Nuclear Fusion and Plasma Physics

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Lecture 2 - 03 October 2022

The two approaches to fusion energy: Basic concepts and status of research

(Chen, Chapter 9)

- Inertial
- Magnetic

A simple approach to the design of a fusion reactor

(Freidberg, Chapter 5)

- The fusion reactor concept
- General layout of a magnetic fusion reactor
- Designs goals and parameters
- Engineering constraints
- Nuclear physics constraints
- Integration of the goals and constraints
  - blanket and shield
  - cost and magnet
  - power density and plasma pressure
  - plasma beta and confinement time

Summary

Last time we have seen that, in order to produce fusion energy at a faster rate than is lost from the plasma, we need

$n\tau_E \geq 10^{20}\,\mathrm{m}^{-3}\,\mathrm{s}$ and $T \geq 10$ keV, or written differently:

$$\boxed{n\tau_E T \geq 10^{21}\mathrm{m}^{-3}\,\mathrm{s\ keV} \qquad \text{Lawson criterion for break-even}}$$

This was the very first estimate telling us in which range of parameters we should be. It is of course incomplete, as one needs to consider:

- that the power that is useful to sustain the plasma is only that carried by the α's (the neutrons are 'lost' from the plasma)
- that engineering systems cannot be 100% efficient

We then defined a

- physics fusion gain factor $Q = \frac{P_{\text{tot out}}}{P_{\text{in}}} = \frac{P_{fusion}}{P_{in}} \begin{array}{l} \nearrow \ \infty \ \ \text{ignition} \\ \searrow \ 1 \ \ \text{break} - \text{even} \end{array}$

and an

- engineering gain factor $Q_E = \frac{\text{net electric power out}}{\text{net electric power in}}$

  $Q_E = \eta Q - (1 - \eta)$
  where $\eta = \eta_e \times \eta_t$ is the product of the efficiency with which we use electricity to heat the plasma, η_e, and the total efficiency for converting fusion power into electricity, η_t.

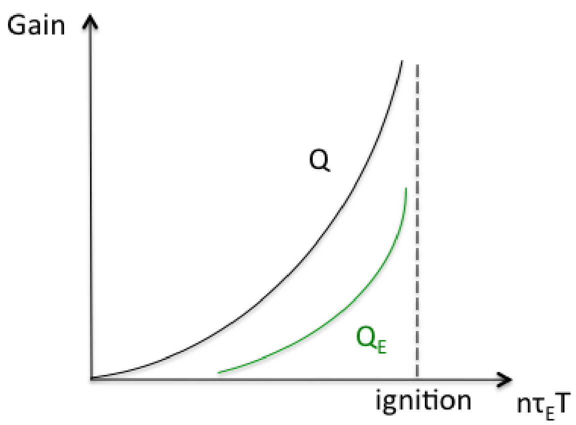

Figure 1: Engineering and physics fusion gain factors.

The first fusion reactors will operate between break-even and ignition, with Q > 10.

We have seen that we need a **plasma** because large energies are needed to start nuclear fusion reactions ($\gtrsim$ keV), energies at which ordinary matter cannot exist.

Two approaches to fusion energy: Basic concepts and status of research

Two approaches, in addition to gravity (stars):

1) Inertial confinement $n \sim 10^{31}\,\mathrm{m}^{-3}$; $\tau_E \simeq 10^{-11}\,\mathrm{s}$
2) Magnetic confinement $n \sim 10^{20}\,\mathrm{m}^{-3}$; $\tau_E \sim 1\,\mathrm{s}$

1. Inertial confinement (also see viewgraphs)

   Little pellets containing D-T compressed ($10^{31}\,\mathrm{m}^{-3} \equiv 1000$ times denser than ice!) and heated (~ 10 keV) **before** particles can escape ('inertia' effect).

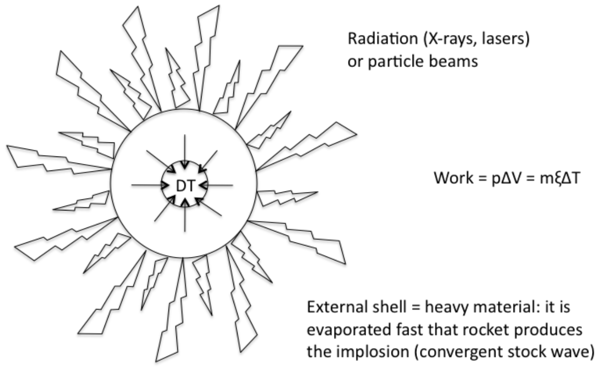

Figure 2: Pellet containing D-T for inertial fusion.

Physics problems:

- avoid heating the core before the shock wave arrives and compresses it $\rightarrow$ pellet design: internal 'screen'
- hydrodynamic instability $\rightarrow$ pellet symmetry
  $\rightarrow$ alignment of beams
  $\rightarrow$ indirect drive

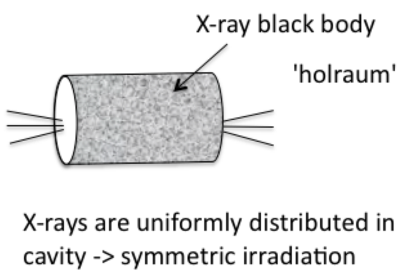

Figure 3: External shell to get a uniformly distributed radiation.

- beams cannot penetrate into the pellet
  - no electrons, no light ions
  - photons (lasers): problem of small efficiency
  - heavy ions: problem of small currents in beams

2. Magnetic confinement

   $n \sim 10^{20}\,\mathrm{m}^{-3}, \tau_E \sim 1\,\mathrm{s}$

   Achieved by using the fact that charged particles tend to gyrate around magnetic field lines. Plasma must not touch any material surface directly.

   A closed field line configuration is needed, as particles tend to move freely **along** magnetic field lines. (We will analyse particle motion in given B-fields in the next lecture.)

   Note: the diamagnetic character of the plasma, determined by the particle motion around field lines, sets an ultimate limit for the plasma confinement.

   $\mathrm{B}_{\mathrm{plasma}} < \mathrm{B}_{\mathrm{external}} \rightarrow$ Limit can be expressed (as we will see next lecture) in terms of

$$\boxed{\beta \equiv \frac{\text{plasma pressure}}{\text{magnetic field pressure}} = \frac{nT}{B^2/2\mu_o}}$$

   If $\beta \rightarrow 1$ the plasma reduces the field too much and the confinement becomes impossible.

   β is a measure of how efficient is a confinement system.

   $\rightarrow$ p = nT (plasma pressure) is what produces fusion power
   $\rightarrow B^2/2\mu_o$ is our 'investment' to confine the plasma
   Note that in present devices β is limited by plasma instabilities to $\beta << 1$.

1 A simple approach to the design of a (magnetic) fusion reactor (Freidberg, Ch. 5)

For **ignition** we have seen that we need $\begin{cases} n\tau_E T & \gtrsim & 8 \text{ atm s, or } 5 \times 10^{21}\ \mathrm{m}^{-3}\ \mathrm{keV\ s} \\ T & \simeq & 15\,\mathrm{keV} \end{cases}$

Although we don't necessarily need to achieve ignition, we need to approach these values (for a 'decent' fusion gain Q that is of interest for a reactor).

The **question** is what is the best combination of p, τ_E, T? We know roughly that it is reasonable to have $n \sim 10^{20}\,\mathrm{m}^{-3}$, $\tau_E \sim 1\,\mathrm{s}$, but can we be more precise?

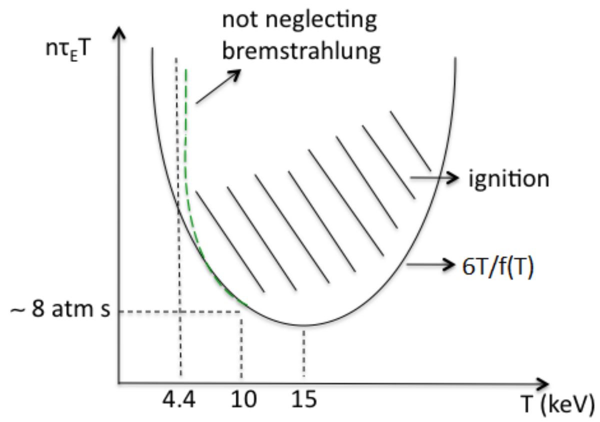

Figure 4: $n\tau_E T$ parameter and ignition curve.

What **size** and what B-field should we use? (These are crucial parameters for economical feasibility)

In general, we can try this optimisation even before we know what a plasma is.

1.1 Concept of magnetic fusion reactor: simplified geometry (toroidal shape with circular cross-section)

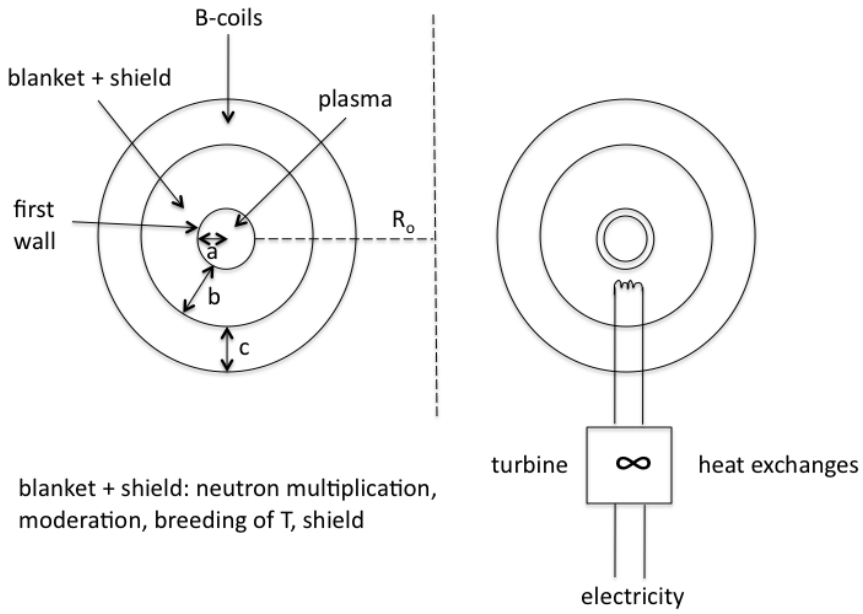

Figure 5: Simplified structure of a toroidal magnetic fusion reactor.

What **parameters** describe the reactor?

- Geometry (a, R_o, b, c)
- Plasma
  - confinement time τ_E
  - n
  - T
  - p = nT (strictly speaking, $p_j = n_j T_j$ for each species j = 1, 2, . . .
  - $\beta = \frac{nT}{B^2/2\mu_0}$ (efficiency, also related to diamagnetism)
- Fusion power density p_f
- Magnetic field B

1.2 Design goals

- Minimize cost of reactor, to minimize the cost of electricity, as in fusion the cost of fuel should be negligible.
- Minimize requirements on τ_E and β to make it less tough for plasma physics.

1.3 Engineering constraints

- $P_E \sim 1$ GW
- Wall loading: $L_W \leq$ a few MW/m^2 (to avoid damaging the wall)
  - Plasma losses (thermal conduction and radiation; the effect of these can be alleviated by a smart choice of geometry, materials, etc.)
  - Neutrons (isotropic, more severe constraint)

  As a limit value we can assume $L_W^{max} = 4$ MW/m^2 (Freidberg)
- Magnets: constraint on a combination of current density (J), temperature (T) and magnetic field intensity (B) (must stay below a curve in J, T, B space to remain superconducting)
  Ex: Niobium tin (Nb_3Sn) (ITER): 10-15 T. Take B_{max} = 13 T
- Magnetic field, to limit J × B force, i.e. the stress on support structure.
  Typically, $\sigma_{max} \simeq 300$ MPa.

1.4 Nuclear physics constraints

- $\langle \sigma v \rangle_{DT} \simeq 10^{-22}\,\mathrm{m^3/s}$ at 15 keV
- Blanket + shield:
  - neutron multiplication
  - slowing down of neutrons at 14 MeV to thermal speed to breed T from Li

- T-breeding
- shielding

→ Moderating material together with Li in blanket.
Size of blanket is therefore dictated by mean free path of neutrons for the different processes.

1.5 How to put these constraints together, and what are their consequences?

- Neutron cross-sections → blanket thickness
- Output power + max. wall loading → major radius
- Cost + magnet → magnet/coil thickness and plasma minor radius
- Power balance → τ_E and plasma pressure
- Plasma pressure + B → β

Let's assess these implications in a simplified way one by one.

1.5.1 Blanket and shield

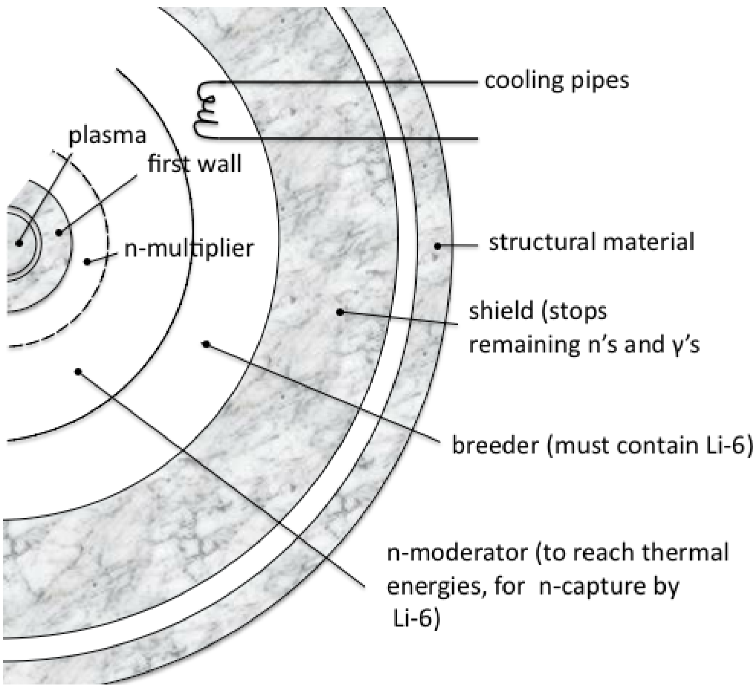

Figure 6: Schematic drawing of a blanket in a fusion reactor.

Note 1: Figure 6 is schematic. In reality, the different layers can, and will be combined.

Note 2: In the breeder, Li^7 also reacts (endothermically) with neutrons, but with a very small cross-section. In fact, even if Li^6 is only ~ 7 %, it may not be necessary to enrich Li with it.

Thickness?

The thickness needed for each process is equivalent to the mean free path for such process, i.e. 1/(target number density × cross section):

- Neutron multiplication, for example for Be:

$$\lambda_{\text{mult}} = \frac{1}{n_{\text{Be}}\sigma_{\text{mult}}} \sim \frac{1}{1.2 \times 10^{29}\text{m}^{-3} \times 0.6 \times 10^{-28}\text{m}^2} \sim 0.13\,\text{m}$$

- Slowing down of fast neutrons:

$$\lambda_{\text{sd}} = \frac{1}{n_{\text{Li}}\sigma_{\text{sd}}} \simeq \frac{1}{4.5 \times 10^{28}\text{m}^{-3} \times 10^{-28}\text{m}^2} \simeq 0.2\,\text{m}$$

- Tritium breeding with slowed down neutrons, for example at $E_n = 2.5 \times 10^{-2}$ eV and Li in its natural composition (7.5% Li^6):

$$\lambda_{\text{br}} = \frac{1}{n_{Li^6}\sigma_{\text{br}}} \sim \frac{1}{0.075 \times 4.5 \times 10^{28}\text{m}^{-3} \times 950 \times 10^{-28}\text{m}^2} \sim 0.3\,\text{cm}$$

- Thickness of shield/breeder to reduce the neutron flux by 100 (i.e. to have 99% of the neutrons that have undergone a breeding reaction, after having slowed down):

$$I = I_0 \exp\left(-\frac{x}{\lambda_{\text{tot}}}\right) \sim I_0 \exp\left(-\frac{x}{\lambda_{\text{sd}}}\right); \qquad \frac{I}{I_0} \sim 0.01 \Rightarrow x_{\text{shield}} \sim \lambda_{\text{sd}} \ln(100) \sim 1\,\text{m}$$

As the different layers are combined, we can consider total thickness of blanket and shield $b \sim \lambda_{\text{mult}} + \lambda_{\text{sd}} + \lambda_{\text{br}} + x_{\text{shield}} \simeq 1.2$ m.

1.5.2 Cost and magnet

1. **Cost**

   Cost of electricity $\simeq$ capital cost

   We assume that the cost is proportional to the volume of 'complex' systems. The quantity to **minimize** is $\frac{\text{cost}}{\text{power}} \sim \frac{\text{volume}}{\text{power}}$ (volume of coils and blanket only, **not** of plasma)

   ⇒ **Minimize:**

$$\frac{\text{volume}}{\text{P}_\text{E}} = \frac{2\pi R_0 \pi[(a+b+c)^2 - a^2]}{\text{P}_\text{E}}; \text{ with}$$

$$\text{P}_E = \frac{1}{4}\eta_t\left(\Delta E_\alpha + \Delta E_n + \Delta E_{Li}\right) n^2 \left\langle \sigma v \right\rangle_{DT} 2\pi R_0 \pi a^2 \qquad (\Delta E_{Li} = 4.8 \text{ MeV})$$

   η_t is the efficiency with which fusion power is transformed into electricity. To get R_0 we use the constraint from the wall, assuming only the isotropic part, the neutrons.

$$\underbrace{L_W^{\max}}_{\text{max wall loading}} \times \text{ surface area of plasma} = \text{P}_n \text{ (total neutron power)}$$

But $P_n = \frac{P_E}{\eta_t}\frac{\Delta E_n}{\Delta E_\alpha+\Delta E_{Li}+\Delta E_n}$. Therefore, $L_W^{\max}\,2\pi a 2\pi R_0 = \frac{P_E}{\eta_t}\frac{\Delta E_n}{\Delta E_\alpha+\Delta E_{Li}+\Delta E_n}$

$$\Longrightarrow \qquad R_0 = \frac{P_E}{\eta_t}\frac{\Delta E_n}{\Delta E_\alpha+\Delta E_{Li}+\Delta E_n}\frac{1}{4\pi^2 a\,L_W^{\max}} \underbrace{\simeq}_{\eta_t\simeq 0.4} 0.04\frac{P_E}{a\,L_W^{\max}}$$

$$\text{So, } \frac{\text{cost}}{\text{power}} \sim \frac{\text{volume}}{P_E} = \frac{2\pi^2}{P_E}[(a+b+c)^2-a^2]\,0.04\frac{P_E}{a\,L_W^{\max}}$$

$$\simeq 0.8\frac{(a+b+c)^2-a^2}{a\,L_W^{\max}} \qquad \text{(quantity to minimize)}$$

b was already determined. What about a and c? We still have **two** free parameters, but we can fix c from considerations on the magnet.

Note: naturally, being able to increase $L_W^{\max}$ would reduce cost ($\rightarrow$ materials studies)

2. **Magnet**

The coil thickness should be minimised, compatibly with the **stress** due to $\vec{J}\times\vec{B}$ force. For tensile stress (see Freidberg):

$$c = \frac{2\xi}{1-\xi}(a+b) \quad \text{with} \quad \xi = \frac{B_c^2}{4\mu_0\sigma_{\max}} \quad (B_c \equiv \text{magnetic field inside the solenoid})$$

We can set $B_c = B_{\max}$, considering that the lower the need for β, the 'easier' it will be for plasma physics.

$$\Rightarrow \begin{cases} B_c = B_{\max} \simeq 13\,\text{T} \\ \sigma_{\max} \simeq 300\,\text{MPa} = 3\times 10^8\,\text{N/m}^2 \end{cases} \quad \Rightarrow \quad \xi \simeq 0.1$$

We have then:

$$c = \frac{2\times 0.1}{1-0.1}(a+b) = \frac{2}{9}(a+b)$$

The quantity to minimize becomes:

$$\frac{\text{volume}}{P_E} = \frac{0.8}{a\,L_W^{\max}}\left\{\left[a+b+\frac{2}{9}(a+b)\right]^2 - a^2\right\} = \frac{0.8}{a\,L_W^{\max}}\left[(a+b)^2\left(\frac{11}{9}\right)^2 - a^2\right] =$$

$$= 0.8\times\left(\frac{11}{9}\right)^2\frac{1}{a\,L_W^{\max}}\left[(a+b)^2-\left(\frac{9}{11}\right)^2 a^2\right] = \frac{1.2}{L_W^{\max}}\left(0.33a+\frac{b^2}{a}+2b\right) = f(a)$$

The minimal value of $\frac{\text{volume}}{P_E}$ can be found minimizing $f(a)$:

$$\frac{df(a)}{da} = 0 \quad \Rightarrow \quad 0.33 - \frac{b^2}{a^2} = 0 \quad \Rightarrow \boxed{a = \frac{b}{\sqrt{0.33}} \simeq 1.74b}$$

$$\boxed{\text{As } b \simeq 1.2\text{m} \quad \Rightarrow \quad \begin{cases} a \simeq 1.74\,b \simeq 2\,\text{m} \\ c \equiv \frac{2}{9}(a+b) = 0.7\,\text{m} \end{cases}}$$

The minimal value of $\frac{\text{volume}}{P_E}$ thus becomes:

$$\text{Min}\left(\frac{\text{volume}}{P_E}\right) \simeq \frac{1.2}{L_W^{\max}}\left(0.33 \times 2 + \frac{1.2^2}{2} + 2 \times 1.2\right) \simeq \frac{4.5}{L_W^{\max}} \underbrace{\simeq}_{L_W^{\max} \simeq 4\text{MW/m}^2} 1\,\text{m}^3/\text{MW}$$

Also:

$$R_0 \simeq \frac{0.04}{a}\frac{P_E}{L_W^{\max}} \simeq \frac{0.04 \times 10^9}{2 \times 4 \times 10^6} \simeq 5\,\text{m} \quad \Rightarrow \quad \begin{cases} \text{Plasma volume}: \ = 2\pi R_0 \pi a^2 \simeq 400\,\text{m}^3 \\ \text{Plasma surface area}: \ = 2\pi R_0 2\pi a \simeq 400\,\text{m}^2 \end{cases}$$

1.5.3 Total power density in the plasma

$$\frac{\text{P}_\alpha + \text{P}_n}{\text{volume}} \simeq 5\ \text{MW/m}^3 \text{ (small compared to fission reactor)} \left(= \frac{\Delta E_\alpha + \Delta E_n}{\Delta E_\alpha + \Delta E_n + \Delta E_{Li}} \times \frac{\text{P}_E}{\eta_t\,\text{volume}}\right)$$

1.5.4 β

Minimum requirement for ignition P $\tau_E \simeq 8$ atm s; remember that to get to the minimum of the ignition curve we need T $\cong$ 15 keV and also $n \cong 10^{20}\text{m}^{-3}$, which gives $\tau_E \approx 1$ s.

$$\beta = \frac{\text{P}}{\text{B}_0^2/2\mu_0}$$

We cannot take $\text{B}_0 \equiv \text{B}_c$, as this B_0 value is the value in the plasma, and B_c is inside the magnet. As B$\propto \frac{1}{R}$ (figure 7), and we know the distances (R_o, a, ...), we can calculate[1] B_0 and β

$$\boxed{B_0 \sim 5\,\text{T}} \qquad \Rightarrow \qquad \boxed{\beta \simeq 8\,\%}$$

This value of β is quite high, but we are not far from it in tokamaks.

This exercise has given to us a very simplistic, yet not too far from reality, estimate of the characteristics of an ideal fusion reactor. So, where is plasma physics?

We must

- create a plasma,
- confine it, with its energy, for a macroscopic time ($\sim$ 1 s),
- heat it to $\sim$ 15 keV
- keep it in a stable equilibrium with $\beta \sim 8$ %,

There are many other aspects of plasma physics that enter into the functioning of a reactor, but at least these provide a general frame, and already a strong motivation to study it.

[1] $B(R) = \frac{\text{const}}{R}$; at $B(R = R_0 - a - b) = \frac{\text{const}}{R_0 - a - b} = B_{\max} \Rightarrow B(R = R_0) = B_{\max}\frac{(R_0 - a - b)}{R_0}$.

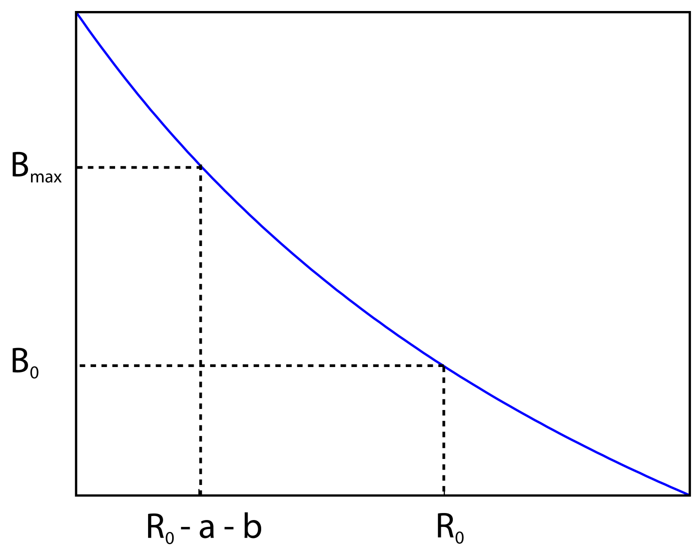

Figure 7: Toroidal magnetic field as a function of R.

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Nuclear Fusion and Plasma Physics

Lecture 2

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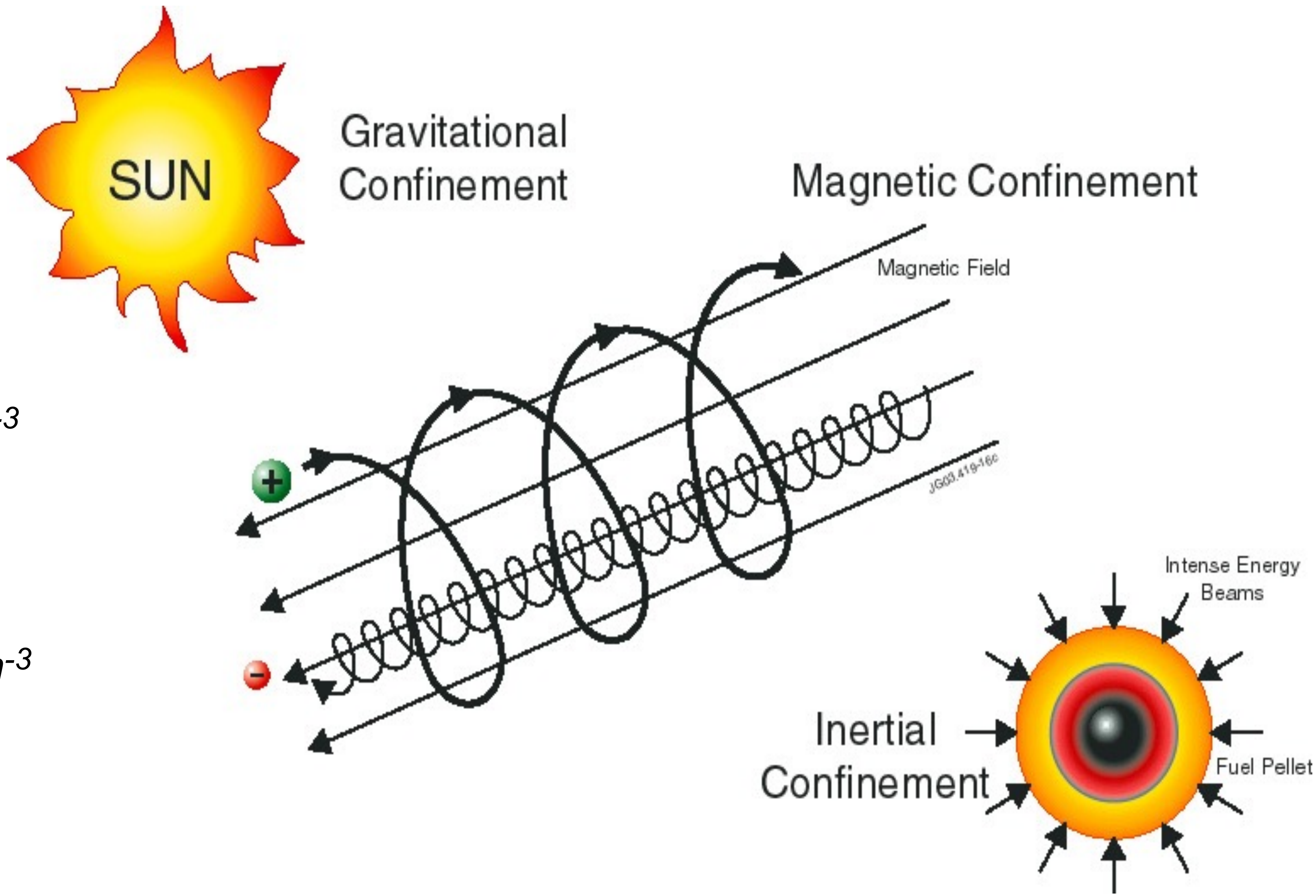
How can a plasma be confined ?

We need $n\tau_E \sim 10^{20}\ m^{-3}\ s$ *and* $T \geq 10keV$



Magnetic

$n \sim 10^{20}\ m^{-3}$

$\tau_E \sim 1\ s$

Inertial

$n \sim 10^{31}\ m^{-3}$

$\tau_E \sim 10^{-11}\ s$

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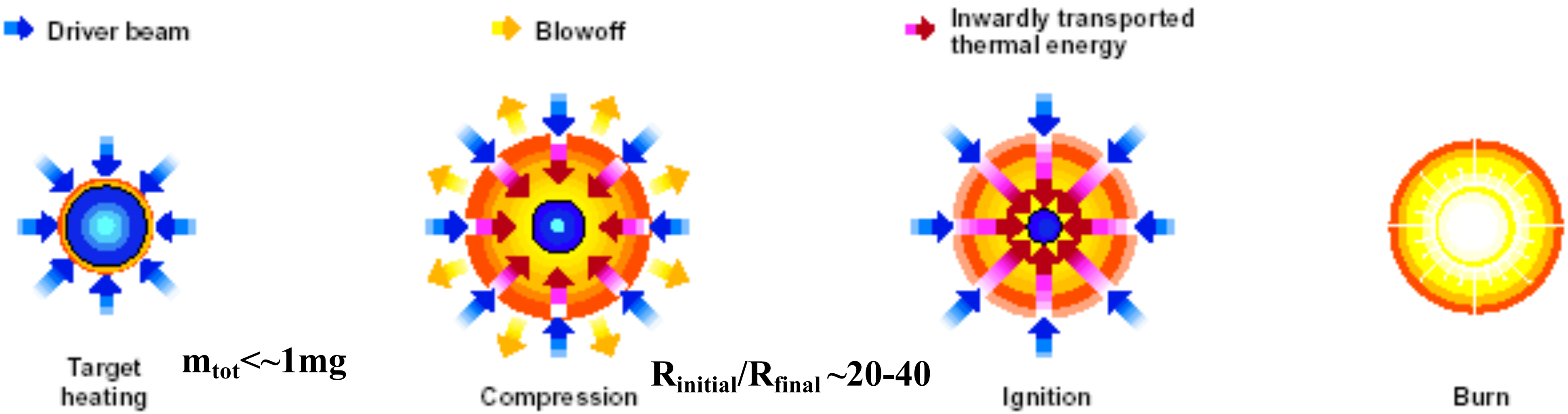
Inertial Confinement Fusion - the basics

A D-T capsule is irradiated by lasers, X-rays, or particle beams



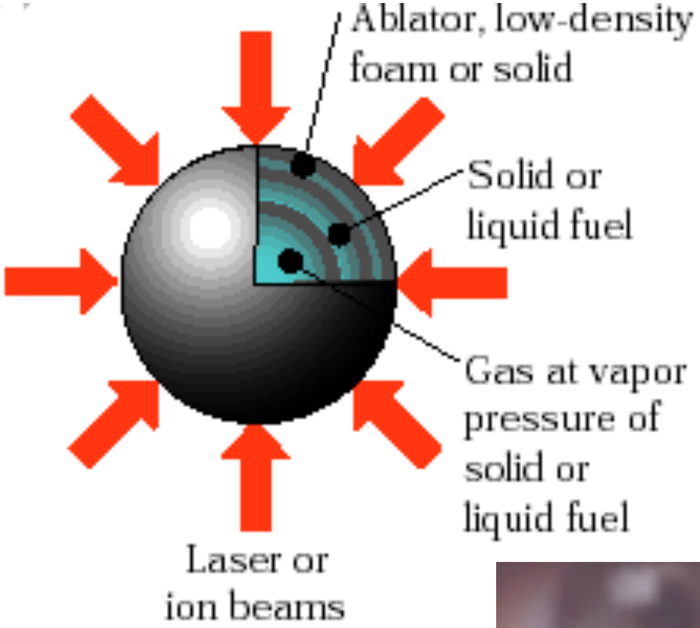
Heating to ignition must occur before ions fly away

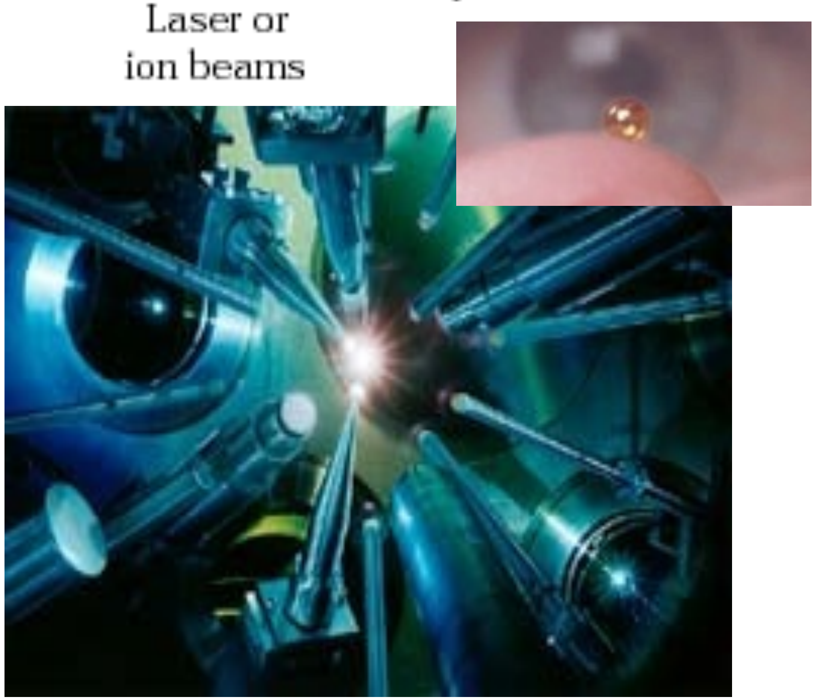
Compression: need ~10^{12} bar to reach 10^{31} m^{-3}

- Light pressure from most intense lasers is ~10^{6} bar, largely insufficient
- Rocket effect
- Shock waves from pellet surface to the center
- Once fusion starts, α heating sustains the reactions

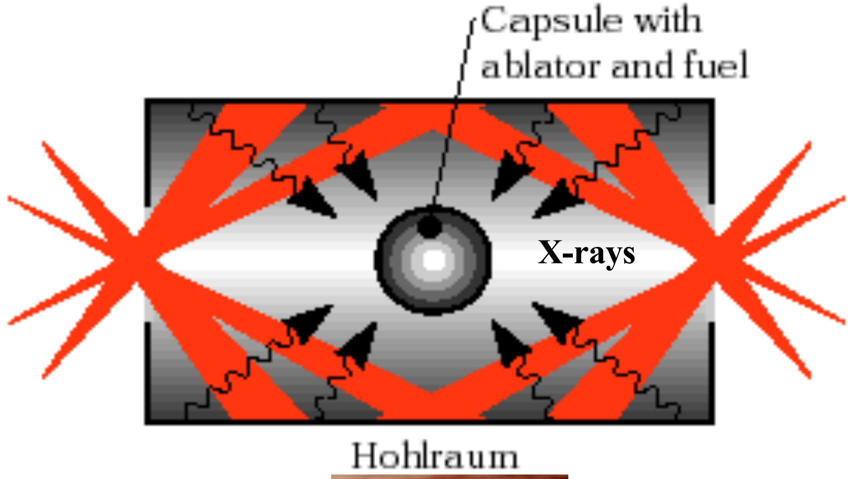
ICF: direct and indirect laser drive

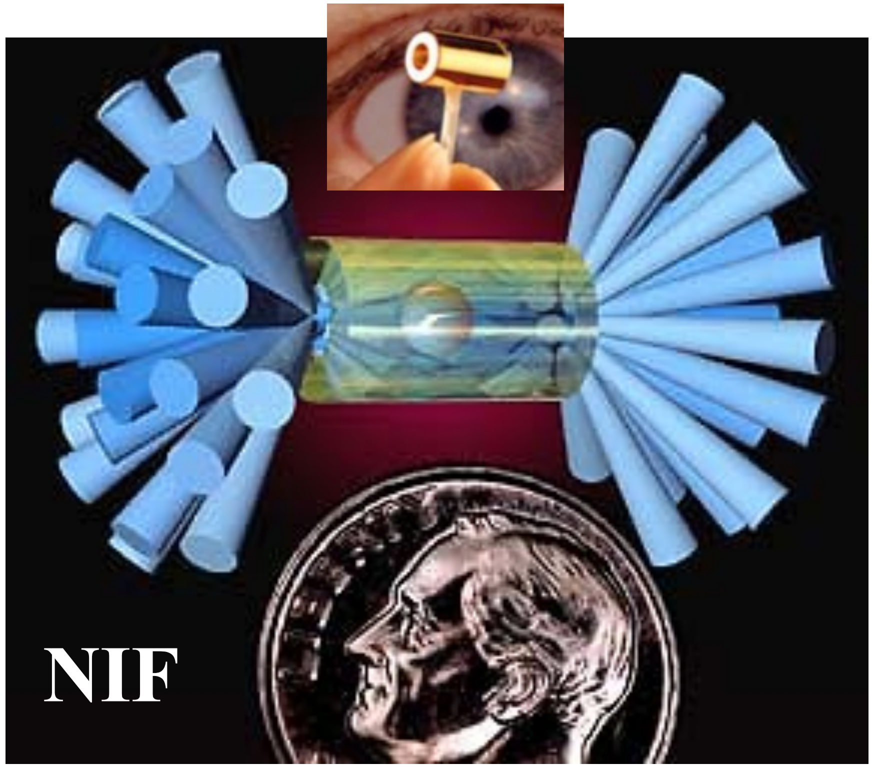
Direct drive





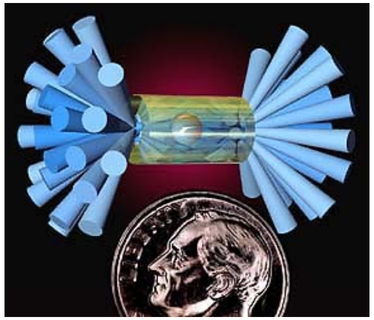
Indirect drive

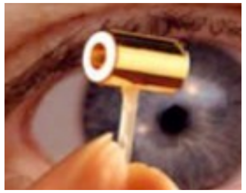


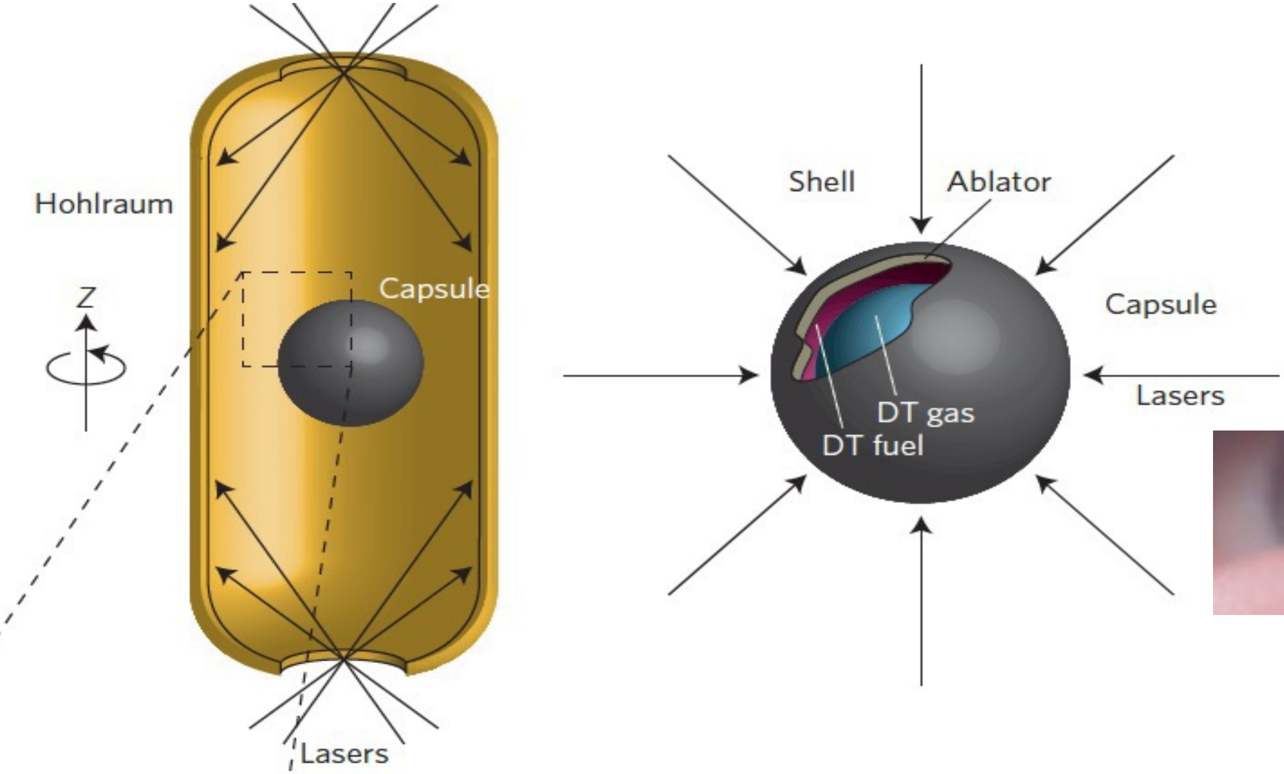


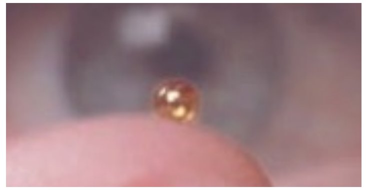
ICF: direct and indirect laser drive

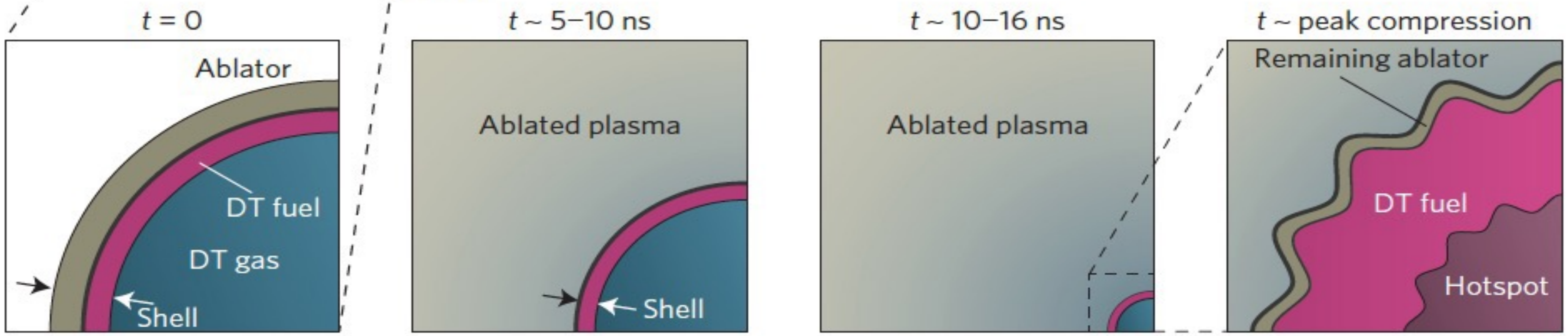
Indirect drive   Direct drive







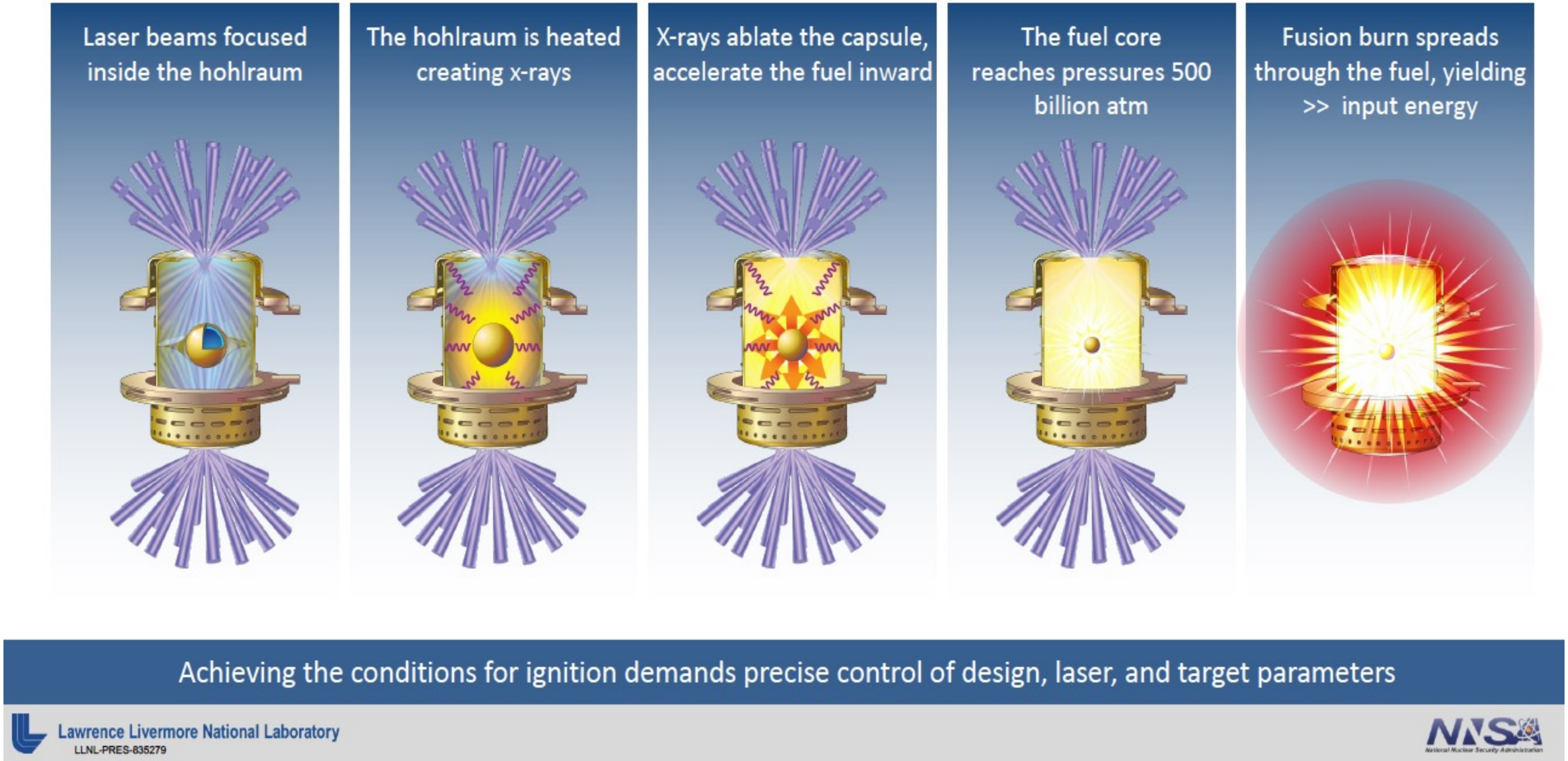




ICF – laser drive: NIF (US)

192 beams, ~1.8MJ, 500TW UV light (0.35μm)

ICF: indirect laser drive at NIF



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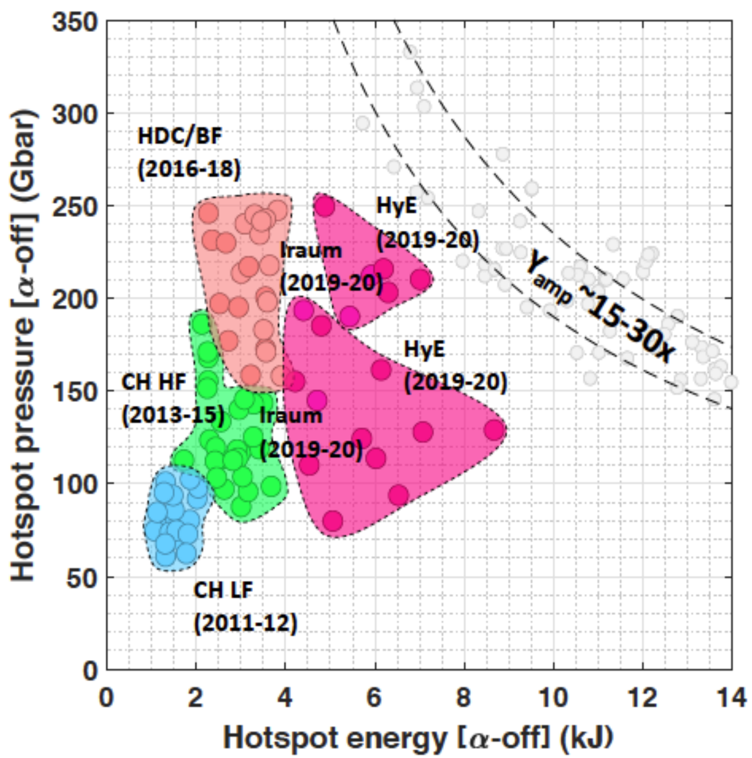
ICF – laser drive: NIF (US)

These experiments reached the "burning plasma" regime and were recently published in Nature

Zylstra et al, Nature **Burning plasma achieved in inertial fusion** (2022)

Kritcher et al, Nature Physics **Design of inertial fusion implosions reaching the burning plasma regime** (2022)

Ignition figure of merit ~ $(\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



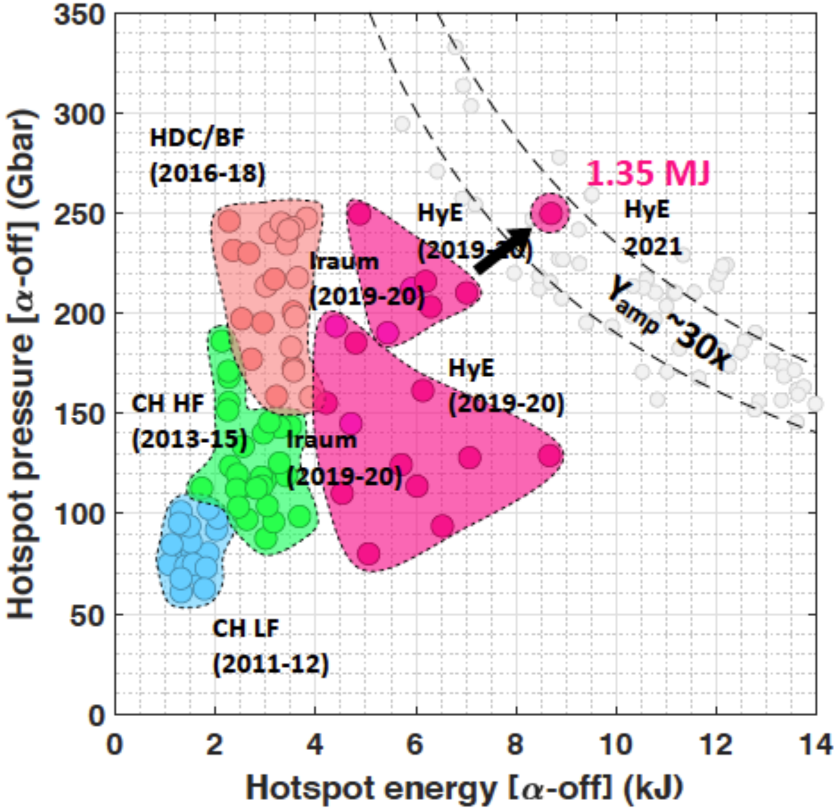
1: O. Hurricane et al., PoP 24, 092706 (2017)
2: O. Hurricane et al., PoP 27, 062704 (2020) and 2nd paper in preparation

Note: in ICF *burning plasma* means that the net α-heating is more than the net heating from pdV work

ICF – laser drive: NIF (US)

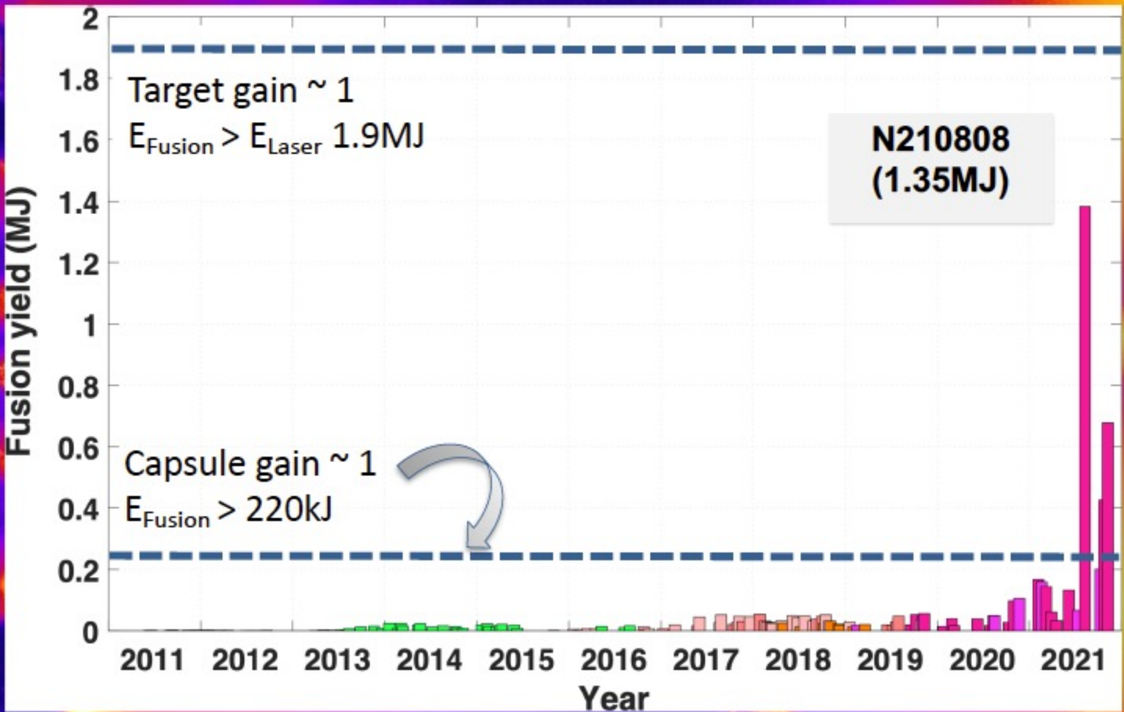
With improved drive and target quality we observed a large increase in performance in August 2021 (N210808)

Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



ICF – laser drive: NIF (US)

Aug 8th shot marks a significant advance in ICF research



- Burning plasmas created for the first time about 18 months ago (starting Nov 2020)
- More recent experiment N210808 had:
- Capsule gain ~5.8 (first >1)
- Target gain ~ 0.72
- Meets scientific definitions of ignition
- Some IFE strategic planning exercises are now underway in the US

Note: in ICF *ignition* means that α-heating > all losses

ICF: physics issues

Core must not be heated before shock waves arrive and compress it

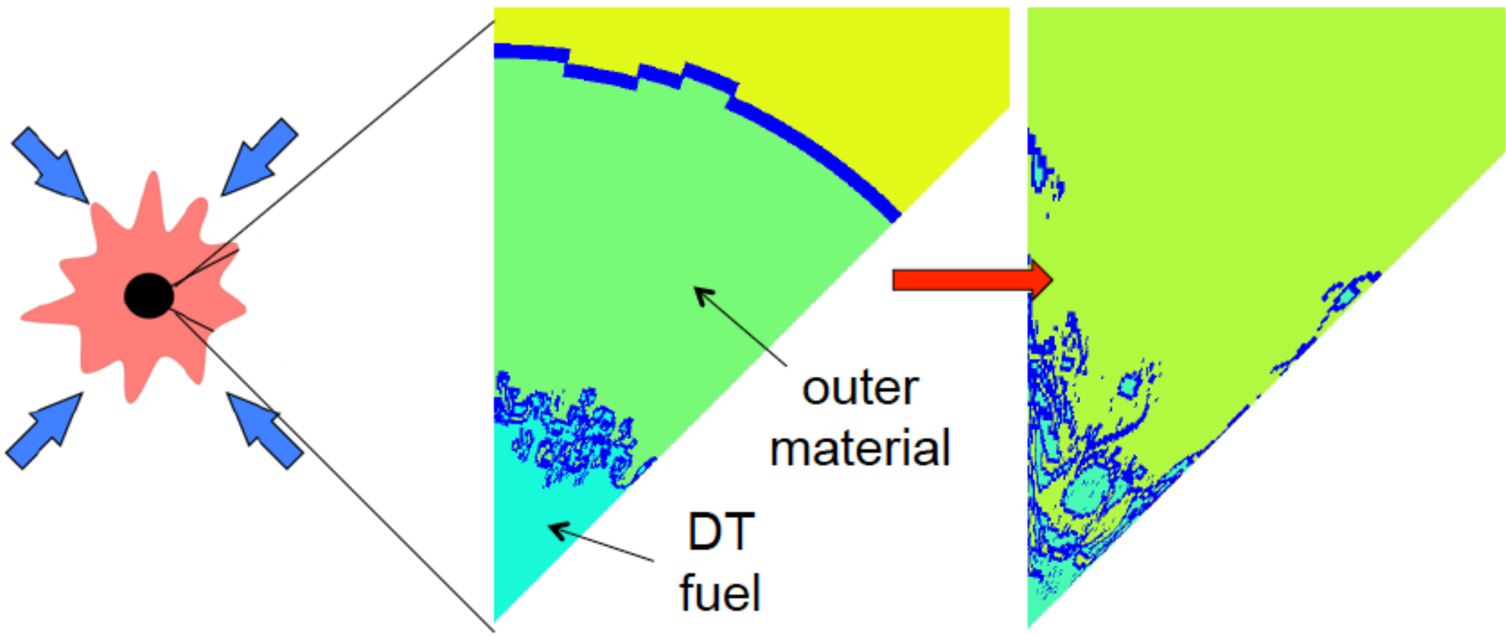
- Pellet design
- Laser pulse timing

Hydrodynamical stability

- Pellet symmetry
- Beam alignment, symmetry of drive

Simulated mixing due to Rayleigh-Taylor instability

Courtesy of Mathias Groth, Aalto Univ.

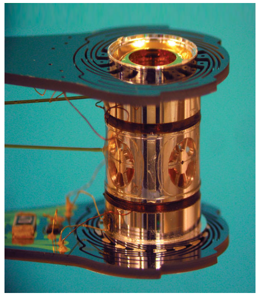


ICF: engineering issues

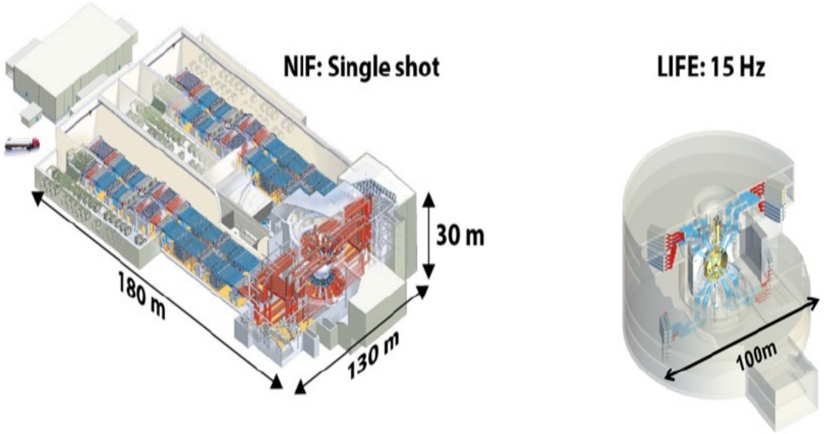
Efficiency, cost and reliability of high energy driver

Materials for first wall of vacuum chamber

Complexity and cost of capsule

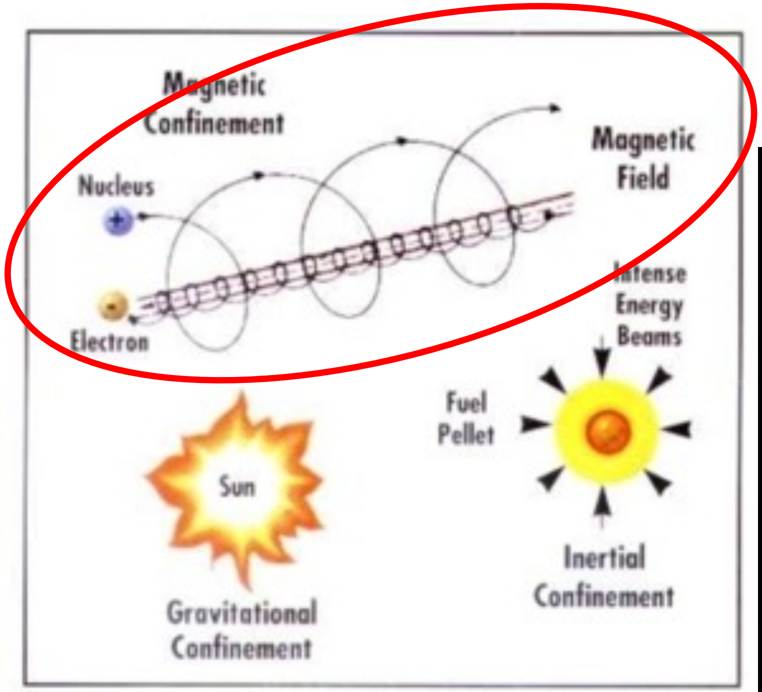


From single to repetitive pulses (3-10Hz)

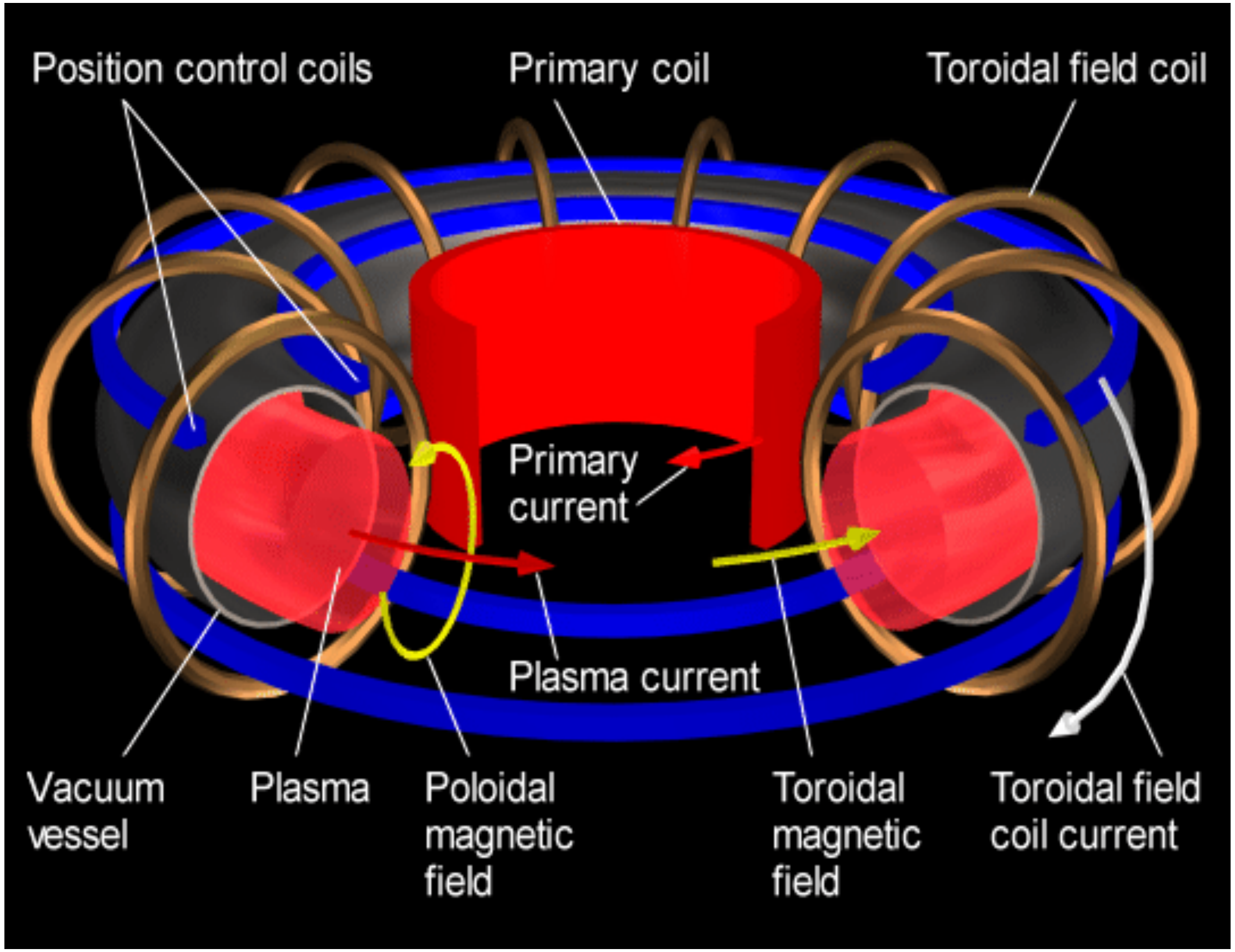


Swiss Plasma Center

Plasma confinement by magnetic fields



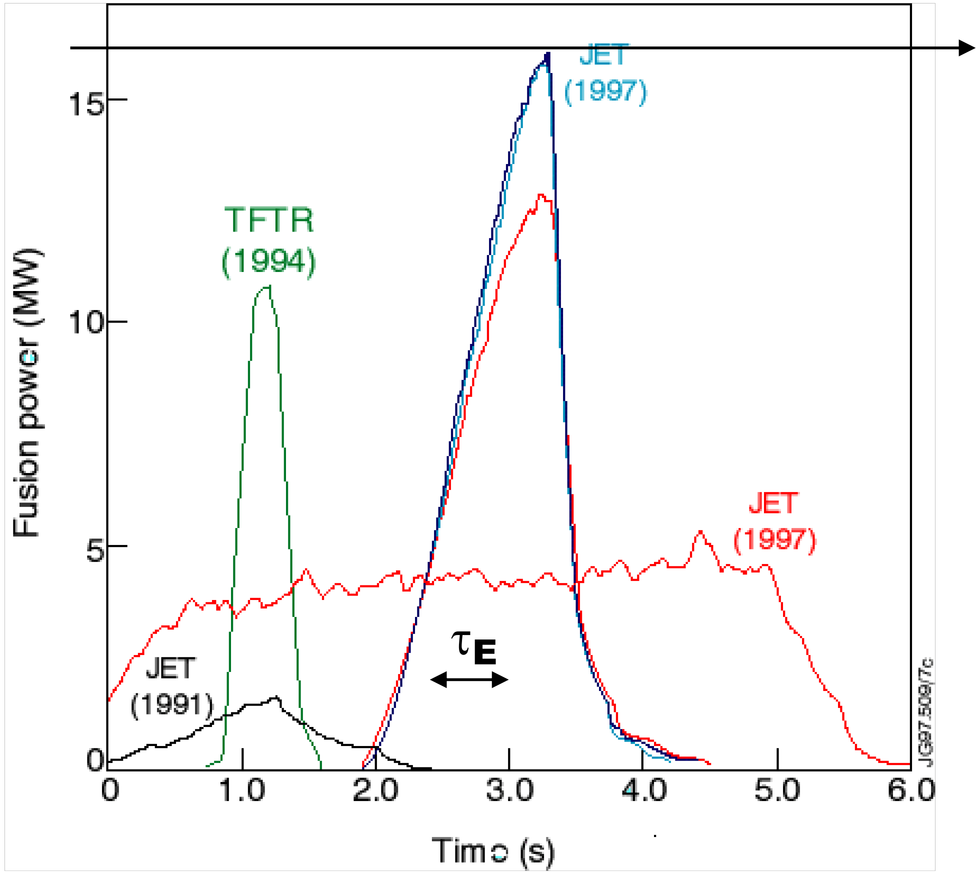
The Tokamak



Efficiency of confinement measured by

β = plasma pressure/B-field pressure = $(nT)/(B^2/2\mu_0)$

What has been achieved ?



16 MW

in a D-T plasma,

with 24 MW input into the plasma

total output : max 16 MW

Record fusion power gain: Q ~ 0.7

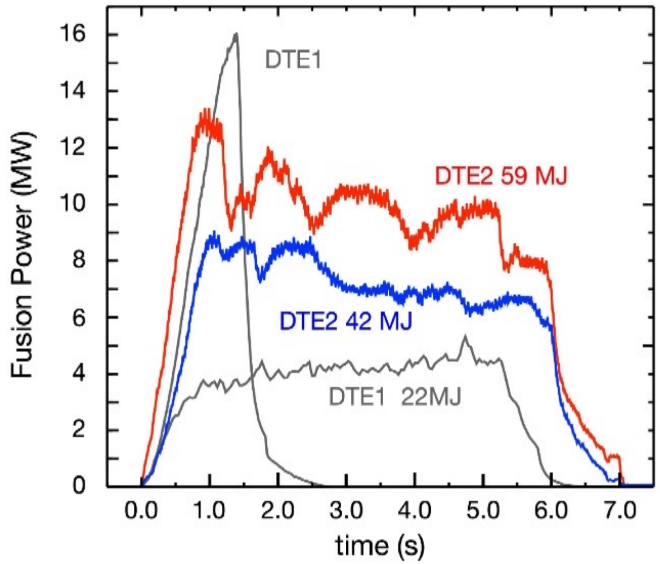
EPFL

What has been achieved - 2021

EUROfusion

5. JET achieved record fusion energy

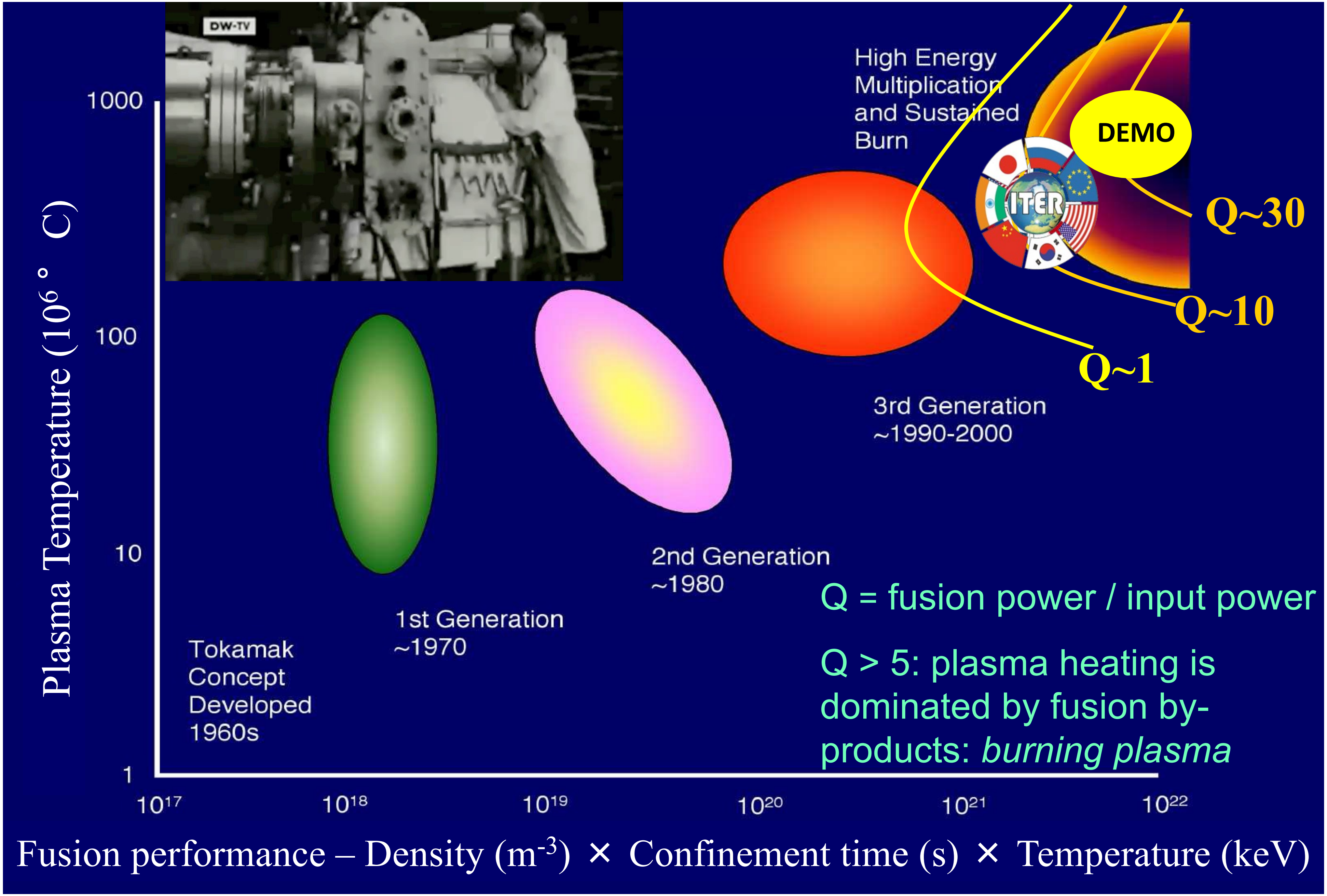
High fusion power produced and sustained for 5 seconds



- **First-ever high confinement plasmas using D-T with Beryllium / Tungsten wall**
- Confirming **predictions** of plasma behaviour advances development of ITER high performance scenarios

Record fusion energy in a shot: 59MJ

Progress in magnetic fusion



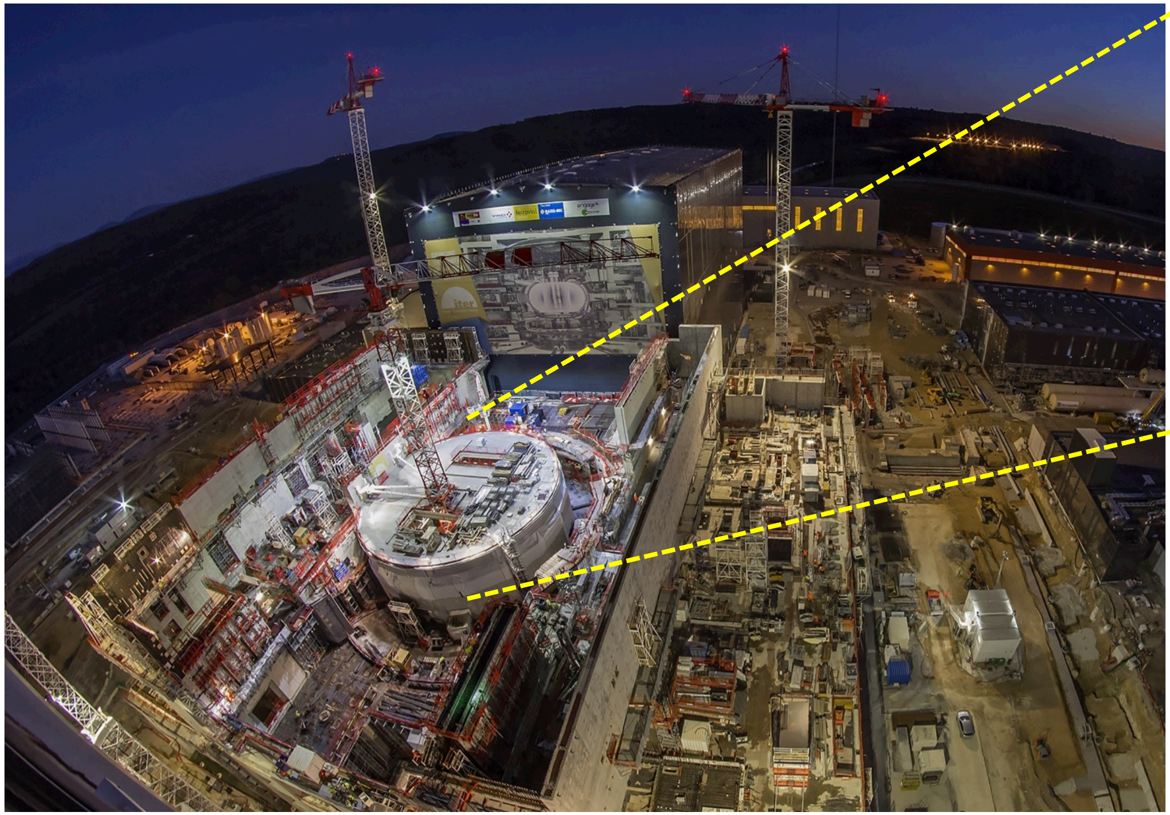
EPFL

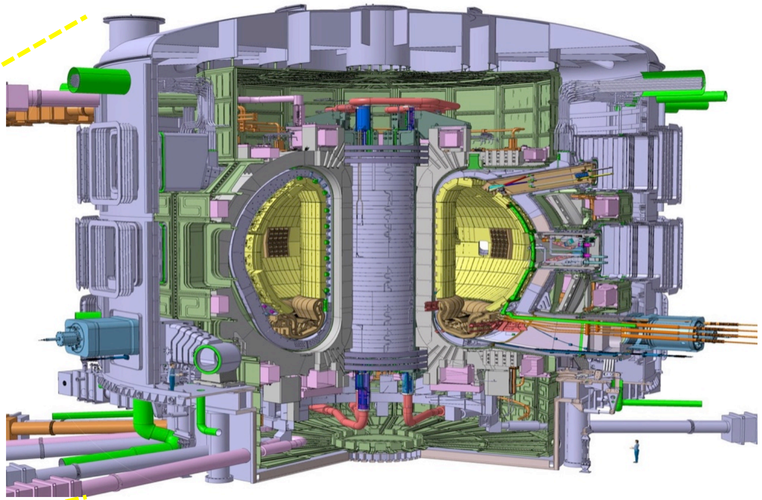
ITER

Scientific and technological feasibility of fusion energy

First burning plasma: Q ≥10; P_{fusion}≥ 500MW; ~500s

~20b€ (EU ~40%, other partners ~10%)





Swiss Plasma Center

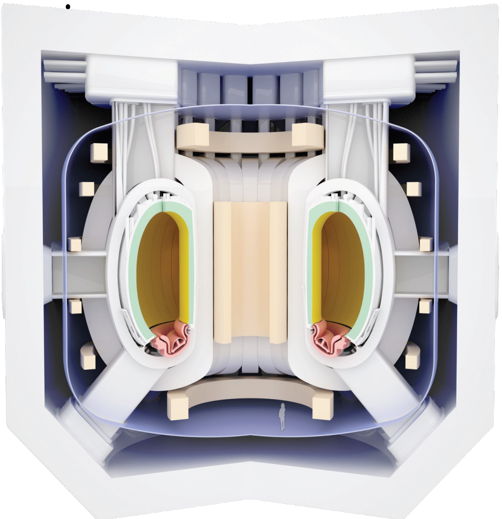
iter china eu india japan korea russia usa

ITER construction site

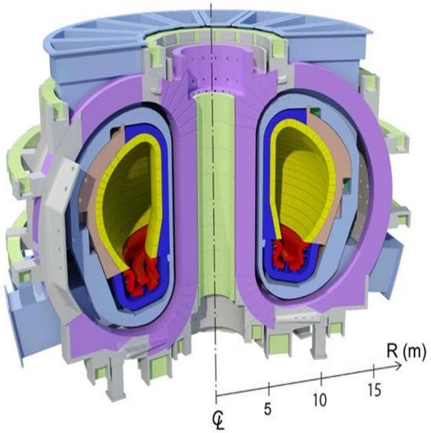
DEMO

Industrial and commercial feasibility of fusion energy

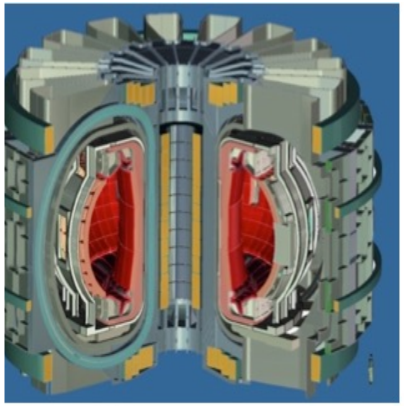
Q ~30; P_{fusion}~ GW, $P_{electrical}$~ hundreds of MW



Europe

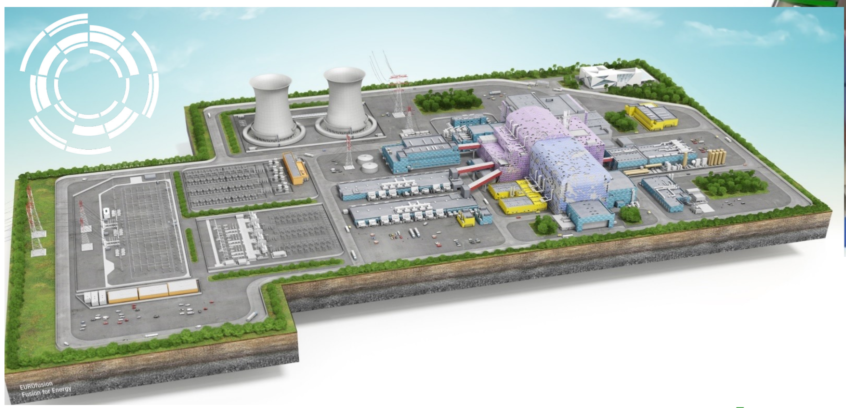


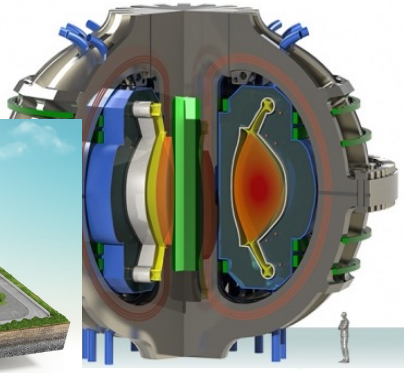
Japan



Korea

China





US

Innovation needed for heat exhaust, T breeding, materials, magnets,…

A magnetic fusion power plant