

Nuclear Fusion and Plasma Physics

Lecture 12

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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

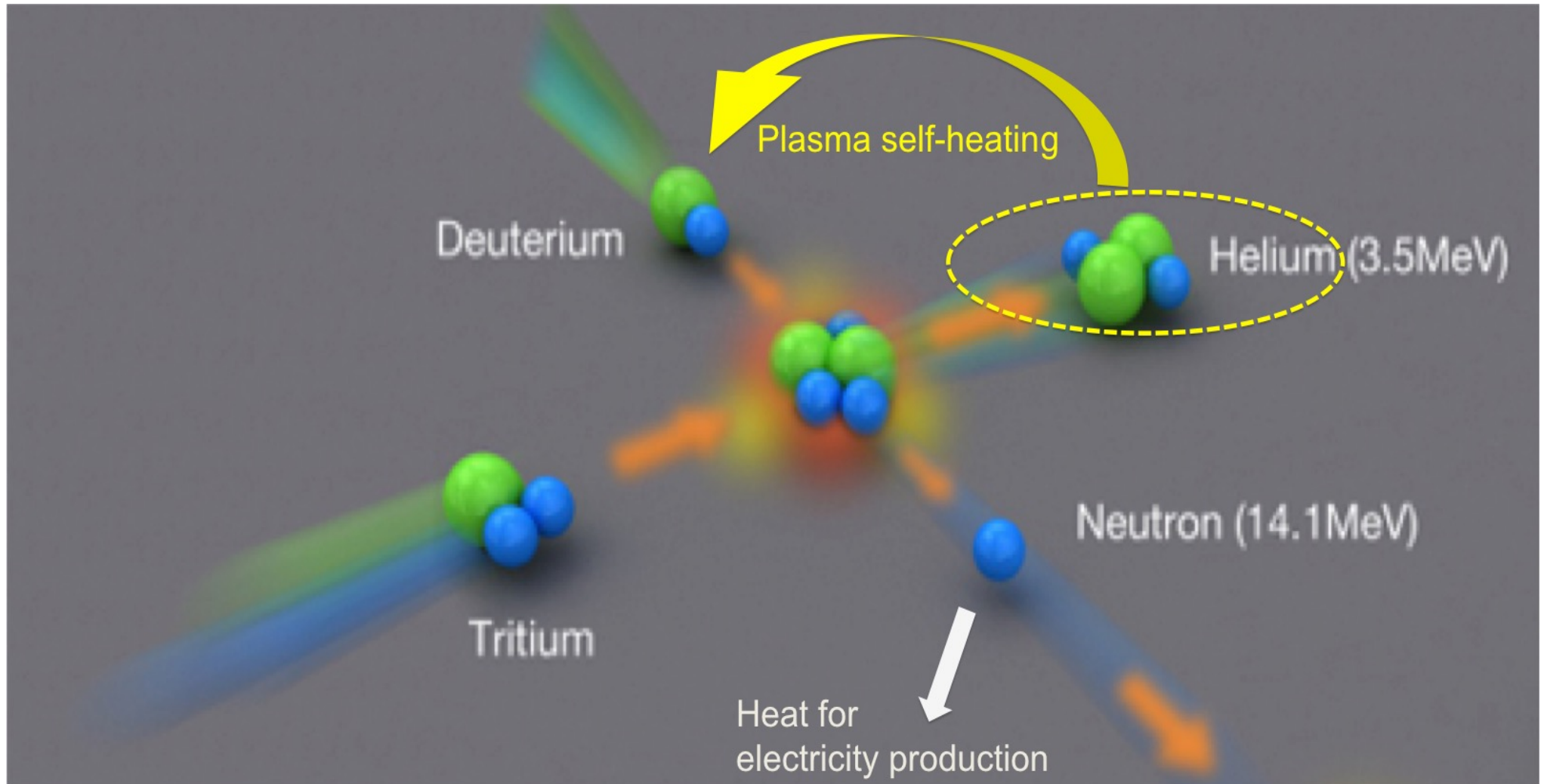
Tritium in fusion

ITER safety and licensing

Toward a fusion power plant

BURNING PLASMAS: GENERALITIES

D-T fusion reaction



Definition of a burning plasma

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

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

Thermal energy density $W \equiv 3nT$

Energy balance

$$dW/dt = P_\alpha + P_{\text{in}}/V - W/\tau_E$$

α -heating
 ext. heating
 losses

confinement
time



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confinement
time

Fusion energy gain: $Q \equiv P_{\text{fusion}}/P_{\text{in}} = 5 P_\alpha/P_{\text{in}}$

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

$Q < 0.7$

$f_\alpha < 12\%$ *present experiments*

$Q = 1$

$f_\alpha = 17\%$ *breakeven*

$Q = 5$

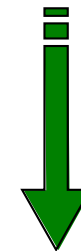
$f_\alpha = 50\%$

$Q = 10$

$f_\alpha = 67\%$

$Q = \infty$

$f_\alpha = 100\%$ *ignition*

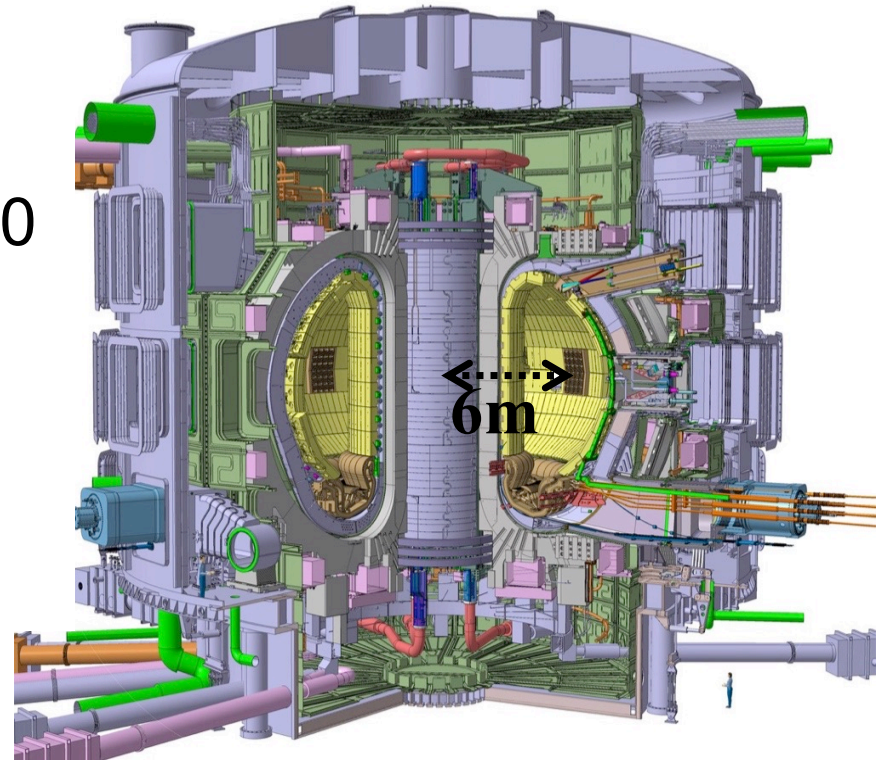


*burning
plasma*

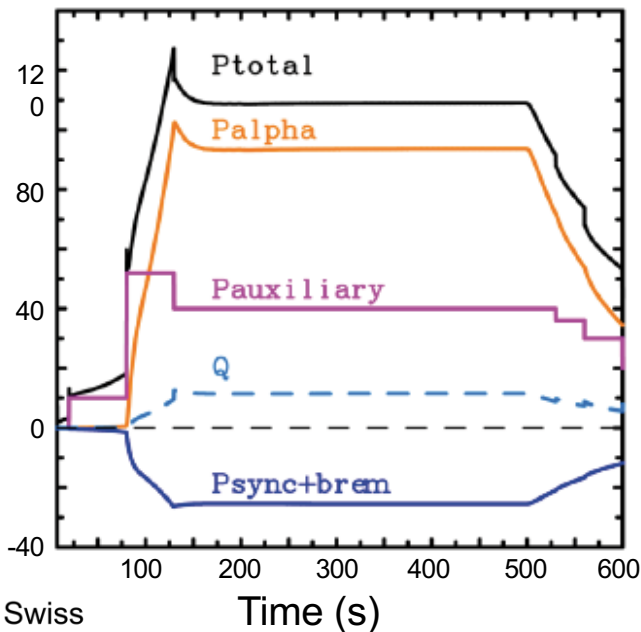
EPFL The first burning plasma: ITER

$Q \geq 10$; $P_{\text{fusion}} \geq 500\text{MW}$; $\sim 500\text{s}$
Explore steady-state $Q \geq 5$, $\leq 3000\text{s}$
May explore 'controlled ignition' $Q \geq 30$

→ burning plasma



Y.Gribov



Q=10 scenario

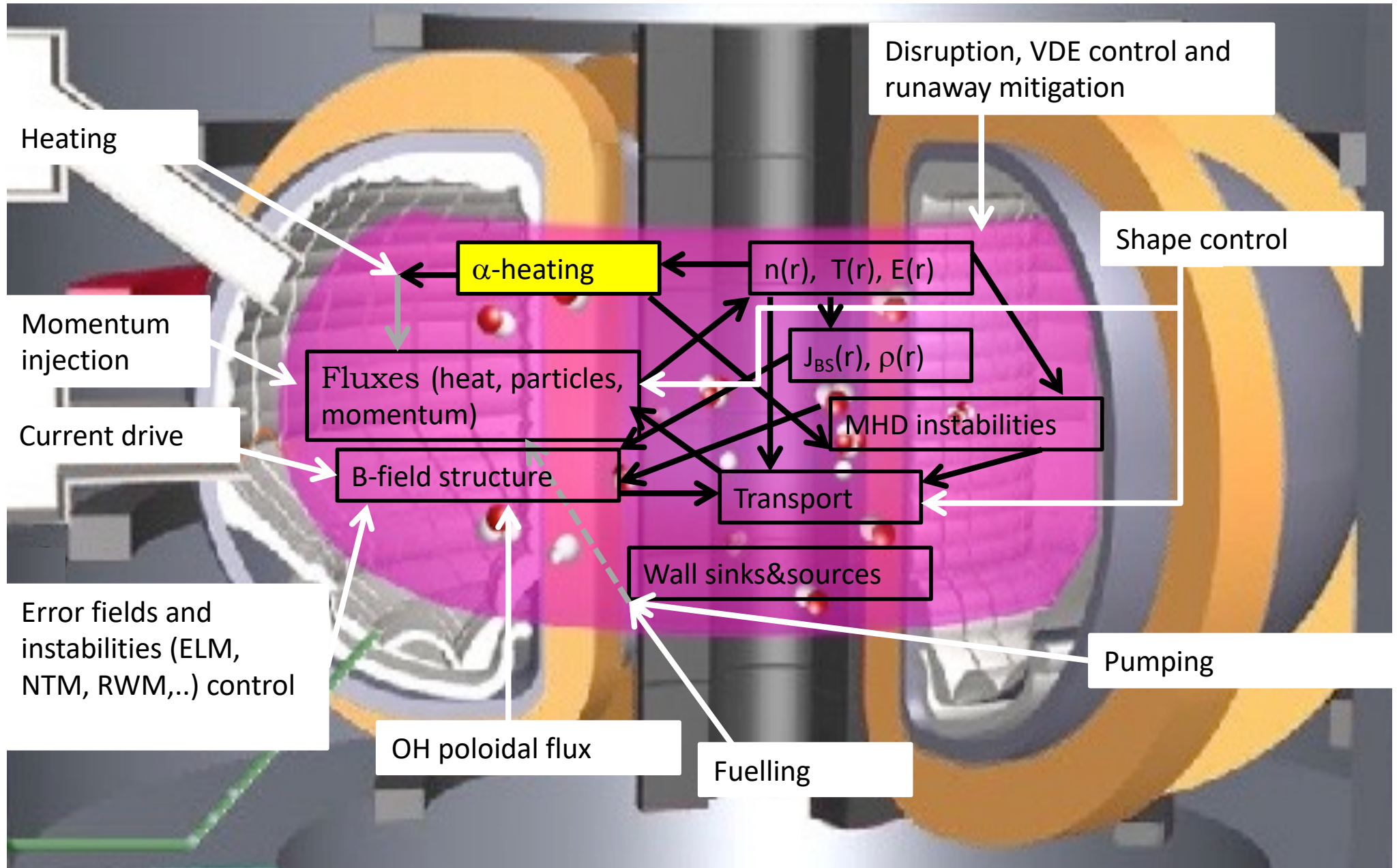
$I_p = 15\text{ MA}$, $P_{\text{fus}} \sim 500\text{ MW}$

Total α energy in single shot: $\sim 50\text{GJ}$

Total α energy produced by JET and

TFTR DT campaigns: $< 10\text{GJ}$

Burning plasmas: interplay of plasma dynamics and external systems



EPFL Specific properties of burning plasmas

High performance

Operational limits, heat flux on plasma facing components

Nuclear environment

Radiation T retention, dust, breeding

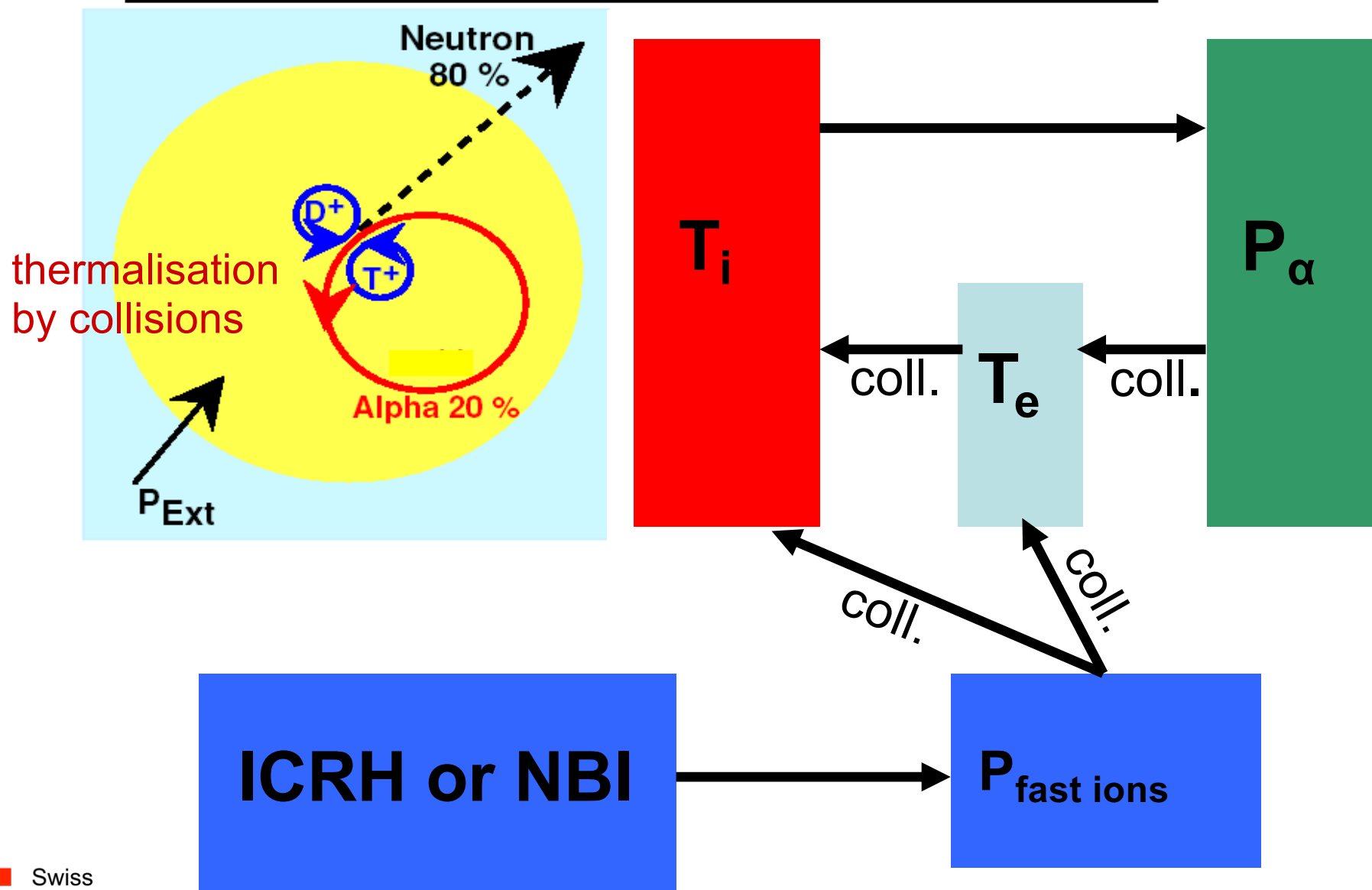
New physics parameter range

Small ρ_{Li}/a , high density and high temperature, low collisionality

Large isotropic population of fusion produced α 's, dominant source of plasma heating

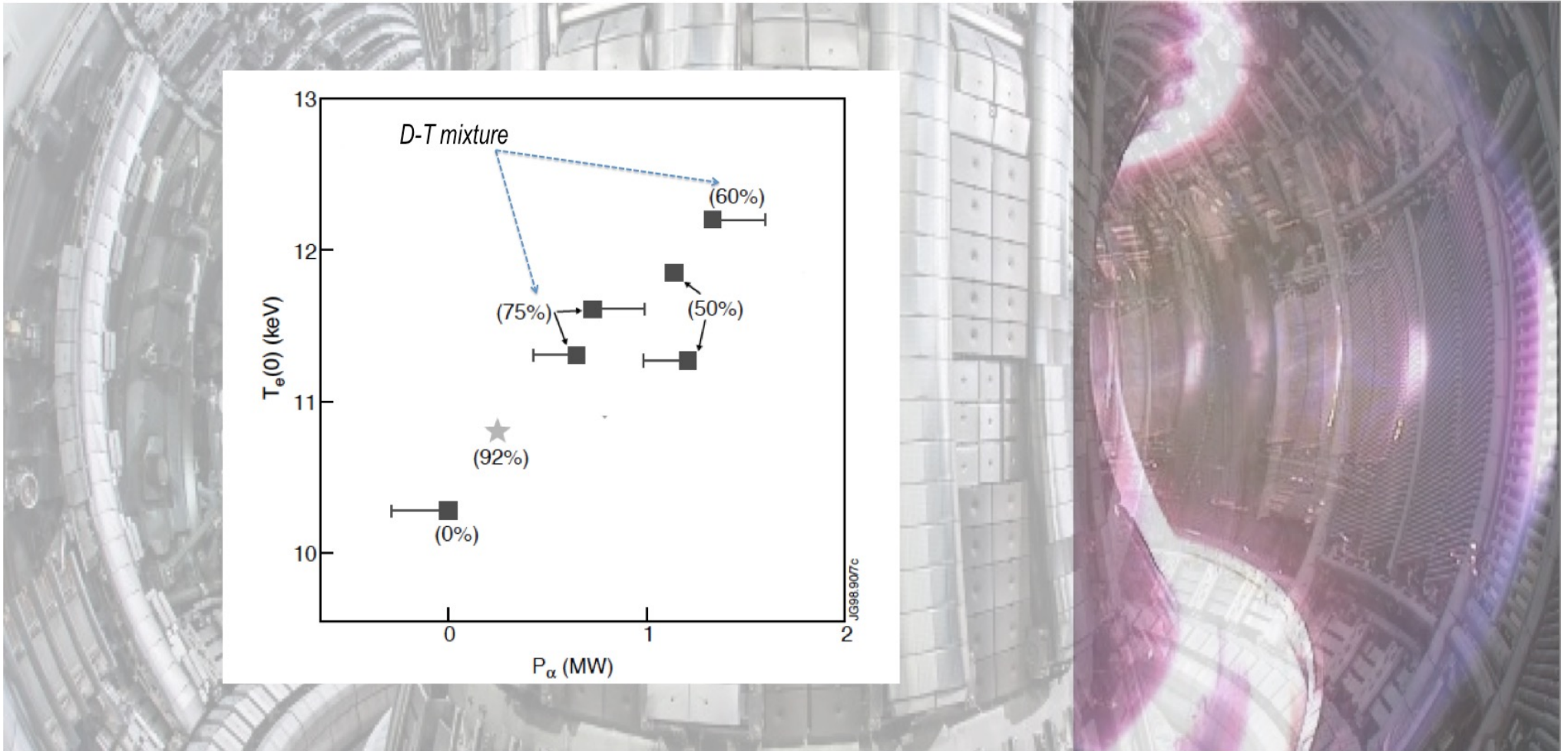
Coupling of profiles $P_\alpha(r)$, $p(r)$, $q(r)$, $E_r(r)$, diffusion coefficient(r), $n_{He}(r)$, ...

External heating and self-heating



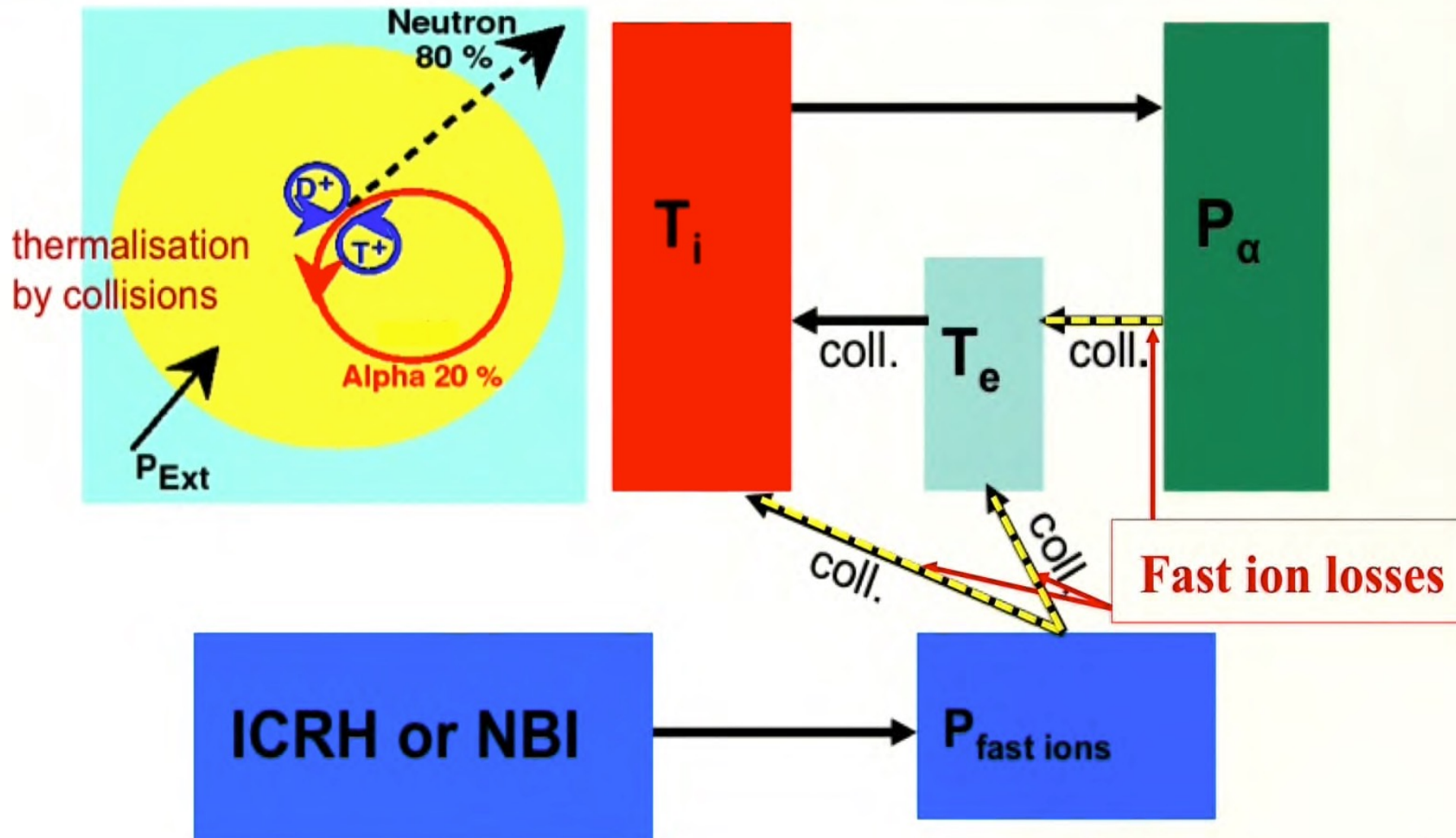
EPFL Fast ions and the self-heating process

Electron heating by fusion α 's



External heating and self-heating

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



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

Need to understand and possibly minimize redistribution and loss mechanisms

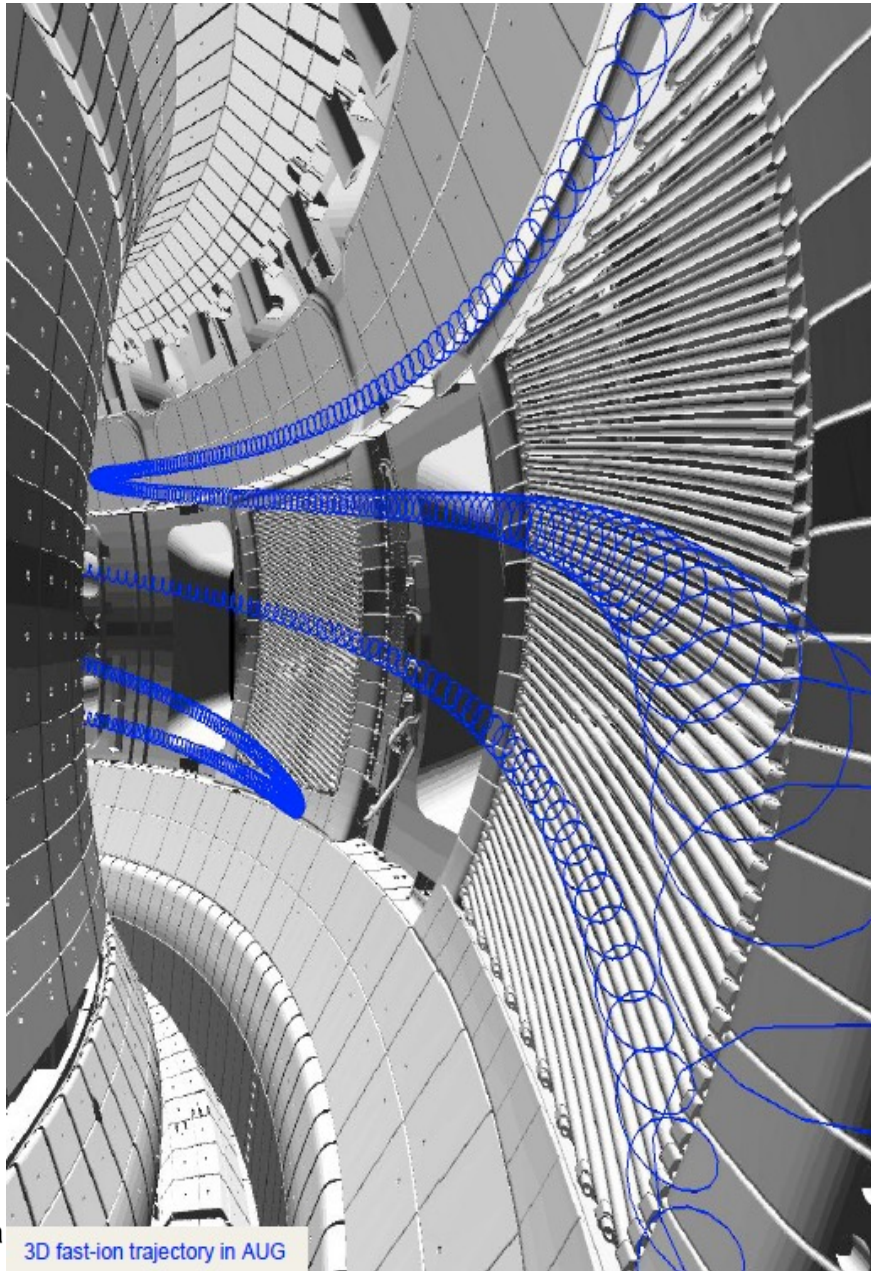
- Magnetic field imperfections

- Low frequency MHD instabilities

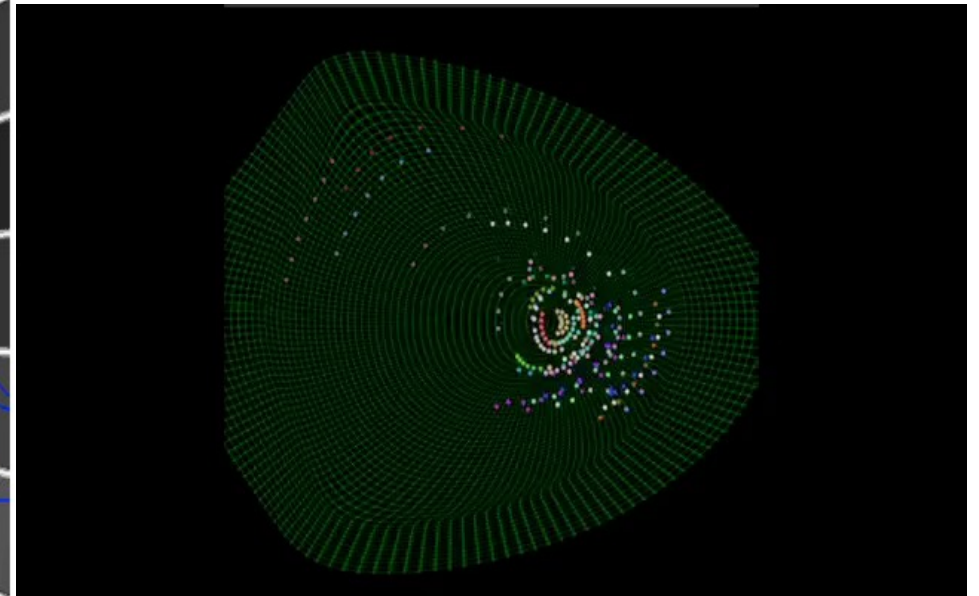
- Turbulence

- Resonant interaction with Alfvén waves

Fast ion orbits in tokamaks



3D fast-ion trajectory in AUG



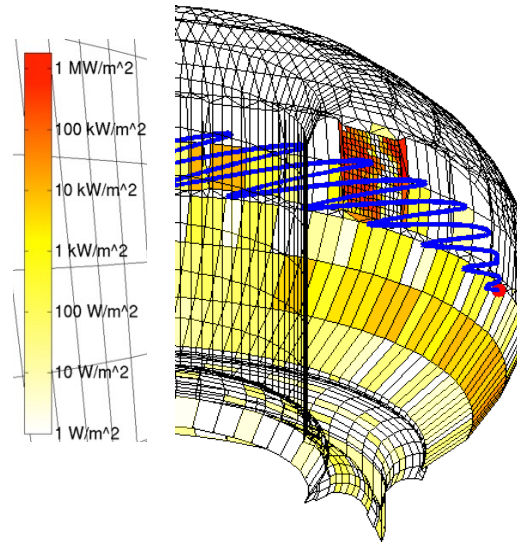
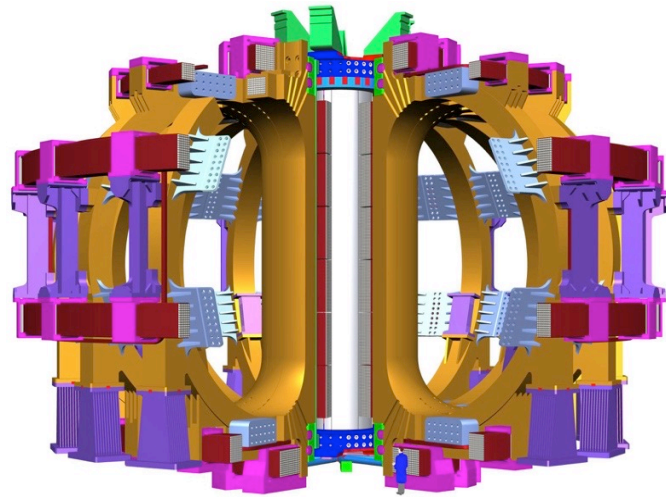
GPU-NUBEAM DIII-D
Simulation

FAST ION LOSS MECHANISMS
MAGNETIC FIELD IMPERFECTIONS

EPFL Fast ions and the self-heating process

Fast ion losses in 3D B-field

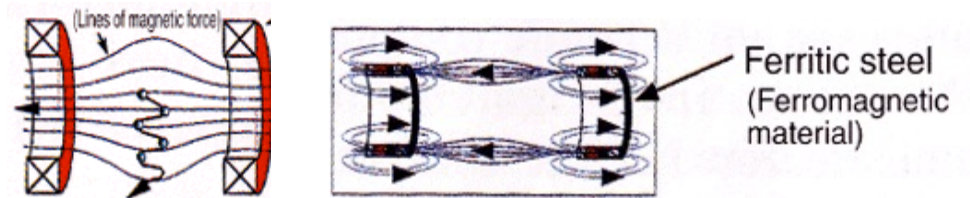
B-field inhomogeneities can lead to orbit trapping and losses



ASCOT code
T.Kurki-Suonio

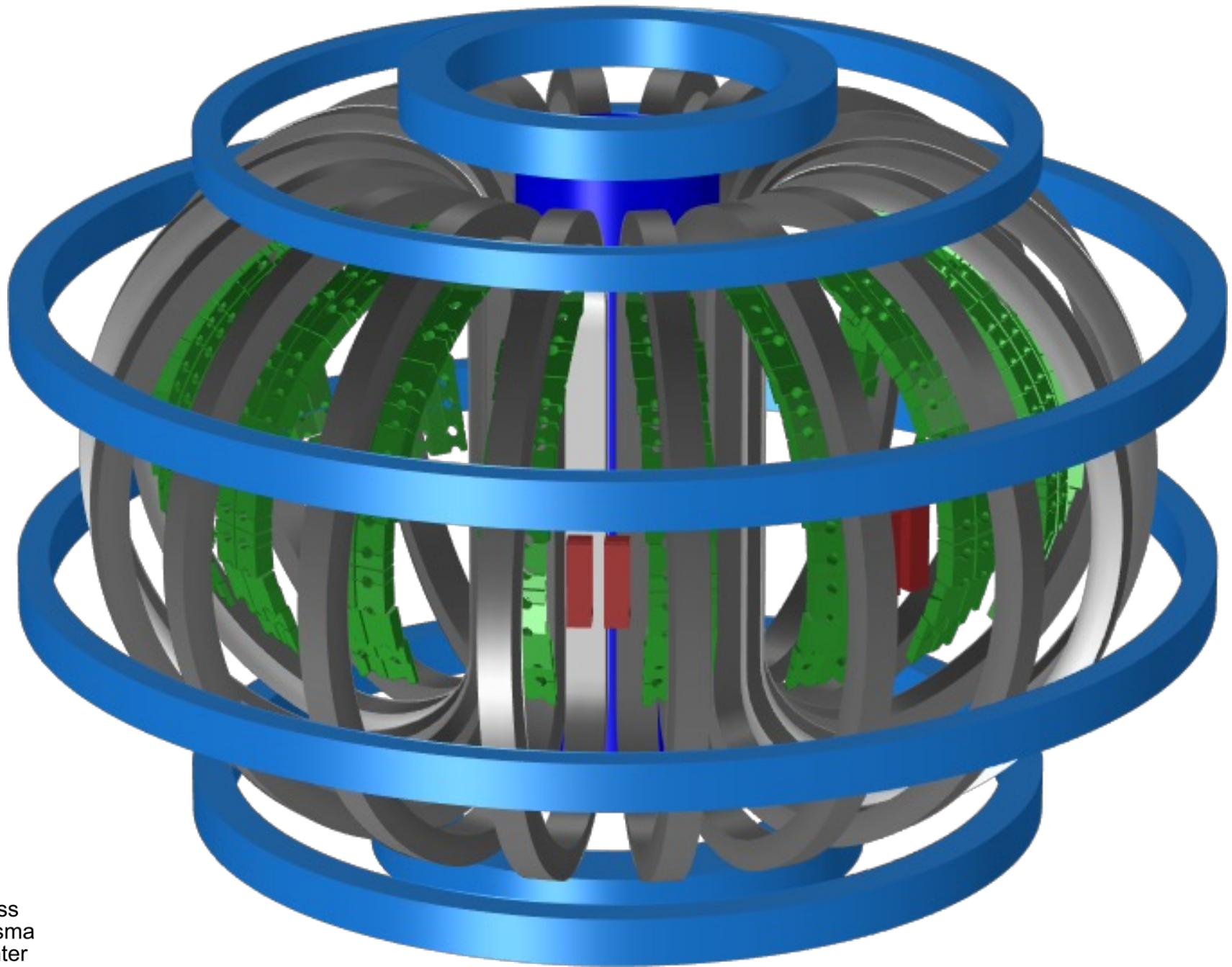
Ripple effects on fast ions qualitatively understood

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



K.Shinohara

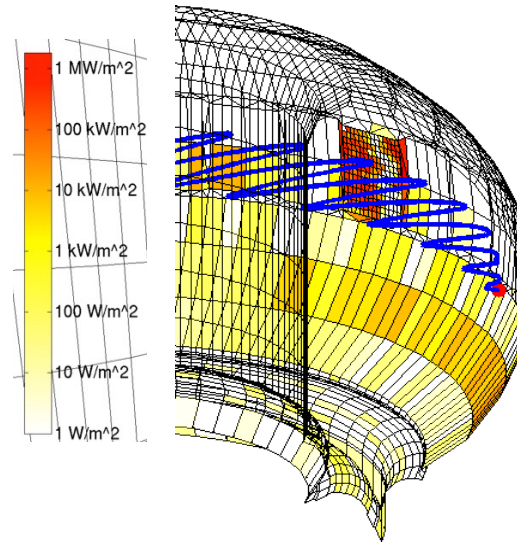
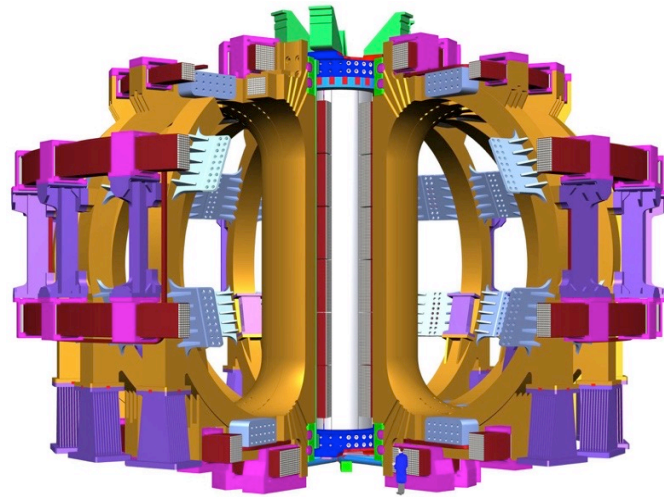
EPFL 3D image of the ferritic inserts in ITER



EPFL Fast ions and the self-heating process

Fast ion losses in 3D B-field

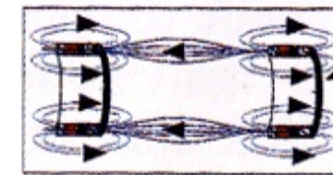
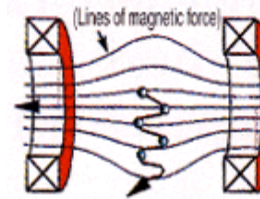
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Ripple effects on fast ions qualitatively understood

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



Ferritic steel
(Ferromagnetic material)

K.Shinohara

Open questions

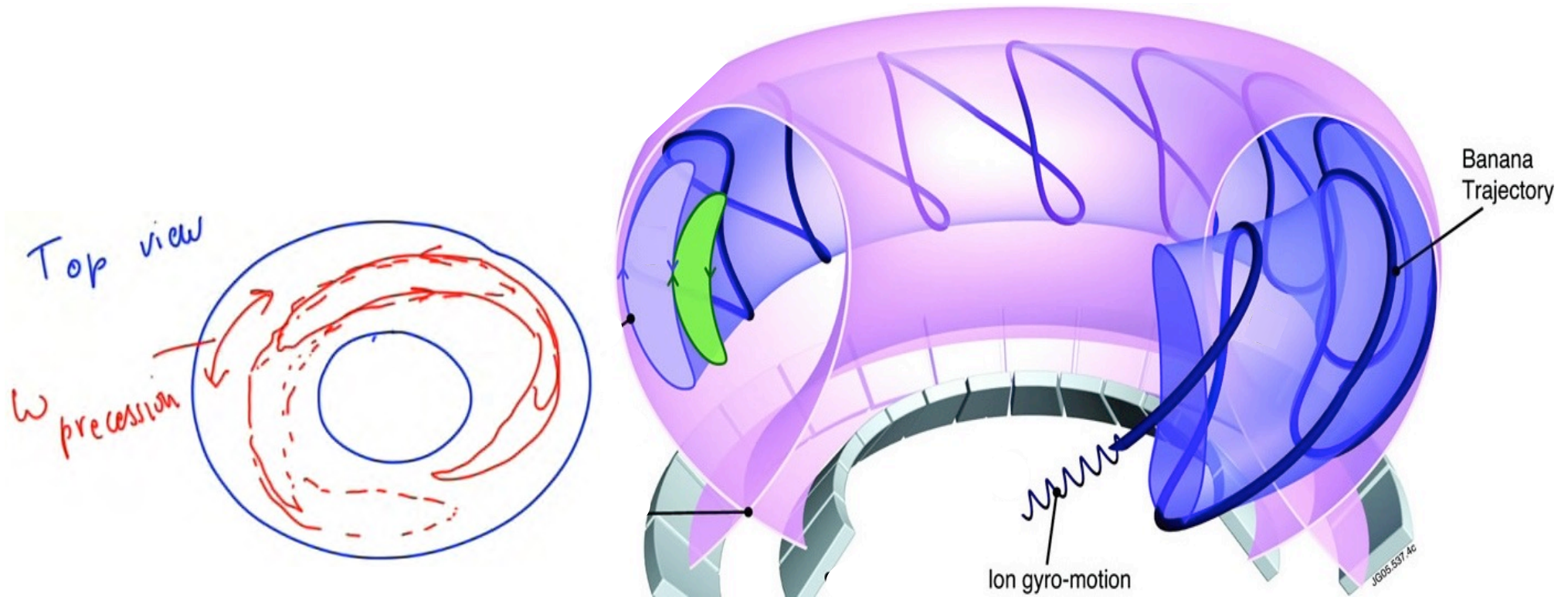
Effect of blanket modules (~1% ripple)

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

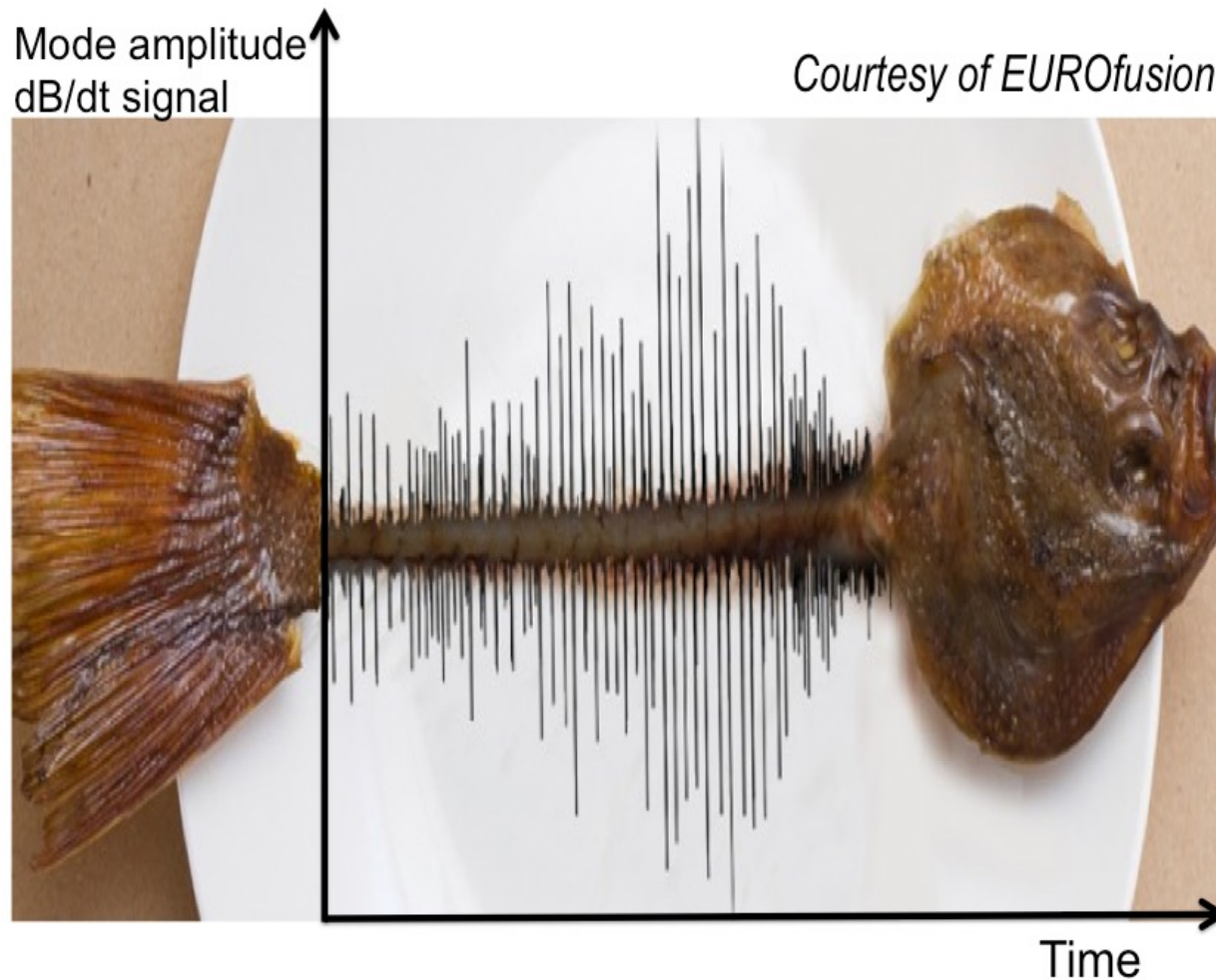
Example: bounce motion of particles along banana orbits and toroidal drift precession of banana orbits : $\omega_{\text{precession}} \ll \omega_{\text{bounce}} \ll \Omega_c$

MHD modes: $\omega \ll \Omega_c$

EPFL 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



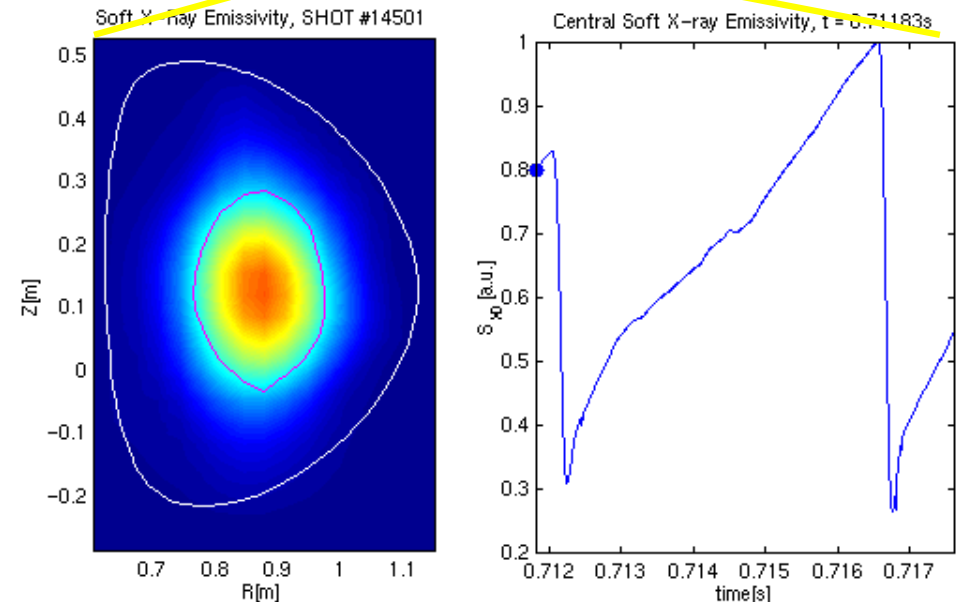
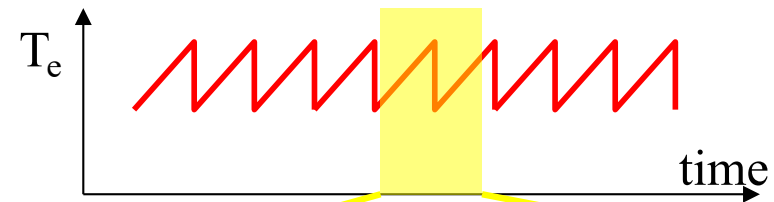
Low frequency MHD Sawtooth instability

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 ($\sim T_e, n$) evolution in TCV



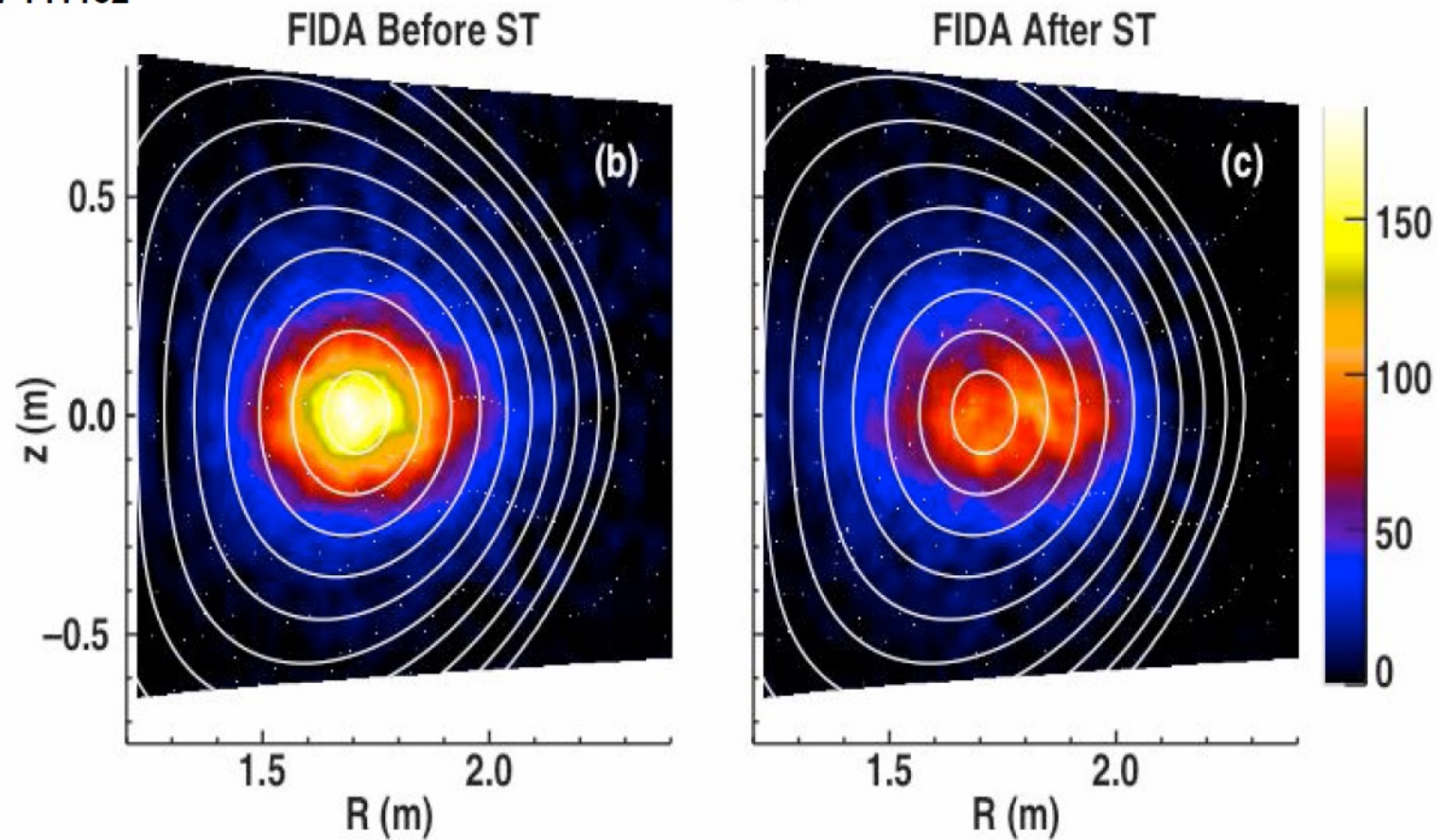
Courtesy of I. Furno

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 $D\alpha$

141182



FAST ION LOSS MECHANISMS

PLASMA TURBULENCE

EPFL Fast ion interaction with turbulence

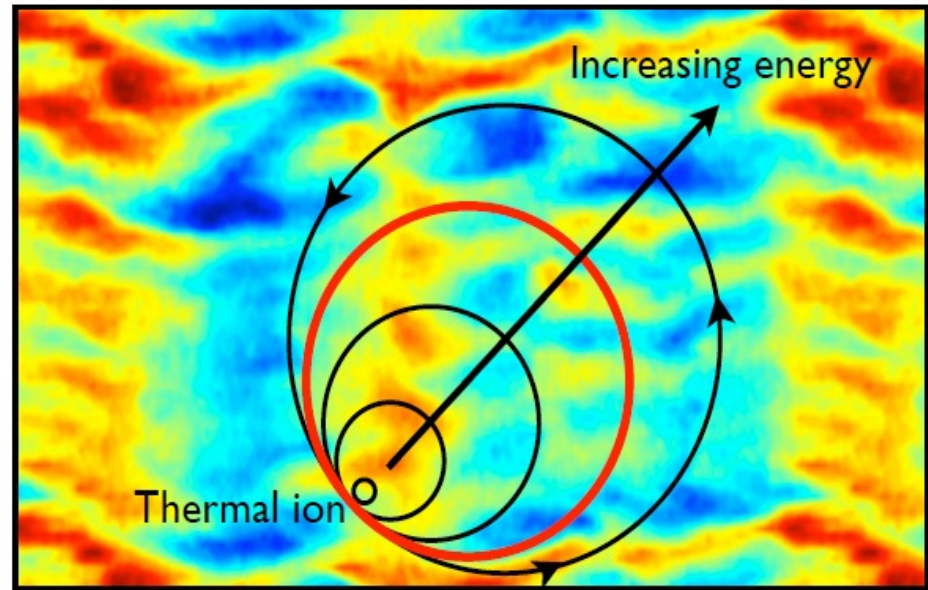
Turbulence could cause transport of fast ions, as for thermal plasma

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

M.Albergante

Gyro-averaging

10 ρ_s



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

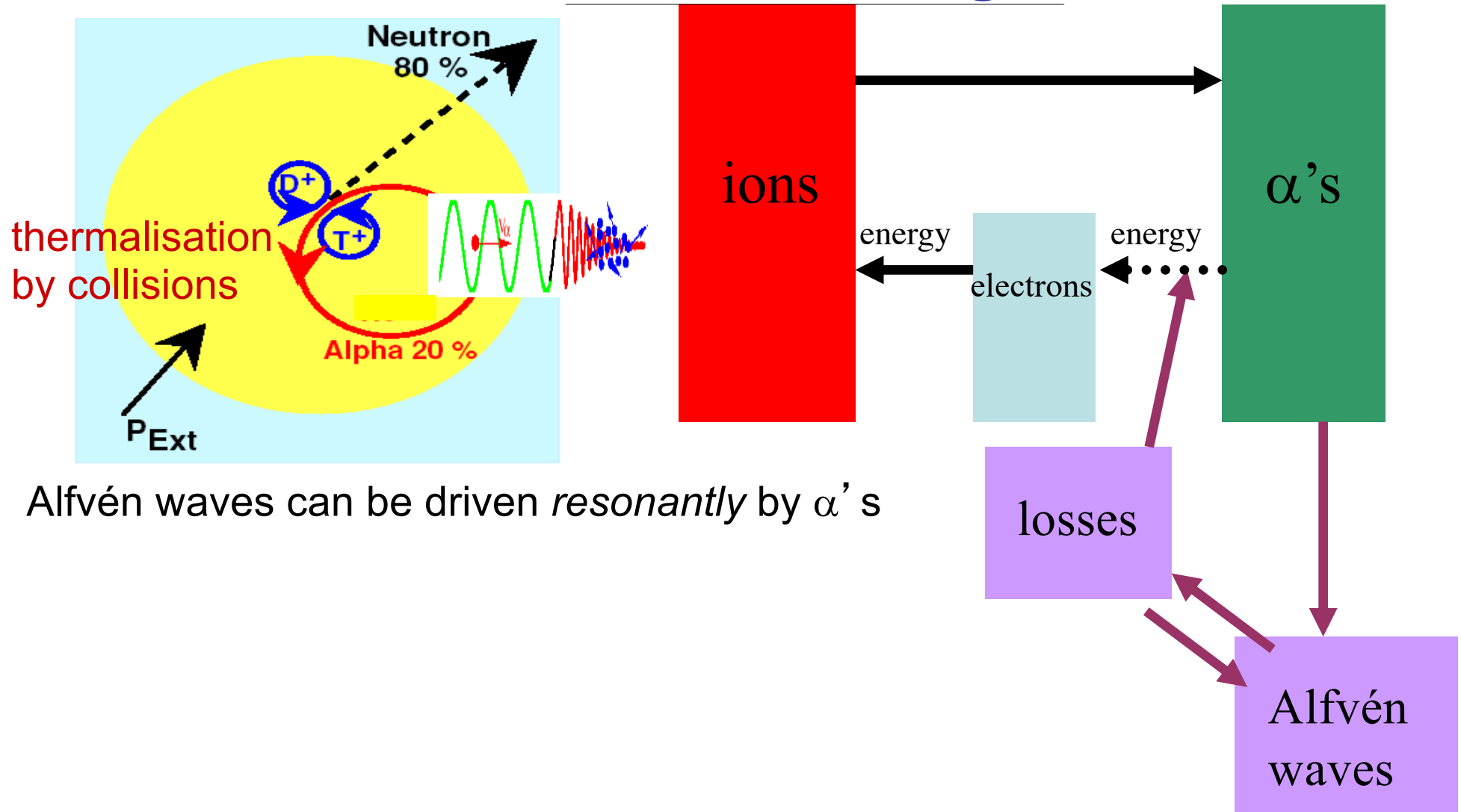
ITER (large $E_{\text{fast ions}}/T_{\text{plasma}}$):

negligible effect for NBI ions and for α 's

FAST ION LOSS MECHANISMS

INTERACTION WITH ALFVEN WAVES

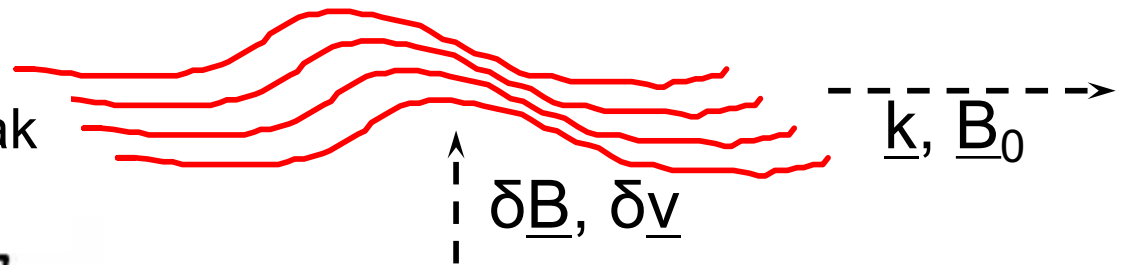
Resonant interaction with waves and self-heating



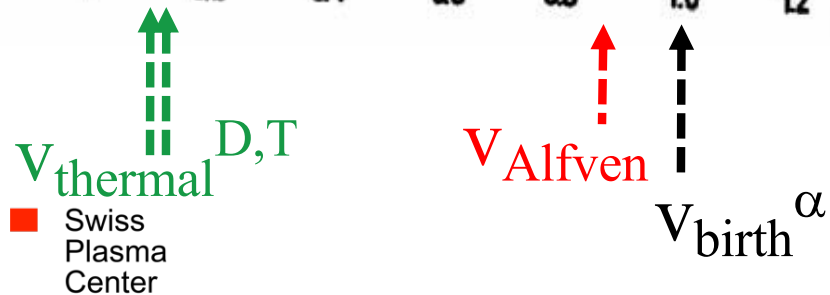
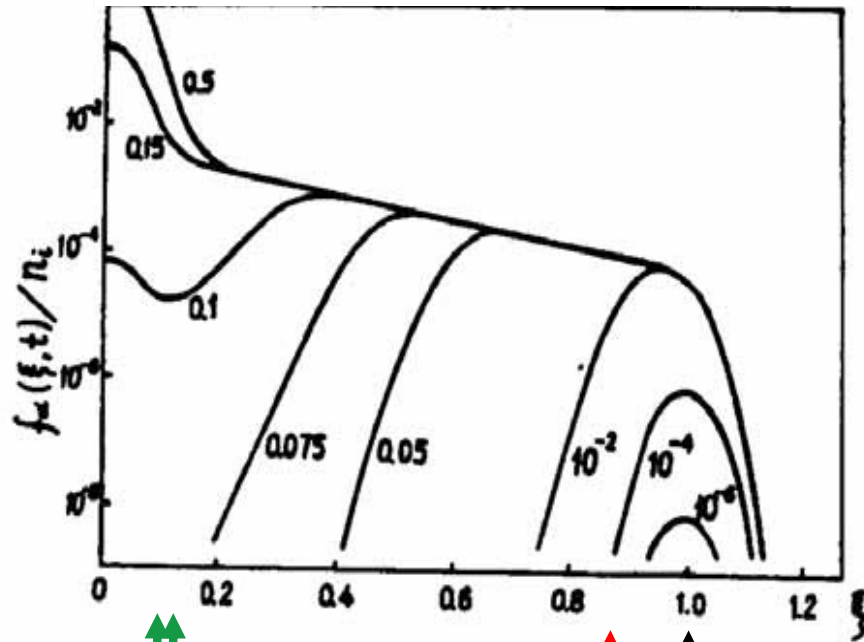
Fast ions and Alfvén waves

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

Typical velocities in a tokamak
 $B=4T$; $T=10keV$; $n=10^{20}m^{-3}$



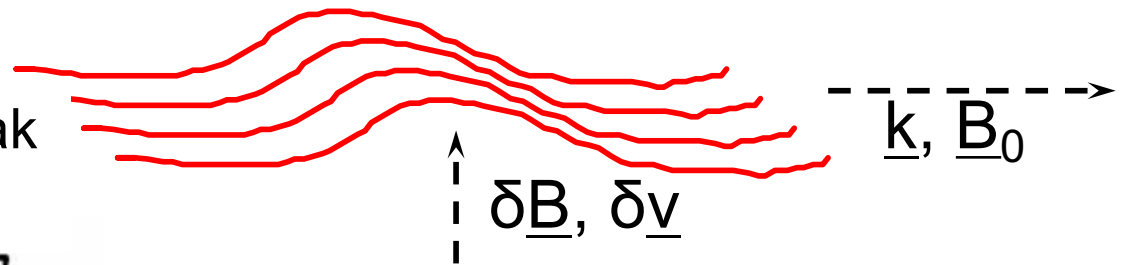
Slowing down α 's (but also fast ions generated by additional heating) can resonate with Alfvén Waves



Fast ions and Alfvén waves

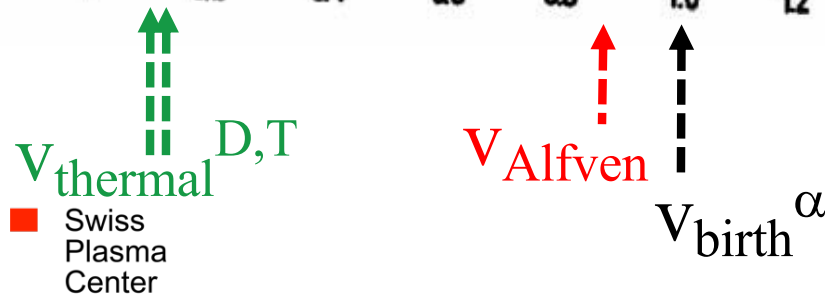
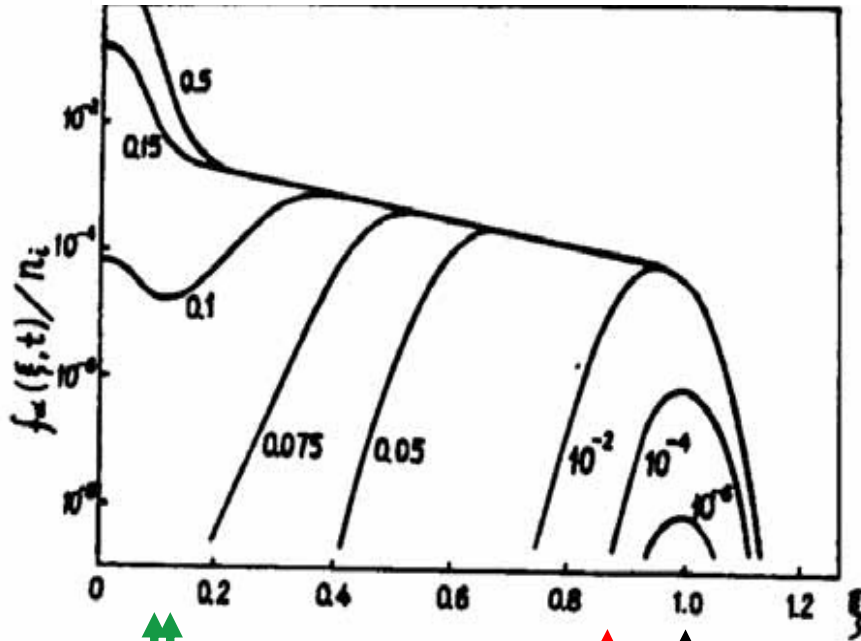
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Slowing down α 's (but also fast ions generated by additional heating) can resonate with Alfvén Waves

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

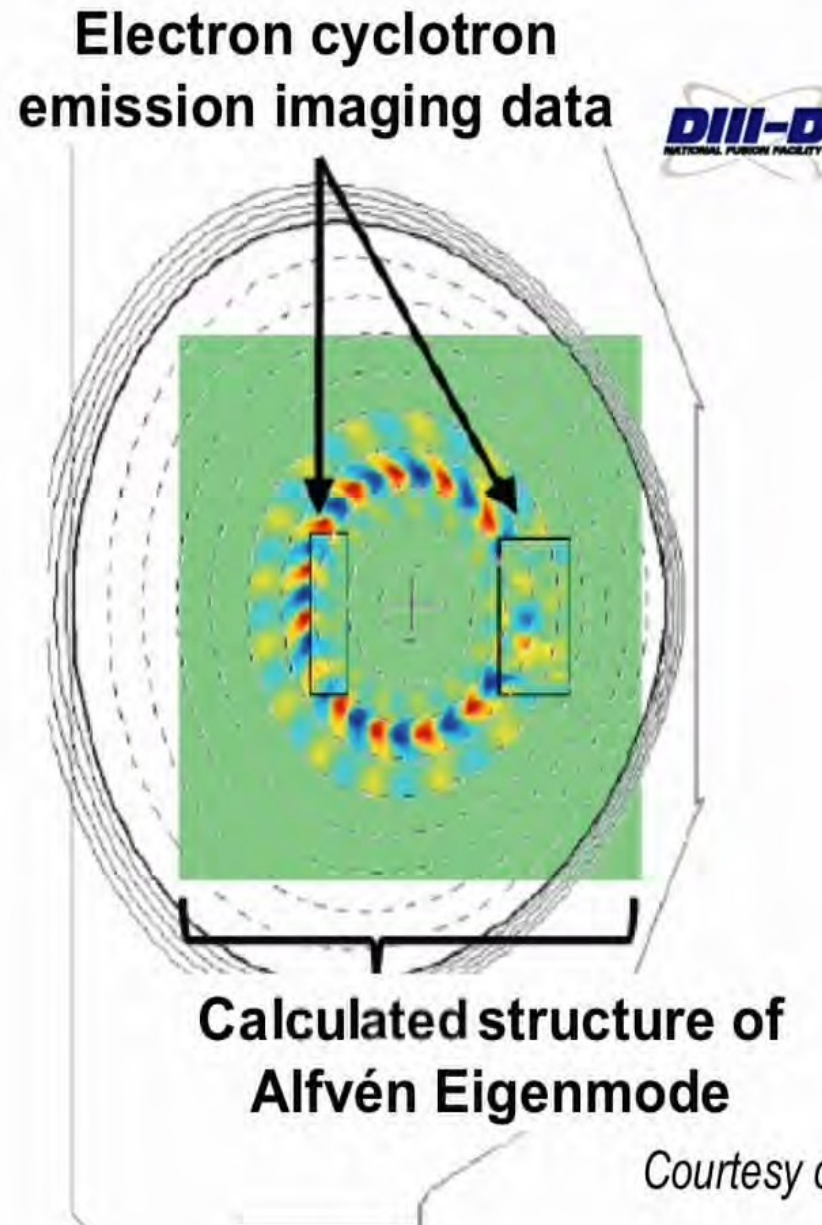


Alfvén waves in tokamaks

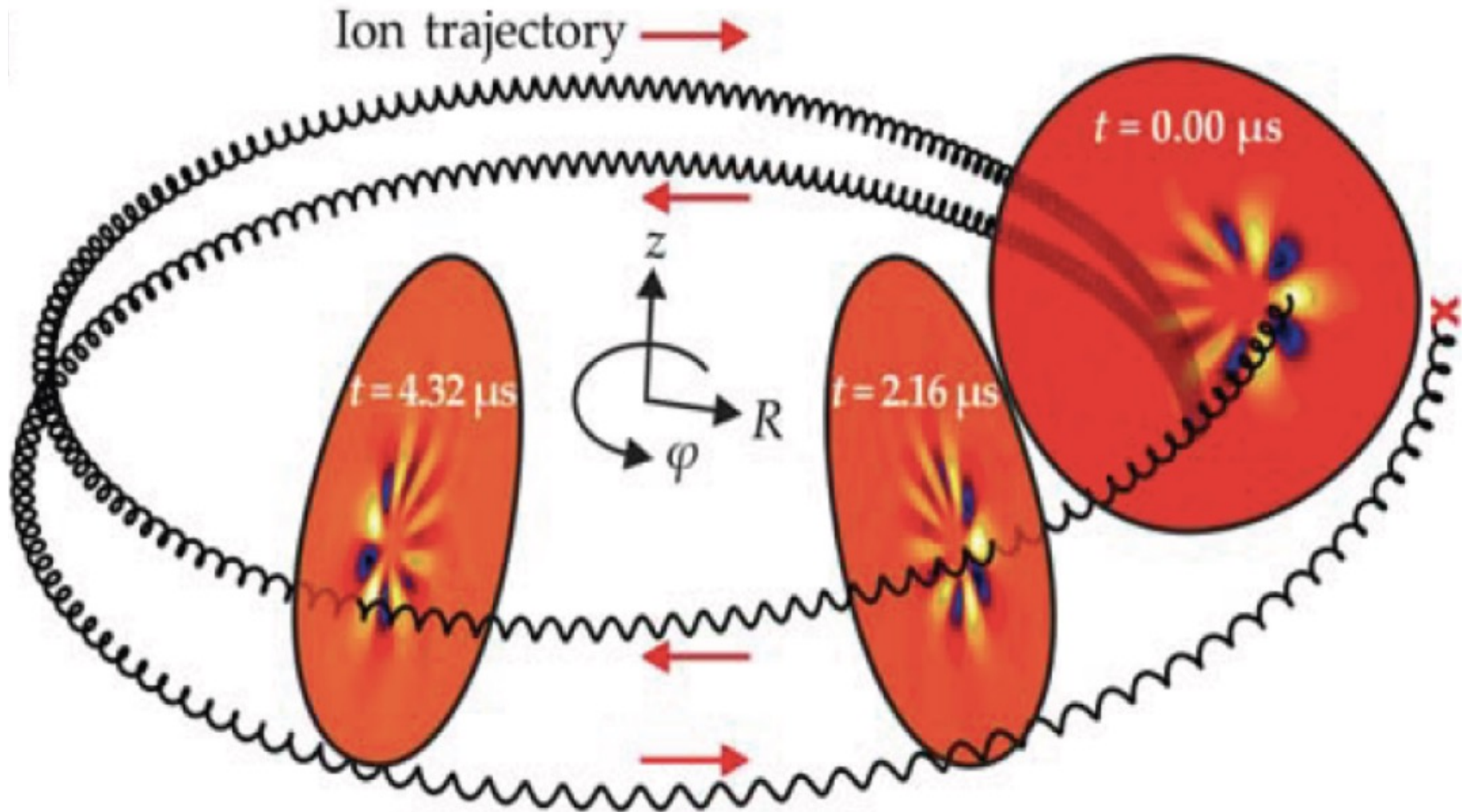
Alfvén Eigenmodes

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



AE resonance condition visualisation



EPFL Fast ions and the self-heating process

Effect of Alfvén Eigenmodes

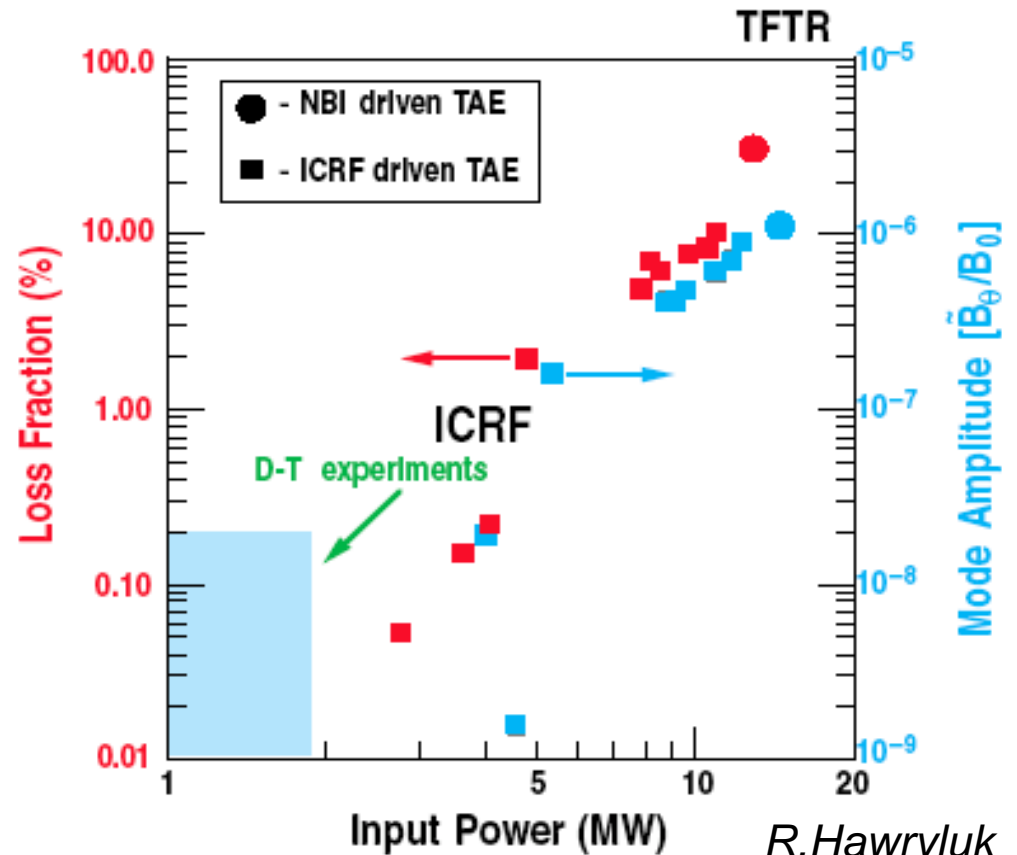
Losses and redistribution seen in many experiments

ITER / DEMO can withstand only a few % of α losses

Questions

Linear stability, balance between damping and drive

Nonlinear evolution and redistribution / losses

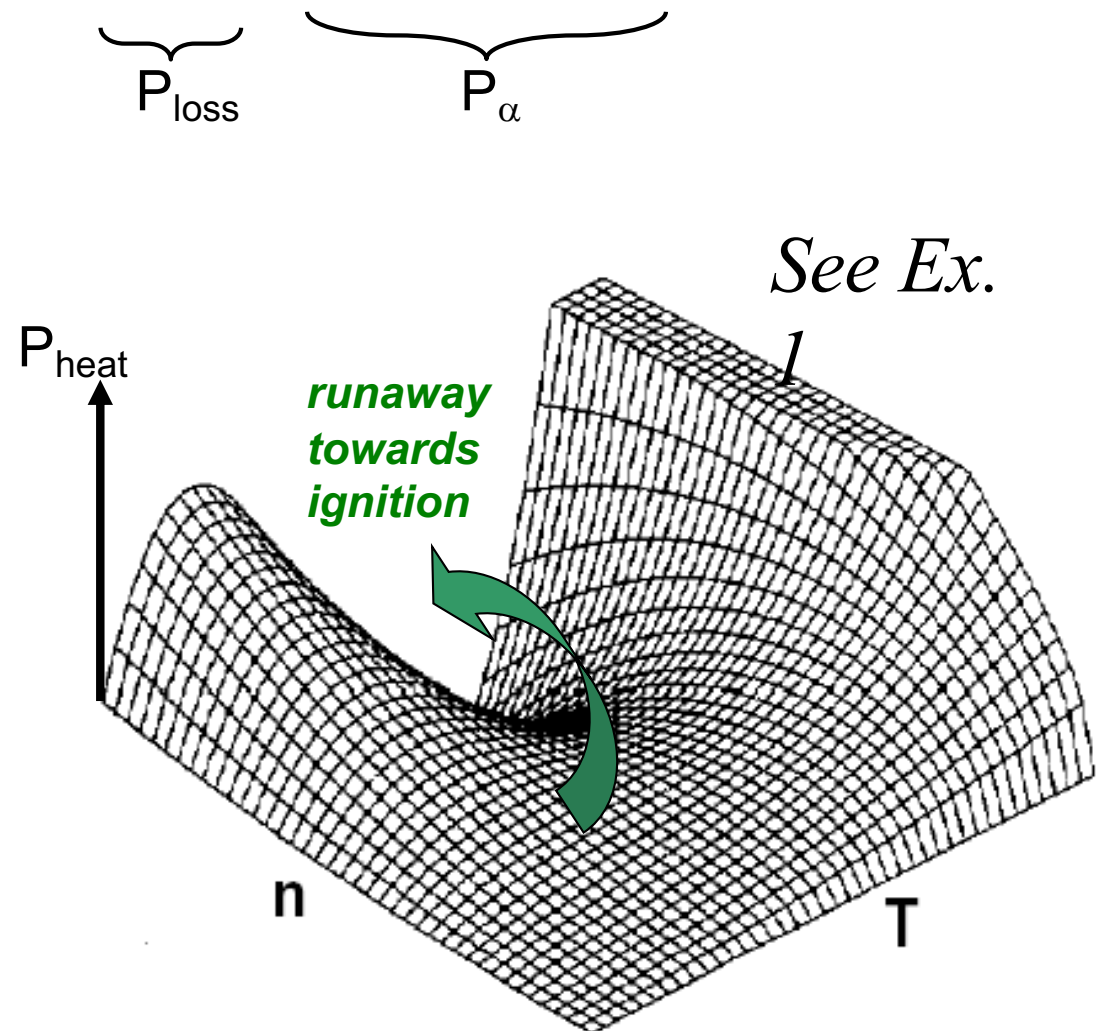
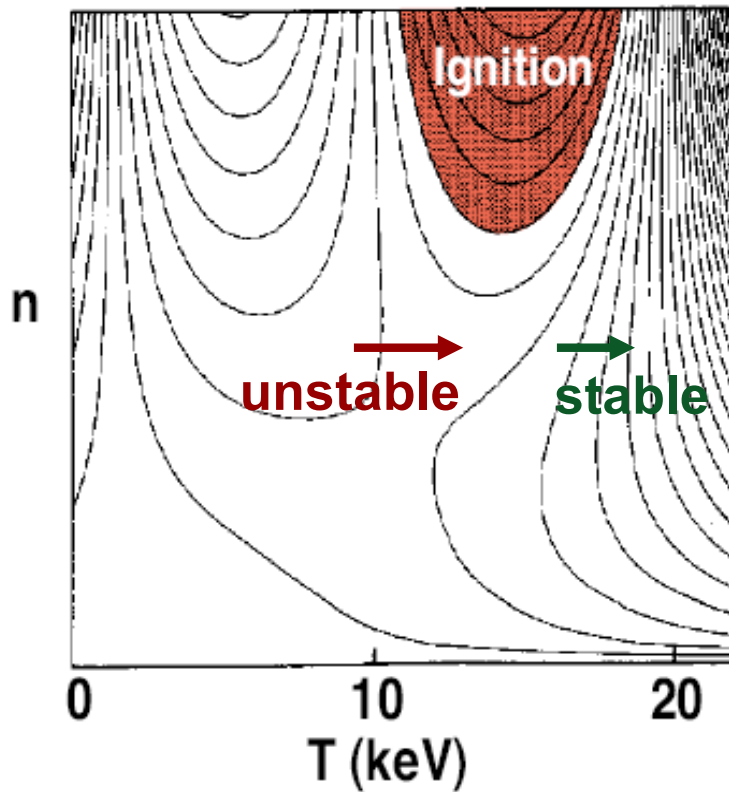


BURN STABILITY AND CONTROL

Burn thermal runaway

At high Q in principle thermal runaway can occur

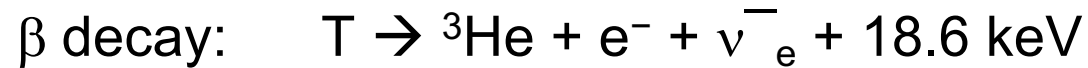
$$\text{Ex. of steady-state } P_{\text{in}}/V = \underbrace{3nT/\tau_E}_{P_{\text{loss}}} - \underbrace{1/4n^2\langle\sigma v\rangle E_\alpha}_{P_\alpha}$$



TRITIUM IN FUSION

Half life time: 12.3 years

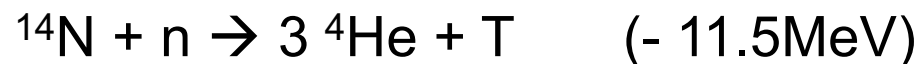
Decay mode



$$\text{Activity} = 3.6 \times 10^{14} \text{ Bq/g}$$

Tritium – natural inventory

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



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

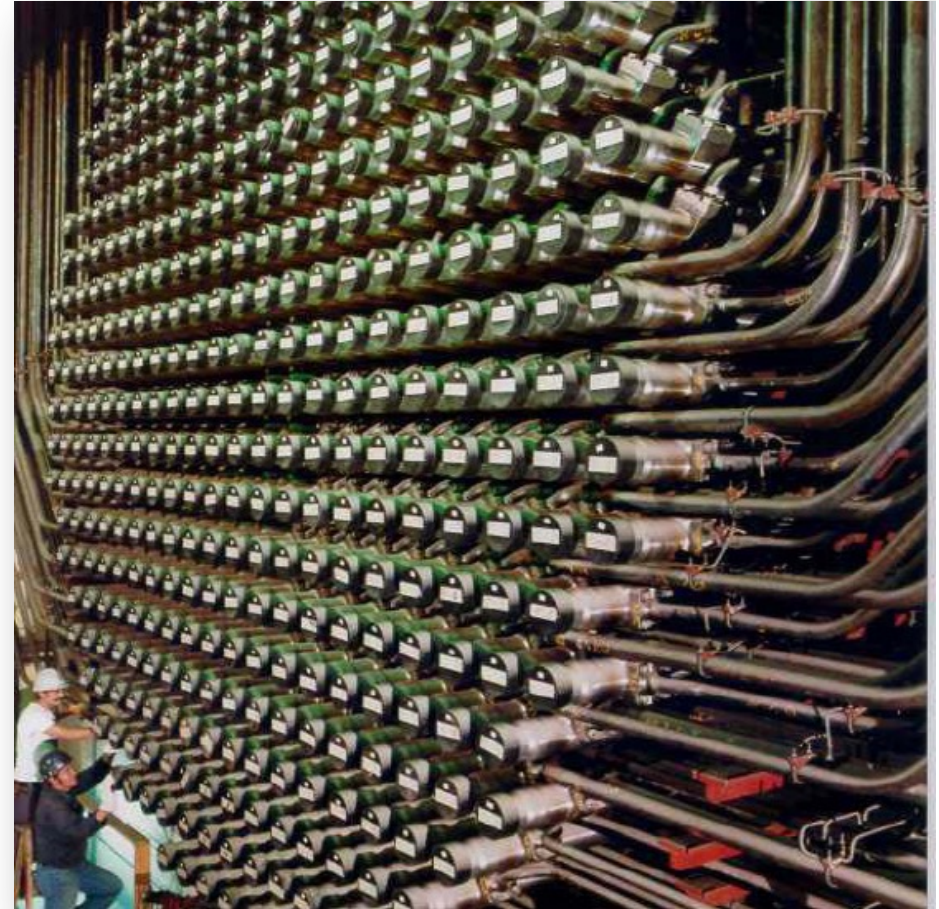
Tritium – anthropogenic inventory

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)

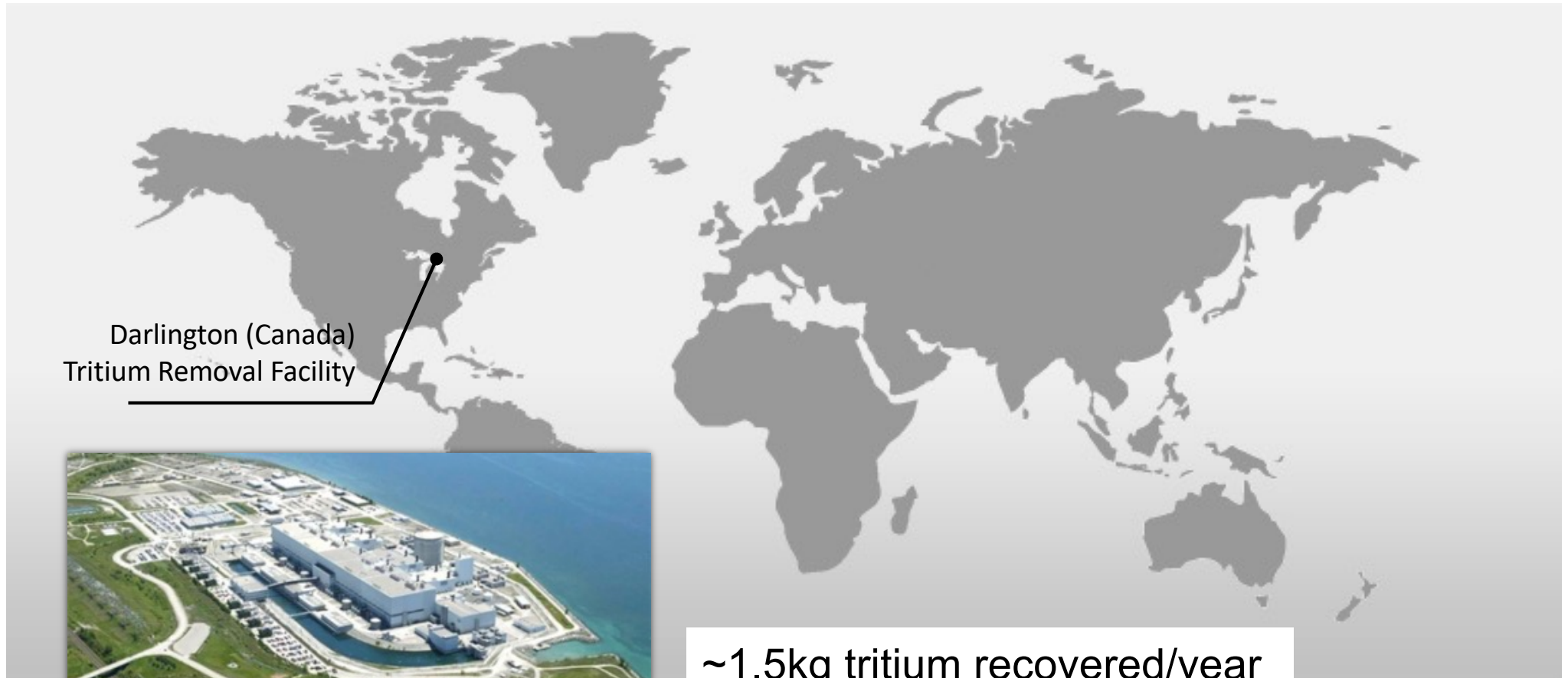
Total production
 $\sim 0.3\text{kg}/(\text{GWe} \cdot \text{year})$

Today 19kg at hands in
Darlington recover facility



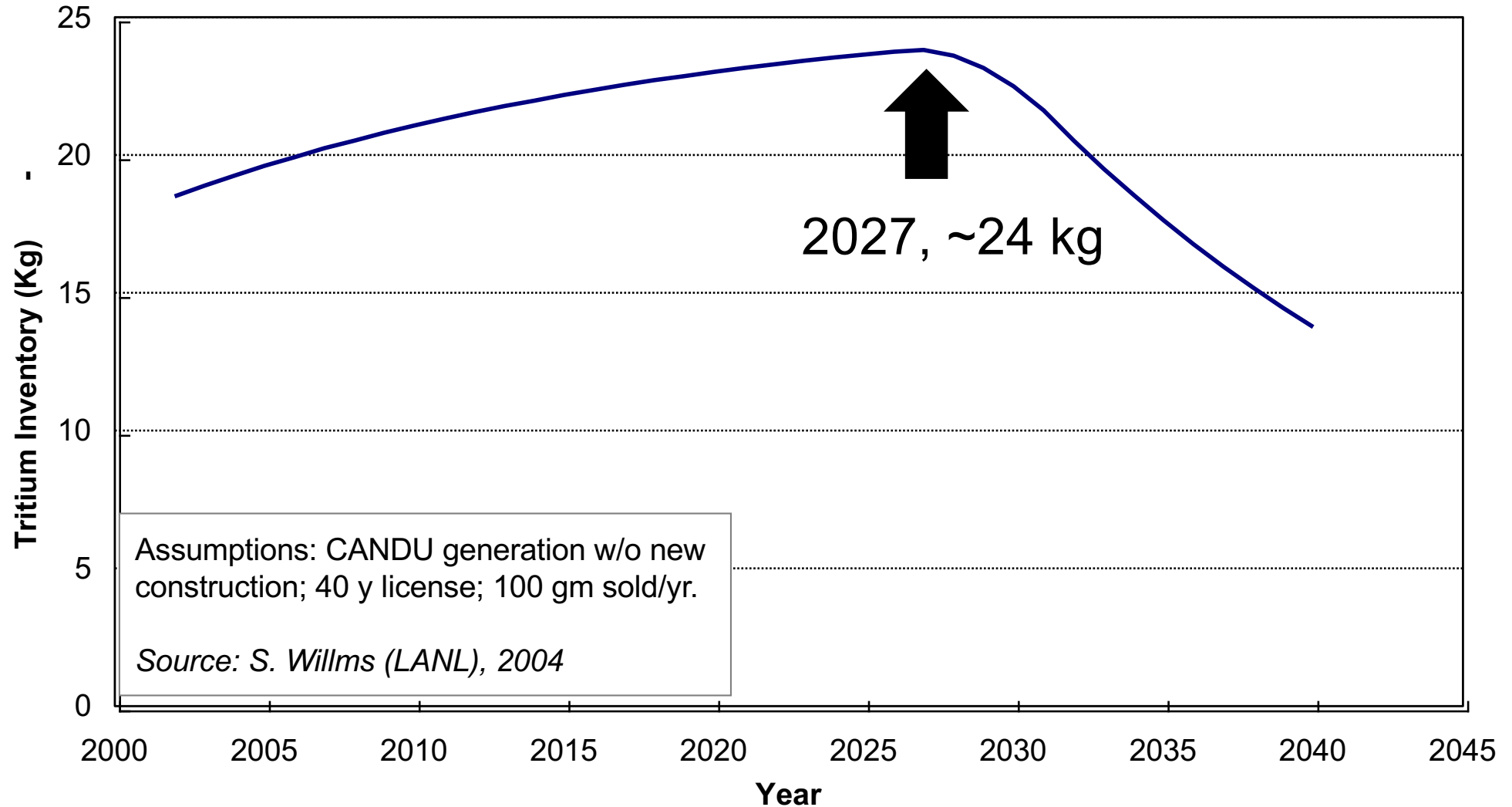
CANDU Pressurized Heavy Water Reactor

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



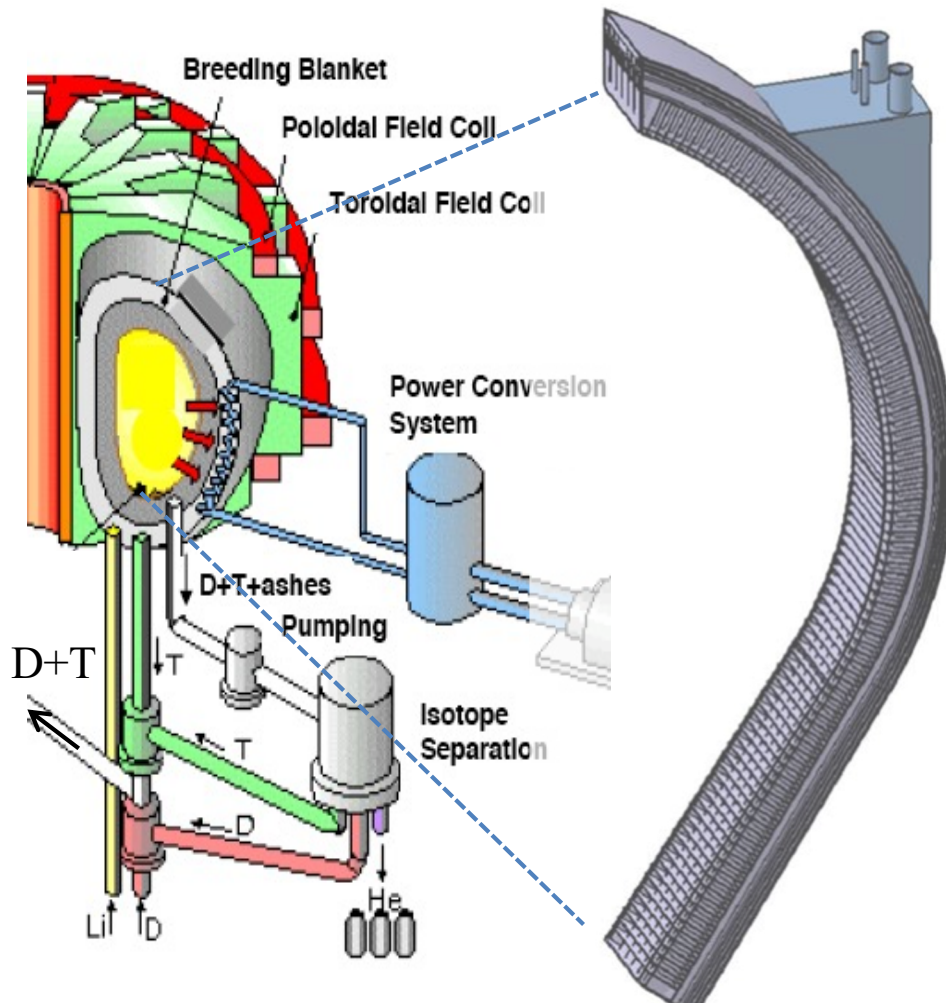
EPFL T availability is foreseen to decrease after 2027

Projection of tritium inventory available from CANDU (Canada)



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

Tritium breeding blanket



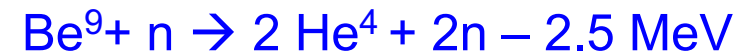
A fusion reactor must be T self sufficient



Tritium breeding ratio

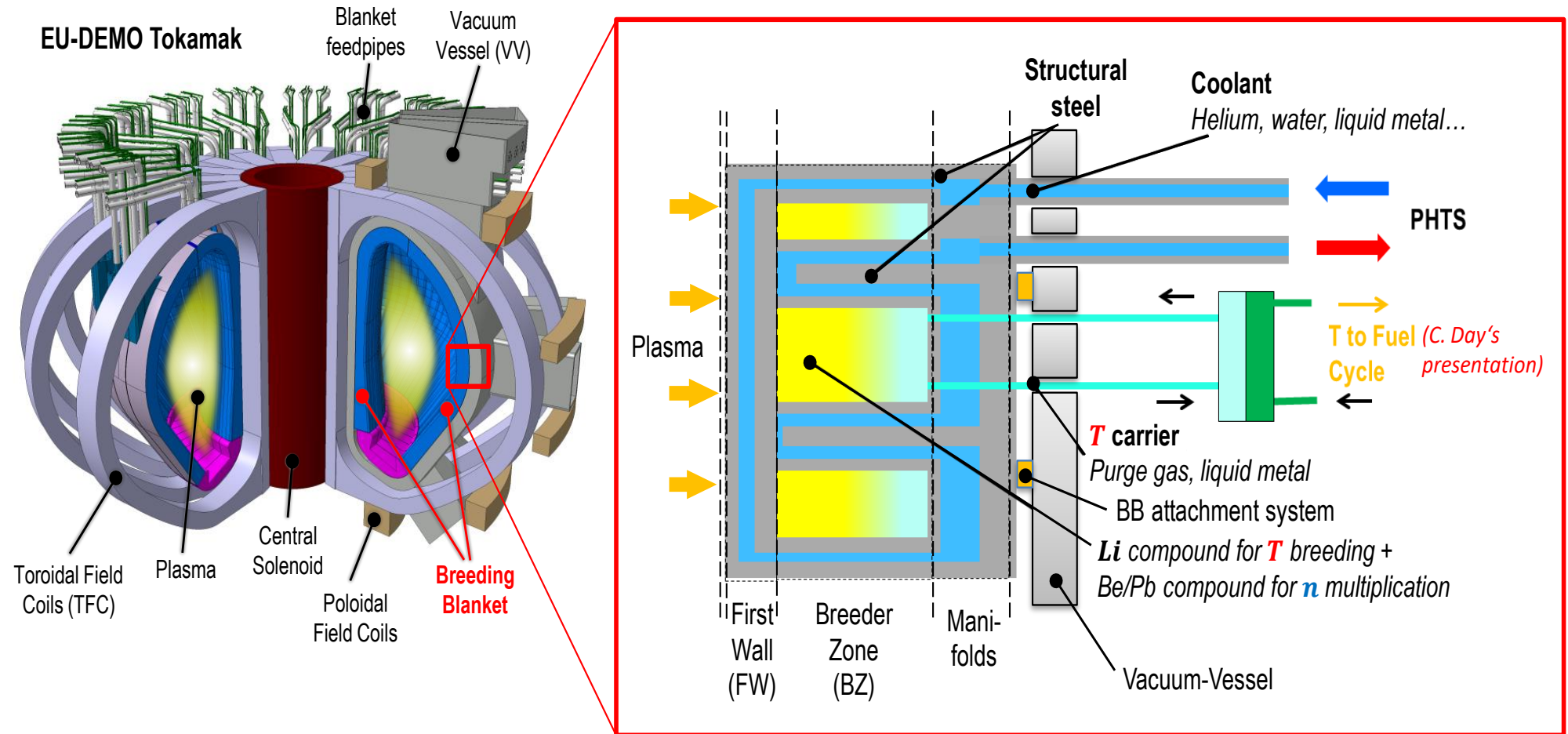
TBR = tritium bred / tritium burnt

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



Several concepts are studies, e.g. Be in Li pebbles, or Pb in the form of LiPb coolant

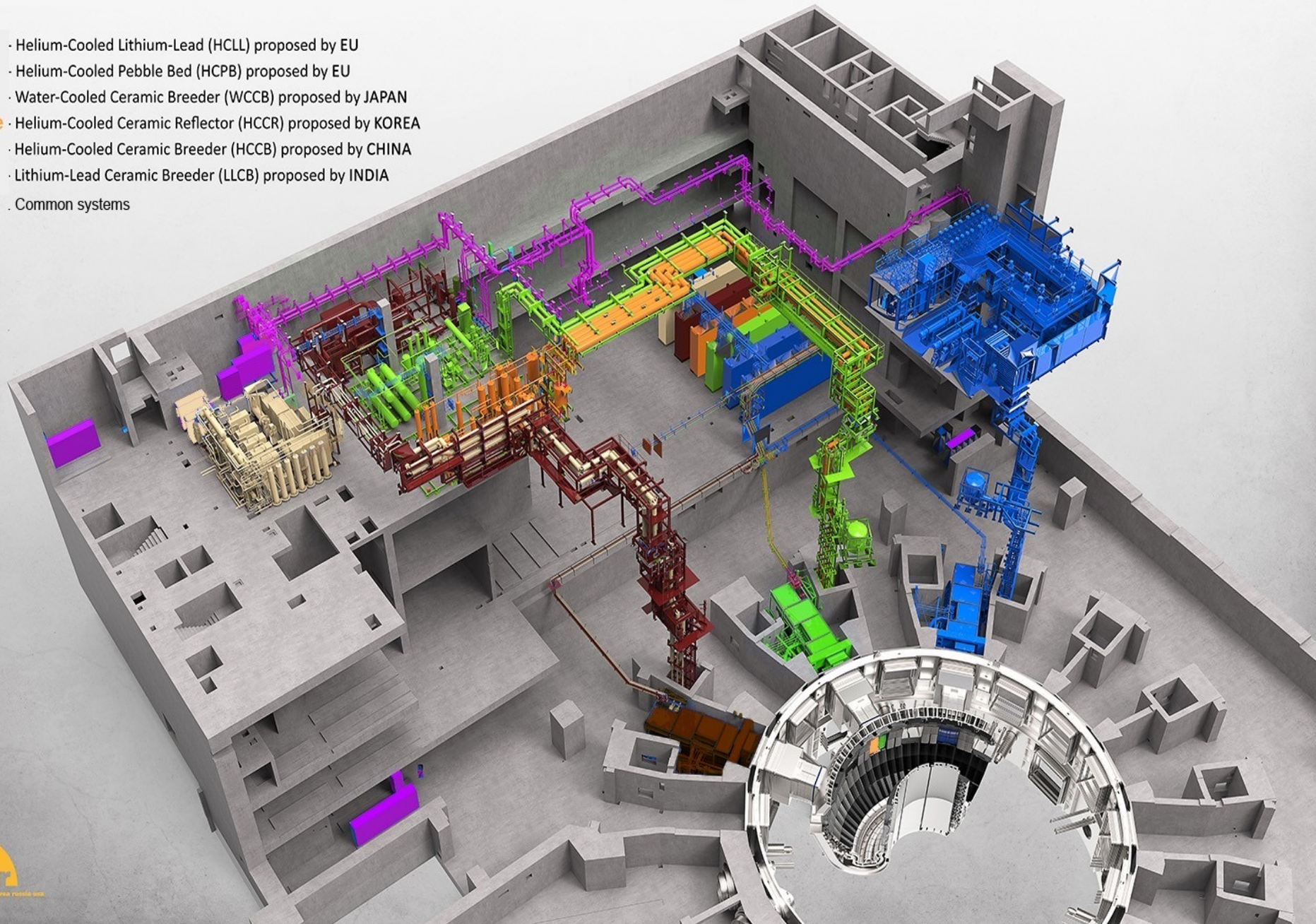
EPFL Breeding blanket – system and functions



F.A. Hernández et al. | BB Functions, Concepts and Associated Issues | Fusion/Fission Workshop, VC | 06.12.2023 | Page 4

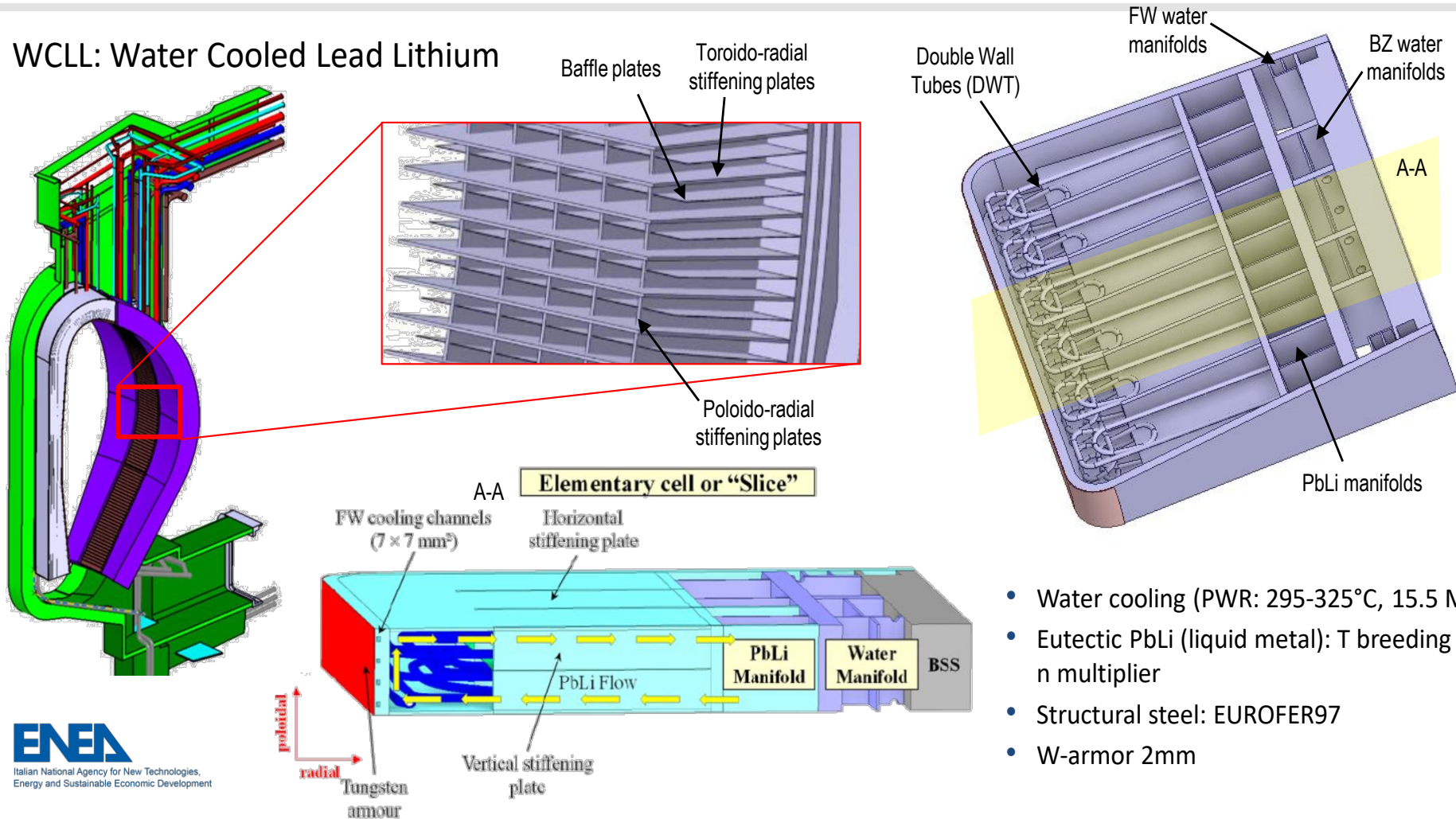
Test breeding blankets in ITER

- Blue** · Helium-Cooled Lithium-Lead (HCLL) proposed by EU
- Blue** · Helium-Cooled Pebble Bed (HCPB) proposed by EU
- Green** · Water-Cooled Ceramic Breeder (WCCB) proposed by JAPAN
- Orange** · Helium-Cooled Ceramic Reflector (HCCR) proposed by KOREA
- Brown** · Helium-Cooled Ceramic Breeder (HCCB) proposed by CHINA
- Ivory** · Lithium-Lead Ceramic Breeder (LLCB) proposed by INDIA
- Violet** · Common systems



EPFL Ex. of BB concept for DEMO - WCLL

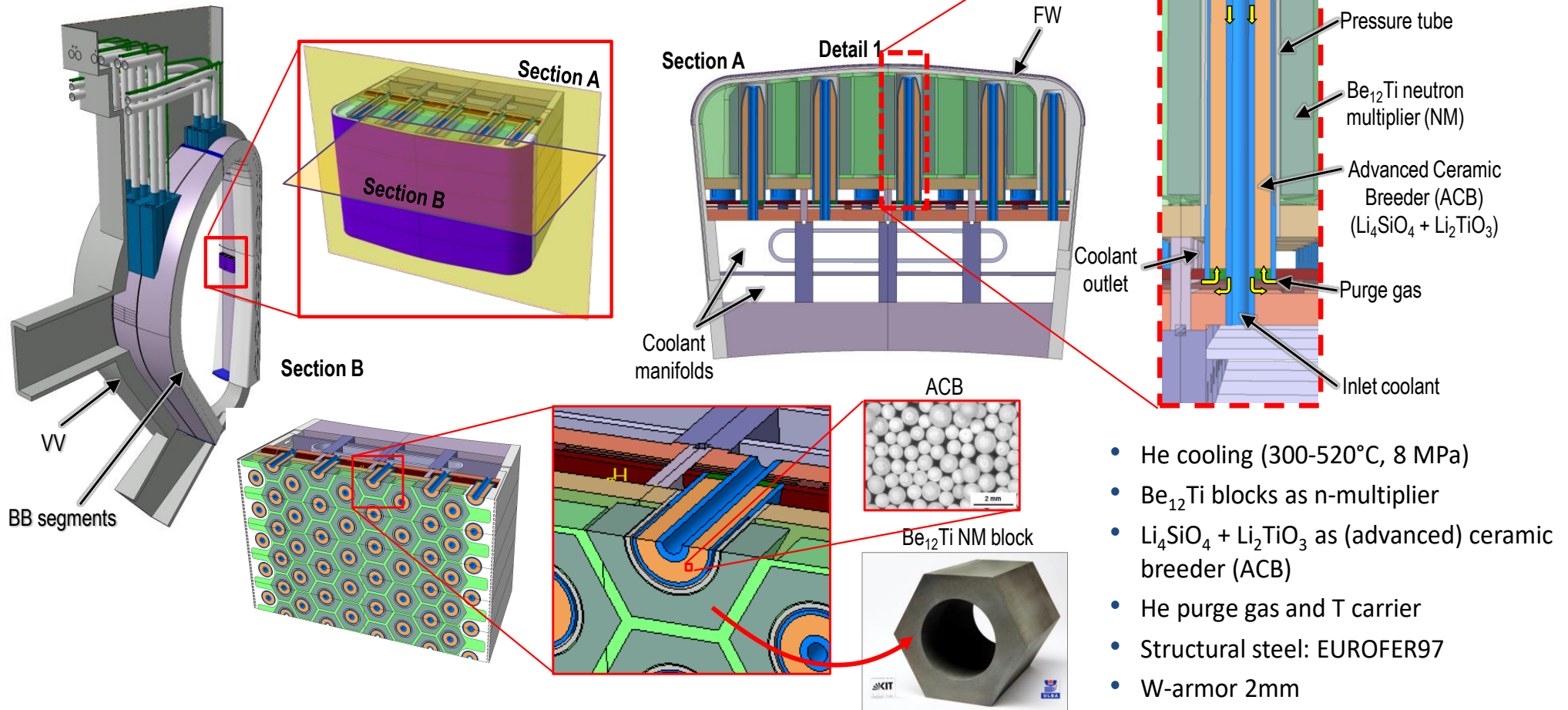
WCLL: Water Cooled Lead Lithium



- Water cooling (PWR: 295-325°C, 15.5 MPa)
- Eutectic PbLi (liquid metal): T breeding and n multiplier
- Structural steel: EUROFER97
- W-armor 2mm

EPFL Ex. of BB concept for DEMO - HCPB

■ HCPB: Helium Cooled Pebble Bed concept



EPFL 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**

EXAMPLE

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**

EXAMPLE

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)*

EXAMPLE

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**

EXAMPLE

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**

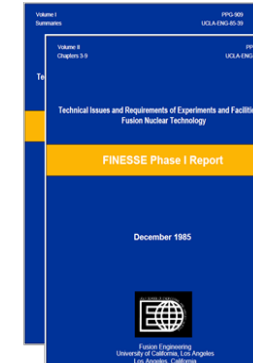
EXAMPLE

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**

EXAMPLE

- 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.

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

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

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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 $R \ll 1$

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

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

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 $R \ll 1$

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

EPFL Tritium inventory in fusion reactor

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

$$dM/dt \sim 56 \times \text{fusion power kg/y/GW}_{\text{thermal}}$$

$$\text{Ex. } 1\text{GW}_e \rightarrow \sim 3\text{GW}_{\text{thermal}} \rightarrow \sim 160\text{kg/y}$$

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 ($= \ln 2 / 12.3 \text{ y}^{-1}$); 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

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

$\underbrace{\hspace{10em}}_{\text{burnt}}$

$\underbrace{\hspace{15em}}_{\text{bred}}$

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

EPFL 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 $TBR \sim 1$

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

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

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

EPFL 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

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

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

$$\frac{dm}{dt} = -\gamma_s m + \underbrace{\left[\frac{\eta_f f_B}{t_p} (TBR - 1) - \gamma_s - \gamma_r \right]}_A M_0 = -\gamma_s m + AM_0$$

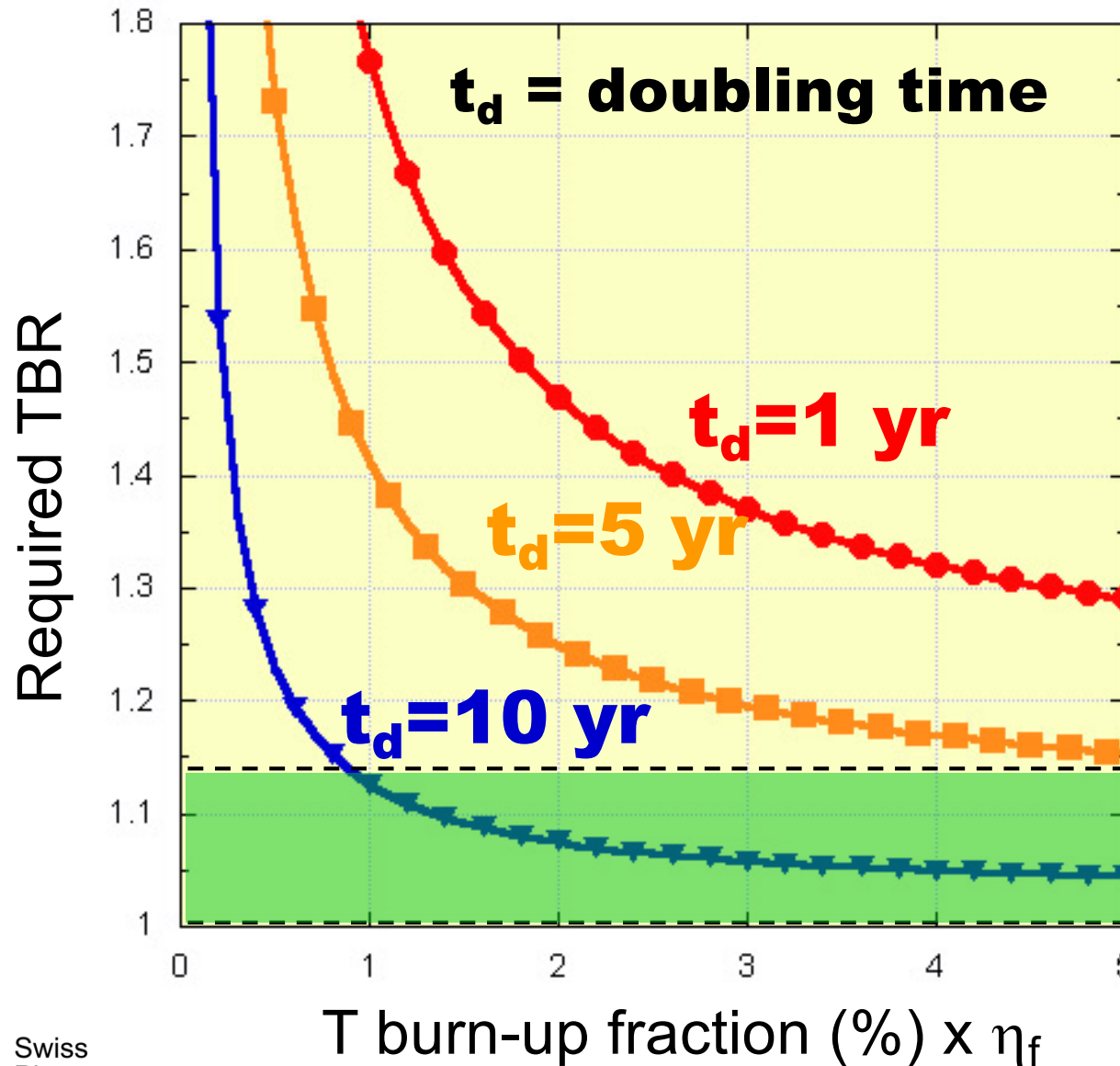
Which gives

$$m(t) = \frac{AM_0}{\gamma_s} (1 - e^{-\gamma_s t})$$

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

EPFL 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 $\sim 1.5 \text{ GW}$
Waste removal efficiency ~ 0.9
(from Prof. Abdou, UCLA)

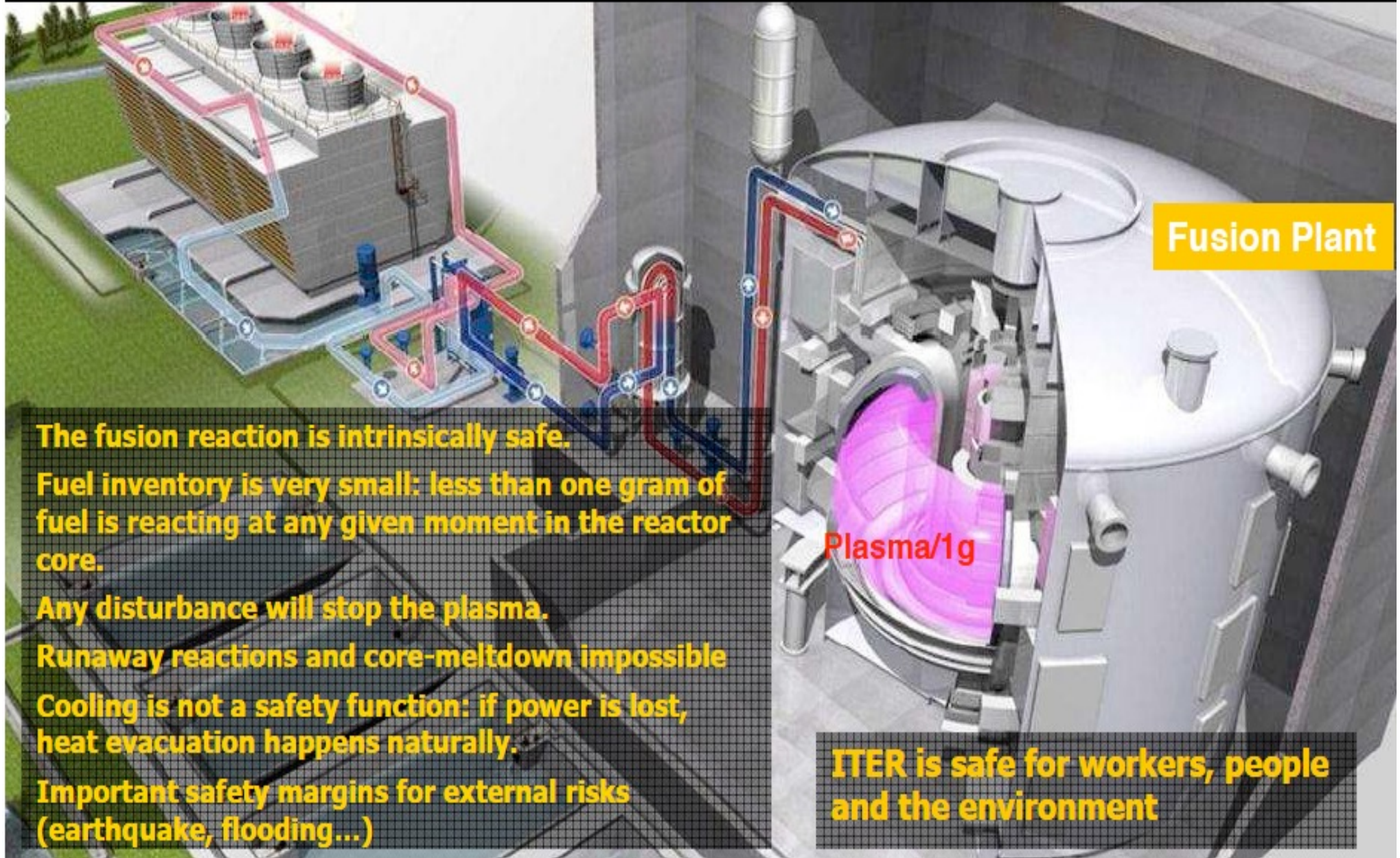
Max TBR ≤ 1.15

“Window” for Tritium self sufficiency

Significant R&D needed to stay in window

ITER SAFETY AND LICENSING

A Fukushima-like accident is impossible in ITER



Temperature in case of loss of cooling

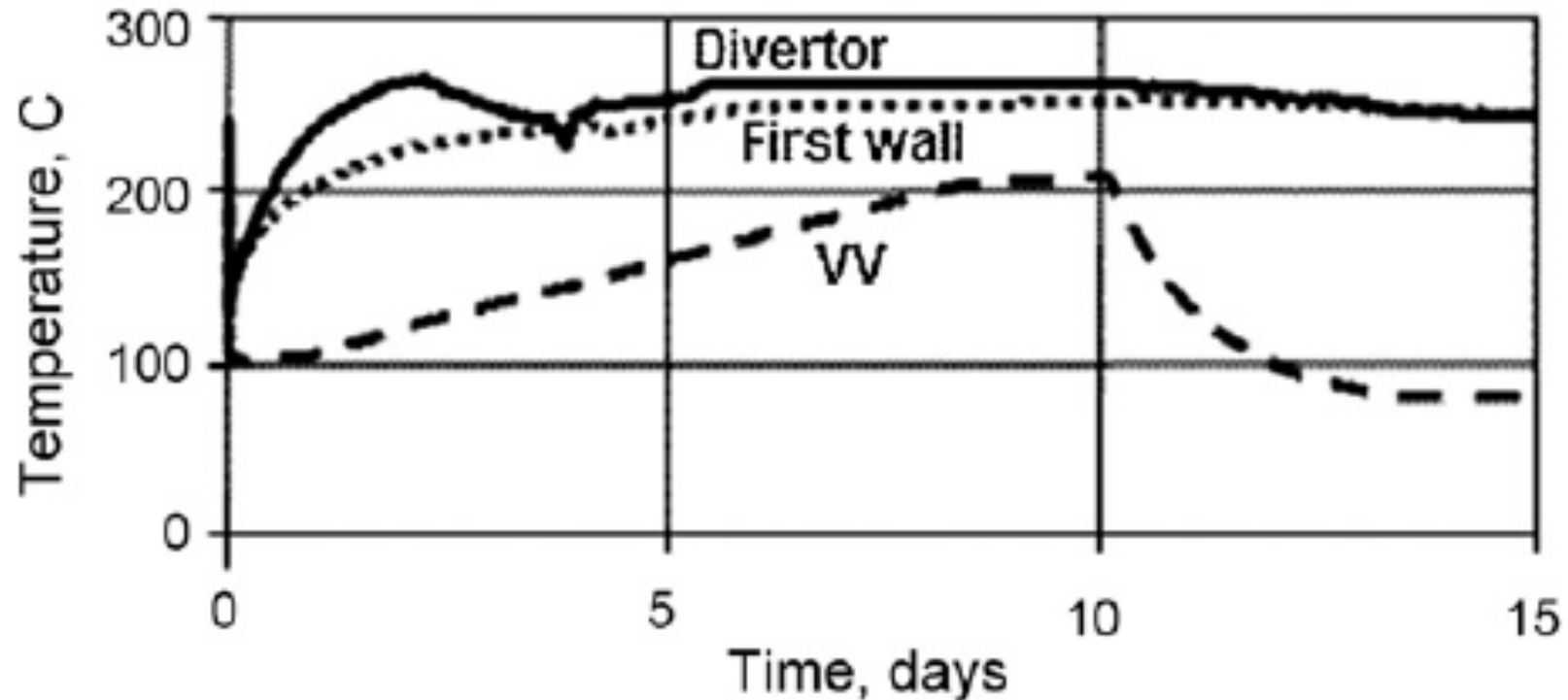


Fig. 1. Temperature evolution of divertor, first wall and vacuum vessel in event of loss of all water coolant flow, with cryostat vented to air after 10 days.

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.**

TOWARD A FUSION POWER PLANT

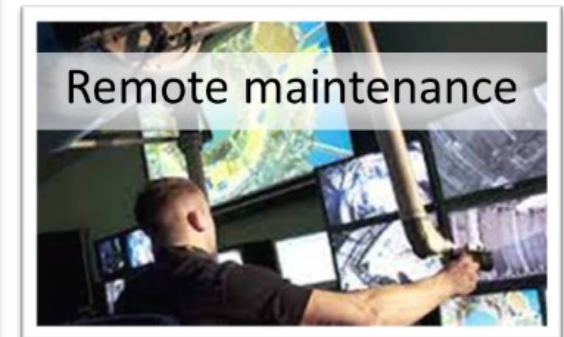
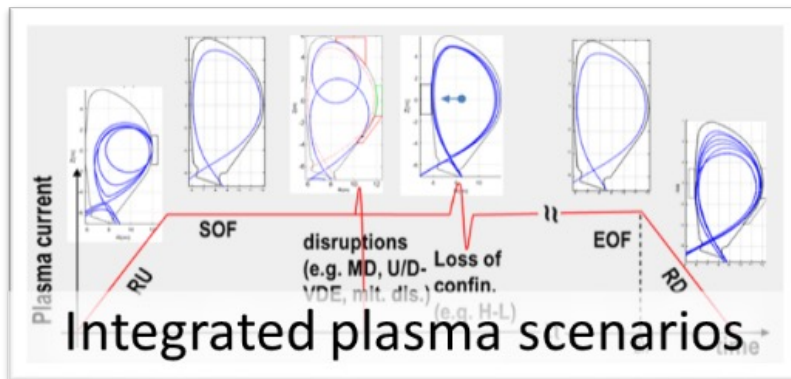
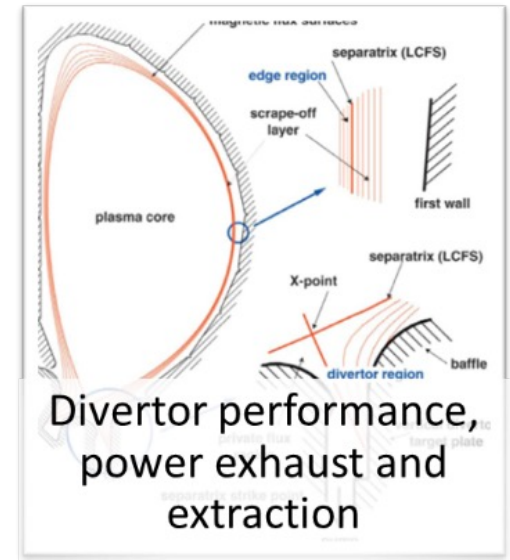
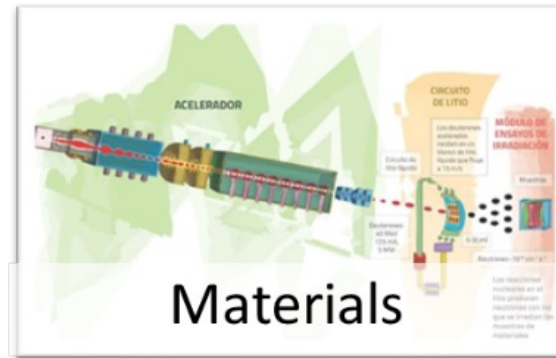
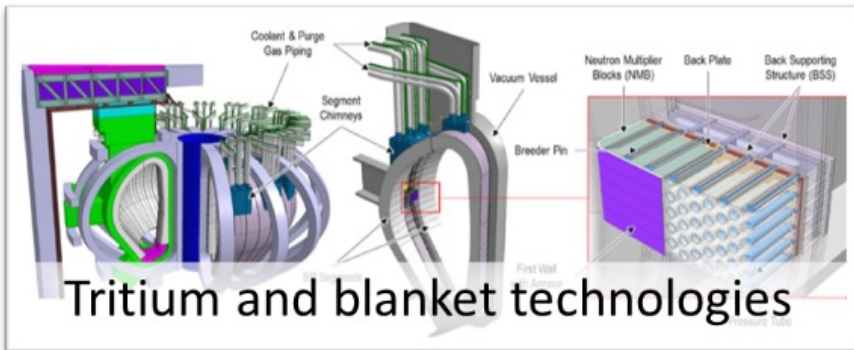
EPFL European DEMO conceptual design

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...

EPFL Remaining open gaps towards DEMO



EPFL The European Roadmap to fusion

