Practice Course in Plasma

Po-Yu Chang

Institute of Space and Plasma Sciences, National Cheng Kung University

2021 spring semester

Thursday 9:10-12:00

Material: http://capst.ncku.edu.tw/PGS/index.php/teaching/

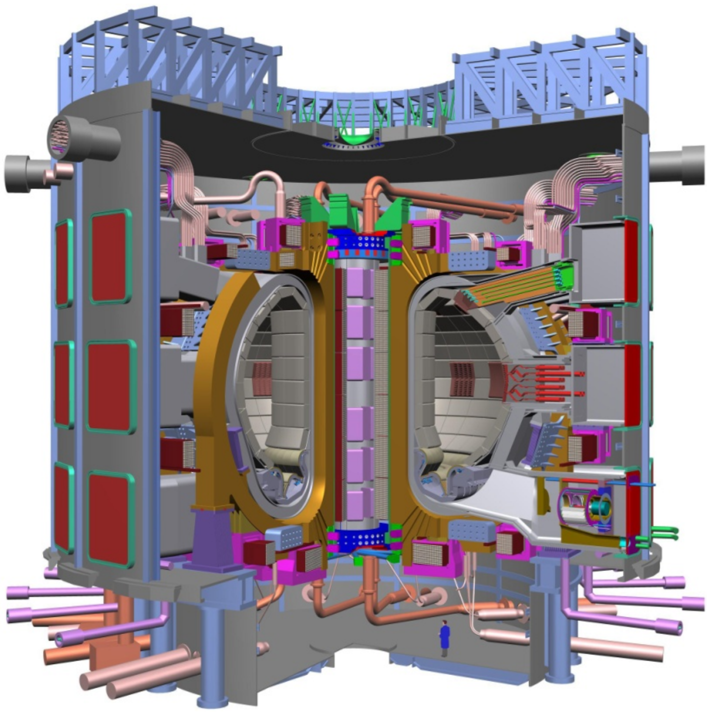
Lecture 3

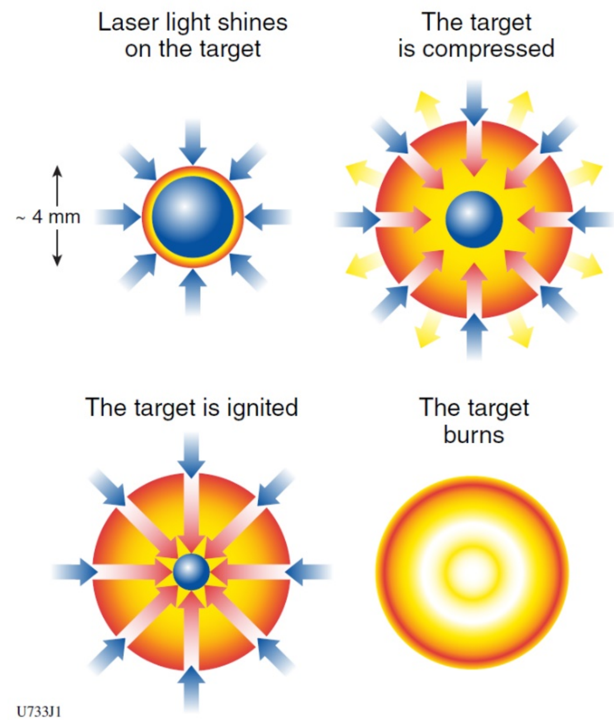
2021/3/11 updated

Reference

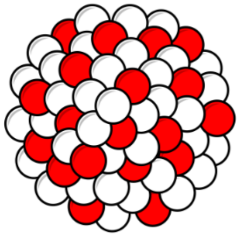
- Riccardo Betti, University of Rochester, HEDSA HEDP summer school, San Diego, CA, August 16-21, 2015.
- Inertial Confinement Fusion, R. Betti, Phy558/ME533, University of Rochester.
- Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

To Fuse, or Not to Fuse...





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



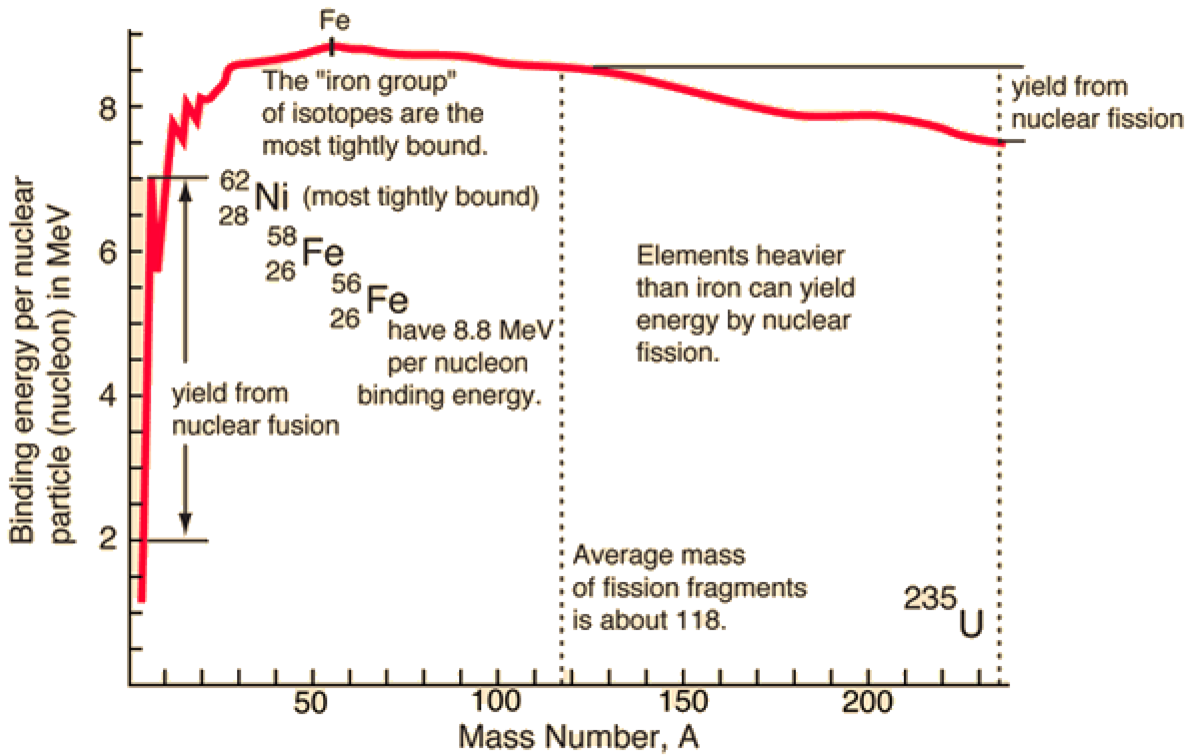
Nucleus

= i ● + j ○

Proton Neutron

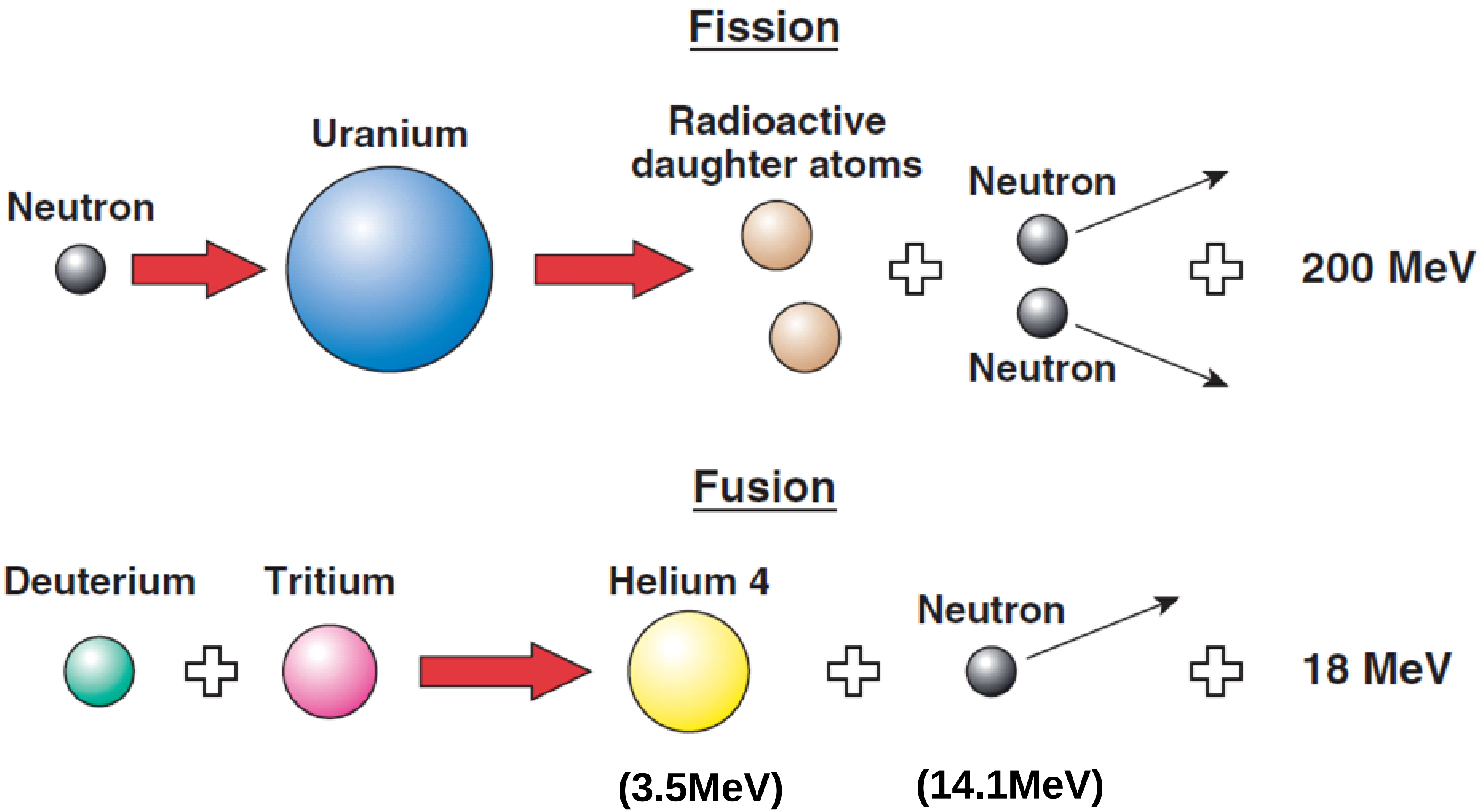
$$M_{Nucleus} < i \times M_{proton} + j \times M_{neutron}$$

$$E_{binding} = (i \times M_{proton} + j \times M_{neutron} - M_{nucleus}) C^2$$



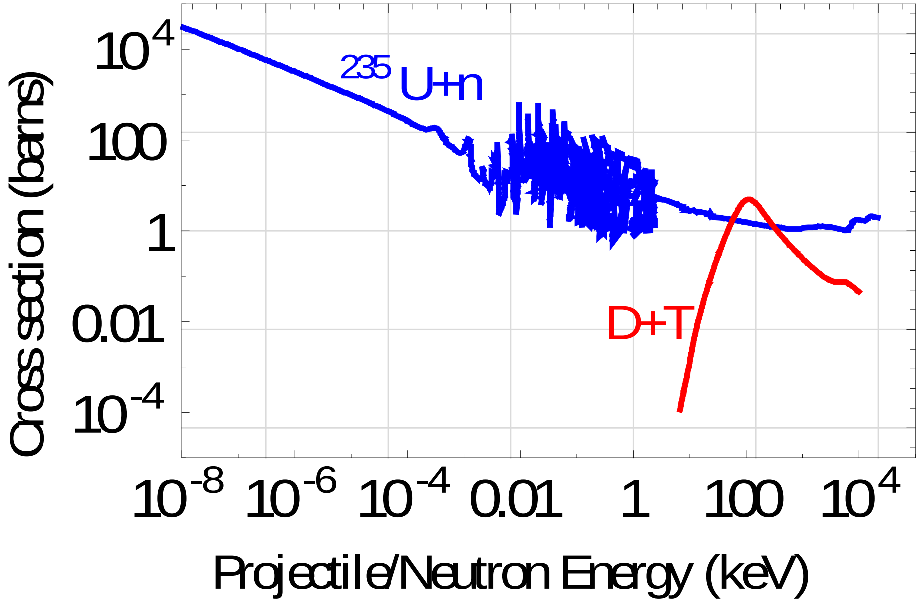
http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html

Nuclear fusion and fission release energy through energetic neutrons



Fusion is much harder than fission

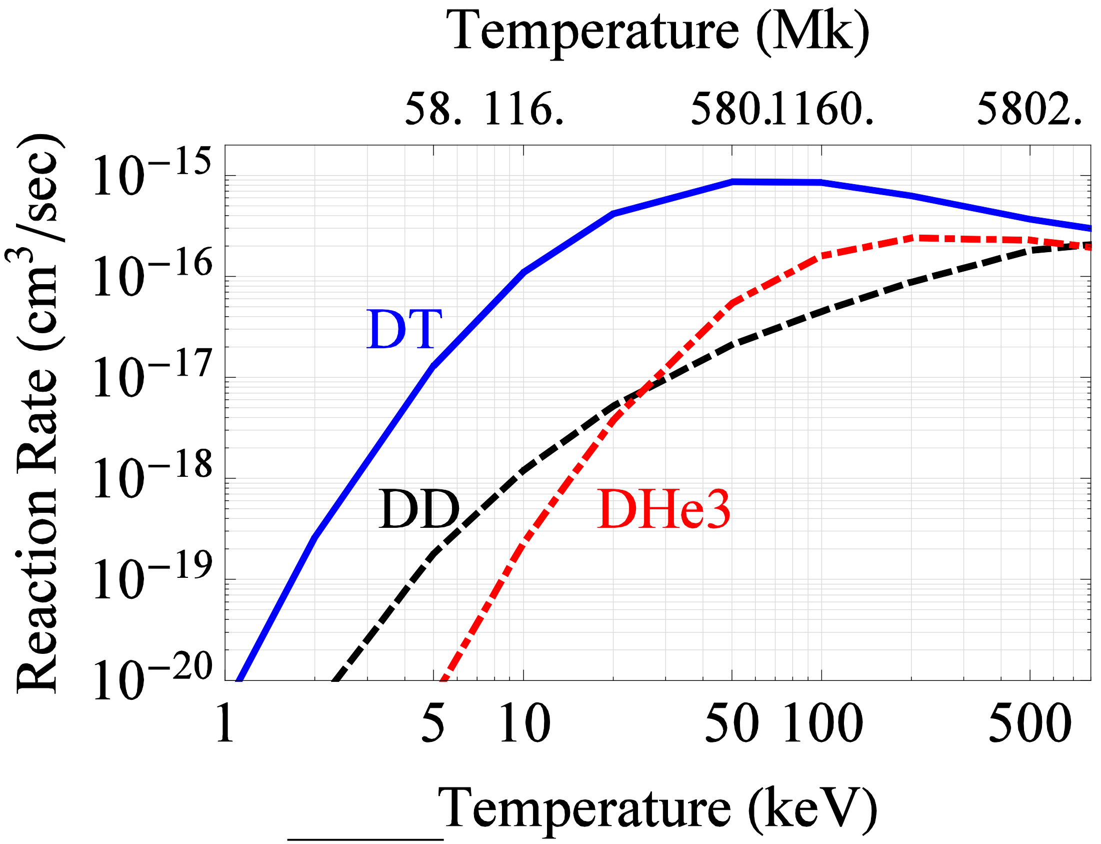
- **Fission:** $n +^{235}_{92} U \rightarrow^{236}_{92} U \rightarrow^{144}_{56} Ba +^{89}_{36} Kr + 3n + 177 \text{ MeV}$
- **Fusion:** $D + T \rightarrow He^4\,(3.5 \text{ MeV}) + n\,(14.1 \text{ MeV})$



Fusion doesn't come easy

averaged reaction rate : $\langle \sigma v \rangle = \int \int d\vec{v}_1 d\vec{v}_2 \sigma_{1,2}(v)\, v f_1(v_1)$

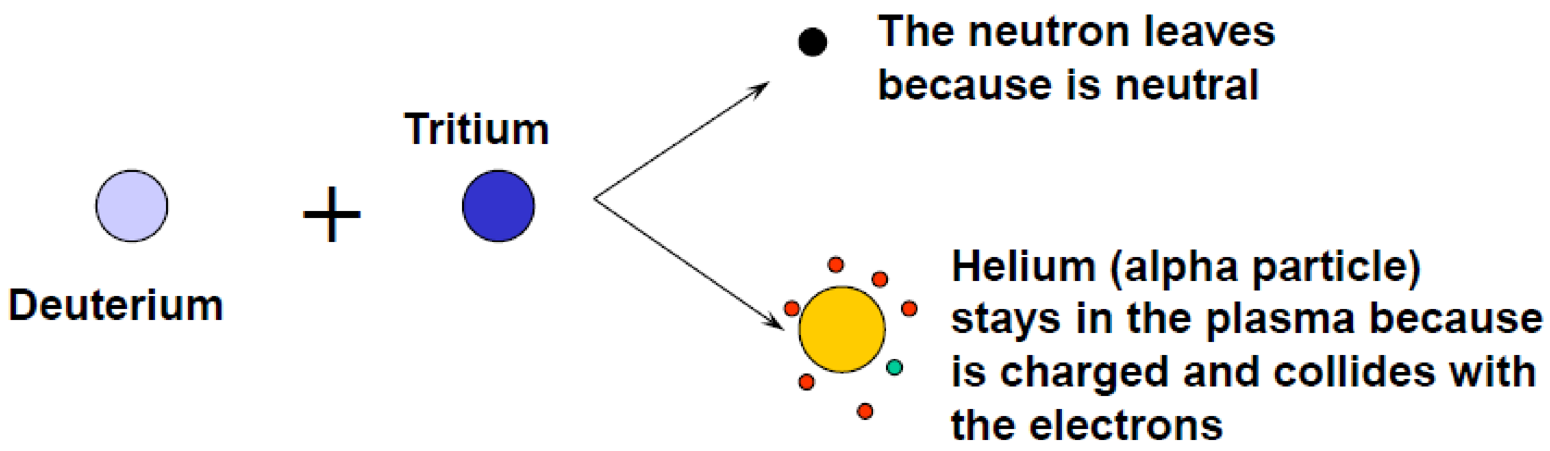
$$f_j(v_j) = \left(\frac{m_j}{2\pi k_B T}\right)^{3/2} \exp\left(-\frac{m_j v_j^2}{2 k_B T}\right)$$



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

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

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



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

*R. Betti, HEDSA HEDP Summer School, 2015

Under what conditions the plasma keeps itself hot?

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

$S_\alpha + S_h = S_B + S_k$

S_α: α particle heating

$$S_\alpha = \frac{1}{4} E_\alpha n^2 < \sigma v >= \frac{1}{16} E_\alpha p^2 \frac{< \sigma v >}{T^2}$$

S_h: external heating

S_B: Bremsstrahlung radiation

$$S_B = \frac{1}{4} C_B Z_{eff} \frac{p^2}{T^{3/2}}$$

S_k: heat conduction lost

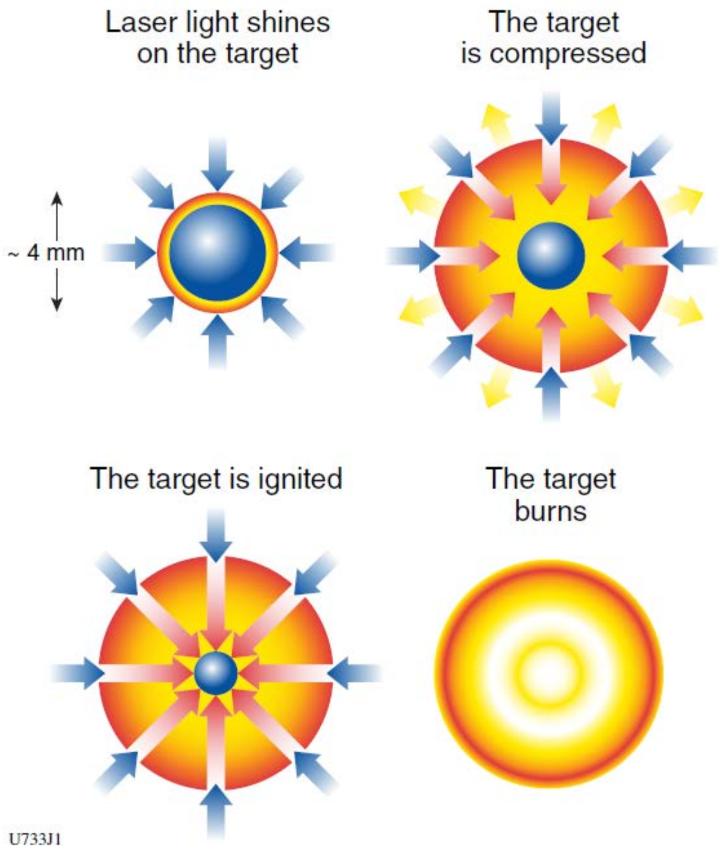
$$S_\kappa = \frac{3}{2} \frac{p}{\tau}$$

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

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

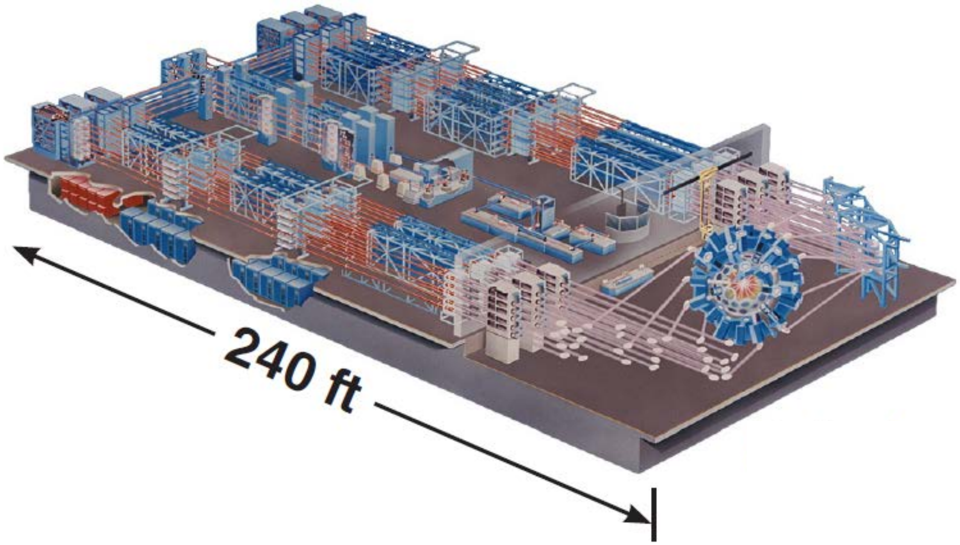
Don’t confine it!

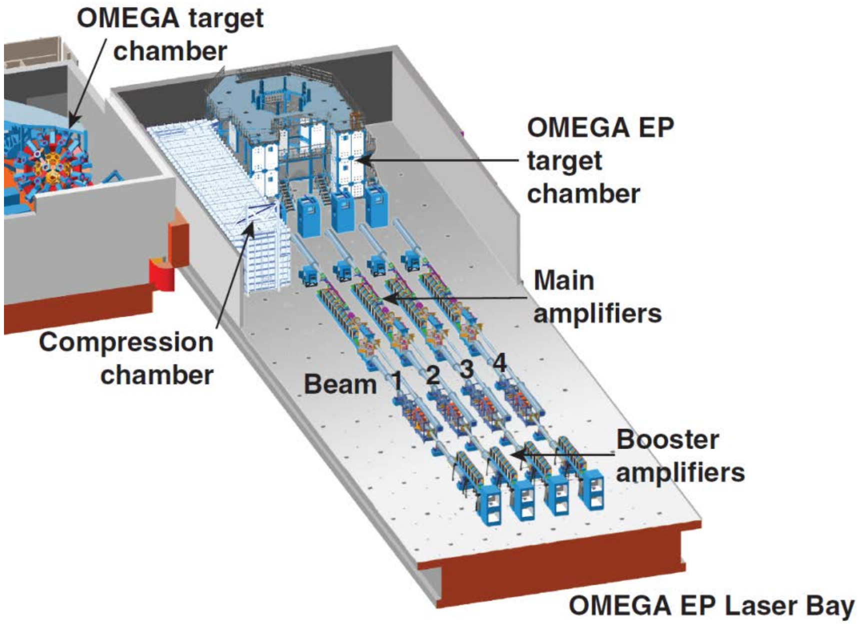
- **Solution 2: Inertial confinement fusion (ICF). Don’t confine it! Or you can say it is confined by its own inertia: P~Gigabar, τ~nsec, T~10 keV**



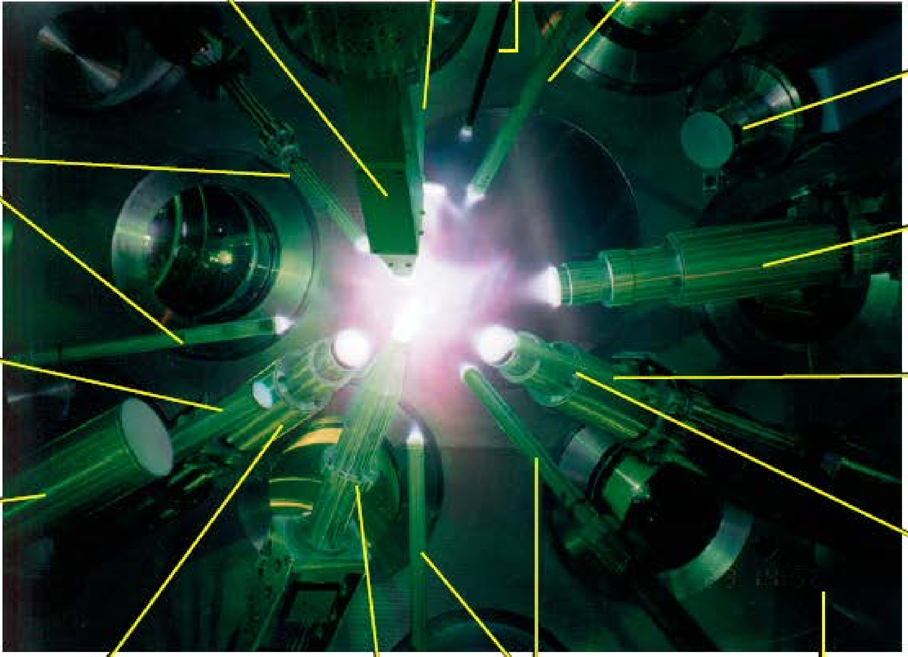
Laboratory for Laser Energetics, University of Rochester is a pioneer in laser fusion

- **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**





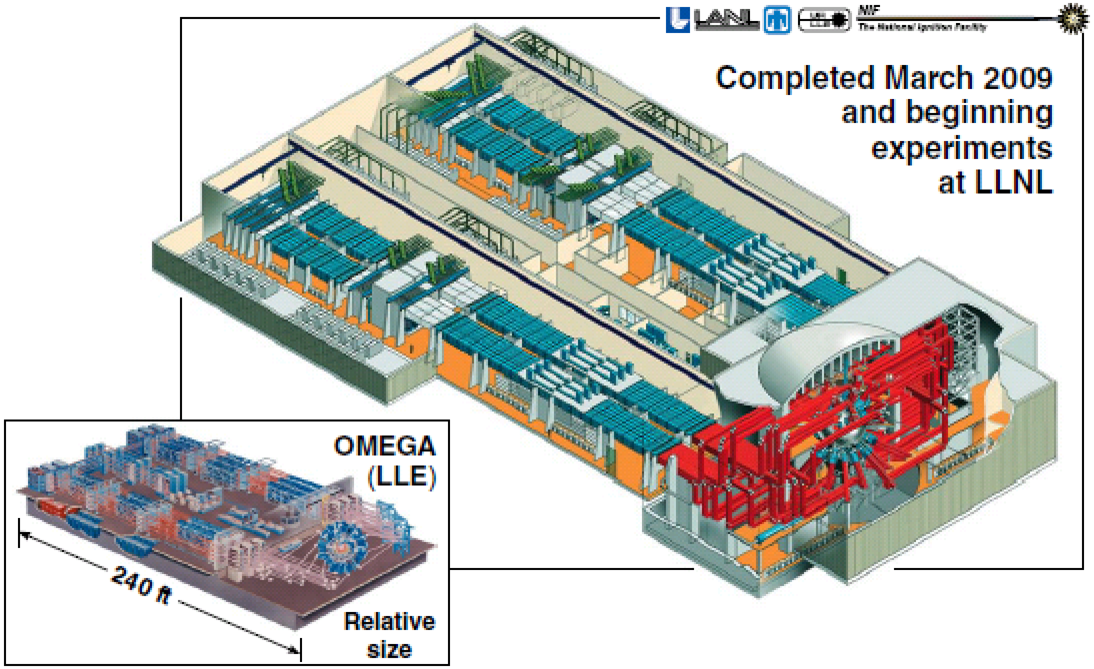
The OMEGA Facility is carrying out ICF experiments using a full suite of target diagnostics



E8012b

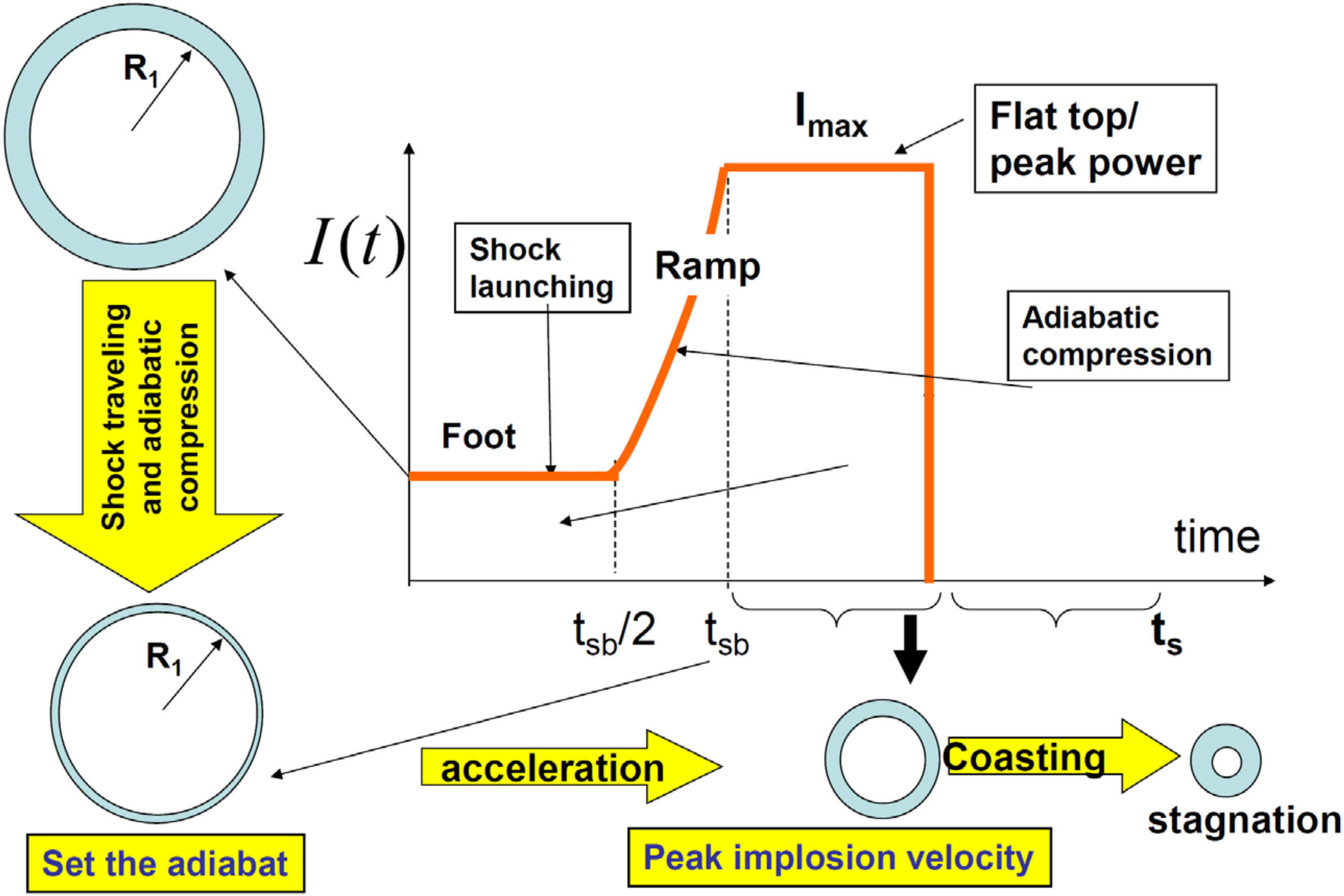
Photo taken from port H11B

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

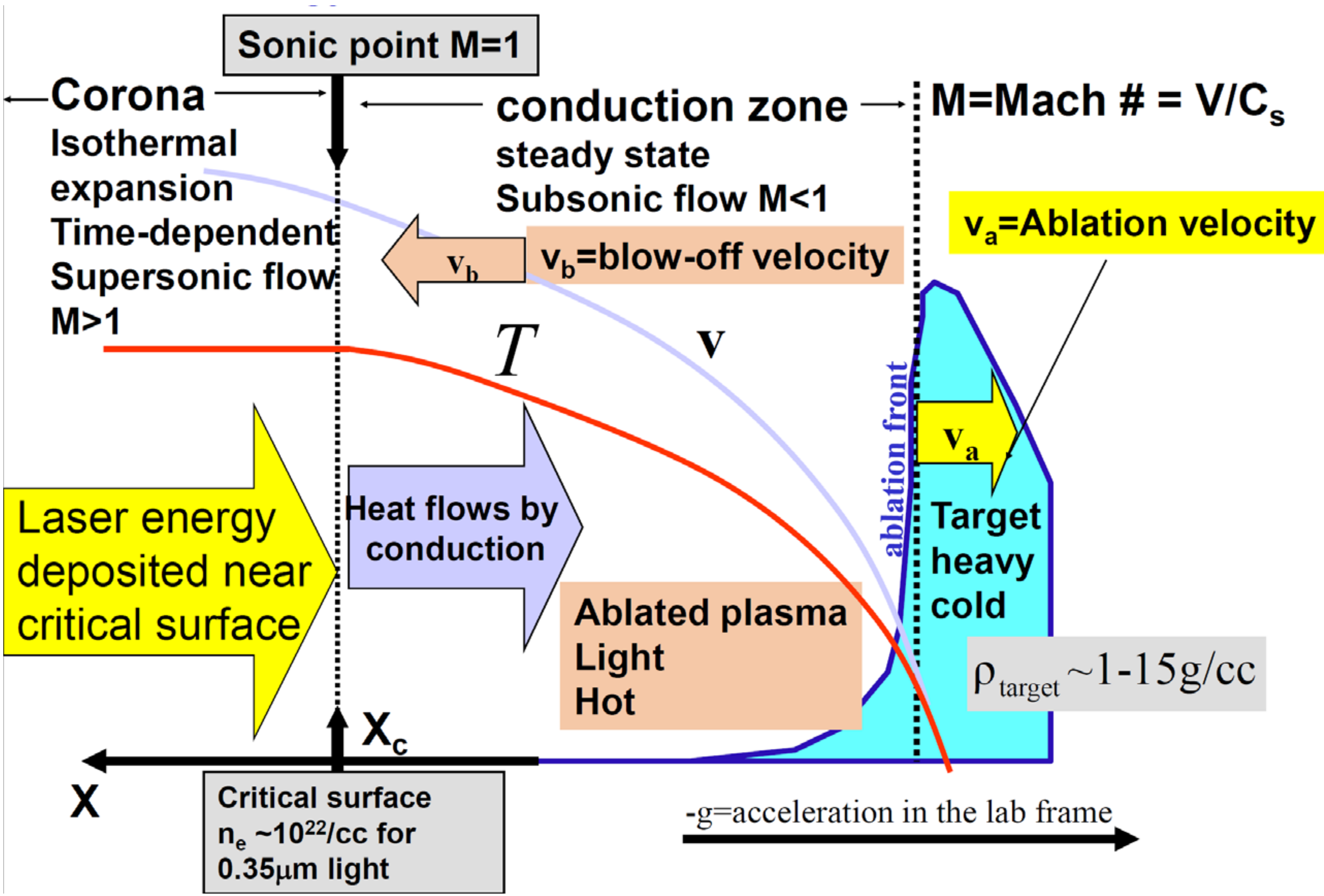


OMEGA experiments are integral to an ignition demonstration on the NIF.

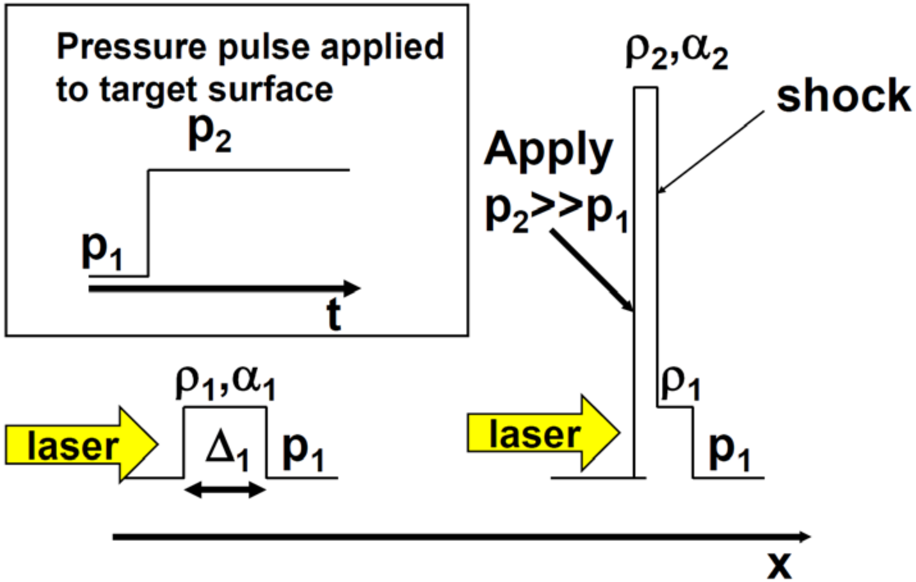
There are three stages in the laser pulse: foot, ramp, and flat top



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



In an ideal gas/plasma, the adiabat α only raises when a shock is present



- **Post-shock density**

$$\rho_2 \approx 4\rho_1$$

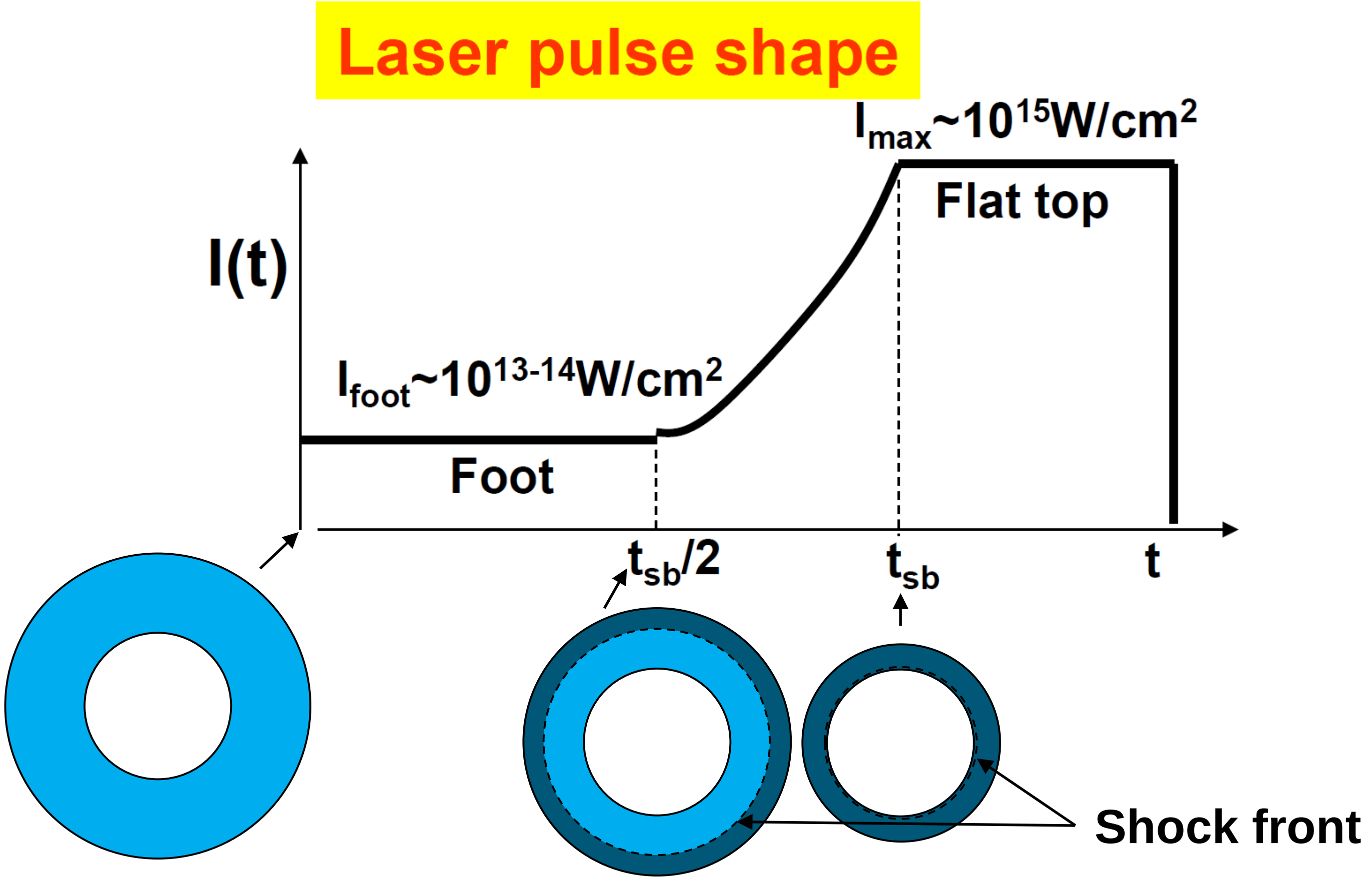
- **Adiabat set by the shock for DT:**

$$\alpha_2 \approx \frac{p_{2,\mathrm{Mbar}}}{2.2\left(4\rho_{1,\mathrm{g/cc}}\right)^{5/3}}$$

- **Time required for the shock to reach the rear target surface (shock break-out time, t_{sb})**

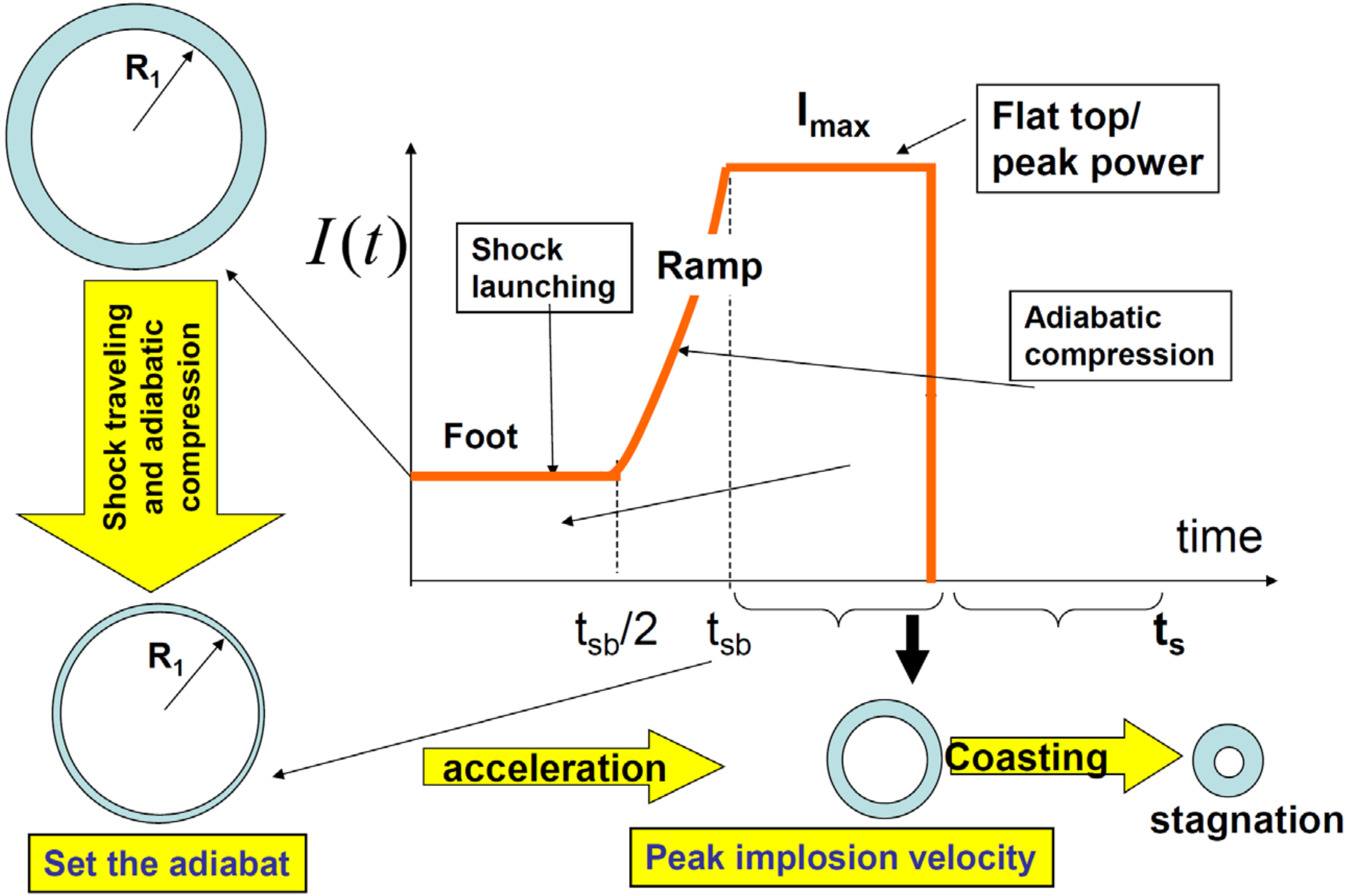
$$t_{\mathrm{sb}} = \frac{\Delta_1}{u_{\mathrm{shock}}} = \Delta_1\sqrt{\frac{3\rho_1}{4p_2}} \propto \sqrt{\frac{1}{\alpha_2\rho_1^{2/3}}}$$

The pressure must be "slowly" increased after the first shock to avoid raising the adiabat

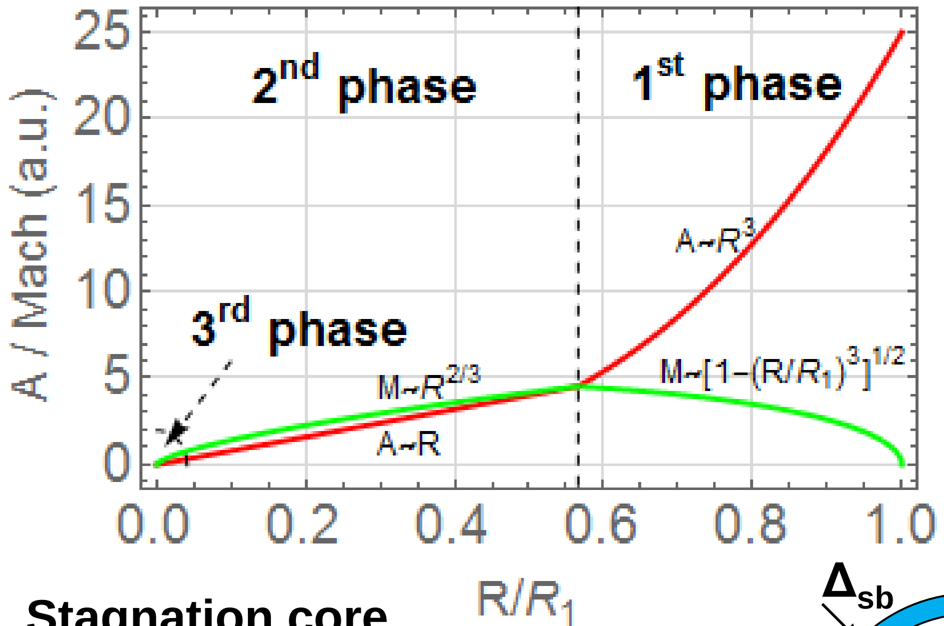


- **After the foot of the laser pulse, the laser intensity must be raised starting at about $0.5t_{sb}$ and reach its peak at about t_{sb}**
- **Reaching I_{max} at t_{sb} prevents a rarefaction/decompression wave to propagate back from the rear target surface and decompress the target.**

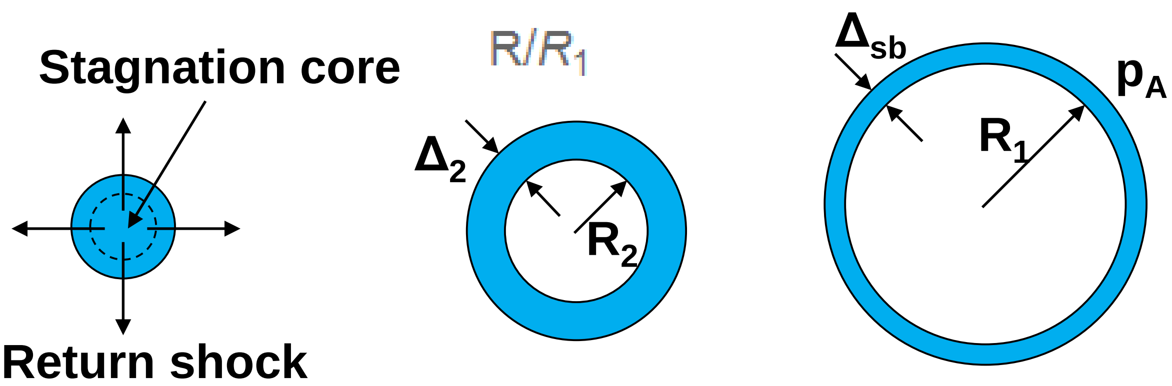
There are three stages in the laser pulse: foot, ramp, and flat top



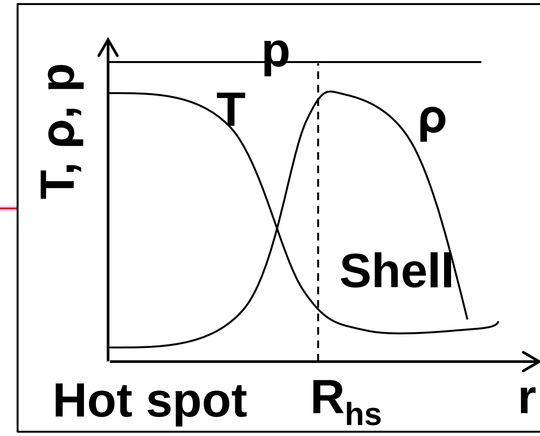
The implosion are divided in 3 phases after the shock break out



- 1^{st} phase: acceleration
- 2^{nd} phase: coasting
- 3^{rd} phase: stagnation

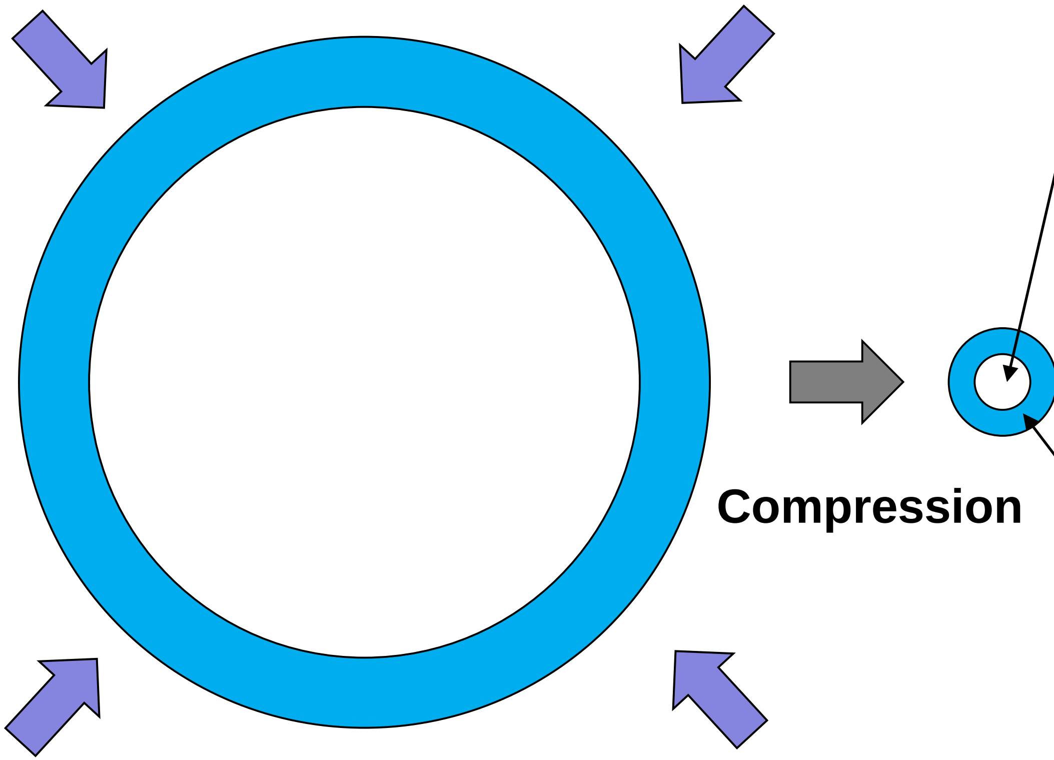


Summary



- **Possible fuel assembly for 1MJ ICF driver**

$E_{\text{laser}} = 1\text{MJ}$ $\eta_h \approx 1\%$



$\rho_{\text{DT}} = 0.25\, g/\text{cm}^3$ $R_{\text{init}} \simeq 2.6\text{mm}$

Hot spot

$M_h \approx 20\mu\text{g}$ $(\rho R)_h \approx 0.3\, g/\text{cm}^2$

$\rho_h \approx 70\, g/\text{cm}^3$ $R_h \approx 40\mu\text{m}$

$\frac{M_h}{M_0} \sim 0.01$

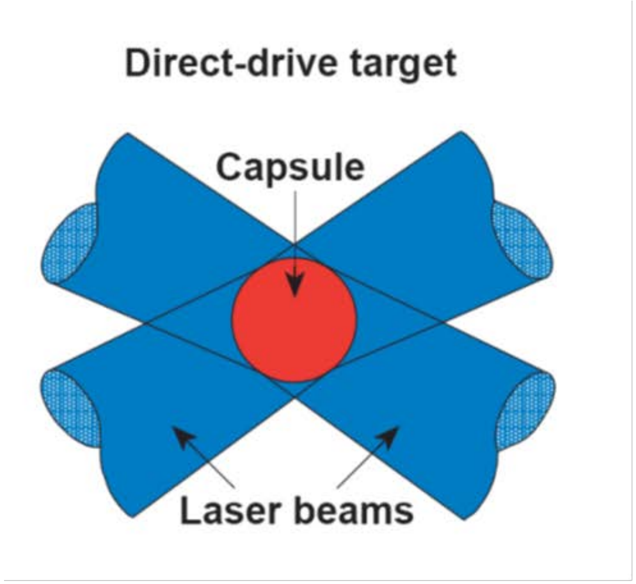
Dense fuel

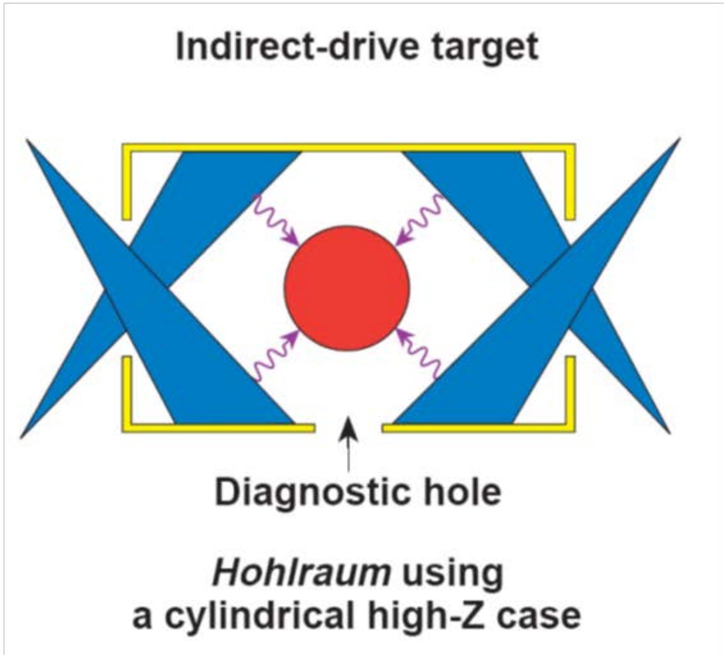
$M_0 \approx 2\text{mg}$ $(\rho R) \approx 3\, g/\text{cm}^2$

$\rho \approx 250\, g/\text{cm}^3$ $R \approx 120\mu\text{m}$

Convergence ratio ~20

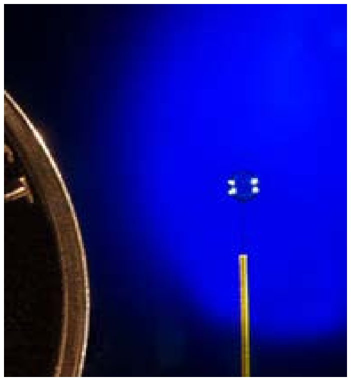
A spherical capsule can be imploded through directly or indirectly laser illumination



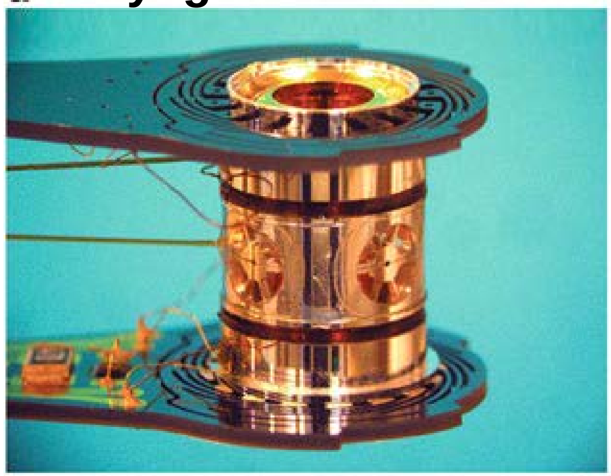


*R. Betti, HEDSA HEDP Summer School, 2015

Targets used in ICF

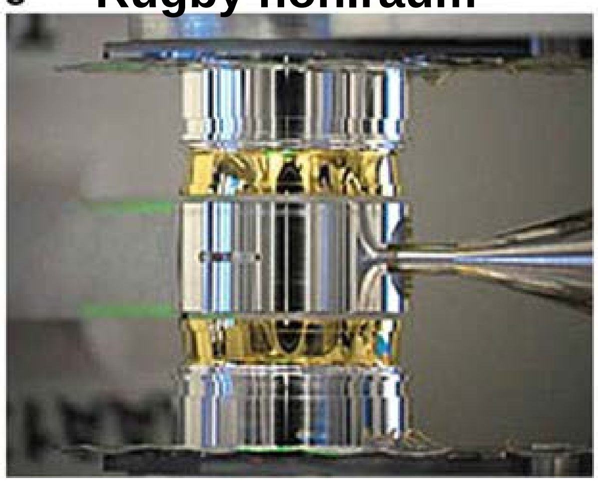


a Cryogenic hohlraum

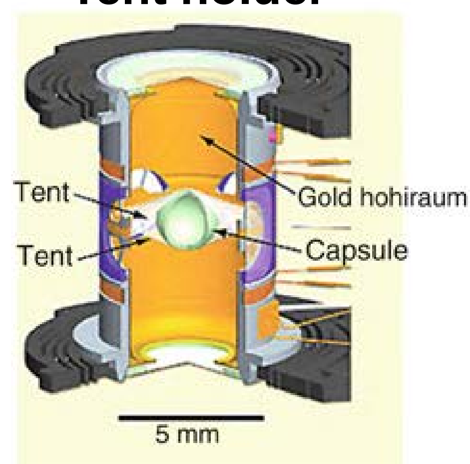


b

c Rugby hohlraum

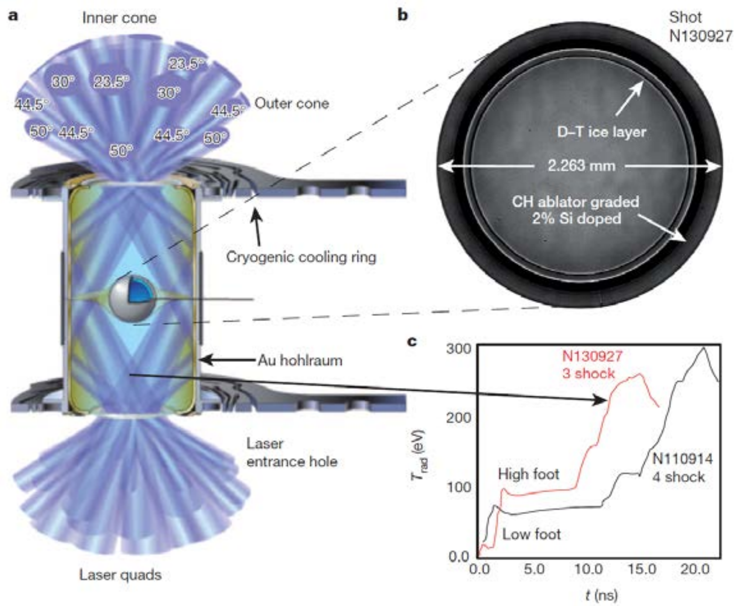


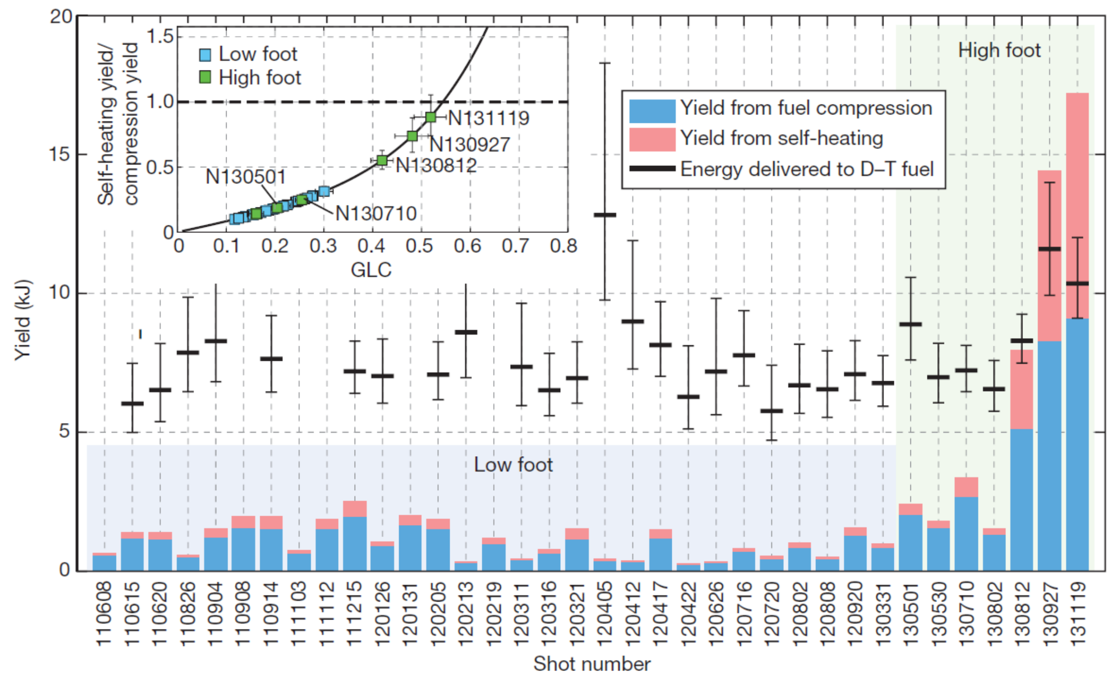
d Tent holder



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

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

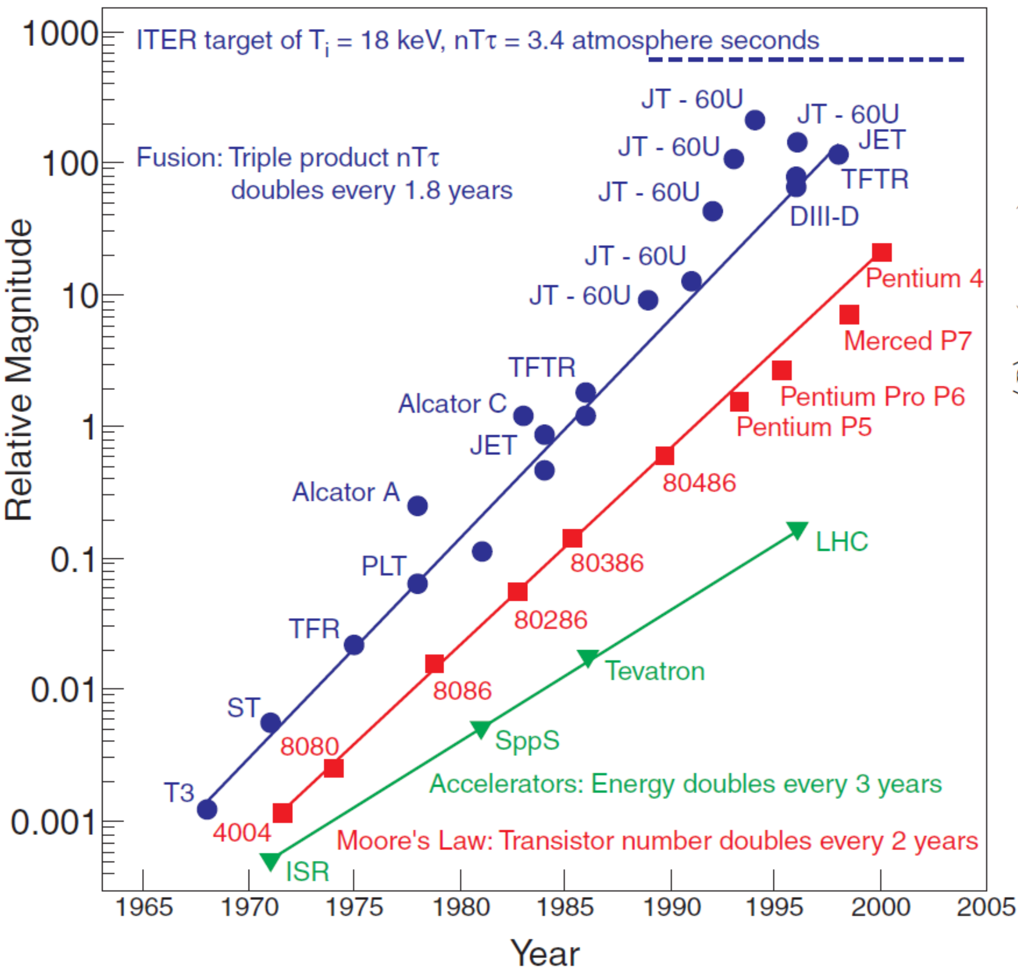


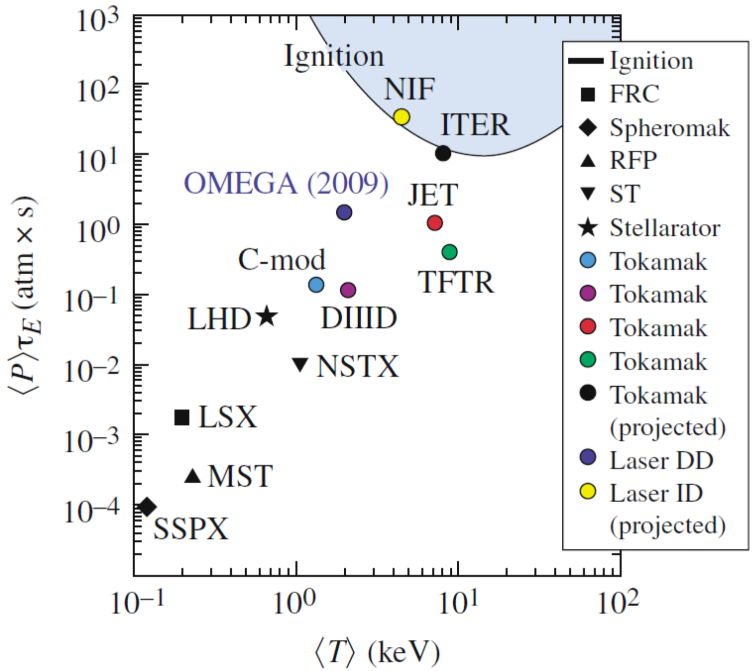


- **Fuel gain exceeding unity was demonstrated for the first time.**

Nature 506, p343, 2014

The performance of a fusion plasma has doubled every 1.8 years like the Moore's law





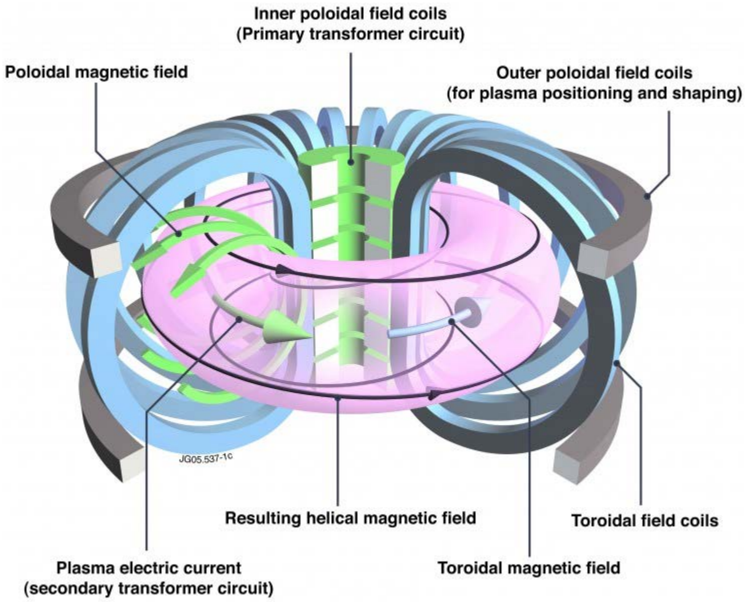
- **Nuclear fusion is coming in the near future.**

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

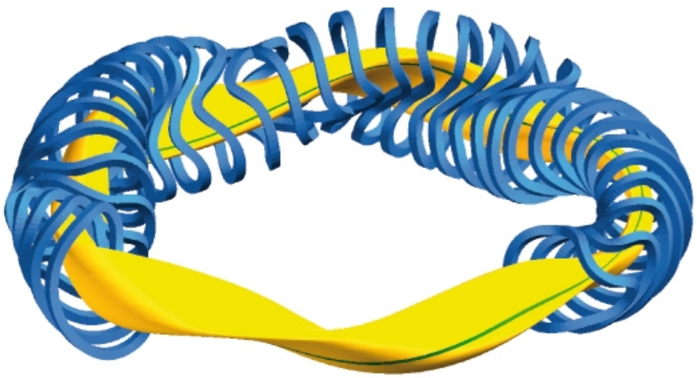
The plasma is too hot to be contained

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

Tokamak

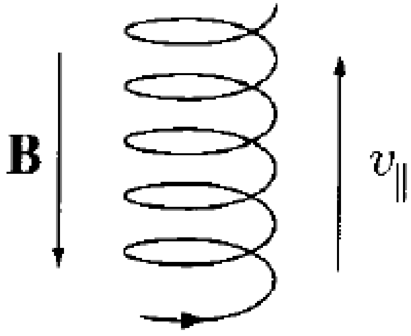


Stellarator

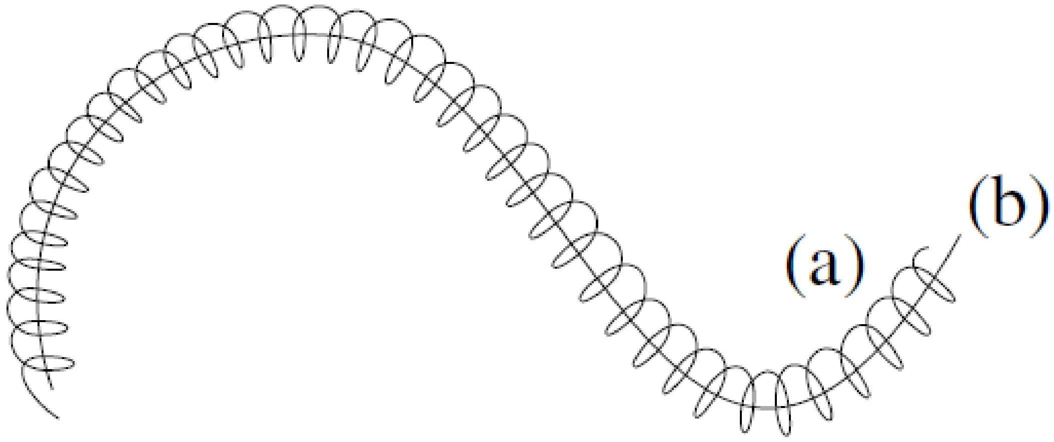


https://www.euro-fusion.org/2011/09/tokamak-principle-2/
https://en.wikipedia.org/wiki/Stellarator

Charged particles gyro around the magnetic fields

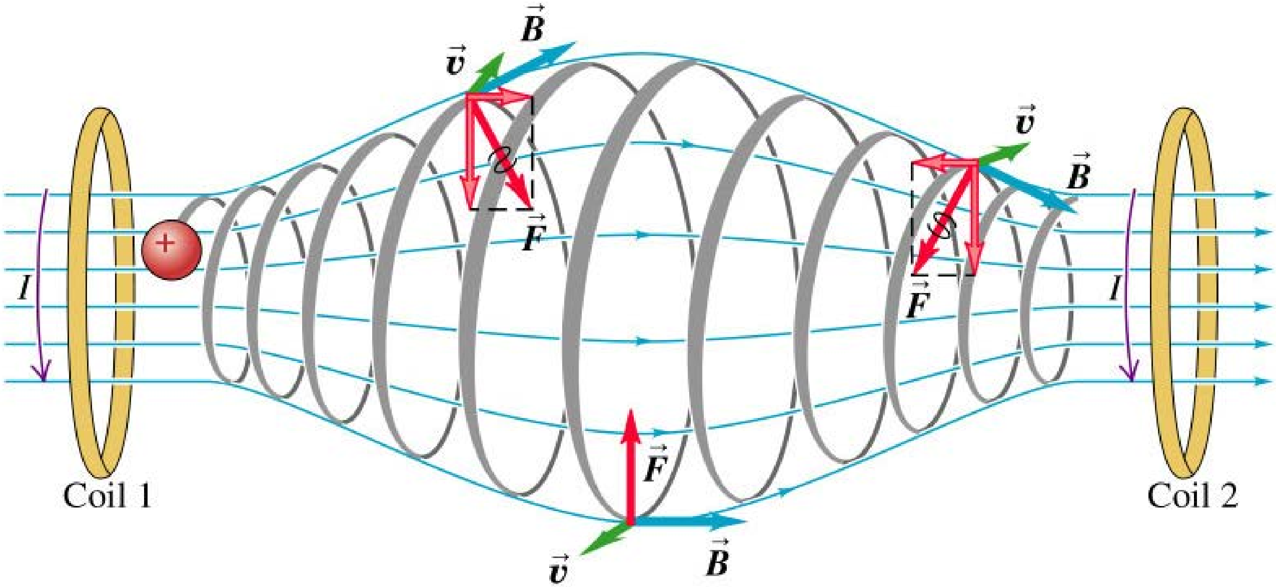


$$r_L = \frac{m v_\perp}{|q| B}$$



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.**



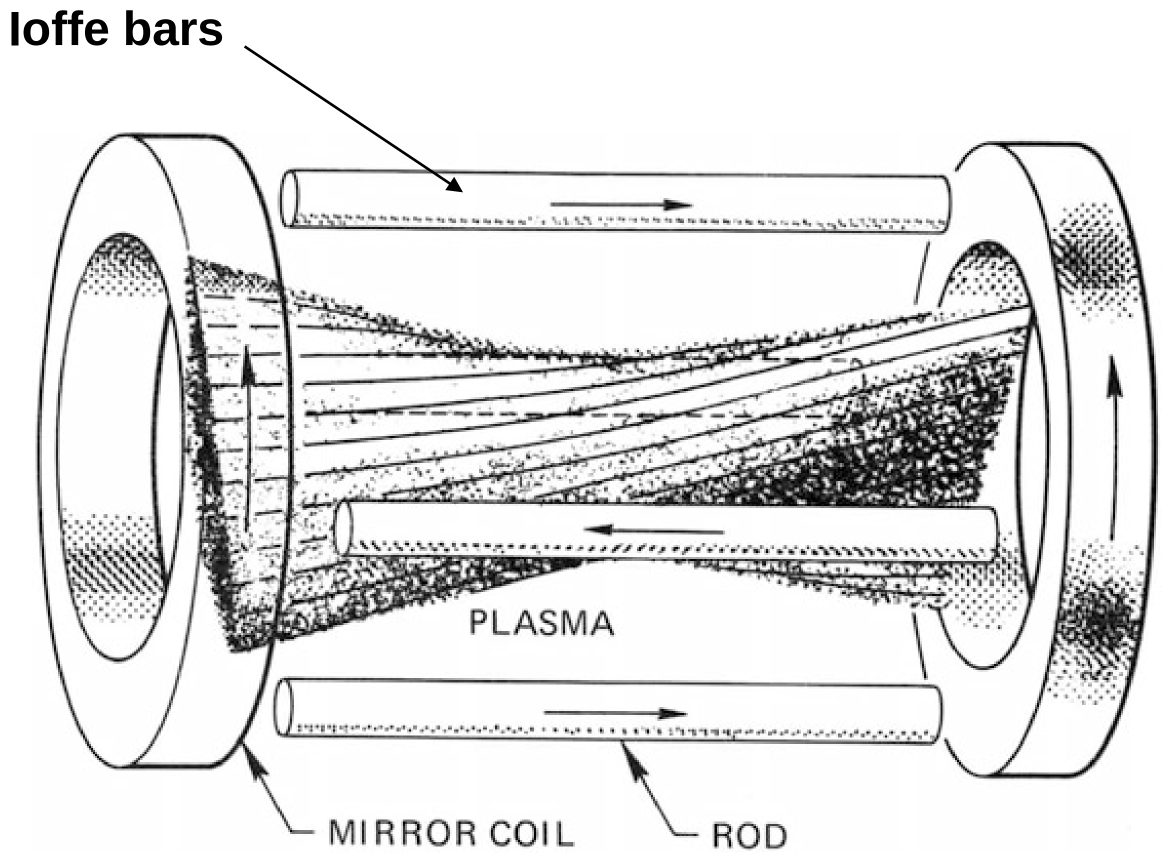
$$\frac{1}{2}mv^2 = \frac{1}{2}mv_{||}^2 + \frac{1}{2}mv_{\perp}^2$$

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

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

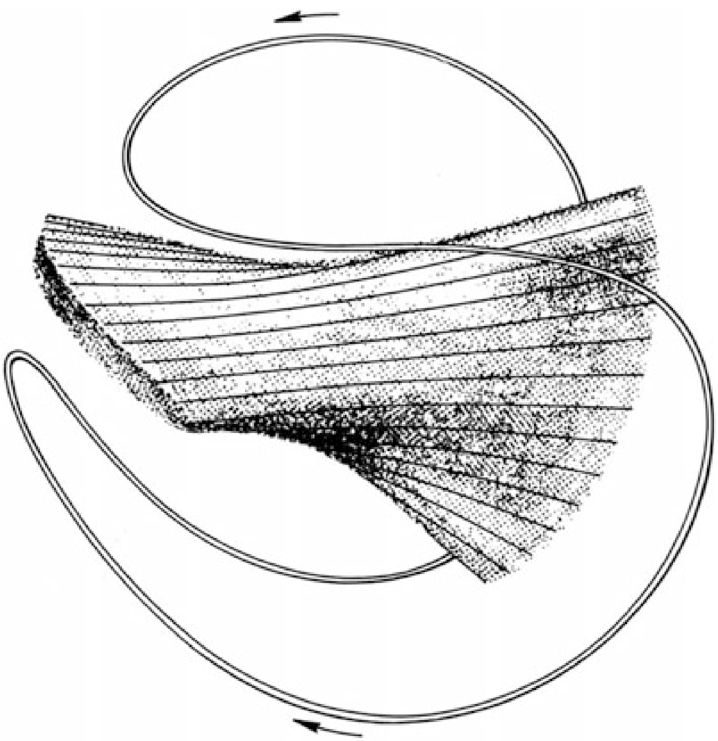
https://i.stack.imgur.com/GlzGZ.jpg

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



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

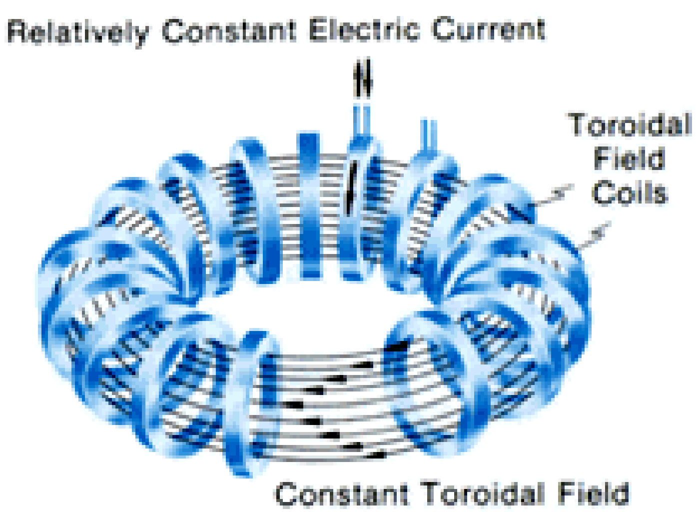
- **Baseball coil**

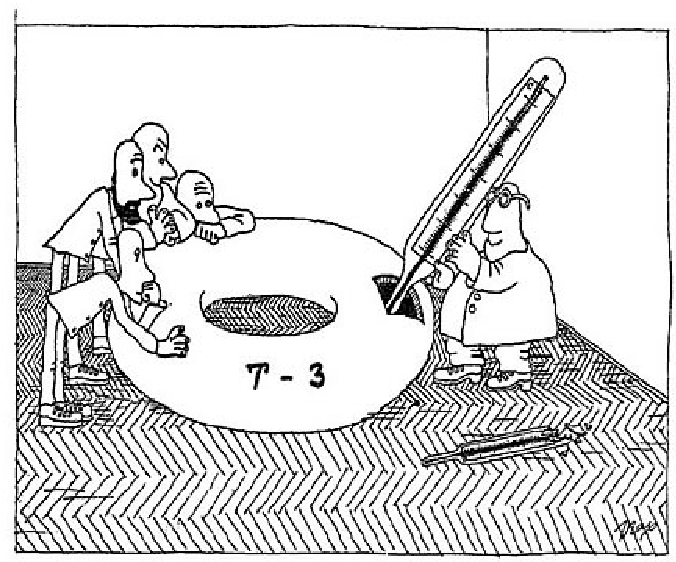


- **MFTF-B mirror machine**

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

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

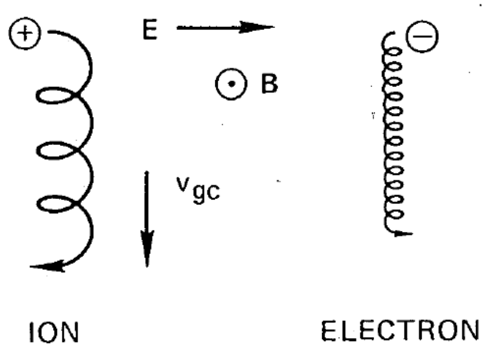




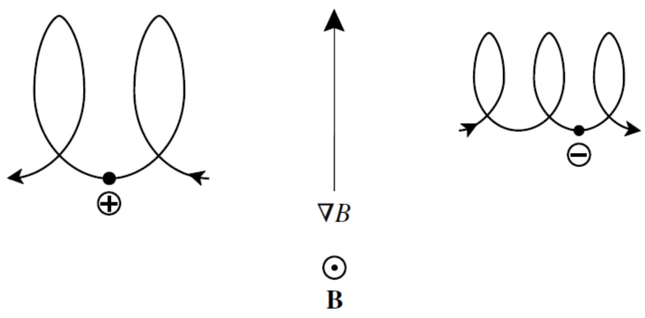
https://www.iter.org/mach/tokamak
https://en.wikipedia.org/wiki/Tokamak#cite_ref-4
Drawing from the talk "Evolution of the Tokamak" given in 1988 by B.B. Kadomtsev at Culham.

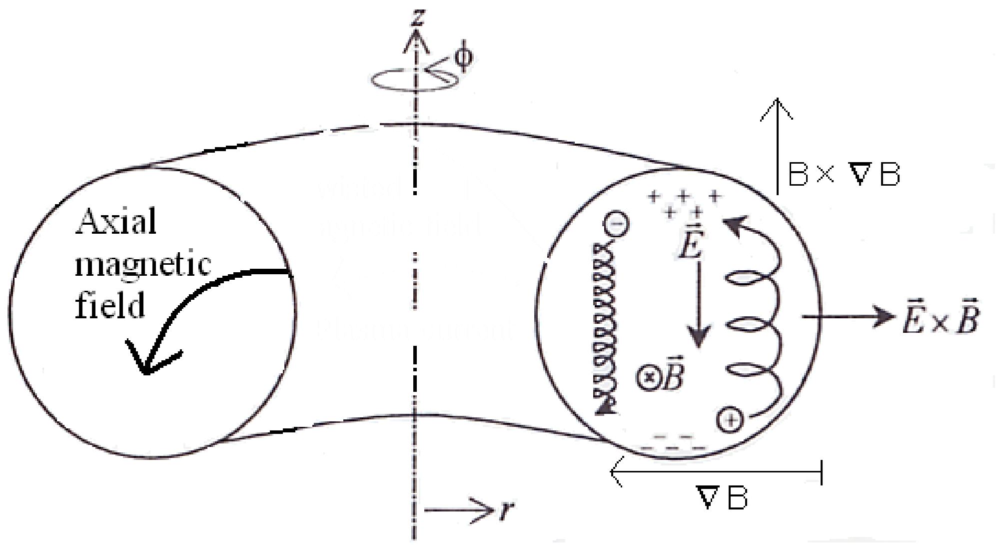
Charged particles drift across field lines

- **ExB drift**



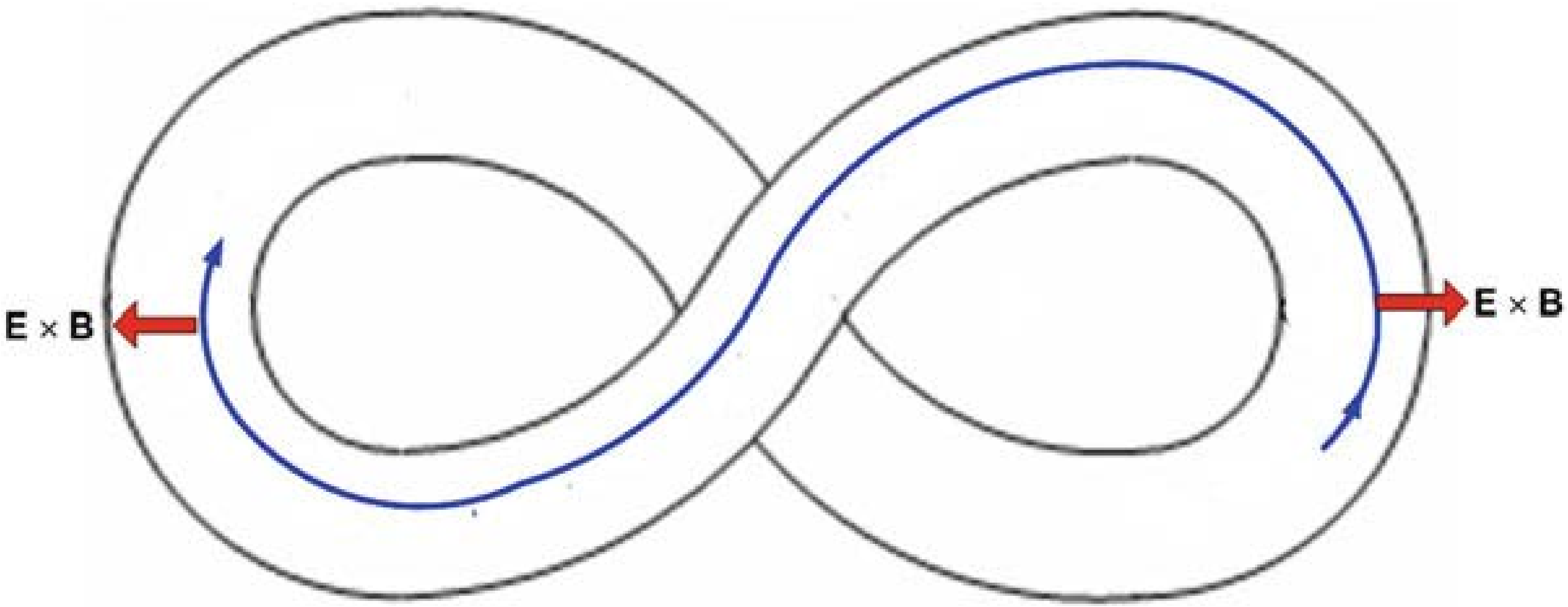
- **Grad-B drift**





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

A figure-8 stellarator solved the drift issues



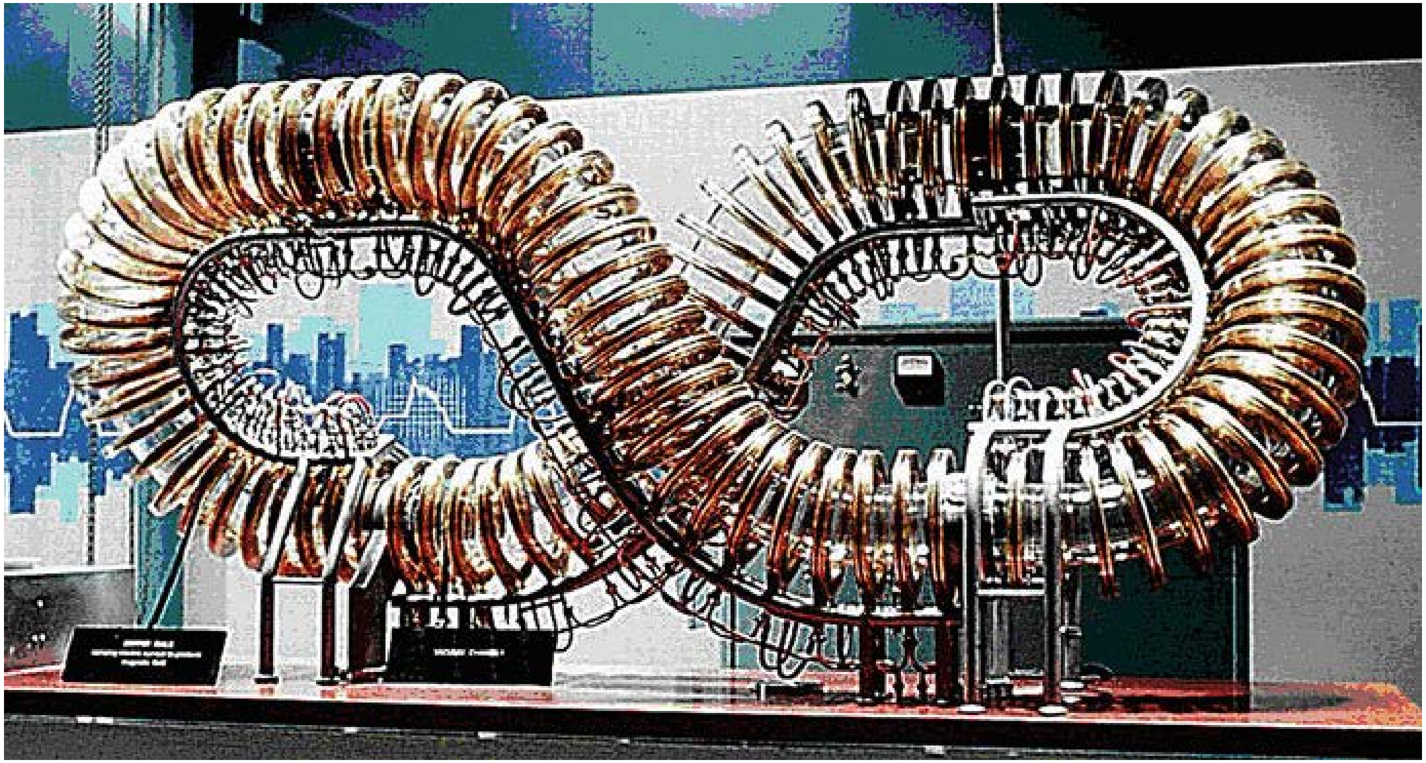
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

A figure-8 stellarator solved the drift issues

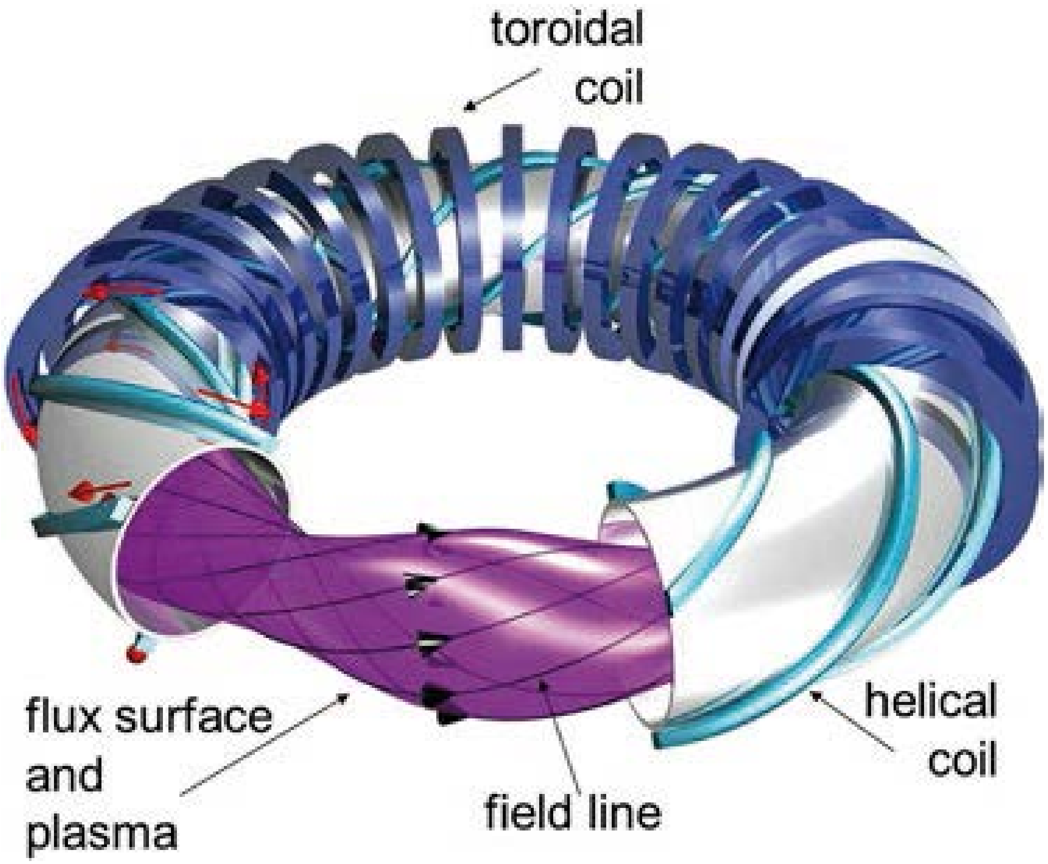
Lyman Spitzer, Jr. came out the idea during a long ride on a ski lift at Garmisch-Partenkirchen

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

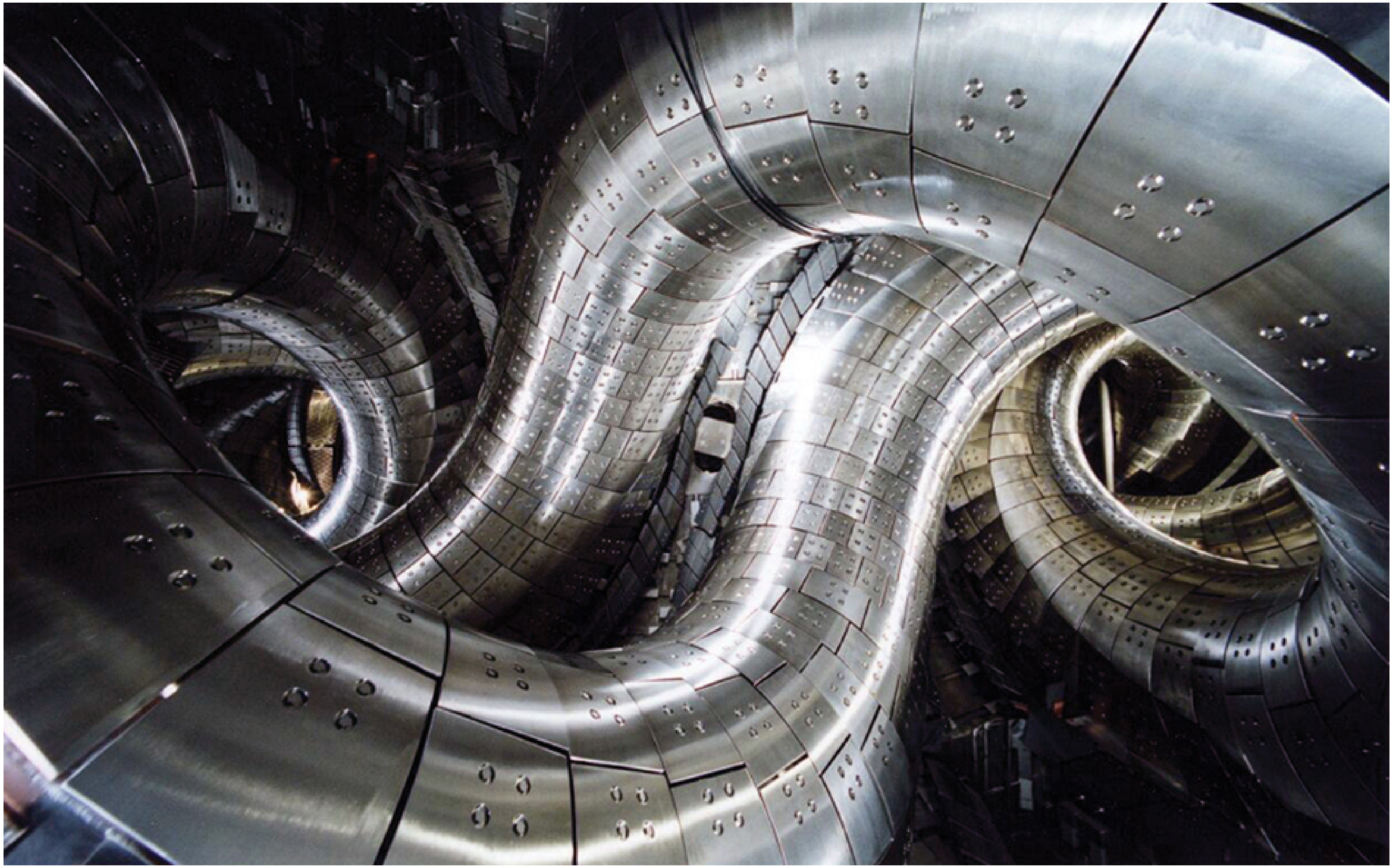


Twisted magnetic field lines can be provided by toroidal coils with helical coils



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

LHD stellarator in Japan

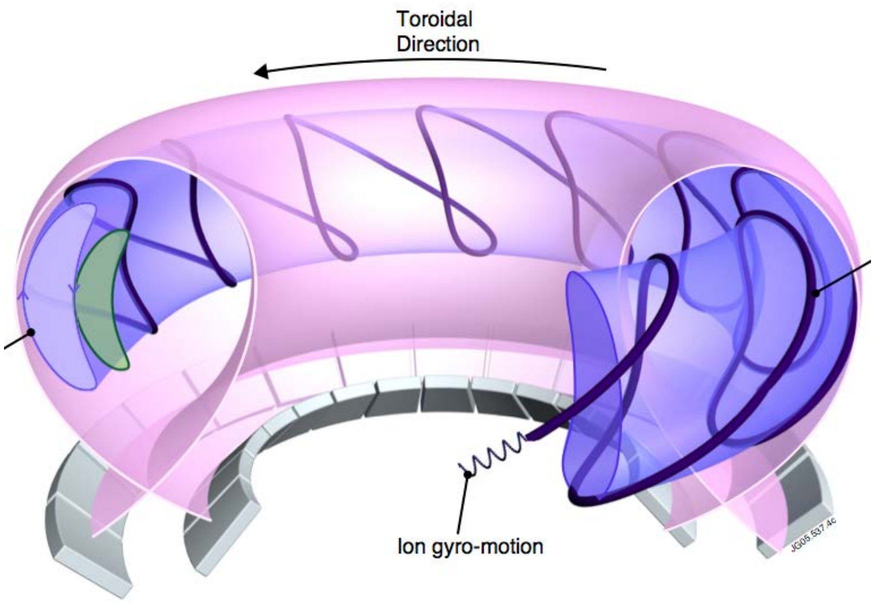


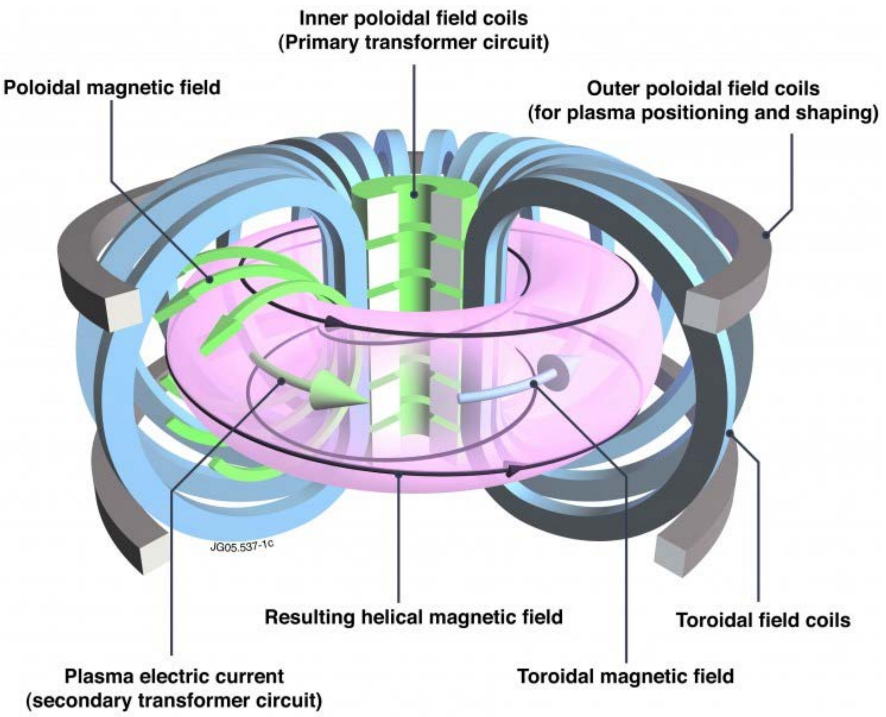
https://en.wikipedia.org/wiki/Large_Helical_Device

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

https://en.wikipedia.org/wiki/Stellarator
http://www.greencareer.net.au/archived-news/germans-seek-sun-s-powerful-secrets

A poloidal magnetic field is generated by plasma current in the toroidal direction



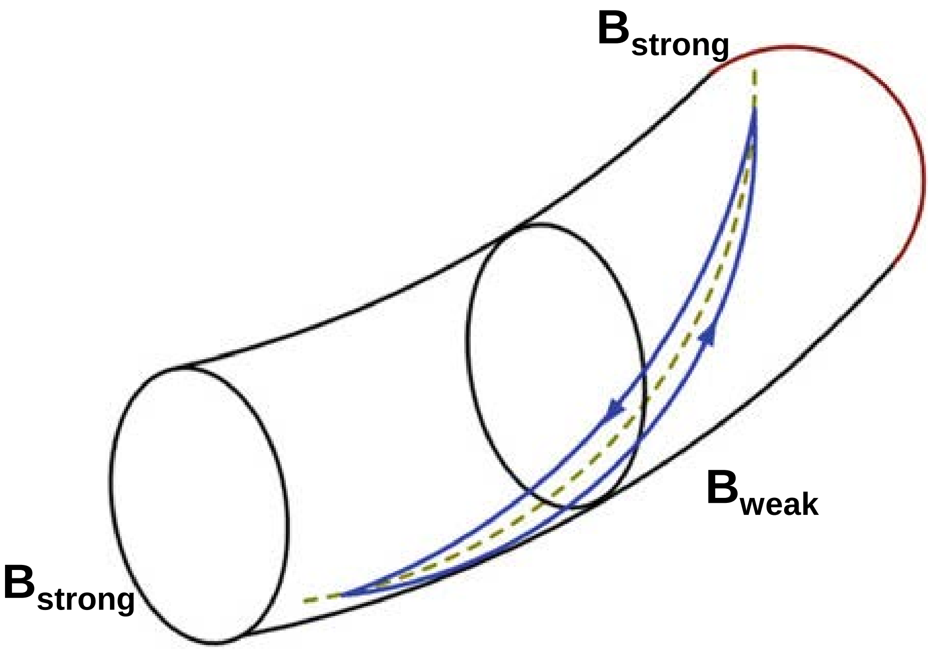


---

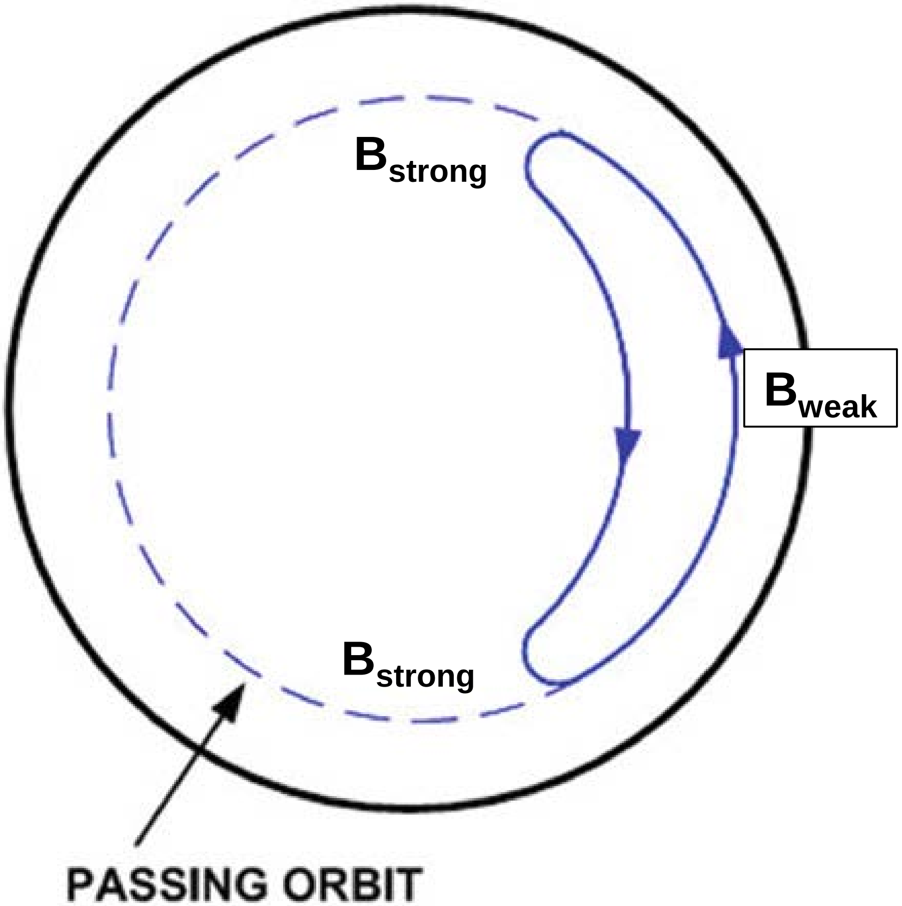
https://www.davidpace.com/keeping-fusion-plasmas-hot/
https://www.euro-fusion.org/2011/09/tokamak-principle-2/

A particle with small $v_{||}$ can be mirror-trapped forming a banana orbit

- Mirror-trapping of a particle



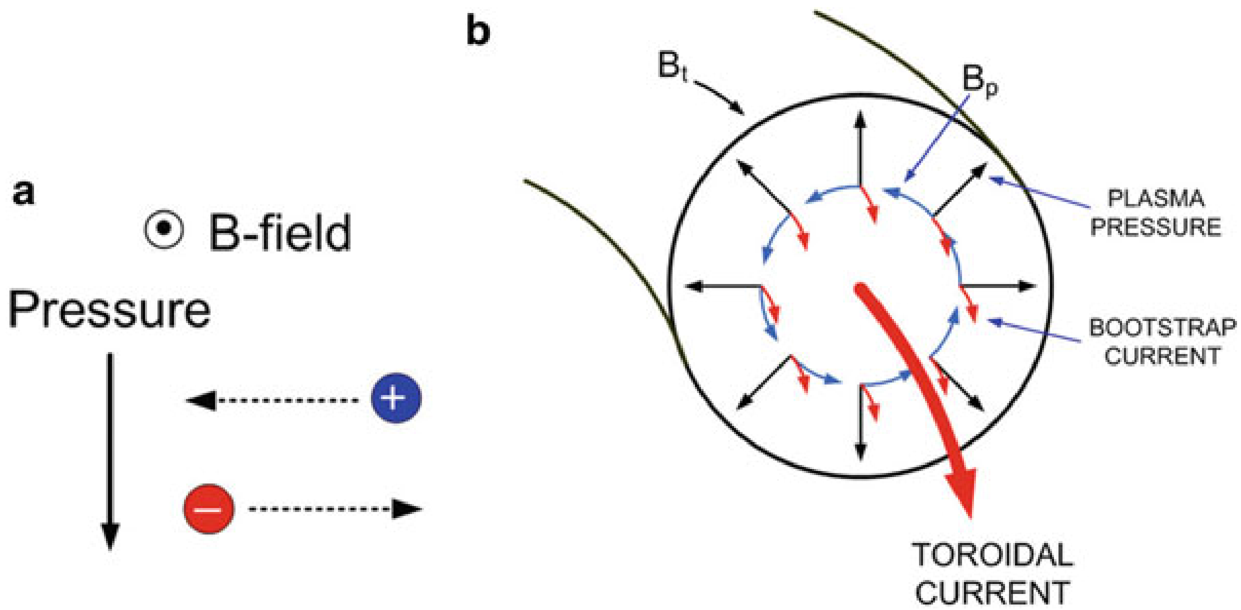
- Banana obit



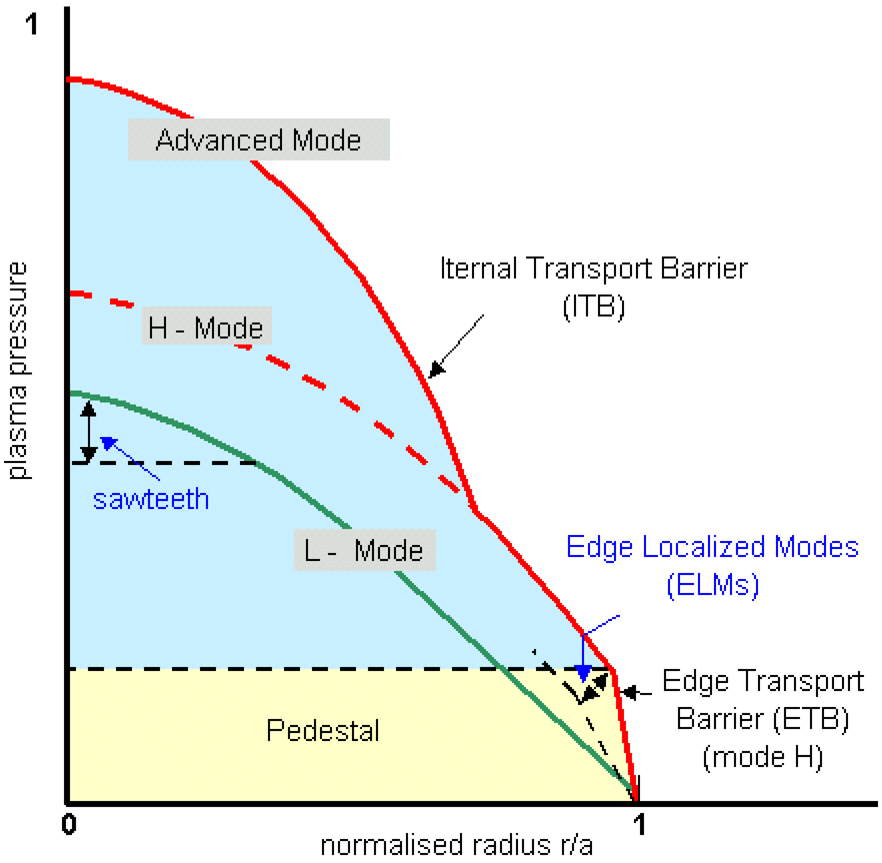
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

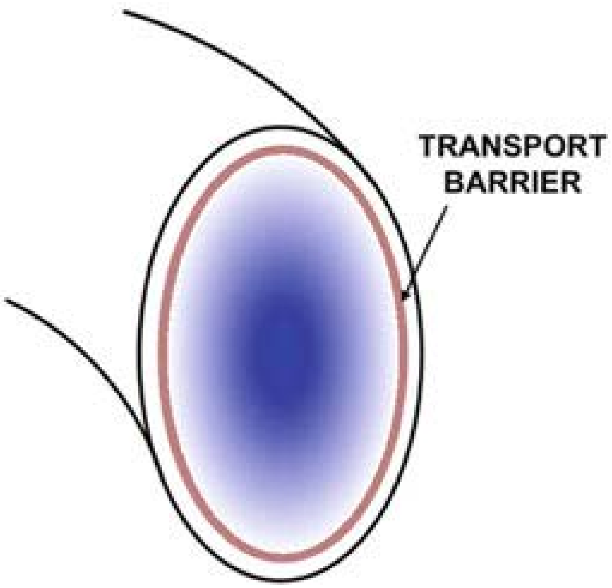
Bootstrap current can contribute to the plasma current

$$\vec{v}_f = \frac{1}{q}\frac{\vec{F}\times\vec{B}}{B^2} = \frac{1}{q}\frac{-\nabla P\times\vec{B}}{B^2}$$



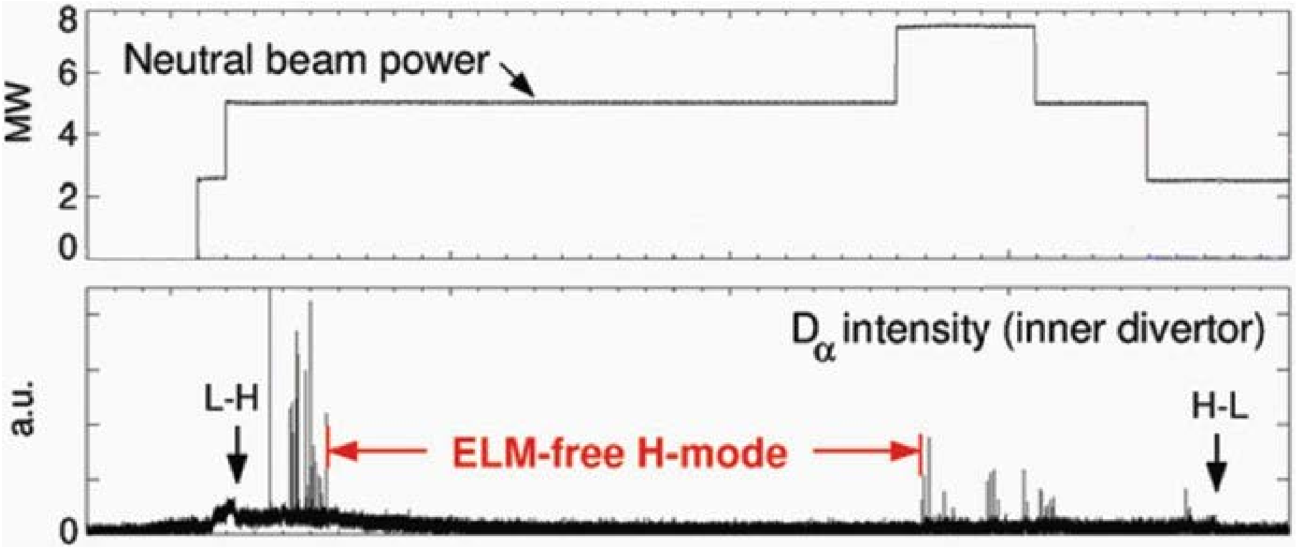
Tokamak operates in H-mode when it is heated above a threshold

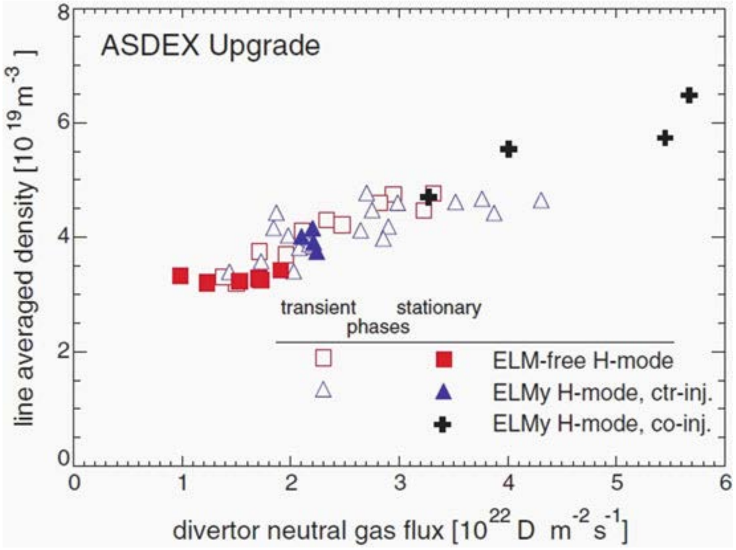




http://www-fusion-magnetique.cea.fr/gb/fusion/physique/modesconfinement.htm
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

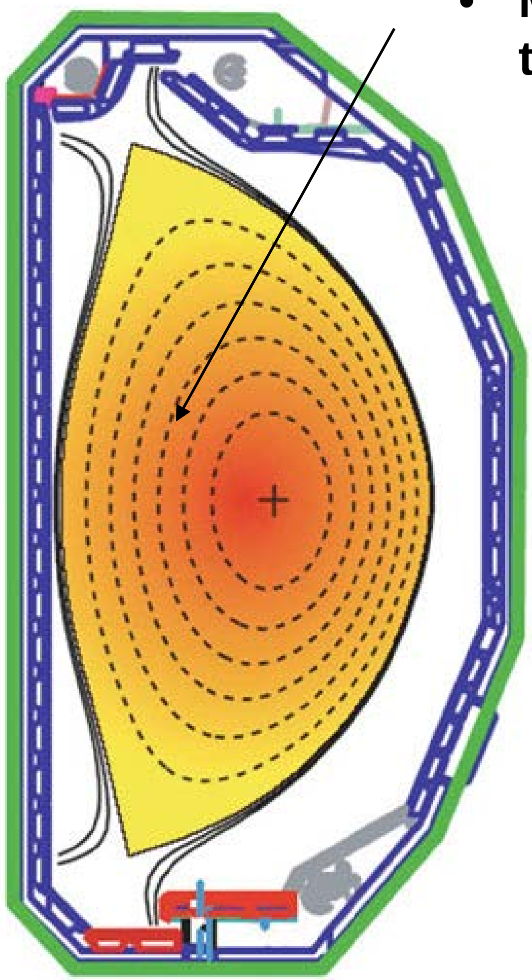
The plasma was lost in bursts called Edge Localized Modes (ELMs)



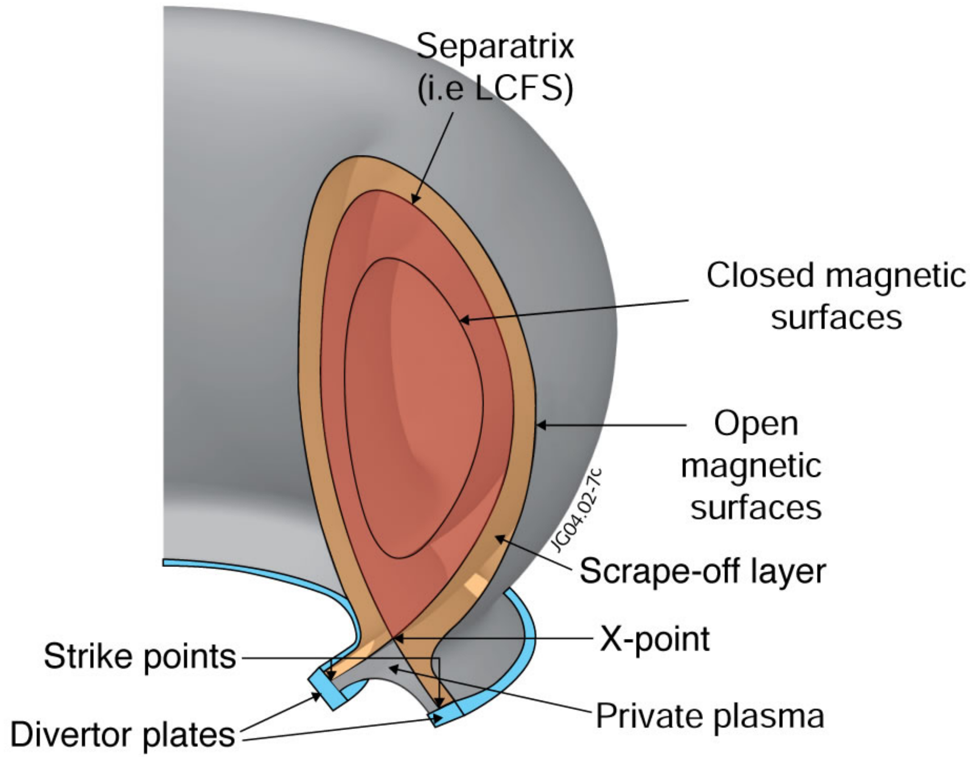


Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

D-shaped tokamak with diverter is more preferred nowadays



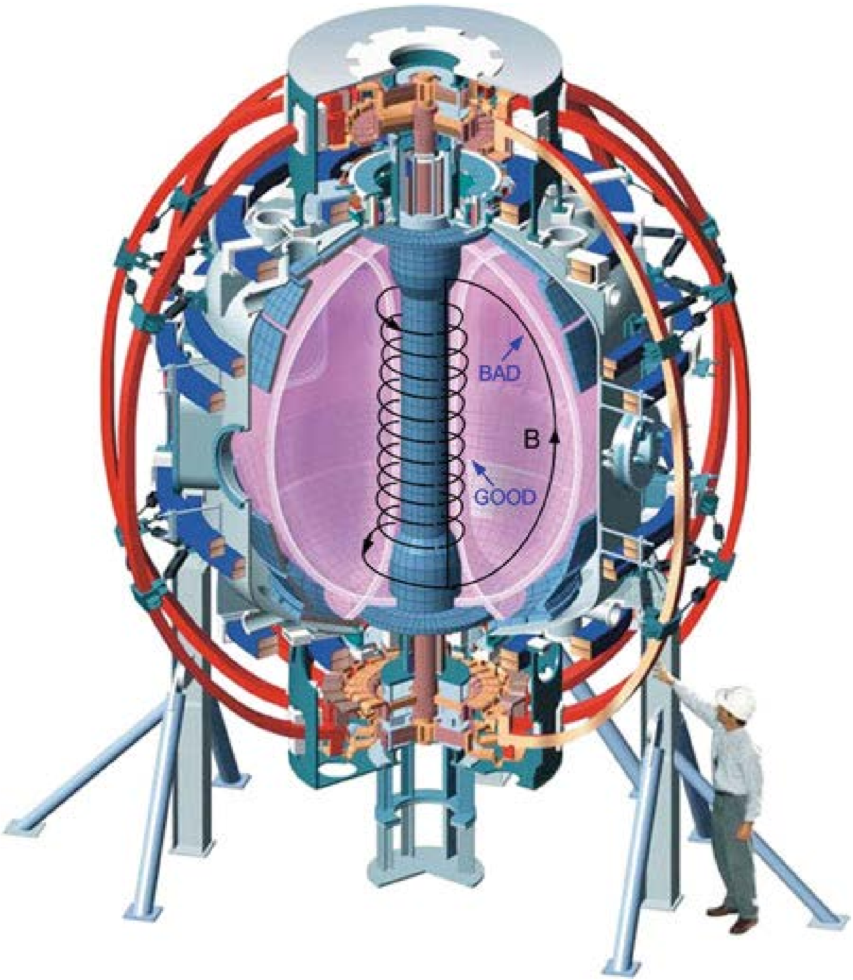
- **Make the plasma closer to the major axis**
  - **A divertor is needed to remove impurities and the power that escapes from the plasma**



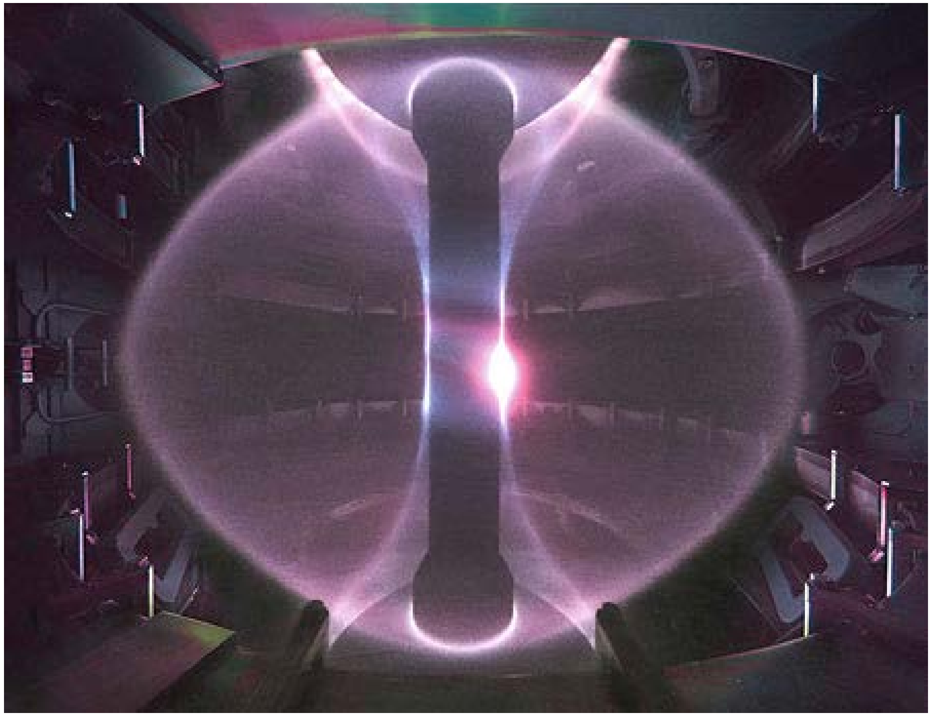
Introduction to Plasma Physics and Controlled Fusion 3rd Edition, by Francis F. Chen

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

- **NSTX @ Princeton**

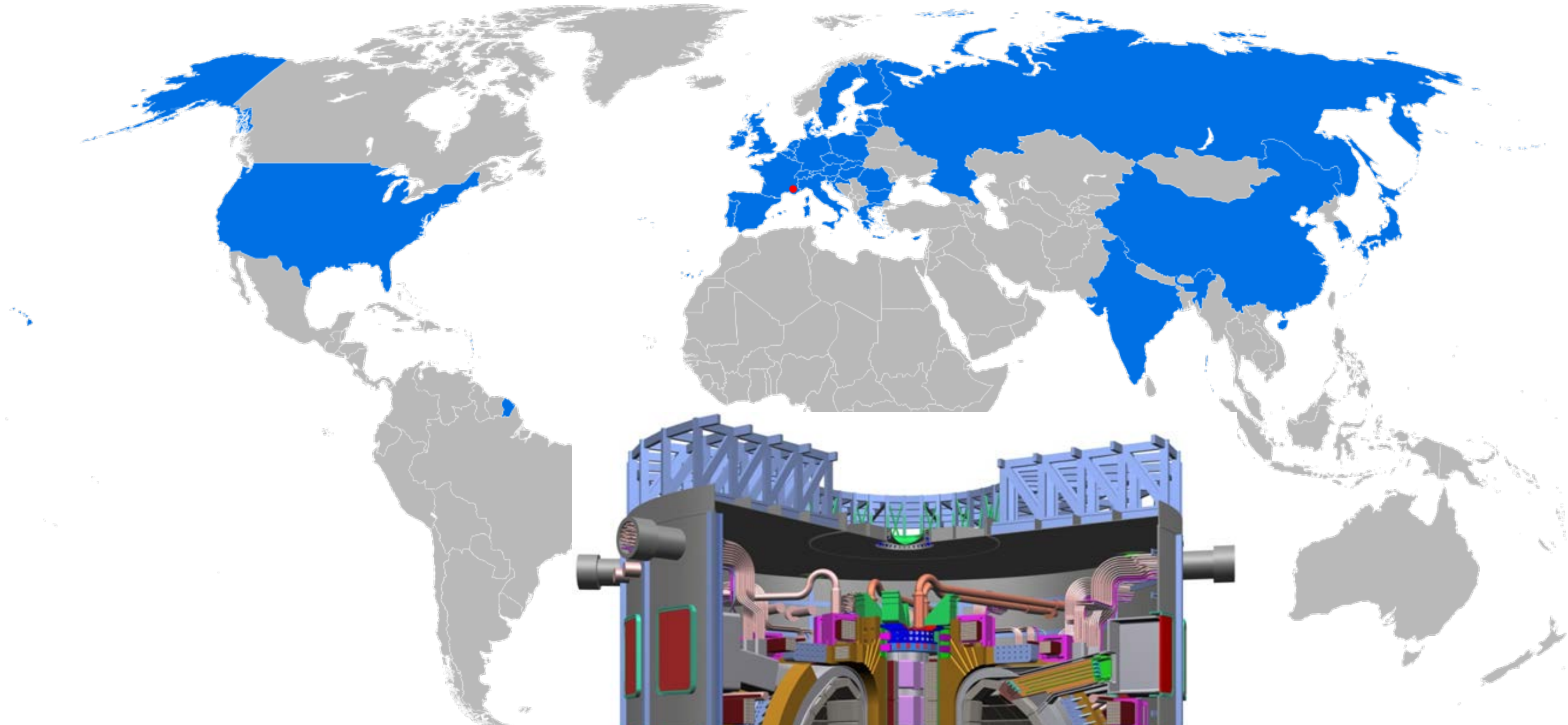


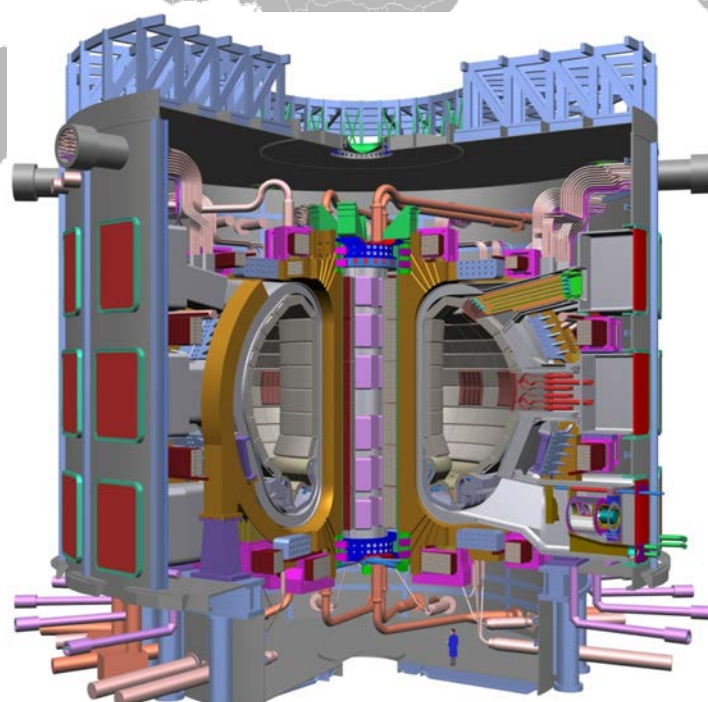
- **MegaAmpere Spherical Tokamak (MAST) @ Culham center for fusion energy, UK**



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

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

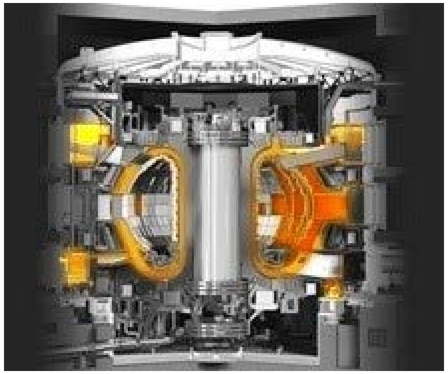




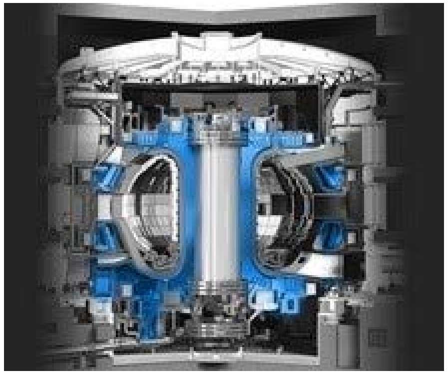
https://www.iter.org

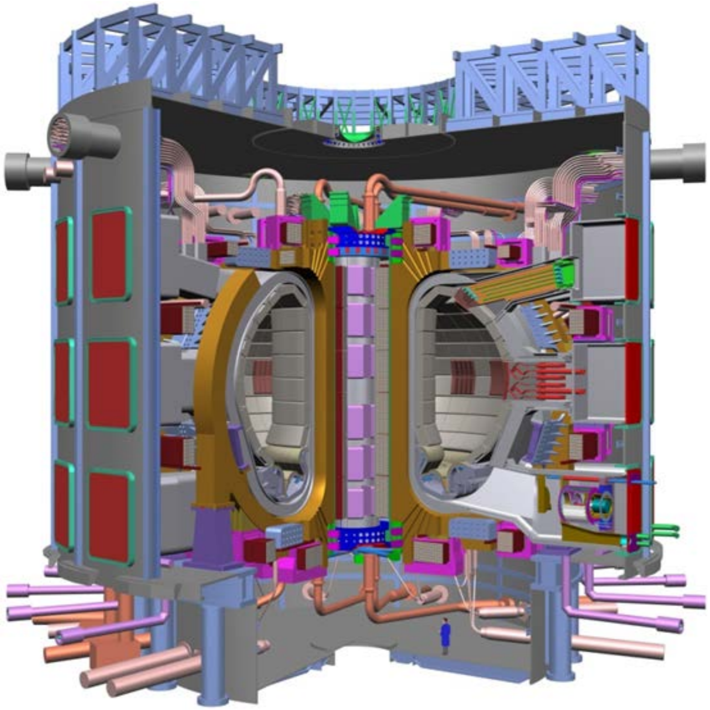
ITER ("The Way" in Latin) is one of the most ambitious energy projects in the world today

- Vacuum vessel

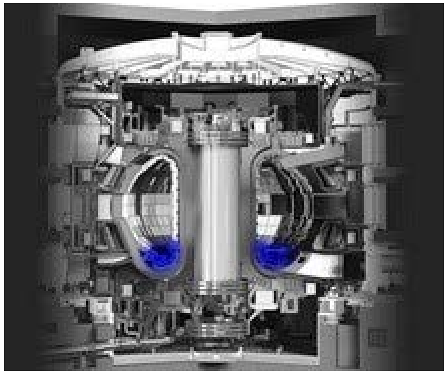


- Magnets

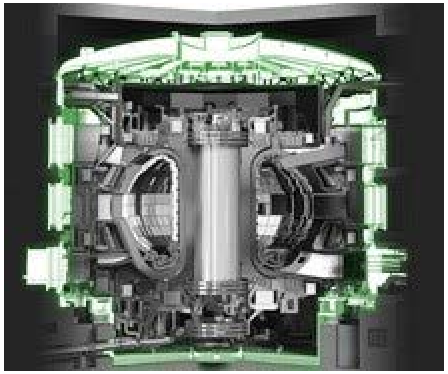




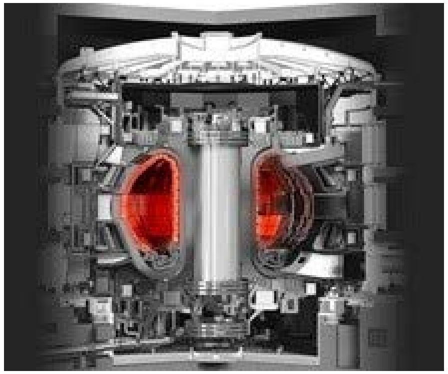
- Divertor



- Cryostat



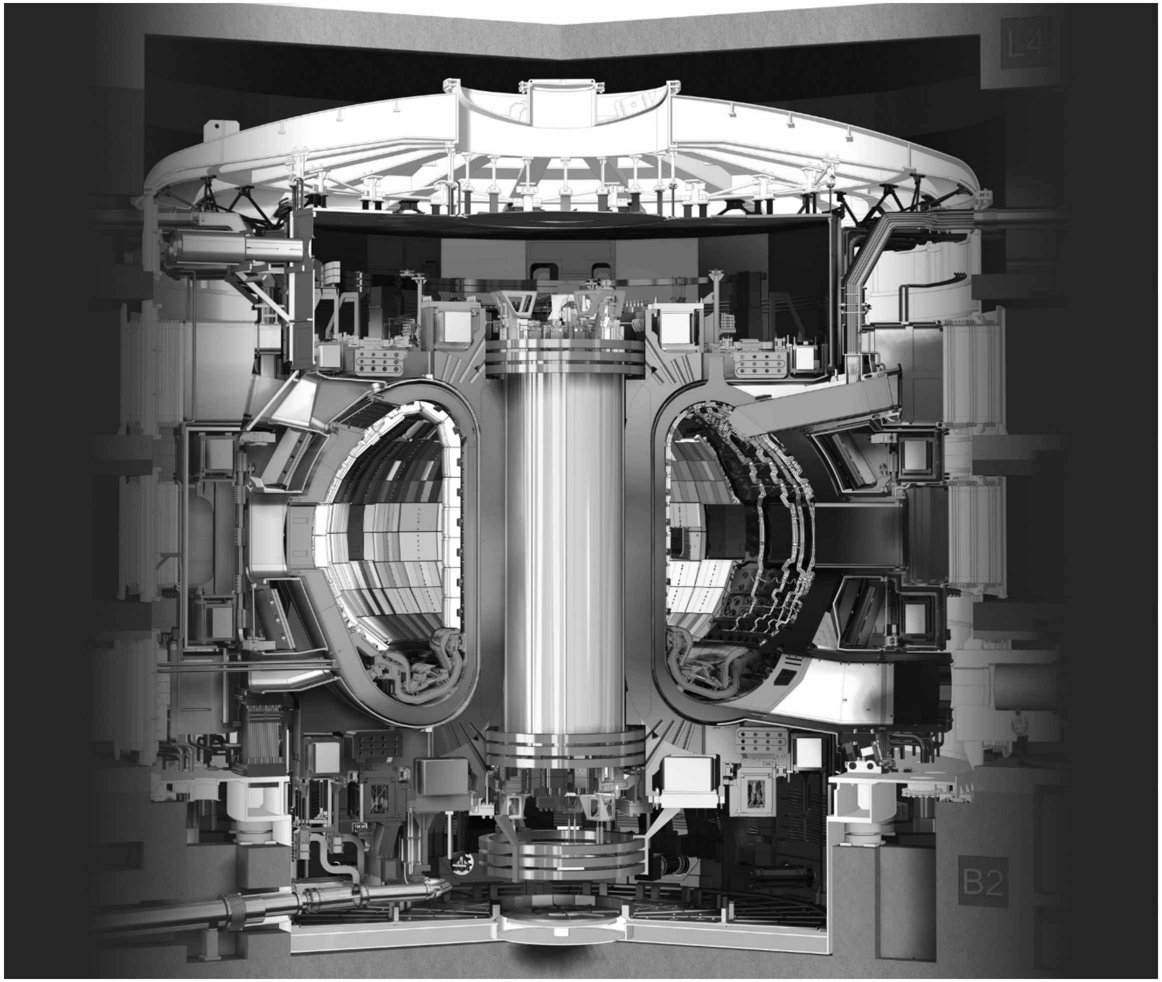
- Blanket



https://www.iter.org/

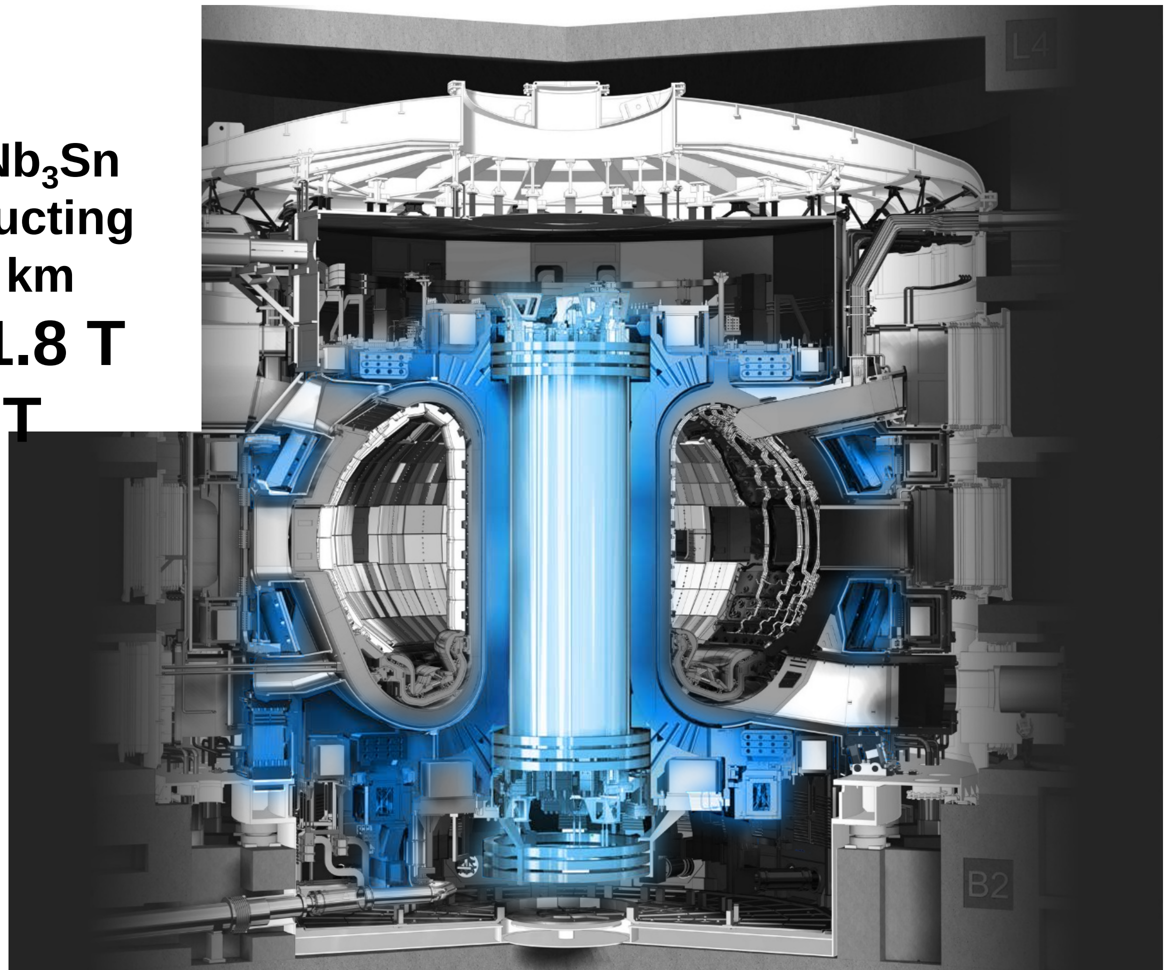
ITER

- **T=150M ⁰C**
- **P=500 MW**



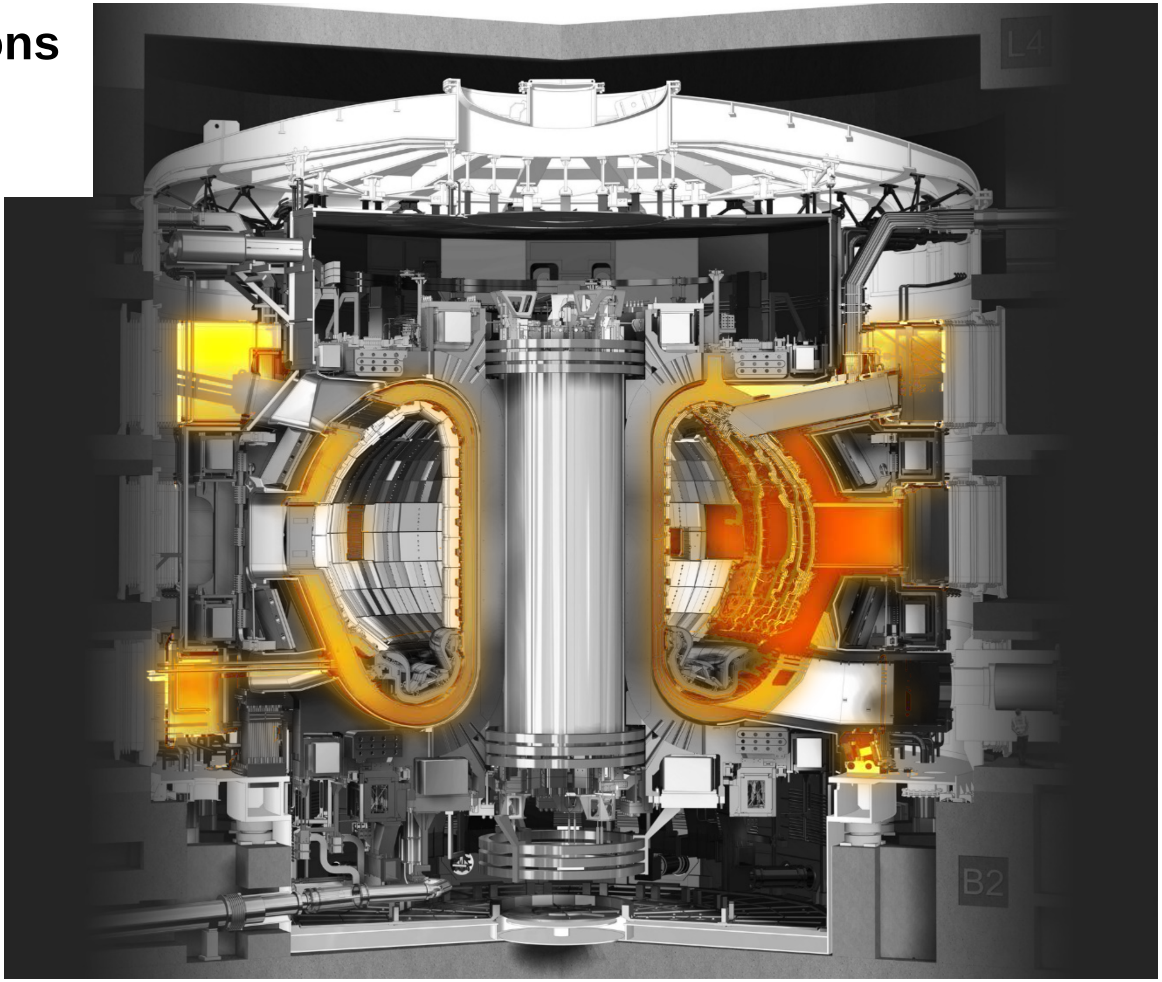
ITER – Magnets

- 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



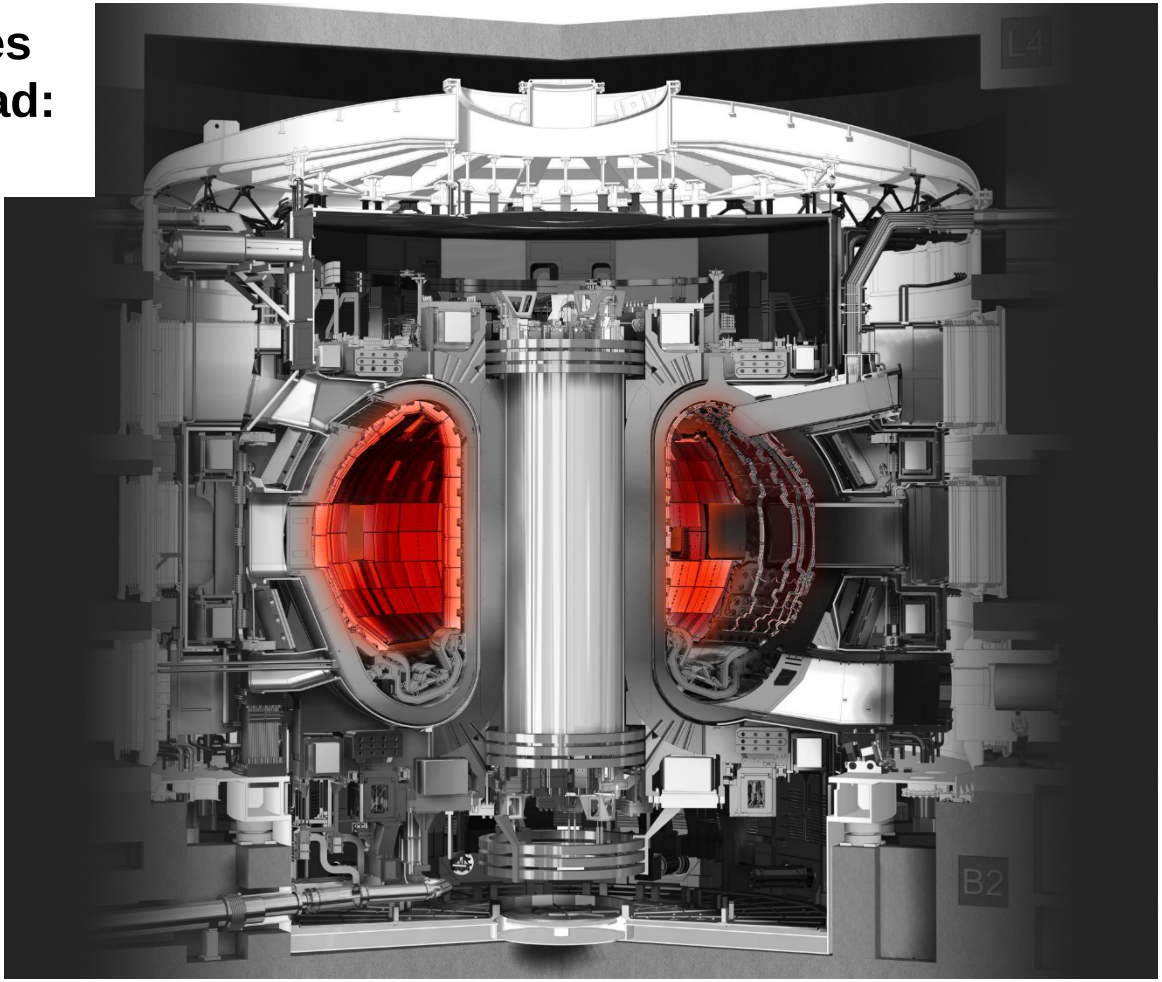
ITER – Vacuum vessel

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



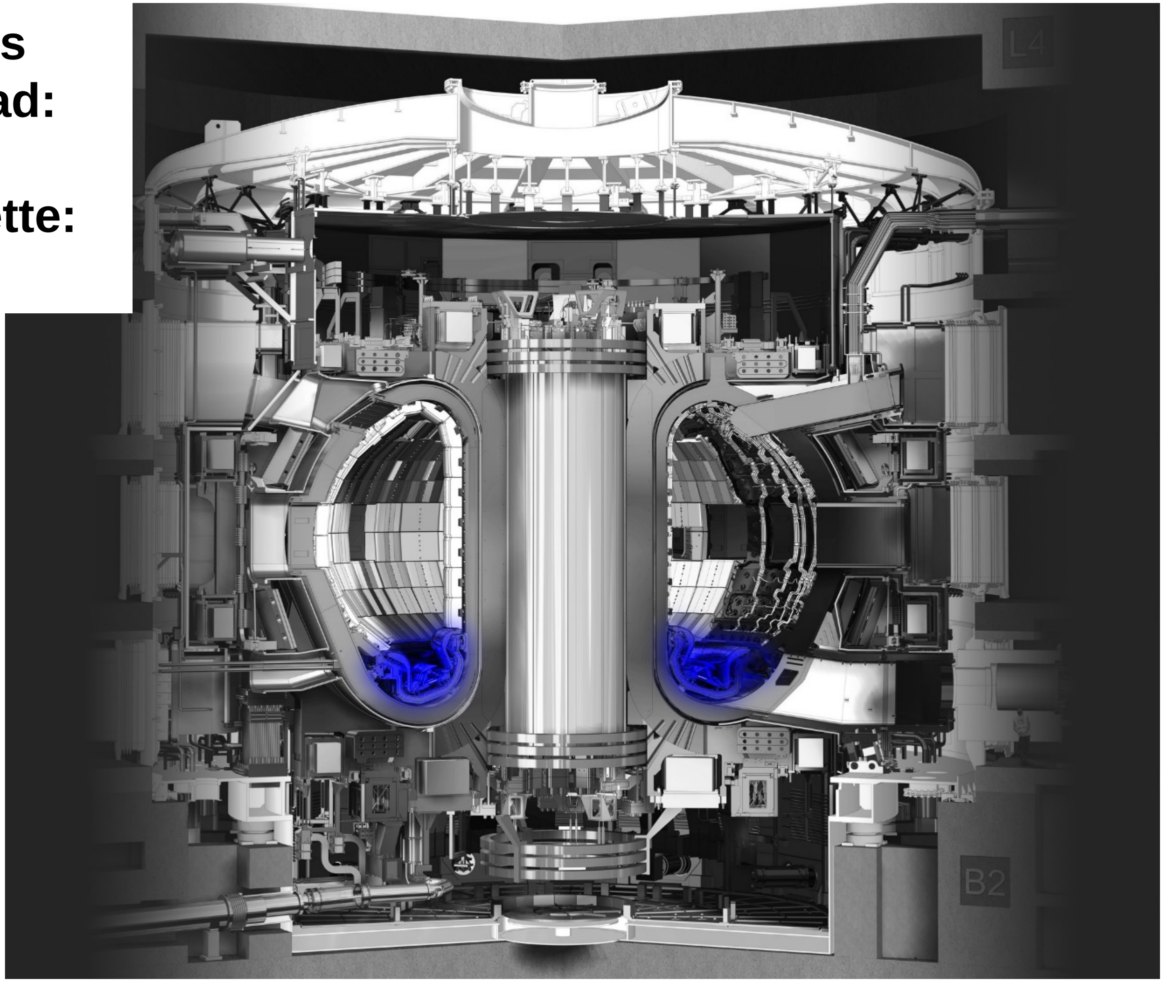
ITER – Blanket

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



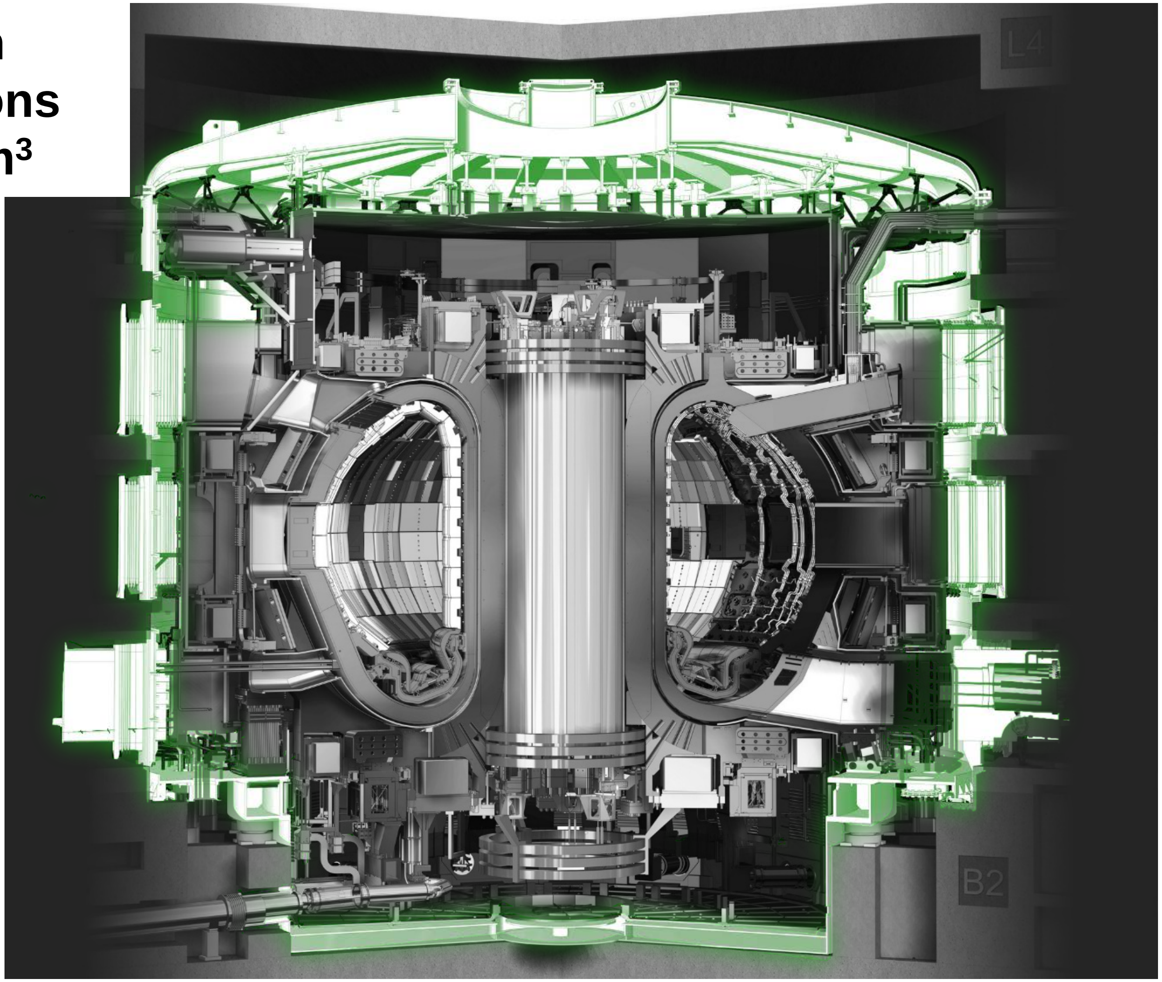
ITER – Divertor

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

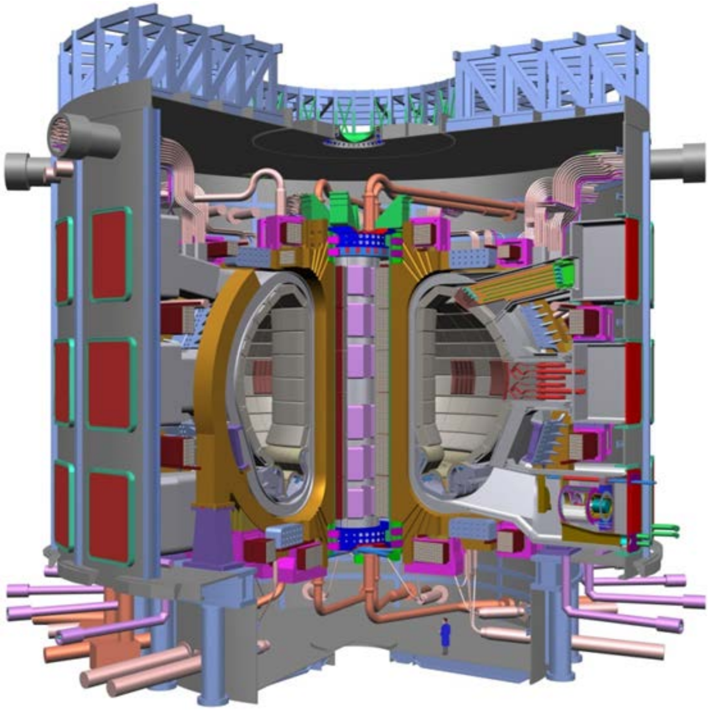


ITER – Crystat

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



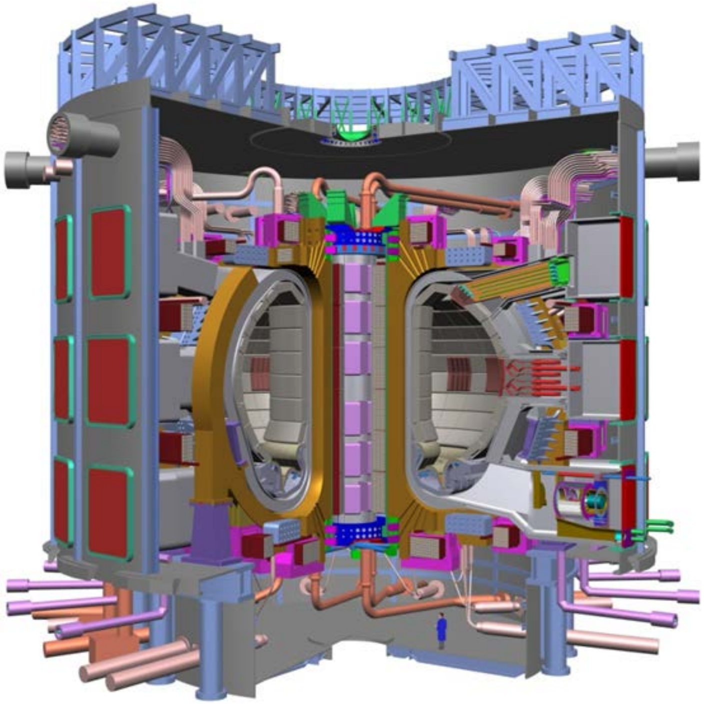
There is a long way to go, but we are on the right path…



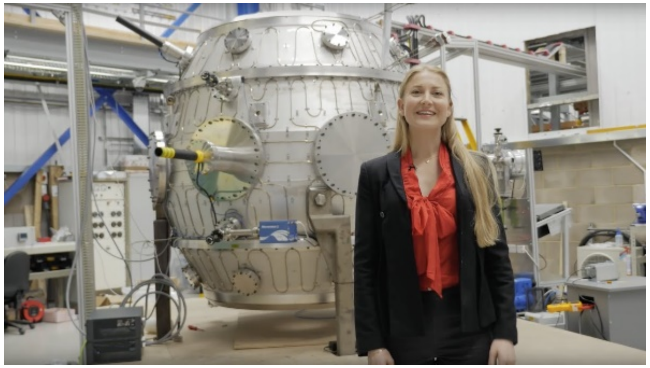
- **Dec 2025 First Plasma**
- **2035 Deuterium-Tritium Operation begins**

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

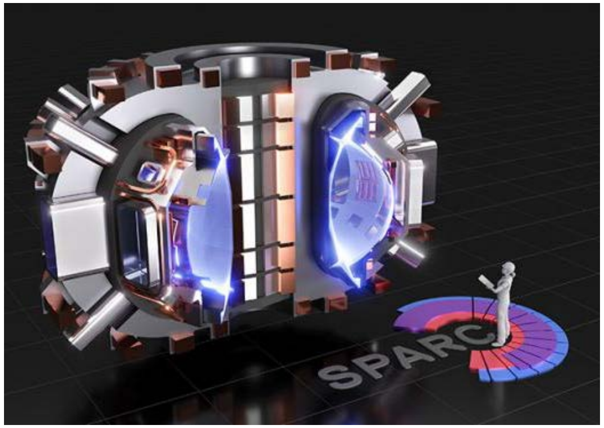
- **ITER – 2025 First Plasma**
  2035 D-T Exps
  2050 DEMO



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

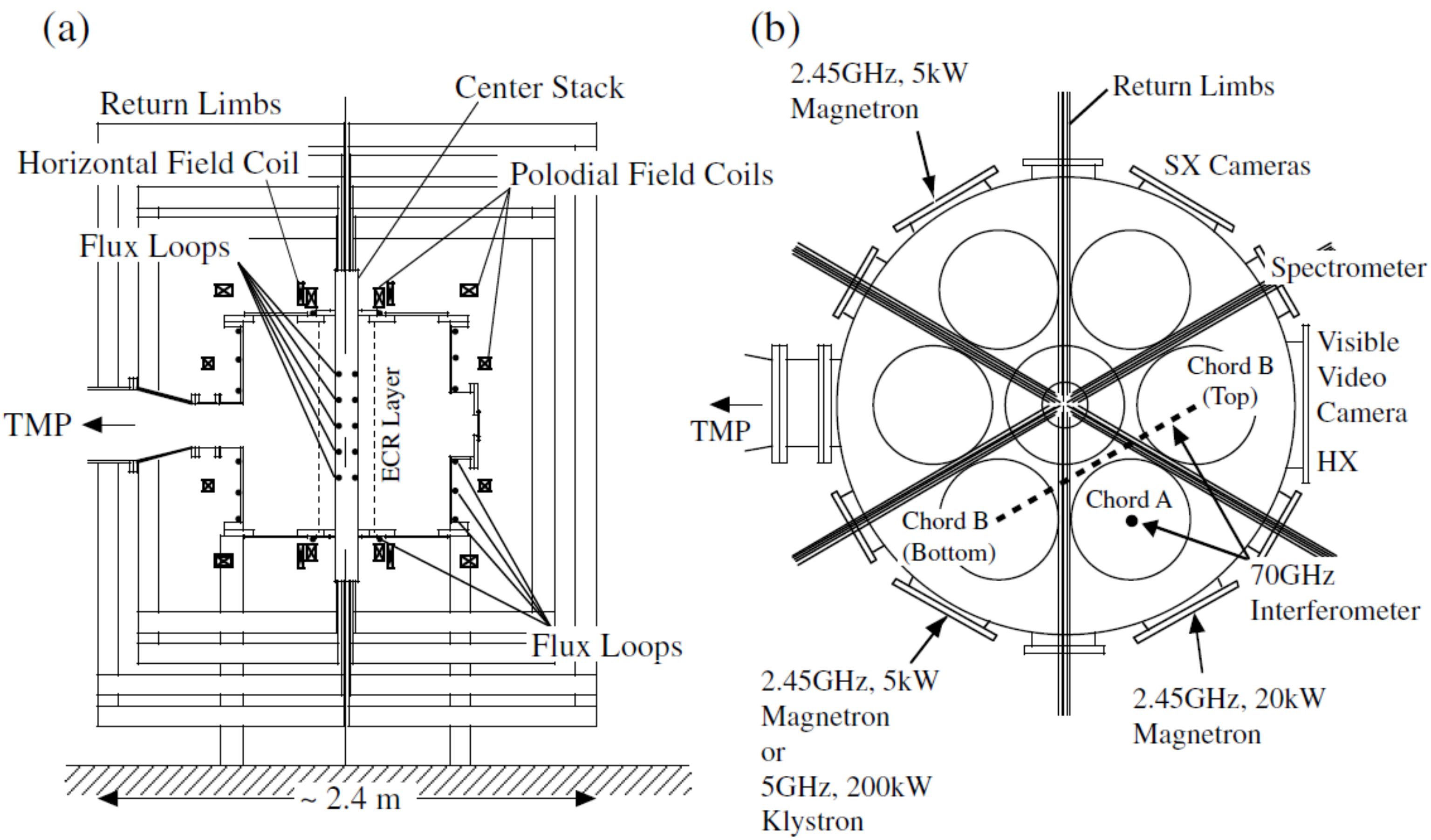


- **Commonwealth Fusion Systems, USA – 2025 Gain**



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

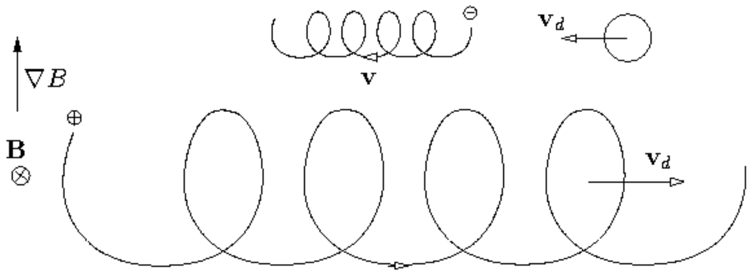
We are going to build a spherical tokamak which is scaled down from LATE device at Kyoto University



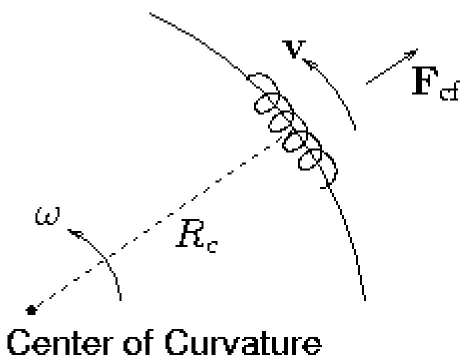
T. Maekawa, *etc*., Nucl. Fusion **45** (2005) 1439

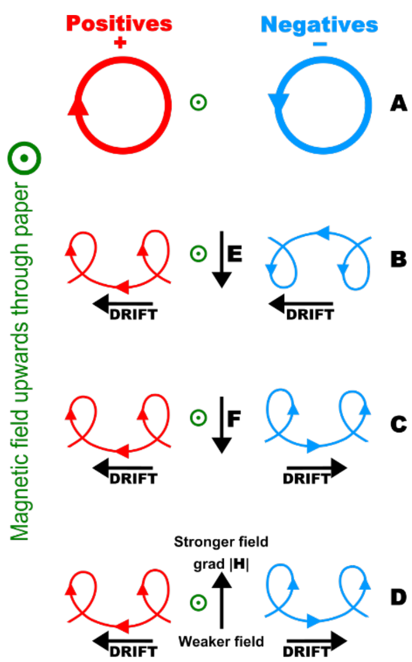
Plasma current will be generated by the Grad-B drift and the Curvature drift current

- **Grad-B drift**

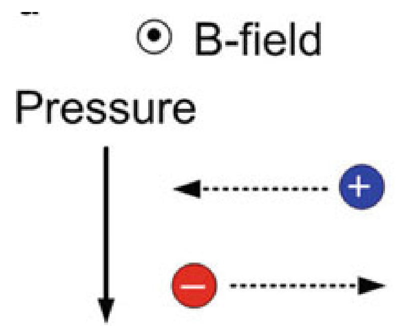


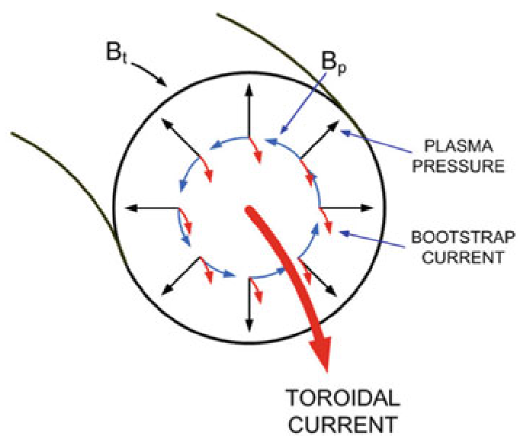
- **Curvature drift**





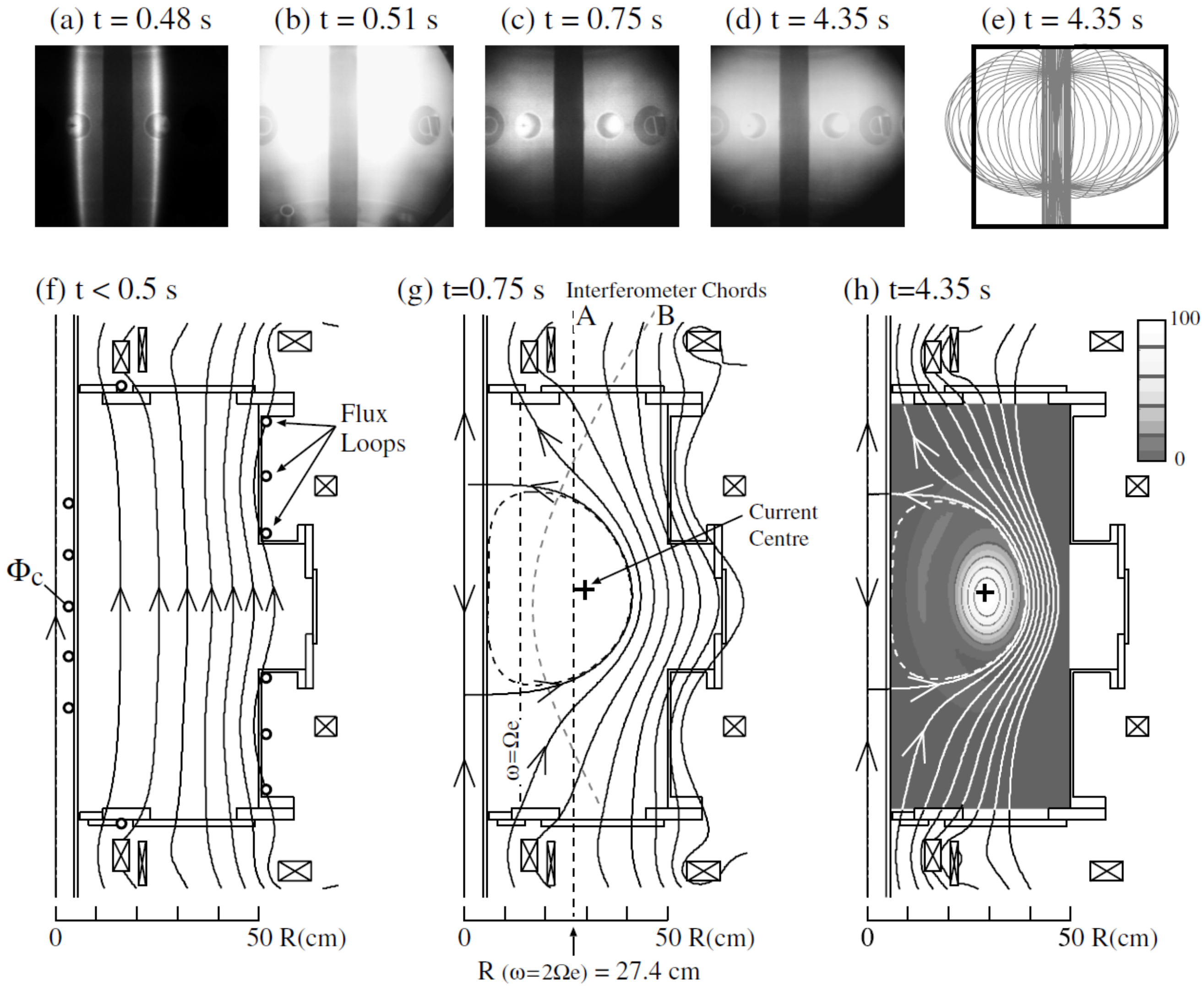
- **Bootstrap current**





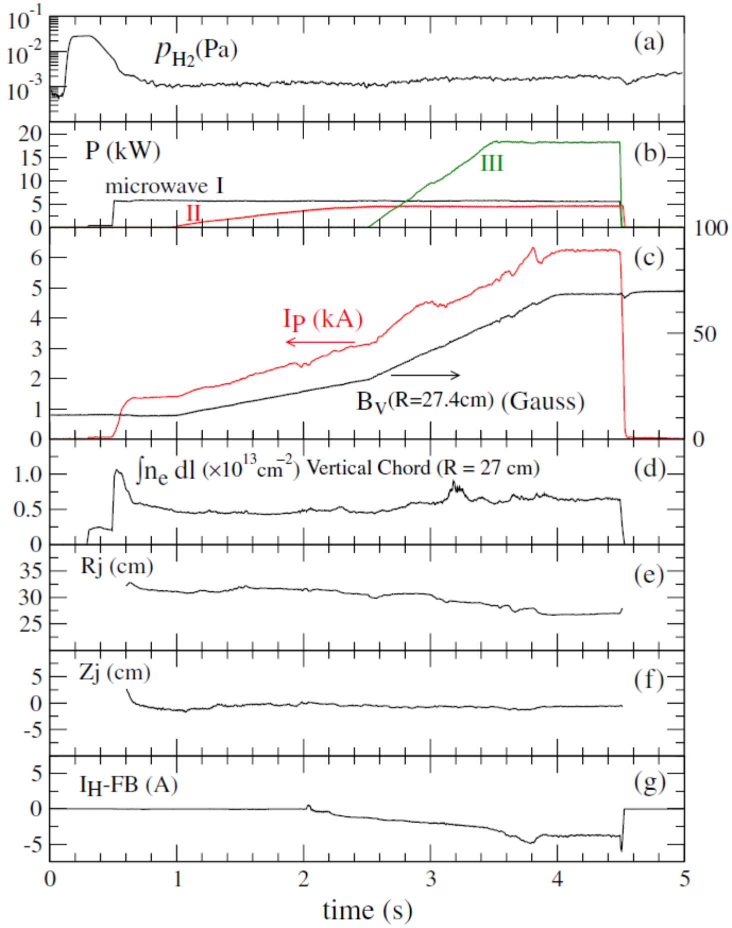
https://en.wikipedia.org/wiki/Guiding_center
http://silas.psfc.mit.edu/introplasma/chap2.html

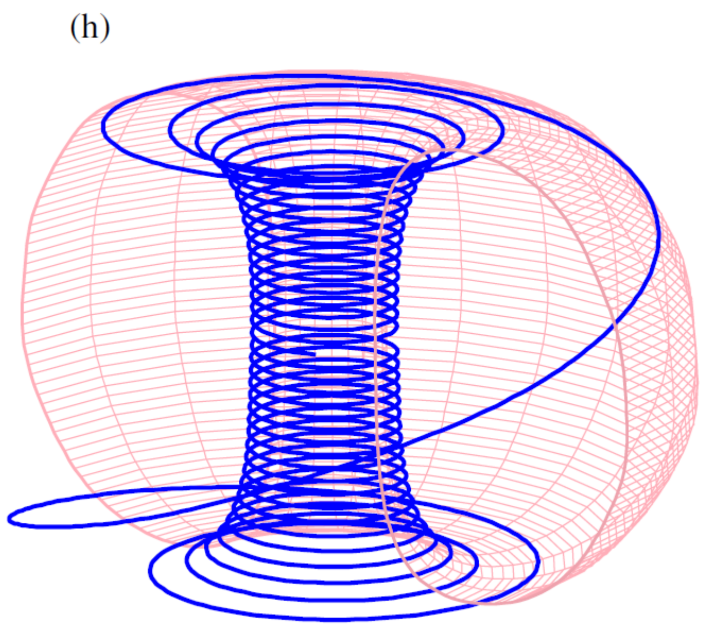
Plasma current is formed from the drift current and the bootstrap current



T. Maekawa, *etc*., Nucl. Fusion **45** (2005) 1439

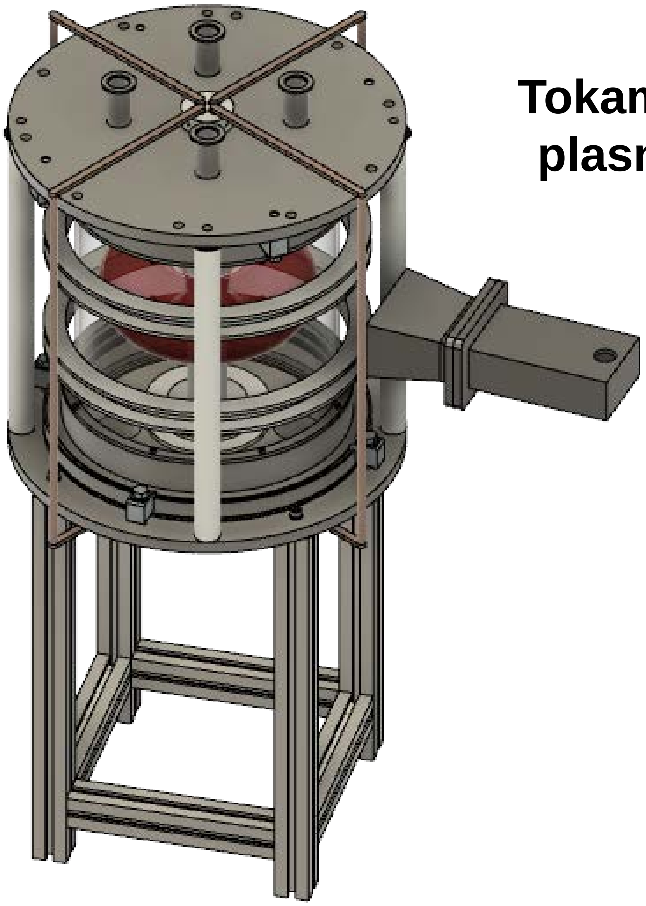
Plasma current of 6.3 kA was generated

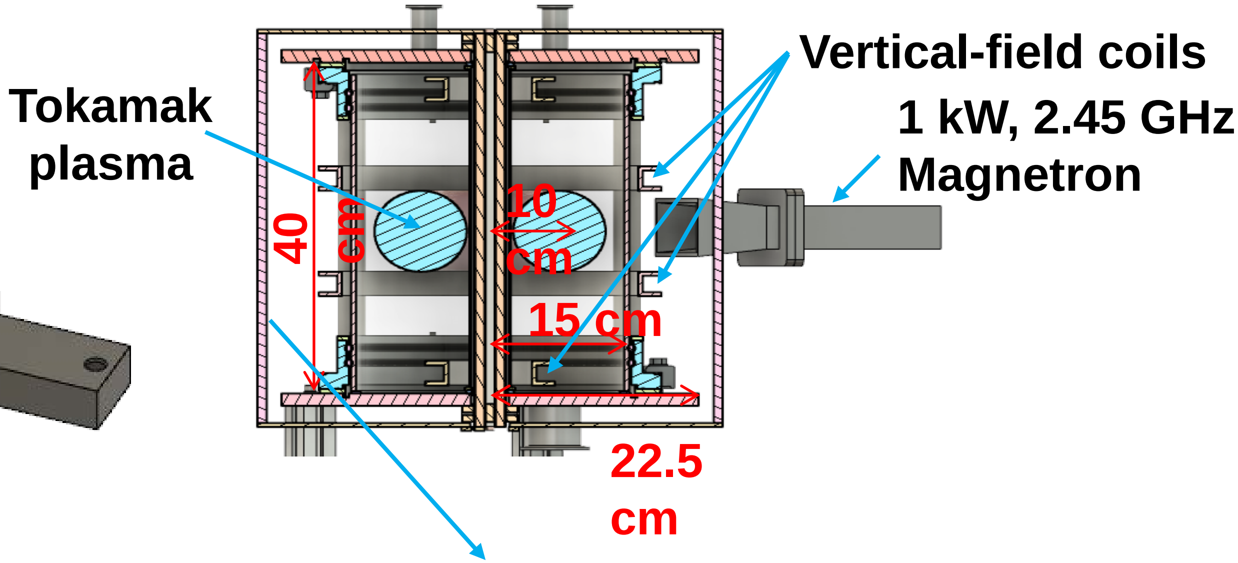




T. Maekawa, *etc*., Nucl. Fusion **45** (2005) 1439

We are going to build a spherical tokamak in this class





4 toroidal-field coil connected in series. Two turns in each coil. 2.5 kA pulsed-current.
B=876 G @ 4.6 cm will be used for ECR heating.

- **Gas: Ar, 10^{-2} Torr.**
- **Initial plasma: generated by RF.**
- **Microwave pulse width: 8 ms.**
- **Magnetic field pulse width: 1 ms.**

Main components of the spherical tokamak is being built by my students

- **Components built by my students:**
  - **Vacuum Chamber.**
  - **Toroidal field coil.**
  - **Microwave heating.**
  - **RF generated plasma.**
- **The missing part of the system:**
  - **Poloidal field generated by the plasma current.**

Four components of the spherical tokamak will be built in class

- Vertical field coil (VF coil).
- Pulse forming network for driving VF coil.
- Rogowski coil for measuring plasma current.
- Triple probe for measuring Plasma characteristics.