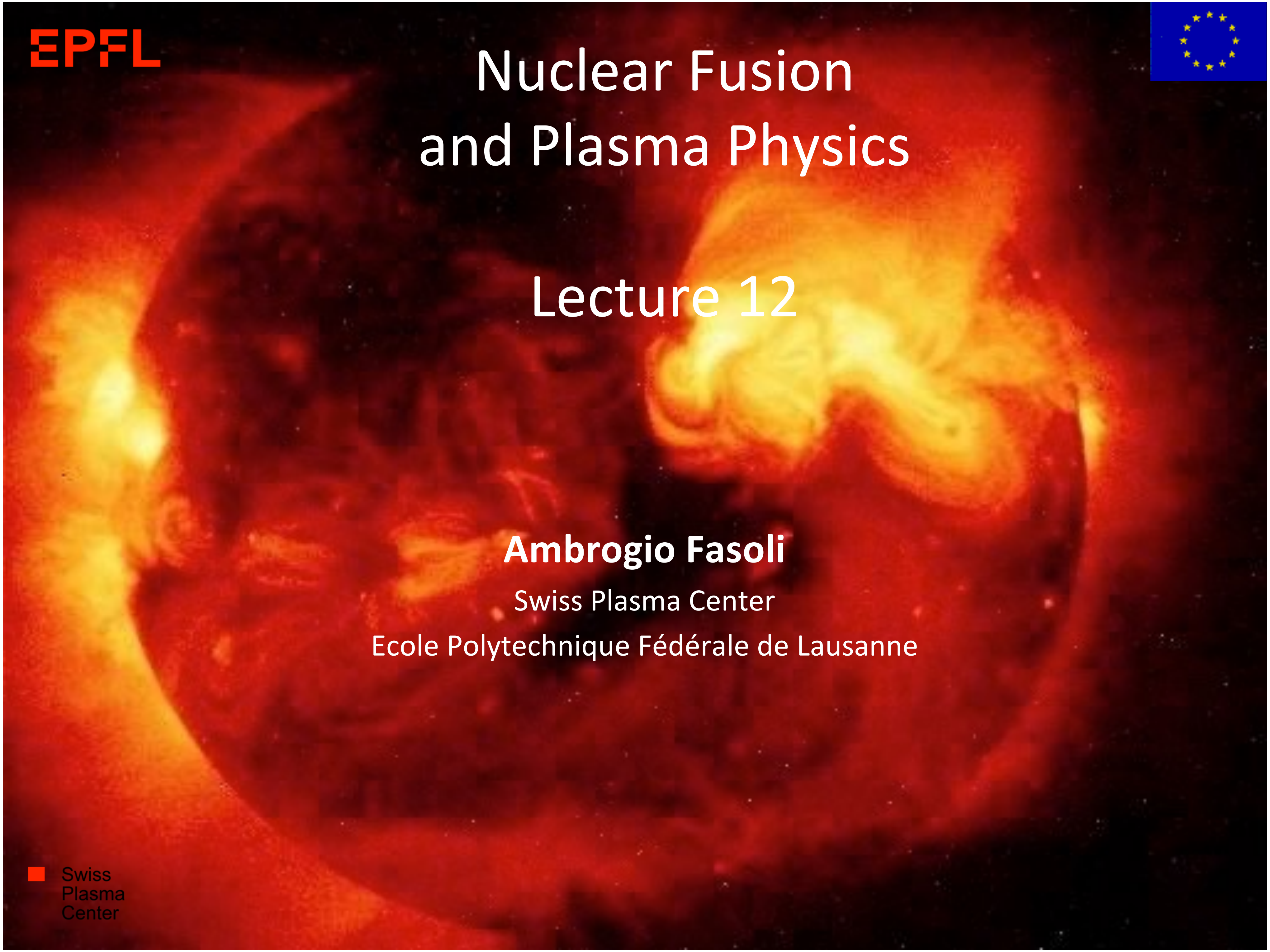


EPFL

Nuclear Fusion and Plasma Physics

Lecture 12

Ambrogio Fasoli

Swiss Plasma Center
Ecole Polytechnique Fédérale de Lausanne

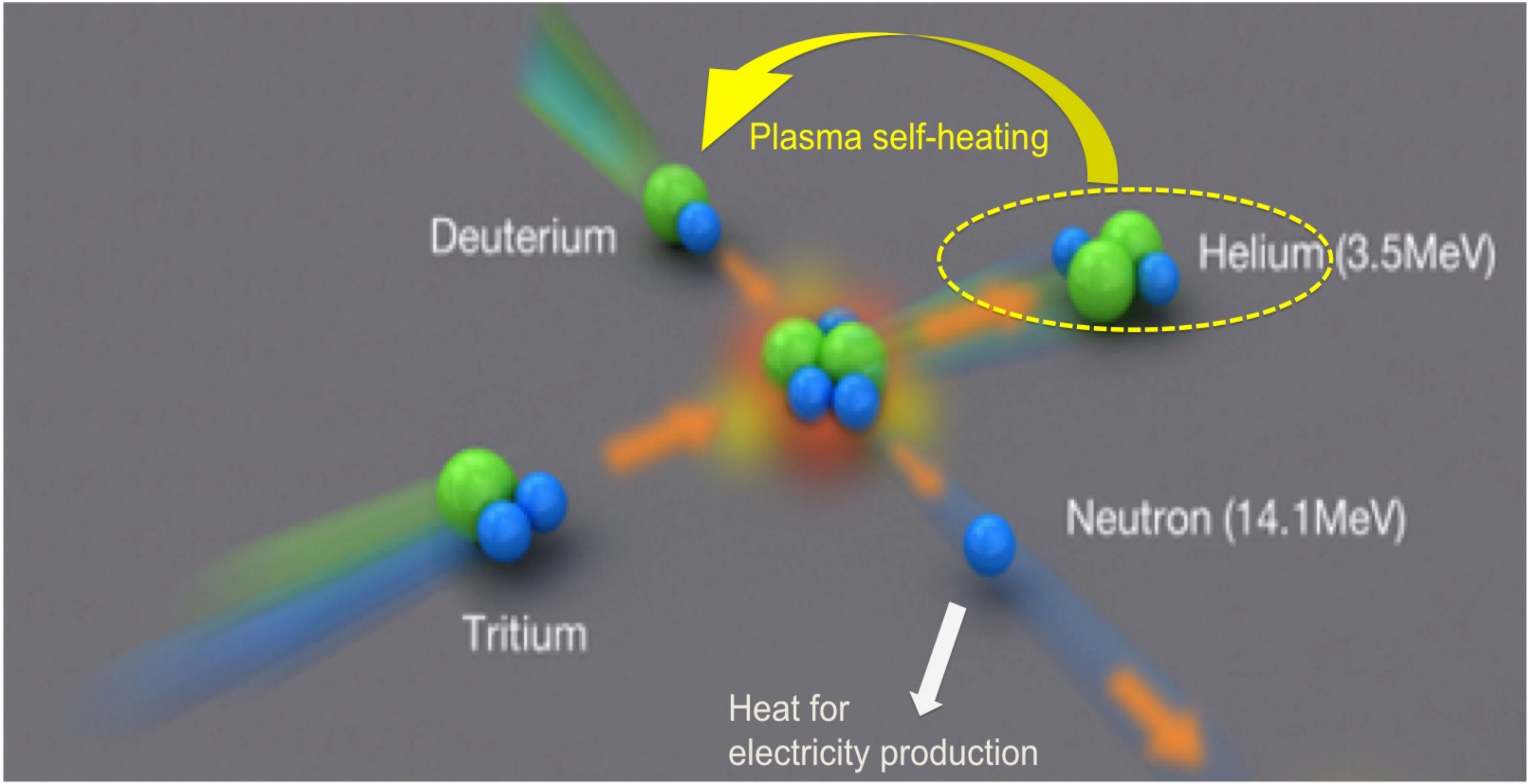
Swiss
Plasma
Center

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

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

Thermal energy density $W \equiv 3nT$

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

Definition of a burning plasma

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

Thermal energy density $W \equiv 3nT$

Energy balance

confinement time

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

α-heating *ext. heating* *losses*

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

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

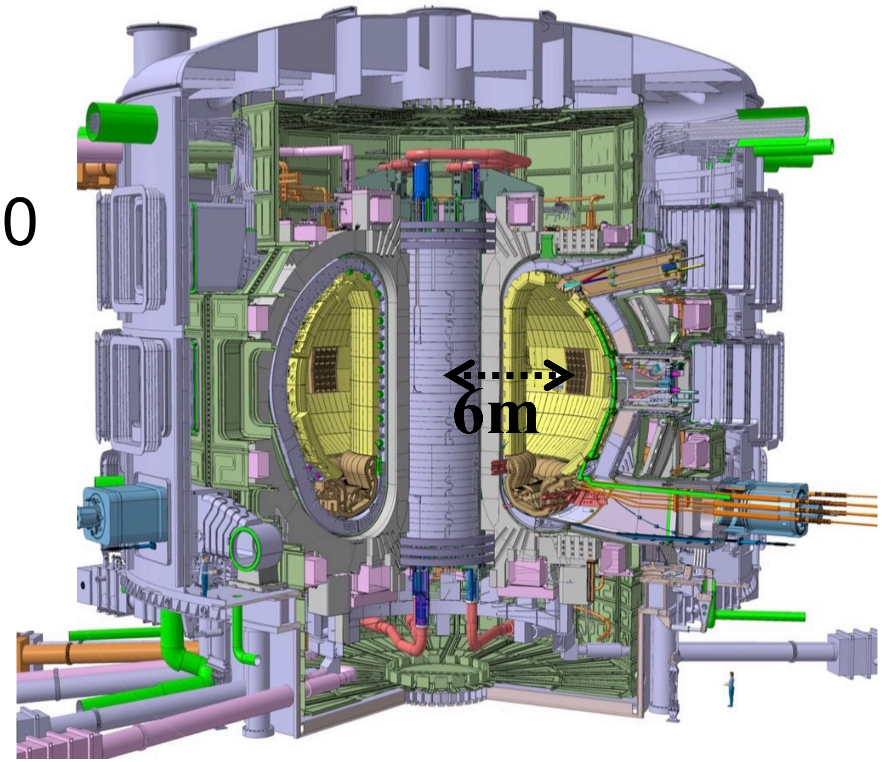
$Q<0.7$	$f_\alpha<12\%$ *present experiments*
$Q=1$	$f_\alpha=17\%$ *breakeven*
$Q=5$	$f_\alpha=50\%$
$Q=10$	$f_\alpha=67\%$
$Q=\infty$	$f_\alpha=100\%$ *ignition*

burning plasma

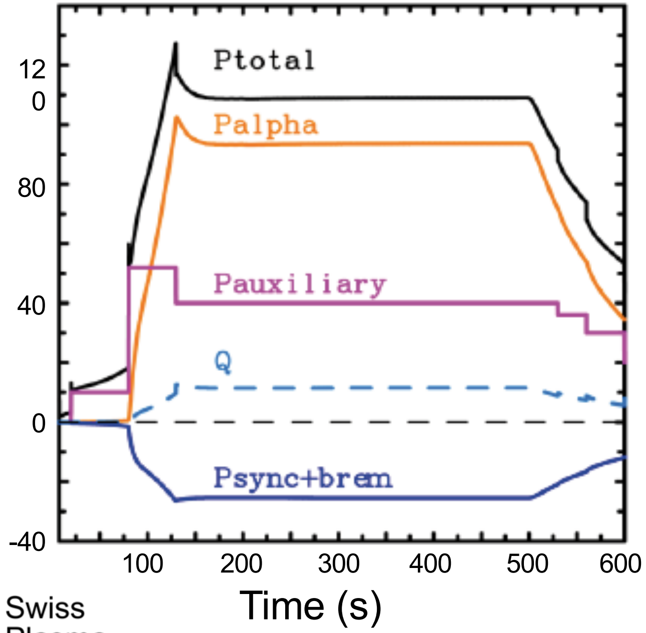
The first burning plasma: ITER

Q ≥ 10; $P_{fusion} \geq$ 500MW; ~500s
Explore steady-state Q ≥5, ≤3000s
May explore ‘controlled ignition’ Q≥30

→ burning plasma



Y.Gribov



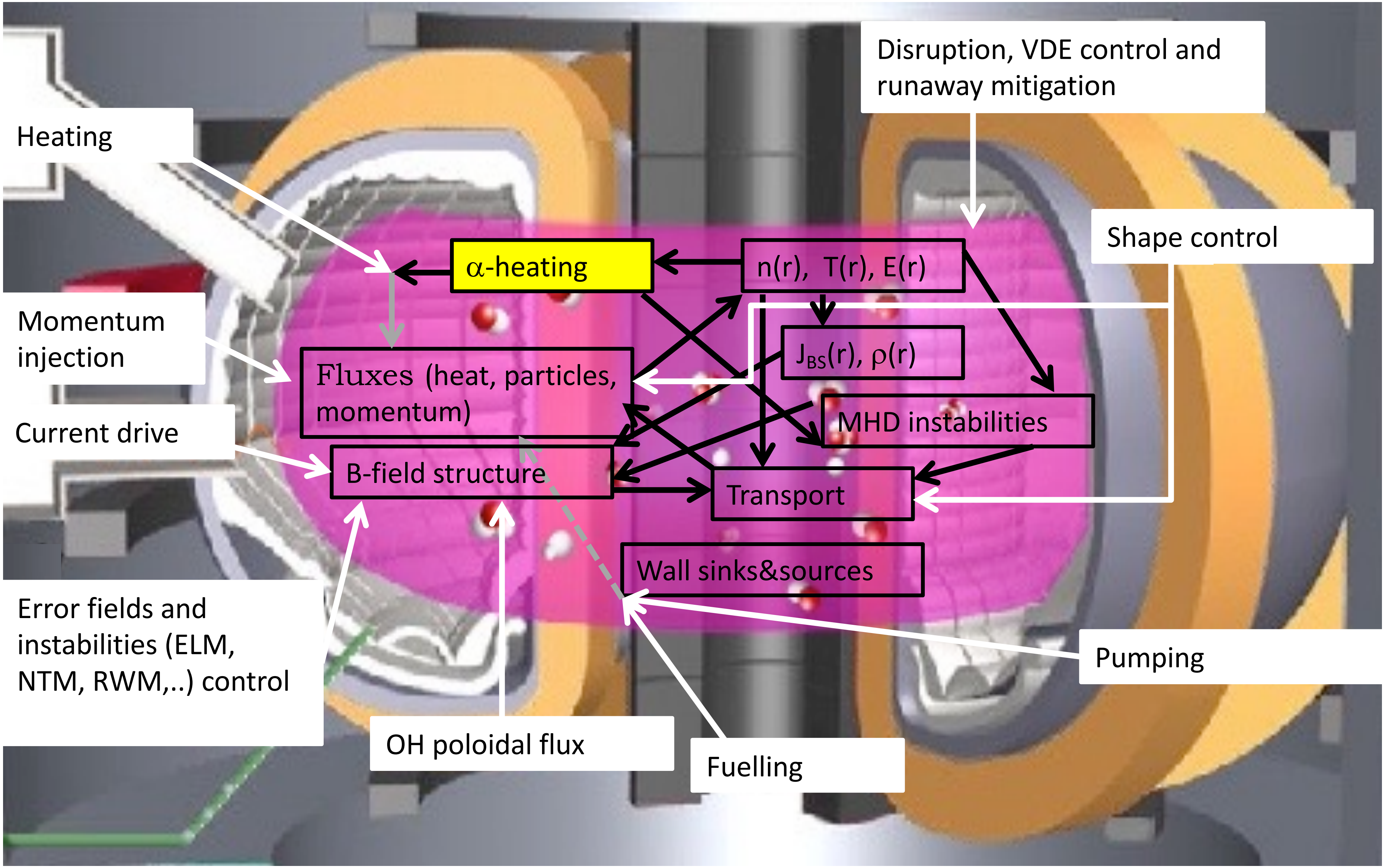
Q=10 scenario

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



Heating

Momentum injection

Current drive

Error fields and instabilities (ELM, NTM, RWM,..) control

OH poloidal flux

Fuelling

Pumping

Shape control

Disruption, VDE control and runaway mitigation

α-heating

n(r), T(r), E(r)

J_{BS}(r), ρ(r)

Fluxes (heat, particles, momentum)

MHD instabilities

B-field structure

Transport

Wall sinks&sources

Specific properties of burning plasmas

High performance

Operational limits, heat flux on plasma facing components

Nuclear environment

    Radiation T retention, dust, breeding

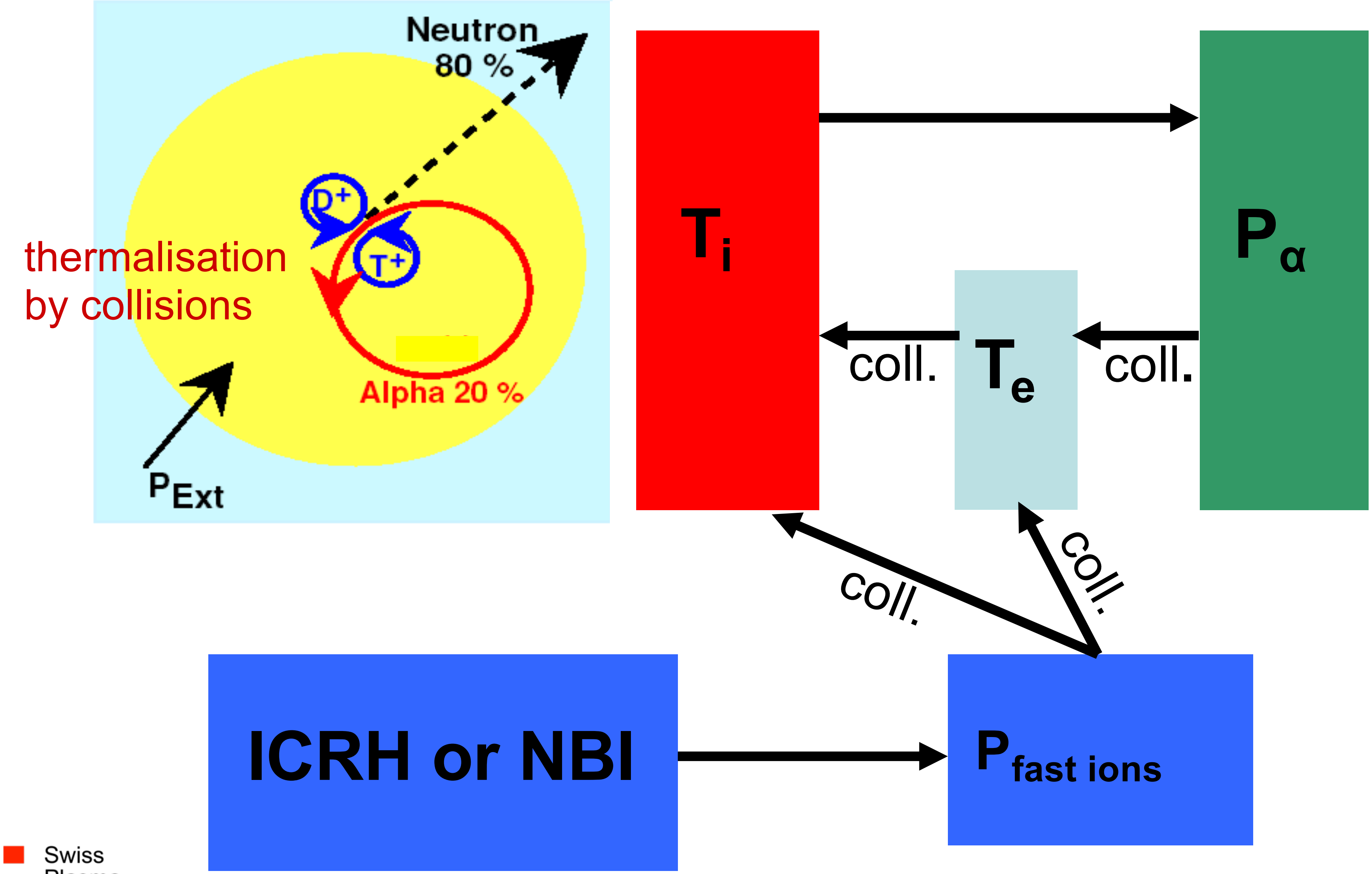
New physics parameter range

    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



T_i

P_α

T_e

coll.

coll.

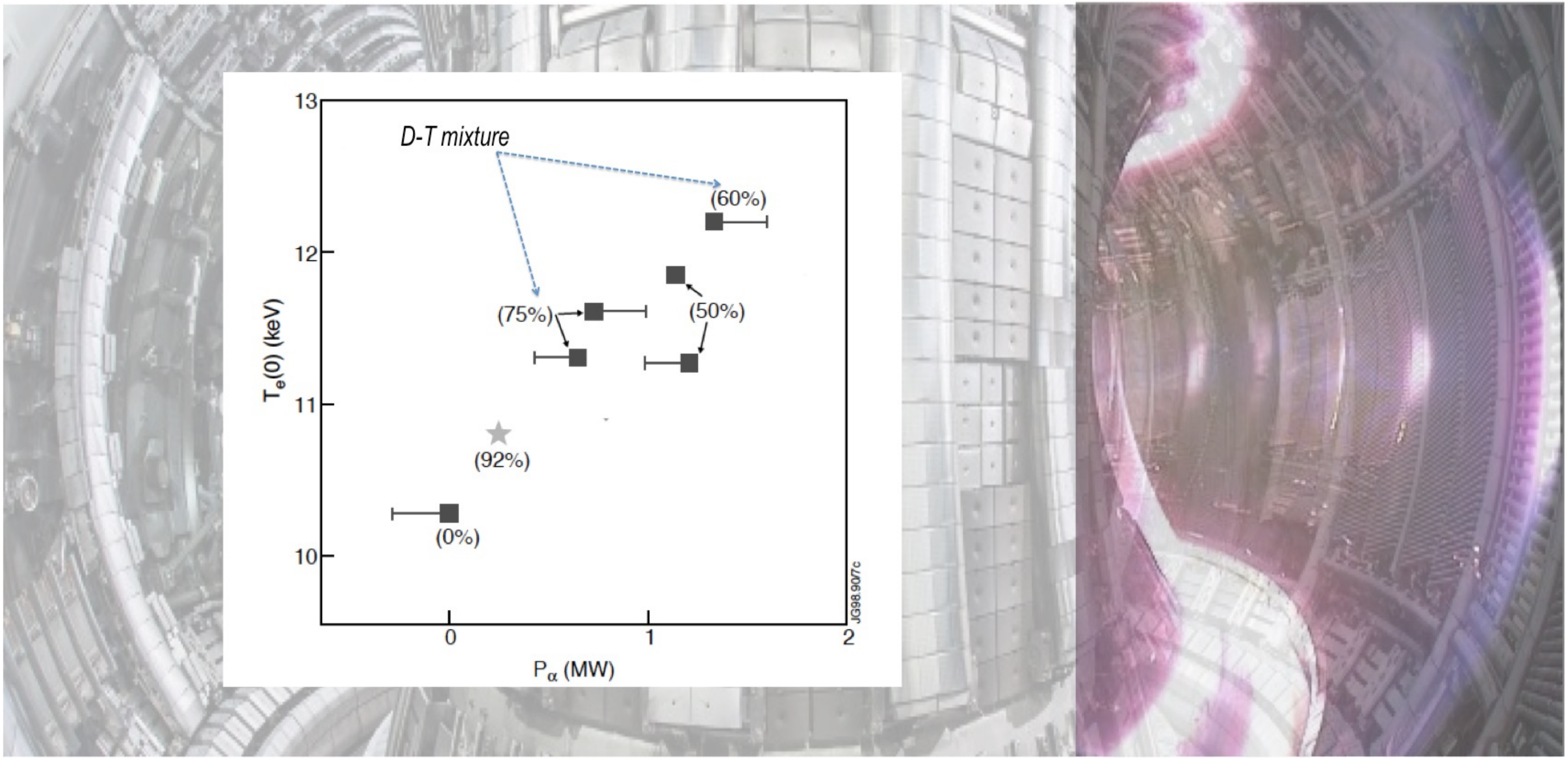
coll.

coll.

ICRH or NBI

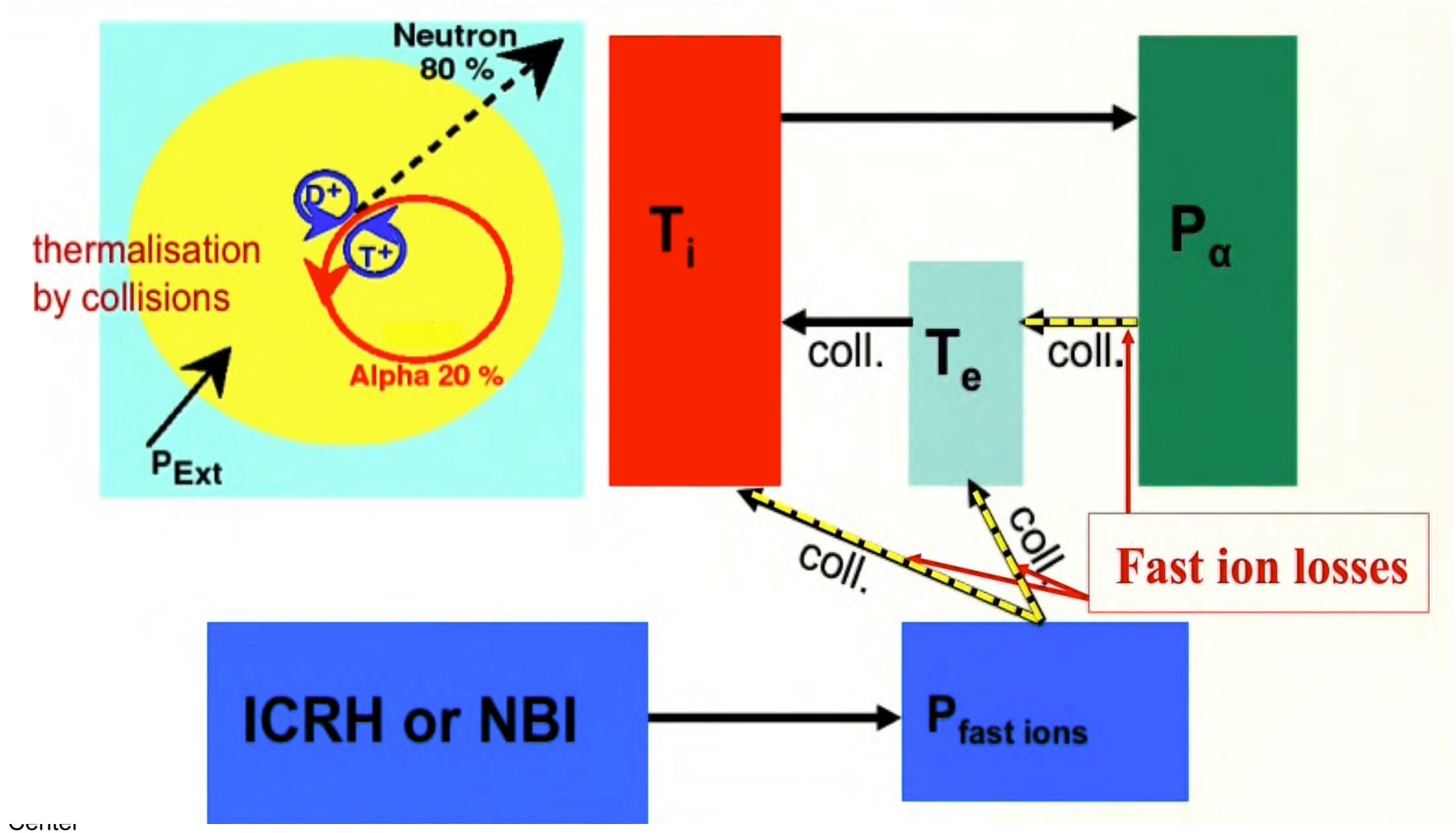
$P_{fast\ ions}$

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



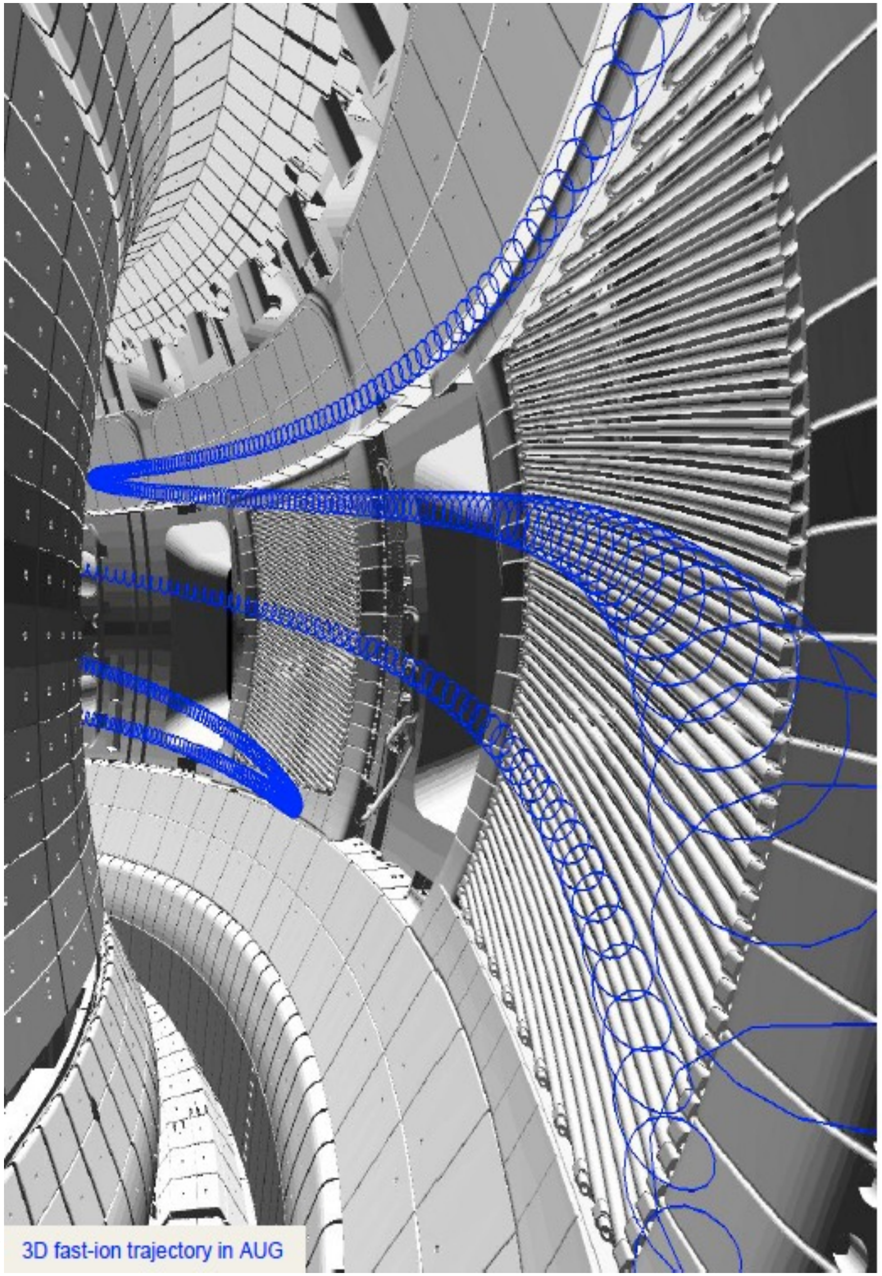
External heating and self-heating

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

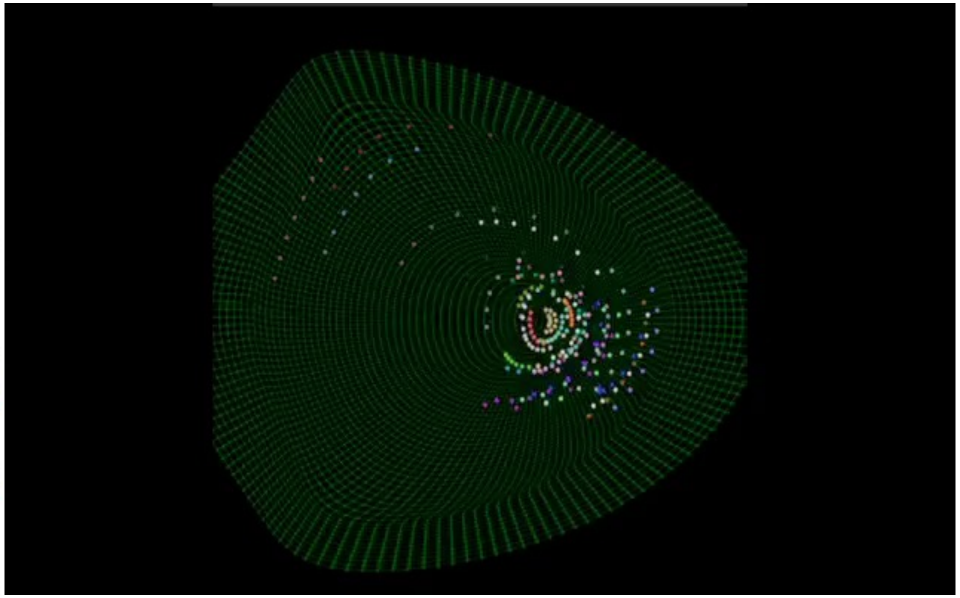
Need to understand and possibly minimize redistribution and loss mechanisms

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

Fast ion orbits in tokamaks



3D fast-ion trajectory in AUG

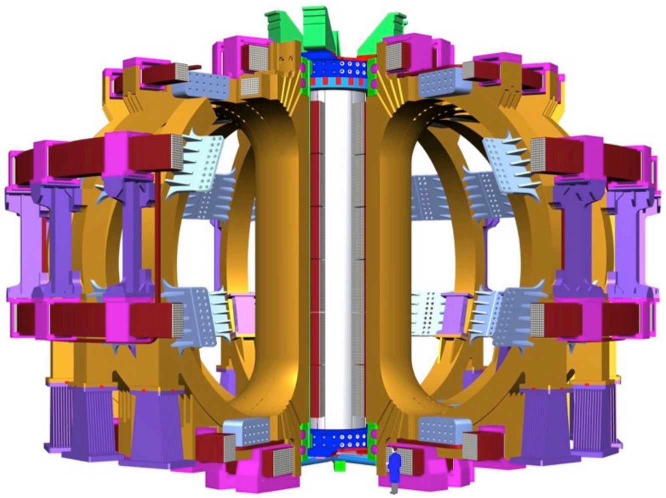


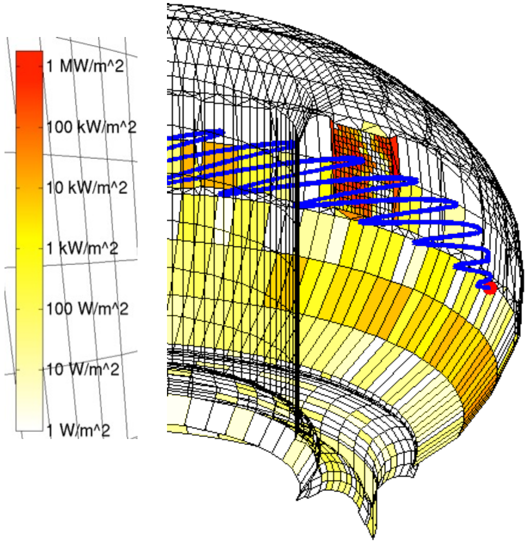
GPU-NUBEAM DIII-D
Simulation

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

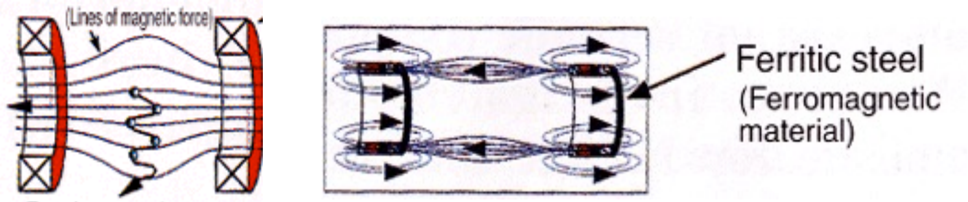




ASCOT code
T.Kurki-Suonio

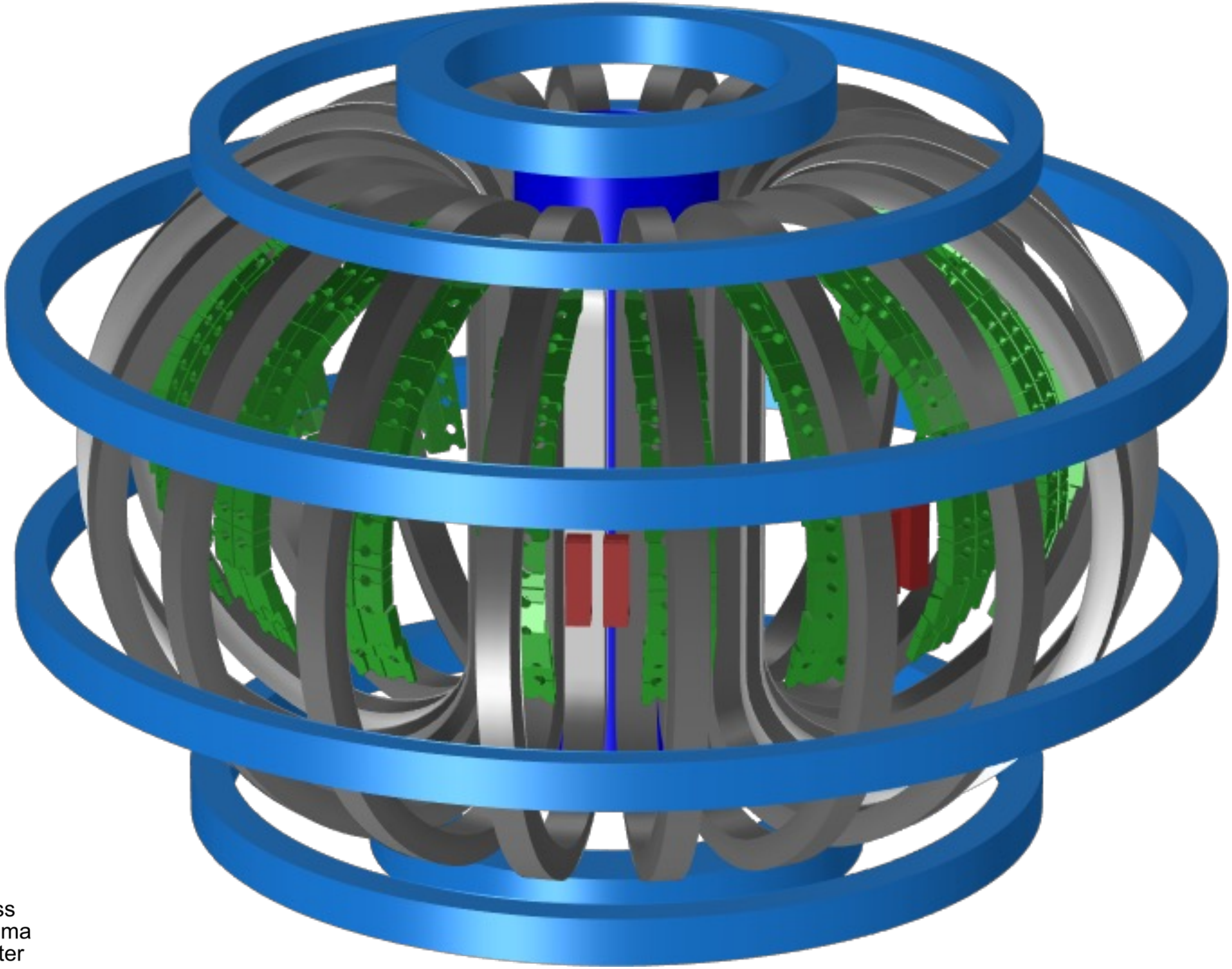
Ripple effects on fast ions qualitatively understood

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



K.Shinohara

3D image of the ferritic inserts in ITER



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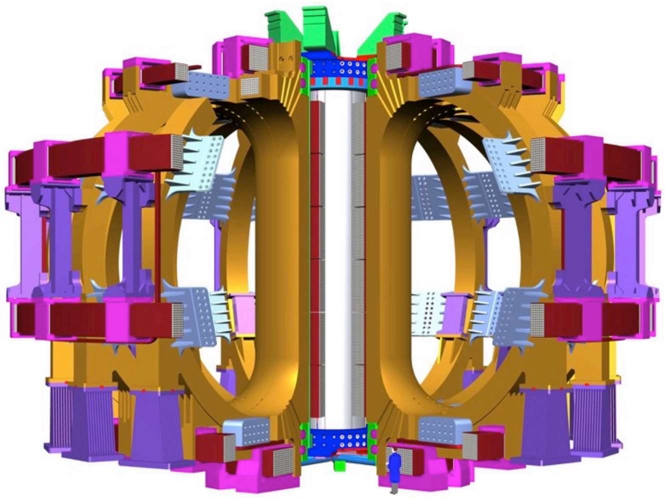

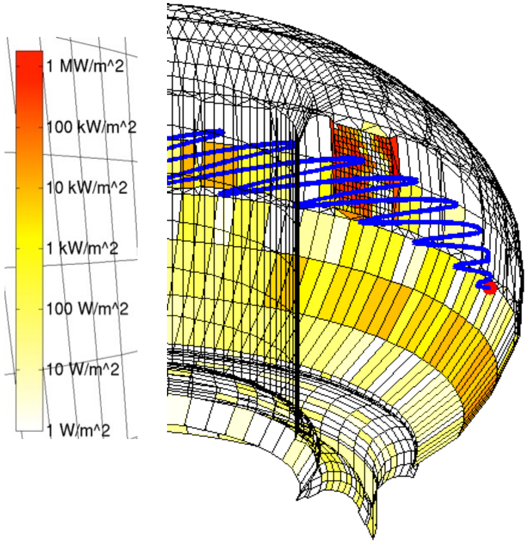

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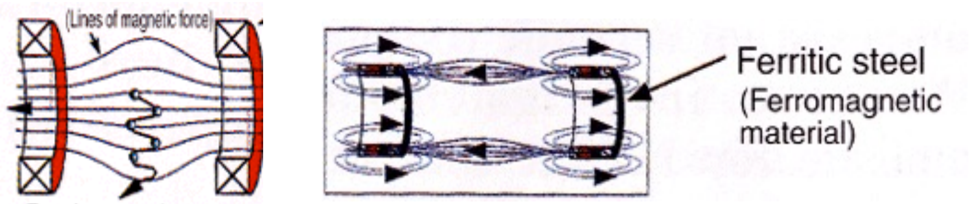


K.Shinohara

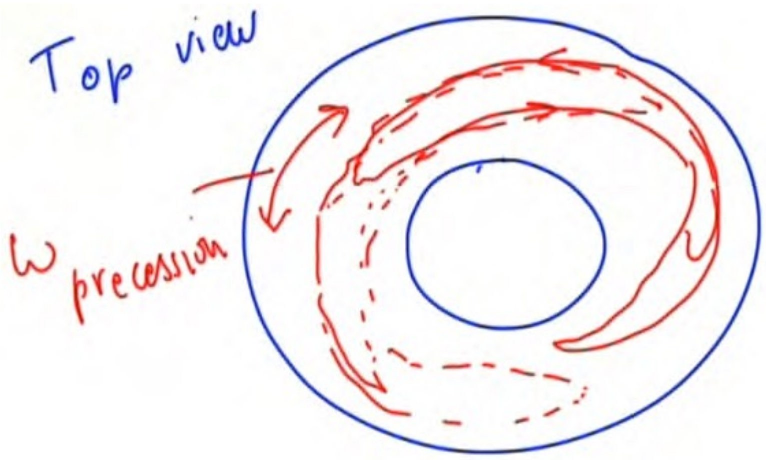
Open questions

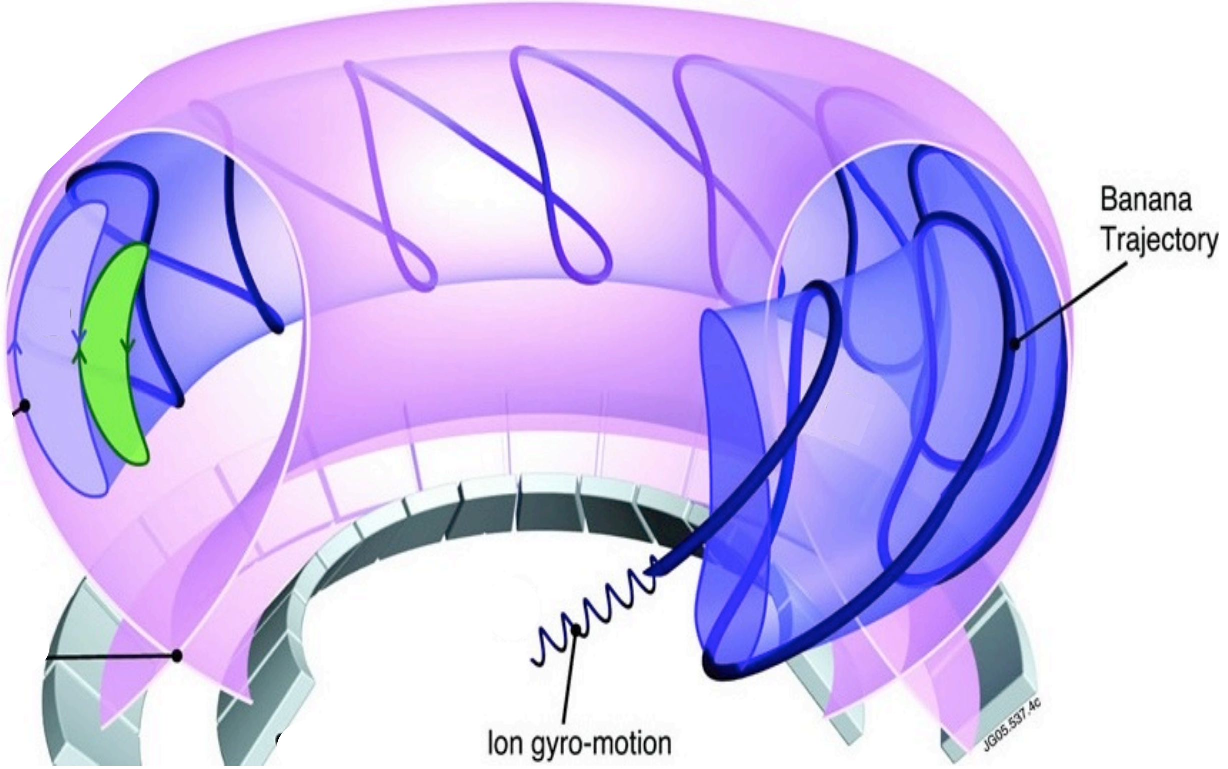
- Effect of blanket modules (~1% ripple)
- Effect of 3D fields induced by coils introduced to mitigate edge instabilities

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

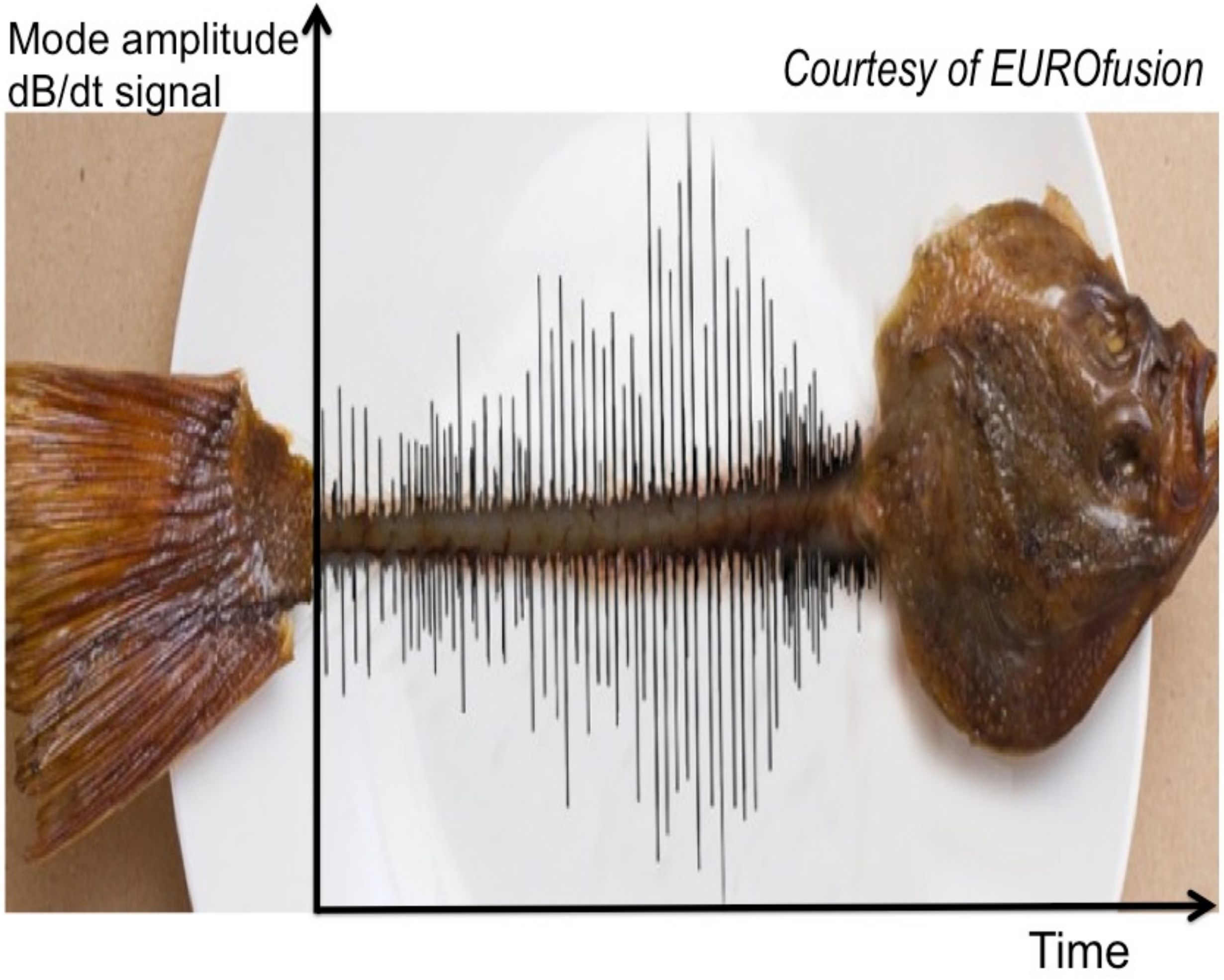
Example: bounce motion of particles along banana orbits and toroidal drift precession of banana orbits : $\omega_{\text{precession}} << \omega_{\text{bounce}} << \Omega_c$

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

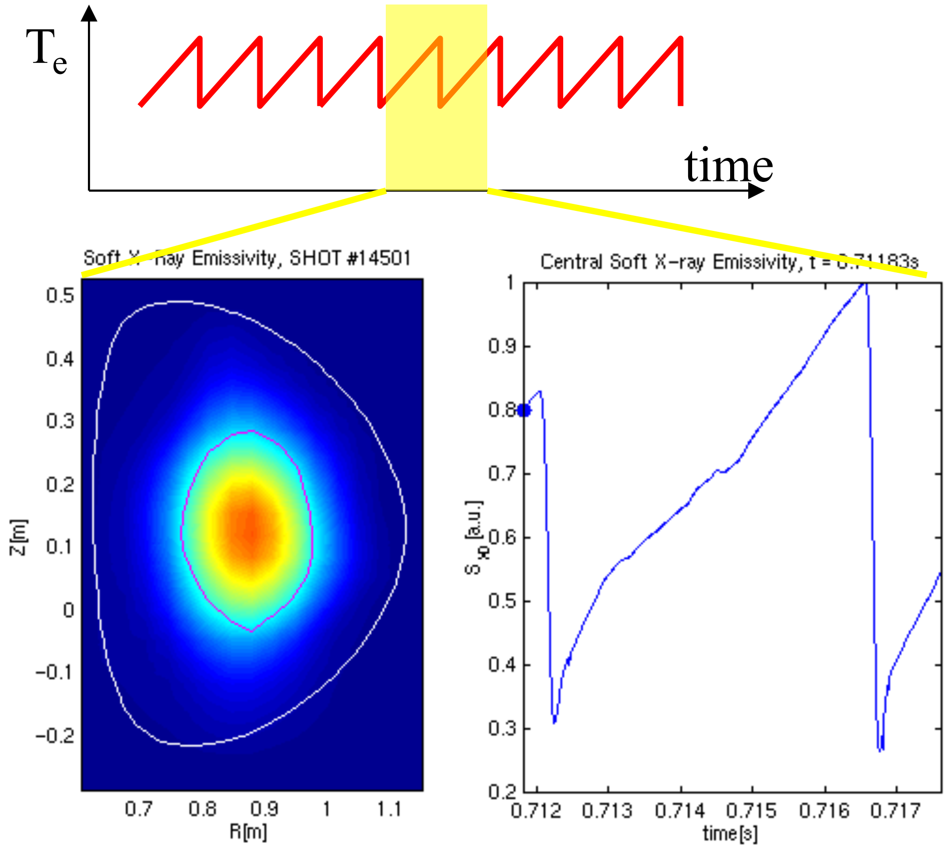
Swiss
Plasma
Center

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



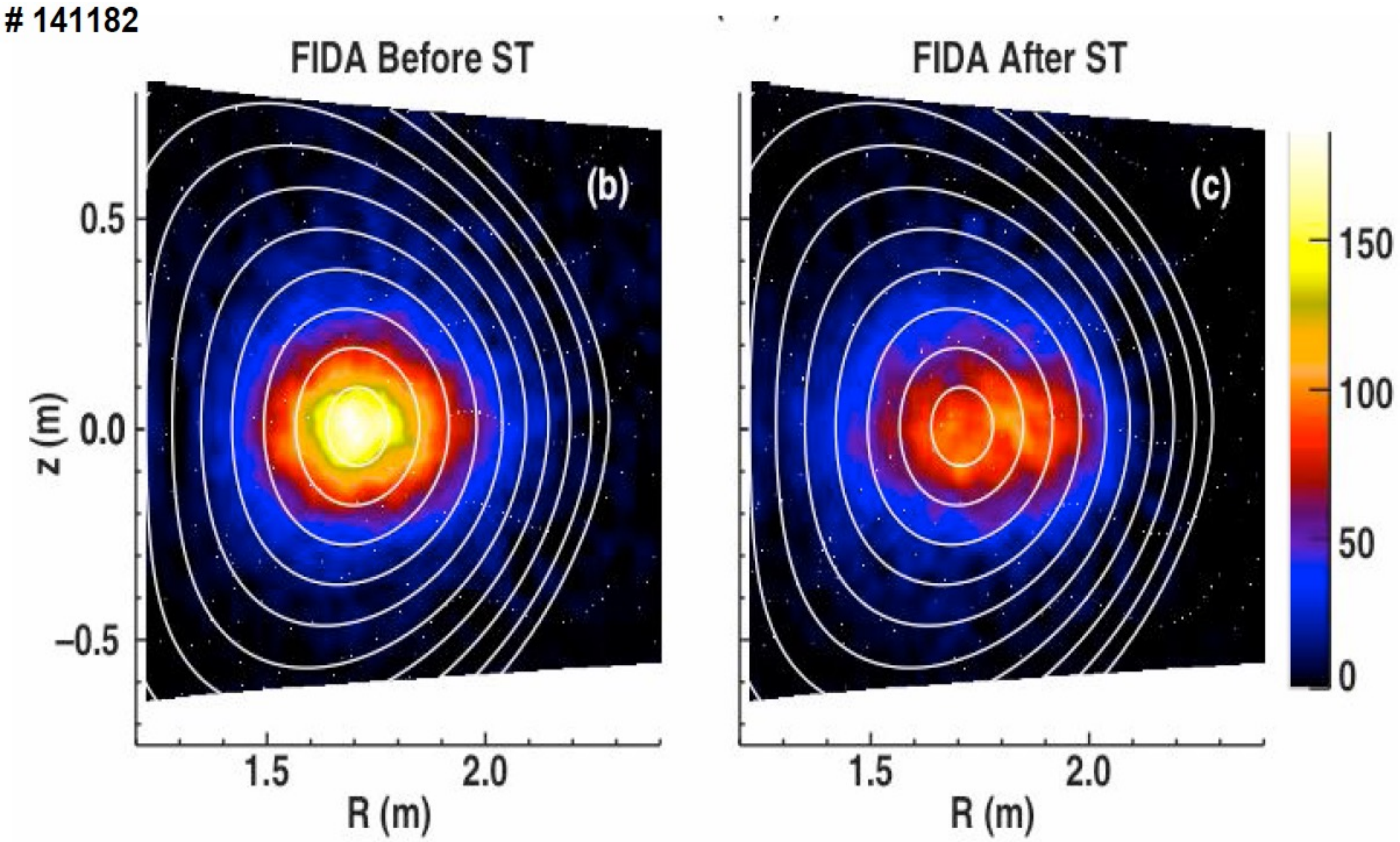
Ex.: X-ray emissivity (~T_e, n) evolution in TCV

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.

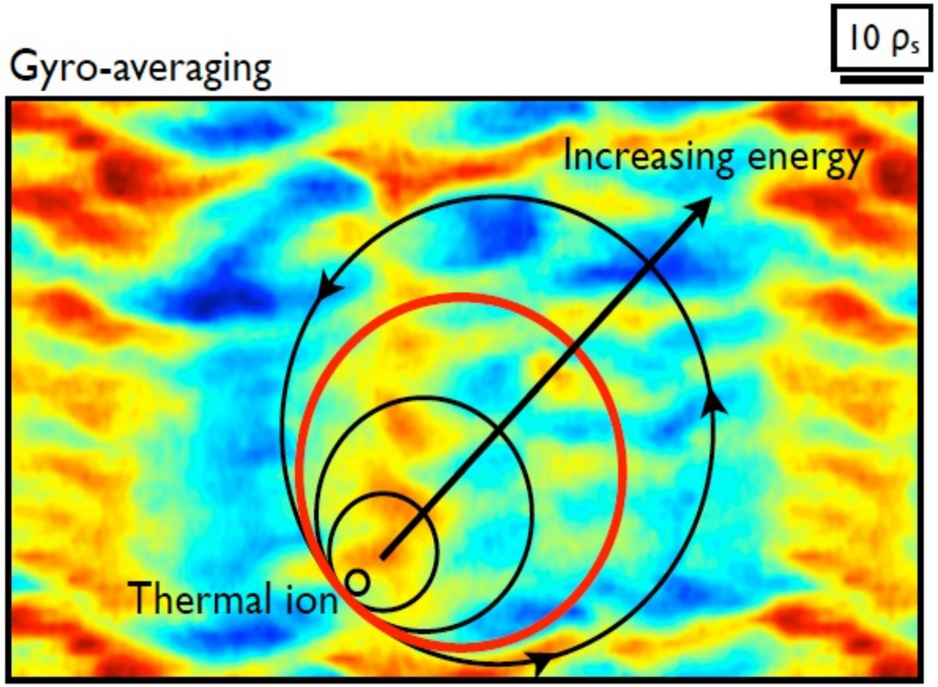
FAST ION LOSS MECHANISMS
PLASMA TURBULENCE

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

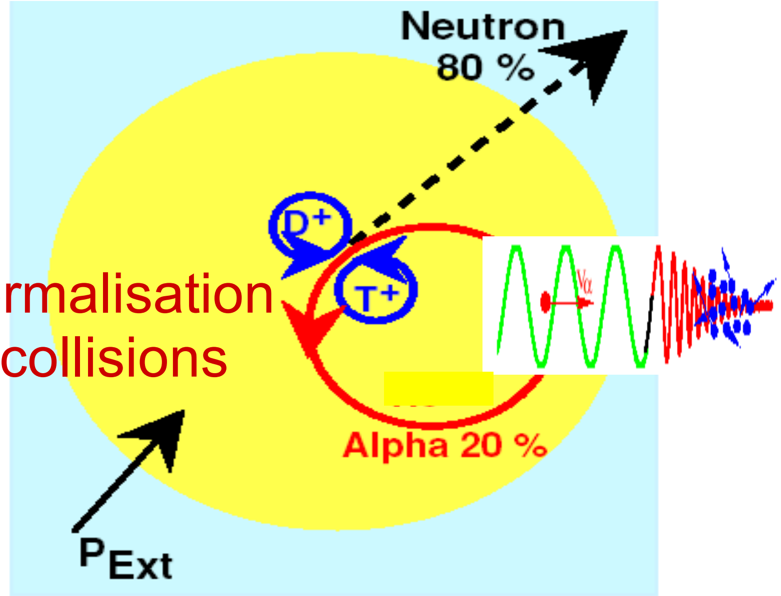
some anomalous transport of NBI ions

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

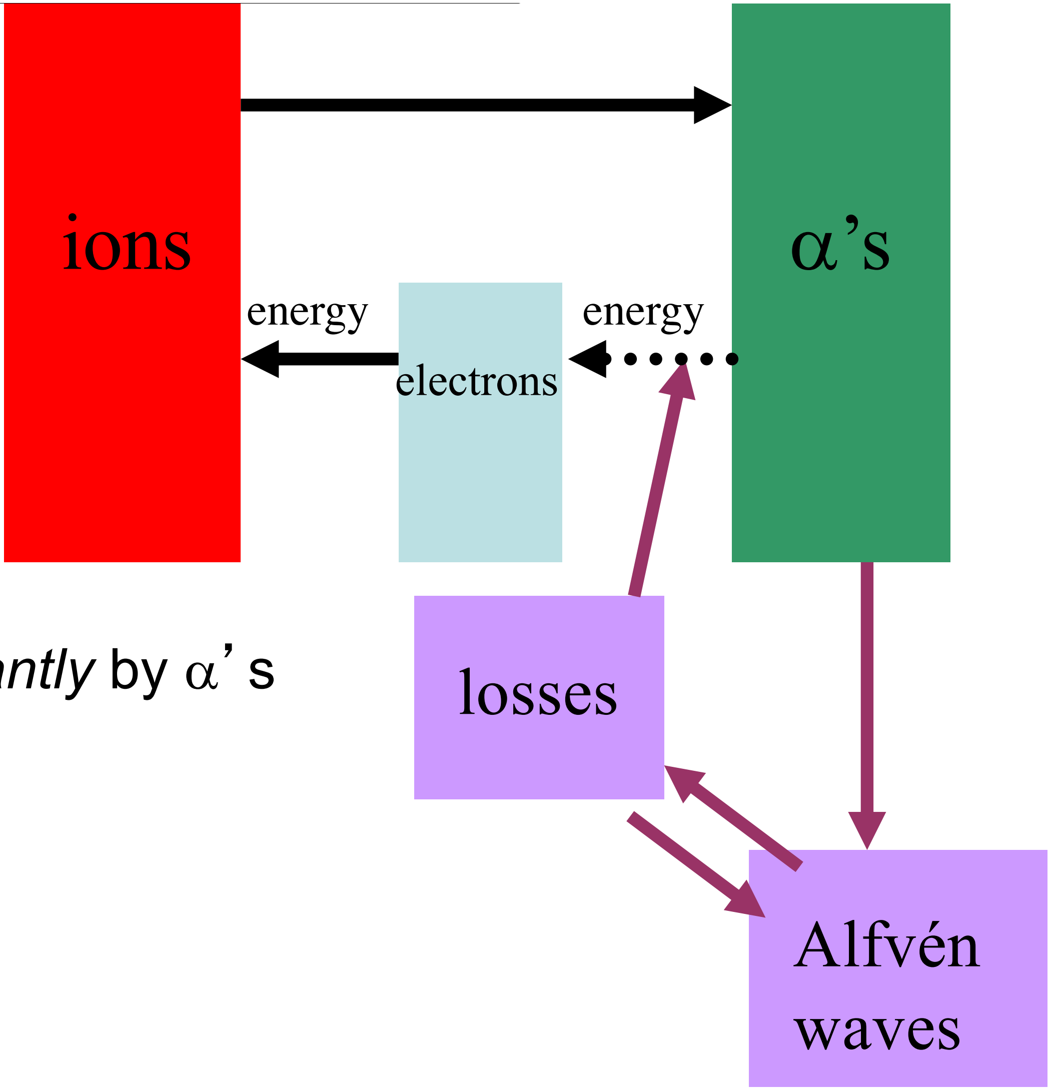
negligible effect for NBI ions and for α' s

FAST ION LOSS MECHANISMS
INTERACTION WITH ALFVEN WAVES

Resonant interaction with waves and self-heating



thermalisation
by collisions



ions

α's

energy

electrons

energy

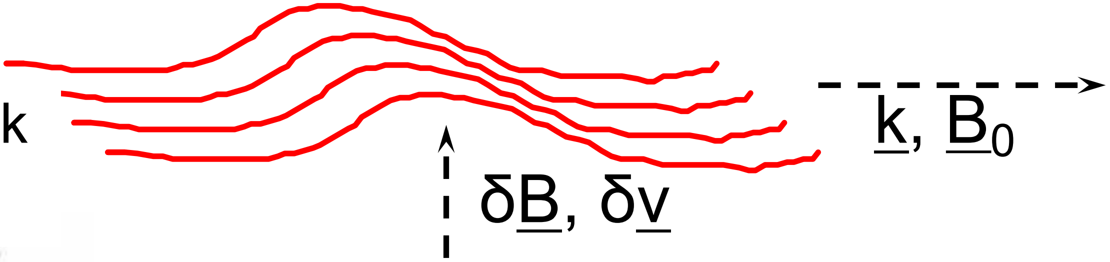
losses

Alfvén
waves

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

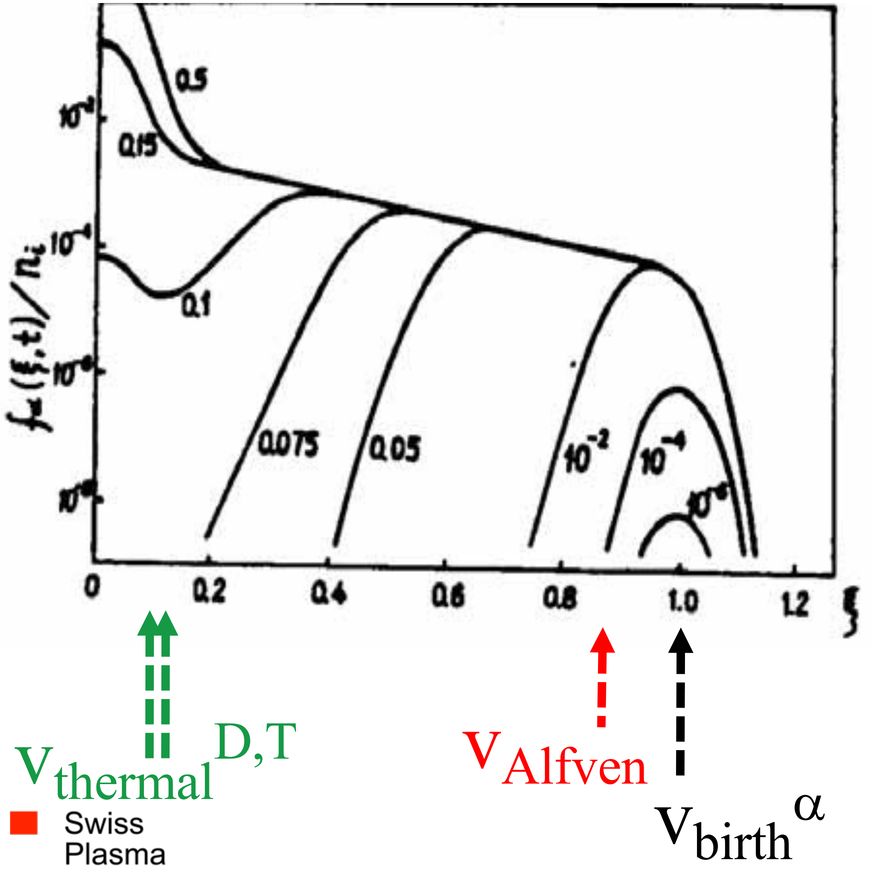
Fast ions and Alfvén waves

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



Typical velocities in a tokamak

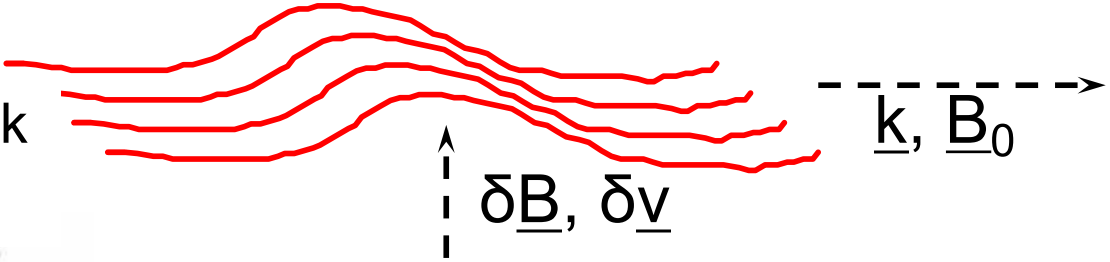
B=4T; T=10keV; n=10^{20}m^{-3}



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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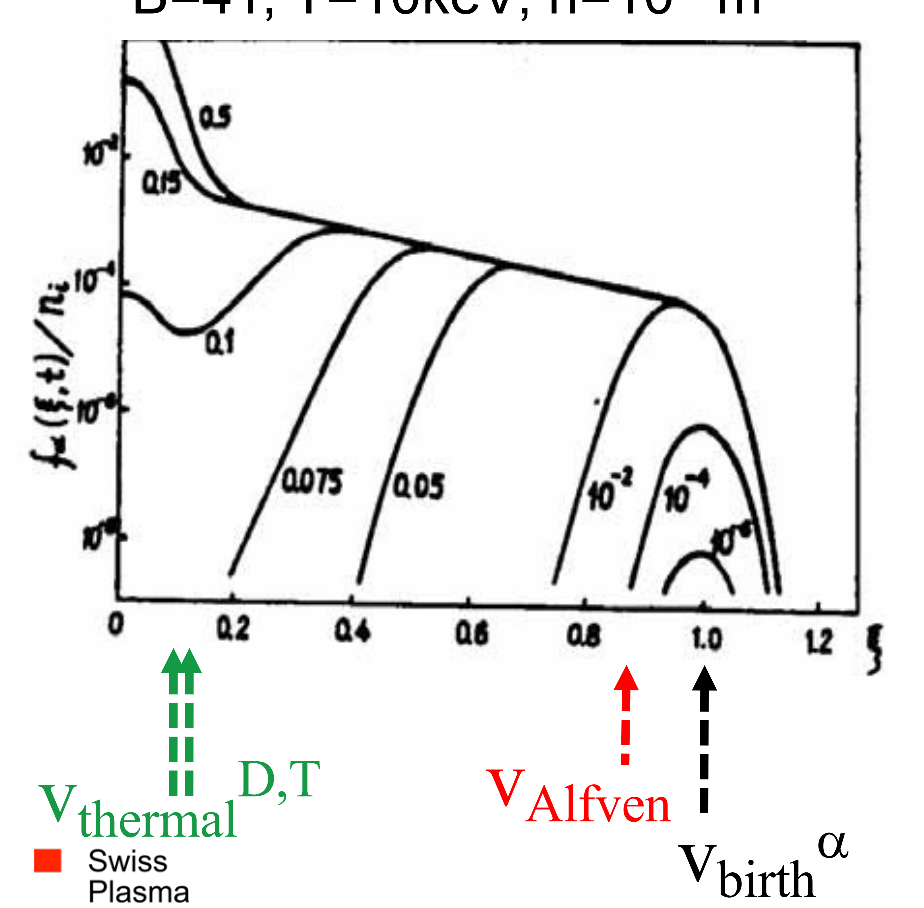


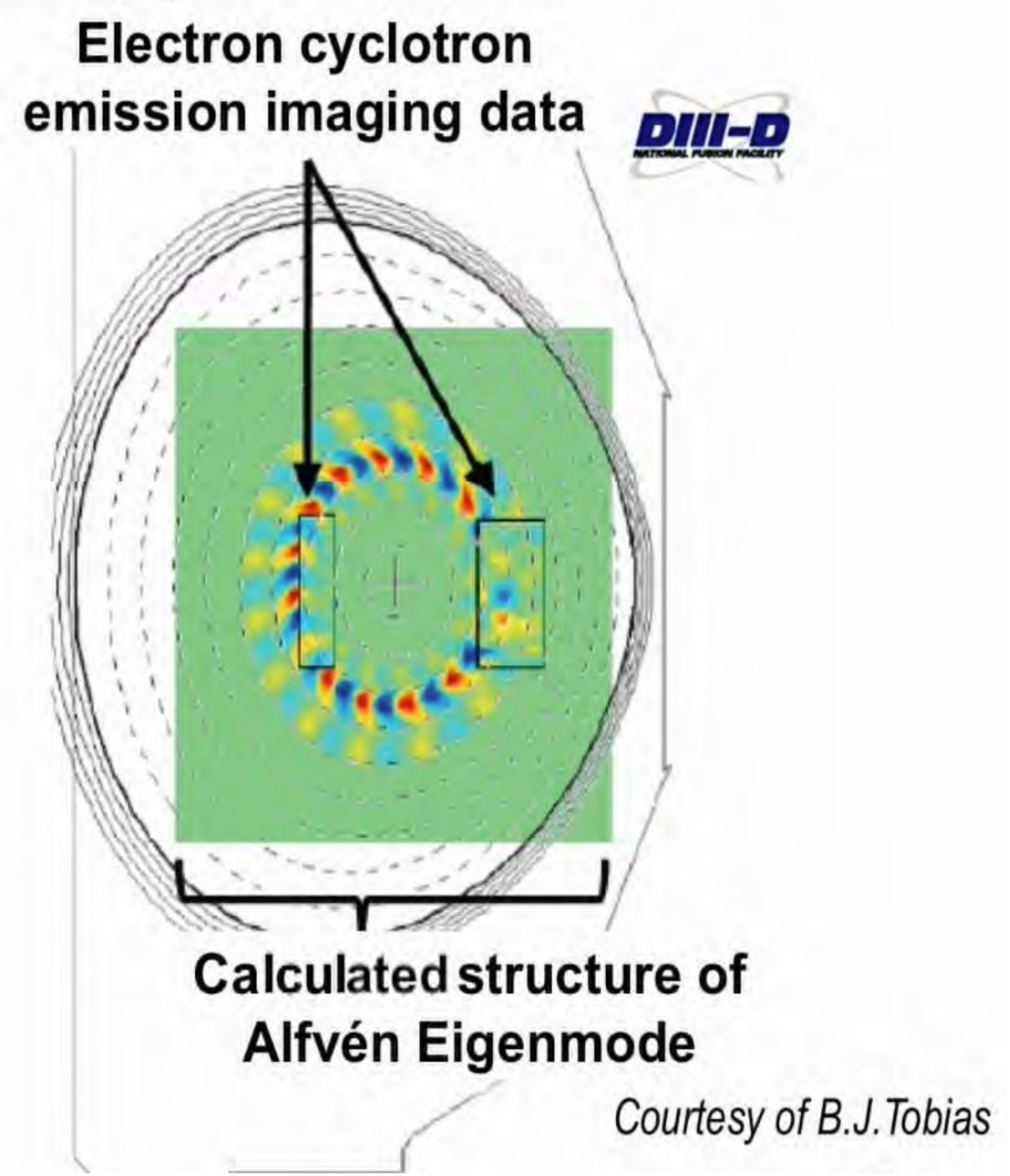
Slowing down α's (but also fast ions generated by additional heating) can resonate with Alfvén Waves

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

Alfvén waves in tokamaks
Alfvén Eigenmodes

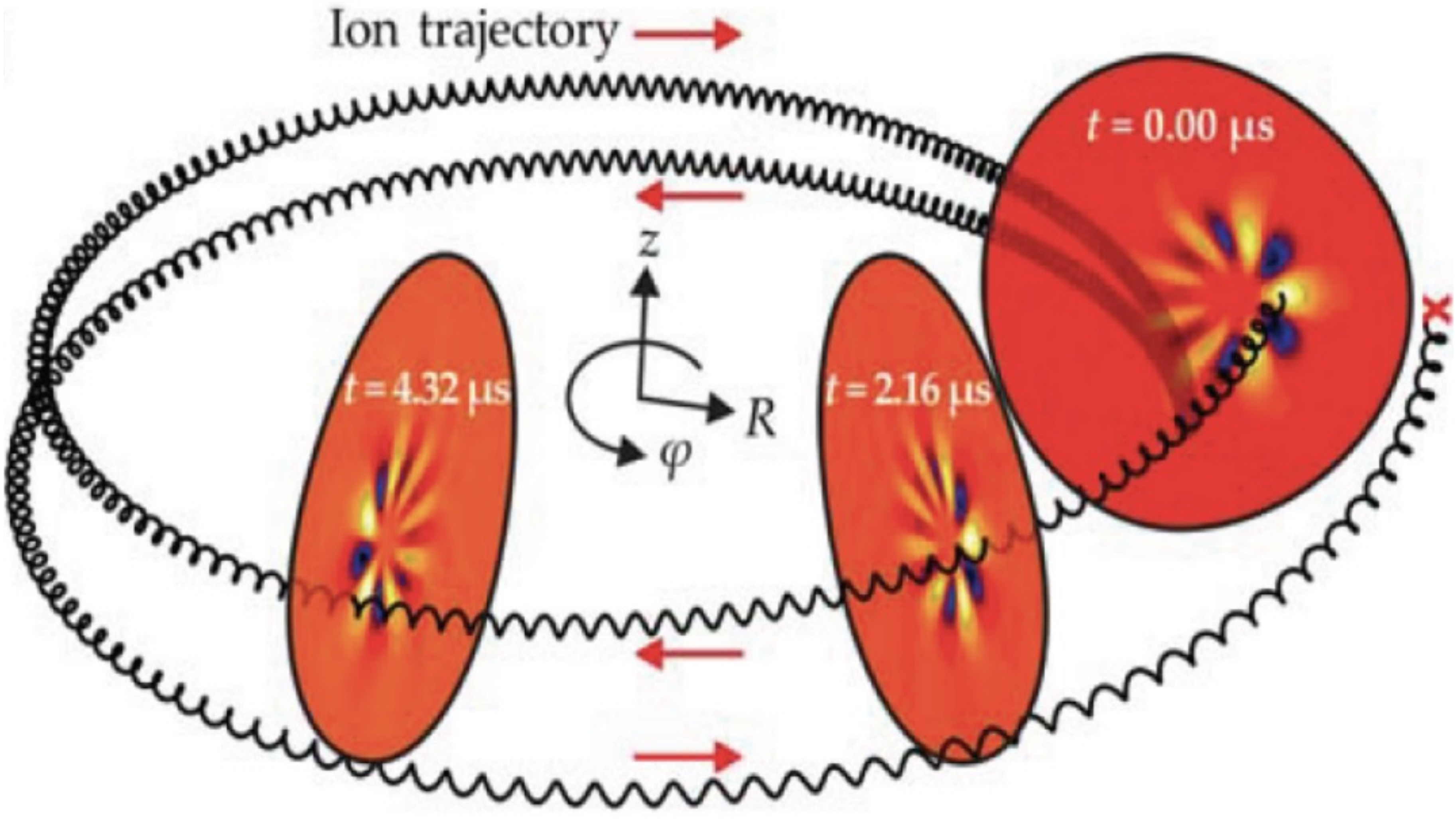
Alfvén waves' dispersion in tokamaks allows for weakly damped global Eigenmodes

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



Courtesy of B.J. Tobias

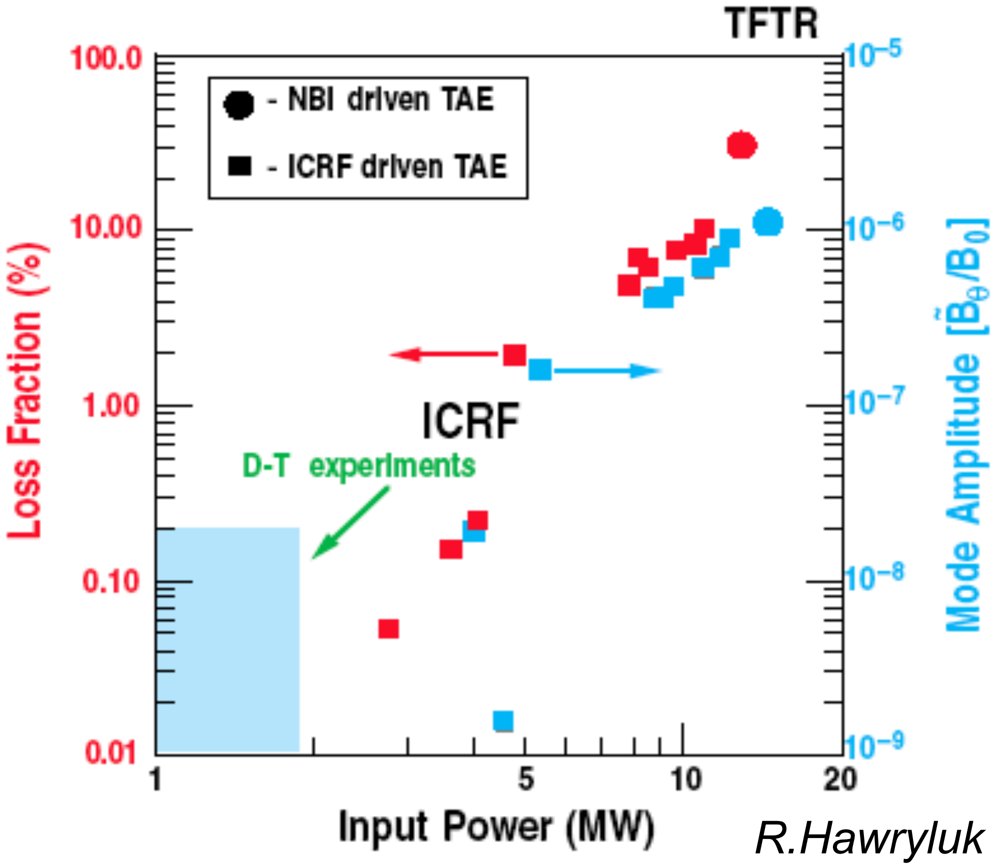
AE resonance condition visualisation



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

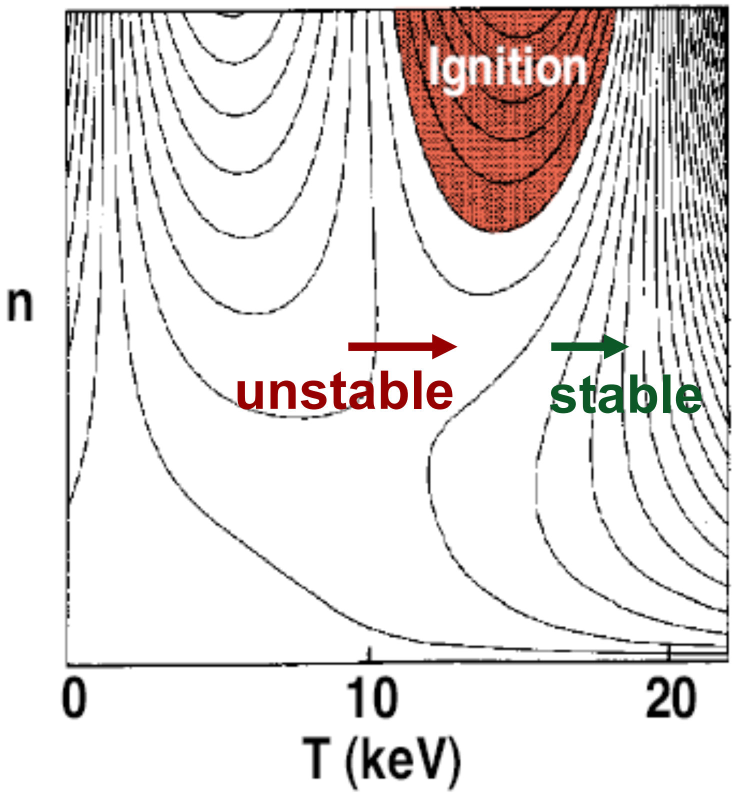
- Linear stability, balance between damping and drive
- Nonlinear evolution and redistribution / losses

BURN STABILITY AND CONTROL

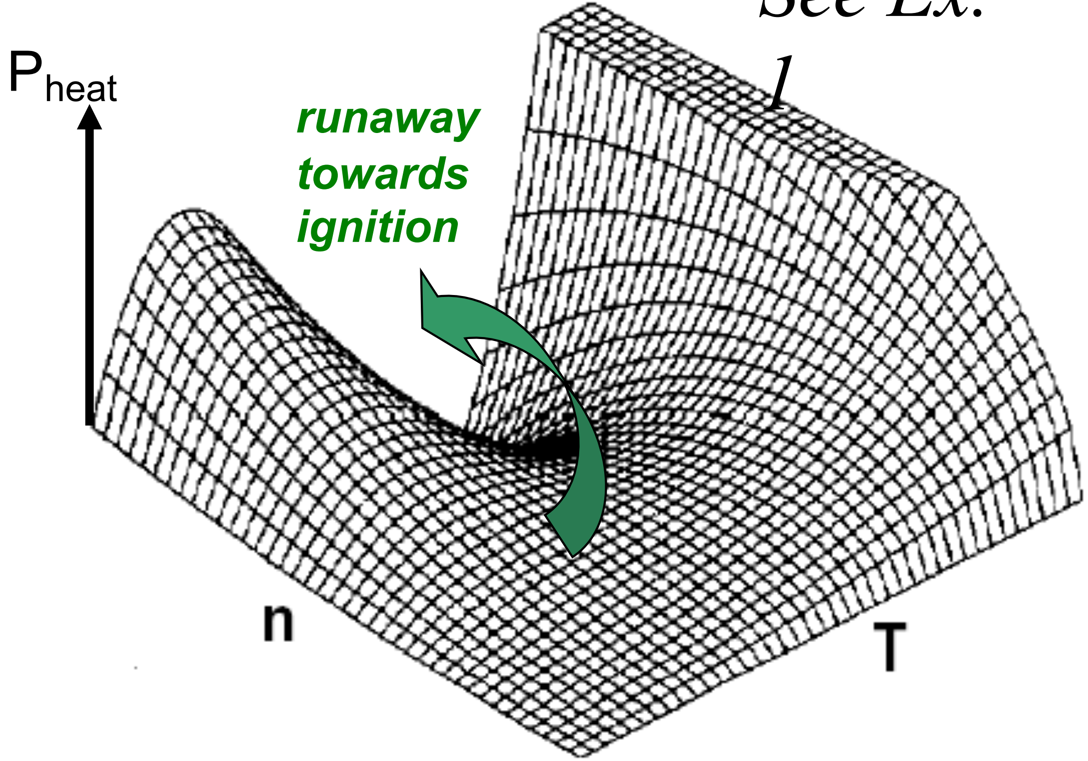
Burn thermal runaway

At high Q in principle thermal runaway can occur

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



See Ex. 1



TRITIUM IN FUSION

Tritium – general properties

Half life time: 12.3 years

Decay mode

β decay: T → ^{3}He + 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 → ^{12}C + T (- 4.3MeV)
^{14}N + n → 3 ^{4}He + T (- 11.5MeV)

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

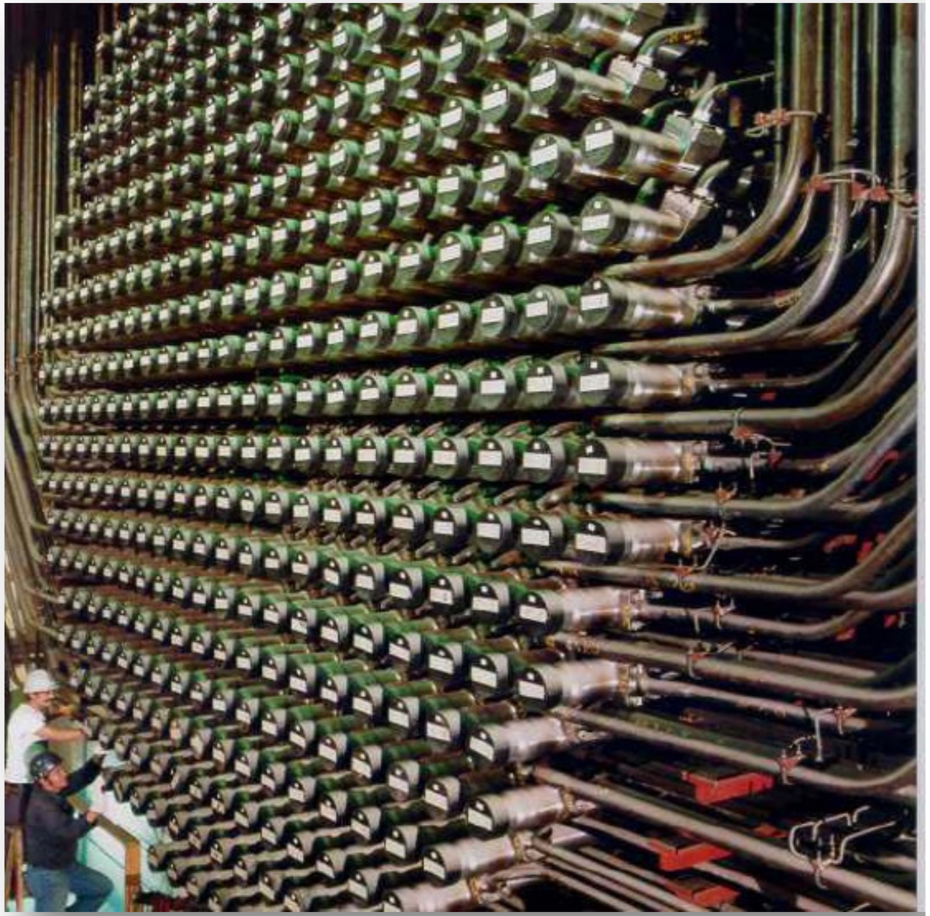
Tritium – anthropogenic inventory

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

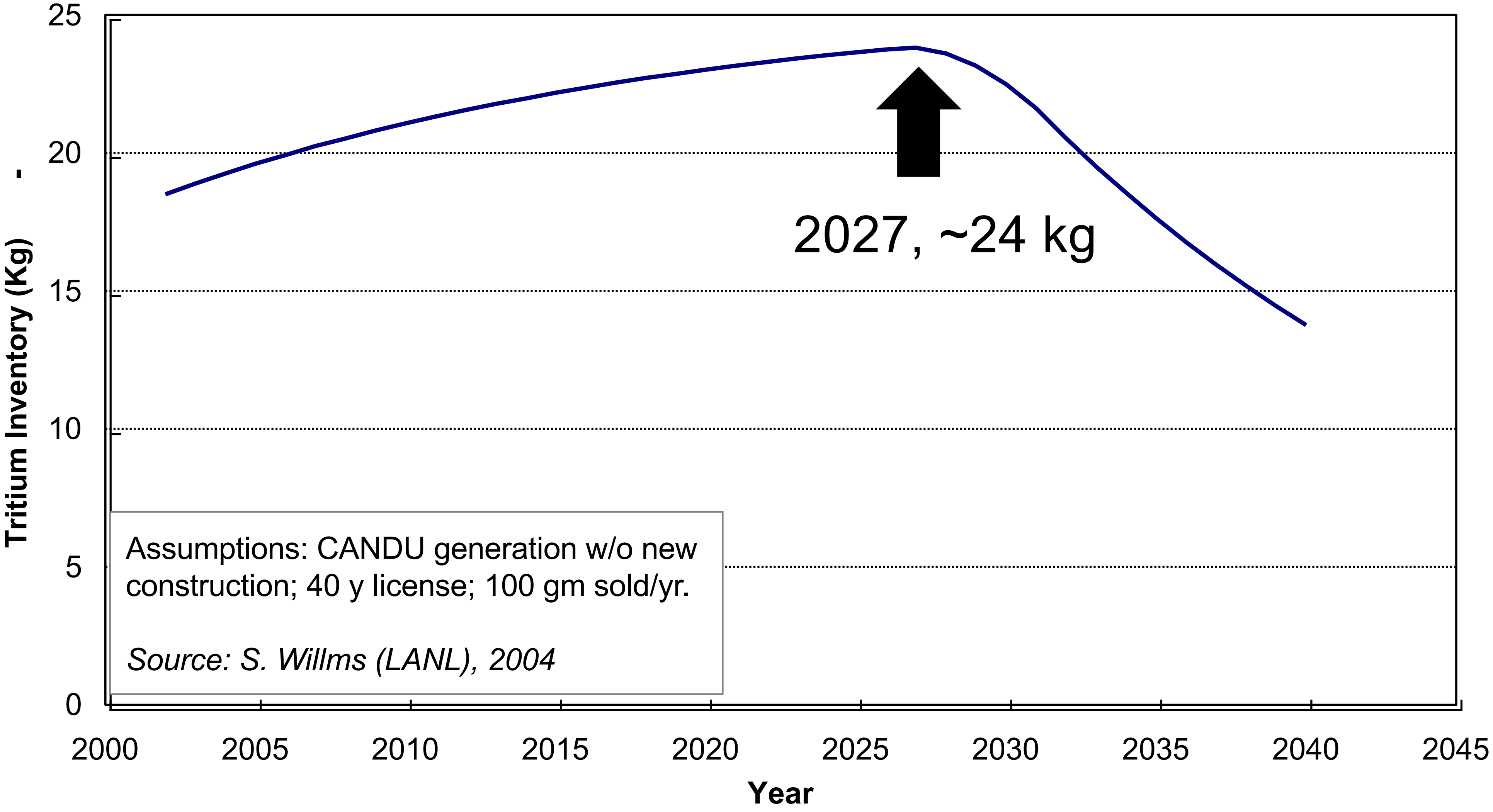
Tritium production is today driven by fission (CANDU) waste management rather than by a market

Darlington (Canada)
Tritium Removal Facility

~1.5kg tritium recovered/year

T availability is foreseen to decrease after 2027

Projection of tritium inventory available from CANDU (Canada)

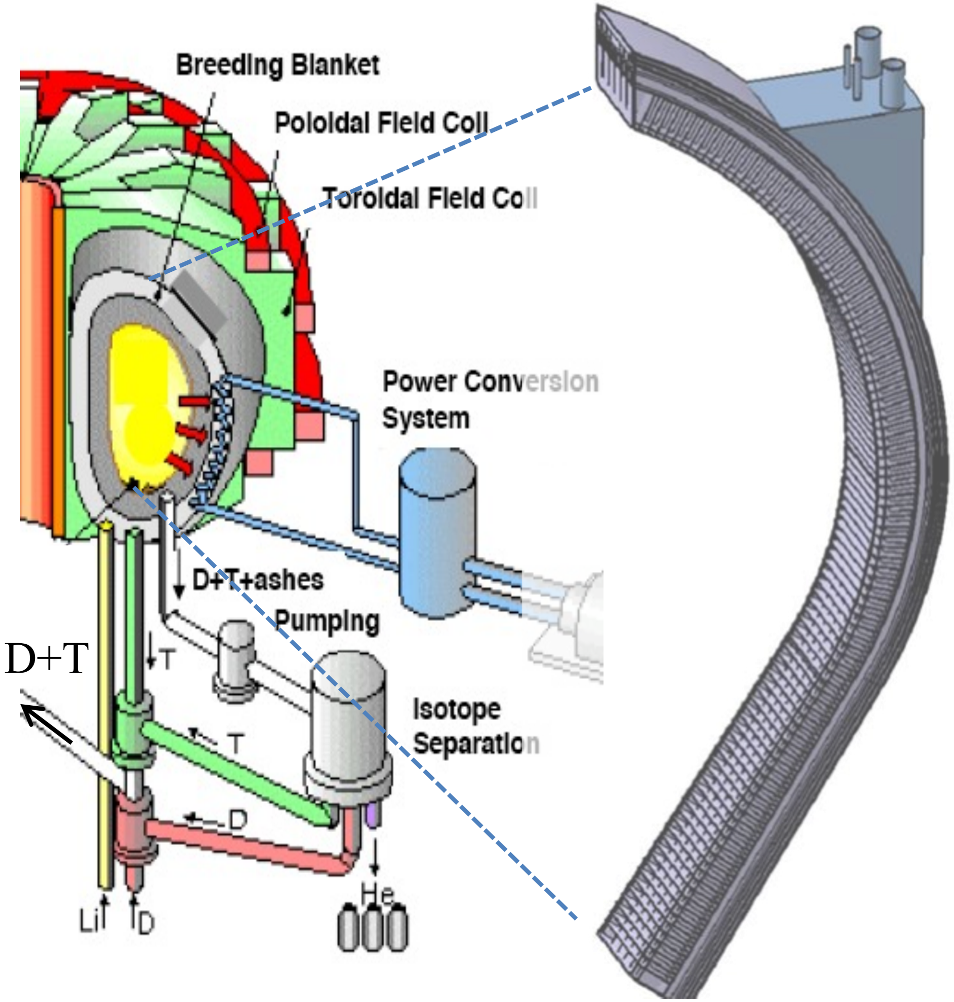


Assumptions: CANDU generation w/o new construction; 40 y license; 100 gm sold/yr.

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

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

Tritium breeding ratio

TBR = tritium bred / tritium burnt

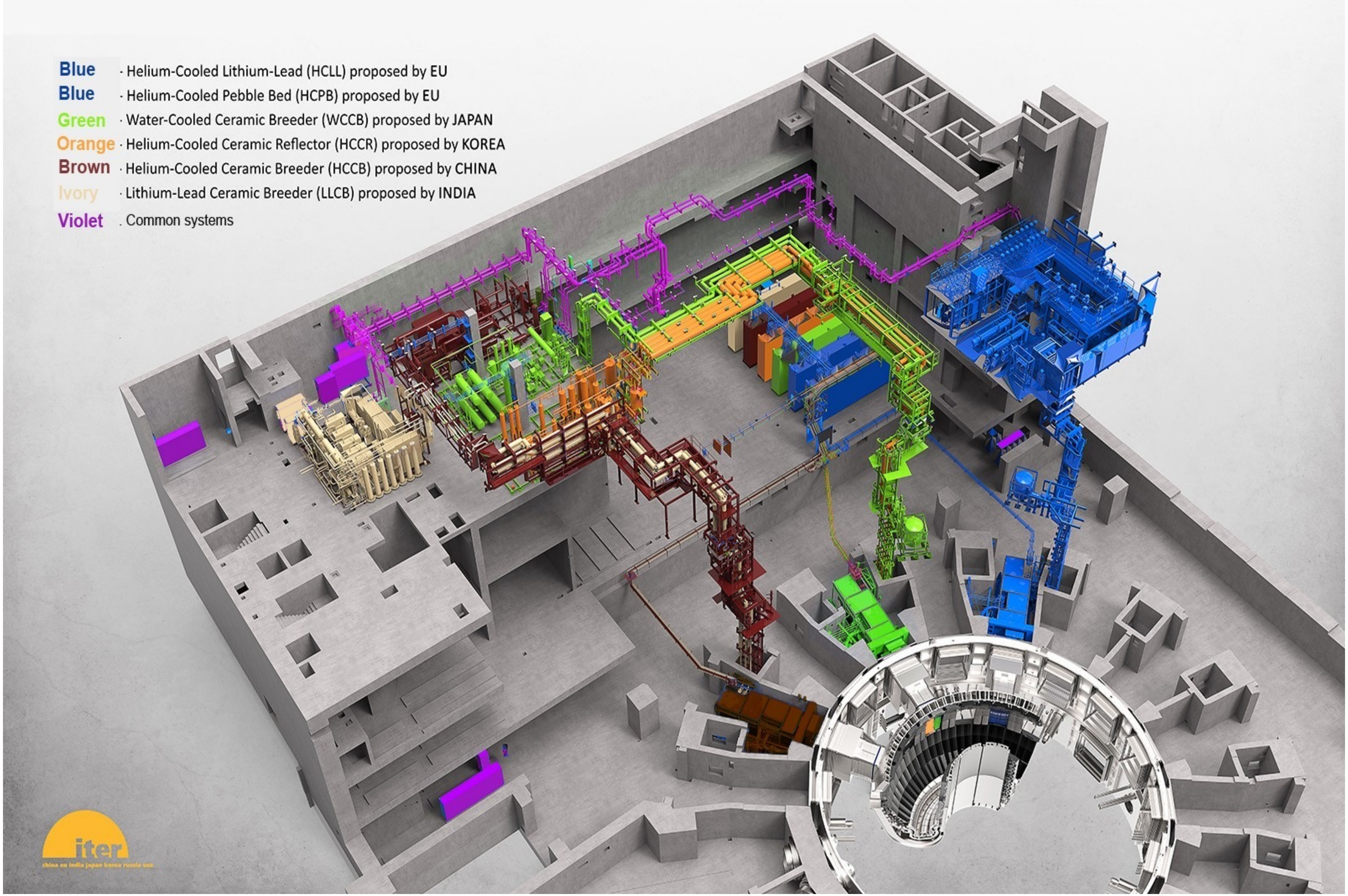
TBR >1 to compensate losses, which implies the use of n-multiplier

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

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

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

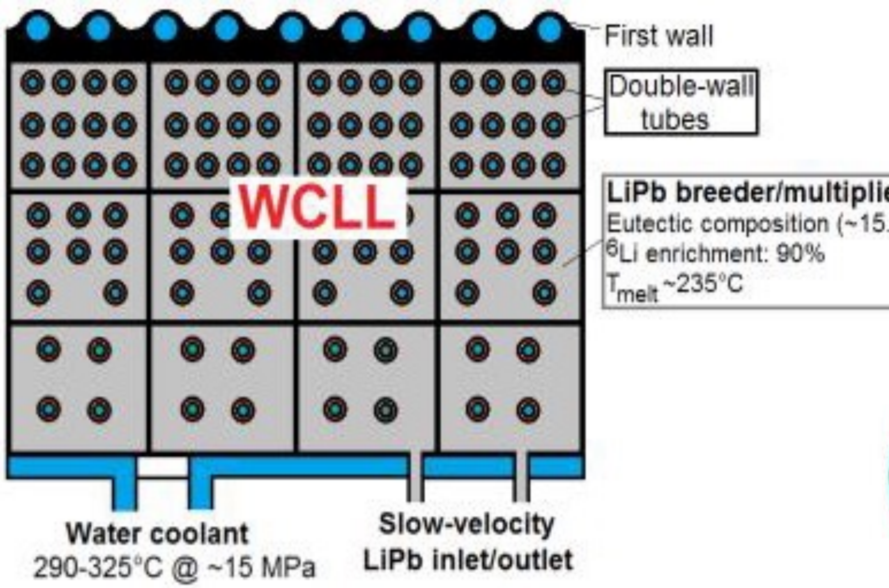
Test breeding blankets in ITER



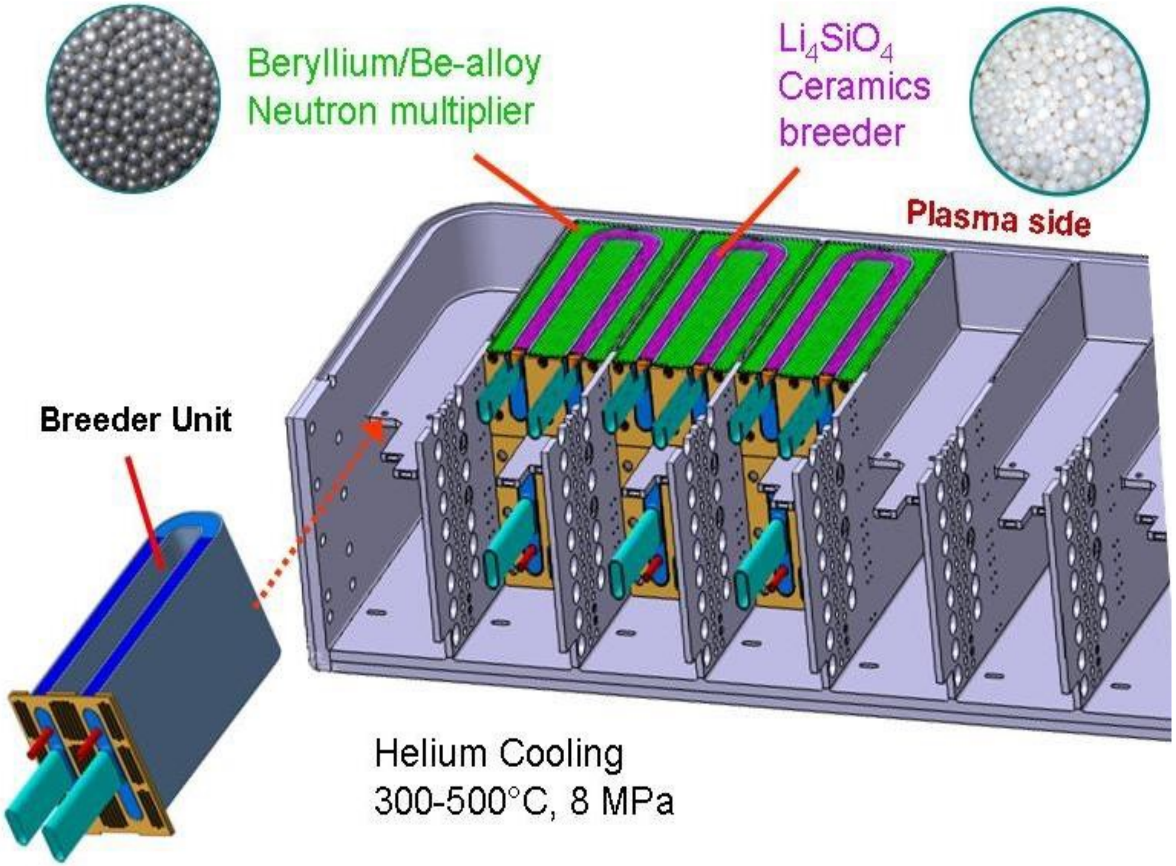
EPFL

Ex. breeding blanket concept for DEMO

Water Coolant Lithium Lead



Helium Cooled Pebble Bed



JÜLICH
FORSCHUNGSZENTRUM

KIT
Karlsruhe Institute of Technology

Swiss
Plasma
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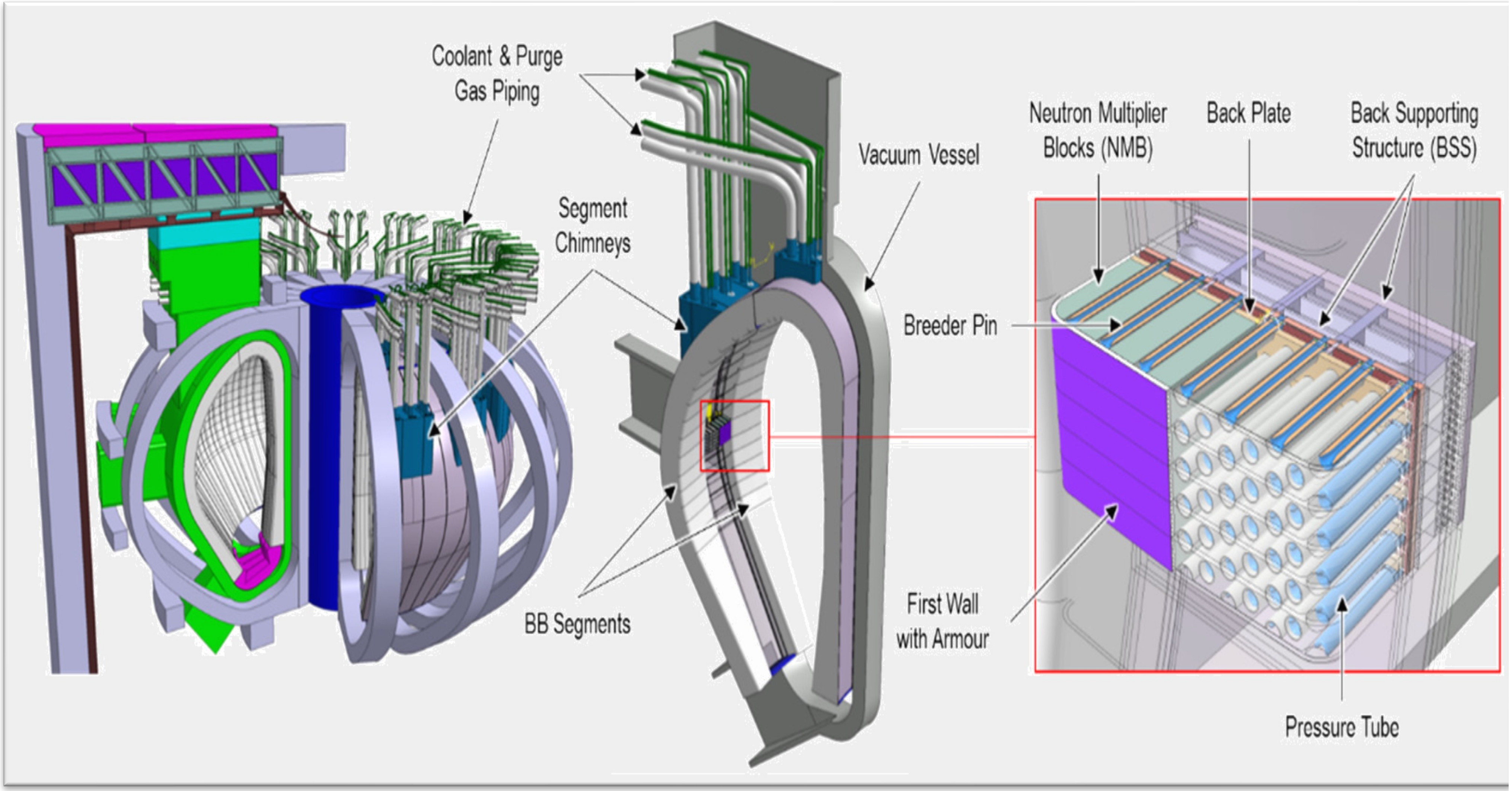
Ex. breeding blanket concept for DEMO

Helium Cooled Pebble Bed



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 = $n_T^2 \langle \sigma v \rangle_{DT} / S_T$

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

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

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 $\tau_T/(1\text{-}R)$,
but generally the recycling coefficient R<<1

EPFL

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

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

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 $\tau_T/(1\text{-}R)$,
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$_{\text{thermal}}$

Ex. 1GW$_e$ → ~3GW$_{\text{thermal}}$ → ~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

Tritium inventory in fusion reactor

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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 = $\eta_f f_B M_0 / t_p$ × TBR – $(\gamma_r + \gamma_s) M_0$

Tritium inventory in fusion reactor

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

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

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

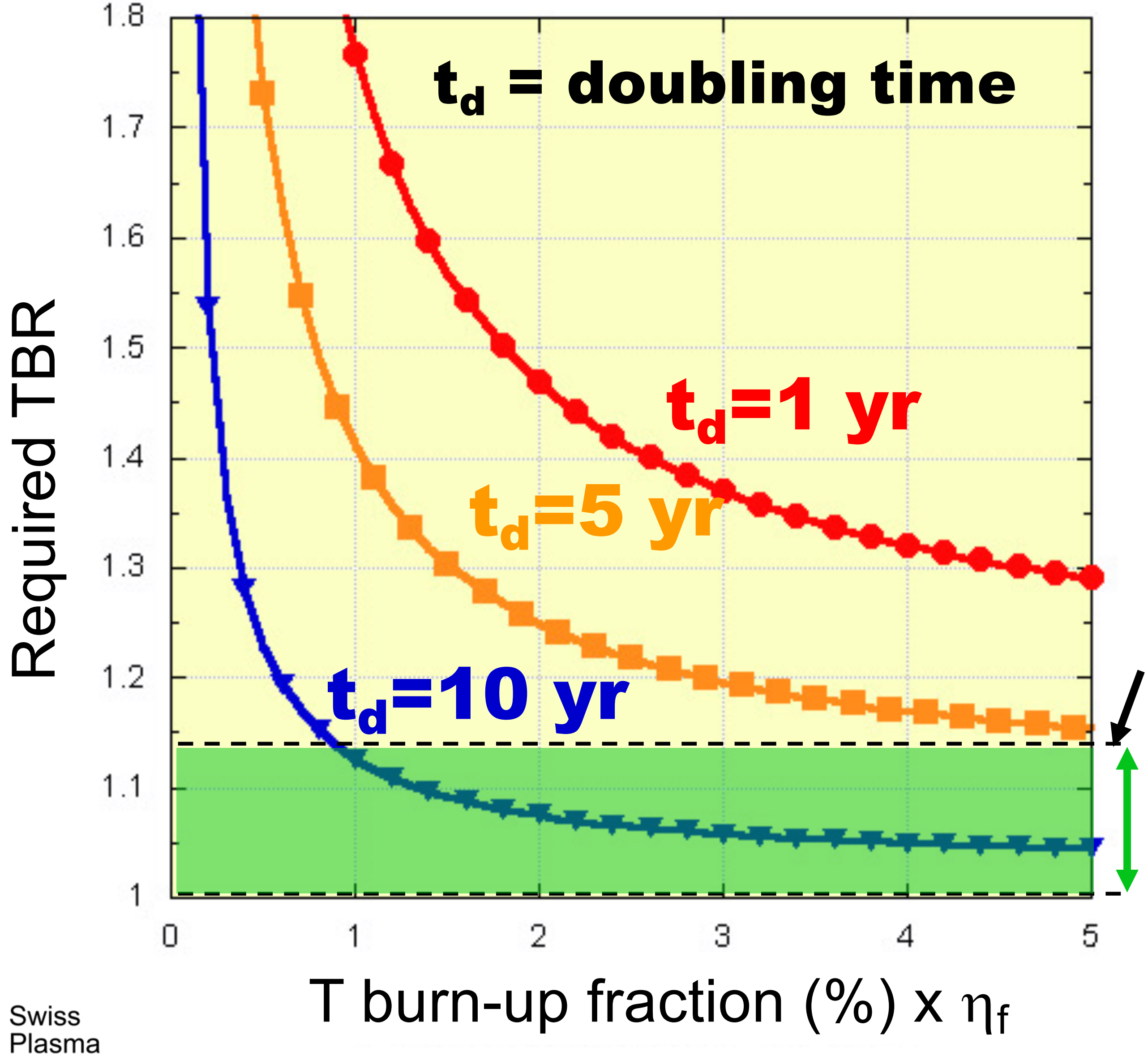
Which gives

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

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

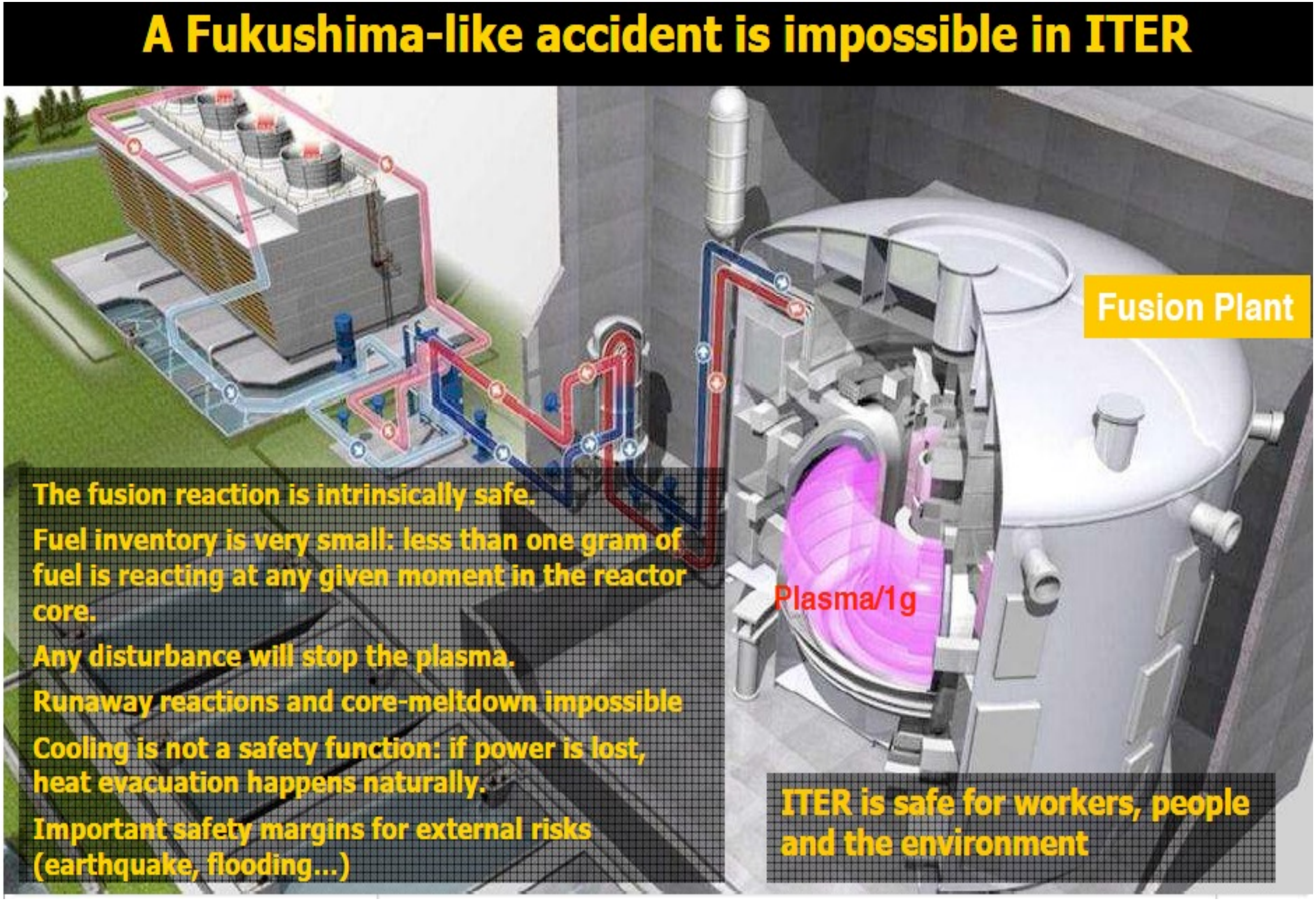
"Window" for Tritium self sufficiency

Significant R&D needed to stay in window

ITER SAFETY AND LICENSING

Swiss
Plasma
Center

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

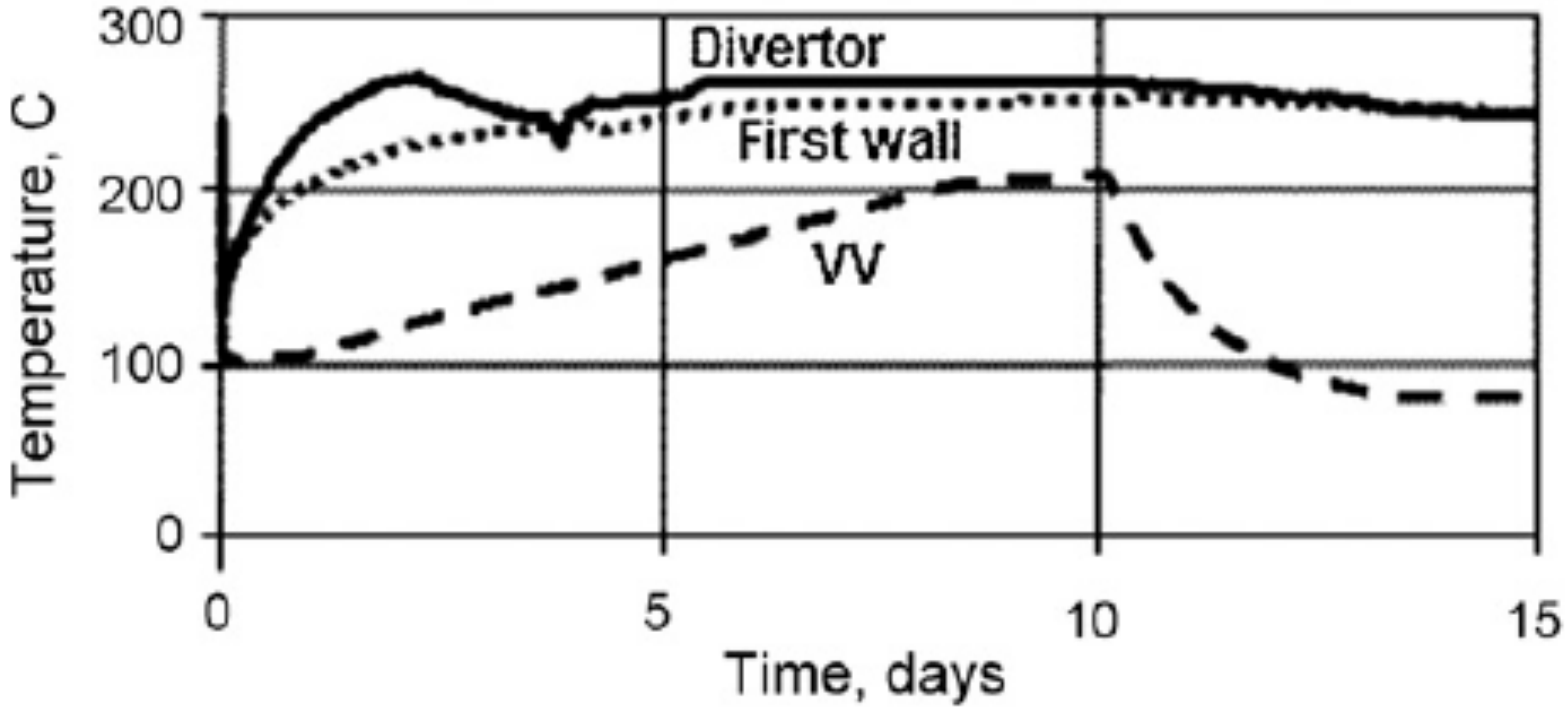
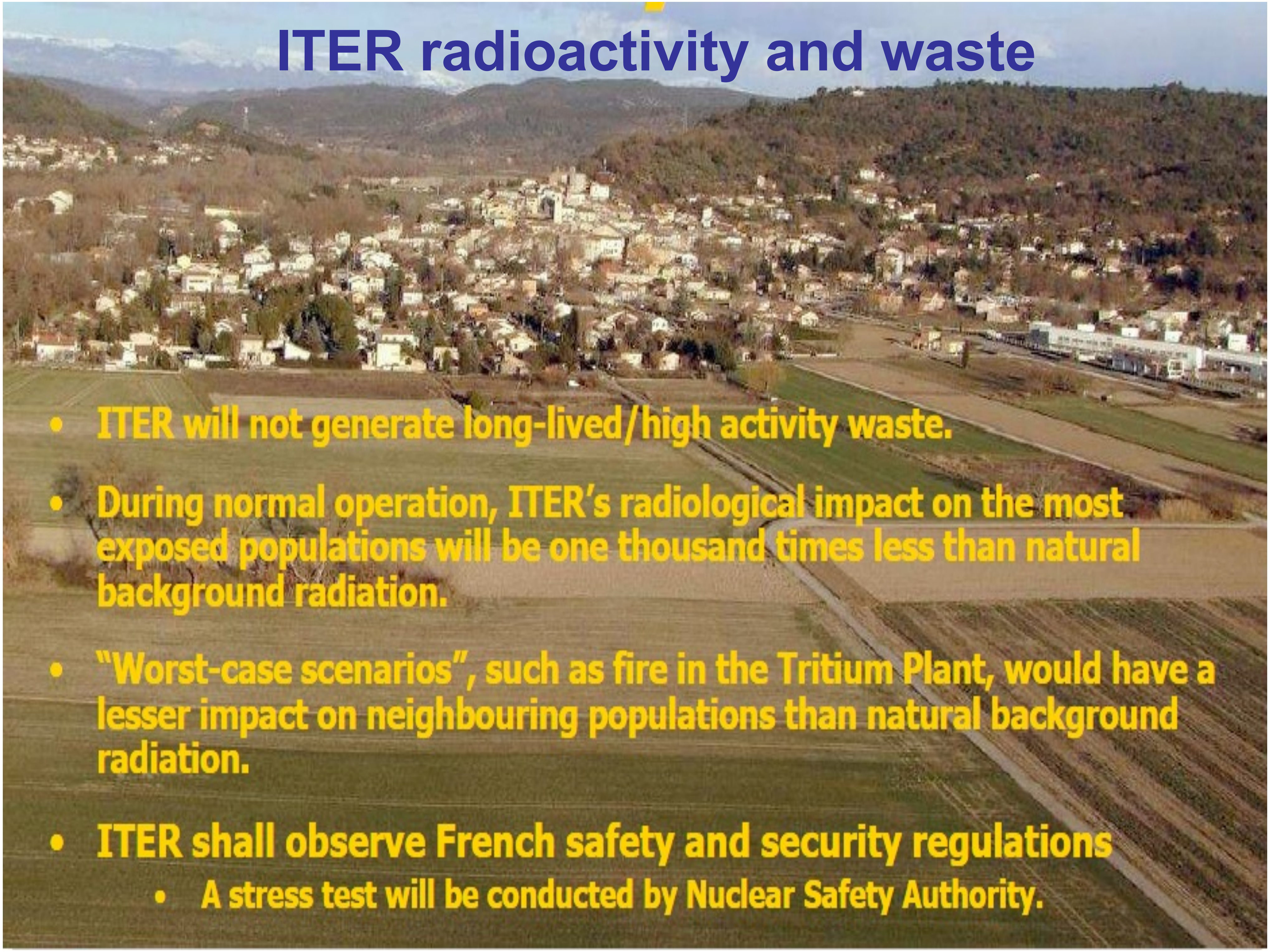


Fig. 1. Temperature evolution of divertor, first wall and vacuum vessel in event of loss of all water coolant flow, with cryostat vented to air after 10 days.



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.

Waste repartition

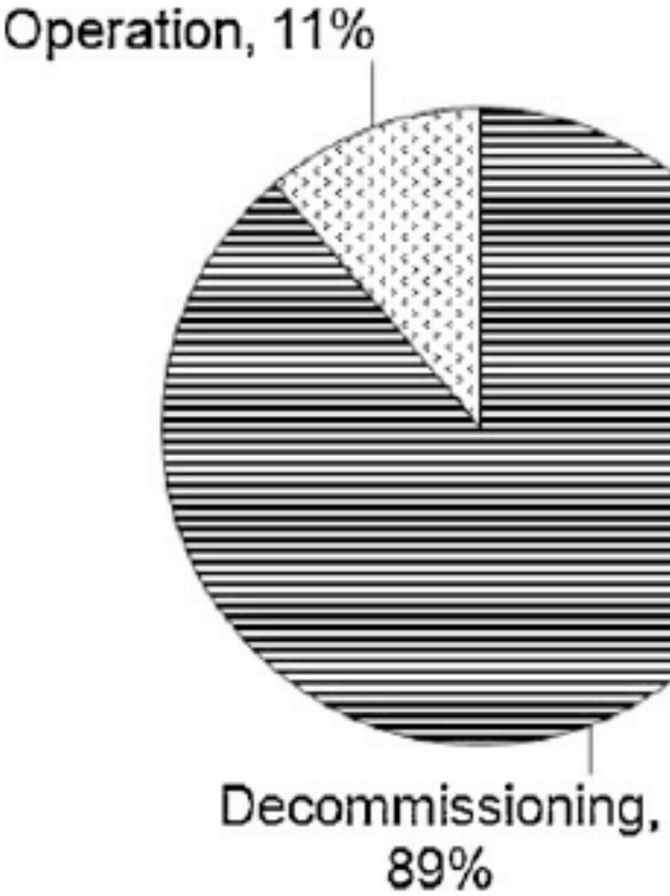


Fig. 1. Mass repartition between operation (component replacement, process and housekeeping waste) and decommissioning waste (without considering building demolition).

ITER licensing procedure

ITER is considered by French licensing authority as «Installation nucléaire de base», as a power plant (due to T and activation level)

Submission of Preliminary Safety Report in March 2010

Detailed examination by French Institut de Radioprotection et de Sécurité Nucléaire and experts

Decree for Authorization of Creation signed on 10.11.2012

→ITER is first fusion device to qualify as nuclear installation

TOWARD A FUSION POWER PLANT

Swiss
Plasma
Center

DEMO conceptual design

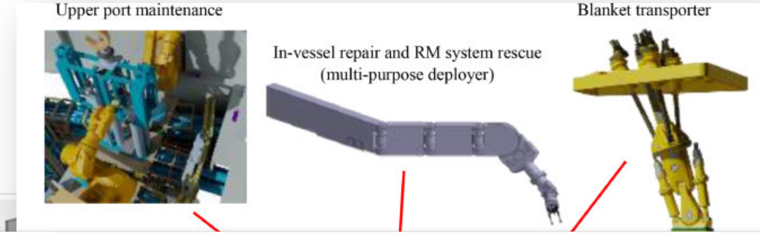
Hundreds of MW of electrical power
Closed fuel cycle
Plant availability

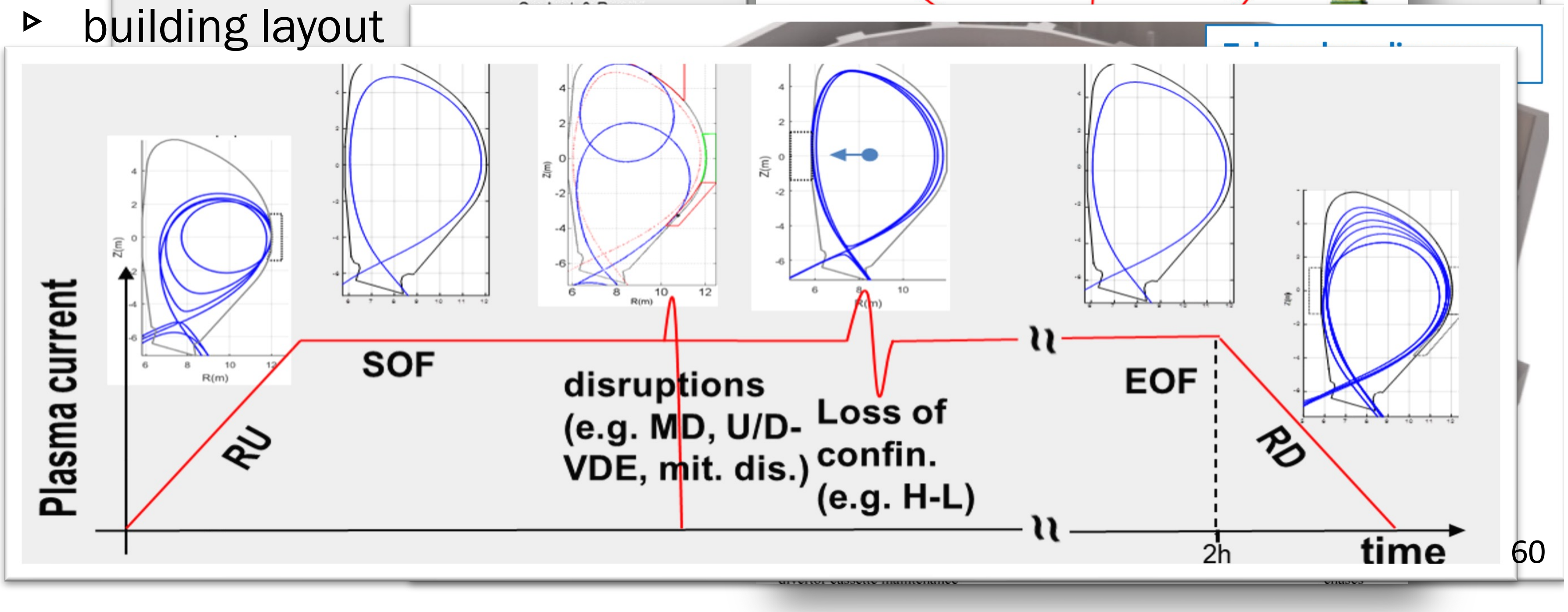
Capitalise on fusion-intrinsic safety features, bringing critical technologies to adequate maturity with an eye to reducing cost of electricity…

DEMO conceptual design

… following the recommendations of the DEMO Gate Review

- Move from research-oriented to design-driven
- Set-up the DEMO Central Team
- Address most critical problems
  - plasma scenarios
  - breeding blanket
  - remote maintenance
  - building layout





DEMO conceptual design

… (continued)

- Increase cost-consciousness
- Maintain industrial supply chain between ITER and DEMO
- Knowledge management and retention strategy
- Develop an adequate licensing plan
- *Train next generation of fusion scientists and engineers*