氫硼核融合實作
Practical course on proton-boron nuclear fusion

Po-Yu Chang (pchang@mail.ncku.edu.tw)

Institute of Space and Plasma Sciences, National Cheng Kung University

2025 summer break

7/14(Mon.) – 7/18(Fri.) 14:00-17:40

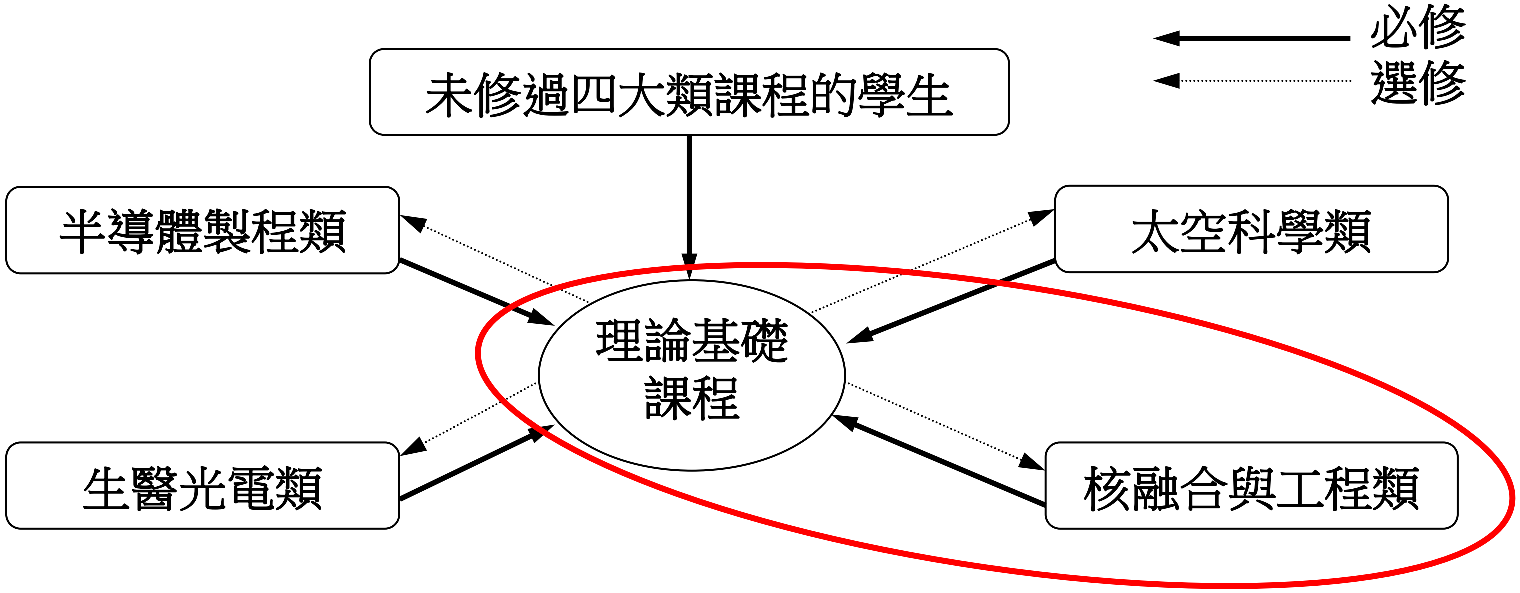
Lecture 1

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

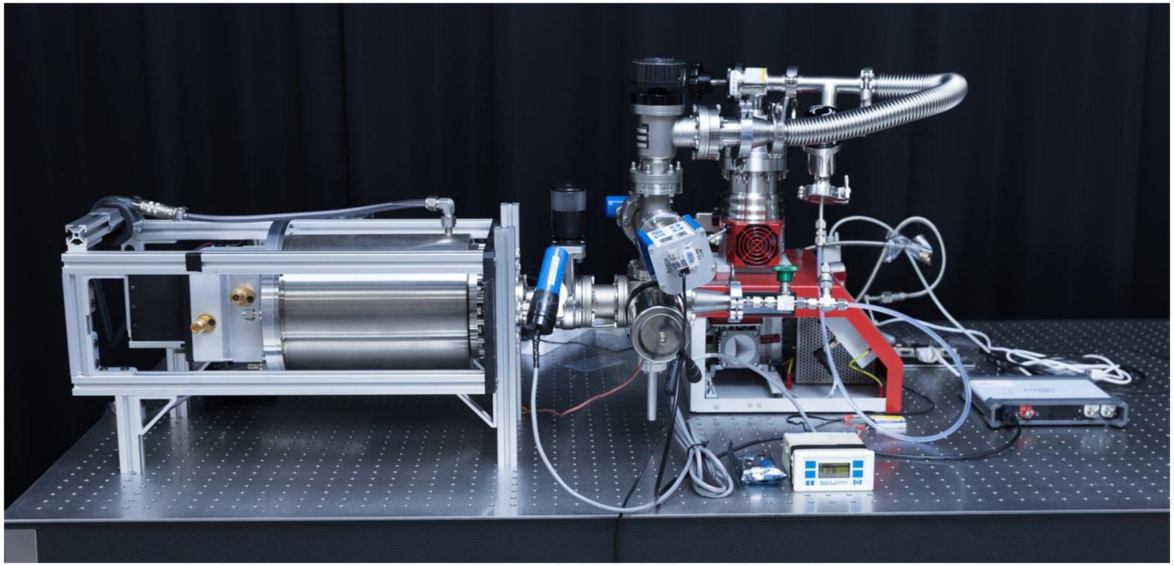
2025/7/14 updated

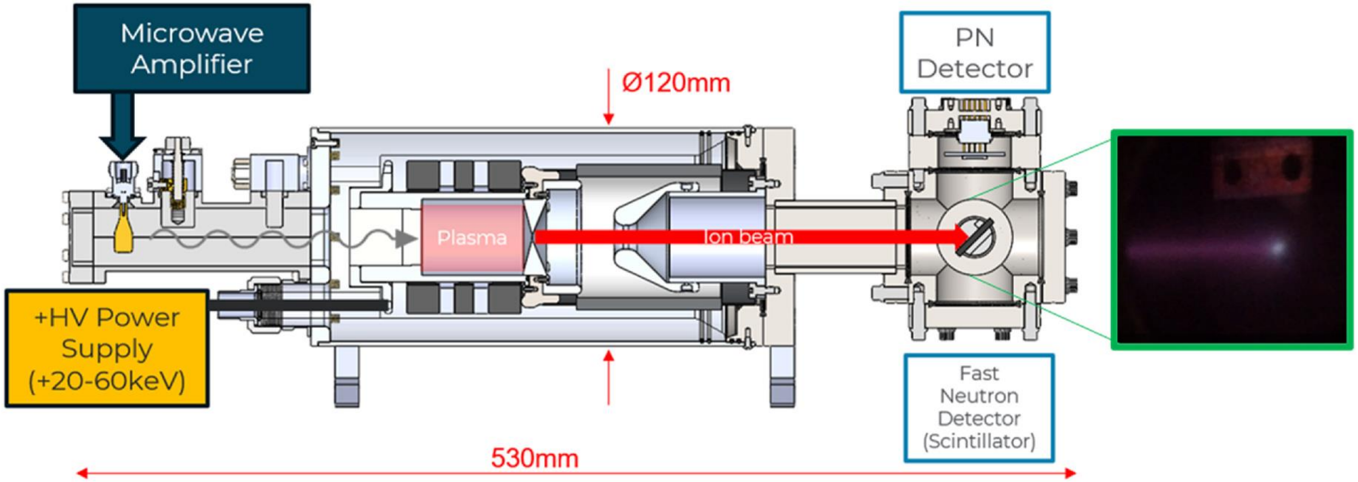
深入的電漿知識請選修
電漿學分學程 或 核融合電漿專長微學程

- 電漿學分學程：培養具備電漿科技研究與產業應用等多元專業且更具競爭力之跨領域人才。
- 核融合電漿專長微學程：培養具備核融合知識之專業人才。



Alpha-E provided by Alpha Ring will be used to demonstrate the proton-boron nuclear fusion



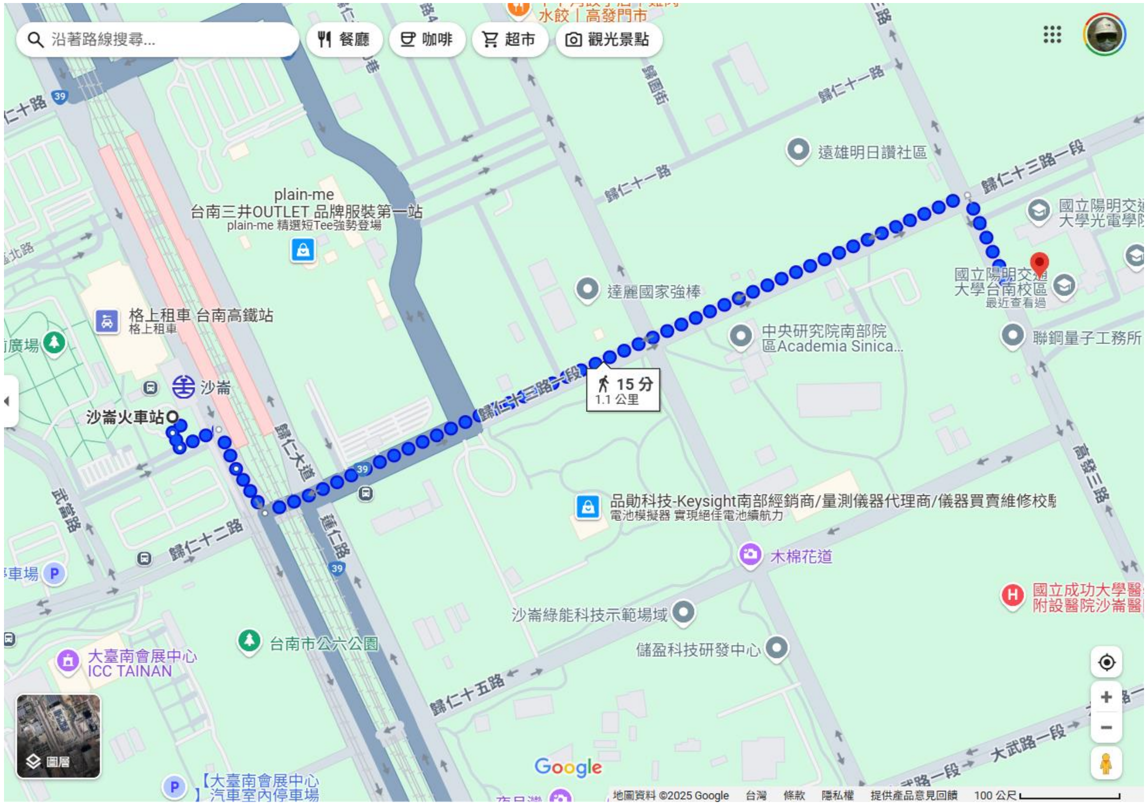


https://alpharing.com/alpha-e/
Allan Xi Chen, etc., Physics Open 21, 100234(2024)

Contents

<table>
<tr><th>Date</th><th>Descriptions</th><th>Location</th></tr>
<tr><td>Mon.</td><td>• Introduction to nuclear fusion.
• Commercial Applications of Alpha-E Particle Accelerator Technology, by Dr. Allan X. Chen from Alpha Ring.</td><td>NCKU</td></tr>
<tr><td>Tue.</td><td>Introduction to the theory of Alpha-E.</td><td>NCKU</td></tr>
<tr><td>Wed.</td><td>Introduction to the hardware of Alpha-E, safety and Regulations, by Dr. Chia-Yi Chen and Dr. Hau Kun Jhuang from Alpha Ring.</td><td rowspan="2">• Alpha Ring @ Shalun
• Meet at Tainan Station at 12:40.
• Train 373, departing at 12:55.
• Walk to Alpha Ring arriving at 13:40.</td></tr>
<tr><td>Thur.</td><td>Conducting experiments on the Alpha-E teaching experiment facility and introduction to data analysis using python, by Dr. Allan X. Chen and Dr. Chia-Yi Chen from Alpha Ring.</td></tr>
<tr><td>Fri.</td><td>Final report and introduction to different schemes of nuclear fusion energy generation.</td><td>NCKU</td></tr>
</table>

We will visit Alpha Ring’s laboratory located in Shalun



- Alpha Ring @ Shalun
- Meet at Tainan Station at 12:40.
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Grading

• **Homework**	**60 %** **(Tue. 10 % +** **Wed. 40 % +** **Thur. 10 %)**	• **One homework per day from Tuesday to Thursday. If missing the class in the previous day, the score of the homework submitted on that day will be zero.** • **On Tuesday, data analysis technique will be introduced. Students will be asked to analyze the data.**
• **Final presentations**	**40 %**	• **Students will be grouped in several groups. Students in the same group need to work together analyzing the experimental data on Thursday and give a presentation on Friday.**

Course Outline

- **What is Plasma?**
- **Nuclear fusion**
  - **Basic**
  - **Magnetic confinement fusion (MCF)**
  - **Inertial confinement fusion (ICF)**
- **Formosa Integrated Research Spherical Tokamak (FIRST), the first Tokamak in Taiwan**

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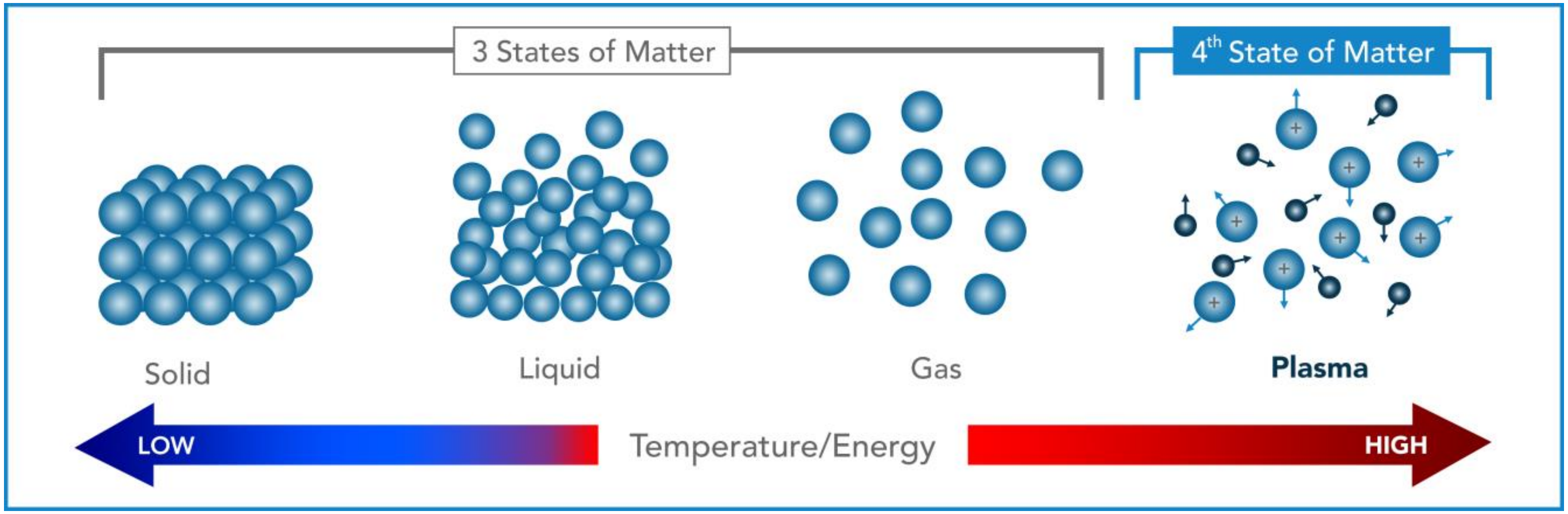
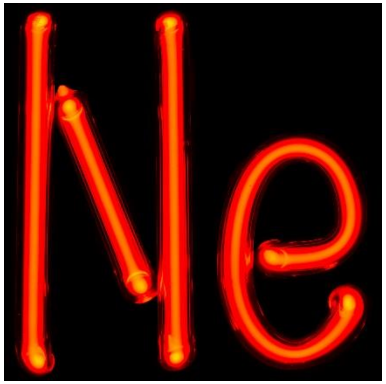
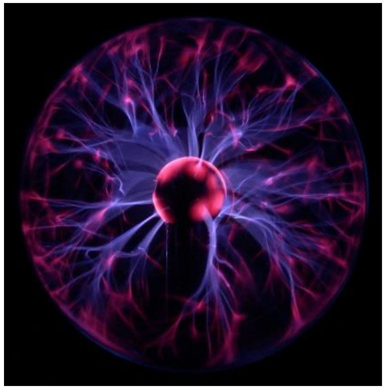
Plasma is the 4th state of matter

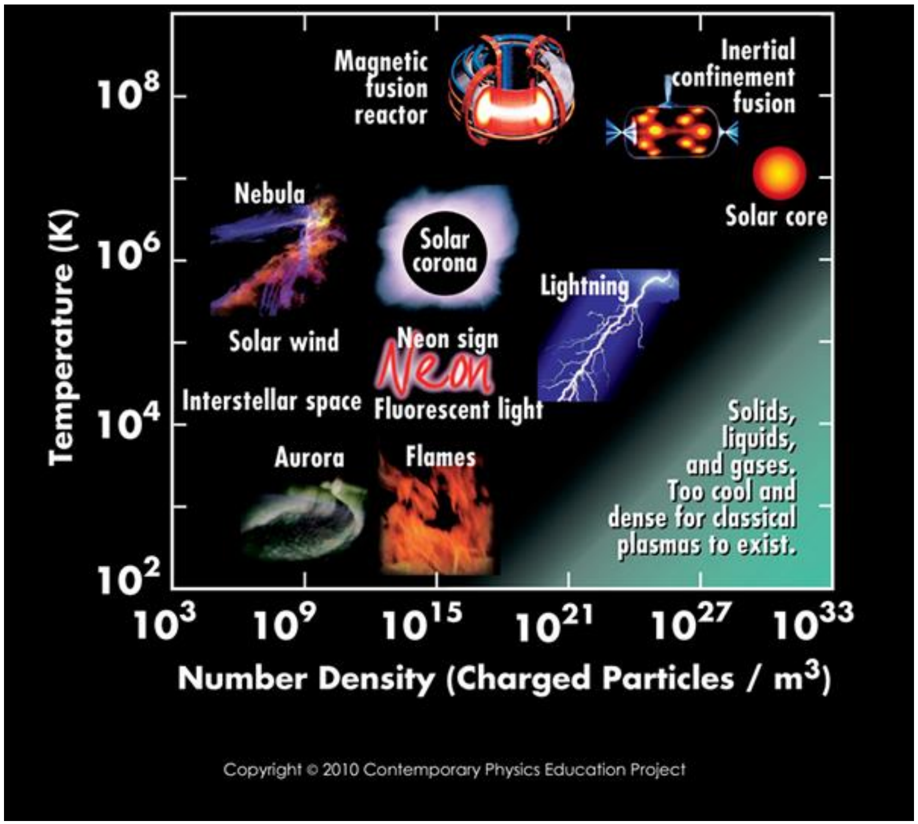


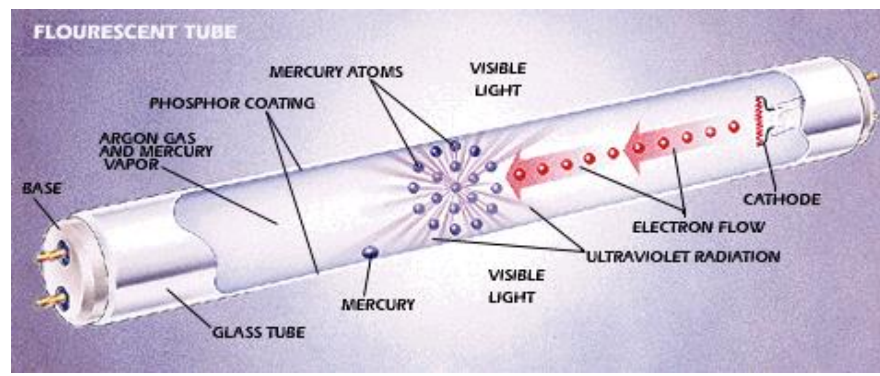




http://tetronics.com/our-technology/what-is-plasma/
https://en.wikipedia.org/wiki/Neon
https://zh.wikipedia.org/zh-tw/%E7%AD%89%E7%A6%BB%E5%AD%90%E7%81%AF

Plasma is everywhere





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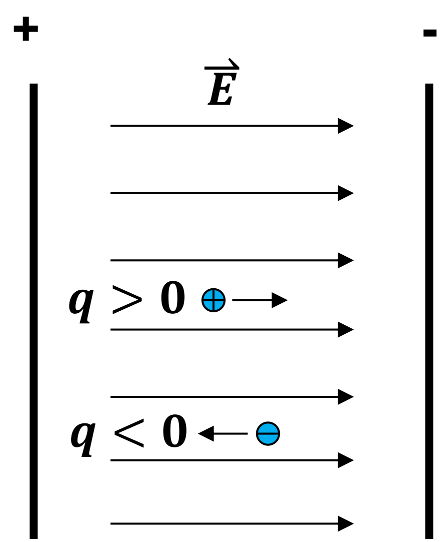
https://lasers.llnl.gov/science/understanding-the-universe/plasma-physics
https://simple.wikipedia.org/wiki/Fluorescent_lamp
https://studyelectrical.com/2014/05/how-fluorescent-tube-lights-work.html

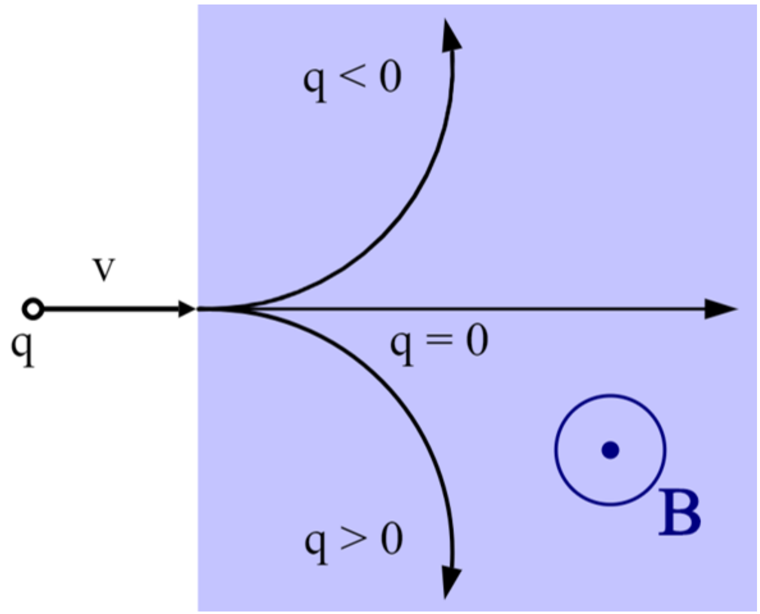
Charged particles are accelerated due to Lorentz force under electromagnetic fields

- **Lorentz force:** $\vec{F} = q\,\vec{E} + q\,\vec{v} \times \vec{B}$

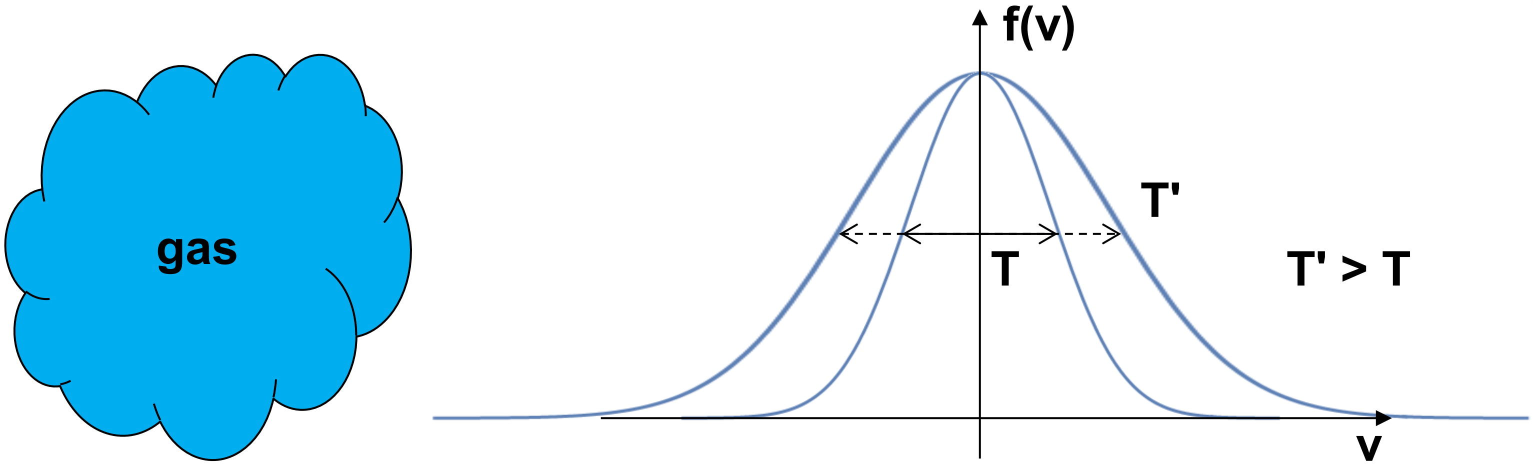
- **Force under electric fields**

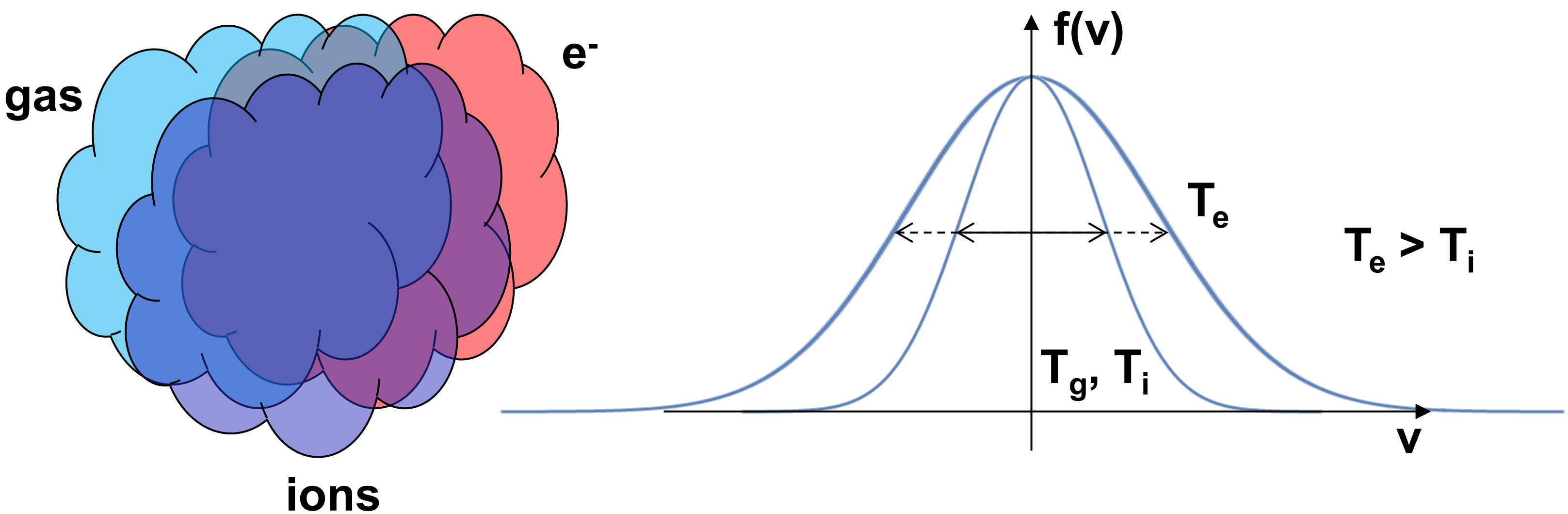


- **Force under magnetic fields**

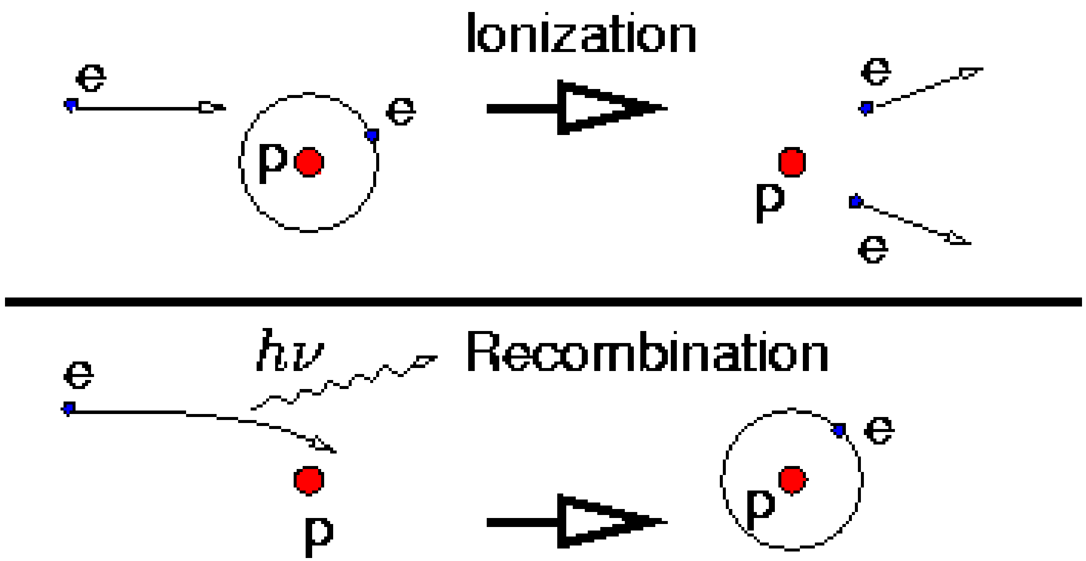


In plasma, there are ions, electrons, and neutral gas



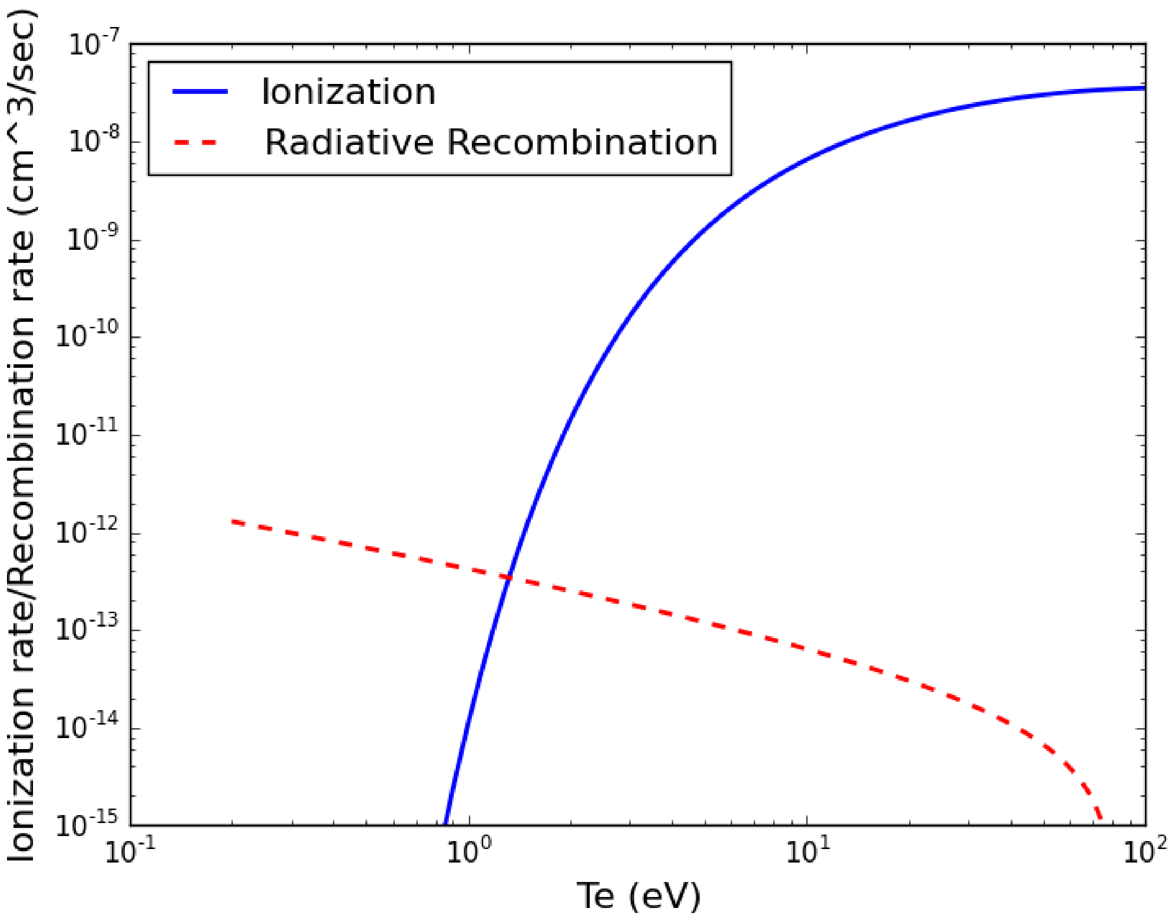


A plasma is a gas in which an important fraction of the atoms is ionized so that the electrons and ions are separated freely



http://ocw.mit.edu/courses/nuclear-engineering/22-611j-introduction-to-plasma-physics-i-fall-2003/lecture-notes/

A plasma can be created when the ionization rate is higher than the recombination rate



J. D. Huba \NRL Plasma Formulary", Naval Research Laboratory, 2013

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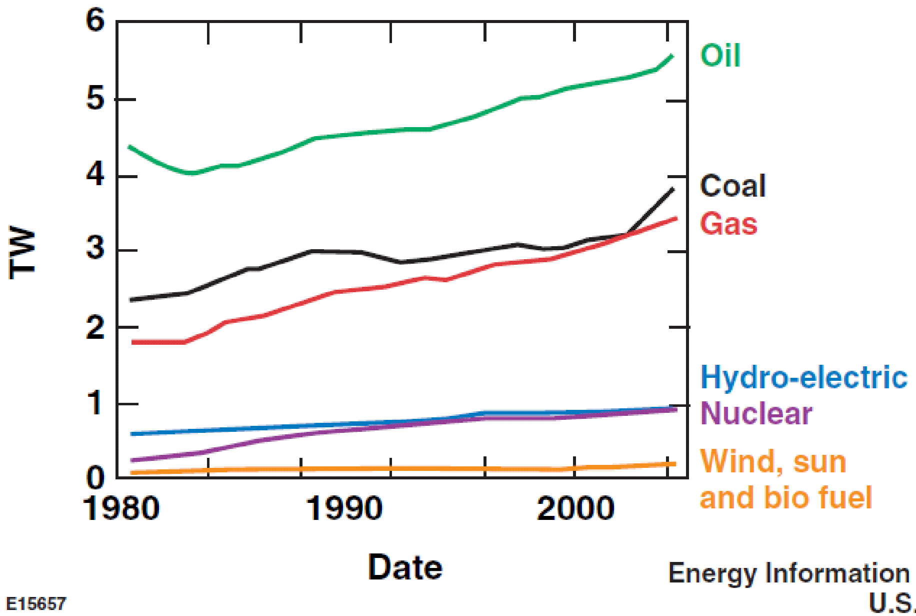
World energy consumption is dominated by the use of dwindling fossil fuels

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

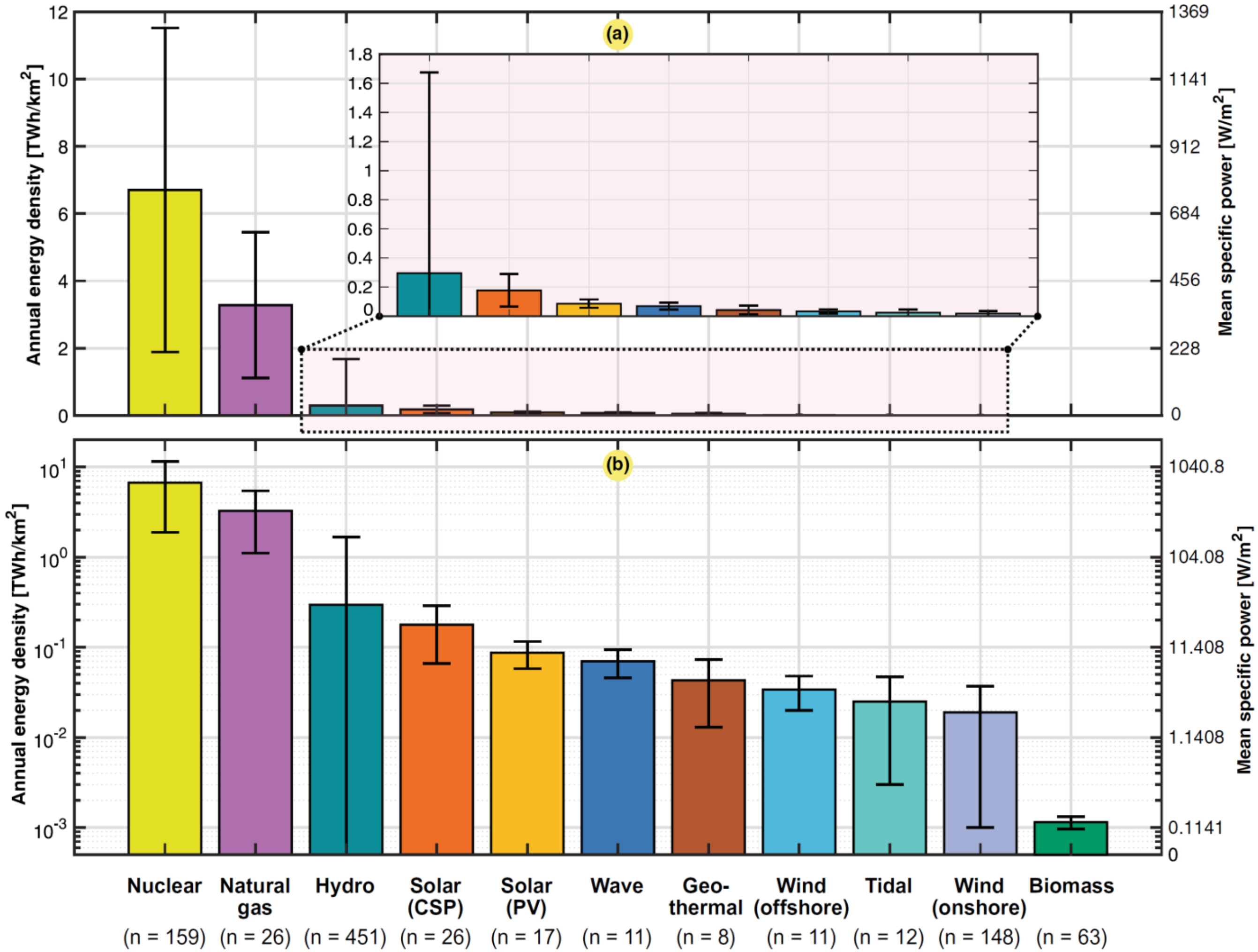


While predictions about the exact number of remaining years vary, fossil fuels will run out.

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

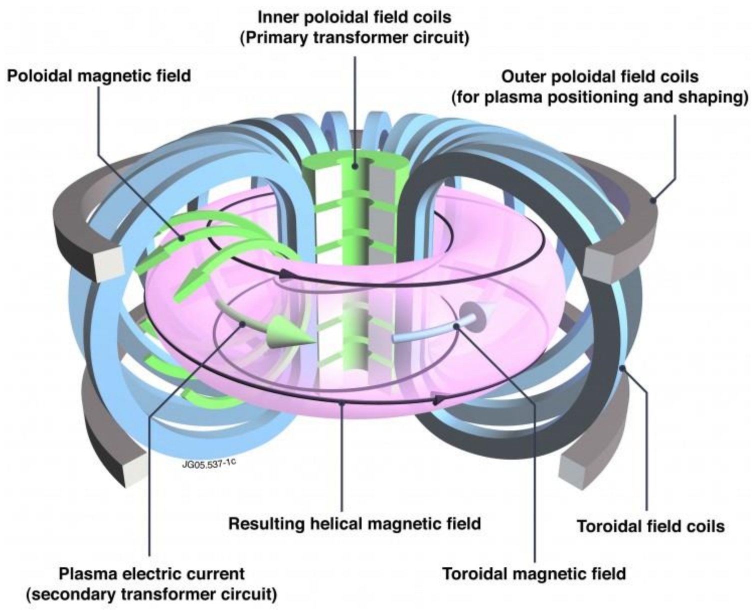
Nuclear (fission) energy has the highest energy density



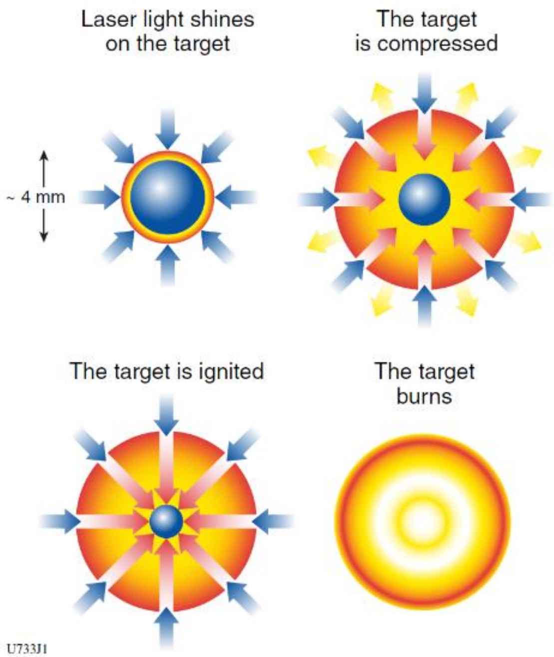
J. K. Noland, etc., Scientific Reports **12**, 21280 (2022)

Nuclear fusion as an energy source is being developed

- **Magnetic confinement fusion (MCF)**



- **Inertial confinement fusion (ICF)**



https://www.euro-fusion.org/2011/09/tokamak-principle-2/
Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

Nuclear fusion as an energy source is being developed

- **Magnetic confinement fusion (MCF)**
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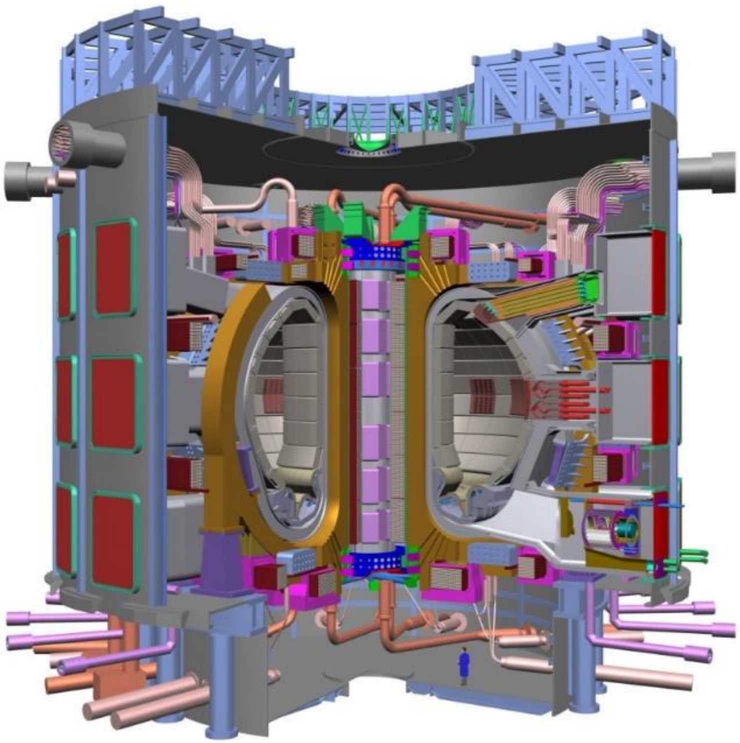
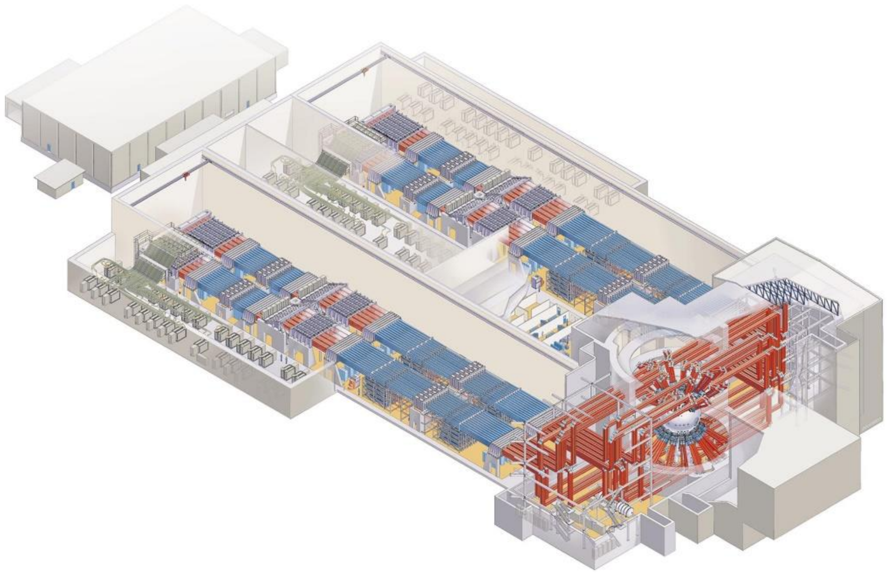
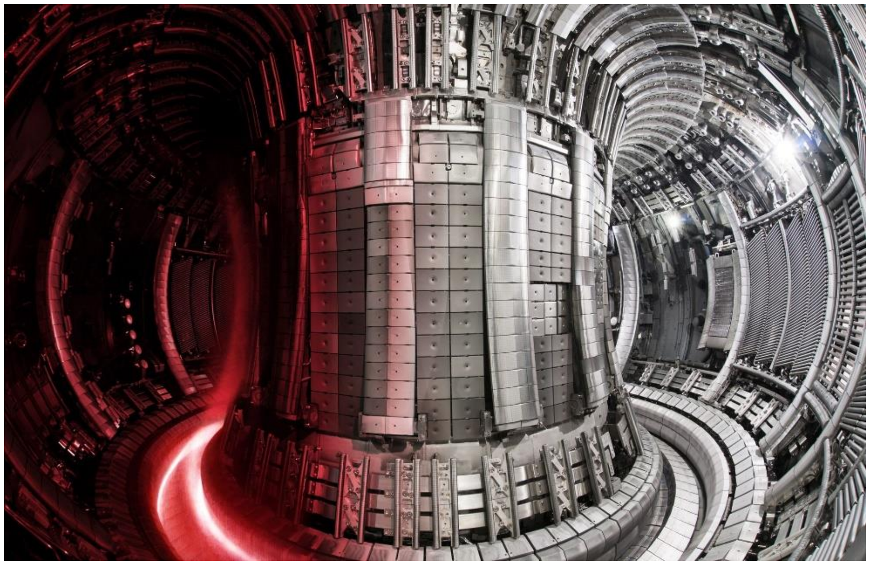




https://www.iter.org
https://zh.wikipedia.org/wiki/國家點火設施

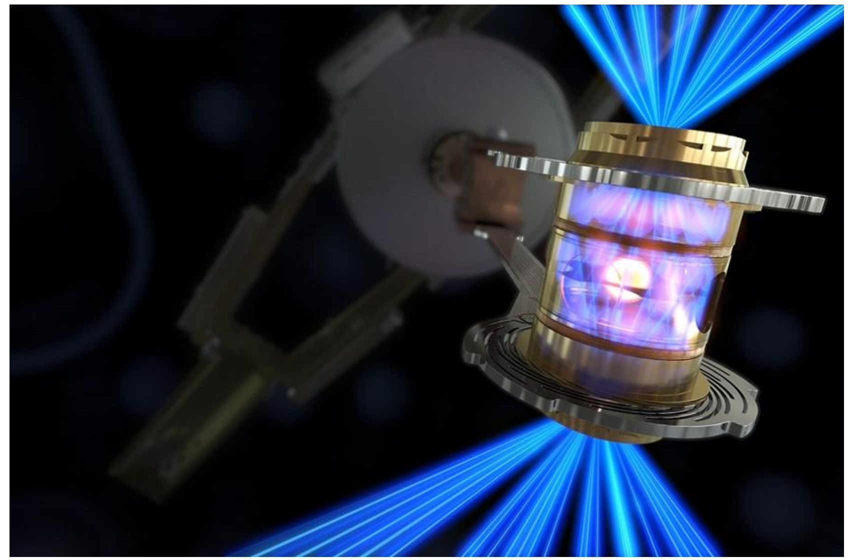
Significant breakthrough is achieved recently

- **Magnetic confinement fusion (MCF)**



- **On 2024/2/(8), record-breaking 69.26 megajoules of sustained fusion energy in Joint European Torus (JET) facility in Oxford demonstrates powerplant potential and strengthens case for ITER.**

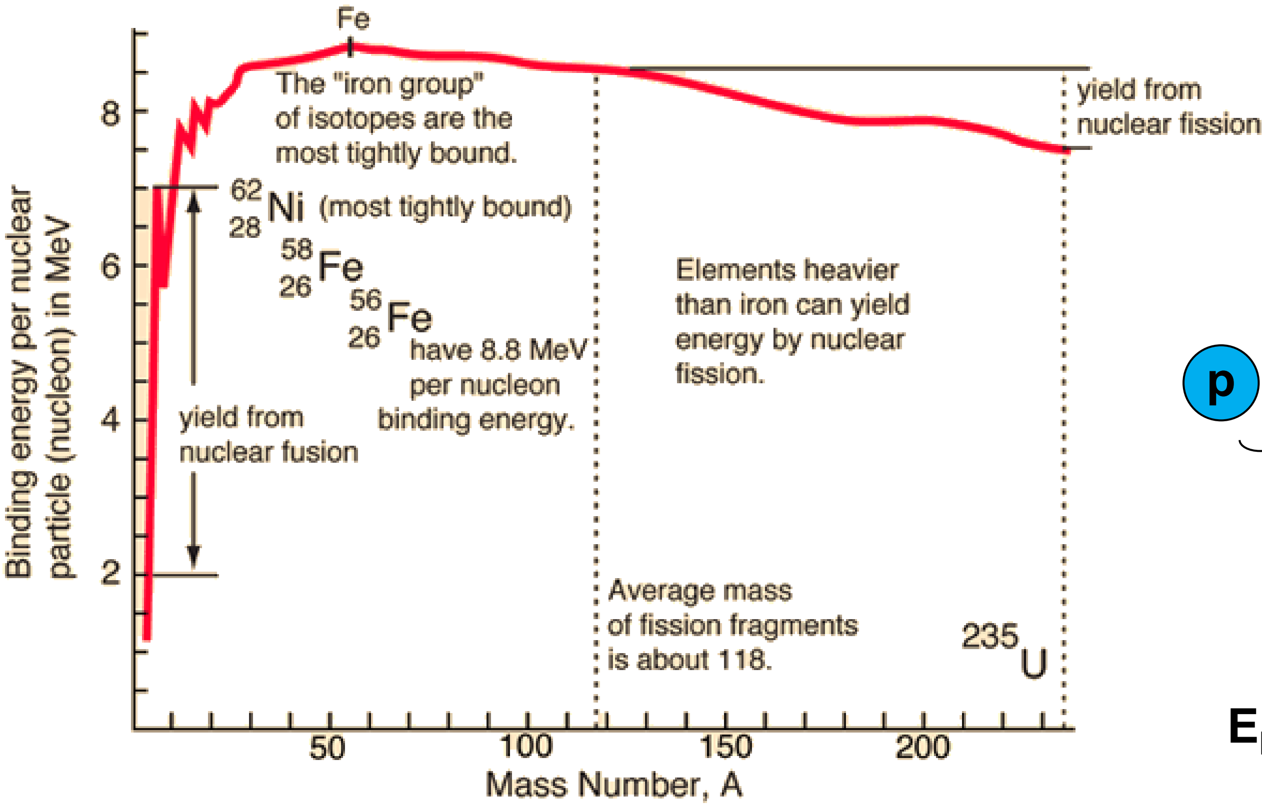
- **Inertial confinement fusion (ICF)**

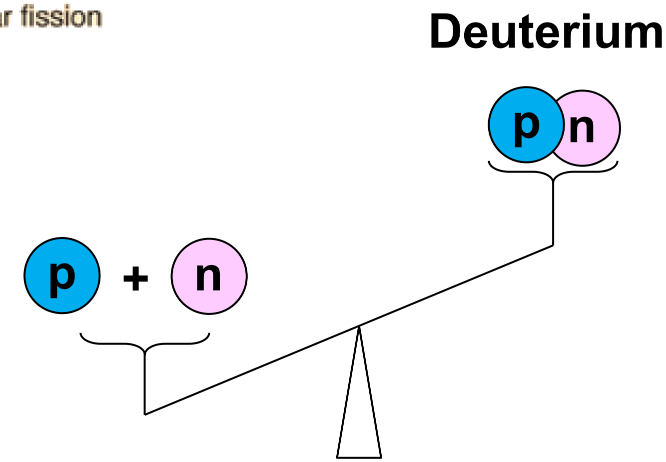


- **National Ignition Facility (NIF) demonstrated a gain grater than 1 for the first time on 2022/12/5. The yield of 3.15 MJ from the 2.05-MJ input laser energy, i.e., Q=1.5.**

https://ccfe.ukaea.uk/resources/#gallery
https://www.science.org/content/article/historic-explosion-long-sought-fusion-breakthrough

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





$m_p + m_n > m_D$

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

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

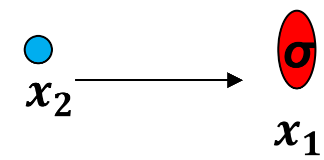
$$\Delta m = z m_{\mathrm{p}} + (A - z) m_{\mathrm{n}} - m$$

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

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

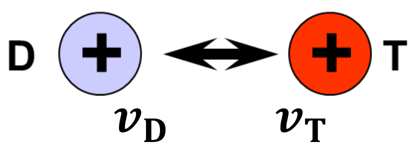
Cross section measures the probability per pair of particles for the occurrence of the reaction

$x_1 + x_2 \rightarrow x_3 + x_4$



- **The hard sphere cross section:**
  σ **≈** ***πR***^{2} **where R ≈ 5x10**$^{-15}$ **m is the nuclear radius, i.e.,**
  σ **=** ***0.8 x 10***$^{-28}$ **m**^{2} **≈ 1 barm. (barm ≡ 10**$^{-28}$ **m**^{2}**)**

- **Classical cross section:**

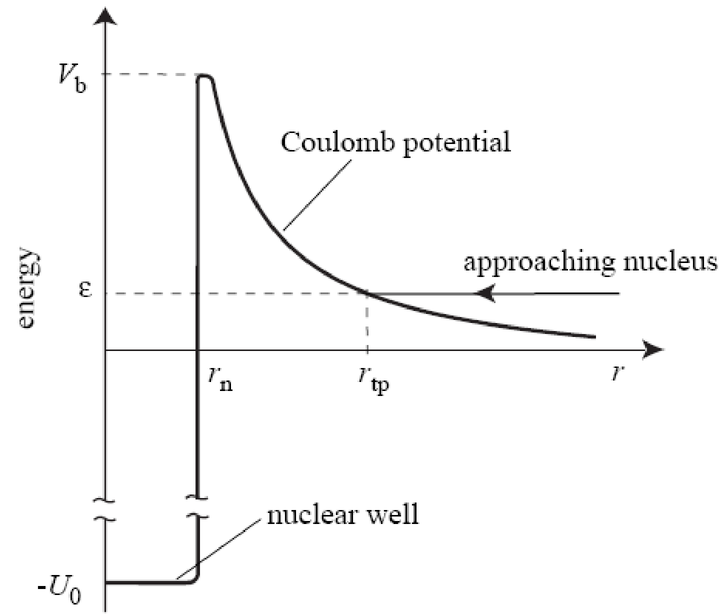


$$\frac{m_D}{2}{v_D}^2 + \frac{m_T}{2}{v_T}^2 \geq \frac{e^2}{4\pi\epsilon_o R}$$

- **Let** $v = \left|\vec{v}_D - \vec{v}_T\right|$

$$v_D = \frac{m_T}{m_D + m_T}v \qquad v_T = \frac{m_D}{m_D + m_T}v$$

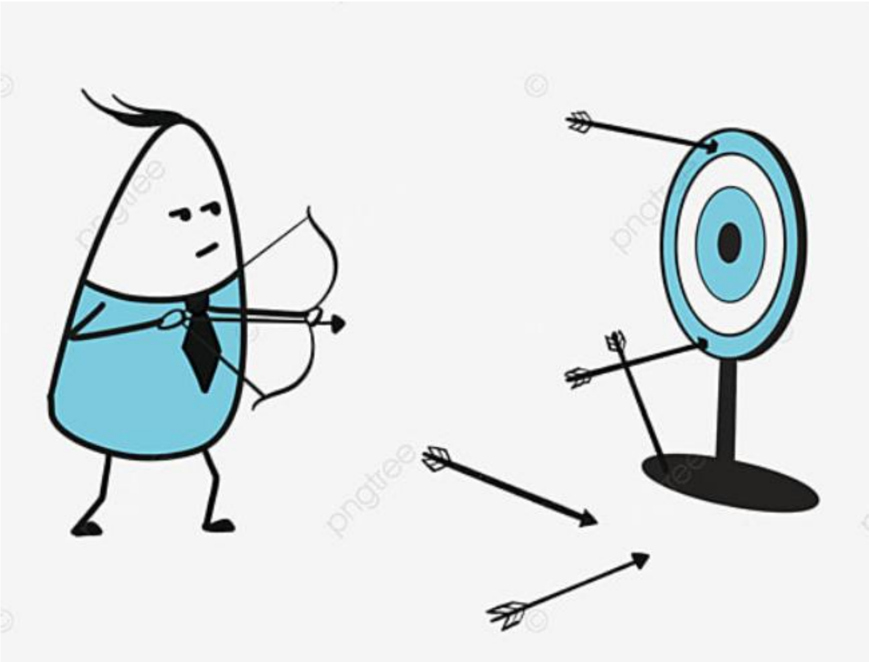
$$\frac{m_r}{2}v^2 \geq \frac{e^2}{4\pi\epsilon_o R} \qquad m_r = \frac{m_D m_T}{m_D + m_T}$$

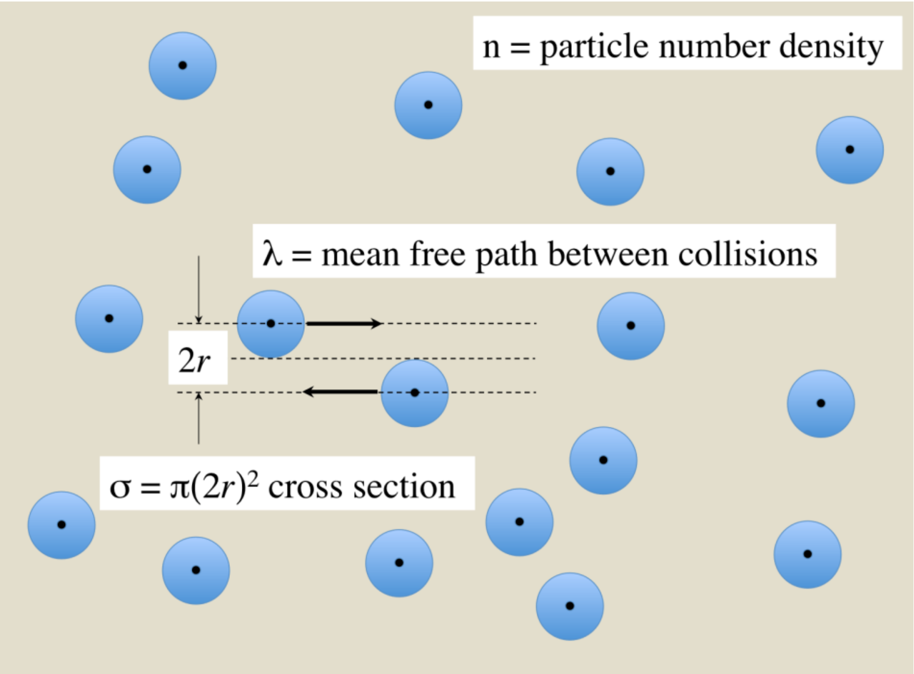


- **Classical kinetic energy required for fusion is**

$$K_{c.m.} > 288\ \text{keV} \quad !!!$$

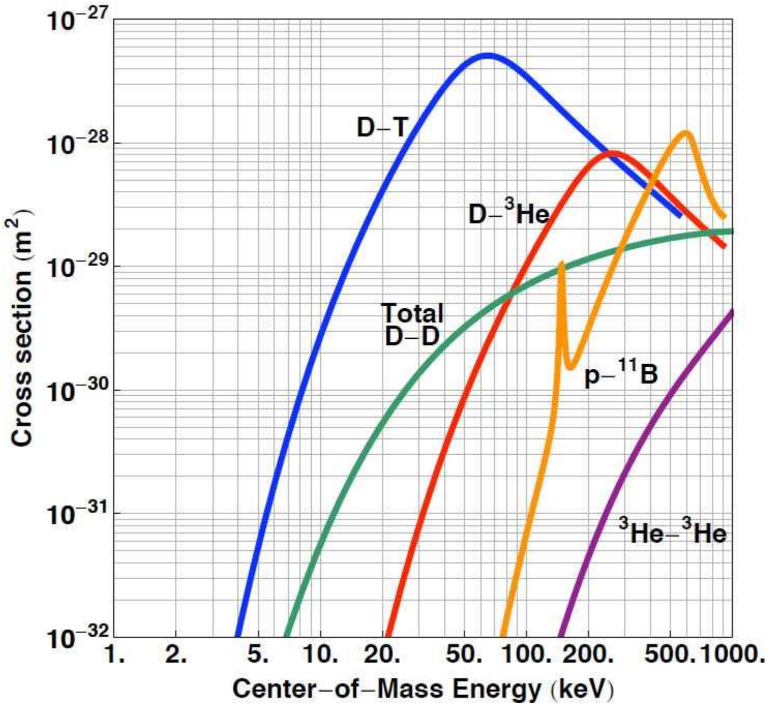
The cross section is a measure of the probability that a specific process will take place in a collision of two particles



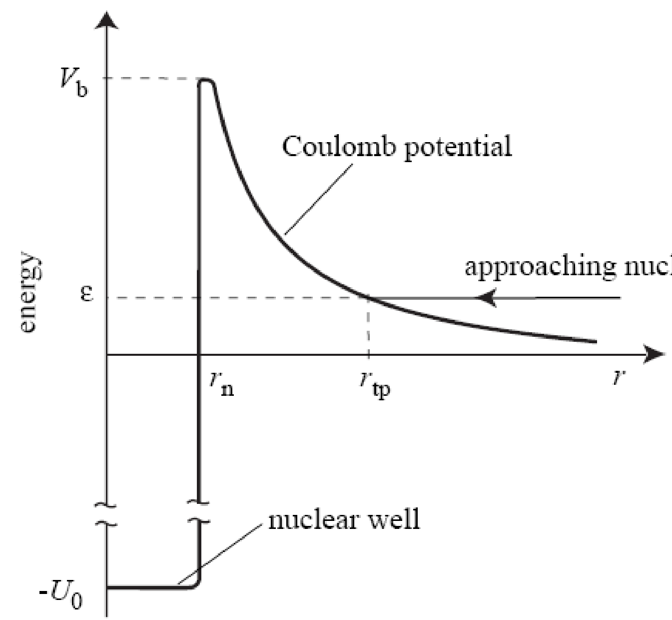


https://zh.pngtree.com/so/%E5%8D%A1%E9%80%9A%E5%B0%84%E7%AE%AD
https://en.wikipedia.org/wiki/Cross_section_(physics)

Cross section of fusion reaction is much larger than the classical approach



- Classical kinetic energy required for fusion is $K_{\text{c.m.}} > 288\ \text{keV}$!!!
- DT cross section has a peak of ~5 barns at 120 keV.
- $\sigma_{DT} \approx 100\sigma_{DD}$ @ 20 keV.



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

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

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

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

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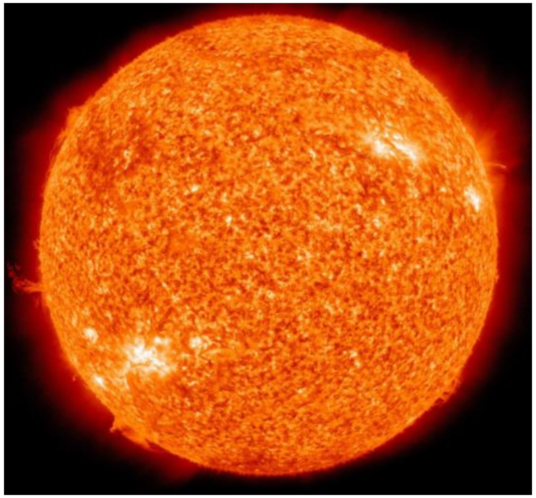
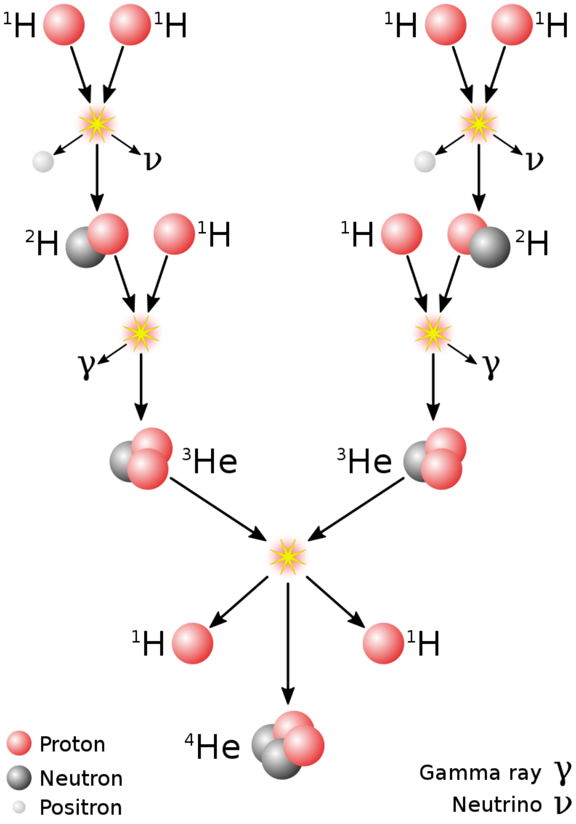
https://i.stack.imgur.com/wXQD5.jpg

Santarius, J. F., "Fusion Space Propulsion – A Shorter Time Frame Than You Think", JANNAF, Monterey, 5-8 December 2005.

Fusion in the sun provides the energy

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

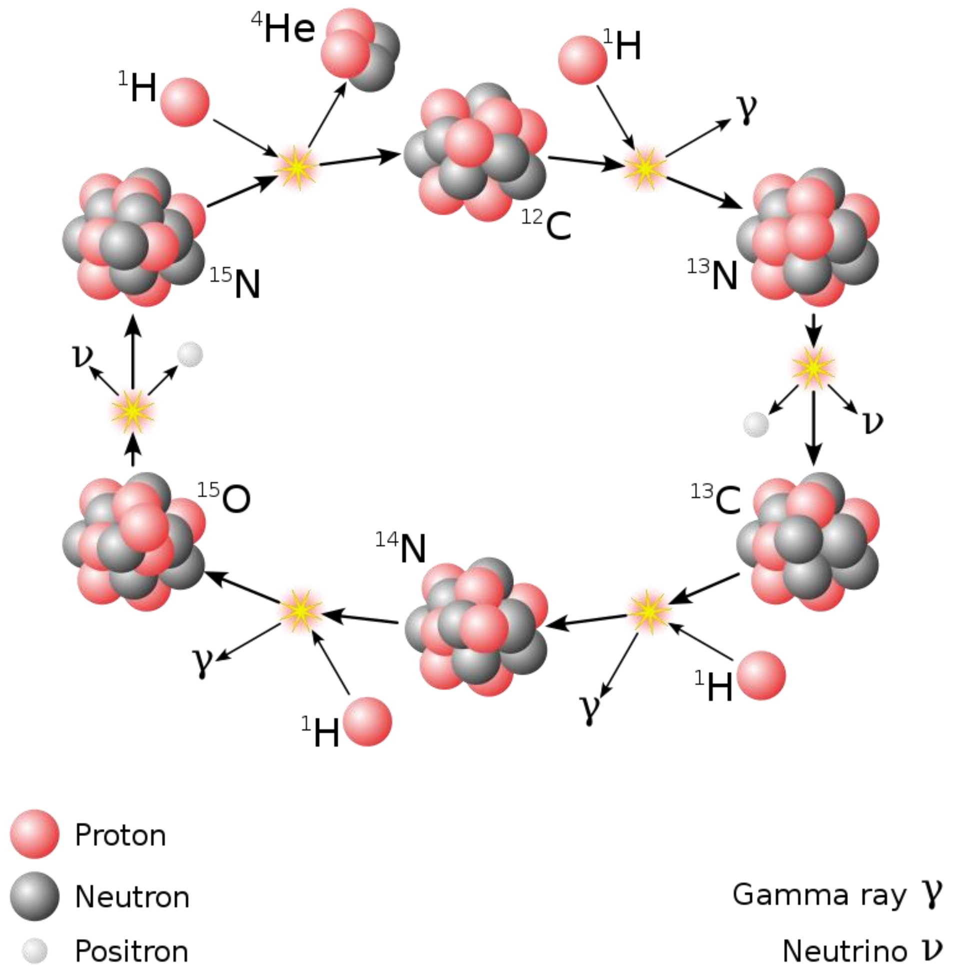




- **Particles are confined by the gravity.**

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

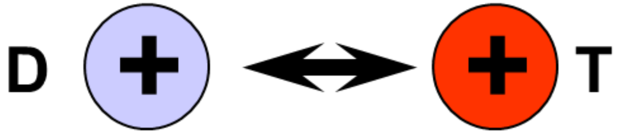
Reaction	$\sigma_{10\ keV}$ (barn)	$\sigma_{100\ keV}$ (barn)	σ_{max} (barn)	ε_{max} (keV)
$D+T \rightarrow \alpha+n$	2.72×10^{-2}	3.43	5.0	64
$D+D \rightarrow T+p$	2.81×10^{-4}	3.3×10^{-2}	0.06	1250
$D+D \rightarrow {}^{3}He+n$	2.78×10^{-4}	3.7×10^{-2}	0.11	1750
$T+T \rightarrow \alpha+2n$	7.90×10^{-4}	3.4×10^{-2}	0.16	1000
$D+{}^{3}He \rightarrow \alpha+p$	2.2×10^{-7}	0.1	0.9	250
$p+{}^{6}Li \rightarrow \alpha+{}^{3}He$	6×10^{-10}	7×10^{-3}	0.22	1500
$p+{}^{11}B \rightarrow 3\alpha$	(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.

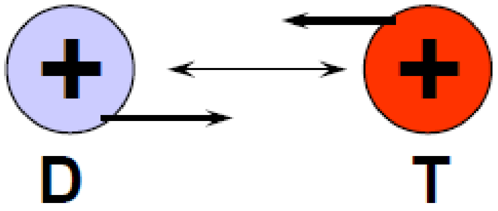
The Physics of Inertial Fusion, by Stefano Atzeni and Jürgen Meyer-Ter-Vehn

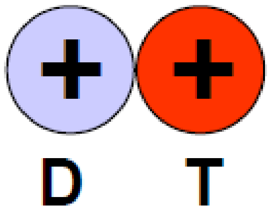
A “hot plasma” at 100M ⁰C is needed

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



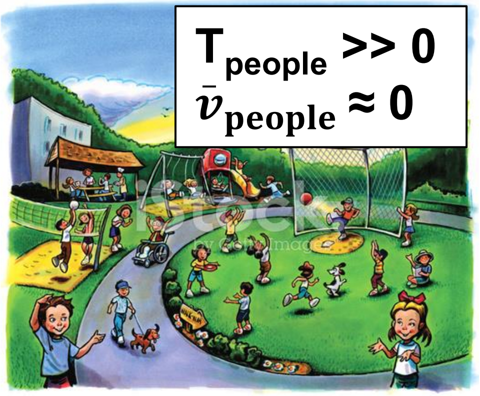
- If the ions are sufficiently hot, i.e., large random velocity, they can collide by overcoming coulomb repulsion

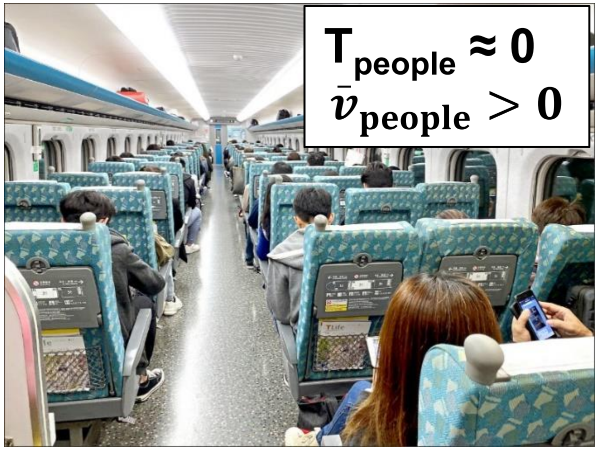




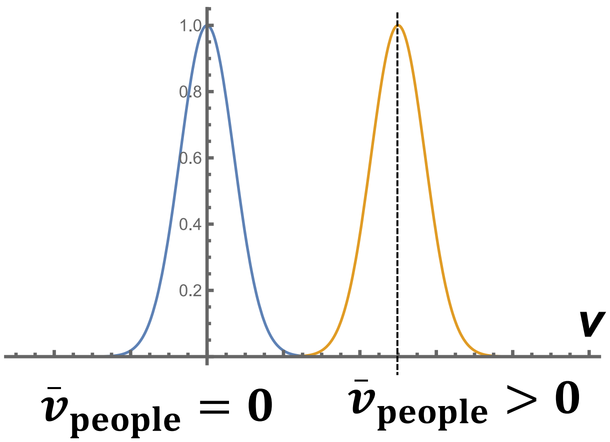
*R. Betti, HEDSA HEDP Summer School, 2015

A temperature describes the randomness of particles



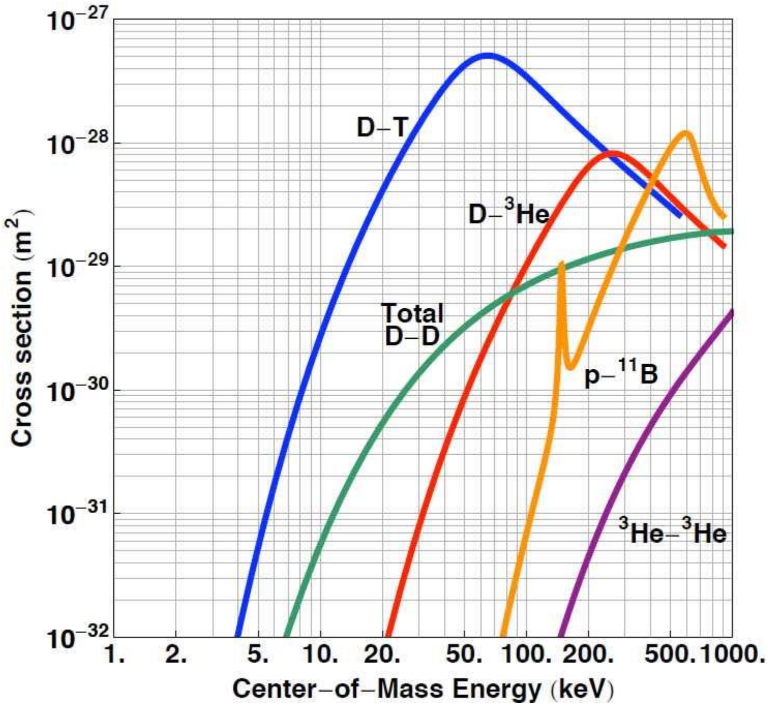


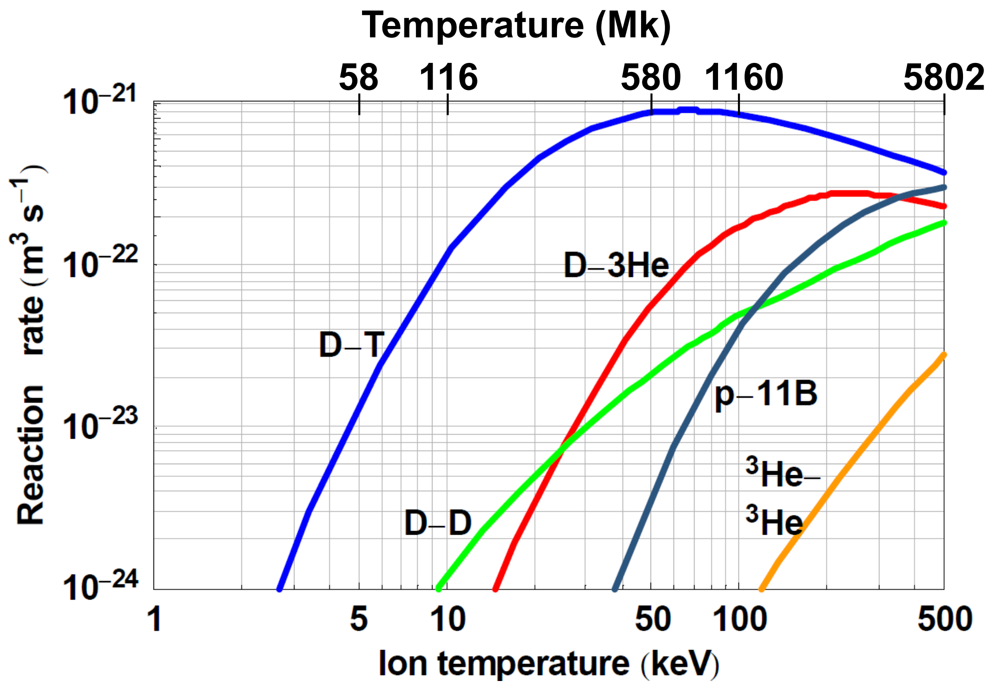
- **Distribution function:**



https://ydweb.yuda.tyc.edu.tw/Page/YDW/School/Home/Post?id=13286&BoardName=%E6%A1%83%E8%82%B2%E6%B4%BB%E5%8B%95%E7%85%A7%E7%89%87&Board_PartialViewName=&Post_PartialViewName=&Page=60&PageSize=3
https://www.freeimages.com/tw/premium/school-playground-with-children-1496555

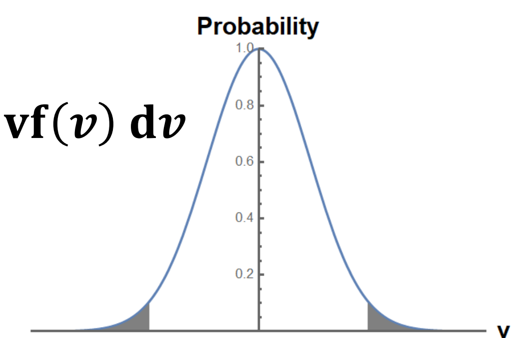
Fusion doesn’t come easy





- **Reaction rate:**

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



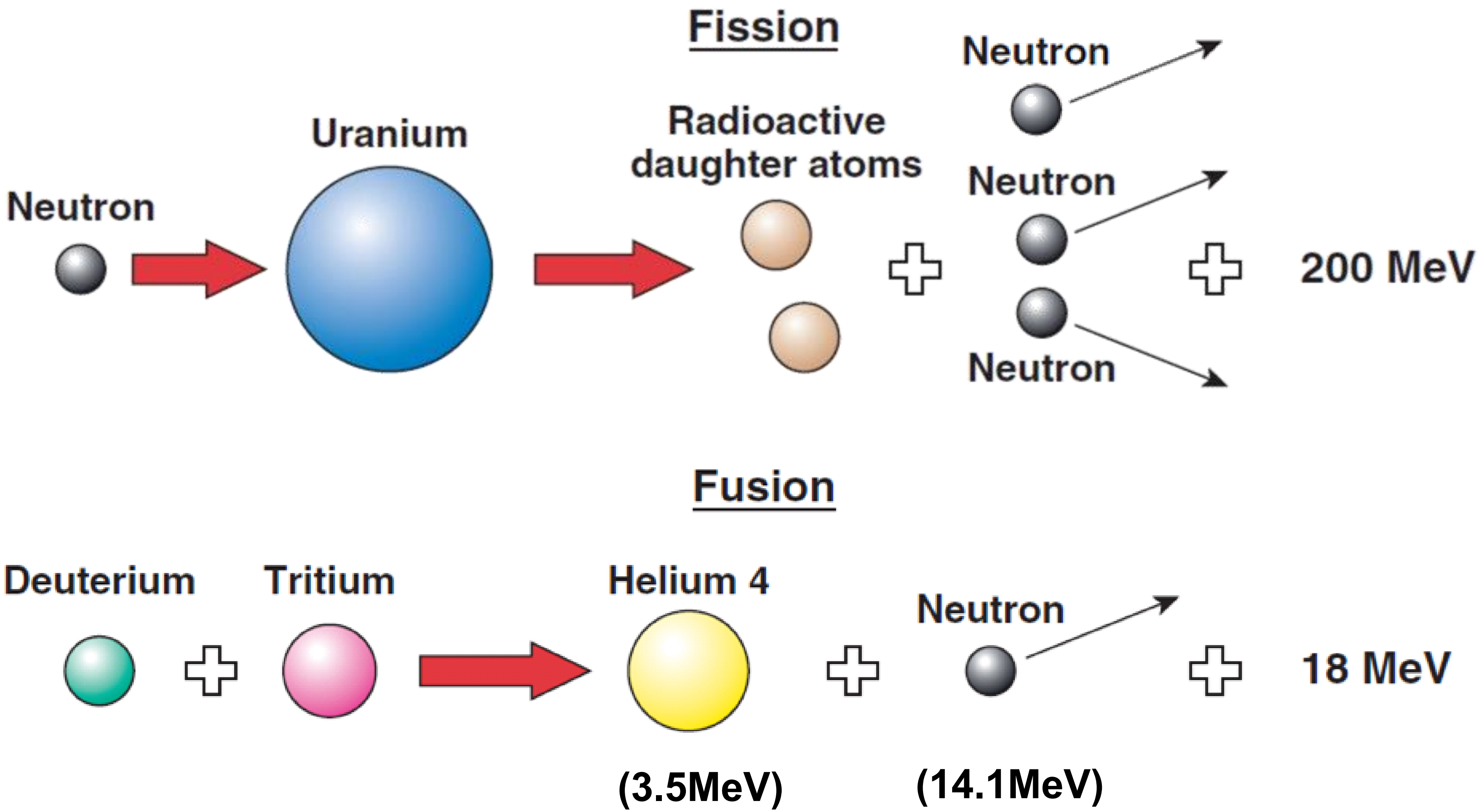
- **The DT fusion reactivity is maximum at T ≈ 64 keV**
- **@ T = 10 keV,** $< \sigma v >_{DT} \approx 100 < \sigma v >_{DD}$

---

https://i.stack.imgur.com/wXQD5.jpg

Santarius, J. F., “Fusion Space Propulsion – A Shorter Time Frame Than You Think”, JANNAF, Monterey, 5-8 December 2005.

Nuclear fusion and fission release energy through energetic neutrons



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

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

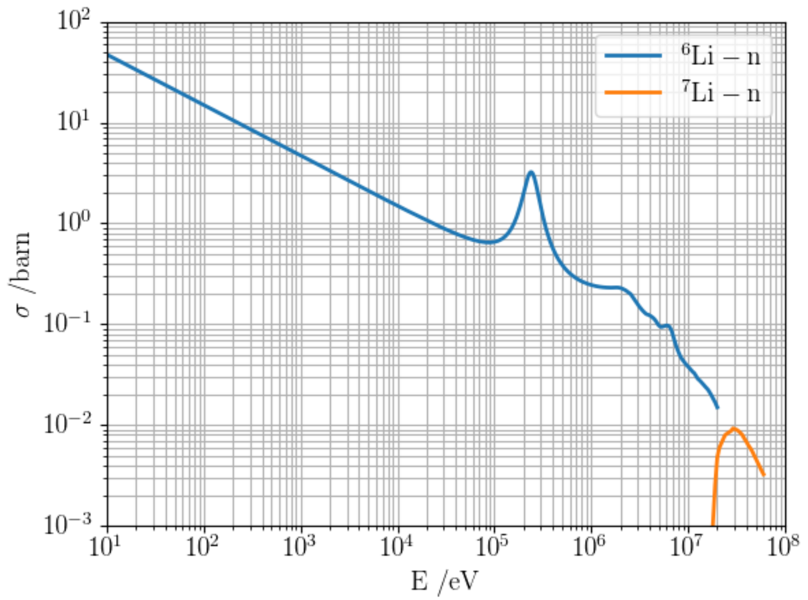
	Half-life (years)
U235	7.04×10^{8}
U238	4.47×10^{9}
…	
Tritium	12.3

- **Tritium breeding:**

  $n + {}^{6}\mathrm{Li} \rightarrow \alpha + \mathrm{T} + 4.86\ \mathrm{MeV}$

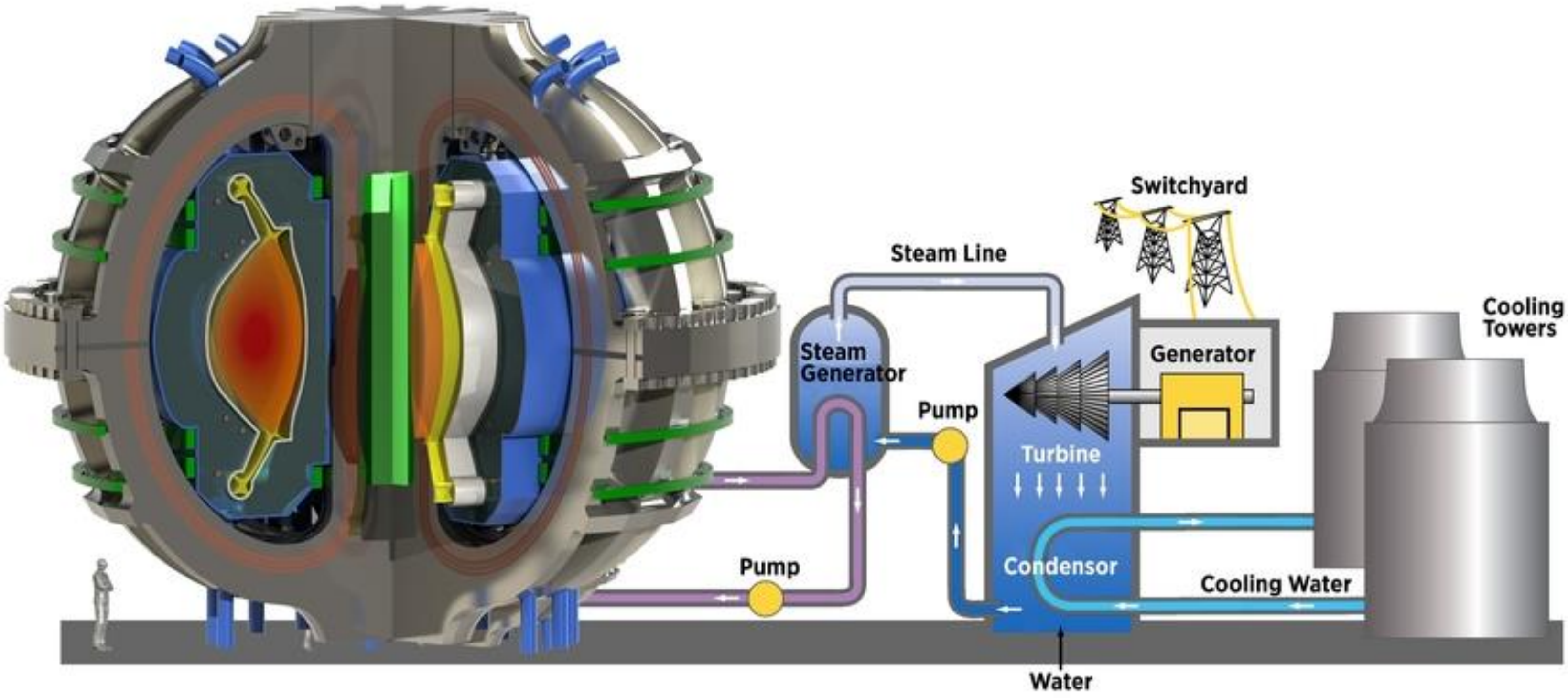
  $n + {}^{7}\mathrm{Li} \rightarrow \alpha + \mathrm{T} + n - 2.87\ \mathrm{MeV}$
- **Neutron multiplier**

$$n + {}^{9}Be \rightarrow 2\,{}^{4}He + 2n$$



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

Nuclear fusion power plant proposed by Commonwealth Fusion Systems (CFS)



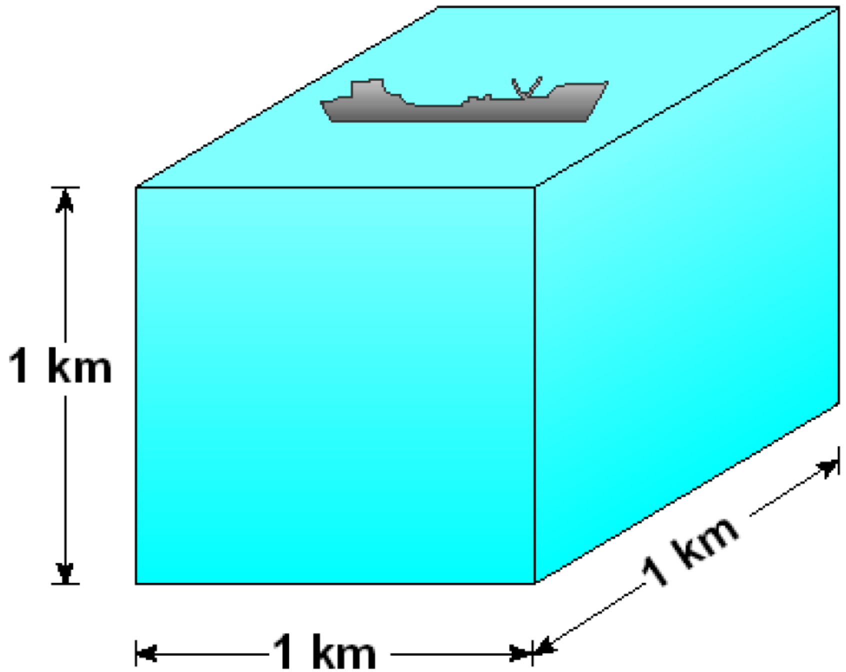
https://news.mit.edu/2018/nas-report-right-path-fusion-energy-1221

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

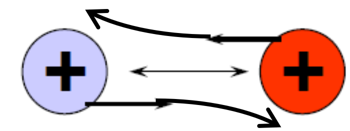


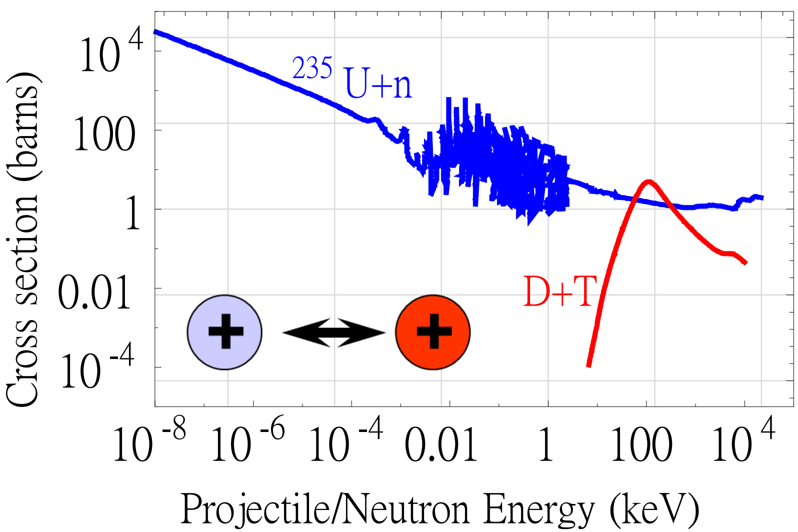
= Total energy of world oil reserve

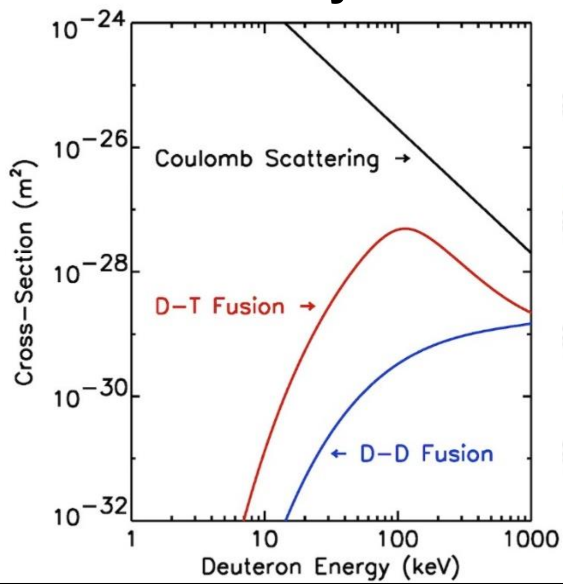
*R. Betti, HEDSA HEDP Summer School, 2015

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:** $D + T \rightarrow {}^{4}_{2}He(3.5\ \mathrm{MeV}) + n(14.1\ \mathrm{MeV})$
  - **Most charged particles do not collide but are scattered with each other.**
  - **Particles are confined and heated so that they collide eventually.**





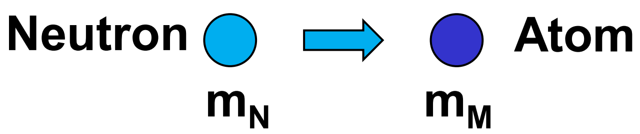


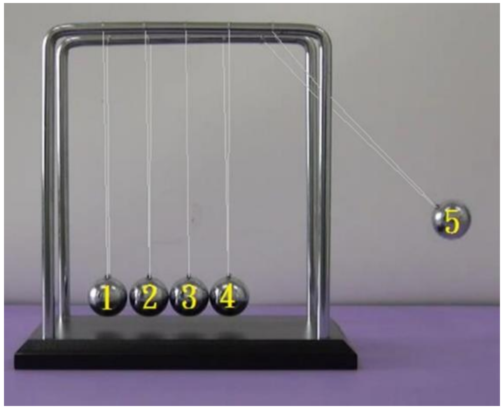
- **Beam particles lose their energy before making a fusion reaction, i.e., they only thermalize the fuel. Therefore, beam fusion does NOT work!**

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

Fast neutrons are slowed down due to the collisions

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



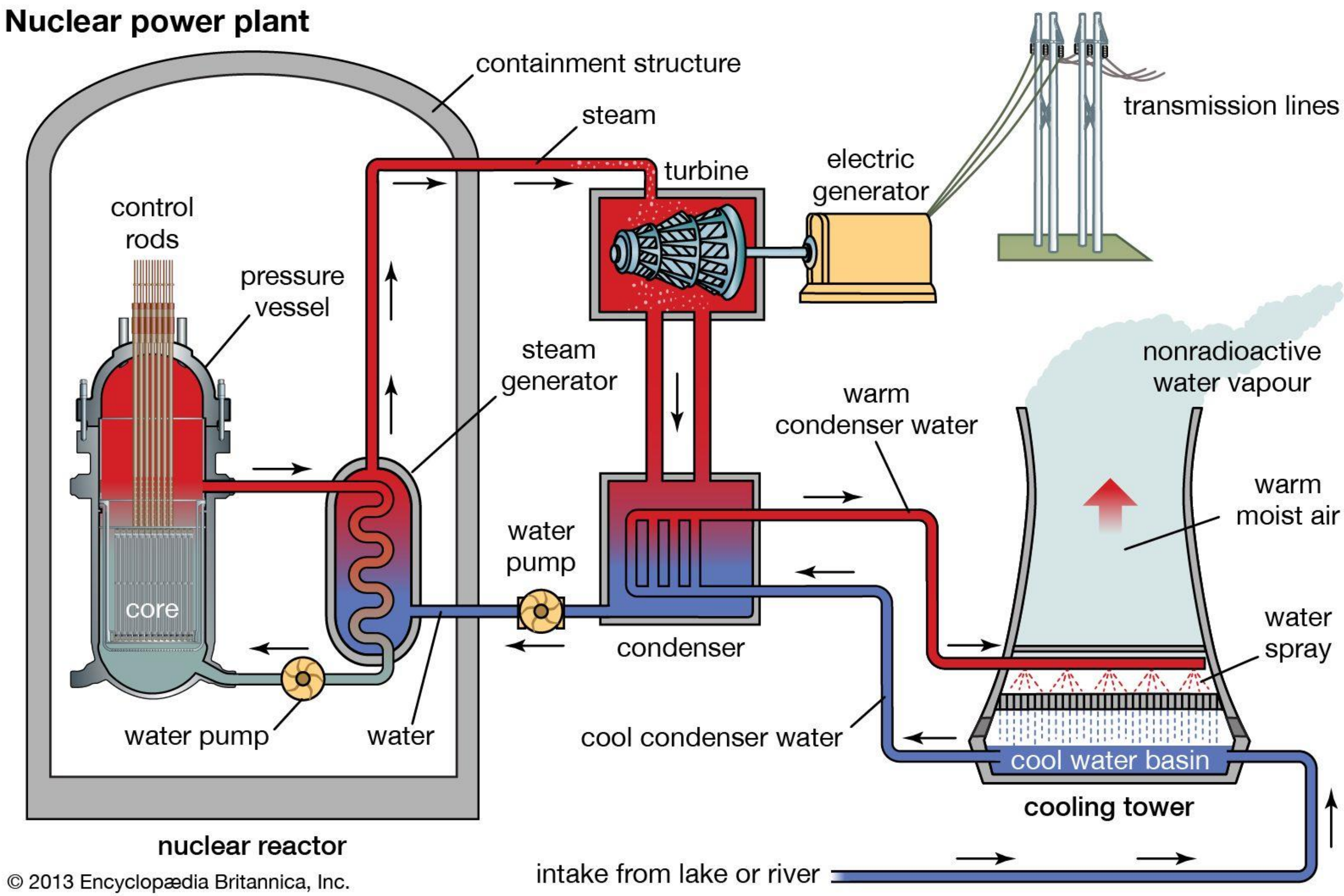


- The best option is the D in the heavy water (D_2O).

	Energy decrement	Neutron scattering cross section (σ_s) (Barns)	Neutron absorption cross section (σ_a) (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

Nuclear power plant

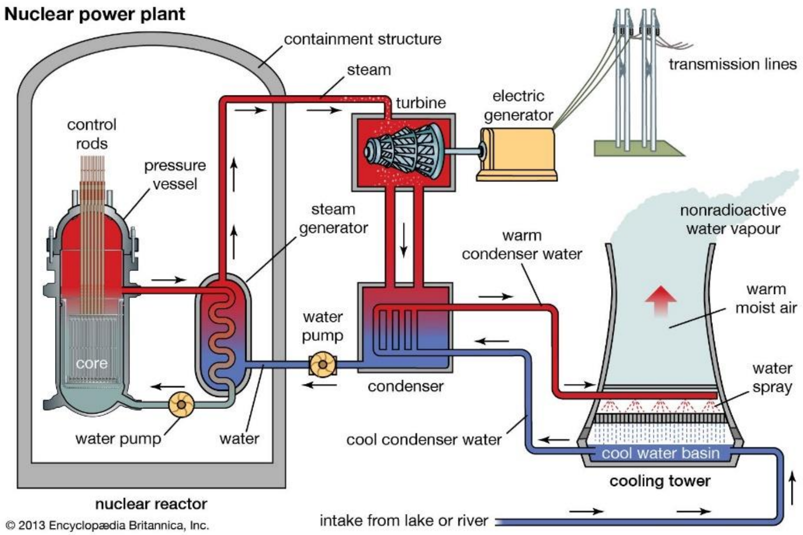


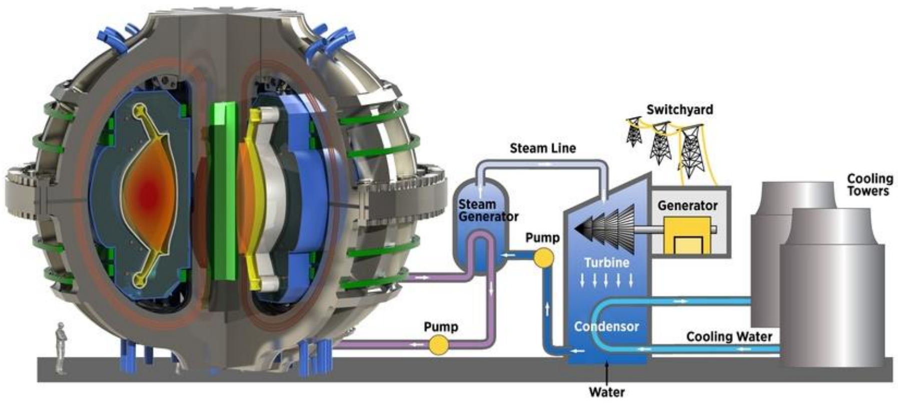
https://www.britannica.com/technology/nuclear-power

Comparison between nuclear fission and nuclear fusion

	Nuclear Fission	Nuclear Fusion
Chain reaction	Yes	No
Melt down	Possible	Impossible
Nuclear waste	High radiative	Low radiative / None

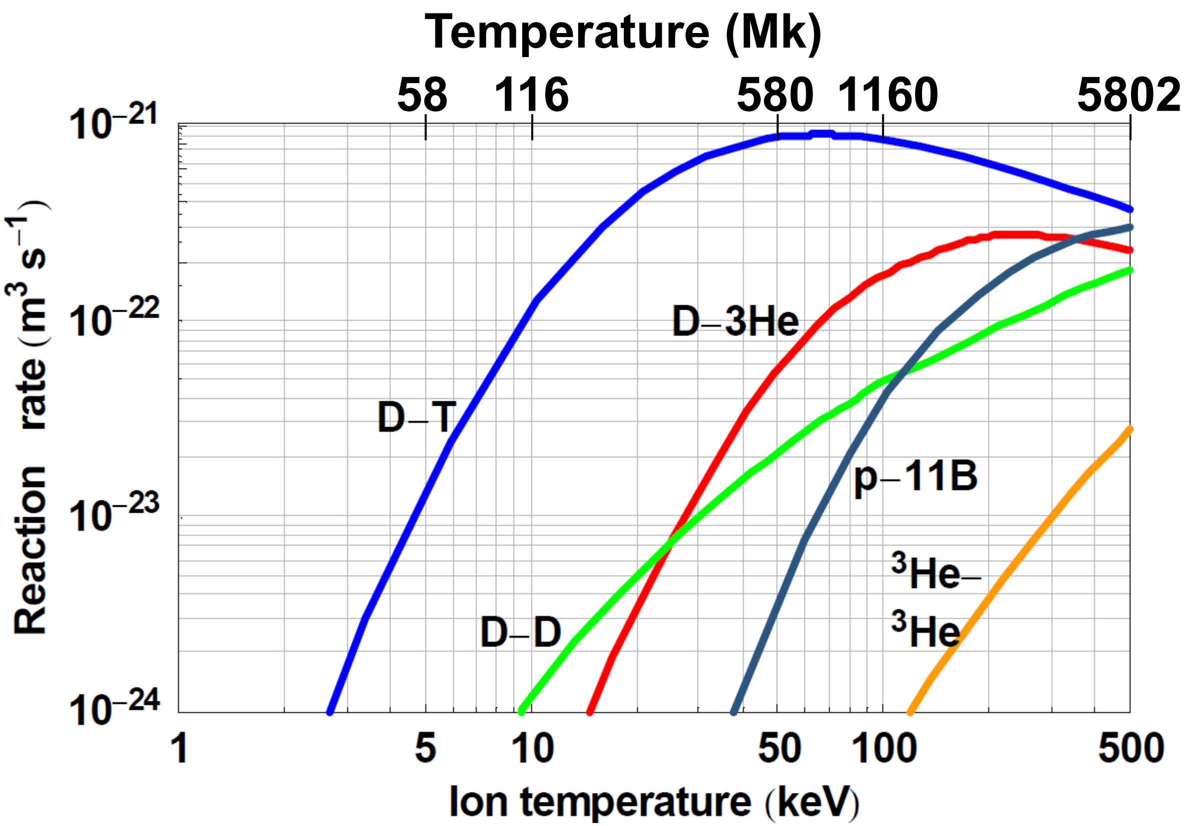
- Nuclear fission power plant
- Nuclear fussion power plant





https://www.britannica.com/technology/nuclear-power
https://news.mit.edu/2018/nas-report-right-path-fusion-energy-1221

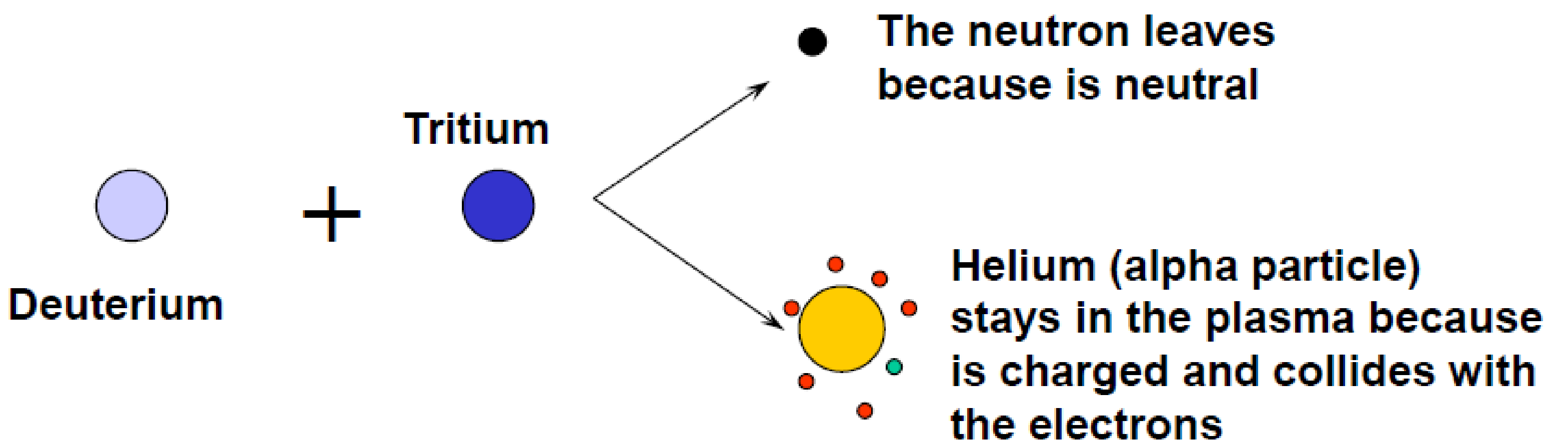
Fusion doesn't come easy



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

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

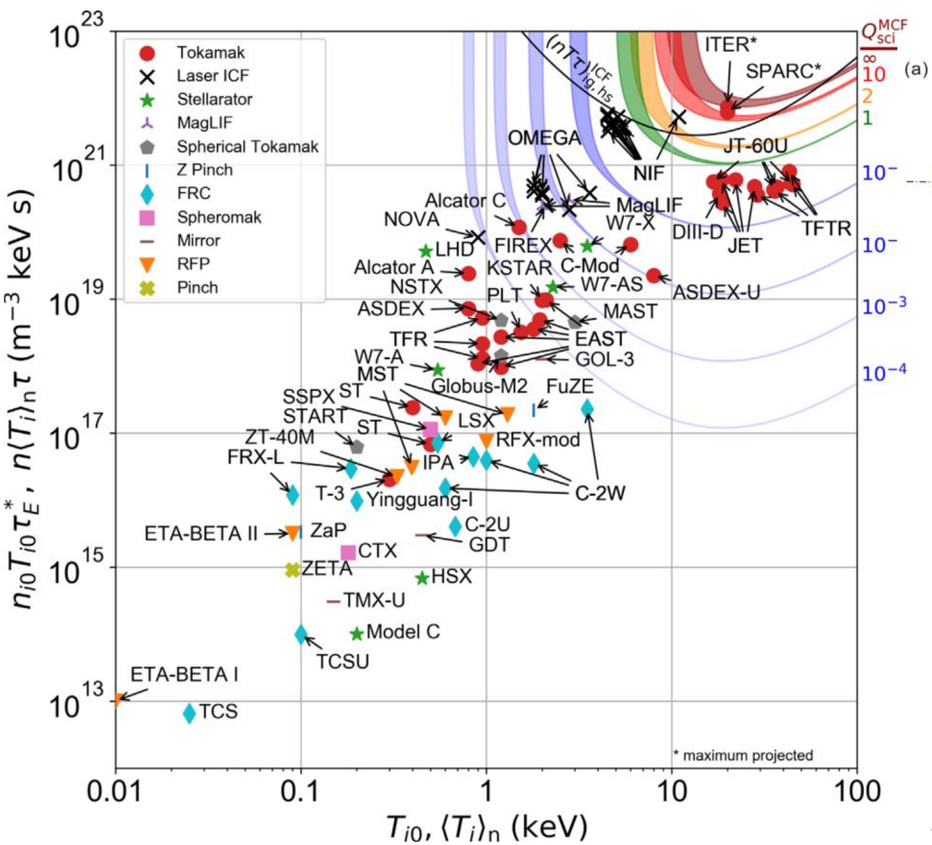
S_B: Bremsstrahlung radiation

S_k: heat conduction lost

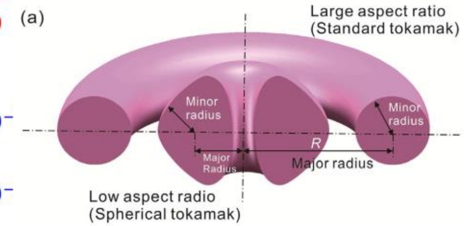
Ignition condition: $P\tau$ > 10 atm-s = 10 Gbar - ns

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

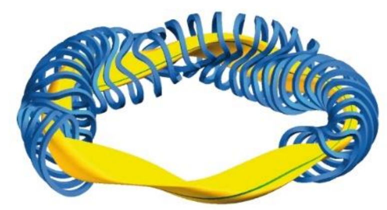
We are closed to ignition!



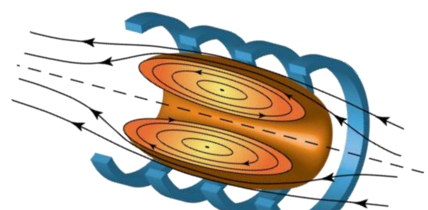
MCF | ICF



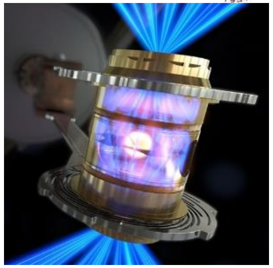
(Spherical) tokamak



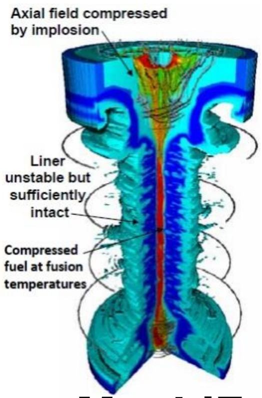
Stellerator



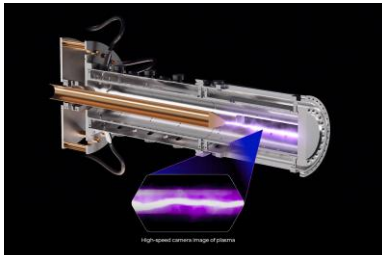
FRC



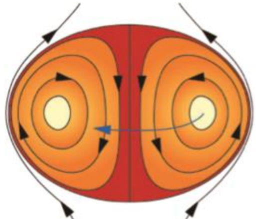
Laser ICF



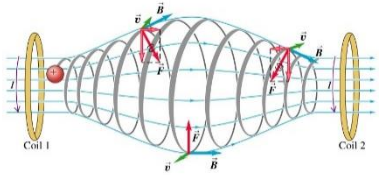
MagLIF



Sheared-flow Z pinch



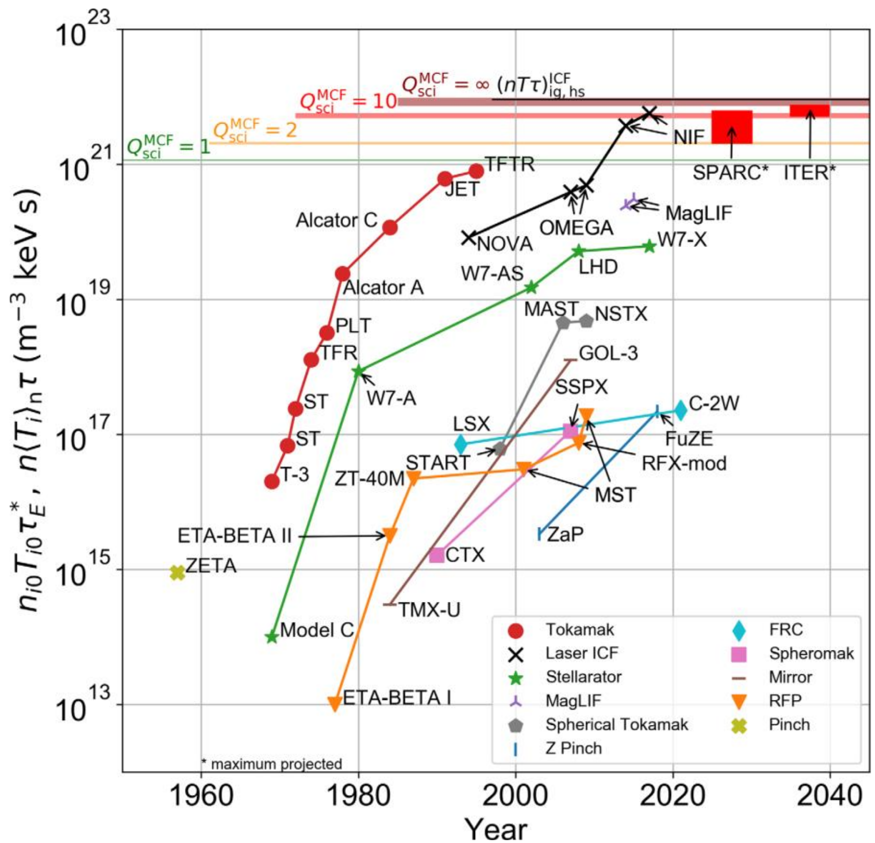
Spheromak

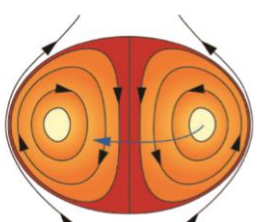


Mirror

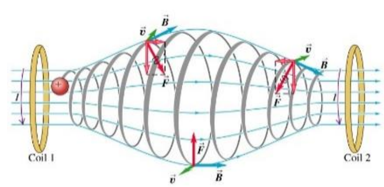
Samuel E. Wurzel and Scott C. Hsu, Phys. Plasmas, **29**, 062103 (2022)

We are closed to ignition!



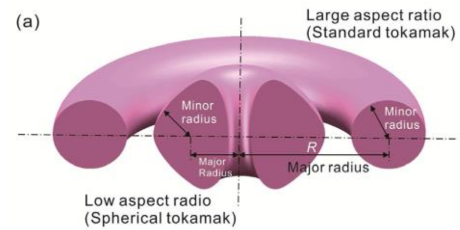


Spheromak

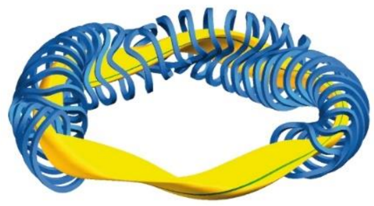


Mirror

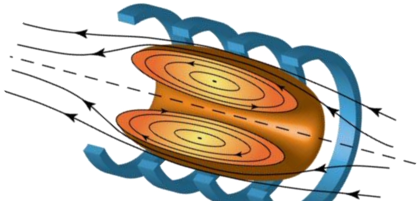
MCF | **ICF**



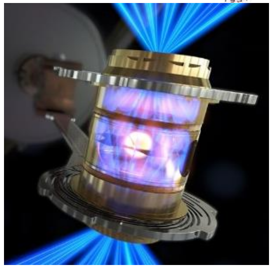
(Spherical) tokamak



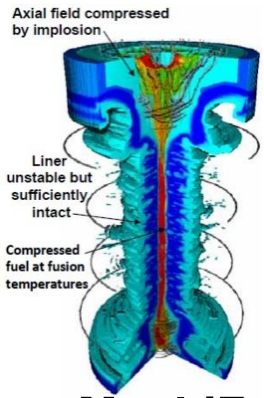
Stellerator



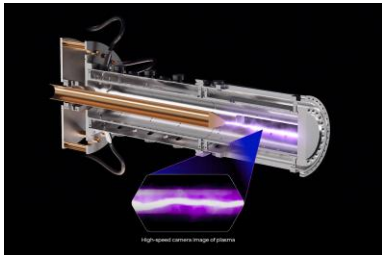
FRC



Laser ICF



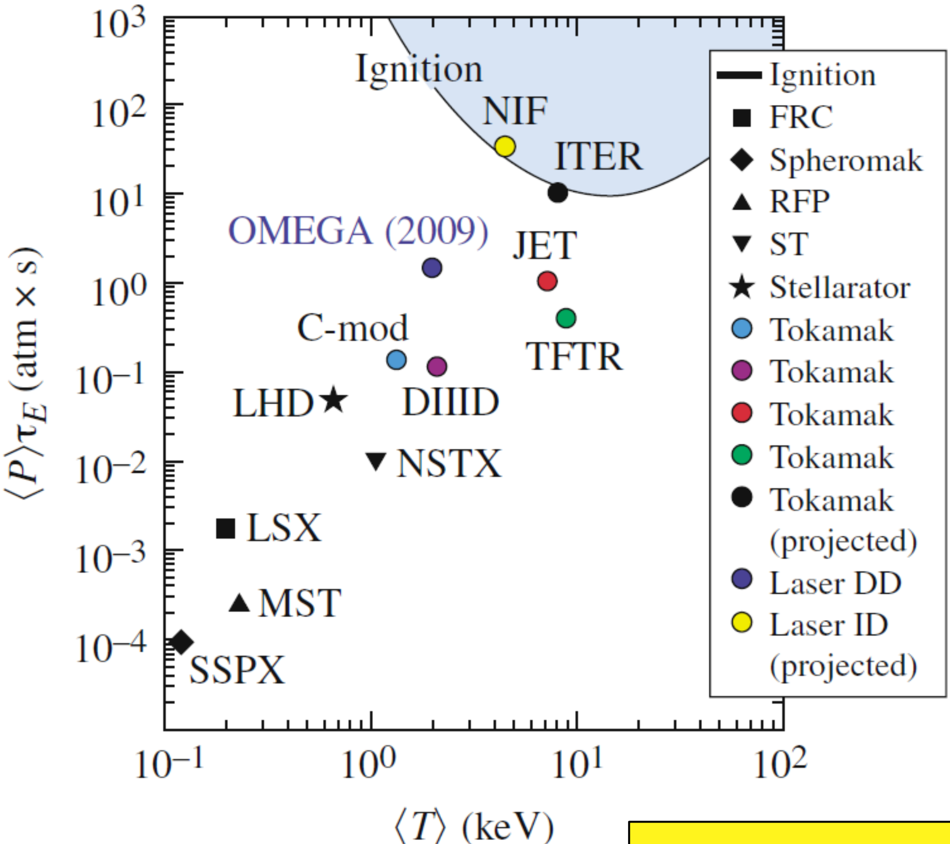
MagLIF

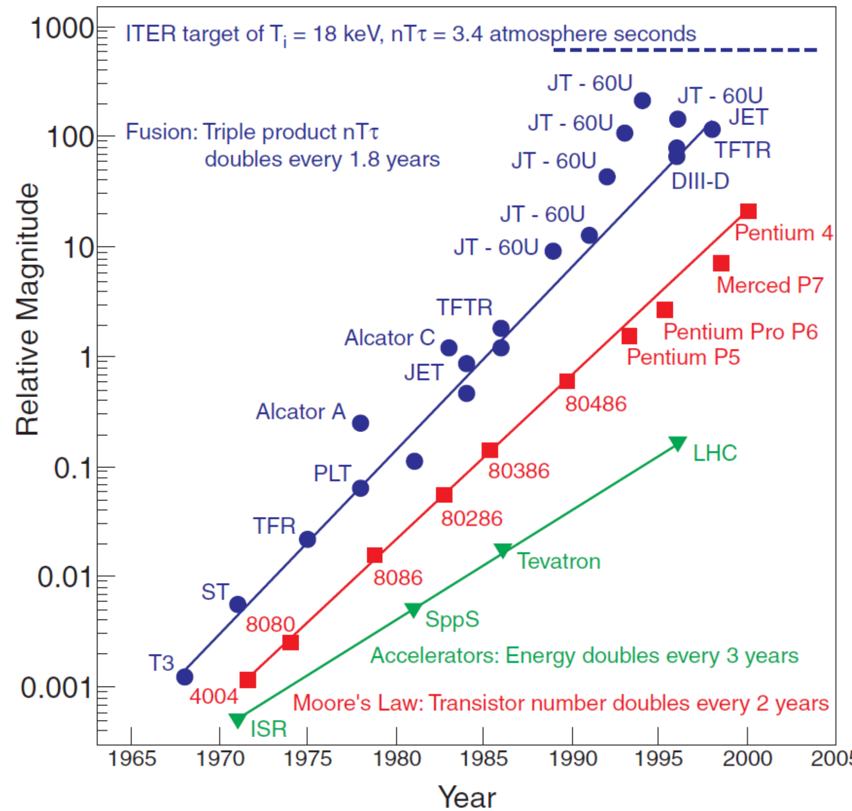


Sheared-flow Z pinch

Samuel E. Wurzel and Scott C. Hsu, Phys. Plasmas, **29**, 062103 (2022)

We are closed to ignition!



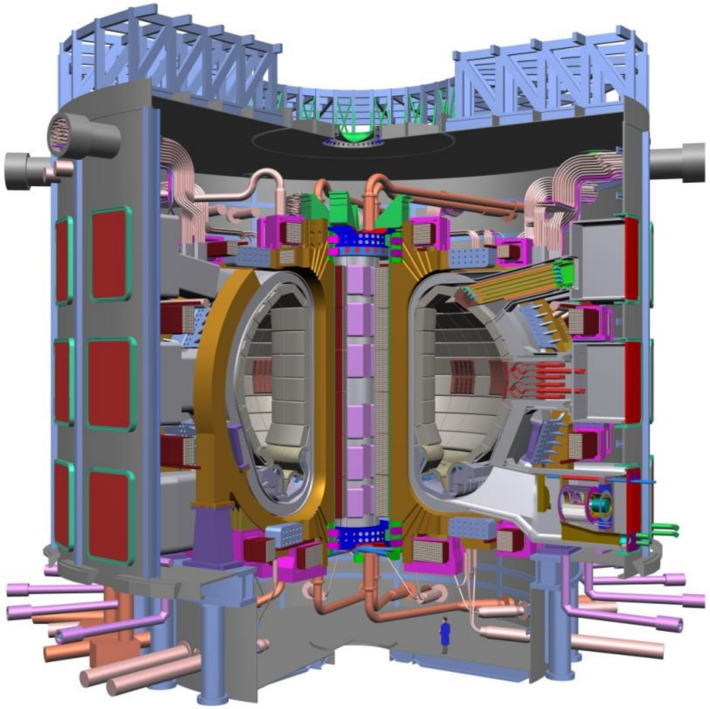


Ignition condition: Pτ > 10 atm-s = 10 Gbar - ns

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

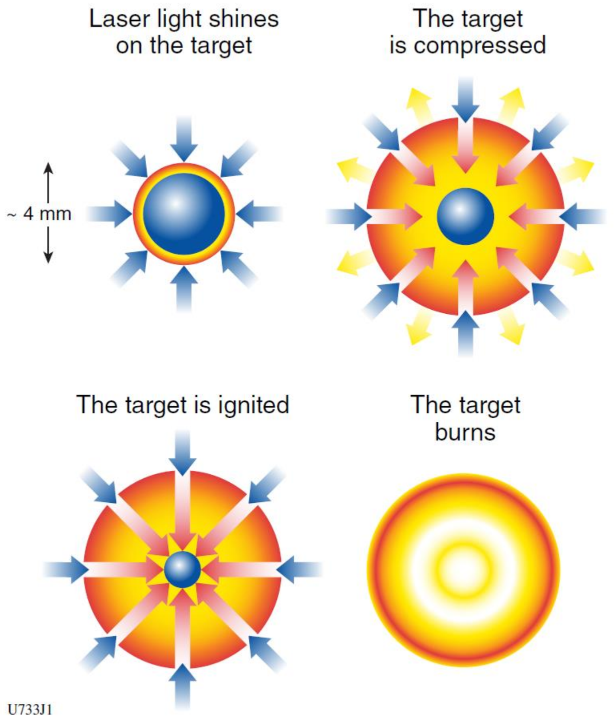
To control? Or not to control?

- **Magnetic confinement fusion (MCF)**



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

- **Inertial confinement fusion (ICF)**

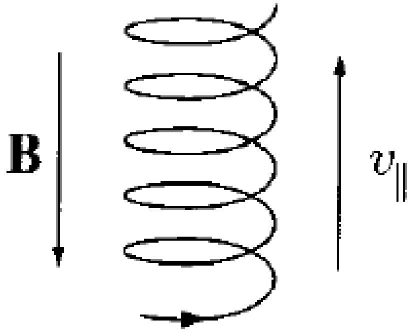


  - **A DT ice capsule filled with DT gas is imploded by laser.**

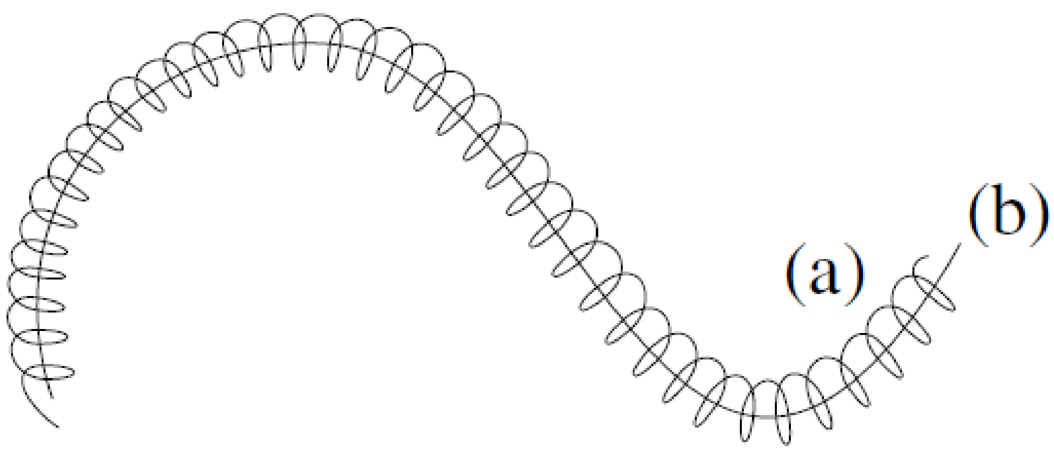
Course Outline

- What is Plasma?
- **Nuclear fusion**
  - Basic
  - **Magnetic confinement fusion (MCF)**
  - Inertial confinement fusion (ICF)
- Formosa Integrated Research Spherical Tokamak (FIRST), the first Tokamak in Taiwan

Charged particles gyro around the magnetic fields

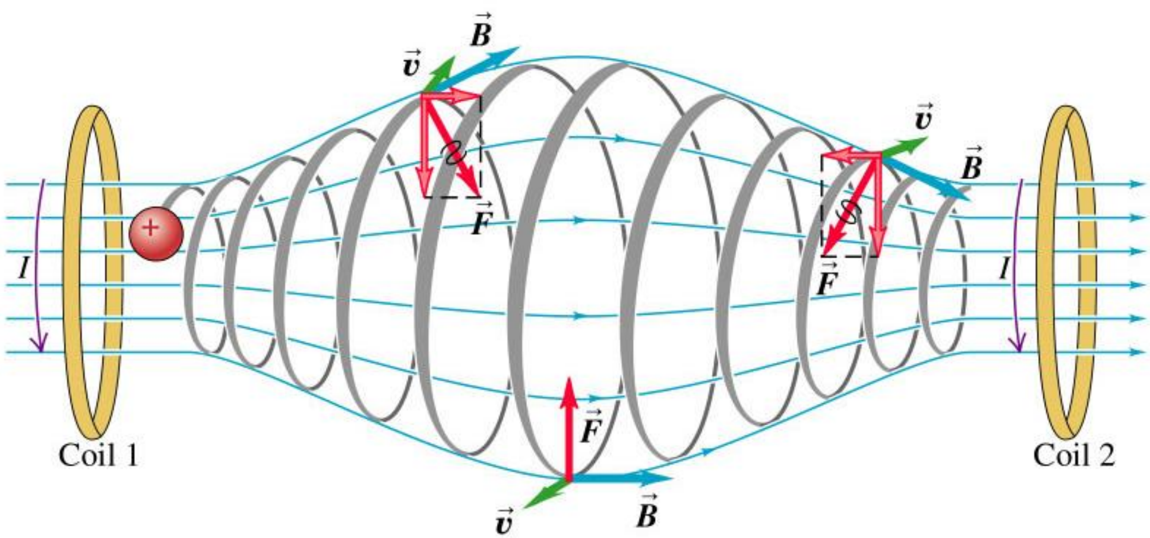


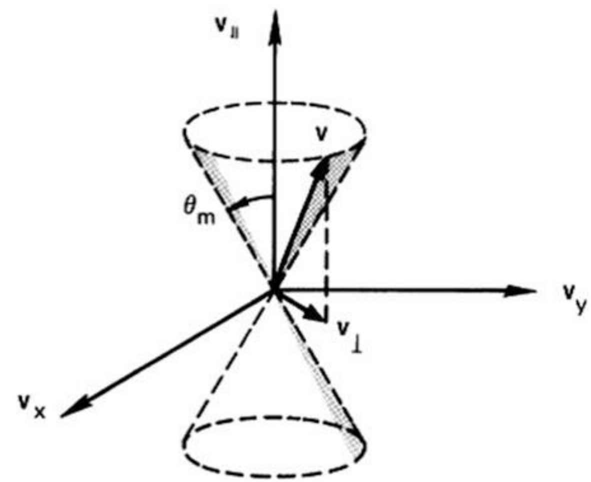
$$r_L = \frac{mv_\perp}{|q|B}$$



Charged particles can be partially confined by a magnetic mirror machine

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





$$v'_{\perp}{}^2 = v_{\perp o}{}^2 + v_{||o}{}^2 \equiv v_o{}^2$$

$$\frac{B_o}{B'} = \frac{v_{\perp o}{}^2}{v'_{\perp}{}^2} = \frac{v_{\perp o}{}^2}{v_o{}^2} \equiv \sin^2\theta$$

$$\frac{1}{2}mv^2 = \frac{1}{2}mv_{||}{}^2 + \frac{1}{2}mv_{\perp}{}^2 \qquad \text{Invarient: } \mu \equiv \frac{1}{2}\frac{mv_{\perp}{}^2}{B}$$

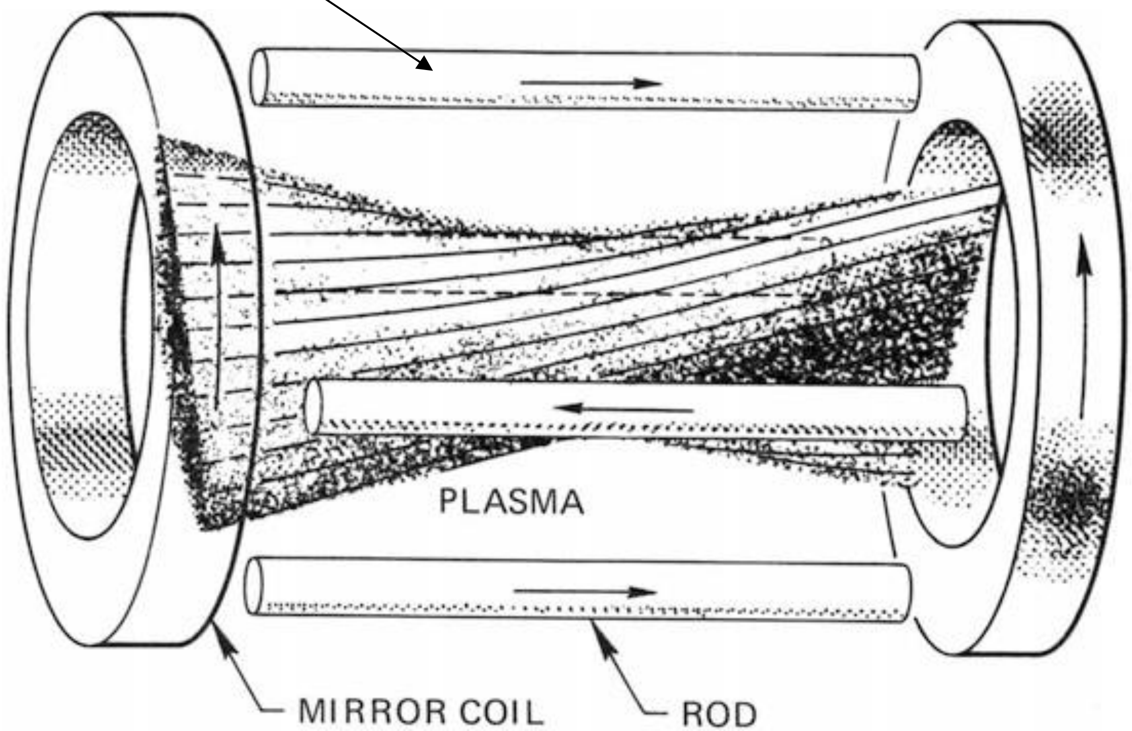
$$\frac{B_o}{B_m} \equiv \frac{1}{R_m} = \sin^2\theta_m$$

- **Large $v_{||}$ may occur from collisions between particles.**
- **Those confined charged particle are eventually lost due to collisions.**

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

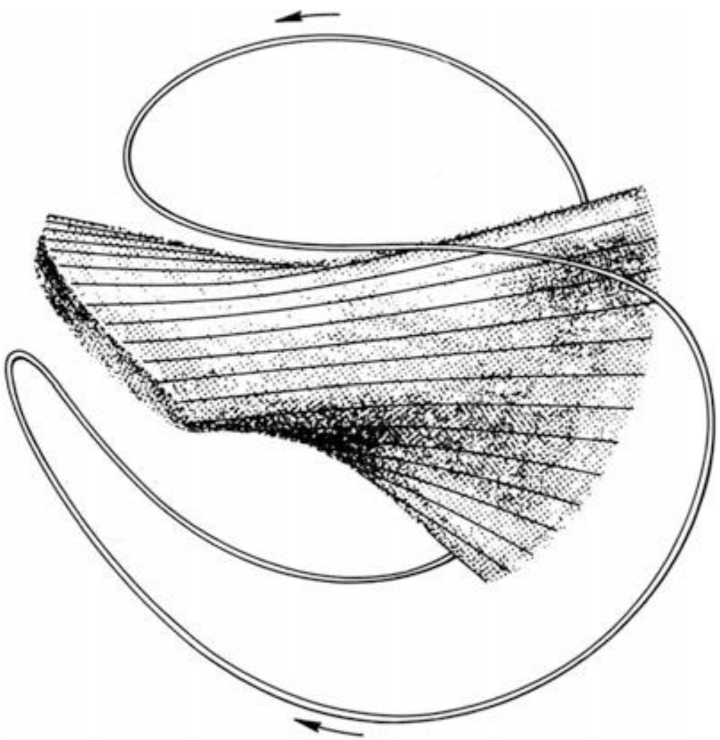
"Ioffe bars" are added to stabilize the Rayleigh-Taylor instabilities at the center of the mirror machine

Ioffe bars



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

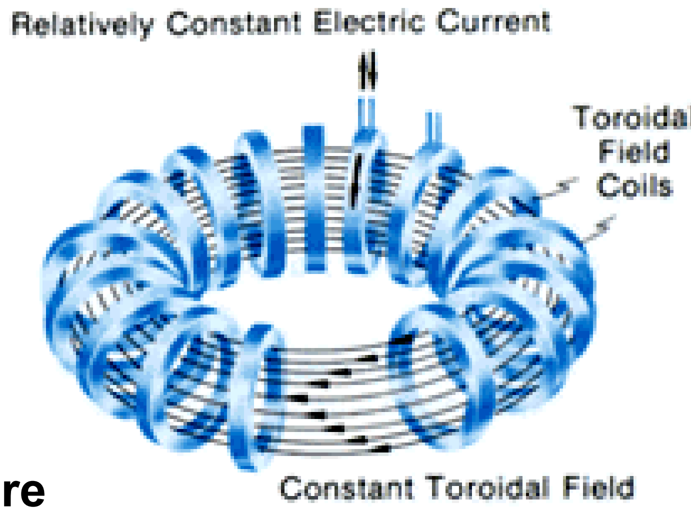
- **Baseball coil**

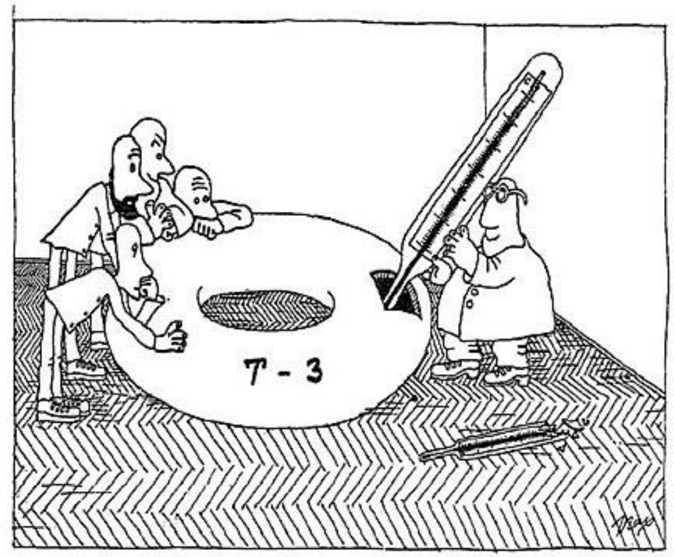


- **MFTF-B mirror machine**

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

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





Nature

Measurement of the Electron Temperature by Thomson Scattering in Tokamak T3

by

N. J. PEACOCK
D. C. ROBINSON
M. J. FORREST
P. D. WILCOCK

UKAEA Research Group,
Culham Laboratory,
Abingdon, Berkshire

V. V. SANNIKOV

I. V. Kurchatov Institute,
Moscow

Electron temperatures of 100 eV up to 1 keV and densities in the range $1\text{–}3 \times 10^{13}$ cm^{-3} have been measured by Thomson scattering on Tokamak T3. These results agree with those obtained by other techniques where direct comparison has been possible.

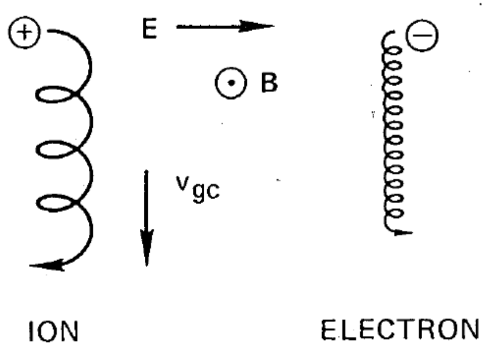
T_e = 100 ~ 1 keV
n_e = 1-3 x 10^{13} cm^{-3}

---

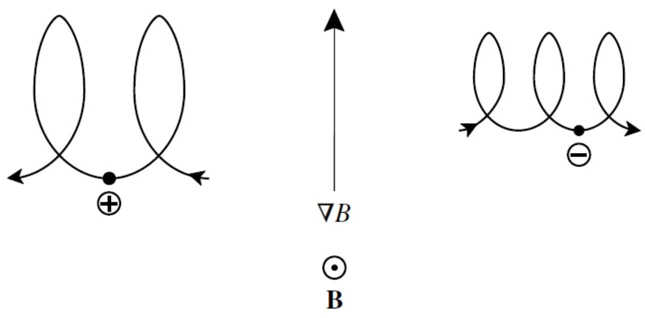
https://www.iter.org/mach/tokamak
https://en.wikipedia.org/wiki/Tokamak#cite_ref-4
Drawing from the talk “Evolution of the Tokamak” given in 1988 by B.B. Kadomtsev at Culham.
N. J. Peacock,et al., Nature **224**, 488 (1969)

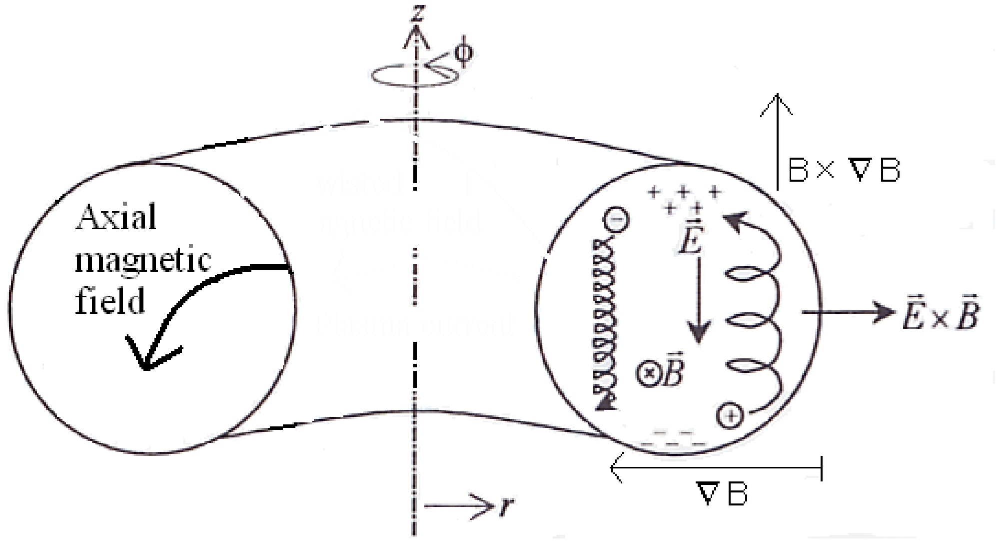
Charged particles drift across field lines

- **ExB drift**



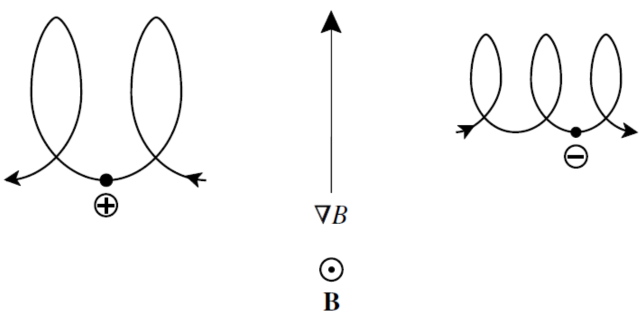
- **Grad-B drift**



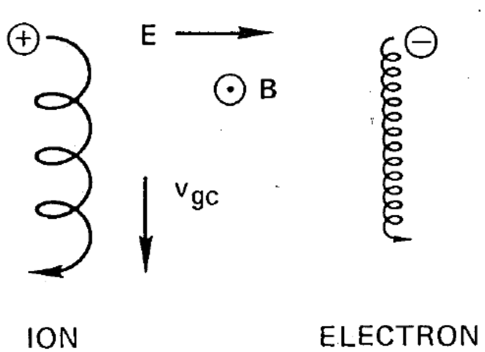


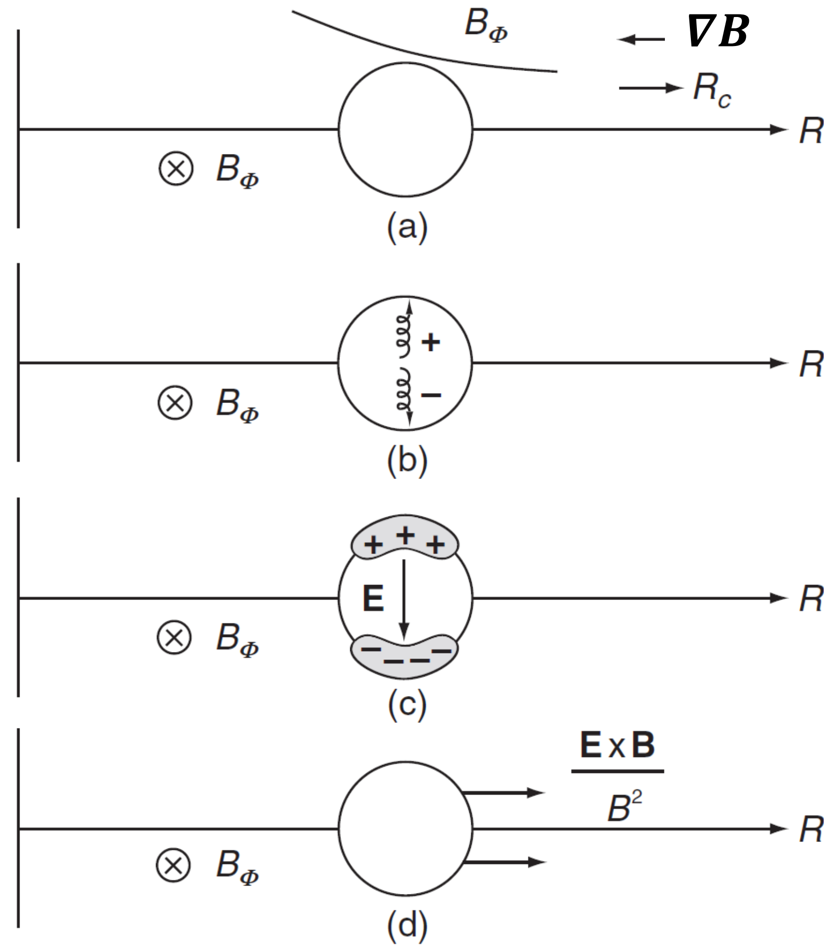
Charged particles drift across field lines

- **Grad-B drift**



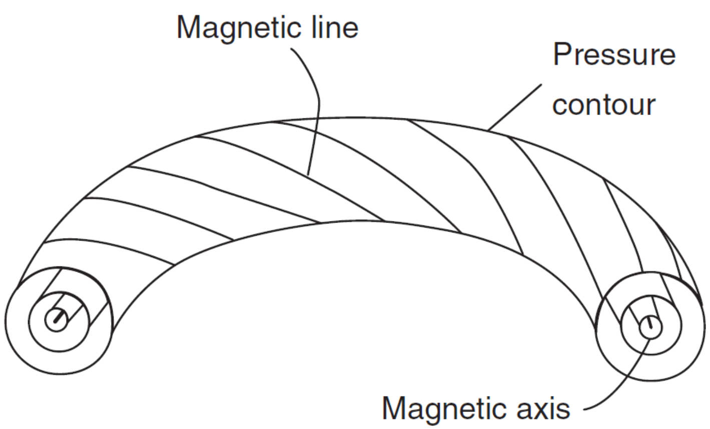
- **ExB drift**

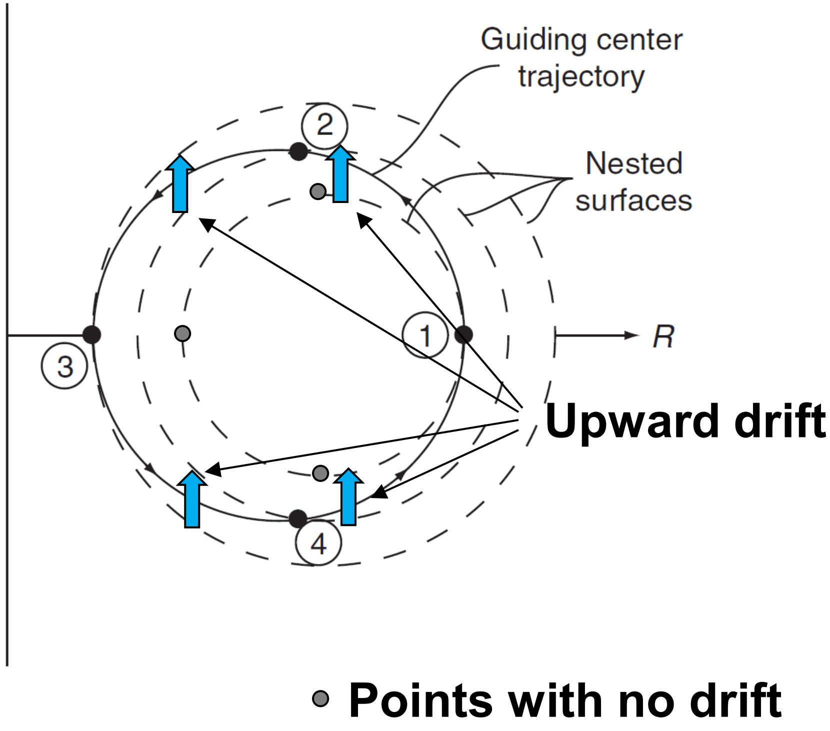




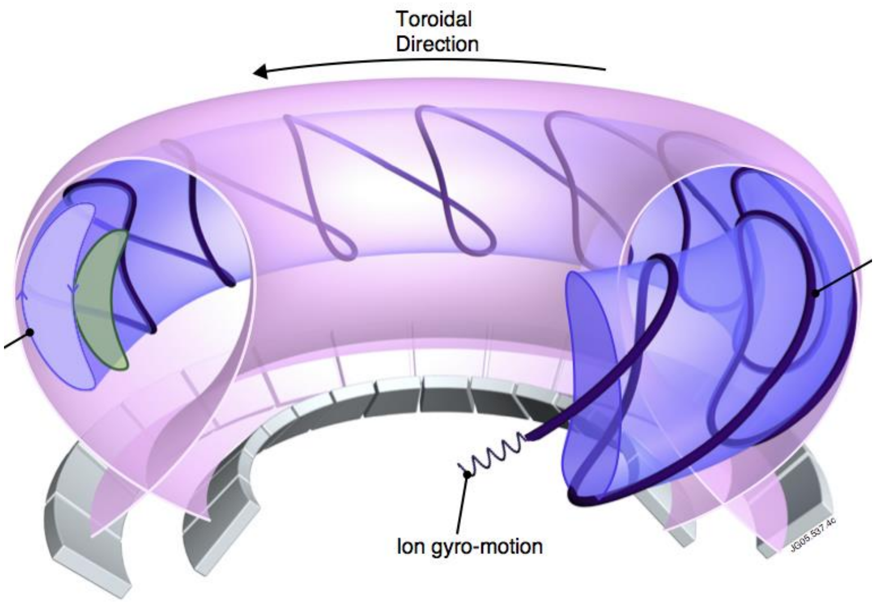
J. P. Freidberg, Ideal Magnetohydrodynamics

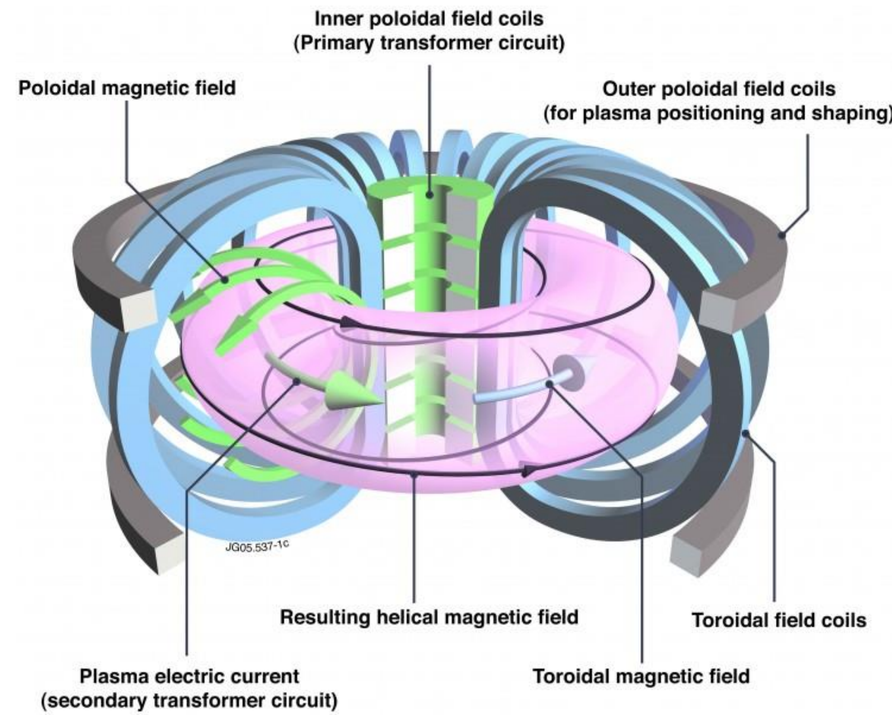
The particle drifts back to the original position if a small poloidal field is superimposed on the toroidal field





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



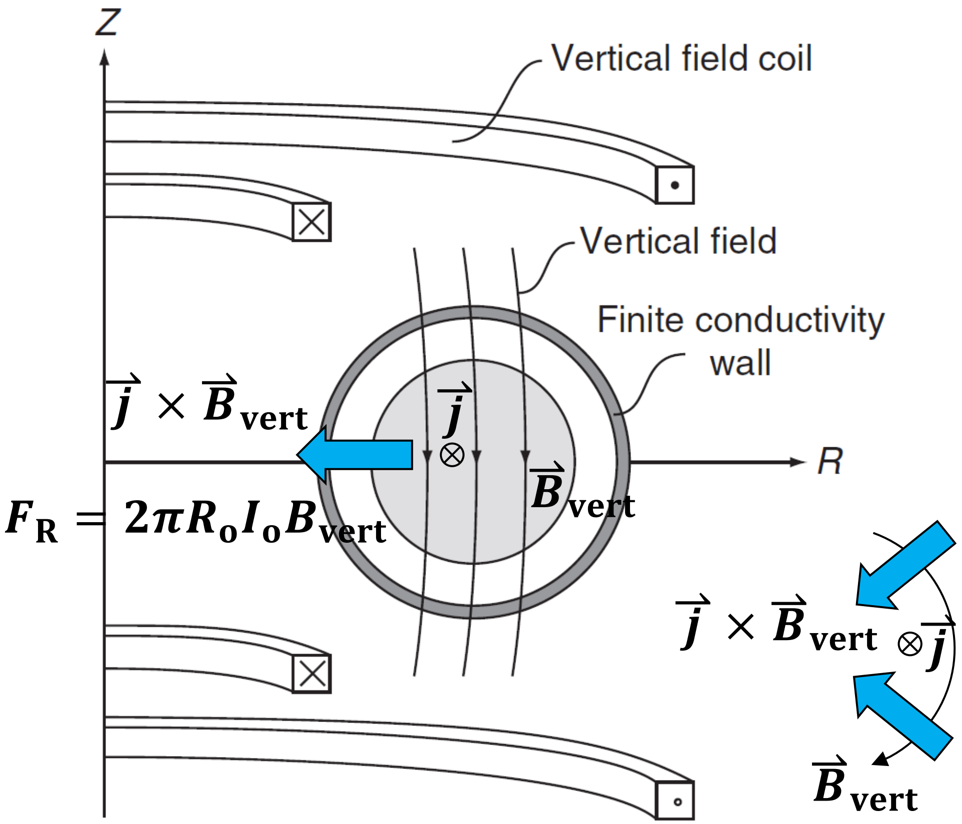


https://www.davidpace.com/keeping-fusion-plasmas-hot/
https://www.euro-fusion.org/2011/09/tokamak-principle-2/

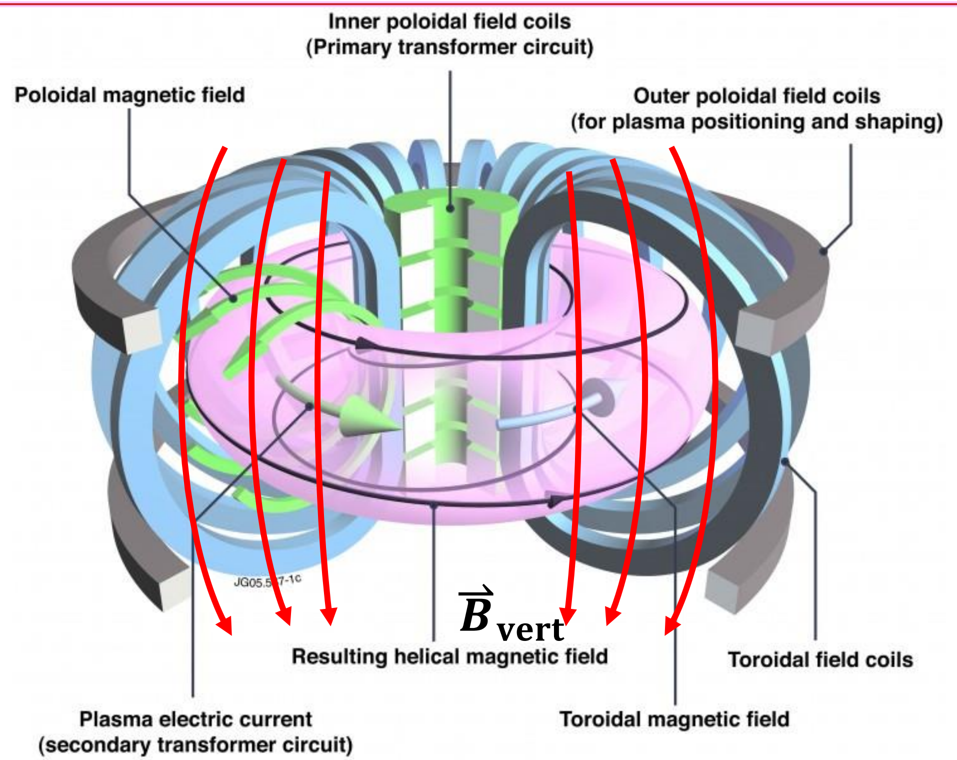
A poloidal magnetic field is required to reduce the drift across field lines

The outward force can be compensated by externally applied vertical fields

- **Externally applied vertical field**



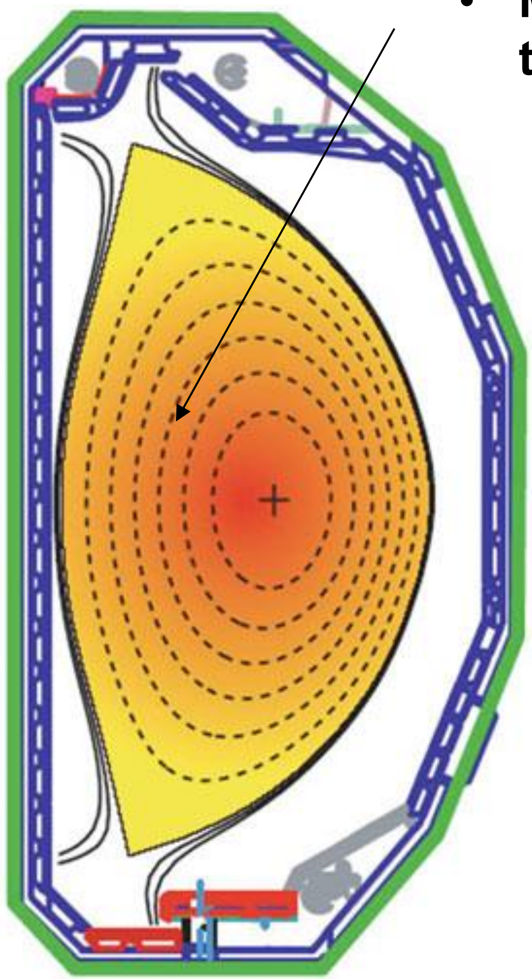
Coils in a tokamak



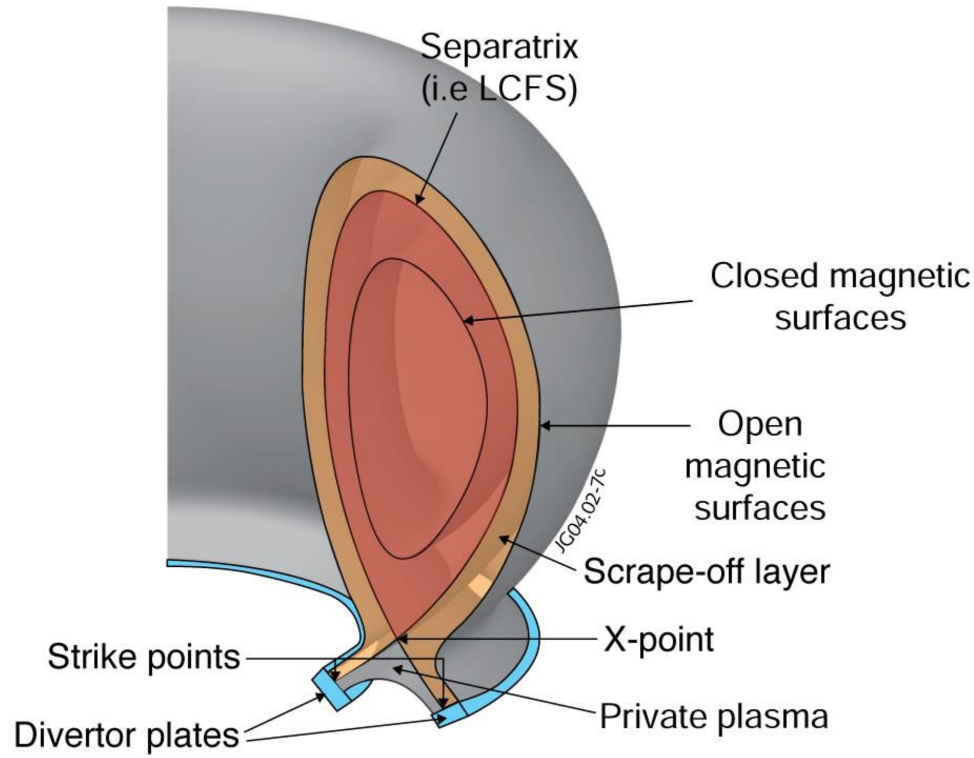
- **Toroidal field coils (in poloidal direction) – generate toroidal field for confinement.**
- **Poloidal field coils – generate vertical field for plasma positioning and shaping.**
- **Central solenoid – for breakdown and generating plasma current (in toroidal direction) and thus generating poloidal field for confinement.**

https://www.euro-fusion.org/2011/09/tokamak-principle-2/

D-shaped tokamak with diverter is more preferred nowadays



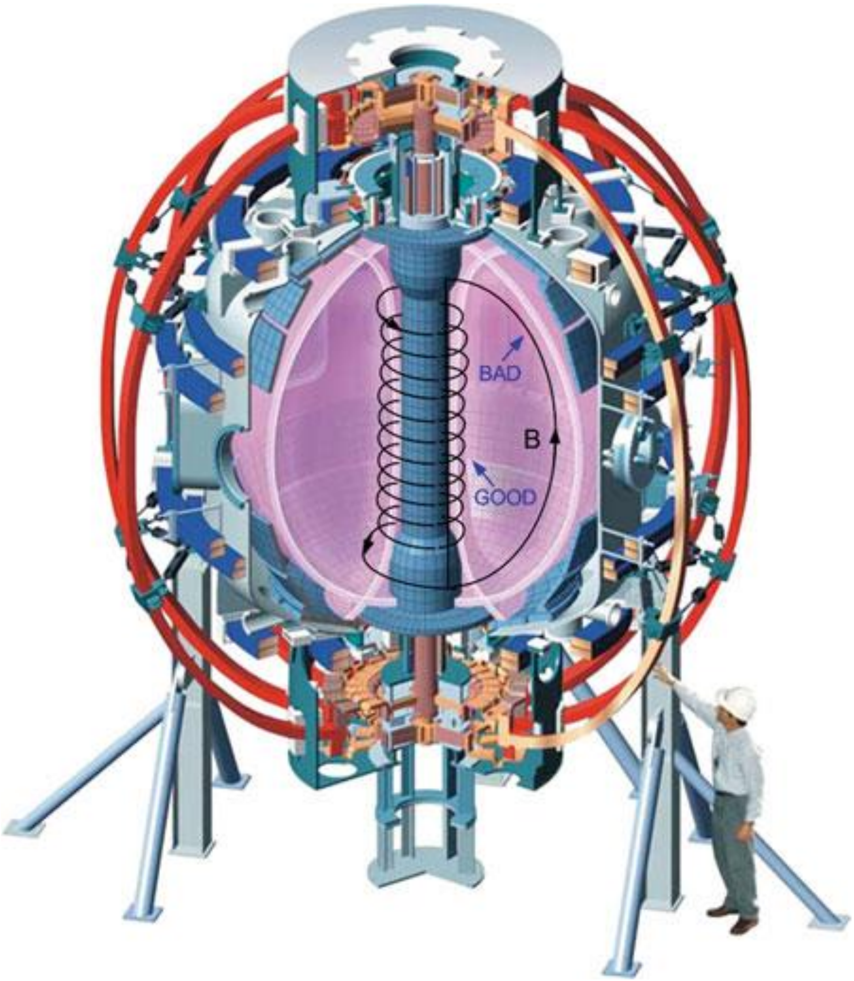
- **Make the plasma closer to the major axis**
  - **A divertor is needed to remove impurities and the power that escapes from the plasma**



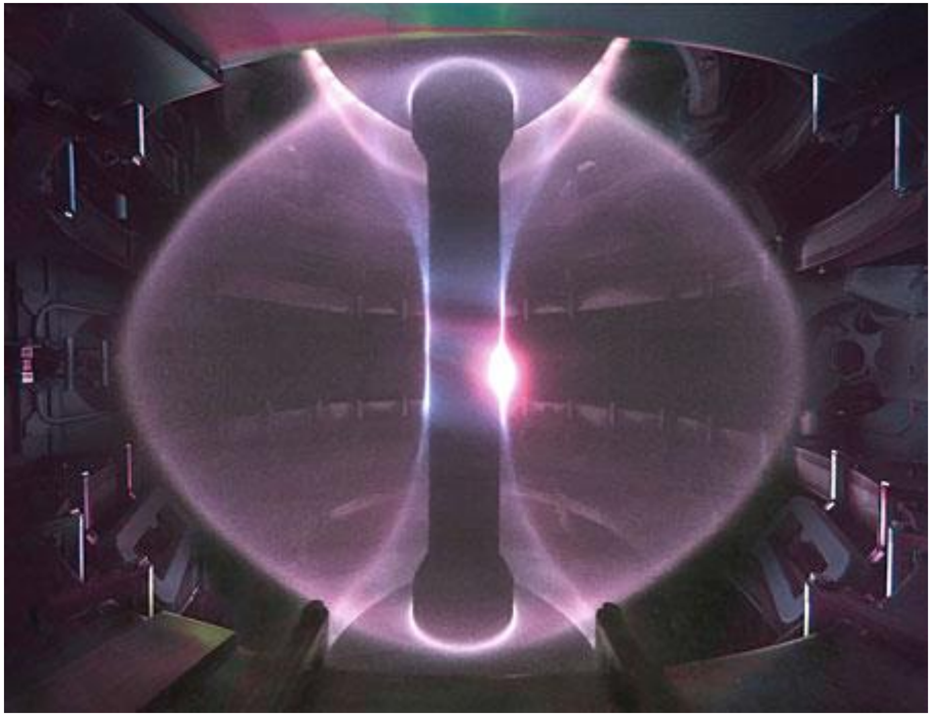
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

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

- **NSTX @ Princeton**

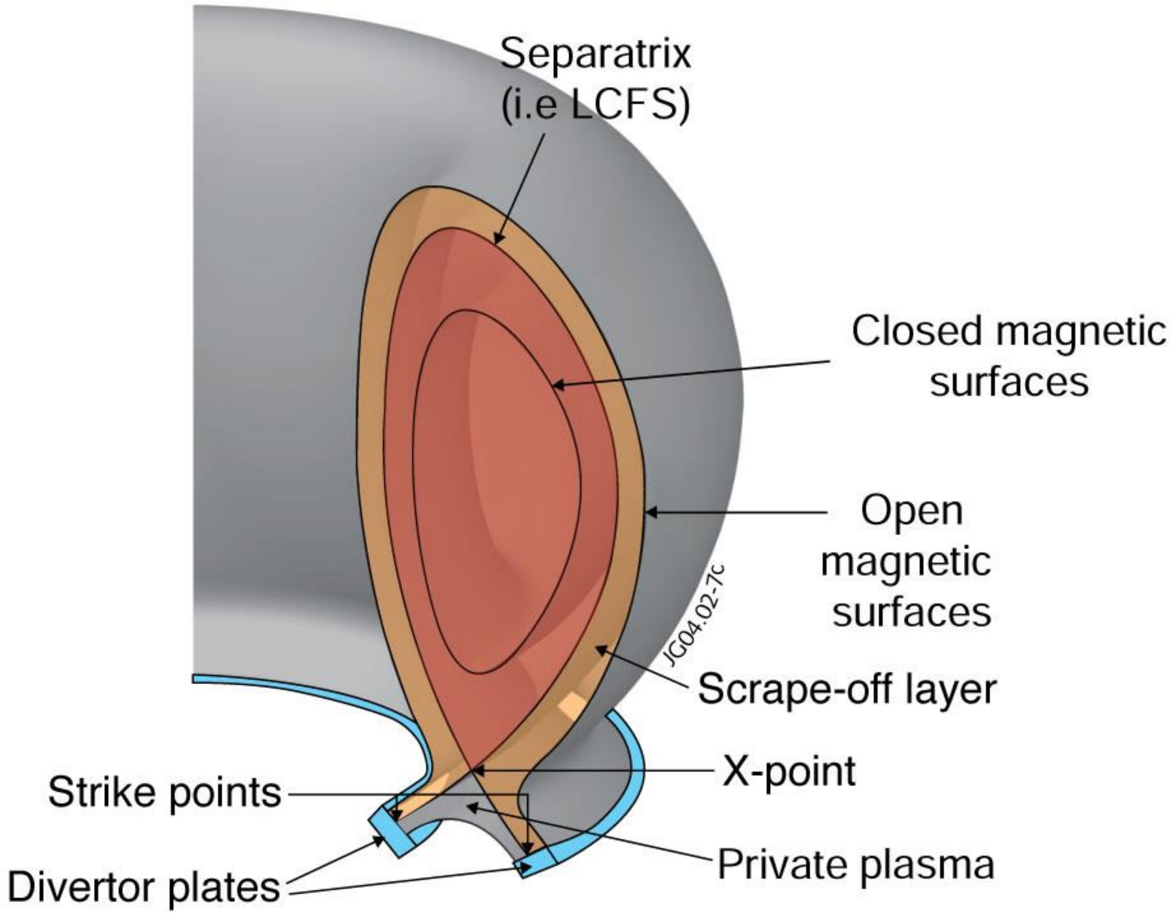


- **MegaAmpere Spherical Tokamak (MAST) @ Culham center for fusion energy, UK**



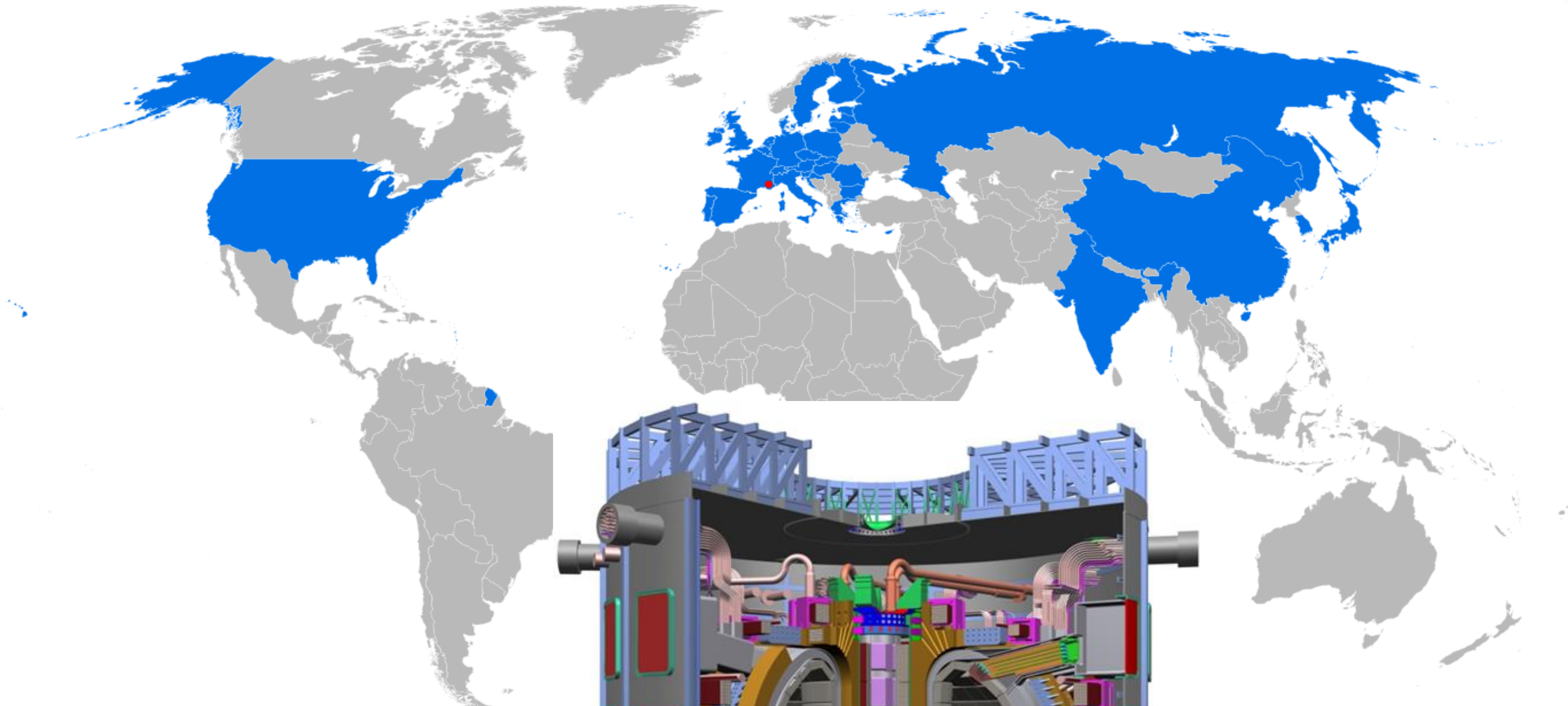
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

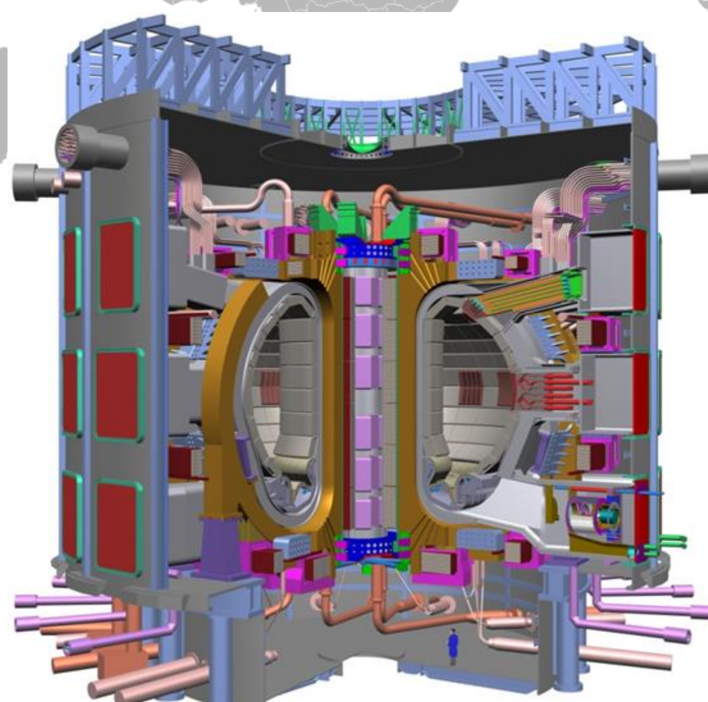
A diverter is needed to remove impurities and the power that escapes from the plasma



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

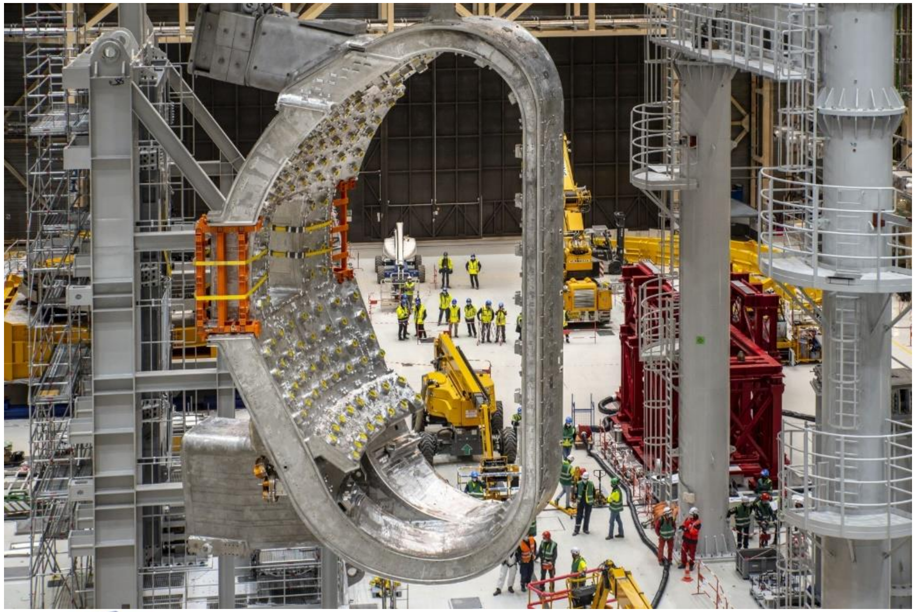
ITER ("The Way" in Latin) is one of the most ambitious energy projects in the world today

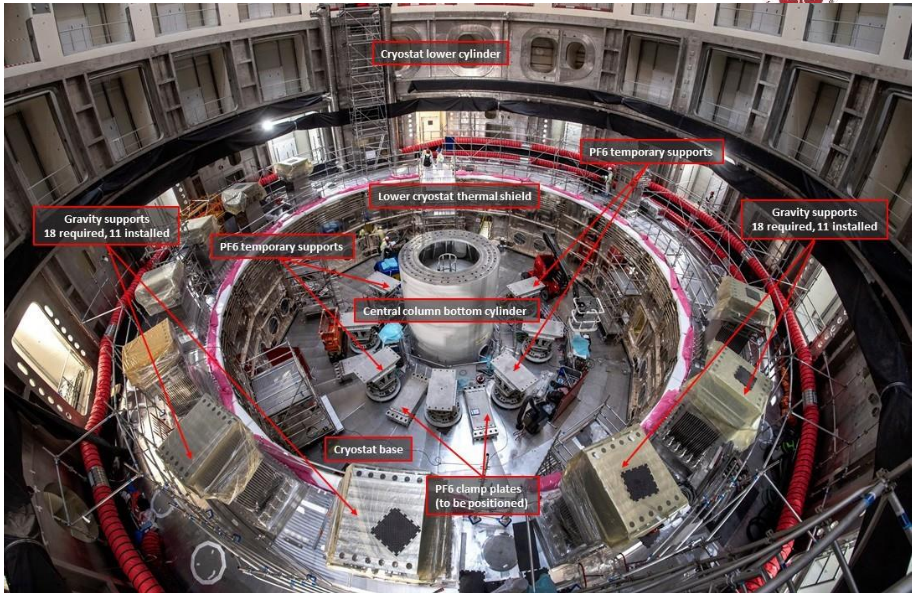


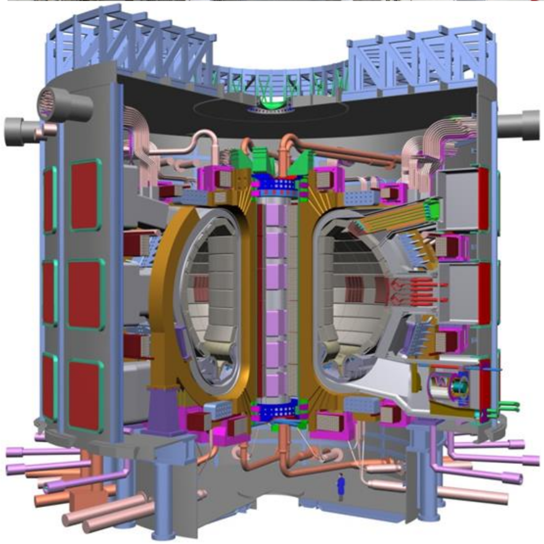


https://www.iter.org

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







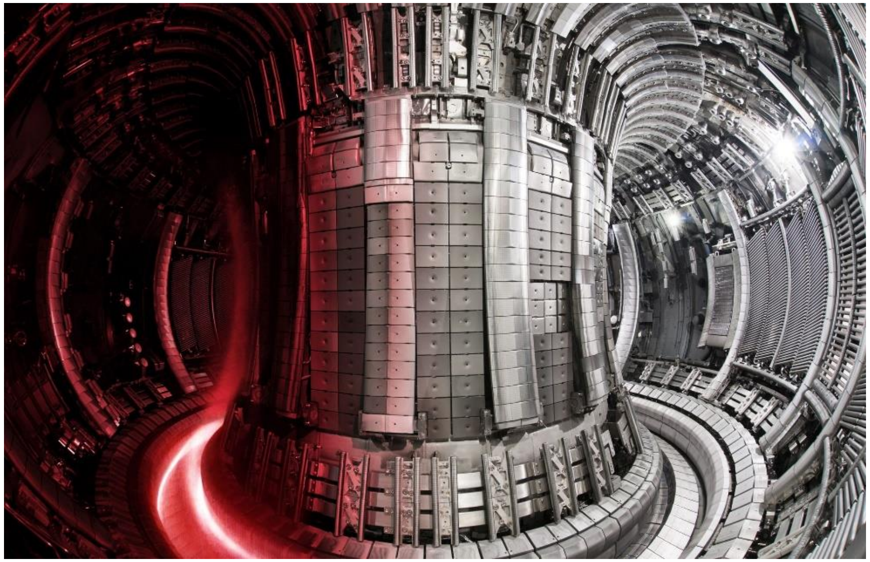
- R_{major} = 6.2 m
- R_{minor} = 2.0 m
- $B_{T,max}$ = 11.8 T
- $B_{P,max}$ = 6 T
- I_{plasma} = 15 MA

- T = 150M ºC
- P = 500 MW
- E_B = 51 GJ
- T_B = 4 K
- Q ≥ 10

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

https://www.iter.org/

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

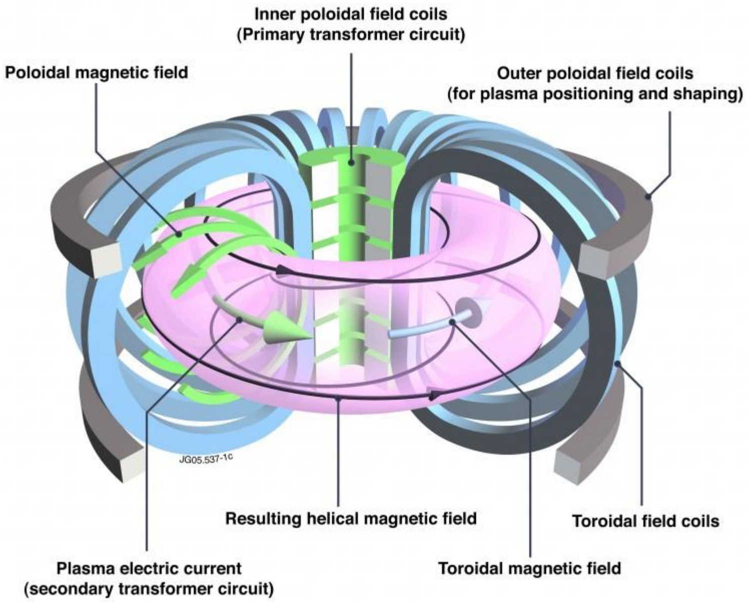


- **Record-breaking 59 megajoules of sustained fusion energy in Joint European Torus (JET) facility in Oxford demonstrates powerplant potential and strengthens case for ITER.**

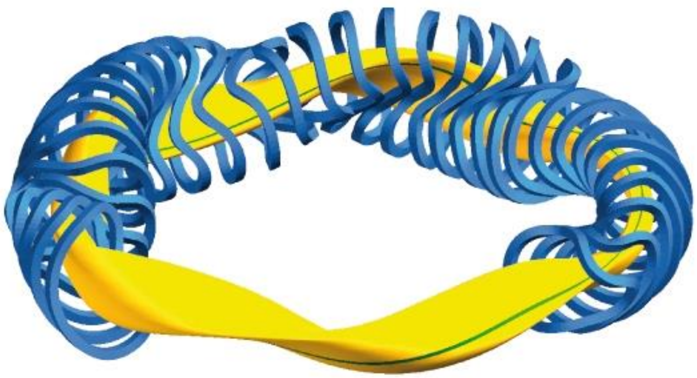
https://ccfe.ukaea.uk/resources/#gallery

Stellarator uses twisted coil to generate poloidal magnetic field

Tokamak

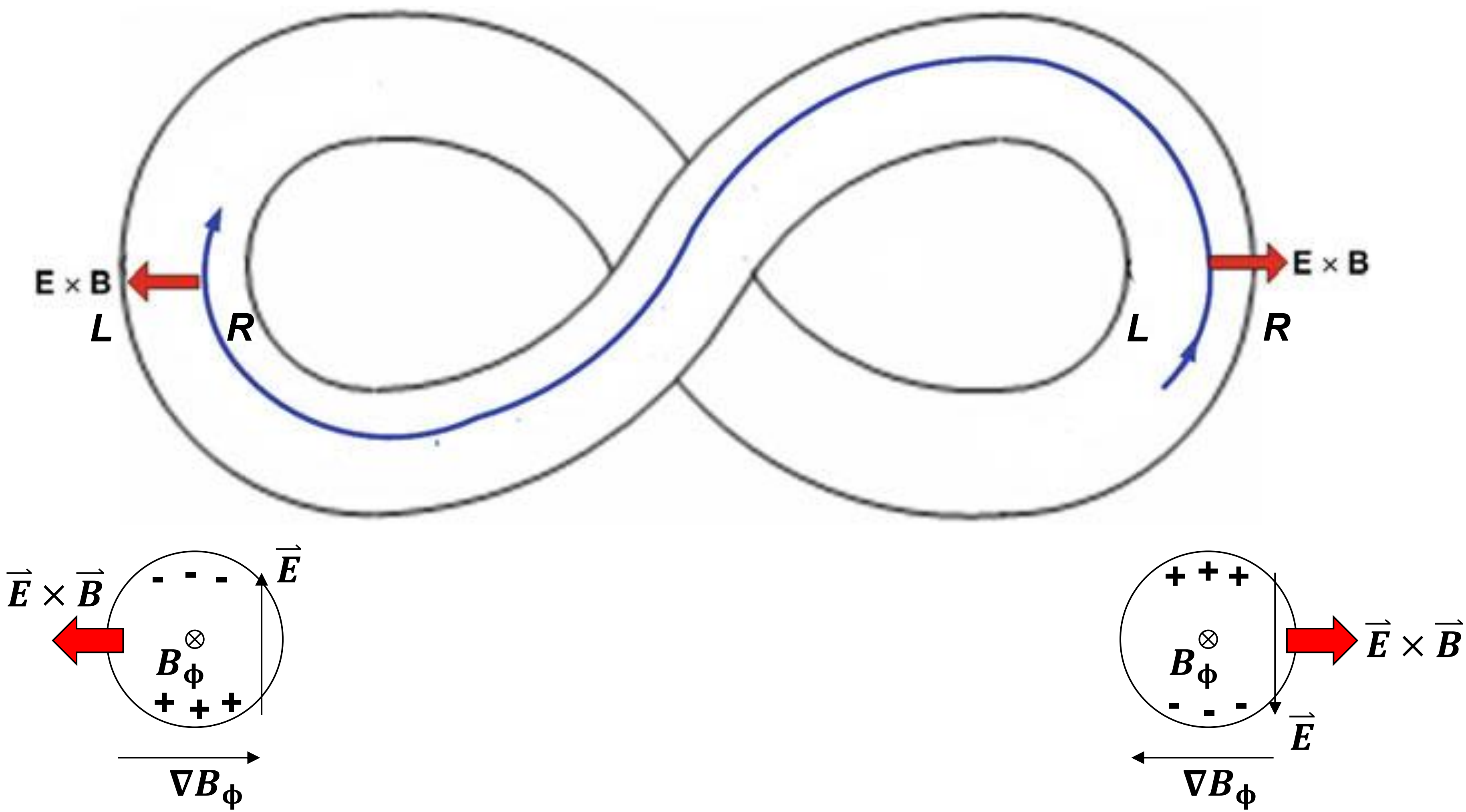


Stellarator



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

A figure-8 stellarator solved the drift issues



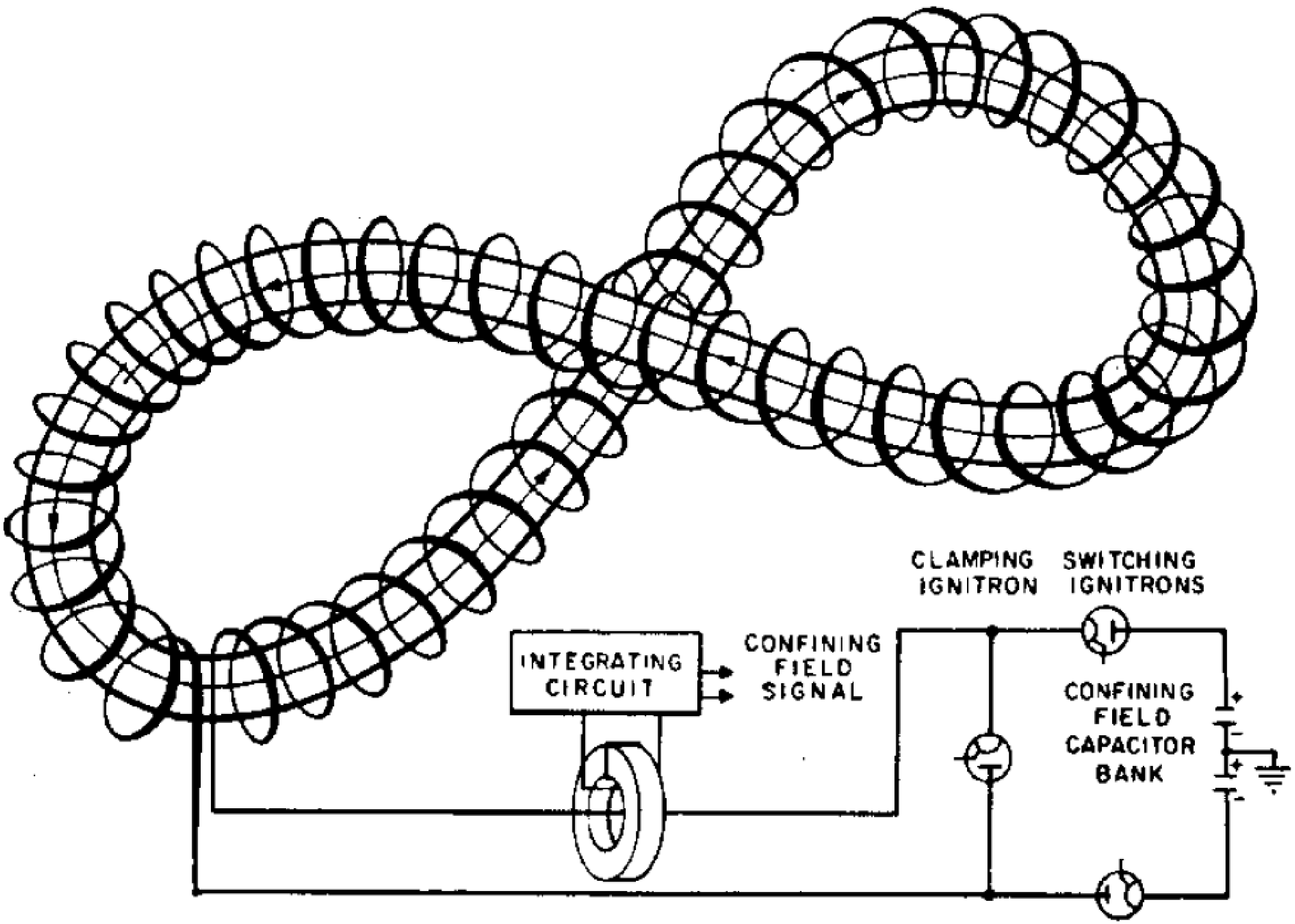
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

A figure-8 stellarator solved the drift issues

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

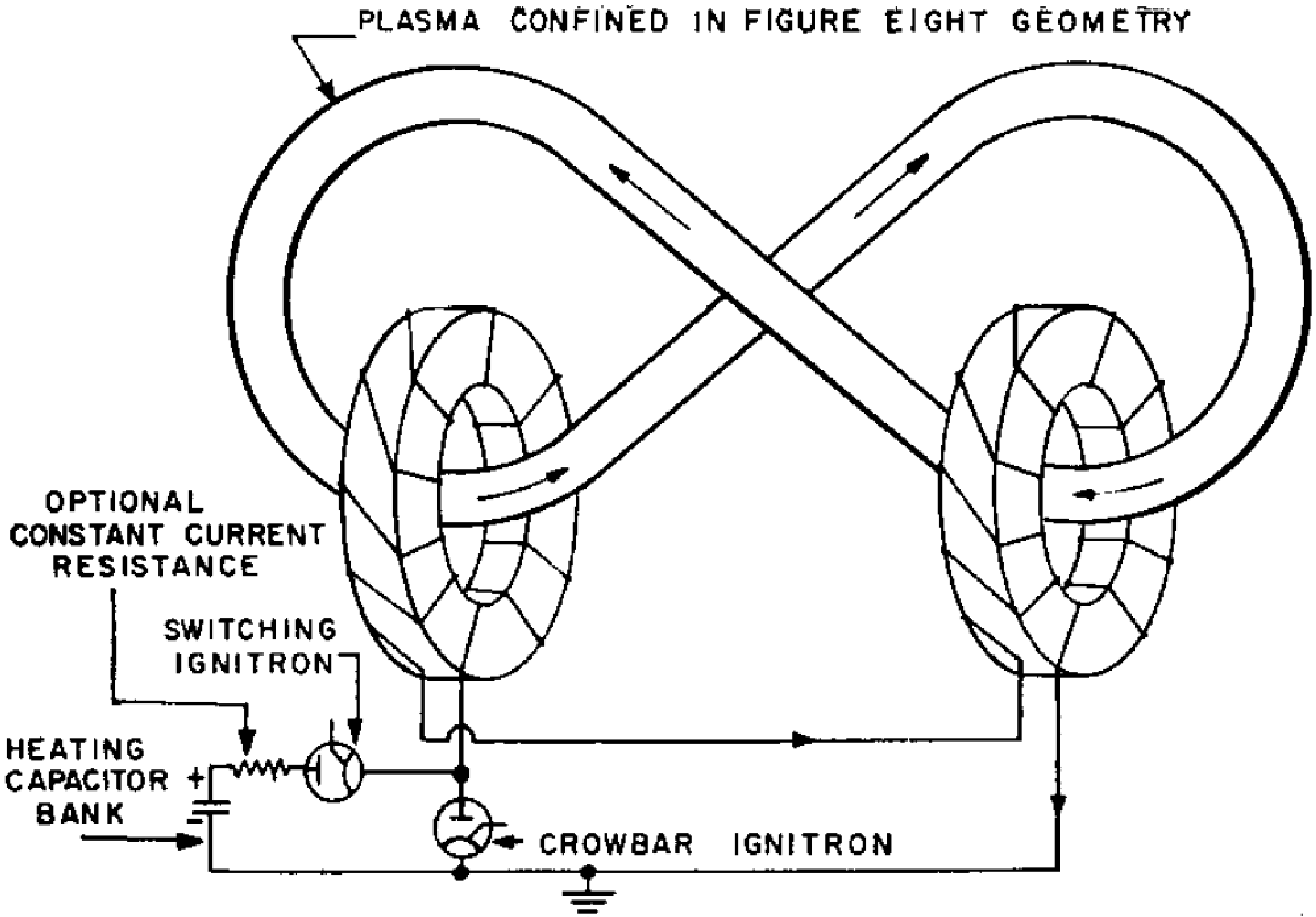
https://www.snowtrex.de/magazin/skigebiete/garmisch-classic-zugspitze/

Concept of figure-8 stellarator



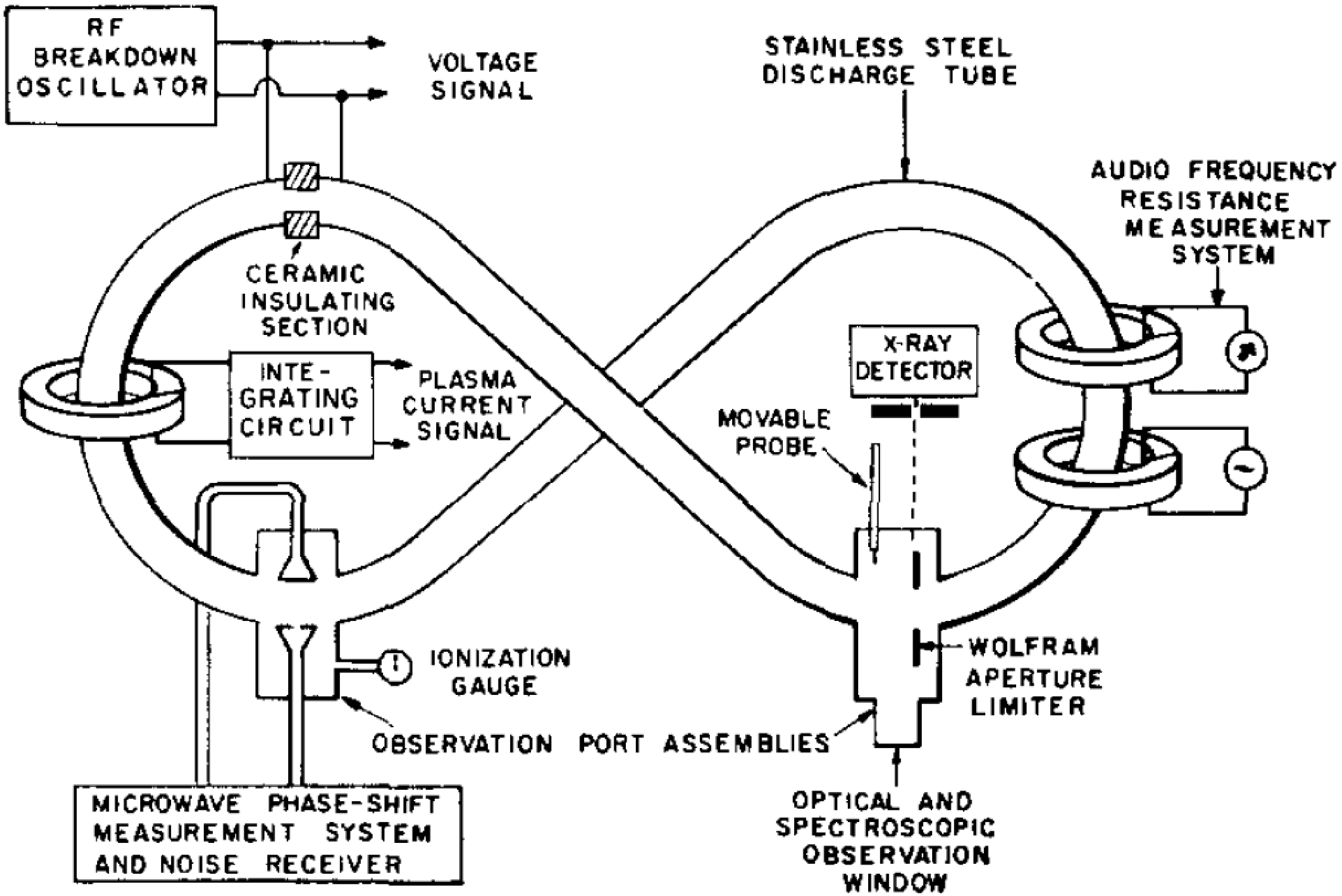
T. Coor, et al., Phys. Fluids **1**, 411 (1958)

Figure-8 stellarator with ohmic heating apparatus



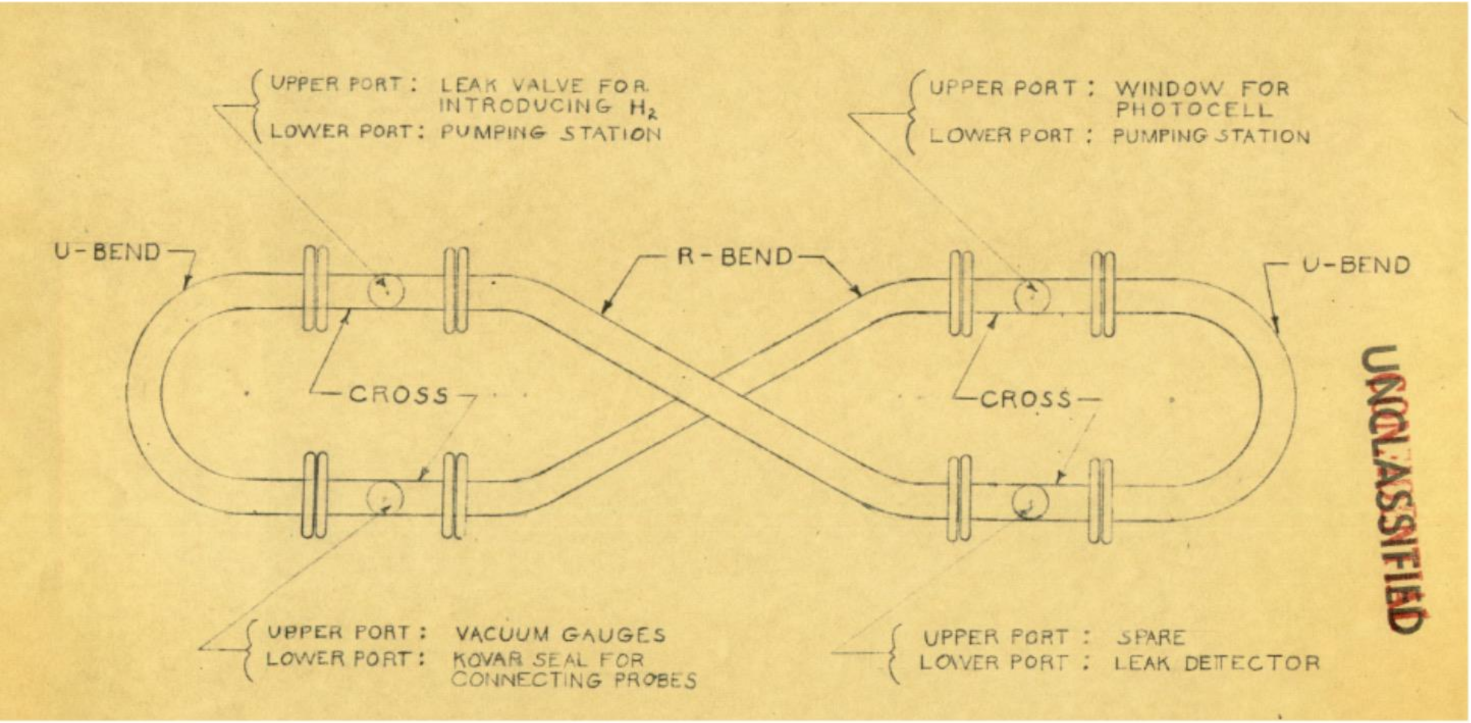
T. Coor, et al., Phys. Fluids **1**, 411 (1958)

Schematic diagram of B-1 stellarator

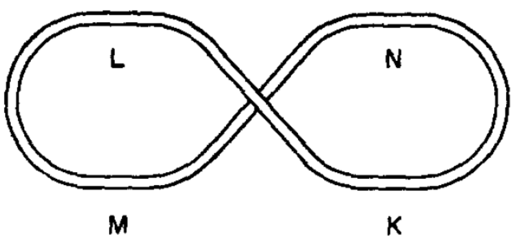


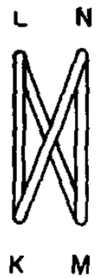
T. Coor, et al., Phys. Fluids **1**, 411 (1958)

Figure-eight (Princeton Model A) – 1953-1958



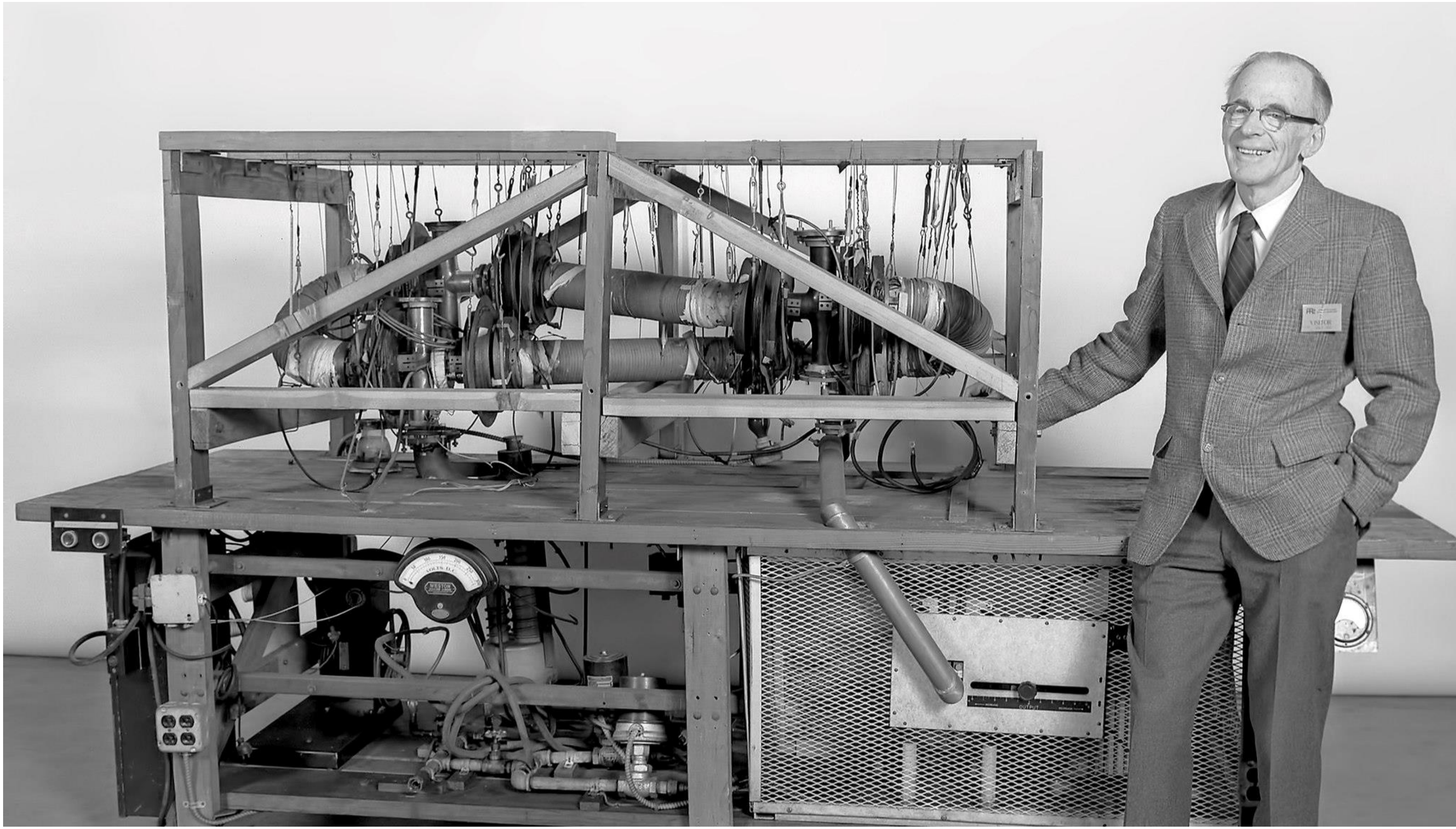
- **Top view**
- **Side view**





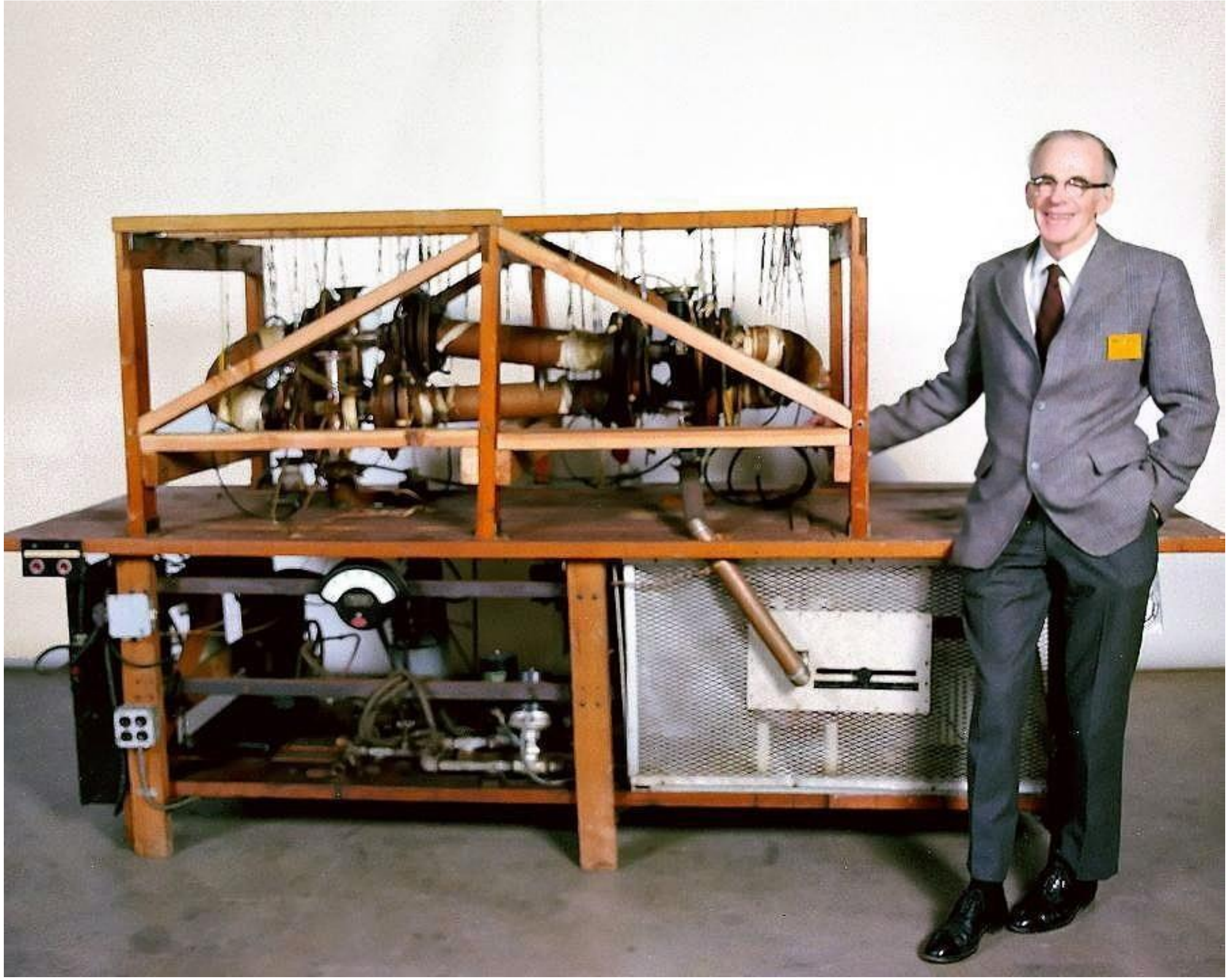
C. H. Willis, NJ Project Matterhorn (1953)
L. Spitzer, Jr., Phys. Fluids **1**, 253 (1958)

Model A stellarator



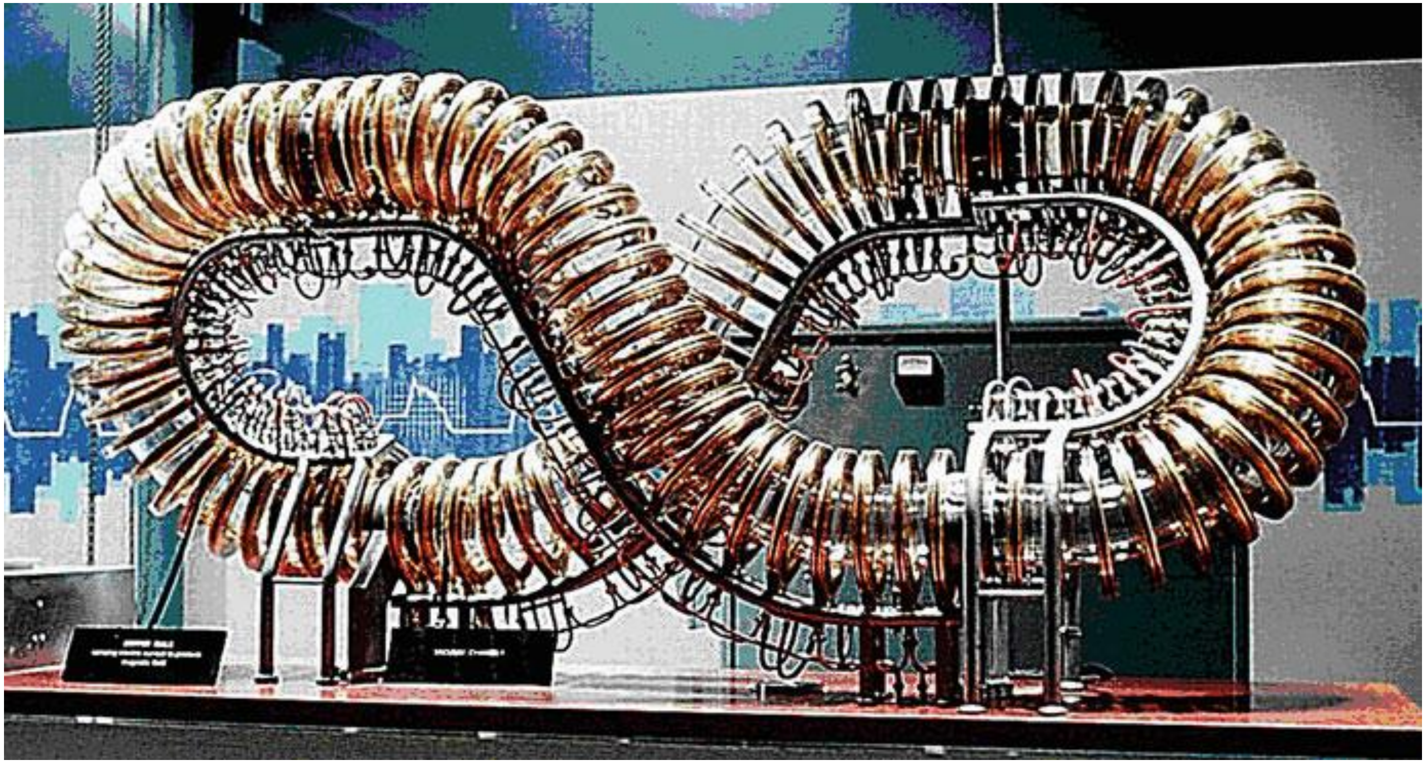
https://www.pppl.gov/timeline

Model A stellarator



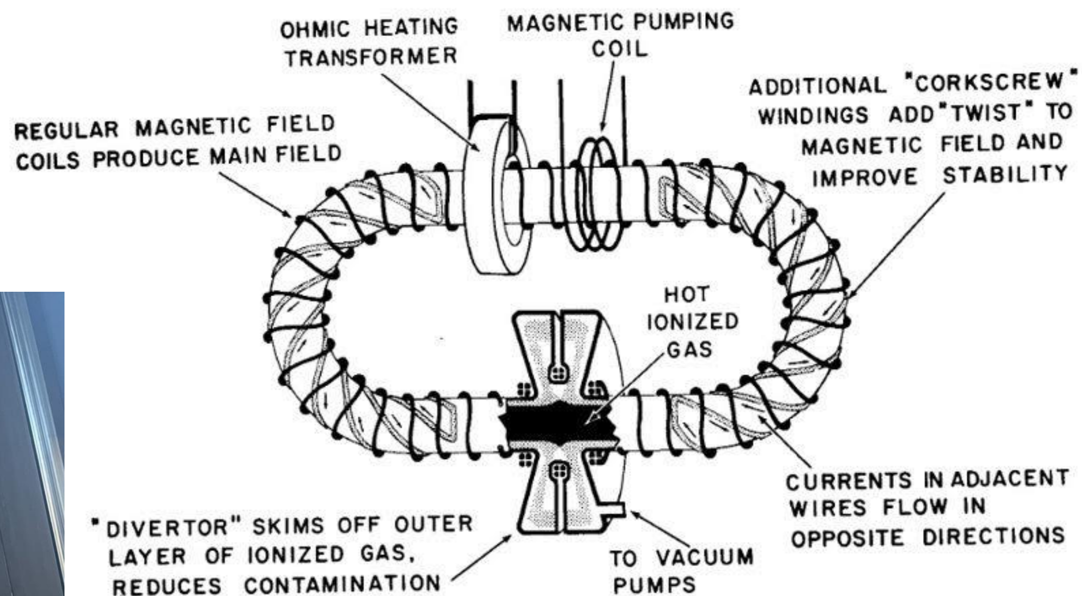
https://www.autoevolution.com/news/stellarator-reactors-the-once-forgotten-all-american-approach-to-nuclear-fusion-209478.html#agal_2

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



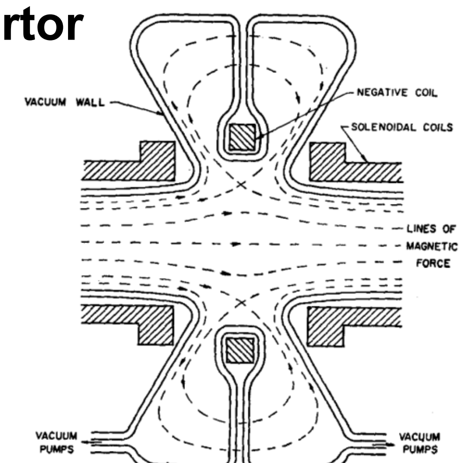
Racetrack Stellarator (Project Matterhorn)

FIG. 4: SCHEMATIC "RACETRACK" STELLARATOR



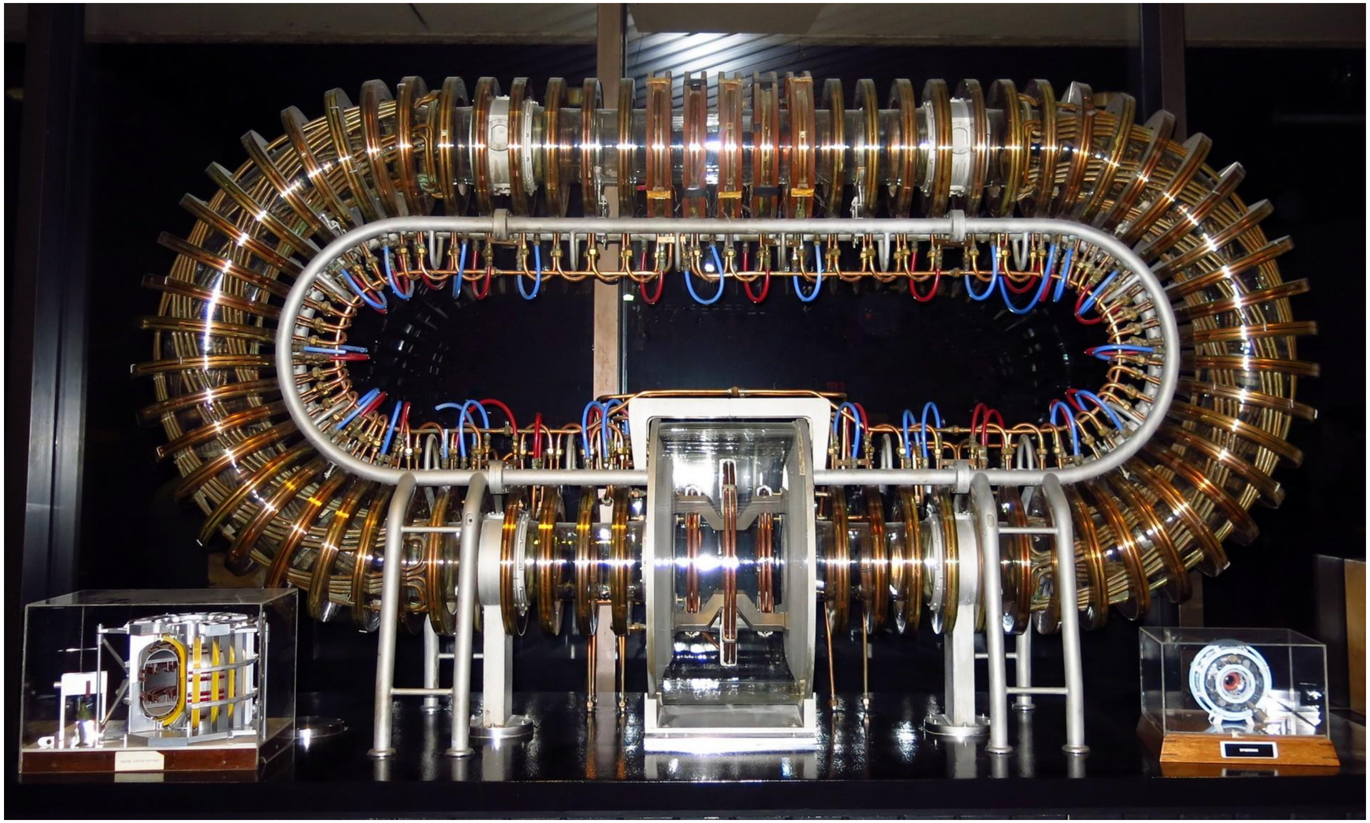
SEPTEMBER 19, 1958 ★ 9

- **Divertor**



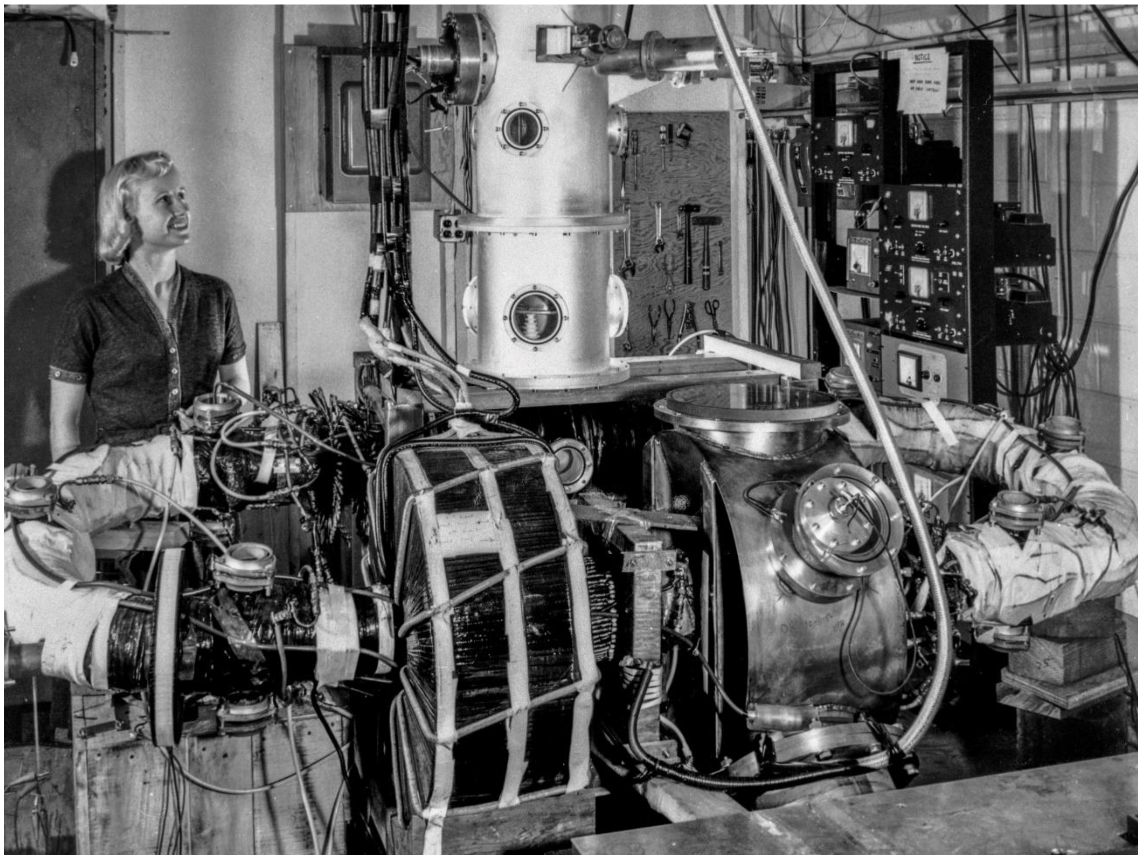
https://twitter.com/quantumwriters/status/1724959216966775270
L. Spitzer, Jr., Phys. Fluids **1**, 253 (1958)

Racetrack Stellarator



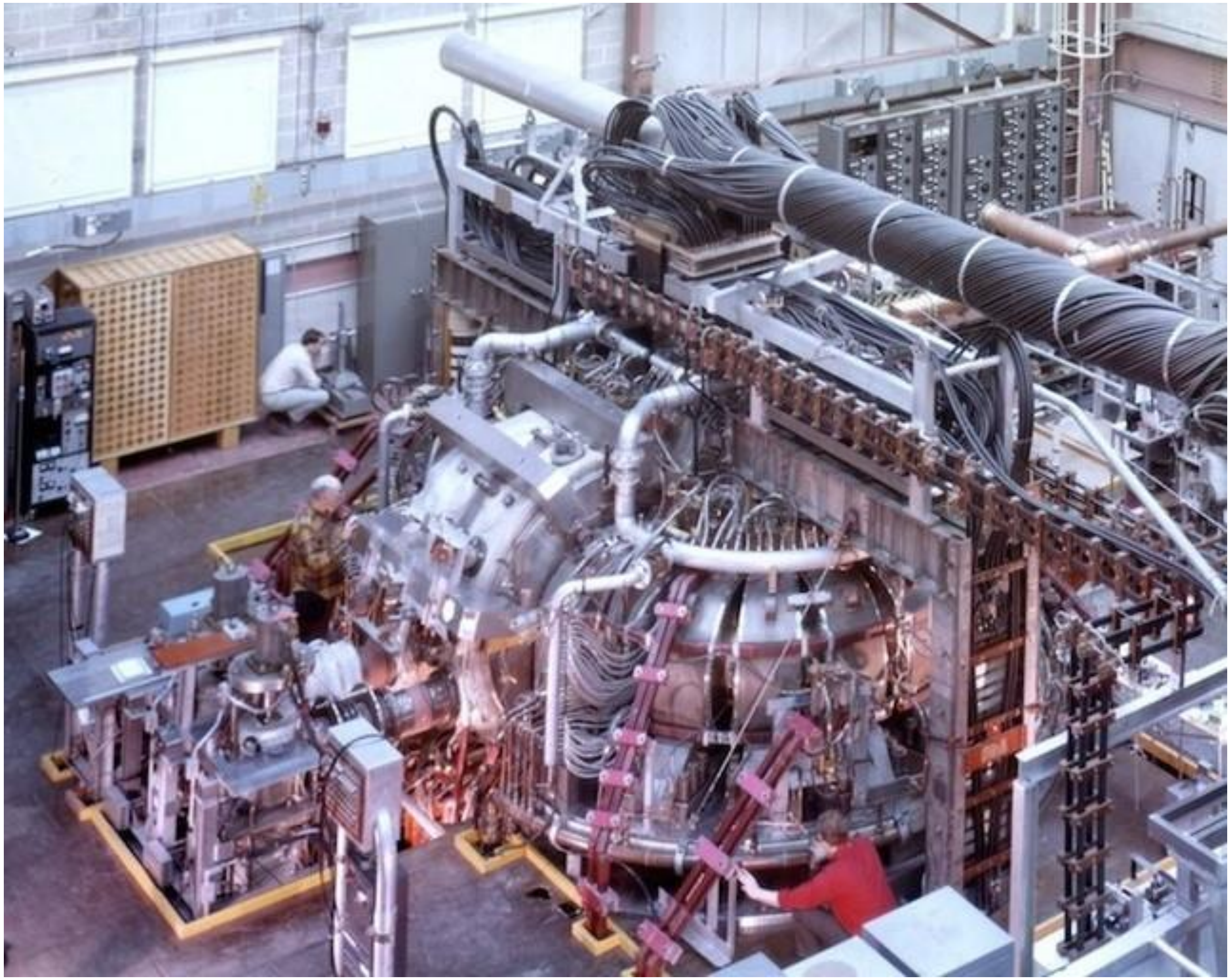
https://www.autoevolution.com/news/stellarator-reactors-the-once-forgotten-all-american-approach-to-nuclear-fusion-209478.html#agal_2

B-65 stellarator



https://www.pppl.gov/timeline
Elizabeth Paul, An introduction to stellarators,
Princeton Alumni Weekly, Sep. 19, 1958

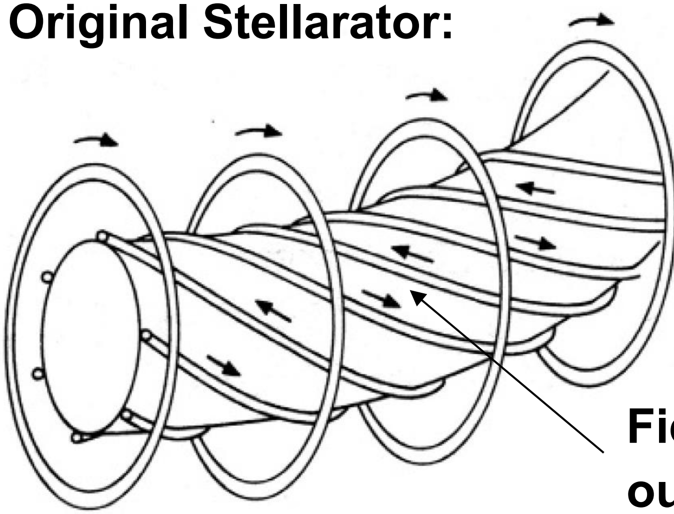
Racetrack (Princeton Model C) – 1962-1969



https://www.autoevolution.com/news/stellarator-reactors-the-once-forgotten-all-american-approach-to-nuclear-fusion-209478.html#agal_2

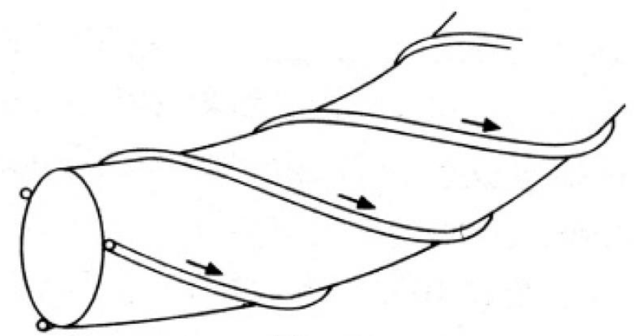
Different types of stellarators

- **Original Stellarator:**

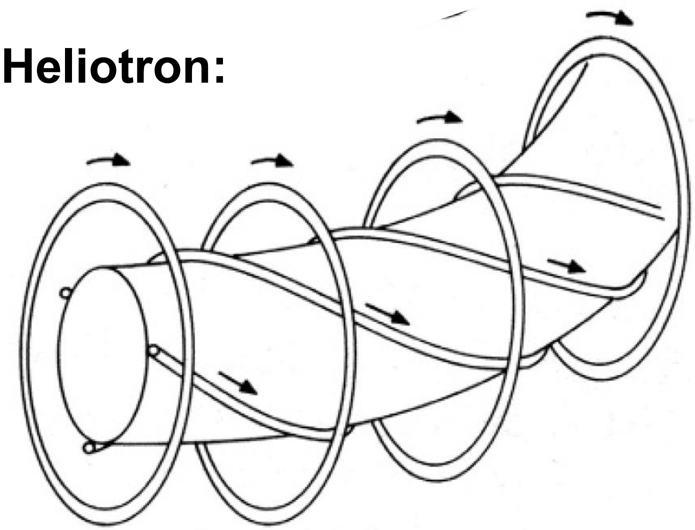


Field cancels out on axis

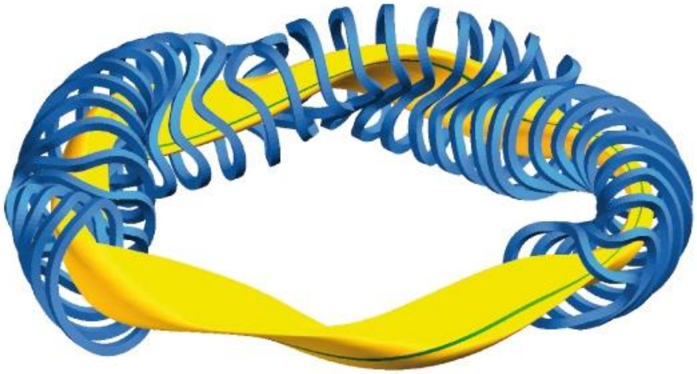
- **Torsatron:**



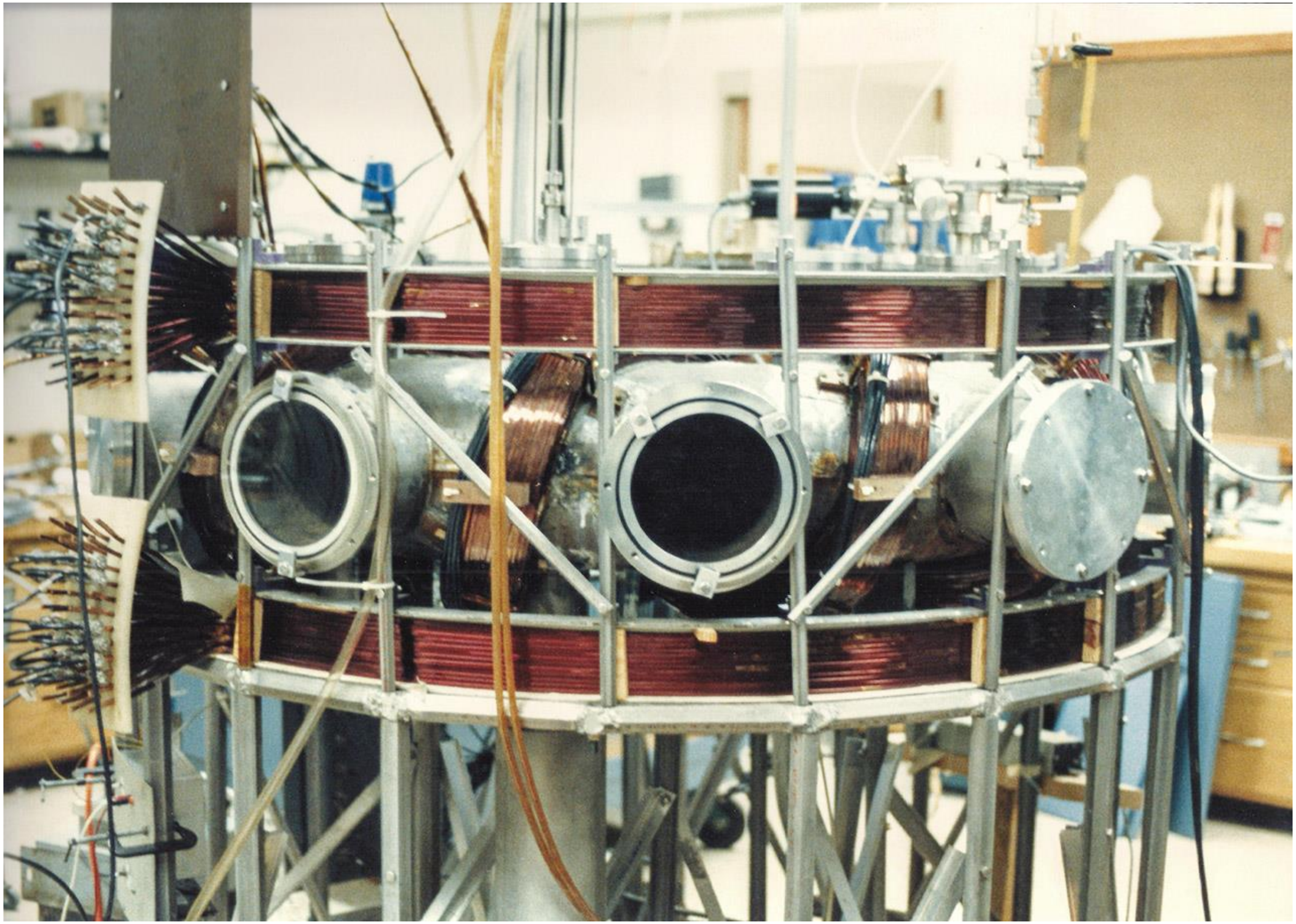
- **Heliotron:**



- **Helias:**

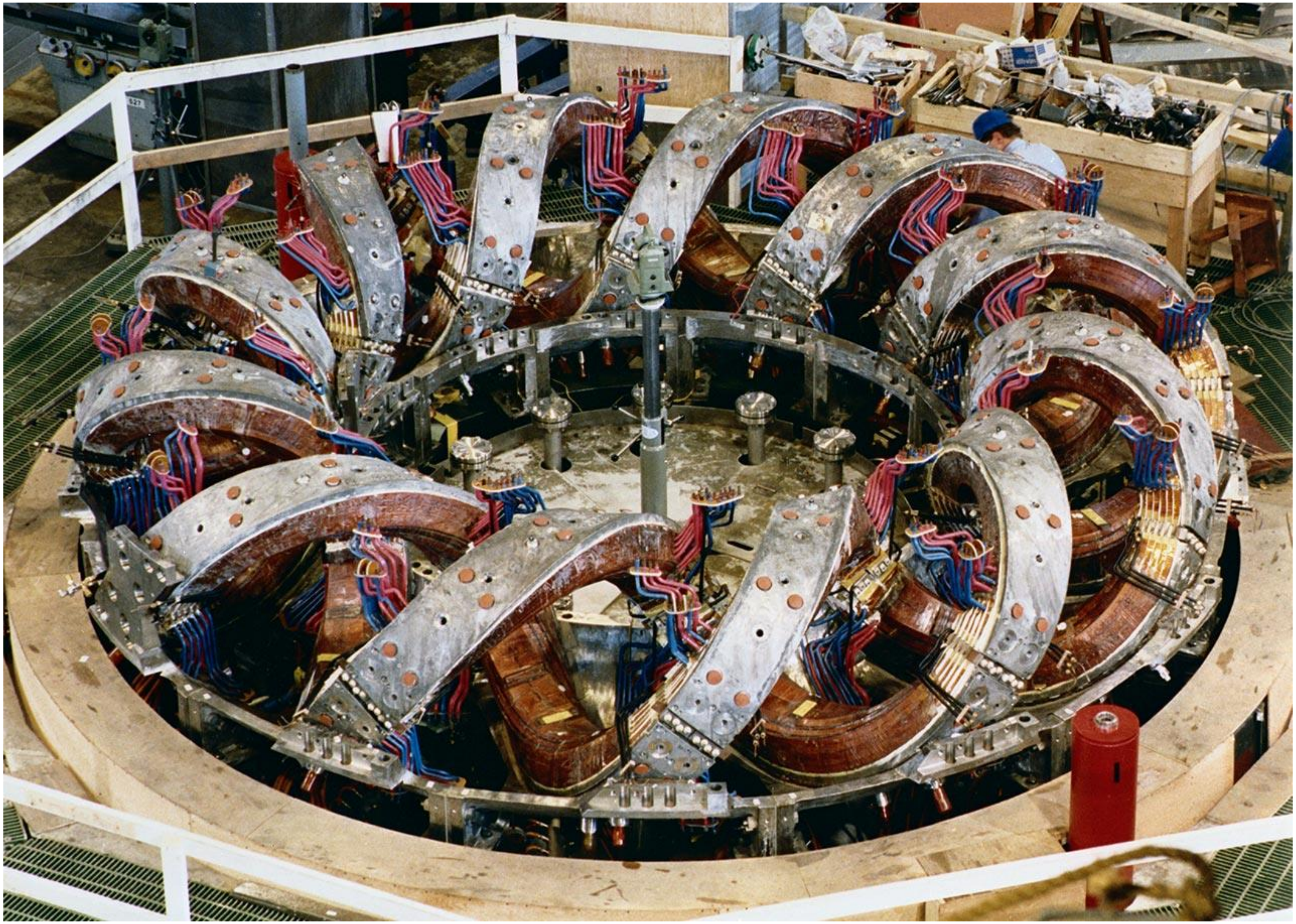


Auburn torsatron — winding of both helical and poloidal coils can be seen



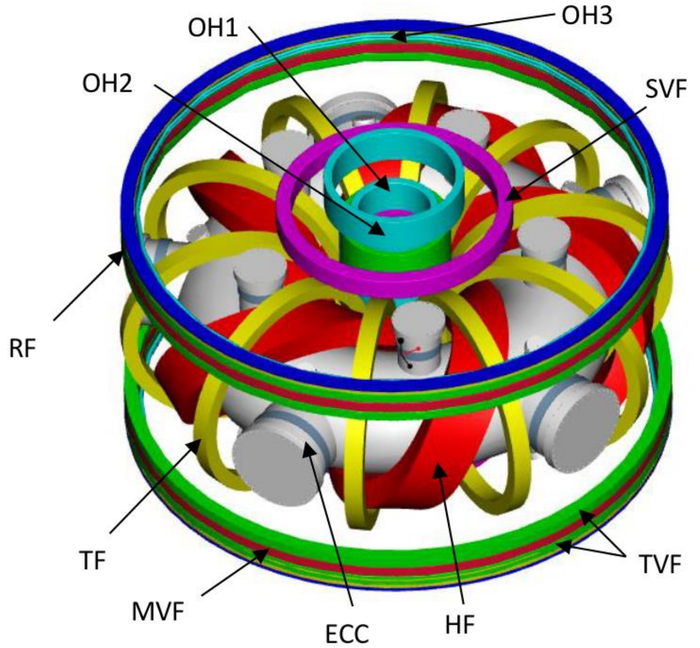
https://www.energyencyclopedia.com/en/glossary/torsatron

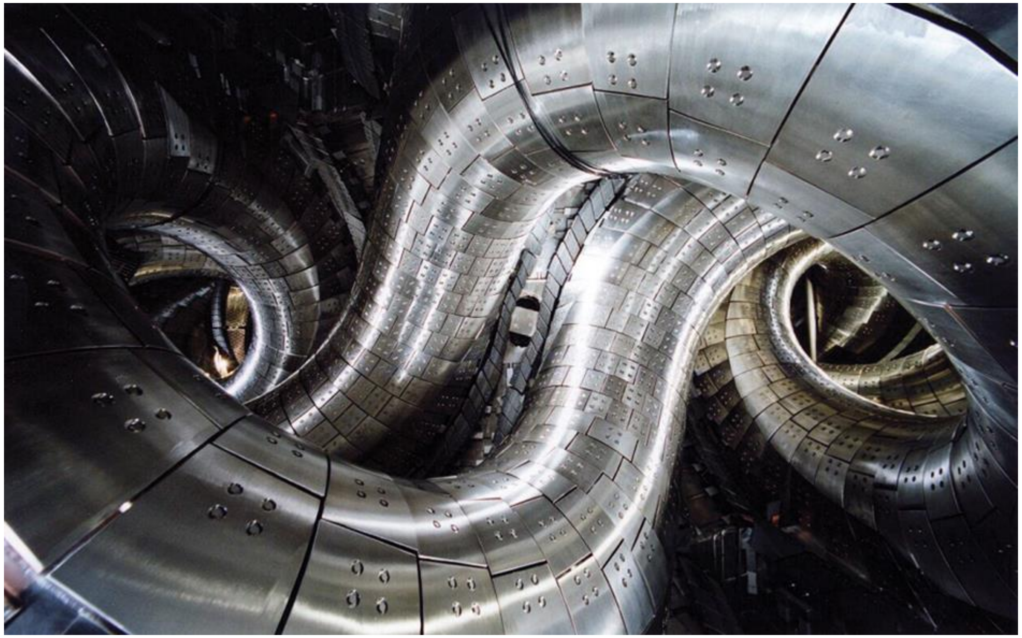
Construction of a pair of helical magnetic coils for the Advanced Toroidal Facility torsatron

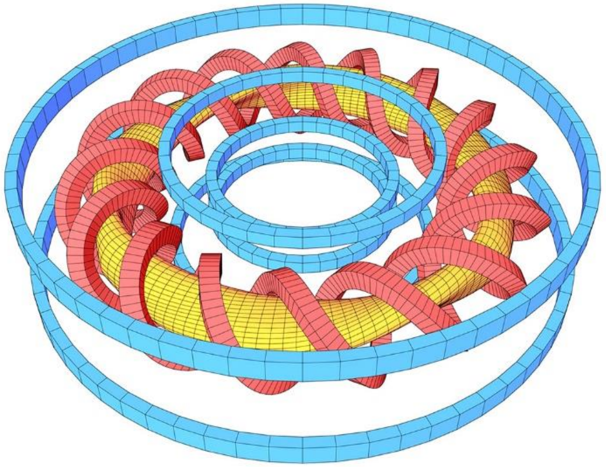


https://www.energyencyclopedia.com/en/glossary/torsatron

LHD stellarator in Japan (Heliotron)

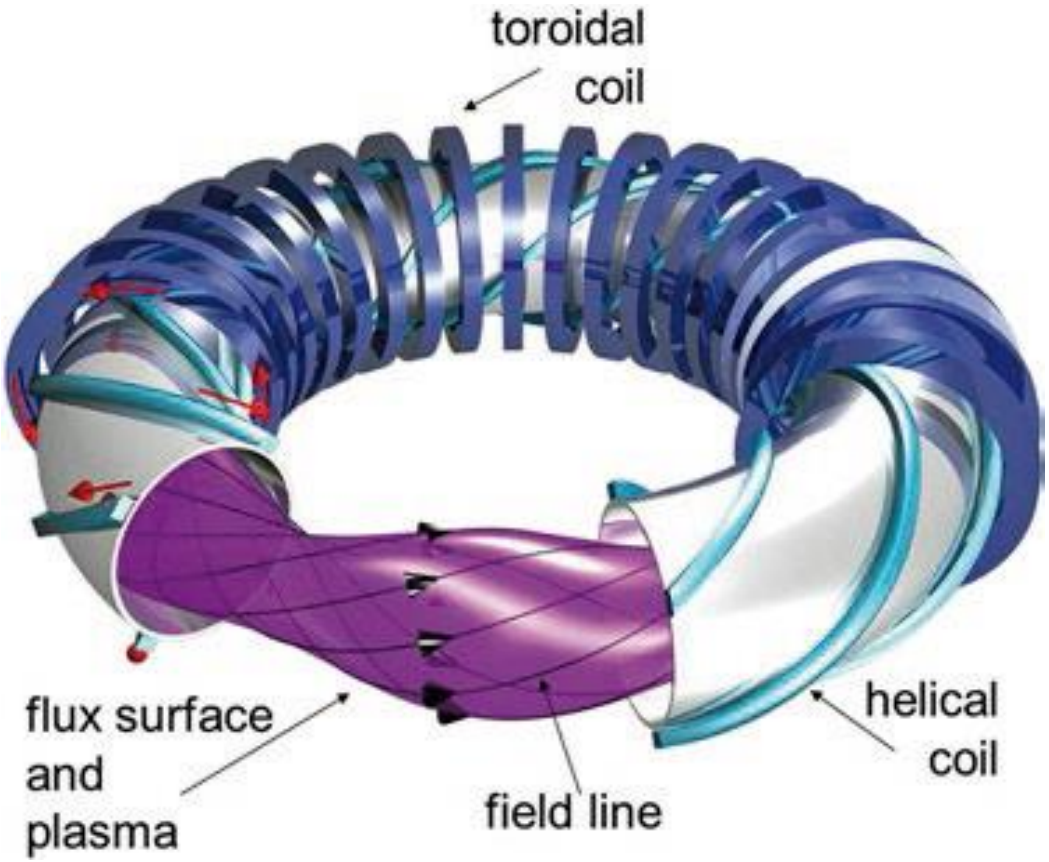






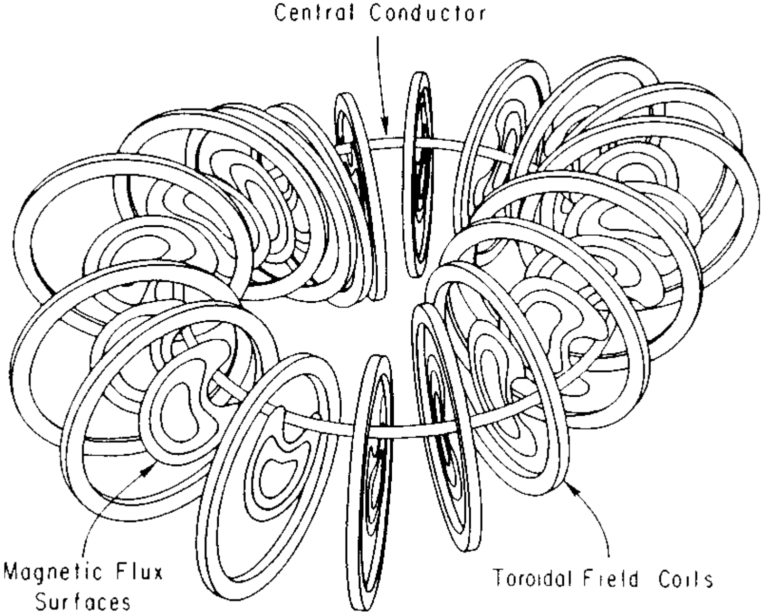
https://en.wikipedia.org/wiki/Compact_Toroidal_Hybrid
https://www.energyencyclopedia.com/en/glossary/heliotron
https://en.wikipedia.org/wiki/Large_Helical_Device

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

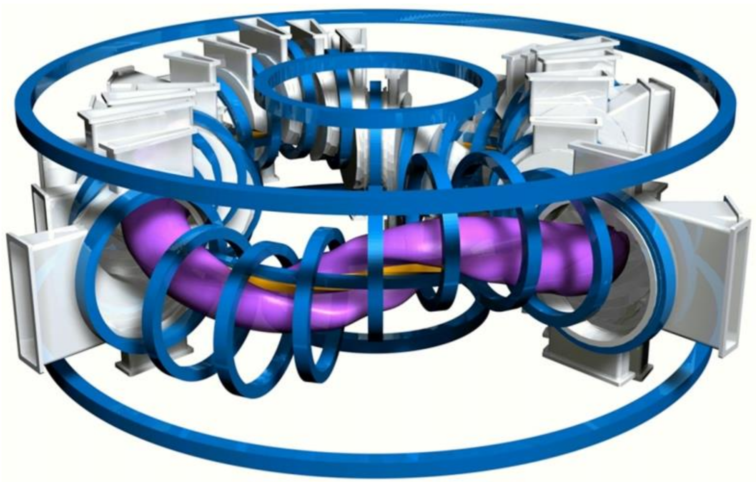


Wagner, F., Fusion energy. MRS Energy & Sustainability, 5, E8 (2018)

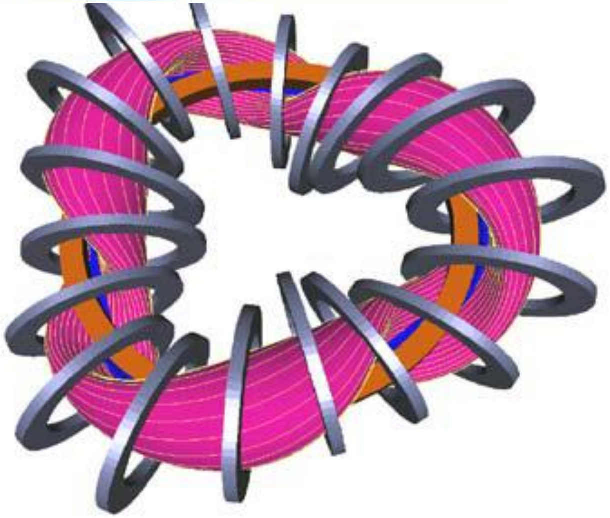
Heliac (Helical Axis stellarator)



- **TJ-II (Spain's National Fusion Laboratory):**

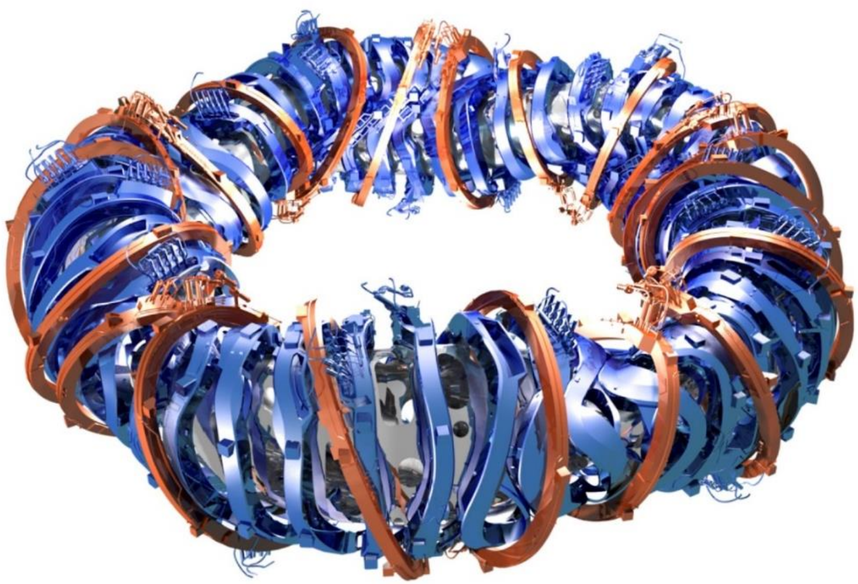


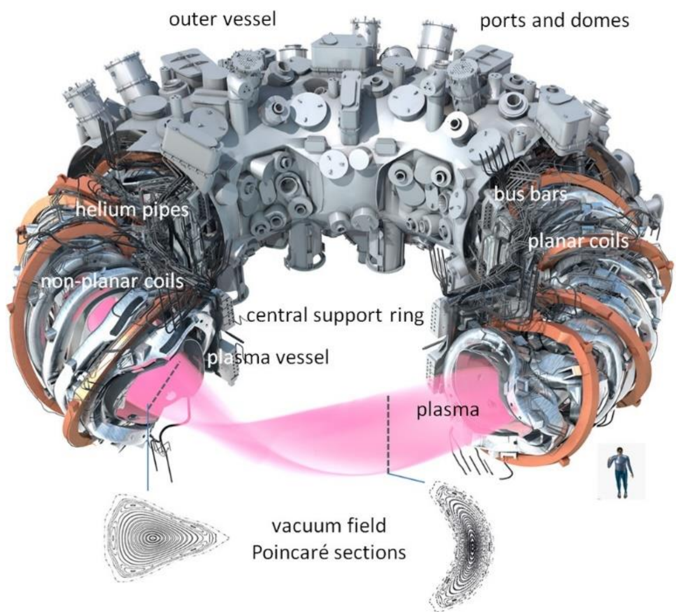
- **H-1 (Australian Plasma Fusion Research Facility):**



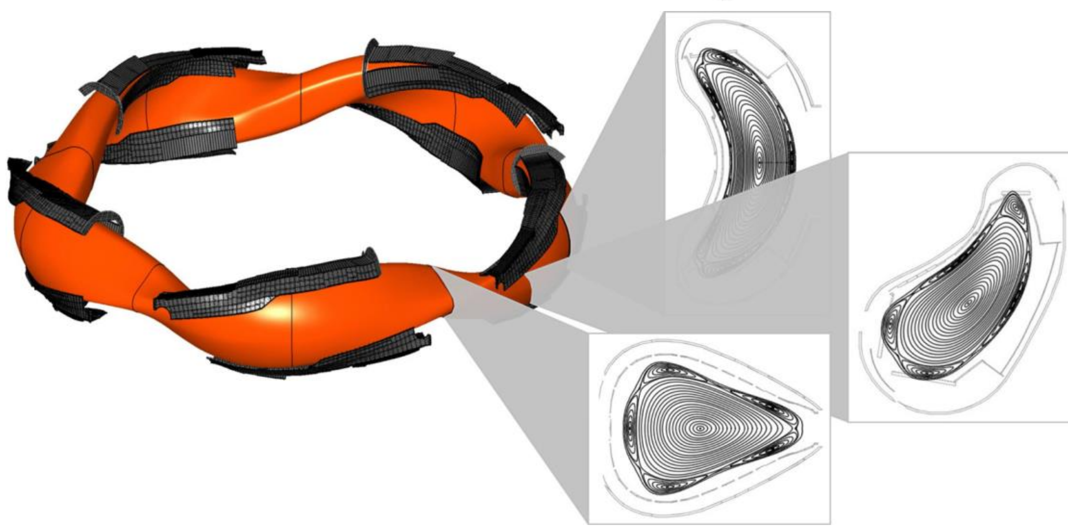
A. H. Boozer, Phys. Plasmas, 5, 1647 (1998)
https://wiki.fusion.ciemat.es/wiki/TJ-II
B. D. Blackwell, et. al, 23rd IAEA Fusion Energy Conference, 2010

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





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



Course Outline

- What is Plasma?
- **Nuclear fusion**
  - Basic
  - Magnetic confinement fusion (MCF)
  - **Inertial confinement fusion (ICF)**
- Formosa Integrated Research Spherical Tokamak (FIRST), the first Tokamak in Taiwan

Under what conditions the plasma keeps itself hot?

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

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

S_α: α particle heating

S_h: external heating

S_B: Bremsstrahlung radiation

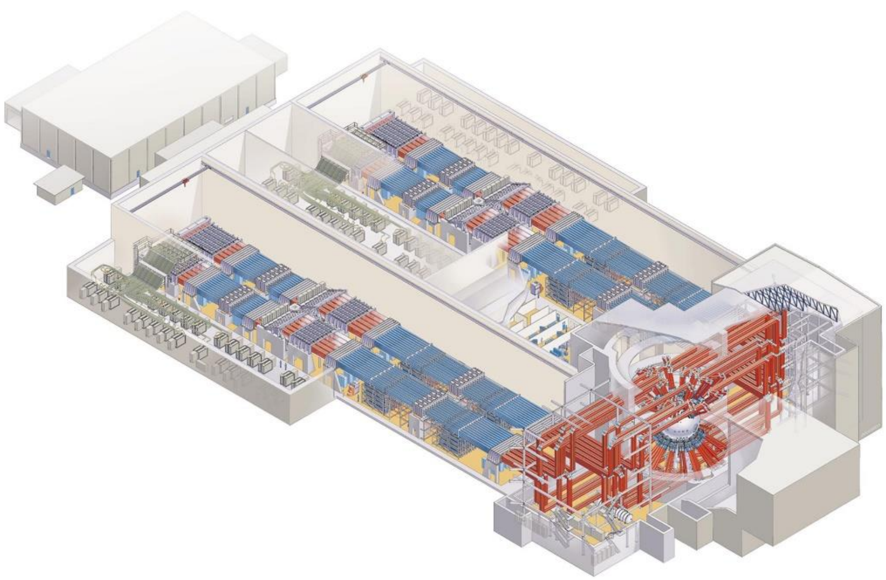
S_k: heat conduction lost

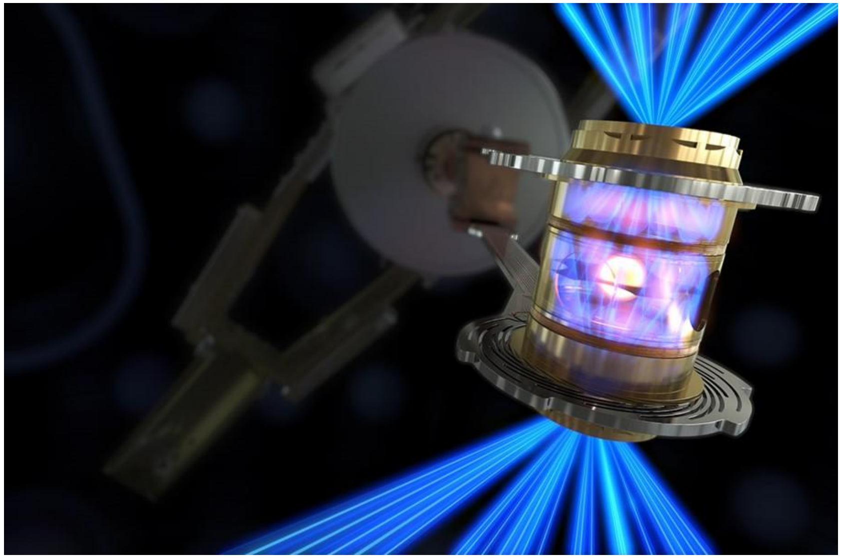
Ignition condition: $P\tau$ > 10 atm-s = 10 Gbar - ns

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

Significant breakthrough was achieved in ICF recently

- **Inertial confinement fusion (ICF)**





- **National Ignition Facility (NIF) demonstrated a gain grater than 1 for the first time on 2022/12/5. The yield of 3.15 MJ from the 2.05-MJ input laser energy, i.e., Q=1.5.**

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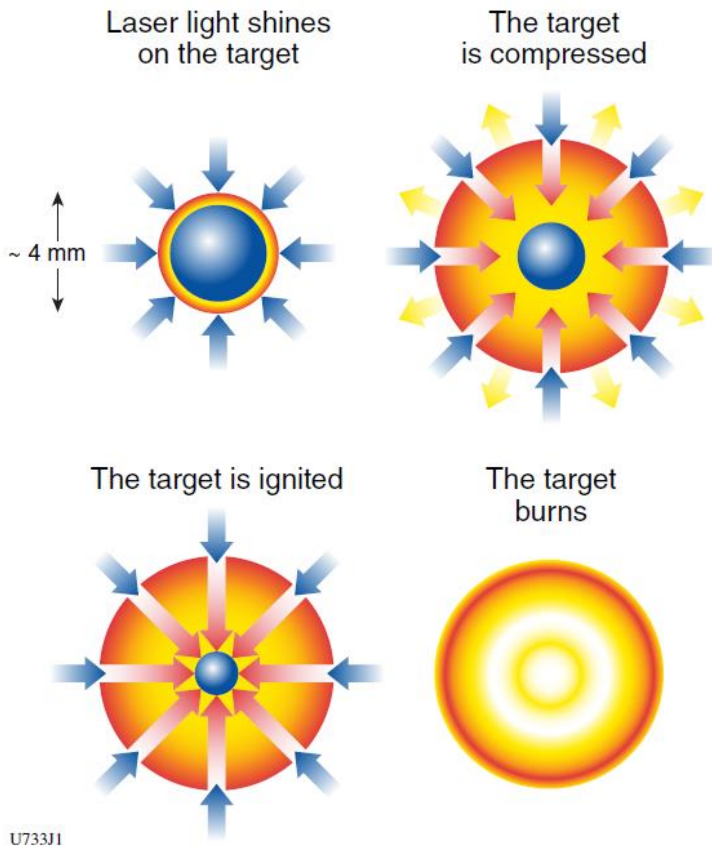
https://zh.wikipedia.org/wiki/國家點火設施
https://www.science.org/content/article/historic-explosion-long-sought-fusion-breakthrough

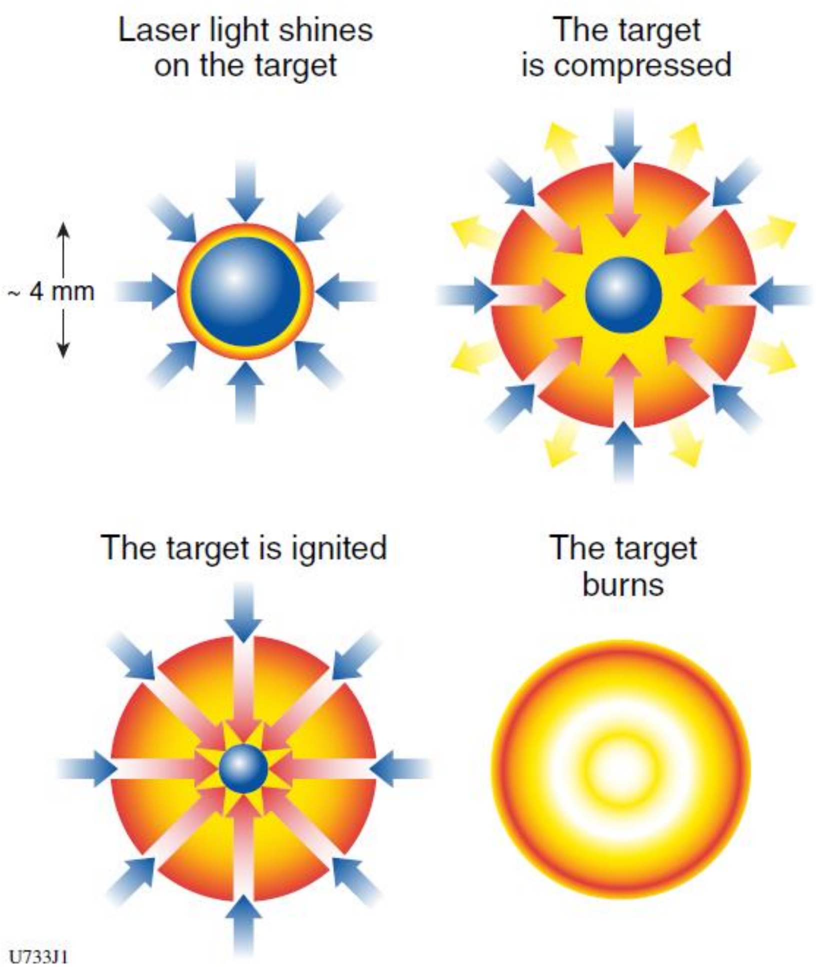
Don’t confine it!

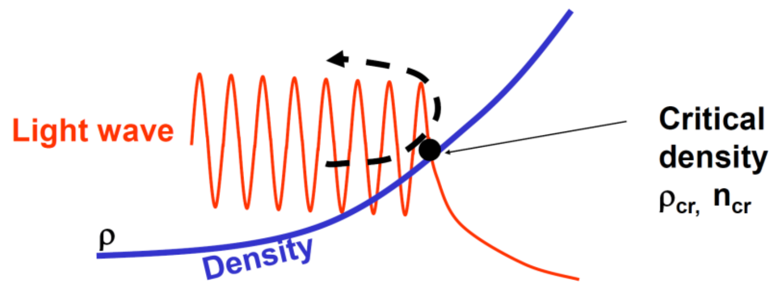
- **Solution 2: Inertial confinement fusion (ICF). Or you can say it is confined by its own inertia: P~Gigabar, τ~nsec, T~10 keV (10^8 ^{0}C)**

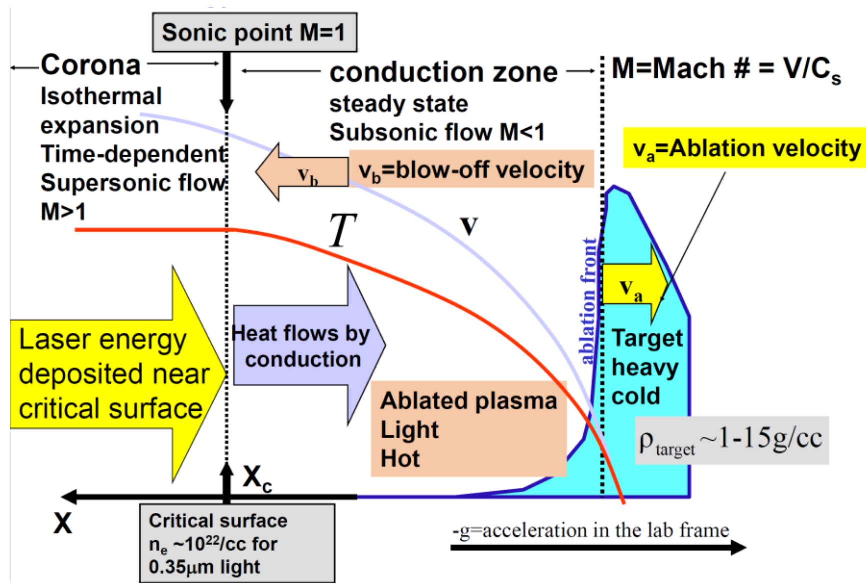


Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

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

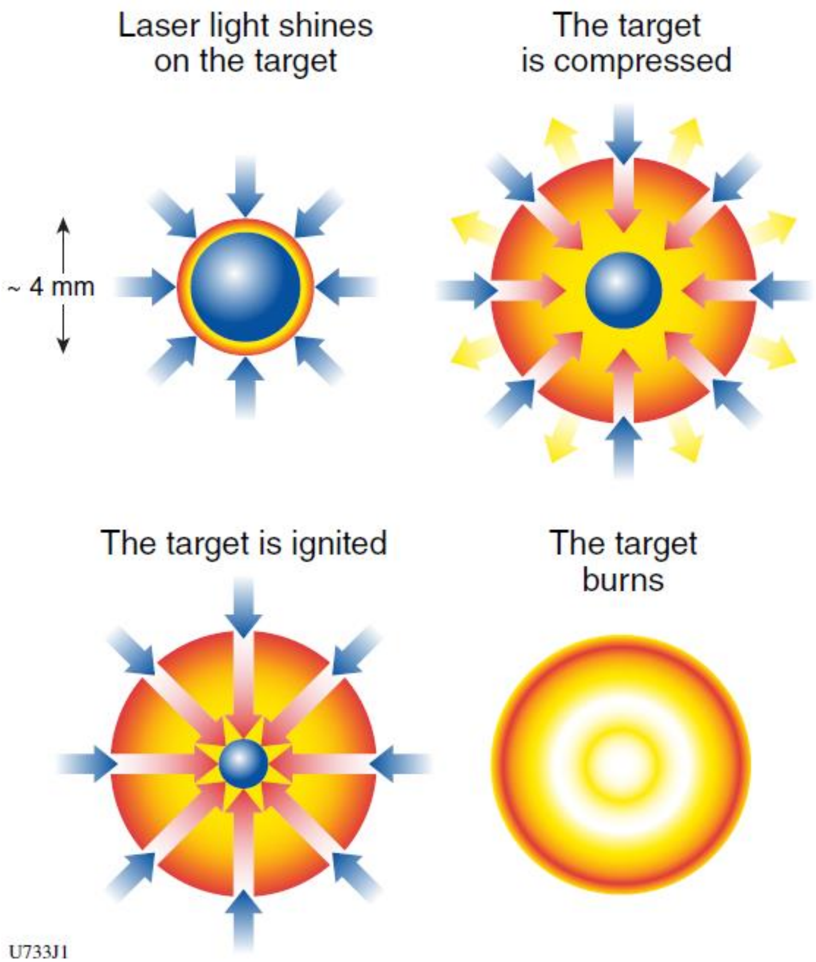




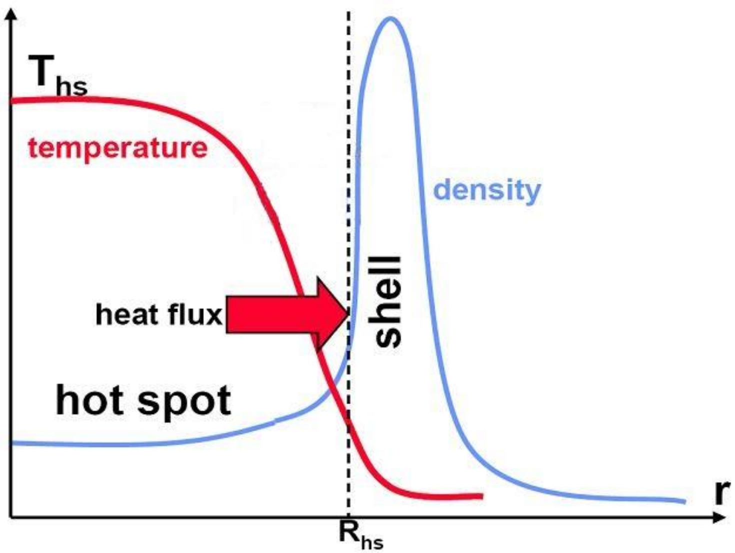


Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester
R. Betti, HEDSA HEDP Summer School, 2015

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

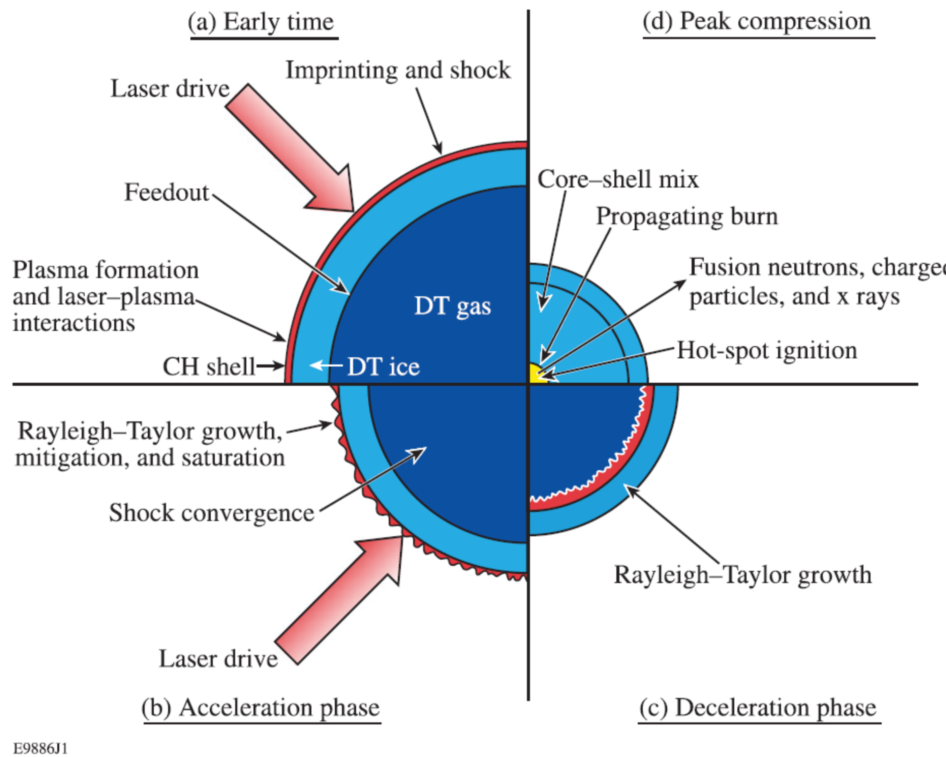


Spatial profile at stagnation

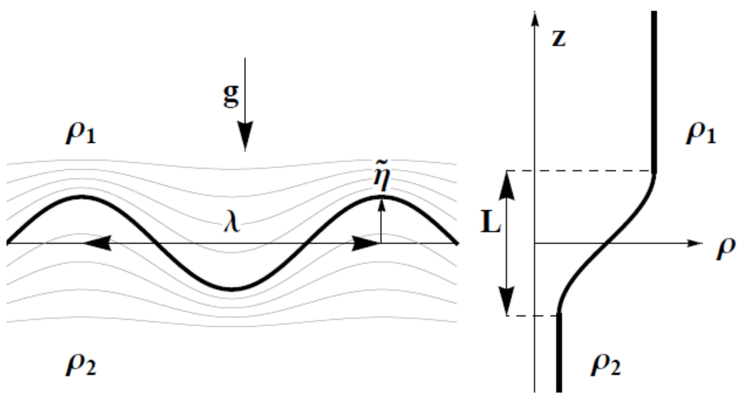


A ball can not be compressed uniformly by being squeezed between several fingers

- **Stages of a target implosion**

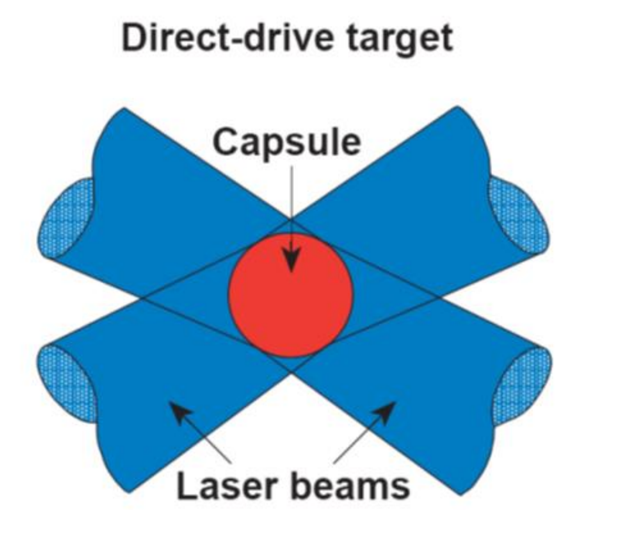


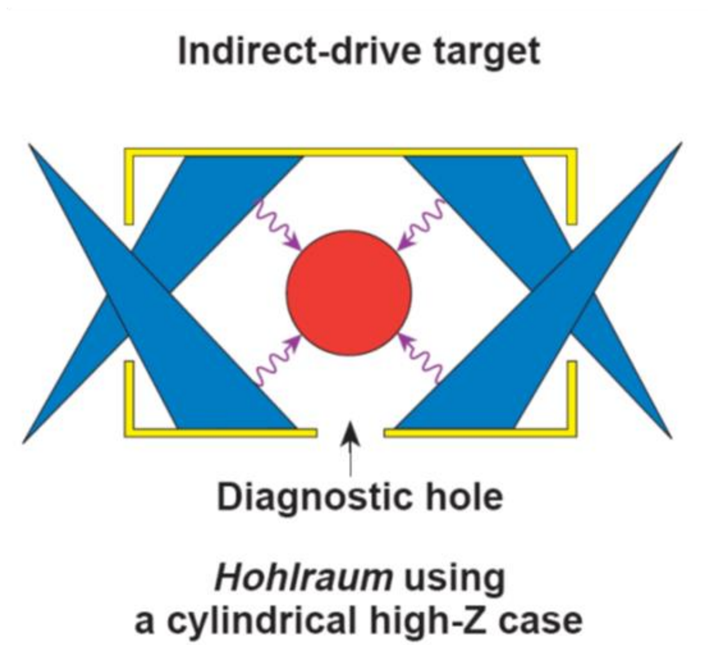
- **Rayleigh-Taylor instability**



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

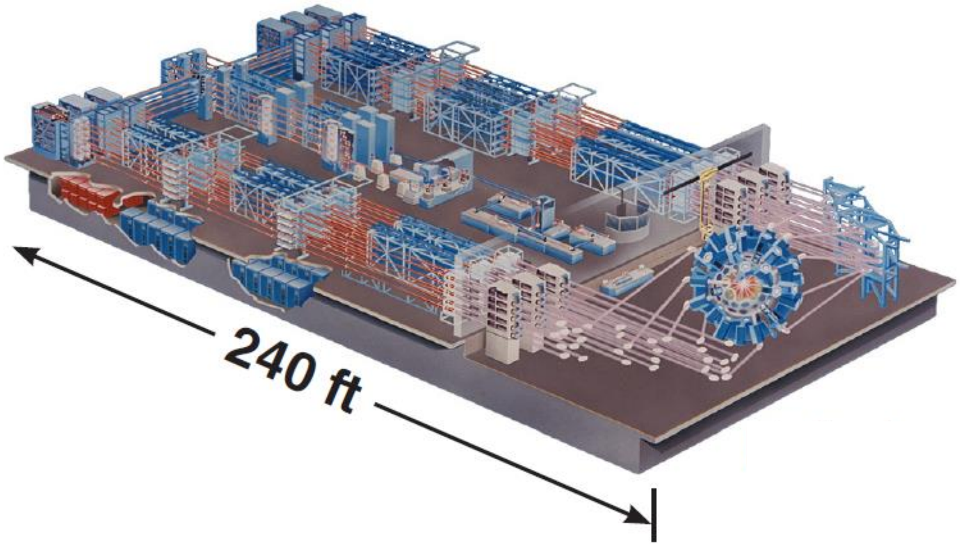
xerox ®

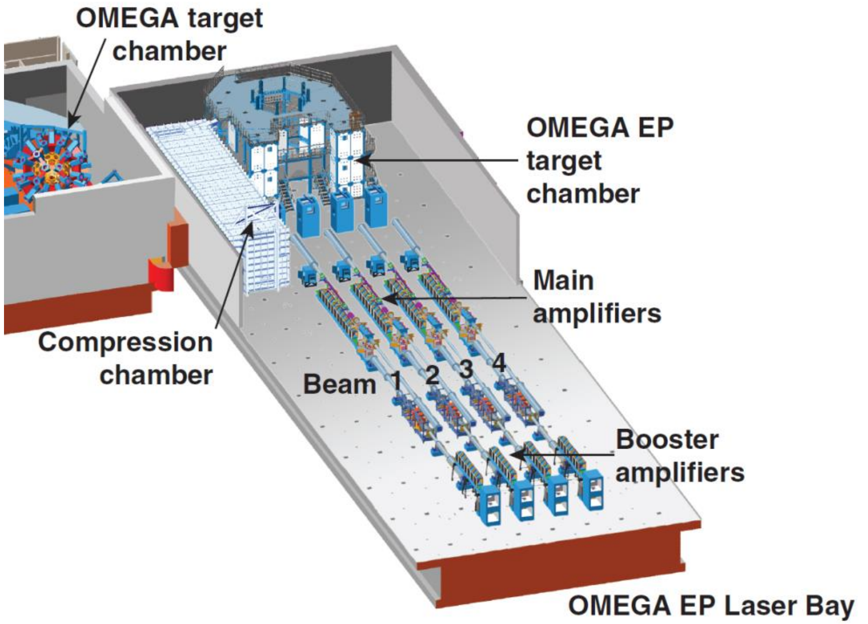
BAUSCH + LOMB

Eastman school of music

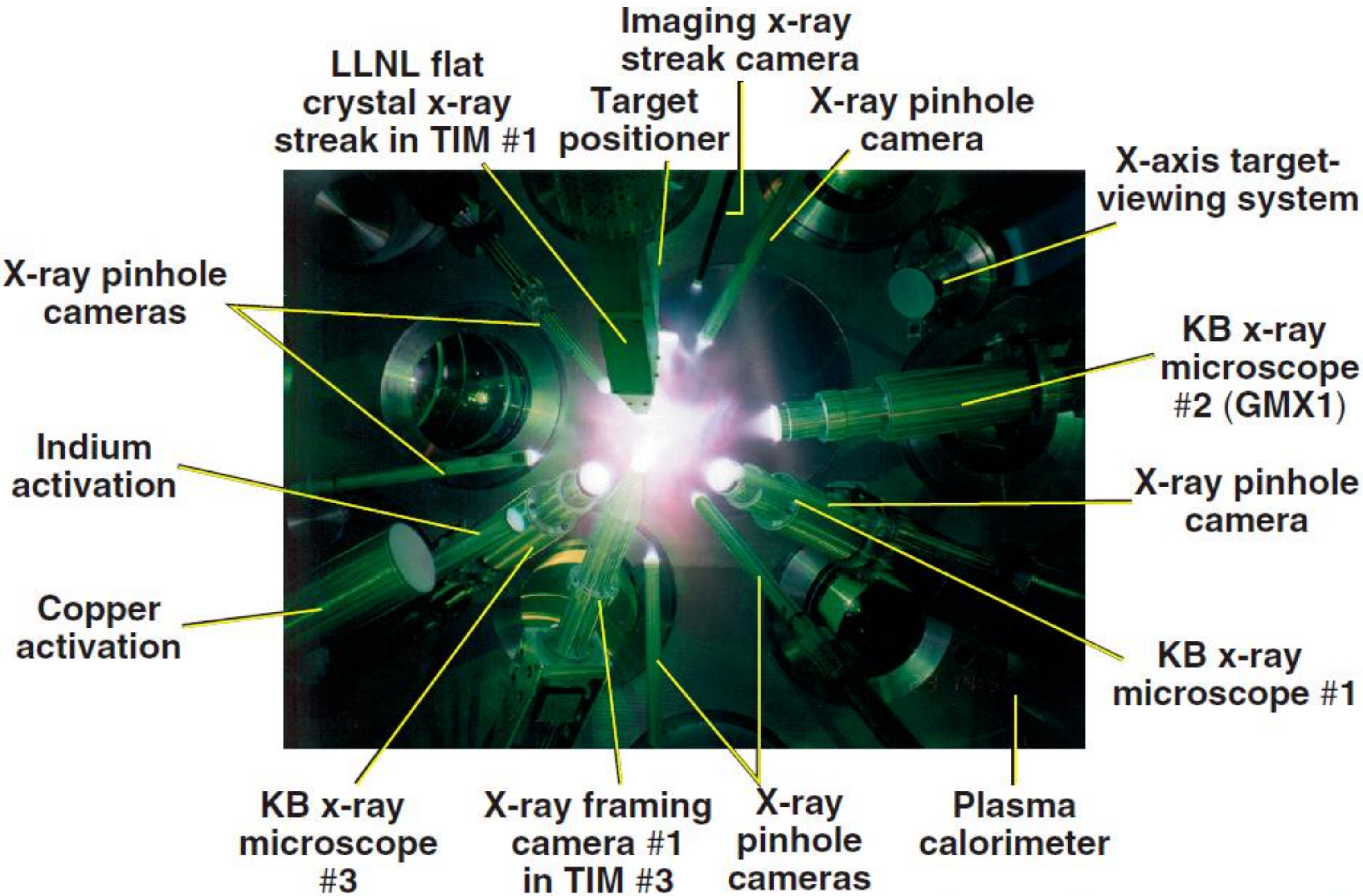
Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion

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





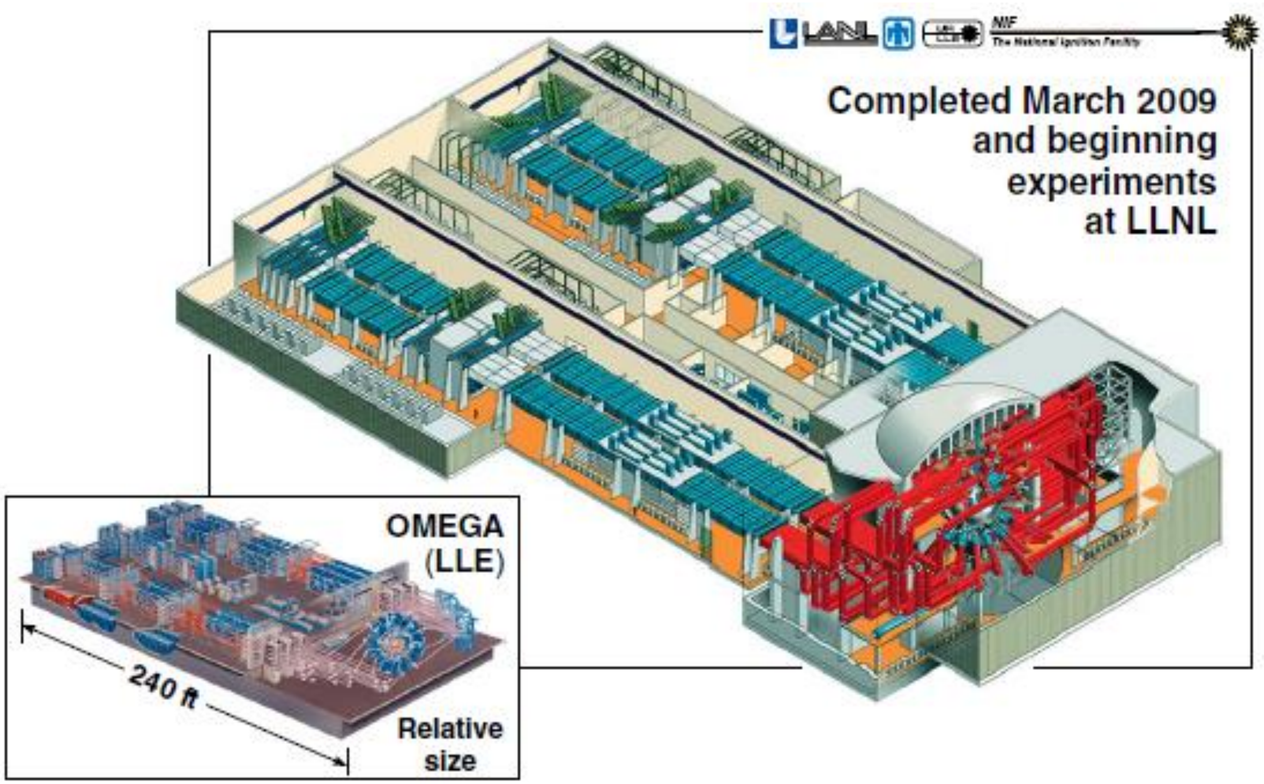
The OMEGA Facility is carrying out ICF experiments using a full suite of target diagnostics



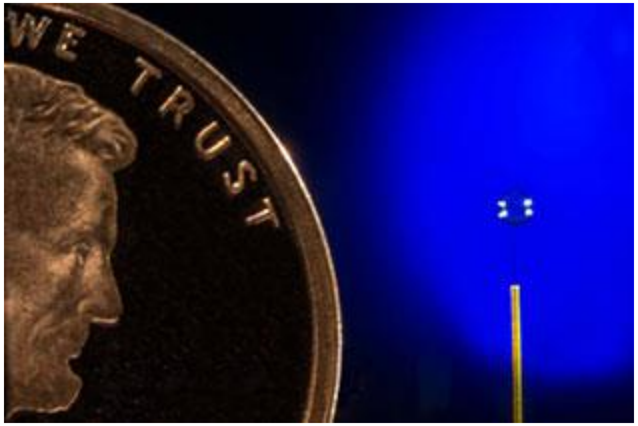
E8012b

Photo taken from port H11B

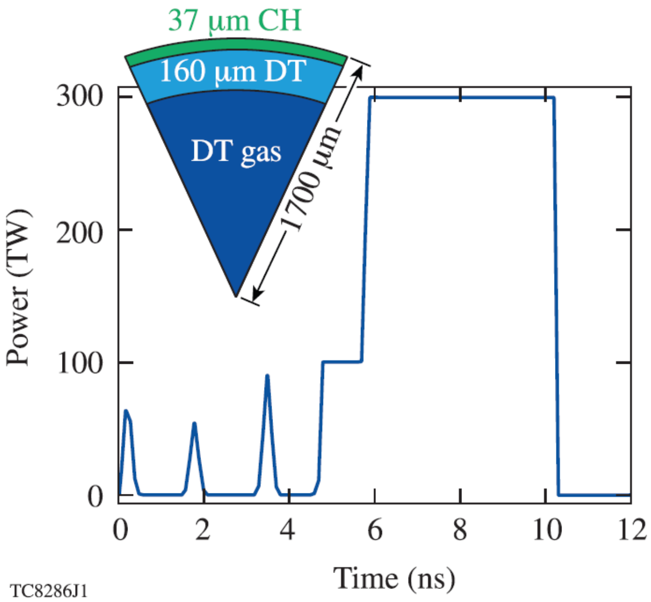
The 1.8-MJ National Ignition Facility (NIF) will demonstrate ICF ignition and modest energy gain



Targets used in ICF



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

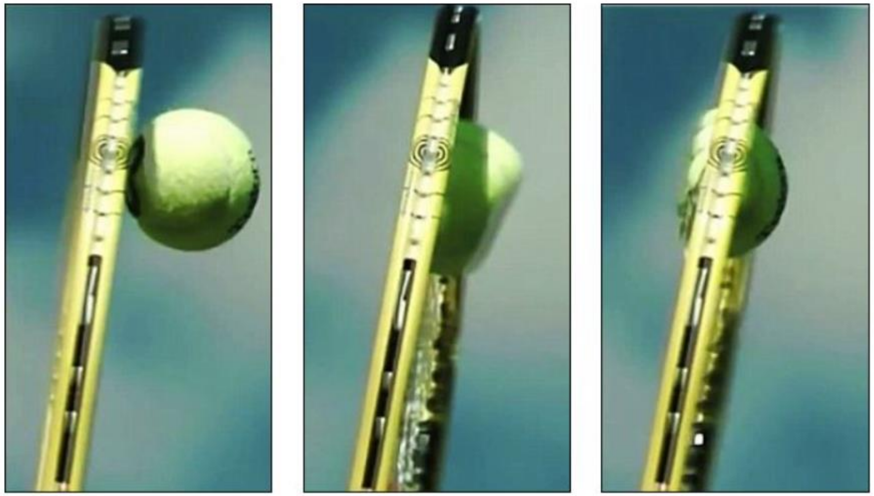


http://www.lle.rochester.ed
https://en.wikipedia.org/wiki/Inertial_confinement_fusion
R. S. Craxton, etc., *Phys. Plasmas* **22**, 110501 (2015)

Softer material can be compressed to higher density

- **Compression of a baseball**

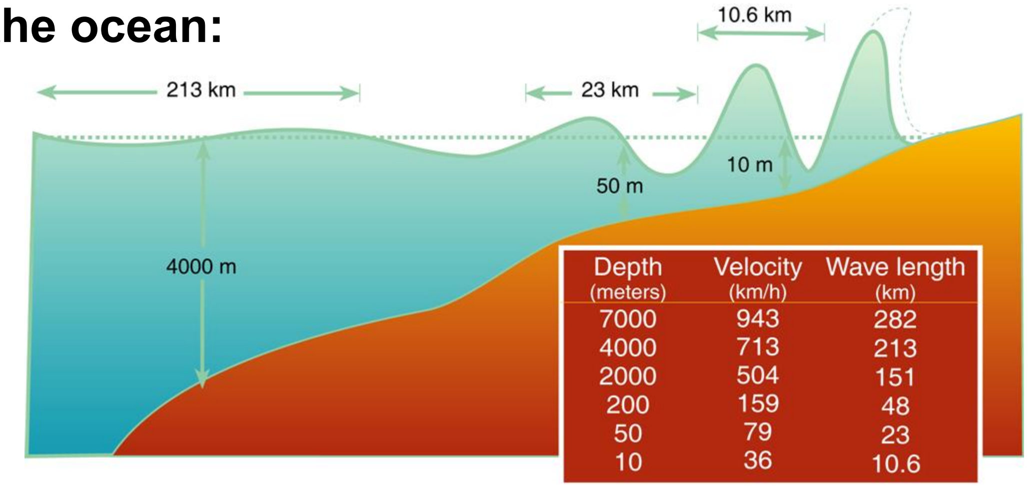
- **Compression of a tennis ball**



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

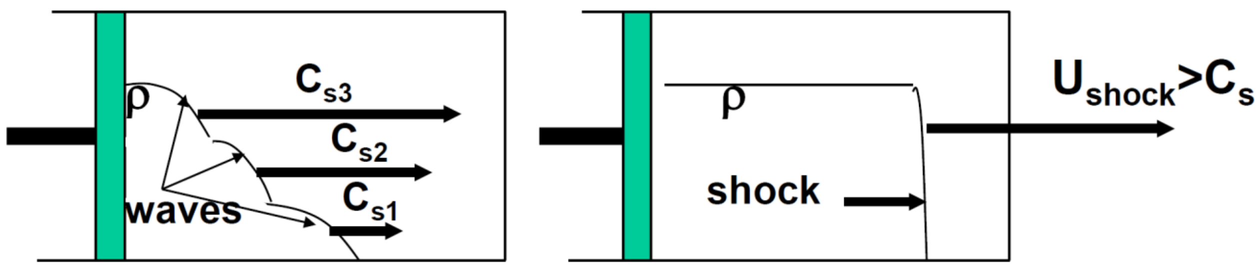
A shock is formed due to the increasing sound speed of a compressed gas/plasma

- **Wave in the ocean:**



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

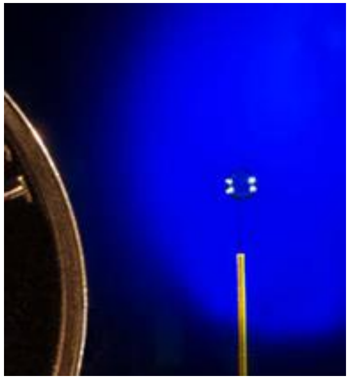
- **Acoustic/compression wave driven by a piston:**



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

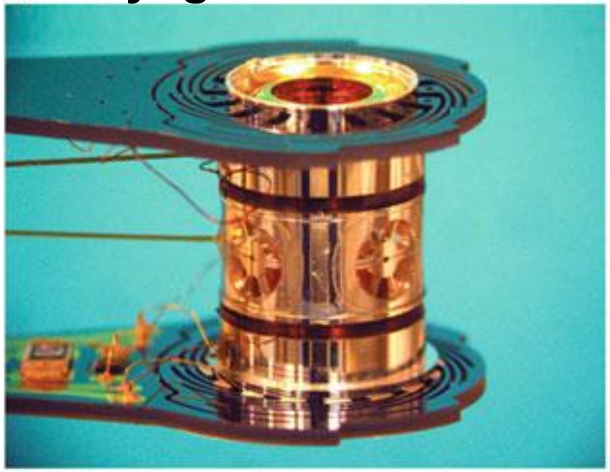
http://neamtic.ioc-unesco.org/tsunami-info/the-cause-of-tsunamis
*R. Betti, HEDSA HEDP Summer School, 2015

Targets used in ICF

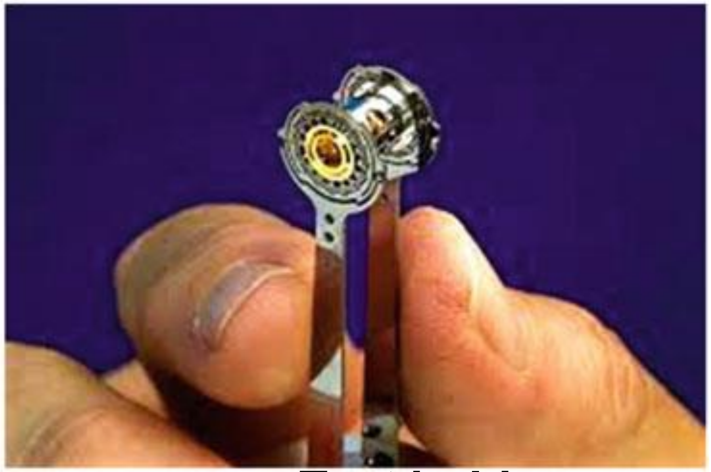


Cryogenic shroud

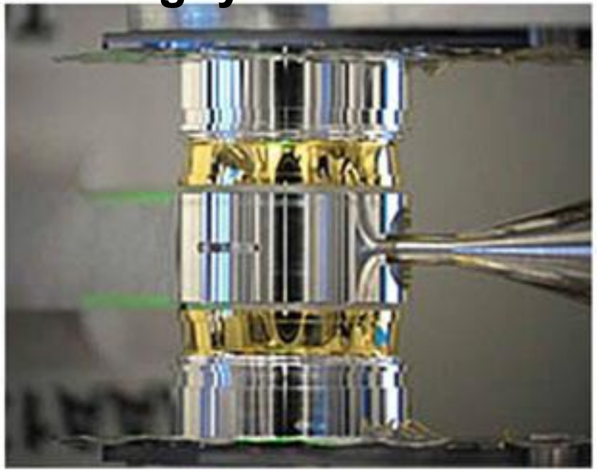
a Cryogenic hohlraum



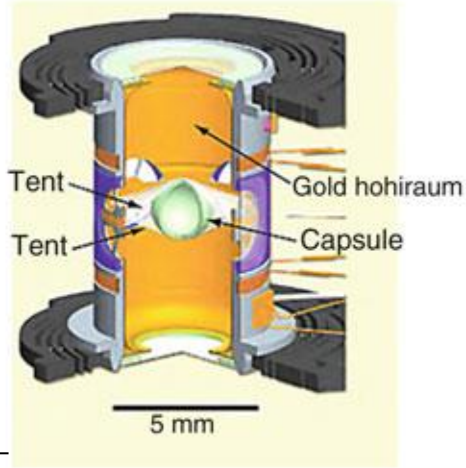
b



c Rugby hohlraum

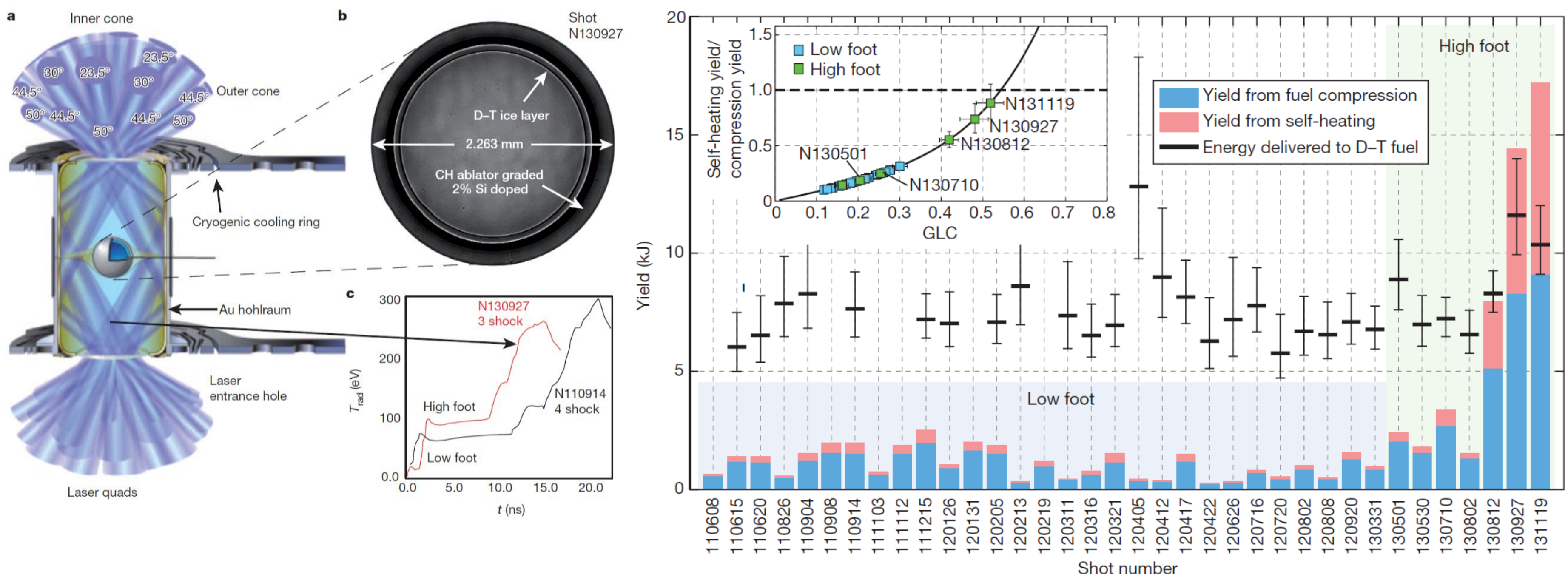


d Tent holder



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

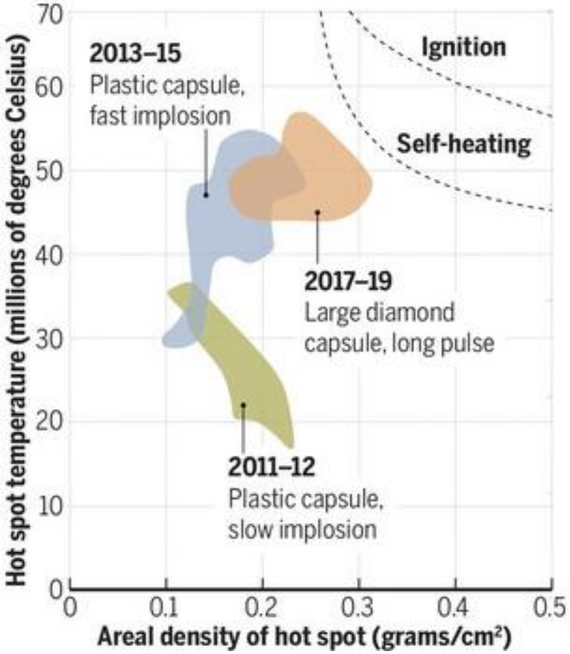
Nature letter “Fuel gain exceeding unity in an inertially confined fusion implosion”



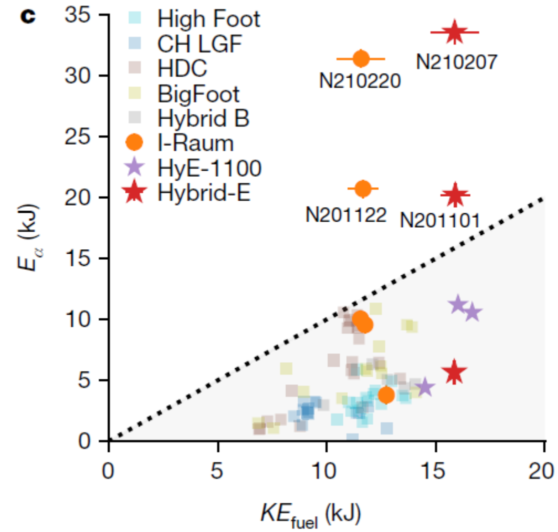
- **Fuel gain exceeding unity (scientific breakeven) was demonstrated for the first time.**

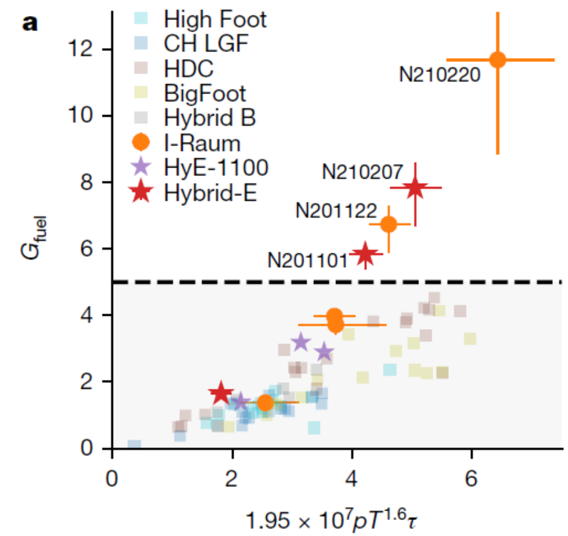
Nature 506, p343, 2014

The hot spot has entered the burning plasma regime



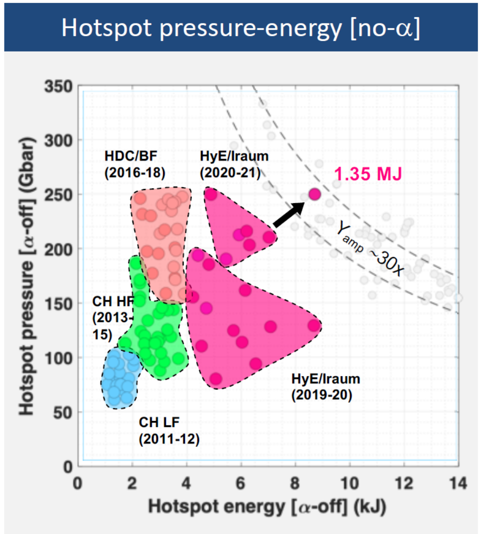
Science 370, p1019, 2020

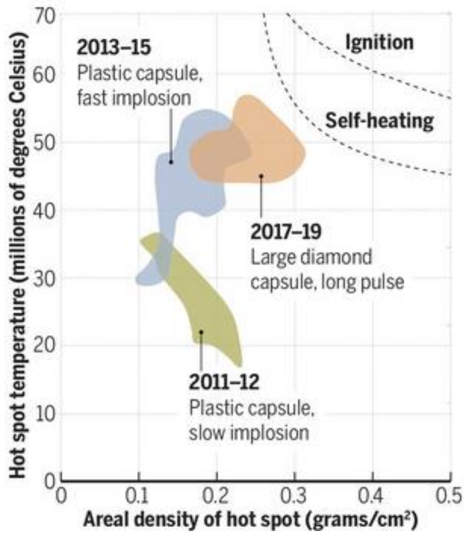




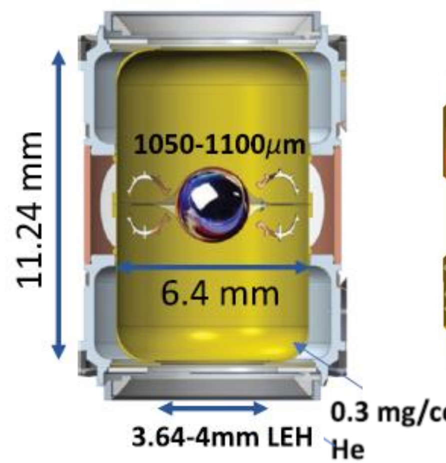
Nature 601, p542, 2022

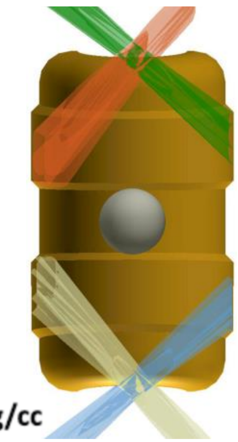
The hot spot has entered the burning plasma regime

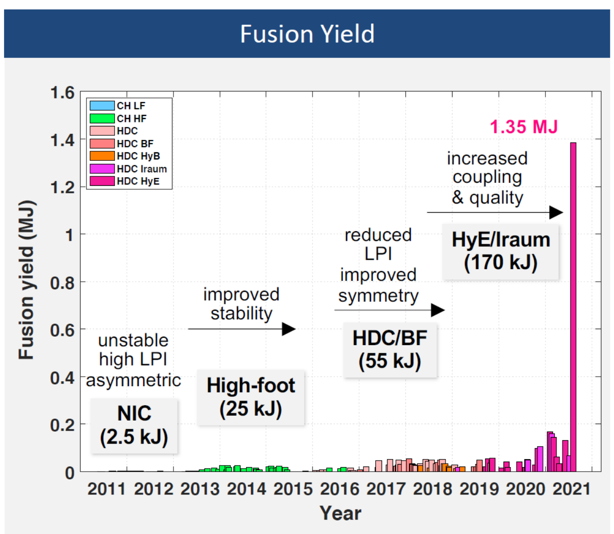




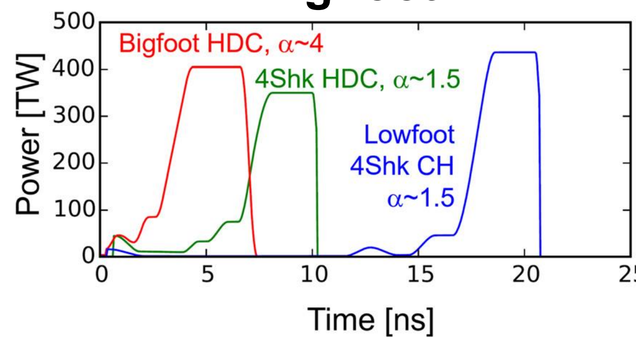
- **Hybrid-E**
- **I-raum**

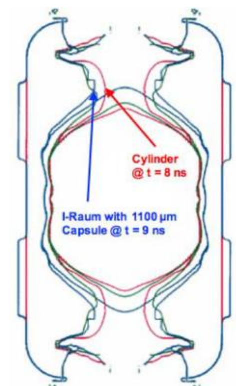






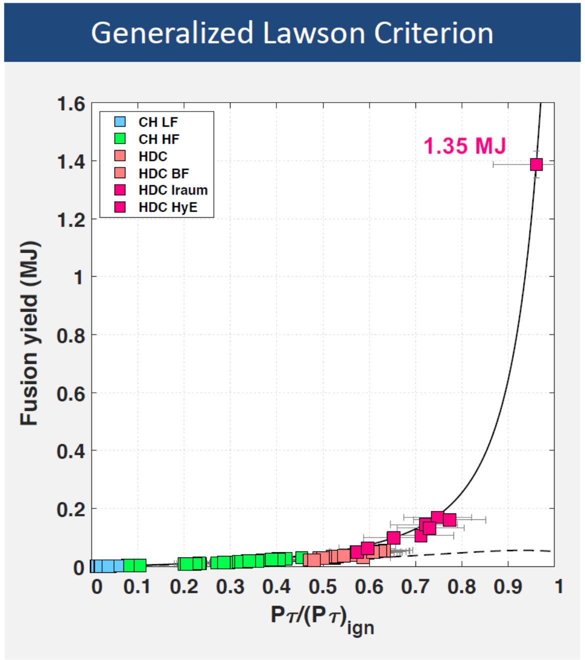
- **Big foot**

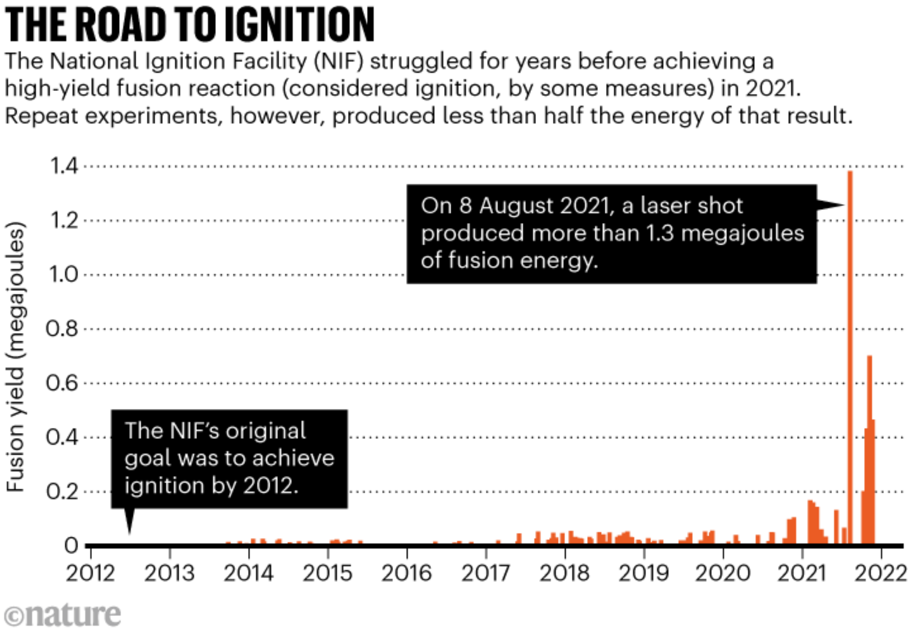




T. Ma, ARPA-E workshop, April 26, 2022
Science 370, p1019, 2020
D. T. Casey, etc., Phys. Plasmas, 25, 056308 (2018)
A. L. Kritcher, etc., Phys. Plasmas, 28, 072706 (2021)
H. F. Robey, etc., Phys. Plasmas, 25, 012711 (2018)

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)



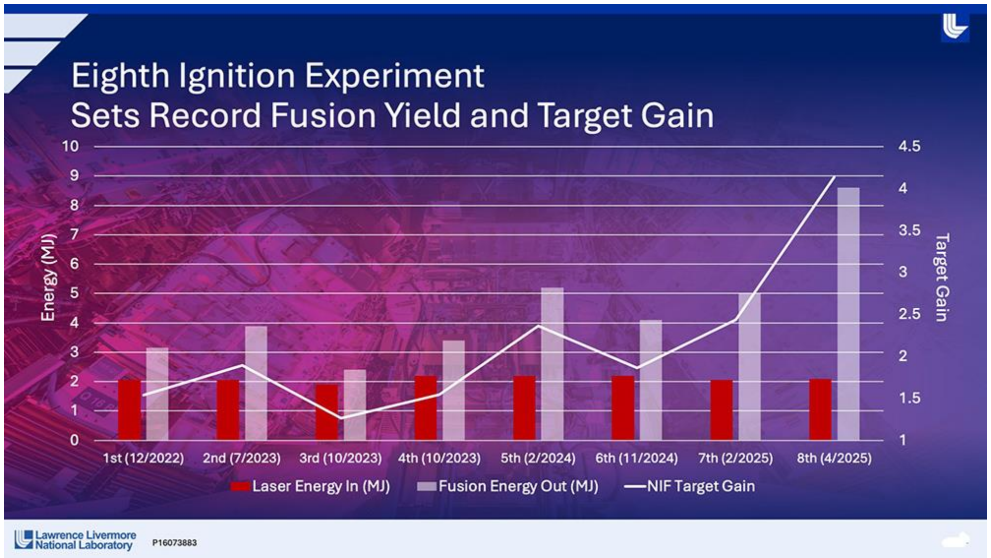


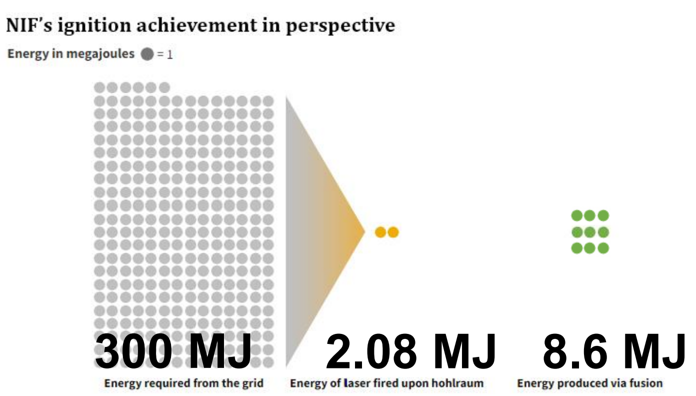
- National Ignition Facility (NIF) achieved a yield of more than 1.3 MJ (Q~0.7). This advancement puts researchers at the threshold of fusion ignition.

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

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

A gain over 4 has been achieved

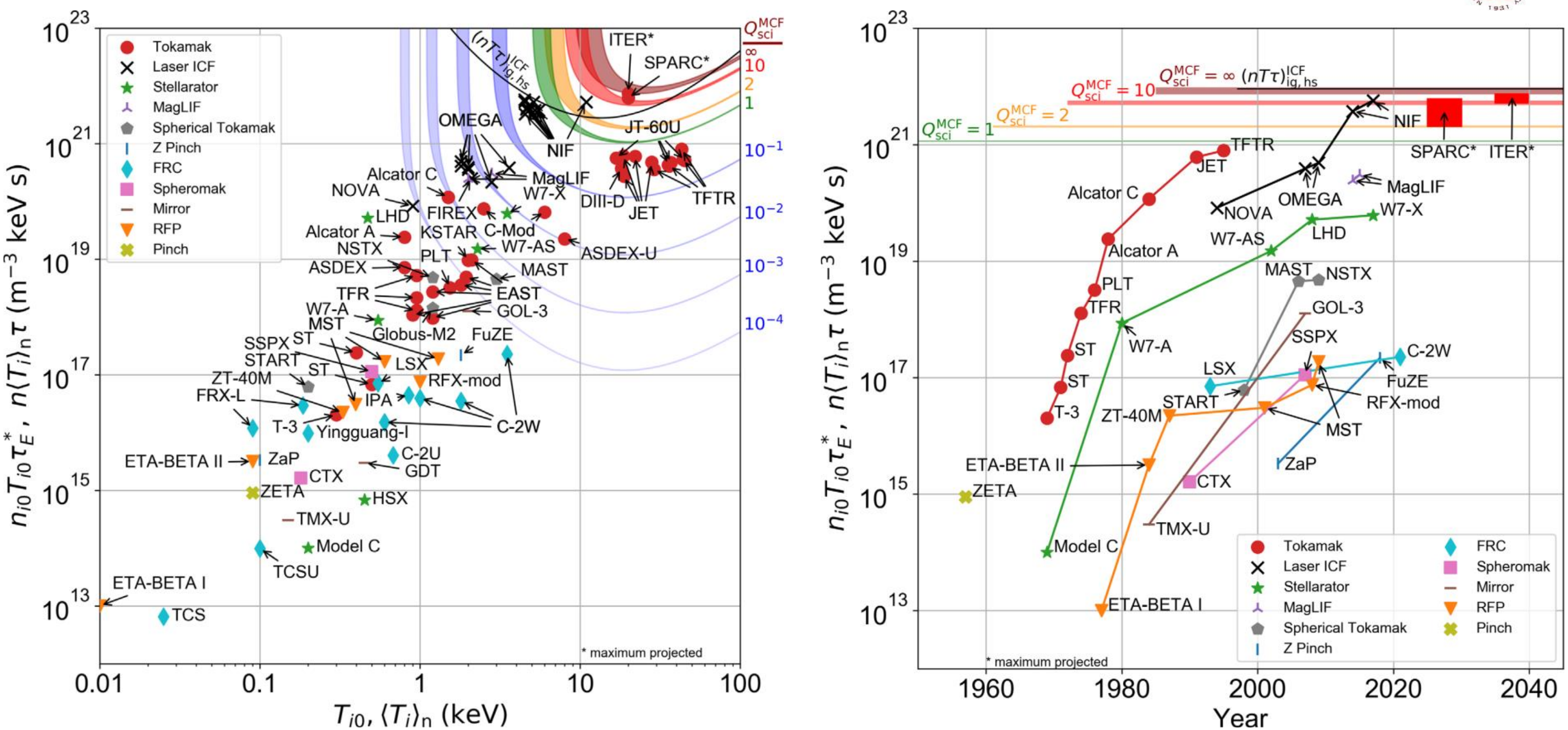




- **In recent attempts, the team at NIF increased the yield of the experiment, first to 5.2 megajoules and then again to 8.6 megajoules, according to a source with knowledge of the experiment.**

https://physicstoday.scitation.org/do/10.1063/PT.6.2.20221213a/full/
https://lasers.llnl.gov/science/achieving-fusion-ignition

We are closed to ignition!



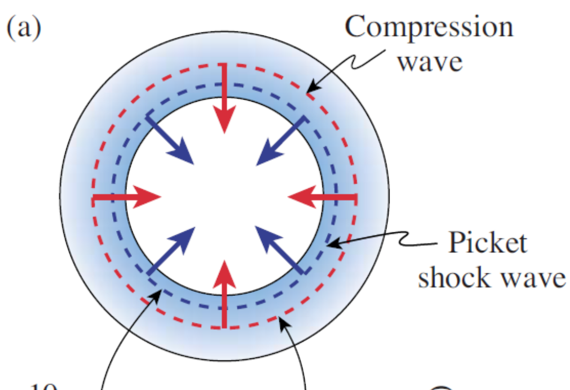
- **Lawson criteria (Ignition condition): Pτ > 10 atm-s = 10 Gbar - ns**

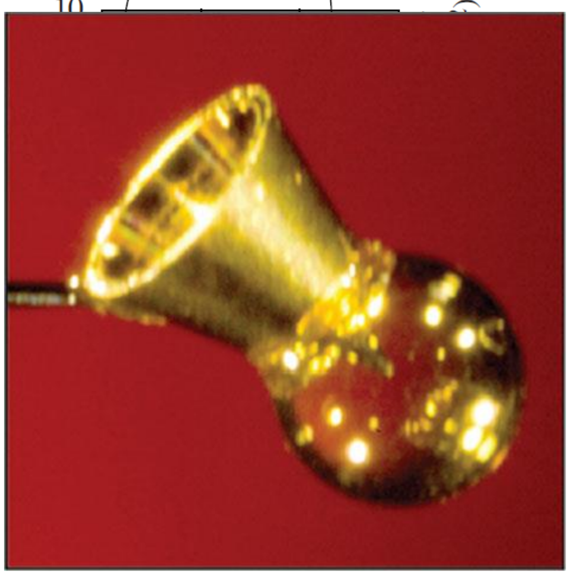
- **P: pressure, or called energy density**
- **τ is confinement time**

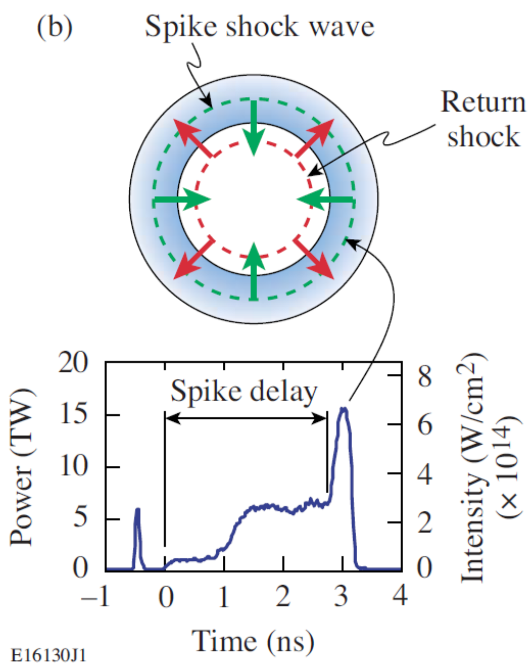
Samuel E. Wurzel and Scott C. Hsu, Phys. Plasmas, **29**, 062103 (2022)

External “spark” can be used for ignition

- **Shock ignition**

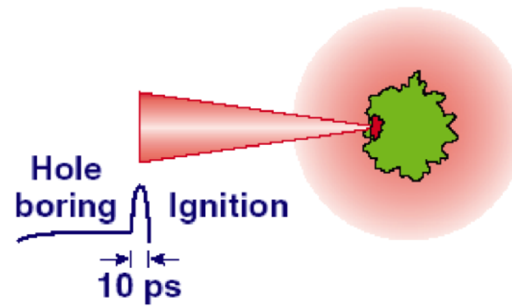




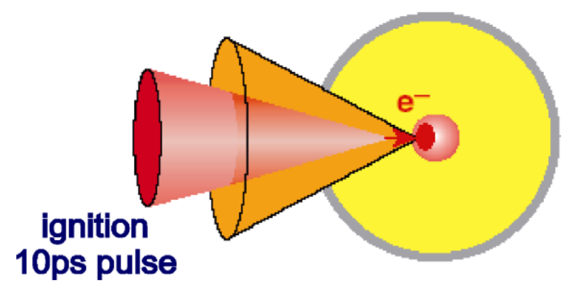


- **Fast ignition**

a) channeling FI concept



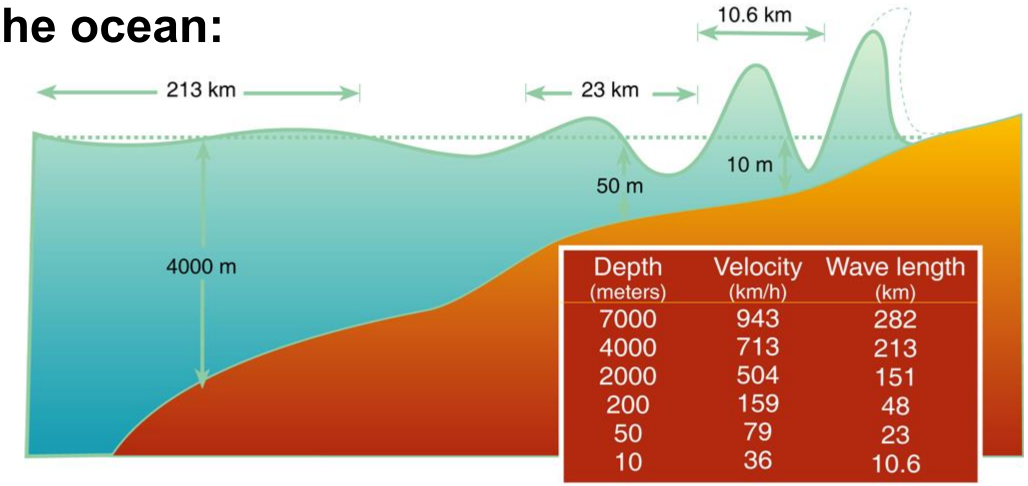
b) cone-in-shell FI concept



J. Badziak, Bull.Polish Acad. Sci. Tech. Sci.Phys. Plasmas 15, 056306 (2008)
T. Ditmire, etc., J. Fusion Energy **42**, 27 (2023)

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

- **Wave in the ocean:**



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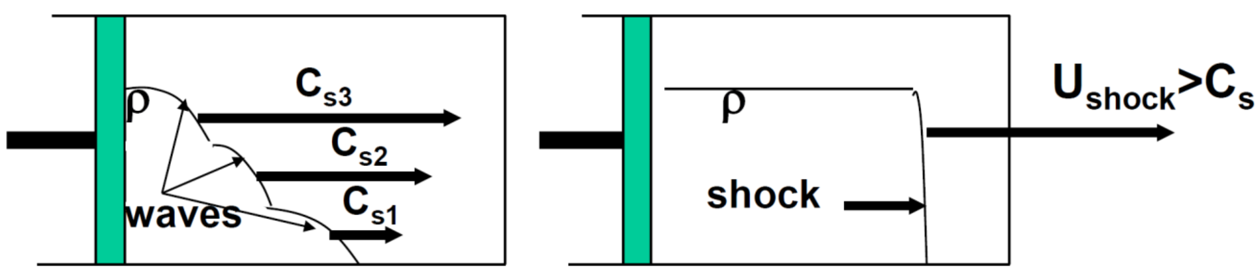
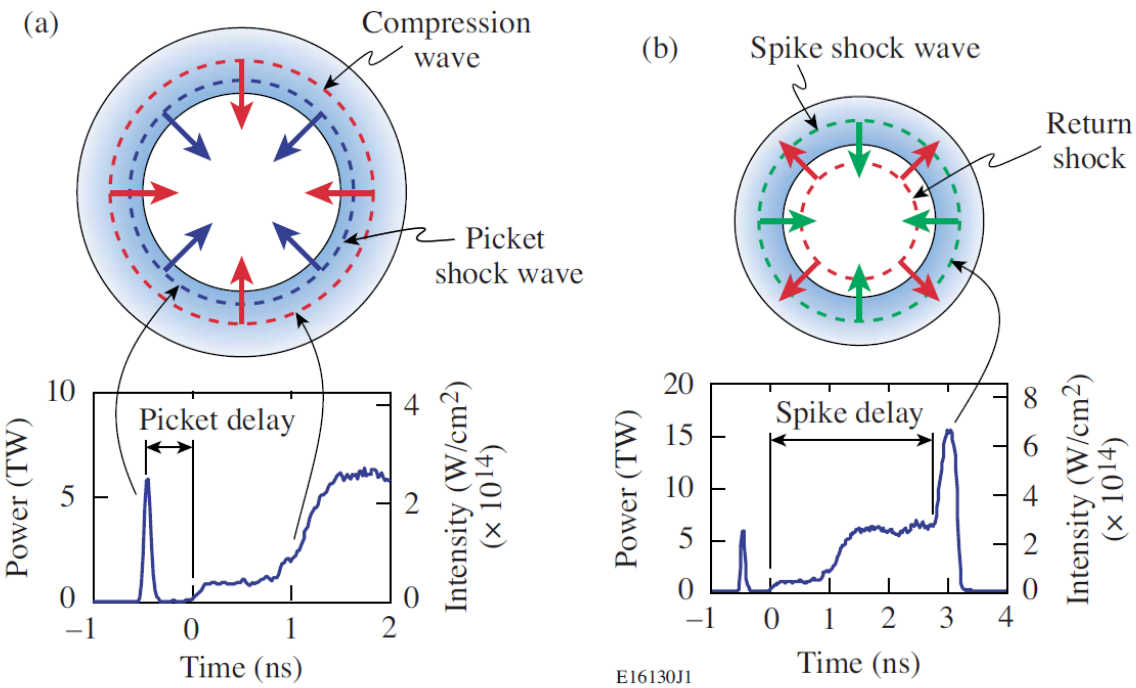


$$C_s \sim \sqrt{\frac{p}{\rho}} \sim \sqrt{\frac{\alpha\rho^{5/3}}{\rho}} \sim \sqrt{\alpha}\rho^{1/3}$$

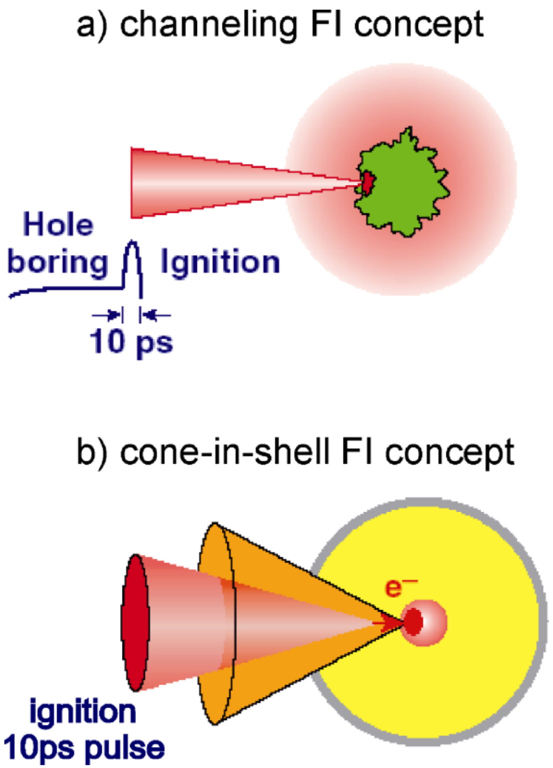
http://neamtic.ioc-unesco.org/tsunami-info/the-cause-of-tsunamis
*R. Betti, HEDSA HEDP Summer School, 2015

External "spark" can be used for ignition

- **Shock ignition**

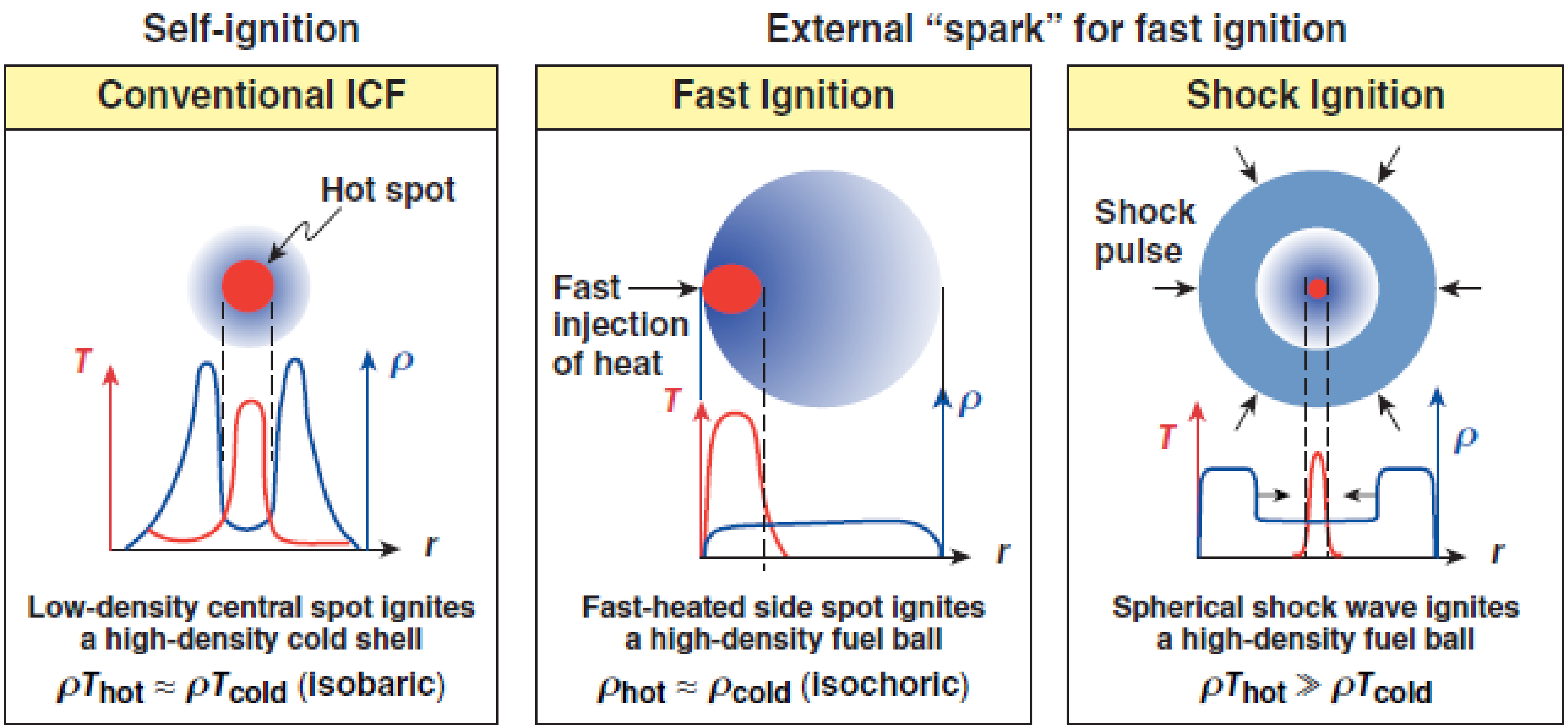


- **Fast ignition**



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

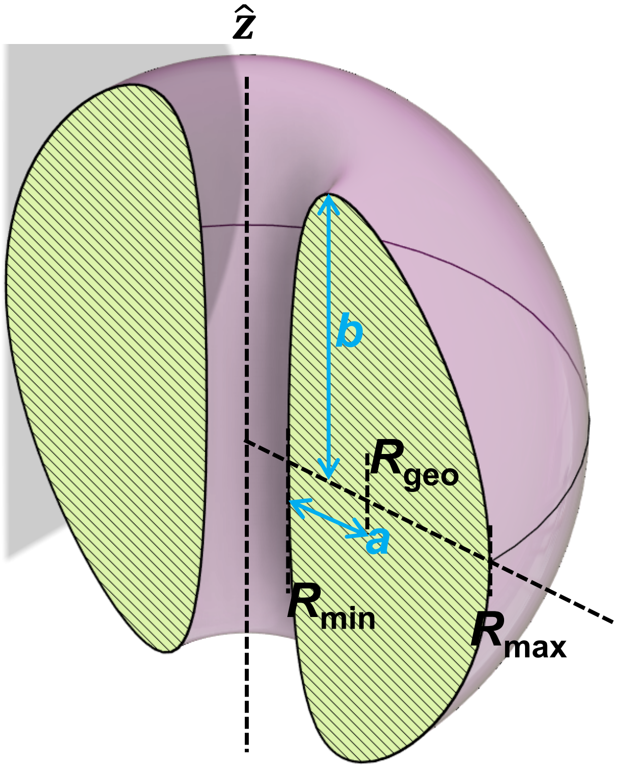
Ignition can happen by itself or being triggered externally



Course Outline

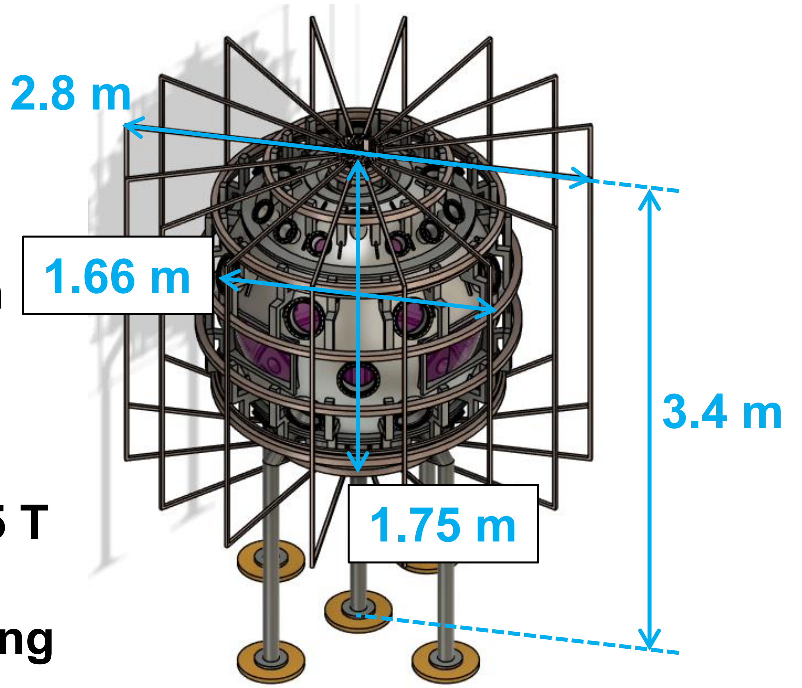
- What is Plasma?
- Nuclear fusion
  - Basic
  - Magnetic confinement fusion (MCF)
  - Inertial confinement fusion (ICF)
- **Formosa Integrated Research Spherical Tokamak (FIRST), the first Tokamak in Taiwan**

Development of Formosa Integrated Research Spherical Tokamak (FIRST), the first Tokamak in Taiwan

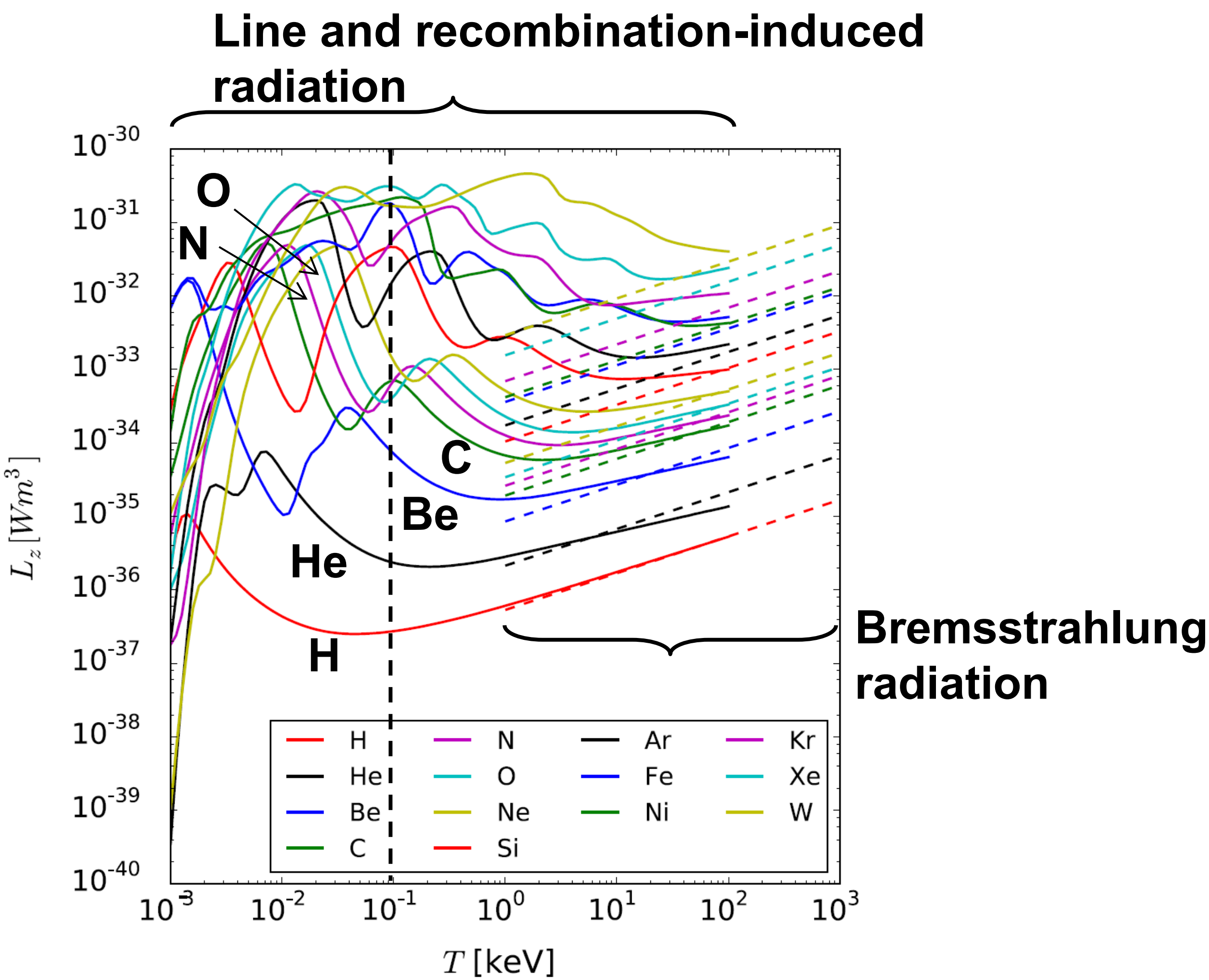


- R_{geo} = 45 cm
- a = 32 cm
- b = 76.8 cm
- T ~ 100 eV
- B_T ~ 0.1 - 0.5 T
- I_p ~ 100 kA
- Ohmic heating
- Gas: H_2
- Duration: 100 ms

- **First plasma: 2026.**



Temperature of 100 eV is the threshold of radiation barrier by impurities



H. Lux, etc., Fusion Eng. Des. **42**, 101 (2015)

Teams

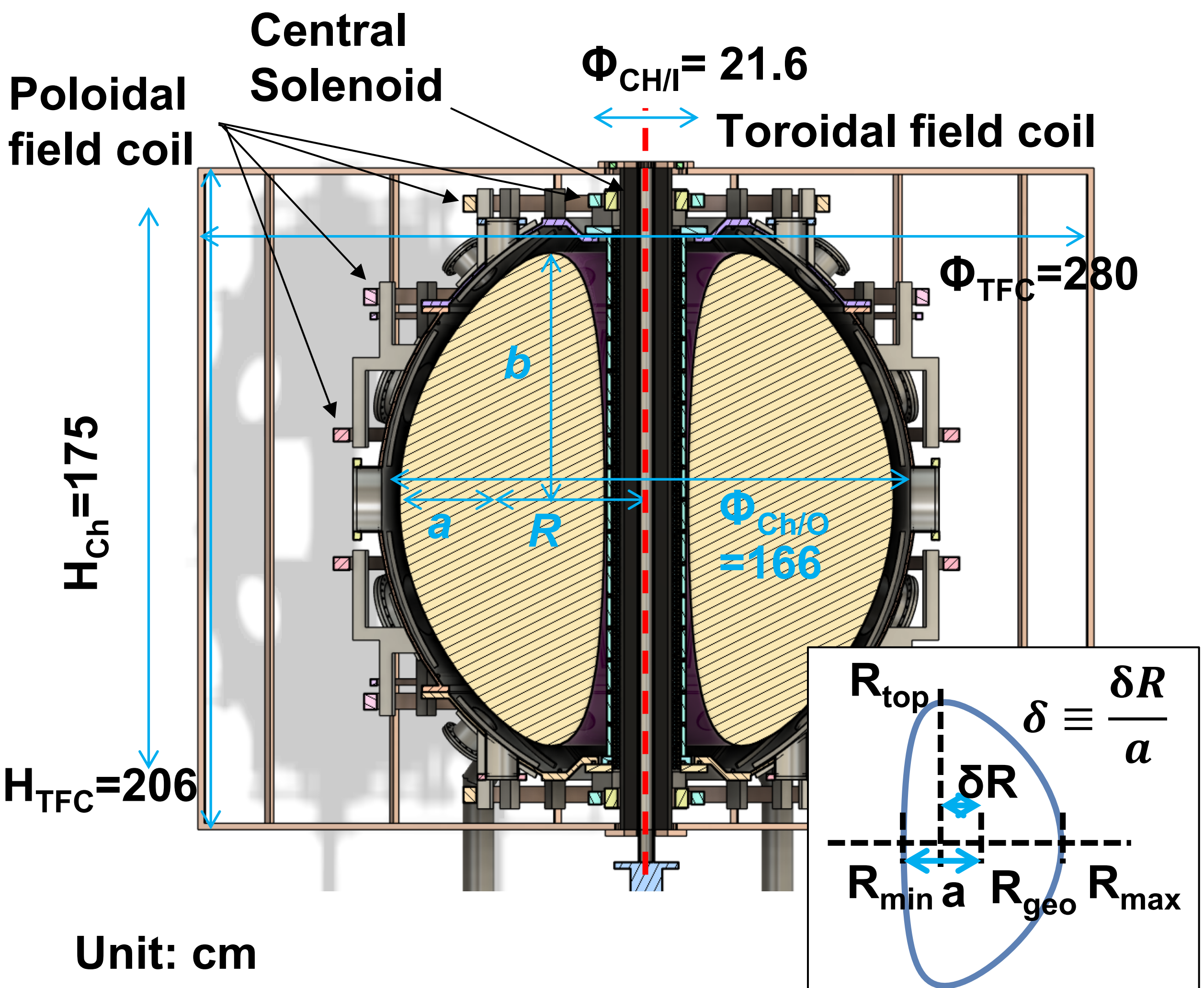
- 馬維揚團隊 @ 國家原子能科技研究院
  - Site
- 張博宇團隊 @ 成功大學 太空與電漿科學研究所
  - System design and development/diagnostics
- 向克強團隊 @ 成功大學 前瞻電漿中心
  - Theoretical design
- 河森榮一郎團隊 @ 成功大學 太空與電漿科學研究所
  - Diagnostics
- 柳克強團隊 @ 清華大學 工程與系統科學系
  - Diagnostics
- 蔡宗哲團隊 @ 國家高速網路與計算中心
  - Simulation
- 張存續團隊 @ 清華大學 物理系
  - RF startup

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

The system will be built in National Atomic Research Institute (NARI, 國家原子能科技研究院) at 龍潭

https://www.sipa.gov.tw/home.jsp?mserno=201001210037&serno=201001210041&menudata=ChineseMenu&contlink=content/introduction_4_1.jsp&serno3=201002010023
https://www.nari.org.tw/newsdetail/activity/353.html

Formosa Integrated Research Spherical Tokamak (FIRST) aiming for the first plasma in 2026



Unit: cm

- *R*/*a*/*b*=45/32/76.8 cm
- Aspect ratio = *R*/*a* = 1.5
- *k* = *b*/*a* = 2.4
- δ = 0.5
- B_T = 0.1 ~ 0.5 T
- *T* ≥ 100 eV
- I_p ≥ 100 kA
- Gas: H_2
- Ohmic heating
- Duration: 100 ms
- FIRST is targeted for
  - Low aspect ratio
  - High beta
  - High bootstrap current

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