Controlled thermonuclear fusion: A brief overview

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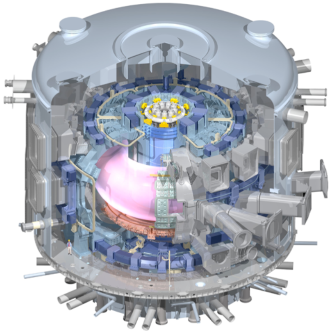
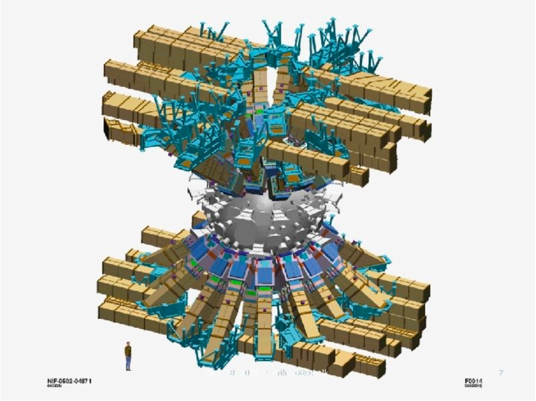
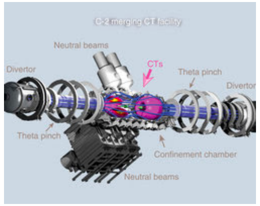
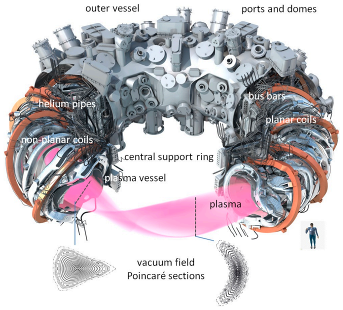
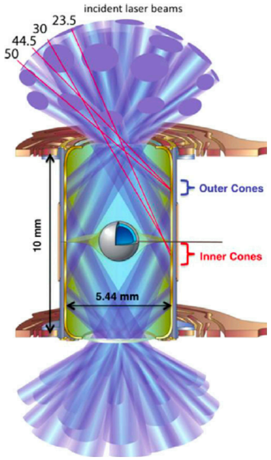
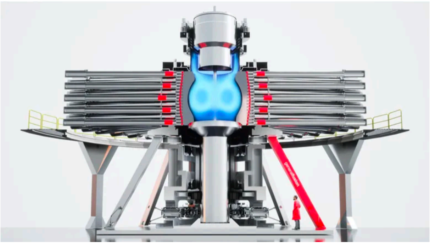


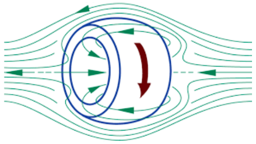


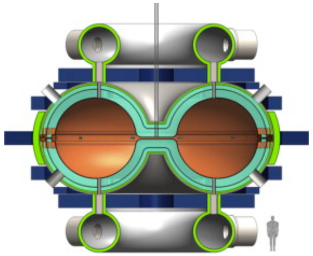








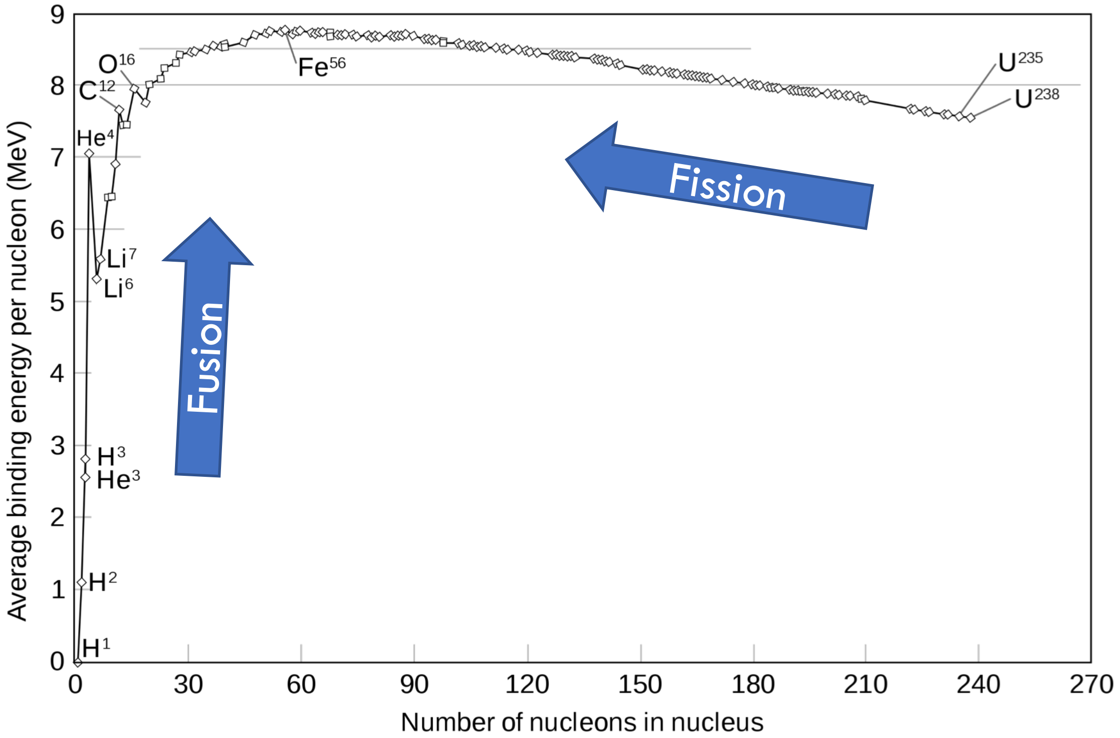




Outline

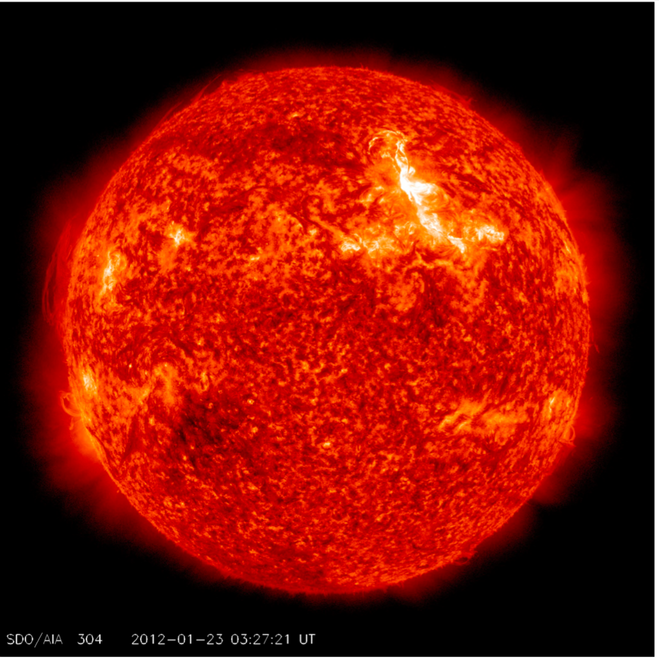
- ☐ Introduction to controlled thermonuclear fusion
- ☐ Why fusion?
- ☐ Magnetic confinement fusion
- ☐ Inertial confinement fusion
- ☐ Alternative approaches

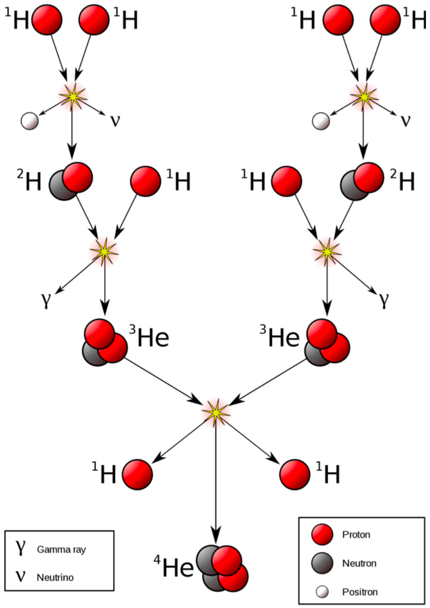
Nucleon binding energy



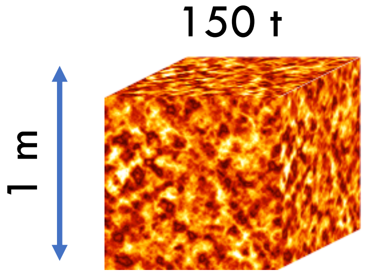
- ~~^{56}Fe is the most stable element~~
- ^{62}Ni is the most stable element
  [Fewell AJP 1995]
- For the others, there is potential energy available for fission or fusion

Fusion in the sun



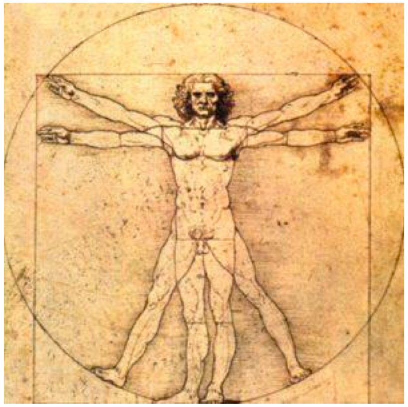


- ☐ Proton-proton chain reaction
- ☐ An **extremely** slow reaction
- ☐ Gravitational confinement



~200 W.m^{-3}

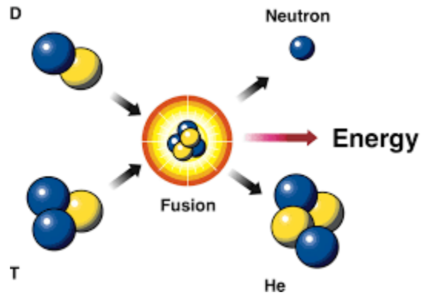
- 15 x 10^6 K
- 150 g.cm^{-3}



~500 W.m^{-3}

Some interesting fusion reactions

Deuterium-Tritium nuclear fusion



- ☐ With neutron emission

$$^2_1\mathrm{D} + ^3_1\mathrm{T} \longrightarrow ^4_2\mathrm{He} + \mathrm{n}^0 + 17.6\mathrm{MeV}$$

$$^2_1\mathrm{D} + ^2_1\mathrm{D} \longrightarrow ^3_1\mathrm{T} + \mathrm{p}^+ + 4.0\mathrm{MeV}$$

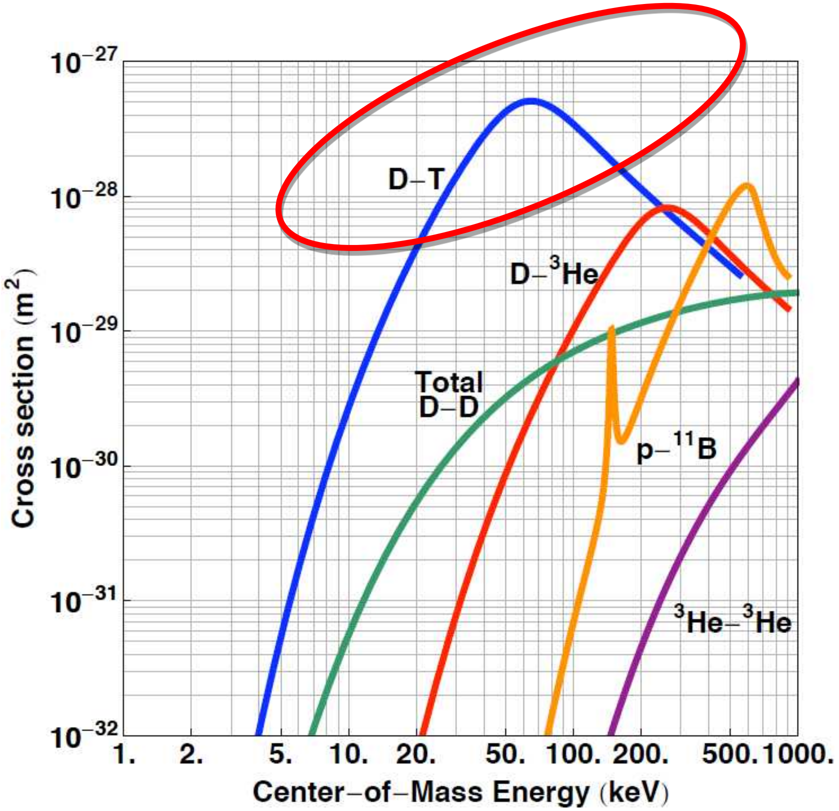
$$\longrightarrow ^3_2\mathrm{He} + \mathrm{n}^0 + 3.3\mathrm{MeV}$$

- ☐ Without neutron emission **(aneutronic) :**

$$^2_1\mathrm{D} + ^3_2\mathrm{He} \longrightarrow ^4_2\mathrm{He} + \mathrm{p}^+ + 18.3\mathrm{MeV}$$

$$^3_2\mathrm{He} + ^3_2\mathrm{He} \longrightarrow ^4_2\mathrm{He} + 2\mathrm{p}^+ + 12.9\mathrm{MeV}$$

$$\mathrm{p} + ^{11}_5\mathrm{B} \longrightarrow 3^4_2\mathrm{He} + 8.7\mathrm{MeV}$$



10 keV ~ 100 Millions K

Plasma physics

Energy flow and ignition criterion

- The plasma is heated by confined alpha particles

$$P_\alpha = \Delta E_f \langle \sigma v \rangle n_e^2 V/20$$

- There are conduction and radiation losses

$$P_{\rm loss} = W_{\rm th}/\tau_E \qquad W_{\rm th} = 3 n_e k_B T$$

- Assuming no external input, losses are balanced by **α particle heating**

Lawson criterion

$$n_e \tau_E = \frac{60T}{\langle \sigma v \rangle \Delta E_f}$$

Lawson criterion

- The reaction rate, $\langle \sigma v \rangle$, only depends on temperature
- Temperature is fixed by the necessity to have a large cross-section

$$n_e \tau_E = \frac{60T}{\langle \sigma v \rangle \Delta E_f}$$

- At T~100·10^6 K, **$n_e \tau_E \gtrsim 3\times10^{20}$ s·m^{-3}** is required (DT fusion)

- **Long** confinement time, **small density**

Magnetic confinement fusion

Intermediate range: many other approaches

- **Short** confinement time, **large density**

Inertial confinement fusion

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- ☐ Inertial confinement fusion
- ☐ Alternative approaches

Why fusion?

- ❑ Fusion energy: safe nuclear power?
  - ➢ A bit more complicated and approach dependent

- ❑ Fusion energy: nuclear power without the waste?
  - ➢ A bit more complicated and approach dependent

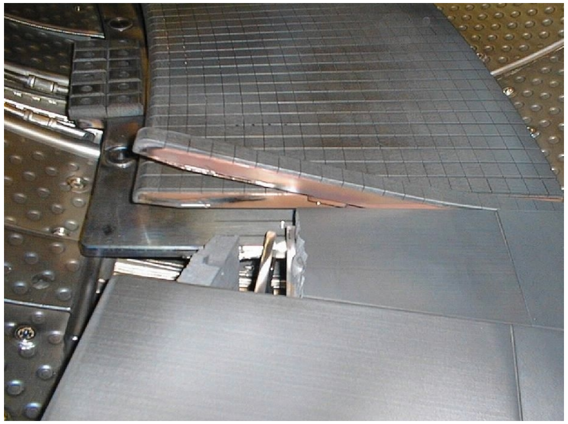
- ❑ Fusion energy: a limitless source of energy?
  - ➢ Slightly more complicated but globally quite true

Fusion energy: safe nuclear power?

- ☐ No notion of critical mass contrary to fission. Meltdowns with centuries-long impacts like **Chernobyl or Fukushima can be ruled out**

- ☐ Half of the fuel (tritium) is radioactive. However the amount of radioactive material to handle on site is much less than for fission (~kg vs ~ton)

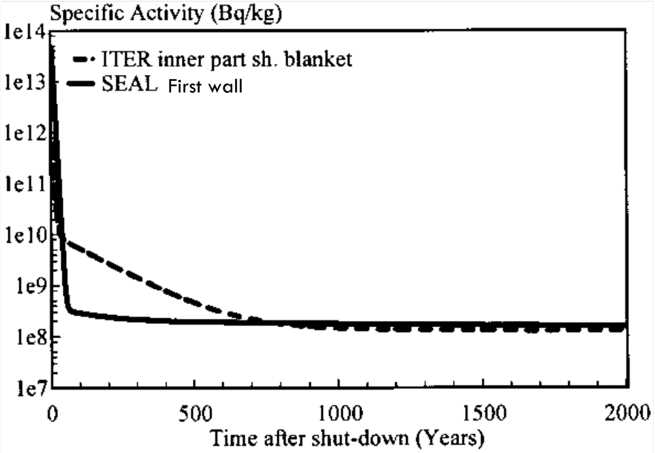
- ☐ A tokamak can **disrupt**. This is a sudden and brutal loss of confinement, which can damage the confinement vessel



Disruption damage (bending of plasma facing component) on the Tore Supra tokamak **[Reux PhD thesis 2010]**

Fusion energy: nuclear power without the waste?

- The reaction emits energetic neutrons, used to boil water in order to produce steam, and finally electricity
- These neutrons induce nuclear reactions in the wall material
- Hence, short-lived radioactive waste is produced. After 50 years, half of it can be disposed of, the other half can be recycled after another 50 years **[Broden el al, Fusion Engineering and Design 1998]**



Fusion energy: a limitless source of electricity?

- 0.015% of all Hydrogen is Deuterium on Earth.
- 1.4x10^{21} kg ocean water ➠ more than 10 billion years of global energetic consumption
- What about tritium? It has 12 years half-life… It is generated from lithium

$$^{6}_{3}\mathrm{Li} + \mathrm{n} \quad \longrightarrow \quad ^{4}_{2}\mathrm{He} + \, ^{3}_{1}\mathrm{T} \qquad \Delta E = +4.8\,\mathrm{MeV}.$$

- Ultimate reserves < 50 Mt ➠ ~ 2000 years of consumption
- Ocean lithium stock: 2 - 3 MJ/kg of sea water (to be compared to 42 MJ/kg for oil)

Only difficulty: breeding ratio > 1

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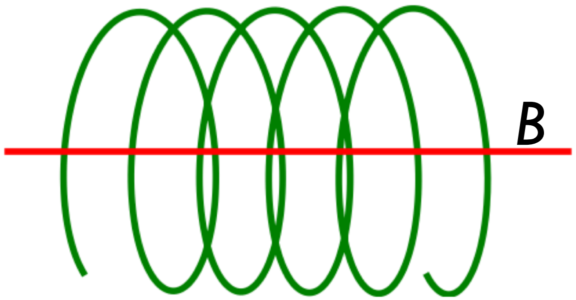
Magnetic confinement

- ☐ Plasma density $n_e \sim 10^{20} - 10^{21}\mathrm{m}^{-3}$
- ☐ Necessary confinement time: $\tau_E \sim 1\mathrm{s}$

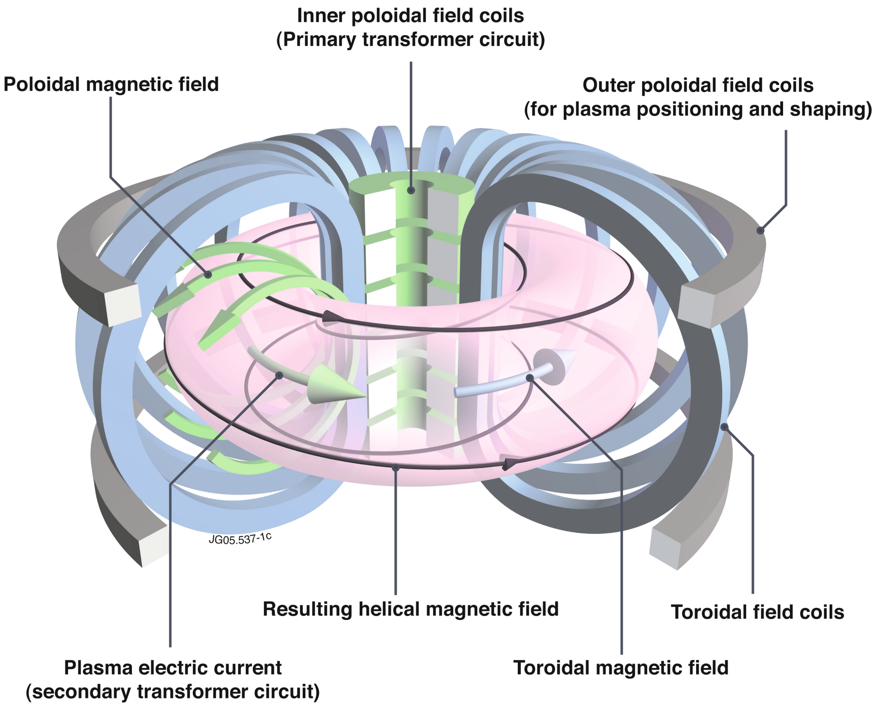
$$\mathcal{E} = \frac{1}{2}mv_{\parallel}^2 + \mu B$$



Larmor radius of charged particle,
inversely proportional to magnetic field

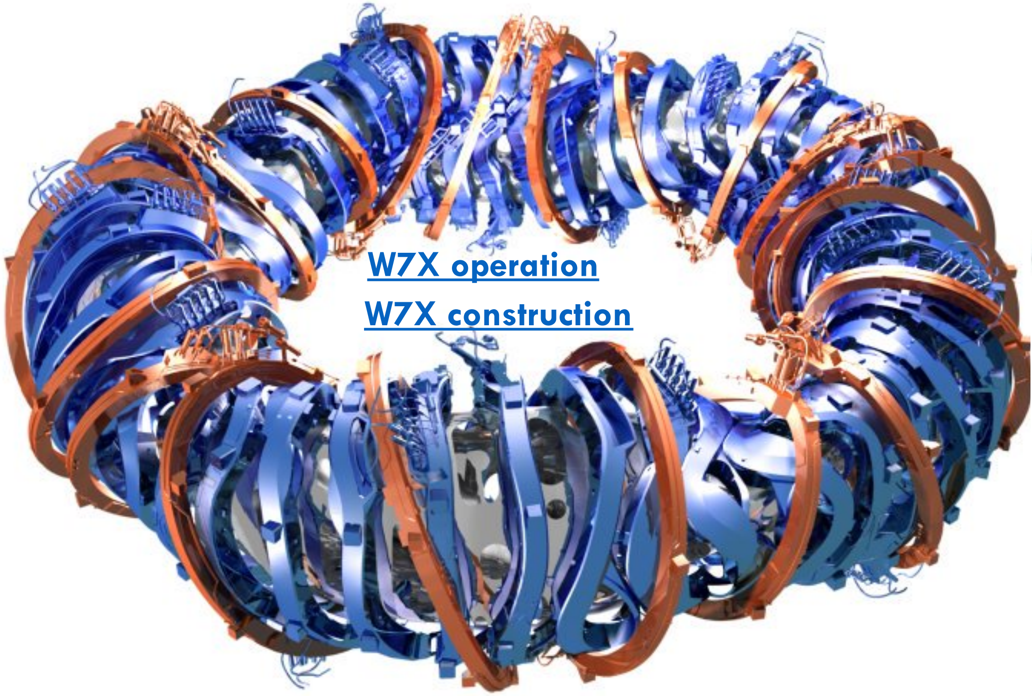
Tokamak configuration

- **A purely toroidal field is useless**
- Centrifugal forces cause too large drifts $\Longrightarrow \tau_E < 1\mu\mathrm{s}$
- One has to add a **poloidal field** in order to get a helical field
- The poloidal field is obtained by driving a **multi-million ampères** current in the plasma
- The current is an important source of magnetohydrodynamic instabilities



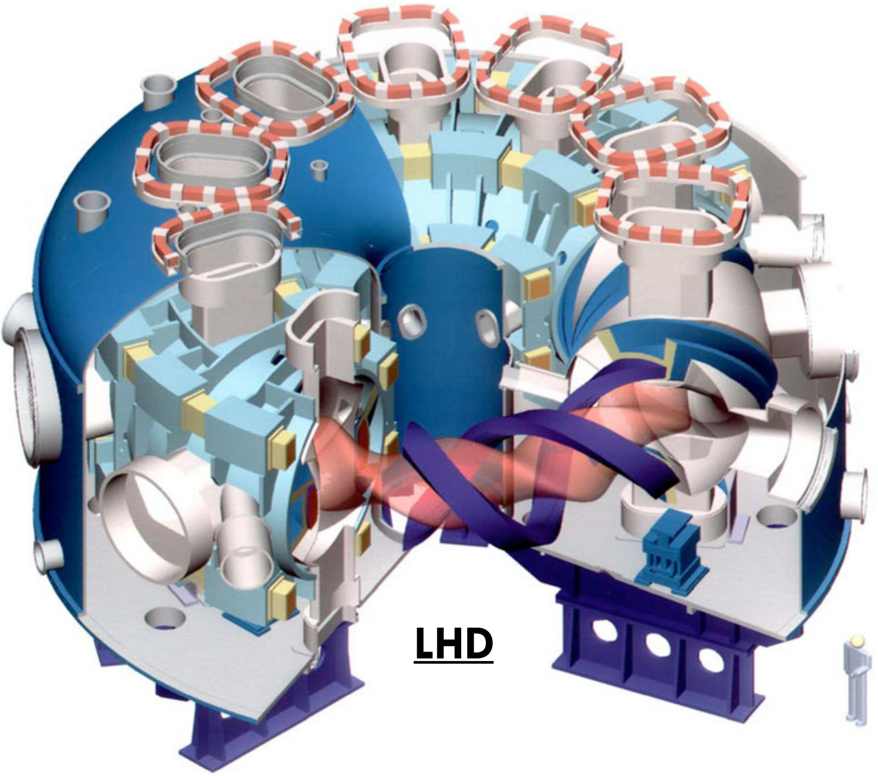
The stellarator configuration

- Can we avoid the plasma current? Yes, but the price to pay is high
- We lose axisymmetry! External coils can no longer remain planar!



[W7X operation]

[W7X construction]

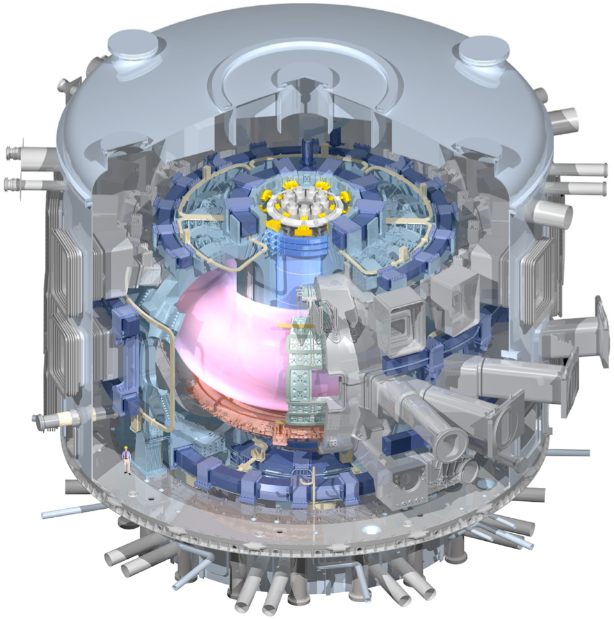


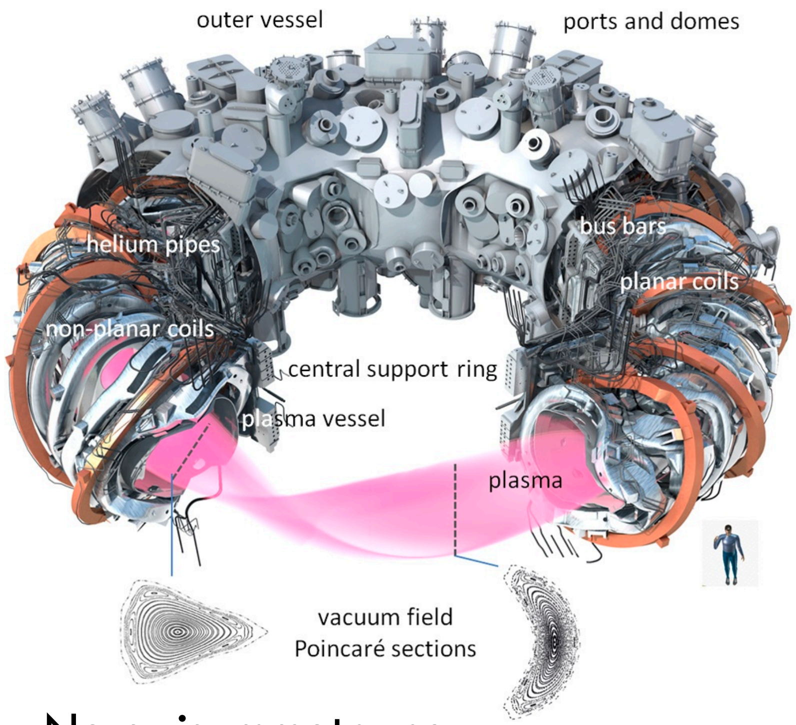
LHD

Tokamak Vs Stellarator

- ✓ Axisymmetry, leading to better confinement

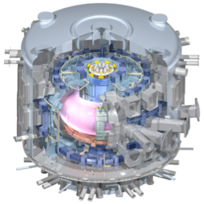
- ✗ No real steady-state
- ✗ Magnetohydrodynamic instabilities
- ✗ Disruptions ✗✗✗



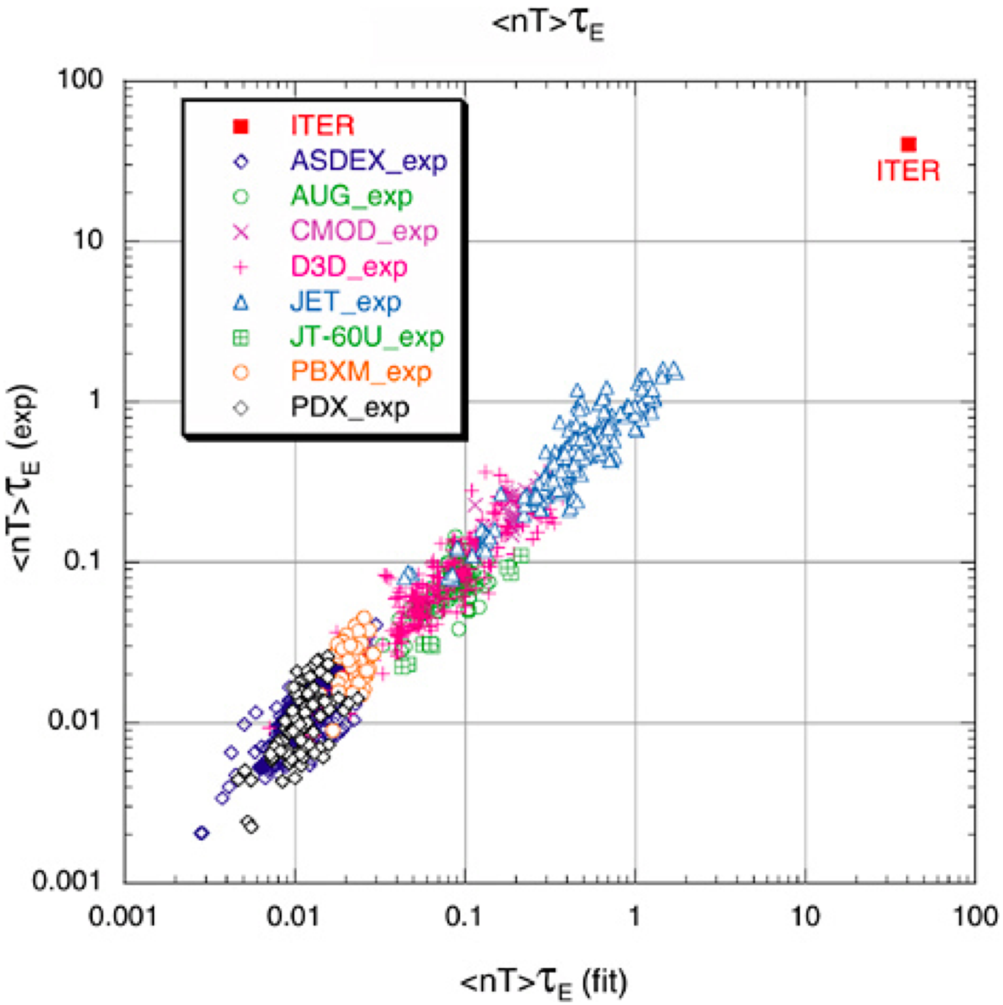


- ✗ No axisymmetry so
  - ✗ More difficult to build
  - ✗ Slightly degraded confinement

- ✓ No steady state problem
- ✓ Better stability
- ✓ No major disruptions



ITER objective



- According to scaling laws, ITER should reach ignition
- The ratio of output power over the power absorbed by plasma

$$Q_{\text{plasma}} = \frac{500\text{MW}}{50\text{MW}} = 10$$

- But the global plant Q, or engineering Q, is much less

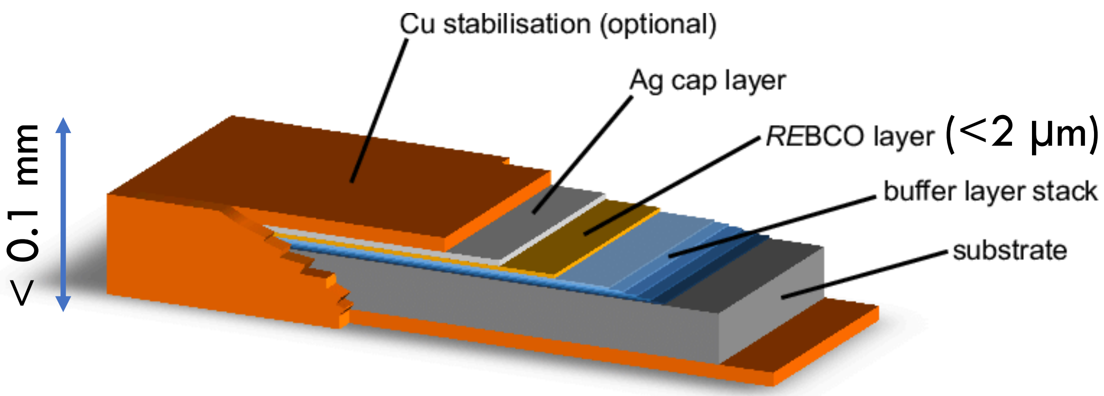
$$Q_{\text{engineering}} < 1$$

Some (yet) unresolved problems of magnetic confinement fusion

- ☐ Disruption prevention and mitigation. More generally stability, **especially in the case of tokamaks**
- ☐ Turbulent transport prediction
- ☐ Power exhaust: power out of confined region gets concentrated in a very small surface
- ☐ Contamination of the plasma by impurities
- ☐ Plasma-wall interaction
- ☐ Confinement of fast particles, especially fusion-borne alphas **(in particular in stellarators)**

Most topics coupled to each other…

Progress exists in the world of fusion science (tokamak)



- ☐ REBCO = Rare Earth Barium Copper Oxyde

[Greenwald, M., et al. "The high-field path to practical fusion energy." *PSFC Report PSFC/RR-18-2* (2018).]

$$P_{\text{fus}} \propto B^4$$

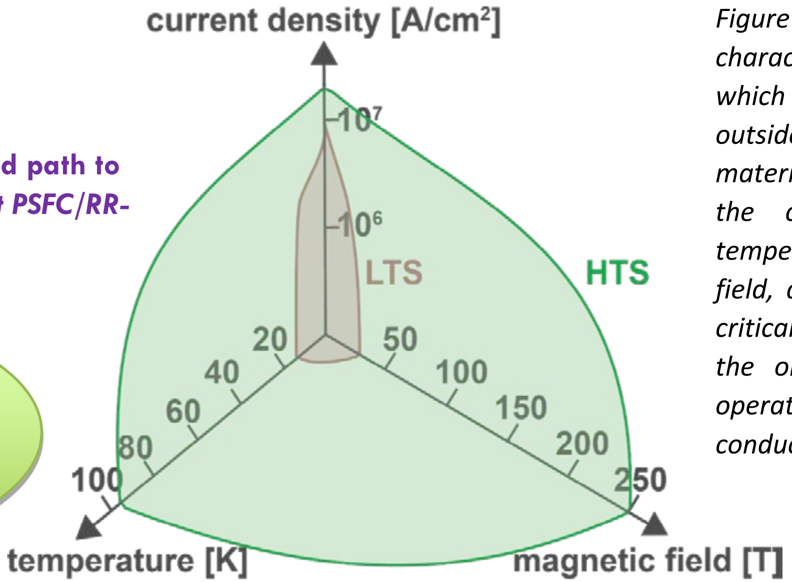
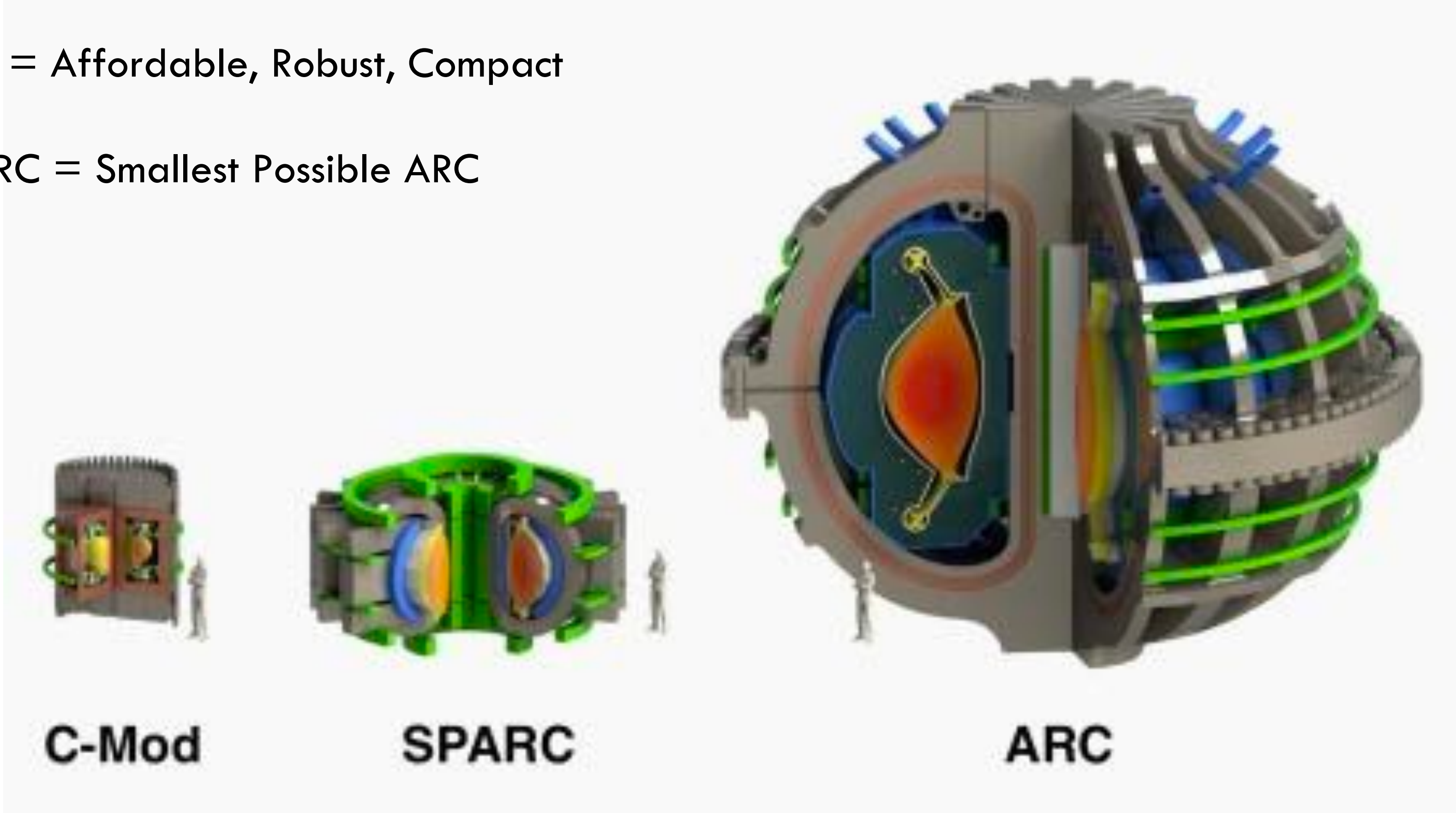


Figure 2.2 Practical superconductors can be characterized by a critical surface below which the material is a superconductor, and outside of which it is a normal conducting material. The primary variables that define the critical surface are the critical temperature, the upper critical magnetic field, and the critical current density. The critical surface of the HTS conductor shows the orders of magnitude advantage in operating space gained over LTS conductors.

Progress exists in the world of fusion science (tokamak)

- ARC = Affordable, Robust, Compact
- SPARC = Smallest Possible ARC



- SPARC developed by Commonwealth Fusion Systems (linked to MIT)
- Should be operational before 2030 (before ITER…)

Progress exists in the world of fusion science (stellarator)

- Stellarator design has made tremendous progress in the last couple years

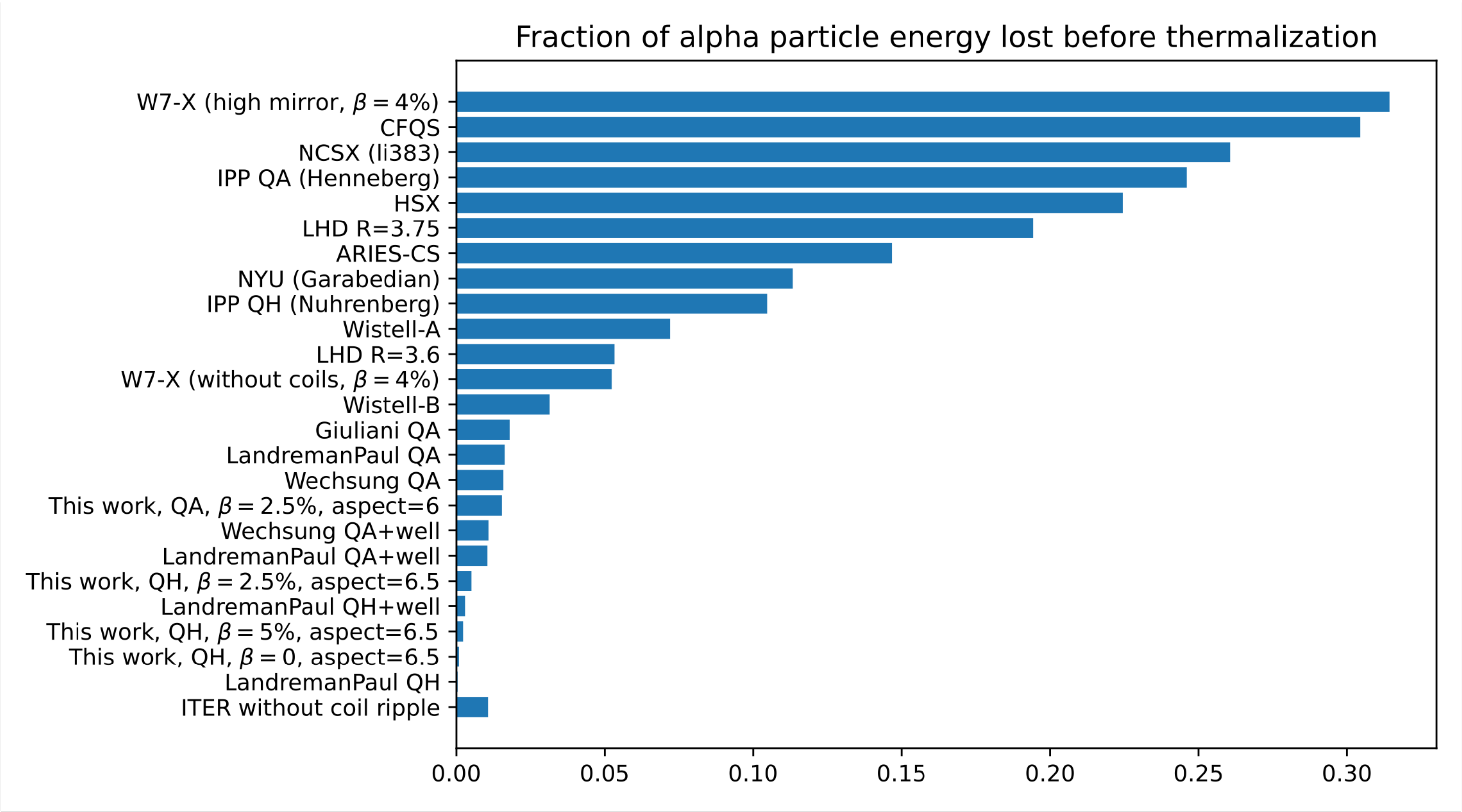


FIG. 17. Significant progress has been made in the confinement of energetic particles in stellarators. Loss of alpha particle energy is shown for a variety of magnetic configurations, all scaled to the same minor radius and average field strength.

[Landreman et al, PoP 2022], already cited 13 times

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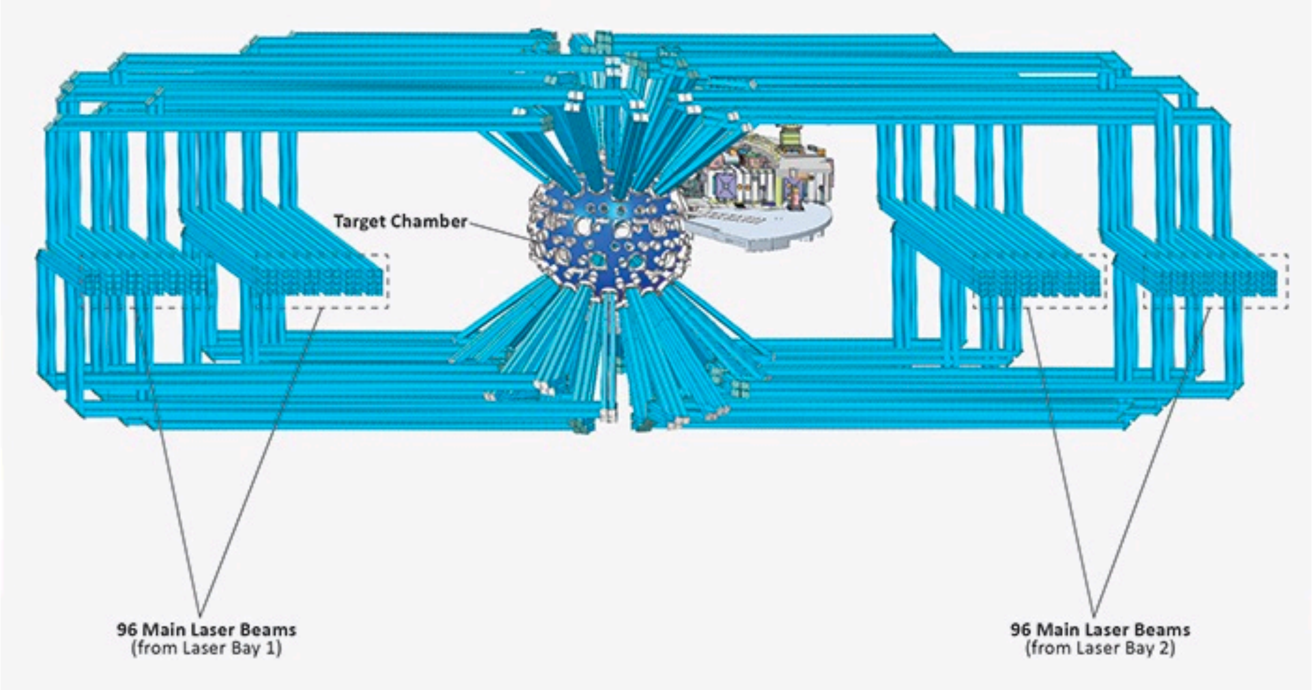
Laser fusion



☐ NIF in the US

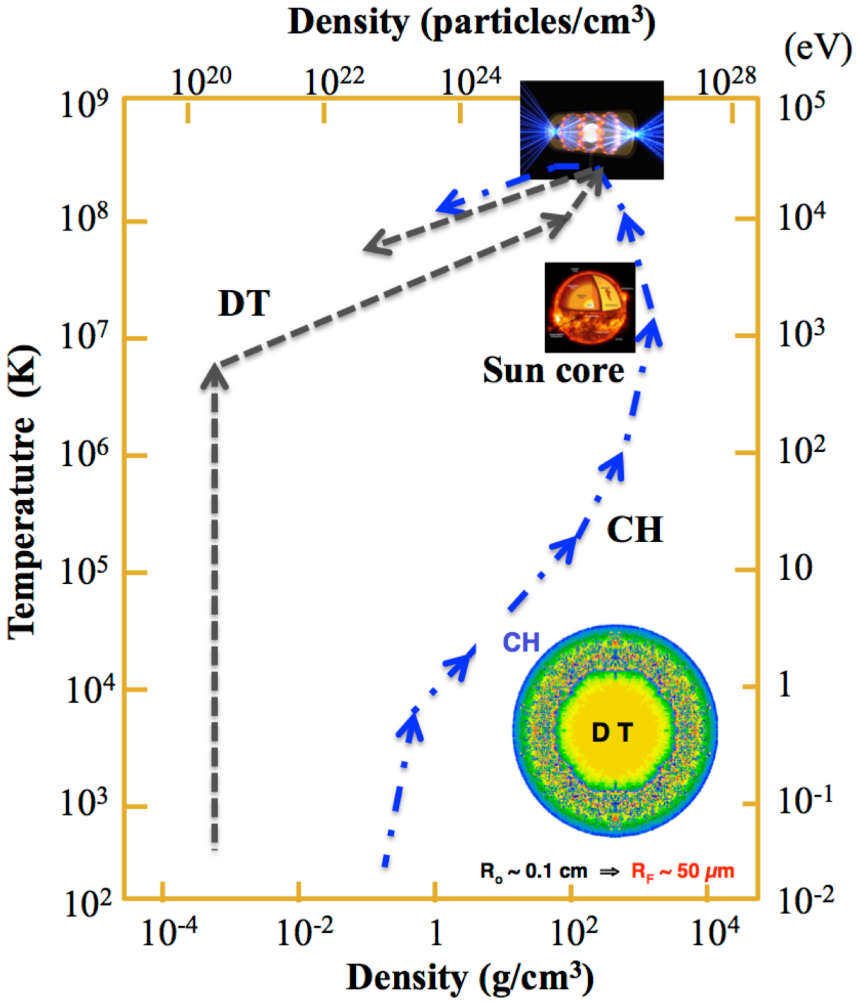
☐ LMJ in France

☐ National Ignition Facility: 192 laser beams

☐ Total energy in the IR lasers: 4MJ (~2MJ after conversion to UV)

☐ Energy deposited to DT fuel ~10 kJ

Laser fusion

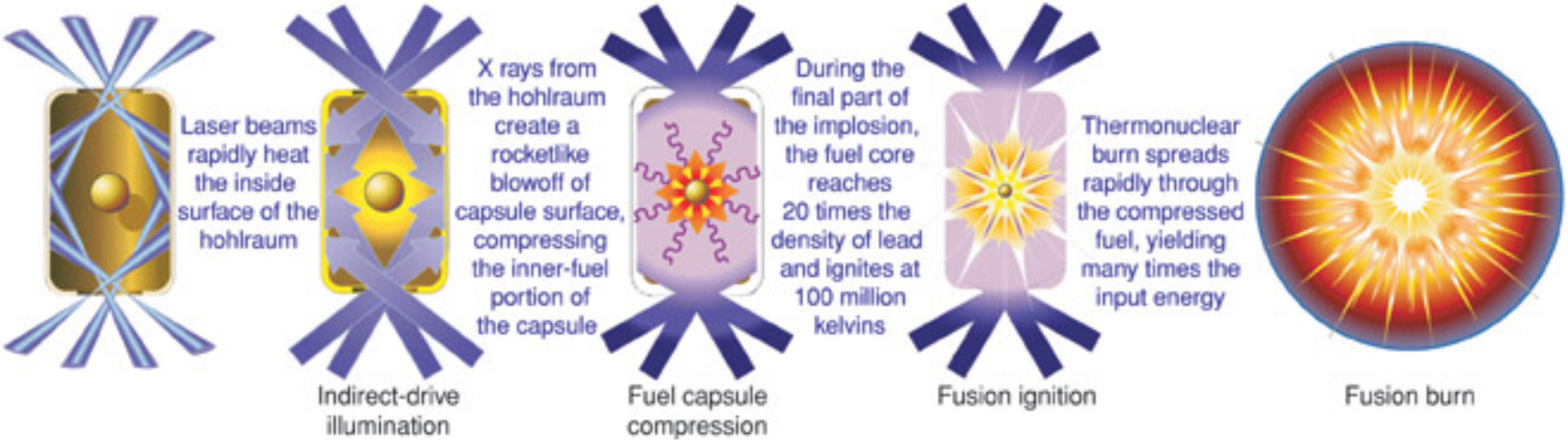


- ☐ Confinement time $\tau_E \sim$ 10 ns
- ☐ Density $n_e > 10^{31}$ m^{-3}, comparable to the sun's core
- ☐ Temperature reaches same order of magnitude as magnetic confinement ($T \sim 100 \cdot 10^6$ K)

Laser fusion: indirect drive

☐ Lasers hit a metallic capsule called « hohlraum »

☐ Laser energy is converted to X-rays, which compress the DT capsule in the center

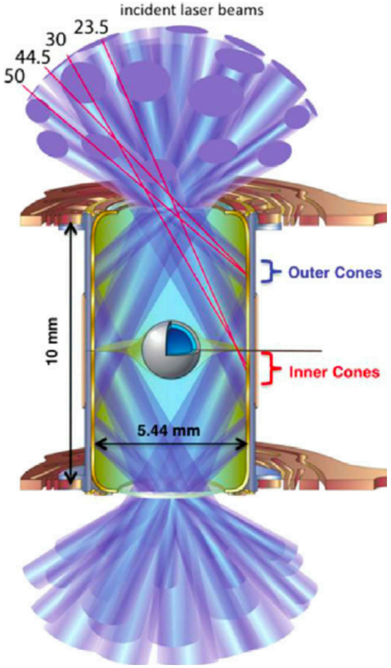


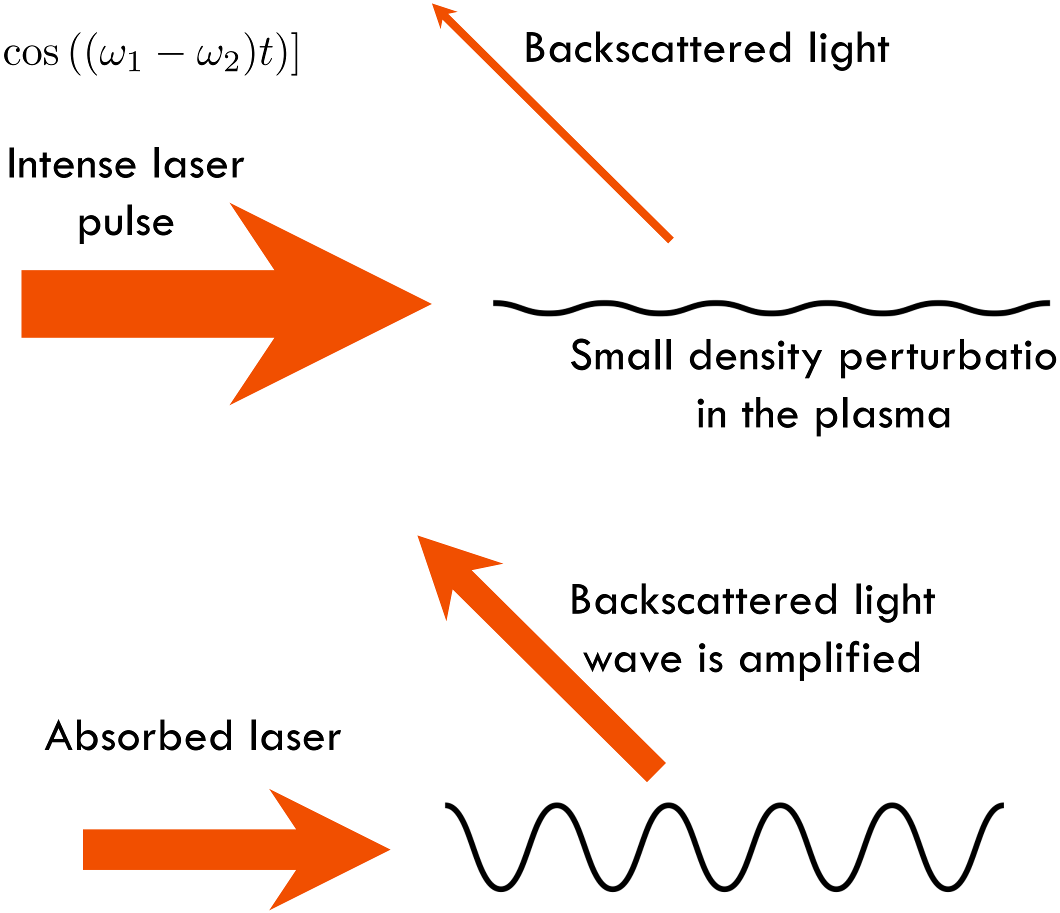
✗ Parametric instabilities can impede laser propagation

✗ Low energy efficiency in heating the fuel

Example: Raman stimulated scattering

$$\cos(\omega_1 t)\cos(\omega_2 t) = \frac{1}{2}\left[\cos\left((\omega_1+\omega_2)t\right) + \cos\left((\omega_1-\omega_2)t\right)\right]$$





Intense laser pulse

Backscattered light

Small density perturbation in the plasma

Backscattered light wave is amplified

Absorbed laser

Amplified density perturbation

Achievements and challenges

- In 2013, the 10 kJ absorbed by the fuel turned into 14 kJ of fusion energy

- In august 2021, a shot yielding **1.35MJ** of fusion energy was produced, for a laser energy of ~2MJ [Abu-Shawareb et al, PRL 2022]

- Breakeven was reported in a similar shot a while later, on December 5th, 2022, with a yield of **3.15 MJ**

- However, the capacitor for laser feeding were charged with **~400MJ of electrical energy**

- More efficient lasers are possible, going **from 0.5% to ~10%**. But even at this level, dramatic physics improvements will be required

- Lasers can be fired a few times a day (instead of **many times per second** as required by a GW range power plant)

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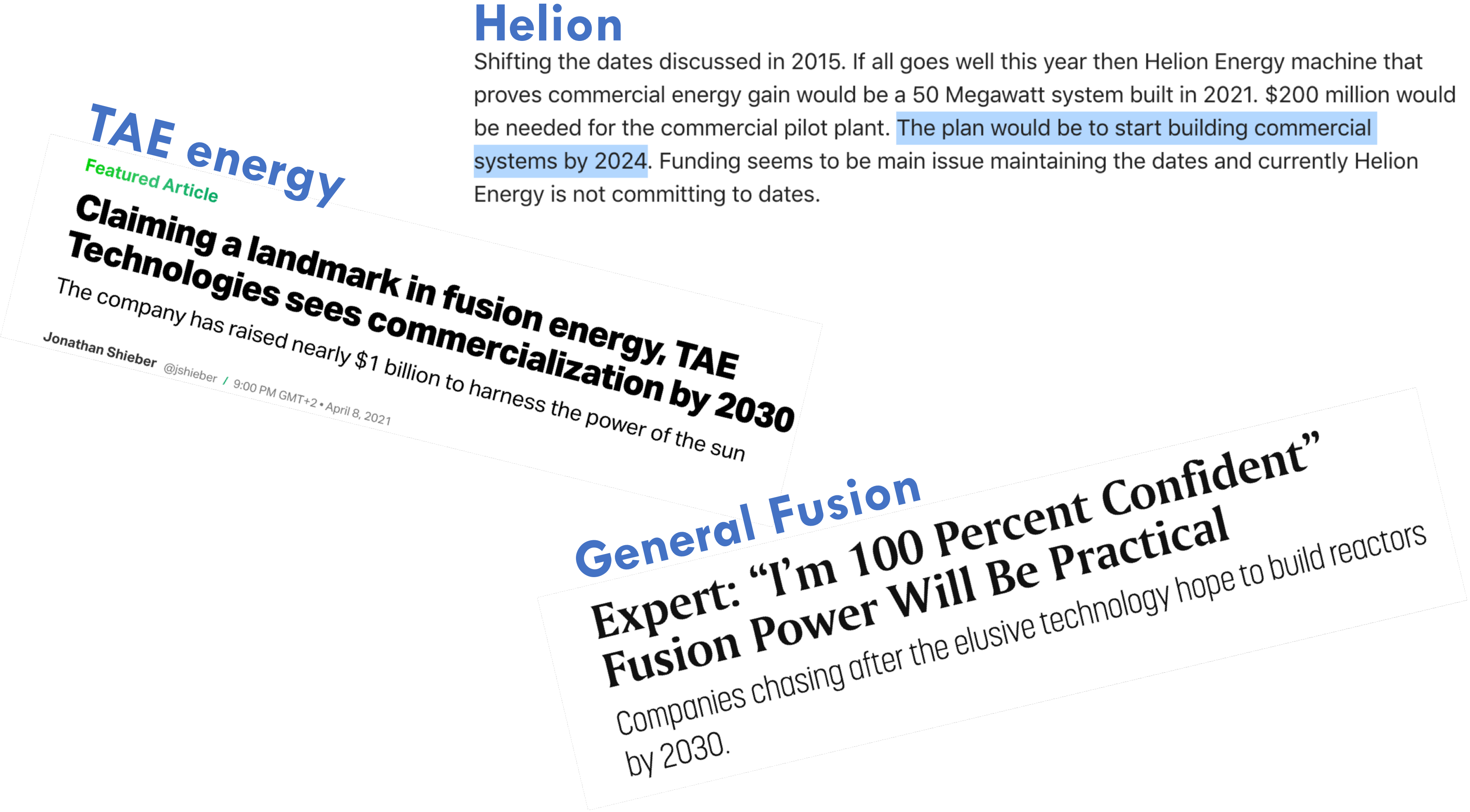
Claims of fusion by 2030



Helion

Shifting the dates discussed in 2015. If all goes well this year then Helion Energy machine that proves commercial energy gain would be a 50 Megawatt system built in 2021. $200 million would be needed for the commercial pilot plant. The plan would be to start building commercial systems by 2024. Funding seems to be main issue maintaining the dates and currently Helion Energy is not committing to dates.

TAE energy

Featured Article

Claiming a landmark in fusion energy, TAE Technologies sees commercialization by 2030

The company has raised nearly $1 billion to harness the power of the sun

Jonathan Shieber @jshieber / 9:00 PM GMT+2 • April 8, 2021

General Fusion

Expert: “I’m 100 Percent Confident” Fusion Power Will Be Practical

Companies chasing after the elusive technology hope to build reactors by 2030.

List of fusion startups and their claims here: http://julien.hillairet.free.fr/wiki/doku.php?id=list_of_fusion_startups

Motivation

[Lindemuth & Siemon, American Journal of Physics, 2009]

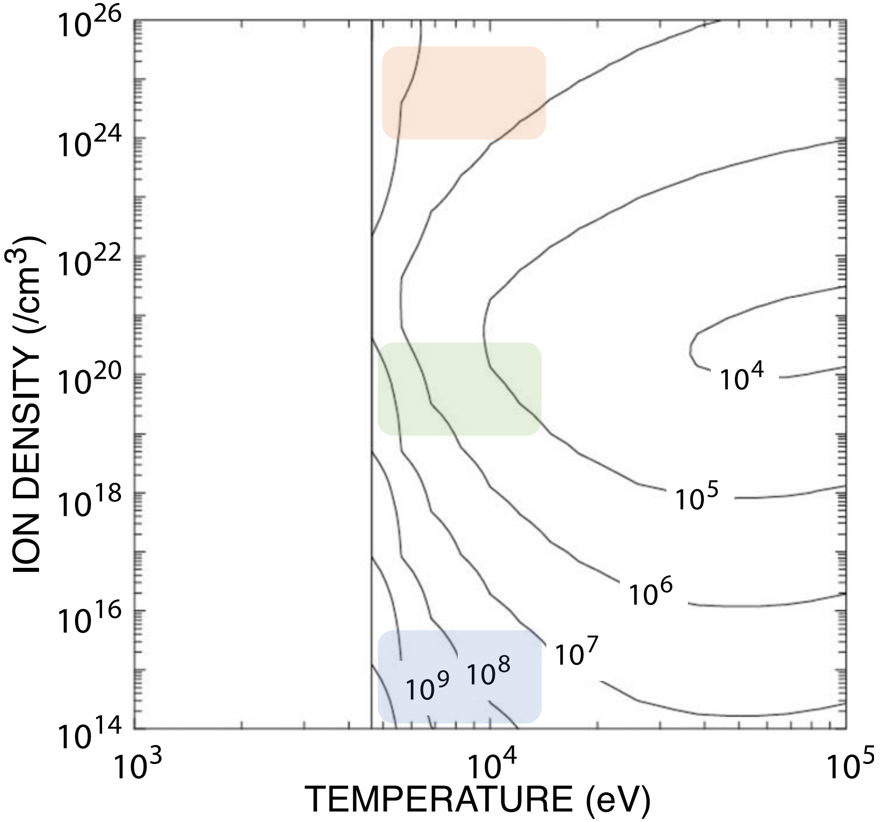


Fig. 6. The minimum facility cost (US \$) for magnetized fuel (classical thermal conductivity, toroidal geometry, $\beta=1$) operating at $\phi \leq 0.2$.

- ☐ There may be a low cost path to fusion, at an intermediate density between magnetic confinement and inertial confinement

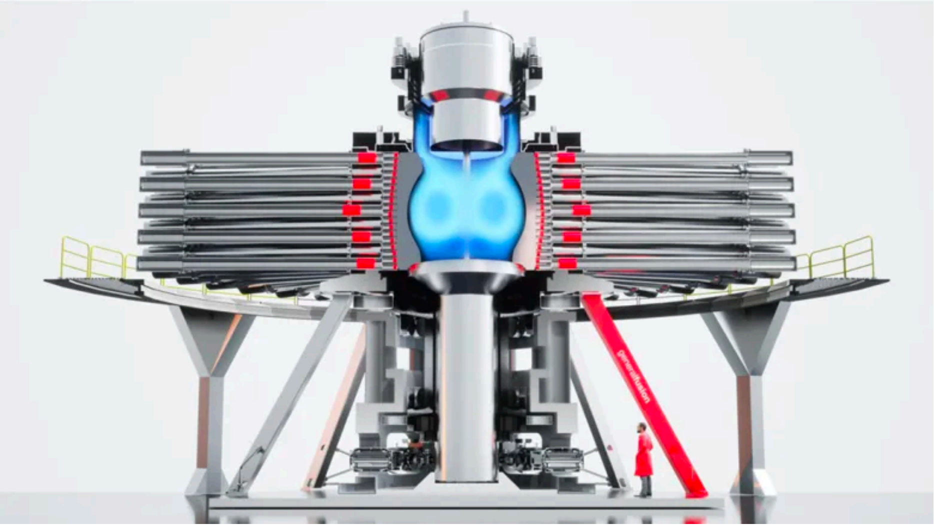
Inertial confinement

Magneto-inertial confinement

Magnetic confinement

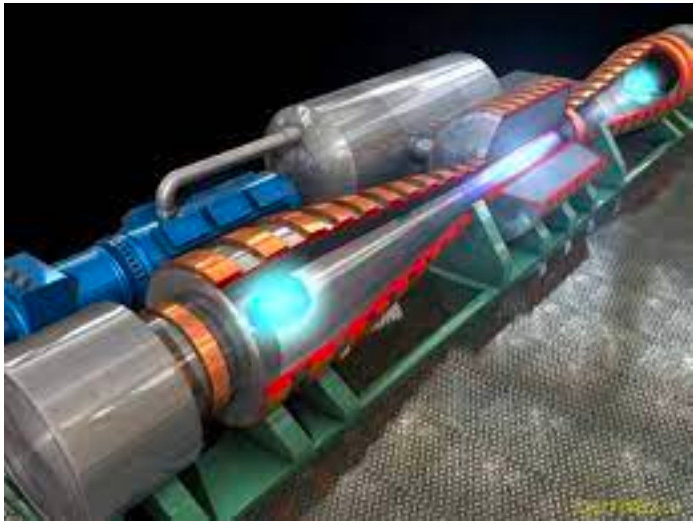
Toroidal magnetic confinement inspired ideas

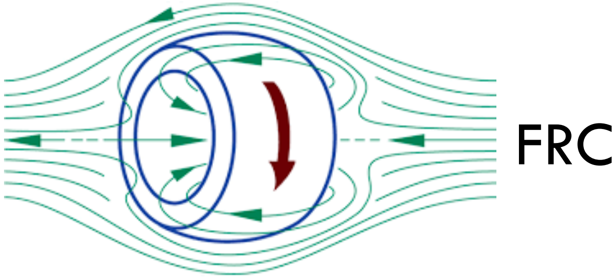
General fusion



- A tokamak plasma encased in a spinning liquid metal (Li-Pb) is compressed when pistons push the metal inwards **[Laberge JFE 2019], [Brennan NF 2020], [Brennan NF 2021]**

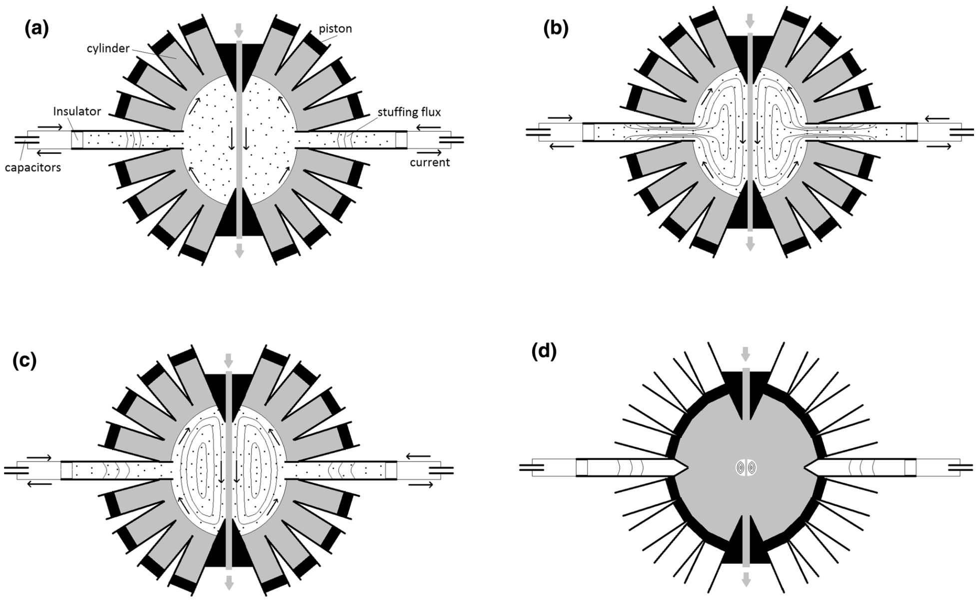
Helion





- Field reversed configurations (FRCs) are ‘smoke rings’ of plasma, confined by self-generated magnetic field **[Slough et al NF 2011]**

Issues for the General Fusion concept



☐ A pulsed current is injected in the central liquid metal shaft to generate the toroidal field **[Laberge, Journal of Fusion Energy 2018]**

☐ One obtains a spherical tokamak plasma, mechanically compressed by the displacement of liquid metal flux conserver

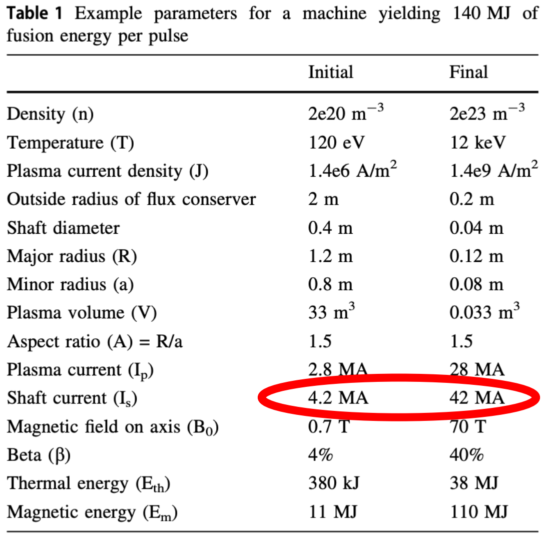


Table 1 Example parameters for a machine yielding 140 MJ of fusion energy per pulse

	Initial	Final
Density (n)	2e20 m^{-3}	2e23 m^{-3}
Temperature (T)	120 eV	12 keV
Plasma current density (J)	1.4e6 A/m^2	1.4e9 A/m^2
Outside radius of flux conserver	2 m	0.2 m
Shaft diameter	0.4 m	0.04 m
Major radius (R)	1.2 m	0.12 m
Minor radius (a)	0.8 m	0.08 m
Plasma volume (V)	33 m^3	0.033 m^3
Aspect ratio (A) = R/a	1.5	1.5
Plasma current (I_p)	2.8 MA	28 MA
Shaft current (I_s)	4.2 MA	42 MA
Magnetic field on axis (B_0)	0.7 T	70 T
Beta (β)	4%	40%
Thermal energy (E_{th})	380 kJ	38 MJ
Magnetic energy (E_m)	11 MJ	110 MJ

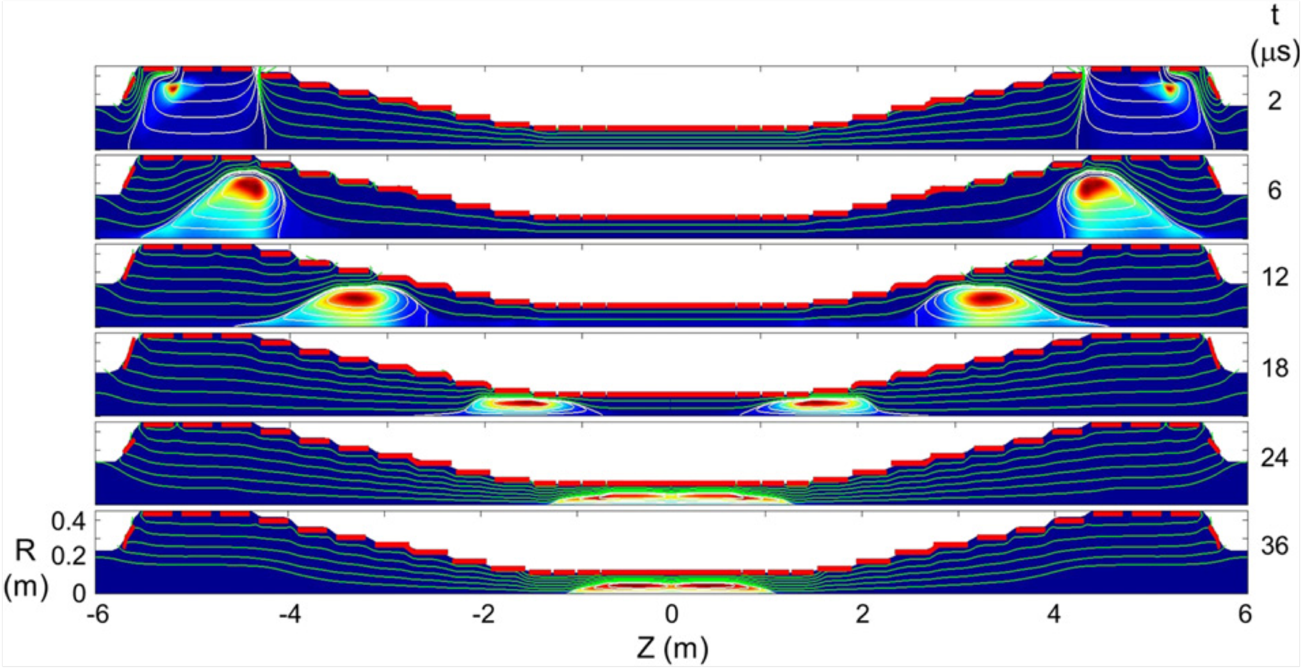
☐ The scaling of fusion power with compression is much less favorable than foreseen, even in the most ideal situation **[Nicolas PPCF 2022]**

☐ Stability of the plasma along the compression **[Brennan NF 2021]**

☐ Compression time is still too slow compared to confinement time

☐ Large current in the shaft will certainly lead to very fast MHD instabilities and disruption of the shaft (including pollution of the plasma)

Issues for the Helion concept

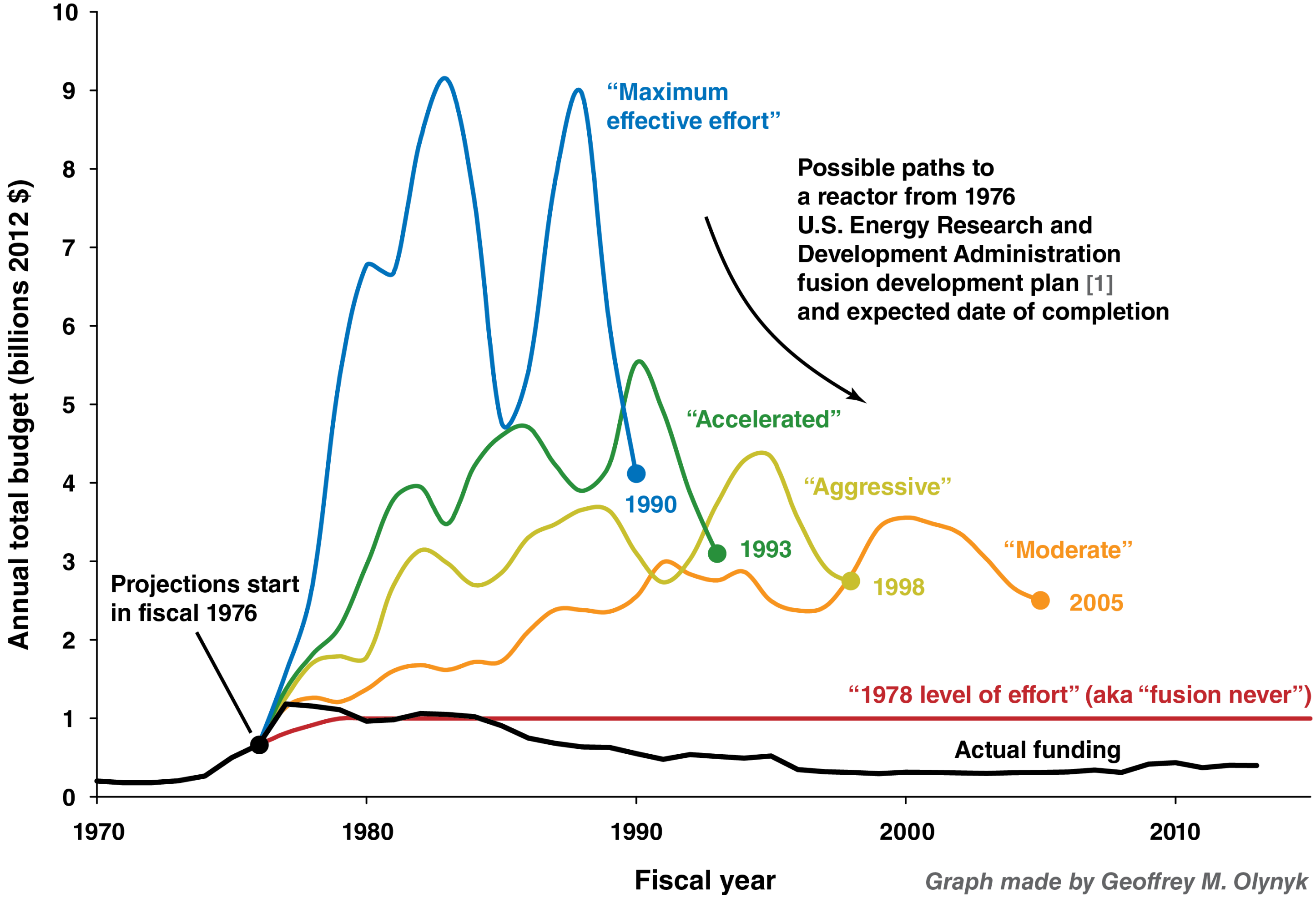


- ☐ Confinement time is low (< 1ms) so need to create, move and compress the plasma rapidly
- ☐ Plasma stability constrains the parameter space and the shape (elongation) of the plasma
- ☐ D-^{3}He reactivity is lower than D-T, so a larger temperature is required
- ☐ Neutron emission rate in a reactor would be high in case of stoechiometric fuel (D = ^{3}He). Non stoechiometric fuel should be used to reduce neutrons, but this further lowers the reaction rate

Conclusion

- ❑ Plasma physics conspiration:
  - ➢ Plasma configurations relevant for fusion are usually far from equilibrium, along many degrees of freedom (thermal, magnetic, kinetic)
  - ➢ The system seems to always find clever ways to relax the system on a time scale faster than that relevant to fusion
- ❑ A lot has been achieved, a lot of approaches are being pursued
- ❑ The challenge remains immense.
- ❑ Contrary to popular belief, fusion is grossly underfunded

Conclusion

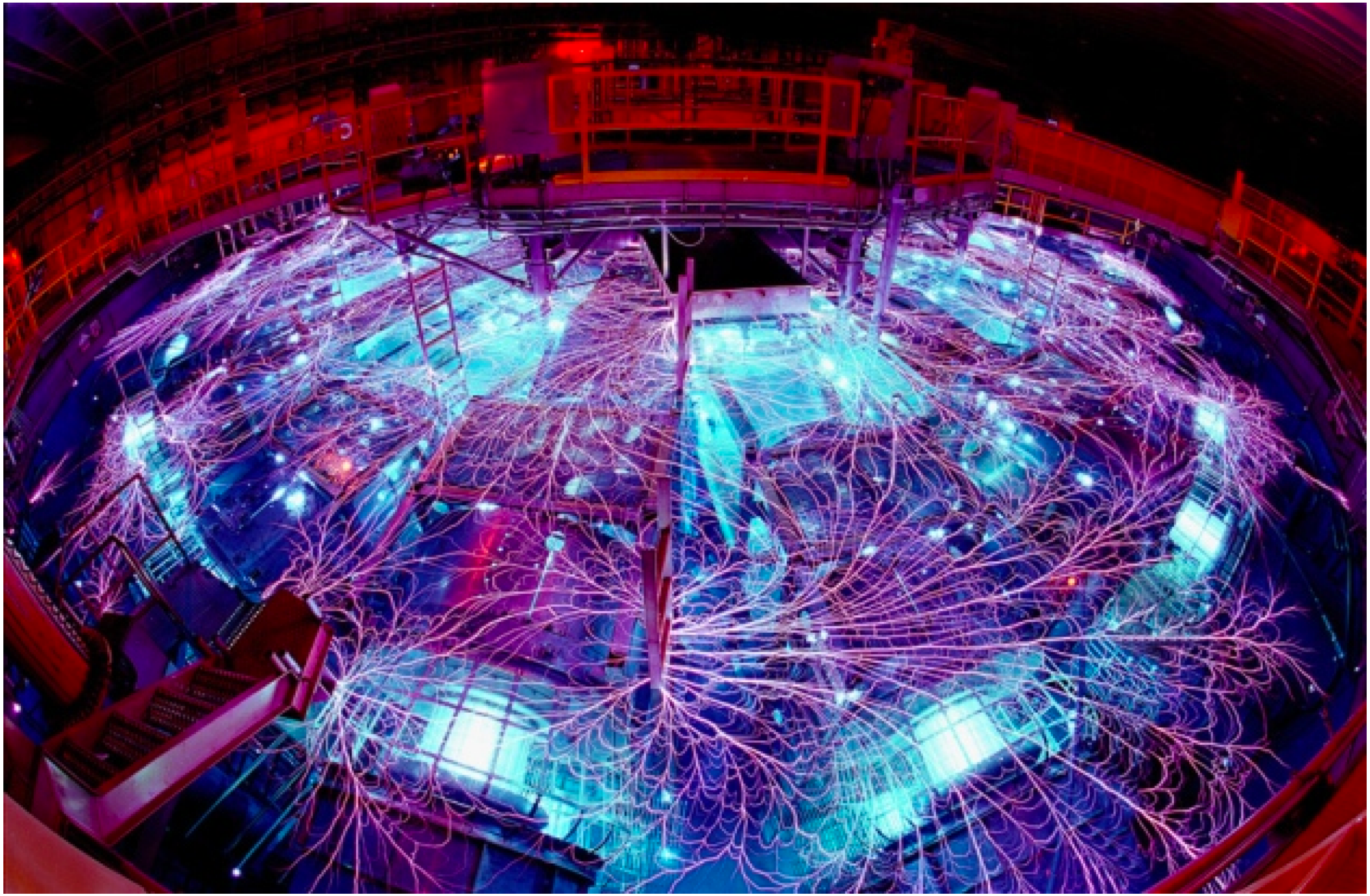


Possible paths to a reactor from 1976 U.S. Energy Research and Development Administration fusion development plan [1] and expected date of completion

Graph made by Geoffrey M. Olynyk

[1] U.S. Energy Research and Development Administration, 1976. “Fusion power by magnetic confinement: Program plan” ERDA report ERDA-76/110. Also published as S.O. Dean (1998), *J. Fus. Energy* **17**(4), 263–287, doi:10.1023/A:1021815909065

Z-pinch inspired ideas

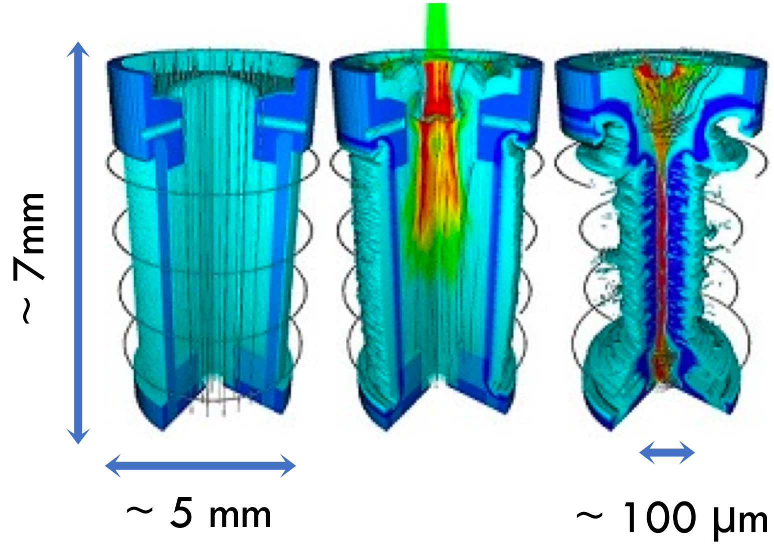


Z-pinch inspired ideas

- Measurement of T $>10^9$ K
  - Standard Z-pinch **[Haines et al., PRL 2006]**
  - Dense plasma focus **[Lerner et al., Physics of Plasmas 2012]**

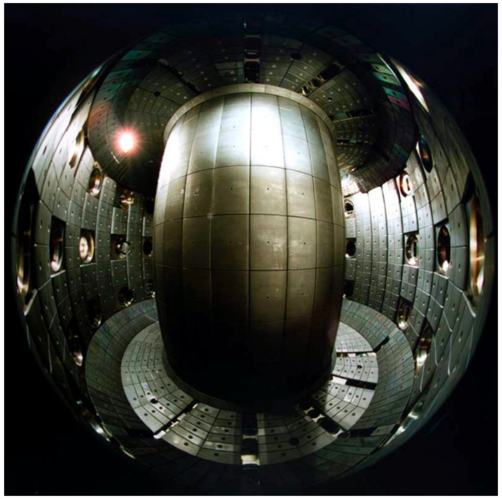
- Density is far from enough for ignition

- Attempts with Magnetized Liner Inertial Fusion (MagLIF), where the target plasma is laser-preheated and compressed by a liner

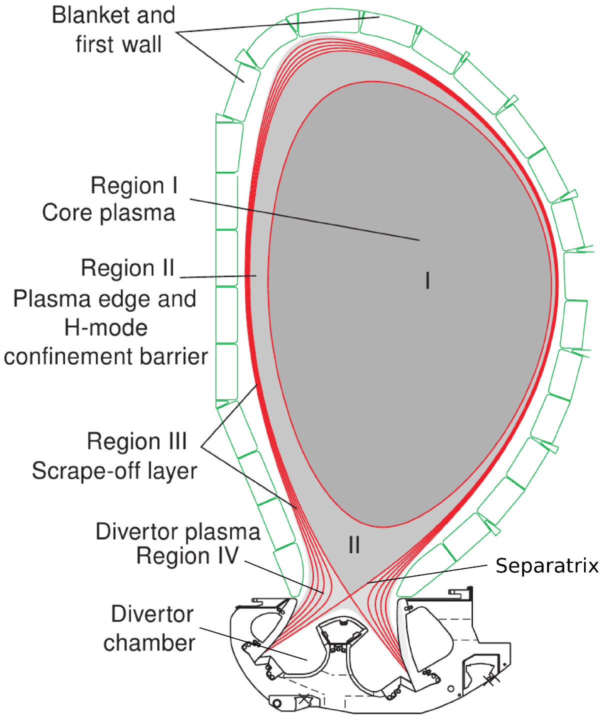


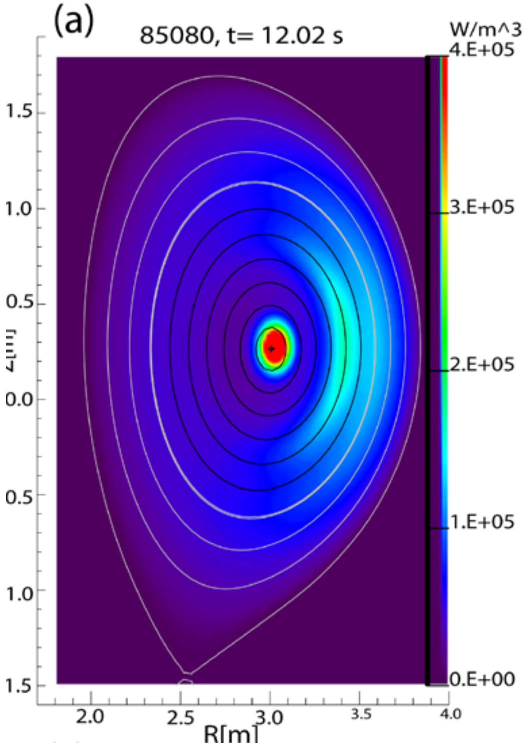
[Slutz *et al.*, Physics of Plasmas, 2016]

Carbon, Tungsten, Tritium and neoclassical transport

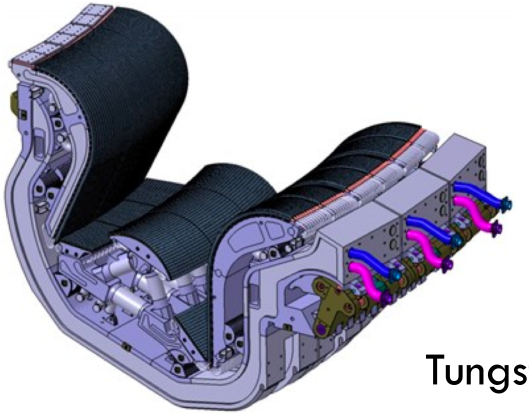


Graphite tiles in the TCV tokamak (EPFL)



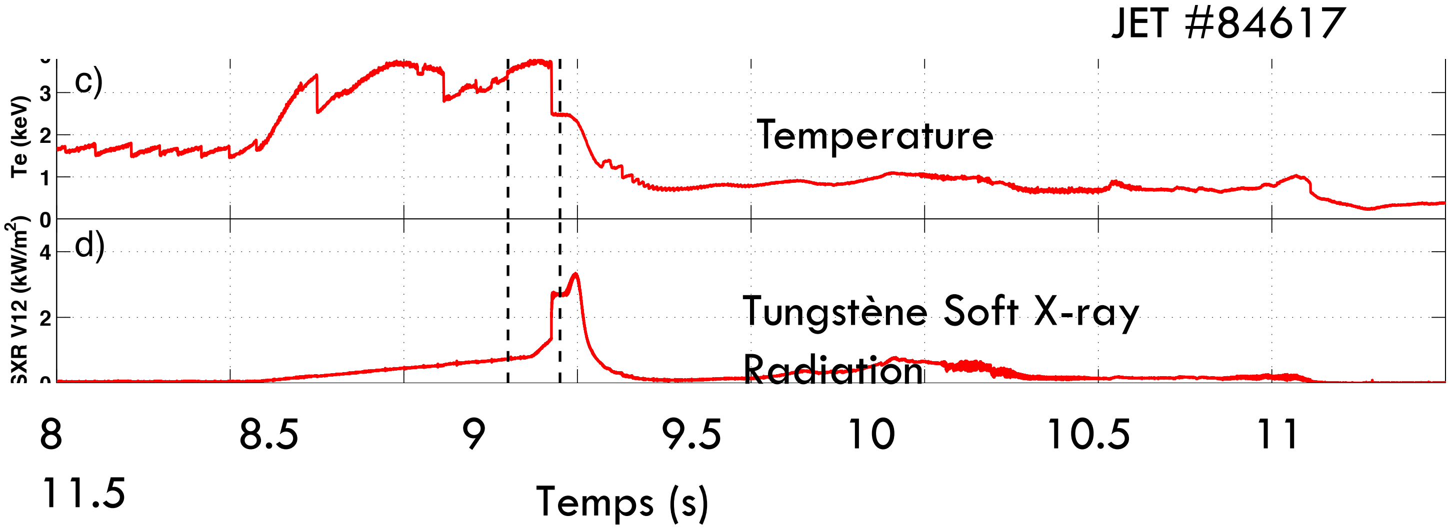


[Graves PPCF 2015]



Tungsten Divertor $_{74}$W

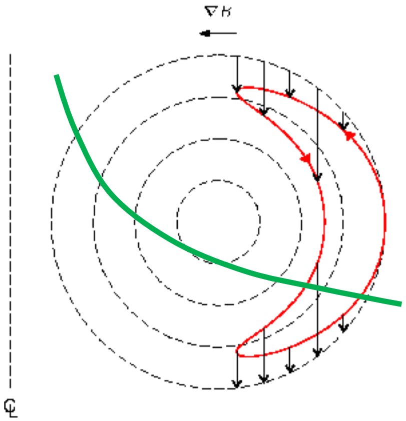
Carbon, Tungsten, Tritium and neoclassical transport

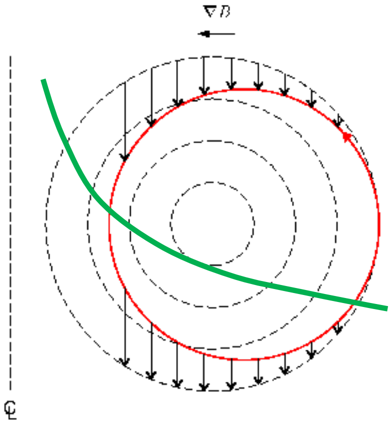


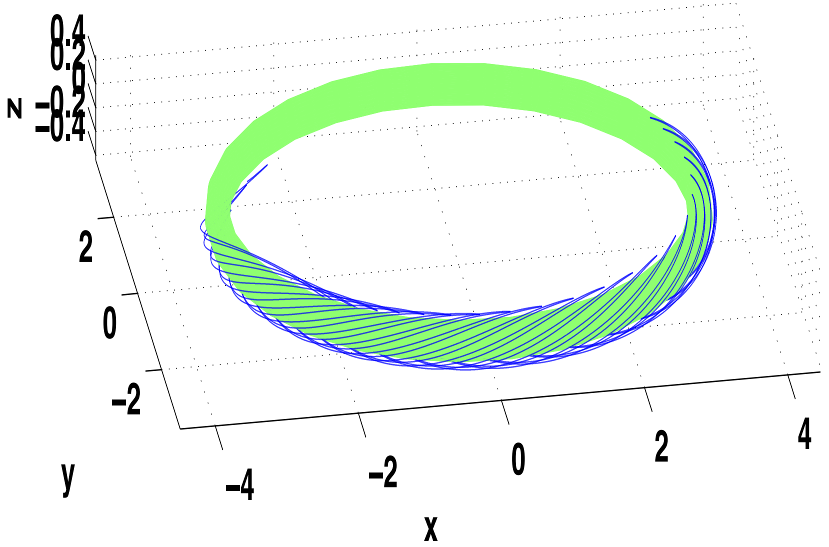
- Tungsten radiation can lead to a disruption (non controlled discharge termination)

Carbon, Tungsten, Tritium and neoclassical transport

- Magnetic field is larger in the inboard side $|B| \sim \dfrac{B_0 R_0}{R}$
- Particles feel, along the field lines, a force $-\mu \nabla_{\|} B$

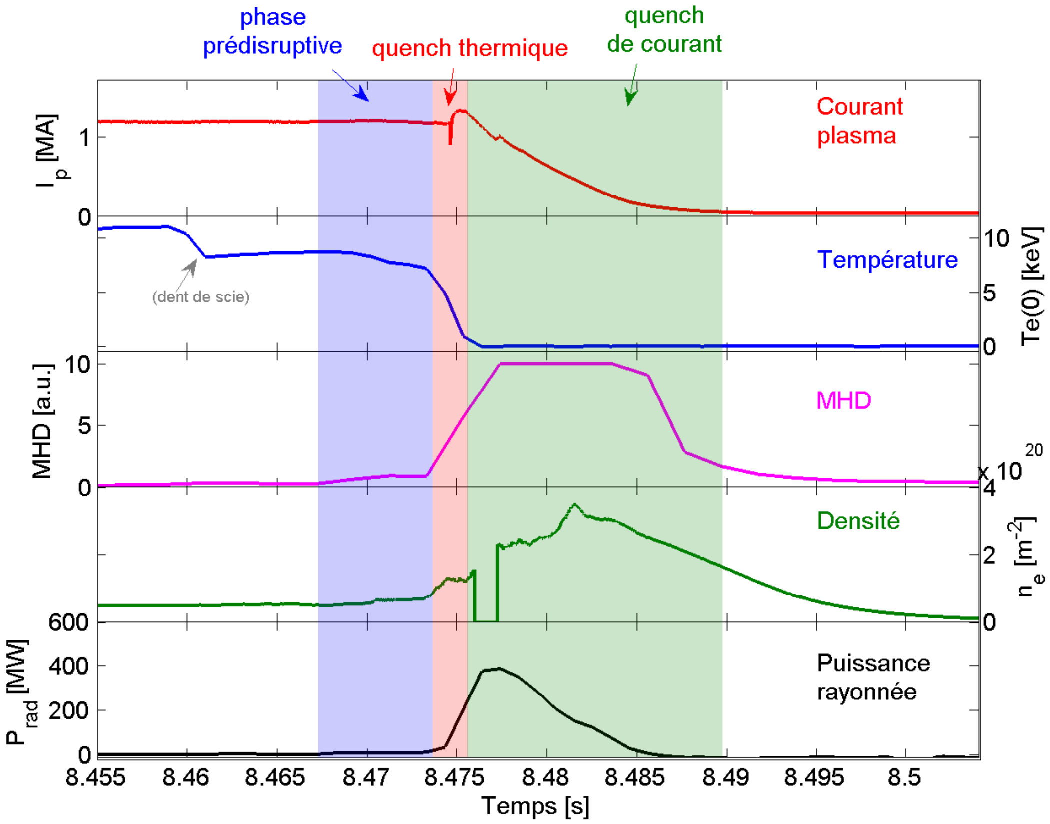






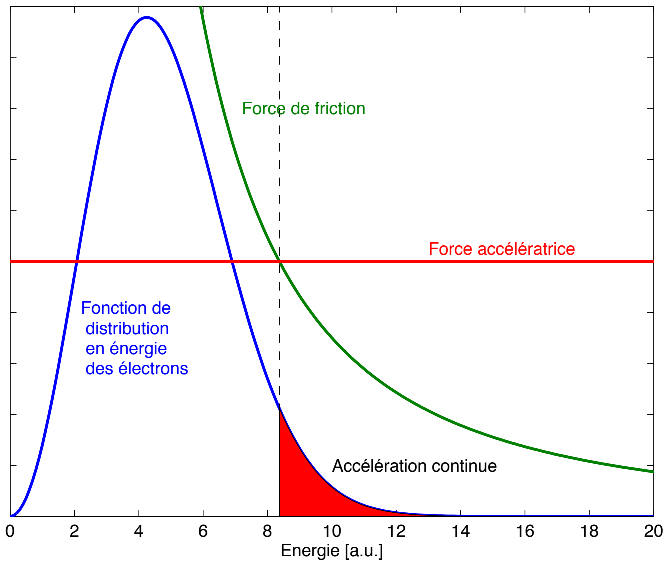
- Discontinuity in the distribution function, $f\left(\boldsymbol{r}, v_{\|}, v_{\perp}\right)$ regularized by collisions ➠ Radial transport

The disruption



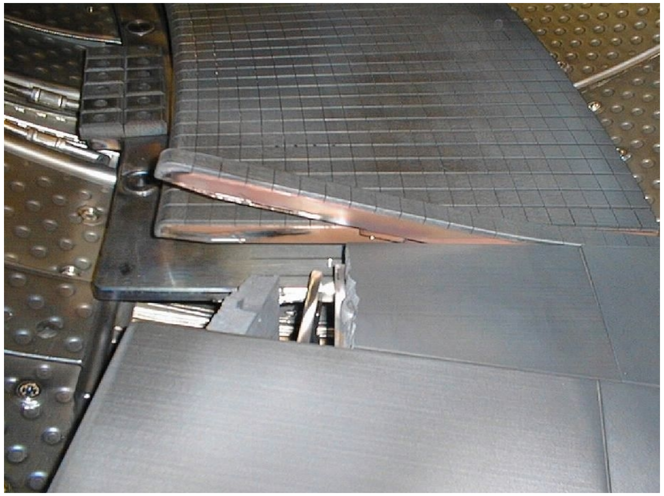
Source : thèse C. Reux

- ❑ Electric field increase above the « Dreicer field »
- ❑ Generation of relativistic Runaway Electrons

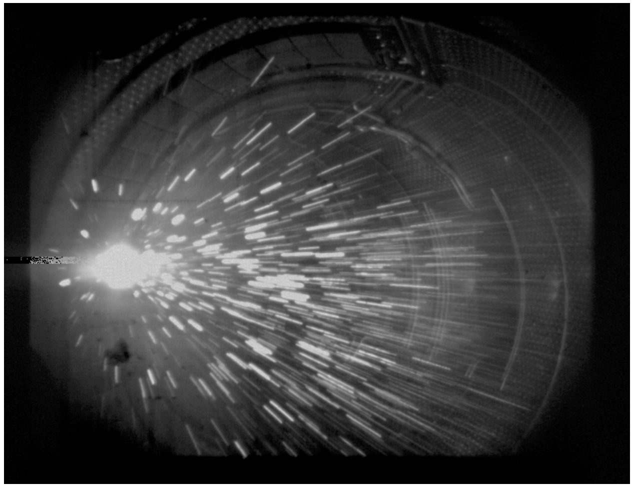


Disruption damage

Disruptions are not to be taken lightly

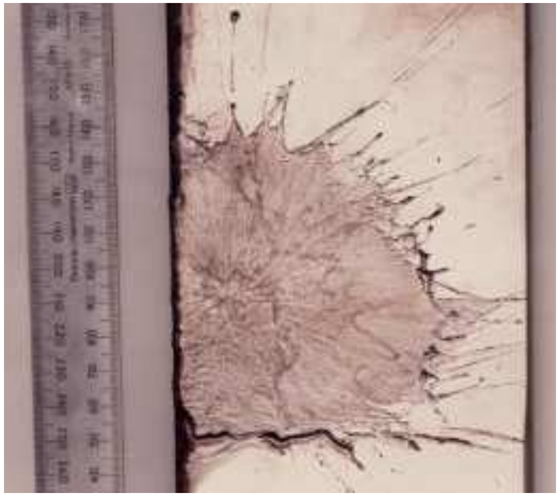


Laplace forces bending plasma facing components (Tore Supra)



Runaway electrons impact (Tore Supra)

https://www.youtube.com/watch?v=Q87QNDeqGHQ

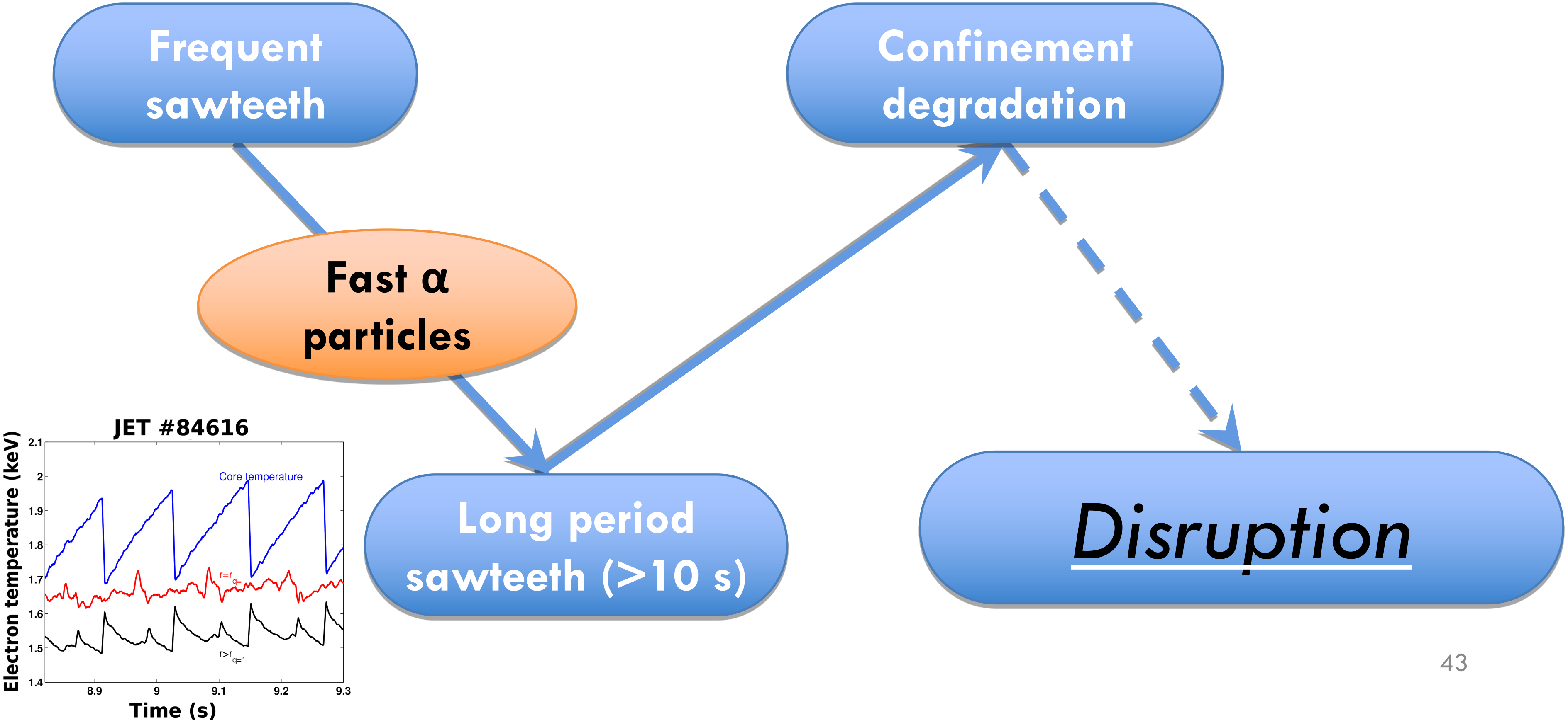


Limiter melting by Runaway electrons (JET)

Source : thèse C. Reux

Link between disruptions and other instabilities

Unavoidable sawteeth will be a concern in ITER



Frequent sawteeth

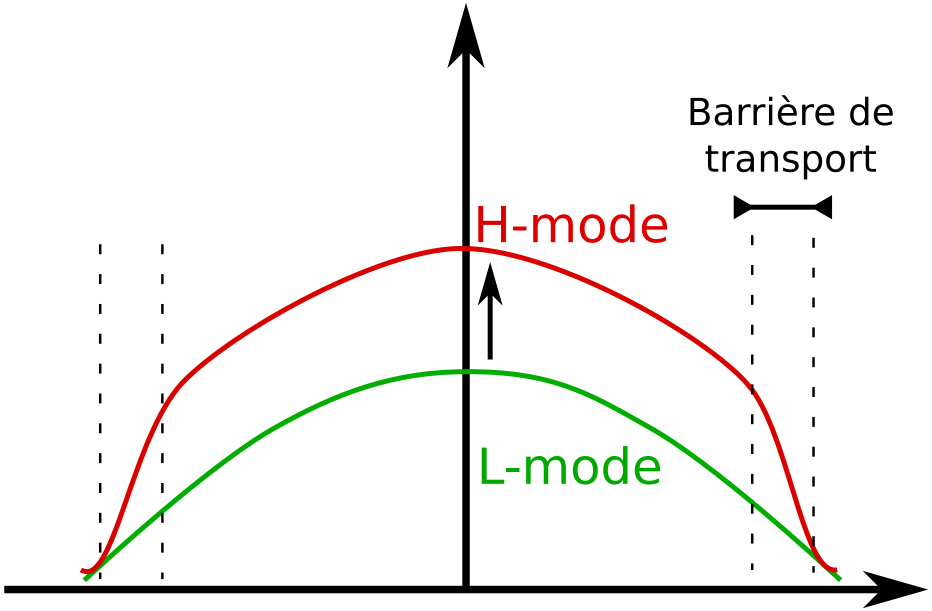
Fast α particles

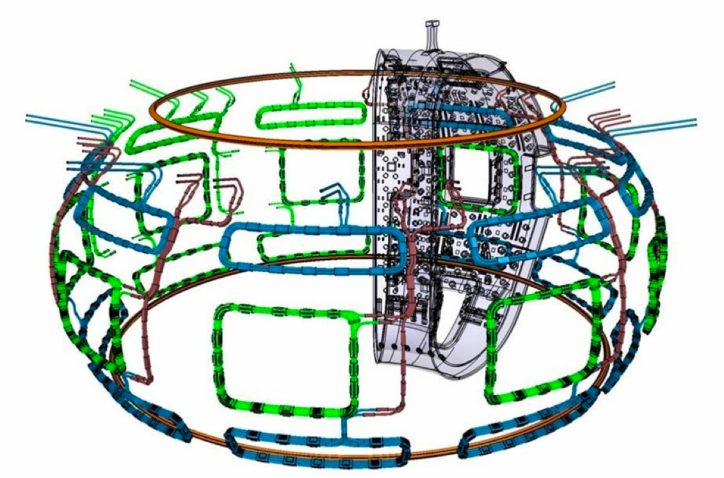
Long period sawteeth (>10 s)

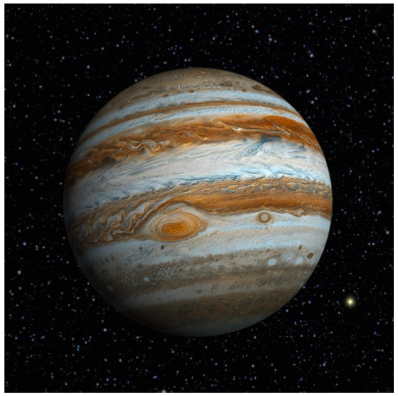
Confinement degradation

Disruption

Mode H and ELMs



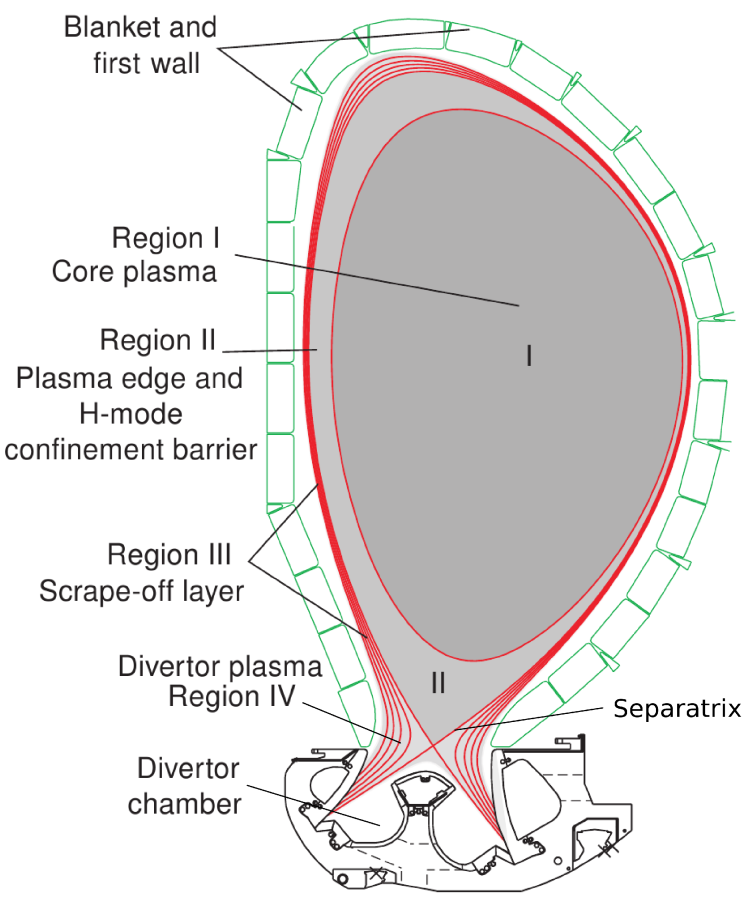


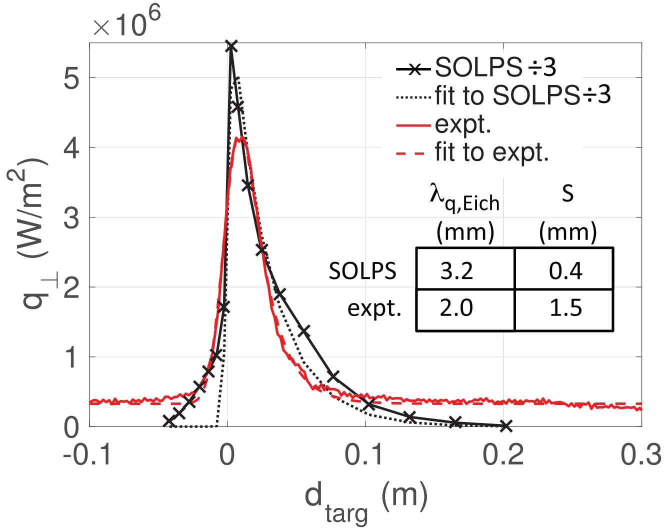


Reynolds and Maxwell stress generated zonal flows

$$\frac{\partial \langle V_\theta \rangle}{\partial t} = -\langle (\mathbf{V} \cdot \nabla \mathbf{V})_\theta \rangle = -\partial_r \langle \tilde{V}_r \tilde{V}_\theta \rangle$$

Power exhaust





	$\lambda_{q,Eich}$ (mm)	S (mm)
SOLPS	3.2	0.4
expt.	2.0	1.5

$$\frac{100MW}{2\cdot 2\pi\lambda_q R_0} \sim 1\mathrm{GW.m}^{-2}$$

☐ Maximum heat flux scales as $1/\lambda_q$

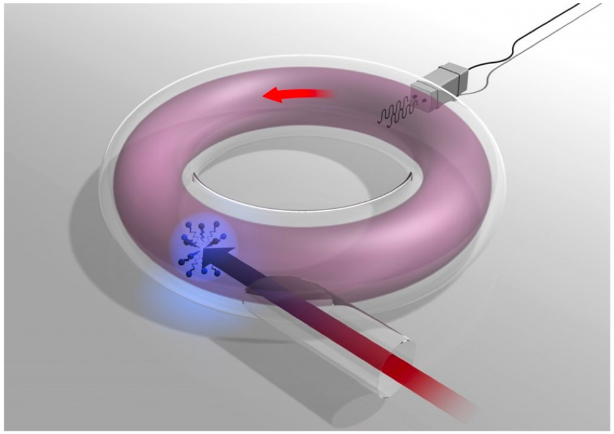
☐ ITER prediction of λ_q : 1 mm !!

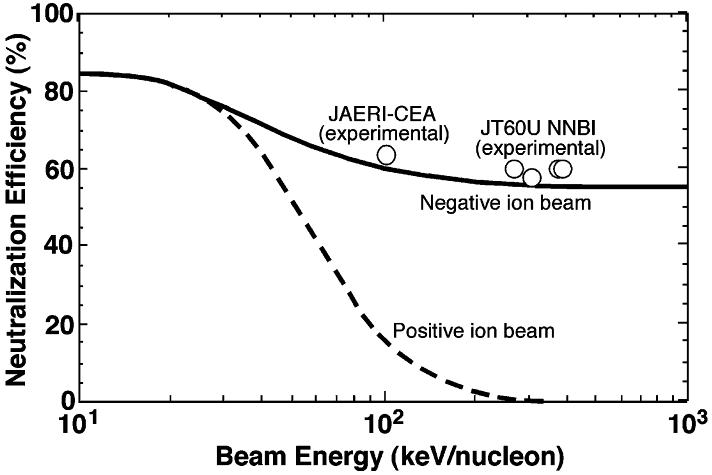
☐ Detachment using impurity radiation must be used

☐ ELM mitigation coils can lead to reattachment of the plasma

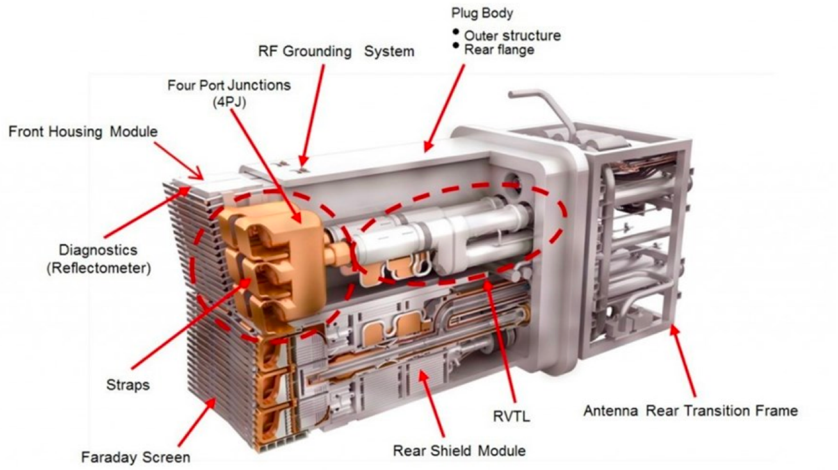
Heating

- Neutral beam injectors





- Ion Cyclotron wave heating



- At the ion cyclotron resonant frequency, there is a cutoff for the main ions. One must cheat by heating a minority ion (H)
- Today, even three-species schemes are designed to reach energies in the range of MeV