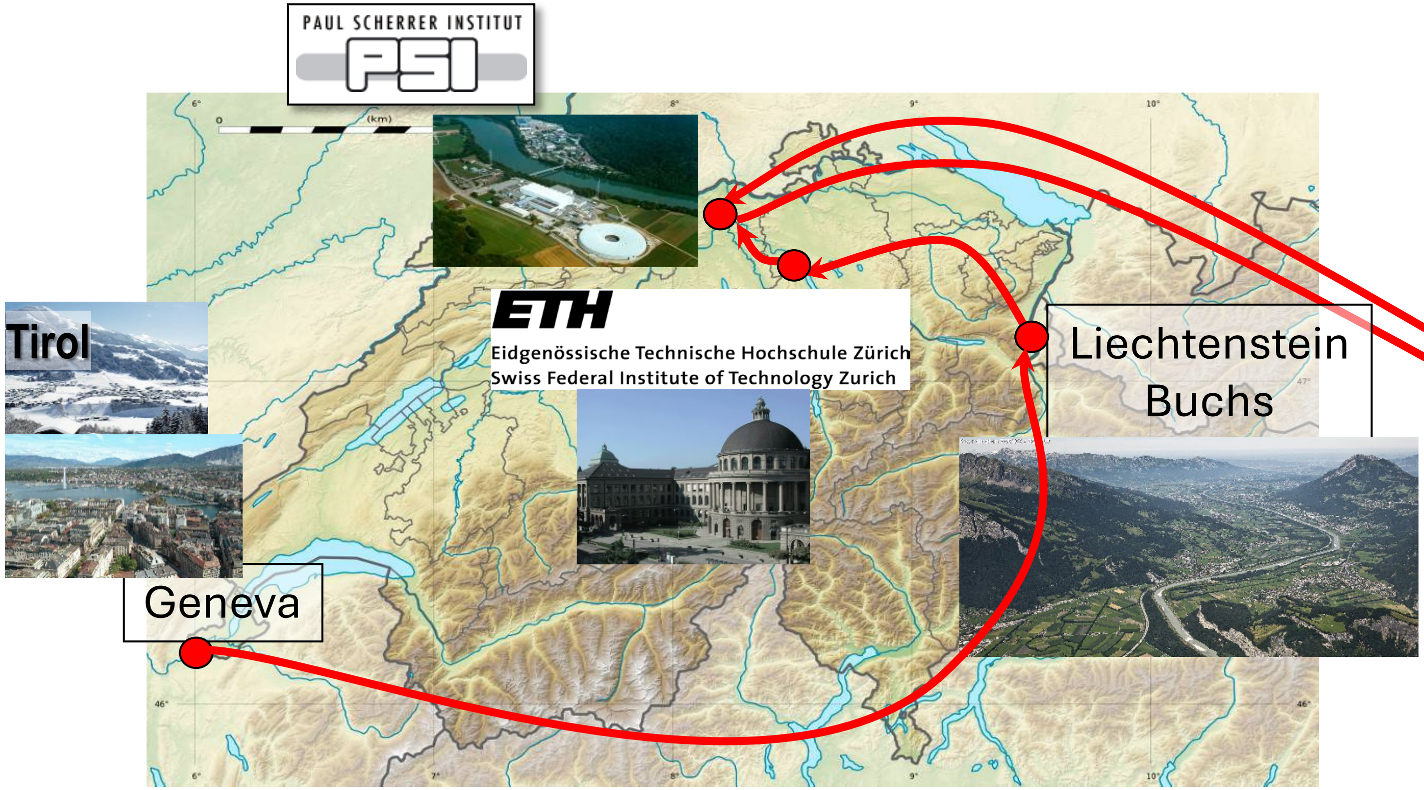
MATERIAL SCIENCE and ITS APLICATION IN FUSION

EPFL :: PHYS-632
Fusion and industrial plasma technologies

Manuel A. Pouchon :: Head of Laboratory for Nuclear Materials :: NES
EPFL :: PPB 019
PSI, June 3rd, 2025

Manuel Pouchon – self-introduction

EPFL PSI



- ETH: Swiss federal institute of technology in Zurich (www.ethz.ch)
- PSI: Largest research institute of Switzerland in Villigen (ww.psi.ch)
- JNC: SFR research institute in Japan Today JAEA after merger with JAERI (www.jaea.go.jp)

Paul Scherrer Institut
Manuel A. Pouchon
Dr. sc. nat. | Physicist ETHZ
Head of Lab. for Nuclear Materials
Nuclear Energy and Safety Department
5232 Villigen PSI
Switzerland

Tel.: +41 56 310 2245
Fax.: +41 56 310 3565
mail: manuel.pouchon@psi.ch

Dr. sc. nat. | *Physicist ETHZ*

- PSI:
  - Head of *Laboratory for Nuclear Materials*
  - Group leader of *Advanced Nuclear Materials*
- EPFL: Maître d'enseignement et de recherche
- ETHZ: Lecturer

What are we going to study?

Some basic notions of metallurgy Irradiation effect on alloy

IFMIF

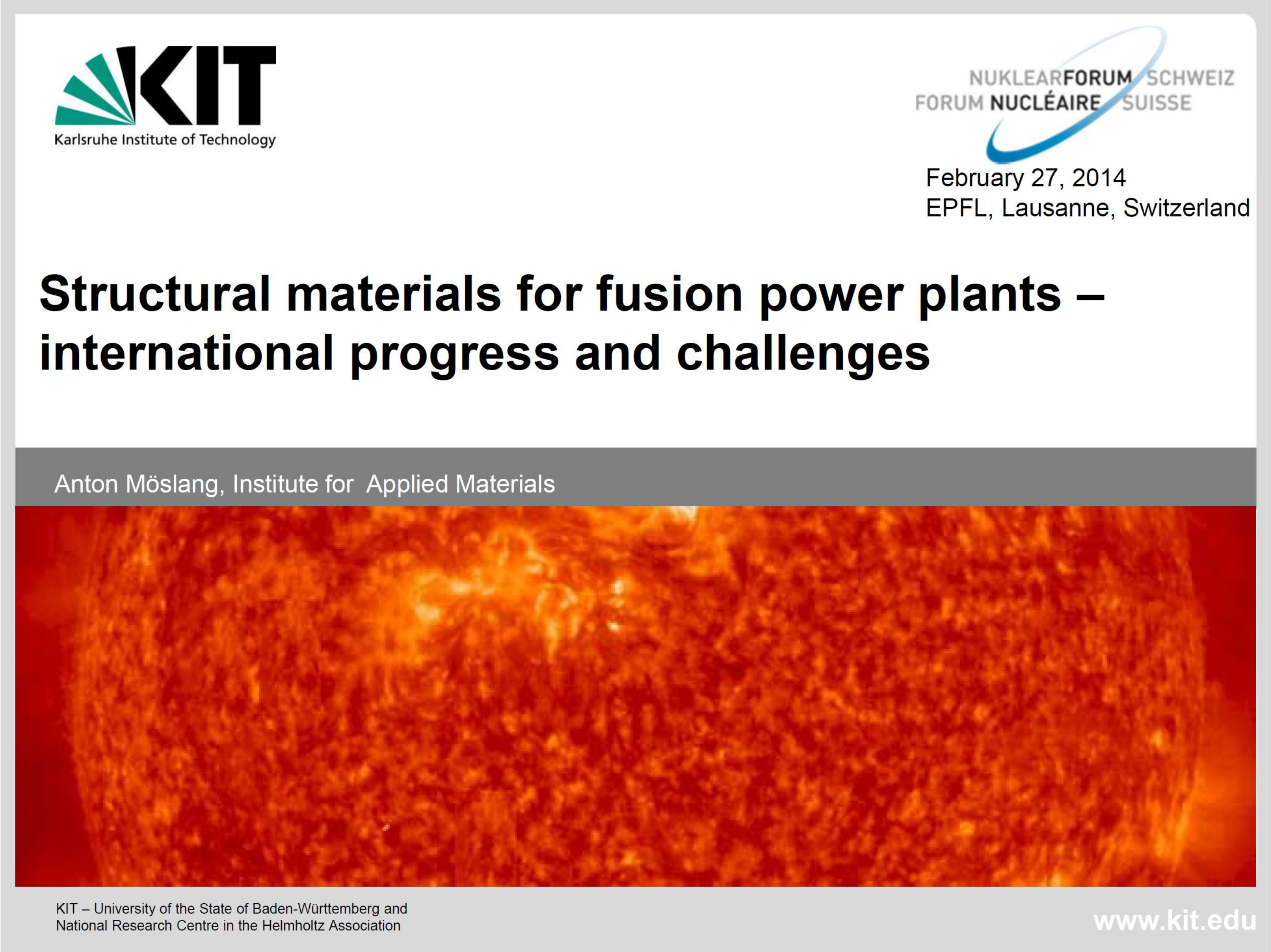
Tritium breeding blanket viewed from the Material

Bibliography

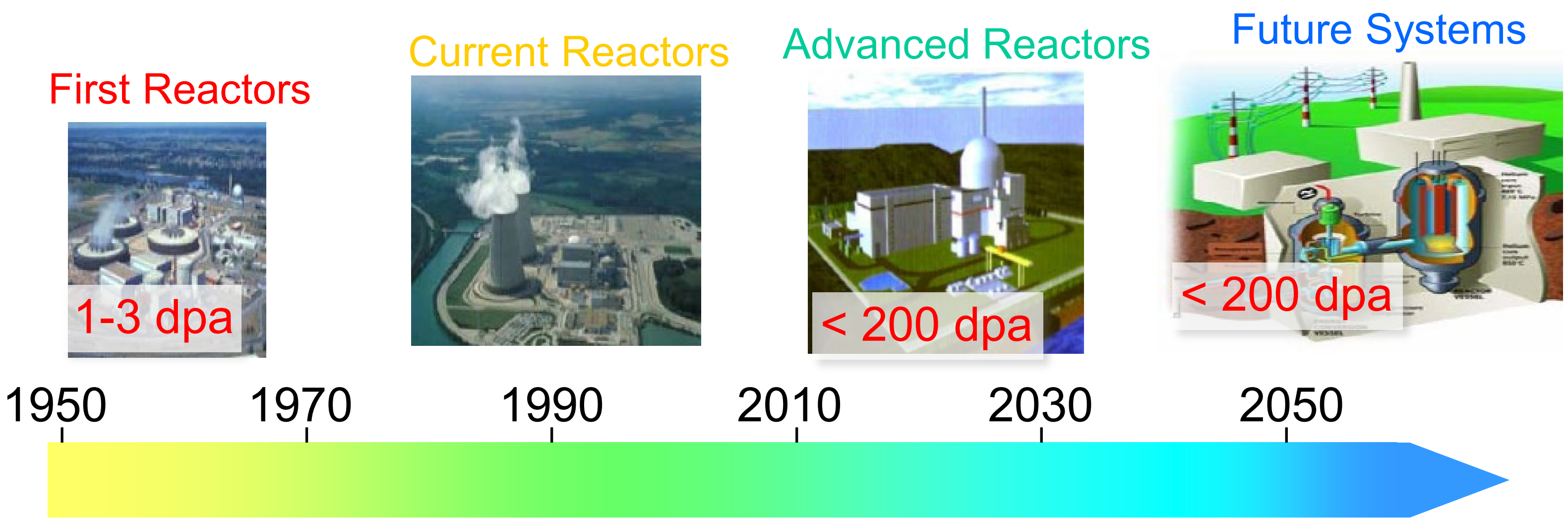
- Physical metallurgy, Peter Haasen
- Mechanical metallurgy, Georges E. Dieter
- Mechanical behavior of Materials,
  Marc Meyer and Krishan Chawla
- Comprehensive nuclear materials,
  Editor in chief: R. J. M. Konings
  (5 volume). Elsevier
- Presentation by Prof. A. Moeslang
  https://publikationen.bibliothek.kit.edu/230095072/3816505
- and Dr. J. Knaster
  (http://www.nuklearforum.ch/fr/forum-nucl%C3%A9aire-suisse/nos-manifestations/premiere-rencontre-du-forum-2015)

Table of Content

Presentation by Prof. A. Moeslang



High Performance Materials for Energy



Strategic Missions:
- Electricity, Heat, Hydrogen
- Environmental compatibility
- Cost effectiveness, sustainability

Safety first

Specific challenges for fusion:
- Short development path
- Loading more demanding (e.g H/He)

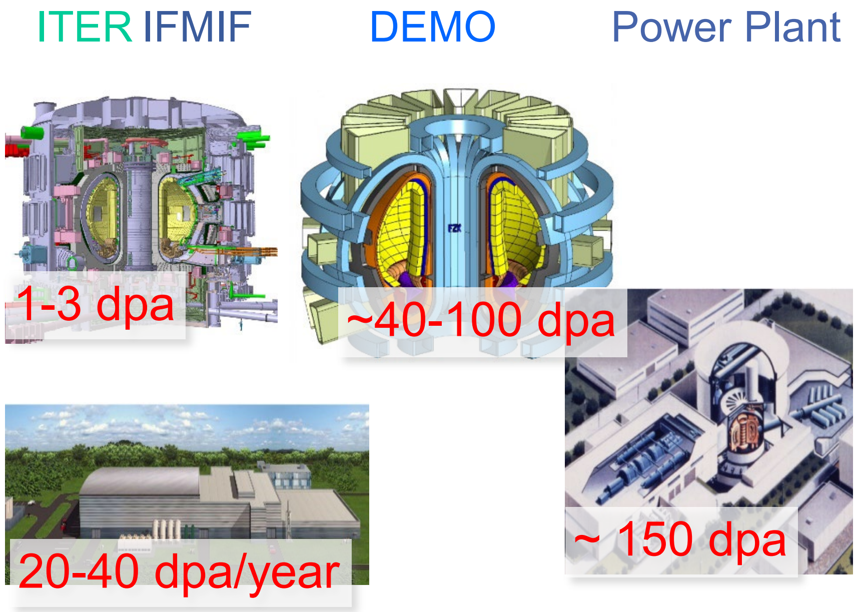
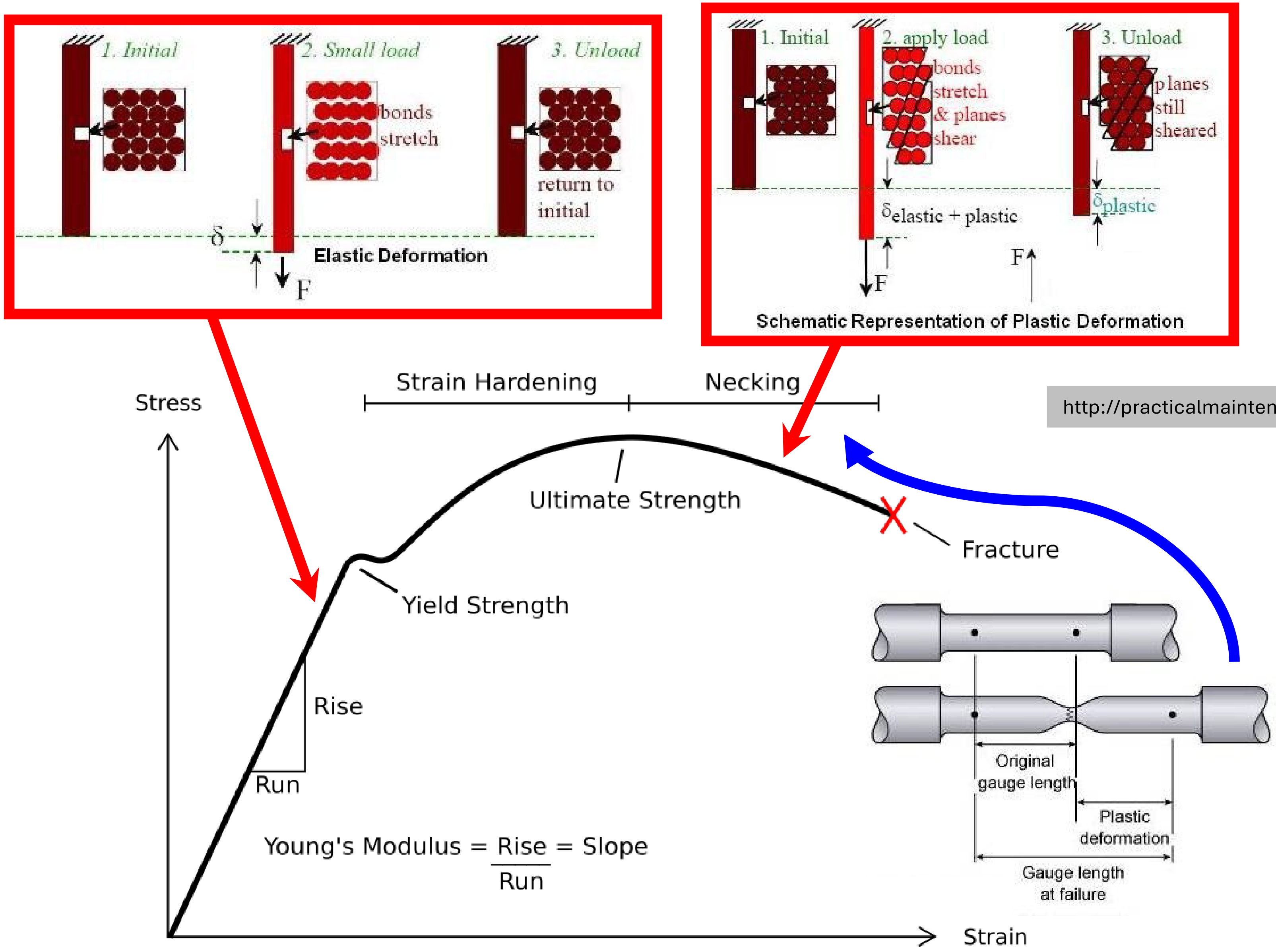


Table of Content

A brief reminder

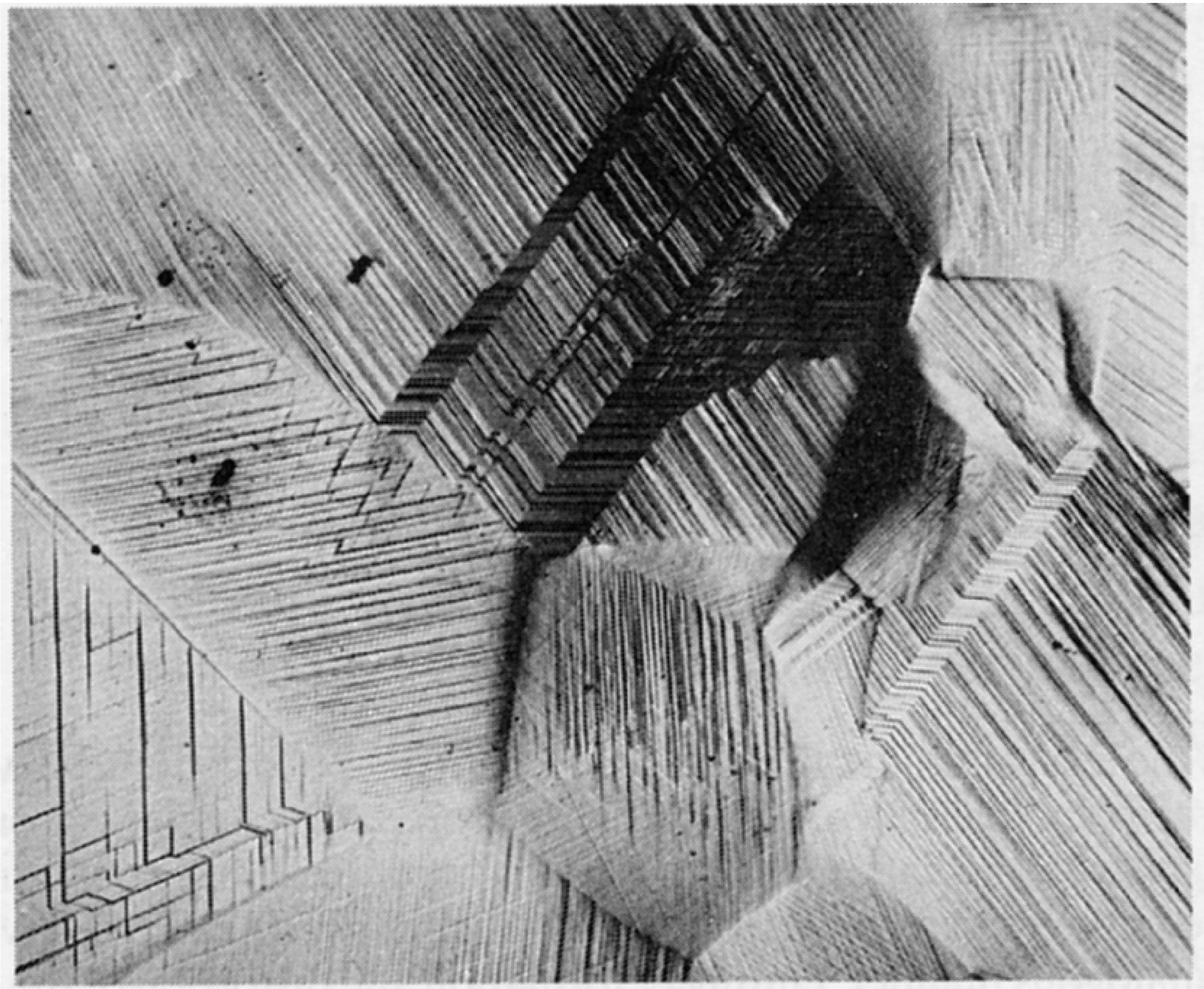
Some simple definition

Stress-strain curve (Constitutive relation)

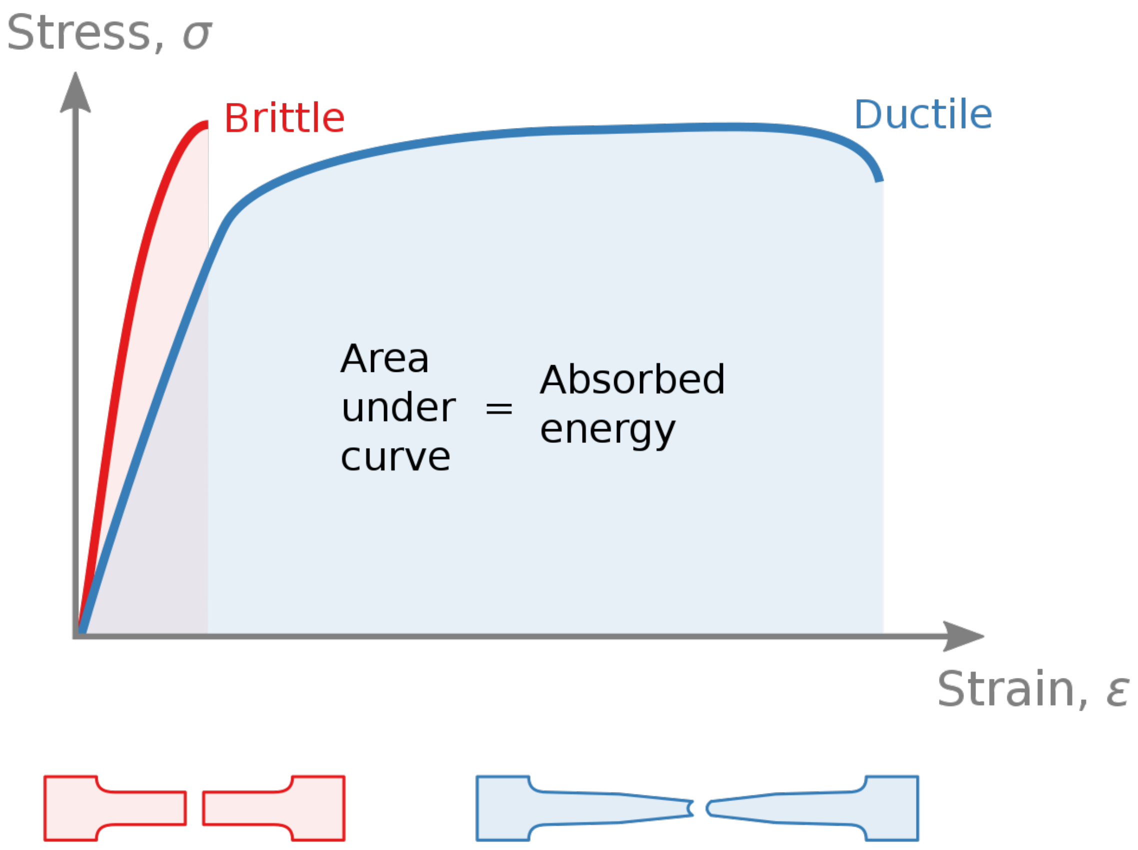


http://practicalmaintenance.net/?p=1135

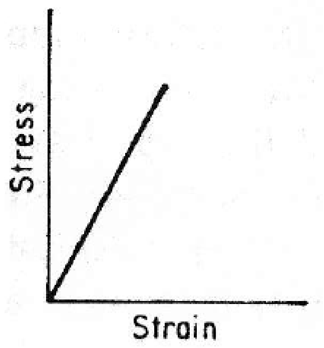
Slip Lines on a Deformed Sample



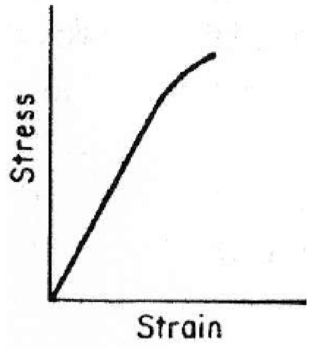
Brittle and ductile material



Purely brittle



Brittle with a slight amount of ductility

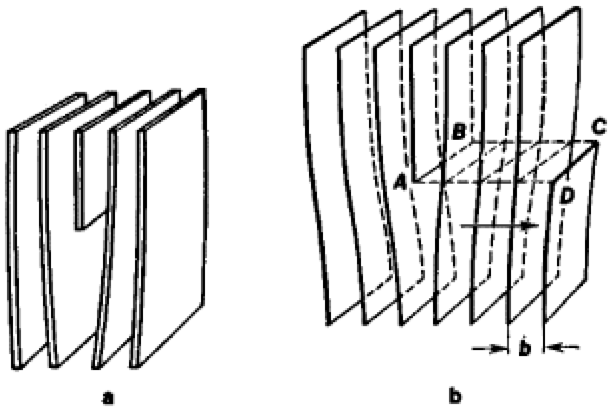


What are dislocations?

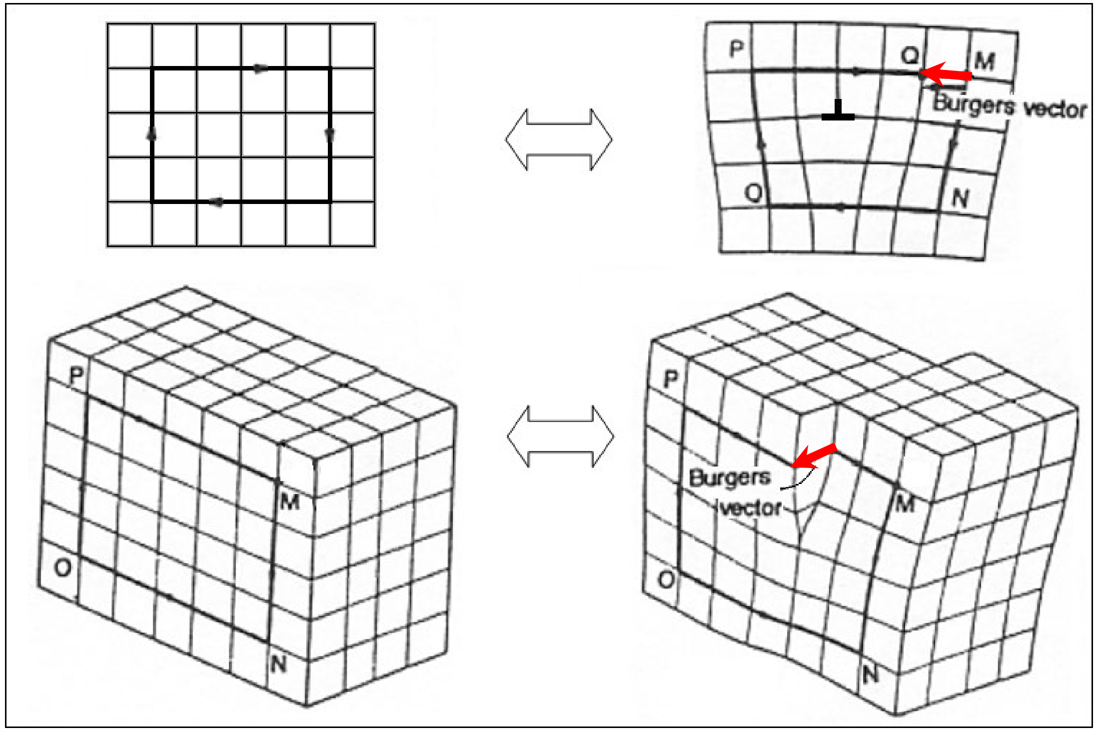
1D Line defects, in which **crystal registry is lost**

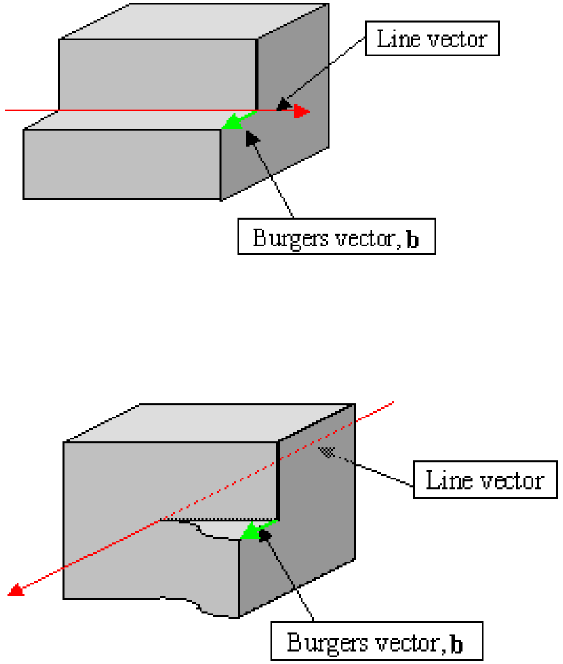
A machine to **cut bonds** on one plane, and **then re-stitch** them together, one by one Dislocation Glide Carry local deformation and stress

Edge, screw, mixed dislocations



Explanation Burgers Vector



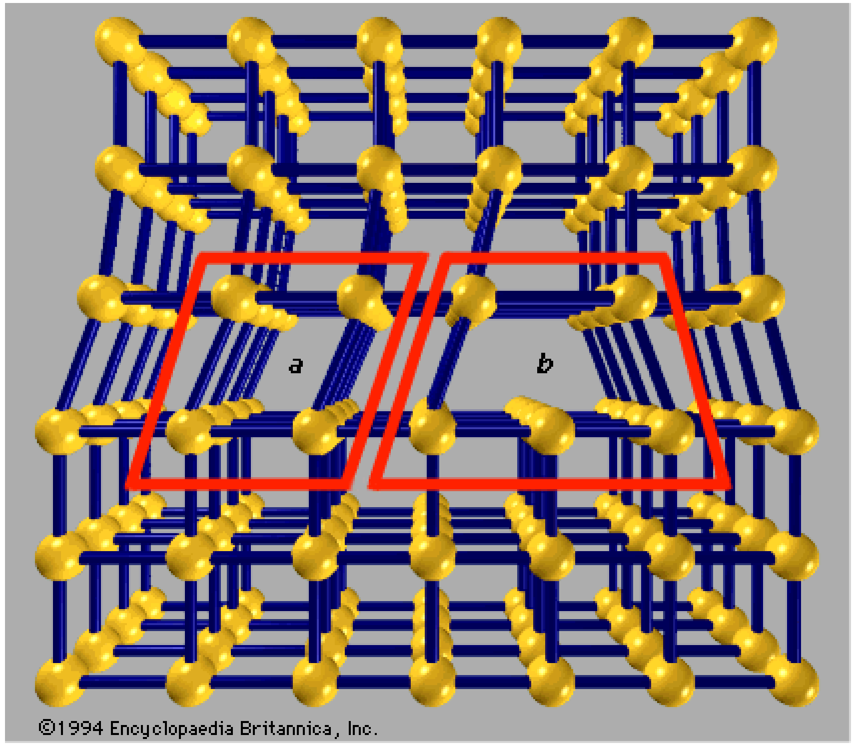


The dislocation line runs along the core of the dislocation, where the distortion with respect to the perfect lattice is greatest.

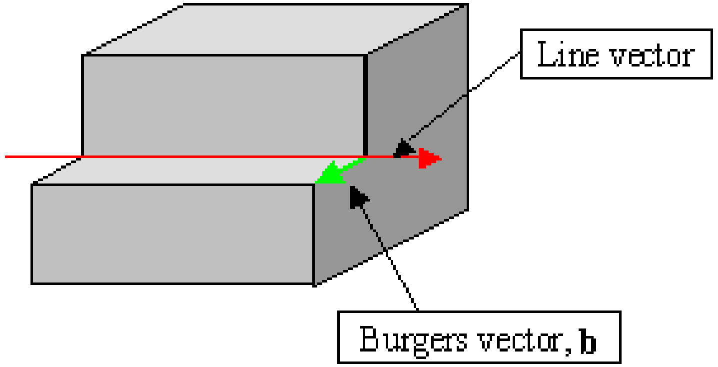
Burgers vector **b**:

Magnitude and direction of the lattice distortion resulting from a dislocation in a crystal lattice

Edge dislocation



- Illustration with bonds
- Local environment is different only at the core.
- Localized shear
- b perpendicular to line direction

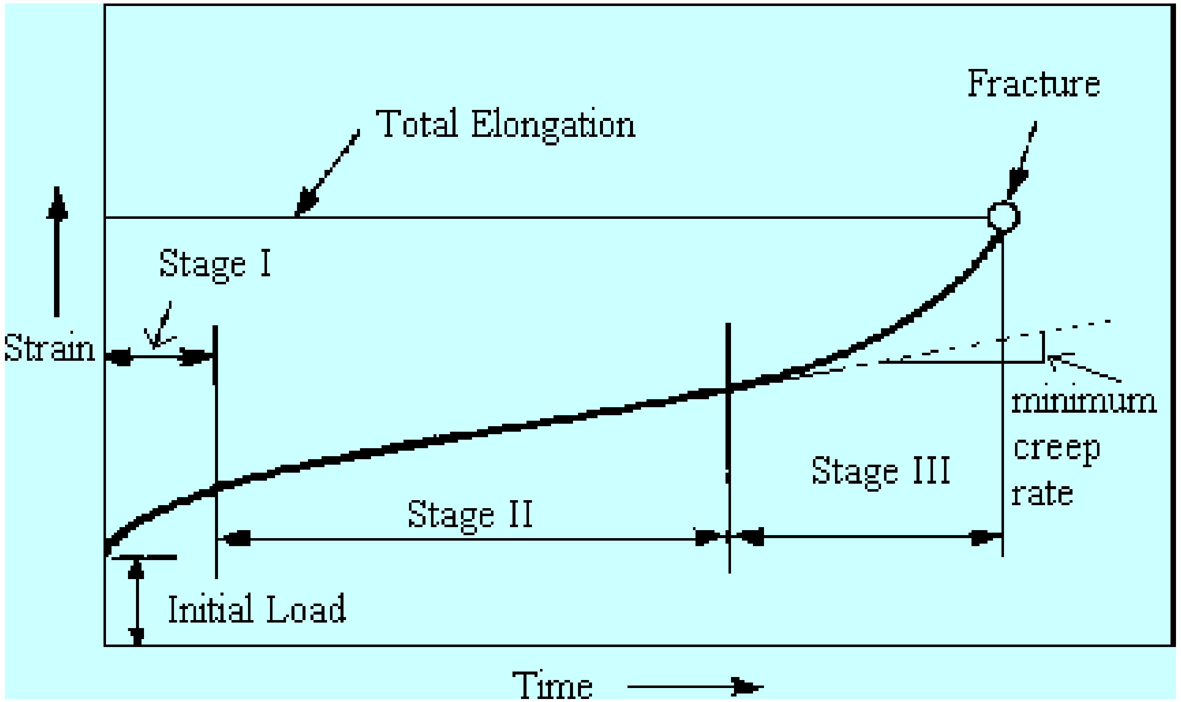


Creep curve

EPFL PSI

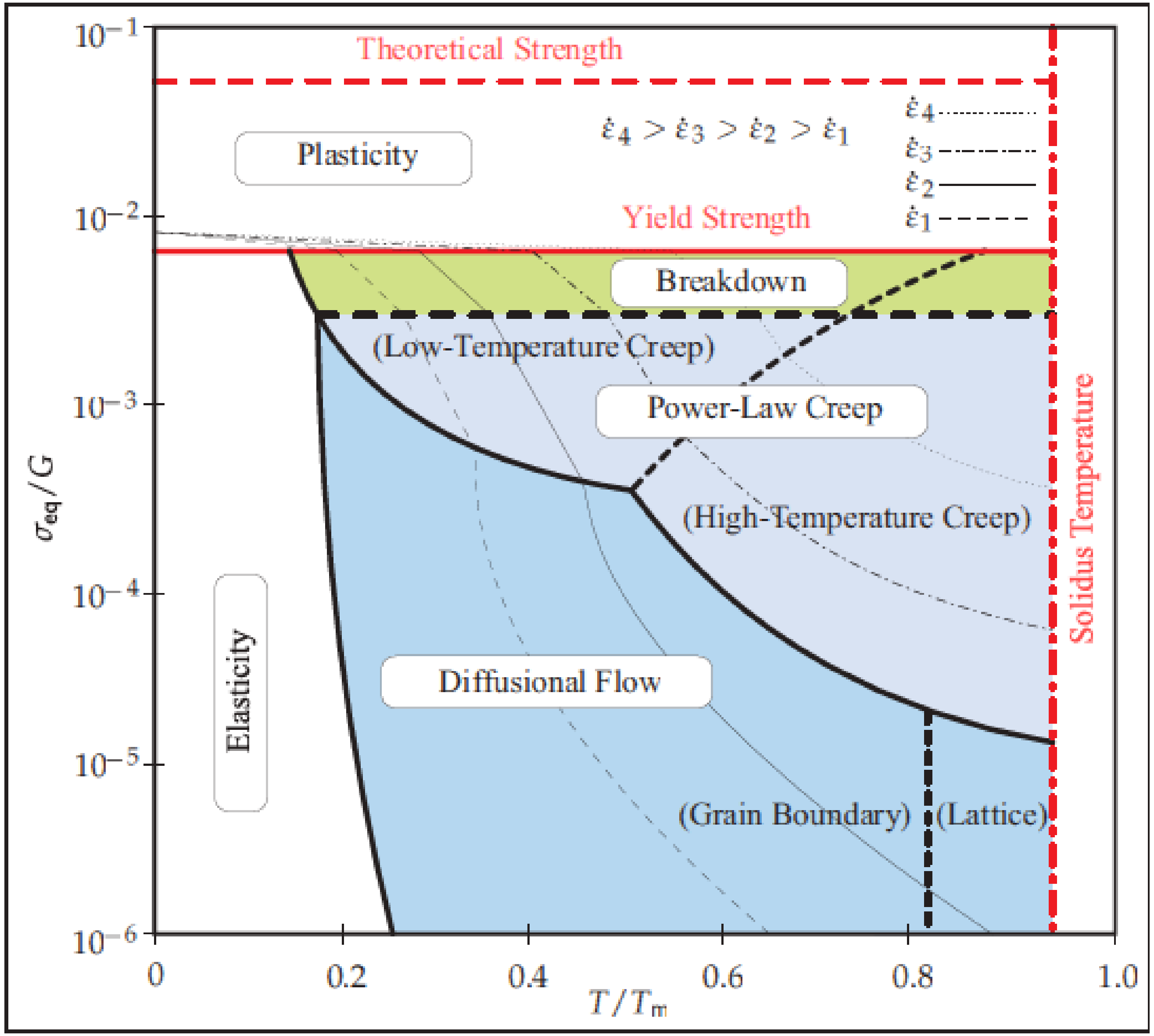
High **temperature progressive deformation** of a material at **constant stress** is called **creep**.

- **Primary creep, Stage I**, is a period of **decreasing creep rate**. Primary creep is a period of **primarily transient creep**. During this period deformation takes place and the resistance to creep increases until stage II.
- **Secondary creep, Stage II**, is a period of roughly **constant creep rate**. **Stage II is referred to as steady state creep**.
- **Tertiary creep, Stage III**, occurs when there is a **reduction in cross sectional area due to necking or effective reduction in area due to internal void formation**.

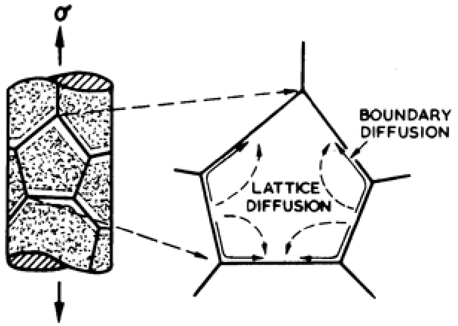


http://www.materialsengineer.com/CA-Creep-Stress-Rupture.htm

Creep mechanisms (schematically)



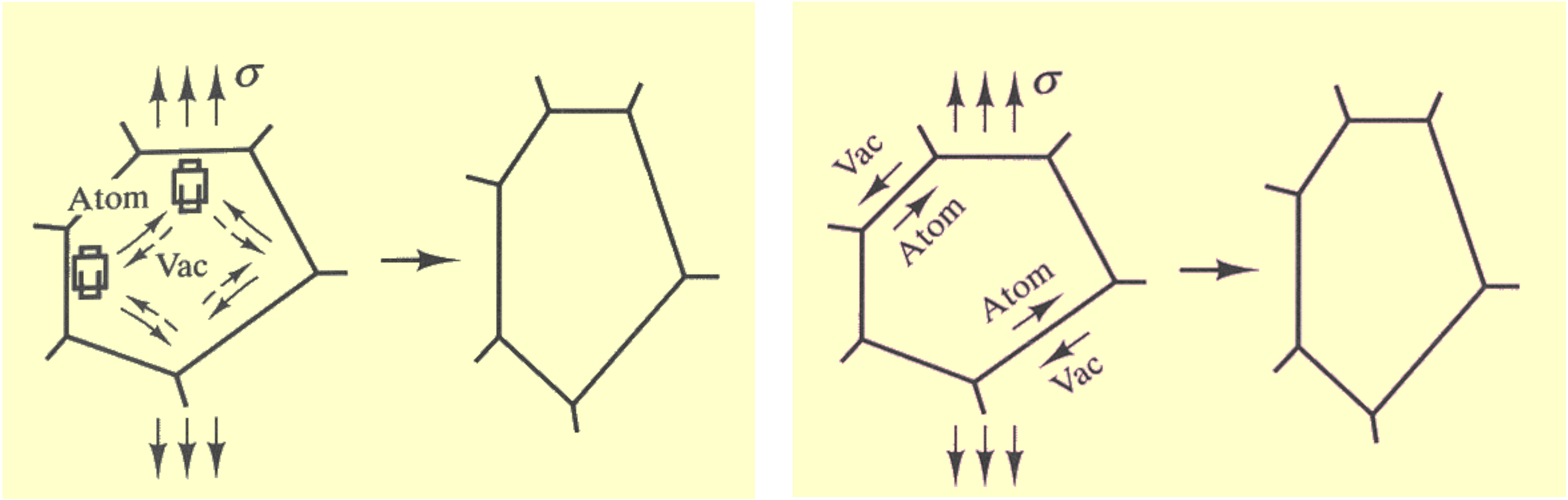
Diffusional Creep: Illustration



Diffusion

Volume

Grain-boundary



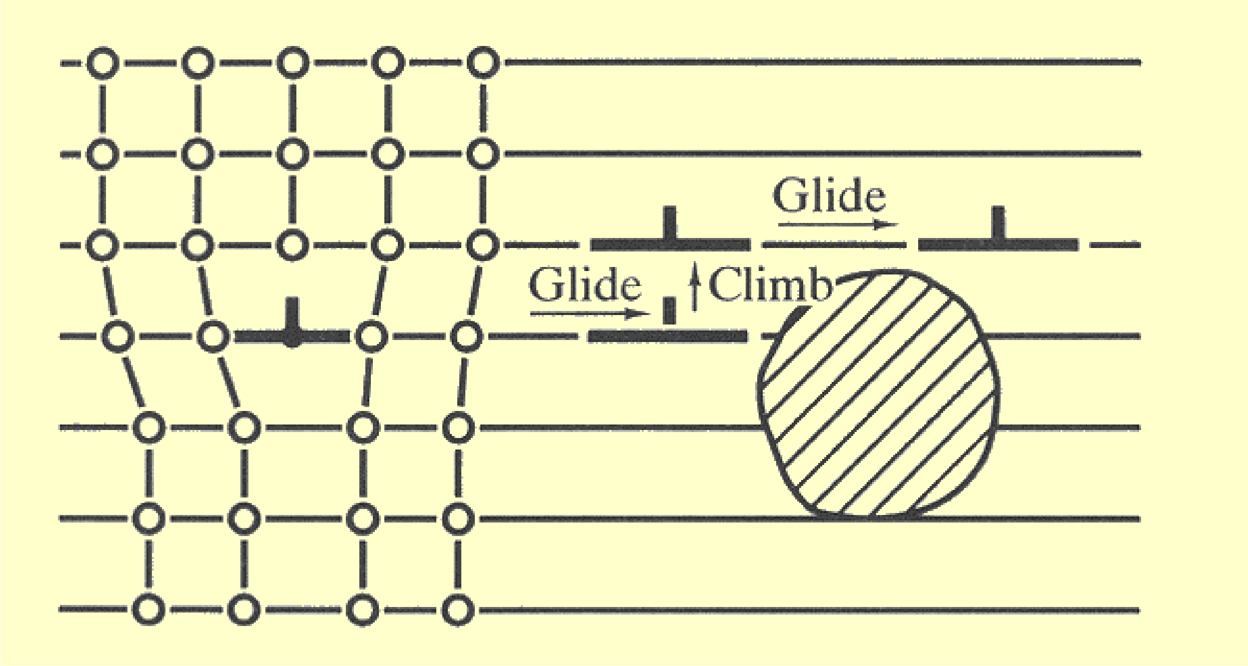
Nabarro-Herring

Coble

Note that the vacancies and atoms move in opposite directions.

Dislocation Creep: Illustration

EPFL PSI



Dislocation Creep

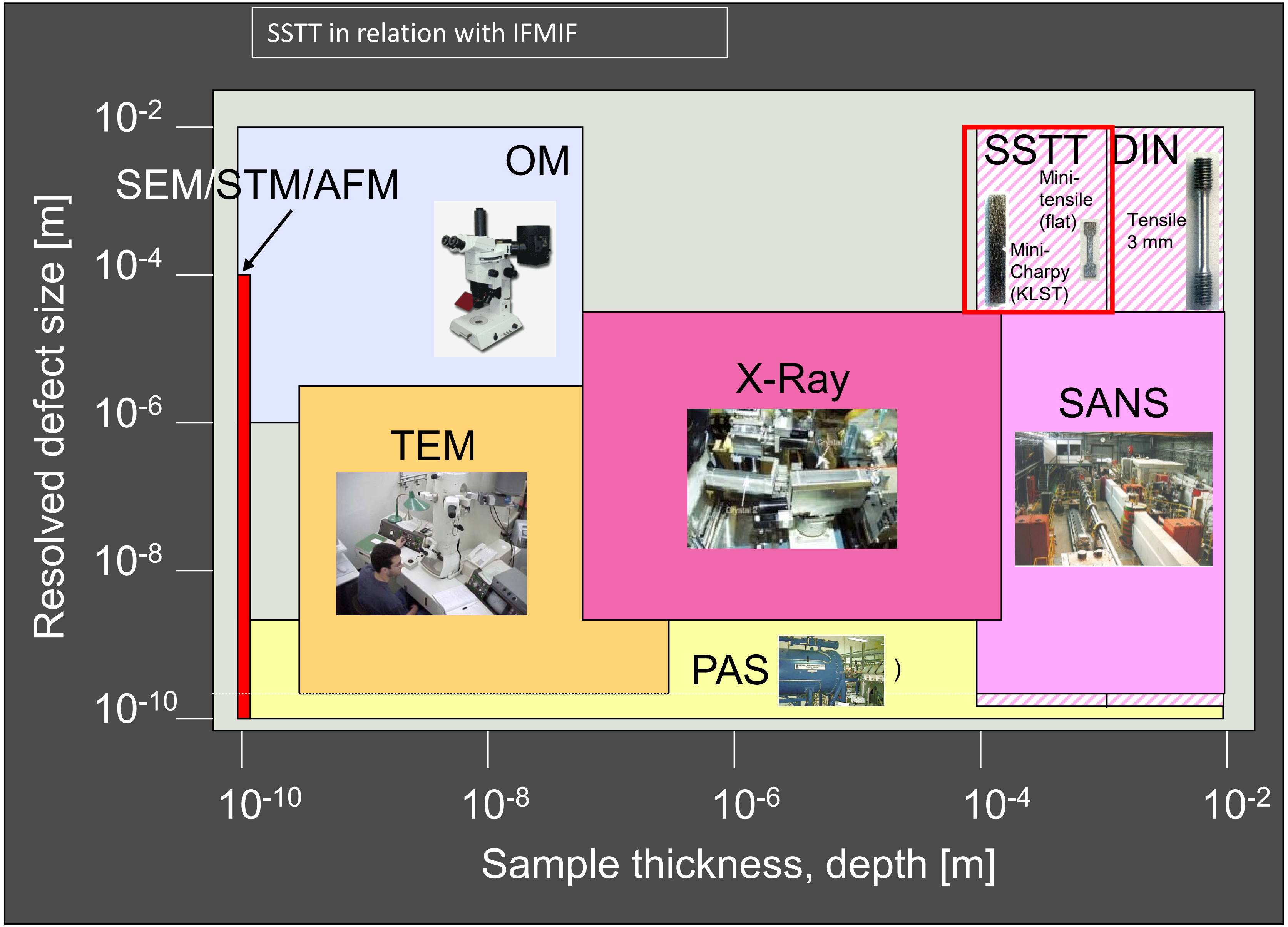
Glide is movement of a dislocation **on its slip plane**. Not particularly temperature sensitive.

Climb is movement of a dislocation **perpendicular to its slip plane**. This occurs when dislocations **absorb or emit vacancies**. It's a **diffusive process**, requiring diffusion of vacancies towards or away from the dislocation core. Much more temperature sensitive than glide.

Table of Content

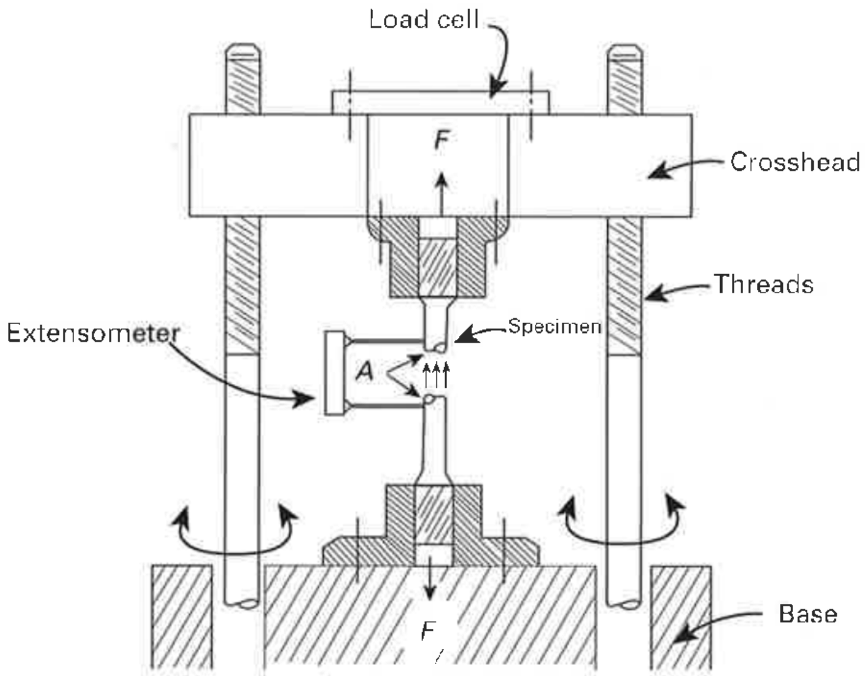
Testing of materials

Testing of materials

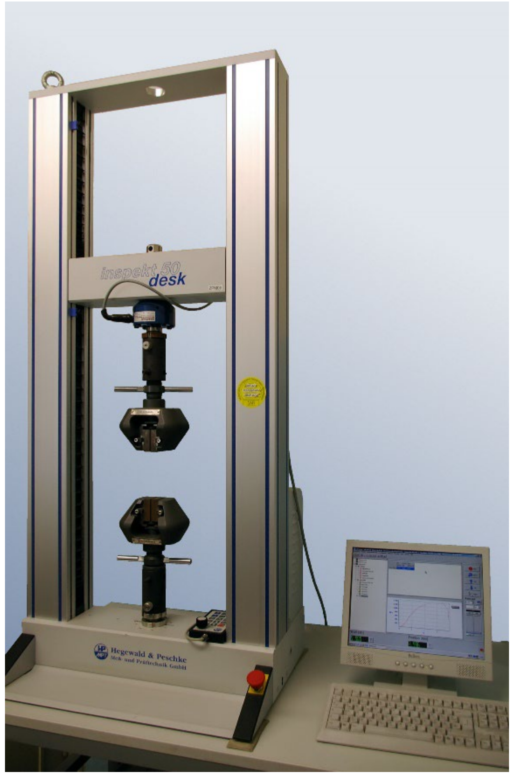


Some metallurgical testing methods

Traction (tensile) machine

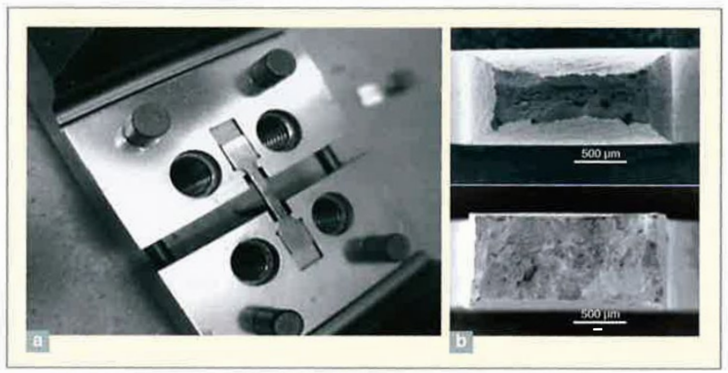


Screw driven tensile machine



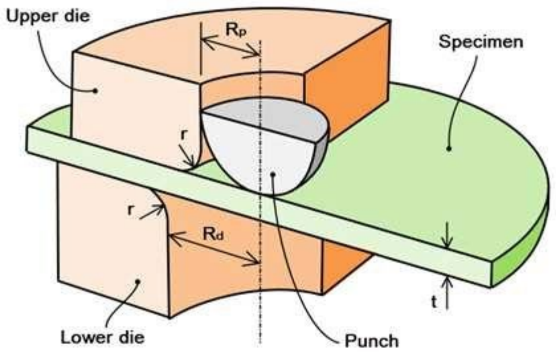
Traction test

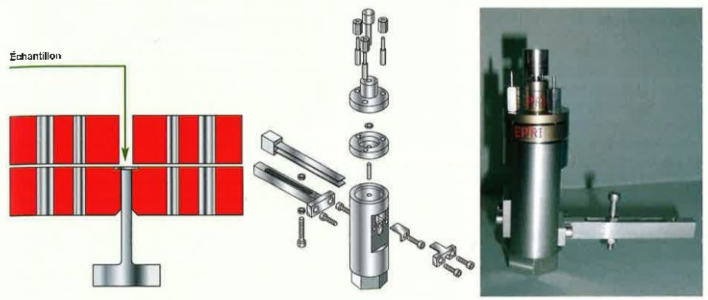
Miniaturized tensile samples (dog-bones) at LECI



a) tensile tester for flat miniature specimens
b) Fracture surface and necking:
top: ductile with important necking,
bottom: brittle with almost no necking

Small punch test

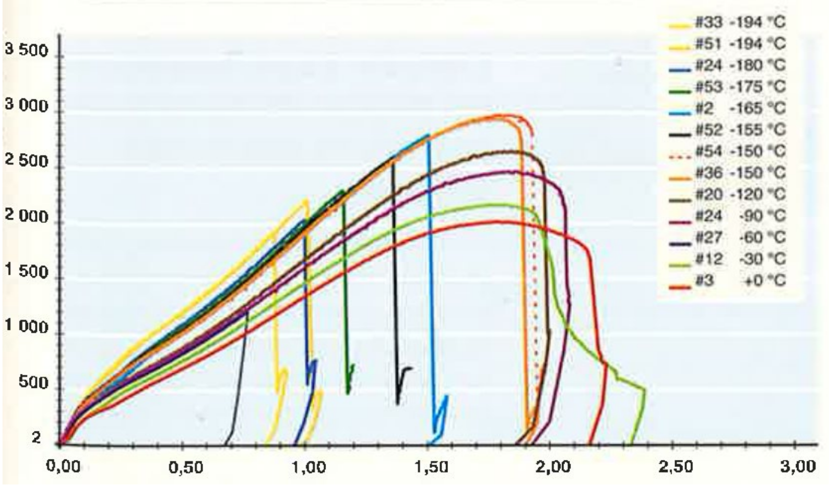




Nuclearized Small Punch Test at LECI

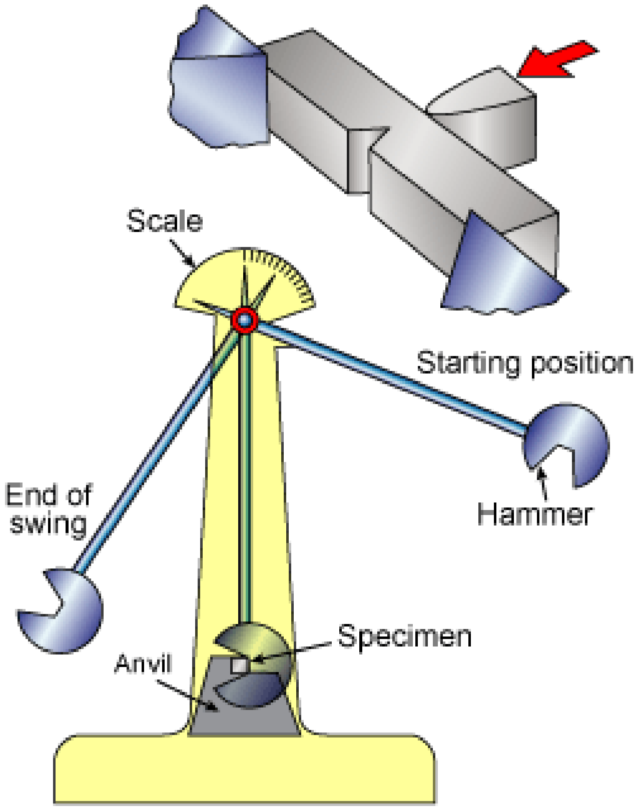
Load-displacement curves as function of temperature: RPV steel 16MND5

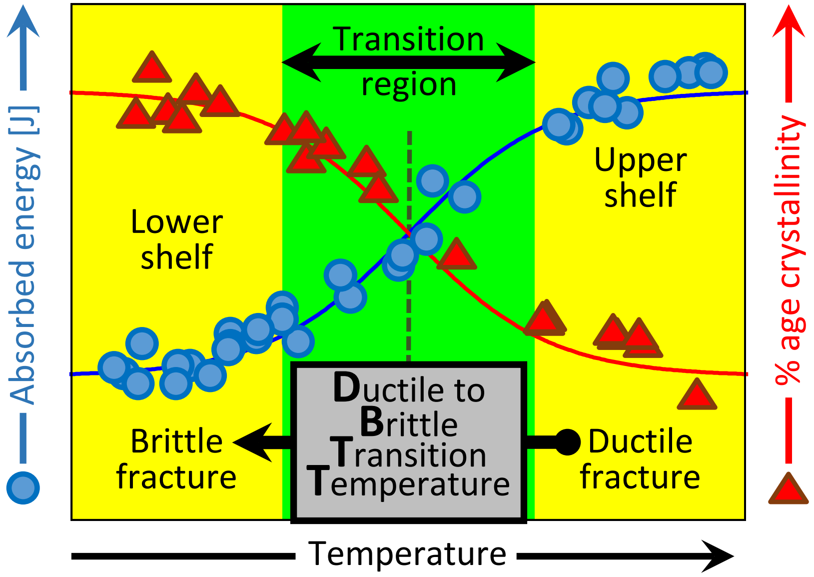
Applied load [N]

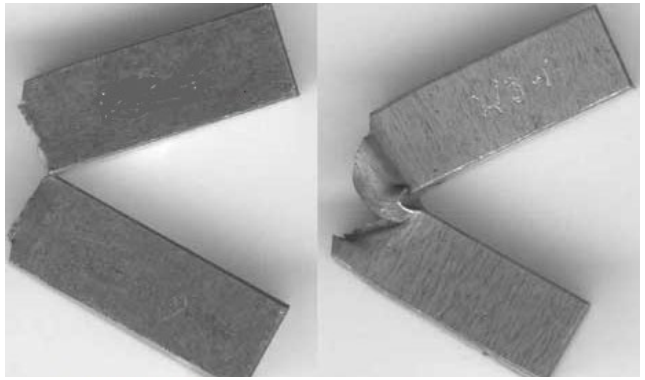


Displacement of punch [mm]

Impact Testing – Charpy Test - DBTT







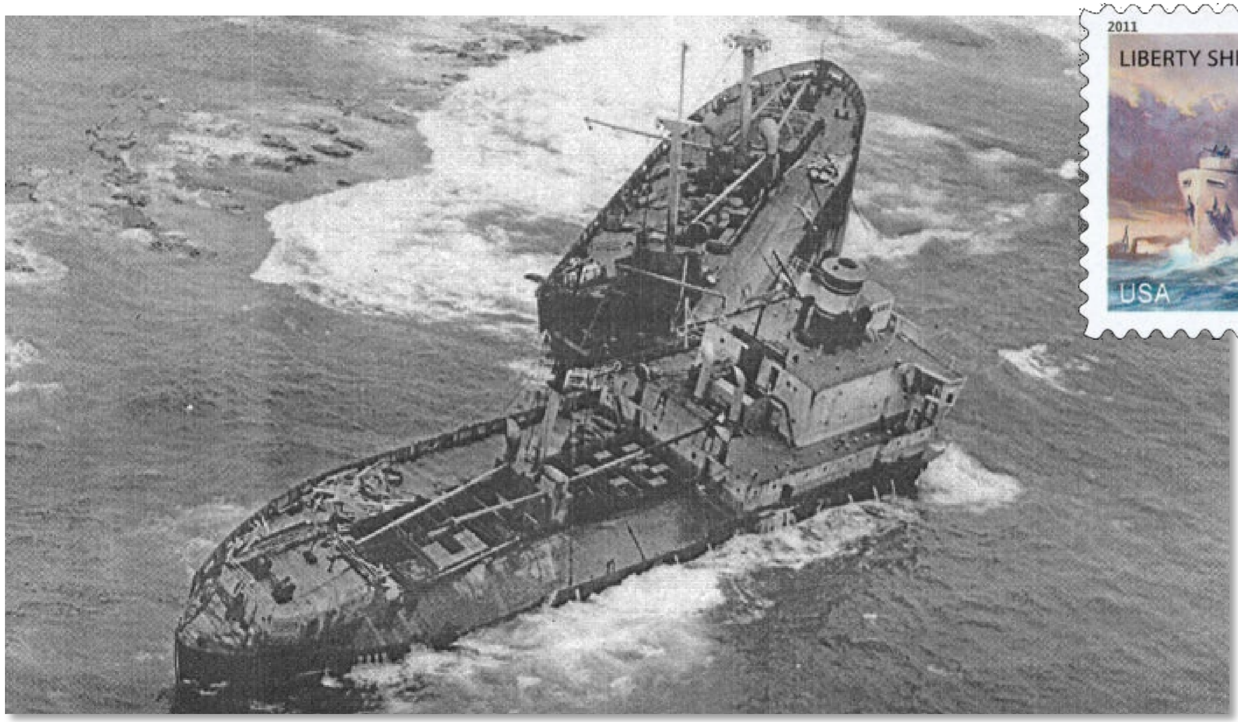
http://www.twi.co.uk/technical-knowledge/job-knowledge/
job-knowledge-71-mechanical-testing-notched-bar-or-impact-testing/

Table of Content

- Introduction: presentation of Anton Moeslang / timeframes / displacement damage
- Basic material science
  - material deformation
  - material testing
  - embrittlement / DBTT
- Motivation (why do we need material science)
- Radiation defects (H / He / displacement)
- Which materials? What are steels?
- Safety aspects (can it melt?)
- Radiation exposure and influence on the mechanical behavior
- “out of fusion” nuclear material science
- How to irradiate materials (14 MeV) / IFMIF

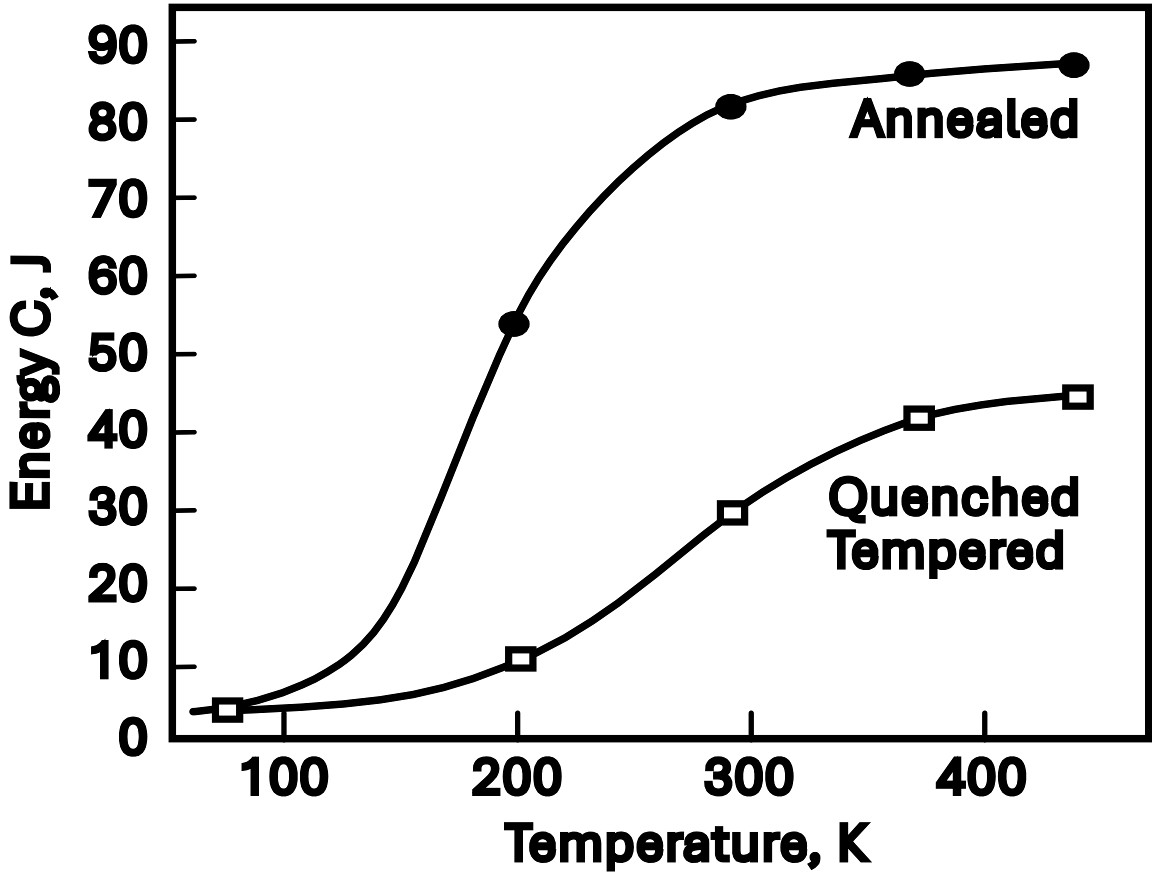
- Exercise

Ductile-to-Brittle Transition – WWII Liberty Ships



Some of the first Liberty Ships completed suffered from hull and deck cracks and some were actually lost to these early defects. During the course of WWII there were nearly 1,500 instances of significant brittle fractures due to low grade of steel which suffered from embitterment. It was discovered by Constance Tipper of Cambridge University that **ships that were used in the North Atlantic were exposed to temperatures that could fall below a critical point and cause the hull to fracture quite easily**. One of the most common types of crack began at the square corner of a hatch with coincided with a welded seam with both the weld and the corner acting as stress concentrators. Along with the poor quality of steal the ships were usually grossly overloaded and many of the problems occurred during severe storms at sea that placed the ships and crew in even more danger. Various reinforcements were applied to the design to deal with the cracks.

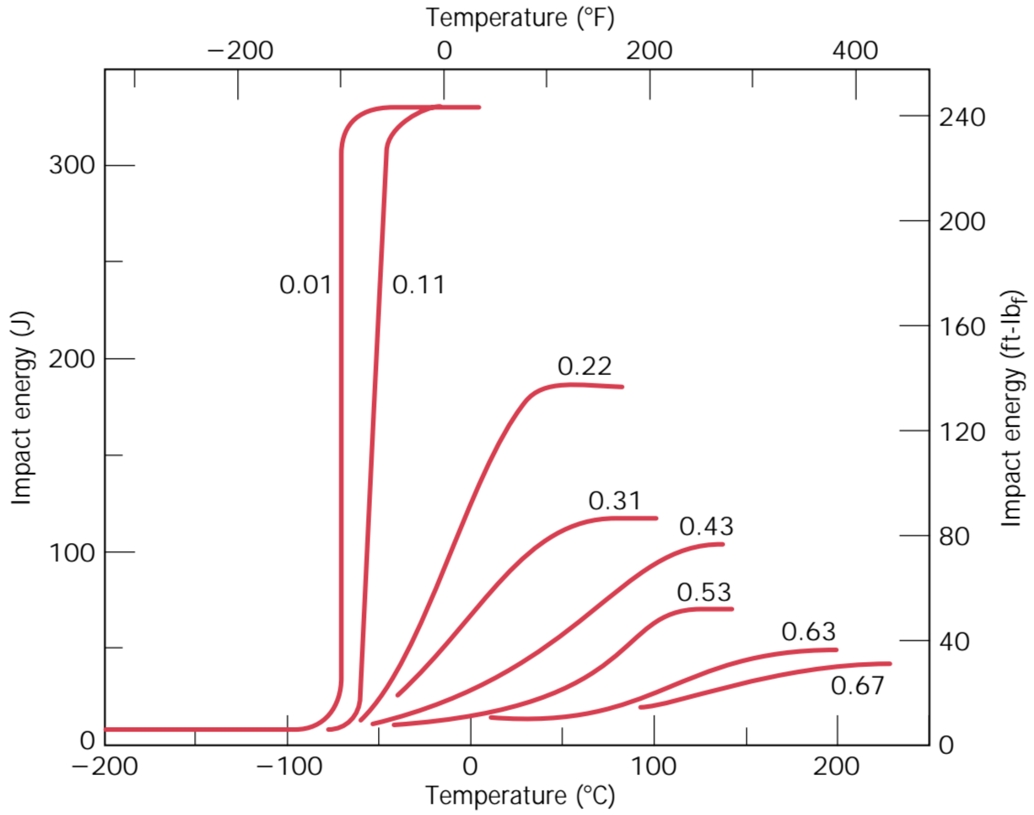
Charpy test – DBTT Quenched / Annealed



Energy absorbed versus temperature for a steel in annealed and in quenched and tempered states

J. C. Miguez Suarez and K. K. Chawla, Metalugia-ABM, 34 (1978)

Charpy test – DBTT Composition



Influence of **carbon content** on the

Charpy V-notch energy-versus temperature behavior for steel

"*Effects* of *Alloying Elements* on *Notch*. *Toughness* of *Pearlitic Steels*,". Trans. *ASM*, V.*43* (*1951*), pp. 1175-1214

& reprinted in "Callister, Materials Science and Engineering, 2nd edition, p 313"

Charpy test – DBTT Irradiation

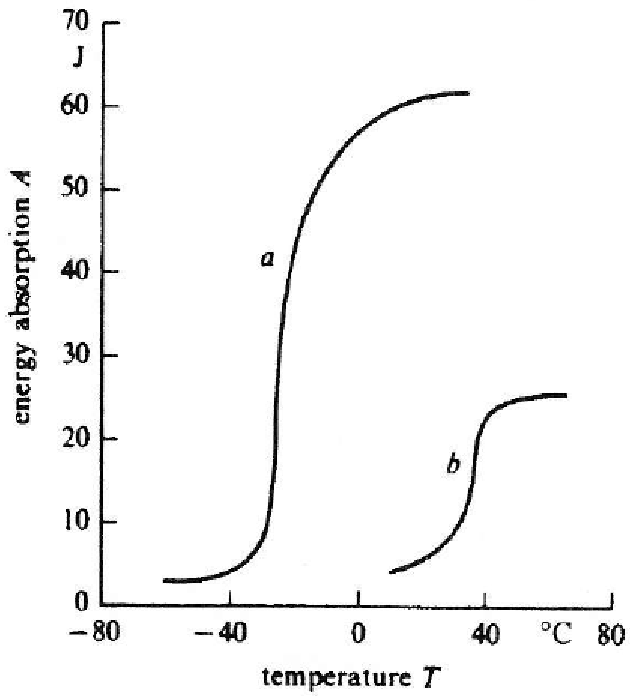
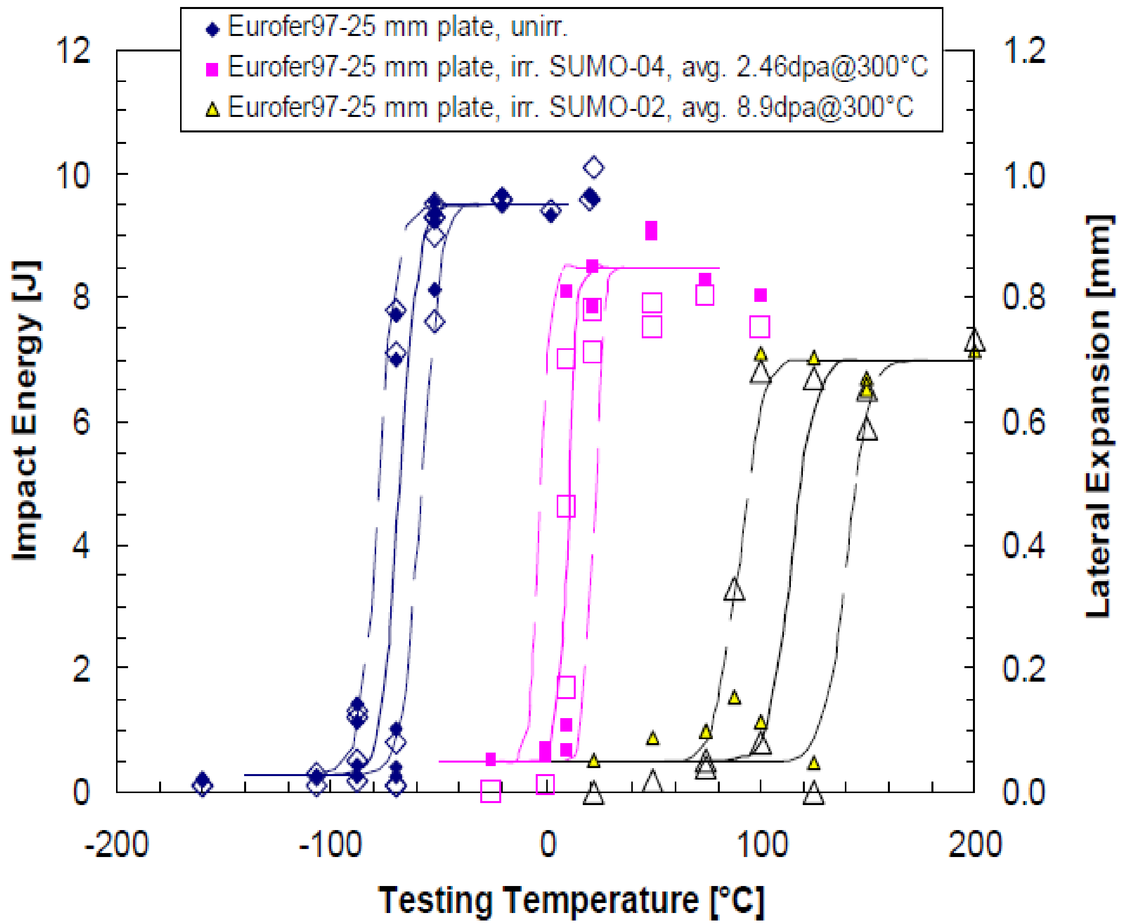


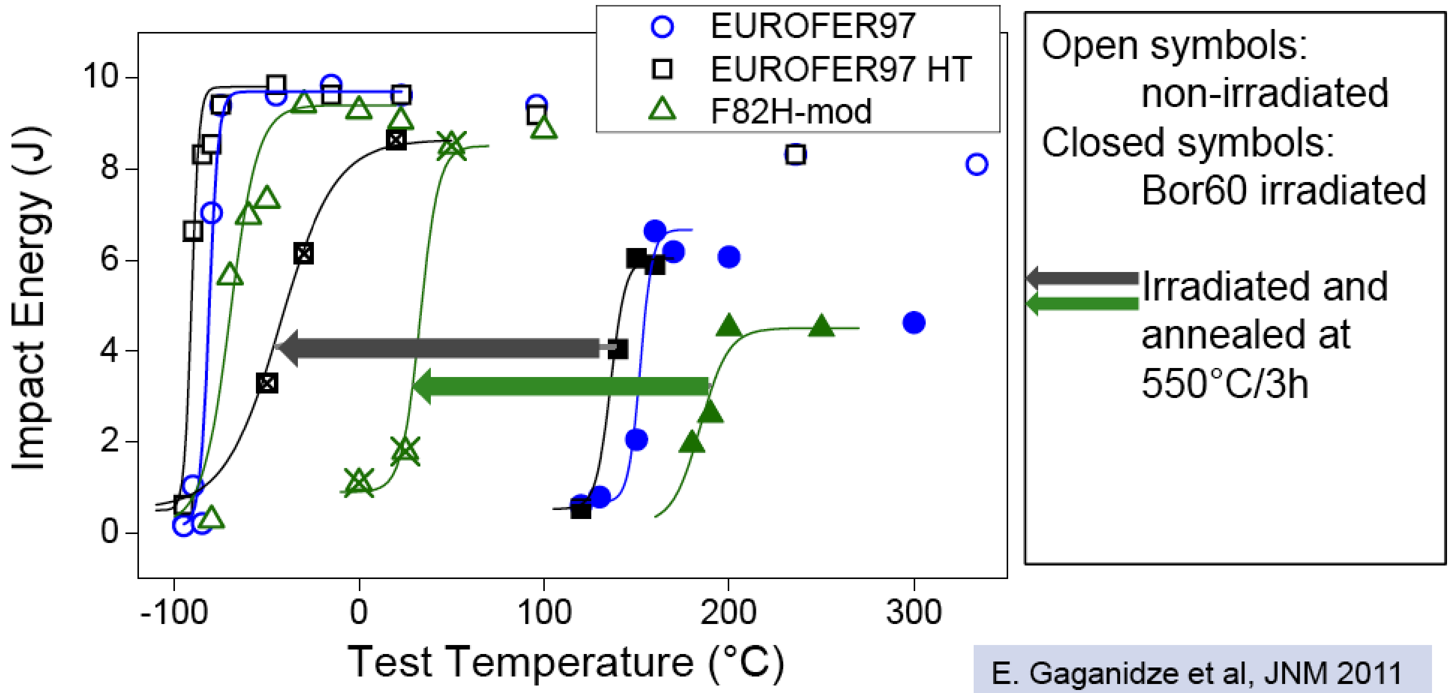
Fig. 12.31. Energy absorbed at fracture as a function of temperature for carbon steel (*a*). After irradiation by 1.9×10^{19} n/cm^2 the transition to brittle fracture (reduced absorption) occurs at a higher temperature (A. H. Cottrell, AERE Harwell) (*b*).

Charpy test – DBTT :: Irradiation



Charpy test – DBTT :: Irradiation and annelaed

Annealing experiment after 65-70 dpa at ~335°C
Strategy for recovery of irradiation embrittlement



E. Gaganidze et al, JNM 2011

- How often can this recovery be repeated?
- What happens if large concentrations of He are present?
- IFMIF would easily answer such important questions

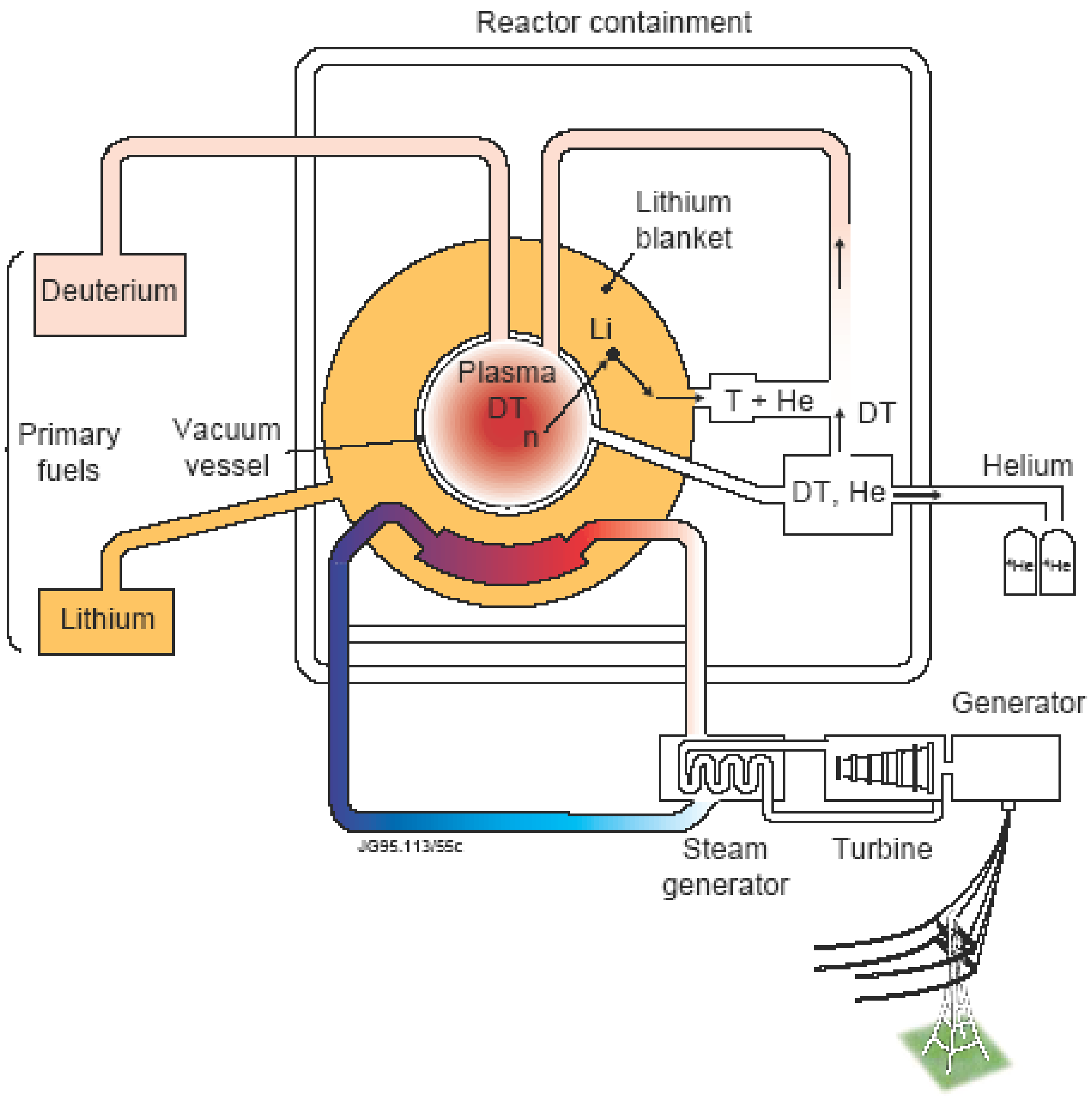
A. Möslang W-GIFT-5 Charleston SC, October 15, 2011

Table of Content

Why do we need to study material science when we work in the field of fusion?

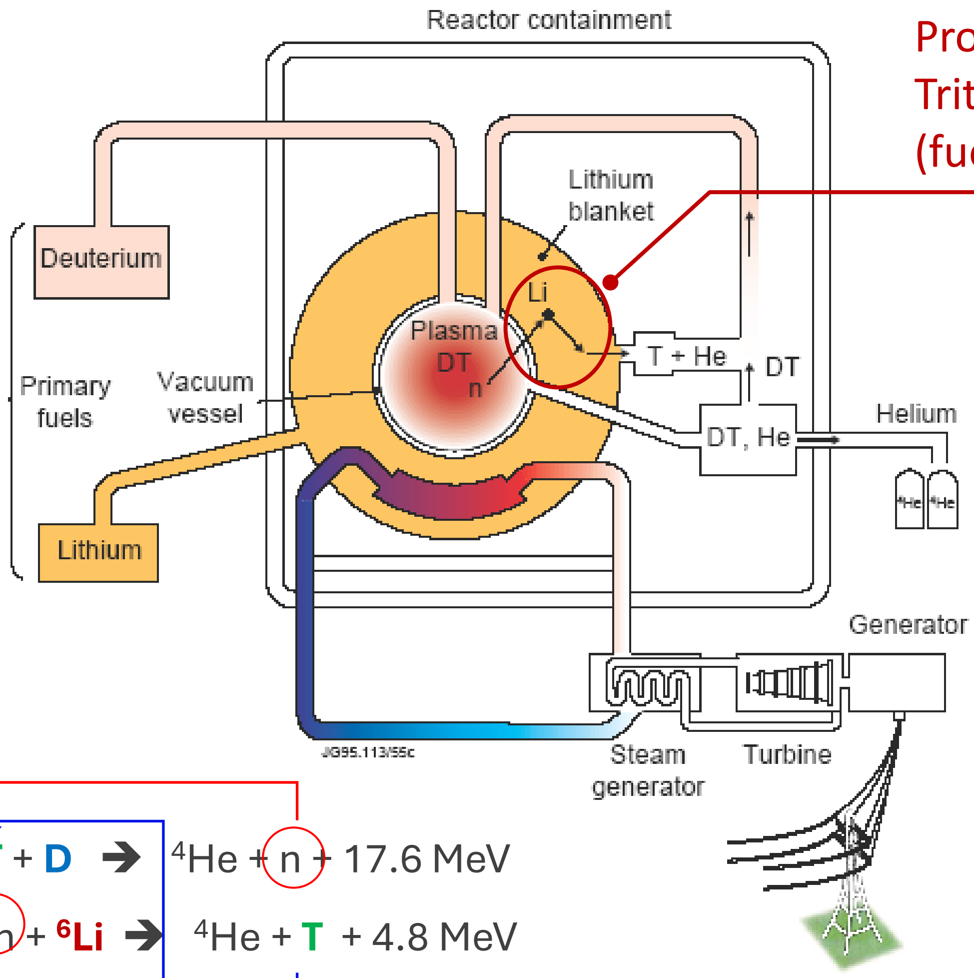
Presentation by Prof. A. Moeslang

The principle of DT fusion reactors



The functions of the Breeder Blanket (1)

EPFL PSI



Produce and recover Tritium
(fuel for DT plasma)

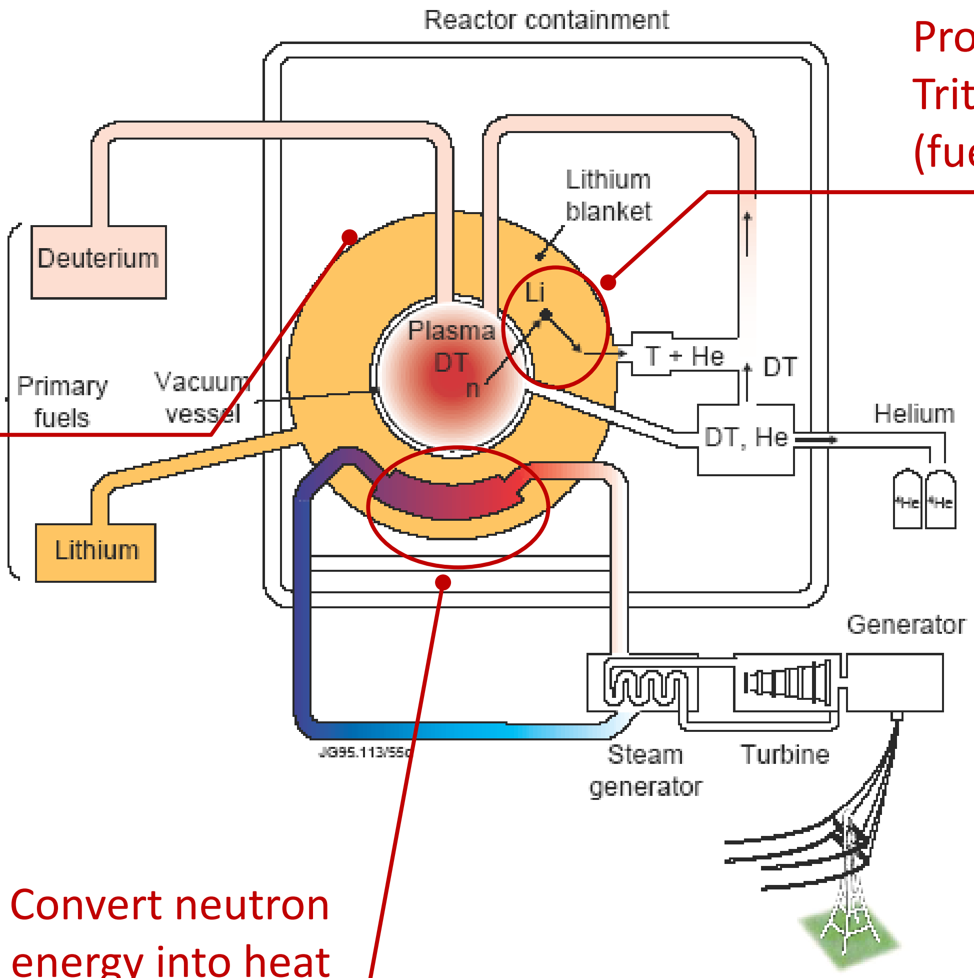
Fusion (plasma): $T + D \rightarrow {}^4He + n + 17.6\ MeV$

Breeding (blanket): $n + {}^6Li \rightarrow {}^4He + T + 4.8\ MeV$

Balance: $D + {}^6Li \rightarrow 2\ {}^4He + 22.4\ MeV$

The functions of the Breeder Blanket (2)

Protect vacuum vessel and coils against radiation damages/heating



Produce and recover Tritium (fuel for DT plasma)

Convert neutron energy into heat

Why are we interested in materials?

Fusion produces high energy neutrons.
These neutrons in turn create two type of effects:

1. Transmutation into other materials (Among others H and He)
2. Mechanical defects (Frenkel pair i.e. vacancy and interstitial atom)

DEMO: neutron spectra in materials

FIGURES 19

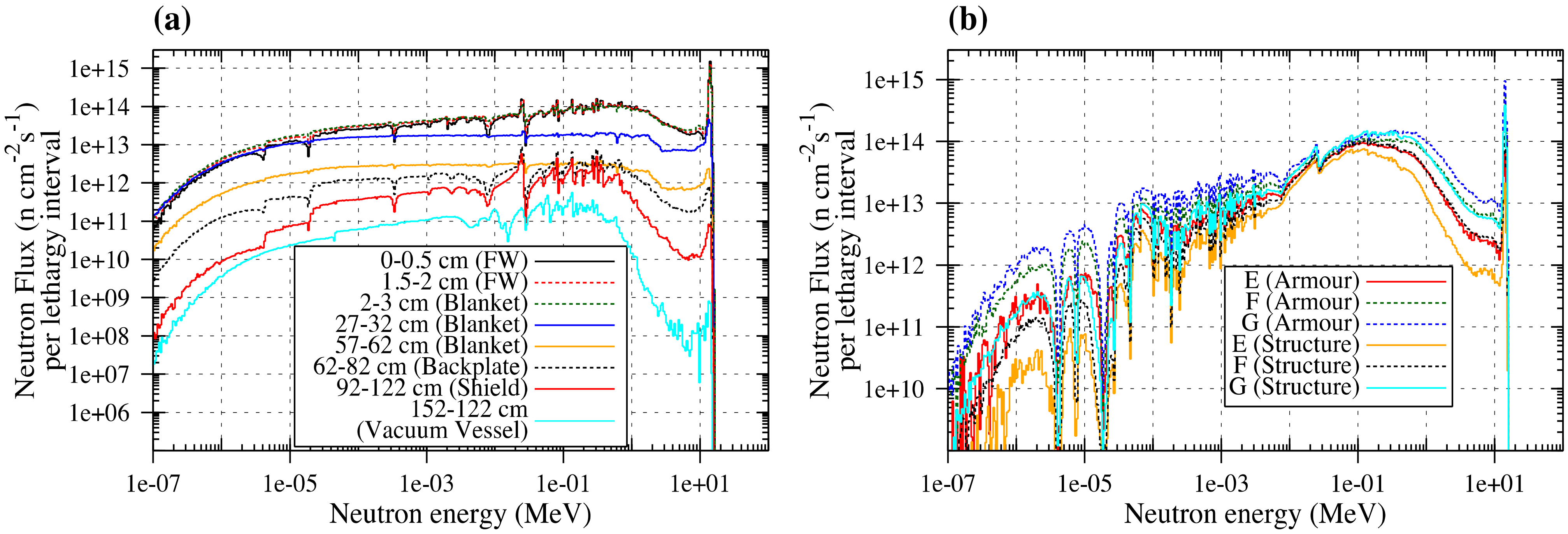


Figure 3. Comparison of the neutron-energy spectra in DEMO; (a) as a function of depth into different regions of the containment vessel at the equatorial position (A) in figure 2; and (b) in the first two layers of the divertor as a function of position ((E–G) in 2).

→defect production

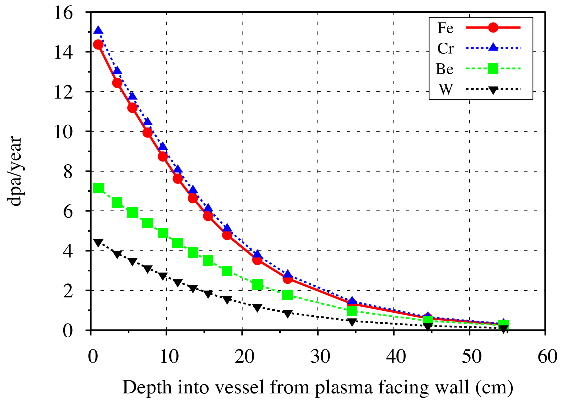


Figure 4. Defect production rates, expressed in dpa per year units for different elements shown as a function of depth into the FW at A in figure 2.

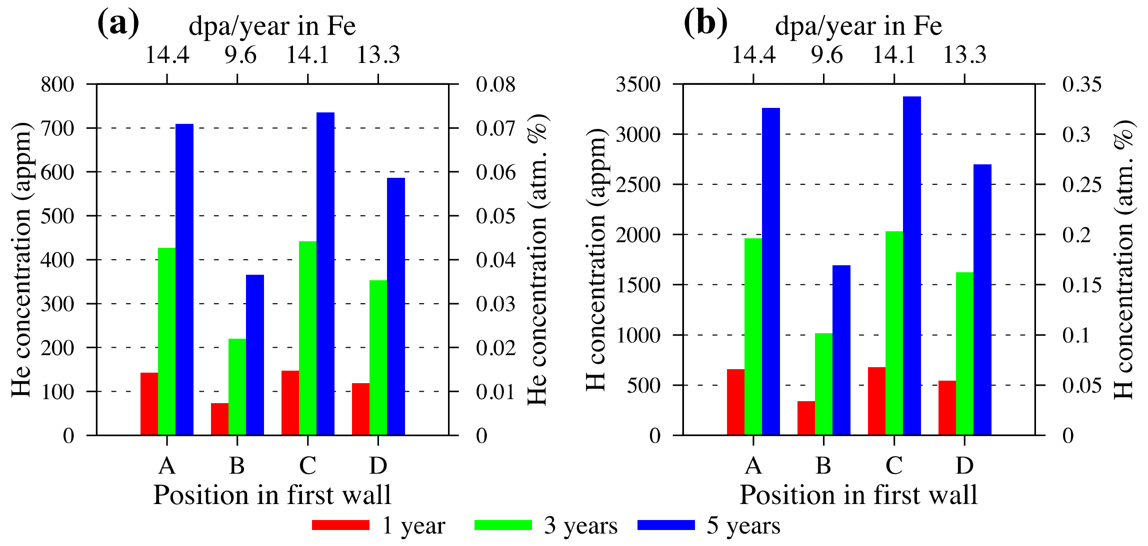


Figure 5. Variation in the (a) He, and (b) H, concentrations in pure Fe as a function of time for the spectra at different FW positions in DEMO – see figure 2. The equivalent dpa/year in pure Fe at each position are also given.

Table of Content

- Introduction: presentation of Anton Moeslang / timeframes / displacement damage
- Basic material science
  - material deformation
  - material testing
  - embrittlement / DBTT
- Motivation (why do we need material science)
- Radiation defects (H / He / displacement)
- Which materials? What are steels?
- Safety aspects (can it melt?)
- Radiation exposure and influence on the mechanical behavior
- “out of fusion” nuclear material science
- How to irradiate materials (14 MeV) / IFMIF

- Exercise

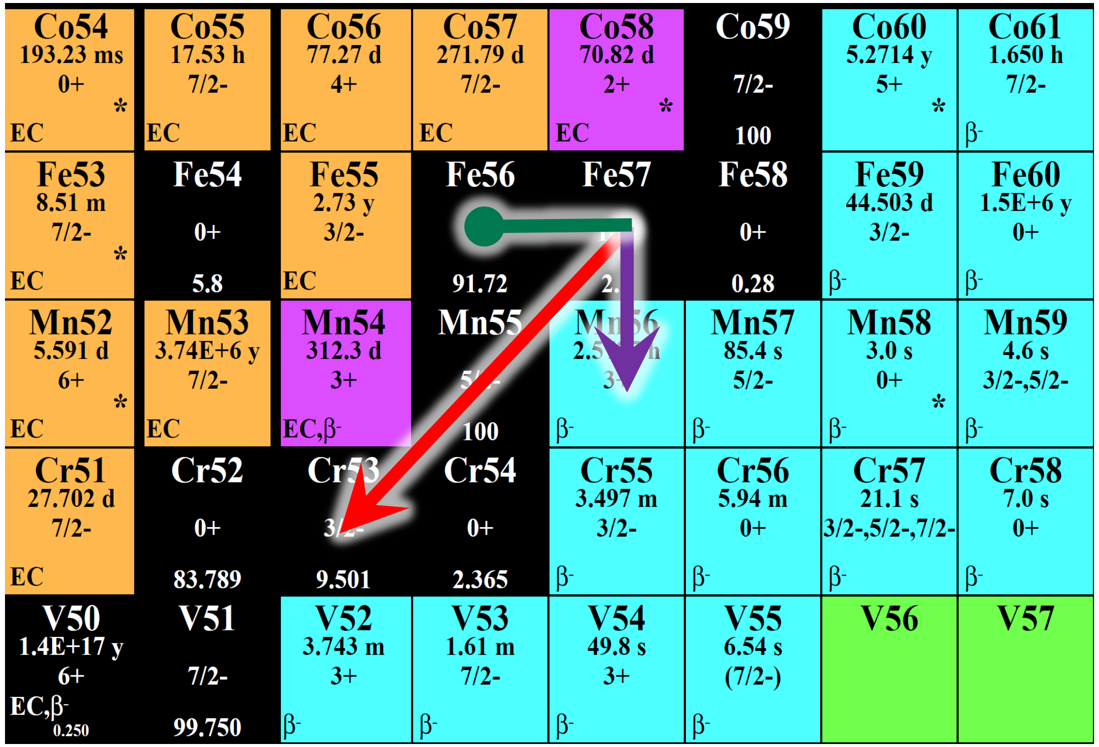
Production of H and He

Fe transmutation producing H and He

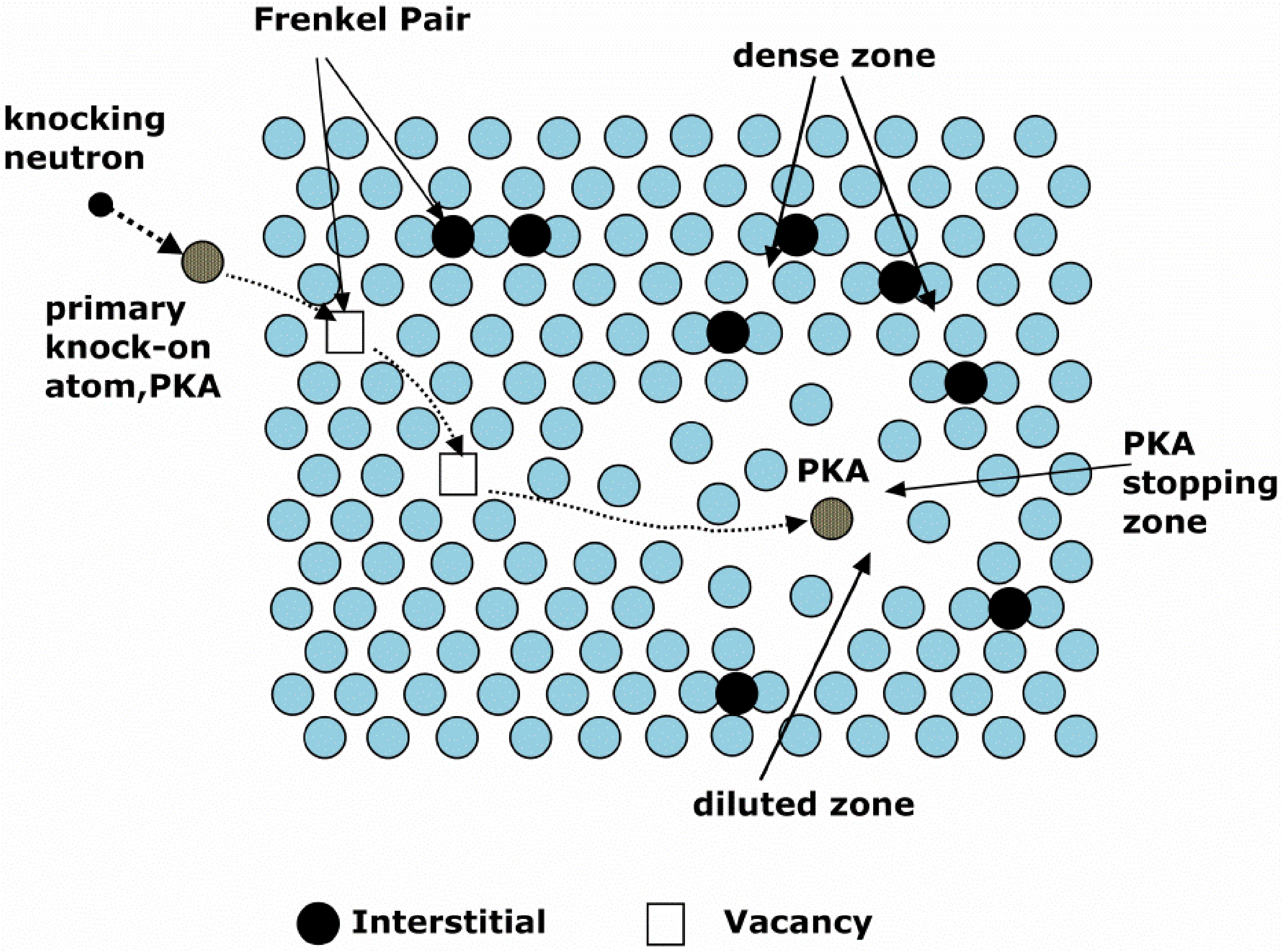
$^{56}Fe(n,\alpha)^{53}Cr$ ($^{56}Fe + n \rightarrow {}^{53}Cr + \alpha$)
(incident n threshold at **2.9 MeV**)

&

$^{56}Fe(n,p)^{56}Mn$
(incident n threshold at **0.9 MeV**)

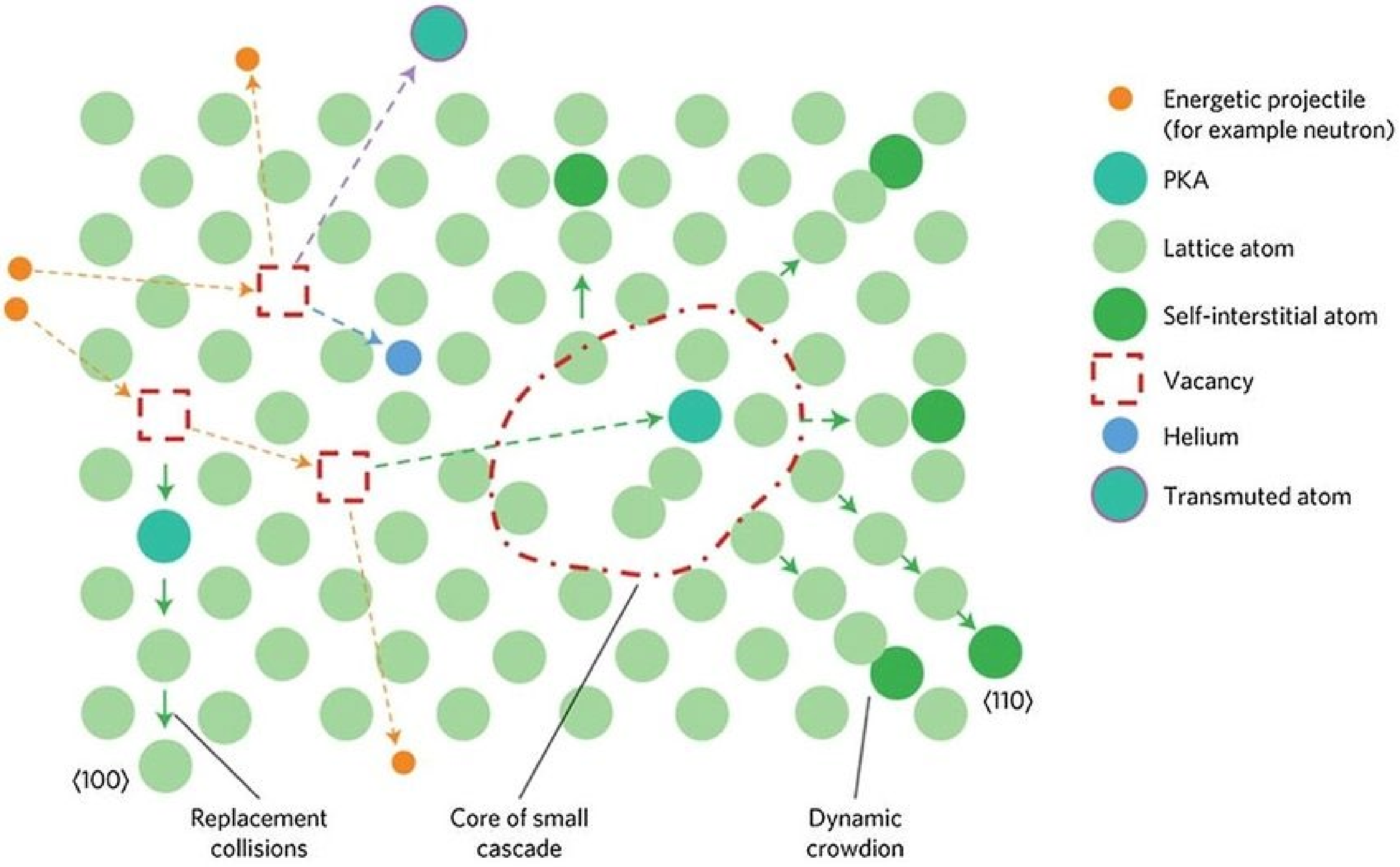


Irradiation effect – point defect / cascade



Seeger A (1962), Radiation damage in solids 1. IAEA Vienna: 101

Irradiation effect – … + transmutation



What happens under irradiation?

M_1: Incident particle with E_k

M_2: Lattice atom

The lattice atom gets:

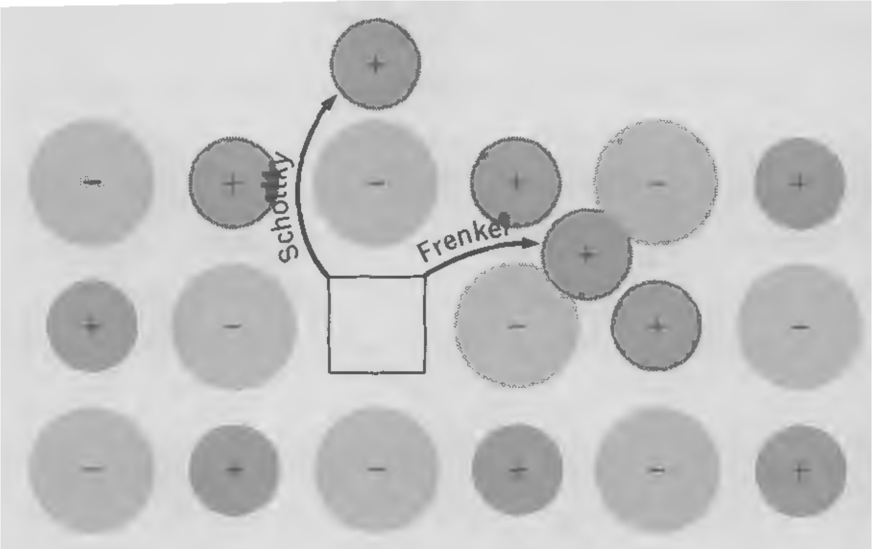
$E_{max} = E_k * 4 * M_1 * M_2 / (M_1 + M_2)^2$

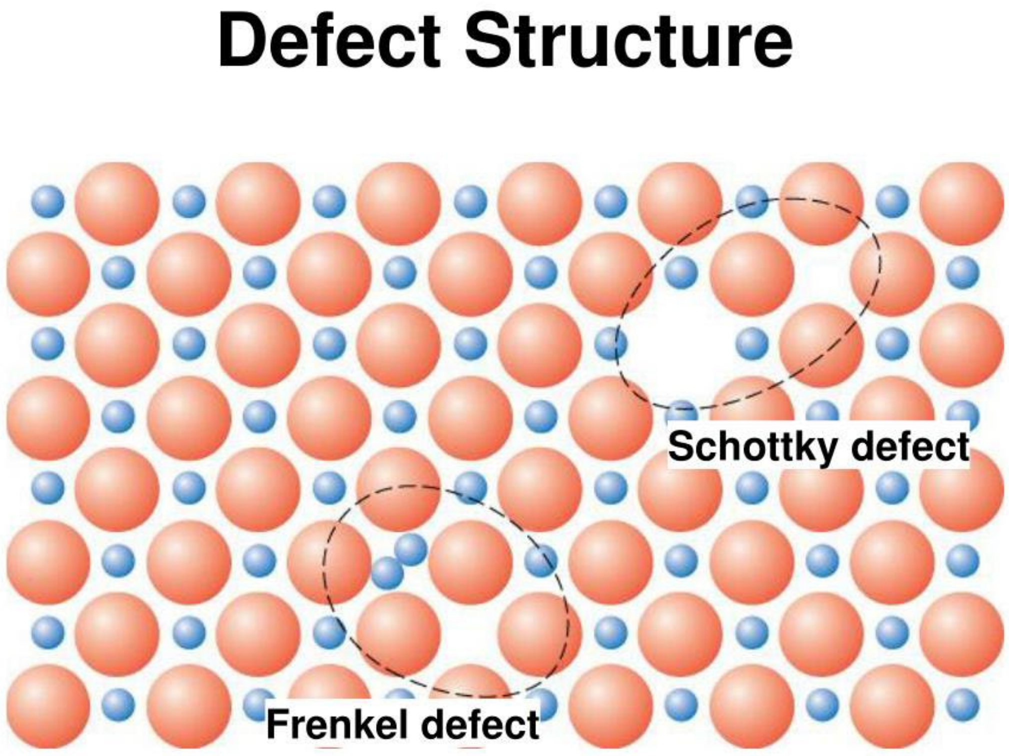
If

- **E_{max} > Wigner energy** (15-25 eV) : the atom is **ejected** from its lattice site
- **E_{max} >> Wigner energy**: displacement **cascade**

Frenkel pair

Kittel: Introduction to solid state physics





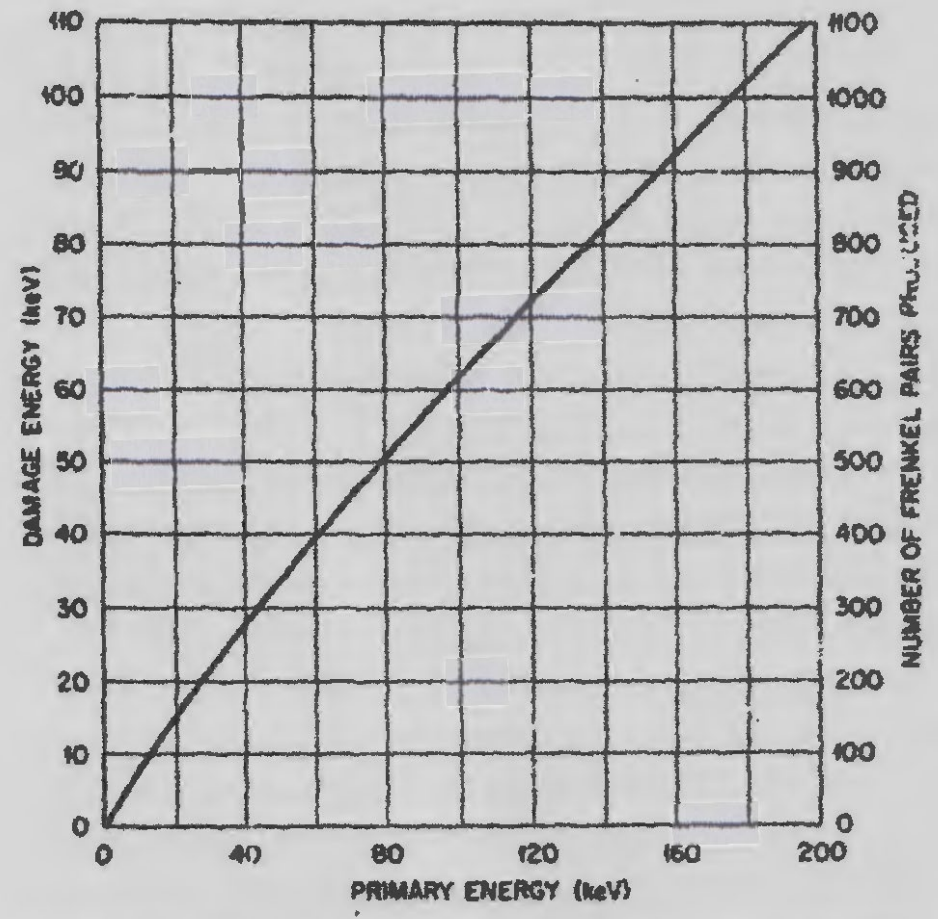
Schottky and **Frenkel** defects in an ionic crystal.
The arrows indicate the displacement of the ions.

- In a **Schottky defect** the ion moved to the surface of the crystal;
- in a **Frenkel defect** it is removed to an interstitial position.

Notion of dpa

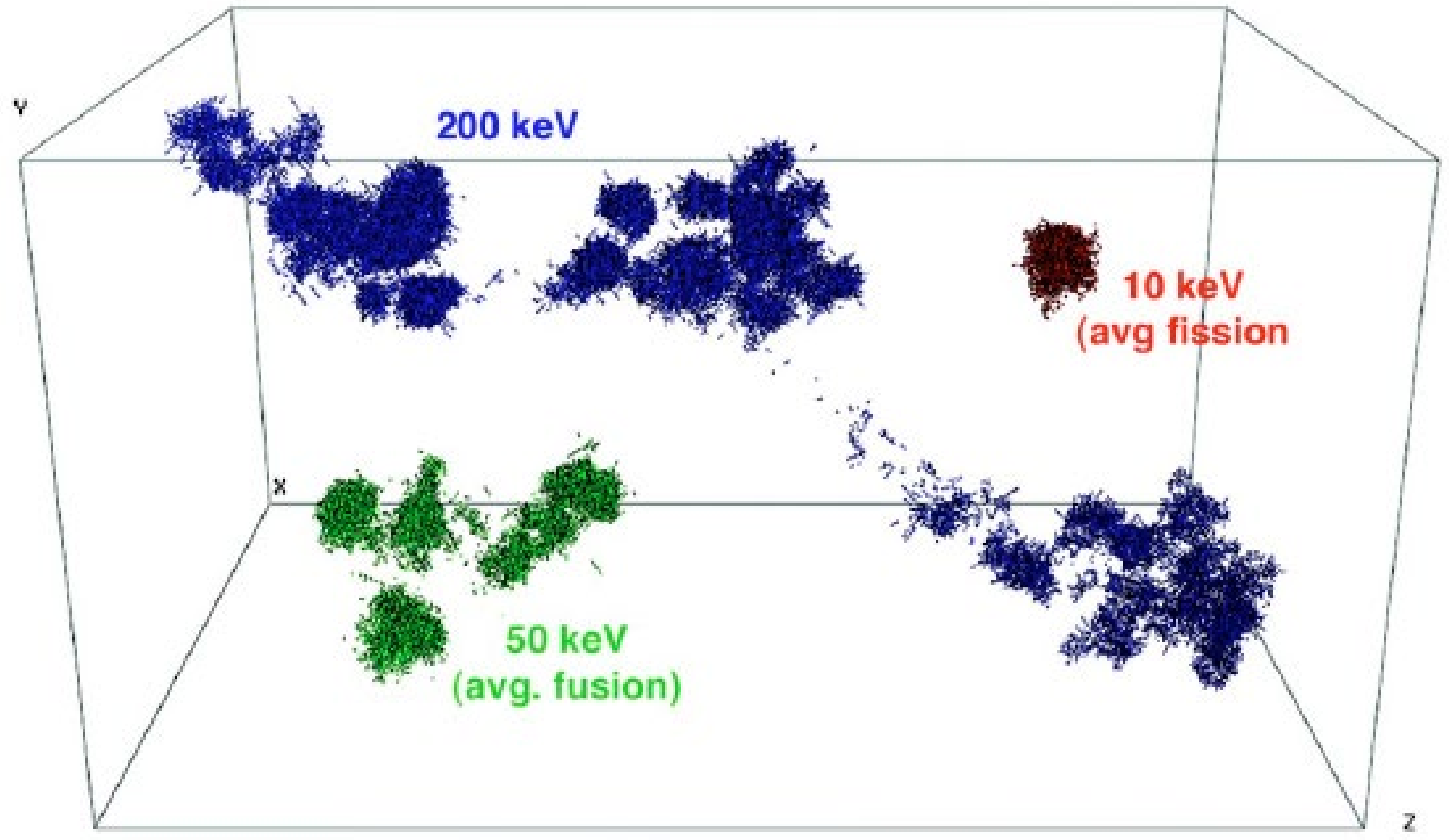
Ref. Norgett, Robinson & Torrens (NRT) Nucl. Eng. Design 33 (1975) p.50-54 .

Number of atoms displaced during irradiation



Plot of
damage energy ***E*** and
number of Frenkel pairs N_d
produced by a
primary know-on atom
of given energy:
calculated for iron using the standard method proposed in the text.

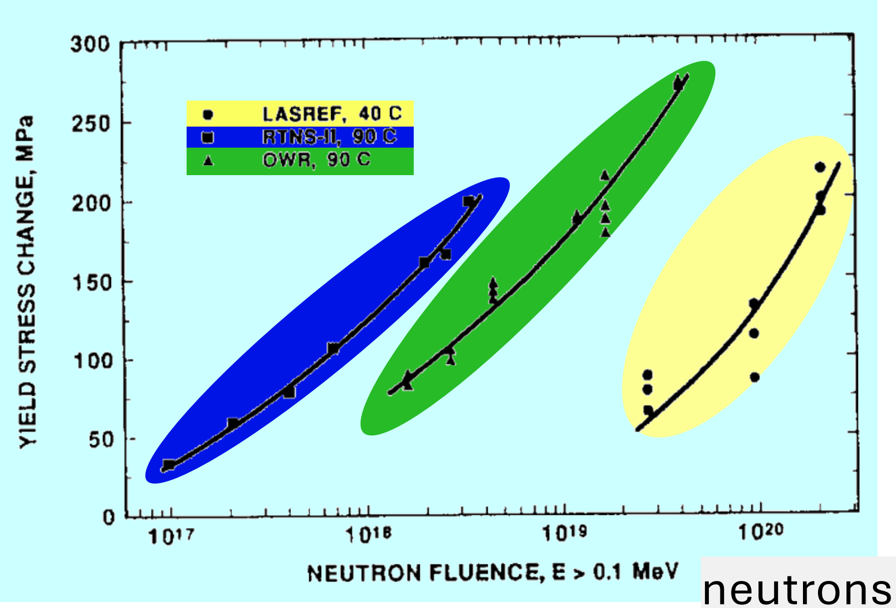
Cascade dependency on energy



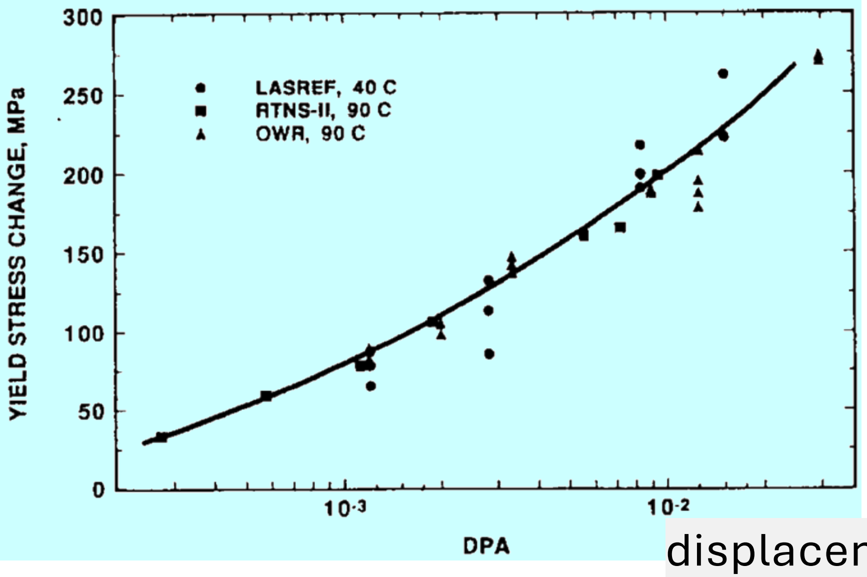
Comparison of MD simulations of displacement cascades in Fe for different PKA energies

http://dx.doi.org/10.1063/1.1880013

Irradiation Damage



neutrons per cm^2



displacements per atom

Irradiation hardening of solution annealed 316 steel

- **LASREF**: Los Alamos Spallation Radiation Effects Facility *(Be(d,n) neutrons: ~**1** MeV)*
- **OWR**: Omega West Reactor *(fission neutrons: keV-10MeV,**1.5** MeV)*
- **RTNS-II**: Rotating Target Neutron Source-II *(**14** MeV neutrons)*

http://dx.doi.org/10.1016/0022-3115(94)90004-3

Irradiation stages – Time scale

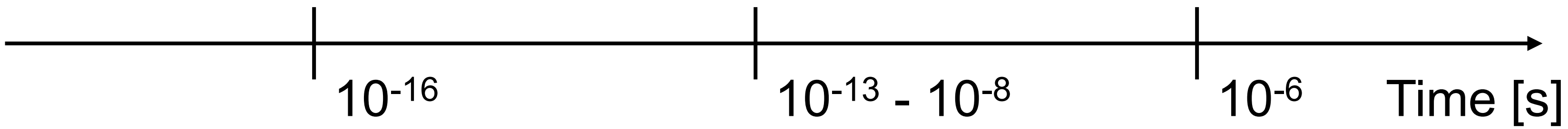
Duration (ps)	Event	Result
10^{-6}	Transfer of recoil energy from irradiation particle	Primary knock-on atom
10^{-6} to 0.2	Slowing down of PKA, generation of collision cascade	Vacancies and low energetic recoils, subcascades
0.2-0.3	Spike formation	Low density hot molten droplet, shock front
0.3 to 3	Spike relaxation, interstitial ejection, transition from heated to undercooled liquid core	Stable self interstitials atomic mixing
3 to 10	Spike core solidification and cooling to ambient temperature	Depleted zone, disordered zone, amorphous zone, vacancy collapse
More than 10	Thermal intercascade recombination, thermal migration of point defects from the cascade, reaction of migrating point defects	Surviving defects, migrating interstitials and vacancies, stationary fluxes of vacancies and interstitials to sinks, growth/shrinkage of point defect clusters, solute segregations

Material science and technology

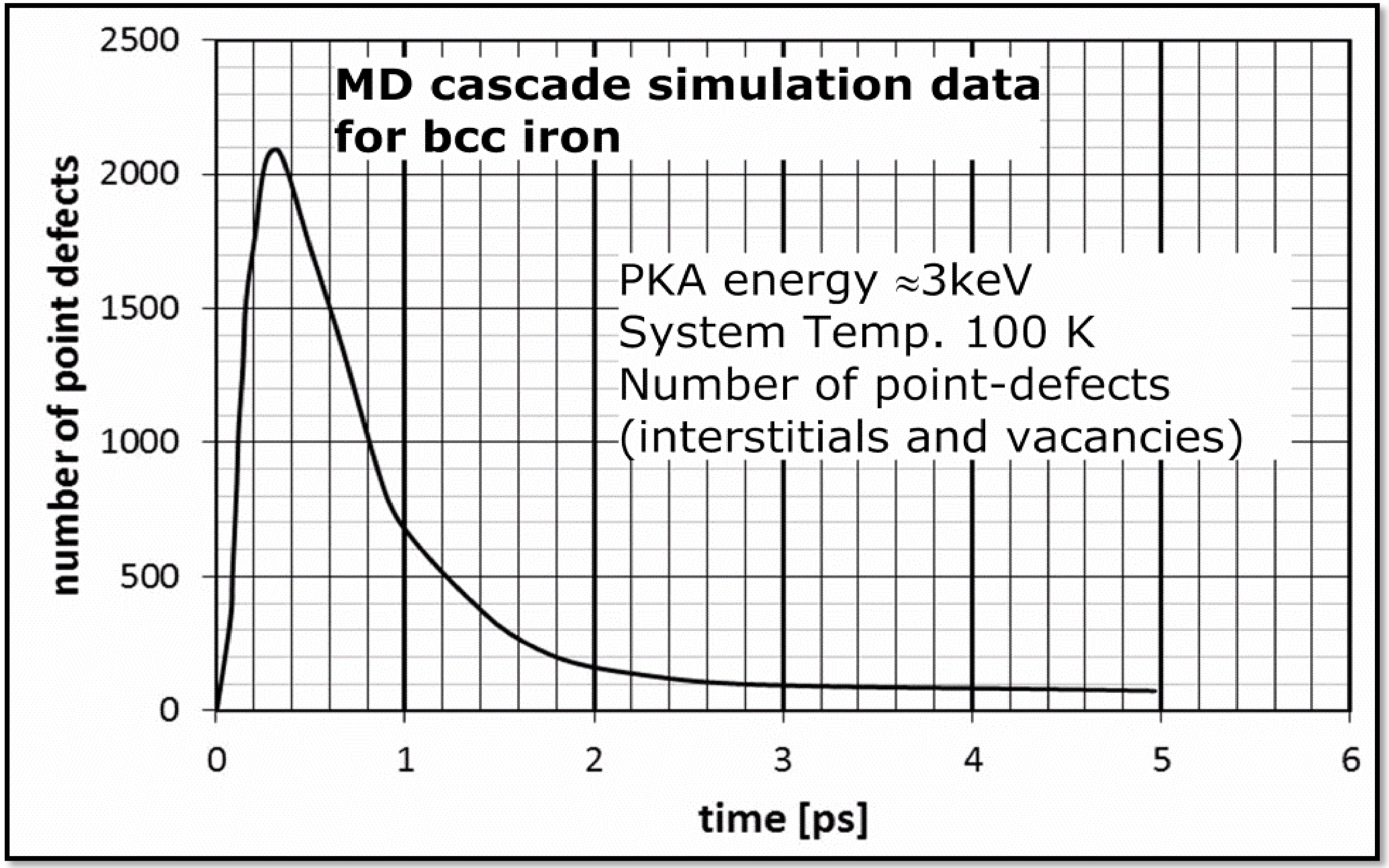
EPFL PSI

Materials for fusion must be low activation and retain their mechanical and thermal properties under irradiation

Nuclear reactions	Cascades	Diffusion processes
Production of impurities (He, H)	Production of vacancies and interstitials	Formation of the final microstructure



MD cascade simulation



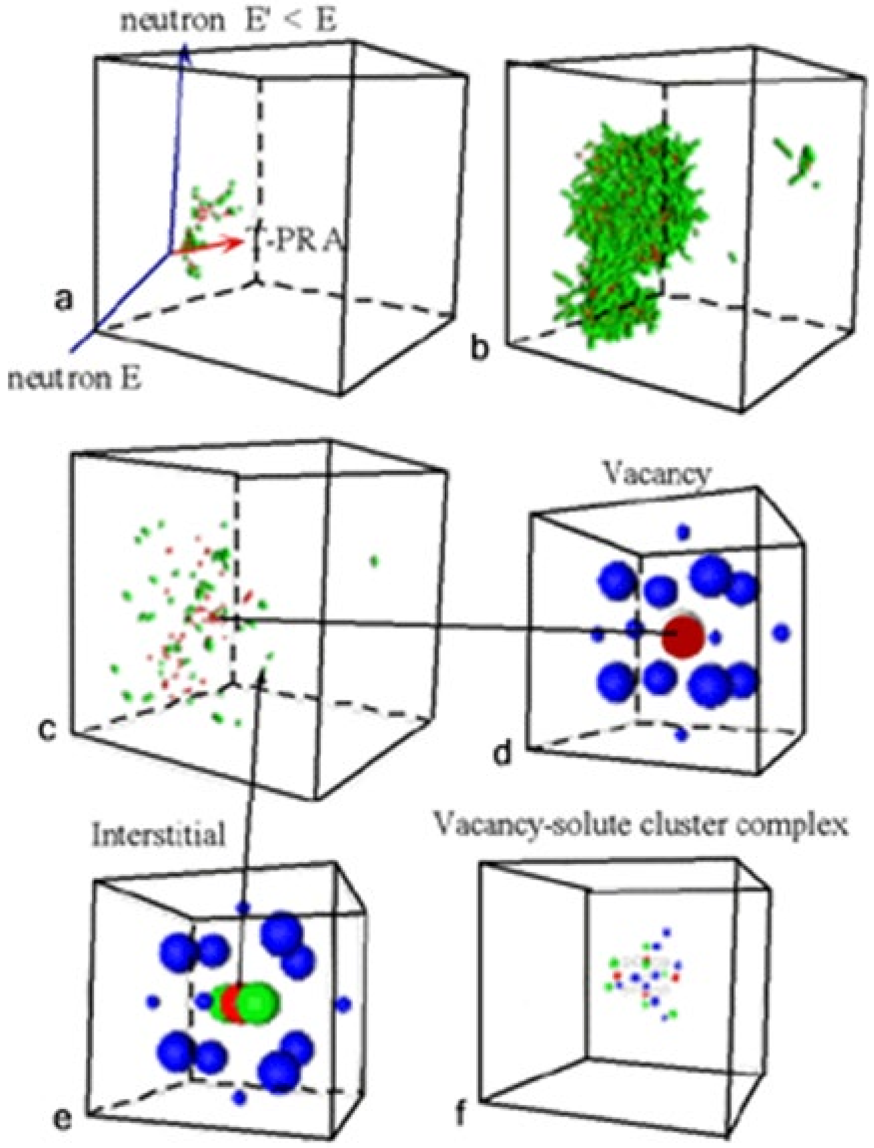
Early period of the development of the center of a cascade in copper as result of a molecular dynamics simulation

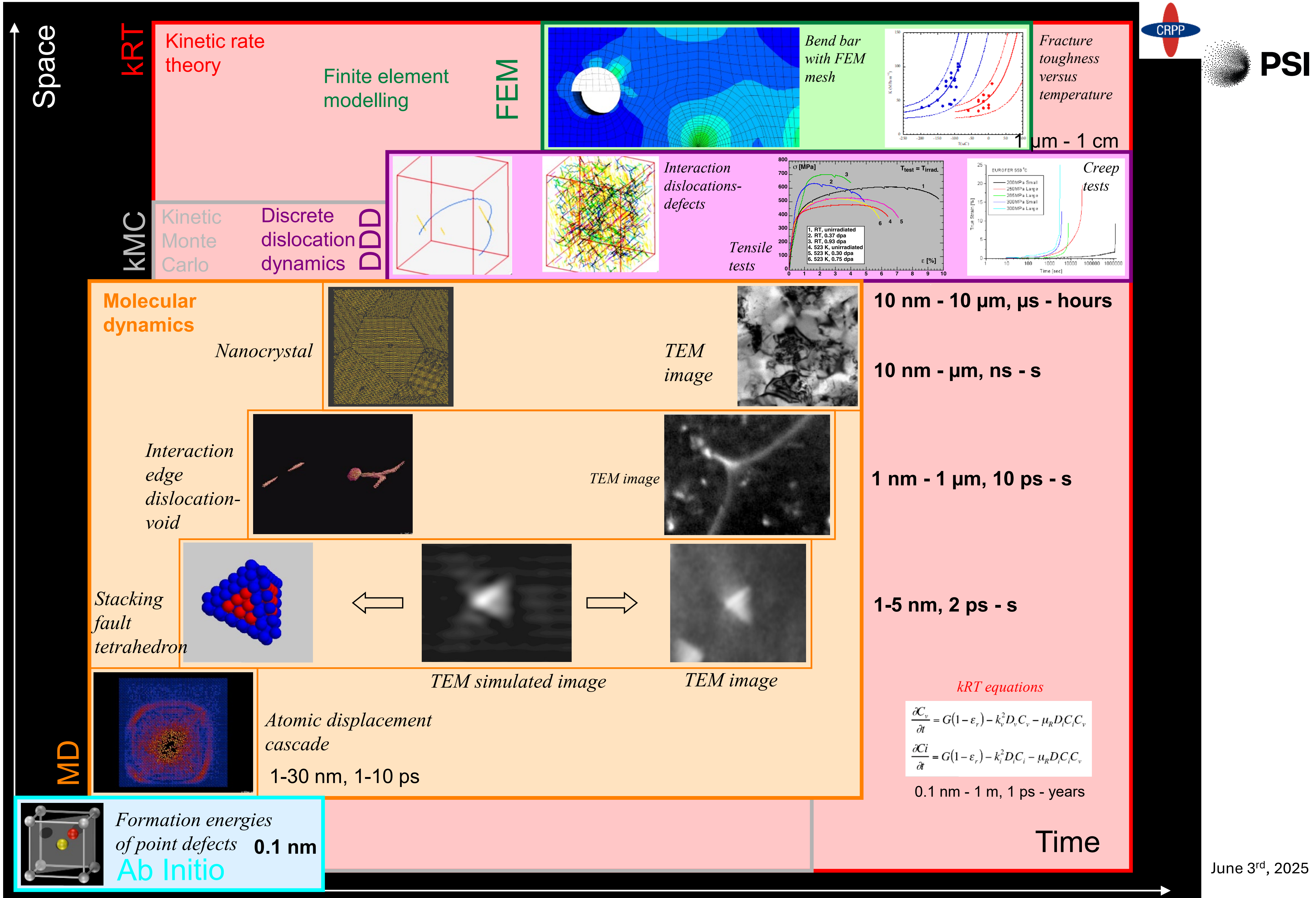
http://msg.igcar.gov.in/mpd/ibcss/index.php/research/77-general/122

Cascade illustration

An illustration of
cascade primary-damage production
(iron atoms not shown in a–c and f):

- **(a–c)** MD simulation snapshots of **initial intermediate and final dynamic stage** of a **displacement cascade**
- **(d–e) vacancy** and **self interstitial** defects
- **(f) vacancy-solute cluster complex** formed after **long-term cascade aging**





Space
kRT
Kinetic rate theory
Finite element modelling
FEM
Bend bar with FEM mesh
Fracture toughness versus temperature
1 µm - 1 cm
kMC
Kinetic Monte Carlo
Discrete dislocation dynamics
DDD
Interaction dislocations-defects
Tensile tests
Creep tests
Molecular dynamics
Nanocrystal
TEM image
10 nm - 10 µm, µs - hours
10 nm - µm, ns - s
Interaction edge dislocation-void
TEM image
1 nm - 1 µm, 10 ps - s
Stacking fault tetrahedron
1-5 nm, 2 ps - s
TEM simulated image
TEM image
kRT equations
$\frac{\partial C_v}{\partial t} = G(1-\varepsilon_r) - k_v^2 D_v C_v - \mu_R D_i C_i C_v$
$\frac{\partial Ci}{\partial t} = G(1-\varepsilon_r) - k_i^2 D_i C_i - \mu_R D_i C_i C_v$
Atomic displacement cascade
1-30 nm, 1-10 ps
MD
0.1 nm - 1 m, 1 ps - years
Formation energies of point defects
0.1 nm
Ab Initio
Time
CRPP
PSI

Table of Content

What material for fusion?

EPFL PSI

Criteria:

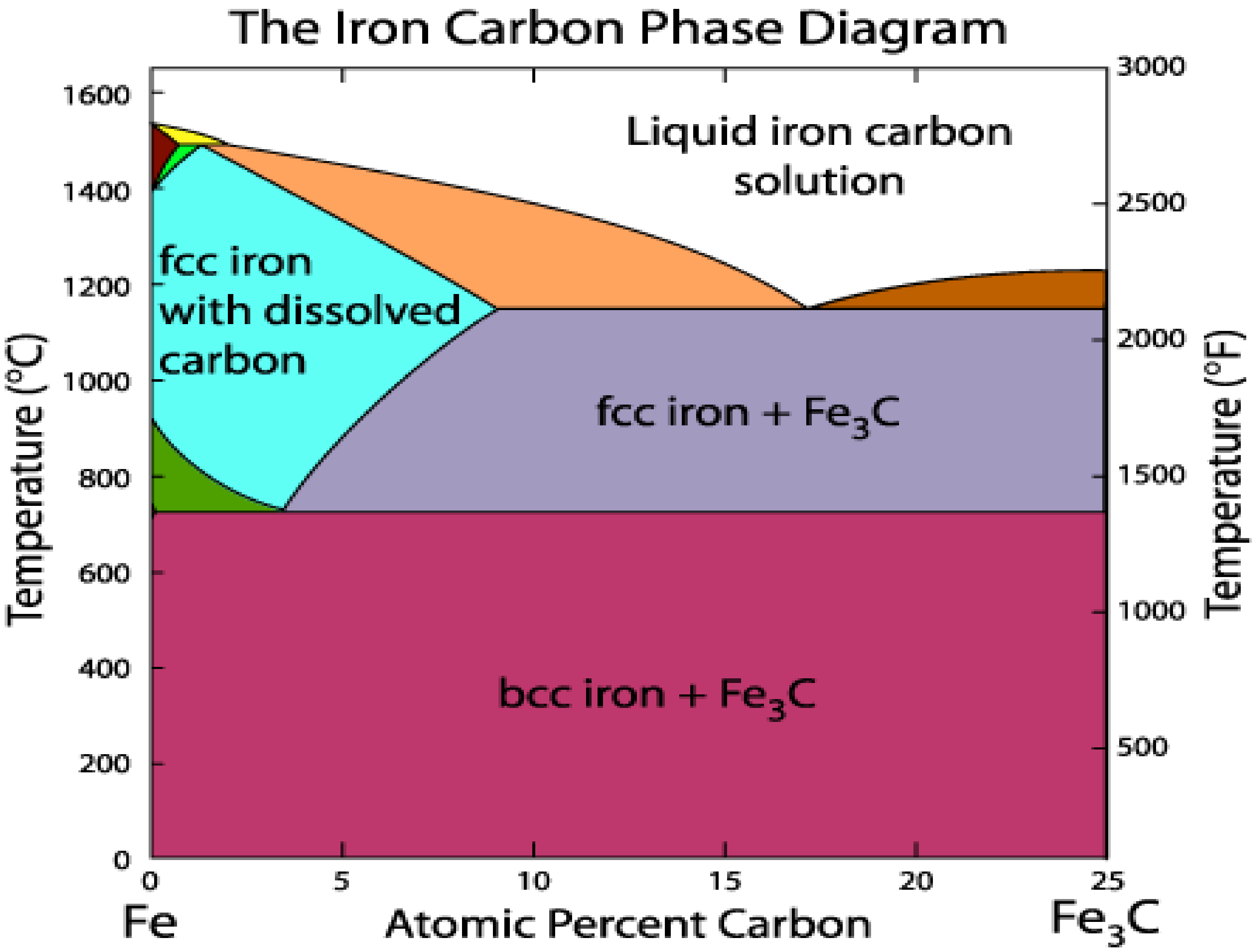
- Specific radioactivity
- Radioactive decay heat
- Half-life radio nuclides
- Waste disposal

Candidate materials presently under development have a chemical composition based on *low activation elements*: **Fe, Cr, V, Ti, W, Ta, Si, C**

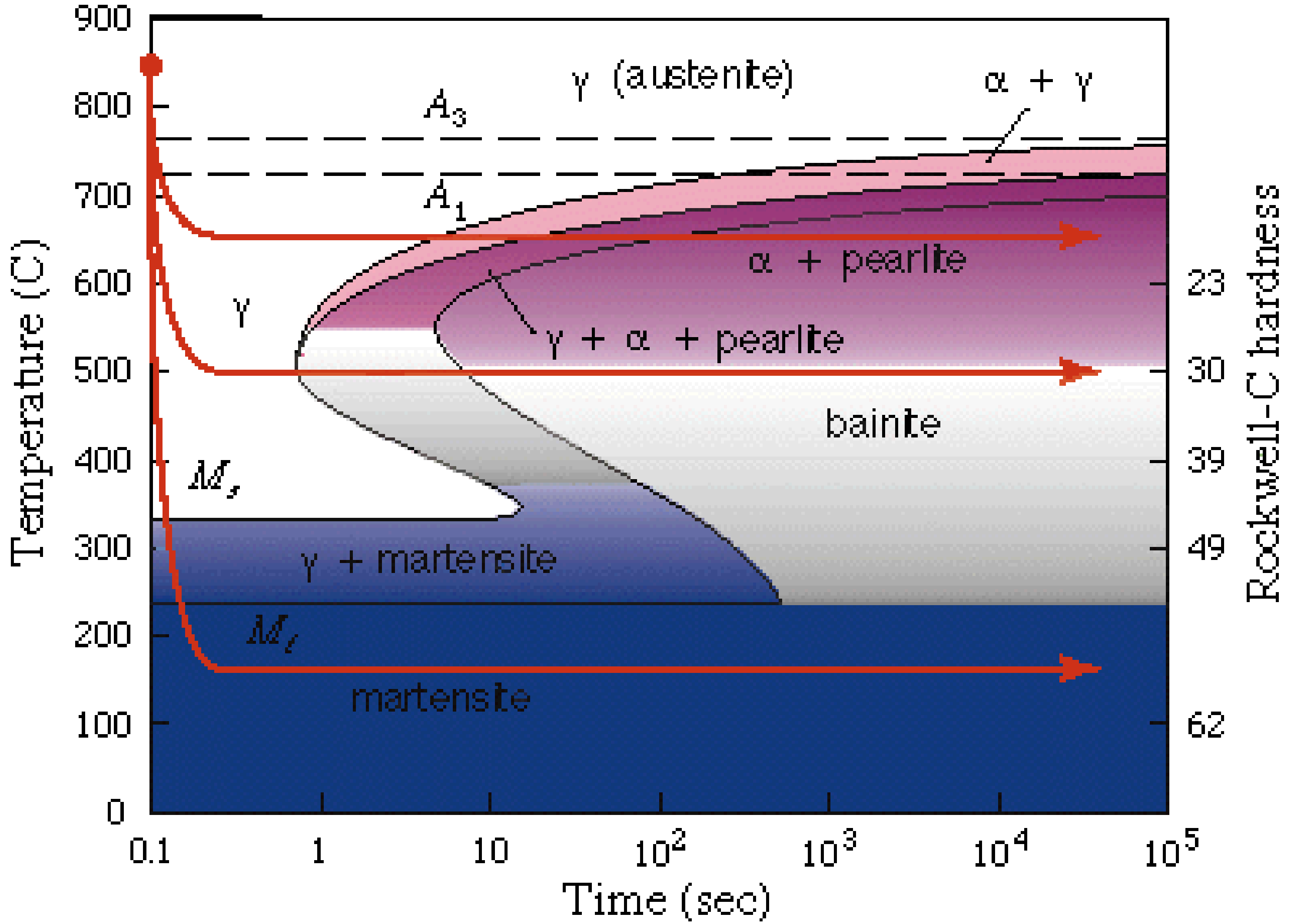
- Steel of the 9Cr type such as **EUROFER 97**:
  8.9 wt.% Cr, 1.1 wt.% W, 0.47 wt.% Mn, 0.2 wt.% V, 0.14 wt.% Ta,
  0.11 wt.% C, Fe for the balance.
- Oxide (Yttria) dispersion strengthened (**ODS**) steel.
- SiC_f/SiC: SiC fiber in SiC matrix
- Va alloys

What is a steel?

Fe-C Phase Diagram

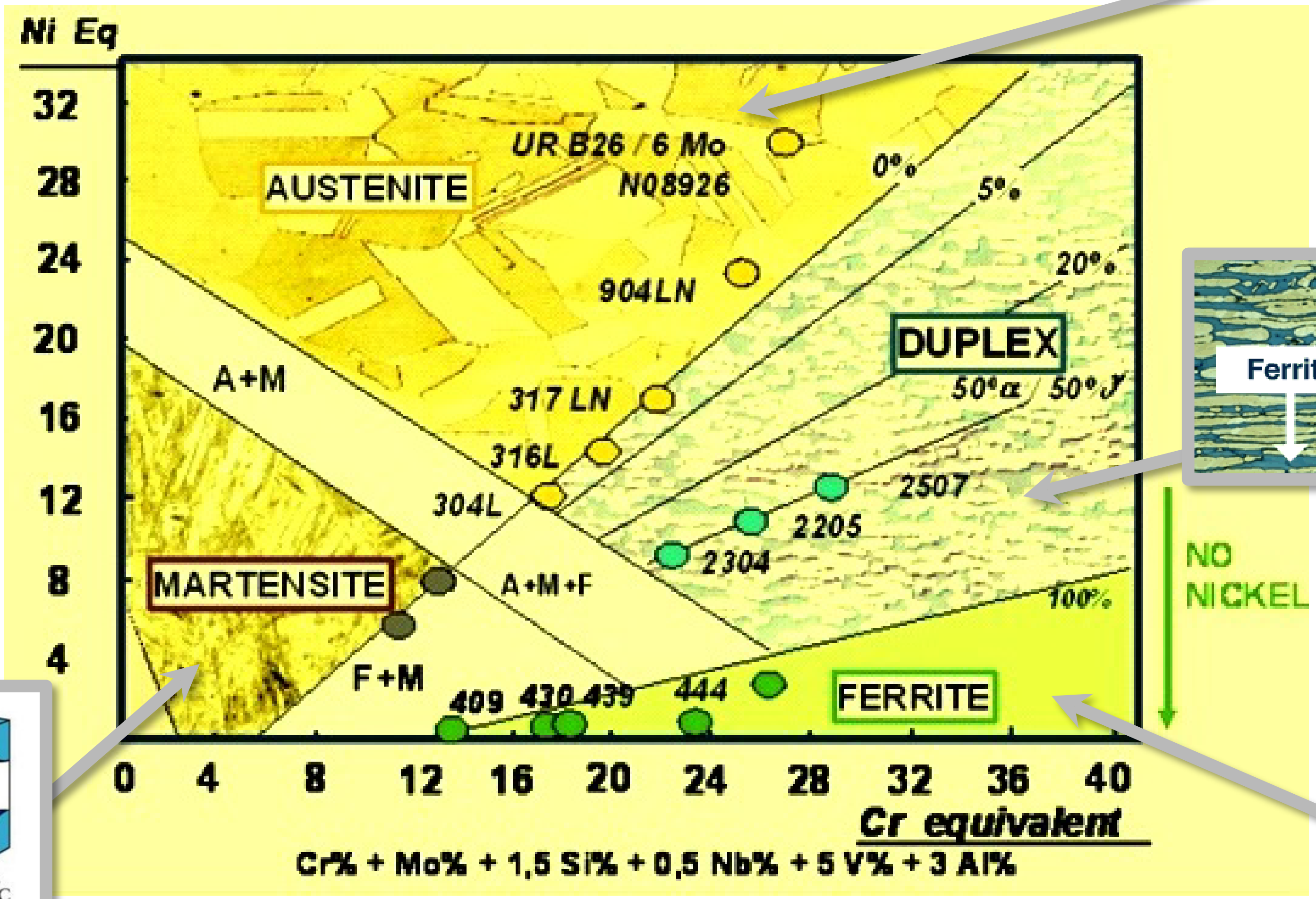


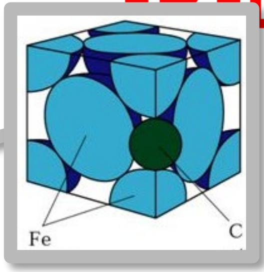
TTT diagram for carbon steels



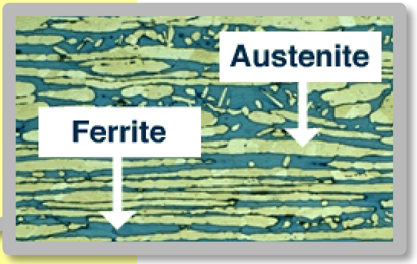
Time-Temperature-Transformation (TTT)

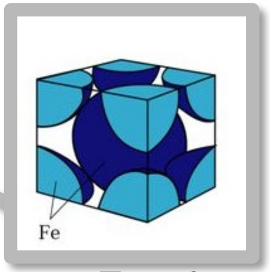
The Schaeffler-Diagram I



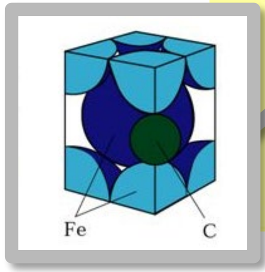


Austenite
Face-Centered Cubic **(FCC)**





Ferrite
Body-Centered Cubic **(BCC)**



Martensite
Body-Centered Tetragonal **(BCT)**

The Schaeffler-Diagram II

Nickel-Equivalent

% Ni + 30 % C + 0.5 % Mn

Nickel is a former of **austenite**

Chromium-Equivalent

% Cr + % Mo + 1.5 % Si + 0,5 % Nb + 2 % Ti + …

Chromium is a former of **ferrite**

The Nickel-Equivalent and the Chromium-Equivalent are the key parameters which determine the microstructure.

Reminder: low activation: Fe, Cr, V, Ti, W, Ta, Si, C

Material for fusion reactor

EPFL PSI

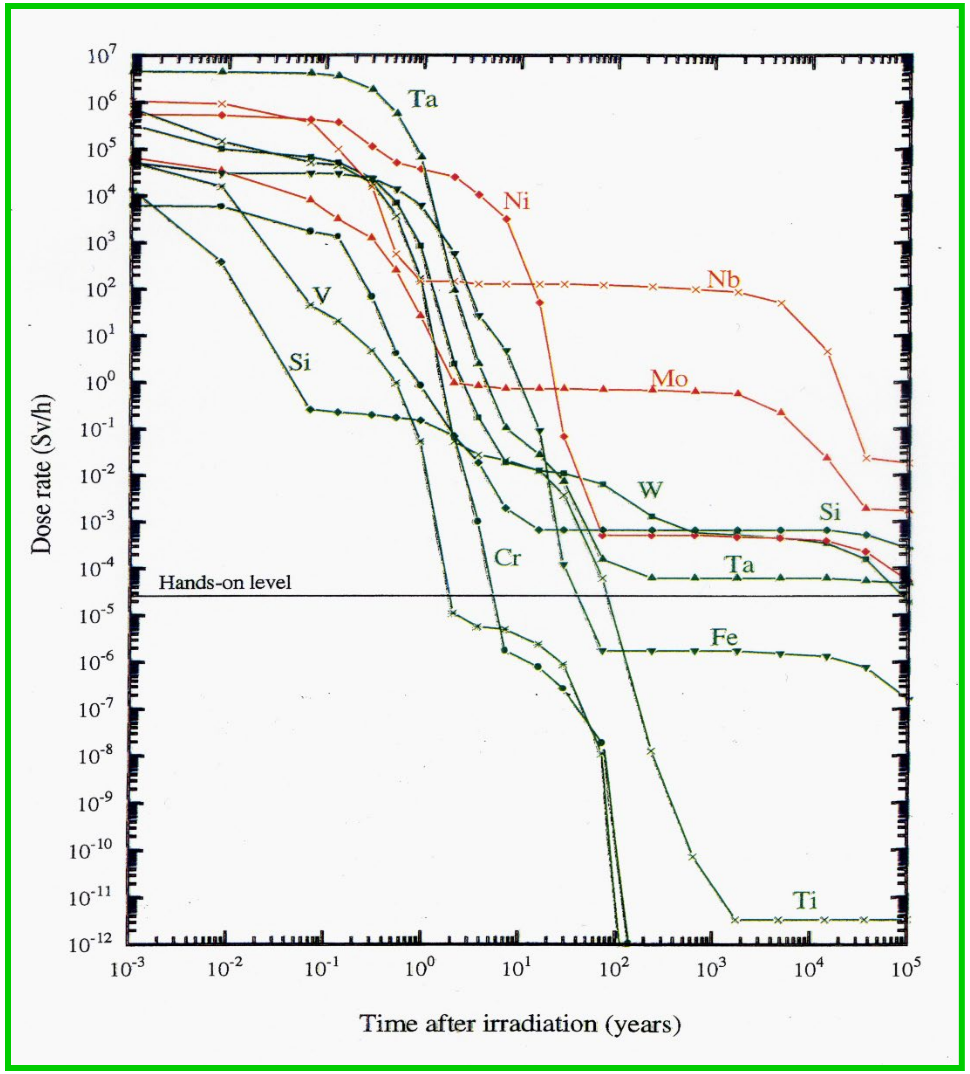
Criteria:

- **Specific radioactivity**
- **Radioactive decay heat**
- **Half-life radio nuclides**
- **Waste disposal**

Candidate materials presently under development
have a chemical composition based on low activation elements:
Fe, Cr, V, Ti, W, Ta, Si, C

- Steel of the 9Cr type such as EUROFER 97:
  8.9 wt.% Cr, 1.1 wt.% W, 0.47 wt.% Mn, 0.2 wt.% V,
  0.14 wt.% Ta, 0.11 wt.% C, Fe for the balance.
- Oxide (Yttria) dispersion strengthened (ODS) steel
- SiC_f in SiC matrix, Va alloys

DECAY TIME of Irradiated elements



EUROfusion - wpMAT

Courtesy: E. Diegele EUROfusion

EUROFER

Chemical composition of EUROFER 97-2

Element	MIN Value (wt%)	MAX Value (wt%)	Remarks
Carbon	0.090	0.120	Target 0.11
Manganese	0.20	0.60	Target 0.4
Phosphorus		0.005	
Sulphur		0.005	
Silicon		0.050	
Nickel		0.01	
Chromium	8.50	9.50	Target 9
Molybdenum		0.005	ALAP
Vanadium	0.15	0.25	
Tantalum	0.10	0.14	Target 0.12
Tungsten	1.0	1.2	Target 1.1
Titanium		0.02	
Copper		0.01	
Niobium		0.005	
Aluminium		0.01	
Nitrogen	0.015	0.045	Target 0.030
Boron		0.002	ALAP
Cobalt		0.01	ALAP
As+Sn+Sb+Zr		0.05	
Oxygen		0.01	

Undesired elements
(Nb, Mo, Ni, Cu, Al, Si, Co)

ALAP: As low as possible

Courtesy: E. Diegele EUROfusion

Steel

EPFL PSI

	Sample				Specification for Eurofer-97
	Plates			bar	
Thickness/Diameter	8 mm	14 mm	25 mm	Ø 100 mm	
Certificate ref (heat, Böhler)	E83698		E83697	E83699	
C	0.12		0.12	0.12	0.09-0.12
Si	0.04		0.06	0.07	≤0.05
Mn	0.49		0.46	0.44	0.20-0.60
P	<0.005		<0.005	<0.005	≤0.005
S	0.004		0.004	0.004	≤0.005
Cr	8.93		8.90	8.97	8.50-9.50
Mo	<0.0010		0.0023	<0.001	≤0.005
Ni	0.020		0.022	0.007	≤0.005
V	0.20		0.20	0.19	0.15-0.25
W	1.08		1.07	1.10	1.0-1.2
Cu	0.0019		0.0039	0.0022	≤0.005
Co	0.006		0.006	0.004	≤0.005
Ti	0.006		0.009	0.009	≤0.01
Al	0.009		0.008	0.008	≤0.01
Nb	0.0017		0.0020	<0.001	≤0.001
B	<0.001		<0.001	<0.001	≤0.001
N	0.021		0.020	0.017	0.015-0.045
Pb	<0.0003		<0.0003	<0.0003	
Ta	0.15		0.15	0.14	0.05-0.09
O	0.006		0.0007	0.0012	≤0.01
As	<0.005		<0.005	<0.005	As+Sn+Sb+Zr ≤0.05
Sn	<0.005		<0.005	<0.005	
Zr	<0.005		<0.005	<0.005	
Sb	<0.005		<0.005	<0.005	
Heat treatment					
Normalising Tempering	980°C – 27 min– air-cool		980°C – 30.6 min- air cool	979°C – 1 h 51 min - air	
Tempering	760°C – 90 min air-cool		760°C – 90 min – air-cool	739C – 3h 42 min - air	

Table 3-1: Chemical compositions and heat-treatments of Böhler Eurofer97 products, from [5].

Specification: alloying elements

Rational behind the specification – alloying elements

Alloy Heat / Analyses		Radiologically desired (theor.)	Specification EUROFER 97		F82H for comparison
A)	Cr		8,5 - 9,5 [9,0]		7.7
	C		0,09 - 0,12 [0,11]		0.09
	Mn		0,20 - 0,60 [0,40]		0.16
	P		< 0,005		0.002
	S		< 0,005		0.002
	V		0, 15 - 0,25		0.16
	B		< 0,001		0.0002
	N_2		0,015 - 0,045		0.006
	O_2		< 0,01		(0,01)
				target values [ ]	
(A) Main alloying elements of 8-10Cr F/M steels					
(B) Varied "substitutional" alloying elements of 8-10Cr F/M steels - Fusion Reduced Activation - Variant - eg replacing Mo by W ...					
(B)	W		1,0 - 1,2 [1.1]		
	Ta		0,06 - 0,09		
	Ti	< 200 ppm	< 0,01 (100 ppm)		

Courtesy: E. Diegele EUROfusion

Specification: impurities

Rational behind the specification – impurity control

C) Radiologically undesired tramp-elements					
Alloy		Radiologically desired (theor.)	Specification EUROFER 97	Achieved EUROFER 97	F82H comparison
C)	Nb	< 0,01 ppm	[< 0,001 (10 ppm)]	2-7 ppm	1 ppm
	Mo	< 1 ppm	[< 0,005 (50 ppm)]	10-30 ppm	30 ppm
	Ni	< 10 ppm	[< 0,005 (50 ppm)]	70-200 ppm	200 ppm
	Cu	< 10 ppm	[< 0,005 (50 ppm)]	15-20 ppm	100 ppm
	Al	< 1 ppm	[< 0,01 (100 ppm)]	60-90	30 ppm
	Ti	< 200 ppm	< 0,01 (100 ppm)	50-90	100 ppm
	Si	< 400 ppm	<0,05 (500 ppm)	400-700	1100 ppm
	Co	< 10 ppm	[< 0,005 (50 ppm)]	30-70	50 ppm

Target for
"low activation"
"low level waste"

Two major heats
Diff. chem. analyses

Courtesy: E. Diegele EUROfusion

Activation

) mainly determined by Nb, Mo and Al

Short-term behaviour (<50 years) mainly determined by Co, Ni and Cu

KIT | Rainer Lindau | EFDA-1244

Courtesy: E. Diegele EUROfusion

Activation

au | EFDA-1244

Courtesy: E. Diegele EUROfusion

Material candidates

EPFL PSI

RAFM steels e.g.

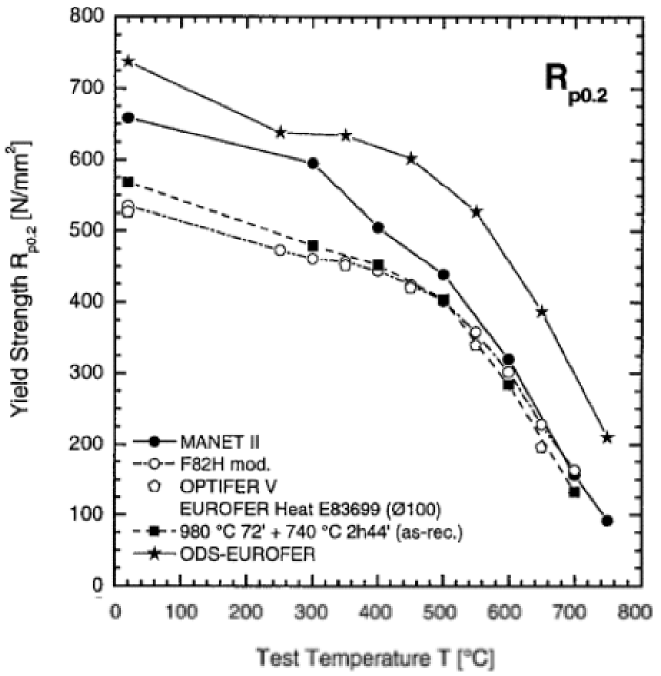
- F82H (Japan): Fe-7.5Cr-2W-0.21Mn-0-15V-0.1Si-0.09C
- JLF-1 (Japan): Fe-9Cr-2-W-0.45Mn-0.25V-0.2Si-0.1Cn
- ORNL 9Cr-2WVTa (US): Fe-9Cr-2W-0.4Mn-0.3Si-0.25V-0.1C
- Sandvik HT9 (US): Fe-12Cr-0.6Mn-0.6Ni-0.52W-0.38Si-0.3V-0.2C
- EUROFER: (Europe) Fe-8.9Cr-1.1W-0.47Mn-0.2V-0.14Ta-0.11C
- CLAM (P.R. of China): Fe-9Cr-1.6W-0.4Mn-0.21V-0.15Ta-0.11C

Better radiation resistance than austenitic steels, but structure thermal stability limited by dislocation glide and the alpha/gamma transition.

Oxide dispersion strengthening (ODS)

→ increases **radiation resistance** and **thermal stability**.

Max operation temperature: 650° C



Waste

Calculation of radioactive life time and recycling limit of a fusion power plant

Ref. EU Fusion Power Plant Conceptual Study (PPCS) , EFDA

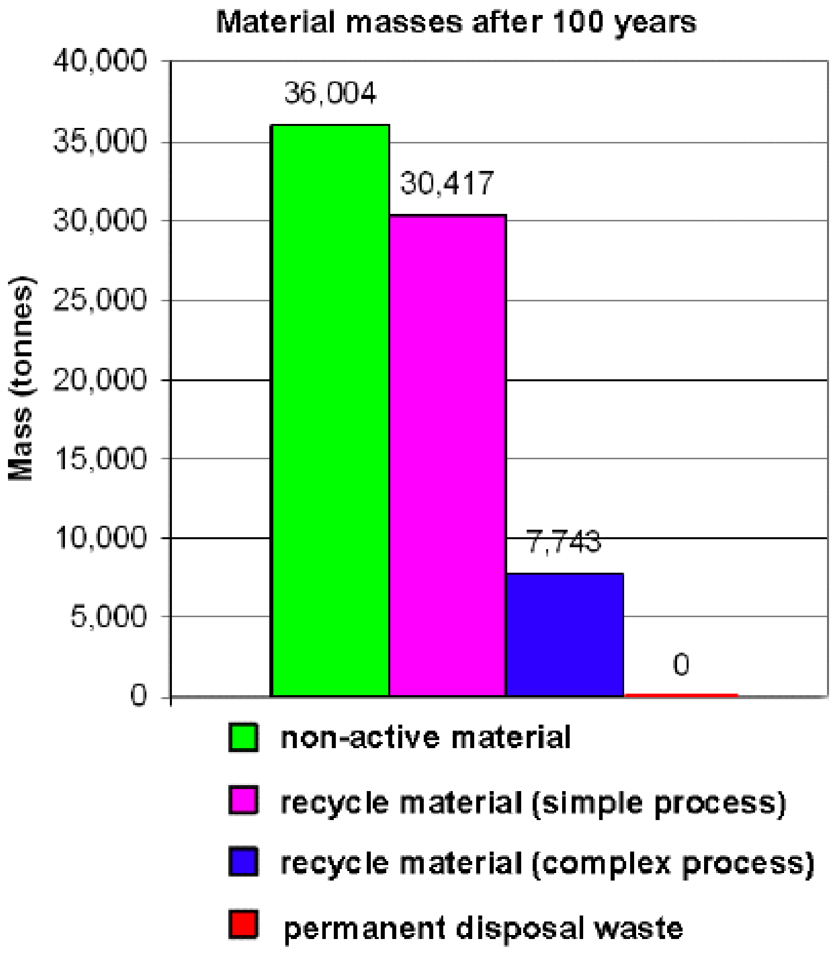


Table of Content

- Introduction: presentation of Anton Moeslang / timeframes / displacement damage
- Basic material science
  - material deformation
  - material testing
  - embrittlement / DBTT
- Motivation (why do we need material science)
- Radiation defects (H / He / displacement)
- Which materials? What are steels?
- Safety aspects (can it melt?)
- Radiation exposure and influence on the mechanical behavior
- “out of fusion” nuclear material science
- How to irradiate materials (14 MeV) / IFMIF

- Exercise

Beneficial aspects

Once the reactor is stopped, there is low « after heat » generation

What could happen then if after the reactor was shut-off there is a loss of cooling?

Two cases: ITER and Fusion Power Plant

Safety Characteristics of ITER
First Fusion Machine Undergoing Full Nuclear License

Carlos Alejaldre

Deputy Director General

Major accident (1)

The fuel is introduced continuously as Deuterium and Tritium gas

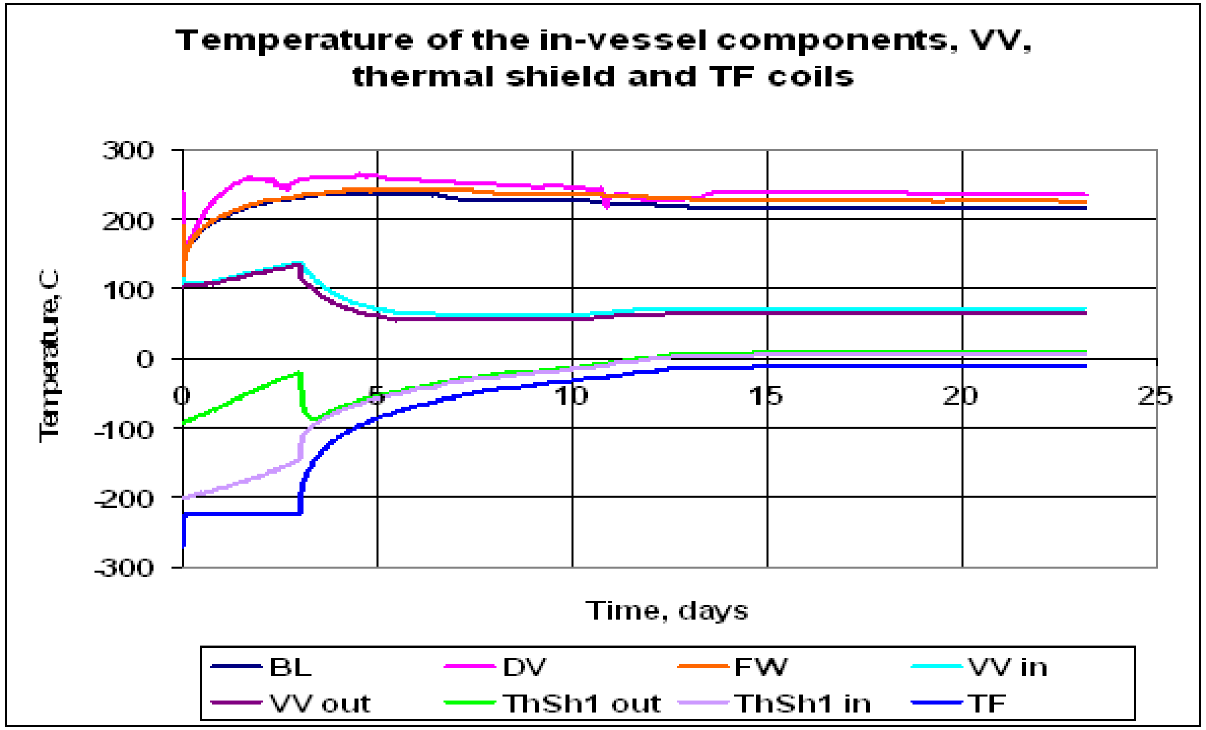
The amount of fuel in the reactor is sufficient only for a few minutes. The gas feed can be easily shut-off

The conditions for the establishing fusion reactions are delicate. Hence any departure from these conditions will lead to the stopping of the reactions. No chain reaction.

„Fukushima type“ accident (loss of cooling) for a fusion reactor is not possible since the amount of „after heat“ is low

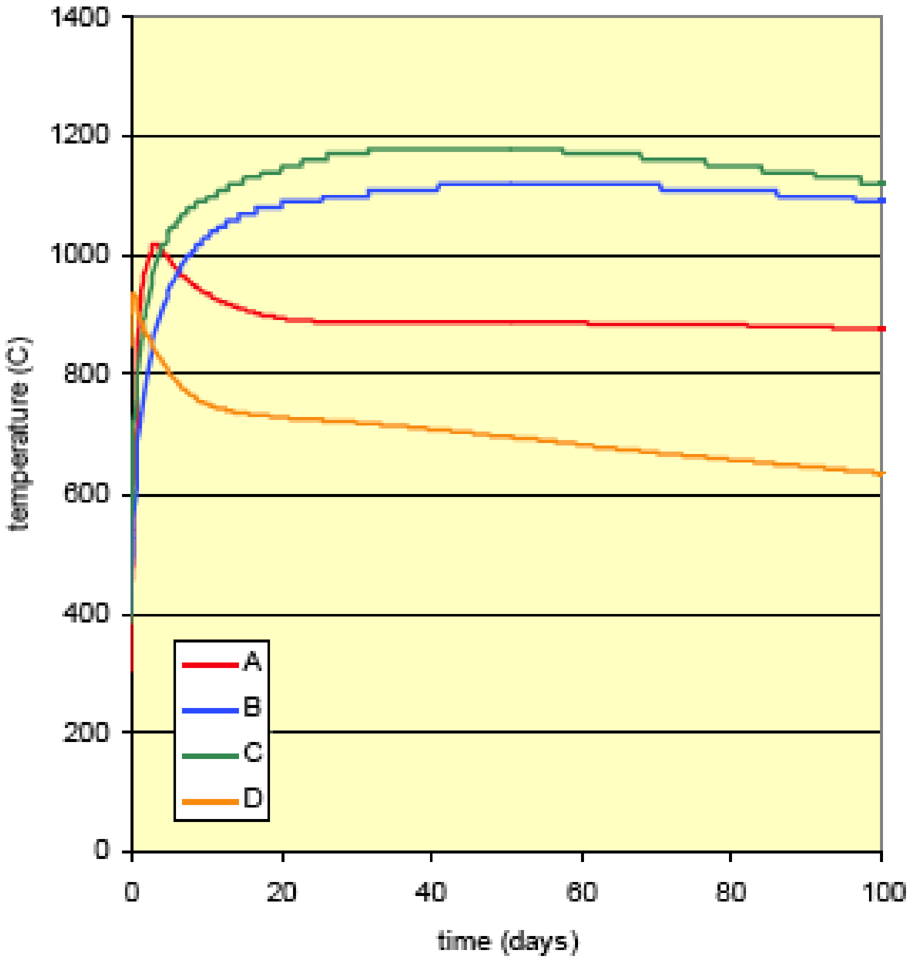
Calculation for ITER
Ref. C. Alejaldre
Nuclear Forum 2012

www.asn.fr/sites/rapports-exploitants-ecs-2012/Autres/ITER/ITER-Cadarache.pdf



Major accident (2)

Loss of cooling after shut down in case of a fusion power plant



Also in a electricity producing reactor, a loss of cooling accident does not lead to the melting of the reactor vessel (Melting temperature of stainless steel: 1500° C).
A, B, C and D refer to models

Ref. EU Power Plant
Conceptual Study
EFDA

Temperature

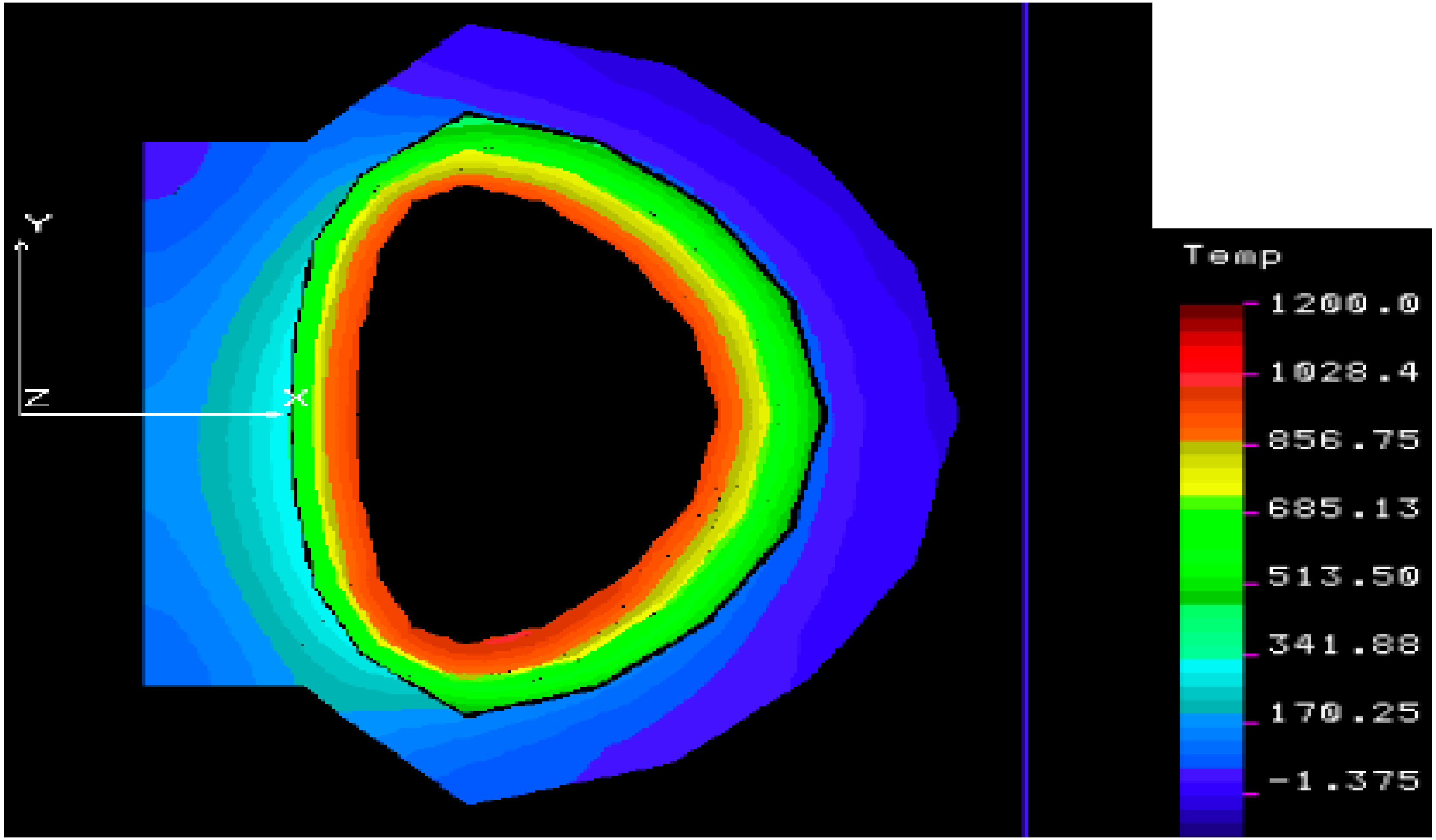


Table of Content

- Introduction: presentation of Anton Moeslang / timeframes / displacement damage
- Basic material science
  - material deformation
  - material testing
  - embrittlement / DBTT
- Motivation (why do we need material science)
- Radiation defects (H / He / displacement)
- Which materials? What are steels?
- Safety aspects (can it melt?)
- Radiation exposure and influence on the mechanical behavior
- “out of fusion” nuclear material science
- How to irradiate materials (14 MeV) / IFMIF

- Exercise

Characterization of irradiation damage

dpa= displacement per atom

MWy/m^2	$n.m^{-2}$	dpa (Fe)
1	$1.4 . 10^{25}$	9.5
0.3 –1 (ITER)	$0.4 – 1.4 . 10^{25}$	2.8 –9.5
3 –4 (DEMO reactor)	$4 – 5.6 . 10^{25}$	28 -76
10 – 15 (REACTOR)	$14 – 21 . 10^{25}$	95 -143

- He production: 10 appm/dpa
- H production: 40 appm/dpa

Main difficulty is the non-availability of suitable neutron sources :
energy = 14 MeV and high fluence

Mechanical effects

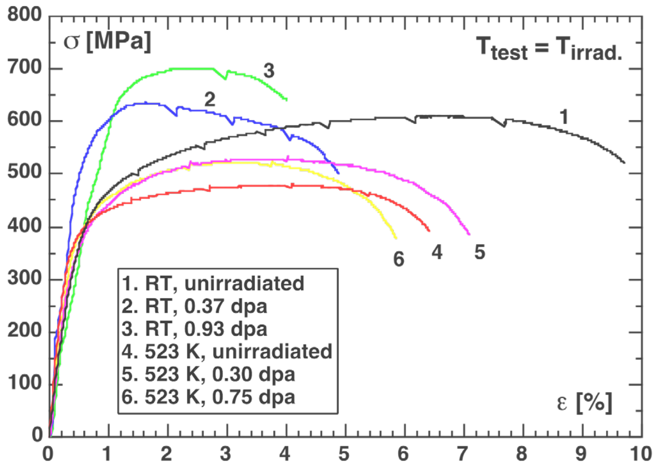
Hardening (H)
Loss of ductility (LD)
Loss of fracture toughness
Loss of creep strength

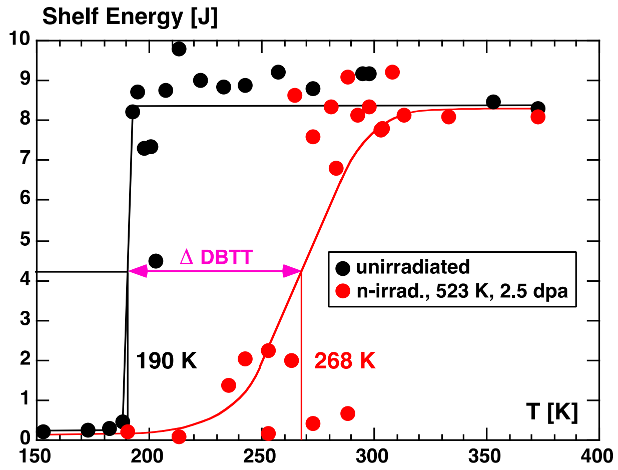
Swelling

Change in the

Ductile to Brittle Transition temperature DBTT

9Cr type of steel





Effect on the microstructure

The final microstructure of the irradiated material results from interactions between the various irradiation-induced defects. It can be formed of:

Small defect clusters
Dislocation loops
Stacking fault tetrahedra
Precipitates
Voids
He bubbles

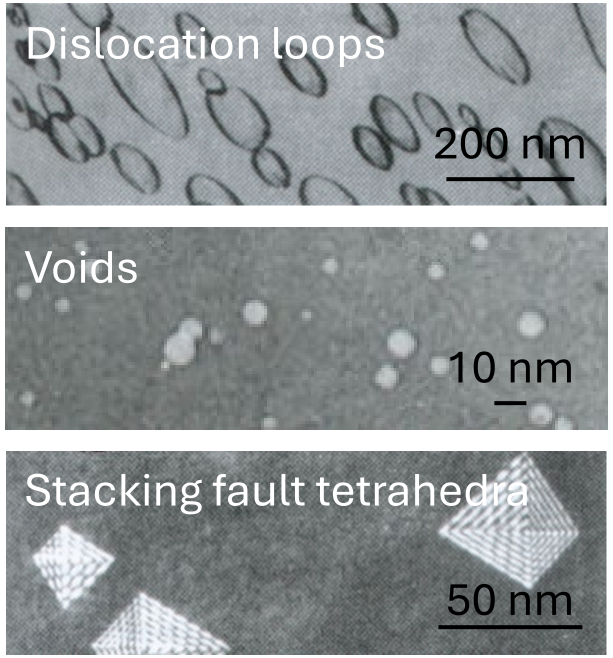
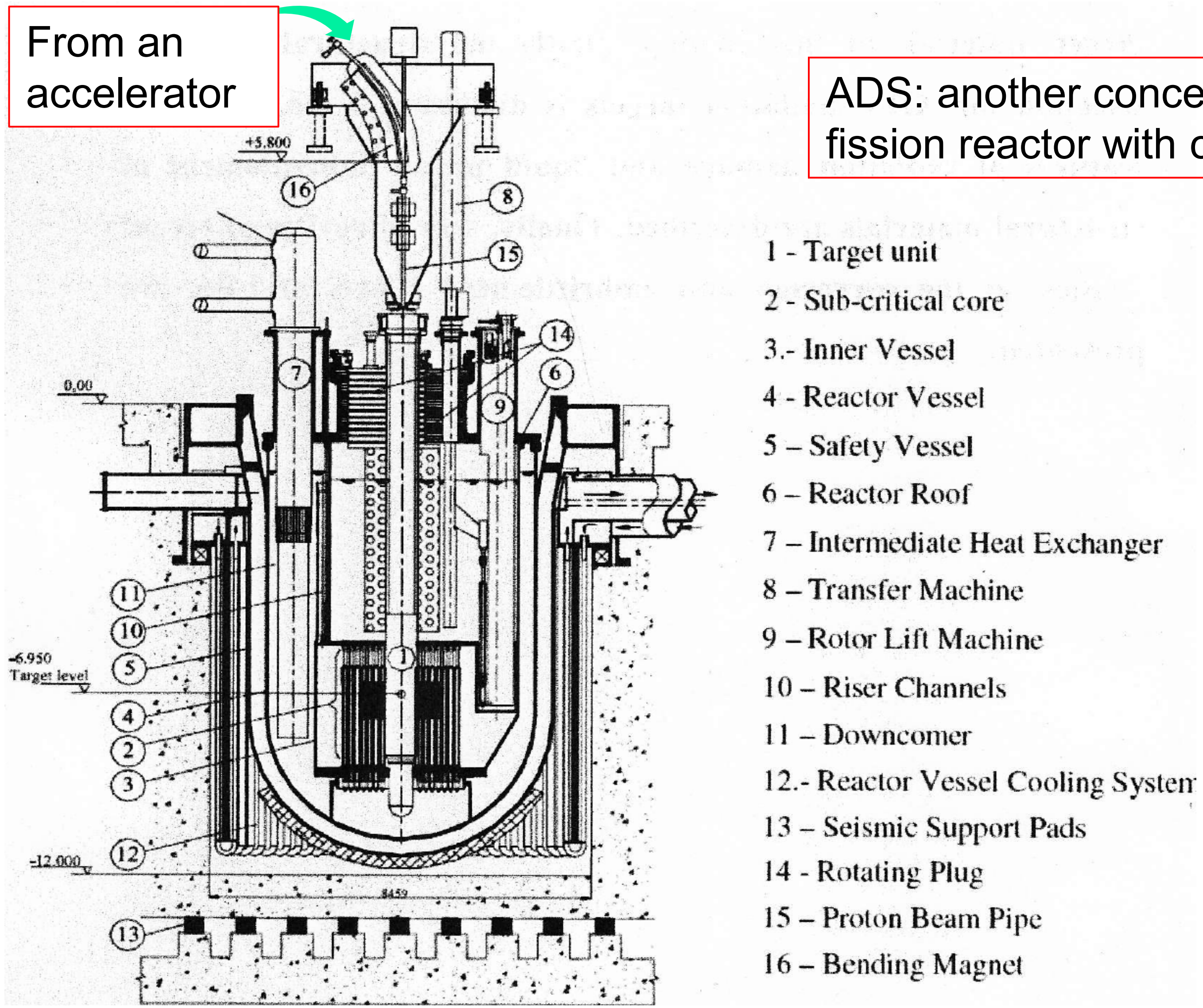


Table of Content

Out-of-Fusion Applications of Material Science

Accelerator driven system ADS

From an accelerator



ADS: another concept for a fission reactor with criticity k<1

Specific Environmental and Irradiation Conditions

Advanced fission reactors

fission neutrons
(Core structure: 3-30 dpa/year)
Max. operating temperature: 1600° C
Compatible with He

Fusion reactor

14 MeV neutrons
(First wall: 30 dpa/year in Fe
15 appm He/dpa and 50 appm H/dpa)
Max. operating temperature ≥ 650° C
Compatible with liquid Pb-17Li

ADS demonstrator

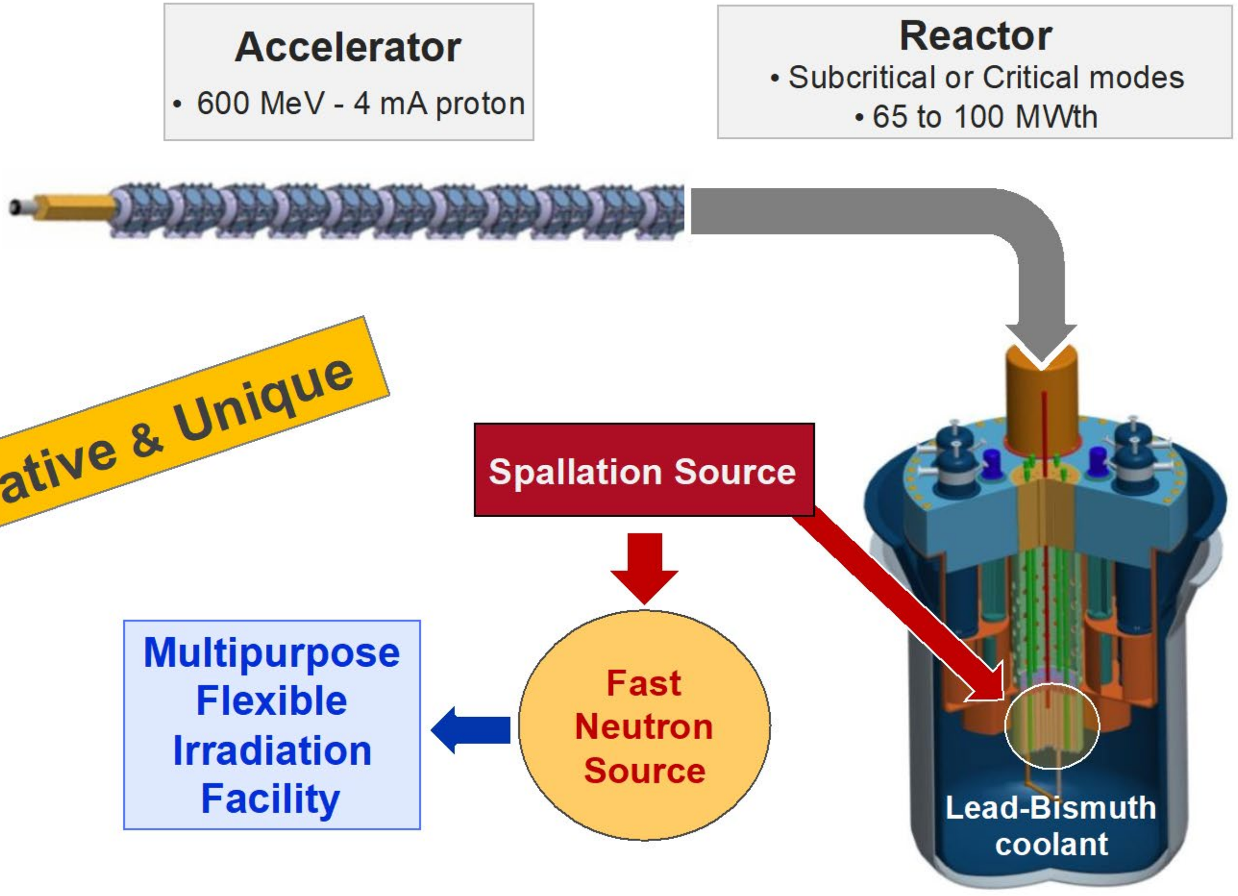
High energy protons and neutrons
(Beam window: 100 dpa/year
50 appm He/dpa, 500 appm H/dpa)
Max. operating temperature: 550° C
Compatible with liquid Pb-Bi

Example

The Myrrha project

http://www.nuklearforum.ch/fr/forum-nucl%C3%A9aire-suisse/nos-manifestations/rencontre-du-forum-accelerator-driven-systems-myrrha

MYRRHA

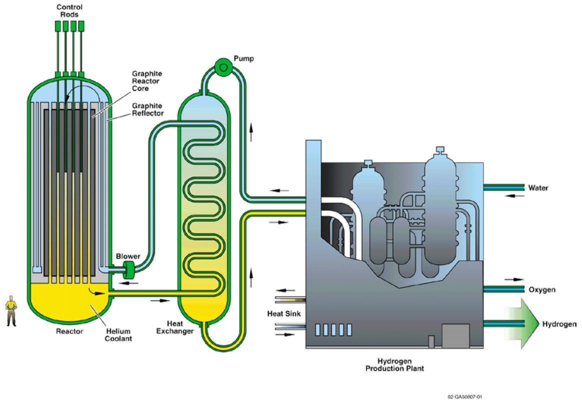


Accelerator
• 600 MeV - 4 mA proton
Reactor
• Subcritical or Critical modes
• 65 to 100 MWth
Innovative & Unique
Spallation Source
Fast Neutron Source
Multipurpose Flexible Irradiation Facility
Lead-Bismuth coolant

Synergy with other fields

Advanced fission reactors-Gen IV

Oxide dispersion strengthened steels
Refractory metals and alloys
C/C, SiC, SiC/SiC ceramic composites
Intermetallic alloys

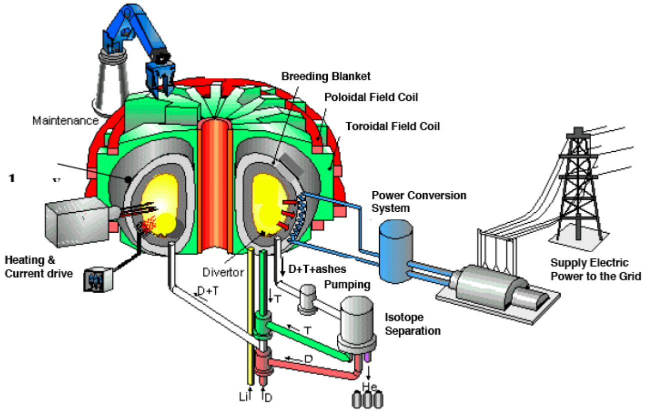


Accelerator Driven System demonstrator (ADS Next slide)

Reduced activation ferritic/martensitic steels
Oxide dispersion strengthened steels

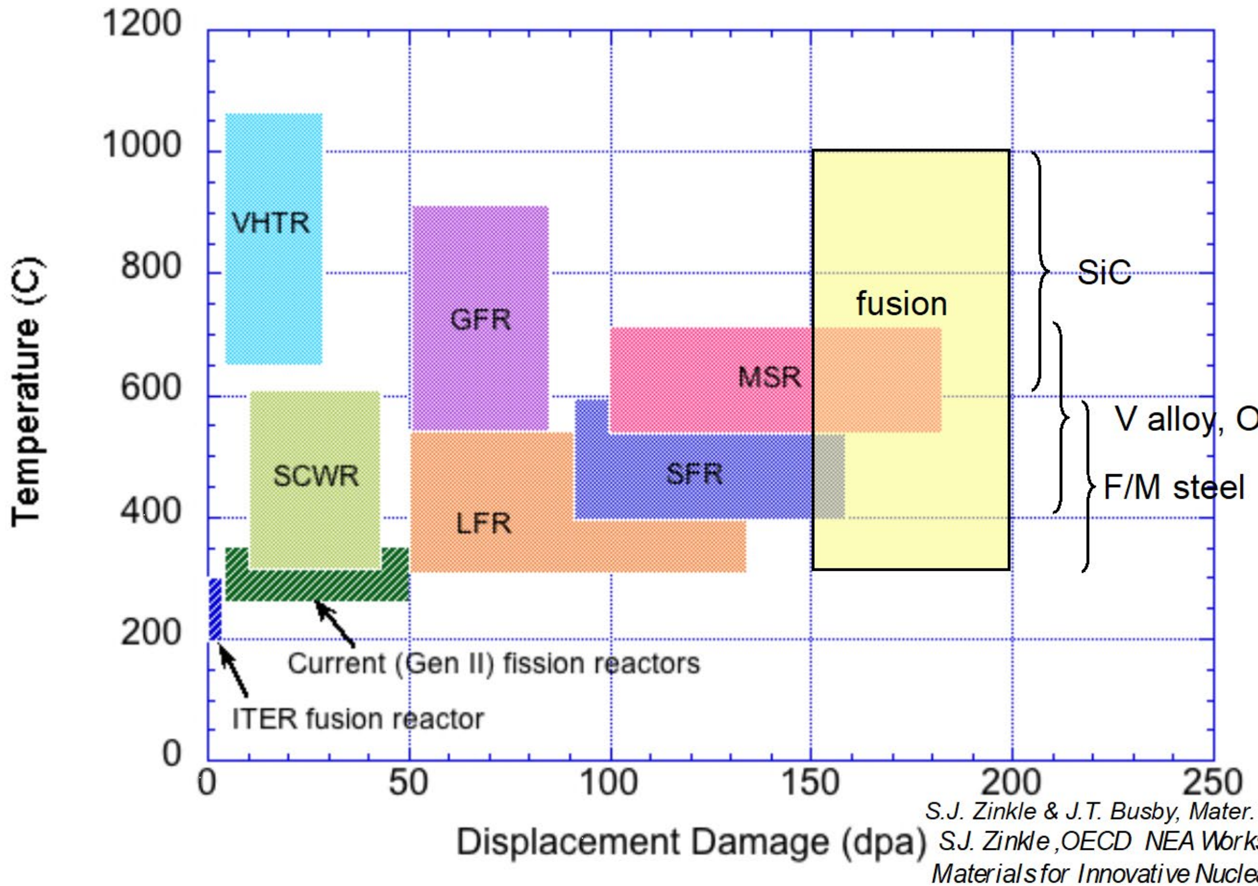
Fusion reactor

Reduced activation ferritic/martensitic steels
Oxide dispersion strengthened steels
Refractory metals and alloys
SiC/SiC ceramic composites
Vanadium alloys



Comparison of material challenges

Comparison of Gen IV and Fusion Structural Materials Environments



S.Zinkle et al., IAEA FEC 2012 San Diego

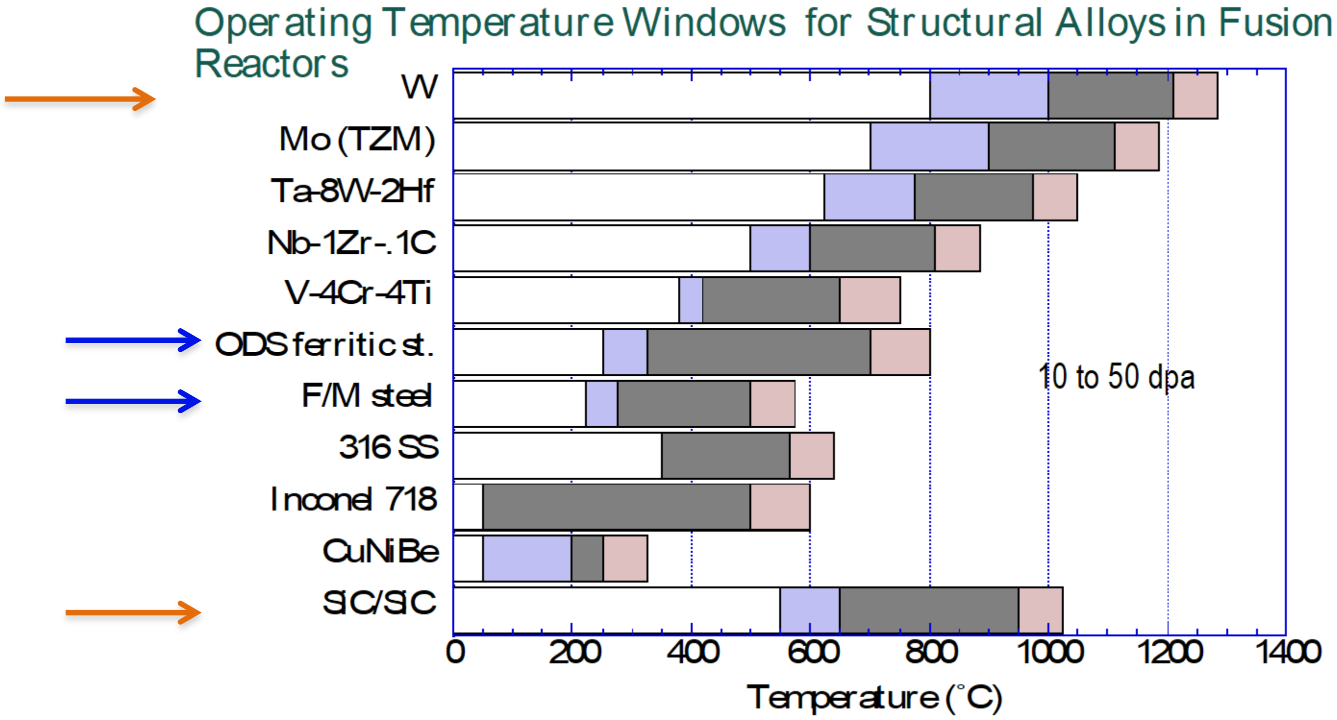
S.J. Zinkle & J.T. Busby, Mater. Today 12 (2009) 12
S.J. Zinkle, OECD NEA Workshop on Structural Materials for Innovative Nuclear Energy Systems, Karlsruhe, Germany, June 2007

All Gen IV and Fusion concepts pose severe materials challenges

18 Managed by UT-Battelle for the U.S. Department of Energy

Temperature window

EPFL PSI



- Lower temperature limit of alloys based on radiation hardening/ fracture toughness embrittlement (K_{1C}< ~30 MPa-m$^{1/2}$)—large uncertainty for W,Mo due to lack of data
- Upper temperature limit based on 150 MPa creep strength (1% in 1000 h); chemical compatibility considerations may cause further decreases in the max operating temp.

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

S.J. Zinkle and N.M. Ghoniem, Fus. Eng. Des. 51-52 (2000) 55; S.J. Zinkle et al. STAIF2002

UT-BATTELLE

Table of Content

How shall we test our material?

We need a 14 MeV neutron source!

With a high flux and fluence!

Characteristics of damage in materials

MWy/m^2	$n.m^{-2}$	dpa (Fe)
1	$1.4 . 10^{25}$	9.5
0.3 –1 (ITER)	$0.4 – 1.4 . 10^{25}$	2.8 –9.5
3 –4 (DEMO reactor)	$4 – 5.6 . 10^{25}$	28 -76
10 – 15 (REACTOR)	$14 – 21 . 10^{25}$	95 -143

- He production: 10 appm/dpa
- H production: 40 appm/dpa

dpa = Displacement per atom

Multimodal Options for Materials Research to Advance the Basis for Fusion Energy in the ITER Era

Steve Zinkle[1], Anton Möslang[2], Takeo Muroga[3], Hiro Tanigawa[4]

[1]Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

[2]Karlsruhe Institute for Technology, Eggenstein-Leopoldshafen, Germany

[3]National Institute for Fusion Science, Toki, Gifu, Japan

[4]Japan Atomic Energy Agency, Aomori, Japan

24th IAEA Fusion Energy Conference

San Diego, California
October 8-13, 2012

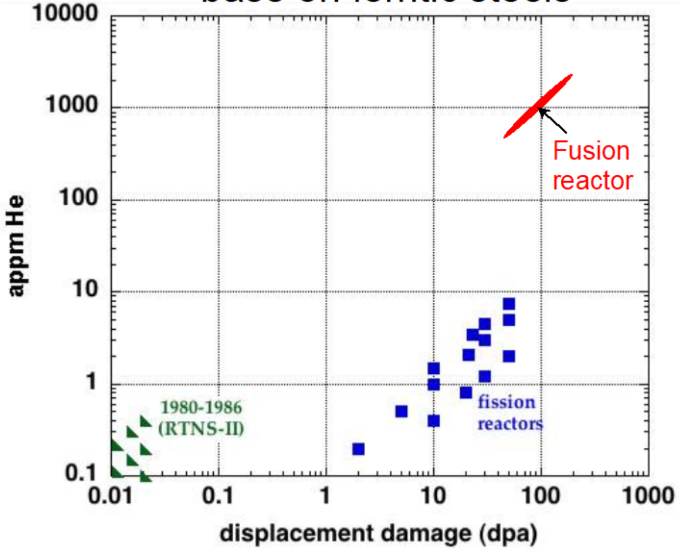
1 Managed by UT-Battelle
for the U.S. Department of Energy

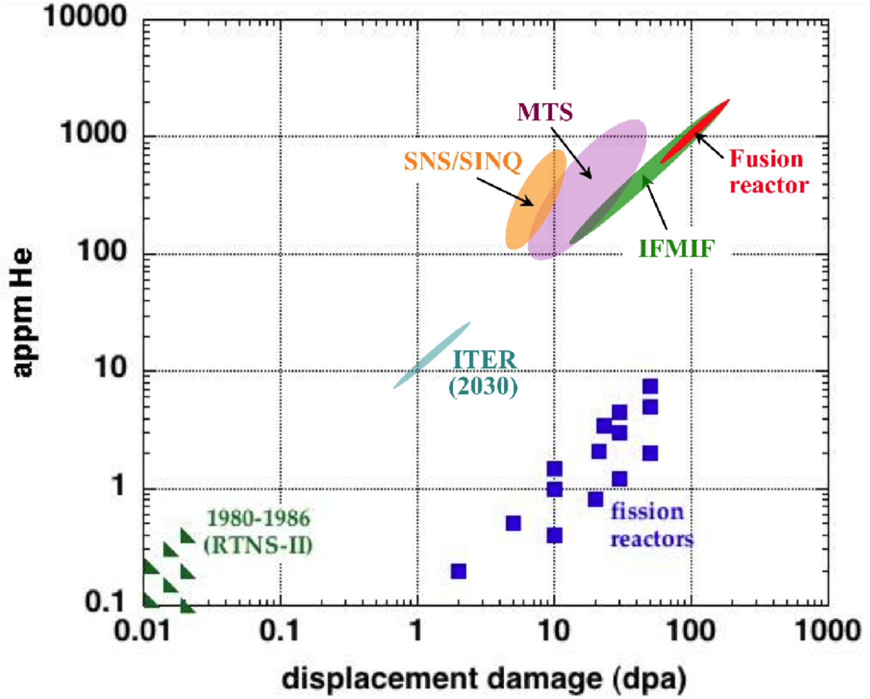
IFMIF

There are several options to close the current knowledge gap in fusion-relevant radiation effects in materials

- An intense neutron source (in concert with enhanced theory and modeling) is needed to improve understanding of basic fusion neutron effects and to develop & qualify fusion structural materials

Current knowledge base on ferritic steels

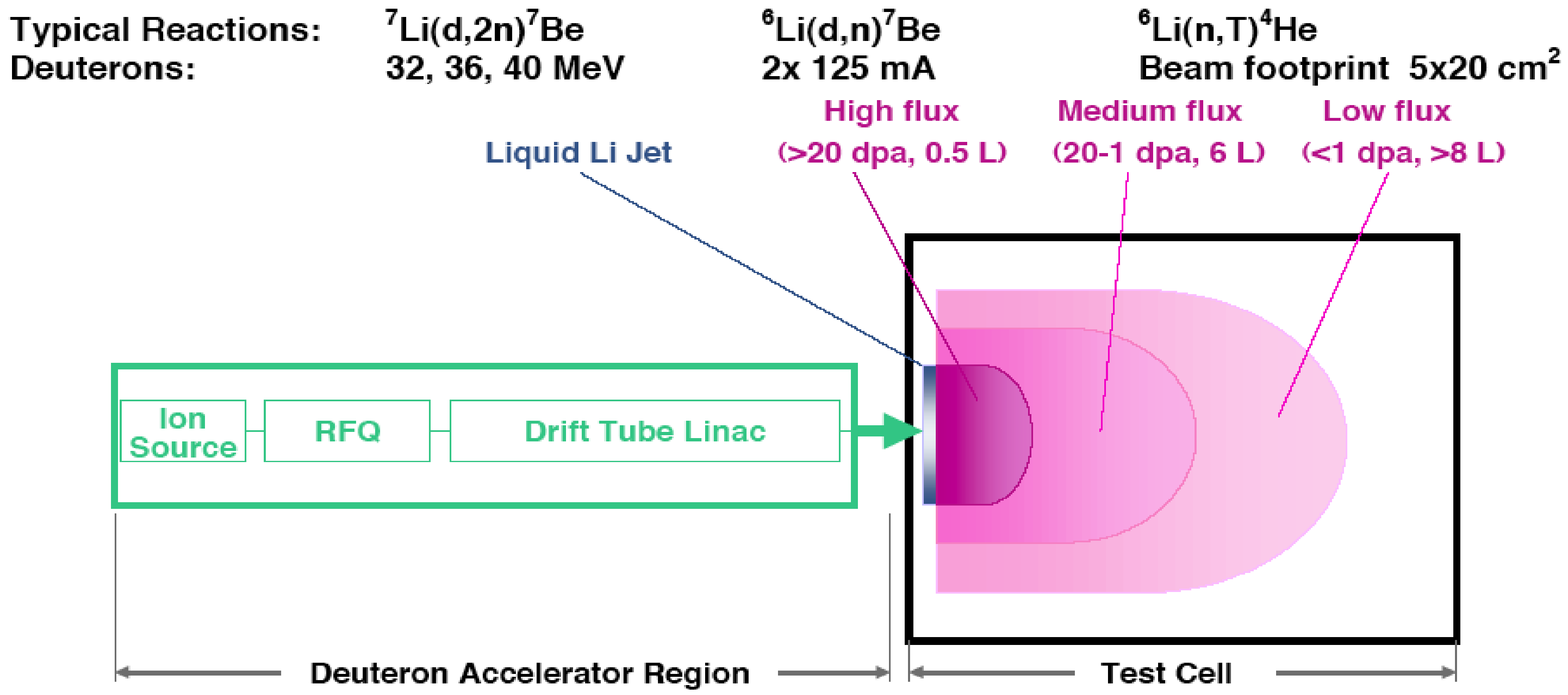




Option A: IFMIF + fission reactors +ion beams + modeling
Option B: robust spallation (e.g., MTS) + fission reactors + ion beams + modeling
Option C: modest spallation (e.g.,SNS/SINQ) + fission reactors + ion beams + modeling

IFMIF (1)

- International fusion material irradiation facility IFMIF: a neutron source capable of simulating the fusion neutron with high flux
- IFMIF is the key infrastructure for fusion material science

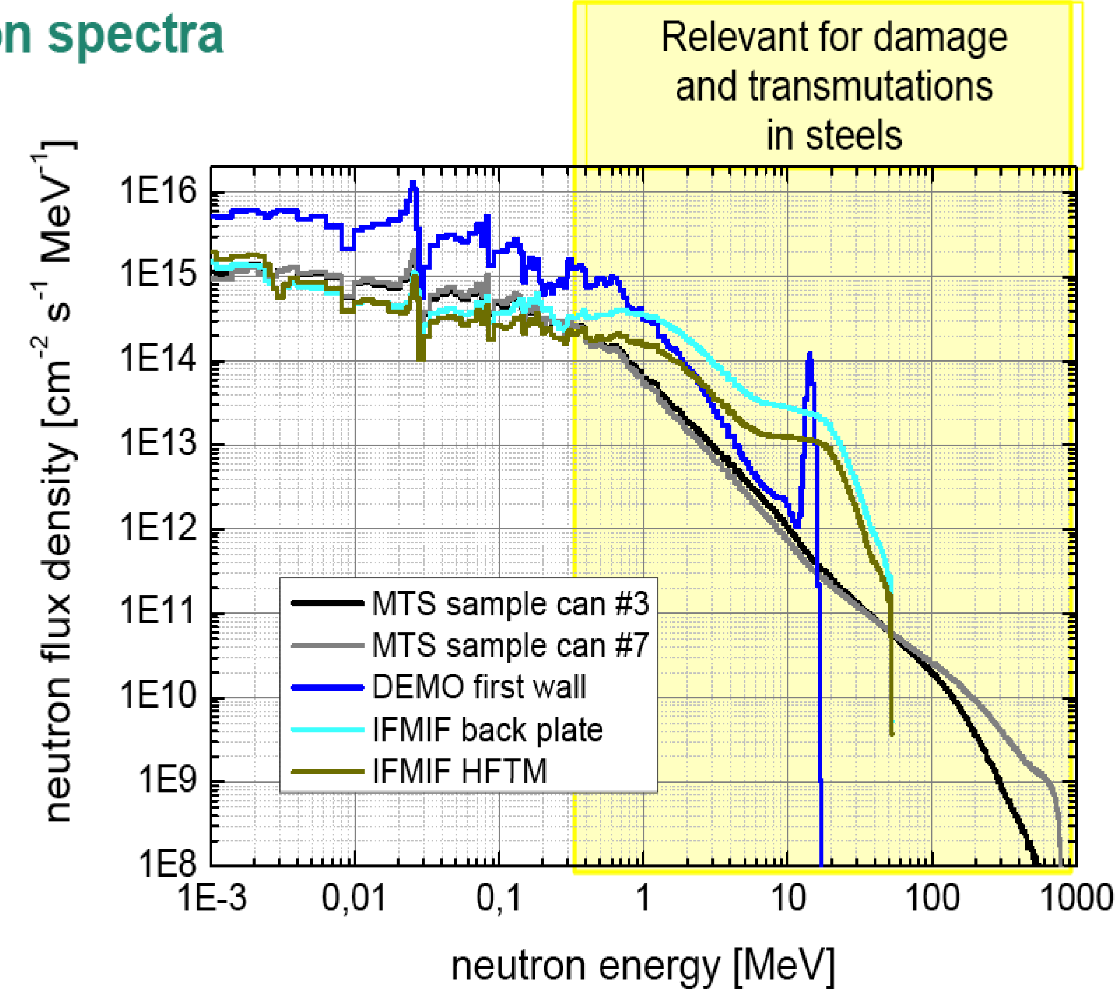


IFMIF: neutron spectrum

IFMIF vs. the Spallation source MaRIE

Neutron spectra

A. Möslang W-GIFT-5 Charleston SC, October 15, 2011

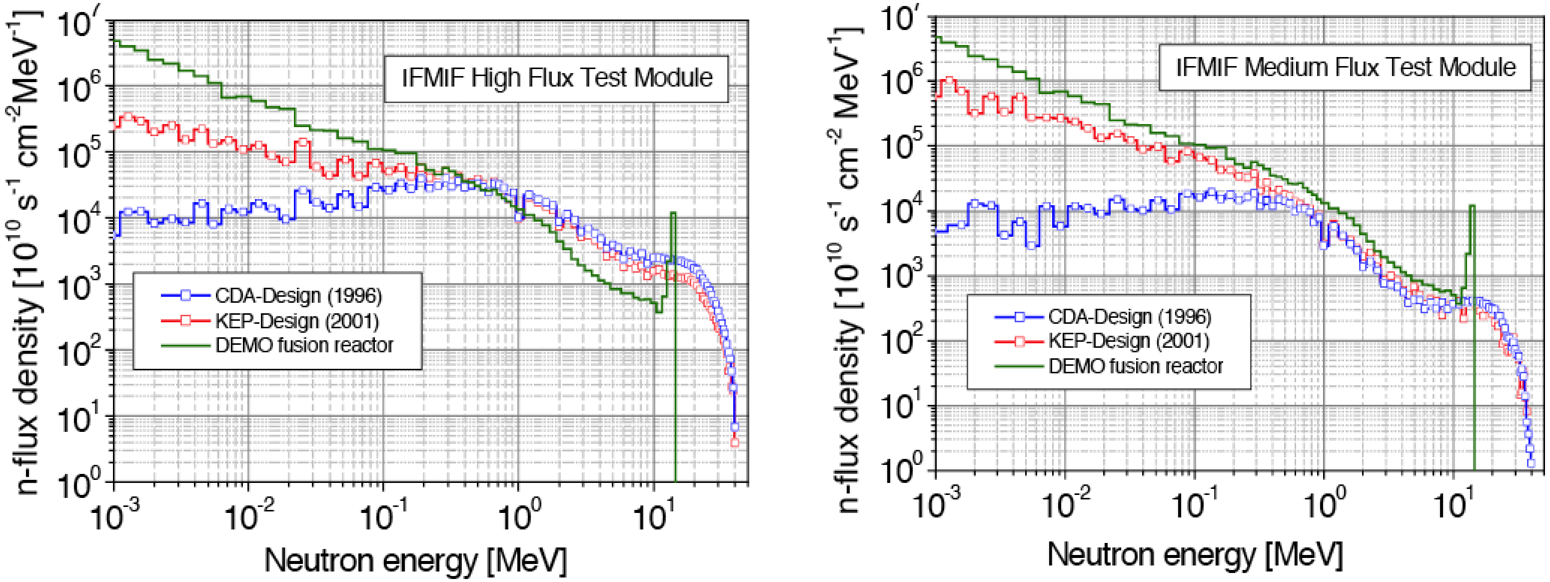


IFMIF: neutron spectra

IFMIF Neutronics - Achievements

International Fusion Materials Irradiation Facility

Improvement of neutron spectra with moderator/reflector



- Moderator/reflector: → Substantial improvements in neutron spectrum adaption
  → Irradiation volume increase by ~20%

Advanced Energy Systems, Inc.

J. Rathke, FESAC Review, Jan 14, 2003, San Diego, CA

A. Moslang - 19th IAEA Fusion Energy Conference, Lyon, France, October, 2002

22

IFMIF: He, H & dpa

IFMIF Neutronics - Achievements

International Fusion Materials Irradiation Facility

Irradiation Parameter	DEMO	ITER	IFMIF HFTM	IFMIF MFTM
Total n-flux, $(n/(cm^2\ s)$	$1.3 \cdot 10^{15}$	$4 \cdot 10^{14}$	$(4 \div 10) \cdot 10^{14}$	$(2 \div 6) \cdot 10^{14}$
H production, (appm/fpy)	1200	500	1000÷1500	300÷500
He production, (appm/fpy)	300	120	250÷600	70÷120
Displacement damage production, (dpa/fpy)	30	12	20÷55	7÷10
H per dpa, (appm/dpa)	40	45	40÷50	30÷50
He per dpa, (appm/dpa)	10	11	10÷12	8÷14

- Correct scaling of He, H and dpa production
- Accelerated irradiation in limited volume

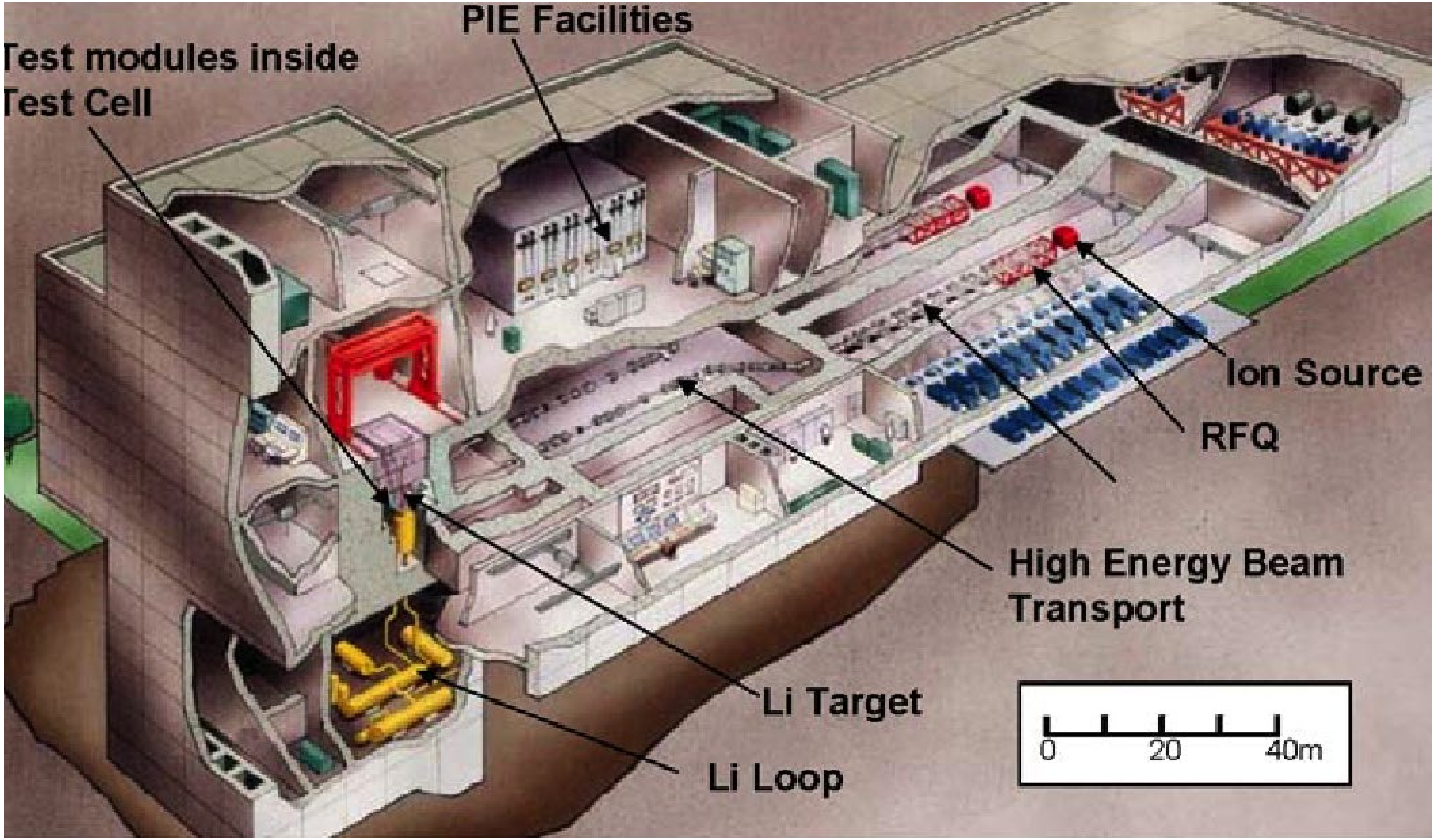
Advanced Energy Systems, Inc.

J. Rathke, FESAC Review, Jan 14, 2003, San Diego, CA

A. Moslang - 19th IAEA Fusion Energy Conference, Lyon, France, October, 2002

23

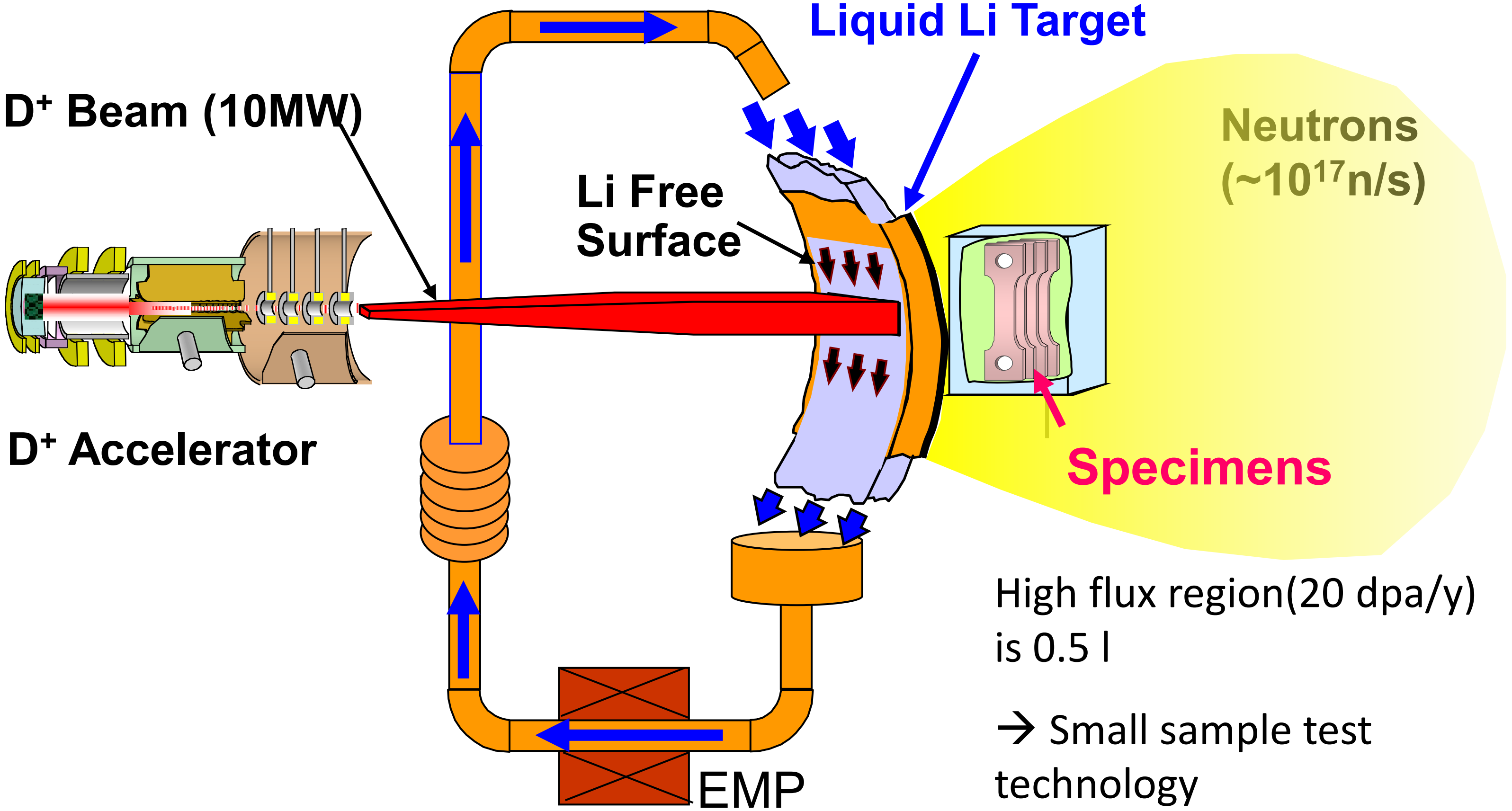
Overview of IFMIF



H. Matsui et al., SOFT Conference, 2004

Schematic View

H. Matsui et al., SOFT Conference, 2004



High flux region(20 dpa/y) is 0.5 l

→ Small sample test technology

accelerator based deuterium–lithium (d–Li) stripping neutron source

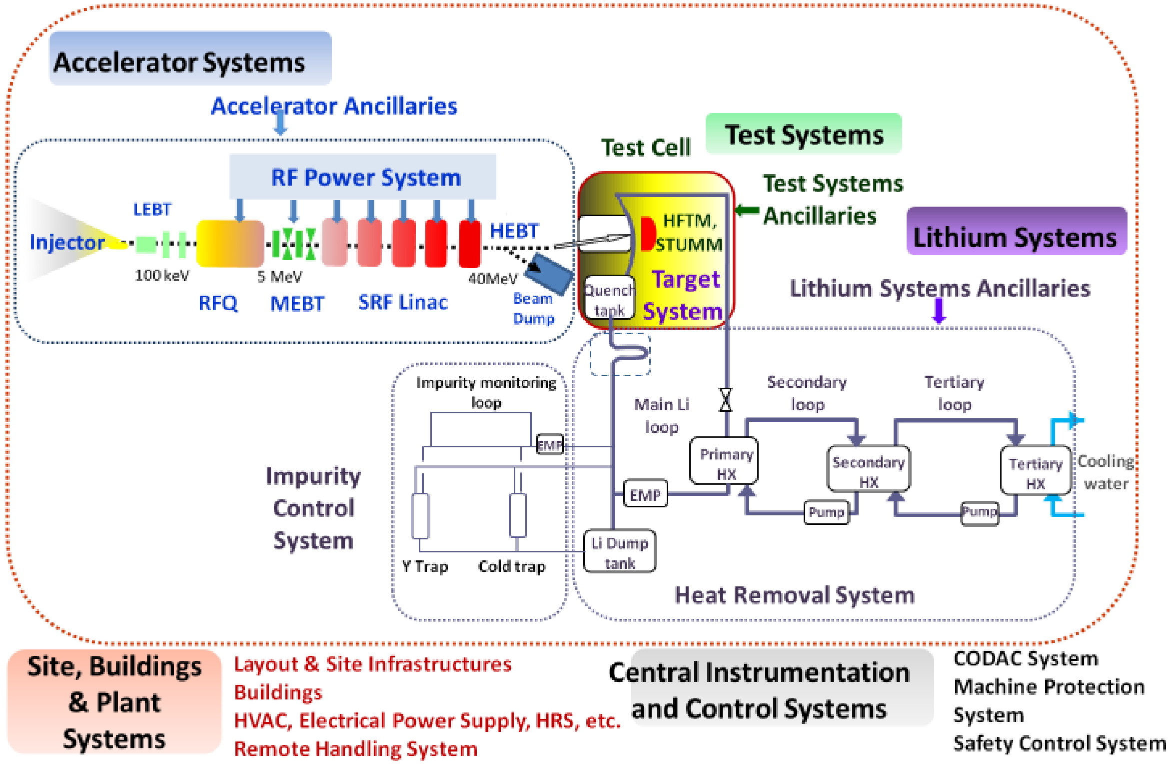


Figure 1. IFMIF-DONES facility schematic plant configuration.

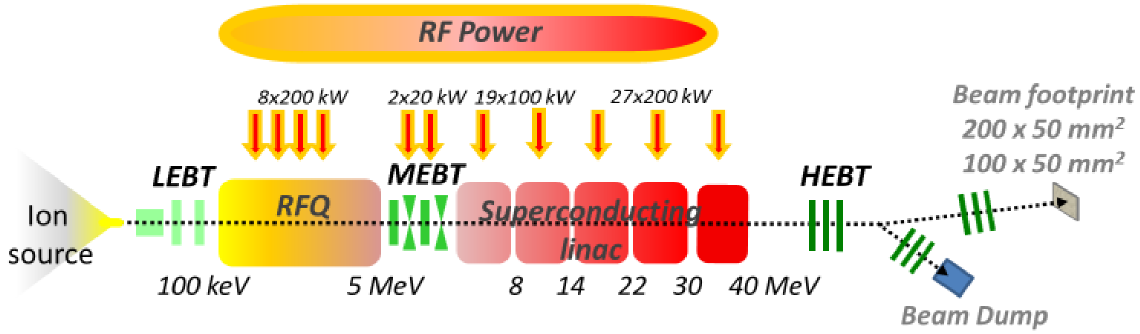
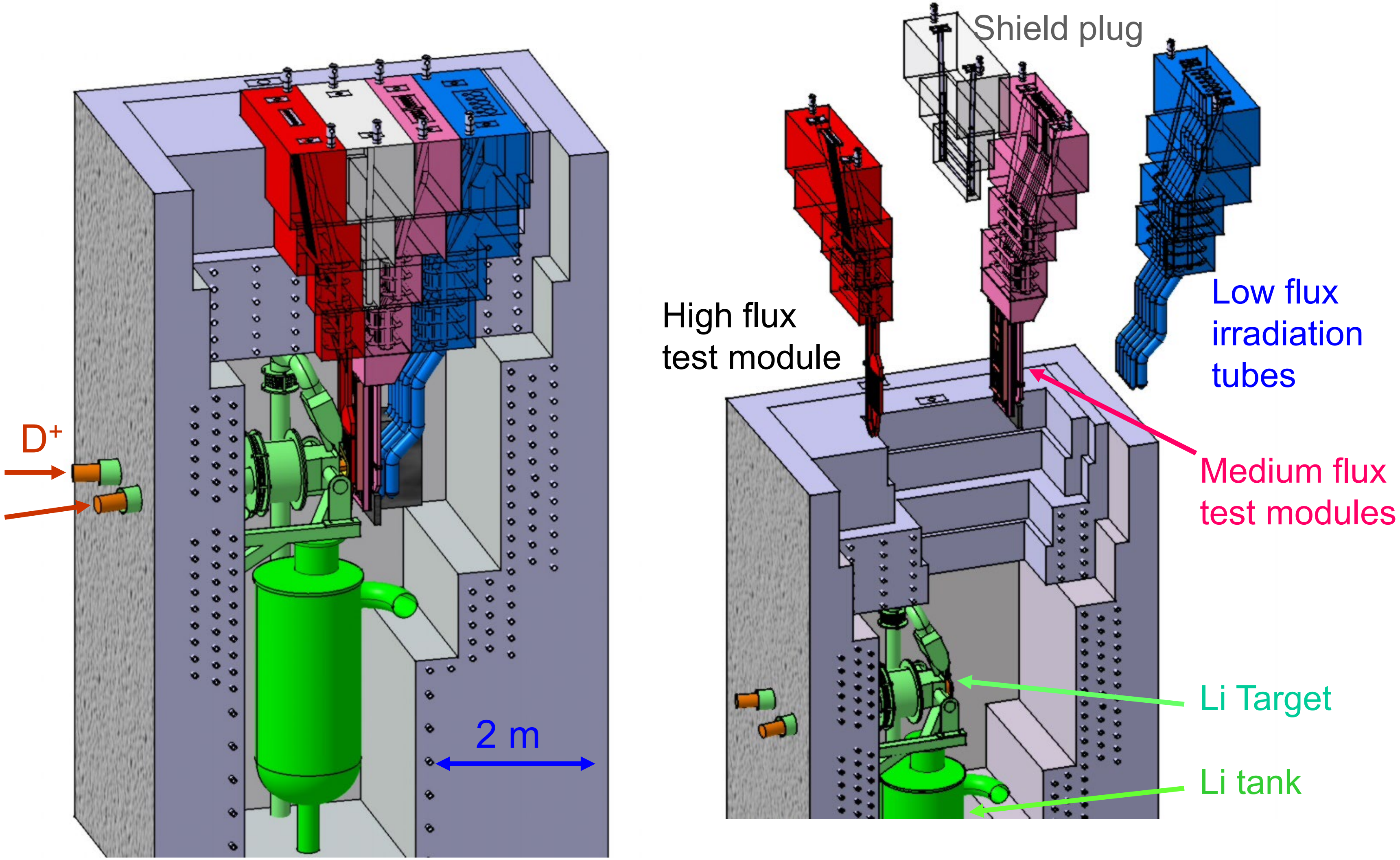


Figure 2. IFMIF-DONES accelerator systems configuration schema.

Test Cell

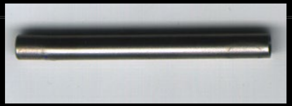
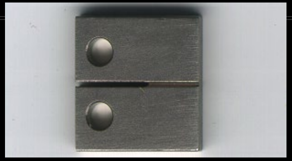
H. Matsui et al., SOFT Conference, 2004



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

DEMO

DEMO : a reactor producing electricity

Last step before the first of a kind commercial reactor

DEMO1: Pulsed plasma reactor – 500 Mw_e- Self sufficient with T

Issue: validation of the mechanical properties of low activation materials under irradiation by high dose of 14 MeV neutrons

14 MeV neutrons caused specific irradiation damage combined with embrittlement by H or He created by transmutation in the material

The Materials Development Strategy – FM Steels

EPFL PSI

EUROFER 9Cr *WVTa* (8.9 wt.% Cr, 1.1 wt.% W, 0.47 wt.% Mn, 0.2 wt.% V, 0.14 wt.% Ta, 0.11 wt.% C, Fe for the balance) **Reduced Activation Ferritic Martensitic Steel**

(7.5 tons heat was ordered in EU in 2004)

- **Target**
  - **Composition tailored to reduce activation and waste.**
  - **Breeding blanket with operational window 300-550 ° C.**
  - **Two more steps:**
    - Optimization of mechanical properties (EUROFER-2).
    - Development towards "low activation" (EUROFER-3).

- **Use for first generation breeding blankets, i.e.**
    - The reference structural material for the DEMO blankets.
    - Used in the ITER TBMs.

The Materials Development Strategy – FM Steels

ODS (oxide dispersion strengthened) steels
First pre industrial heat of 50 kG was produced

- **Target**
  - **Increased operating temperature up to**
    - 650° C using EUROFER (9Cr) type ODS material
    - 750° C using nano-composited ferritic steels (12-14Cr)
  - **Improved (creep) strength (HT) and still good properties at LT of ~300° C.**
- **Use**
  - **To replace step-by-step EUROFER in more “advanced” concepts.**
  - **As Back bone material for gas-cooled divertor concepts**

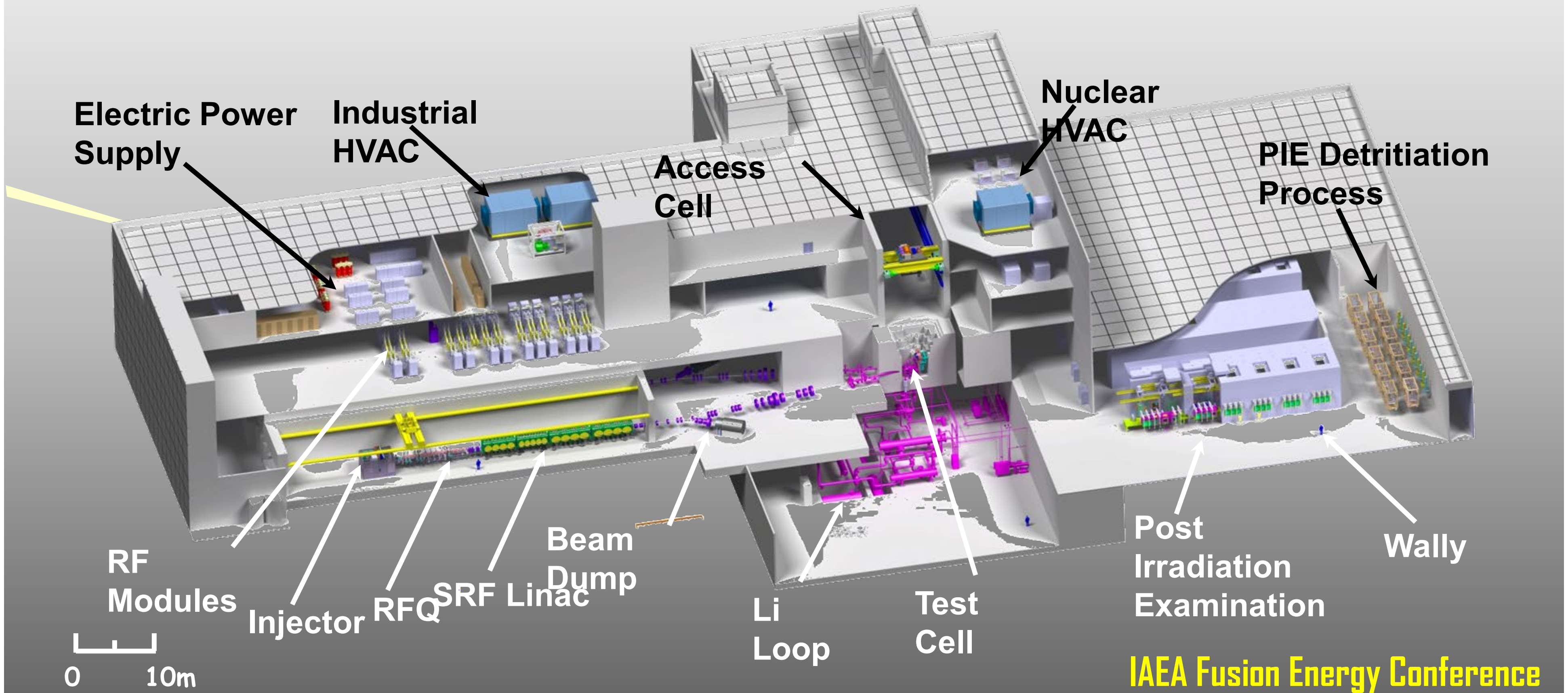
Discussion points

What are the important points from this lesson according to you?

IFMIF

the neutron source for the Fusion Program

J. Knaster, R. Heidinger and S. O'hira
on behalf of IFMIF/EVEDA team



IAEA Fusion Energy Conference
Kyoto
October 2016

Table of Content

- Introduction: presentation of Anton Moeslang / timeframes / displacement damage
- Basic material science
  - material deformation
  - material testing
  - embrittlement / DBTT
- Motivation (why do we need material science)
- Radiation defects (H / He / displacement)
- Which materials? What are steels?
- Safety aspects (can it melt?)
- Radiation exposure and influence on the mechanical behavior
- “out of fusion” nuclear material science
- How to irradiate materials (14 MeV) / IFMIF

- Exercise

Things to know / Exercise

a. What do you know about material deformation (behavior, types, factors, ...)
b. How can you test materials. Why do we care for sample miniaturization
c. What is embrittlement. Why does it happen. Why is it relevant for us.
d. What is a steel. How is it formed.
e. How do the mechanical properties change with radiation
f. Motivation and setup of IFMIF

3 Groups: Discuss the points above, maybe extend. Ask questions. Present the essentials.

- Group1: a,d
- Group2: b,e
- Group3: c,f