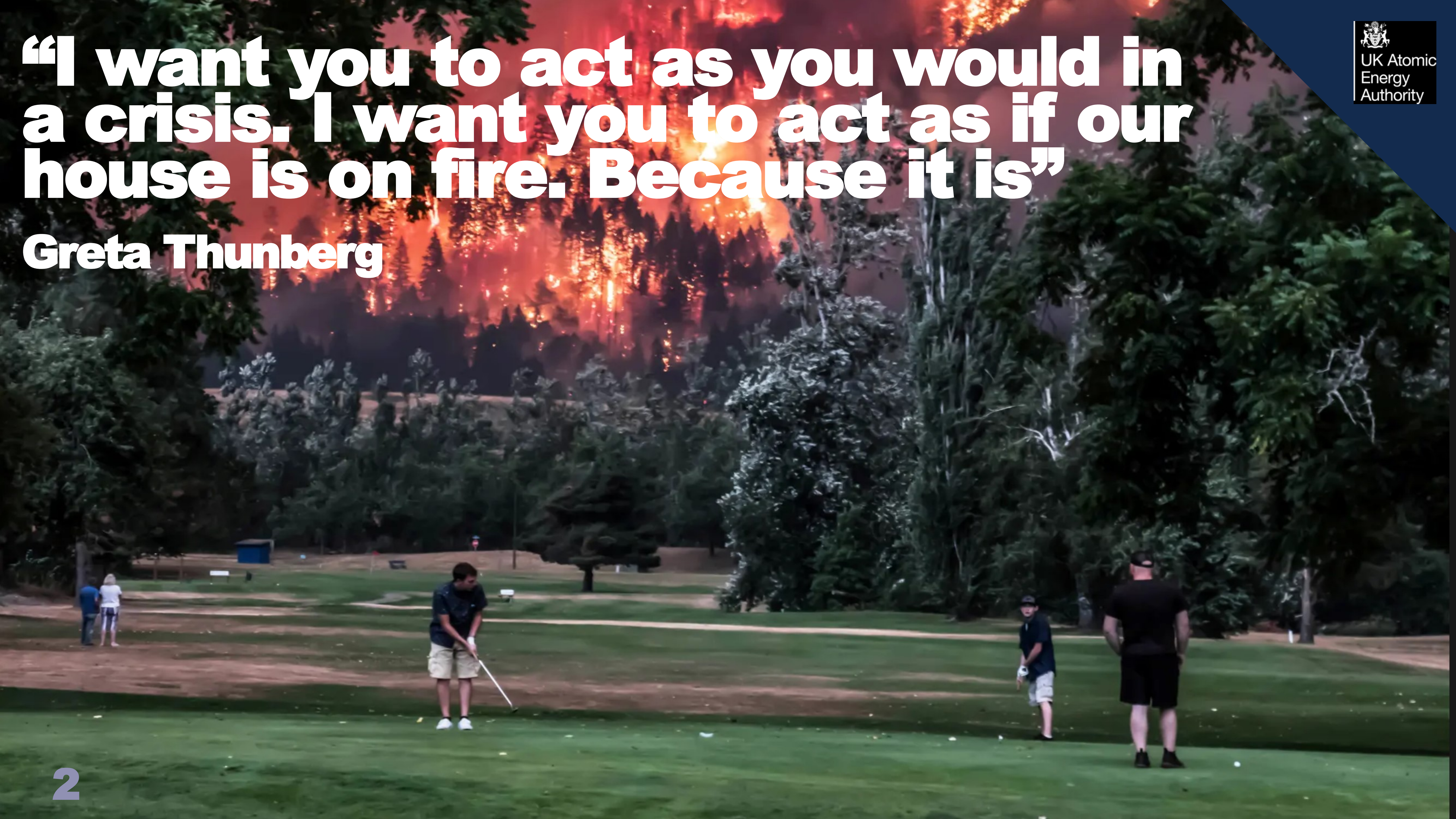
Prospects and Challenges of Nuclear Fusion

Fulvio Militello

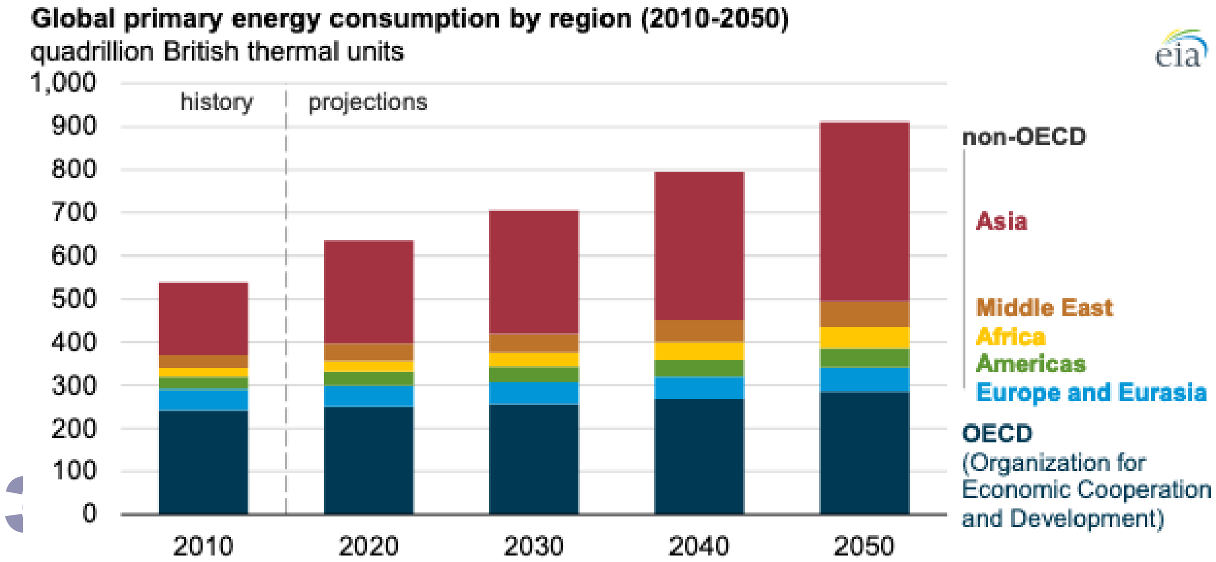
“I want you to act as you would in a crisis. I want you to act as if our house is on fire. Because it is”

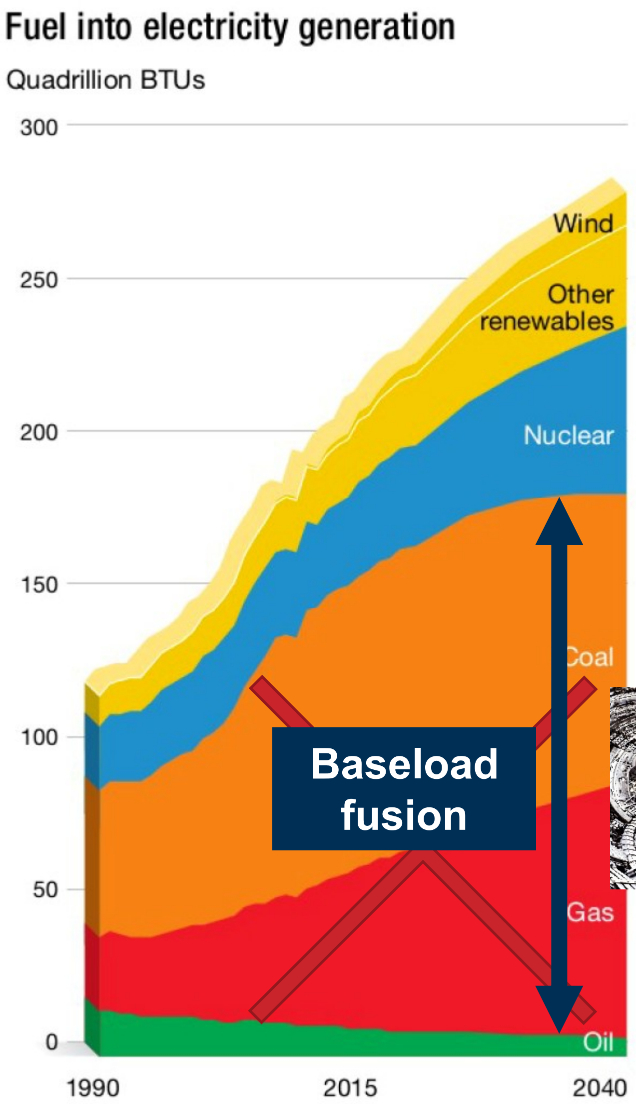
Greta Thunberg

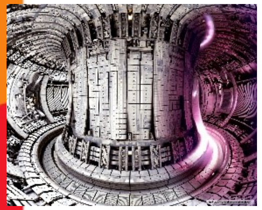


Changing the ‘energy mix’ away from fossil fuels

- 80% of the world’s energy comes from fossil fuels.
- 80% more coal burnt since 2000.
- Renewables and nuclear fission will play a part but are not enough alone.
- Fusion energy will aim to provide baseload power to replace fossil fuels in the long term.







Exxon-Mobil: The Outlook for Energy: A View to 2040, 2014

Benefits of fusion

UK Atomic Energy Authority

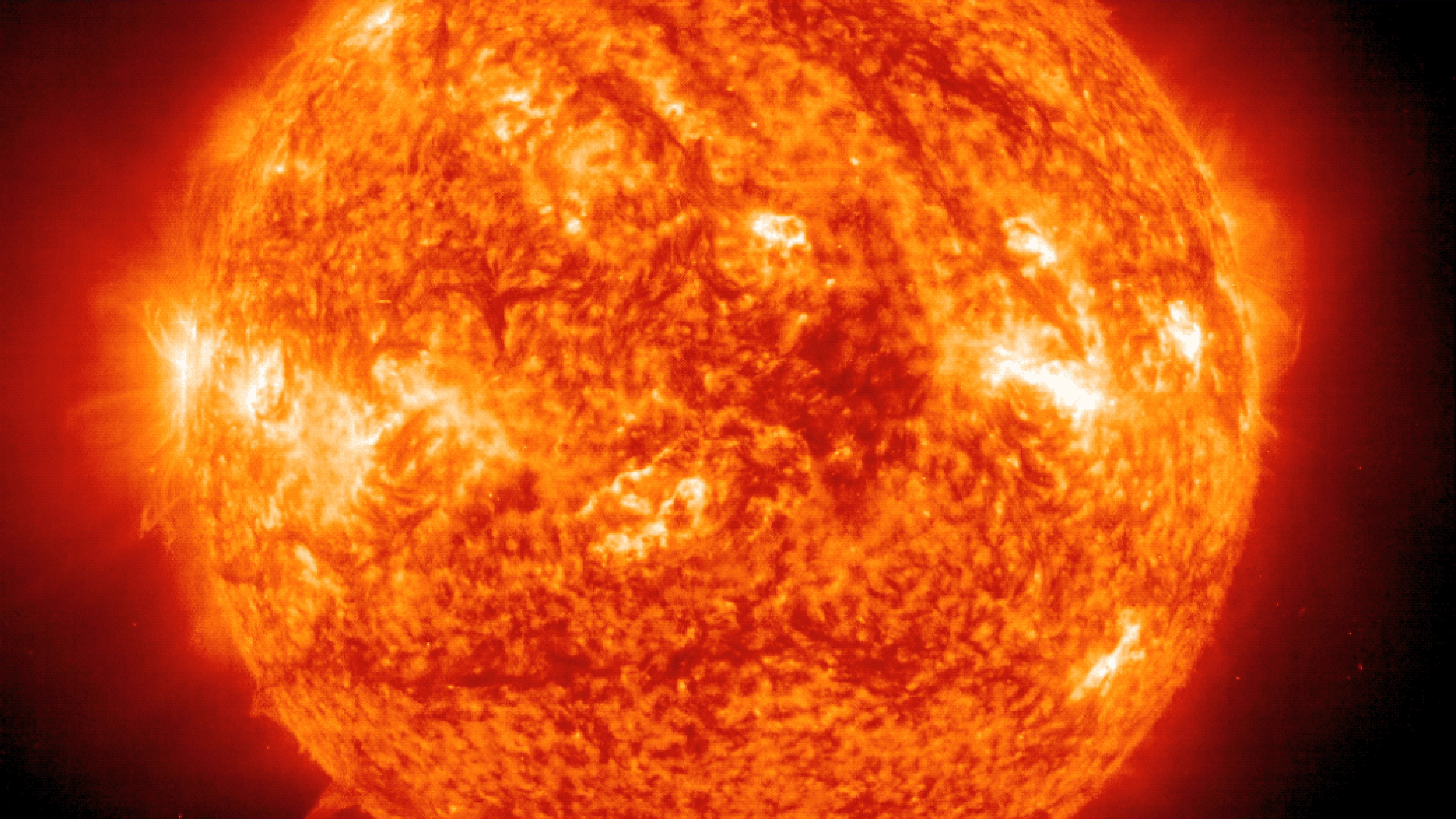
1. **LOW CARBON**
   Fusion is low carbon, with low land usage

2. **SAFE**
   The fusion process is readily and safely controllable

3. **RELIABLE**
   Fusion energy will be baseload and does not depend on seasonal variation, the sun, or the wind

4. **SUSTAINABLE**
   Fusion fuel is potentially abundant in our seas and the Earth's crust

5. **ENERGY EFFICIENCY**
   Fusion provides the most power-dense process available on Earth

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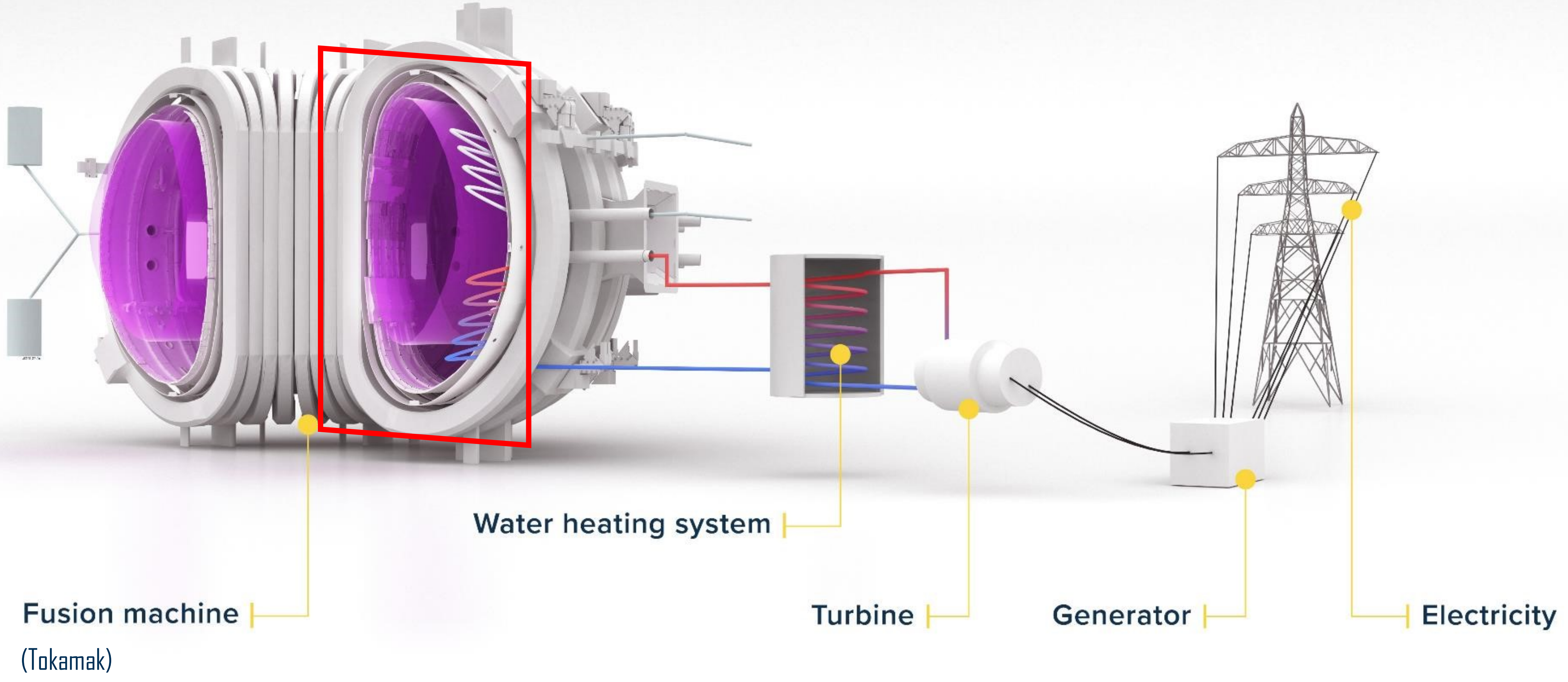
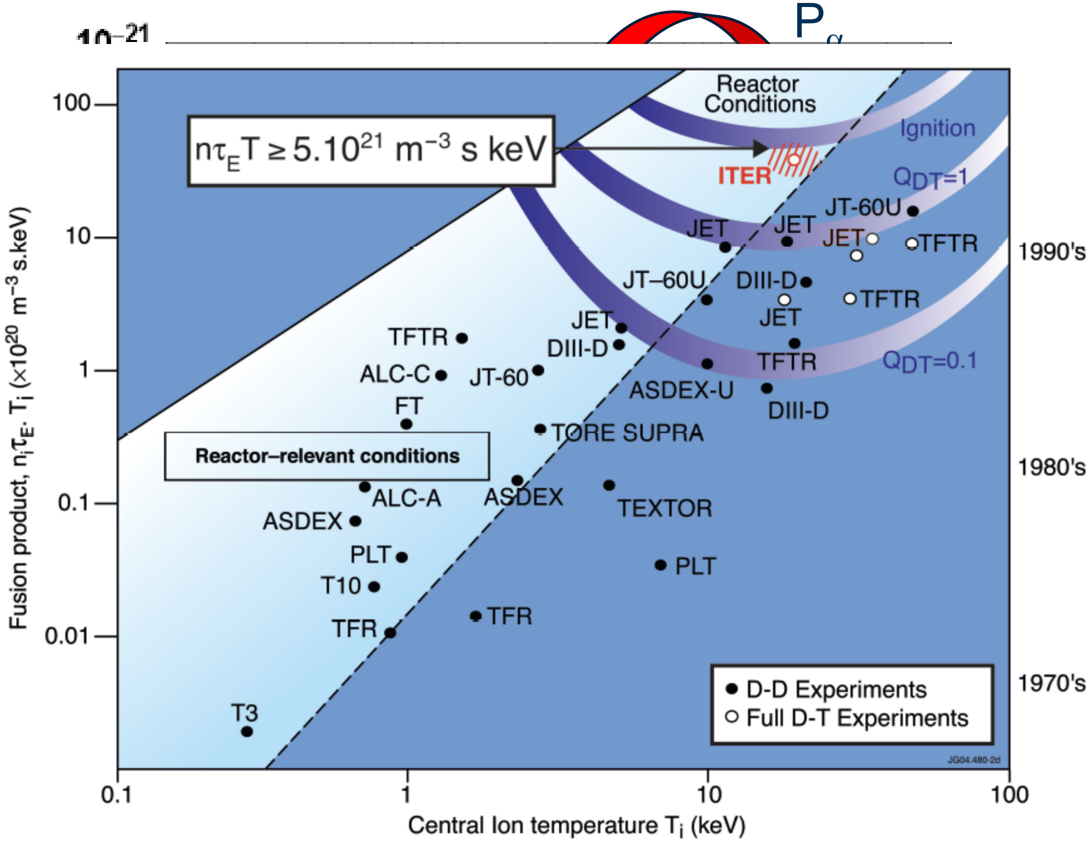
Fusion on Earth



Fusion power plants are energy amplifiers (and very sophisticated kettles!).

Power balance in fusion



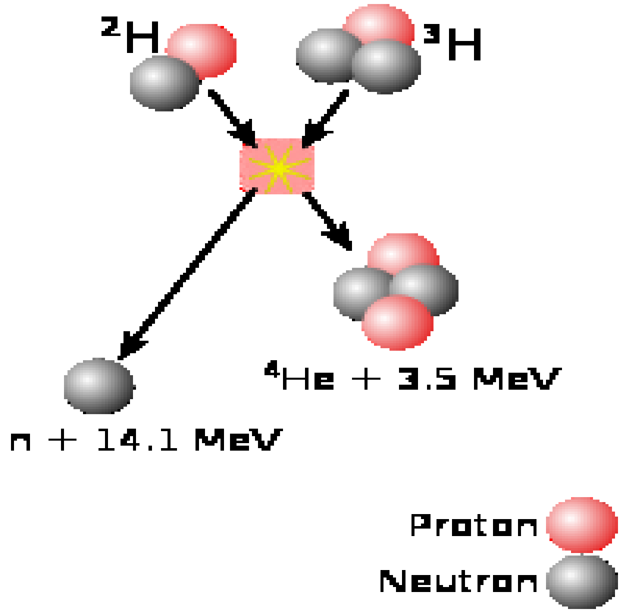
- High energies have to be invested to initiate the reaction.
- We do not want to reach ignition.

$$P_H + P_\alpha =$$

$$P_H \cong \left(\frac{3nT}{\tau_E} \right.$$

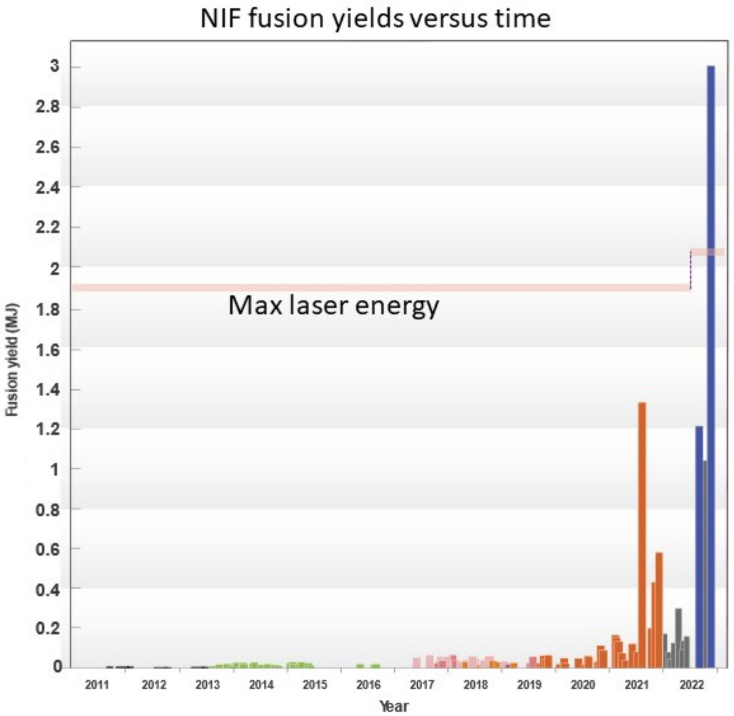
$$Q$$

D-T reactions

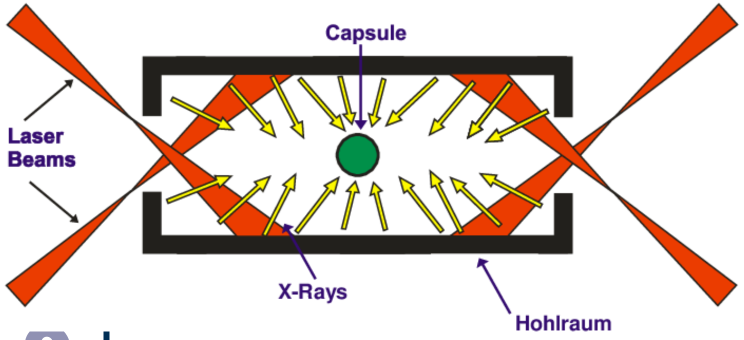


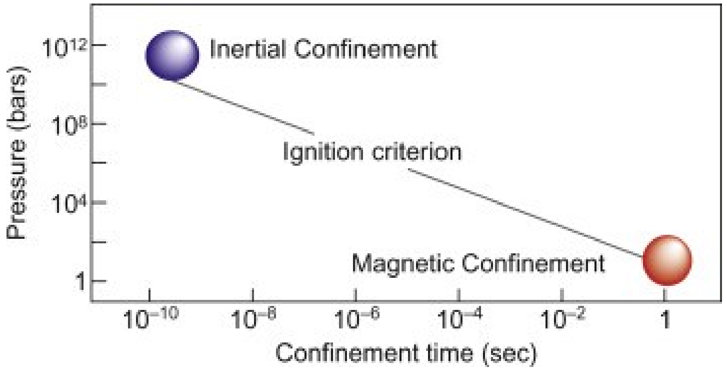
$$P_F = \frac{1}{4} n^2 \langle \sigma v \rangle \mathcal{E} V \propto (nT)^2 V$$

Recent Fusion Records



Mark Herrmann/LLNL (2022)





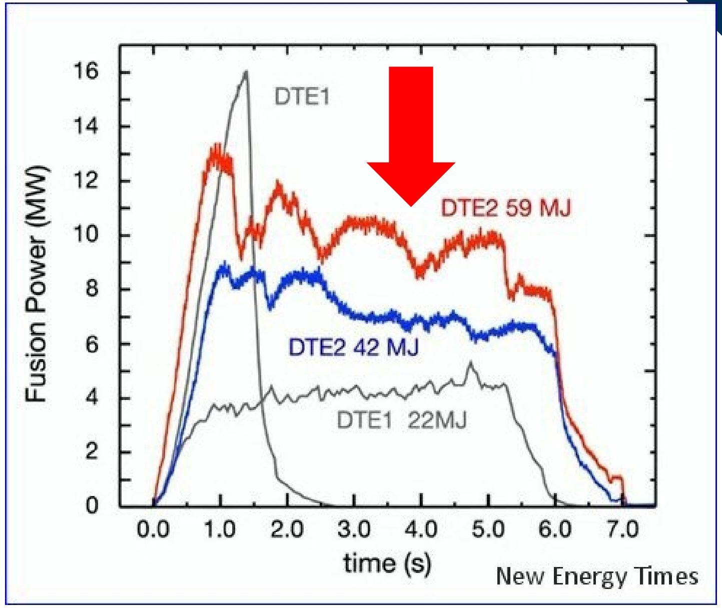
$$nT\tau_E$$

Inertial

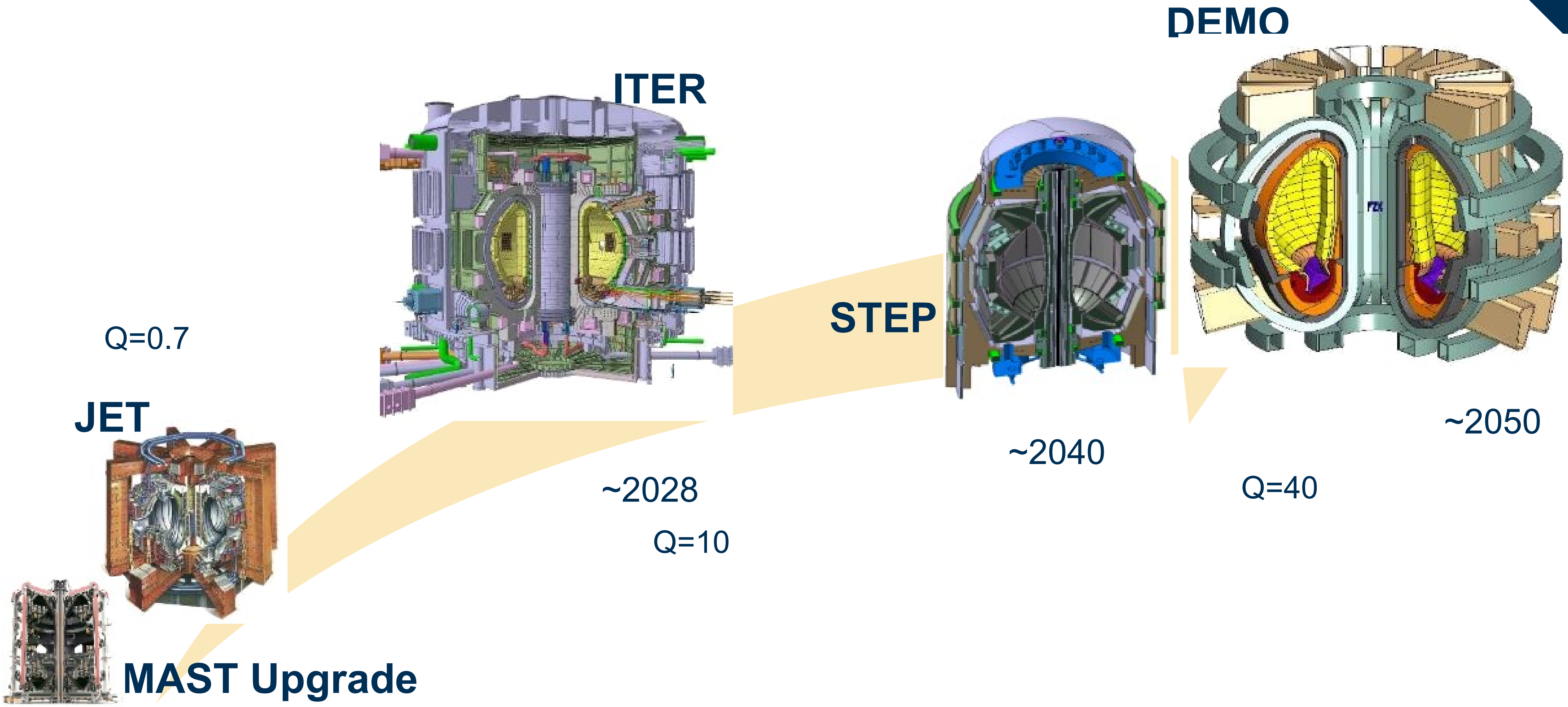
Magnetic

Record Q (Q=1.2) 12/22

Record E_{fus} (E_{fus}=59MJ) 8/21



Roadmap to fusion power



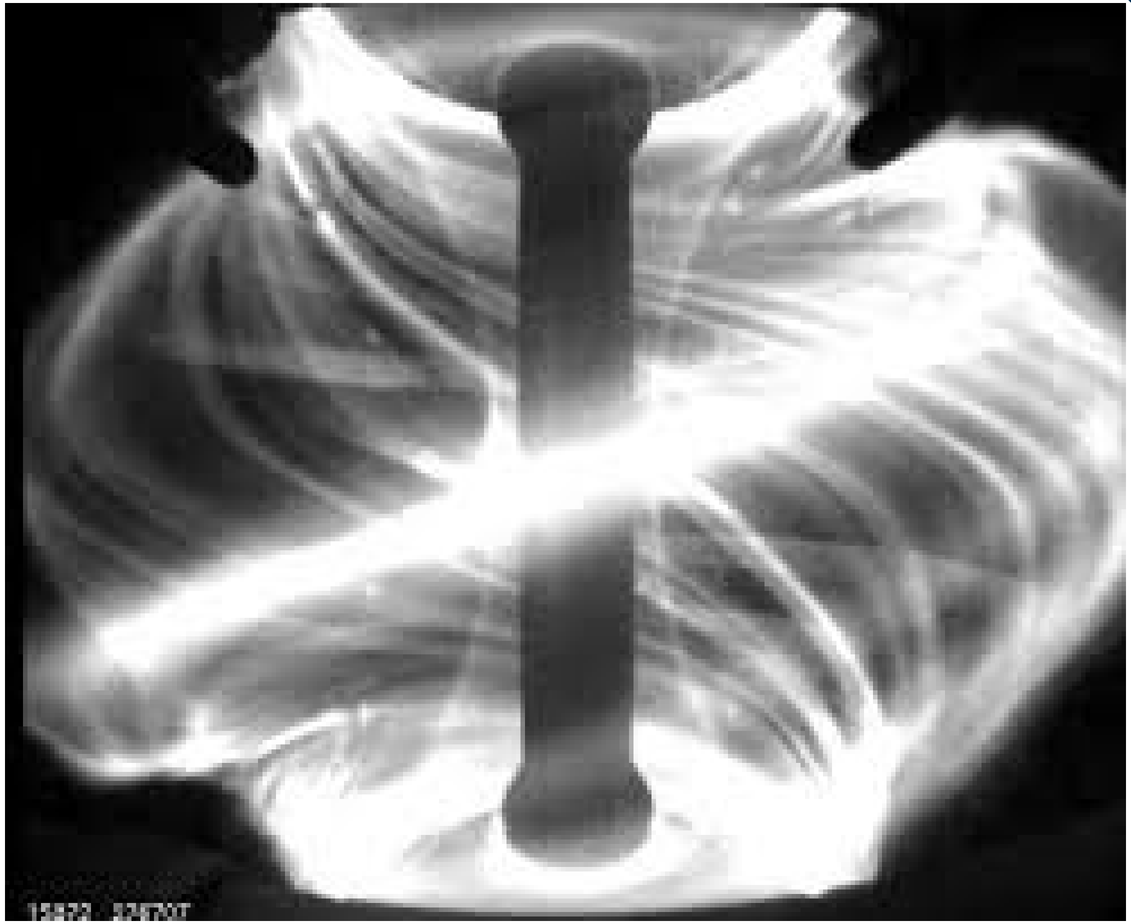
Physics challenges

- Tokamak as a paradigm of an open nonlinear non-equilibrium thermodynamic system (a dissipative system in Prigogine’s sense).
- Complexity, self-organisation and emergent phenomena.

$$\frac{\partial}{\partial t}\left[\sum_{\alpha}\left(m_{\alpha}n_{\alpha}\frac{u_{\alpha}^{2}}{2}+\frac{3}{2}p_{\alpha}\right)+\frac{B^{2}}{2\mu_{0}}+\frac{\epsilon_{0}E^{2}}{2}\right]+\frac{\partial}{\partial \mathbf{x}}\cdot\left(\sum_{\alpha}\mathbf{Q}_{\alpha}+\frac{1}{\mu_{0}}\mathbf{E}\times\mathbf{B}\right)=0,$$

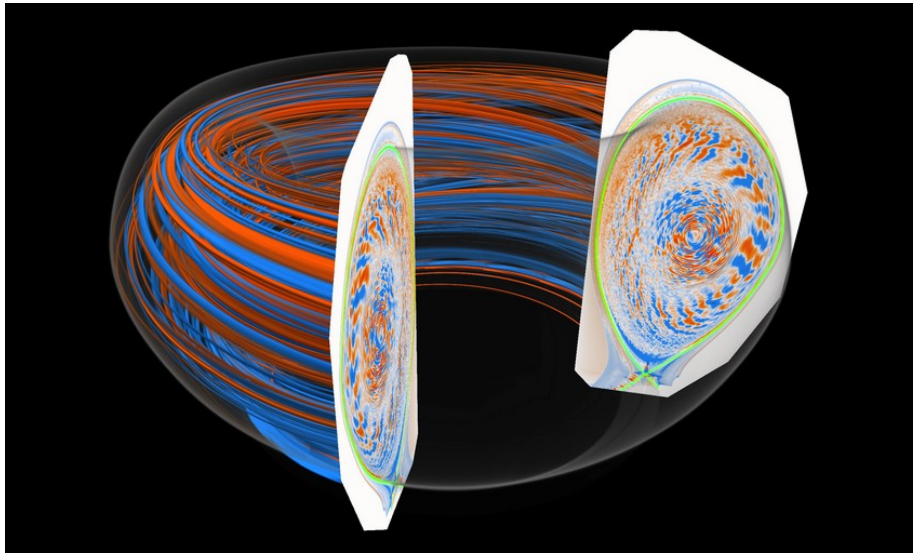
$$\frac{\partial}{\partial t}(n_{\alpha}s_{\alpha})+\frac{\partial}{\partial \mathbf{x}}\cdot(n_{\alpha}s_{\alpha}\boldsymbol{u}_{\alpha})=-\frac{\partial \mathbf{q}_{\alpha}/\partial \mathbf{x}}{T_{\alpha}}+\frac{\sum_{\beta}W_{\alpha\beta}}{T_{\alpha}}-\frac{\mathbf{\Pi}_{\alpha}:\nabla \boldsymbol{u}_{\alpha}}{T_{\alpha}}-\left(\frac{5}{2}+s_{\alpha}\right)S_{\alpha}^{(n)}$$

- Multi-scale nature
- Long-range interactions
- Collective behaviour
- Integrated and intercorrelated physics



Problems to solve

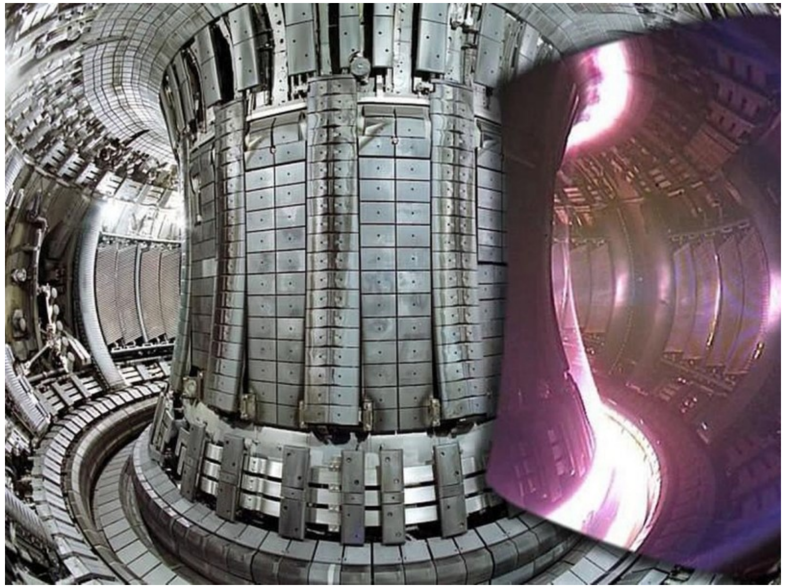
Confinement



Chang 2017

τ_E

Exhaust

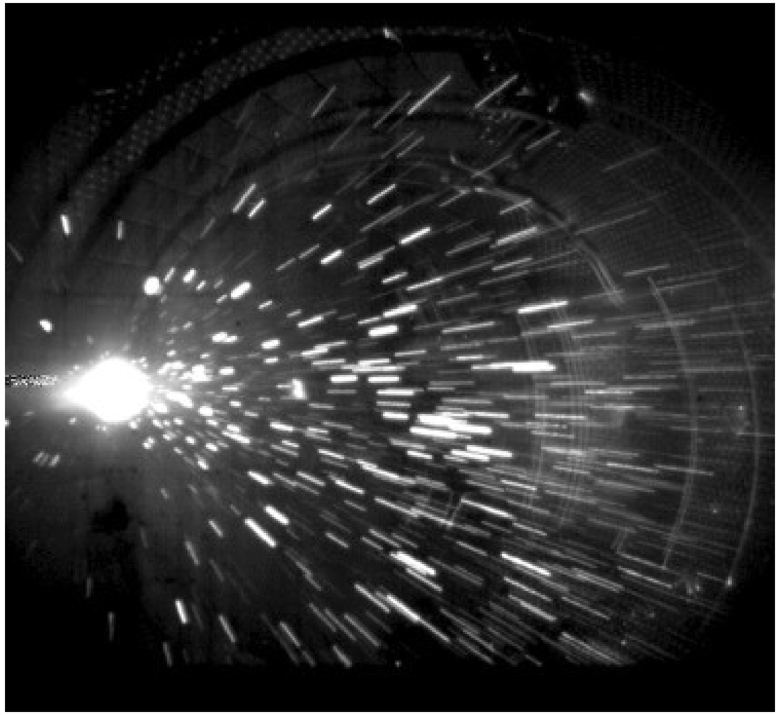


JET

P_L

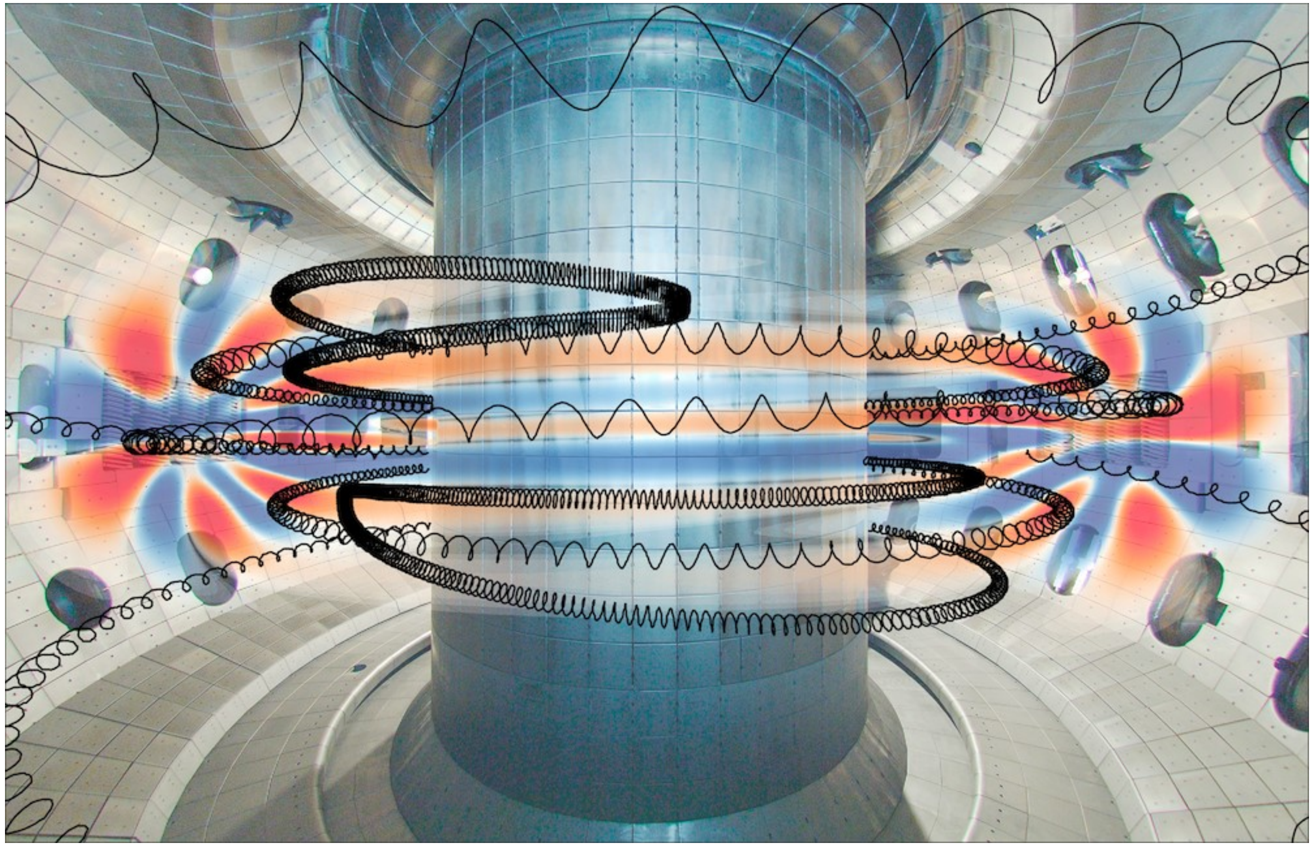
W

Disruptions

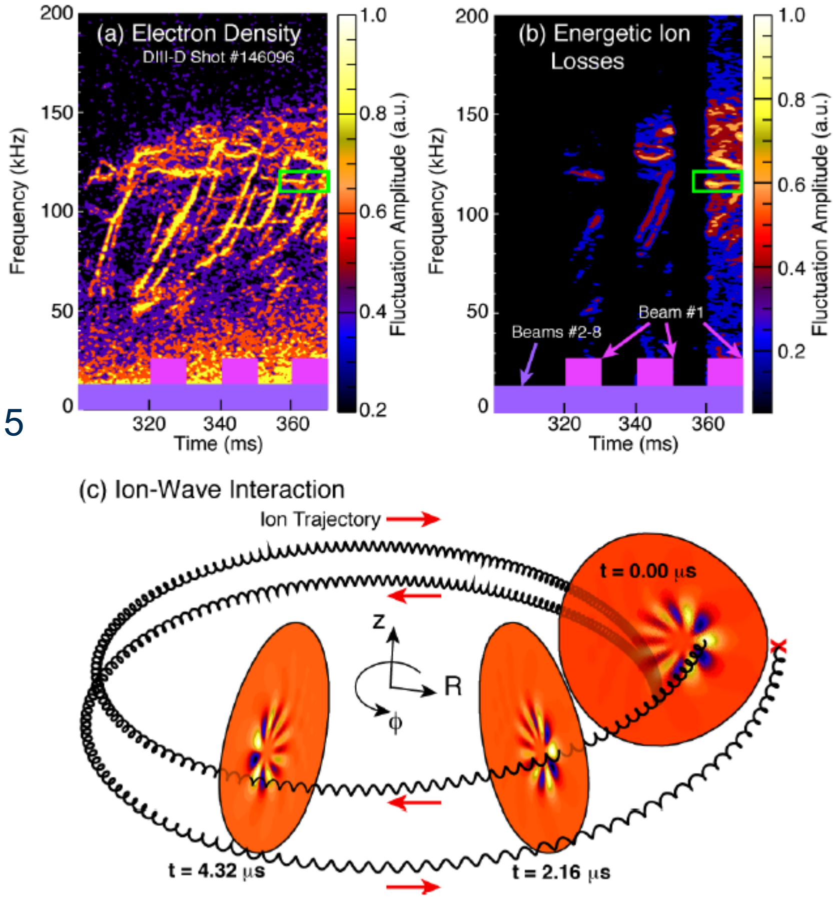


Bucalossi 2016

Self-heating and α particles



Pace 2015



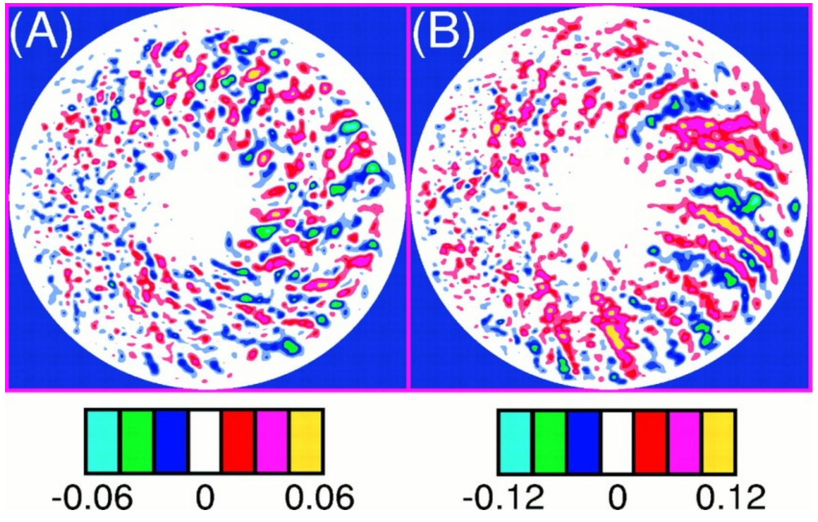
The fusion generated α particles keep the plasma hot and self-heat it (unless they escape!).

A fascinating non-linear self-organisation mechanism (feedback) is established between waves and particles.

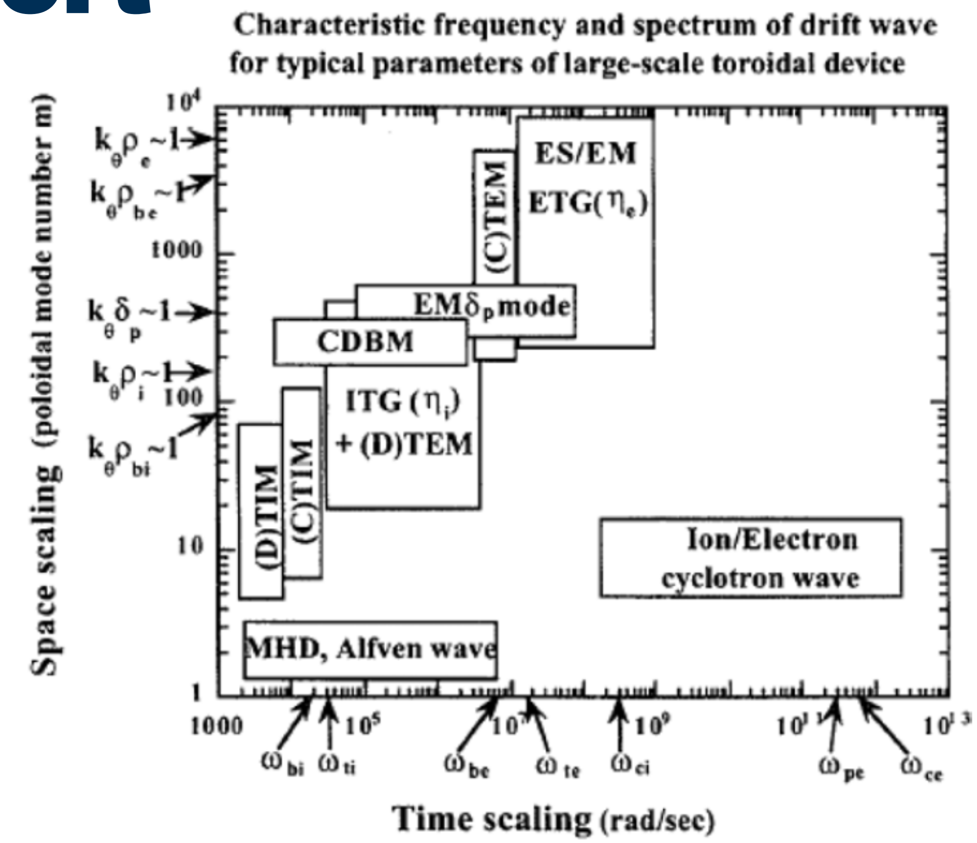
When Q=10, the α particles provide twice the heating than the external sources.

Turbulence and transport

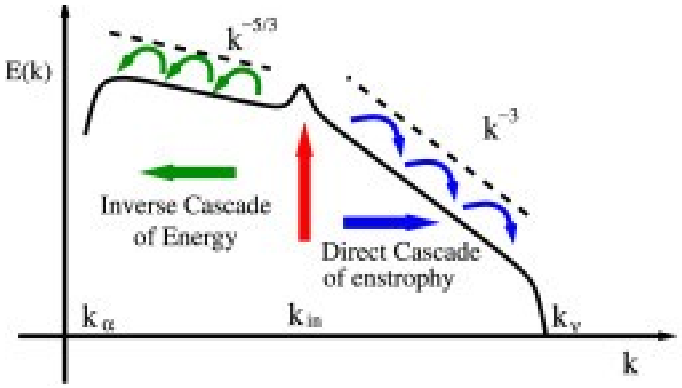
- Spectra and lack of inertial range (no Kolmogorov)
- Quasi-2D nature and inverse cascade
- Structure formation (e.g. streamers)



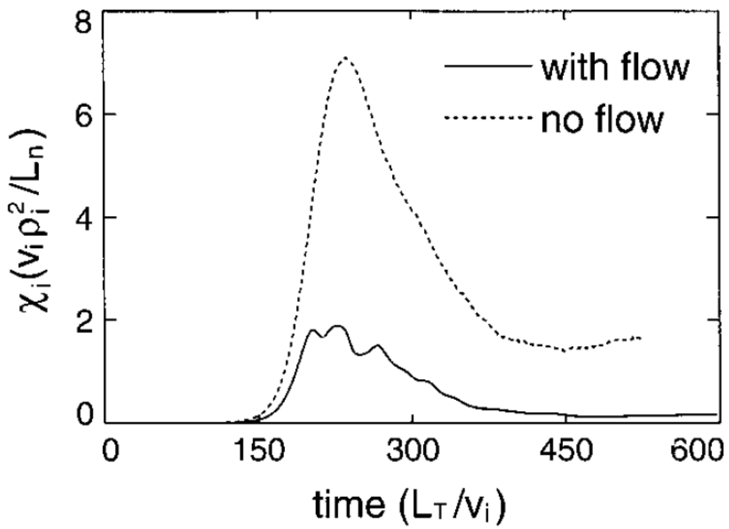
Lin 1998

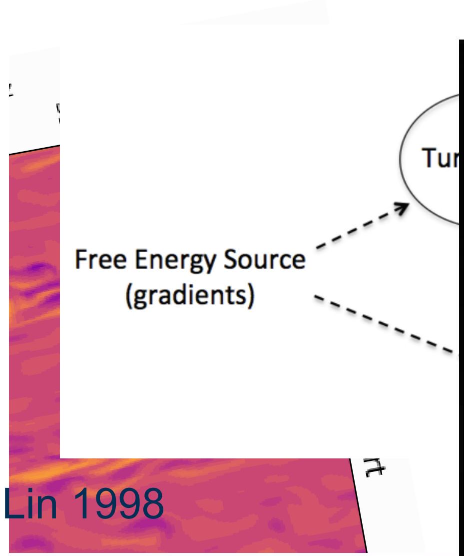


Kishimoto 2000



Zonal flows

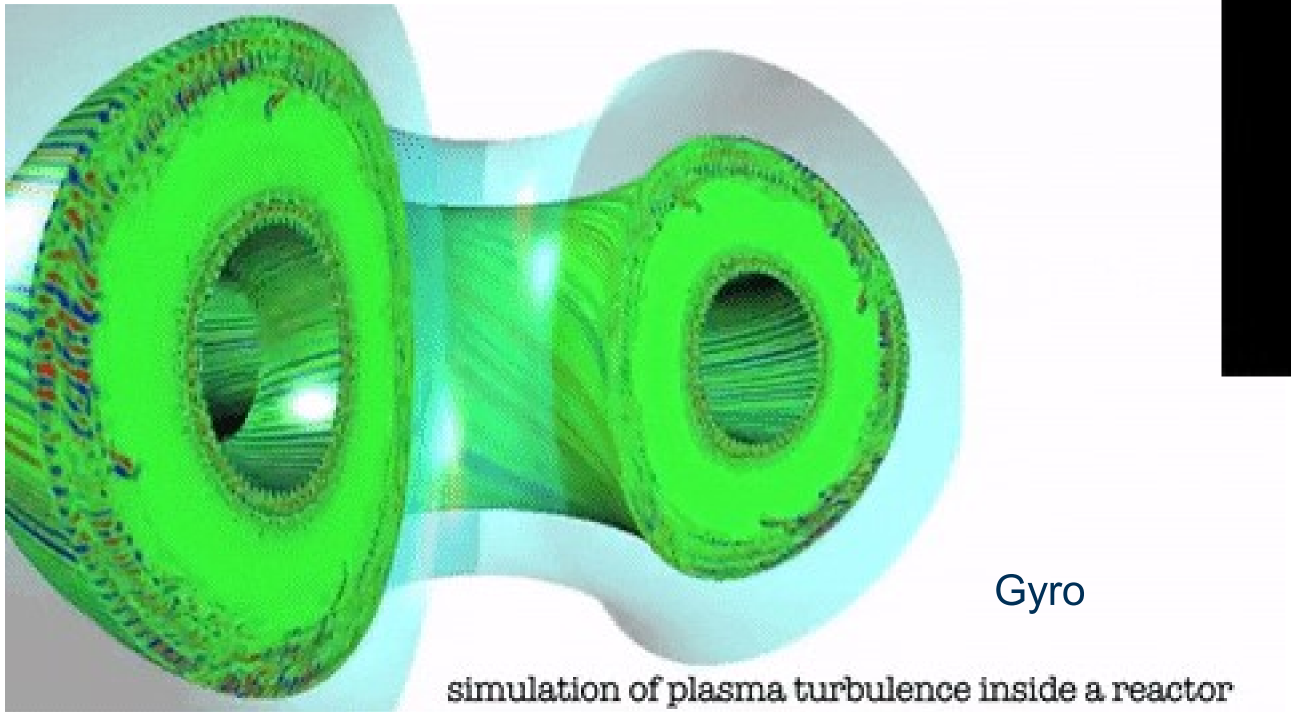




Lin 1998

ature

interaction



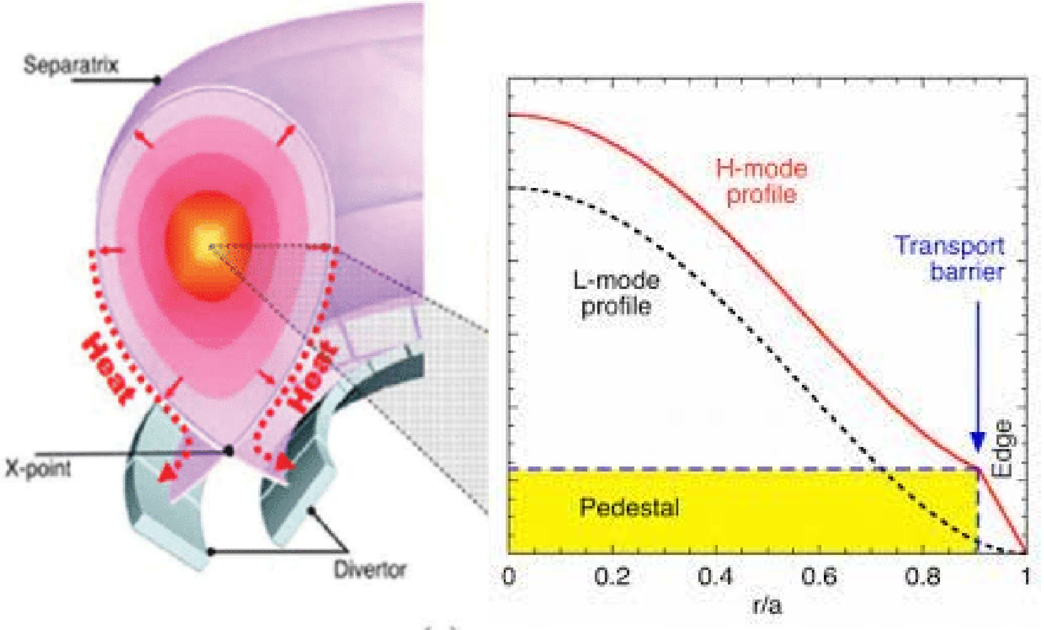
Gyro

L-H transition

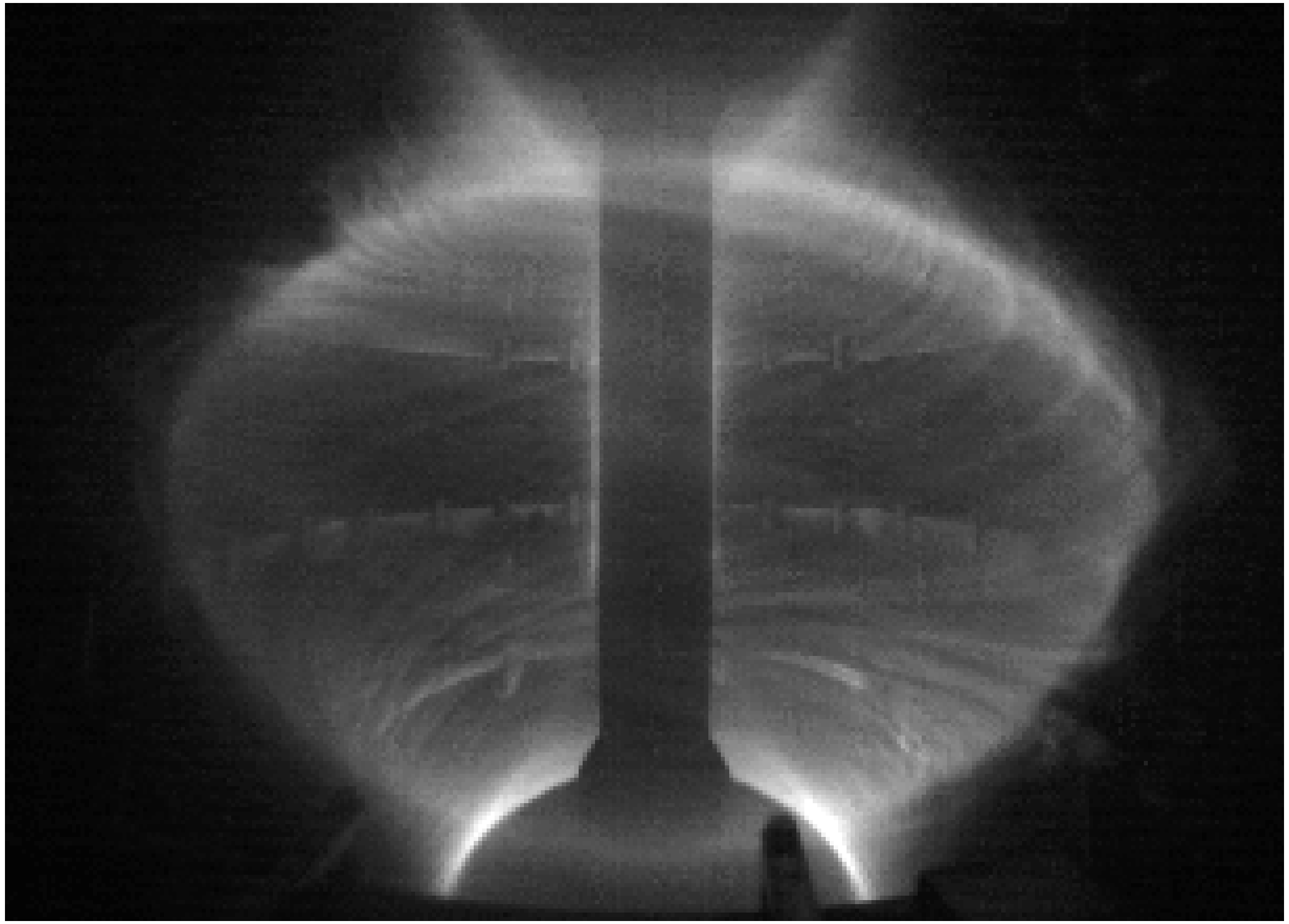
$$P_{\text{Thresh}} = 0.0488\ e^{\pm 0.057}\ n_{e20}^{\ 0.717\pm 0.035}\ B_T^{\ 0.803\pm 0.032}\ S^{0.941\pm 0.019}$$

Martin (2008)

- Sudden improvement in confinement.
- Critical/phase transition with hysteresis properties
- Not yet understood (since 1983!)

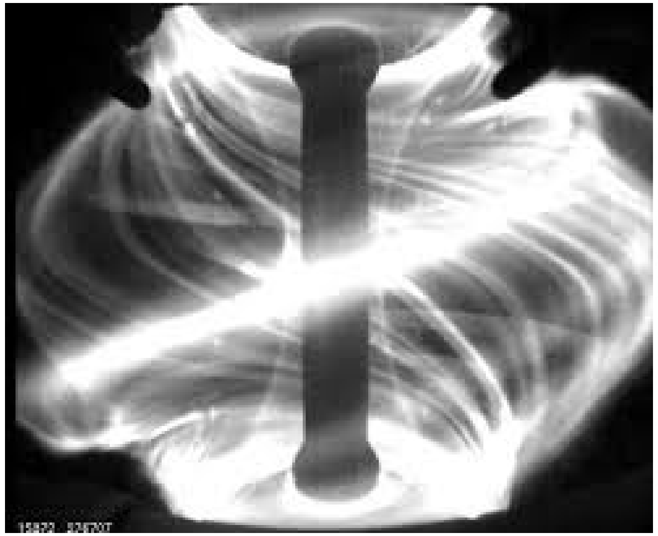


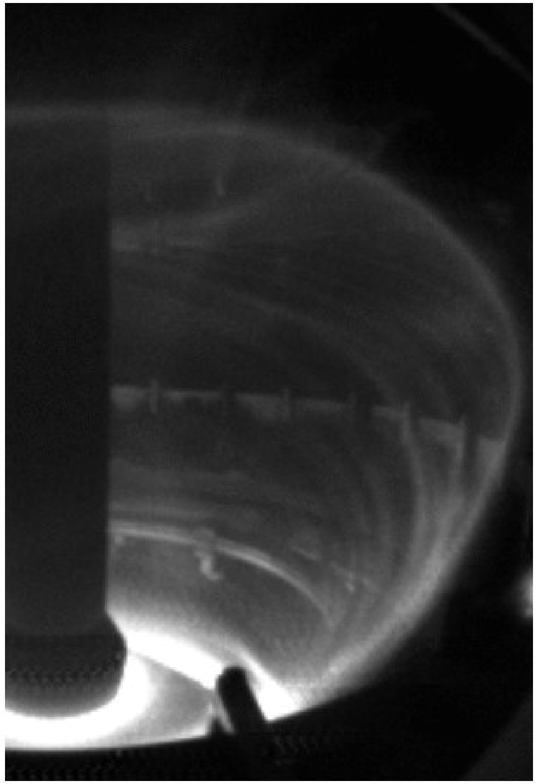
(a)

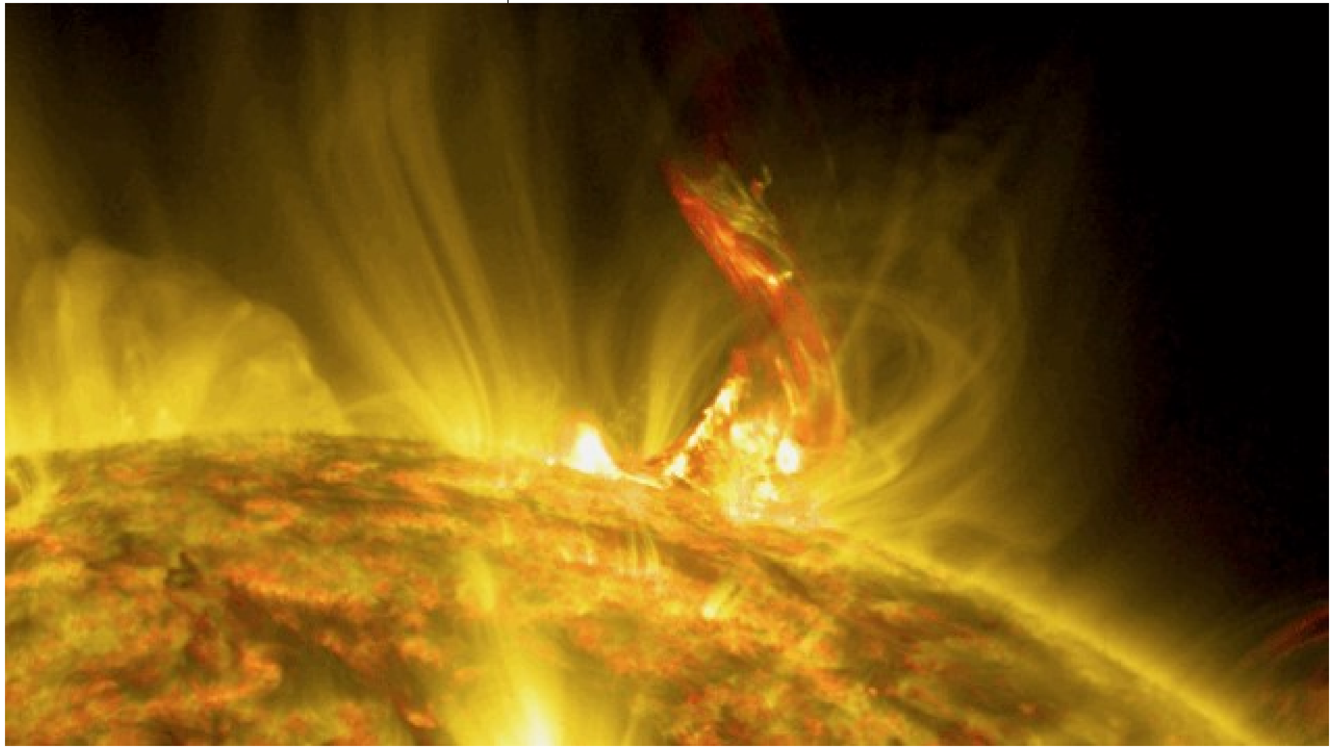


ELMs and filaments

- Edge Localised Modes (ELMs) are the plasma response to large local gradients.
- Similarities with coronal mass ejection? Role of magnetic reconnection?
- The plasma self-organizes into filamentary structures, which have a highly nonlinear dynamics.

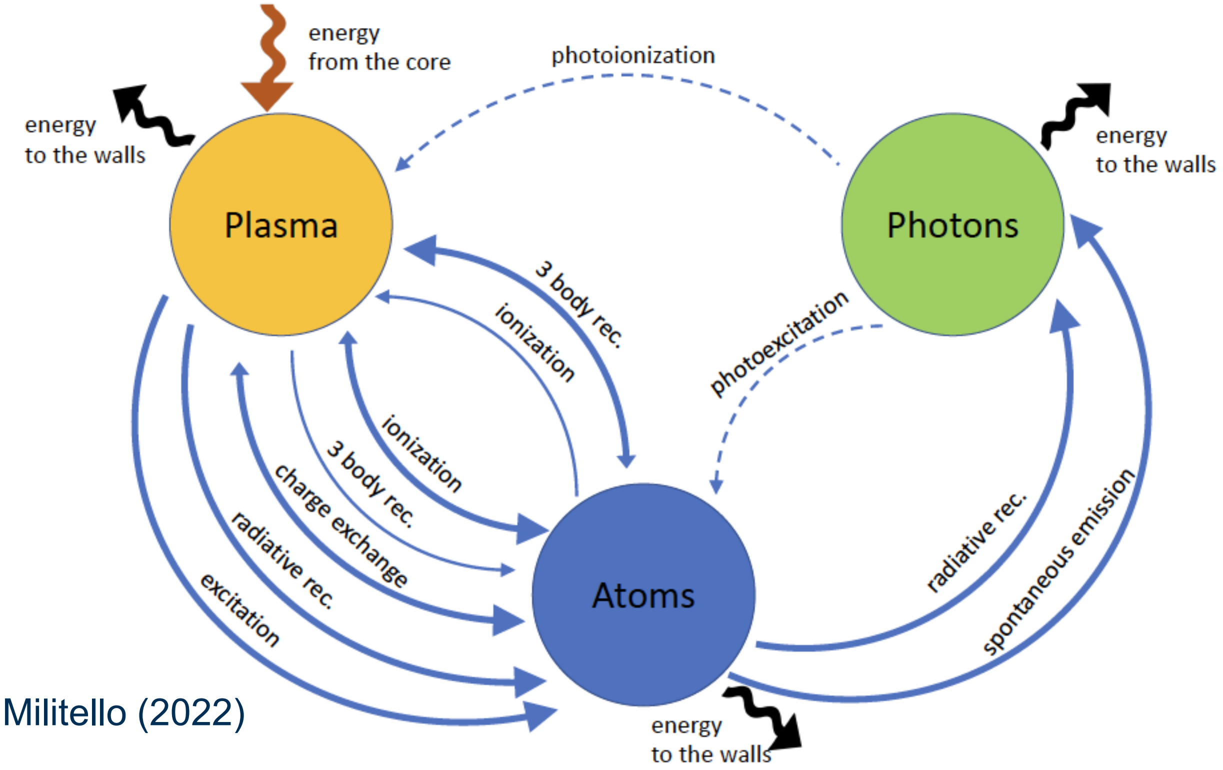




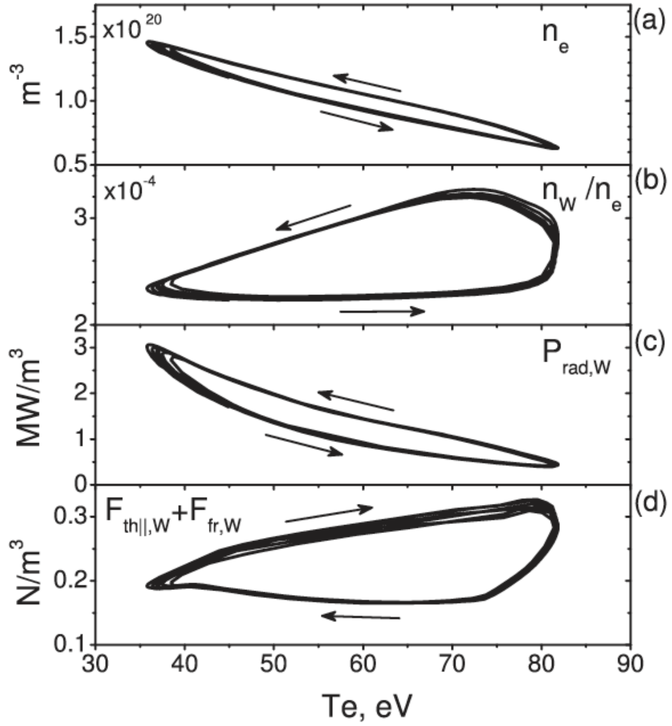


Ecosystem in the boundary plasma

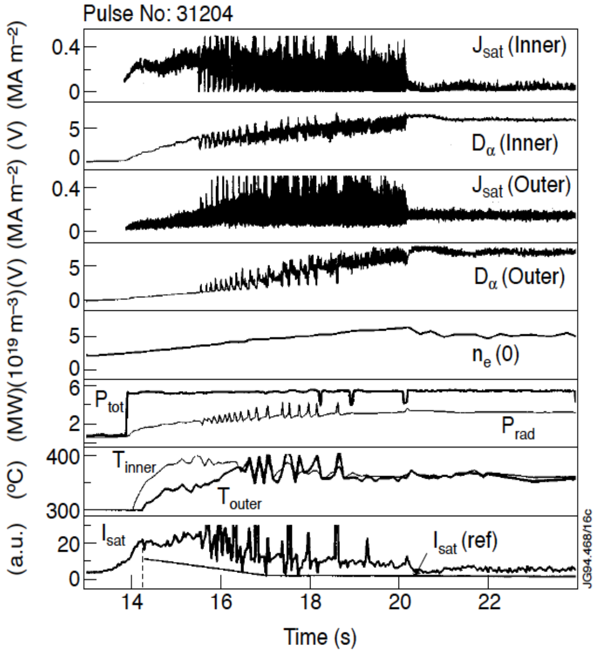
Reaction-diffusion-(advection) equations govern the cold plasma.



Militello (2022)



Smirnov (2016)



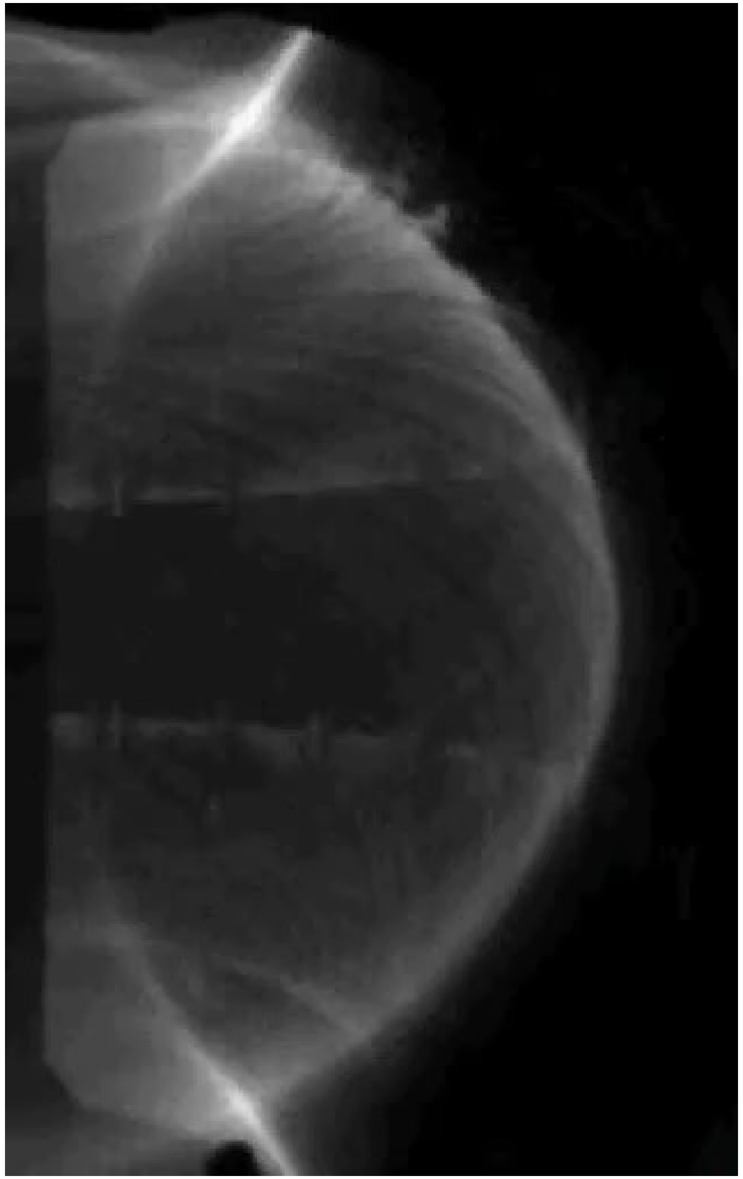
Loarte (1997)

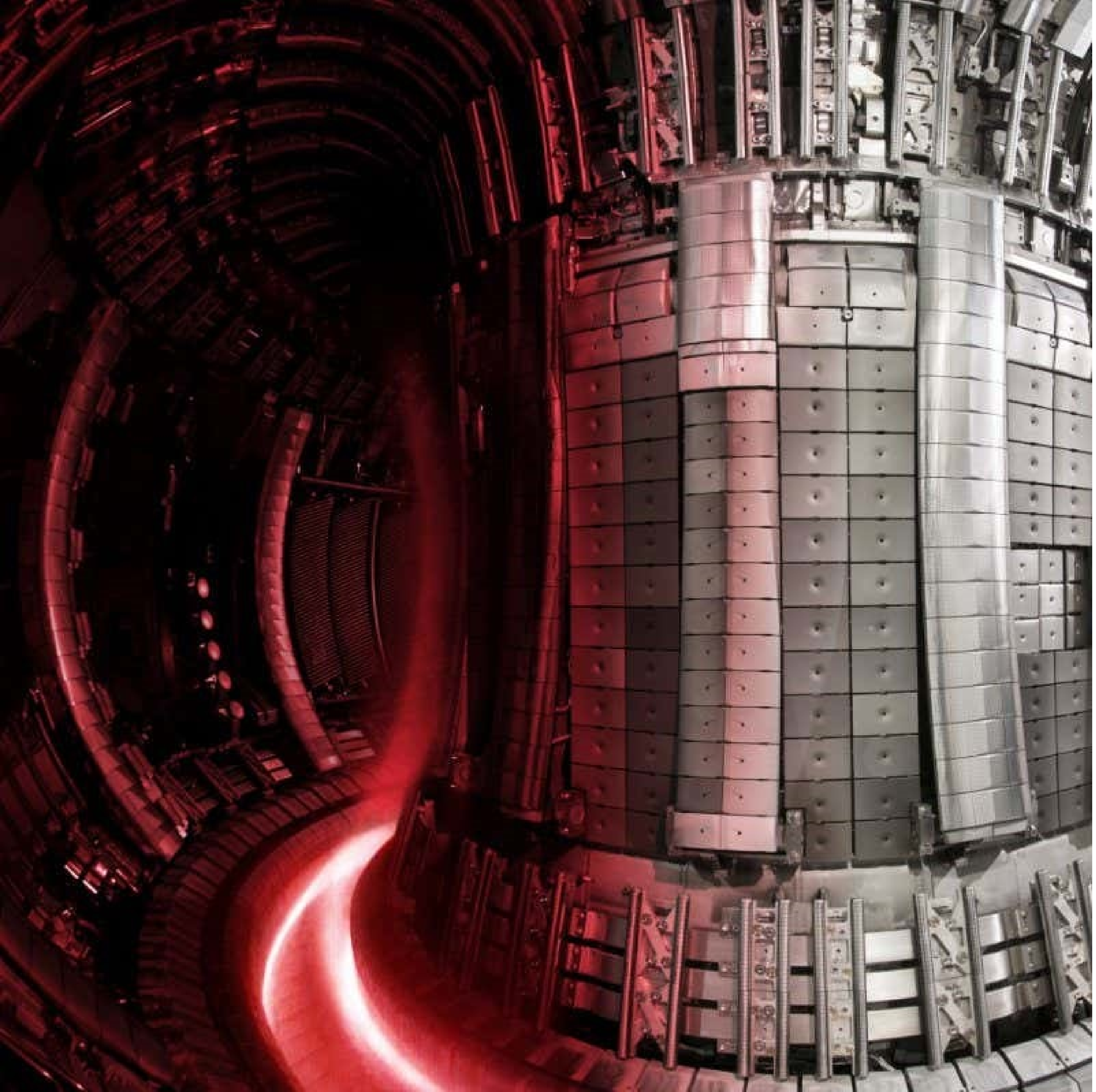
Despite the complexity of the system, the solution is typically just a regular motion of the cold front from the wall (Fisher-like travelling wave?).

Limit cycle behaviour and large oscillations are sometimes observed

Conclusions

- Fusion physics is a rich field, with many phenomena not yet understood.
- We are now starting to achieve new regimes that will take us in unexplored land.
- Fusion plasmas are a paradigm for open non-equilibrium nonlinear, strongly driven systems.
- Emergence, complexity, self-organisation lead to fascinating phenomena.
- We have a path forward to fusion energy, but we need to de-risk it with Theory and Modelling.
- We need fresh ideas and brilliant scientists to join us.





Thank you for your attention!

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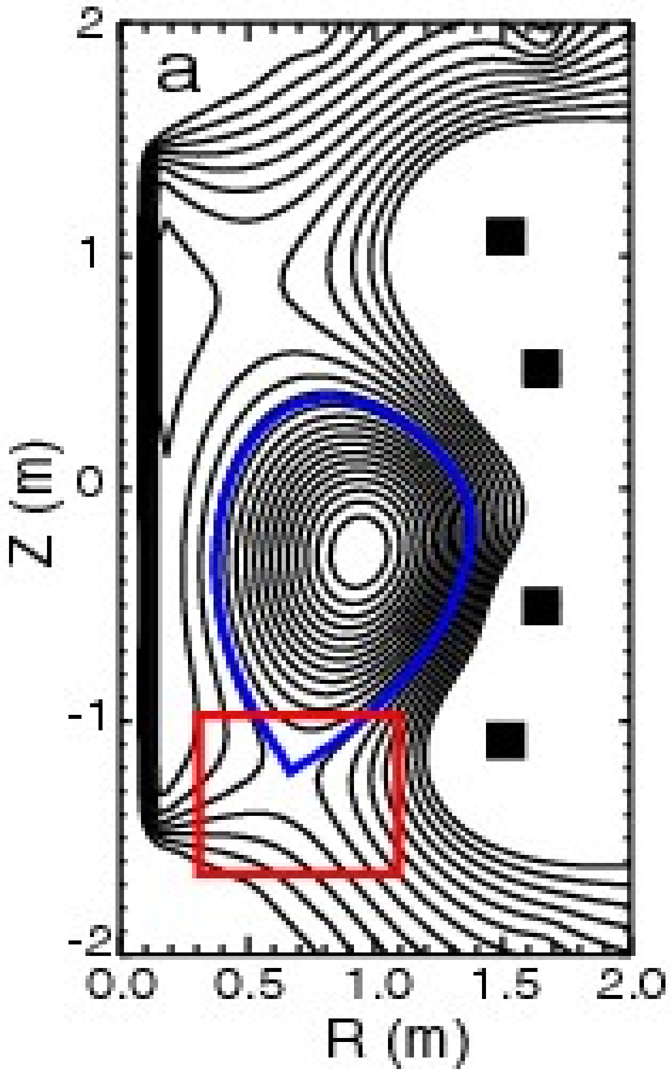
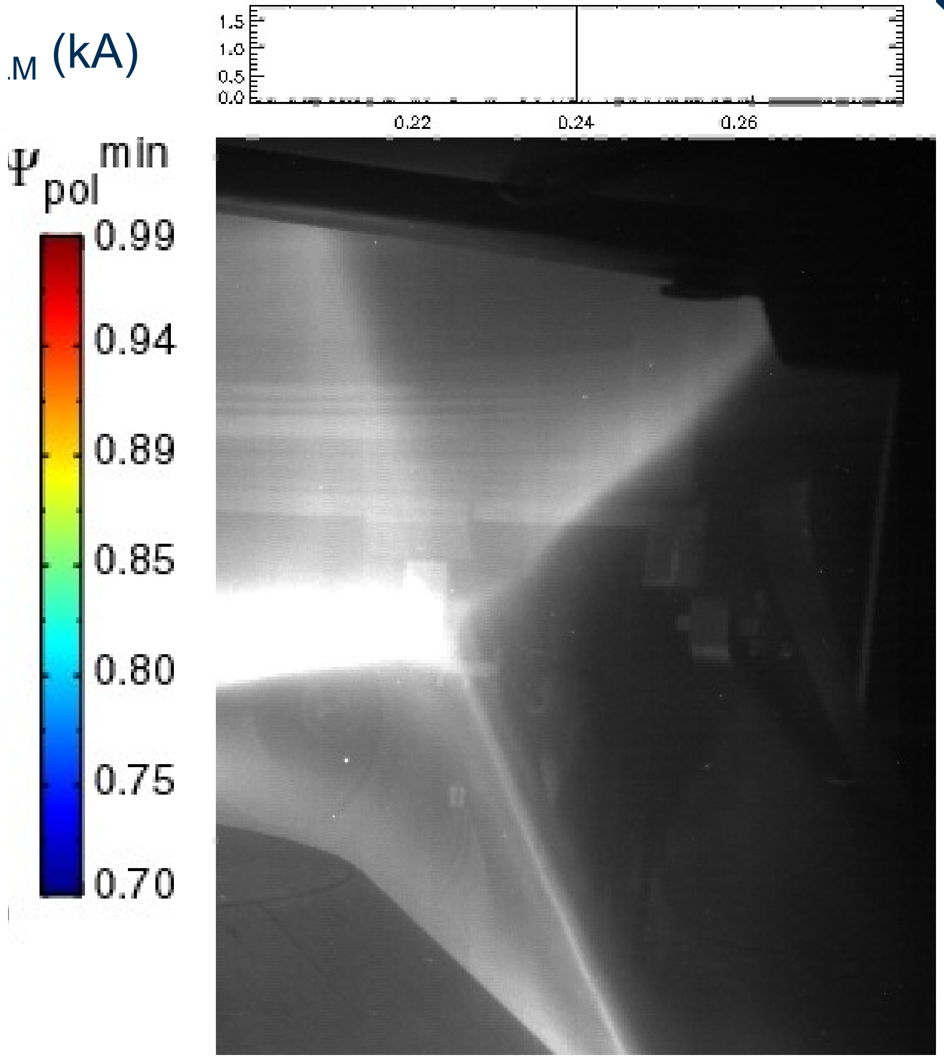
https://ccfe.ukaea.uk/

https://www.gov.uk/government/organisations/uk-atomic-energy-authority

A bit of mathematical fun!

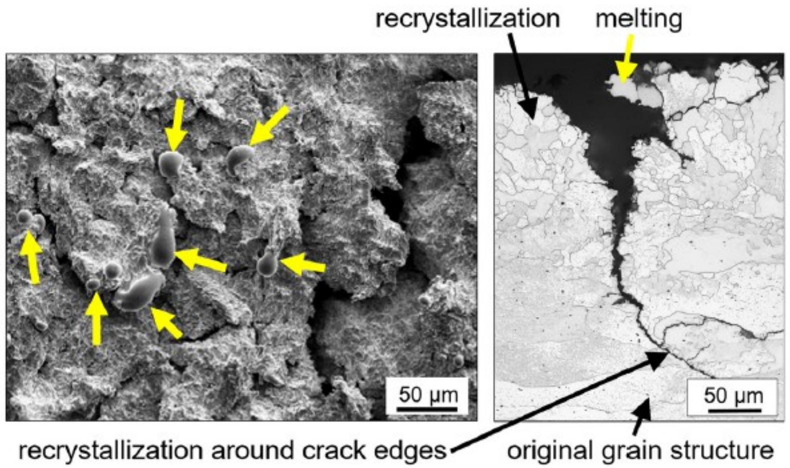
- The magnetic field has an Hamiltonian nature;
- Lack of symmetry in 3D induces chaotic trajectories and the field becomes stochastic.
- Homoclinic tangle displayed in real plasmas!



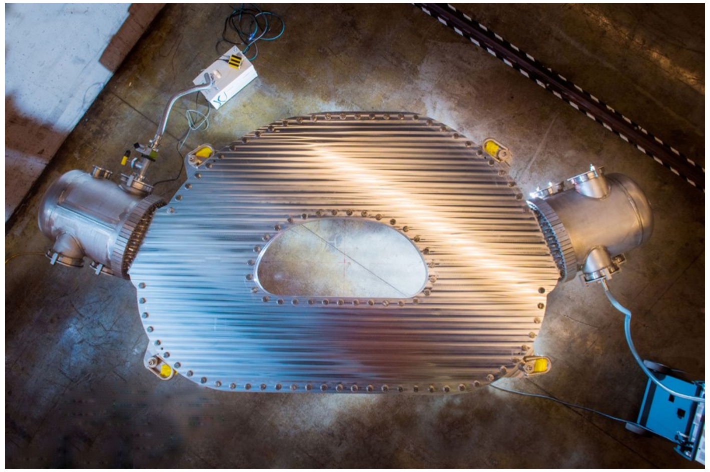


Kirk et al, Phys Rev Letters, 2012

Technological challenges



Linke 2019



Gretchen Ertl, CFS/MIT-PSFC, 2021

- Materials able to sustain large plasma and neutron irradiation (no degradation of thermomechanical properties, transmutation or activation)
- Integration in engineering – finding optimal solution
- Large magnetic fields are good, but difficult to obtain in a neutron rich environment (superconductors don't like them).
- The supply chain must grow quickly to provide an industrial basis
- Basic scientific principles cannot be tested on a small scale, hence: cost!

UK Atomic Energy Authority

Q: What world-changing idea, small or big, would you like to see implemented by humanity?

A: This is easy. I would like to see the development of fusion power to give an unlimited supply of clean energy

Stephen Hawking

'Brief Answers to the Big Questions', 2018