



Introduction to Controlled Magnetic Fusion

Scientific & technological challenges



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Acknowledgements: X. Garbet, Ph. Ghendrih,
G. Dif-Pradalier

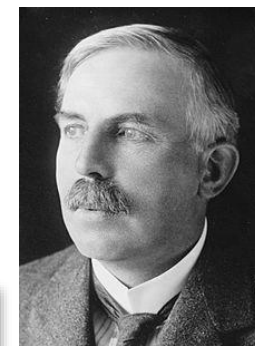
IMT, 25.05.2022



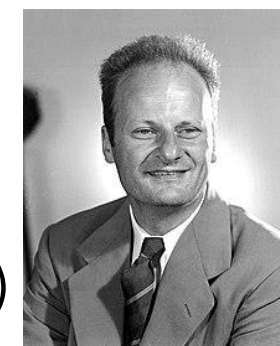
1920: **Arthur Eddington** (UK) suggests that **stars** draw their energy from the fusion of hydrogen into helium



1928: **George Gamow** (Ukraine-USA) introduces the mathematical basis for **quantum tunneling** (→ explains α -radioactivity)

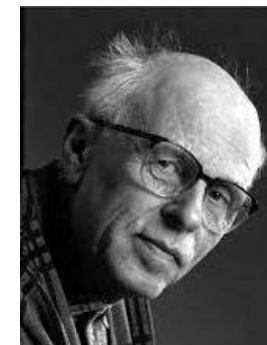
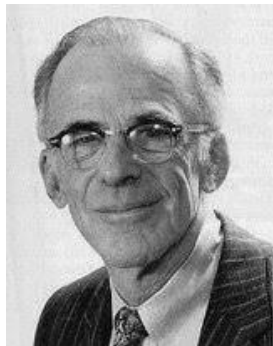


1934: **Ernest Rutherford** (NZ-UK) & Mark Oliphant (UK) perform 1st beam-target D-**fusion** in Cavendish lab



1938: **Hans Bethe** (USA) explains **what is thought to power the sun**: C-N-O fusion reaction (actually p-p, as proposed by Gamow & Von Weizsäcker, 1937)

- 1950: **Tokamak** concept by **Andrei Sakharov** & **Igor Tamm** (USSR)



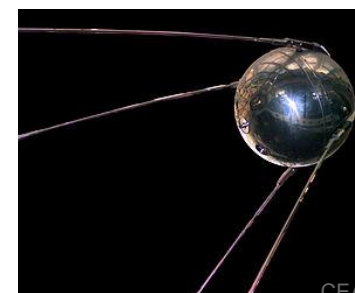
- 1950: **Stellarator** concept by **Lyman Spitzer** (USA)

- 1952: First **H-bomb** "Ivy Mike" (USA) of 10.5 Mt TNT in Marshall islands, Teller-Ulam design (Hiroshima & Nagasaki atomic bombs ~12 kt)



- 1955: "Atoms for Peace" conf. on D. Eisenhower's initiative → **IAEA** created in 1956

- 1957: **Sputnik 1** → Space Race as part of Cold War



- 1958: 2nd IAEA conf. "Atoms for Peace" (Geneva): many \neq concepts for controlled magnetic confinement
- 1968: Breakthrough at IAEA (Novosibirsk) by **Lev Artsimovich** (USSR) \rightarrow **1 keV** achieved in T3 Tokamak (< 100 eV in other machines)
- 1969: UKAEA team confirms Russian results (Thomson scattering)
- 1983: 1st plasma in **Joint European Torus** (Culham, UK)
- 1985: launch of an international effort on fusion by **Ronald Reagan** & **Andrei Gorbachev** \rightarrow **ITER**



■ Basics on fusion

- Fusion on Earth
- Advantages & drawbacks

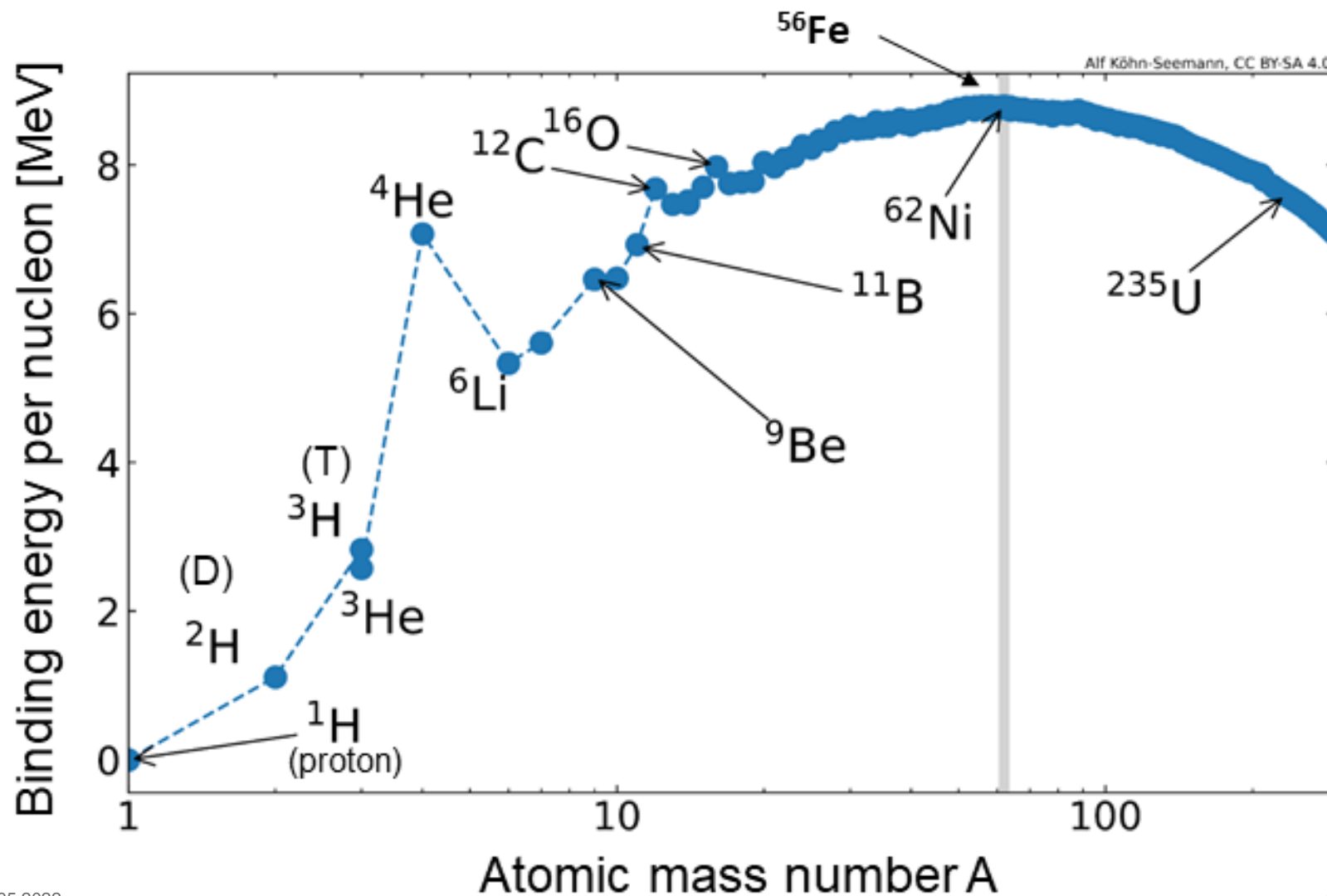
■ Controlled magnetic fusion

- Confinement
- Key physics issues

■ ITER

- Scientific program... paved by decades of experiments
- Present status

Binding energy per nucleon $B(A, Z) \equiv (Zm_p + Nm_n)c^2 - M(A, Z)c^2$



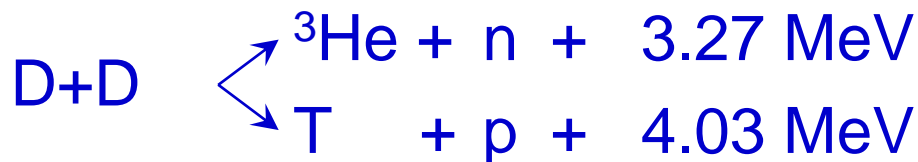
Three main reactions

$$\text{Cross-section} = \frac{\text{Nb of reacting nuclei / time}}{\text{Nb of impacting nuclei / time / surface}}$$

Most "easy"

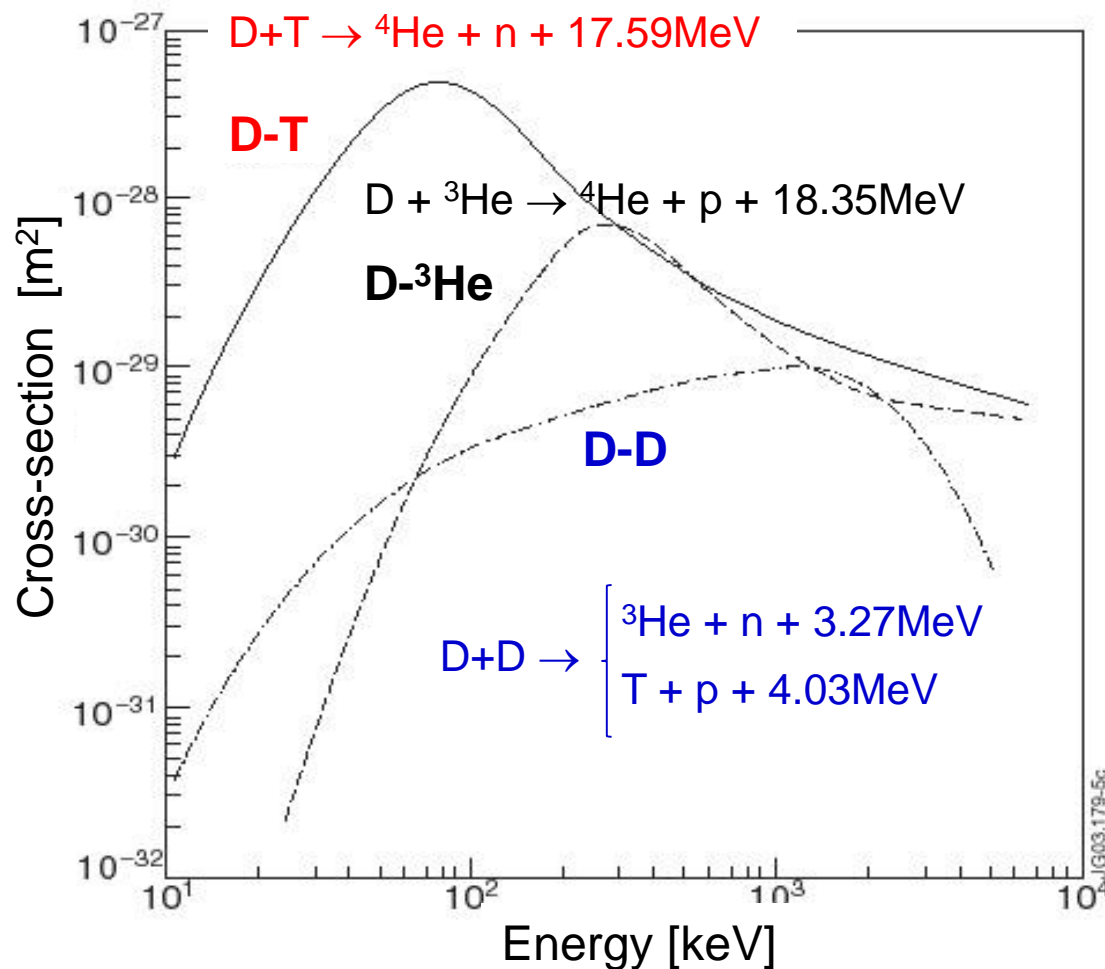
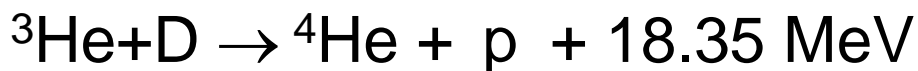


Abundant fuel



No neutrons

(actually non-vanishing amount)



D-T fusion – the principles (I)



Hydrogen isotopes

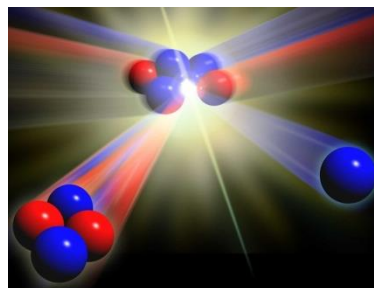
Stable **Unstable**

Helium

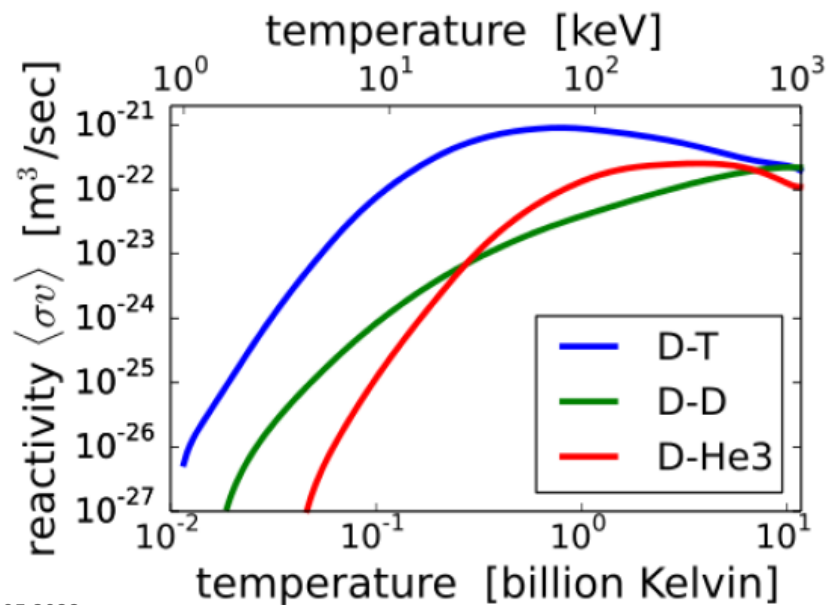
stable φ & χ

Neutron

- **must be produced**
- **not key for ITER**



- **impact on device**
- **used to produce T**
- **not key for ITER**



Threshold condition for fusion

$E_{\text{th}} \geq 10 \text{ keV} \rightarrow$ **Plasma state**

\rightarrow interaction distance 10^{-13} m

Self-heated Fusion (ignition)

$$nT \tau_E > 6 \cdot 10^{21} \text{ m}^{-3} \cdot \text{keV} \cdot \text{s}$$

MHD Turbulent
stability transport

$$\tau_E = \frac{\text{energy content}}{\text{loss power}} \Rightarrow \text{governs fusion performance}$$

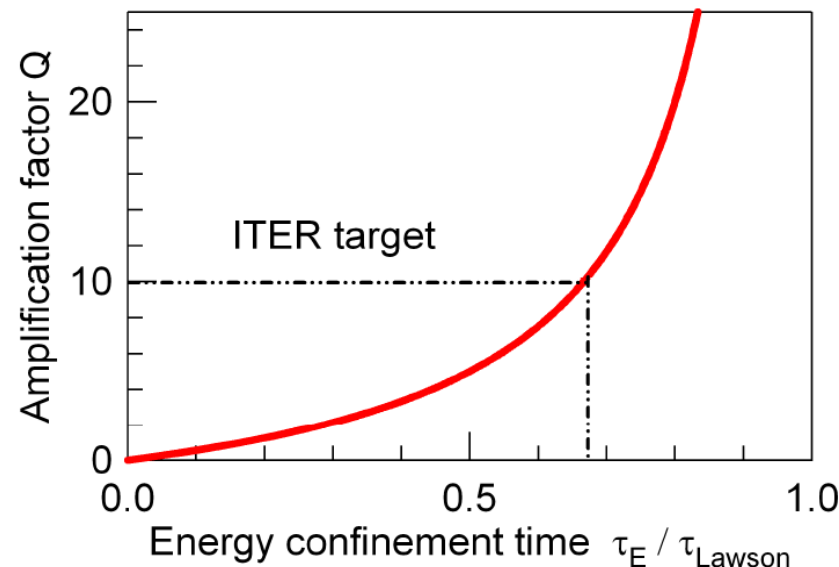
► Magnetic confinement

$T \approx 20 \text{ keV}$ (threshold reaction)

$n \approx 10^{20} \text{ m}^{-3}$ ($\beta = P_{\text{kin}}/P_{\text{magn}} < 1$)

⇒ Requires $\tau_E \approx 3 \text{ s}$

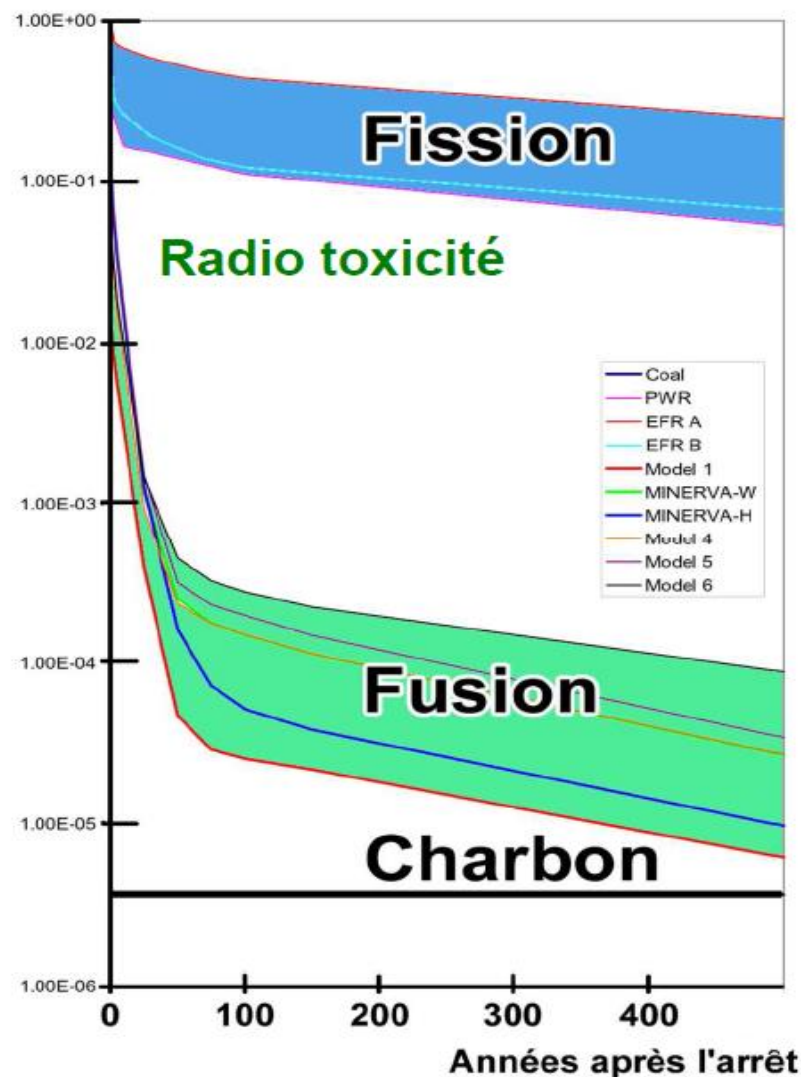
$$Q = P_{\text{fus}} / P_{\text{add}}$$



⇒ Pressure ~ few atm
($P_{\text{Sun}} \sim 10^{11} \text{ atm}$)

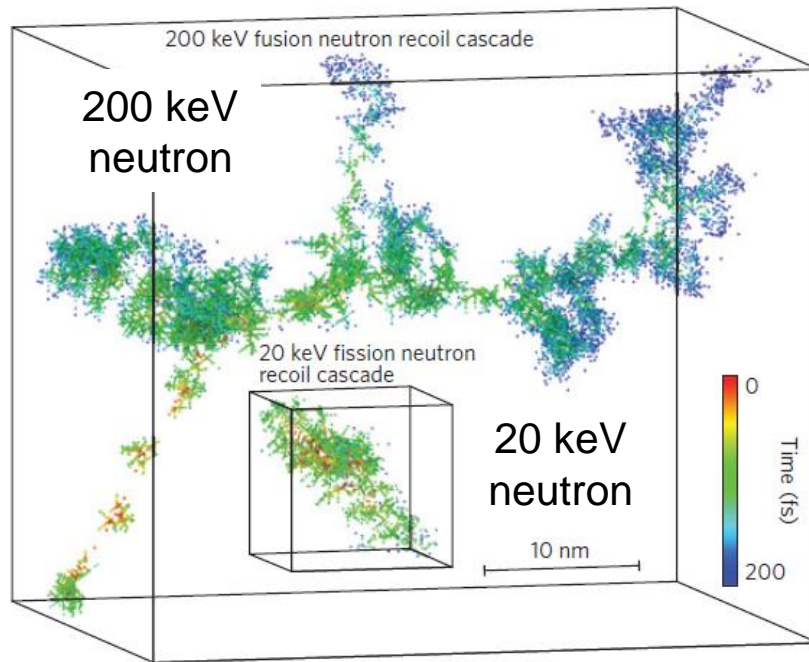
- **Safety: no chain reaction**
(neutrons do NOT participate to reaction)
- **Fuel: Deuterium** (sea 32mg/kg)
Lithium (earth 20mg/kg)
 - abundant
 - well distributed on Earth
- **Waste:**
 - Small quantity of long life
 - No CO₂ production
 - Limited risk of proliferation

G. Charpak, R.L. Garwin

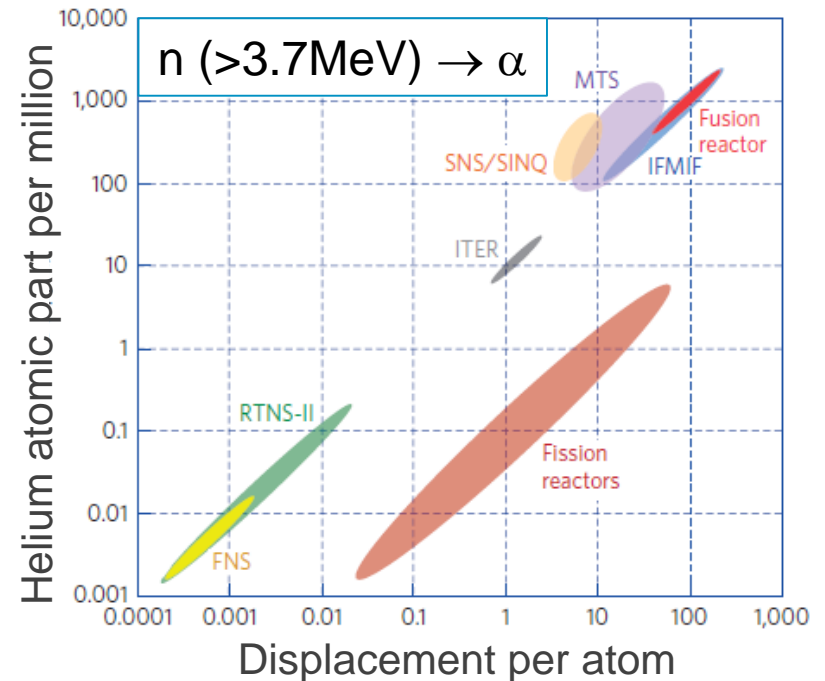


- ❑ **Threshold reaction** regarding temperature
- ❑ Constraints on **materials: neutron** and heat flux

Knocked on atoms of iron following neutron impact



J. Knaster et al., Nature Physics (2016)



⇒ **IFMIF** (International Fusion Materials Irradiation Facility): Accelerator / Target / Test facilities

- ❑ **Tritium production** ⇒ breeding blankets $n + \text{Li}$

1 GW (thermic) reactor → 56 kg / year

■ Basics on fusion

- Fusion on Earth
- Advantages & drawbacks

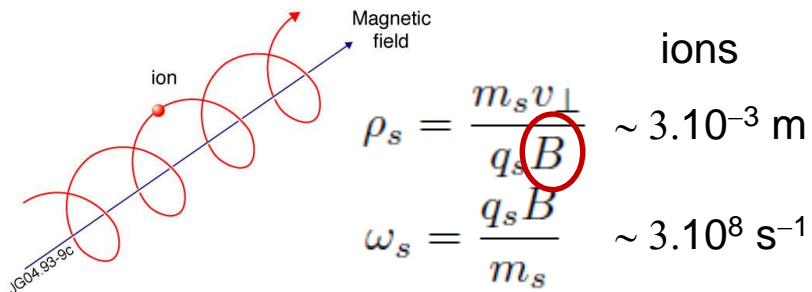
■ **Controlled magnetic fusion**

- **Confinement**
- Key physics issues

■ ITER

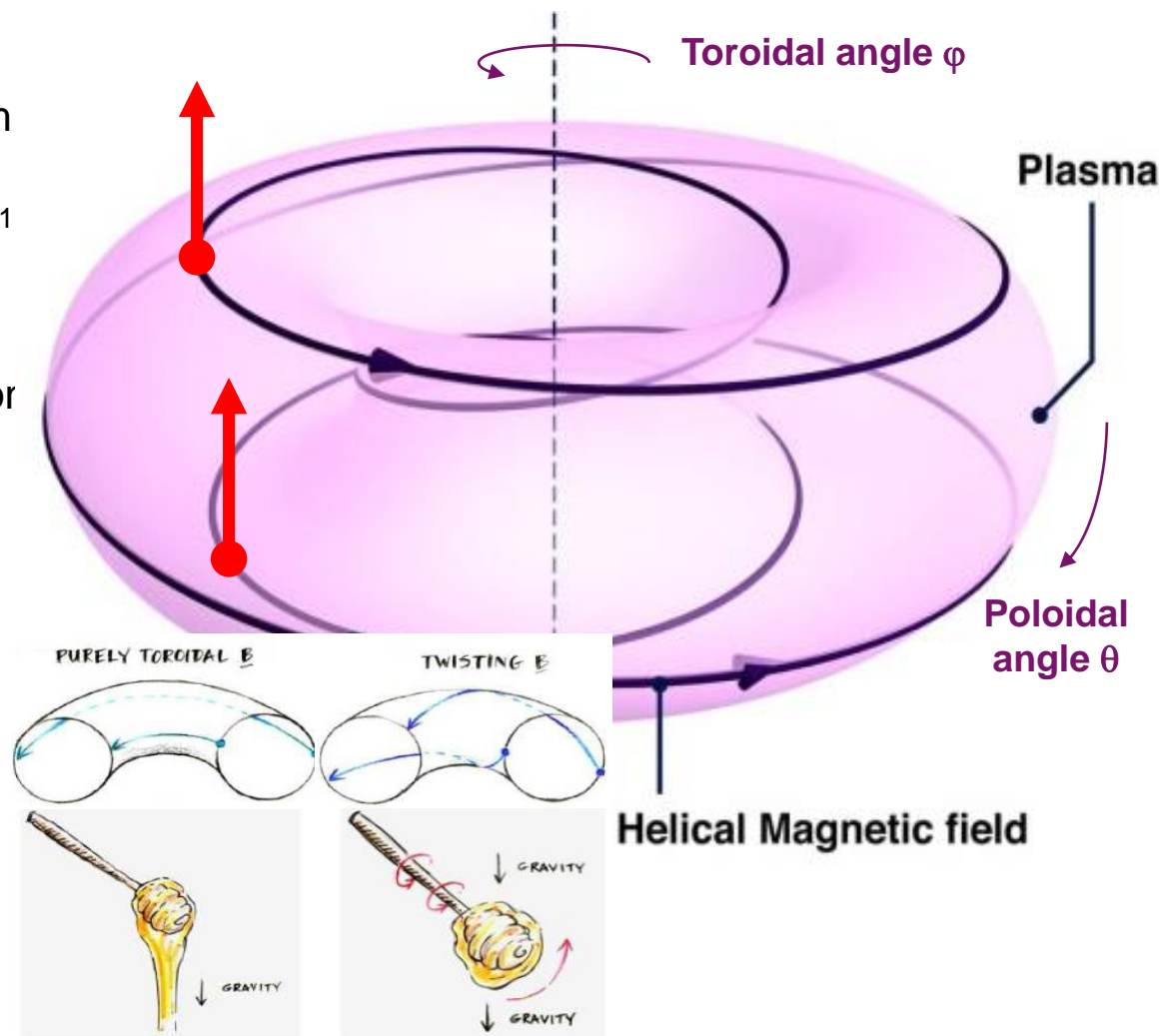
- Scientific program... paved by decades of experiments
- Present status

- ❑ Particles confined in 2-dim. by **strong magnetic field B**:

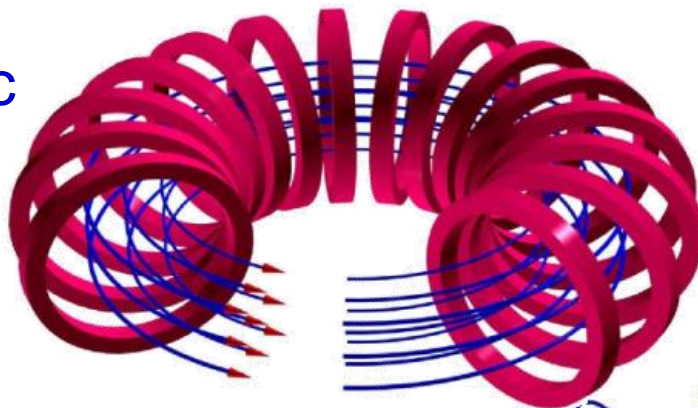


- ❑ Inhomogeneous **B** (norm. & direction) e.g. circular field lines
 - ⇒ vertical **particle drifts**
 - ⇒ still 2-dim. confinement only

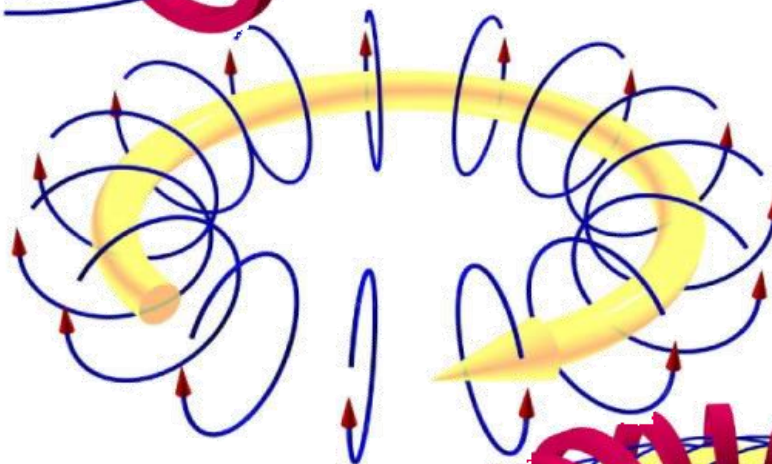
- ❑ Solution: magnetic field lines twist around **tori** called **magnetic surfaces**
 - ⇒ **helicity** “annihilates” drift effect
 - ⇒ **3-dim. confinement**



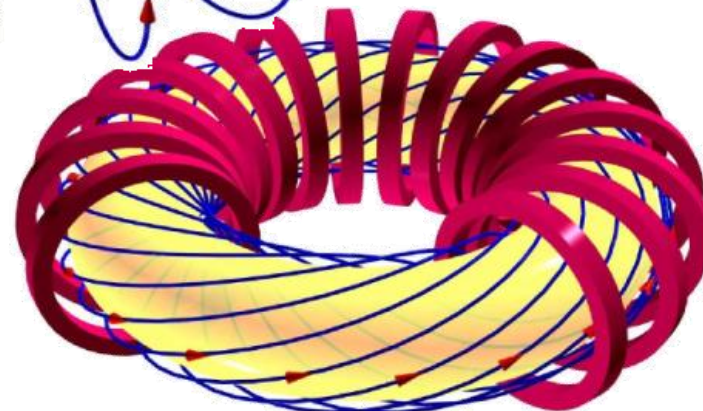
- “Toroidal” magnetic field generated by external coils



- “Poloidal” magnetic field generated by toroidal plasma current (inductive & non-inductive)



- Resulting magnetic field lines ($\mathbf{OM} \times \mathbf{B} = 0$) are helical



■ Confining particles is not sufficient → their collective effects (e.g. plasma pressure) have to be balanced

■ **Magnetic surfaces** are (leading order)

■ isobar

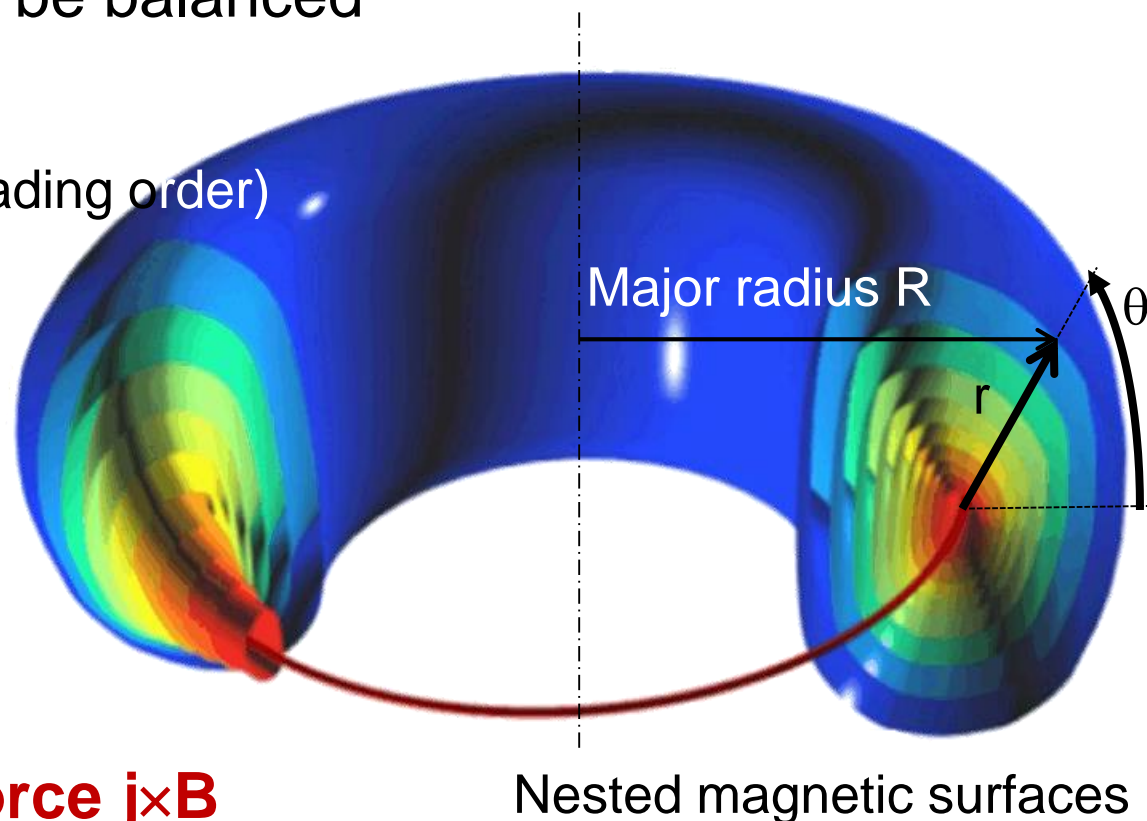
■ isothermal

■ **Pressure gradient ∇p**

⇒ plasma expands

⇒ **balanced by Lorentz force $\mathbf{j} \times \mathbf{B}$**

= Magneto-HydroDynamical equilibrium

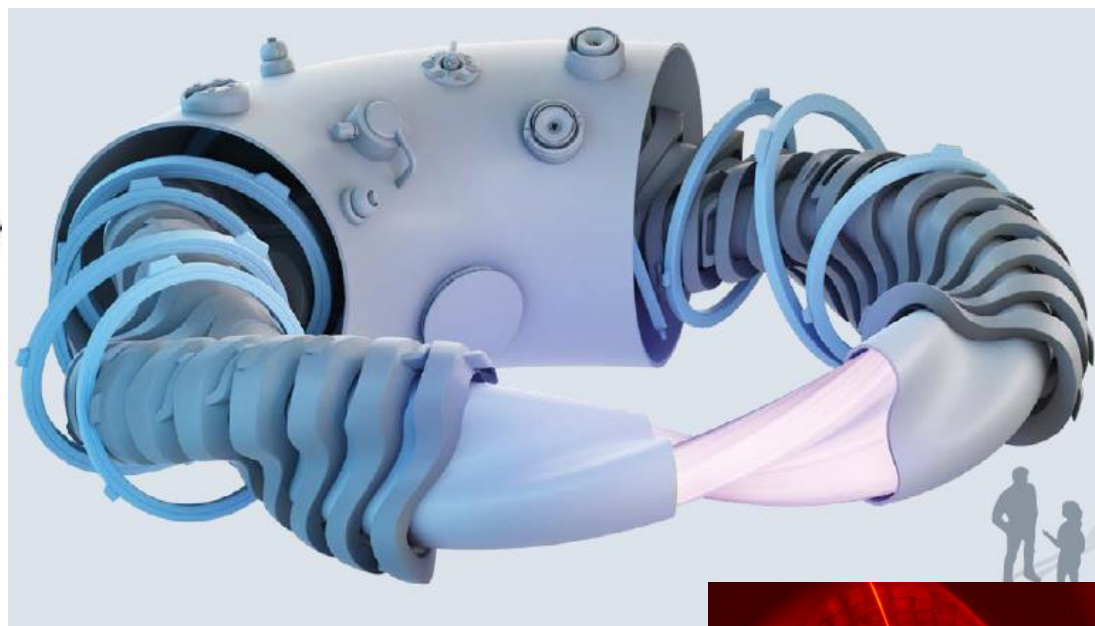
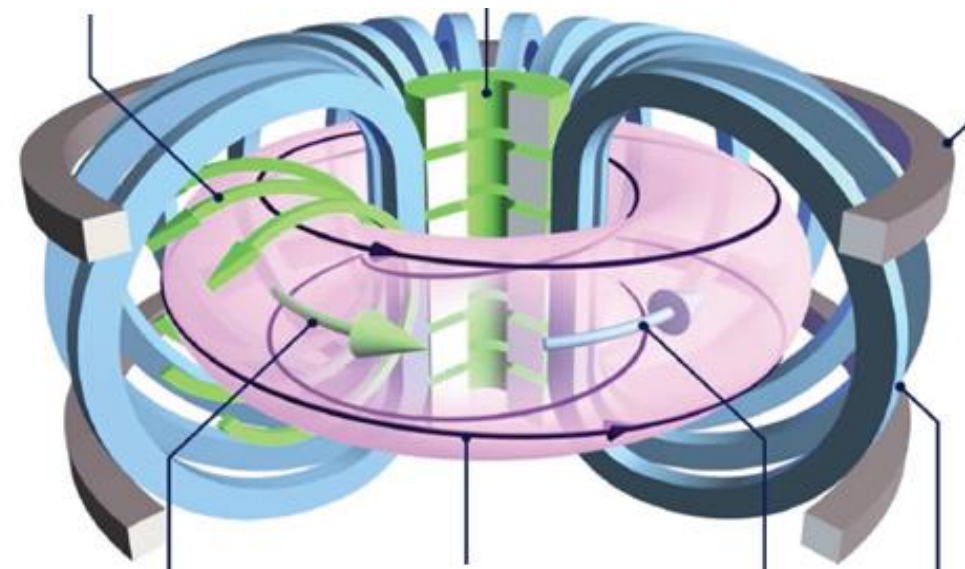


■ Tokamak

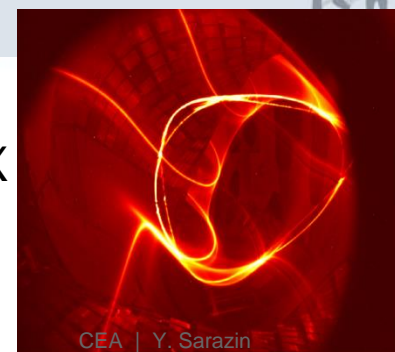
- ☺ Confinement
- ☹ Plasma current, Disruptions

■ Stellarator

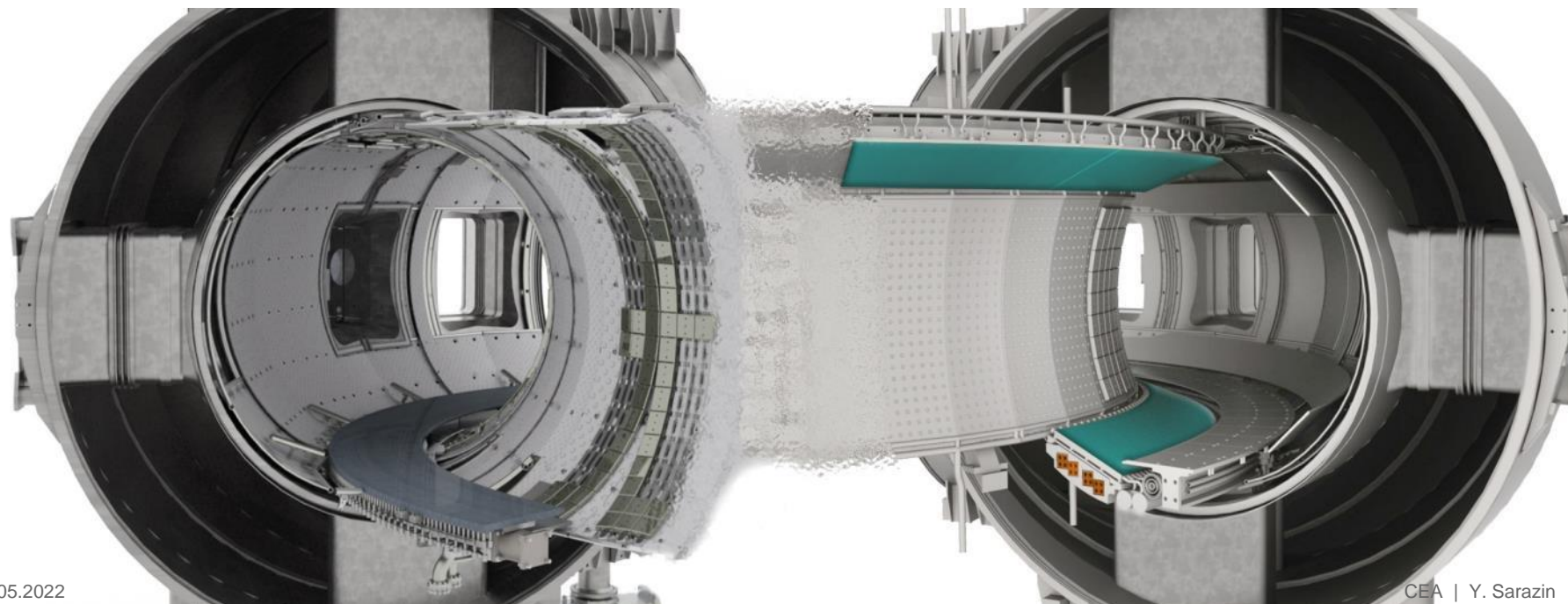
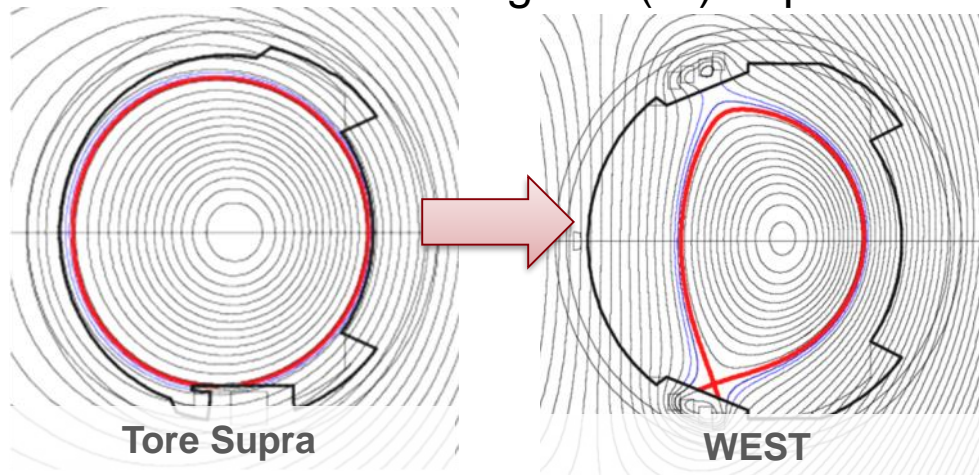
- ☺ Stability
- ☹ α -confinement, Technology



Wendelstein 7-X
(Germany)



WEST: Tungsten (W) Experimental Steady-state Tokamak



■ Basics on fusion

- Fusion on Earth
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■ **Controlled magnetic fusion**

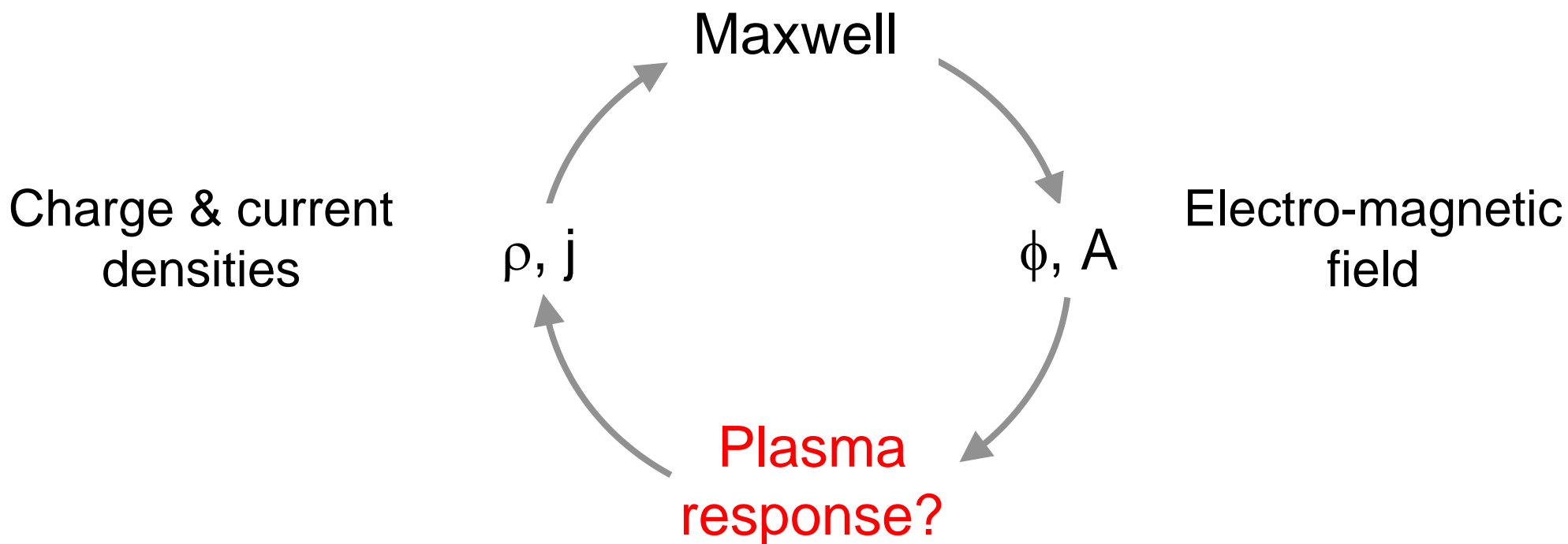
- Confinement
- **Key physics issues**

■ ITER

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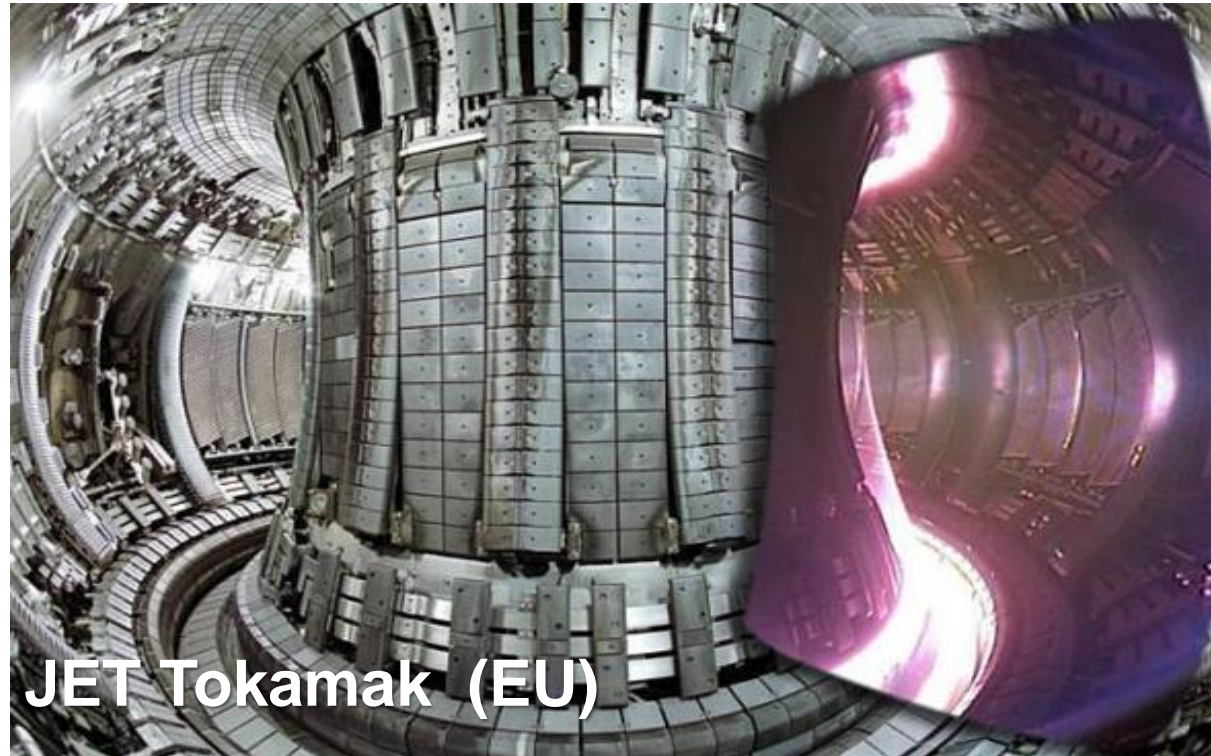
Quasi-neutrality: $\rho = 0$

Ampère: $\nabla \times B = \mu_0 j$



Several approaches: Kinetic / GyroKinetic
Fluid / MHD

- ❶ Plasma heating, fueling & current drive (tokamaks)
- ❷ Plasma-surface interaction: particle & heat exhaust
- ❸ Stability of magnetic configuration
- ❹ Plasma confinement



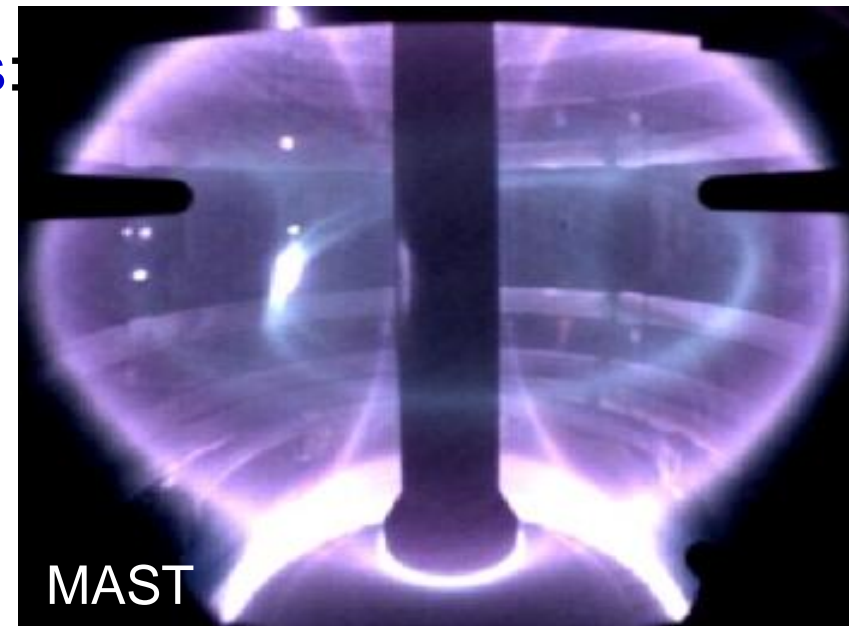
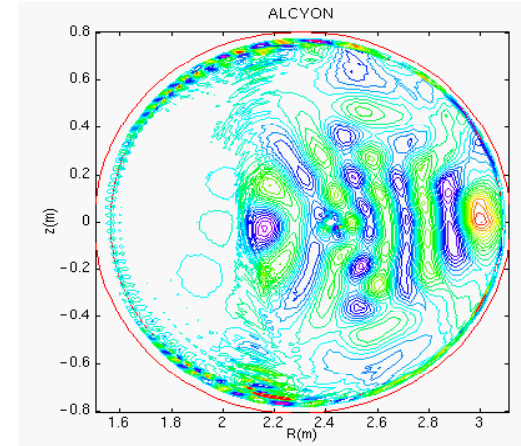
1

□ **Temperature** (10-20 keV ~ 150 10⁶ °C)

→ **heating & current drive**

- **Joule effect** (but resistivity ~ nT^{-3/2})
- **Radio-frequency waves**: resonant absorption by charged particles
- Beams of **energetic neutral particles**: positive/negative ion source, acceleration, neutralization
- **Alpha particles** (self-heating/burning)

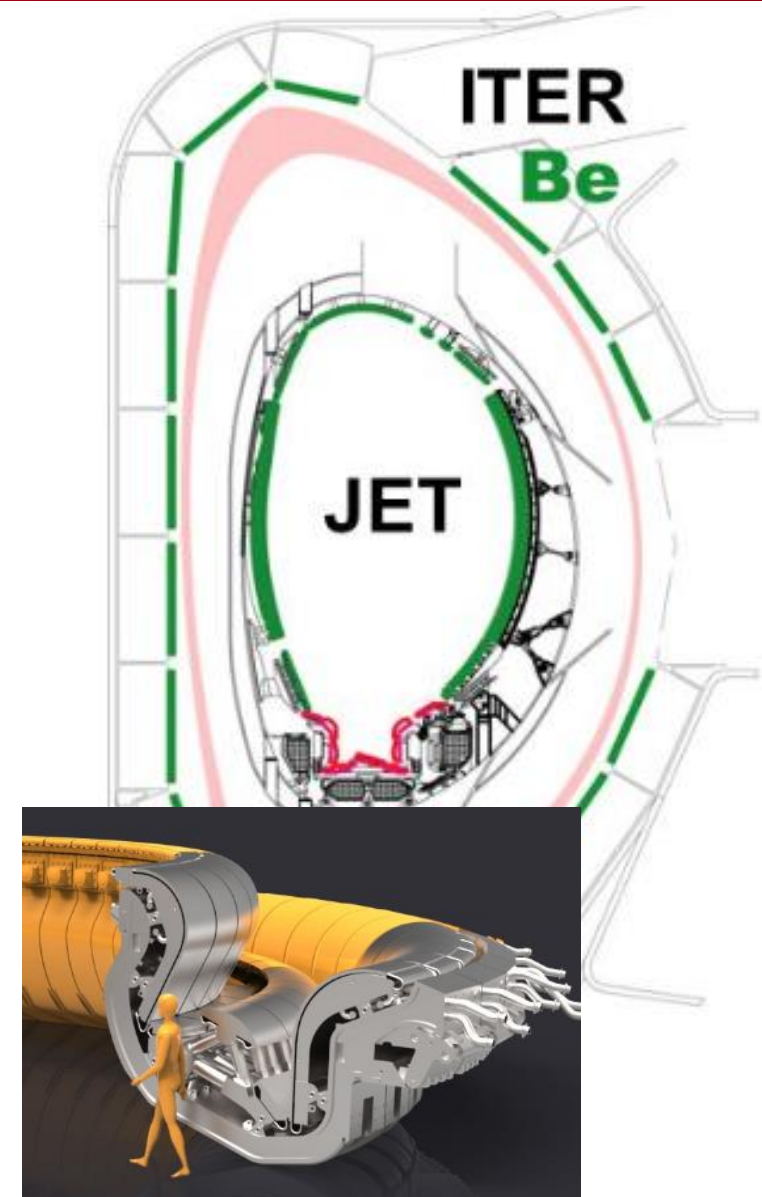
□ **Particles** → **Fueling**: gas / pellets



2

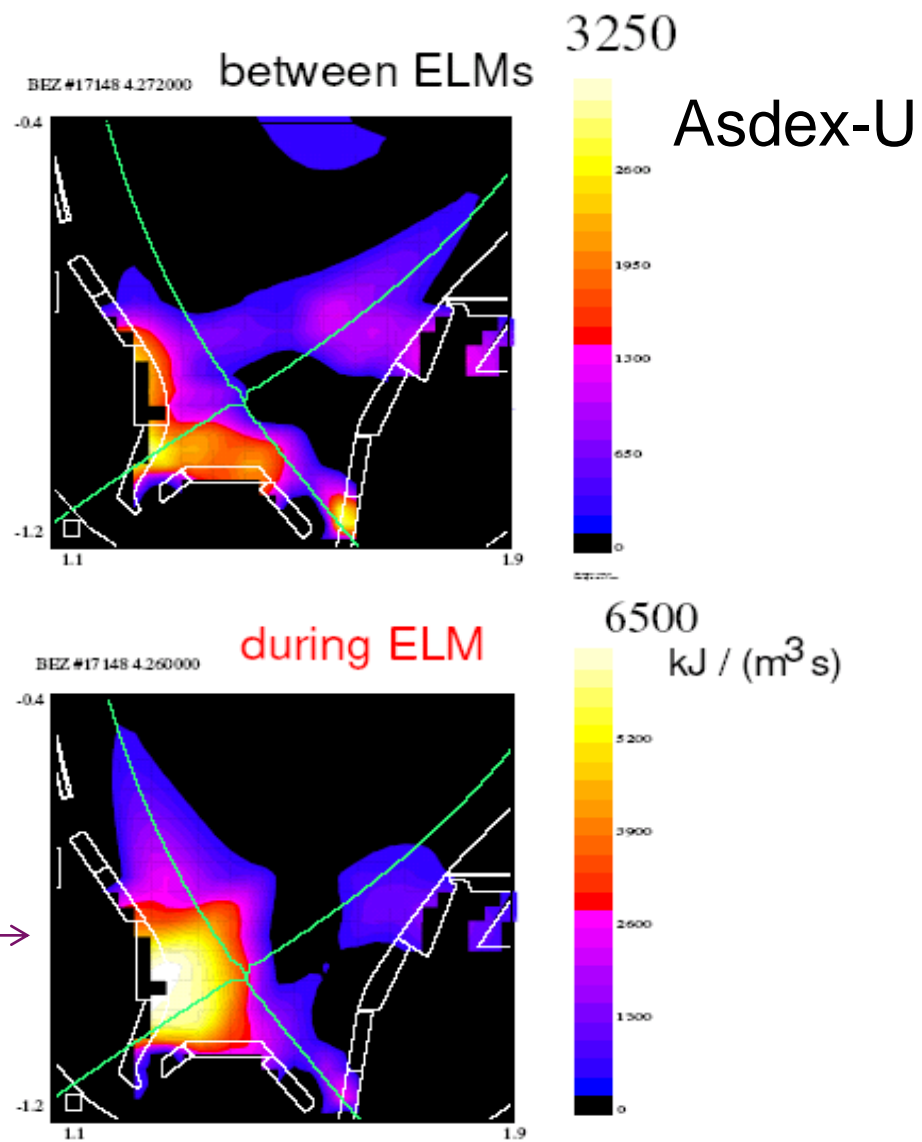
Interface with plasma facing components:

- ❑ **In general:** hot & diluted plasma
 - emission of impurities
 - non efficient pumping
- ❑ **Preferable solution:** dense, cold & radiating plasma
 - appropriate device = divertor



2

- ❑ Heat exhaust ($\sim 10 \text{ MW.m}^{-2}$)
 - \sim Shuttle thermal shield \times 2-3
 - \sim Surface of the Sun / 6
- ❑ Pumping ashes (He)
- ❑ Controlling impurity influx
- ❑ Fueling the plasma with DT
- ❑ Resilience to transient heat loads



3

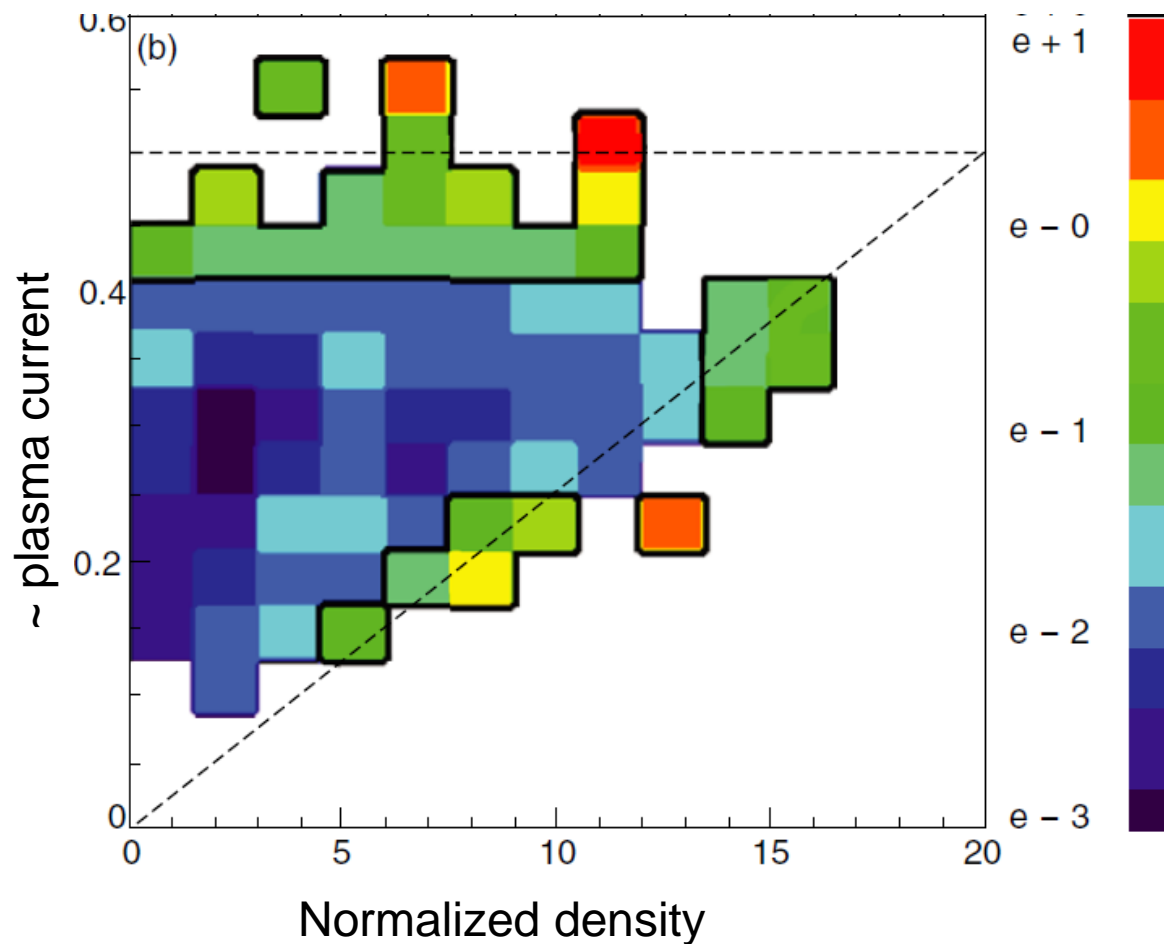
Magneto-hydrodynamic (MHD) instabilities

- Pressure
- Current
- Radiative losses

- Instabilities can
 - Reach steady-state
 - Oscillate
 - **Disrupt**

Disruptivity at JET

De Vries et al. (2009)

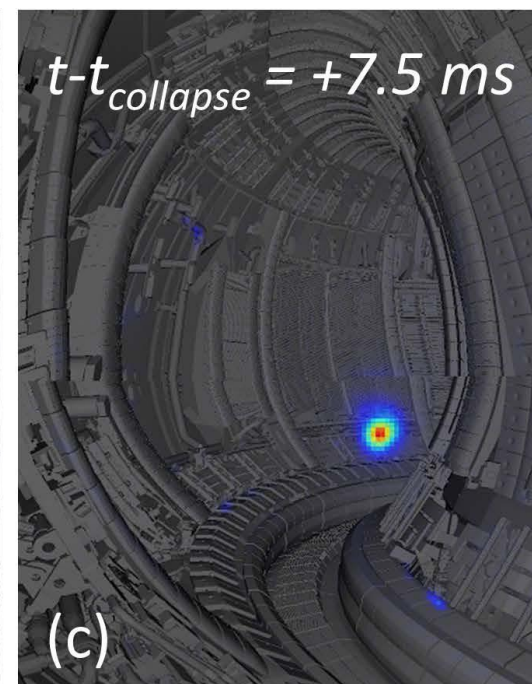
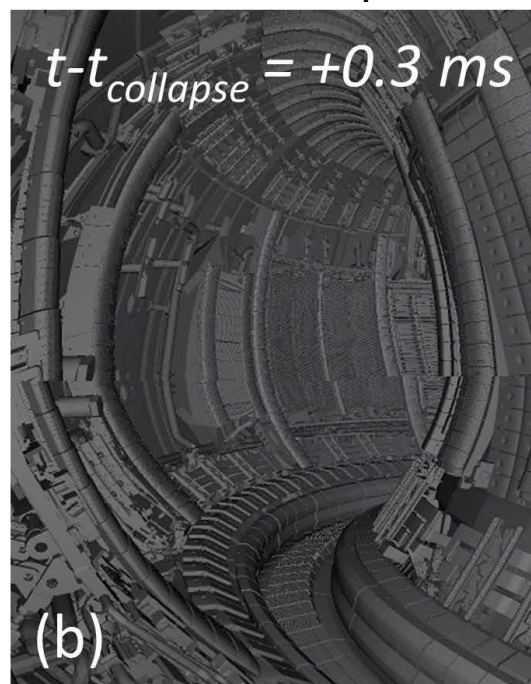
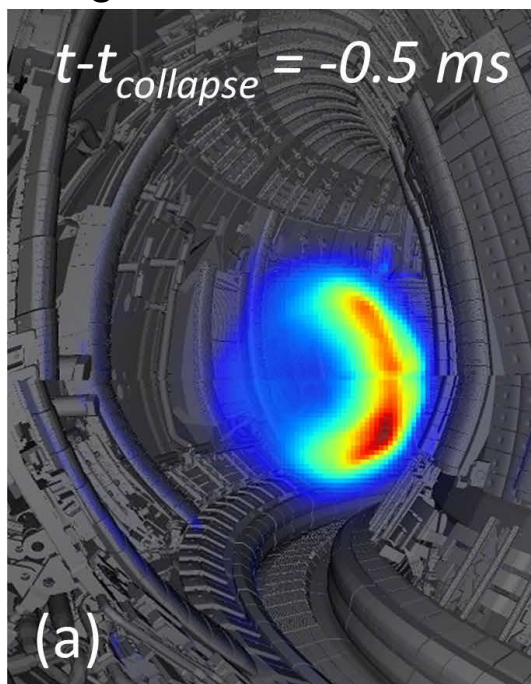


3

- Disruptions = sudden (few ms) loss of confinement
 - Huge forces on plasma vessel
 - Runaway Electron beam $v_e \sim c \rightarrow$ up to 100 MJ in ITER
- Strategies: avoidance and/or mitigation

Mitigation of RE at JET with shattered D2 pellets

[Reux et al., PRL 2021]



4

■ Departure from thermodynamical equilibrium: $\nabla n, \nabla T$

■ Instabilities above thresholds

→ Nonlinear saturation

→ Turbulence

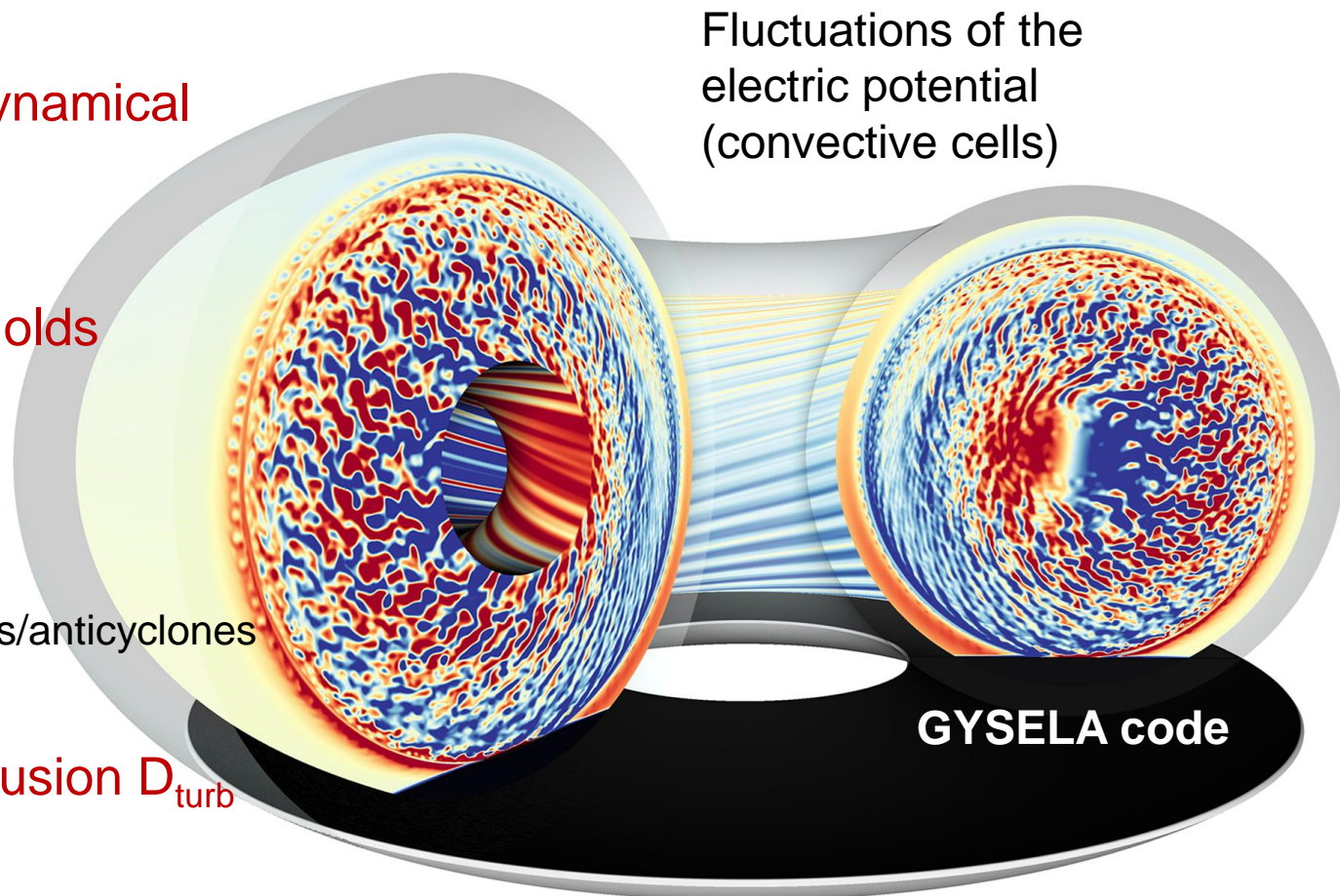
■ Convective cells ~ cyclones/anticyclones

→ Cross-field transport

→ Effective turbulent diffusion D_{turb}

■ $D_{\text{turb}} \uparrow \Rightarrow$ confinement time \downarrow

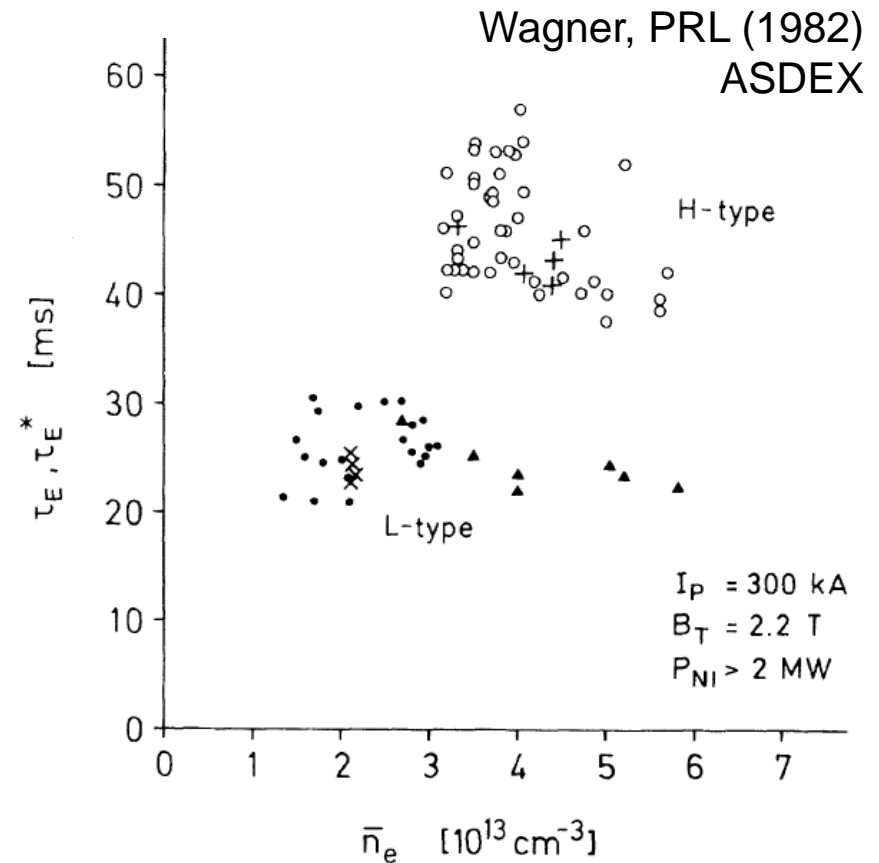
$\tau_E \sim (\text{machine size})^2 / D_{\text{turb}}$



V. Grandgirard, G. Dif-Pradalier, P. Donnel, X. Garbet, Ph. Ghendrih, K. Obrejan, C. Passeron, Y. Sarazin

4

- Spontaneous bifurcation of plasma: confinement time τ_E doubles above power threshold P_{L-H} (prediction of P_{L-H} = ongoing research)
- Discovered on ASDEX in 1982 (all tokamaks since then)



4

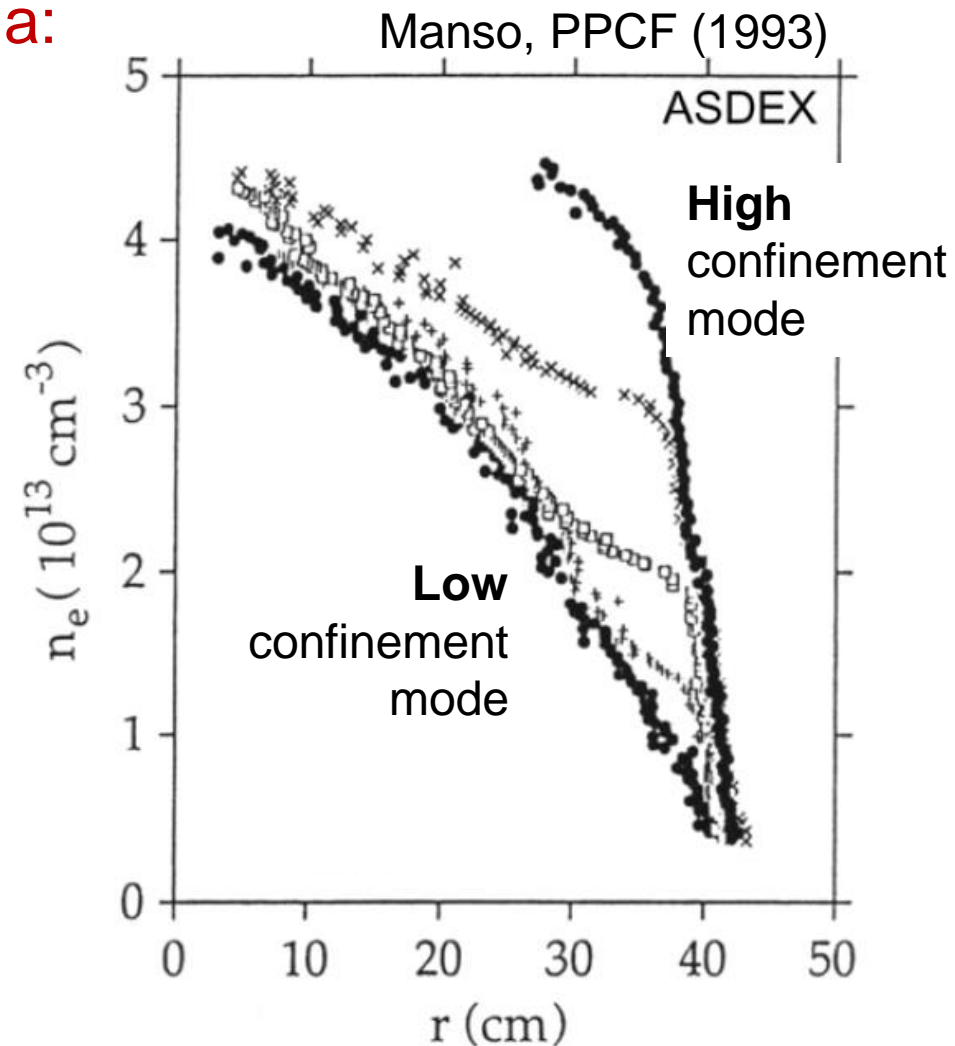
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■ Gradients increase in a boundary layer

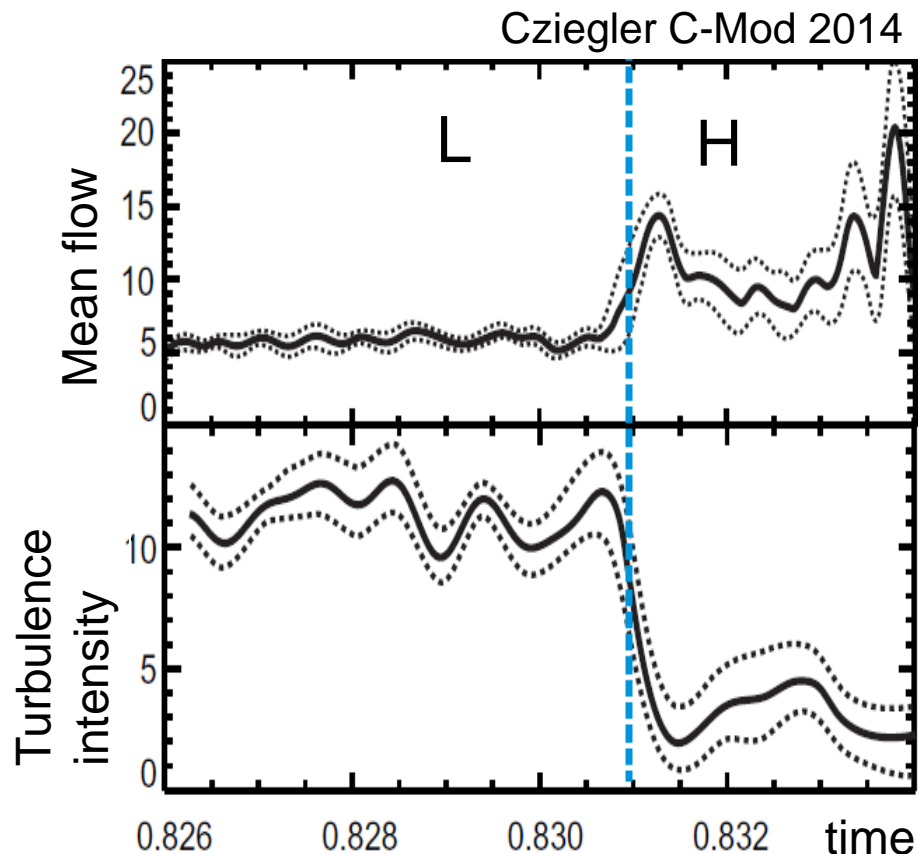
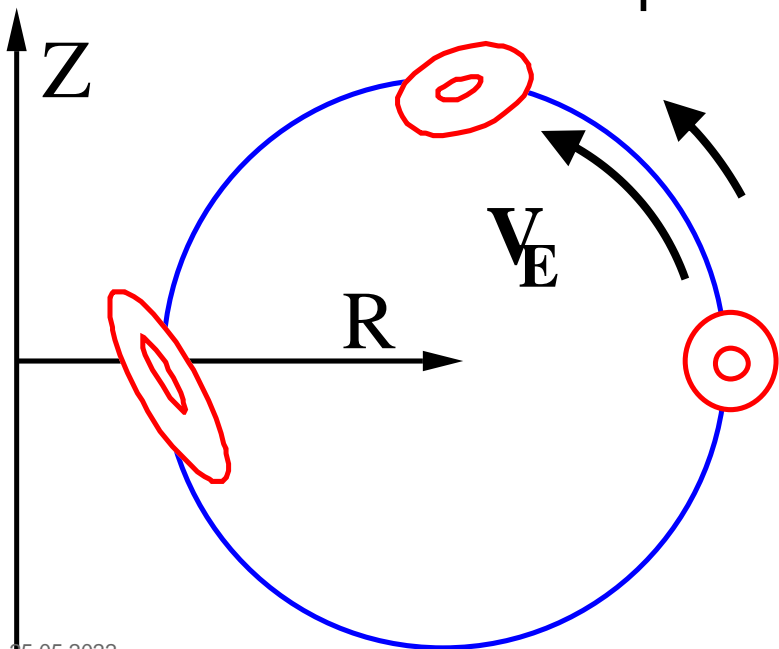
$$q = -\chi n \nabla T = q_{in}$$

$\chi \downarrow \Rightarrow \nabla T \uparrow \Rightarrow$ transport barrier



4

- Turbulence \Rightarrow radially elongated convective cells
- Sheared flow V_E can tear apart the cells
- \Rightarrow turbulence decorrelation
- \Rightarrow reduction of transport

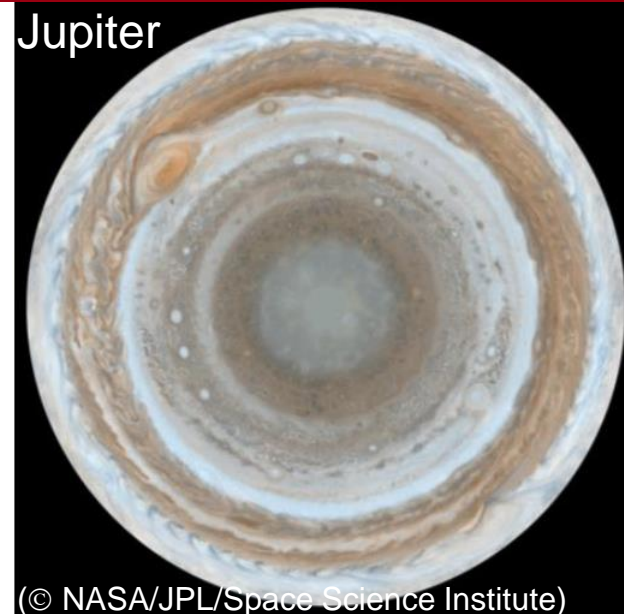


4

Small-scale turb. can generate large-scale fields:

Magnetic field ? (turbulent dynamo?)

Zonal Flows in stratified rotating turb. (e.g. Jupiter)



Zonal Flows in tokamak plasmas:

- Excited by modulational instab.

[Review by
Diamond-Itoh-
Itoh-Hahm
(2005)]

$$\frac{\partial \langle v_{E\theta} \rangle}{\partial t} = -\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \underbrace{\langle \tilde{v}_{Er} \tilde{v}_{E\theta} \rangle}_{\text{Reynolds stress}} \right)$$

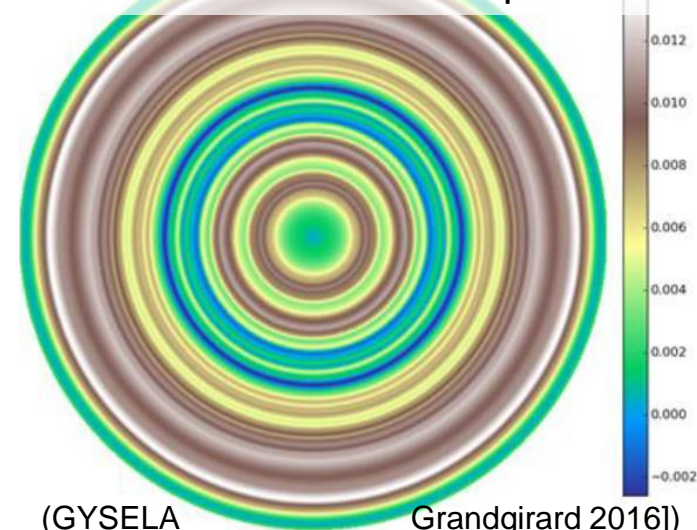
Reynolds stress

- Linearly damped by collisions only

[Rosenbluth-Hinton (1998)]

- Saturation: Kelvin-Helmholtz instability?

Zonal Flows in tokamak plasma



4

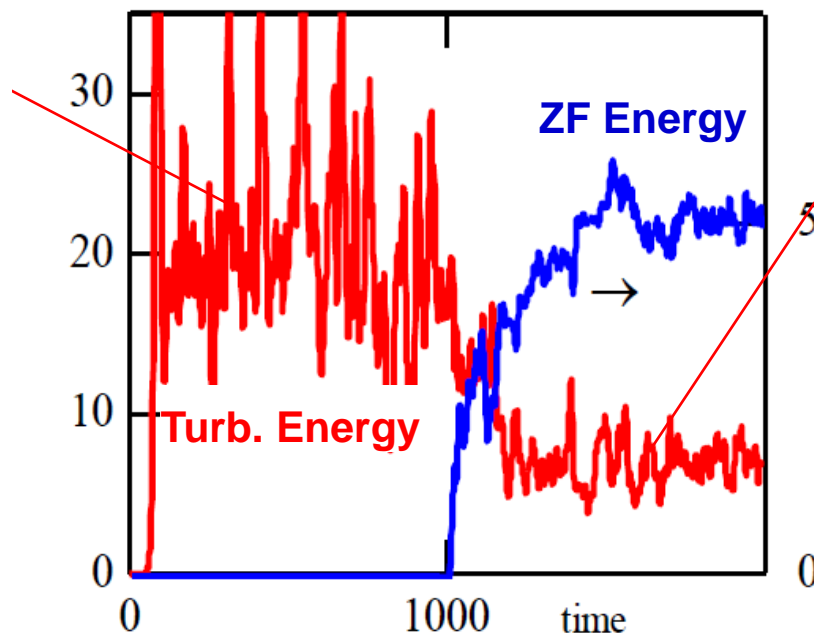
Zonal Flows

- tear apart convective cells
- do not contribute to \perp transport

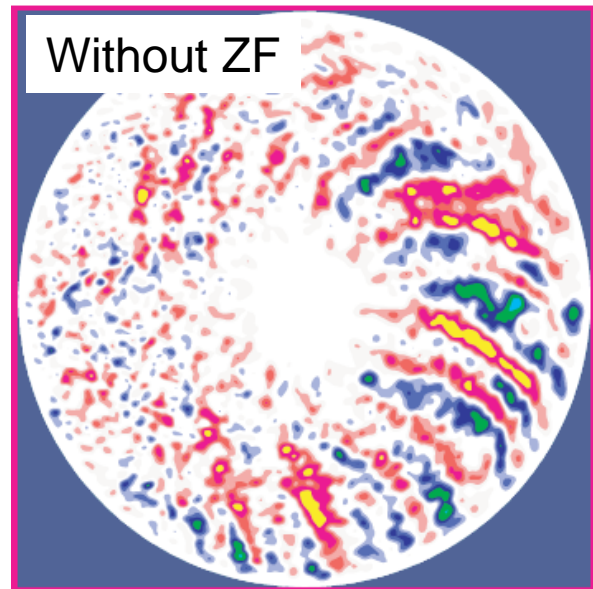


reservoir of energy for turbulence

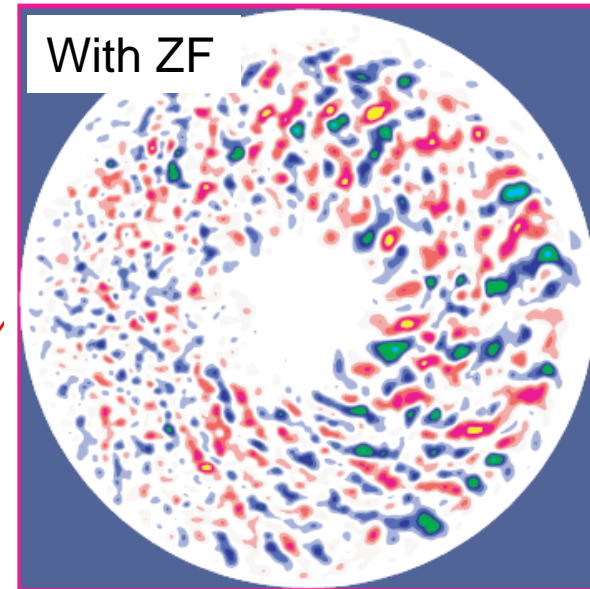
[Beyer, PRL (2000)]



Without ZF



With ZF



[Lin et al., Science (1998)]

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■ Controlled magnetic fusion

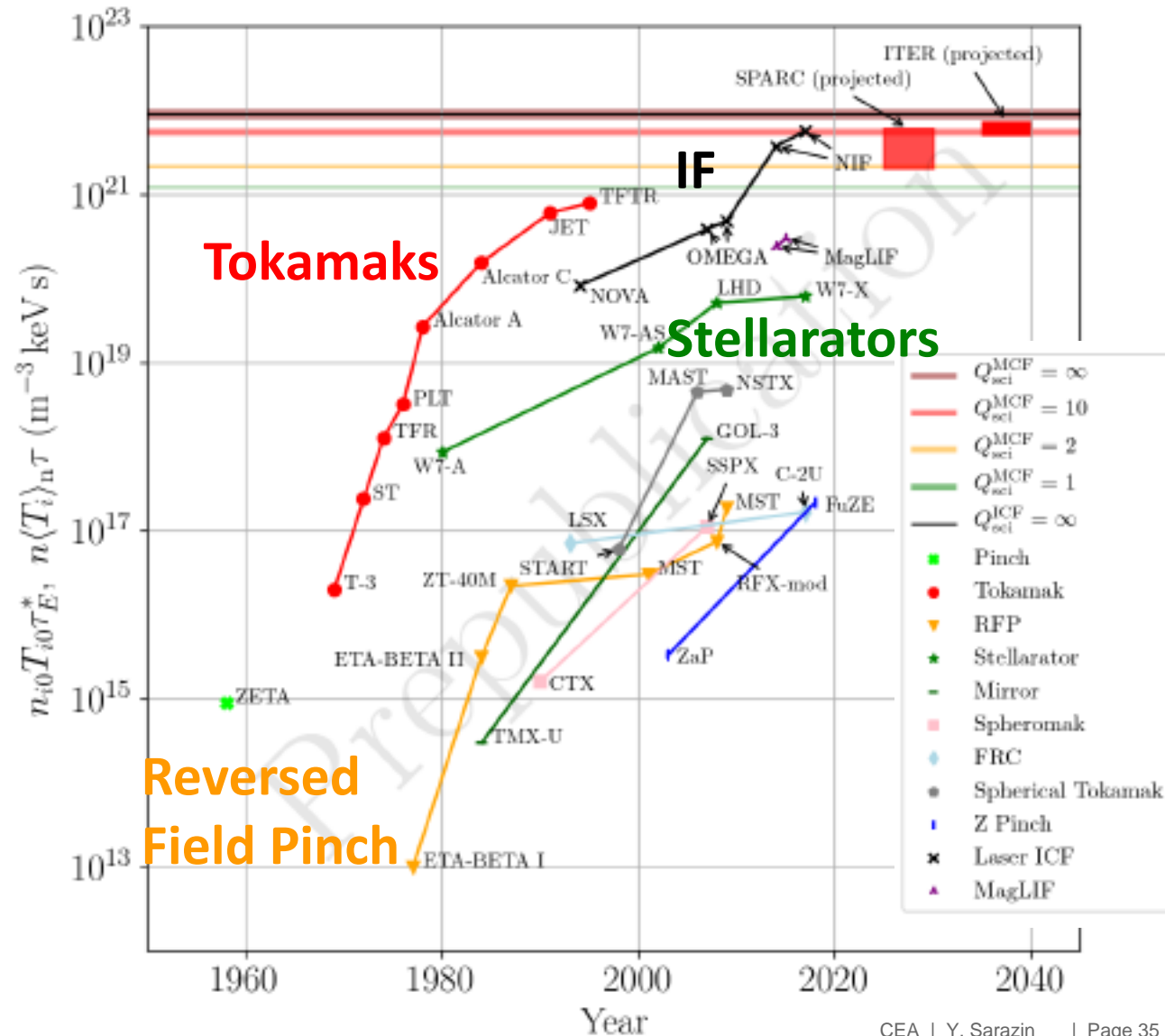
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Wurzel & Hsu 2021

- ❑ Constant progress towards ignition (i.e. self heating)
- ❑ Caveat: Ignition \neq efficient power plant
 - **Magnetic Controlled Fusion:** pulse duration (pulsed vs stationary)
 - **Inertial Fusion (IF):** shock repetition rate (1/day vs. @ 10 Hz)



□ 1994 TFTR

$P_{\text{fus}} = 11 \text{ MW peak}$

□ 1997 JET

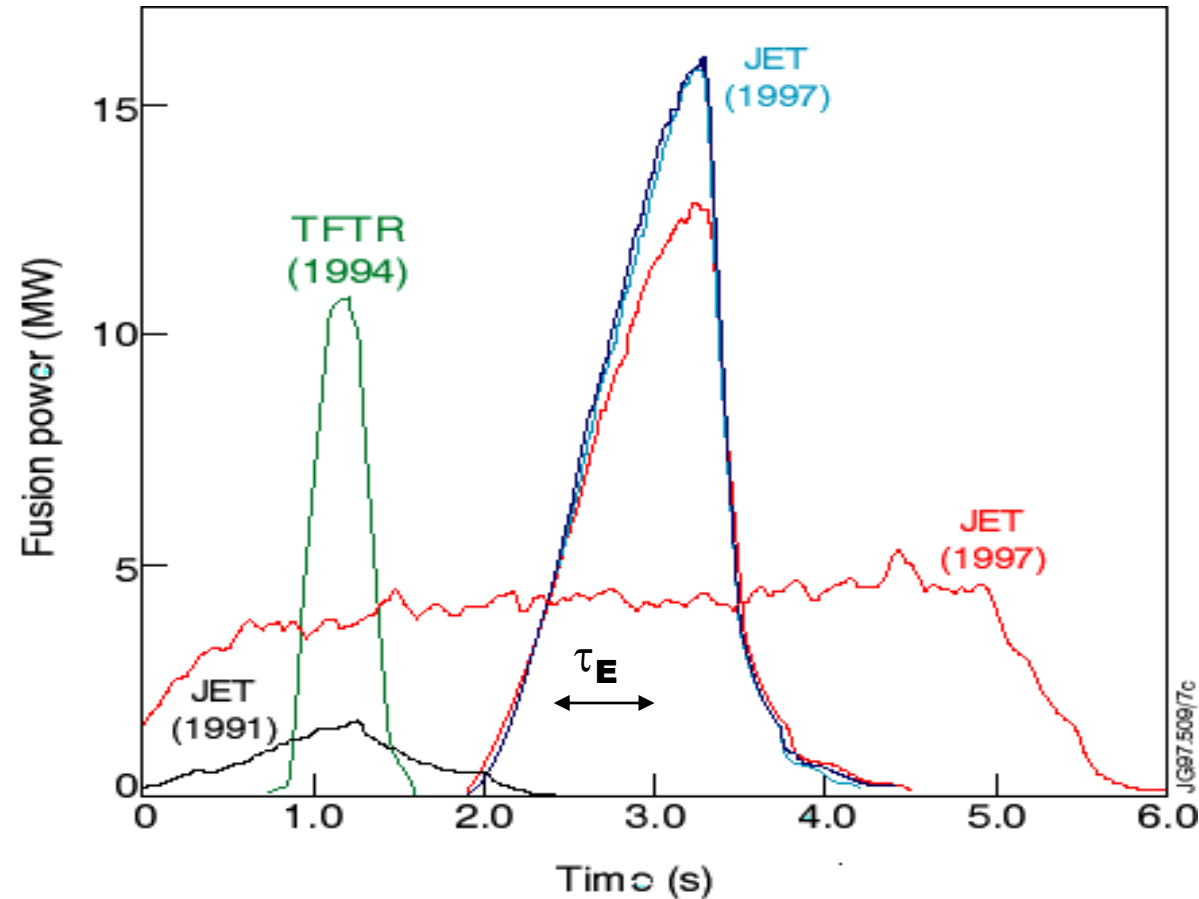
- Peak performance:

$P_{\text{fus}} = 16 \text{ MW}$

$Q_{\text{DT}} = P_{\text{fus}} / P_{\text{add.}} = 0.67$

- Quasi-stationary:

$P_{\text{fus}} = 4 \text{ MW}$



□ 1994 TFTR

$P_{fus} = 11$ MW peak

□ 1997 JET

- Peak performance:

$P_{fus} = 16$ MW

$Q_{DT} = P_{fus}/P_{add.} = 0.67$

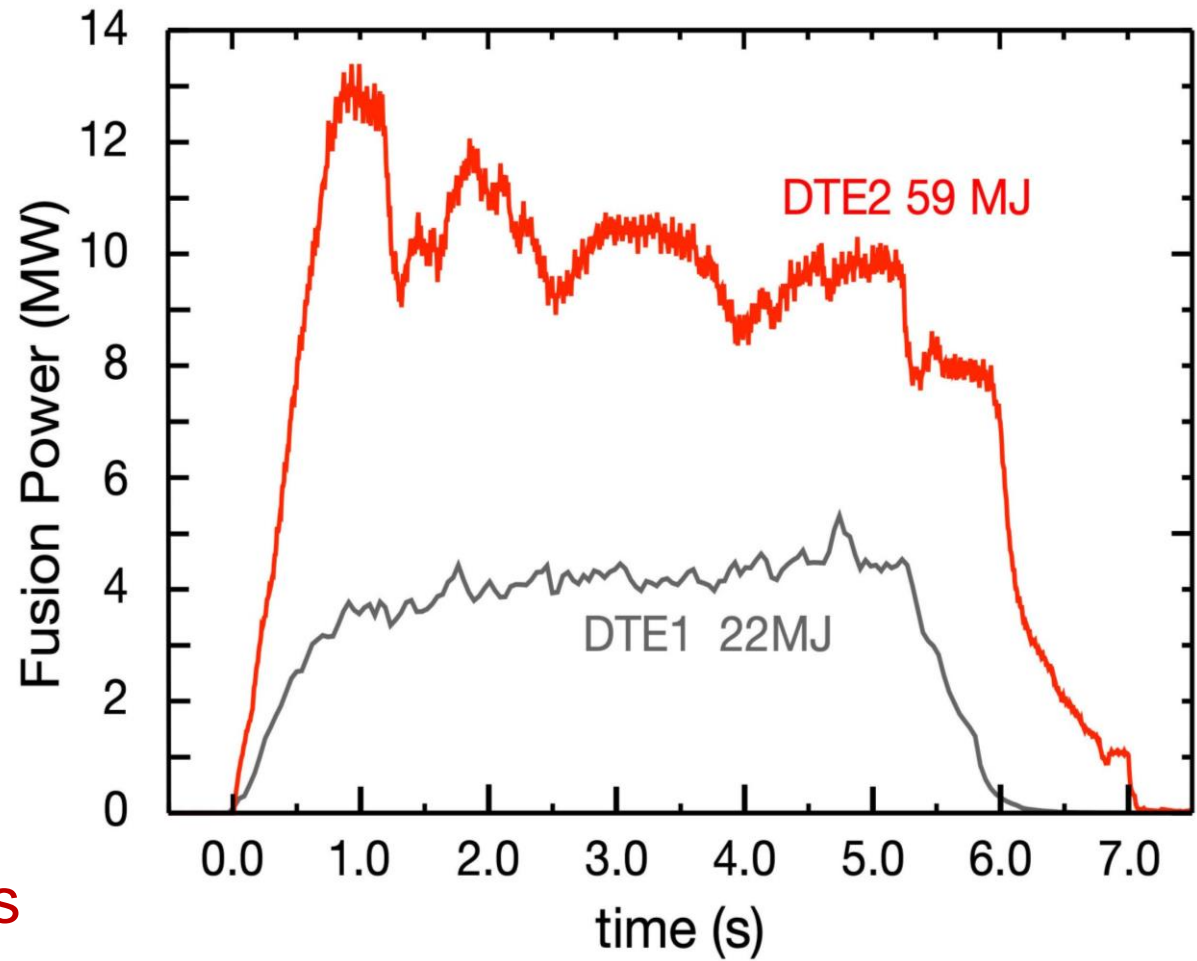
- Quasi-stationary:

$P_{fus} = 4$ MW

□ 2021 JET

- $P_{fus} \approx 10$ MW during 5s

- $Q_{DT} \approx 0.3$

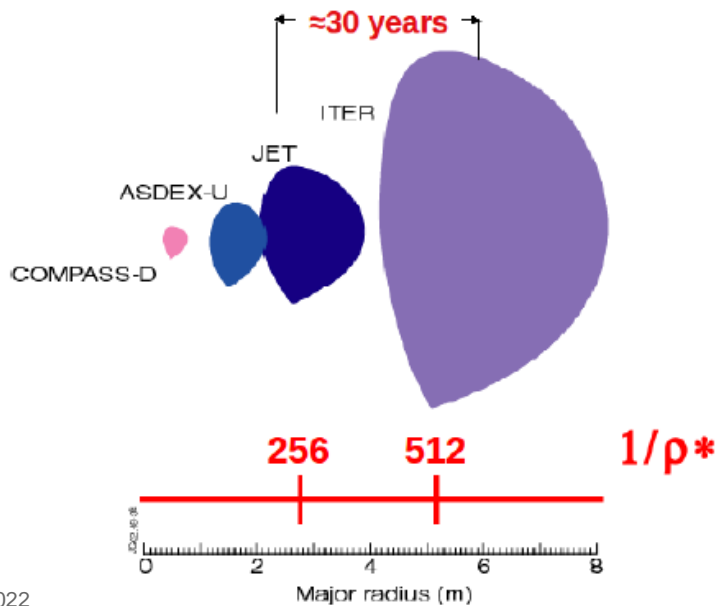


- International database
(dimensionless formulation)

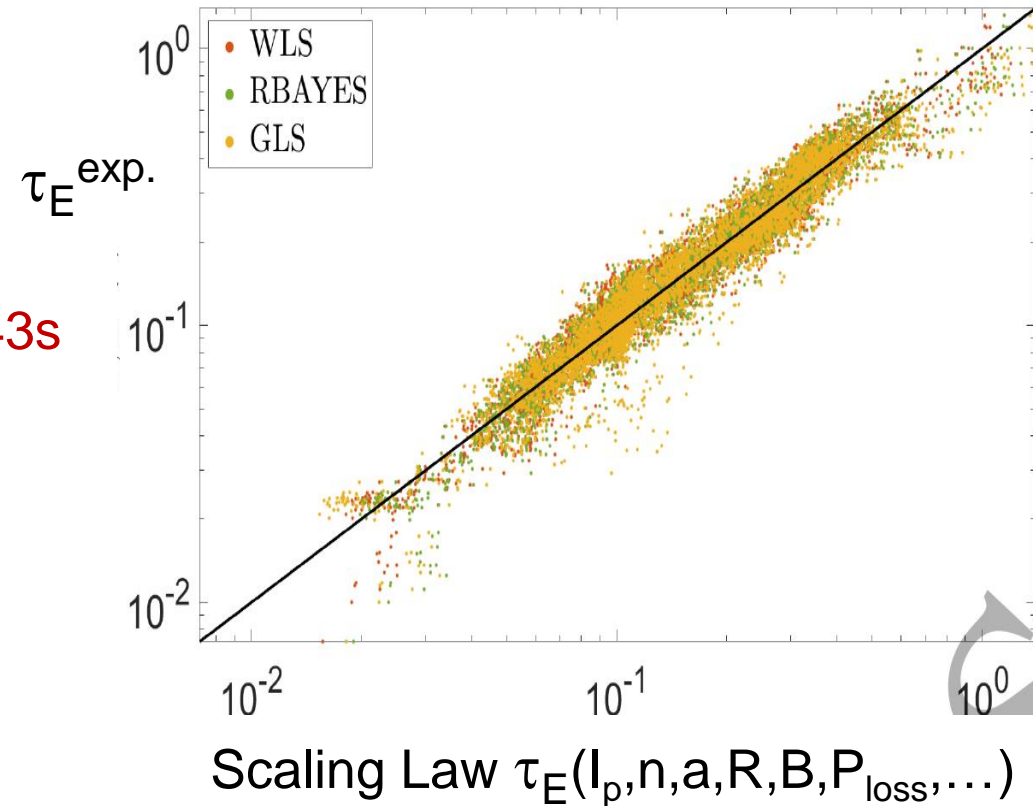
$$\omega_{ci} \tau_E \sim \rho_*^{-1.97 \pm 0.32} v_*^{-0.425 \pm 0.061} \times \beta^{0.12 \pm 0.21}$$

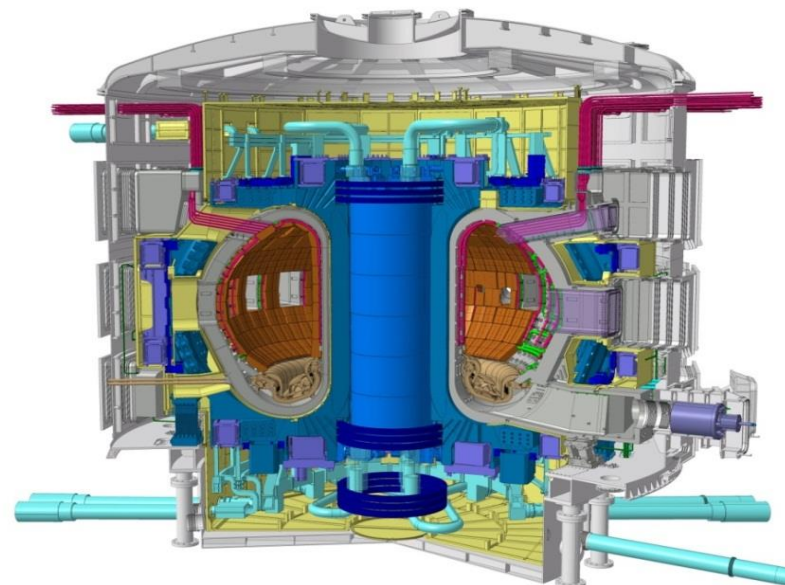
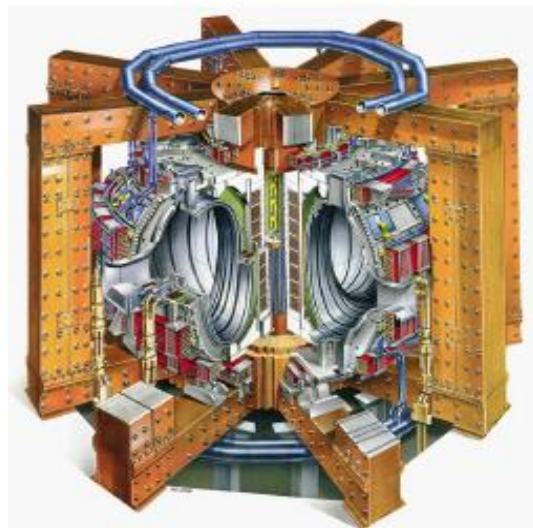
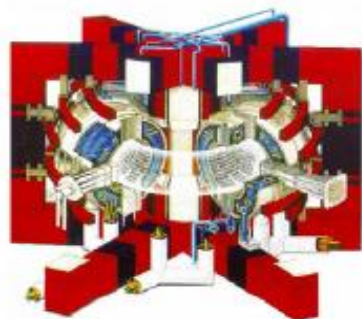
$\rho_* = \rho_i/a \sim 2 \cdot 10^{-3}$ in ITER

- ITER prediction: $\tau_E = 2.79 \text{ s} \pm 0.43 \text{ s}$



ITPA20-IL [Verdoolaege, NF 2021]





Tore Supra (1988)

25 m³

~ 0

Q ~ 0

~ 0.3 B€

JET (1983)

80 m³

~ 16 MWth

Q ~ 1

~ 1 B€

ITER (2025)

800 m³

~ 500 MWth

Q ~ 10

~ 22 B€

"Demonstrate scientific & technical feasibility of fusion energy for peaceful purposes"

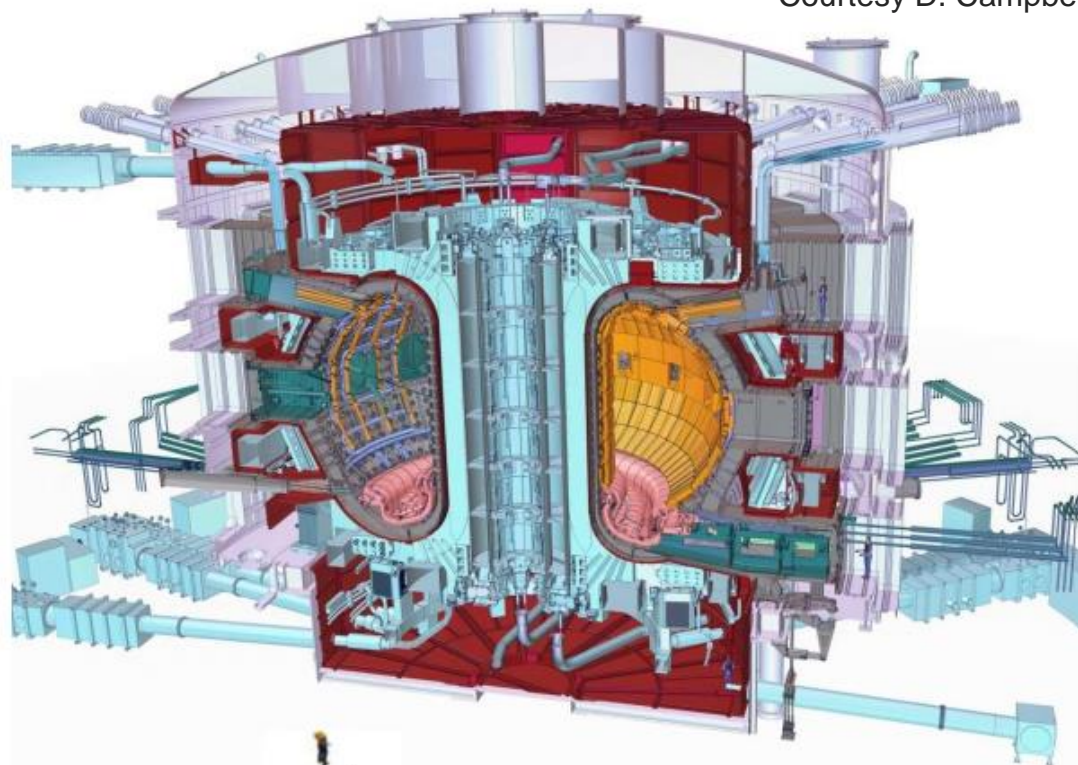
Performance:

- Stationary $Q > 5$ – Inductive $Q > 10$
- Nb of pulses: $\sim 10^4$ of 300-500s duration
- Average neutron flux $> 0,5 \text{ MW/m}^2$

Scientific program:

- **MHD**: active control of instabilities – effect of α particles
- **Confinement** : control of turbulent transport → improved confinement
- **Main heating (2/3) by α particles**: plasma self-organisation
- **Particle & heat exhaust** in stationary burning regime
- Prototype for a **Tritium breeding blanket**

Courtesy D. Campbell



Main construction milestones:

2006 Signature of ITER Agreement

2007-2009 Land clearing & levelling

2010-2014 Ground structure & seismic foundations for Tokamak

2010-2021 Construction of ITER plant & auxiliary buildings

2014-2021 Construction of Tokamak Building

2018-2025 Assembly phase 1

Dec 2025 First Plasma

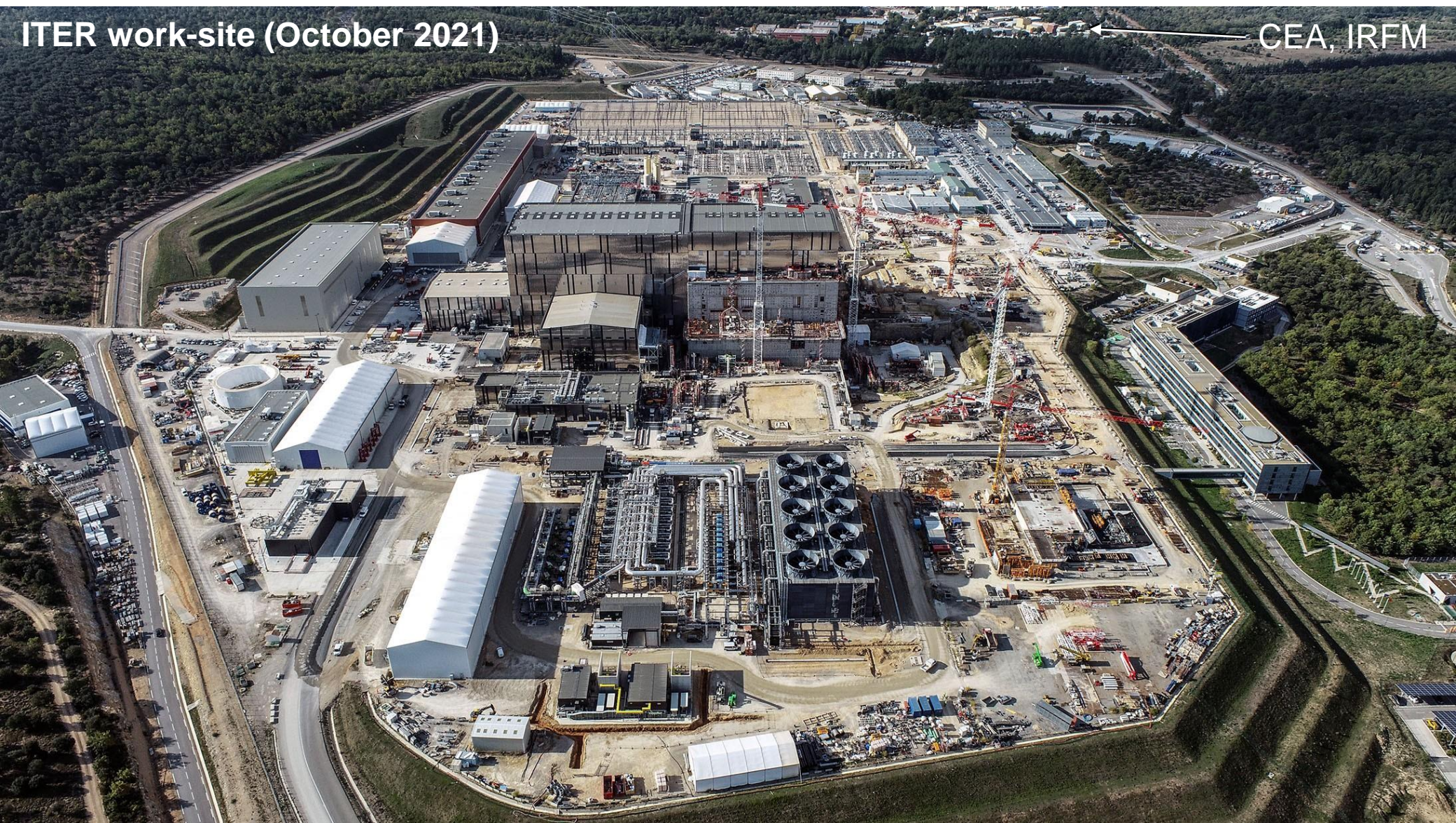
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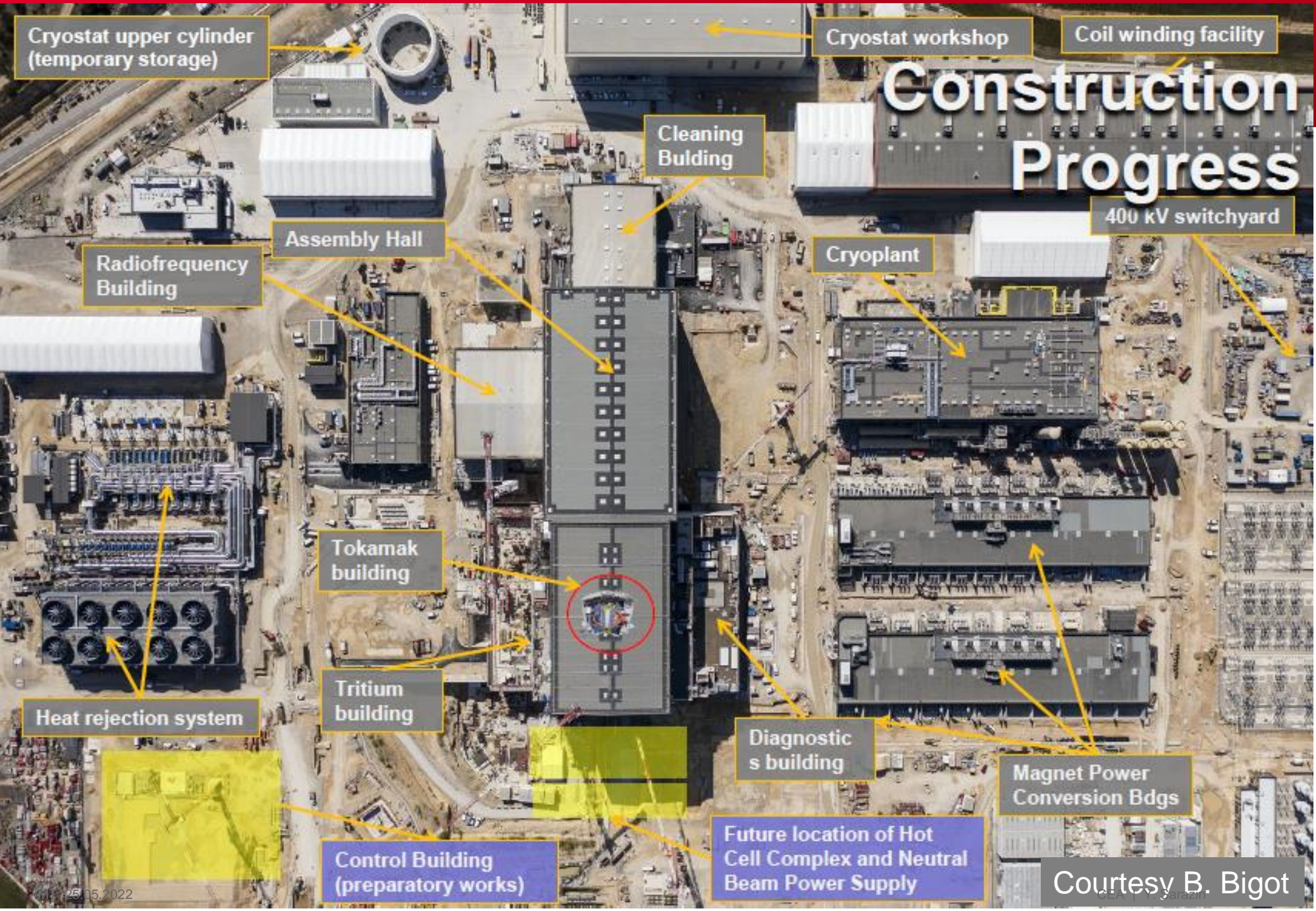
203X First D-T plasma



ITER work-site (October 2021)

CEA, IRFM





Cryostat upper cylinder (temporary storage)

Cryostat workshop

Coil winding facility

Construction Progress

Cleaning Bldg

400 kV switchyard

Assembly Hall

Cryoplant

Radiofrequency Building

Tokamak building

Tritium building

Diagnostic s building

Magnet Power Conversion Blds

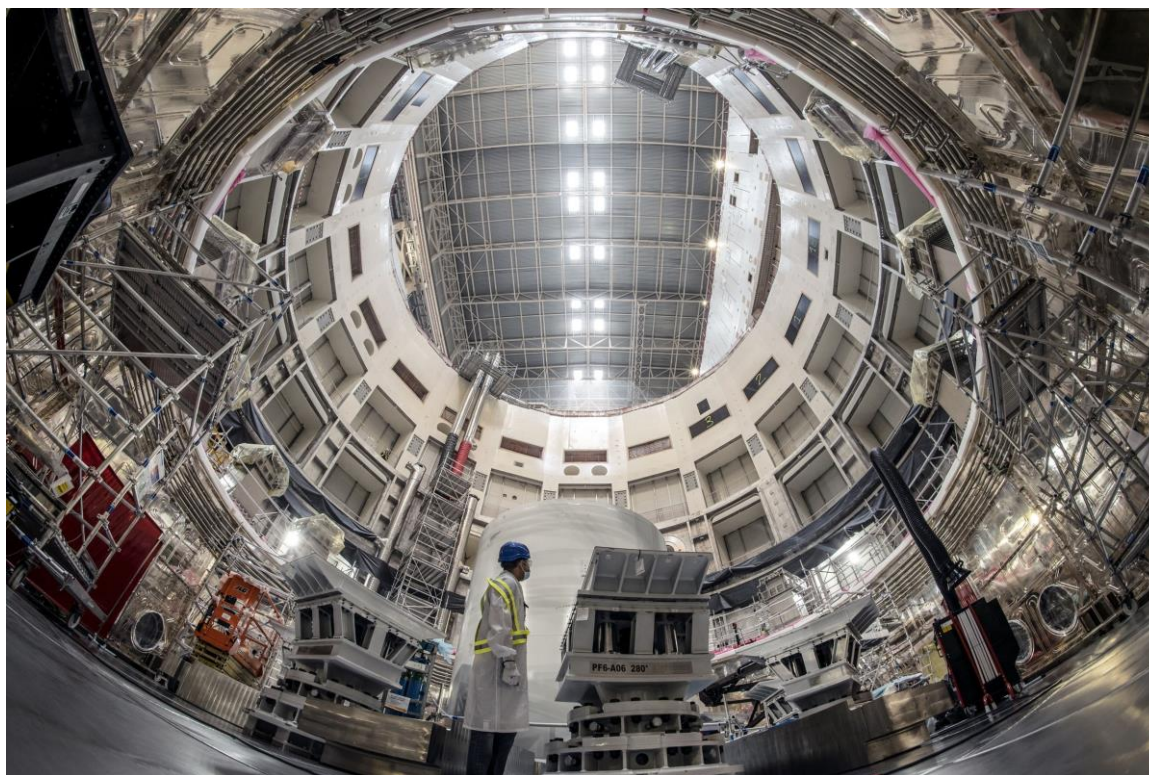
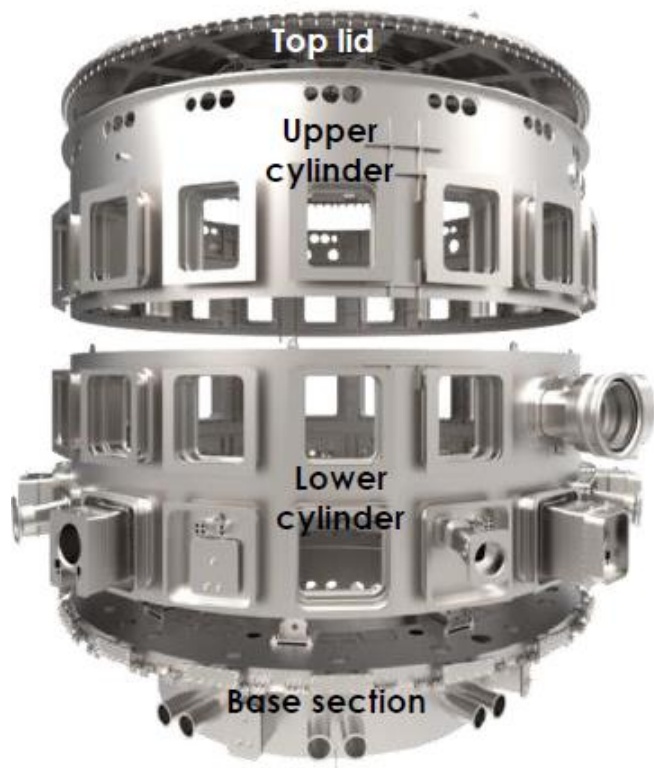
Heat rejection system

Control Building (preparatory works)

Future location of Hot Cell Complex and Neutral Beam Power Supply

Courtesy B. Bigot

- ❑ 3 out of 4 cryostat sections manufactured and two already installed in the tokamak pit; top lid under assembly on site
- ❑ Cryostat base (~ 1250 tonnes, 30 metres diameter) → heaviest ITER component rests on 18 bearings



Base & cylinder of cryostat in place (2021-03)

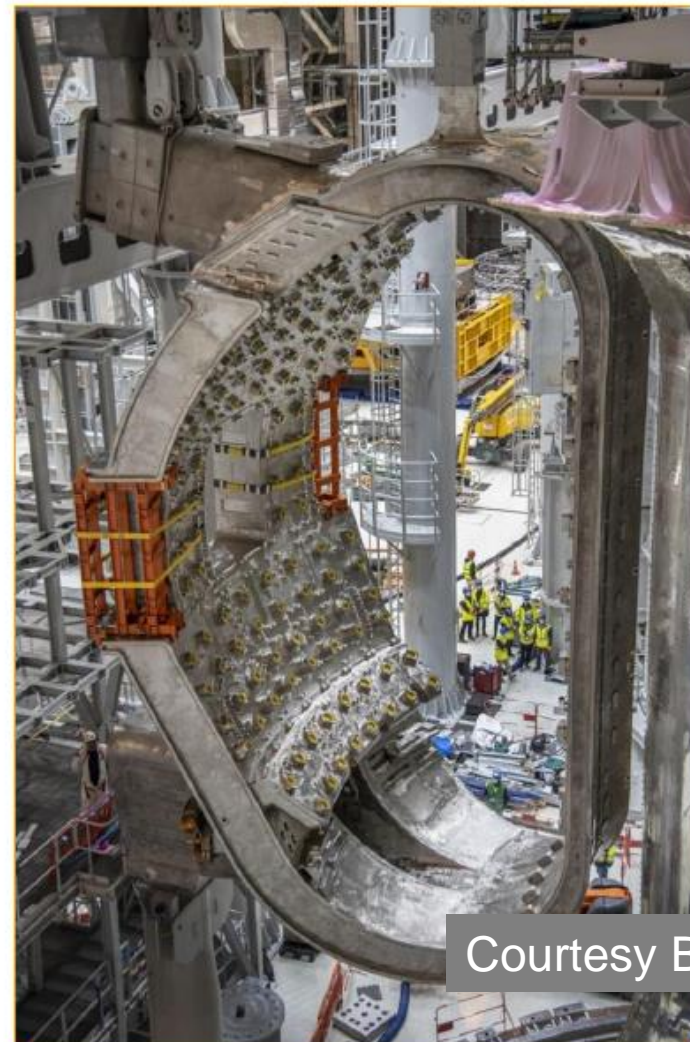
❑ VV Sector 6 positioned in SSAT (March-April 2021)



Up-ending VV Sector 6 with special tool



VVS6 lifted into the sector sub-assembly tool (SSAT)



Courtesy B. Bigot

Final position in the SSAT

- Fusion: abundant fuel, intrinsic safety and waste handling

- Short term:
 - preparation of the ITER scientific program
 - modelling & experiments on available tokamaks

- Longer term:
 - exploitation of ITER
 - structure materials under high neutron fluence
 - plasma facing components
 - high field superconductors

Web sites: CEA <http://irfm.cea.fr/> - ITER: <http://www.iter.org/>

