Structural Materials for Fusion Power Plants
Part I: Radiation Effects and Major Issues

Presented by J. L. Boutard[1]

[1] EDFA-CSU Garching (Germany)

How a fusion reactor would work?

- **Deuterium-Tritium fusion reaction:**

$$D + T \rightarrow {}^{4}He(3.56MeV) + n(14.03MeV)$$

  - 80% of the fusion energy produced is carried by 14 MeV neutrons,
  - 20% by He ions at 3.5 MeV

- **Kinetic energy of D and T high enough** for significant effective cross section or in term of temperature (1eV ~10 ^{4}K)

$T \sim 100 \times 10^{6}$ K

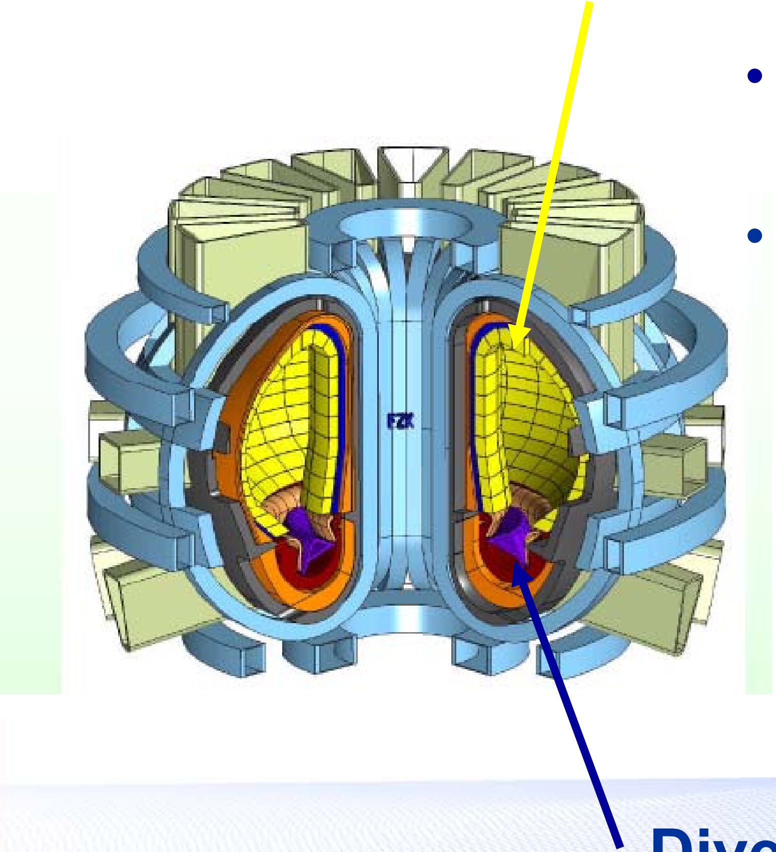
- **Confinement criterion** for self sustained plasma for a reactor

$nT\tau_E > 5 \times 10^{21} m^{-3} keVs$

- The **Tokamak magnetic configuration** is the most promising and will be likely used. It is the configuration of JET and of ITER.

A Tokamak Fusion Reactor

Tritium Breeding Blankets



- Extract the power deposited by the 14 MeV fusion neutrons to produce energy
- Produce tritium using the following nuclear reaction with ^{6}Li

$$n + {}^6Li \rightarrow T + {}^4He + 4.78 MeV$$

- Shield the vacuum vessel & super-conductive coils of the magnets

Divertor

- Exhaust of the alpha particles and impurities from the plasma

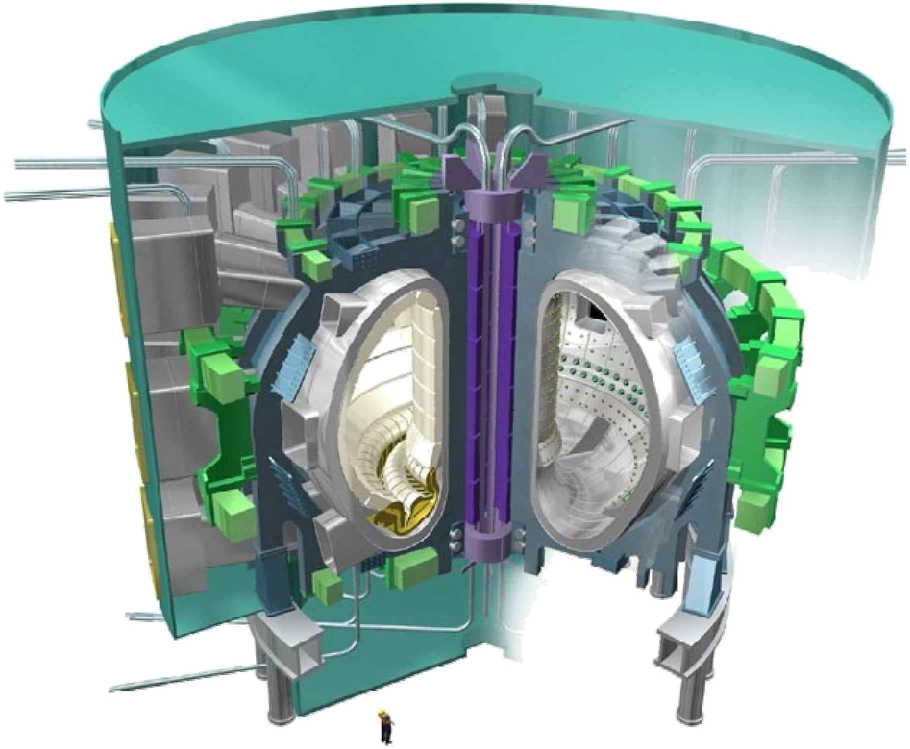
Main Irradiation Conditions

	ITER	DEMO	*Reactor*
Fusion Power	0.5 GW	2-2.5 GW	*3-4 GW*
Heat Flux (First Wall)	0.1-0.3 MW/m^2	0.5 MW/m^2	*0.5 MW/m^2*
Neutron Wall Load (First Wall)	0.78 MW/m^2	< 2 MW/m^2	*~2 MW/m^2*
Integrated wall load (First Wall)	0.07 $MW.year/m^2$ (3 yrs inductive operation)	5-8 $MW.year/m^2$	*10-15 $MW.year/m^2$*
Displacement per atom	<3 dpa	50-80 dpa	*100-150 dpa*
Transmutation product rates (First Wall)	~10 appm He/dpa ~45 appm H/dpa	~10 appm He/dpa ~45 appm H/dpa	

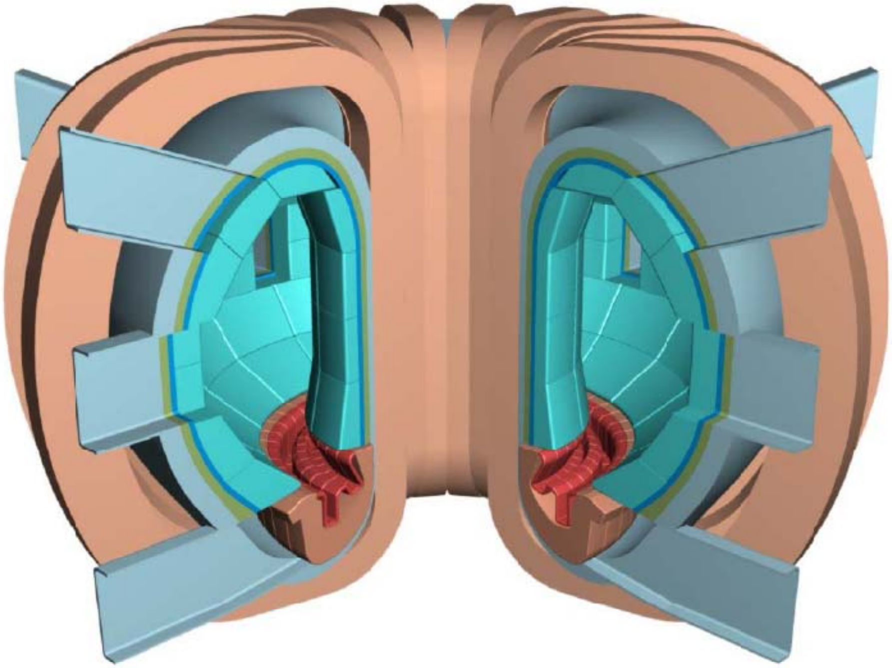
Fission Reactors: 0.2 to 0.3 appmHe/dpa

Increasing Challenge

ITER



Fusion Power Plant



Stepping from ITER to a DEMOnstration power plant:

- Involves addressing **new materials science problems**.
- Requires **scientific innovation, new knowledge**, and the **exploration of a range of *new* materials.**

Fusion Materials Topical Group: Objectives

- Materials development is recognised as a top priority for the fusion programme

- Strengthened coordination in a reinforced programme:

Fusion Materials Topical Group

⇒ Long term materials development

⇒ Materials science and Modelling

- Increased cooperation between *Associations*

- Increased involvement of *Universities and other Institutions* providing scientific capabilities

Fusion Materials Topical Group: Structure

EFDA Leader: J. Paméla

Fusion Materials Topical Group

Co-Chair persons : S. Dudarev (UKAEA) and M. Rieth (FZK)

Responsible Officer: J. L. Boutard (EFDA)

***Structure*:**

Three Research Projects and one Research Area

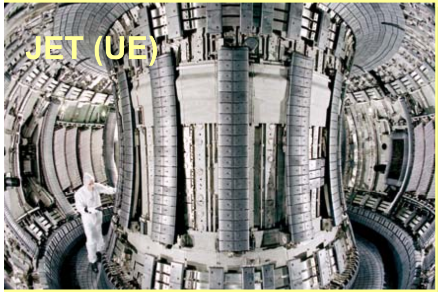
MAT-REMEV: Radiation Effects Modelling and Experimental Validation

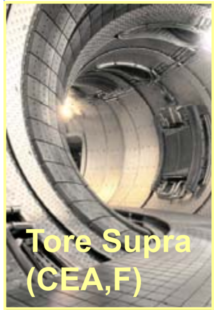
MAT-W&WALLOYS: W&W-alloy Development for Plasma Facing Components:

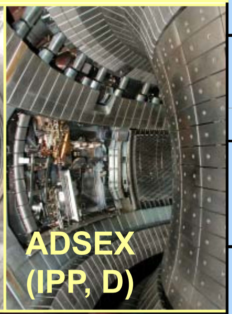
MAT-ODSFS: Nano-structured ODS ferritic steel Development

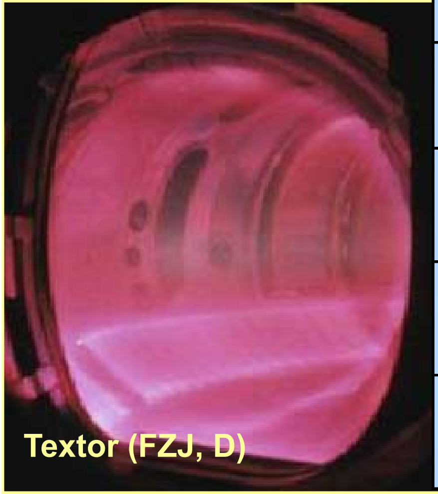
MAT-SiCSiC: Development of SiC_f/SiC for Structural Application

The Associations within EURATOM


JET (UE)


Tore Supra (CEA,F)


ADSEX (IPP, D)


Textor (FZJ, D)

Euratom – CEA	France	(1958)
Euratom – ENEA	Italy	(1960)
Euratom – IPP	Germany	(1961)
Euratom – FOM	The Netherlands	(1962)
Euratom – FZJ	Germany	(1962)
Euratom – Belgian State	Belgium	(1969)
Euratom – RISØ	Denmark	(1973)
Euratom – UKAEA	United Kingdom	(1973)
Euratom – VR	Sweden	(1976)
Euratom – Conf. Suisse	Switzerland	(1979)

● **Joint European Torus (JET)**
Culham, UK (1978)

Euratom – FZK	Germany	(1982)
Euratom – CIEMAT	Spain	(1986)
Euratom - IST	Portugal	(1990)
Euratom – TEKES	Finland	(1995)
Euratom – DCU	Ireland	(1996)
Euratom – ÖAW	Austria	(1996)
Hellenic Rep	Grèce	(1999)
Euratom – IPP.CR	Chech Republik Slovakia	(1999)
Euratom – HAS	Hungary	(1999)
Euratom – MEC	Romania	(1999)
Univ. of Latvia	Latvia	(2002)

Structural Materials for Fusion Pwer Plants
Part I: Radiation Effects and Major Issues

- Co-Chairmen: S. Dudarev (UKAEA), M. Rieth (FZK)
- NRG (NL): B. Van der Schaaf, J. van der Laan, J. W. Rensman
- SCK.CEN Mol (B): A. Almazouzi, E. Lucon, W, Vandermeulen
- FZK (D): A.Moslang, M. Rieth, M. Klimenkov, R. Lindau
- FZJ (D): H. Ulmaier, P. Jung
- Eric Schmid Institute (A): R. Pippan
- CEA (F): A. Alamo, A. Bougault,
- CRPP (CH): N. Baluc, P. Spätig

Fission Programme

- France: J. Henry, M.H. Mathon, P.Vladimirov

Open Literature

Outline

- Design and Structural Materials for Div & TBB
- Radiation Effects and Simulating 14 MeV Neutrons
- Radiation effects in LA 9%Cr and ODS F/M steels
- In-situ versus Post-Irradiation Mechanical Testing
- SiC_f/SiC composites for High Temperature Fusion application
- Need for Physical Modelling of Radiation Effects

Materials for Blanket and Divertor

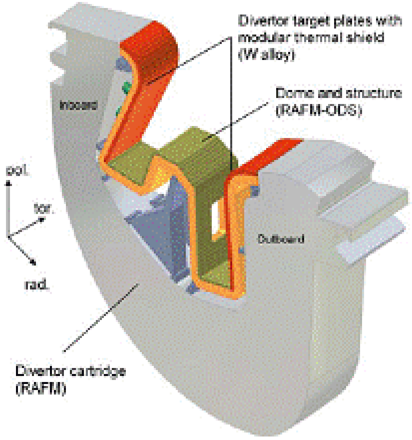
PPCS: http://www.efda.org/eu_fusion_programme/scientific_and_technical_publications.htm

Power Plant Conceptual Studies (PPCS)			Tritium Blanket Module in ITER		Advanced Tritium Breeding Blamket	
		Modell A or WCLL	Modell AB or HCLL	Modell B or HCPB	Modell C or dual coolant	Modell D or Self-cooled
Tritium-Breeding Blanket	Structural Material	EUROFER	EUROFER	EUROFER	EUROFER with Thermal insulator	SiC_f/SiC
	Coolant	H_2O	He	He	He & LiPb	LiPb
	Coolant Inlet/Outlet $T(^0C)$	285/325	300/500	300/500	300/480 480/700	700/1100
	Breeder Material	LiPb	LiPb	Li4SiO4	LiPb	LiPb
	Tritium Breeding Ratio	1.06	1.13	1.12	1.15	1.12
Divertor	Structural Material	CuCrZr	W alloys & ODS Steels	W alloys & ODS Steels	W alloys & ODS Steels	SiC_f/SiC
	Armour Material	W	W	W	W	W
	Coolant	H_2O	He	He	He	LiPb
	Coolant Inlet/Outlet $T(^0C)$	140/170	~540/720	~540/720	~540/720	~600/990
Power Plant Net Efficiency		0.31	0.35	0.36	0.42	0.6

Increasing Net Efficiency → **Strong Drive for Heat & Radiation Resistant Materials**

T-Breeding Blanket & Divertor
Design, Materials, Operating Temperature

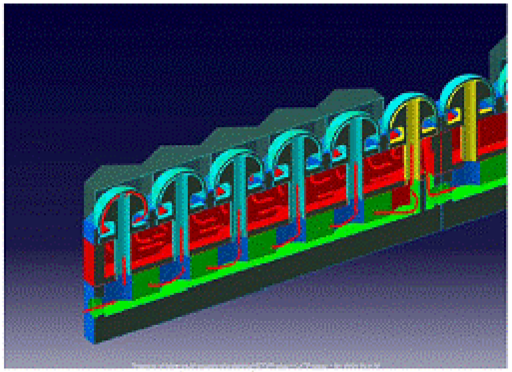
10 MW/m^2

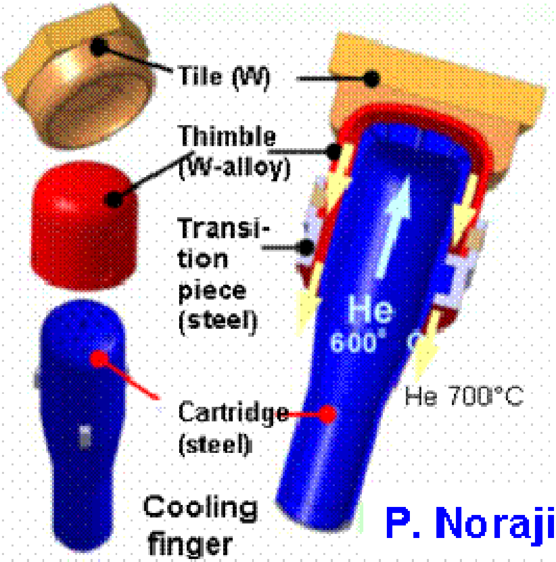


W tile: max. allow temp. 2500°C
max. calc. temp. 1711°C
DBTT (irr.): 700°C

Thimble: max. allow. temp. 1300°C
max. calc. temp. 1170°C
DBTT (irr.): 600°C

ODS-Eurofer: He-out temp. 700°C
He-in temp. 600°C
DBTT (irr.): 300°C



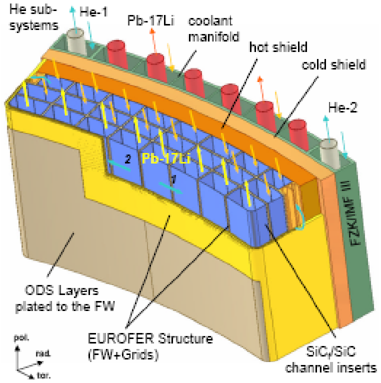


P. Norajitra, FZK

Fusion Power Reactor
Dual-Coolant T-Blanket

He, 80 bars	**Pb-17Li, ~**bar
300, 480 ^{0}C	480-700 ^{0}C

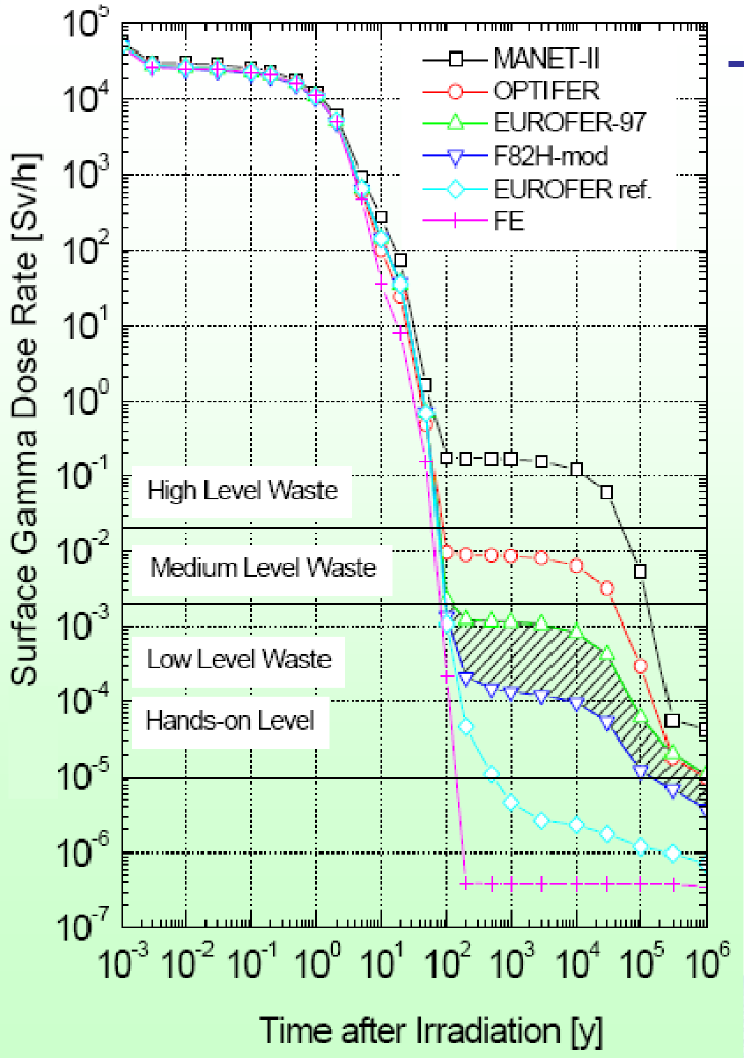
Dual-Coolant T-Blanket



Martensitic Steels (550 ^{0}C)
ODS Ferritic steels (700 ^{0}C)
SiCf-SiC th. & elect. insulator

F W: T max= 625 ^{0}C
Channel: Tmax= 500 ^{0}C
Insert: Tmax~1000 ^{0} C

Low Activation
8-10%CrWTaV Ferritic Martensitic Steels



Long term irradiation of a DEMO First Wall: 12.5MWa/m^2: ~115 dpa

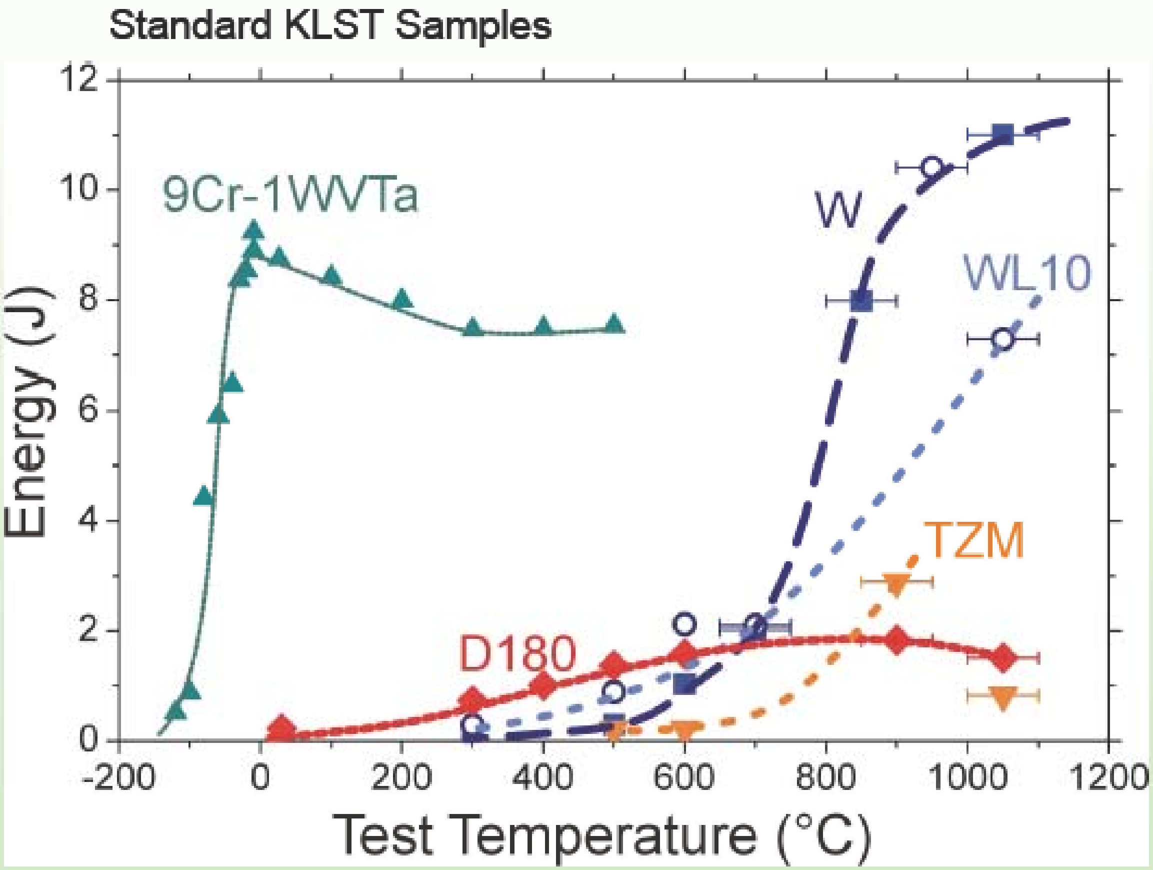
- **Belongs to the series of 9%Cr F/M Steels used in the tempered martensite microstructure**
- **Reduced Activation:**
  - **Low level waste already after 80-100 years**
  - **Nb and Mo are dominating**

Radiologically Undesired		R.A .EUROFER	
		Specified	Achieved (*)
Nb	<0.01	<10	2 to 7
Mo	<1	<50	10 to 32
Ni	<10	<50	70-280
Cu	<10	<50	15-220
Al	<1	<100	60-90
Ti	<200	<100	50-90
Si	<400	<500	400-700
Co	<10	<50	30-70

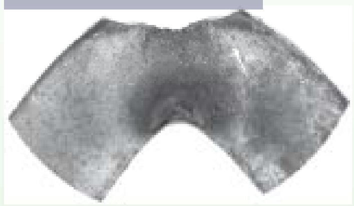
(*) On 10 heats i.e. 11 tonnes of different prodicts (forged bar, plates, tubes, wire)

R. Lindau et al., Fusion Eng. and Design 75-79 (2005) 989-996.

Initial Brittleness of W, W and Mo-Alloys



W, 1050°C



Ductile

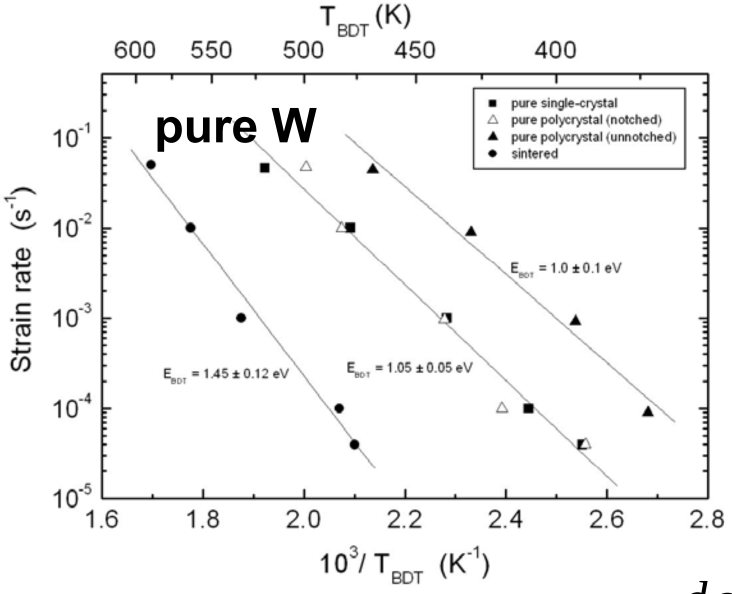
WL10, 1050 °C

Partly brittle

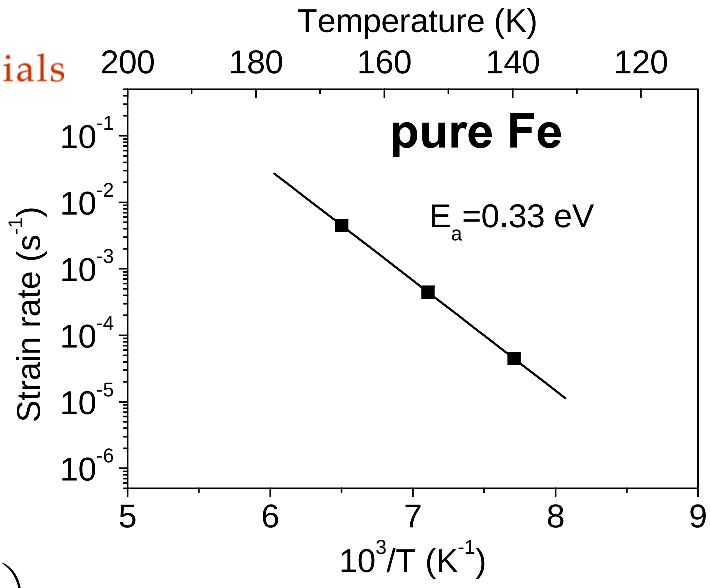
M. Rieth et al, IMF I

Ways of Improvements: heavily deformed W, ODS-W, K-doped W

Dislocation Mobility and Ductile-Brittle Transition (DBT) Temperature



OxfordMaterials

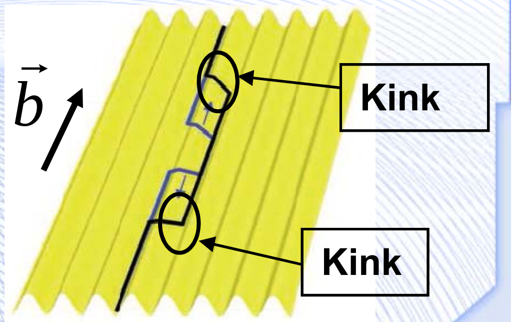


$$\frac{d\varepsilon}{dt} = A\exp\left(-\frac{\Delta H_{DBT}}{k.T_{DBT}}\right)$$

ΔH_{DBT} is equal to the activation energy of the yield strength

$$\Delta H_{DBT} = \Delta H_d = H^{formation}_{double.kink} - \Omega.\sigma \approx 0.5H^{formation}_{double.kink}$$

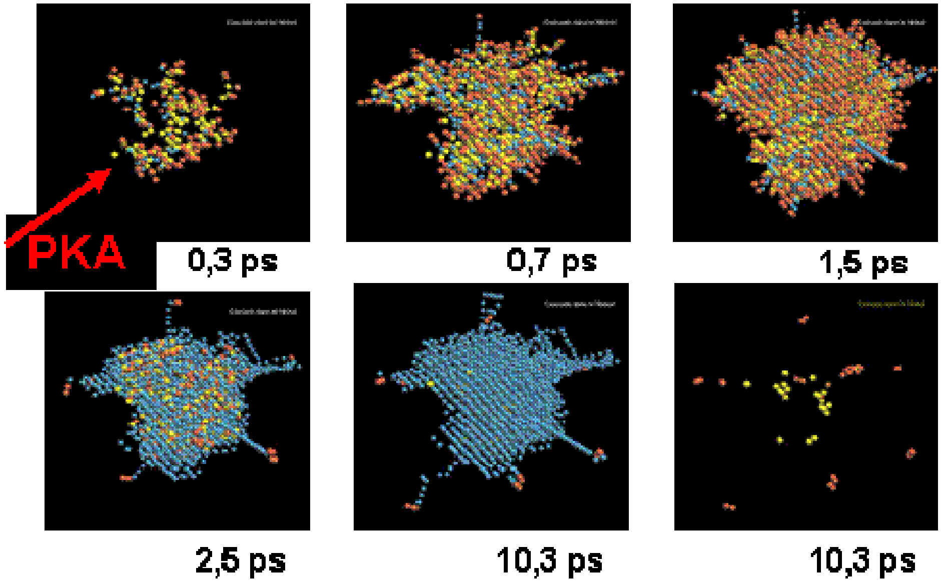
	Fe	W
H (kink-pair) eV	**0.8**	**2**
ΔH_{DBT} eV	**0.2 to 0.3**	**1.05**
$T_{DBT}(10^{-3}\ s^{-1})$ K	**150**	**475-525**



A. Giannattasio, M. Tanaka, T. D. Joseph, and S. G. Roberts, Phys. Scripta T128 (2007)87-90

Radiation Effects under D-T Spectrum

- **Displacement Cascades strain the Crystalline Structure**



Creation of point defects

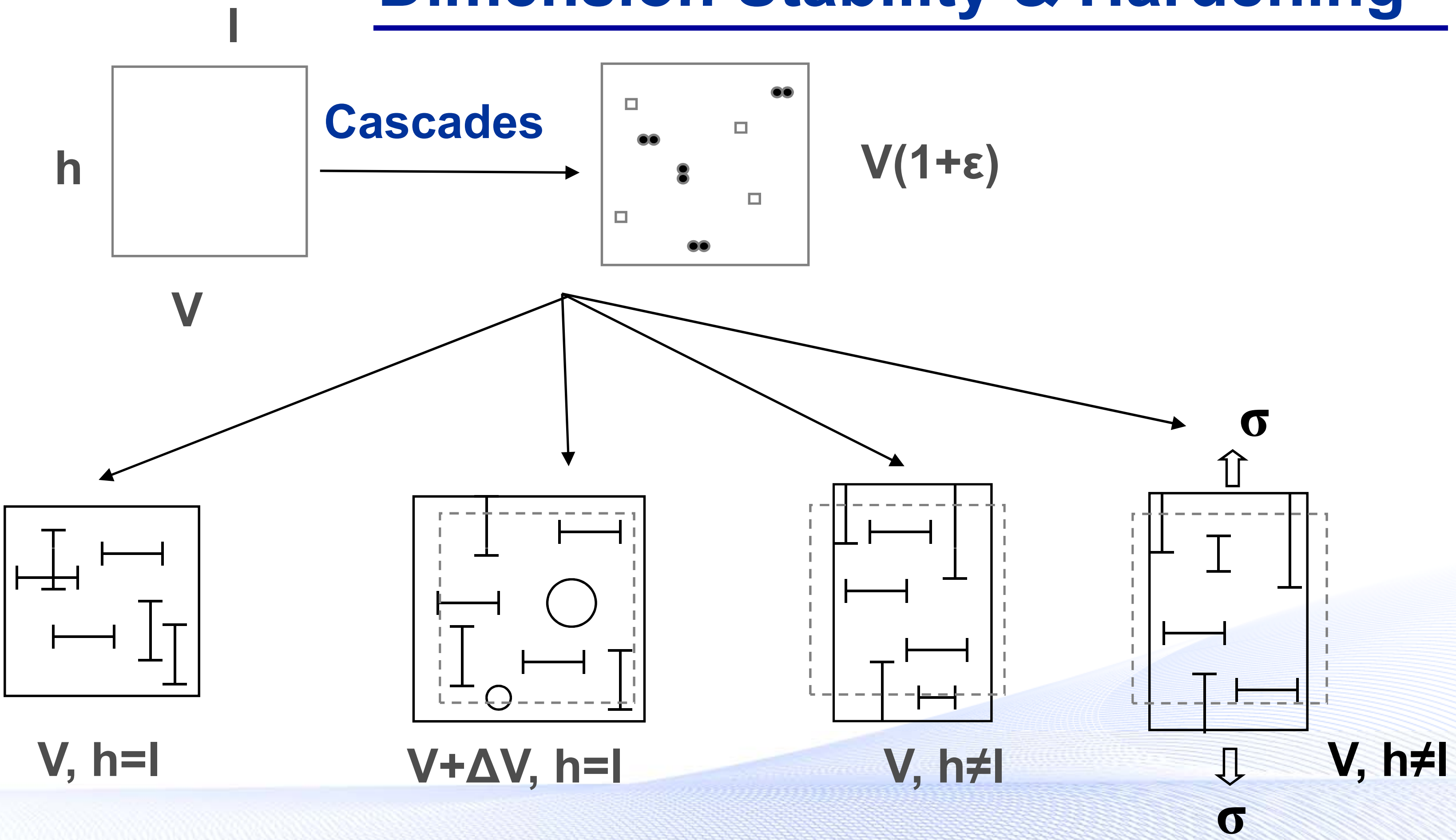
- **V and V-clusters**
- **I- and I-clusters**
- **Replaced atoms or ballistic jumps**

7 keV Cascade in Ni (fcc)

- He (and H) production affects the **Chemical Composition**

- Long term diffusion will result in modifying the **Microstructure**

Diffusion of Defects & Clustereing: Dimension Stability & Hardening



l

h

V

Cascades

$V(1+\varepsilon)$

σ

$V, h=l$

$V+\Delta V, h=l$

$V, h\neq l$

$V, h\neq l$

σ

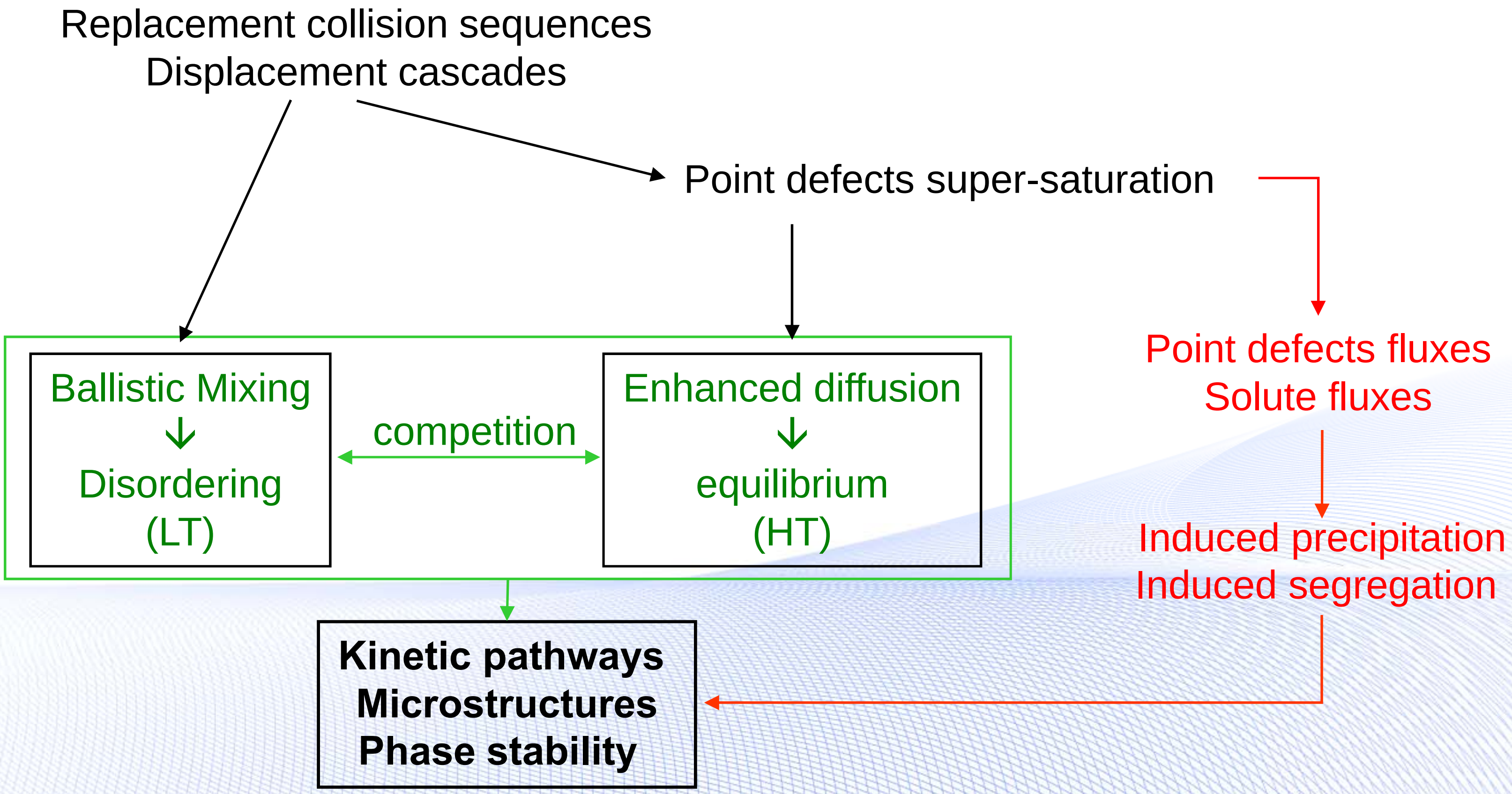
Swelling **Growth** **Irradiation Creep**

Point Defects and dislocation loops : Hardening and Embrittlement

After Lecture Viewgraphs by A. Barbu CEA/Saclay

Ballistic Effects and Point Defect Diffusion: Phase Stability under Irradiation

Long Term Phase Stability of Alloys : Precipitation / Dissolution of Precipitates
Ordering / Disordering
Radiation Induced Segregation



Replacement collision sequences
Displacement cascades

Point defects super-saturation

Ballistic Mixing
↓
Disordering
(LT)

competition

Enhanced diffusion
↓
equilibrium
(HT)

Point defects fluxes
Solute fluxes

Induced precipitation
Induced segregation

Kinetic pathways
Microstructures
Phase stability

After F. Soisson CEA/Saclay

Neutron Sources to Simulate 14 MeV Neutrons

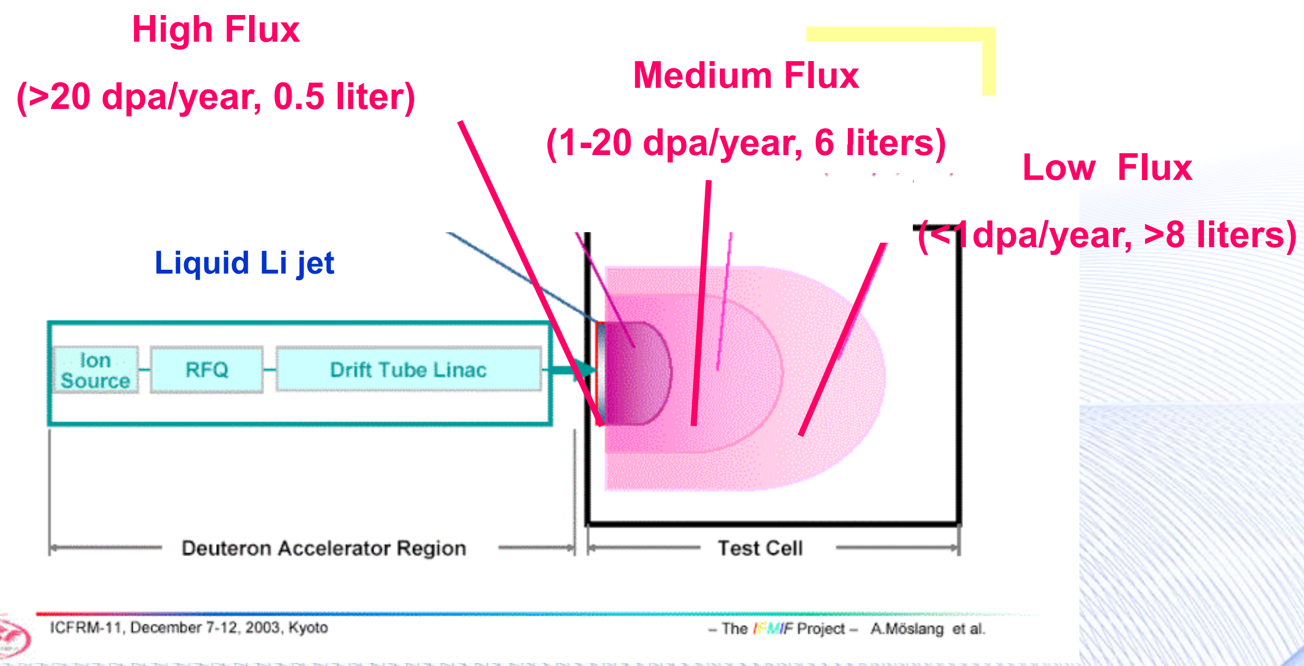
- **Fission Reactors (MTR, Fast reactors), Spallation Targets**
- **International Fusion Materials Irradiation Facility (IFMIF)**
  - **Typical Stripping Reactions: ^{7}Li(D, 2n)^{7}Be, ^{6}Li(D,n)^{7}Be ^{6}Li(n, T) 4He**
  - **Deuterons: 40MeV, 2x125mA, beam footprint 5x20 cm^{2}**
  - **EVEDA (in Japan): 2007-2012**
  - **Construction:2013-2018 –Operation 3 campaigns of 5 years each**

IFMIF will have

the correct scaling in He & H production:

~12 appmHe/dpa

~45 appmH/dpa

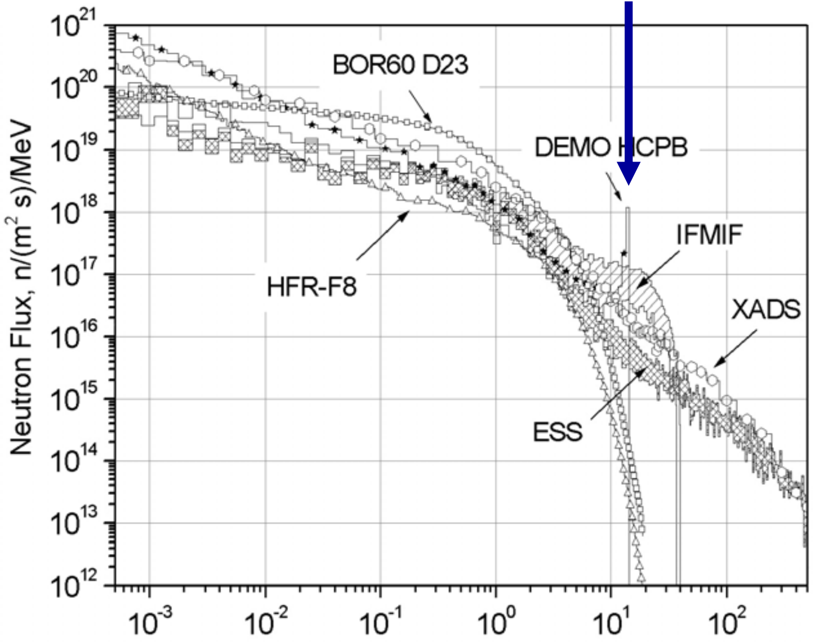


ICFRM-11, December 7-12, 2003, Kyoto – The IFMIF Project – A.Möslang et al.

Fission Reactor, Spallation Target, IFMIF: Neutron & PKA Spectra

Neutron Spectra

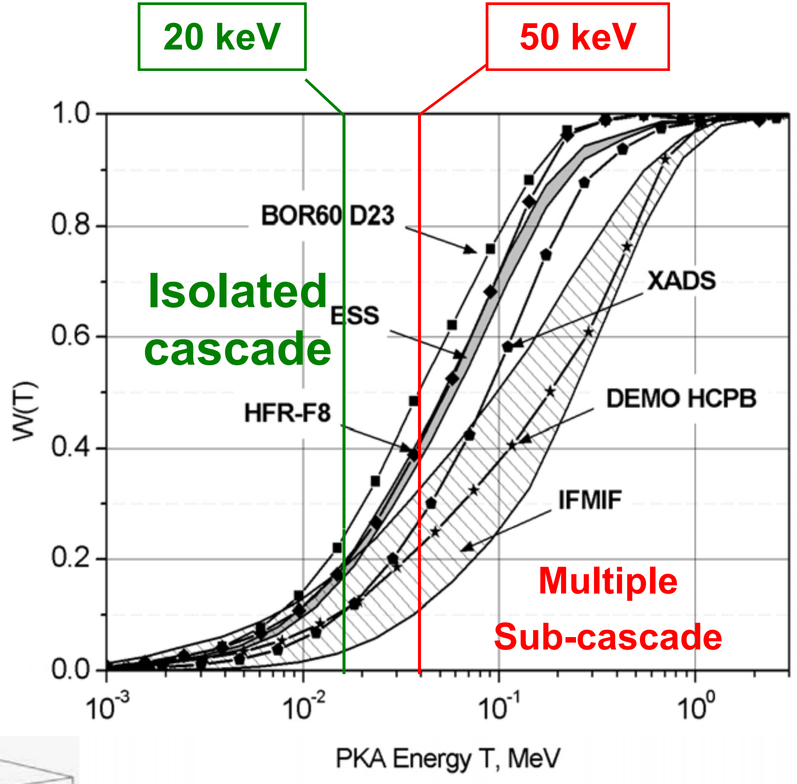
14 MeV neutrons



PKA Spectra in Fe

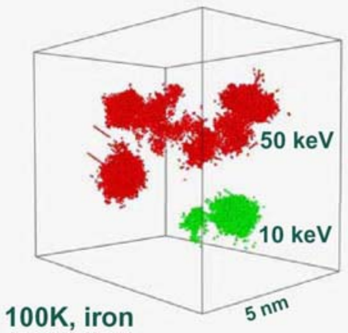
20 keV

50 keV



Isolated cascade

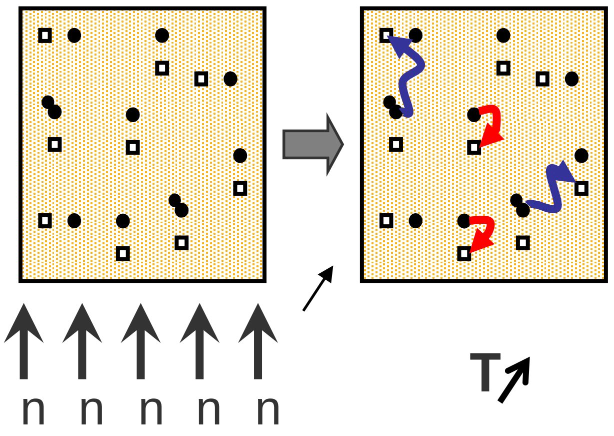
Multiple Sub-cascade

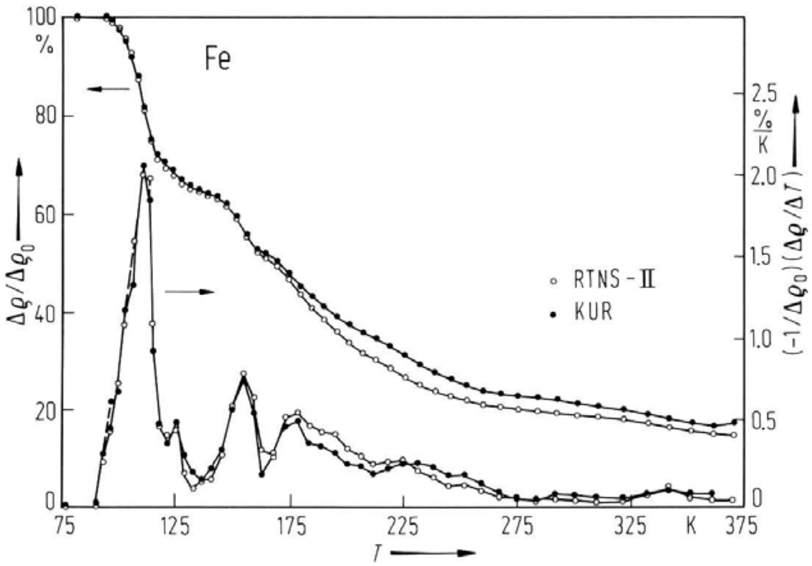


R. E. Stoller J. Nucl. Mater. 276 (2000) 22-32

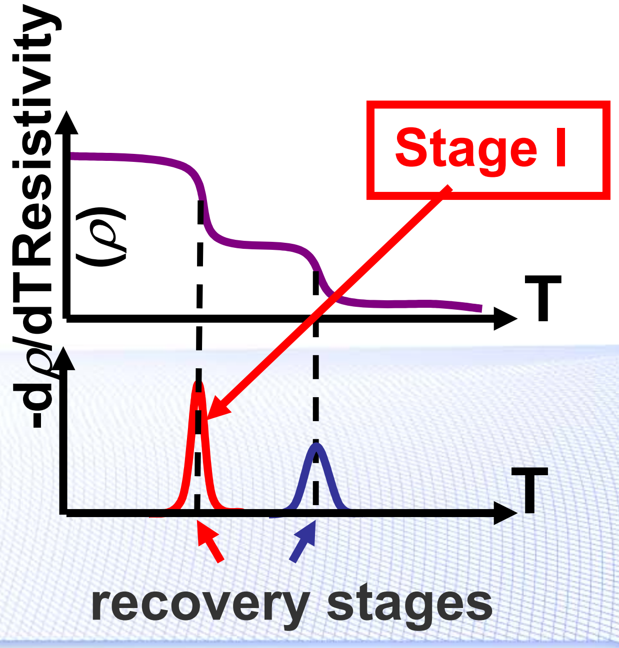
Fission & 14 MeV Defect Production

- **14 MeV Damage Recovery Stages**





M. Matsui et al. J. Nucl. Mater. 155-157 (1988) 1284



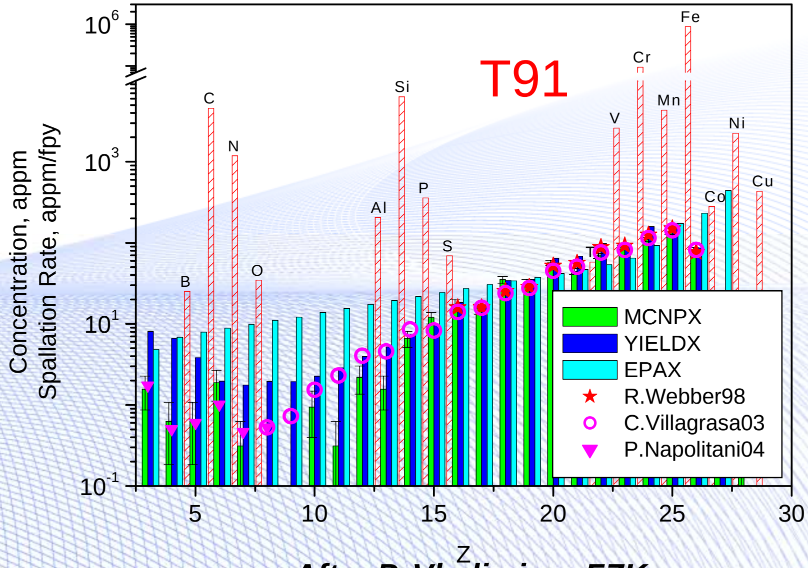
14 MeV and Fission Neutrons: Same Surviving Defects

14 MeV neutrons: transmutation

- **In the absence of a 14 MeV neutrons source: Simulation using different methods or tricks**

He-producing technique	Irradiation Device	appmHe/dpa
Ferritic/martensitic steels	D-T Fusion Reactor	~10
Ferritic/martensitic steels	MTR	~0.3
B or Ni-doped steels	MTR	~a few
Fe^{54} enriched steels	MTR	~2
Mixed spallation-neutron spectrum	Spallation target	~100
Energetic (20-100 MeV) alpha particles	Cyclotron	~1,000 to 10,000
Dual/Triple ion (~1 MeV) beam	Electrostatic accelerators	0 to ~10,000

- **Some drawbacks and difficulties:**
  - **B doping:** *B segregates to GB so that the He production is not homogeneous. B(n,α)Li.*
  - **Ni doping:** *Ni strongly changes the mechanical properties before irradiation*
  - **Mixed spallation-neutron spectrum:** *other spallation residues with 1<Z<Z(Fe) are also produced*

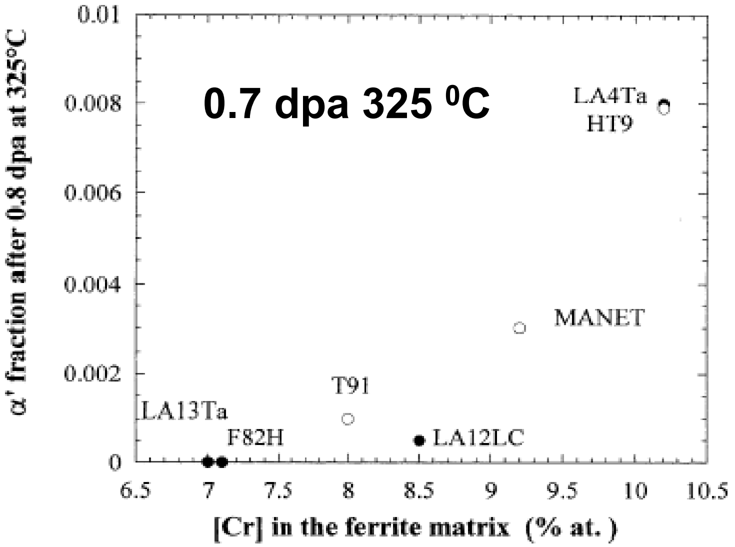


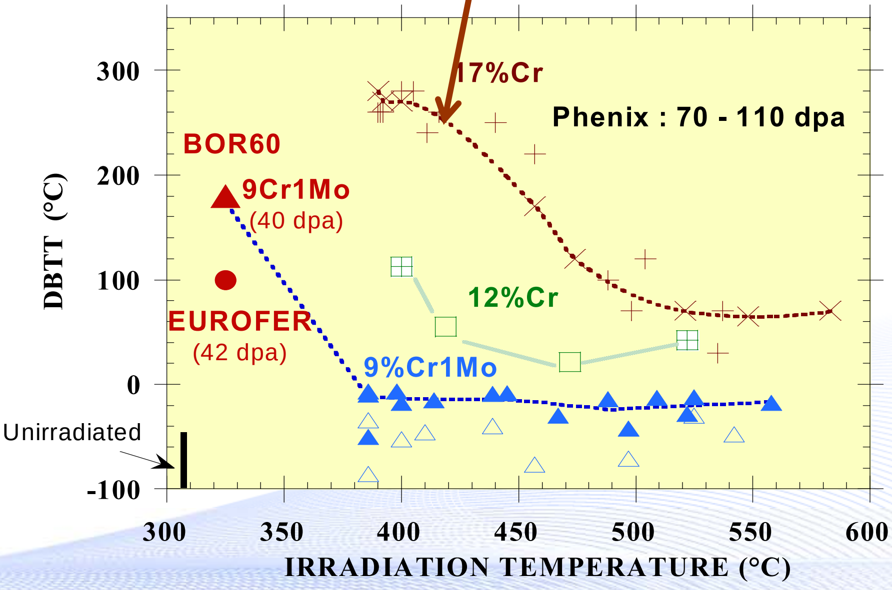
After P. Vladimirov FZK

Ferritic/Martensitic Steels
α/α' Unmixing and Loss of Fracture Toughness

F/M steels with Cr >7.5 %
α/α' unmixing at T = 325 ^{0}C

17%Cr Ferritic steels
α/α' unmixing for T>400 ^{0}C





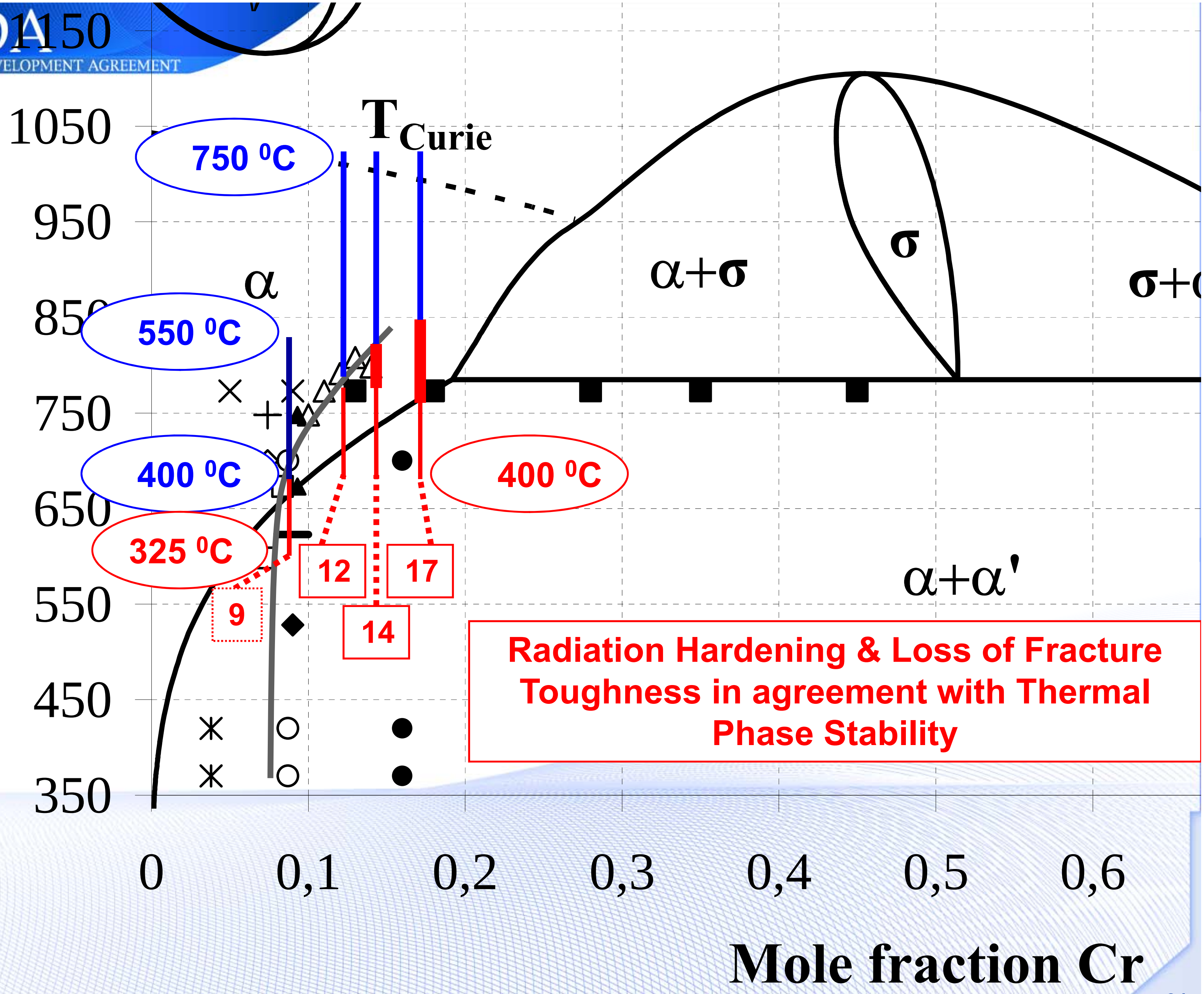
M. H. Mathon et al

J. Nucl. Mater. 312 (2003) 236-248

J.L. Séran et al.J. Nucl. Mater. 212-215 (1994) 588-593
A. Alamo et al. Final Report TW2-TTMS-001-D02.

Fe-Cr Phase Diagram

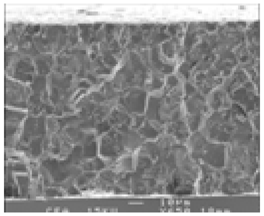
After A. Caro et al.



Radiation Hardening & Loss of Fracture Toughness in agreement with Thermal Phase Stability

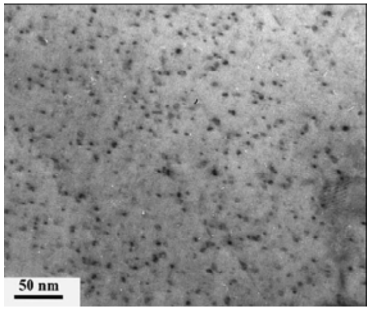
He-Implanted 9 % Cr martensitic steel (1) Hardening & Microstructure

23 MeV α- Particle Implantation up to 0.5 % at He (FZJ)

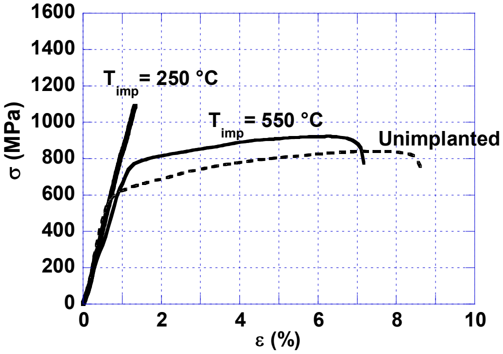


SEM: 250 ^{0}C

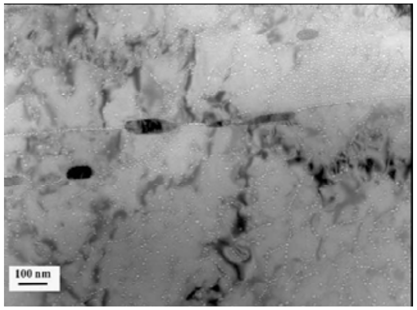
TEM: 250 ^{0}C



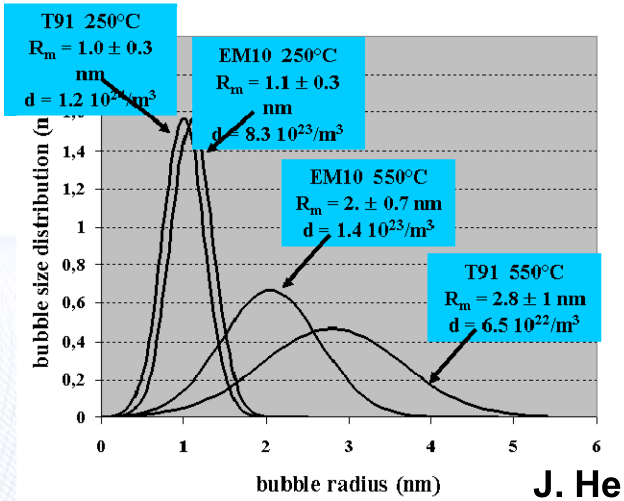
Tensile: 250 ^{0}C & 550 ^{0}C



TEM : 550 ^{0}C



SANS: Analyzing the magnetic Scattered intensity (LLB,CEA/Saclay)



$$\Delta\sigma = M\alpha Gb(Nd)^{1/2}$$

$$\Delta\sigma \approx 870MPa$$

M~3 : Taylor factor

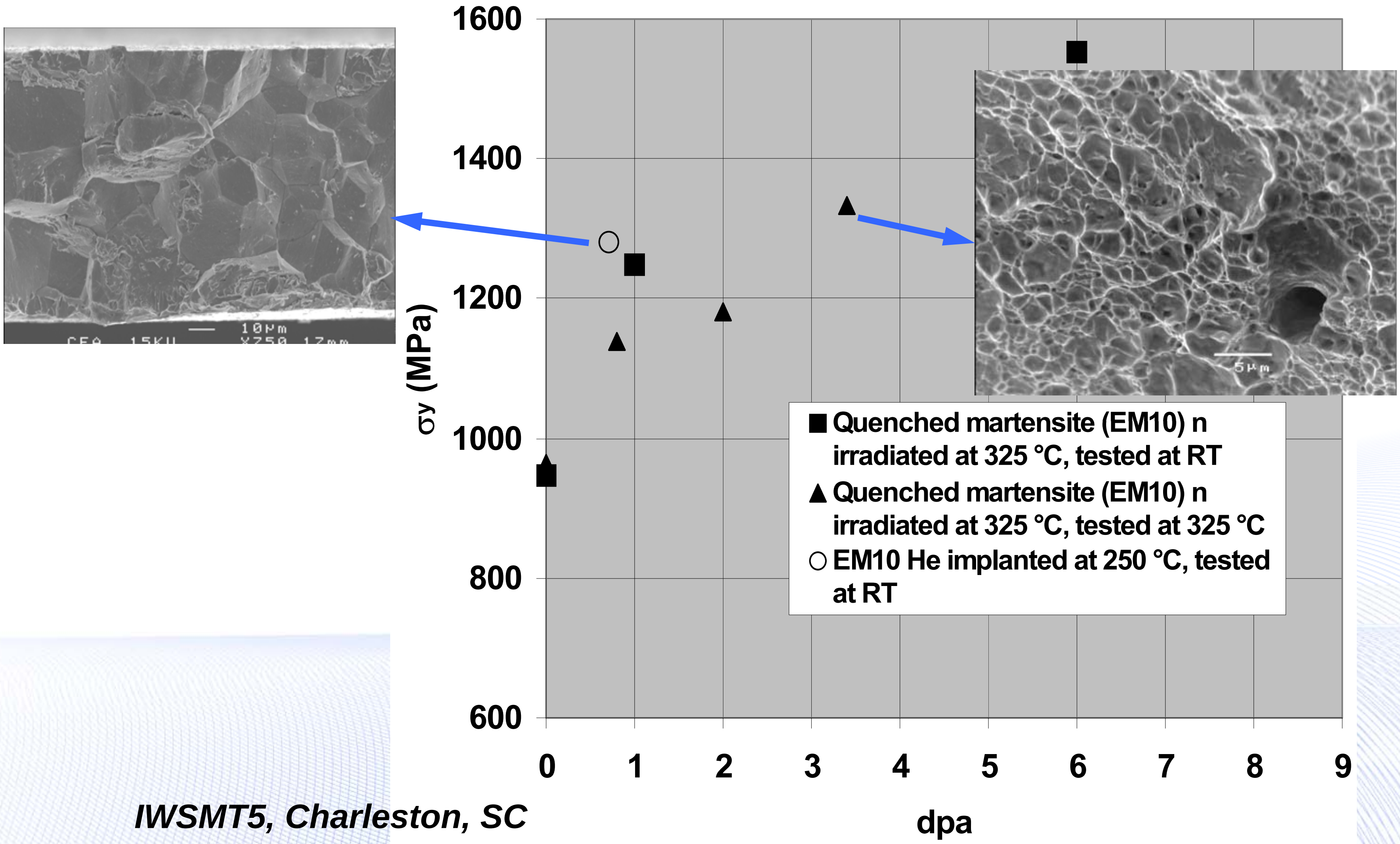
$\alpha \sim 0.3$ **: Obstacle strength**

G=8 x10^4 MPa : Shear modulus

b=0.2 nm : Bürgers vector

J. Henry, M. H. Mathon, and P. Jung J. Nucl. Mater. 318 (2003) 249-259

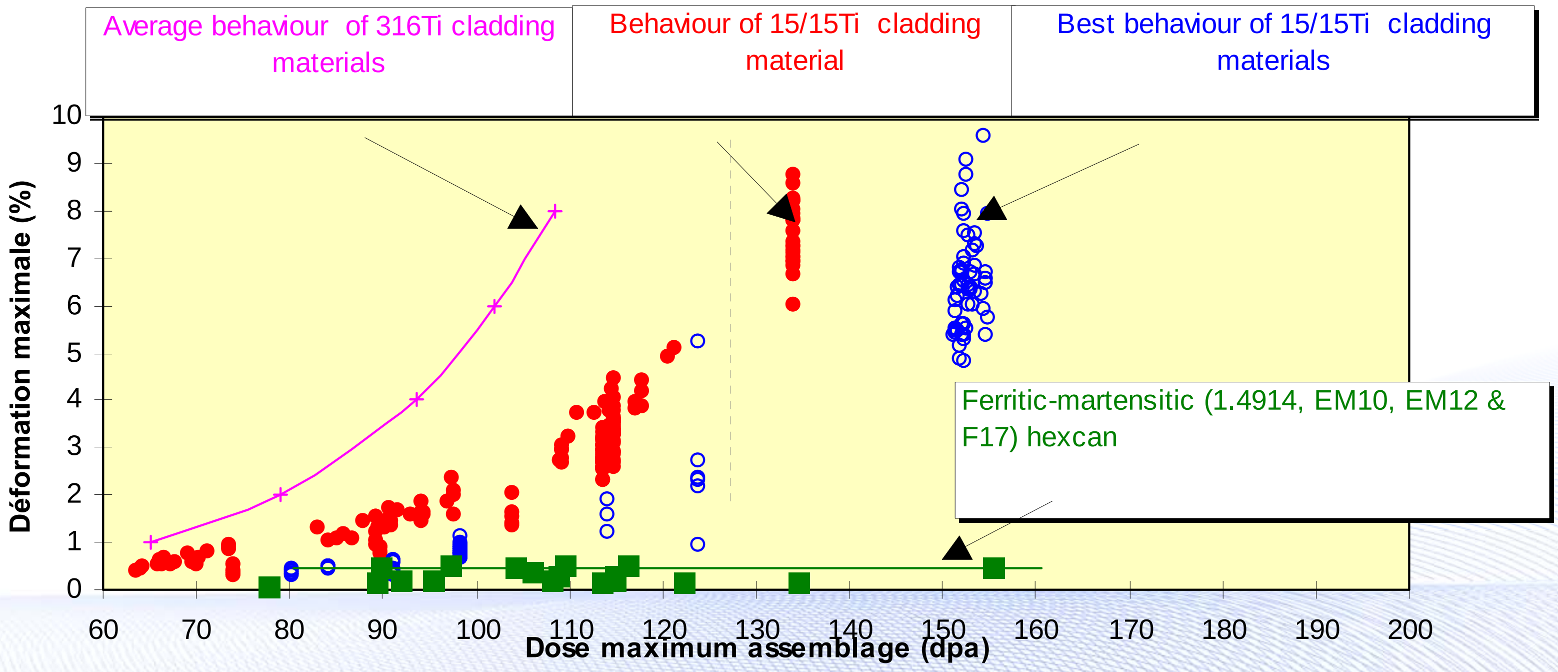
He-Implanted 9 % Cr martensitic steel (2)
Loss of Cohesive Energy Grain-Boundary



IWSMT5, Charleston, SC

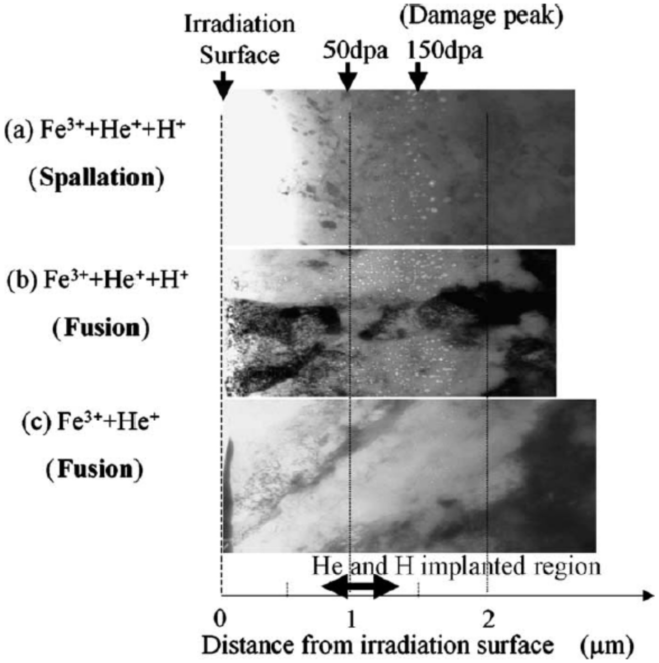
Swelling of F & F/M Steels:
(1) Under Fast Fission Neutrons

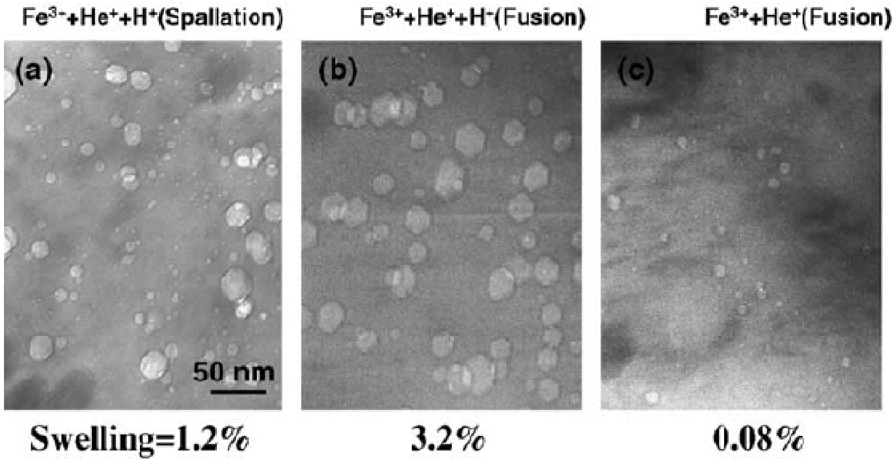
Phénix : Fuel Element Clad (austenitic steels) and Hexcan (ferritic-martensitic steels) Hoop Strain



High Resistance of Swelling of Ferritic and Ferritic/Martensitic Steels Irradiated in Phenix

Swelling of 9% Cr F/M Steels: Under Triple Beam





Swelling 3.2%: 470 ^{0}C, 50dpa, 900 appm He, 3500 appm H

Ions	Energy (MeV)	appm/dpa for Fusion Simulation	appm/dpa for Spallation Target Simulation
Fe3+	10.5		
He+	1.05	18	180
H+	0.38	70	1700

E. Wakai et al. J. Nucl. Mater. 318 (2003) 267-273

ODS Ferritic Martensitic Steels: a long R&D effort

- **Early 80's:**

ODS of 1st generation *(Mol, Belgium):*

Ferritic matrix + χ-intermetallic phase + Oxide dispersion

Fe –13 Cr – 1.5 Mo – 2.4 Ti with TiO2 or Y2O3

Very brittle alloys due to the χ - phase precipitation

- **Presently :**

Commercial ODS-alloys :

Ferritic matrix + Oxide dispersion

MA956 & PM2000: Fe - 20 Cr – Al - Ti – 0.5 Y2O3

→ **MA957 : Fe – 14 Cr – 1 Ti – 0.3 Mo – 0.25 Y2O3**

Experimental ODS – alloys :

Ferritic matrix + Oxide dispersion

→ **12YWT : Fe-12Cr-3W-0.4Ti-0.25wt%Y_20_3**

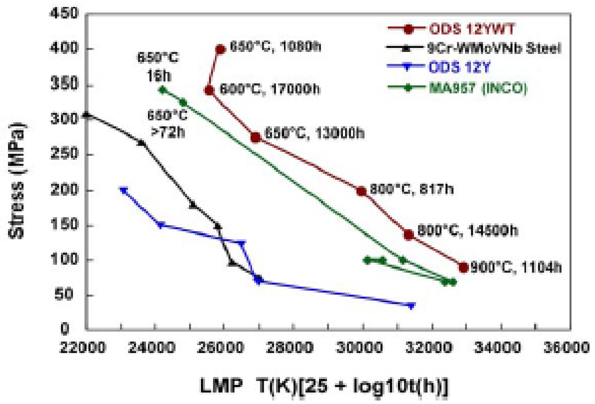
Martensitic matrix + Oxide dispersion

CM2: Fe - 9 Cr – 2W - 0.1Ti – 0.25wt%Y2O3

- **Development towards refined oxide particles & higher creep resistance**

ODS 12-14%Cr (1)
Creep Resistance Needs Nano-Dispersion

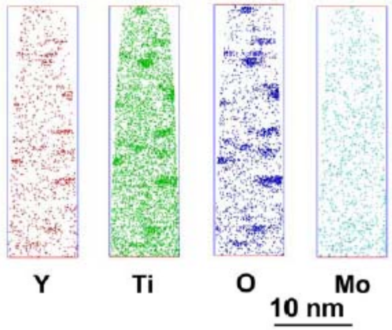
Creep rupture of ODS-14% Cr (ORNL)



by Courtesy of R. Stoller (ORNL)

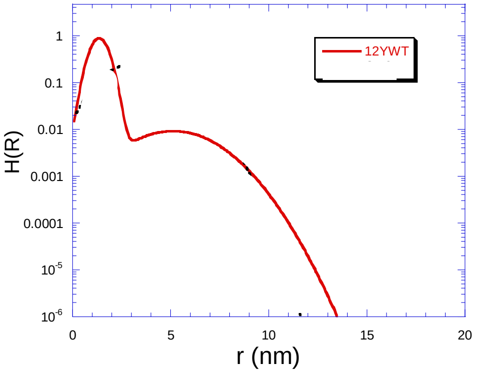
MA-957

Tomography Atom Probe (ORNL)



After M.K. Miller et al. J. Nucl. Mater. 329-333 (2004) 338

Small Angle Neutron Scattering (CEA): high creep resistance → fine dispersion



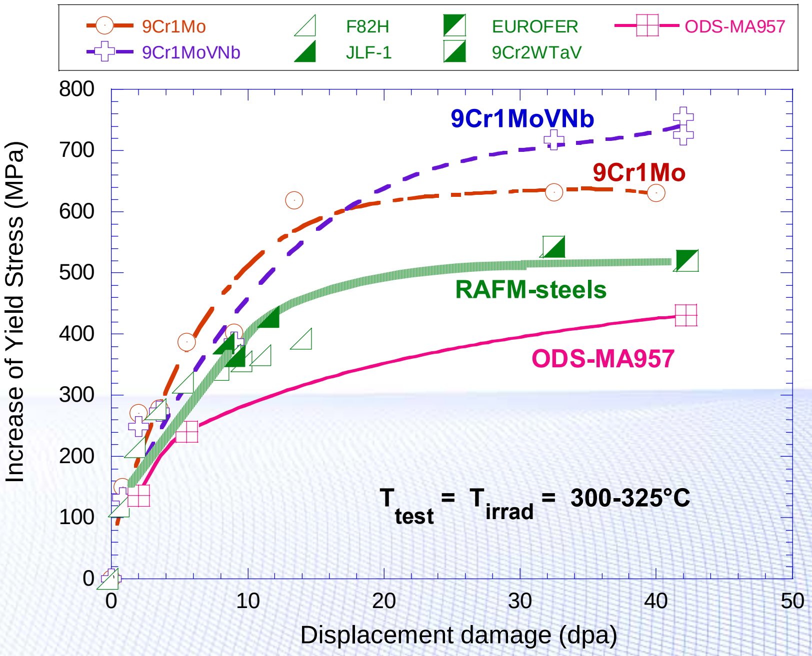
MA957		12YWT	
F_{pv}(oxide) = 0,64		F_{pv}(oxide) = 1,07	
r (nm)	F_{pv} (%)	r (nm)	F_{pv} (%)
5,2	0,13	5	0,05
1,5	0,51	1,4	1,02

After M. H. Mathon and A. Alamo (CEA/Saclay) to be published at ICFRM-12 UCSB, December 2005

ODS 12-14%Cr (1)

Nano-Structuring Ferritic ODS steels

ODS Ferritic Steels (14% Cr)	Dose	Yield Stress (MPa)	UTS (MPa)	Uniform Elong. (%)	Total Elong. (%)	Reduction of Area (%)
Micrometer Grains (50µm)	0	566	718	6.9	19.1	79
Micrometer Grains (50µm)	32.5	1181	1201	0.3	0.3	0.3
Submicron Grain (0.500 µm)	0	1071	1190	5.9	***14.7***	***80***
Submicron Grain (0.500 µm)	42.2	1552	1611	1.3	***7***	***79***



Better Resistance to Displacement Induced Embrittlement

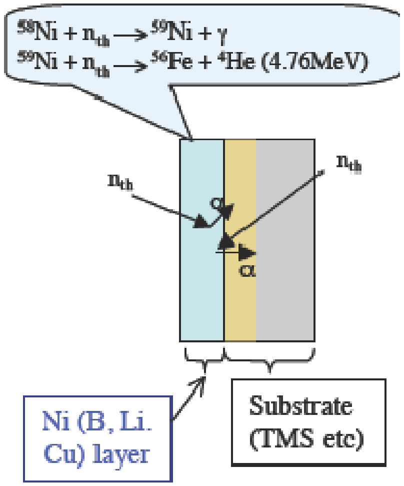
BUT

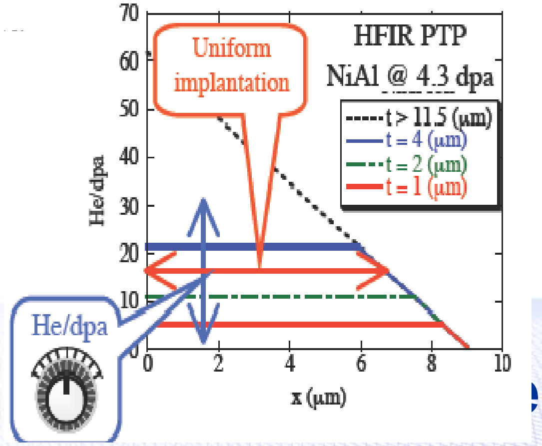
Microstructure Characterization strongly required

Are the Oxide Dispersion Particles still there?

Then do they trap He ?

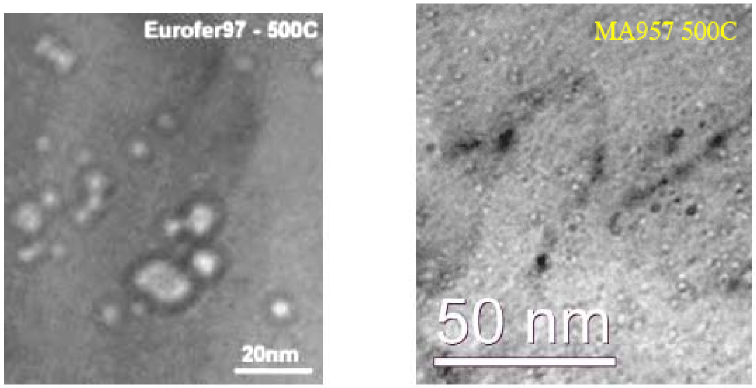
Ferritic/Martensitic Steels: ODS for High Density of Effective He-Trapping within the Grain





HFIR In-pile He Injection Experiments

Temp. °C	T_i (°C)	dpa-He	<d> (nm)	N (m^{-3})
Eurofer	500	9-372	4.3 ± 1.6	$1.5x10^{22}$
MA957	500	9-380	1.2 ± 0.2	$4.3x10^{23}$



Helium bubbles in Eurofer97 and MA957

T. Yamamoto et al. IEA Modelling Workshop Gatlinburg (USA), May 2008.

ODS Should Mitigate Inter-granular

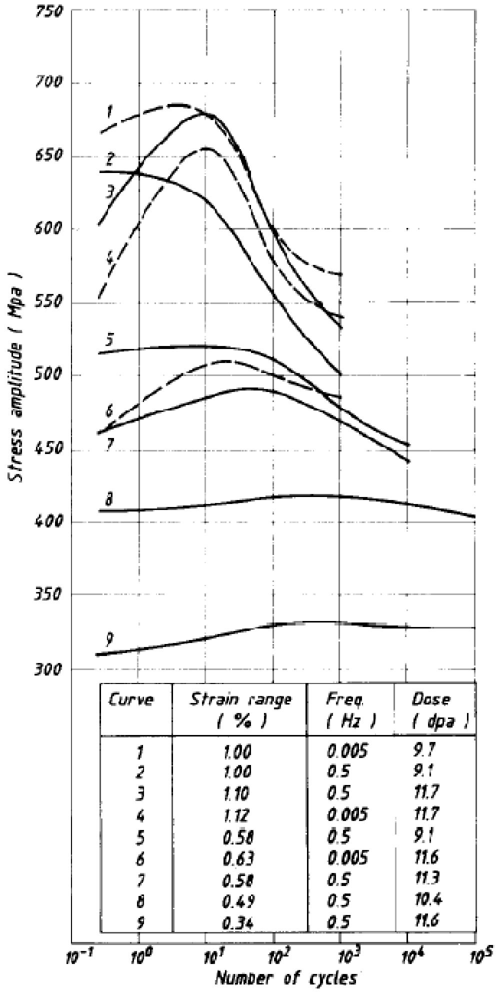
Embrittlement (low & high T) and Swelling

Main Issue:

Characterisation of these clusters and their stability under irradiation

Post Irradiation Low Cycle Fatigue Cyclic Hardening and Softening

Irradiated 316 ~10 dpa:
T_{irr}=T_{test}=430 ^{0}C



Curve	Strain range (%)	Freq. (Hz)	Dose (dpa)
1	1.00	0.005	9.7
2	1.00	0.5	9.1
3	1.10	0.5	11.7
4	1.12	0.005	11.7
5	0.58	0.5	9.1
6	0.63	0.005	11.6
7	0.58	0.5	11.3
8	0.49	0.5	10.4
9	0.34	0.5	11.6

Irradiated 316

~10 dpa and 85-145 appm He

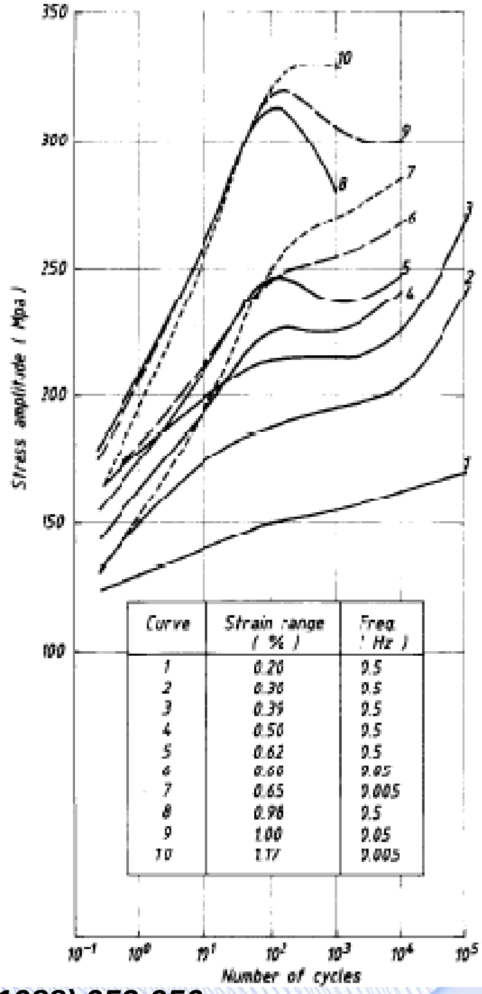
- ***High Strain range : > ~0.5%***

Significant Cyclic Softening

- ***Low strain range:<~0.5%***

The stress amplitude of the first cycle is hardly changed

Non-Irradiated 316
tested at 430 ^{0}C



Curve	Strain range (%)	Freq. (Hz)
1	0.20	0.5
2	0.30	0.5
3	0.39	0.5
4	0.50	0.5
5	0.62	0.5
6	0.60	0.05
7	0.65	0.005
8	0.98	0.5
9	1.00	0.05
10	1.17	0.005

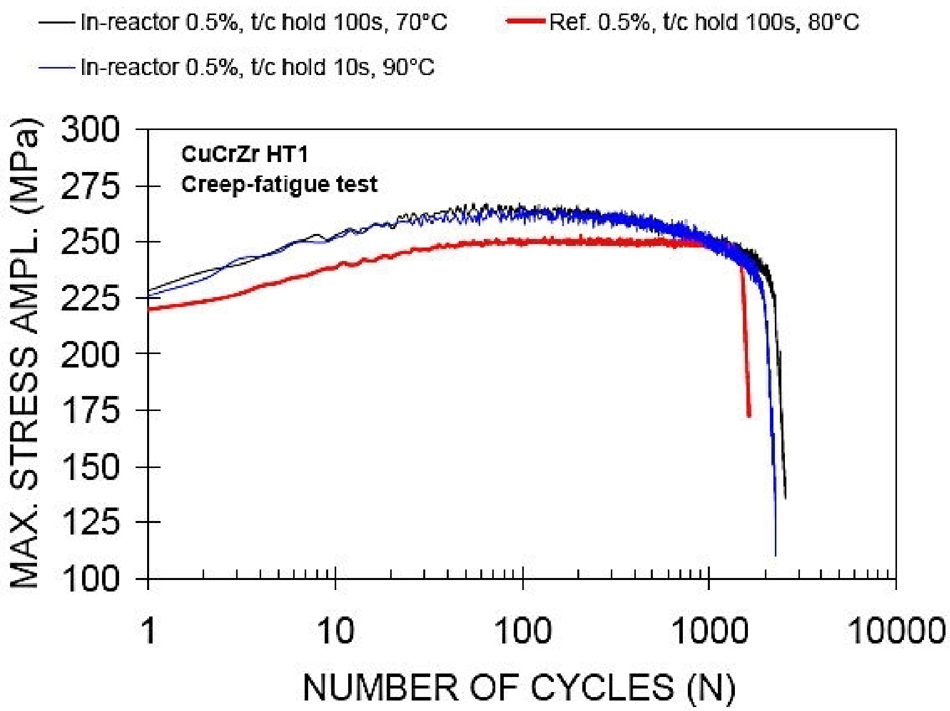
After W. Vandermeulen et al. J. Nucl. Mater. 155-157 (1988) 953-956

Dynamical Response of Metallic Alloys
Low Cycle Fatigue under Fast Neutrons

In reactor Strain-Controlled LCF:

~0.5 dpa for hold time of 100s

Creep-fatigue cycle life behaviour of CuCrZr alloy

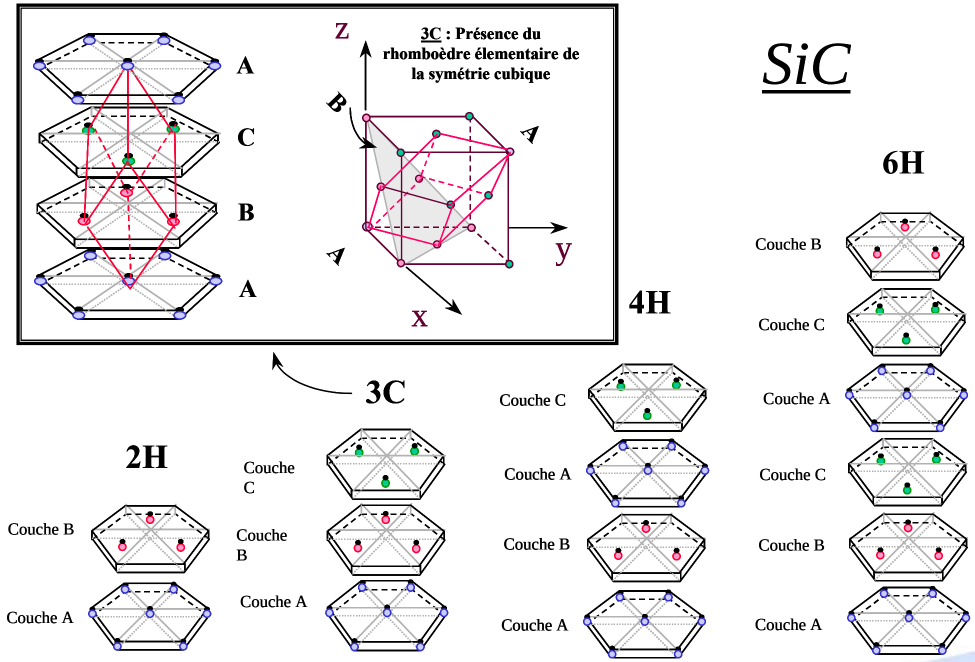


(a) The lifetime is not affected by neutron irradiation,
(b) Hold-time has no significant effect on the lifetime and
(c) Electron Microscopy shows:
the damage accumulation during the IN-PILE experiments is extremely low

Unpublished Results by Courtesy of B. Singh (Riso National Lab, Dk), S. Tähtinen (VTT-Finland) & P. Jacquet (SCK.CEN, B)

Dense high purity SiC : some Physical properties

SiC : some polytypes



(1) *C. Kittel Introduction to Solid State Physics*

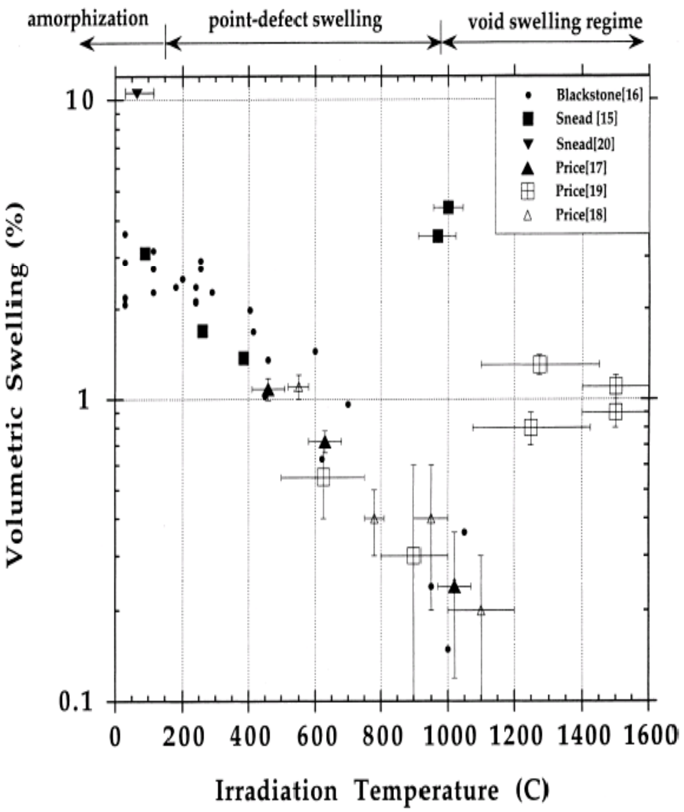
(2) *L.L. Snead J. Nucl. Mater. 329-333 (2004)*

- **T_m = 2545+/-40°C**
- **Semi-conductor**: E_{gap} ~3.2 eV **(1)**
- **Thermal Conductivity**
  - RT : K ~380 W/m/K for high-purity fully dense SiC **(2)**
  - T>~500°C umklapp phonon interaction controls mean free path of phonons

    scaling law K ~1/T **(1)**
- **Point defect : extreme variety**
  - V_{Si}, V_C, I_{Si}, I_C
  - Clusters
  - Electrical Charges

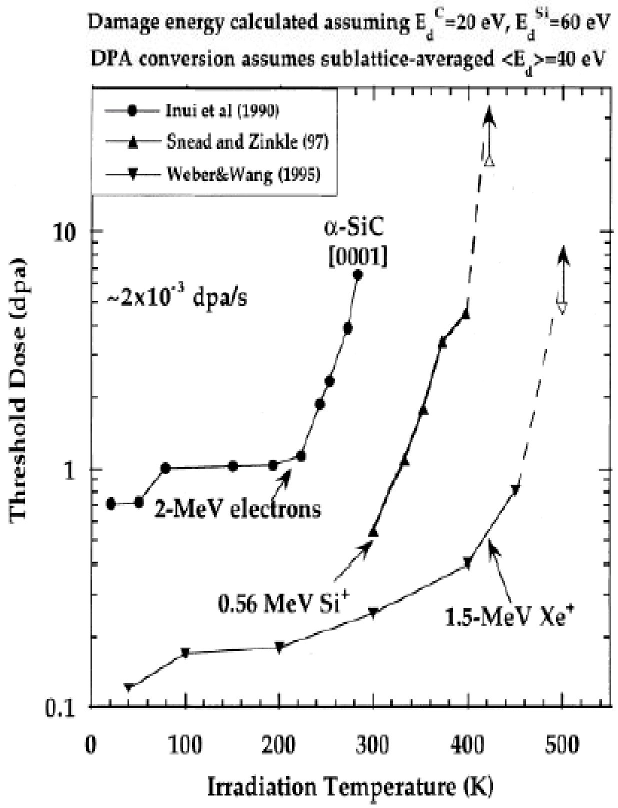
Dense high purity SiC : some irradiation effects
Volume Changes & amorphisation

Three Regimes versus Temperature



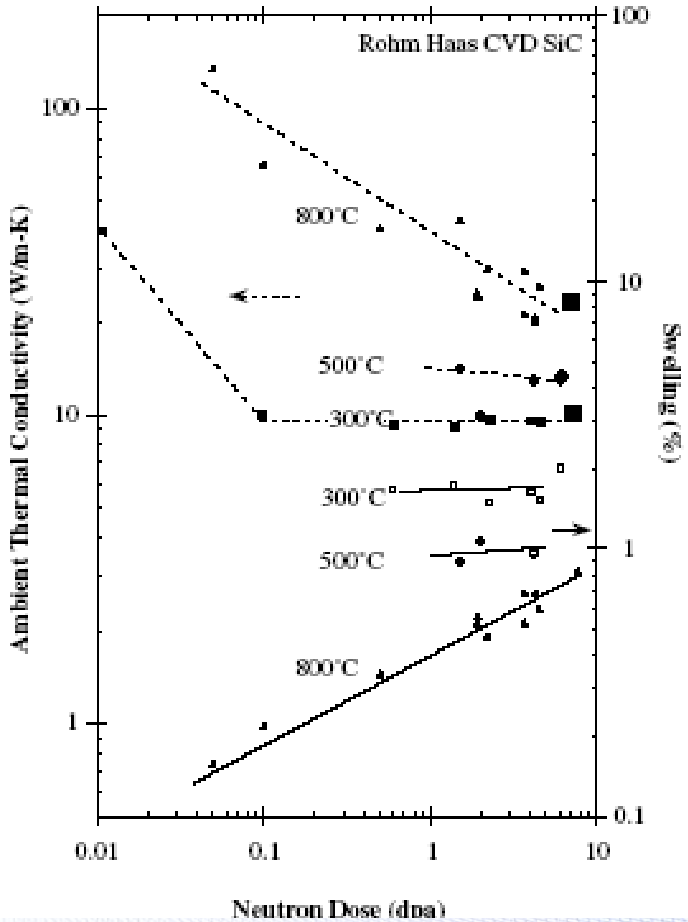
After E. Bloom J. Nucl. Mater. 258-263 (1998) 7

Amorphisation Threshold Dose (dpa)



After L. L. Snead et al. J. Nucl. Mater. 233-237 (1996) 26

Dense high purity SiC : some irradiation effects
Volume Changes & Thermal conductivity (1)



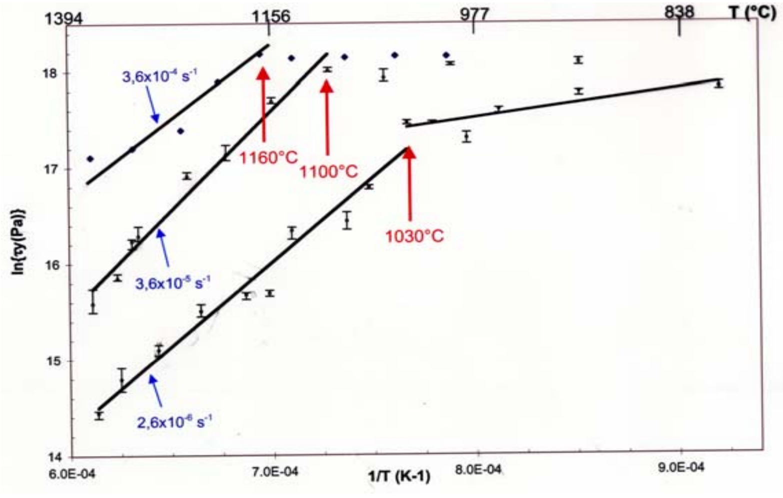
Saturation is achieved :

- **around 10 dpa**
- **for 300°C<Tirr<800°C**

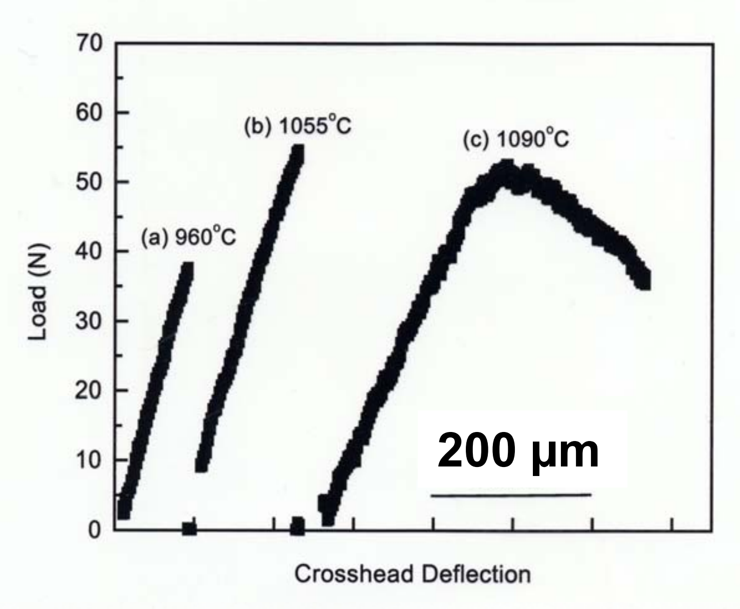
L. L. Snead J. Nucl. Mater. 329-333 (2004) 524

Monolithic 4H-SiC :
Ductile Brittle Transition Temperature (DBTT)

J.-L. Demenet, M. H. Hong and P. Pirouz, Scripta mater. 43(9), 865-870 (2000)



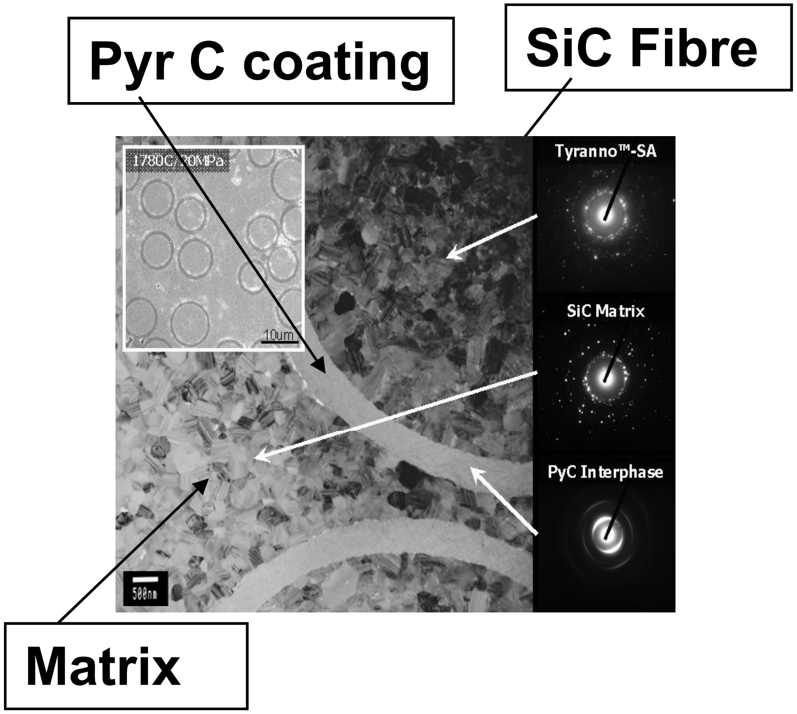
DBTT > In Service Temperature



Brittleness even for T>DBTT

Need for Composite to Improve Fracture Toughness

Microstructure SiCf-SiC composite



After A. Kohyama

- Volume fraction of matrix ~60%
- Some process for dense matrix like NITE (1) introduces additional element :

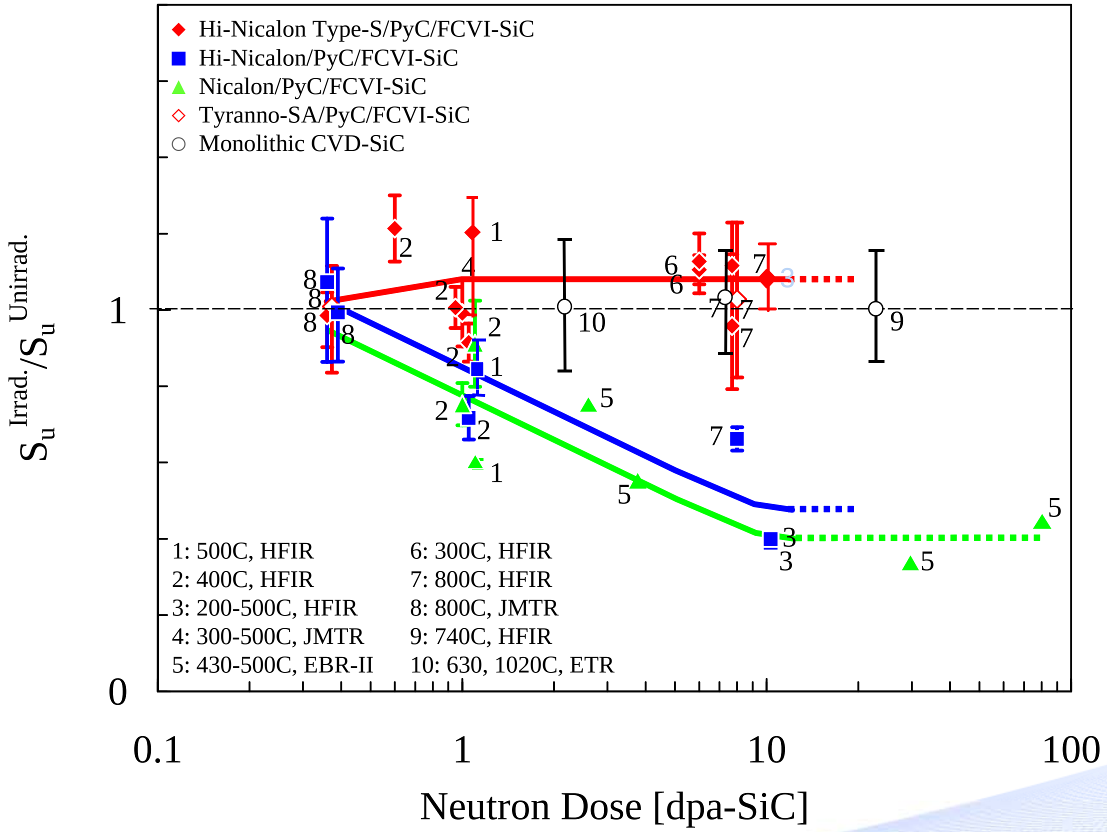
Al2O3, Y2O3, SiO2
Al2O3+Y2O3=12wt%
SiO2=3wt%

(1) Nano-Infiltration and Transient eutectic

Even with dense matrix:

- **Gas (He) permeation is high : ~ a few 10^{-13} m^2/s**
- **Liner is mandatory for $SiC_{f/}SiC$ to be used as tight safety barrier**

Irradiation Effect on Flexural Strength of SiCf/SiC



After R. H. Jones et al. J. Nucl. Mater. 307-311 (2002) 1057

[1, 2] L.L. Snead, et al., JNM 283-287 (2000) 551-555.
[3, 4] T. Hinoki, et al., Mater. Trans., 43 [4] (2002) 617-621
[5] R.H. Jones, et al., 1st IEA-SiC/SiC (1996)
[6, 7] T. Hinoki, et al., JNM, 307-311(2002) 1157-1162.
[8] T. Nozawa, et al., JNM 307-311 (2002) 1173-1177.
[9] R.J. Price, et al., JNM 108-109 (1982) 732-738.
[10] R.J. Price, et al., JNM 33 (1969) 17-22.

Re-assessment of SiC$_f$/SiC Programme

SiCf/SiC Properies and parameters	Desired values	2D EU Ref	3D EU Ref	
Density (kg/m3)	~3000	2730	2650	
Porosty (%)	5	13	>13	
Young's Modulus (GPa) (in plane)	300-500	296	**252**	
Poisson's ratio	0.16-0.18	nd	nd	
Thermal Expansion Coefficient (10^{-6}/^{o}C) (30-1000^{o}C) In-plane Normal	4	4.7 7.0	**4.7** **6.8**	
Thermal Conductivity (in plane) (W/m/K)	20	nd	nd	
Thermal Conductivity (through thickness) (W/m/K)	20	17	28	
Maximum allowable combined stress (MPa)	190	**110**	**nd**	
Maximum allowable temperature (swelling basis) (^{o}C)	1000			
Minimum allowable temperature (thermal conductivity) (^{o}C	600			

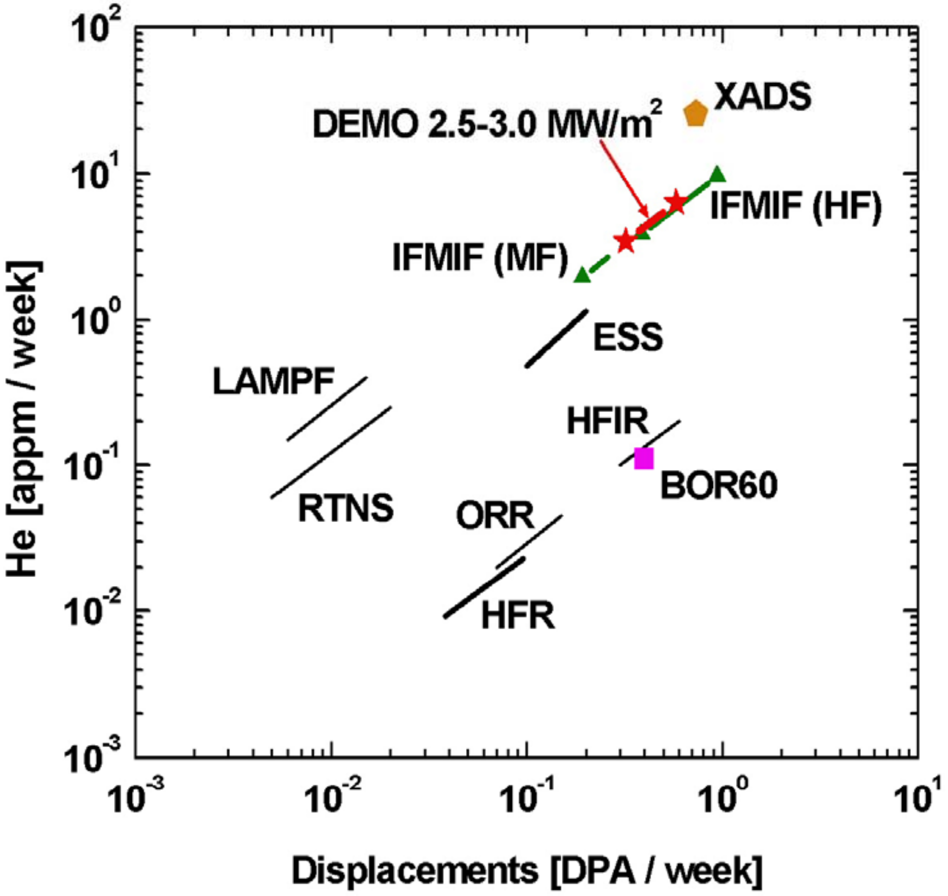
Table 1: Desired values from the TAURO design activity and measured one on the 2D-EU reference SiC$_f$/SiC composites.

Experimental results on Radiation Effects under High Energy Neutrons Main Conclusions and opened issues

- **Ferritic/martensitic steels at low temperature**
  - He and point defect accumulation induces strong hardening
  - Segregation of He to grain-boundaries triggers intergranular embrittlement
  - Phase instability (α/α'unmixing) contributes also to hardening
- **ODS steels**
  - Nano-structuration should improve the radiation resistance
- **Opened issues**
  - Possible occurrence of swelling at high dose and high production of Helium (and hydrogen)
  - Optimisation of the microstructure to trap He inside the grain avoiding inter-granular embrittlement
  - Optimisation of the Cr content to mitigate the α/α' unmixing at low temperature
  - Suitability of SiC_f/SiC composite
- **How to extrapolate these data to the actual D-T fusion spectrum**

EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT

The various facilities in a diagram: dpa/week, appmHe/week



Interpolation, Correlation and Extrapolation to Fusion Reactor require modelling

Radiation Effects Modelling (1)
Objectives of the EU Programme

- **To study the radiation effects in the EUROFER RAFM steel**
  - **In the range of temperatures from RT to 550 ^{0}C**
  - **Up to high dose ~100dpa**
  - **In the presence of high concentrations of transmutation impurities (i.e. H, He)**

- **To Develop modelling tools and database capable of:**
  - **Correlation of results from:**
    - **The present fission reactors & spallation sources**
    - **The future intense fusion neutron source IFMIF**
  - **Extrapolation to high fluences and He & H contents of fusion reactors**

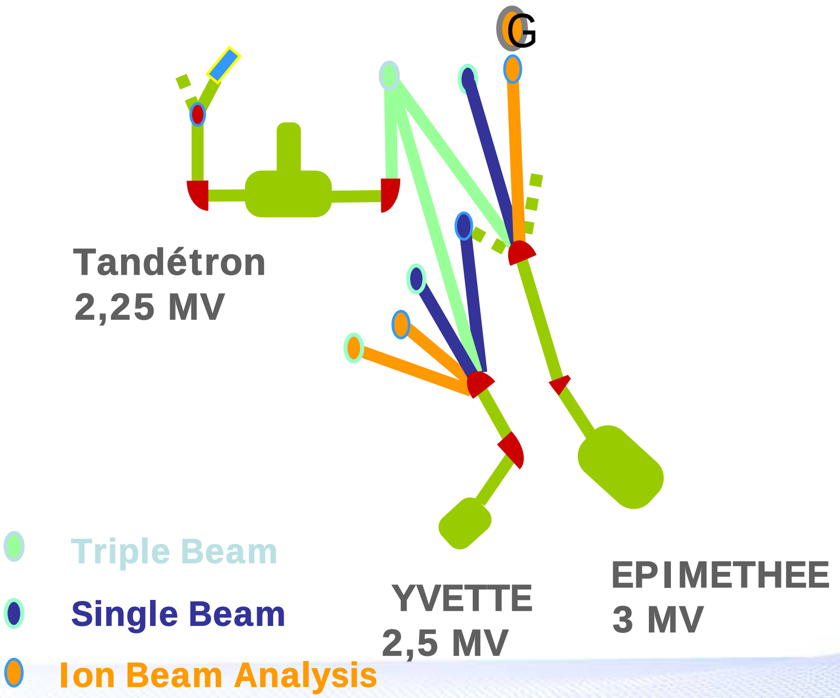
- **To experimentally validate the models on the adequate system & at the relevant scale**

M. Victoria, G. Martin and B. Singh,
The Role of the Modelling Radiation Effects in metals in the EU Fusion Materials Long Term Program (2004)

Thank you for your Attention

Modelling Oriented Experiments with Rapid Feedback

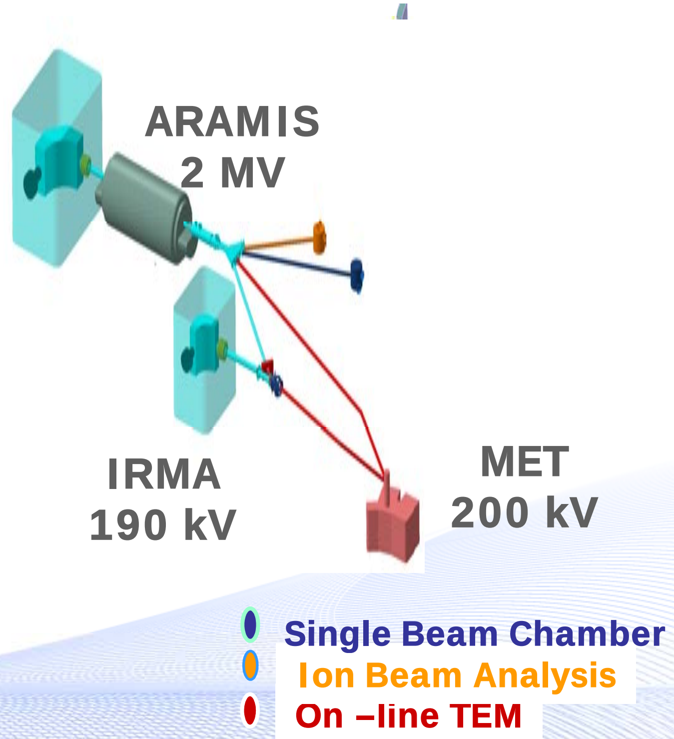
Triple beam : dpa and 2 implantations



Kinetic Pathway up to ~0.5T_M:

dpa & transmutation

In-Situ TEM : one beam (dpa, implantation)



Point Defect Dynamics (<0.3T_M):

dpa and/or Implantation

Start of Operation as a Users Facility: Start January 2009

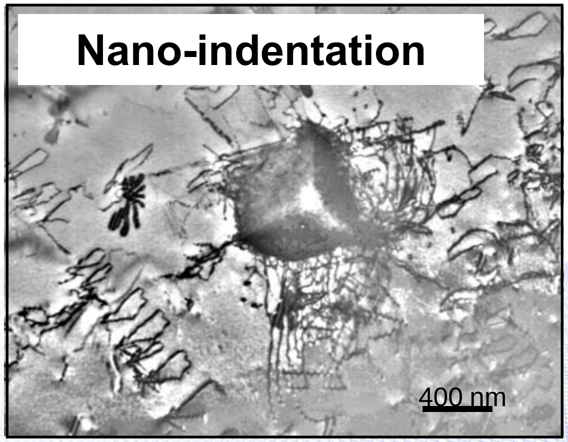
JANNUS : modelling oriented irradiation & characterisation

- Volume → experimental and simulated volumes are identical
- Surfaces → taken into account
- Flux and time conditions → explore wide enough ranges (ΔT ~200°,

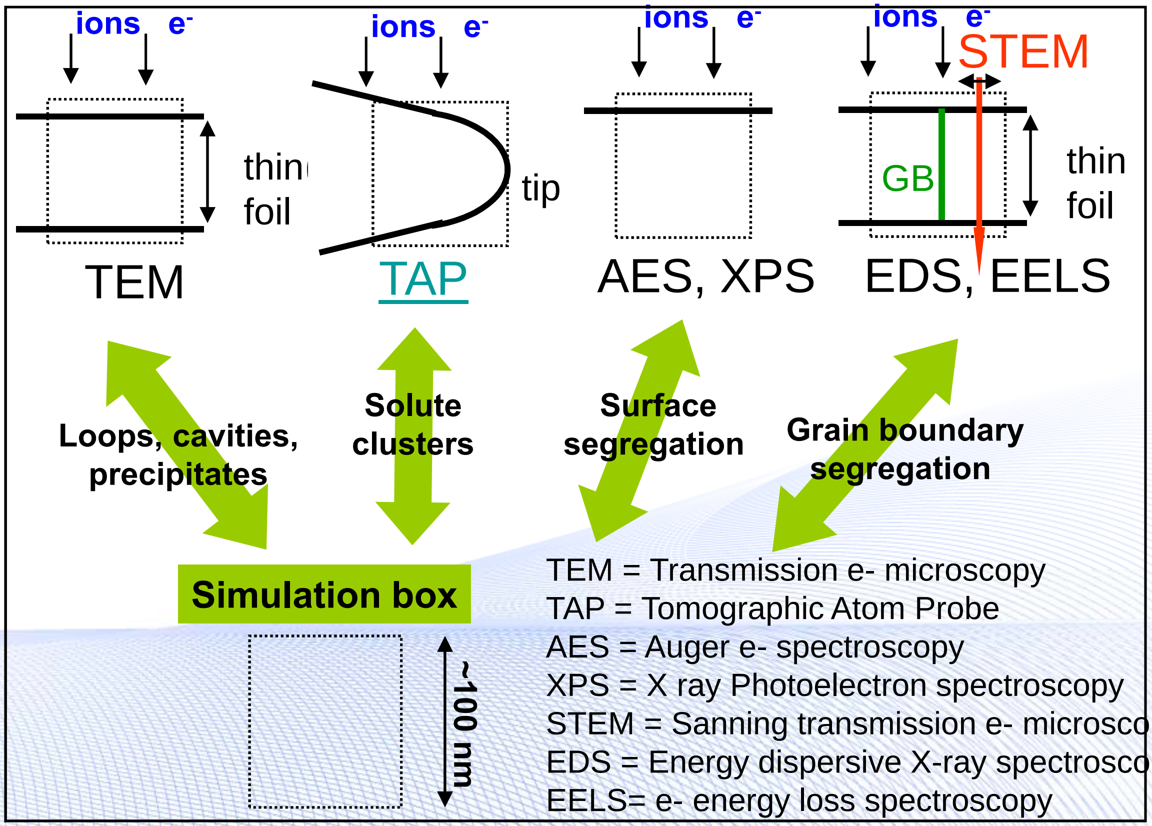
Irradiation → **Charged particles: Dual Beam + in situ TEM, e$^-$ VDG, HVTEM**

Direct observation →

Mechanical testing



Nano-indentation



Loops, cavities, precipitates

Solute clusters

Surface segregation

Grain boundary segregation

Simulation box

TEM = Transmission e- microscopy
TAP = Tomographic Atom Probe
AES = Auger e- spectroscopy
XPS = X ray Photoelectron spectroscopy
STEM = Sanning transmission e- microscopy
EDS = Energy dispersive X-ray spectroscopy
EELS= e- energy loss spectroscopy