Nuclear Fusion and Plasma Physics

Lecture 2

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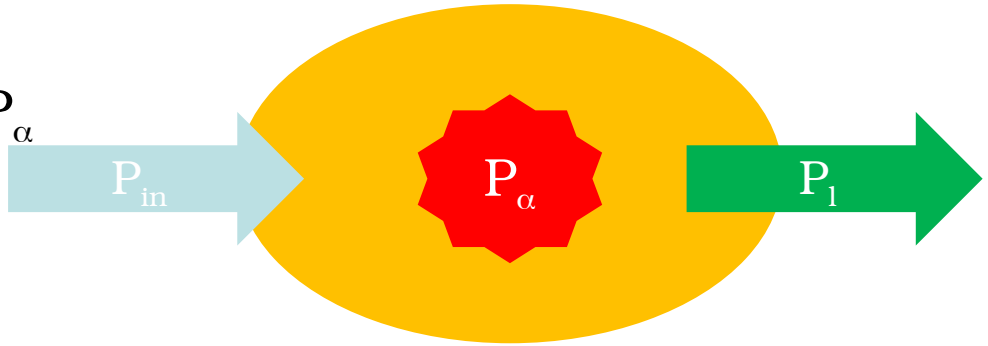
Reminder: the Lawson criterion

- Steady-state $P_l = P_{in} + P_\alpha$



- Losses

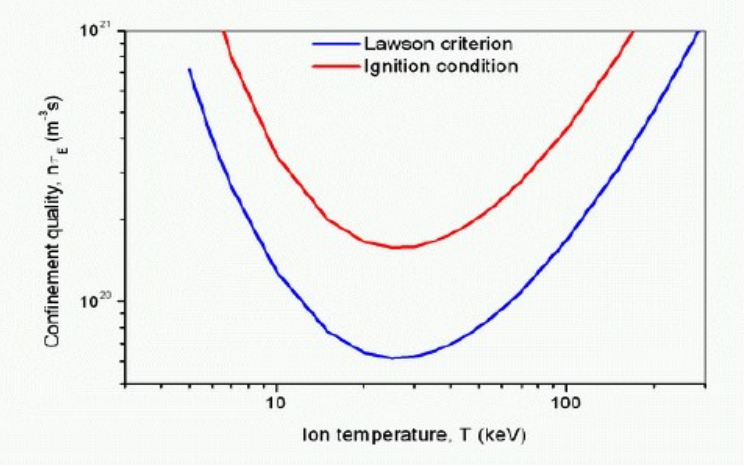
$$\frac{P_l}{\text{volume}} = \frac{3n_eT}{\tau_E} + \cancel{An_e^2 Z_{\text{eff}} T^{1/2}} \qquad (T_e = T_i = T)$$

$$n_e\tau_E\left\{\frac{6/5\langle\sigma v\rangle_{DT}\Delta E_f}{12T}\right\} = n_e\tau_E\left\{\frac{\langle\sigma v\rangle_{DT}\Delta E_f}{10T}\right\} \geq 1 \qquad \boxed{n_e\tau_e \geq \frac{1}{f(T)}}$$ **breakeven**

- $P_f/P_{in} \geq 1 \rightarrow$

$$\frac{1}{4}n_e^2\langle\sigma v\rangle_{DT}\Delta E_\alpha \geq \frac{3n_eT}{\tau_E} \qquad \boxed{n_e\tau_E \geq \frac{6}{f(T)}}$$ **ignition**

- $P_\alpha/P_l \geq 1 \rightarrow$



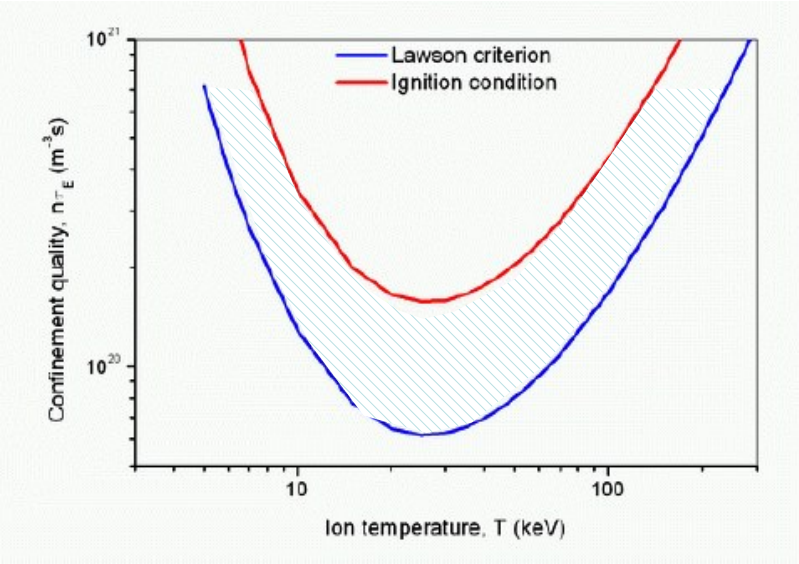
Reminder: physics & engineering gain factors

Physics gain factor

$$Q = \frac{P_{\text{fusion out}} - P_{\text{in}}}{P_{\text{in}}} = \frac{P_f + P_{in} - P_{\text{in}}}{P_{\text{in}}} = \frac{P_f}{P_{\text{in}}}$$

Break-even: $Q = 1$

Ignition: $Q \to \infty$



Engineering gain factor

$$Q_E = \frac{\text{net electric power out}}{\text{net electric power in}} = \frac{P_{\text{out}}^{(E)} - P_{\text{in}}^{(E)}}{P_{\text{in}}^{(E)}}$$

$$Q_E = \frac{\eta[P_f + P_{in}] - P_{\text{in}}}{P_{\text{in}}} = \eta\frac{P_f}{P_{\text{in}}} - (1-\eta) = \eta Q - (1-\eta)$$

Example: $\eta_e \simeq 70\%$; $\eta_t \simeq 40\% \Rightarrow \eta \simeq 28\%$ and $Q_E \simeq 0.28Q - 0.72$

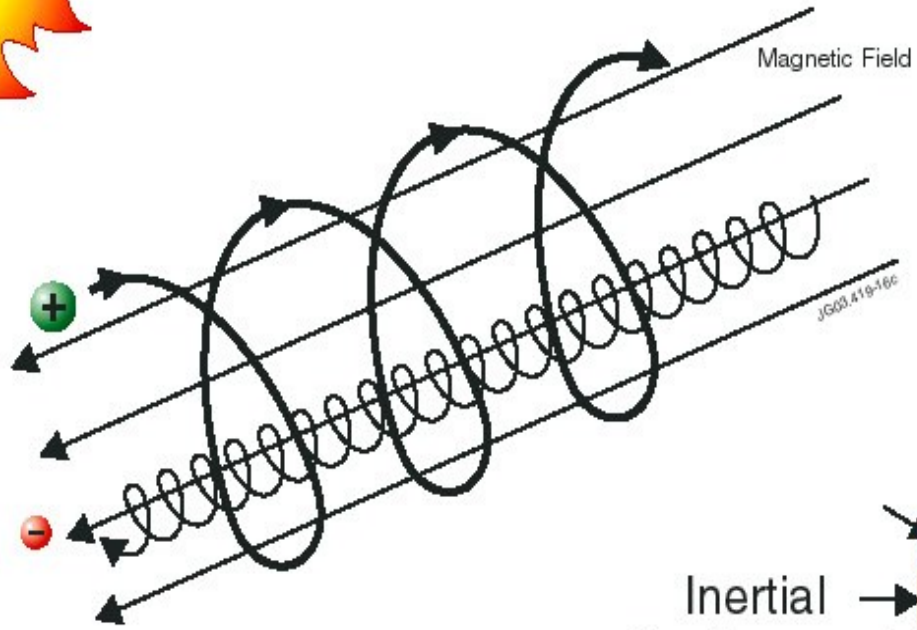
How can a plasma be confined ?

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



Gravitational Confinement

Magnetic Confinement



Magnetic

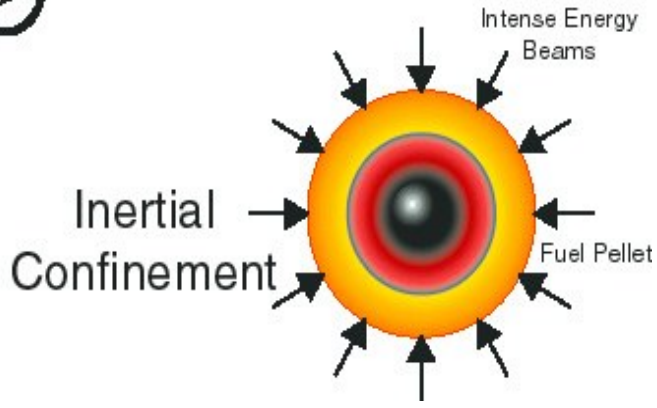
$n \sim 10^{20}\ m^{-3}$

$\tau_E \sim 1\ s$

Inertial

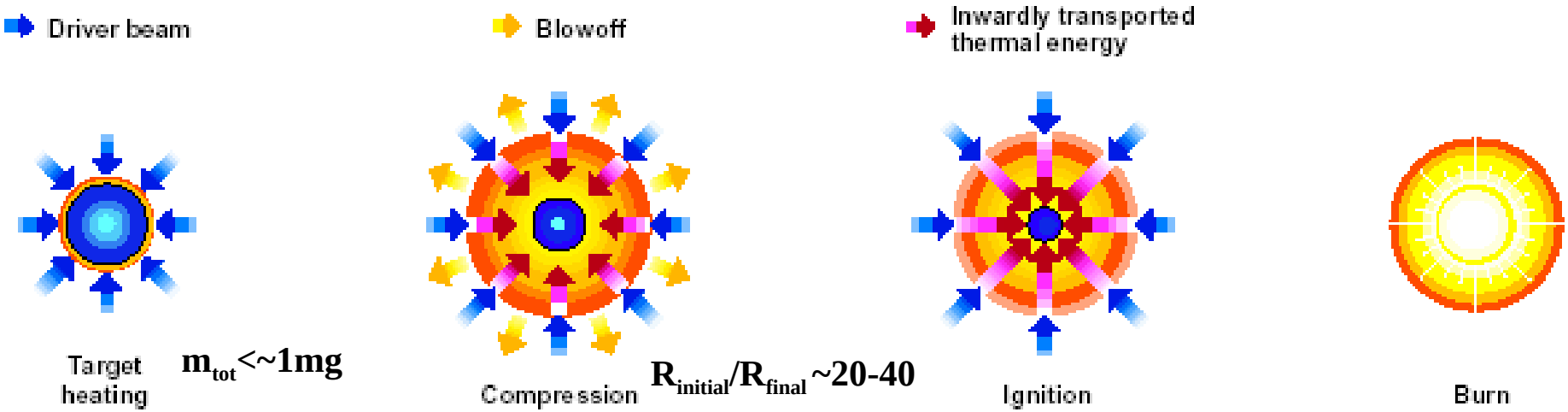
$n \sim 10^{31}\ m^{-3}$

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



Inertial Confinement Fusion - the basics

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



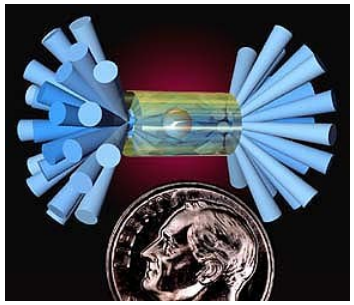
Heating to ignition must occur before ions fly away

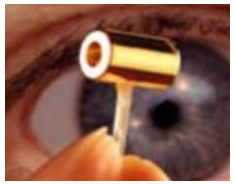
Compression: need ~10^{12} bar to reach 10^{31} m^{-3}

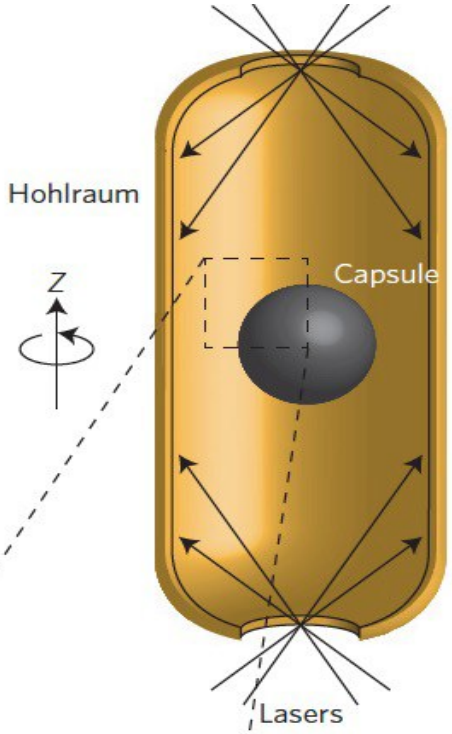
- Light pressure from most intense lasers is ~10^{6} bar, largely insufficient
- Rocket effect
- Shock waves from pellet surface to the center
- Once fusion starts, α heating sustains the reactions

ICF: direct and indirect laser drive

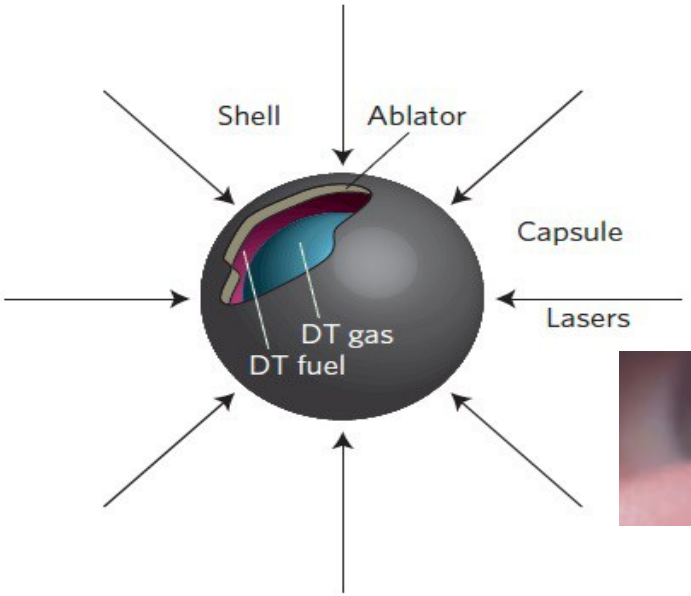
Indirect drive

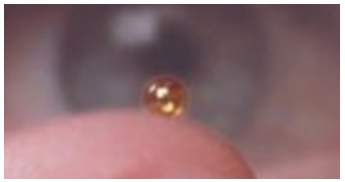


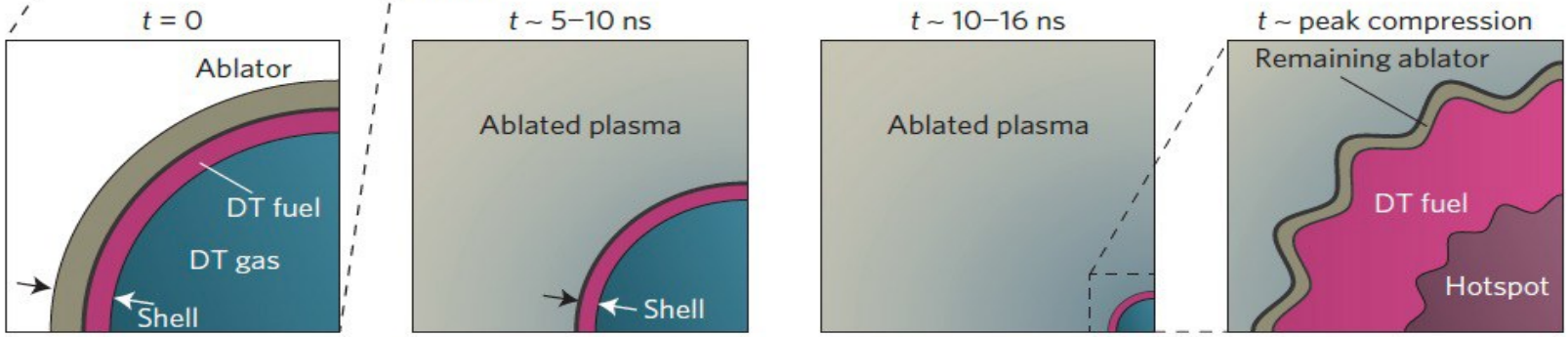




Direct drive





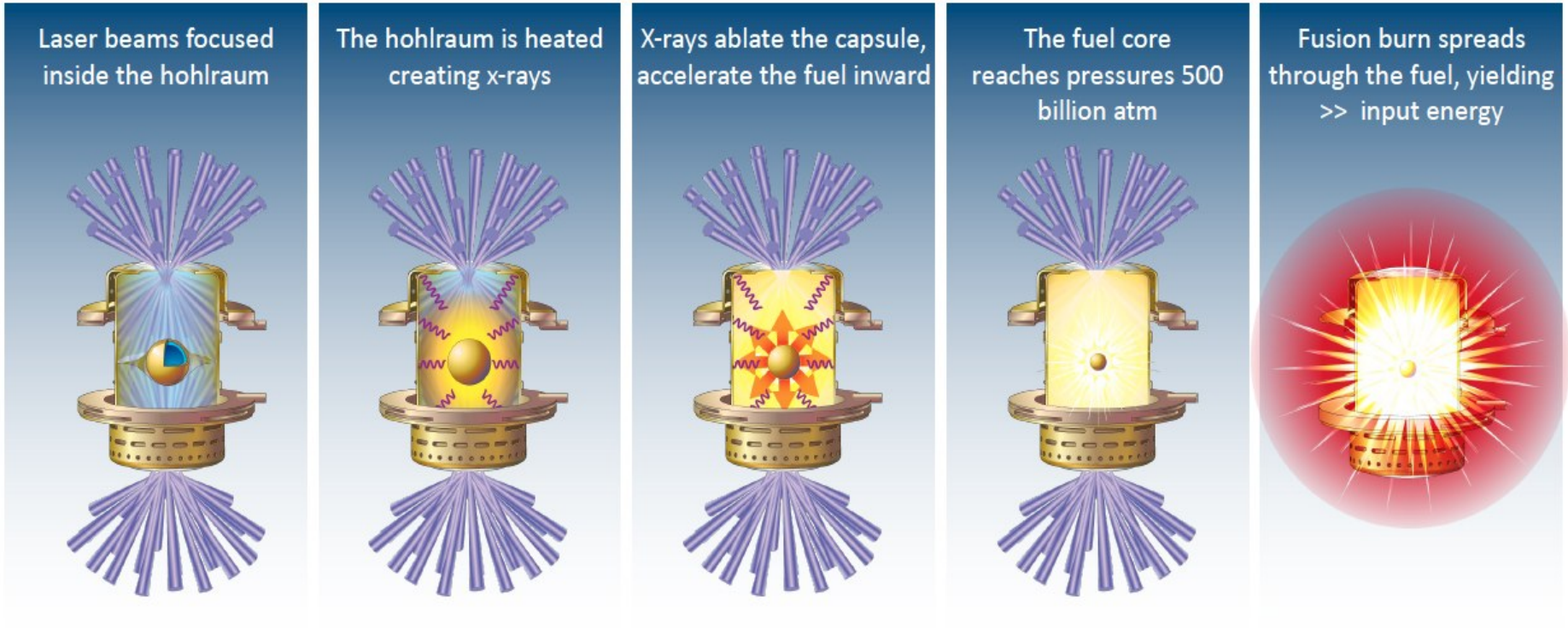


ICF – laser drive: NIF (US)



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

ICF: indirect laser drive at NIF

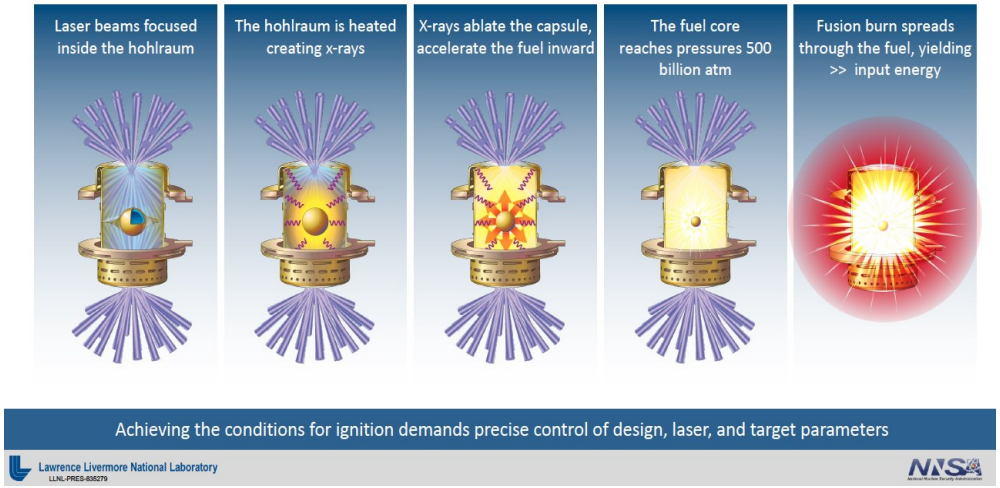


Achieving the conditions for ignition demands precise control of design, laser, and target parameters

Lawrence Livermore National Laboratory
LLNL-PRES-835279

NNSA

ICF: indirect laser drive at NIF



How X-Ray Generation Works:

1.Laser Deposition: High-energy laser beams (often infrared or UV) enter the hohlraum through small apertures.

2.Plasma Formation: These lasers strike the inner surface of the high-Z (high atomic number, e.g., gold, uranium) hohlraum wall, rapidly heating a small layer of the wall material into a super-hot, dense plasma.

3.Energy Conversion: The laser energy is absorbed by the plasma, primarily through inverse bremsstrahlung, causing electrons to gain significant energy.

4.X-Ray Emission: This energetic plasma then emits thermal x-rays, which fill the hohlraum cavity.

5.Radiation Transport: The x-rays bounce around inside the hohlraum, creating a uniform bath of radiation that heats the outer surface of the fuel capsule suspended in the center.

ICF – results @ NIF (US)



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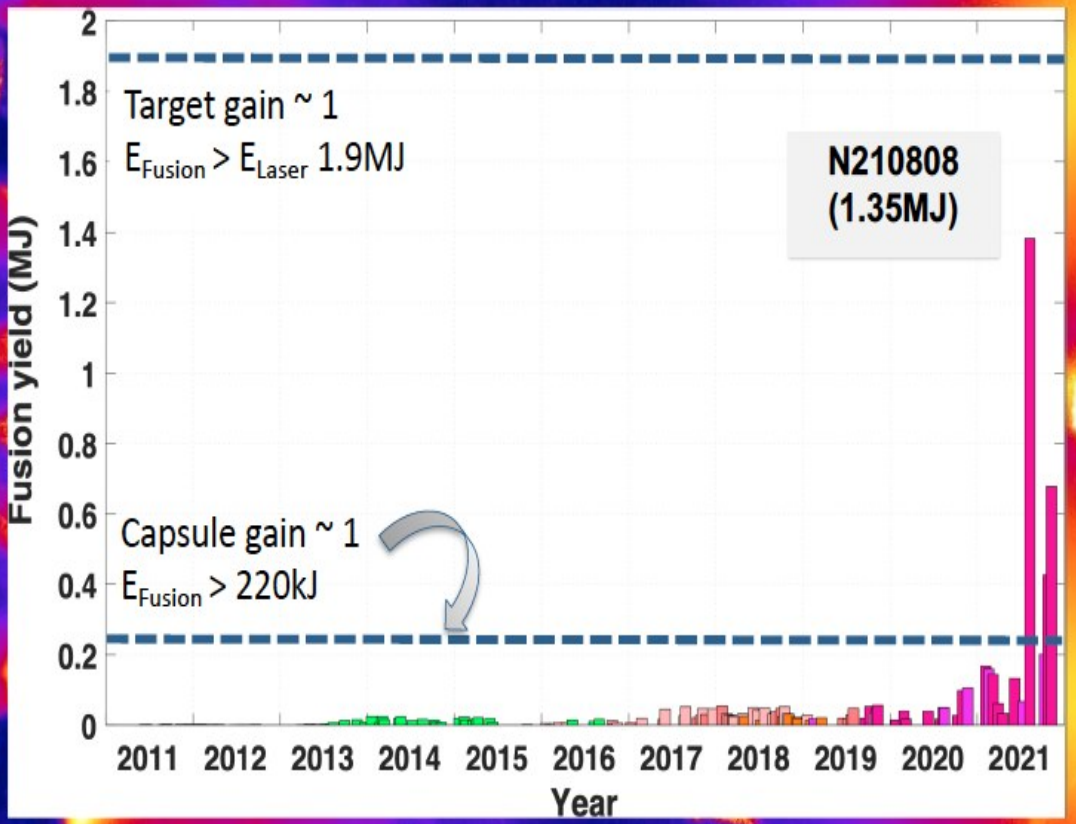
Aug 8th shot marks a significant advance in ICF research



- 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

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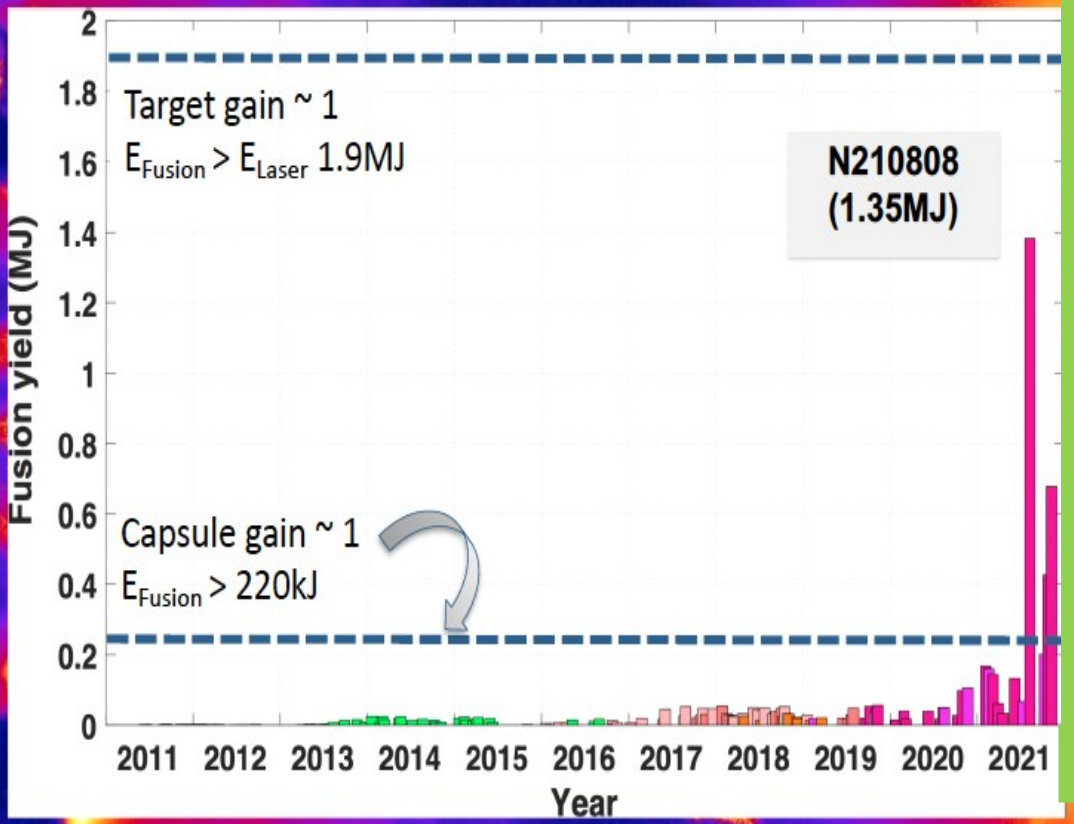

2022

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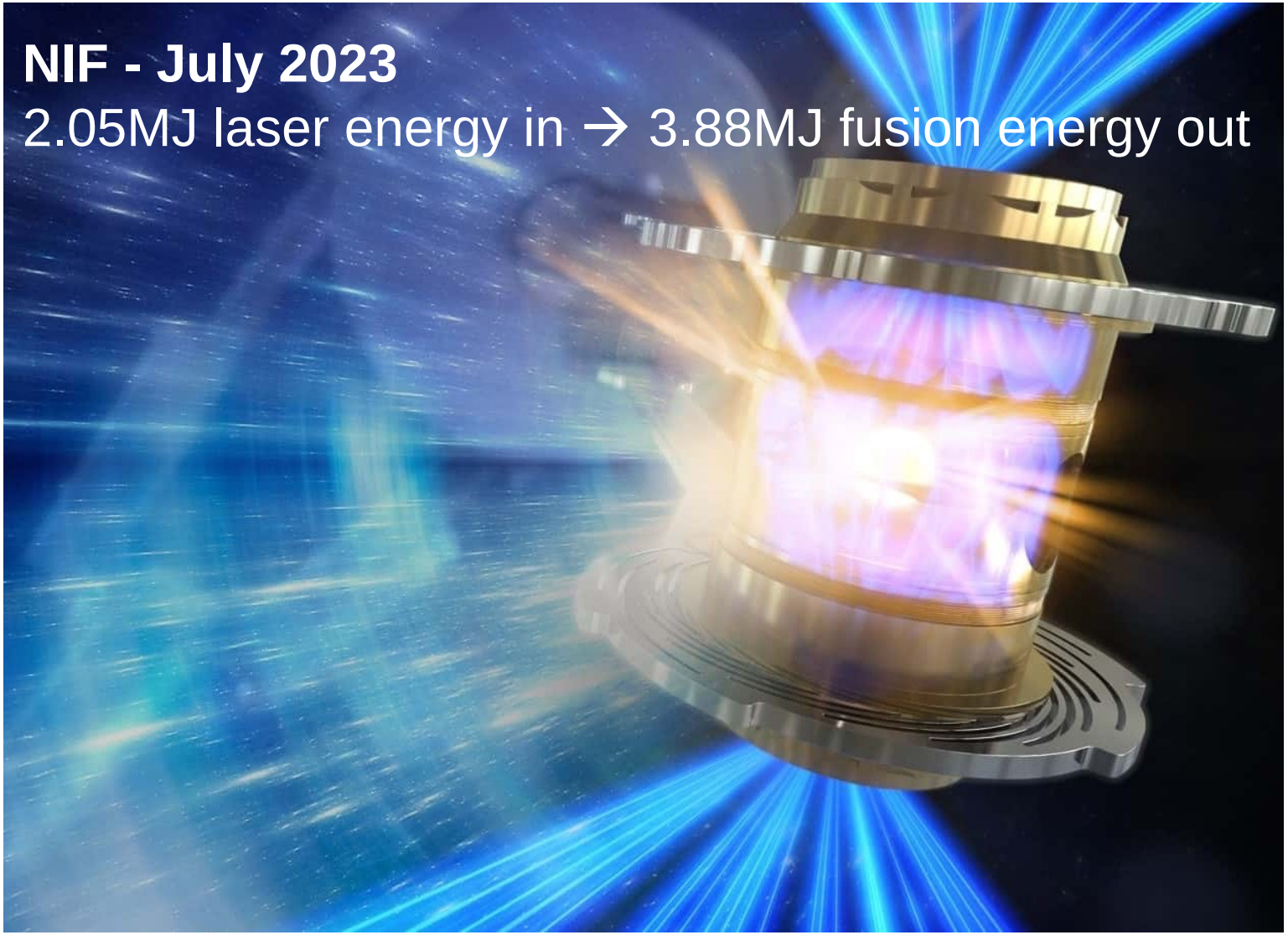


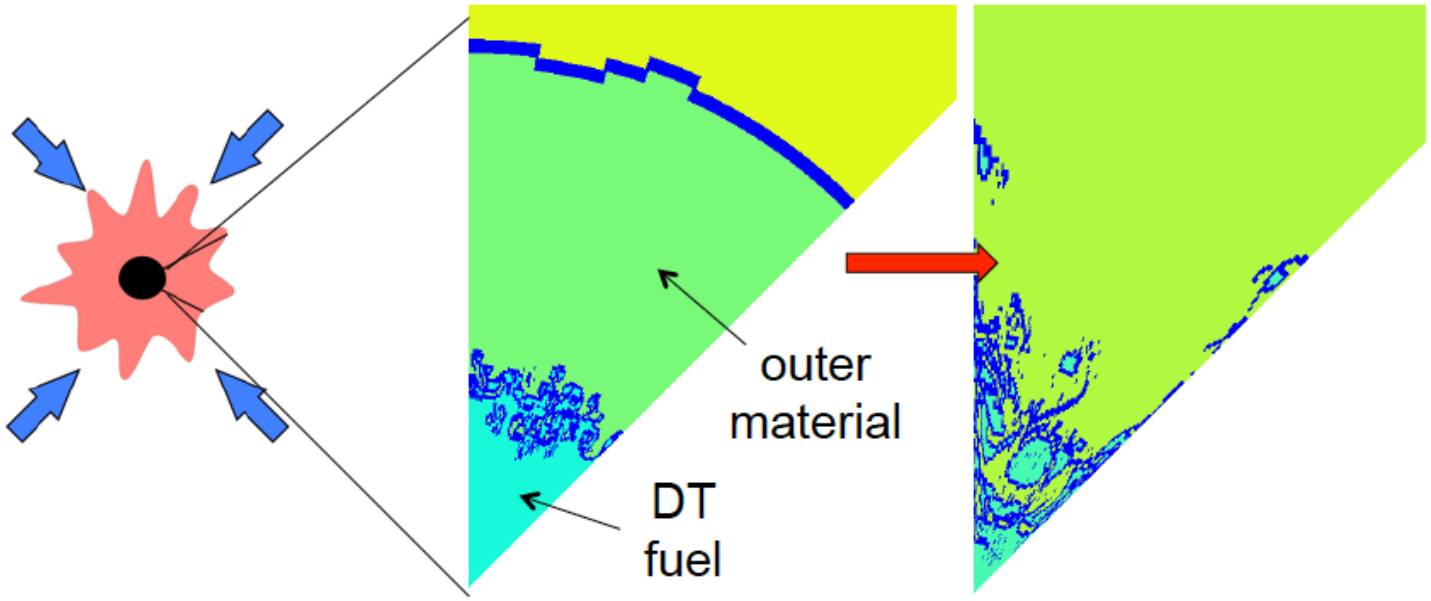
ICF: physics issues

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

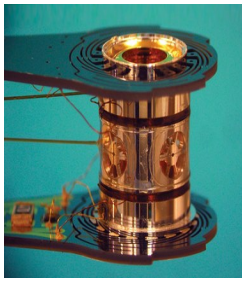
Efficiency, cost and reliability of high energy driver



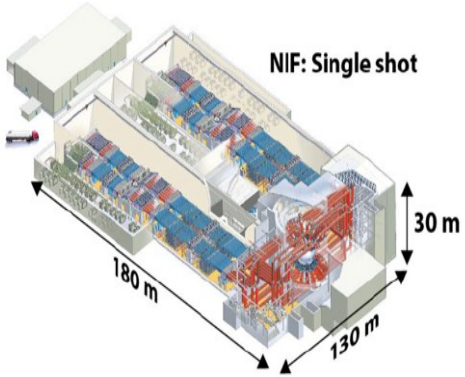
Materials for first wall of vacuum chamber



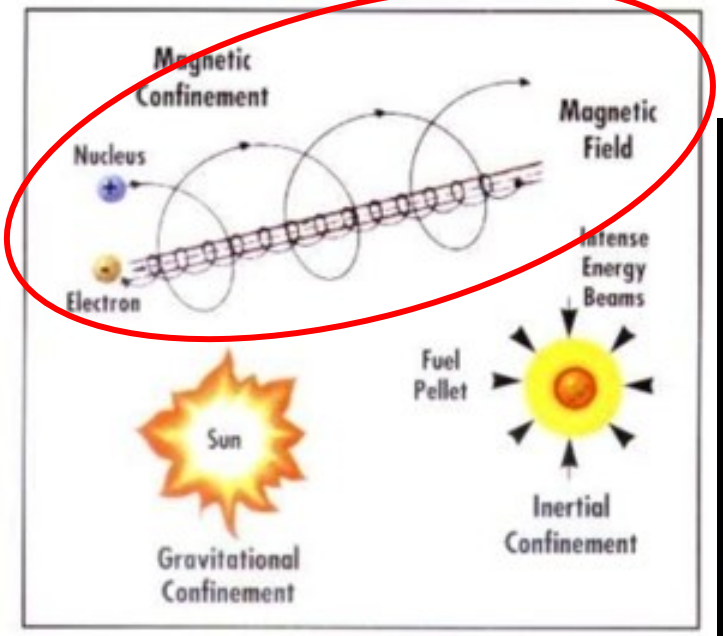
Complexity and cost of capsule



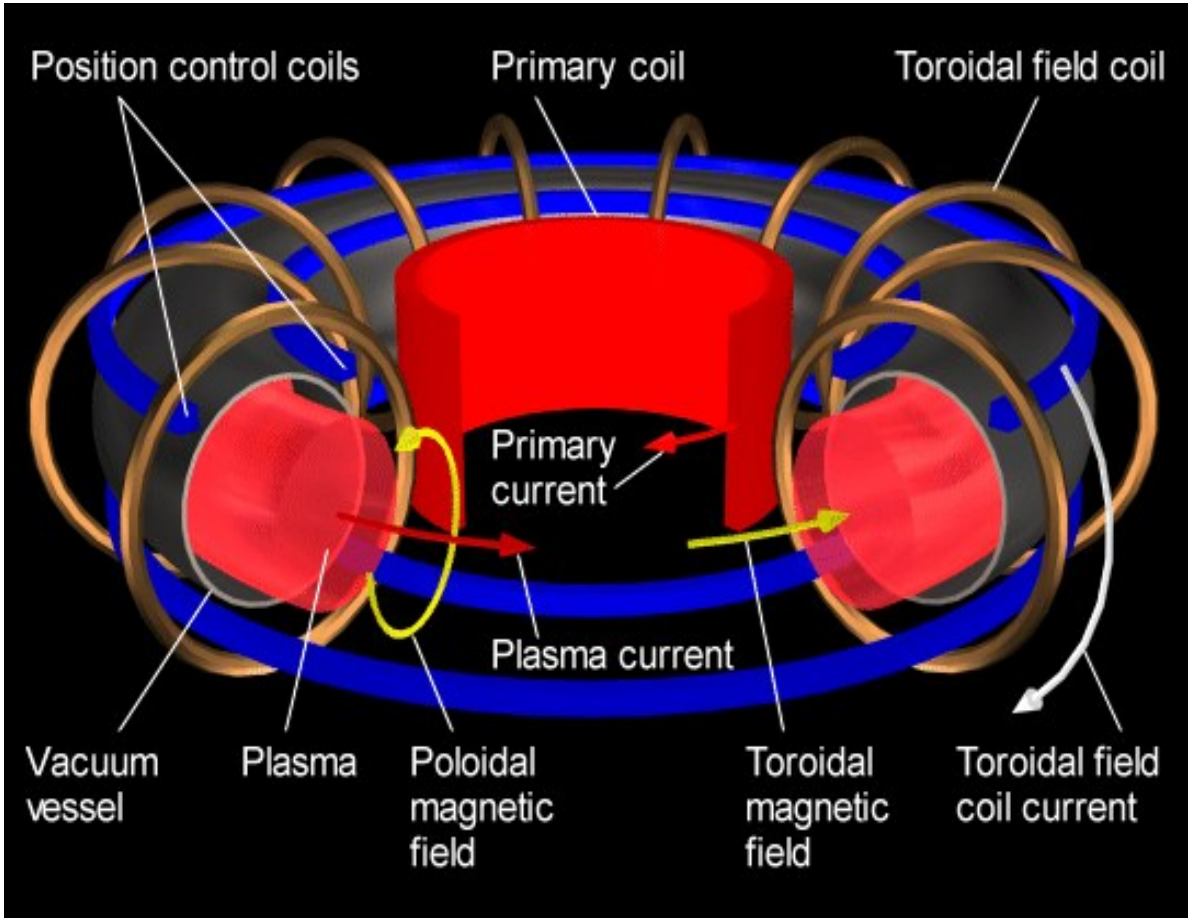
From single to repetitive pulses
(3-10Hz)



Plasma confinement by magnetic fields



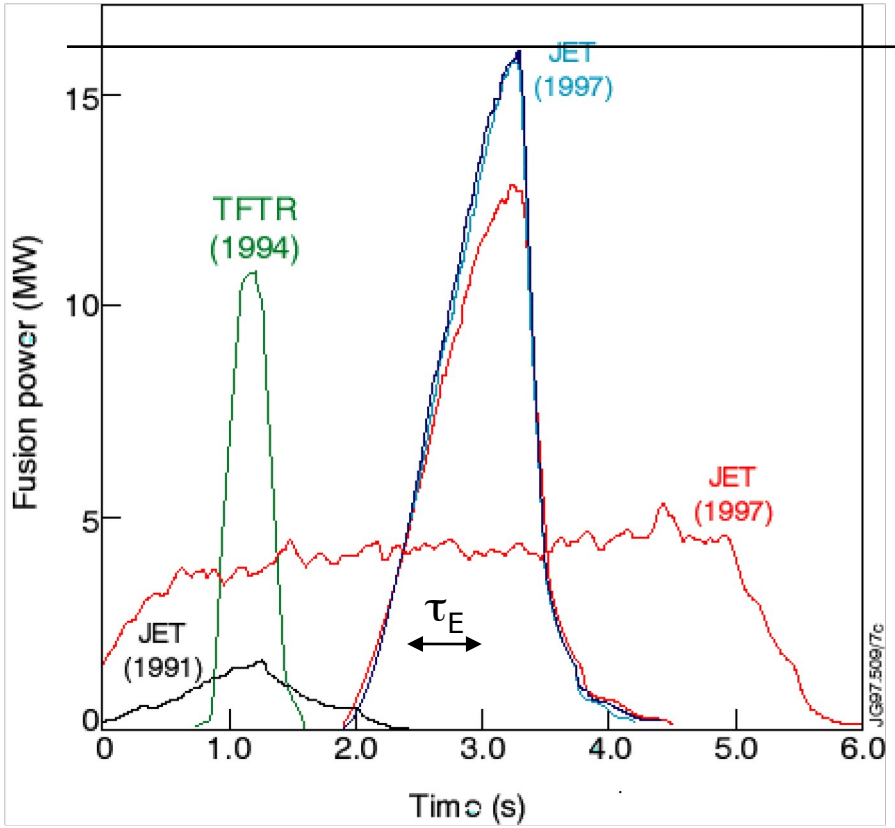
The Tokamak



Efficiency of confinement measured by

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

What has been achieved ?



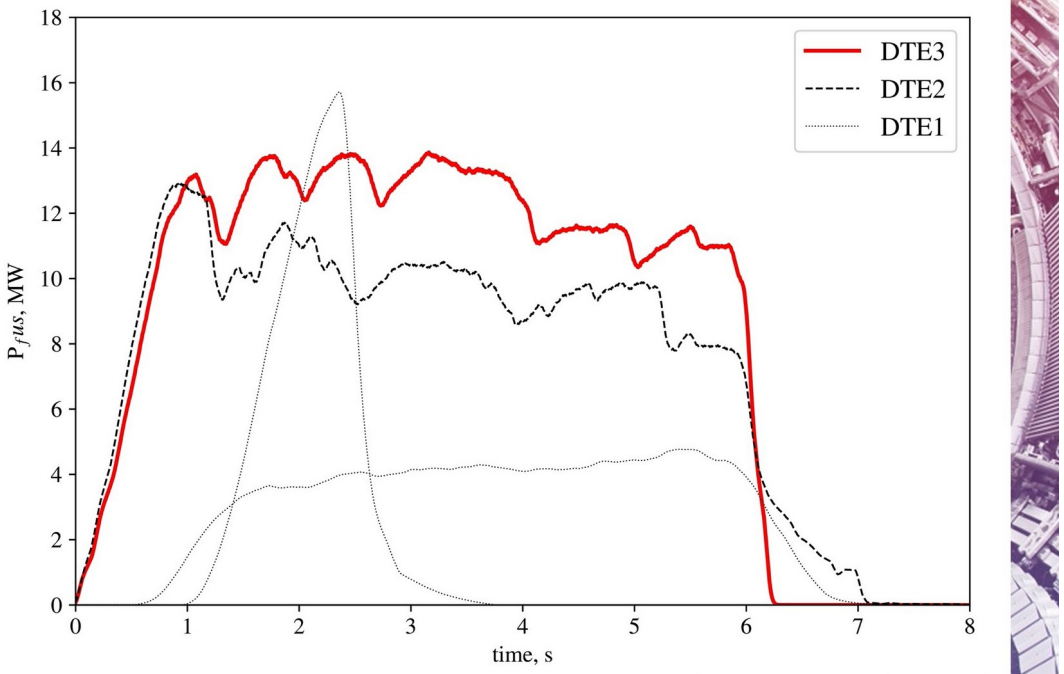
in a D-T plasma,

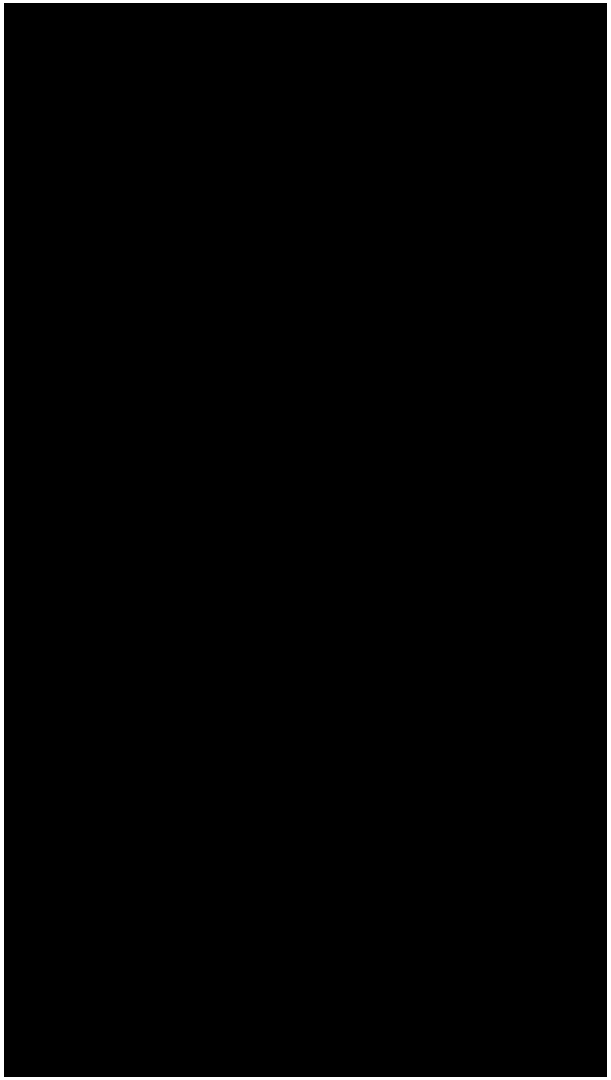
with 24 MW input into the plasma

total output : max 16 MW

Record fusion power gain: Q ~ 0.7

JET – October 2023
Fusion energy record 69MJ (0.2mg DT)



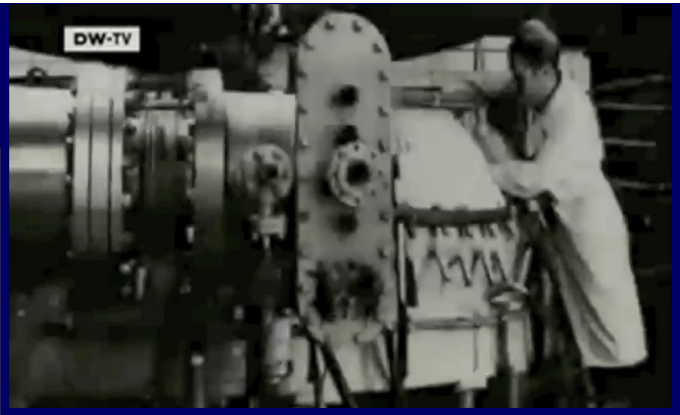


Swiss Plasma Center

EUROfusion

UK Atomic Energy Authority

Progress in magnetic fusion



Plasma Temperature (10^6 °C)

1000
100
10
1

10^{17} 10^{18} 10^{19} 10^{20} 10^{21} 10^{22}

Tokamak Concept Developed 1960s

1st Generation ~1970

2nd Generation ~1980

3rd Generation ~1990-2000

High Energy Multiplication and Sustained Burn

DEMO

ITER

Q~30

Q~10

Q~1

Q = fusion power / input power

Q > 5: plasma heating is dominated by fusion by-products: *burning plasma*

Fusion performance – Density (m^{-3}) × Confinement time (s) × Temperature (keV)

ITER

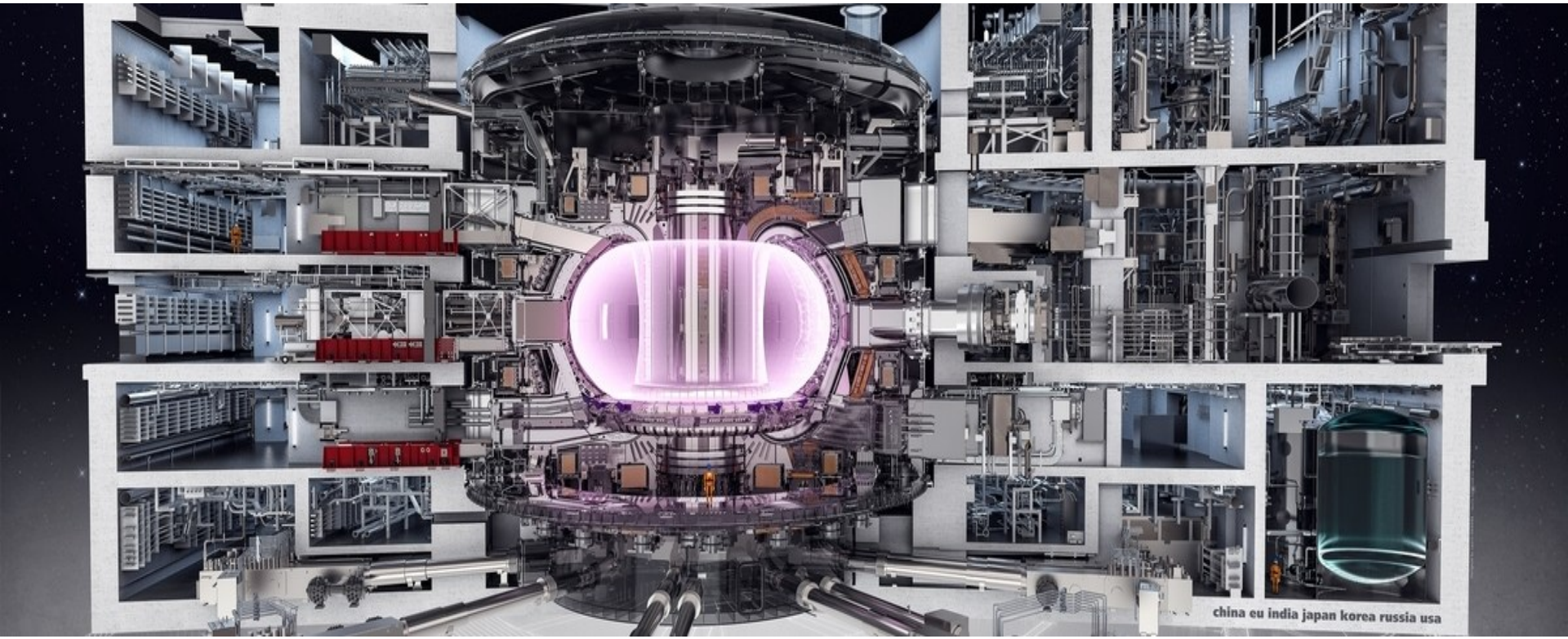
Scientific and technological feasibility of fusion

Q =10: first *burning* plasma

P_{fusion}= 500MW for ~500s

Under construction in the south of France





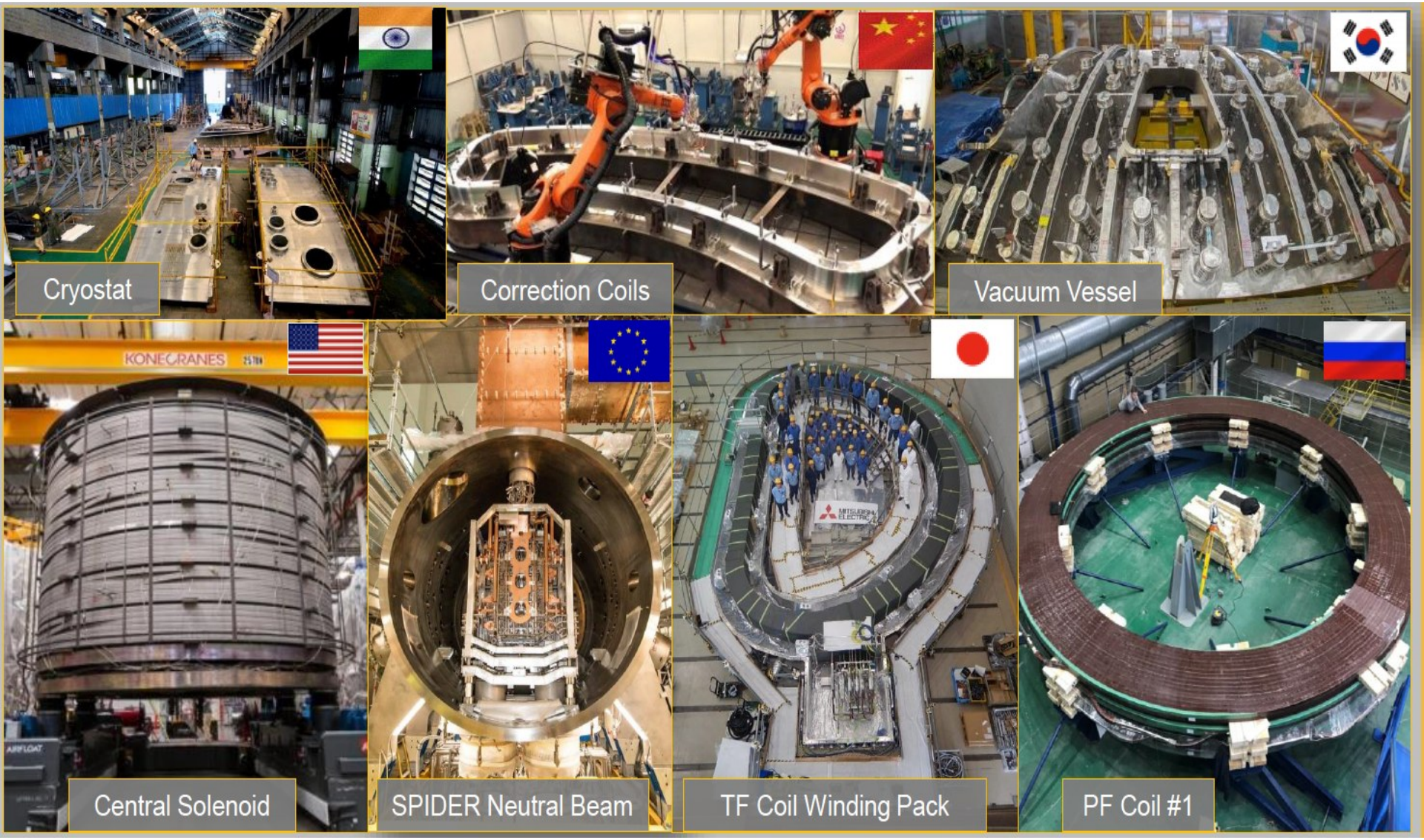
ITER site



Swiss Plasma Center

china eu india japan korea russia usa

ITER construction is under way all over the world

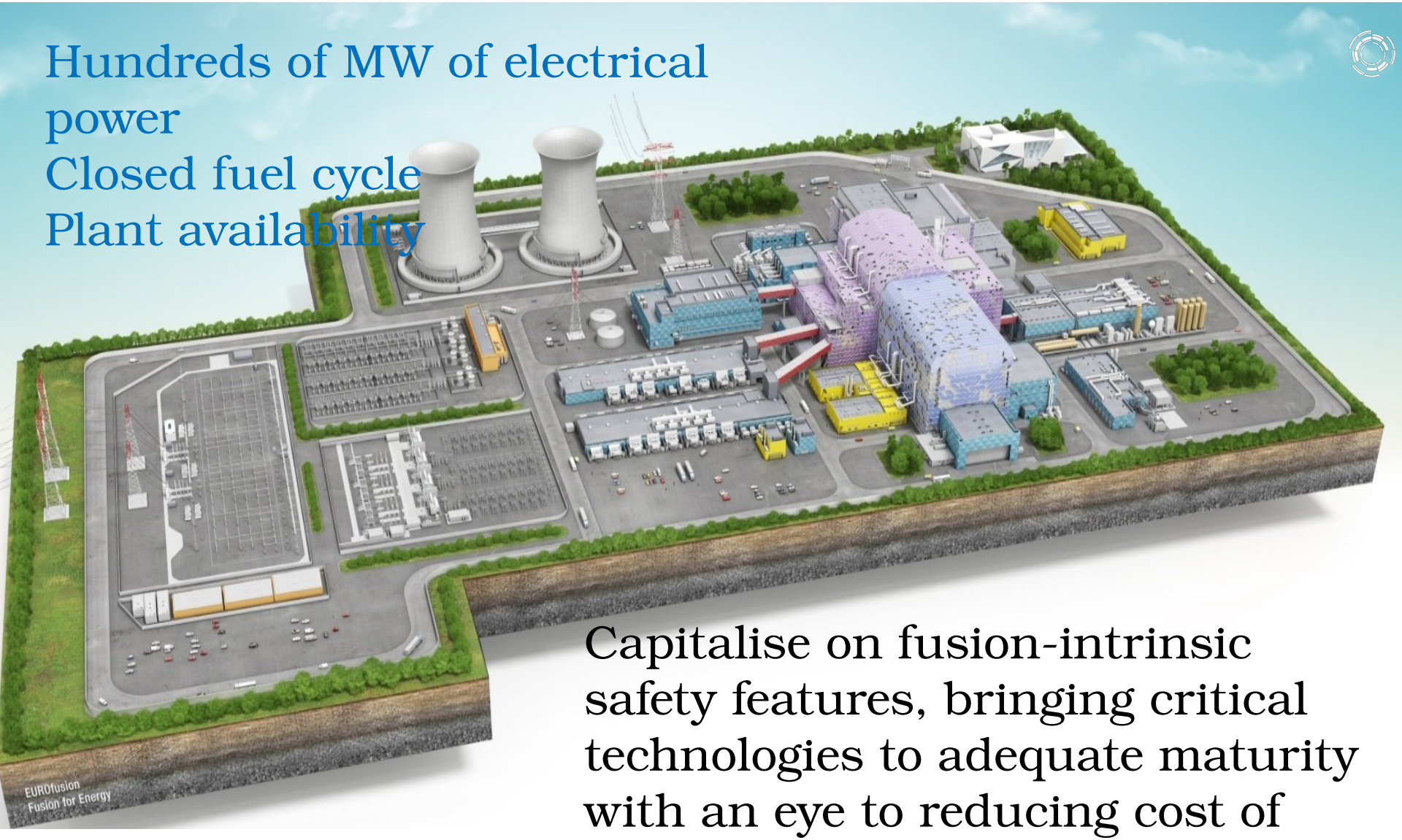


EPFL ....and assembly is in full steam on site



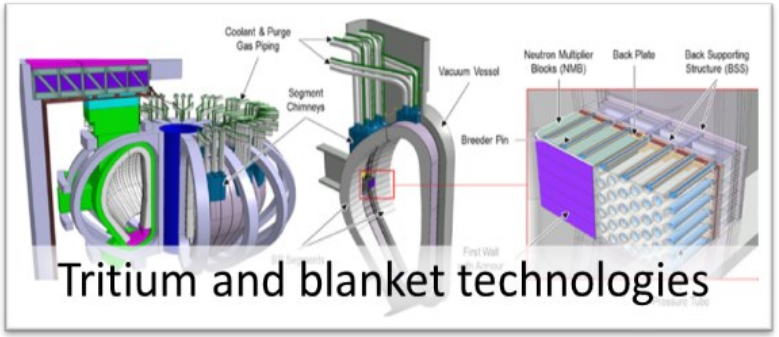
The future: DEMO

Hundreds of MW of electrical power
Closed fuel cycle
Plant availability

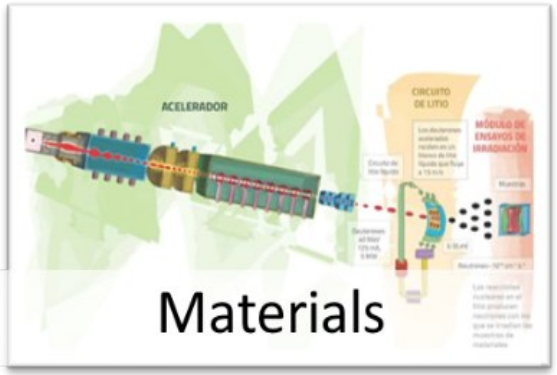


Capitalise on fusion-intrinsic safety features, bringing critical technologies to adequate maturity with an eye to reducing cost of electricity…

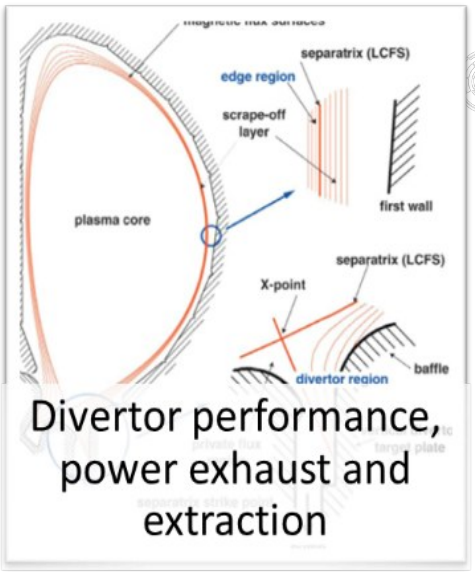
Major gaps in view of DEMO



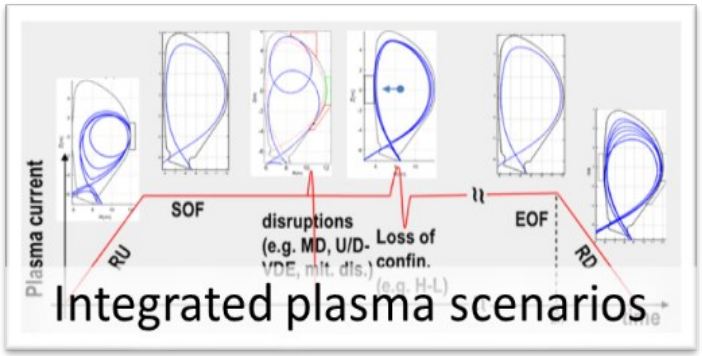
Tritium and blanket technologies



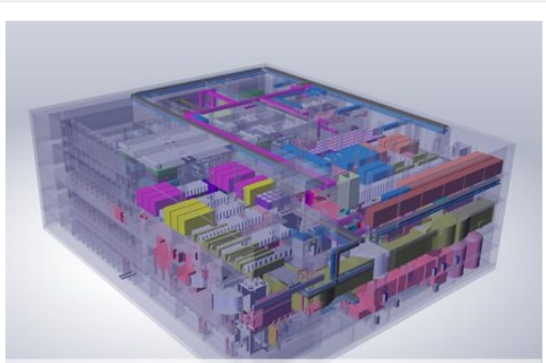
Materials



Divertor performance, power exhaust and extraction



Integrated plasma scenarios


Safety and waste



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EUROfusion

A magnetic fusion power plant

