Nuclear Fusion and Plasma Physics

Lecture 10

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EPFL

Lay-out

Part I

Plasma wall interaction

Part II

Structural materials

Part I – Plasma-wall interaction

Requirements for reactor first wall

Limiters and divertors

The plasma scrape off layer

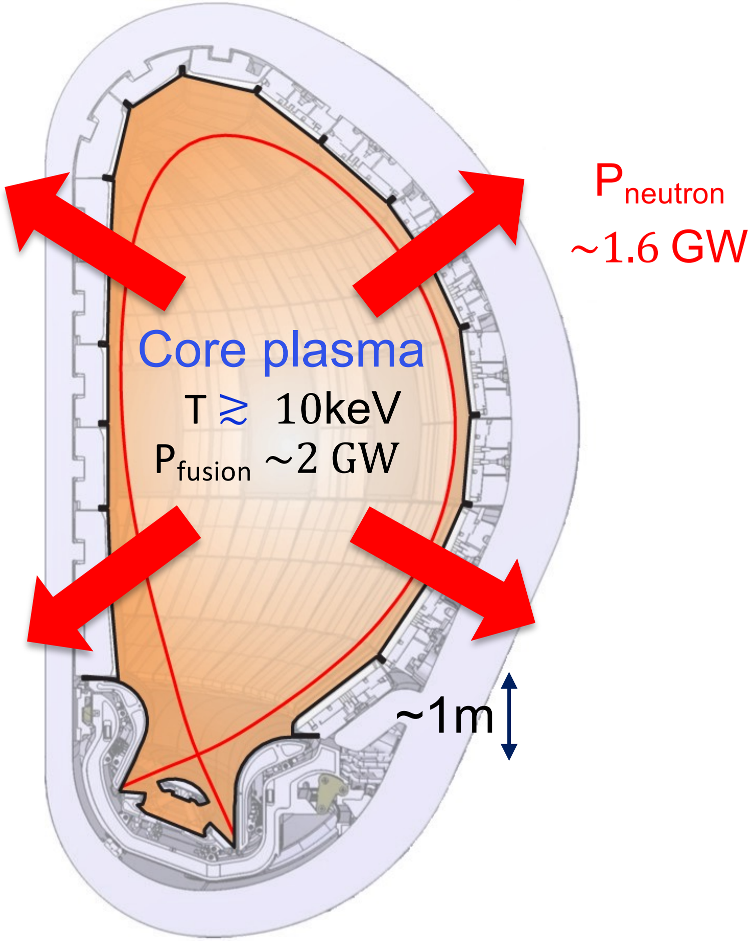
Advantages of divertor concept

Plasma facing materials for ITER

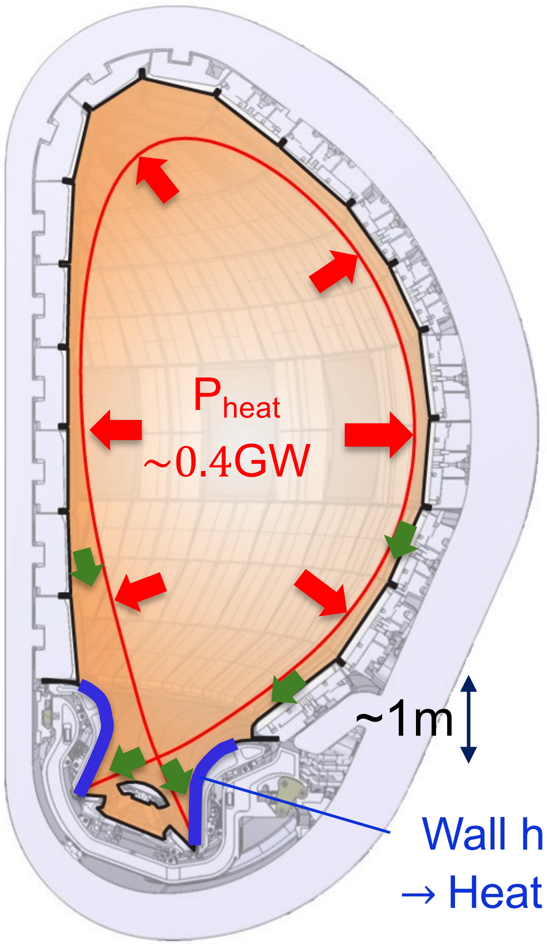
Further challenges for divertors

Innovative divertor configurations

Power on a tokamak reactor first wall



Power on a tokamak reactor first wall



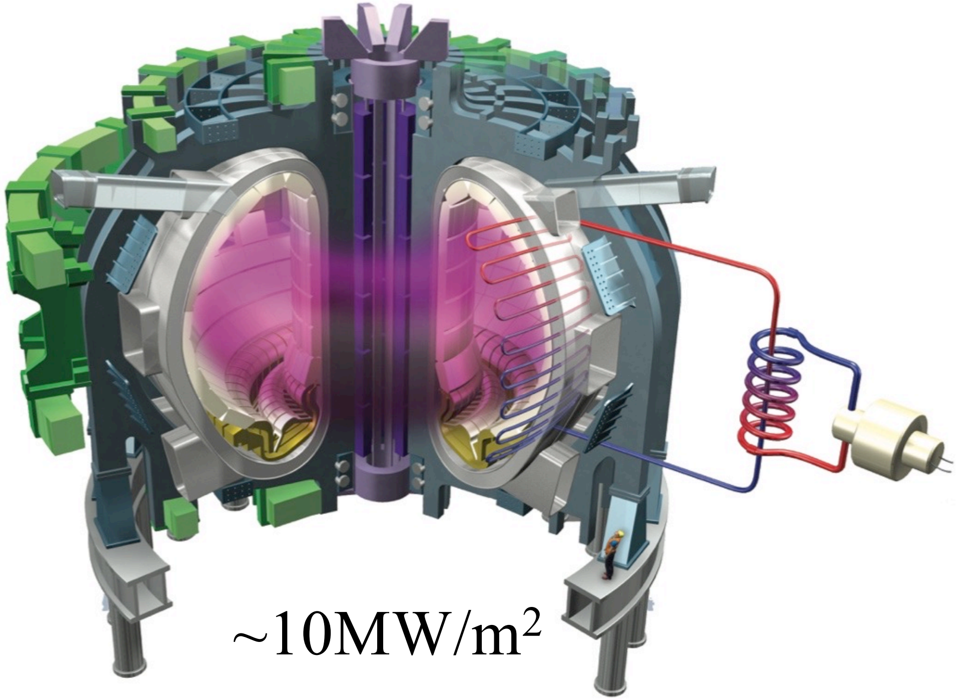
Wall heat flux ≲ 10MW/m^2; T_{plasma} ≲ a few eV
→ Heat exhaust challenge

Requirements for reactor first wall

Withstand very large heat fluxes on the material

Limit erosion, melting

~1MW/m^2



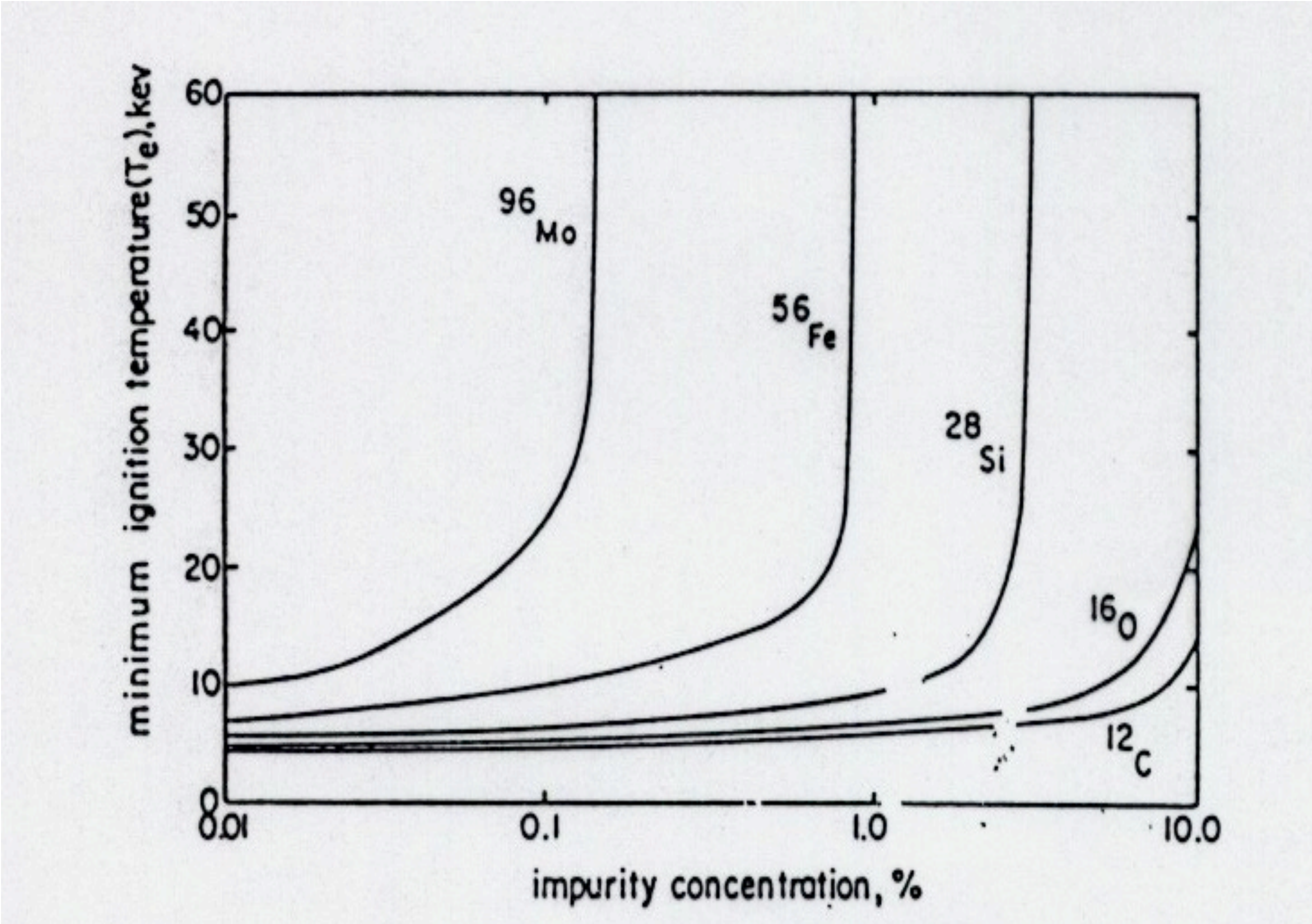
~80MW/m^2

~10MW/m^2

Requirements for reactor first wall

Keep the plasma pure

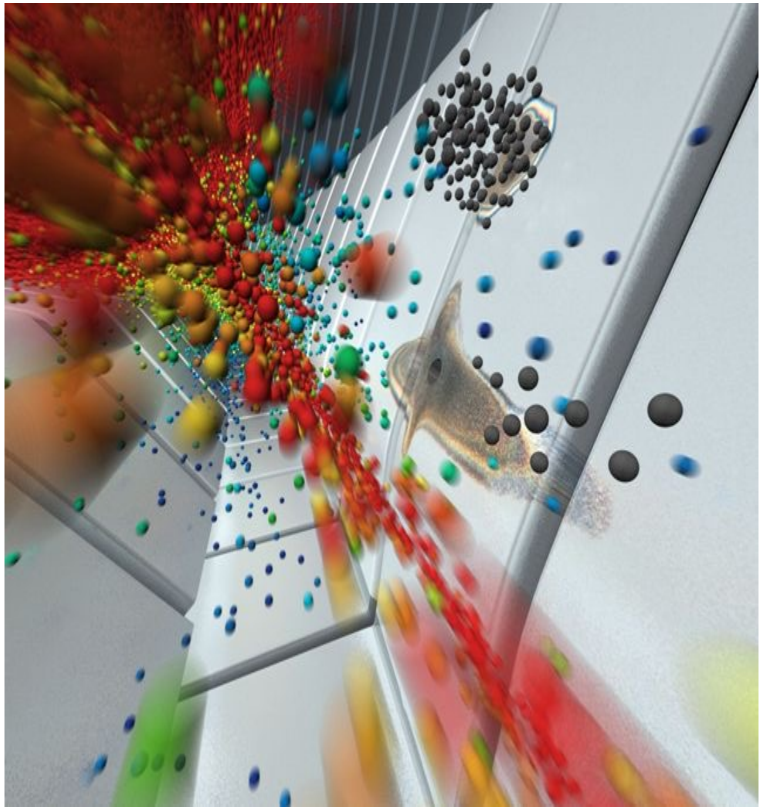
$$\frac{P_b}{\text{volume}} \simeq A n^2 Z_{\text{eff}} T_e^{1/2}$$



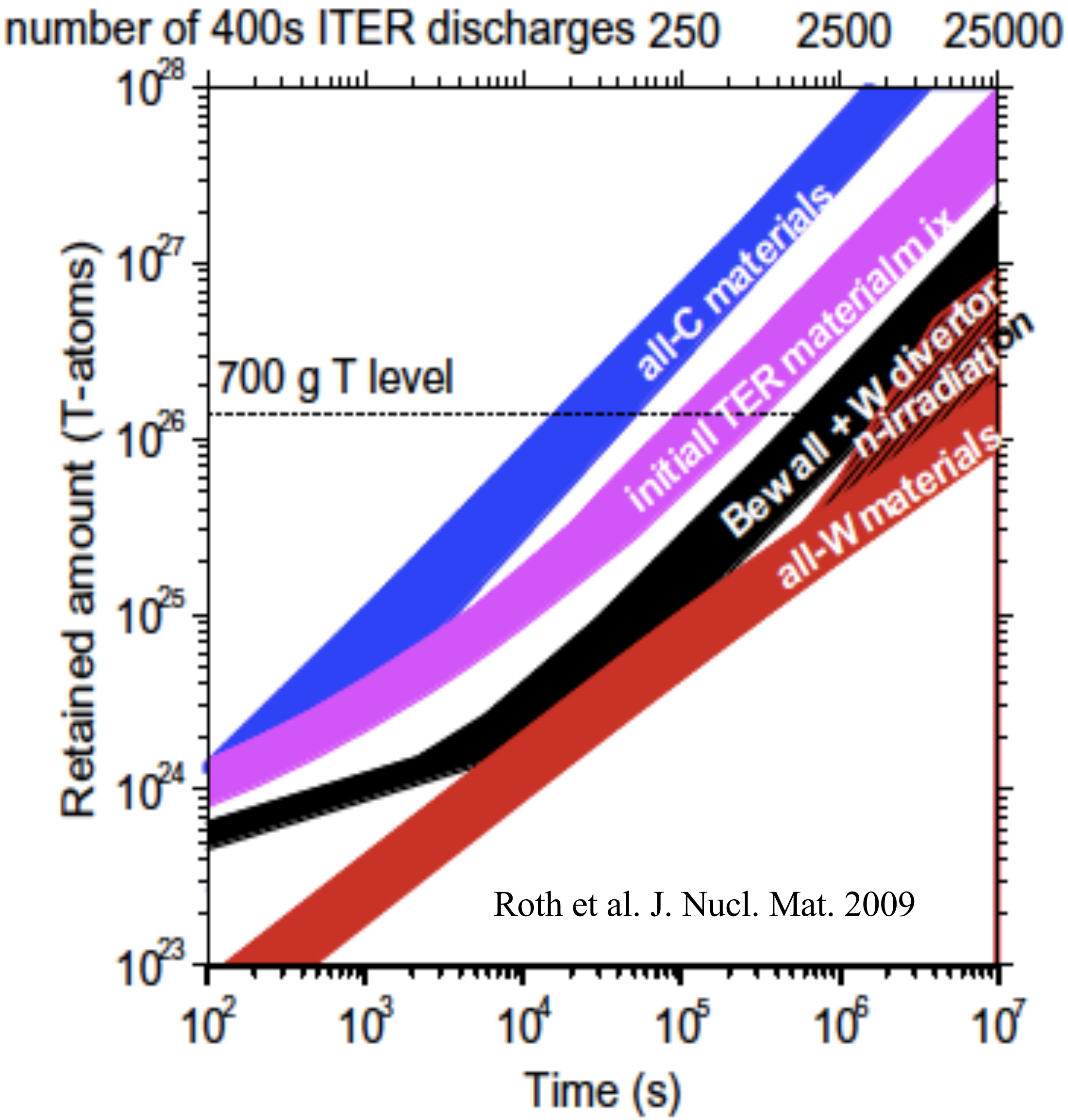
Minimum ignition temperature goes up with impurity concentration and with the atomic number of the impurity species

Requirements for reactor first wall

Minimise retention of Tritium
(co-deposition with Carbon)



Courtesy of Leena Aho-Mantila and Jyrki Hokkanen
(CSC – IT Center for Science Ltd).



Requirements for reactor first wall

Exhaust fusion & external heating power, withstanding large heat fluxes

Keep the plasma pure

Minimise retention of Tritium

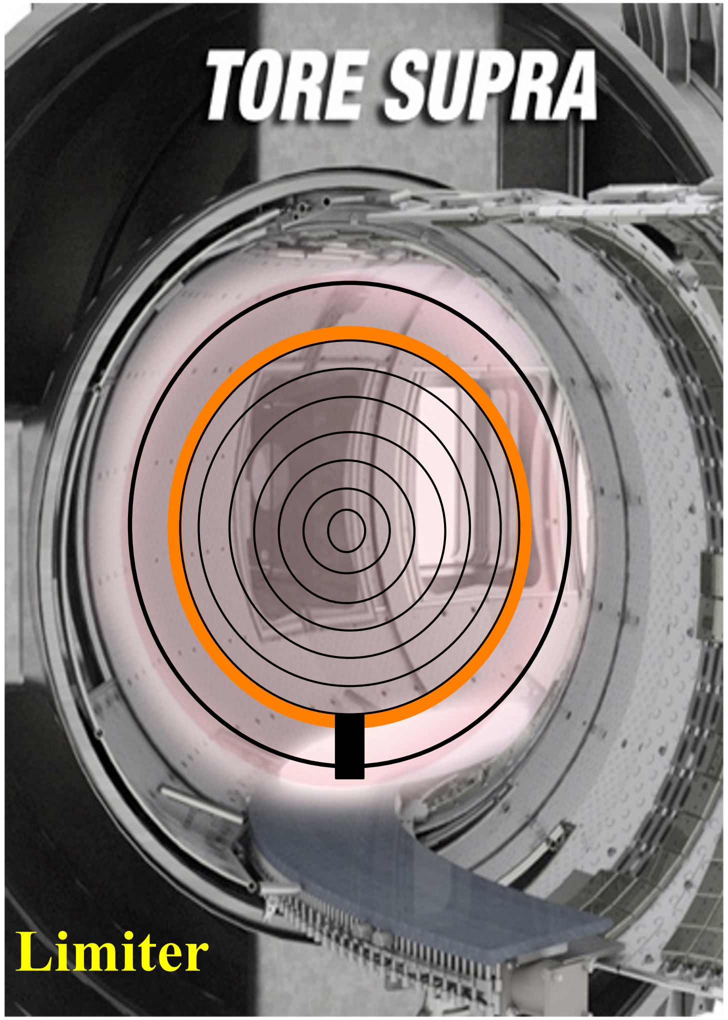
Minimise dust production

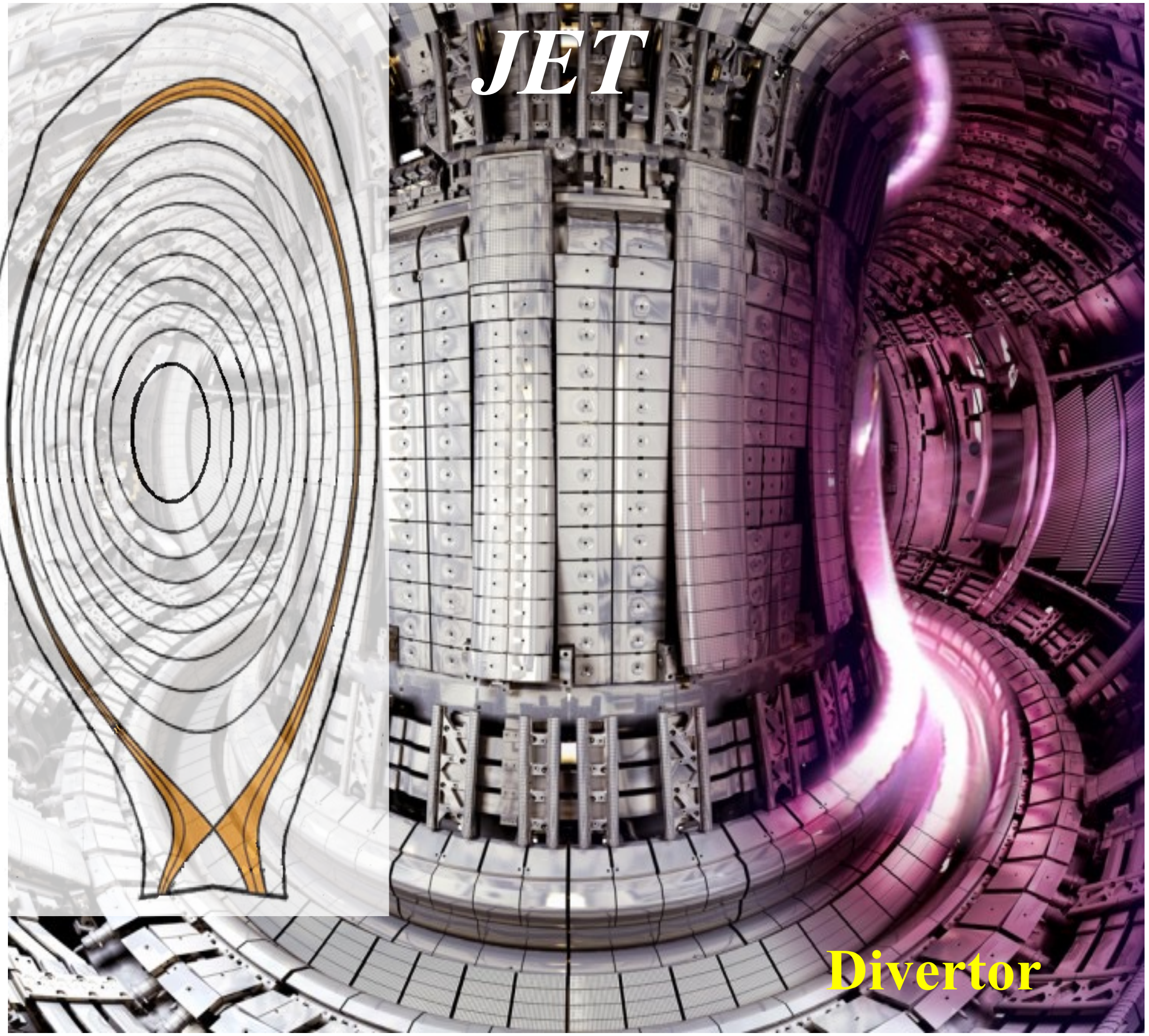
Provide vacuum containment

Remove Helium ashes (pumping)

Limiter and divertor configurations

Direct contact of plasma with vessel wall must be limited to well-defined areas, which take the power carried by particles and not radiated by plasma

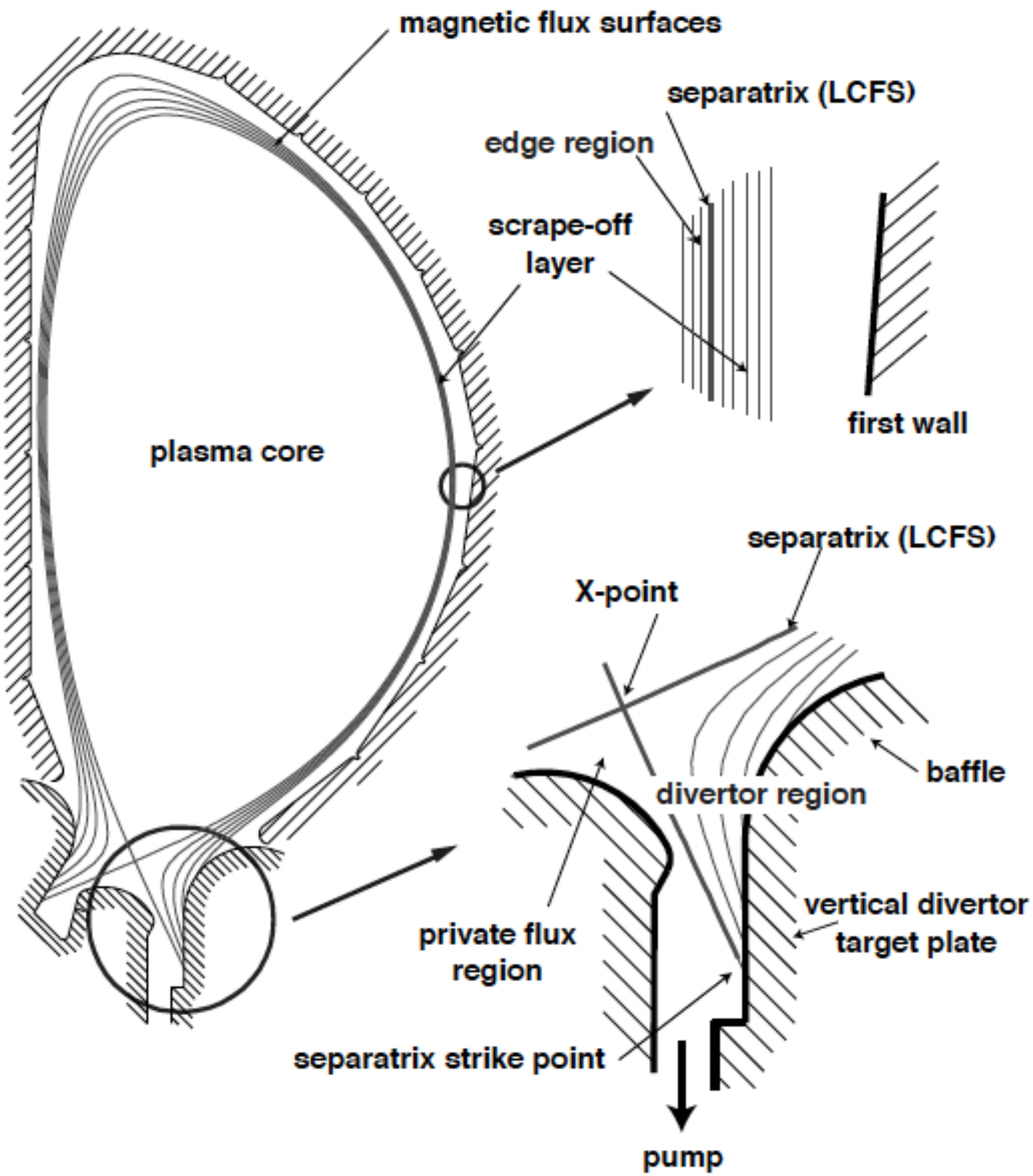




The divertor concept

The Scrape-Off-Layer (SOL) is the outer layer of plasma in direct contact with the material wall

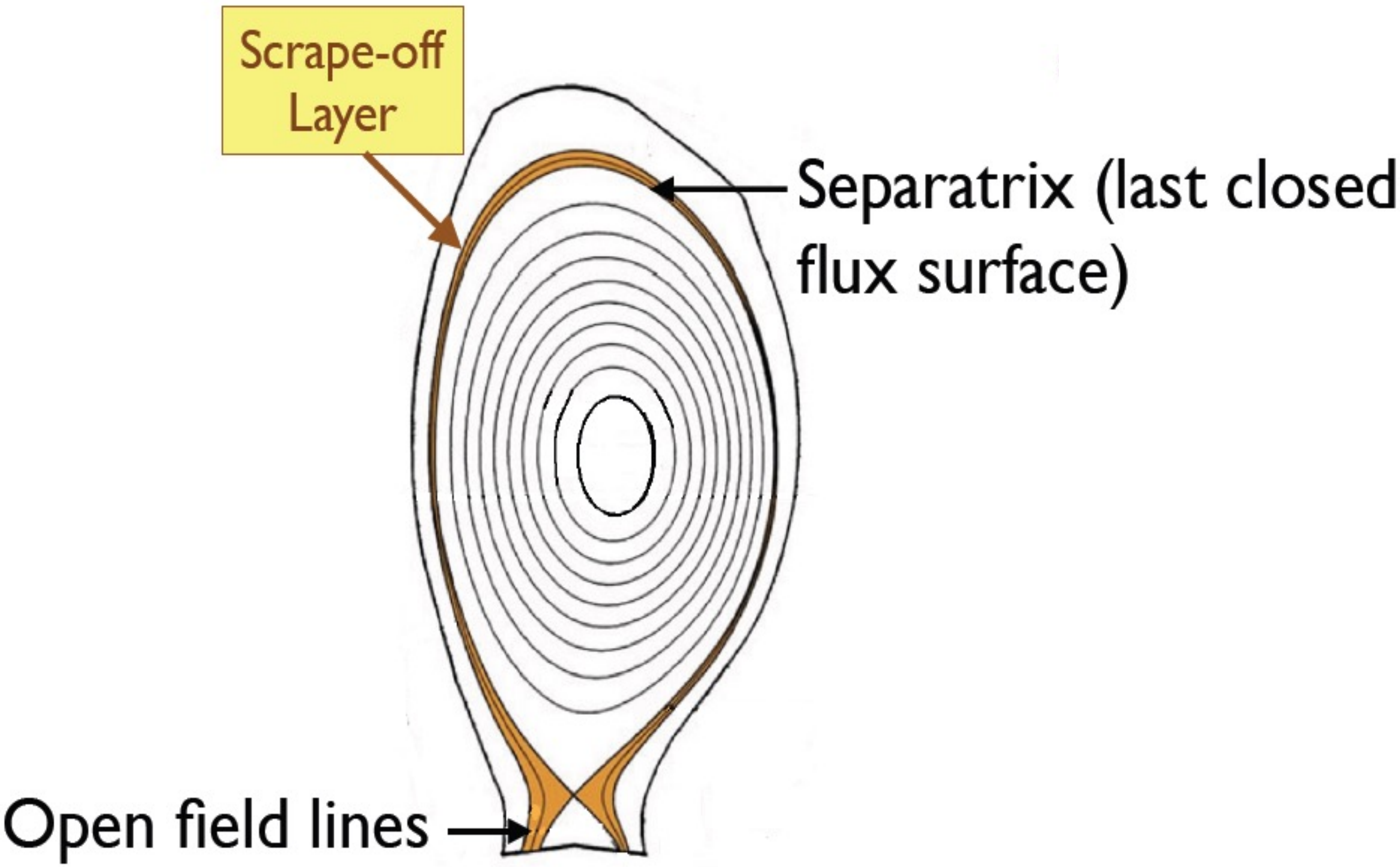
The SOL thickness results from balance between cross-field and parallel dynamics



Advantages of divertor concept -1-

Long connection length parallel to B (= length of field line before it touches the wall, e.g. in ITER ~150m) reduces parallel power flux arriving to target

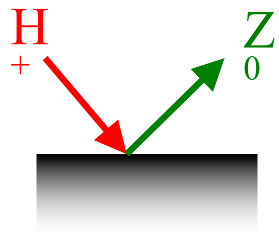
Parallel gradient of T allows low T in divertor chamber (~5eV)



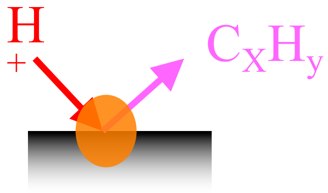
Advantages of divertor concept -2-

Because of lower plasma temperature, reduction in erosion and impurity production by

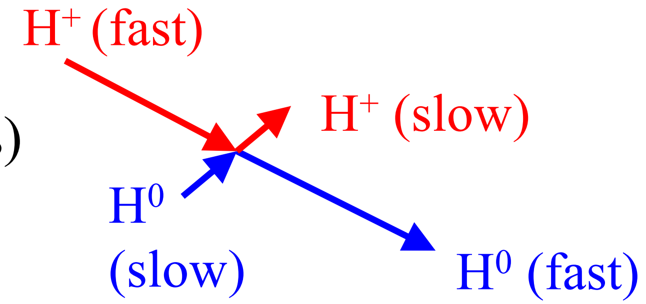
Physical sputtering by ions



Chemical sputtering by ions

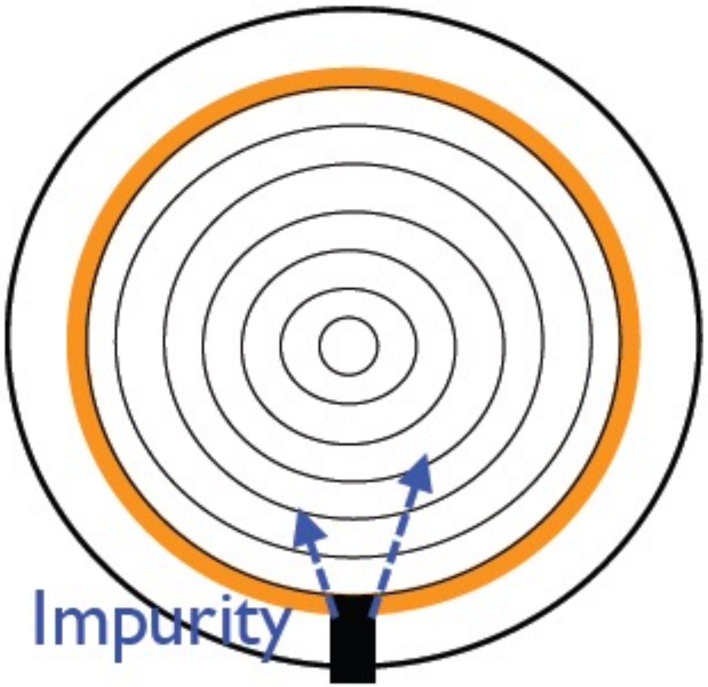


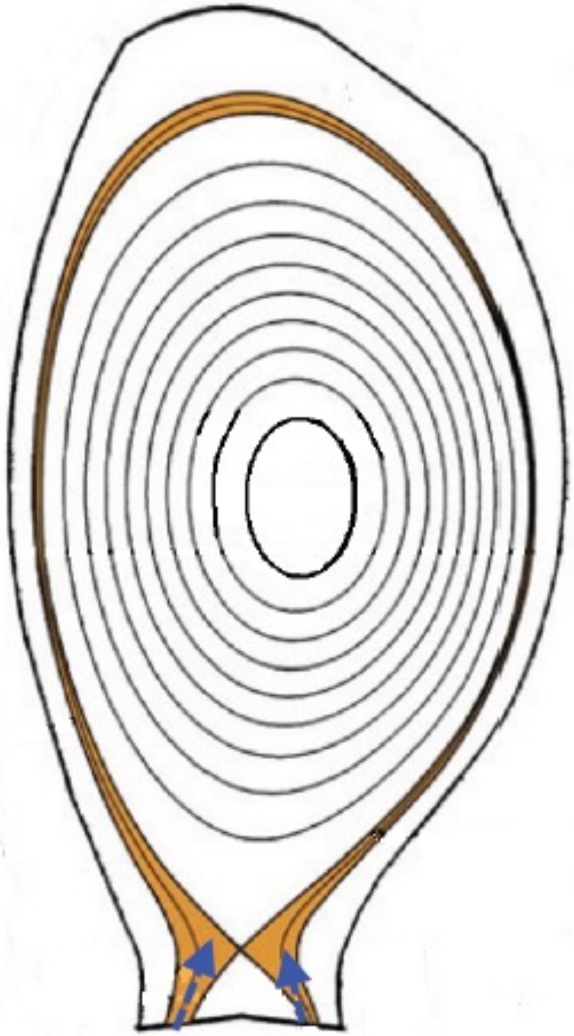
Neutral impact (charge exchange collisions)



Advantages of divertor concept -3-

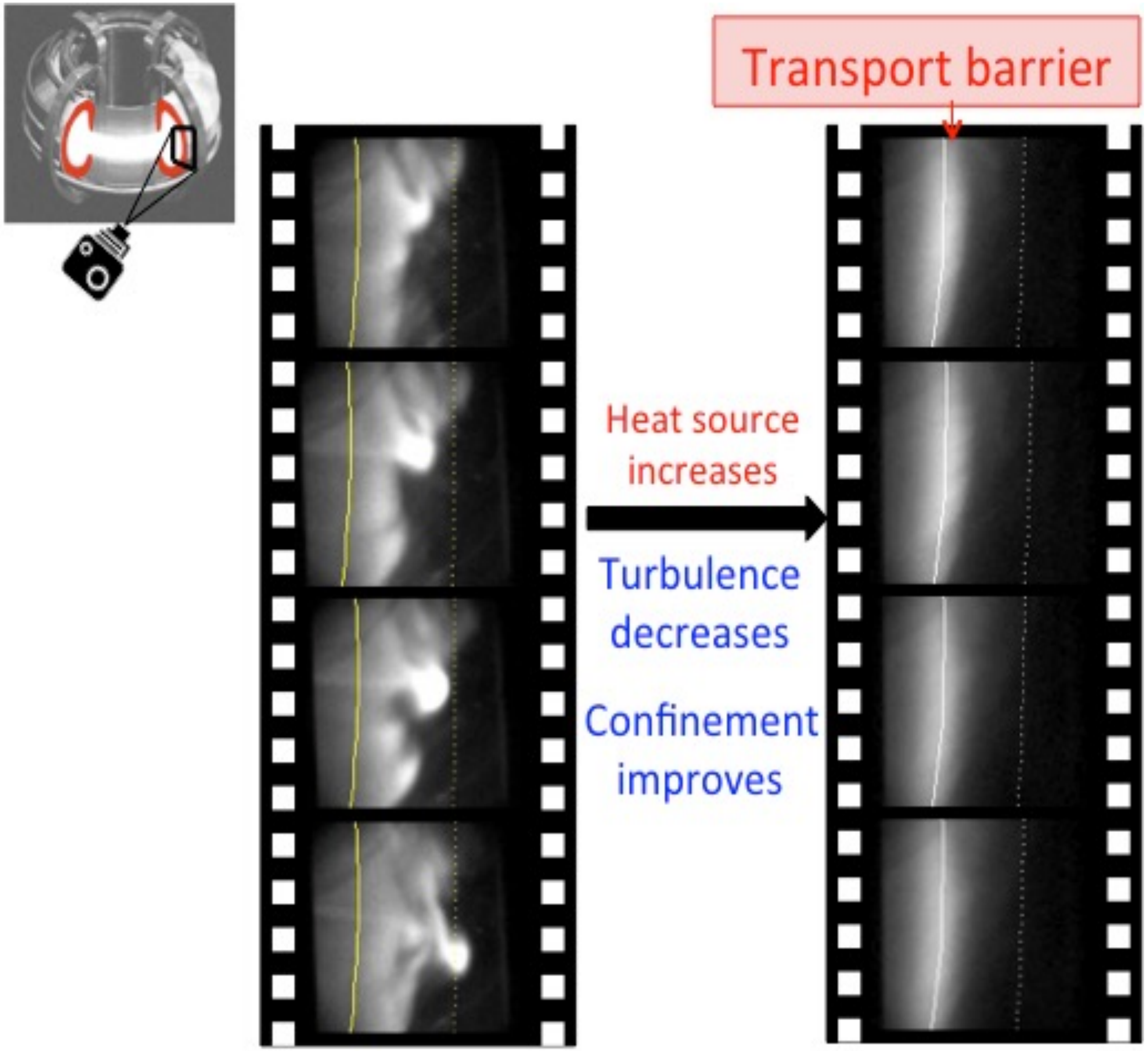
Reduction in impurity transport back to core plasma





Advantages of divertor concept -4-

Easier access to high confinement regimes

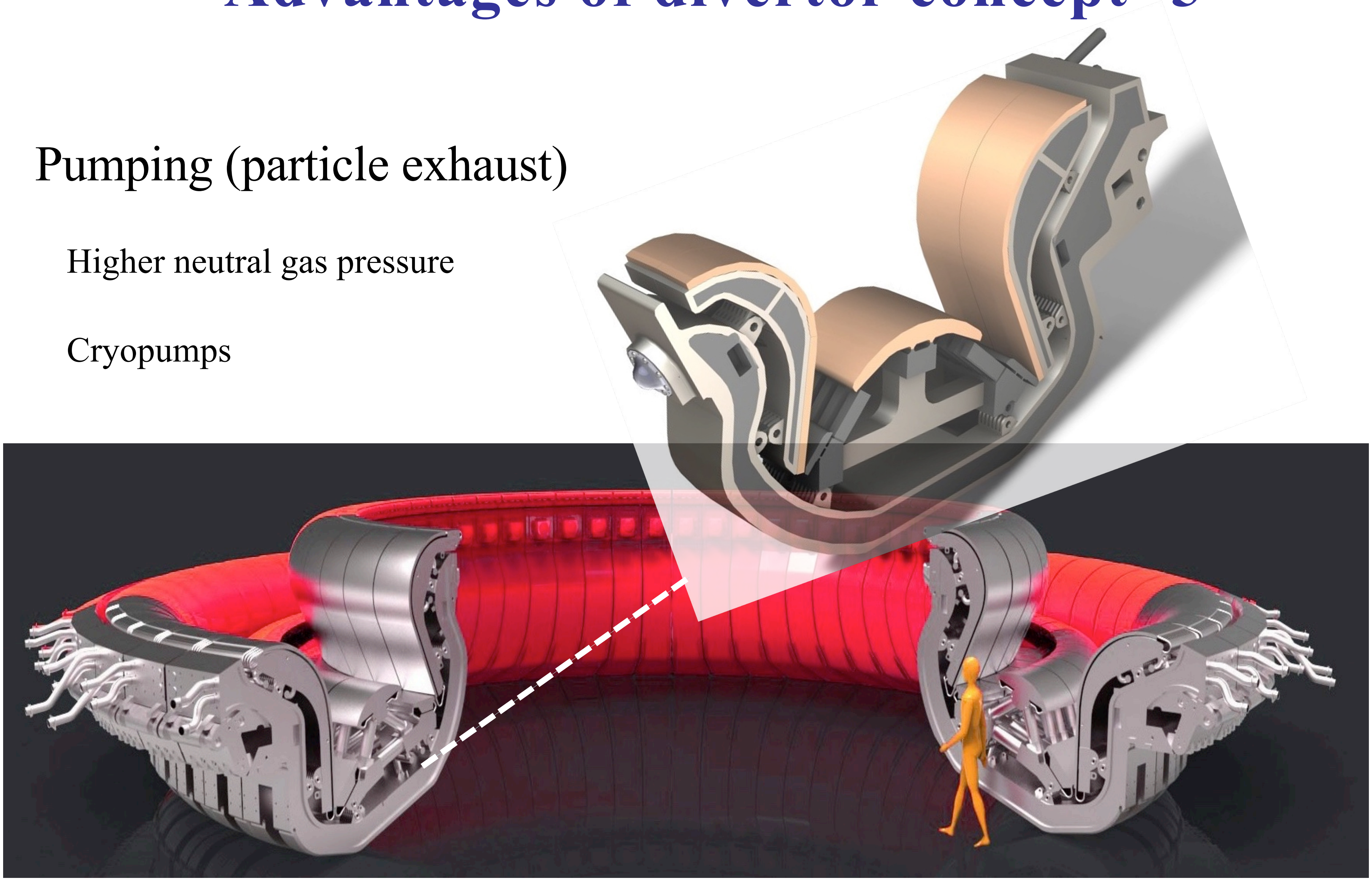


Advantages of divertor concept -5-

Pumping (particle exhaust)

Higher neutral gas pressure

Cryopumps



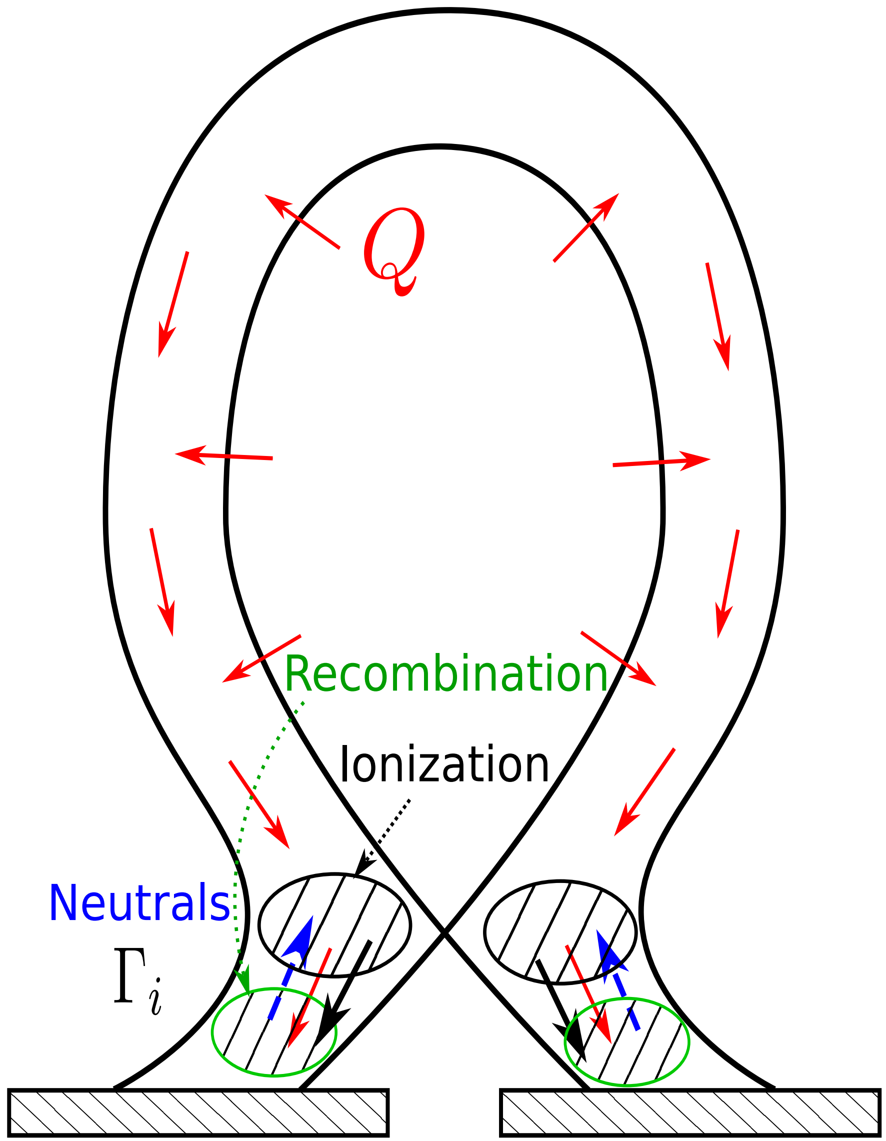
Advantages of divertor -6- *detachment*

At ~5eV $\sigma_{ionisation} < \sigma_{charge\ exchange}$

Energy is transferred from ions to neutrals, which spread power deposition (*neutral cushion*)

T is further reduced and e-i volumetric recombination occurs close to the targets

Low energy flux to the target as most of power is dissipated in radiation



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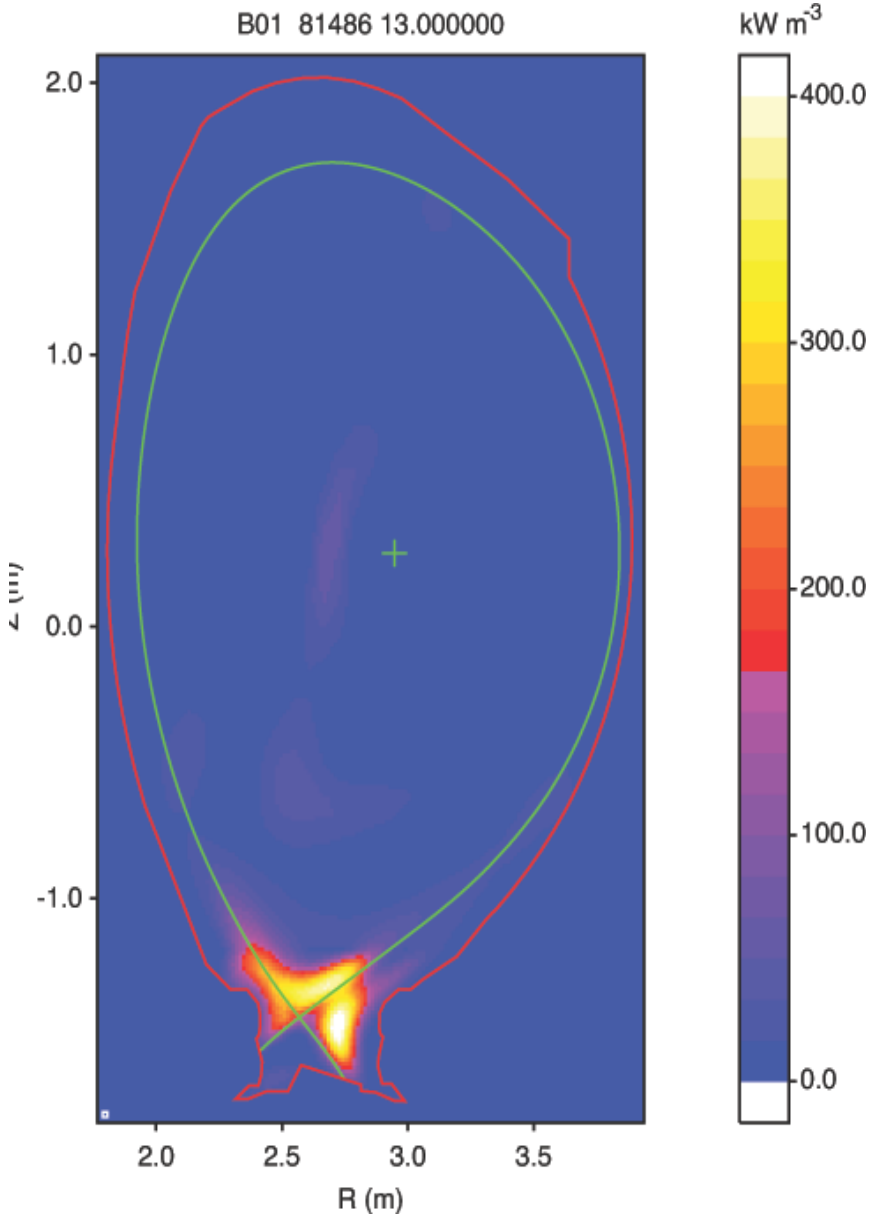
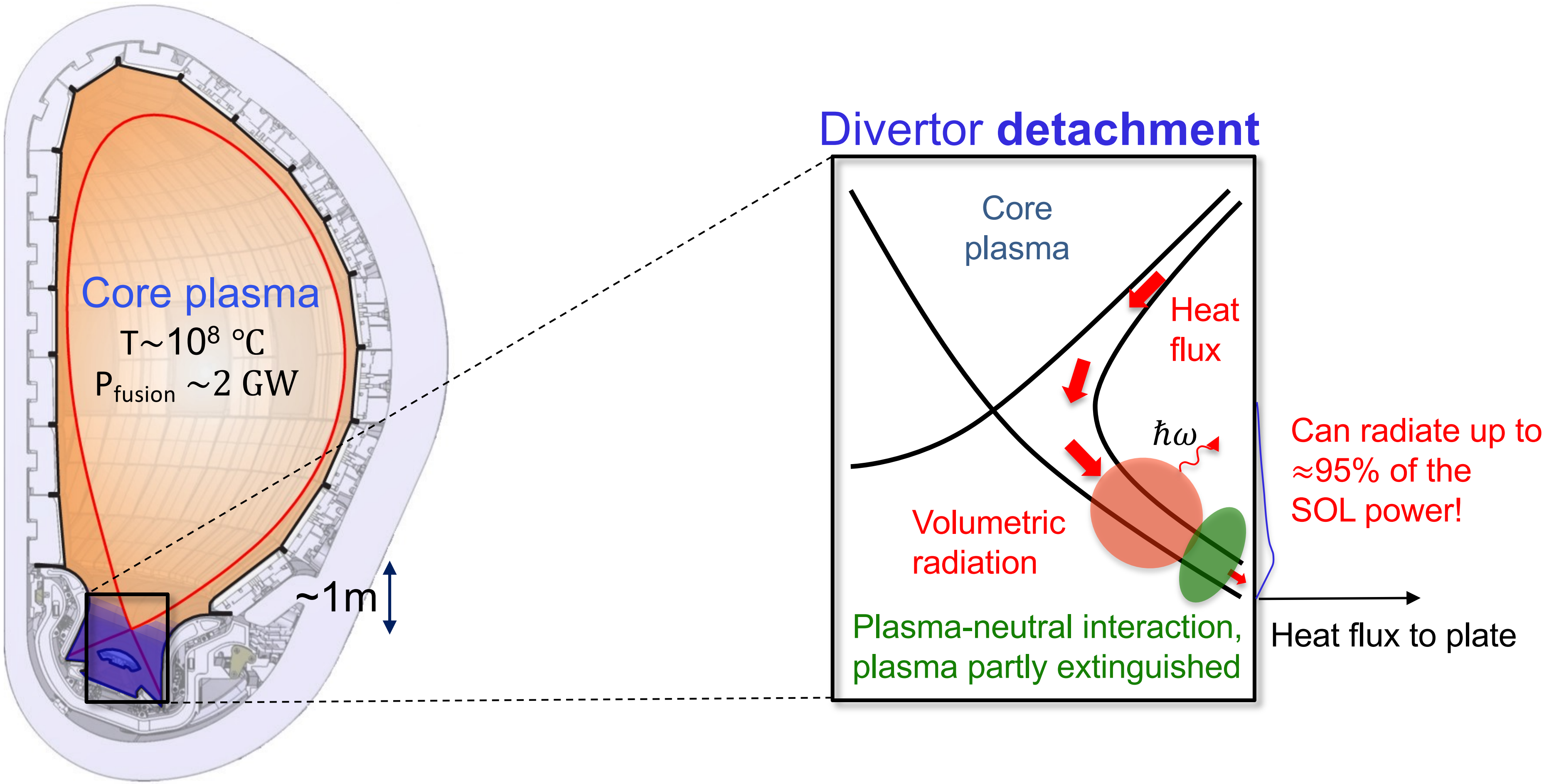


Advantages of divertor -6- *detachment*



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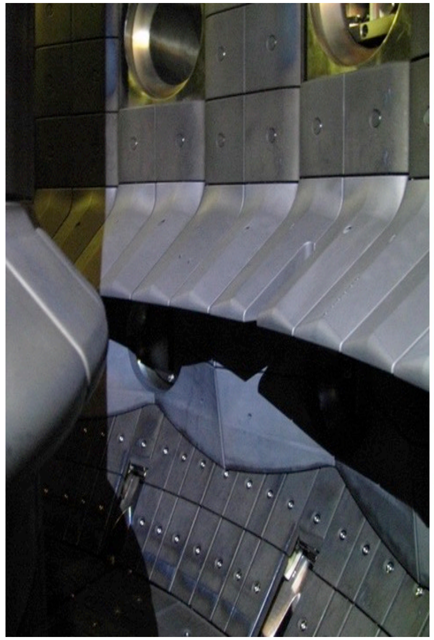
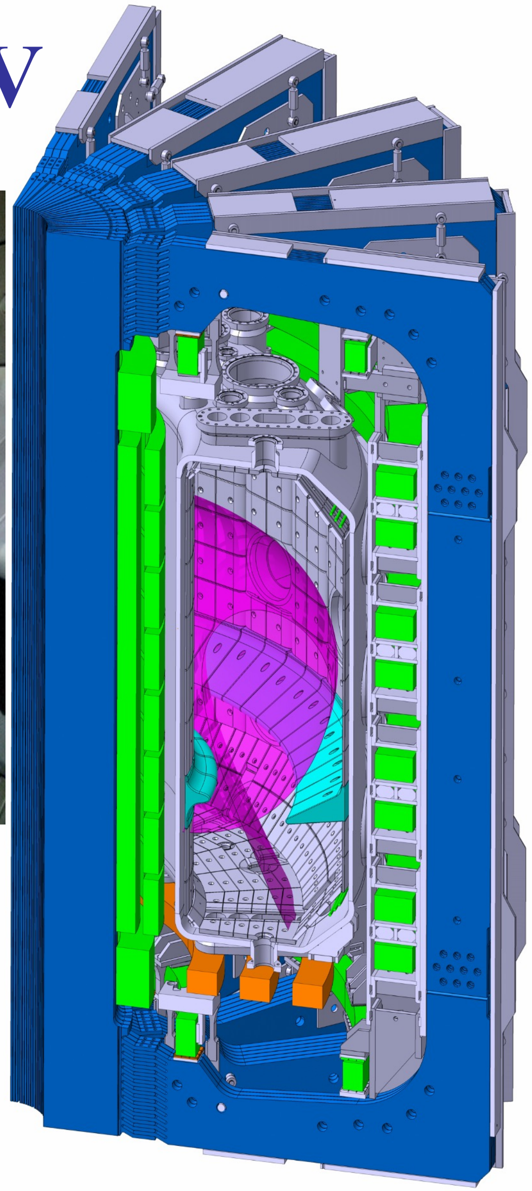
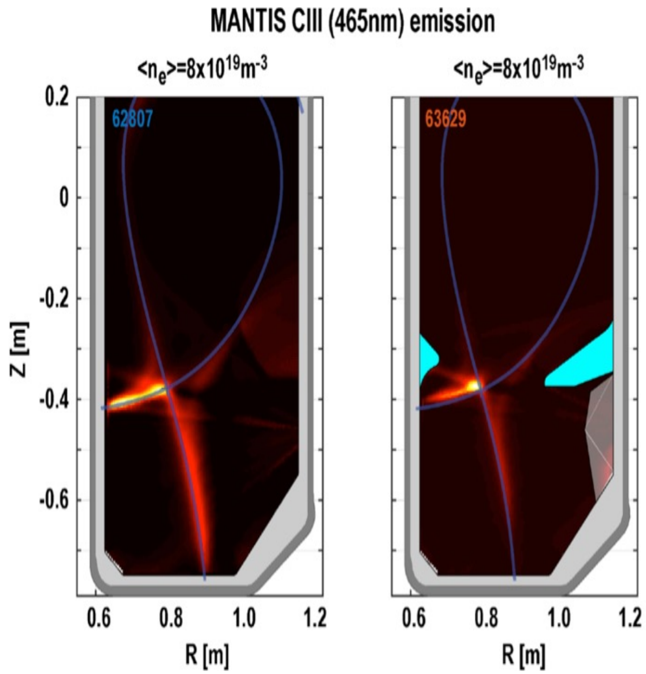
Plasma detachment on TCV

Internal baffles creating a divertor chamber of variable closure for plasma and heat exhaust control





The results show higher neutral and plasma pressure in the divertor, as expected, and easier plasma detachment



EUROfusion

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First wall materials for ITER

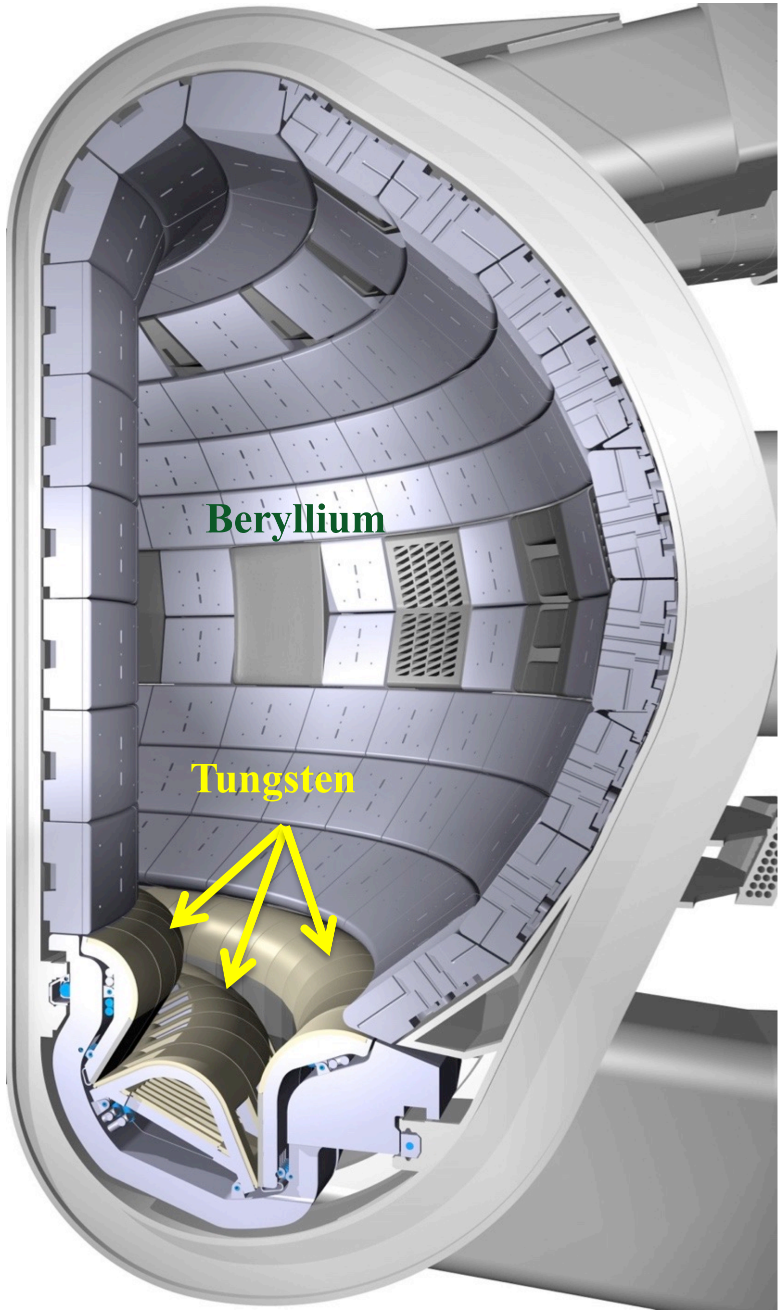
ITER divertor will be made of W

Low T-retention, high threshold for sputtering

Walls will be made of beryllium

Low-Z, low T-retention, good oxygen getter

Materials chosen also to minimise deterioration of thermo-mechanical properties under neutron irradiation

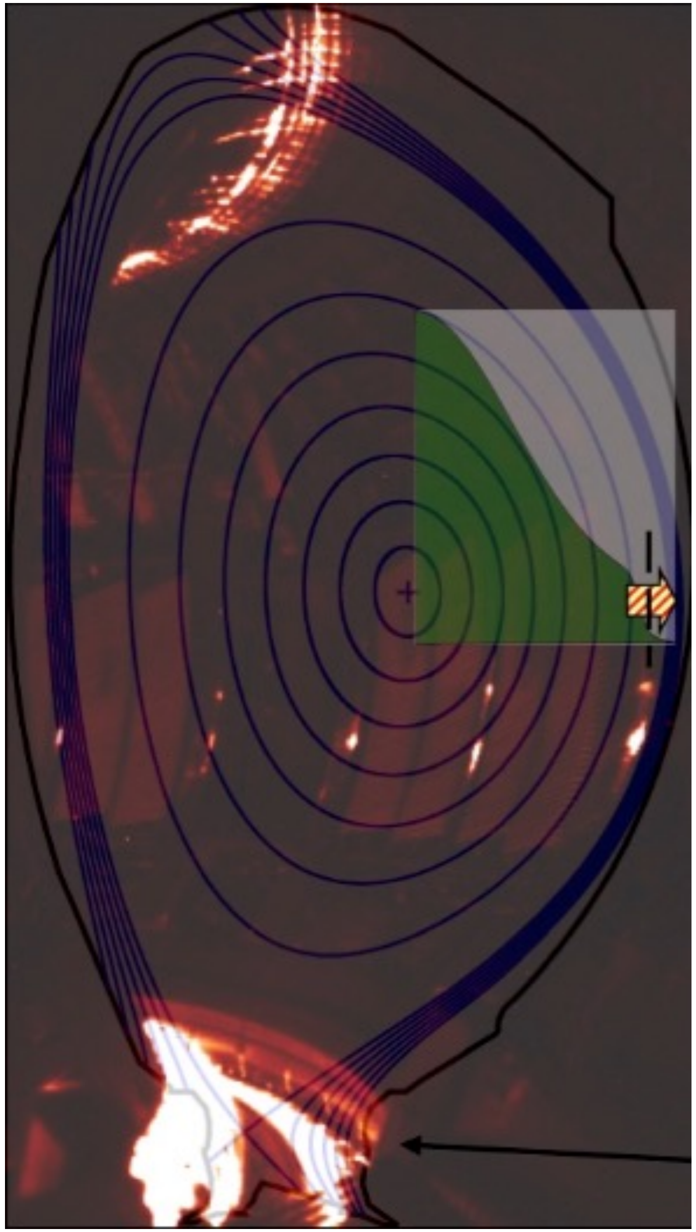


Further challenges for divertors
Transients

Edge Localised Modes, ELMs
Large edge gradients give rise to instabilities that generate outwards bursts of energy and particles → large thermal loads

Ex. ELMs in ITER

15MJ in 0.2ms over $6m^2$
→ $10GW/m^2$
→ surface temperature ~ 6000° C
→ melting

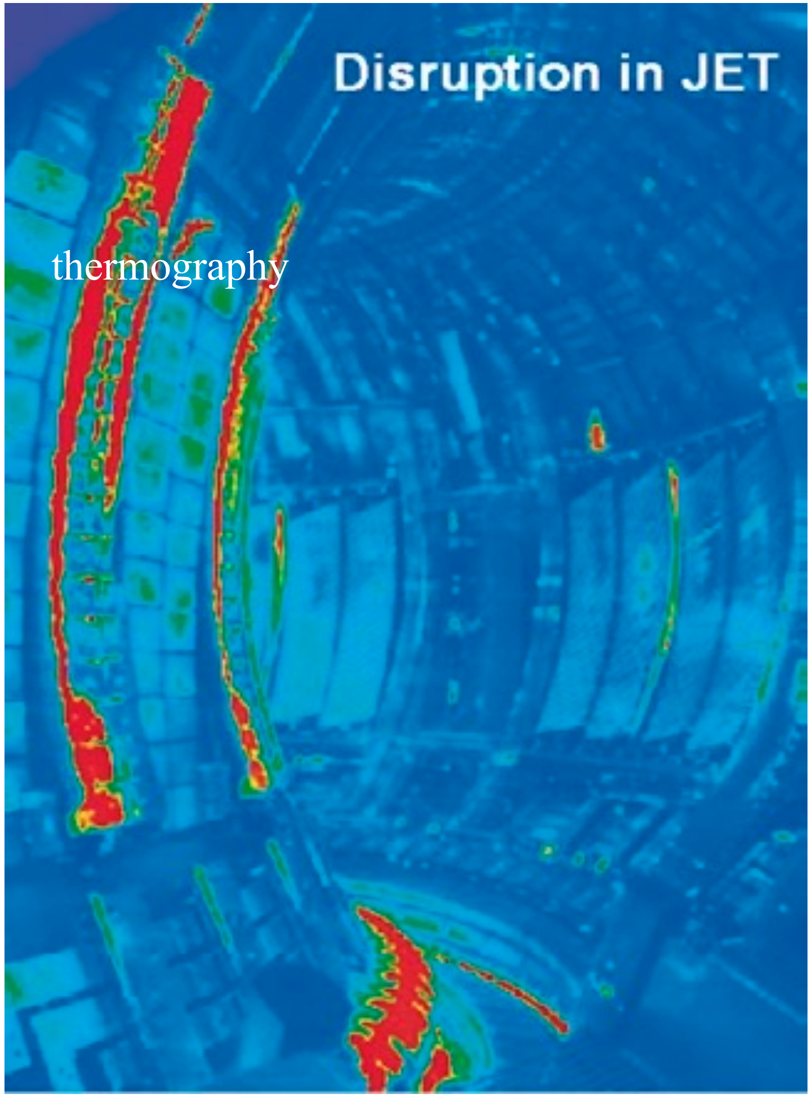


Further challenges for divertors
Transients

Disruptions
Sudden loss of plasma leading to large deposition of energy on walls

Ex. ITER full energy disruptions: peak energy densities on divertor of 5-20 MJ/m^{-2} over 3ms
W divertor lifetime exceeded in ~300 disruptions

We don't have materials that withstand for sufficiently long time these thermal loads, therefore we need to act on plasma to avoid or mitigate these violent transient events

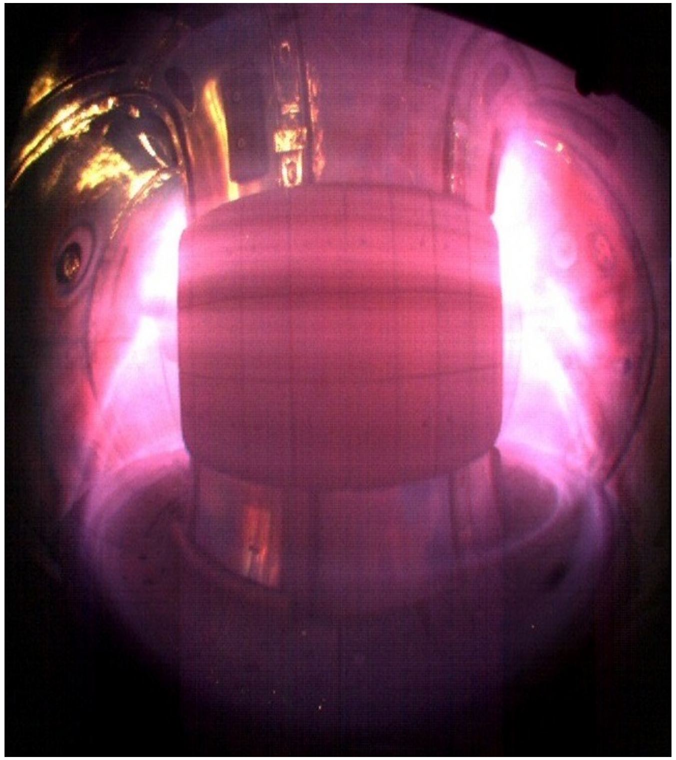


Innovative divertor configurations

New divertor configurations are explored for DEMO and reactors

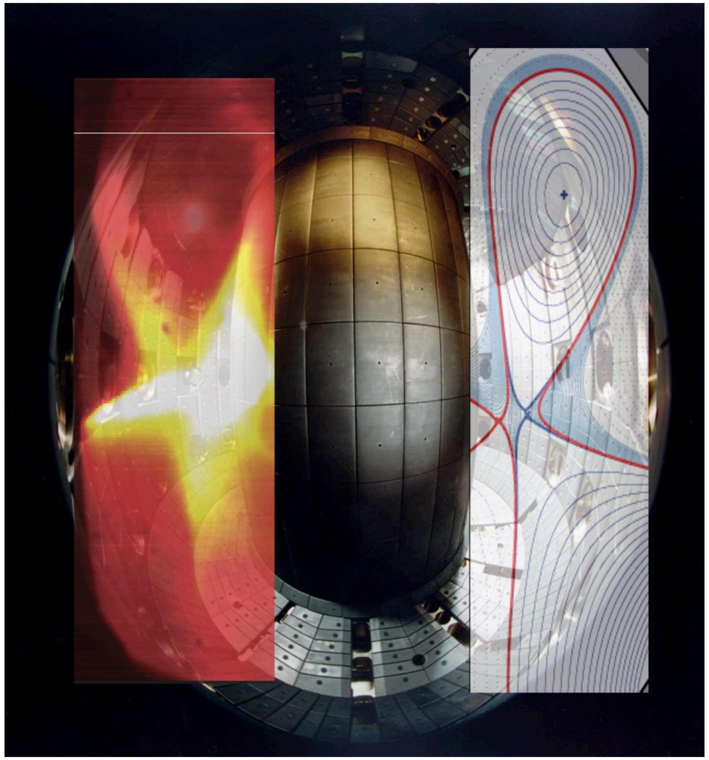
Limit material erosion, increase radiated power with detached plasma, keep plasma pure

Ex. of alternative concepts: liquid metal, super-X, snowflake, …



Liquid metal walls
Compass (CZ)

Super-X divertor
MAST-U (UK)



Snowflake divertor
TCV (CH)

Summary of part I

Reactor first wall must satisfy a number of stringent requirements

Divertor concept is adopted as it has several advantages

New divertor configurations are explored for DEMO and reactors

Plasma wall interaction results from integration of plasma, atomic and materials physics

Part II – Structural materials

Requirements for fusion materials

Fusion vs. fission

Effects of 14 MeV neutrons

Evolution of materials properties

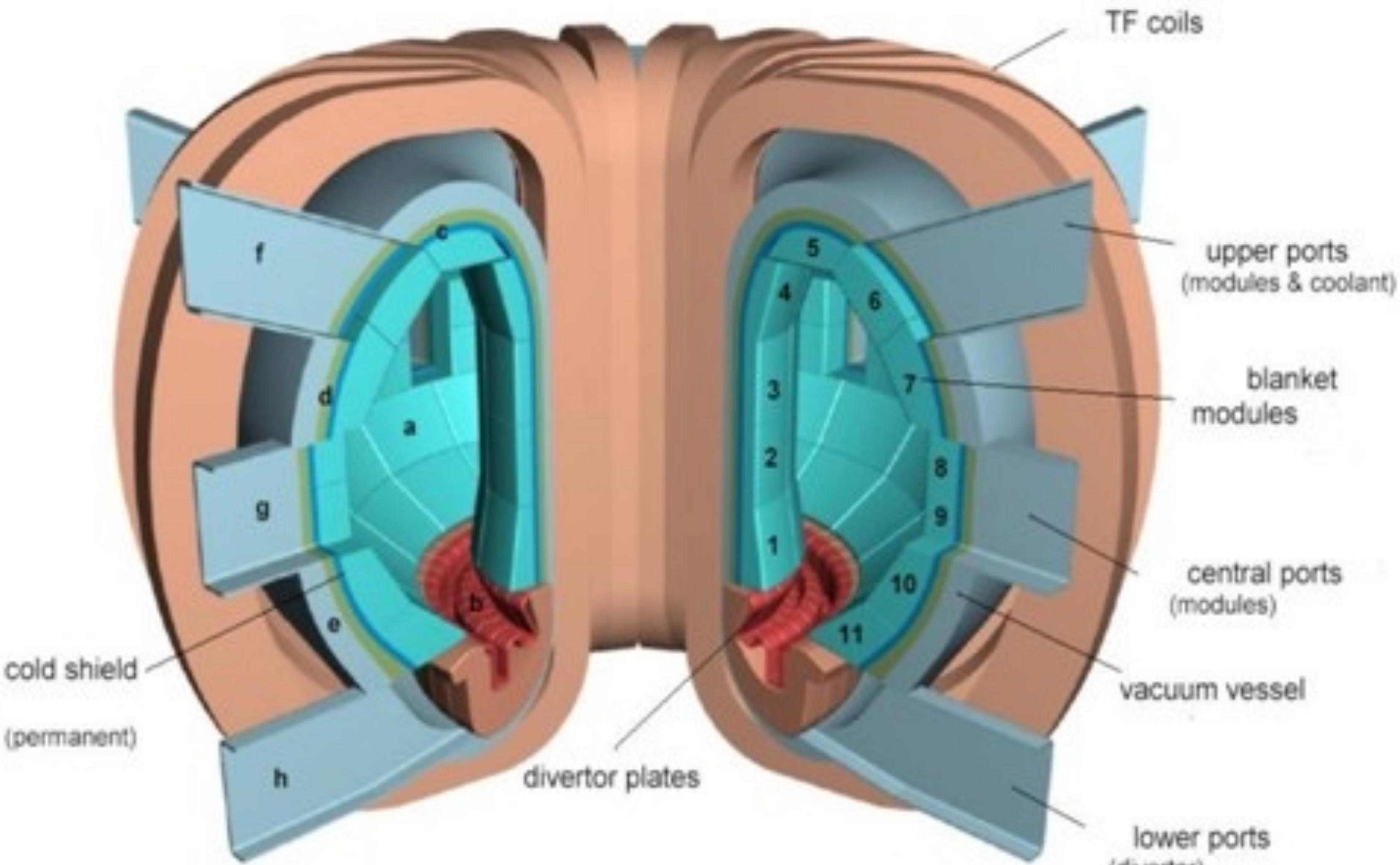
Candidate structural materials

How to test fusion materials

EPFL

Part II – Structural materials

Main irradiated components



Requirements for structural materials

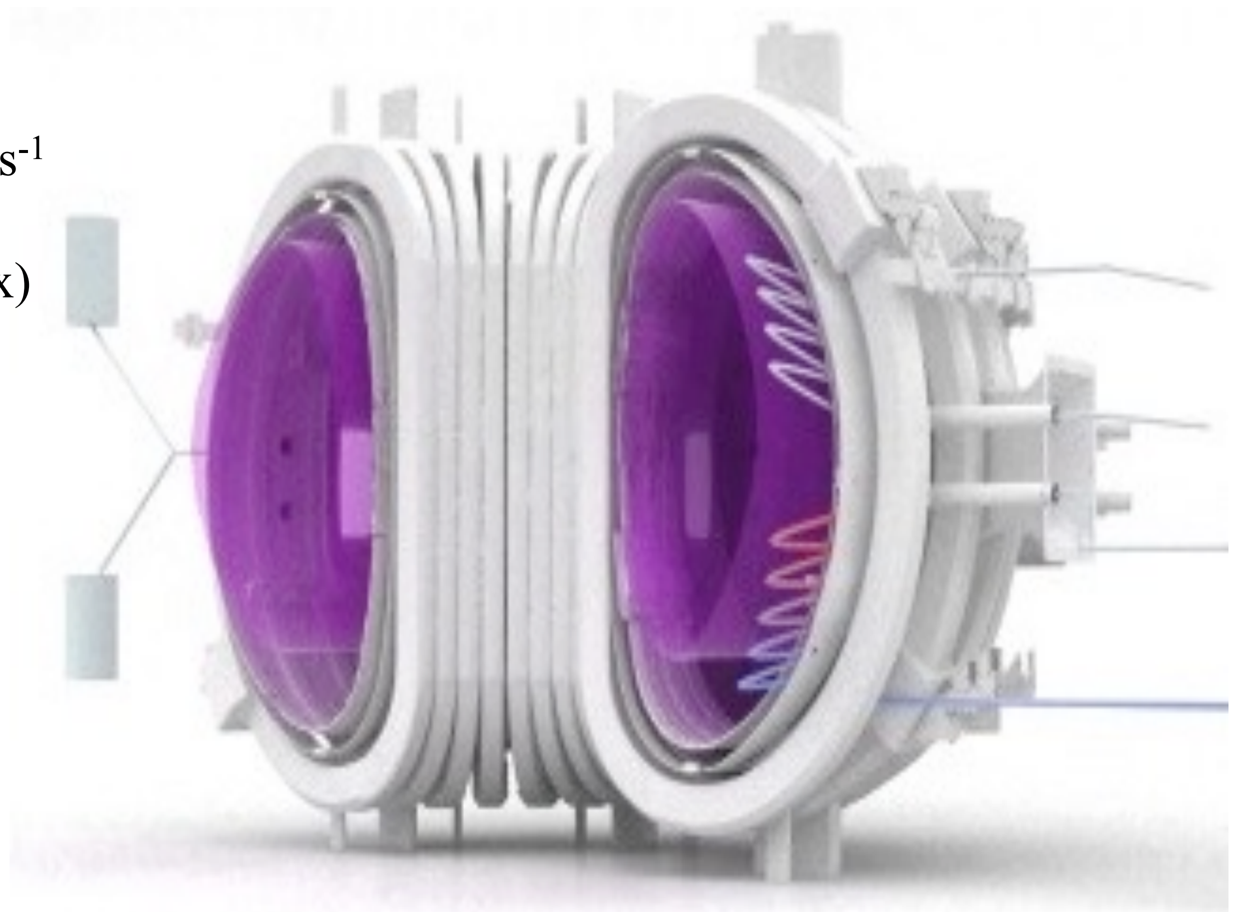
Withstand very large fluxes of 14.1MeV neutrons

Ex. DEMO

flux ~ 10^{19}-10^{20} neutrons $m^{-2}s^{-1}$

fluence ~ 5MW y m^{-2}

(fluence is the integral of flux)

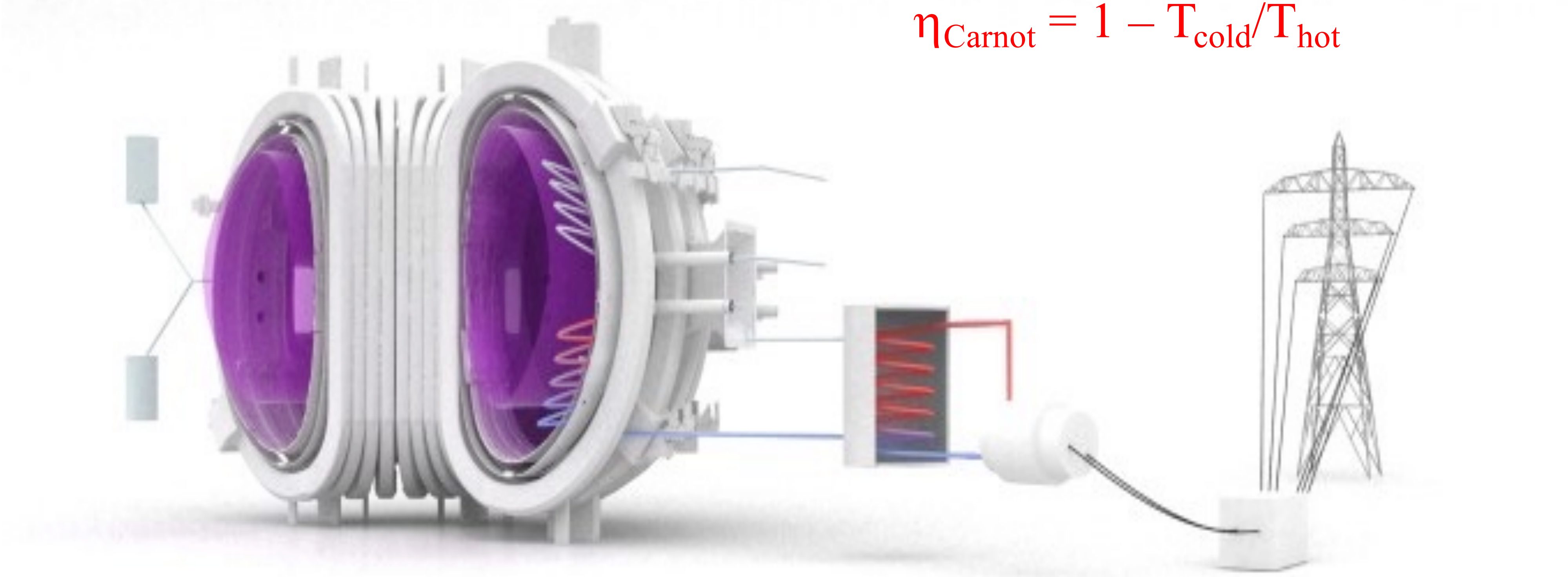


As low activation as possible

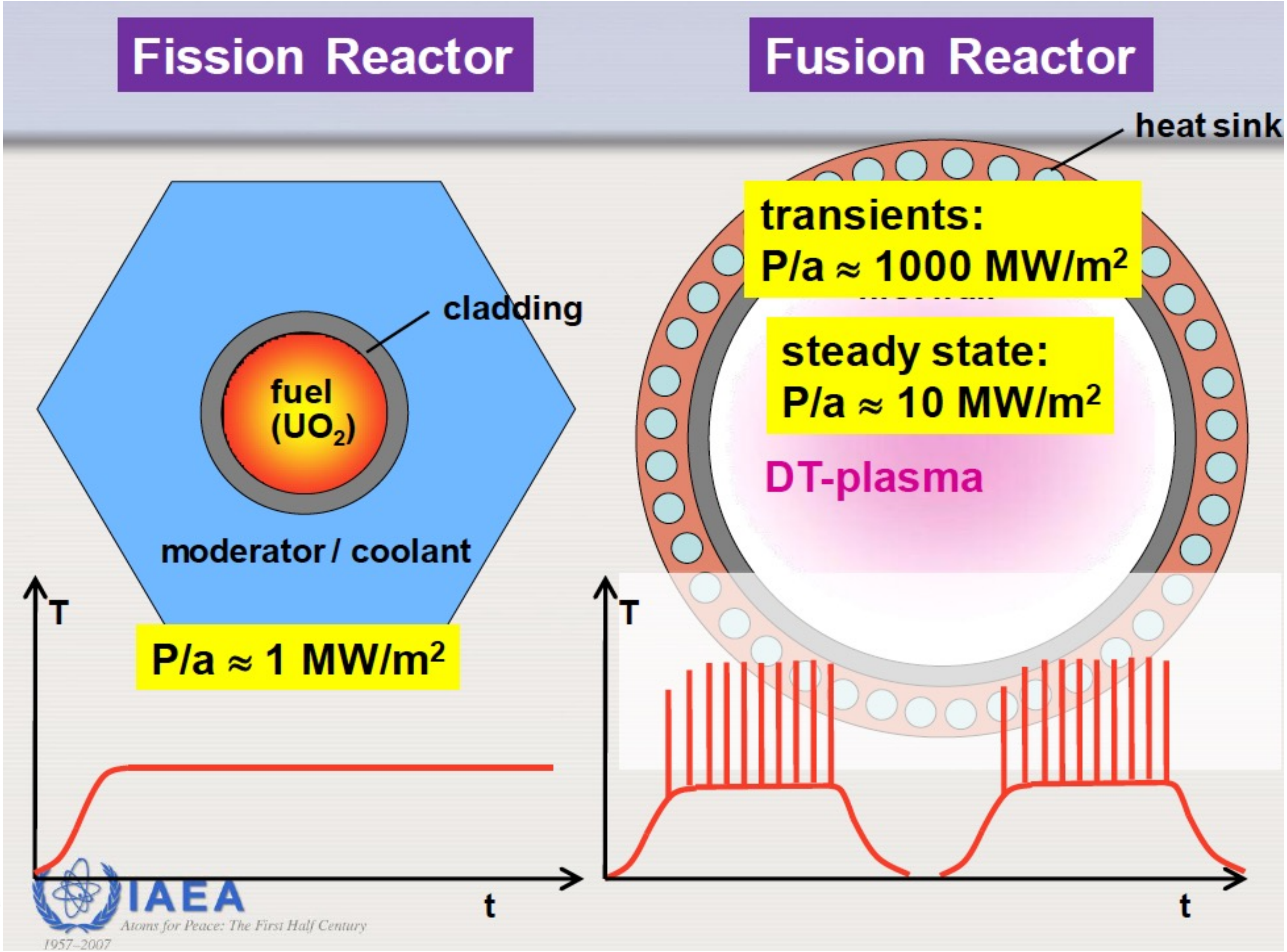
EPFL Requirements for structural materials

Operate at the highest possible temperatures to optimise thermal efficiency of power plant

$$\eta_{Carnot} = 1 - T_{cold}/T_{hot}$$



Fusion vs. fission



Courtesy of R.Kamendje

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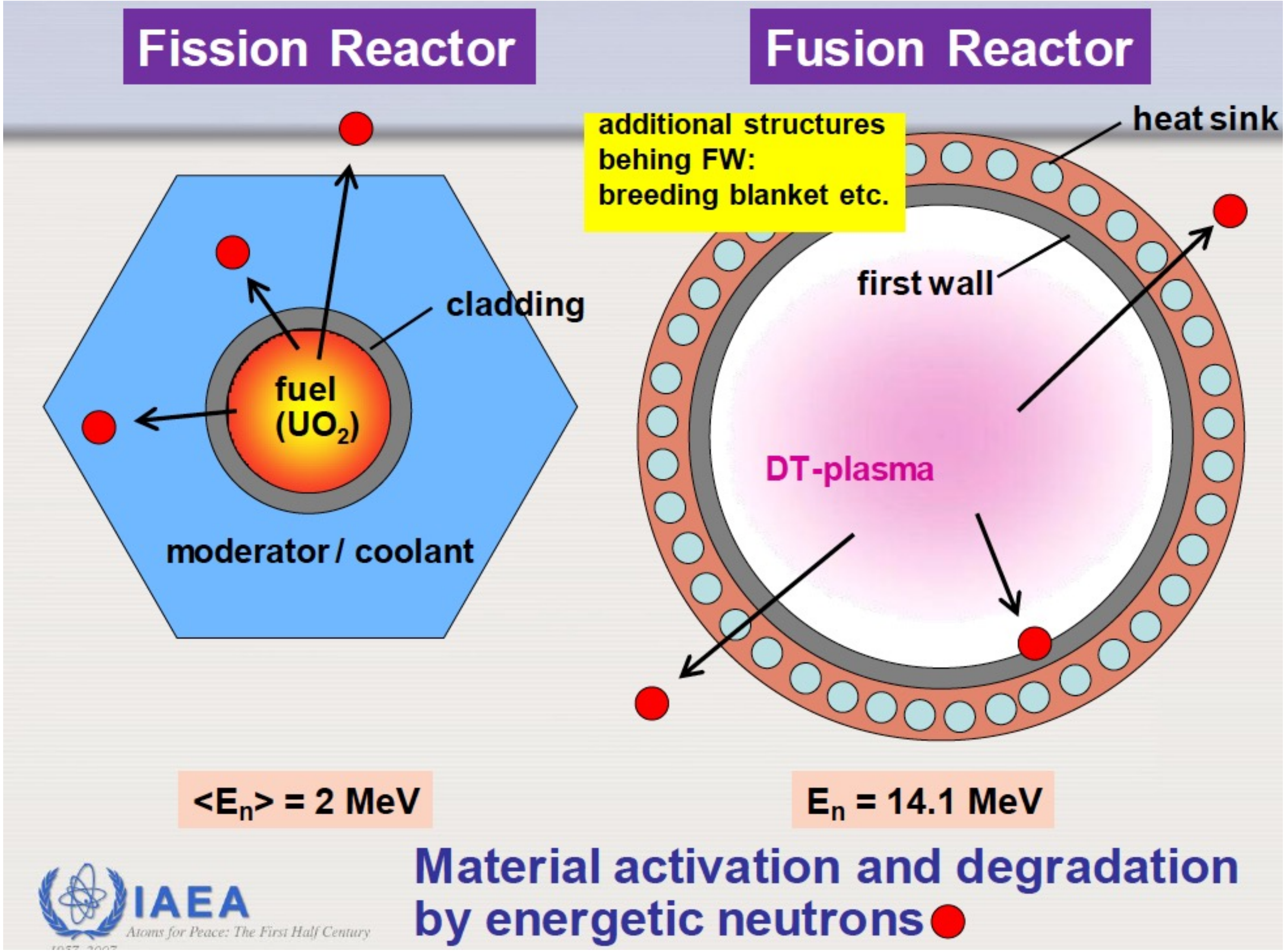
Fusion vs. fission



Courtesy of
R.Kamendje

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Effects of 14MeV neutrons

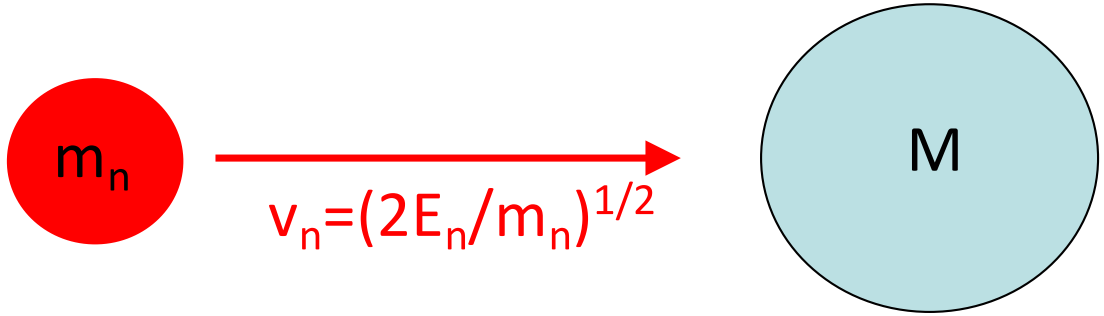
The 14MeV neutrons produce

atomic displacement cascades

transmutation nuclear reactions

Atomic displacement

Mechanical effect of neutron of energy E_n hitting atom of mass M at rest in lattice



Max energy transfer $E_{max} = E_n \frac{4m_n M}{(m_n+M)^2} \sim E_n \frac{4m_n}{M}$

Ex. iron M = 56 amu, E_n = 14.1MeV : $E_{max} = 14.1\times\frac{4}{56}\,MeV \sim 1MeV$

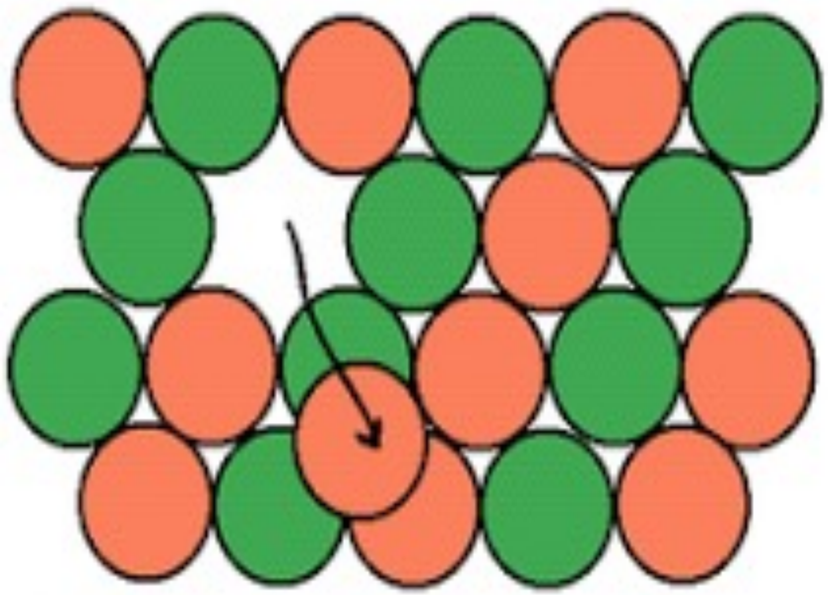
Note: $E_{max} >> E_{Wigner}$ (~25eV) (threshold energy for displacement)

→ iron atom is displaced and ejected from lattice

Atomic displacement

Point structure defects

The ejected atom leaves behind a vacancy and goes to an interstitial location (Frenkel pair)

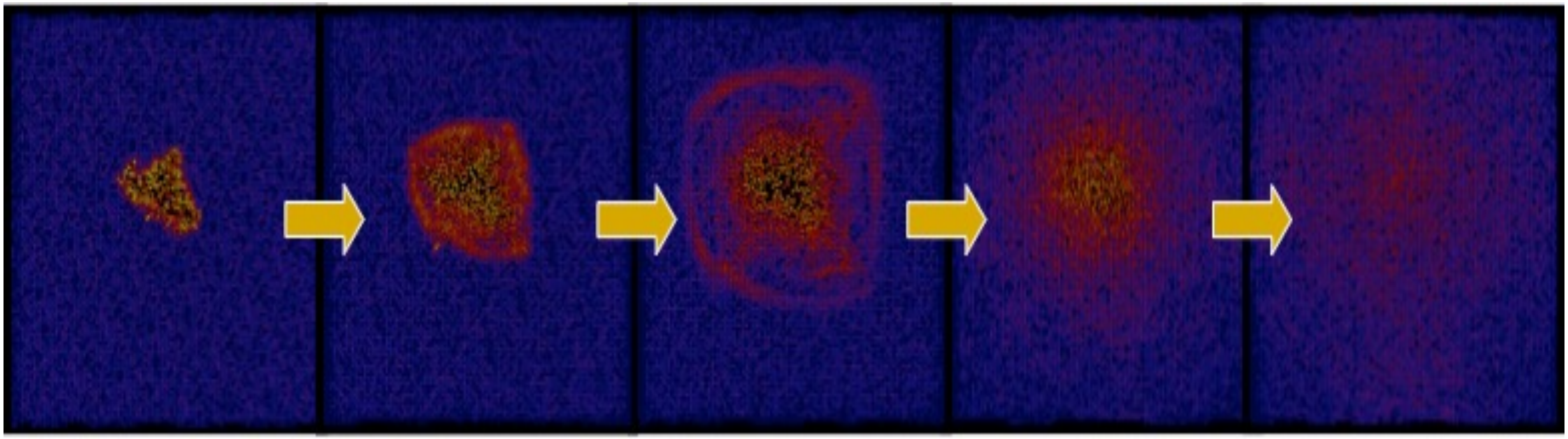


Atomic displacement cascades

As $E_{max} >> E_{Wigner}$, the primary knock-on atom initiates a series of other knock-on events, leading to an atomic displacement *cascade*

Vacancies and interstitials form clusters (swelling)

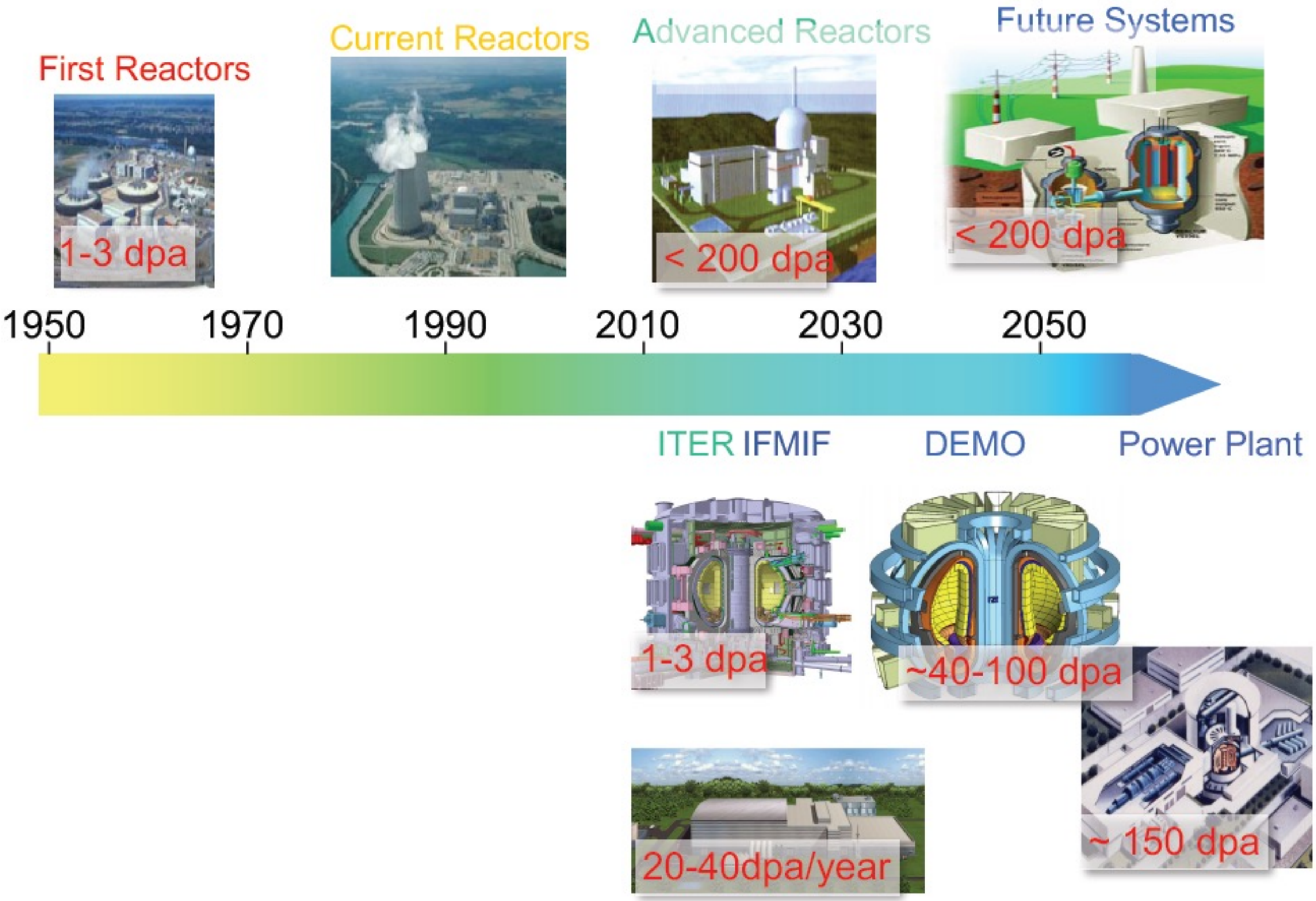
The strength of the material is affected



Damage is quantified in average number of displacements per atom (*dpa*) during the working life of a material

dpa is proportional to neutron fluence (time integrated flux)

Neutron induced dpa in fission and fusion



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Transmutation nuclear reactions

Nuclear reactions between fusion neutrons and lattice atoms

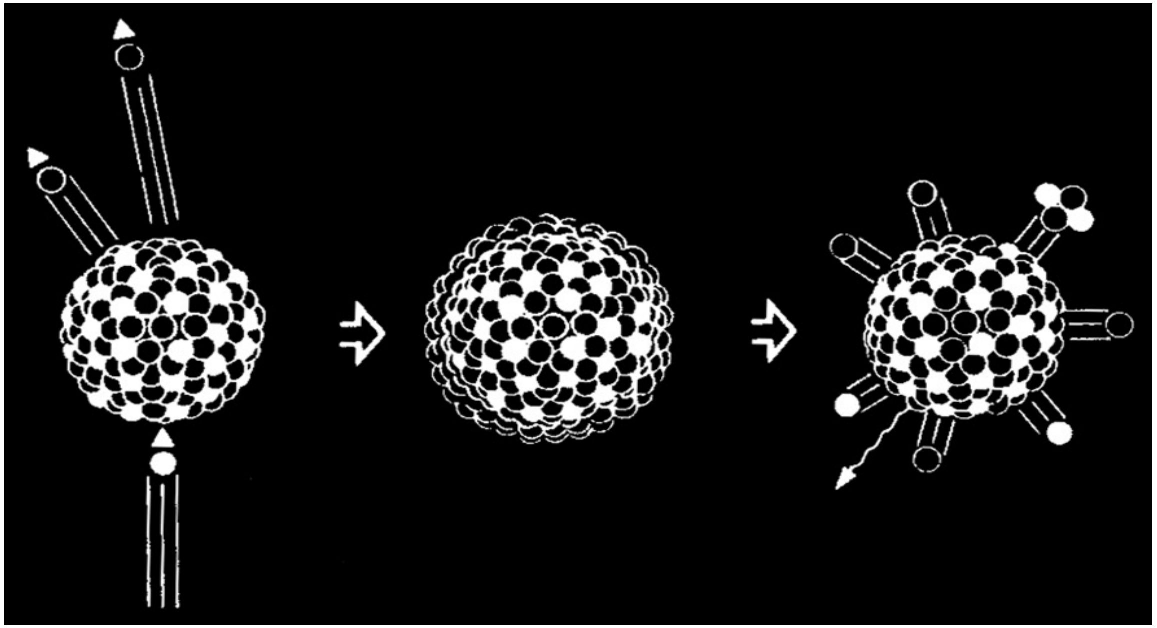
Generation of of radioactive atoms and of He and H

$^{56}Fe + n \rightarrow {}^{53}Cr + \alpha$

(n energy threshold 2.9MeV)

$^{56}Fe + n \rightarrow {}^{56}Mn + p$

(n energy threshold 0.9MeV)



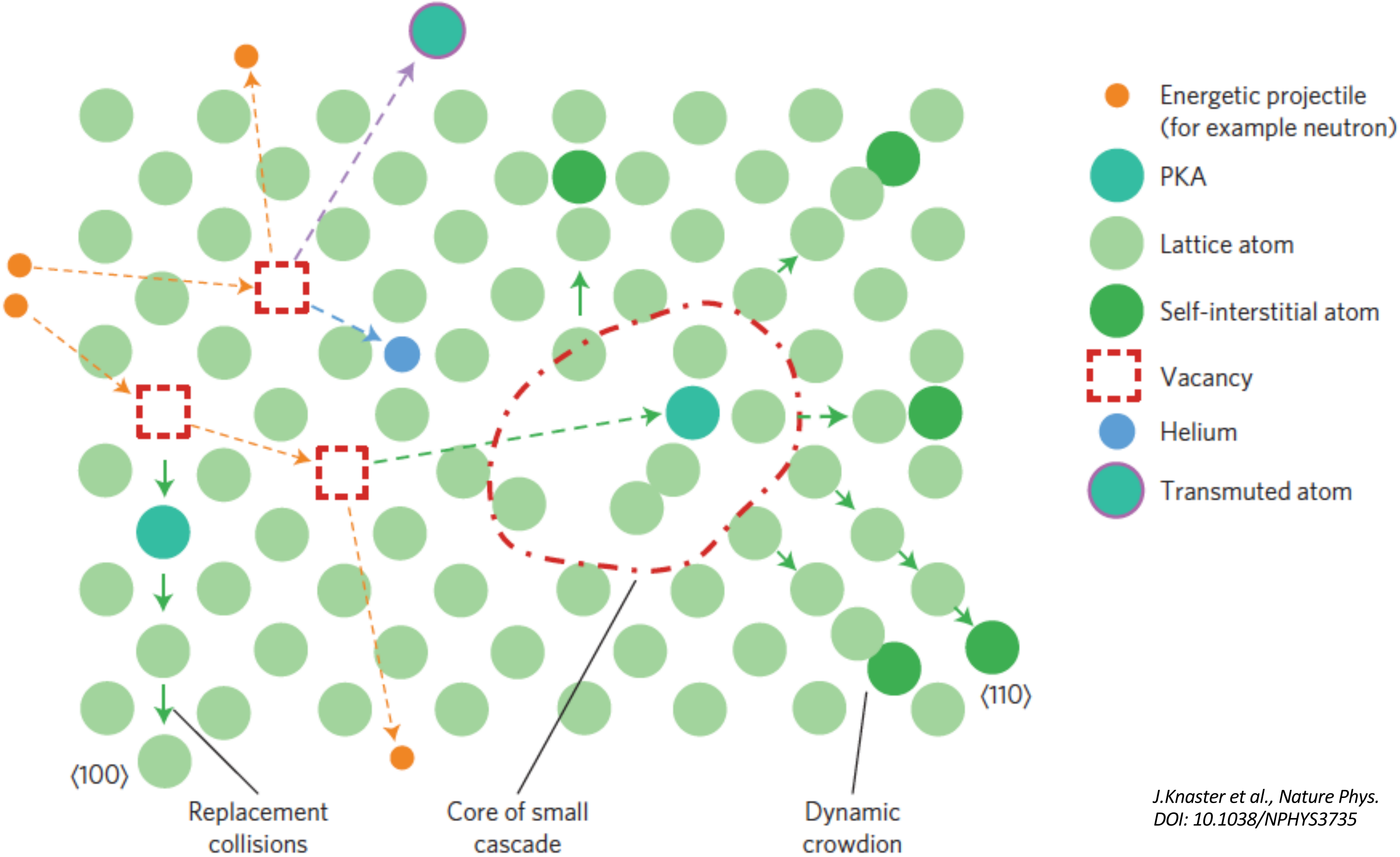
Individual He and H atoms tend to coalesce, forming gas bubbles that weaken the material

Effect is quantified in atomic parts per million (*appm*) of He or H

in fusion the *appm/dpa* ratio is much higher than in fission:

~10-15 *appm* He/*dpa* and ~40-50 *appm* H/*dpa*

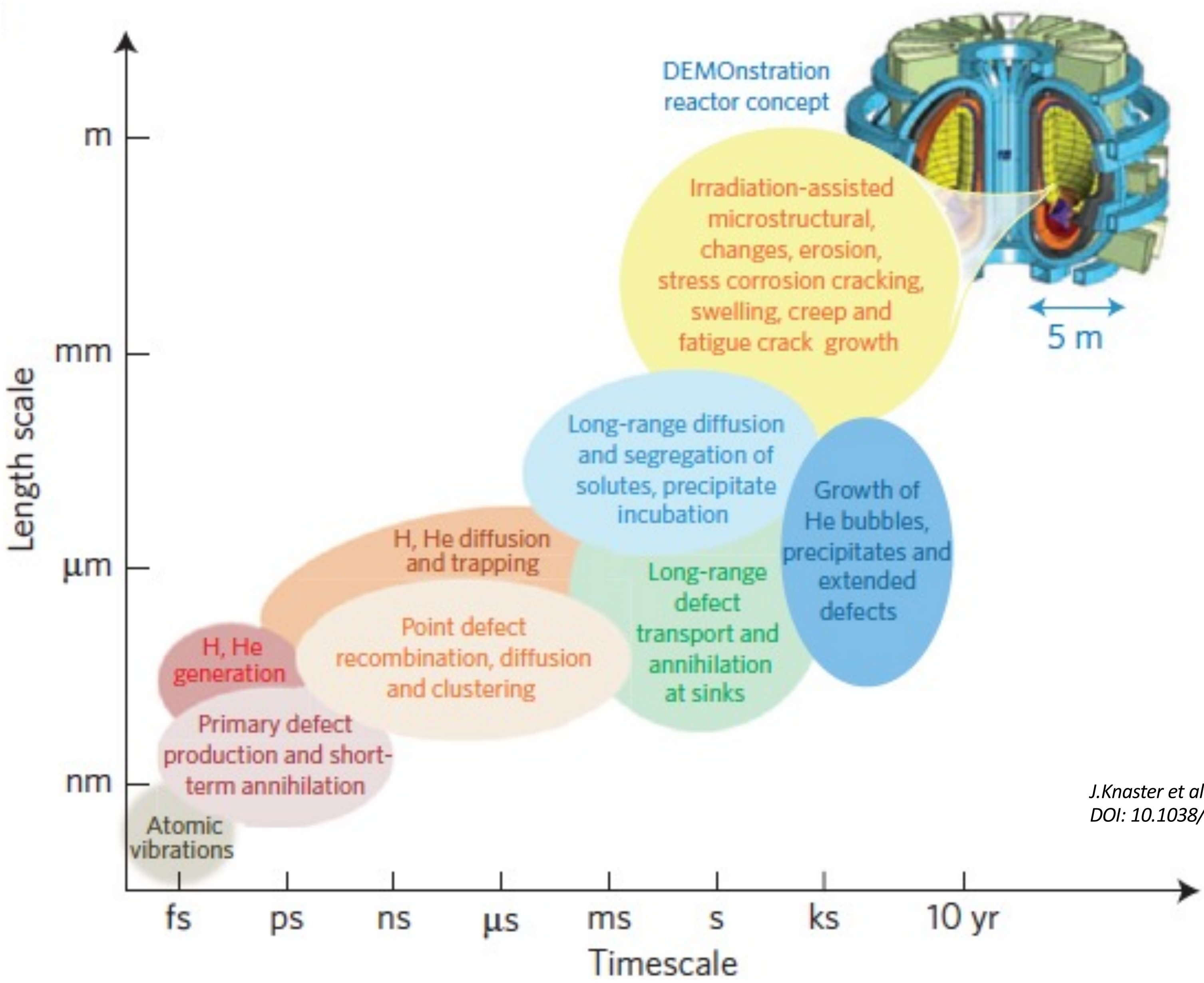
The two effects together



J.Knaster et al., Nature Phys.
DOI: 10.1038/NPHYS3735

The modifications of the microstructure degrade the macroscopic chemical, physical and mechanical properties

Irradiation time and length scales



J.Knaster et al., Nature Phys.
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Evolution of materials properties

Change in the chemical composition

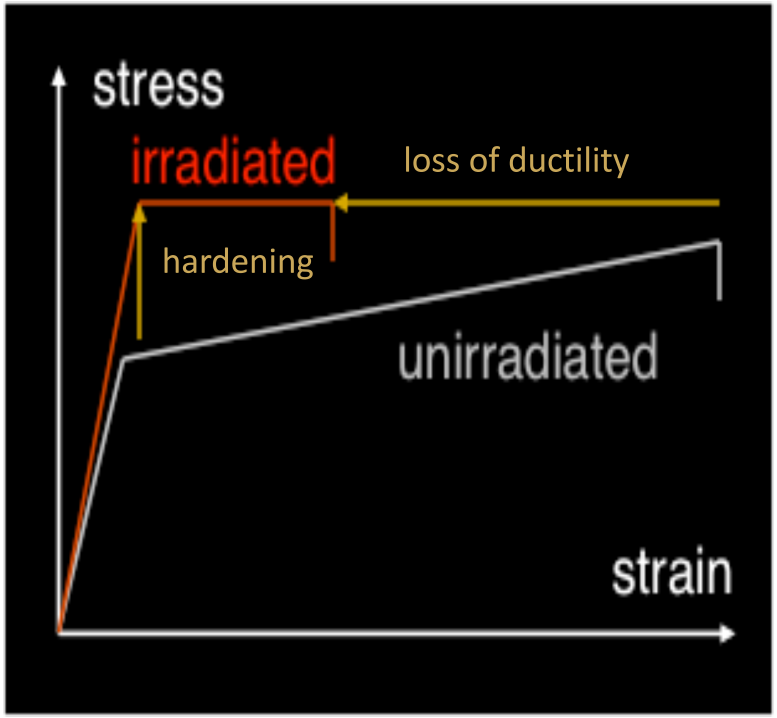
Physical properties – important for functional materials

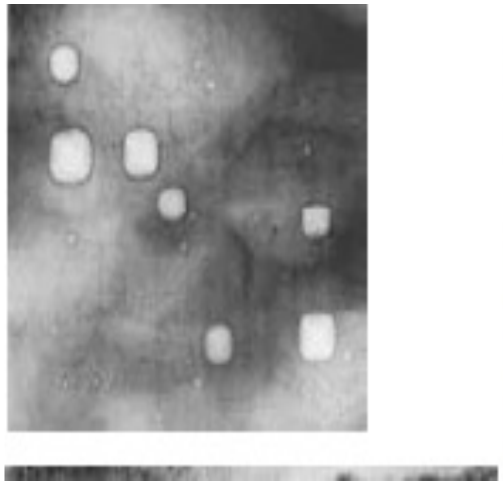
Decrease of electrical conductivity and of thermal conductivity

Evolution of materials properties

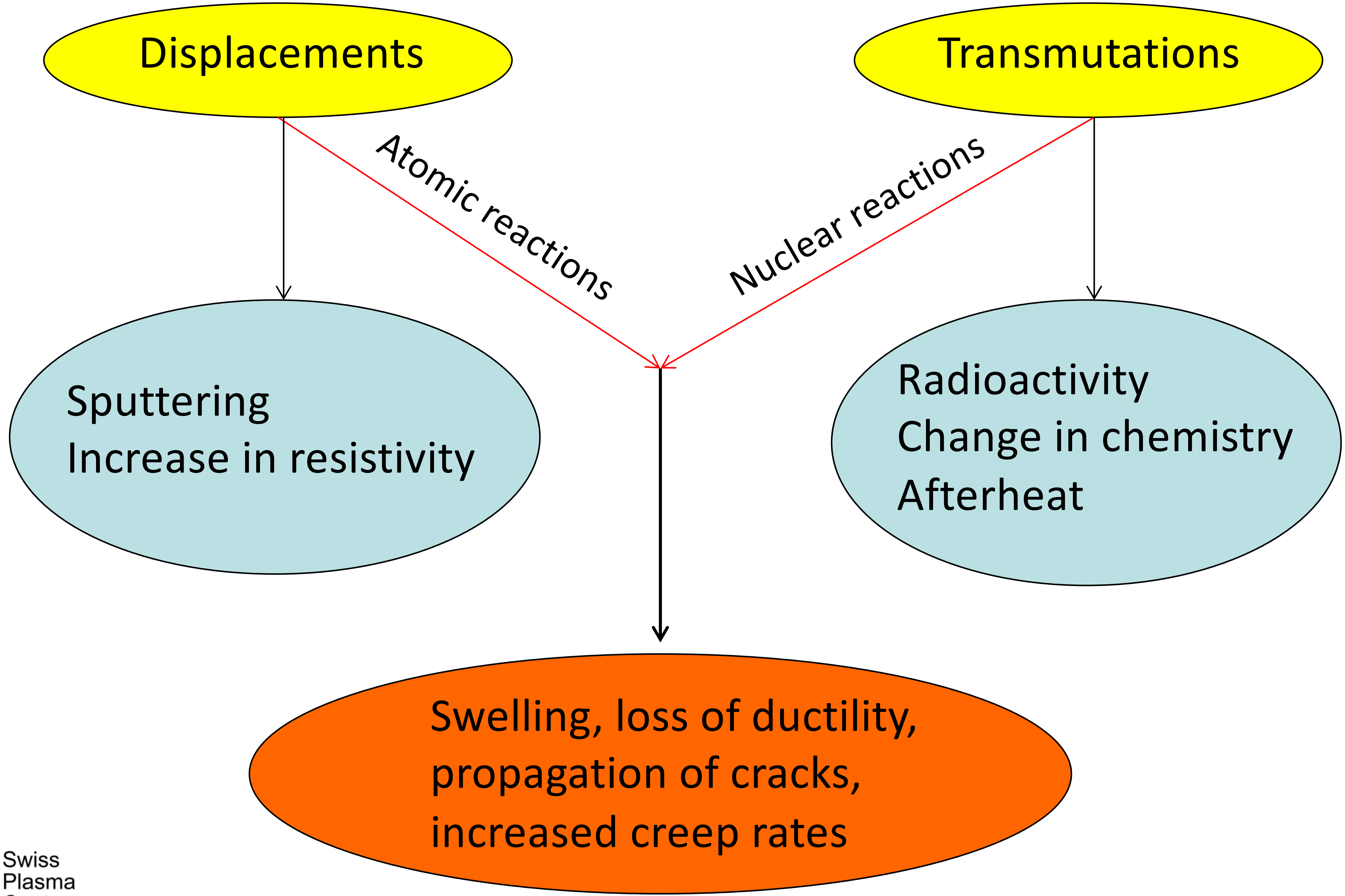
Mechanical properties – important for structural materials

Loss of creep strength, change in ductile to brittle transition temperature
Embrittlement (hardening, loss of ductility, loss of fracture toughness)
Change in mechanical dimensions (swelling)





Overview of radiation effects in fusion

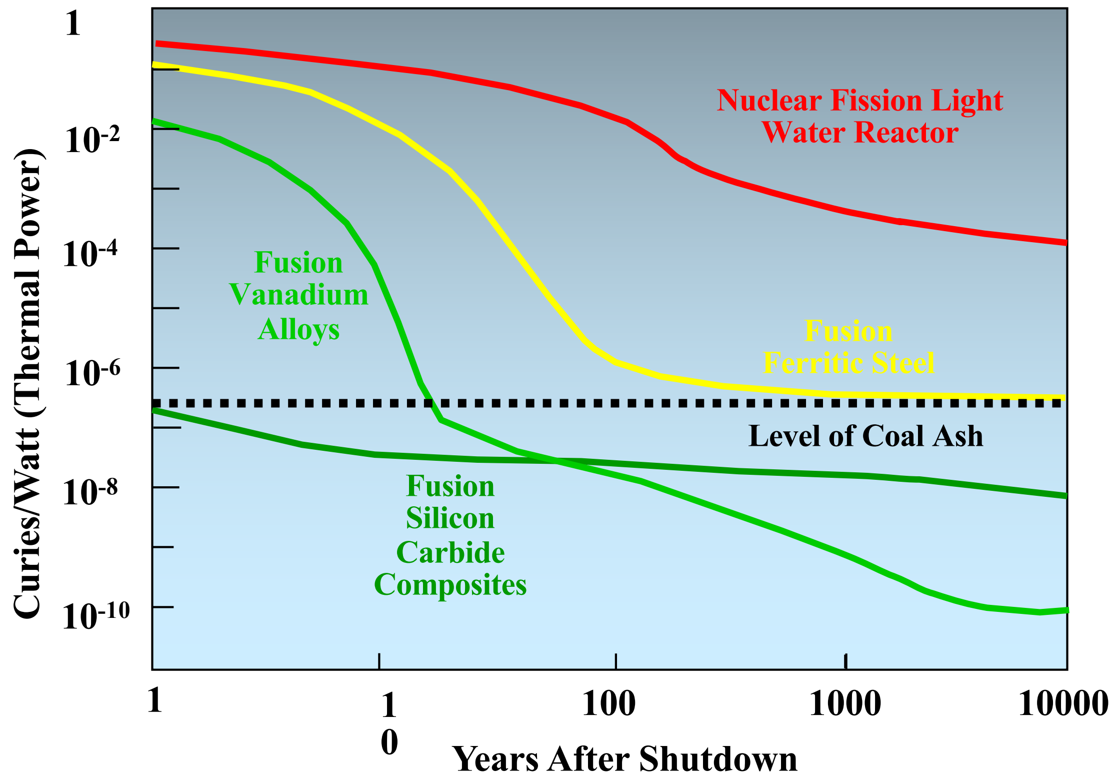


Structural materials for fusion

Candidate structural materials must have a chemical composition based on low activation elements: Fe, Cr, V, Ti, W, Si, C

Based on safety, waste disposal, and performance, the leading candidate structural materials are

- Reduced activation ferritic/martensitic steels (ex. EUROFER 97)
- Vanadium alloys
- Tungsten alloys
- SiC/SiC composites (but dpa/fluence is 3 times larger in SiC than in steel)



Fusion needs large amounts of steel

Ex. present version of European DEMO

Components	Steel	Quantity needed / tons
Blanket	EUROFER	~ 2,180
Divertor Cassette Body	EUROFER	~ 1,170
Vacuum Vessel	SS (ITER grade)	> 10,000
Superconducting Coils	SS (ITER grade)	~ 29,300
Cryostat	SS (ITER grade)	~ 15,300
BoP	SS	~ 4,500

- **3,300 tons EUROFER**
- **> 62,450 tons SS**

cf ~ **406 M€**

The need to test materials for fusion

Experimental knowledge of materials behavior in fusion reactor conditions is very limited

- Extrapolations from current conditions to fusion regime is much larger for fusion materials than for core plasma parameters

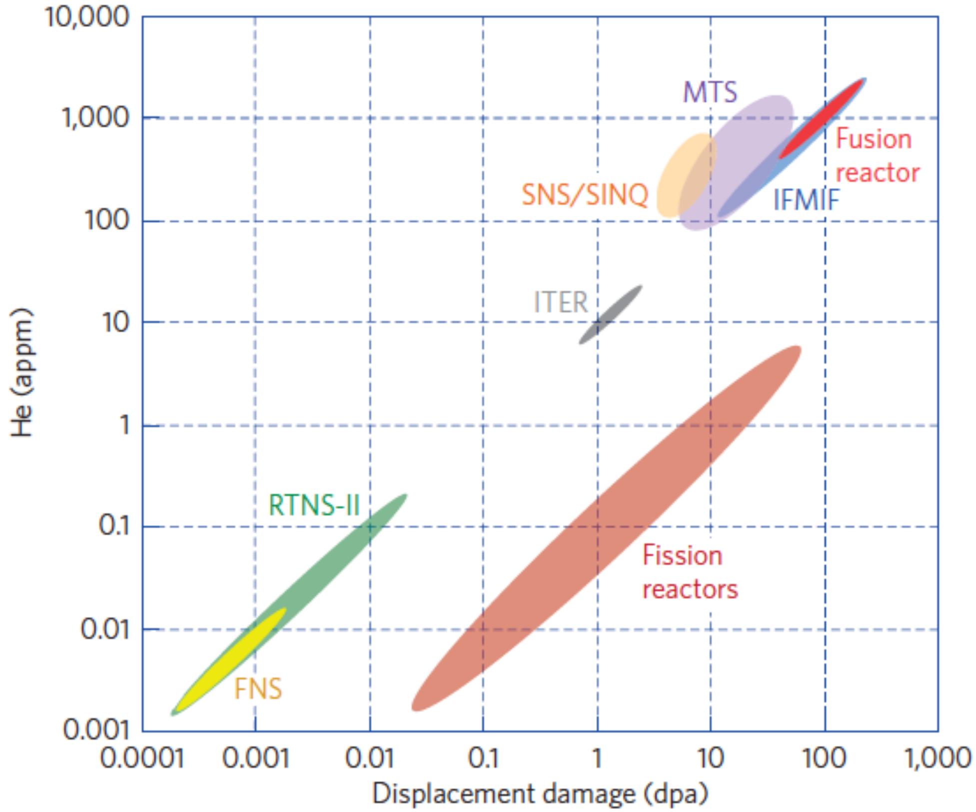


Figure 4 | Graph showing the correlation of dpa_{NRT} versus appm of He generated for the different possibilities of testing materials (alternative and IFMIF) compared with fusion reactor conditions. MTS, Materials Test Station spallation source at Los Alamos National Laboratory; RTNS-II, Rotating Target Neutron Source-II, previously at Lawrence Livermore National Laboratory; SINQ, Swiss Spallation Source at Paul Scherrer Laboratory; SNS, Spallation Neutron Source at Oak Ridge National Laboratory; FNS, Fusion Neutron Source at Japan Atomic Energy Agency. Figure modified from ref. 31, © 2014 Annual Reviews.

J.Knaster et al., Nature Phys. DOI: 10.1038/NPHYS3735

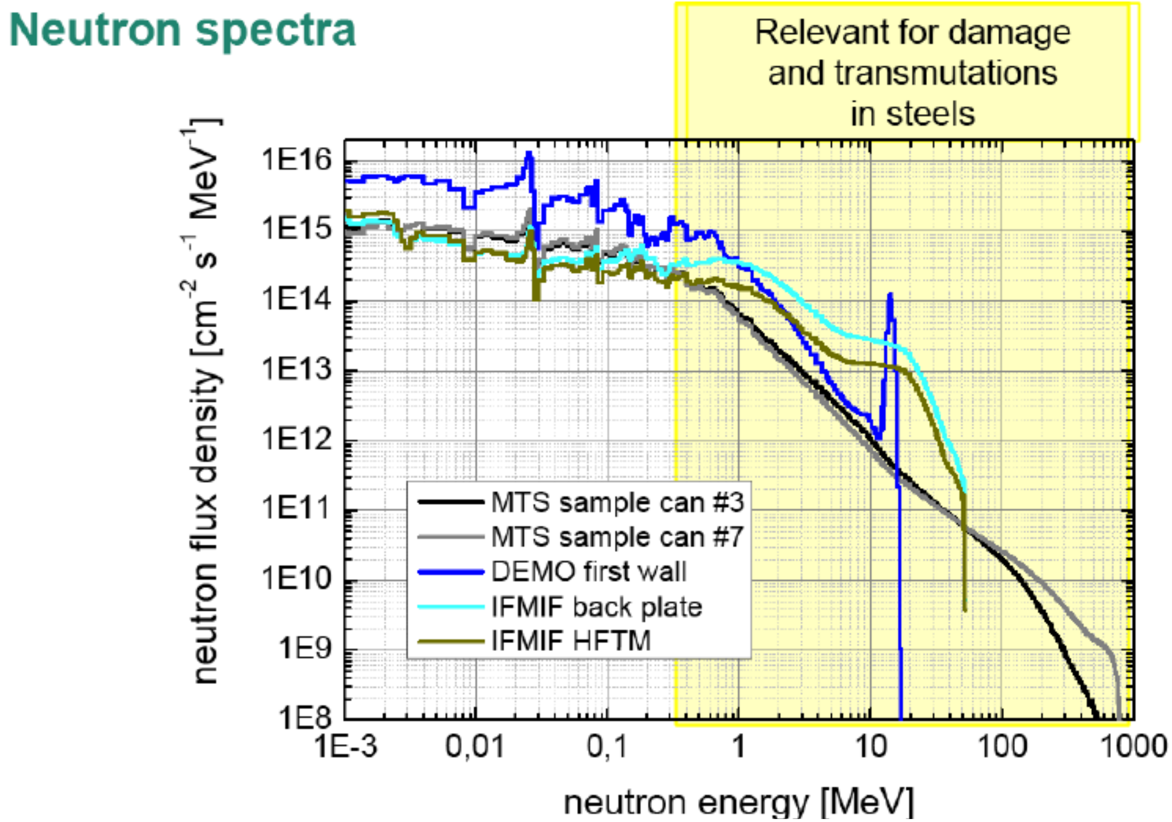
The need to test materials for fusion

Urgency of fusion materials tests is universally recognized

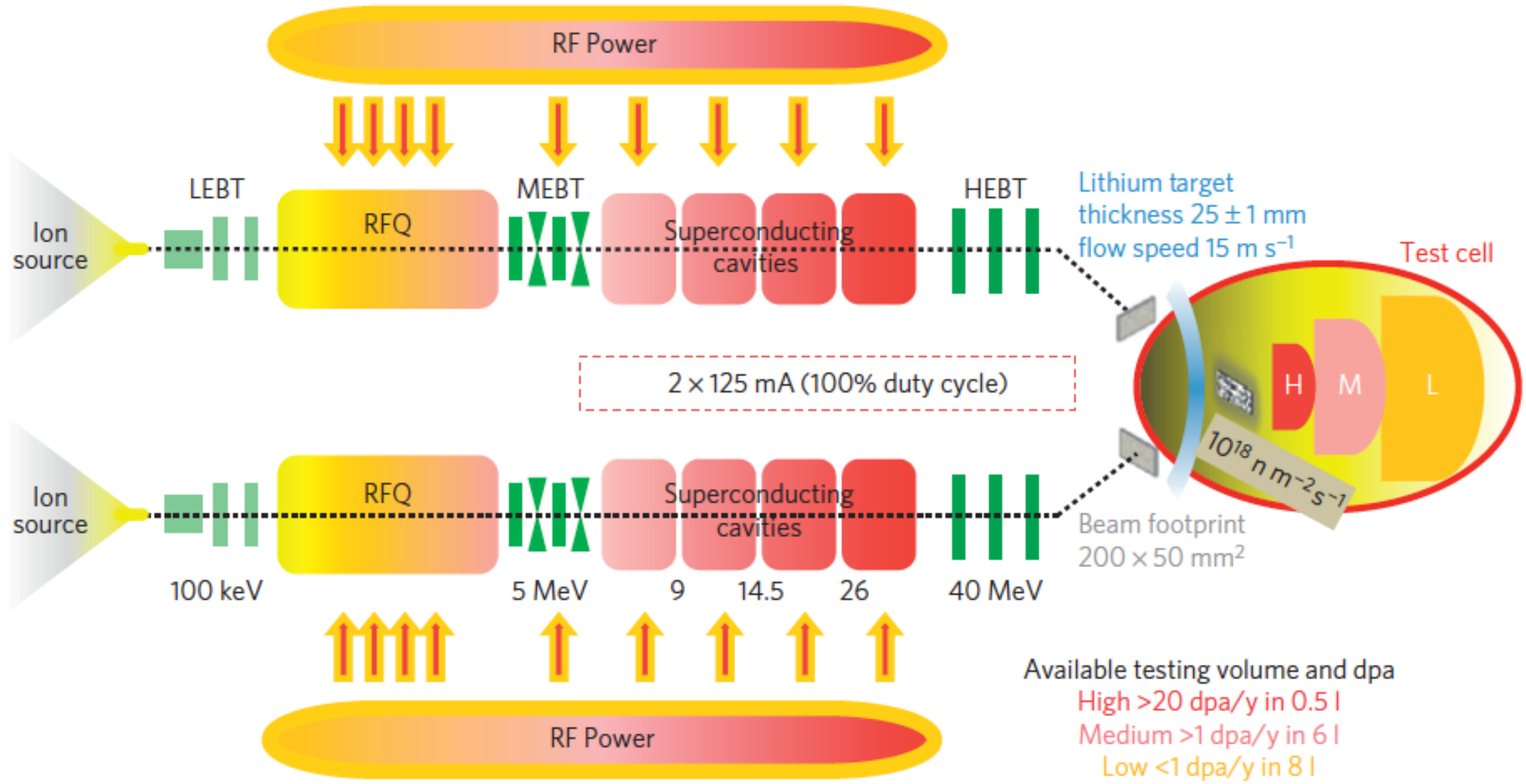
But how can we produce the relevant spectrum of neutrons ?

Volumetric neutron sources, e.g. low fusion gain tokamak producing DT neutrons

Accelerator based irradiation facilities (e.g IFMIF), producing neutrons from Li + d → Be + n



IFMIF irradiation test facility



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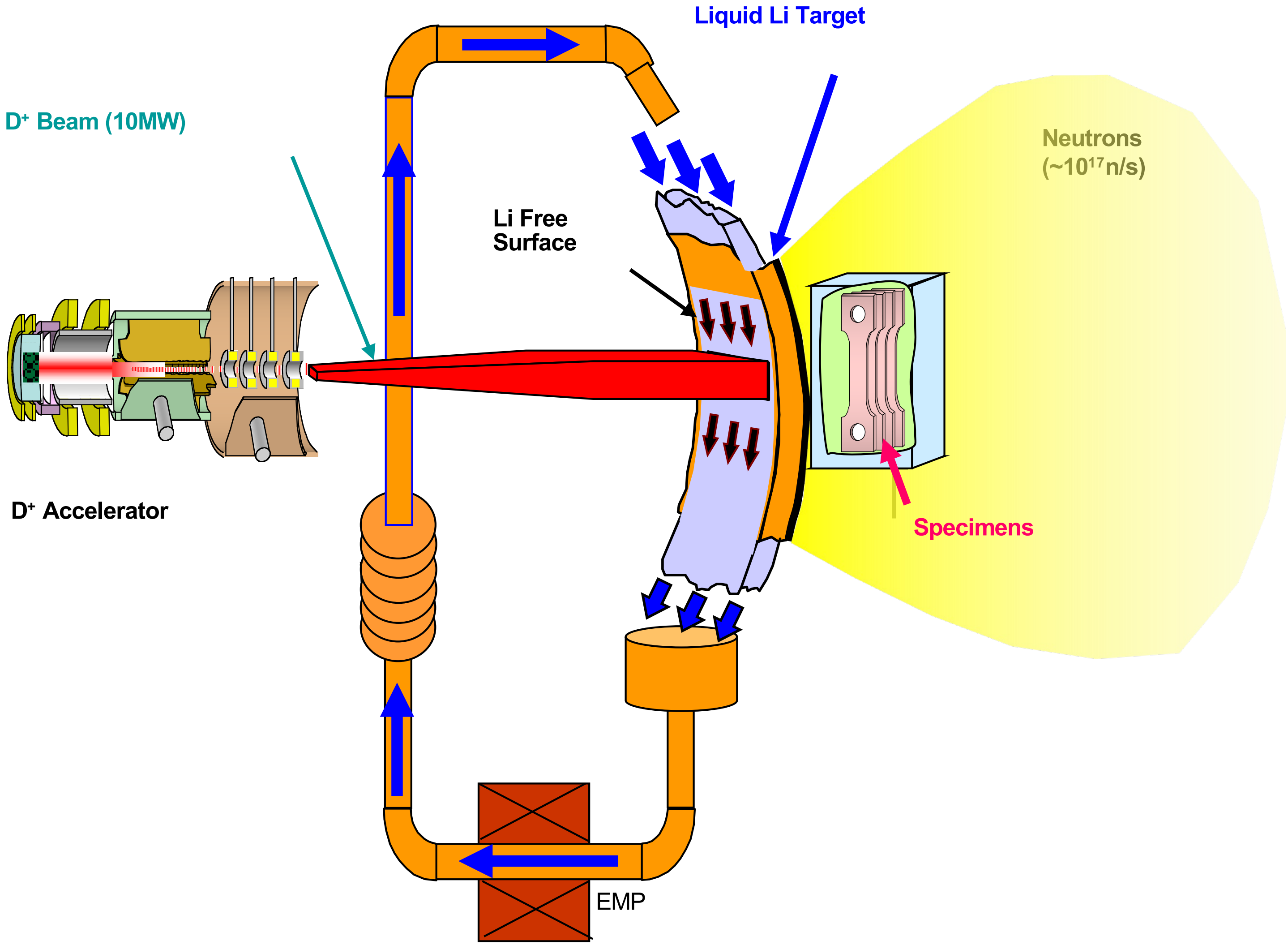
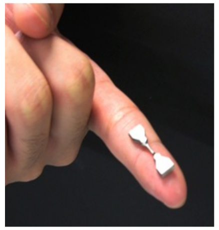
J.Knaster et al., Nature Phys. DOI: 10.1038/NPHYS3735

IFMIF irradiation test facility



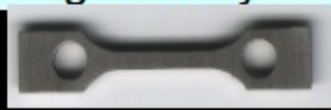
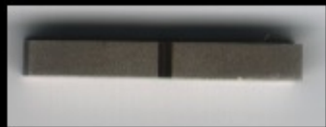


Must extrapolate results obtained in small volume (0.5l at 20dpa/y) to large reactor: small specimen test technology

Small specimen test technology

- On the basis of miniaturized specimens, 0.5 liter (high flux test module) is sufficient to get within 15-20 years a representative test matrix up to about 150 dpa for a variety of materials.

H. Matsui et al., SOFT Conference, 2004

Specimen type	Present geometry	Comments
Tensile		developed
Fatigue		developed
Bend/Charpy DFT		Standard achieved R&D ongoing
Creep		Miniaturization needs verification
Crack growth		International R&D ongoing
Fracture toughness		International R&D ongoing

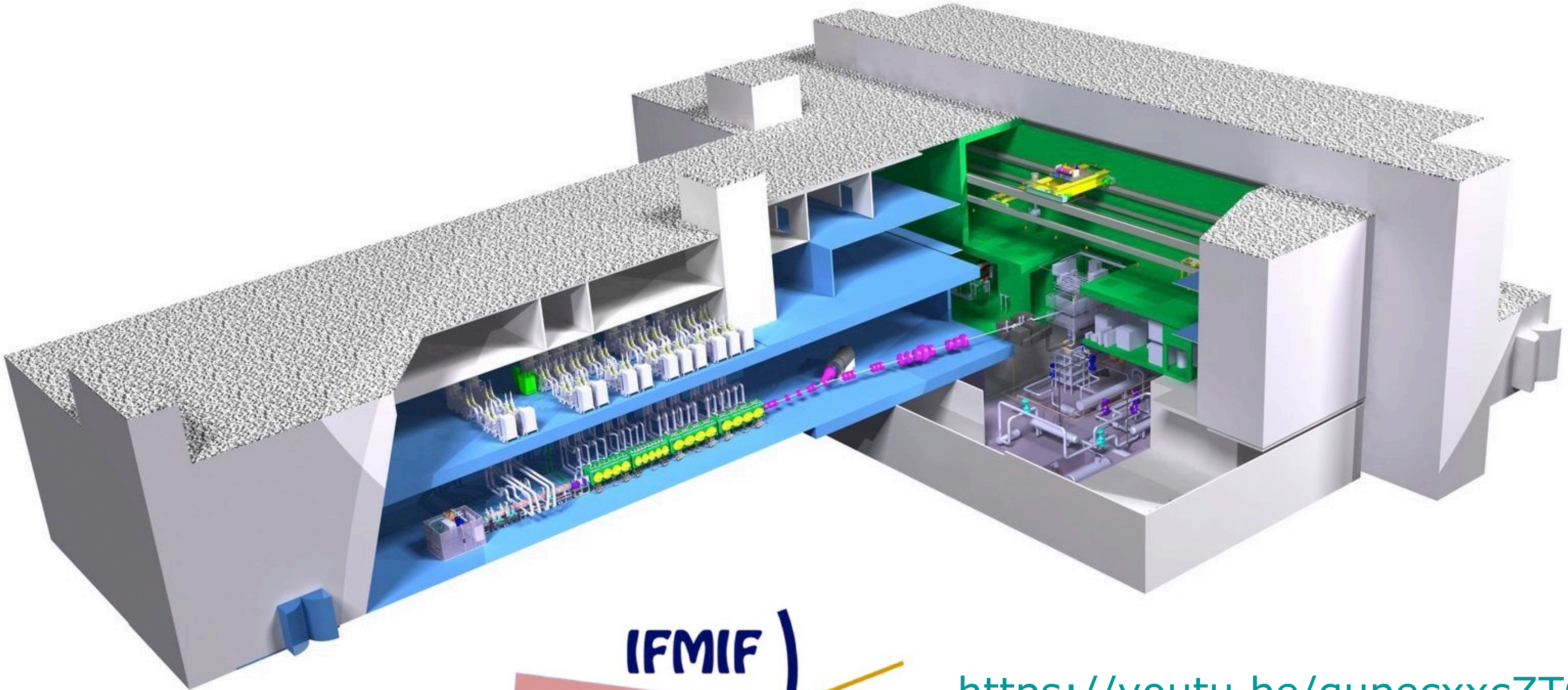
1 cm

EU irradiation test facility

DONES - Demo Oriented Neutron Source in Grenada (Spain)

Under development to start material tests for DEMO

Based on IFMF concept – just one accelerator instead of two, half size of irradiated volume



https://youtu.be/qupecxxcZTQ

EPFL

Summary of part II

Fusion structural materials must satisfy stringent requirements

Material properties affected by n-irradiation, but exp. knowledge of effects is incomplete

Need tests of candidate materials

Material science plays a crucial role in fusion energy research