# Nuclear Fusion and Plasma Physics

## Lecture 2

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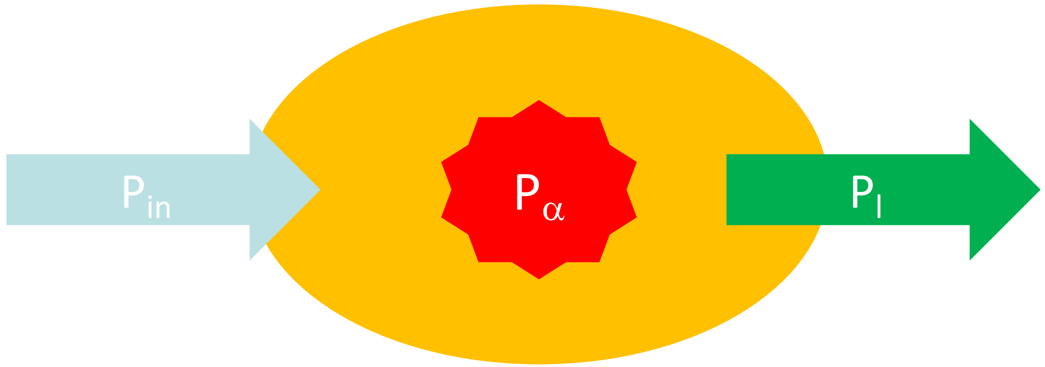
# Reminder: the Lawson criterion

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




- Losses

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

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

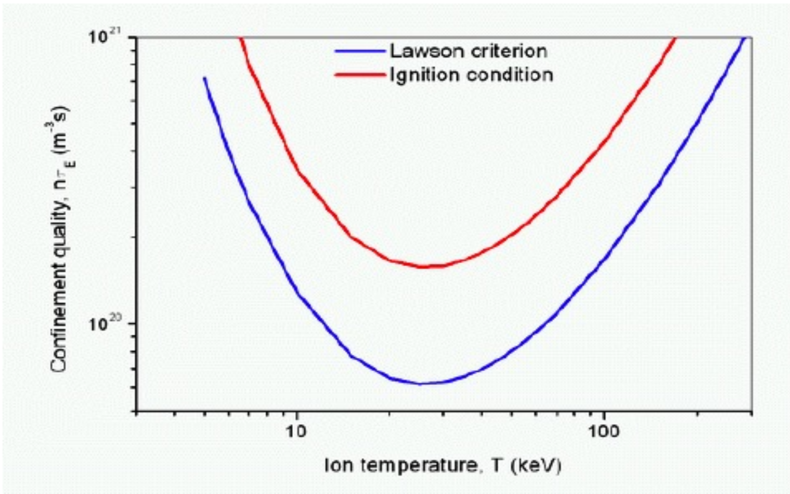
$$n_e\tau_E \left\{ \frac{6/5\langle\sigma v\rangle_{DT}\Delta E_f}{12T} \right\} = n_e\tau_E \left\{ \frac{\langle\sigma v\rangle_{DT}\Delta E_f}{10T} \right\} \geq 1 \qquad \boxed{n_e\tau_e \geq \frac{1}{\mathrm{f(T)}}}$$

**breakeven**

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

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

**ignition**

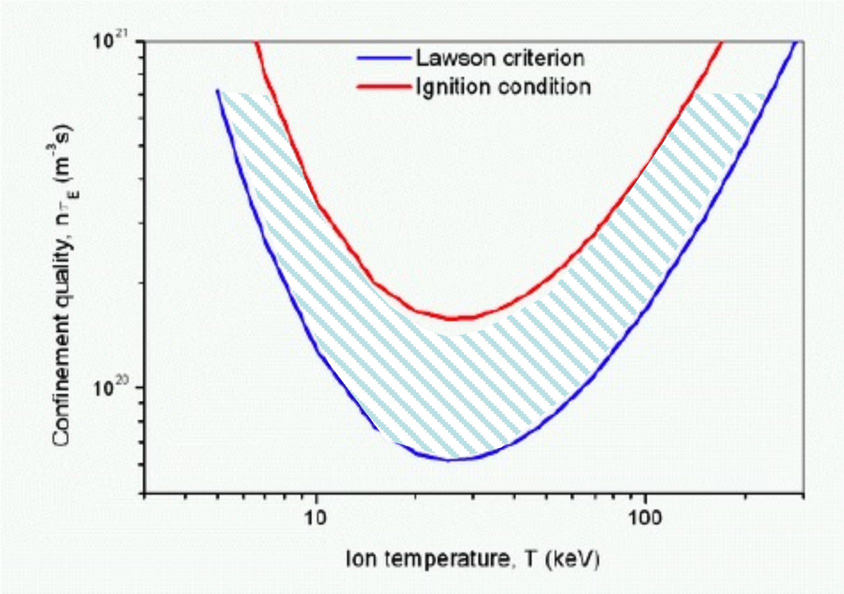


# Reminder: physics & engineering gain factors

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

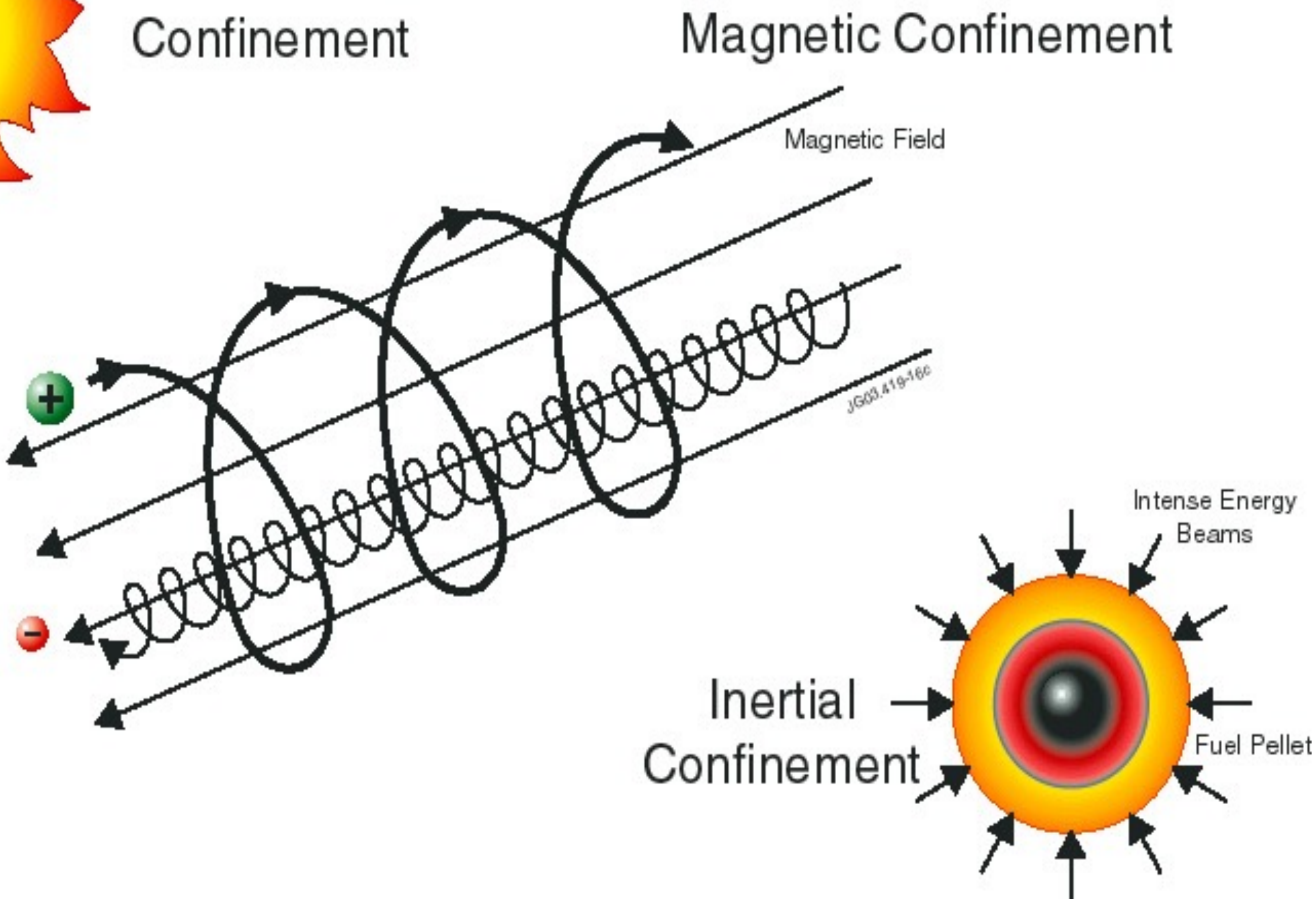
$$Q_E = \frac{\eta[P_f + P_{in}] - P_{\text{in}}}{P_{\text{in}}} = \eta\frac{P_f}{P_{\text{in}}} - (1-\eta) = \eta Q - (1-\eta)$$



**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* $T \geq 10keV$


*Magnetic*

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

$\tau_E \sim 1\ s$

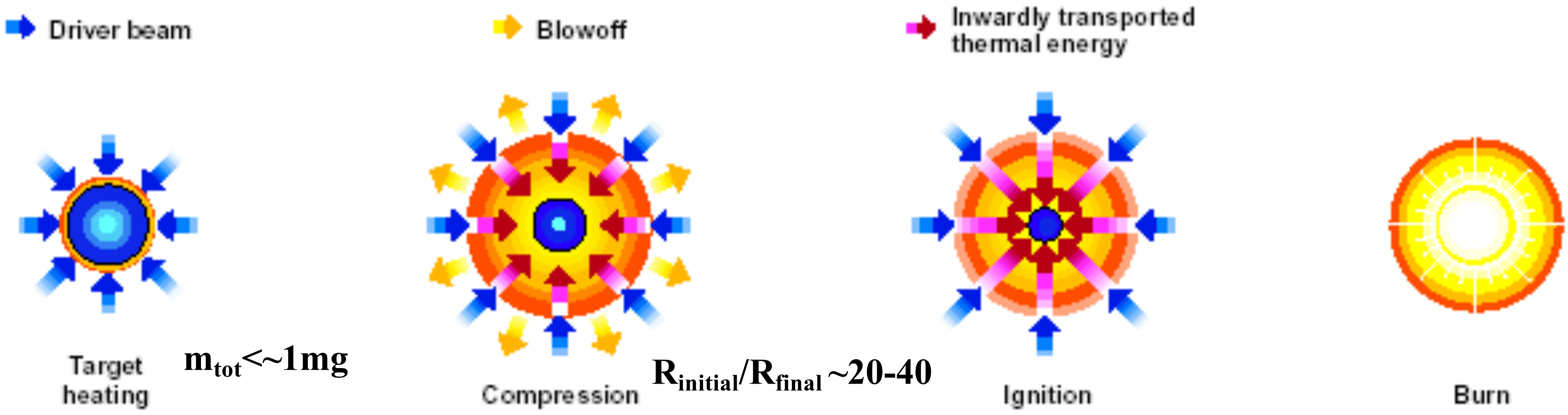
*Inertial*

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

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

# EPFL 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

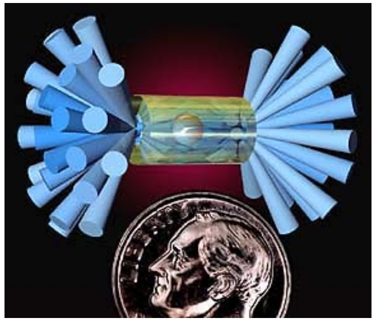
Compression: need ~$10^{12}$ bar to reach $10^{31}$ $m^{-3}$

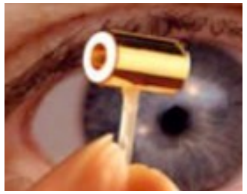
- Light pressure from most intense lasers is ~$10^{6}$ bar, largely insufficient
- Rocket effect
- Shock waves from pellet surface to the center
- Once fusion starts, $\alpha$ heating sustains the reactions

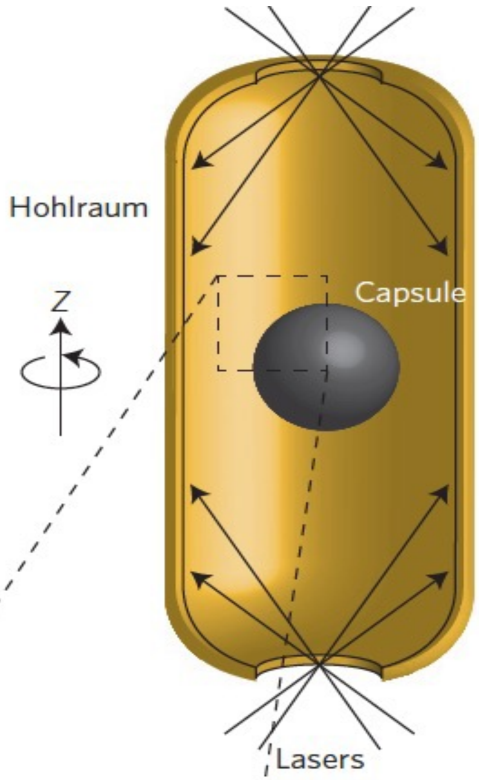
# ICF: direct and indirect laser drive

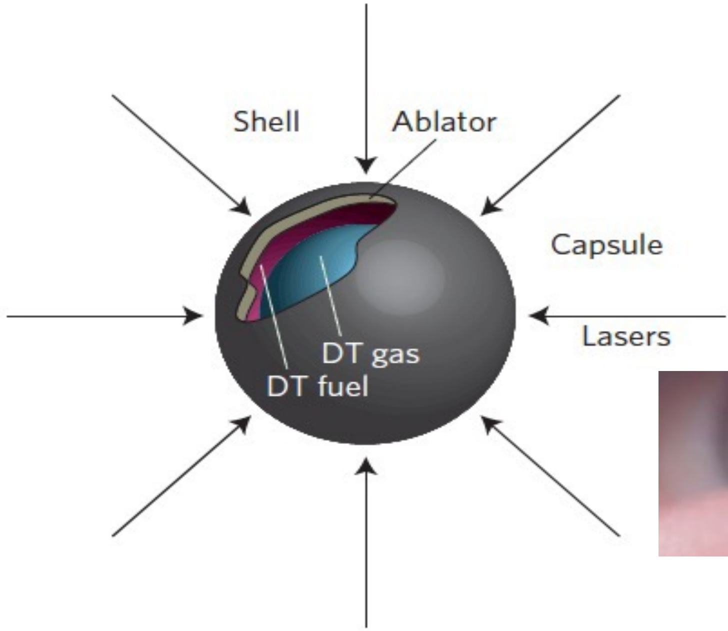
## Indirect drive

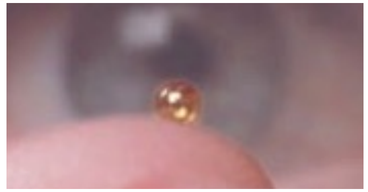
## Direct drive

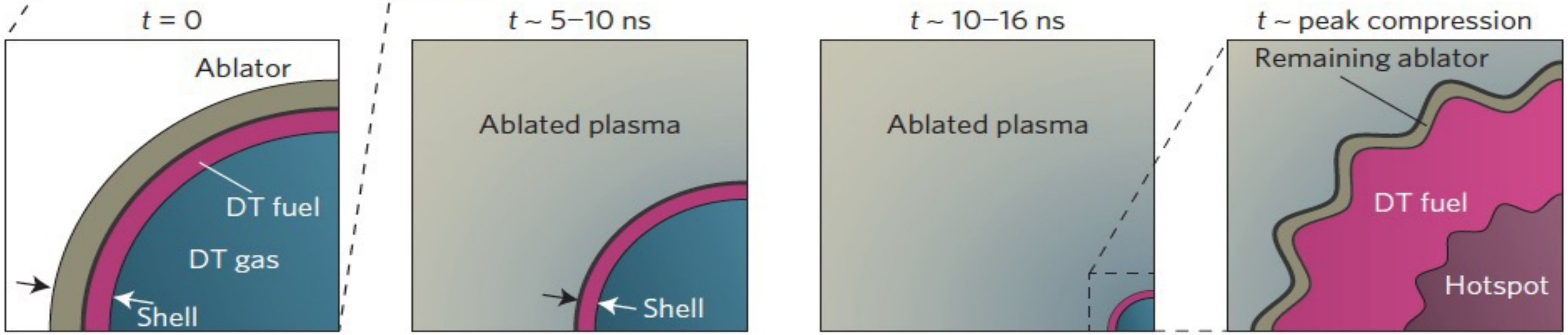








# ICF – laser drive: NIF (US)

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

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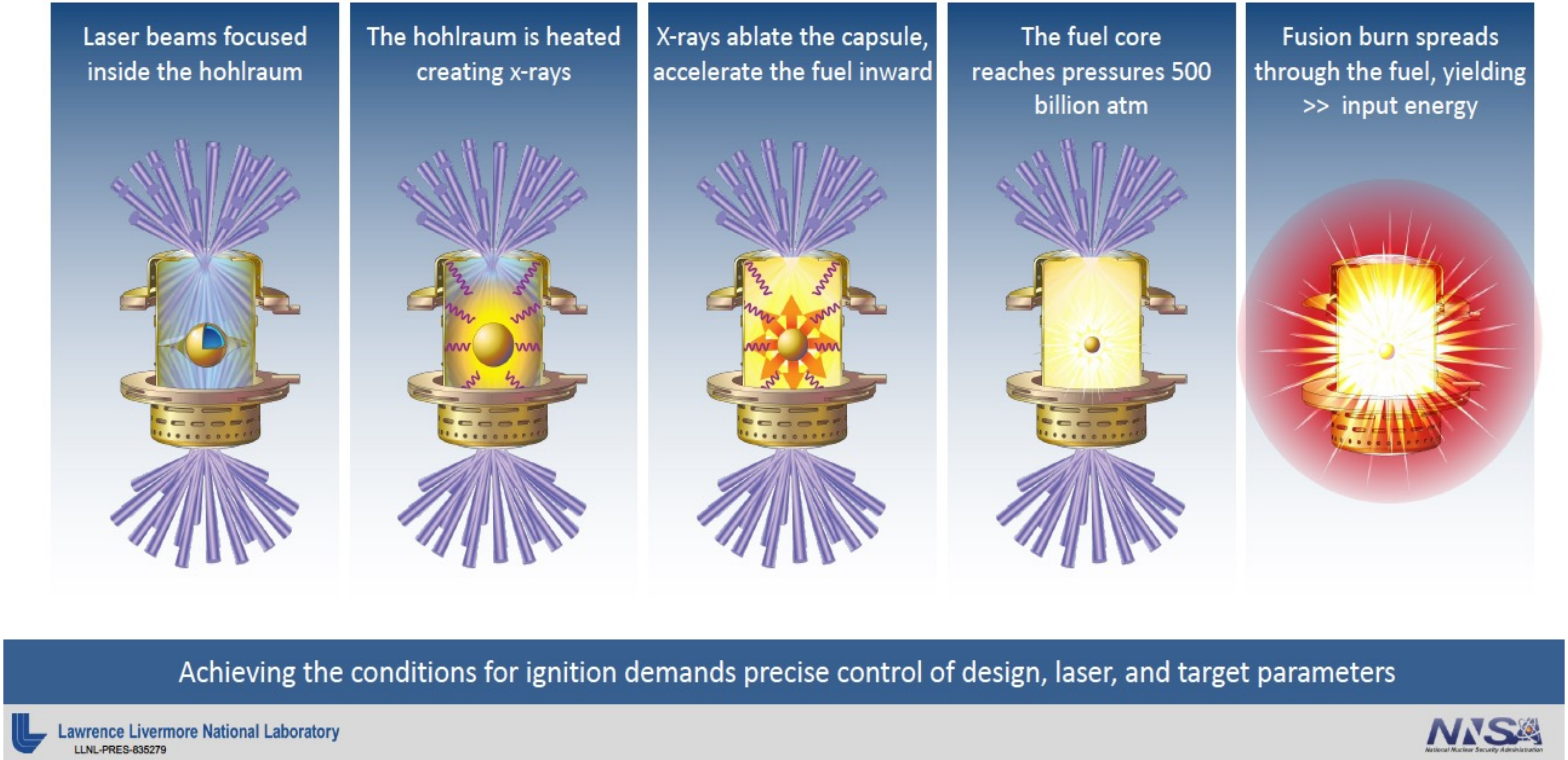
# ICF: indirect laser drive at NIF



# ICF – results @ NIF (US)


nature

nature › news explainer › article

NEWS EXPLAINER | 13 December 2022

## Nuclear-fusion lab achieves 'ignition': what does it mean?

Researchers at the US National Ignition Facility created a reaction that made more energy than they put in.

Jeff Tollefson & Elizabeth Gibney

ENERGY Published December 13, 2022 10:57am EST

## US scientists produce first successful nuclear fusion reaction resulting in net energy gain

Energy leaders called the achievement of fusion ignition a 'major breakthrough'

By Julia Musto | Fox News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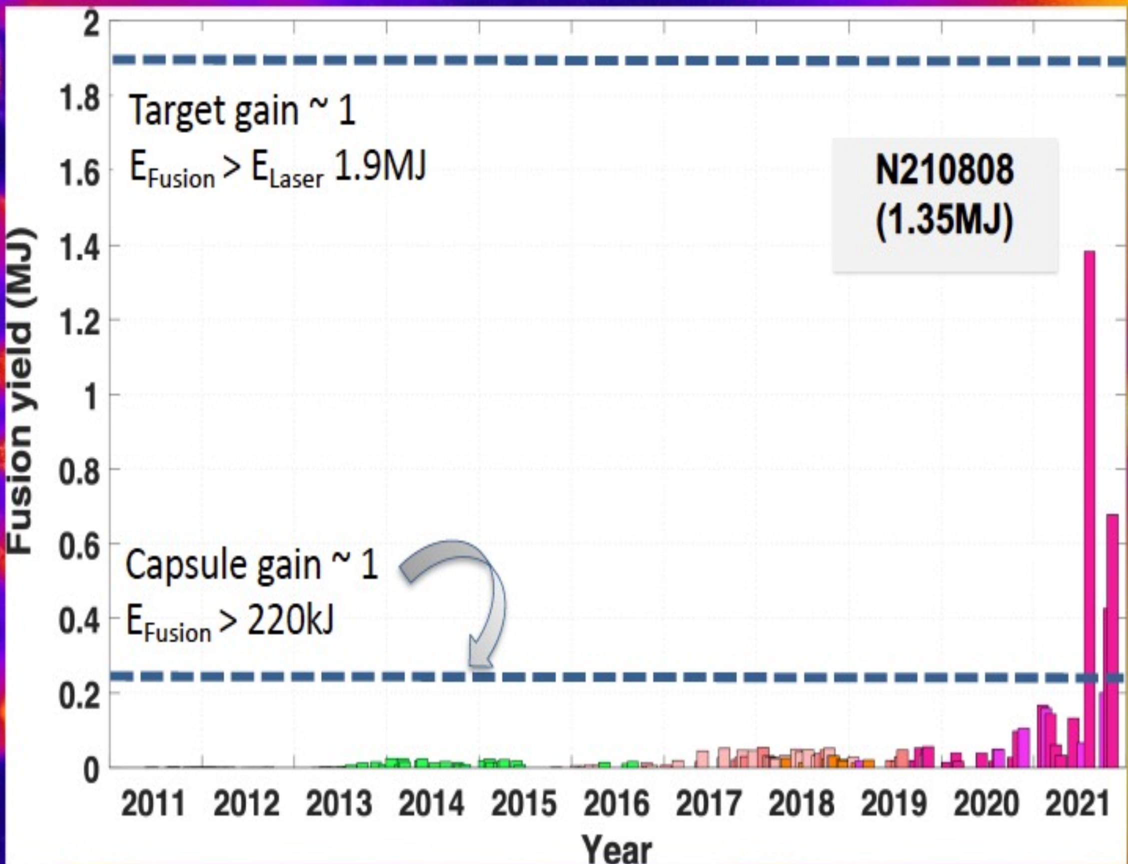
# ICF – results @ NIF (US)

## 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

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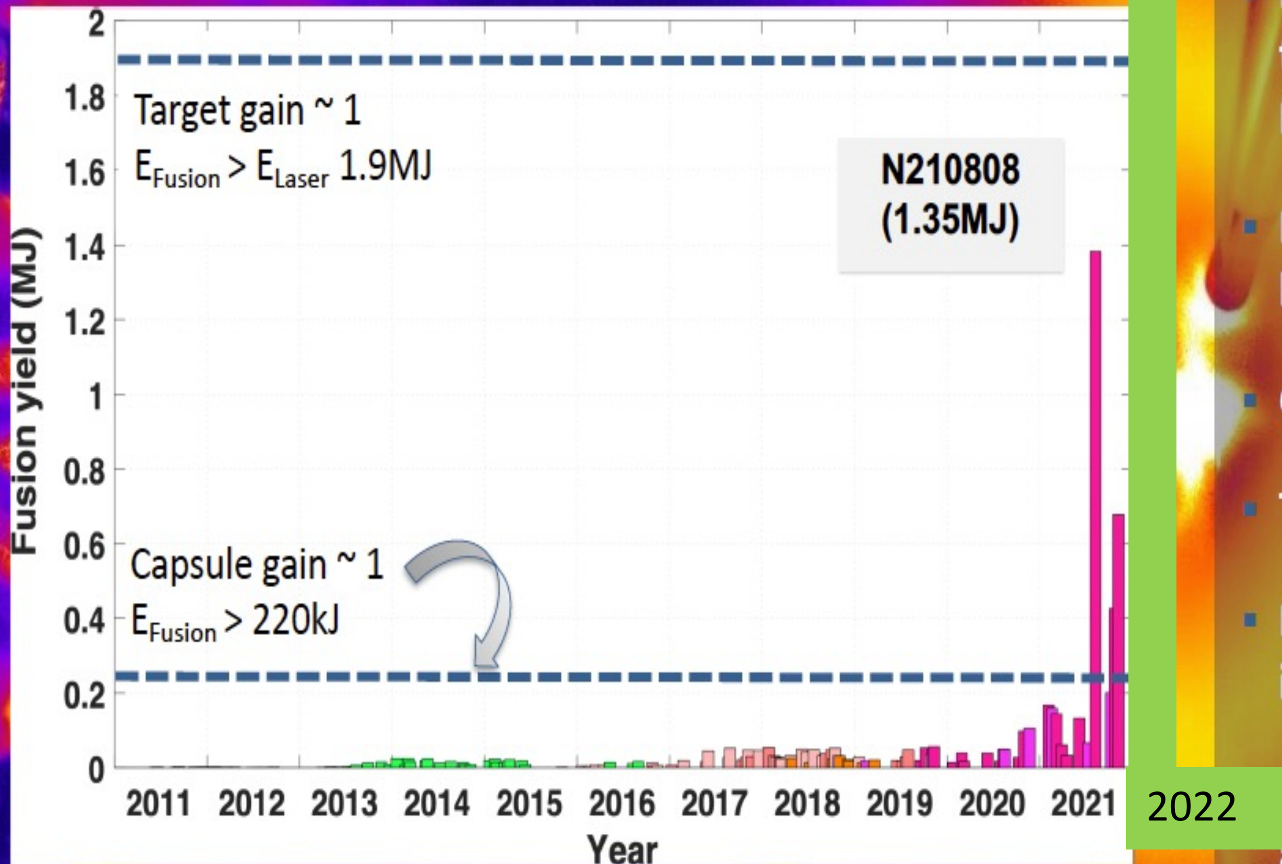


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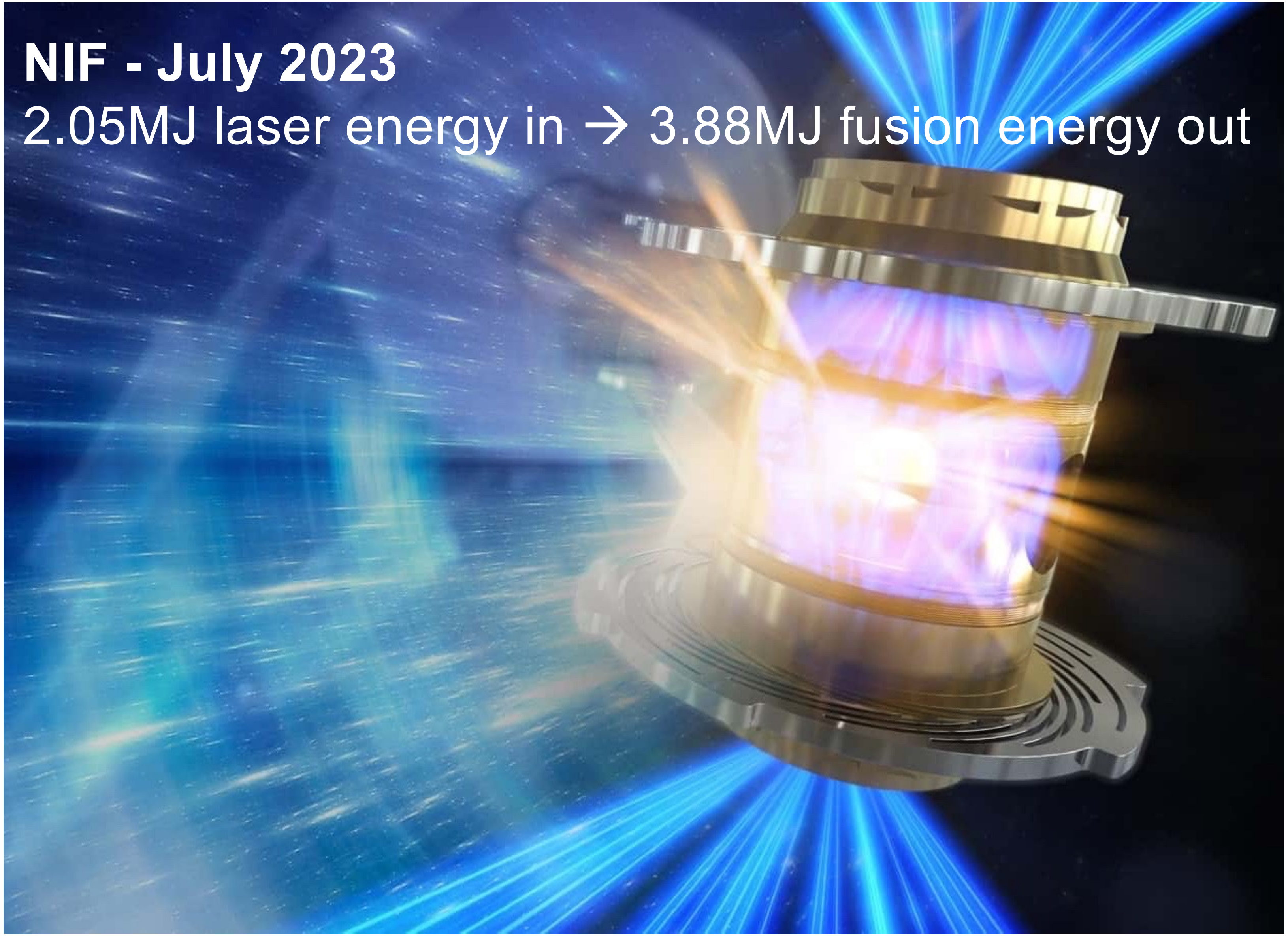
# Most recent ICF – result @ NIF (US)



# ICF: physics issues

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

Pellet design

Laser pulse timing

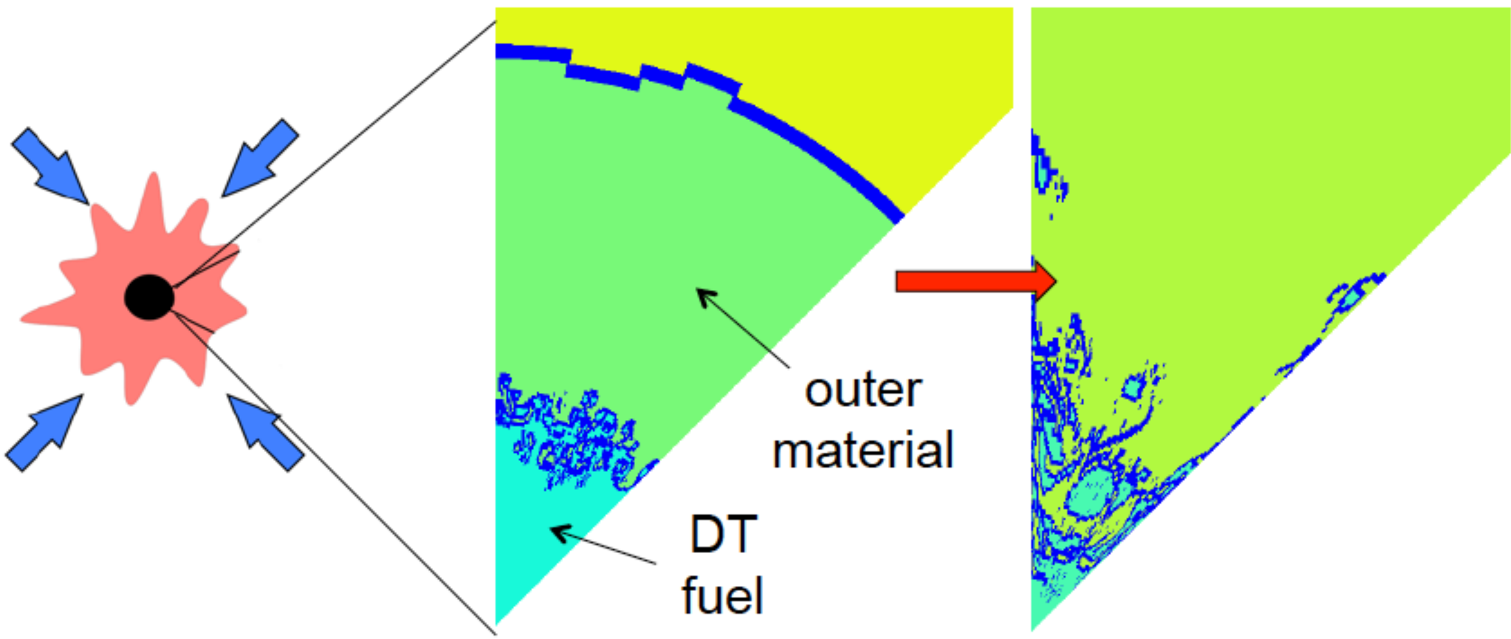
Hydrodynamical stability

Pellet symmetry

Beam alignment, symmetry of drive

Simulated mixing due to Rayleigh-Taylor instability

*Courtesy of Mathias Groth, Aalto Univ.*

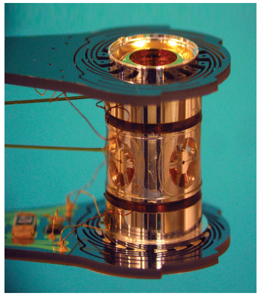


# ICF: engineering issues

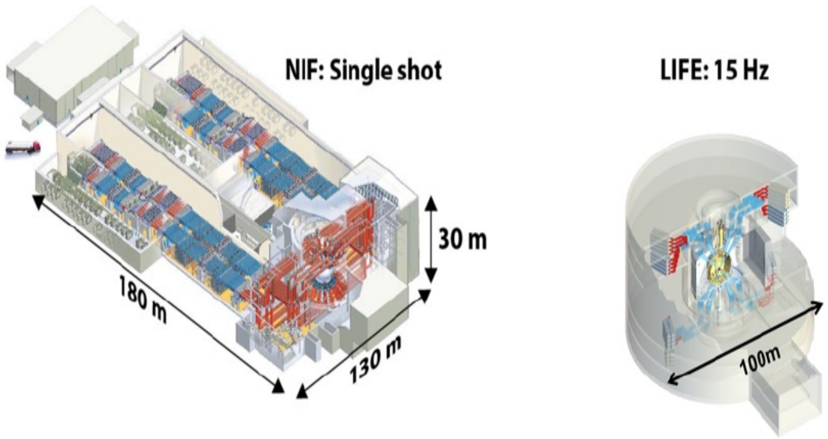
Efficiency, cost and reliability of high energy driver

Materials for first wall of vacuum chamber

Complexity and cost of capsule



From single to repetitive pulses (3-10Hz)

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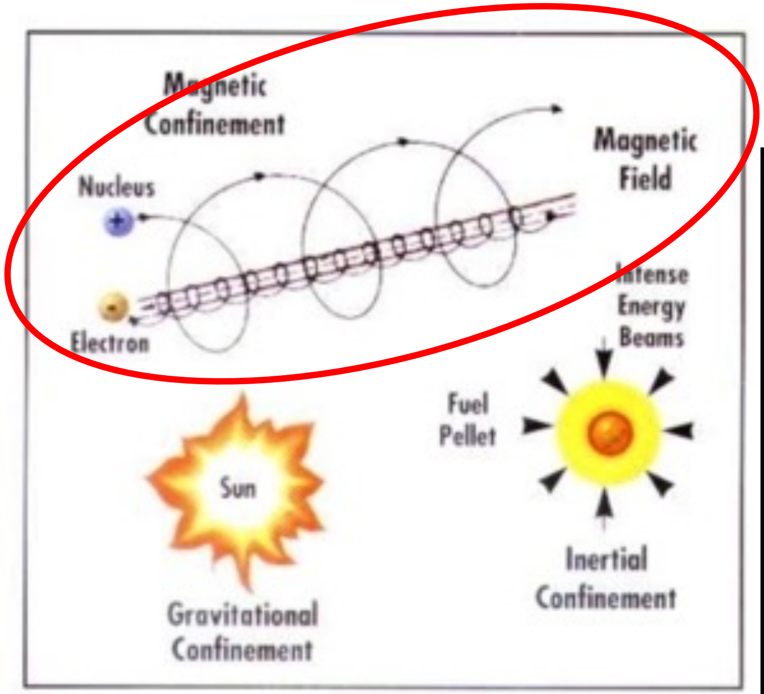
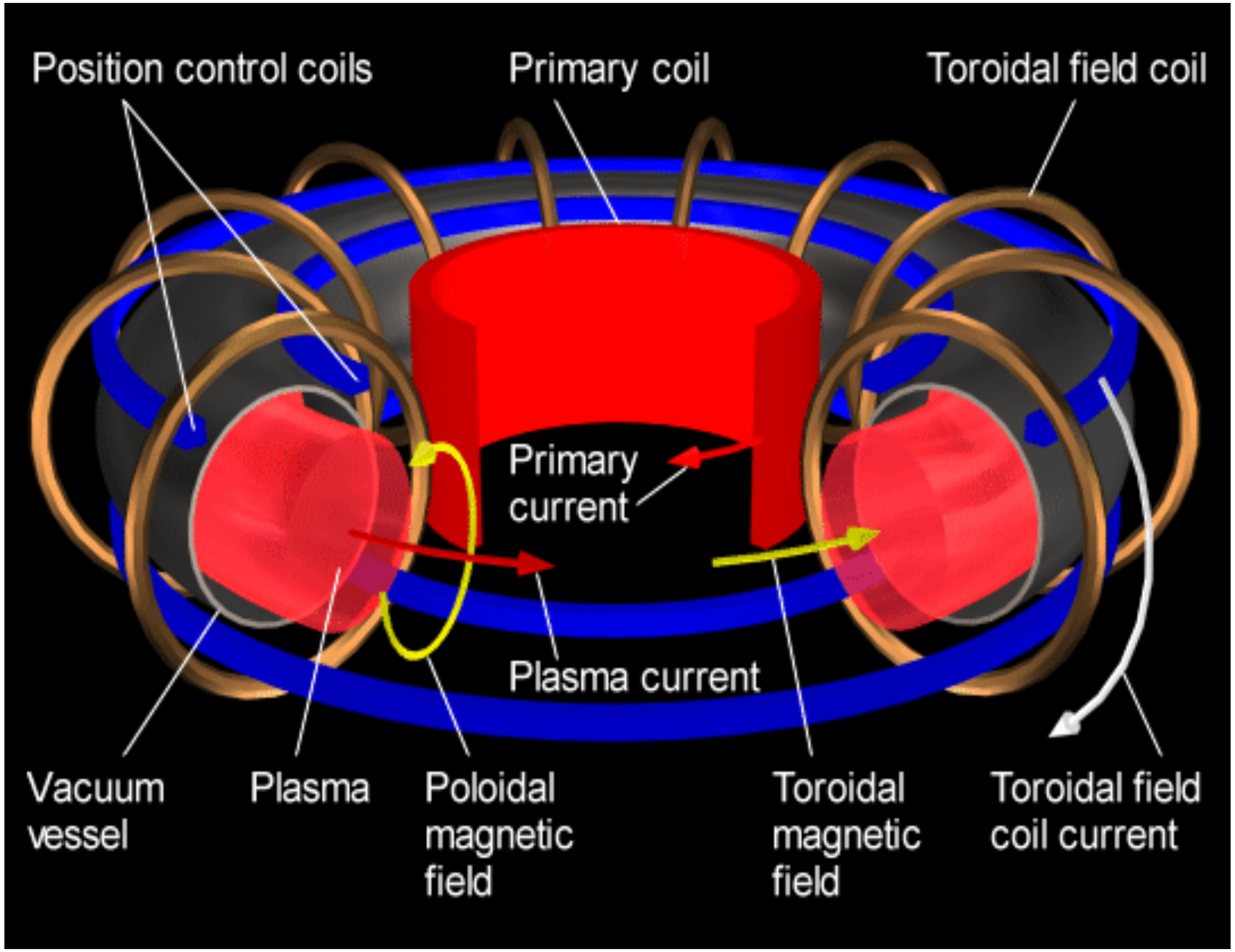
# Plasma confinement by magnetic fields

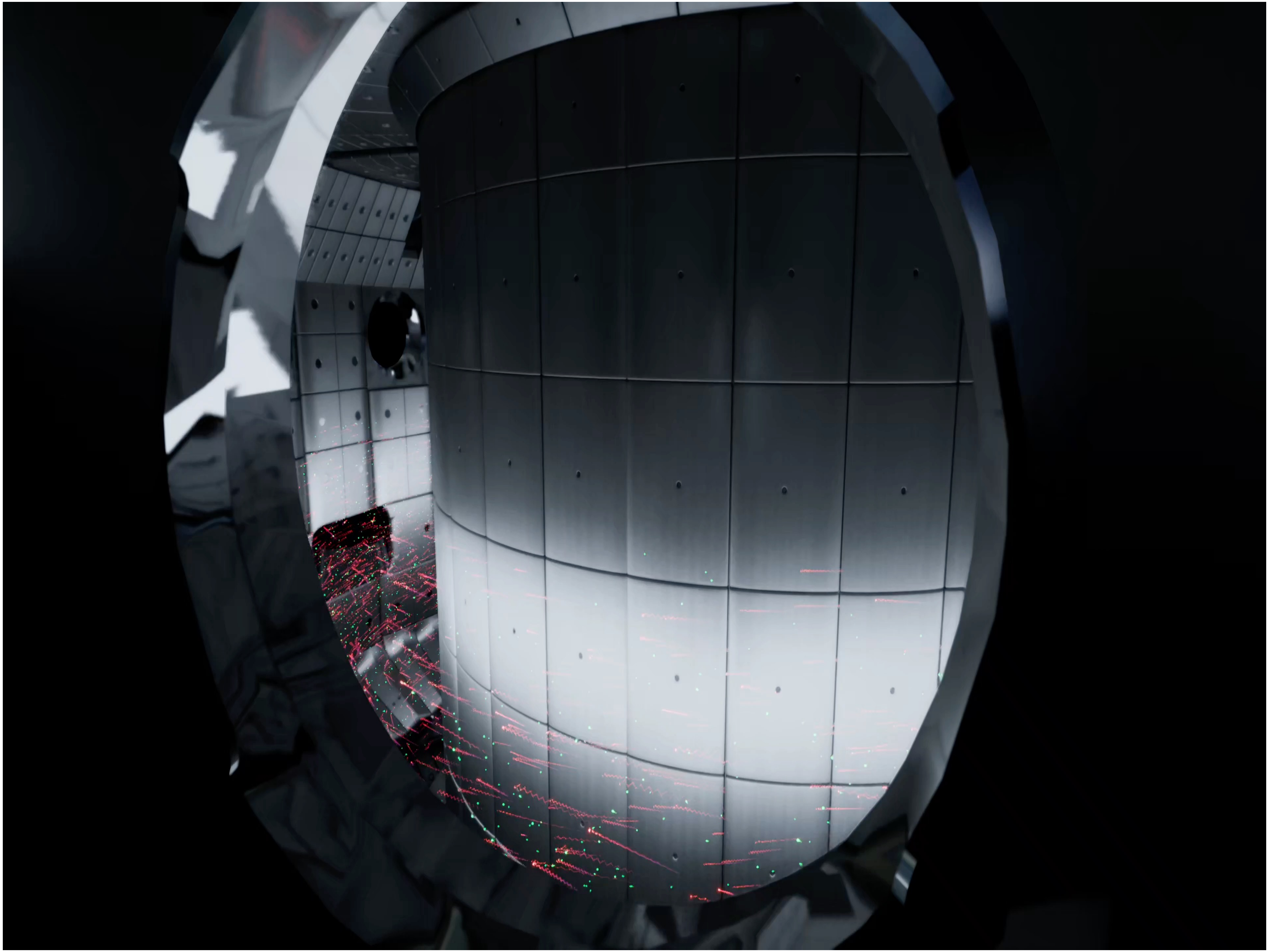



The Tokamak

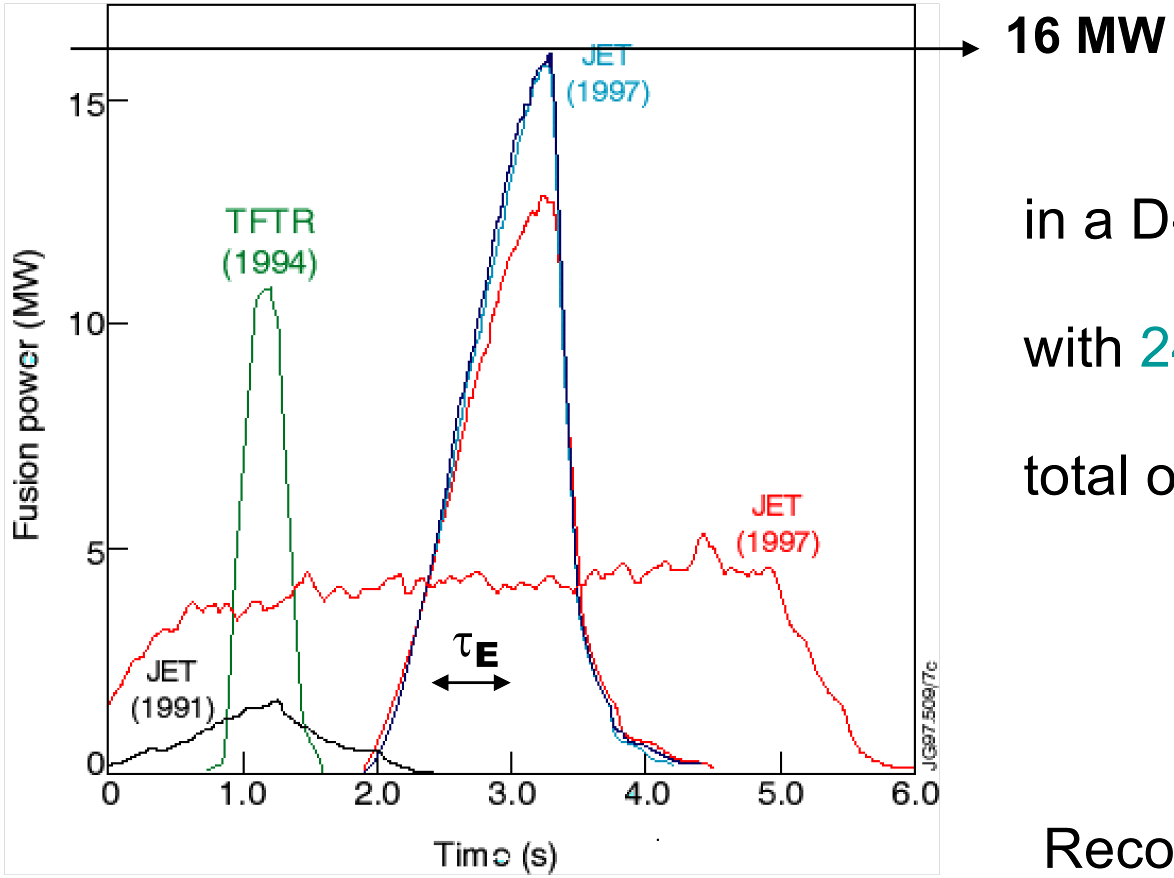



Efficiency of confinement measured by

$\beta$ = 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

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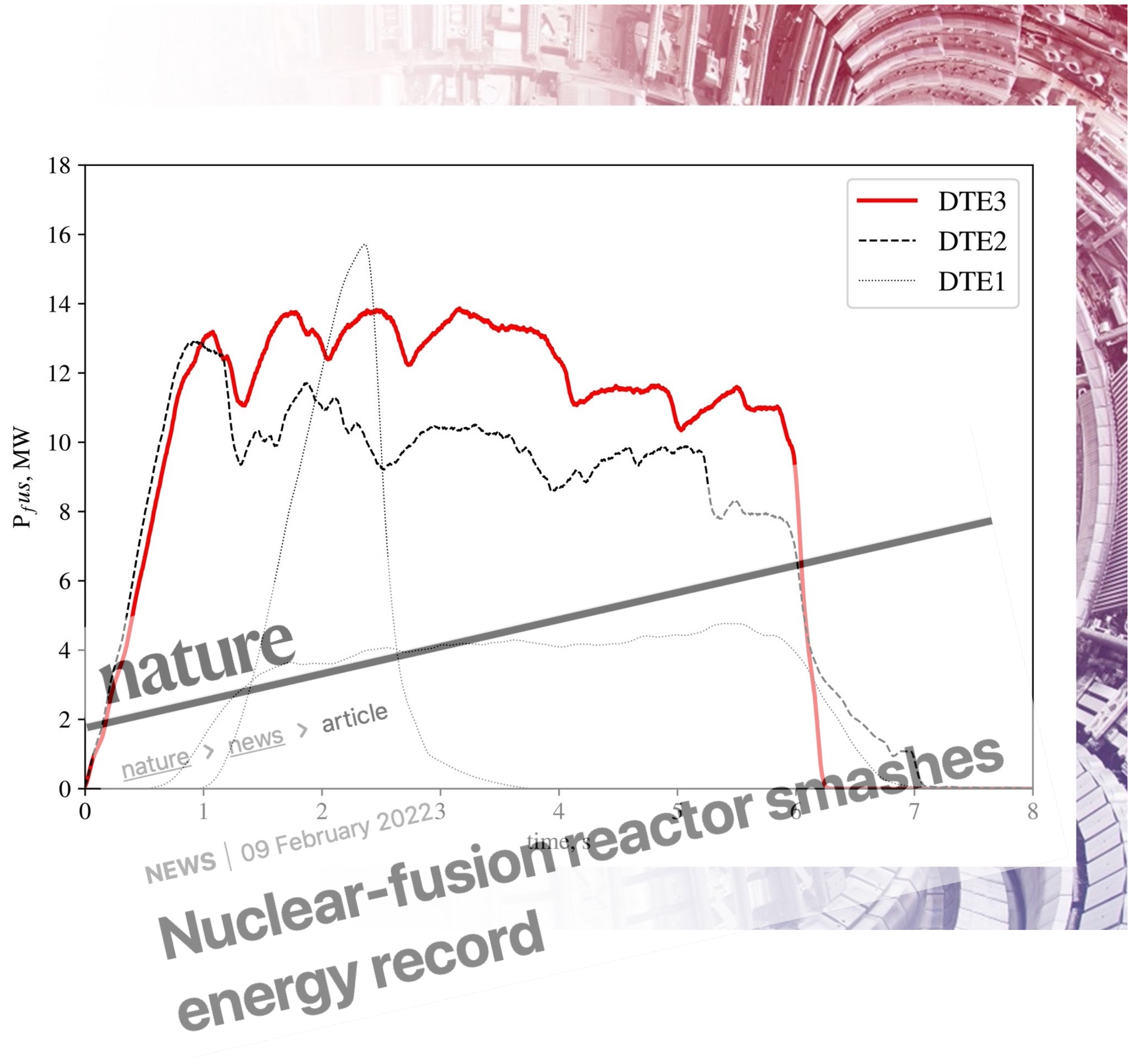
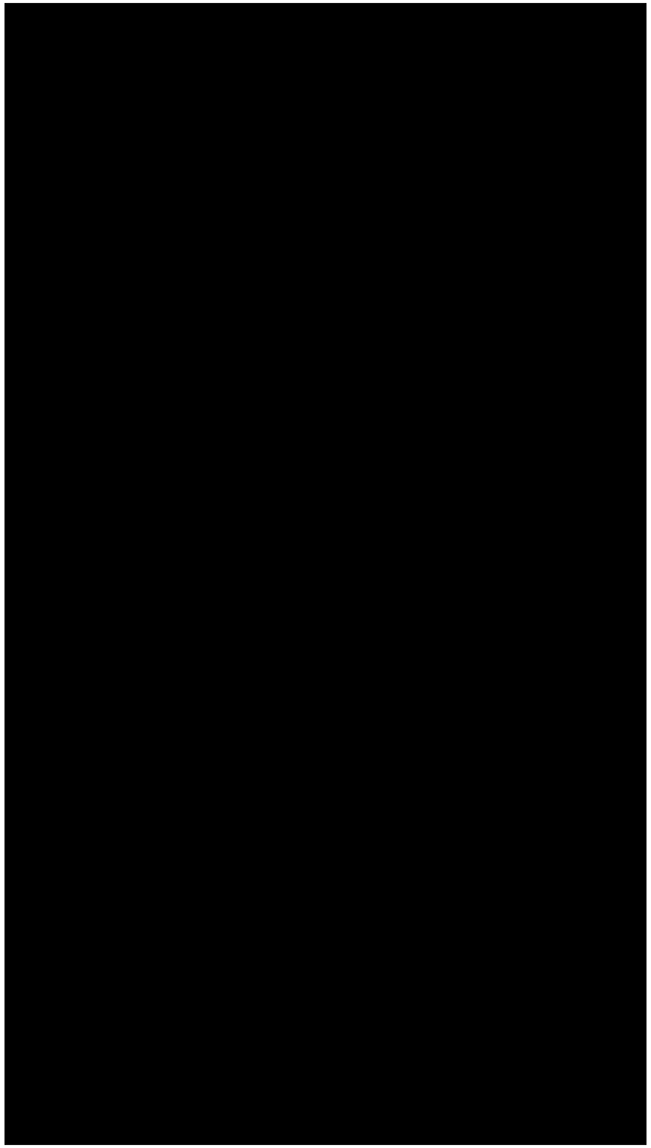
# JET – October 2023
# Fusion energy record 69MJ (0.2mg DT)



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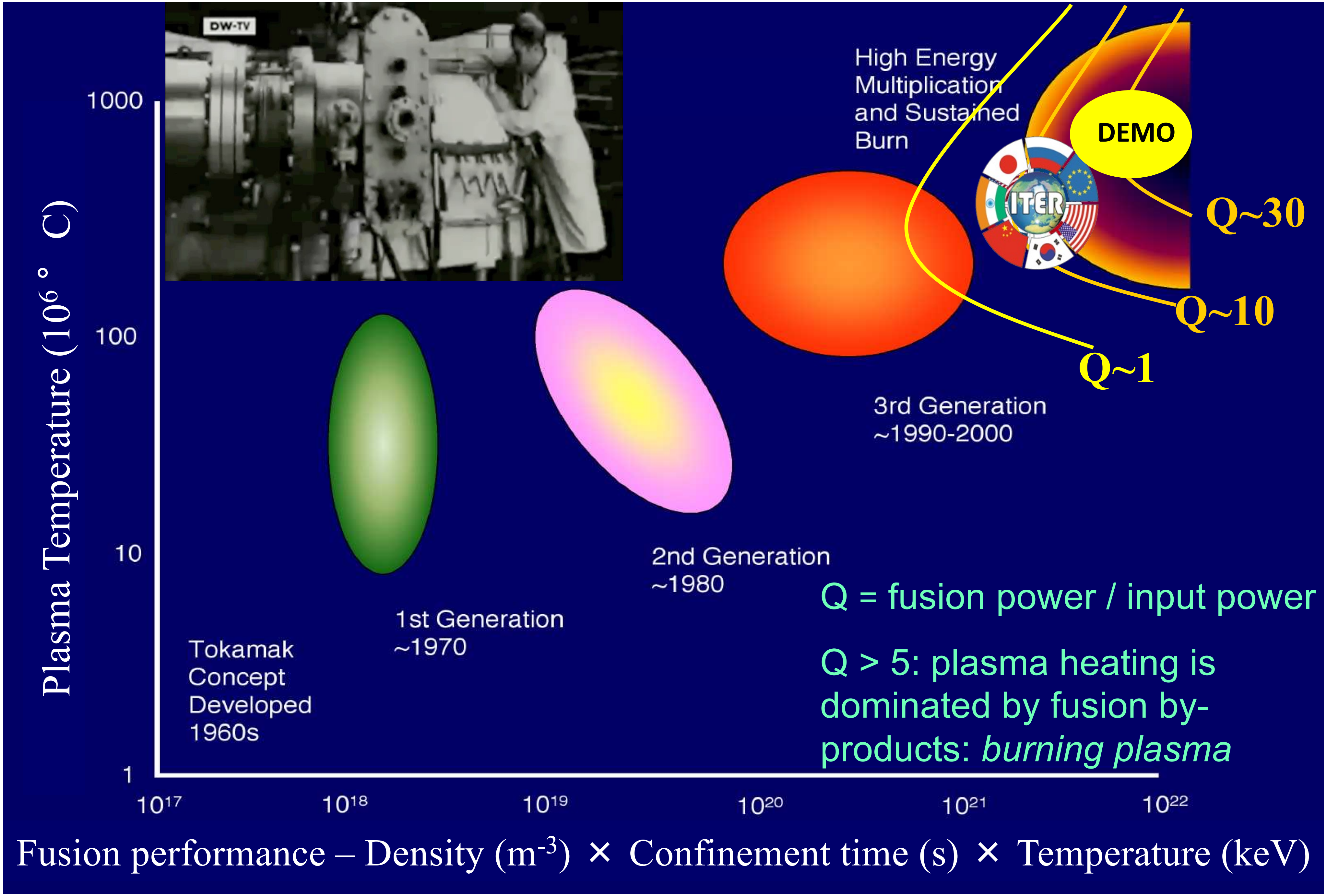
EUROfusion

UK Atomic Energy Authority

# Progress in magnetic fusion



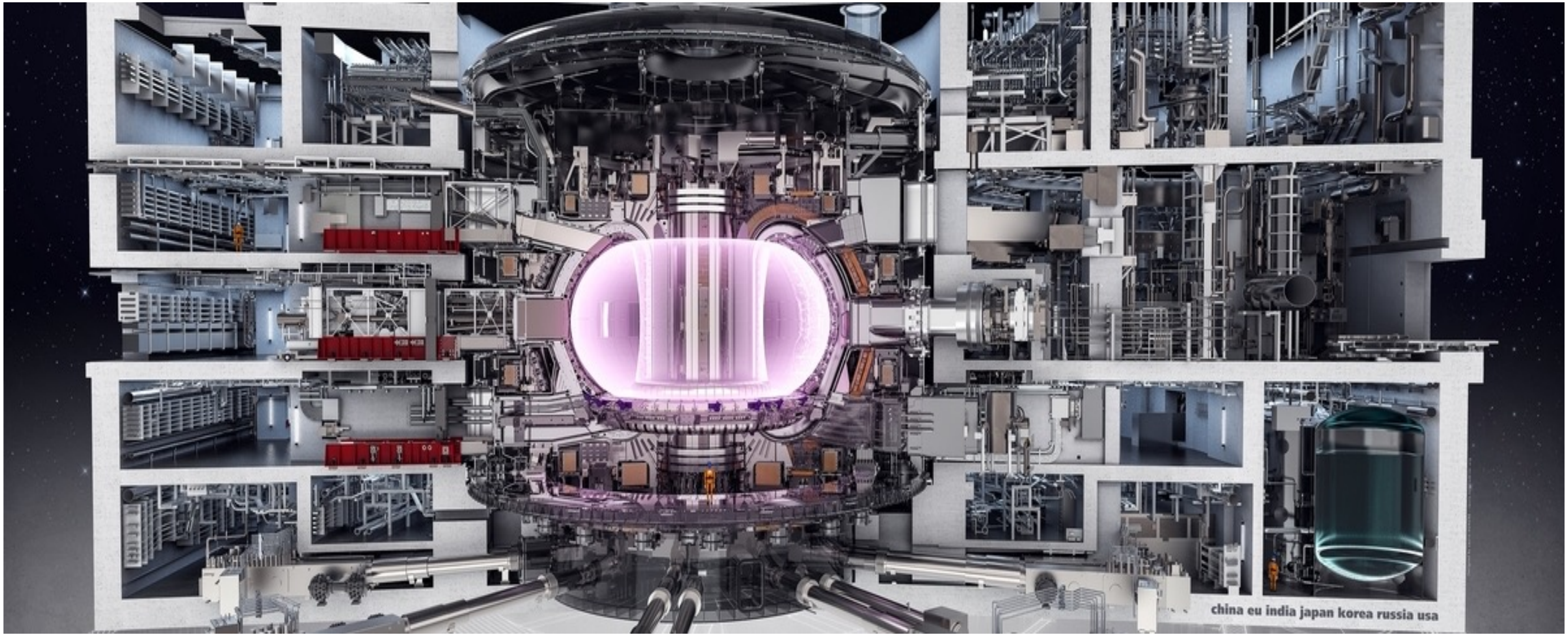
# ITER

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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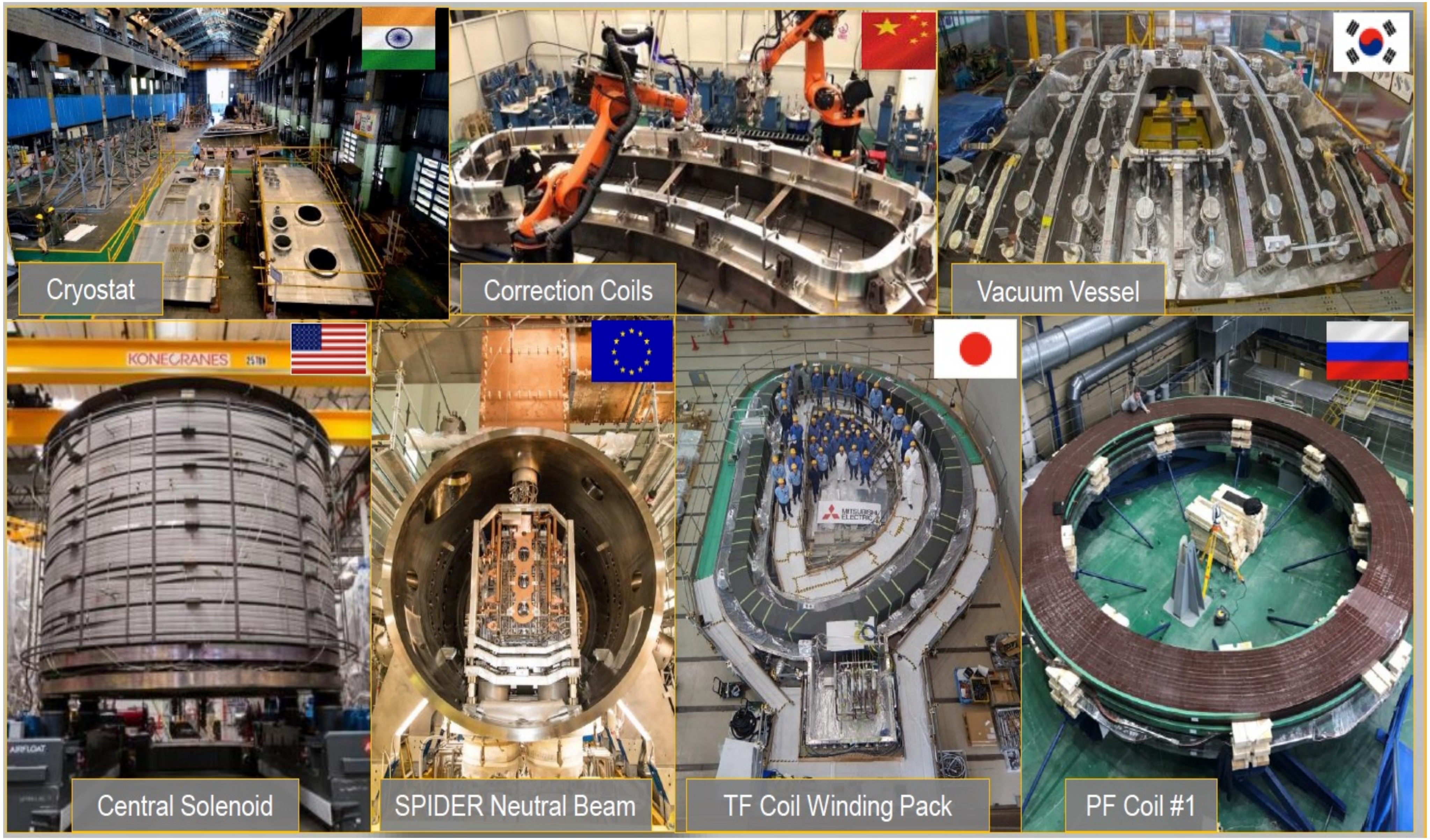
iter china eu india japan korea russia usa

# ITER construction is under way all over the world



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


**New Baseline: start of research operation in 2034; full magnetic energy in 2036 (~3y delay); D-T Operations Phase in 2039 (~4y delay)**

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# 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…

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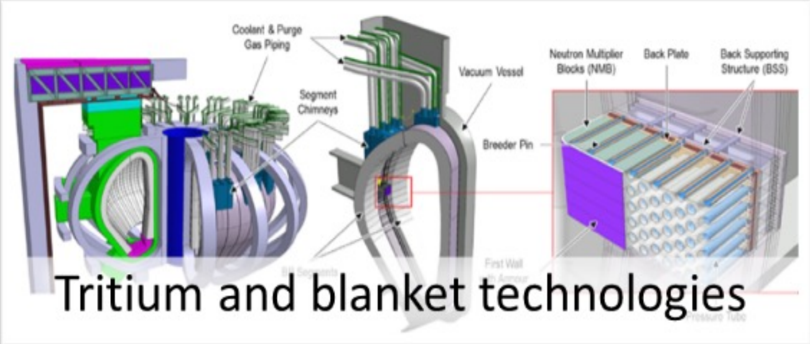
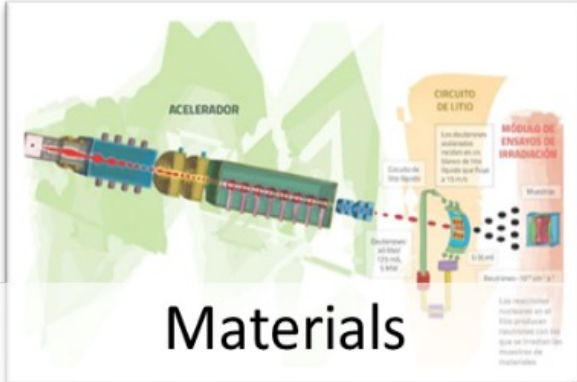
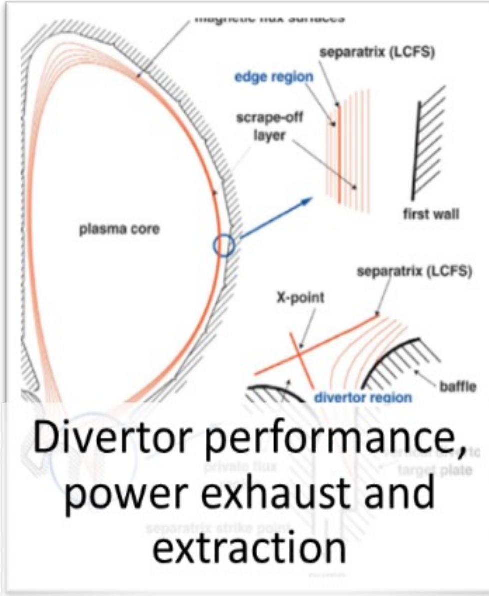
# Major gaps in view of DEMO



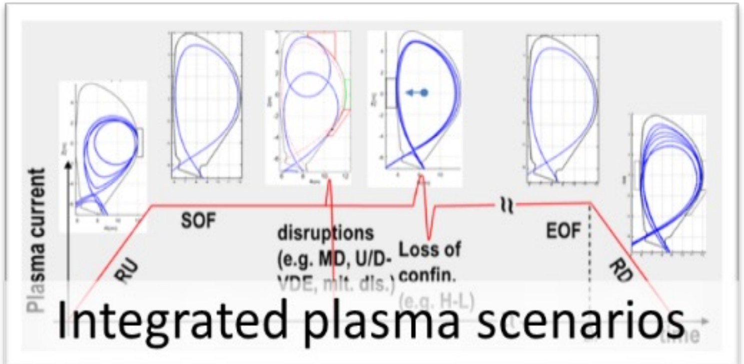
Tritium and blanket technologies



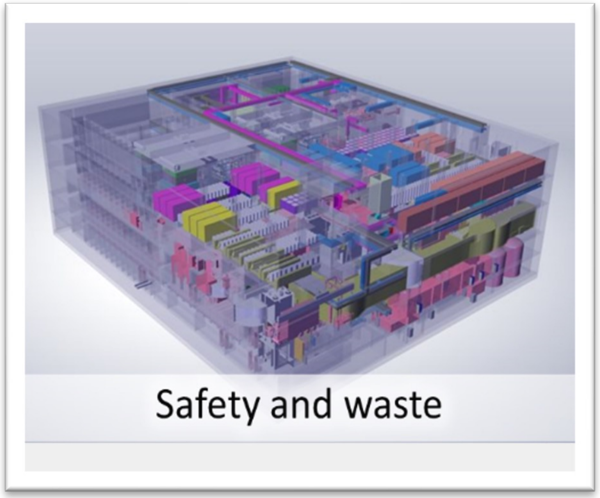
Materials




Divertor performance, power exhaust and extraction




Integrated plasma scenarios



Safety and waste

Remote maintenance

# A magnetic fusion power plant