Introduction to plasma theory and demonstration
電漿基礎理論與實作

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2023 summer break

8/28(Mon.) – 9/1(Fri.) 14:00-17:40

Except: 8/29(Tue.) 13:30-17:10

Lecture 3

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

https://nckucc.webex.com/nckucc/j.php?MTID=mb9ccf65ba2c981ce1f0f02ea60e1dbf2

開放式教育平台：

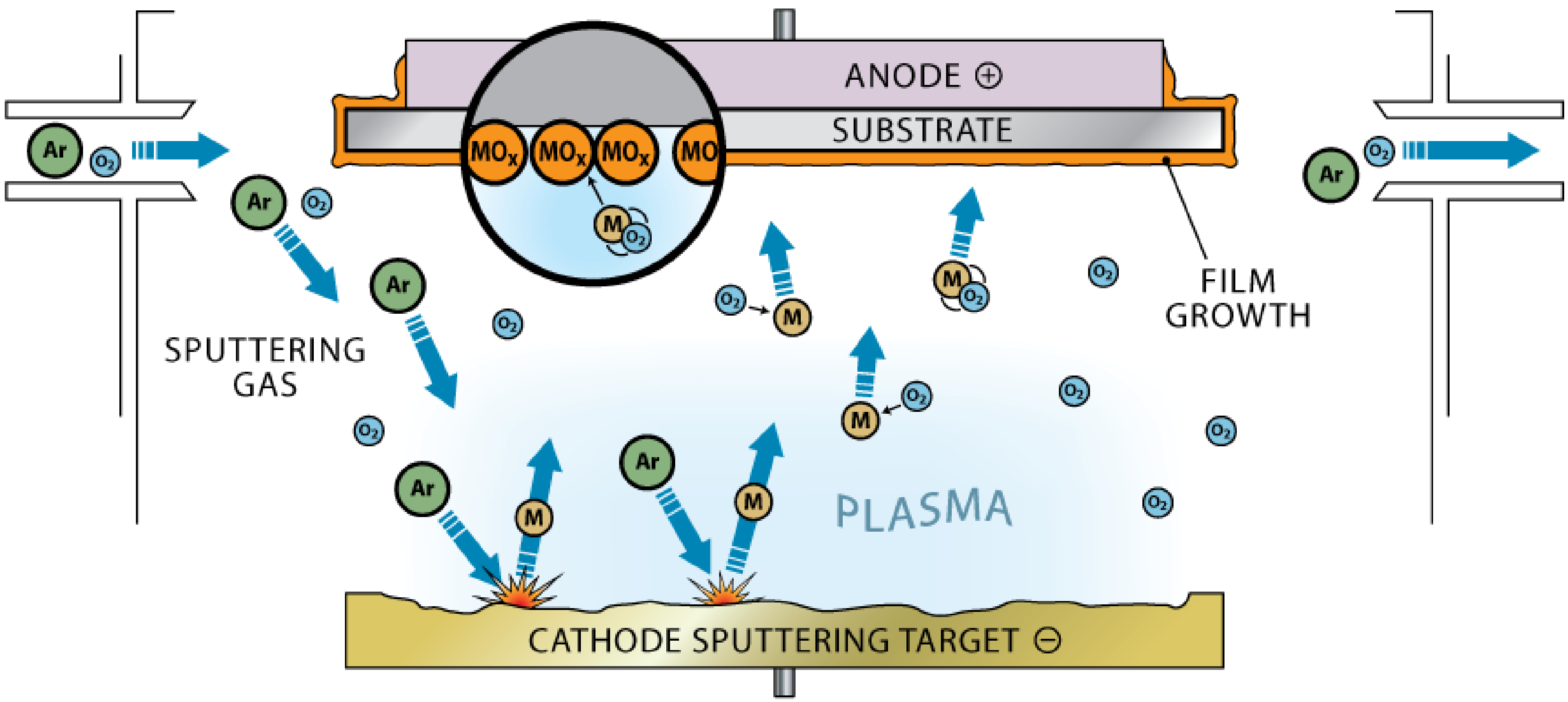
https://i-ocw.ctld.ncku.edu.tw/site/course_content/FTqT2RS1h7j

2023/8/30 updated

Course Outline

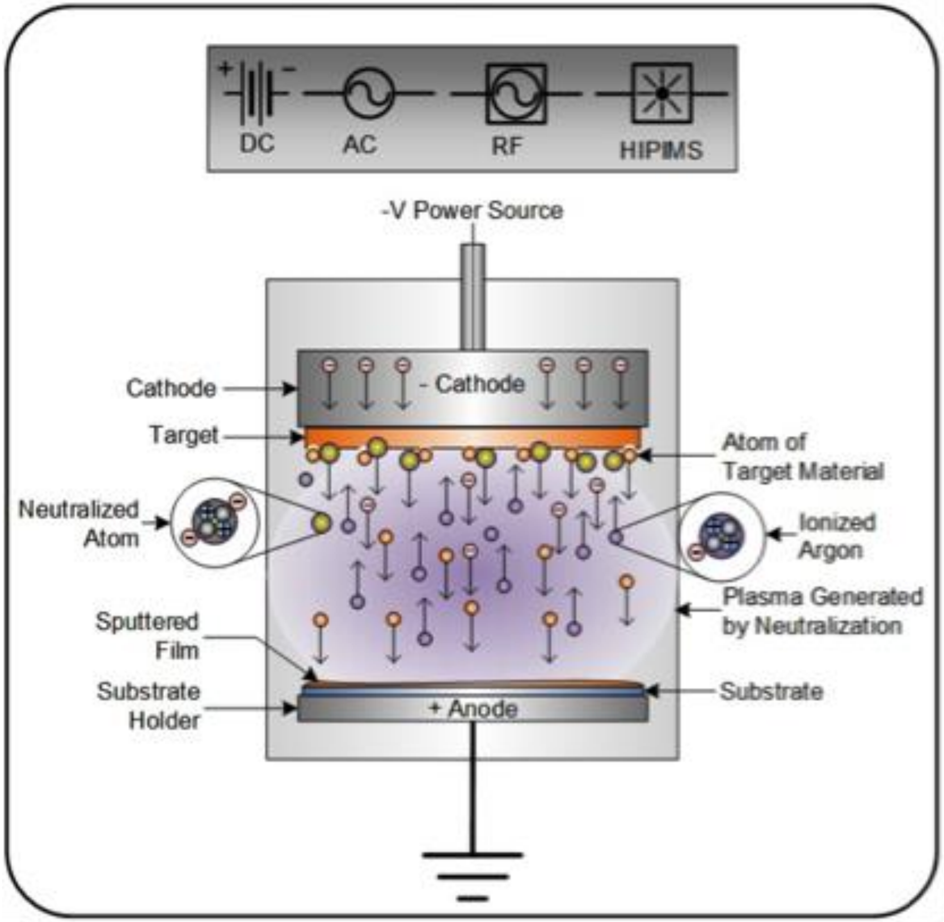
1. What is Plasma?
2. Varies kinds of plasma
    a. How plasma is generated
    b. Plasma in space
    c. **Material Processing**
    d. Biomedical application
    e. Particle beam source
    f. High energy particle accelerator
    g. Controlled thermonuclear fusion
    h. Neutral beam source
    i. Electrical propulsion

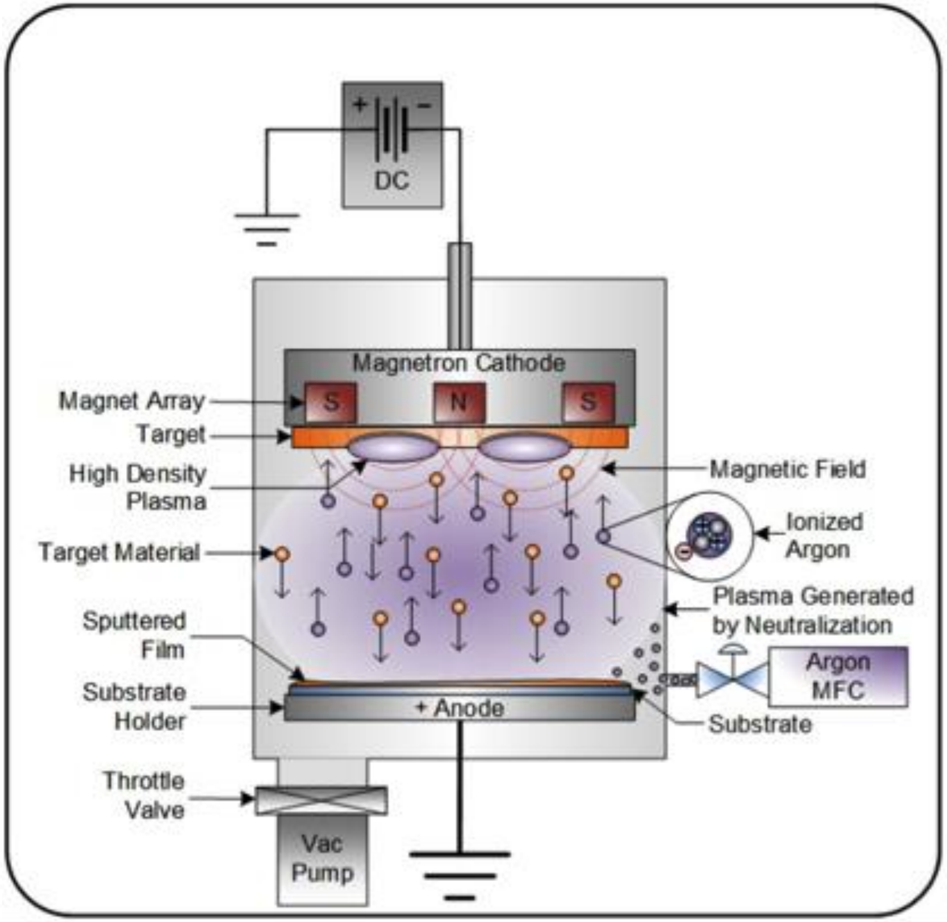
Sputtering deposition



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

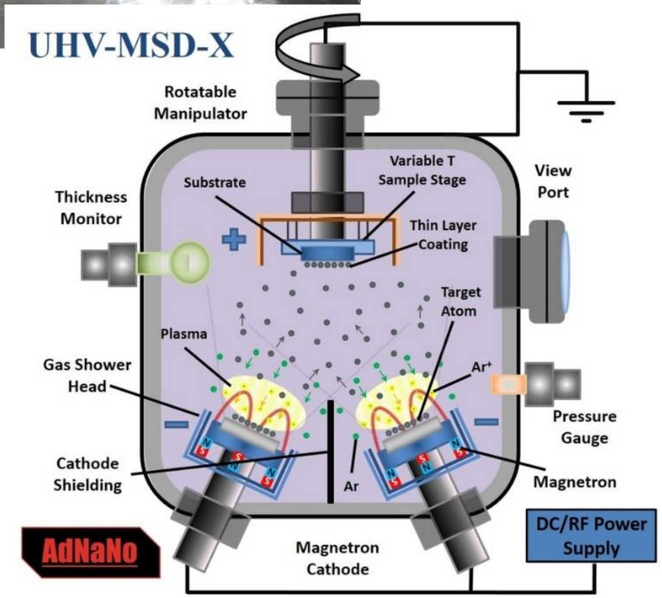
Magnetron sputtering provides higher deposition rates than conventional sputtering





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

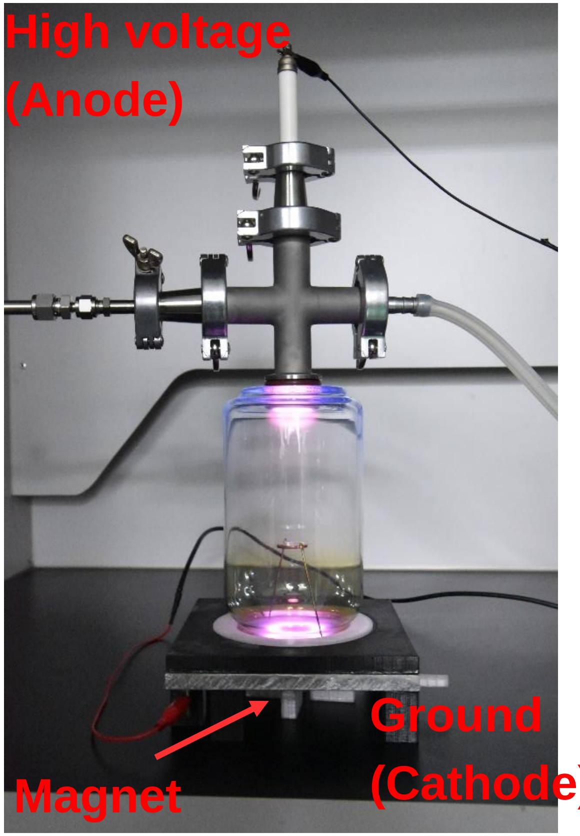
Examples of magnetron sputtering deposition



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

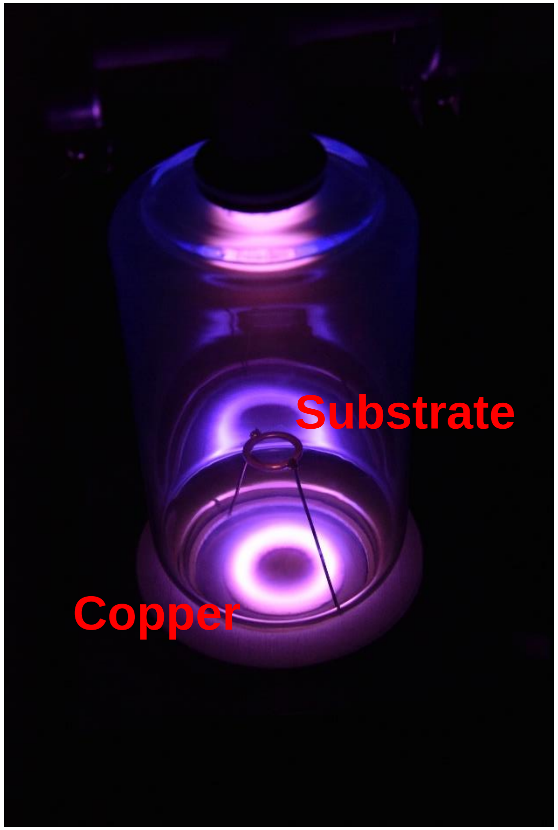
Demonstration experiments – magnetron sputtering

- System



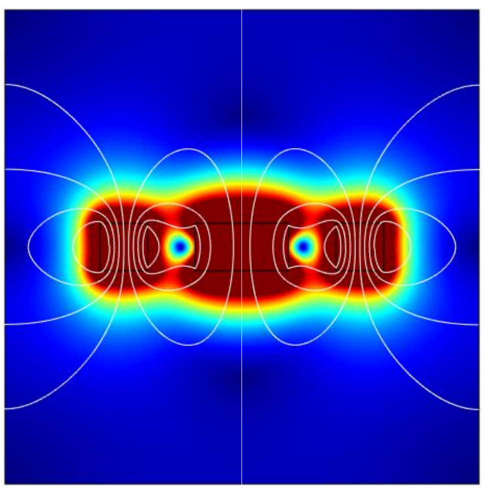
- Without magnet

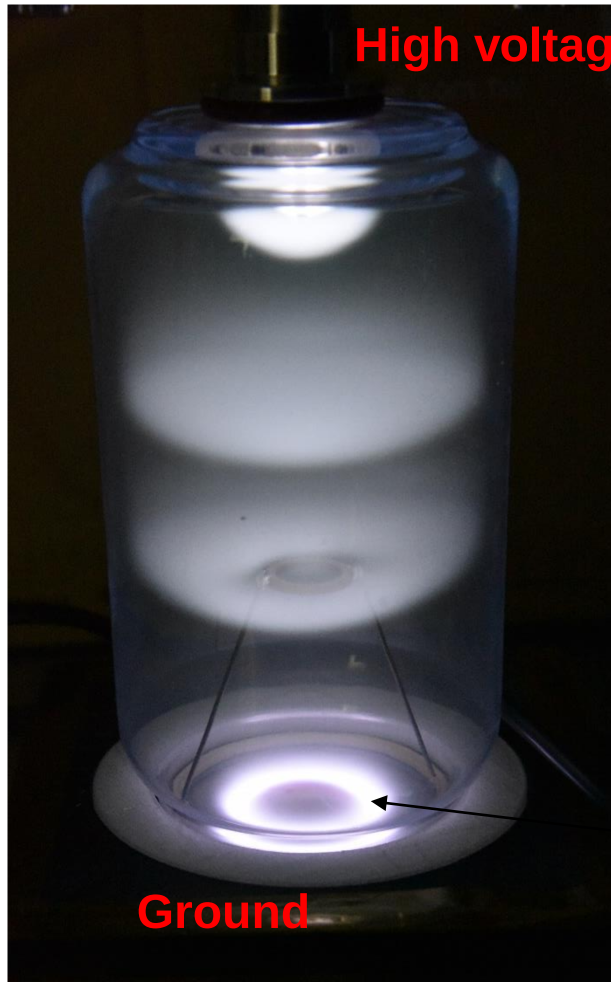
- With magnet



Show video.

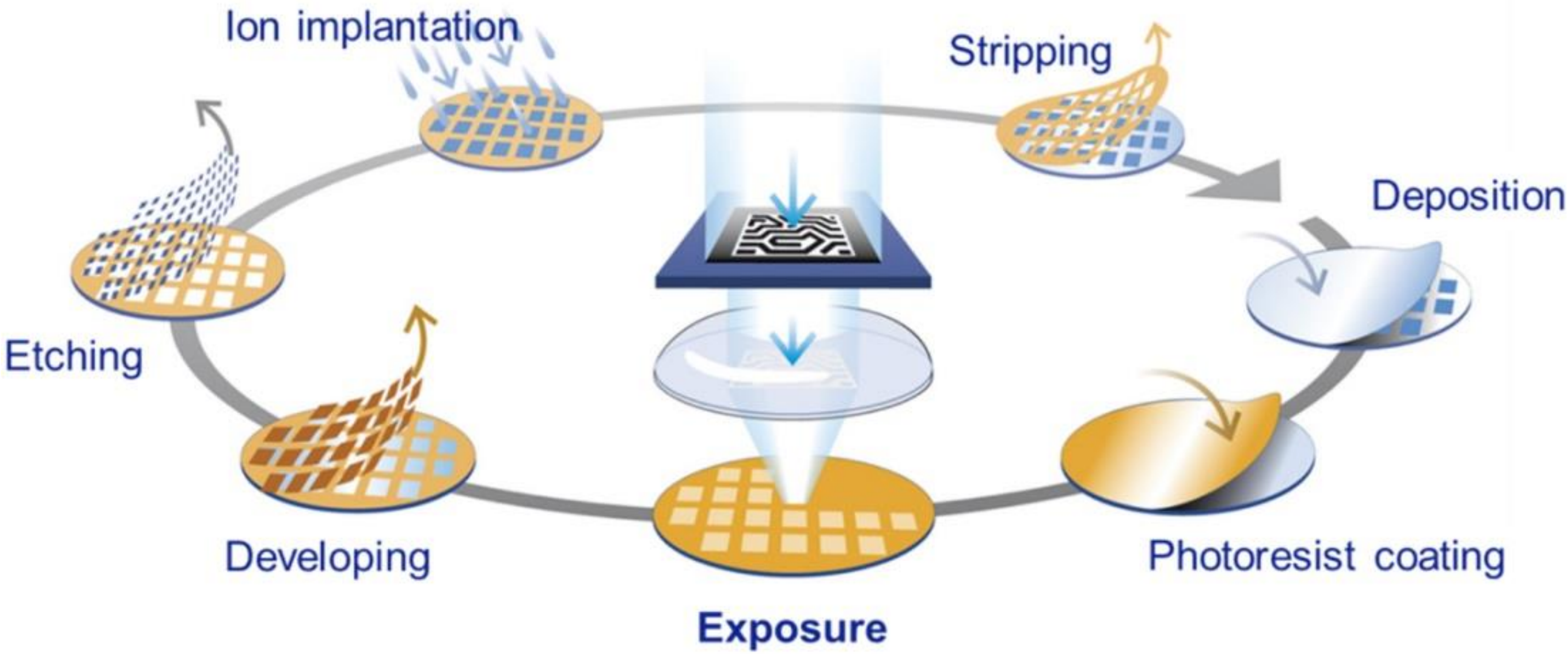
A bright ring occurs when the magnet is inserted into the system





Confined electrons

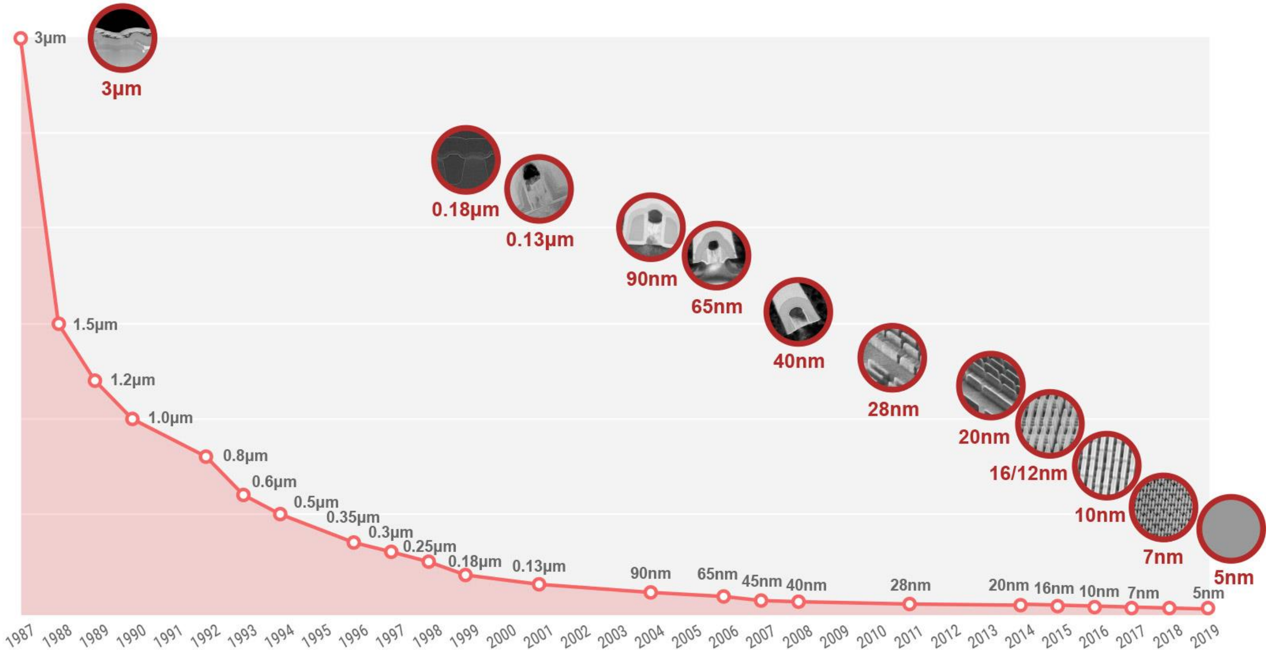
A semiconductor device is fabricated by many repetitive production process



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

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

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

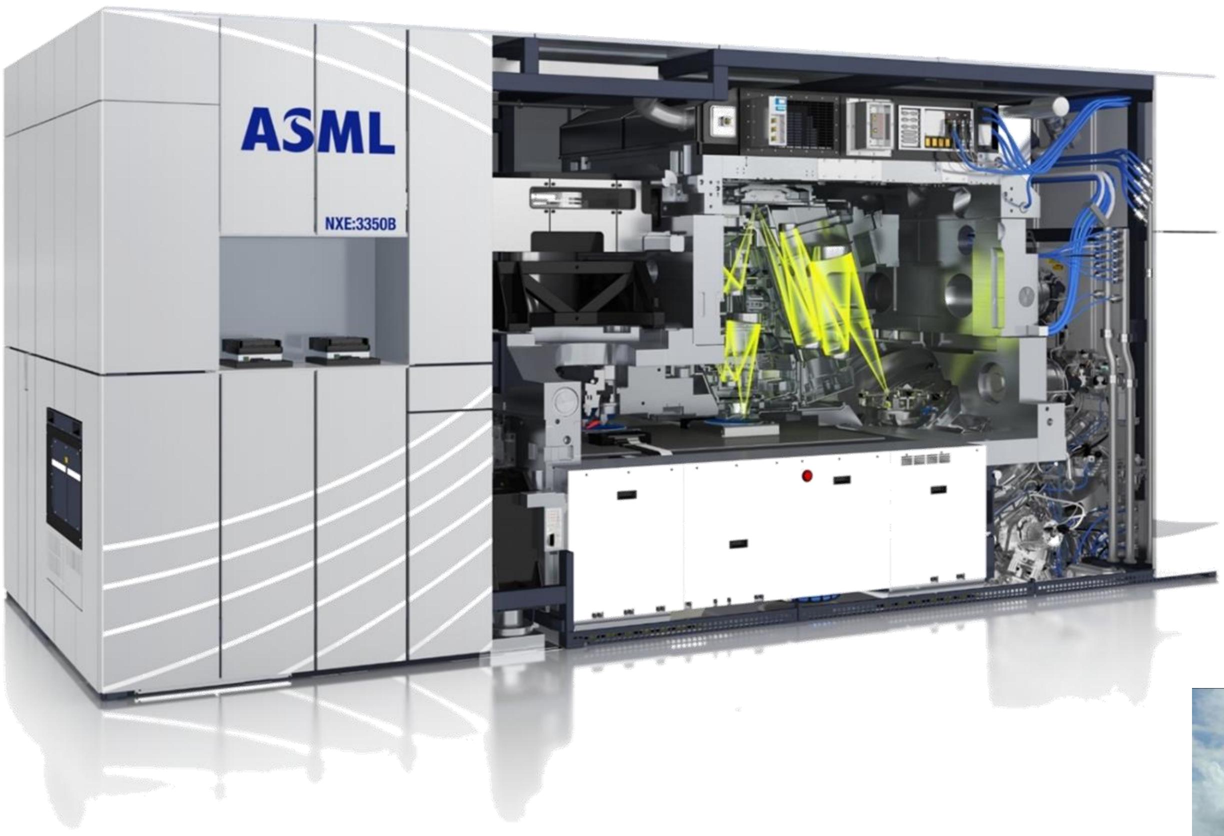


- **Optical diffraction needs to be taken into account.**
- **Shorter wavelength is preferred.**

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

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

EUV lithography becomes important for semiconductor industry



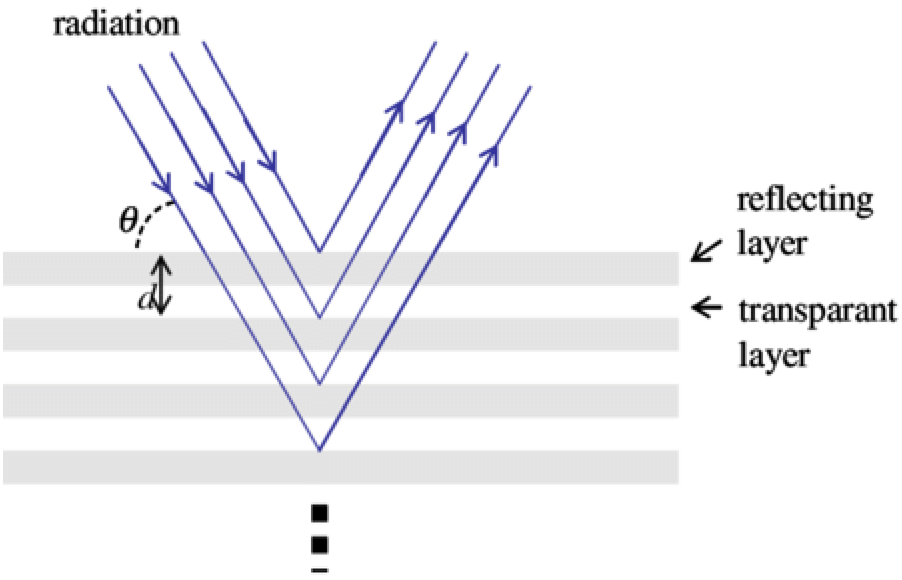
- 0.15 billion USD for each EUV light source.

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

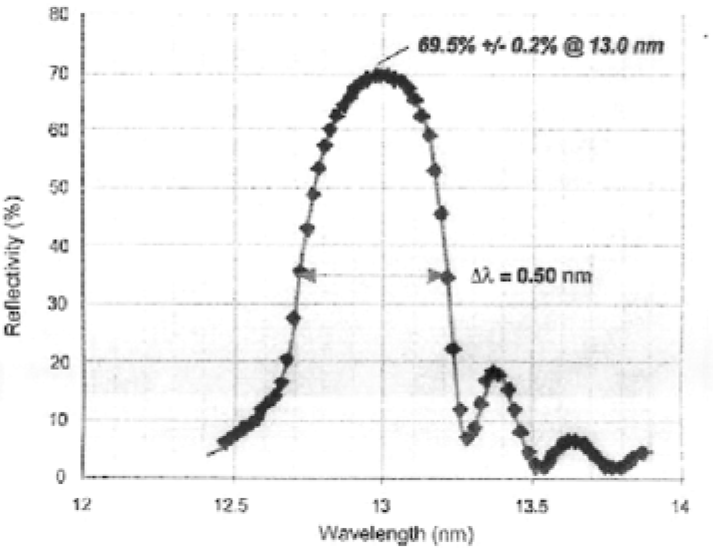
http://finance.technews.tw/2019/01/25/euv-asml-2018/

EUV light can only be reflected using multilayer mirrors

a)

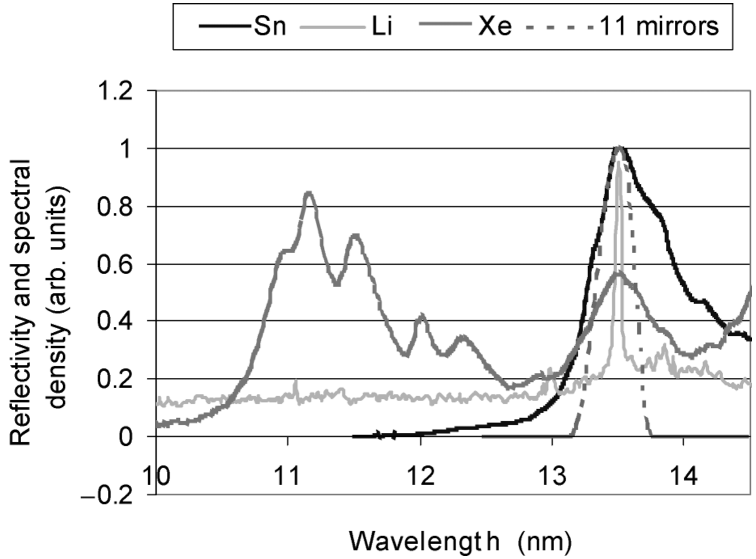


b)



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

13.5-nm EUV light is picked for EUV lithography



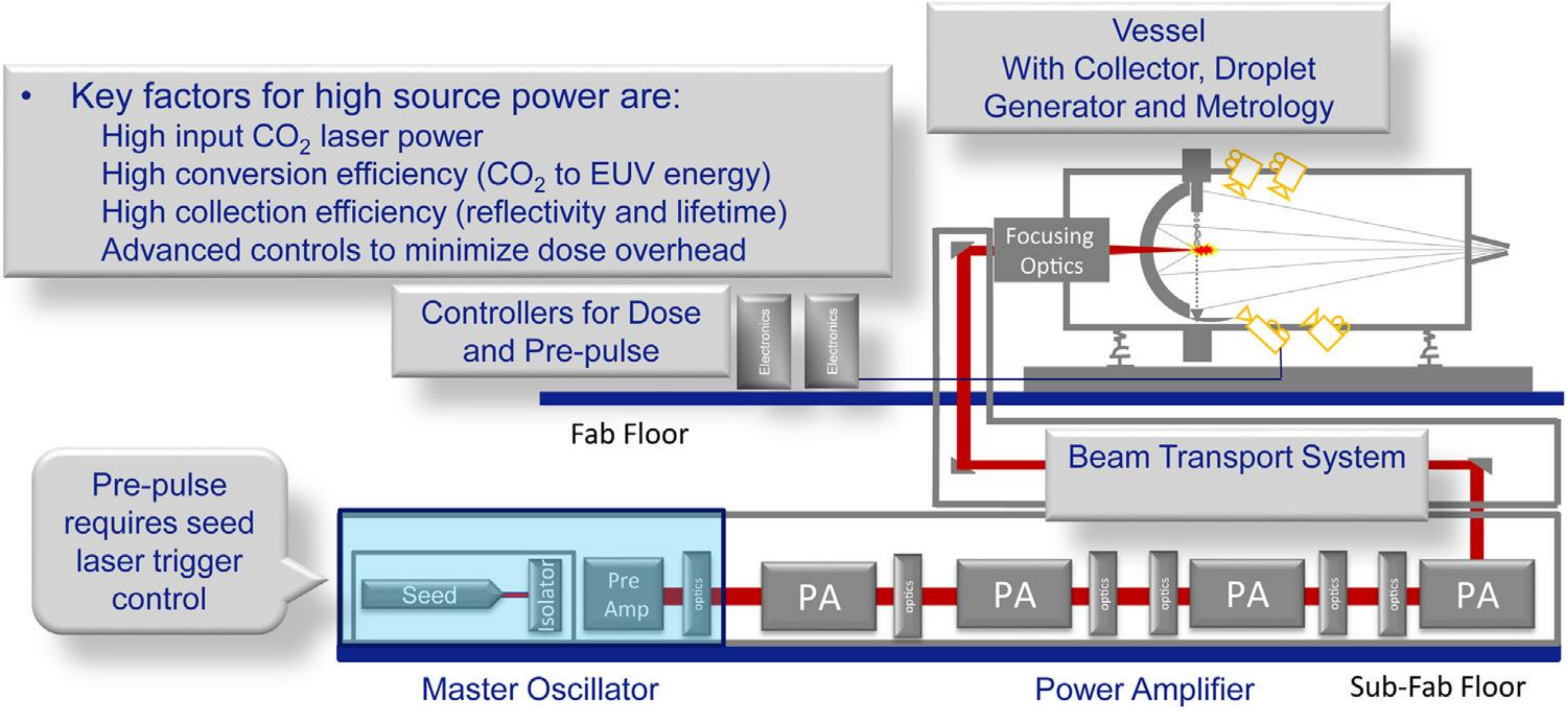
- **$\boldsymbol{\lambda = 13.5\ \mathrm{nm} \pm 1\%}$ is required.**
- **At T=35-40 eV (~450,000 K), in-band emission occurs.**
- **Xenon:**
  - **$4p^6 4d^8 \rightarrow 4p^6 4d^7 5p$ from single ion stage Xe^{10+}**
  - **UTA @ 11 nm**
- **Tin:**
  - **$4p^6 4d^N \rightarrow 4p^5 4d^{N+1} + 4p^6 4d^{N-1}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

- UTA: unresolved transition array

V. Bakshi, EUV sources for lithography

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

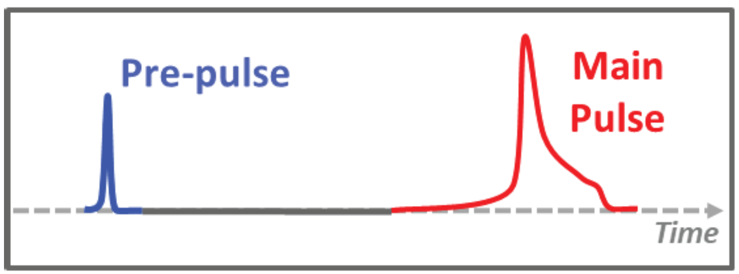
EUV light is generated from laser-produced plasma (LPP)



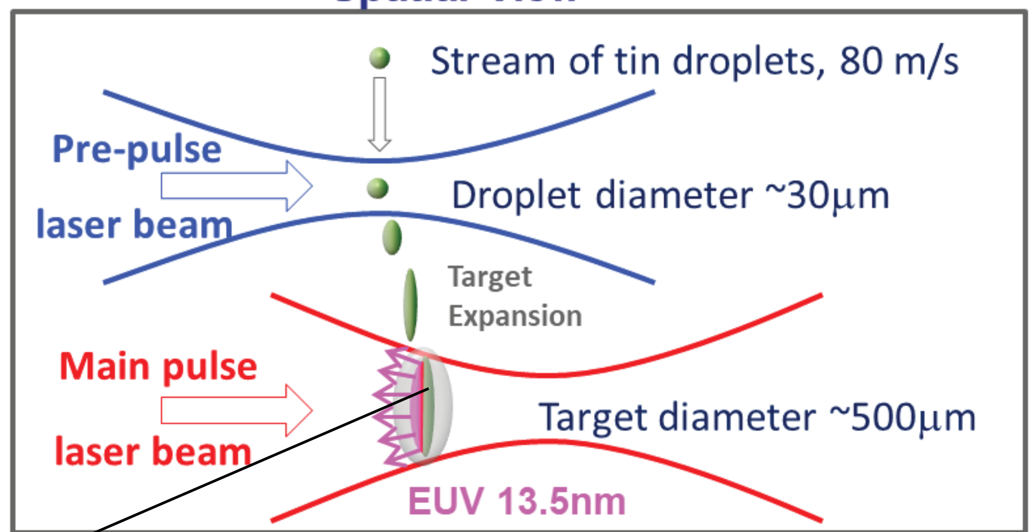
D.-K. Yang, etc., *Chip*, **1**, 100019 (2022)

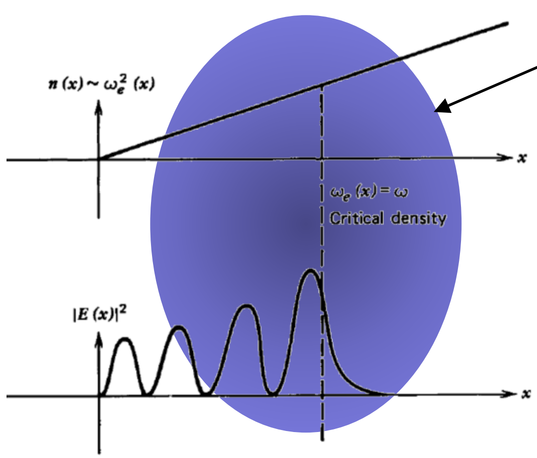
Two laser pulses are used to heat the plasma

Temporal View



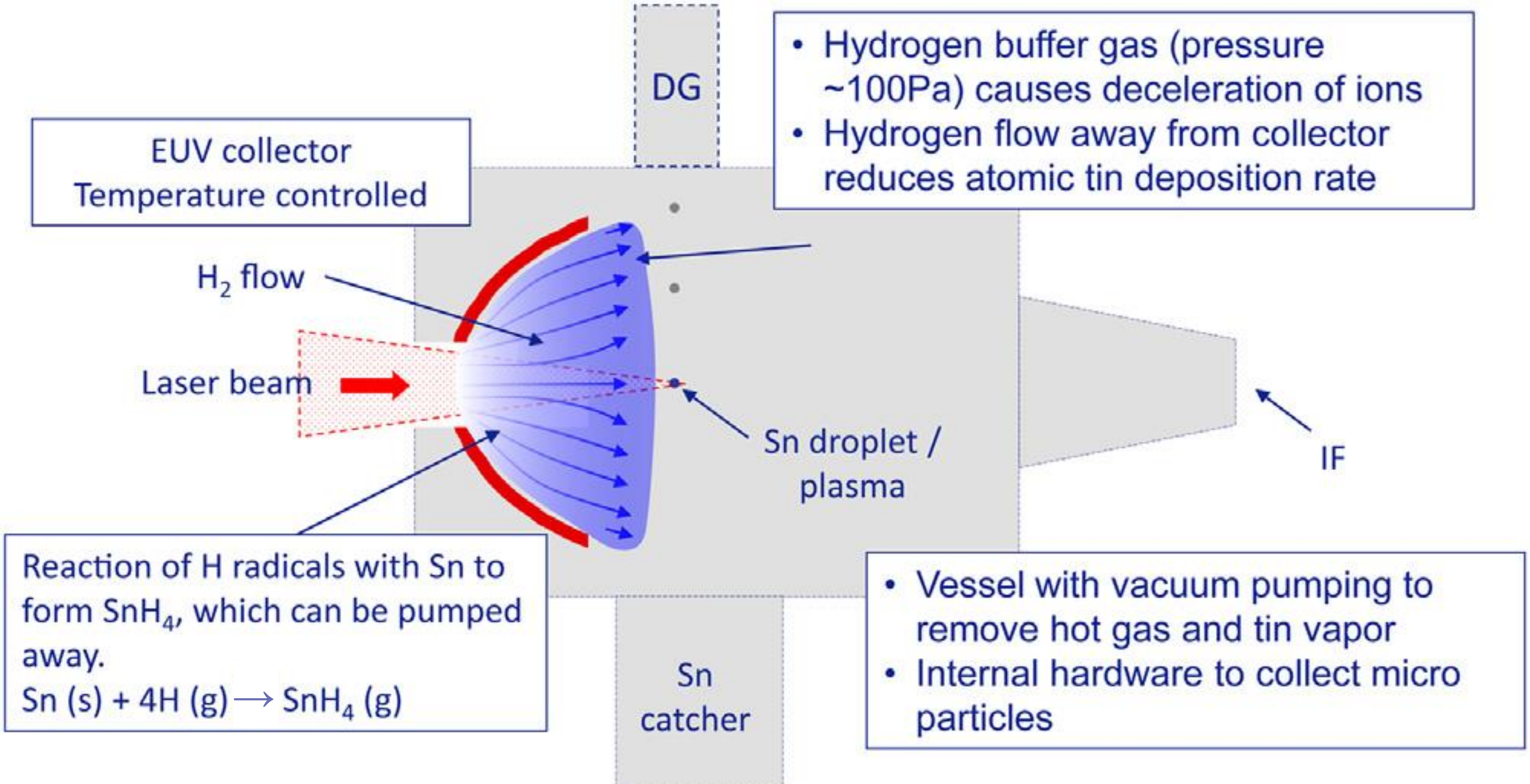
Spatial View





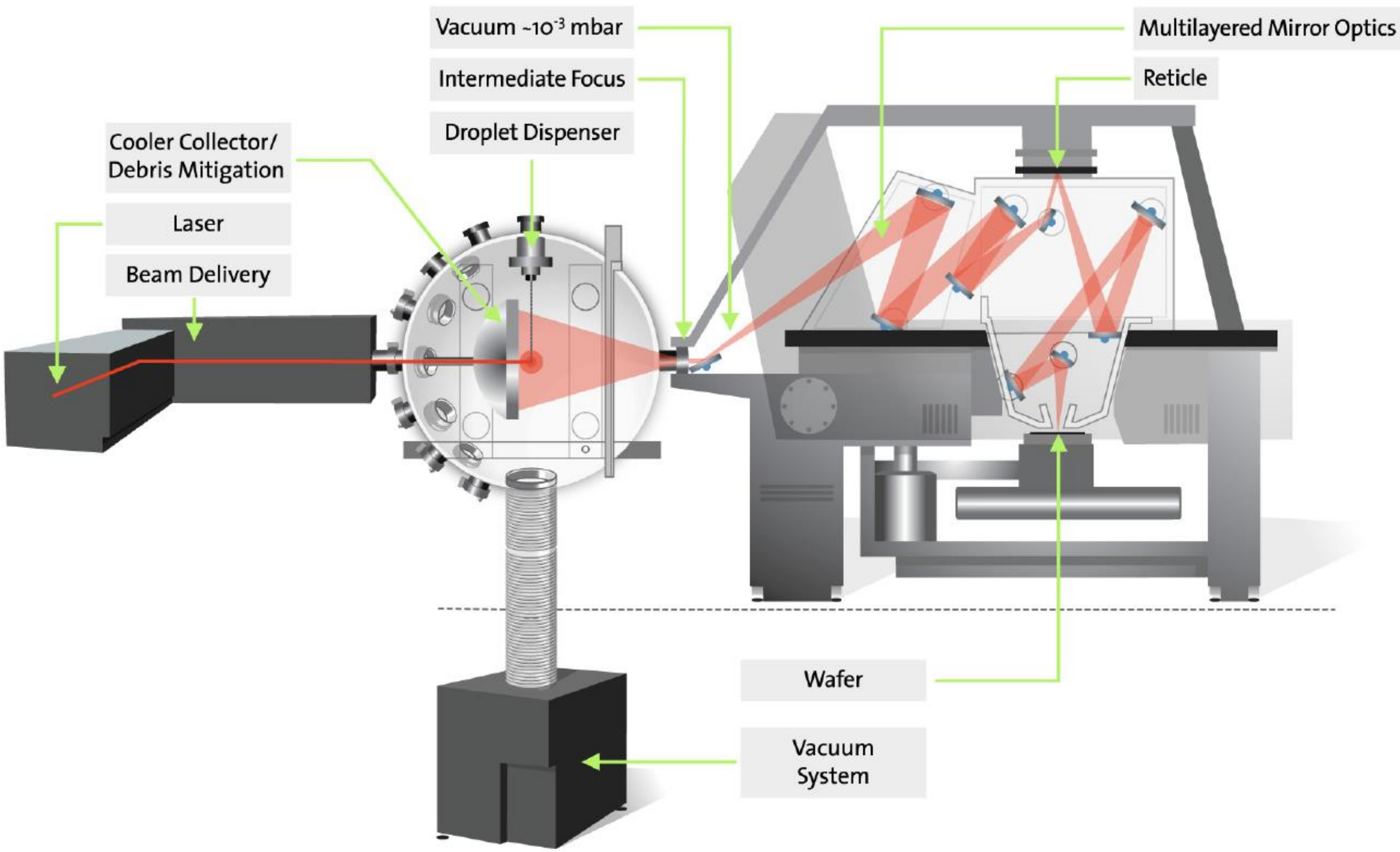
I. Fomenkov, etc., *Synch. Rad. News*, **32**, 3 (2019)

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



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

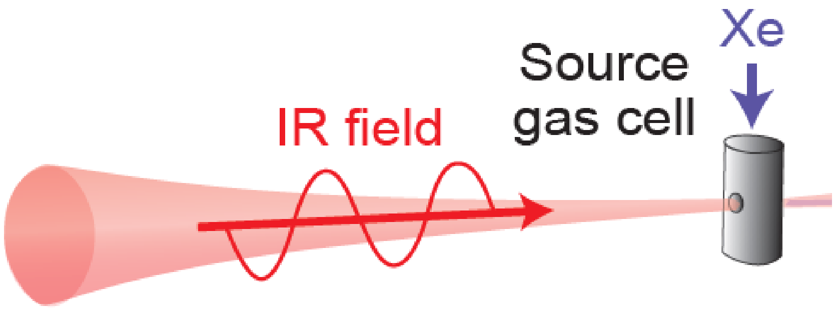
Laser-produced plasma (LPP) is used in the EUV lithography

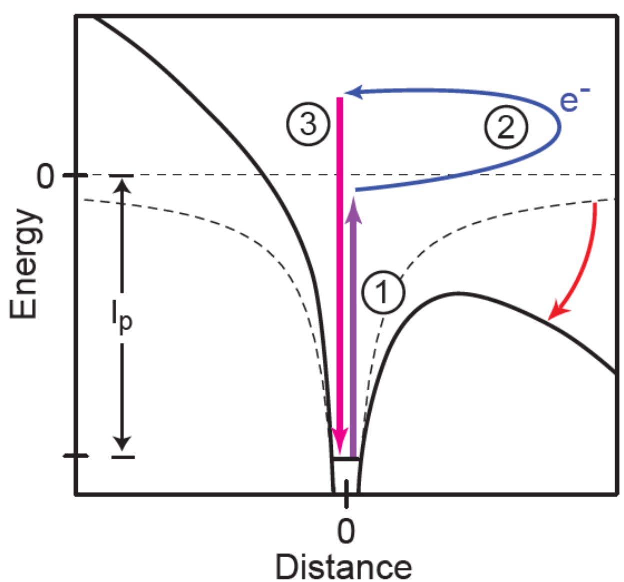


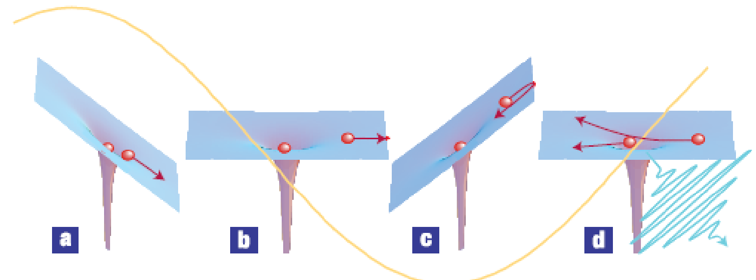
R. S. Abhari, etc., J. Micro/Nanolithography, MEMS, and MOEMS, 11, 021114 (2012)

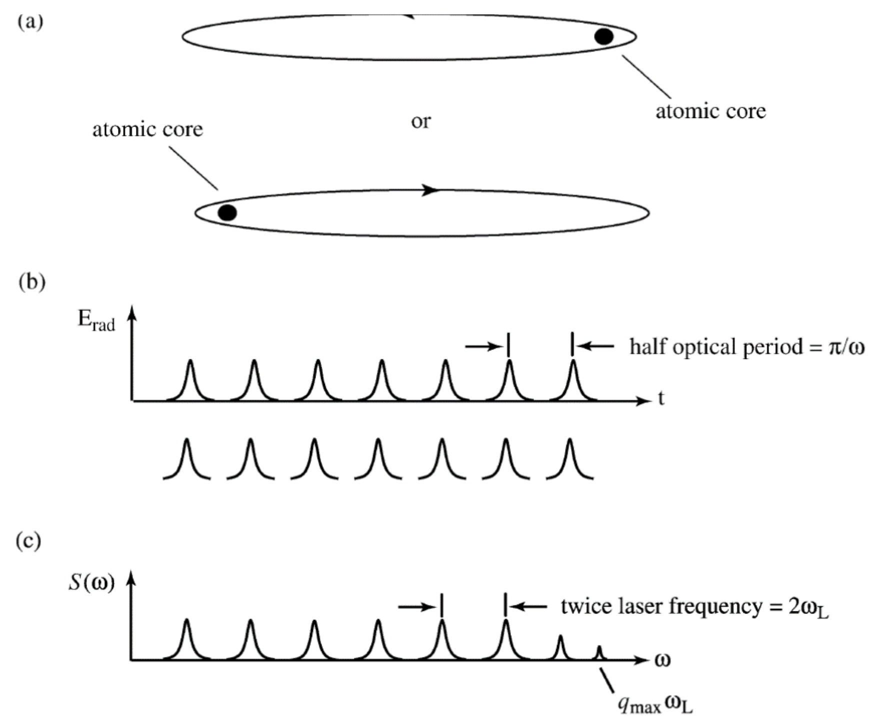
High harmonic generation from high-power laser

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



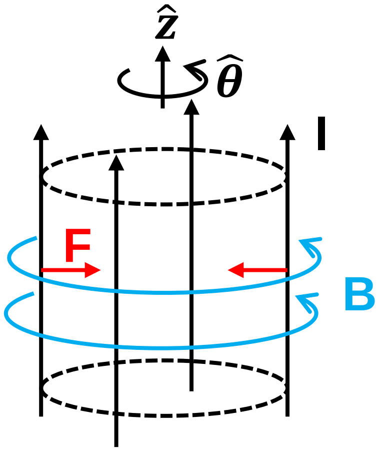






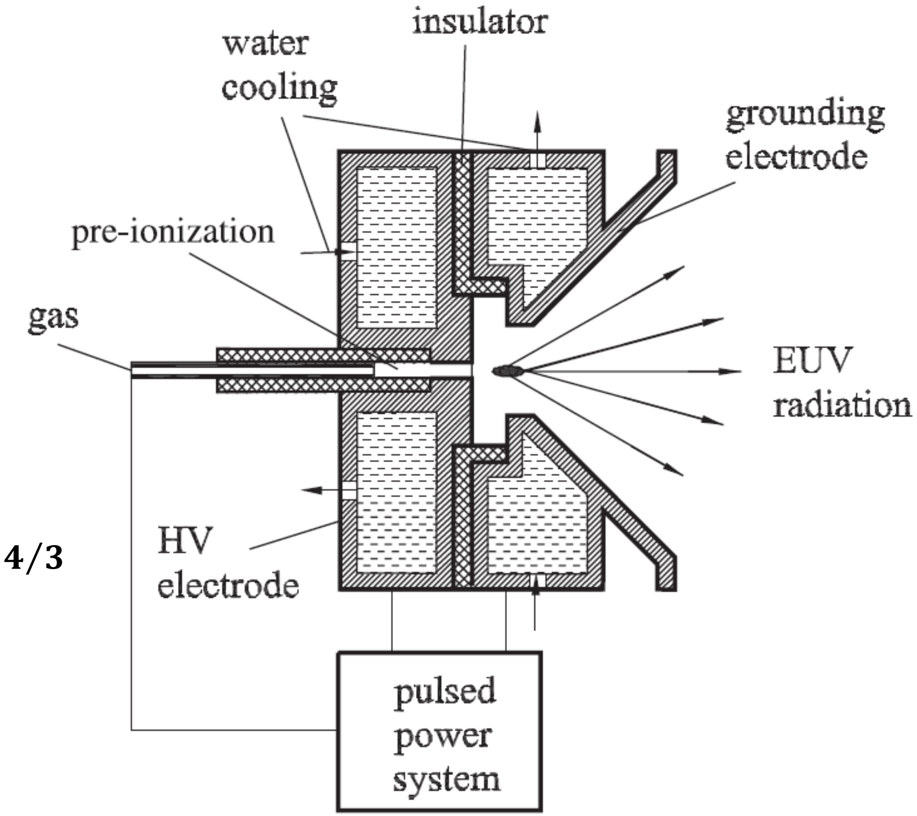
- M. Krüger, etc., Appl. Sci. 9, 378 (2019)
- Nonlinear Optics 3rd edition , by Robert W. Boyd
- P. B. Corkum and F. Krausz, Nature Phys., 3, 381 (2007)

EUV light can be generated using discharged-produced plasma



- **Adiabatic compression:**

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

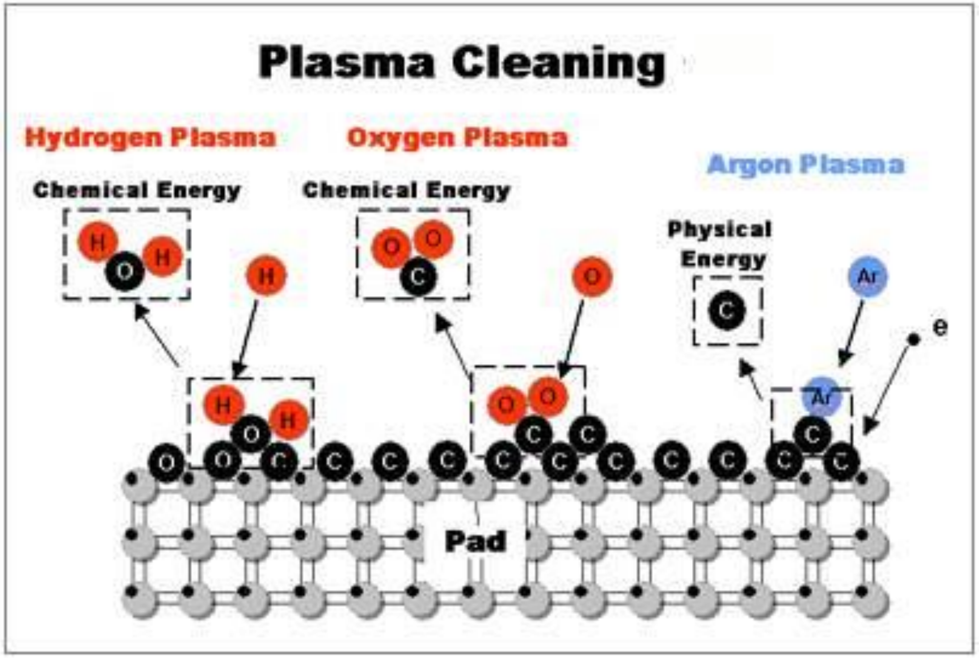


- JPDAP_37_p3254_2004_EUV sources using Xe and Sn discharge plasmas

Plasma cleaning

Plasma can be used for cleaning surface

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



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

Free radicals are generated and used in chemical reactions

$$e^- + H_2 \rightarrow 2H\bullet \qquad e^- + O_2 \rightarrow 2O\bullet \qquad \mathrm{O}\bullet + O_2 \rightarrow O_3$$

- **Highly reactive free radicals generated in plasma may react with the hydrocarbon contaminants of surface oxide.**
- **Both H• and O• can react with grease or oil on surface to form volatile hydrocarbons.**

$$\mathrm{H}\bullet_{(g)} + C_nH_{2n+2(s)} \rightarrow \mathrm{CH}_{4(s)}$$

$$\mathrm{O}\bullet_{(g)} + C_nH_{2n+2(s)} \rightarrow \mathrm{CO}_{(s)} + \mathrm{CH}_xO_{y(g)} + H_2O_{(g)}$$

- **O• is more reactive than H•. But O• may also react with surface metal to form oxide, deteriorating the material properties. Nevertheless, H• can make metal oxide back to metal.**

$$\mathrm{O}\bullet + \mathrm{Me} \rightarrow \mathrm{MeO}$$

$$\mathrm{H}\bullet + \mathrm{MeO} \rightarrow \mathrm{Me} + H_2O$$

The effect of chemical reactions is increased as the pressure increases

- **Advantages:**
  - **Stable gas products are formed.**
  - **No redeposition problem.**
  - **High etching selectivity.**

- **Disadvantages:**
  - **Higher concentration of H_2 or O_2 is required to ensure an appropriate etching rate.**
  - **H_2 safety or O_2 strong oxidation ability needs to be monitored.**

High energy ions are used in physical sputtering cleaning

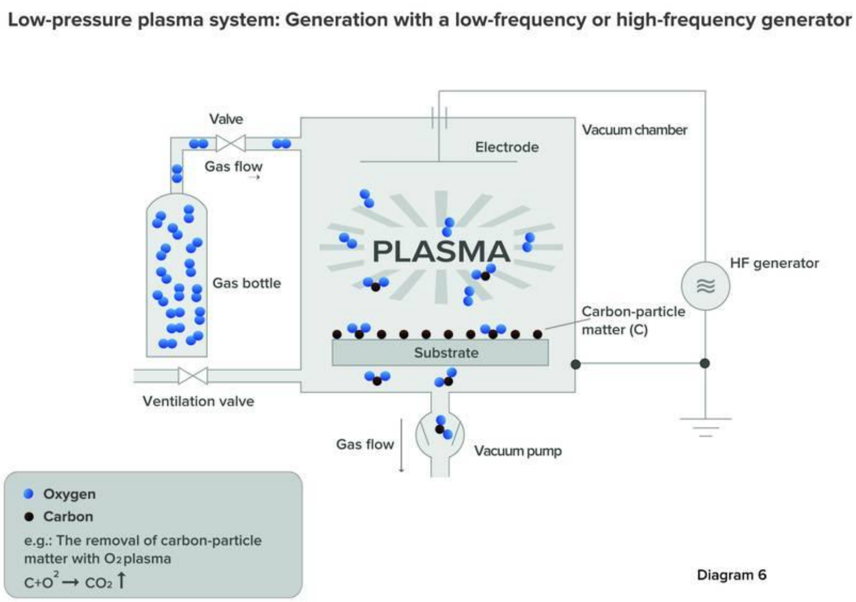
- Ions generated in plasma can be accelerated toward the substrate to physically bombard away the atoms of contaminants.
- The physical sputtering rate increases as the following quantities increase:
  - Plasma density;
  - Accelerating voltage;
  - Mass of bombardment atoms.
- The physical sputtering is also enhanced by lowering the pressure.
- High cathode bias is used.
- Ar^+ has strong sputtering effect.

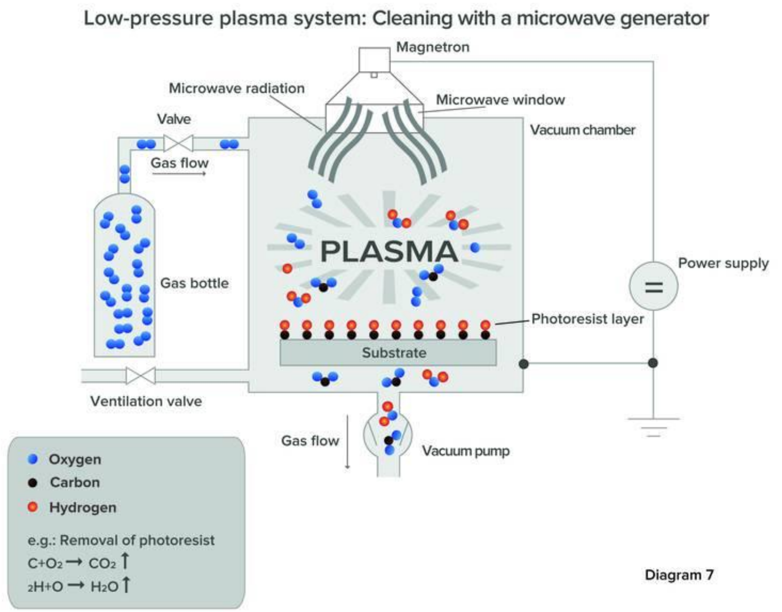
The physical sputtering rate increases with higher cathode bias and Ar concentration and lower pressure

- **Advantages:**
  - **Highly efficient cleaning effect can be achieved.**
  - **Gas consumption rate can be very low.**

- **Disadvantages:**
  - **Etching problems – non-selective etching by physical sputtering.**
  - **Redeposition problems: the products sputtered out may be highly unstable and tend to deposit again downstream.**

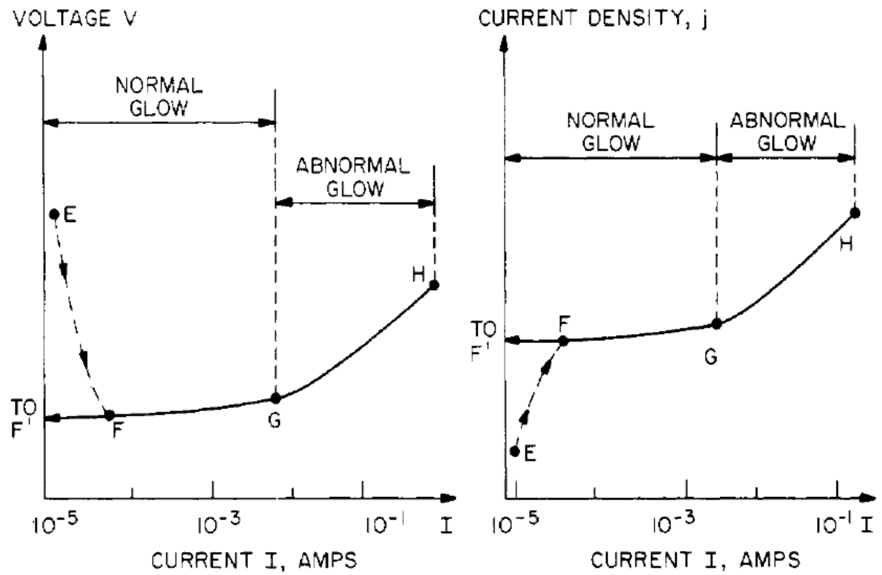
Plasma cleaning examples





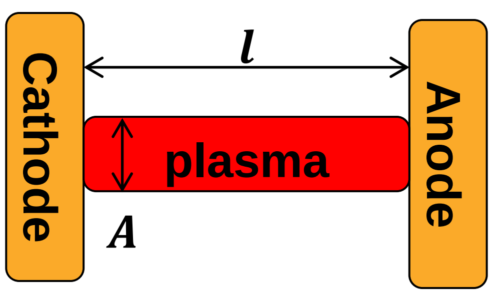
https://www.plasma.com/en/plasmatechnik/low-pressure-plasma/cleaning/

Abnormal glow discharge occurs when the cross section of the plasma covers the entire surface of the cathode

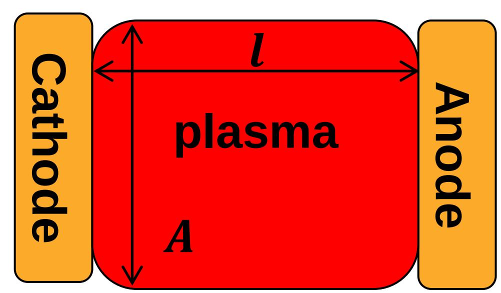


$$R = \eta \frac{l}{A}$$

- **Normal glow discharge:**

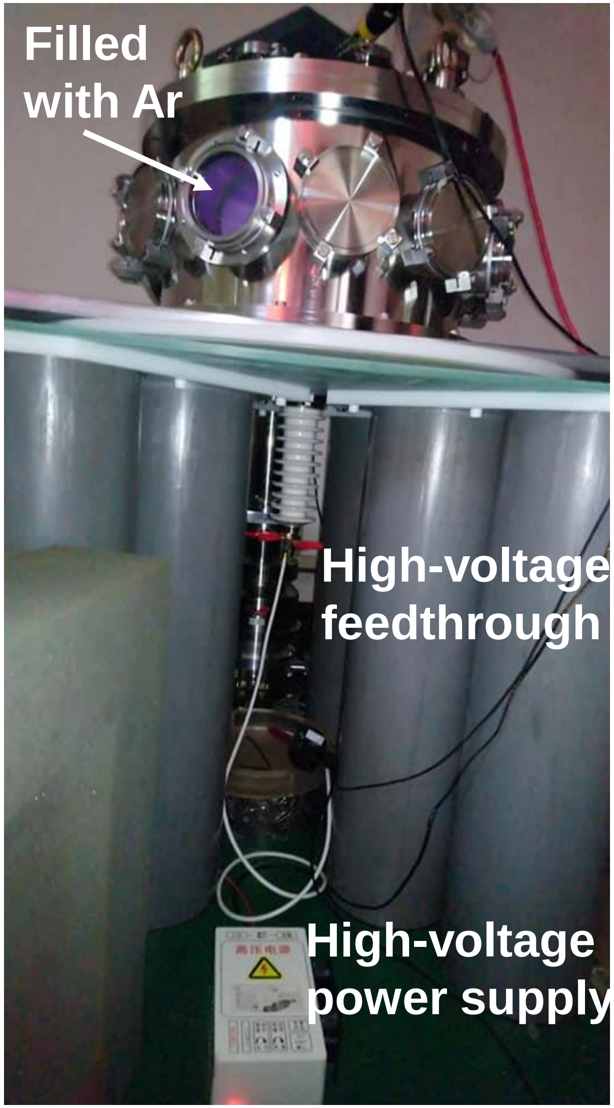


- **Abnormal glow discharge:**



- **Surface cleaning using plasma needs to work in the abnormal glow discharge region.**

Plasma cleaning needs to work in the regime of abnormal glow discharge



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    a. How plasma is generated
    b. Plasma in space
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    g. Controlled thermonuclear fusion
    h. Neutral beam source
    i. Electrical propulsion

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
- Facemask regeneration
- Mushroom yield enhancement

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**
- **Mushroom yield enhancement**

Plasma is characterized by the electron and ion temperatures

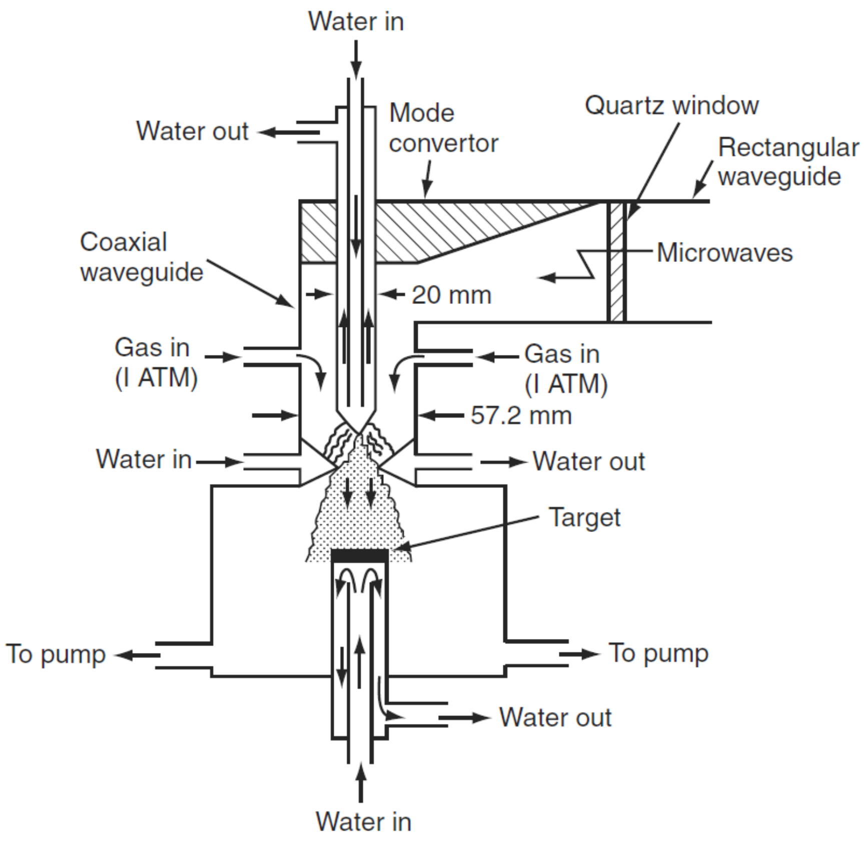
- Non-thermal plasma
  - $T_i << T_e$
  - Also called non-equilibrium plasma
- Thermal plasma
  - $T_i \approx T_e$
- Earlier applications of plasma in medicine – thermal effects of plasma

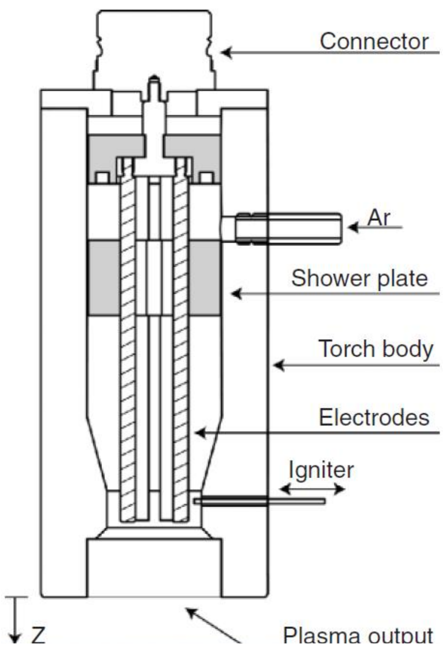
Plasma can provide good surface treatment with low temperature

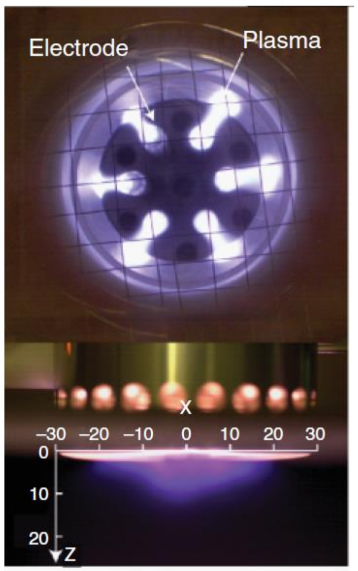
Treatment	Surface treatment level	Depth	Temperature	Cost
Chemical	Large	Deep	Room temperature ~200 ℃	Medium
Heat	Only oxidizing	Deep	High temperature	Cheap
Radiation	Small	Whole sample	High temperature	Expensive
Plasma	Large	Surface	Room temperature ~100 ℃	Cheap ~ Medium

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

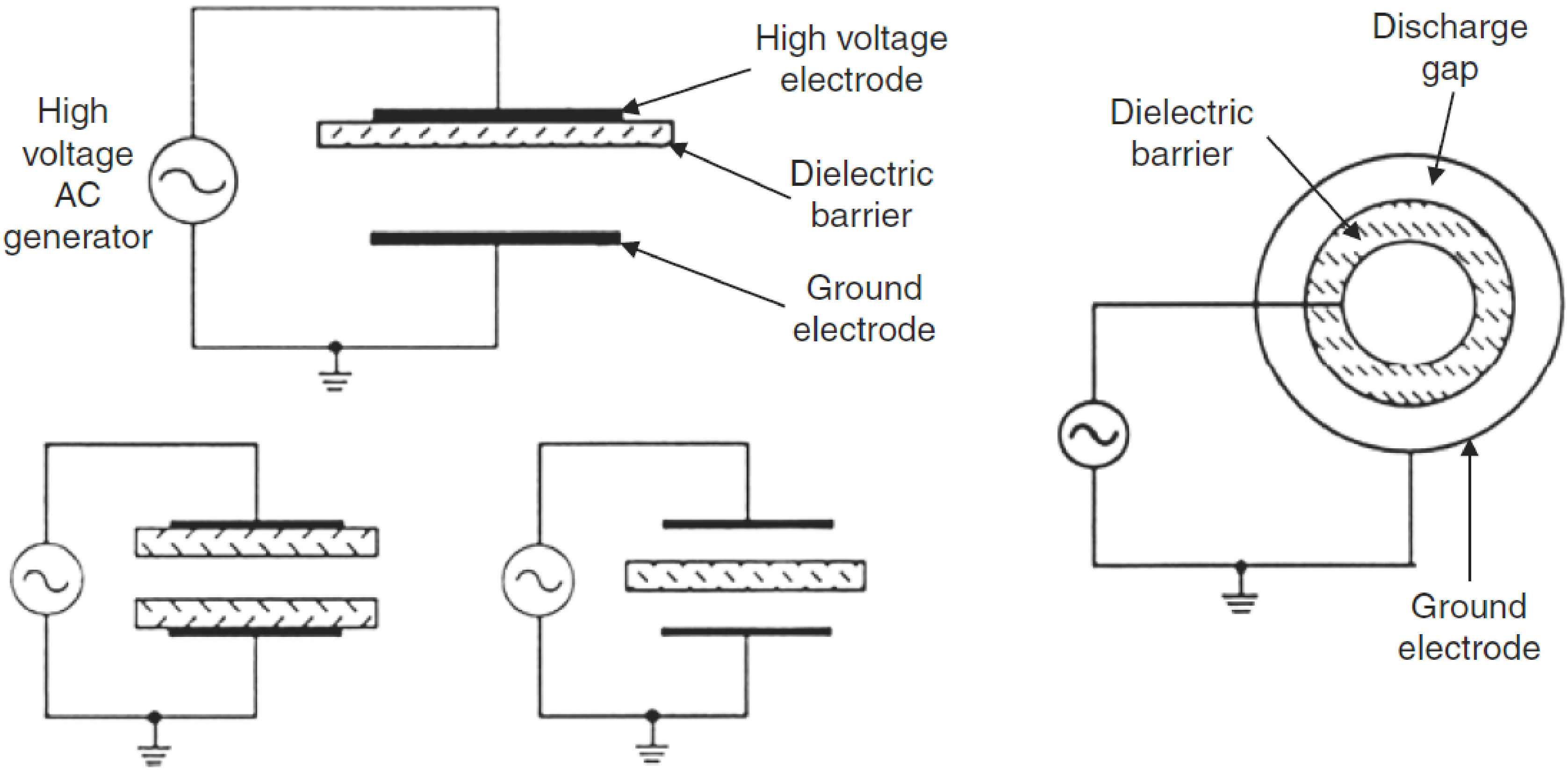
Microwave plasma torch



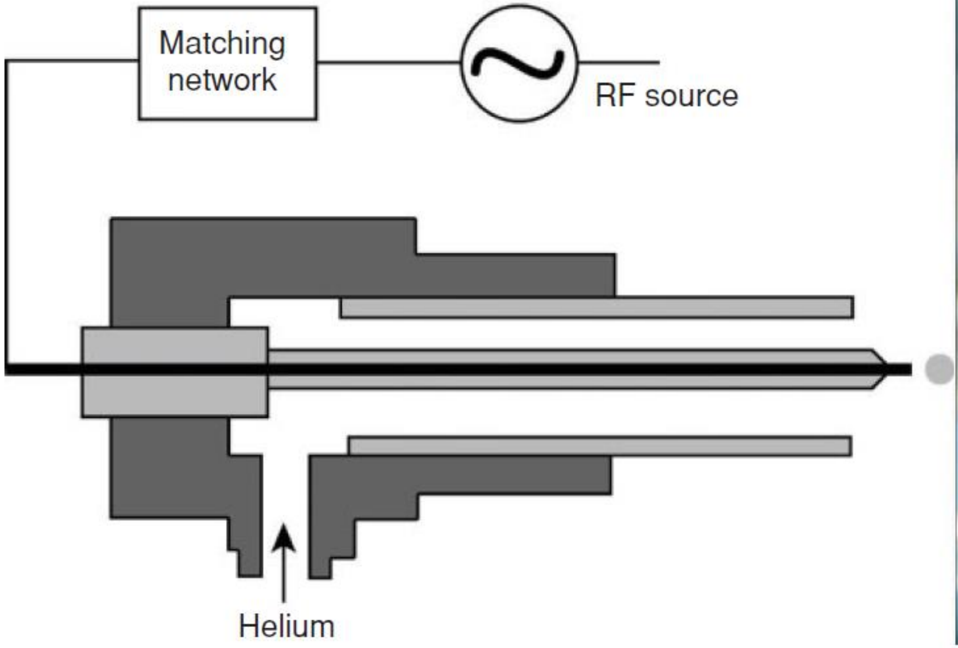


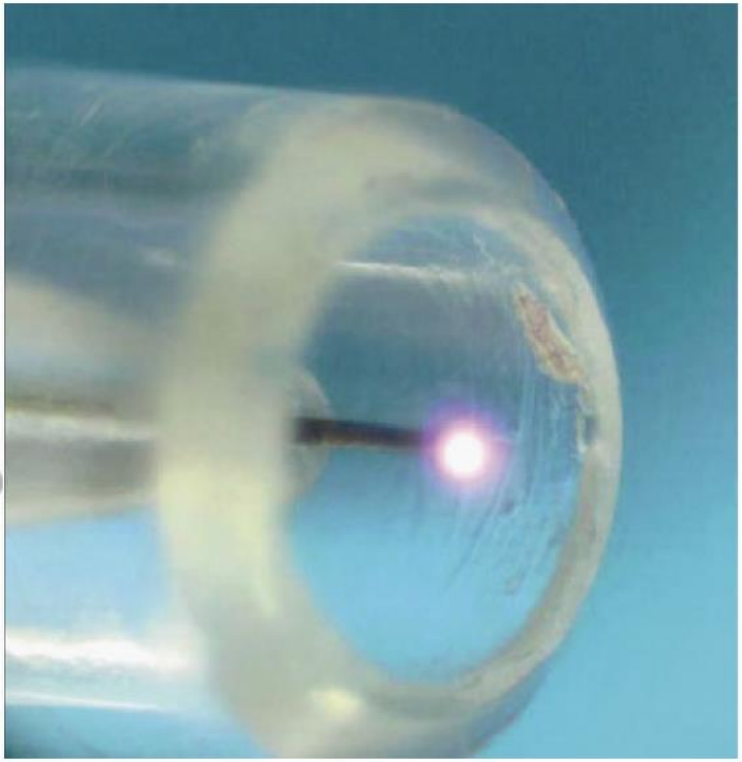


Dielectric-barrier discharges (DBDs)

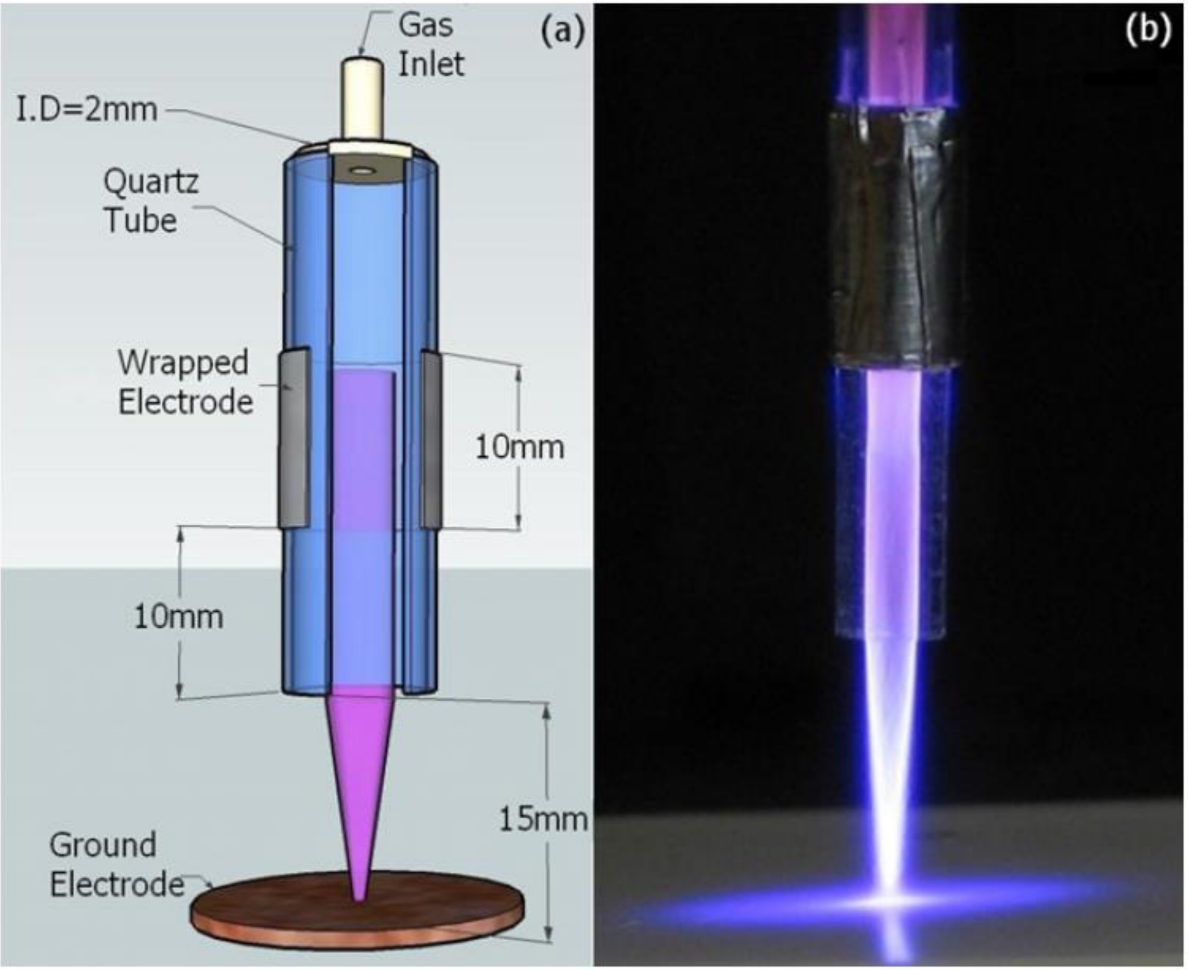


Plasma-needle discharge



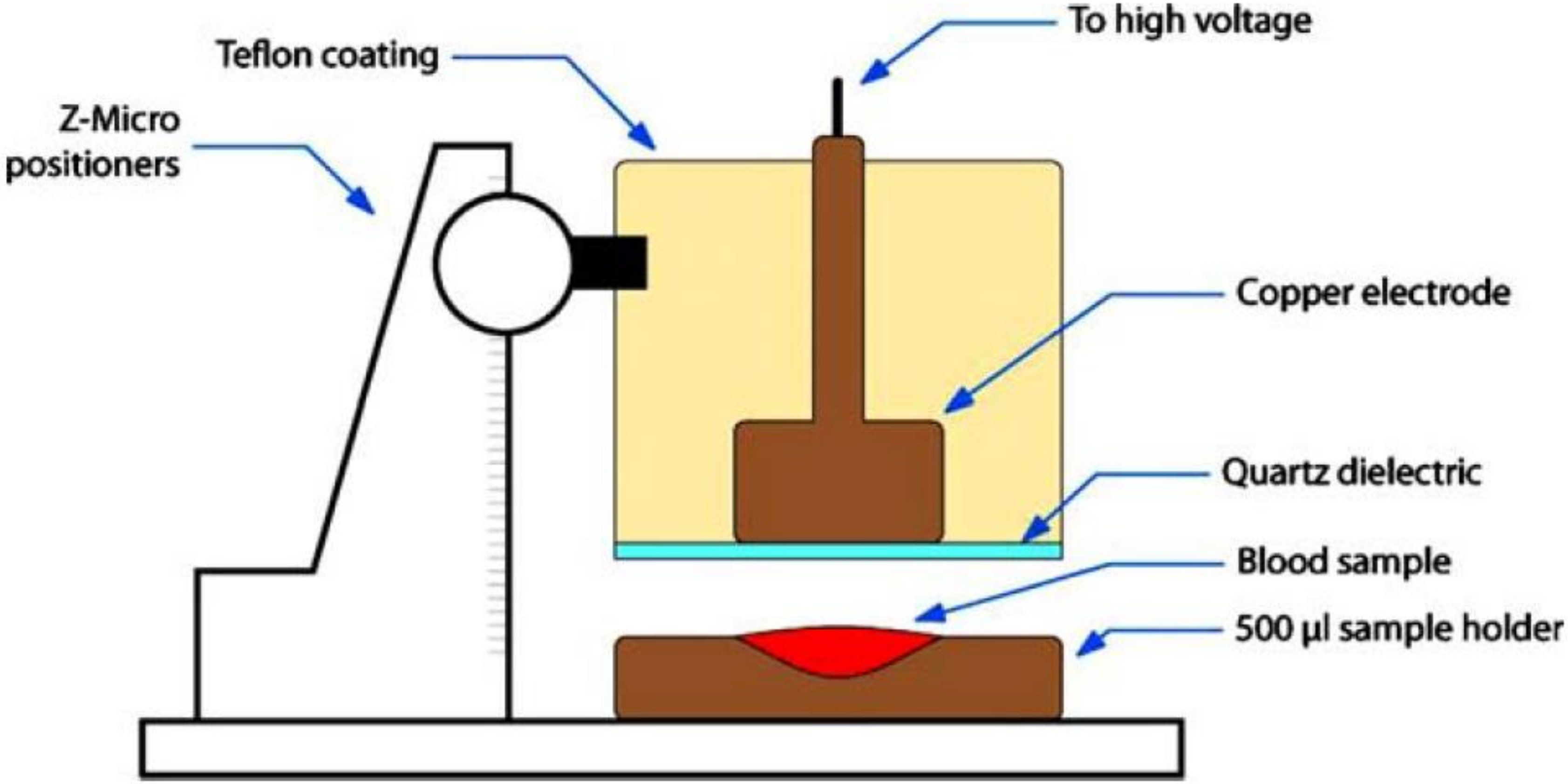


Atmospheric-pressure cold helium microplasma jets



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

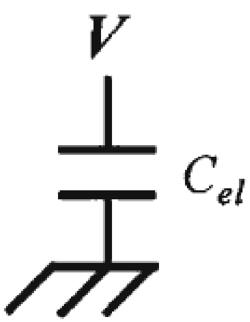
Floating-electrode dielectric barrier discharge (FE-DBD)

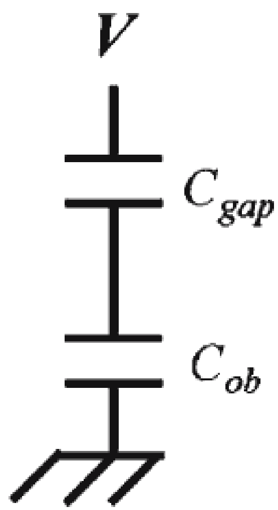


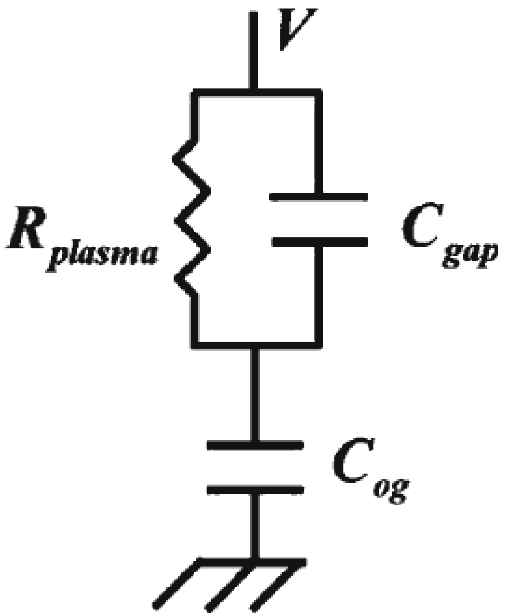
G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

Simplified electrical schematic of FE-DBD

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





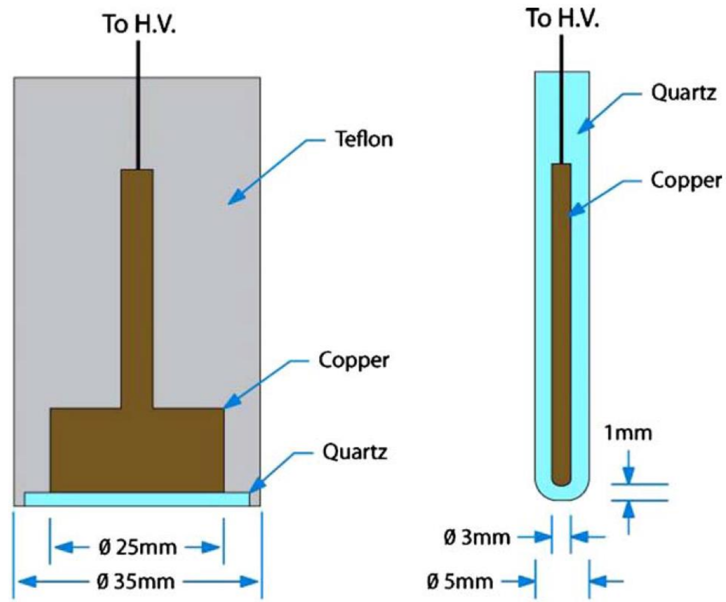


$$C_{\text{ob}} >> C_{\text{gap}} \Rightarrow V_{\text{ob}} << V_{\text{gap}}$$

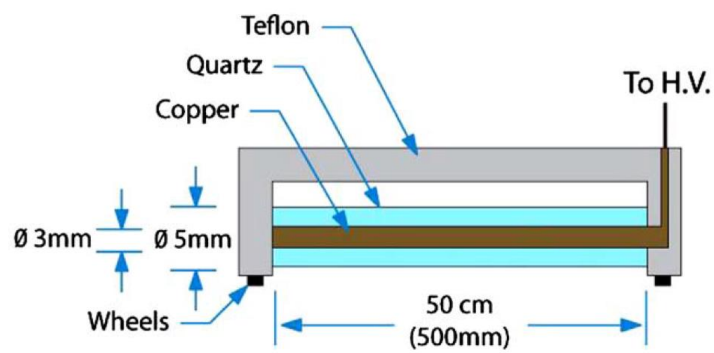
G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

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

- **Round**
- **Wand**

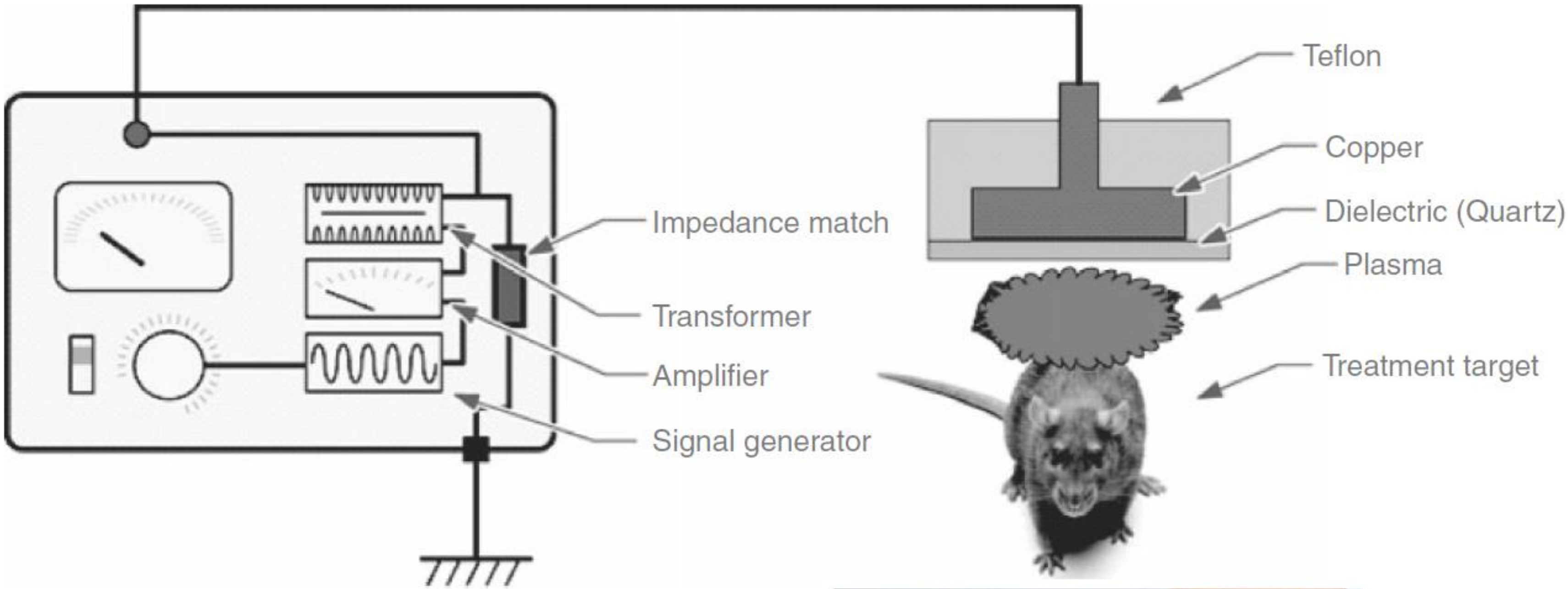


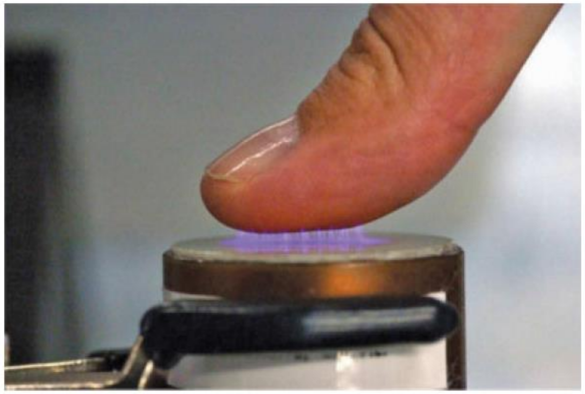
- **Roller**



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

FE-DBD is a direct plasma medicine





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

Outline

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

Bacteria concentration reduces after being treated with FE-DBD

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

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

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

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

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

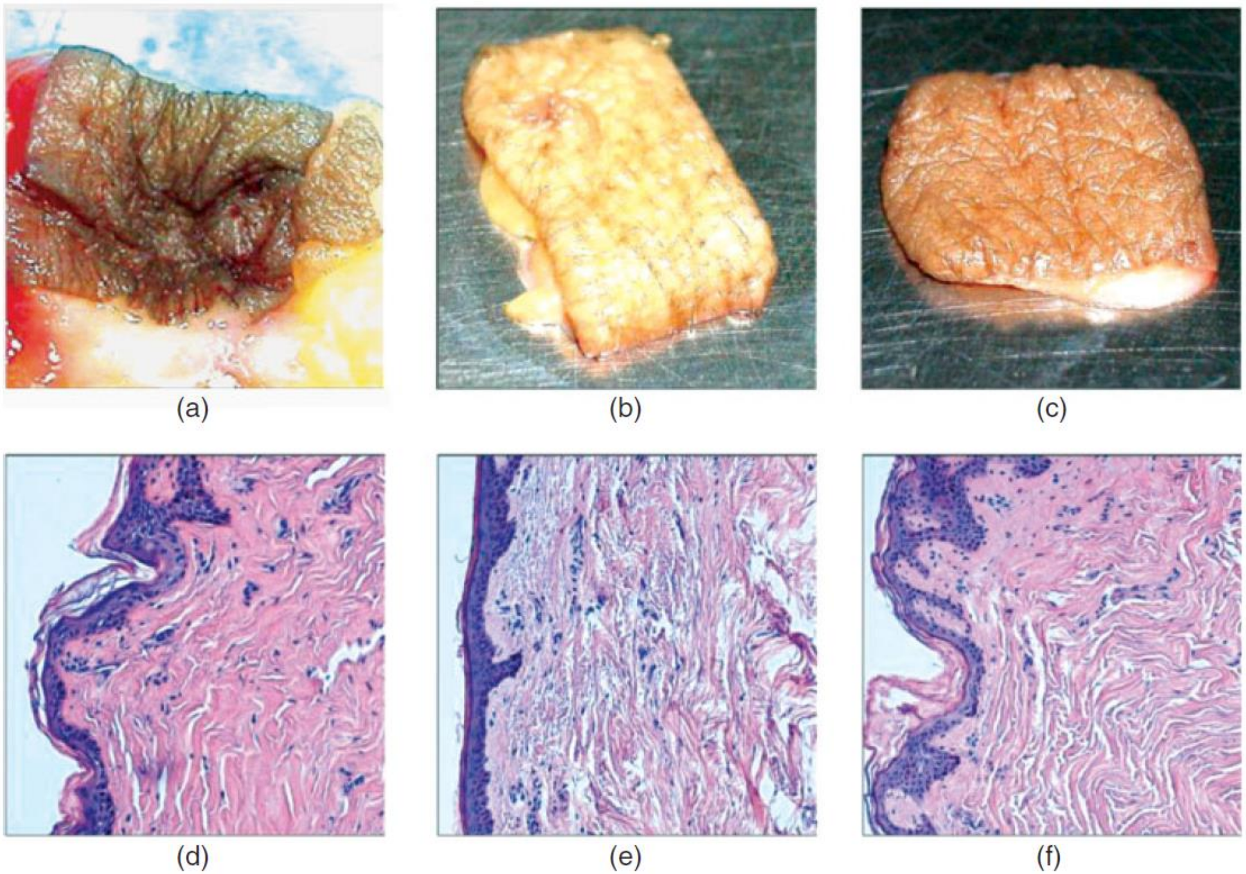
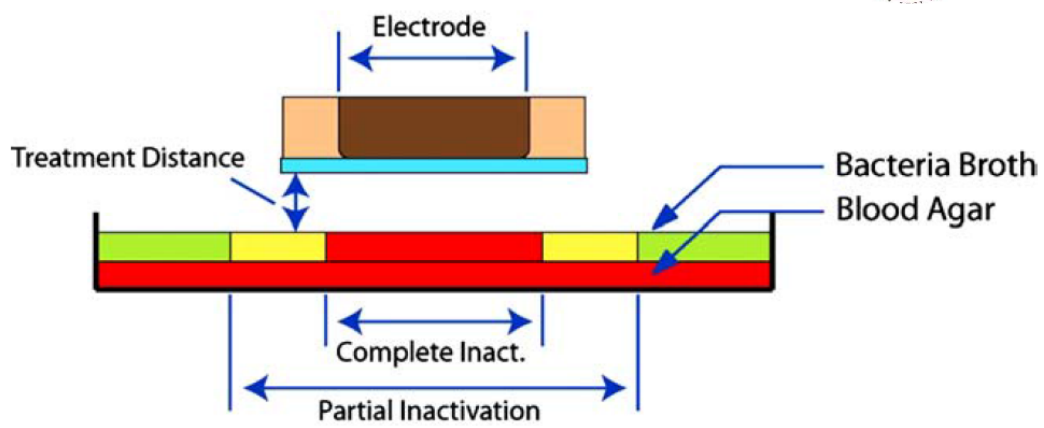


Figure 6.23 *Photos (top) and tissue histology (bottom) of cadaver skin samples after FE-DBD treatment: (a, d) control; (b, e) after 15 s of treatment; and (c, f) after 5 min of treatment – no visible damage is detected.*

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

Bacteria is inactivated by the plasma



- ~1.3x10^{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)

Outline

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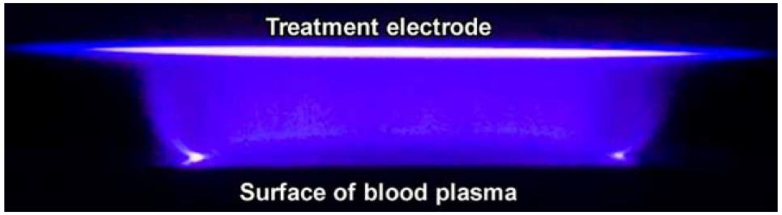
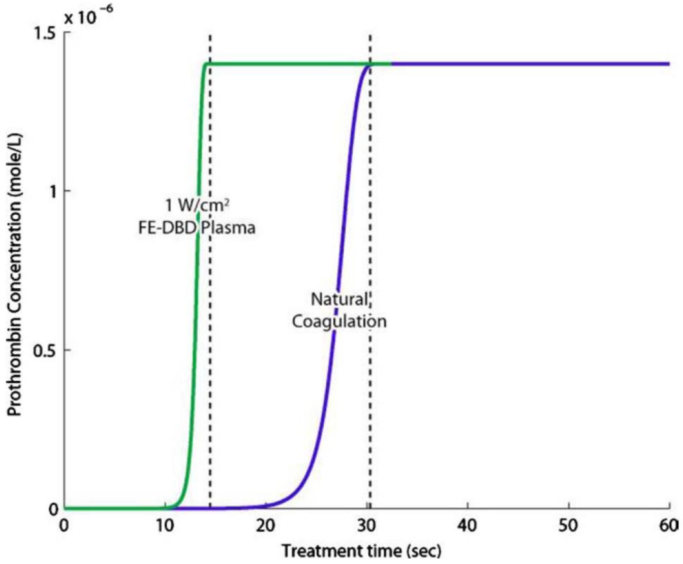
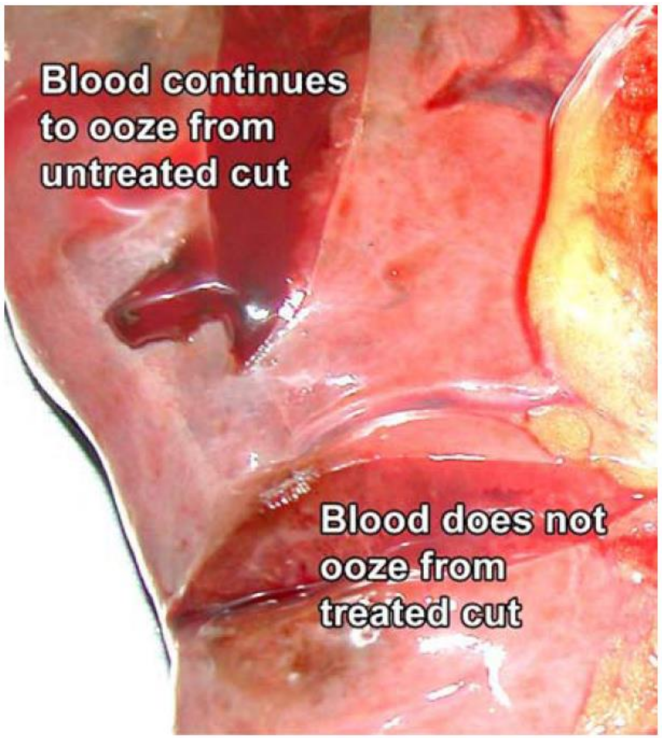
Plasma can stimulate blood coagulation

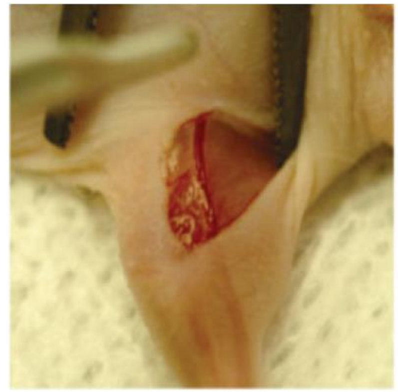




G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)

Example of blood coagulation using plasma





Saphenous vein
is a major blood vessel for a mouse

(a)

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

(b)

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

(c)

G. Fridman, *et al.*, Plasma Process. Polym., **5**, 503 (2008)
G. Fridman, *et al.*, Plasma Chem. Plasma Process., **26**, 425 (2006)
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 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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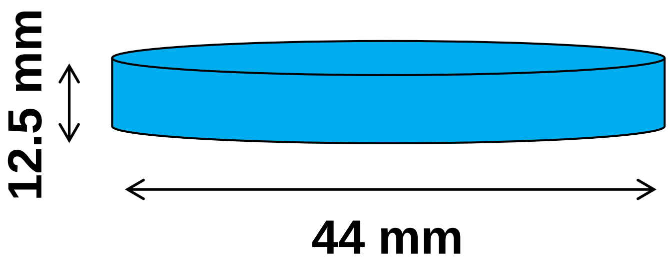
- Mushroom yield enhancement

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

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



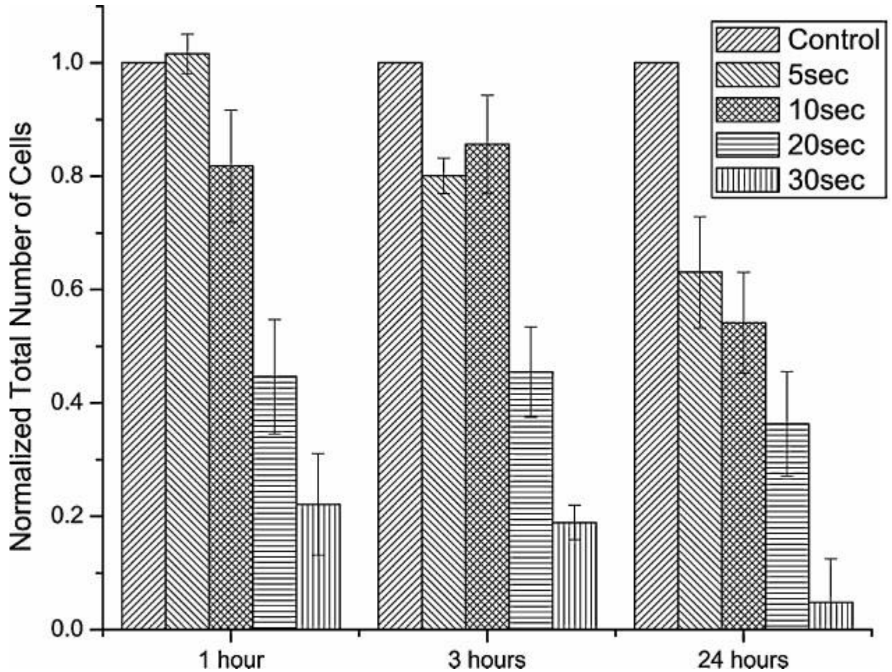
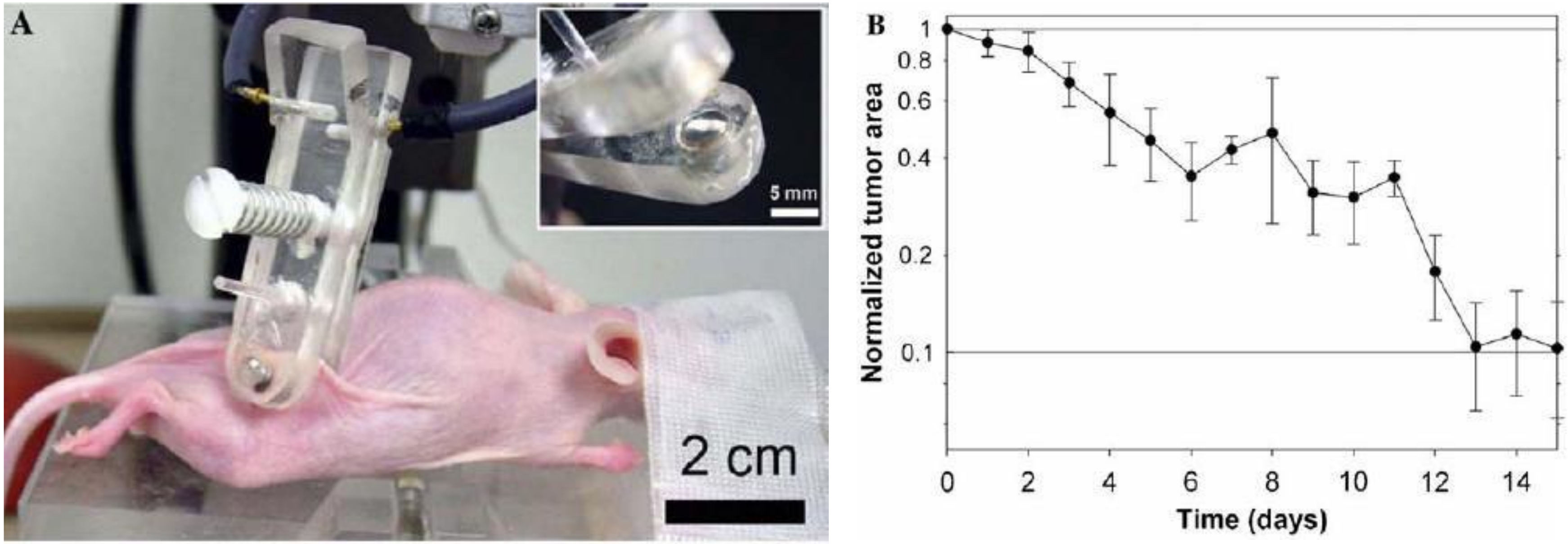


Figure 22. Results of FE-DBD treatment of melanoma cancer cells: Control, 5, 10, 20, and 30 s, counted 1, 3, and 24 h post-treatment.[27]

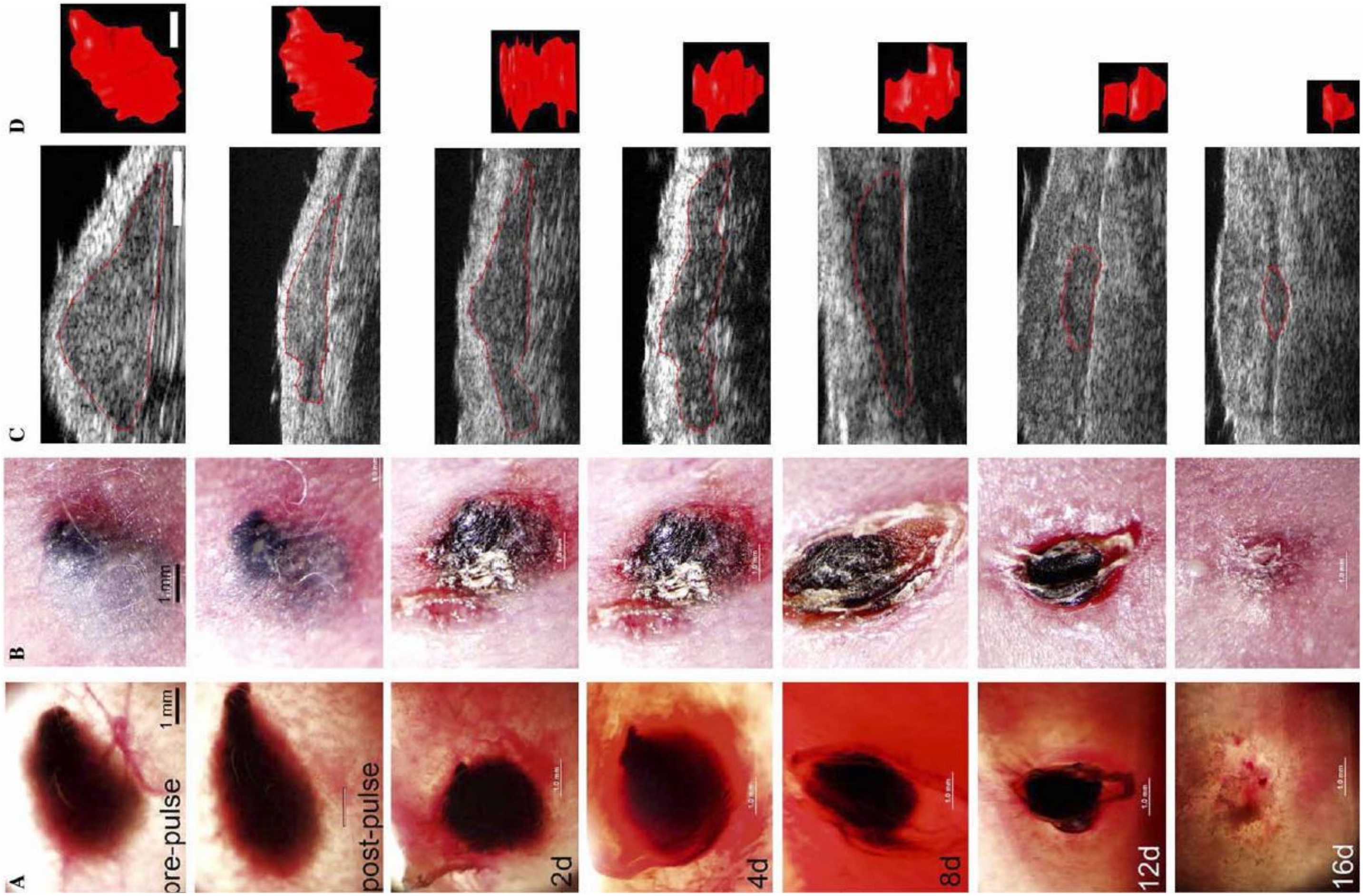
G. Fridman, *et al.*, Plasma Process. Polym., **5**, 503 (2008)

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



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

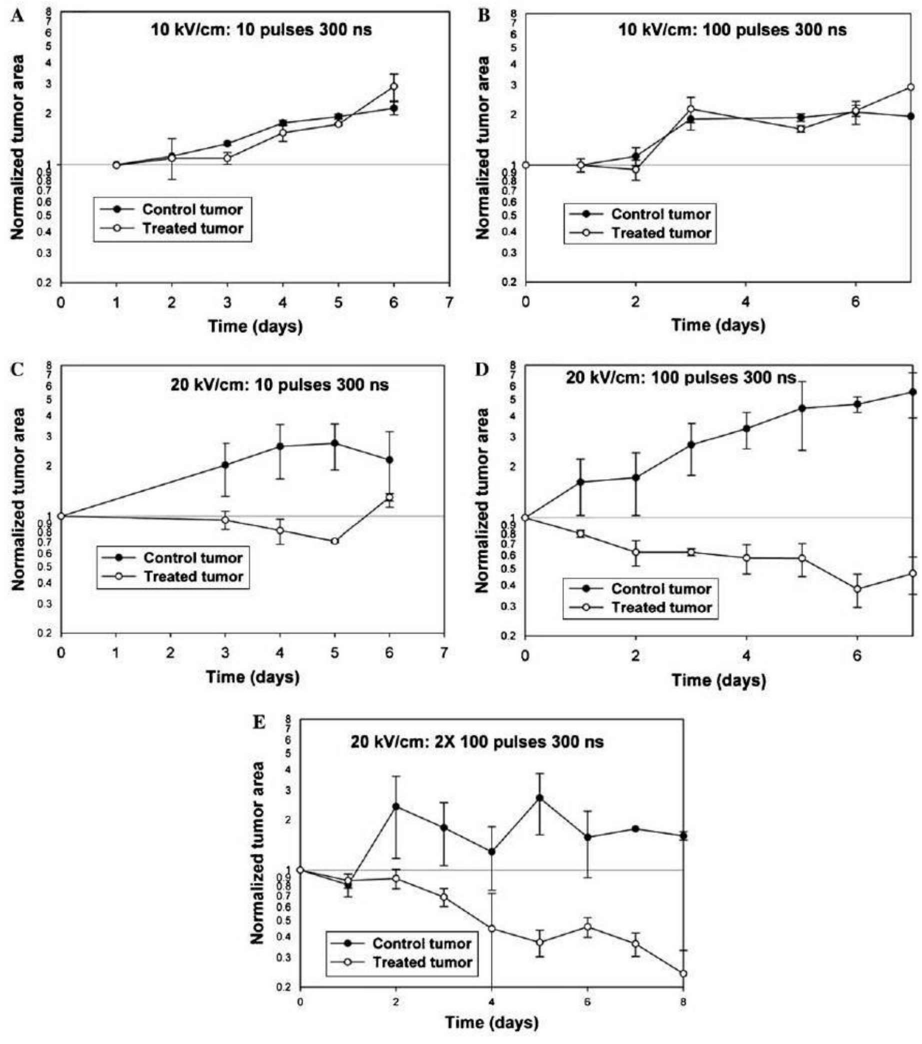
Melanoma shrinks after the treatment



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

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

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



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

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- Example of several plasma discharges for plasma medicine
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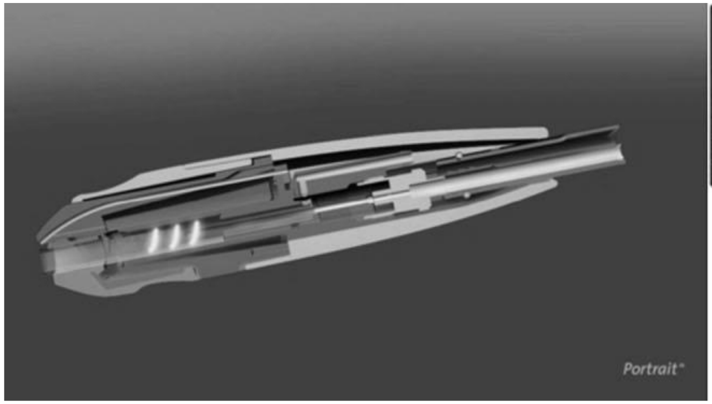
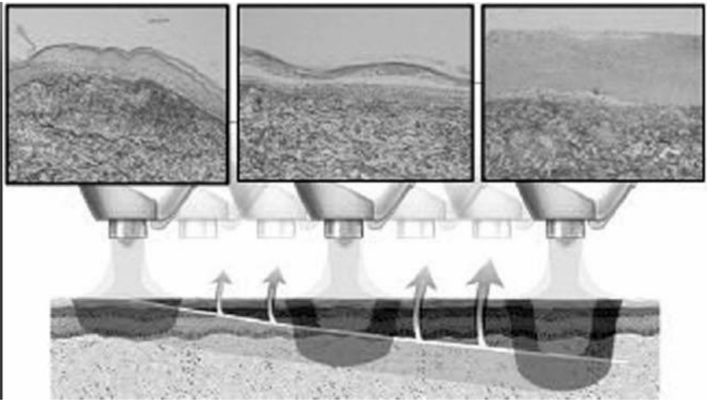
Plasma skin regeneration (PSR) is a novel skin treatment device





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

Zones of the face and associated treatment energy settings

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

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

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

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

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- Skin regeneration
- **Egg sterilization**
- Facemask regeneration
- Mushroom yield enhancement

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

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

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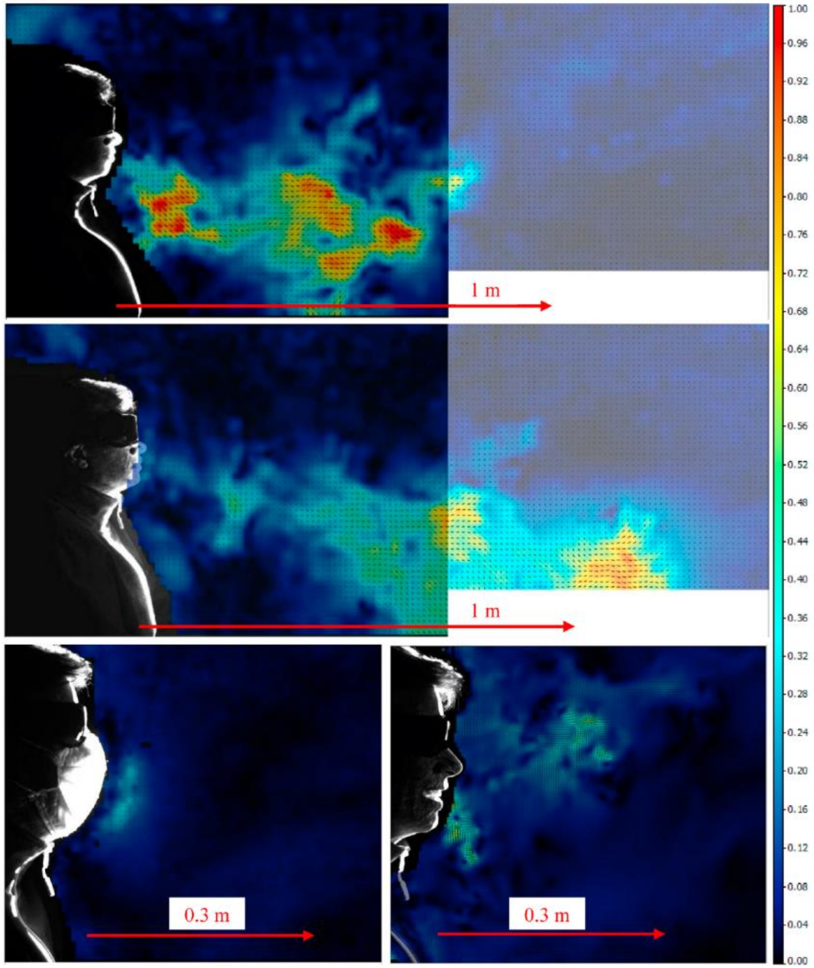
- Egg sterilization
- **Facemask regeneration**
- Mushroom yield enhancement

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



Coughing over one breath w/o mask.

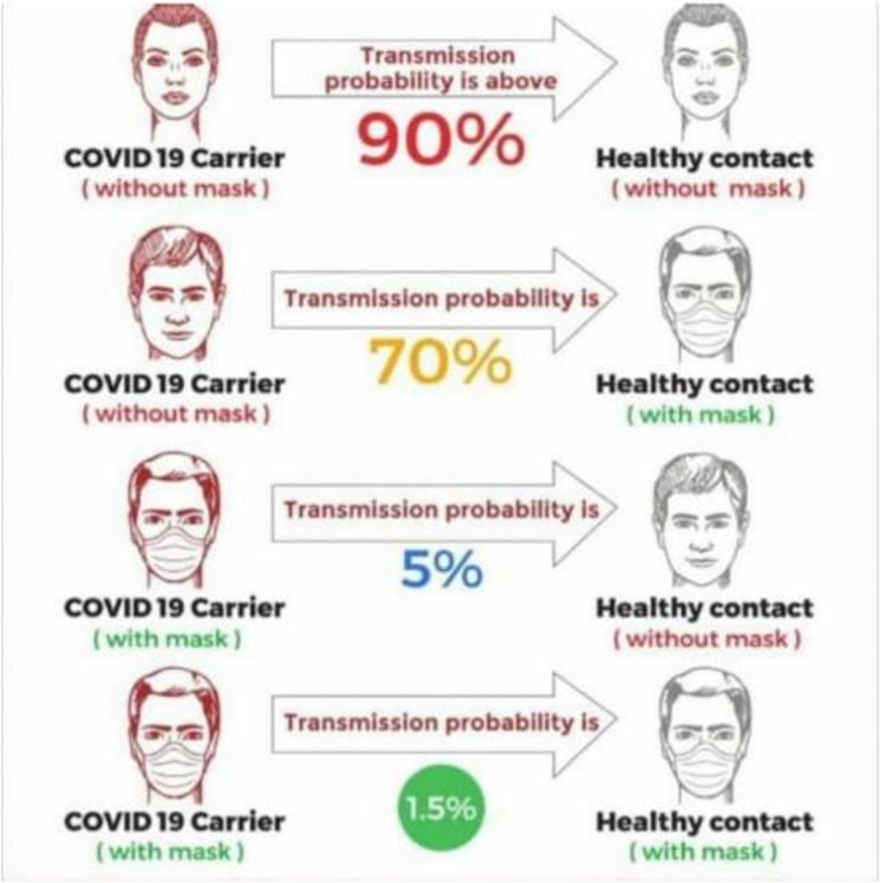
Coughing over a longer periods of time w/o mask.

Coughing over one breath w/ mask.

Talking w/o mask.

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

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



http://www.riderta.com/coronavirus

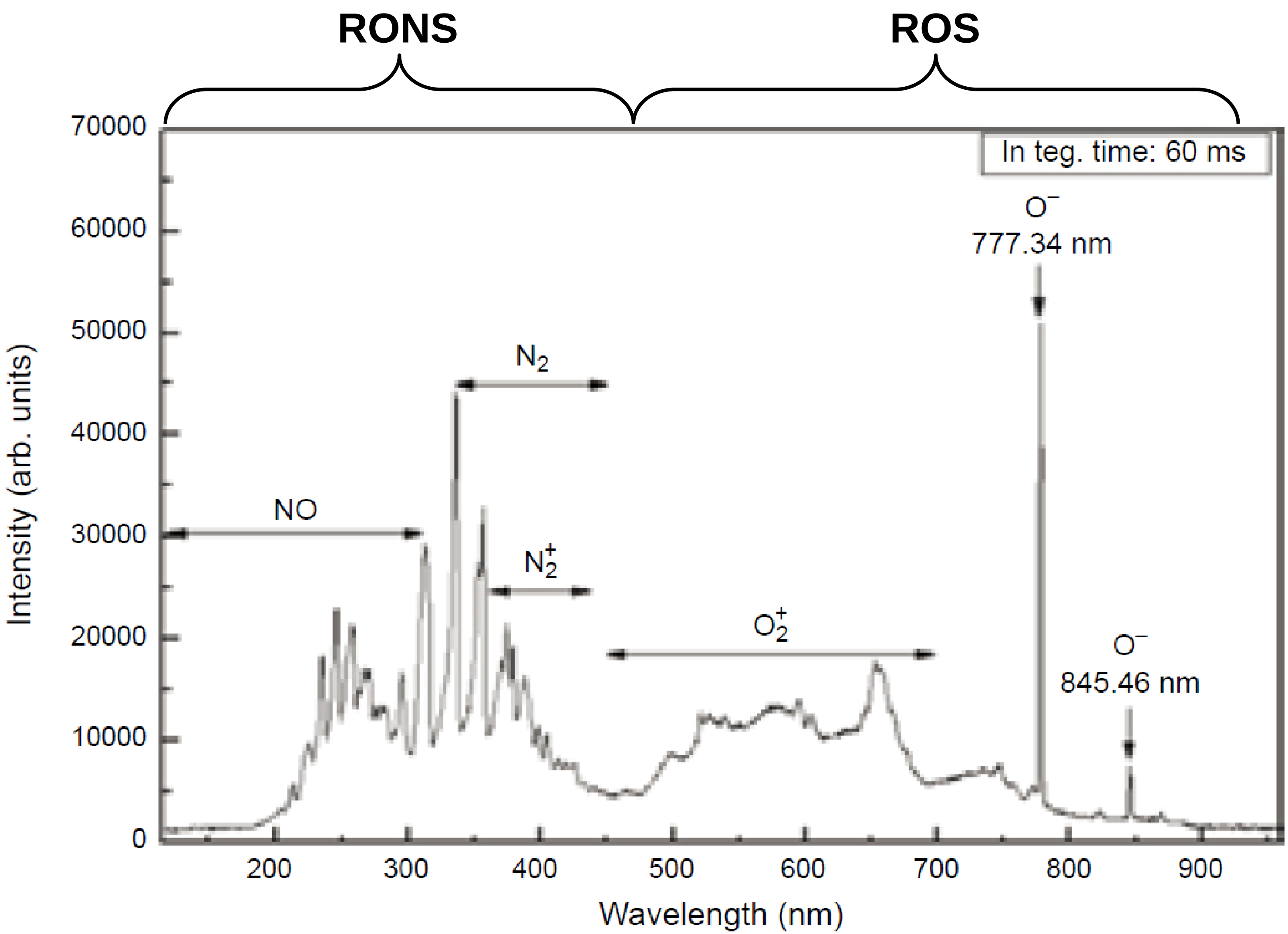
Plasma can provide good surface treatment with low temperature

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

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

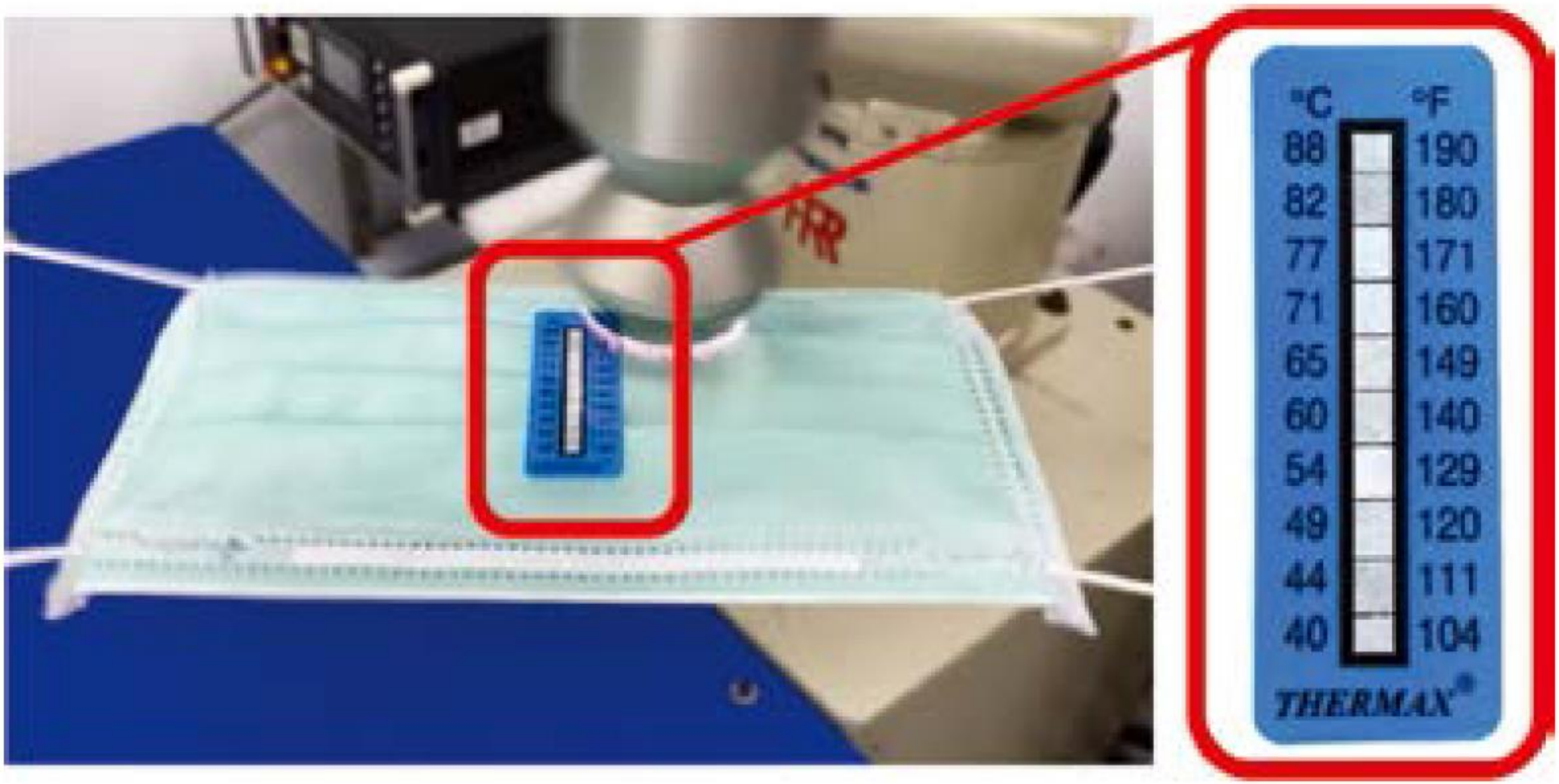
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

Plasma can generate ROS and RONS



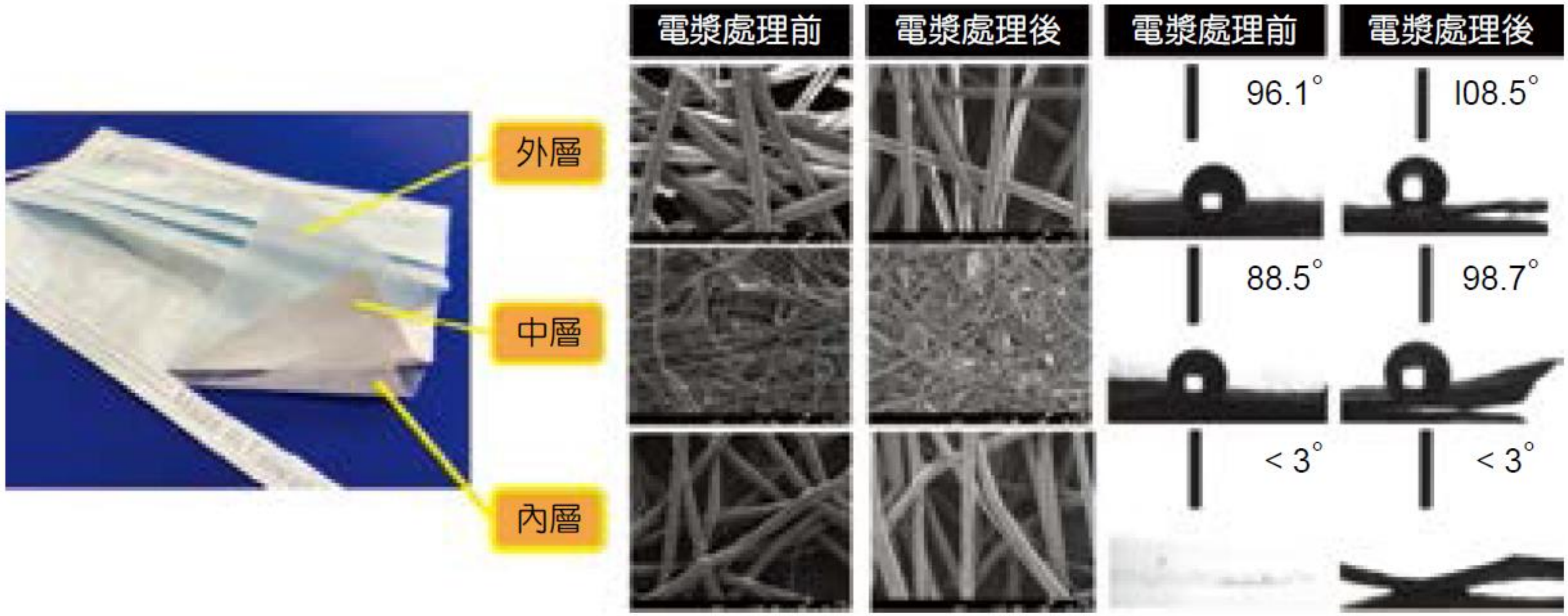
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

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



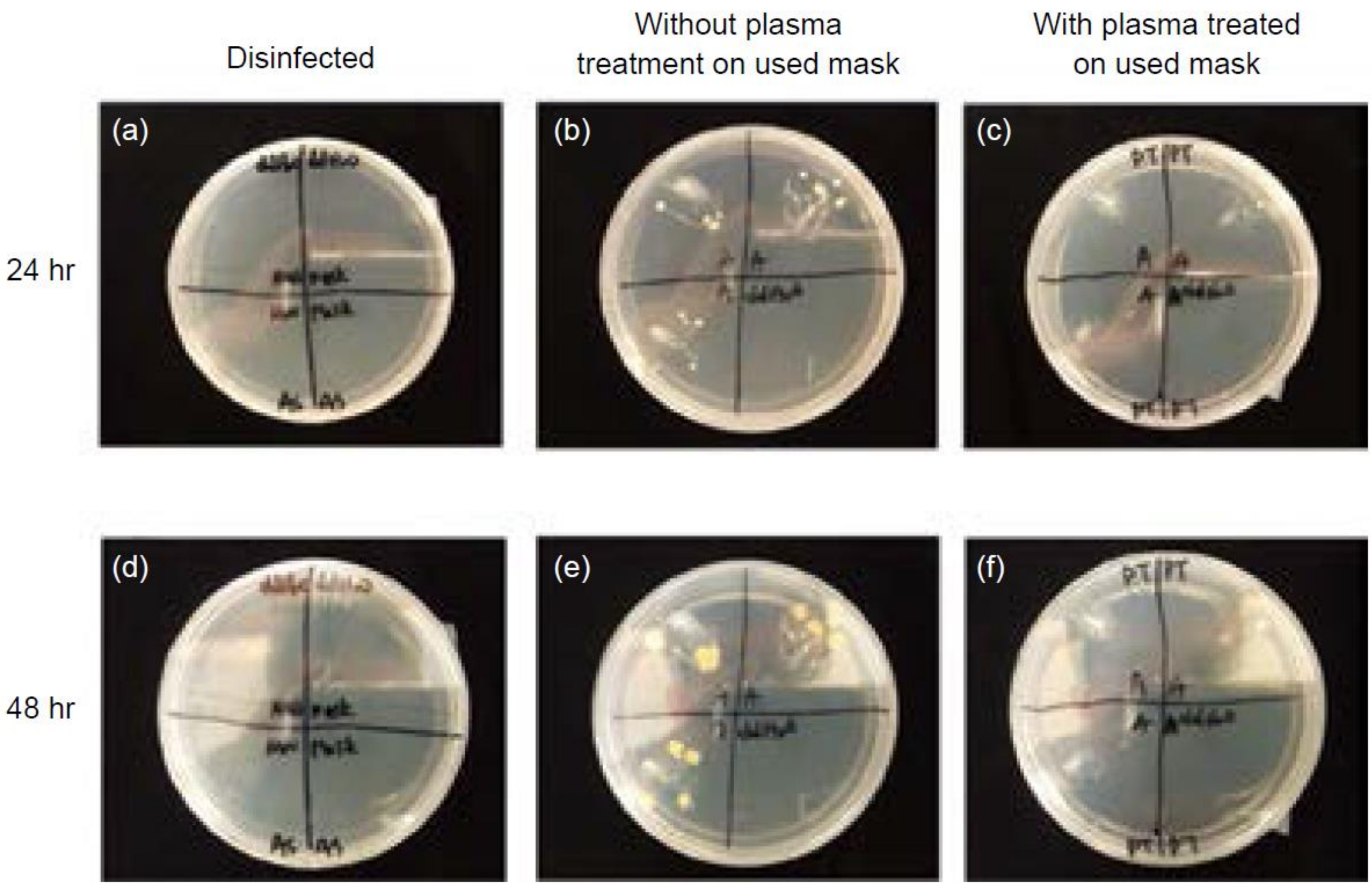
Yu-Lin Kuo, etc., 自動化大氣電漿設備建置與醫療用口罩去異味活化,科儀新知227 期 p50

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



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

The growth of the bacteria on the face mask was suppressed



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

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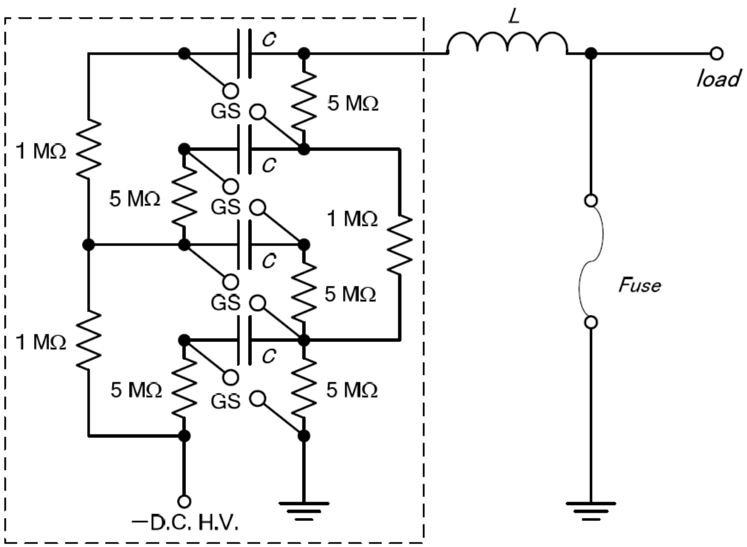
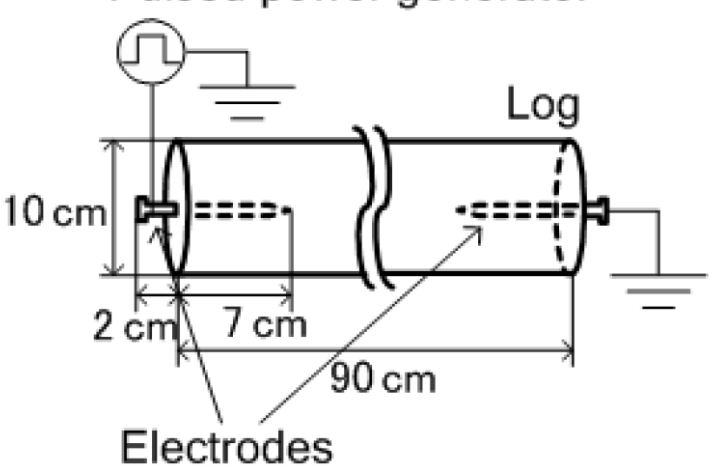
- Egg sterilization
- Facemask regeneration
- **Mushroom yield enhancement**

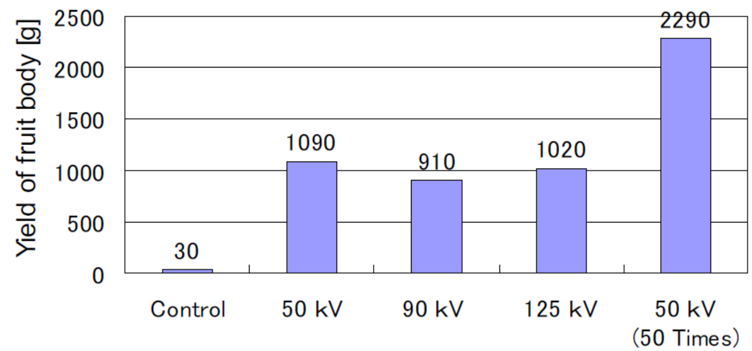
The mushroom yield is enhanced by electric stimulations



Primary energy accumulator

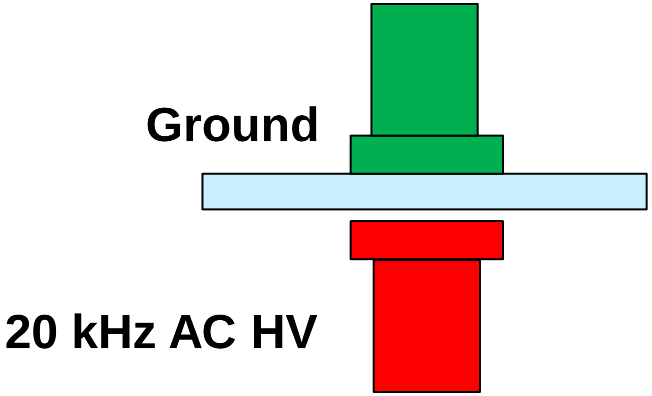
Pulsed power generator





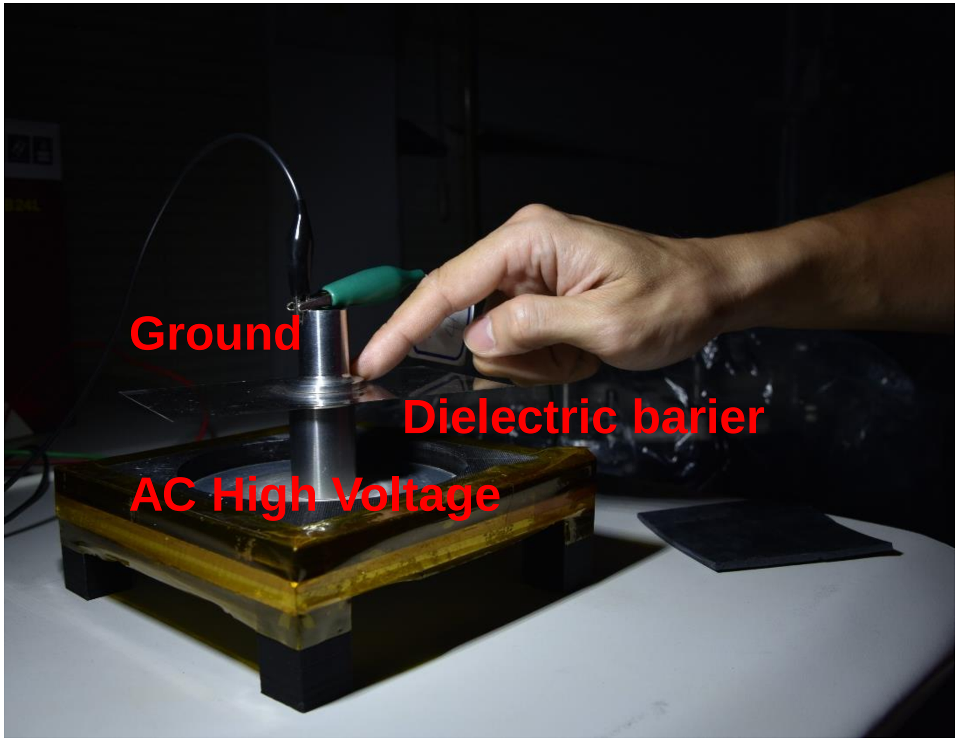
K. Takaki, etc., J. Plasma Fusion Res. Series 8, 556 (2009)

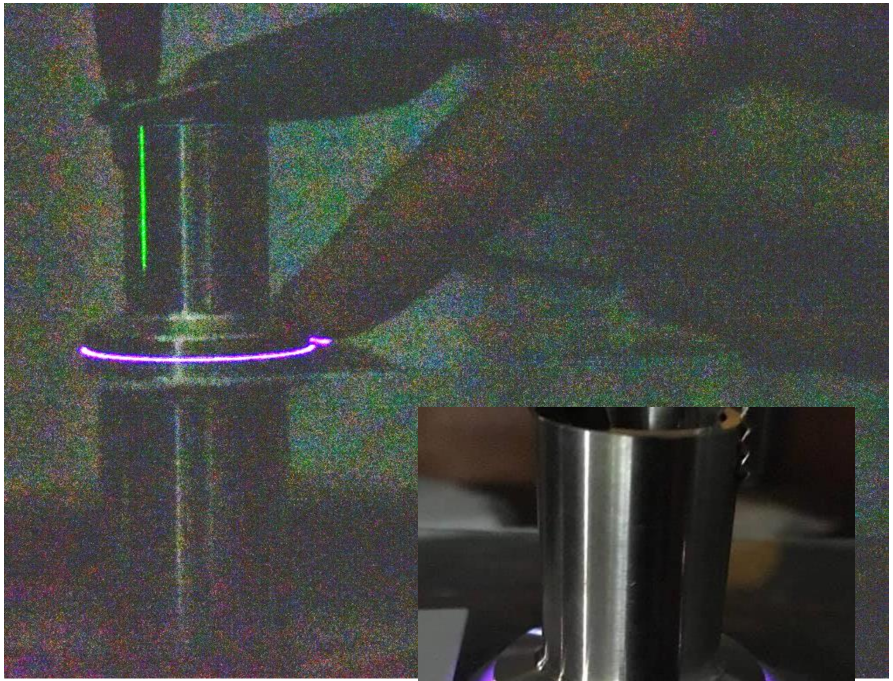
DBD plasma demonstration



Show video.

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



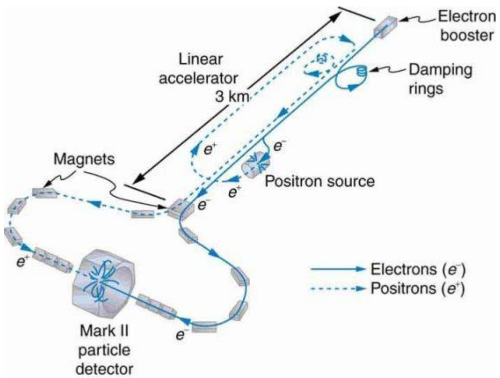


Course Outline

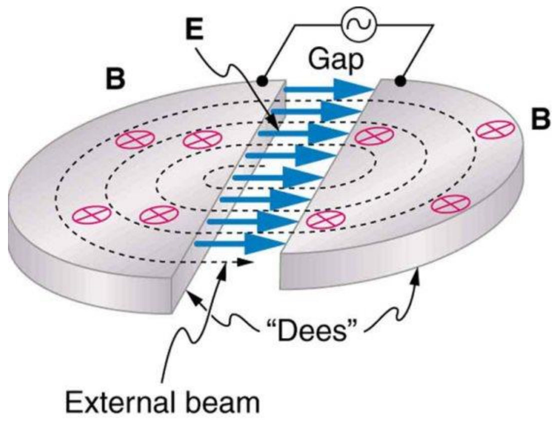
1. What is Plasma?
2. Varies kinds of plasma
    a. How plasma is generated
    b. Plasma in space
    c. Material Processing
    d. Biomedical application
    e. Particle beam source
    f. High energy particle accelerator
    g. Controlled thermonuclear fusion
    h. Neutral beam source
    i. Electrical propulsion

High energy particle accelerator

- **linear particle accelerator (Linac)**



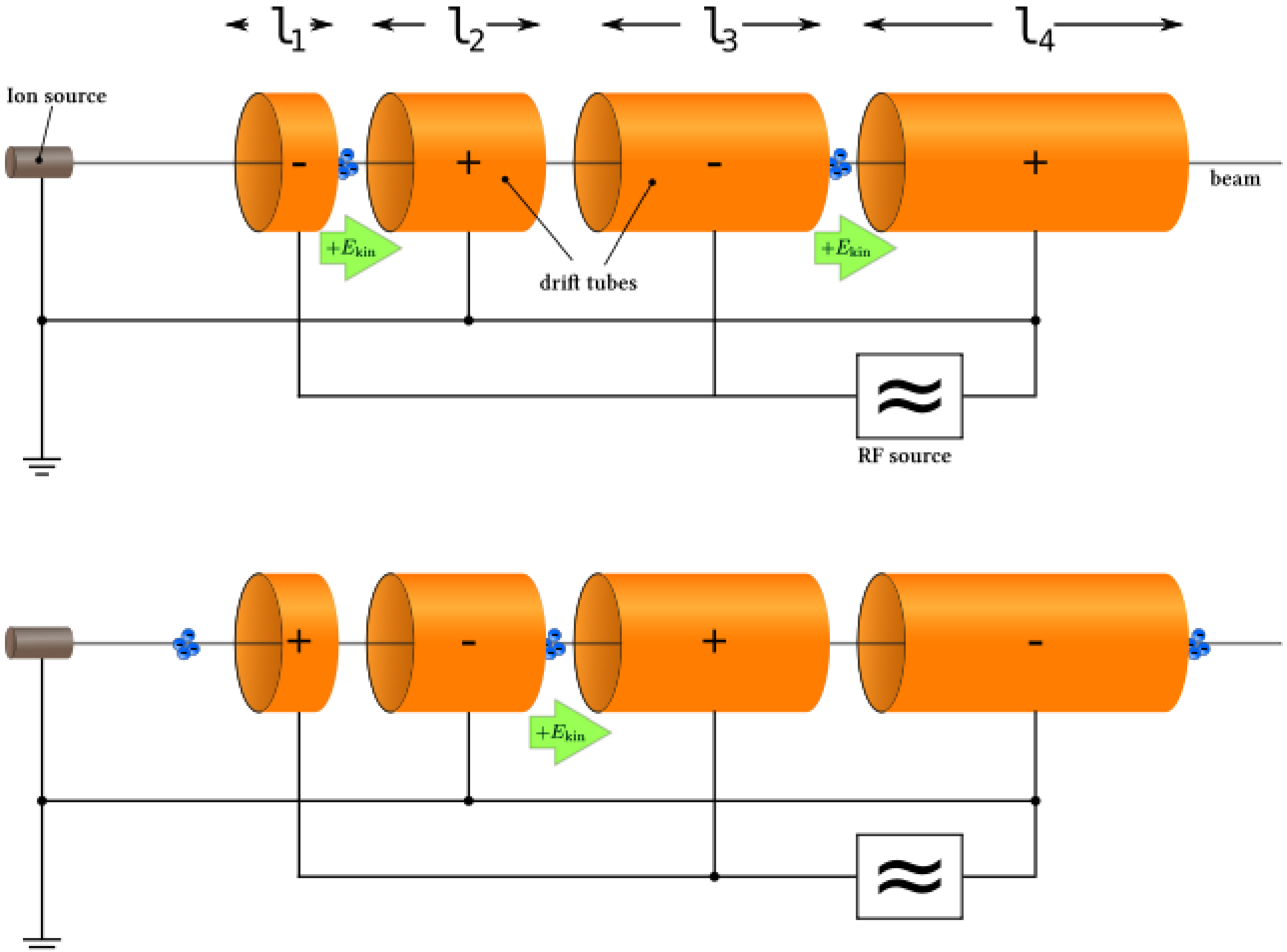
- **Cyclotron**



- **Synchrotron**

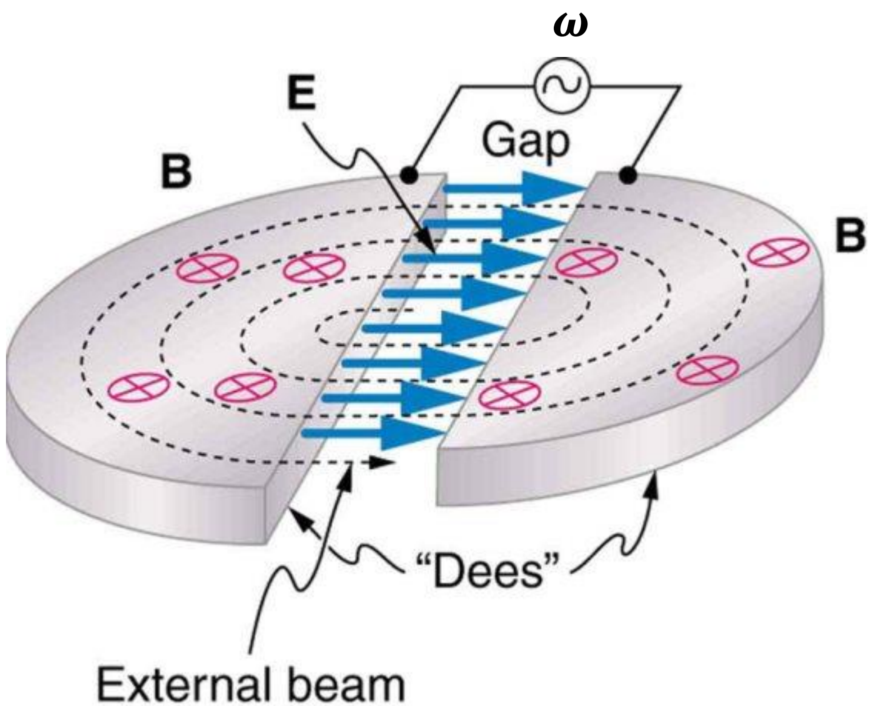
- **Reference: Introduction to plasma phenomena and plasma medicine, Y. Nishida and K.-L. Ou**

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



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

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



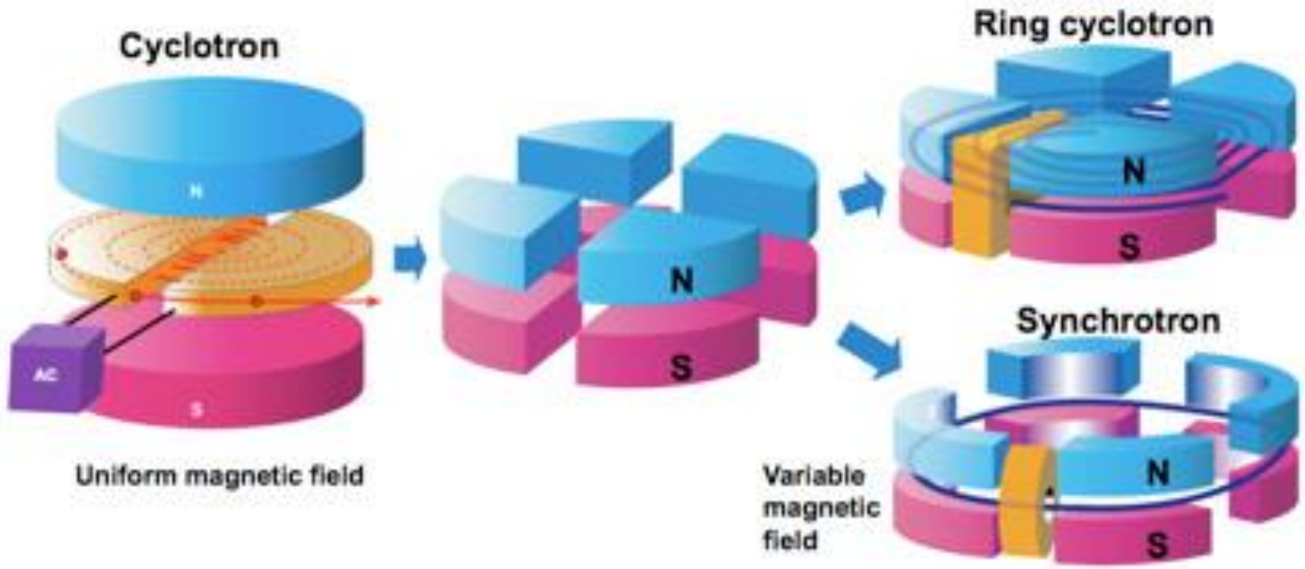
$$\omega_{ce} = \frac{eB}{m_e c}$$

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

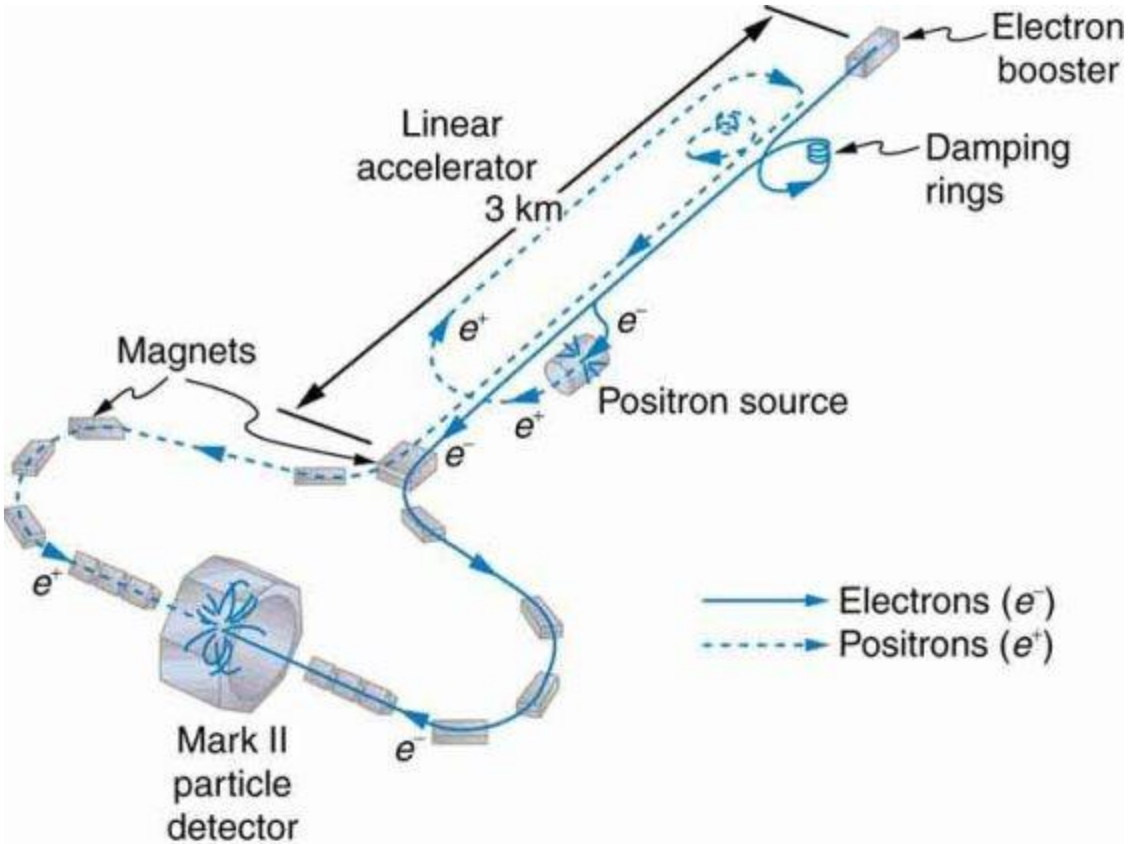
- **Cyclotron was invented by Ernest Lawrence who earned the 1939 Nobel price in physics**

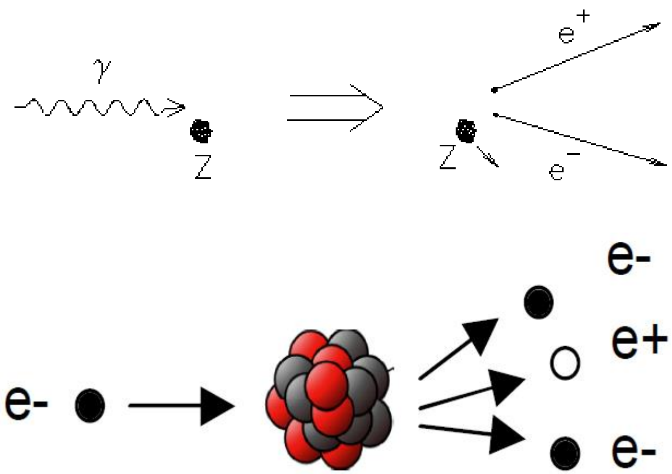
http://math.ubooks.pub/Books/ON/M1/1704/C33S4M004.html

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



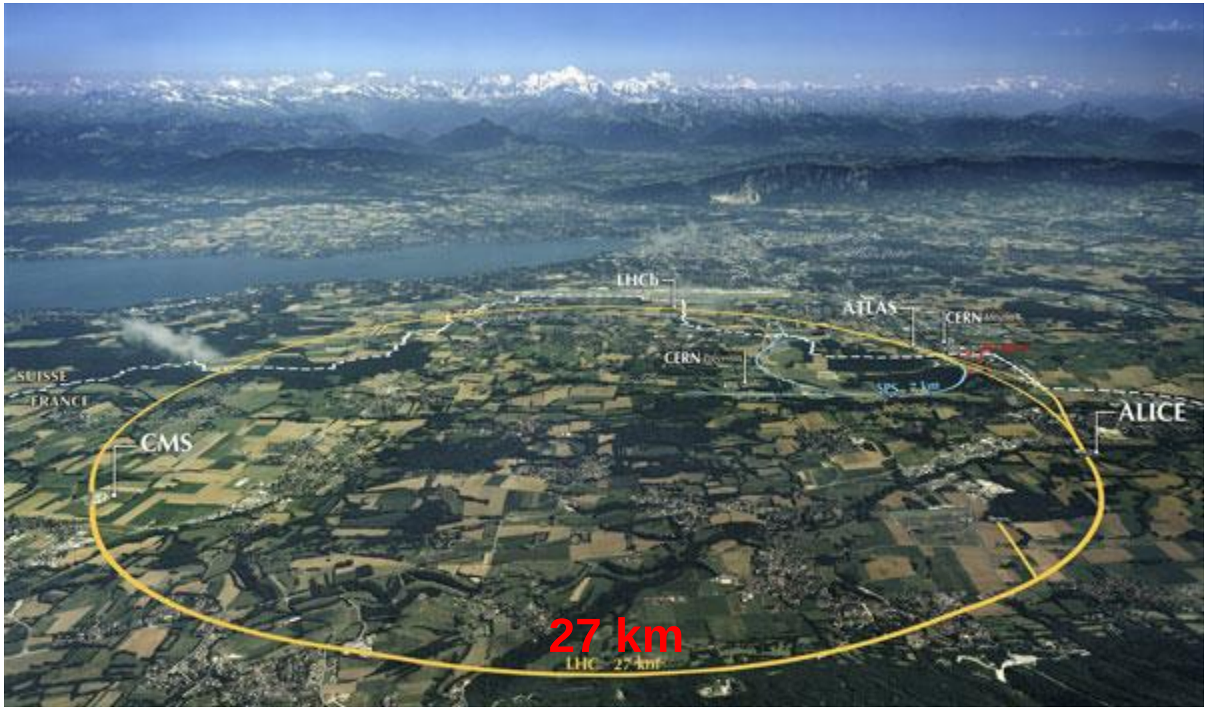
Stanford linear accelerator center (SLAC) is a 50 GeV electron / positron accelerator





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

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



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

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

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

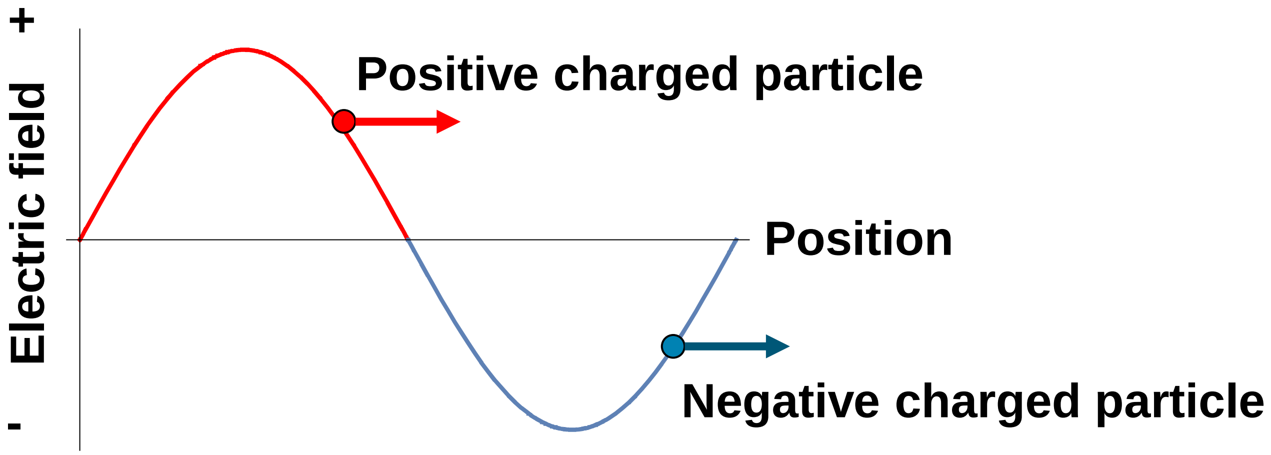
- **Plasma based high energy accelerators:**
  - **Plasma wakefield accelerator (PWFA)[3]**
  - **Laser wakefield accelerator (LWFA)[2]**
  - **V_pxB or surfatron accelerator[4]**
  - **Plasma beat wave accelerator (PBWA)[2]**

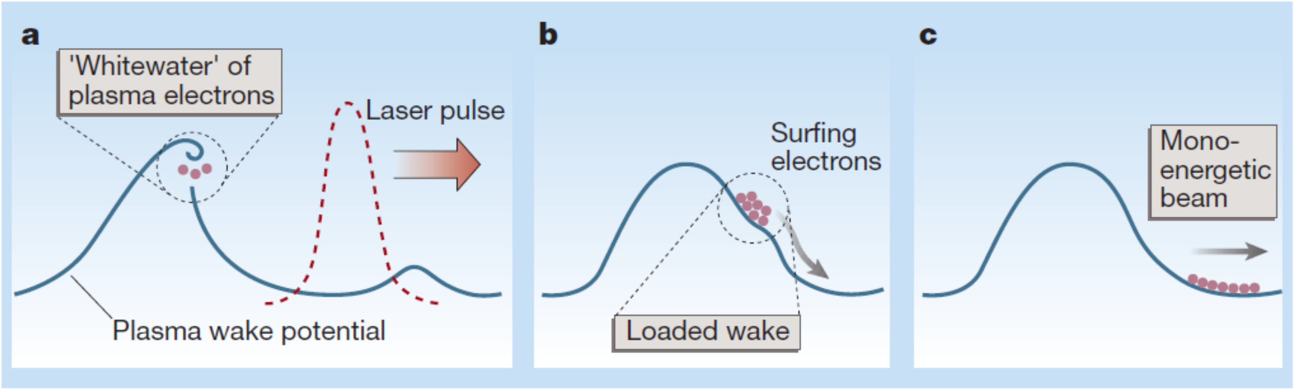
[1] N. A. M. Hafz, *et al.*, Nature Photonics **2**, 571 (2008)
[2] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979)
[3] P. Chen, *et al.*, Phys. Rev. Lett. **54**, 693 (1985)
[4] T. Katsouleas and J. Dawson, Phys. Rev. Lett. **51**, 392 (1983)

Dream beam – the dawn of compact particle accelerators

Front page of nature, 30 Sep., 2004

Charged particles can be accelerated in the wave electric field

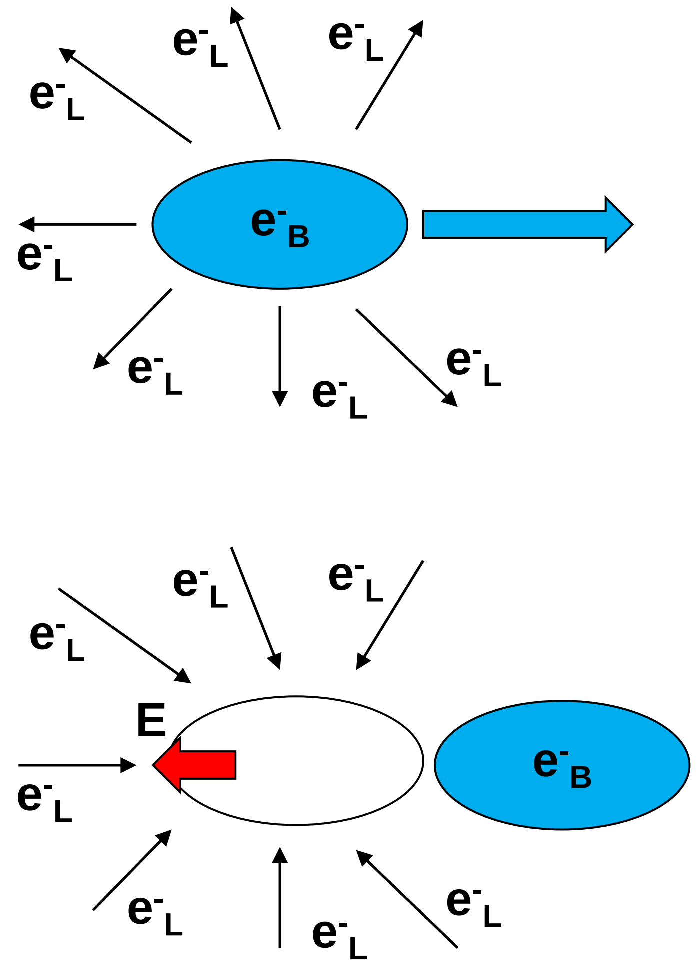




Plasma wakefield accelerator employs two beams

- 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

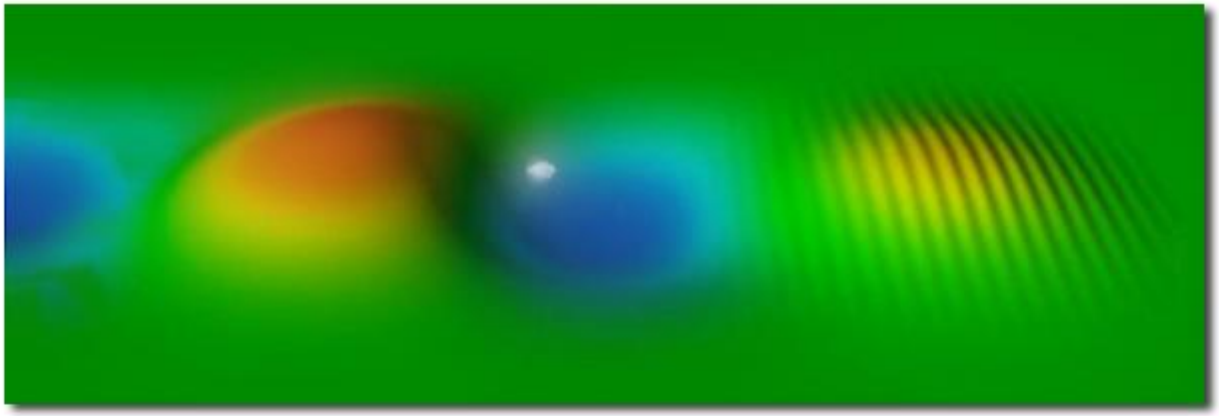


T. Katsouleas, Phys. Rev. A **33**, 2056 (1986)

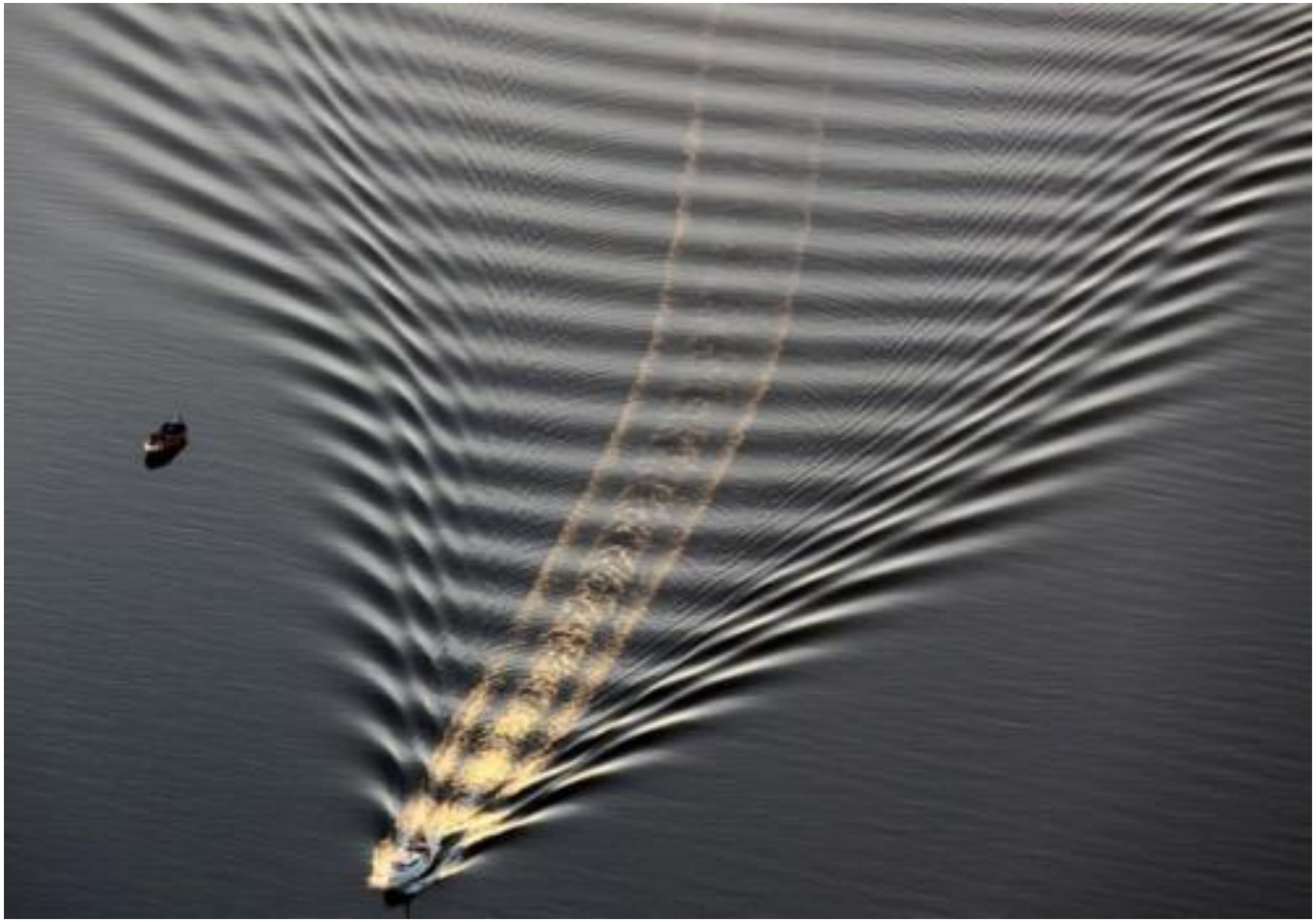
Who will catch the wave?

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

Plasma wake field accelerator is just like boat wake surfing



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



http://wakeworld.com/forum/showthread.php?p=1885710

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

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

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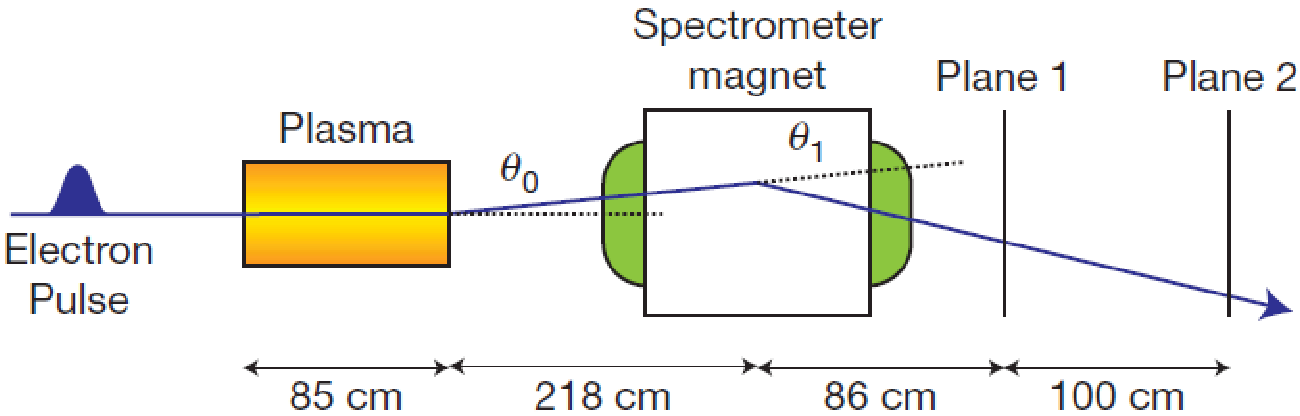
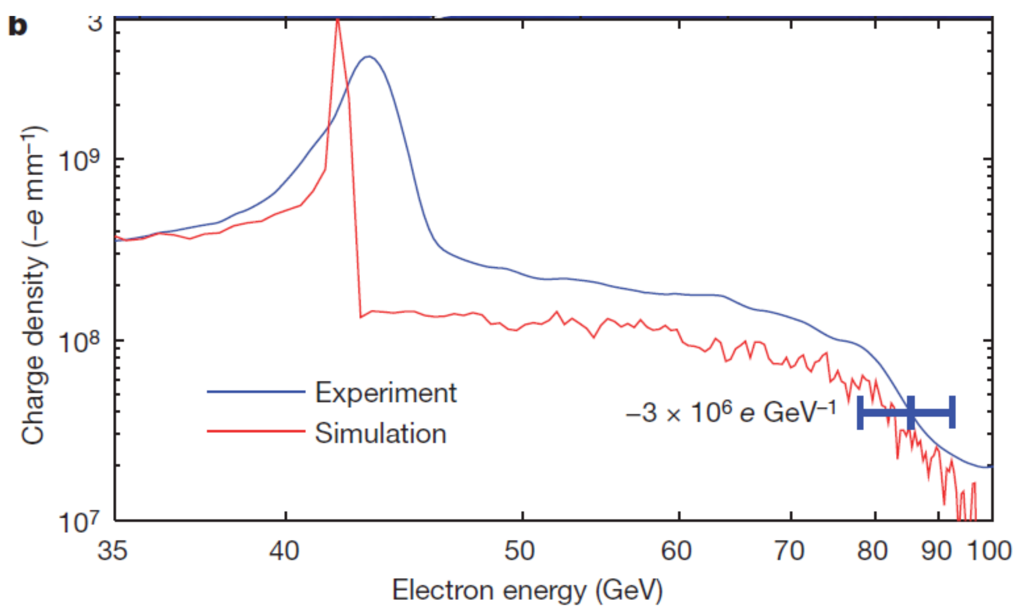
https://learntosurfkona.com/featured/wake-surfing-vs-regular-surfing/
https://i.ytimg.com/vi/CA-SDf1wvTQ/maxresdefault.jpg

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

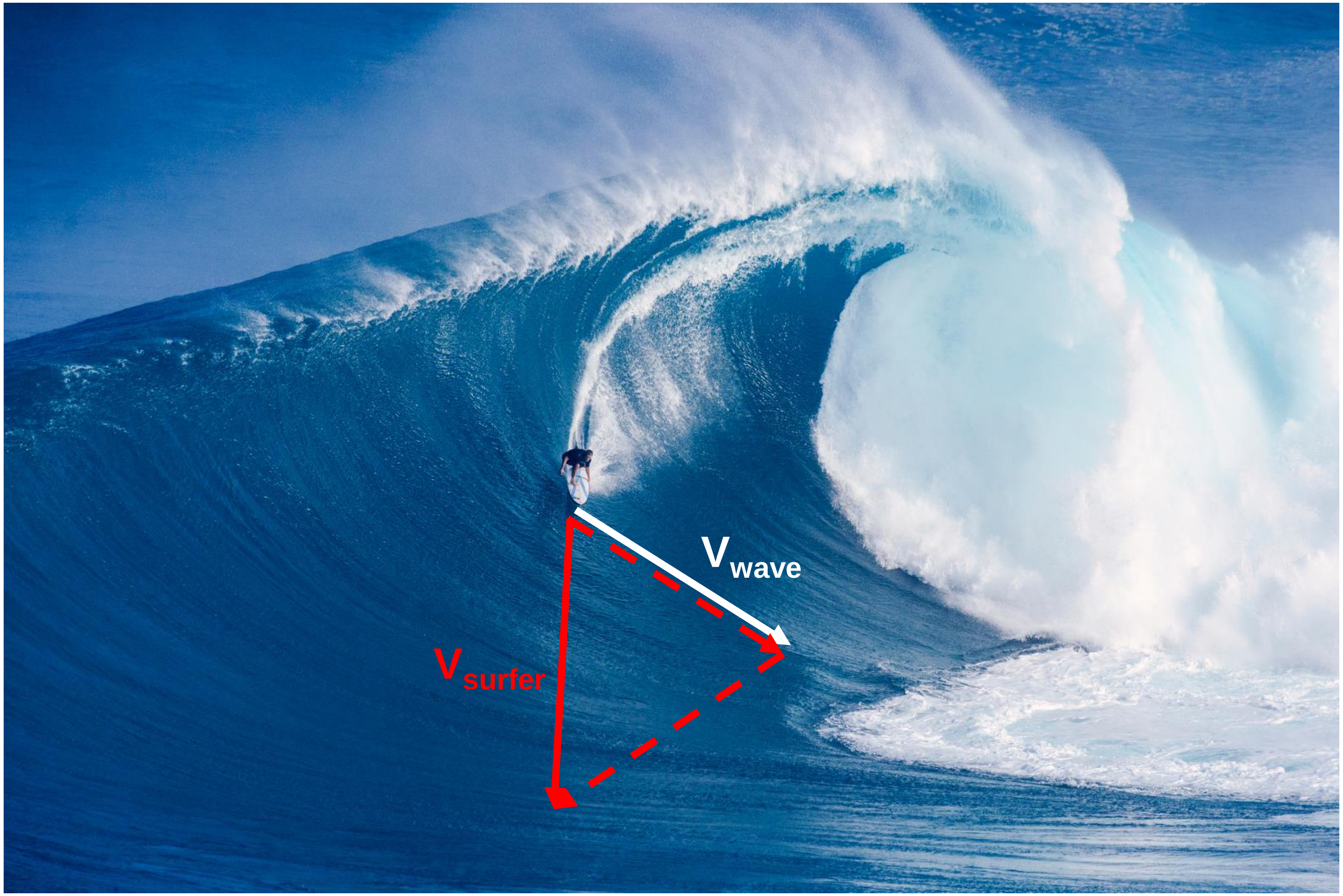




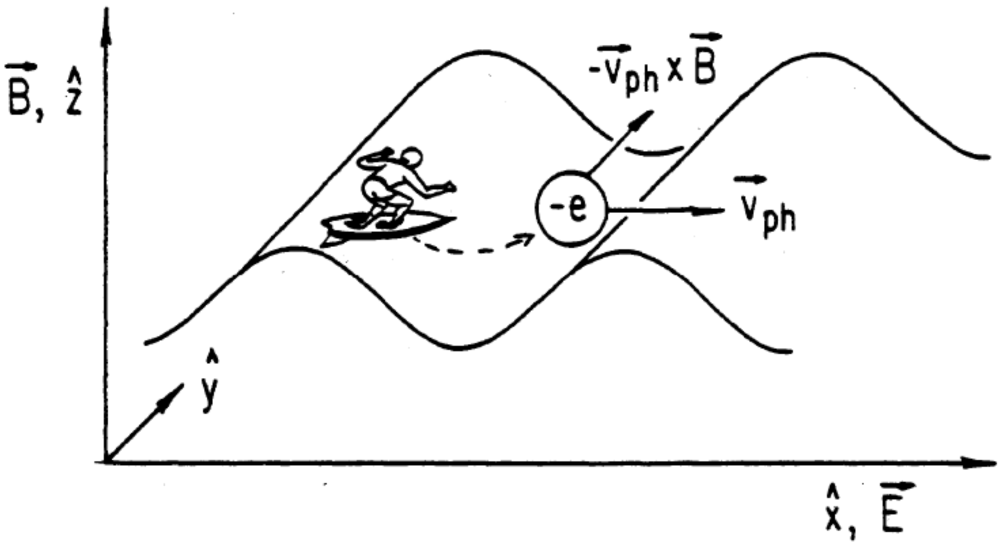
I. Blumenfeld, *et al.*, Nature **445**, 741 (2007)

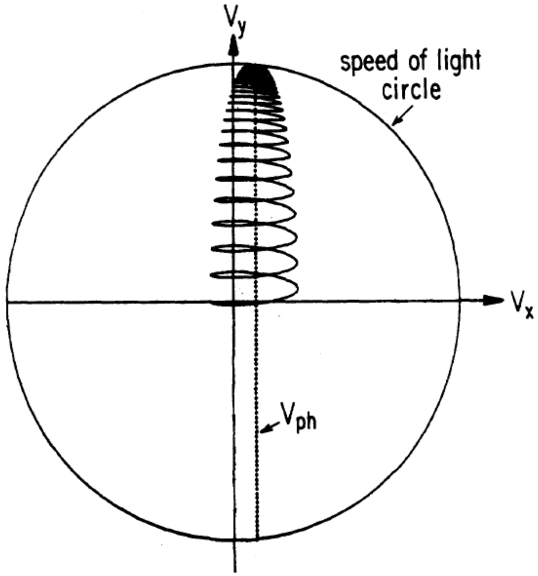
The surfer glides in a direction not parallel to the wave direction to be in phase to the wave propagation

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



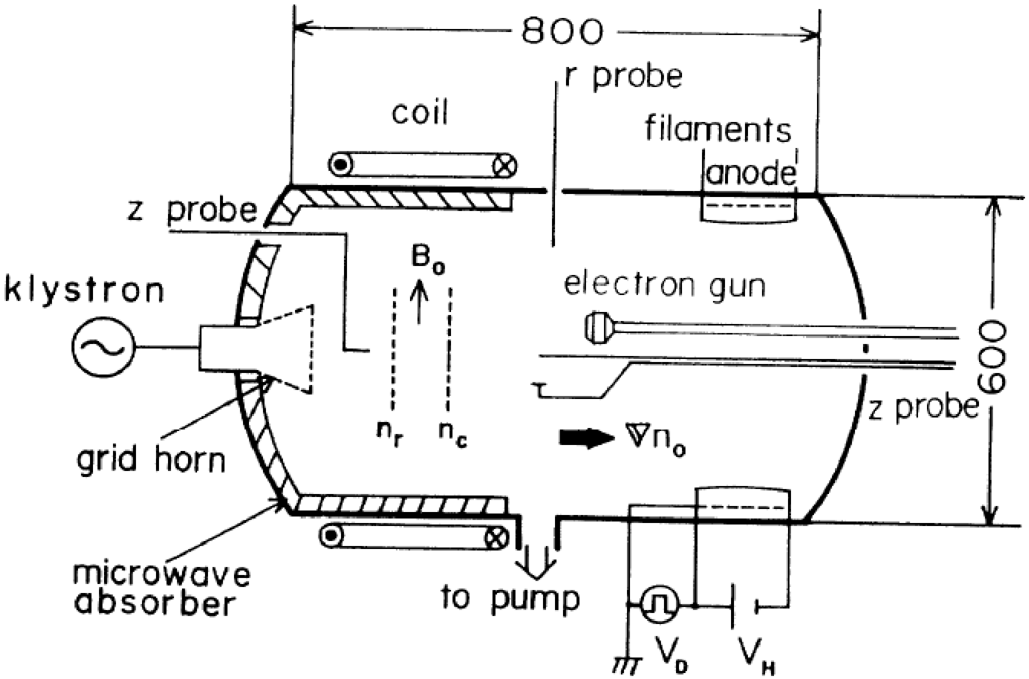
Electrons may be accelerated to speed of light using V_pxB acceleration (Surfatron)

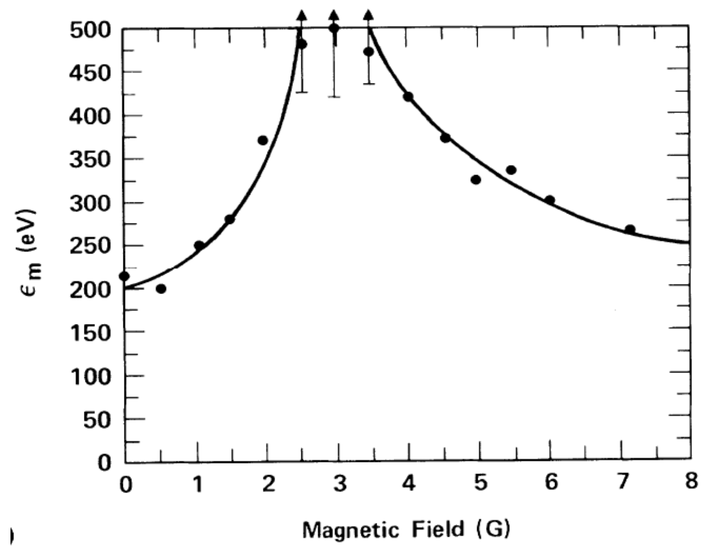




- T. Katsouleas, *et al.*, PRL **51**, 392 (1983)
- T. Katsouleas, *et al.*, IEEE TNS. **NS-30**, 3241 (1983)
- Y. Nishida, *et al.*, AIP Conf Proc. **737**, 957 (2004)

Experimental results of $V_p xB$ acceleration (Surfatron)





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

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

Ponderomotive force expelled electrons away from the higher electric field region

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

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

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

- Take time average:

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

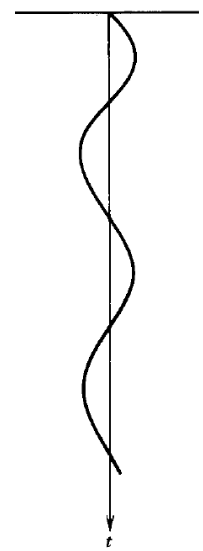
- $\ddot{x}_1 \gg \ddot{x}_0 \quad , \quad E_0 >> x_1\frac{dE_0}{dx}$

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

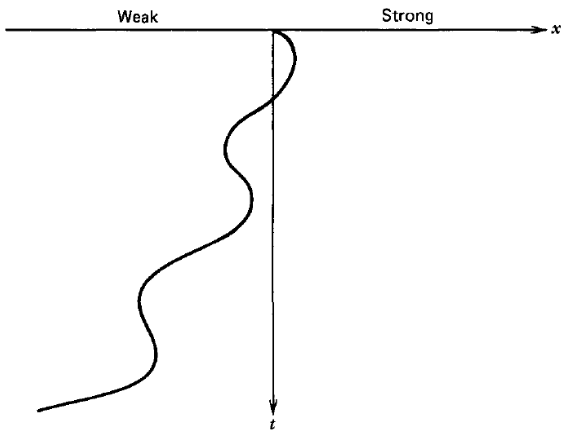
$$x_1 = -\frac{q_s E_0}{m_s\omega^2}\cos\omega t$$

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

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

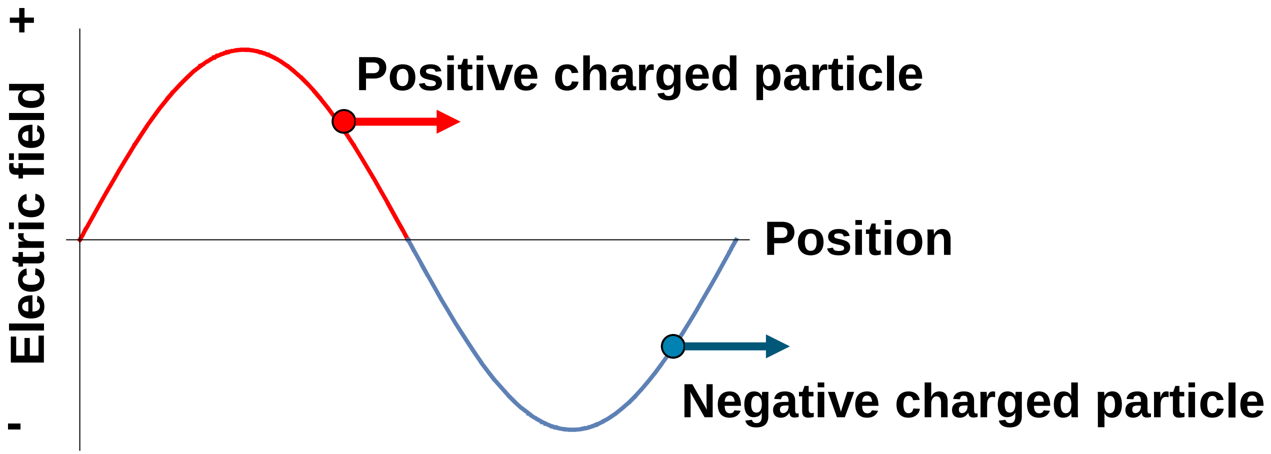


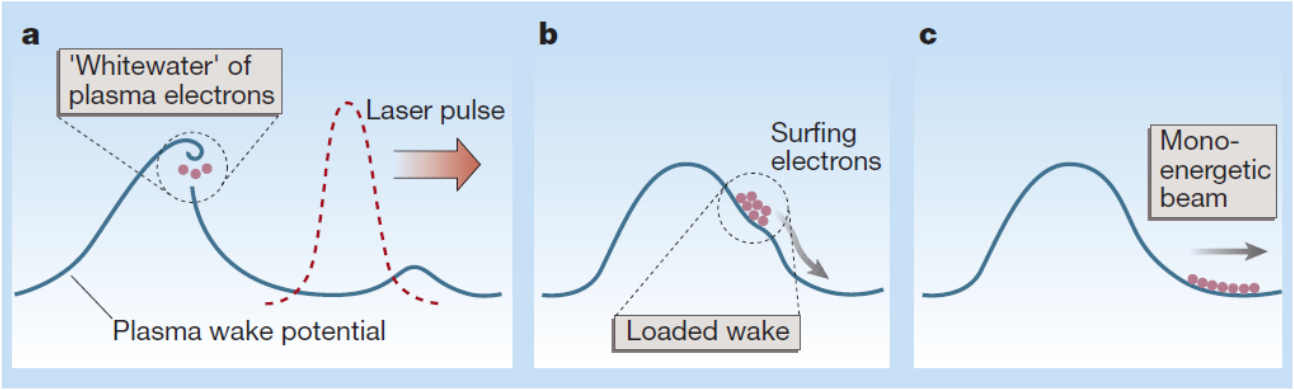
$$\frac{dE_0}{dx} > 0$$



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

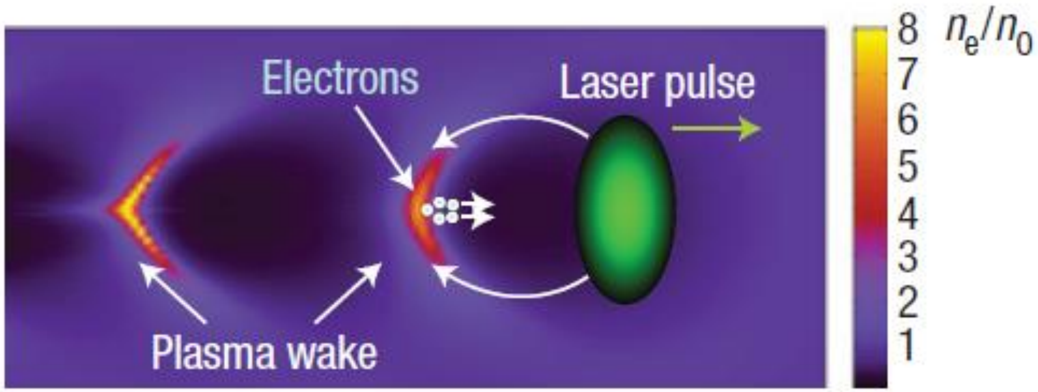
Charged particles can be accelerated in the wave electric field

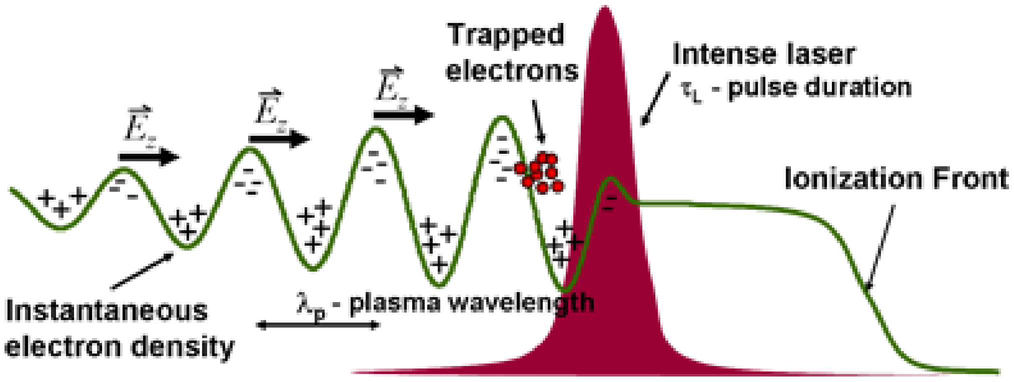




T. Katsouleas, Nature **431**, 515 (2004)

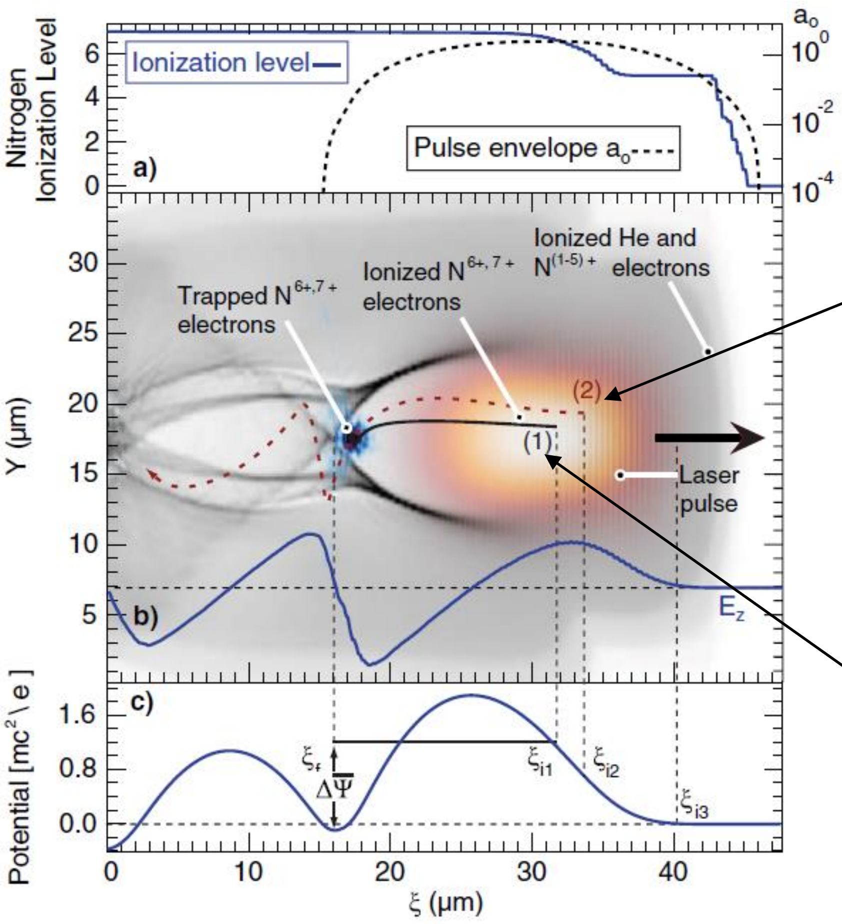
A plasma wake is generated by a short pulse laser





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

Ionization injection



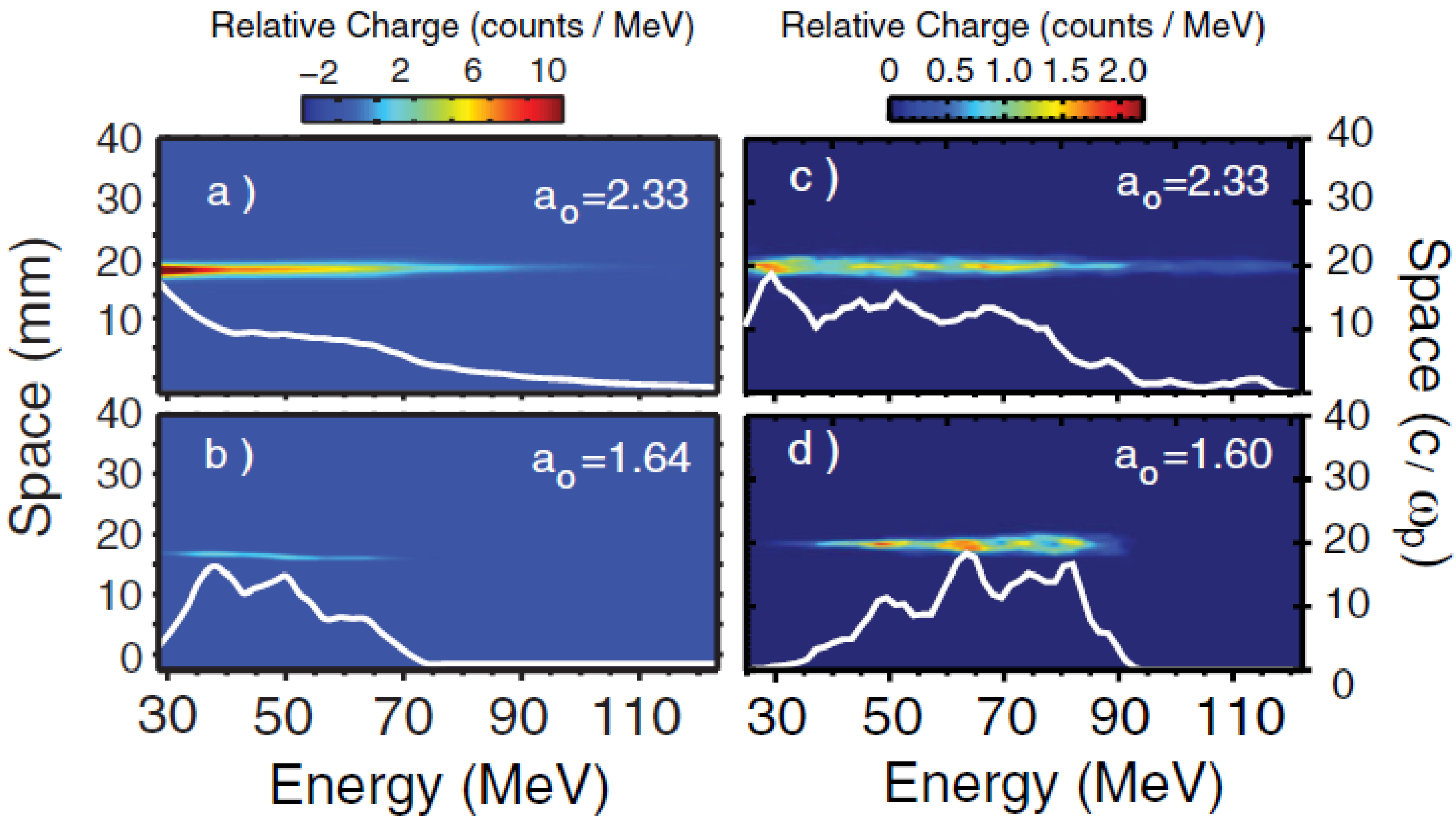
Electrons ionized earlier and off axis slip over the potential well and are not trapped.

Electrons ionized closed to the axis get enough energy from the first wake are trapped and keep being accelerated.

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

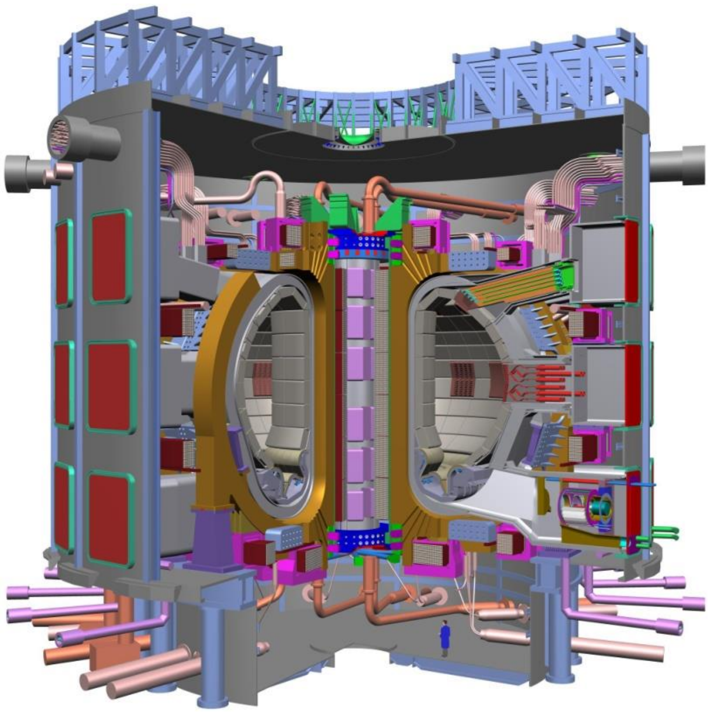
Electrons with energy up to ~90 MeV were generated

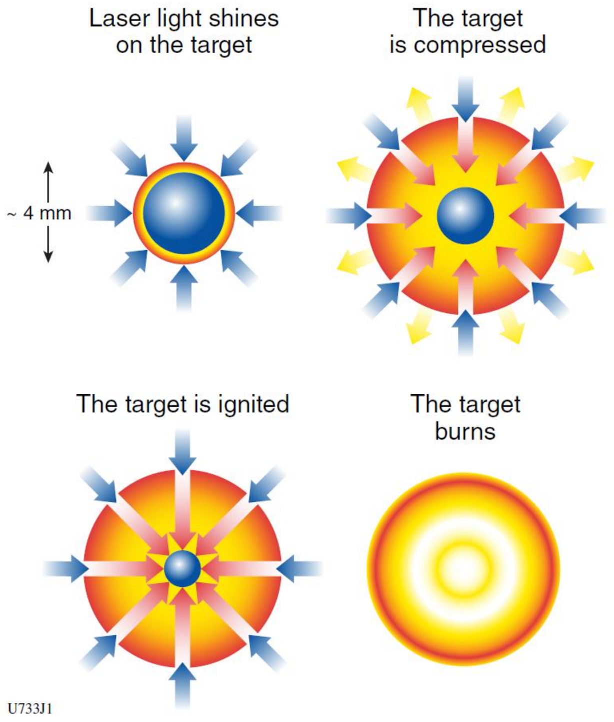
- **Simulation:**
- **Experiments**



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

To Fuse, or Not to Fuse...





Outline

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

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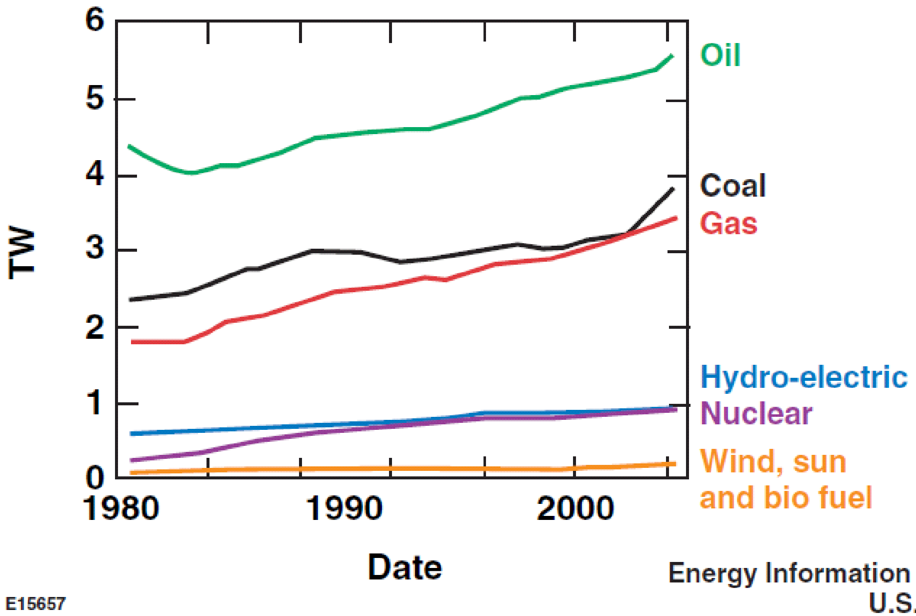
World energy consumption is dominated by the use of dwindling fossil fuels

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

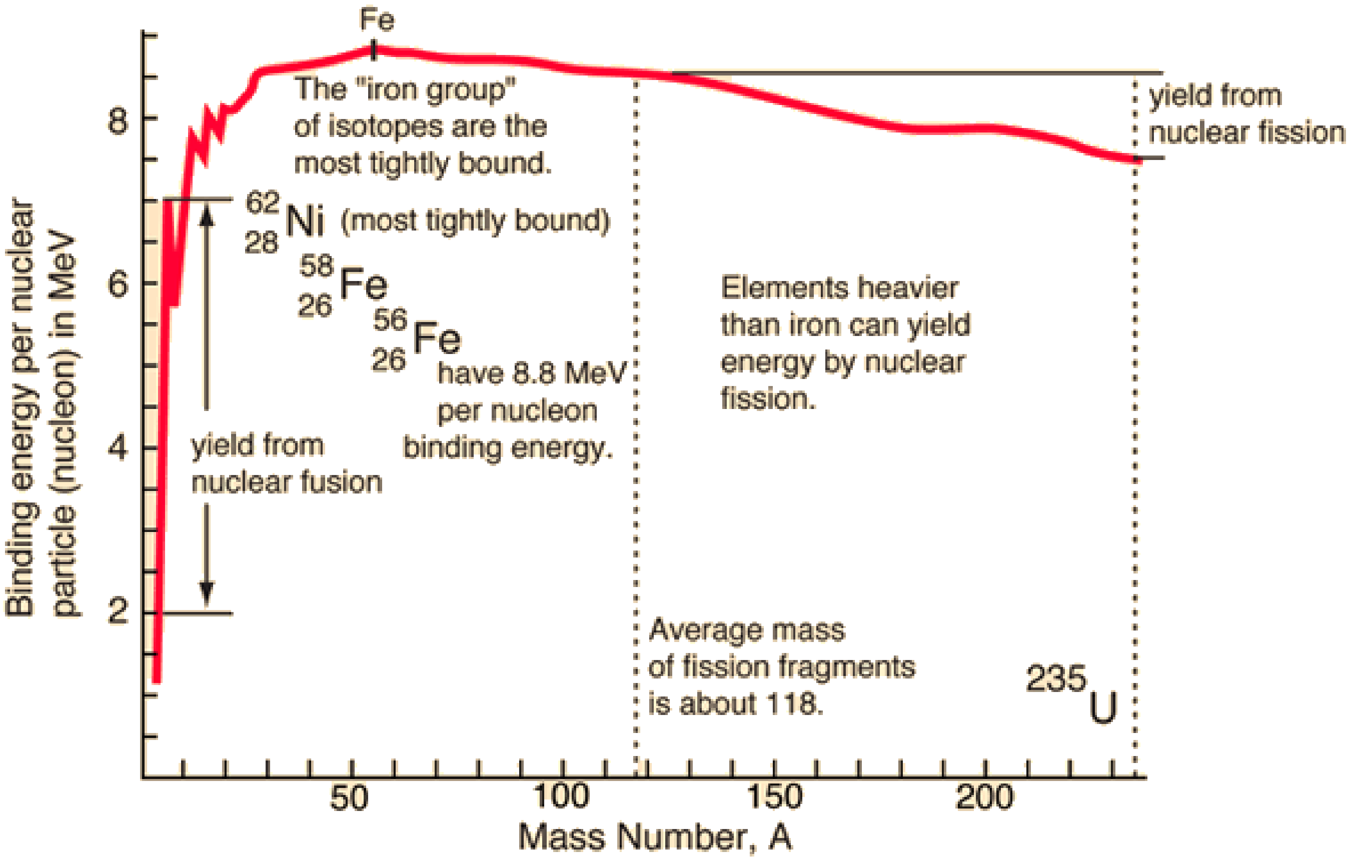


While predictions about the exact number of remaining years vary, fossil fuels will run out.

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

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

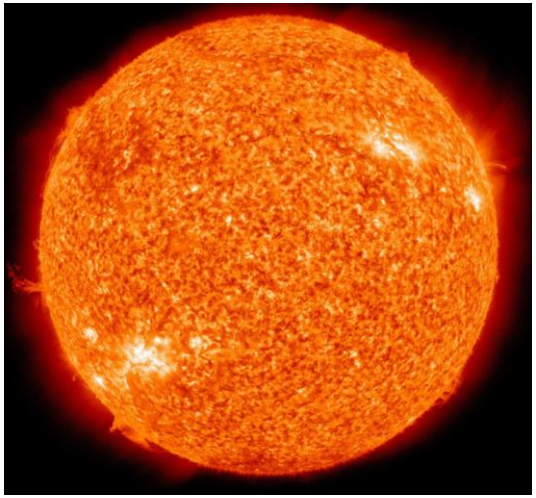
The "iron group" of isotopes are the most tightly bound

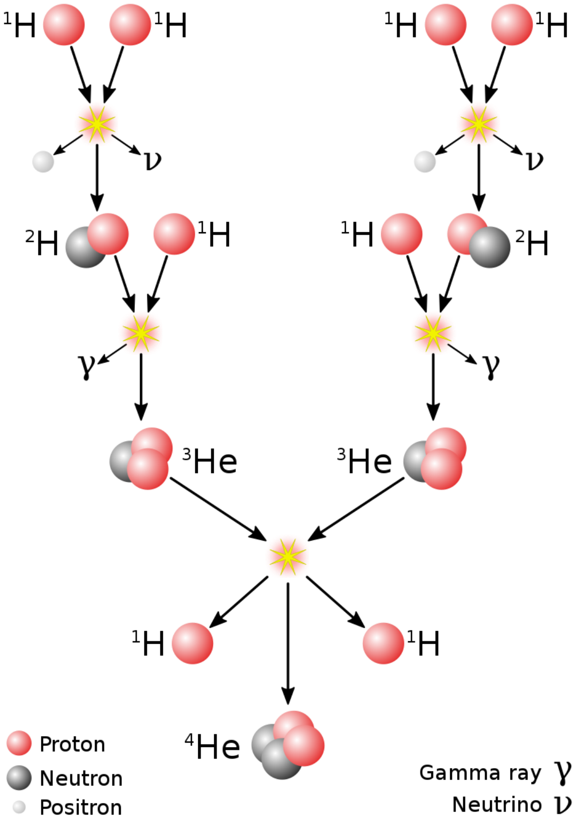


http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html

Fusion in the sun provides the energy

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

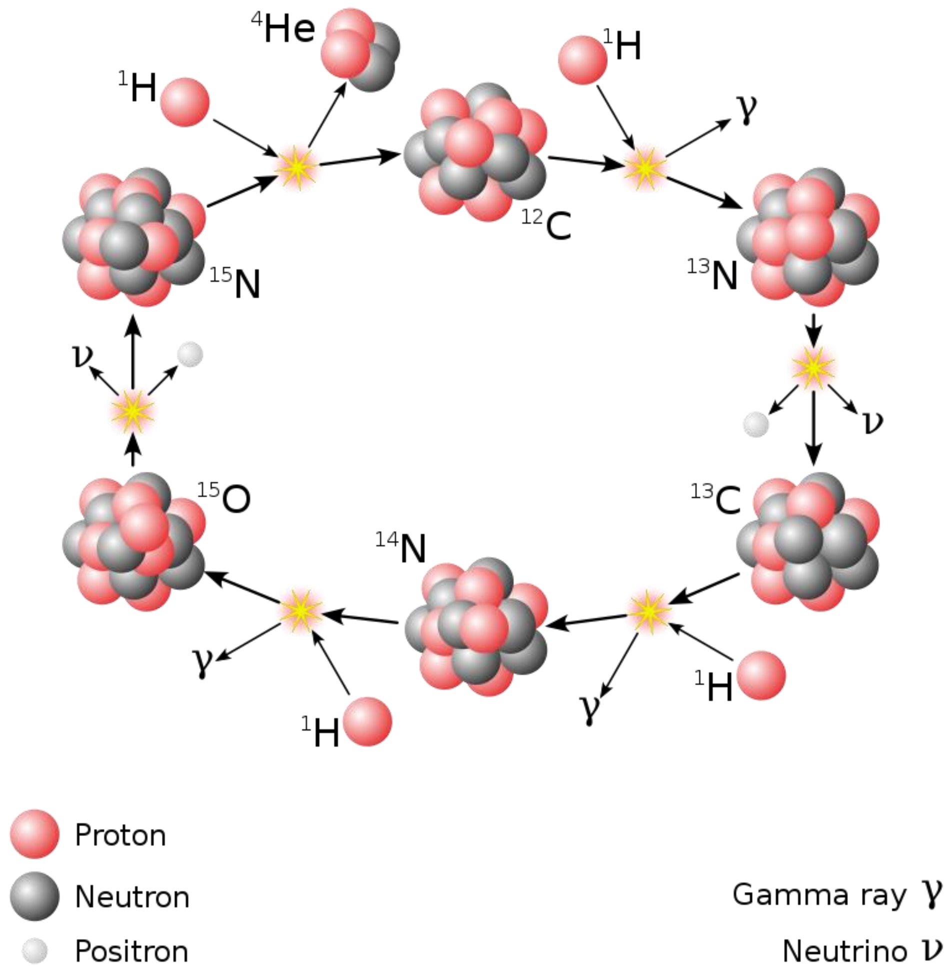




- **Particles are confined by the gravity.**

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

In heavy sun, the fusion reaction is the CNO cycle



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

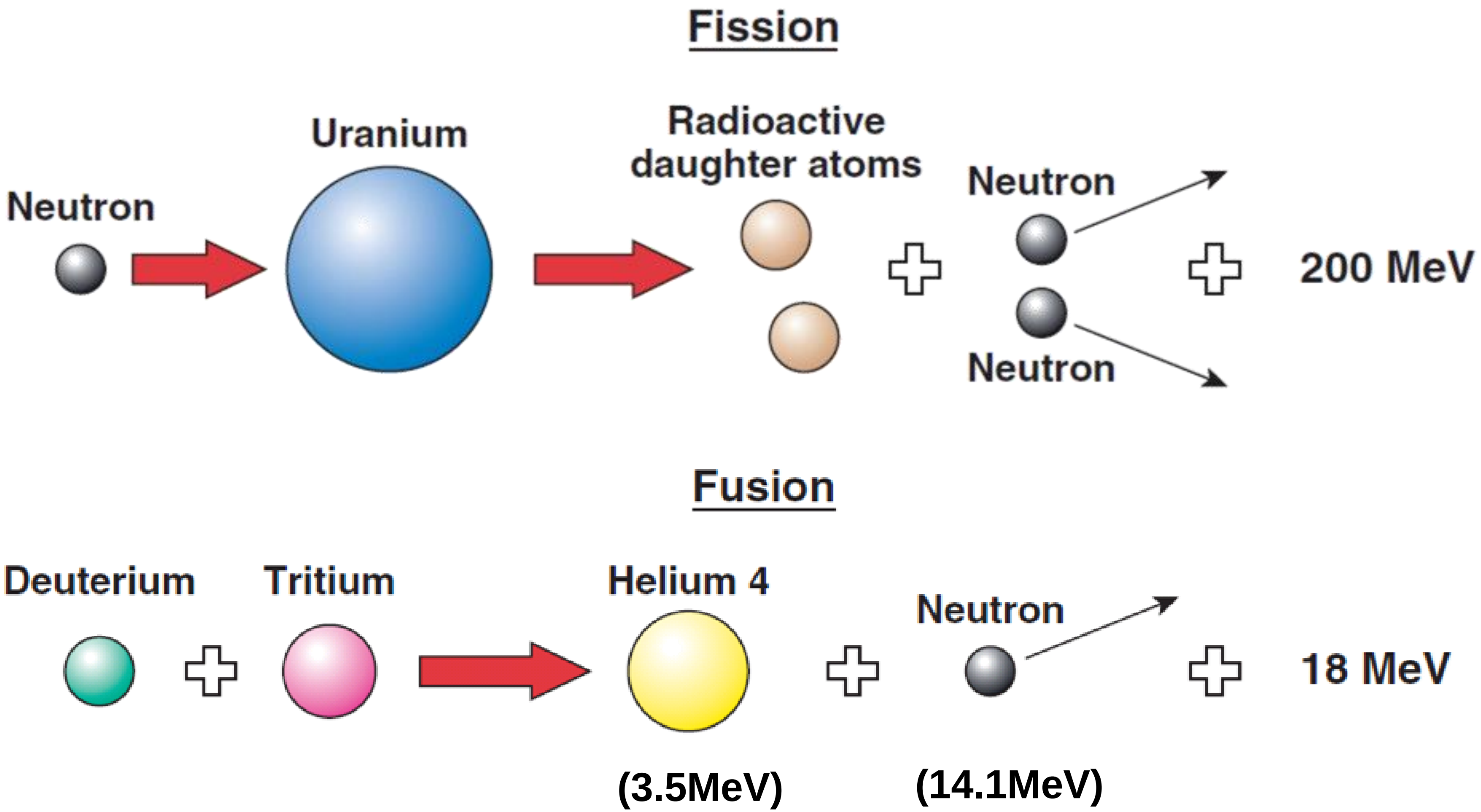
The cross section of proton-proton chain is much smaller than D T fusion

Reaction	$\sigma_{10\ keV}$ (barn)	$\sigma_{100\ keV}$ (barn)	σ_{max} (barn)	ε_{max} (keV)
$D+T \rightarrow \alpha+n$	2.72×10^{-2}	3.43	5.0	64
$D+T \rightarrow T+p$	2.81×10^{-4}	3.3×10^{-2}	0.06	1250
$D+T \rightarrow {}^{3}He+n$	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
$p+{}^{11}B \rightarrow 3\alpha$	(4.6×10^{-17})	3×10^{-4}	1.2	550
$p+p \rightarrow D+e^{+}+v$	(3.6×10^{-26})	(4.4×10^{-25})		
$p+{}^{12}C \rightarrow {}^{13}N+\gamma$	(1.9×10^{-26})	2.0×10^{-10}	1.0x10.4	400
${}^{12}C+{}^{12}C$ (all branches)		(5.0×10^{-103})		

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

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

Nuclear fusion and fission release energy through energetic neutrons



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

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

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

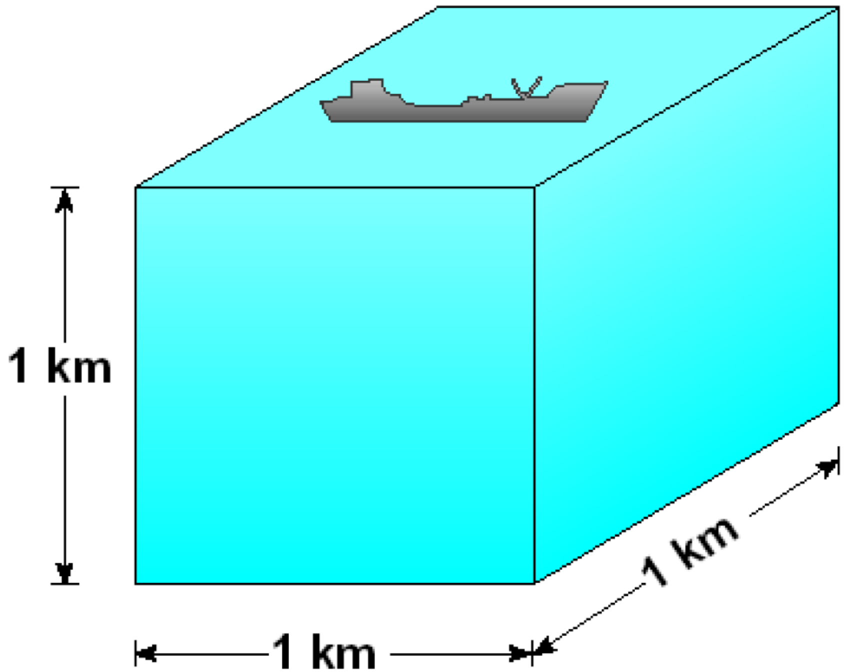
	Half-life (years)
U235	7.04×10^8
U238	4.47×10^9
…	
Tritium	12.3

What could you do with 1 kg DT?

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

*R. Betti, HEDSA HEDP Summer School, 2015

Enormous fusion fuel can be produced from sea water

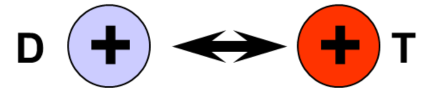


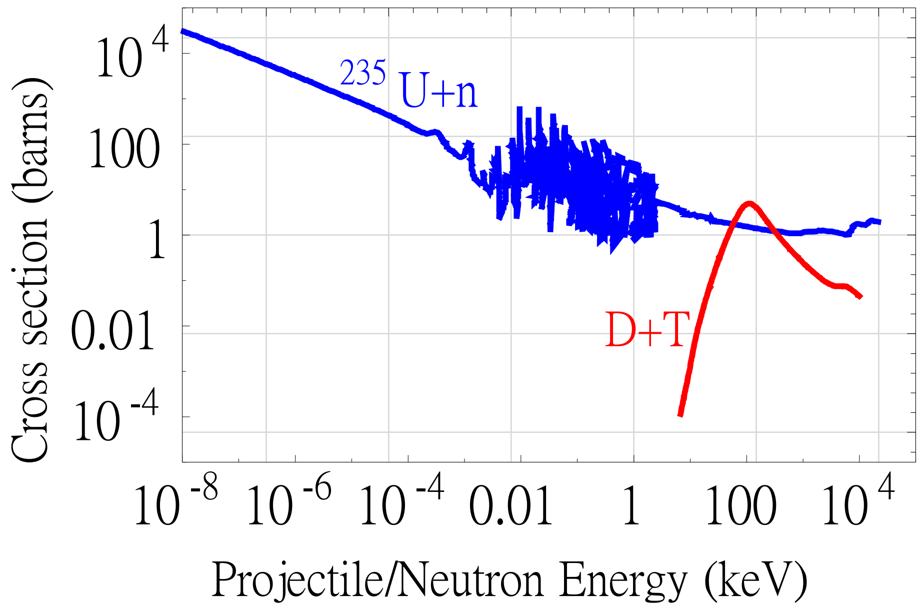
= Total energy of world oil reserve

*R. Betti, HEDSA HEDP Summer School, 2015

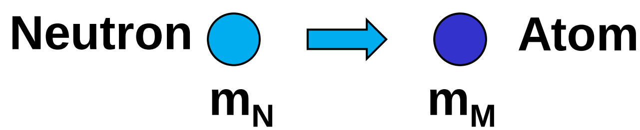
Fusion is much harder than fission

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





Fast neutrons are slowed down due to the collisions

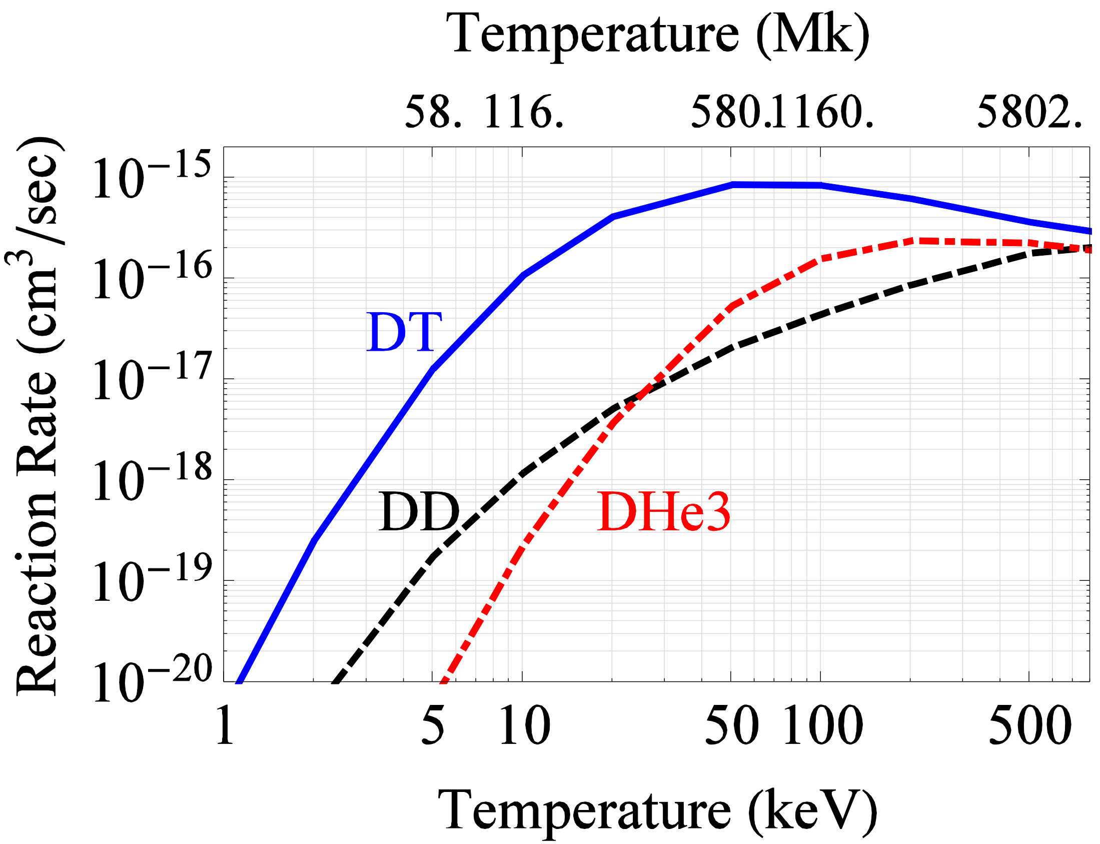


- **A moderator is used to slow down fast neutrons but not to absorb neutrons.**
- **For $m_M \sim m_N$, the energy decrement is higher. Therefore, H slows down neutron most efficiently.**
- **However, H + n → D, i.e., H absorbs neutrons.**
- **The best option is the D in the heavy water (D_2O).**

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

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

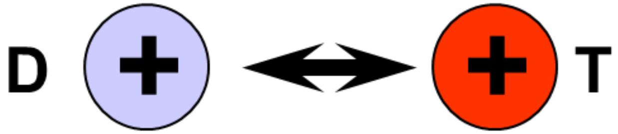
Fusion doesn't come easy



*NRL Plasma Formulary, Naval Research Laboratory, Washington, DC 203785-5320

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.**

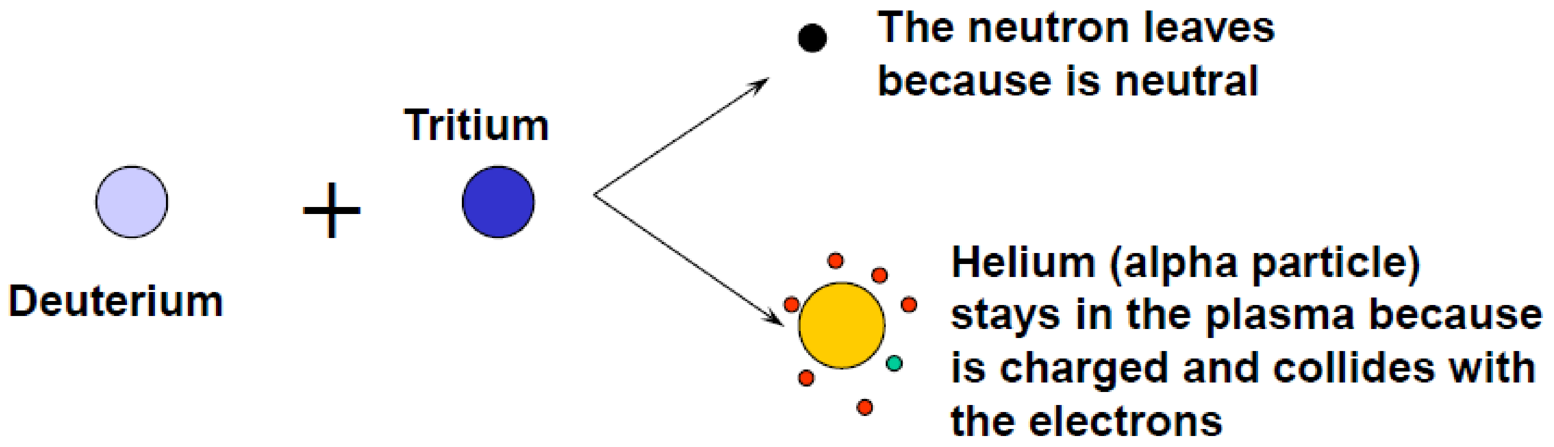


- **If the ions are sufficiently hot, i.e., large random velocity, they can collide by overcoming coulomb repulsion**

*R. Betti, HEDSA HEDP Summer School, 2015

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

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



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

*R. Betti, HEDSA HEDP Summer School, 2015

Under what conditions the plasma keeps itself hot?

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

  $S_\alpha + S_h = S_B + S_k$

  S_α: α particle heating

  S_h: external heating

  S_B: Bremsstrahlung radiation

  S_k: heat conduction lost

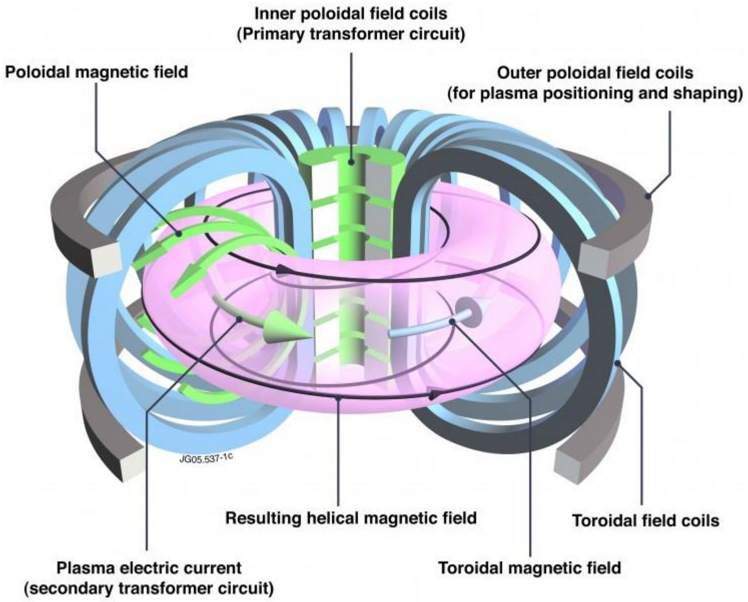
Ignition condition: Pτ > 10 atm-s = 10 Gbar - ns

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

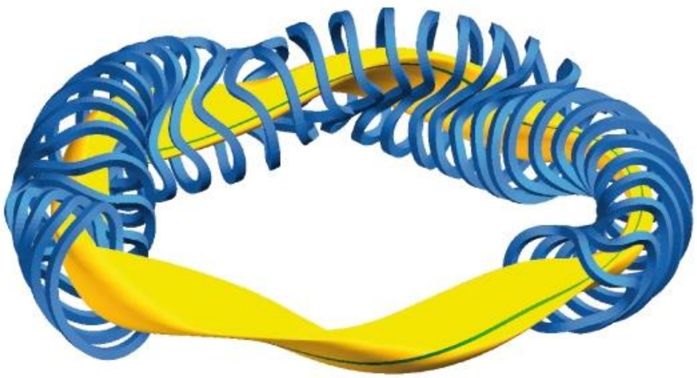
The plasma is too hot to be contained

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

Tokamak



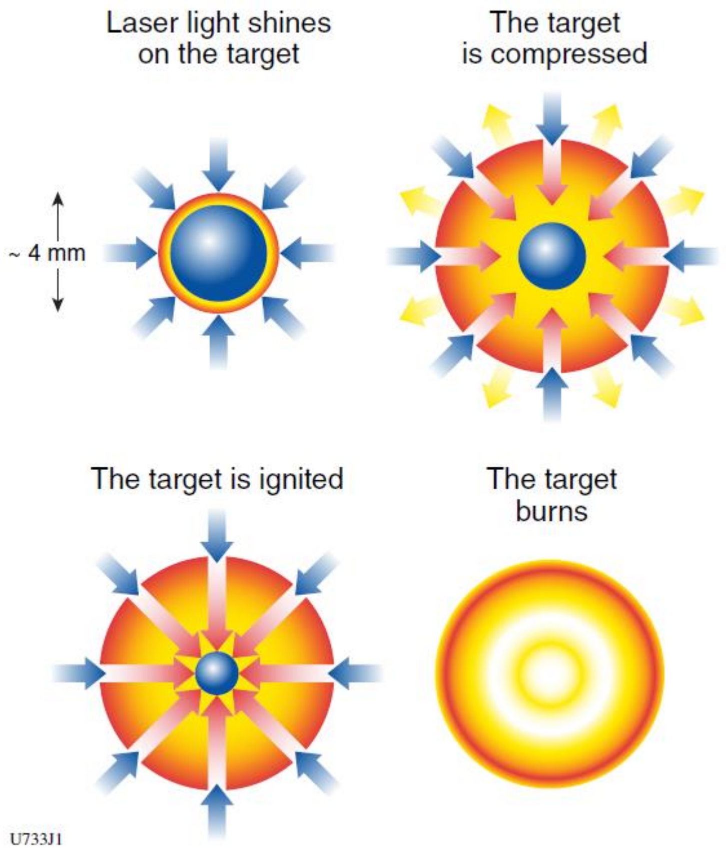
Stellarator



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

Don’t confine it!

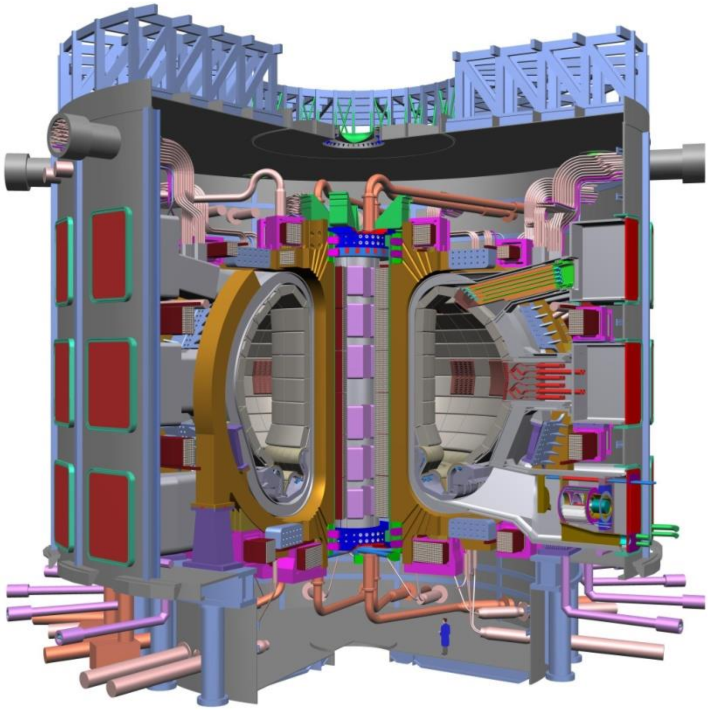
- **Solution 2: Inertial confinement fusion (ICF). Or you can say it is confined by its own inertia: P~Gigabar, τ~nsec, T~10 keV (10^8 ^{0}C)**



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

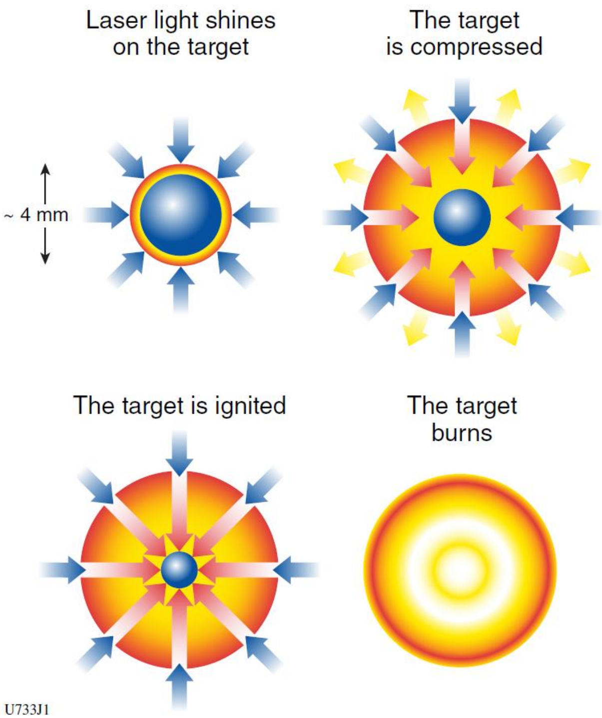
To control? Or not to control?

- **Magnetic confinement fusion (MCF)**



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

- **Inertial confinement fusion (ICF)**



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

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

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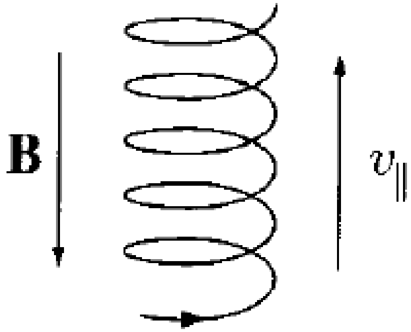
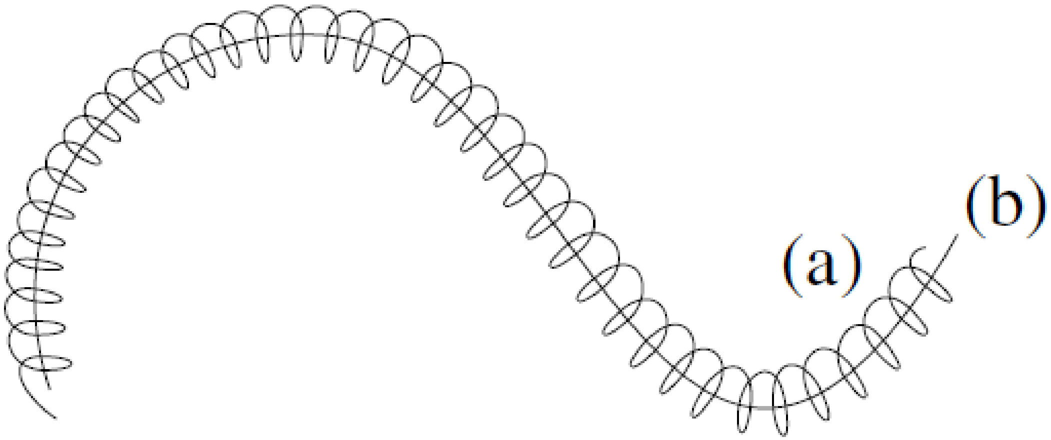
Charged particles gyro around the magnetic fields

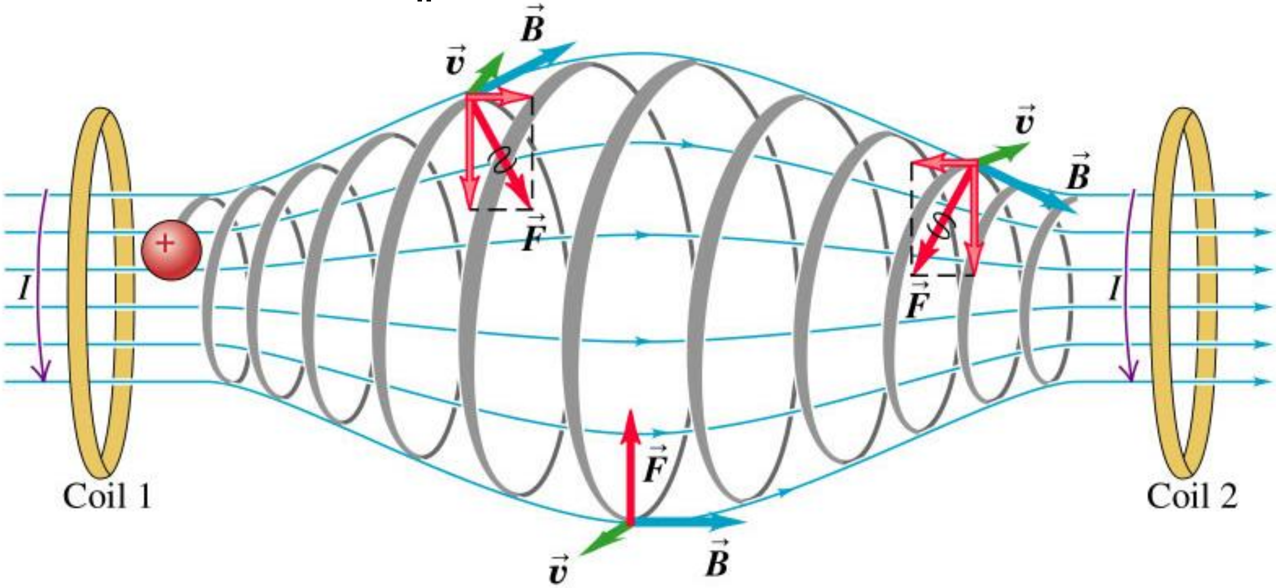


$$r_L = \frac{m v_{\perp}}{|q| B}$$



Charged particles can be partially confined by a magnetic mirror machine

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



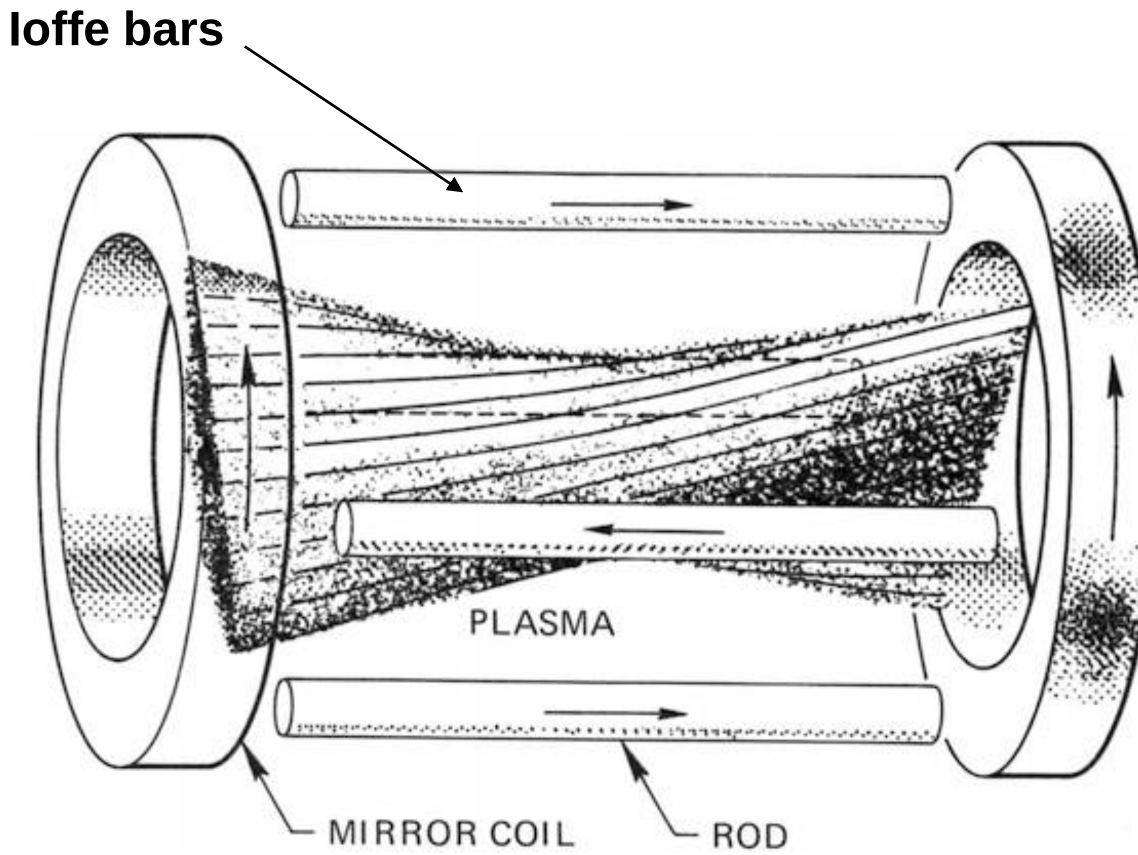
$$\frac{1}{2}mv^2 = \frac{1}{2}m{v_{||}}^2 + \frac{1}{2}m{v_{\perp}}^2$$

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

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

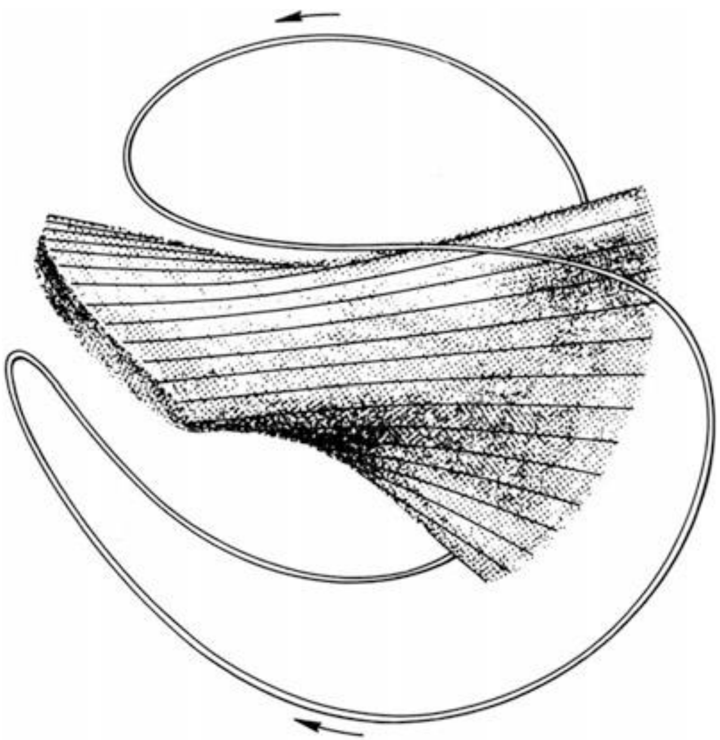
https://i.stack.imgur.com/GlzGZ.jpg

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



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

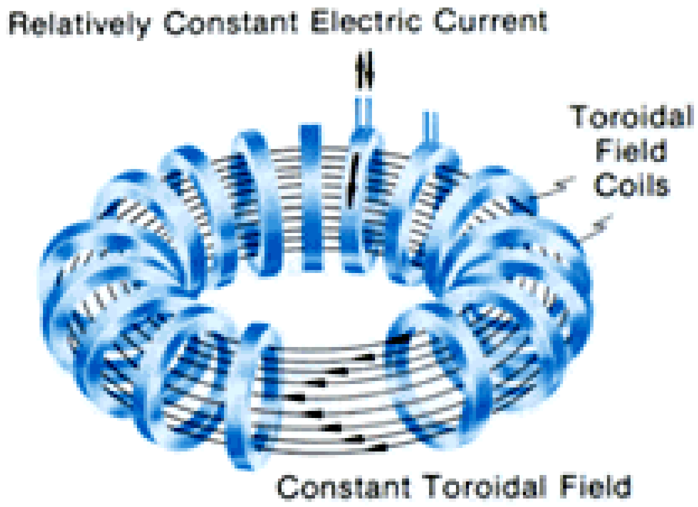
- **Baseball coil**

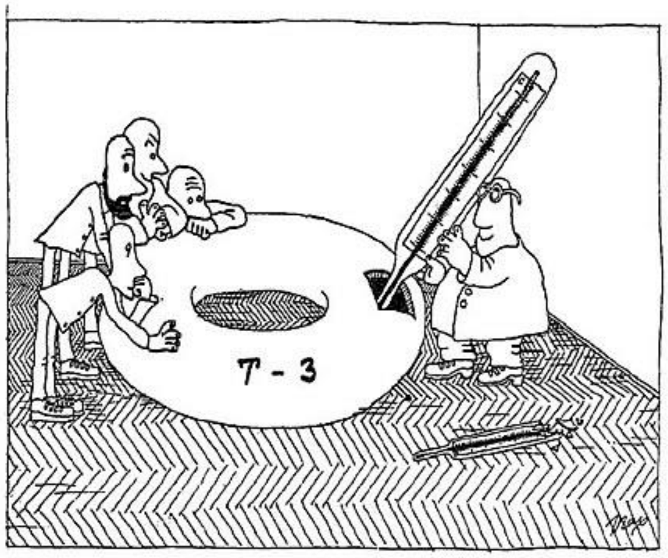


- **MFTF-B mirror machine**

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

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

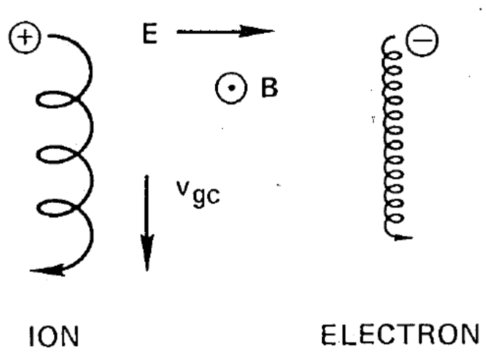




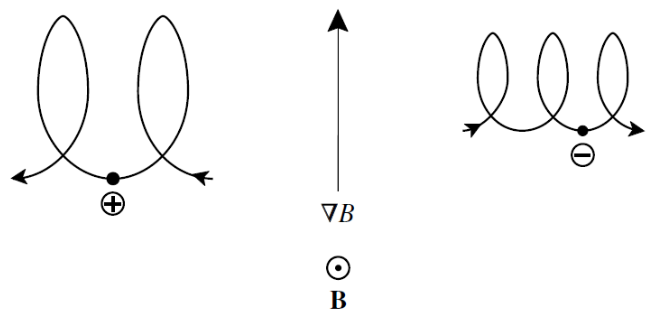
https://www.iter.org/mach/tokamak
https://en.wikipedia.org/wiki/Tokamak#cite_ref-4
Drawing from the talk "Evolution of the Tokamak" given in 1988 by B.B. Kadomtsev at Culham.

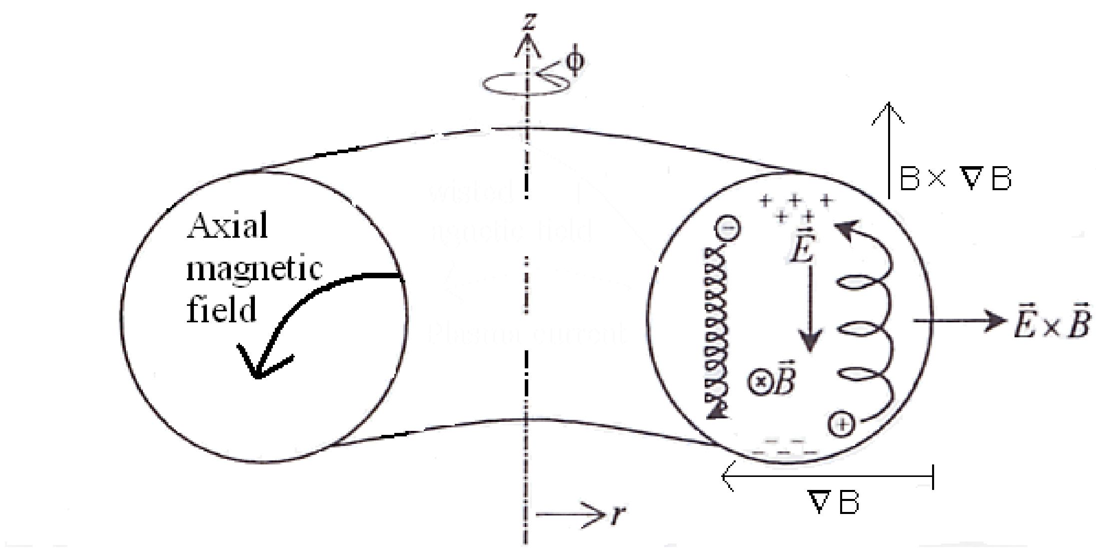
Charged particles drift across field lines

- **ExB drift**



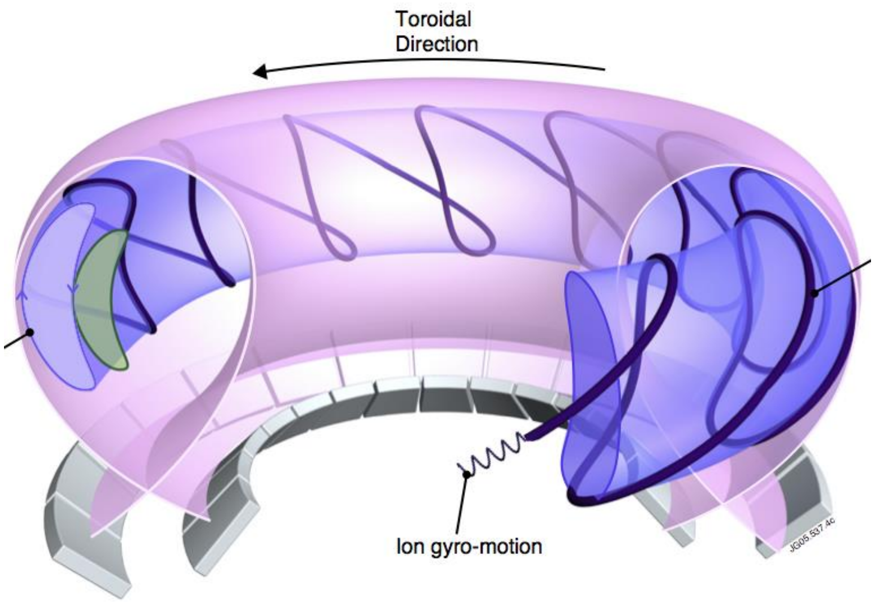
- **Grad-B drift**

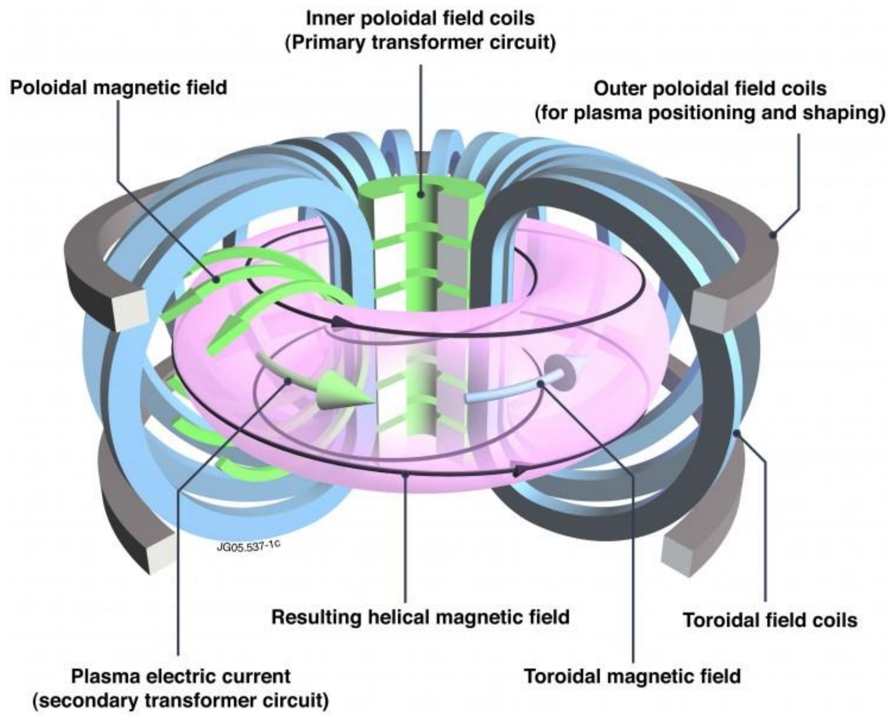




http://www.geocities.jp/tomoyahirata417/fusion/gennkou.htm

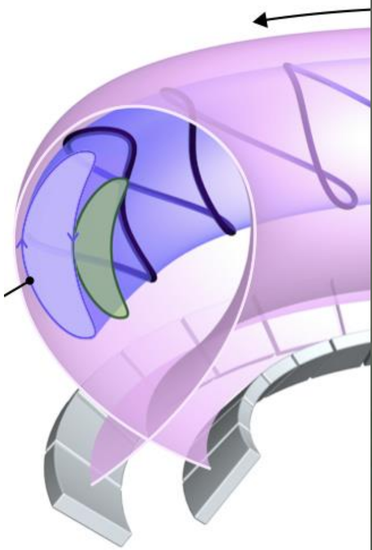
A poloidal magnetic field is required to reduce the drift across field lines

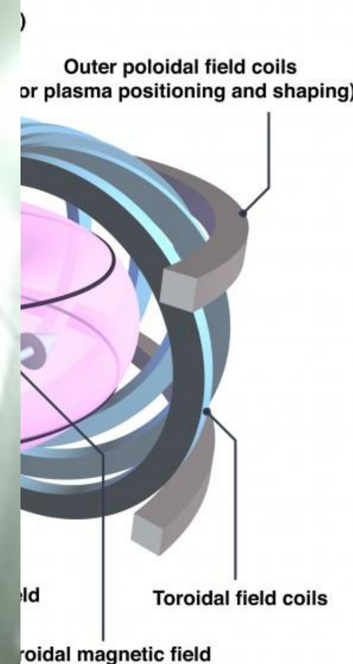




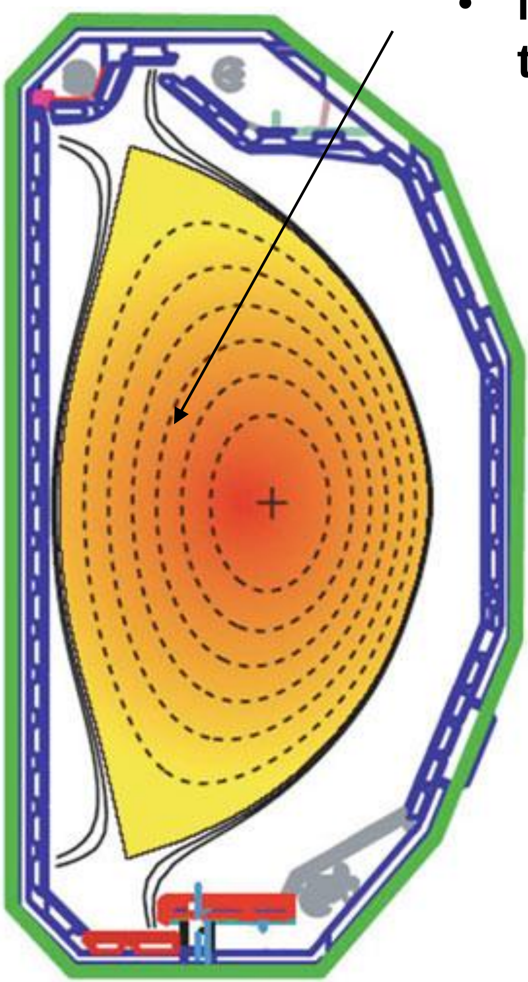
https://www.davidpace.com/keeping-fusion-plasmas-hot/
https://www.euro-fusion.org/2011/09/tokamak-principle-2/

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

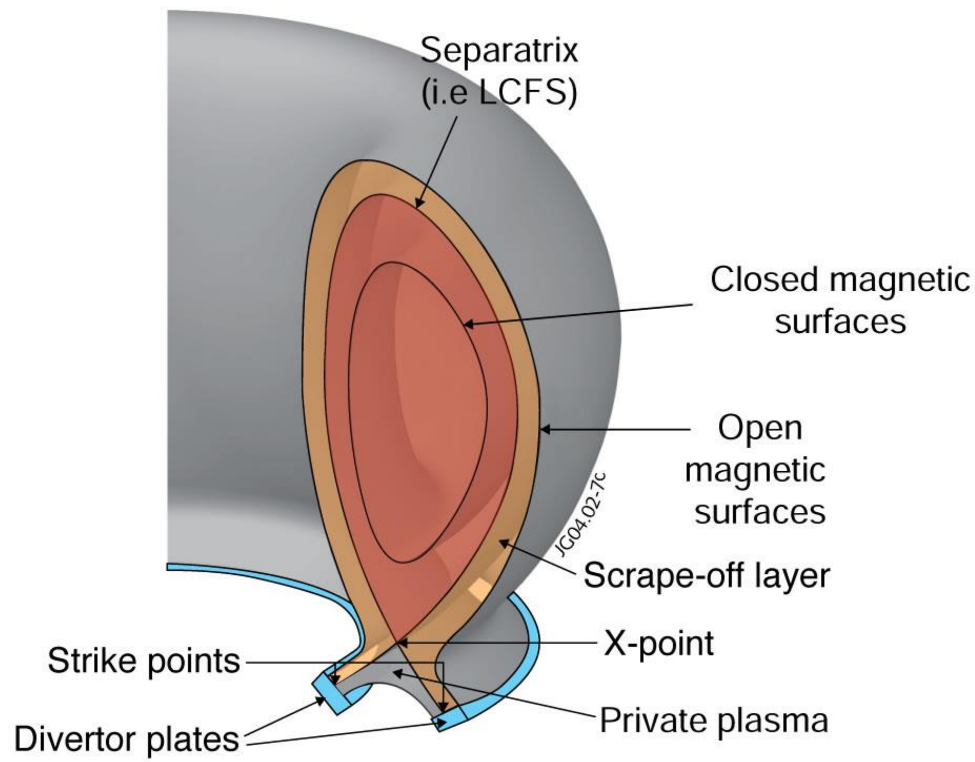




D-shaped tokamak with diverter is more preferred nowadays

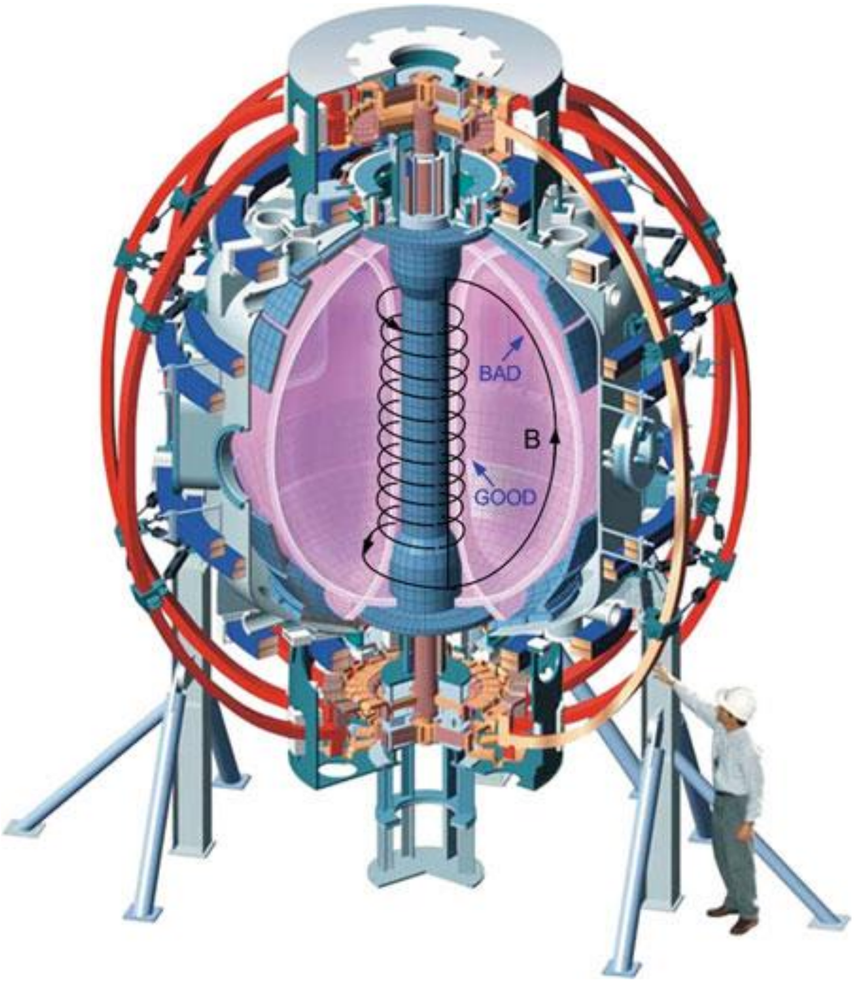


- **Make the plasma closer to the major axis**
    - **A divertor is needed to remove impurities and the power that escapes from the plasma**

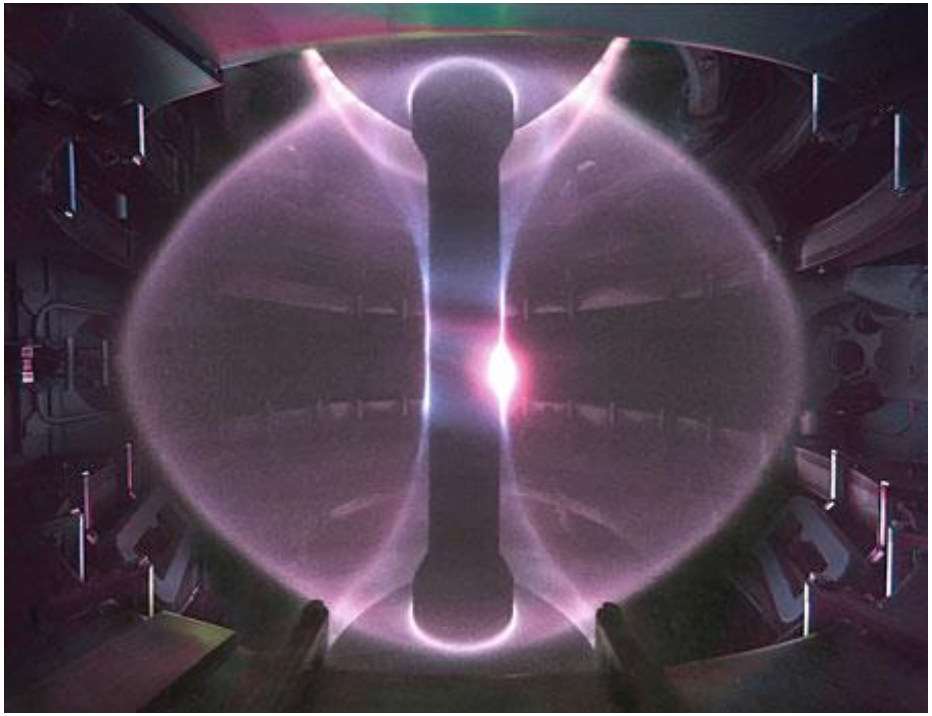


Spherical tokamak is formed when the aspect ratio of a tokamak is reduced to the order of unity

- **NSTX @ Princeton**

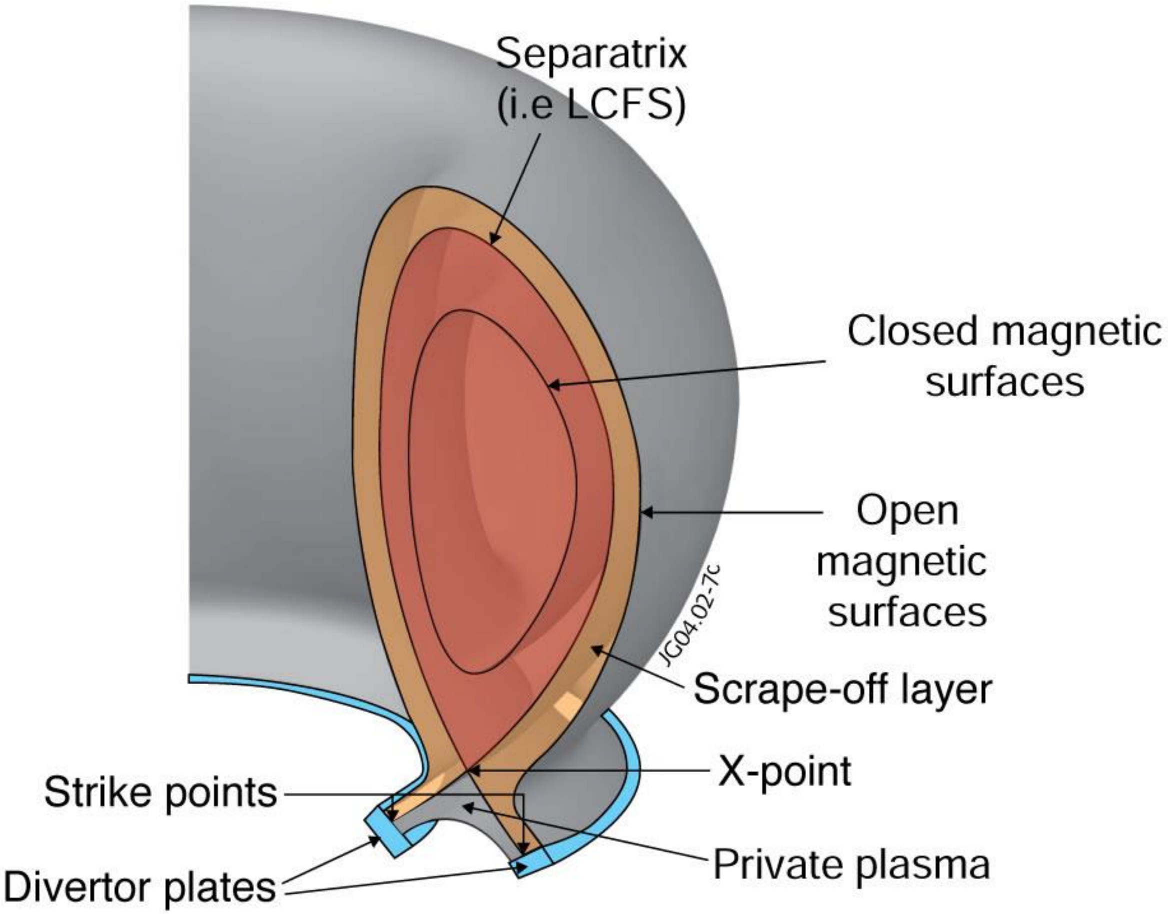


- **MegaAmpere Spherical Tokamak (MAST) @ Culham center for fusion energy, UK**



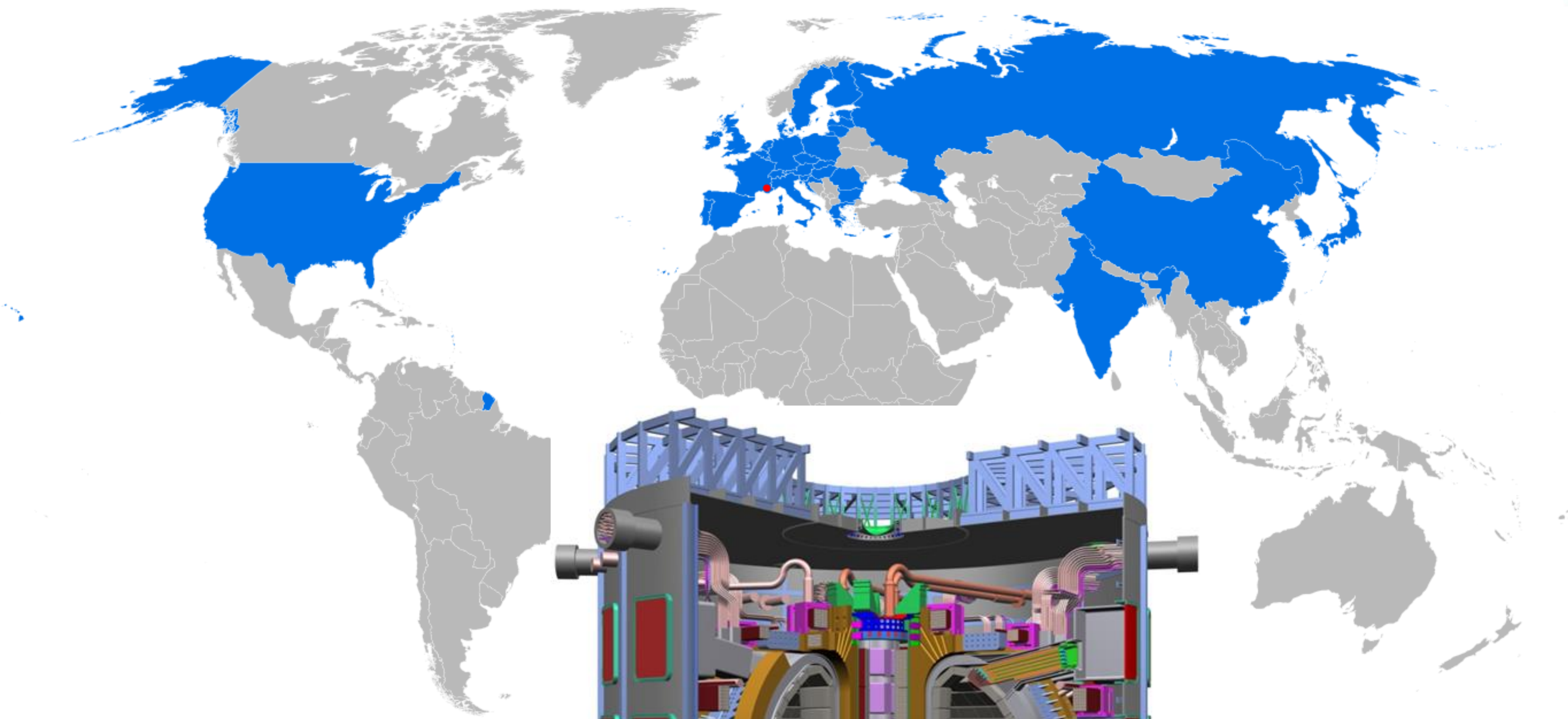
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

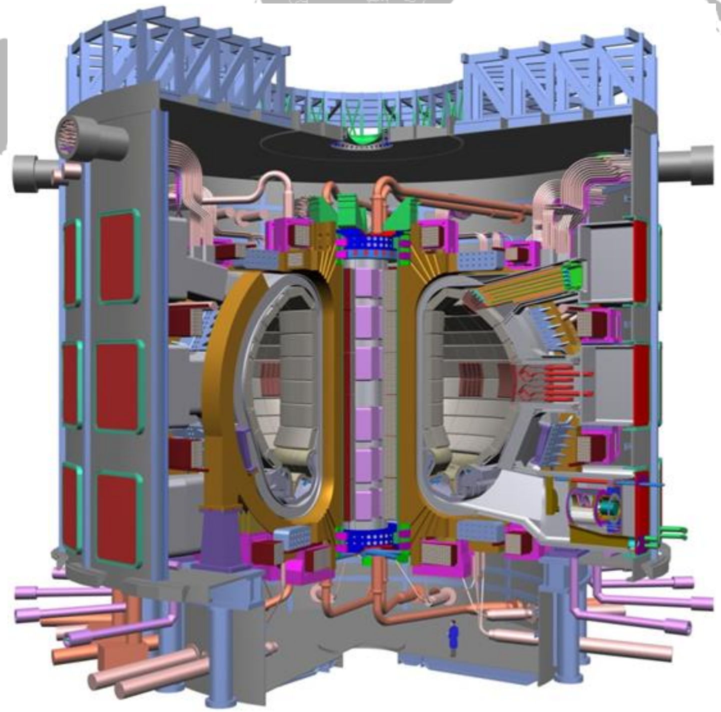
A diverter is needed to remove impurities and the power that escapes from the plasma



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

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

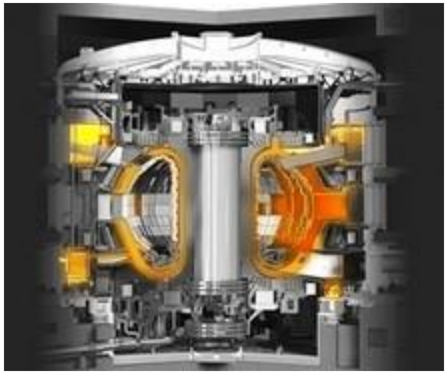




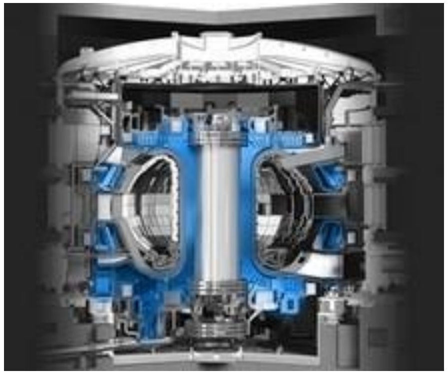
https://www.iter.org

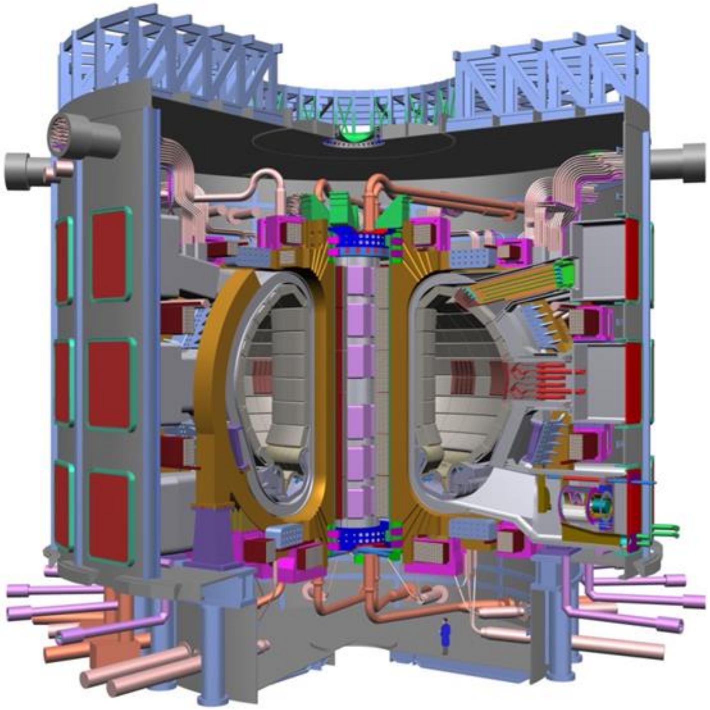
ITER ("The Way" in Latin) is one of the most ambitious energy projects in the world today

- **Vacuum vessel**

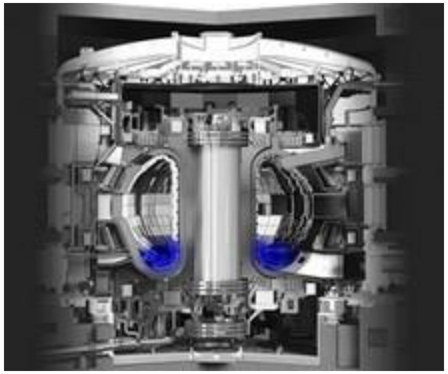


- **Magnets**

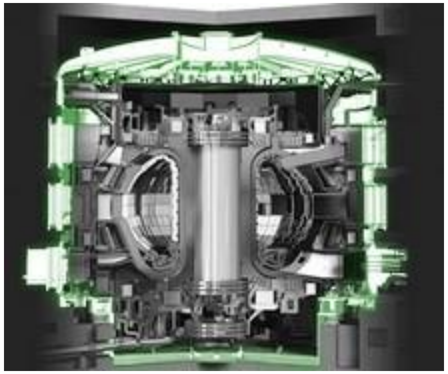




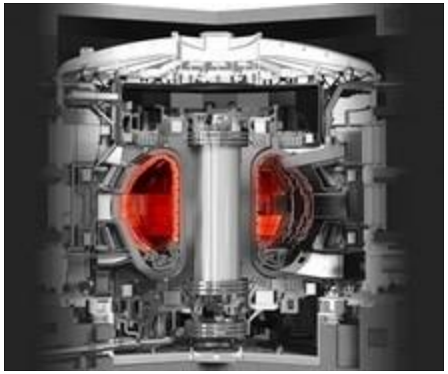
- **Divertor**



- **Cryostat**



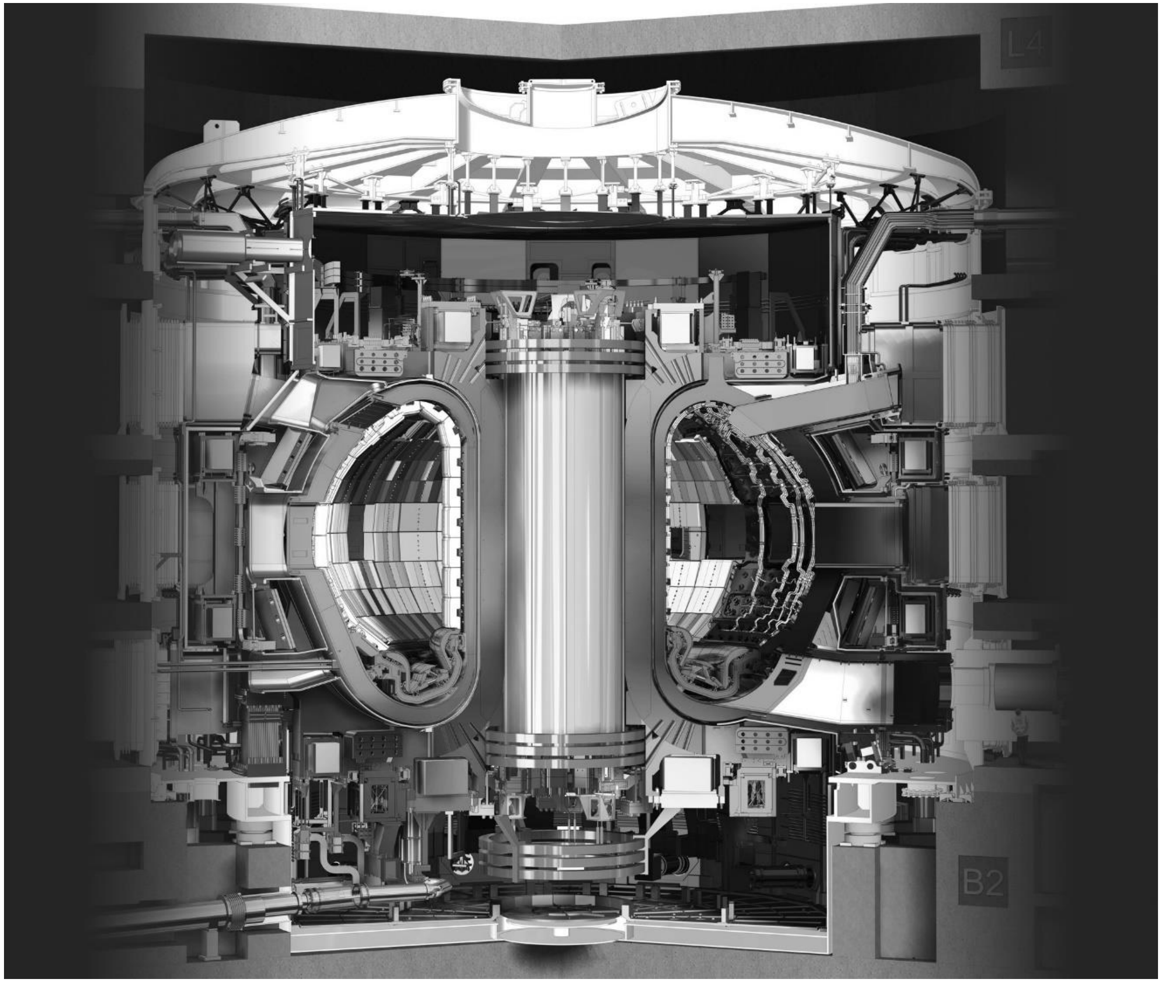
- **Blanket**



https://www.iter.org/

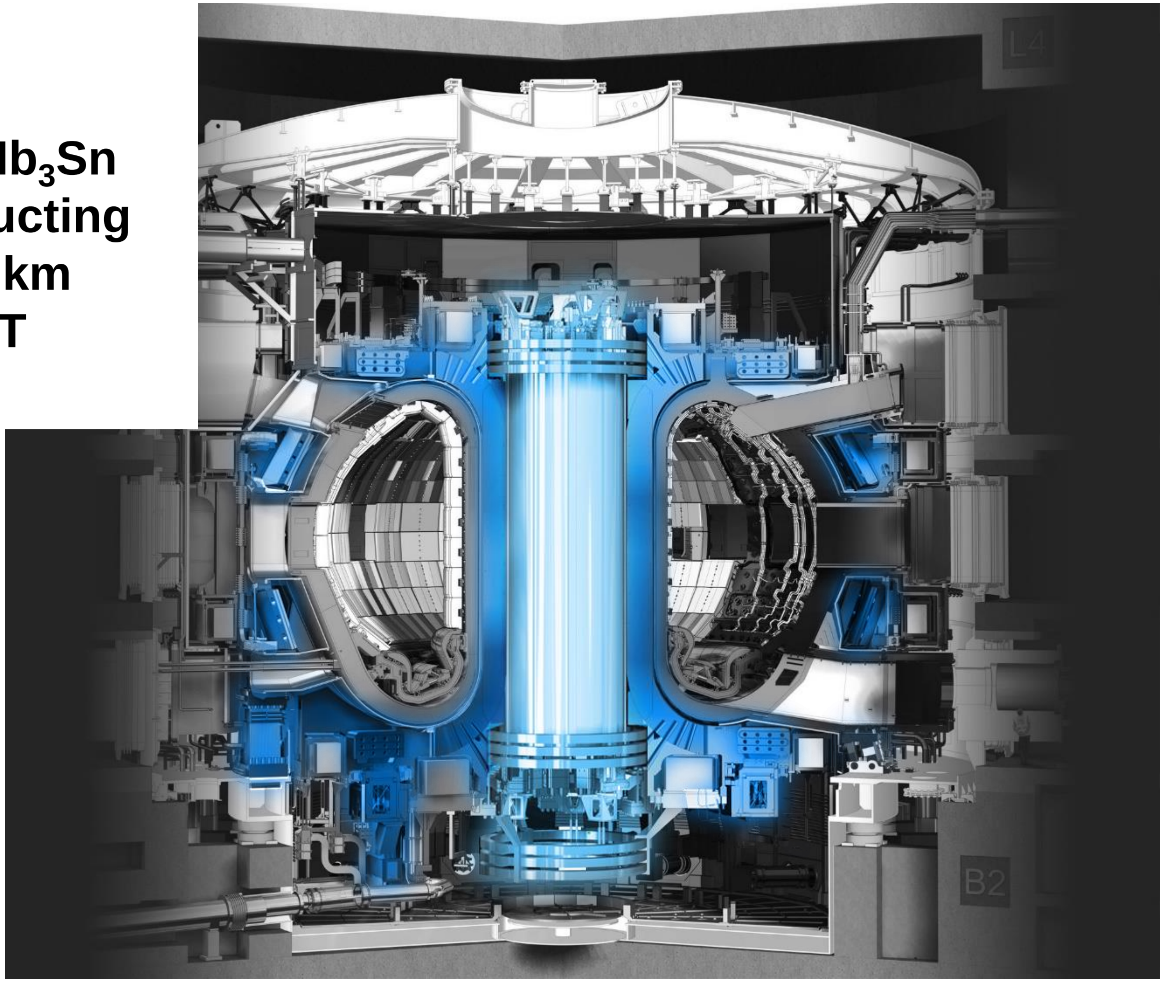
ITER

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



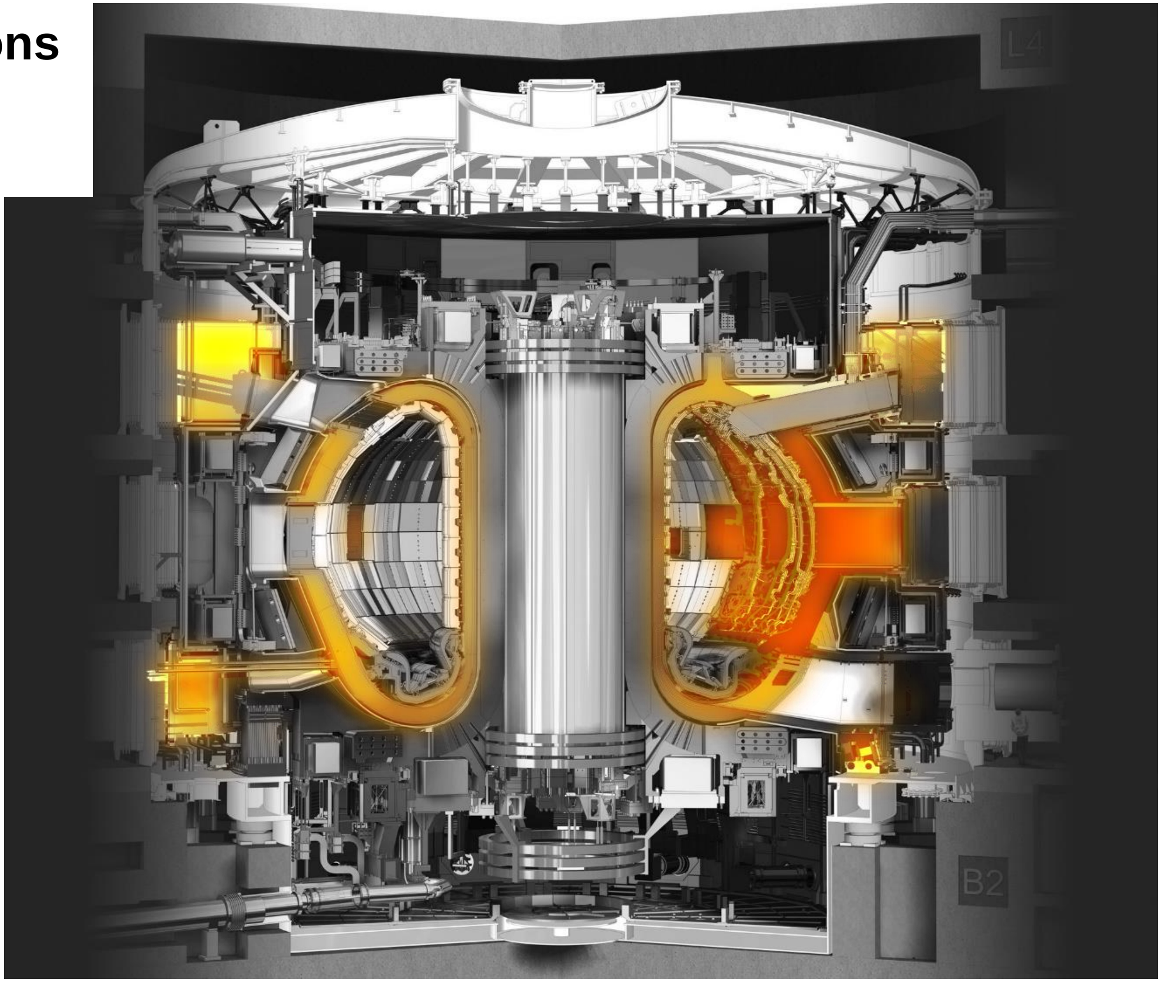
ITER – Magnets

- 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



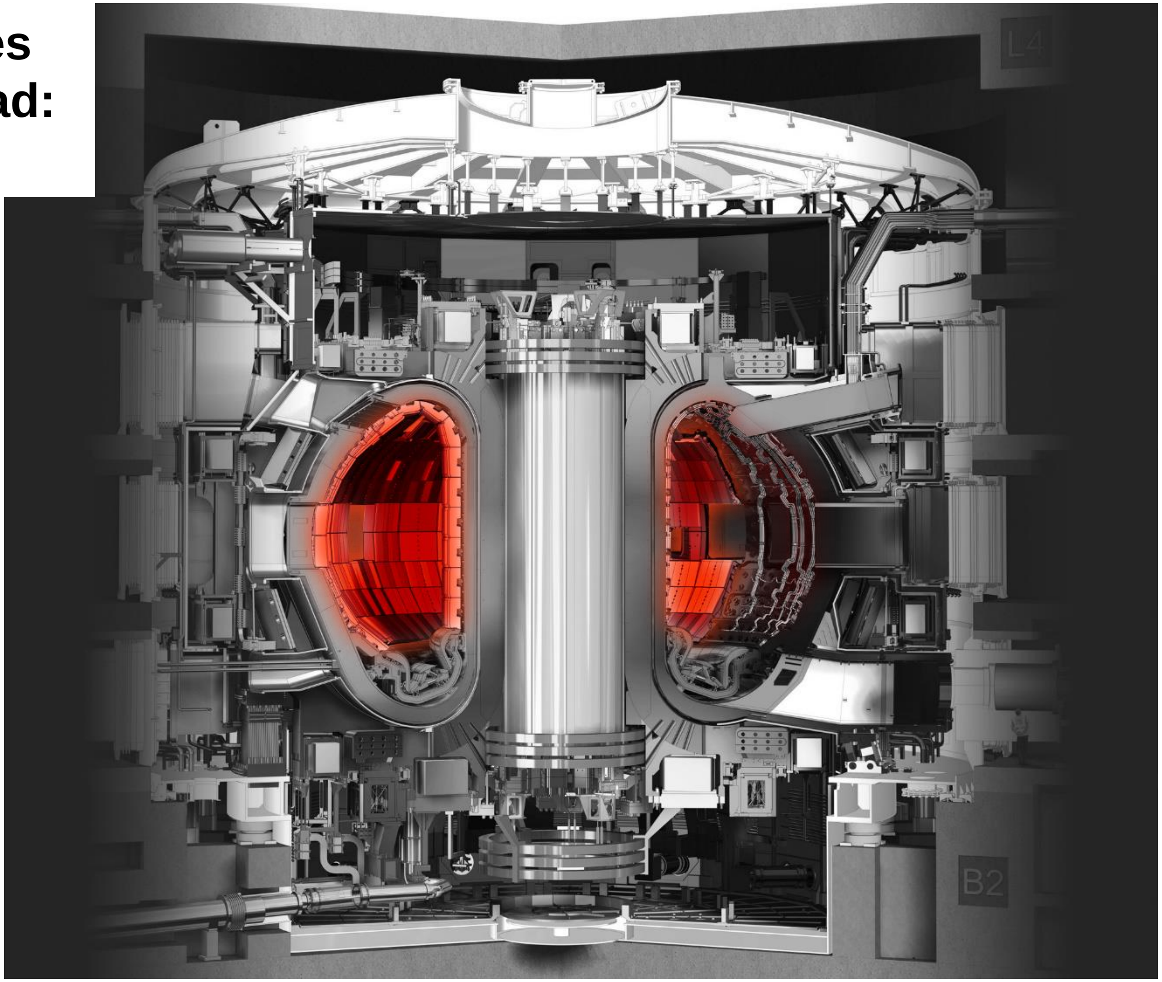
ITER – Vacuum vessel

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



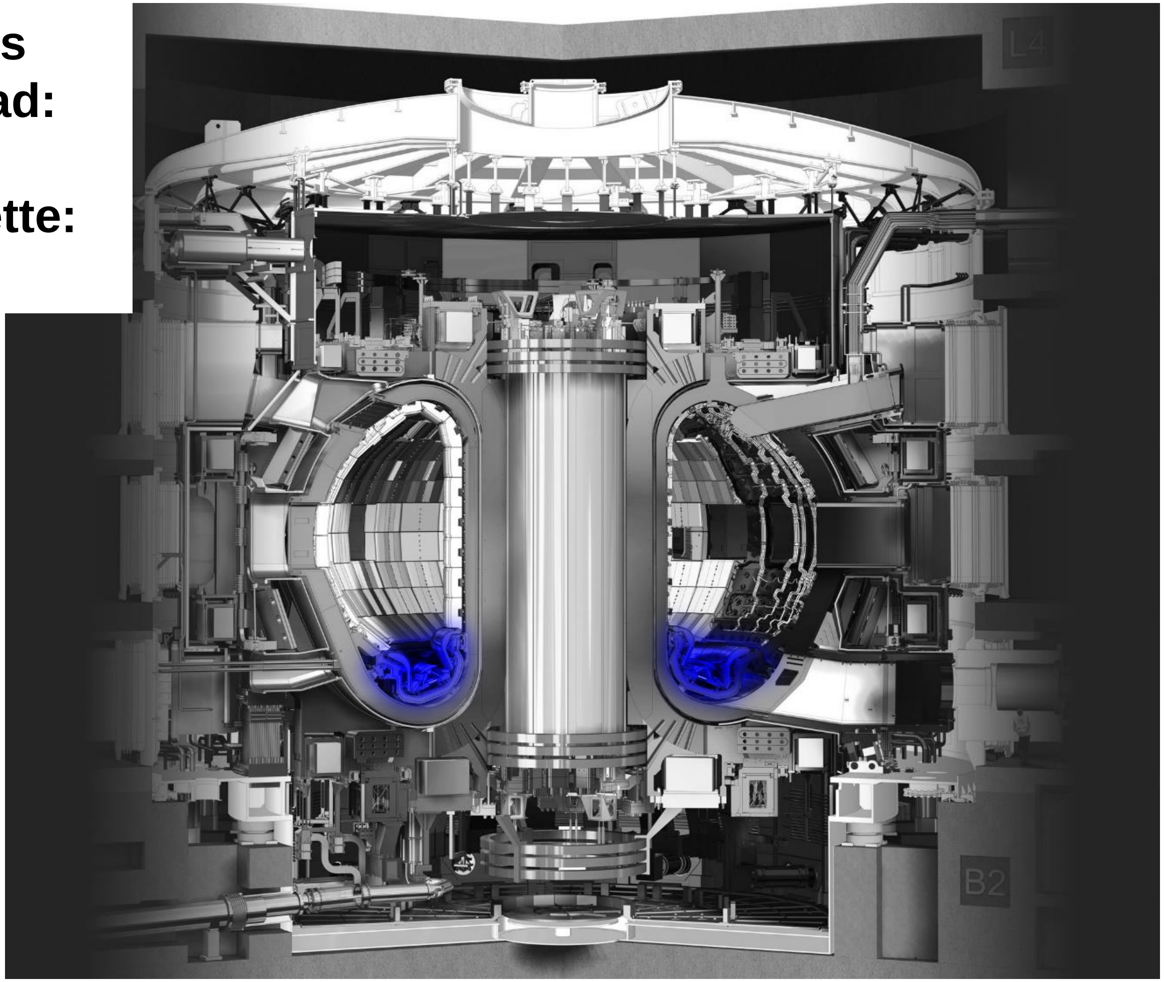
ITER – Blanket

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



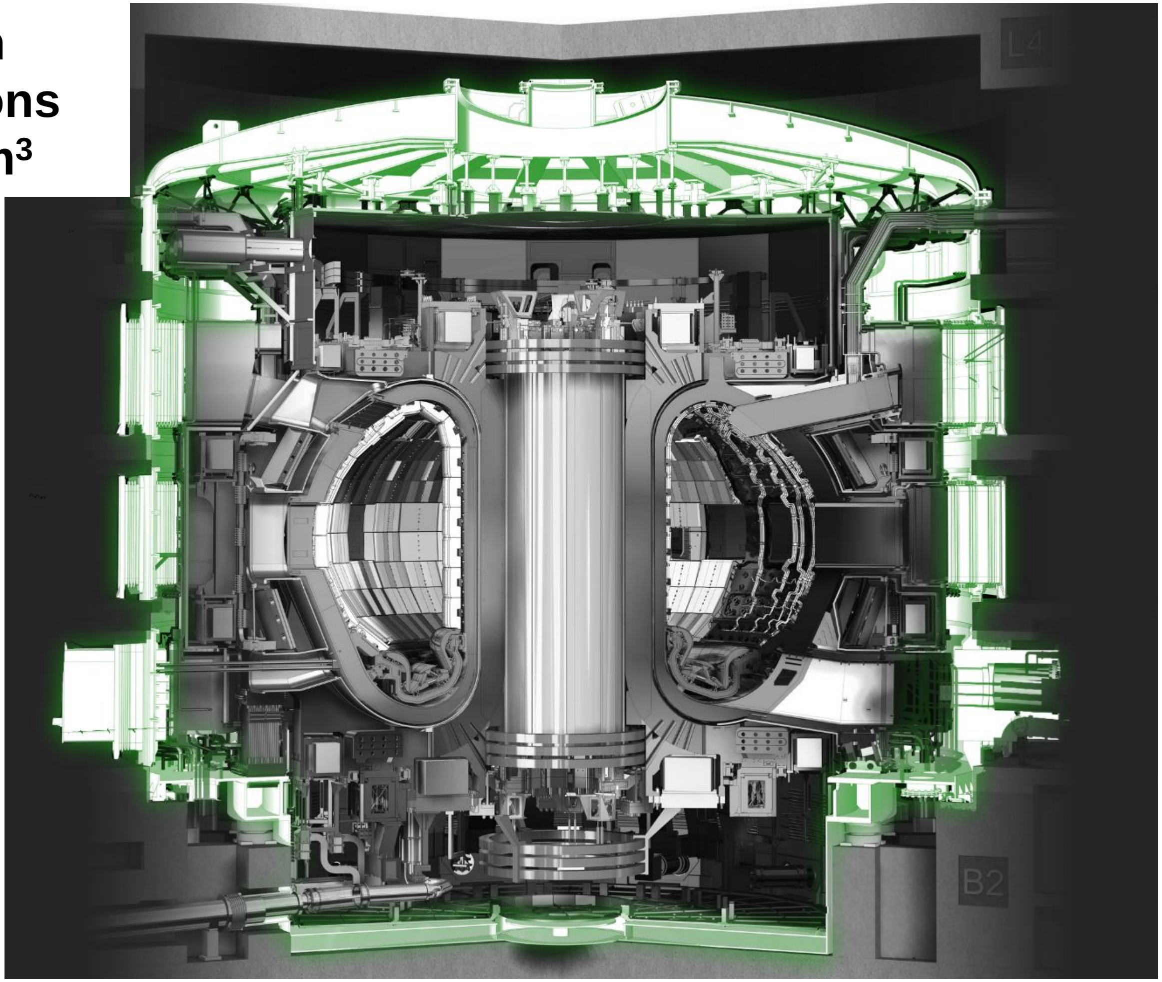
ITER – Divertor

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



ITER – Crystat

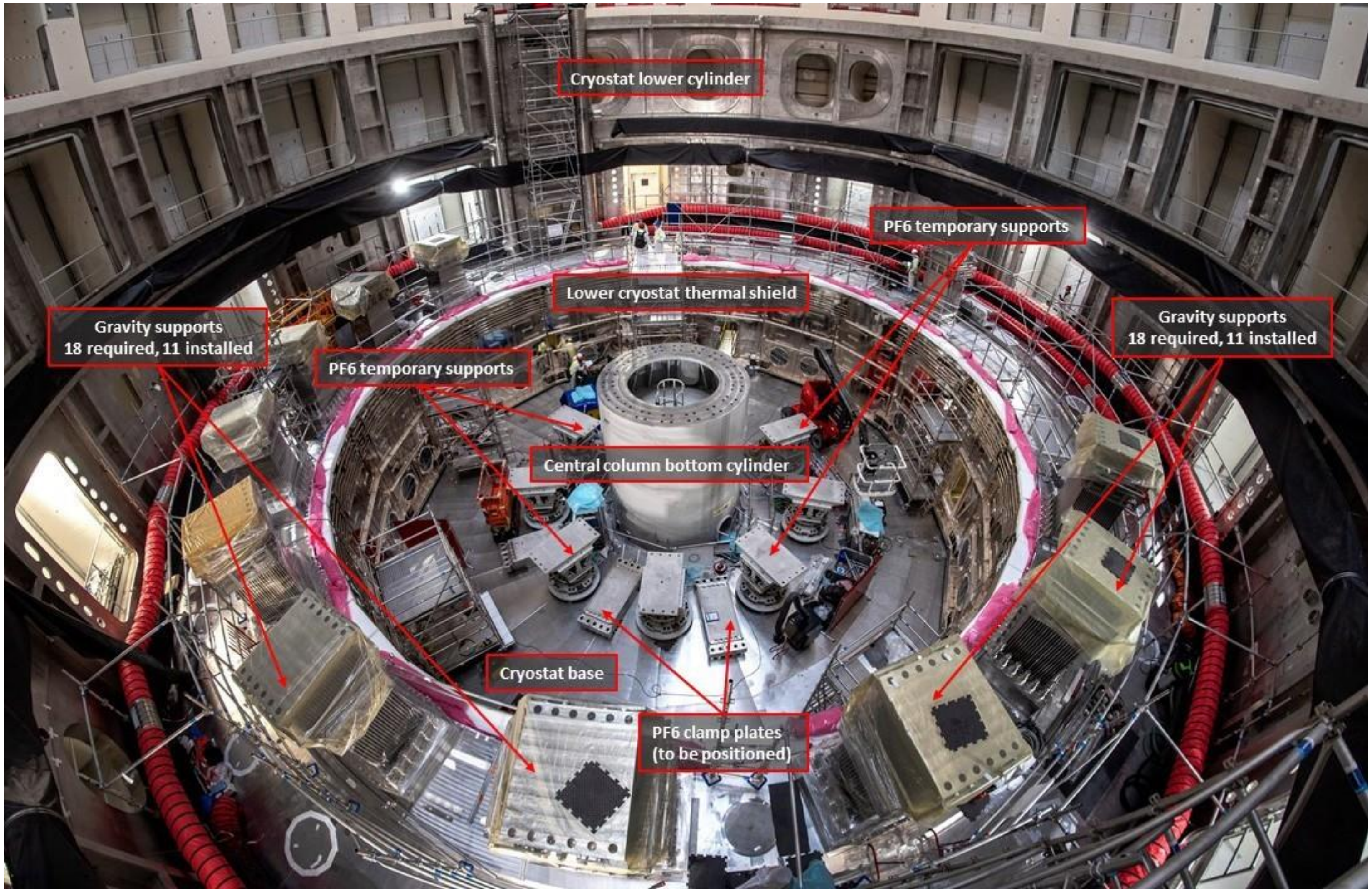
- **P = 10^{-6} atm**
- **W = 3800 tons**
- **V = 16000 m^3**



Supporting systems

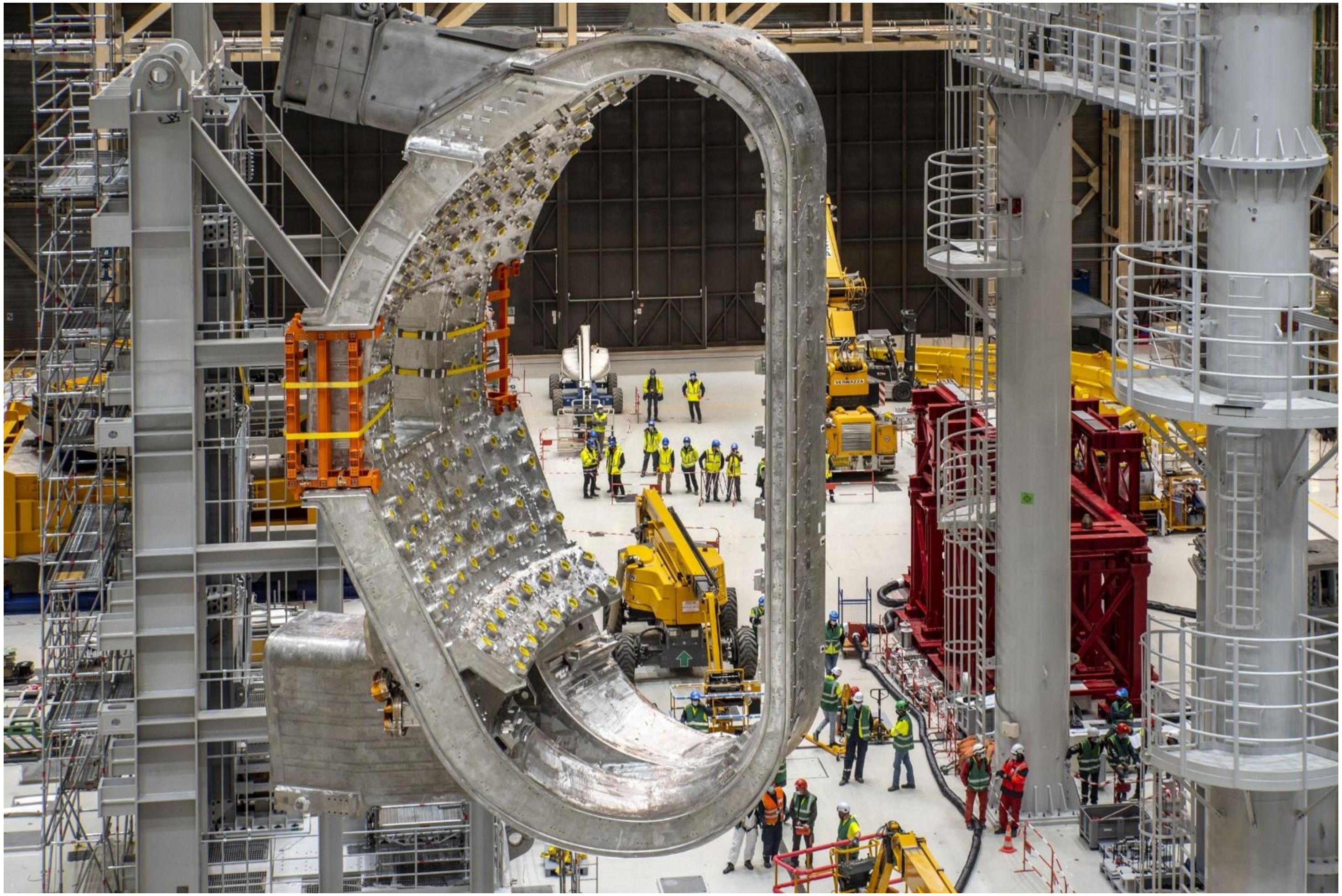
- Tritium breeding
- Control, Data access and Communication (CODAC)
- Cooling water
- Cryogenics
- Diagnostics
- Fuel cycle
- Hot cell - a secure environment for processing, repair or testing, etc., of components that have become activated by neutrons.
- Power supply
- Remote handling
- Heating and current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

ITER is being assembled



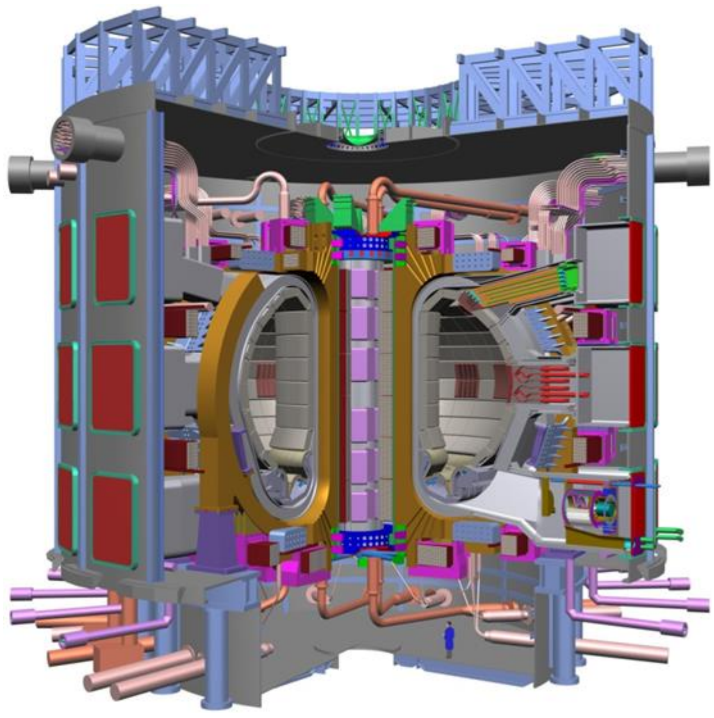
https://www.iter.org

ITER is being assembled



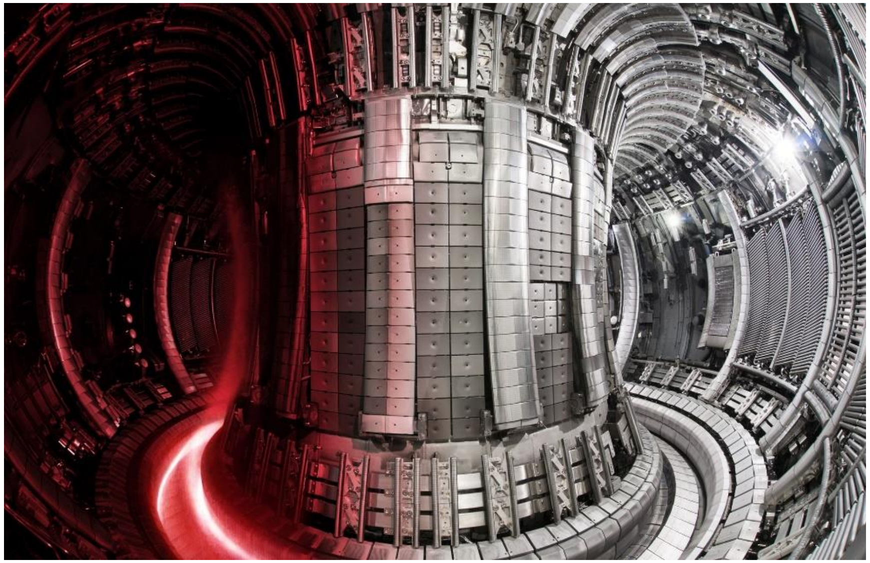
https://www.iter.org

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



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

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

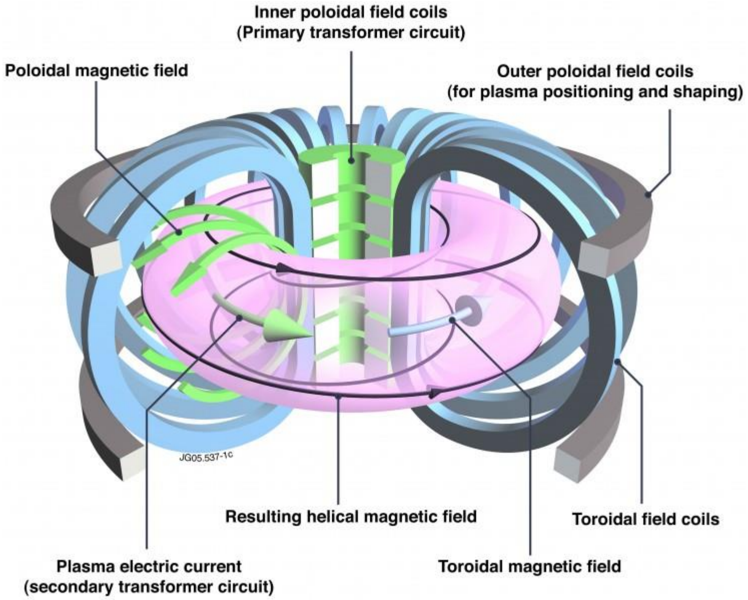


- **Record-breaking 59 megajoules of sustained fusion energy in Joint European Torus (JET) facility in Oxford demonstrates powerplant potential and strengthens case for ITER.**

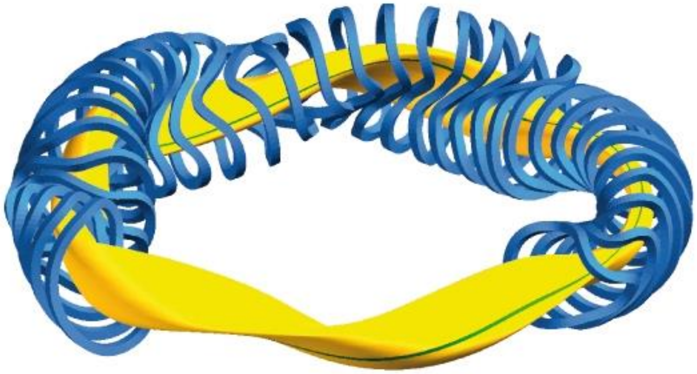
https://ccfe.ukaea.uk/resources/#gallery

Stellarator uses twisted coil to generate poloidal magnetic field

Tokamak



Stellarator



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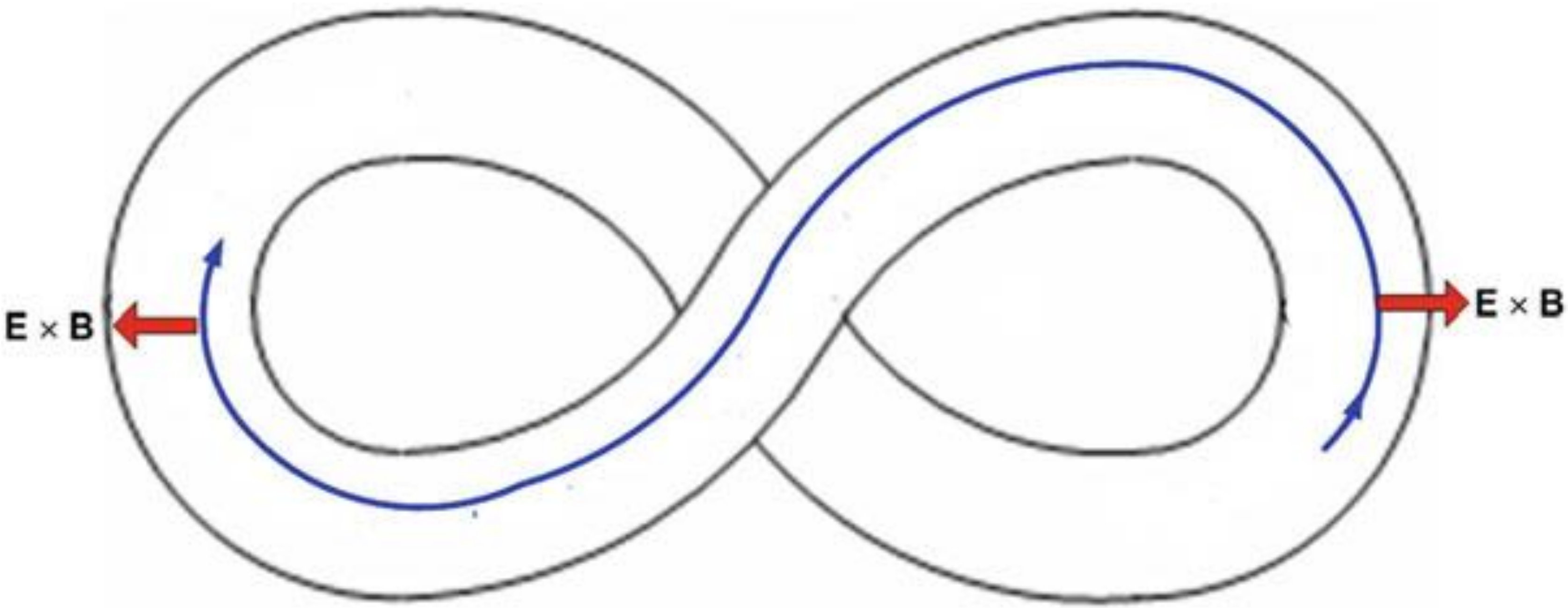
https://www.euro-fusion.org/2011/09/tokamak-principle-2/
https://en.wikipedia.org/wiki/Stellarator

A figure-8 stellarator solved the drift issues



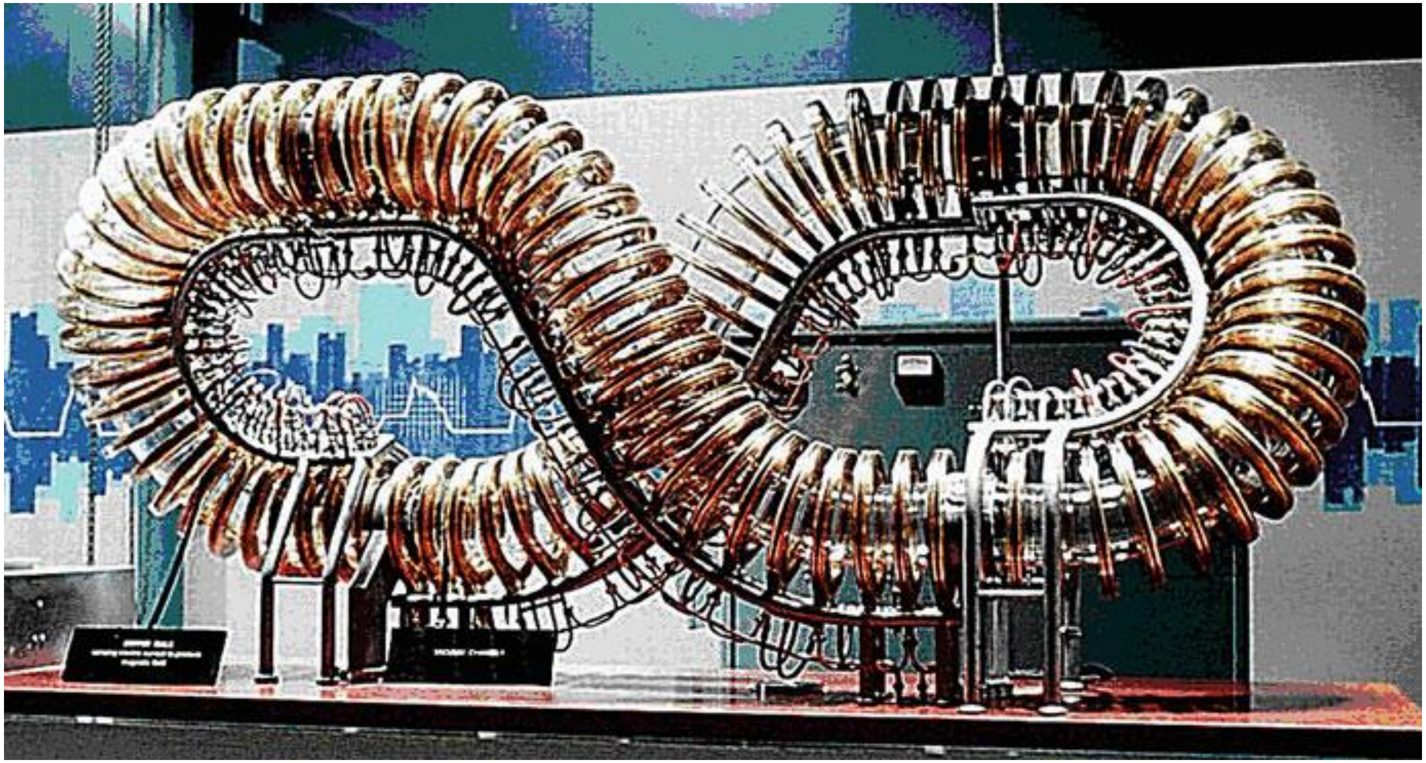
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

A figure-8 stellarator solved the drift issues

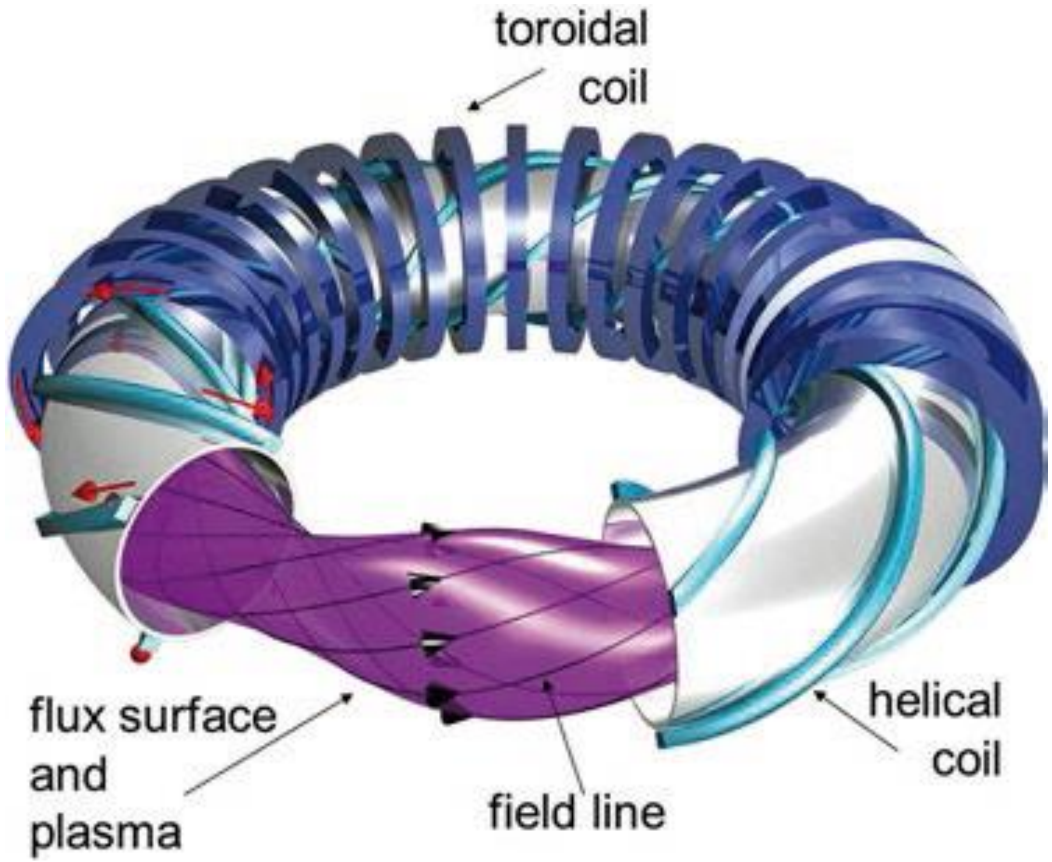
Lyman Spitzer, Jr. came out the idea during a long ride on a ski lift at Garmisch-Partenkirchen

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

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

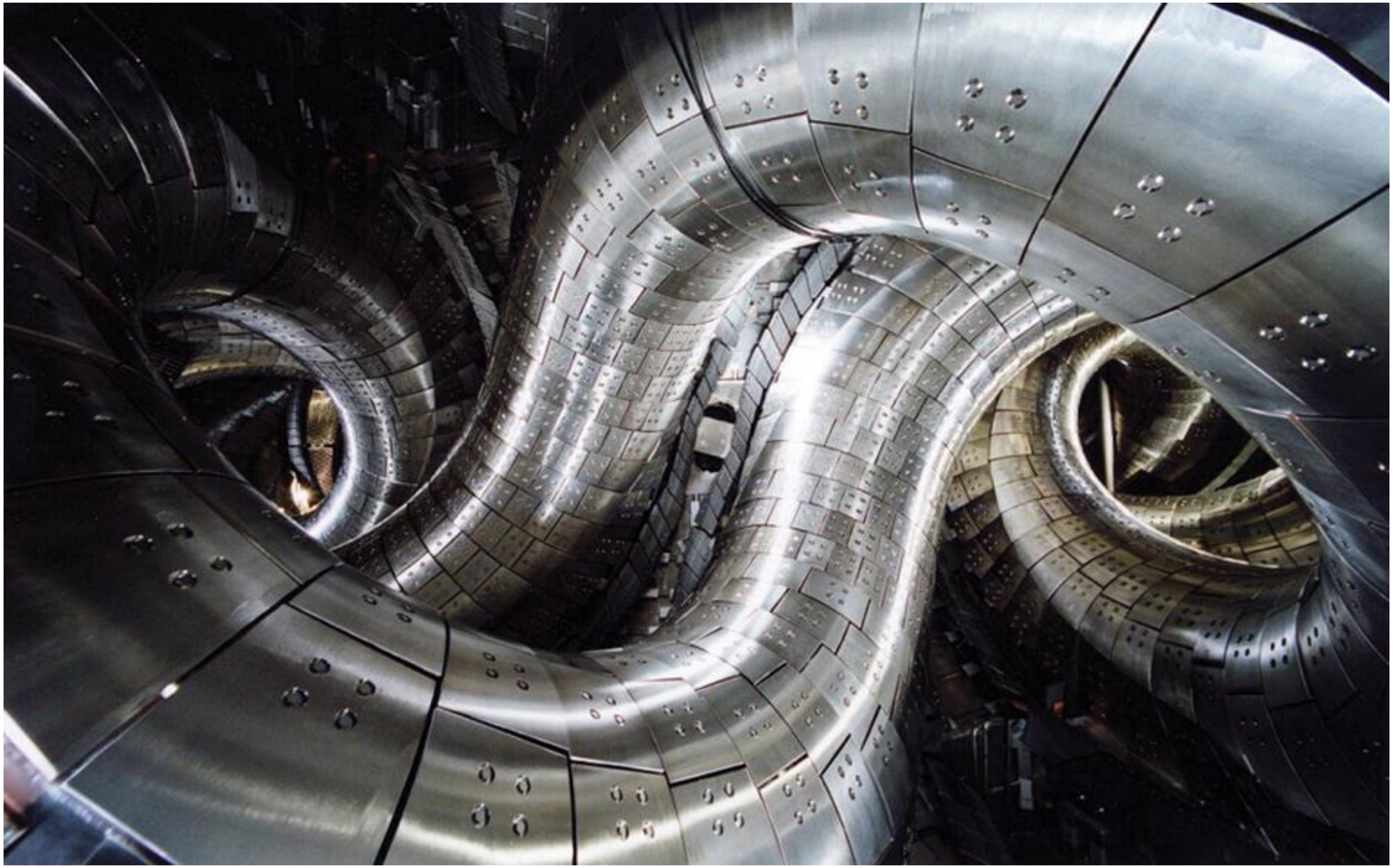


Twisted magnetic field lines can be provided by toroidal coils with helical coils



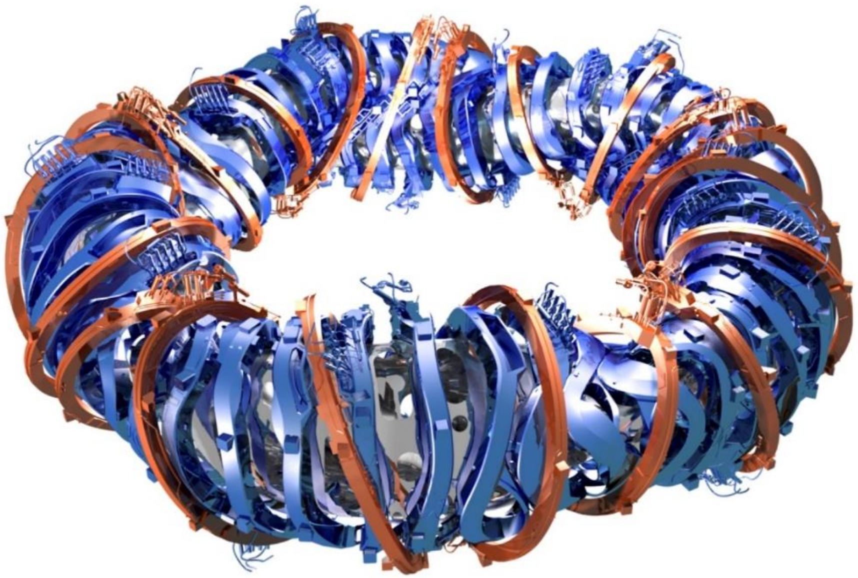
Wagner, F., Fusion energy. MRS Energy & Sustainability, 5, E8 (2018)

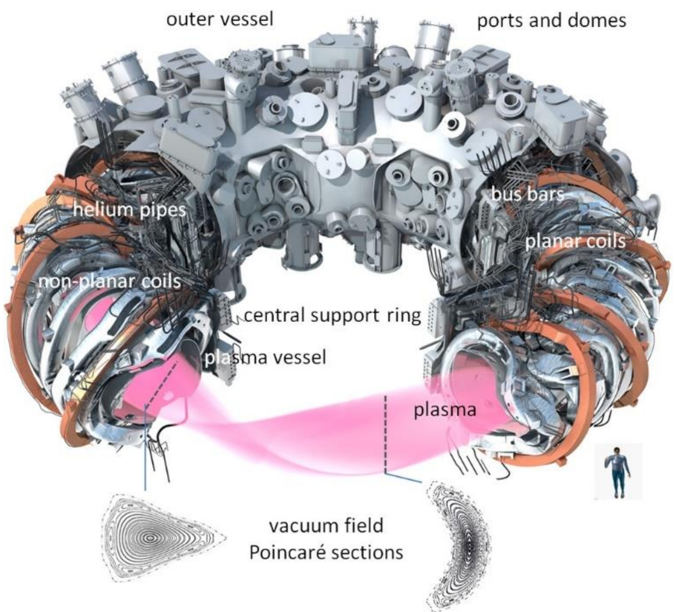
LHD stellarator in Japan



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

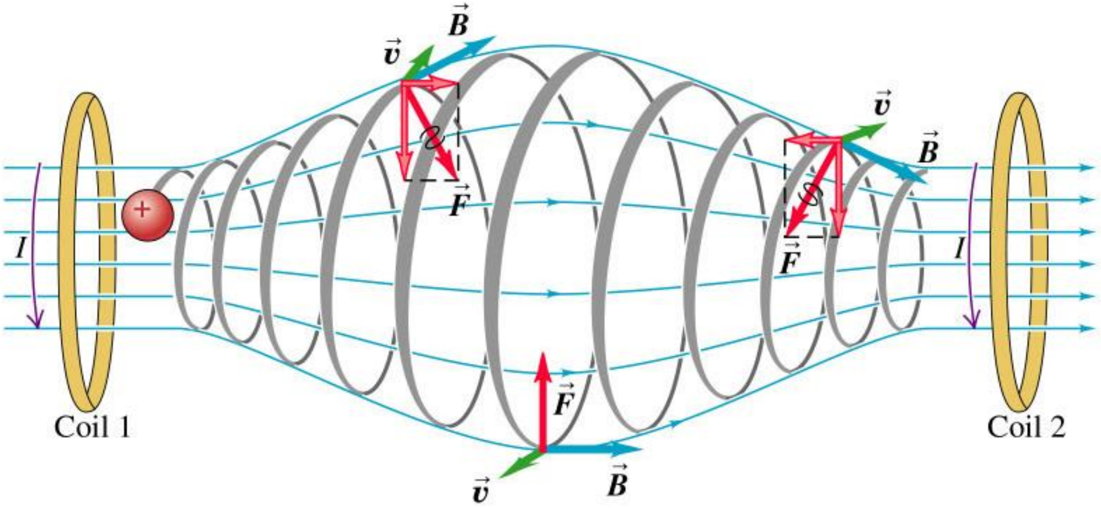
Wendelstein 7-X is a stellarator built by Max Planck Institute for Plasma Physics (IPP)

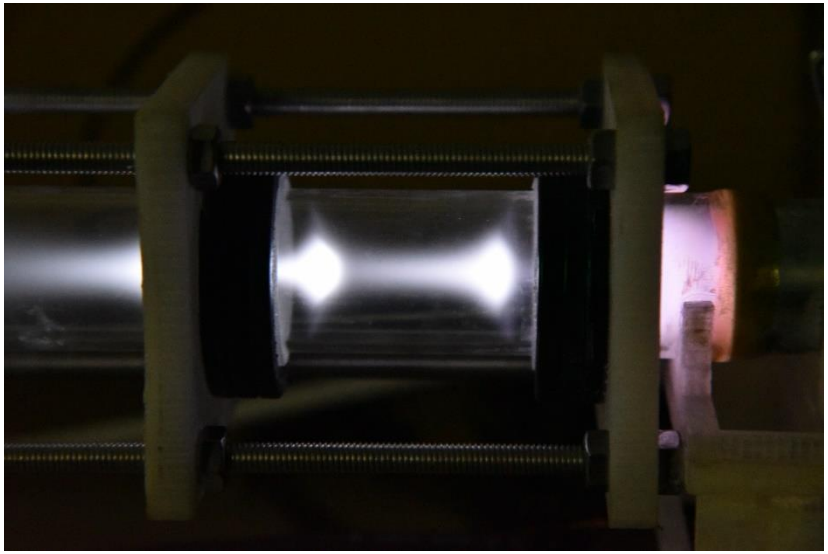




- **Wemdelstein 7-x is now installing new diverters.**

Demonstration of a magnetic mirror machine

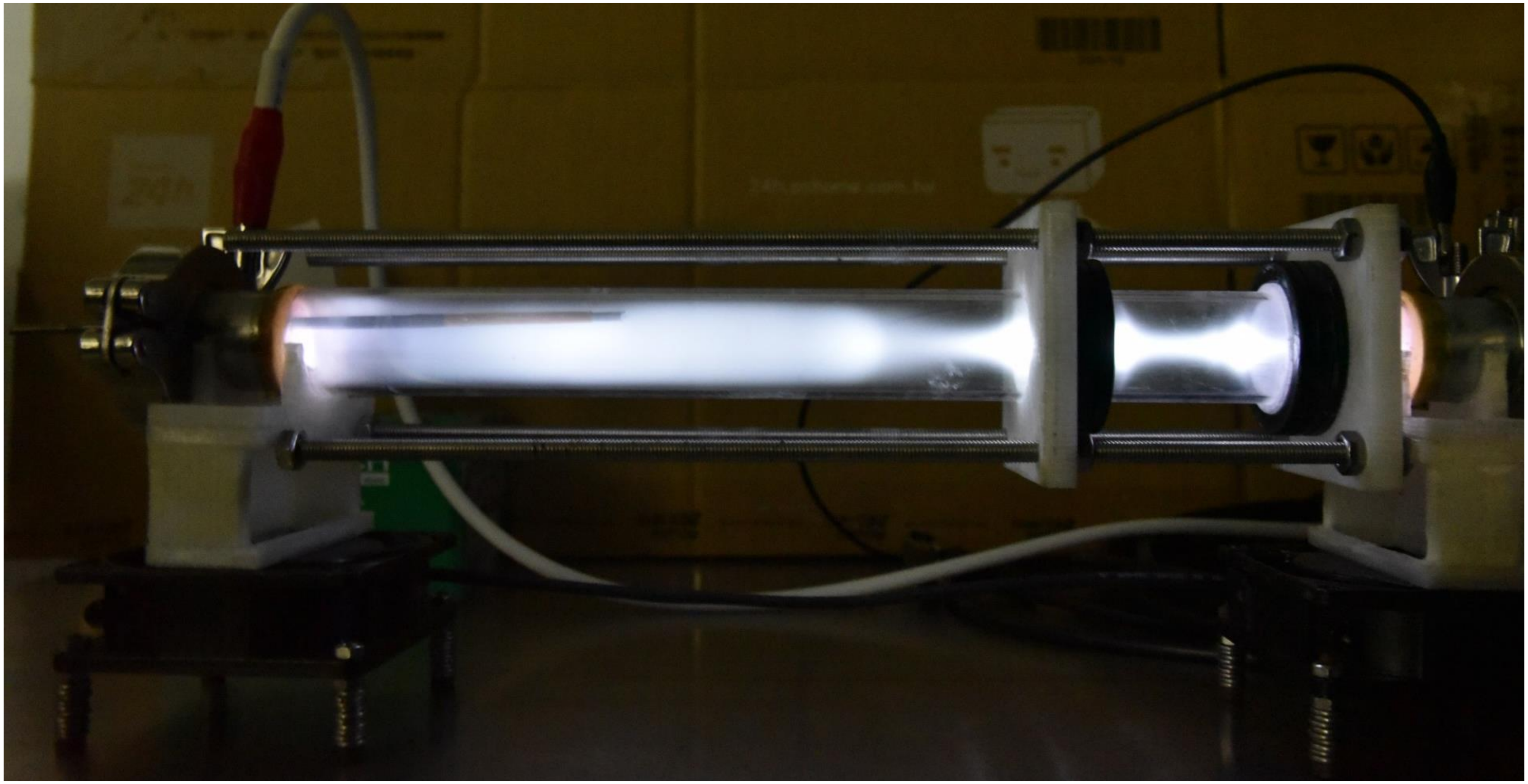




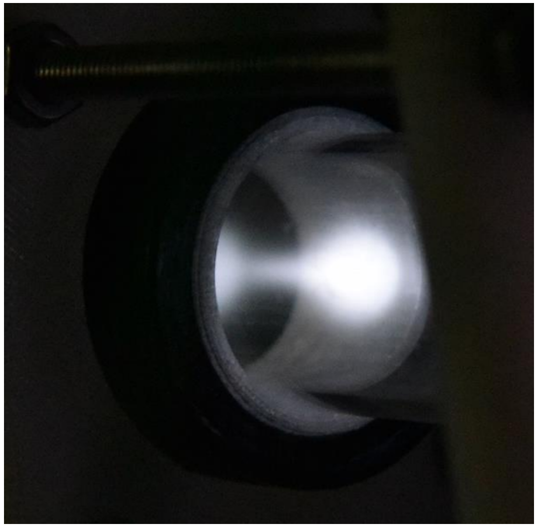
Show video.

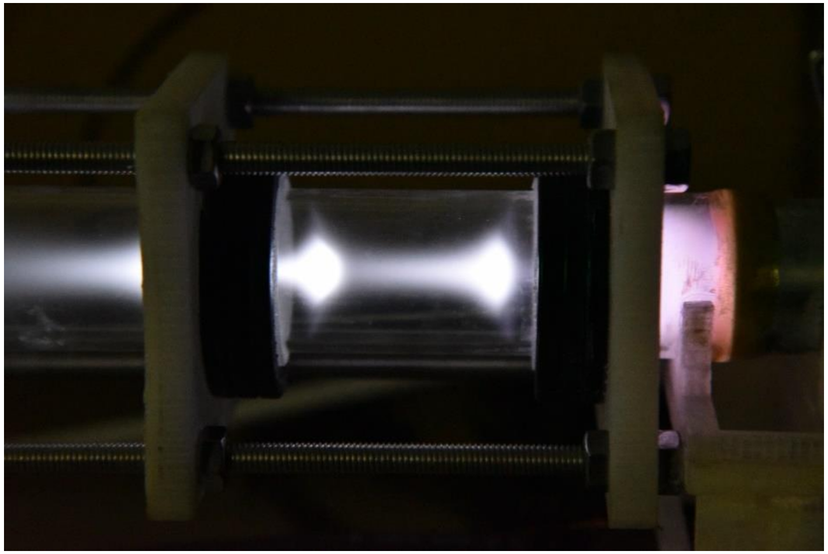
https://i.stack.imgur.com/GIzGZ.jpg

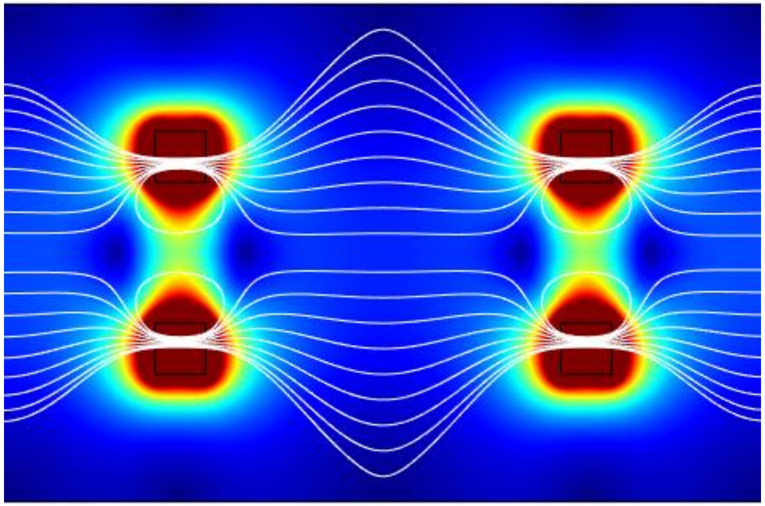
Plasma is partially confined by the magnetic field



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



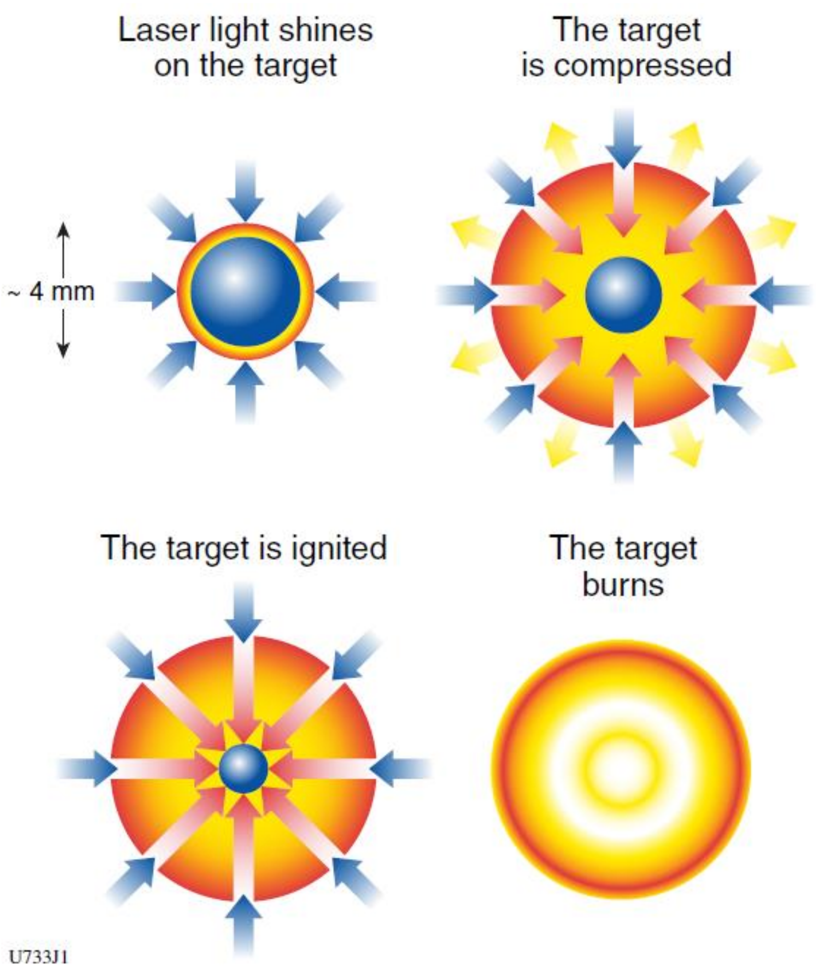


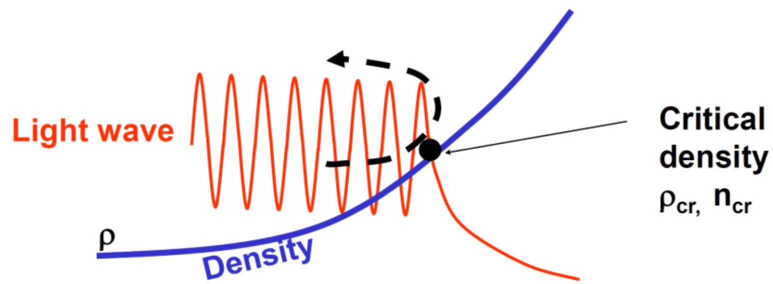


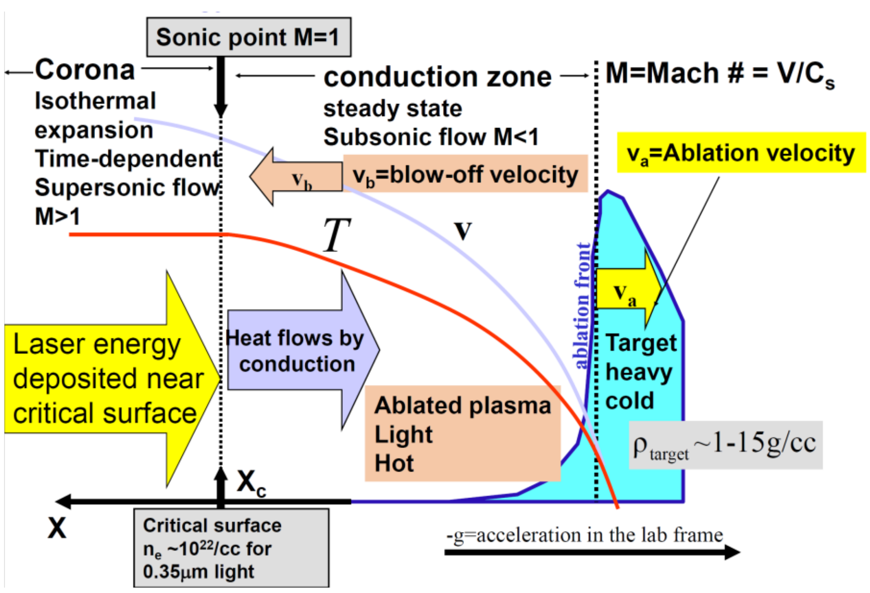
Outline

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

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



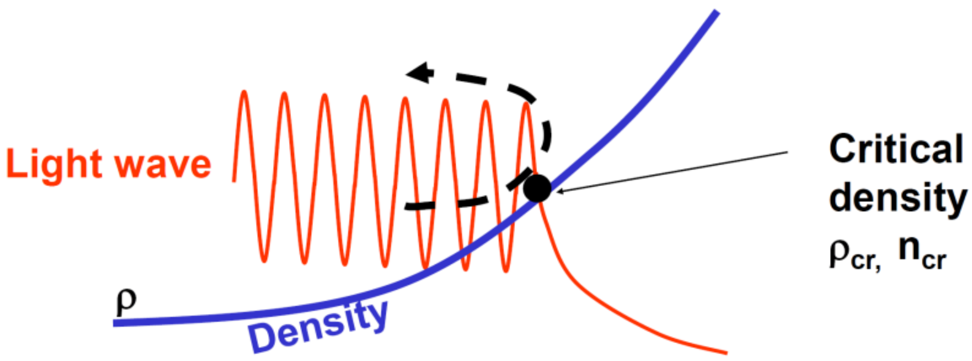


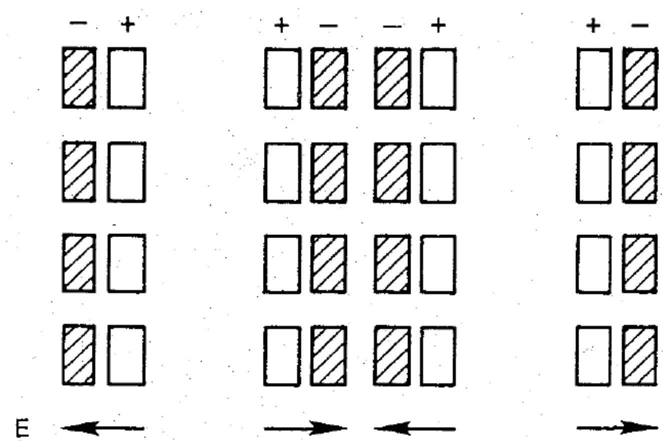


Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

R. Betti, HEDSA HEDP Summer School, 2015

The laser light cannot propagate past a critical density





Mechanism of plasma oscillations.

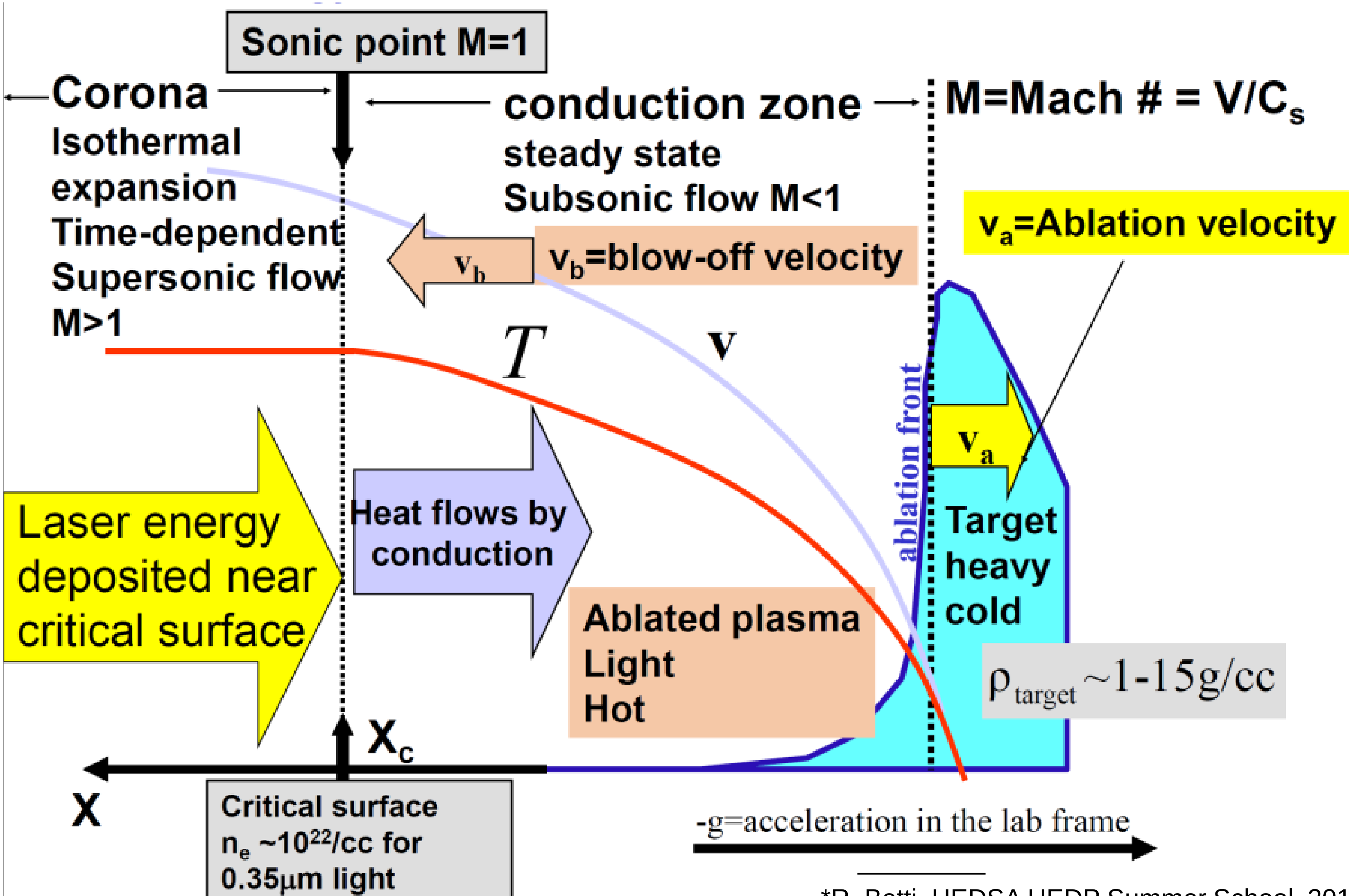
- **Critical density is given by plasma frequency=laser frequency**

$$\omega_{\rm L} = \frac{2\pi c}{\lambda_{\rm L}} \qquad \omega_{\rm pe} = \sqrt{\frac{4\pi n_{\rm e} e^2}{m_{\rm e}}}$$

$$\omega_{\rm L}^2 = \omega_{\rm pe}^2 \qquad n_e{}^{cr} = \frac{1.1\times 10^{21}}{\lambda_{L,\mu m}{}^2}\,\mathrm{cm}^{-3}$$

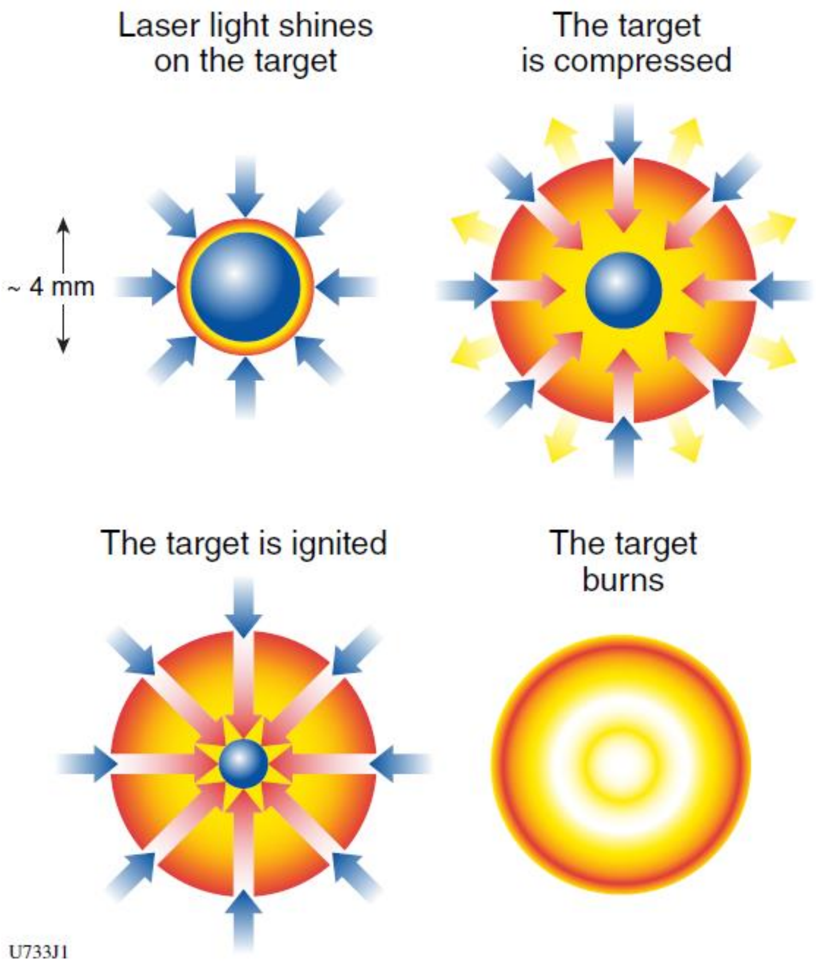
*R. Betti, HEDSA HEDP Summer School, 2015

The laser generates a pressure by depositing energy at the critical surface

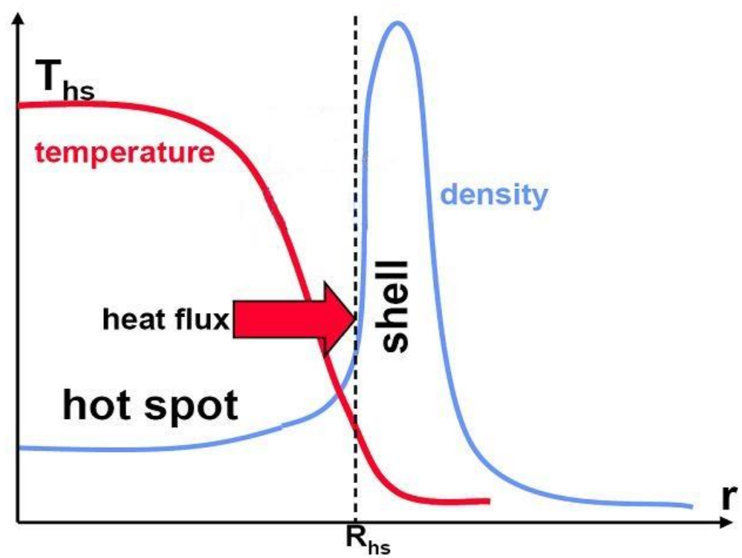


*R. Betti, HEDSA HEDP Summer School, 2015

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

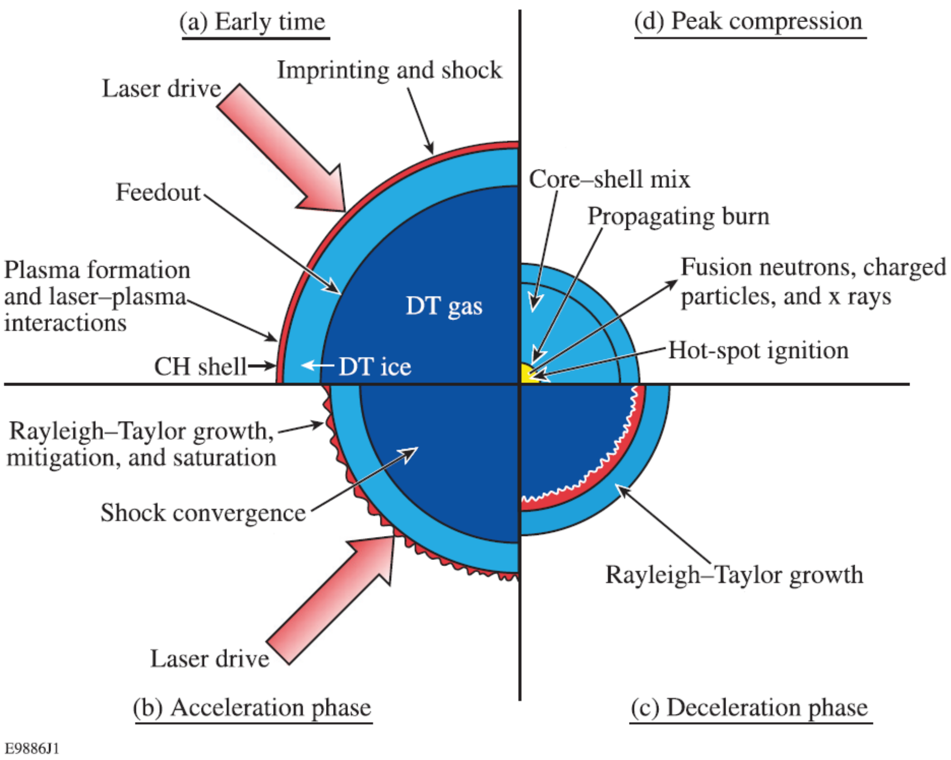


Spatial profile at stagnation

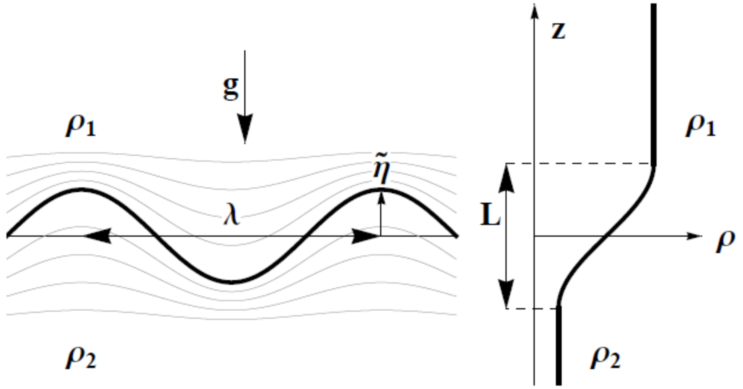


A ball can not be compressed uniformly by being squeezed between several fingers

- **Stages of a target implosion**

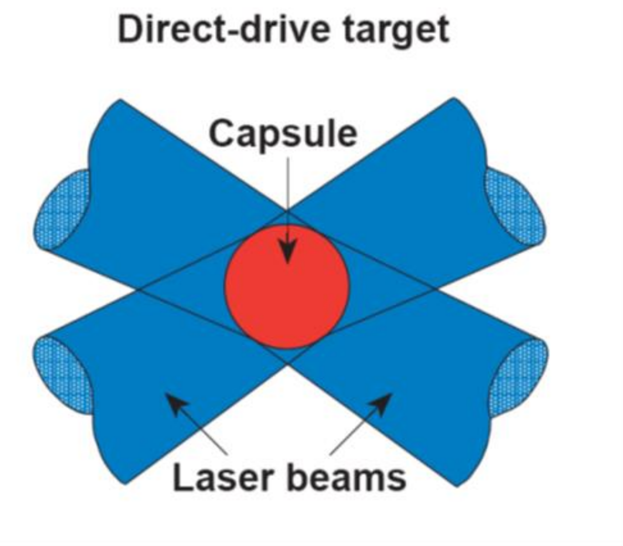


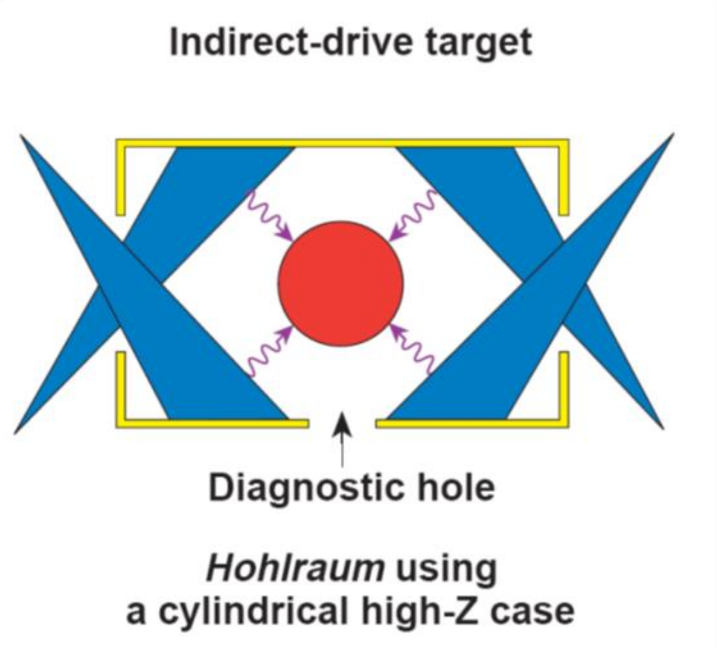
- **Rayleigh-Taylor instability**



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

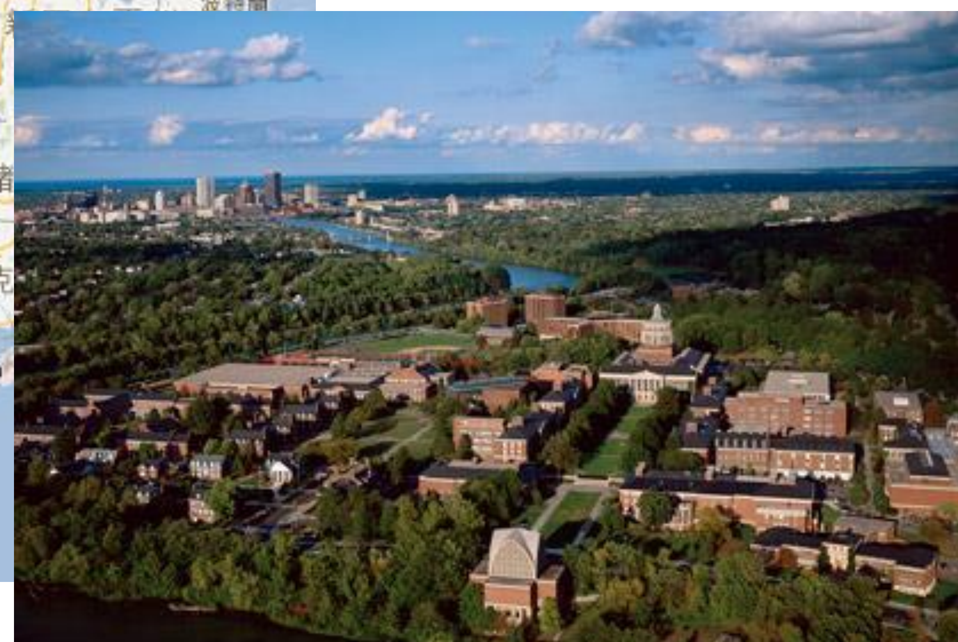
A spherical capsule can be imploded through directly or indirectly laser illumination





*R. Betti, HEDSA HEDP Summer School, 2015

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



There are many famous optical companies at Rochester

Kodak

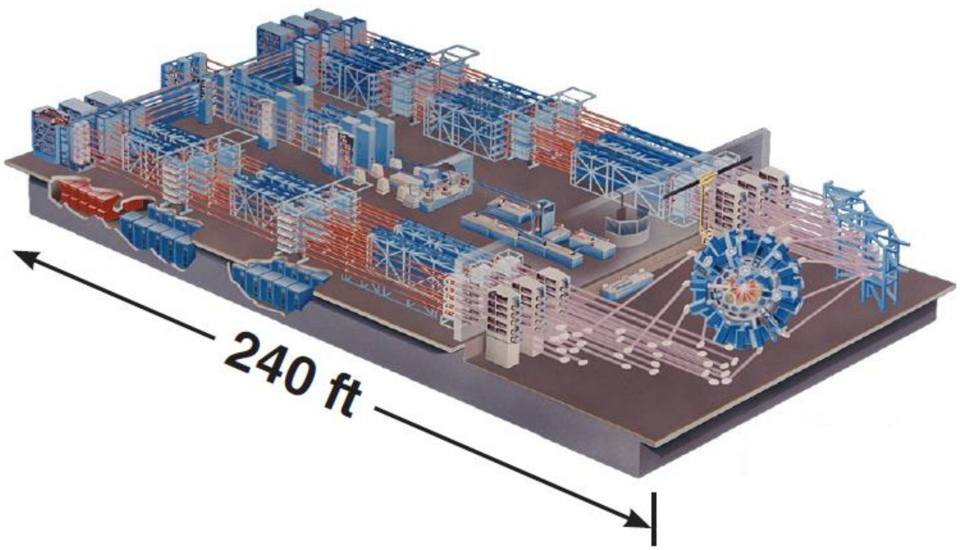
xerox

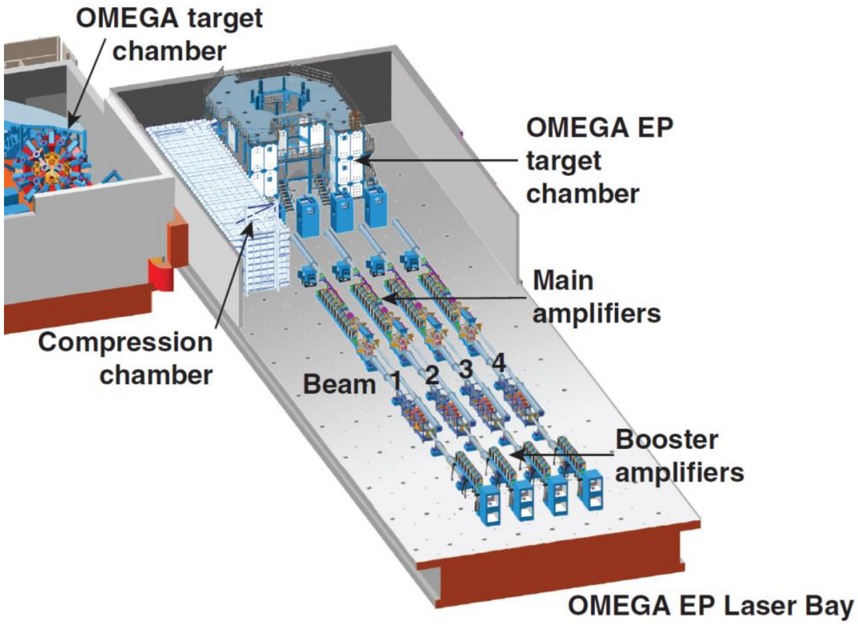
Eastman school of music

BAUSCH + LOMB

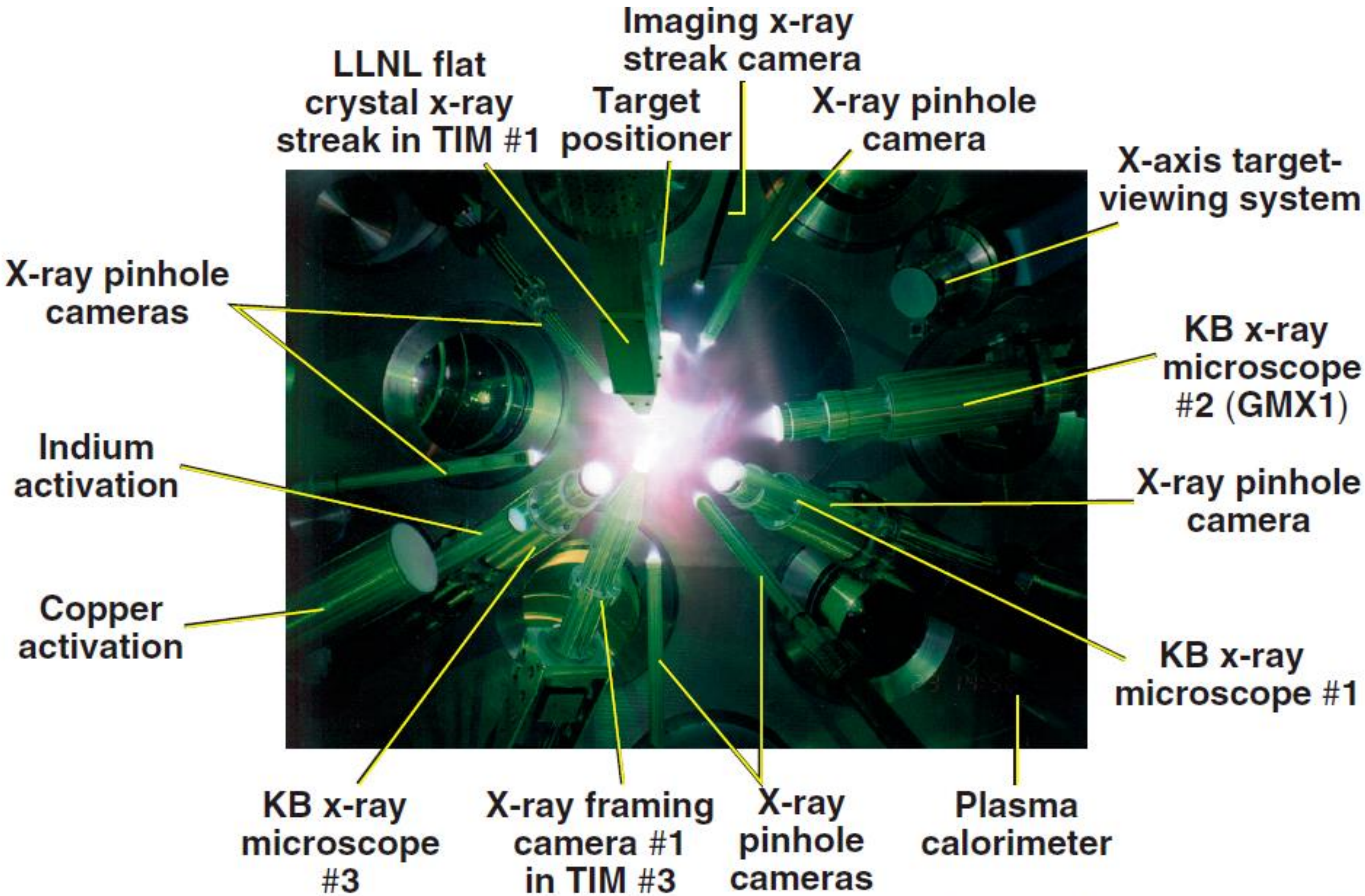
Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion

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





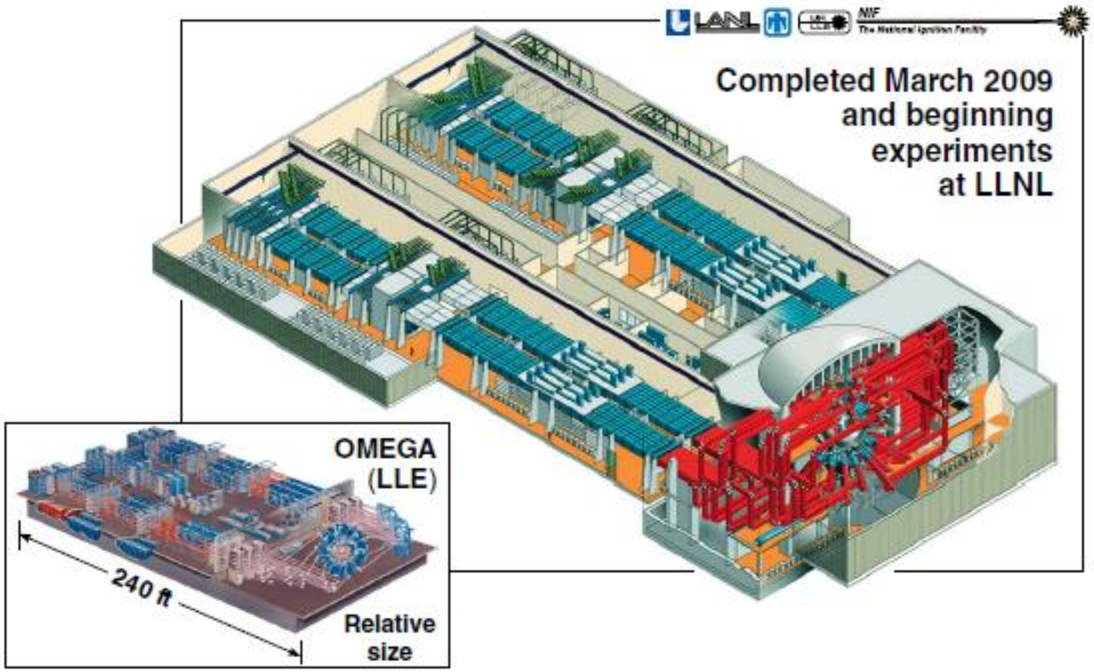
The OMEGA Facility is carrying out ICF experiments using a full suite of target diagnostics



E8012b

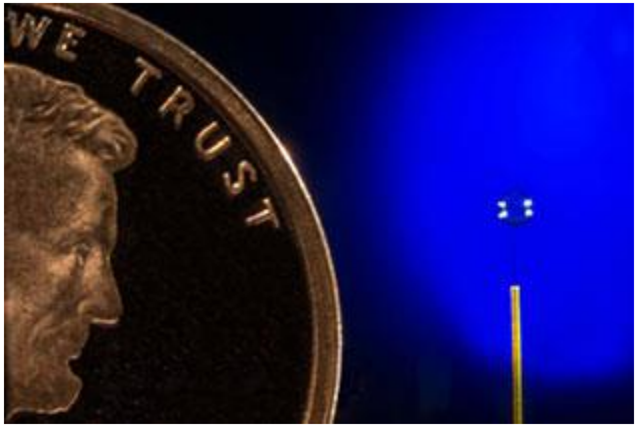
Photo taken from port H11B

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

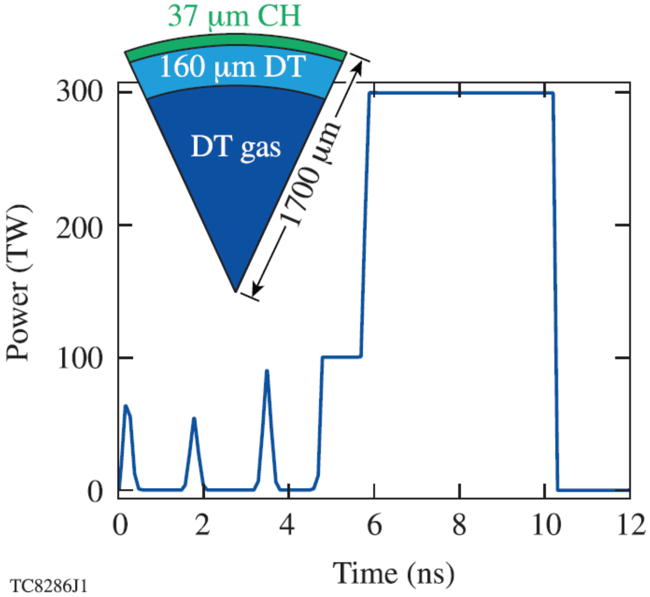


OMEGA experiments are integral to an ignition demonstration on the NIF.

Targets used in ICF



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



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

Softer material can be compressed to higher density

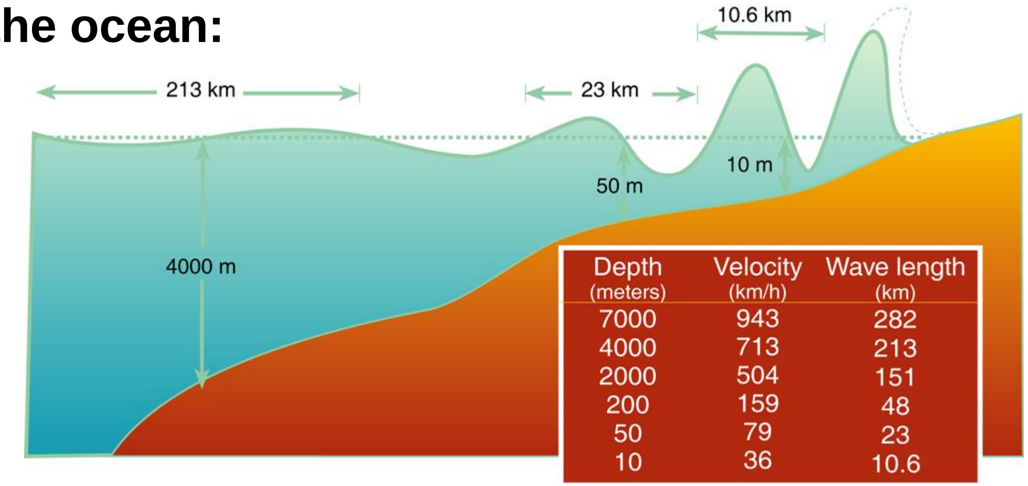
- **Compression of a baseball**

- **Compression of a tennis ball**

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

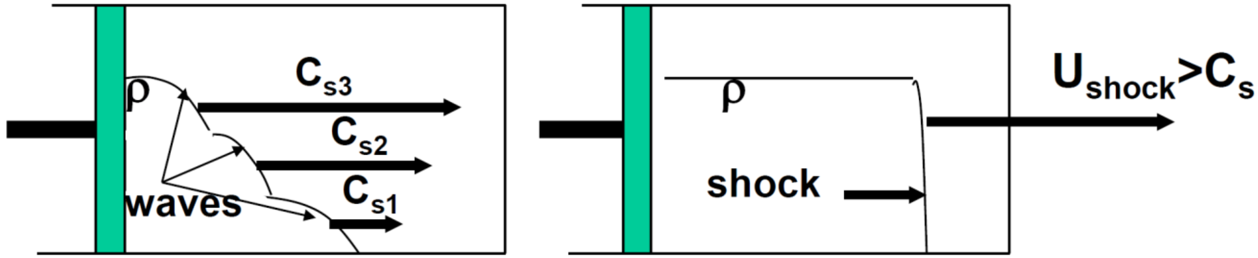
A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **Wave in the ocean:**



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

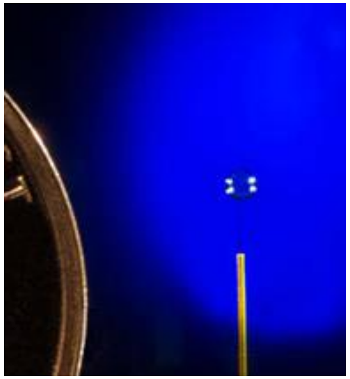
- **Acoustic/compression wave driven by a piston:**



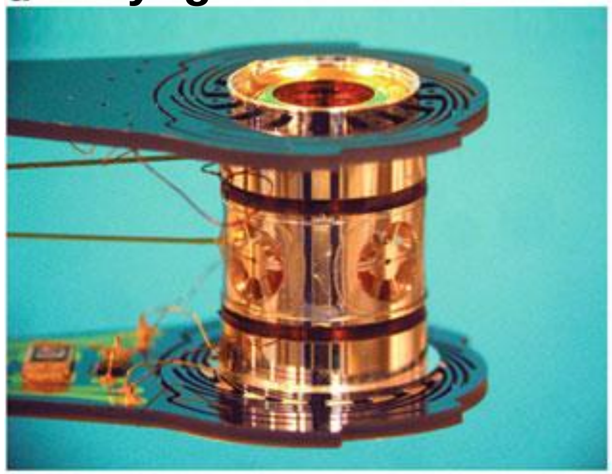
$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha\rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\rho^{1/3}$$

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

Targets used in ICF



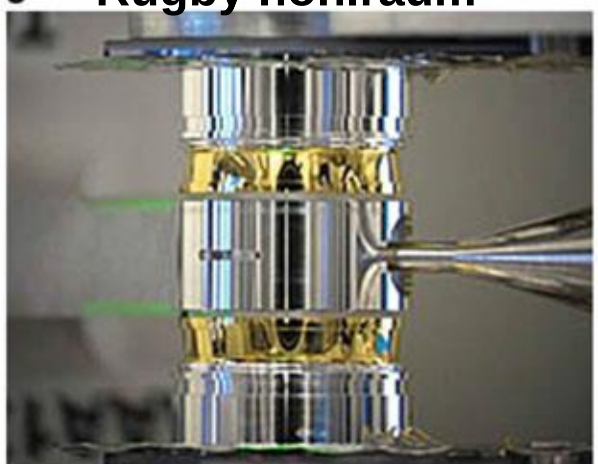
a Cryogenic hohlraum



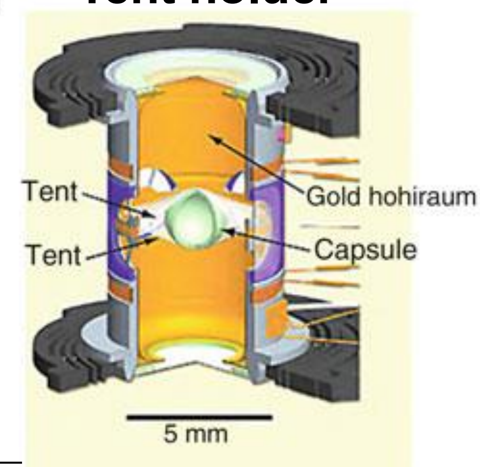
b

Cryogenic shroud

c Rugby hohlraum

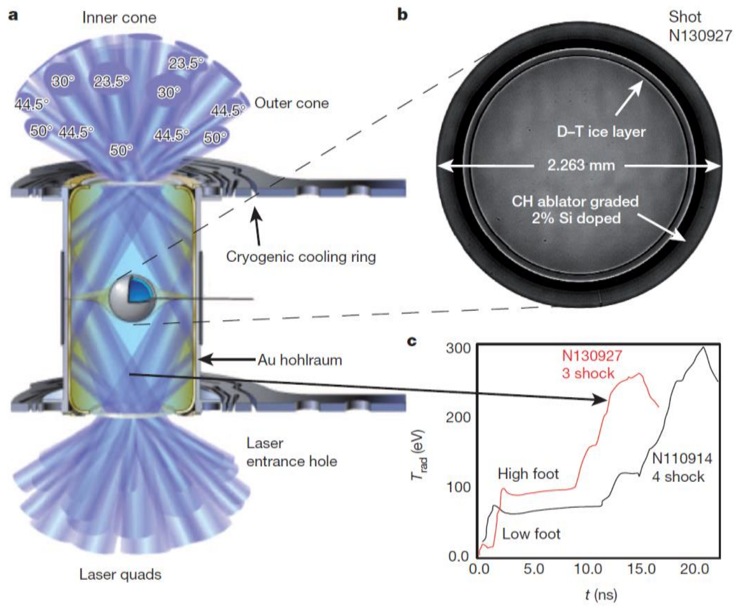


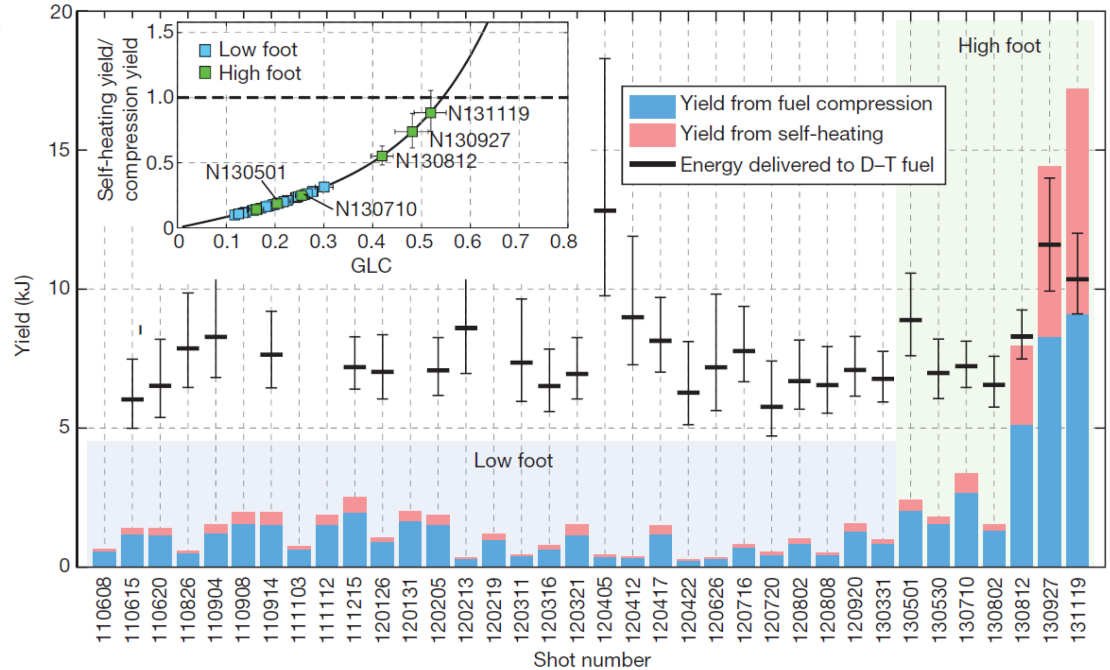
d Tent holder



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

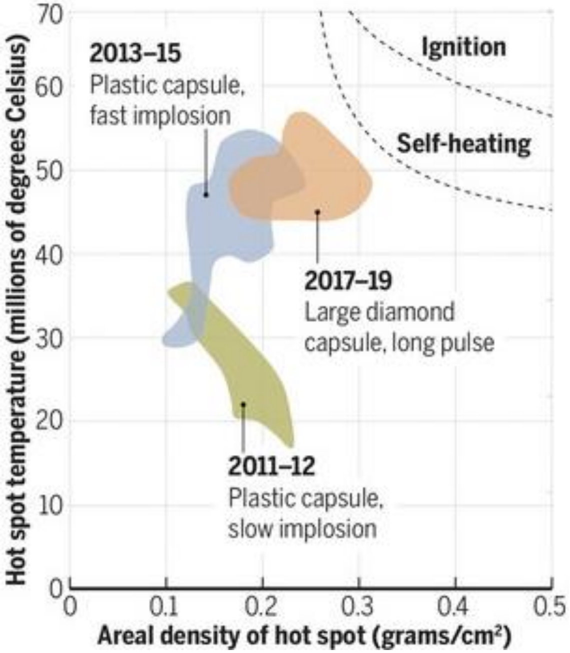
Nature letter “Fuel gain exceeding unity in an inertially confined fusion implosion”

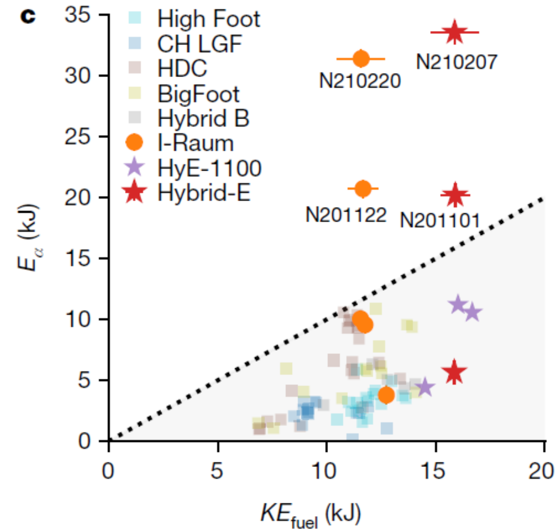


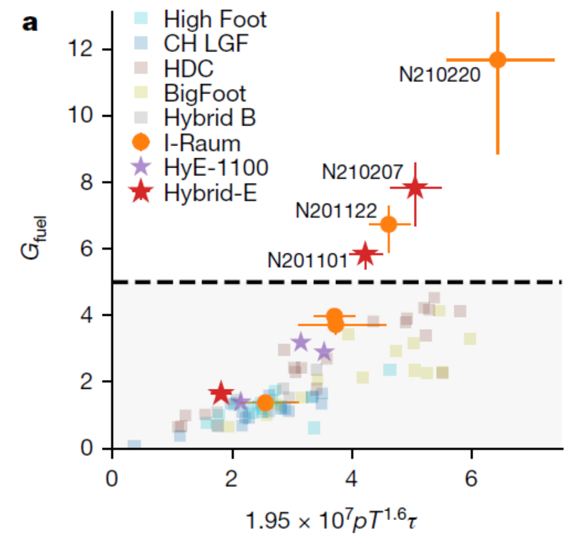


- **Fuel gain exceeding unity (scientific breakeven) was demonstrated for the first time.**

The hot spot has entered the burning plasma regime



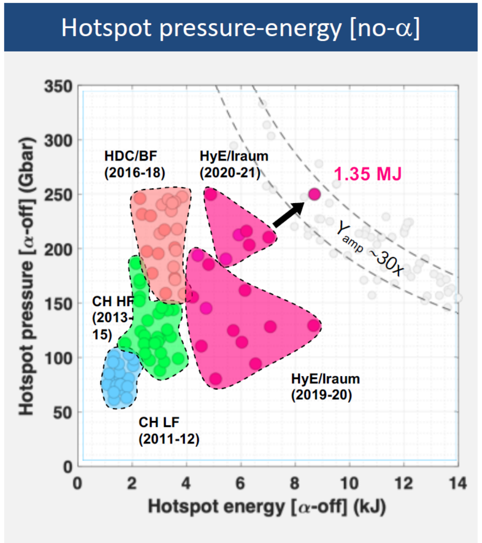


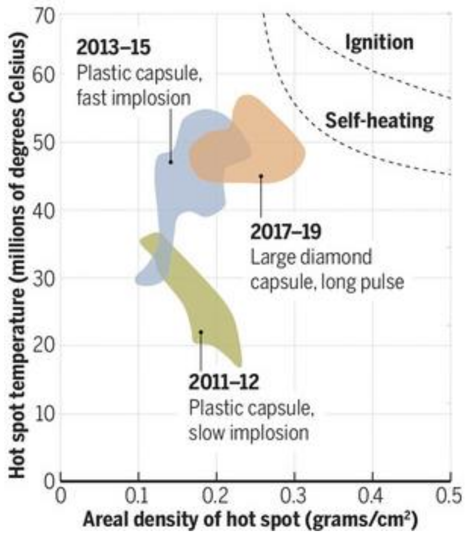


Science 370, p1019, 2020

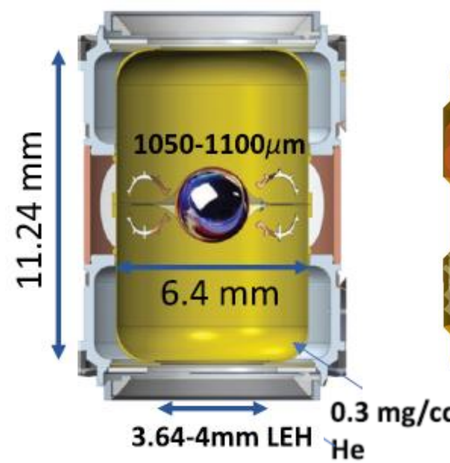
Nature 601, p542, 2022

The hot spot has entered the burning plasma regime

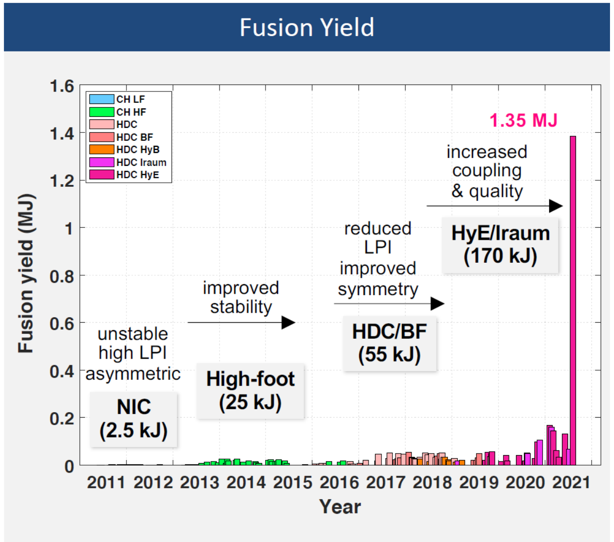




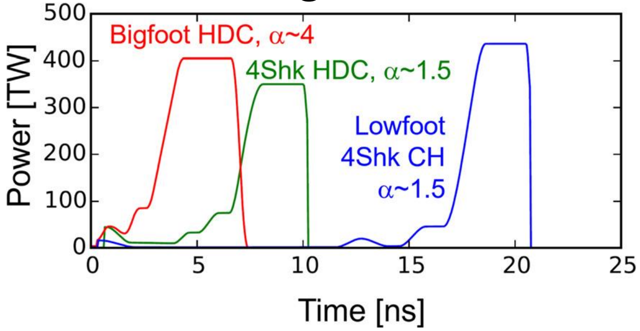
- **Hybrid-E**

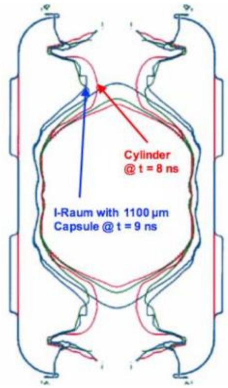


- **I-raum**



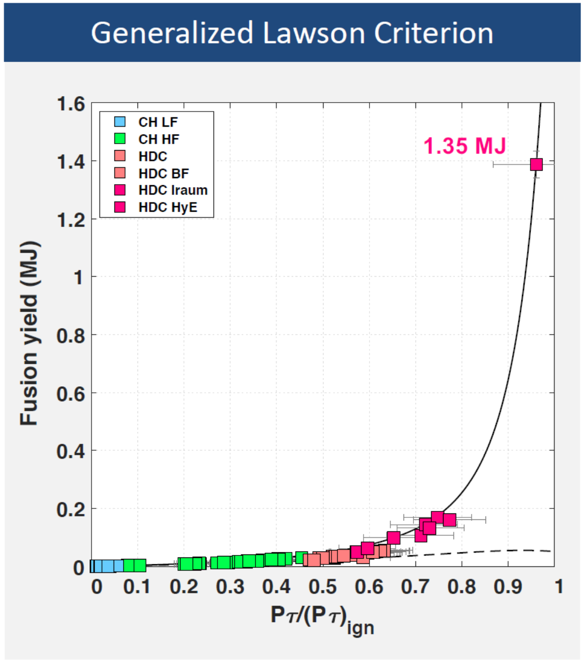
- **Big foot**

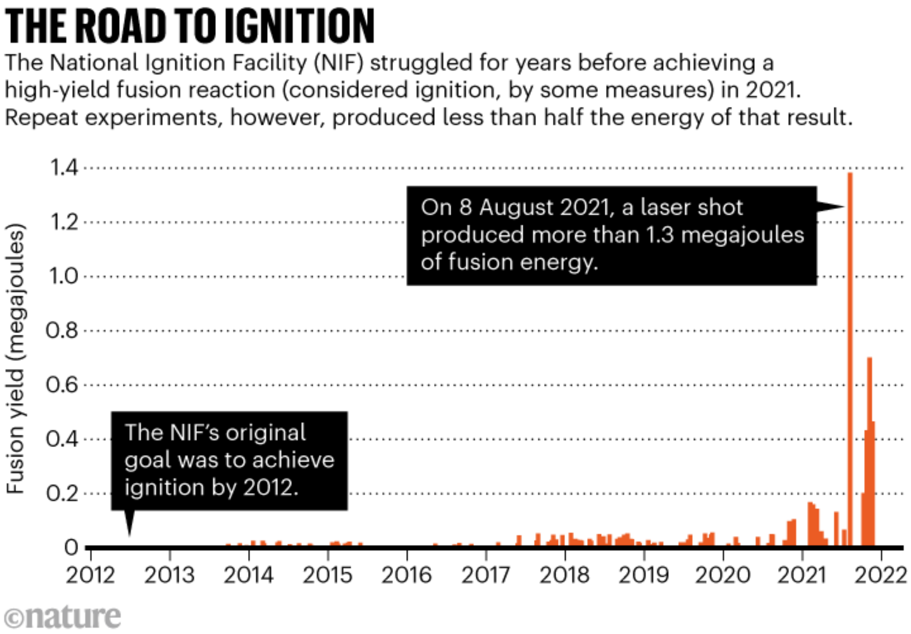




T. Ma, ARPA-E workshop, April 26, 2022
Science 370, p1019, 2020
D. T. Casey, etc., Phys. Plasmas, 25, 056308 (2018)
A. L. Kritcher, etc., Phys. Plasmas, 28, 072706 (2021)
H. F. Robey, etc., Phys. Plasmas, 25, 012711 (2018)

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

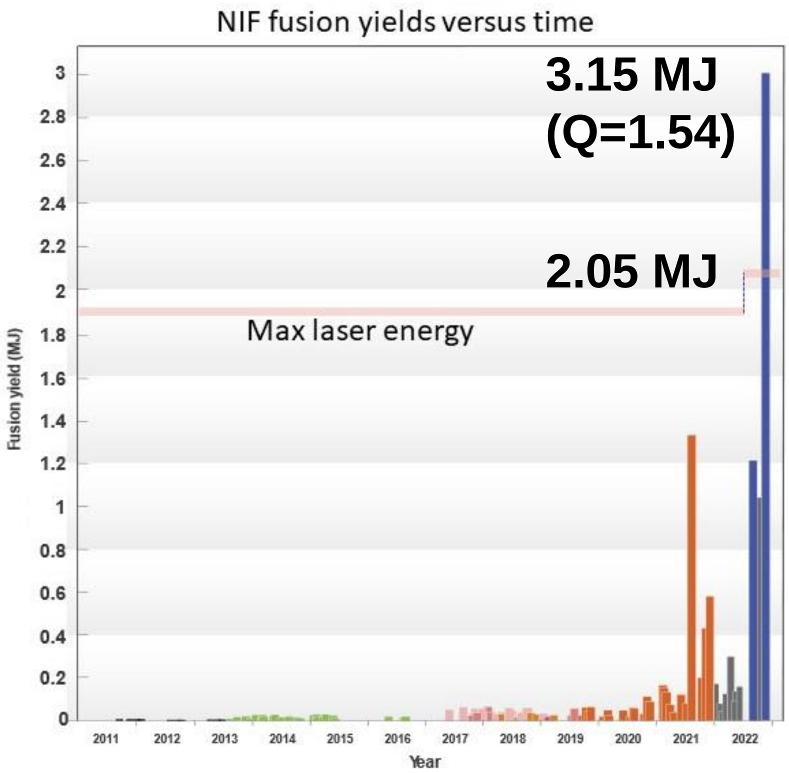


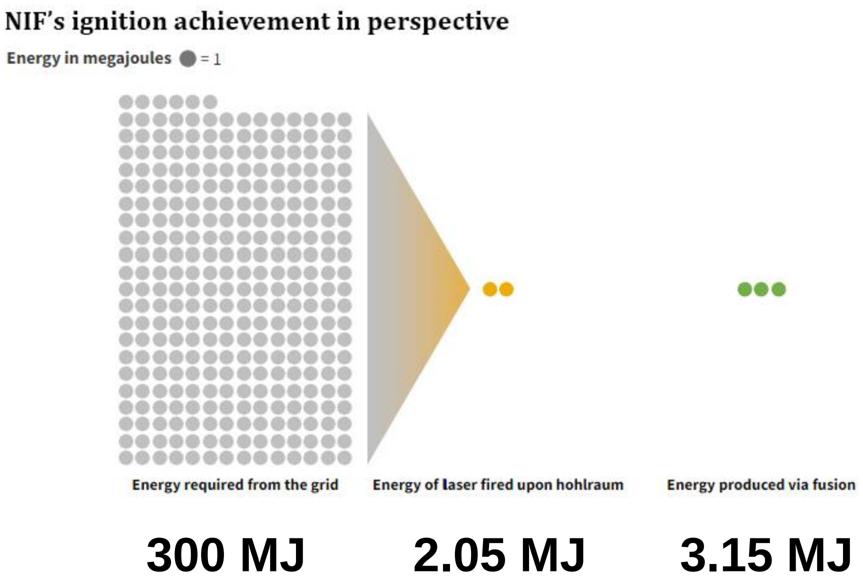


- National Ignition Facility (NIF) achieved a yield of more than 1.3 MJ (Q~0.7). This advancement puts researchers at the threshold of fusion ignition.
- Laser-fusion facility heads back to the drawing board.

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

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

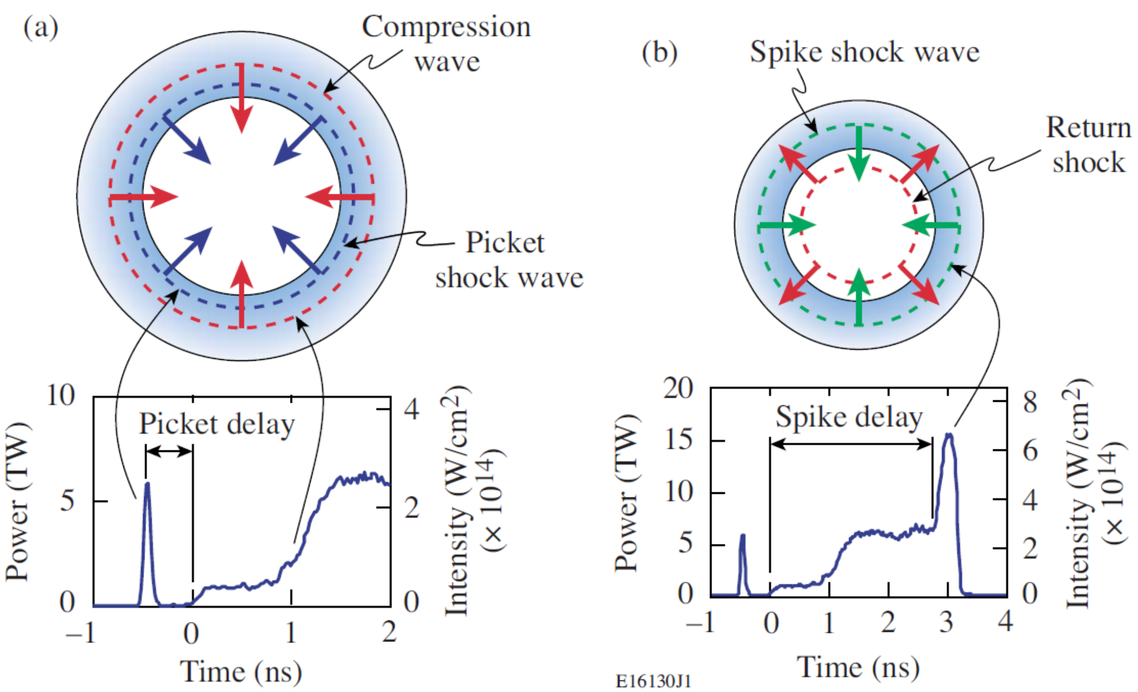




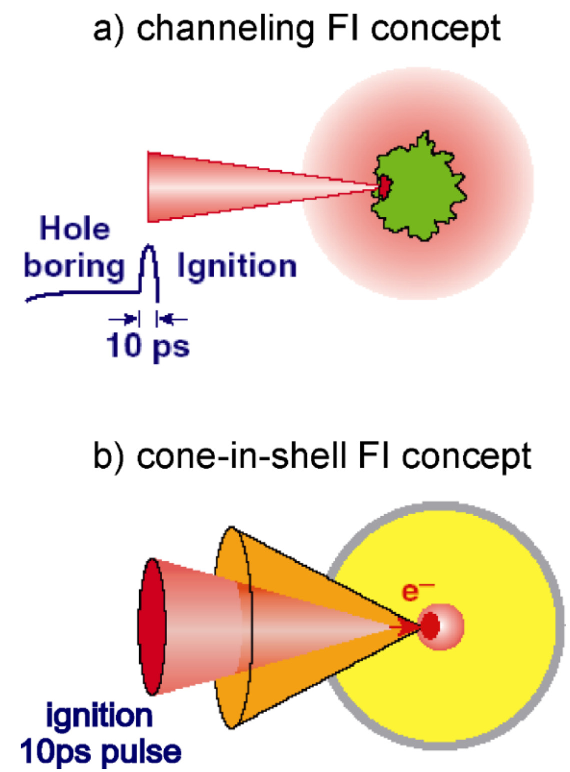
https://physicstoday.scitation.org/do/10.1063/PT.6.2.20221213a/full/

External "spark" can be used for ignition

- **Shock ignition**



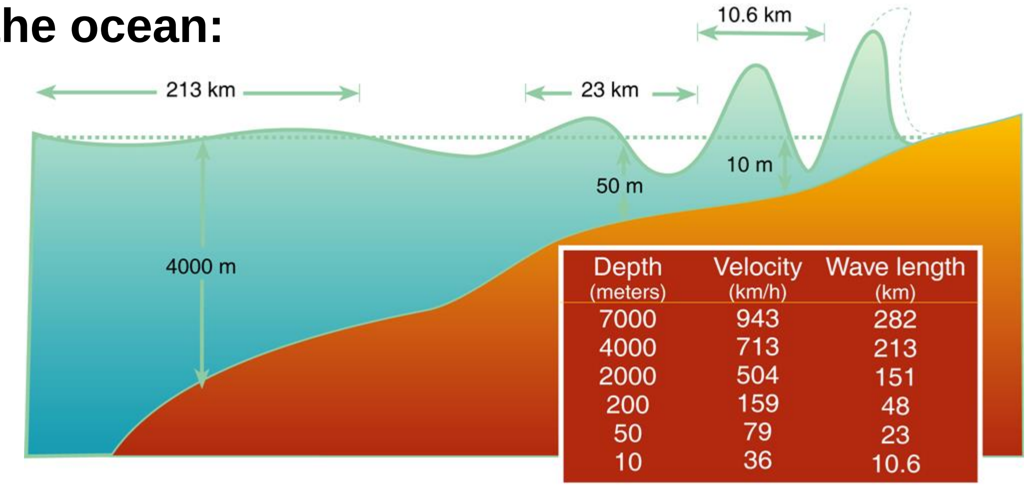
- **Fast ignition**



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

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

- **Wave in the ocean:**



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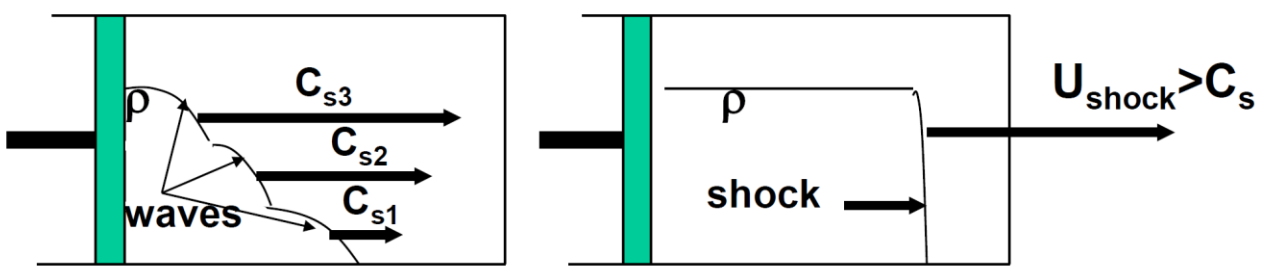
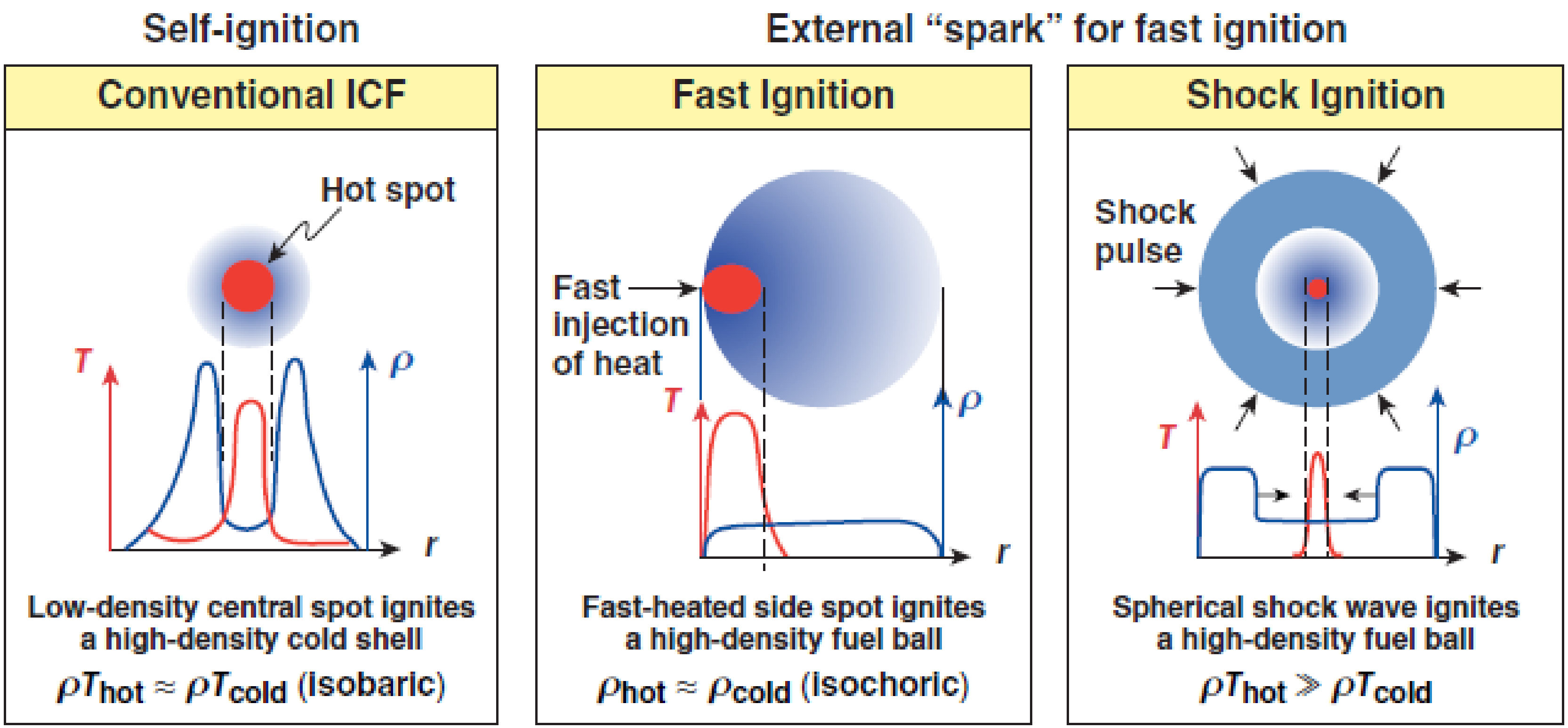


$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha\rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\rho^{1/3}$$

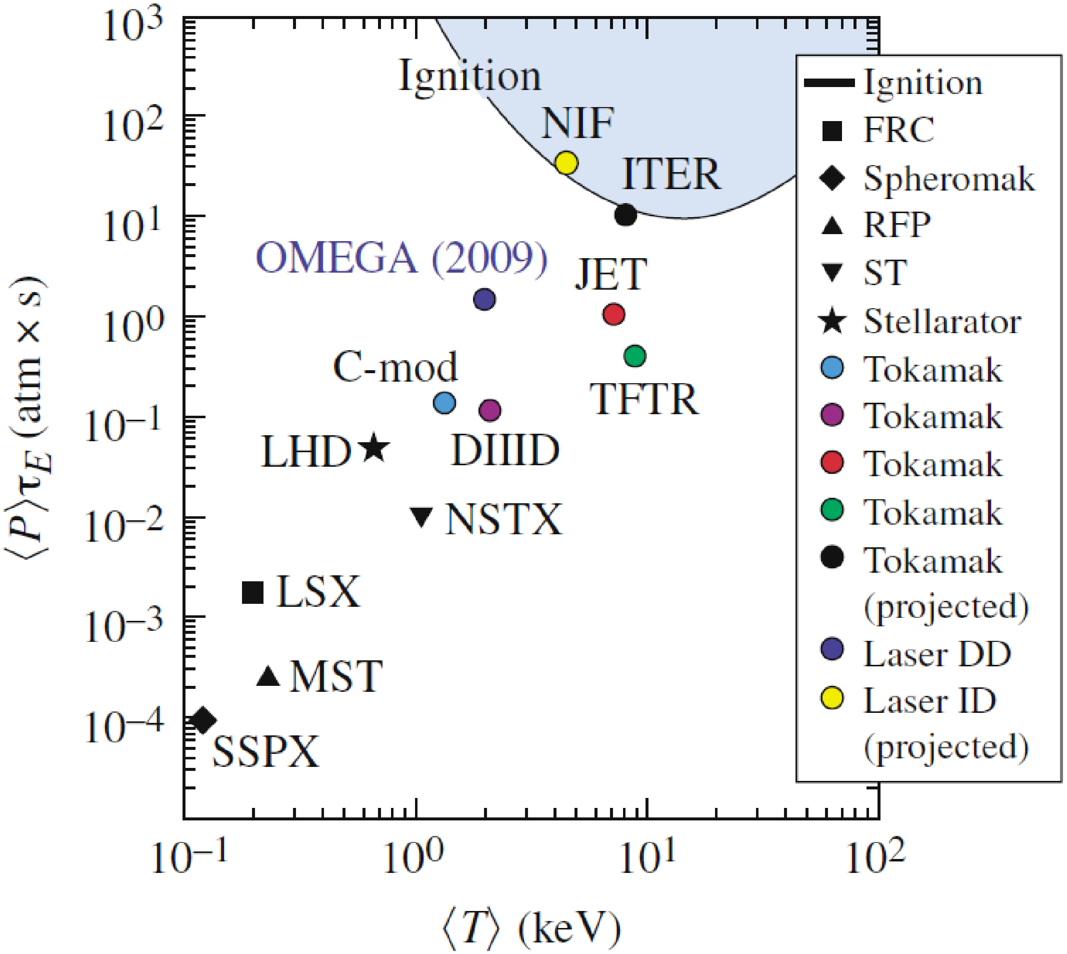
http://neamtic.ioc-unesco.org/tsunami-info/the-cause-of-tsunamis
*R. Betti, HEDSA HEDP Summer School, 2015

Ignition can happen by itself or being triggered externally



P. B. Radha, Fusion Energy Conference,2018

We are closed to ignition!

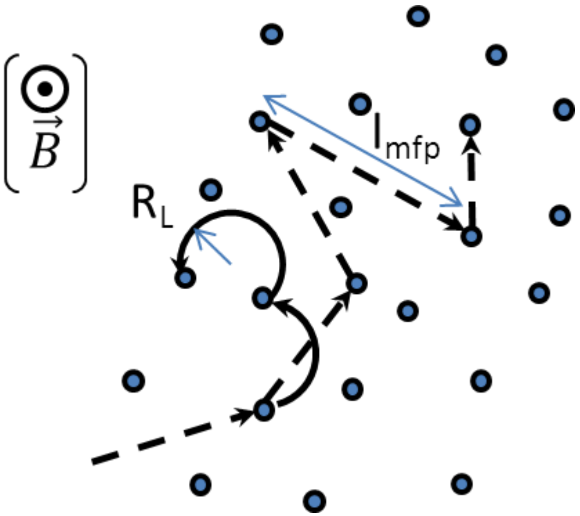


R. Betti, etc., Phys. Plasmas, **17**, 058102 (2010)

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**
- Pulsed-power system at NCKU

A strong magnetic field reduces the heat flux



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

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

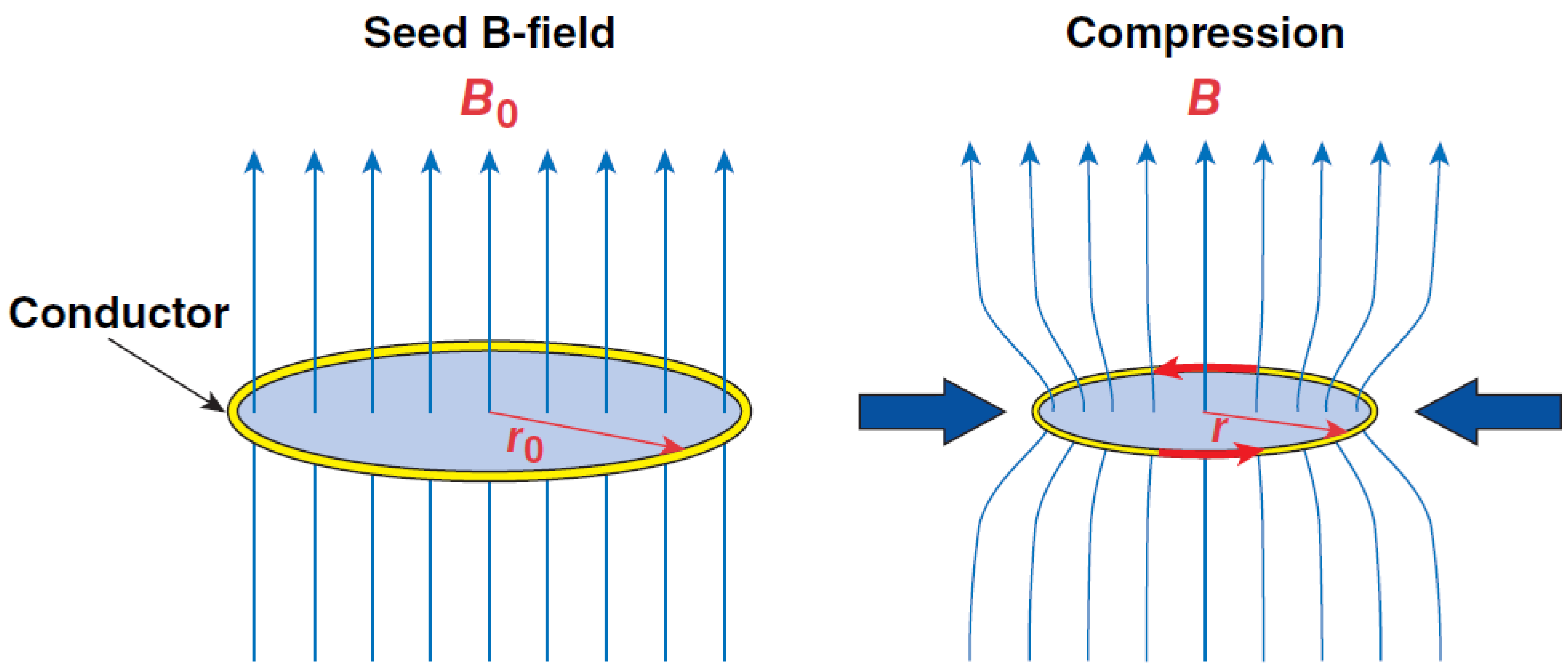
$$\kappa_{\perp} = \frac{\kappa_{||}}{\chi^2} \quad \text{for large Hall parameter } \chi \propto \frac{l_{mfp}}{R_L} >> 1$$

- **Typical hot spot conditions:**
  R_{hs} ~ 40 μm, ρ ~ 20 g/cm^3, T ~ 5 keV:

  $B > 10$ **MG is needed for** $\chi > 1$

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

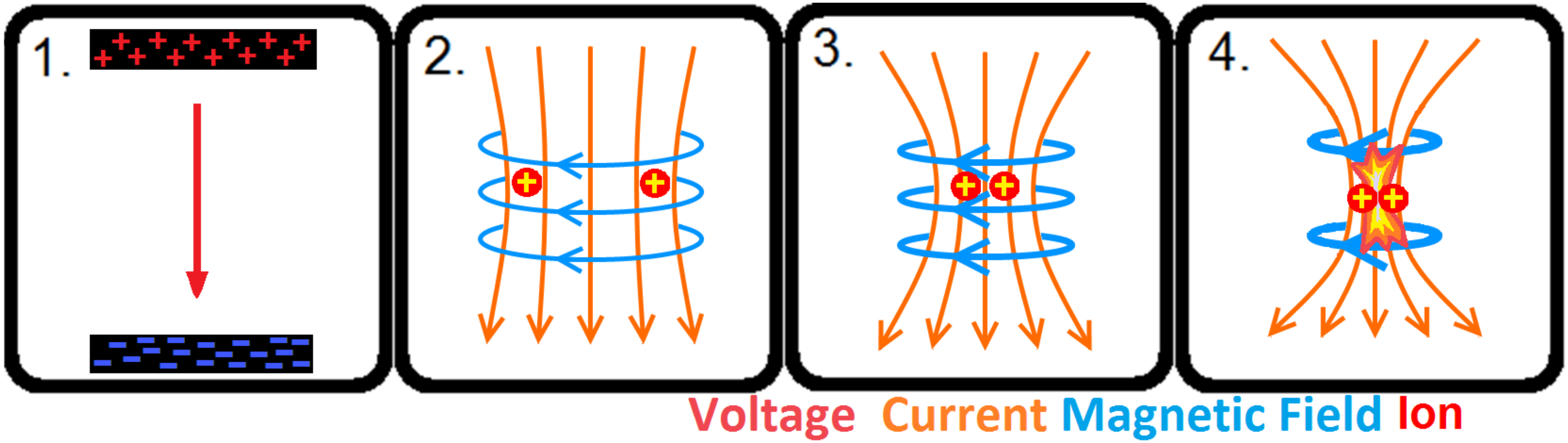
Principle of frozen magnetic flux in a good conductor is used to compress fields



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

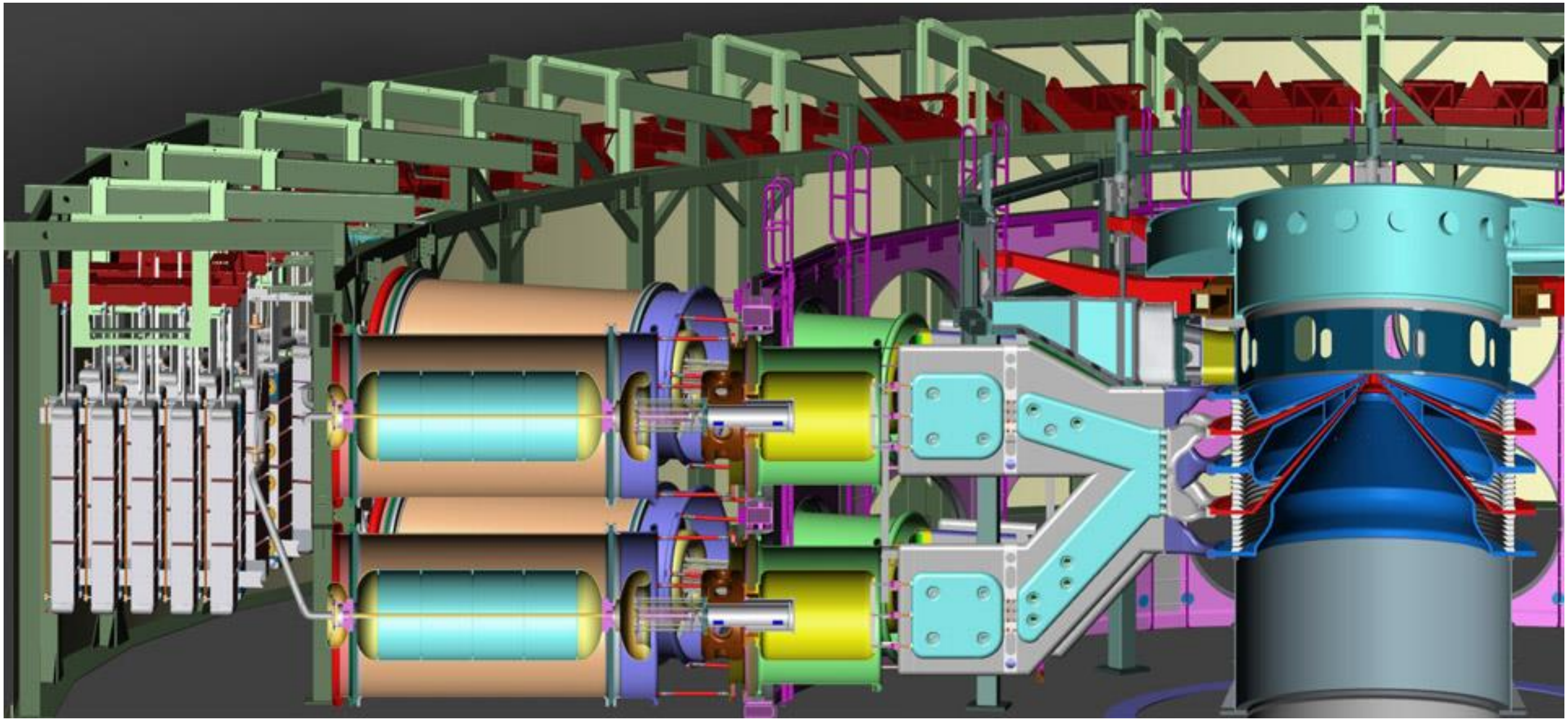
M. Hohenberger, P.-Y. Chang, *et al*., Phys. Plasmas 19, 056306 (2012).

Plasma can be pinched by parallel propagating plasmas



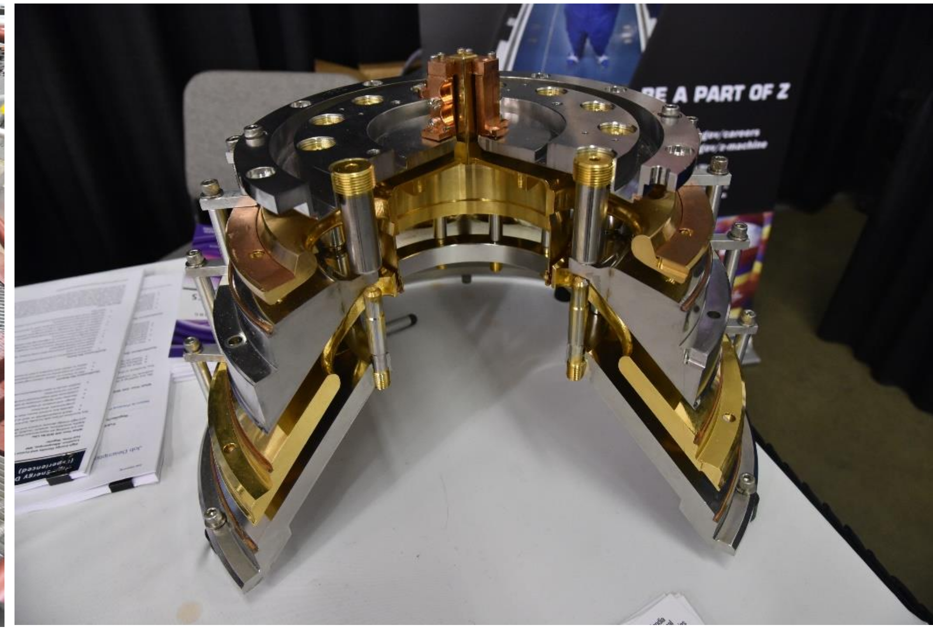
https://en.wikipedia.org/wiki/Pinch_(plasma_physics)

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

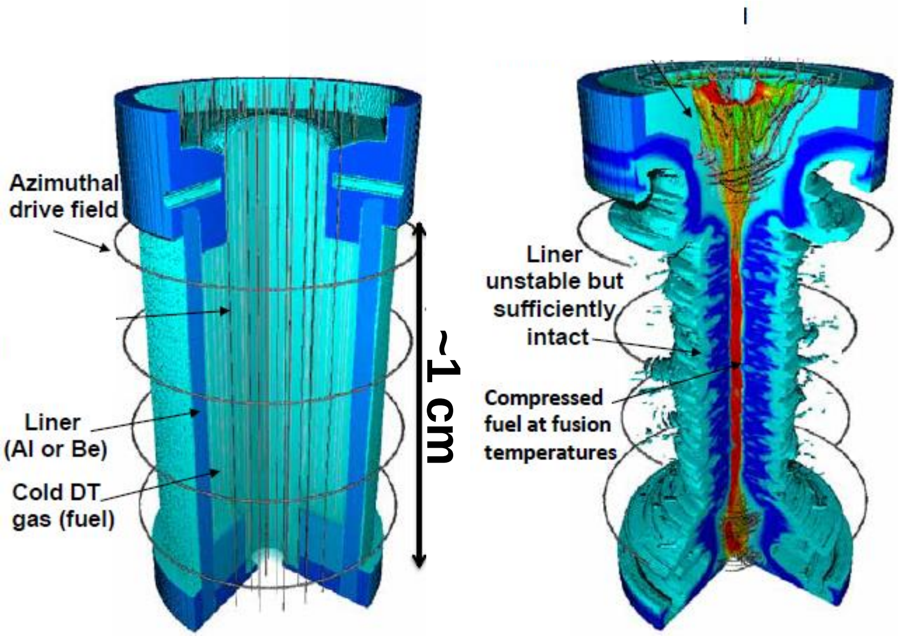


- **Stored energy: 20 MJ**
- **Marx charge voltage: 85 kV**
- **Peak electrical power: 85 TW**
- **Peak current: 26 MA**
- **Rise time: 100 ns**
- **Peak X-ray emissions: 350 TW**
- **Peak X-ray output: 2.7 MJ**

Z machine



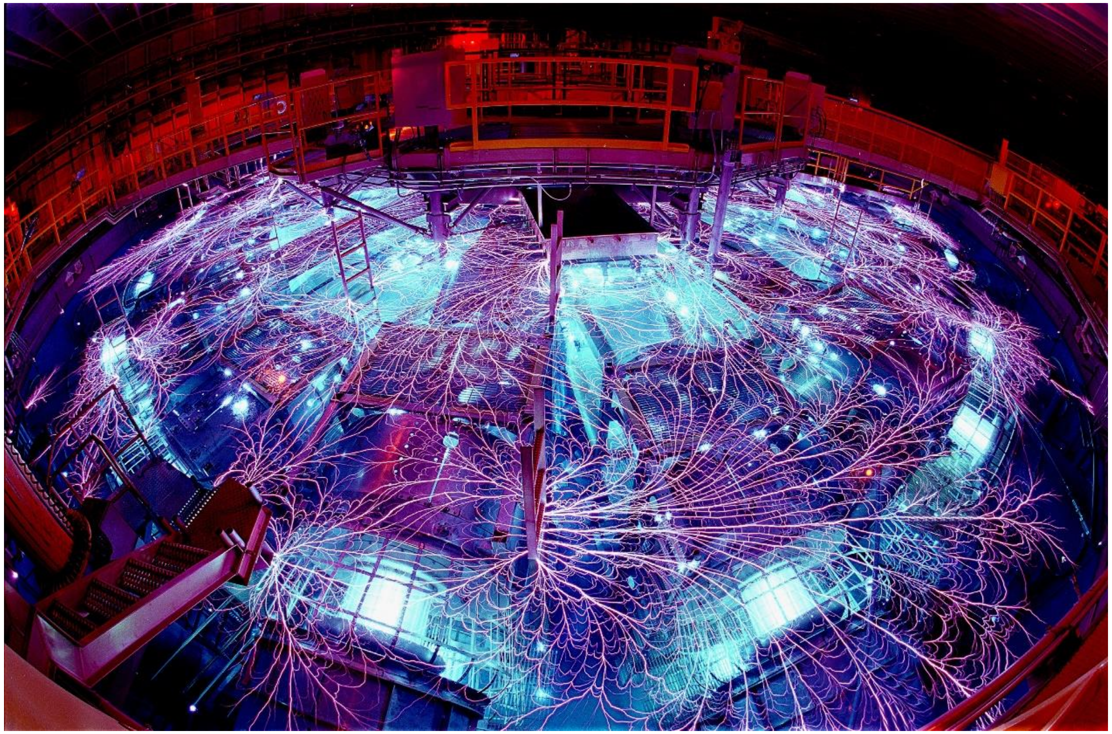
Z machine



- Stored energy: 20 MJ
- Peak electrical power: 85 TW

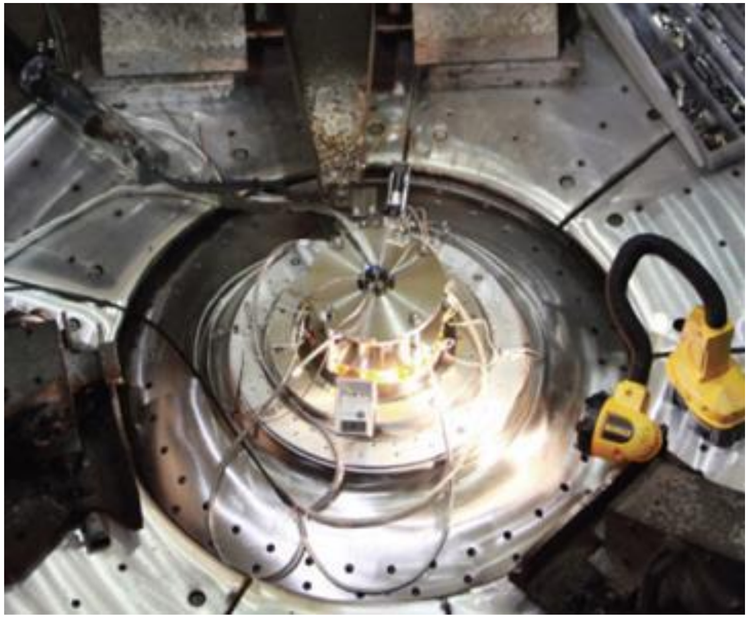
- Peak current: 26 MA
- Rise time: 100 ns
- Peak X-ray output: 2.7 MJ

Z machine discharge



Before and after shots

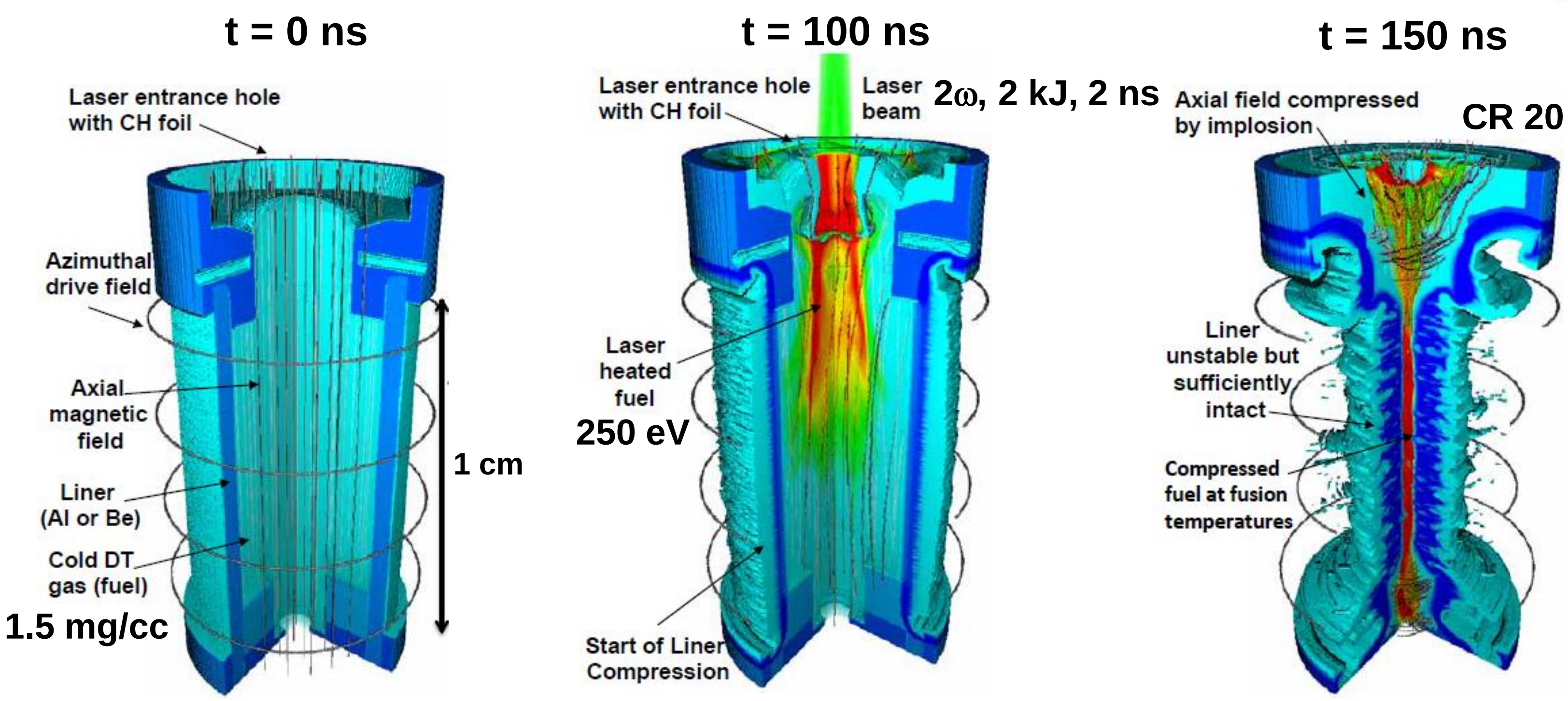
- **Before shots**



- **After shots**

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

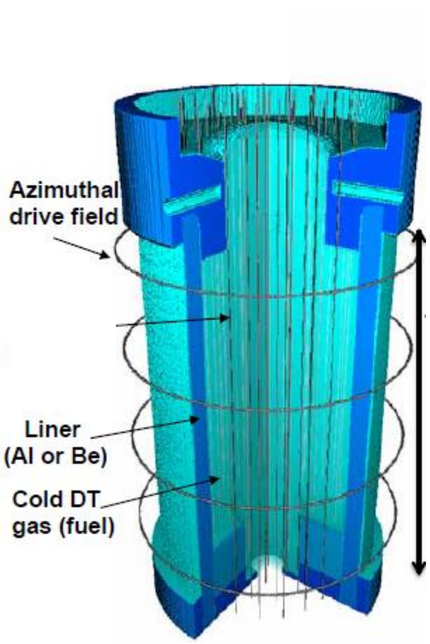
Promising results were shown in MagLIF concept conducted at the Sandia National Laboratories

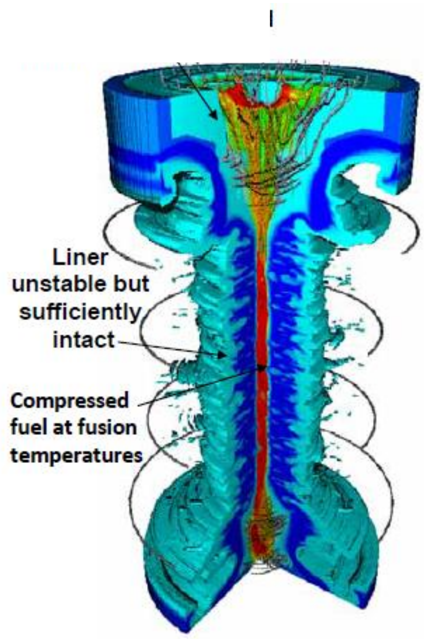


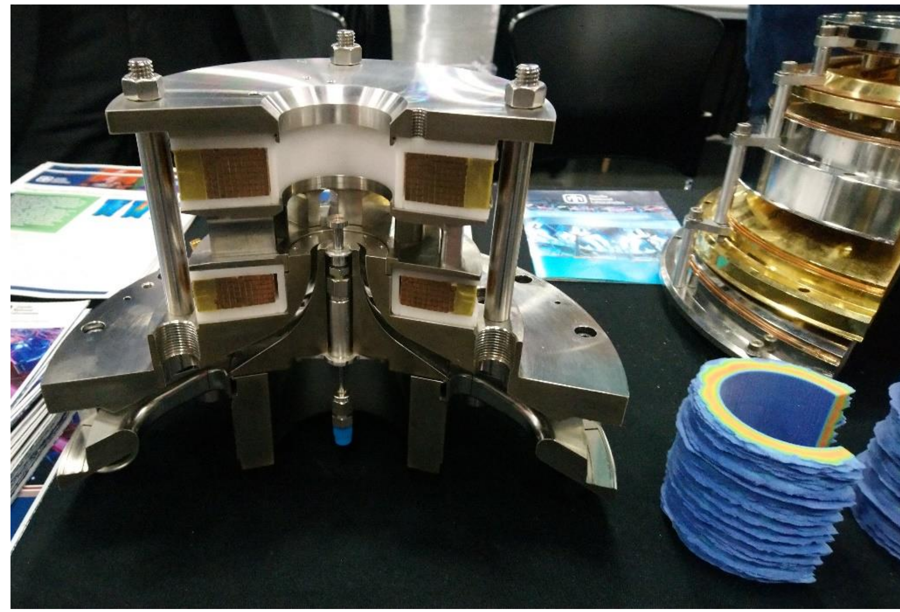
The stagnation plasma reached fusion-relevant temperatures with a 70 km/s implosion velocity

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

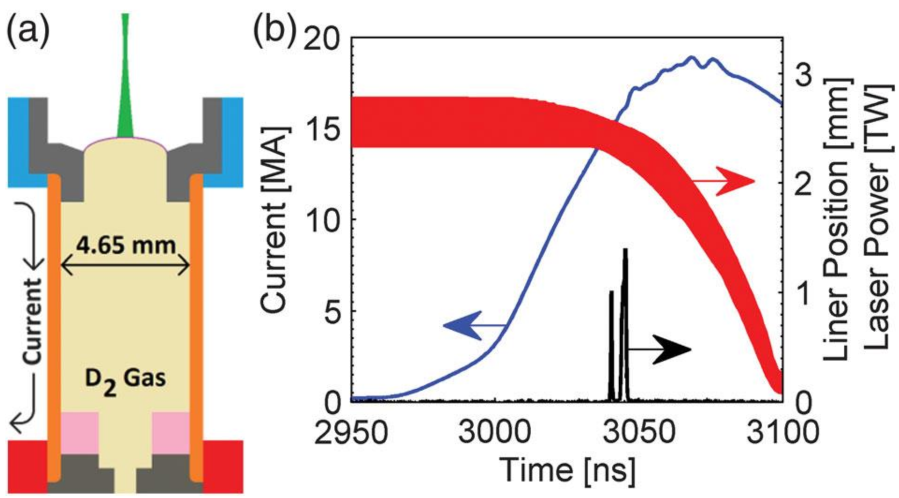
MagLIF target

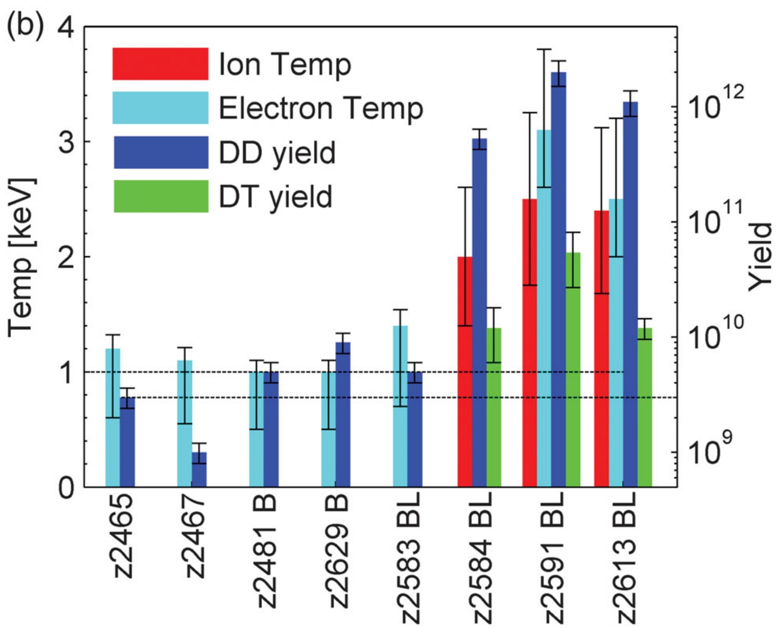






Neutron yield increased by 100x with preheat and external magnetic field.



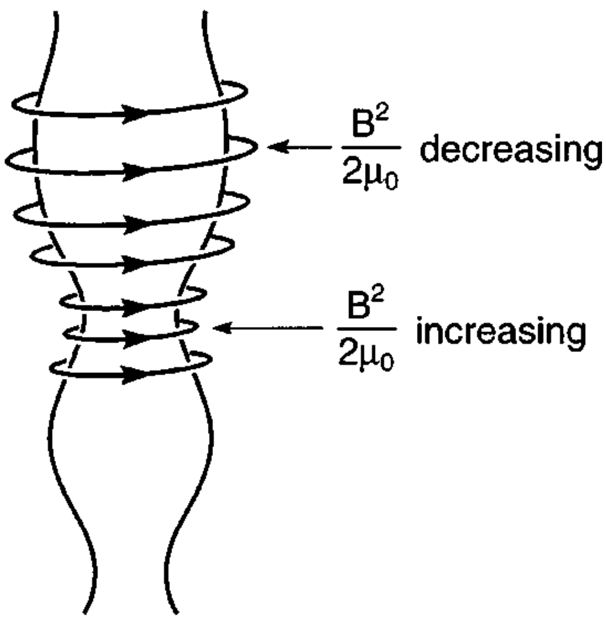


M. R. Gomez *et al* Phys. Rev. Lett. 113 155003 (2014)

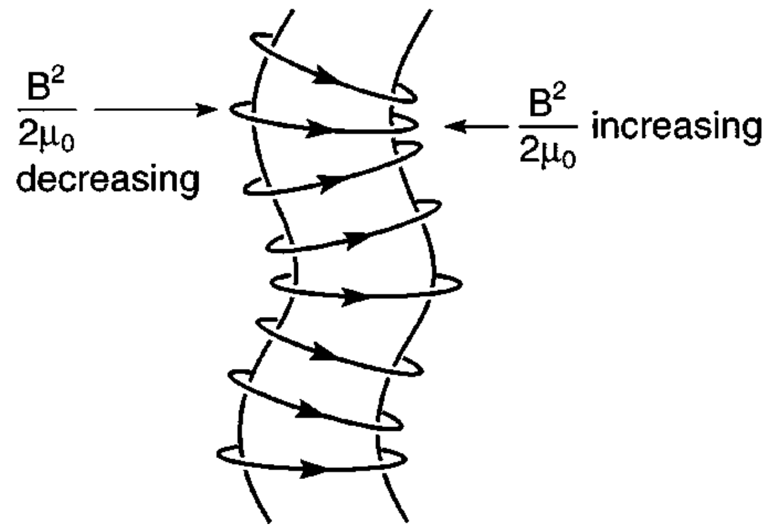
Sheared flow stabilizes MHD instabilities

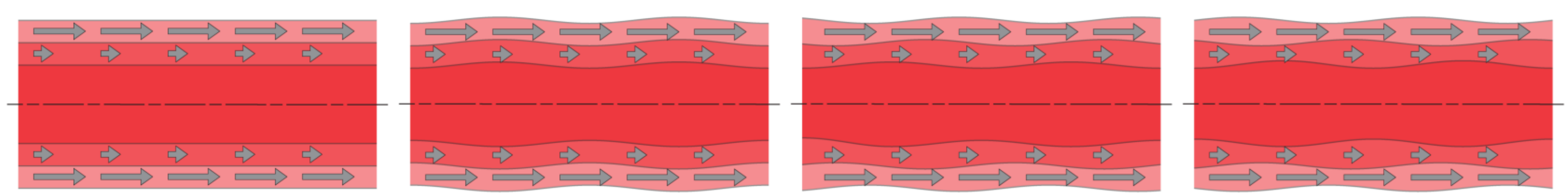
m = 0 (sausage)

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



m = 1 (kink)

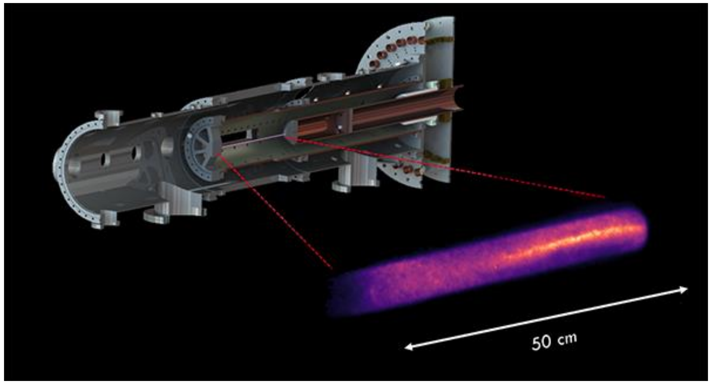


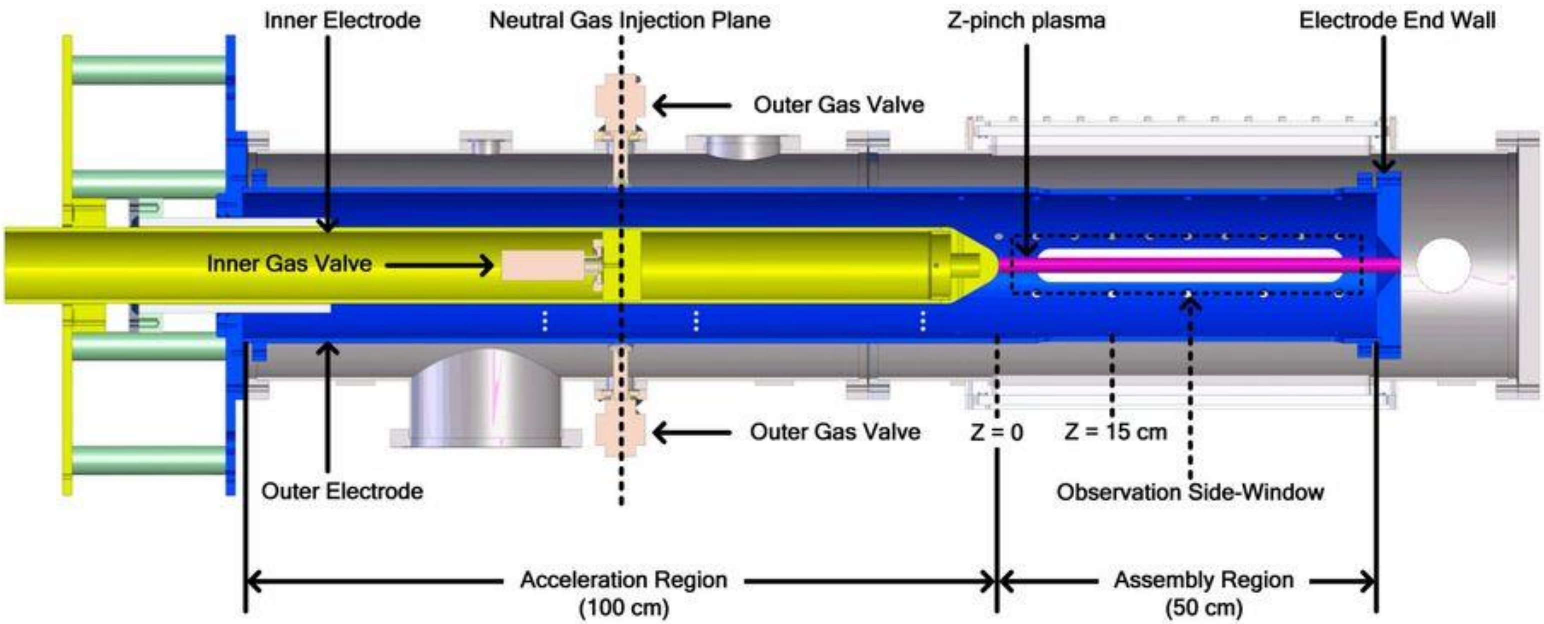


$$\frac{dV_Z}{dr} \neq 0$$

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

A z-pinch plasma can be stabilized by sheared flows

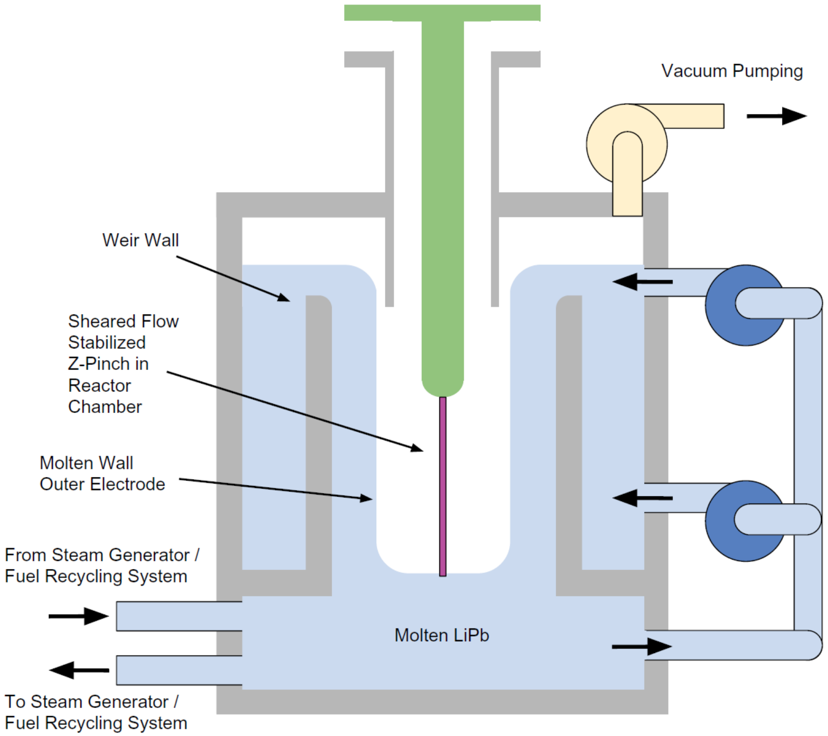


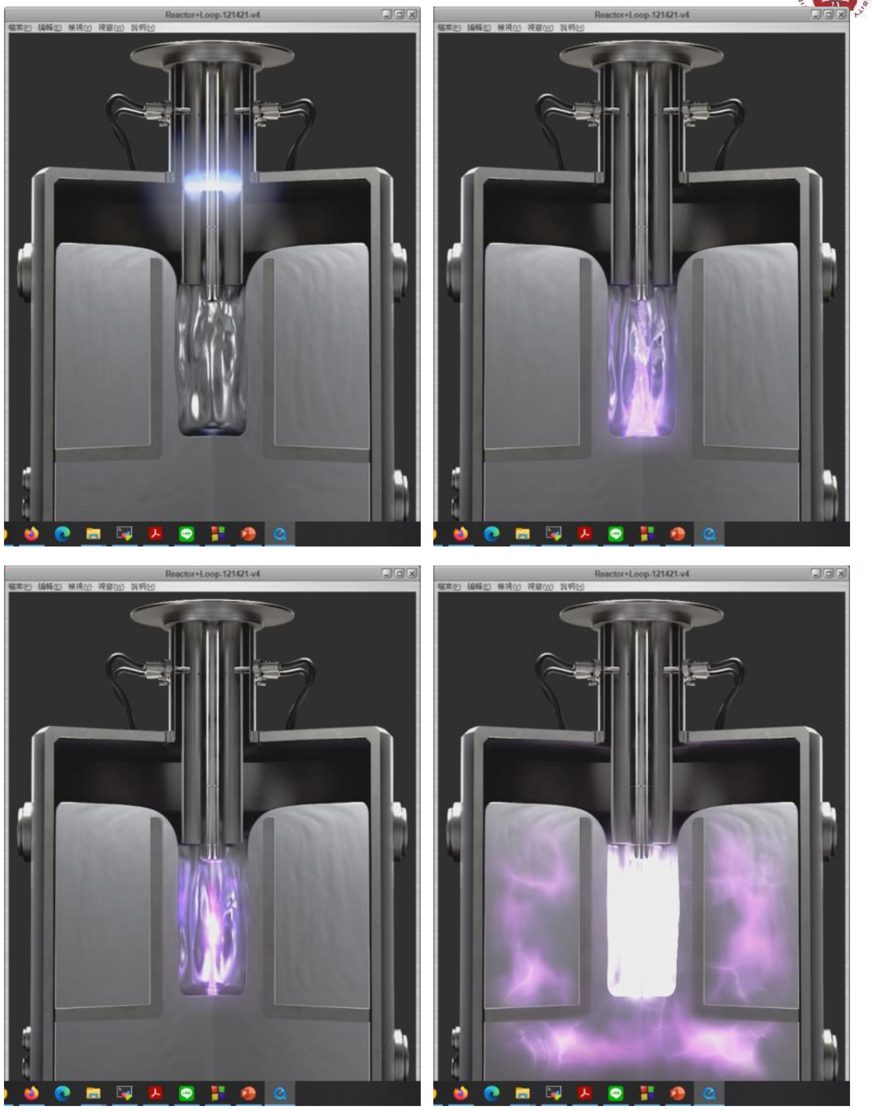


https://www.zapenergyinc.com/about

A. D. Stepanov, etc., Phys. Plasmas 27, 112503 (2020)

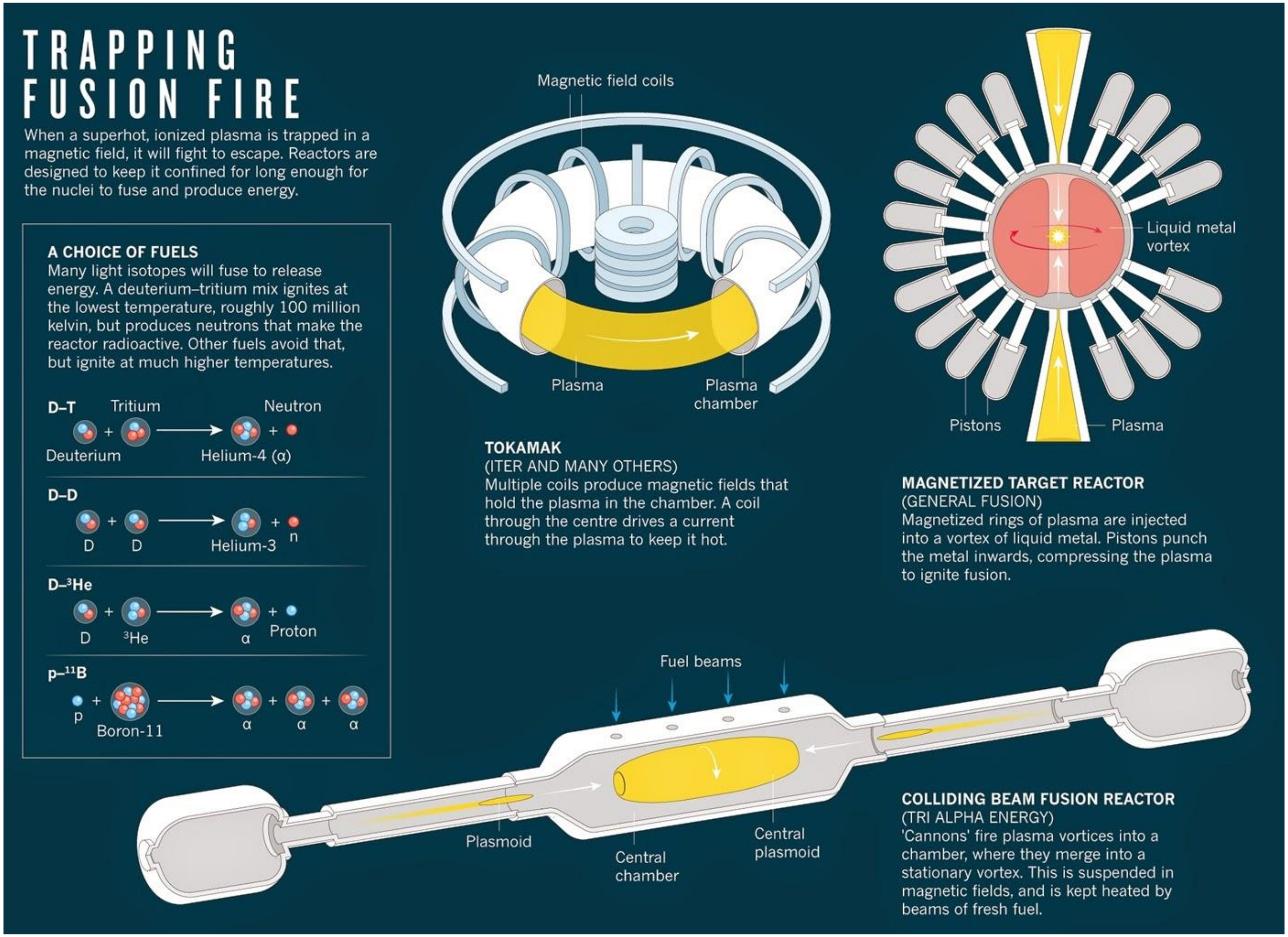
Fusion reactor concept by ZAP energy





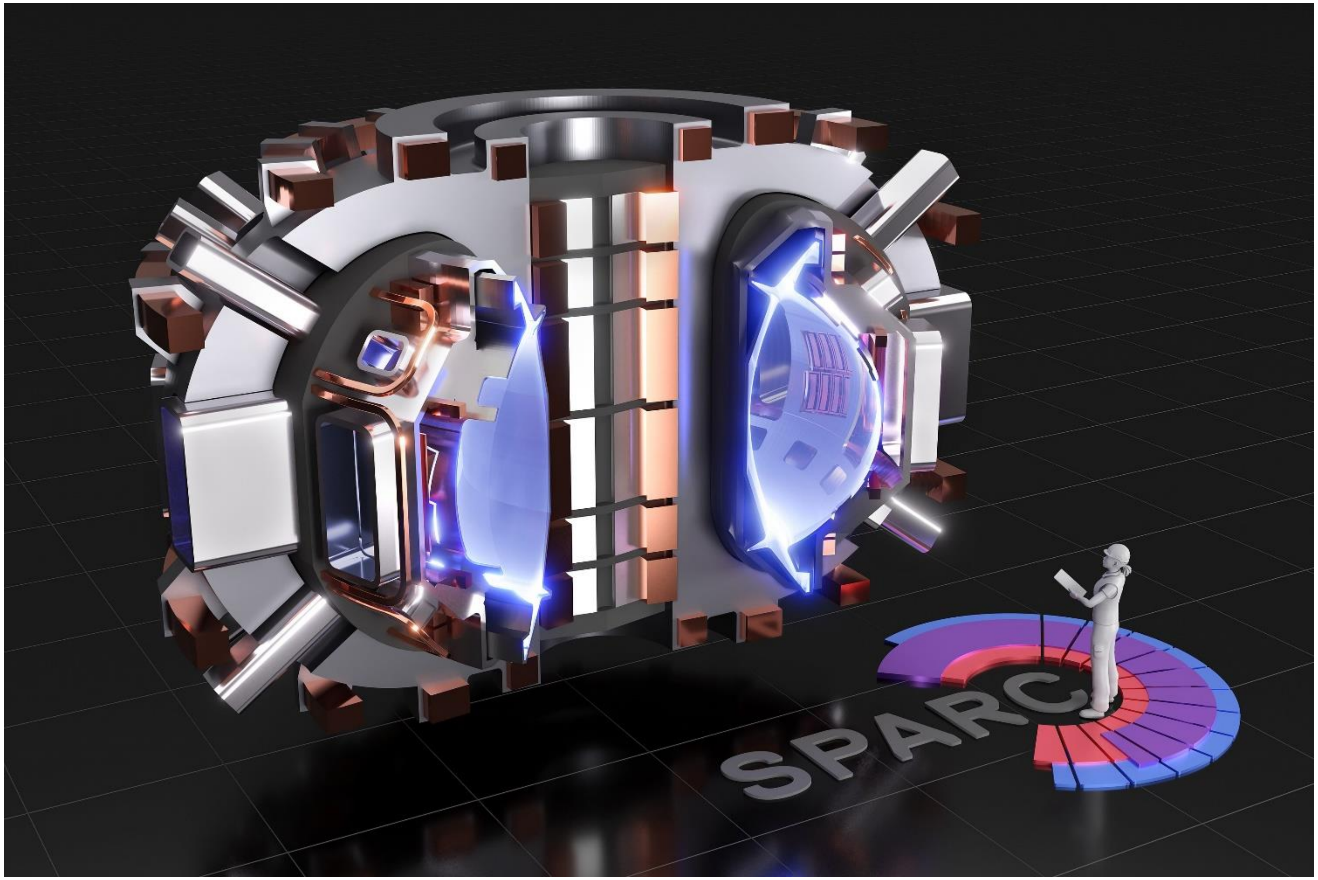
https://www.zapenergyinc.com/about
E. G. Forbes, etc., Fusion Sci. Tech. 75, 599 (2019)

There are alternative



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

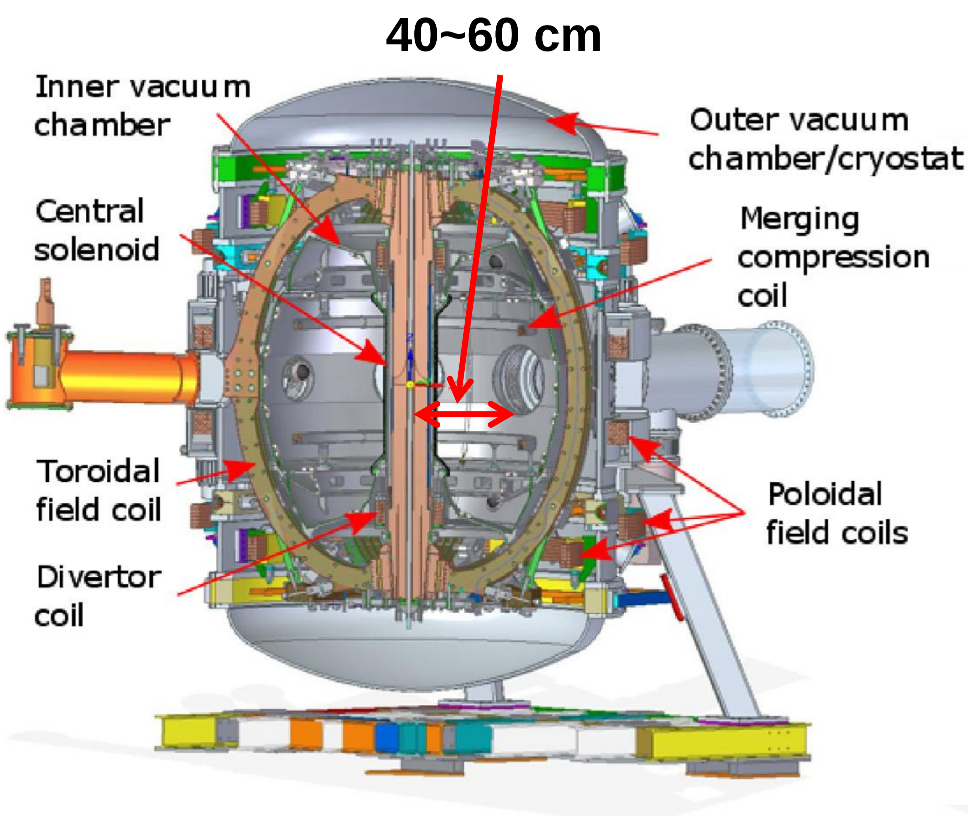
Commonwealth Fusion Systems, a MIT spin-out company, is building a high-magnetic field tokamak



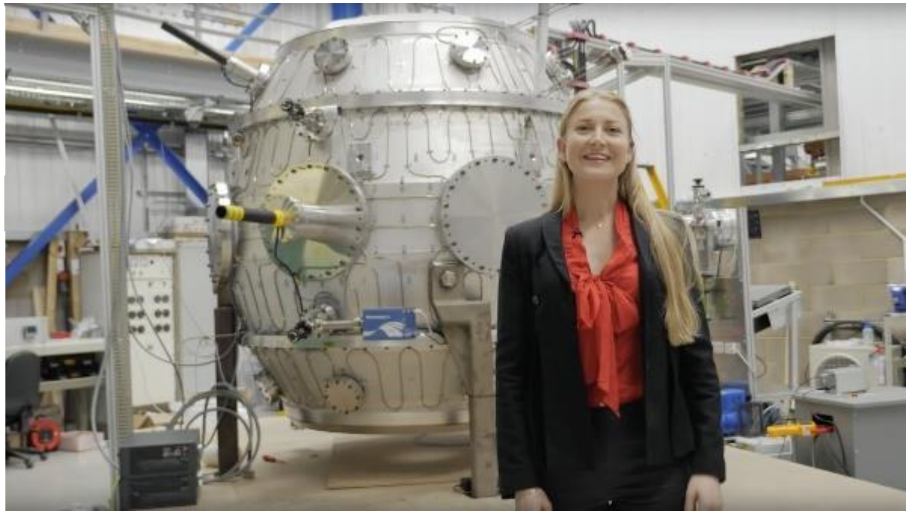
- **Fusion power ∝ B^4.**
- **The fusion gain Q > 2 is expected for SPARC tokamak.**

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

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

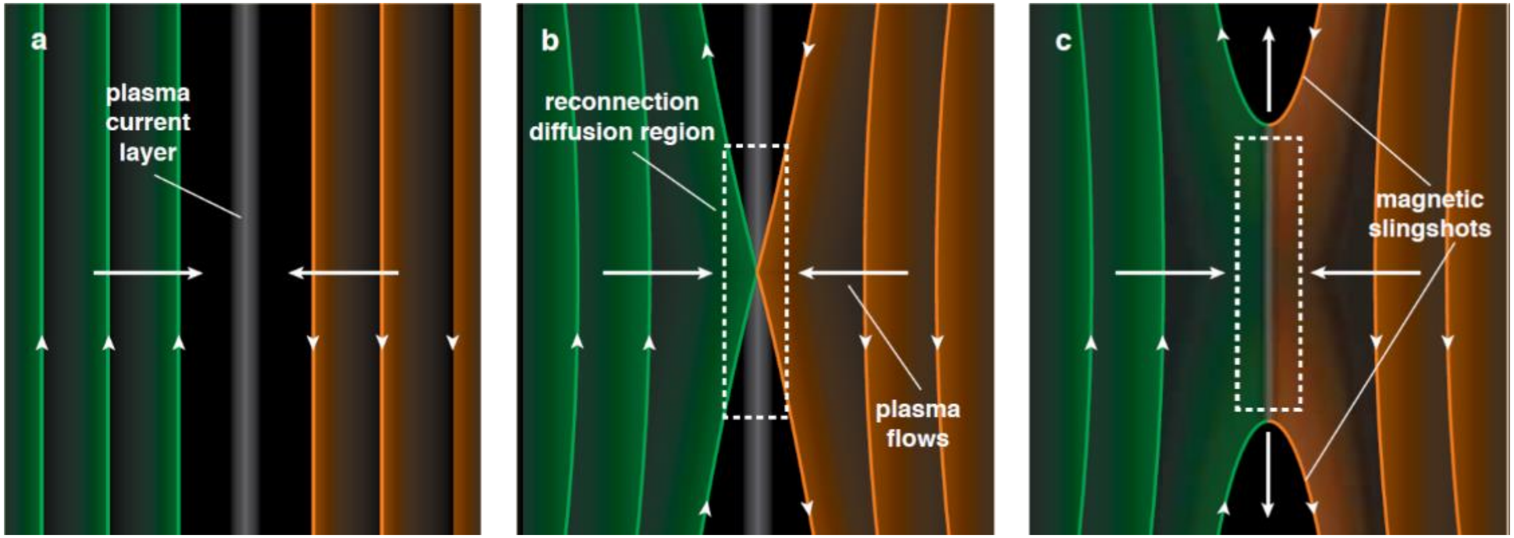


- **High temperature superconductors are used.**
- **B_T ~ 3 T**



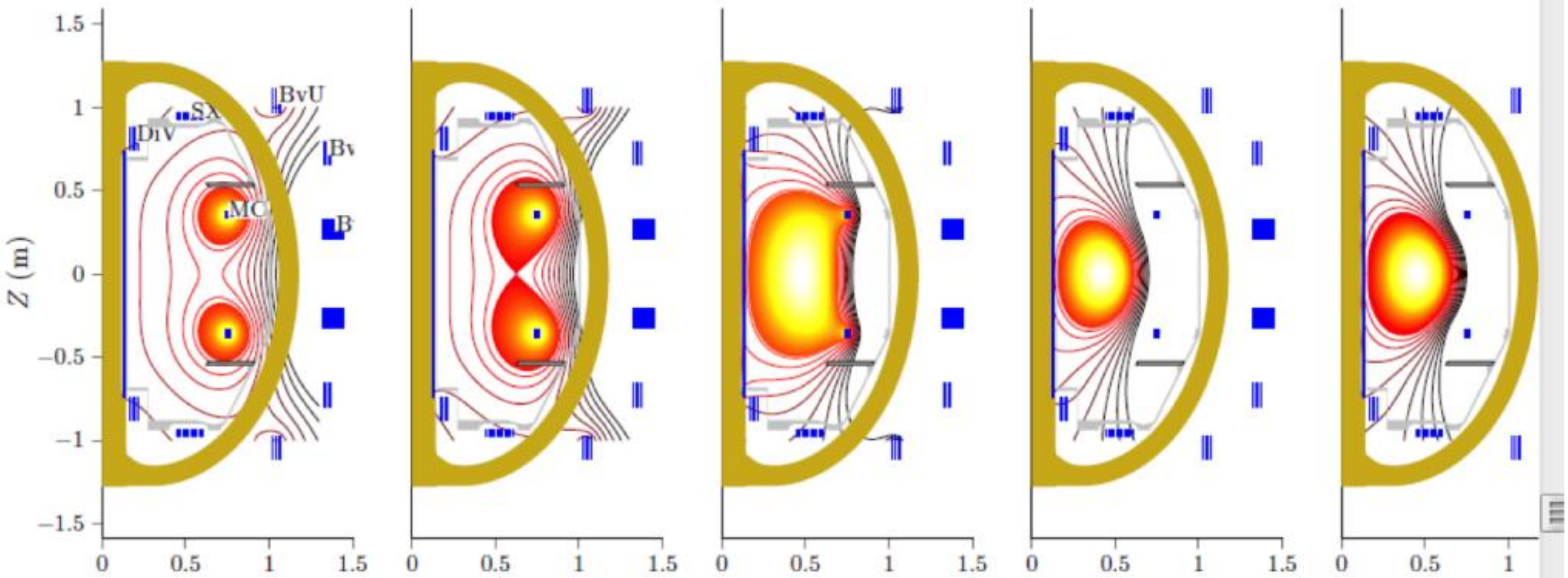
M. Gryaznevich, etc., Fusion Eng. Design, **123**,177 (2017)
https://www.tokamakenergy.co.uk/
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

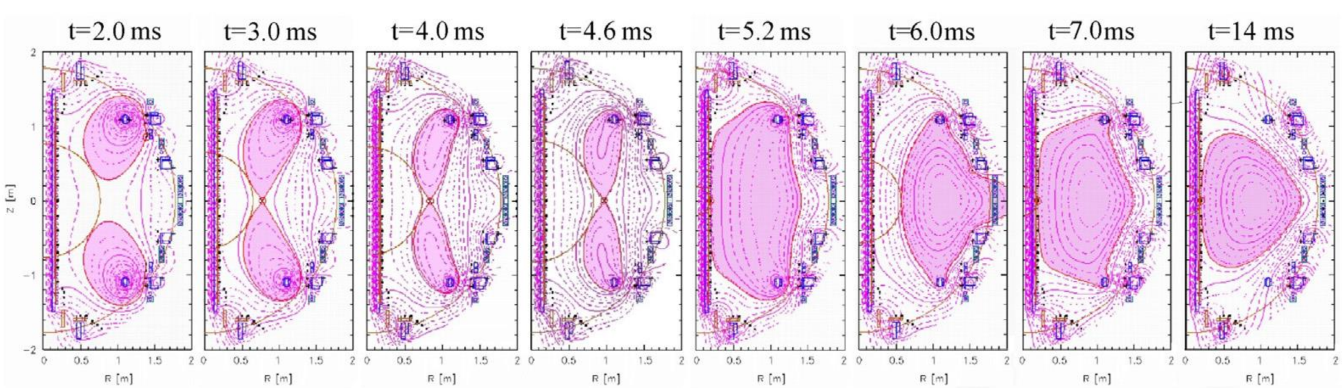
Reconnection



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

Merging compression is used to heat the plasma



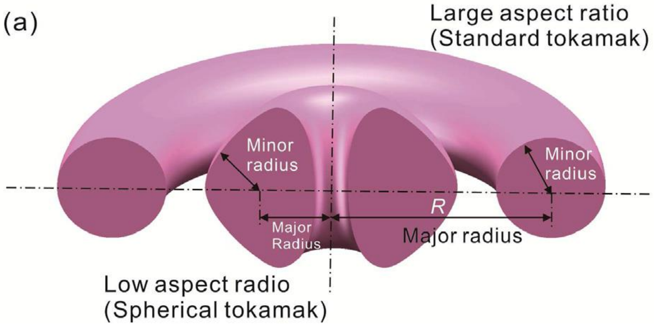


http://www.100milliondegrees.com/merging-compression/

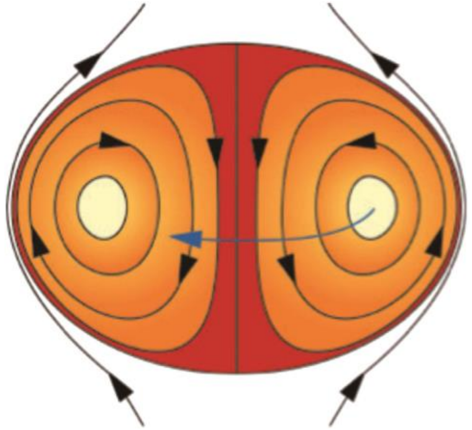
P. F. Buxton, etc., Fusion Eng. Design, **123**, 551 (2017)

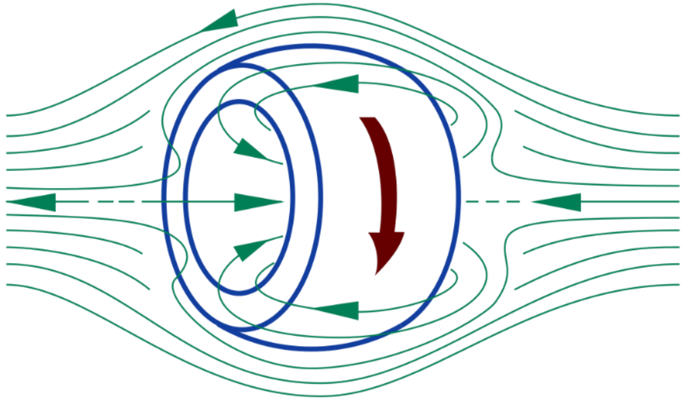
Spherical torus (ST) and compact torus (CT)

- **Spherical torus (ST)**



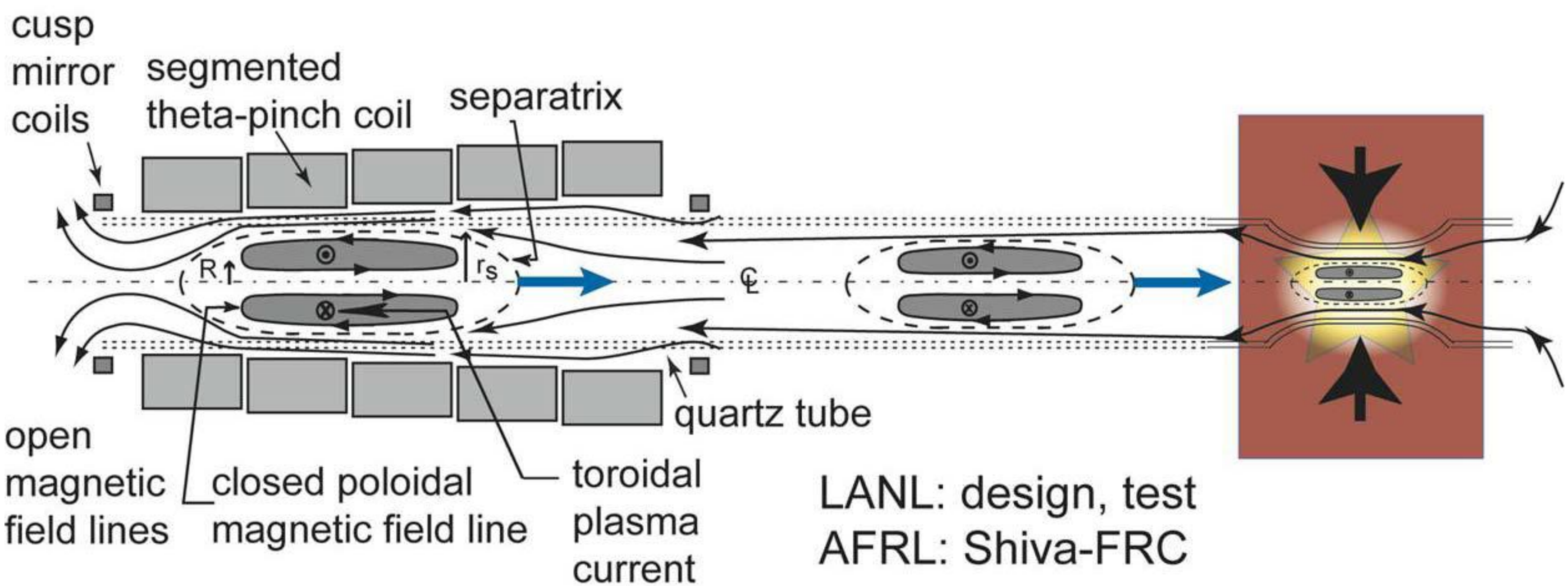
- **Compact torus (CT)**
  - **Spheromak**
  - **Field reversed configuration (FRC)**

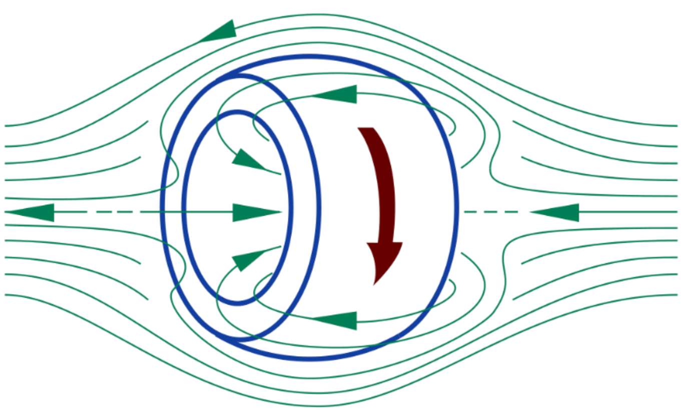




Zhe Gao, Matter Radiat. Extremes **1**, 153 (2016)
https://en.wikipedia.org/wiki/Field-reversed_configuration

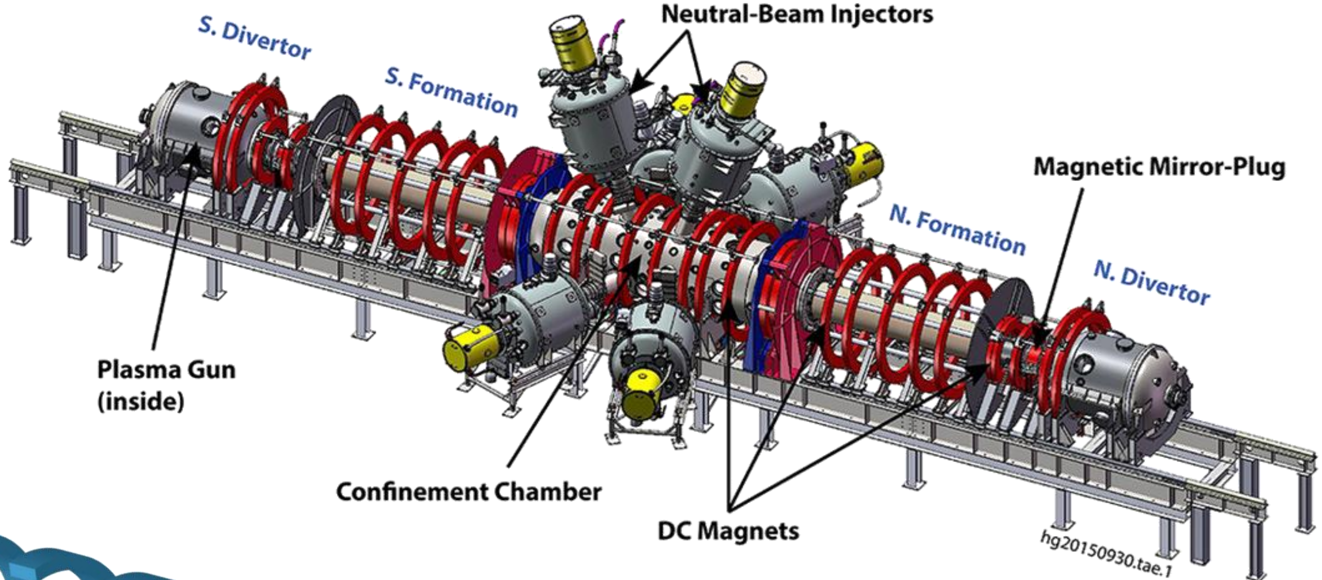
Field reverse configuration is used in Tri-alpha energy

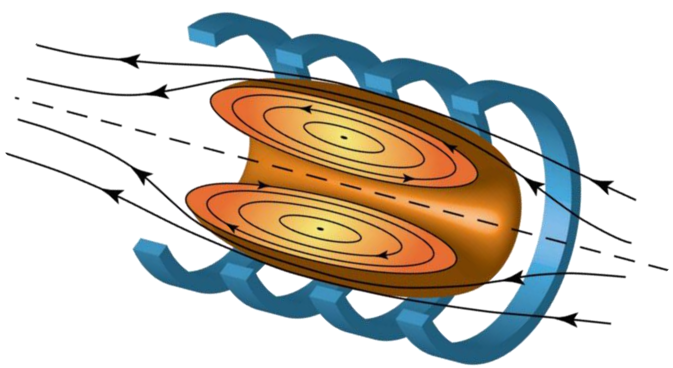




*Magneto-Inertial Fusion& Magnetized HED Physics by Bruno S. Bauer, UNR & Magneto-Inertial Fusion Community
**https://en.wikipedia.org/wiki/Field-reversed_configuration

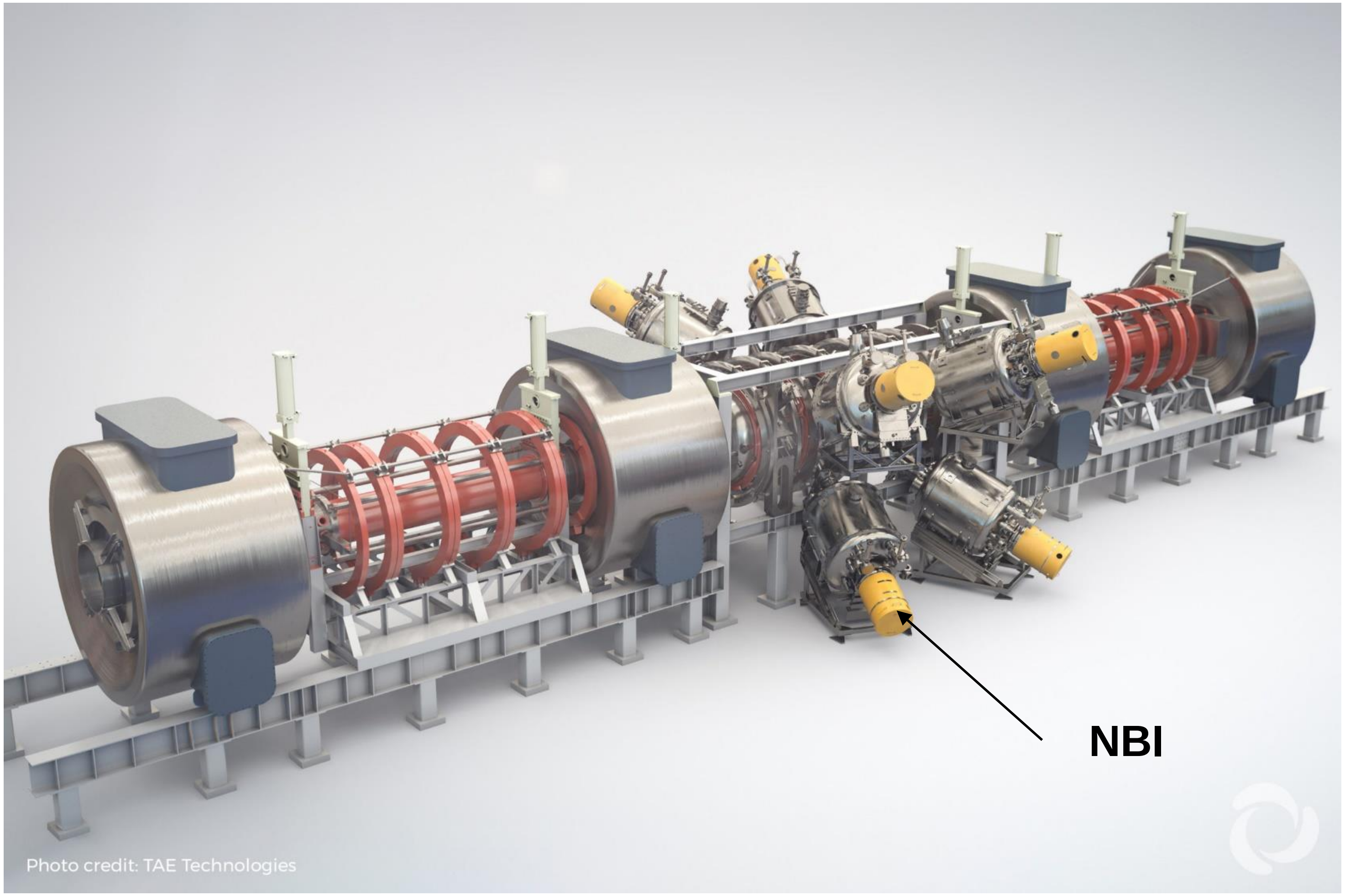
Field reverse configuration is used in Tri-alpha energy





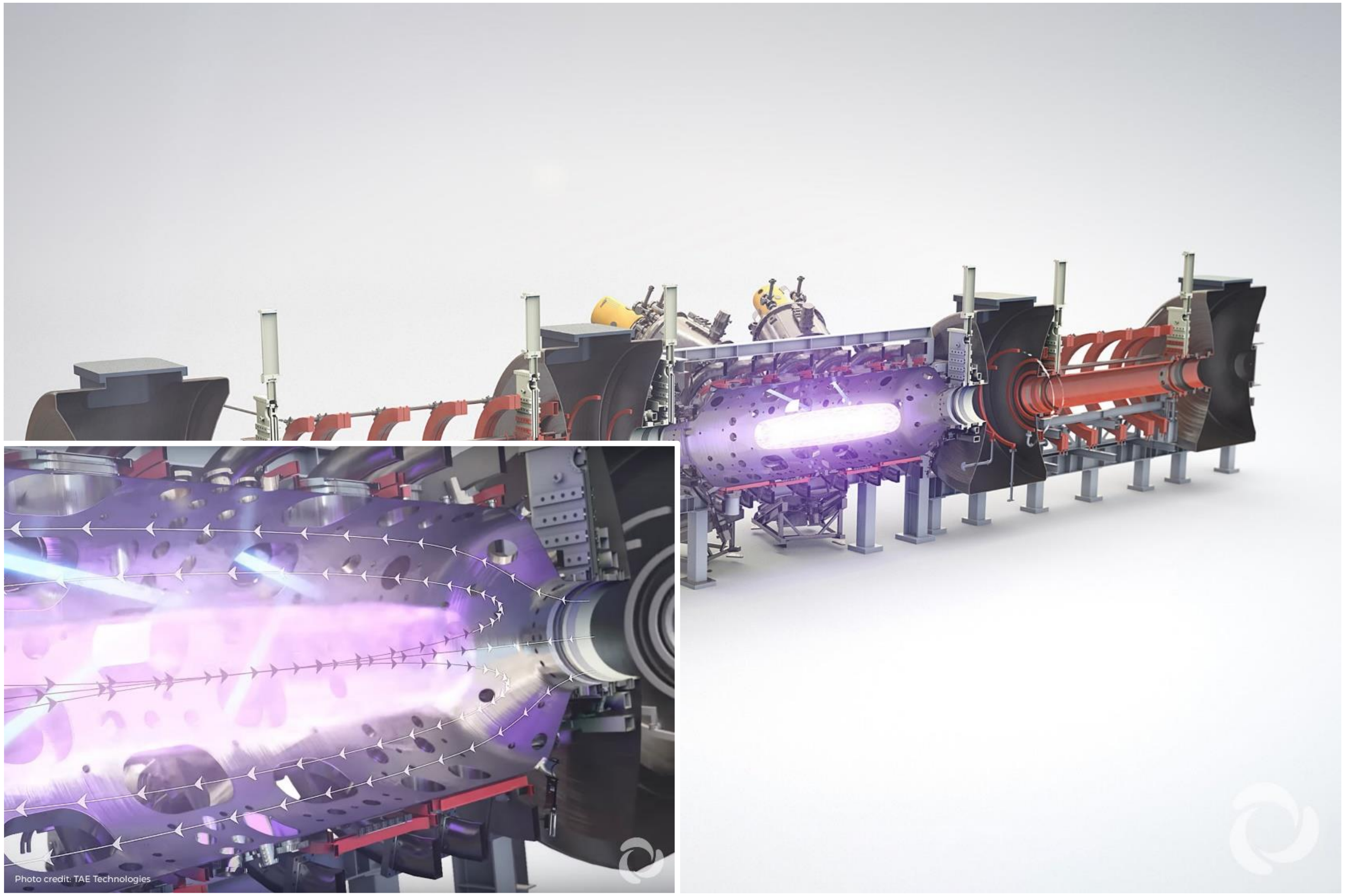
http://trialphaenergy.com/

NBI for Tri-Alpha Energy Technologies



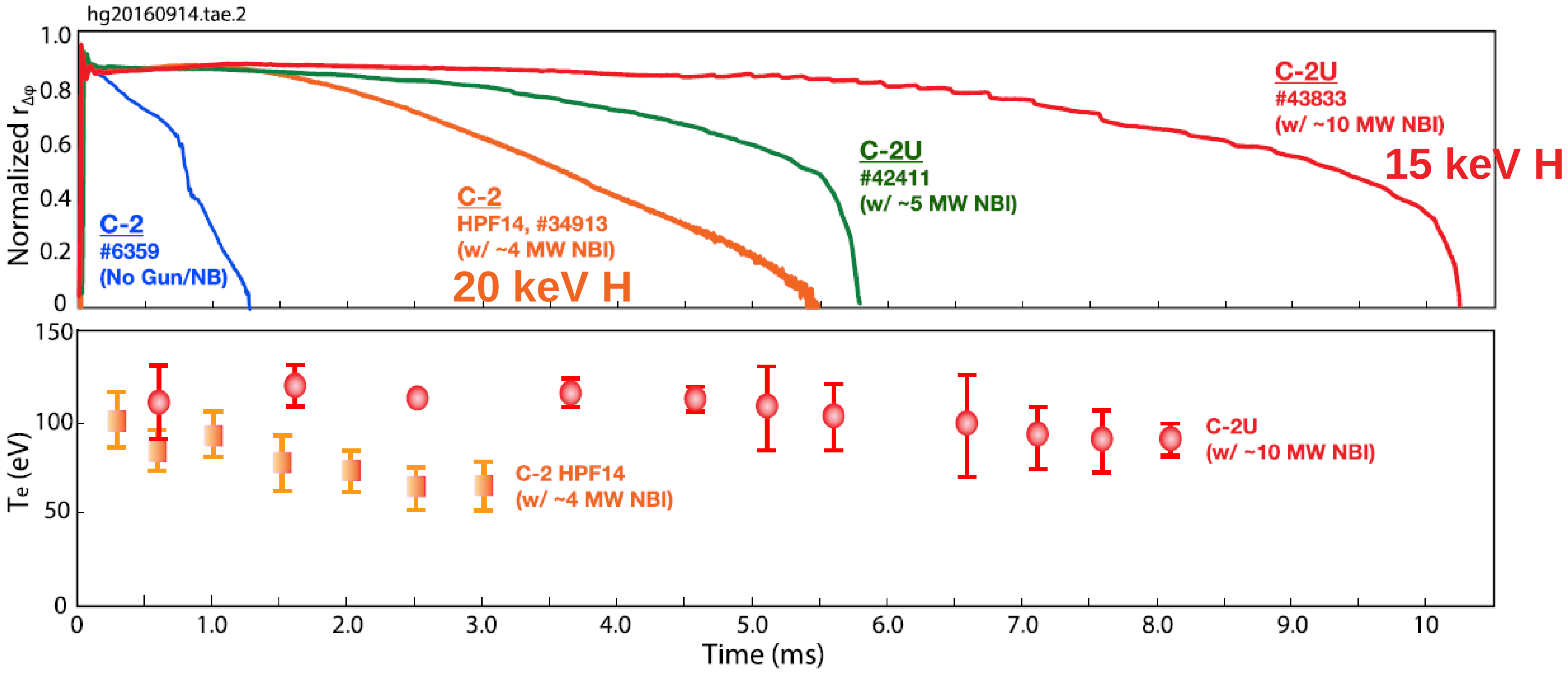
https://tae.com/media/

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



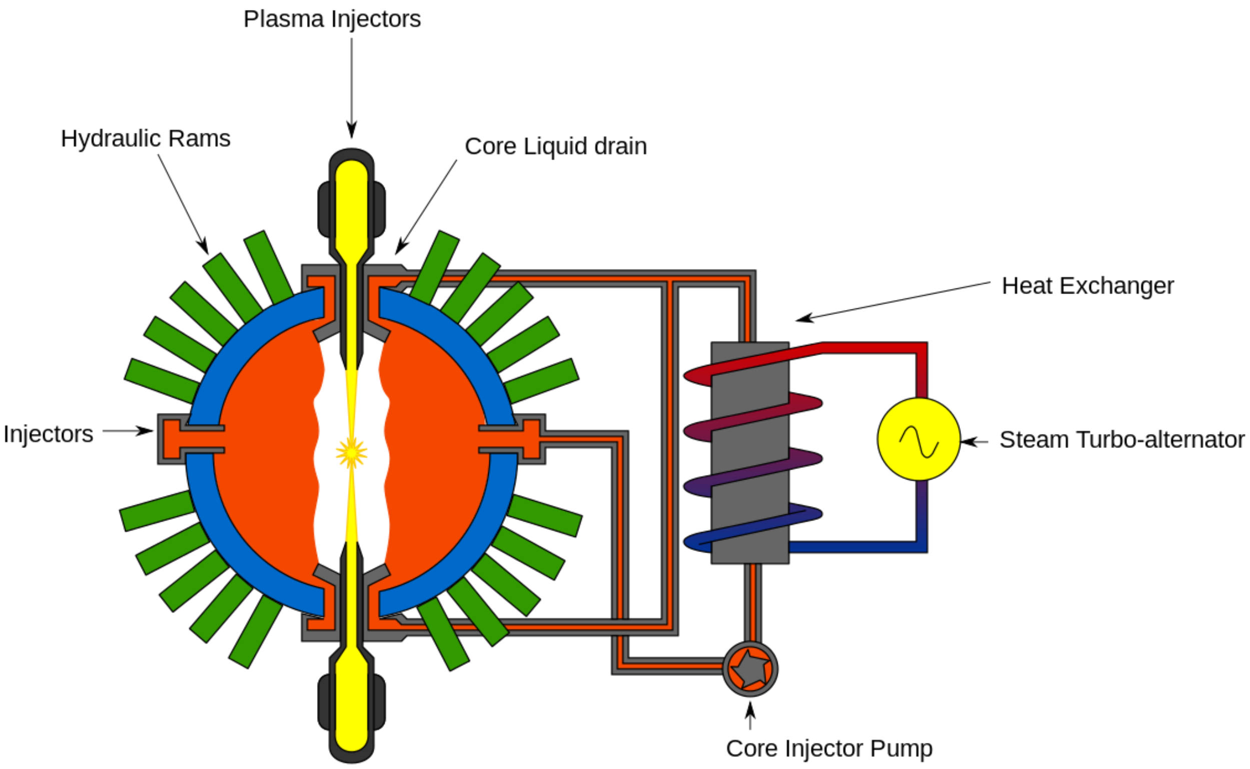
https://tae.com/media/

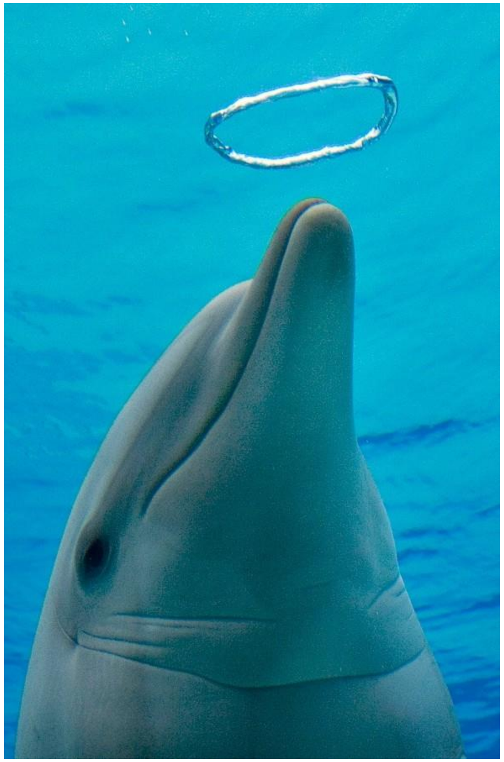
FRC sustain longer with neutral beam injection



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

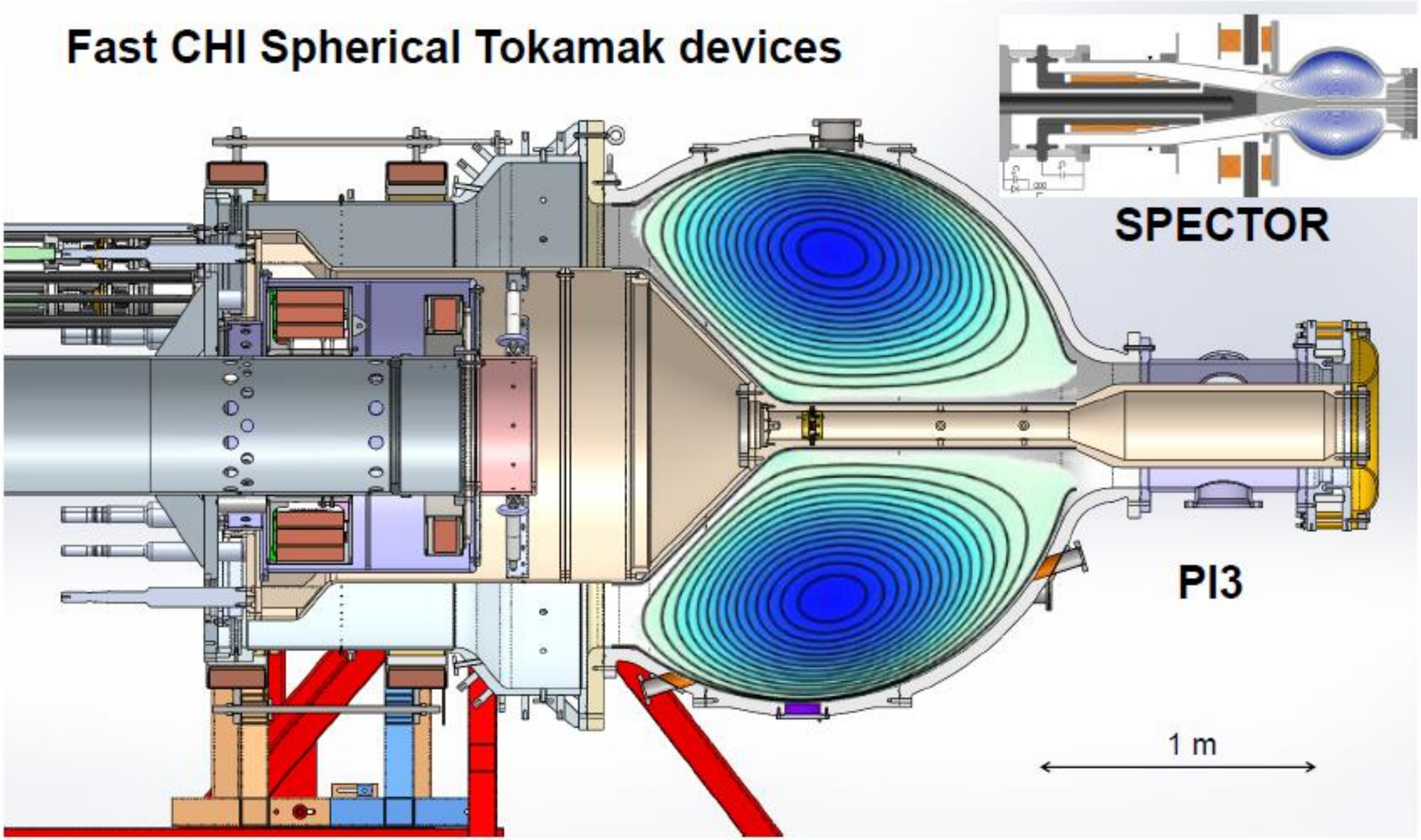
General fusion is a design ready to be migrated to a power plant





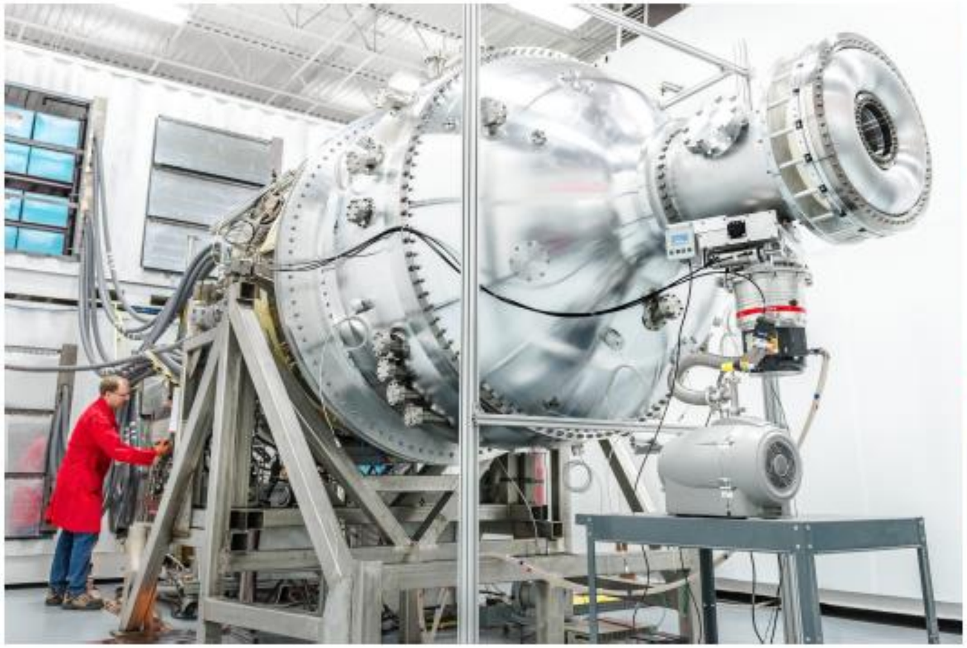
https://en.wikipedia.org/wiki/General_Fusion

A spherical tokamak is first generated



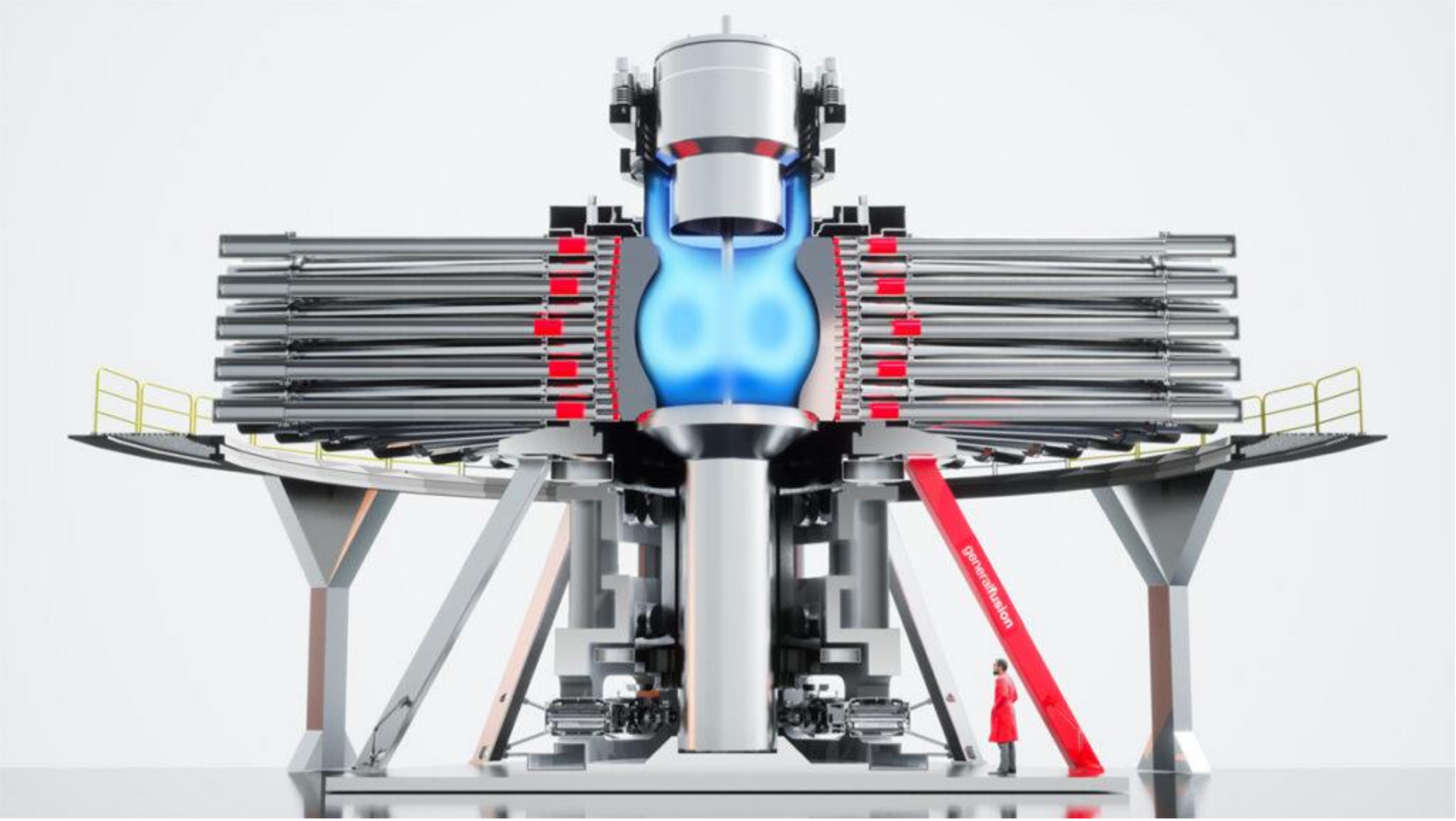
K. EPP, etc., 60th APS-DPP, CP11.00192

Plasma injector for the spherical tokamak

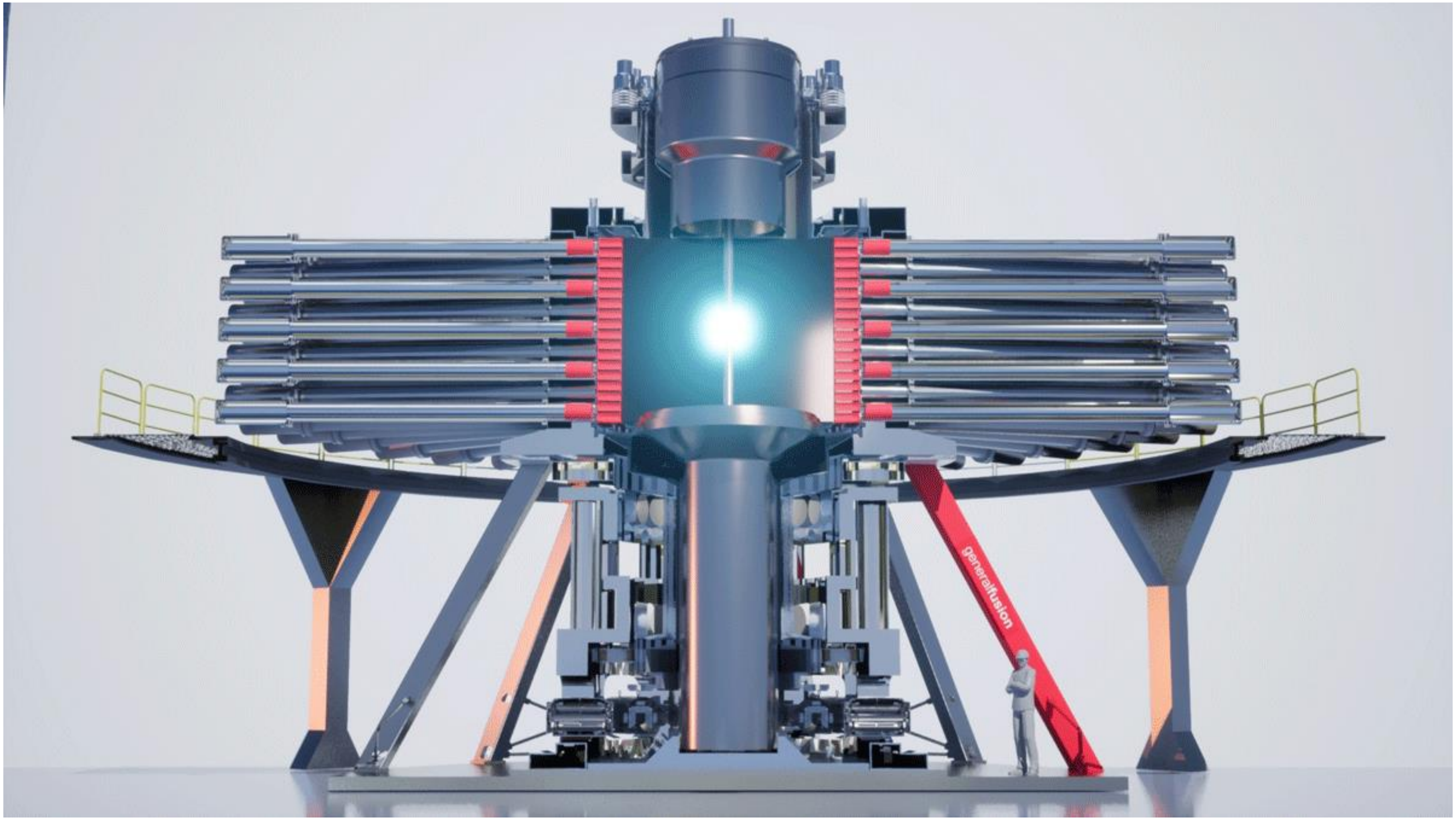


K. EPP, etc., 60th APS-DPP, CP11.00192

A spherical tokamak is generated in a liquid metal vortex



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



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

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

By Matt McGrath
Environment correspondent

17 June

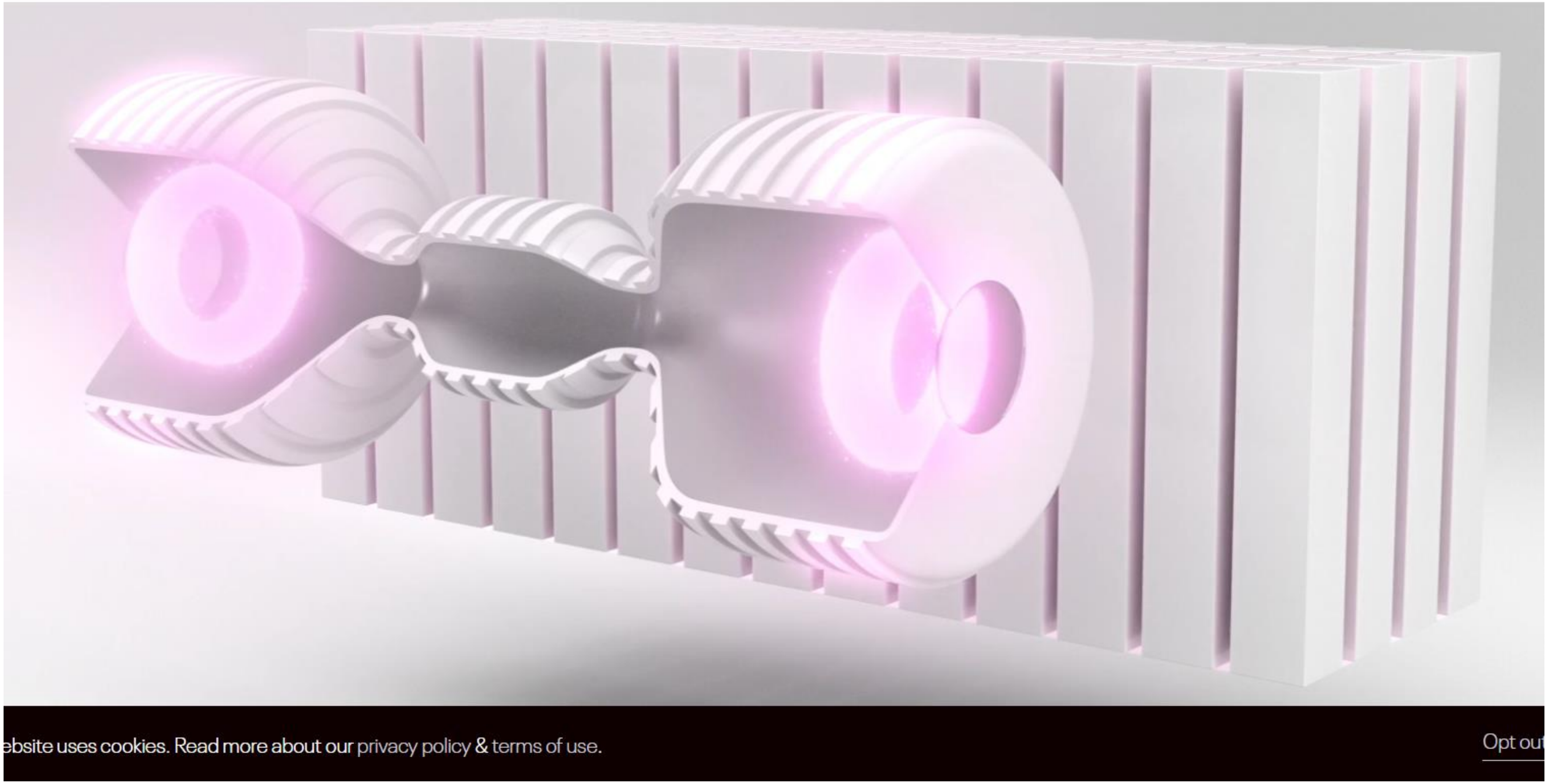
An artist's impression of what the new demonstration plant might look like

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

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

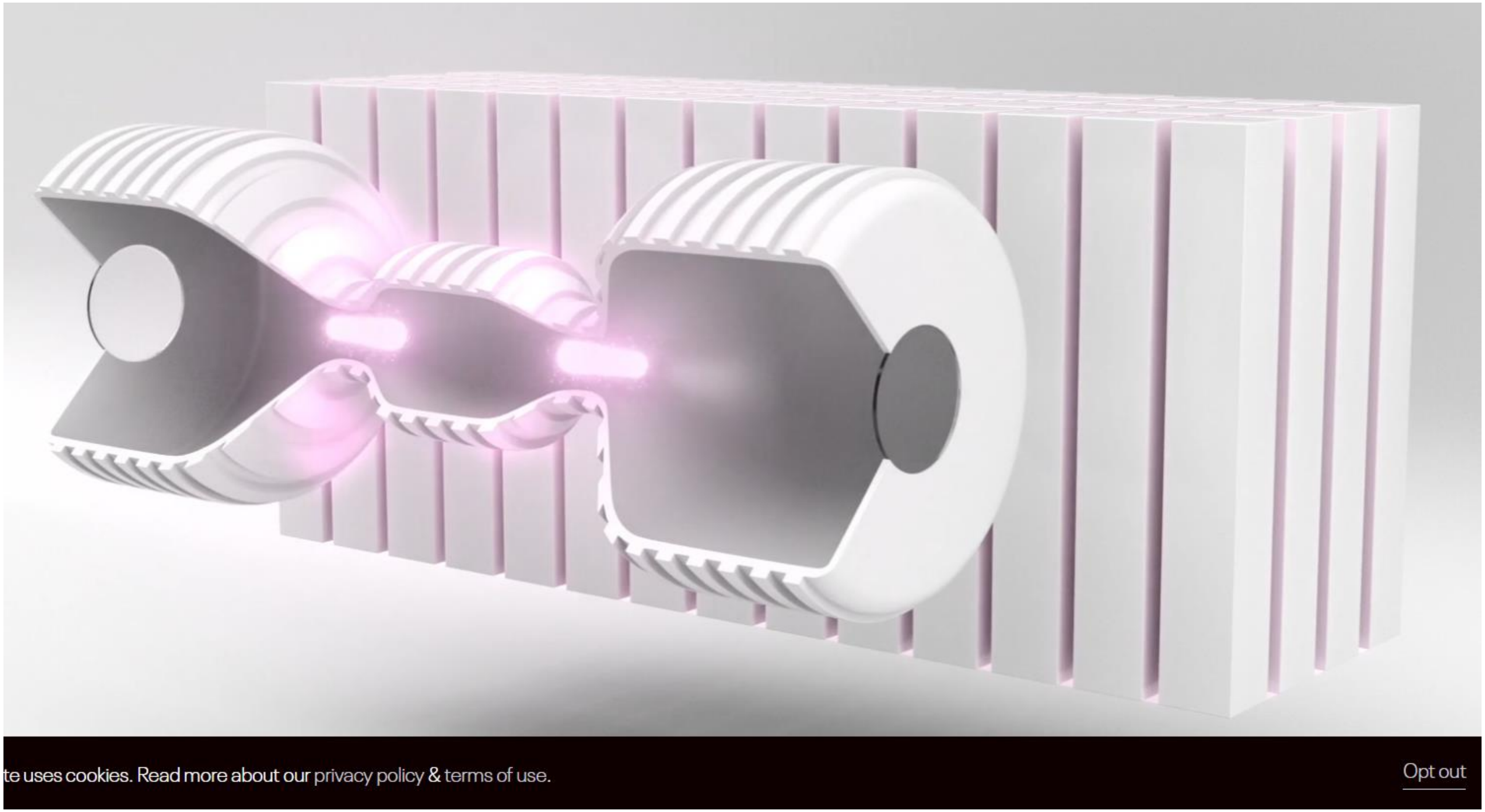
https://www.bbc.com/news/science-environment-57512229

Helion energy is compressing the two merging FRCs



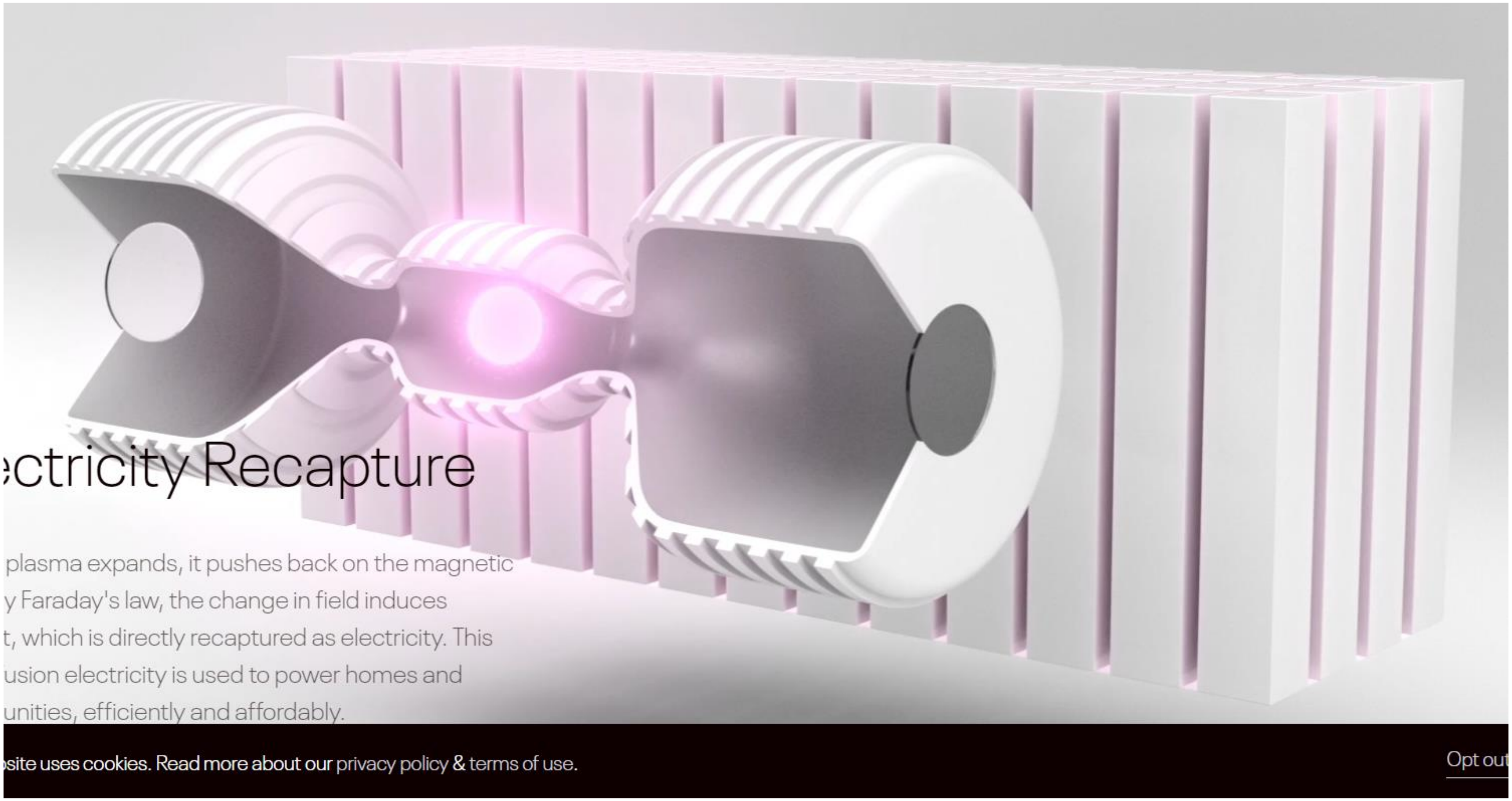
https://www.helionenergy.com/

Two FRCs are accelerated toward each other



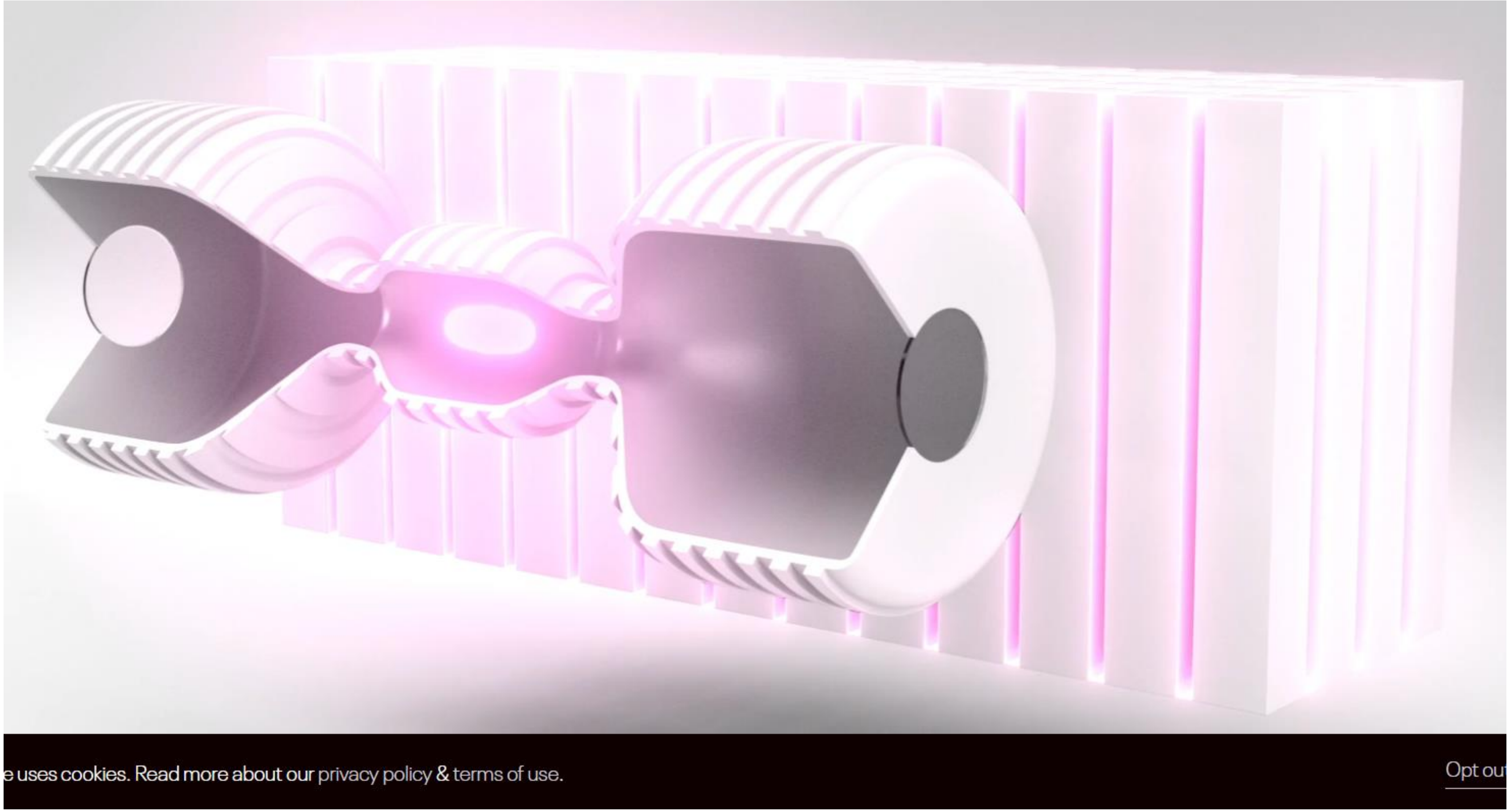
https://www.helionenergy.com/

Two FRCs merge with each other



https://www.helionenergy.com/

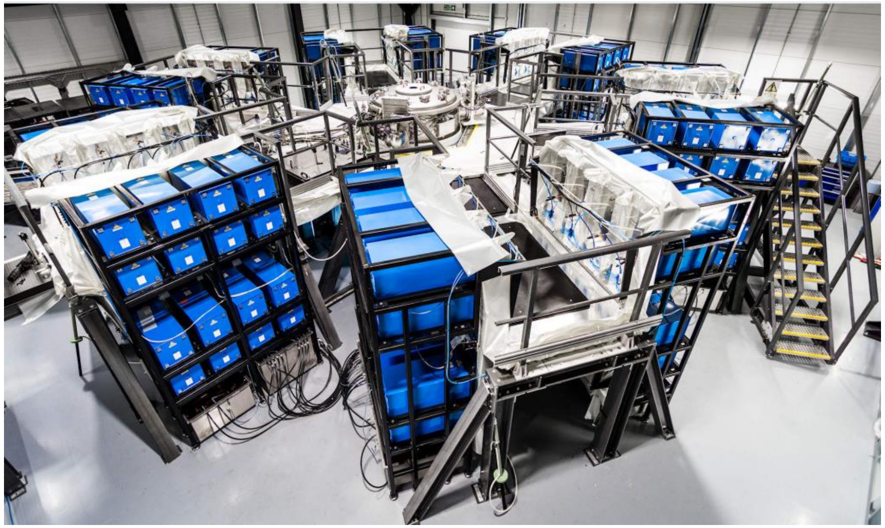
The merged FRC is compressed electrically to high temperature



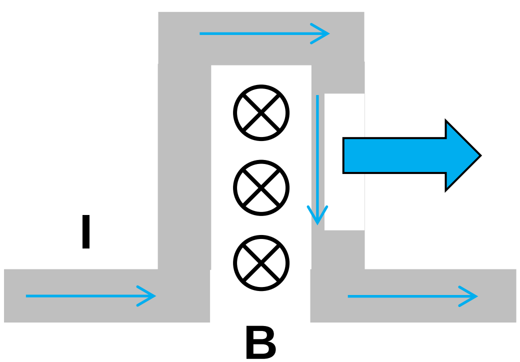
- **Similar concept will be studied in our laboratory.**

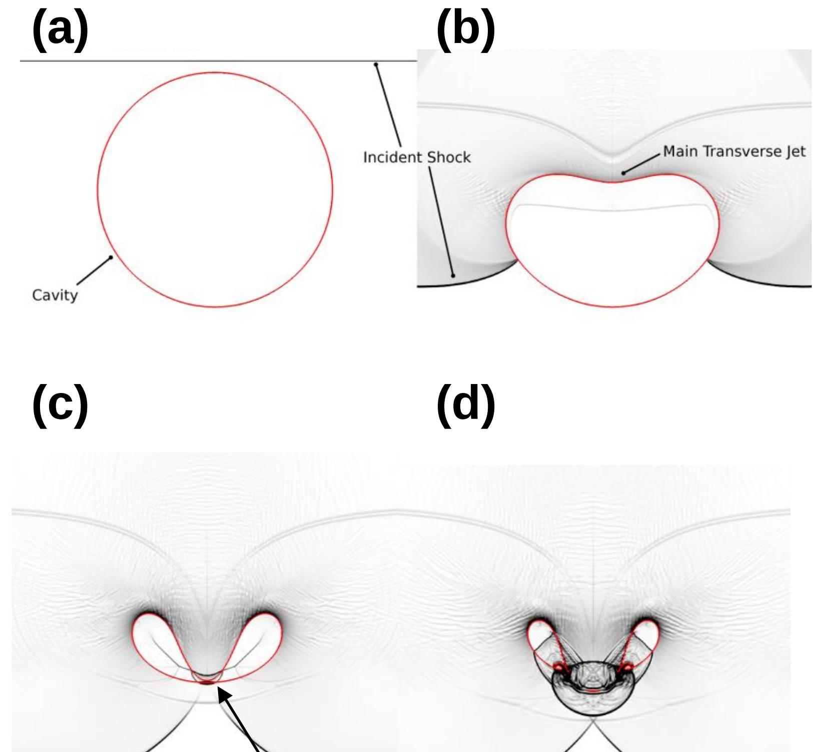
https://www.helionenergy.com/

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



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





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

https://www.youtube.com/watch?v=aTMPigL7FB8

https://firstlightfusion.com/

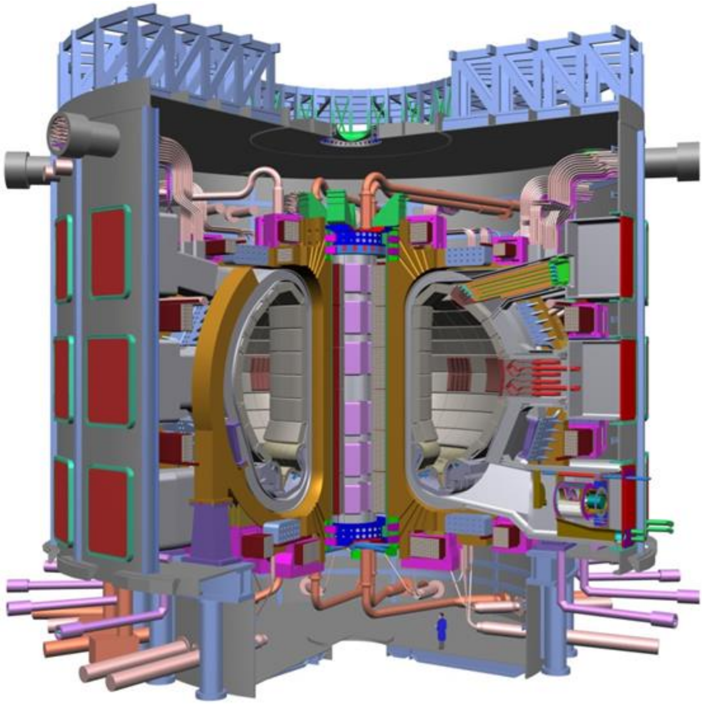
B. Tully and N. Hawker, Phys. Rev. **E93**, 053105 (2016)

A gas gun is used to eject the projectile

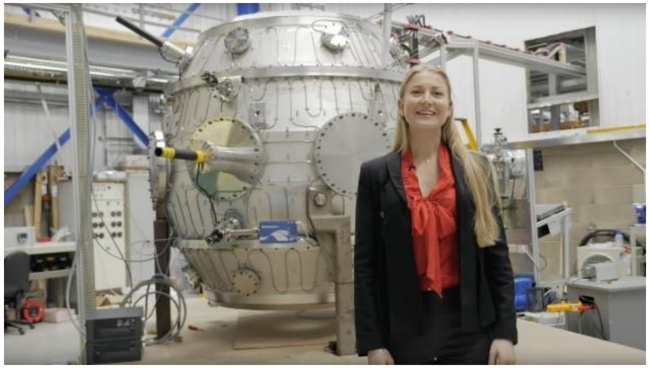
https://www.youtube.com/watch?v=JN7lyxC11n0
https://www.youtube.com/watch?v=aW4eufacf-8

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

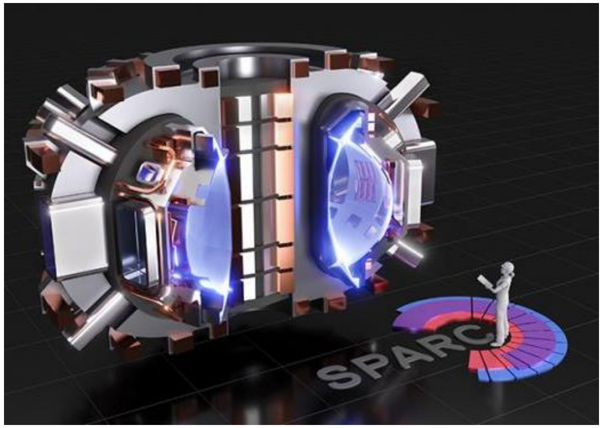
- **ITER – 2025 First Plasma**
  2035 D-T Exps
  2050 DEMO



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



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



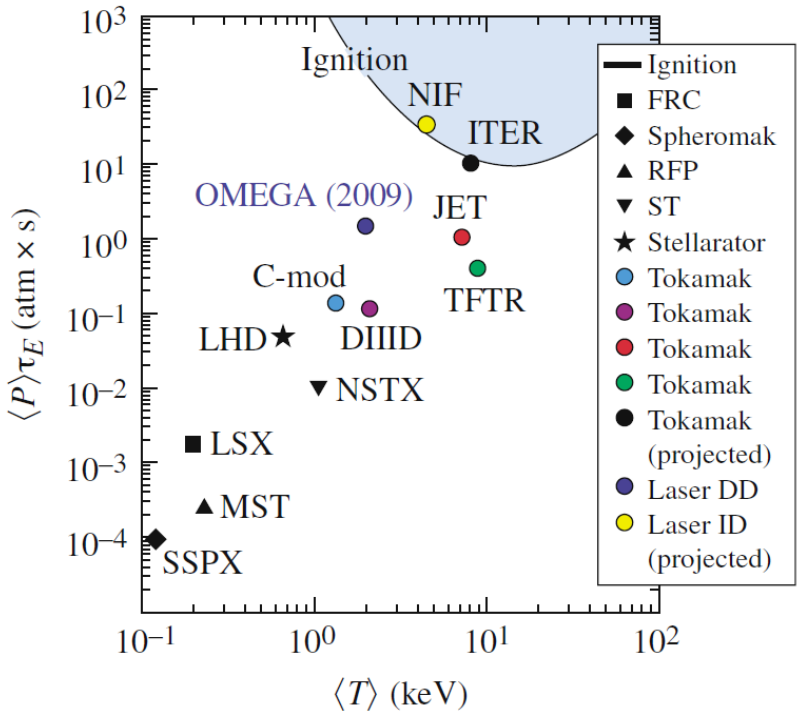
https://www.iter.org
https://www.tokamakenergy.co.uk/
https://www.psfc.mit.edu/sparc

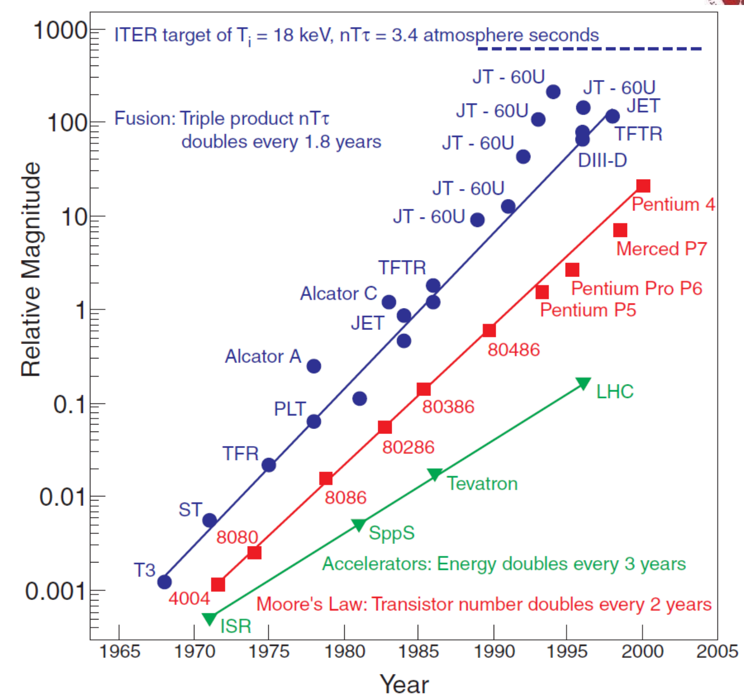
Fusion is blooming!

⋮

https://www.fusionindustryassociation.org/members

We are closed to ignition!





- **Other private companies:**

CFS

generalfusion

first light

...

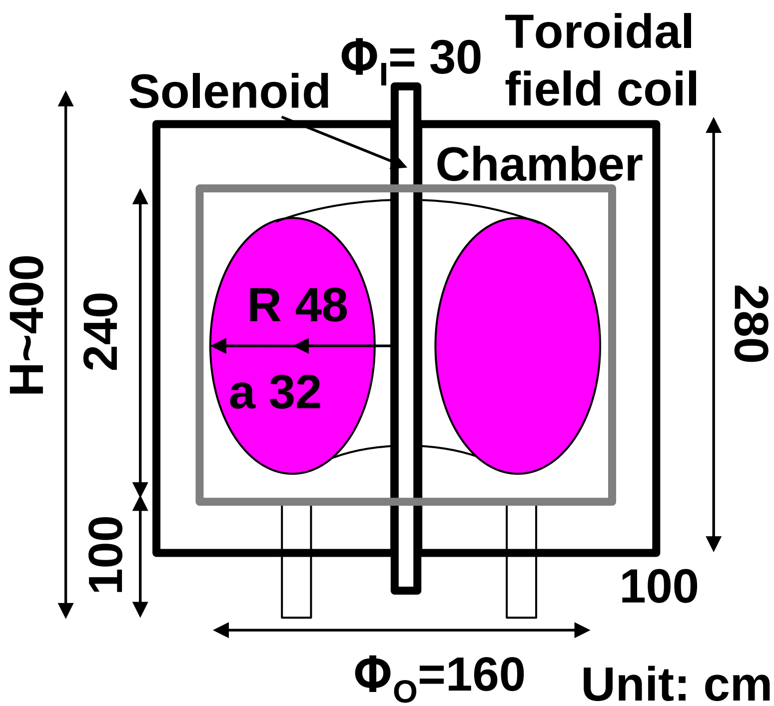
Tokamak **MTF** **ICF**

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

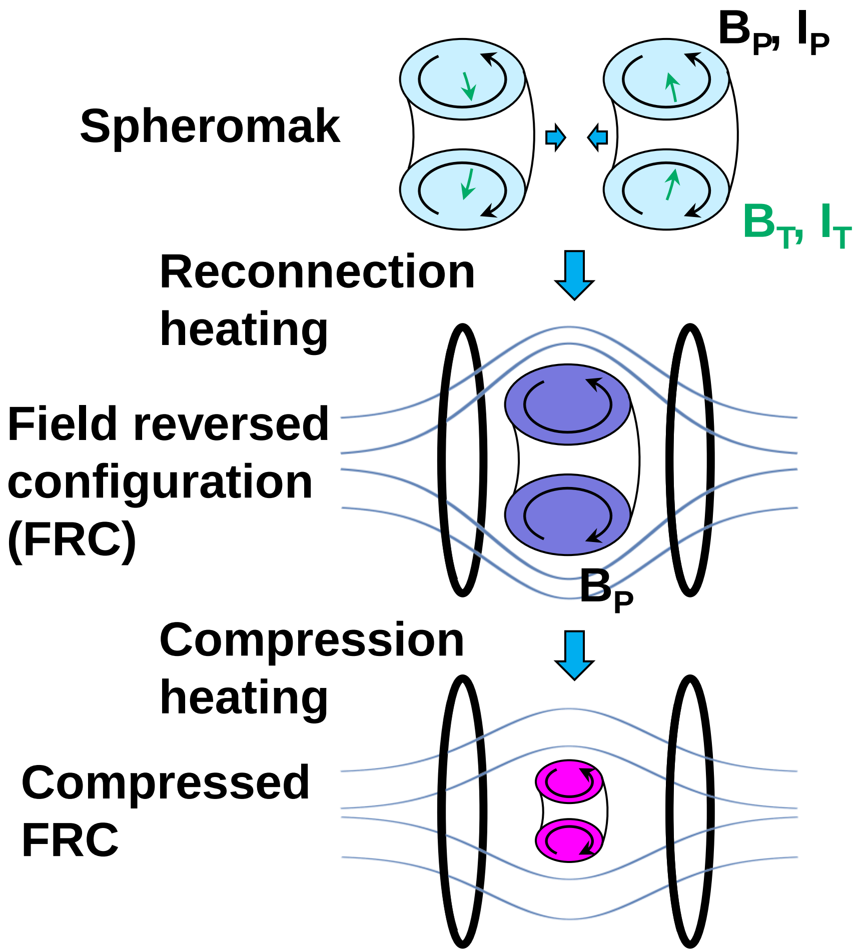
Fusion projects in Inst. Space and Plasma Sciences , National Cheng Kung University

- 國科會計畫 - 磁約束高溫電漿研究

Formosa Integrated Research Spherical Tokamak (FIRST)



- Magneto-inertial fusion (MIF)



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