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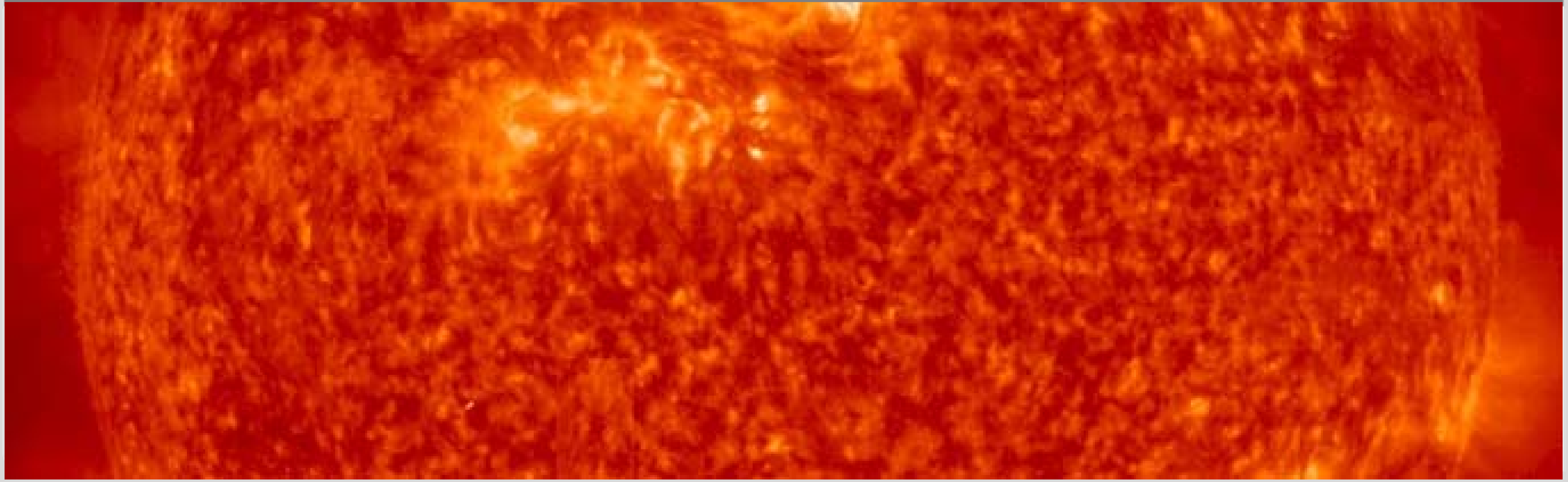
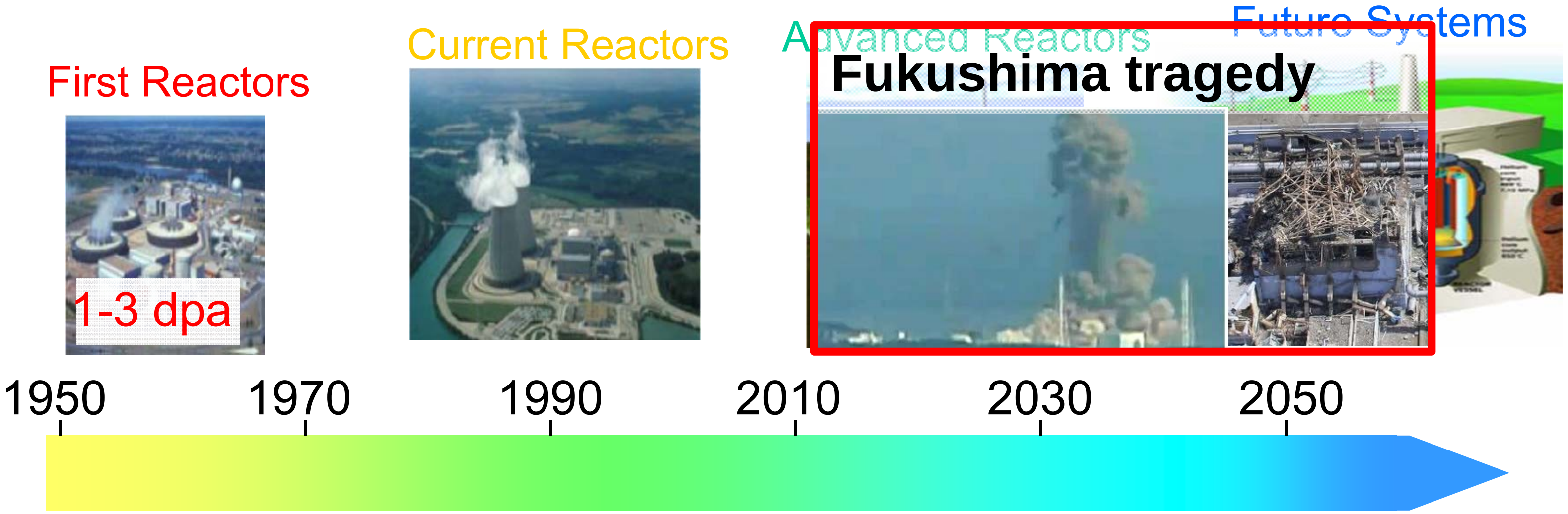
February 27, 2014
EPFL, Lausanne, Switzerland

Structural materials for fusion power plants – international progress and challenges

Anton Möslang, Institute for Applied Materials



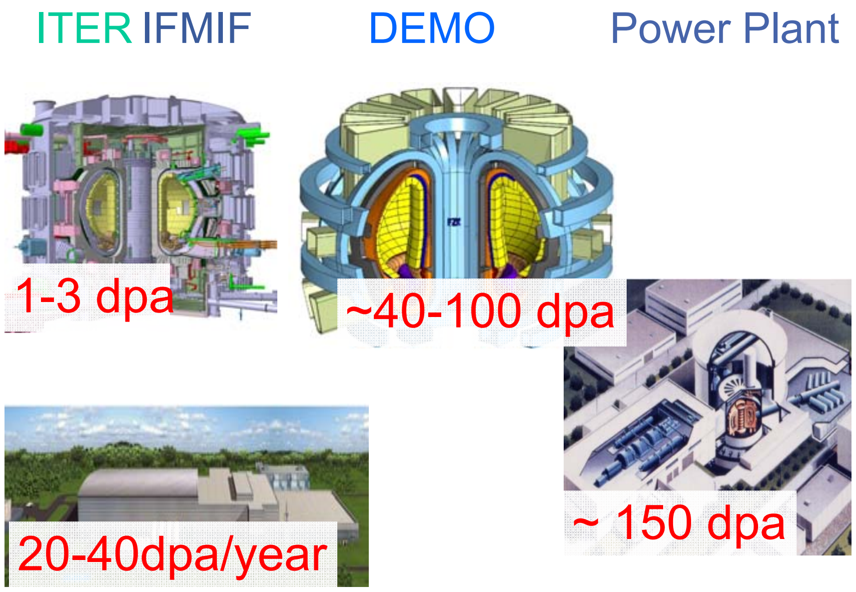
High Performance Materials for Energy



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)



Outline

- Short introduction to Fusion
- International roadmaps to fusion power
- Materials challenges: fusion – fission – spallation
- Materials R&D: examples of recent progress
  - Reduced activation steels and iron based “super alloys”
  - Neutron irradiation behaviour
  - Tungsten alloys and composites
- Irradiation facilities & intense fusion neutron source IFMIF
- Conclusions

Why Nuclear Fusion?

Features

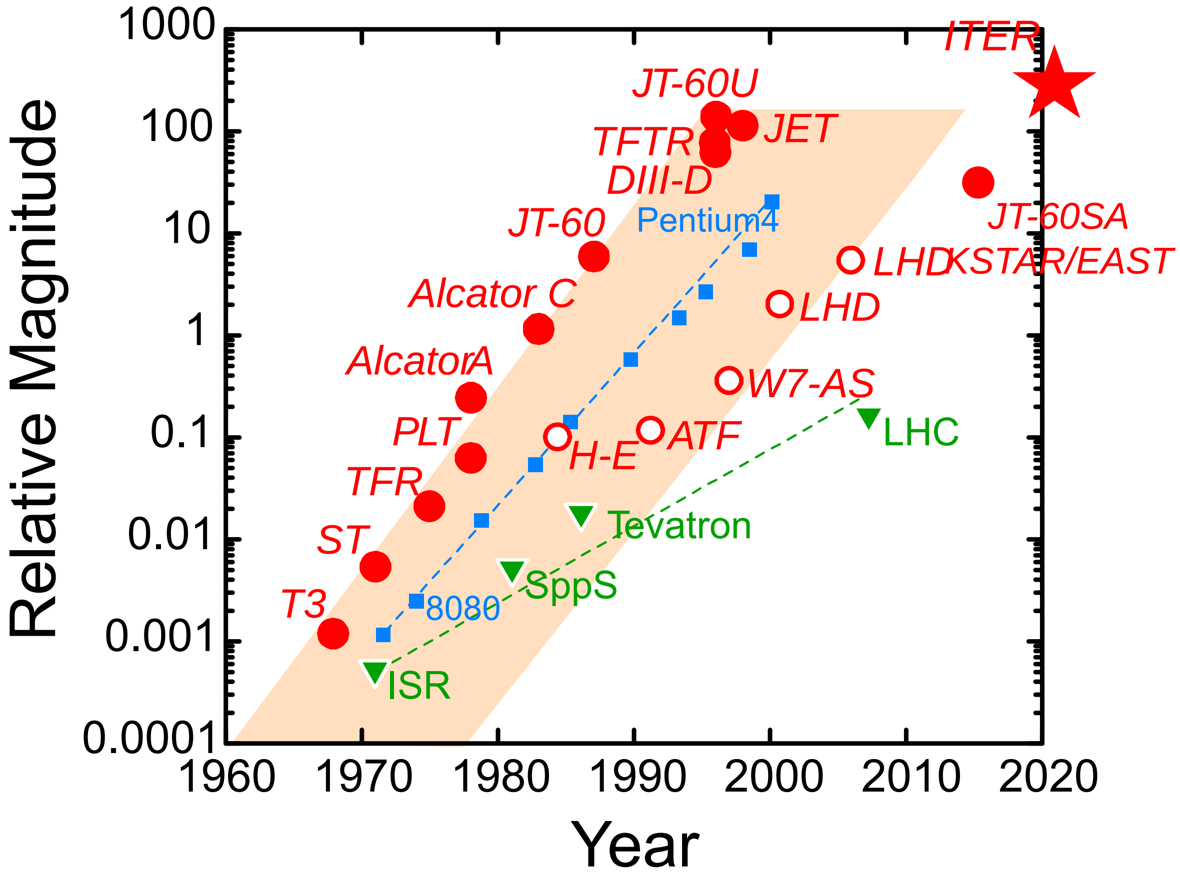
- Virtually inexhaustible
- No CO_2 emissions
- High energy density fuel

  1 gram of fully reacted Deuterium-Tritium = 26000 kW·hr of electricity (~10 Tons of Coal !)
- Inherently Safe Controllability
  - low fuel inventory
  - no chain reaction to control
  - low power and energy densities

Issues

- Fusion reaction is difficult to start and maintain
  - High temperatures (Millions of degrees) are required
  - Technically complex & LARGE devices are required

In the past, fusion research has progressed as rapidly as other areas of big science and high-technology



Fusion:
Triple product $nT\tau_E$
doubled every 2 years

Moore’s law :
Transistor number
doubles every 2 years

Accelerators :
Energy doubles every
3 years

In construction:
International Tokamak Experimental Reactor ITER

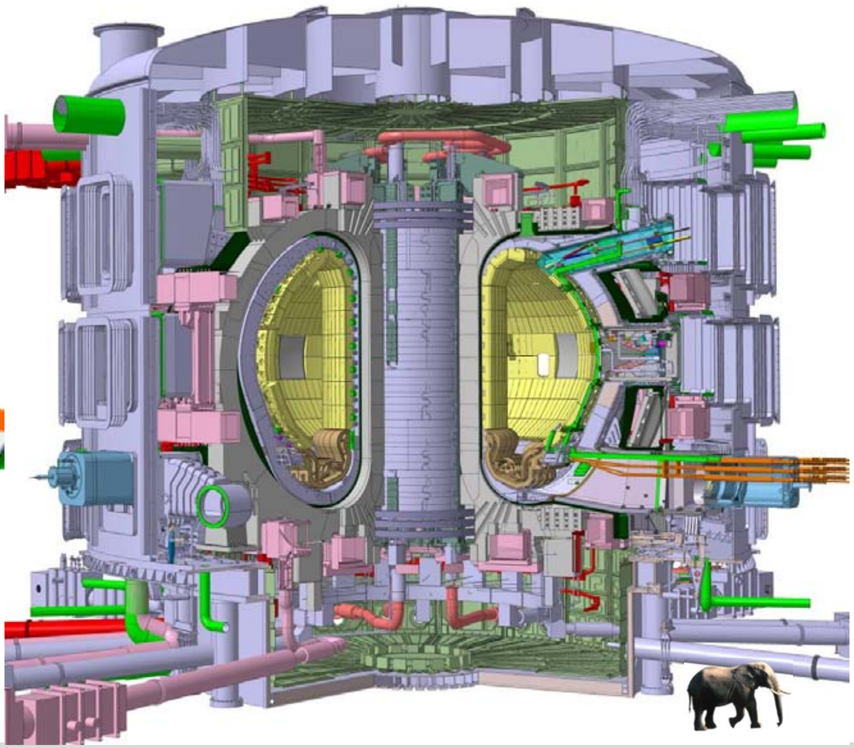
- Objective - to demonstrate the scientific and technological feasibility of fusion power:

  500 MW, 300-500s, Q=10

  837 m^3 Plasma volume

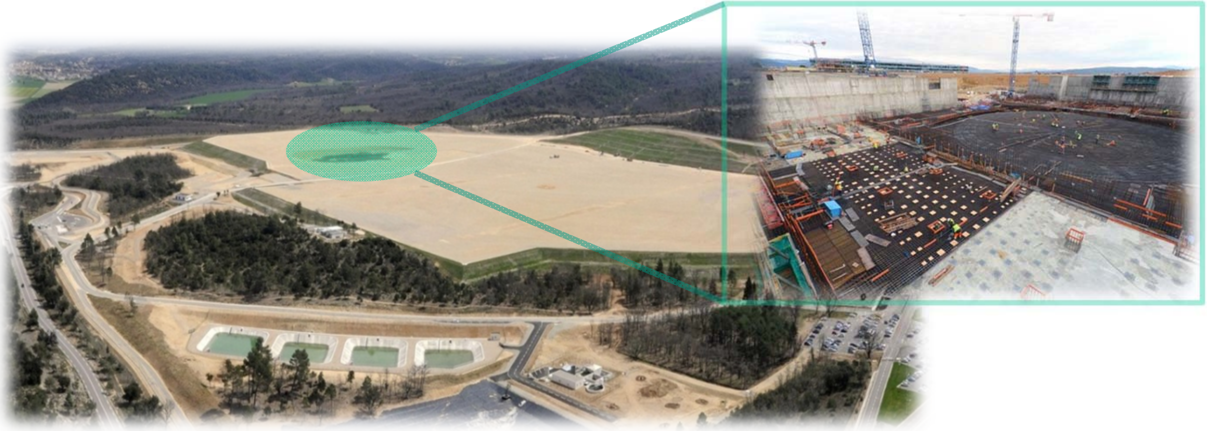
- The world’s biggest fusion energy research project.

- An international collaboration



ITER Site Cadarache France

The ITER site
February 2014



Architect
view of the
future
buildings

Direct Construction Cost ~ 10 billion € within 12 years
Operation 20years / ~ 250 million €/year
International Organization 600 staff

Role of Materials in Fusion Road Maps - simplified -

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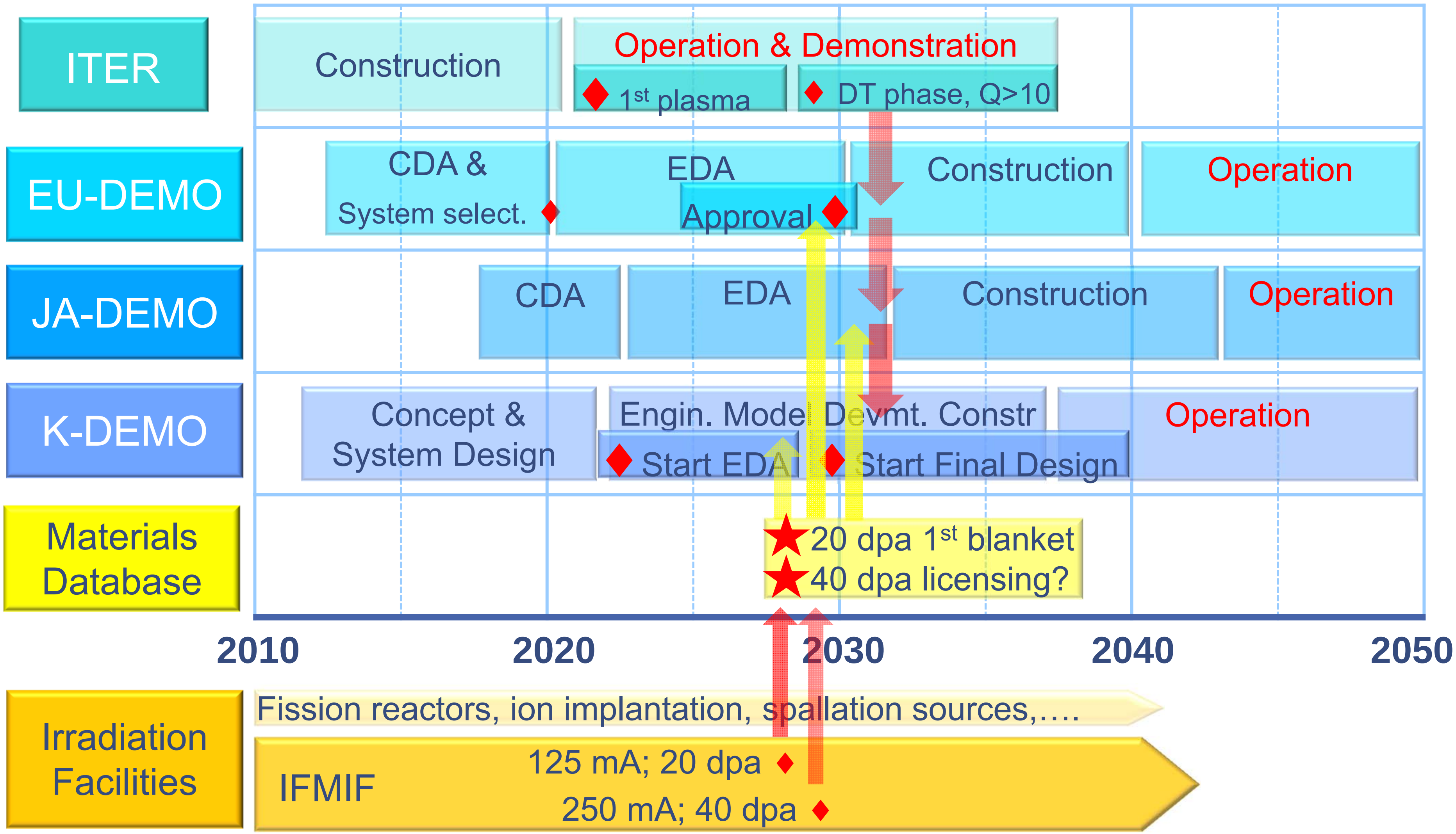
DEMO concepts based on ISFNT-11 plenary talks (Sept. 2013):



ITER
Construction
Operation & Demonstration
♦ 1st plasma
♦ DT phase, Q>10

EU-DEMO
CDA & System select. ♦
EDA
Approval ♦
Construction
Operation

JA-DEMO
CDA
EDA
Construction
Operation

K-DEMO
Concept & System Design
Engin. Model Devmt. Constr
♦ Start EDA
♦ Start Final Design
Operation

Materials Database
★ 20 dpa 1st blanket
★ 40 dpa licensing?

2010
2020
2030
2040
2050

Irradiation Facilities
Fission reactors, ion implantation, spallation sources,….
IFMIF
125 mA; 20 dpa ♦
250 mA; 40 dpa ♦

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Requirements for “in vessel” structural materials

Fission – Fusion – Spallation: Three different irradiation loadings

	Fission (Gen. I)	Fission (Gen. IV)	Fusion (DEMO/PROTO)	Spallation (MYRRHA)
Structural alloy T_{max}	<300˚C	500-1000˚C	550-1000˚C	400-600˚C
Max dose for core internal structures	**~1 dpa**	**~30-150 dpa**	**~150 dpa**	**≤60 dpa/fpy**
Max transmutation helium concentration	**~0.1 appm**	**~3-10 appm**	**~1500 appm (~10000 appm for SiC)**	**~2000 appm/fpy**
Particle Energy E_{max}	**<1-2 MeV**	**<1-3 MeV**	**<14 MeV**	**several hundred MeV**

Materials R&D towards:
- improved irradiation resistance
- enhanced temperature window
- convincing compatibility with coolants

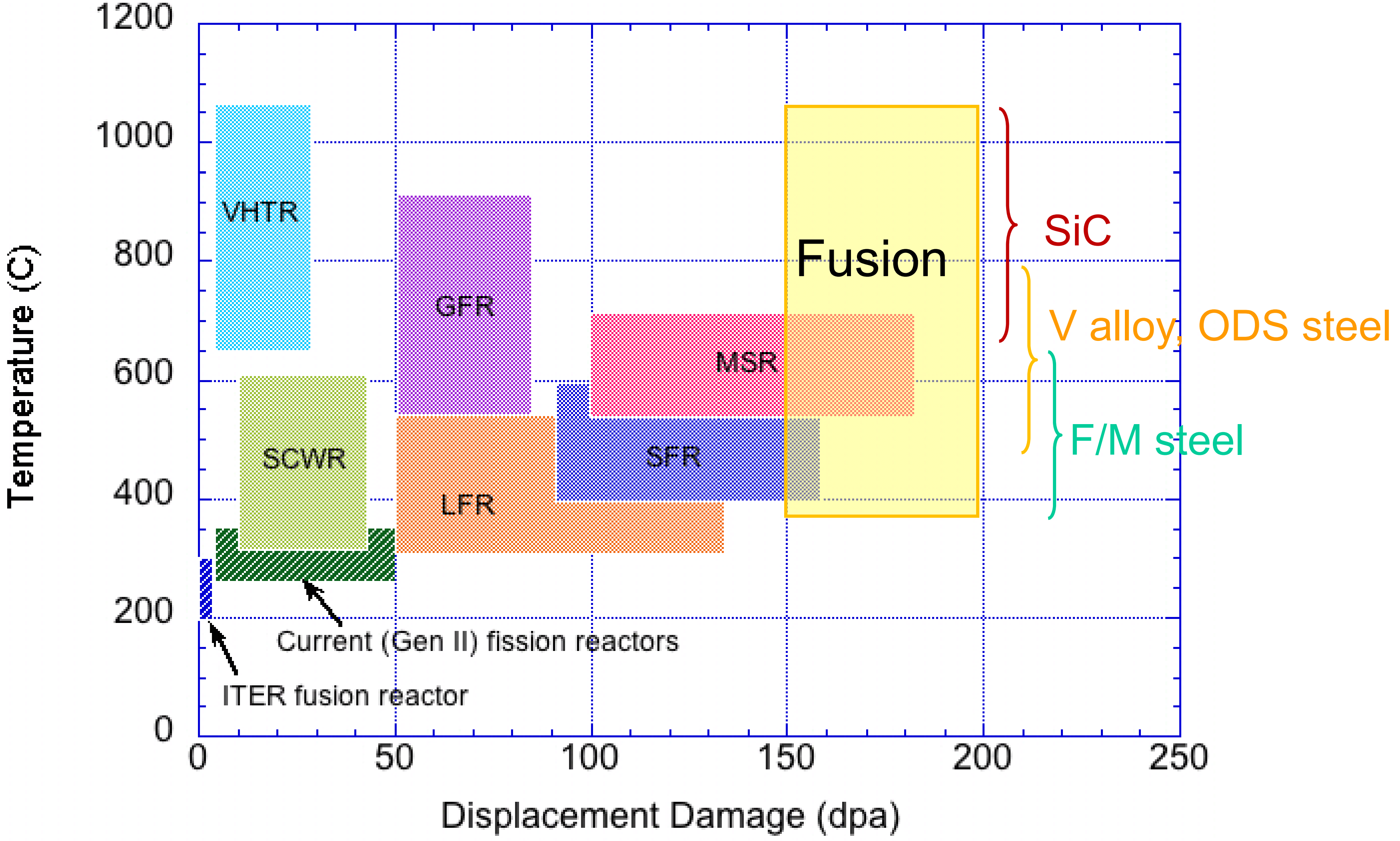
EU Fusion reactor study „PPCS“

Material – coolant combinations

		Model A	Model B	Model AB	Model C	Model D
Blanket	Structural material First Wall Channel inserts	EUROFER	EUROFER	EUROFER	EUROFER EUFER/ODS SiC/SiC	SiC/SiC
	Coolant	Water	Helium	Helium	Helium	LiPB
	Coolant temp. in/out (°C)	285/325	300/500	300/500	480 / 700 300 / 480	700 / 1100
	Breeder	LiBb	Li_4SiO_4	LiPb	LiPb	LiPb
	Tritium breeding ratio	1.06	1.12	1.13	1.15	1.12
Divertor	Structural material	CuCrZr	W alloy	W alloy	W alloy	SiC/SiC
	Armor material	W	W	W	W	W
	Coolant	Water	Helium	Helium	Helium	LiPb
	Coolant temp. in/out (°C)	140/167	540/717	540/717	540/717	600/990

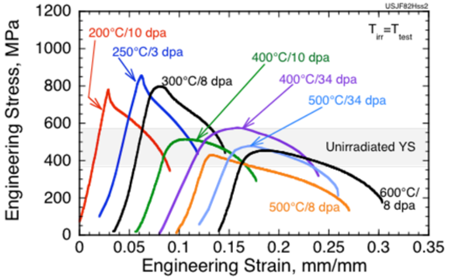
Gen IV and Fusion reactors pose severe materials challenges

S.J. Zinkle & J.T. Busby, Mater. Today 12 (2009) 12



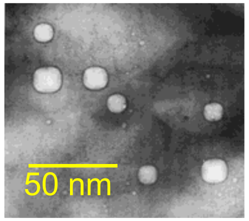
Neutron irradiation: Severe Materials degradation

- Radiation hardening and embrittlement (<0.4 T_M, >0.1 dpa)

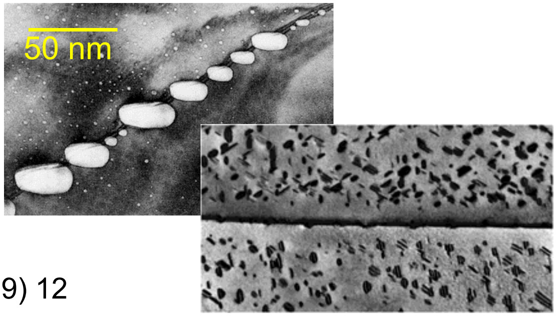


- Irradiation creep (<0.45 T_M, >10 dpa)

- Volumetric swelling from void formation (0.3-0.6 T_M, >10 dpa)



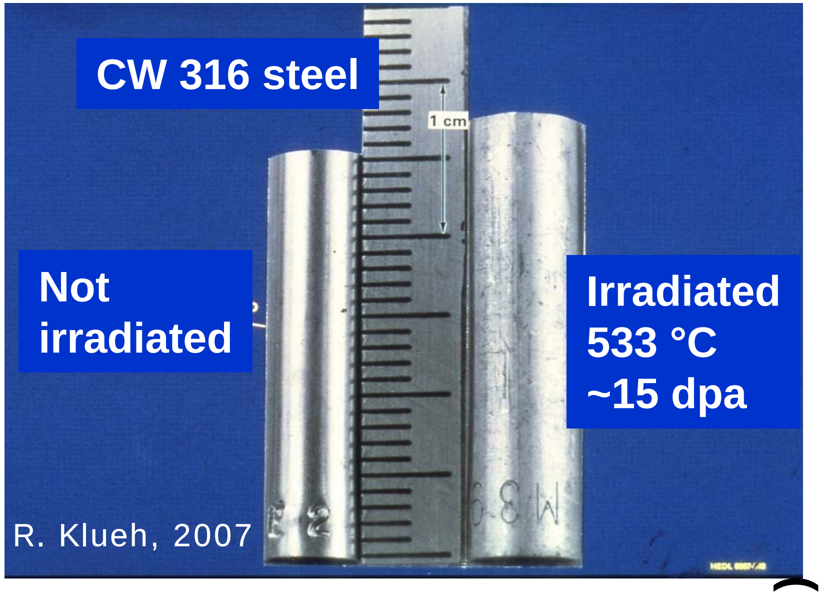
- High temperature He embrittlement (>0.5 T_M) and phase instabilities (0.3-0.6 $T_{M,}$ >10 dpa)



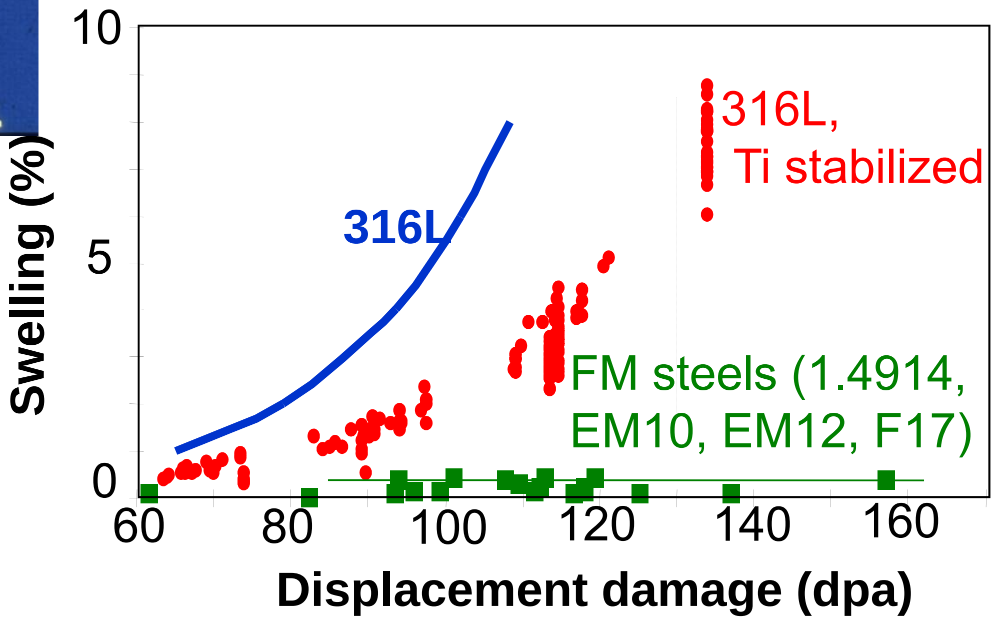
Zinkle & Busby, Mater. Today 12 (2009) 12

“in vessel” components: Why not austenitic steels?

Irradiation induced swelling: Austenitic steels vs. FM steels



Phénix :
Fuel Element Cladding irradiation



Fusion Power Plants:
Structural Material Challenges beyond ITER

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Blanket: ≤30 dpa/yr, ≤ 2.5MW/m²

- Plasma Facing Materials
- Reduced Activation Structural Materials:
  - RAFM Steels (EUROFER, F82H) 350-550 °C
  - RAFM ODS Steels 300-650 °C
- Functional Materials
  - Neutron Multipliers (Be), Li ceramics

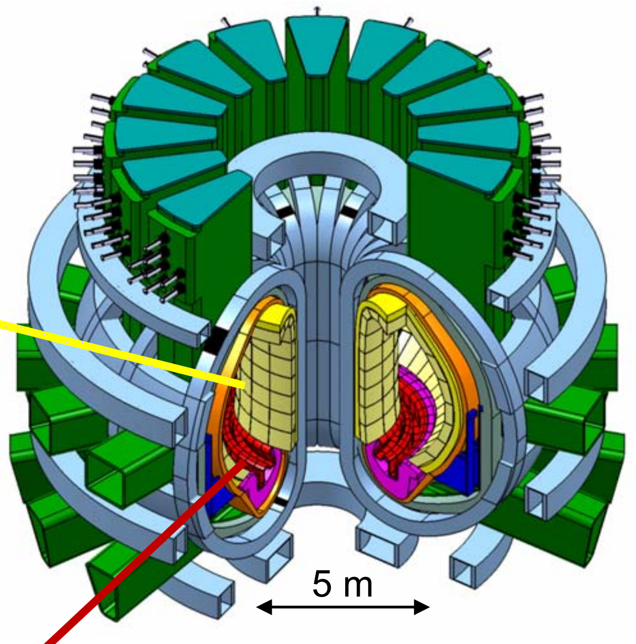
Divertor: ≤10 dpa/yr, 10-15 MW/m²

- Refractory alloys (e.g. W-materials)

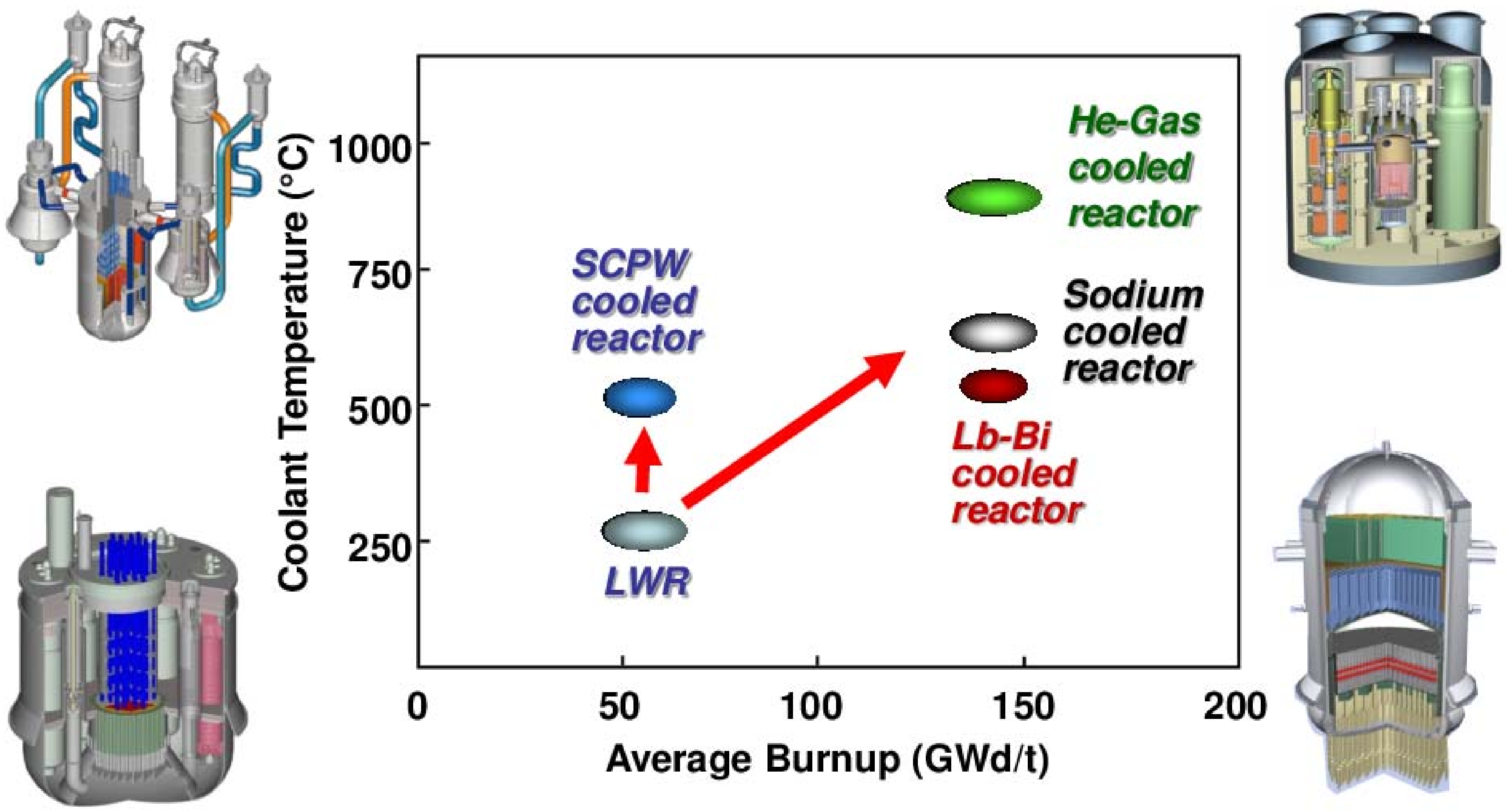
850-1100 °C → ~600 - 1300 °C

- Nano-scaled RAF(M)-ODS Steels

350-650 °C → ~300 - 800 °C



Gen IV Materials challenges:
High burn-up and high temperature



A. Kimura, Kyoto Univ. 2009

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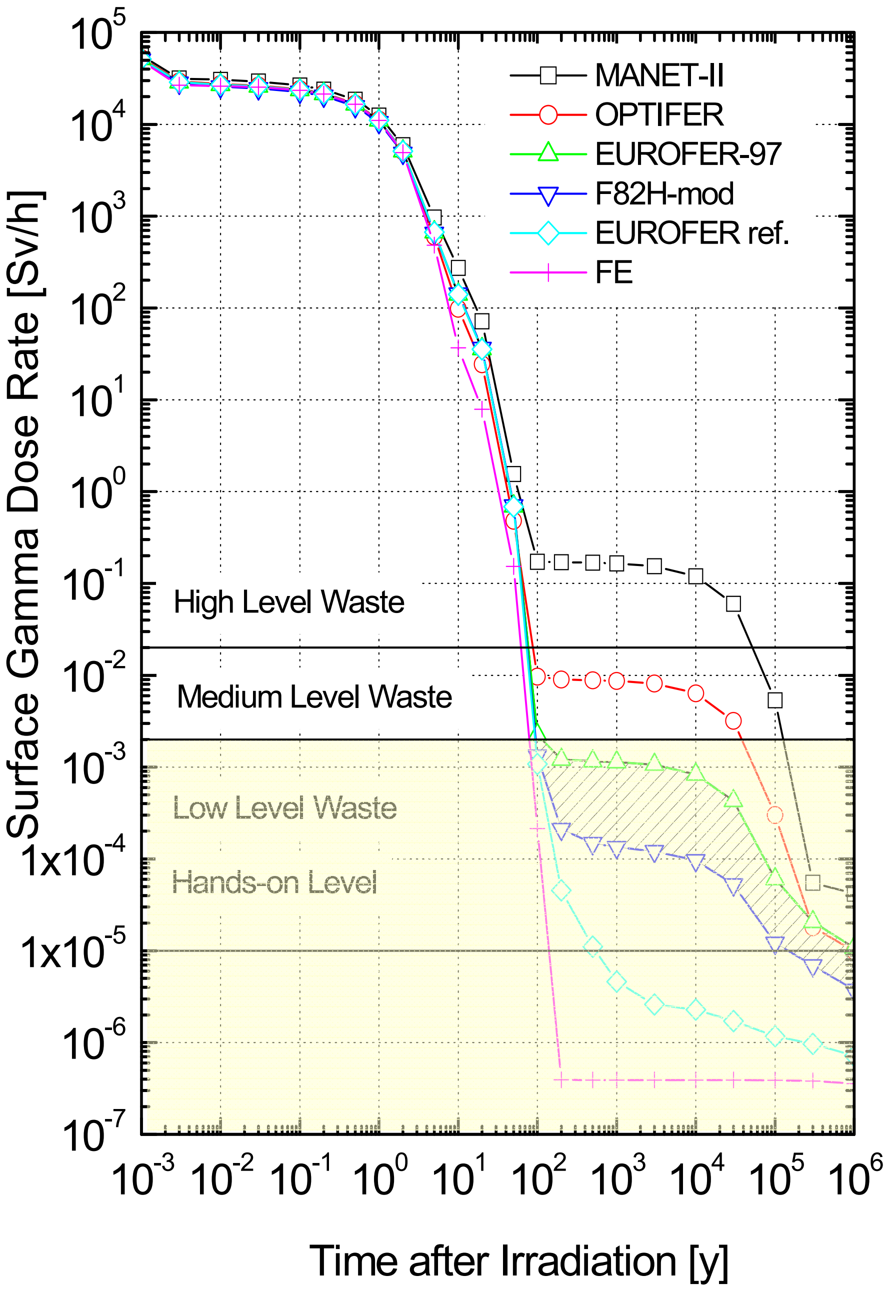


FUSION Priority:
Low activation capability

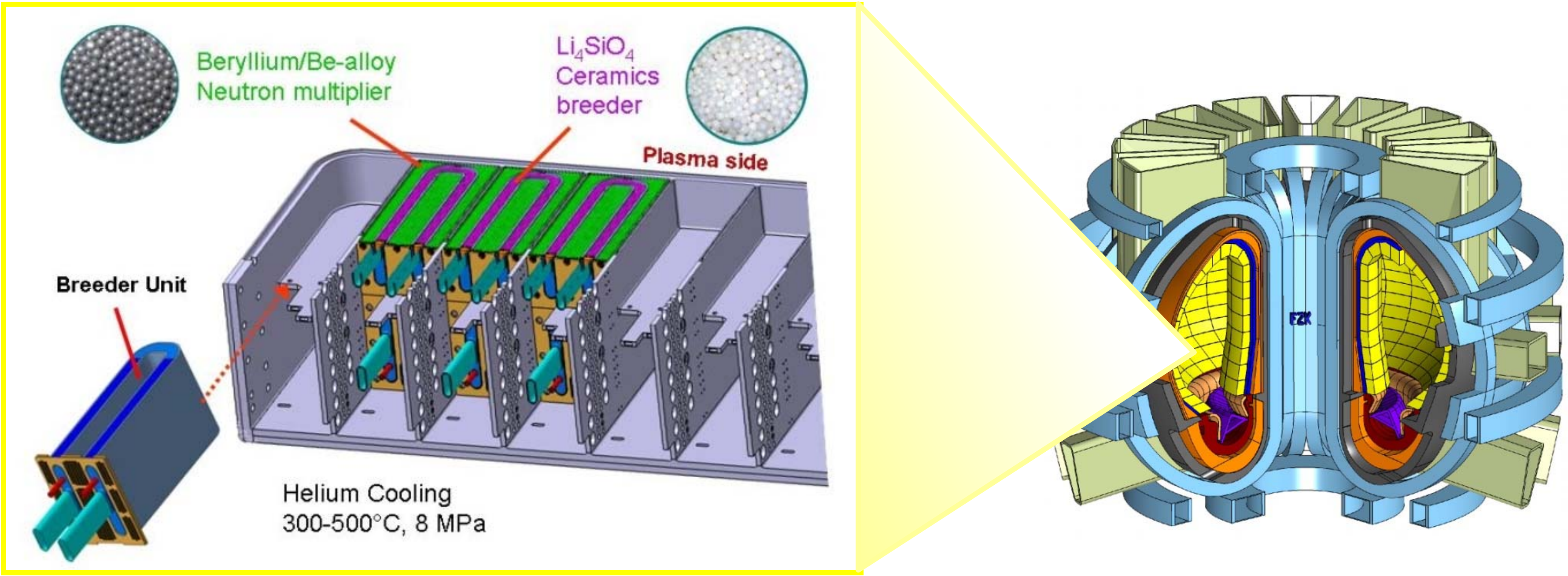
RAFM 8-10%CrWTaV steels

- Substantial progress since the early 90-ies
- „Low level waste“ already after 80-100 years
- No “high level” waste disposal
- The impurities Nb and Mo are dominating the hatched area

The European reference steel EUROFER is presently characterized and code qualified (RCC-Mx)

Long term irradiation
(12.5 MWa/m^2) of a
DEMO reactor first wall
Source: IMF I, FZK

European Helium Cooled Pebble Bed Blanket



L. Boccaccini et al, KIT, 2011

Neutron Multiplier:

Beryllium pebbles

~ 400 Kg per ITER TBM

~ 320 tons per DEMO

T-breeder:

Li-ceramic

~90 Kg per ITER TBM

~ 72 tons per DEMO

Recent past and present: Qualification of Reduced Activation Ferritic-Martensitic (RAFM) steel EUROFER

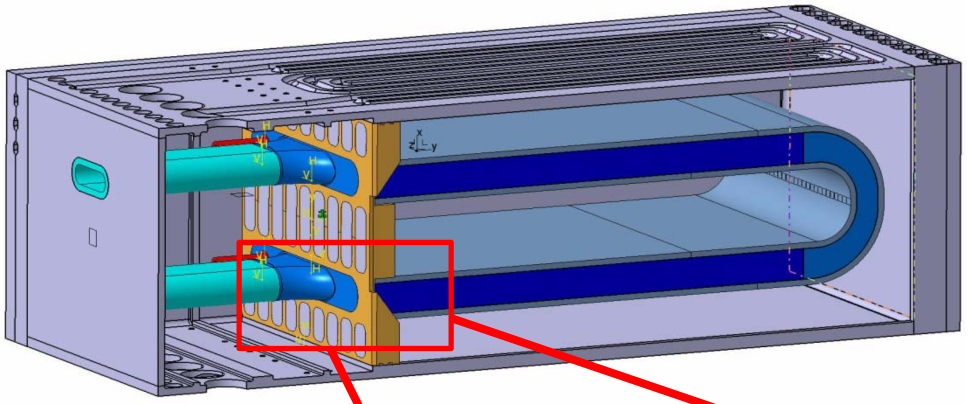
Eurofer alloy composition

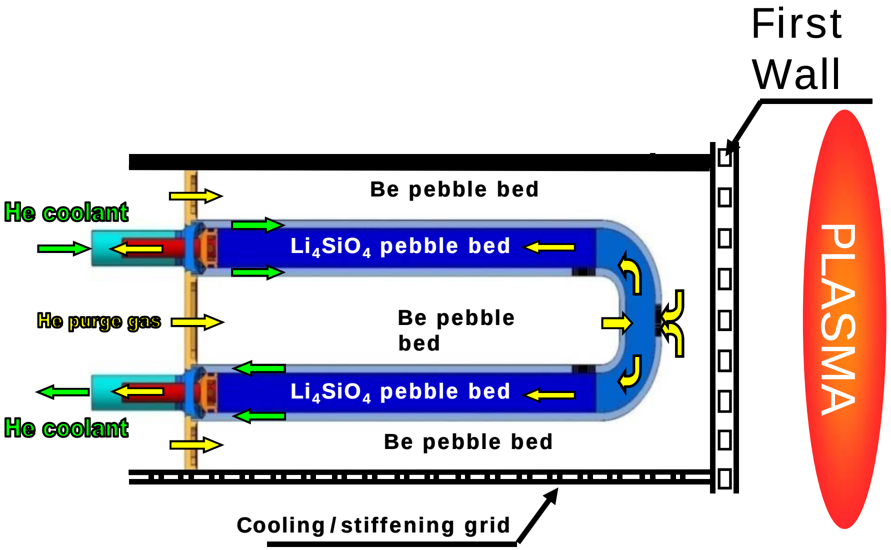
									longterm activation			shortterm activation		
Alloy		**C**	**Si**	**Mn**	**Cr**	**V**	**W**	**Ta**	**Nb**	**Mo**	**Al**	**Co**	**Ni**	**Cu**
EUROFER	**wt.-%**	**0.11**	**0.05**	**0.4**	**9.0**	**0.2**	**1.1**	**0.12**	**0,001**	**0,005**	**0,01**	**0,005**	**0,005**	**0,005**

Achievements (EFDA & F4E coordinated)

- Meanwhile ~35 tons of EUROFER delivered in various product forms
- Broad based Qualification Programme, including joining technologies and corrosion
- Materials database also on irradiated EUROFER advanced (up to 40% of DEMO lifetime)

Breeding blanket manufacturing (ITER TBM)





First Wall

He coolant

He purge gas

He coolant

Be pebble bed

Li_4SiO_4 pebble bed

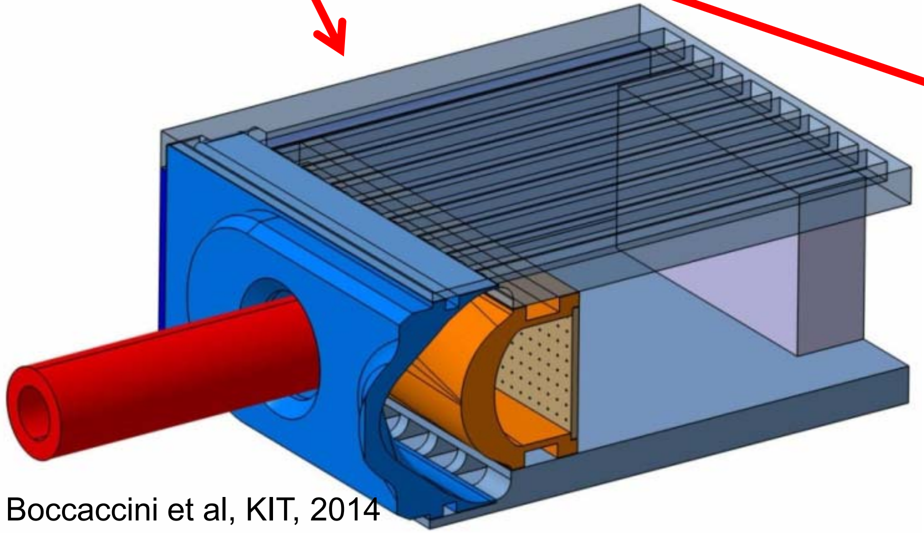
Be pebble bed

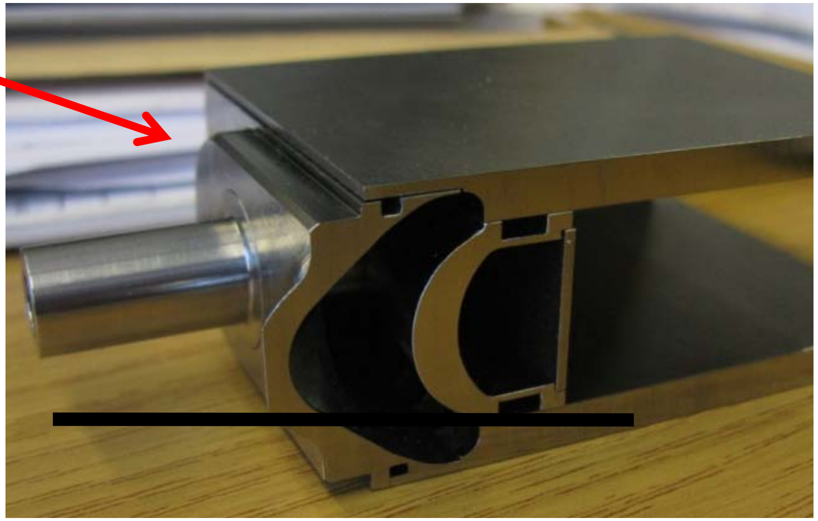
Li_4SiO_4 pebble bed

Be pebble bed

Cooling / stiffening grid

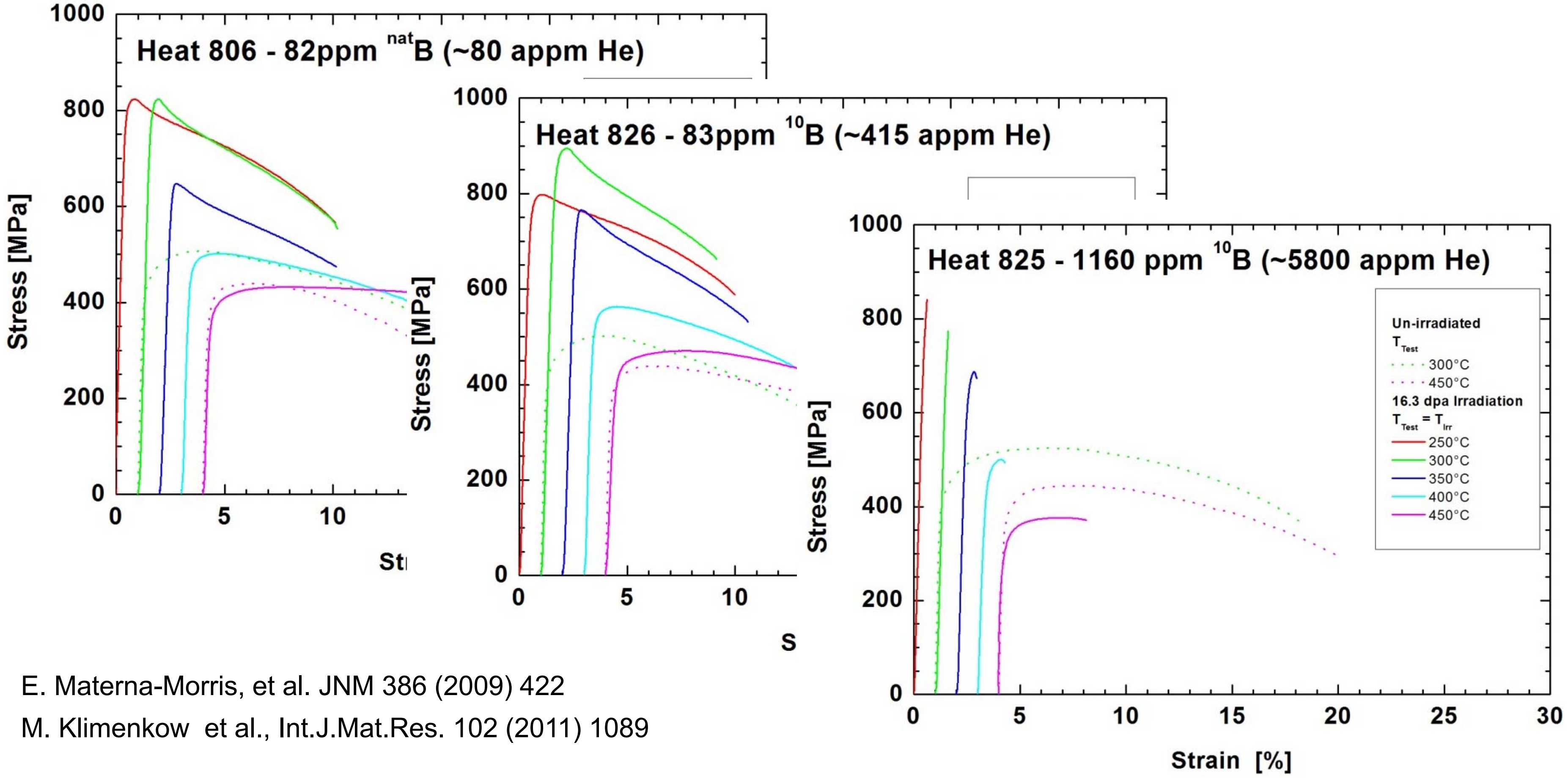
PLASMA





L. Boccaccini et al, KIT, 2014

Helium effect on tensile properties: 16 dpa, B-doped



E. Materna-Morris, et al. JNM 386 (2009) 422

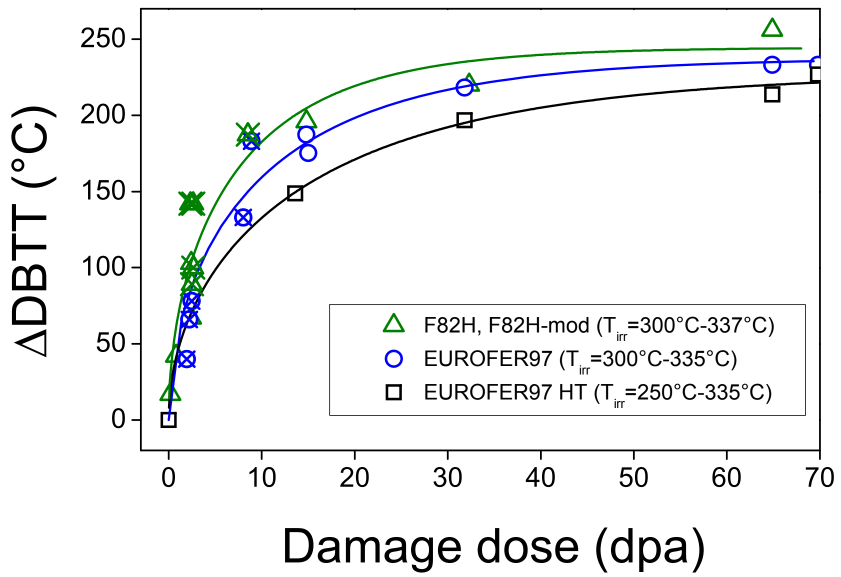
M. Klimenkow et al., Int.J.Mat.Res. 102 (2011) 1089

- 415 appm He: Strength increase but hardly reduction of total elongation
- 5800 appm He: Entirely brittle fracture; total loss of plasticity
- What is the behavior under **real** fusion condition?

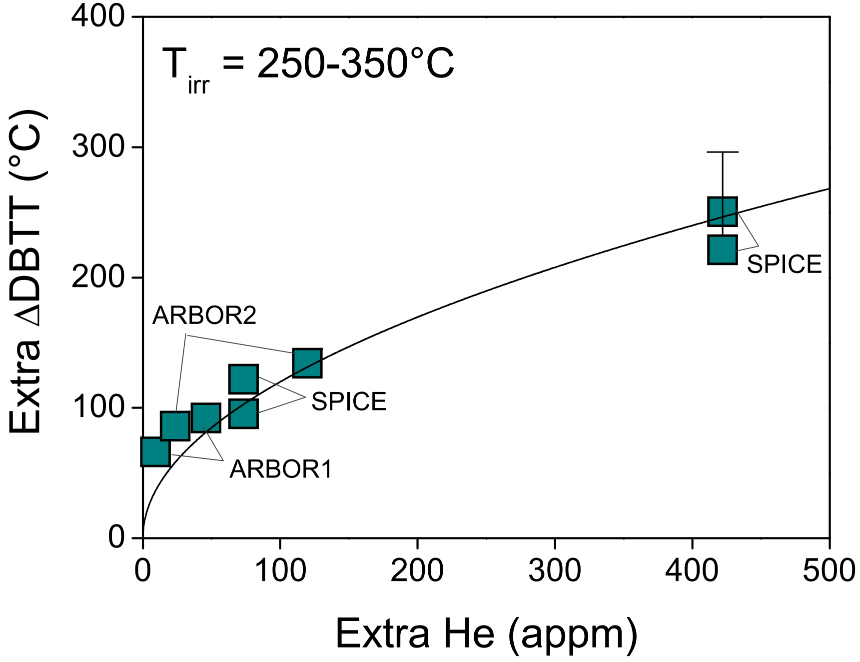
“Helium” effect on Ductile Brittle Transition: Neutron irradiation after B-doping

E. Gaganidze et al.; J. Nucl. Mater. 411 (2011) 417 93–98

EUROFER, <10 appm He



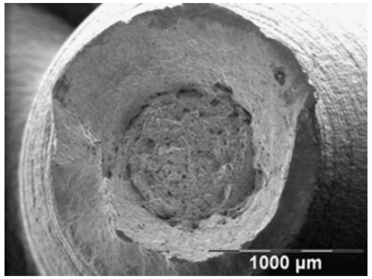
EUROFER, 10-500 appm He

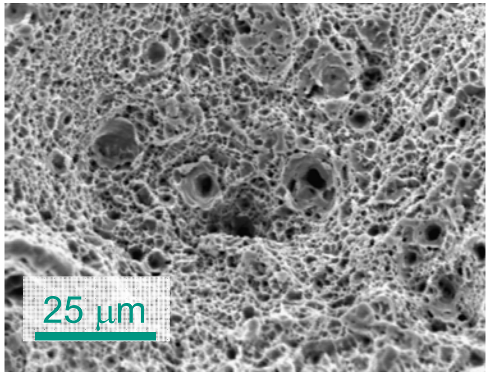


- Helium increases substantially the DBTT and consequently the lower operation temperature in breeder blankets. **Saturation ??**
- B-doping too aggressive
- Embrittlement behavior depends also sensitively on stain rate

Fracture behavior of tensile tested EUROFER
16 dpa, $T_{irr} = T_{test} = 300$ °C

EUROFER97, <10 appm He



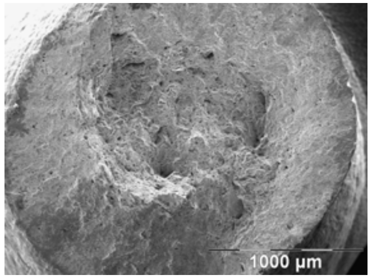


E. Materna-Morris et al., JNM 386-388 (2009) 422-425

M. Klimenkov et al., Micron 46 (2013) 51–56

- ^{10}B-doping: He and Li effects cannot really be decoupled

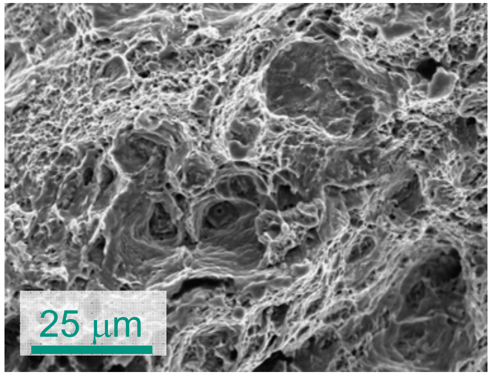
EUROFER-type, 415 appm He

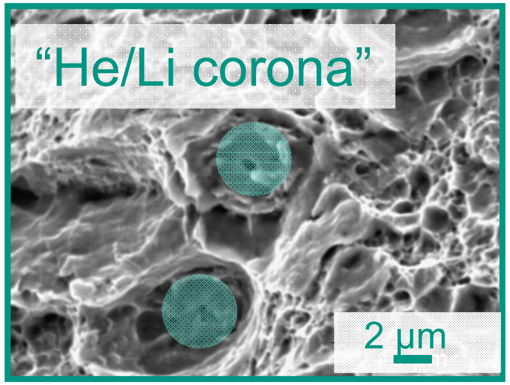


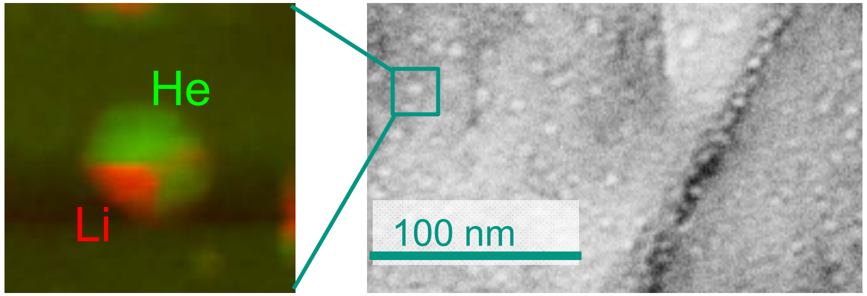
$n + {}^{10}B \rightarrow {}^{4}He + {}^{7}Li + 2.7895$ MeV

range of He (1.0 MeV): 1.6 µm

range of Li (1.8 MeV): 2.0 µm

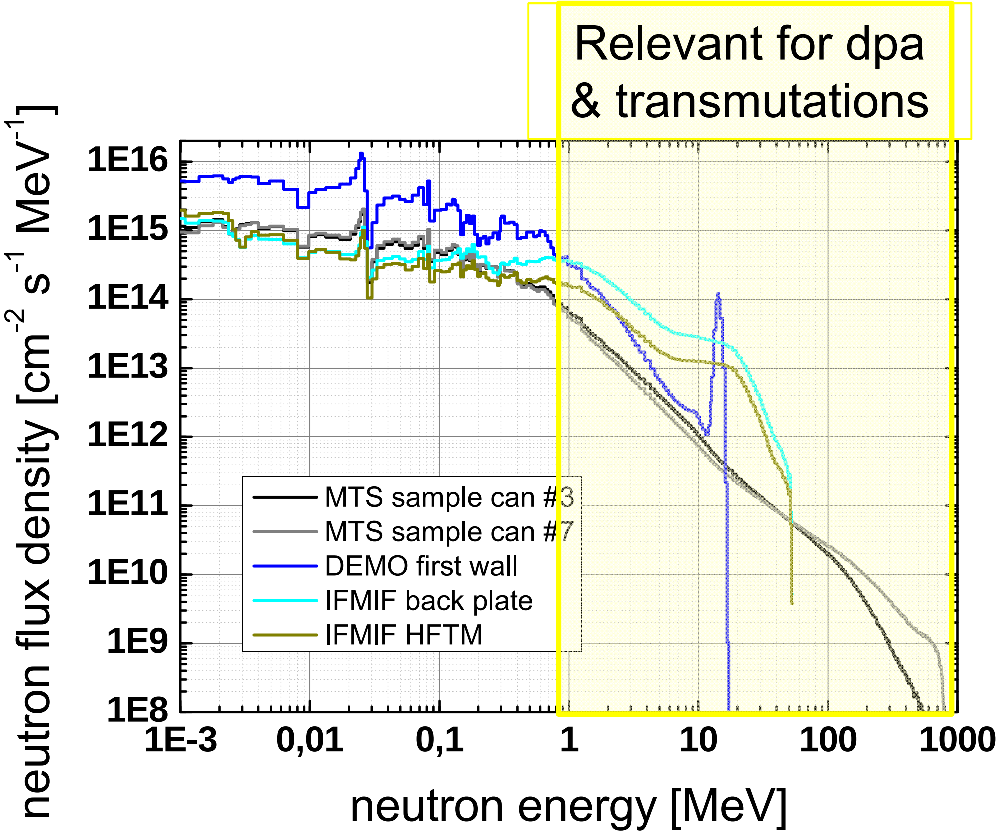






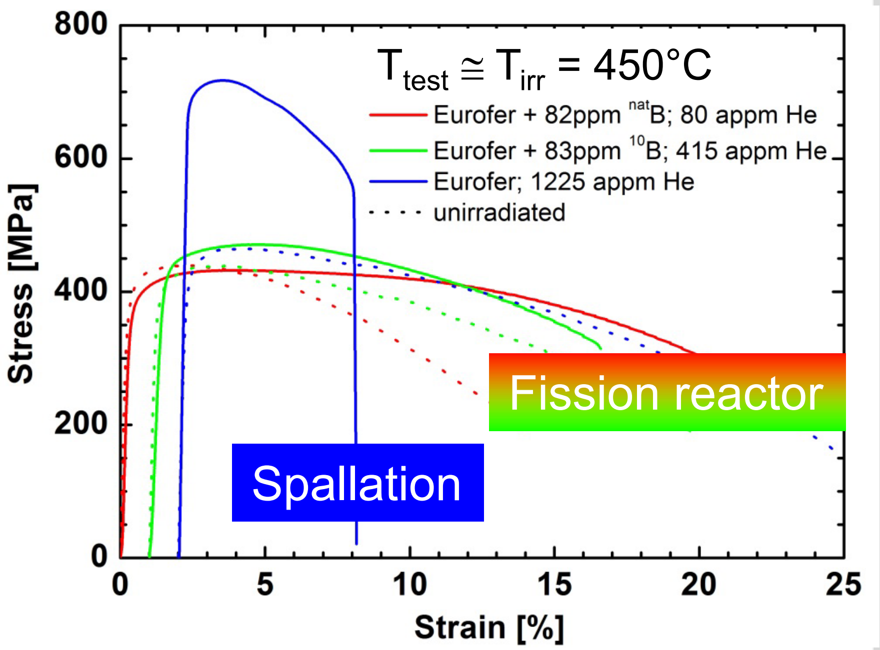
Neutron spectra effects: Tensile properties

N-spectra: DEMO, IFMIF, Spallation



Fission vs. Spallation (PSI)

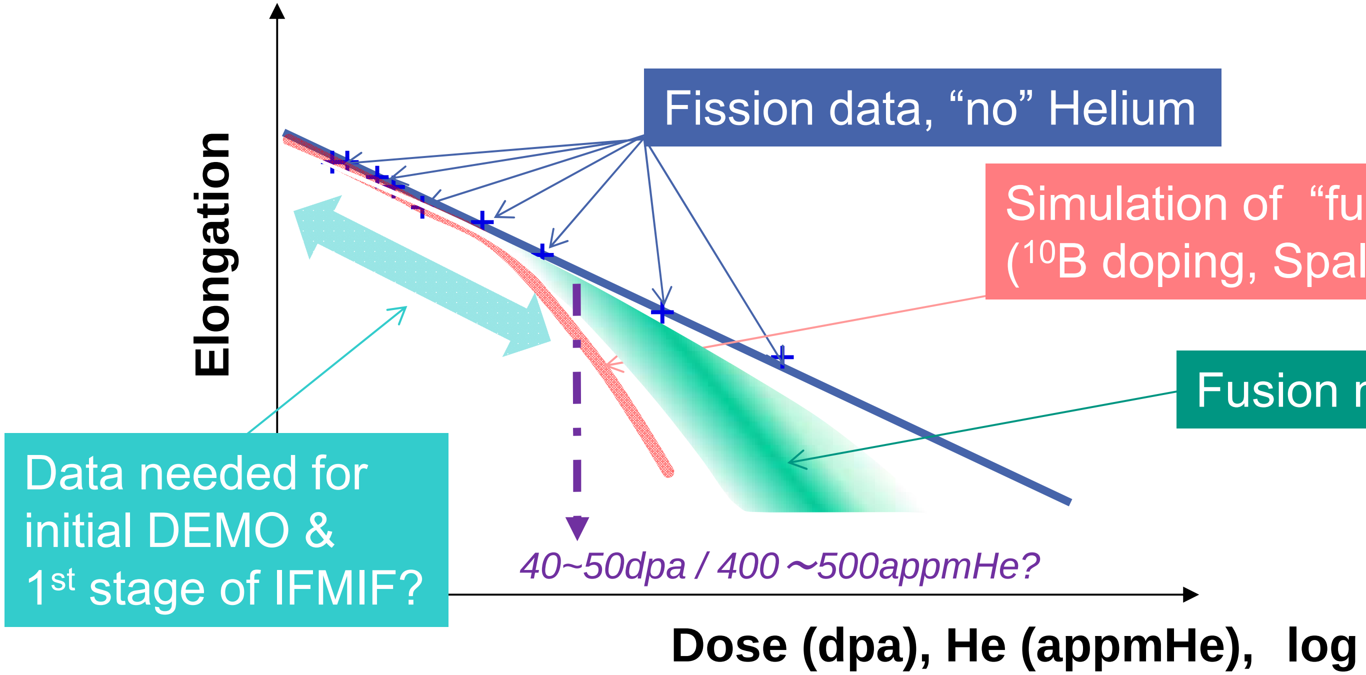
Y. Dai et al, He-dpa workshop, June 2009, PSI



- Spallation irradiation shows above $T_{irr} \cong 400°C$ much higher strength $\Delta\sigma_{irr}$
- What is the real fusion behavior? Intense N-source would answer this question

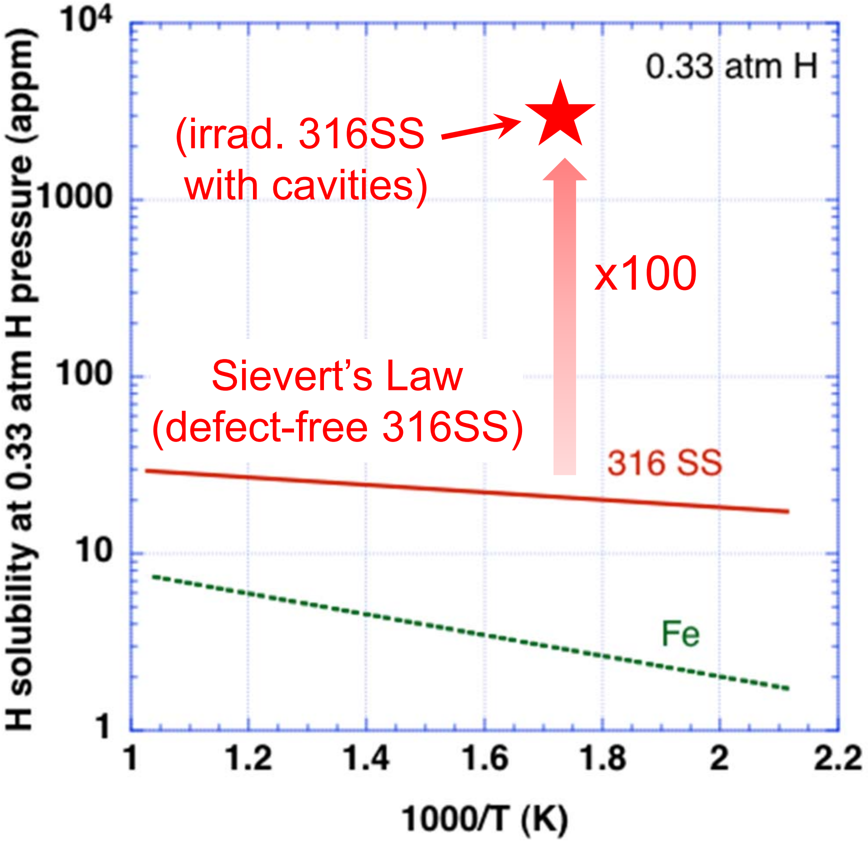
Possible steps towards a fusion design code: Tensile properties as example

In the style of H. Tanigawa, E.Wakai



- Critical condition around 40~50 dpa / 400~500 appm He?
- This might be also the parameter window for initial DEMO and 1st stage of IFMIF and related design code development

Hydrogen effects:
Retention of hydrogen in Fe and austenitic Steel 316

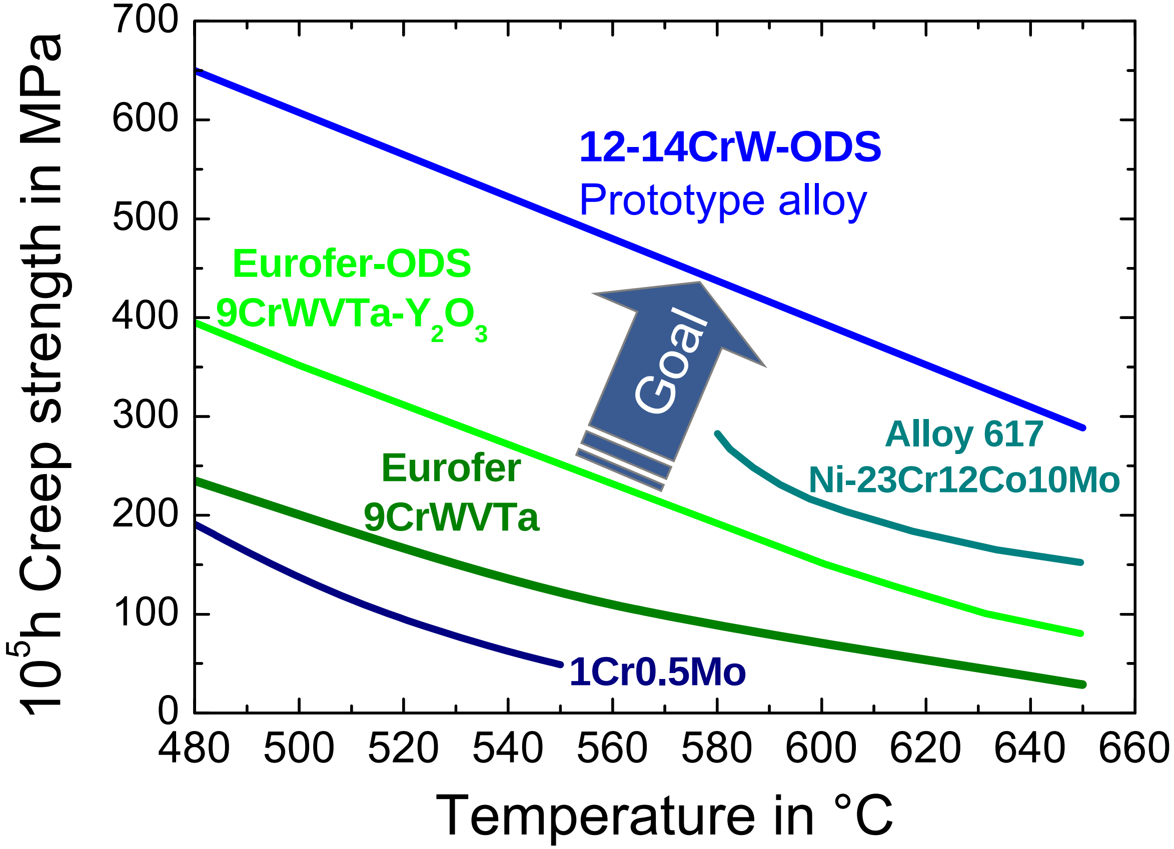


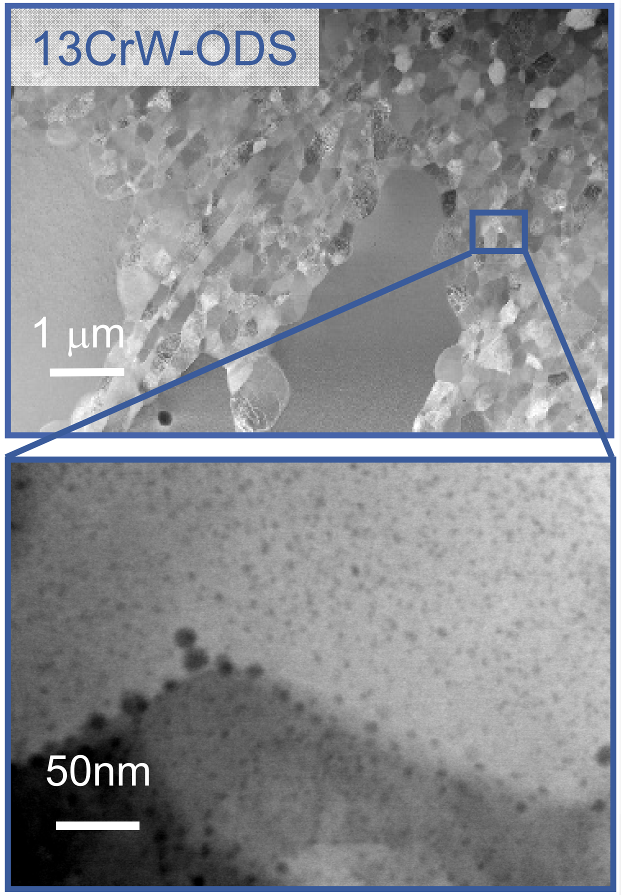
F.A. Garner; J. Nucl. Mater. **356** (2006) 122-135

S. Zinkle et al.; Nuclear Fusion **53** (2013), in press

- Hydrogen effects may become a serious issue in fusion environments
- Typical for 14 MeV fusion neutrons is the simultaneous production of dpa, hydrogen and Helium → Intense fusion neutron source indispensable for realistic validation

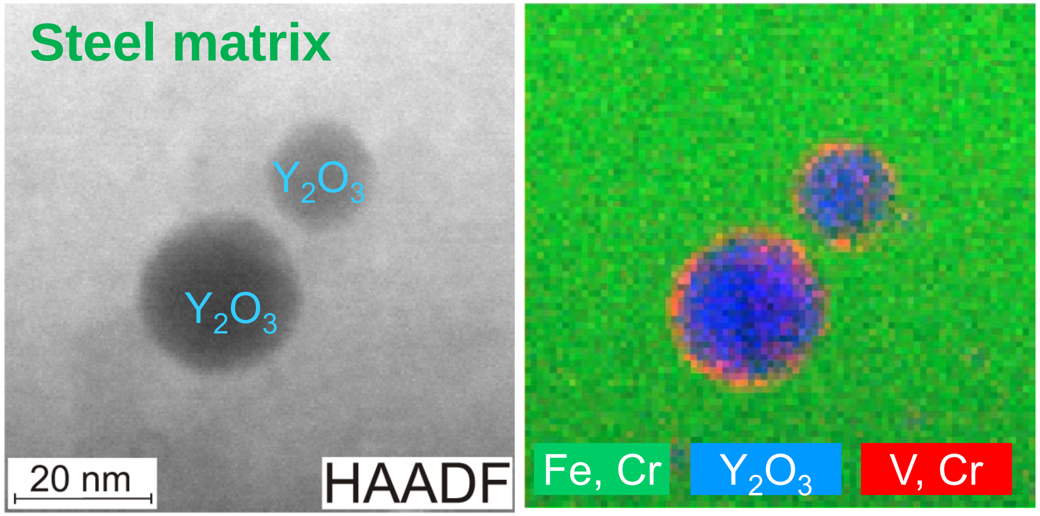
International challenge: Development of nanoscaled iron based “super alloys” (RAF-ODS)





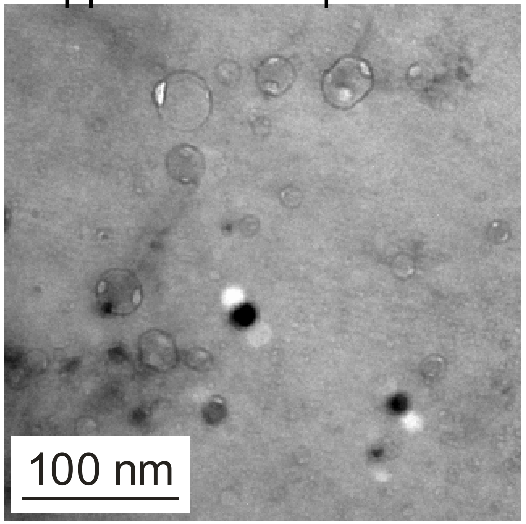
E. Eiselt, M. Klimenkov, R. Lindau, A. Möslang
J. Nucl. Mater 2010

Nanoscaled ODS-steels



P. He, M. Klimenkov et al., J. Nucl. Mater. 428 (2012)131-138

Noble gas bubbles (white) trapped at ODS particles

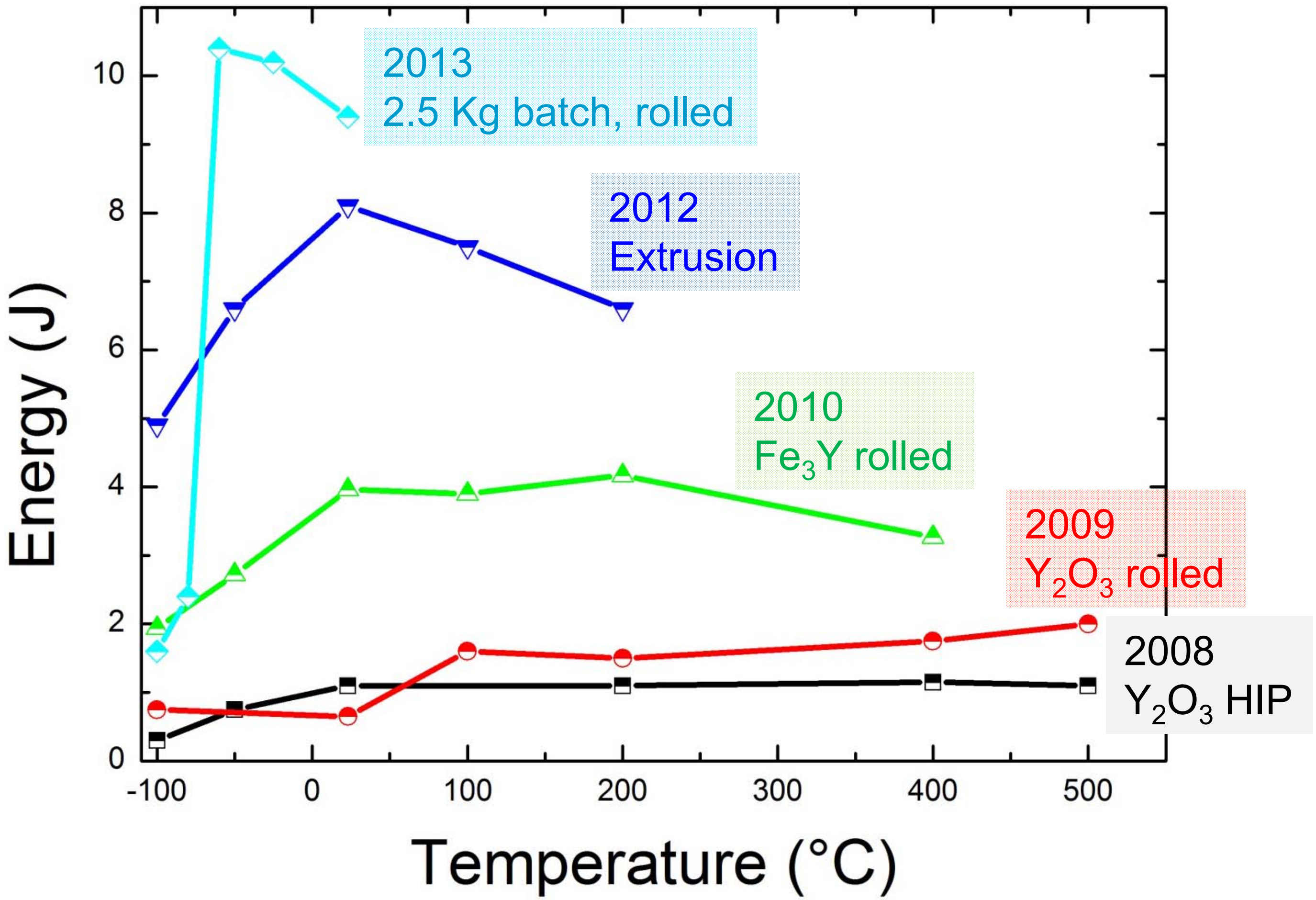


M. Klimenkov J. Nucl. Mater. 411 (2011) 160

- Nano-scaled ODS particles like Y_2O_3 or $Y_2Ti_2O_7$ are efficient trapping centers for diffusing alloying elements (Cr, V) and irradiation induced defects (vacancies, He)
- Therefore, nanoscaled ODS steels have potential for outstanding aging and irradiation resistance

Nanoscaled ODS-steels:

Substantial improvement of dynamic fracture toughness

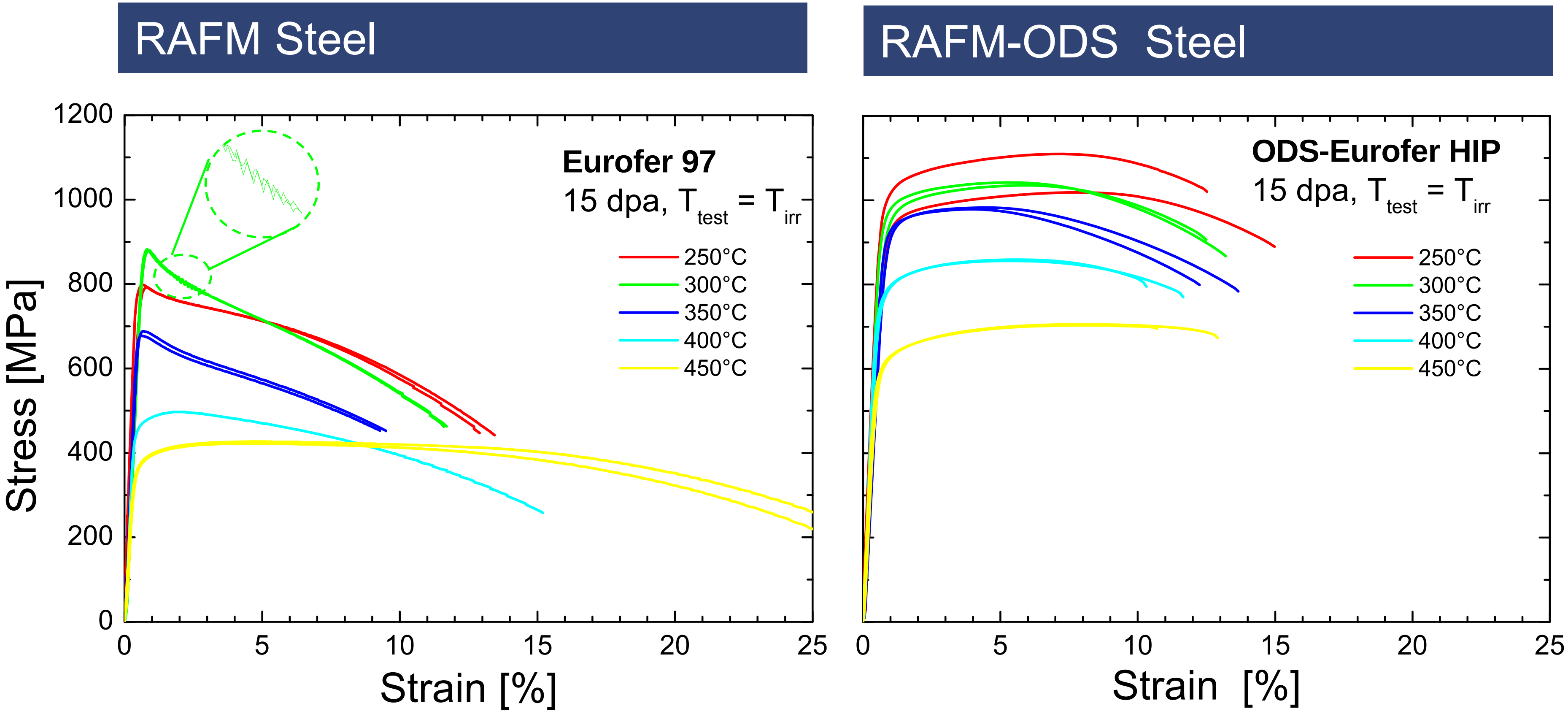


J. Hoffmann et al, KIT, 2014

ODS EUROFER after Neutron irradiation:

Substantial improvement of tensile properties

A. Moeslang et al., Int. J. Mat. Res. 99 (2008) 10



- Substantial irradiation hardening
- Early strain localization due to dislocation channeling → A_u ~0.3%

- Still work hardening → almost no loss of uniform elongation (A_u ~7%)

9Cr ODS steel fuel pins:
Production in Japan, irradiation in FBR BOR60, Russia

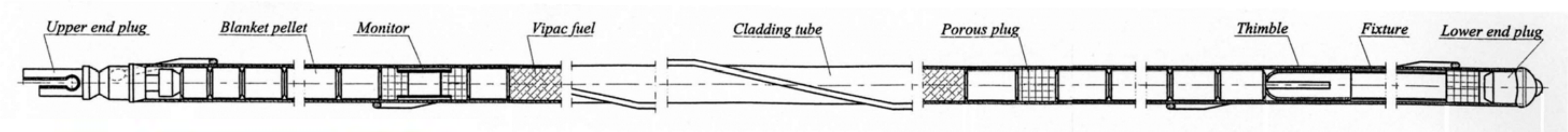
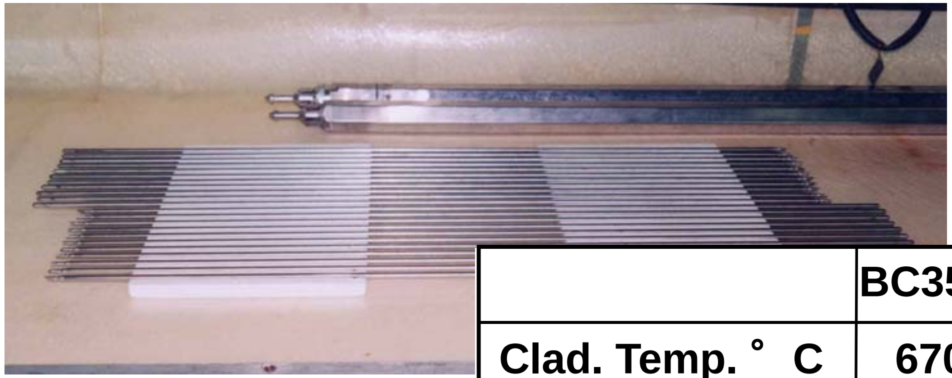


Fig. 12 Appearance of fabricated ODS fuel assemblies (BC358E and BC359E)



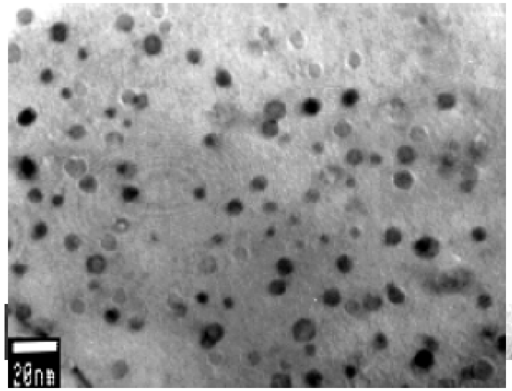
	BC358	BC359
Clad. Temp. ° C	670	720
Burnup at%	15	
Dose dpa	75	

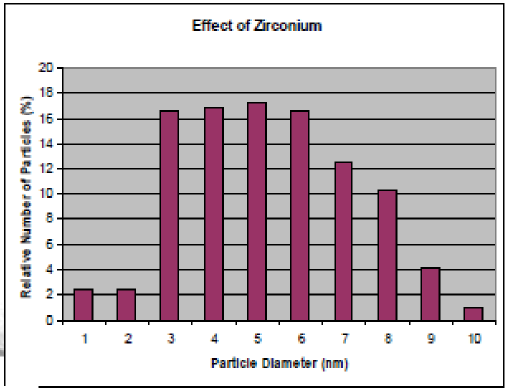
S. Ukai et al., Hokkaido University, Japan

High temperature ODS steel with Aluminum: Improved strength by size reduction of ODS particles

Oxide particles in Al-ODSS
Ave. Diameter: 7 nm
Density: 1.6×10^{22} m^{-3}

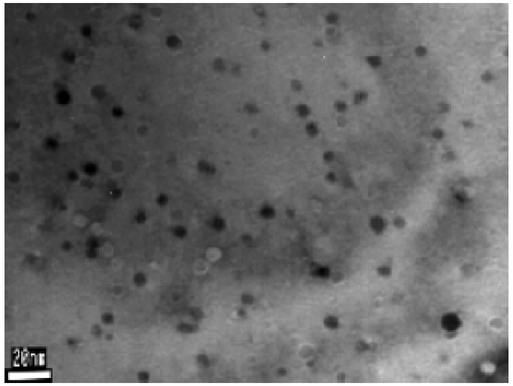
Zr or Hf addition resulted in fine oxide dispersion.

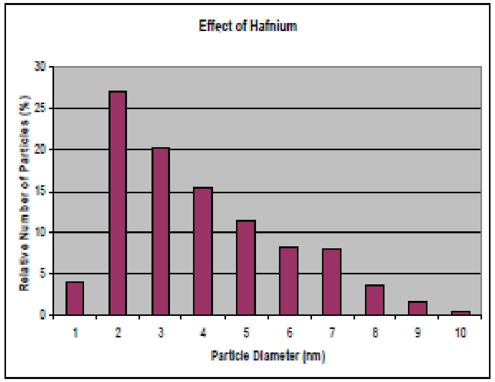




Zr addition

Ave. diameter: 4.7 nm
Density: 7.2 × 10^{22} m^{-3}



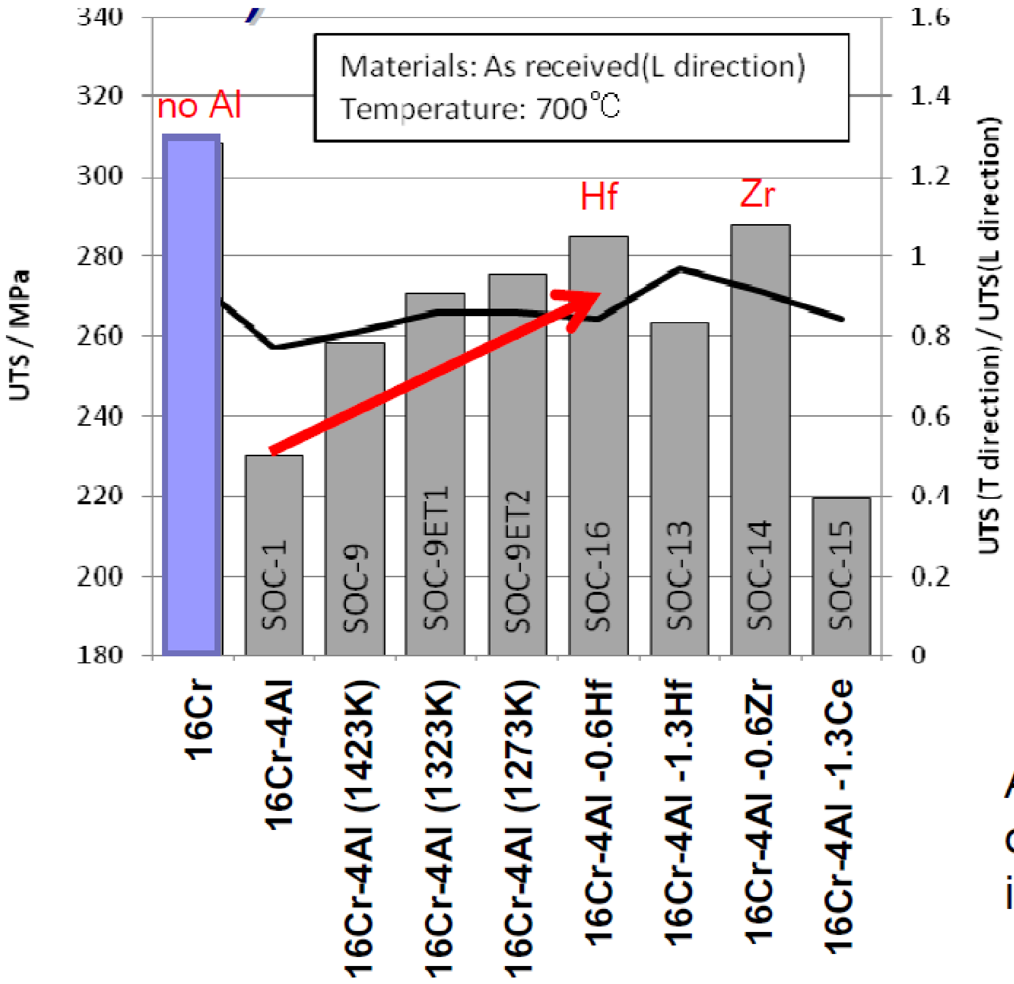


Hf addition

Ave. diameter: 3.5 nm
Density: 4.8×10^{22} m^{-3}

A. Kimura, Kyoto Univ,

High temperature corrosion resistance: Ad Aluminum to the ODS steels



Al addition reduces the strength of ODSS at 973K.

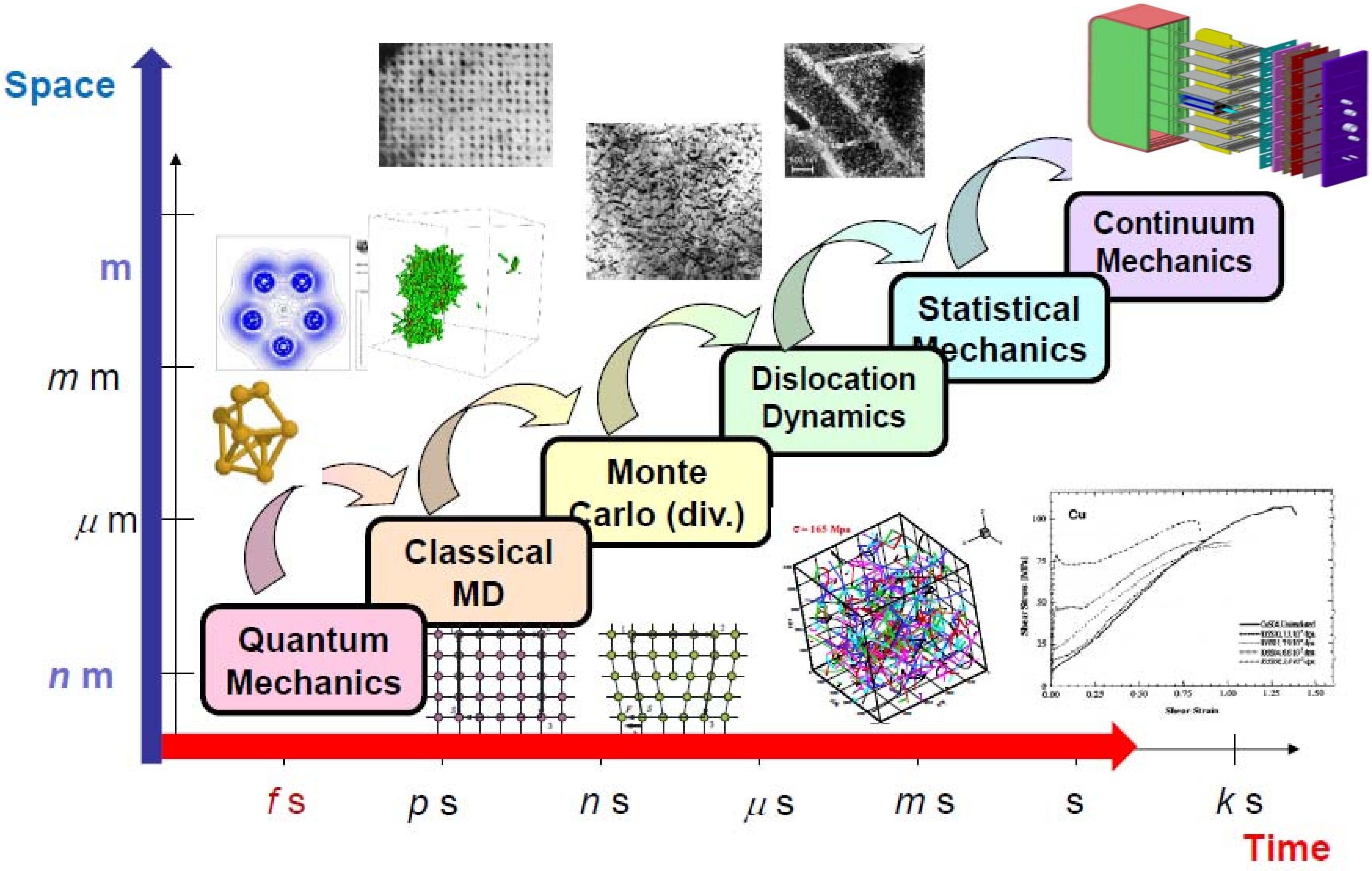
Strengthening of Al-ODSS

1)Processing
-> Extrusion temp.
2)3rd alloying
-> Hf, Ce, Zr

Additions of a small amount of Zr and Hf is effective to increase the strength.

A. Kimura, Kyoto Univ

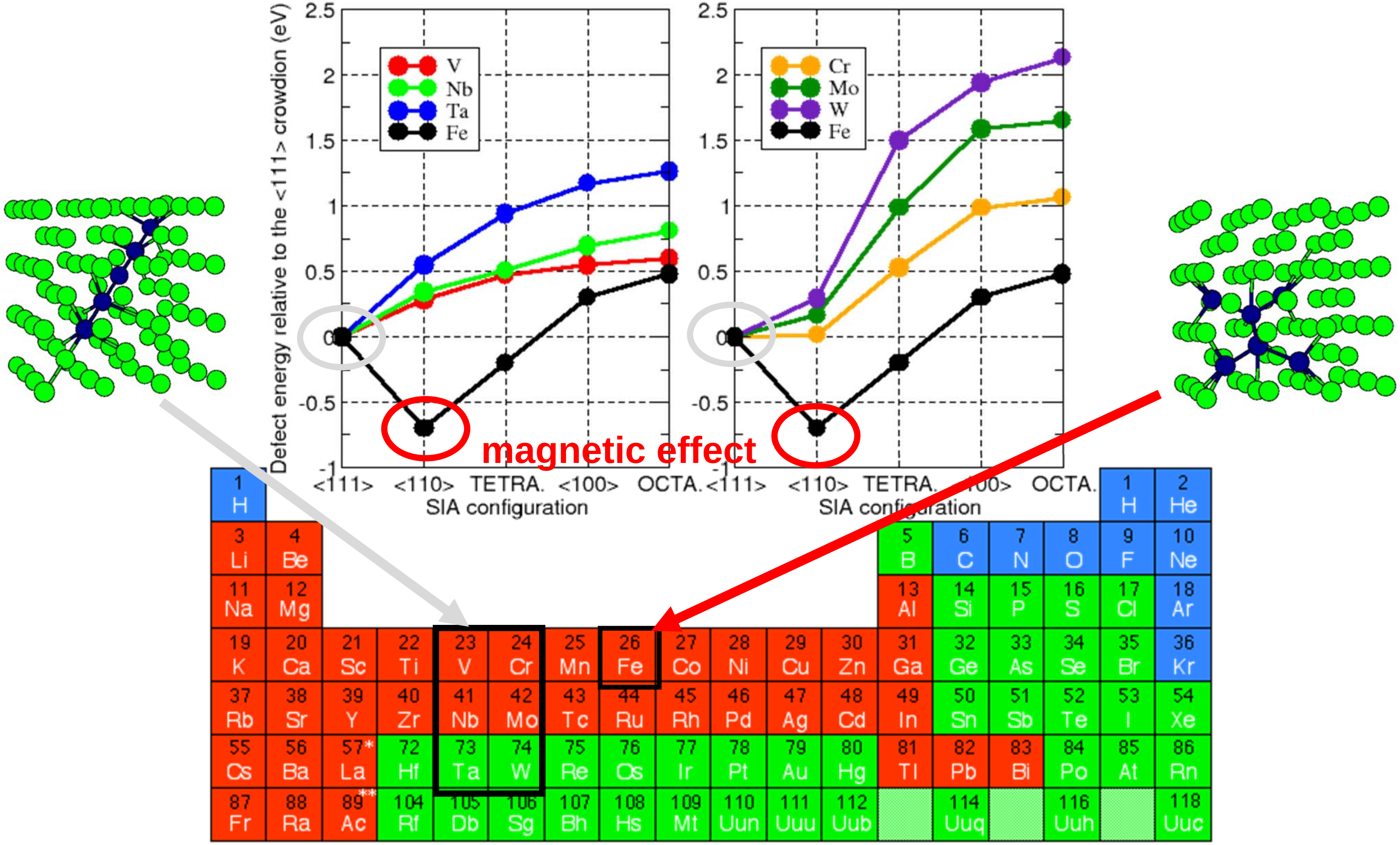
Multi-scale modeling strategy



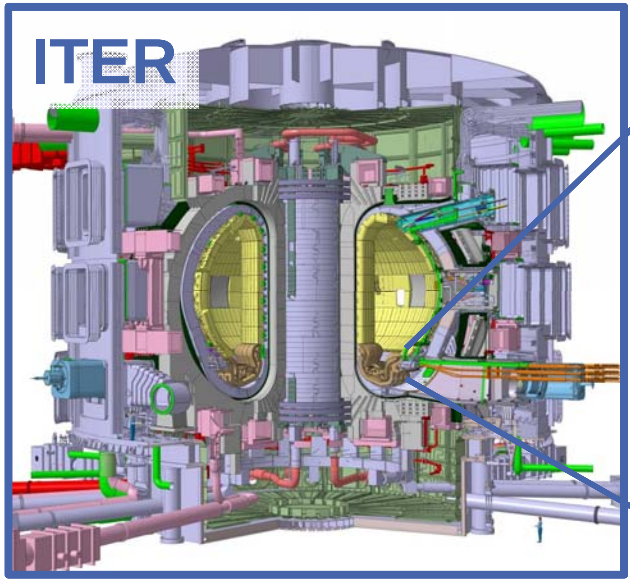
- Quantum Mechanics
- Classical MD
- Monte Carlo (div.)
- Dislocation Dynamics
- Statistical Mechanics
- Continuum Mechanics

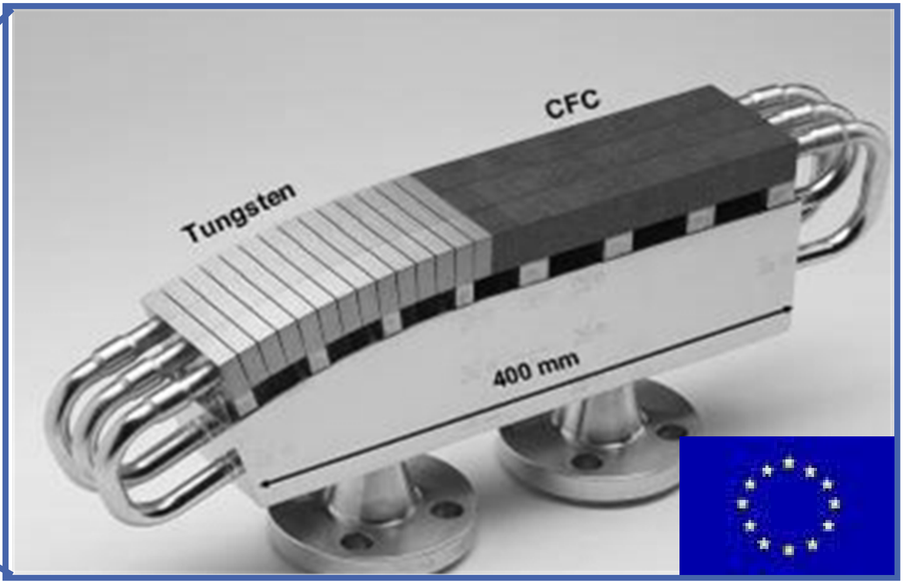
Defects in bcc metals: are they 111 or 110?

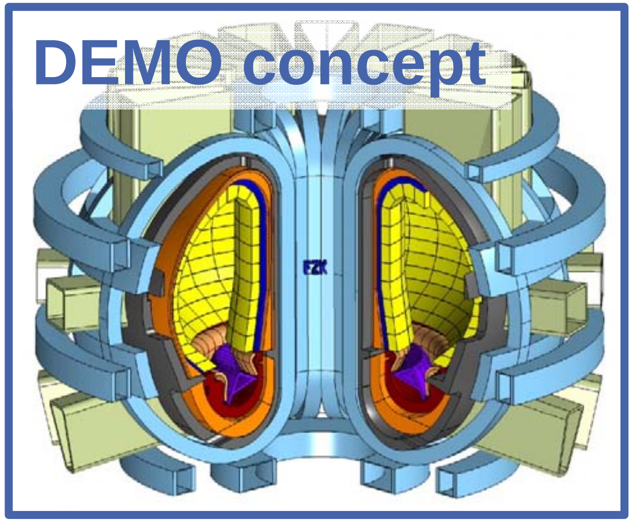
D. Nguyen-Manh et al.; PHYSICAL REVIEW B **73**, 020101R 2006



Materials challenge: Divertor, ~10MW/m^2



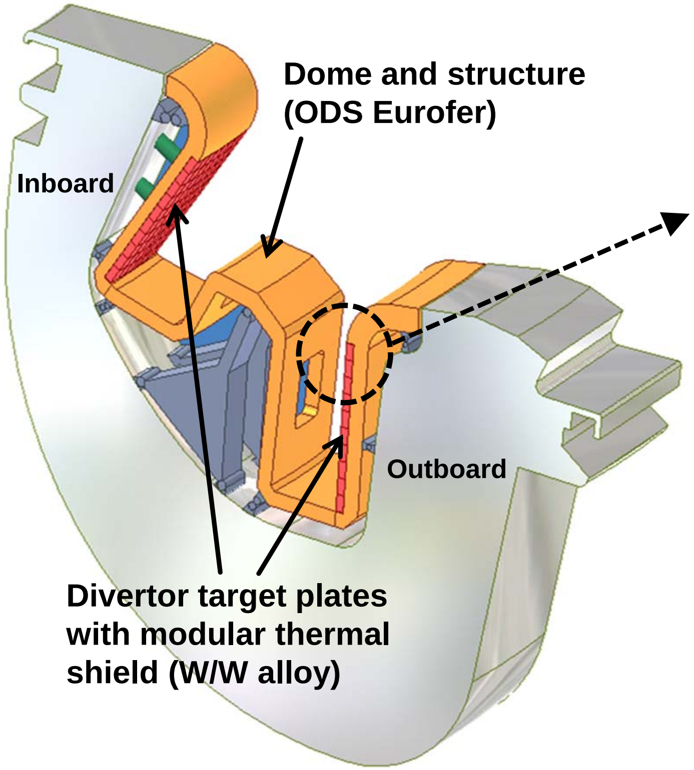




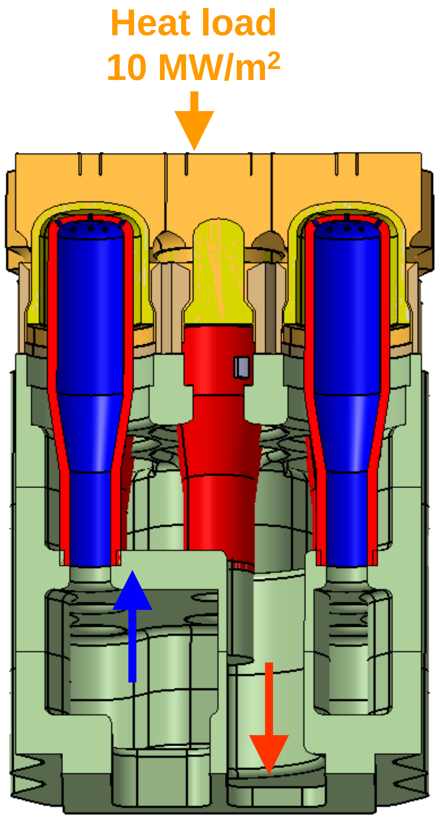
Requirements:

- W products for structural parts
- p ≅ 100 bar
- T ≅ 500°C – 1300°C

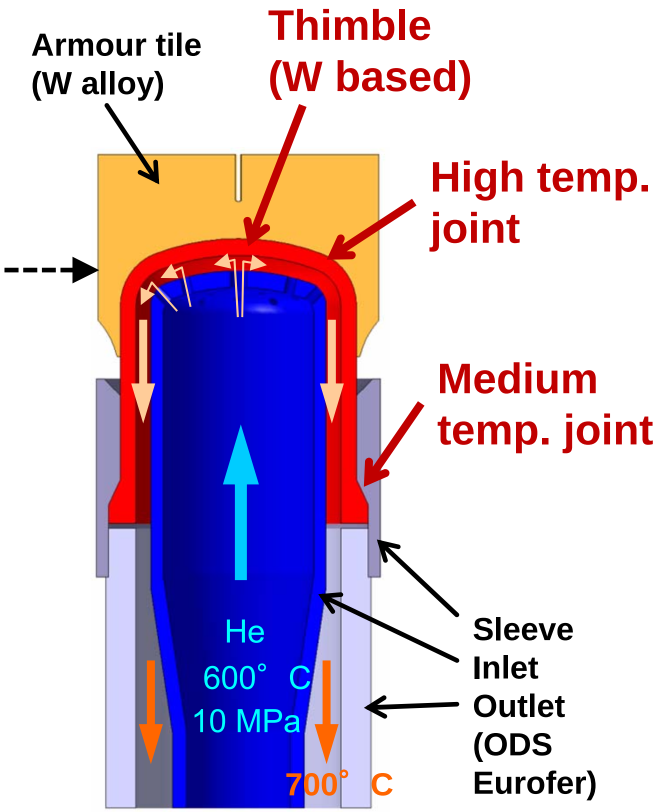
Divertor concept fro DEMO reactor:
Helium gas cooled, modular “finger” design



Divertor cassette

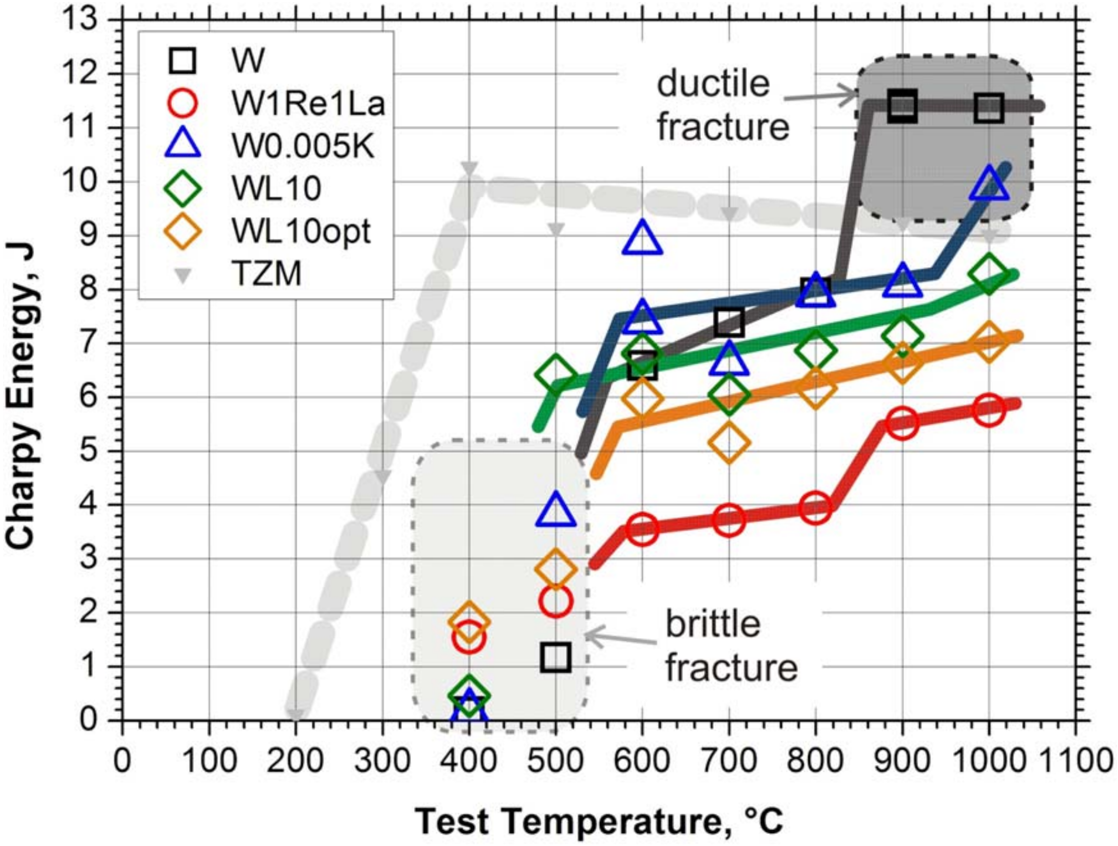


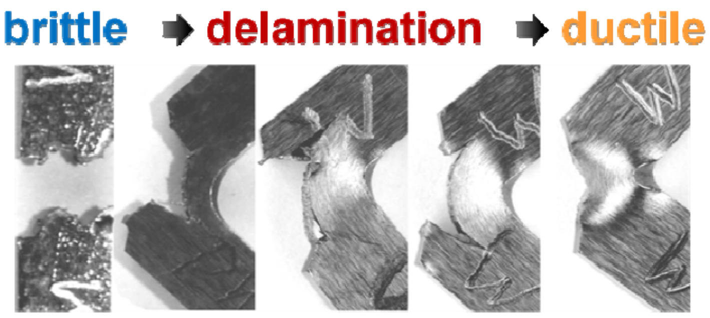
9-Finger module

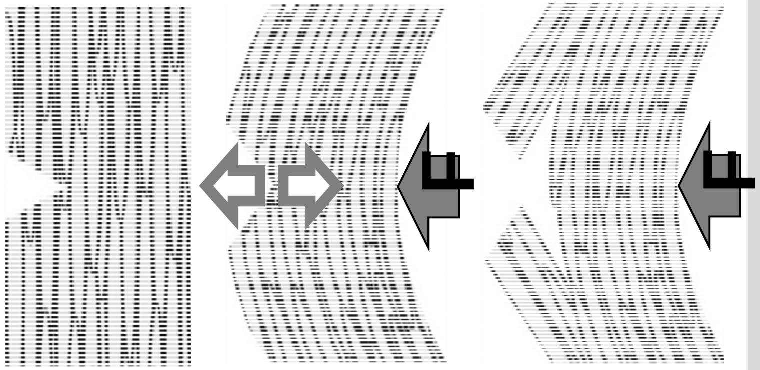


1-Finger module

Problem of W & W alloys: Fracture at „low“ Temp.

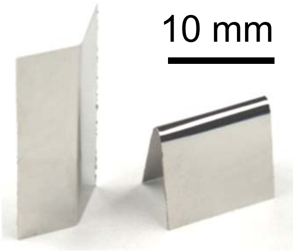






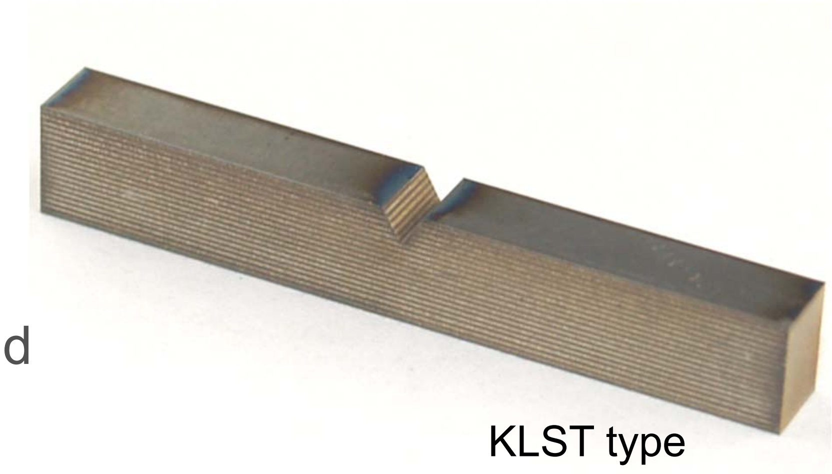
M. Rieth, A. Hoffmann, Adv. Mater. Res. **59**, 101 (2009)

Are ductile tungsten products possible at all?



- **Strategies to improve ductility**
  - Thin foils (0.1 mm) are ductile, plates (> 0.5 mm) not
  - Allow movement of dislocations
    - edge disl. (0.3 eV),
    - screw disl. (1.05 eV)
  - Allow disl. annihilation (foil effect)
  - Increase mobile edge dislocations

- **Suggested Solution: W-laminates**
  - Stack of alternating W (20 layers) and e.g. Cu (19 layers)
  - Brazing or diffusion welding
  - Sample fabrication and Charpy impact testing

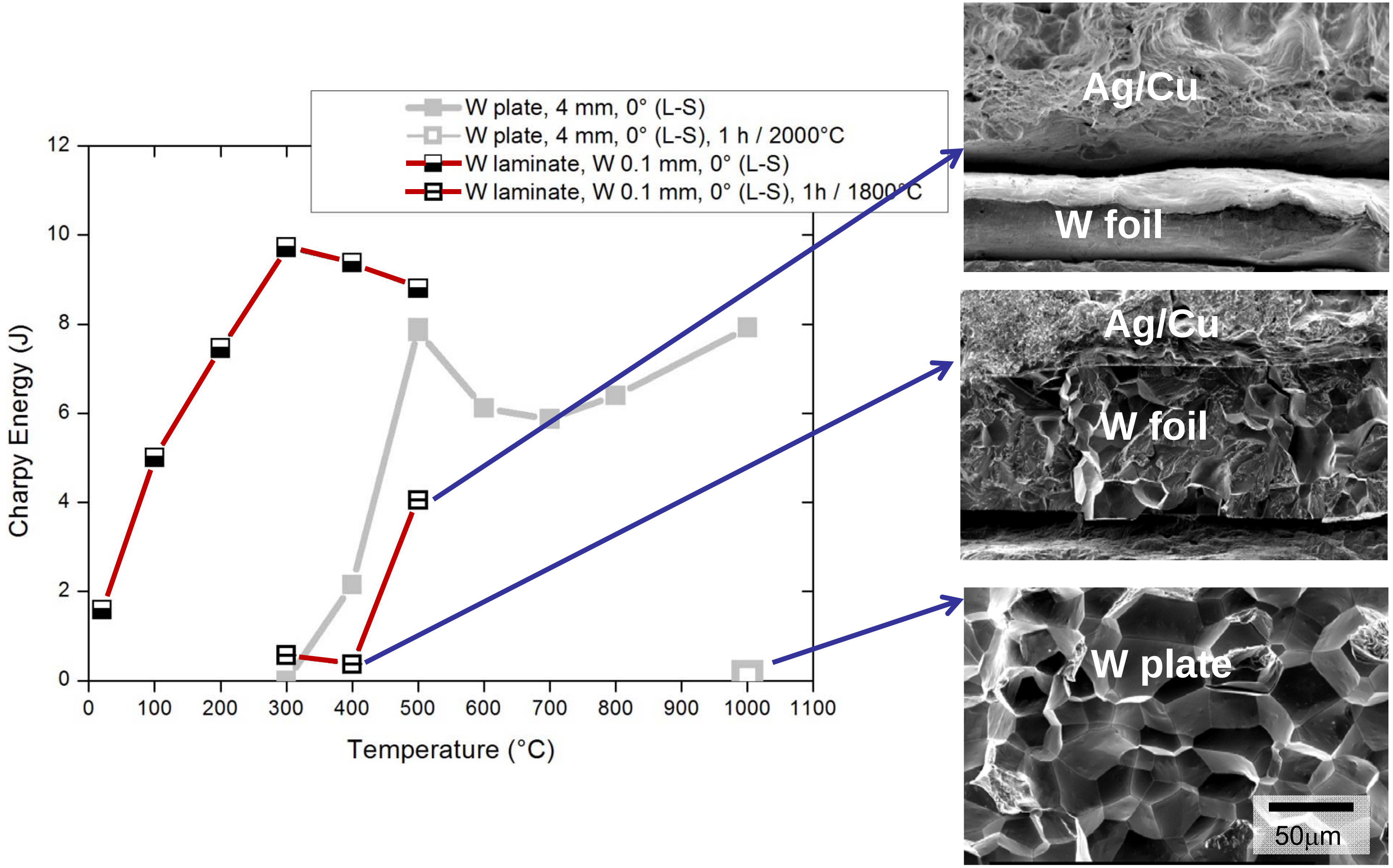


KLST type
$3 \times 4 \times 27$ mm^3

J. Reiser et al, J. Nucl. Mater 424 (2012)197-203

Refractory materials: W laminates

Very promising results of Charpy impact tests

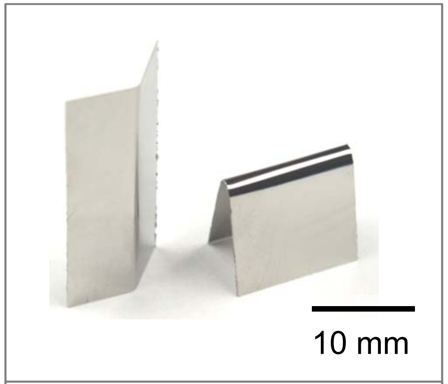


J. Reiser et al, J. Nucl. Mater 424 (2012)197-203

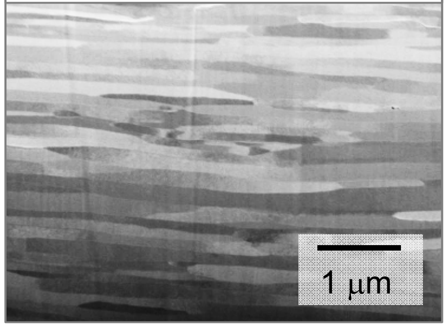
W as structural material: W-foil laminates

J. Reiser et al, KIT, 2014

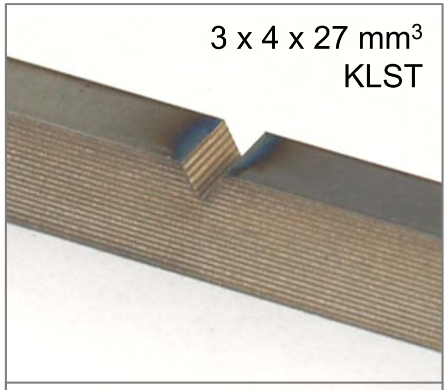
W-foil



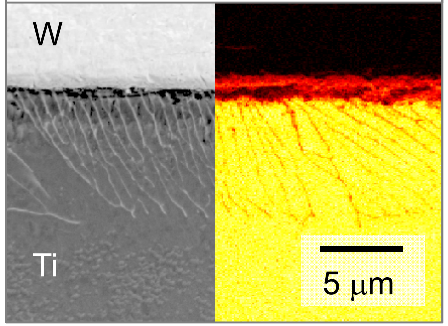
- Metal physics



W laminate plate

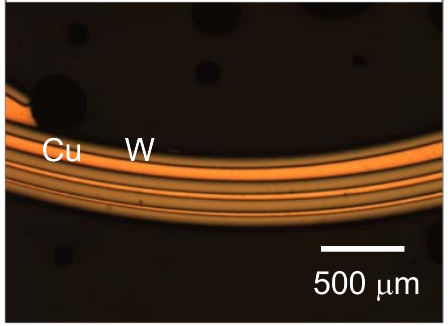

3 x 4 x 27 mm^3
KLST

- Bonding and ageing

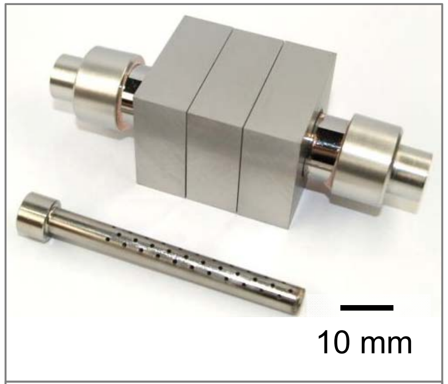


W laminate pipe

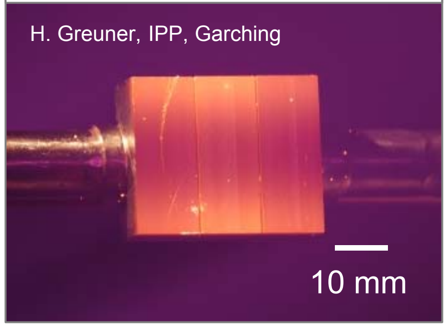
- Joining technology



Applications



- Fabrication and testing


H. Greuner, IPP, Garching

Irradiation effects: Materials Database Maturity

	FNSF, CTF 1st DEMO Blanket						2nd DEMO Blanket						Adv. DEMO						
Data base need	<20 dpa/200appm He						~50 dpa/500appm He						>100 dpa/1000appm He						
Materials	RAFM	FM-ODS	W	SiC	Be	Li ceramic	RAFM	FM-ODS	W	SiC	Be	Li ceramic	RAFM	FM-ODS	W	SiC	Be	Li ceramic	RAFM
Irradiation effects																			
Hardening/Embrittlement	🟩	🟨	🟥	🟨	🟨	🟥	🟨	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Phase stabilities	🟩	🟨	🟥	🟨	🟨	🟨	🟨	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
creep & fatigue	🟩	🟨	🟥	🟨	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Volumetric swelling	🟩	🟨	🟥	🟨	🟩	🟨	🟨	🟥	🟥	🟨	🟨	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥
High Temp He&H effects	🟨	🟥	🟥	🟥	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

🟩 Adequate knowledge base exists
🟨 Partial knowledge base exists
🟥 No knowledge base

Note: He levels are only for FM steels

Strategy element to close knowledge gaps: Integrated materials qualification in Europe

Advanced steels
- RAFM technology completion
- TMT steels
- ODS steels

High heat flux materials
- Refractories (e.g. armour)
- Joining & fabrication techn.
- Composites
- Mock-up testing

Functional Materials
- Neutron multipl. (Be alloys)
- T-breeders (Li ceramics)
- Sensors, actors, fibers
- Dielectrics, windows

Materials database, codes and standards

Irradiation campaigns
- Near term DEMO
- Advanced DEMO
- Promising novel materials
- Exp. validation of modeling

Radiation effects modeling & experimental validation
- Understand irrad. embrittlem.
- Accelerate materials R&D
- Support SSTT qualification
- Guide irradiation test matrix

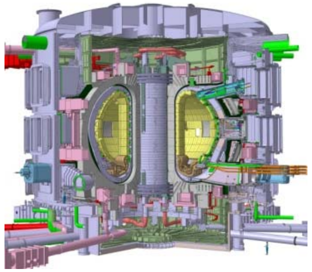
Outline

- Short introduction to Fusion
- International roadmaps to fusion power
- Materials challenges: fusion – fission – spallation
- Materials R&D: examples of recent progress
  - Reduced activation steels and iron based “super alloys”
  - Neutron irradiation behaviour
  - Tungsten alloys and composites
- Irradiation facilities & intense fusion neutron source IFMIF
- Conclusions

“New” Roadmaps to fusion power:

Pathway considerations for materials database – simplified –

ITER,DT-phase
beyond 2027

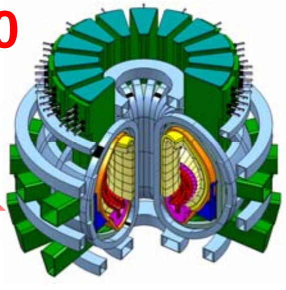


Early DEMOs

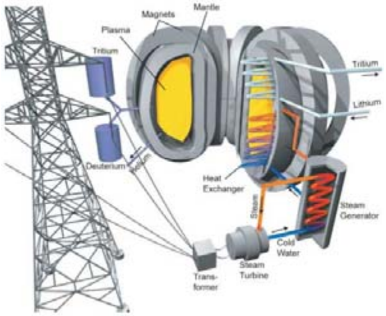
EDA end ♦

♦ Start operat.

~2030



FPP
beyond 2060



Materials Database

D-Li type fusion
n-source

♦ 20 dpa 1st blanket

♦ 50 dpa licensing?

♦ 100 dpa, small volume

preferable option

“Simulation”: Fission reactors, ion implantation, spallation

ongoing

Plasma based n-sources (e.g. FNSF):
≤10 dpa/fpy; 0.1-0.3 duty cycle, start~2030
→ 40 dpa (≥ 15 yrs) not before 2045

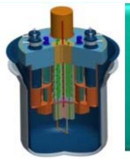
For DEMOs too late

Major available Fission Reactors

	Facility Name, country	Fast neutron > 0.1 MeV [10^{18}/m^2 s]	[dpa/fpy] in Fe	Volume [cm^3]	Temp [°C]
Mixed spectr. Reactors	BR-2, B	1.5-3 <1.0	<3 <1	90 250	50-1000 50-1000
	HFR, NL	2.5	< 7	>1500	80-1100
	HFIR, US	1.1 5.3	< 18 <7	100 700	300-1500
Fast Breeders	BOR-60, Russia	~30 total	~20	350	320-700
	BN-600, Russia	~ 65 total	>20	350	375-700
	JOYO, Japan	> 50 total	~30		300-700
	FBTR Kalpakkam, In	1-10, in 15 campaigns			

Future Large Scale Materials Irradiation Facilities

Being in advanced design or construction phase



Accelerator driven spallation source

MYRRHA/XT-ADS, at MOL 🇧🇪

Accelerator driven D-Li source source

IFMIF, presently bilateral 🇯🇵 🇪🇺

Thermal spectrum reactor

JHR, Cadarache 🇫🇷

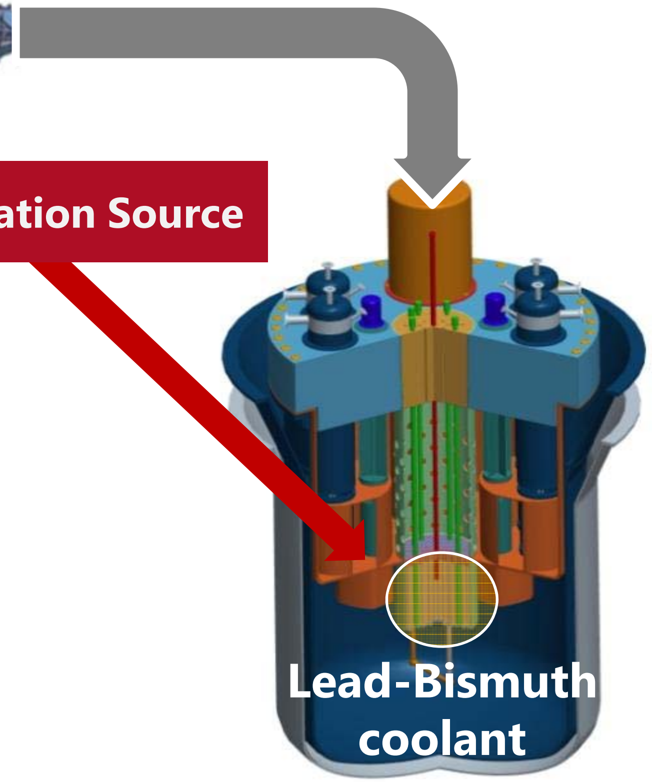
MYRRHA - An Accelerated Driven System

Accelerator

(600 MeV - 4 mA proton)

Reactor

- Subcritical or Critical modes
- 65 to 100 MW_{th}


Spallation Source

Jules Horowitz Reactor, Cadarache, France

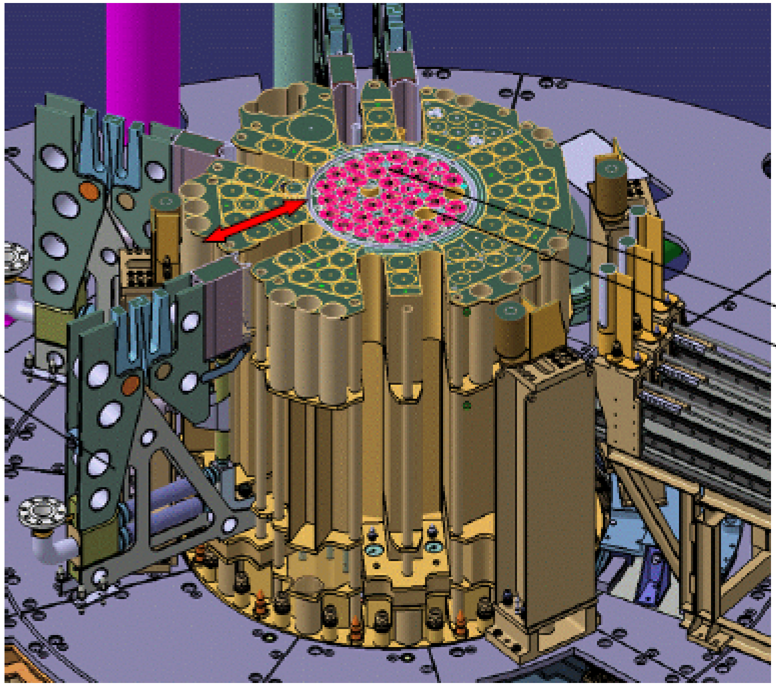
http://www.cad.cea.fr/rjh/index.html

Start operation ~ 2015, instrumented rigs, high flux: ≤16 dpa/y

In reflector

Up to 5.5 10^{14} n/cm^2.s
~20 fixed positions
and 6 displacement systems

Displacement systems:
- Adjust the power
- Study transients

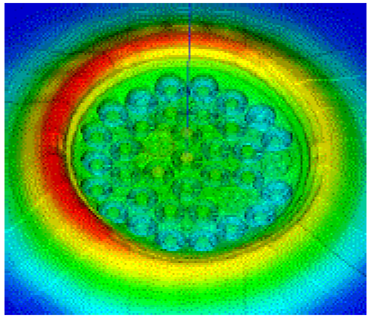


In core

Up to 5.5 10^{14} n/cm^2.s > 1 MeV
Up to 10^{15} n/cm^2.s > 0.1 MeV

7 Small locations

3 large locations

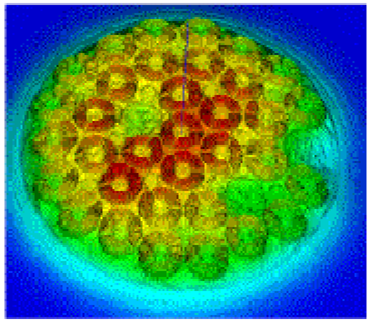


Material ageing
(up to 16 dpa/y)

Thermal neutron flux

Fuel experiment
(fast neutron flux)

Fast neutron flux



Need for Intense Fusion Neutron Source

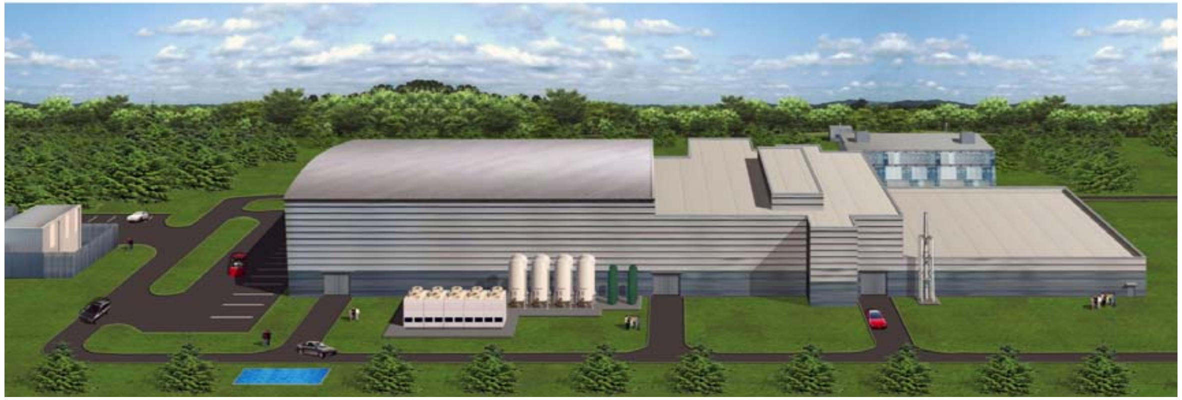
Main Missions

- **Qualification of candidate materials**, in terms of generation of *engineering data* for **design**, **licensing** and **safe operation** of a fusion DEMO reactor, up to about full lifetime
- **Completion, calibration and validation of databases** (today mainly generated from fission reactors and particle accelerators)
- **High performance material irradiation** for fusion power plants (>100 dpa)

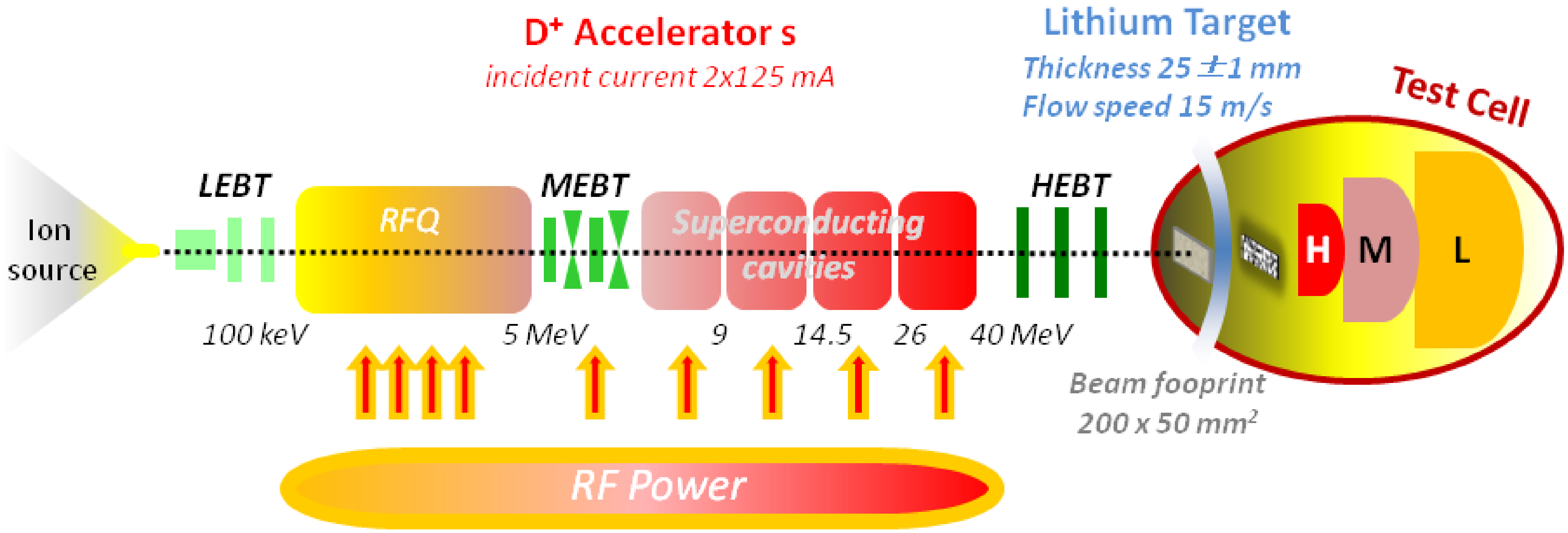
  ➡ Promote, verify or confirm selection processes
- Solid Validation of computational material science

  ➡ Vital for Predictive Capability

High ranking International Advisory Panels:
Can be best fulfilled with a D-Li stripping source.
➡ **IFMIF**



International **F**usion **M**aterials **I**rradiation **F**acility



D^+ Accelerator s

incident current 2x125 mA

Lithium Target

Thickness 25 ±1 mm

Flow speed 15 m/s

Test Cell

Ion source

LEBT

RFQ

MEBT

Superconducting cavities

HEBT

H

M

L

100 keV

5 MeV

9

14.5

26

40 MeV

Beam fooprint

200 x 50 mm^2

RF Power

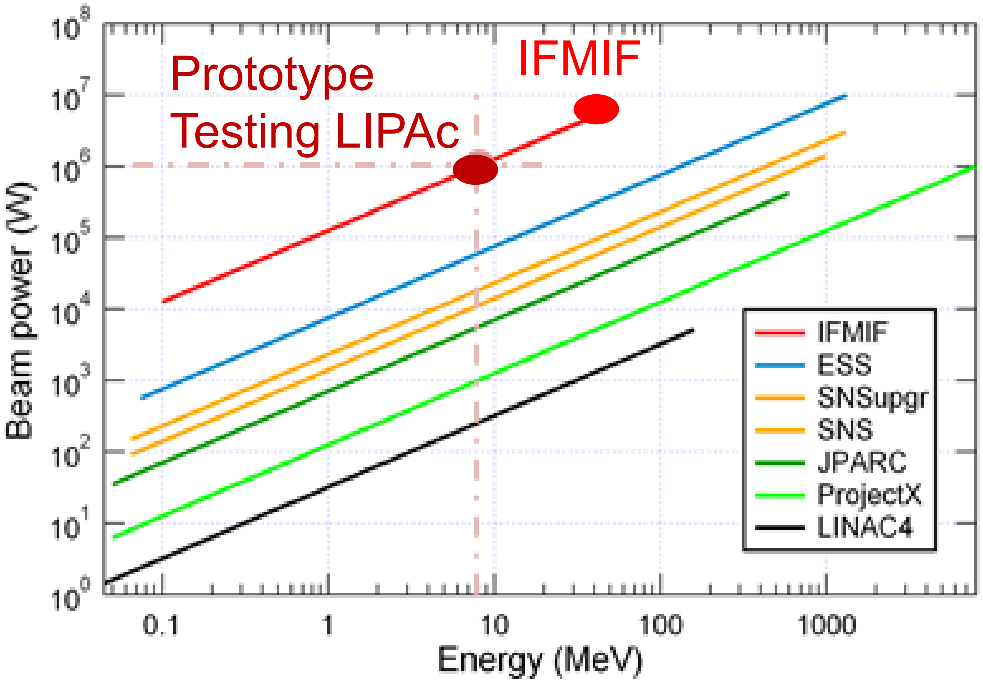
International Fusion Materials Irradiation Facility

Unprecedented accelerator:

- Highest intensity
- Highest beam power
- Highest space charge

consequently

- Highest power Injector
- Longest RFQ

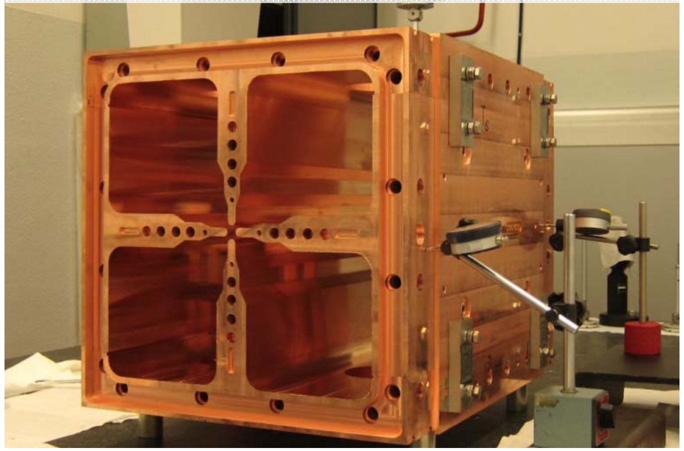


1:1 size prototype fabrication and testing

Injector (CEA), Rokkasho

Li-loop, Oarai

RFQ Module, INFN, Italy



He-gas loop, KIT

Conclusions

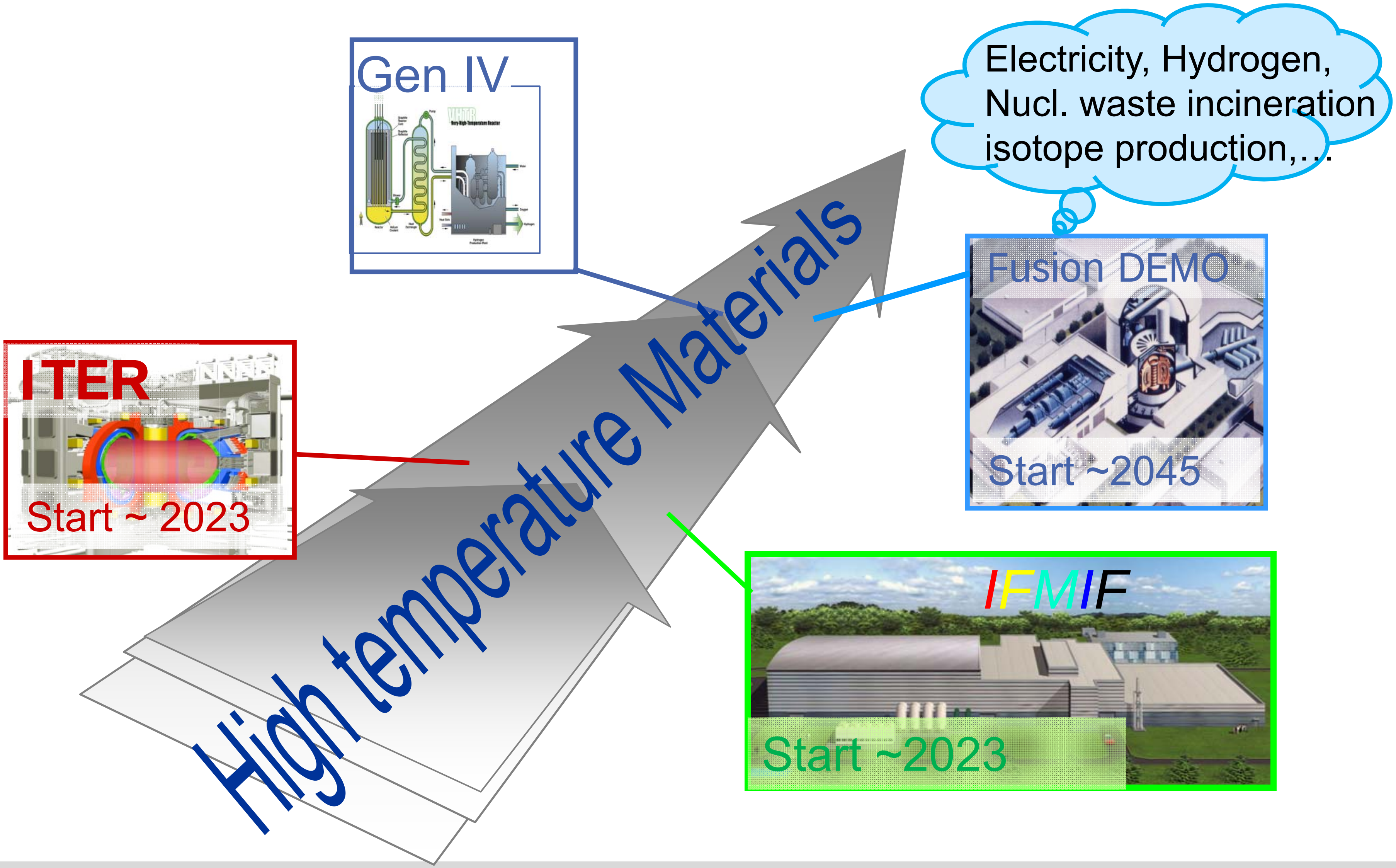
- **The European Integrated Fusion Program aims at fully qualified materials ("Horizon 2020")**
  - Materials must be tested in a fusion neutron environment (e.g. IFMIF, ~40 dpa by 2030) to enable licensing and safety.
  - Materials science assisted development
  - Code qualified materials database within two decades

- The **integrated Fusion Materials** Program is based on
  - **More than 20 Associations** coordinated by EUROFUSION and F4E with support from Universities and industry, and
  - **International collaboration** (ITER, Broader Approach, IEA, IAEA,…)

- Advanced Materials for High Temperature Applications (≥750°C):
  - **Tremendous synergies:** Fusion, Fission, Spallation, Hydrogen production, concentrated solar,…..
  - **Substantial for efficient and sustainable energy production**

International Road Map

High-temperature Materials are at a critical path



Gen IV

Electricity, Hydrogen,
Nucl. waste incineration
isotope production,….

Fusion DEMO

Start ~2045

ITER

Start ~ 2023

High temperature Materials

IFMIF

Start ~2023