Application of Plasma Phenomena

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Institute of Space and Plasma Sciences, National Cheng Kung University

Lecture 14

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

Grading

- **Quizzes   50 % (2-min Q&A at the beginning of each class)**

- **Presentations 50 % (10-min presentation on any**

  plasma applications or phenomena)

Final presentations

Name	Random
賴柏佑	0.001
畢永葳	0.090
陳春祿 TRAN XUAN LOC	0.106
雷子霆	0.124
張博傑	0.647
洪子軒	0.708
黎明心 LE MINH TAM	0.758
林伯鴻	0.762
張書熏	0.830
歐亞瑟 KAYSE SACAD OSMAN	0.852
皮倪書 SUSIT PIMSANIT	0.952

- **Time: 6/11 9:10**
- **Time for each person: 10 mins**
- **Topics: anything related to plasma. You can talk about a plasma phenomenon or a plasma application. In your presentation, you need to describe how plasma is involved. What rule does the plasma play in the phenomenon or application.**
- **Your scores (34 points in total) will depend on:**
  - **(2 points) Presentation time.**
    < 8 min: 0
    8~9 min: 1
    9~11 min: 2
    11~12 min: 1
    > 12 min: 0
  - **(2 points) Plasma related.**
  - **(10 points) How clear the physics is explained?**
  - **(10 points) The presentation skill.**
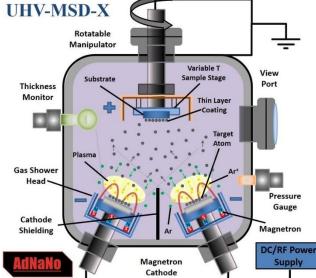 - **(10 points) Your slides.**

Final exam

- Time: 6/16 10:30 ~ 12:00 (noon), right after the final presentation.

- Question sheet will be sent to you via email at 10:30 on 6/16. Only hand-writing is allowed for answering questions. Please take pictures or scan your answer sheet and send them back to me by 12:00 (noon).

- The final exam is an open-book exam. Search on internet is also allowed. However, discussions are prohibited. Please search by yourself if necessary. The final exam will cover everything taught in this semester.

- Please send an email to me before 6/16 and make sure I reply to you so that we both confirm we have each other's email address.

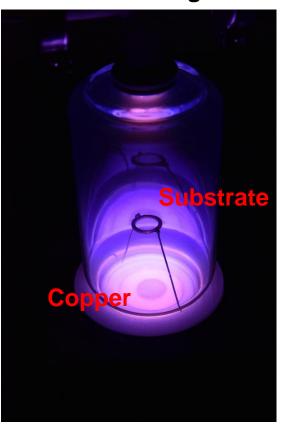# Examples of magnetron sputtering deposition

Demonstration experiments – magnetron sputtering

- **System**
- **Without magnet**
- **With magnet**

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

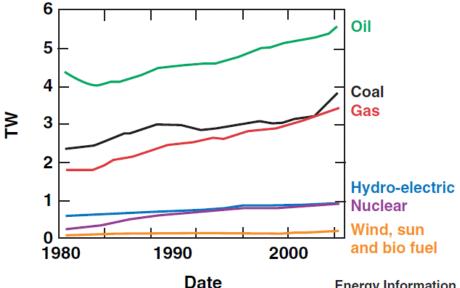High voltage

Ground
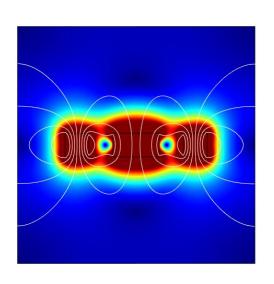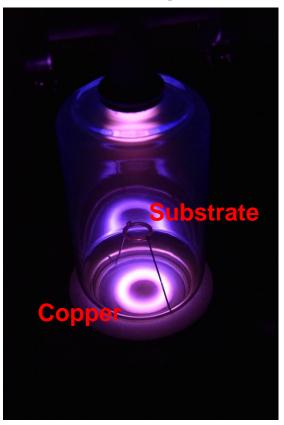
Confined electrons

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

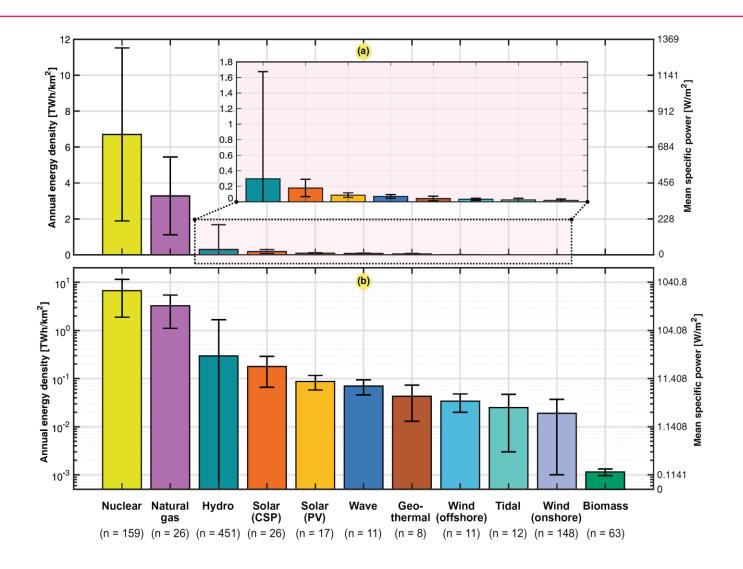| Fossil fuel	Estimated reserve	(2005 consumption rate) Years remaining
Oil	1,277,702 million barrels	32 years
Natural gas	~6,500,000 billion cubic ft	72 years
Coal	1,081,279 million tons	252 years

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

E15657

Energy Information Administration (EIA) 2006 Annual Report, U.S. Department of Energy, Washington, D.C.
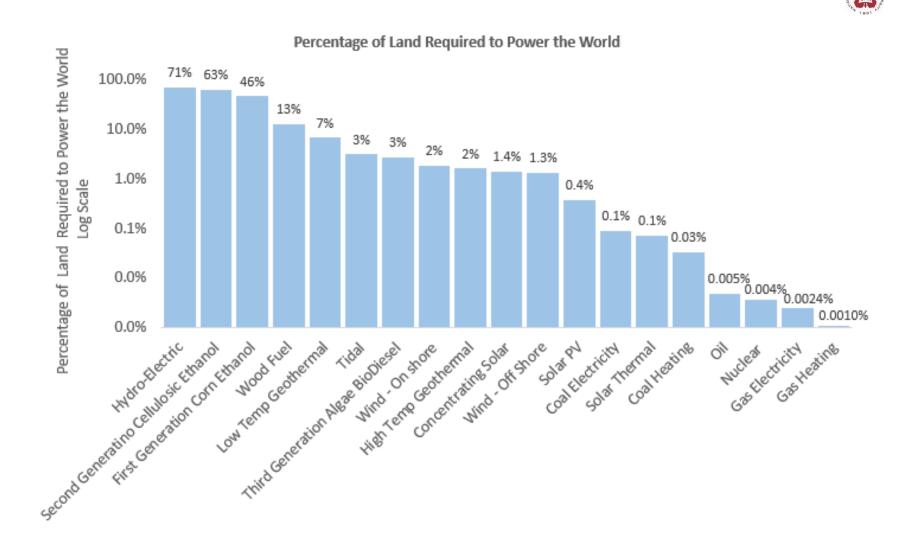
*from Laboratory for Laser Energetics, University of Rochester, Rochester, NY
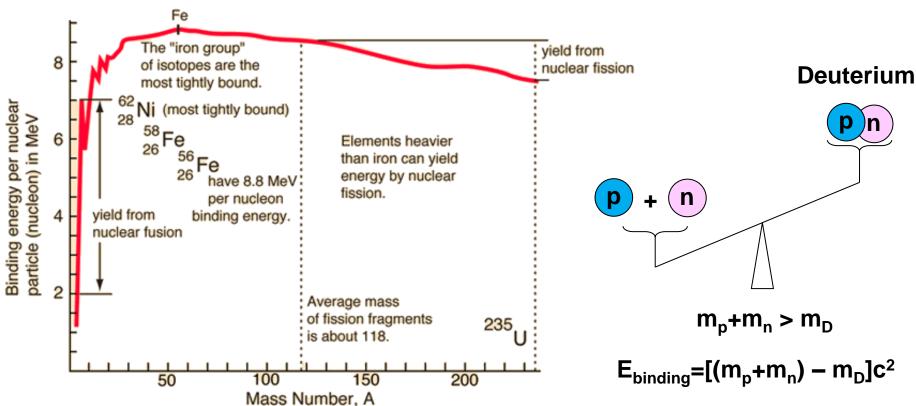
Nuclear energy has the highest energy density

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

Percentage of Land Required to Power the World

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

Deuterium

$m_p + m_n > m_D$

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

$$Q = \left(\sum_i m_i - \sum_f m_f\right) c^2$$

$$\Delta m = z m_p + (A - z) m_n - m$$
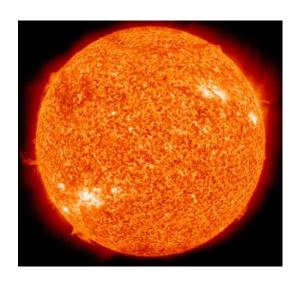
- **Binding energy:** $B = \Delta m c^2$

- **Output energy:** $Q = \sum_f B_f - \sum_i B_i$
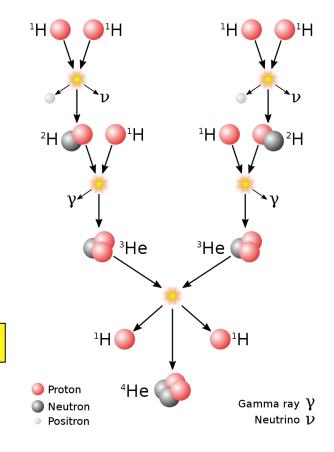
Fusion in the sun provides the energy

- **Proton-proton chain in sun or smaller**
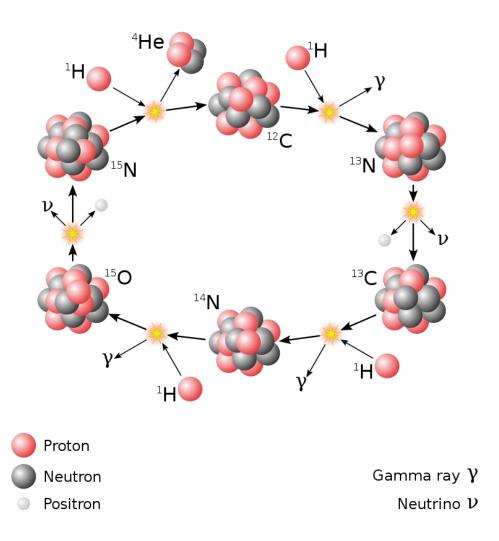
- **Particles are confined by the gravity.**

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

In heavy sun, the fusion reaction is the CNO cycle

Proton
Neutron
Positron

Gamma ray γ
Neutrino ν

https://en.wikipedia.org/wiki/Nuclear_fusion
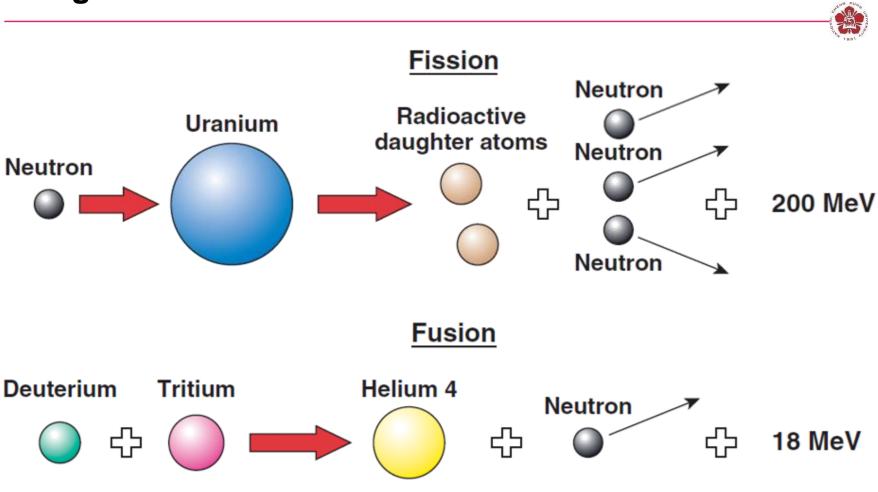
The cross section of proton-proton chain is much smaller than D T fusion

Reaction	$\sigma_{10\,keV}$ (barn)	$\sigma_{100\,keV}$ (barn)	σ_{max} (barn)	ϵ_{max} (keV)
$D+T\rightarrow\alpha+n$	2.72×10^{-2}	3.43	5.0	64
$D+D\rightarrow T+p$	2.81×10^{-4}	3.3×10^{-2}	0.06	1250
$D+D\rightarrow{}^{3}He+n$	2.78×10^{-4}	3.7×10^{-2}	0.11	1750
$T+T\rightarrow\alpha+2n$	7.90×10^{-4}	3.4×10^{-2}	0.16	1000
$D+{}^{3}He\rightarrow\alpha+p$	2.2×10^{-7}	0.1	0.9	250
$p+{}^{6}Li\rightarrow\alpha+{}^{3}He$	6×10^{-10}	7×10^{-3}	0.22	1500
$p+{}^{11}B\rightarrow3\alpha$	(4.6×10^{-17})	3×10^{-4}	1.2	550
$p+p\rightarrow D+e^{+}+v$	(3.6×10^{-26})	(4.4×10^{-25})		
$p+{}^{12}C\rightarrow{}^{13}N+\gamma$	(1.9×10^{-26})	2.0×10^{-10}	1.0×10.4	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

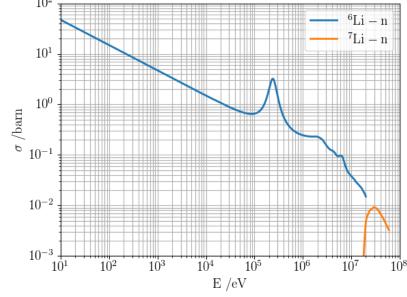# Nuclear fusion and fission release energy through energetic neutrons

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

- **Fission of ^{235}U:** $\dfrac{Q}{A} = \dfrac{200 \text{ MeV}}{(235+1)\text{amu}} = 0.85 \text{ MeV/amu}$

- **Fusion of D+T:** $\dfrac{Q}{A} = \dfrac{17.6 \text{ MeV}}{(2+3)\text{amu}} = 3.5 \text{ MeV/amu}$

	Half-life (years)
U235	**7.04x10^8**
U238	**4.47x10^9**
…	
Tritium	**12.3**

- **Tritium breeding:**

  n + ^{6}Li → α + T + 4.86 MeV
  n + ^{7}Li → α + T + n – 2.87 MeV
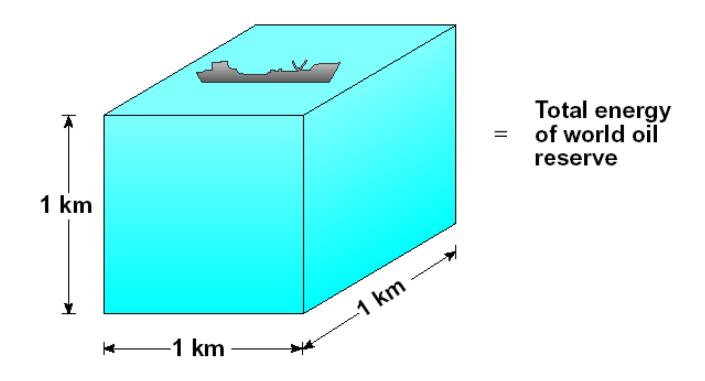
What could you do with 1 kg DT?

- **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.**

Enormous fusion fuel can be produced from sea water

1 km (height) × 1 km × 1 km = Total energy of world oil reserve

*R. Betti, HEDSA HEDP Summer School, 2015
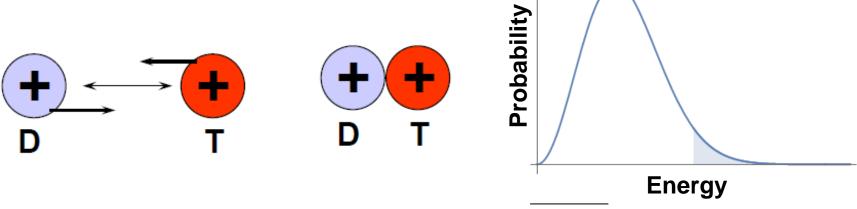
A "hot plasma" at 100M ⁰C is needed

- **Probability for fusion reactions to occur is low at low temperatures due to the coulomb repulsion force.**
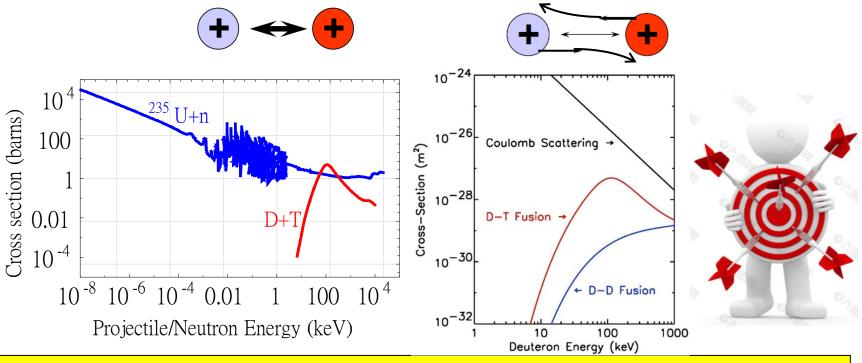
- **If the ions are sufficiently hot, i.e., large random velocity, they can collide by overcoming coulomb repulsion**

*R. Betti, HEDSA HEDP Summer School, 2015

Fusion is much harder than fission

- **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!**

Fast neutrons are slowed down due to the collisions
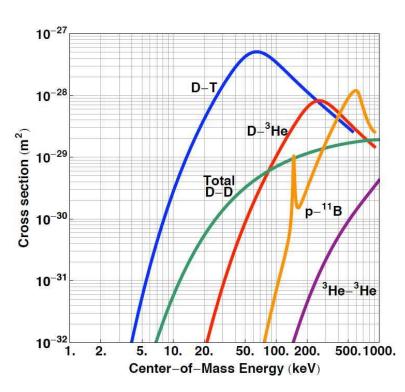
Neutron ⬤ ⮕ ⬤ Atom
m_N m_M

- **A moderator is used to slow down fast neutrons but not to absorb neutrons.**
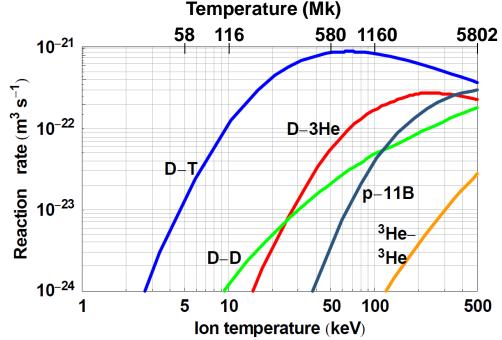
- **For $m_M \sim m_N$, the energy decrement is higher. Therefore, H slows down neutron most efficiently.**

- **However, H + n → D, i.e., H absorbs neutrons.**

- **The best option is the D in the heavy water (D_2O).**

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

Fusion doesn't come easy

$$D + D \rightarrow T + p$$
$$\rightarrow He^3 + n$$

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

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

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

- **Reaction rate:**

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

Cross section
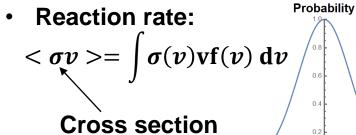
https://i.stack.imgur.com/wXQD5.jpg
Santarius, J. F., "Fusion Space Propulsion – A Shorter Time Frame Than You Think", JANNAF, Monterey, 5-8 December 2005.
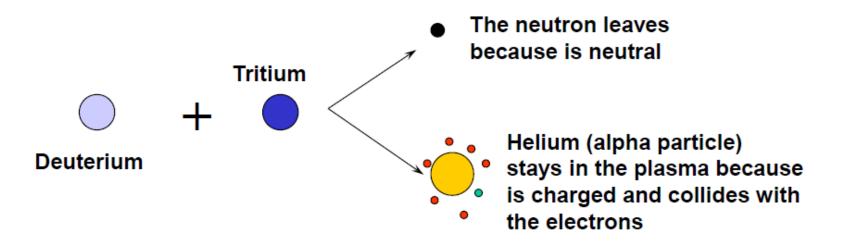
It takes a lot of energy or power to keep the plasma at 100M ⁰C

- **Let the plasma do it itself!**

Deuterium + **Tritium**

The neutron leaves because is neutral

Helium (alpha particle) stays in the plasma because is charged and collides with the electrons

- **The α-particles heat the plasma.**

Under what conditions the plasma keeps itself hot?

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

  $$S_\alpha + S_h = S_B + S_k$$

  S_α: α particle heating

  S_h: external heating

  S_B: Bremsstrahlung radiation

  S_k: heat conduction lost
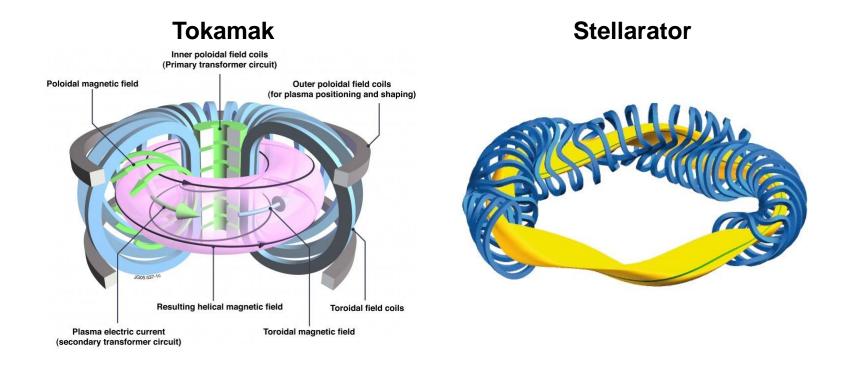
  Ignition condition: Pτ > 10 atm-s = 10 Gbar - ns

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

The plasma is too hot to be contained
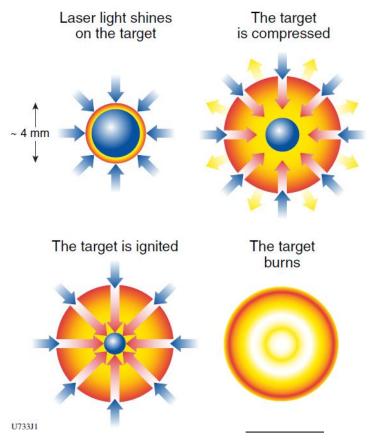
- **Solution 1: Magnetic confinement fusion (MCF), use a magnetic field to contain it. P~atm, τ~sec, T~10 keV (10^8 ⁰C)**

Tokamak

Poloidal magnetic field

Inner poloidal field coils
(Primary transformer circuit)

Outer poloidal field coils
(for plasma positioning and shaping)

JG05.537-1c

Resulting helical magnetic field

Toroidal field coils

Plasma electric current
(secondary transformer circuit)

Toroidal magnetic field

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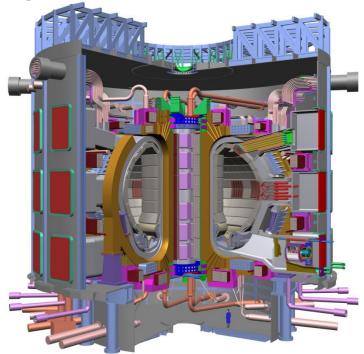
Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

To control? Or not to control?

- **Magnetic confinement fusion (MCF)**

- **Inertial confinement fusion (ICF)**

Laser light shines on the target

~ 4 mm

The target is compressed

The target is ignited

The target burns

U733J1
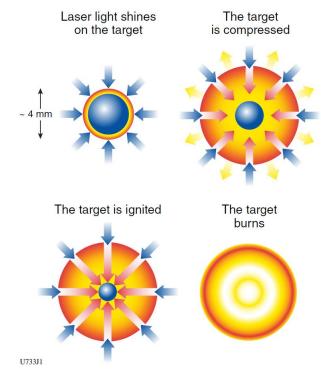
- **Plasma is confined by toroidal magnetic field.**

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

Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion
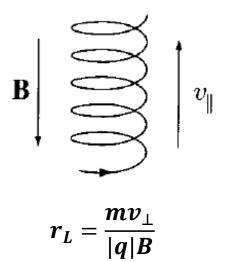
Outline
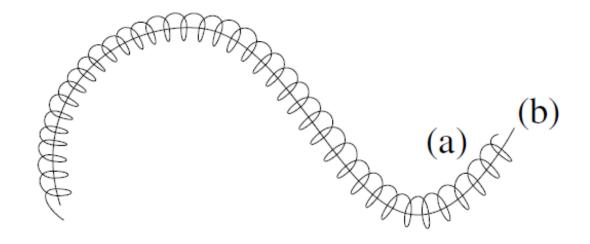
- **Introduction to nuclear fusion**

- **Magnetic confinement fusion (MCF)**

  - **Tokamak**

  - **Stellarator**

- Inertial confinement fusion (ICF)

  - Indirection drive ICF

  - Direct drive ICF

- Innovation idea – MCF + ICF

- Plasma in space

- Pulsed-power system at NCKU

Charged particles gyro around the magnetic fields

$$r_L = \frac{mv_\perp}{|q|B}$$
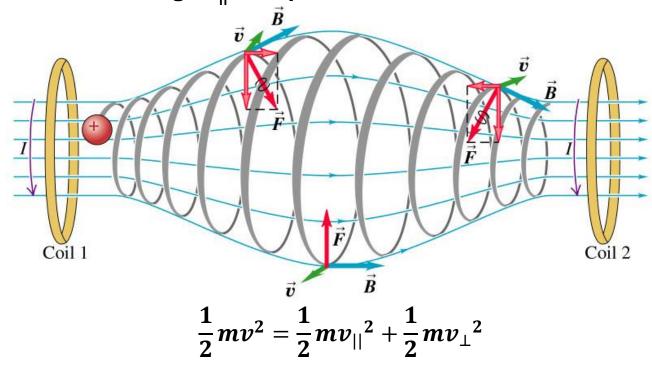
Charged particles can be partially confined by a magnetic mirror machine
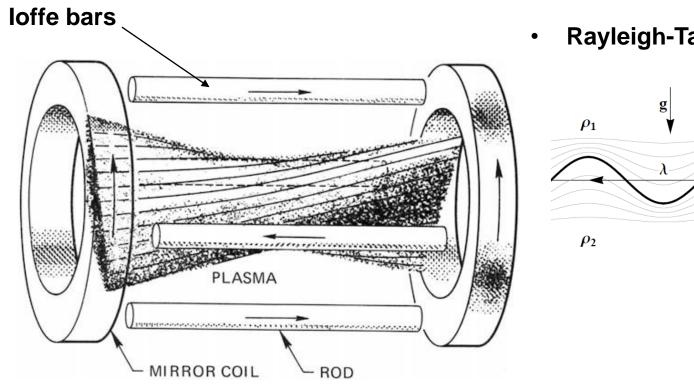
- **Charged particles with small $v_{||}$ eventually stop and are reflected while those with large $v_{||}$ escape.**

$$\frac{1}{2} m v^2 = \frac{1}{2} m v_{||}^2 + \frac{1}{2} m v_{\perp}^2$$
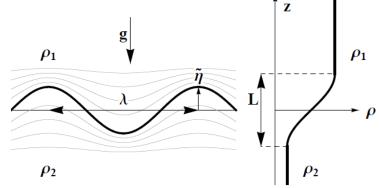
- **Large $v_{||}$ may occur from collisions between particles.**

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

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

Ioffe bars
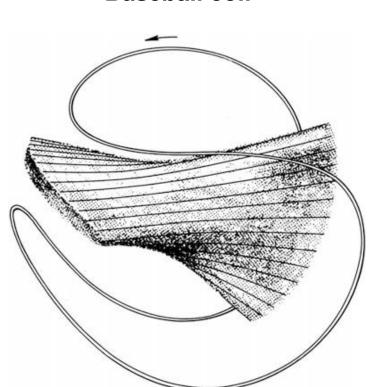
- **Rayleigh-Taylor instability**

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

- **Baseball coil**
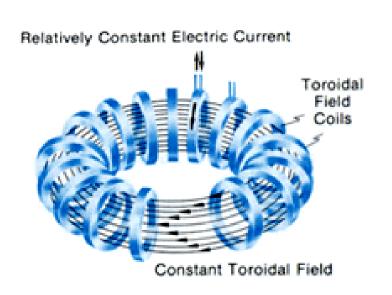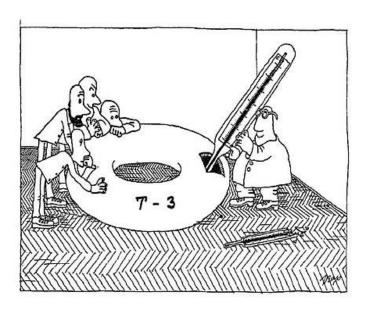
- **MFTF-B mirror machine**

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

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

Relatively Constant Electric Current

Toroidal Field Coils

Constant Toroidal Field

7 - 3
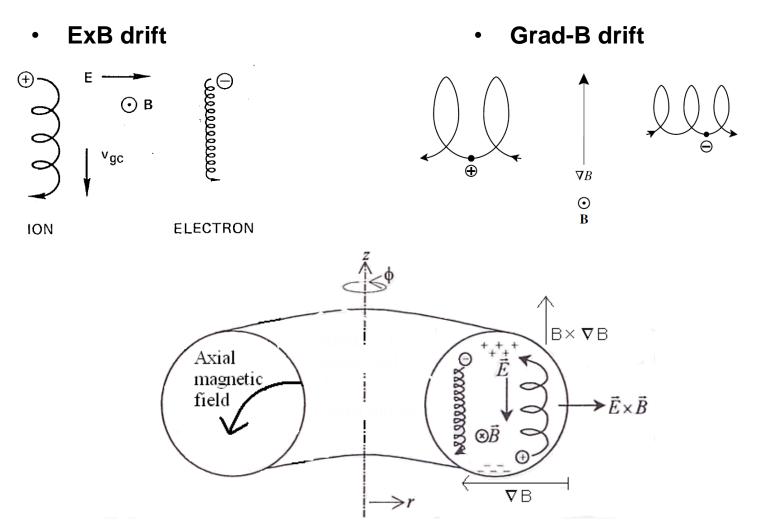
https://www.iter.org/mach/tokamak
https://en.wikipedia.org/wiki/Tokamak#cite_ref-4
Drawing from the talk "Evolution of the Tokamak" given in 1988 by B.B. Kadomtsev at Culham.
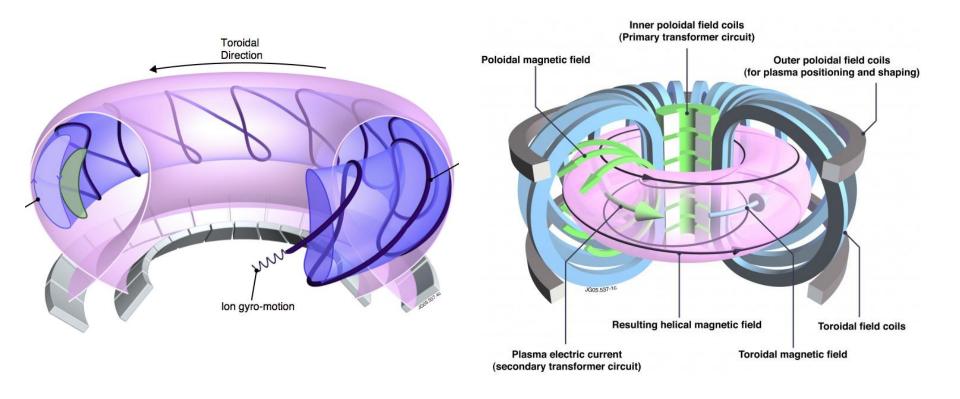
Charged particles drift across field lines

- **ExB drift**

- **Grad-B drift**

ION   ELECTRON

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

Toroidal Direction

Ion gyro-motion

Inner poloidal field coils (Primary transformer circuit)

Poloidal magnetic field

Outer poloidal field coils (for plasma positioning and shaping)

Resulting helical magnetic field

Toroidal field coils

Plasma electric current (secondary transformer circuit)

Toroidal magnetic field

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

Outer poloidal field coils
(for plasma positioning and shaping)

Toroidal field coils

...roidal magnetic field
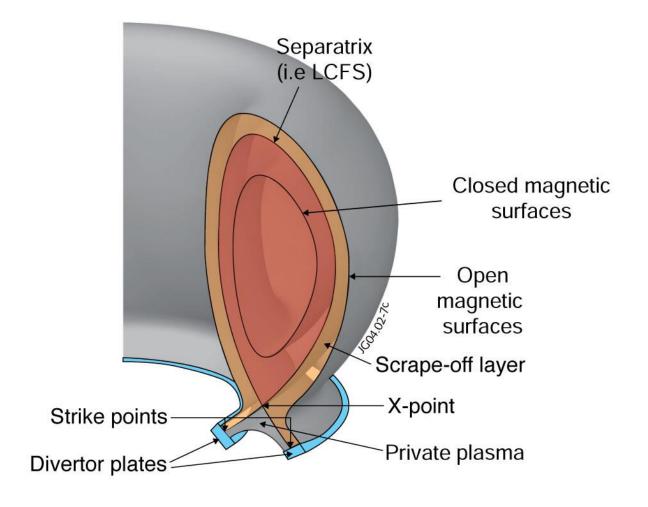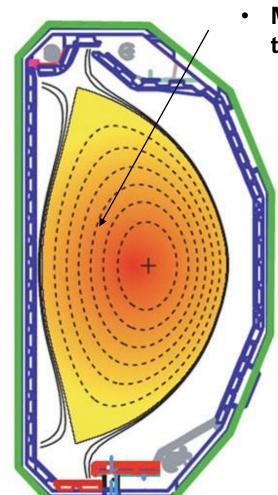
A divertor is needed to remove impurities and the power that escapes from the plasma

D-shaped tokamak with diverter is more preferred nowadays
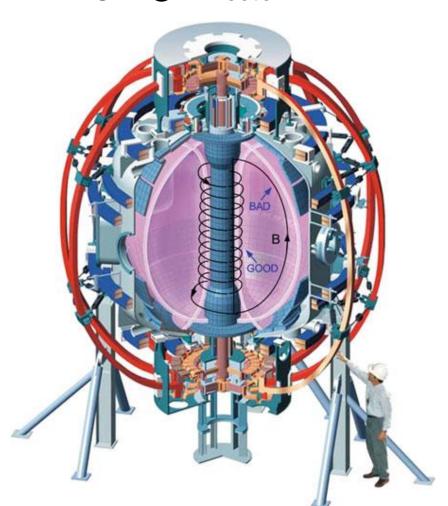
- **Make the plasma closer to the major axis**

Spherical tokamak is formed when the aspect ratio of a tokamak is reduced to the order of unity
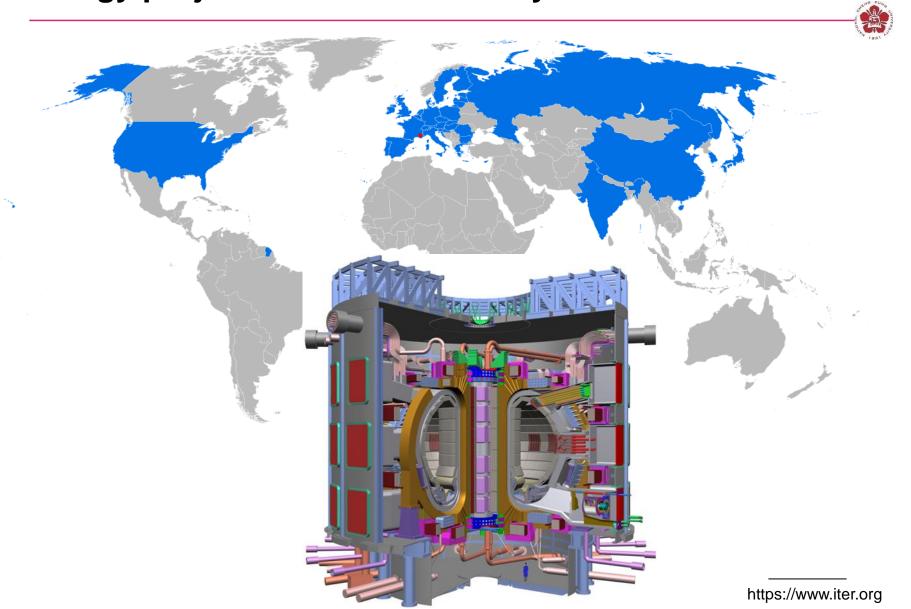
- **NSTX @ Princeton**

- **MegaAmpere Spherical Tokamak (MAST) @ Culham center for fusion energy, UK**
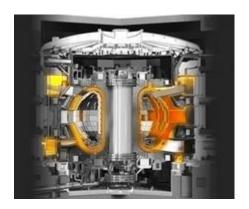
ITER ("The Way" in Latin) is one of the most ambitious energy projects in the world today
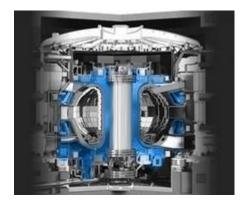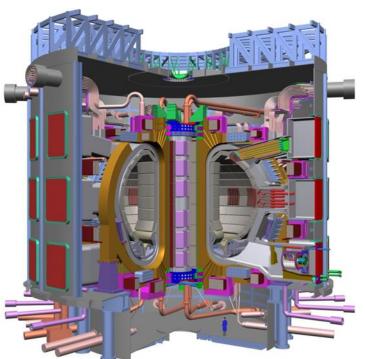
ITER ("The Way" in Latin) is one of the most ambitious energy projects in the world today

- **Vacuum vessel**

- **Magnets**

- **Cryostat**

- **Blanket**

- **Divertor**

ITER
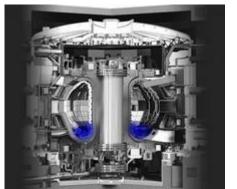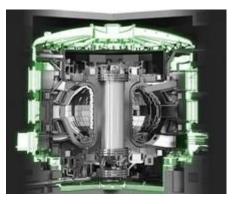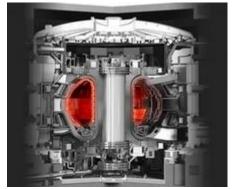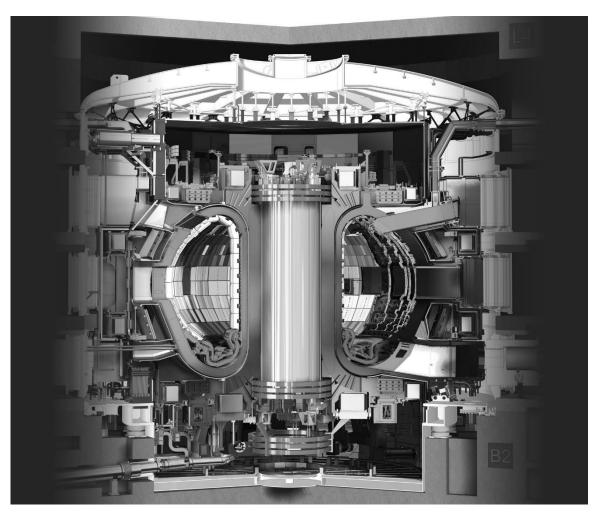
- **T=150M ºC**
- **P=500 MW**

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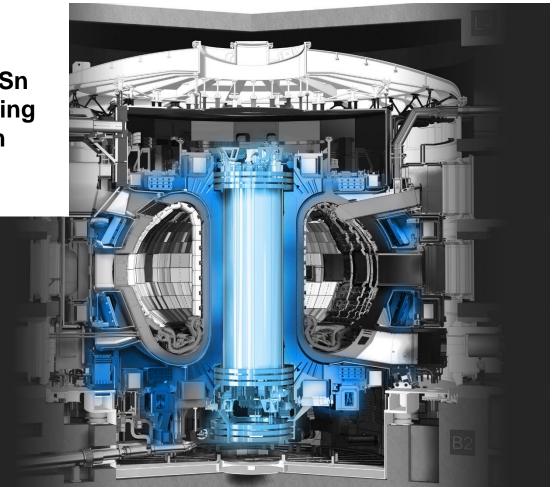
- $E_B = 51$ GJ
- $T_B = 4$ K
- Length of Nb_3Sn superconducting strand: 10^5 km
- $B_{T,max} = 11.8$ T
- $B_{P,max} = 6$ T
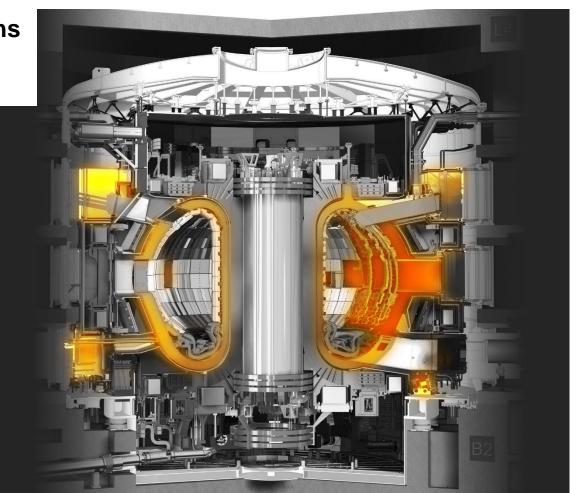
ITER – Vacuum vessel

- **W = 8000 tons**
- **V = 840 m³**
- **R = 6 m**
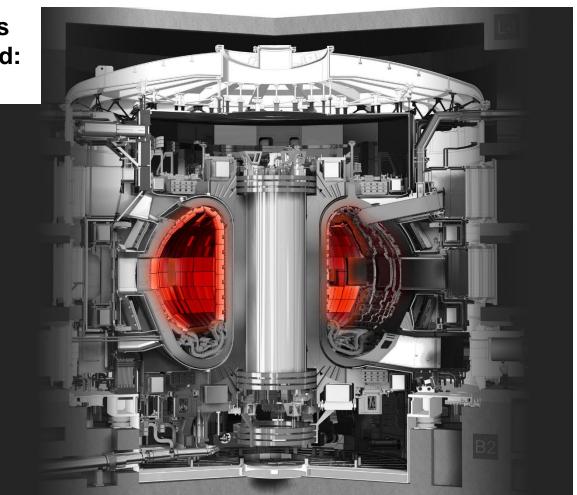
ITER – Blanket

- **440 modules**
- **Thermal load: 736 MW**
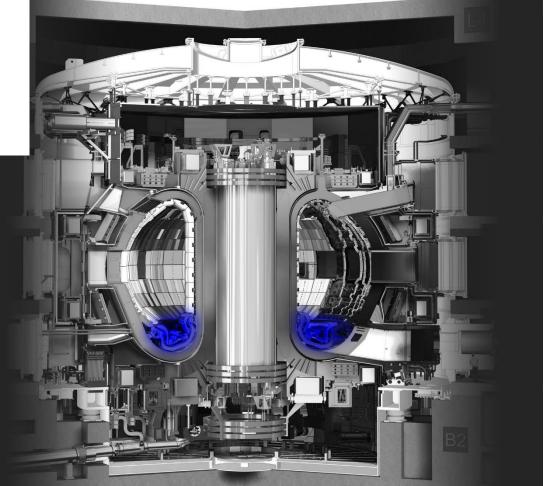
ITER – Divertor

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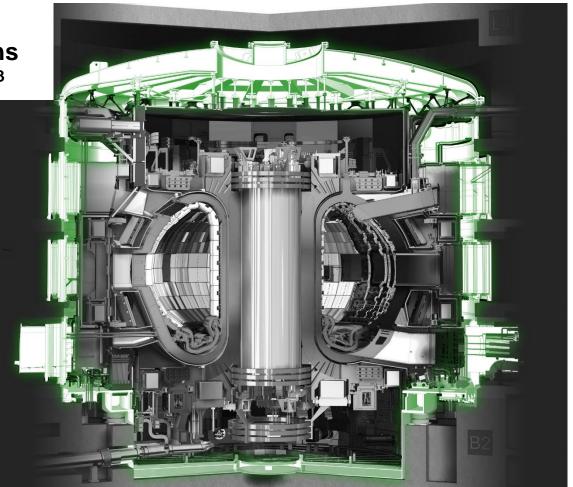
ITER – Crystat

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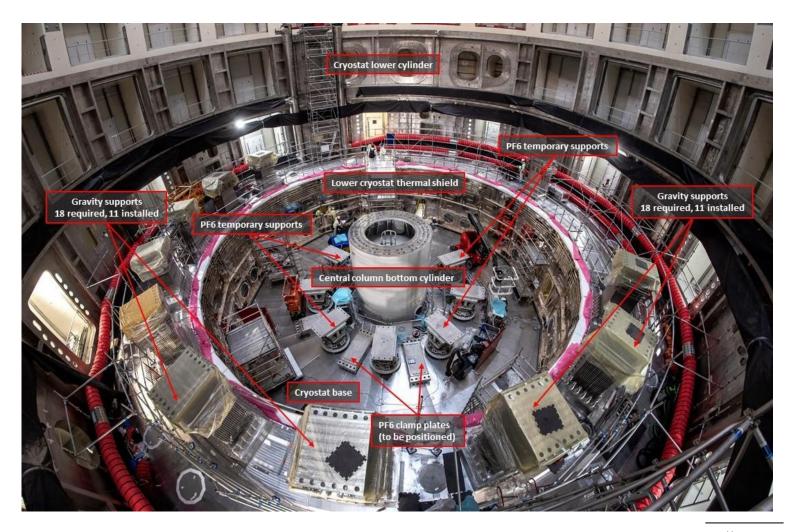
Supporting systems

- **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**
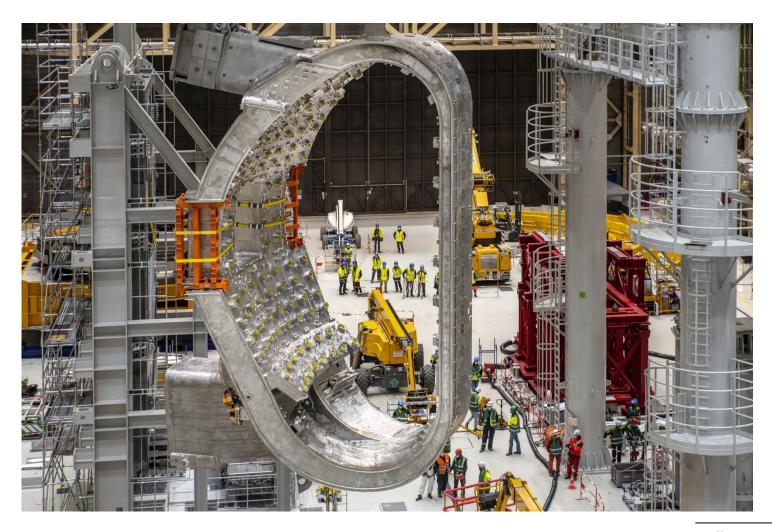
ITER is being assembled
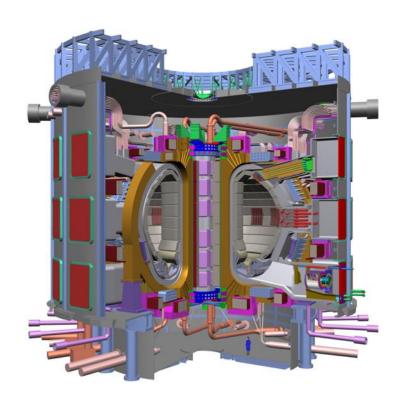
ITER is being assembled

There is a long way to go, but we are on the right path…
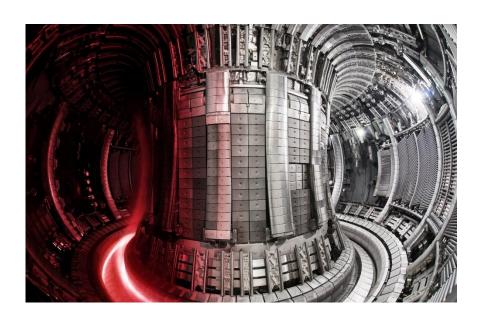
•	**Dec 2025**	**First Plasma**
•	**2035**	**Deuterium-Tritium Operation begins**

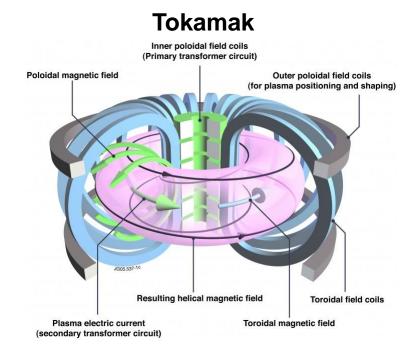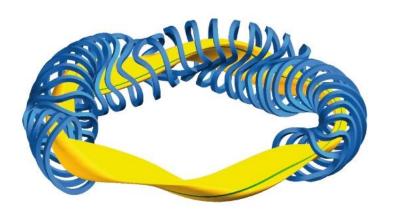# Joint European Torus (JET) facility has a record-breaking 59 megajoules of sustained fusion energy

- **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

Poloidal magnetic field

Inner poloidal field coils
(Primary transformer circuit)

Outer poloidal field coils
(for plasma positioning and shaping)

JG05.537-1c

Resulting helical magnetic field

Toroidal field coils

Plasma electric current
(secondary transformer circuit)

Toroidal magnetic field
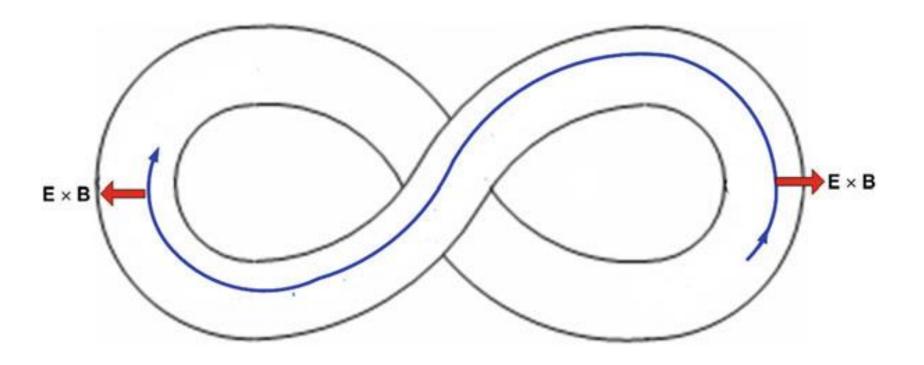
Stellarator

A figure-8 stellarator solved the drift issues

A figure-8 stellarator solved the drift issues
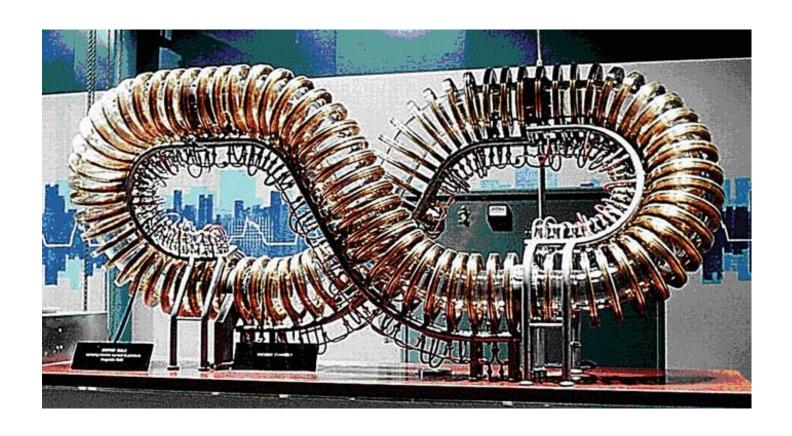
Lyman Spitzer, Jr. came out the idea during a long ride on a ski lift at Garmisch-Partenkirchen

$E \times B$

$E \times B$
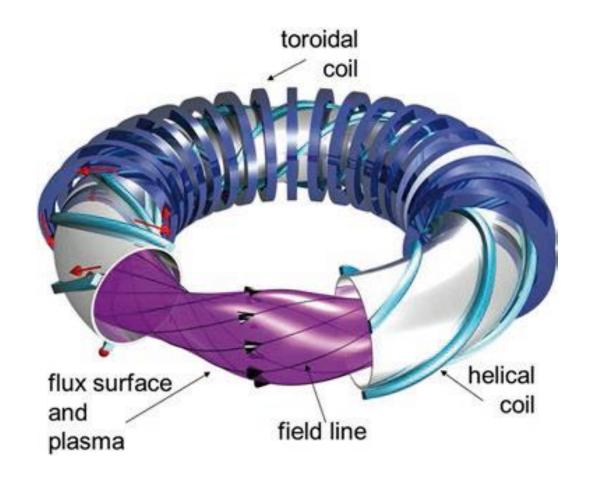
Exhibit model of a figure-8 stellarator for the Atoms for Peace conference in Geneva in 1958

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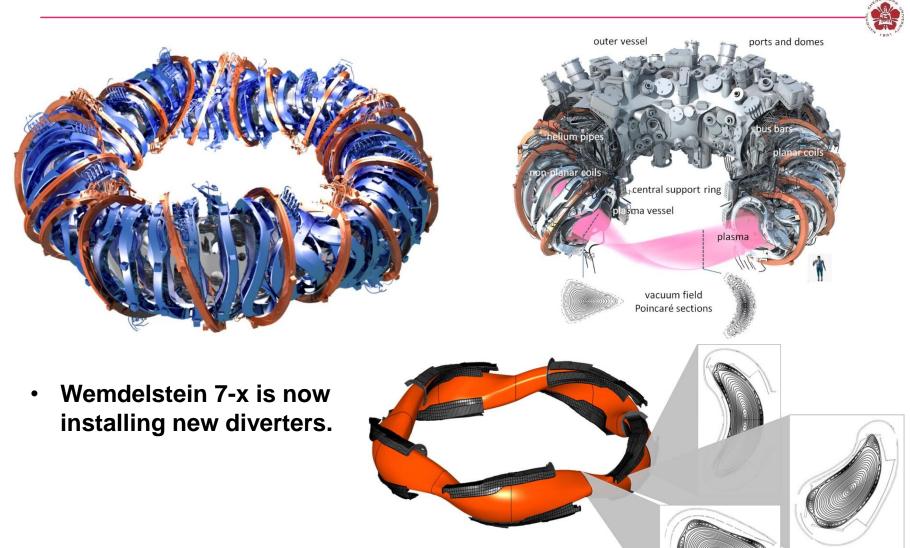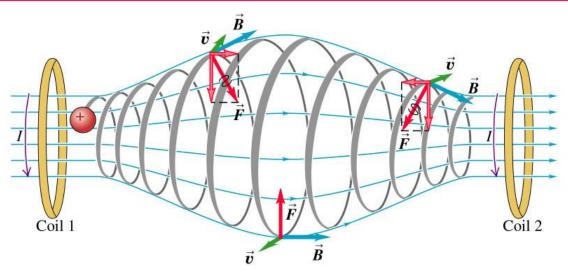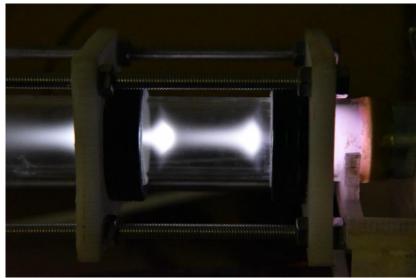

toroidal coil

flux surface and plasma

field line

helical coil

LHD stellarator in Japan

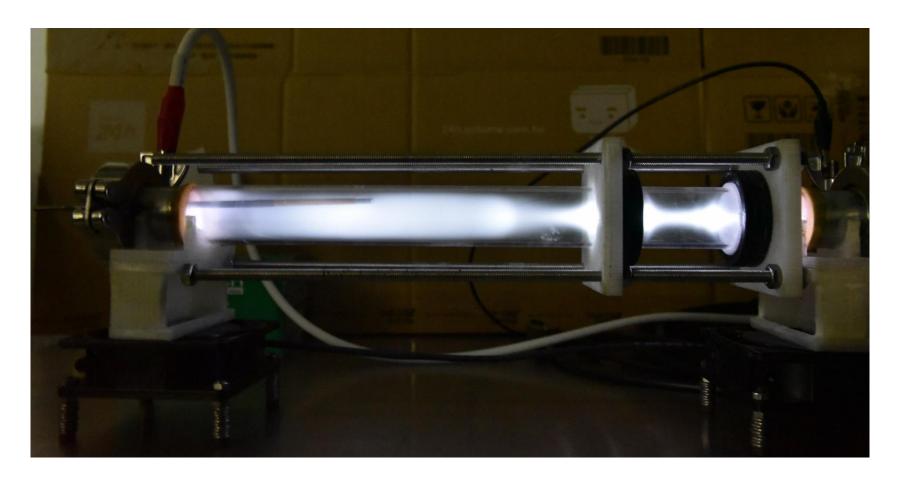# Wendelstein 7-X is a stellarator built by Max Planck Institute for Plasma Physics (IPP)
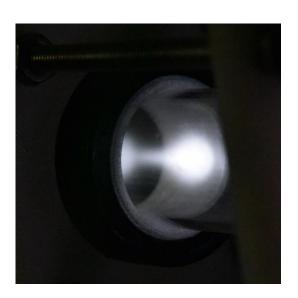
outer vessel

ports and domes

helium pipes

bus bars

non-planar coils

planar coils

central support ring

plasma vessel

plasma

vacuum field
Poincaré sections

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

Demonstration of a magnetic mirror machine

Show video.
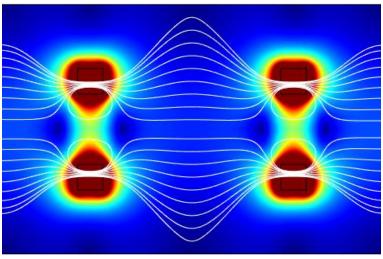
Plasma is partially confined by the magnetic field
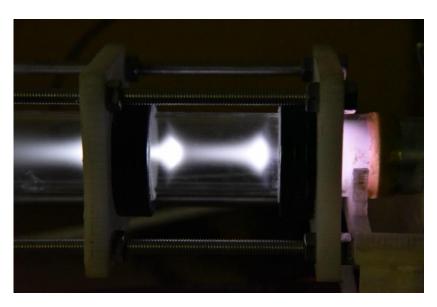
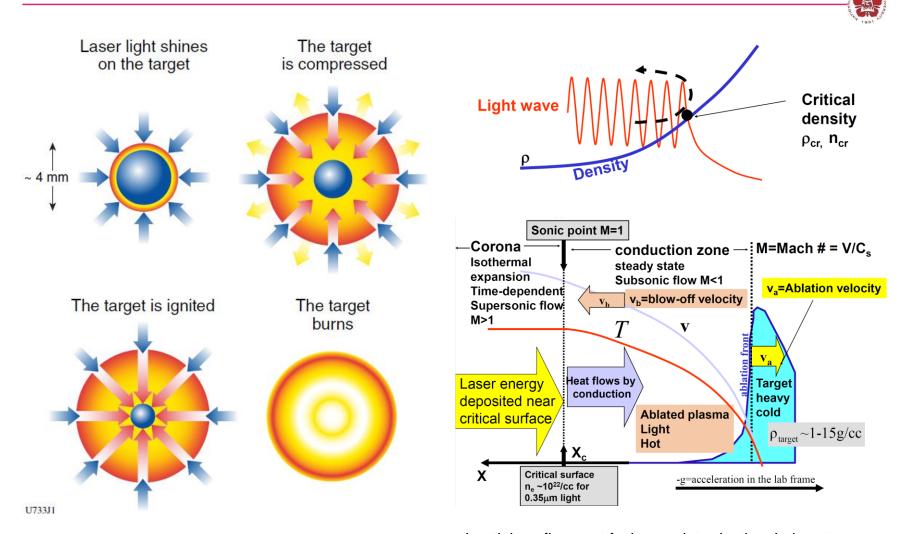# Many mirror points are provided by a pair of ring-type magnets

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**

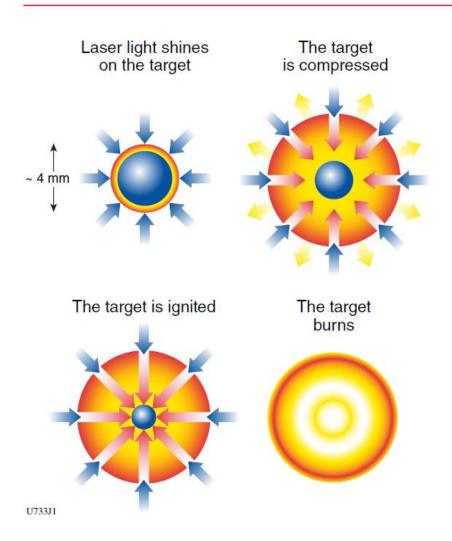- **Pulsed-power system at NCKU**

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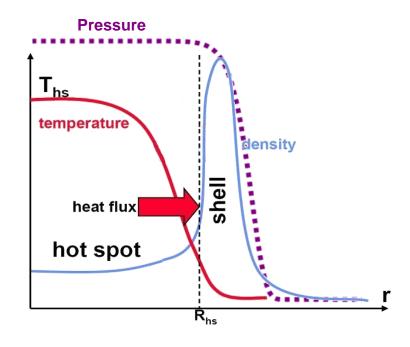

Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester
R. Betti, HEDSA HEDP Summer School, 2015

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

Laser light shines on the target

The target is compressed

~ 4 mm

The target is ignited

The target burns

U733J1

Spatial profile at stagnation

Pressure

T_{hs}

temperature

density

heat flux

shell

hot spot

R_{hs}

r

Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester
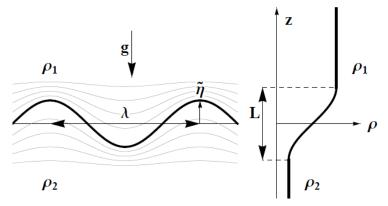
A ball can not be compressed uniformly by being squeezed between several fingers
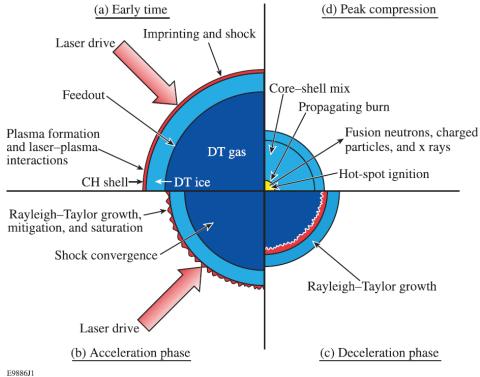
- **Stages of a target implosion**

(a) Early time
Laser drive
Imprinting and shock
Feedout
Plasma formation and laser–plasma interactions
CH shell
DT ice
DT gas

(d) Peak compression
Core–shell mix
Propagating burn
Fusion neutrons, charged particles, and x rays
Hot-spot ignition

(b) Acceleration phase
Rayleigh–Taylor growth, mitigation, and saturation
Shock convergence
Laser drive

(c) Deceleration phase
Rayleigh–Taylor growth

E9886J1

- **Rayleigh-Taylor instability**

ρ_1
g
λ
$\tilde{\eta}$
ρ_2
z
ρ_1
L
ρ
ρ_2

P.-Y. Chang, PhD Thesis, U of Rochester (2013)
R. S. Craxton, etc., *Phys. Plasmas* **22**, 110501 (2015)
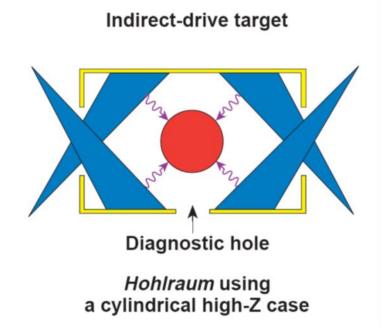
A spherical capsule can be imploded through directly or indirectly laser illumination

Direct-drive target

Capsule

Laser beams

Indirect-drive target

Diagnostic hole

Hohlraum using a cylindrical high-Z case

*R. Betti, HEDSA HEDP Summer School, 2015

Rochester is known as "The World's Image Center"

There are many famous optical companies at Rochester
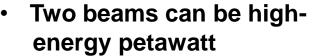

Eastman school of music

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

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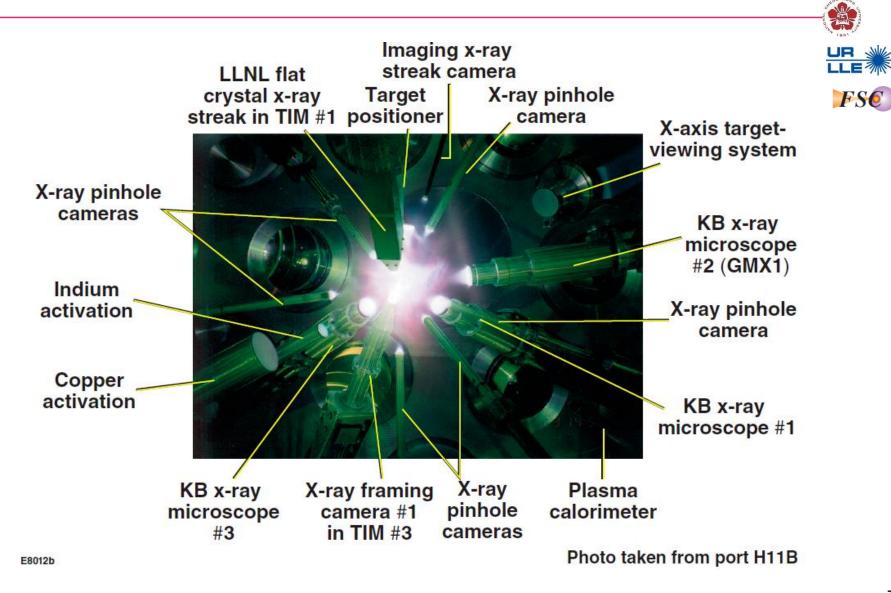   - **1%~2% irradiation nonuniformity**
    - **Flexible pulse shaping**
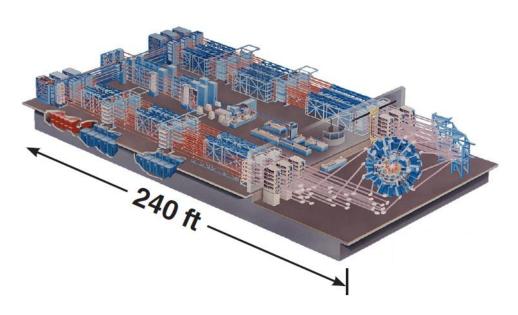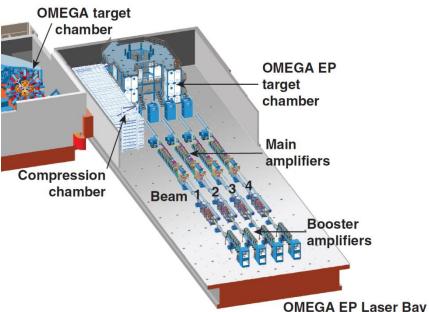
- **OMEGA EP Laser System**
    - **4 beams; 6.5 kJ UV (10ns)**
    - **Two beams can be high-energy petawatt**
        - **2.6 kJ IR in 10 ps**
        - **Can propagate to the OMEGA or OMEGA EP target chamber**

240 ft

OMEGA target chamber

OMEGA EP target chamber

Main amplifiers

Compression chamber

Beam 1 2 3 4

Booster amplifiers

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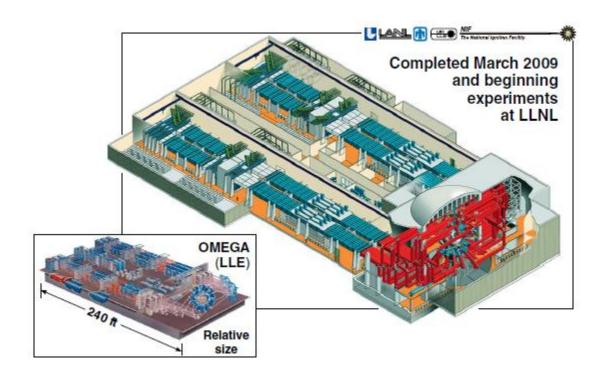
The OMEGA Facility is carrying out ICF experiments using a full suite of target diagnostics

E8012b

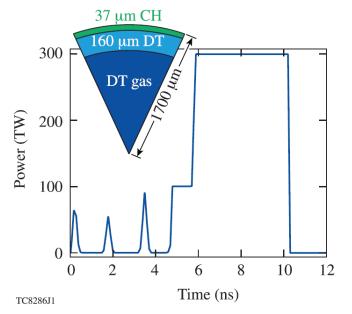# The 1.8-MJ National Ignition Facility (NIF) will demonstrate ICF ignition and modest energy gain

Completed March 2009 and beginning experiments at LLNL

OMEGA (LLE)

240 ft

Relative size

OMEGA experiments are integral to an ignition demonstration on the NIF.
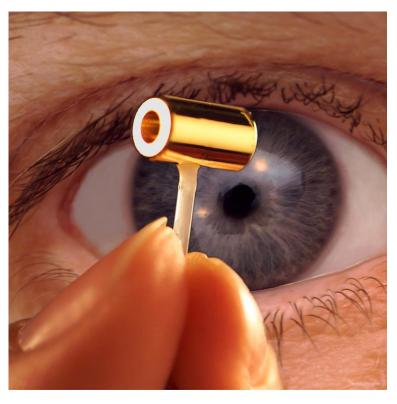
Targets used in ICF

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

37 μm CH
160 μm DT
DT gas
1700 μm

TC8286J1

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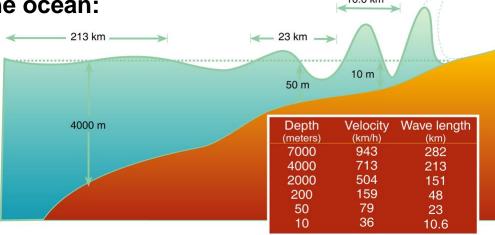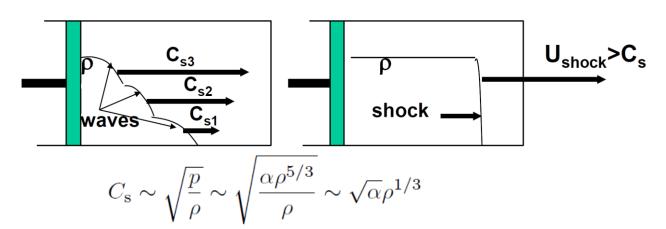
https://www.youtube.com/watch?v=uxIIdMoAwbY
https://newsghana.com.gh/wimbledon-slow-motion-video-of-how-a-tennis-ball-turns-to-goo-after-serve/

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:**

$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha \rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\, \rho^{1/3}$$
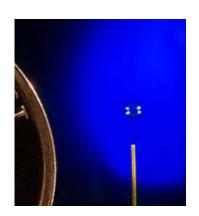
Targets used in ICF
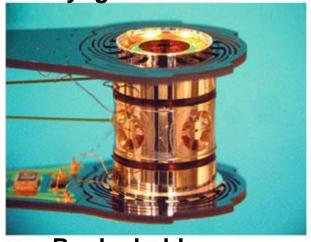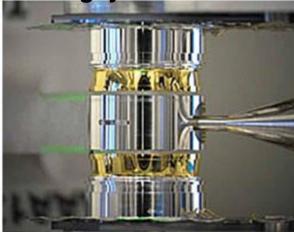
Cryogenic hohlraum
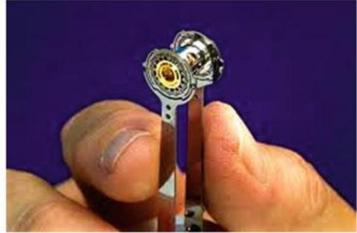
Cryogenic shroud

Rugby hohlraum
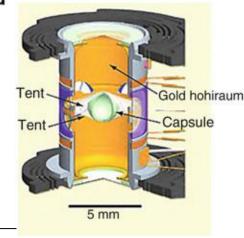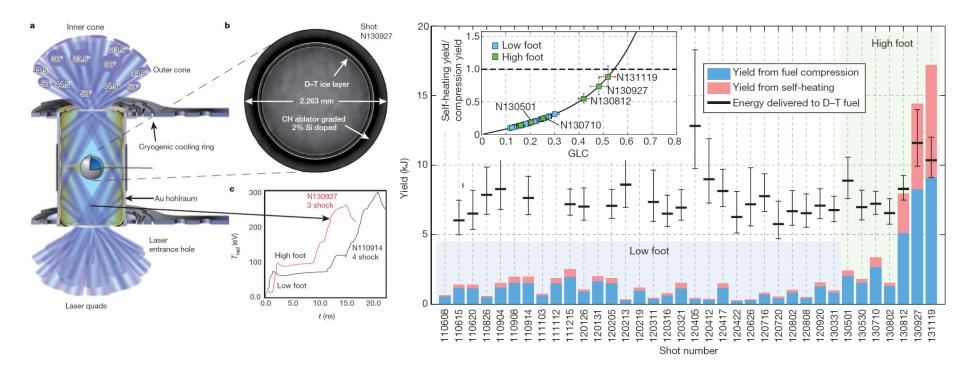
Tent holder

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
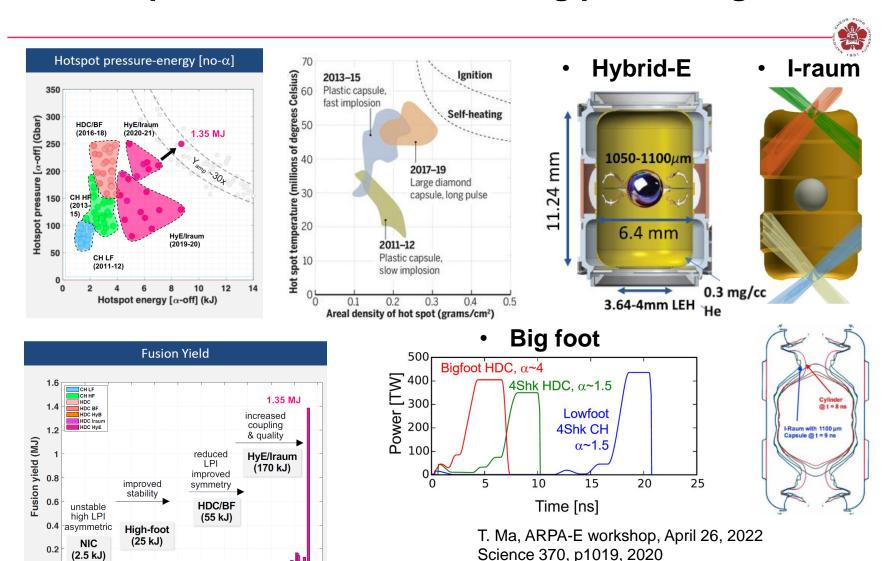https://www.llnl.gov/news/nif-shot-lights-way-new-fusion-ignition-phase

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

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

The hot spot has entered the burning plasma regime

Hotspot pressure-energy [no-α]

- ## Hybrid-E

11.24 mm
1050-1100μm
6.4 mm
3.64-4mm LEH
0.3 mg/cc He

- ## I-raum

- ## Big foot

Bigfoot HDC, α~4
4Shk HDC, α~1.5
Lowfoot 4Shk CH α~1.5

Fusion Yield
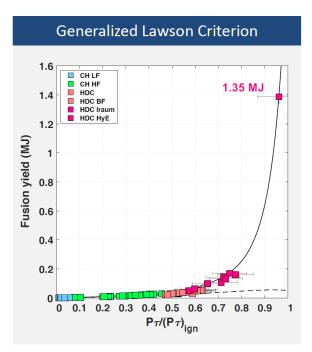
T. Ma, ARPA-E workshop, April 26, 2022
Science 370, p1019, 2020
D. T. Casey, etc., Phys. Plasmas, 25, 056308 (2018)
A. L. Kritcher, etc., Phys. Plasmas, 28, 072706 (2021)
H. F. Robey, etc., Phys. Plasmas, 25, 012711 (2018)
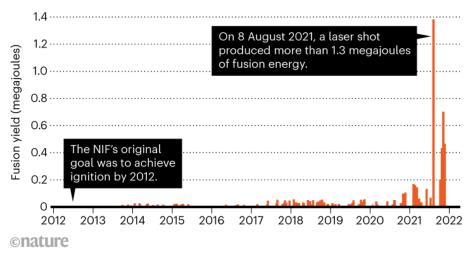
National Ignition Facility (NIF) achieved a yield of more than 1.3 MJ from ~1.9 MJ of laser energy in 2021 (Q~0.7)

Generalized Lawson Criterion

1.35 MJ

Legend: CH LF, CH HF, HDC, HDC BF, HDC Iraum, HDC HyE

Fusion yield (MJ) vs $P_T/(P_T)_{ign}$

THE ROAD TO IGNITION

The National Ignition Facility (NIF) struggled for years before achieving a high-yield fusion reaction (considered ignition, by some measures) in 2021. Repeat experiments, however, produced less than half the energy of that result.
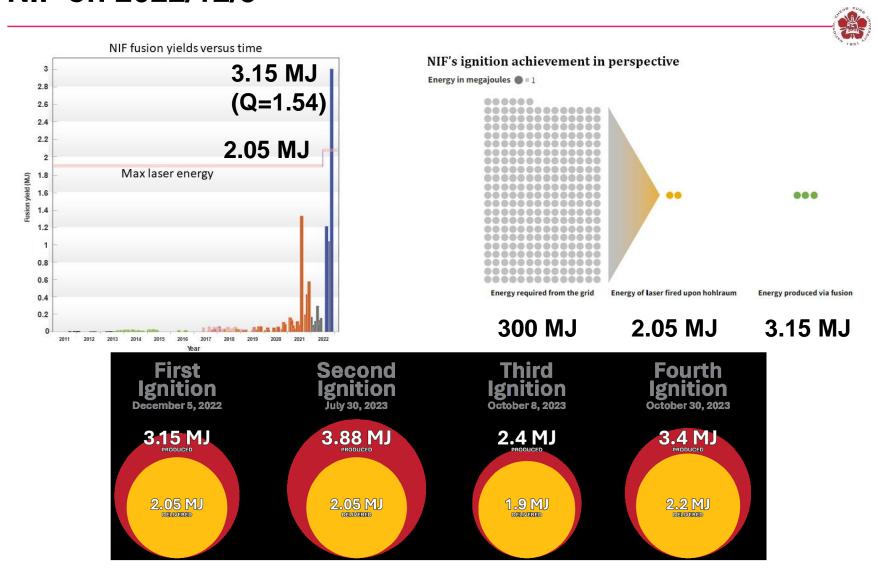
On 8 August 2021, a laser shot produced more than 1.3 megajoules of fusion energy.

The NIF's original goal was to achieve ignition by 2012.

Fusion yield (megajoules) vs years 2012–2022

©nature

- **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.**

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

NIF fusion yields versus time

3.15 MJ
(Q=1.54)

2.05 MJ

Max laser energy

NIF's ignition achievement in perspective

Energy in megajoules ● = 1

Energy required from the grid	Energy of laser fired upon hohlraum	Energy produced via fusion
300 MJ	**2.05 MJ**	**3.15 MJ**

First Ignition
December 5, 2022
3.15 MJ PRODUCED
2.05 MJ DELIVERED

Second Ignition
July 30, 2023
3.88 MJ PRODUCED
2.05 MJ DELIVERED

Third Ignition
October 8, 2023
2.4 MJ PRODUCED
1.9 MJ DELIVERED

Fourth Ignition
October 30, 2023
3.4 MJ PRODUCED
2.2 MJ DELIVERED

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
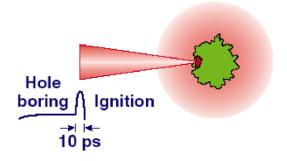
- **Shock ignition**
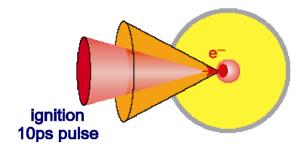
- **Fast ignition**

A shock is formed due to the increasing sound speed of a compressed gas/plasma
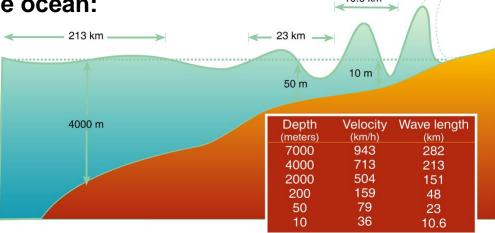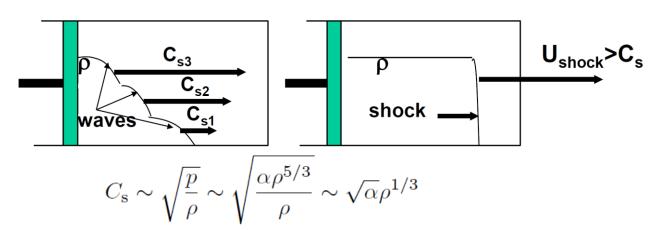
- **Wave in the ocean:**

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

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

http://neamtic.ioc-unesco.org/tsunami-info/the-cause-of-tsunamis
*R. Betti, HEDSA HEDP Summer School, 2015
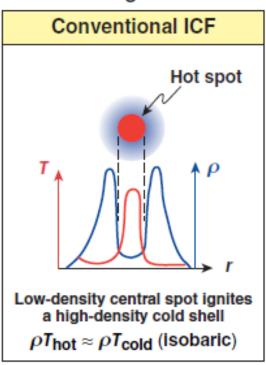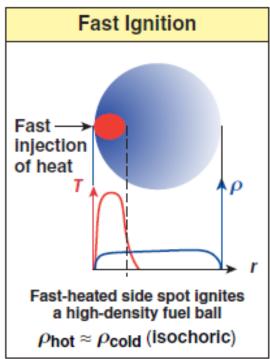
Ignition can happen by itself or being triggered externally
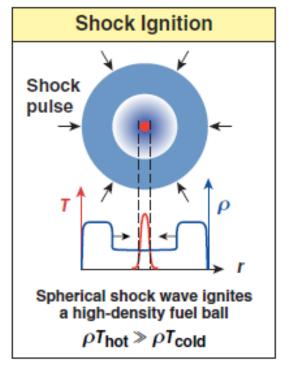
Self-ignition

External "spark" for fast ignition
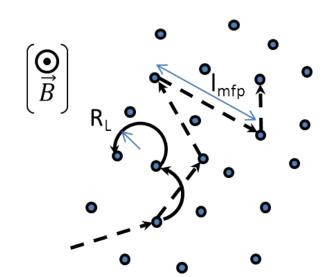
Conventional ICF

Hot spot

T ρ

r

Low-density central spot ignites
a high-density cold shell

$\rho T_{hot} \approx \rho T_{cold}$ (isobaric)

Fast Ignition

Fast
injection
of heat

T ρ

r

Fast-heated side spot ignites
a high-density fuel ball

$\rho_{hot} \approx \rho_{cold}$ (isochoric)

Shock Ignition

Shock
pulse

T ρ

r

Spherical shock wave ignites
a high-density fuel ball

$\rho T_{hot} \gg \rho T_{cold}$

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

$$\boldsymbol{q}_T = -\kappa_{\|}\nabla_{\|}\boldsymbol{T} - \kappa_{\perp}\nabla_{\perp}\boldsymbol{T}$$

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

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

- Typical hot spot conditions:
  $R_{hs} \sim 40$ μm, $\rho \sim 20$ g/cm^3, $T \sim 5$ keV:
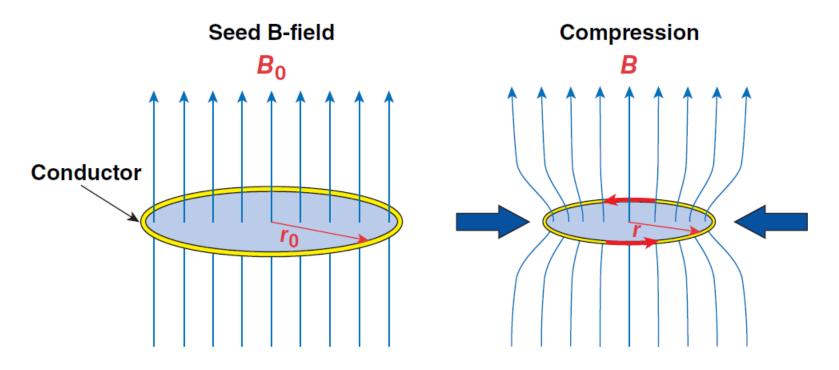
  $B > 10\,\text{MG}$ is needed for $\chi > 1$

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 <u>19</u>, 056306 (2012).
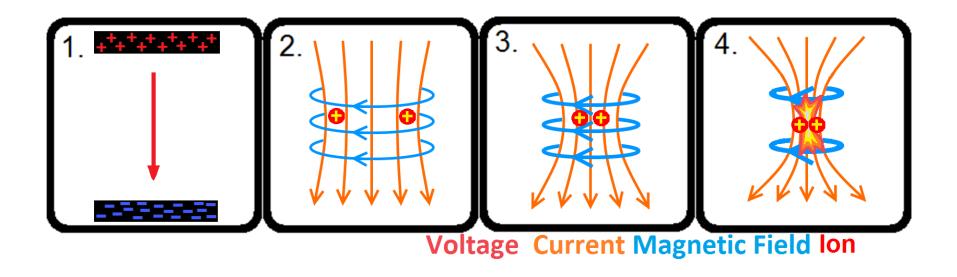
Plasma can be pinched by parallel propagating plasmas

Voltage   Current   Magnetic Field   Ion
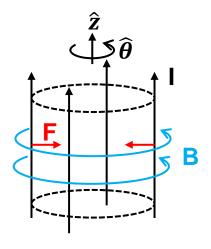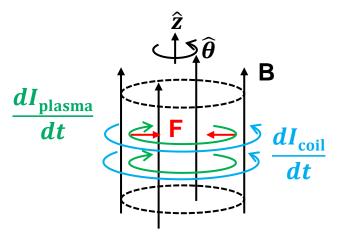
Plasma can be heated via pinches

Z pinch

Theta pinch

$$\frac{dI_{\text{plasma}}}{dt}$$

$$\frac{dI_{\text{coil}}}{dt}$$
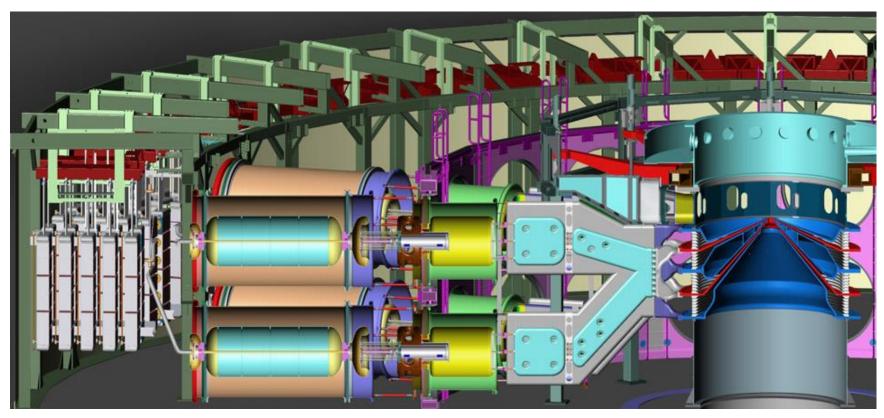
Sandia's Z machine is the world's most powerful and efficient laboratory radiation source

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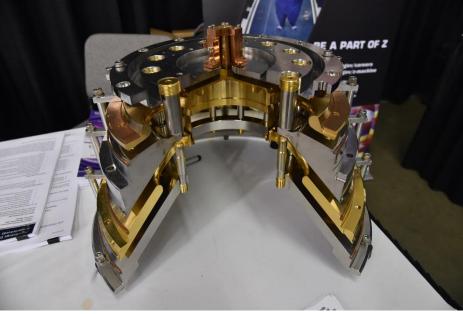
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray emissions: 350 TW
- Peak X-ray output: 2.7 MJ

Z machine

Z machine

Azimuthal drive field

Liner (Al or Be)

Cold DT gas (fuel)

~1 cm

Liner unstable but sufficiently intact

Compressed fuel at fusion temperatures
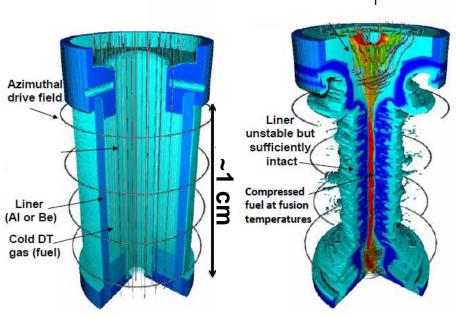
- Stored energy: 20 MJ
- Peak electrical power: 85 TW
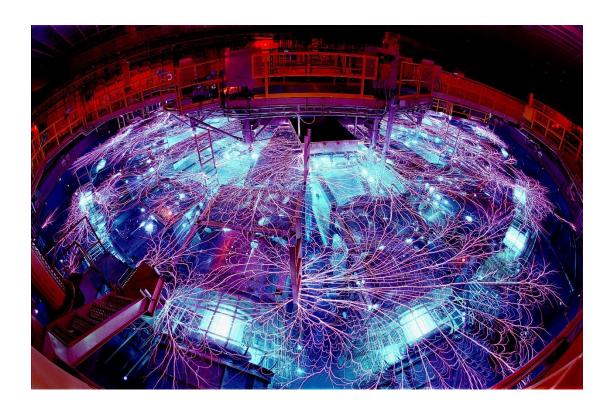
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray output: 2.7 MJ
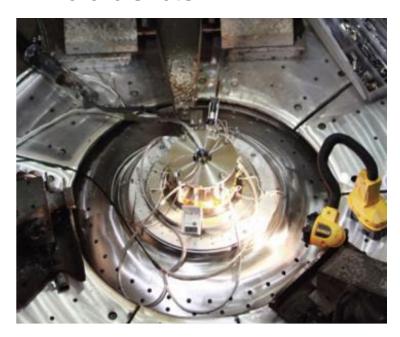
Z machine discharge
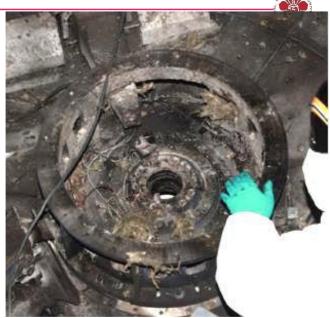
Before and after shots

- **Before shots**
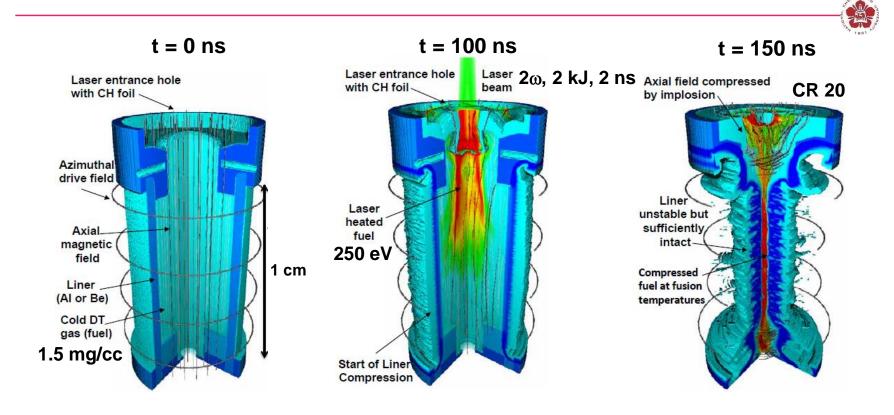
- **After shots**

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

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

t = 0 ns

Laser entrance hole with CH foil

Azimuthal drive field

Axial magnetic field

Liner (Al or Be)

Cold DT gas (fuel)

1.5 mg/cc

1 cm

t = 100 ns

Laser entrance hole with CH foil

Laser beam **2ω, 2 kJ, 2 ns**

Laser heated fuel

250 eV

Start of Liner Compression

t = 150 ns

Axial field compressed by implosion

CR 20

Liner unstable but sufficiently intact

Compressed fuel at fusion temperatures

The stagnation plasma reached fusion-relevant temperatures with a 70 km/s implosion velocity
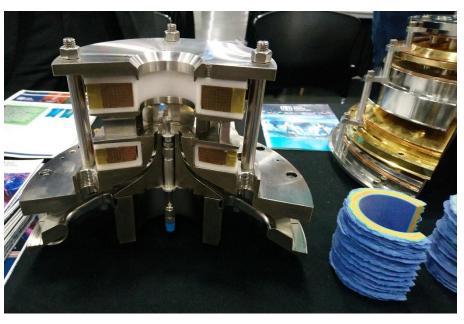
S. A. Slutz *et al* Phys. Plasmas 17 056303 (2010)
M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

MagLIF target

Azimuthal drive field

Liner (Al or Be)

Cold DT gas (fuel)

Liner unstable but sufficiently intact

Compressed fuel at fusion temperatures
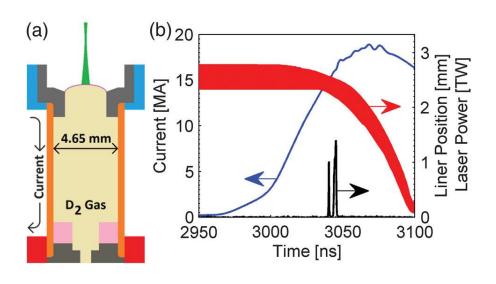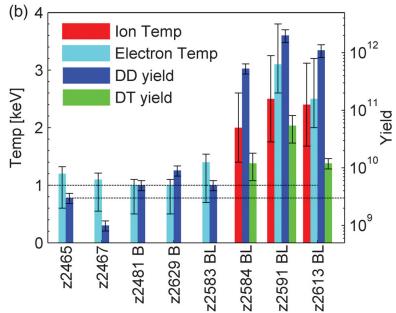
Neutron yield increased by 100x with preheat and external magnetic field.

M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)
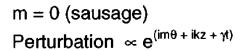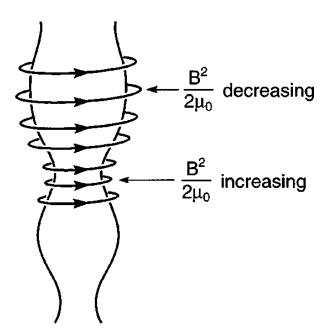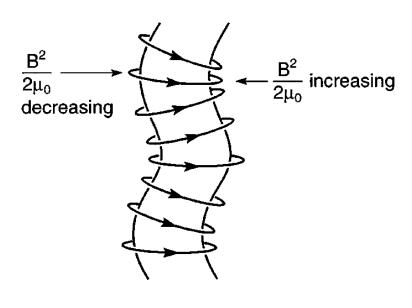
Sheered flow stabilizes MHD instabilities

m = 0 (sausage)

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

m = 1 (kink)

$$\frac{B^2}{2\mu_0} \text{ decreasing}$$

$$\frac{B^2}{2\mu_0} \text{ increasing}$$

$$\frac{B^2}{2\mu_0} \text{ decreasing}$$

$$\frac{B^2}{2\mu_0} \text{ increasing}$$
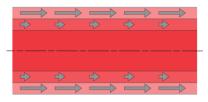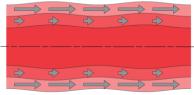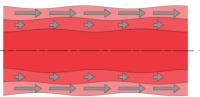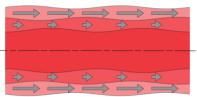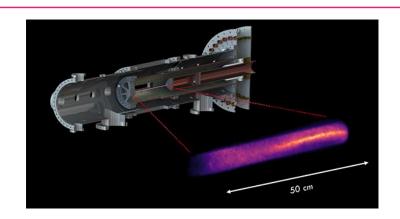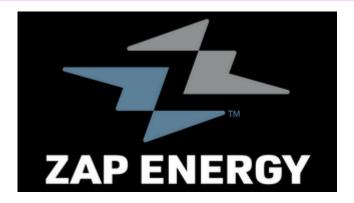
$$\frac{dV_z}{dr} \neq 0$$
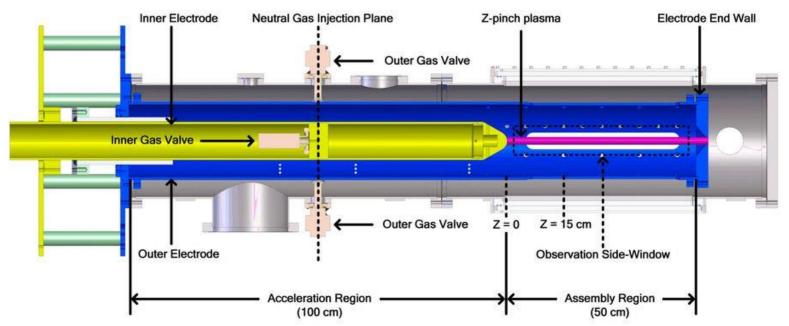
M. G. Haines, etc., Phys. Plasmas 7, 1672 (2000)
U. Shumlak, etc., Physical Rev. Lett. 75, 3285 (1995)
U. Shumlak, etc., ALPHA Annual Review Meeting 2017

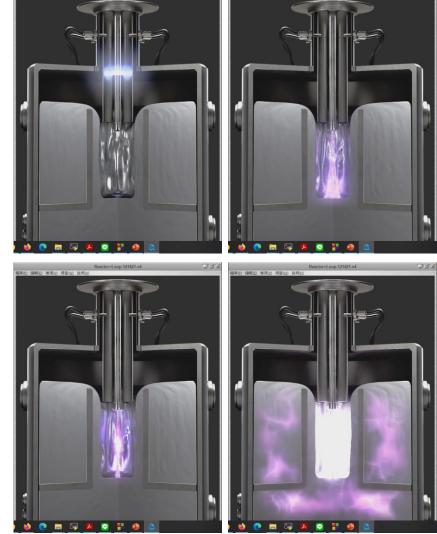# A z-pinch plasma can be stabilized by sheared flows

50 cm

ZAP ENERGY™

Inner Electrode   Neutral Gas Injection Plane   Z-pinch plasma   Electrode End Wall

Outer Gas Valve

Inner Gas Valve

Outer Gas Valve

Z = 0   Z = 15 cm

Outer Electrode

Observation Side-Window

Acceleration Region (100 cm)   Assembly Region (50 cm)
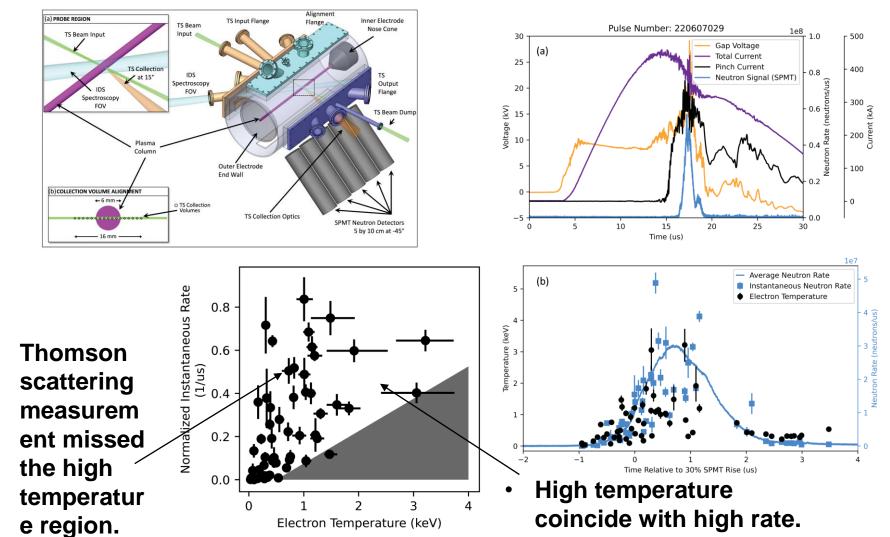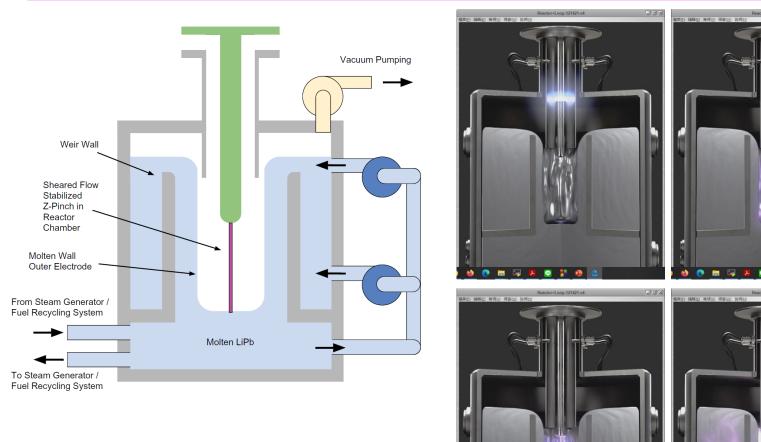
https://www.zapenergyinc.com/about
A. D. Stepanov, etc., Phys. Plasmas 27, 112503 (2020)

100

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

Vacuum Pumping

Weir Wall

Sheared Flow Stabilized Z-Pinch in Reactor Chamber

Molten Wall Outer Electrode

From Steam Generator / Fuel Recycling System

To Steam Generator / Fuel Recycling System

Molten LiPb

There are alternative

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

- **Fusion power $\propto$ B^4.**
- **The fusion gain Q > 2 is expected for SPARC tokamak.**
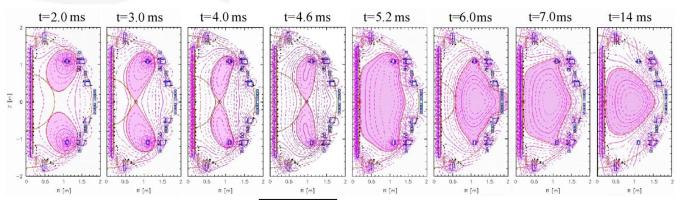
Merging compression is used to heat the tokamak at the start-up process in ST40 Tokamak at Tokamak Energy Ltd

40~60 cm

Inner vacuum chamber

Outer vacuum chamber/cryostat

Central solenoid

Merging compression coil

Toroidal field coil

Poloidal field coils

Divertor coil

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

- **Merging compression**

t=2.0 ms t=3.0 ms t=4.0 ms t=4.6 ms t=5.2 ms t=6.0 ms t=7.0ms t=14 ms
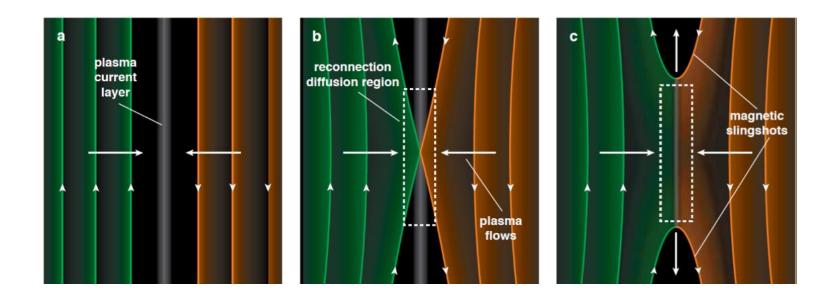
M. Gryaznevich, etc., Fusion Eng. Design, **123**,177 (2017)
https://www.tokamakenergy.co.uk/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

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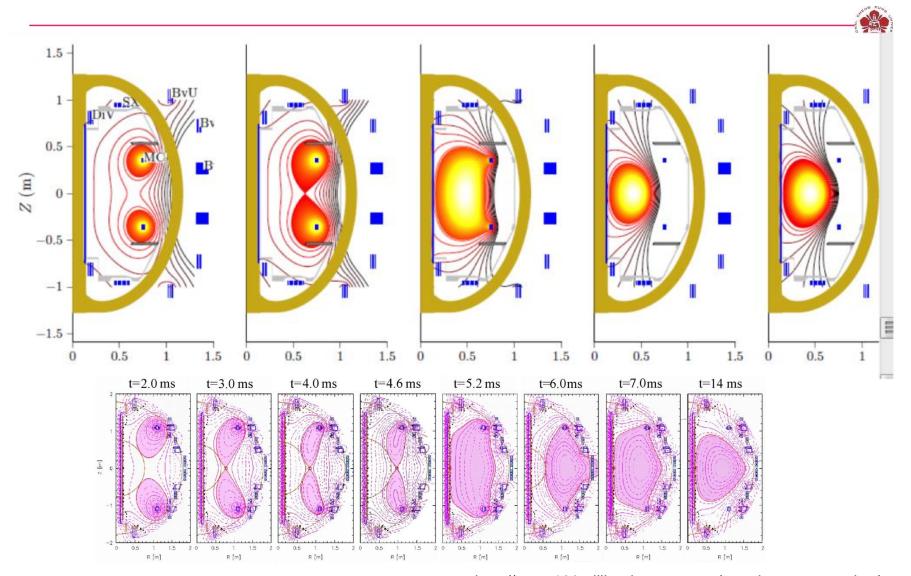
https://www.youtube.com/watch?v=7sS3Lpzh0Zw

Merging compression is used to heat the plasma
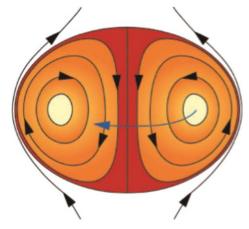
Spherical torus (ST) and compact torus (CT)

- **Spherical torus (ST)**

(a)

Large aspect ratio
(Standard tokamak)

Minor radius

Minor radius

Major Radius

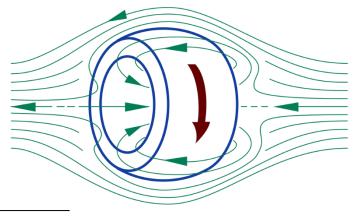*R*

Major radius

Low aspect radio
(Spherical tokamak)

- **Compact torus (CT)**

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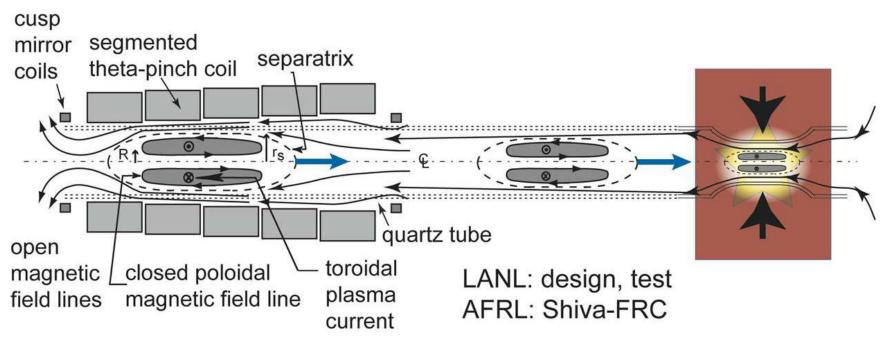
  - **Field reversed configuration (FRC)**
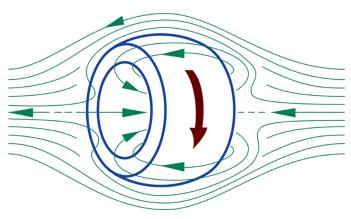
Zhe Gao, Matter Radiat. Extremes **1**, 153 (2016)
https://en.wikipedia.org/wiki/Field-reversed_configuration

Field reverse configuration is used in Tri-alpha energy

cusp mirror coils

segmented theta-pinch coil

separatrix

open magnetic field lines

closed poloidal magnetic field line

quartz tube

toroidal plasma current

LANL: design, test
AFRL: Shiva-FRC
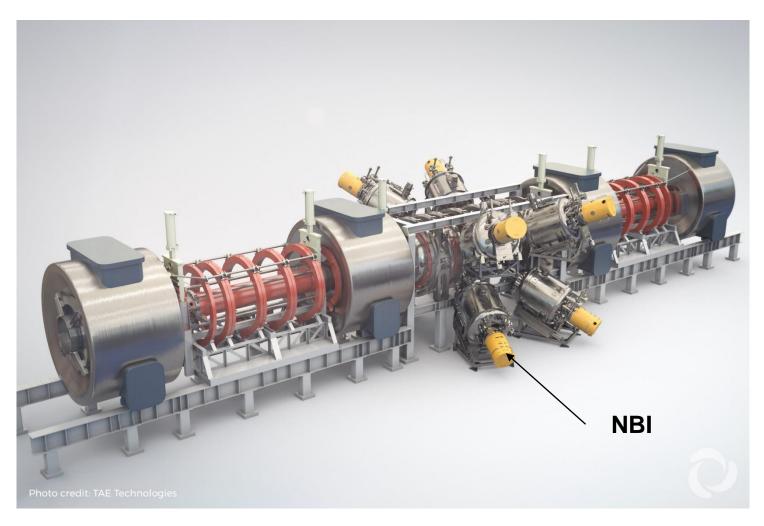
Field reverse configuration is used in Tri-alpha energy

NBI for Tri-Alpha Energy Technologies

Photo credit: TAE Technologies

NBI

https://tae.com/media/

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

Photo credit: TAE Technologies

FRC sustain longer with neutral beam injection

hg20160914.tae.2

C-2
#6359
(No Gun/NB)

C-2
HPF14, #34913
(w/ ~4 MW NBI)
20 keV H

C-2U
#42411
(w/ ~5 MW NBI)

C-2U
#43833
(w/ ~10 MW NBI)
15 keV H

C-2 HPF14
(w/ ~4 MW NBI)

C-2U
(w/ ~10 MW NBI)
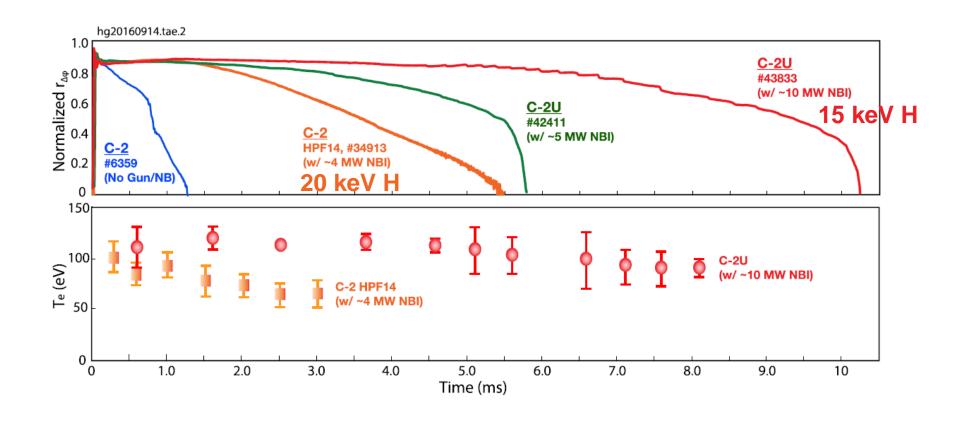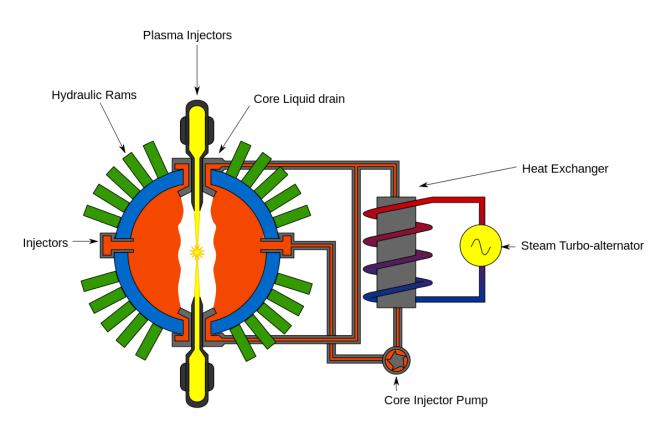
General fusion is a design ready to be migrated to a power plant

Plasma Injectors

Hydraulic Rams

Core Liquid drain

Injectors

Heat Exchanger

Steam Turbo-alternator

Core Injector Pump
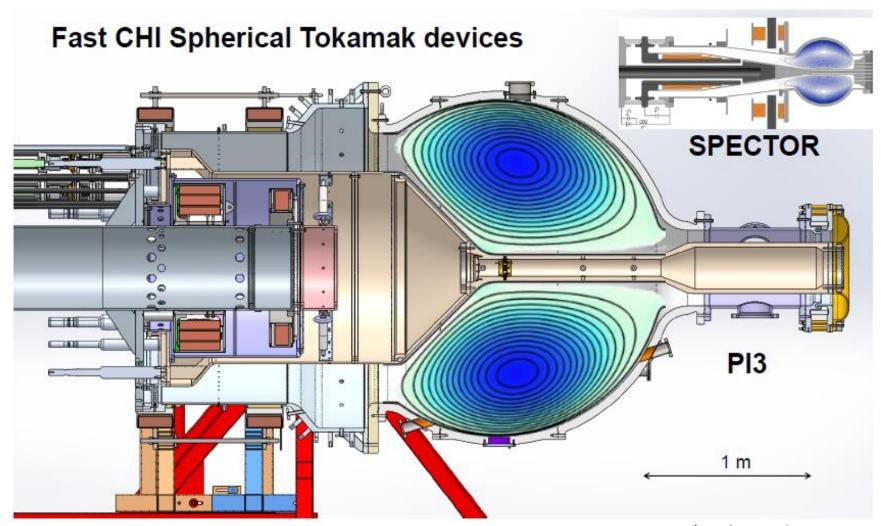
A spherical tokamak is first generated

Fast CHI Spherical Tokamak devices

SPECTOR

PI3

1 m

Plasma injector for the spherical tokamak
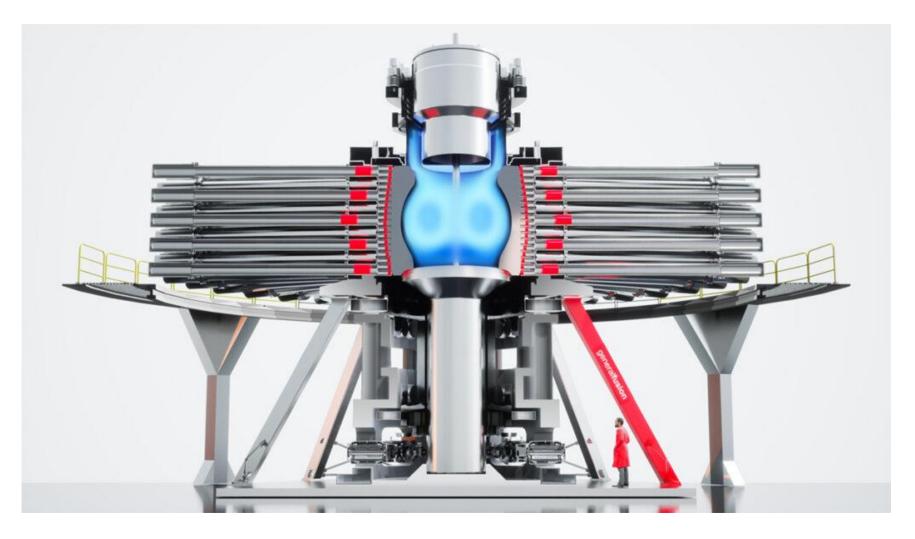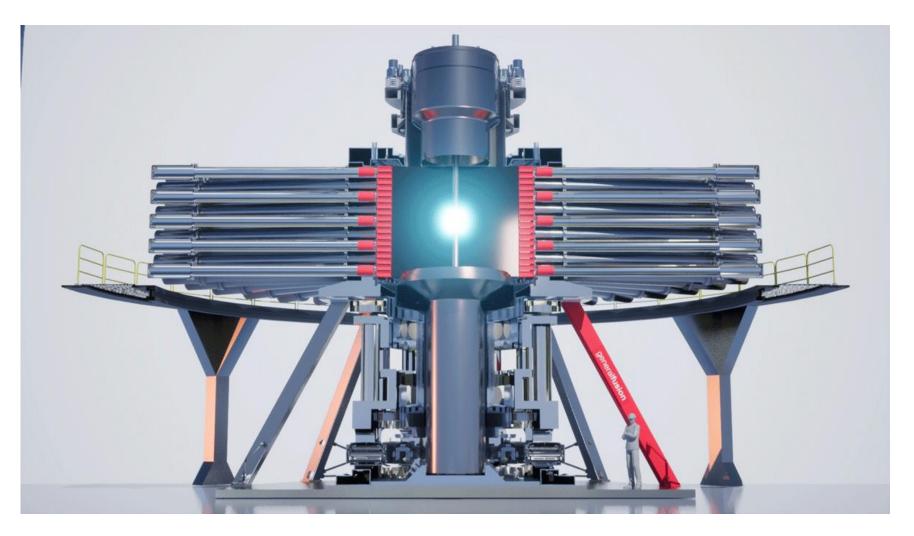
A spherical tokamak is generated in a liquid metal vortex

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

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

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

By Matt McGrath
Environment correspondent

🕐 17 June

An artist's impression of what the new demonstration plant might look like
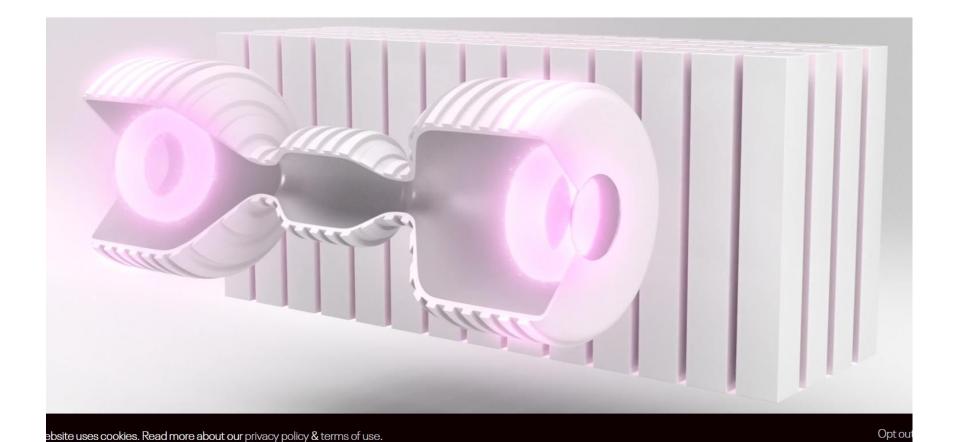
A company backed by Amazon's Jeff Bezos is set to build a large-scale nuclear fusion demonstration plant in Oxfordshire.

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

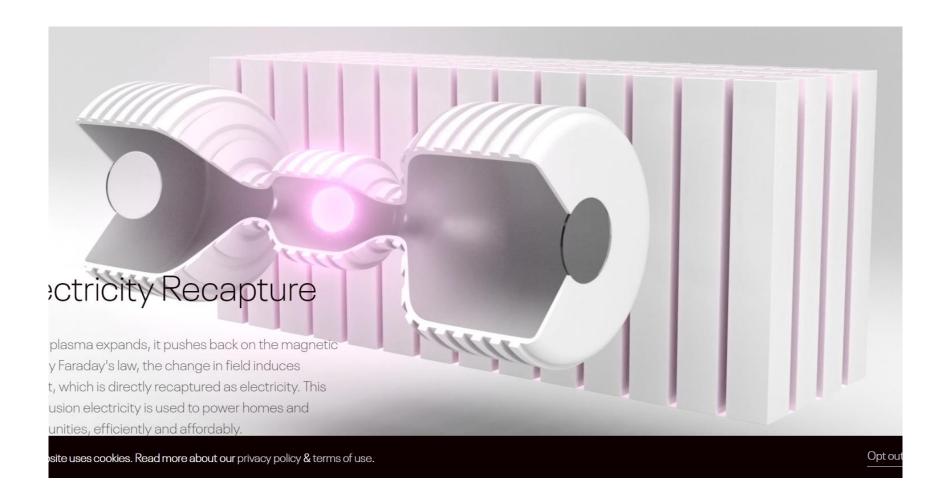# Helion energy is compressing the two merging FRCs
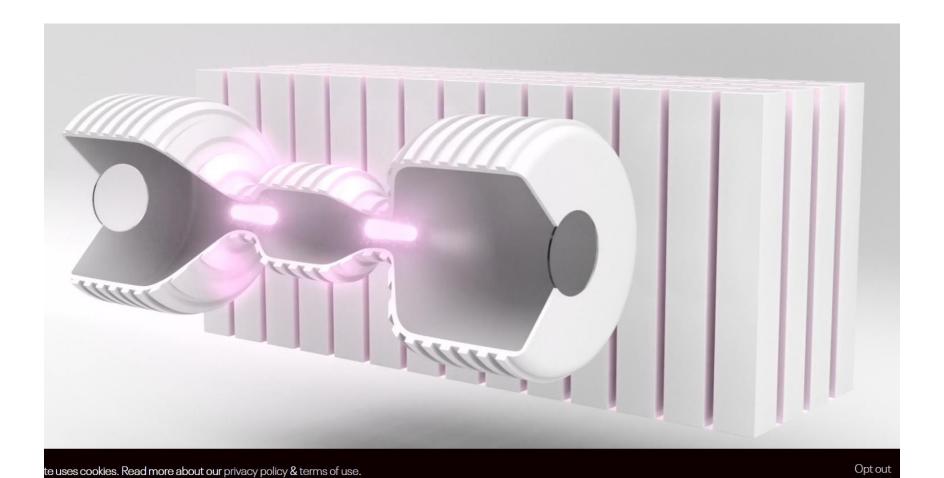
https://www.helionenergy.com/
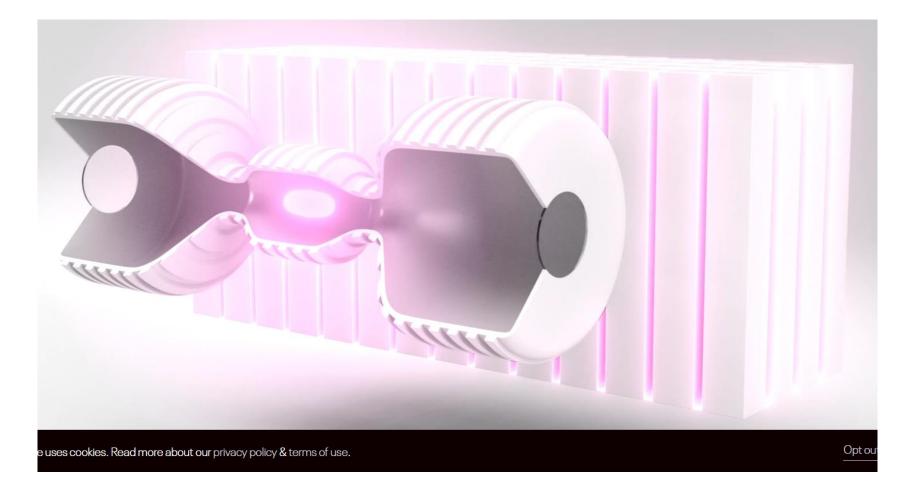
Two FRCs are accelerated toward each other

https://www.helionenergy.com/

Two FRCs merge with each other

The merged FRC is compressed electrically to high temperature

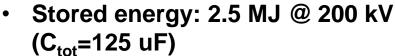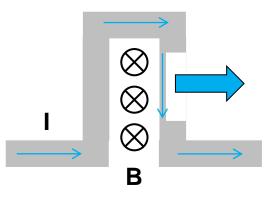e uses cookies. Read more about our privacy policy & terms of use.   Opt ou

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

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

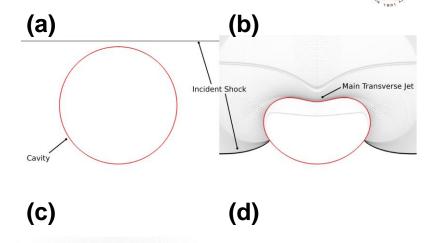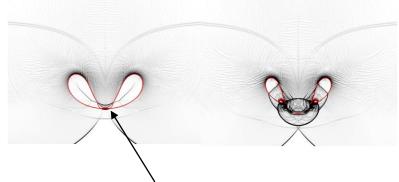- **Stored energy: 2.5 MJ @ 200 kV (C_{tot}=125 uF)**
- **I_{peak}=14 MA w/ T_{rise}~2us.**

(a)

(b)

Incident Shock

Main Transverse Jet

Cavity

(c)

(d)

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

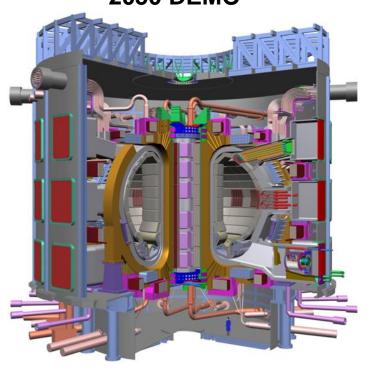# A gas gun is used to eject the projectile

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/
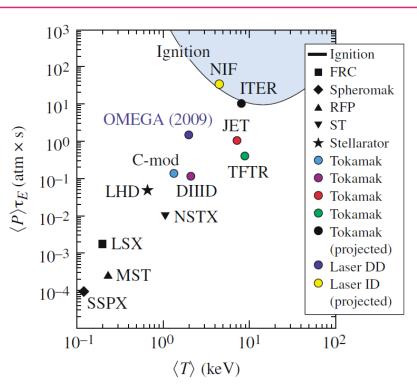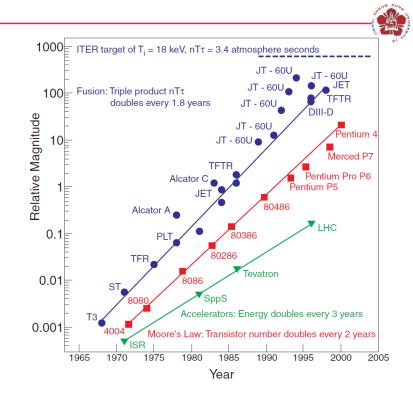https://www.psfc.mit.edu/sparc
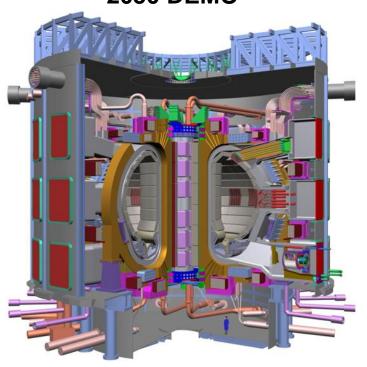
Fusion is blooming

We are closed to ignition!

- **Other private companies:**
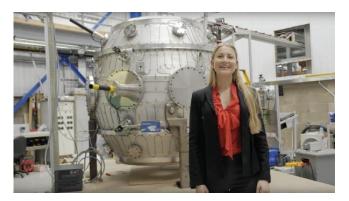

Tokamak   **MTF**   **ICF**

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

- **ITER – 2025 First Plasma**
  2035 D-T Exps
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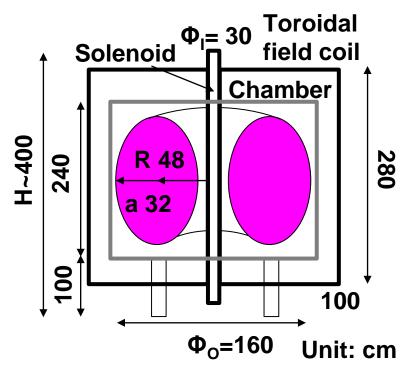- **Commonwealth Fusion Systems, USA – 2025 Gain**

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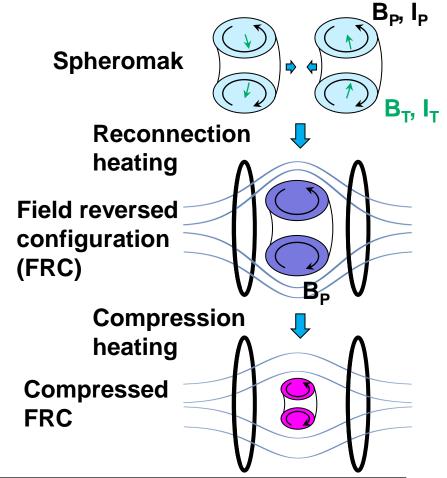https://www.psfc.mit.edu/sparc

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

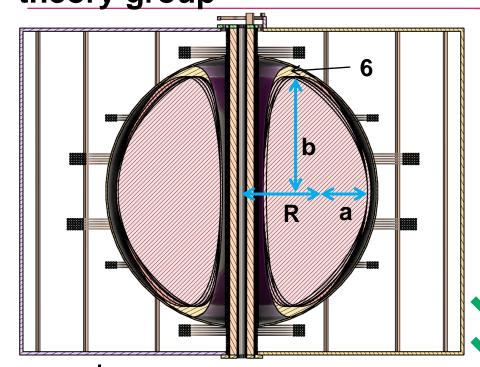 **Formosa Integrated Research Spherical Tokamak (FIRST)**

- **Magneto-inertial fusion (MIF)**

Spheromak

B_P, I_P

B_T, I_T

Reconnection heating

Field reversed configuration (FRC)

B_P

Compression heating

Compressed FRC

$\Phi_I = 30$

Solenoid

Toroidal field coil

Chamber

$H \sim 400$

240

R 48

a 32

100

280

100

$\Phi_O = 160$

Unit: cm

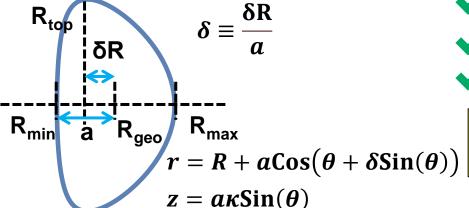- **We welcome anyone interested in fusion research to join our team!**

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

- Parameters:
  - Elongation $\kappa = b/a$
  - Triangularity δ
  - $T \sim 100$ eV
  - $B_T \sim 0.5$ T
  - $I_p \sim 100$ kA

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

$$r = R + a\cos(\theta + \delta\sin(\theta))$$

$$z = a\kappa\sin(\theta)$$

	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

- **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**

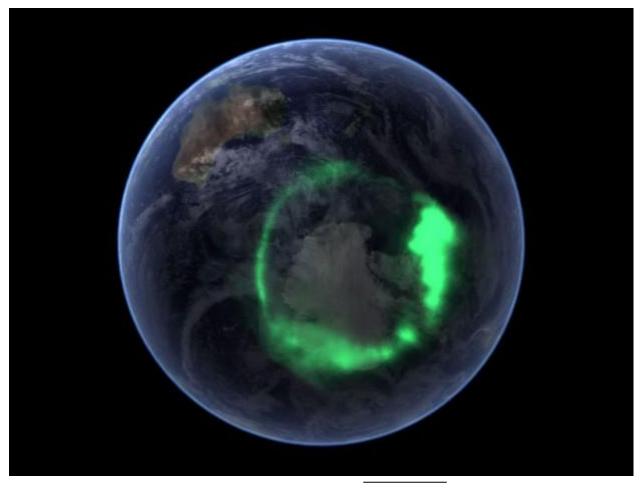- **Innovation idea – MCF + ICF**

- **Plasma in space**

- **Pulsed-power system at NCKU**

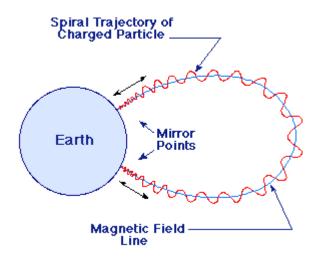# Aurora

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/
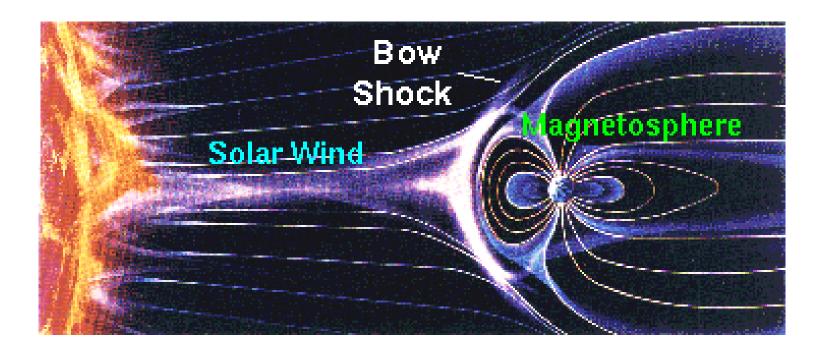
Earth's magnetic field

The Earth's Magnetic Field

North Magnetic Pole
Geographic North Pole
11.5°
Geographic South Pole
South Magnetic Pole
Peter Reid (peter.reid@ed.ac.uk), 2009

Spiral Trajectory of Charged Particle
Earth
Mirror Points
Magnetic Field Line

Earth magnetic fields are strongly influenced by solar wind

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

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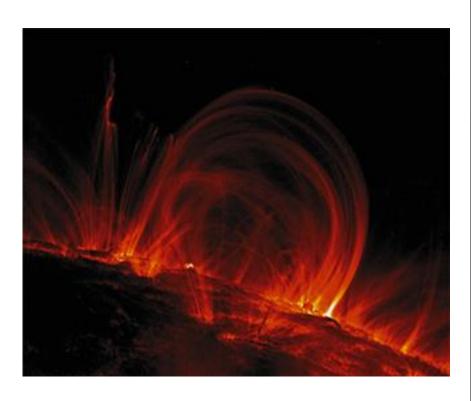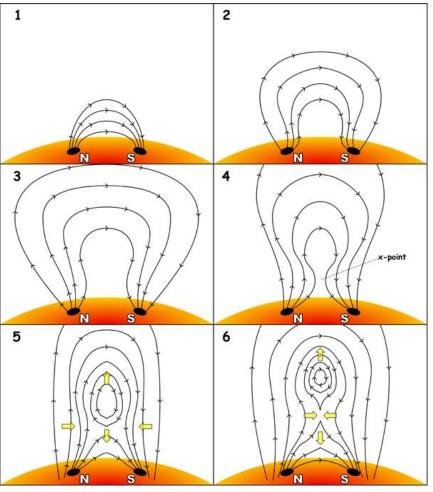
https://www.youtube.com/watch?v=7sS3Lpzh0Zw

Corona mass ejection (CME)
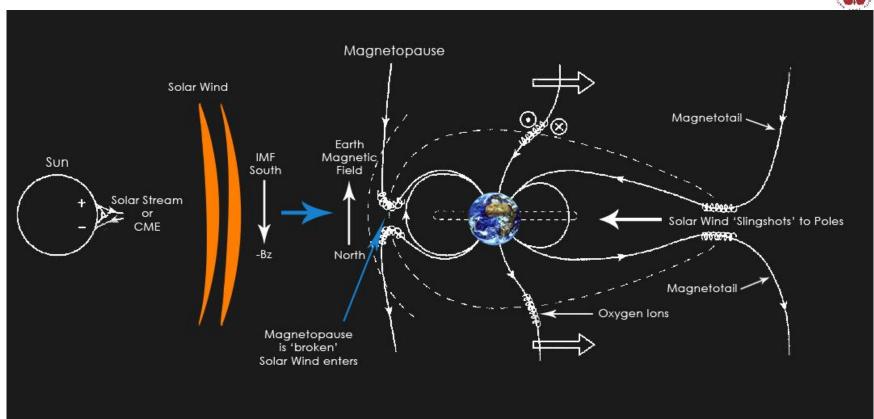
Reconnections occur in many locations
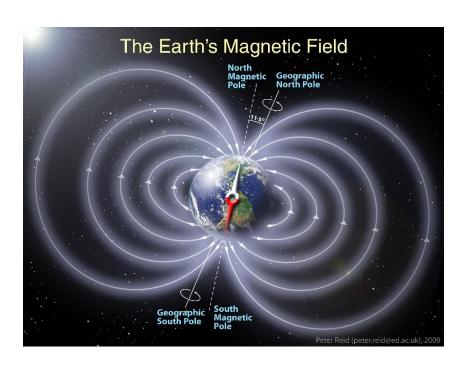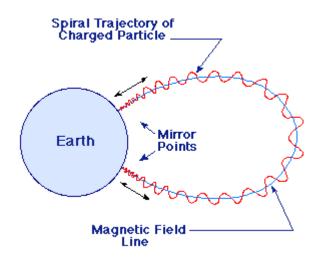
- **The Aurora Borealis:**

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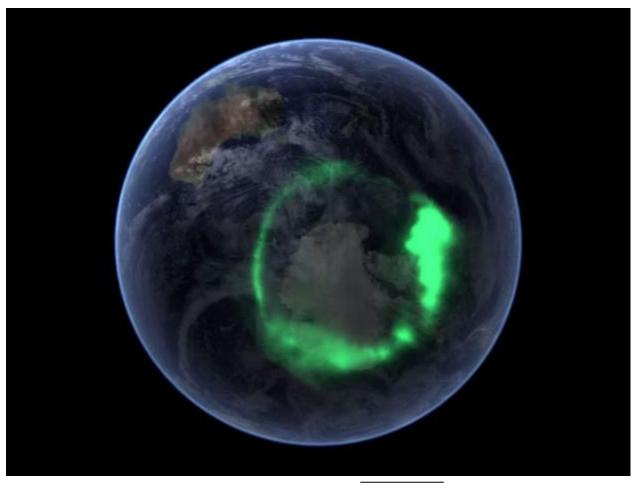http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html

Aurora

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

Aurora seen from a satellite

Neutral beam source

- **Neutral beam injection for heating plasma in Tokamak**

  – **Jure Maglica, Seminar at University in Ljubljana**

  – **Ian G. Brown, The Physics and Technology of Ion Sources**

- **Electric propulsion (plasma thrusters)**

  – **D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters**

Neutral beam source

- **Neutral beam injection for heating plasma in Tokamak**

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  - **Ian G. Brown, The Physics and Technology of Ion Sources**

- Electric propulsion (plasma thrusters)

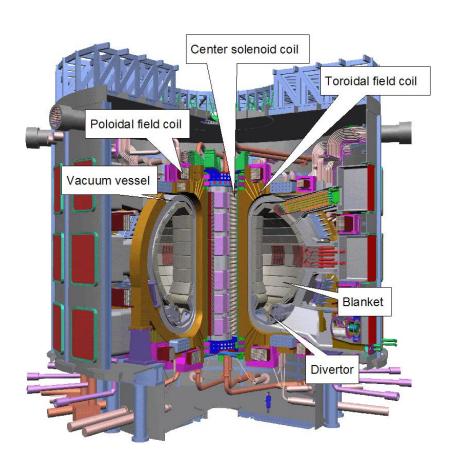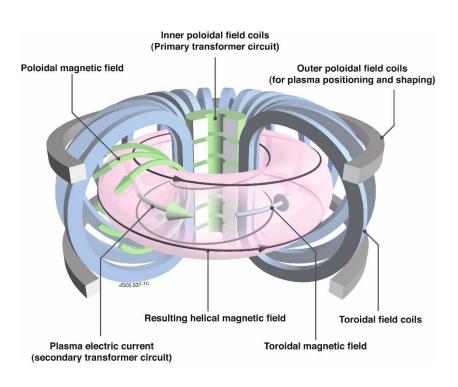 - D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters

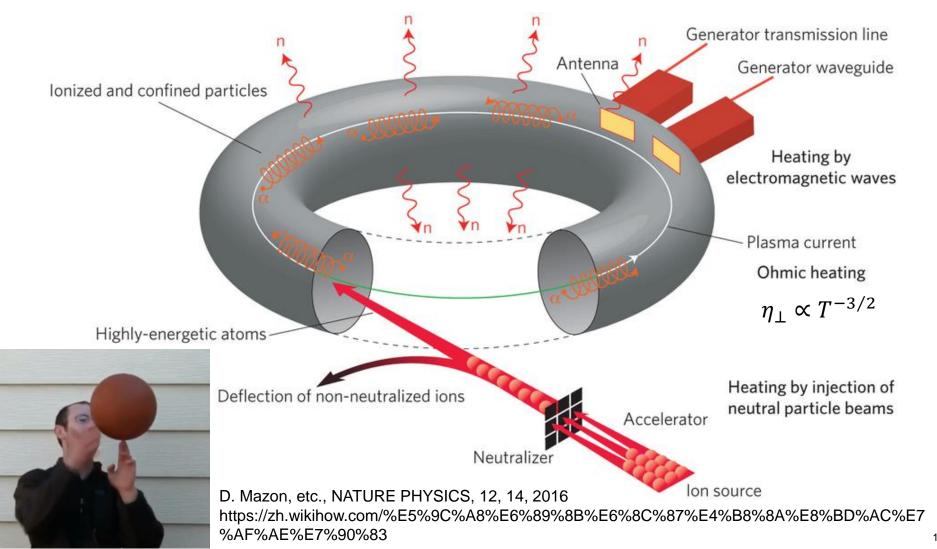# Hot plasma is confined by the magnetic field in magnetic confinement fusion

Center solenoid coil
Toroidal field coil
Poloidal field coil
Vacuum vessel
Blanket
Divertor

Inner poloidal field coils
(Primary transformer circuit)
Poloidal magnetic field
Outer poloidal field coils
(for plasma positioning and shaping)
Resulting helical magnetic field
Toroidal field coils
Plasma electric current
(secondary transformer circuit)
Toroidal magnetic field

JG05.537-1c

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

Ionized and confined particles

Highly-energetic atoms

Deflection of non-neutralized ions

Neutralizer

n n n n

Generator transmission line

Antenna

Generator waveguide

Heating by electromagnetic waves

Plasma current

Ohmic heating

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

Heating by injection of neutral particle beams

Accelerator

Ion source

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
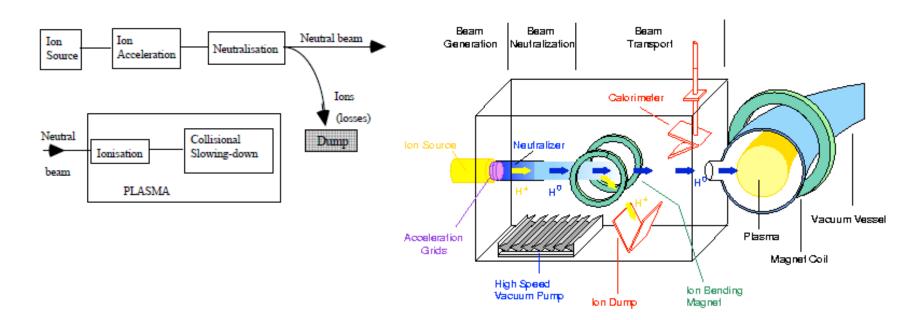
	System	Frequency/ energy	Maximum power coupled to plasma	Overall system efficiency	Development/ demonstration required	Remarks
ECRF	Demonstrated in tokamaks	28–157 GHz	2.8 MW, 0.2 s	30–40%	Power sources and windows, off-axis CD	Provides off-axis CD
	ITER needs	150–170 GHz	50 MW, SS			
ICRF	Demonstrated 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, SS			
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, SS			
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, SS	∼37%	System, tests on tokamak, plasma CD	provides rotation

'SS' indicates steady state
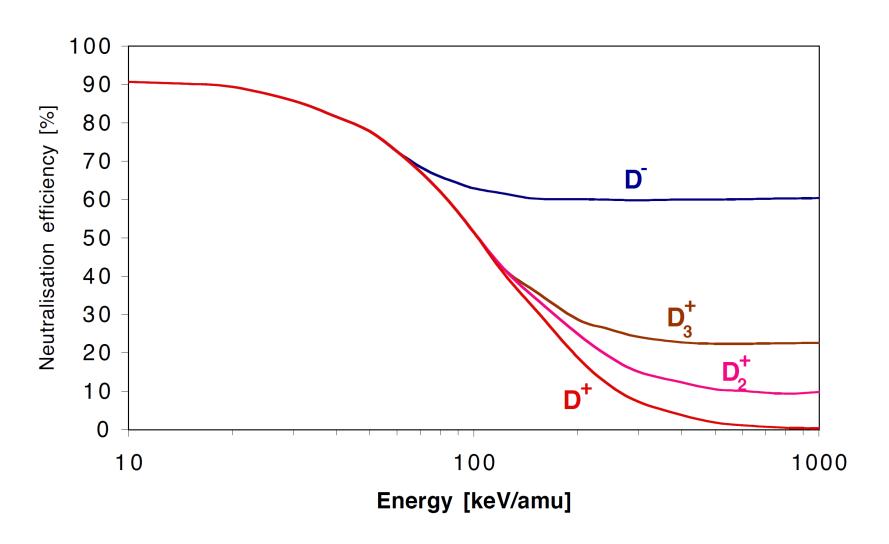
Neutral particles heat the plasma via coulomb collisions

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

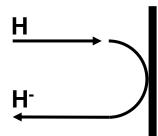# Negative ion source is preferred due to higher neutralization efficiency

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

- **Surface production, depends on :**

  - **Work function Φ**

  - **Electron affinity level, 0.75 eV for H⁻**

  - **Perpendicular velocity**

  - **Work function can be reduced by covering the metal surface with cesium**

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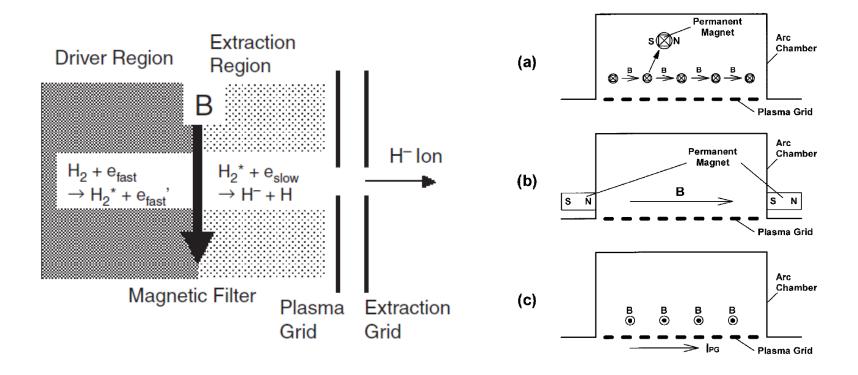
$$H^+ + 2e^- \longrightarrow H^-$$

- **Volume production:**

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

$$H_2^*(\text{excited state}) + e_{slow}(\approx 1 \text{ eV}) \rightarrow H^- + H.$$
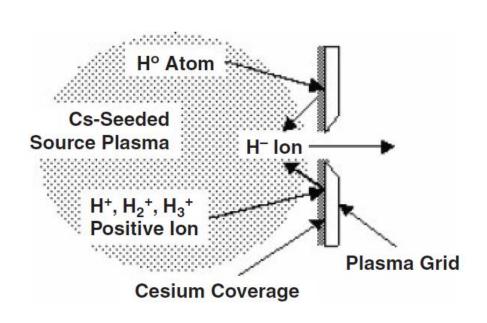
Two-chamber method of negative ions in volume production with a magnetic filter
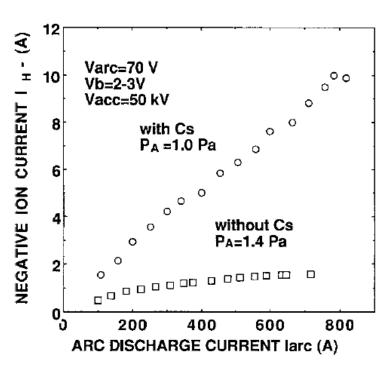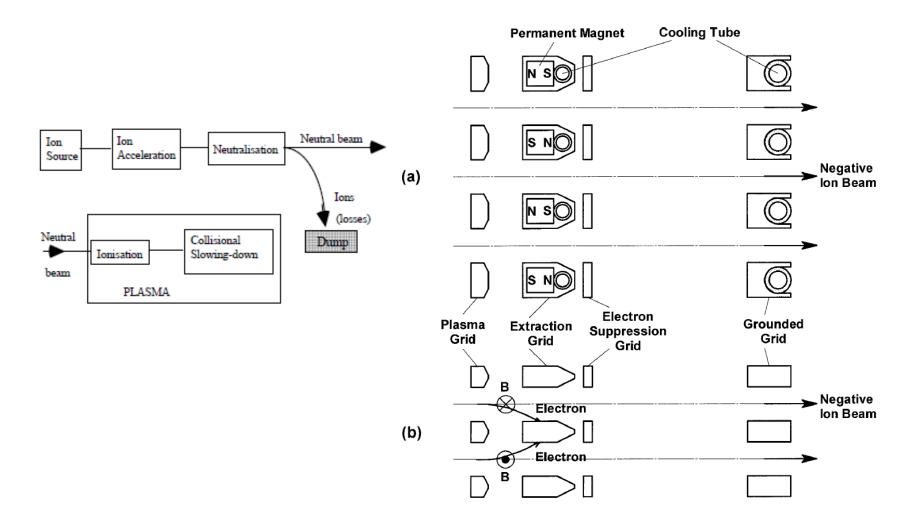
Adding cesium increases negative ion current

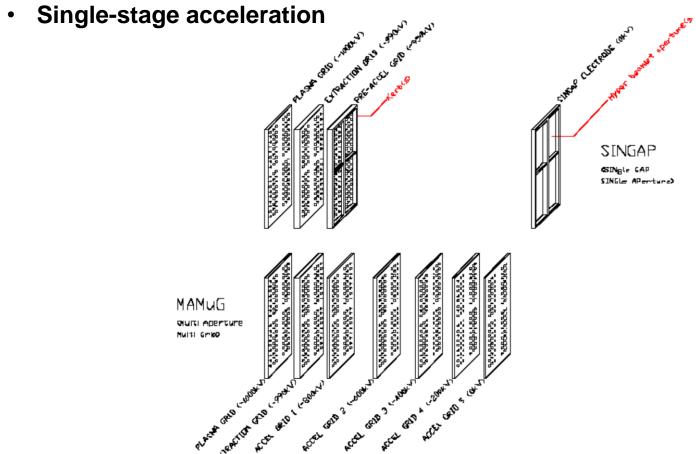# Electrons need to be filtered out since they are extracted together with negative ions

Acceleration

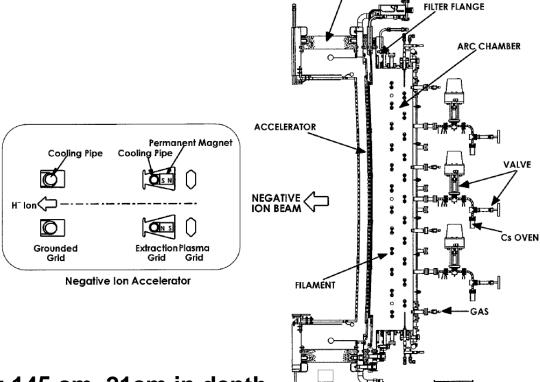- **Multi-stage acceleration**
- **Single-stage acceleration**

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

NBI system of the LHD fusion machine

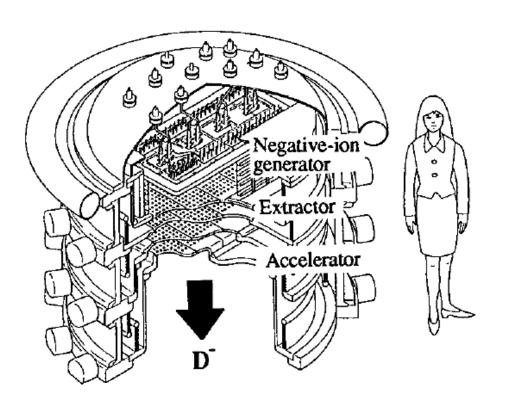- **180 keV and 30 A**
- **Arc chamber: 35 cm x 145 cm, 21cm in depth**
- **Single stage accelerator**

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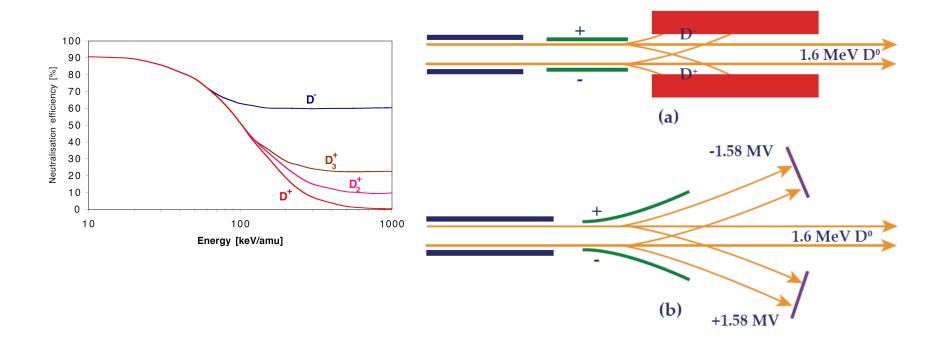
    $$H + H_2 \longrightarrow H^+ + H_2 + e^-$$

- **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**
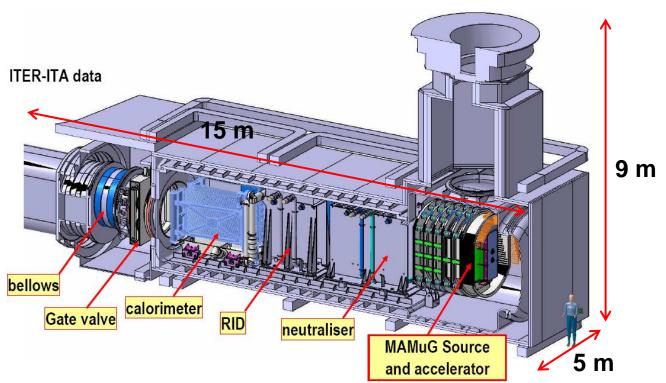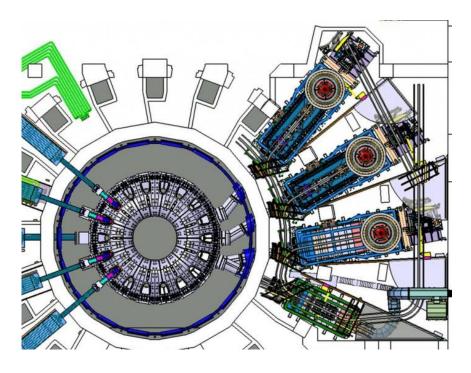
Beam dump

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
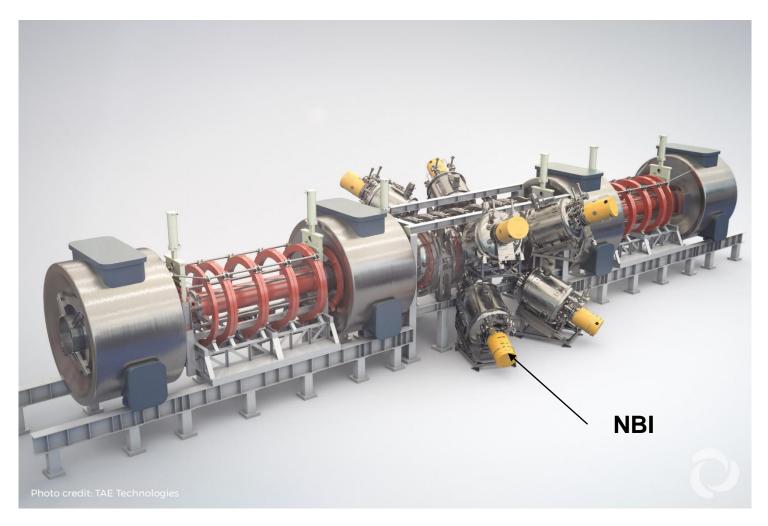
Neutral beam penetration

- **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

NBI

Photo credit: TAE Technologies

https://tae.com/media/

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

Photo credit: TAE Technologies
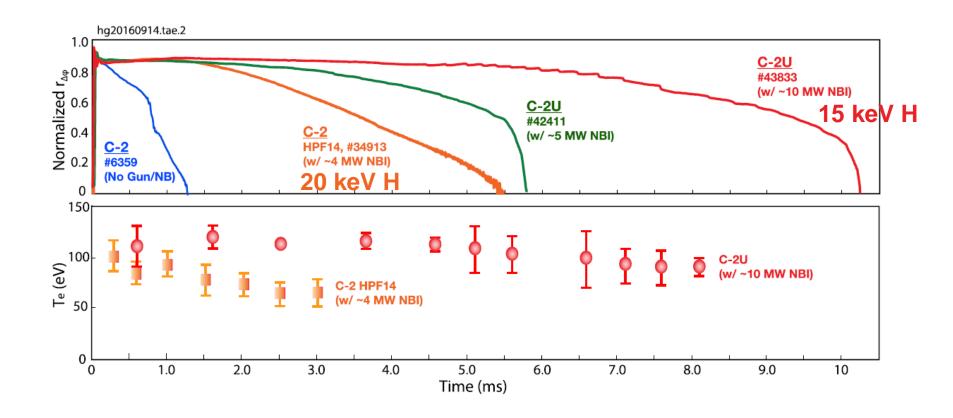
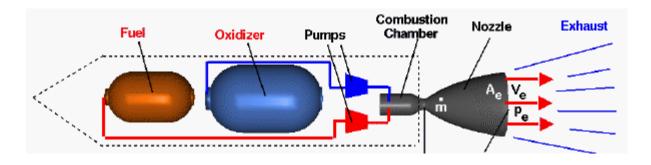# FRC sustain longer with neutral beam injection

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**
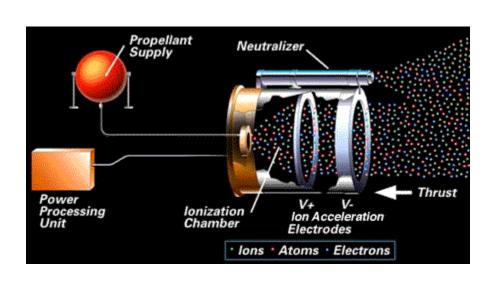
Comparison between liquid rockets and ion thrusters

- **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**
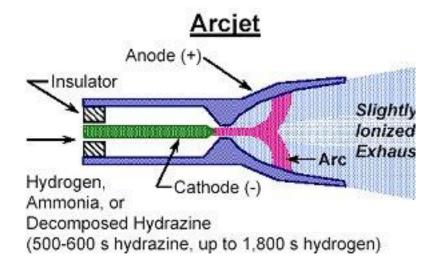
Electric thruster types - electrothermal

- **Resistojet**

- **Arcjet**

Resistojet

AC or DC Power

Hot Gas Exhaust

Hydrogen, Ammonia, or Decomposed Hydrazine
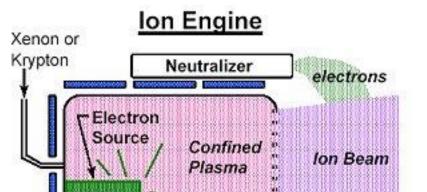300 s (hydrazine)
900 s (hydrogen)

Heater

Arcjet

Insulator

Anode (+)

Slightly Ionized Exhaust

Arc

Cathode (-)

Hydrogen, Ammonia, or Decomposed Hydrazine
(500-600 s hydrazine, up to 1,800 s hydrogen)

Electric thruster types - electrostatic
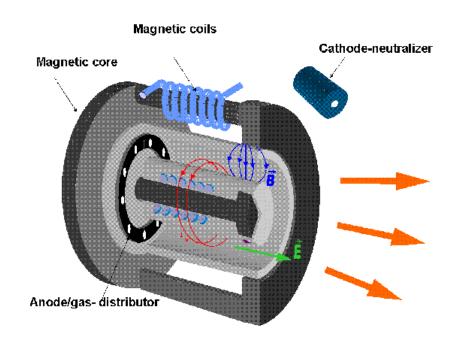
- **Ion thruster**
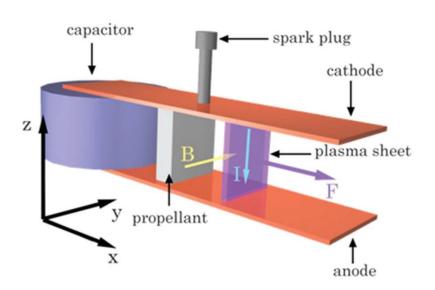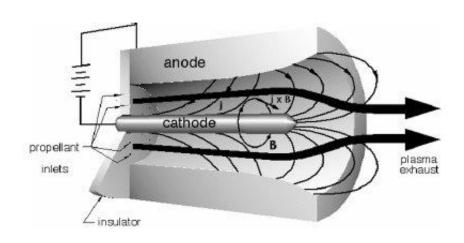- **Hall thruster**

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

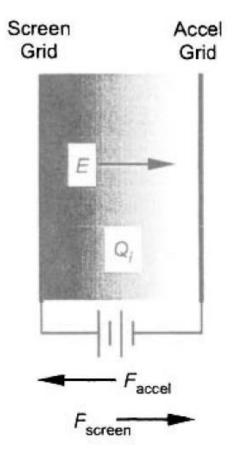$$\frac{dE(x)}{dx} = \frac{\rho(x)}{\varepsilon_0} = \frac{qn_i(x)}{\varepsilon_0}$$

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

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

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

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

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

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

Screen Grid — Accel Grid

E

Q_i

F_{accel}

F_{screen}

The rocket equation

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

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

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

$$dv \sim -v_{\mathrm{ex}} \frac{dM}{M} \quad \text{where} \quad dm_{\mathrm{p}} dv \quad \text{is neglected and} \quad dm_{\mathrm{p}} = -dM$$
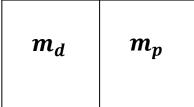
$$\int_{v_i}^{v_f} dv = -v_{\mathrm{ex}} \int_{m_d + m_p}^{m_d} \frac{dM}{M}$$

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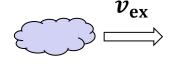
$$\boxed{\begin{aligned} m_p &= m_d [e^{\Delta \mathbf{v}/v_{\mathrm{ex}}} - 1] \\ &= m_d [e^{\Delta \mathbf{v}/(\mathbf{Isp} \times g)} - 1] \end{aligned}}$$

M

m_d | m_p

v_{ex}

Force transfer

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

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

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

Q = propellant particle flow rate in particles/s

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

M = atomic mass in kg

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

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

I_b = ion current

$$v_i = \sqrt{\frac{2qV_b}{M}}$$

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

$$-\dot{m}_i = \frac{I_b M}{q}$$
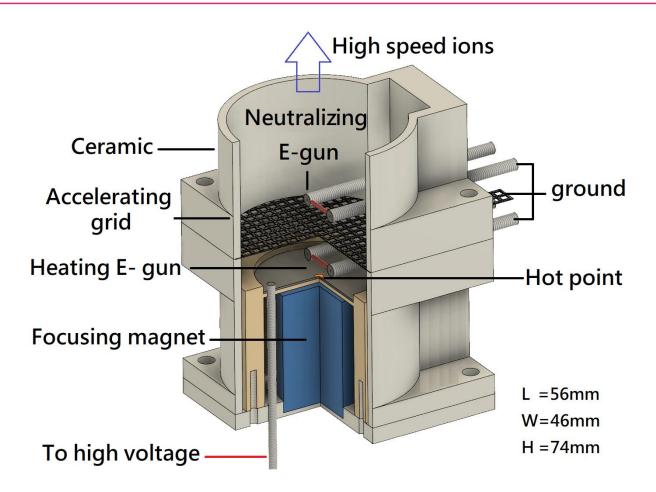
Ion thruster has the highest specific impulse (Isp)
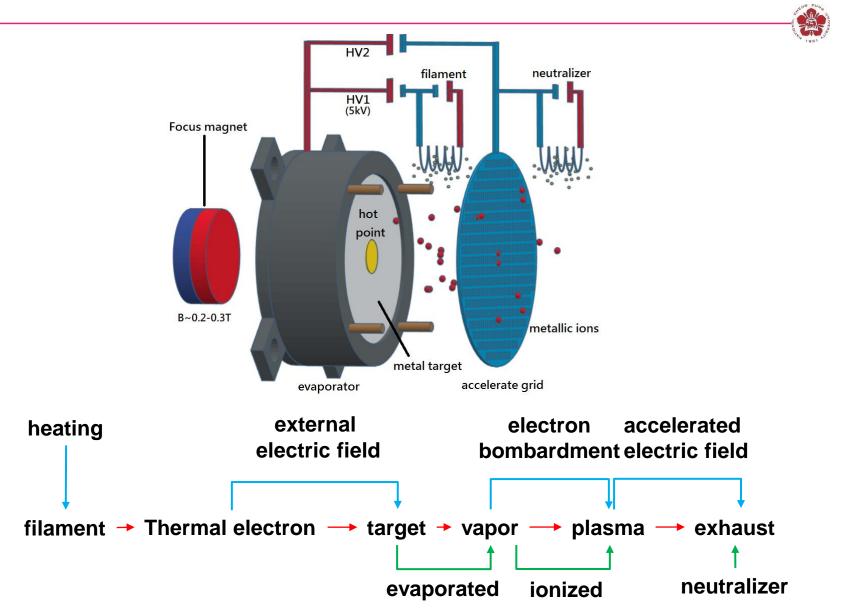
Thruster	Specific Impulse (s)	Input Power (kW)	Efficiency Range (%)	Propellant
Cold gas	50–75	—	—	Various
Chemical (monopropellant)	150–225	—	—	N_2H_4 H_2O_2
Chemical (bipropellant)	300–450	—	—	Various
Resistojet	300	0.5–1	65–90	N_2H_4 monoprop
Arcjet	500–600	0.9–2.2	25–45	N_2H_4 monoprop
Ion thruster	2500–3600	0.4–4.3	40–80	Xenon
Hall thrusters	1500–2000	1.5–4.5	35–60	Xenon
PPTs	850–1200	<0.2	7–13	Teflon

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

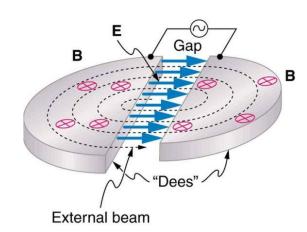# Electrons are used to generate metallic gas, metallic plasma and to neutralize ions

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

external electric field → target

electron bombardment → plasma

accelerated electric field → exhaust

evaporated → vapor

ionized → plasma

neutralizer → exhaust
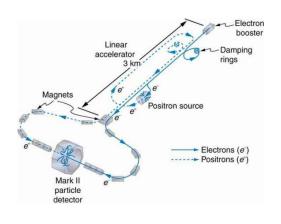
High energy particle accelerator

- **linear particle accelerator (Linac)**

- **Cyclotron**

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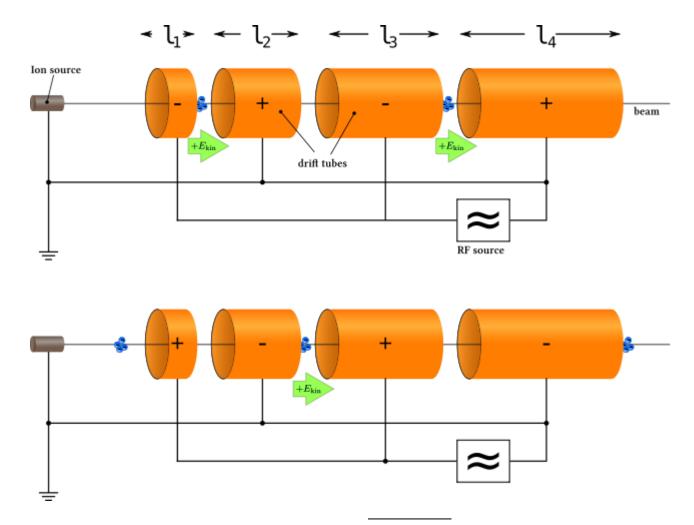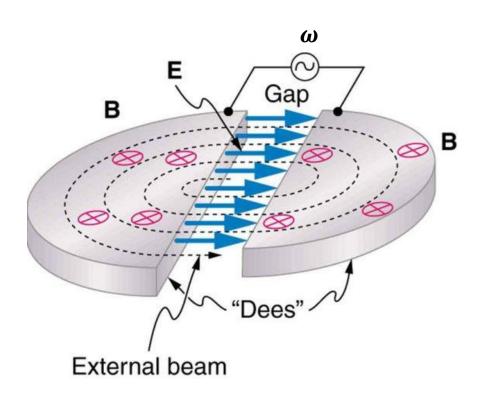
- **Reference: Introduction to plasma phenomena and plasma medicine, Y. Nishida and K.-L. Ou**

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

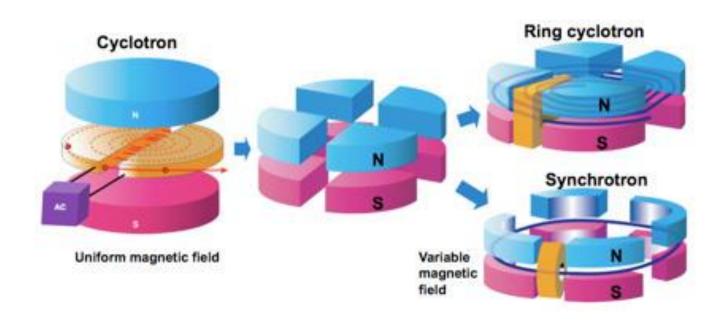# Cyclotrons use a magnetic field to cause particles to move in circular orbits

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

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

- **Cyclotron was invented by Ernest Lawrence who earned the 1939 Nobel price in physics**
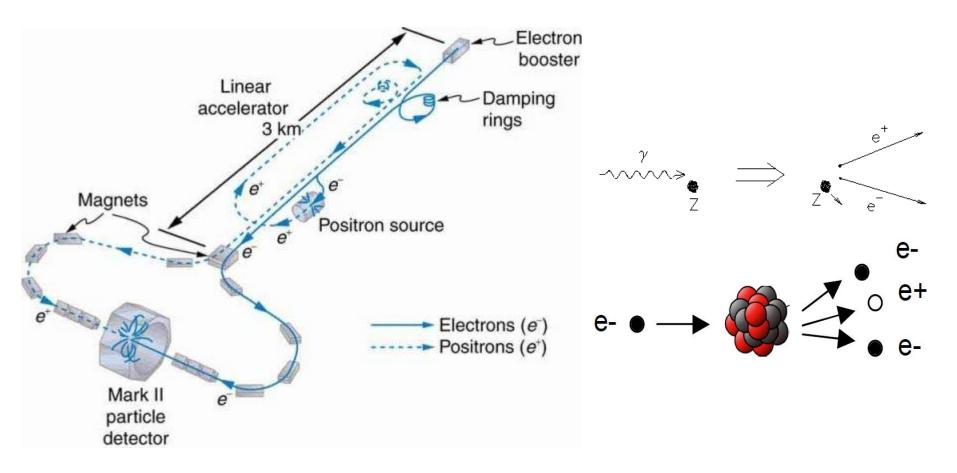
Synchrotron uses time-dependent guiding magnetic field synchronized to a particle beam

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

179

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

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)
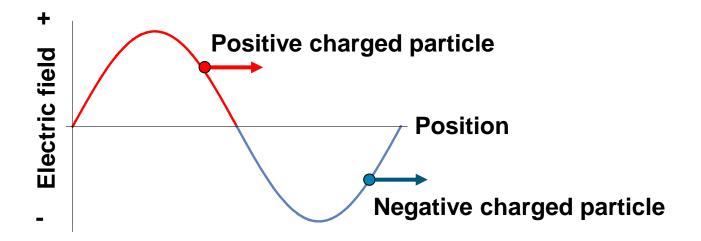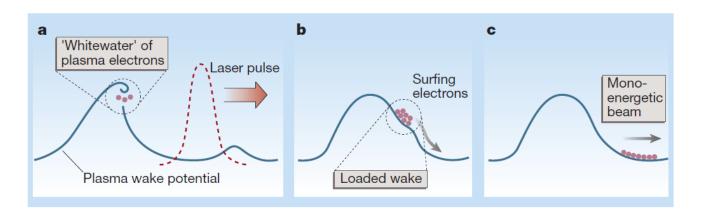
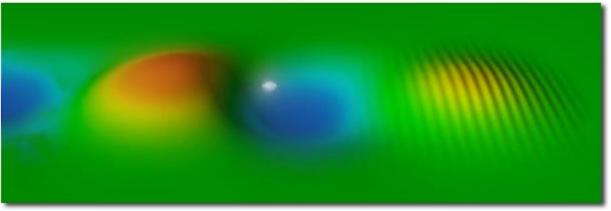# Charged particles can be accelerated in the wave electric field

Positive charged particle

Position

Negative charged particle

Electric field +/-

a
'Whitewater' of plasma electrons
Laser pulse
Plasma wake potential

b
Surfing electrons
Loaded wake

c
Mono-energetic beam

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

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

https://www.youtube.com/watch?v=VFp7SIoeAnk
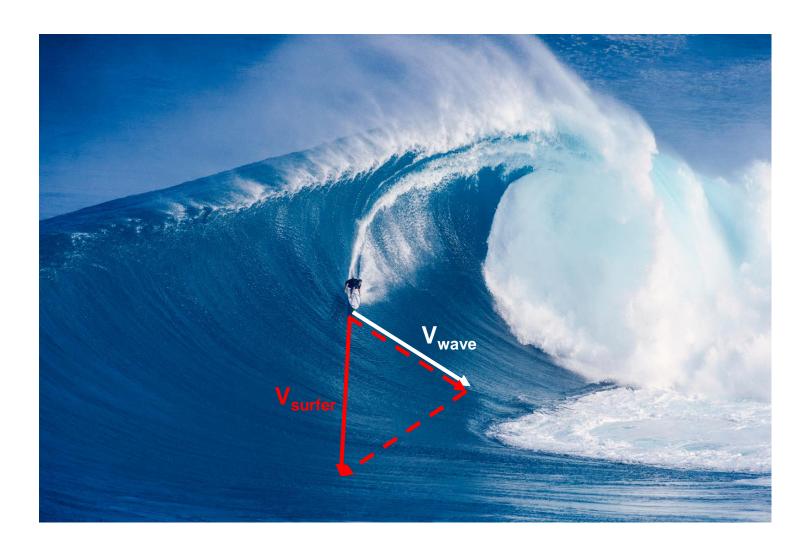
The surfer glides in a direction not parallel to the wave direction to be in phase to the wave propagation
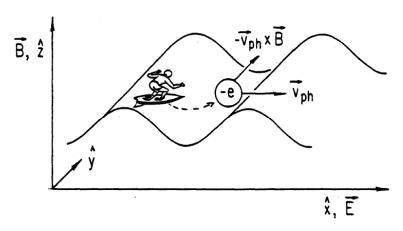
The surfer glides in a direction not parallel to the wave direction to be in phase to the wave propagation

Electrons may be accelerated to speed of light using $V_p x B$ acceleration (Surfatron)

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

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

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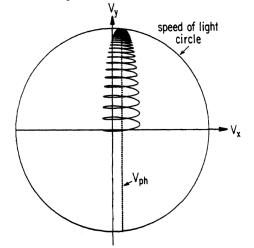
$$\frac{d}{dt}(\gamma v_x) = \frac{qE_0}{m}\sin(kx - \omega t) + \omega_c v_y$$

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

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

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

$$v_x \rightarrow v_{ph}$$

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

- T. Katsouleas, *et al.*, PRL **51**, 392 (1983)

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

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

Experimental results of $V_p \times B$ acceleration (Surfatron)
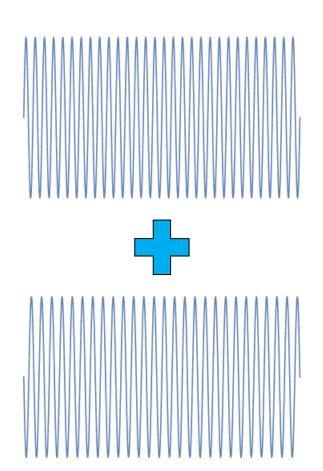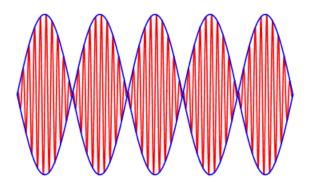
- $n_0 \sim 1\text{-}30 \times 10^{17}$ m^{-3}
- $T_e \sim 2\text{-}5$ eV

- $T_i \sim 0.1\text{-}0.2$ eV
- Microwave frequency: 3-10 GHz

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

Plasma beat wave accelerator

$$sin(x_1) + \sin(x_2) = 2\sin\left(\frac{x_1 + x_2}{2}\right)\cos\left(\frac{x_1 - x_2}{2}\right)$$
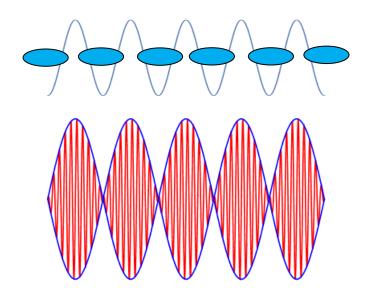
A plasma wave is driven by the laser beat wave

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

$$k_0 = k_2 - k_1$$

$$v_{\text{ph}} = v_g = c\sqrt{1 - \frac{\omega_p{}^2}{\omega_0{}^2}}$$
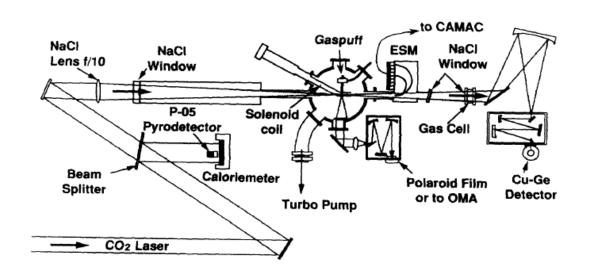
$$F = -e\nabla\phi_p = -\nabla\frac{e^2 E^{(1)} \cdot E^{(2)*}}{m\omega_1\omega_2}$$

Plasma wave

Electrons were accelerated to over 20 MeV using plasma beat wave accelerator
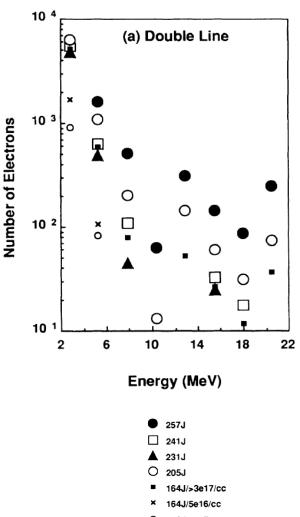
Laser: 10.6 um + 9.57 um
Intensity: $2 \times 10^{13} \sim 2 \times 10^{14}$ W/cm^2
Injected E-beam: 0.1~1 MeV
$n_0 = 3 \times 10^{16} \sim 7 \times 10^{17}$ cm^{-3}

Y. Kitagawa, *et al.*, Phys. Rev. Lett. **68**, 48 (1992)
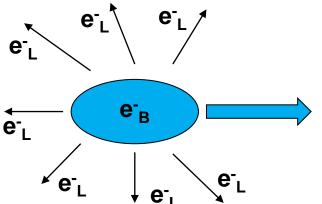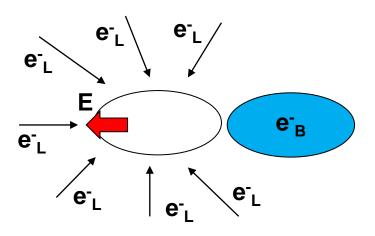
Plasma wakefield accelerator employs two beams
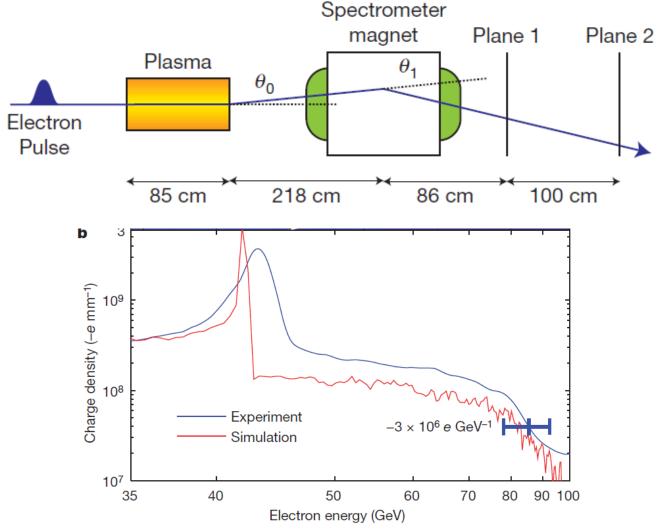
- **When a bunch of electrons enter the plasma, they expel local electrons.**
- **When the bunch of electrons leave the plasma, the local electrons try to return but oscillate around their original locations and generate a wake field behind the bunch.**
- **The longitudinal field of the wake can accelerate 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** $x_0 = \bar{x}$

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

- **Take time average:**

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

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

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

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

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

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

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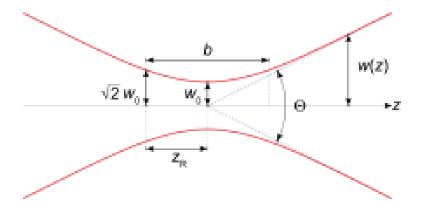
$$\boxed{F_p = m_s \ddot{x}_0 = -\frac{q_s^2}{4m_s \omega^2} \frac{d}{dx}\left(E_0^2\right)}$$

Laser is used to create a bunch in laser wakefield accelerator
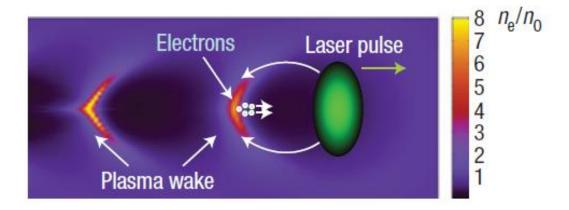
$$I(r,z) = \frac{2P}{\pi w^2(z)} \exp\left[-\frac{2r^2}{w^2(z)}\right]$$

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

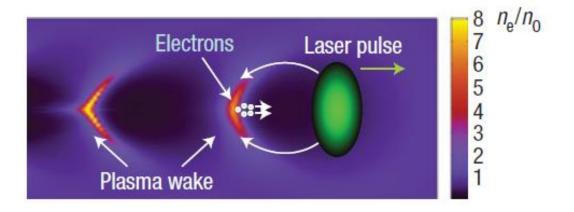- **Rayleigh length:** $z_R = \frac{\pi w_0^2}{\lambda_L}$
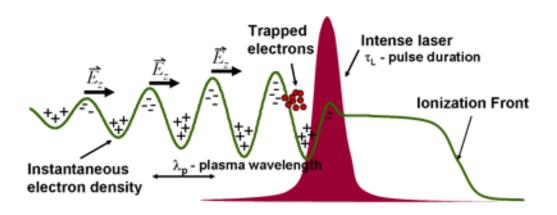
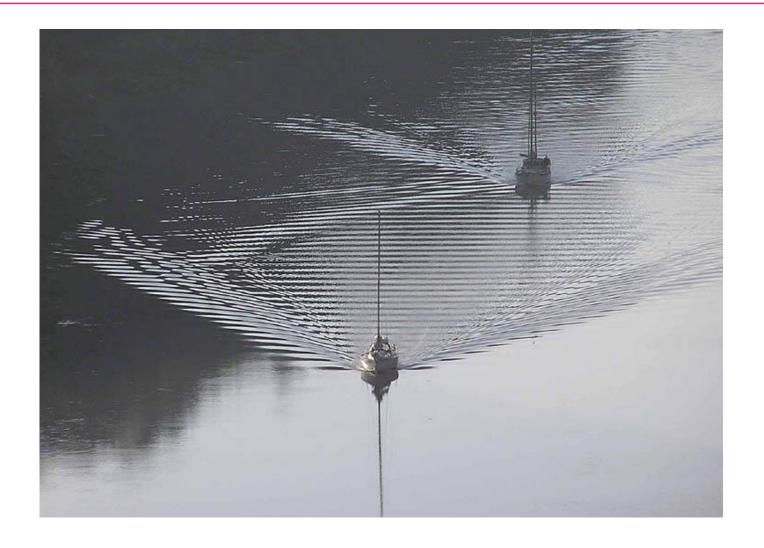# Bubble/blow-out regime

A plasma wake is generated by a short pulse laser

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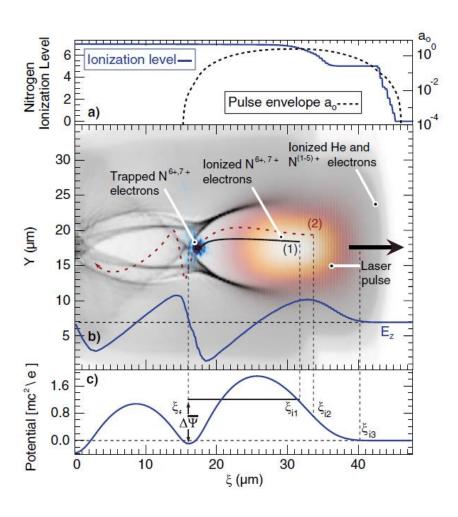http://cuos.engin.umich.edu/researchgroups/hfs/research/laser-wakefield-acceleration/

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
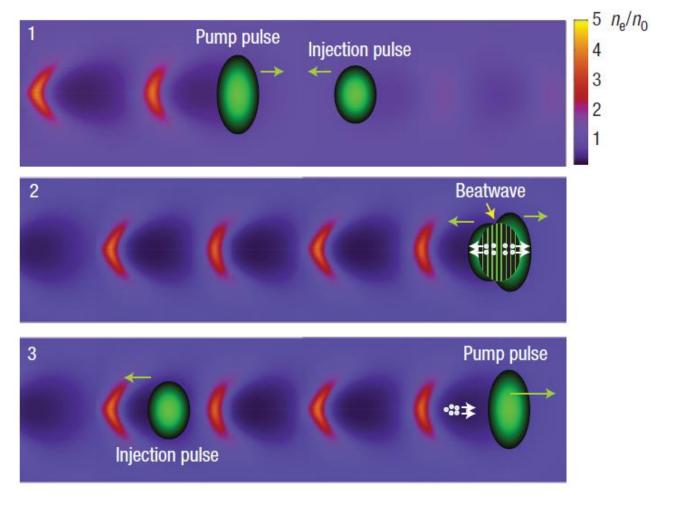
- **Large relative energy spread**

- **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)
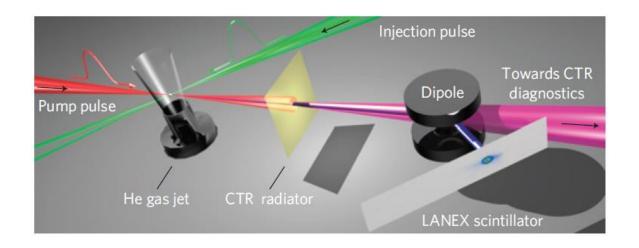
Colliding laser pulses injection
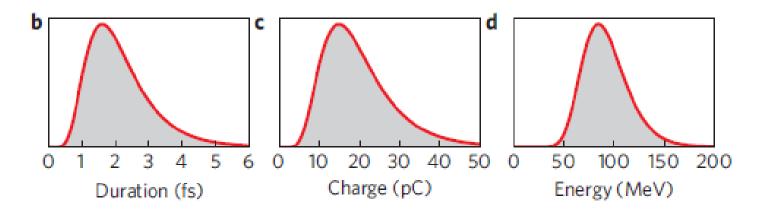
Few femtosecond, few kiloampere electron bunch is produced by a laser–plasma accelerator

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**

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**

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- Facemask regeneration

Plasma is characterized by the electron and ion temperatures

- **Non-thermal plasma**
  - $T_i \ll T_e$
  - **Also called non-equilibrium plasma**
- **Thermal plasma**
  - $T_i \approx T_e$
- **Earlier applications of plasma in medicine – thermal effects of plasma**
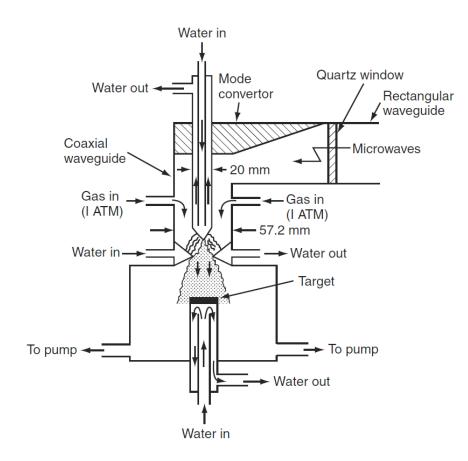
Plasma can provide good surface treatment with low temperature
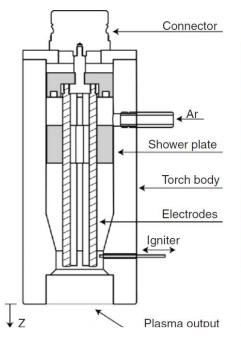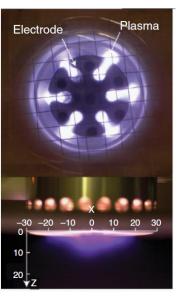
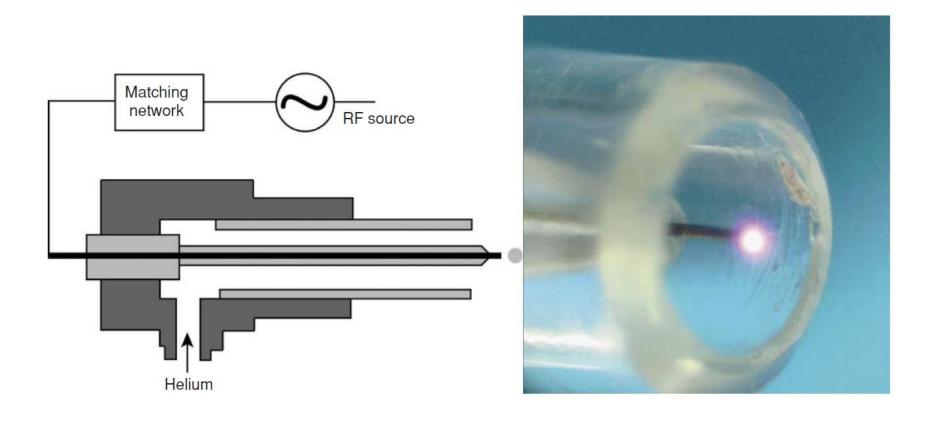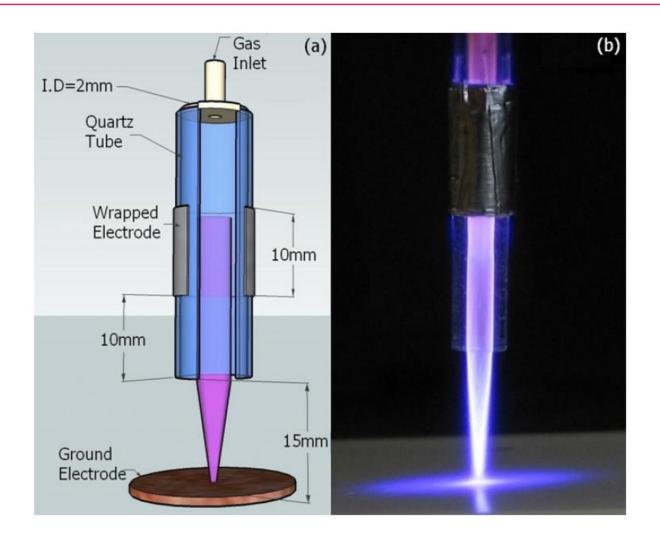| Treatment	Surface treatment level	Depth	Temperature	Cost
Chemical	Large	Deep	Room temperature ~200 ℃	Medium
Heat	Only oxidizing	Deep	High temperature	Cheap
Radiation	Small	Whole sample	High temperature	Expensive
Plasma	Large	Surface	Room temperature ~100 ℃	Cheap ~ Medium

Microwave plasma torch
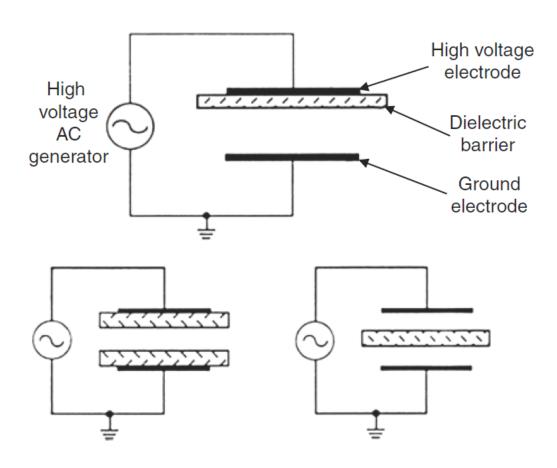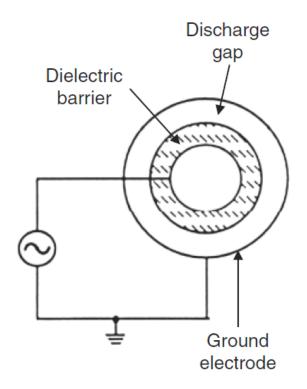
Dielectric-barrier discharges (DBDs)

Plasma-needle discharge
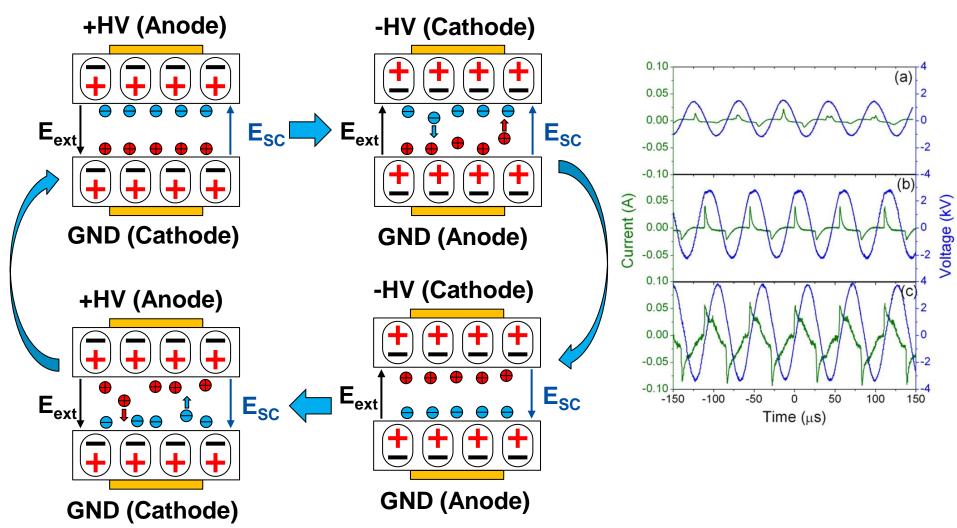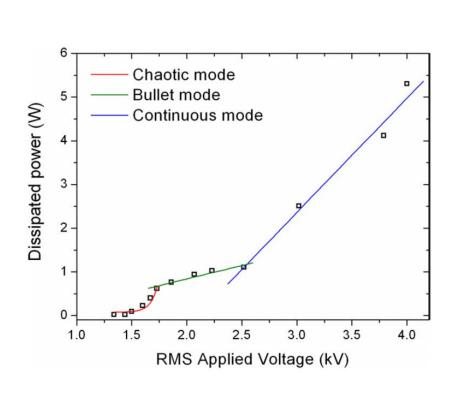
Atmospheric-pressure cold helium microplasma jets
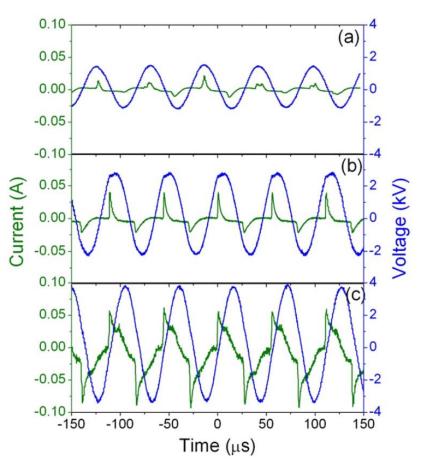
Space charge effect enhance the electric field

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

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

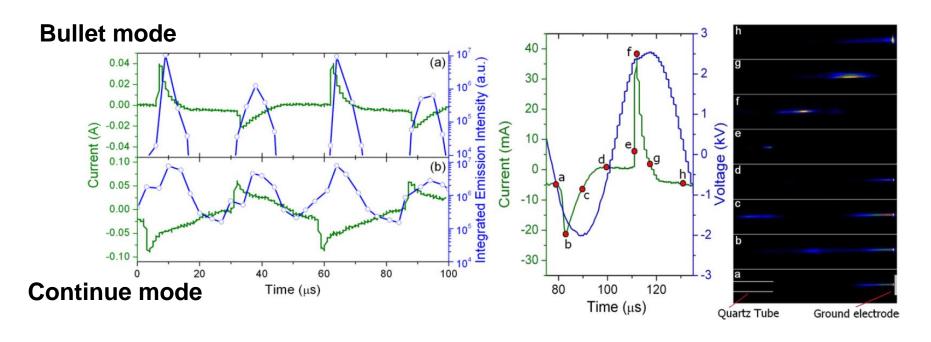J. L. Walsh, *et al.*, J. Phys. D: Appl. Phys., **43**, 075201 (2010)

In bullet mode, the plasma jet comes out as a pulse
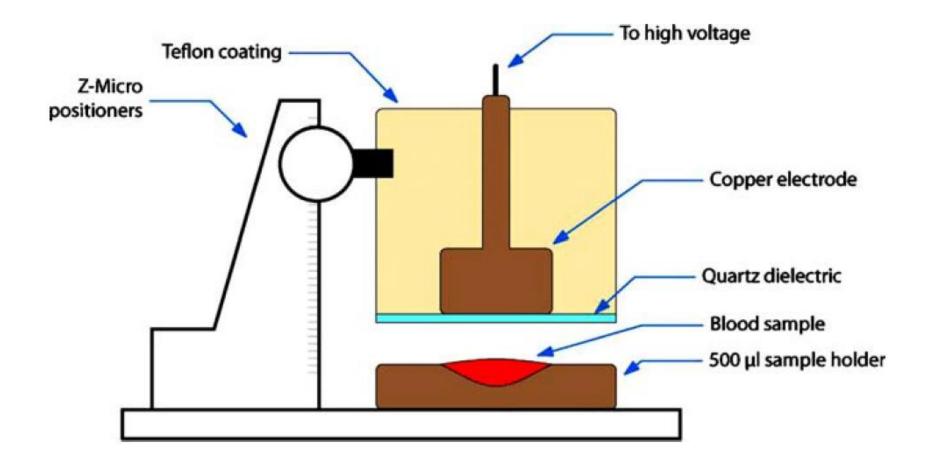
- **wavelength-integrated optical emission signal (350–800 nm)**

- **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)

Teflon coating

Z-Micro positioners

To high voltage

Copper electrode

Quartz dielectric

Blood sample

500 µl sample holder

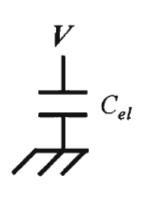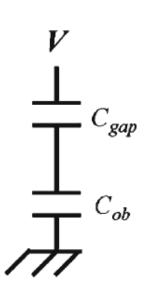G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)
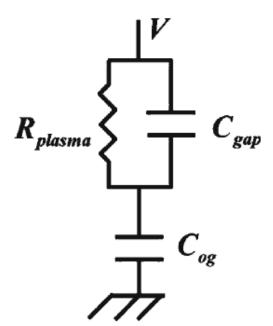
Simplified electrical schematic of FE-DBD

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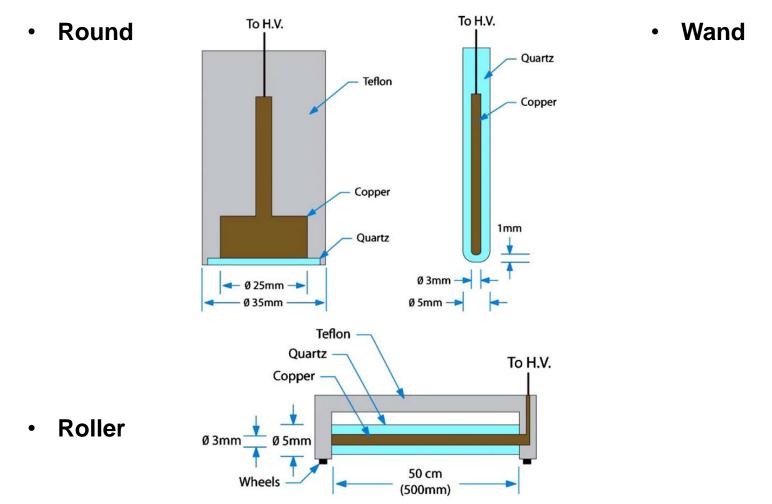- **electrode near the treated object**
- **e-plasma discharge**

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

G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)
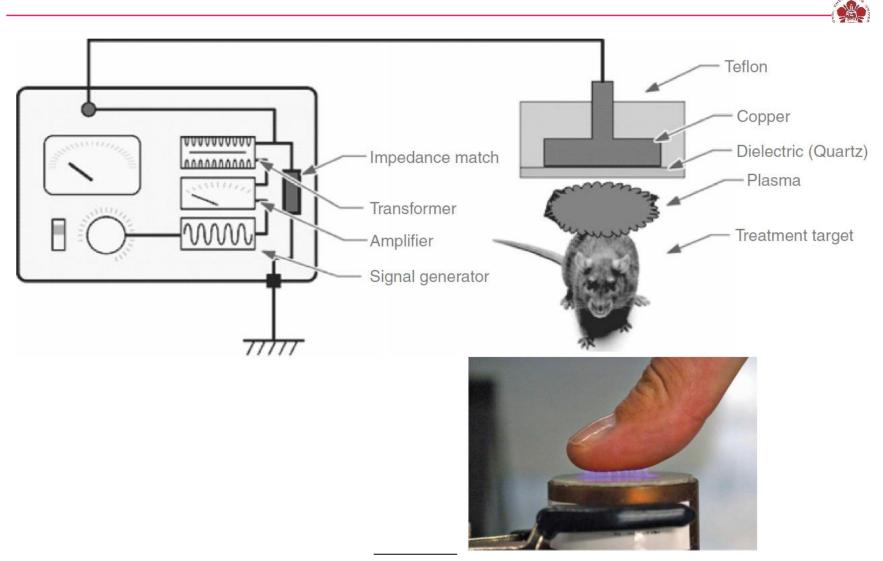
Depending on the needs, the size and the shape of FE-DBD treatment electrodes can vary

- **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**

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- **Skin regeneration**

- **Egg sterilization**

- **Facemask regeneration**

Bacteria concentration reduces after being treated with FE-DBD

Table 1. Bacteria sterilization results (in $cfu \cdot mL^{-1}$).[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
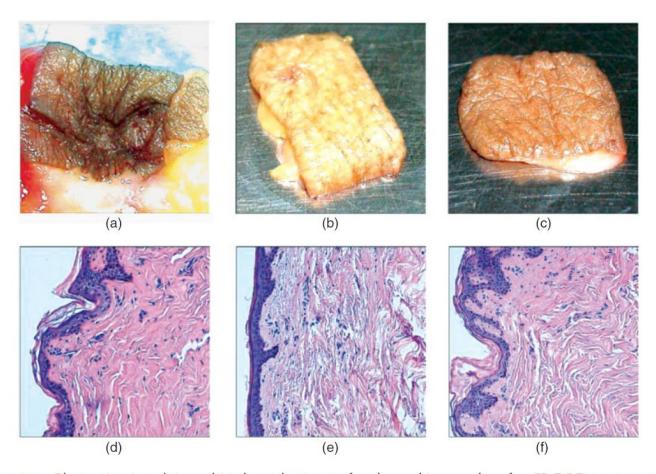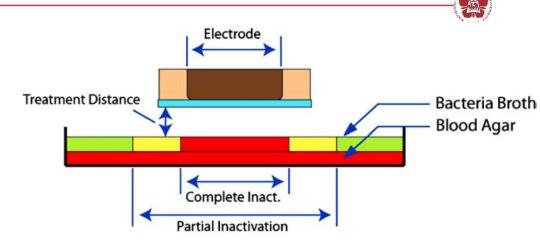

Figure 6.23 *Photos (top) and tissue histology (bottom) of cadaver skin samples after FE-DBD treatment: (a, d) control; (b, e) after 15 s of treatment; and (c, f) after 5 min of treatment – no visible damage is detected.*

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)
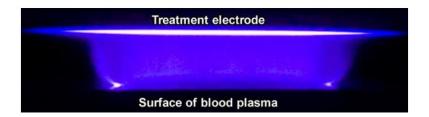
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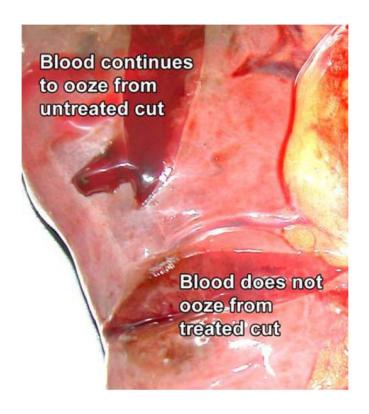- **Facemask regeneration**
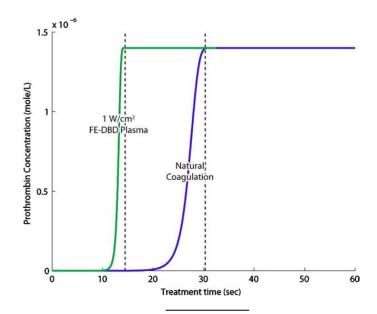
Plasma can stimulate blood coagulation

Treatment electrode

Surface of blood plasma

1 W/cm² FE-DBD Plasma

Natural Coagulation

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

Example of blood coagulation using plasma

Blood continues to ooze from untreated cut

Blood does not ooze from treated cut
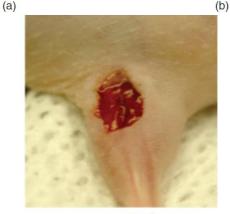
Saphenous vein is a major blood vessel for a mouse

(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)
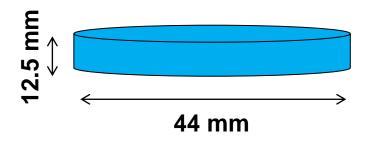Plasma medicine, by Alexander Fridman and Gary Friedman

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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**

12.5 mm

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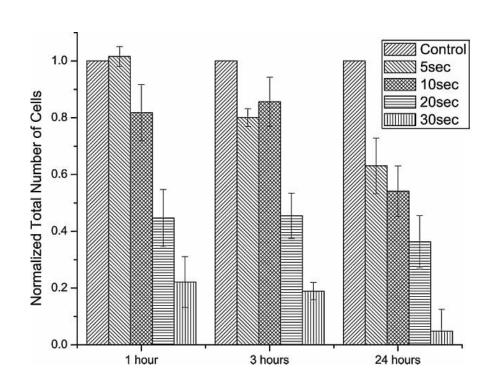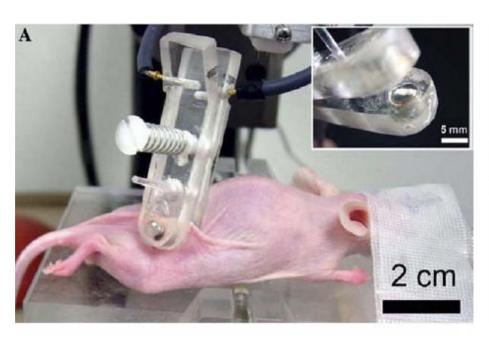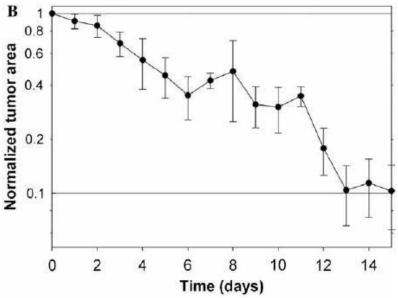
Figure 22. Results of FE-DBD treatment of melanoma cancer cells: Control, 5, 10, 20, and 30 s, counted 1, 3, and 24 h post-treatment.[27]

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

SKH-1 hairless mouse is treated with parallel plate electrode under isoflurane inhalation anesthesia
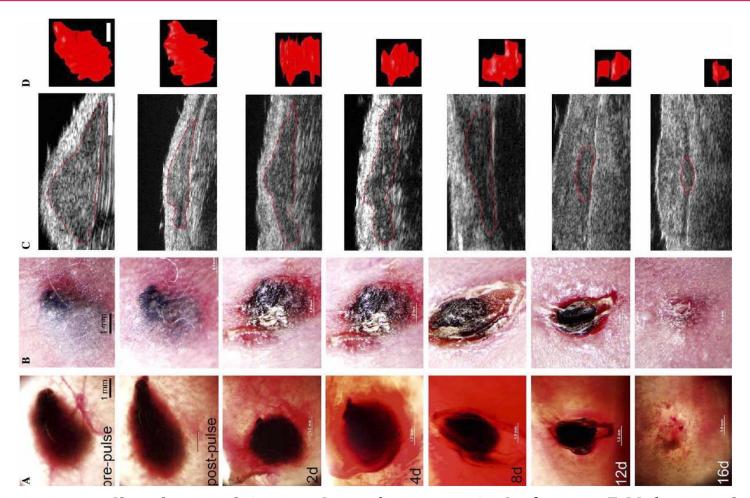
Melanoma shrinks after the treatment
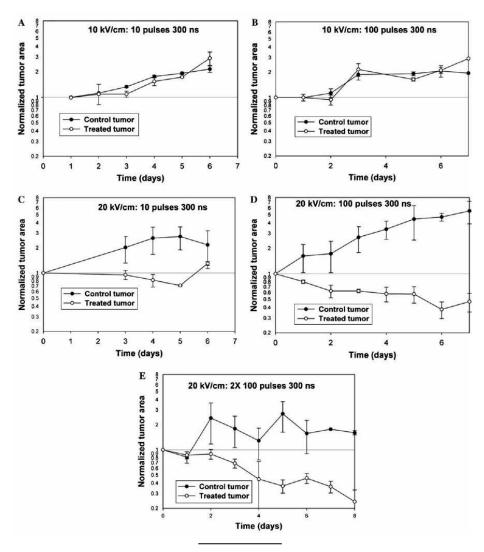
- **Day 0-3: 3 applications of 100 pulses (300 ns, 40 kv/cm, 0.5 Hz), 30 min apart**

- **Day 4: single application using 5 mm diameter parallel plate electrode**

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

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# Electric field of 20 kV/cm is needed to treat Melanoma
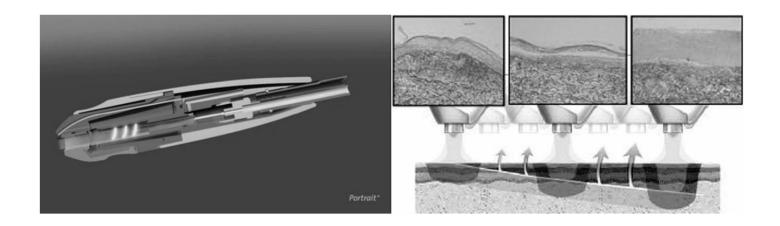
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Plasma skin regeneration (PSR) is a novel skin treatment device

- **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

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

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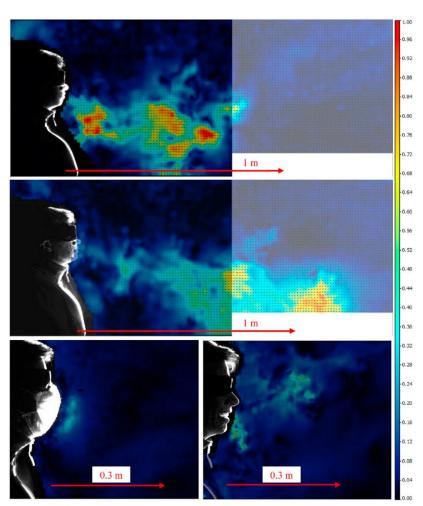
- **Facemask regeneration**

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

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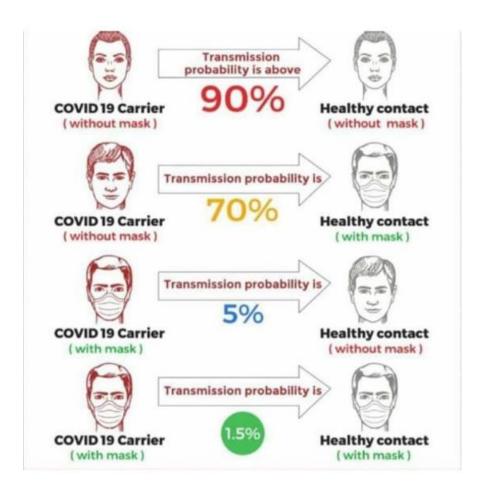
Coughing over a longer periods of time w/o mask.

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
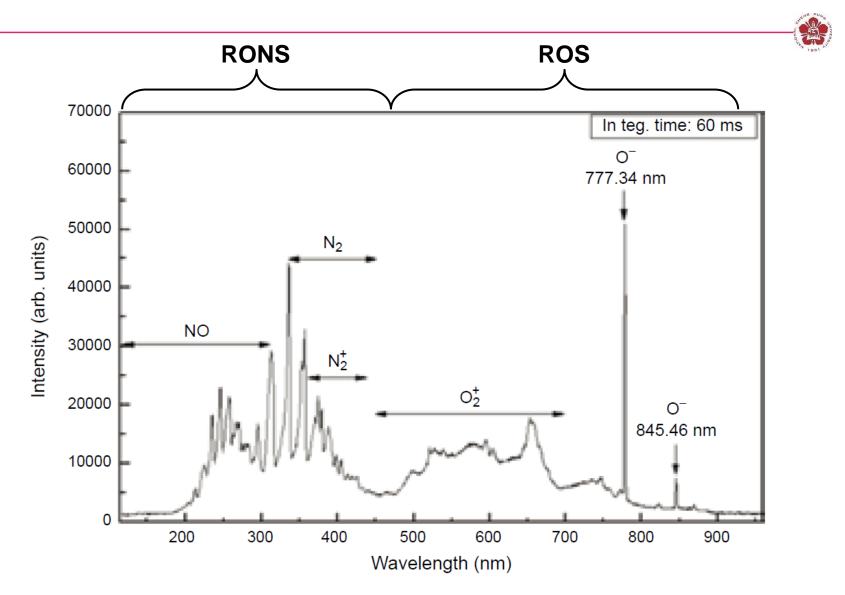
Plasma can provide good surface treatment with low temperature

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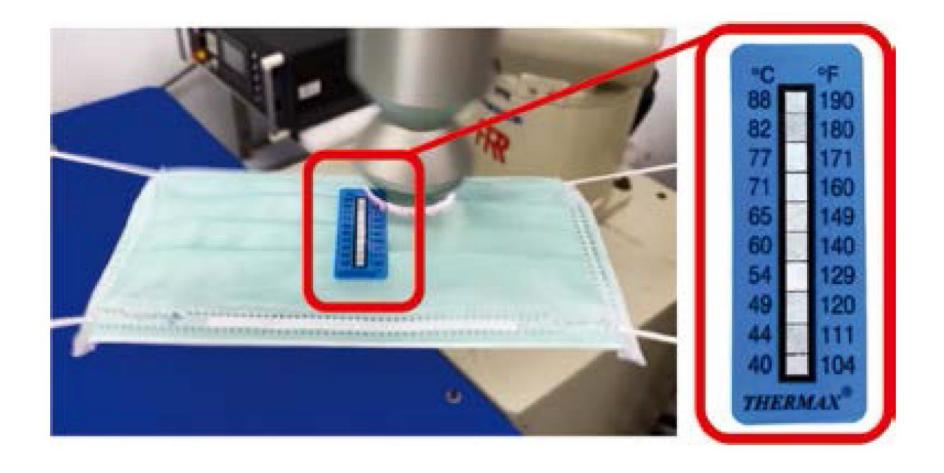
- **Atmospheric plasma can generate radicals, ozone, reactive oxygen/nitrogen/NH (ROS，RONS), UV light, electrons, charged particles.**

Plasma can generate ROS and RONS
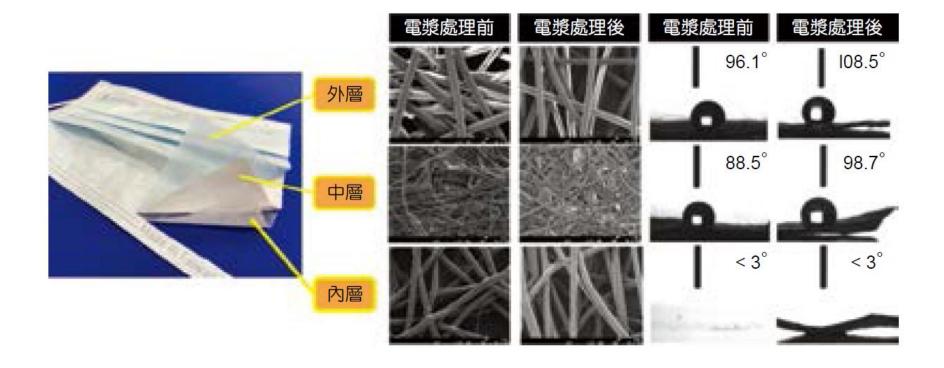
The temperature of the mask under plasma treamtment is below 40 ℃
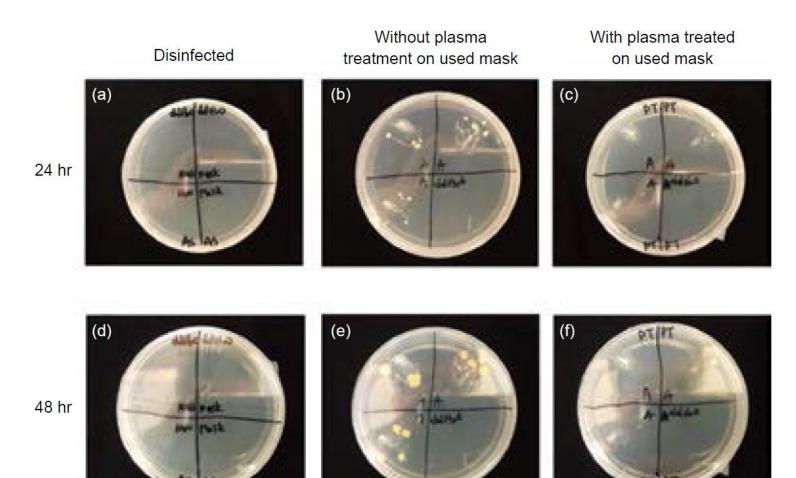
The surface quality of the face mask was not influenced by the plasma treament

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
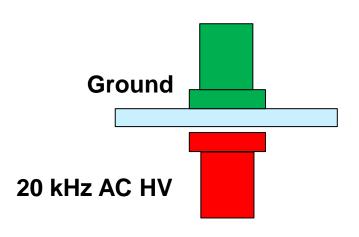
DBD plasma demonstration

Ground

20 kHz AC HV
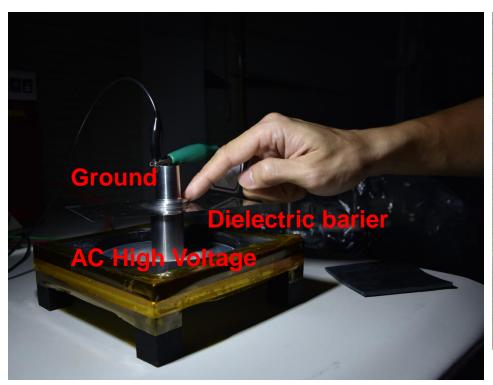
Show video.

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

Ground

Dielectric barier

AC High Voltage
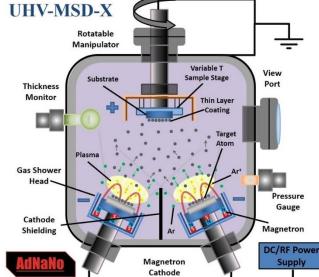
Examples of magnetron sputtering deposition
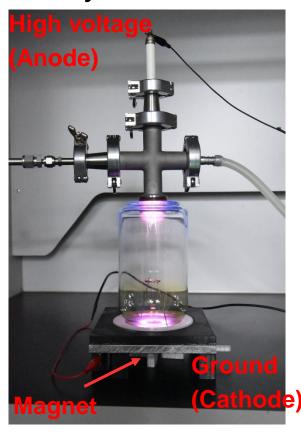
https://angstromengineering.com/tech/magnetron-sputtering/pulsed-dc/
https://dynavac.com/wp-content/uploads/2017/09/Confocal-Sputtering-2.jpg
https://www.adnano-tek.com/magnetron-sputtering-deposition-msd.html
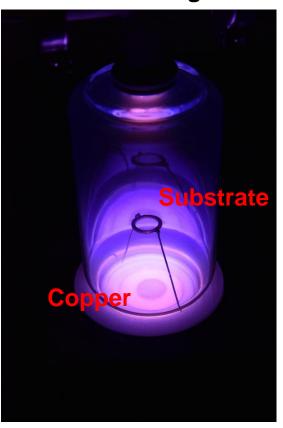
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Demonstration experiments – magnetron sputtering

- **System**
- **Without magnet**
- **With magnet**

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

High voltage

Ground
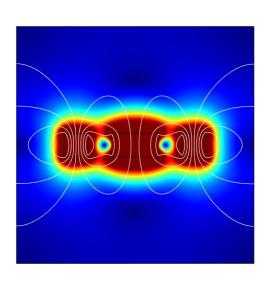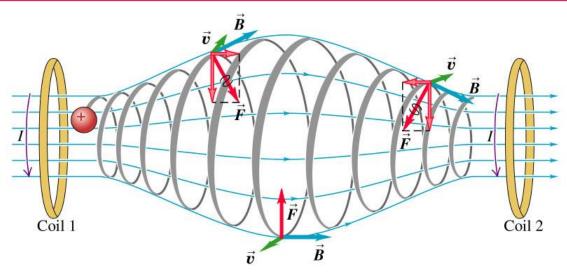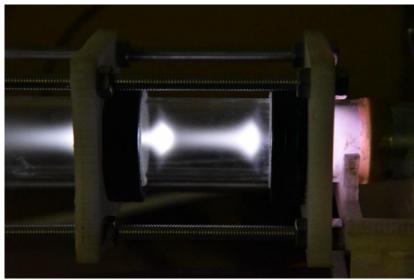
Confined electrons

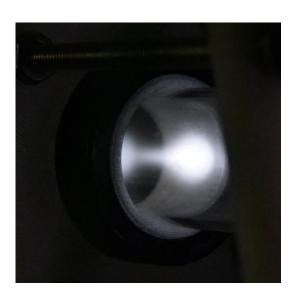# Demonstration of a magnetic mirror machine
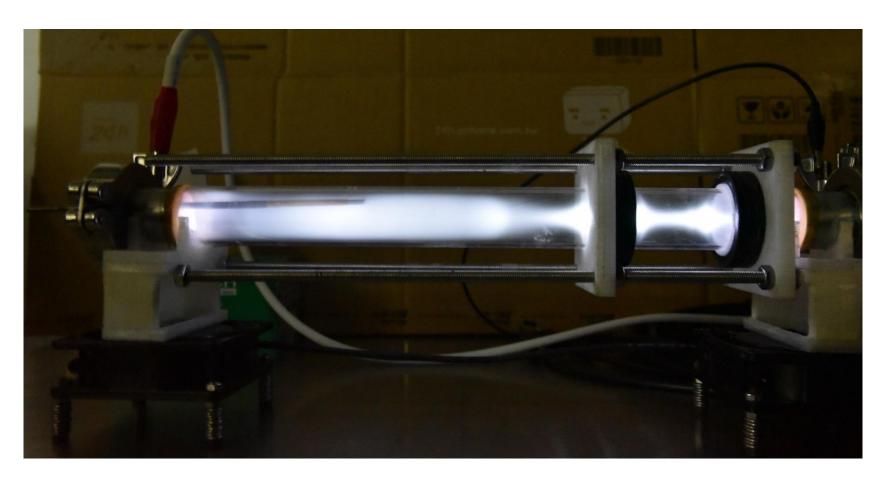
Show video.

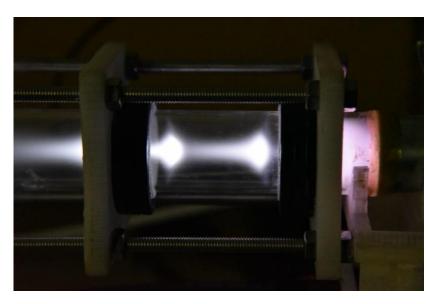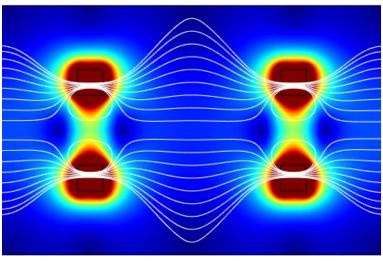# Plasma is partially confined by the magnetic field

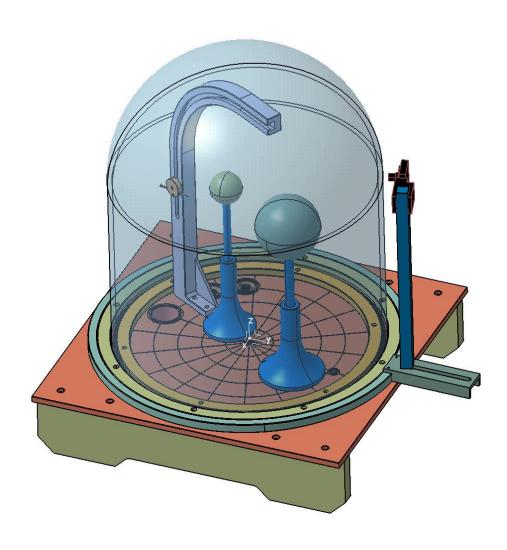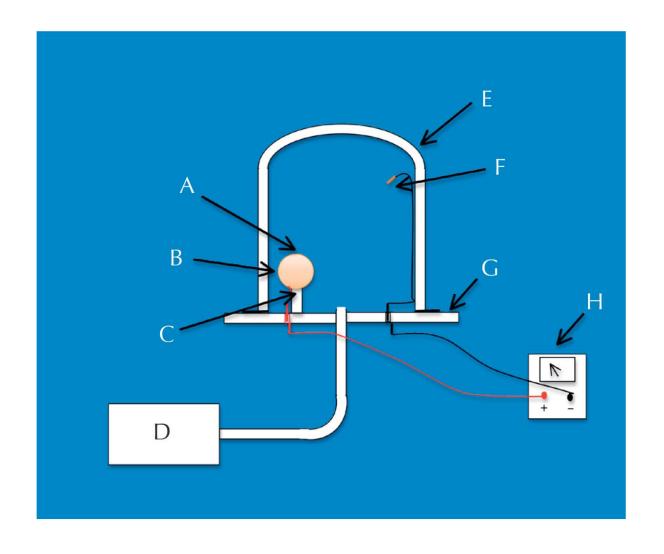# Many mirror points are provided by a pair of ring-type magnets
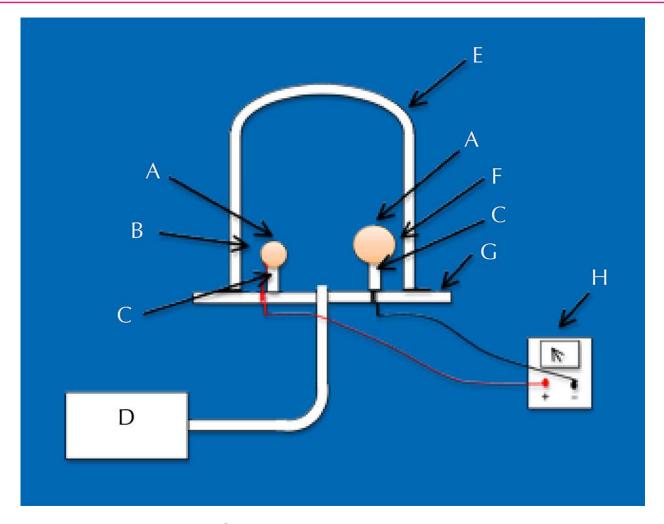
Planeterrella is an aurora simulator

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