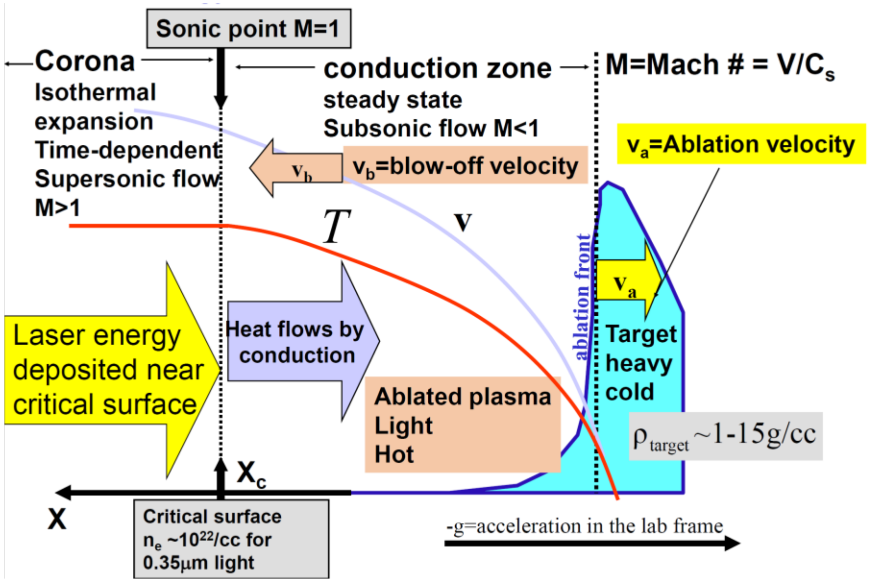
Outline

- 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

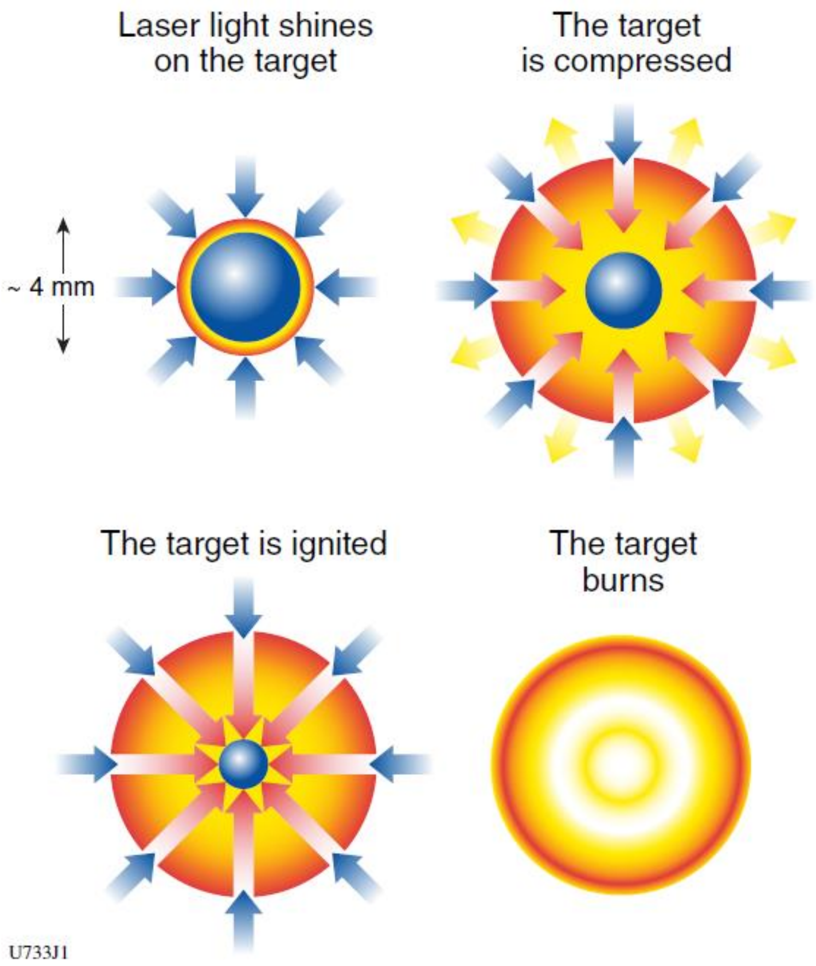




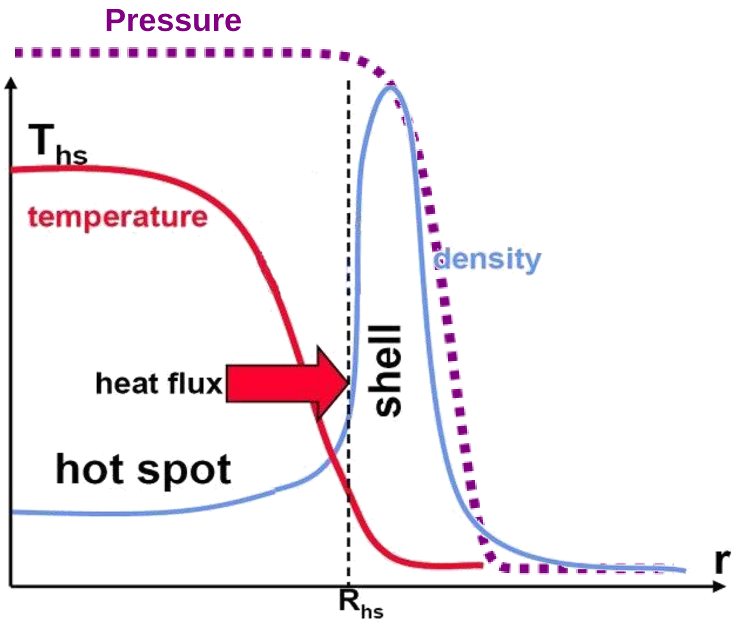


Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester
R. Betti, HEDSA HEDP Summer School, 2015

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



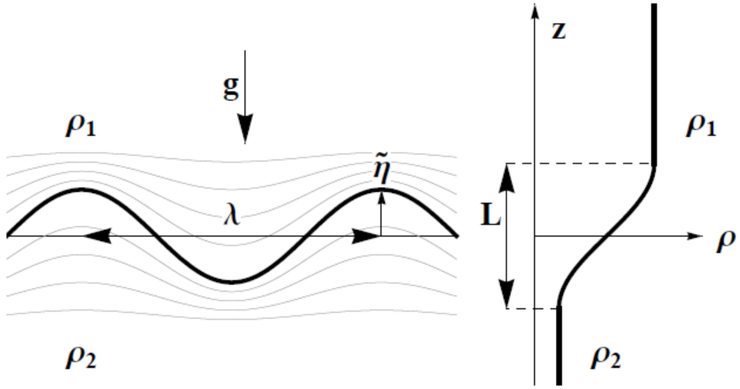
Spatial profile at stagnation



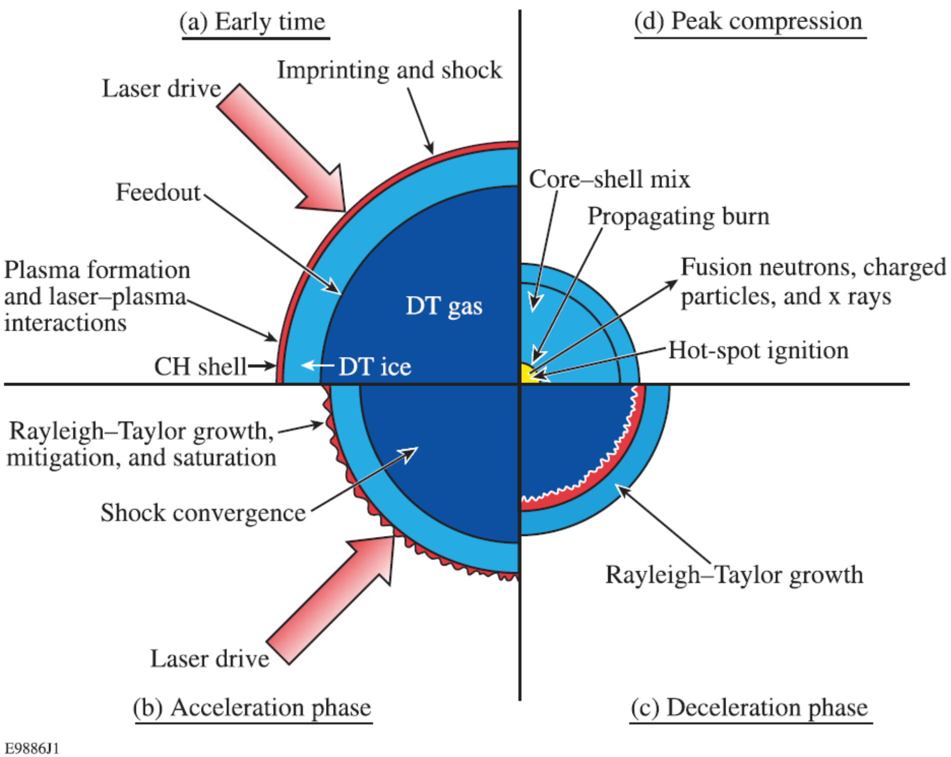
Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

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

- **Rayleigh-Taylor instability**

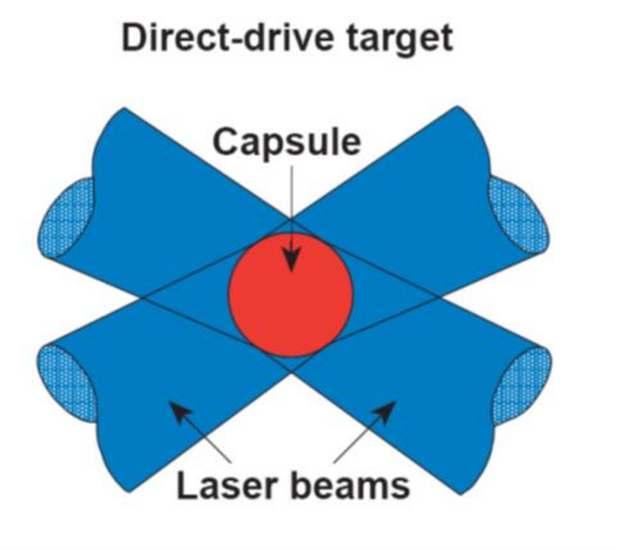


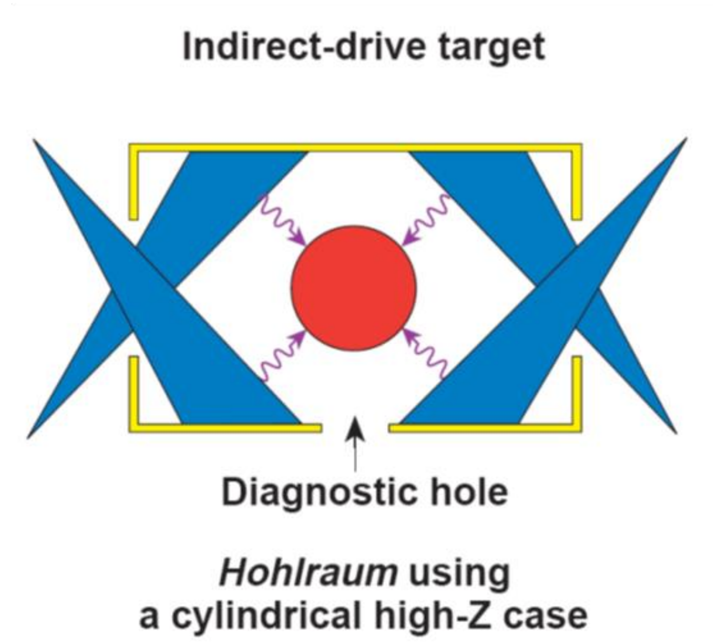
- **Stages of a target implosion**



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

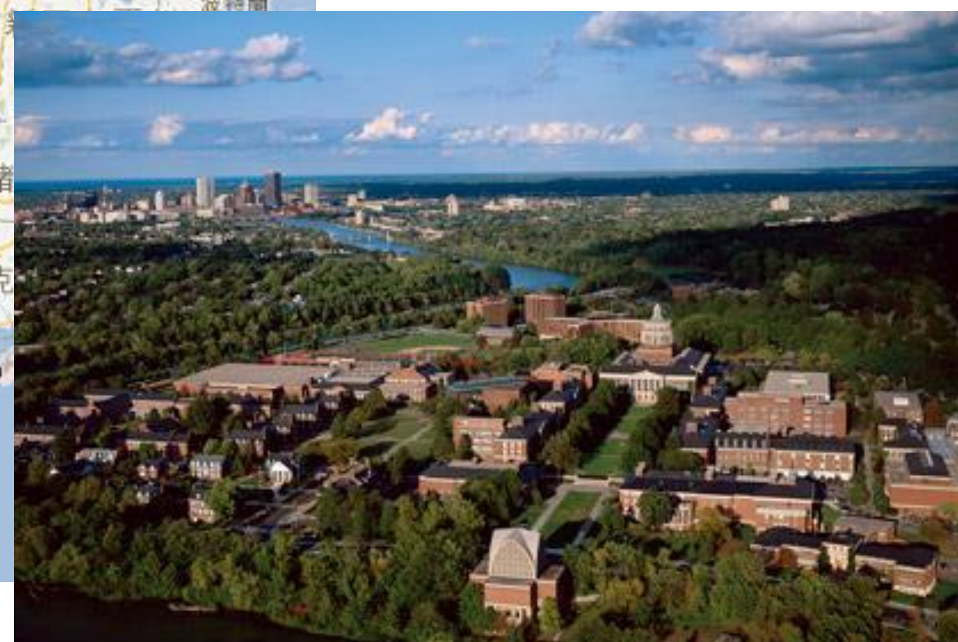
A spherical capsule can be imploded through directly or indirectly laser illumination





*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

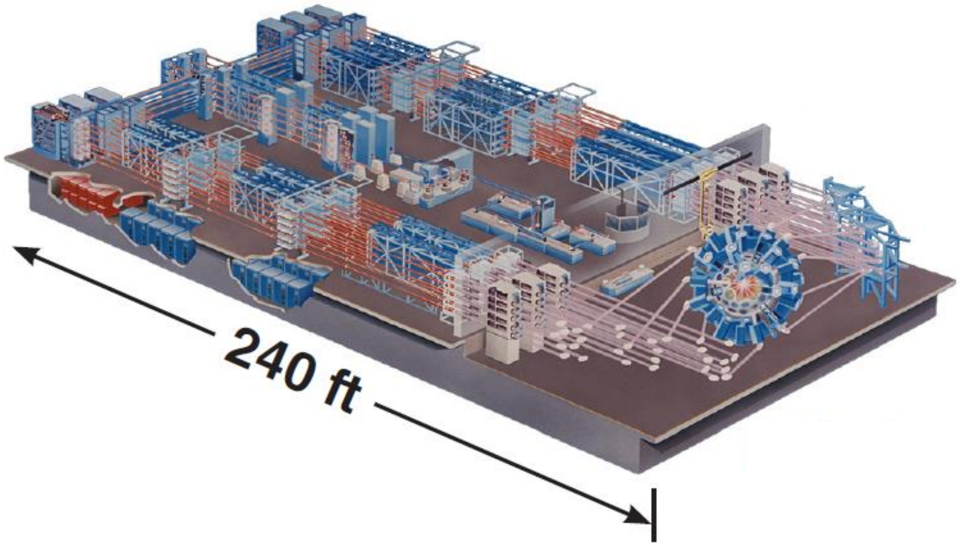
xerox ®

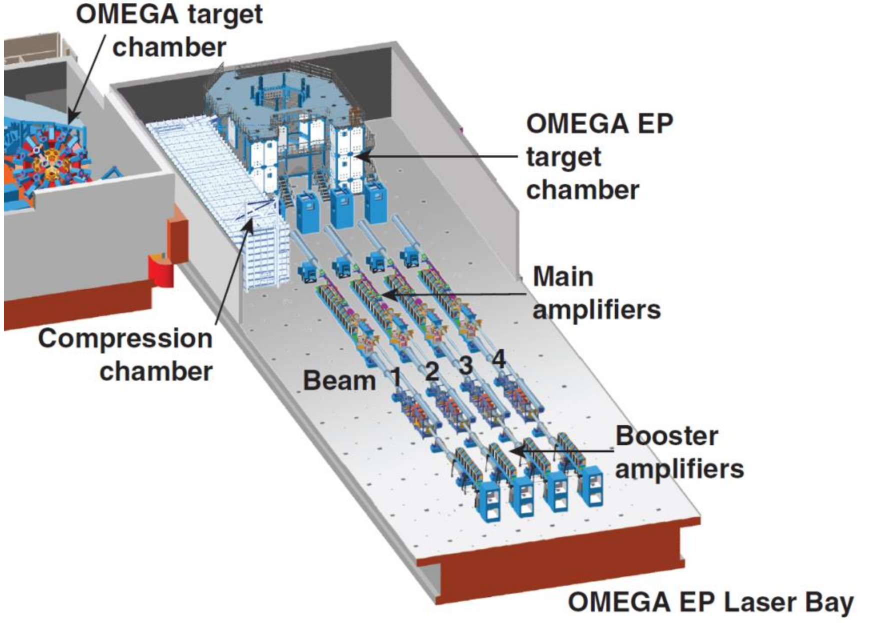
Eastman school of music

BAUSCH + LOMB

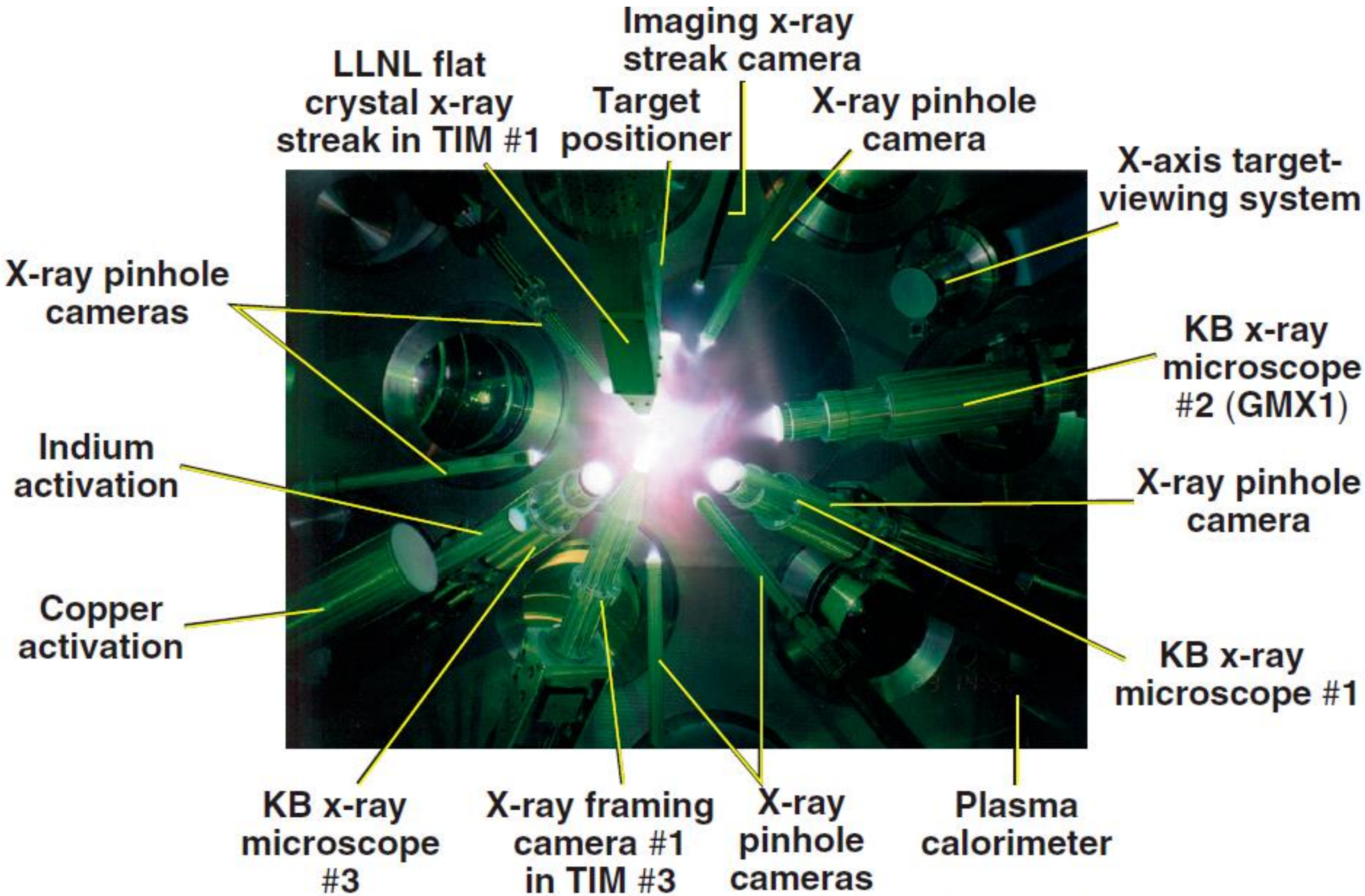
Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion

- 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





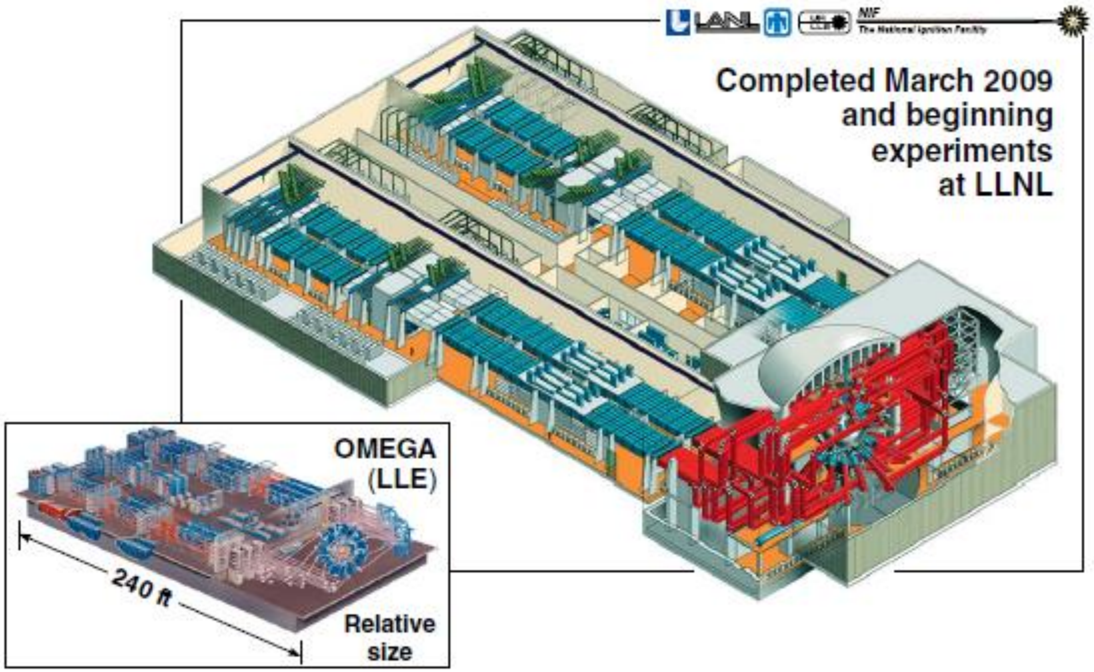
The OMEGA Facility is carrying out ICF experiments using a full suite of target diagnostics



E8012b

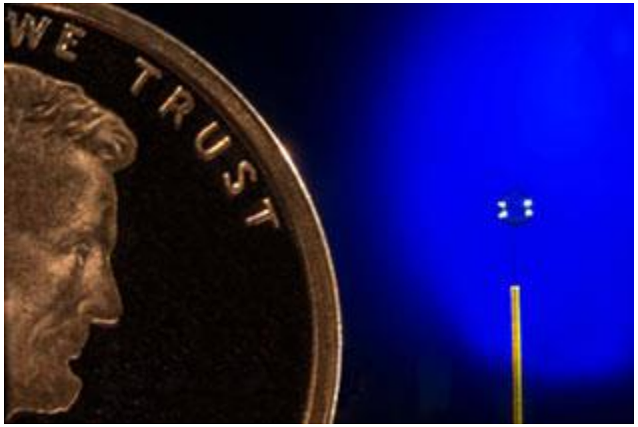
Photo taken from port H11B

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

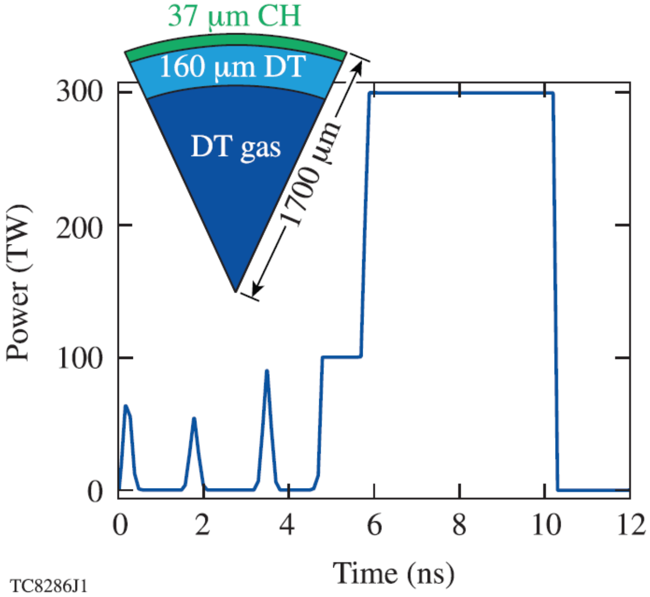


OMEGA experiments are integral to an ignition demonstration on the NIF.

Targets used in ICF



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

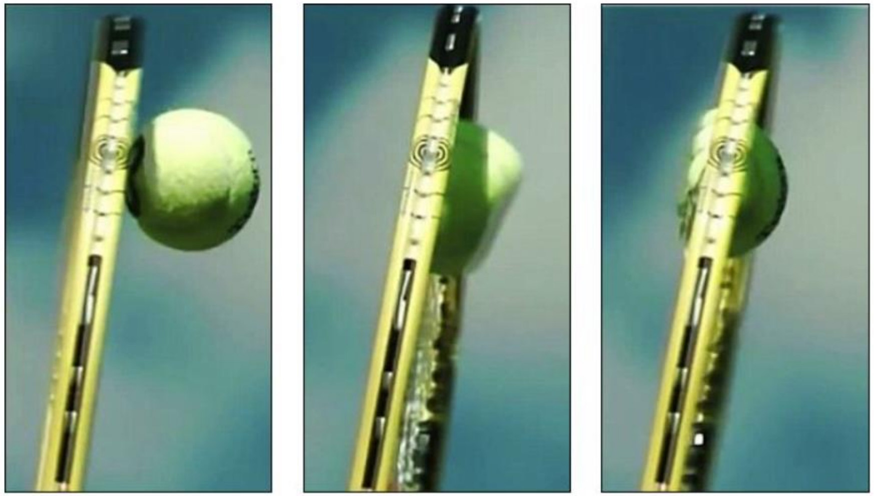


http://www.lle.rochester.ed
https://en.wikipedia.org/wiki/Inertial_confinement_fusion
R. S. Craxton, etc., *Phys. Plasmas* **22**, 110501 (2015)

Softer material can be compressed to higher density

- **Compression of a baseball**

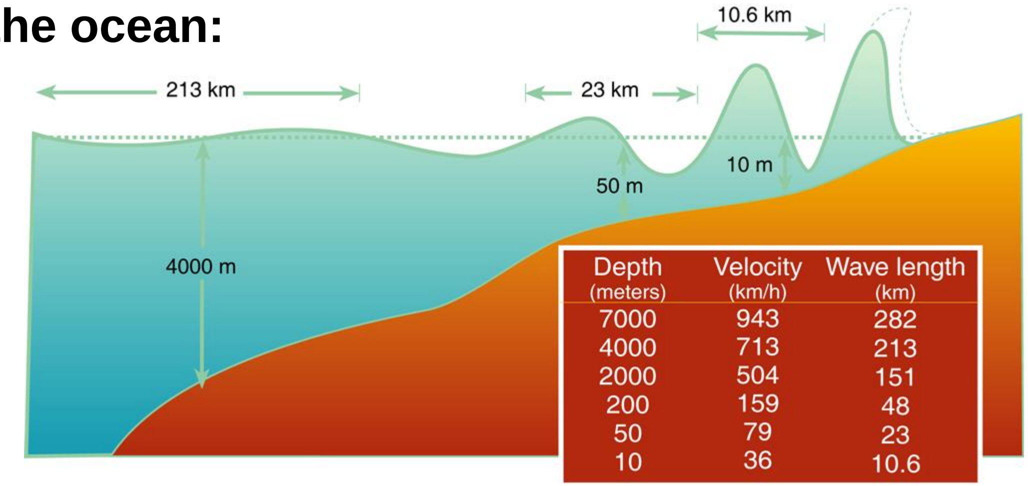
- **Compression of a tennis ball**



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/

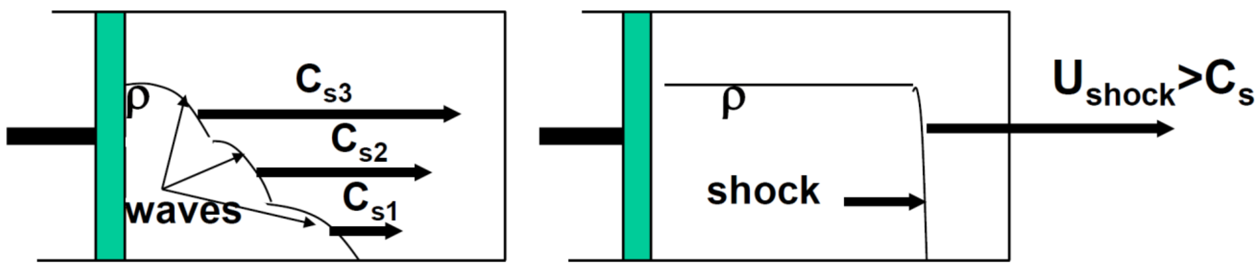
A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **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

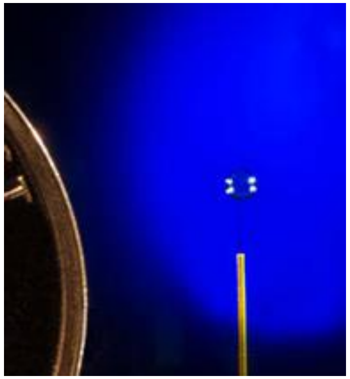
- **Acoustic/compression wave driven by a piston:**



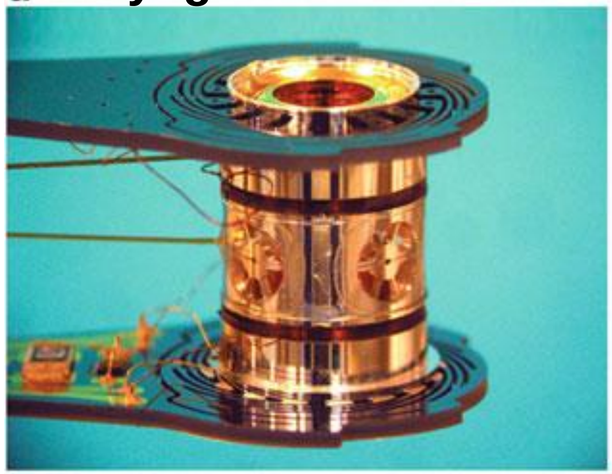
$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha \rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\rho^{1/3}$$

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

Targets used in ICF



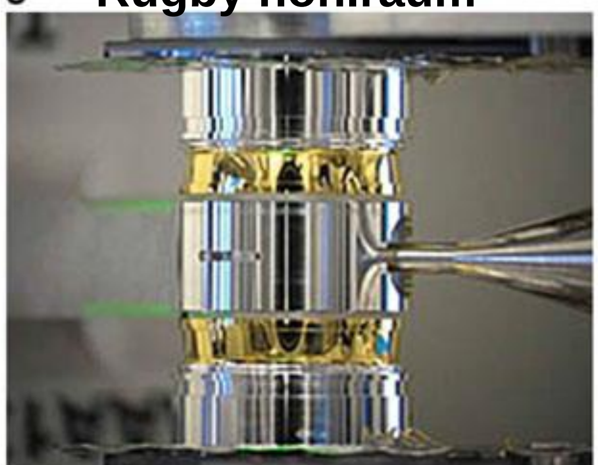
a **Cryogenic hohlraum**



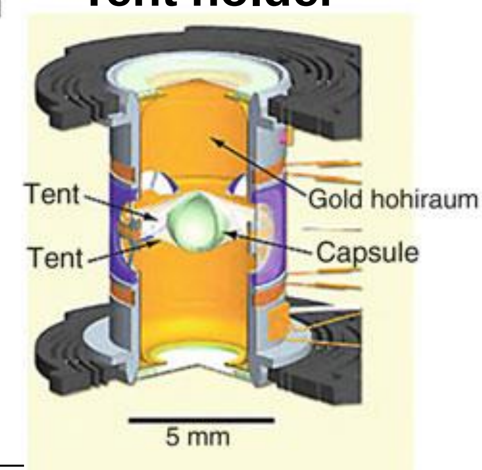
b

Cryogenic shroud

c **Rugby hohlraum**

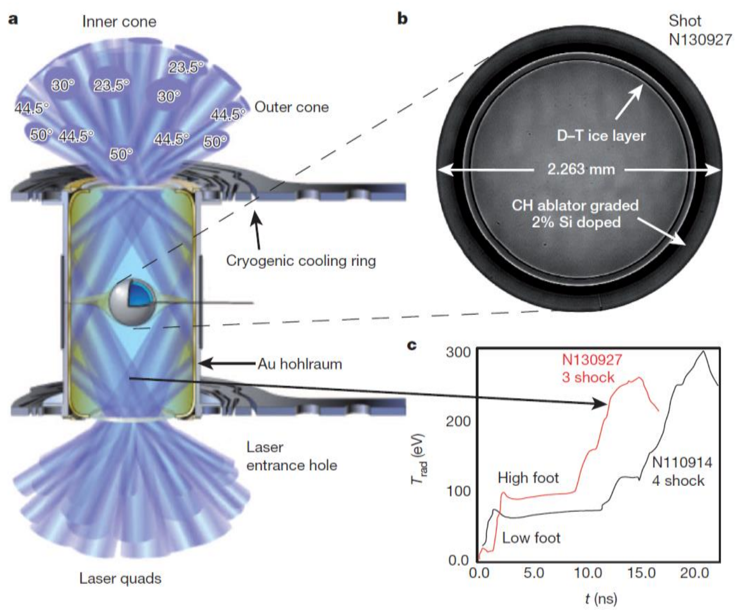


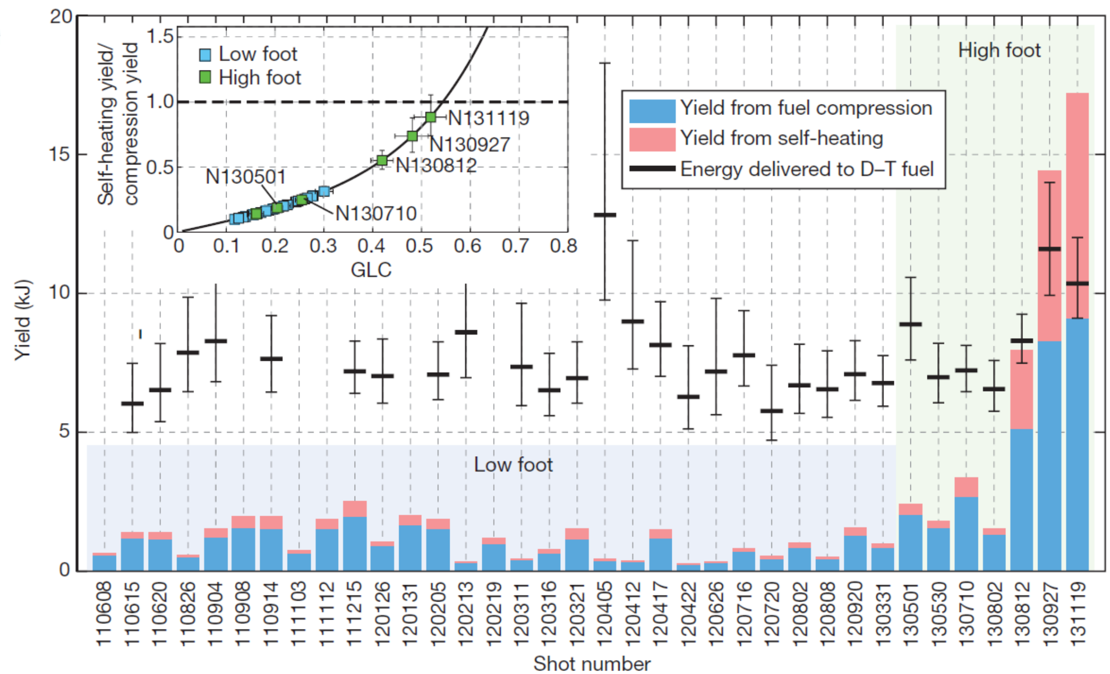
d **Tent holder**



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”

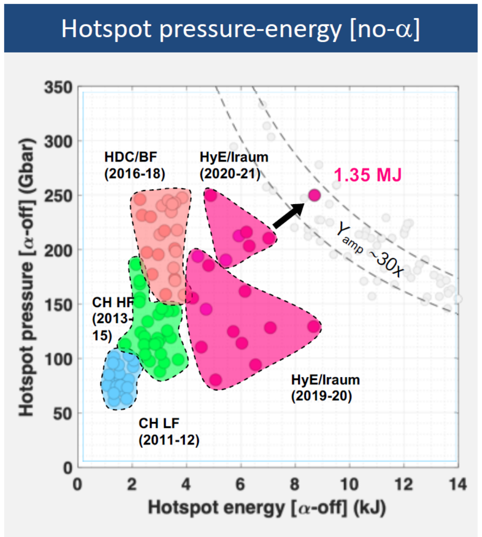


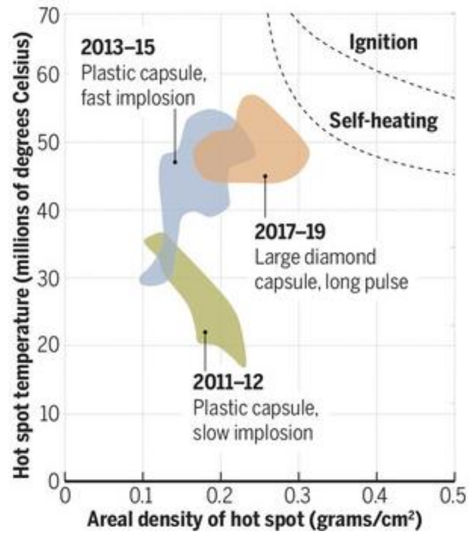


- **Fuel gain exceeding unity was demonstrated for the first time.**

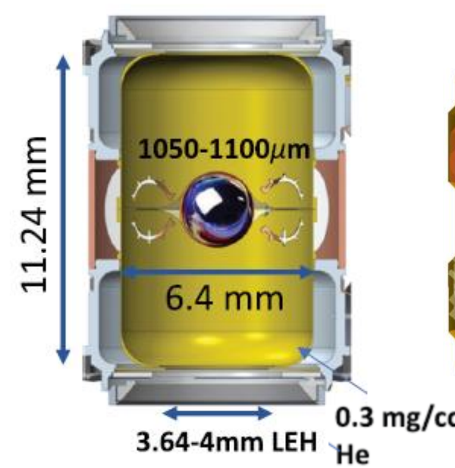
Nature 506, p343, 2014

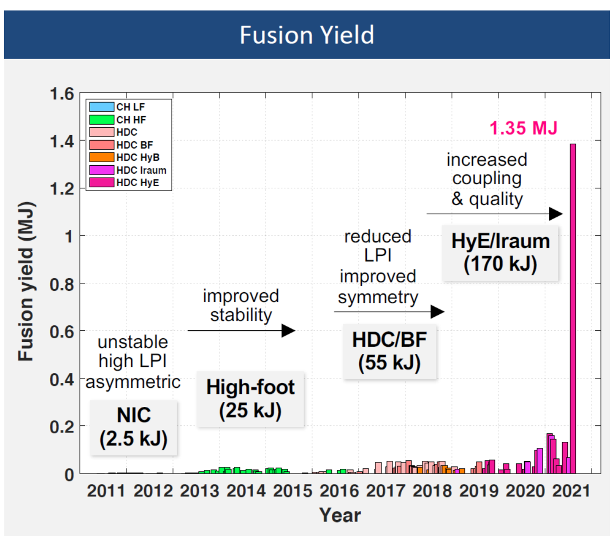
The hot spot has entered the burning plasma regime



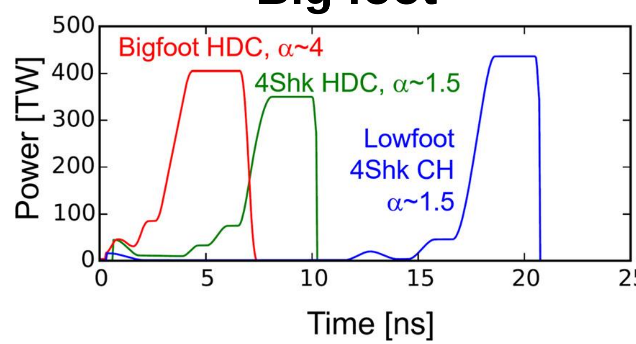


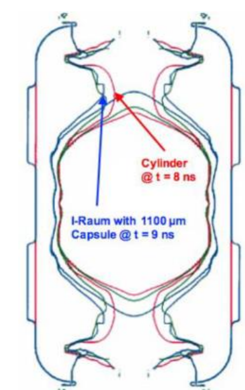
- **Hybrid-E**
- **I-raum**





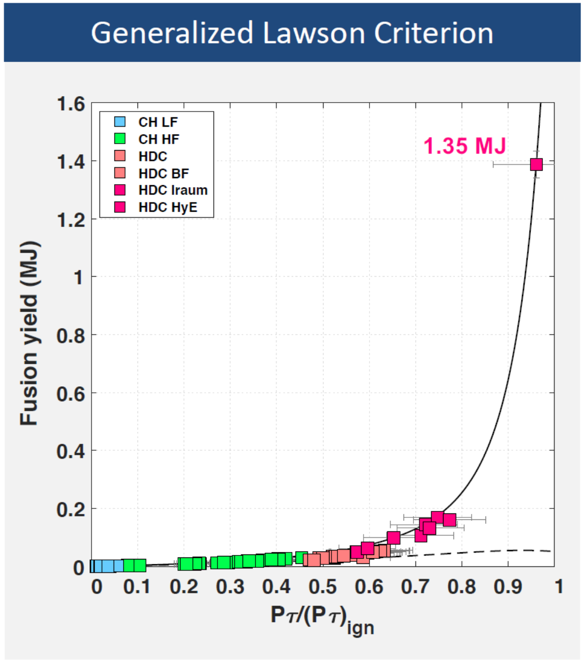
- **Big foot**

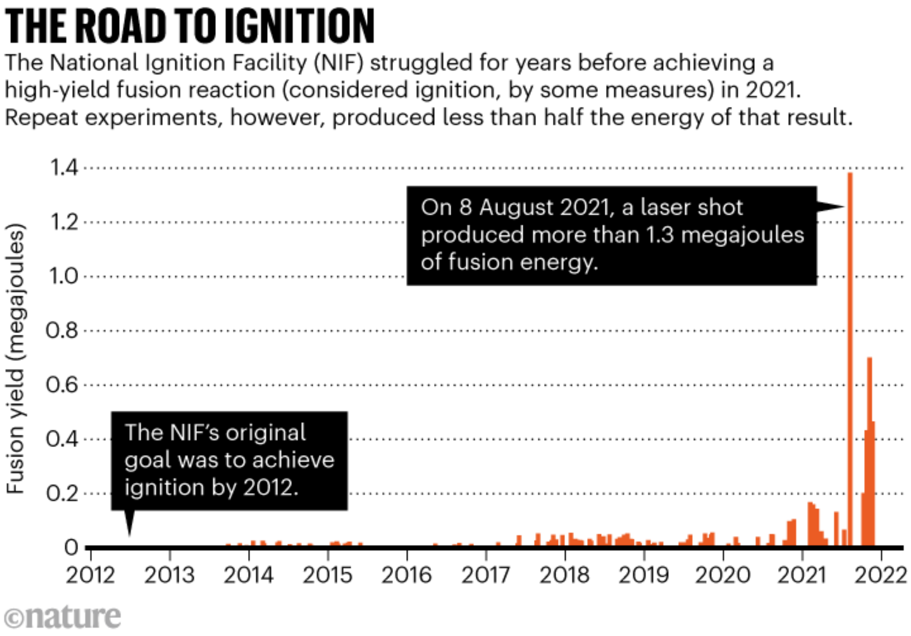




T. Ma, ARPA-E workshop, April 26, 2022
Science 370, p1019, 2020
D. T. Casey, etc., Phys. Plasmas, 25, 056308 (2018)
A. L. Kritcher, etc., Phys. Plasmas, 28, 072706 (2021)
H. F. Robey, etc., Phys. Plasmas, 25, 012711 (2018)

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)



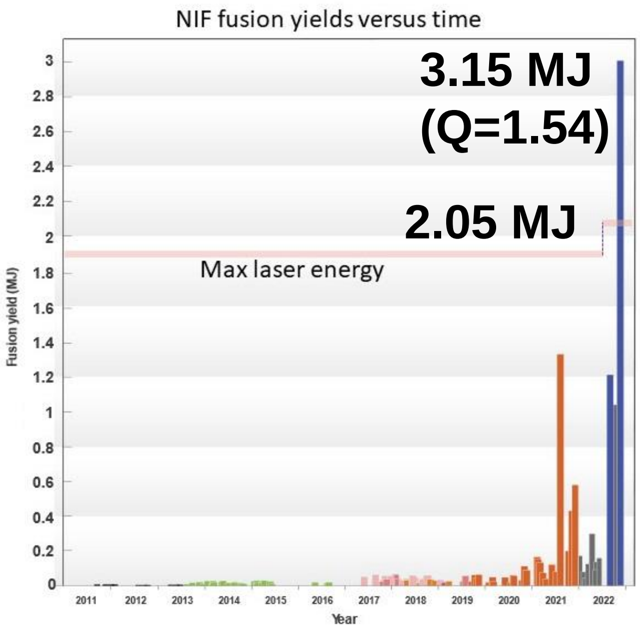


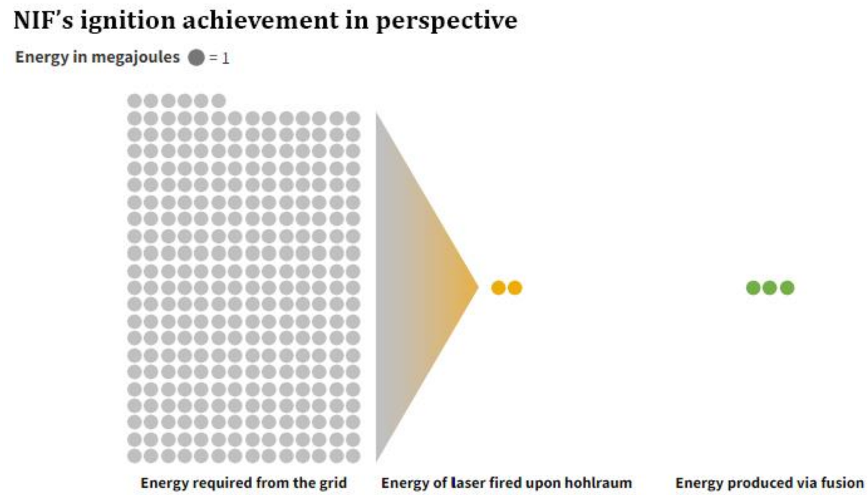
- **National Ignition Facility (NIF) achieved a yield of more than 1.3 MJ (Q~0.7). This advancement puts researchers at the threshold of fusion ignition.**

- **Laser-fusion facility heads back to the drawing board.**

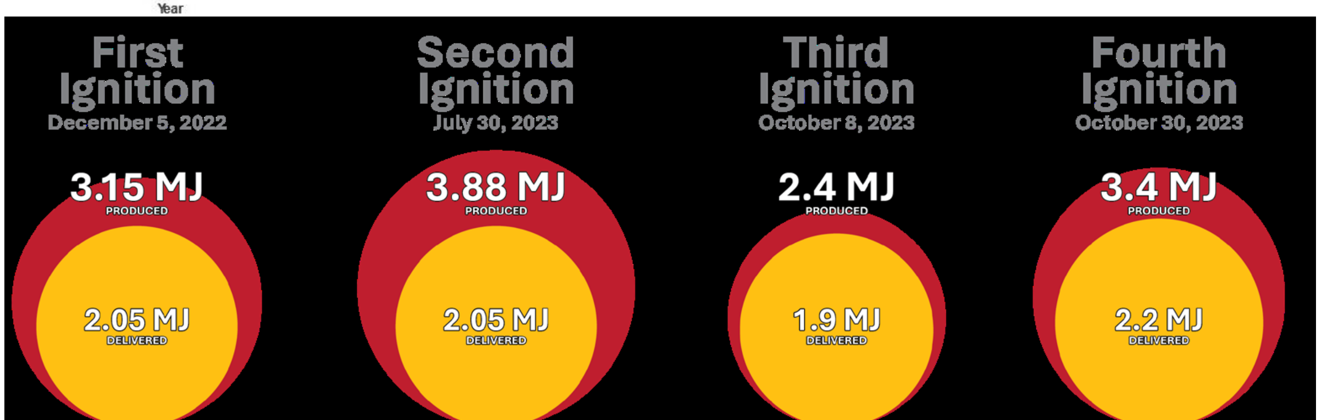
T. Ma, ARPA-E workshop, April 26, 2022
J. Tollefson, Nature (News) 608, 20 (2022)

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





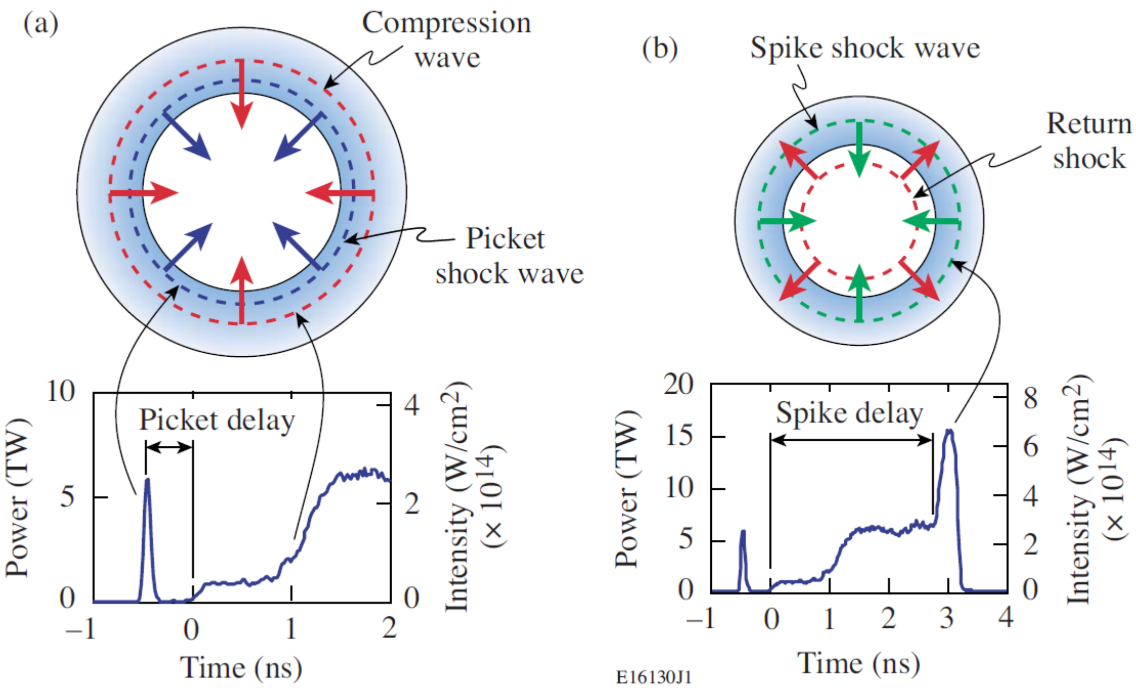
300 MJ **2.05 MJ** **3.15 MJ**



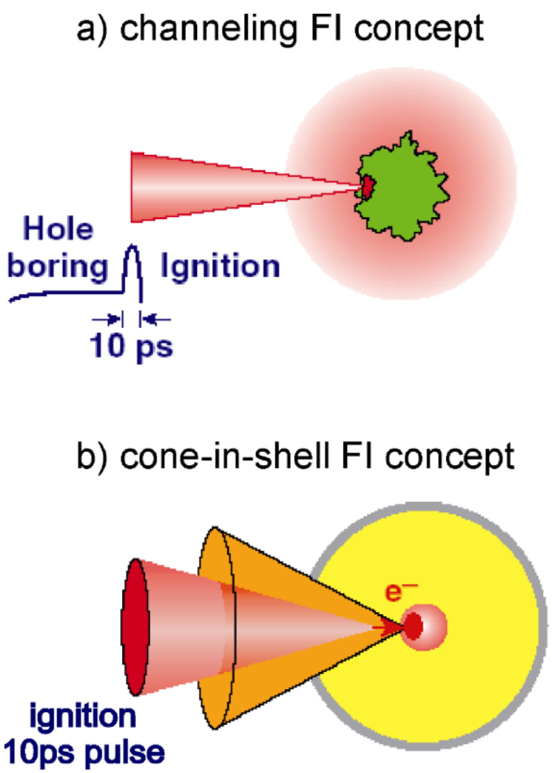
https://physicstoday.scitation.org/do/10.1063/PT.6.2.20221213a/full/
The age of ignition: anniversary edition, LLNL-BR-857901

External “spark” can be used for ignition

- **Shock ignition**



- **Fast ignition**



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

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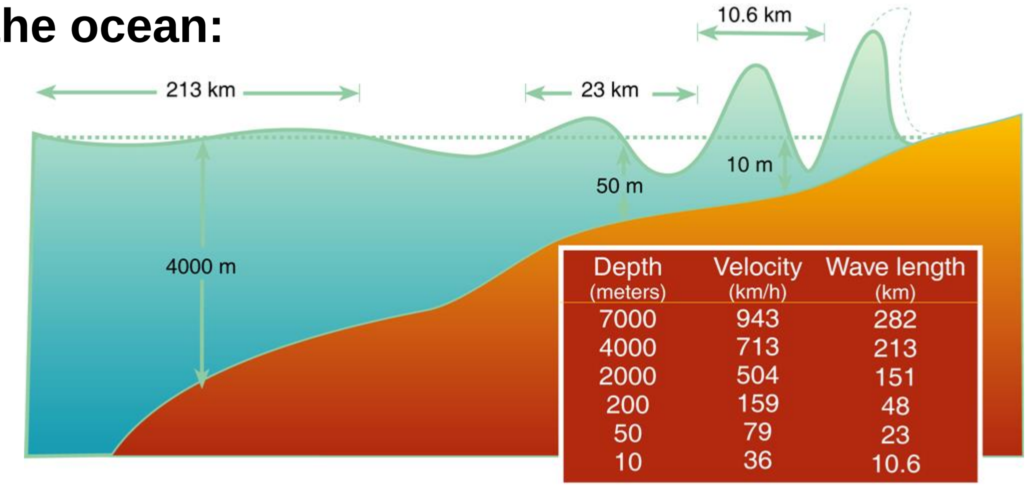

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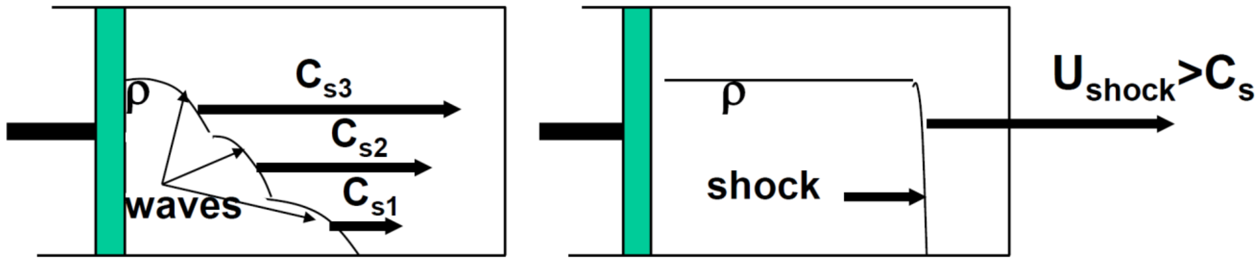
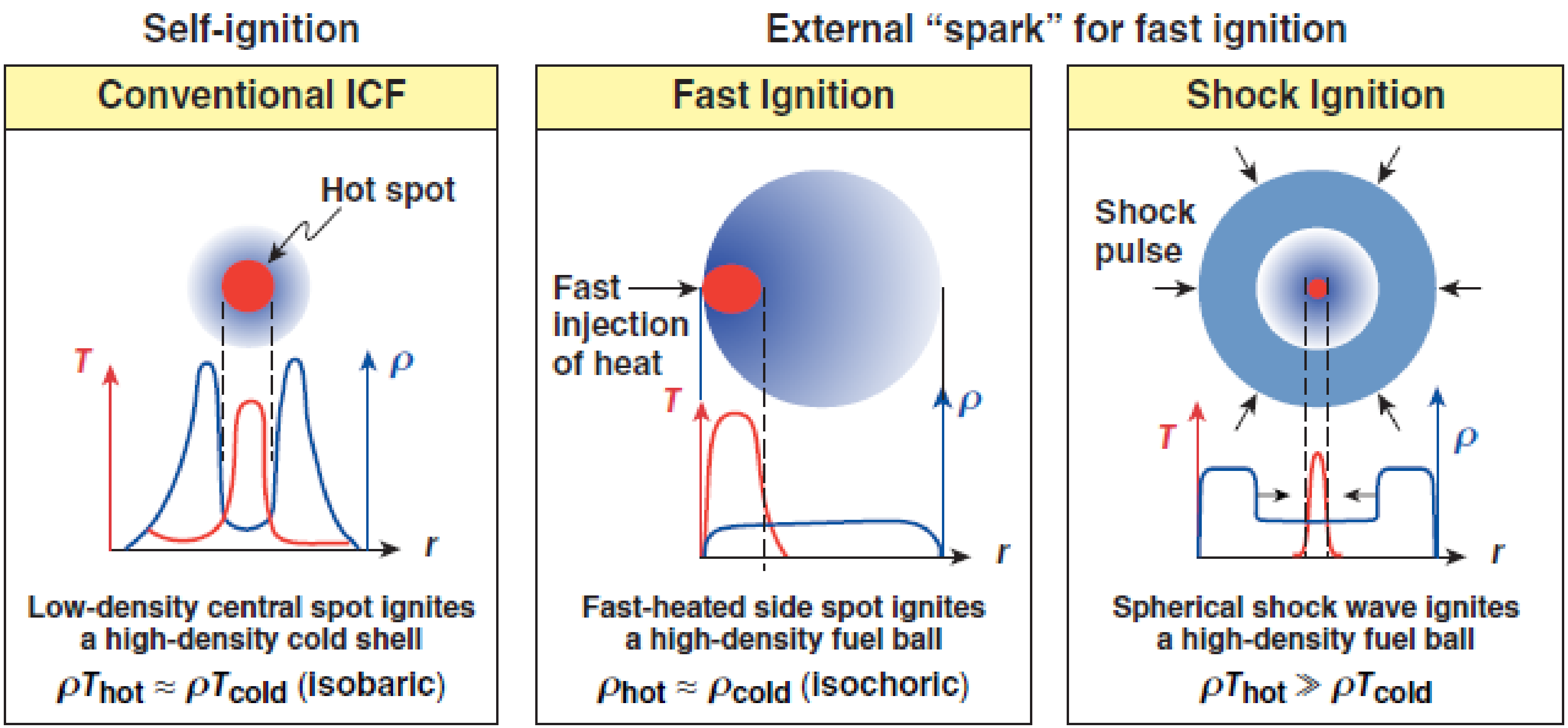


$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha \rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\rho^{1/3}$$

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

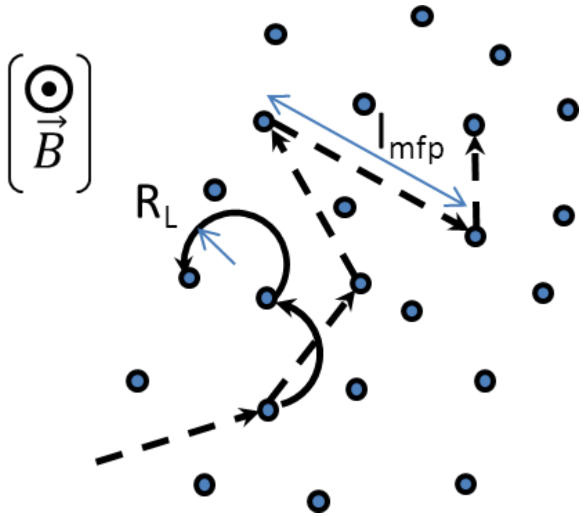


P. B. Radha, Fusion Energy Conference,2018

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



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

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

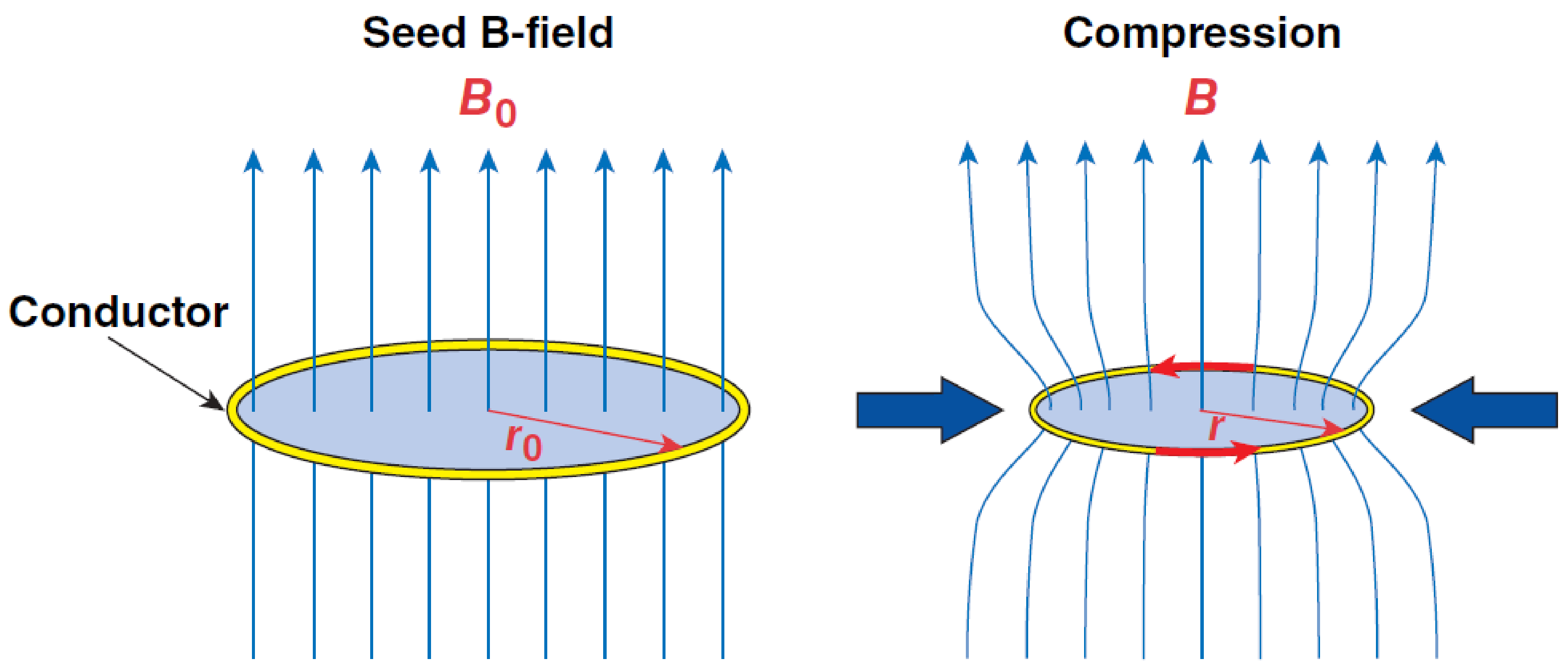
$$\kappa_{\perp} = \frac{\kappa_{||}}{\chi^2} \quad \text{for large Hall parameter } \chi \propto \frac{l_{mfp}}{R_L} >> 1$$

- **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.

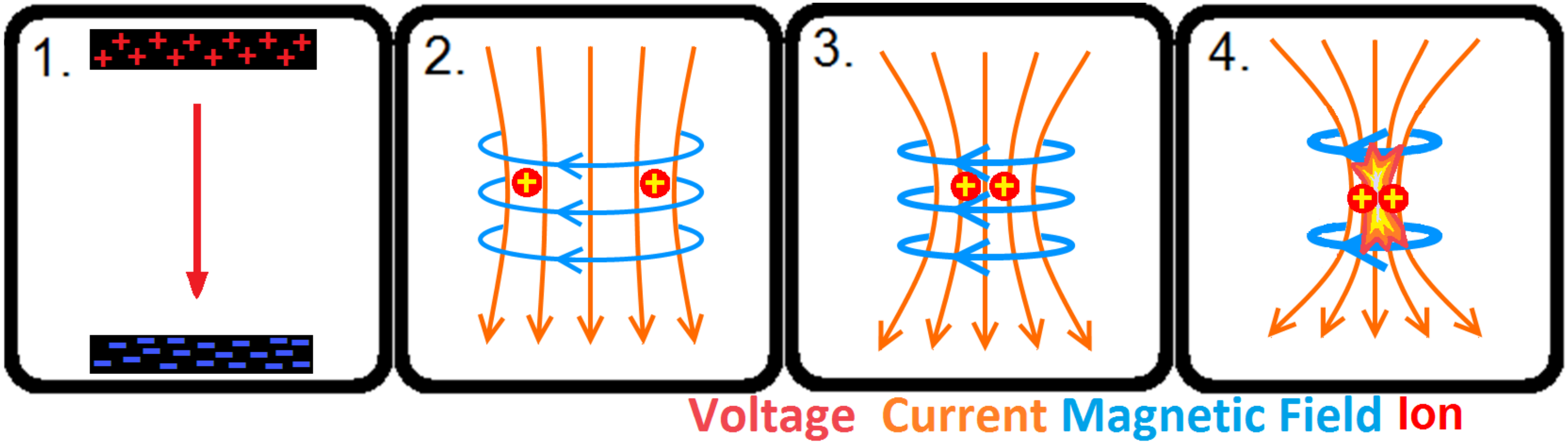
Principle of frozen magnetic flux in a good conductor is used to compress fields



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

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

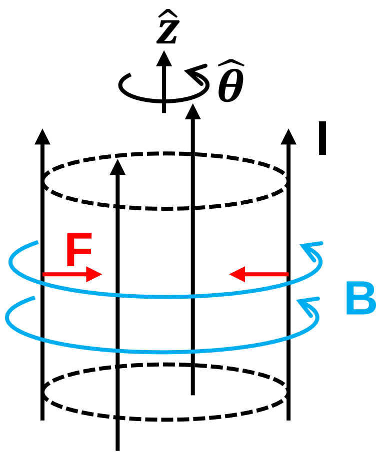
Plasma can be pinched by parallel propagating plasmas



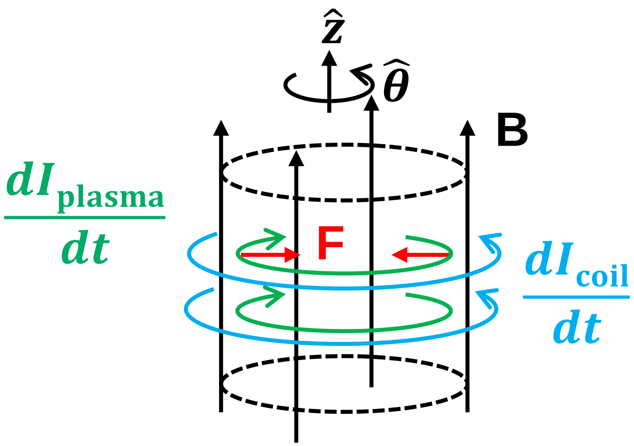
https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

Plasma can be heated via pinches

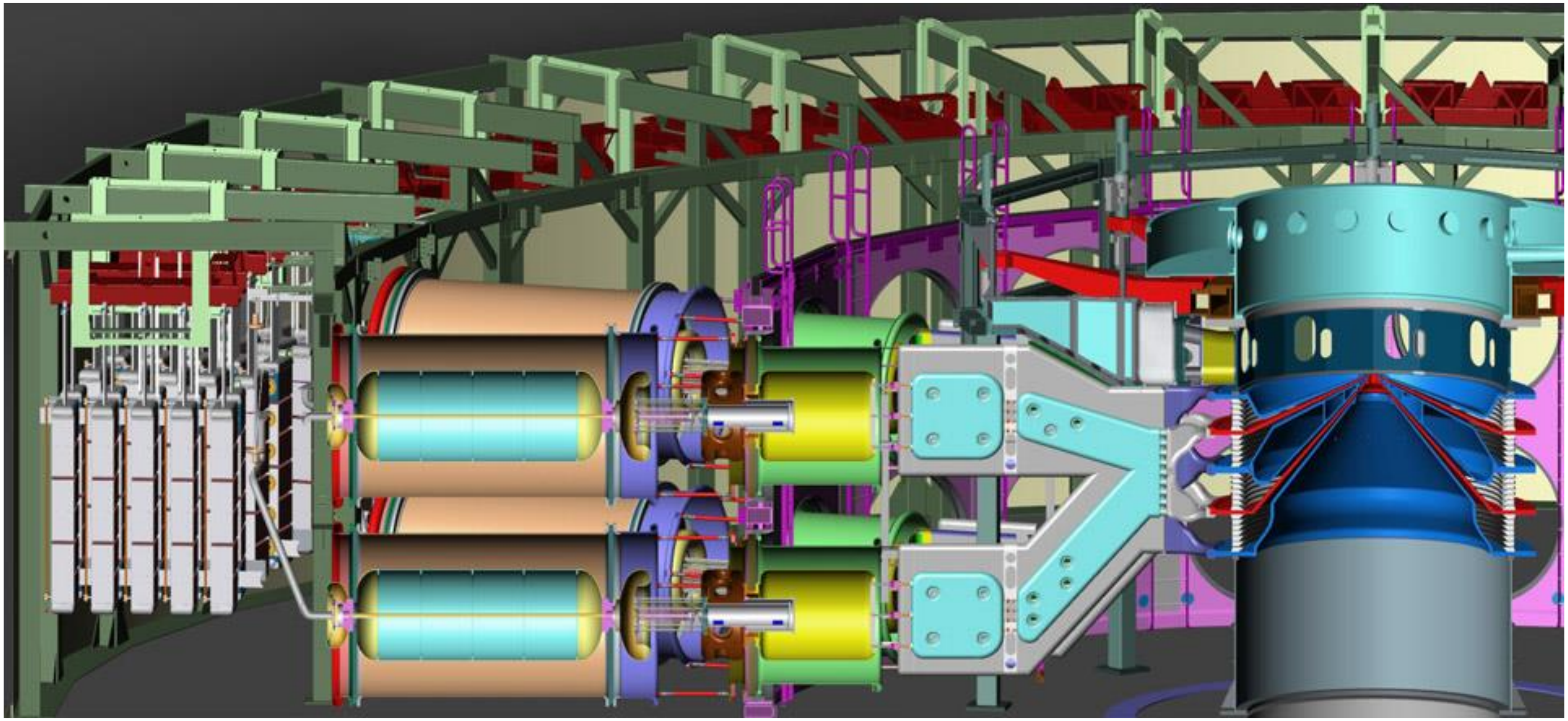
Z pinch



Theta pinch

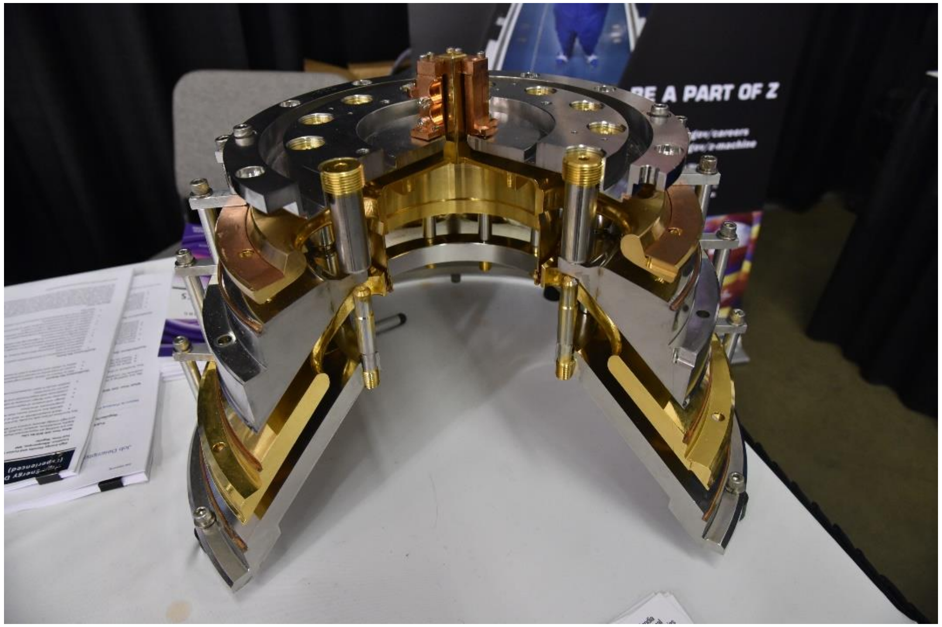


Sandia's Z machine is the world's most powerful and efficient laboratory radiation source

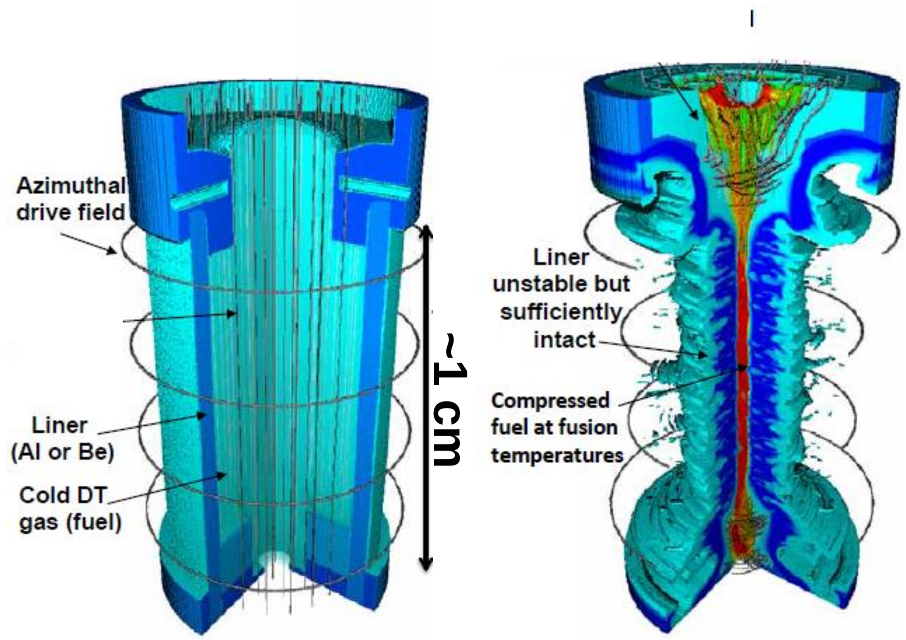


- Stored energy: 20 MJ
- Marx charge voltage: 85 kV
- Peak electrical power: 85 TW
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray emissions: 350 TW
- Peak X-ray output: 2.7 MJ

Z machine



Z machine



- Stored energy: 20 MJ
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- Peak current: 26 MA
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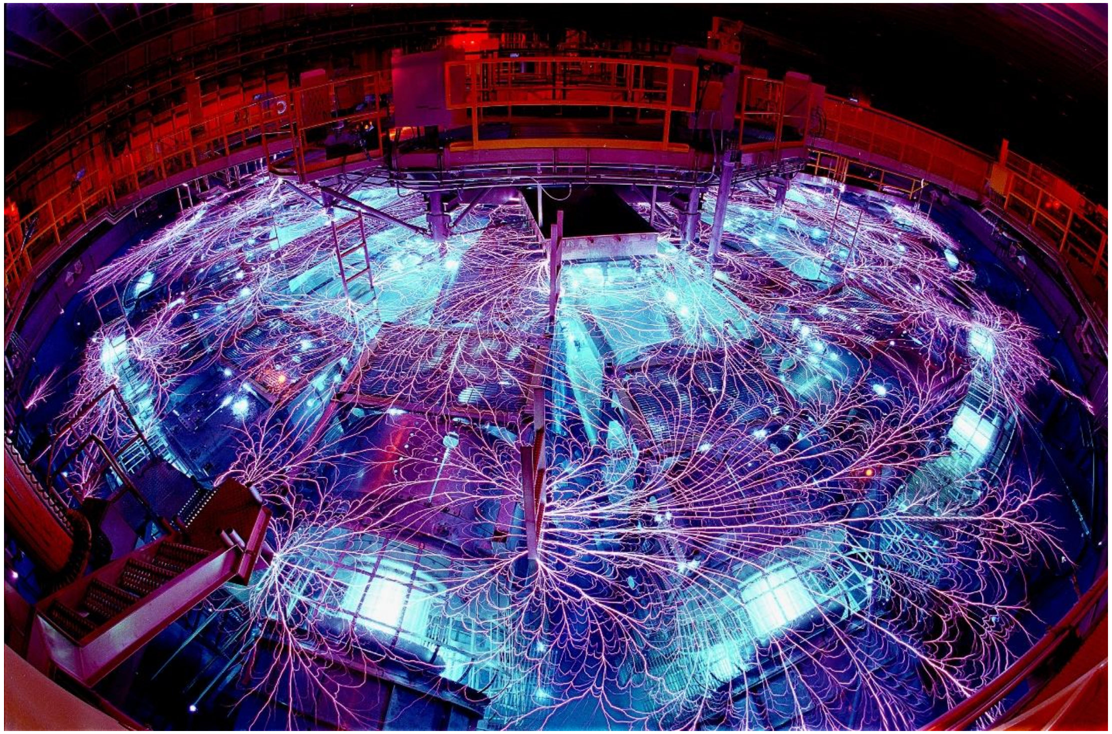
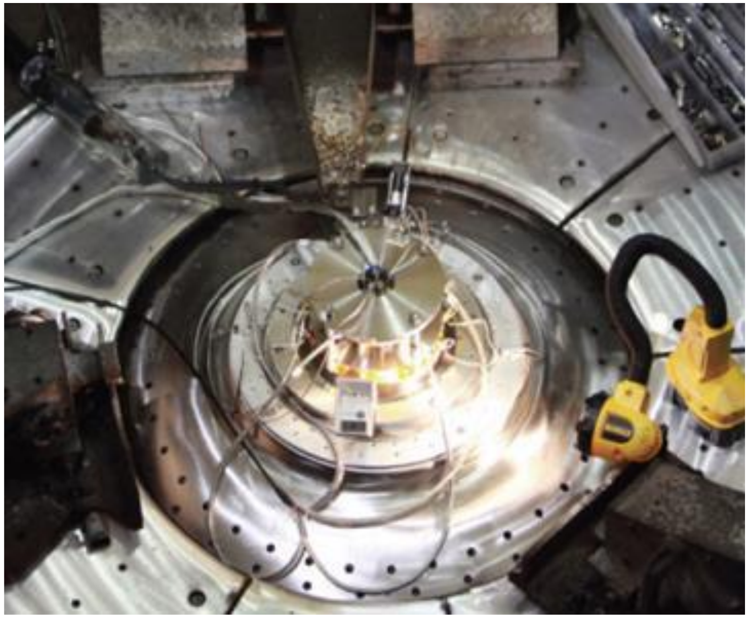
Z machine discharge



Before and after shots

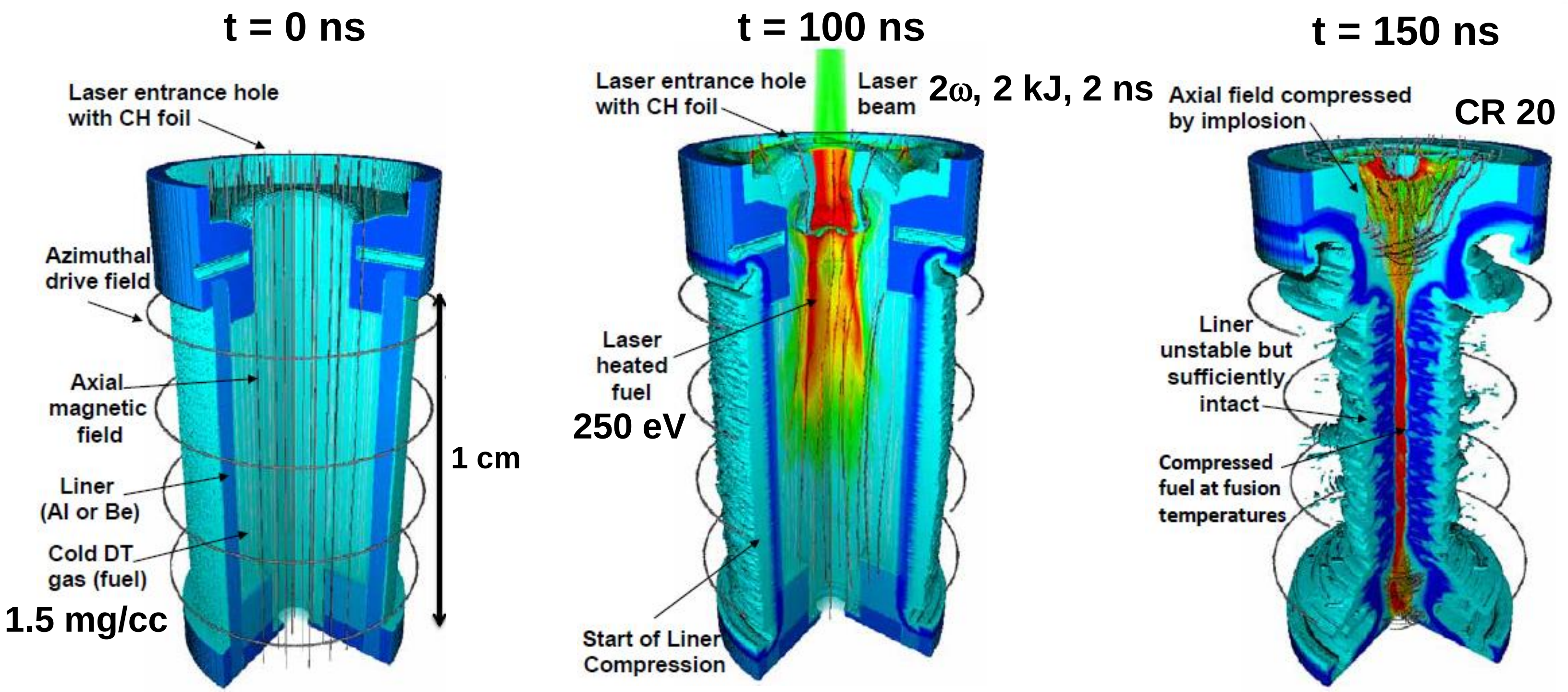
- **Before shots**



- **After shots**

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

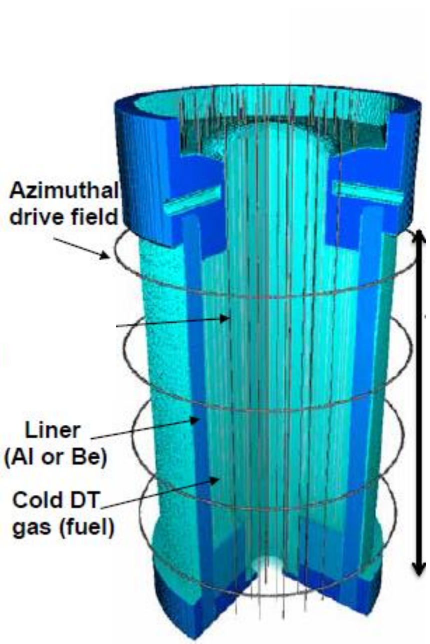
Promising results were shown in MagLIF concept conducted at the Sandia National Laboratories

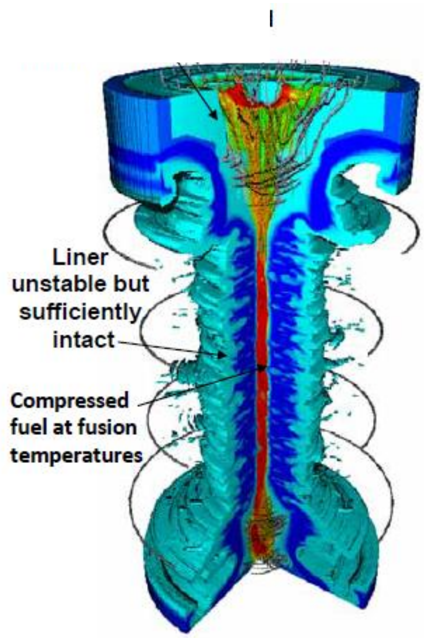


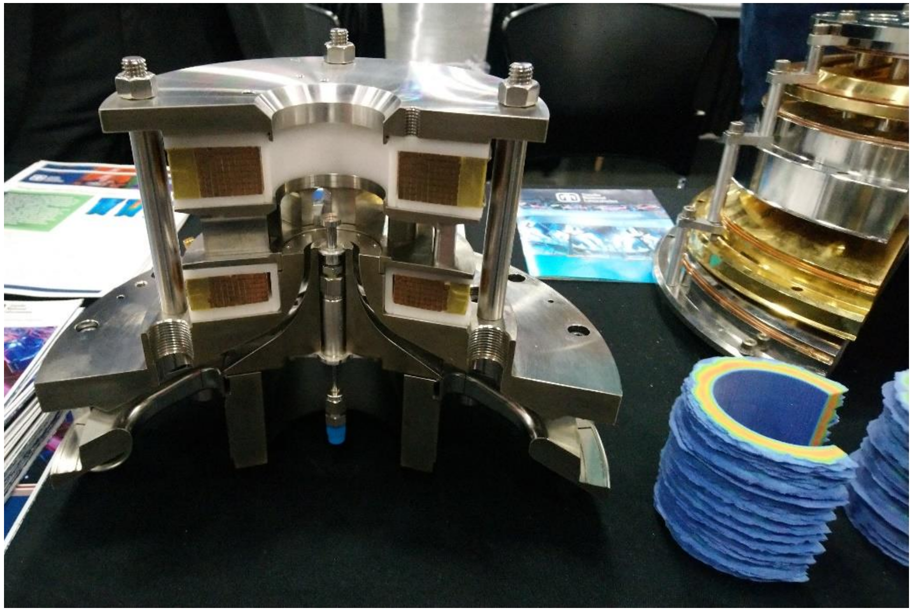
The stagnation plasma reached fusion-relevant temperatures with a 70 km/s implosion velocity

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

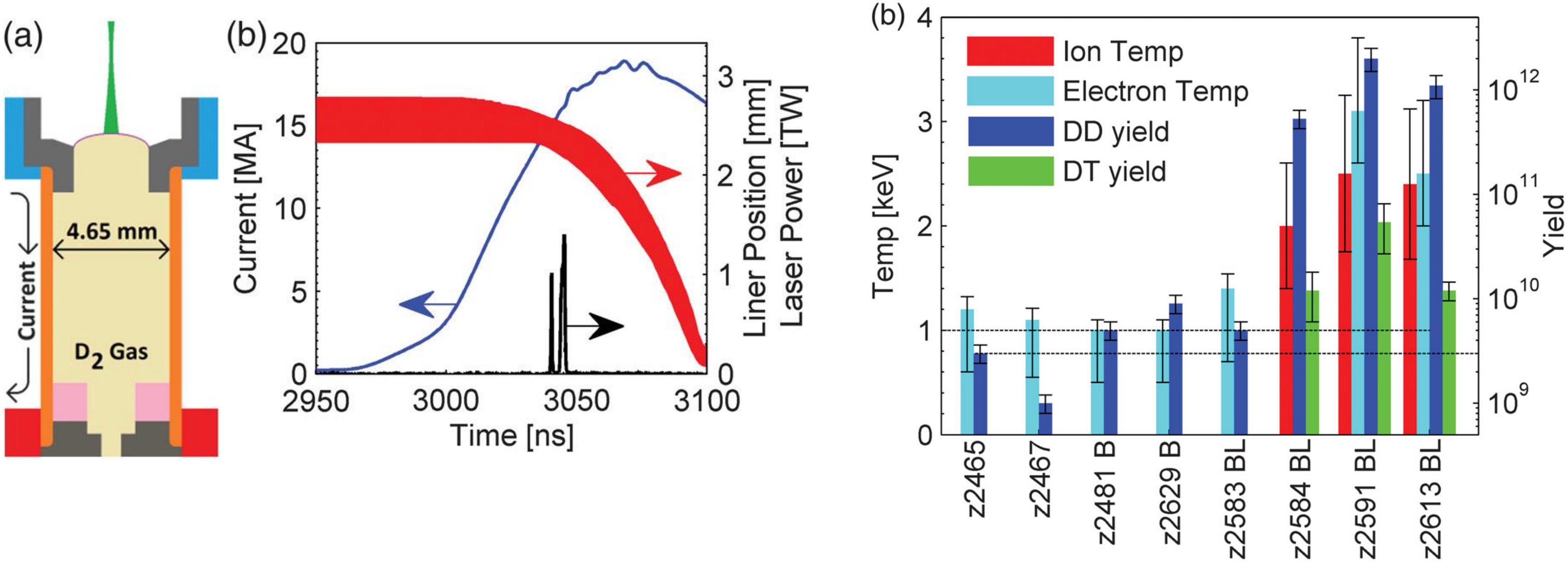
MagLIF target







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

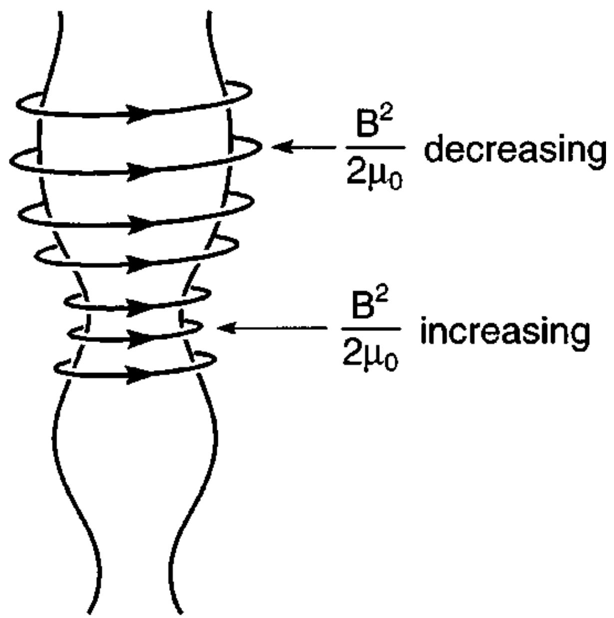


M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

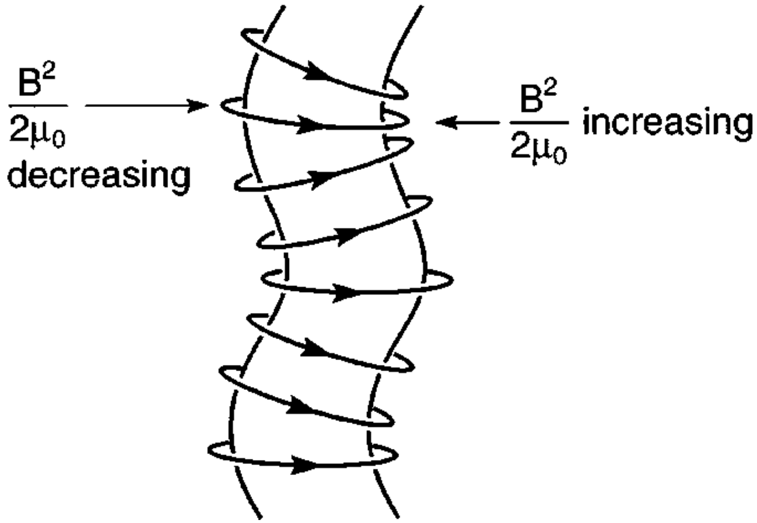
Sheared flow stabilizes MHD instabilities

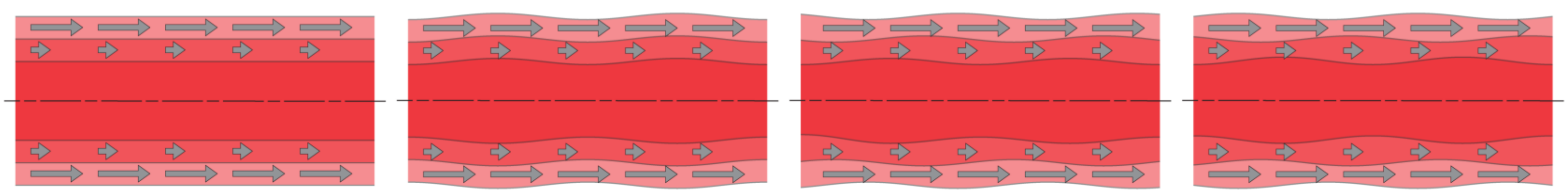
m = 0 (sausage)

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



m = 1 (kink)

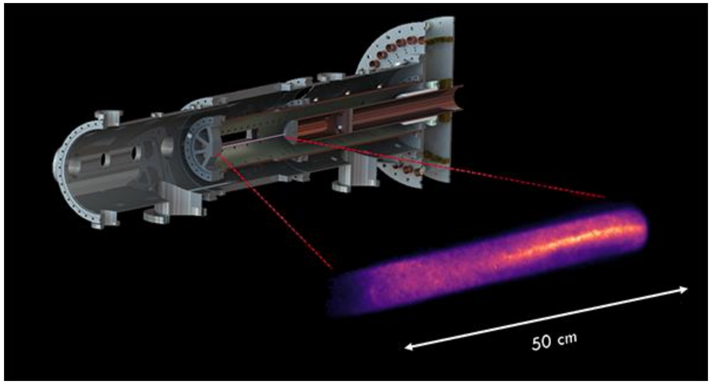




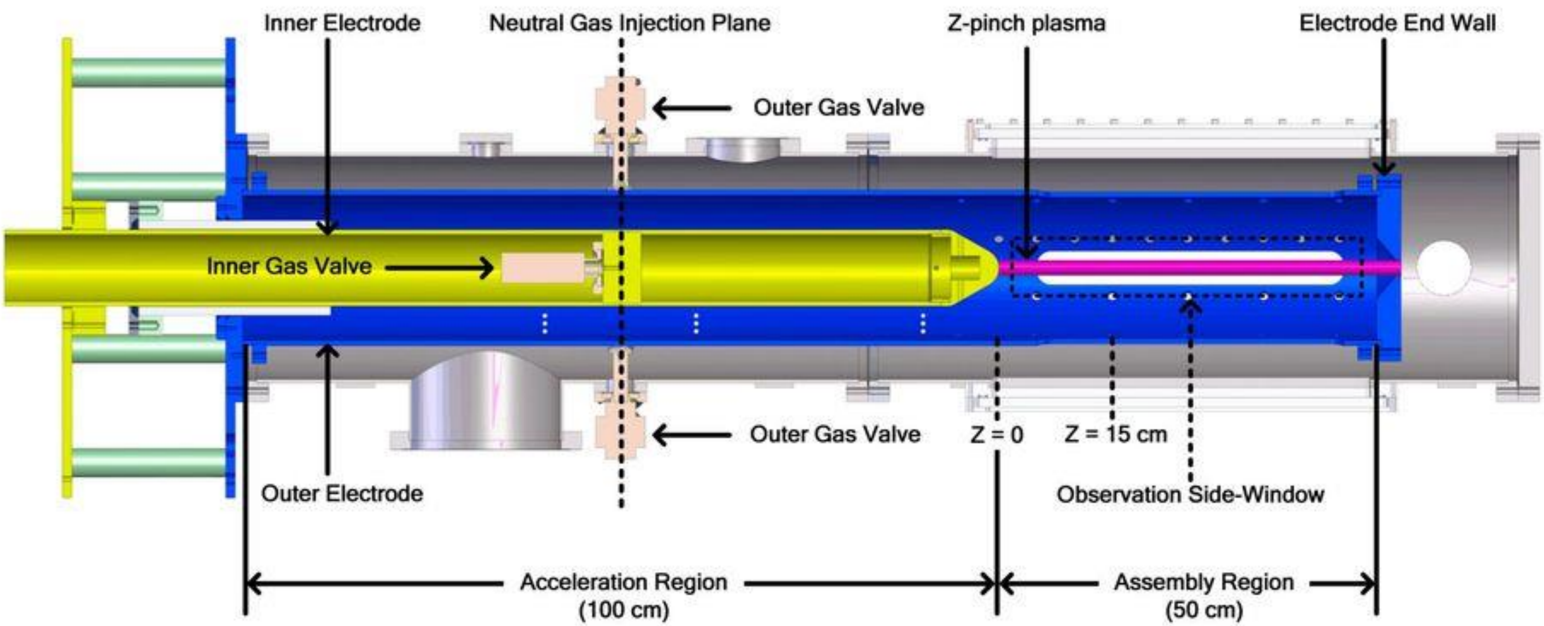
$$\frac{dV_Z}{dr} \neq 0$$

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

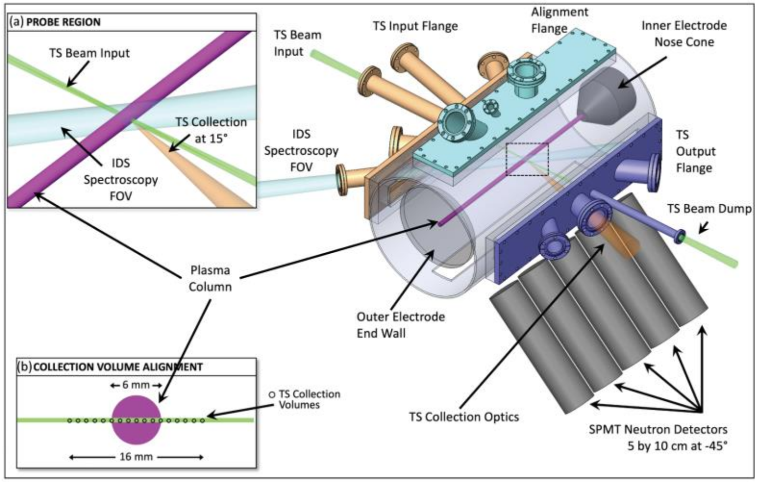


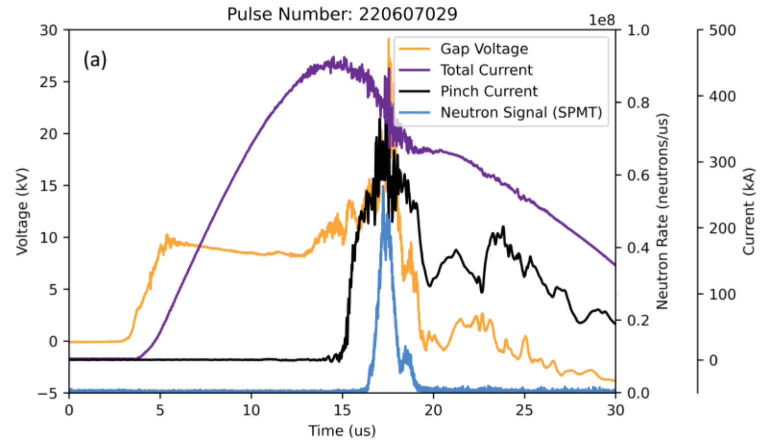
ZAP ENERGY

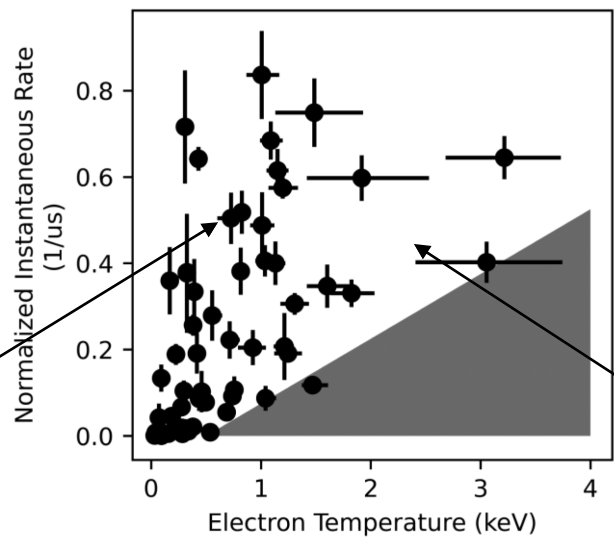


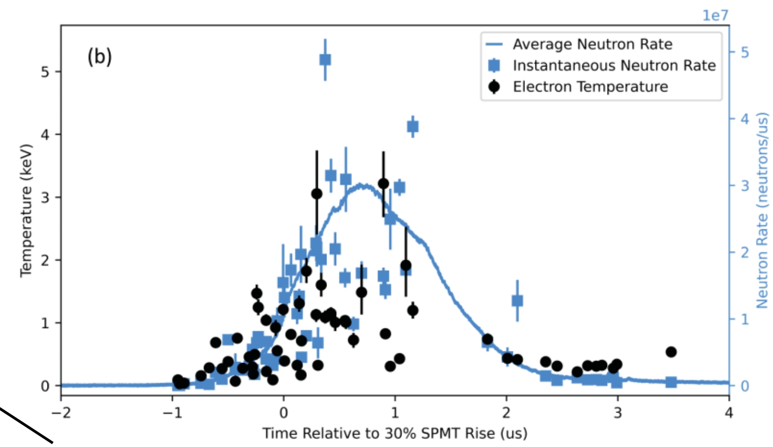
https://www.zapenergyinc.com/about
A. D. Stepanov, etc., Phys. Plasmas 27, 112503 (2020)

Elevated electron temperature coincident with observed fusion reactions in a sheared-flow-stabilized z pinch





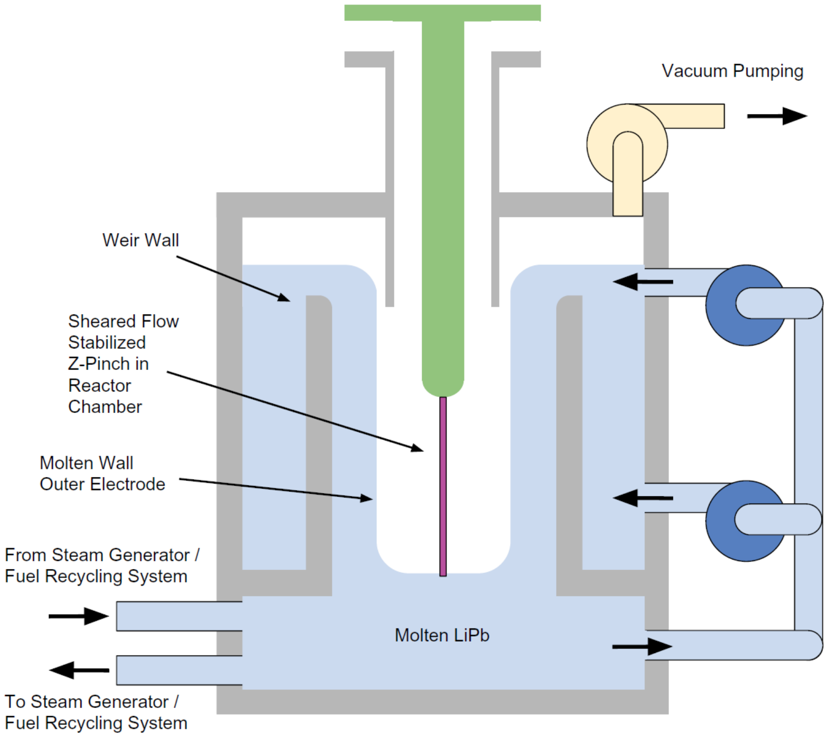


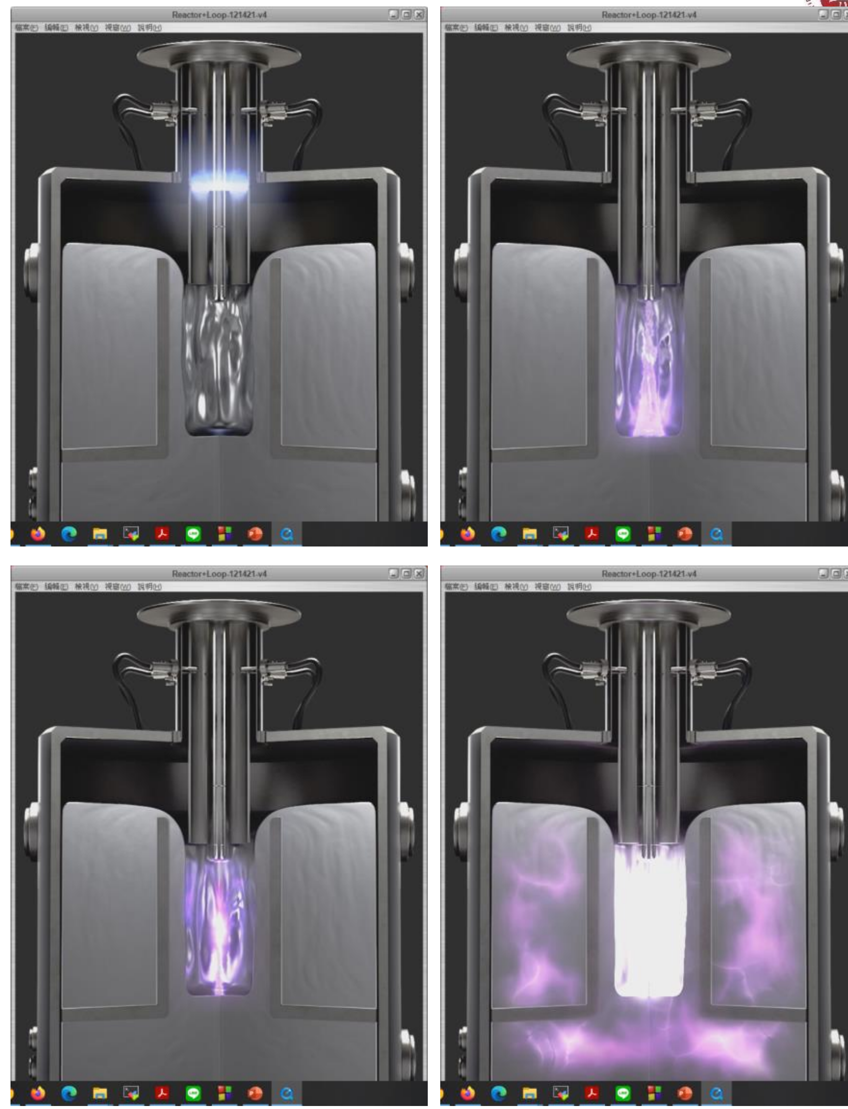


- **Thomson scattering measurement missed the high temperature region.**
- **High temperature coincide with high rate.**

B. Levitt, etc., Phys. Rev. Lett. **132**, 155101 (2024)

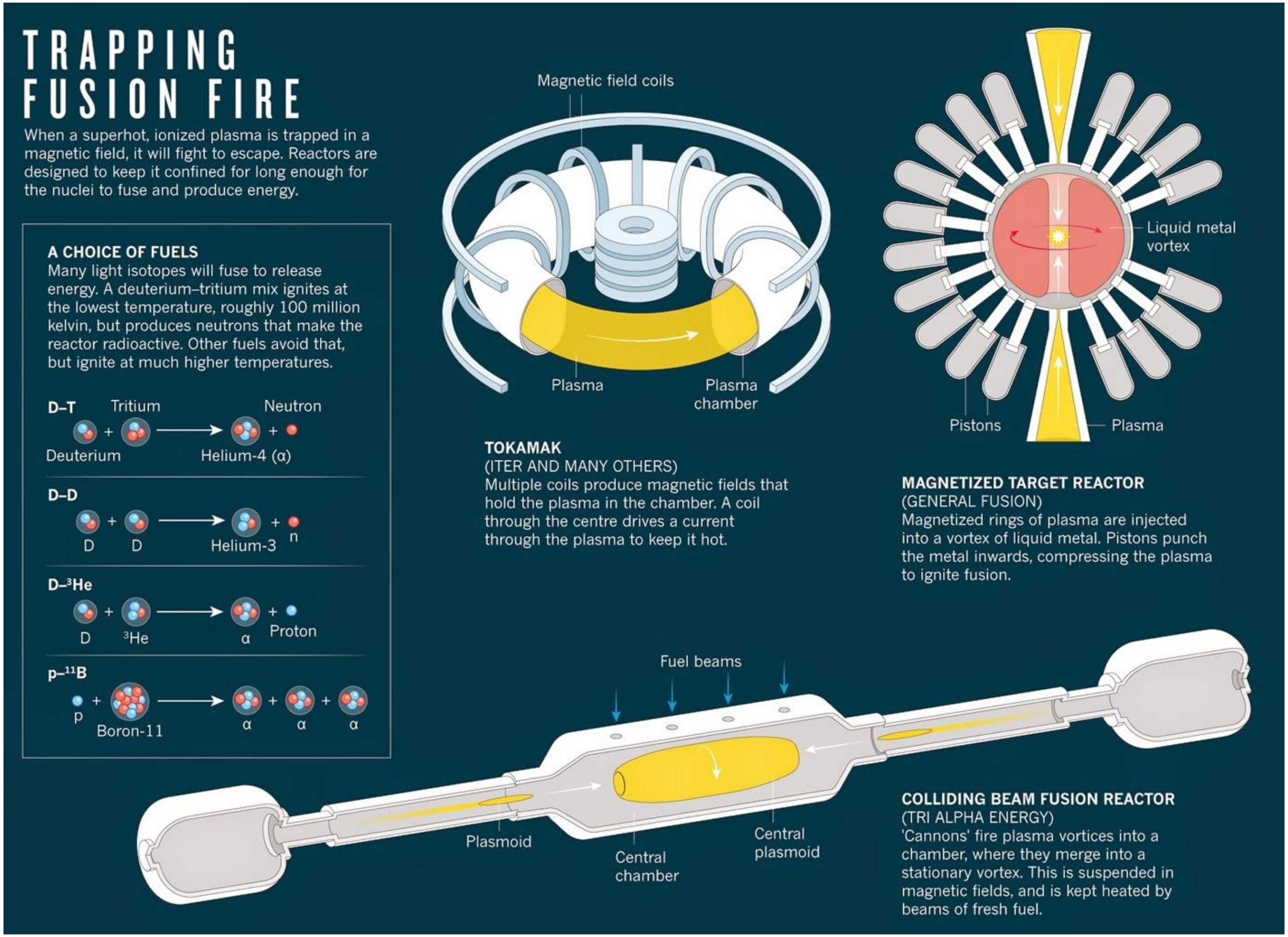
Fusion reactor concept by ZAP energy





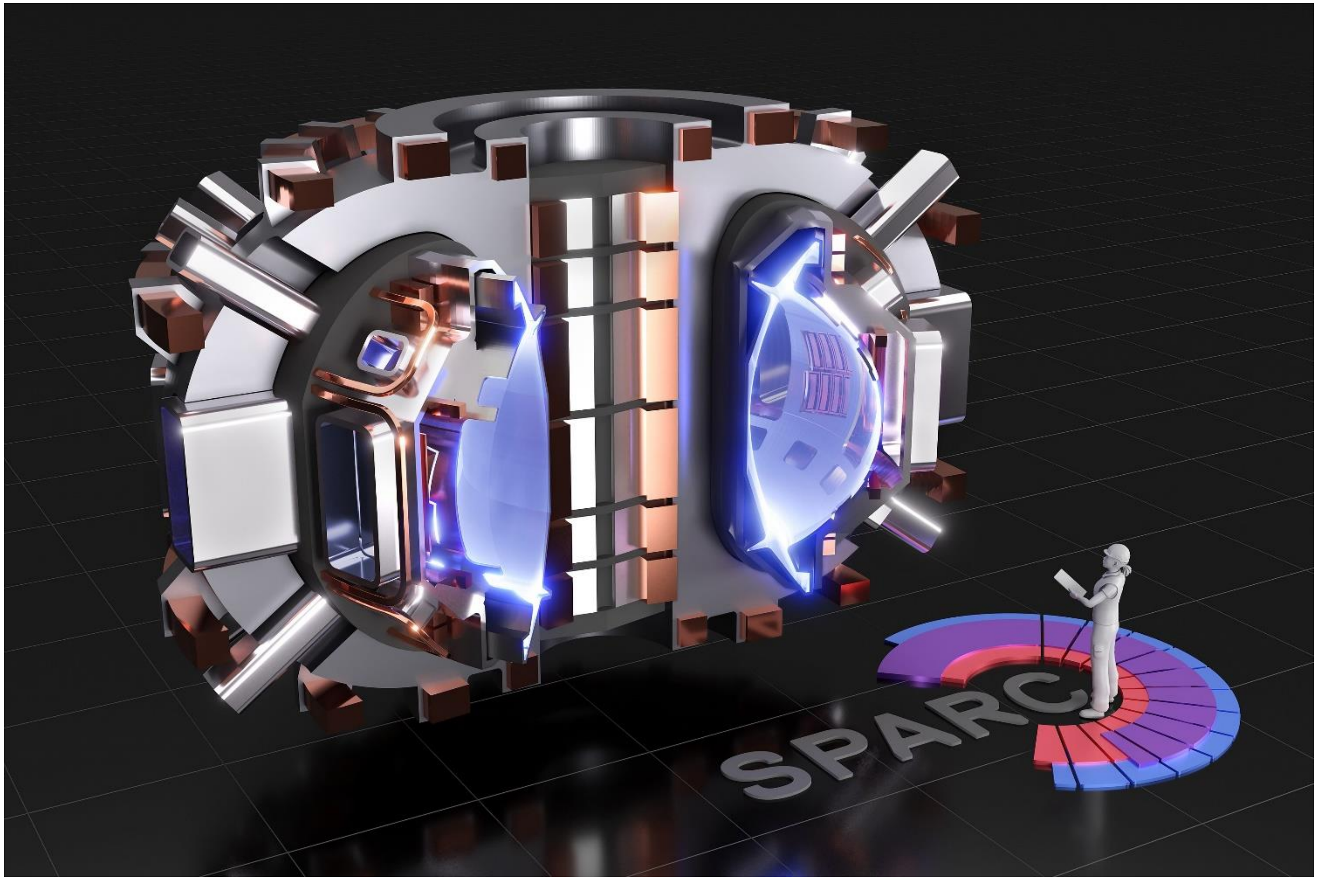
https://www.zapenergyinc.com/about
E. G. Forbes, etc., Fusion Sci. Tech. 75, 599 (2019)

There are alternative



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

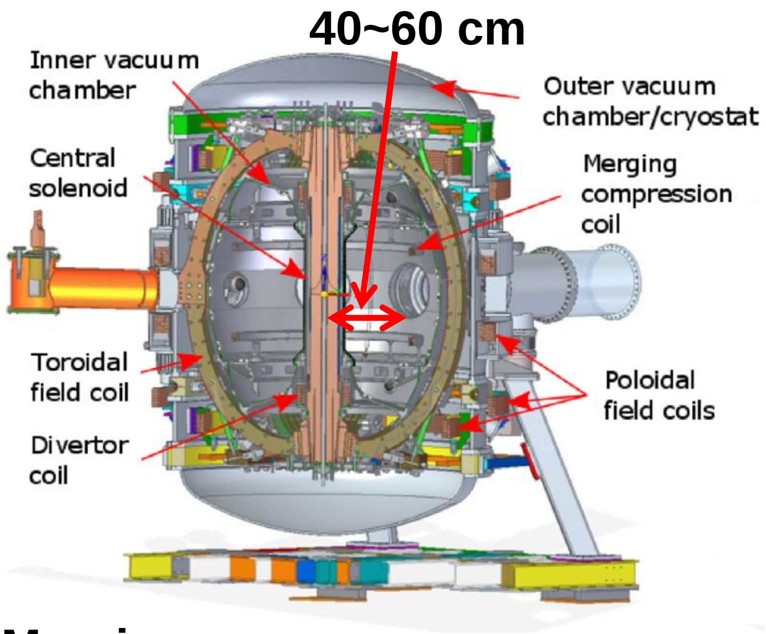
Commonwealth Fusion Systems, a MIT spin-out company, is building a high-magnetic field tokamak



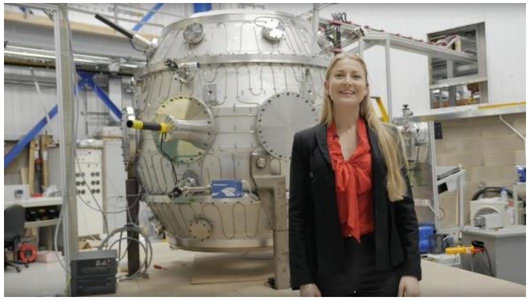
- **Fusion power ∝ B^4.**
- **The fusion gain Q > 2 is expected for SPARC tokamak.**

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

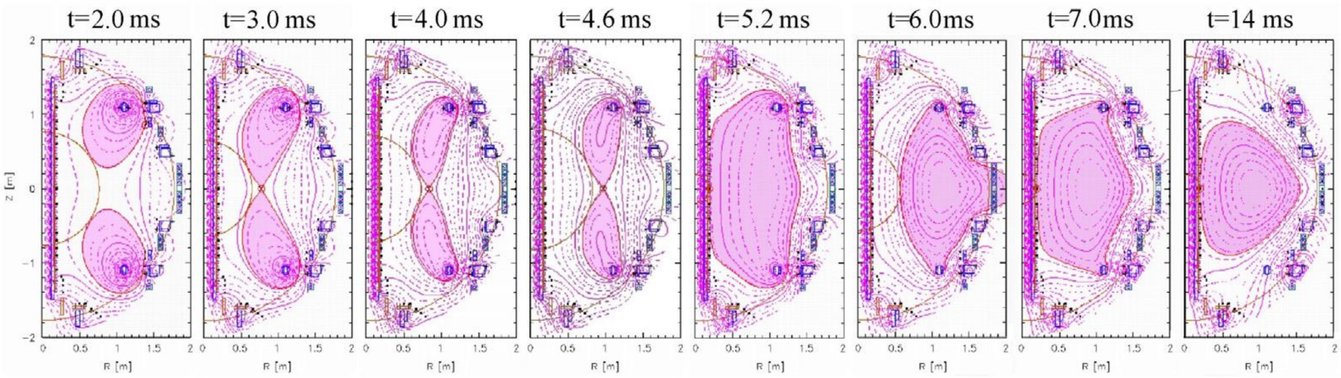
Merging compression is used to heat the tokamak at the start-up process in ST40 Tokamak at Tokamak Energy Ltd



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

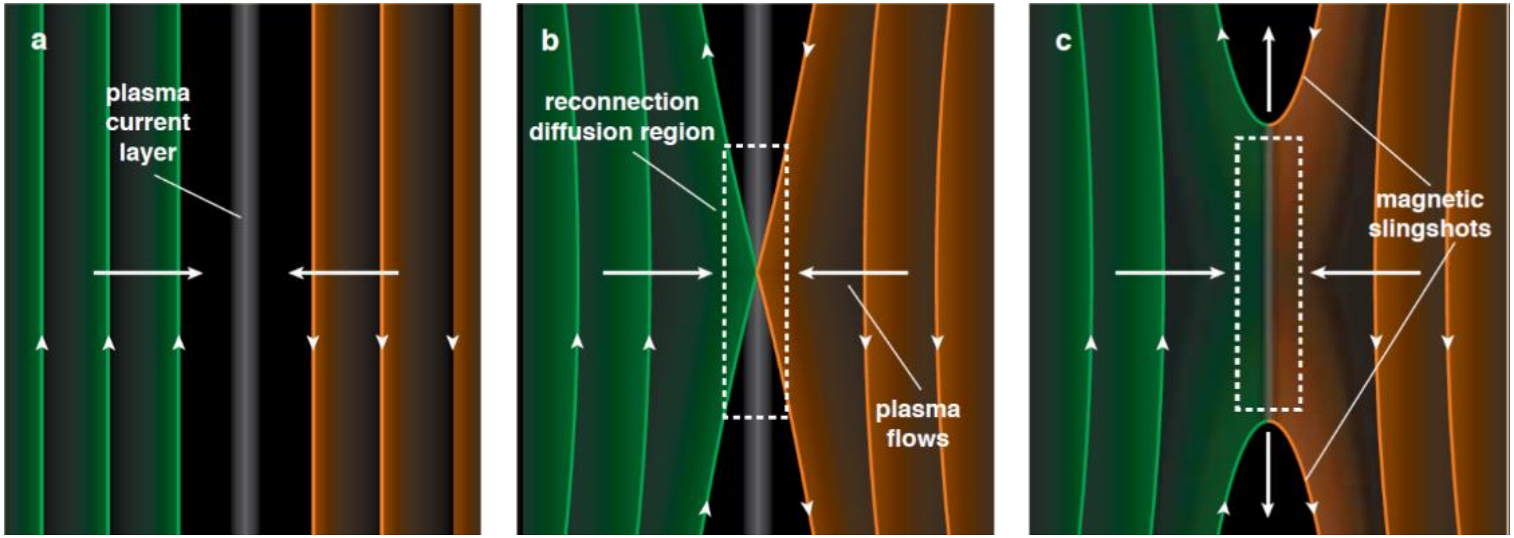


- **Merging compression**



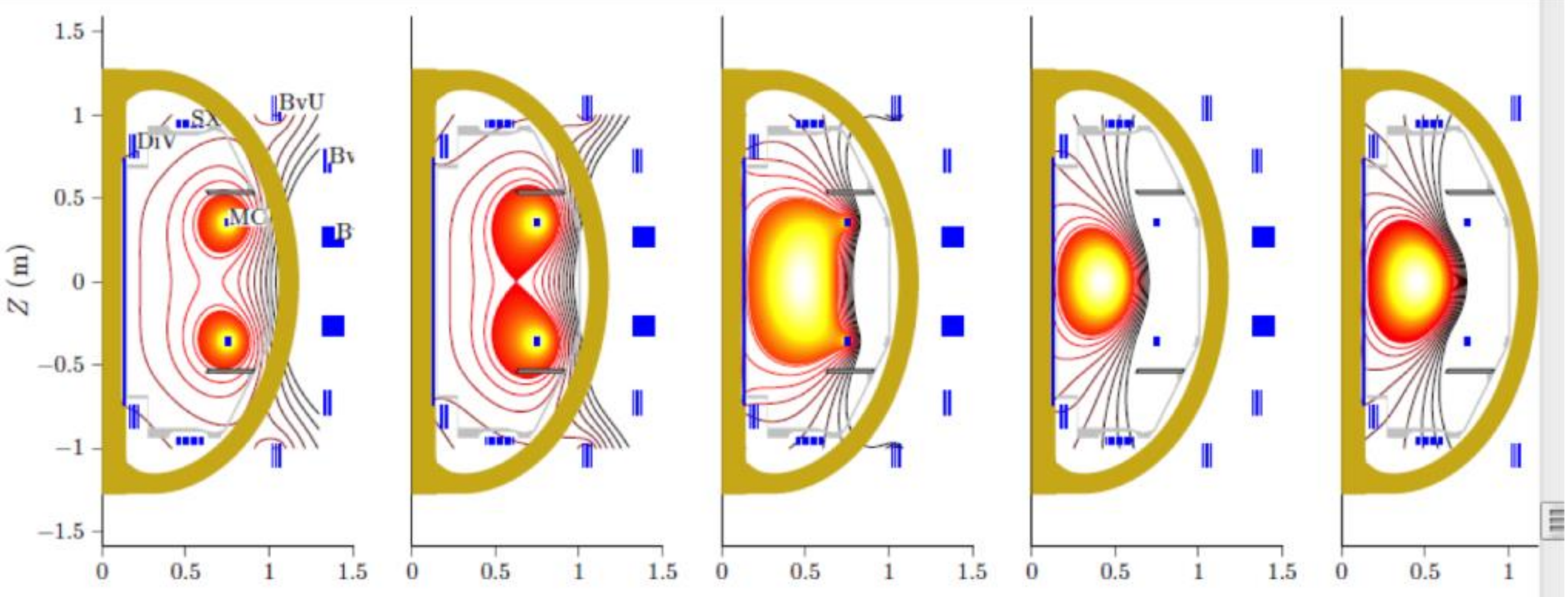
M. Gryaznevich, etc., Fusion Eng. Design, **123**,177 (2017)
https://www.tokamakenergy.co.uk/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

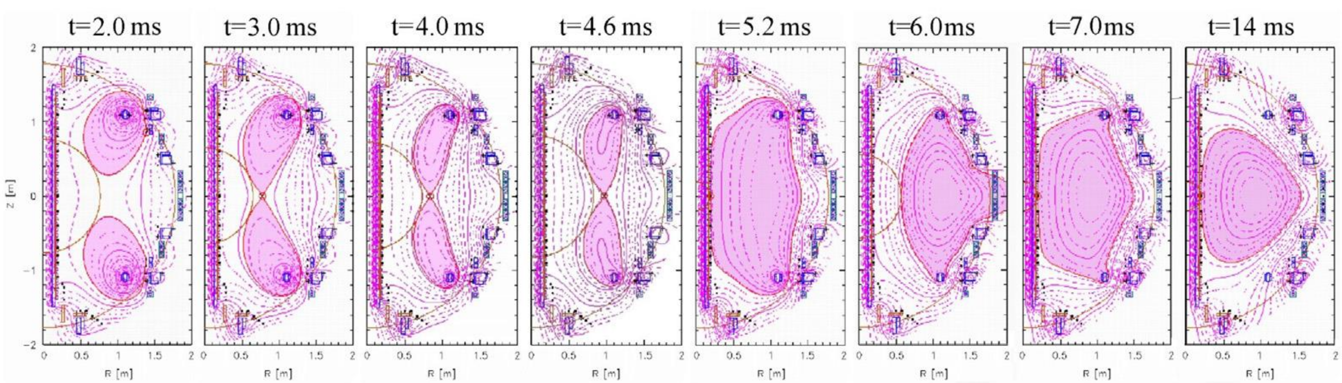
Reconnection



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

Merging compression is used to heat the plasma



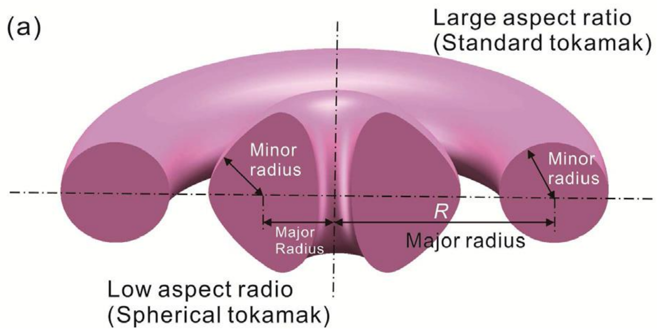


http://www.100milliondegrees.com/merging-compression/

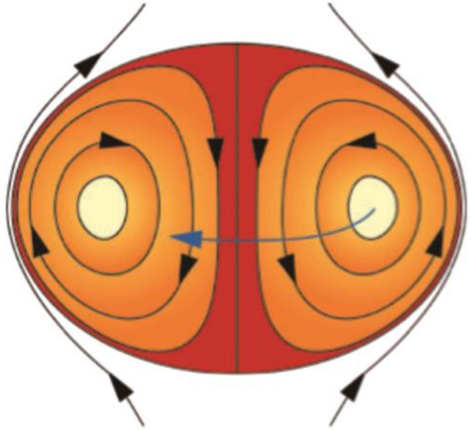
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

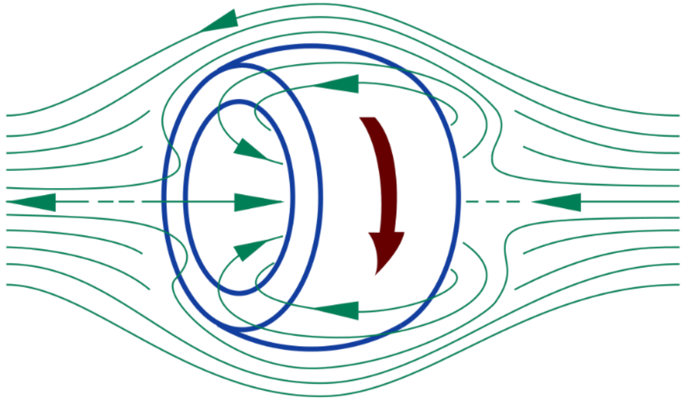
Spherical torus (ST) and compact torus (CT)

- **Spherical torus (ST)**



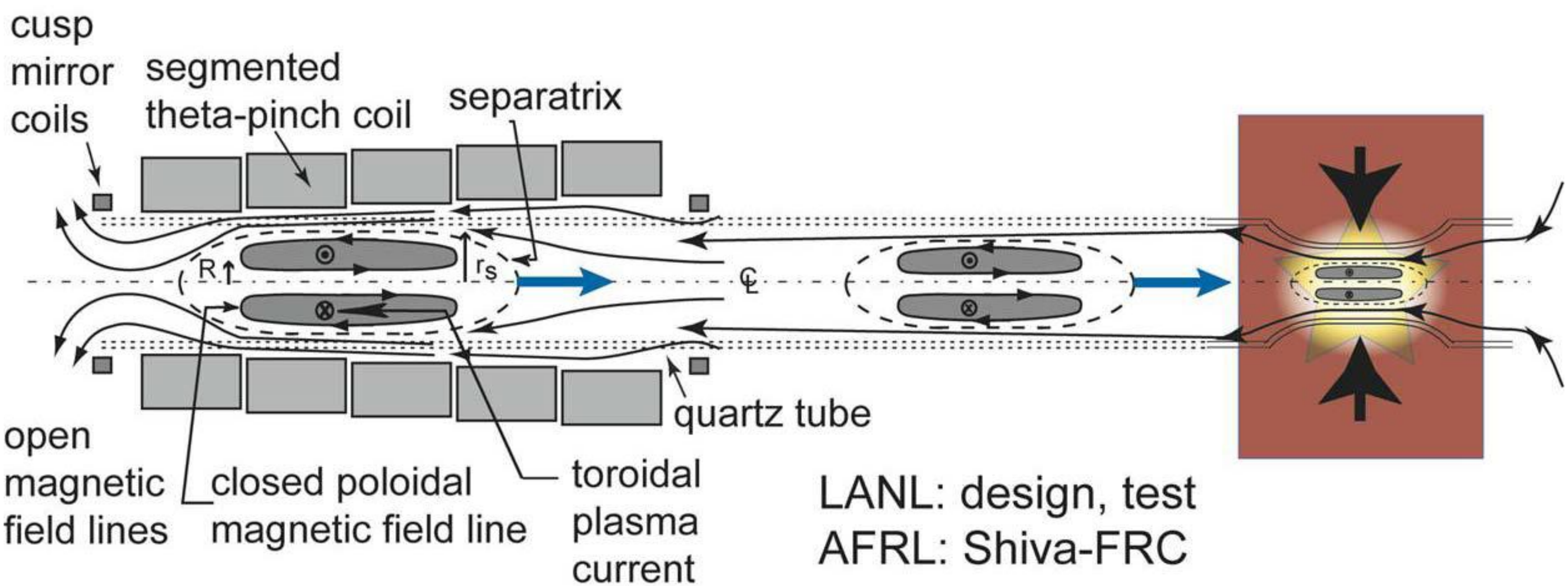
- **Compact torus (CT)**
  - **Spheromak**
  - **Field reversed configuration (FRC)**



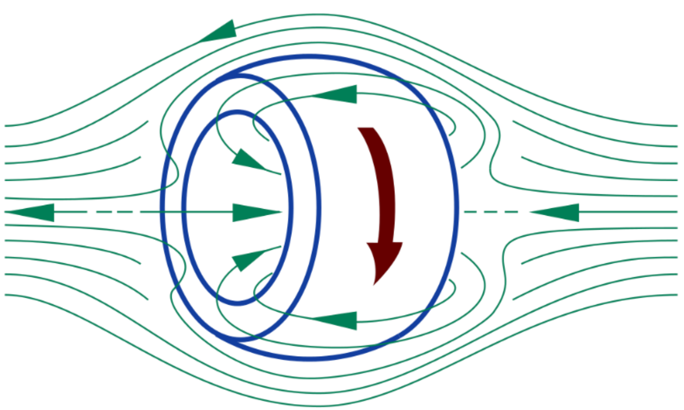


Zhe Gao, Matter Radiat. Extremes **1**, 153 (2016)
https://en.wikipedia.org/wiki/Field-reversed_configuration

Field reverse configuration is used in Tri-alpha energy

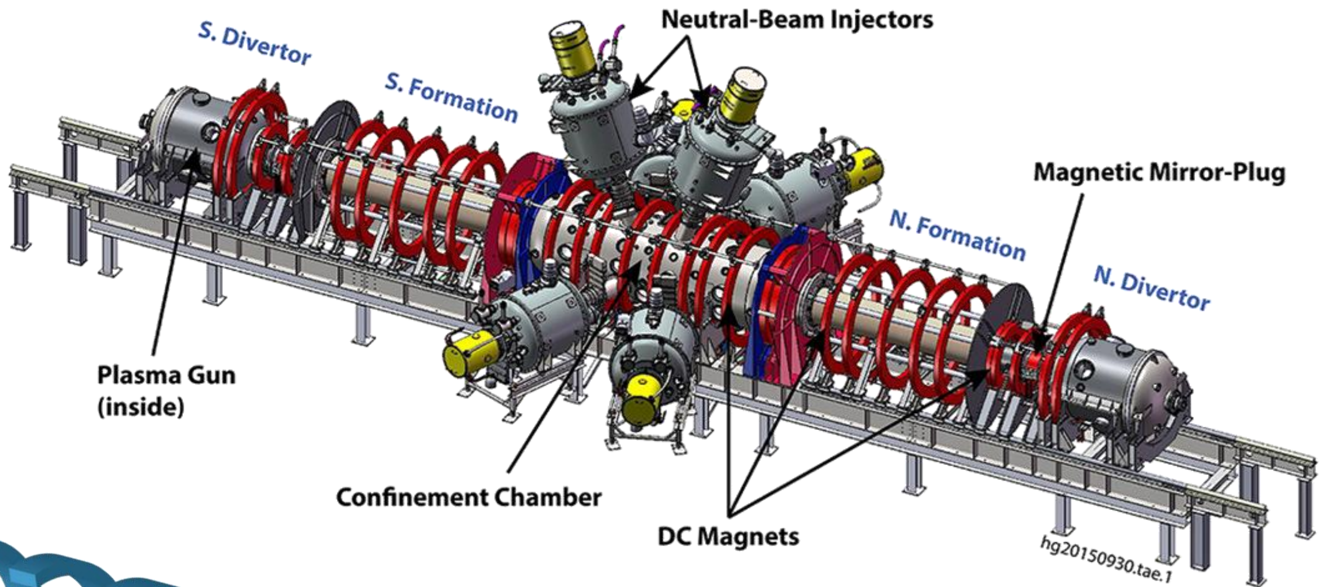


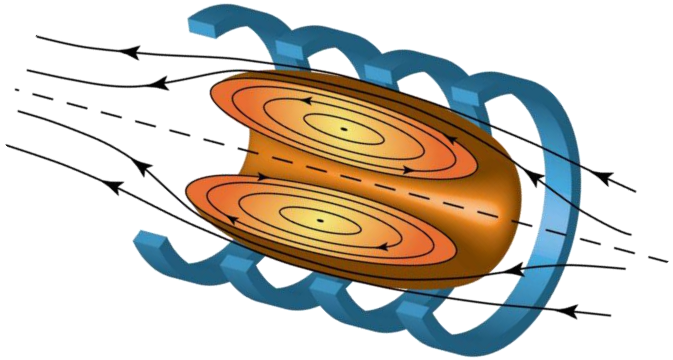
LANL: design, test
AFRL: Shiva-FRC



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

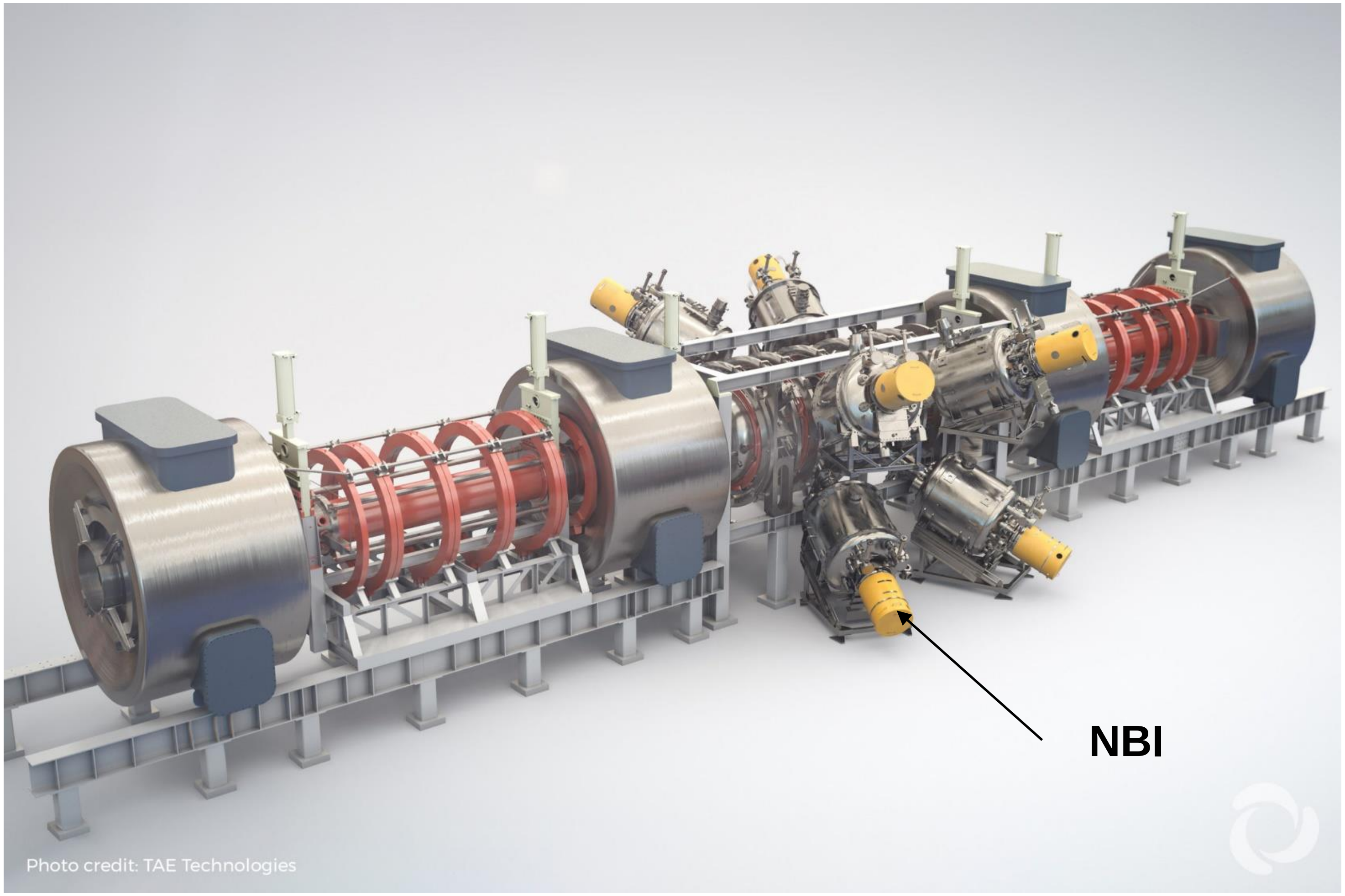
Field reverse configuration is used in Tri-alpha energy





http://trialphaenergy.com/
Zhe Gao, Matter Radiat. Extremes **1**, 153 (2016)

NBI for Tri-Alpha Energy Technologies

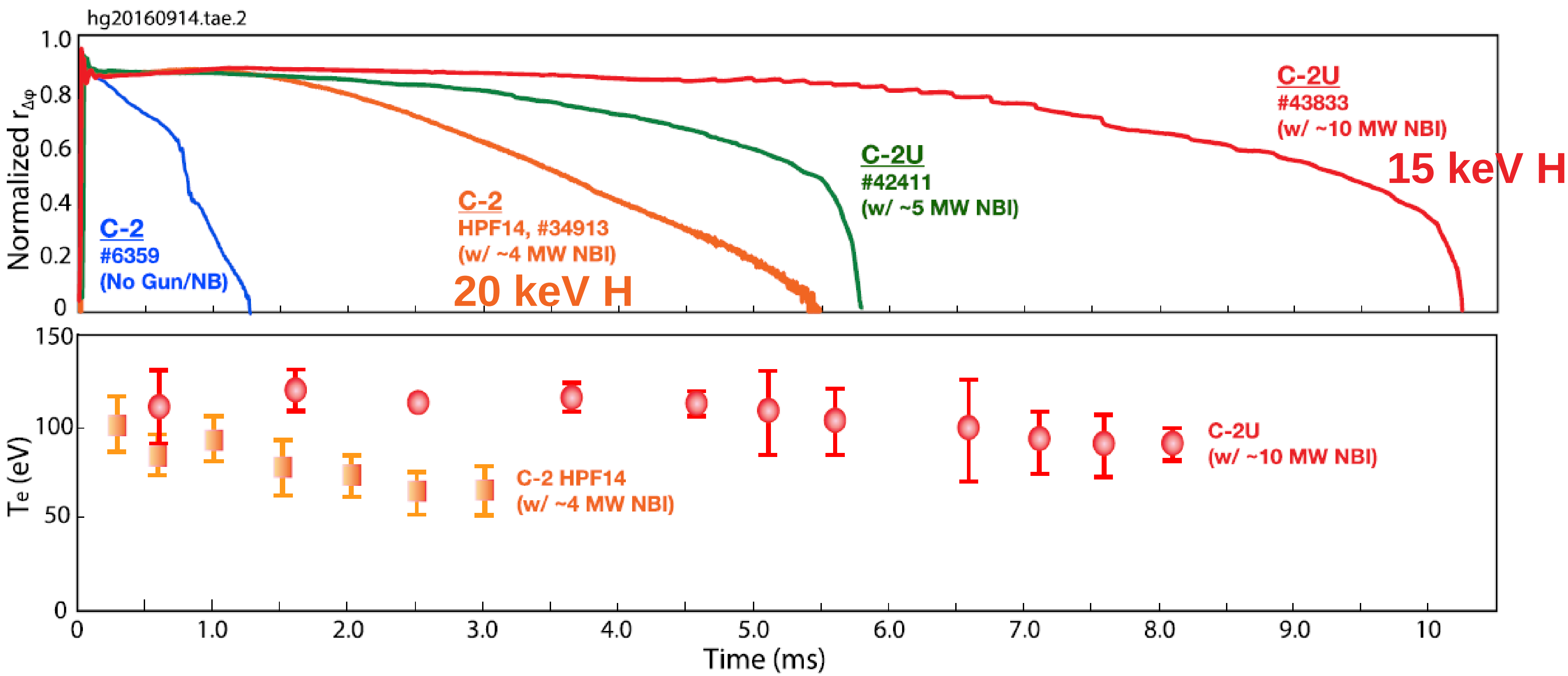


https://tae.com/media/

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

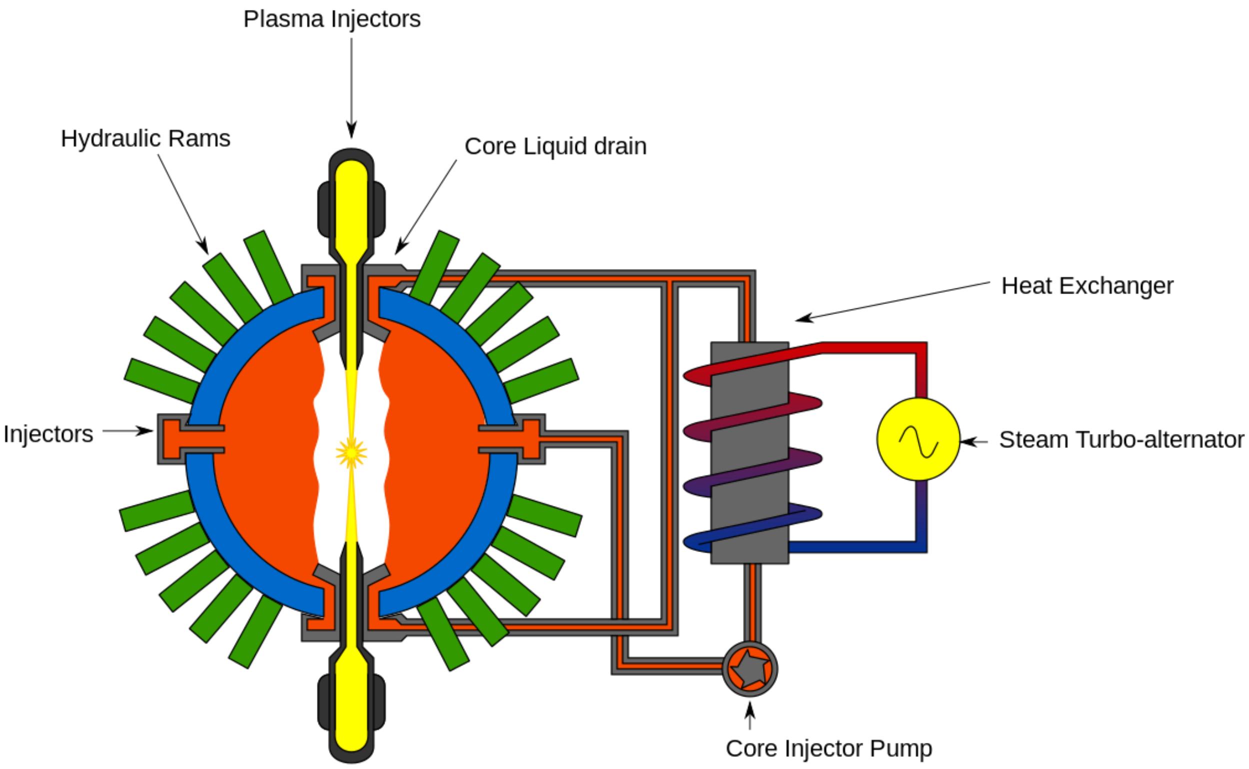
https://tae.com/media/
https://zh.wikihow.com/%E5%9C%A8%E6%89%8B%E6%8C%87%E4%B8%8A%E8%BD%AC%E7%AF%AE%E7%90%83

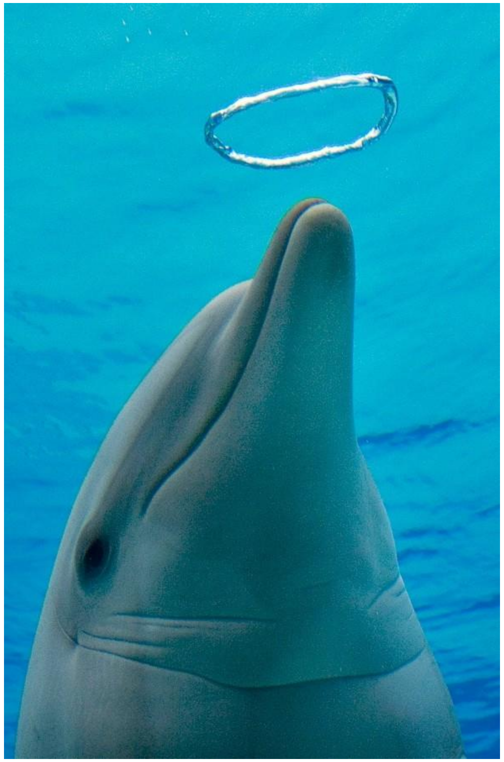
FRC sustain longer with neutral beam injection



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

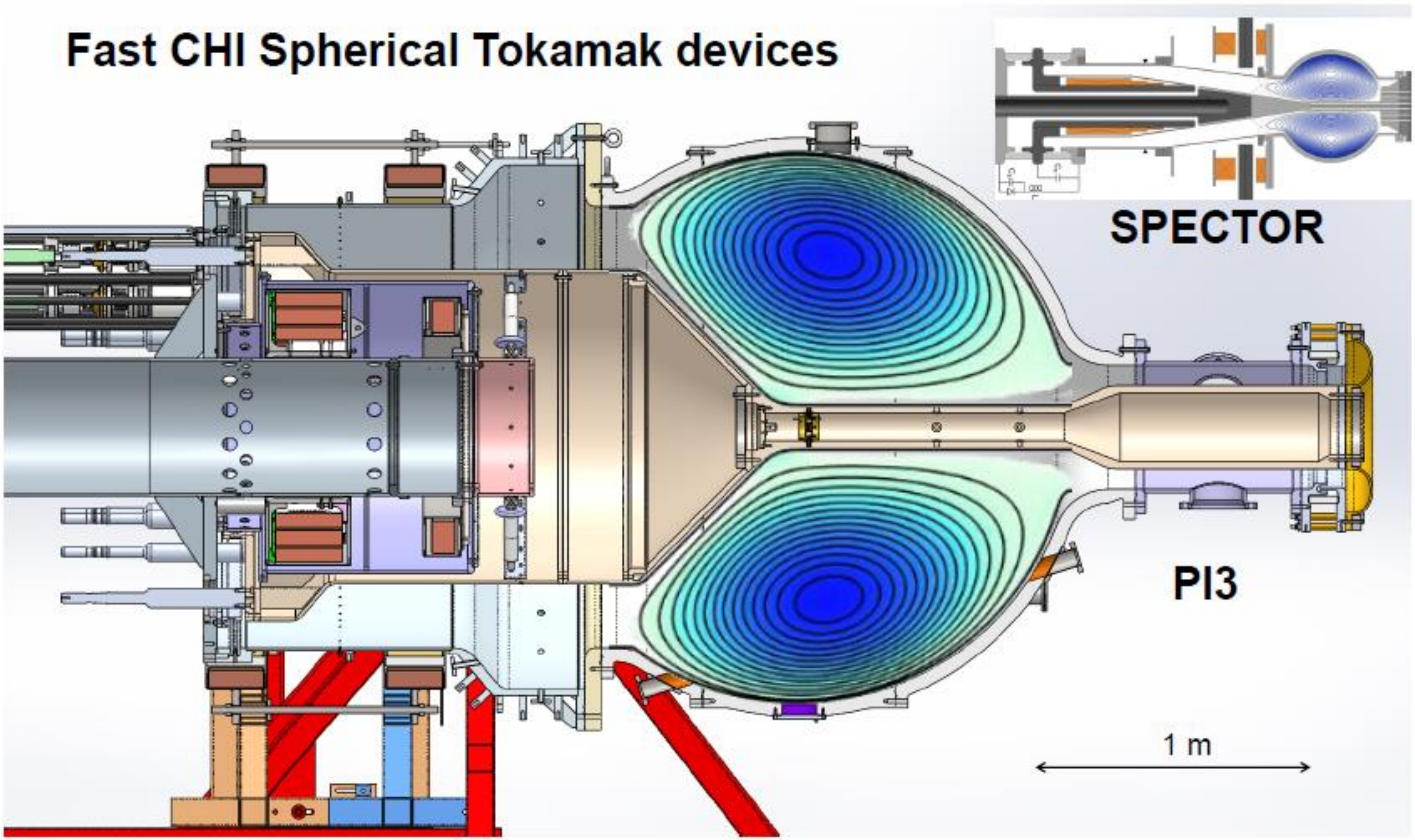
General fusion is a design ready to be migrated to a power plant





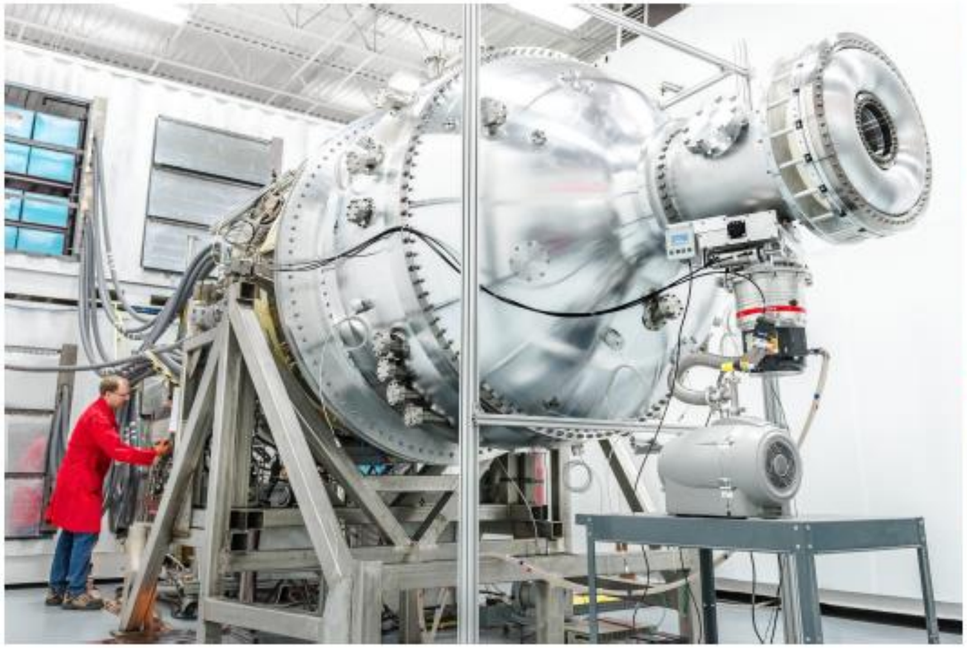
https://en.wikipedia.org/wiki/General_Fusion

A spherical tokamak is first generated



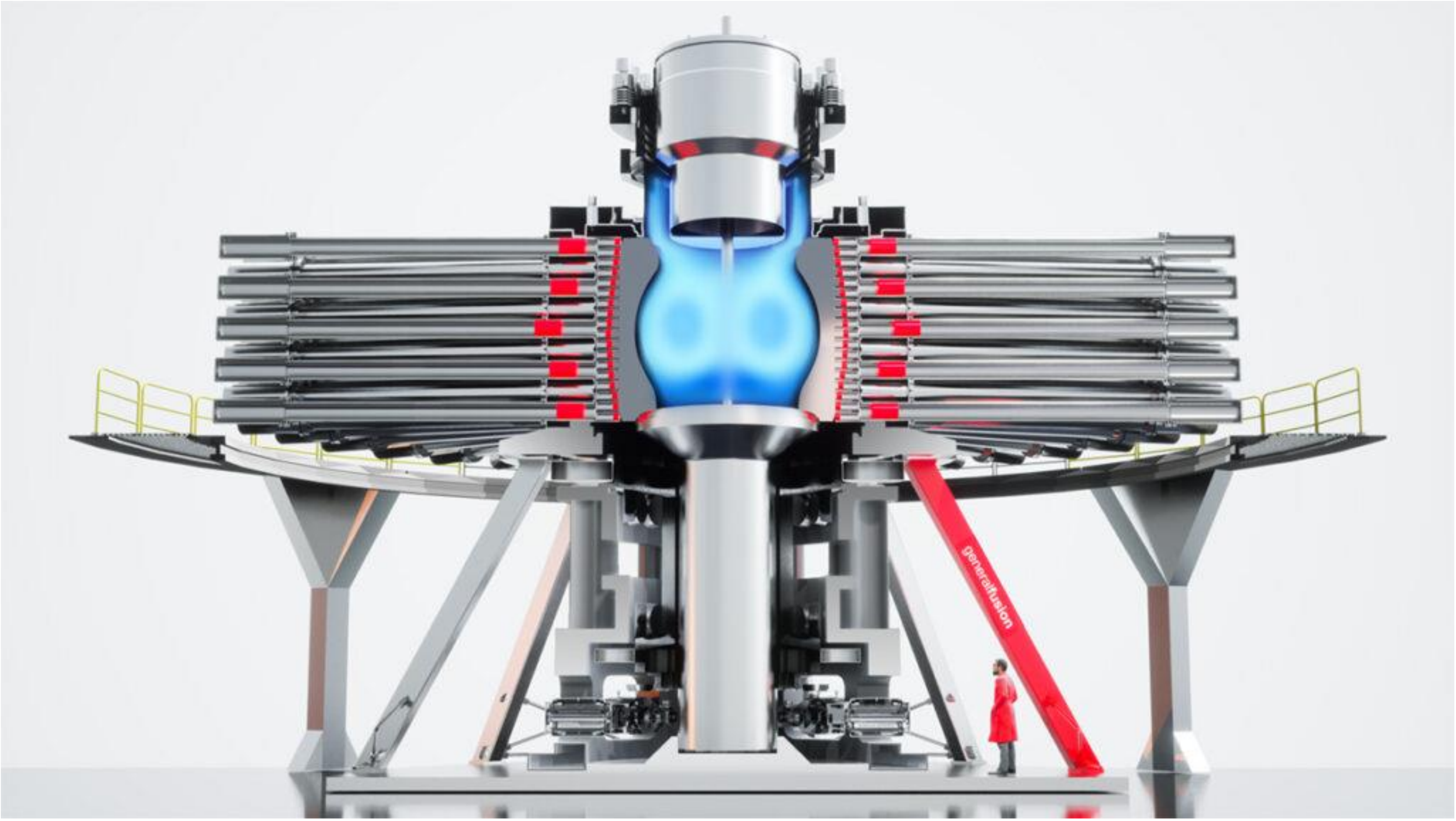
K. EPP, etc., 60th APS-DPP, CP11.00192

Plasma injector for the spherical tokamak

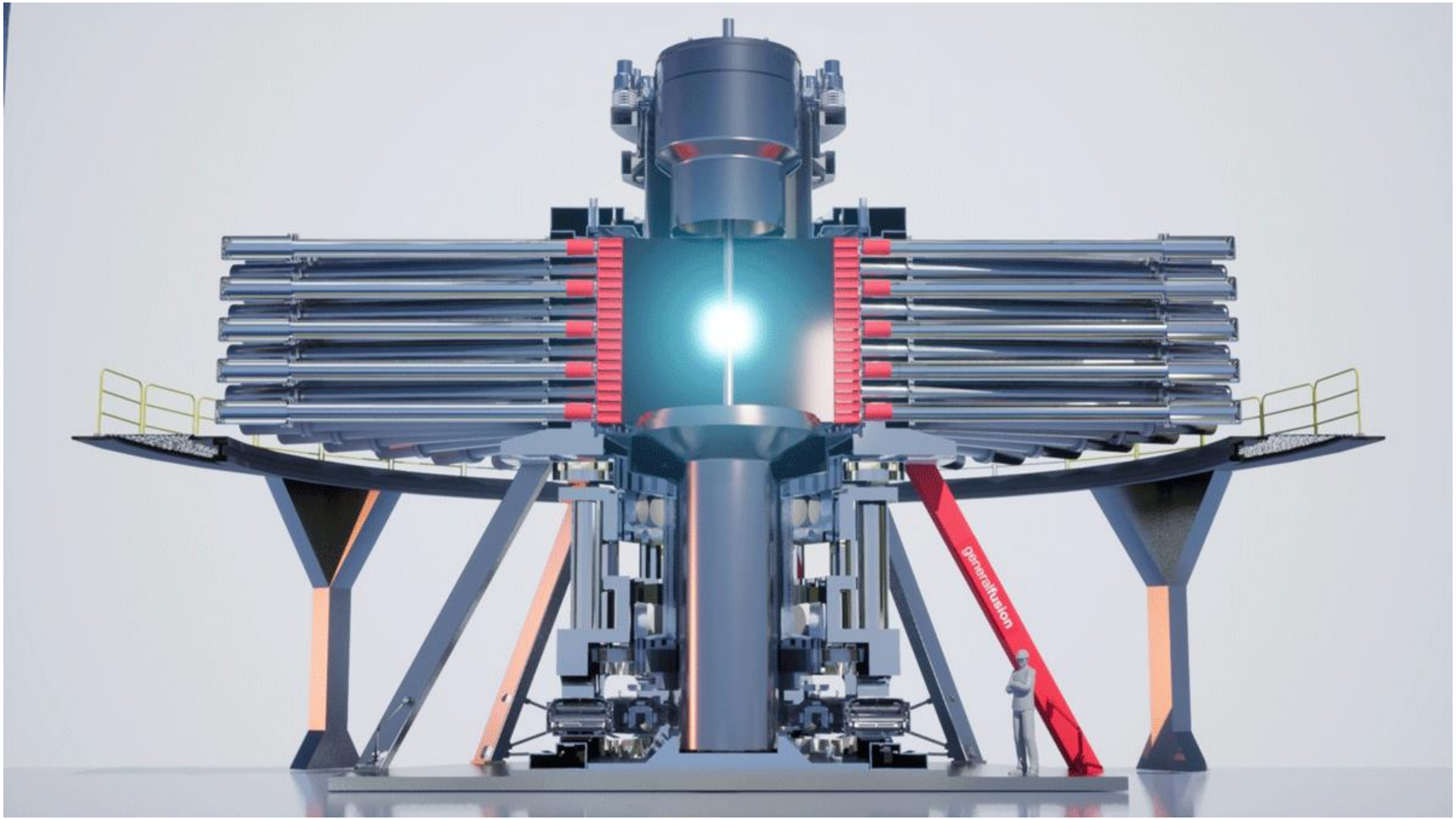


K. EPP, etc., 60^{th} APS-DPP, CP11.00192

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

GENERAL FUSION

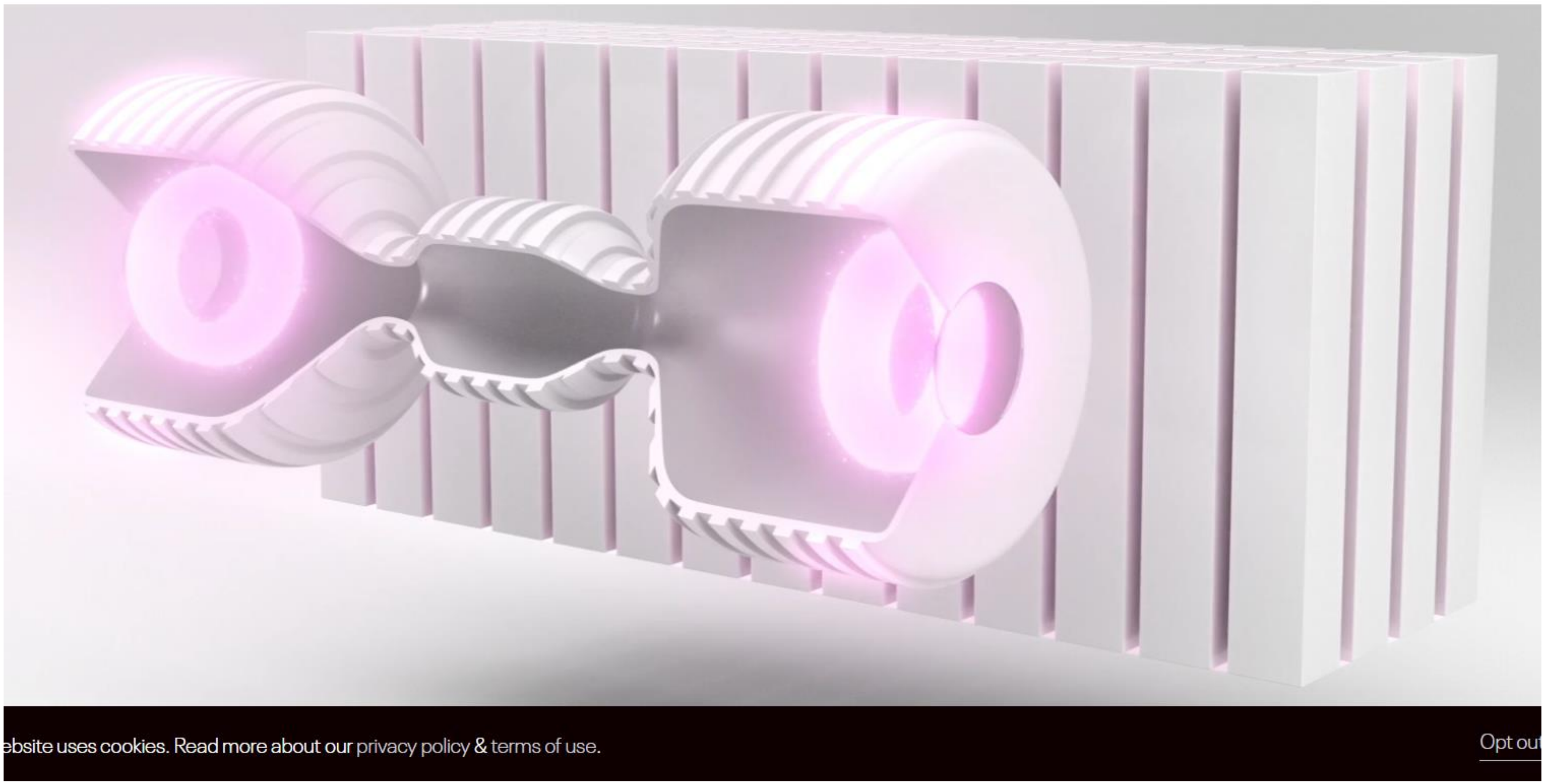
An artist's impression of what the new demonstration plant might look like

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

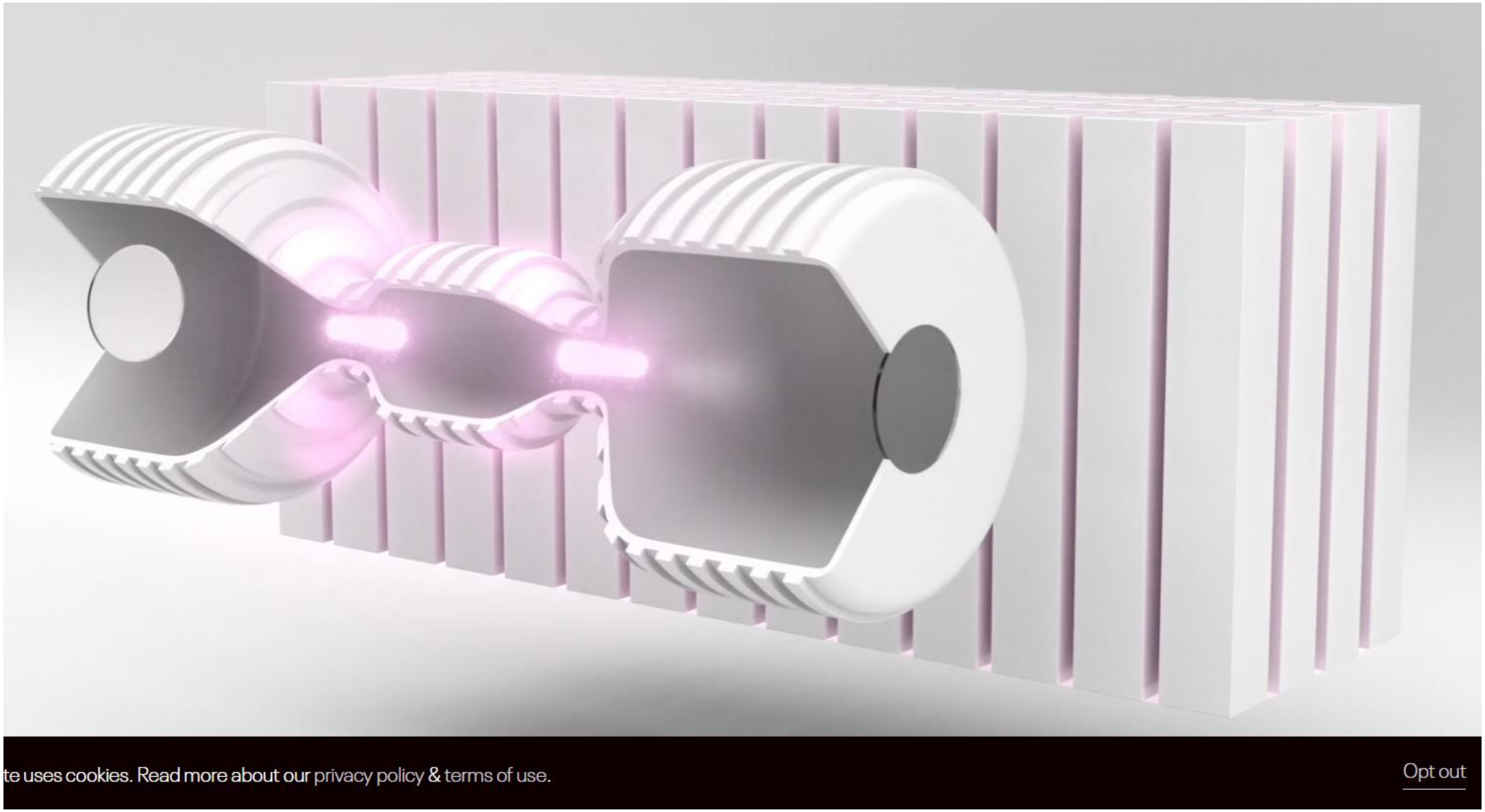
https://www.bbc.com/news/science-environment-57512229

Helion energy is compressing the two merging FRCs



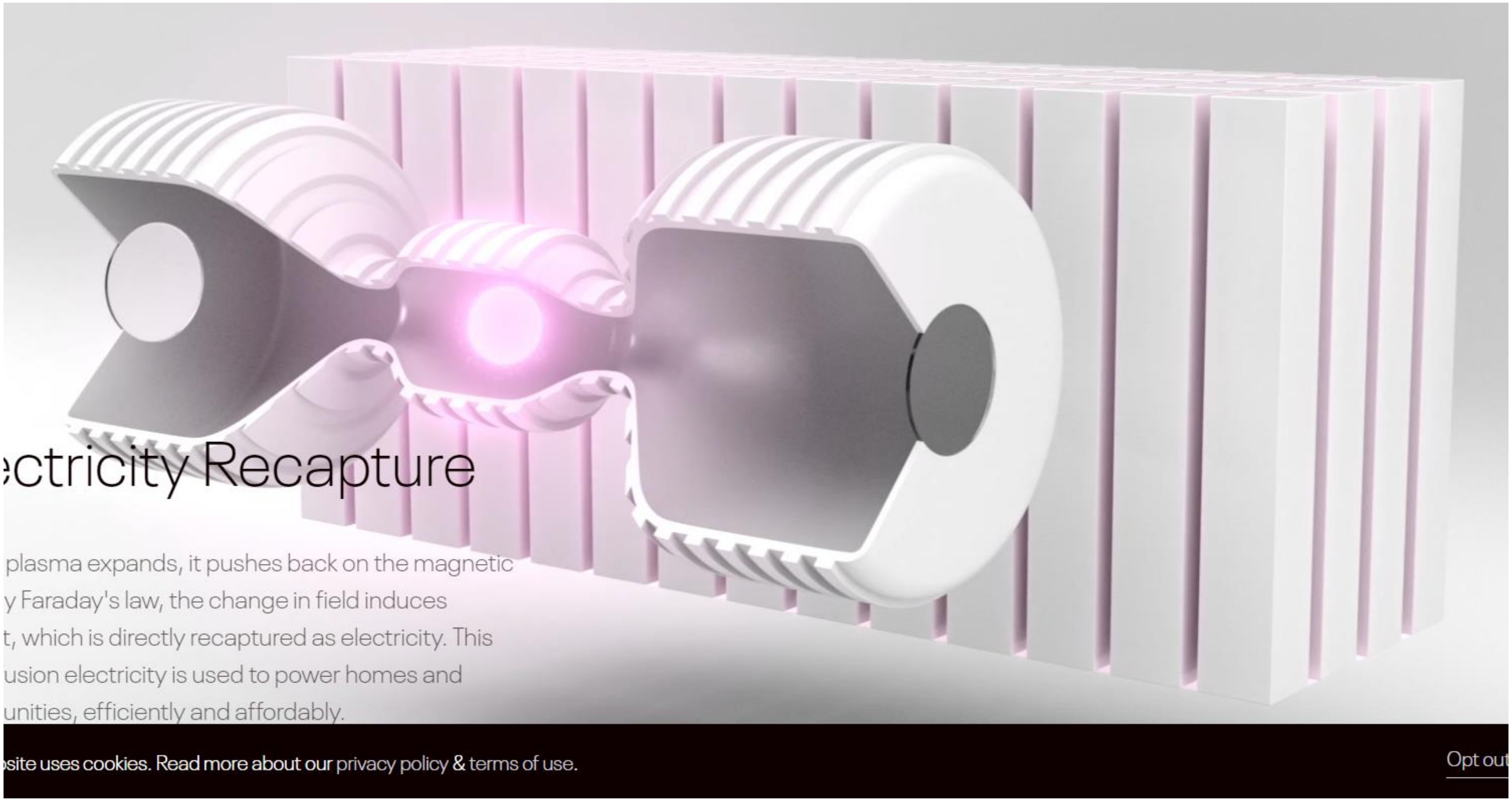
https://www.helionenergy.com/

Two FRCs are accelerated toward each other



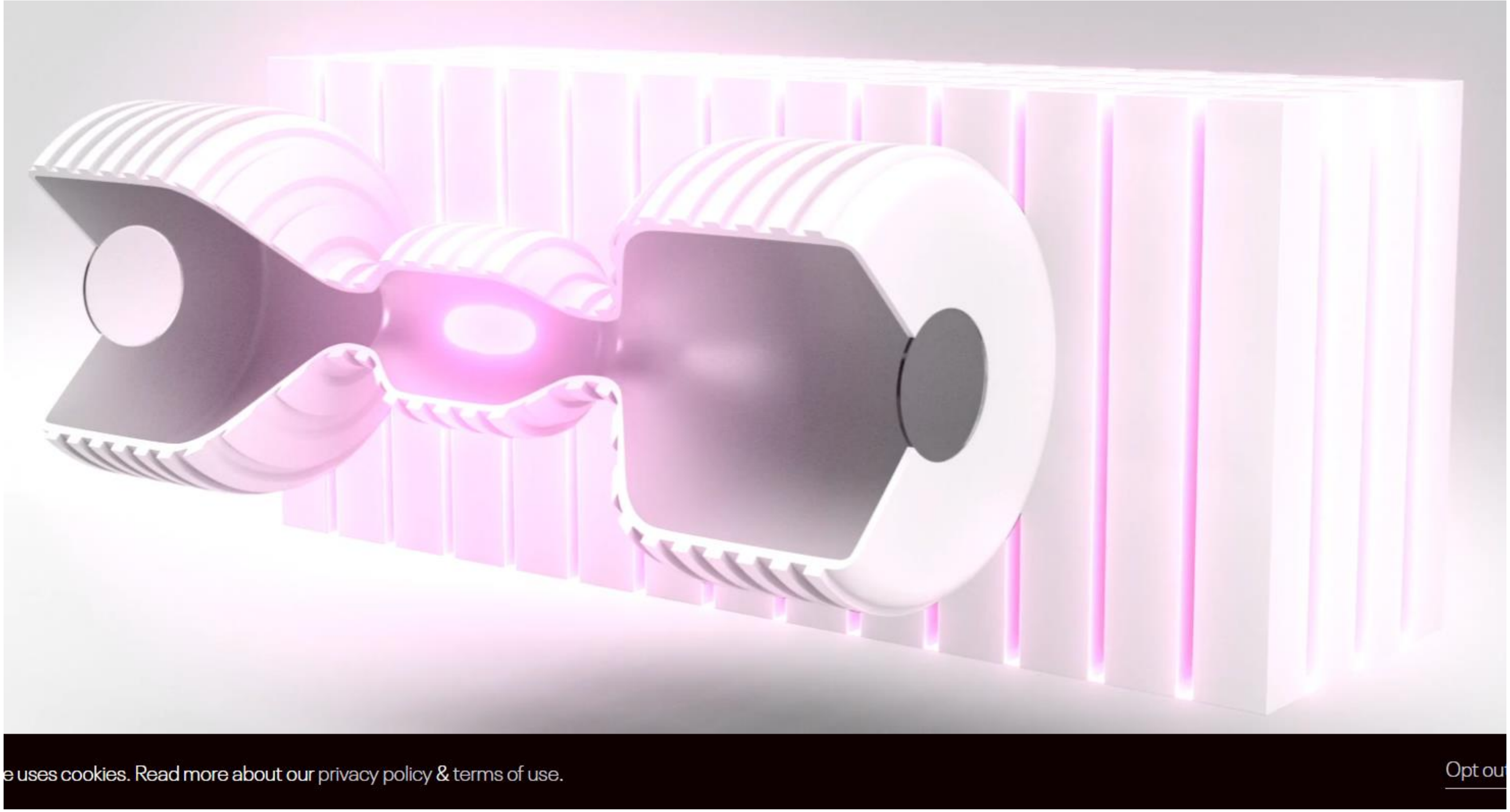
https://www.helionenergy.com/

Two FRCs merge with each other



https://www.helionenergy.com/

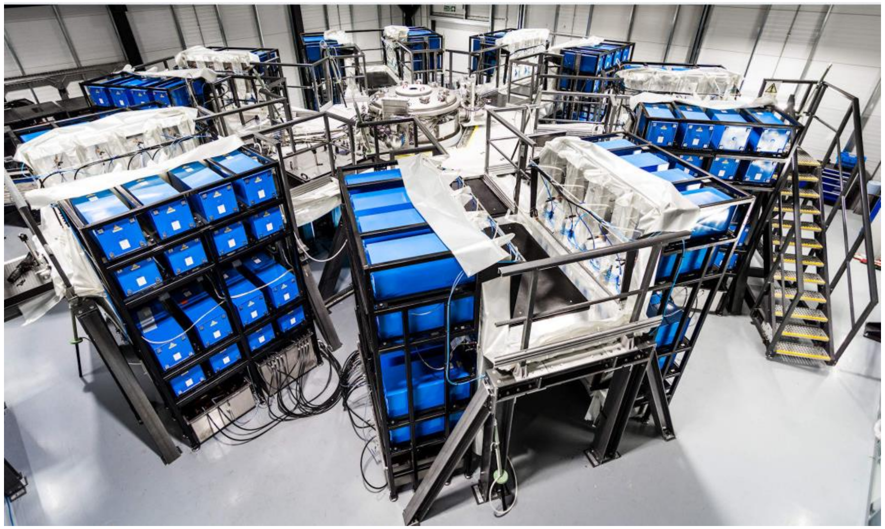
The merged FRC is compressed electrically to high temperature



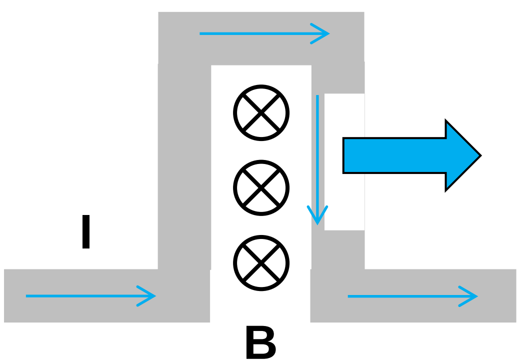
- **Similar concept will be studied in our laboratory.**

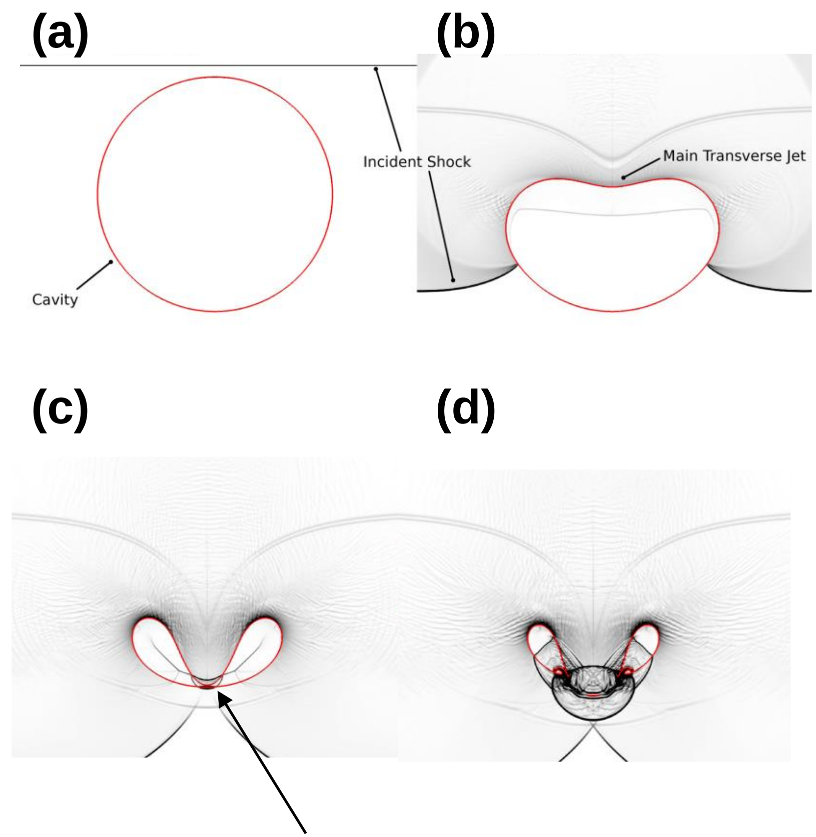
https://www.helionenergy.com/

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.**

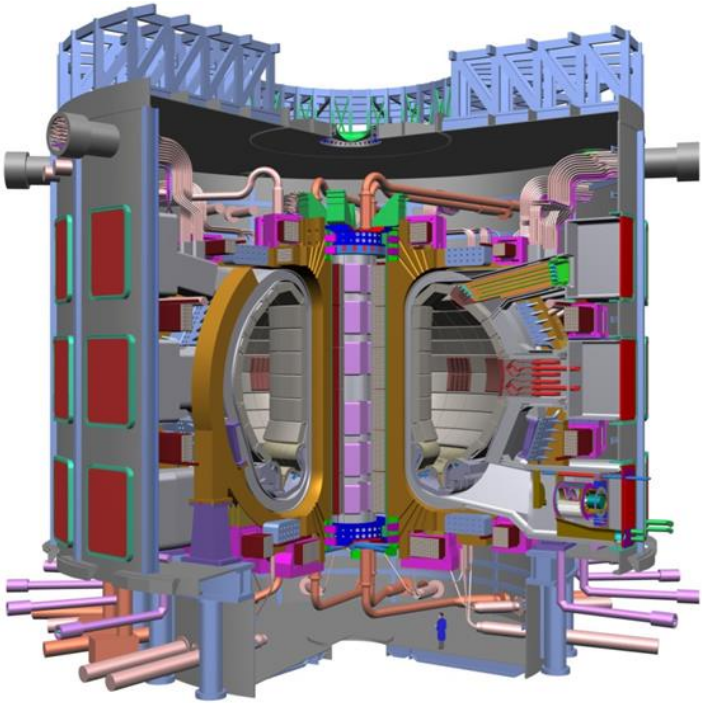
https://firstlightfusion.com/
B. Tully and N. Hawker, Phys. Rev. **E93**, 053105 (2016)

A gas gun is used to eject the projectile

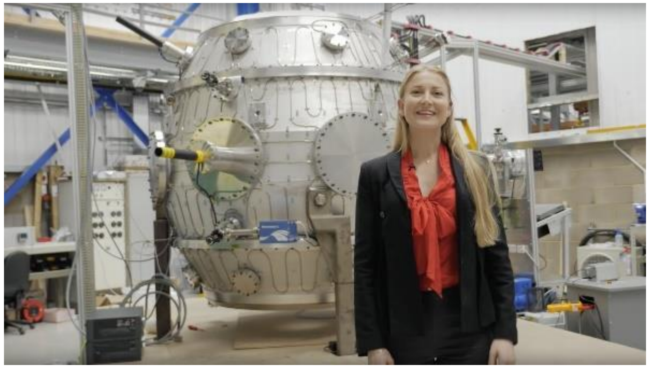
https://www.youtube.com/watch?v=JN7lyxC11n0
https://www.youtube.com/watch?v=aW4eufacf-8

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

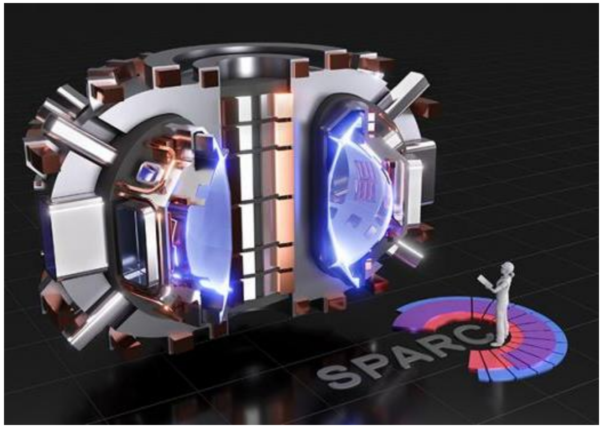
- **ITER – 2025 First Plasma**
  2035 D-T Exps
  2050 DEMO



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



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



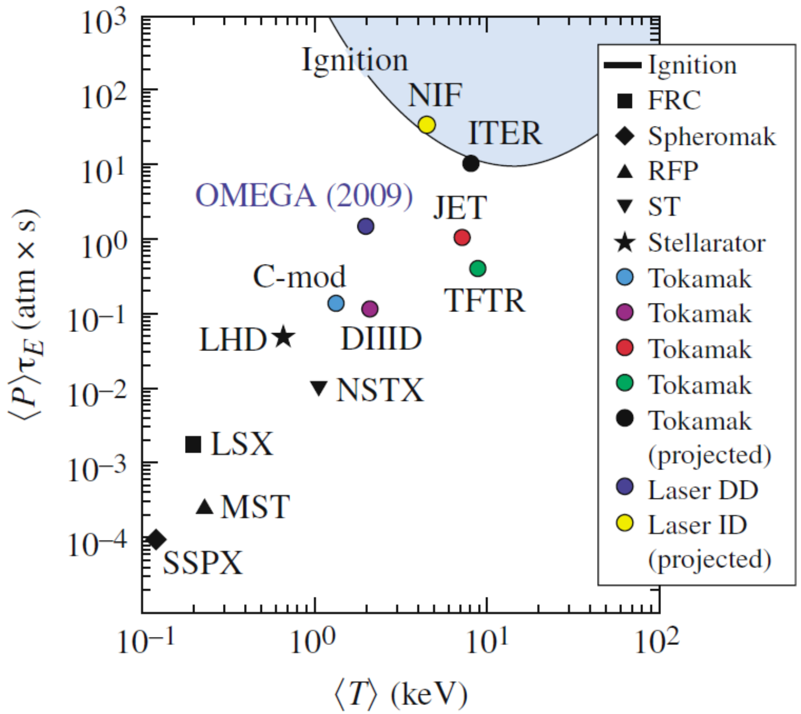
https://www.iter.org
https://www.tokamakenergy.co.uk/
https://www.psfc.mit.edu/sparc

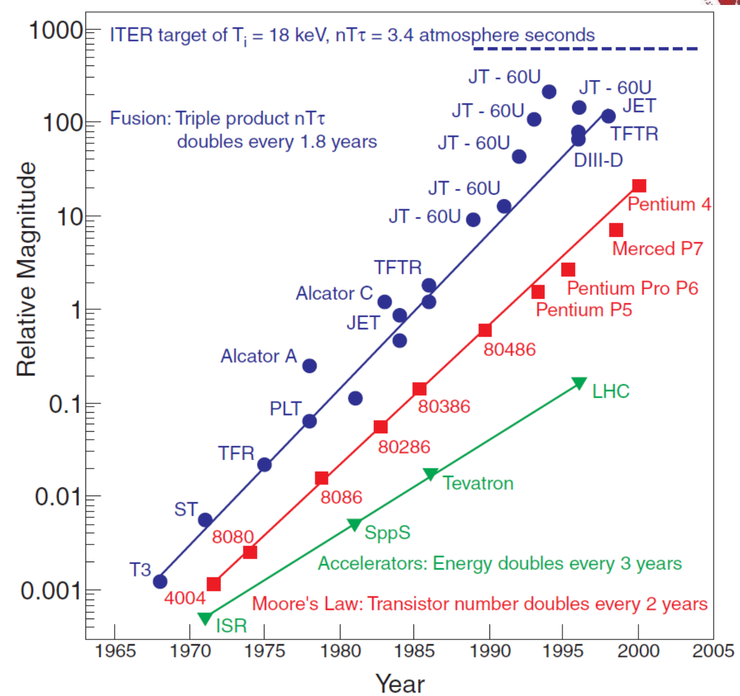
Fusion is blooming

⋮

https://www.fusionindustryassociation.org/members

We are closed to ignition!





- **Other private companies:**

...

Tokamak **MTF** **ICF**

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

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

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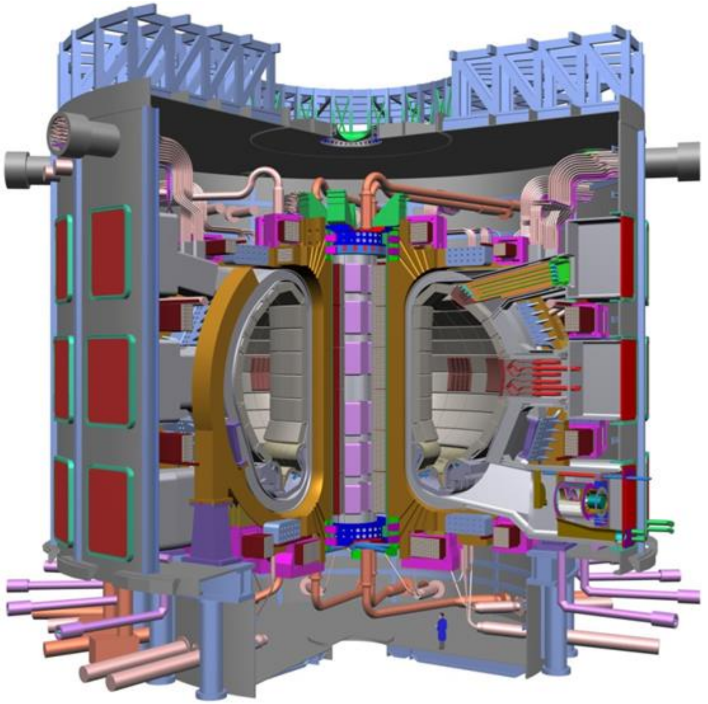

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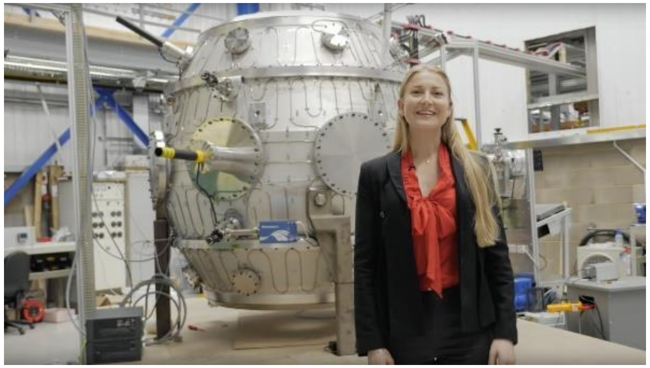

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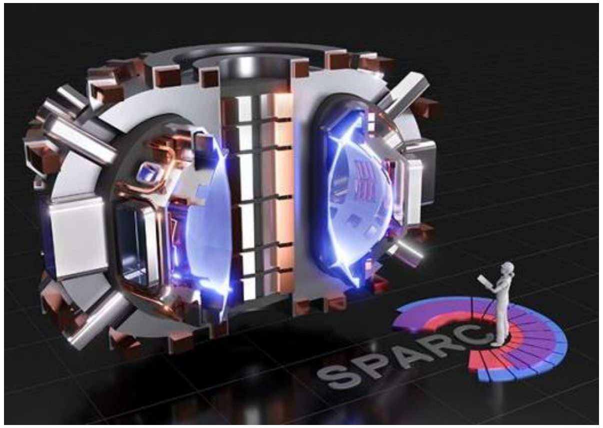
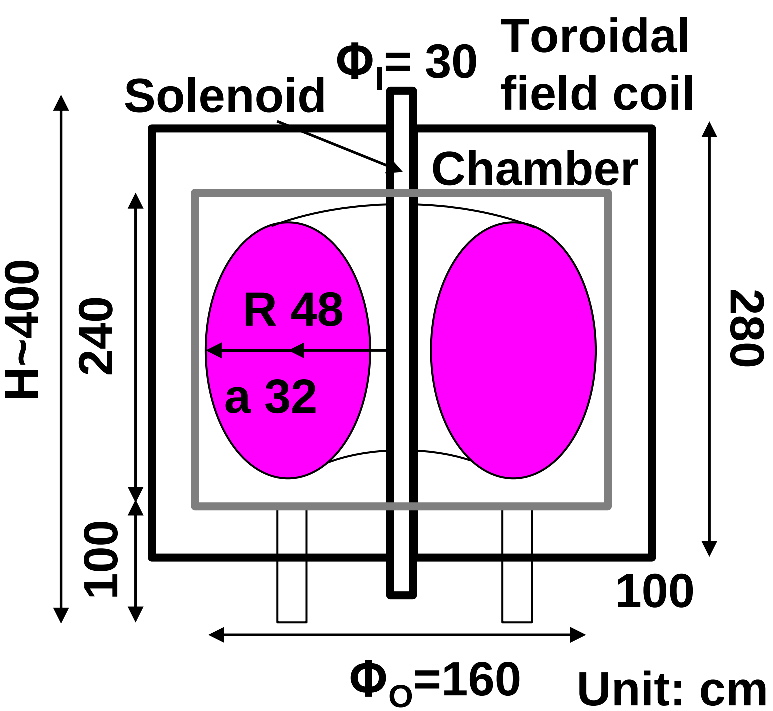


https://www.iter.org
https://www.tokamakenergy.co.uk/
https://www.psfc.mit.edu/sparc

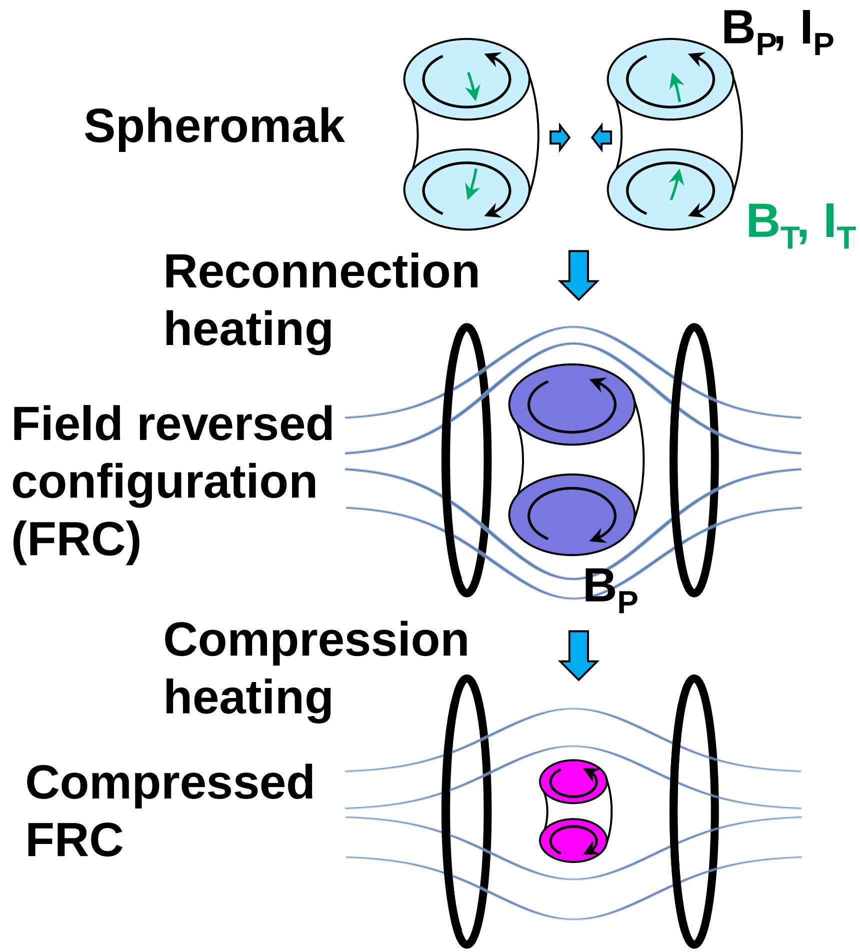
Fusion projects in Inst. Space and Plasma Sciences , National Cheng Kung University

- 國科會計畫 - 磁約束高溫電漿研究

Formosa Integrated Research Spherical Tokamak (FIRST)

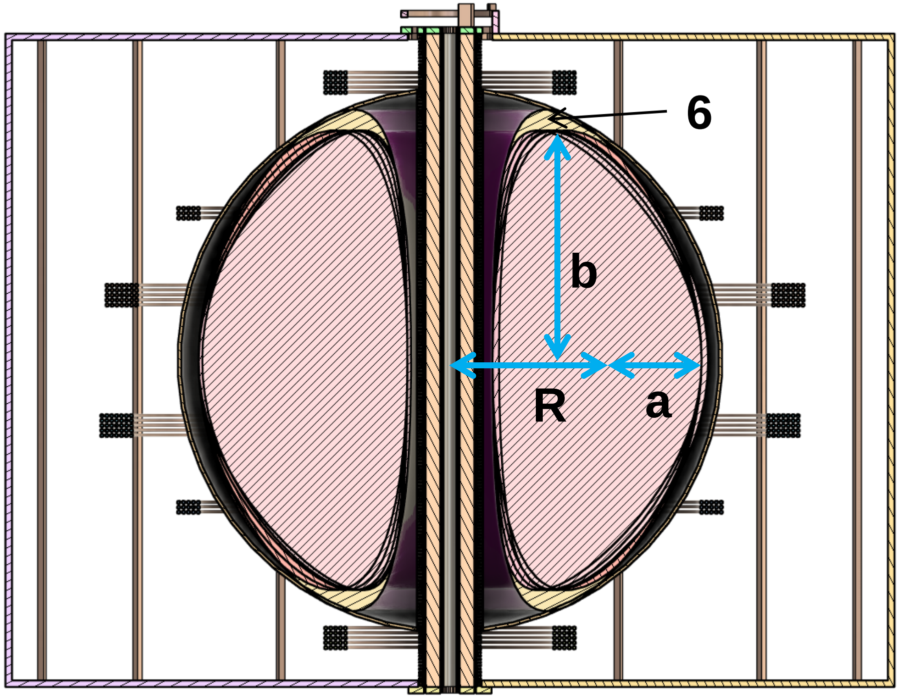


- Magneto-inertial fusion (MIF)



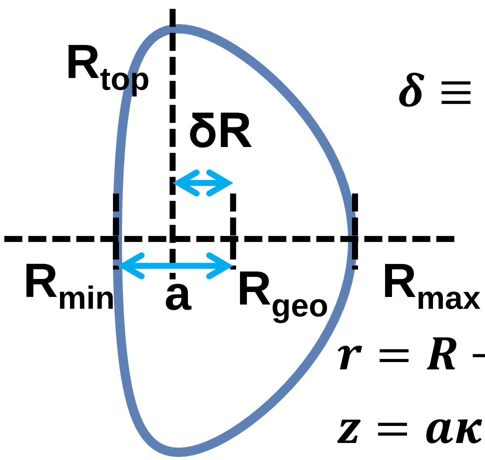
- **We welcome anyone interested in fusion research to join our team!**

A new design using a spherical chamber can tolerate several potential shapes and sides calculated by the theory group



- **Parameters:**
  - **Elongation κ=b/a**
  - **Triangularity δ**
  - **T~100 eV**
  - **B_T~0.5 T**
  - **I_p~100 kA**

	R (cm)	a (cm)	R/a	κ	δ
✔ 1	45	32	1.41	2.2	0.5
✔ 2	45	32	1.41	2.2	0.3
✔ 3	45	32	1.41	2.2	0.4
✔ 4	45	32	1.41	2.2	0.6
✔ 5	47	32	1.47	2.2	0.5



$$\delta \equiv \frac{\delta R}{a}$$

$$r = R + a\mathrm{Cos}(\theta + \delta \mathrm{Sin}(\theta))$$

$$z = a\kappa \mathrm{Sin}(\theta)$$

- **We welcome anyone interested in fusion research to join us!**

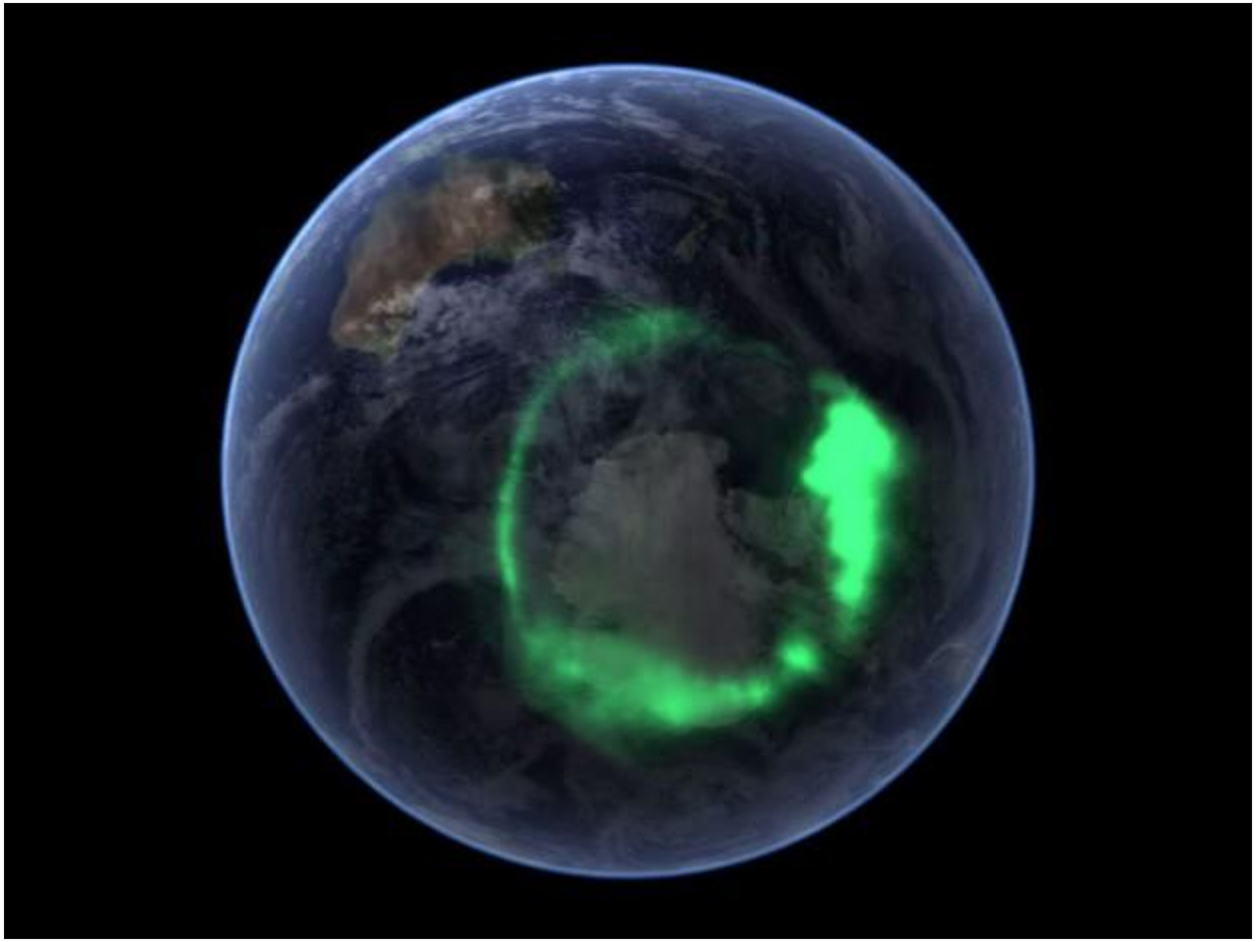
Outline

- 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

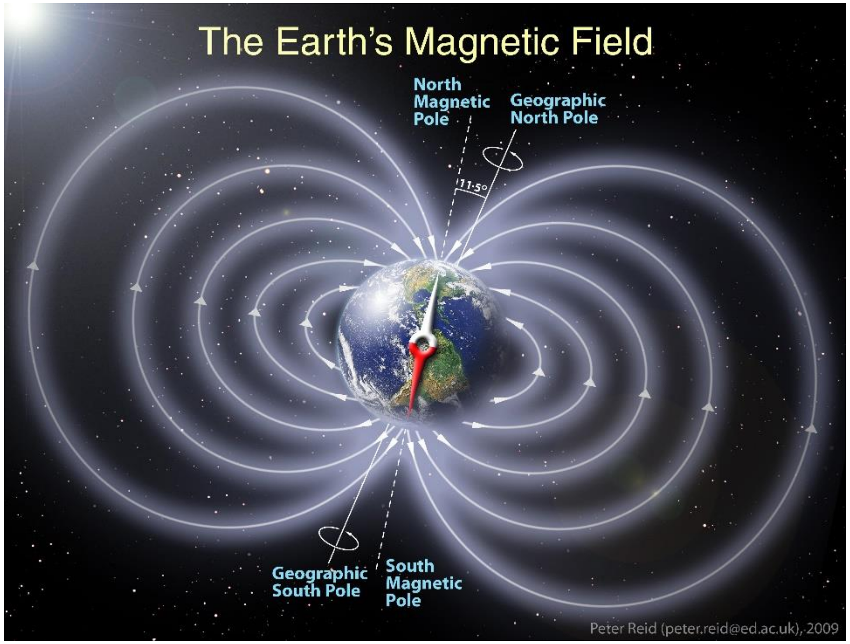
https://en.wiktionary.org/wiki/aurora

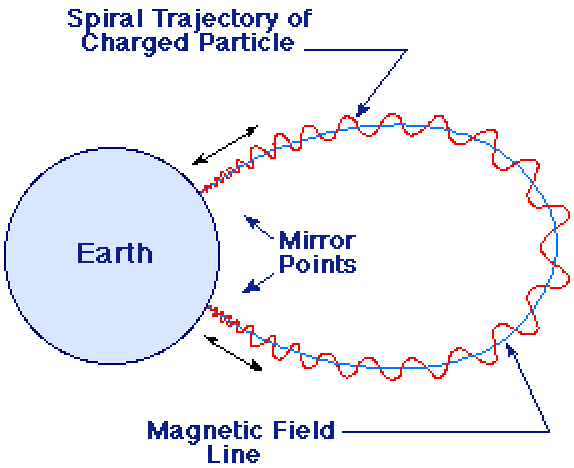
Aurora seen from a satellite



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

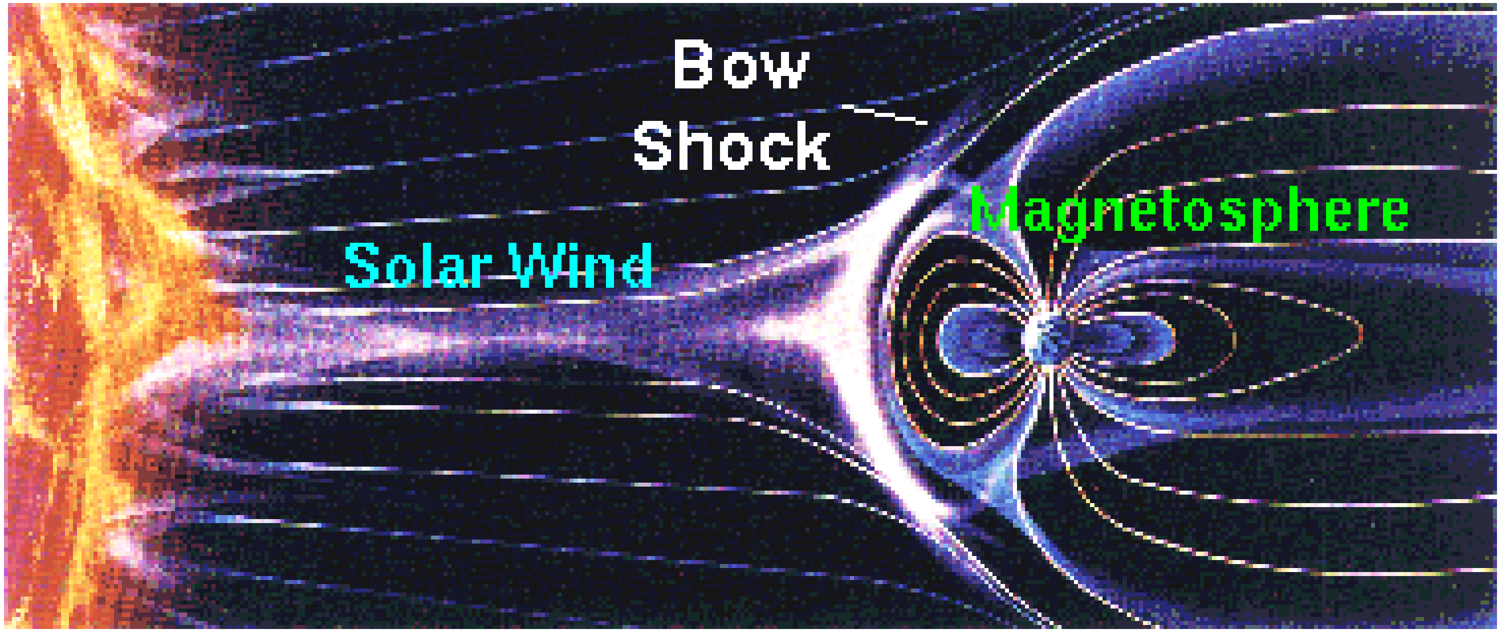
Earth’s magnetic field





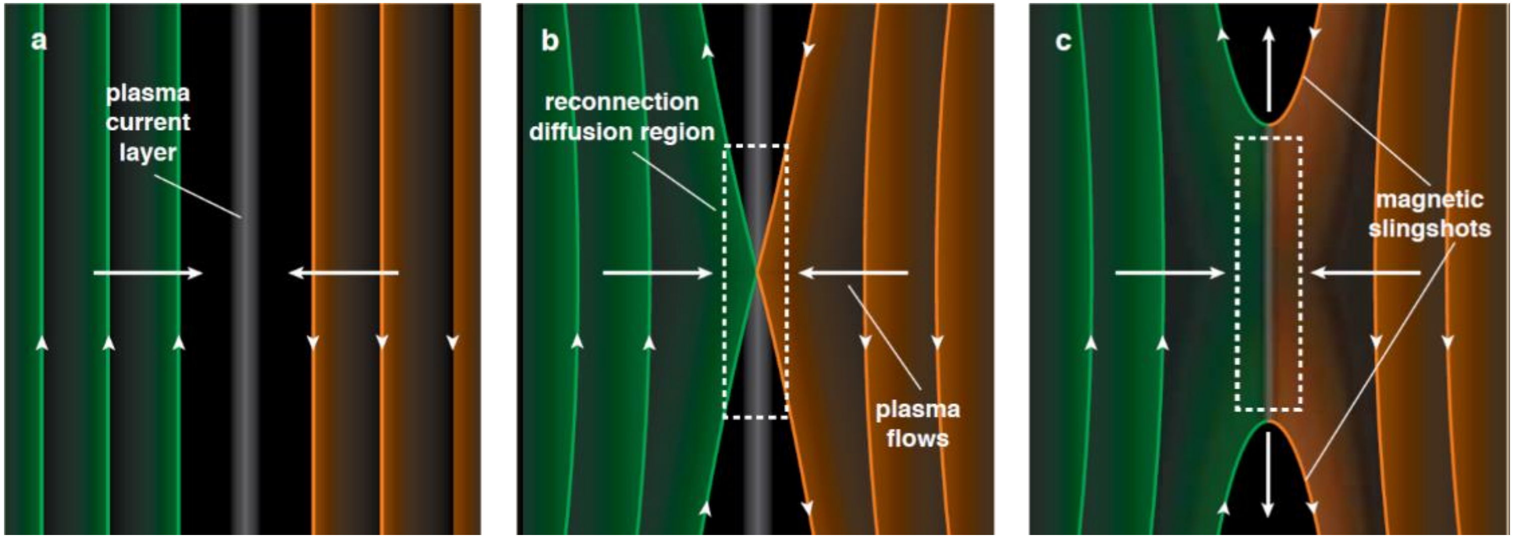
https://www.nasa.gov/mission_pages/sunearth/news/gallery/Earths-magneticfieldlines-dipole.html
http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html

Earth magnetic fields are strongly influenced by solar wind



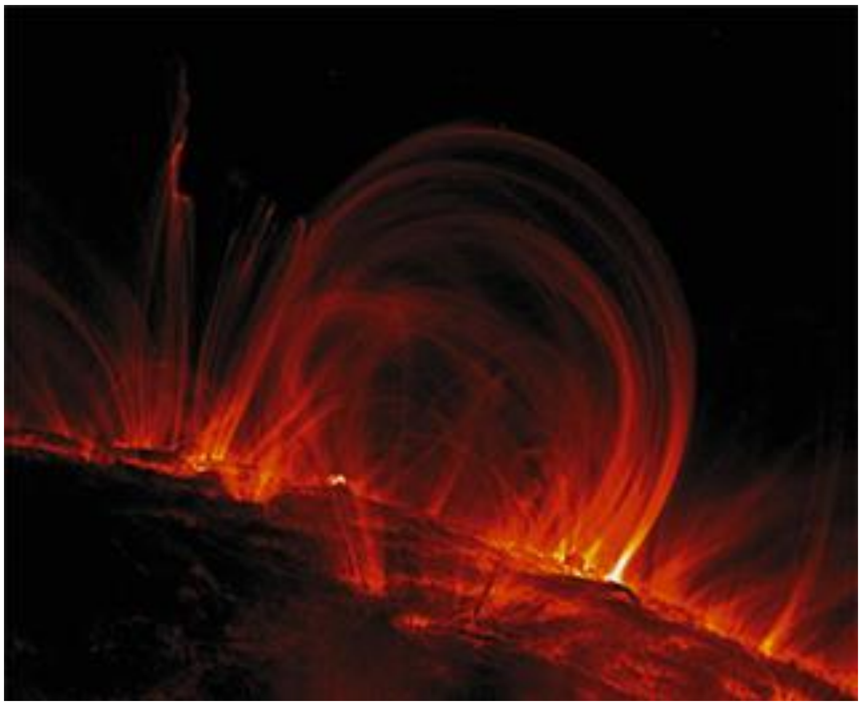
http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html

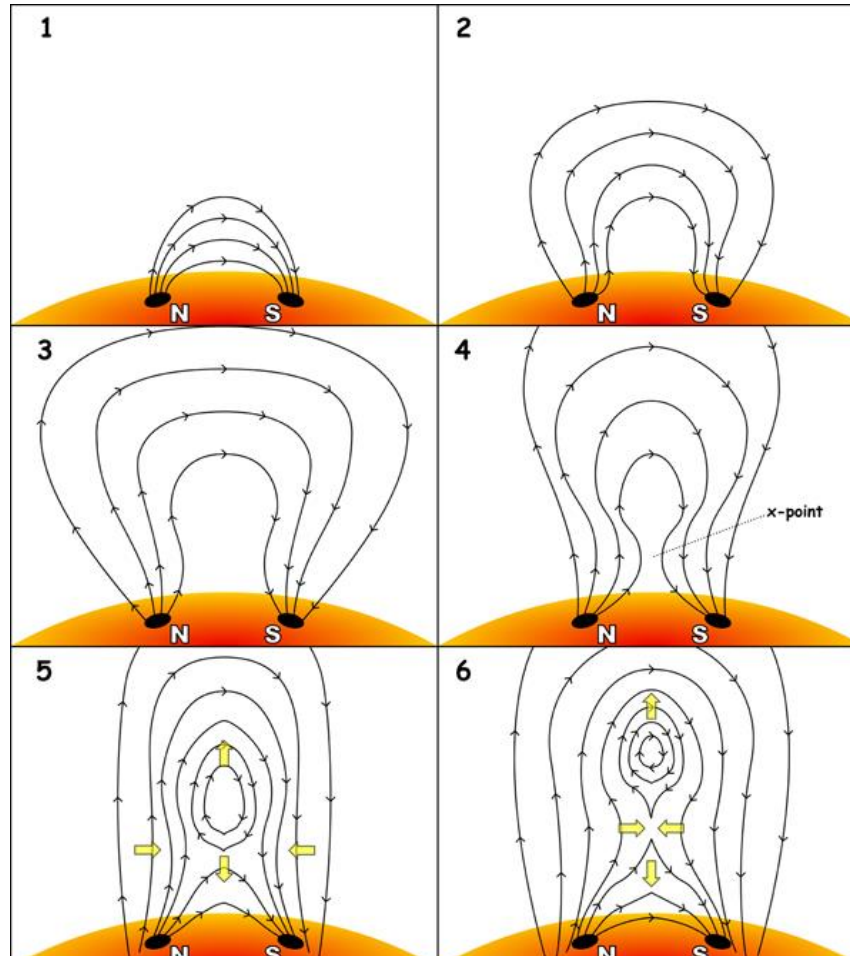
Reconnection



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

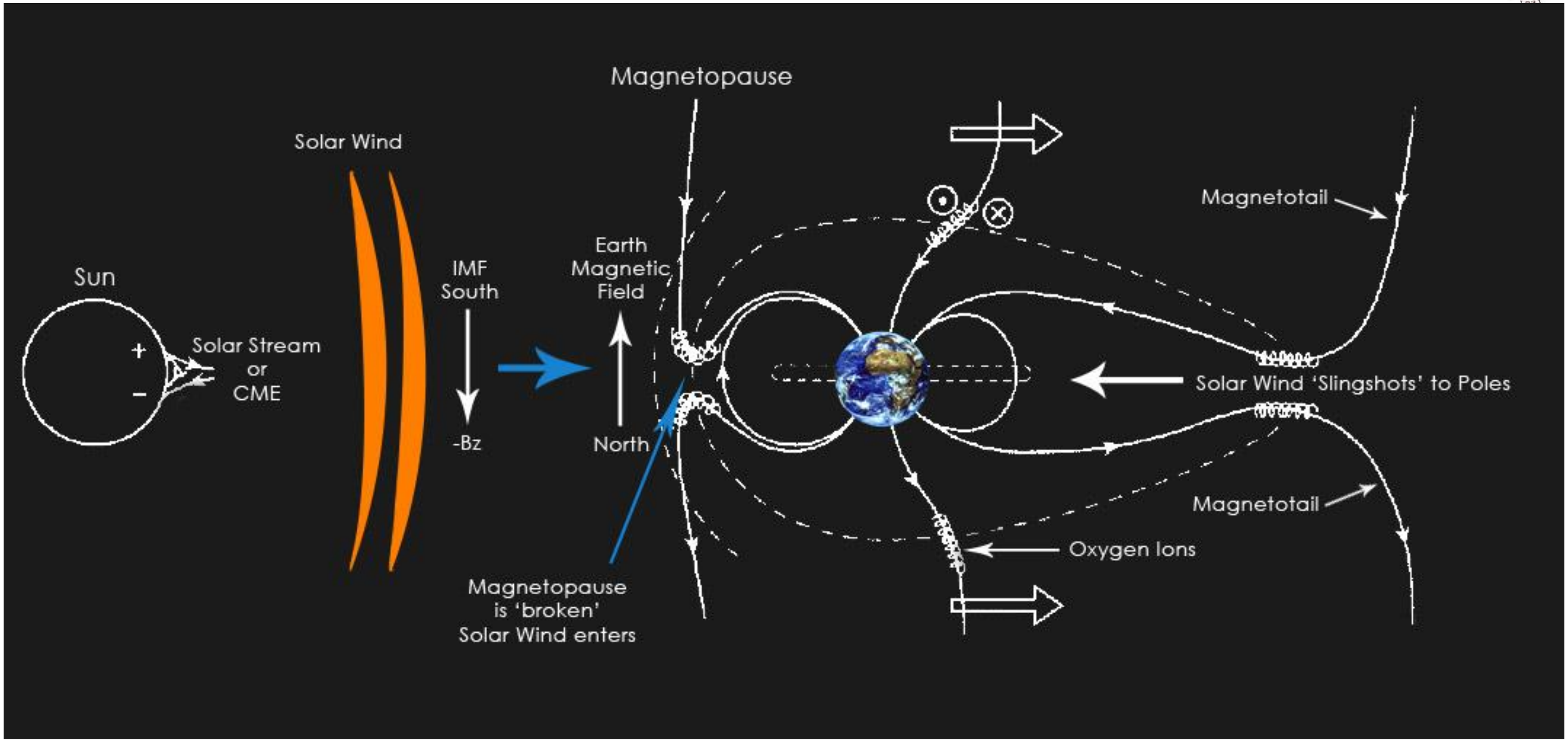
Corona mass ejection (CME)





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

Reconnections occur in many locations

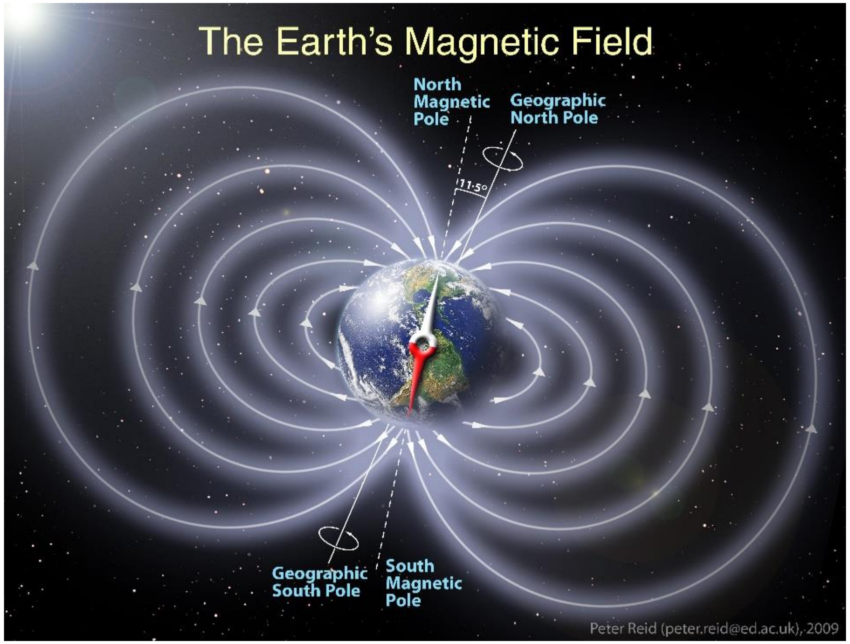


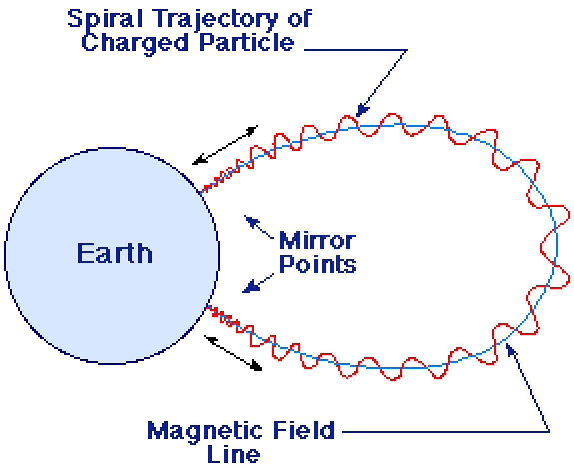
- **The Aurora Borealis:**

  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/

Earth’s magnetic field



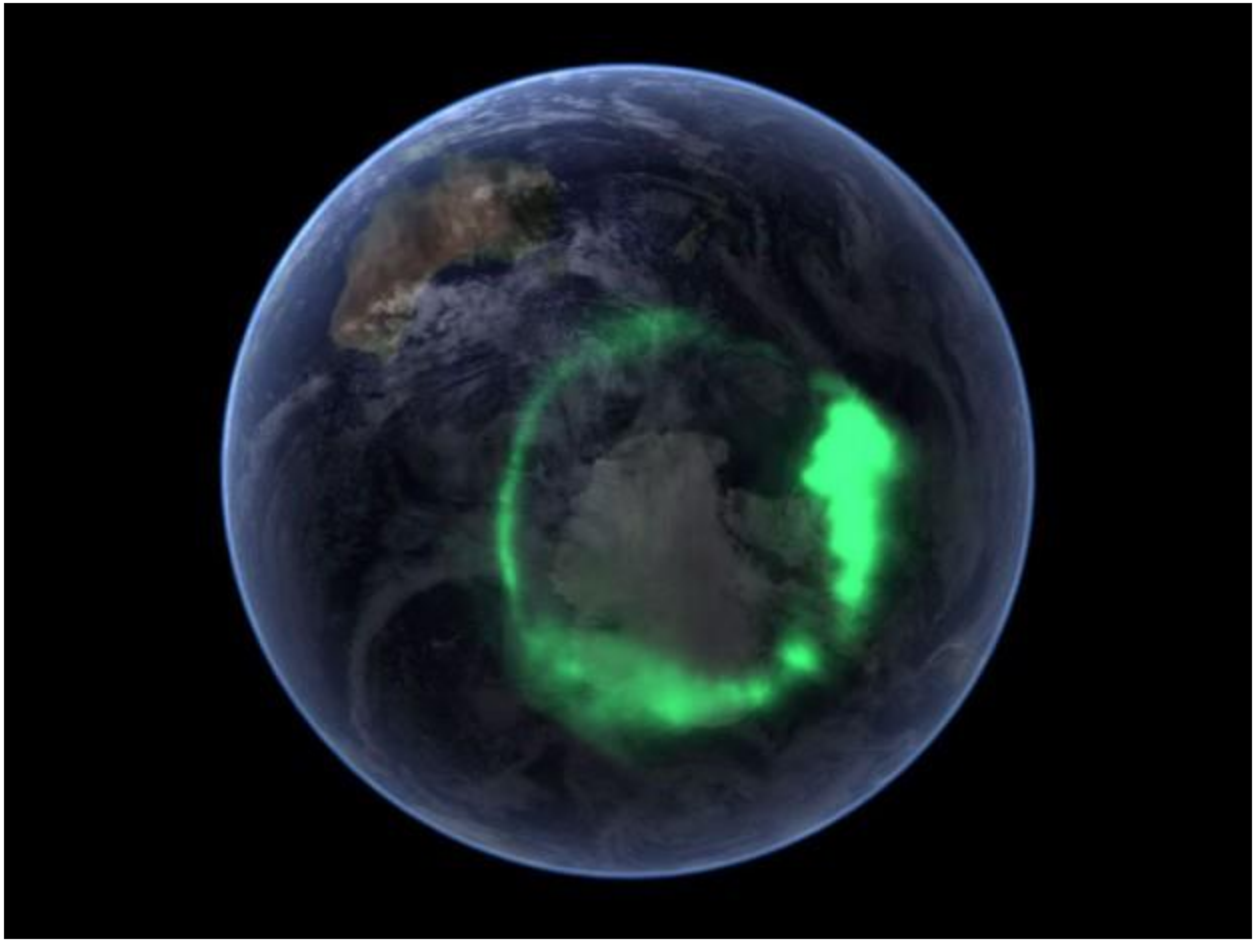


https://www.nasa.gov/mission_pages/sunearth/news/gallery/Earths-magneticfieldlines-dipole.html
http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html

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/

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

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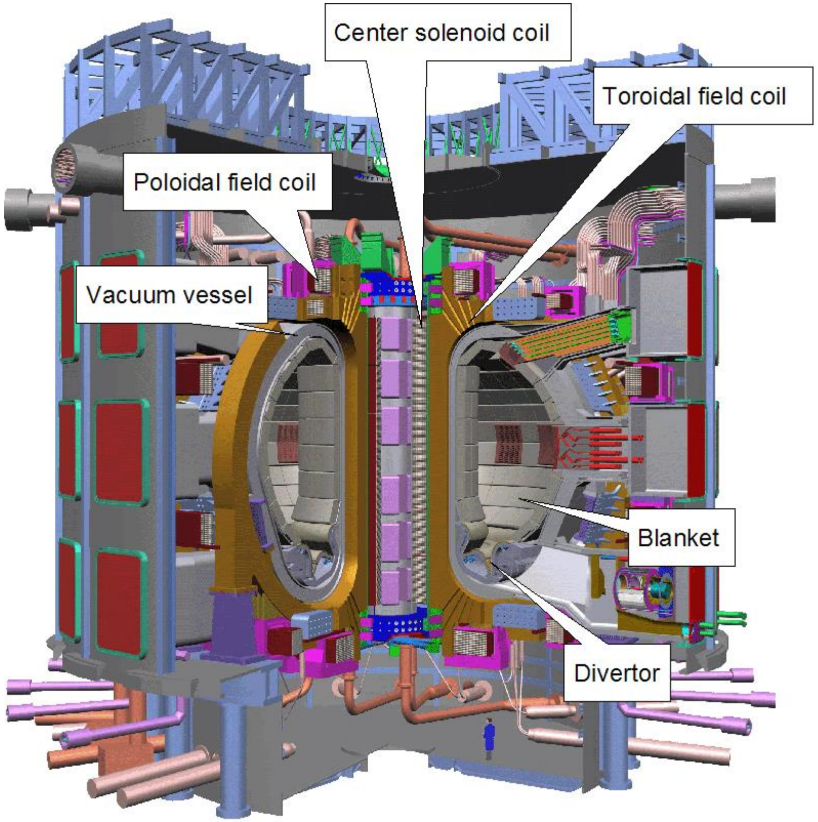
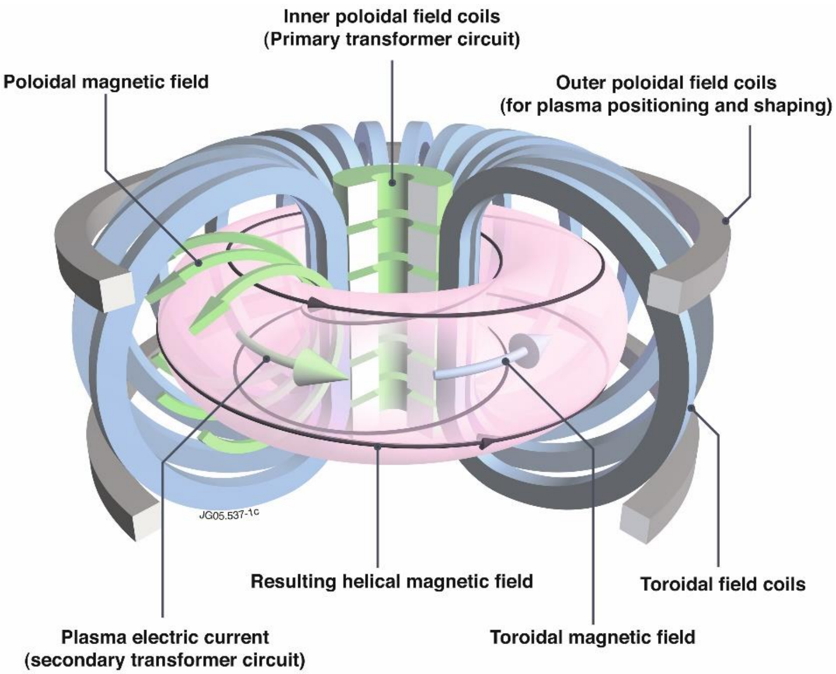
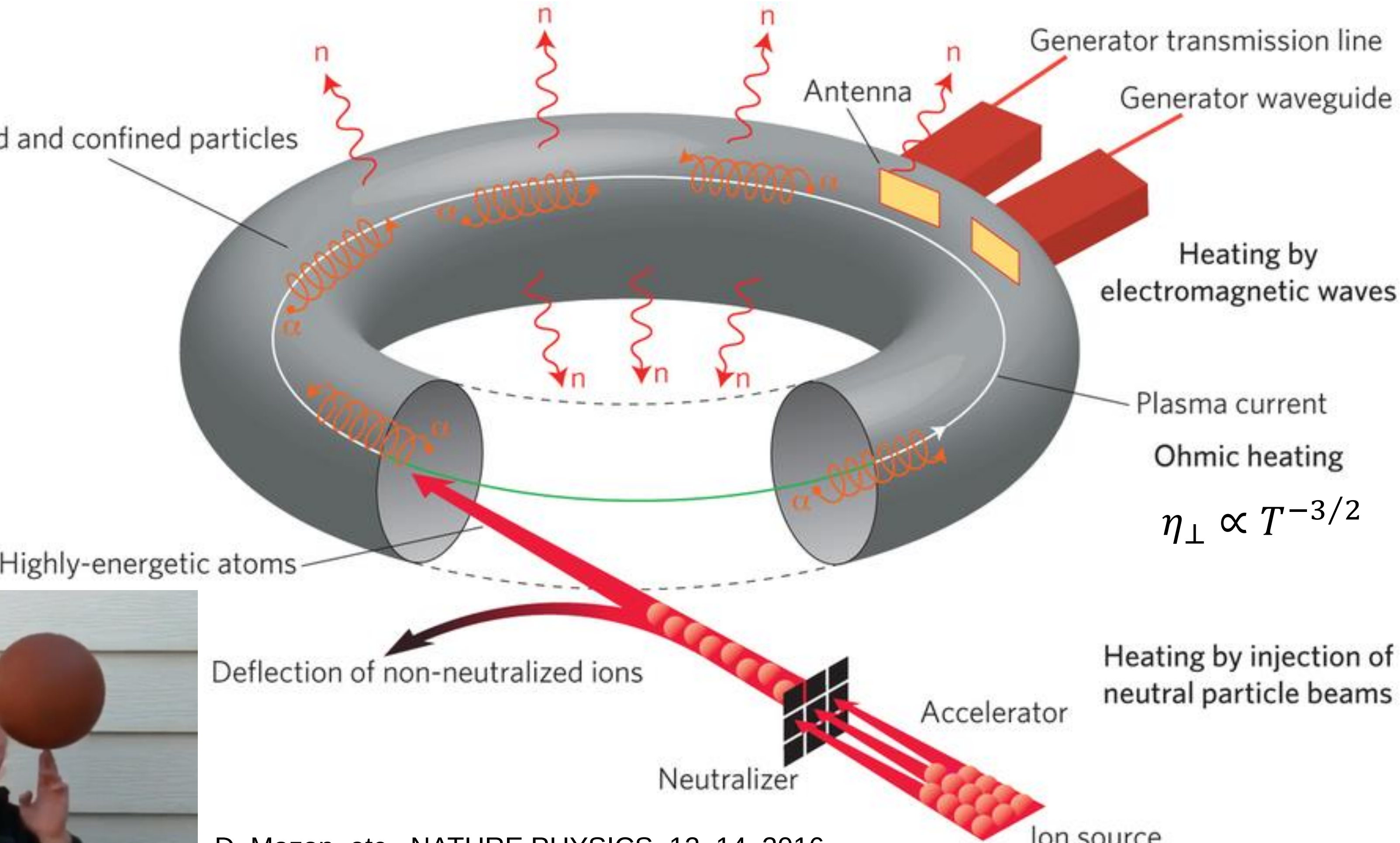
Hot plasma is confined by the magnetic field in magnetic confinement fusion





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
https://zh.wikihow.com/%E5%9C%A8%E6%89%8B%E6%8C%87%E4%B8%8A%E8%BD%AC%E7%AF%AE%E7%90%83

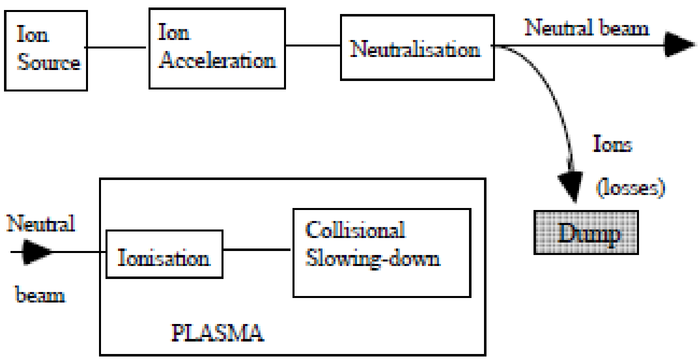
Varies way of heating a MCF device

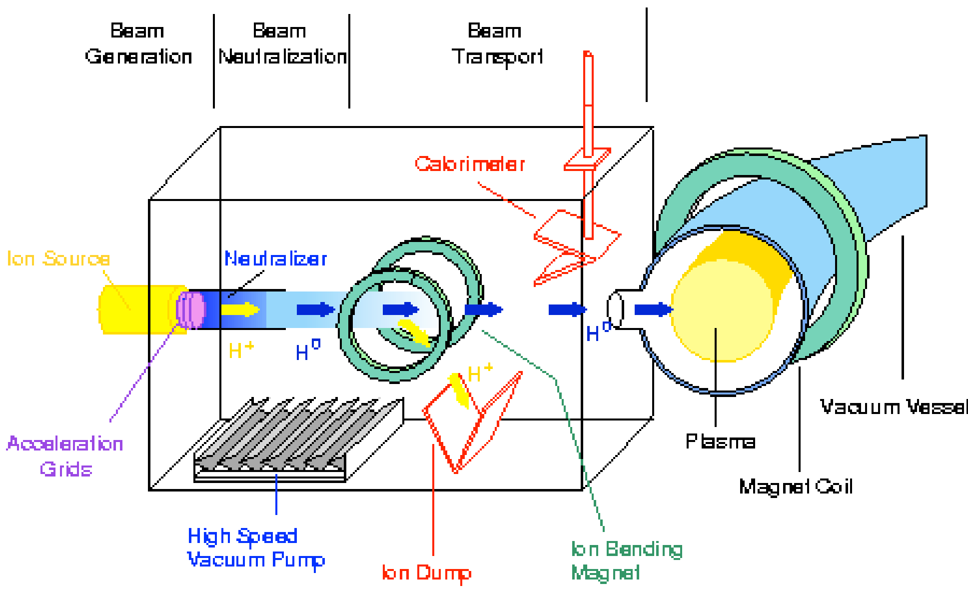
System		Frequency/ energy	Maximum power coupled to plasma	Overall system efficiency	Development/ demonstration required	Remarks
ECRF	Demonstrated in tokamaks	28–157 GHz	2.8 MW, 0.2 s	30–40%	Power sources and windows, off-axis CD	Provides off-axis CD
	ITER needs	150–170 GHz	50 MW, S S			
ICRF	Demonstrated 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

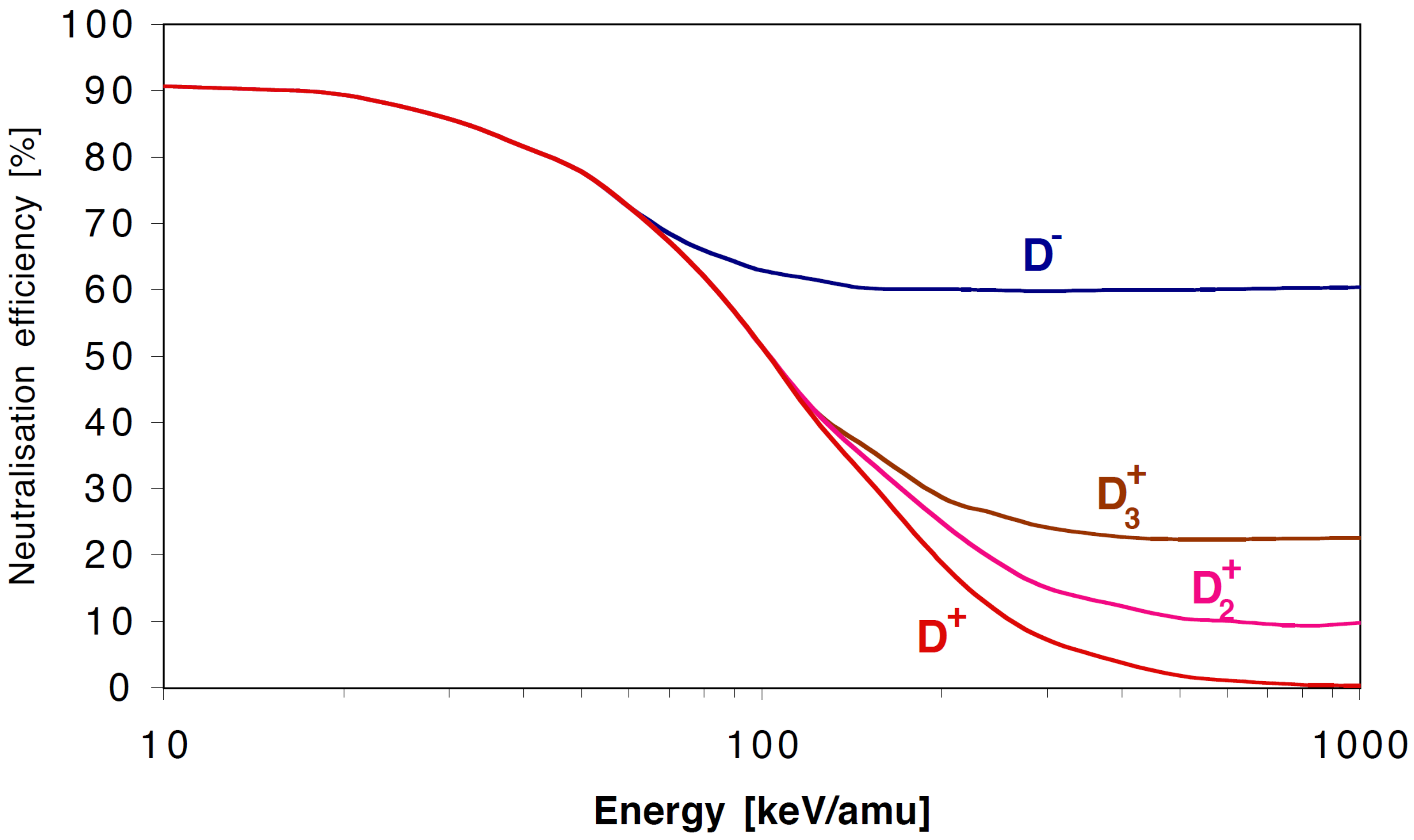
Neutral particles heat the plasma via coulomb collisions





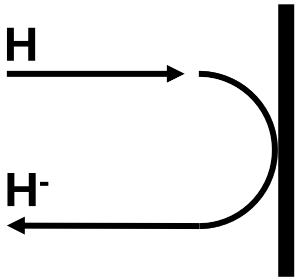
1. **create energetic (fast) neutral ions**
2. **ionize the neutral particles**
3. **heat the plasma (electrons and ions) via Coulomb collisions**

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



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

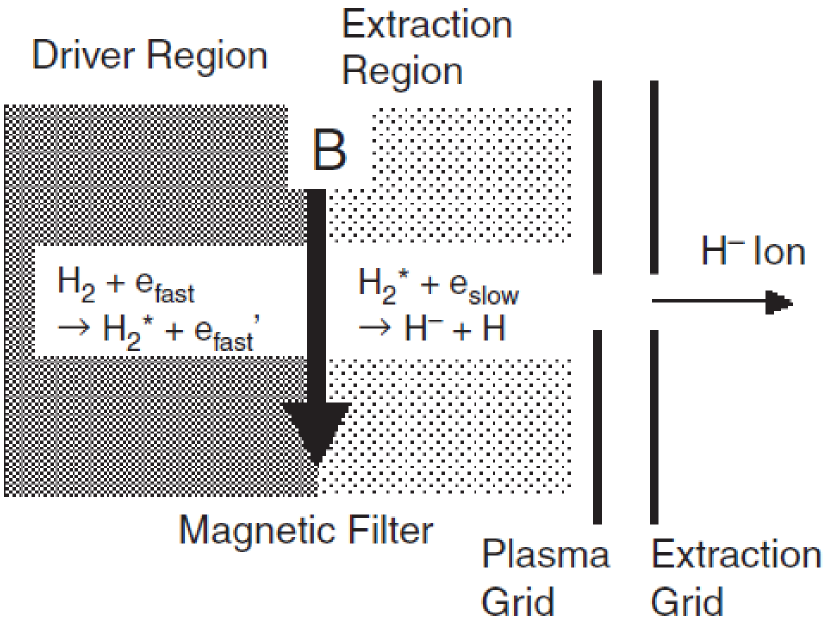
$$H^+ + 2e^- \longrightarrow H^-$$

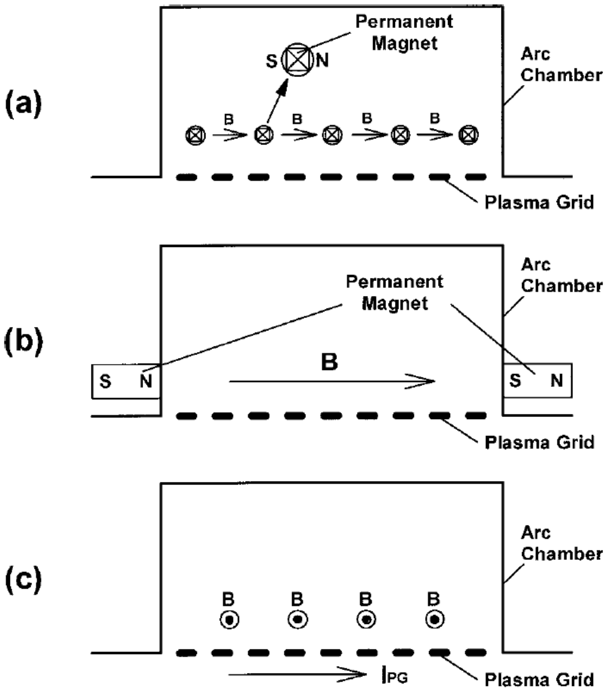
- Volume production:

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

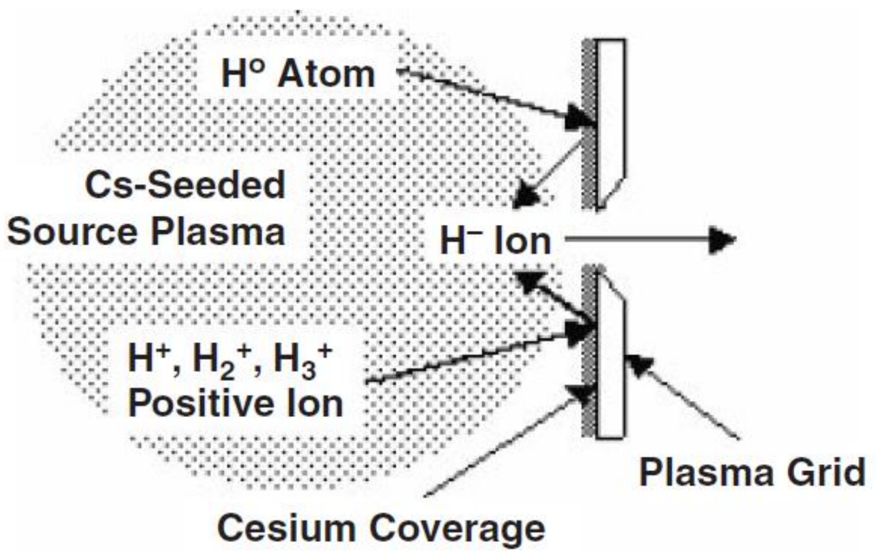
$$H_2^*(\text{excited state}) + e_{slow}(\approx 1\ eV) \rightarrow H^- + H.$$

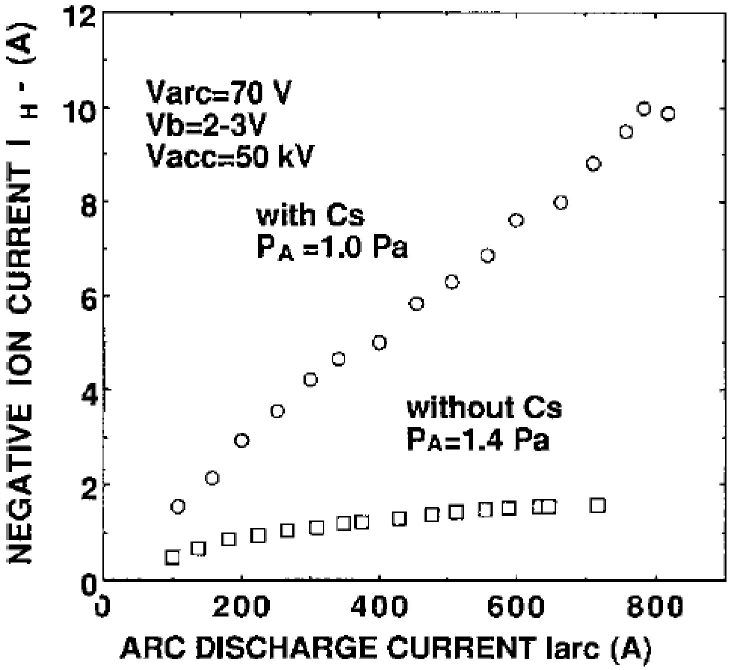
Two-chamber method of negative ions in volume production with a magnetic filter



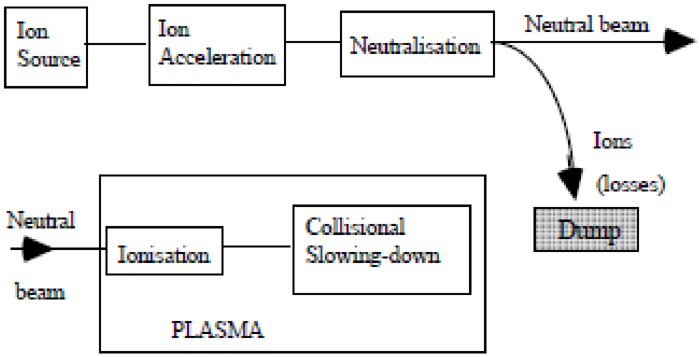


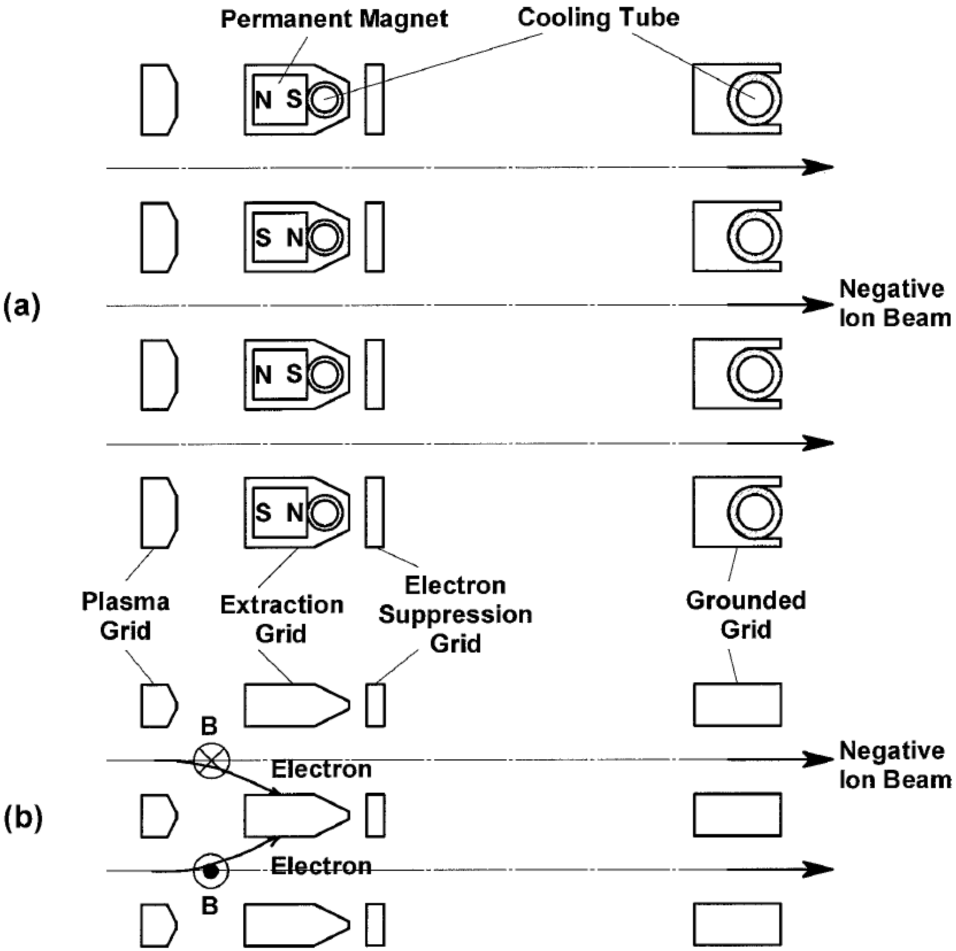
Adding cesium increases negative ion current





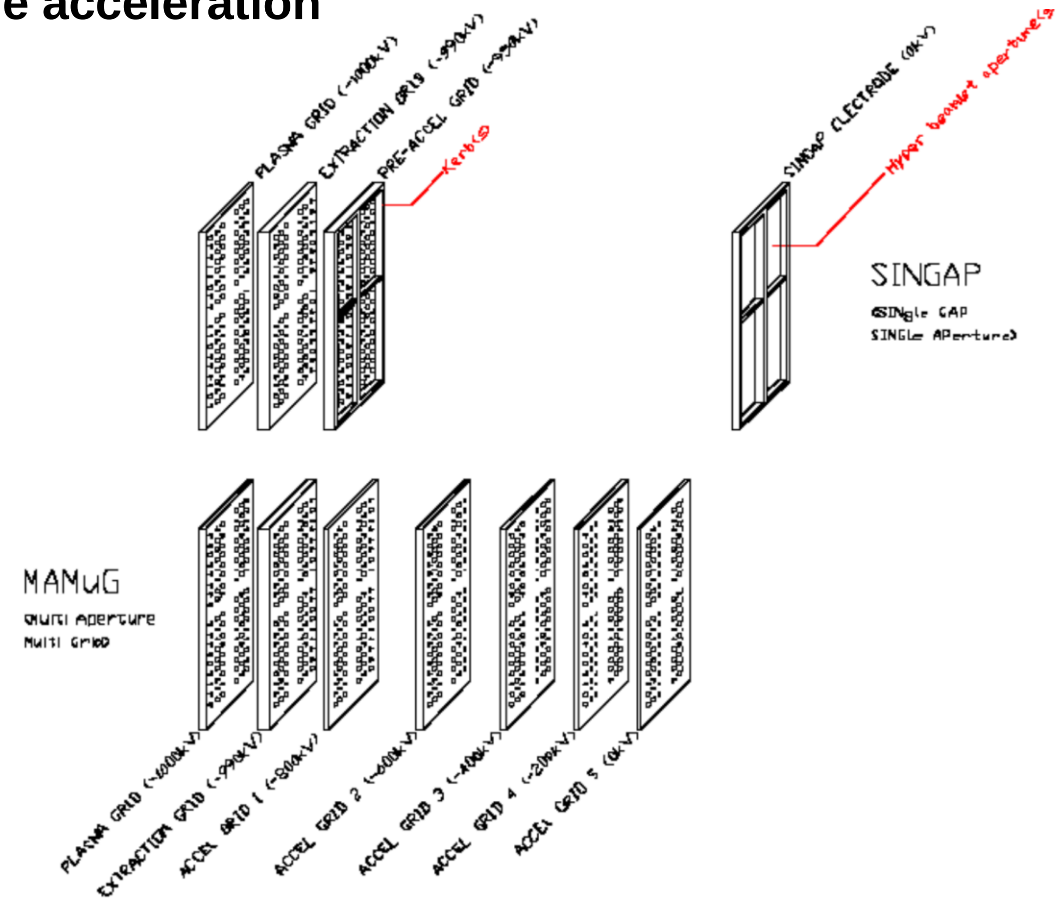
Electrons need to be filtered out since they are extracted together with negative ions





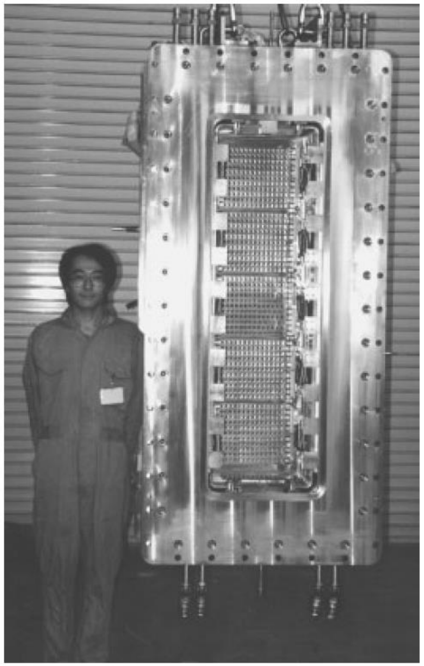
Acceleration

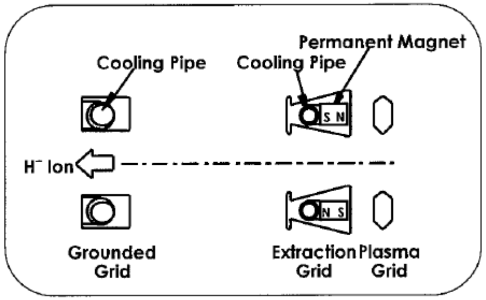
- **Multi-stage acceleration**
- **Single-stage acceleration**



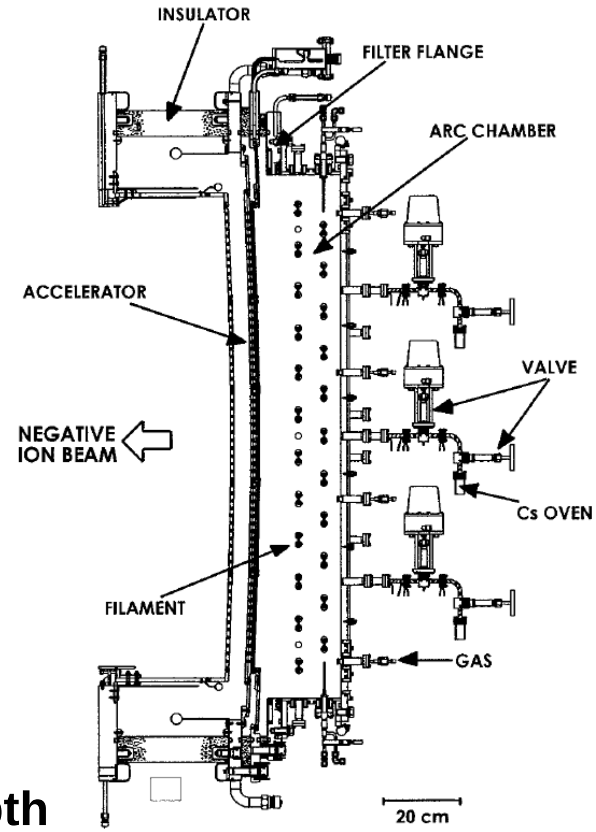
The ITER neutral beam system: status of the project and review of the main technological issues, presented by V. Antoni

NBI system of the LHD fusion machine





Negative Ion Accelerator

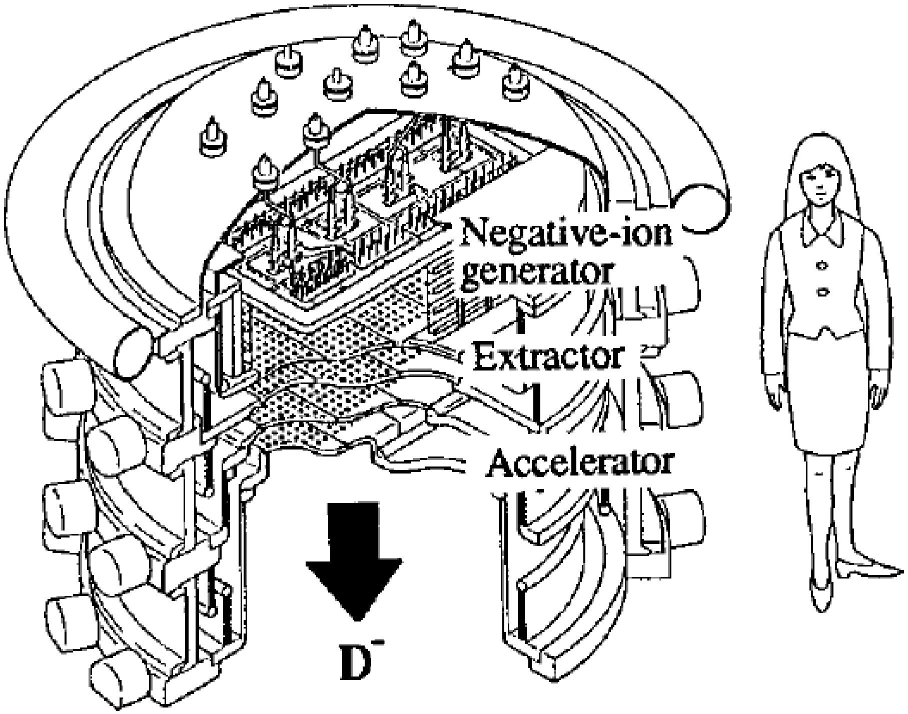


- 180 keV and 30 A
- Arc chamber: 35 cm x 145 cm, 21cm in depth
- Single stage accelerator

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**

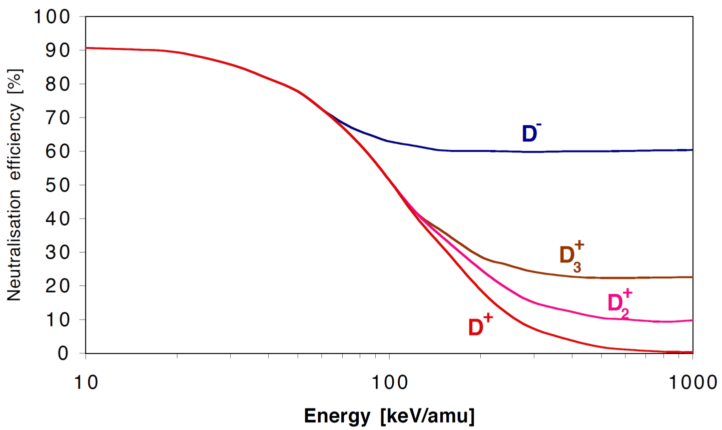
$$H + H_2 \longrightarrow H^+ + H_2 + e^-$$

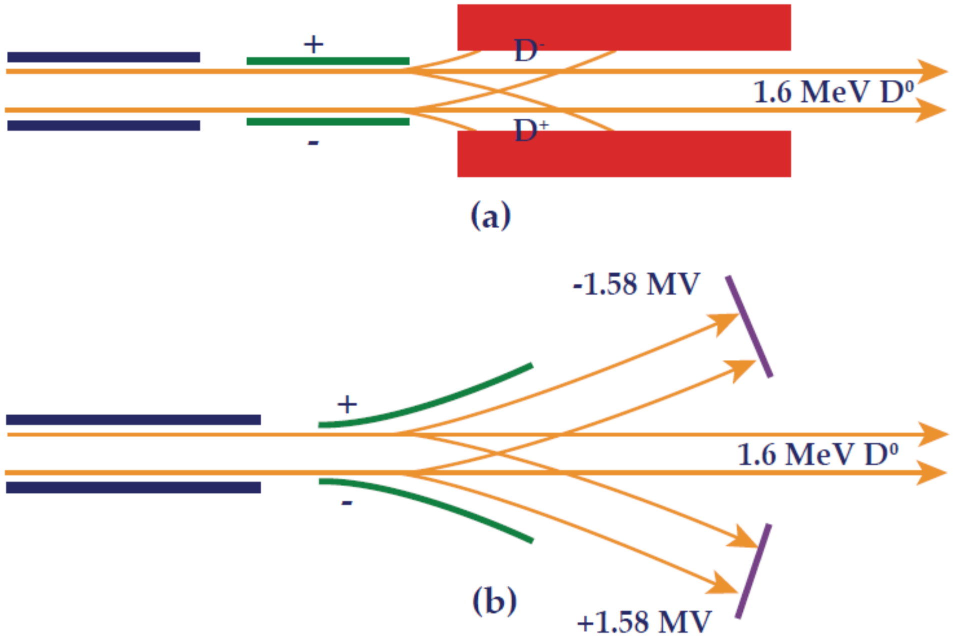
- **Plasma neutralization**
  - **Collisions with charged particles in plasma**

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

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

Beam dump

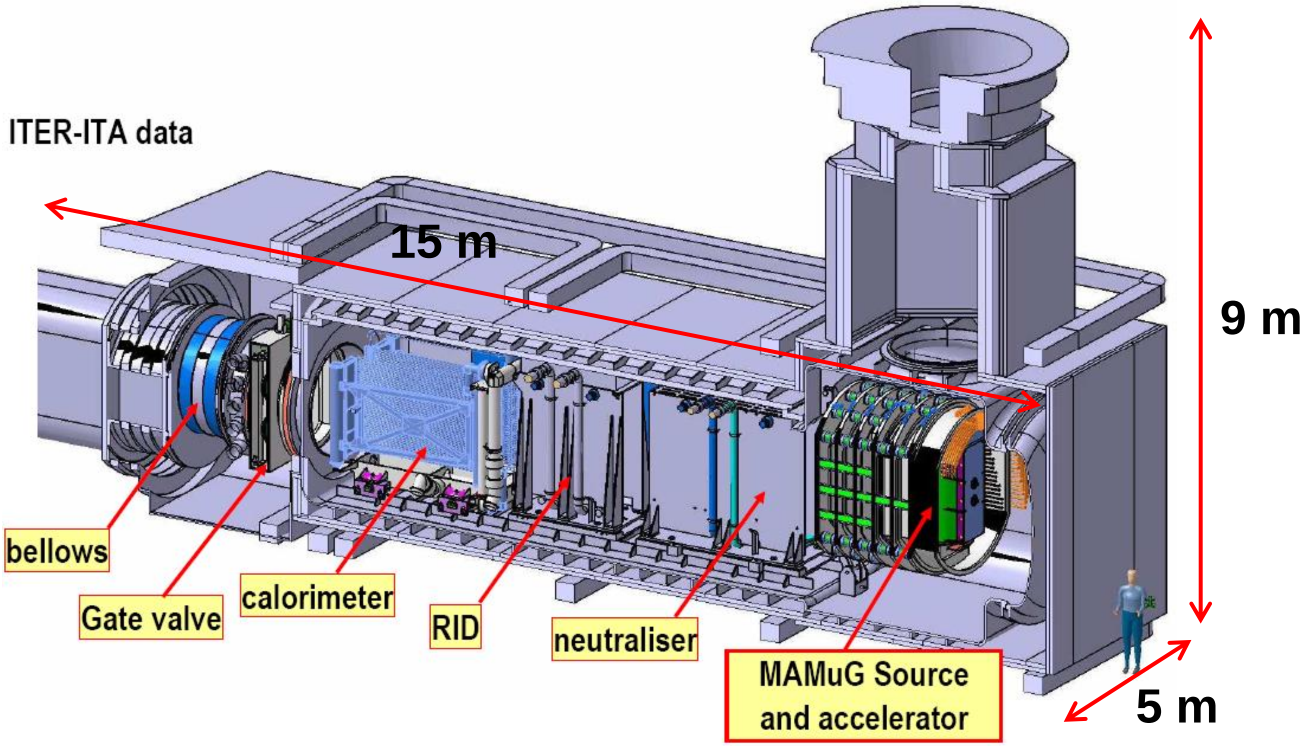




R. W. Moir, Fusion Technology, 25, 129, 1994

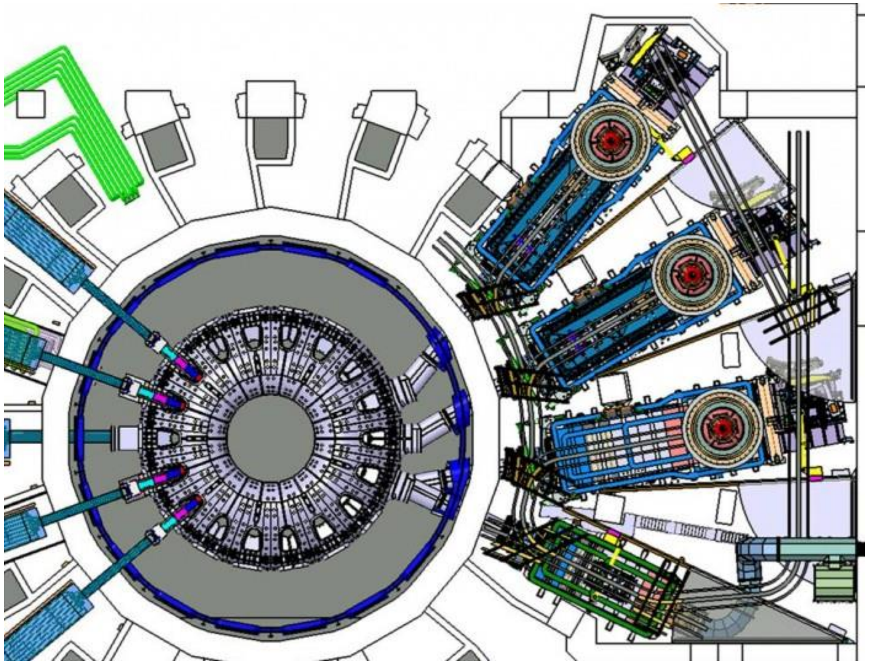
NBI for ITER

- **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

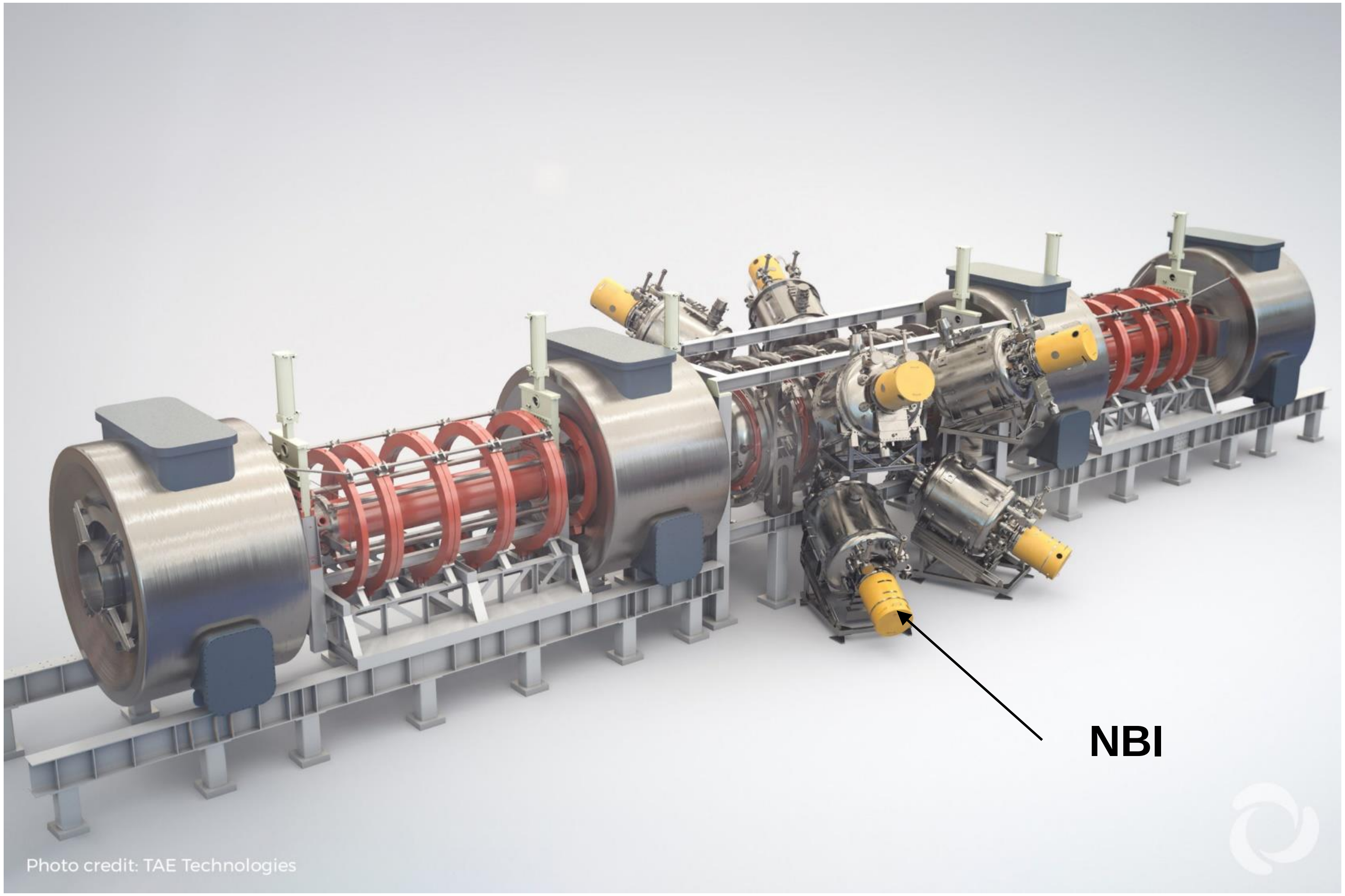
Neutral beam penetration



- **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**

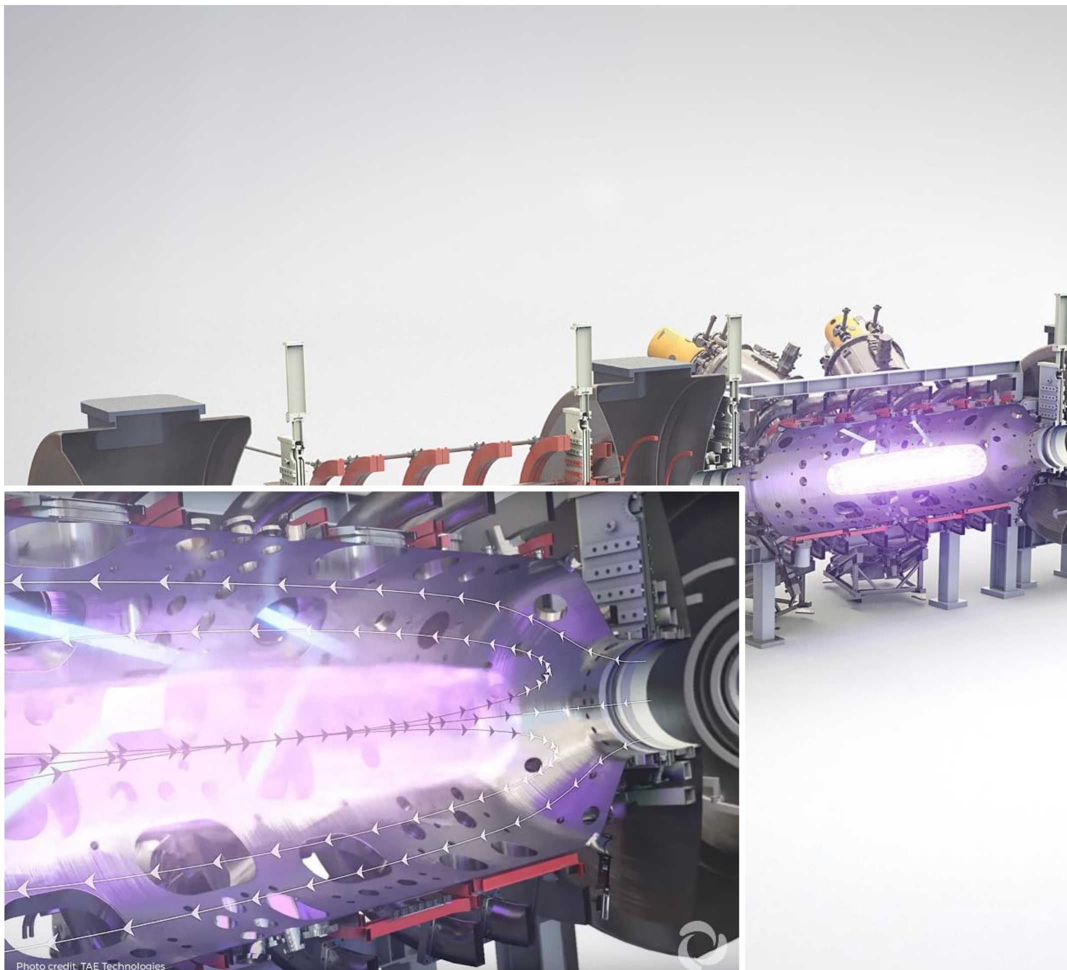
https://www.iter.org

NBI for Tri-Alpha Energy Technologies



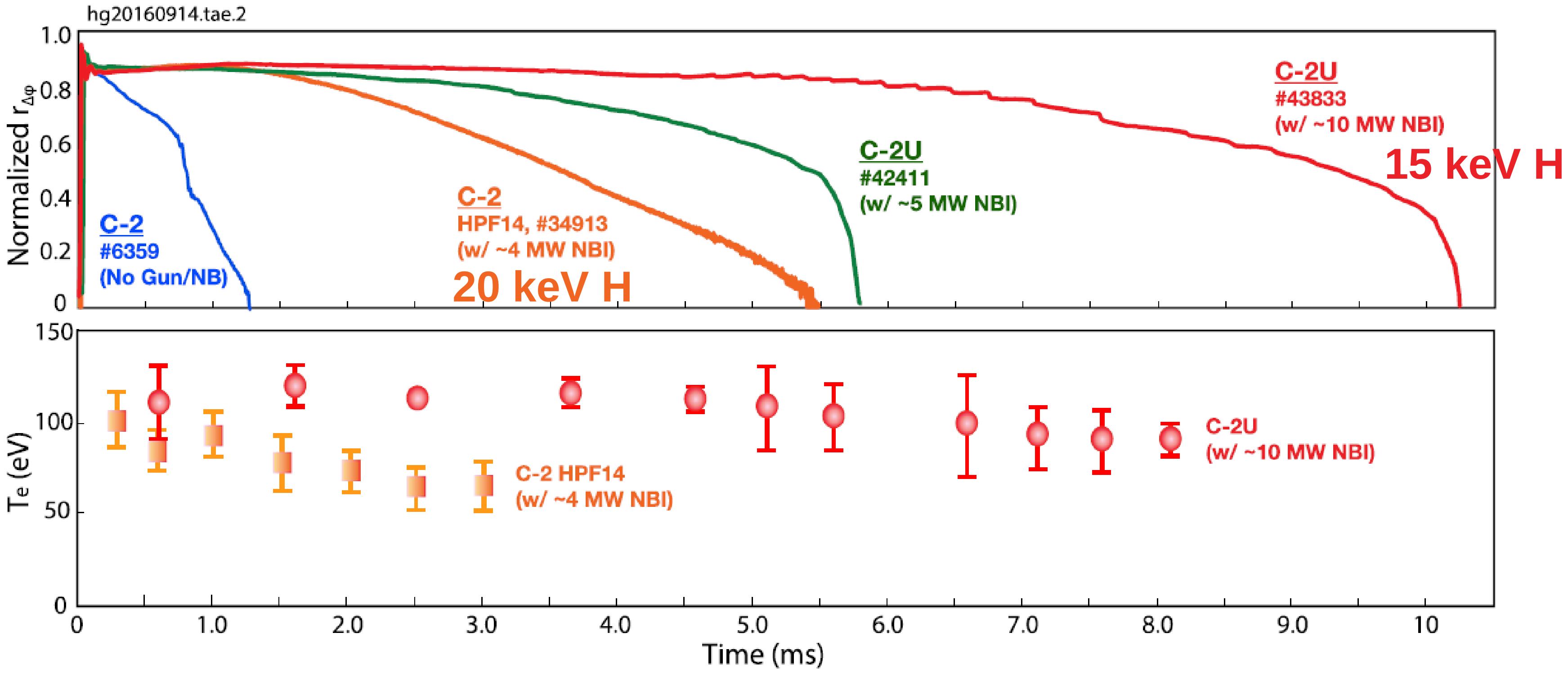
https://tae.com/media/

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



https://tae.com/media/
https://zh.wikihow.com/%E5%9C%A8%E6%89%8B%E6%8C%87%E4%B8%8A%E8%BD%AC%E7%AF%AE%E7%90%83

FRC sustain longer with neutral beam injection



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

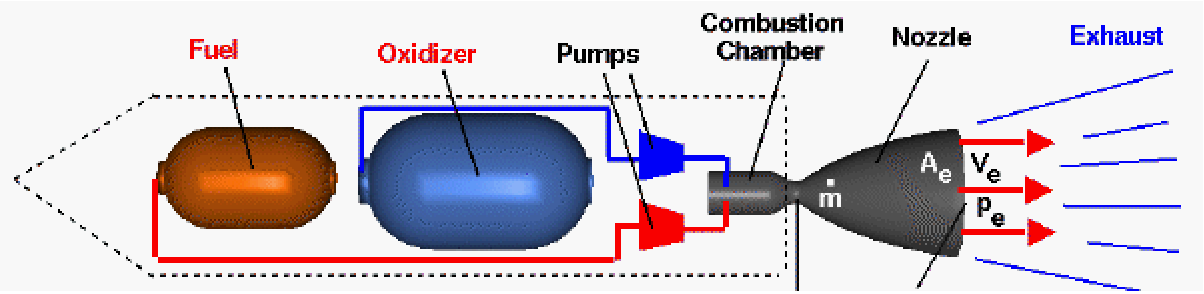
Neutral beam source

- 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

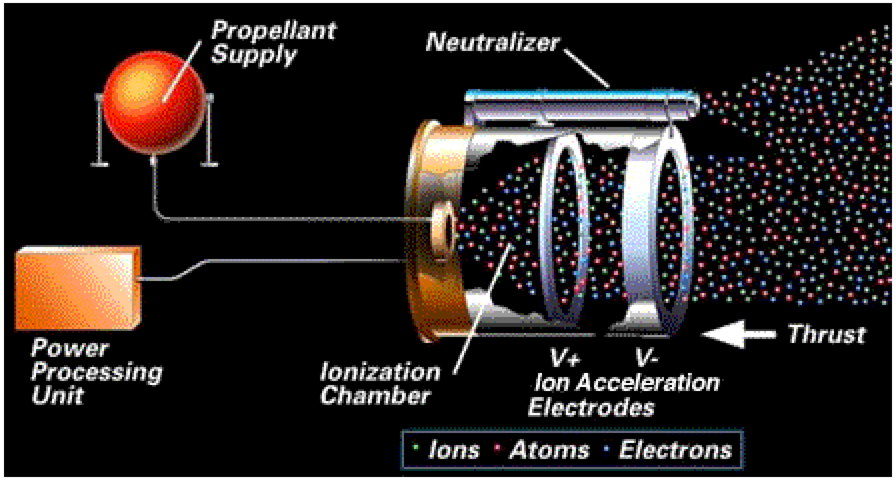
- **Electric propulsion (plasma thrusters)**
  - **D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters**

Comparison between liquid rockets and ion thrusters

- Liquid rockests
  - u~4500 m/s
  - Isp~450 s
  - Energy ~ 100GJ
  - Power ~ 300MW
  - Thrust ~ 2x10^6 N

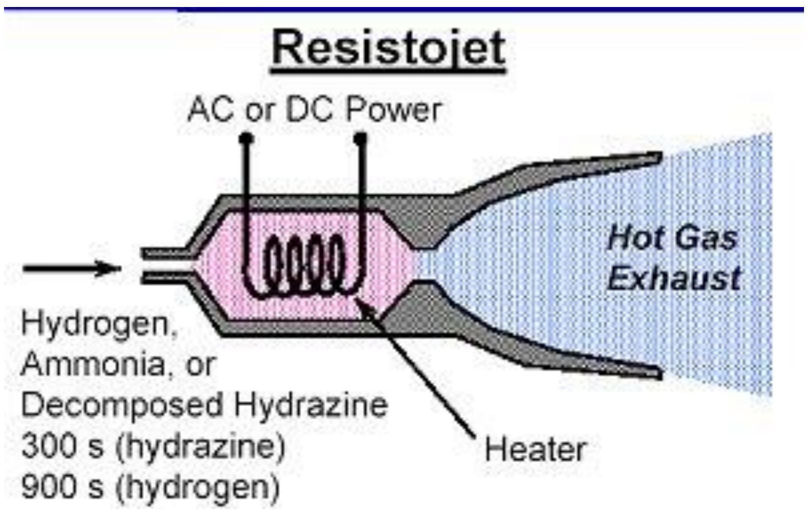


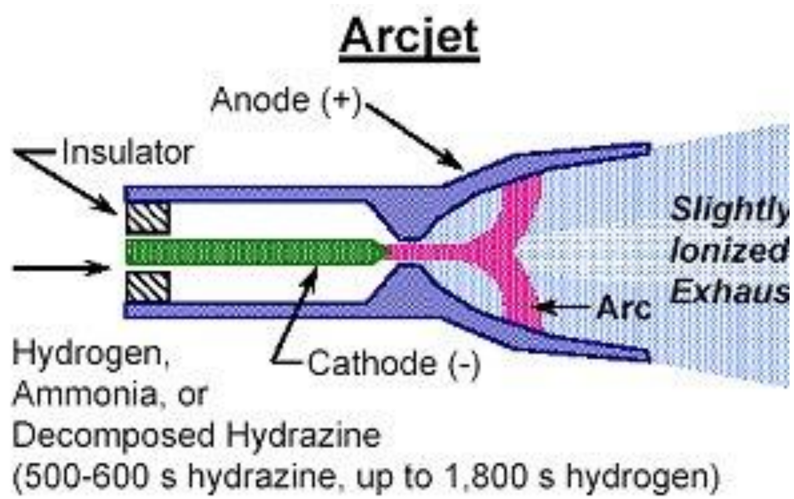
- Ion thrusters
  - u~30000 m/s
  - Isp~3000 s
  - Energy ~ 1000GJ
  - Power ~ 1kW
  - Thrust ~ 0.1 N



Electric thruster types - electrothermal

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

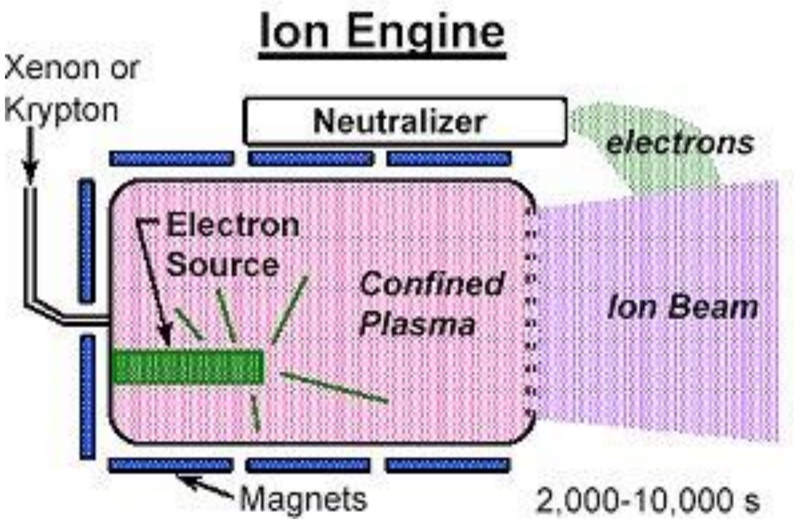


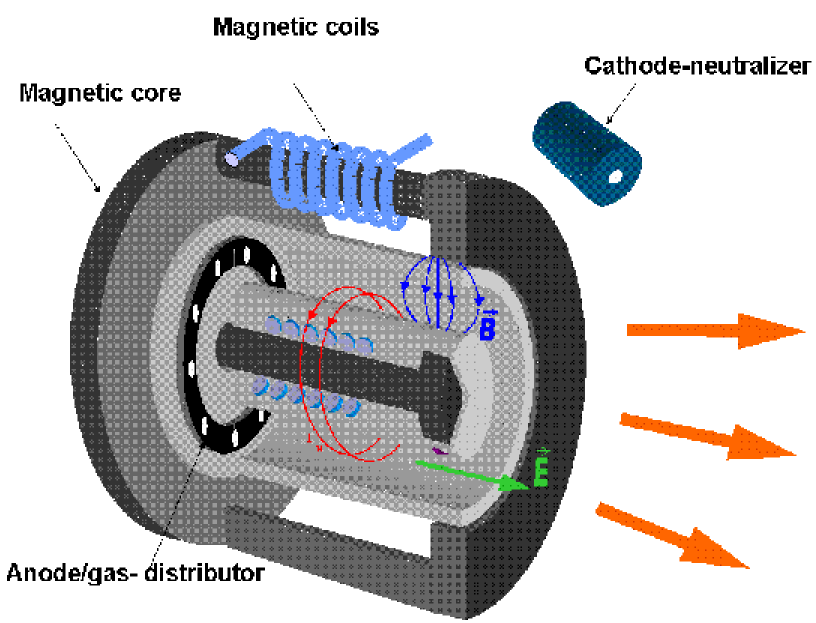


http://pages.erau.edu/~ericksol/courses/sp300/ch5/propul_ch5.html

Electric thruster types - electrostatic

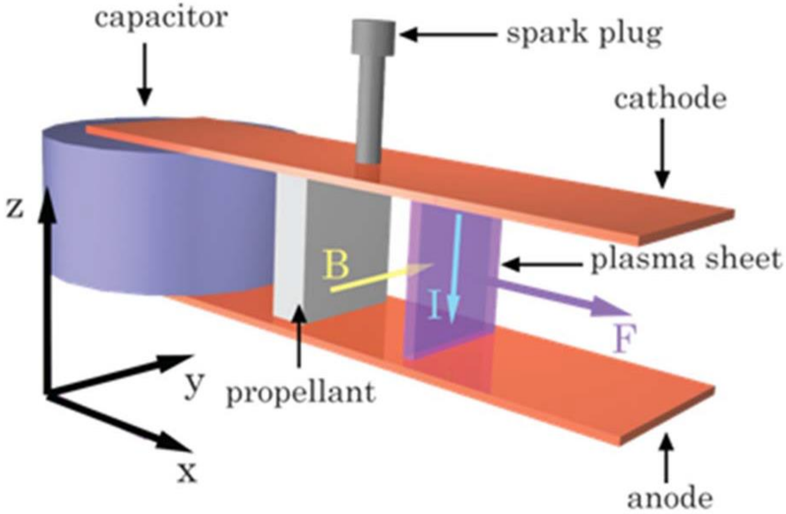
- **Ion thruster**
- **Hall thruster**



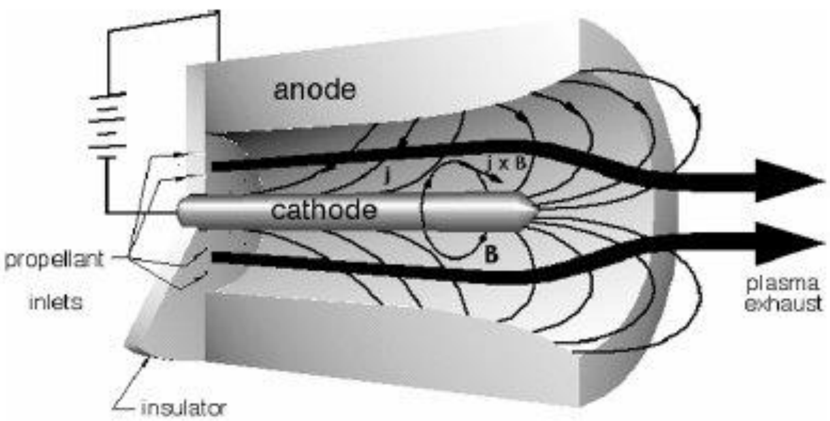


Electric thruster types - Electromagnetic

- **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

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

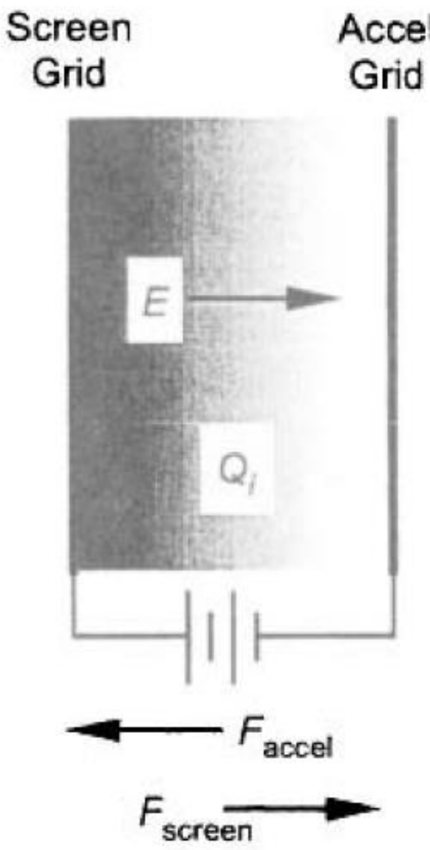
$$E(x) = \frac{q}{\varepsilon_0}\int_0^x n_i(x')\mathrm{dx}' + E_{\mathrm{screen}}$$

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

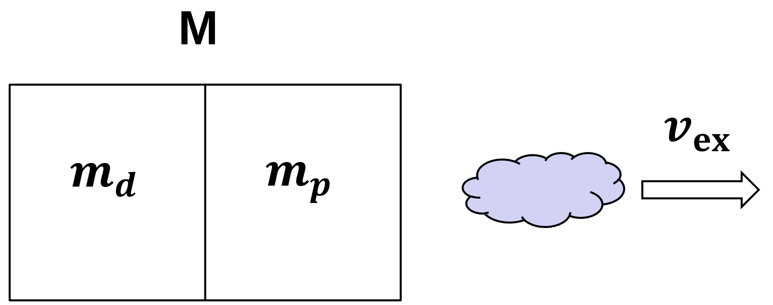
$$p(t) = p(t + \mathrm{dt})$$

$$Mv = \left(M - dm_{\mathrm{p}}\right)(v + dv) + dm_{\mathrm{p}}(v - v_{\mathrm{ex}})$$

$$\cancel{Mv} = \cancel{Mv} + Mdv - \cancel{dm_p v} - dm_p dv + \cancel{dm_p v} - dm_p v_{\mathrm{ex}}$$

$$dv \sim -v_{\mathrm{ex}} \frac{dM}{M} \quad \text{where } dm_{\mathrm{p}} dv \text{ is neglected and } dm_{\mathrm{p}} = -dM$$

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



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

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

Force transfer

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

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

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

$$T = -\frac{dm_{\text{p}}}{dt}v_{\text{ex}} \approx -\dot{m}_i v_i$$

$$v_i = \sqrt{\frac{2\text{q}\text{V}_b}{M}}$$

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

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

Q = propellant particle flow rate in particles/s

M = atomic mass in kg

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

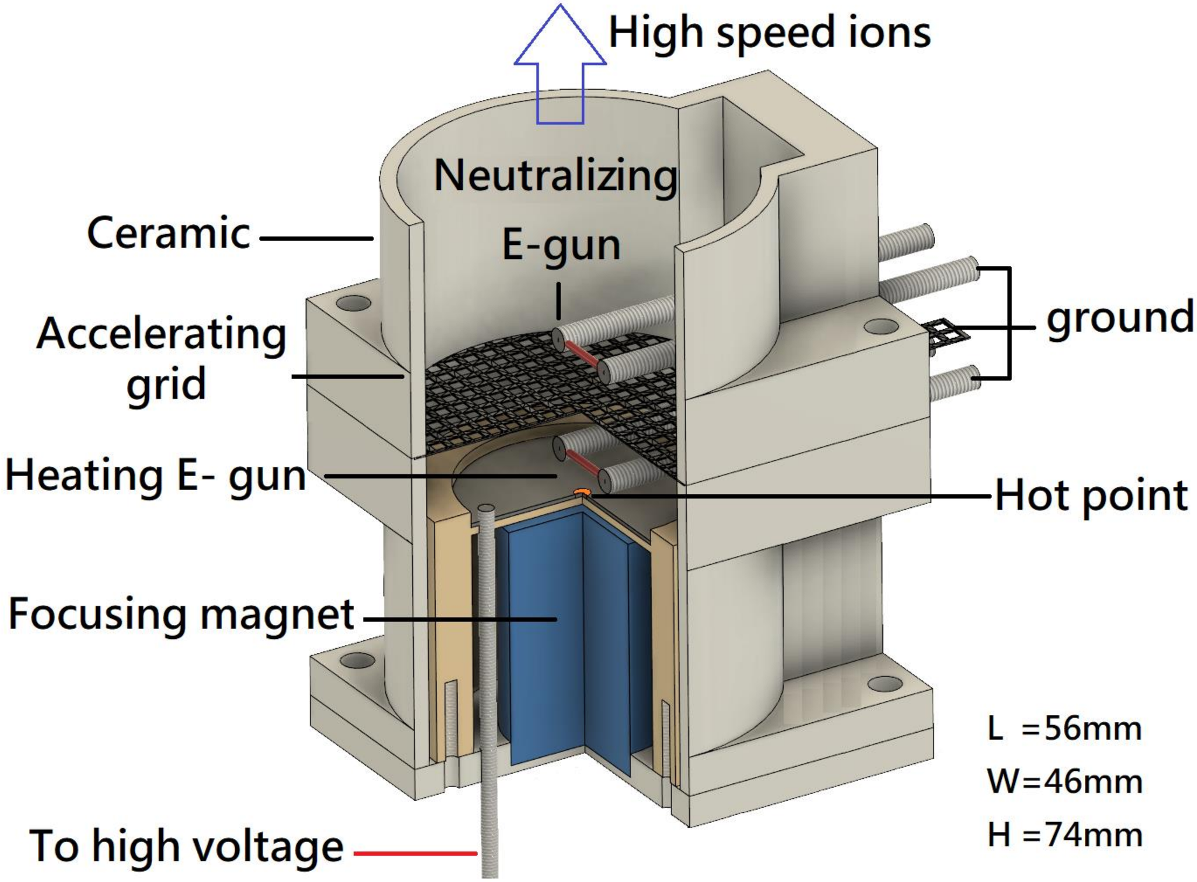
I_b = ion current

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

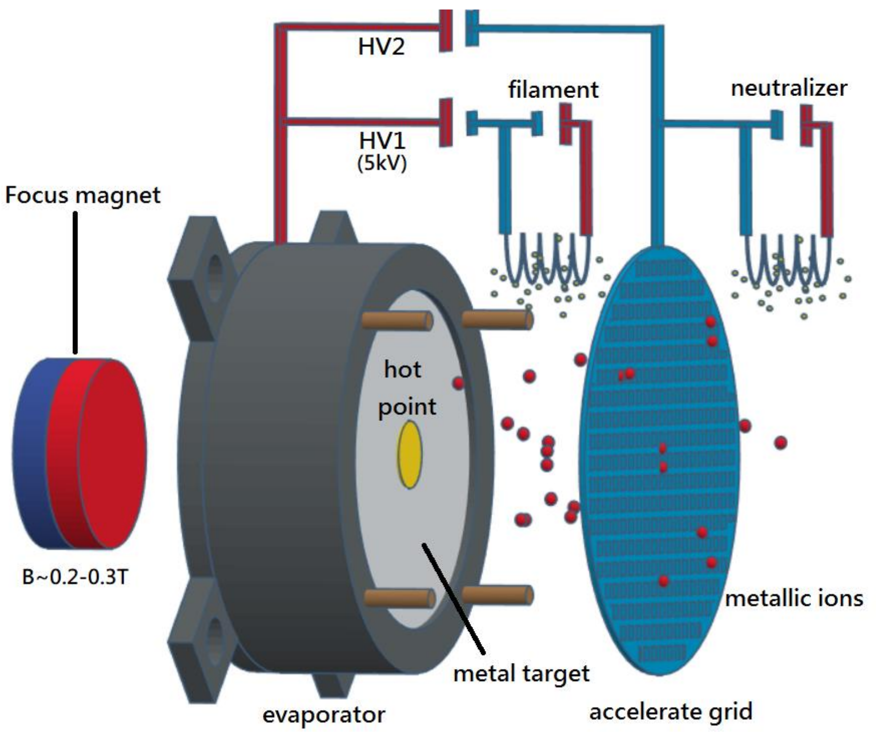
Ion thruster has the highest specific impulse (Isp)

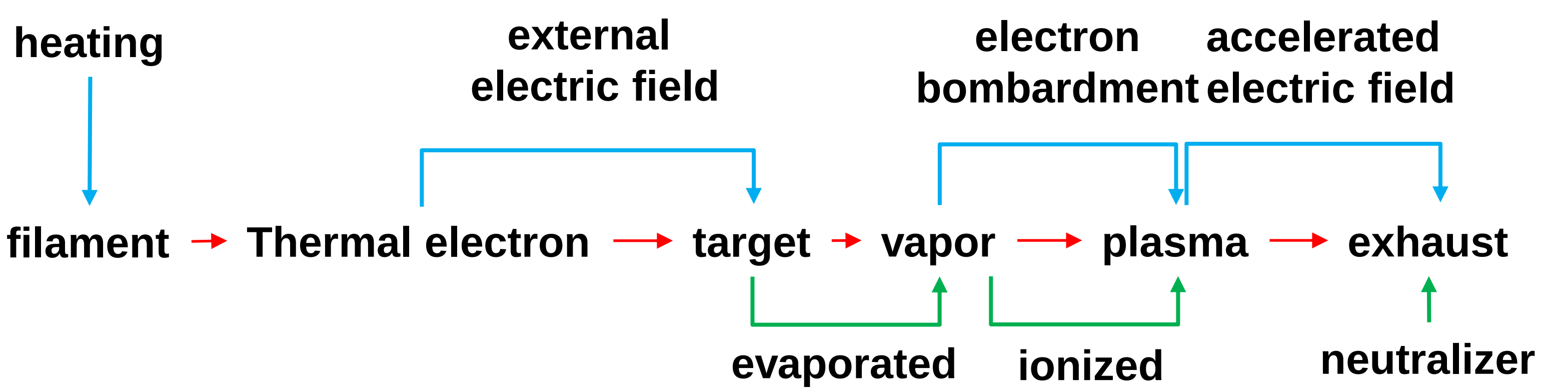
Thruster	Specific Impulse (s)	Input Power (kW)	Efficiency Range (%)	Propellant
Cold gas	50–75	—	—	Various
Chemical (monopropellant)	150–225	—	—	N_2H_4 H_2O_2
Chemical (bipropellant)	300–450	—	—	Various
Resistojet	300	0.5–1	65–90	N_2H_4 monoprop
Arcjet	500–600	0.9–2.2	25–45	N_2H_4 monoprop
Ion thruster	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)



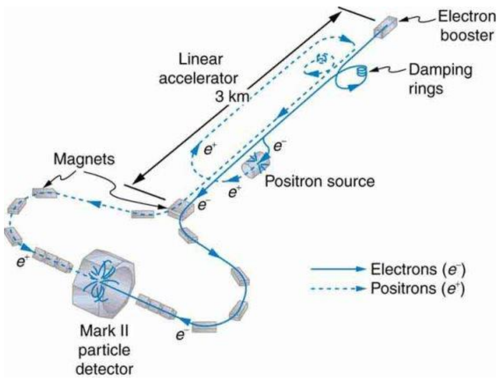
Electrons are used to generate metallic gas, metallic plasma and to neutralize ions



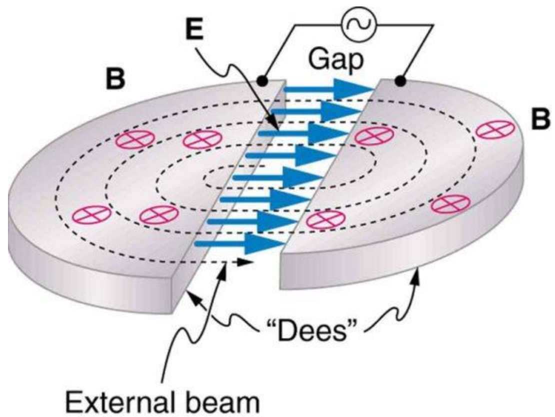


High energy particle accelerator

- linear particle accelerator (Linac)



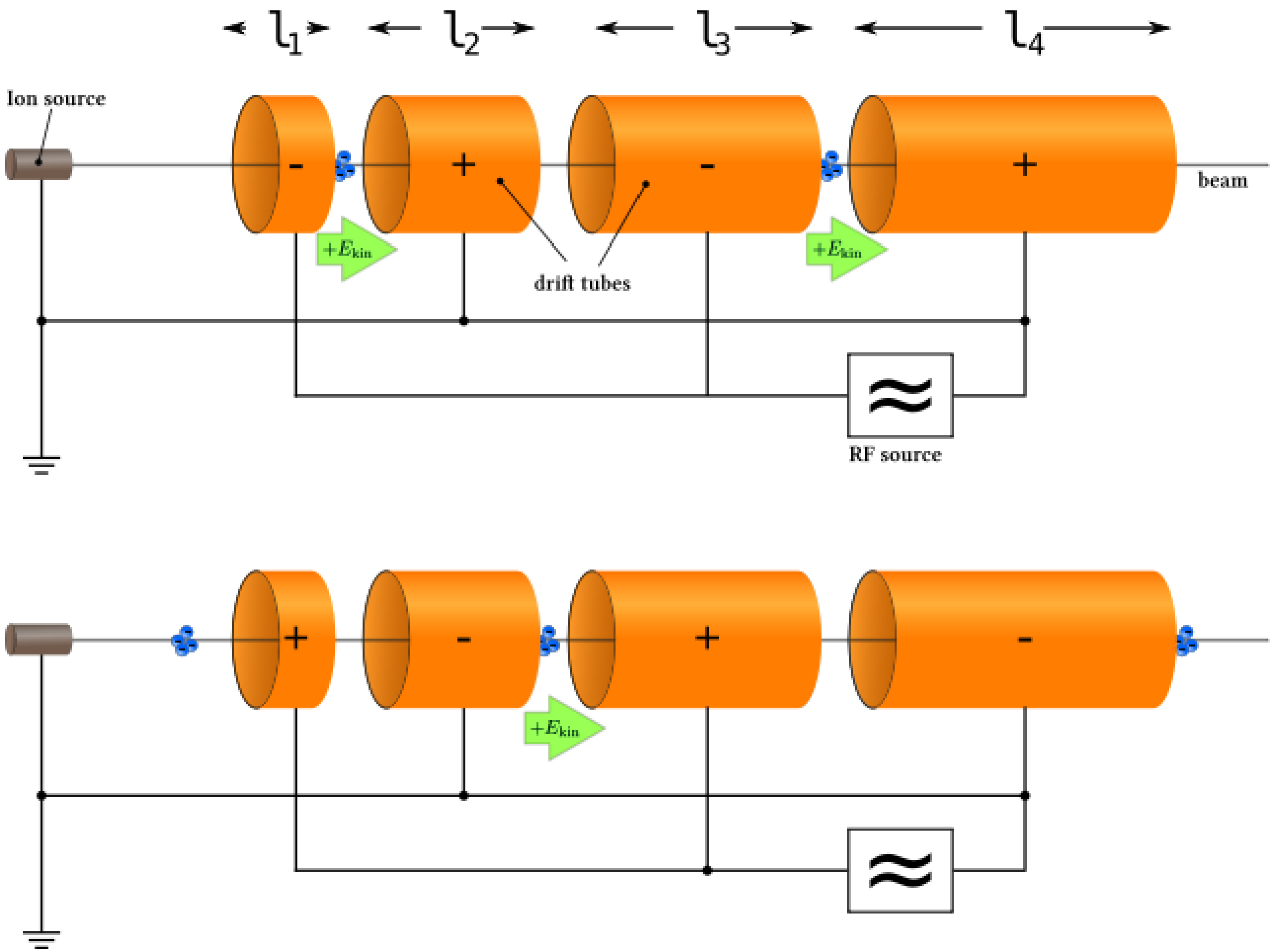
- Cyclotron



- Synchrotron

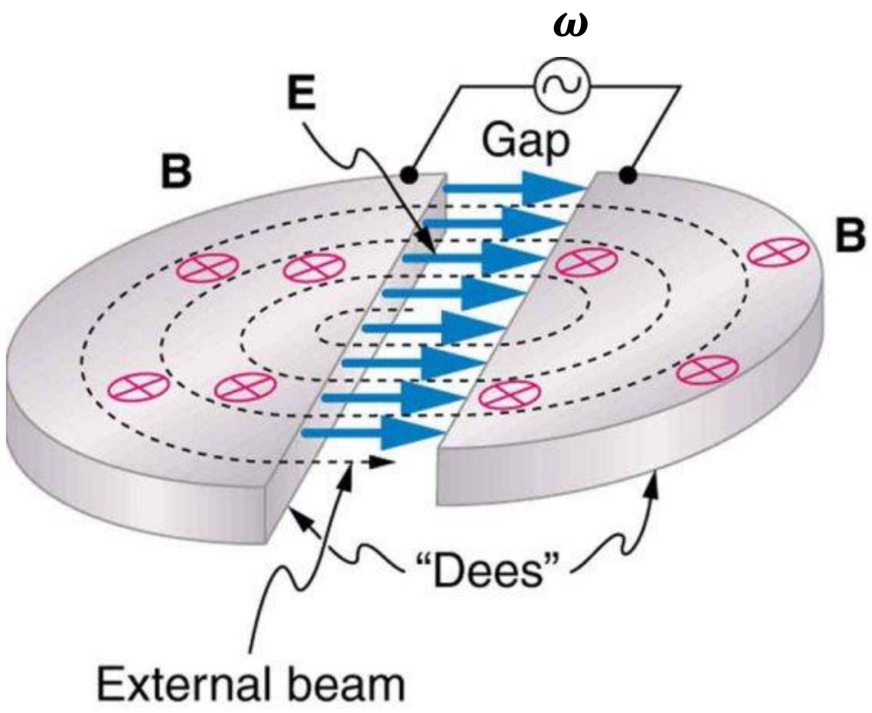
- **Reference: Introduction to plasma phenomena and plasma medicine, Y. Nishida and K.-L. Ou**

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



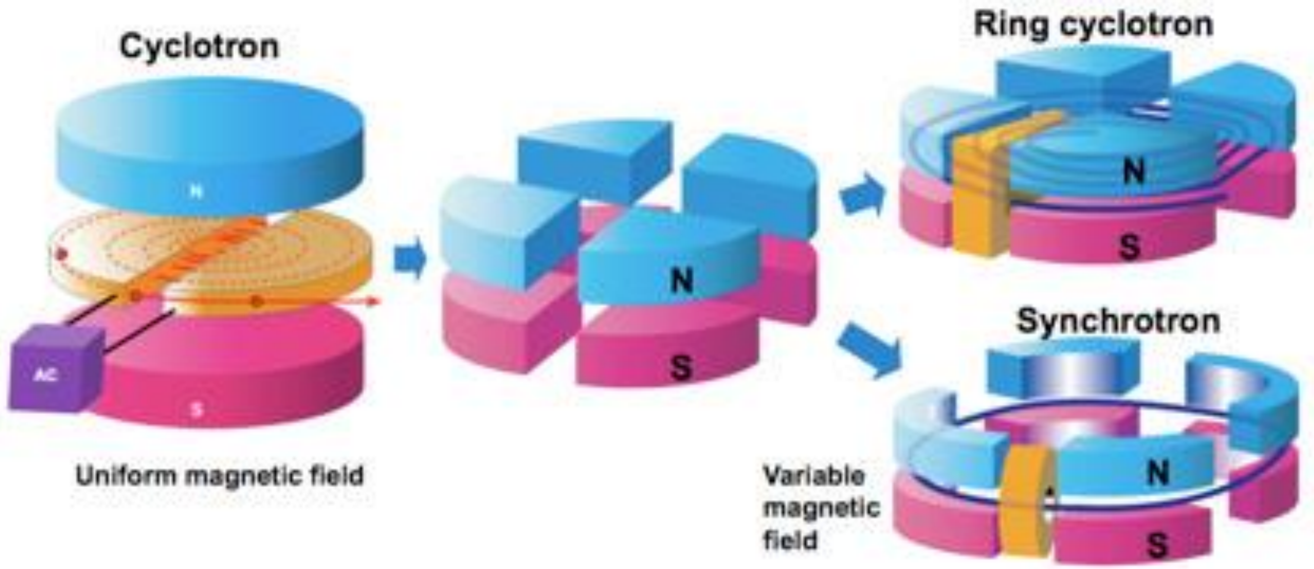
$$\omega_{\mathrm{ce}} = \frac{eB}{m_e c}$$

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

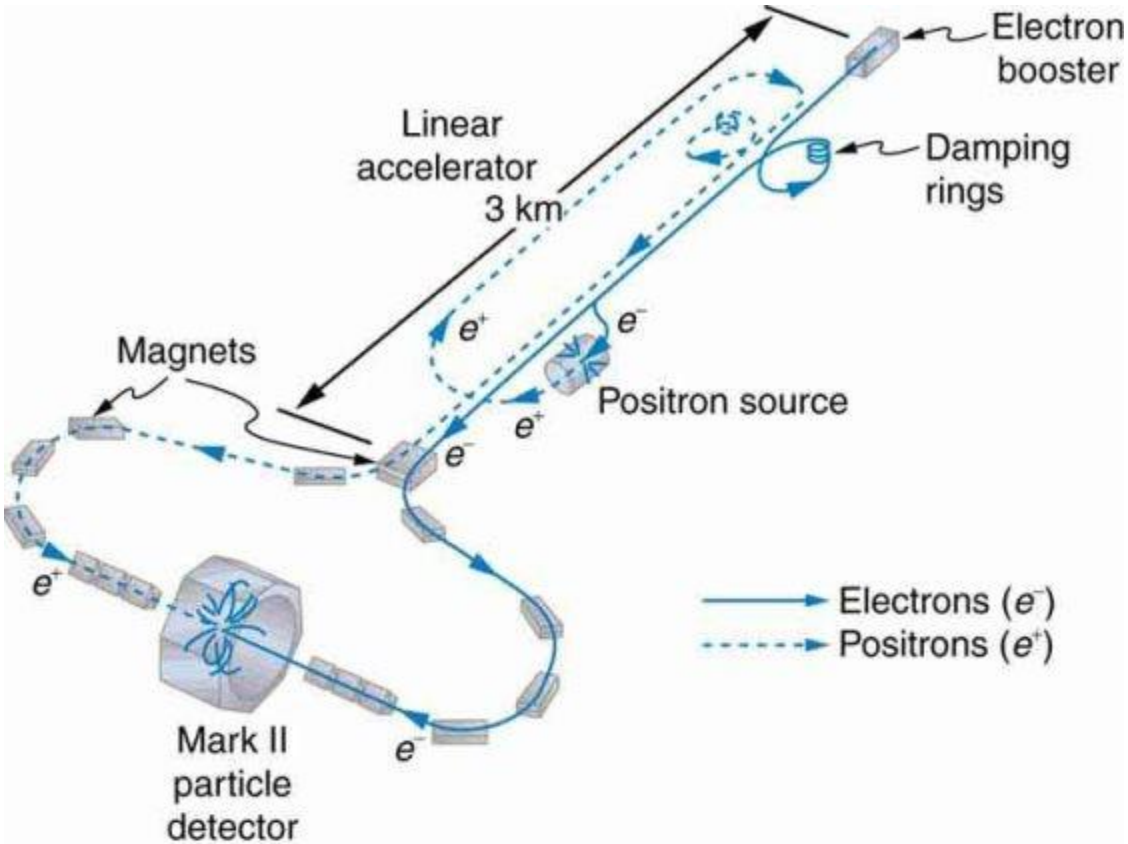
- **Cyclotron was invented by Ernest Lawrence who earned the 1939 Nobel price in physics**

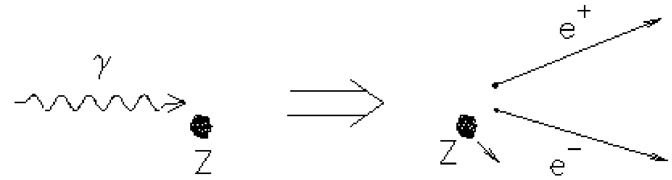
http://math.ubooks.pub/Books/ON/M1/1704/C33S4M004.html

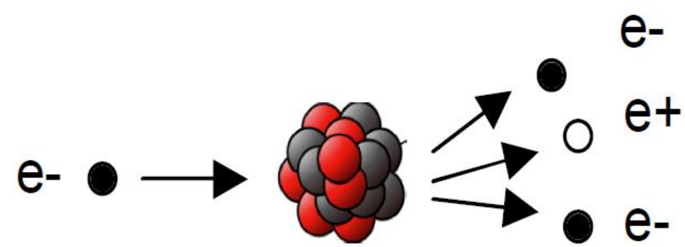
Synchrotron uses time-dependent guiding magnetic field synchronized to a particle beam



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

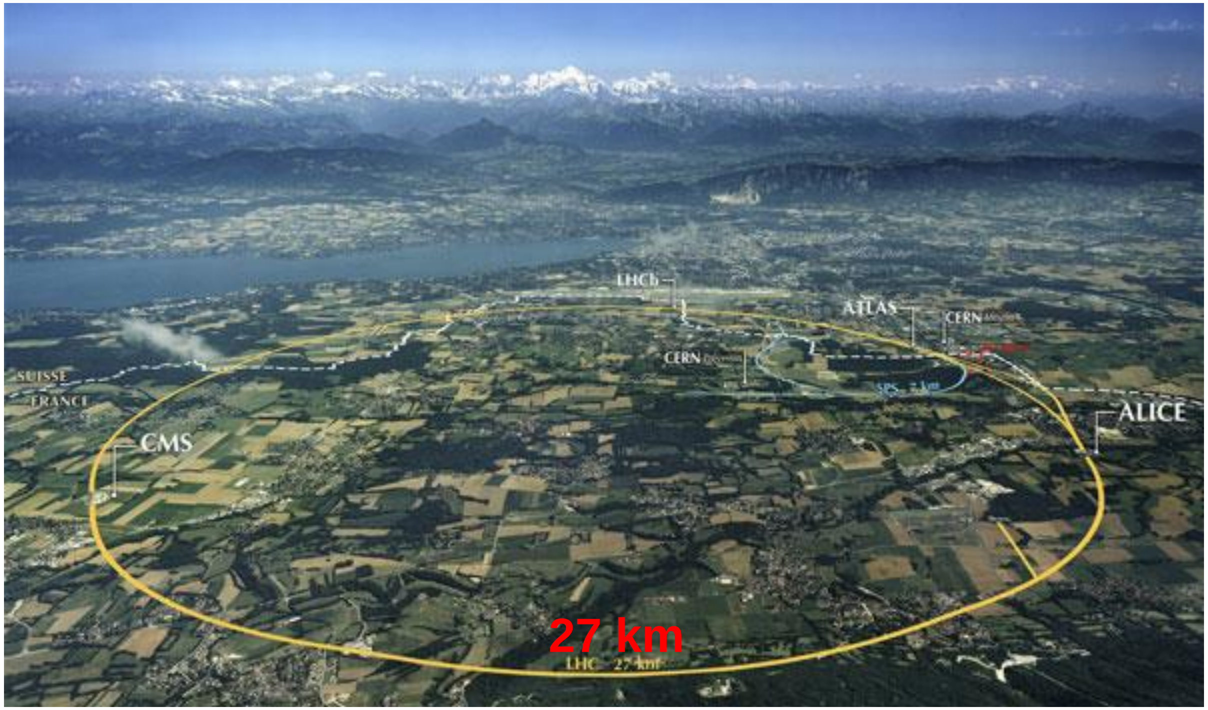






http://cnx.org/contents/aypTUEkP@4/Accelerators-Create-Matter-fro
https://upload.wikimedia.org/wikipedia/commons/6/64/Pair_production_Cartoon.gif

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

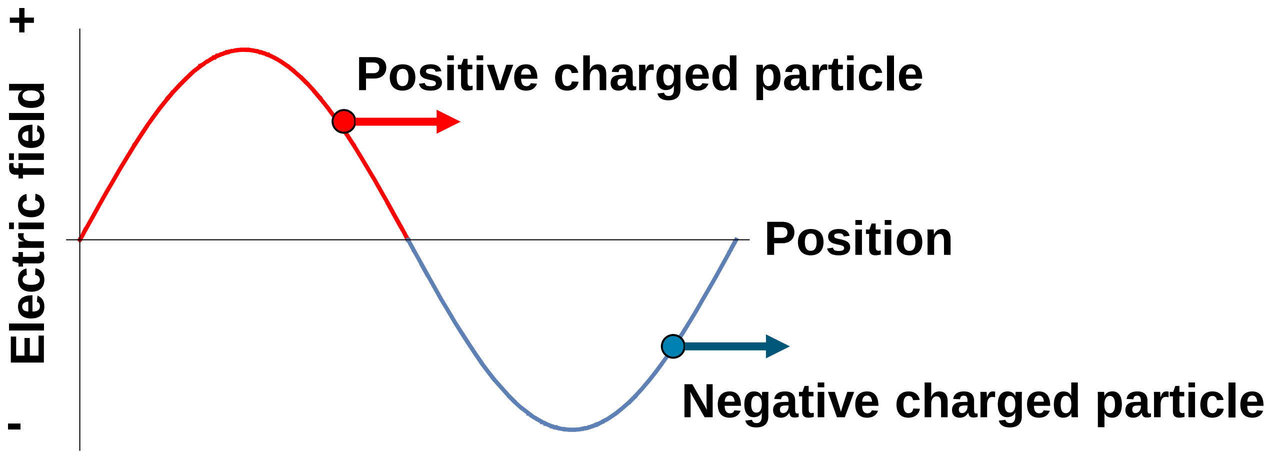
Plasma based accelerators will become 3 orders smaller than the regular microwave based accelerator

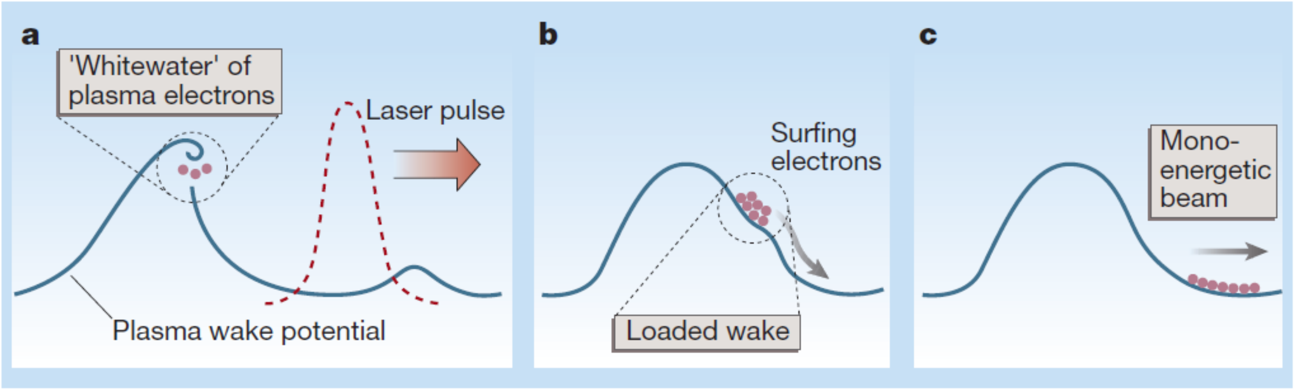
- **Maximum field strength:**
  - **Microwave: 100 MV/m**
  - **Plasma: >10 GV/m, 300 GV/m was achieved using laser wakefield accelerator[1]**

- **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]**

[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



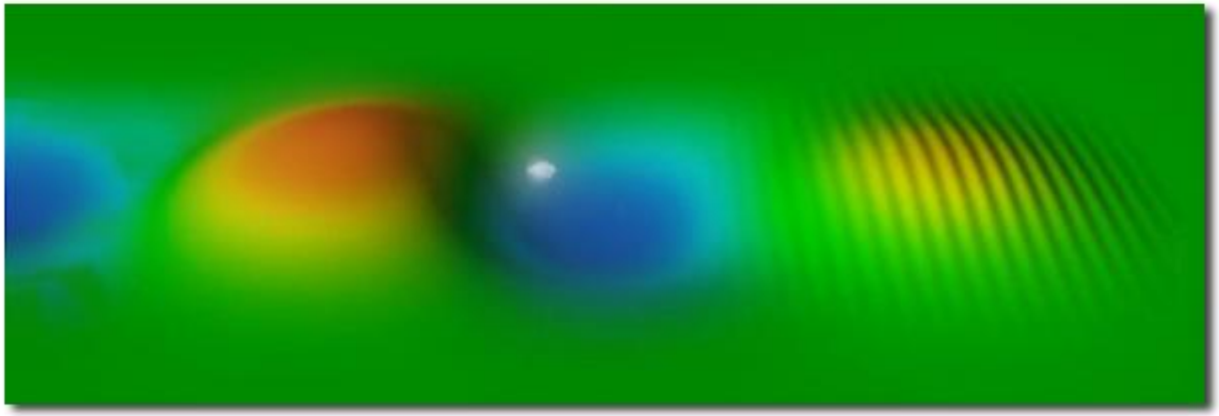


T. Katsouleas, Nature **431**, 515 (2004)

Who will catch the wave?

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

Plasma wake field accelerator is just like boat wake surfing



http://newscenter.lbl.gov/2011/03/17/simulating-at-lightspeed/

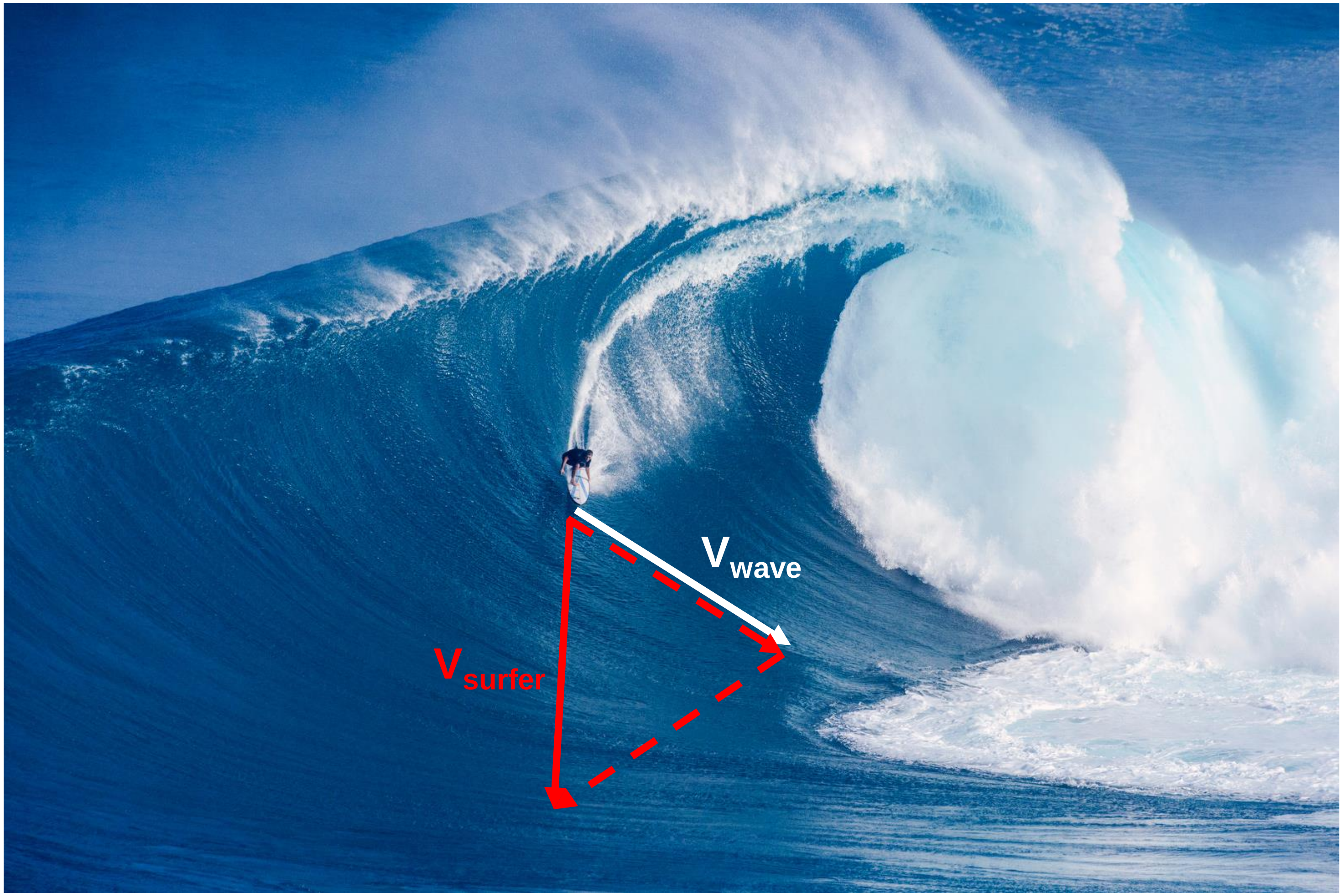
A wake surfer catches the wake field via being pulled by the boat using a roap

https://www.youtube.com/watch?v=VFp7SIoeAnk

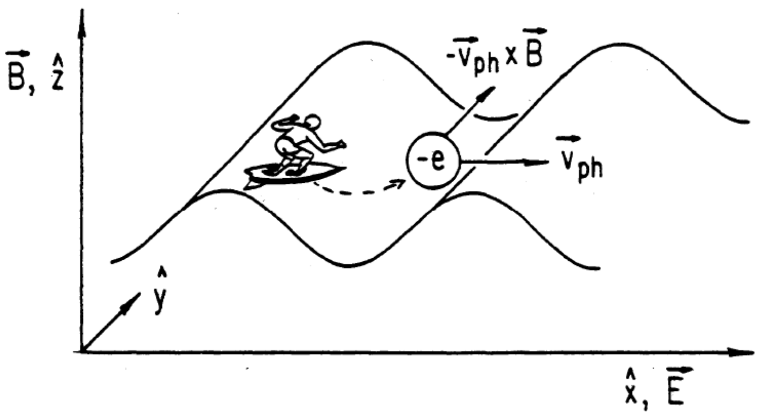
https://learntosurfkona.com/featured/wake-surfing-vs-regular-surfing/
https://i.ytimg.com/vi/CA-SDf1wvTQ/maxresdefault.jpg

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

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:**

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

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

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

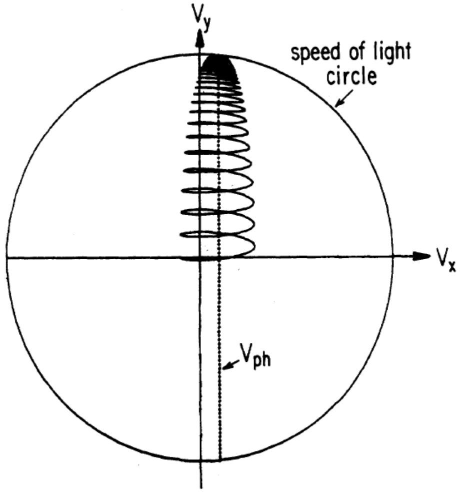
$$\frac{d}{dt}(\gamma v_y) = -\omega_c v_x \qquad \gamma = \frac{1}{\sqrt{1 - \frac{{v_x}^2 + {v_y}^2}{c^2}}}$$

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

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

$$v_x \to v_{\mathrm{ph}}$$

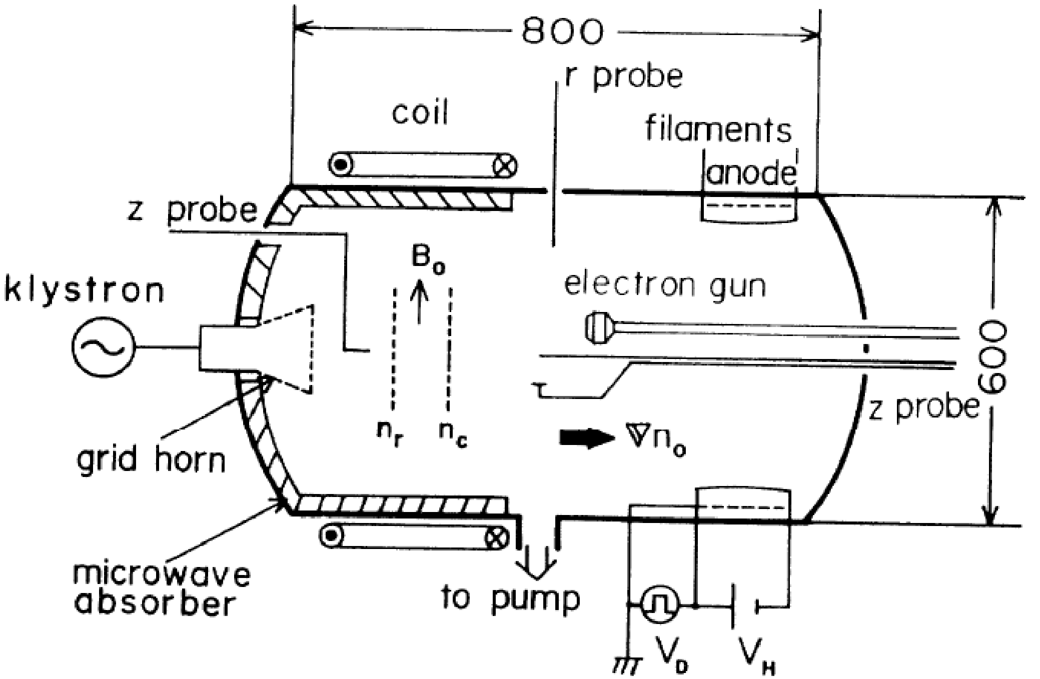
$$v_y = -\frac{\omega_c v_{\mathrm{ph}} t}{\gamma_{\mathrm{ph}}\sqrt{1 + \frac{{\omega_c}^2 t^2 {v_{\mathrm{ph}}}^2}{c^2}}}$$

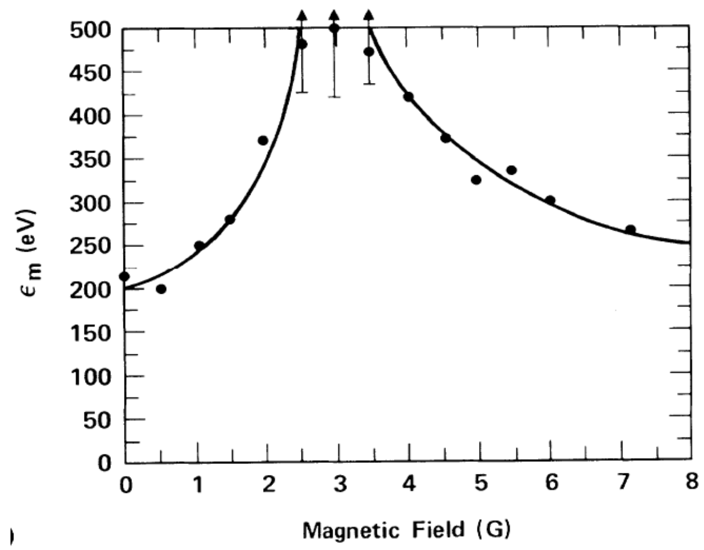


- T. Katsouleas, *et al.*, PRL **51**, 392 (1983)
- T. Katsouleas, *et al.*, IEEE TNS. **NS-30**, 3241 (1983)

- Y. Nishida, *et al.*, AIP Conf Proc. **737**, 957 (2004)

Experimental results of V_pxB acceleration (Surfatron)

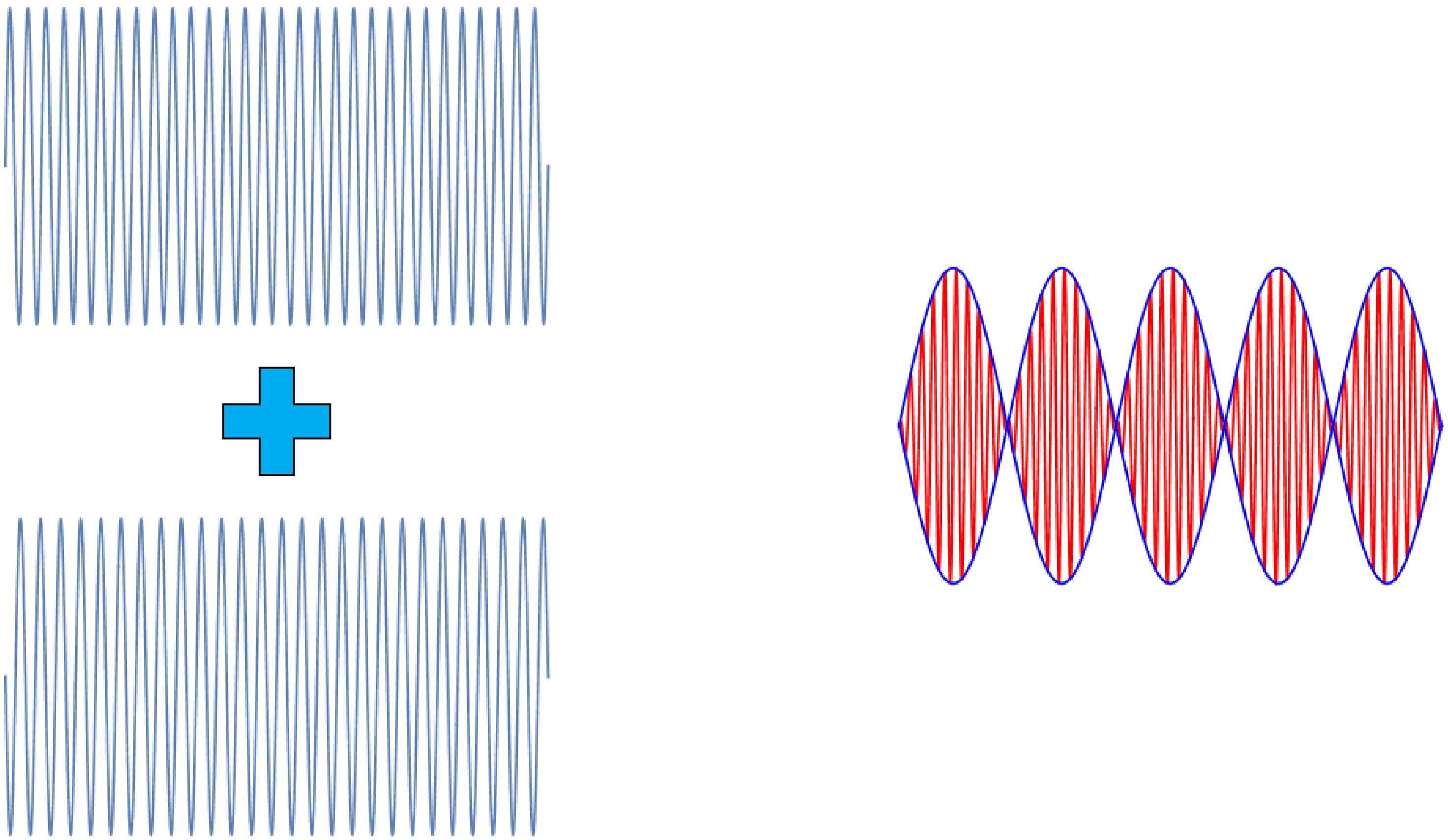




- **n_0 ~ 1-30 x 10^{17} m^{-3}**
- **T_e ~ 2-5 eV**
- **T_i ~ 0.1-0.2 eV**
- **Microwave frequency: 3-10 GHz**

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

Plasma beat wave accelerator



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

A plasma wave is driven by the laser beat wave

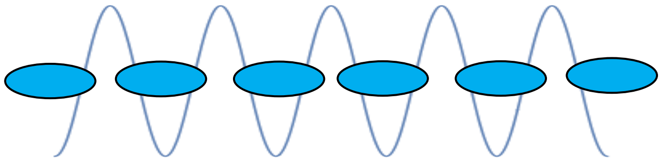
$$\omega_0 = \omega_2 - \omega_1$$

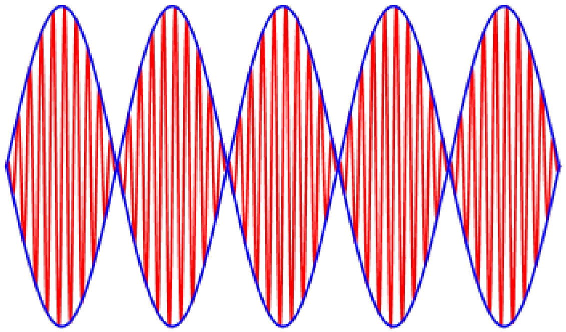
$$k_0 = k_2 - k_1$$

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

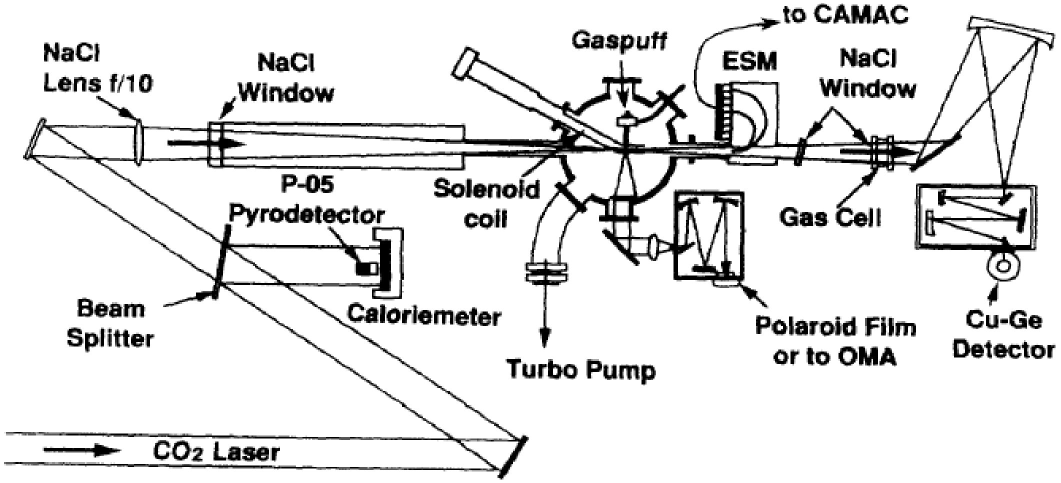
$$F = -e\nabla\phi_p = -\nabla\frac{e^2 E^{(1)} \cdot E^{(2)*}}{\mathrm{m}\omega_1\omega_2}$$

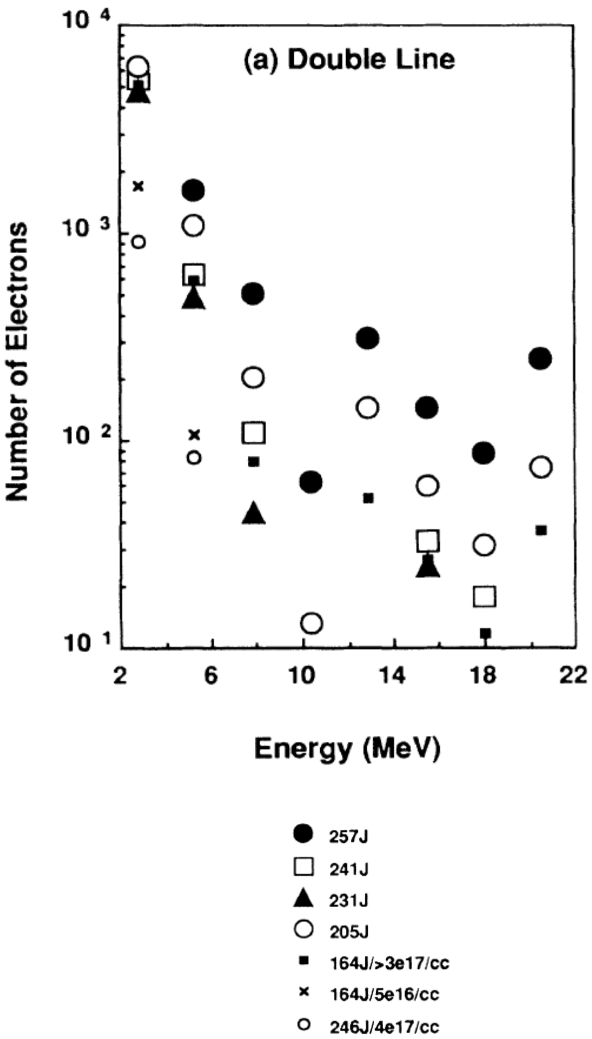
Plasma wave





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





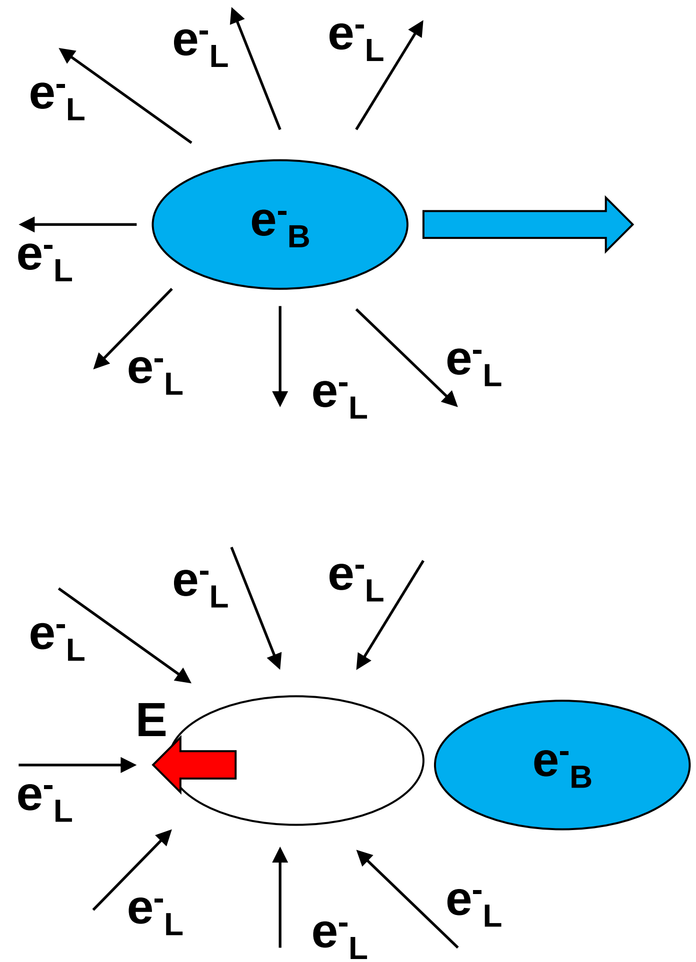
Laser: 10.6 um + 9.57 um
Intensity: $2\text{x}10^{13}$ ~ $2\text{x}10^{14}$ W/cm^2
Injected E-beam: 0.1~1 MeV
$n_0=3\text{x}10^{16}$ ~ $7\text{x}10^{17}$ cm^{-3}

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

Plasma wakefield accelerator employs two beams

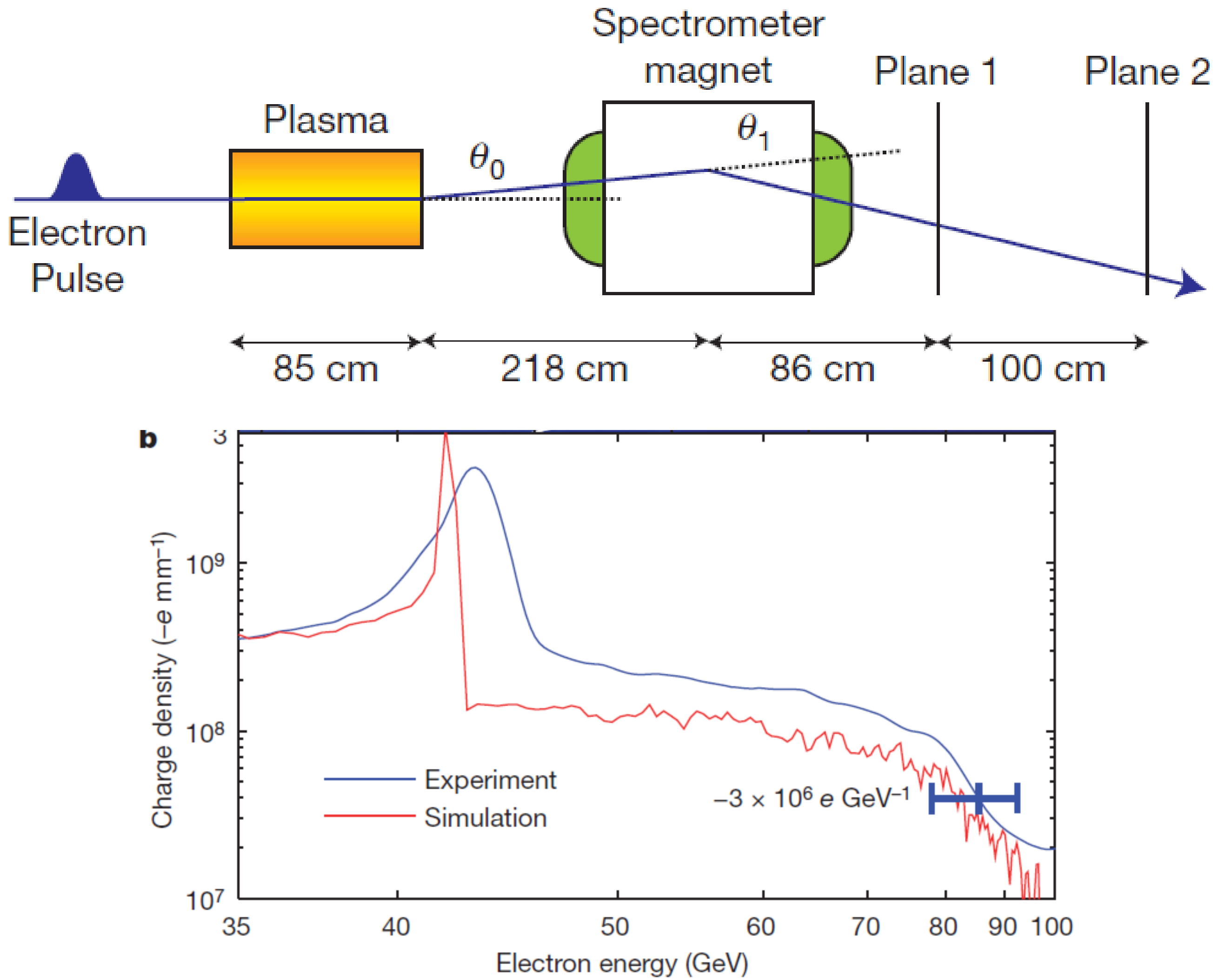
- When a bunch of electrons enter the plasma, they expel local electrons.
- When the bunch of electrons leave the plasma, the local electrons try to return but oscillate around their original locations and generate a wake field behind the bunch.
- The longitudinal field of the wake can accelerate the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

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

$x = x_0 + x_1$ 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:**

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

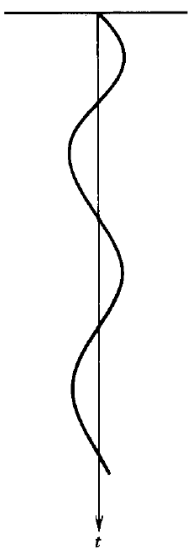
- $\ddot{x}_1 \gg \ddot{x}_0$, $E_0 >> x_1\frac{dE_0}{dx}$

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

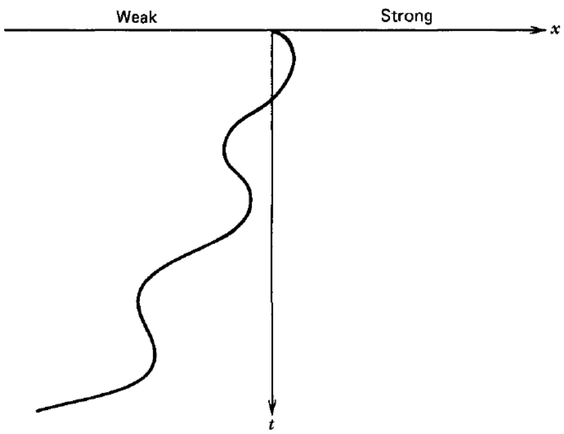
$$x_1 = -\frac{q_s E_0}{m_s\omega^2}\cos\omega t$$

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

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



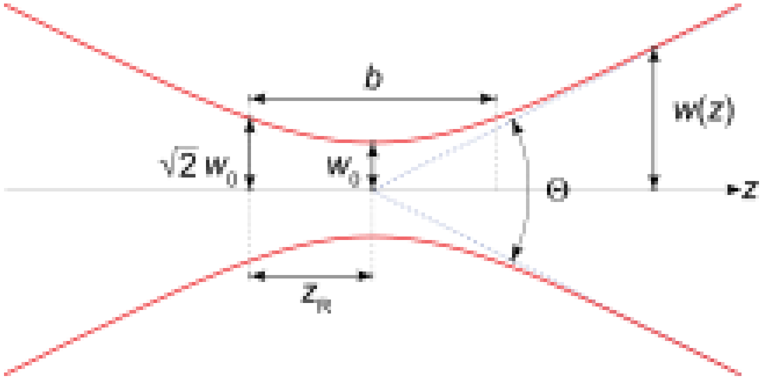
$$\frac{dE_0}{dx} > 0$$



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

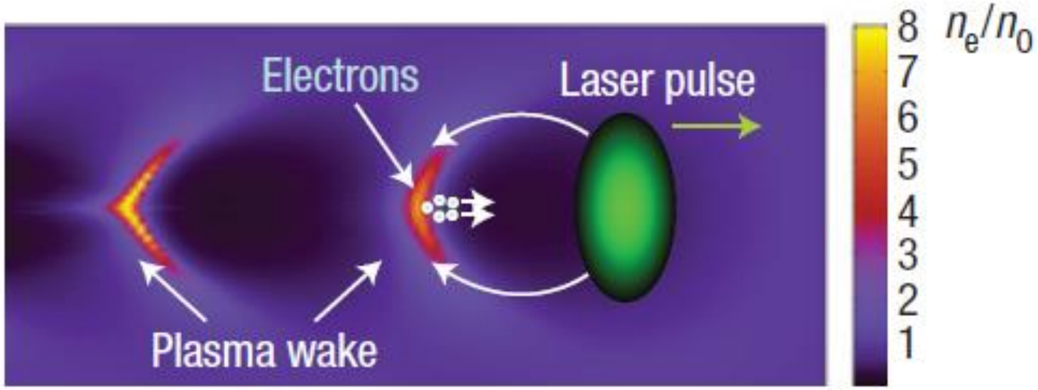
Laser is used to create a bunch in laser wakefield accelerator

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



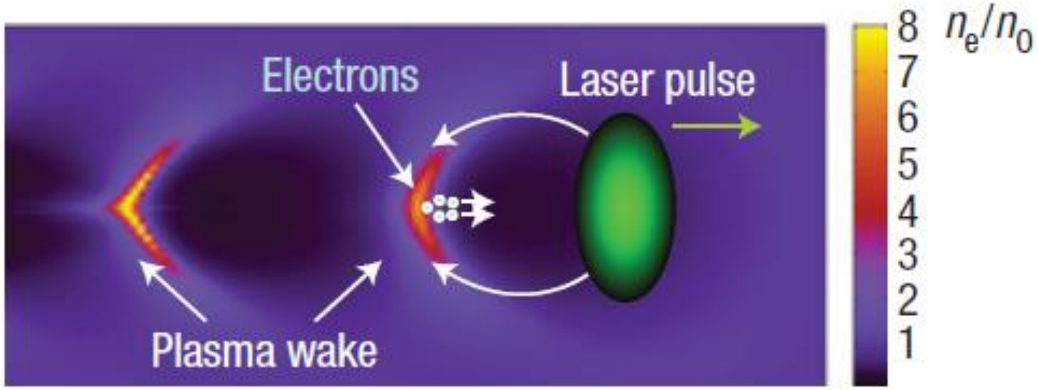
- **Waist:** $w(z) = w_0\sqrt{1 + \frac{z^2}{{z_R}^2}}$
- **Rayleigh length:** $z_R = \frac{\pi {w_0}^2}{\lambda_L}$

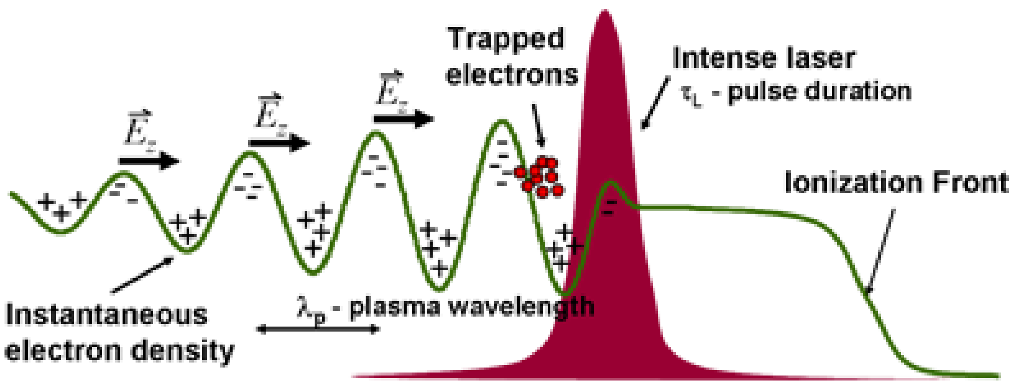
Bubble/blow-out regime



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

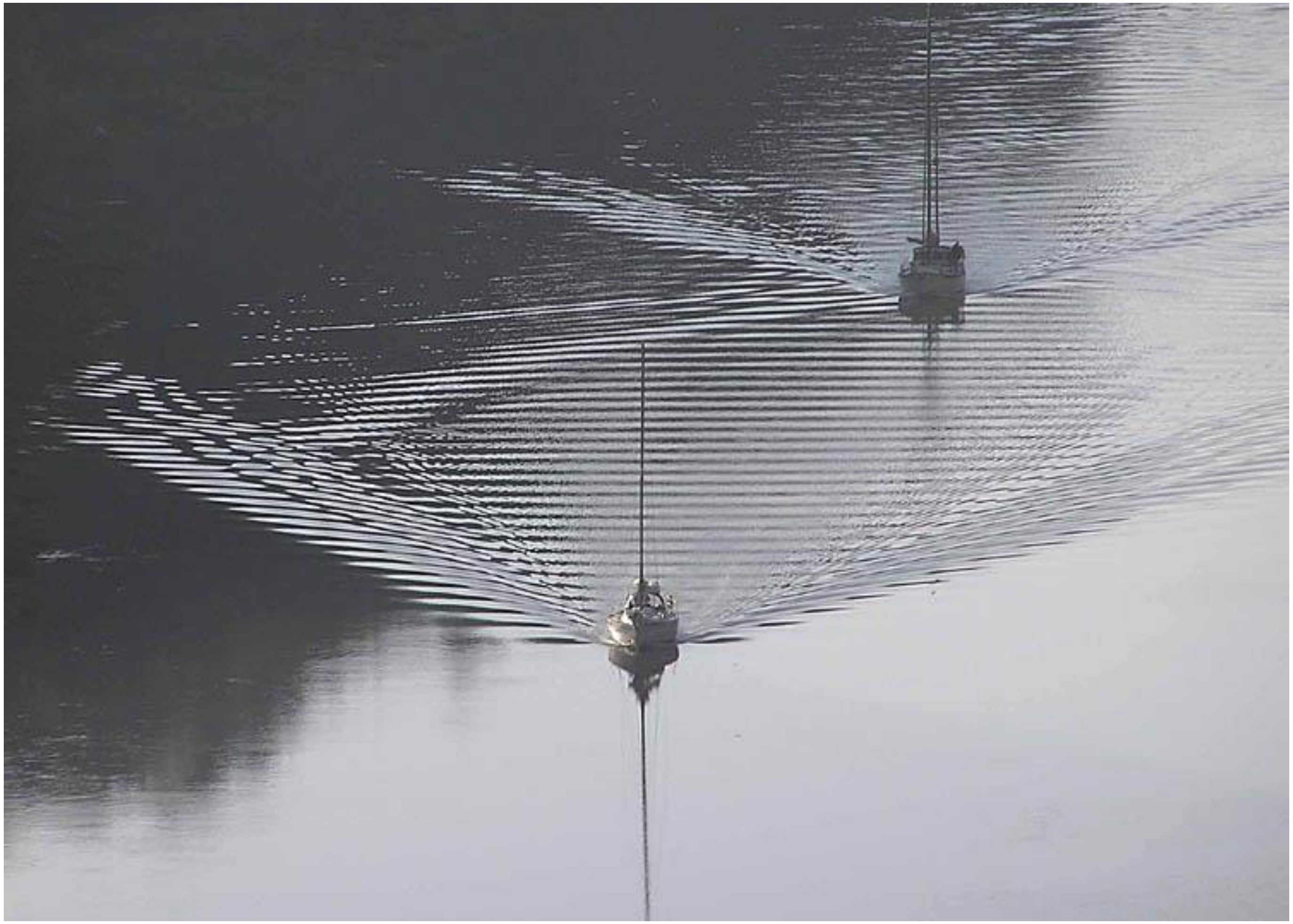
A plasma wake is generated by a short pulse laser





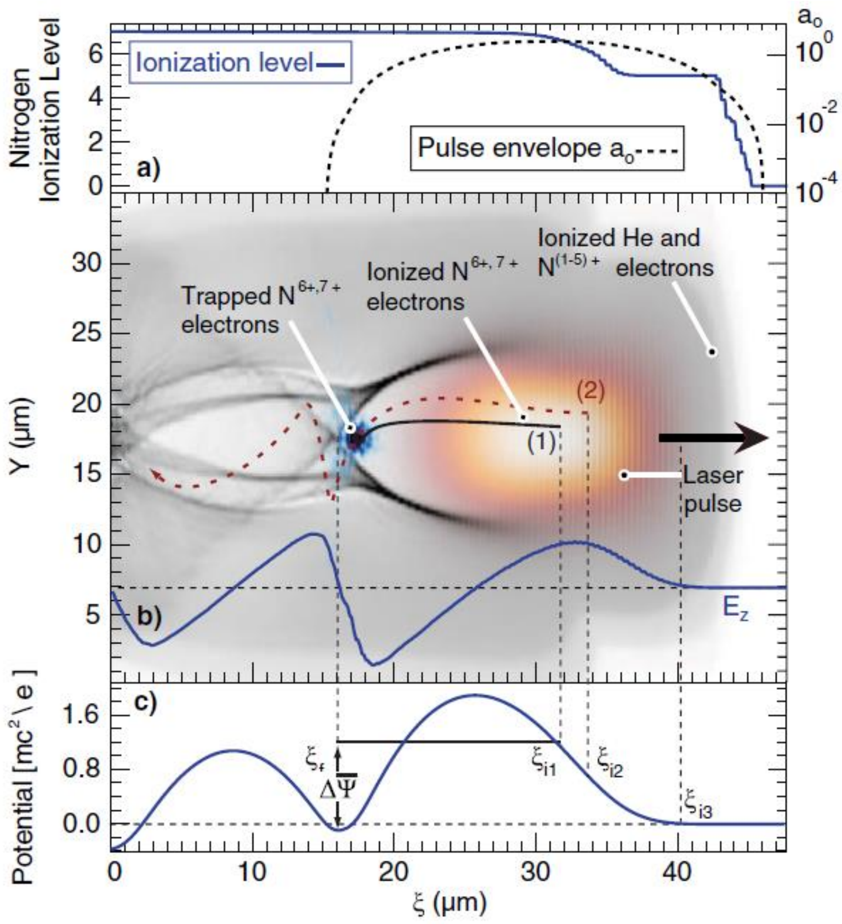
V. Malka, *et al.*, Nature Physics **4**, 447 (2008)
http://cuos.engin.umich.edu/researchgroups/hfs/research/laser-wakefield-acceleration/

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

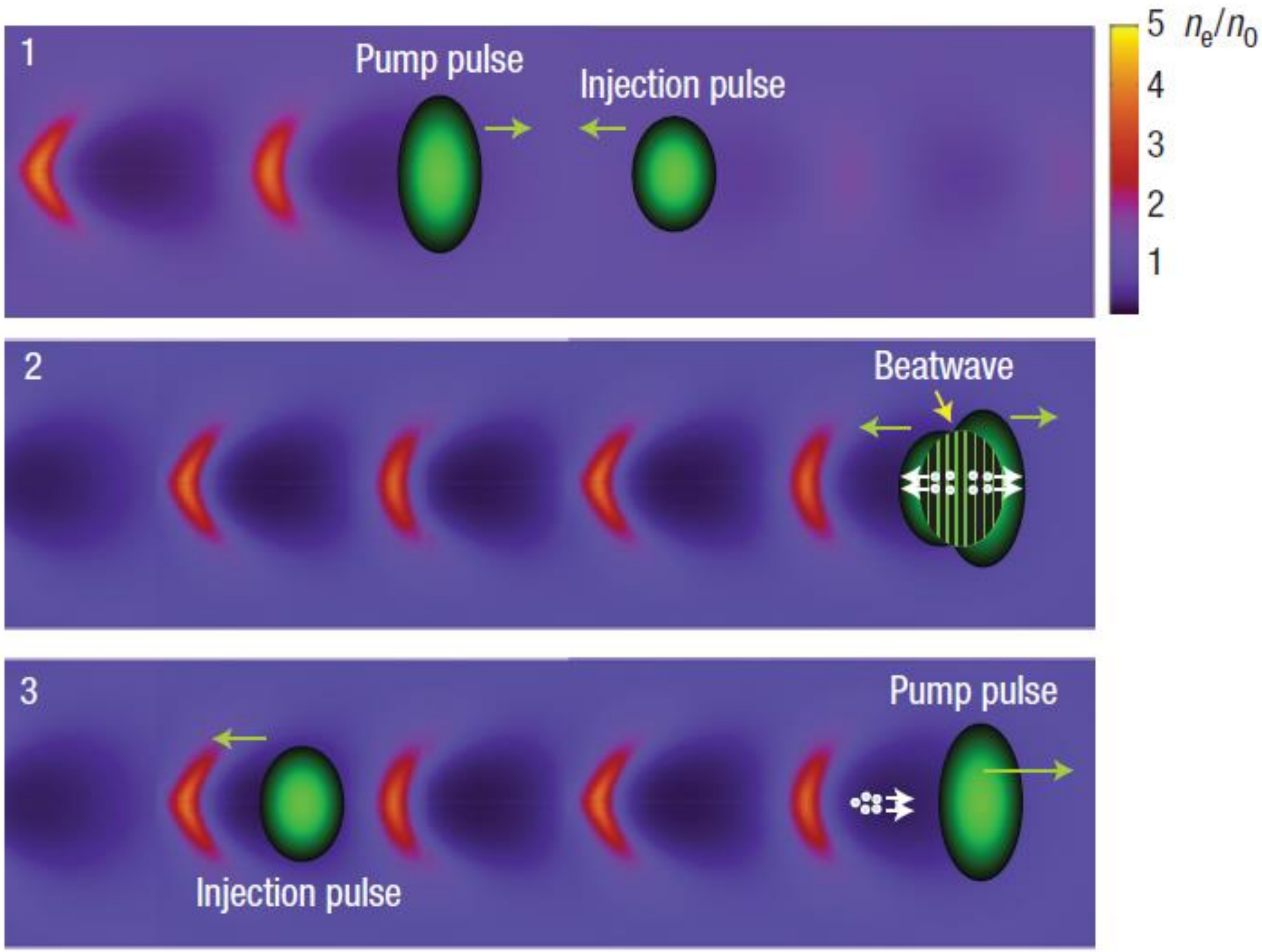
Ionization injection



- **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**

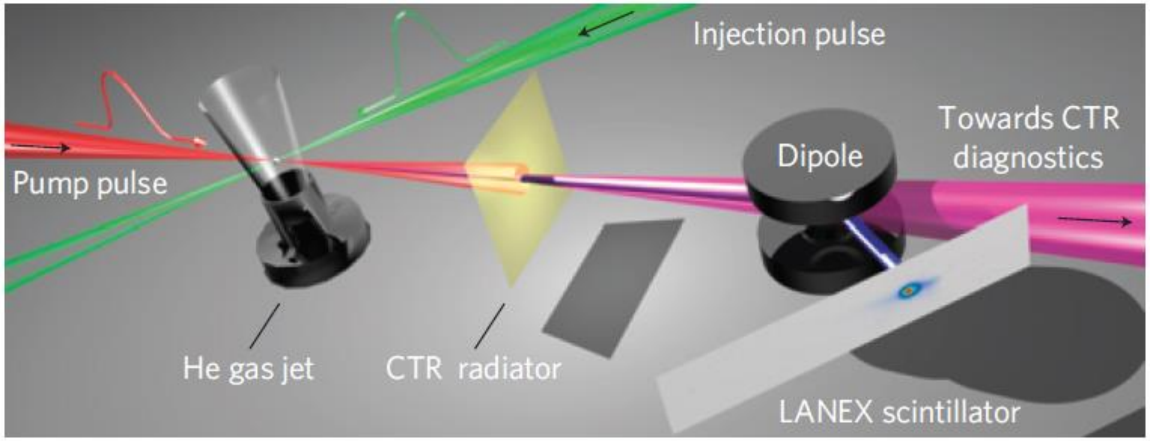
A. Pak, *et al.*, Phys. Rev. Lett. **104**, 025003 (2010)

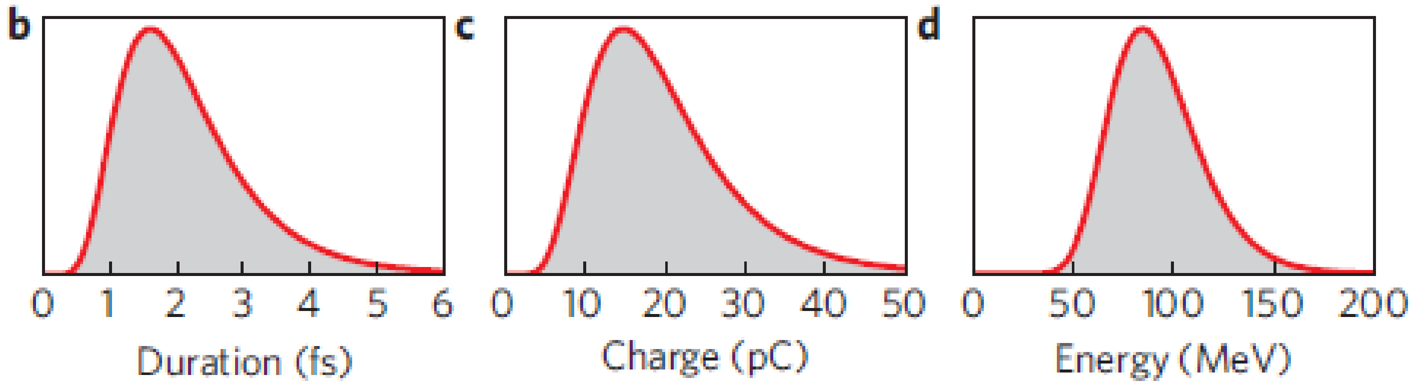
Colliding laser pulses injection



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

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



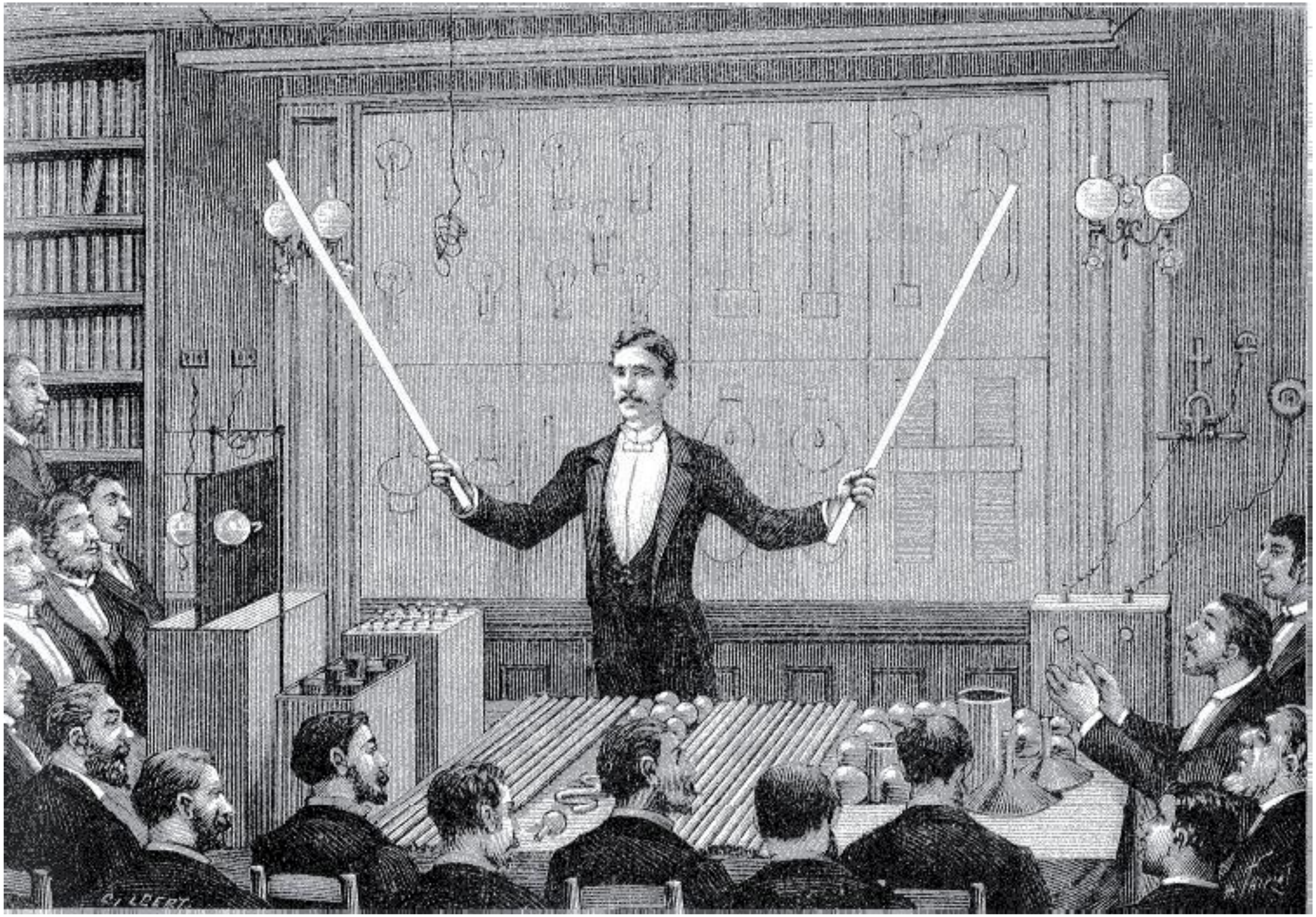


O. Lundh, *et al.*, Nature Physics **7**, 219 (2011)

Plasma medicine

- **Reference:**
  - **“Applied Plasma Medicine”, by G. Fridman, et al., Plasma Process. Polym., 5, 503, 2008**
  - **“Plasma Medicine”, by A. Fridman and G. Fridman**

Nikola Tesla’s demonstrations of high frequency currents passing through his body

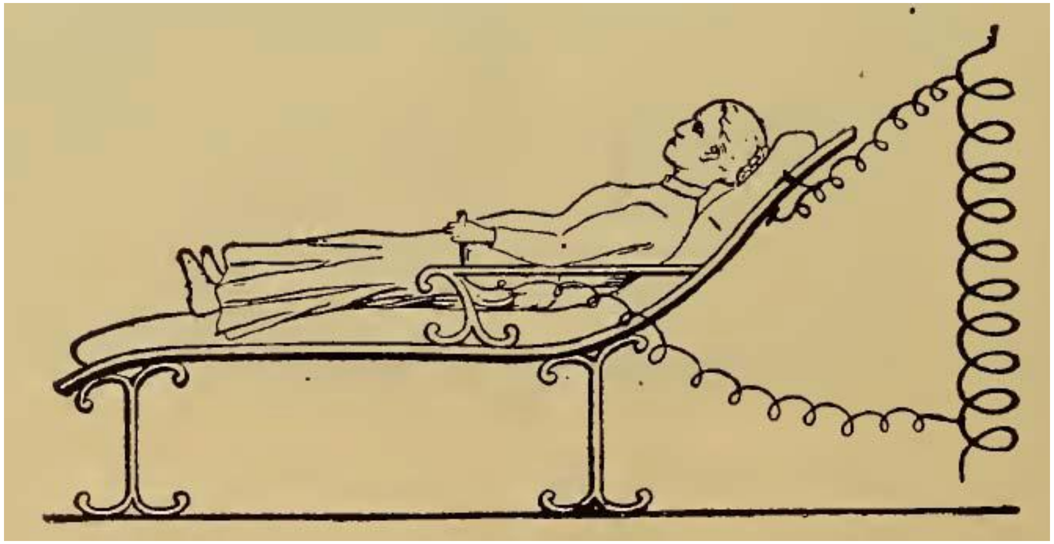


D. B. Graves, IEEE Transactions on Radiation and Plasma Medical Sciences, **2**, 594 (2018)

d’Arsonval’s device for coupling currents to a body via a large, enclosing induction coil

D. B. Graves, IEEE Transactions on Radiation and Plasma Medical Sciences, **2**, 594 (2018)

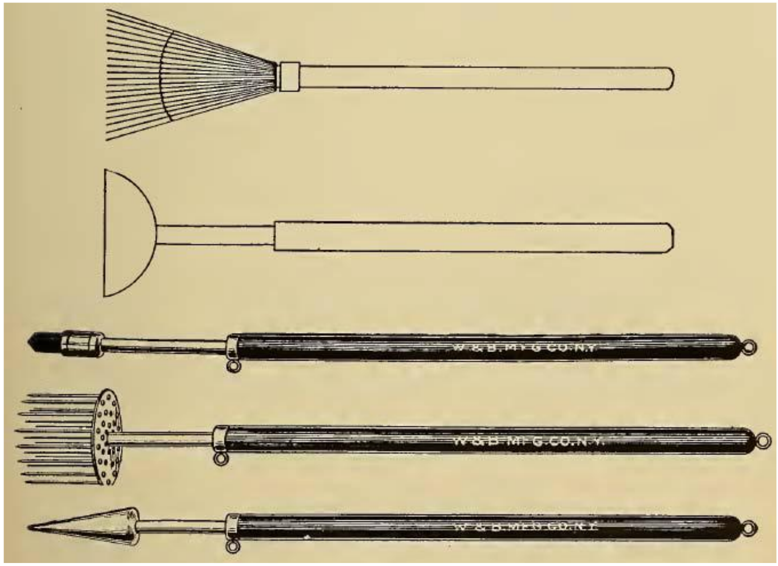
d’Arsonval’s device for coupling currents to a body as part of a large capacitor or condenser



D. B. Graves, IEEE Transactions on Radiation and Plasma Medical Sciences, **2**, 594 (2018)

Paul Oudin used spark to cure patient's knee's problems

- **Effluviation electrodes**



D. B. Graves, IEEE Transactions on Radiation and Plasma Medical Sciences, **2**, 594 (2018)

Outline

- Example of several plasma discharges for plasma medicine
- Living tissue sterilization
- Blood coagulation
- Nitrogen oxide (NO) treatment
- Non-thermal plasma treatment of melanoma skin cancer
- Skin regeneration
- Egg sterilization
- Facemask regeneration

Outline

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Plasma is characterized by the electron and ion temperatures

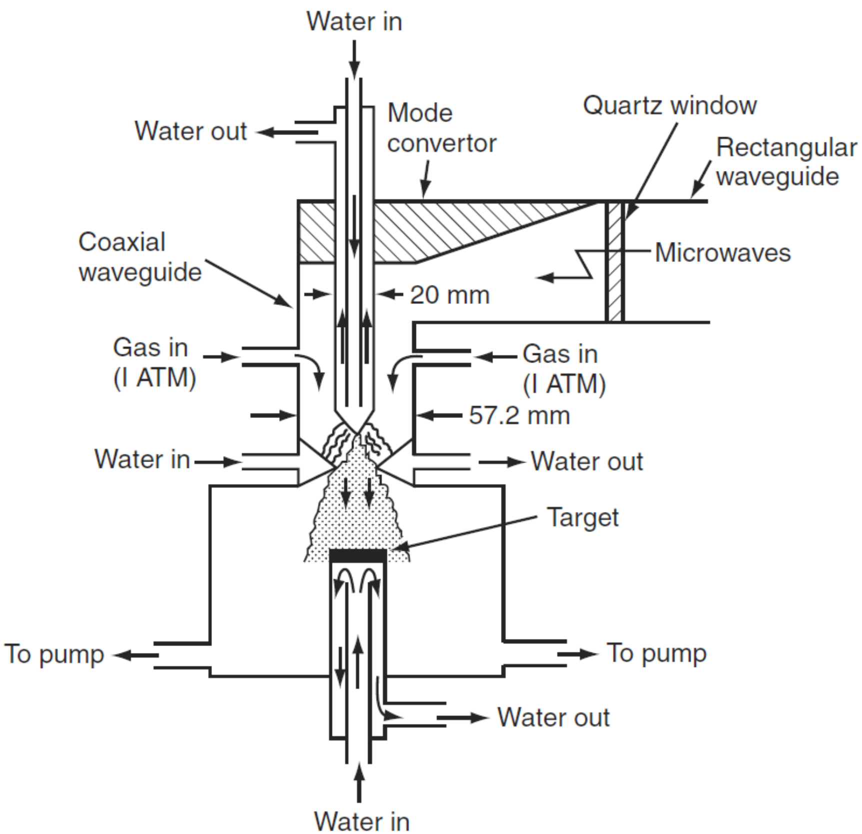
- **Non-thermal plasma**
  - **$T_i << T_e$**
  - **Also called non-equilibrium plasma**
- **Thermal plasma**
  - **$T_i \approx T_e$**
- **Earlier applications of plasma in medicine – thermal effects of plasma**

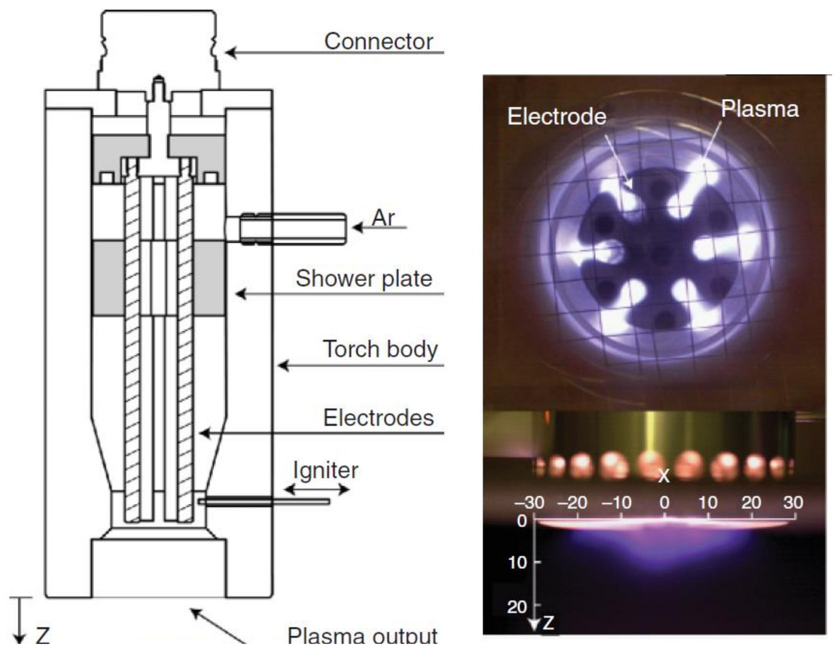
Plasma can provide good surface treatment with low temperature

Treatment	Surface treatment level	Depth	Temperature	Cost
Chemical	Large	Deep	Room temperature ~200 ℃	Medium
Heat	Only oxidizing	Deep	High temperature	Cheap
Radiation	Small	Whole sample	High temperature	Expensive
Plasma	Large	Surface	Room temperature ~100 ℃	Cheap ~ Medium

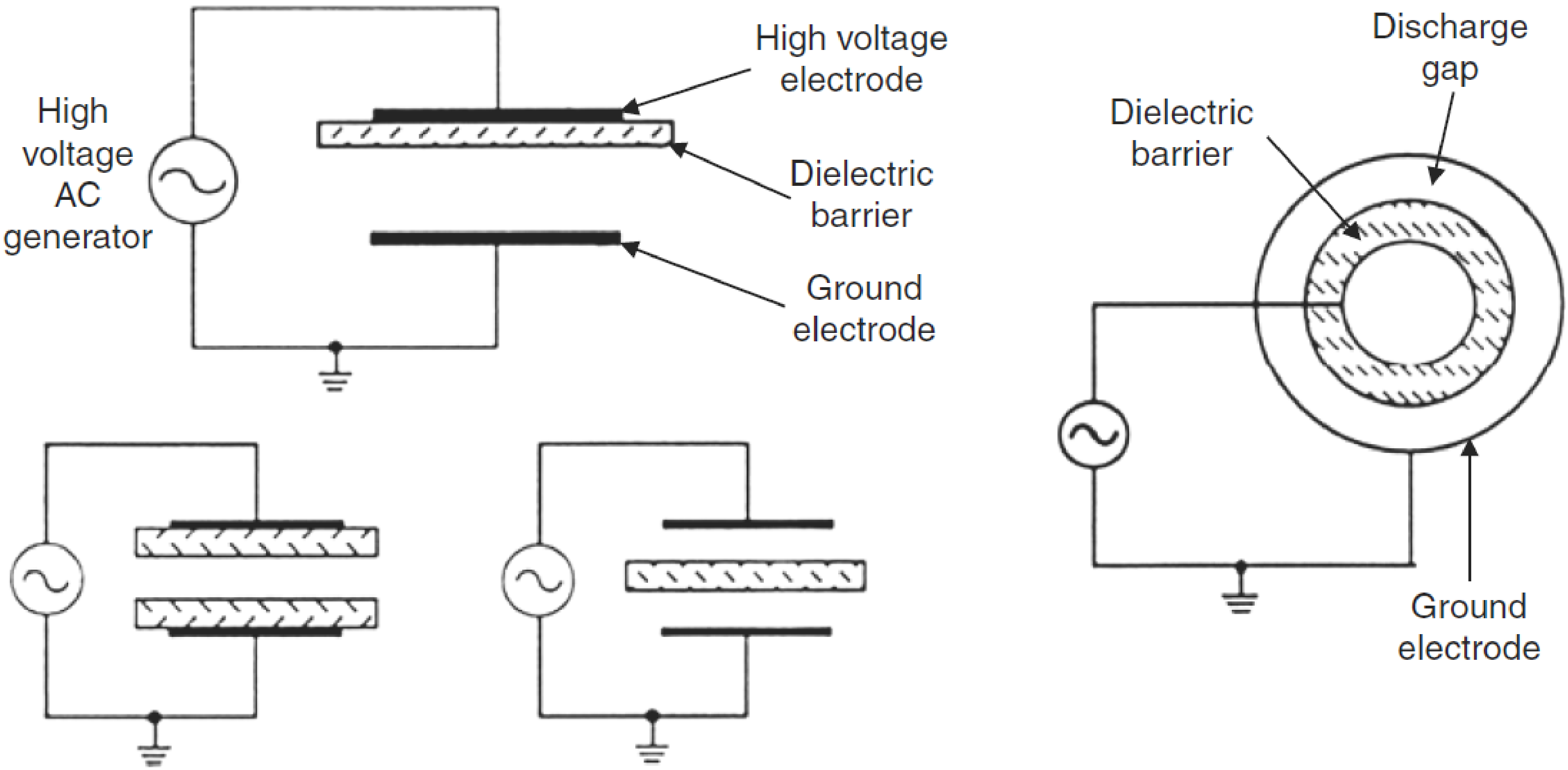
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

Microwave plasma torch

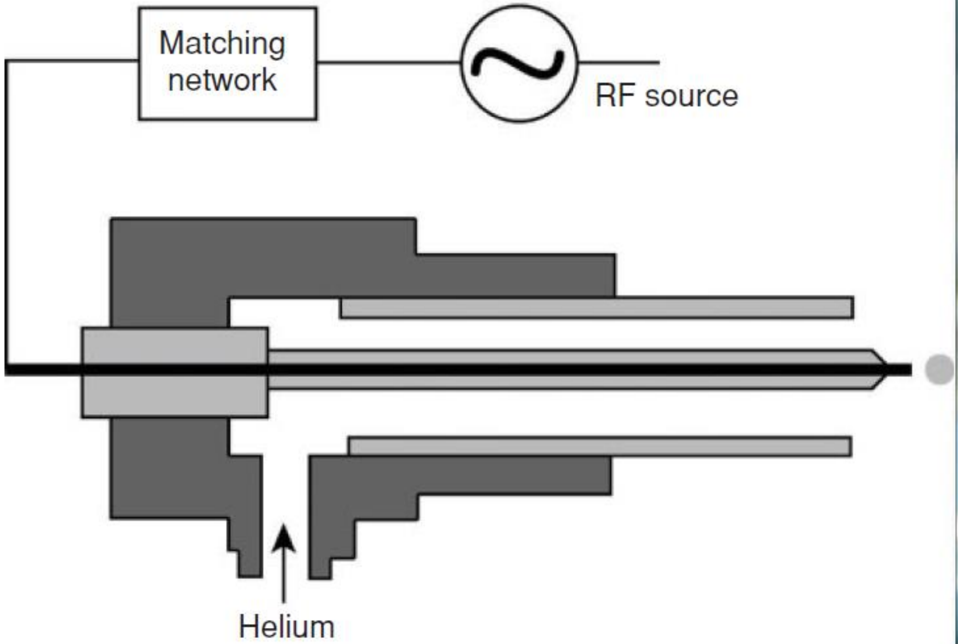


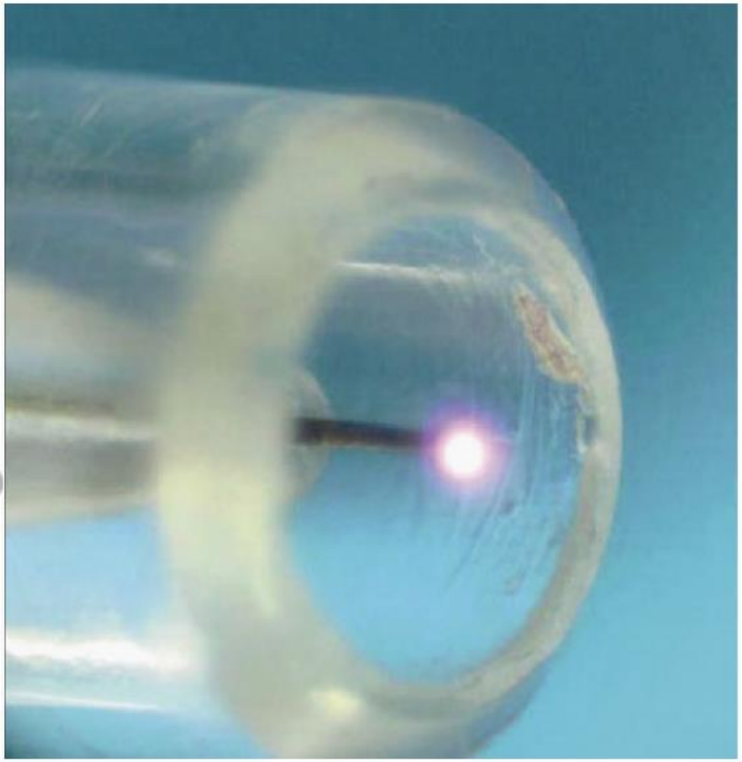


Dielectric-barrier discharges (DBDs)

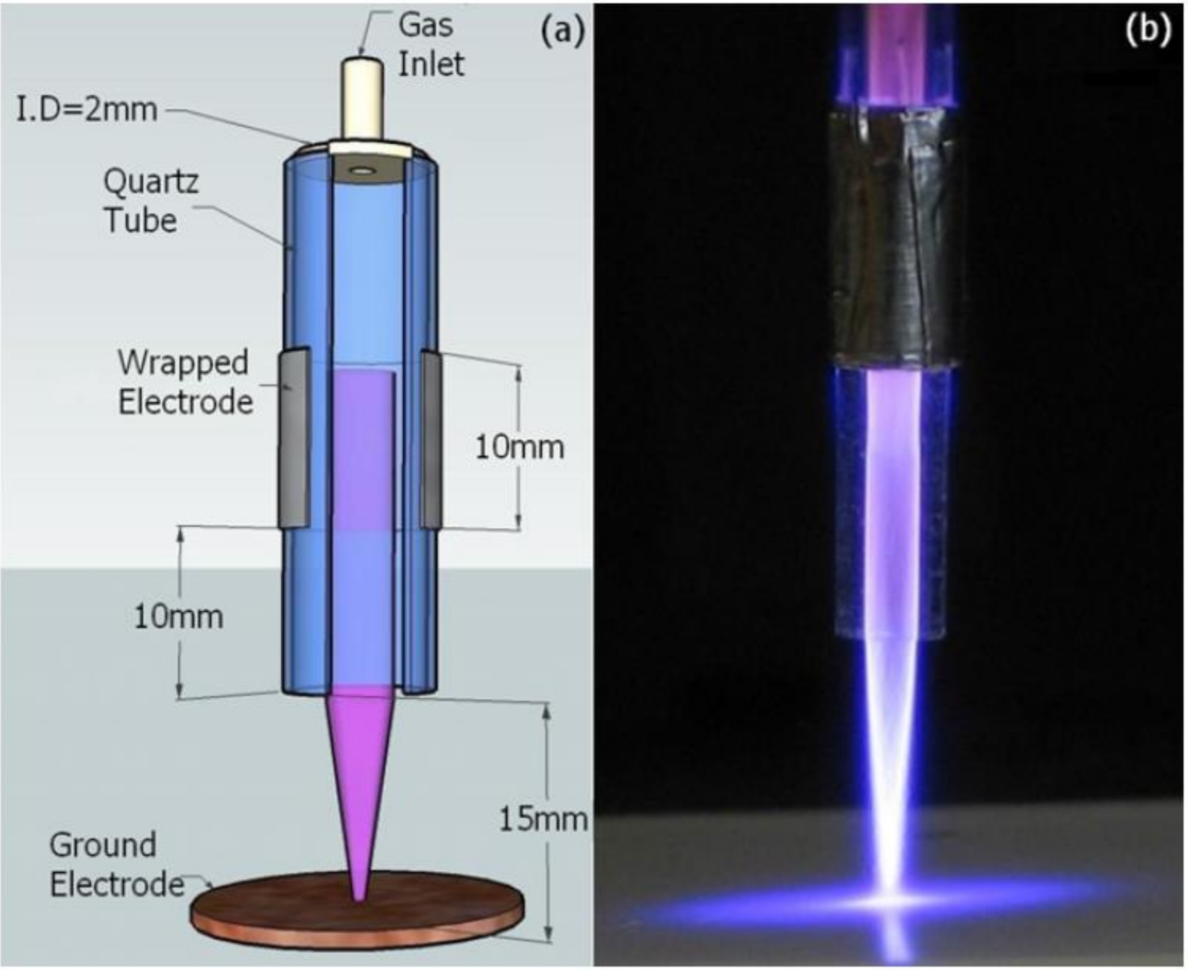


Plasma-needle discharge



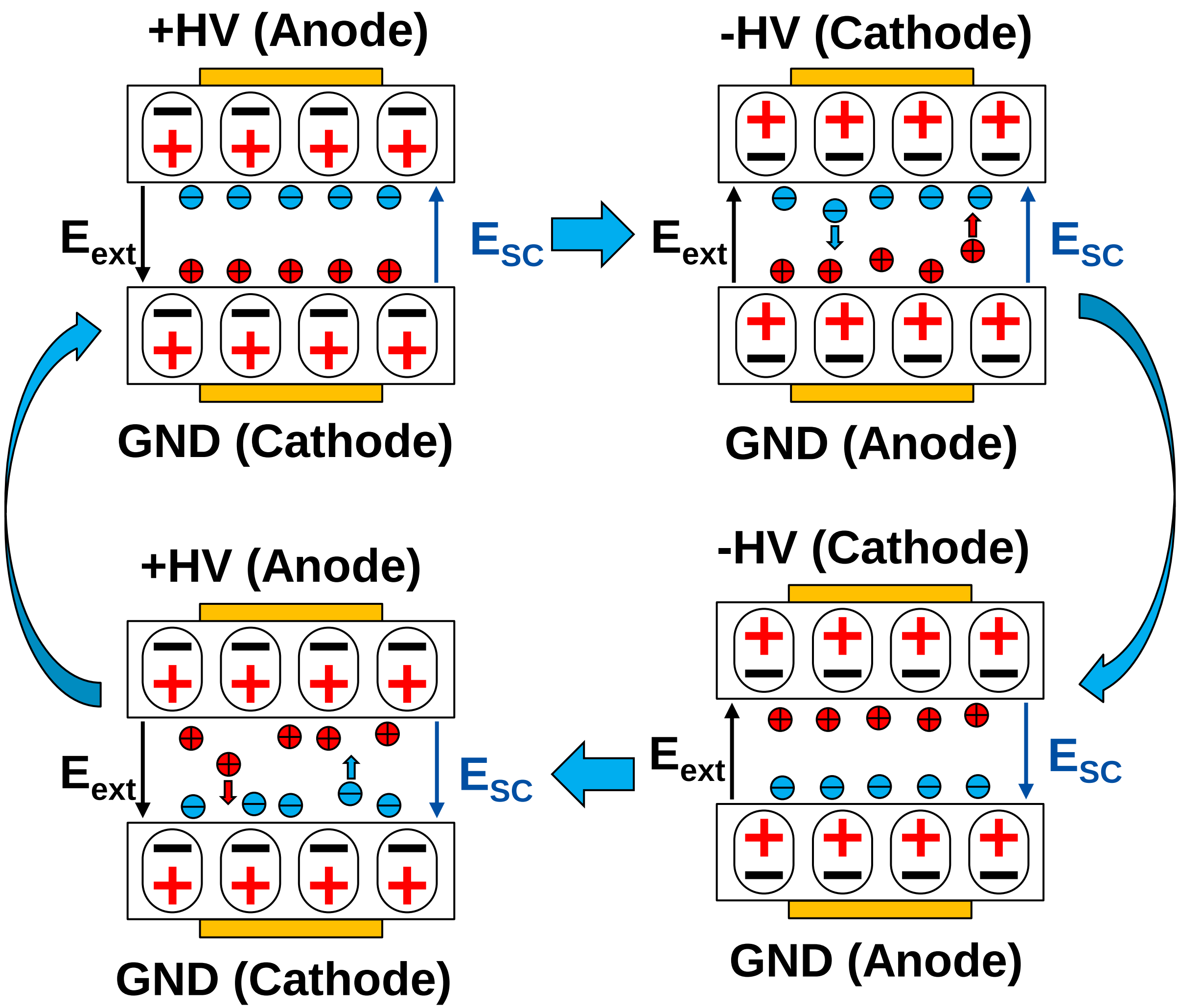


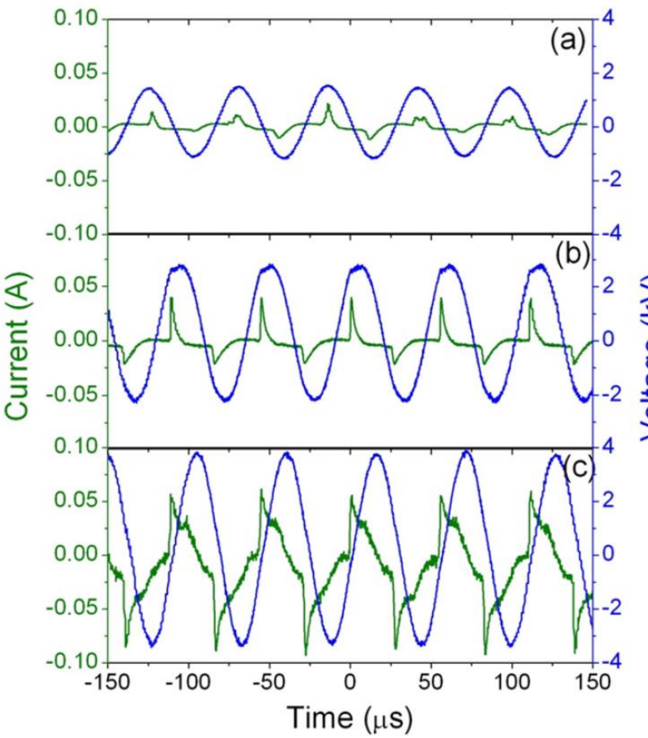
Atmospheric-pressure cold helium microplasma jets



J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

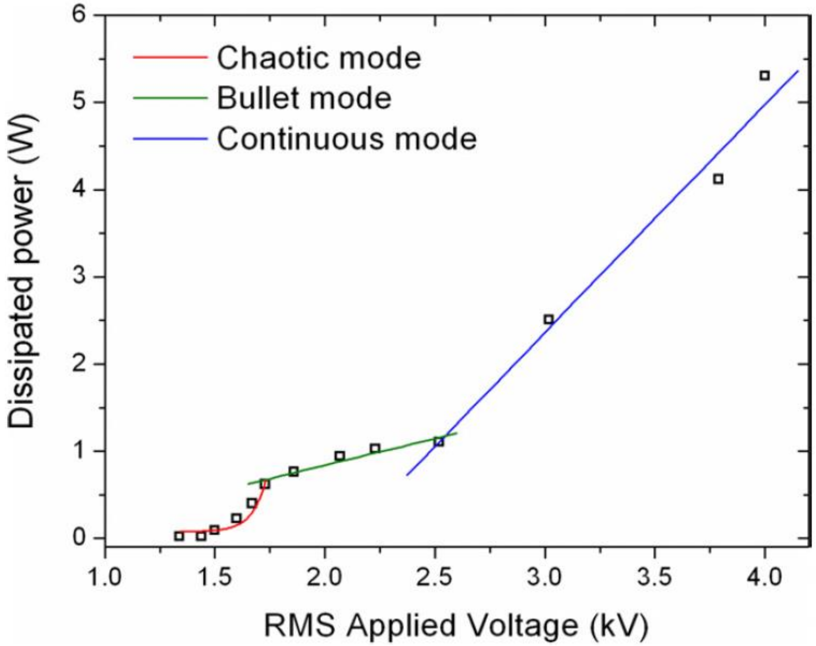
Space charge effect enhance the electric field

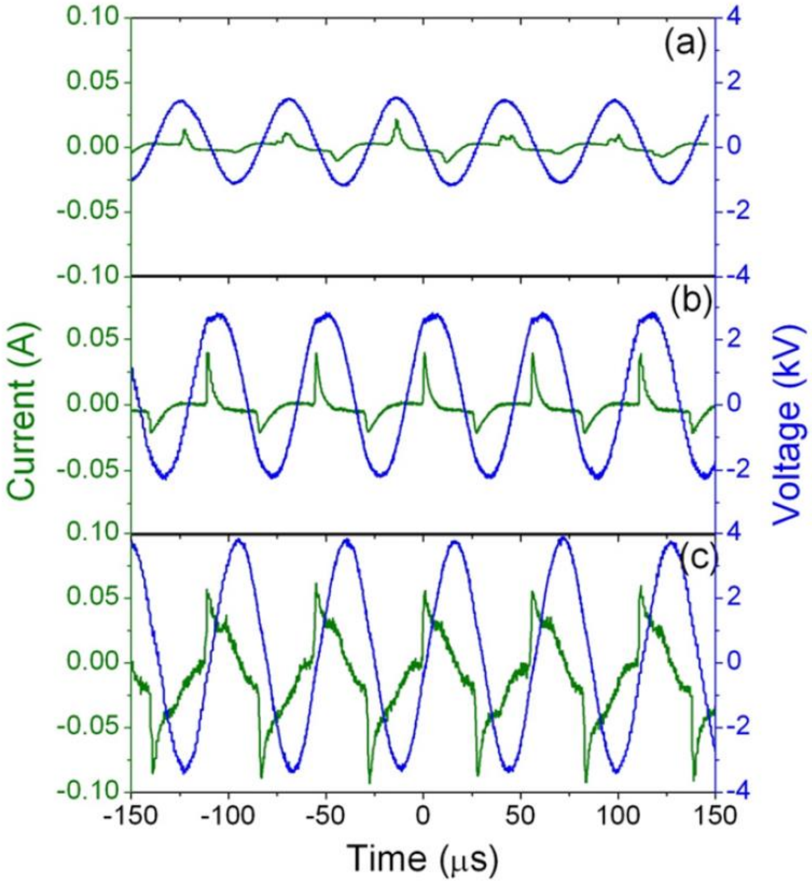




J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

There are three different modes: chaotic, bullet, and continuous mode



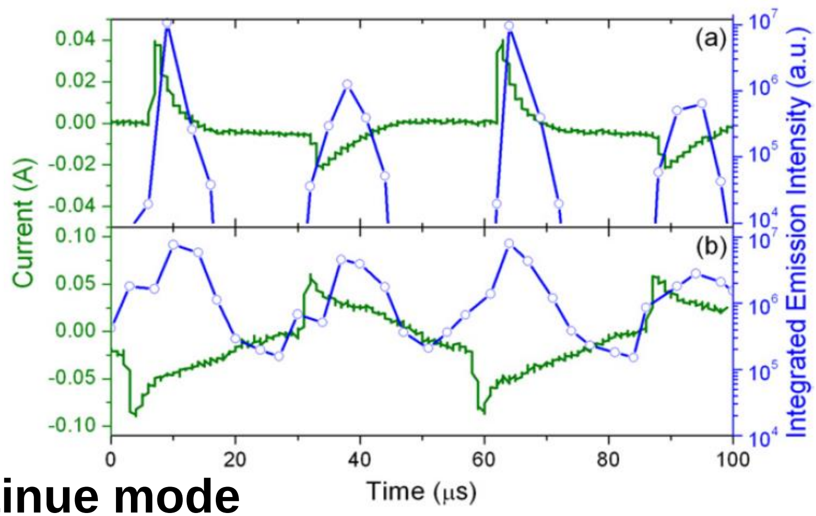


J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

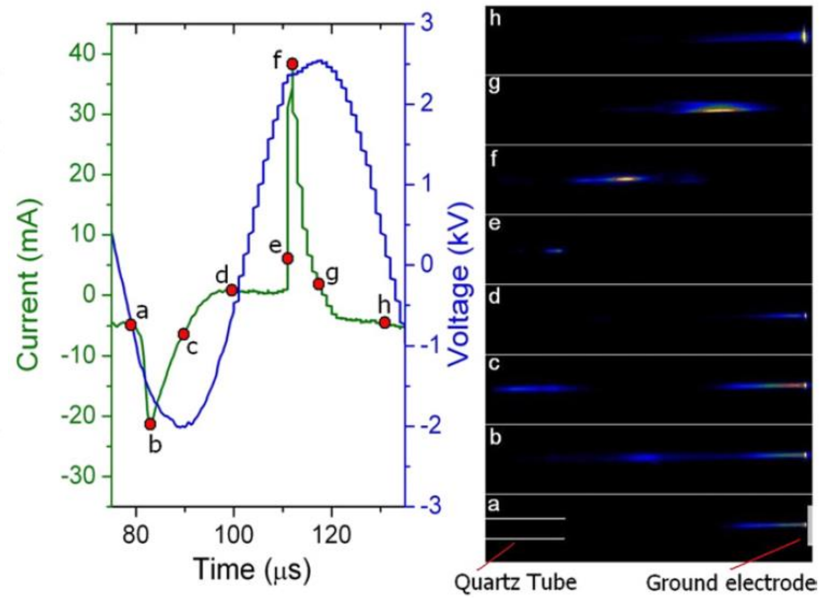
In bullet mode, the plasma jet comes out as a pulse

- **wavelength-integrated optical emission signal (350–800 nm)**
- **Images of bullet mode**

Bullet mode

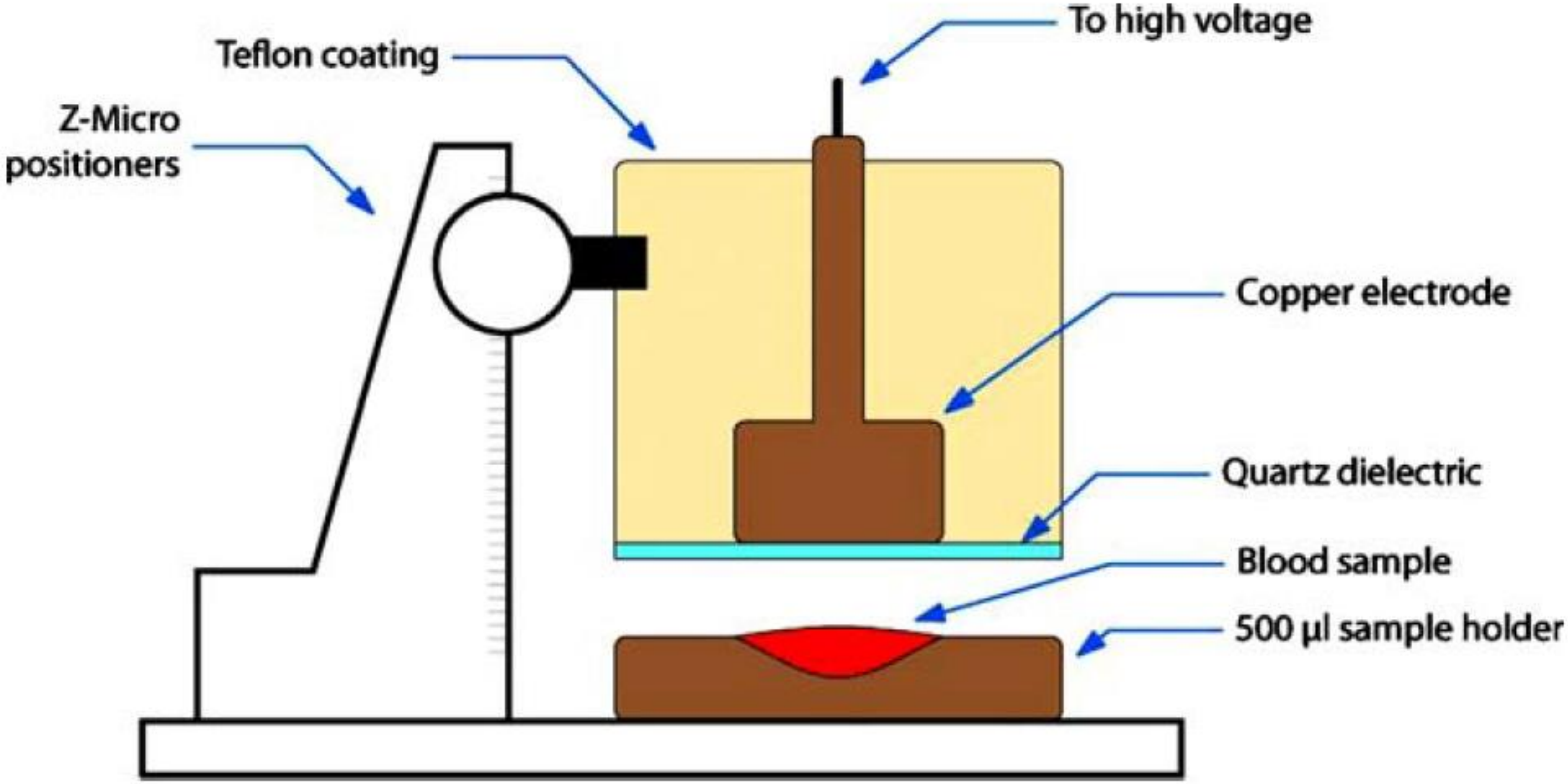


Continue mode



J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

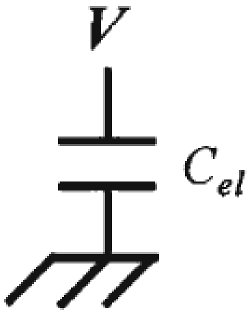
Floating-electrode dielectric barrier discharge (FE-DBD)

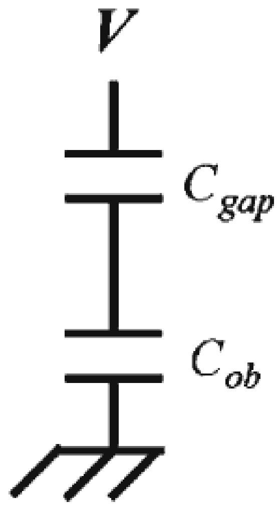


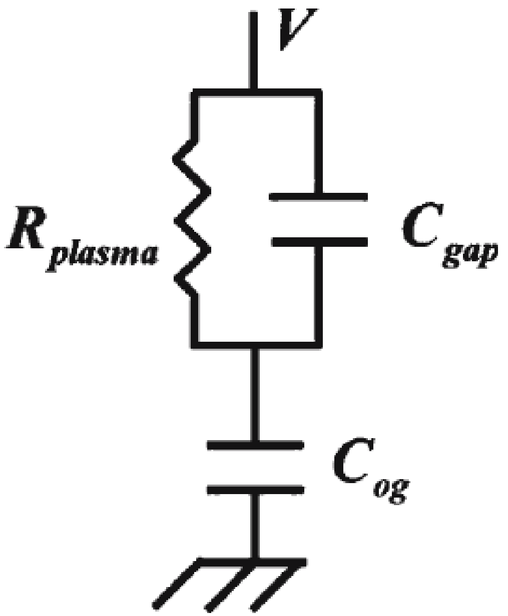
G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

Simplified electrical schematic of FE-DBD

- **electrode itself**
- **electrode near the treated object**
- **e-plasma discharge**





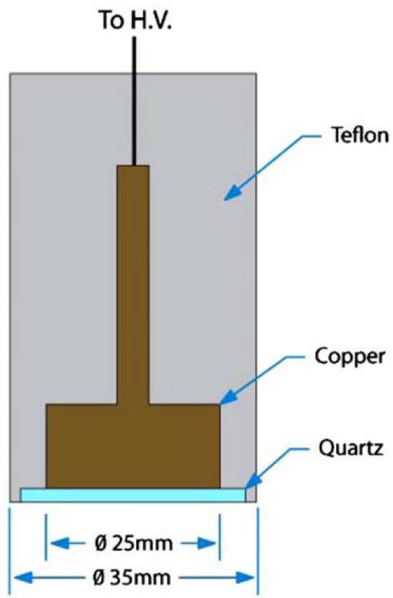


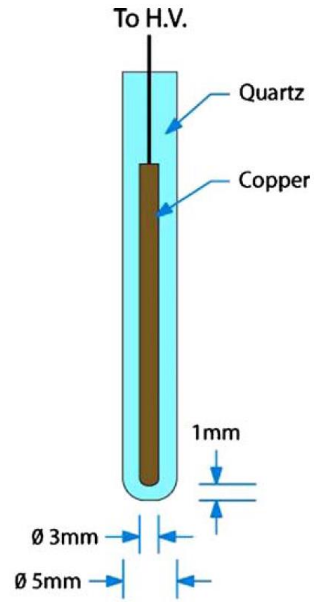
$$C_{\mathrm{ob}} >> C_{\mathrm{gap}} \Rightarrow V_{\mathrm{ob}} << V_{\mathrm{gap}}$$

G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

Depending on the needs, the size and the shape of FE-DBD treatment electrodes can vary

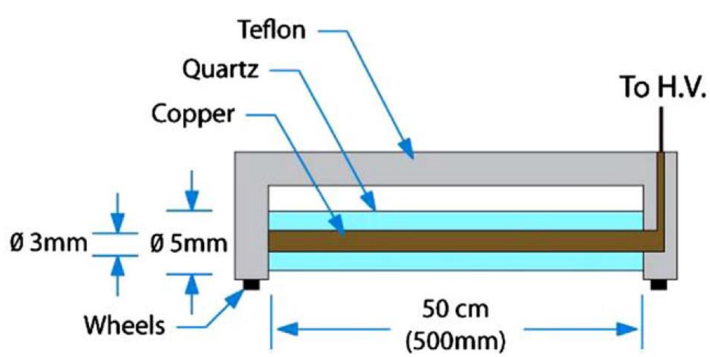
- **Round**





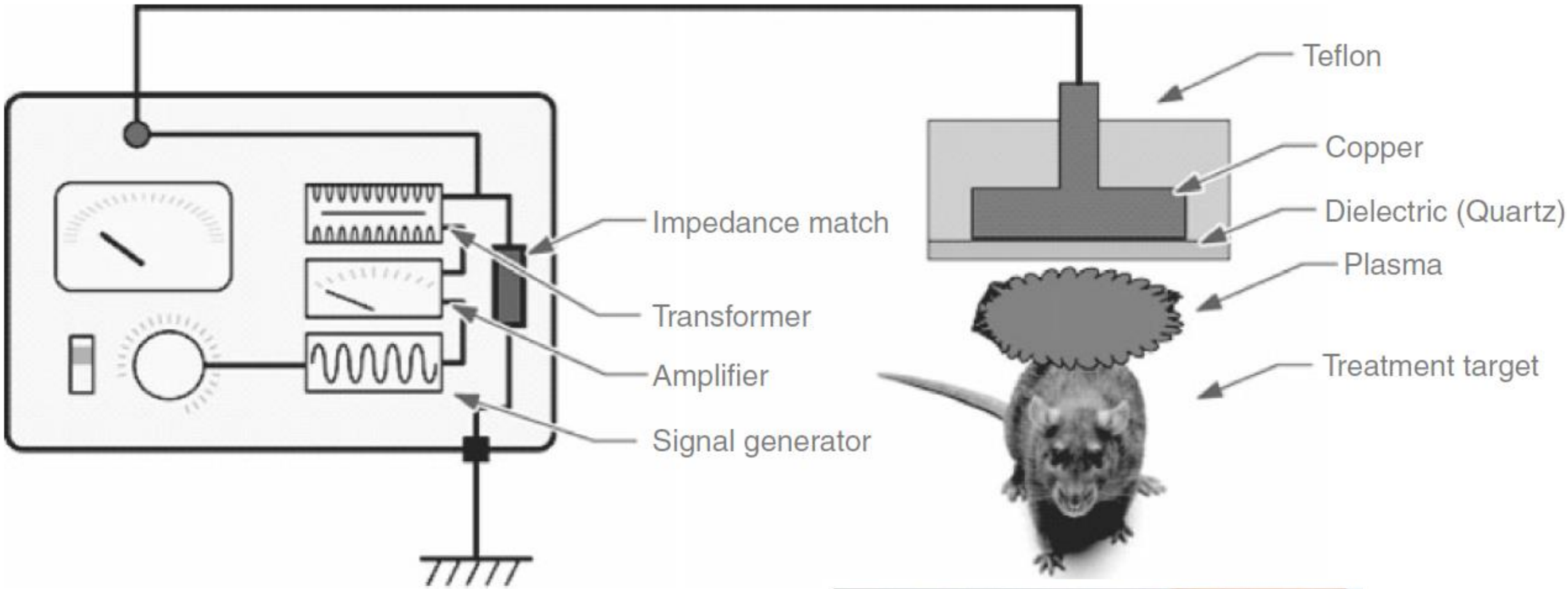
- **Wand**

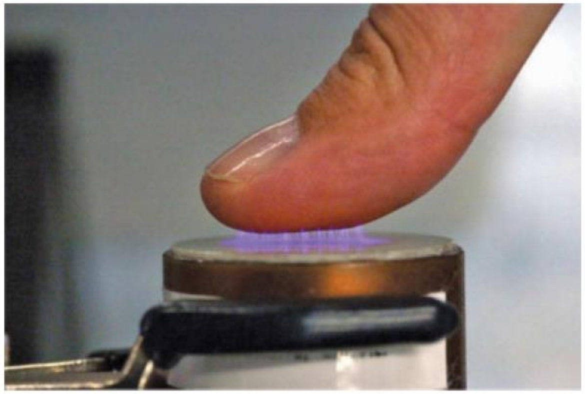
- **Roller**



G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

FE-DBD is a direct plasma medicine





G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)
Plasma medicine, by Alexander Fridman and Gary Friedman

Outline

- Example of several plasma discharges for plasma medicine
- Living tissue sterilization
- Blood coagulation
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- Non-thermal plasma treatment of melanoma skin cancer
- Skin regeneration
- Egg sterilization
- Facemask regeneration

Bacteria concentration reduces after being treated with FE-DBD

Table 1. Bacteria sterilization results (in cfu · mL^{-1}).[26]

Original concentration	5 s of FE-DBD	10 s of FE-DBD	15 s of FE-DBD
10^9	850 ± 183	9 ± 3	4 ± 4
10^8	22 ± 5	5 ± 5	0 ± 0
10^7	6 ± 6	0 ± 0	0 ± 0

- **Maximum acceptable dose – the highest dose that doesn't cause a damage on skin**

G. Fridman, *et al.*, Plasma Process. Polym., **5**, 503 (2008)

The power of FE-DBD is low enough such that the tissue is not damaged by the plasma

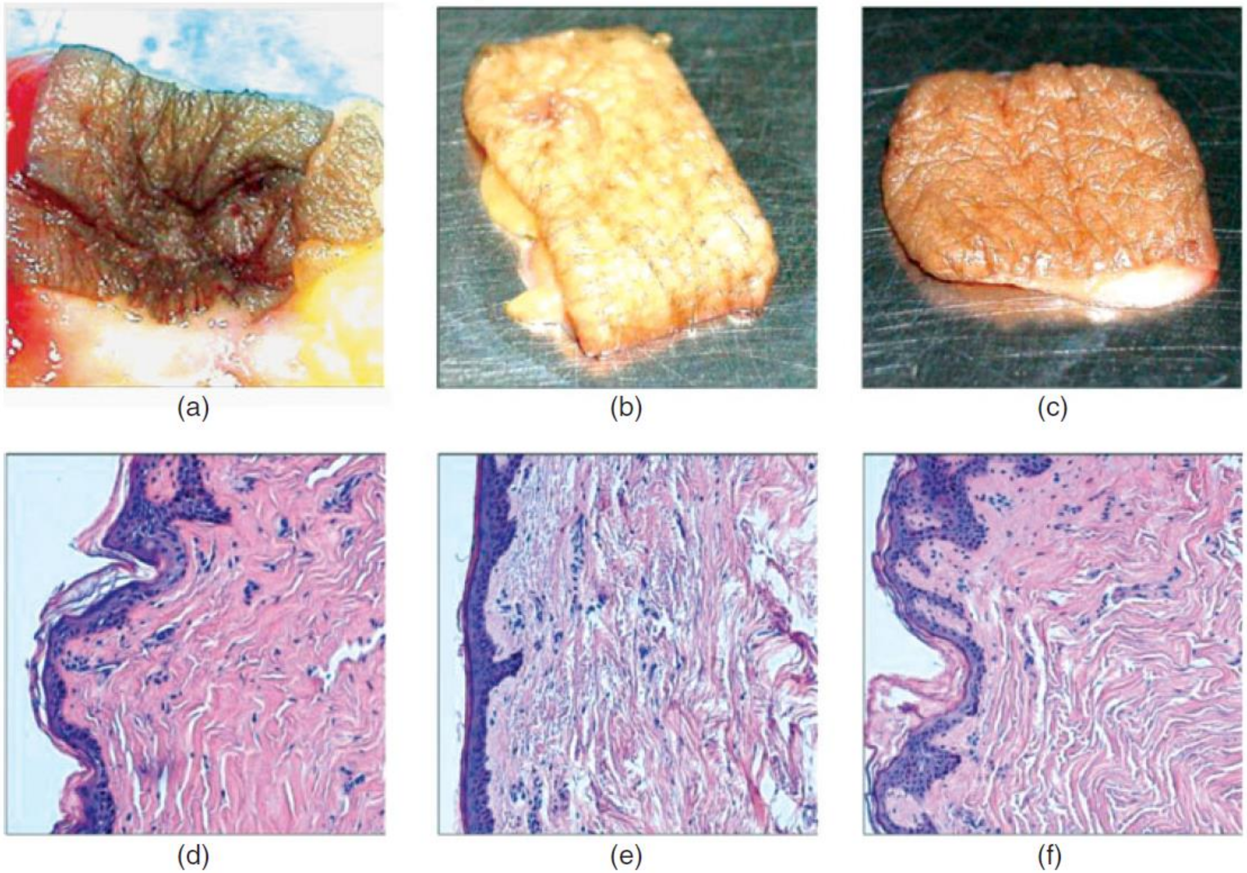
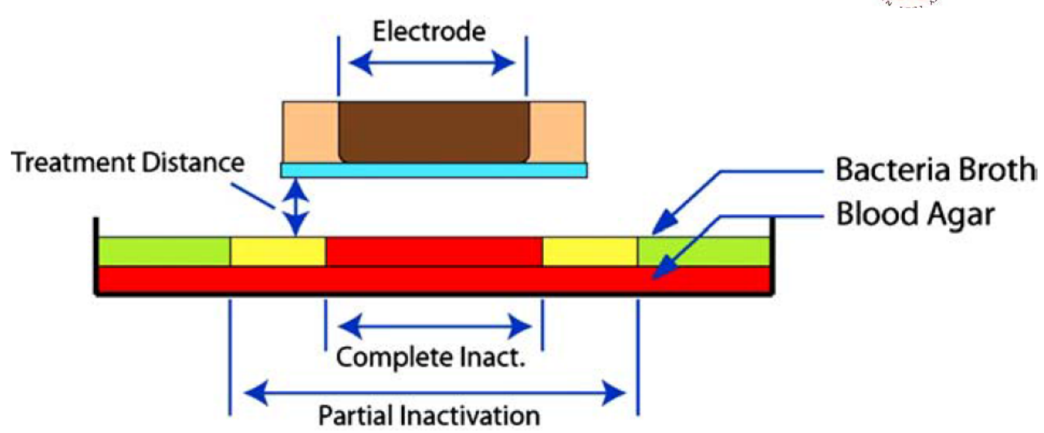


Figure 6.23 *Photos (top) and tissue histology (bottom) of cadaver skin samples after FE-DBD treatment: (a, d) control; (b, e) after 15 s of treatment; and (c, f) after 5 min of treatment – no visible damage is detected.*

G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)
Plasma medicine, by Alexander Fridman and Gary Friedman

Bacteria is inactivated by the plasma



- ~1.3×10^7 cfu/cm^2 (10^9 cfu/ml) of skin flora (CFU: colony-forming unit)
- Treated by FE-DBD plasma for 10 s

G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

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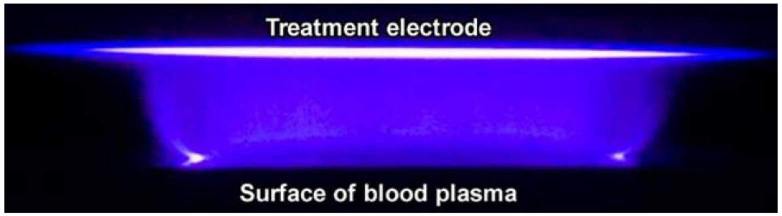
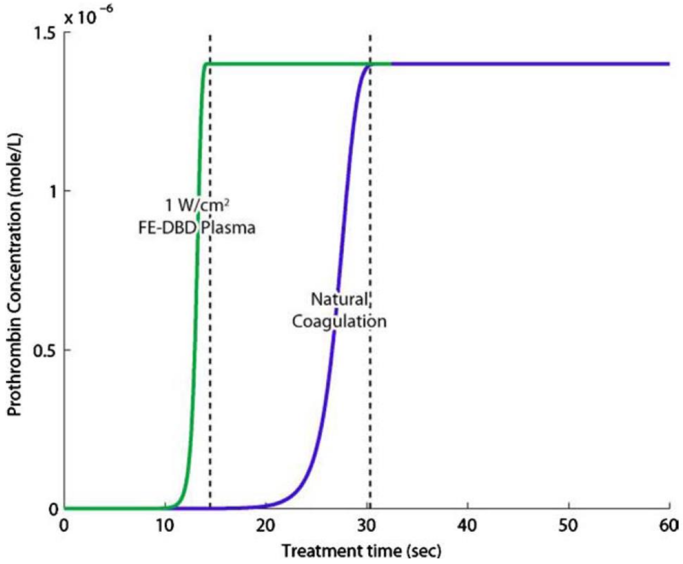
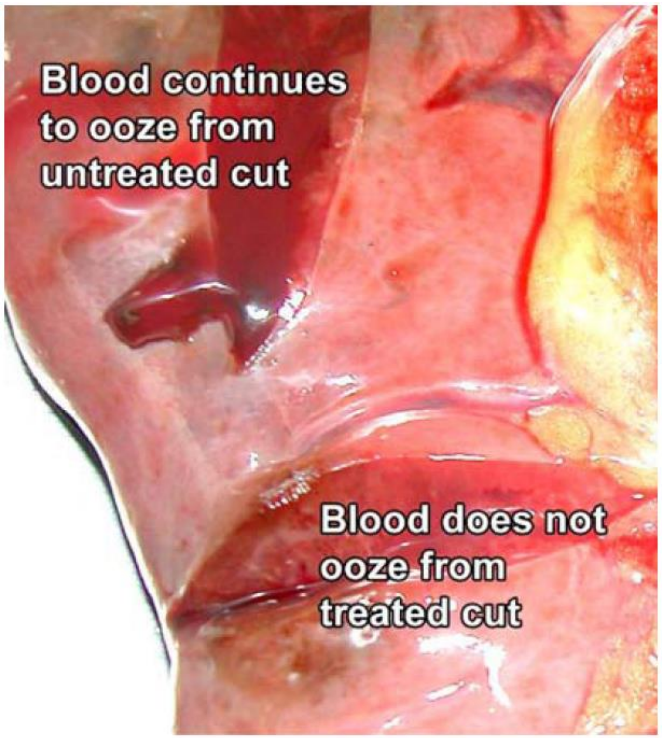
Plasma can stimulate blood coagulation

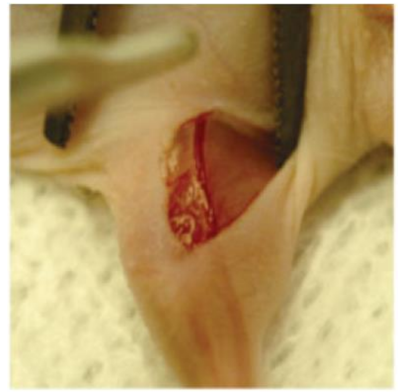




G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

Example of blood coagulation using plasma





Saphenous vein
is a major blood vessel for a mouse

(a)

If left untreated following a cut
animal will bleed out (control)

(b)

15 seconds at 0.8 Watt/cm^2 stops the
bleeding completely right after treatment

(c)

G. Fridman, *et al.*, Plasma Process. Polym., **5**, 503 (2008)
G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)
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Nitrogen oxide (NO) serves a multitude of essential biological functions

- **Blood coagulation**
- **Immune system**
- **Early apoptosis (細胞凋亡)**
- **Neural communication and memory**
- **Relaxation of flat bronchial (支氣管) and gastrointestinal muscles (胃腸肌肉)**
- **Hormonal (激素) and sex functions**
- **Anti-microbial (抗微生物) and anti-tumor (抗腫瘤) defense**
- **Play an important role in tumor growth, immunodeficiency (免疫缺陷), cardiovascular (心血管), liver (肝), gastrointestinal tract (胃腸道) disease**

NO treatment of wound pathologies

Before treatment

21st day of NO-therapy (10 seances)

After 2 months of NO-therapy

- **Decrease in the trophic ulcer (營養性潰瘍) area:**

  - Traditional treatment methods: 0.7% per day

  - NO treatment methods: 1.7% per day

G. Fridman, *et al.*, Plasma Process. Polym., **5**, 503 (2008)
Plasma medicine, by Alexander Fridman and Gary Friedman

NO treatment of wound pathologies

Before treatment

After 4.5 months of NO-therapy
(3 courses; 12 seances per course)

G. Fridman, *et al.*, Plasma Process. Polym., **5**, 503 (2008)
Plasma medicine, by Alexander Fridman and Gary Friedman

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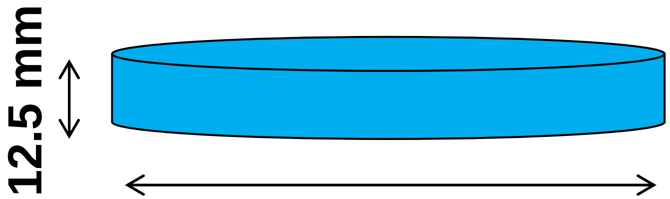
Non-thermal plasma treatment of melanoma skin cancer (黑色素瘤皮膚癌)

- Melanoma cancer cell line (ATCC A2-58) was used
- ~1.5x10^{6} per dish



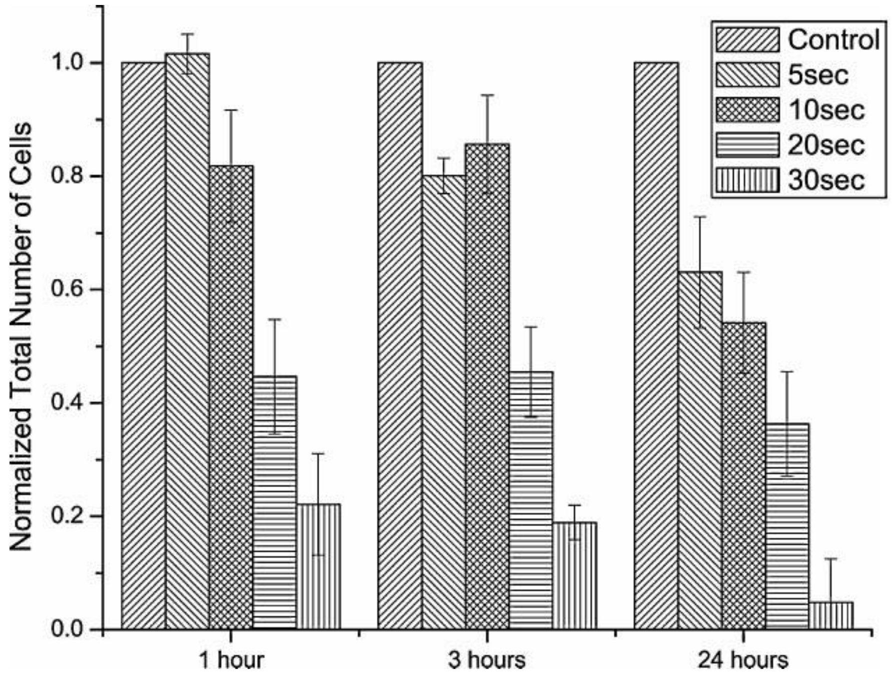
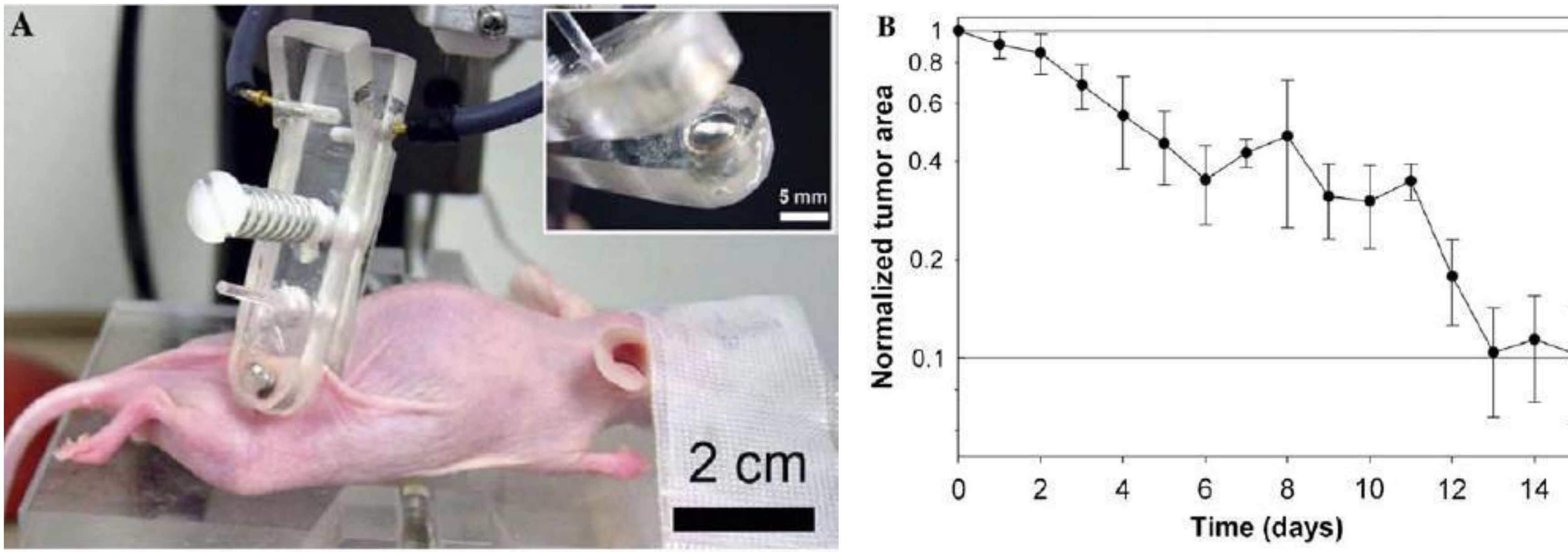


Figure 22. Results of FE-DBD treatment of melanoma cancer cells: Control, 5, 10, 20, and 30 s, counted 1, 3, and 24 h post-treatment.[27]

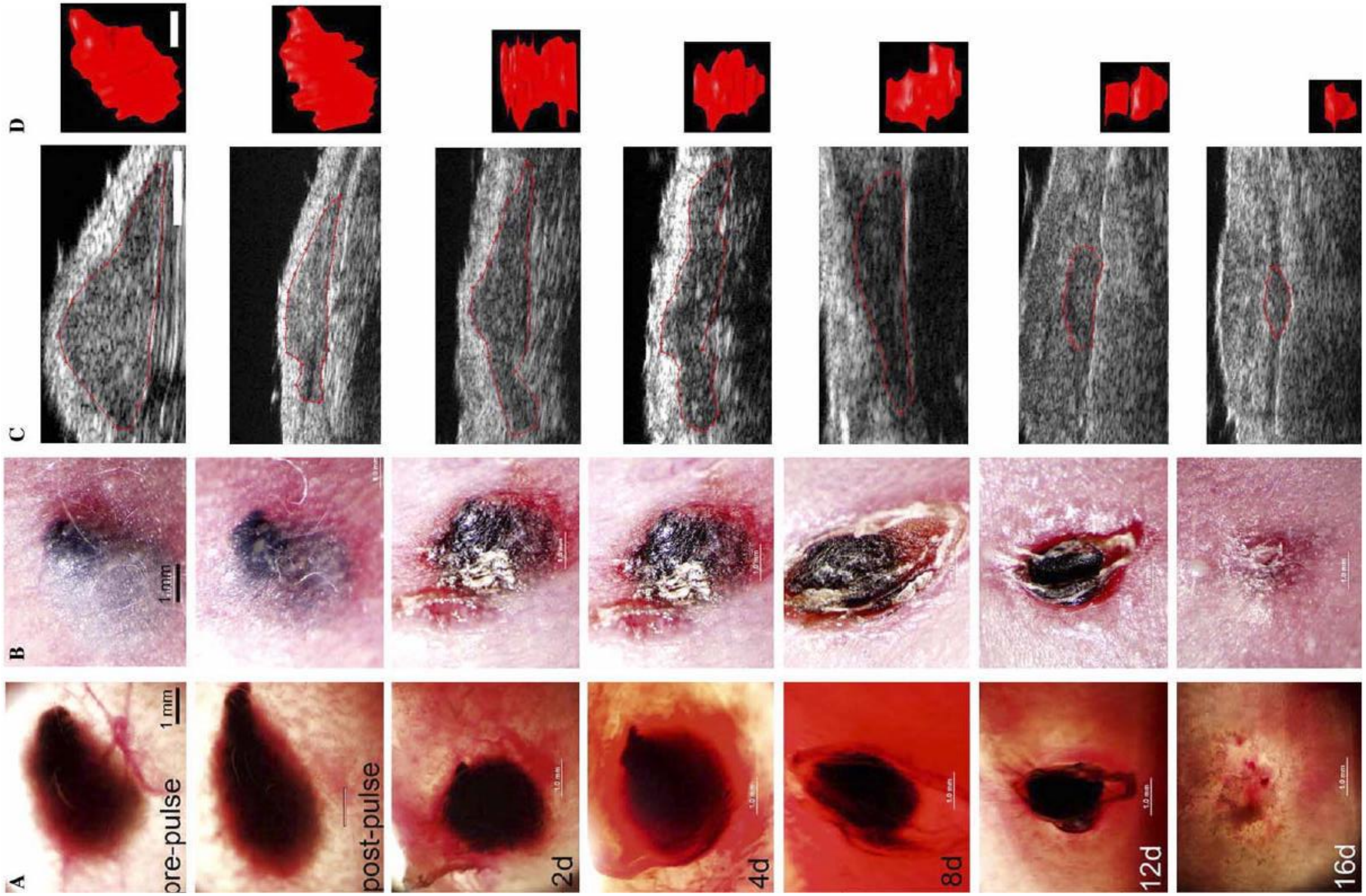
G. Fridman, *et al.*, Plasma Process. Polym., **5**, 503 (2008)

SKH-1 hairless mouse is treated with parallel plate electrode under isoflurane inhalation anesthesia



Biochem Biophys Res Commun. 2006 May 5; 343(2): 351–360.

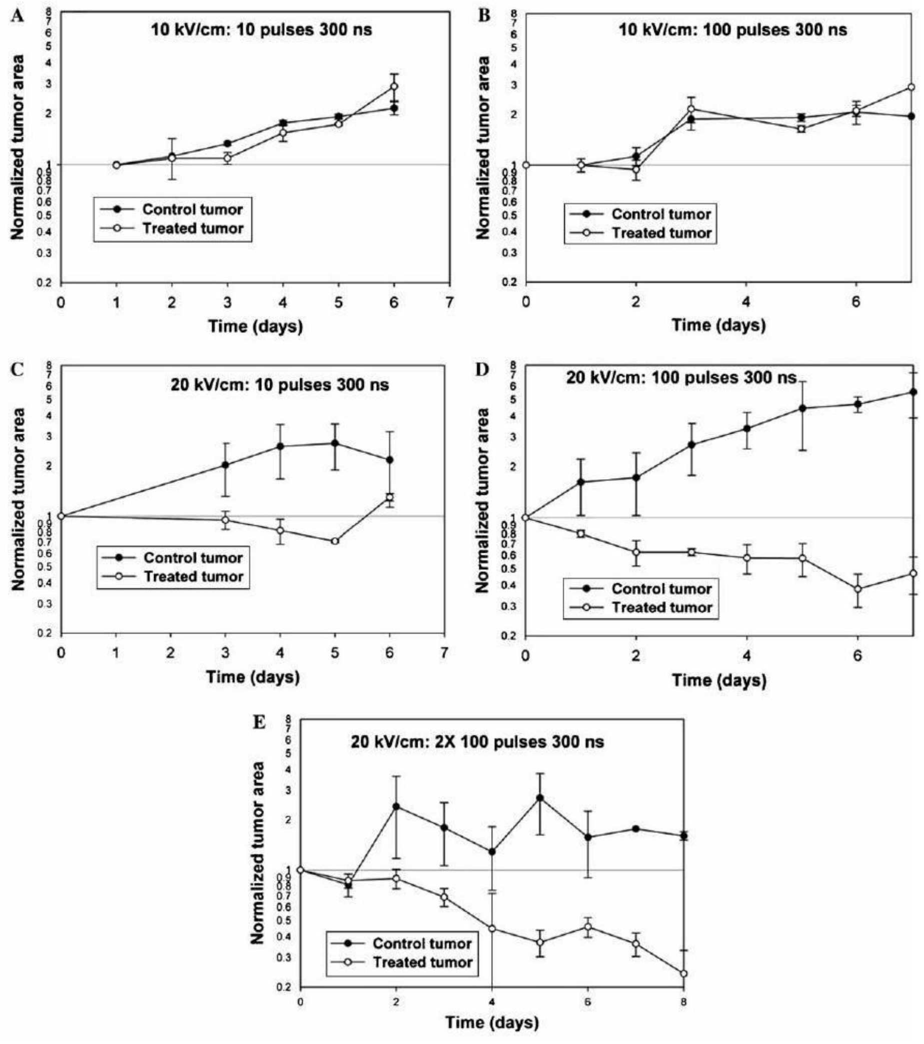
Melanoma shrinks after the treatment



- **Day 0-3: 3 applications of 100 pulses (300 ns, 40 kv/cm, 0.5 Hz), 30 min apart**
- **Day 4: single application using 5 mm diameter parallel plate electrode**

Biochem Biophys Res Commun. 2006 May 5; 343(2): 351–360.

Electric field of 20 kV/cm is needed to treat Melanoma



Biochem Biophys Res Commun. 2006 May 5; 343(2): 351–360.

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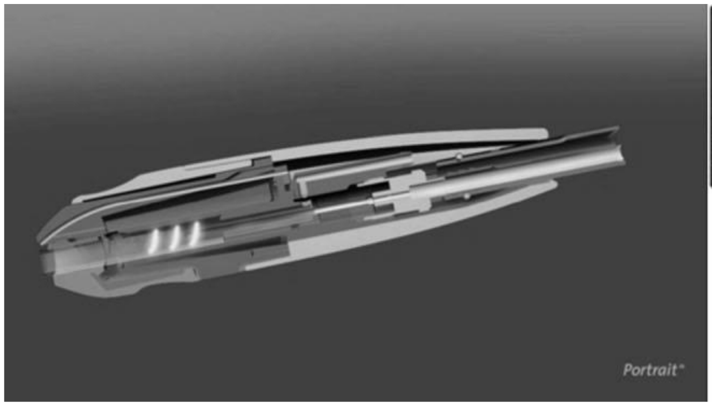
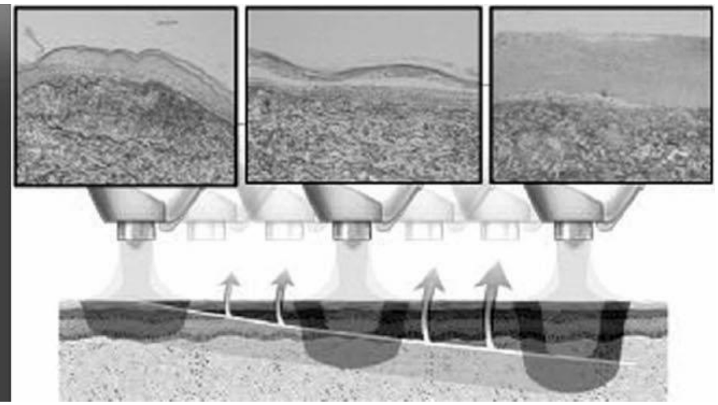
Plasma skin regeneration (PSR) is a novel skin treatment device





- **PSR provides 1-2 J or 3-4 J per pulse for lower or higher power, respectively**
- **The skin is damaged slightly by the nitrogen plasma jet**
- **Skin regeneration is stimulated**
- **Local anesthetic (麻藥) is required and a systemic anesthetic, administered orally is recommended**
- **Ablative-like effect, similar to that of laser skin resurfacing can also be achieved, but with higher doses**

Zones of the face and associated treatment energy settings

M. A. Bogle, *et al.*, Arch. Dermatol.,**143**, 168 (2007)

This particular patient-rated improvement in overall skin rejuvenation was 85%

- **Patients reported minimal discomfort following the procedure and reported over 60% improvement in their skin condition**

M. A. Bogle, *et al.*, Arch. Dermatol.,**143**, 168 (2007)

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Atmospheric-Pressure Plasma sterilization 99.9999% bacteria on surfaces of eggs

https://www.itri.org.tw/chi/Content/Publications/contents.aspx?SiteID=1&MmmID=2000&MSid=745416417706673311

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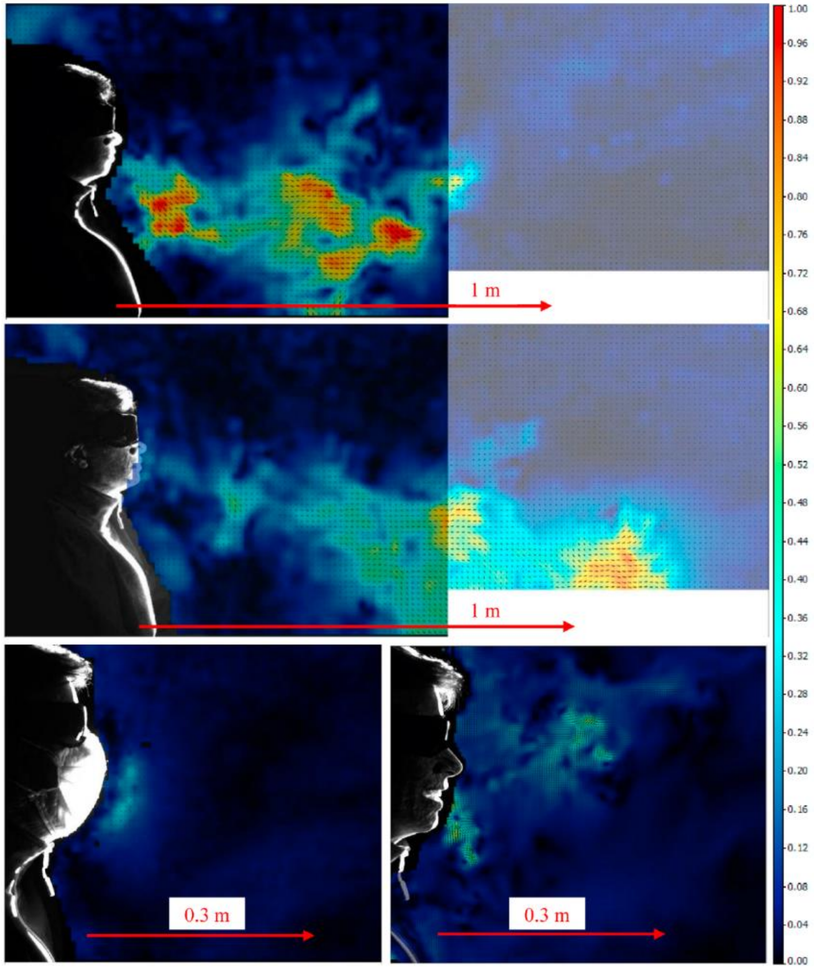
A face mask do restrict the air flow from the mouth and the nose



Coughing over one breath w/o mask.

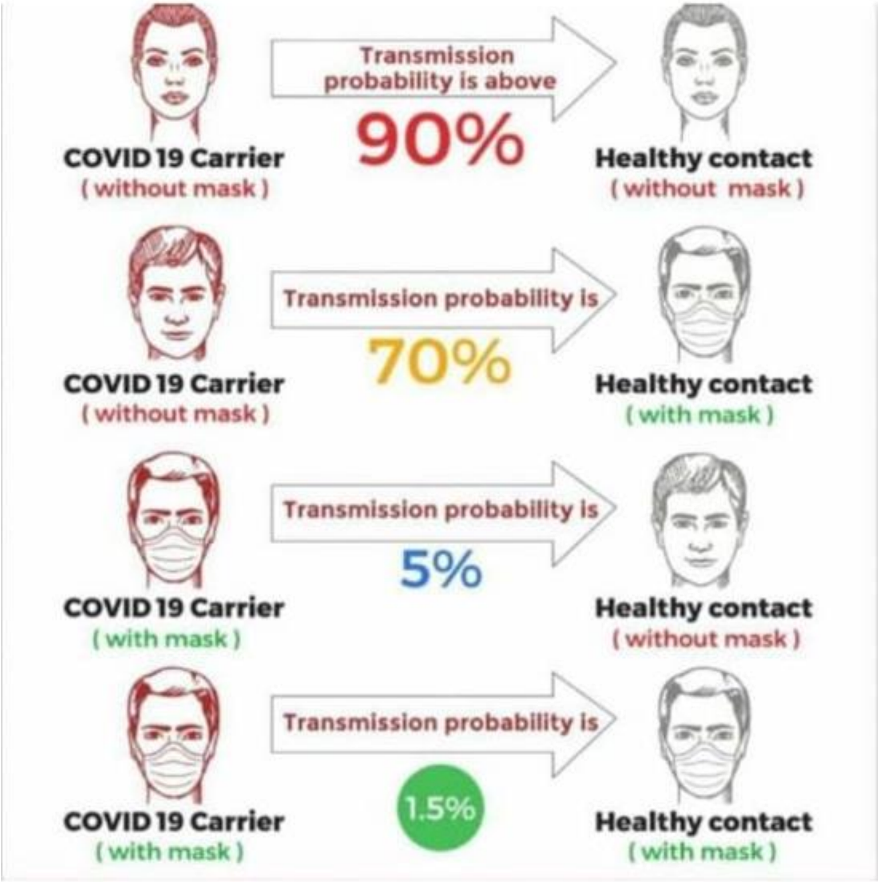
Coughing over a longer periods of time w/o mask.

Coughing over one breath w/ mask.

Talking w/o mask.

C. J. Kähler , *et al.*, J. Aerosol Science, **148**, 105617 (2020)

Wearing face mask can reduce the Covid-19 transmission probability significantly



http://www.riderta.com/coronavirus

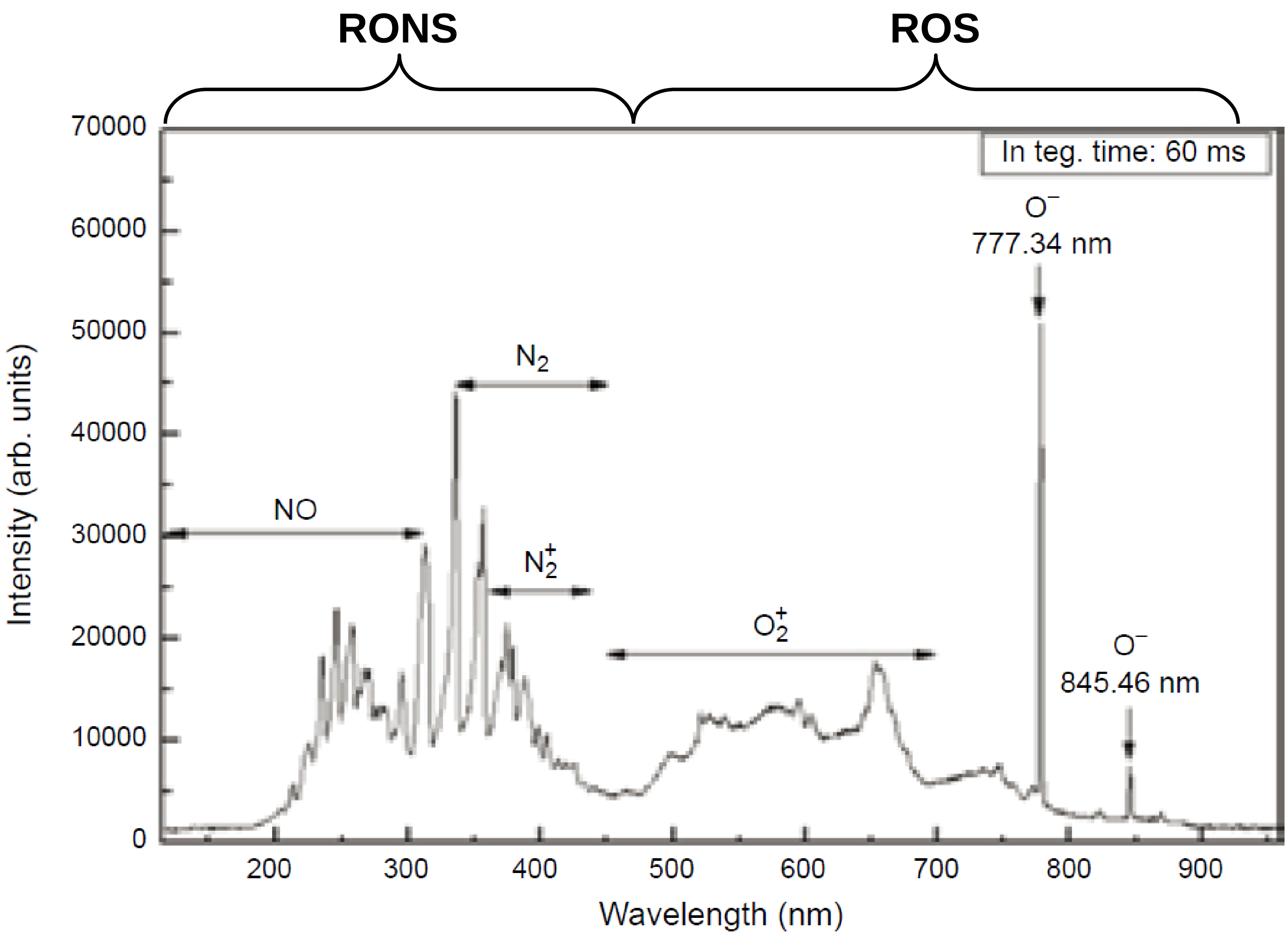
Plasma can provide good surface treatment with low temperature

Treatment	Surface treatment level	Depth	Temperature	Cost
Chemical	Large	Deep	Room temperature ~200 ℃	Medium
Heat	Only oxidizing	Deep	High temperature	Cheap
Radiation	Small	Whole sample	High temperature	Expensive
Plasma	Large	Surface	Room temperature ~100 ℃	Cheap ~ Medium

- **Atmospheric plasma can generate radicals, ozone, reactive oxygen/nitrogen/NH (ROS，RONS), UV light, electrons, charged particles.**

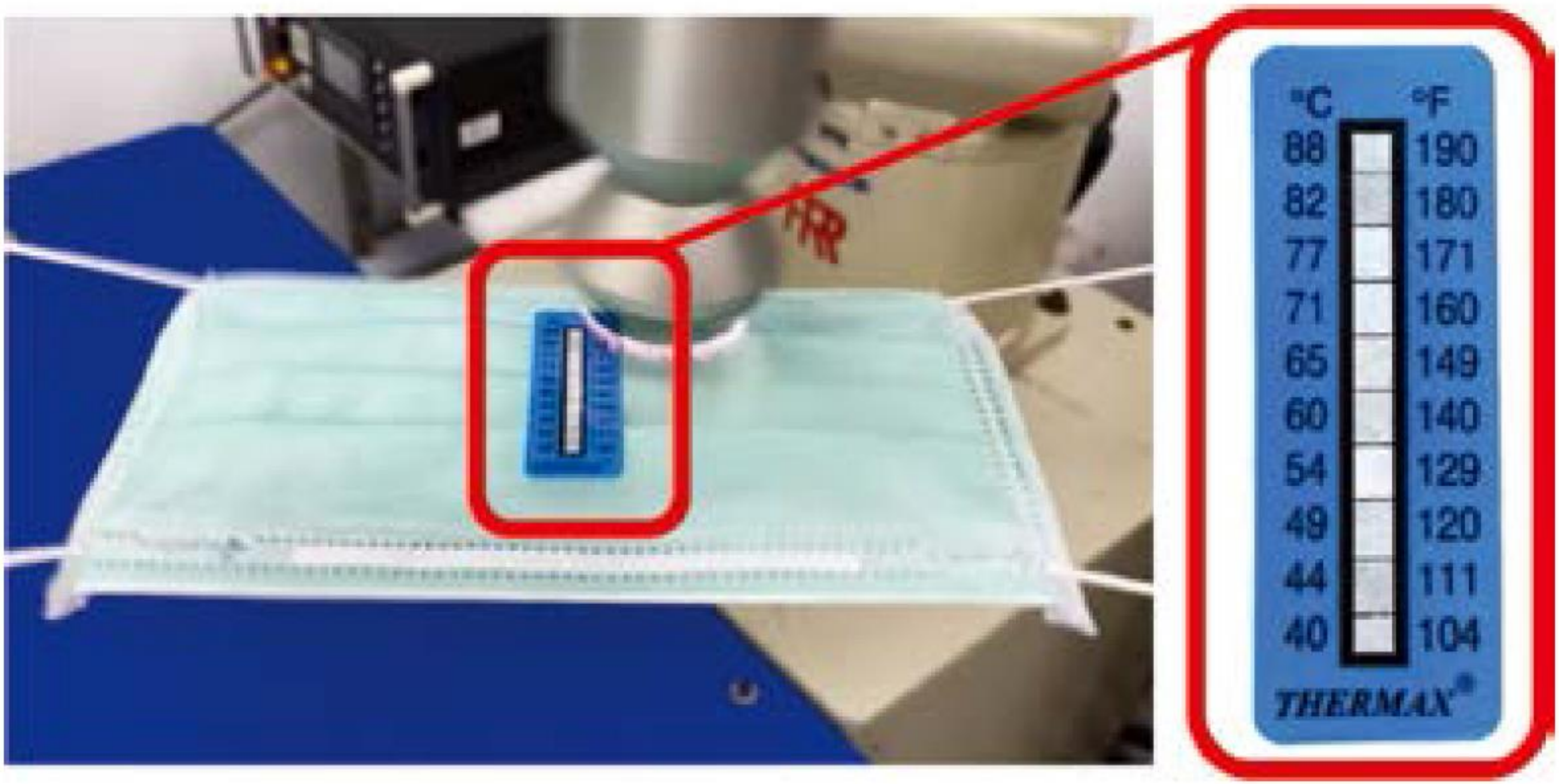
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

Plasma can generate ROS and RONS



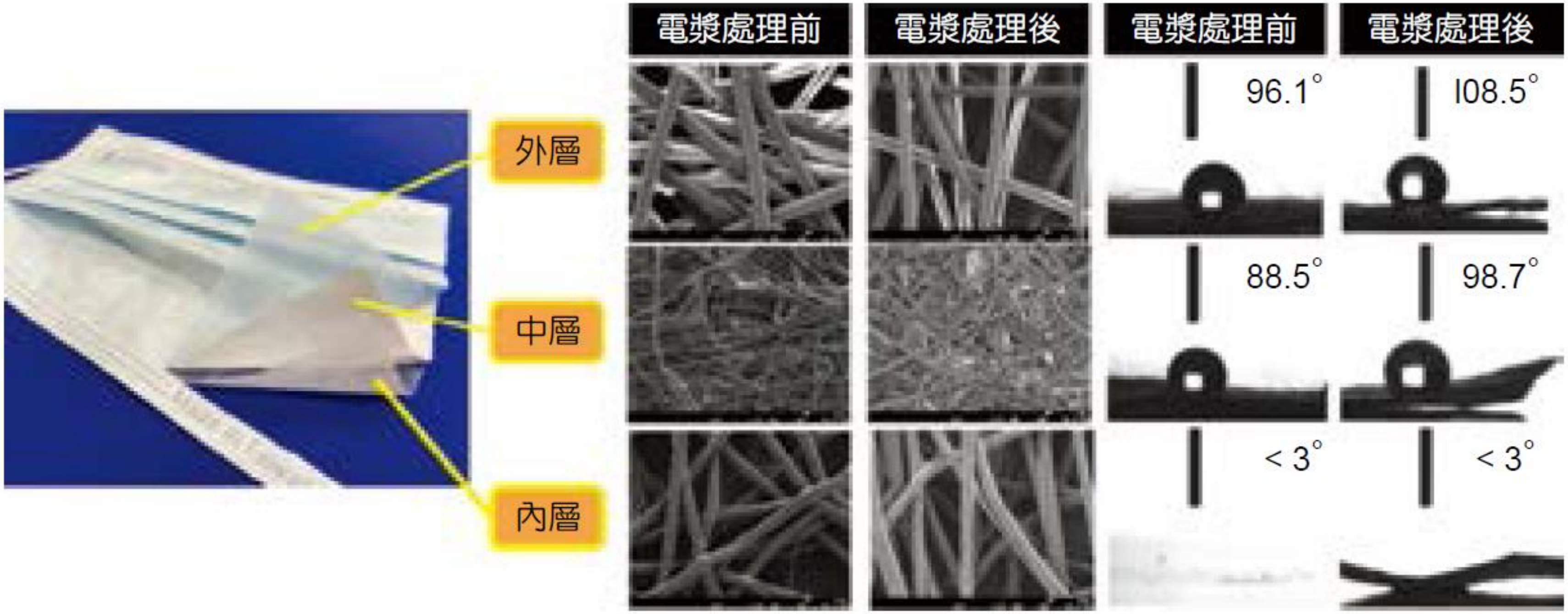
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

The temperature of the mask under plasma treamtment is below 40 ℃



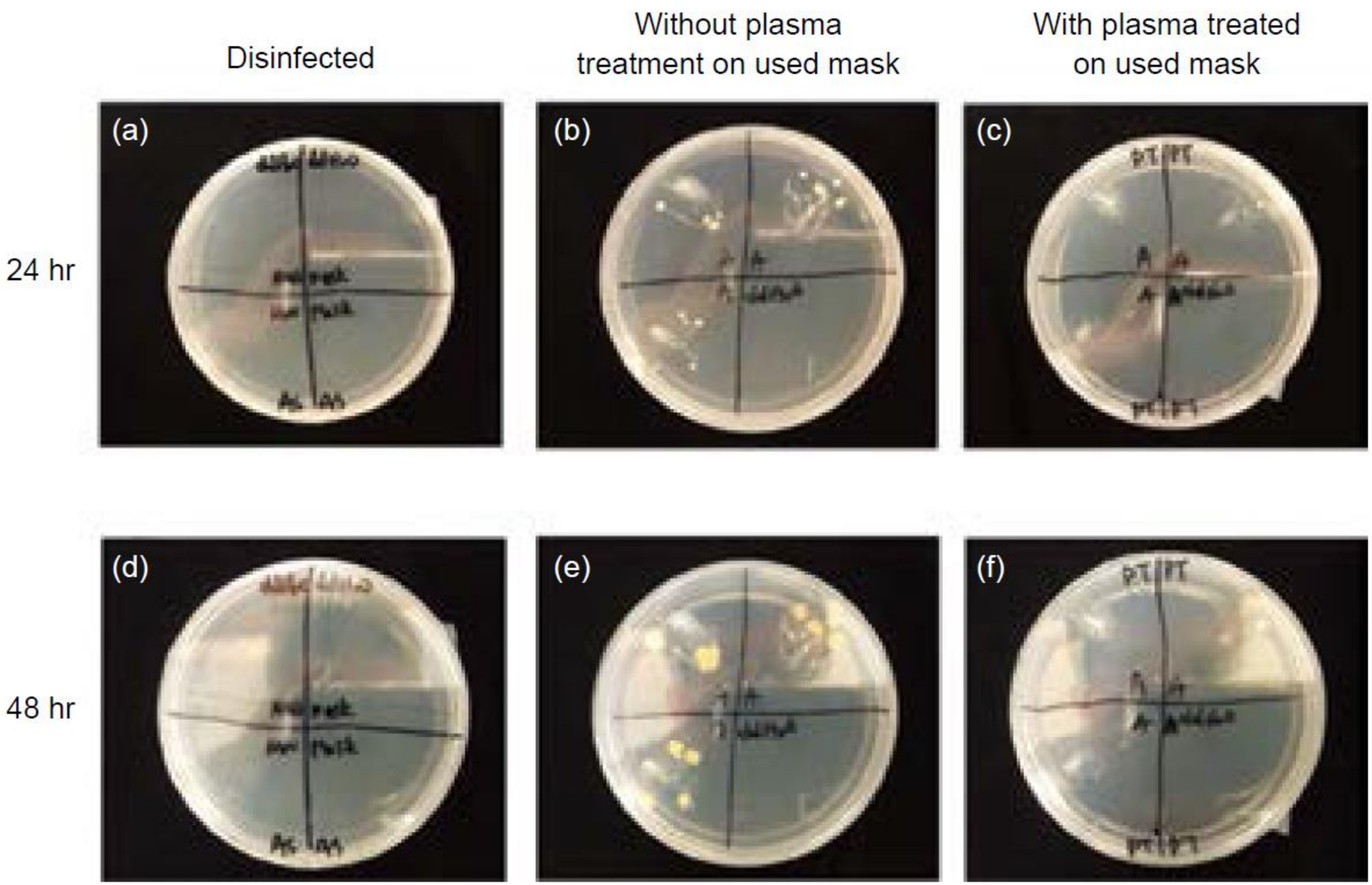
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

The surface quality of the face mask was not influenced by the plasma treament



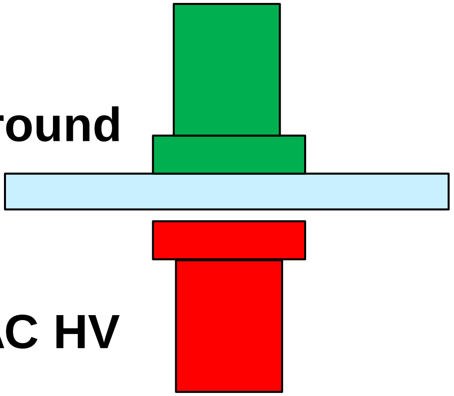
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

The growth of the bacteria on the face mask was suppressed



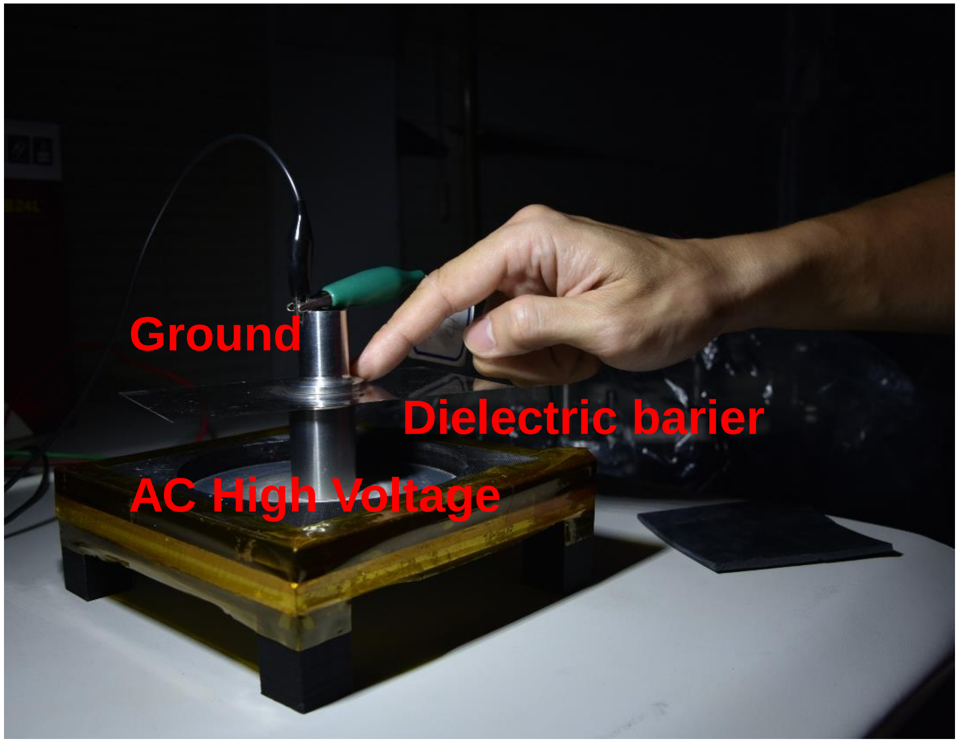
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

DBD plasma demonstration

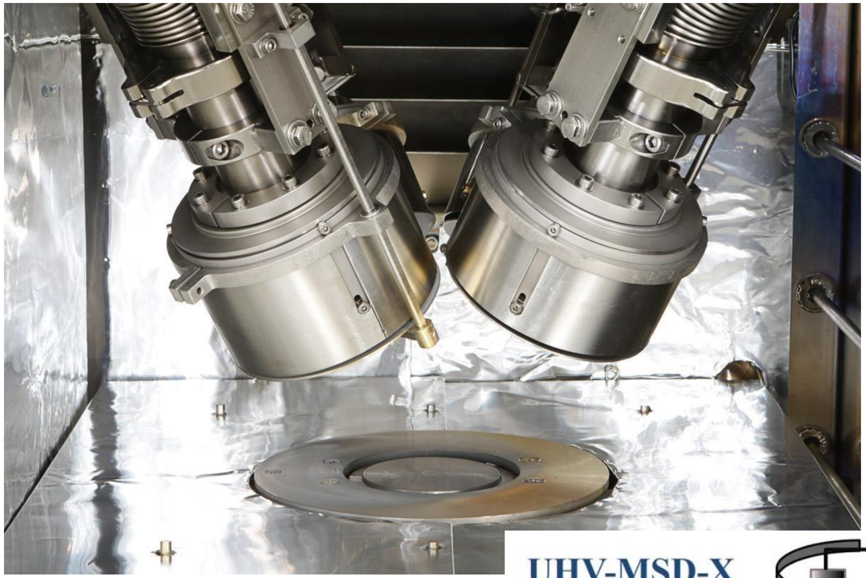


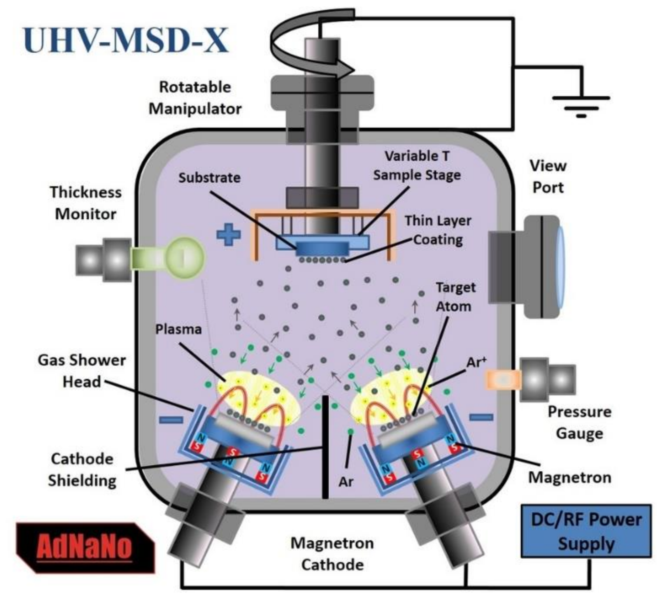
Show video.

DBD plasma can be generated between the finger and the dielectric layer



Examples of magnetron sputtering deposition

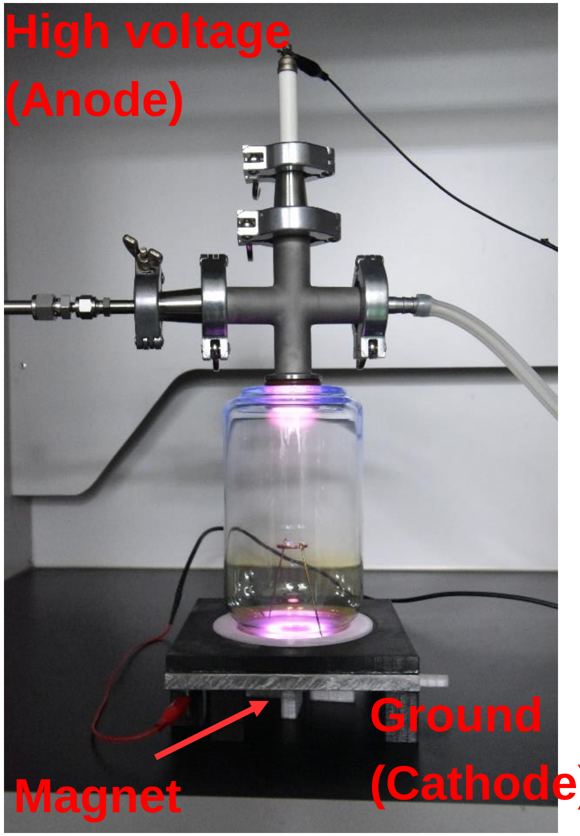




https://angstromengineering.com/tech/magnetron-sputtering/pulsed-dc/
https://dynavac.com/wp-content/uploads/2017/09/Confocal-Sputtering-2.jpg
https://www.adnano-tek.com/magnetron-sputtering-deposition-msd.html

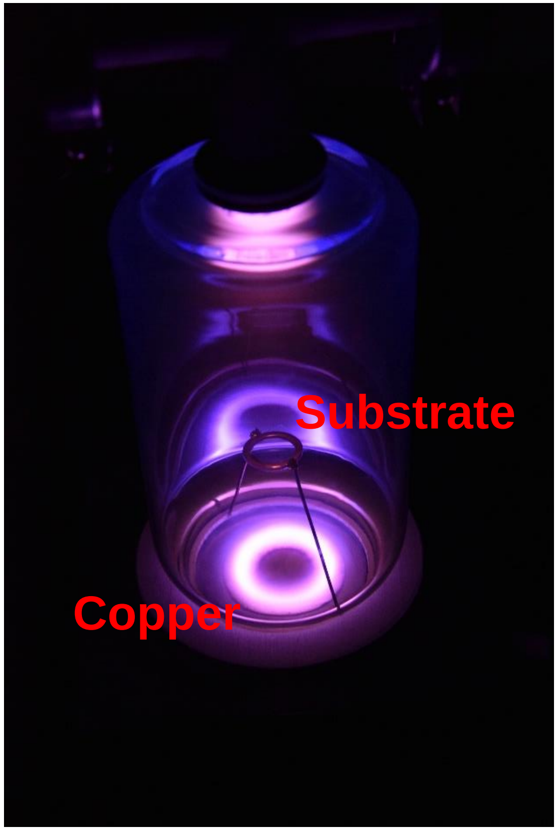
Demonstration experiments – magnetron sputtering

- System

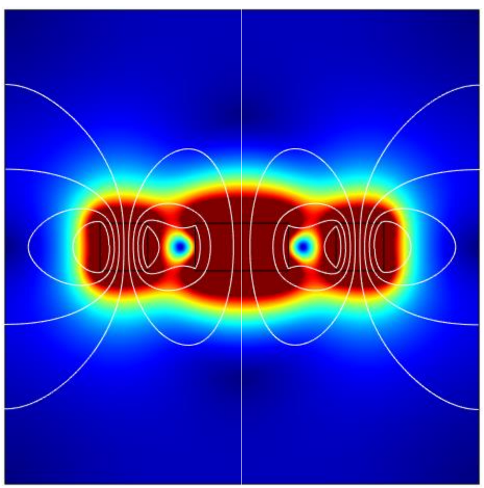


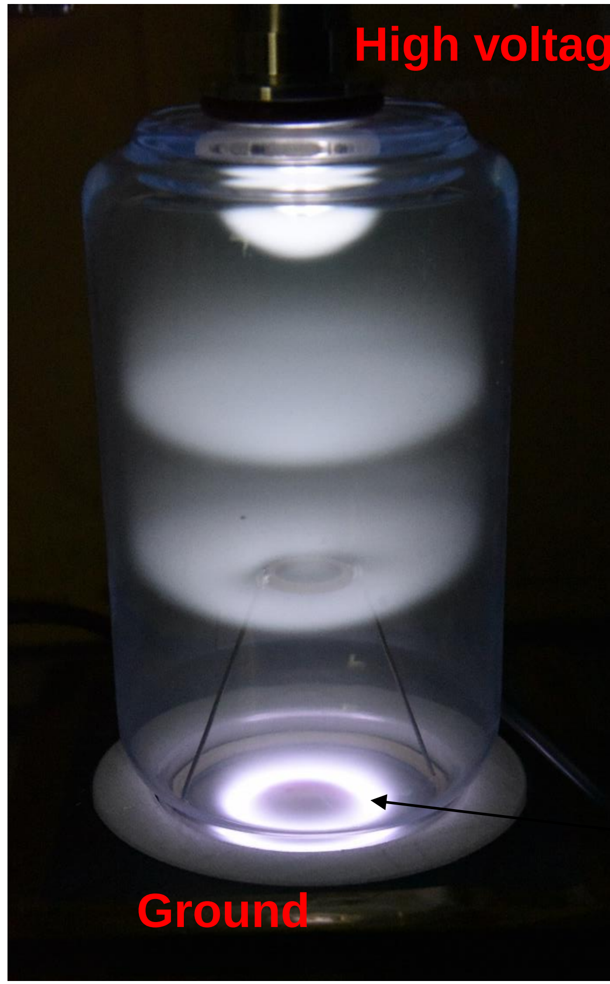
- Without magnet

- With magnet

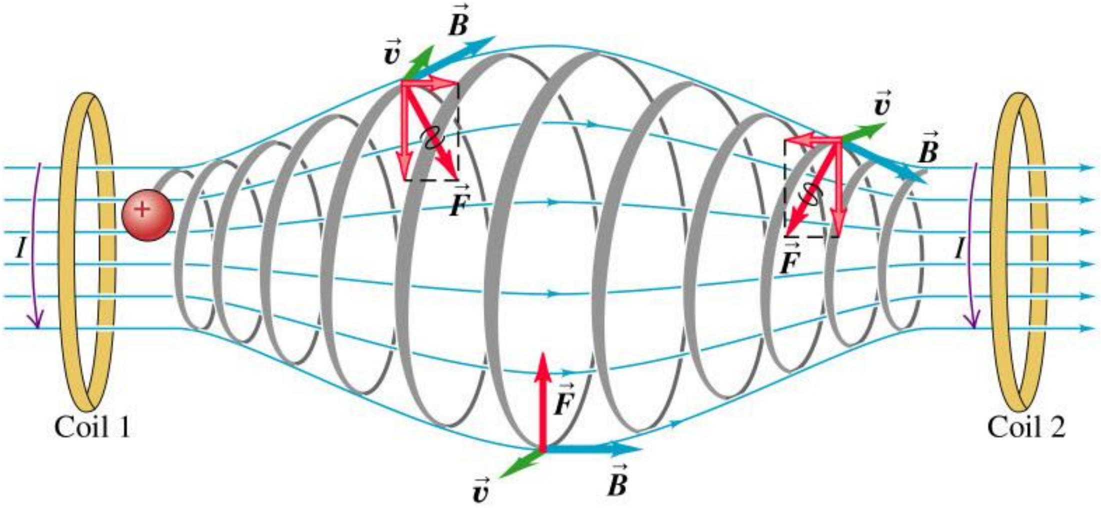


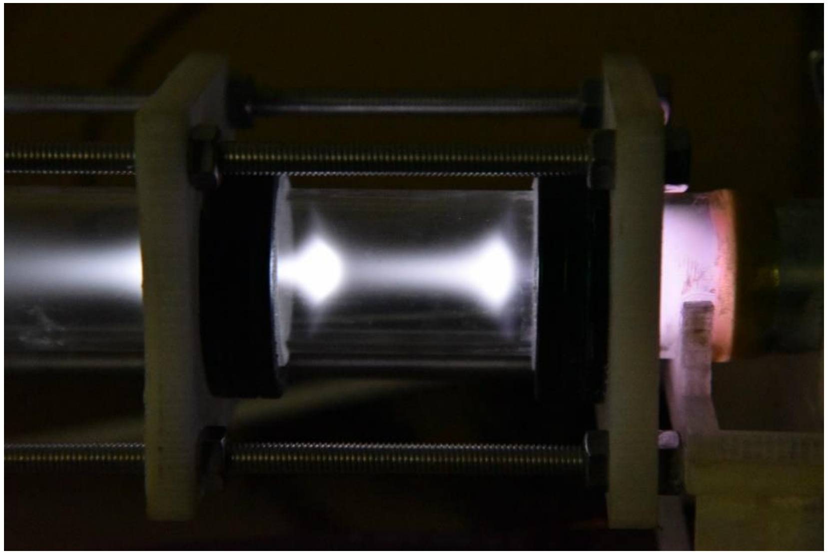
A bright ring occurs when the magnet is inserted into the system





Demonstration of a magnetic mirror machine

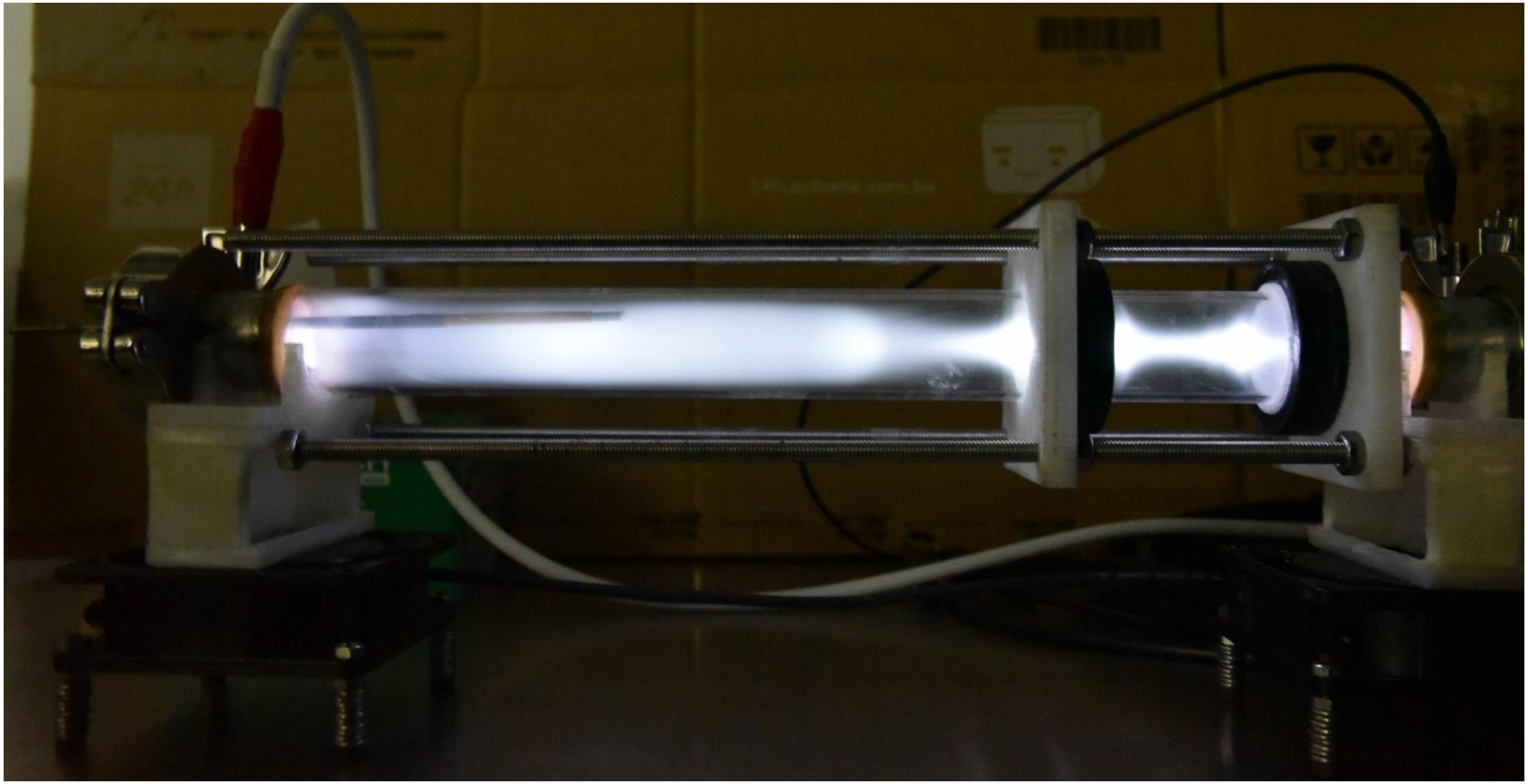




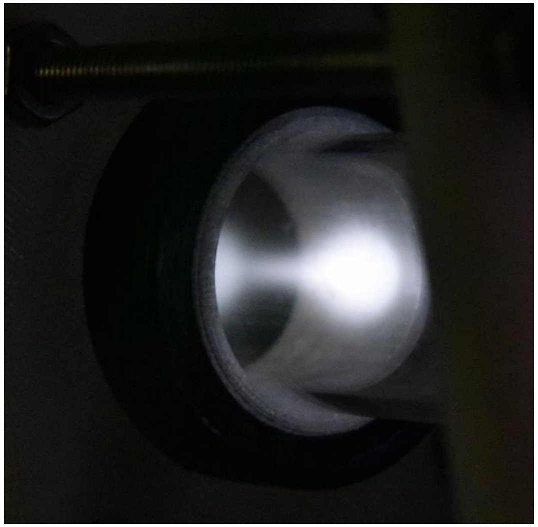
Show video.

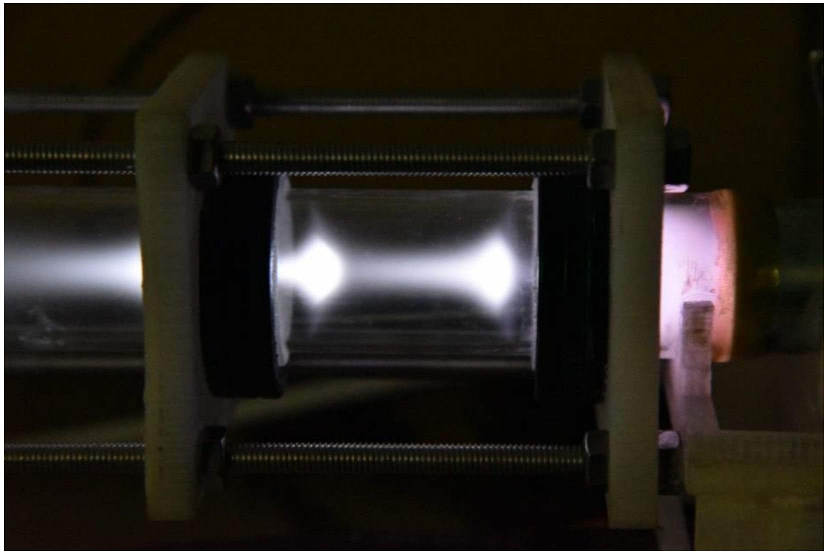
https://i.stack.imgur.com/GlzGZ.jpg

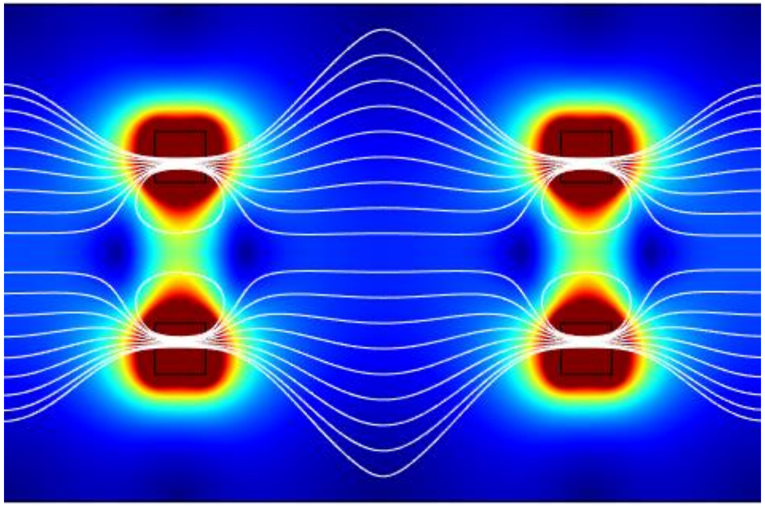
Plasma is partially confined by the magnetic field



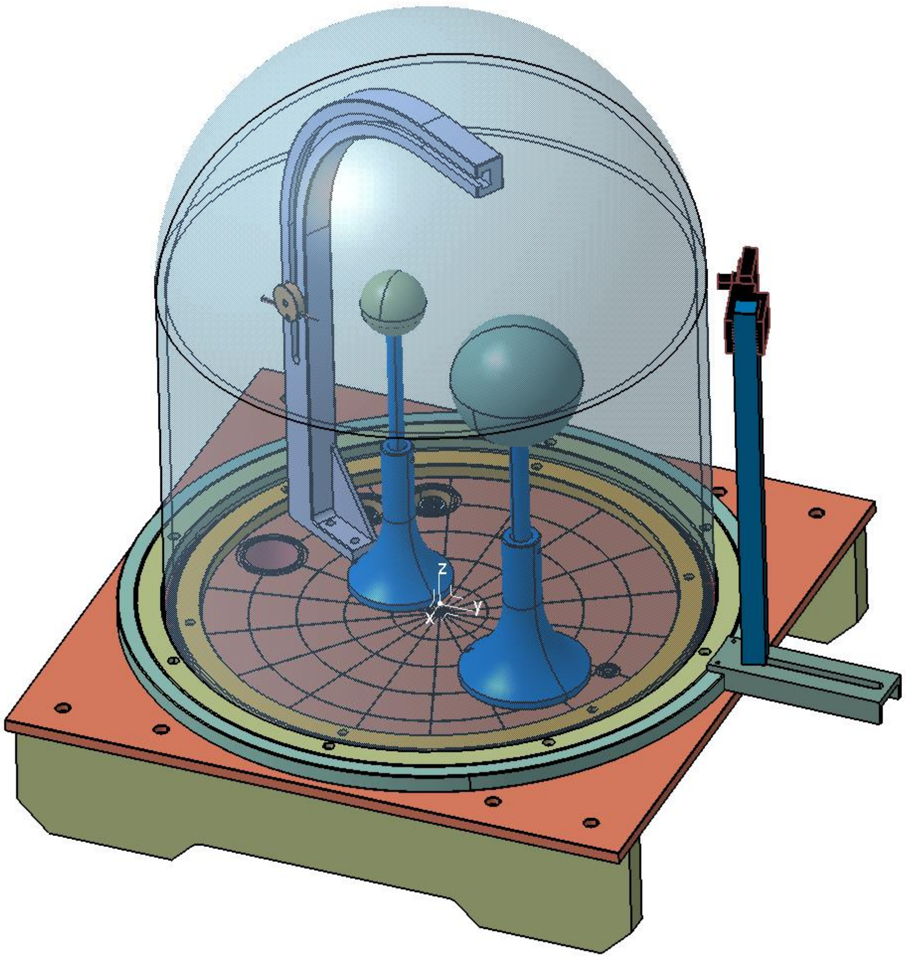
Many mirror points are provided by a pair of ring-type magnets



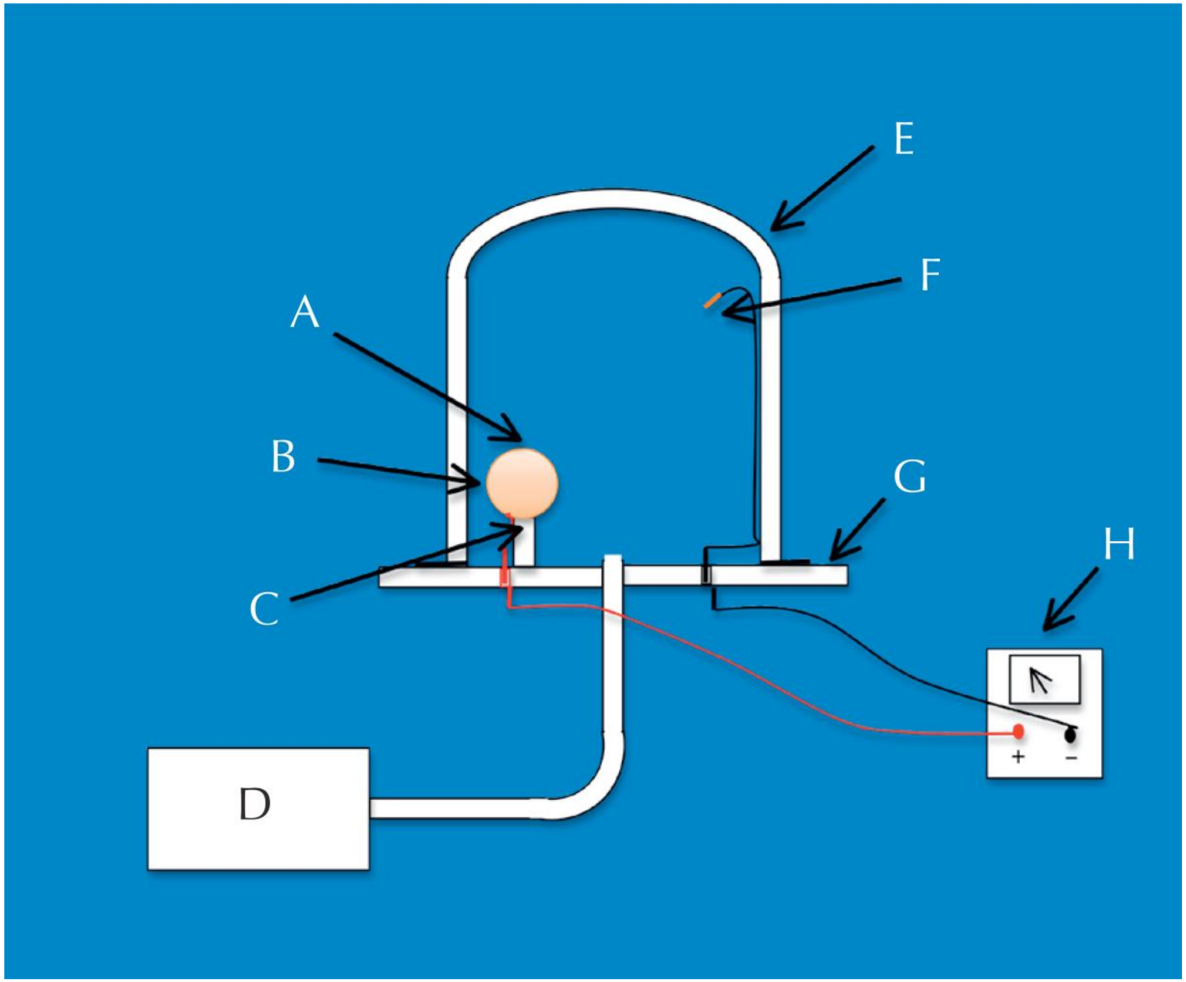




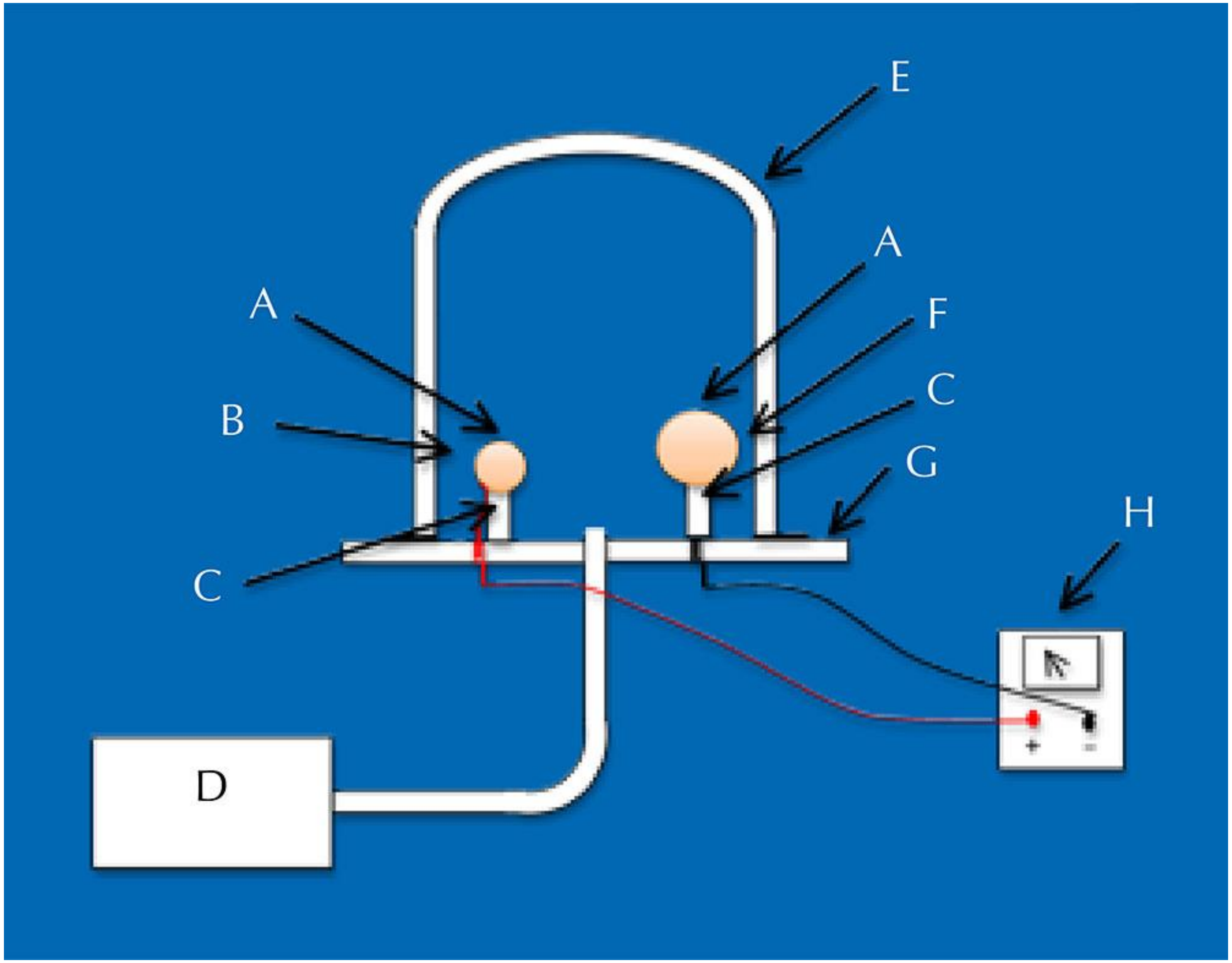
Planeterrella is an aurora simulator



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