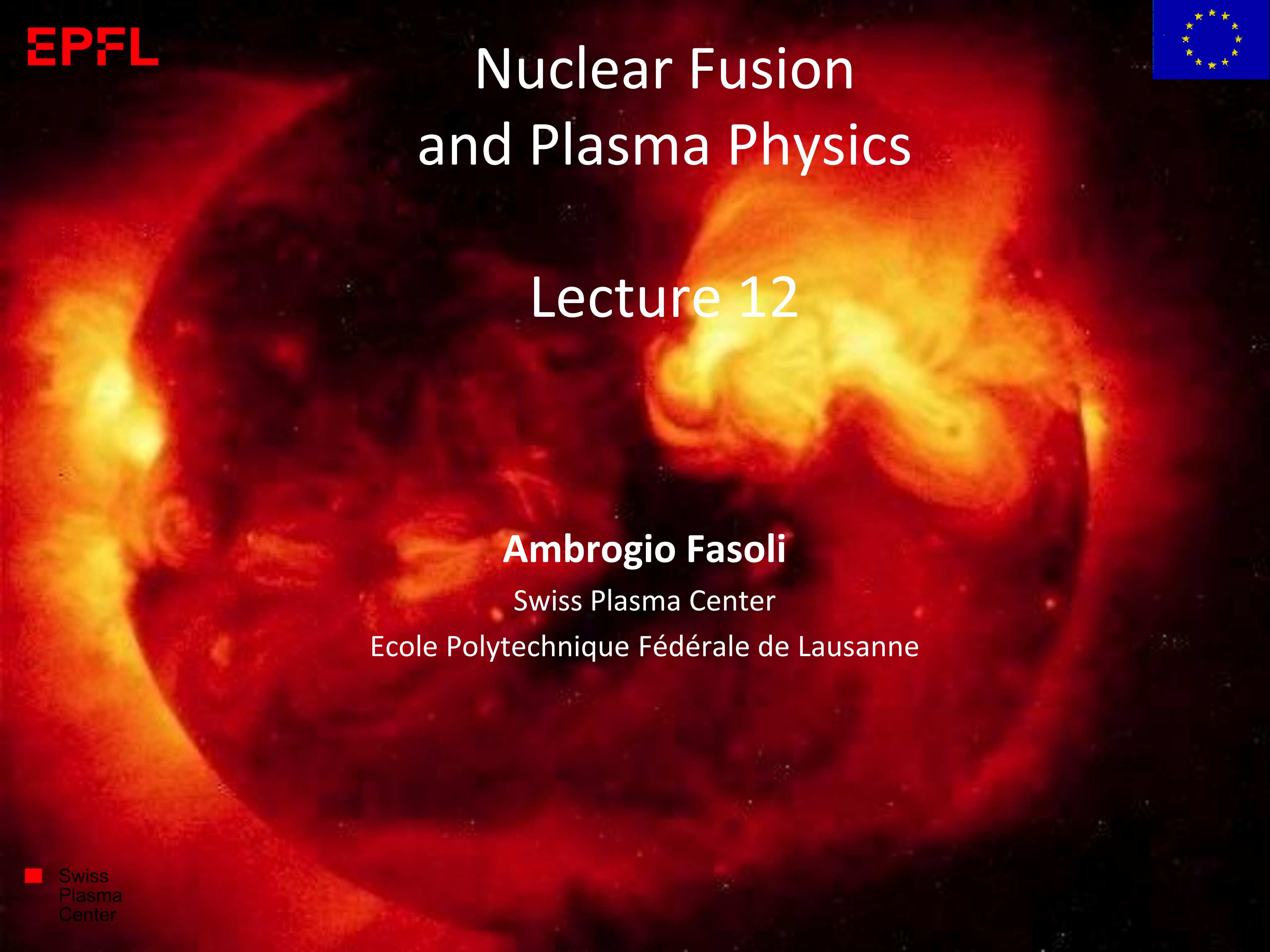

Nuclear Fusion and Plasma Physics

Lecture 12

Ambrogio Fasoli

Swiss Plasma Center
Ecole Polytechnique Fédérale de Lausanne

Wrapping it up….
Burning plasmas, ITER safety, and route to a fusion power plant

Burning plasma: generalities

Fast ion loss mechanisms

Burn stability and control

Tritium in fusion

ITER safety and licensing

Toward a fusion power plant

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BURNING PLASMAS: GENERALITIES

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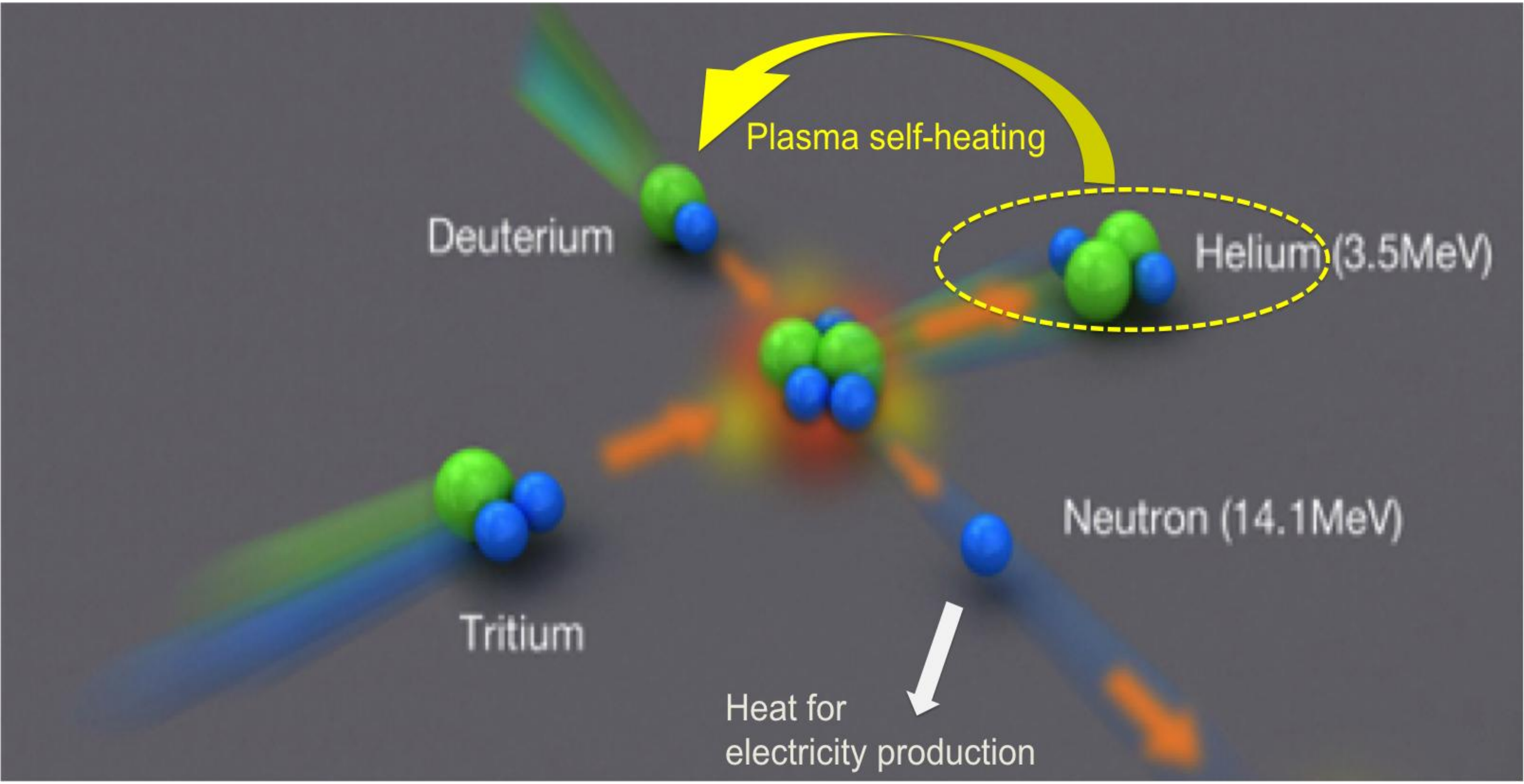
D-T fusion reaction



Definition of a burning plasma

Fusion power density ≡ $P_{fusion} = \frac{1}{4} n^2 \langle \sigma v \rangle E_{fusion}$ ($n_D = n_T = n/2$)

α power density ≡ $P_\alpha = 0.2\ P_{fusion}$

Thermal energy density $W \equiv 3nT$

Energy balance

$$\frac{dW}{dt} = \underbrace{P_\alpha}_{\alpha\text{-heating}} + \underbrace{P_{in}/V}_{\text{ext. heating}} - \underbrace{W/\tau_E}_{\text{losses}}$$

confinement time

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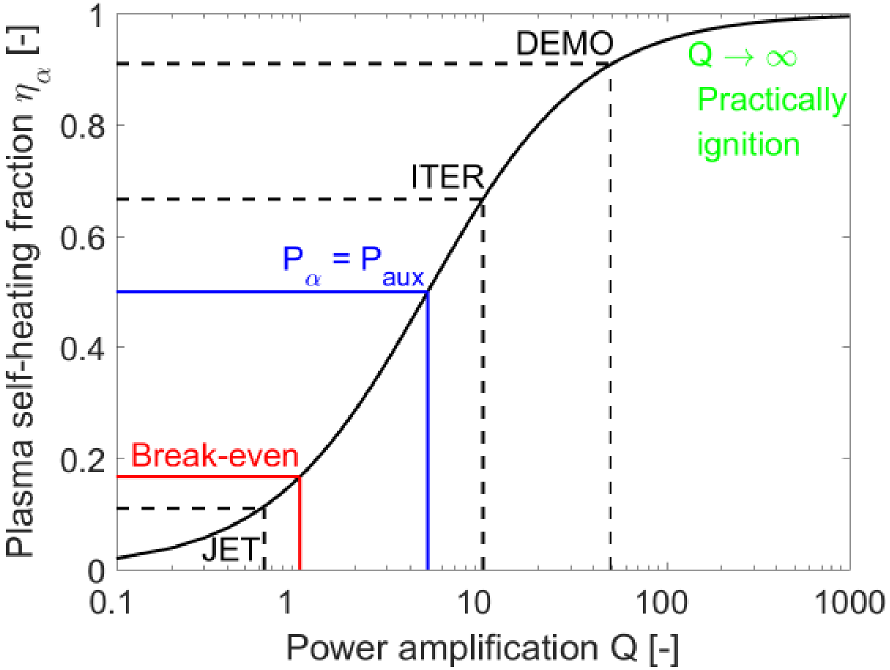
Energy balance

$$\mathbf{dW/dt} = \underbrace{P_\alpha}_{\alpha\text{-heating}} + \underbrace{P_{in}/V}_{\text{ext. heating}} - \underbrace{W/\tau_E}_{\text{losses}}$$

confinement time

$Q \equiv P_{fusion}/P_{in} = 5\ P_\alpha/P_{in}$

α heating fraction: $f_\alpha \equiv P_\alpha/(P_\alpha + P_{in}) = Q/(Q+5)$



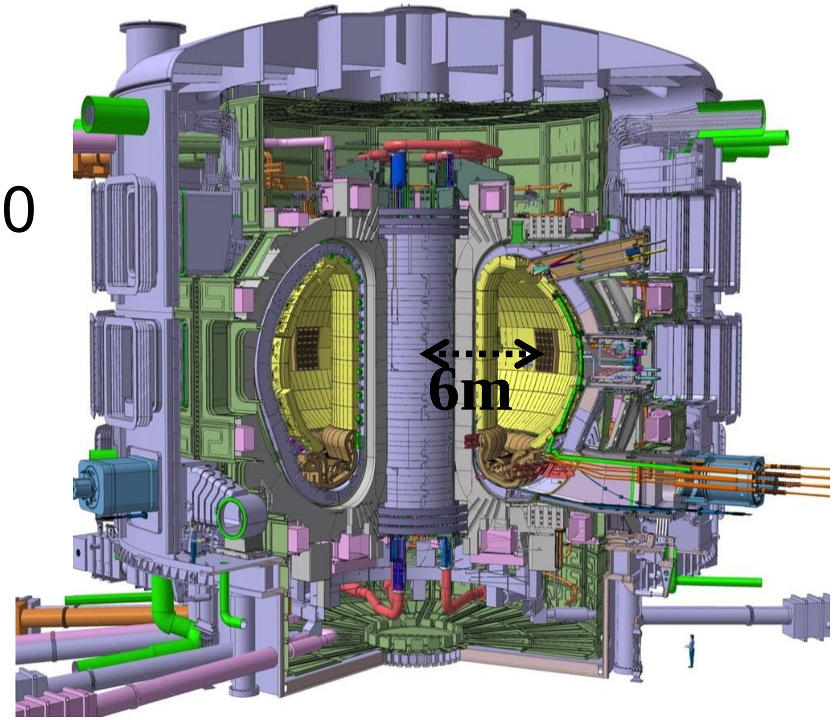
The first burning plasma: ITER

$Q \geq 10$; $P_{fusion} \geq 500$MW; ~500s

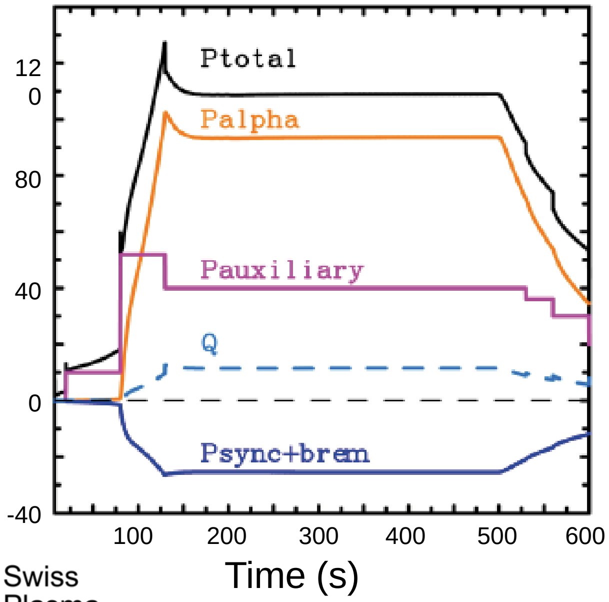
Explore steady-state $Q \geq 5$, ≤3000s

May explore ‘controlled ignition’ $Q \geq 30$

→ burning plasma



Y.Gribov



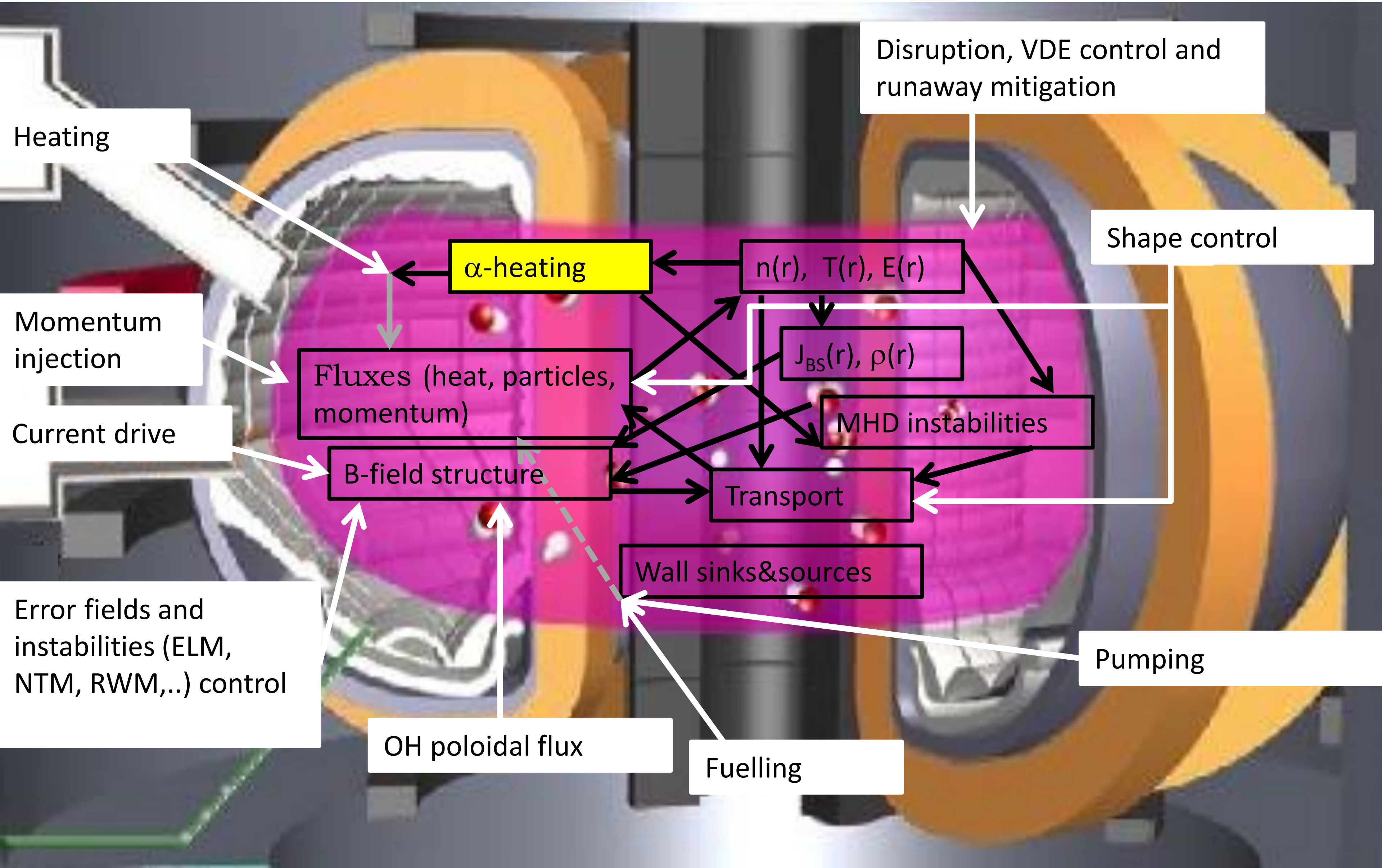
Q=10 scenario

I_p=15 MA, P_{fus}~500 MW

Total α energy in single shot: ~50GJ

Total α energy produced by JET and TFTR DT campaigns: <10GJ

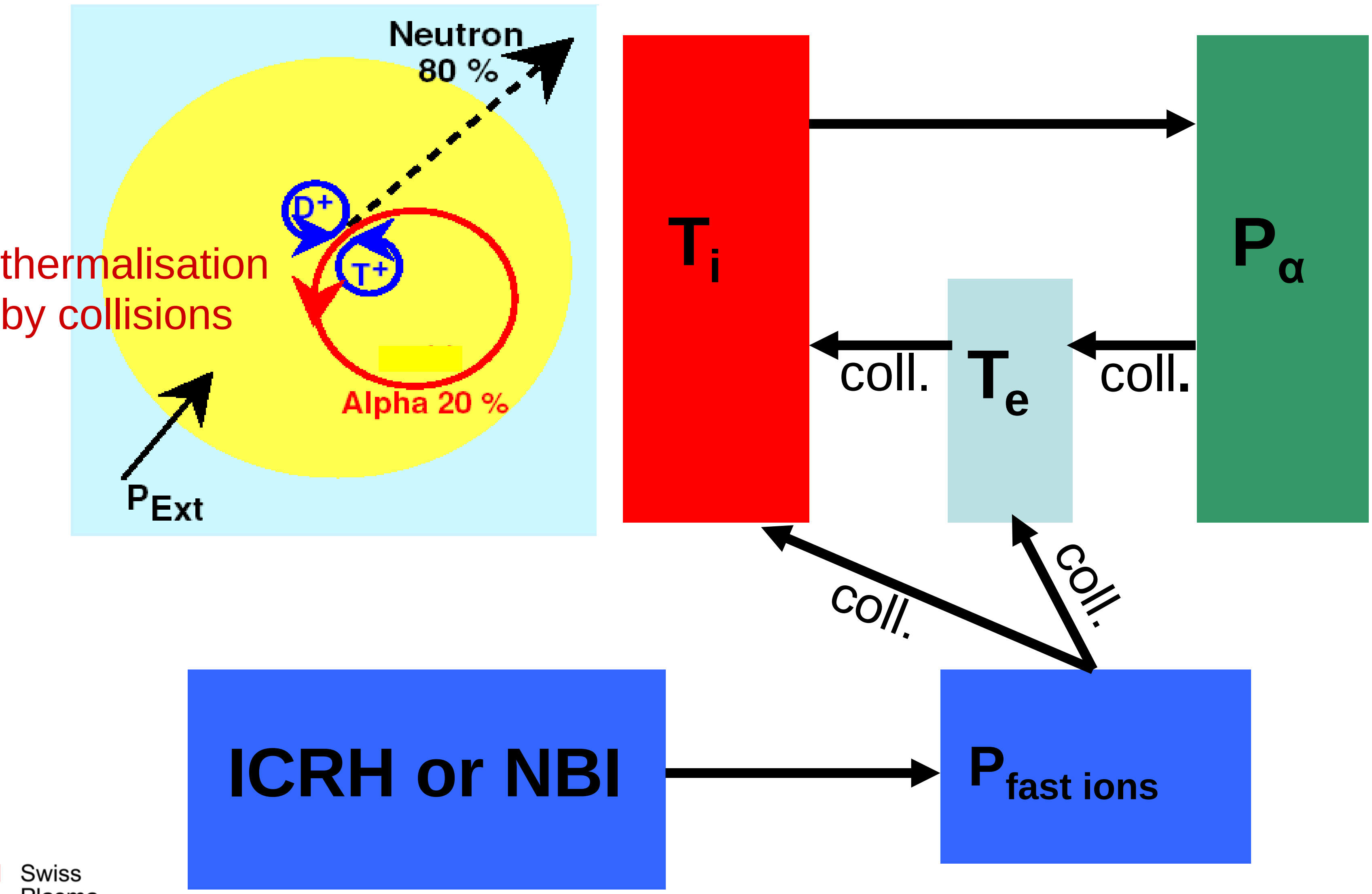
Burning plasmas: interplay of plasma dynamics and external systems



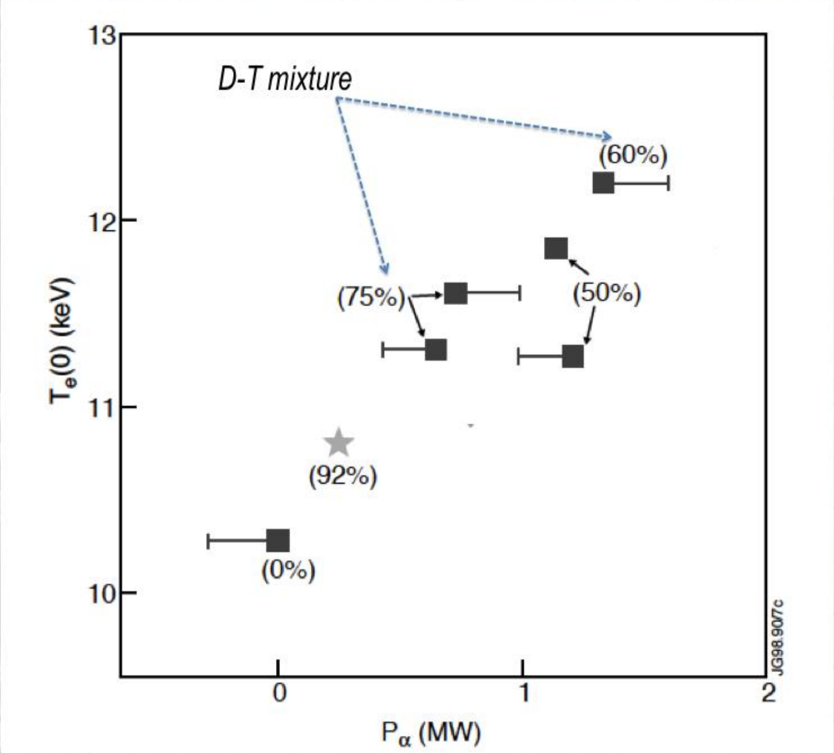
Specific properties of burning plasmas

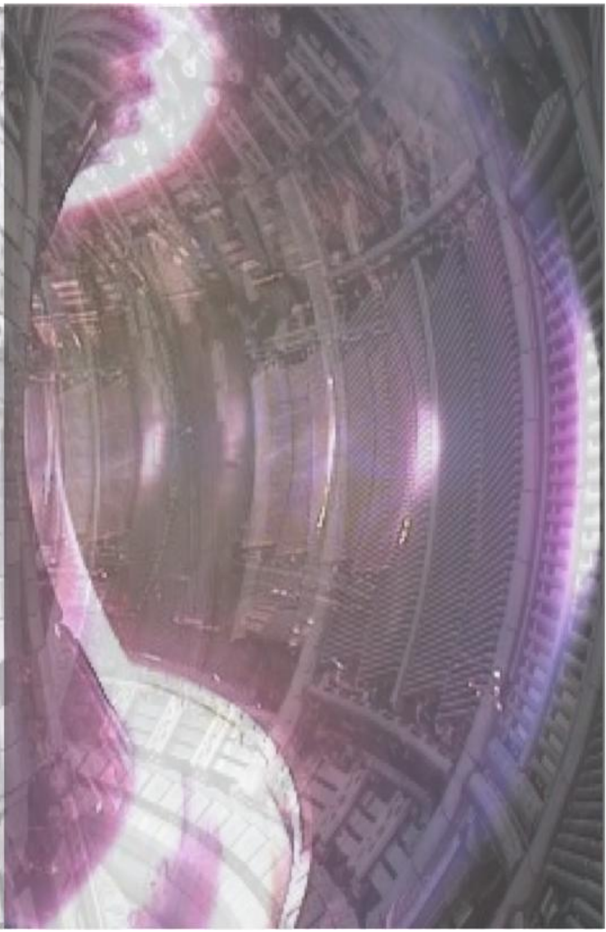
- High performance
- Operational limits, heat flux on plasma facing components
- Nuclear environment
  - Radiation T retention, dust, breeding
- New physics parameter range
  - Small ρ_{Li}/a, high density and high temperature, low collisionality
- Large isotropic population of fusion produced α's, dominant source of plasma heating
  - Coupling of profiles $P_\alpha(r)$, $p(r)$, $q(r)$, $E_r(r)$, diffusion coefficient(r), $n_{He}(r)$, …

External heating and self-heating



Fast ions and the self-heating process
Electron heating by fusion α's - 1997





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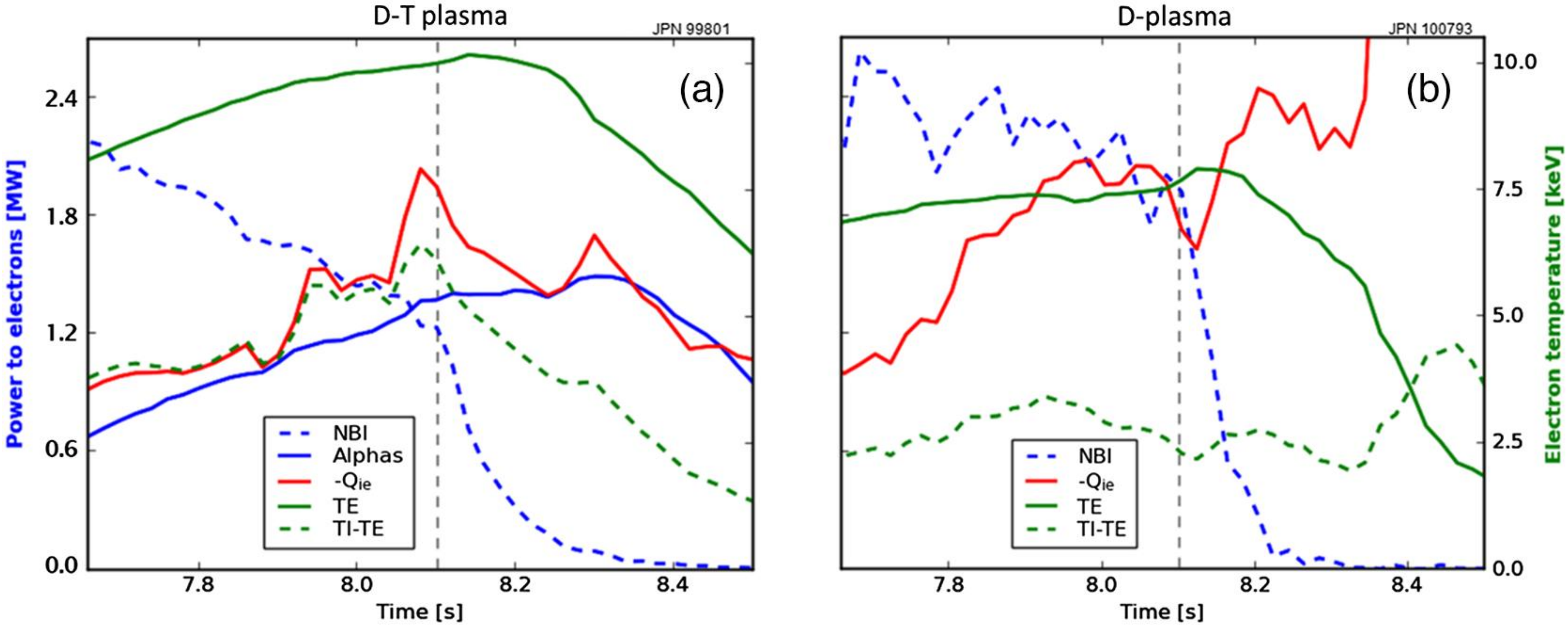
P.Thomas et al., PRL 80, 5548 (1998)

Fast ions and the self-heating process
Electron heating by fusion α's - 2023

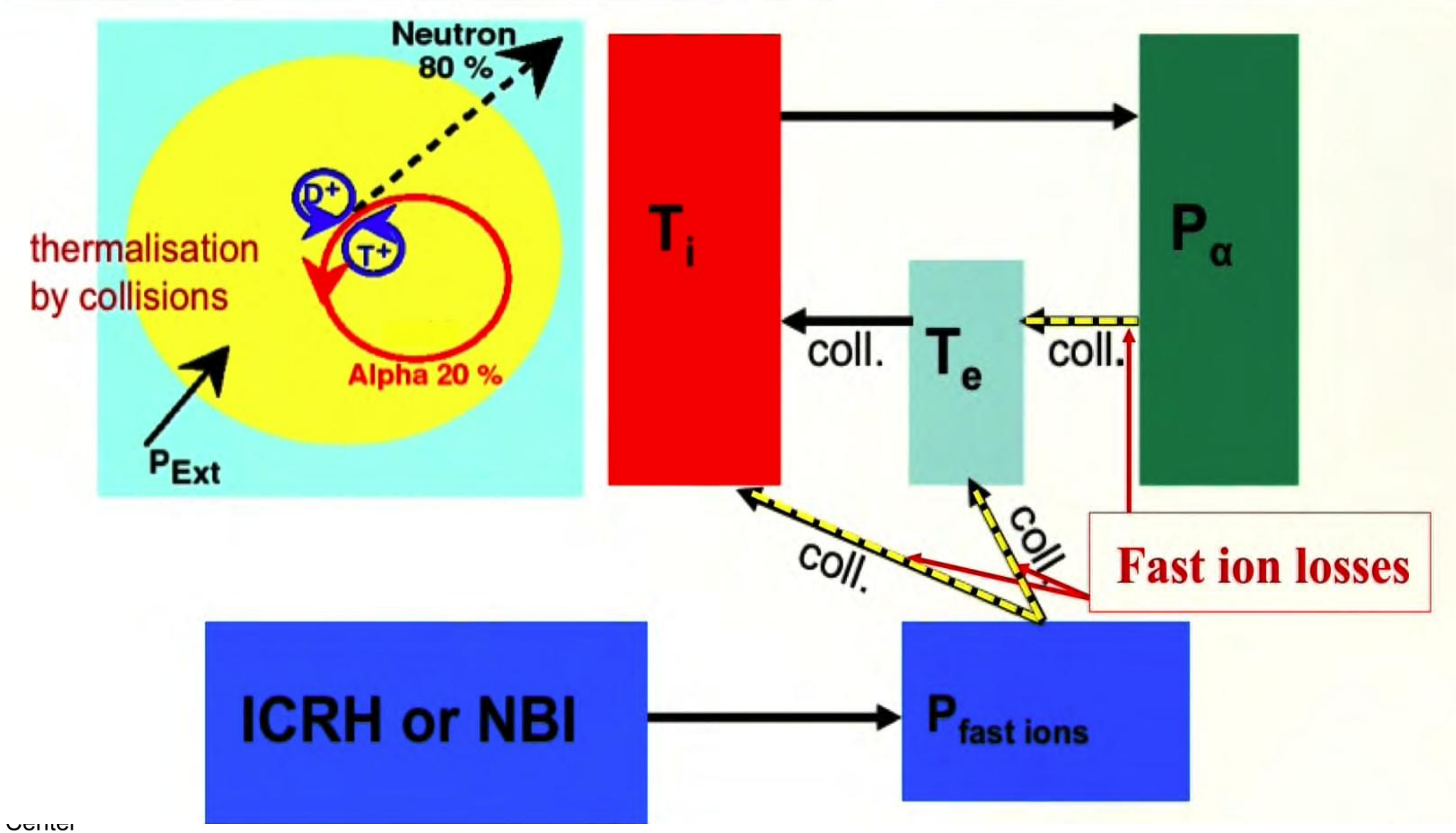


TRANSP [10] analysis of electron heating in JET D-T discharge No. 99801(a) and deuterium discharge No. 100793 (b). The power transferred to electrons (left scale) by alphas, NBI, and thermal ions (-Qie) are presented as well as electron temperature on axis (TE) and a difference between the ion and electron temperatures (TI-TE) in the plasma core (right scale); dashed line marks the NBI power cut.

V. G. Kiptily et al., PRL 131, 075101 (2023)

External heating and self-heating

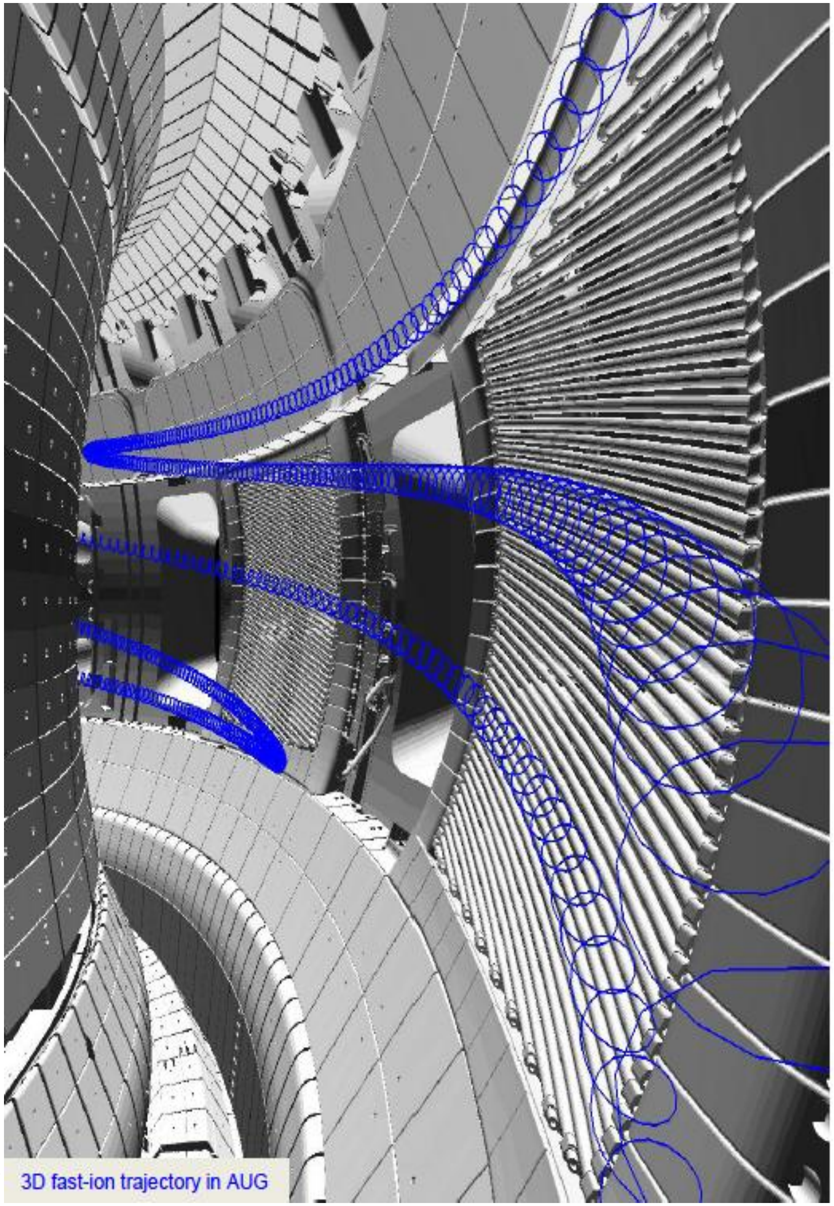
To reach and sustain burning plasma regime, fast ions must be well confined

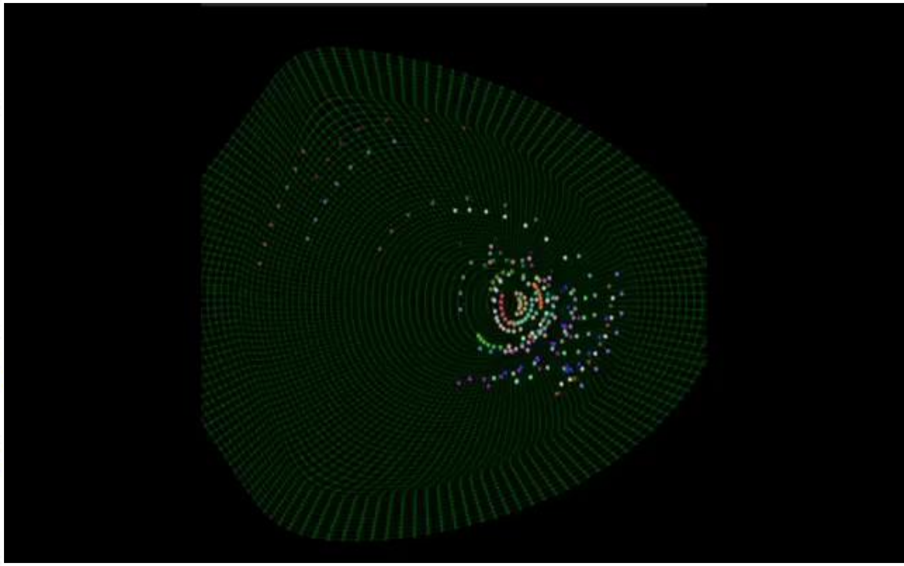


External heating and self-heating

To reach and sustain burning plasma regime, fast ions must be well confined

Fast ion orbits in tokamaks


3D fast-ion trajectory in AUG


GPU-NUBEAM DIII-D Simulation

External heating and self-heating

To reach and sustain burning plasma regime, fast ions must be well confined

Need to understand and possibly minimize redistribution and loss mechanisms

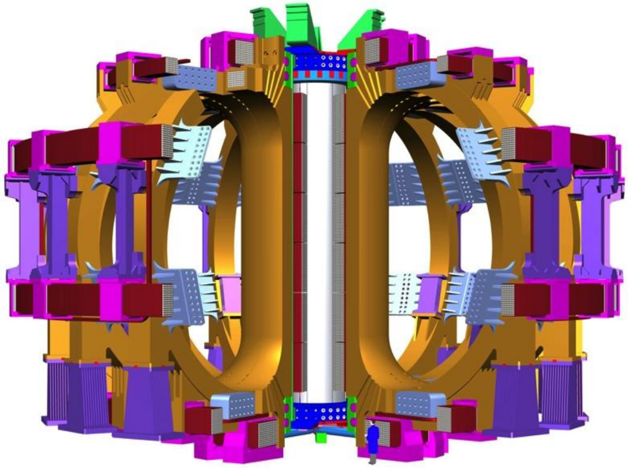
- Magnetic field imperfections
- Low frequency MHD instabilities
- Turbulence
- Resonant interaction with Alfvén waves

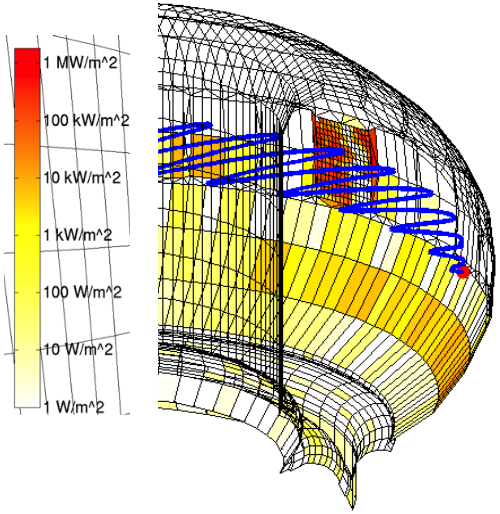
FAST ION LOSS MECHANISMS

MAGNETIC FIELD IMPERFECTIONS

Fast ions and the self-heating process
Fast ion losses in 3D B-field

B-field inhomogeneities can lead to orbit trapping and losses

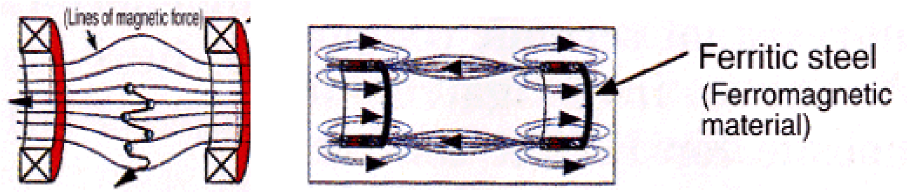




ASCOT code
T.Kurki-Suonio

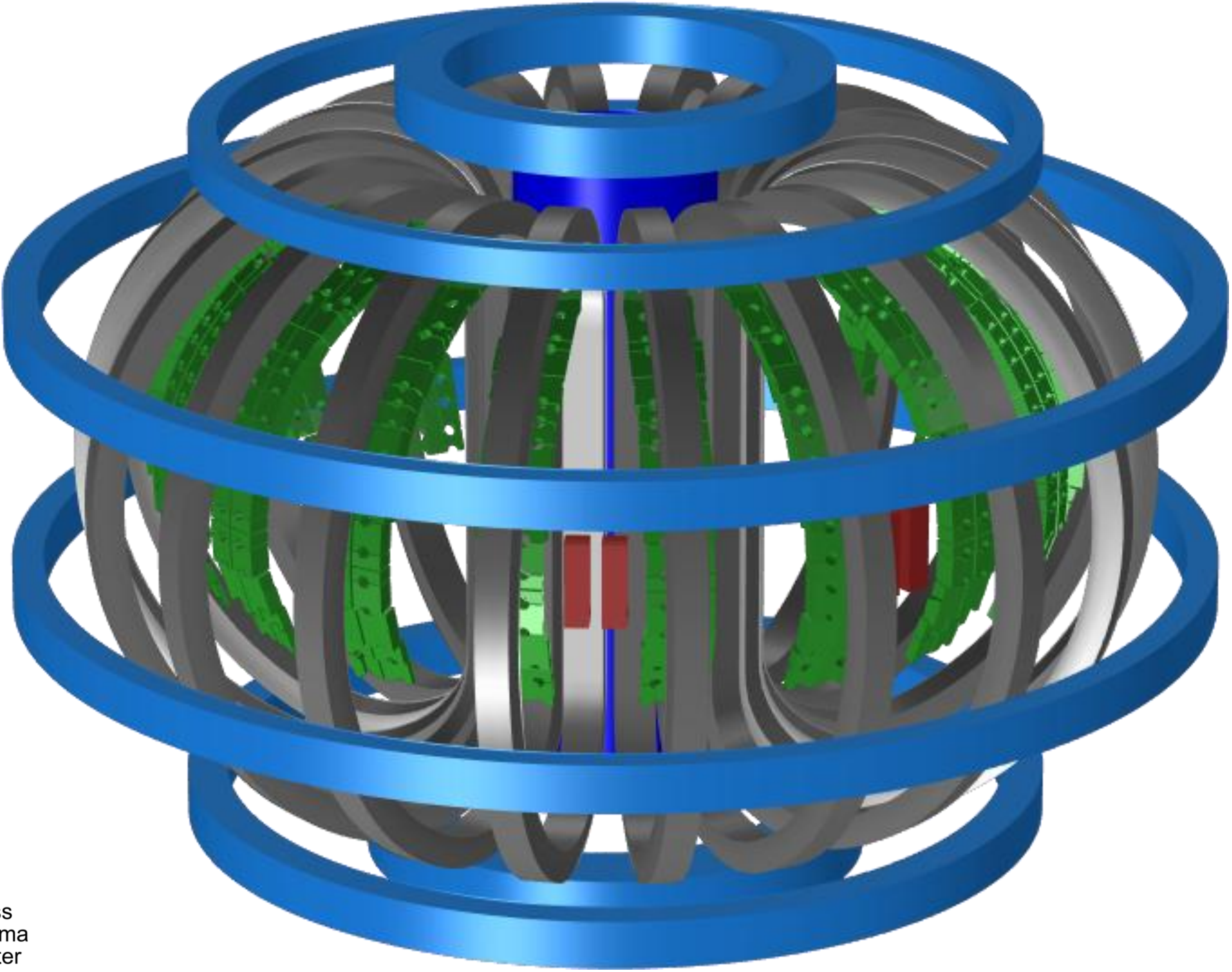
Ripple effects on fast ions qualitatively understood

Ferritic inserts in ITER to reduce ripple losses (from ~6% to ~0.4%)



K.Shinohara

3D image of the ferritic inserts in ITER



Fast ions and the self-heating process
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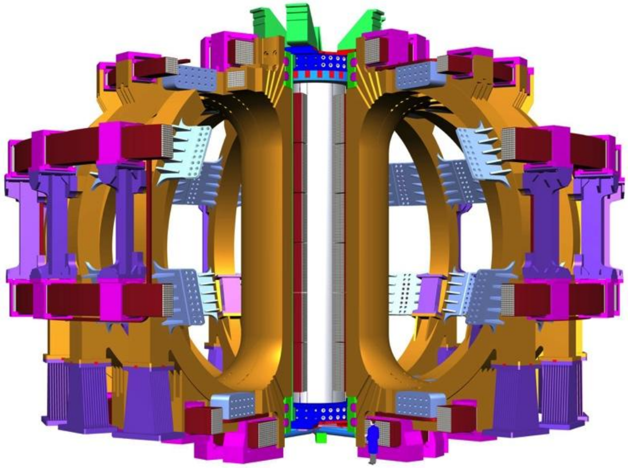

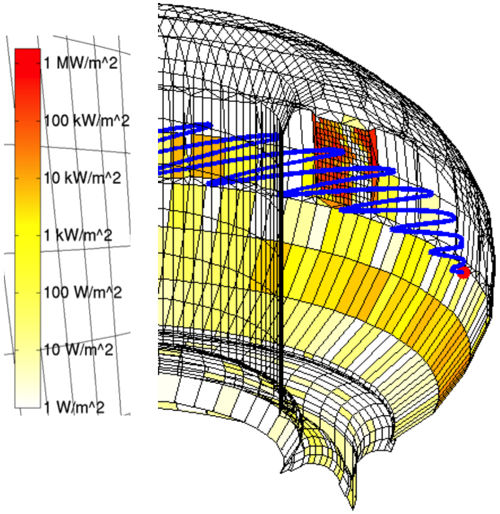

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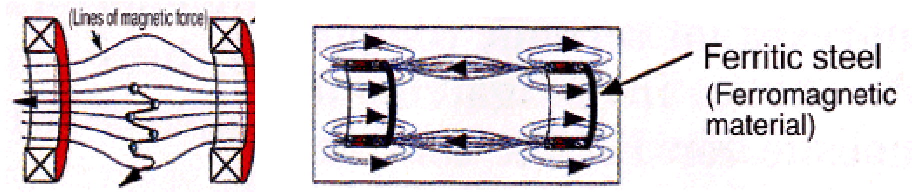


K.Shinohara

Open questions

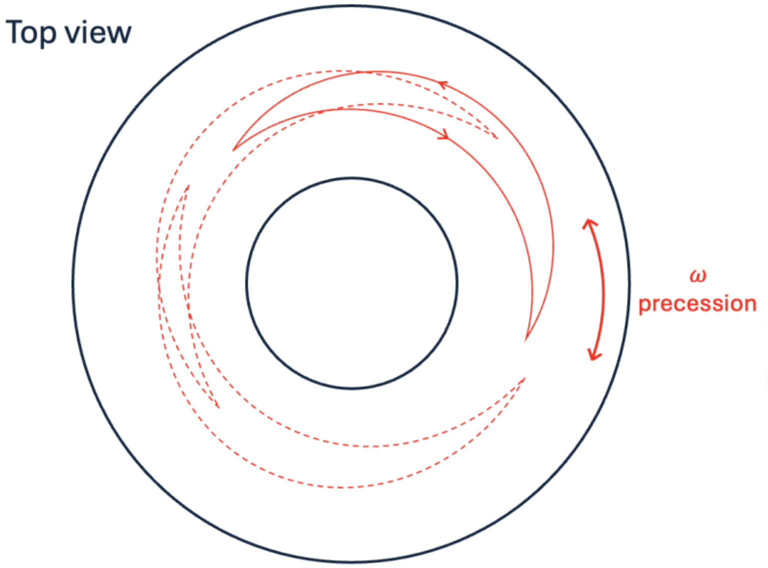
Effect of blanket modules (~1% ripple)

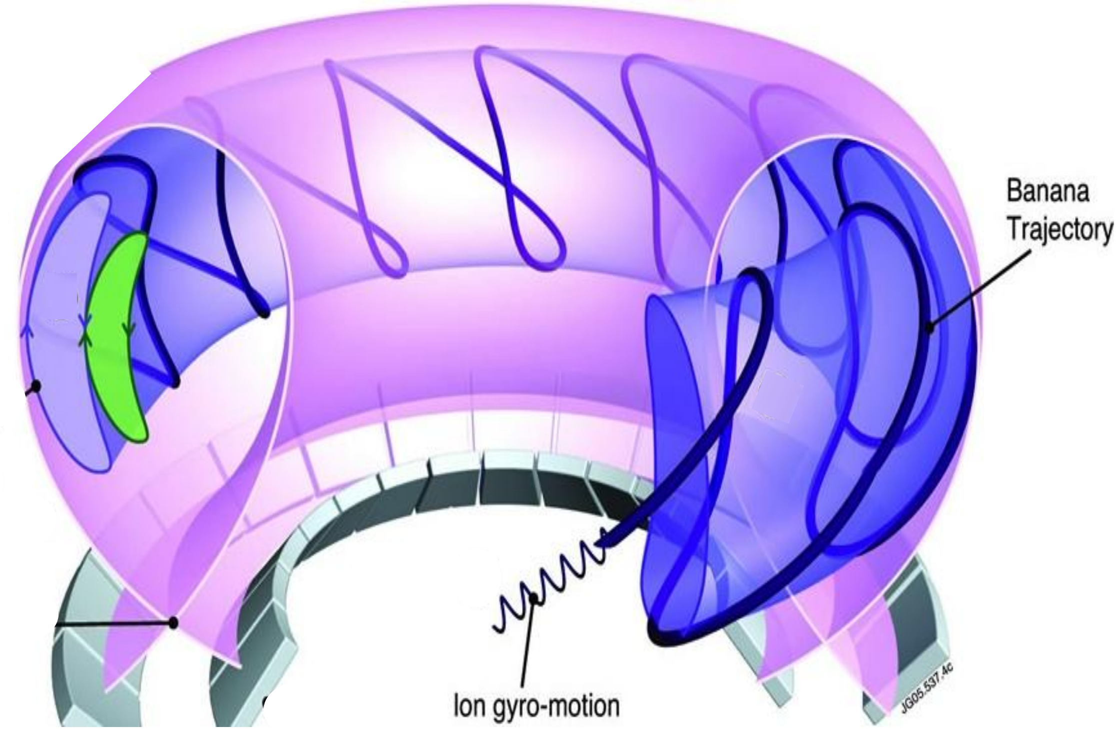
Effect of 3D fields induced by coils introduced to mitigate edge instabilities

FAST ION LOSS MECHANISMS

LOW FREQUENCY MHD

Low frequency MHD Resonance condition





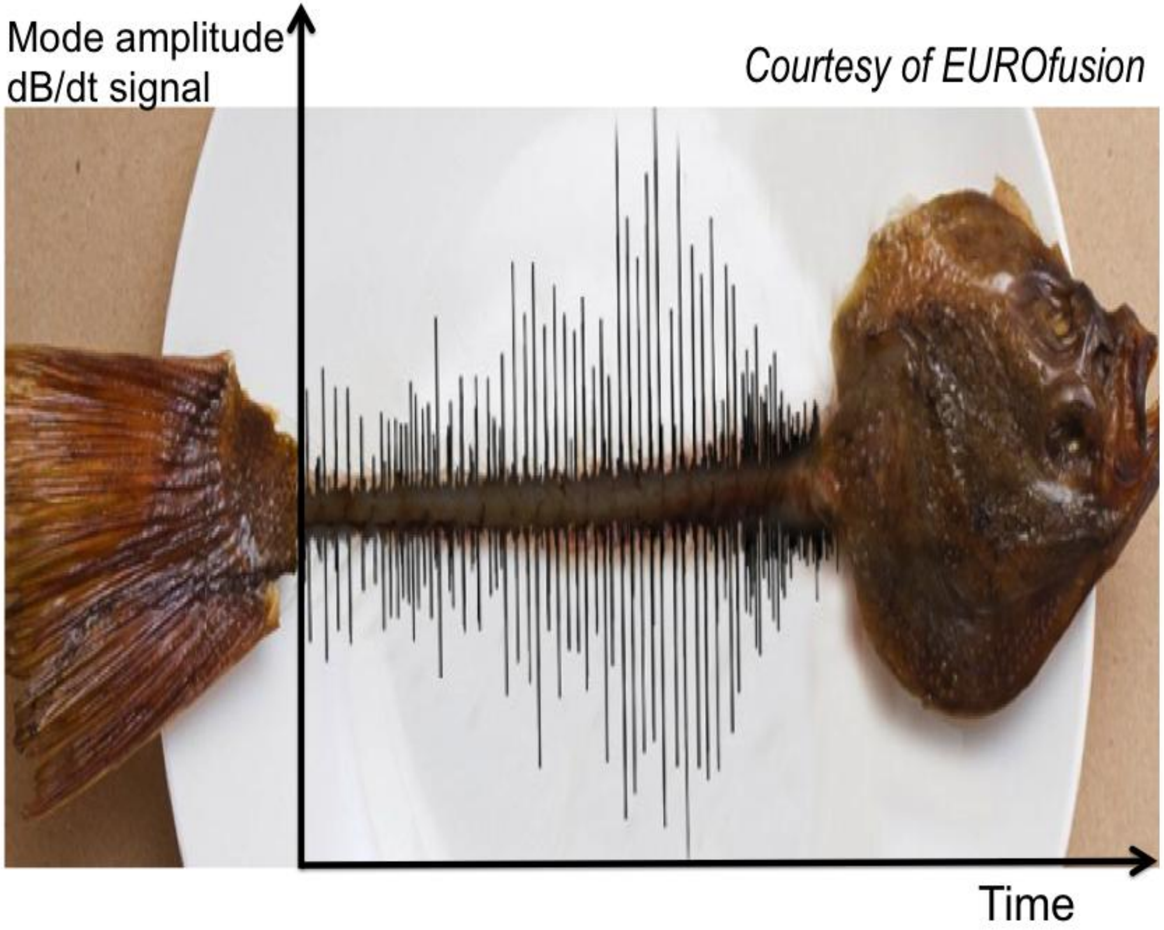
Different kinds of resonances associated with complex particle orbits lead to different possible interactions

- Example: bounce motion of particles along banana orbits and toroidal drift precession of banana orbits : $\omega_{\text{precession}} << \omega_{\text{bounce}} << \Omega_c$
- MHD modes: $\omega << \Omega_c$

Low frequency MHD – fishbones

Resonant de-stabilisation of MHD kink mode with $\omega = \omega_{\text{precession, fast ions}}$

Driven by the fast ions, the mode can reach amplitudes that cause ejection of the fast ions themselves - the mode then disappears as its source is gone - a sequence of bursts can occur



Courtesy of EUROfusion

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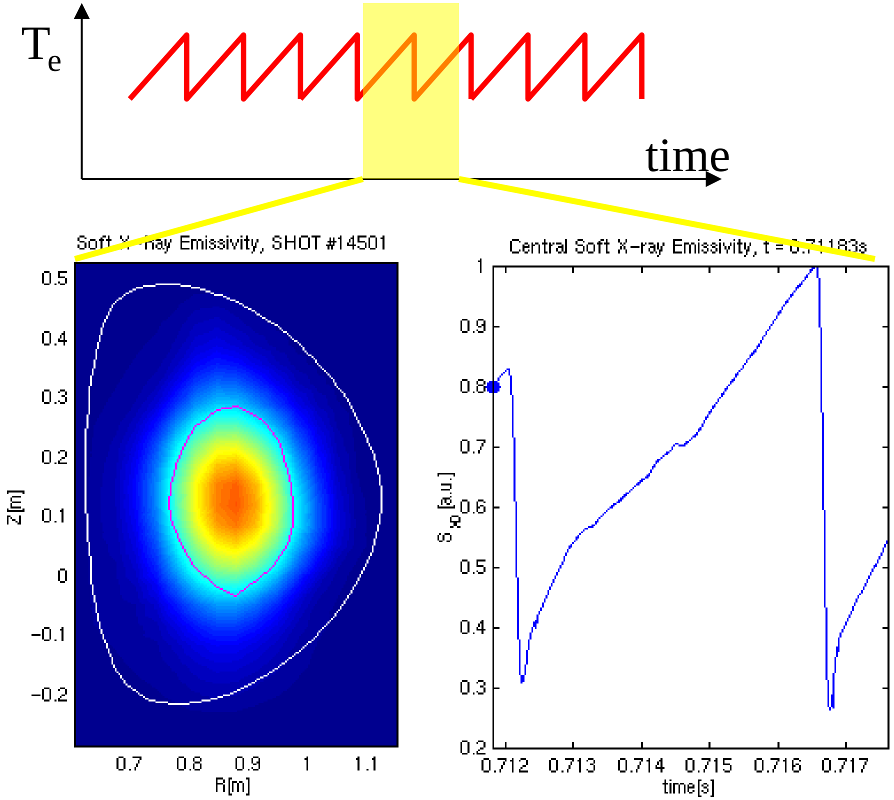
Low frequency MHD
Sawtooth instability

Sudden losses of energy and particles in core, with local breaking of magnetic structure (magnetic reconnection)

Kink mode with $\omega < \omega_{\text{precession, fast ions}}$

Fast ions are not the cause of the instability, but are ejected together with core plasma

Ex.: X-ray emissivity (~T_e, n) evolution in TCV

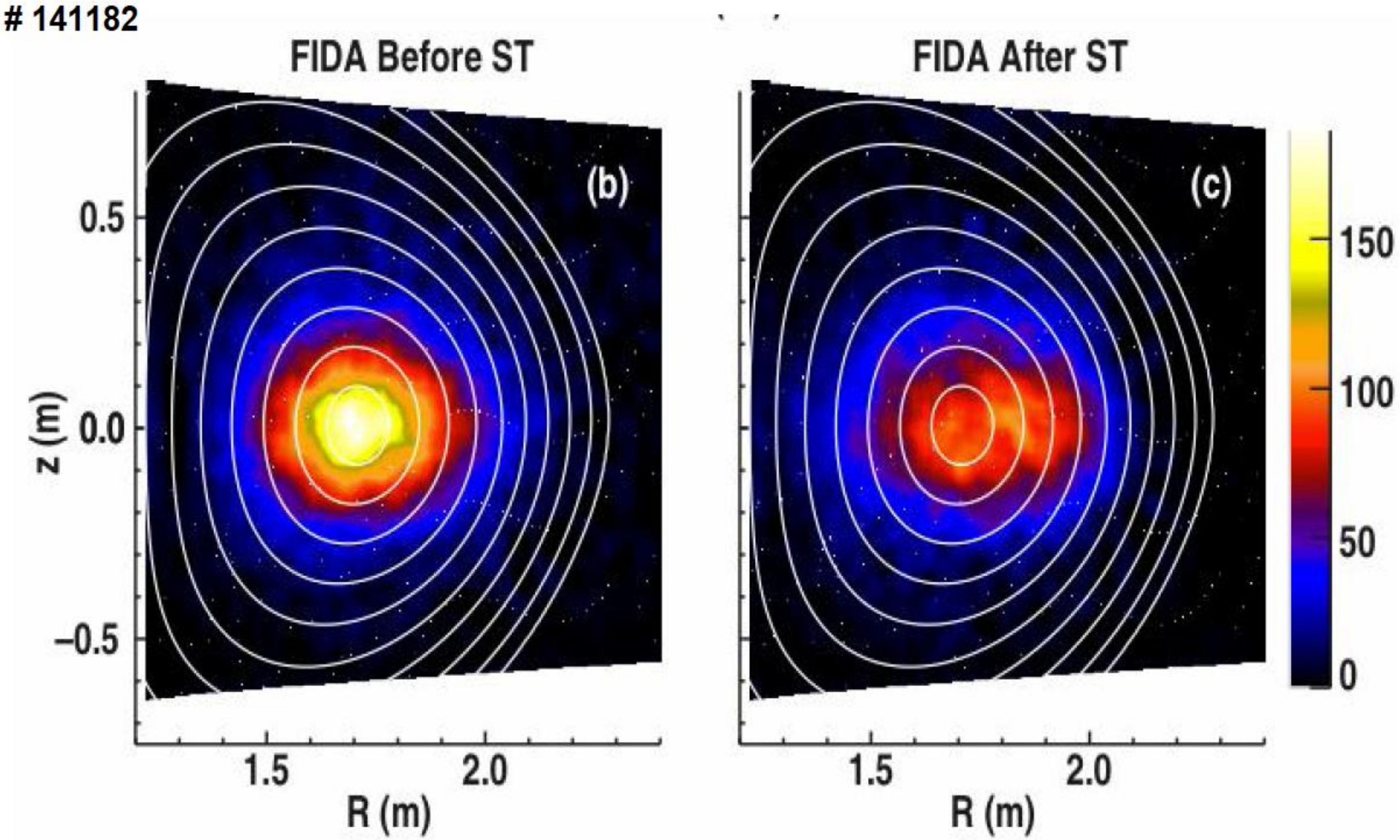


Courtesy of I.Furno

Collapses can trigger secondary instabilities: as fast ions influence the sawtooth period, hence the strength of the collapse, they can be used to control the secondary instabilities

Low frequency MHD
Sawtooth instability

Redistribution measured by Fast ion Dα



Swiss Plasma Center

Van Zeeland et al, Nucl. Fusion **50** (2010) 084002.

FAST ION LOSS MECHANISMS

PLASMA TURBULENCE

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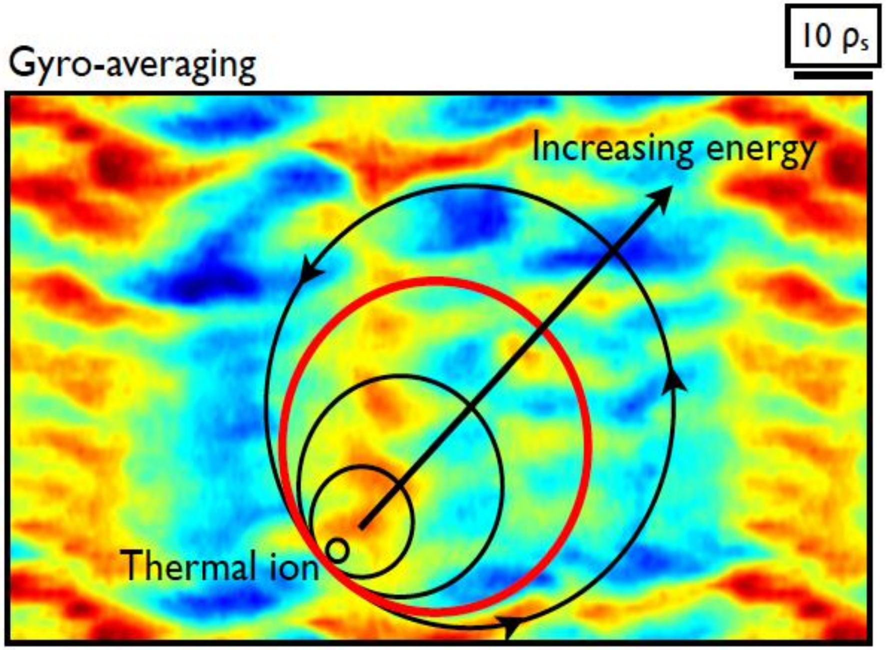
Fast ion interaction with turbulence

Turbulence could cause transport of fast ions, as for thermal plasma

Large fast ion orbits are expected to average out effect of turbulence

M.Albergante



Key parameters: $E_{\text{fast ions}}/T_{\text{plasma}}$ & fast ion slowing down time

Present devices (small $E_{\text{fast ions}}/T_{\text{plasma}}$):

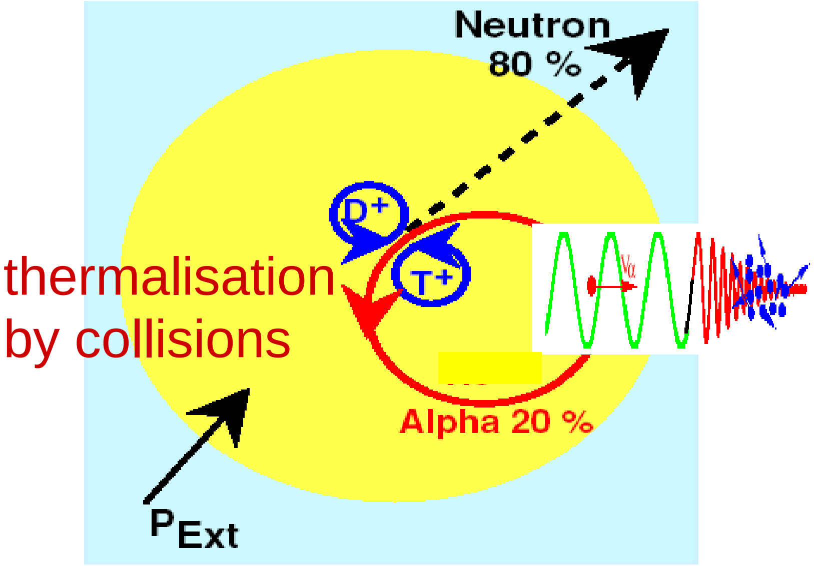
some anomalous transport of NBI ions

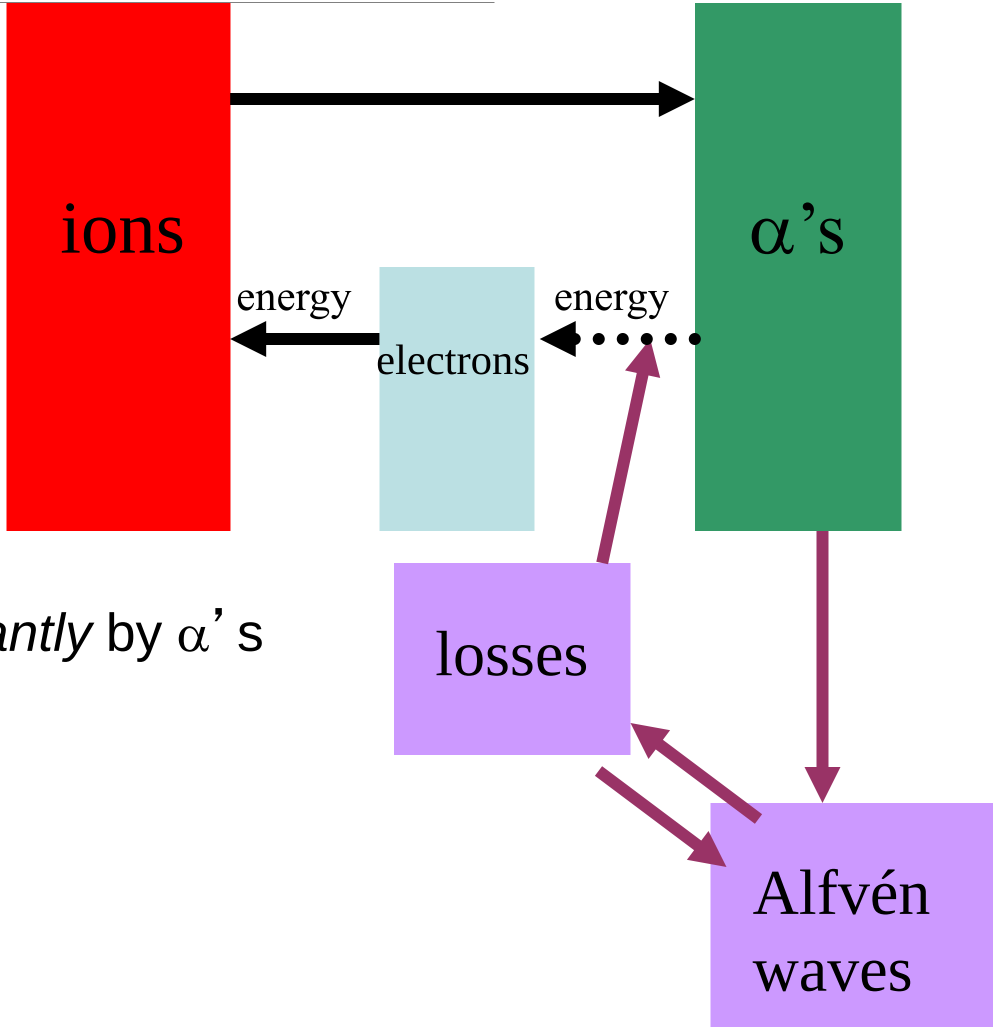
ITER (large $E_{\text{fast ions}}/T_{\text{plasma}}$):

negligible effect for NBI ions and for α's

FAST ION LOSS MECHANISMS
INTERACTION WITH ALFVEN WAVES

Resonant interaction with waves and self-heating




ions

α's

energy

electrons

energy

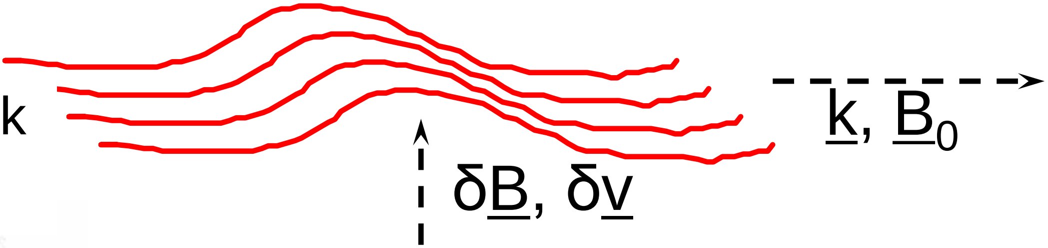
losses

Alfvén
waves

Alfvén waves can be driven *resonantly* by α' s

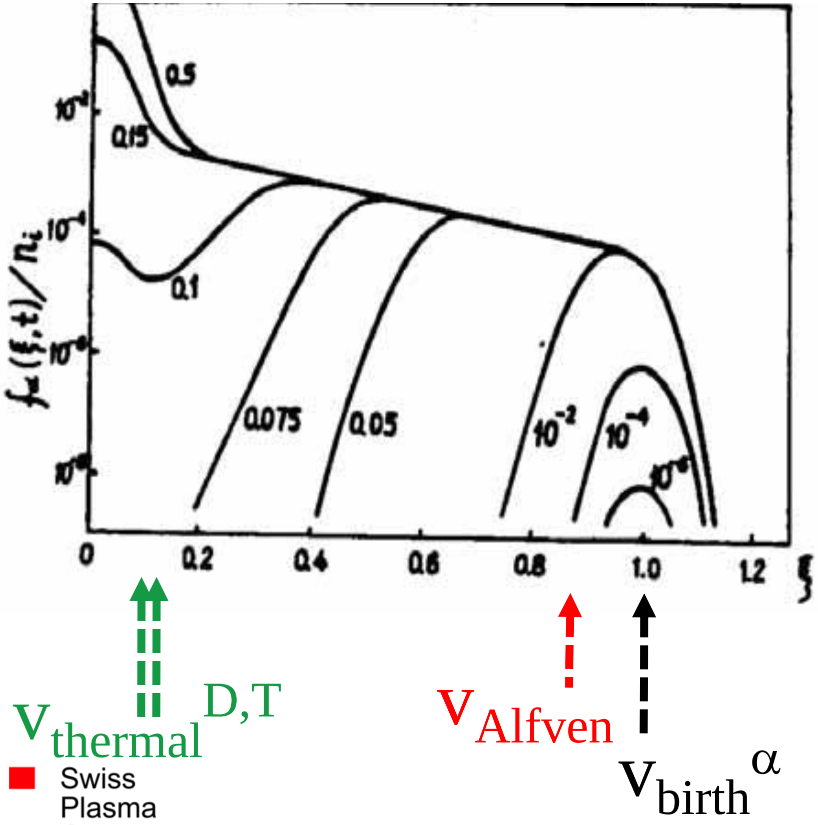
Fast ions and Alfvén waves

B-field and plasma frozen together; field lines are strings with tension and inertia → Alfvén wave propagation



Typical velocities in a tokamak

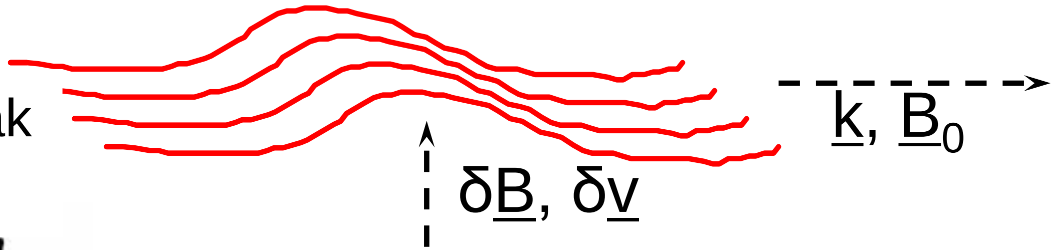
B=4T; T=10keV; n=10^{20}m^{-3}



Slowing down α's (but also fast ions generated by additional heating) can resonate with Alfvén Waves

Fast ions and Alfvén waves

B-field and plasma frozen together; field lines are strings with tension and inertia → Alfvén wave propagation



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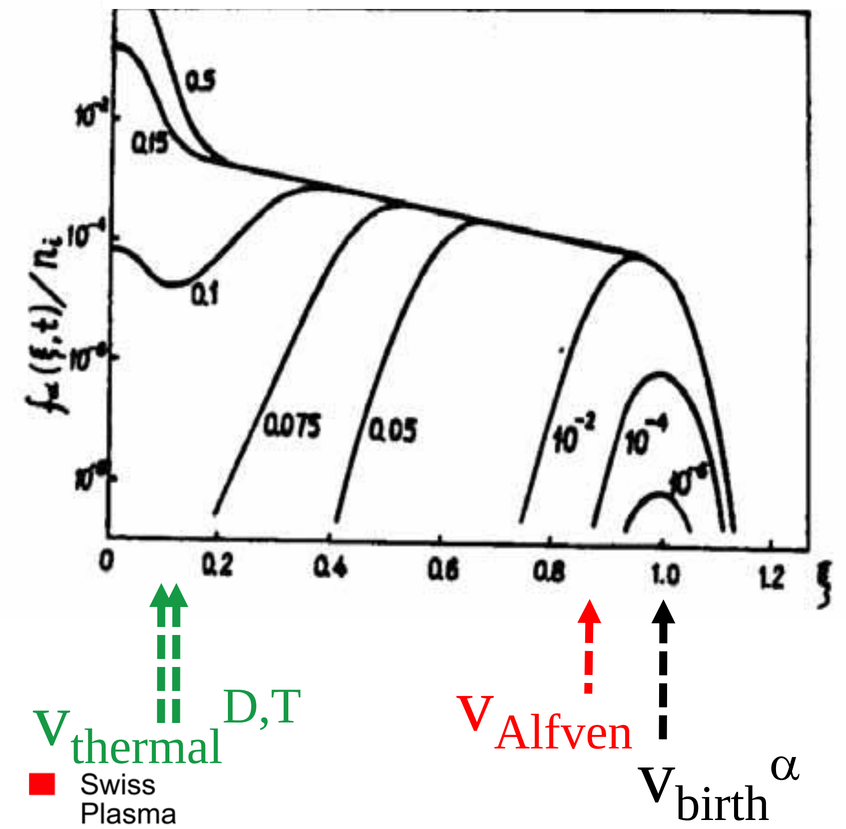


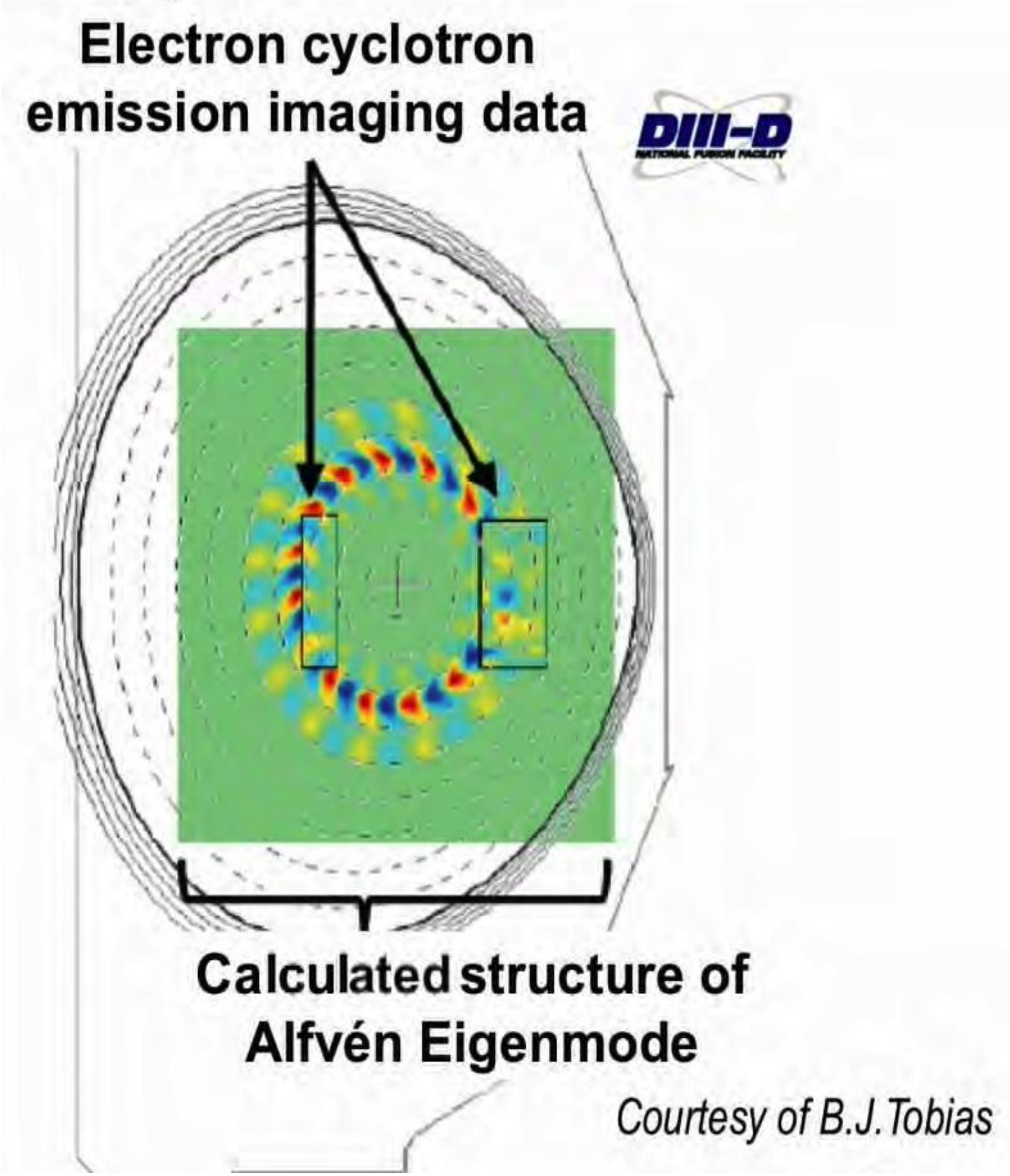
Slowing down α's (but also fast ions generated by additional heating) can resonate with Alfvén Waves

Alfvén Waves are driven unstable if the 'free' energy ∇p_α is sufficient and α drive > plasma damping

Alfvén waves in tokamaks
Alfvén Eigenmodes

Alfvén waves' dispersion in tokamaks allows for weakly damped global Eigenmodes

MHD theory has successfully predicted the existence and the main features of these modes, then verified experimentally

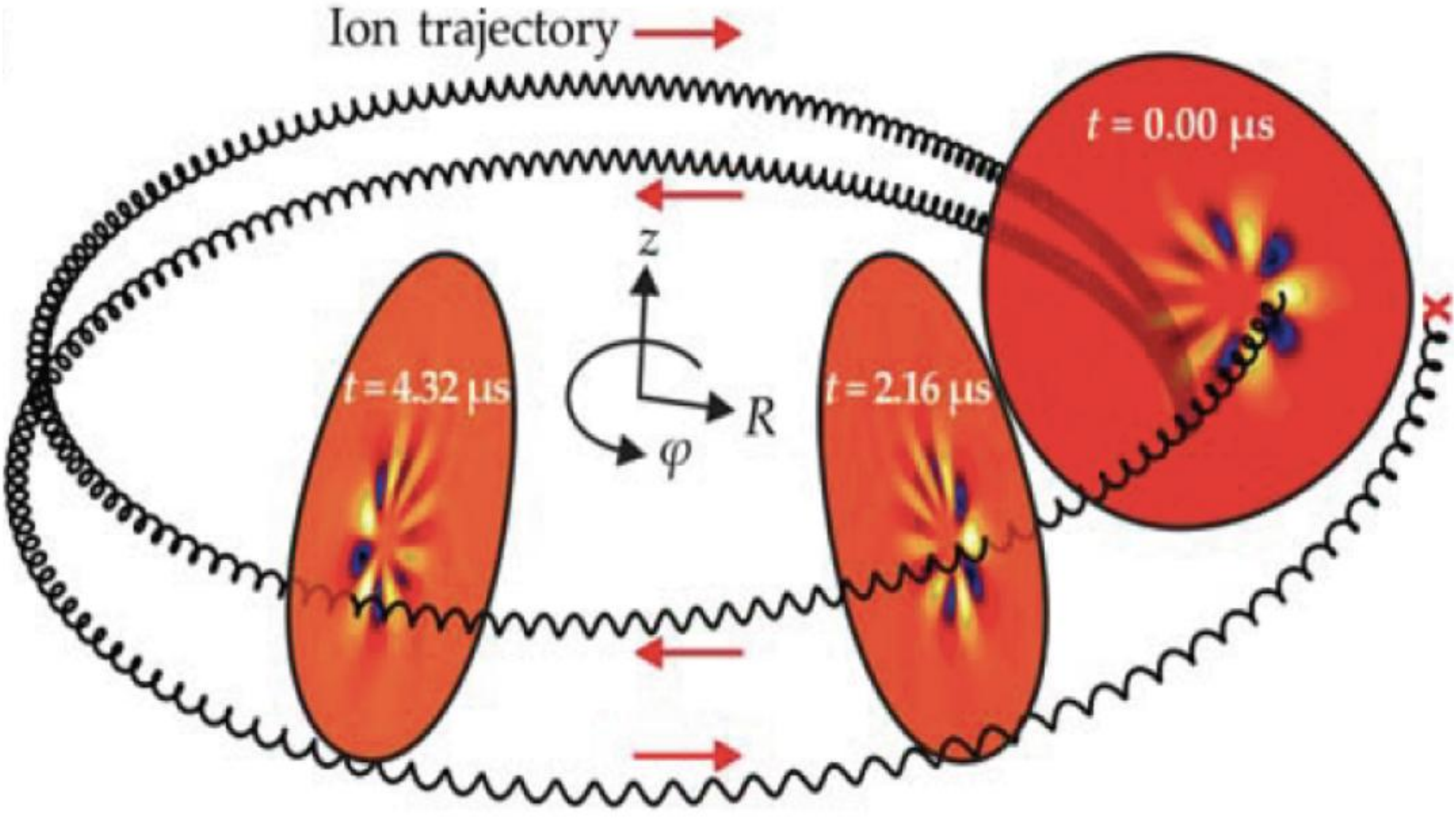


Electron cyclotron emission imaging data

Calculated structure of Alfvén Eigenmode

Courtesy of B.J.Tobias

AE resonance condition visualisation

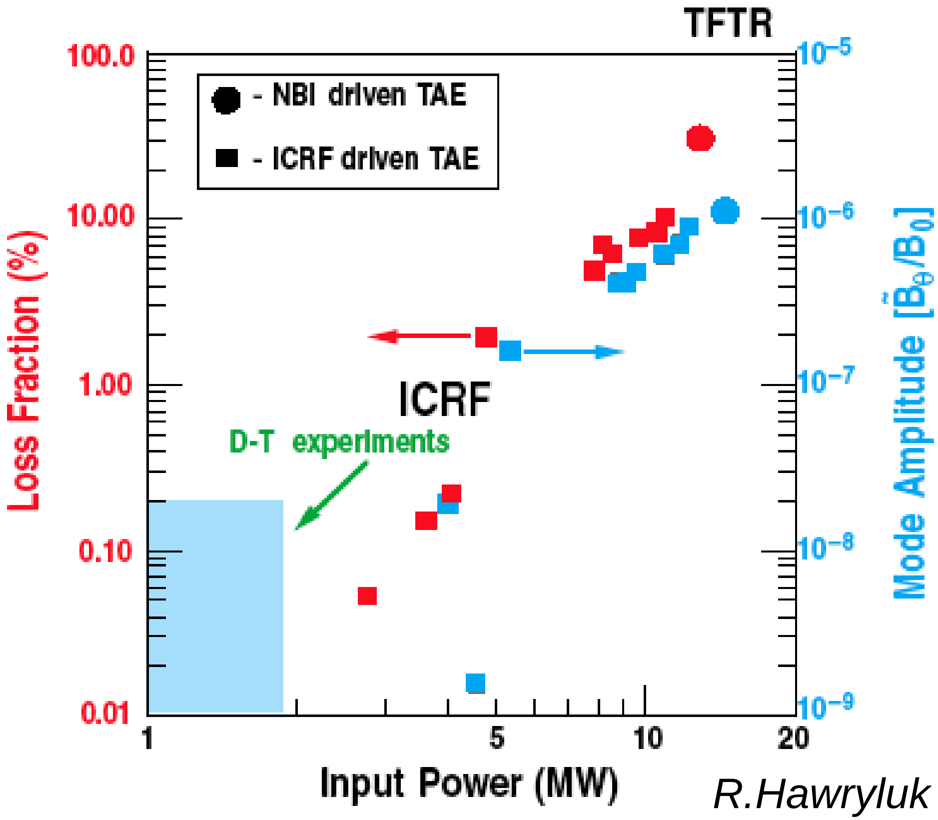


Swiss Plasma Center

Pace, Physics Today (October 2015)

Fast ions and the self-heating process
Effect of Alfvén Eigenmodes

Losses and redistribution seen in many experiments



R.Hawryluk

ITER / DEMO can withstand

only a few % of α losses

Questions

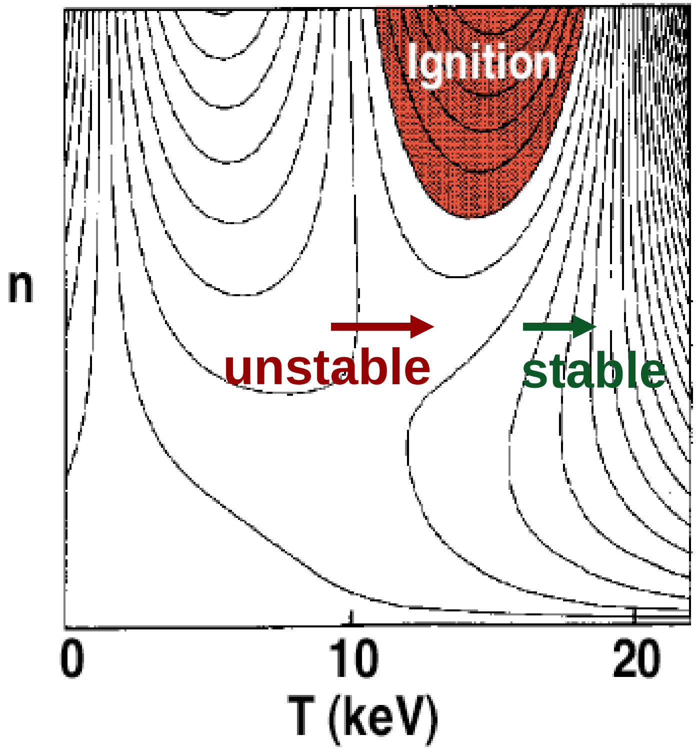
- Linear stability, balance between damping and drive
- Nonlinear evolution and redistribution / losses

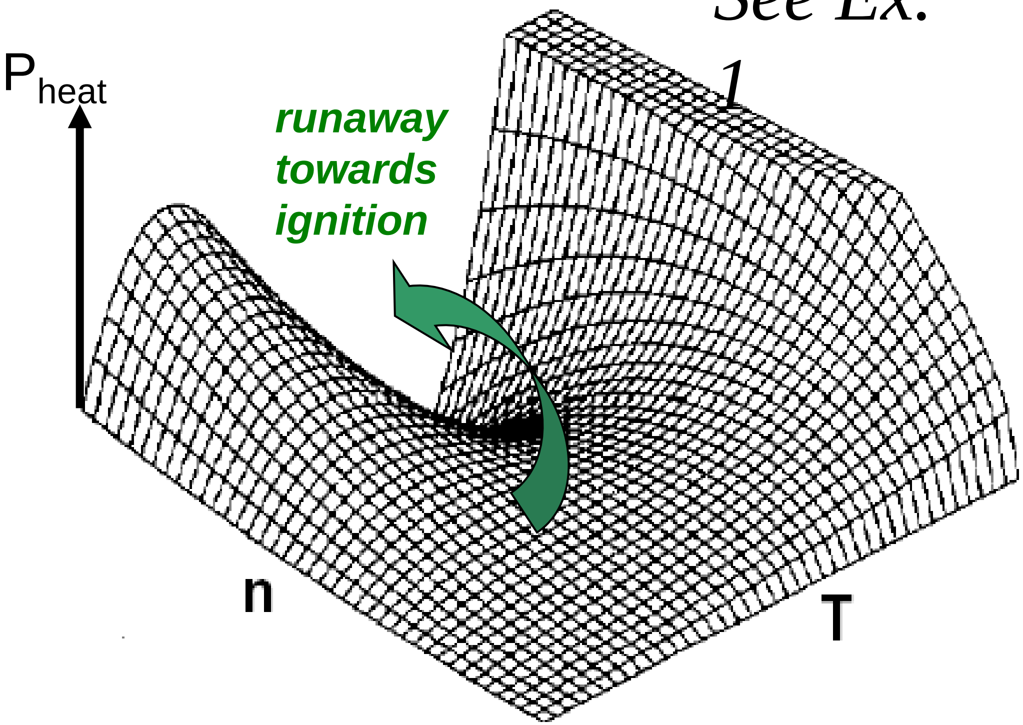
BURN STABILITY AND CONTROL

Burn thermal runaway

At high Q in principle thermal runaway can occur

Ex. of steady-state $P_{in}/V = \underbrace{3nT/\tau_E}_{P_{loss}} - \underbrace{\frac{1}{4}n^2\langle\sigma v\rangle E_\alpha}_{P_\alpha}$





See Ex. 1

TRITIUM IN FUSION

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Tritium – general properties

Half life time: 12.3 years

Decay mode

β decay: $T \rightarrow {}^3He + e^- + \bar{\nu}_e + 18.6$ keV

Activity = 3.6×10^{14} Bq/g

Tritium – natural inventory

~3.6 kg produced mostly by impact of cosmogenic neutrons on Nitrogen

$^{14}N + n \rightarrow {}^{12}C + T$ (- 4.3MeV)

$^{14}N + n \rightarrow 3\ {}^4He + T$ (- 11.5MeV)

~30 kg left from atmospheric testing of nuclear weapons (1945-1963)

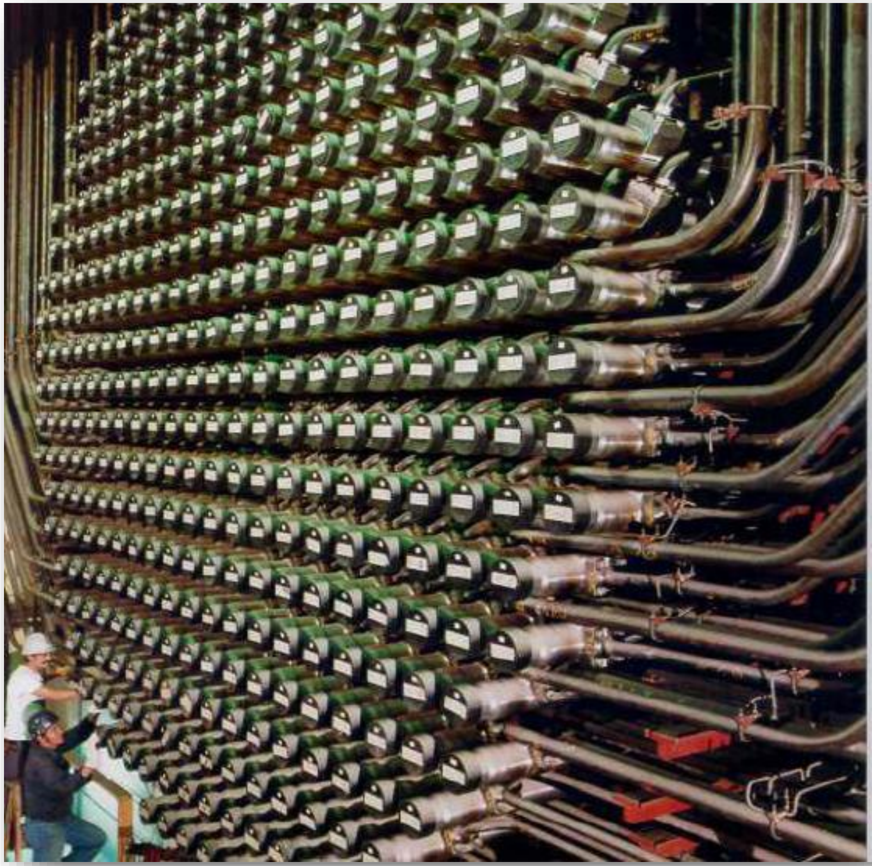
Tritium – anthropogenic inventory

T is generated mainly in heavy water fission reactors of CANDU type (CANadian Deuterium natural Uranium reactor)

- 2003: 20 operating CANDU reactors (40 years license)

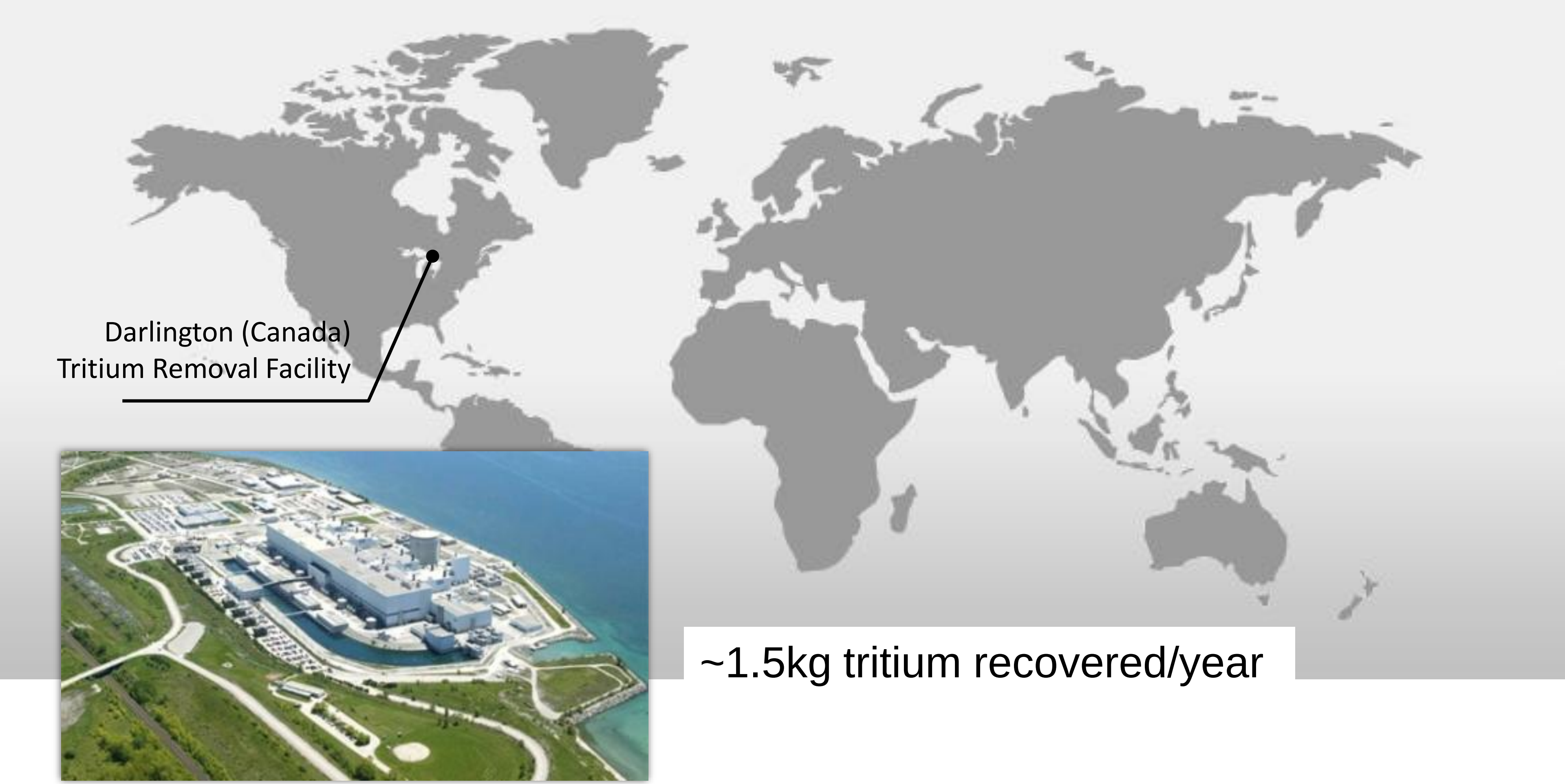
Total production ~0.3kg/(GWe*year)

Today 19kg at hands in Darlington recover facility



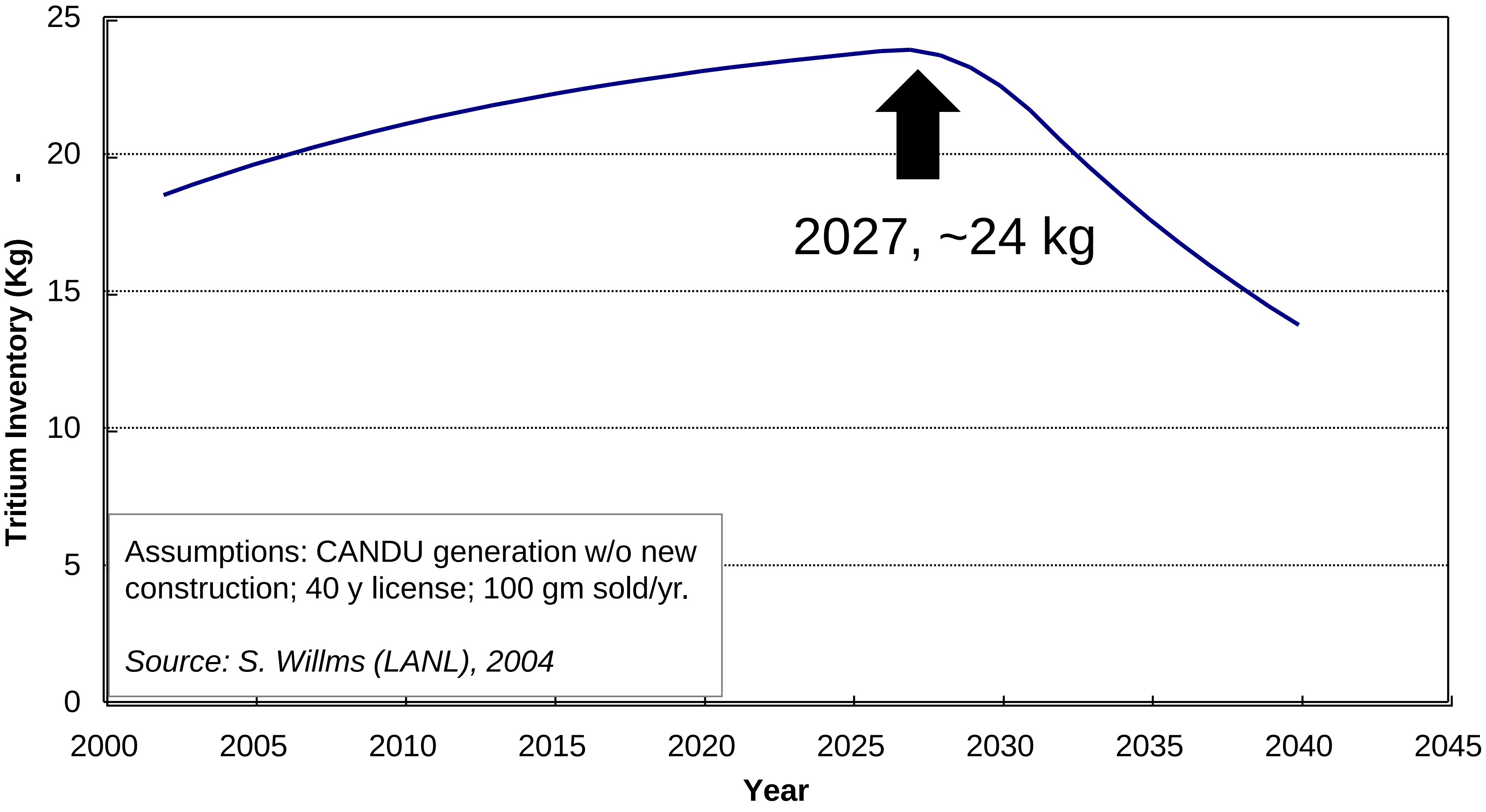
CANDU Pressurized Heavy Water Reactor

Tritium production is today driven by fission (CANDU) waste management rather than by a market



~1.5kg tritium recovered/year

T availability is foreseen to decrease after 2027



Projection of tritium inventory available from CANDU (Canada)

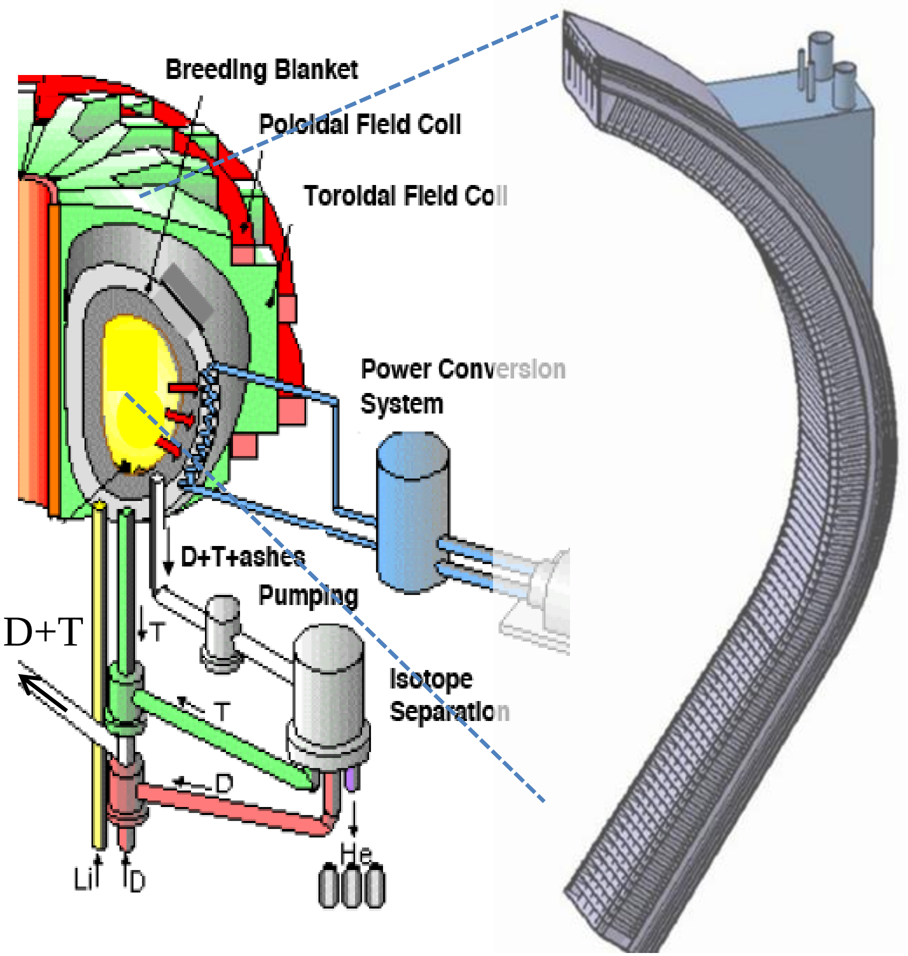
2027, ~24 kg

Assumptions: CANDU generation w/o new construction; 40 y license; 100 gm sold/yr.

Source: S. Willms (LANL), 2004

But other countries (e.g. India) also build heavy water reactors

Tritium breeding blanket



A fusion reactor must be T self sufficient

$Li^6 + n \rightarrow T + He^4 + 4.8\ \text{MeV}$

Tritium breeding ratio

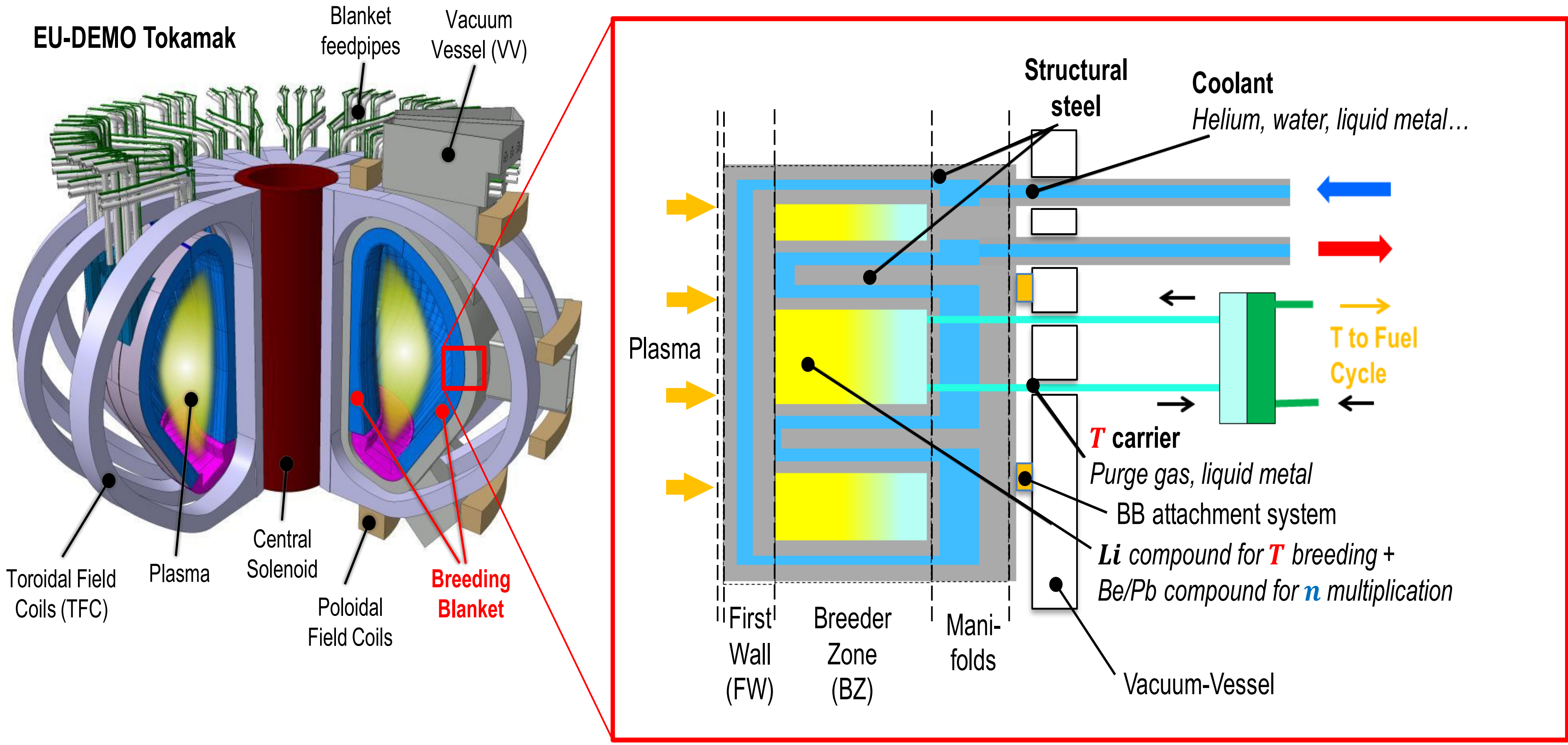
TBR = tritium bred / tritium burnt

TBR >1 to compensate losses, which implies the use of n-multiplier

$Be^9 + n \rightarrow 2\ He^4 + 2n - 2.5\ \text{MeV}$

$Pb^{208} + n \rightarrow Pb^{207} + 2n - 7.4\ \text{MeV}$

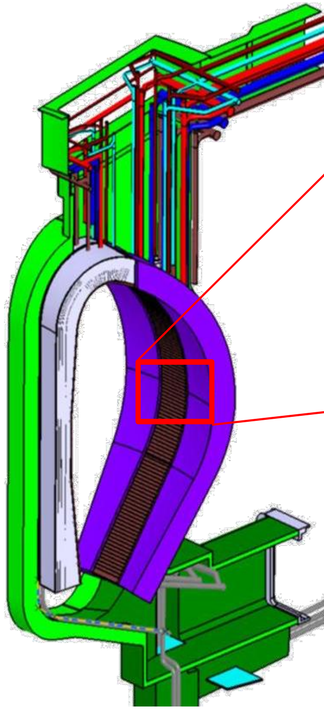
Breeding blanket – system and functions

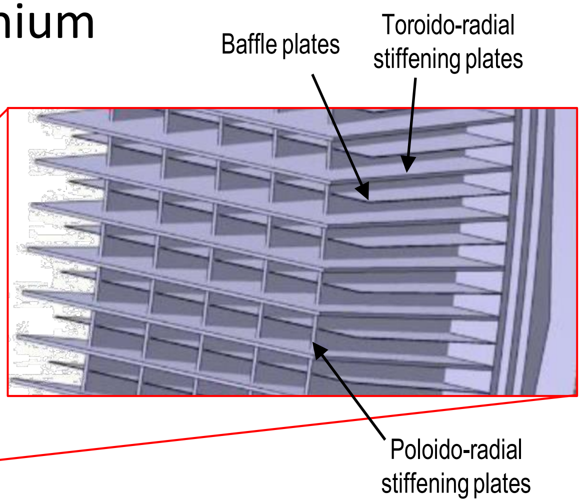


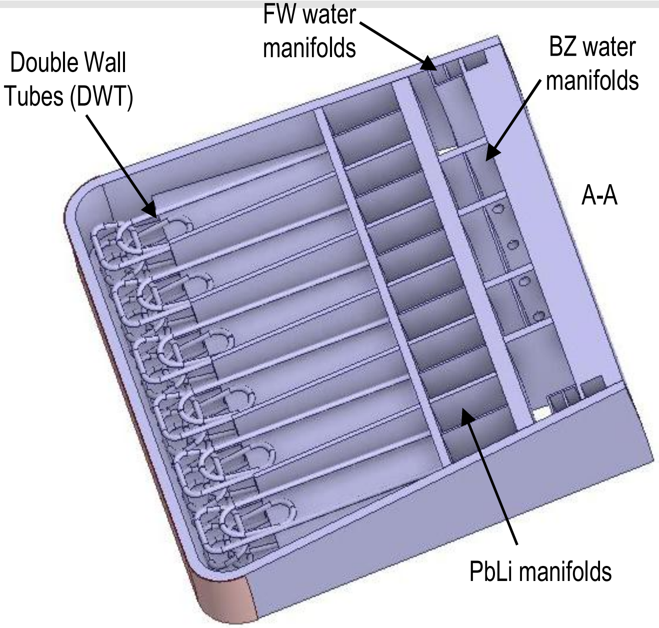
Several concepts are studied …

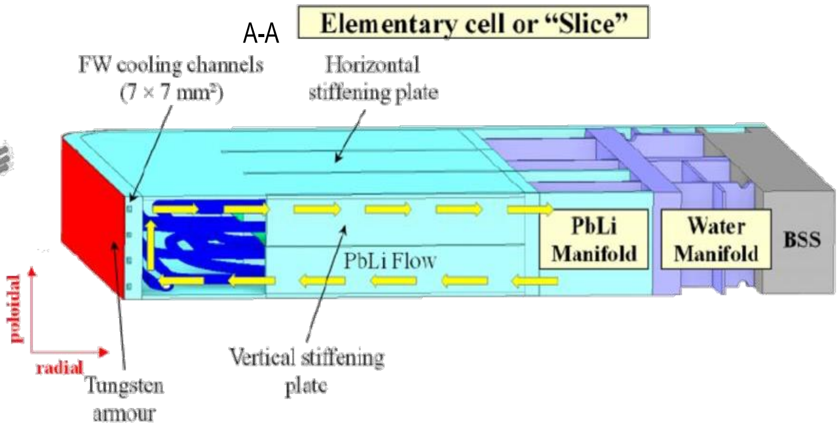
Ex. of BB concept for DEMO - WCLL

Water Cooled Lead Lithium









ENEA
Italian National Agency for New Technologies, Energy and Sustainable Economic Development

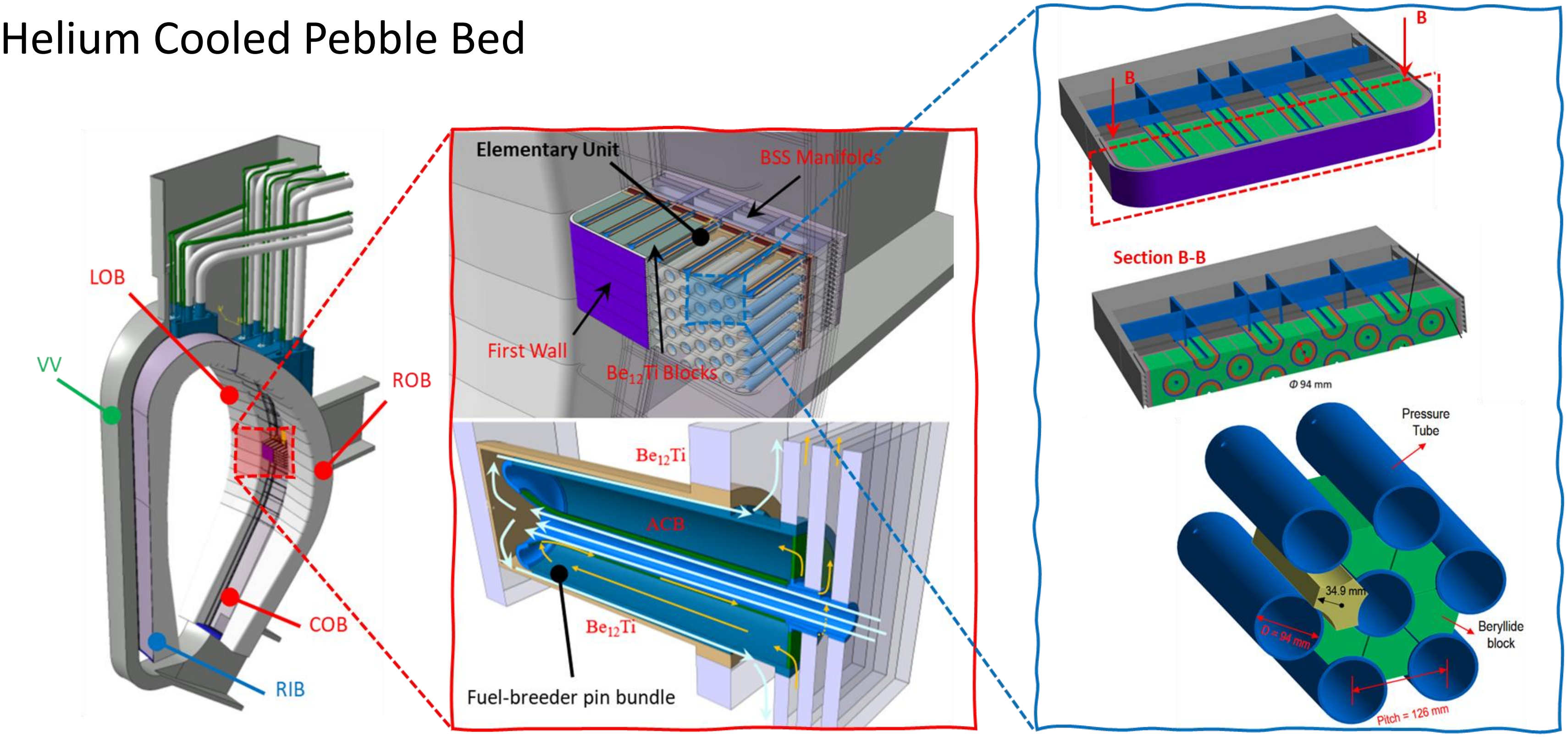
Structural Material: EUROFER
Breeder/neutron multiplier: PbLi (^{6}Li at 90%) liquid (330° C)
Coolant: Water (295-328° C)
Plasma protection: W layer
T extraction from recirculating PbLi

P. Arena et al, (2023) Design and Integration of the EU-DEMO Water-Cooled Lead Lithium Breeding Blanket, Energies, 16, 2069

Courtesy of S. d'Amico, F. Hernandez

Ex. of BB concept for DEMO - HCPB

Helium Cooled Pebble Bed



Structural Material: EUROFER

Breeder: Li_4SiO_4 + Li_2TiO_3 in form of a pebble bed, ^6Li at 60%

Neutron multiplier: Beryllide ($TiBe_{12}$) rods

Coolant: He 300-520° C @ 8 MPa

Plasma protection: W layer

T extraction with purge Helium

Courtesy of S. d'Amico, F. Hernandez

Challenges related to the BB

Structure

- ❖ Changes in properties and behaviour of materials
  - ➢ *Effect of heat flux and cycling on fatigue or crack growth-related failure*
  - ➢ *Premature failure at welds and discontinuities*
  - ➢ *Effect of swelling, creep and thermal gradients on stresses conc.*
- ❖ Tritium permeation through the structure
  - ➢ *Effectiveness of tritium permeation barriers*
  - ➢ *Effect of radiation on tritium permeation*
- ❖ **Structural activation product inventory and volatility**

Solid Breeder / multiplier / structure interactions

- ❖ Solid breeder mechanical and materials interactions
  - ➢ *Strain accommodation by creep and plastic flow*
  - ➢ *Stress concentrations at cracks and discontinuities*
- ❖ Neutron multiplier mechanical interactions
  - ➢ *Beryllium/beryllide swelling (swelling driving force in beryllium)*
  - ➢ *Strain accommodation by creep in Beryllium/beryllide*
- ❖ Thermal interactions
  - ➢ *Breeder/multiplier-structure heat transfer (gap conductance)*

Coolant / liquid breeder-multiplier

- ❖ MHD pressure drop and pressure stresses
- ❖ MHD and geometric effects on flow distribution
- ❖ **Helium bubble formation leading to hot spots**
- ❖ **Activation products in PbLi**

Coolant / structure interactions

- ❖ Mechanical and materials interactions
  - ➢ *Corrosion*
  - ➢ *Failure of coolant wall due to stress corrosion cracking*
  - ➢ *Failure of coolant wall due to liquid-metal embrittlement*
- ❖ Thermal interactions
- ❖ **Coolant/coatings/structure interactions**

Breeder and purge

- ❖ **Tritium recovery and inventory in solid breeder**
- ❖ **Liquid breeder tritium extraction**
- ❖ **Thermal conductivity changes under irradiation**
- ❖ **Effect of T mass transfer**
- ❖ **Breeder behaviour at high burn-up/high dpa**

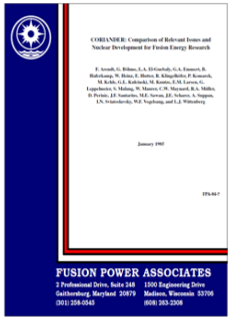
General blanket

- ❖ **Tritium trapping**
- ❖ **Uncertainties in achievable breeding ratio**
- ❖ **Uncertainties in required breeding ratio**
- ❖ **Permeation to blanket coolant**
- ❖ **Failure modes and frequencies**
- ❖ **Nuclear heating rate predictions**
- ❖ **Prediction and control of radioactive effluent**

⬛ **w/o neutrons**

🟧 **w/ neutrons**

🟥 **Fusion environment**



Efforts should be planned to test mock-ups and prototypes under relevant conditions to improve the understanding and knowledge of phenomena/processes. Separate effect tests can be foreseen initially. However, integral testing are needed for a full BB qualification.

BB in DEMO: improved variants

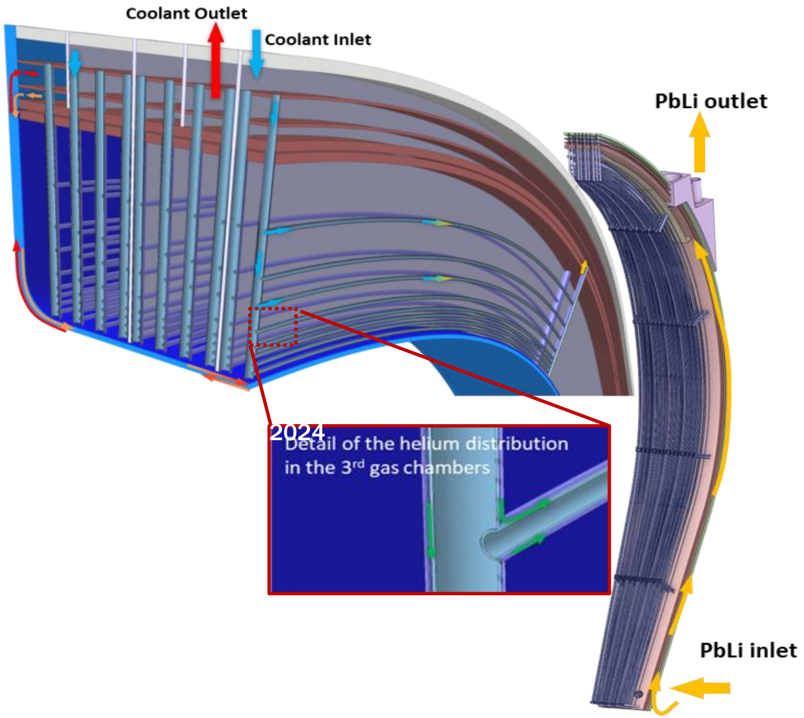
Water Cooled Lead Lithium Concept – Double Bundle

Breeder zone and first wall in series ($T_{in,FW} \approx 315$ ° C)

Less tubes, less welds, less surface, less water, more PbLi

→ more reliable, lower T permeation, better TBR

Avoids PbLi - water interaction



P. Pereslavtsev et al, (2023) Neutronic Activity for Development of the Promising Alternative Water-Cooled DEMO Concepts, Appl. Sci., 13, 7383,

Water-cooled Lead and Ceramic Breeder

Neutron multiplier: molten Pb or solid Pb compound

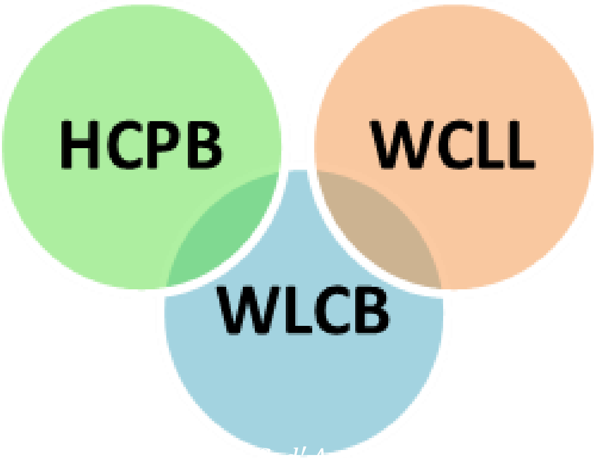
Coolant: Water (285-325°C @15.5 MPa)

T extraction with purge Helium

Breeder zone and first wall in series ($T_{in,FW} \approx 315$ °C)

Available TER and water PWR technology

Good TBR and neutron shielding, low T permeation



Tritium Burn-up Fraction

Tritium Burn-up Fraction f_B = probability that a tritium atom injected into the plasma will undergo a fusion reaction before it escapes

f_B = fusion reaction rate / tritium fueling rate = $n_T^2 \langle \sigma v \rangle_{DT} / S_T$

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T particle balance ($n_T = n_D$): $dn_T/dt = S_T - n_T^2 \langle \sigma v \rangle_{DT} - n_T/\tau_T$

τ_T = particle confinement time - with edge recycling τ_T becomes $\tau_T/(1-R)$,
but generally the recycling coefficient R<<1

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but generally the recycling coefficient R<<1

Steady-state: $$S_T = n_T^2 \langle \sigma v \rangle_{DT} + n_T/\tau_T$$

and

$$f_B = n_T^2 \langle \sigma v \rangle_{DT} / S_T = n_T^2 \langle \sigma v \rangle_{DT} / (n_T^2 \langle \sigma v \rangle_{DT} + n_T/\tau_T) = 1/(1+1/(\tau_T n_T \langle \sigma v \rangle_{DT}))$$

f_B can be increased by increasing the confinement time

Tritium inventory in fusion reactor

dM/dt = mass consumption rate to produce the necessary fusion power

dM/dt ~ 56 x fusion power kg/y/$GW_{thermal}$

Ex. $1GW_e \rightarrow$ ~$3GW_{thermal} \rightarrow$ ~160kg/y

T reprocessing system takes a mean time t_p to clean up and recycle tritium

The reprocessed tritium is injected into the plasma with efficiency η_f

γ_s = radioactive decay rate (= ln2/12.3 y^{-1}); γ_r = loss rate in reprocessing T

M_0 = time-independent, re-circulating tritium inventory

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Over a time interval t_p

$$\underbrace{\underbrace{\underbrace{M_0 \times \eta_f}_{\text{injected}} \times f_B}_{\text{burnt}} \times TBR}_{\text{bred}} = \int_0^{t_p} \left[\frac{dM}{dt} + (\gamma_r + \gamma_s) M_0 \right] dt = \left[\frac{dM}{dt} + (\gamma_r + \gamma_s) M_0 \right] \times t_p$$

$dM/dt = \eta_f f_B M_0 / t_p \times TBR - (\gamma_r + \gamma_s) M_0$

Tritium inventory in fusion reactor

$$dM/dt = \eta_f f_B M_0/t_p \times TBR - (\gamma_r+\gamma_s)M_0$$

If breeding rate is large compared to loss rate, and TBR~1

$$M_0 \sim t_p\, dM/dt\, /\, \eta_f f_B$$

Ex.: 1 $GW_{thermal}$ reactor, with $f_B = 5\%$, $\eta_f = 50\%$, $t_p = 1day \rightarrow M_0 \sim 6kg$
ITER → M_0~3kg (~$100M)
DEMO → M_0~7kg

Naturally, the un-burnt T is also recycled, with the same processing time t_p

Problems with large T inventory

Safety; Power required to heat fueled T to plasma temperature; Required TBR

T inventory can be minimized by minimizing the reprocessing time and by increasing the injection efficiency and burn-up fraction

Tritium build-up in fusion reactors

In reality, the total tritium mass in a reactor should increase with time

$M = M_0 + m$, with m the mass produced in reactor blanket

$$\frac{dm}{dt} = -\gamma_s m - \left[\gamma_s + \gamma_r\right] M_0 - \frac{dM}{dt} + \frac{dM}{dt} TBR$$

As $dM/dt \sim M_0 \eta_f f_B / t_p$

$$\frac{dm}{dt} = -\gamma_s m + \underbrace{\left[\frac{\eta_f f_B}{t_p} (TBR - 1) - \gamma_s - \gamma_r \right]}_{A} M_0 = -\gamma_s m + A M_0$$

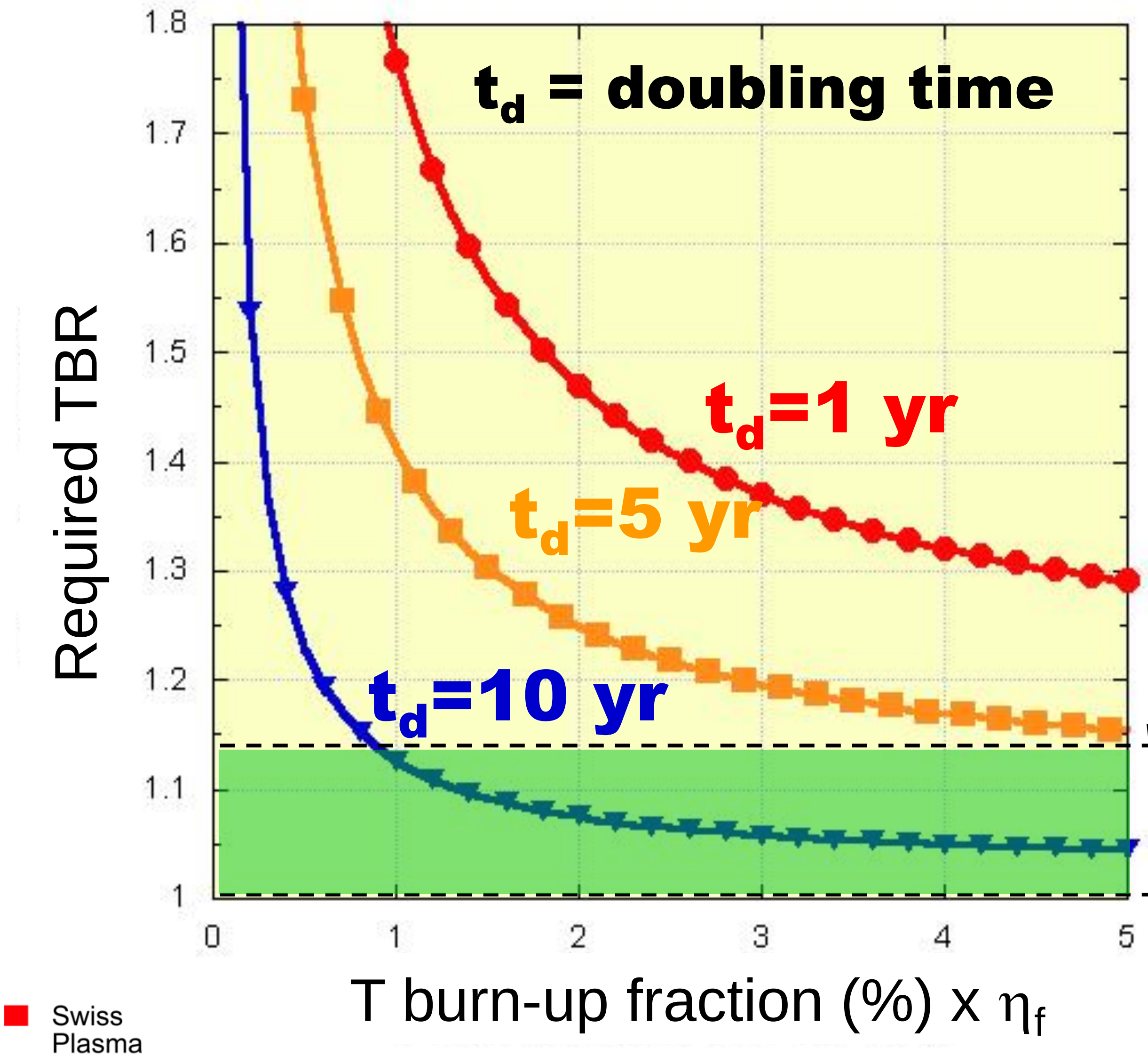
Which gives

$$m(t) = \frac{A M_0}{\gamma_s} \left(1 - e^{-\gamma_s t}\right)$$

This regulates the 'tritium economy' and tells us how fast we can deploy reactors

Impact of T cycle parameters on fusion

Required TBR for T self-sufficiency depends on burn-up fraction, fuelling efficiency and fusion reactor doubling time



Fusion power ~1.5GW
Waste removal efficiency ~0.9
(from Prof. Abdou, UCLA)

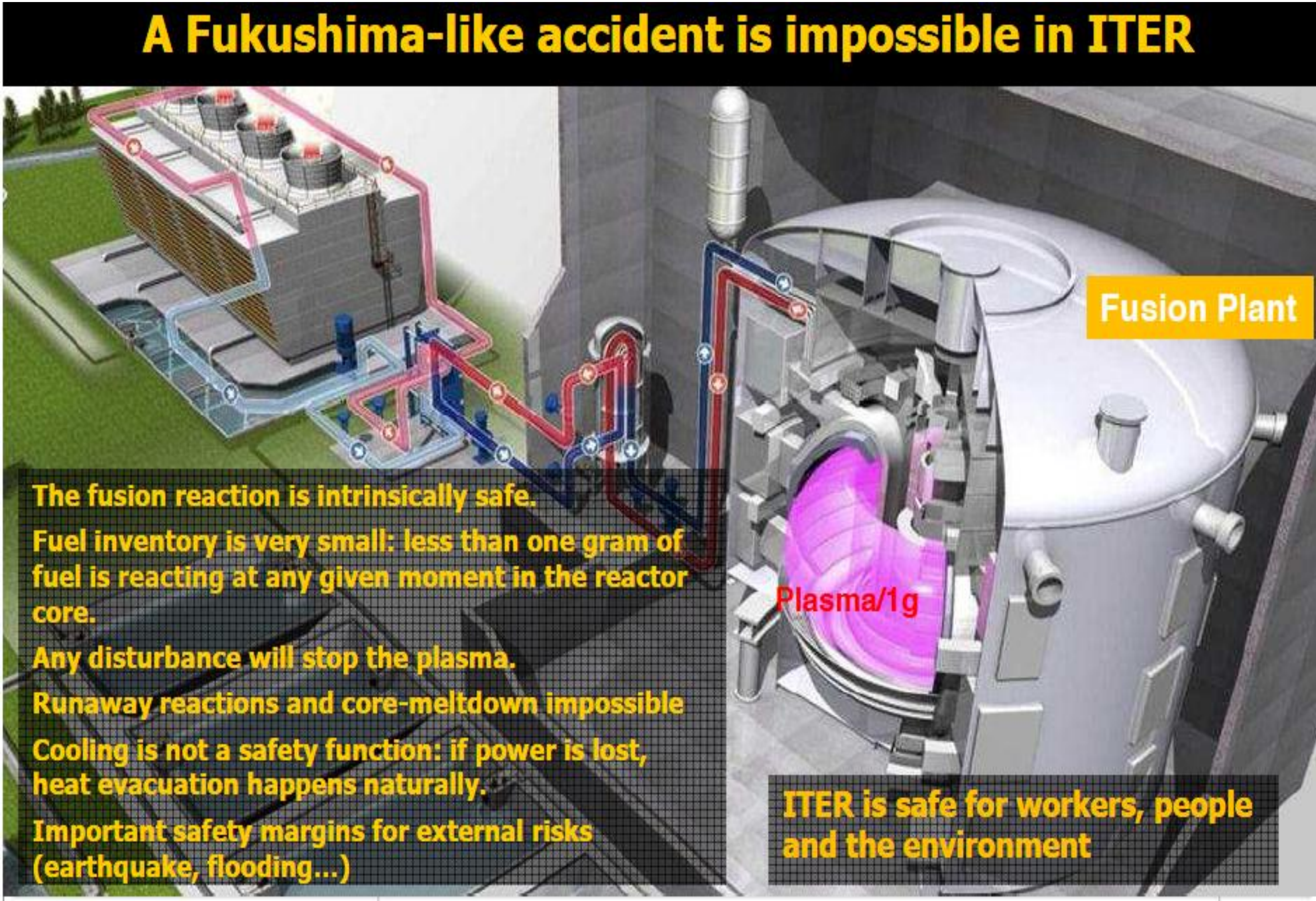
Max TBR ≤ 1.15

“Window” for Tritium self sufficiency

Significant R&D needed to stay in window

ITER SAFETY AND LICENSING

ITER safety



A Fukushima-like accident is impossible in ITER

The fusion reaction is intrinsically safe.

Fuel inventory is very small: less than one gram of fuel is reacting at any given moment in the reactor core.

Any disturbance will stop the plasma.

Runaway reactions and core-meltdown impossible

Cooling is not a safety function: if power is lost, heat evacuation happens naturally.

Important safety margins for external risks (earthquake, flooding...)

ITER is safe for workers, people and the environment

Temperature in case of loss of cooling

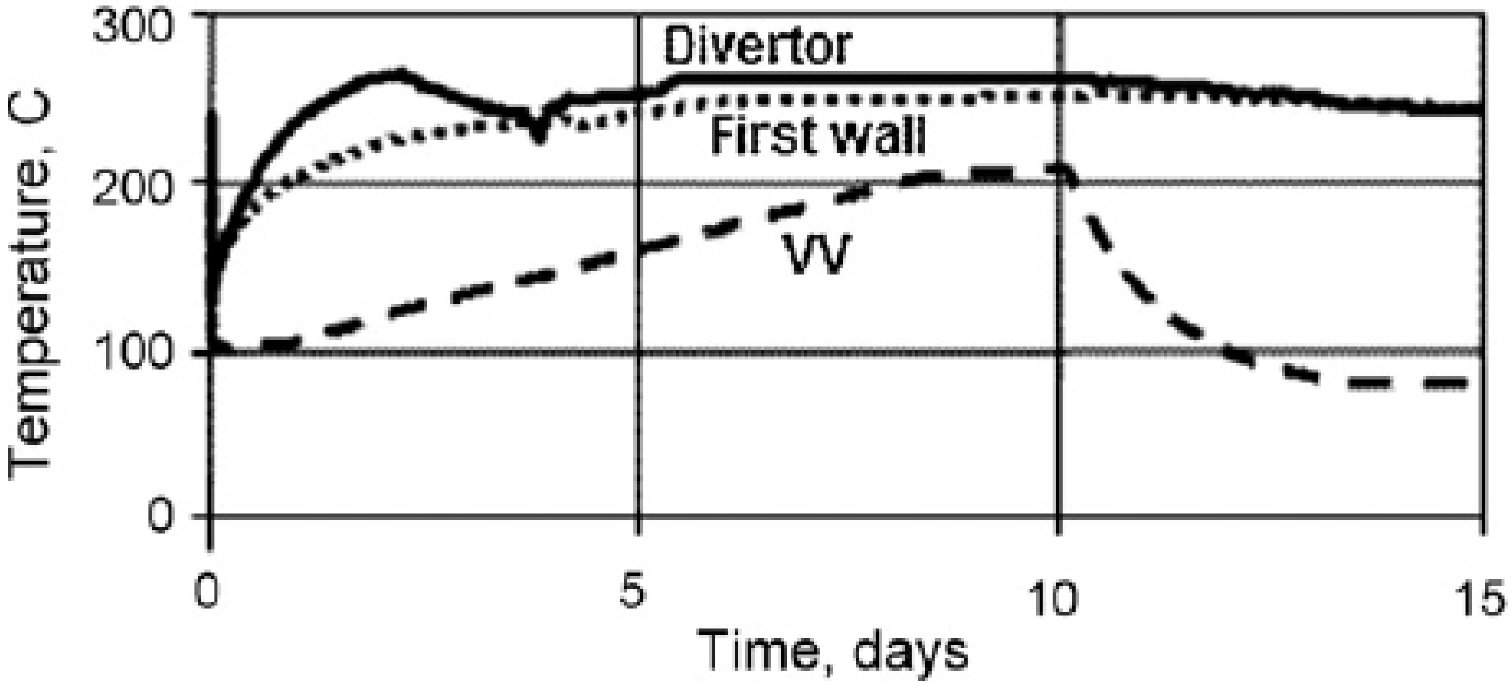


Fig. 1. Temperature evolution of divertor, first wall and vacuum vessel in event of loss of all water coolant flow, with cryostat vented to air after 10 days.

ITER radioactivity and waste

- ITER will not generate long-lived/high activity waste.
- During normal operation, ITER's radiological impact on the most exposed populations will be one thousand times less than natural background radiation.
- "Worst-case scenarios", such as fire in the Tritium Plant, would have a lesser impact on neighbouring populations than natural background radiation.
- ITER shall observe French safety and security regulations
  - A stress test will be conducted by Nuclear Safety Authority.

EPFL

TOWARD A FUSION POWER PLANT

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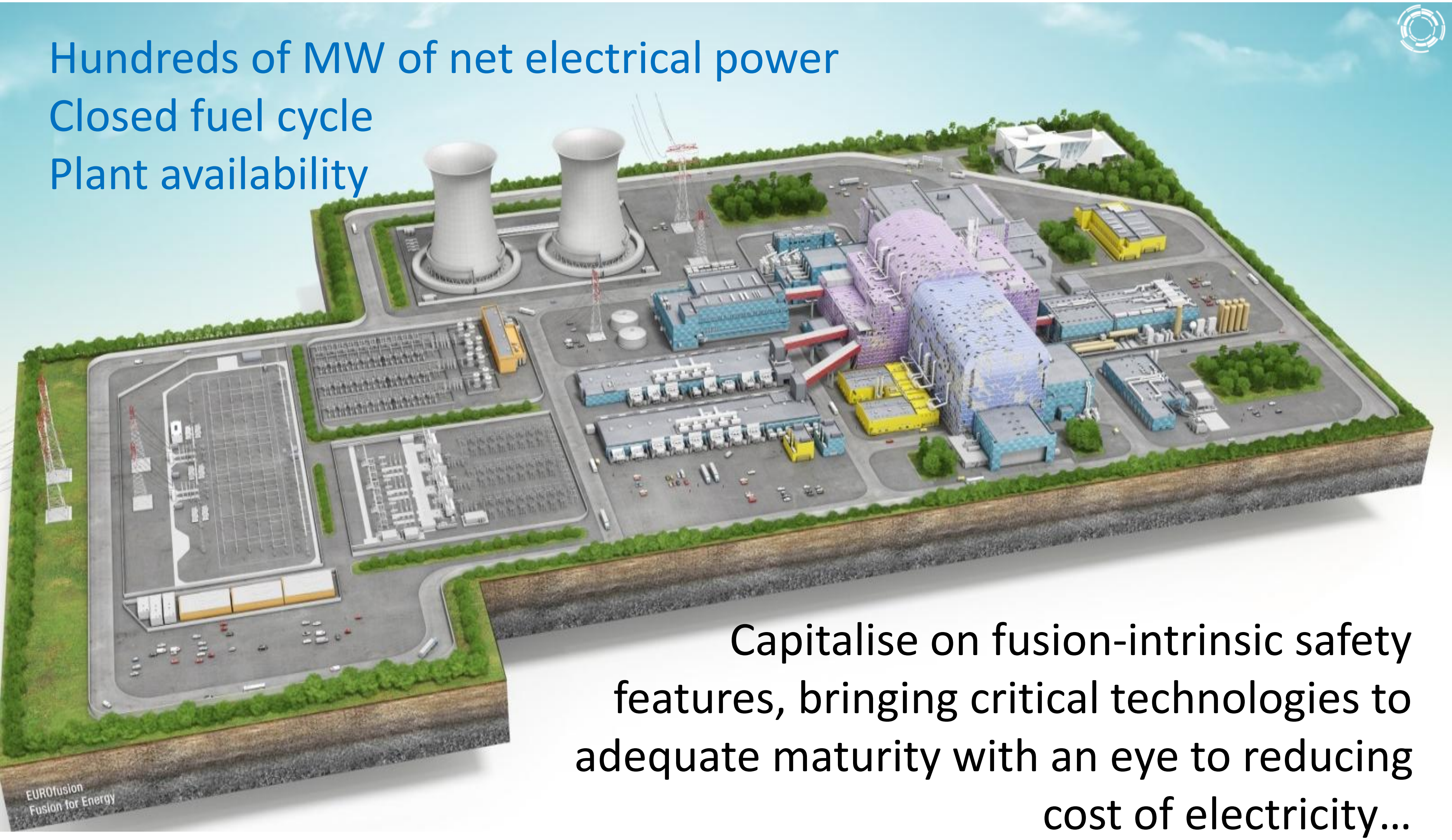
European DEMO conceptual design



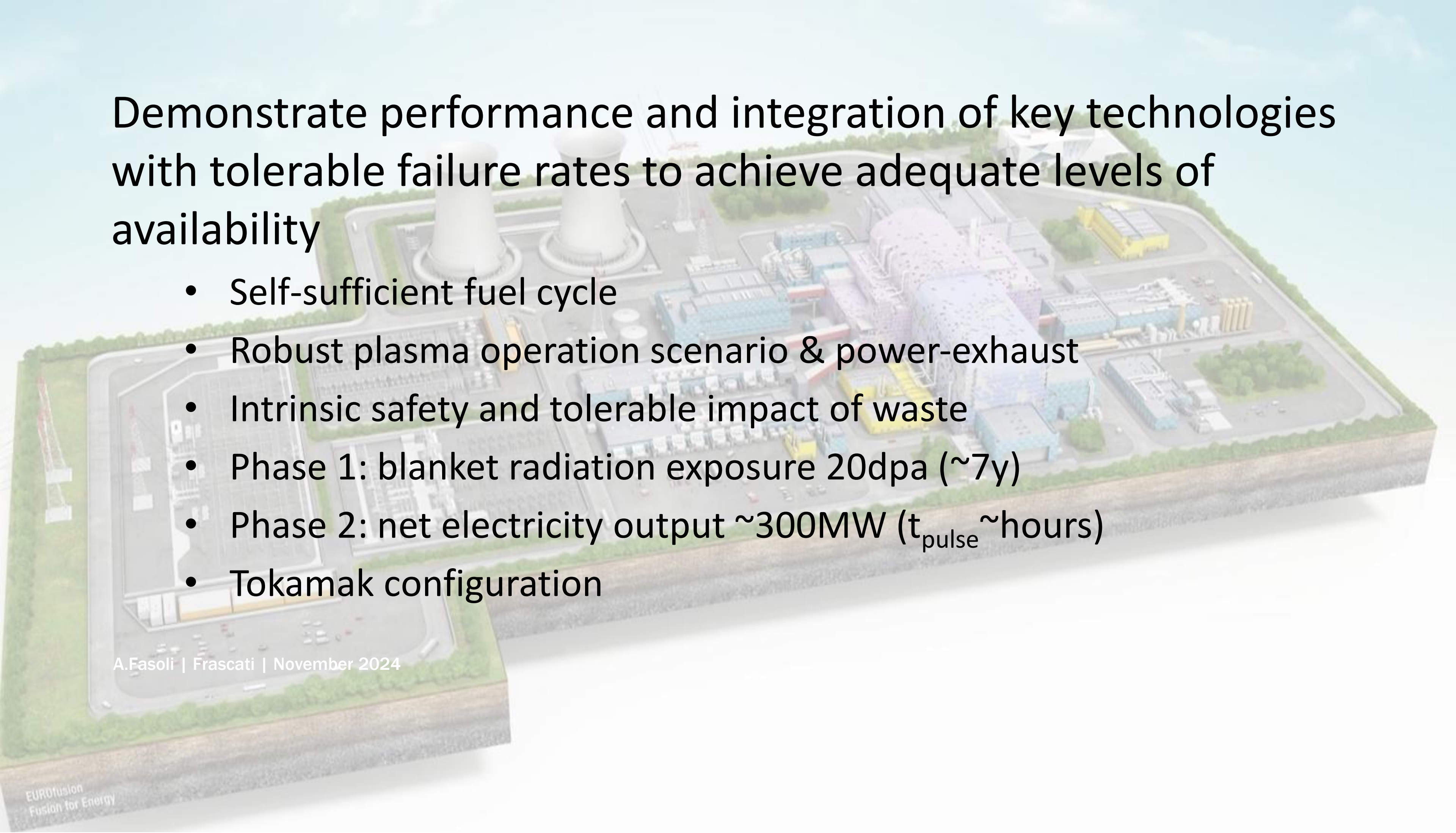
Hundreds of MW of net electrical power

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…

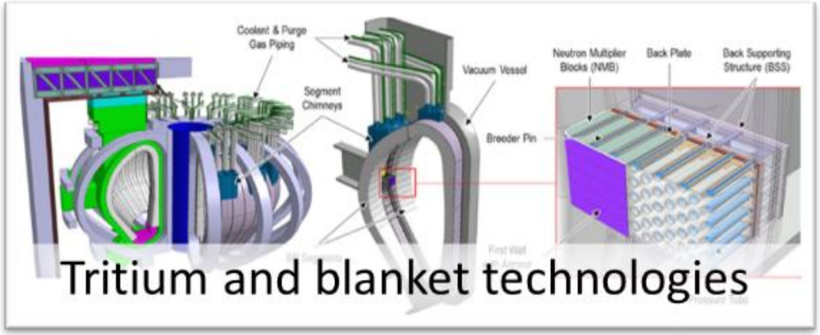
Definition of the DEMO step – high level goals



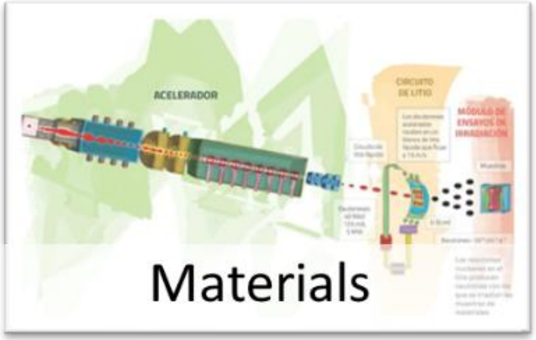
Demonstrate performance and integration of key technologies with tolerable failure rates to achieve adequate levels of availability

- Self-sufficient fuel cycle
- Robust plasma operation scenario & power-exhaust
- Intrinsic safety and tolerable impact of waste
- Phase 1: blanket radiation exposure 20dpa (~7y)
- Phase 2: net electricity output ~300MW (t_{pulse}~hours)
- Tokamak configuration

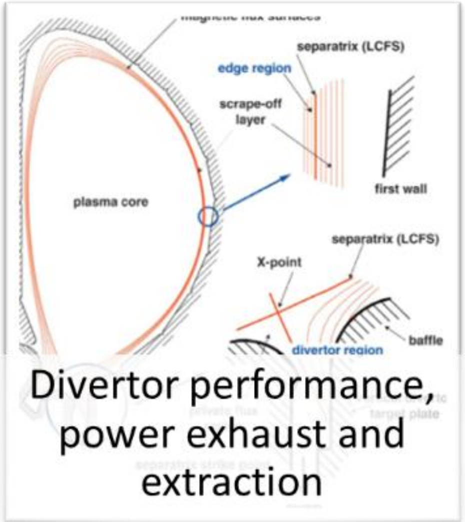
Remaining open gaps towards DEMO



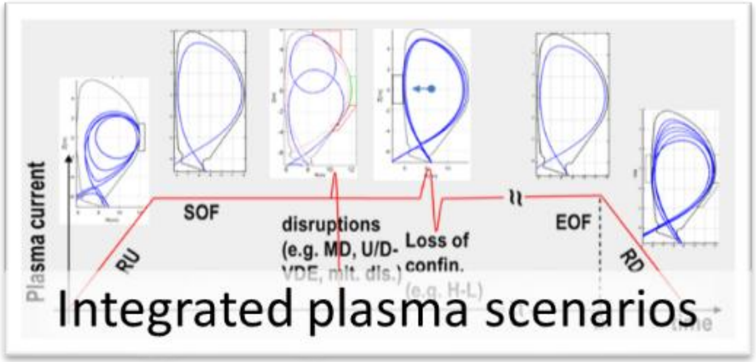
Tritium and blanket technologies



Materials



Divertor performance, power exhaust and extraction

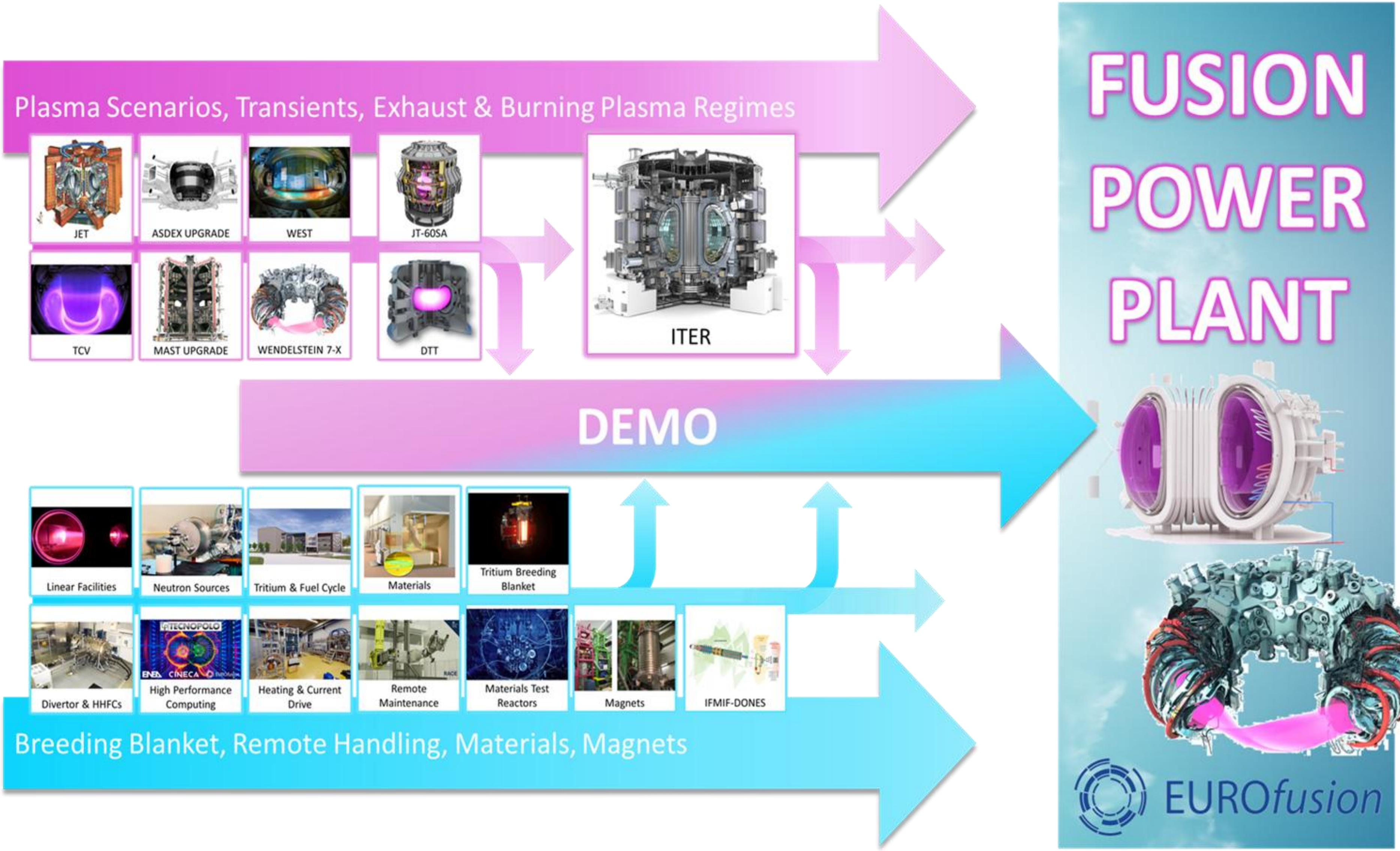


Integrated plasma scenarios

Safety and waste

Remote maintenance

The European Roadmap to fusion



Plasma Scenarios, Transients, Exhaust & Burning Plasma Regimes

JET

ASDEX UPGRADE

WEST

JT-60SA

TCV

MAST UPGRADE

WENDELSTEIN 7-X

DTT

ITER

DEMO

Linear Facilities

Neutron Sources

Tritium & Fuel Cycle

Materials

Tritium Breeding Blanket

Divertor & HHFCs

High Performance Computing

Heating & Current Drive

Remote Maintenance

Materials Test Reactors

Magnets

IFMIF-DONES

Breeding Blanket, Remote Handling, Materials, Magnets

FUSION POWER PLANT

EUROfusion