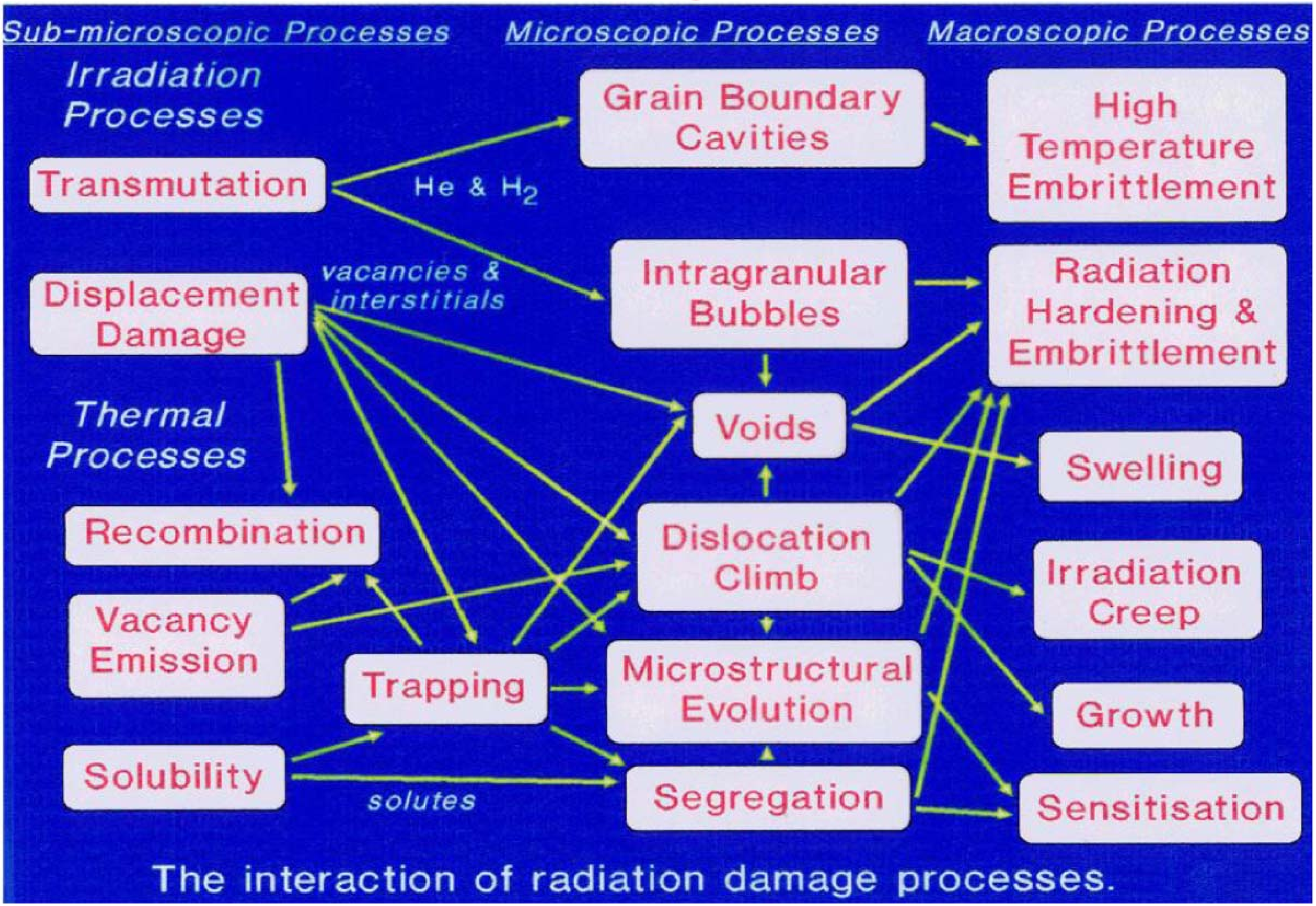
Overview of Radiation Damage Effects

Steve Roberts
U. Oxford
May 19, 2015

2nd RaDIATE Collaboration Meeting
RAL

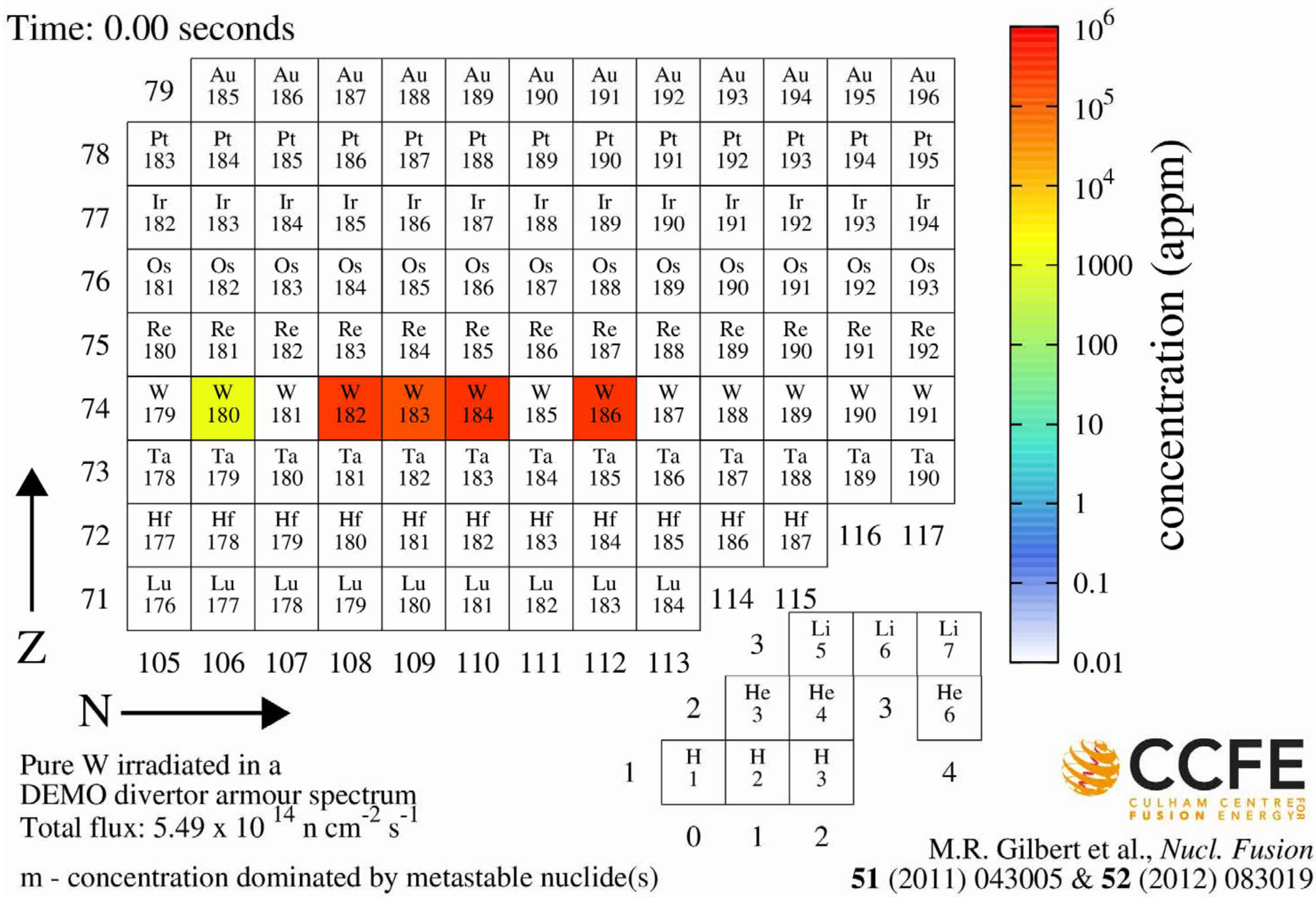
Radiation damage in Materials



C.A. English (2011)

Transmutation

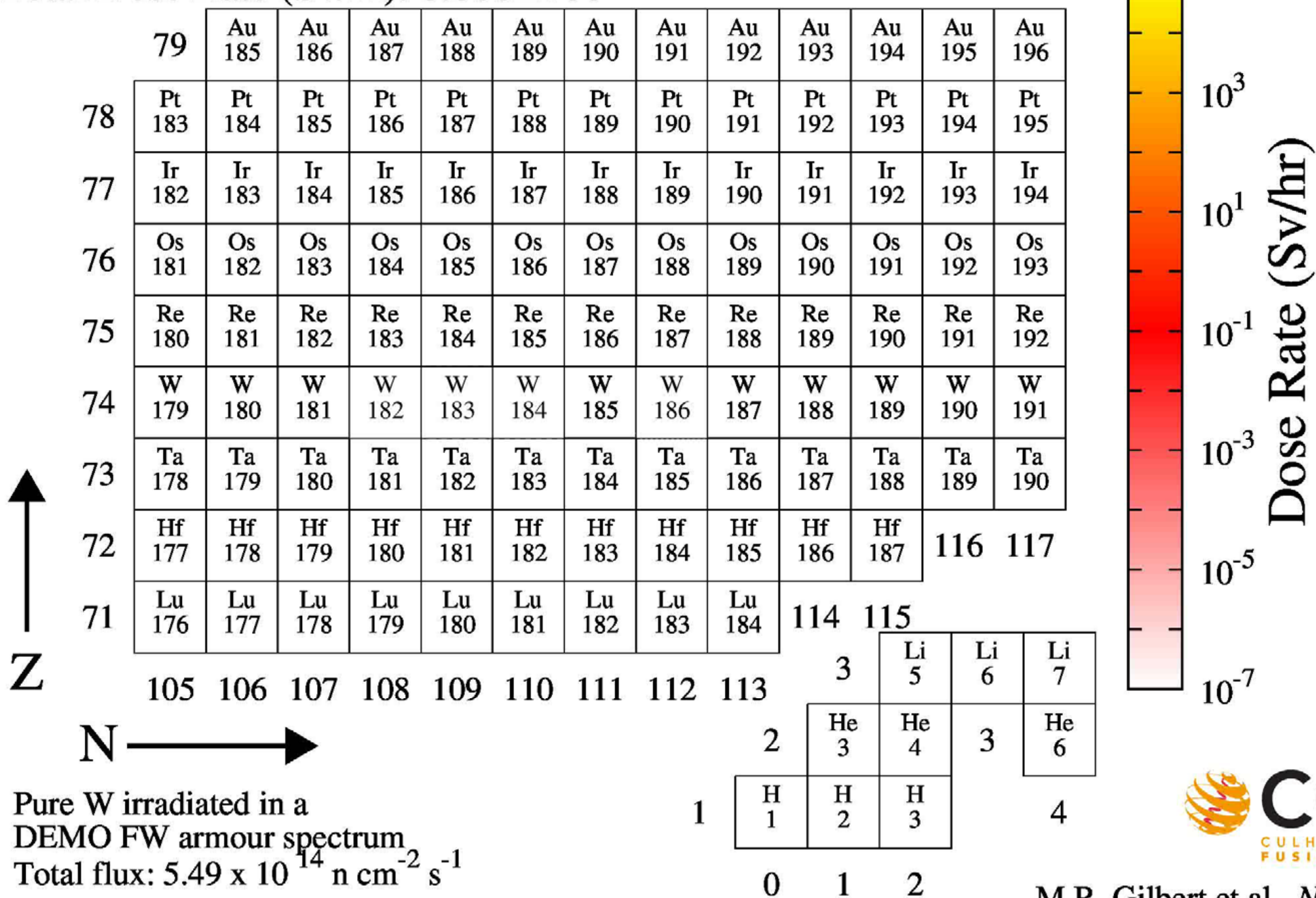
Tungsten Transmutations in Fusion Reactor



Tungsten Transmutations - activity

Time: 0.00 seconds

Total Dose Rate (Sv/hr): 0.000E+00



Pure W irradiated in a DEMO FW armour spectrum

Total flux: 5.49×10^{14} n cm^{-2} s^{-1}

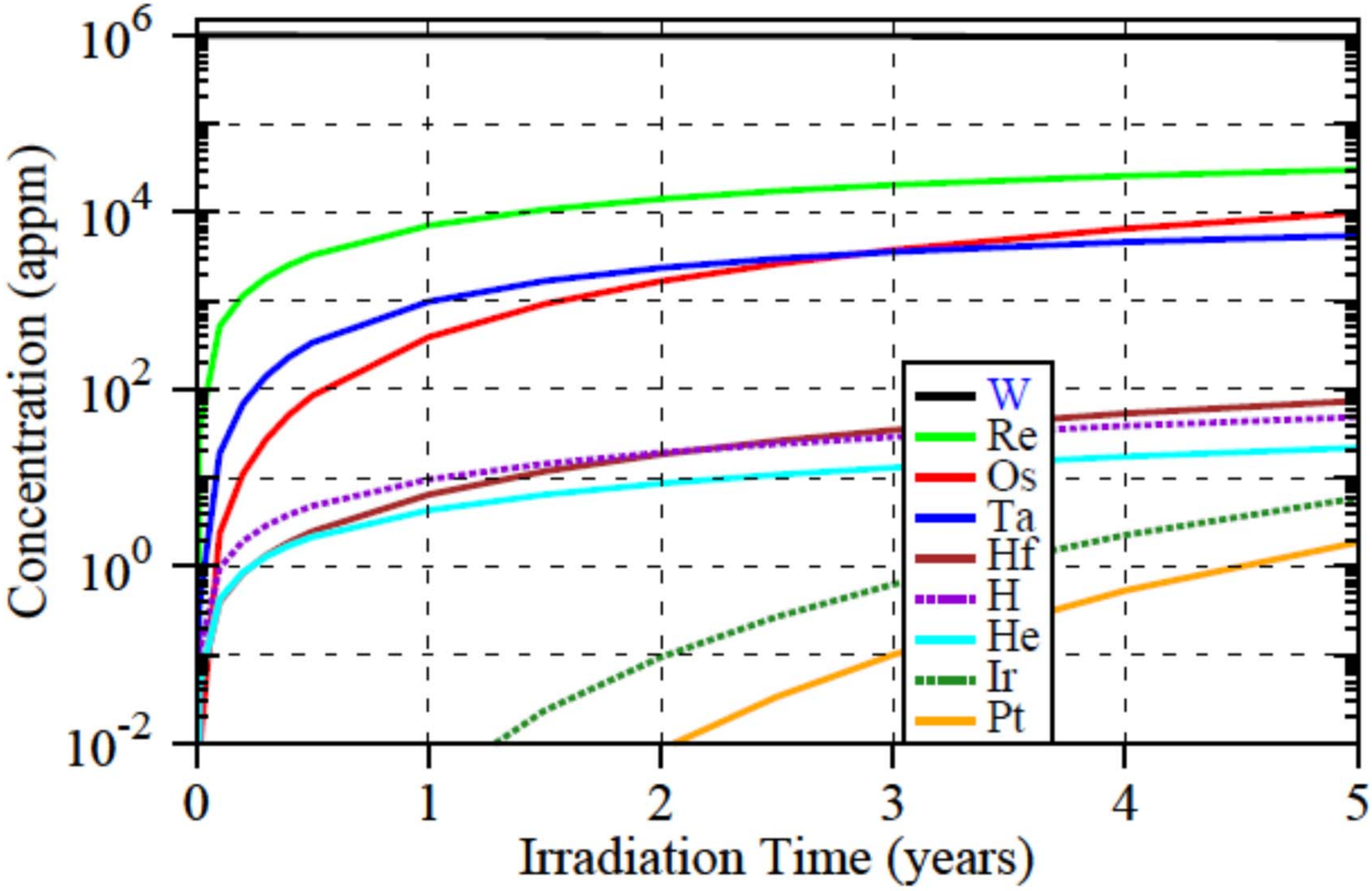
m - Dose Rate dominated by metastable nuclide(s)

CCFE CULHAM CENTRE FOR FUSION ENERGY

M.R. Gilbert et al., *Nucl. Fusion* **51** (2011) 043005 & **52** (2012) 083019

Tungsten transmutation in fusion power reactor

- Pure W under outboard equatorial FW armour flux for 5 fpy



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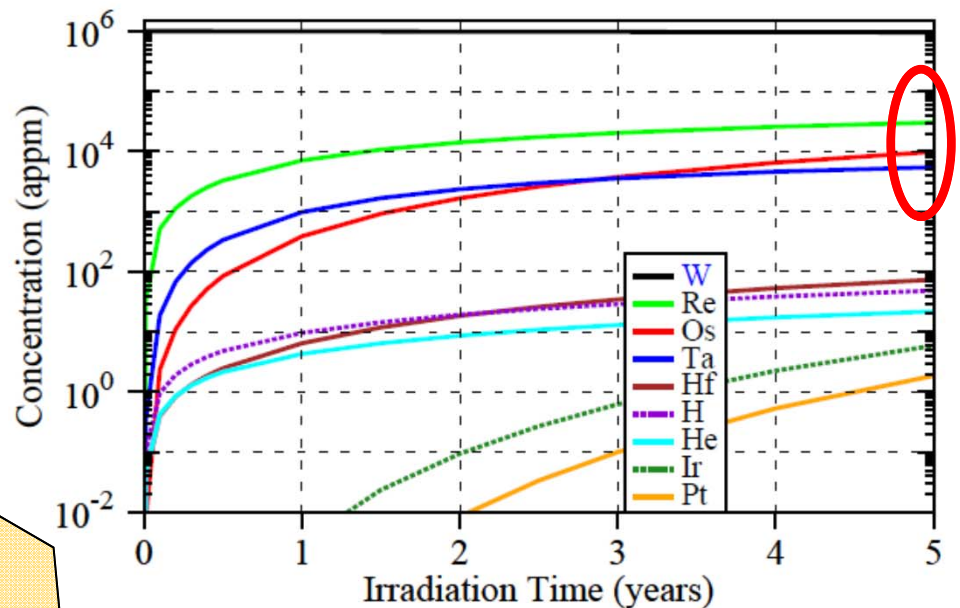
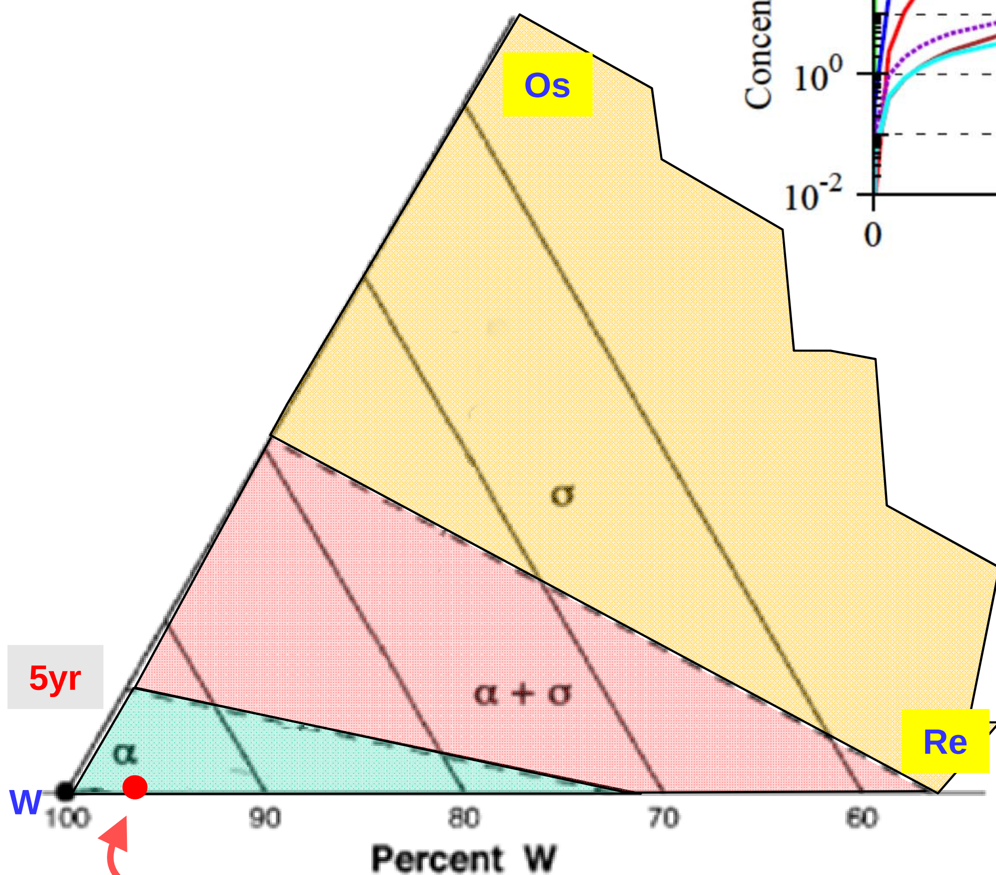
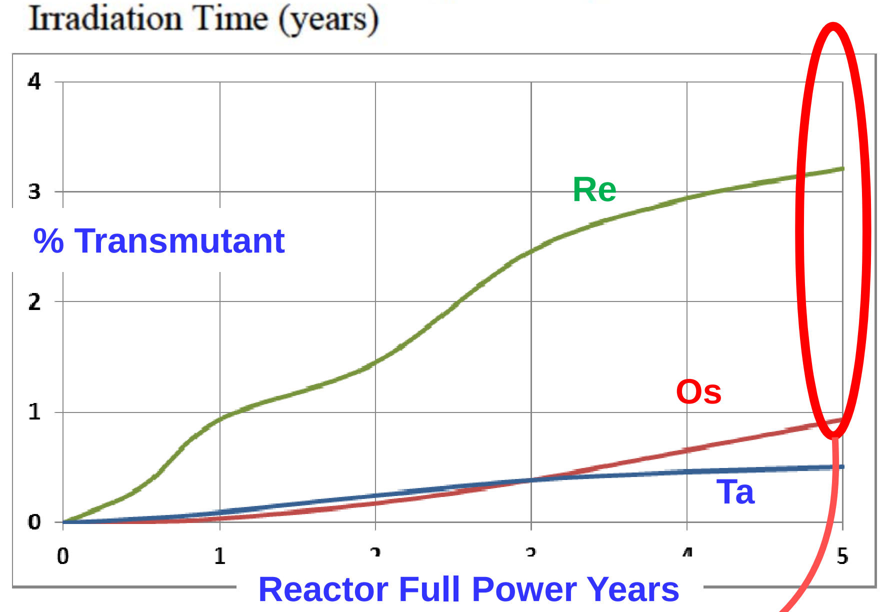






M.R. Gilbert et al., *Nucl. Fusion* **51** (2011) 043005 & **52** (2012) 083019

Tungsten transmutation in fusion power reactor

Ion irradiation can’t mimic transmutation effects

But we can MODEL what transmutations we expect

And can ion-irradiate pre-made W alloys

To see what effect displacement damage -

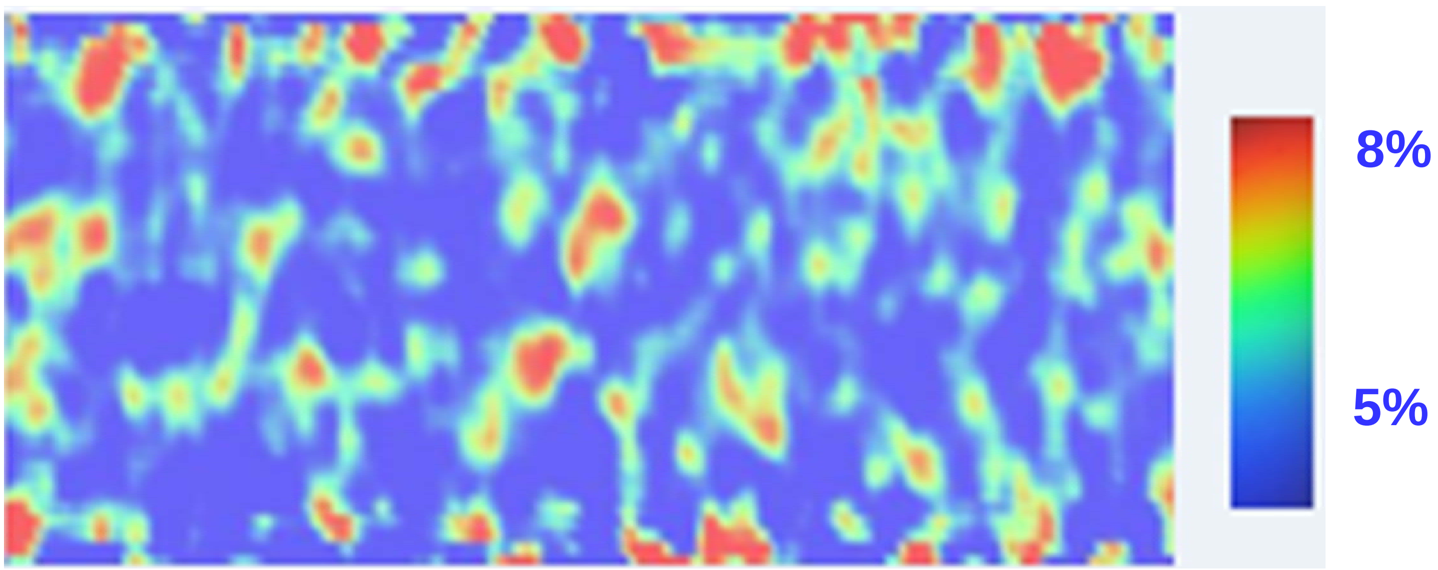
(and if we like, He, H)

have on microstructures and properties.

Radiation-induced clustering in alloys

W- 5%Re should be a stable solid solution
… but it's not when it is irradiated

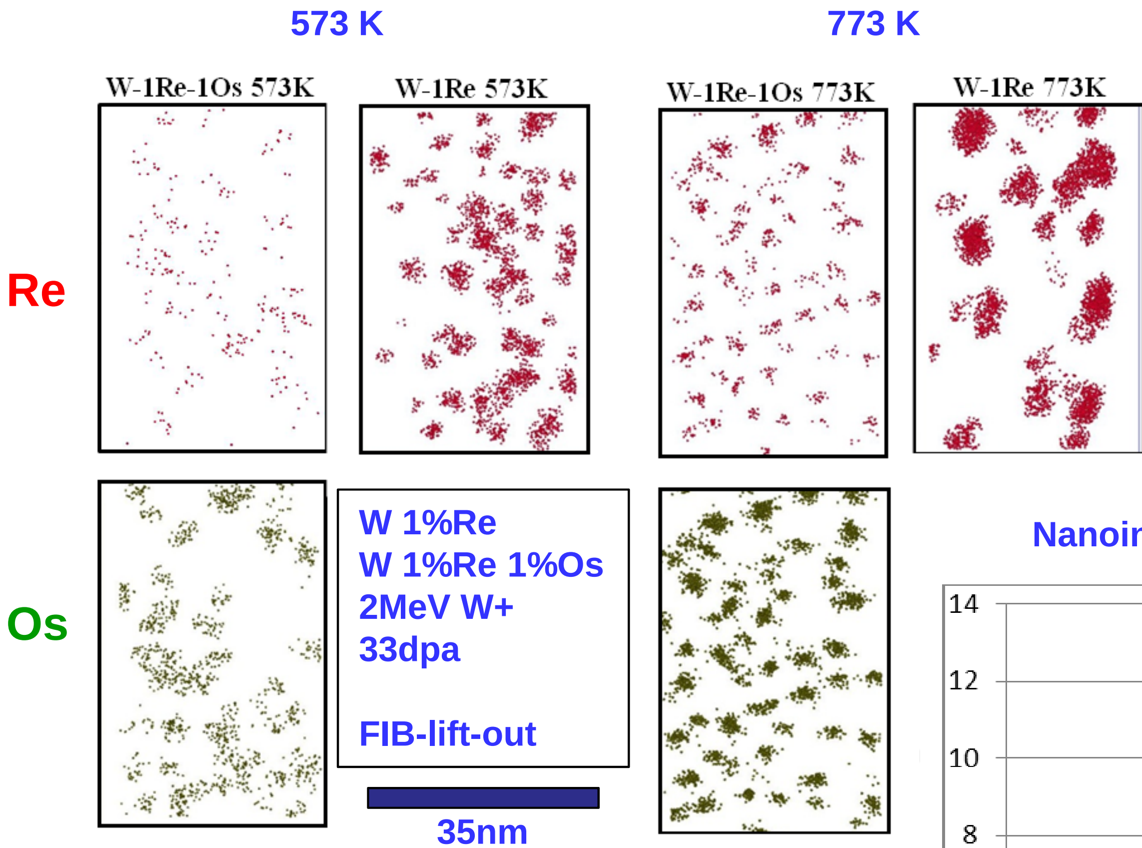
Under Fusion Power Reactor conditions,
pure W transmutes to give 5%Re in ~ 7 years.



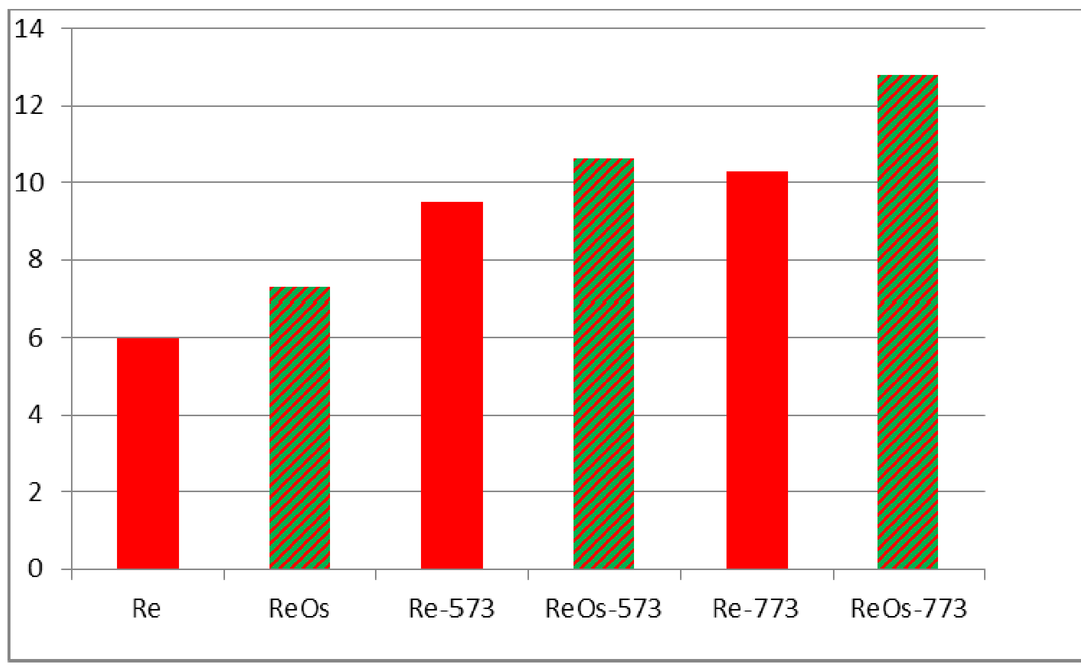
Ion irradiation to 2.64 x 10^{15} W^{+}/cm^{2} (33dpa)
Dose rate: 3.57 x 10^{-4} dpa / s
Temperature: 300°C

A. Xu (Oxford) *unpublished* 2013

Clustering and Hardening in “Transmuted” W



Nanoindentation hardness (GPa) (100nm depth)



Preliminary analysis indicates that the clusters are very weak obstacles:

$\Phi_c \approx 85°$

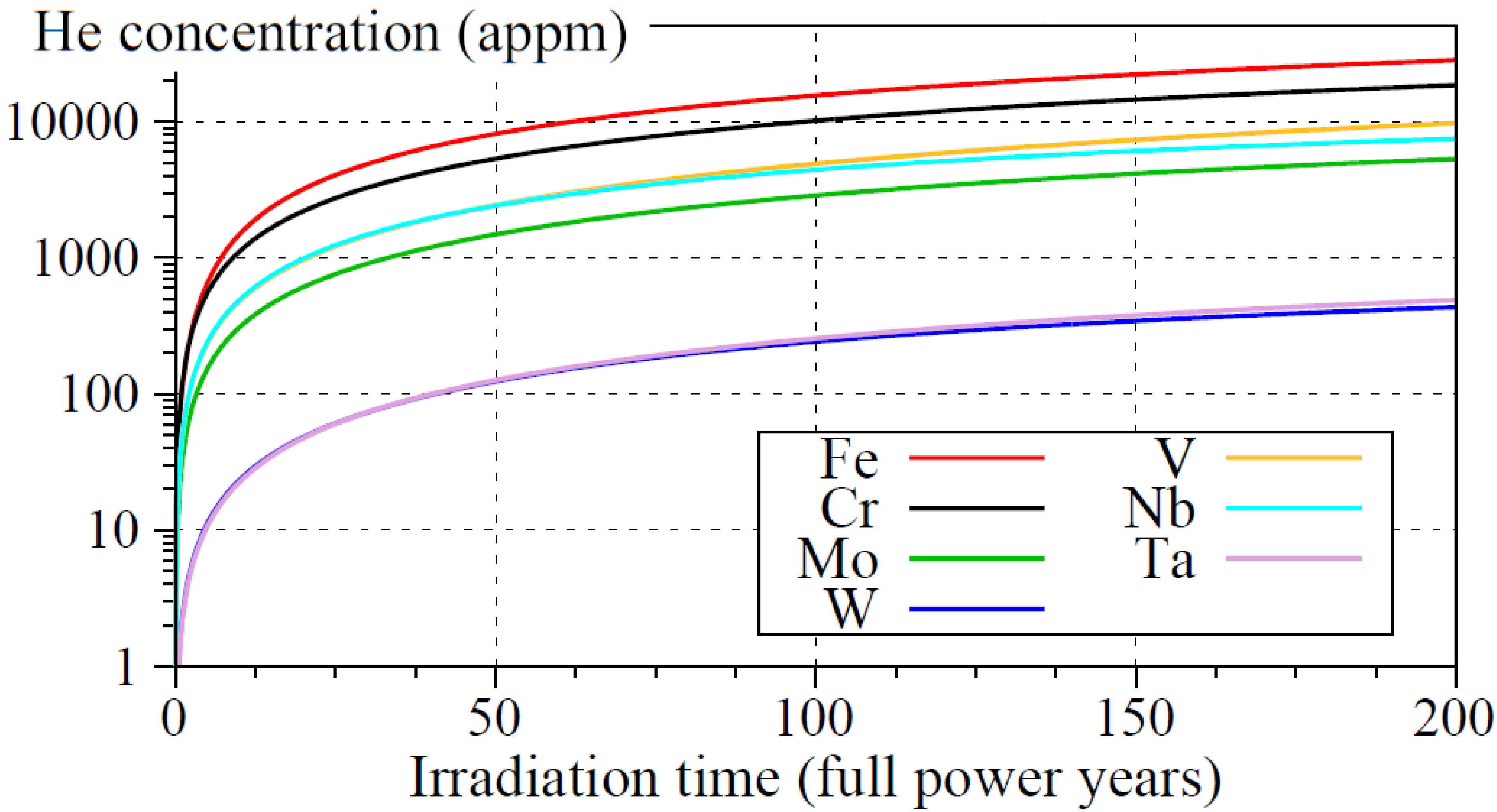
But there are lots of them, very closely spaced
- especially in W-Re-Os

Same would apply to neutron irradiation ???

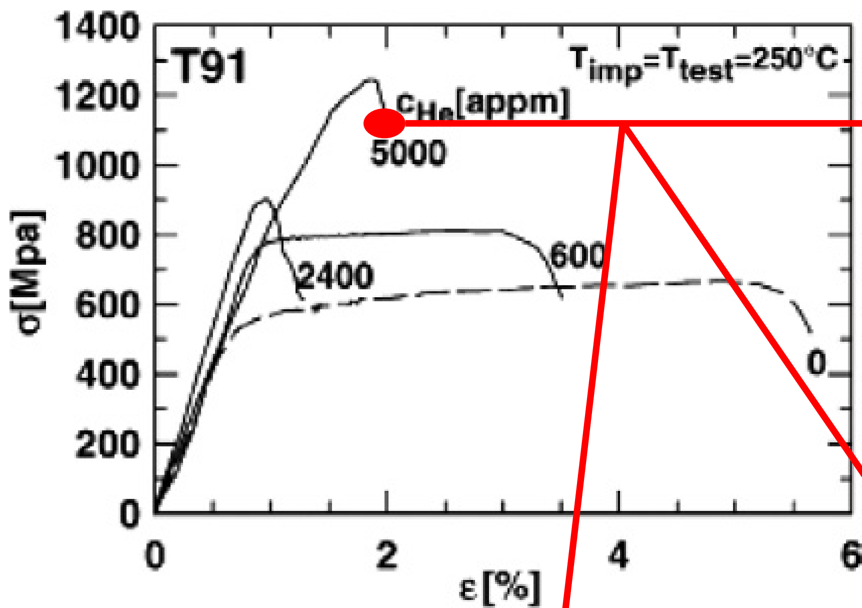
A. Xu, D.E.J. Armstrong (Oxford) K. Rajan (Iowa State) *unpublished* 2014

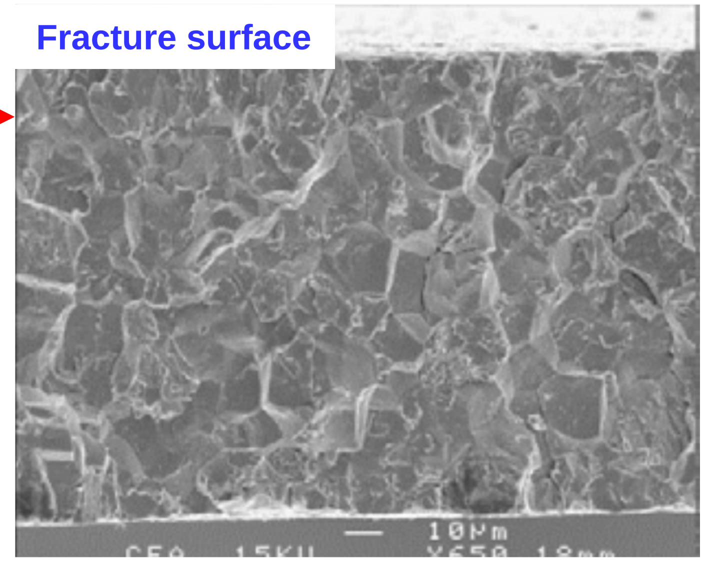
Transmutation gases

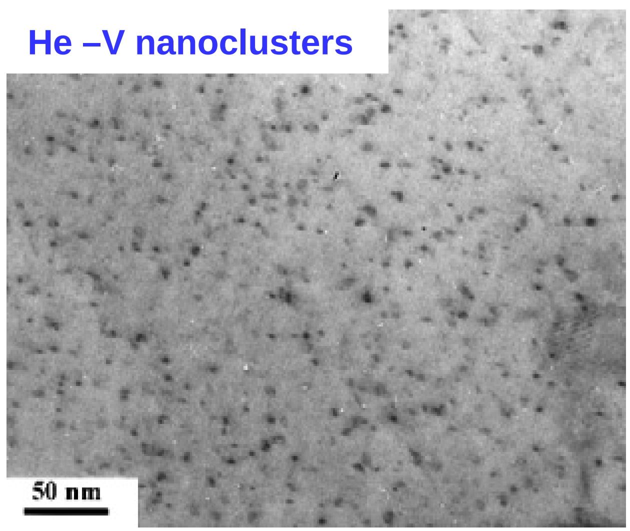
Transmutations producing He in fusion power reactor

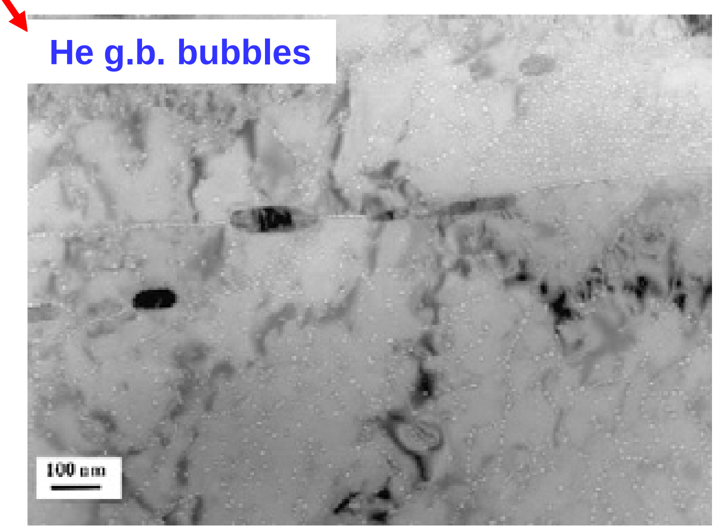


Effects of Implanted He on T91 steel







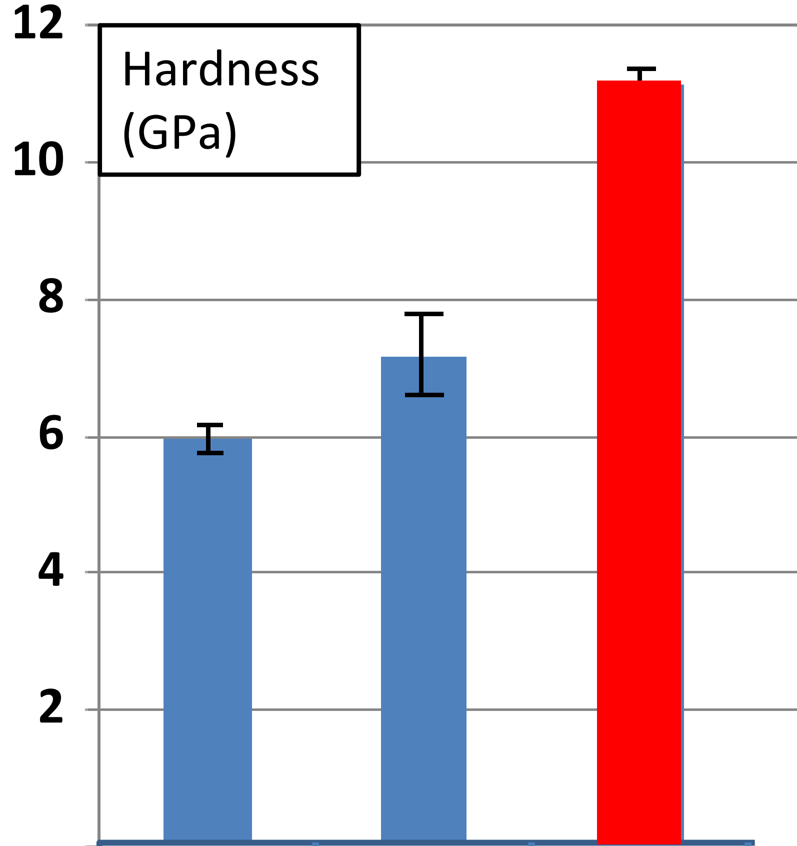


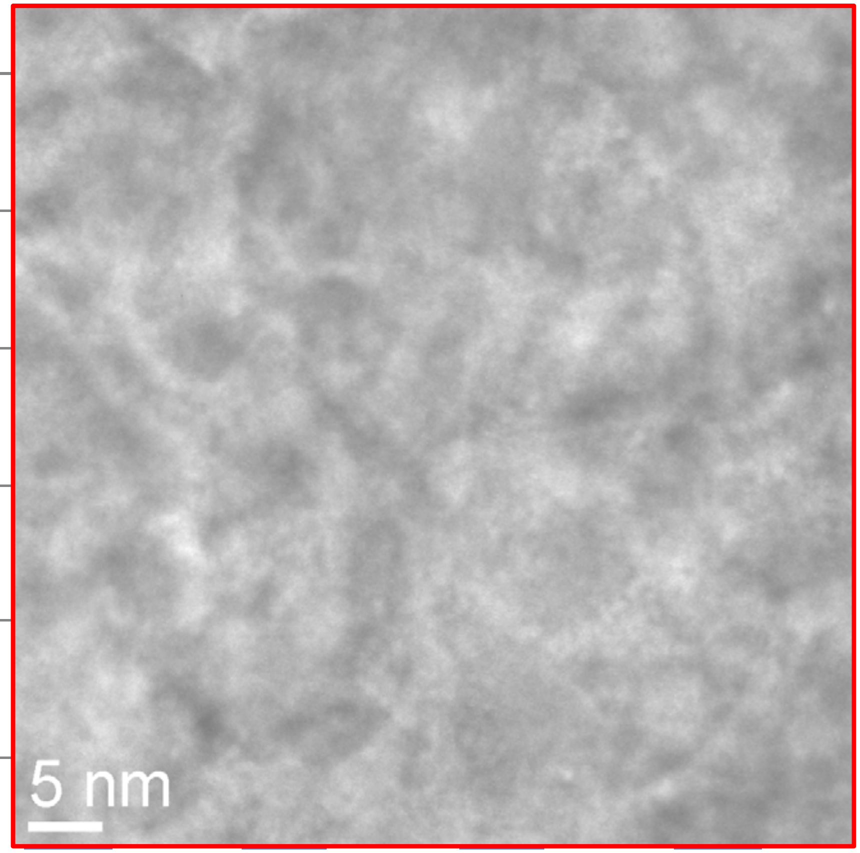
"Uniform implantation of 23 MeV *α*-particles up to 5000 appm at 250°C carried out at the compact cyclotron of Forschungszentrum Jülich (FZJ)"

J.-L. Boutard et al. C. R. Physique 9 (2008) 287–302

P. Jung, J. Henry, J. Nucl. Mater. 318 (2003) 241–248 & 249–259.

Tungsten – Hardening by Displacement Damage and Helium



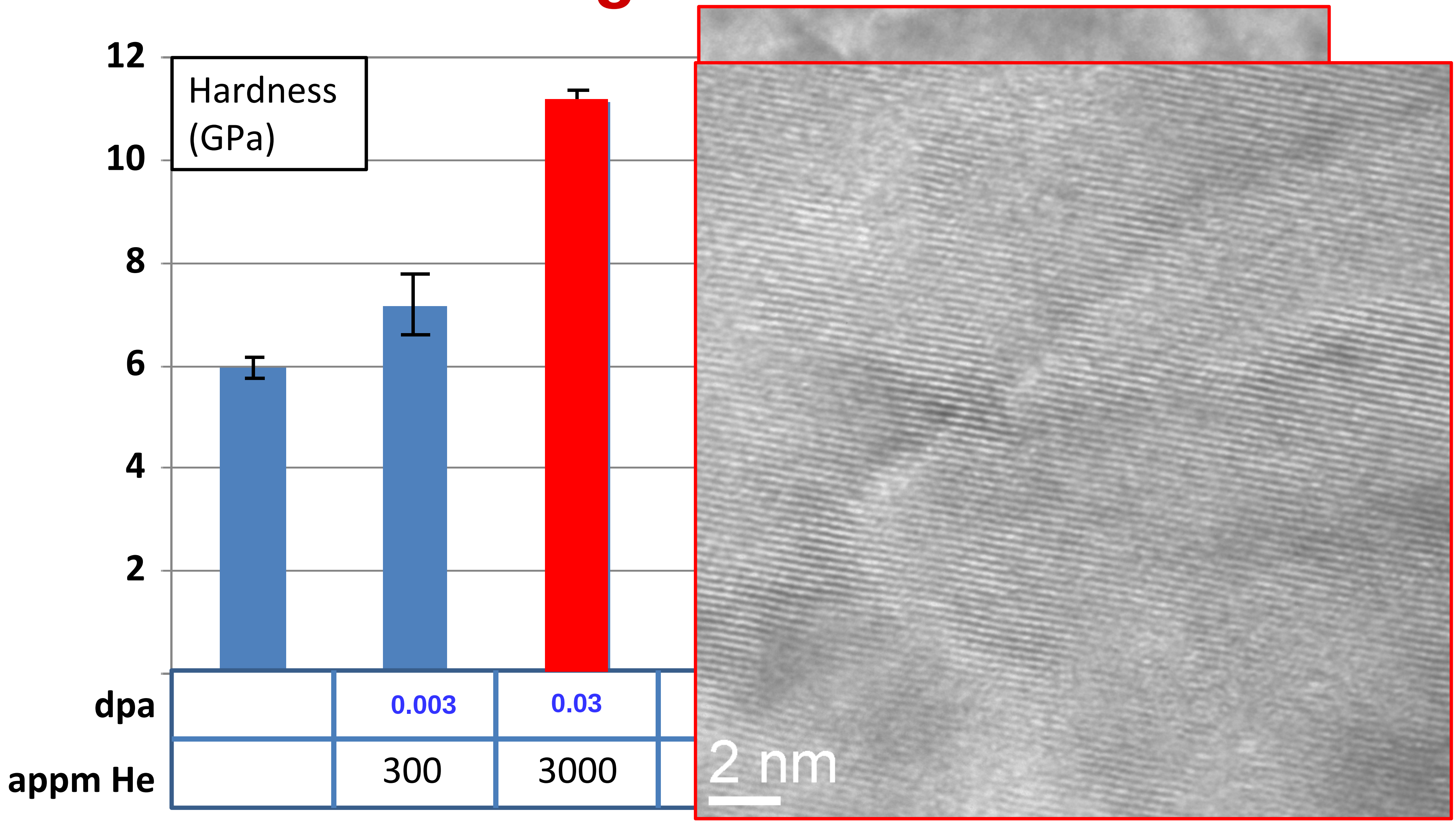


dpa		0.003	0.03
appm He		300	3000

Polycrystalline W 99.99% pure, sequentially ion-implanted with W^+ and He^+ at 300°C
W implantation depth 0 - 200nm; He implantation depth range 0 - 2500 nm
Hardness data at 100 nm indenter depth .

C. Beck & D. Armstrong (Oxford) *unpublished* 2013

Tungsten – Hardening by Displacement Damage and Helium



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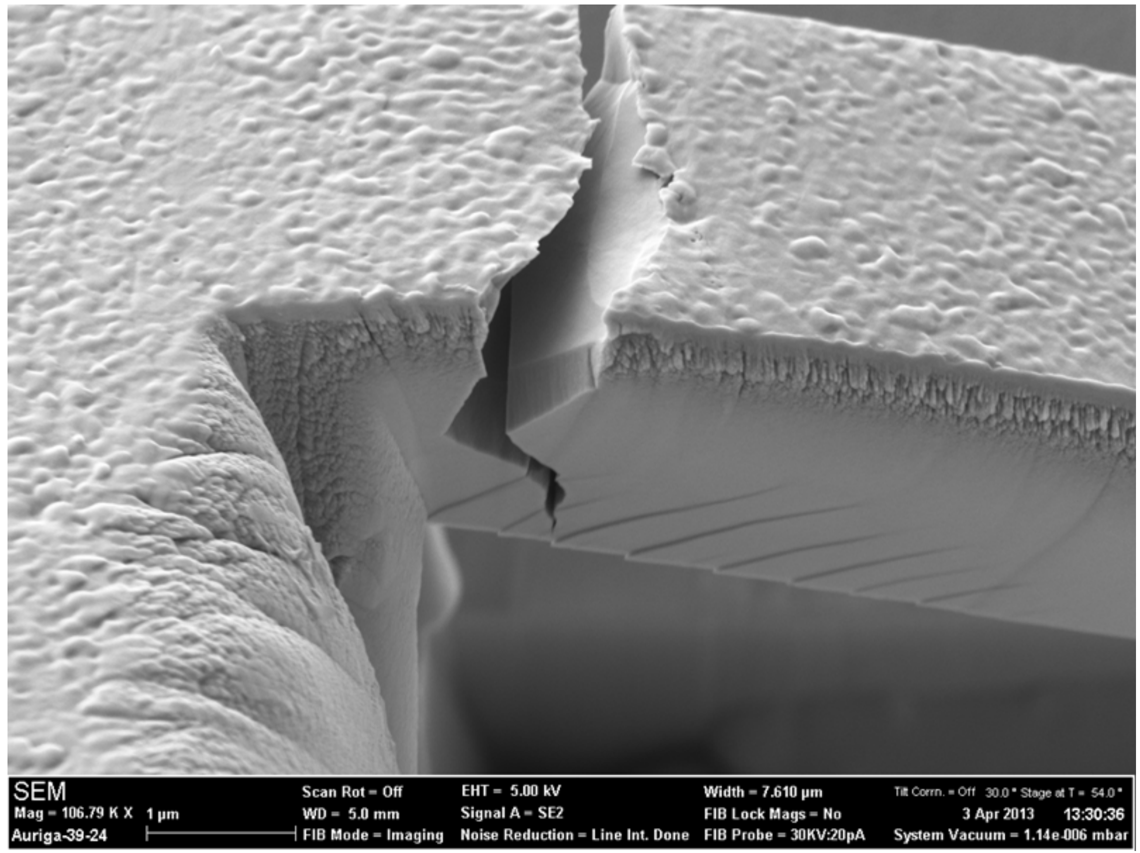
W implantation depth 0 - 200nm; He implantation depth range 0 - 2500 nm
Hardness data at 100 nm indenter depth .

C. Beck & D. Armstrong (Oxford) *unpublished* 2013

Tungsten – Embrittlement by Displacement Damage and Helium

Irradiation	Fracture ?
none	0 / 7
1.7 dpa W^{12+}	1 / 16
600 appm He	0 / 13
1.7 dpa W^{12+} + 600 appm He	7 / 10



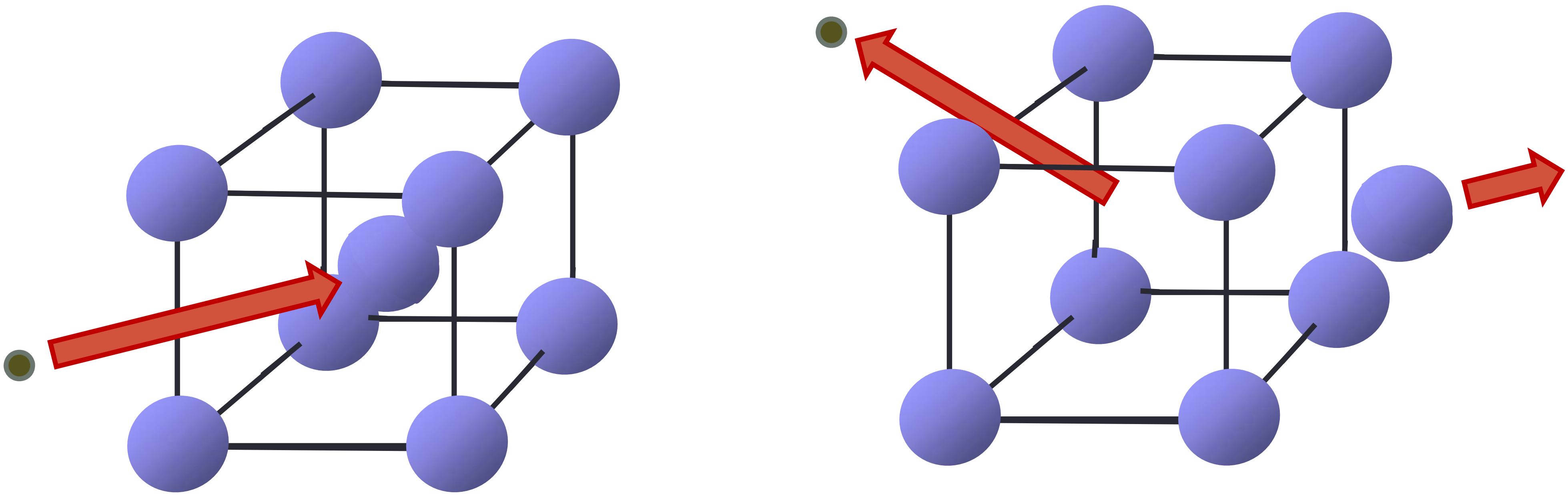
Polycrystalline W 99.99% pure, ion-implanted with W^{12+} (36MeV) and He^{+} at 800°C
W + He simultaneously implanted
W implantation depth ~2.5 μm; He depth range ~ 2.8 μm
Fracture data from microbeams 3 μm deep .

J. Gibson & D. Armstrong (Oxford) *unpublished* 2013

“Damage”

Elastic scattering of neutrons

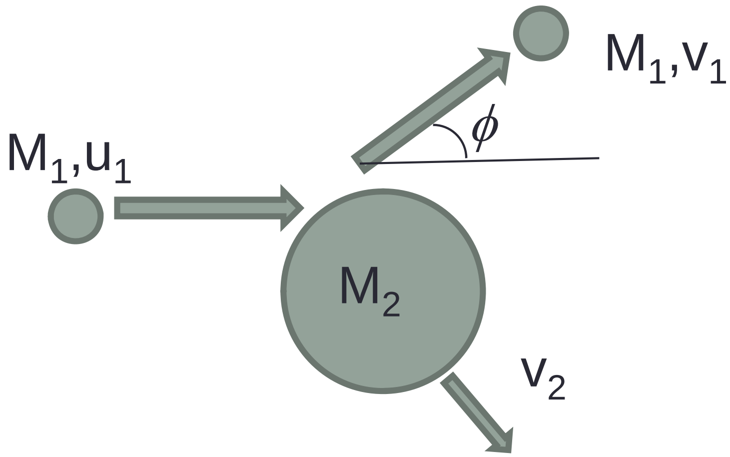
…. What about the “target” atoms?



	E_d		E_d		E_d
Al	~32eV	Fe	~24eV	Si	~13eV
Cu	~25eV	W	~40eV	C (graphite)	~25-60eV

Fusion neutrons are ~14MeV !

Elastic scattering of neutrons



$$v_1^2 = 2(1 - \cos \emptyset)\frac{u_1^2 M_1^2}{(M, +M_2)^2}$$

$$E_2 = \Lambda E_1 \sin^2(\emptyset/2)$$

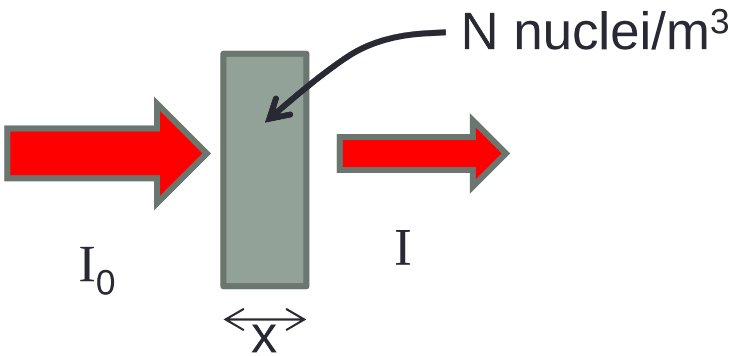
$$\Lambda = \frac{4M_1 M_2}{(M_1 + M_2)^2}$$

$$\bar{E}_2 = \Lambda E_1/2$$

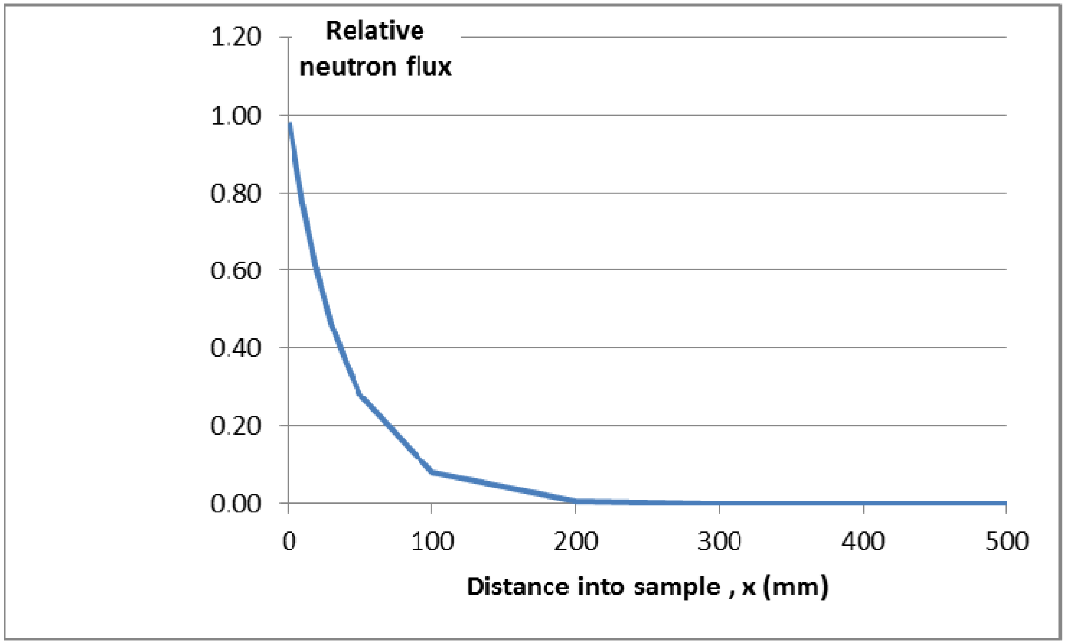
For 14 MeV neutrons into iron, M_1 = 1, M_2 = 56, so Λ = 0.069

So $\bar{E}_2$ = 482 keV …. about 34 collisions per neutron

Elastic scattering of neutrons



$$I = I_0 \exp(-N\sigma x)$$

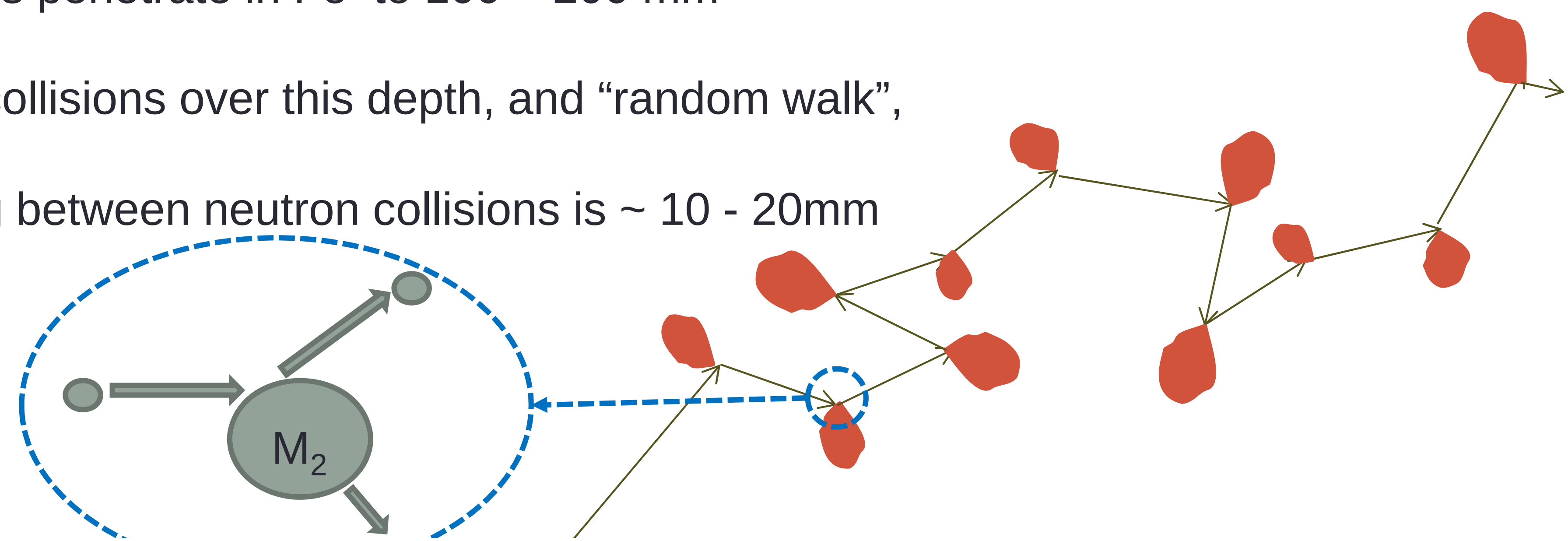


For σ = 3.2 barns,
N = 8×10^{28} m^{-3}

Neutrons penetrate in Fe to 100 – 200 mm

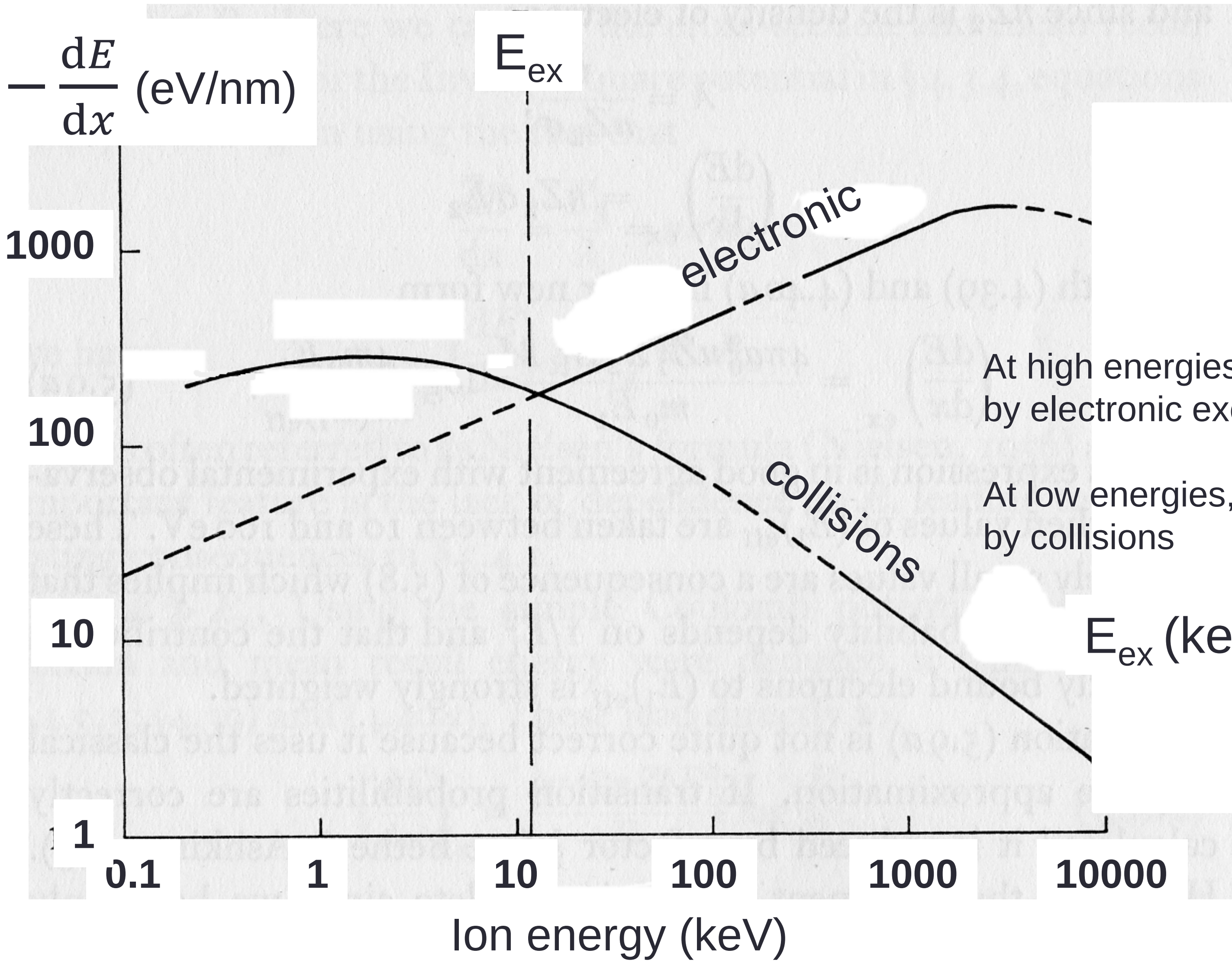
If ~ 30 collisions over this depth, and "random walk",

Spacing between neutron collisions is ~ 10 - 20mm



The collision cascade

Energy loss from C ions in graphite

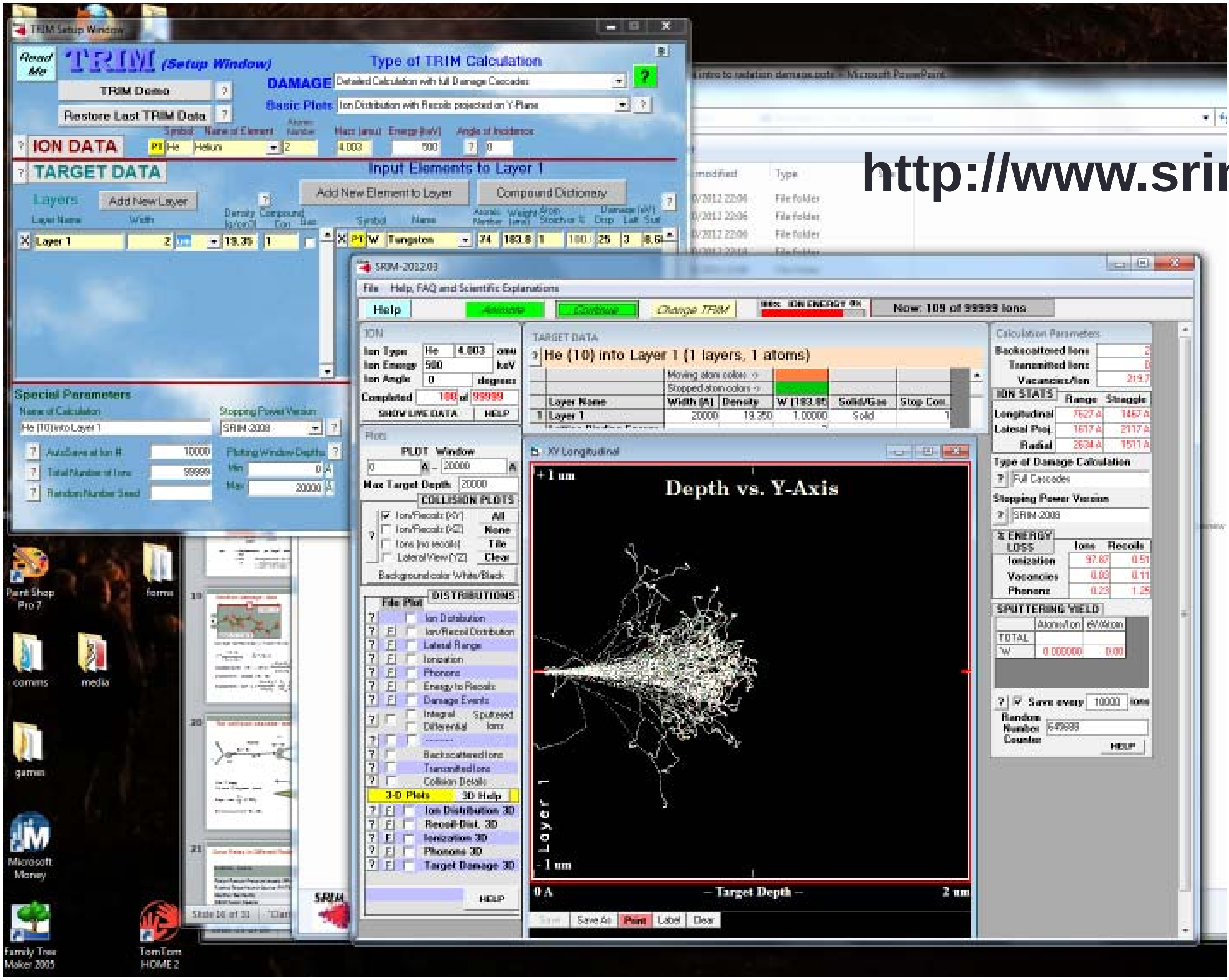


At high energies, ions lose energy mostly by electronic excitation

At low energies, ions lose energy mostly by collisions

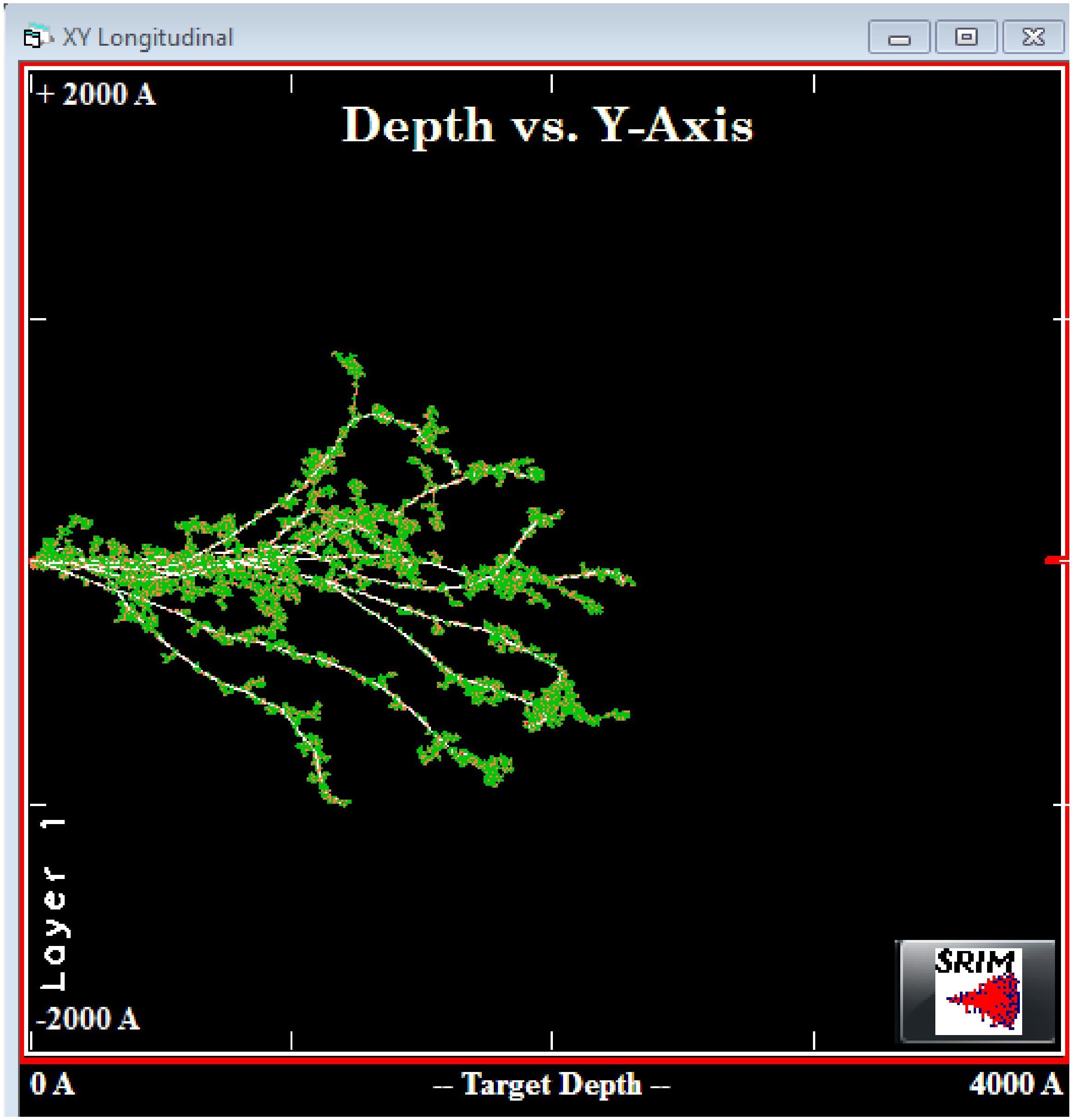
E_{ex} (keV) ~ M_2 (a.m.u.)

SRIM / TRIM



http://www.srim.org/

The collision cascade

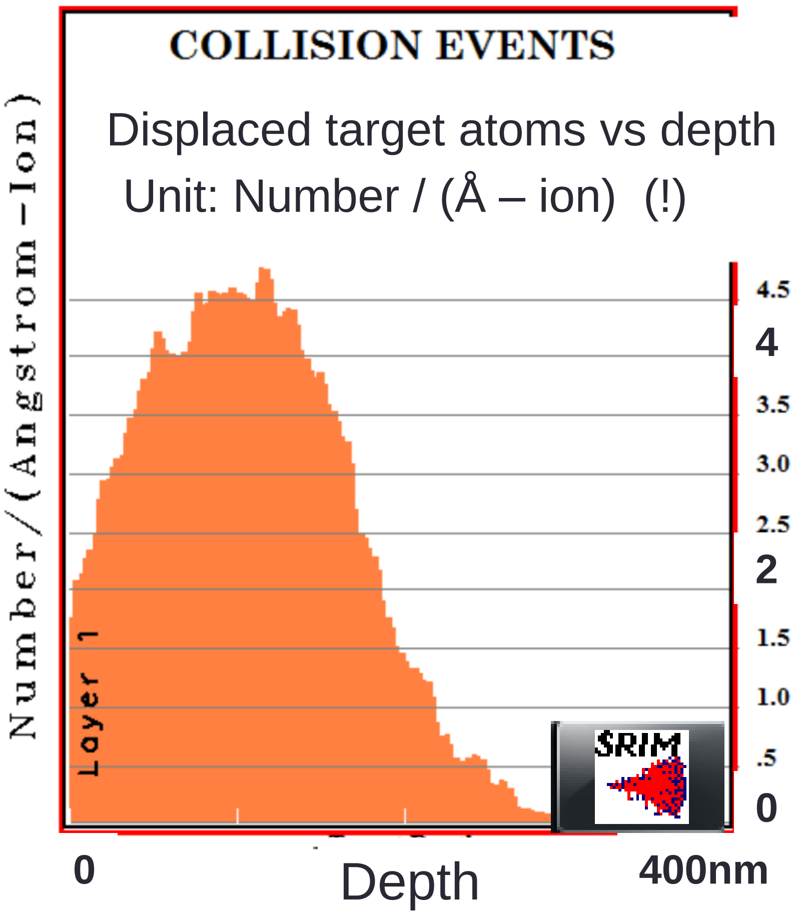


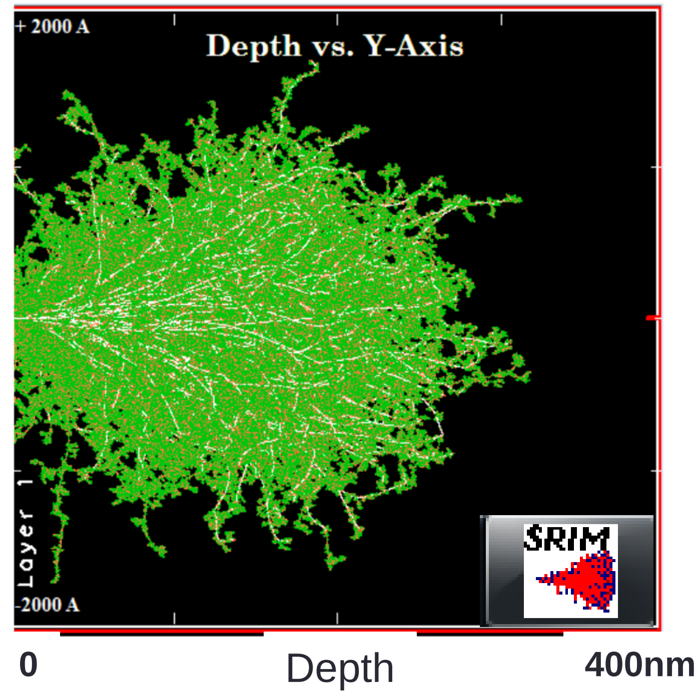
Tracks of ten 482keV Fe ions in Fe target.

“Consequent events” show in red and green.

Note long gaps between sub-cascades, and randomness of process.

Ion irradiation: dpa





750 ion tracks:
482keV Fe ion in Fe target

Here: Fe ions into Fe

dpa = displacements per (target) atom

$$= \frac{D\phi}{\rho}$$

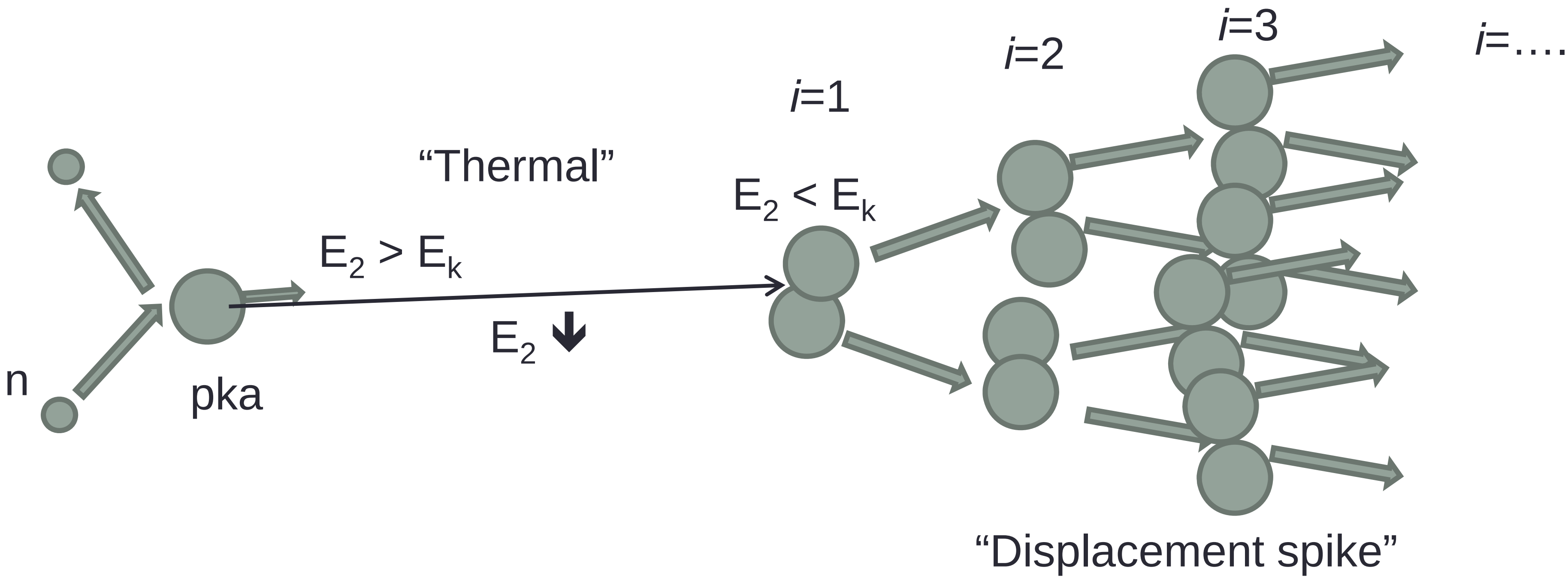
D: displacements / (m – ion)
ϕ: irradiating particles / m^2
ρ: atoms / m^3 in target

D: ~ 4.5 at peak
ρ: $8 \times 10^{28} m^{-3}$

ϕ: typically 10^{18} m^{-2} ($10^{14} cm^{-2}$)

= 0.56 dpa

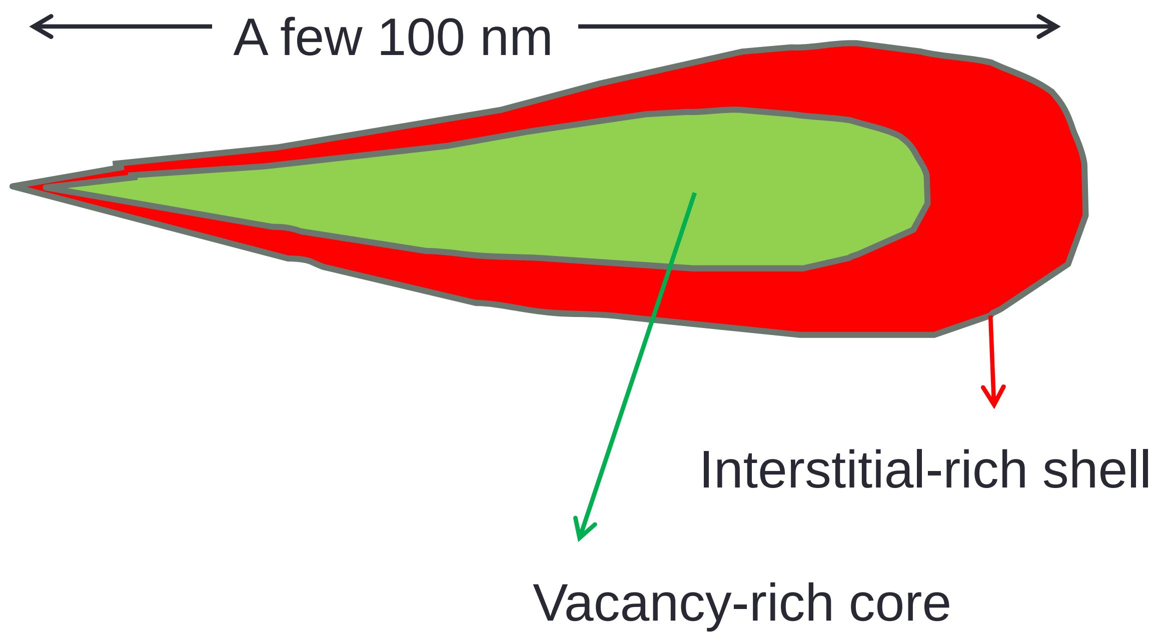
The collision cascade: evolution after initiation



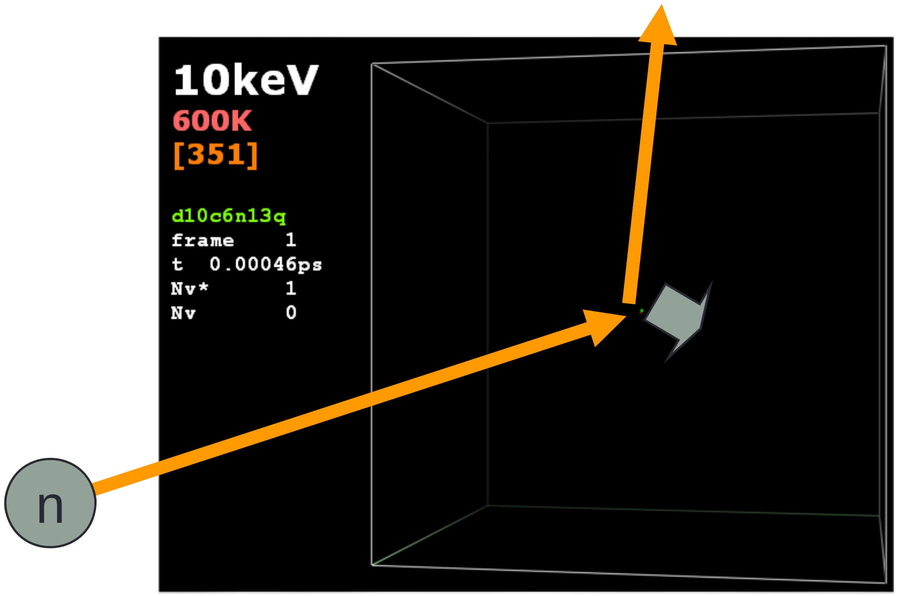
After i^{th} stage,
We have 2^i displaced atoms:

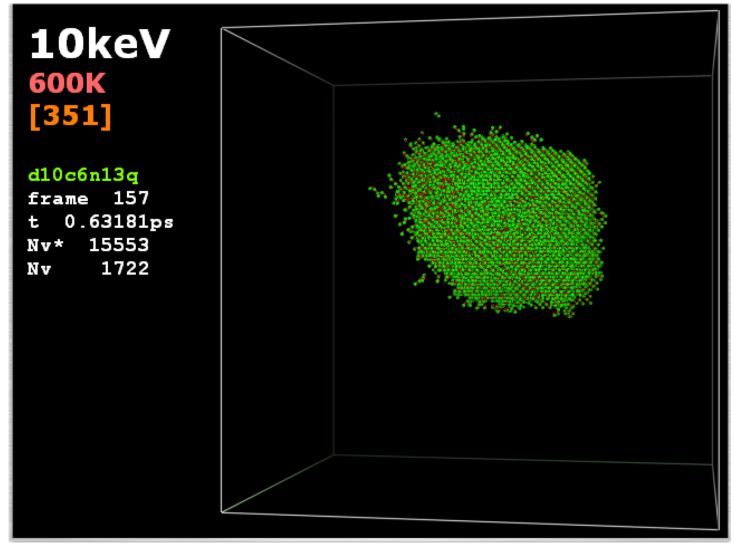
Stops when: $\frac{E_k}{2^i} < 2E_d$

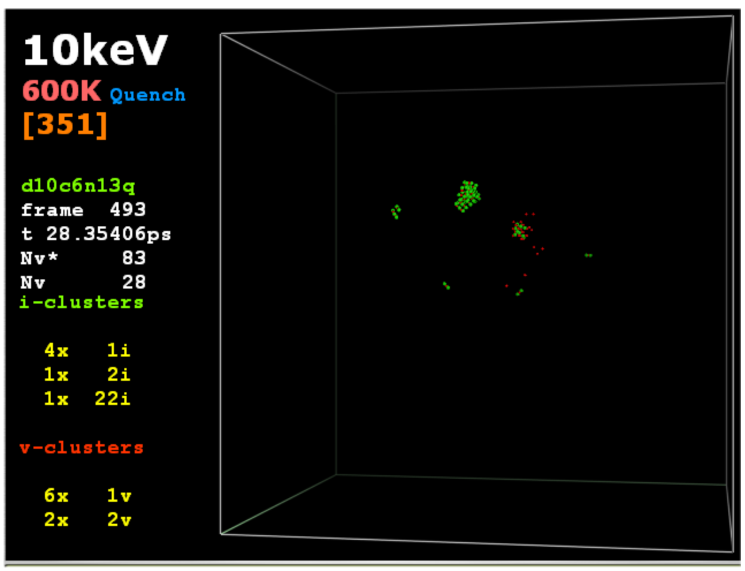
So $N_{displacements}$ $2^i = E_k / 2E_d$



The collision cascade: evolution after initiation







D. Bacon, Y. Osetsky, U. Liverpool

“Molecular dynamics” simulation: up to 30 ps.

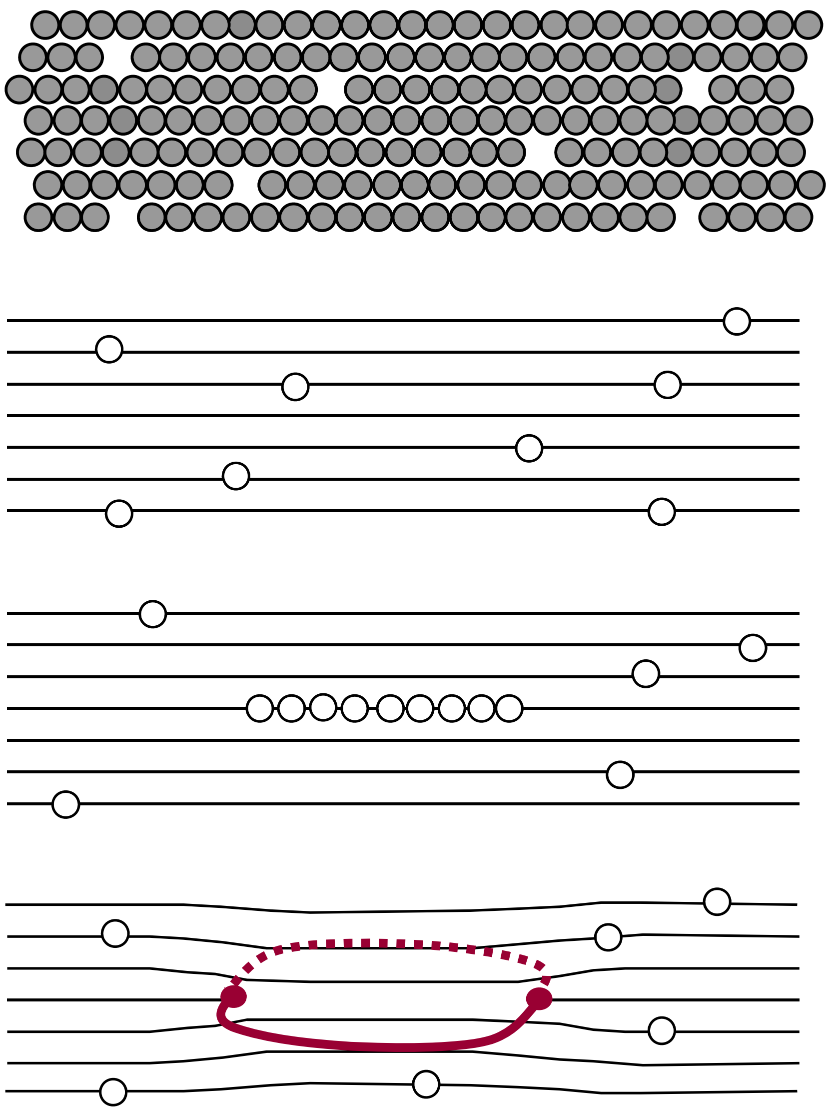
Only the out-of-place atoms are shown – vacancies in green; self interstitials in red.

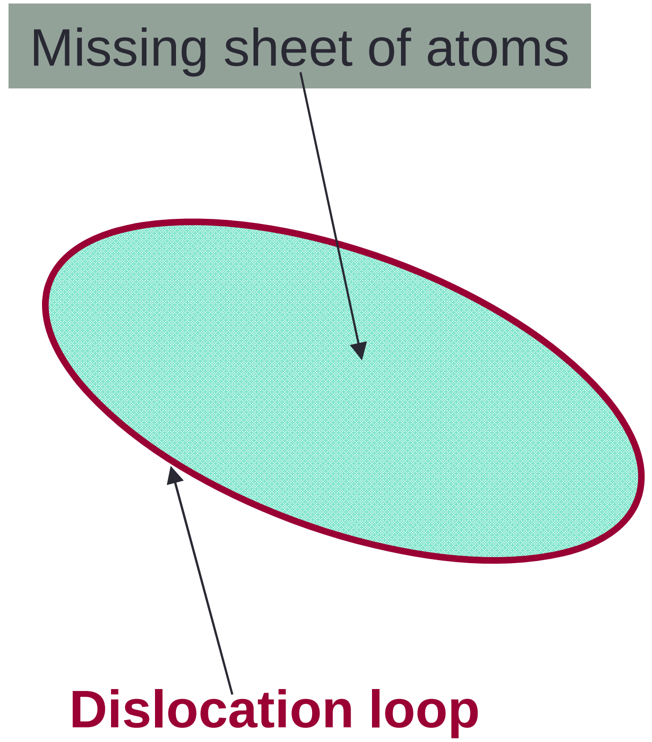
Started by a low-energy collision (10keV ion): end of cascade branch.

10 keV < E_{ex},

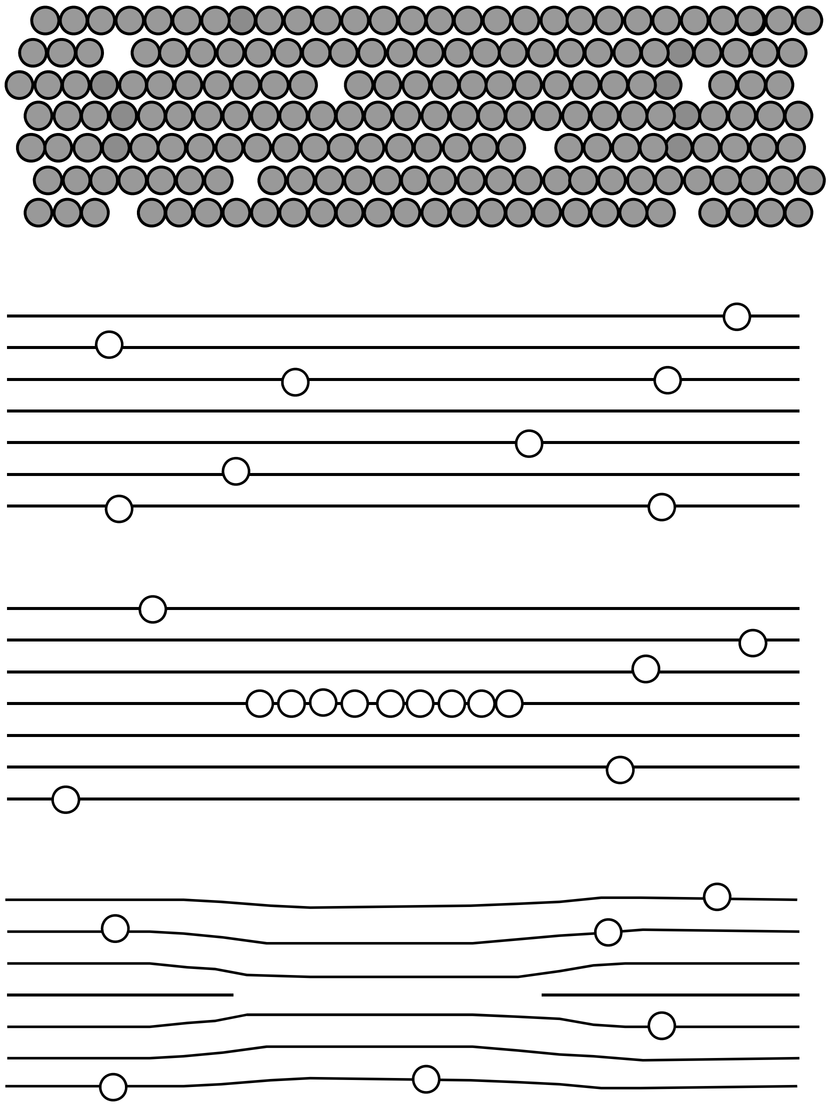
so $N_{displacement}$ ~ 10000/25 = 400

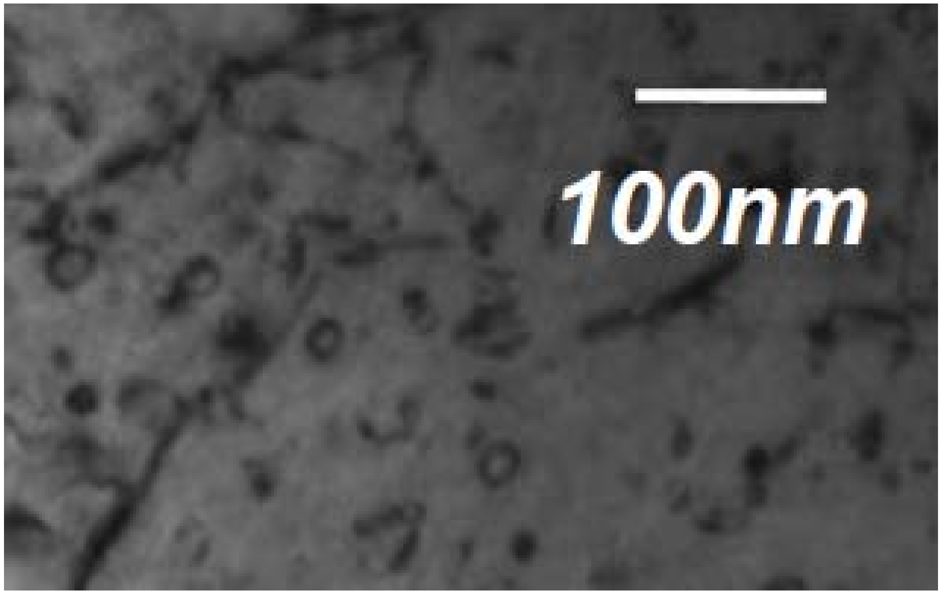
Radiation ➔ dislocation loops





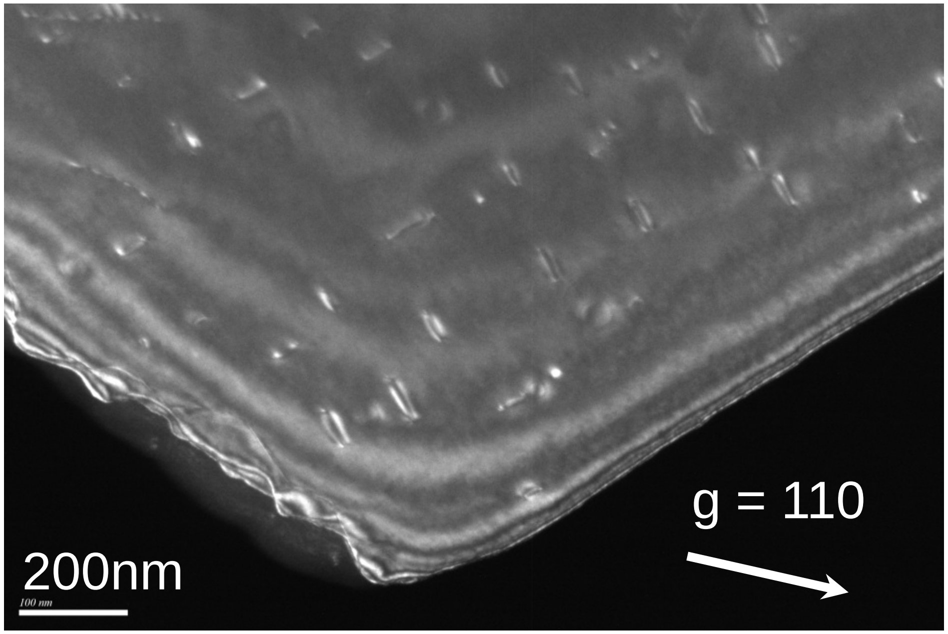
Radiation → dislocation loops

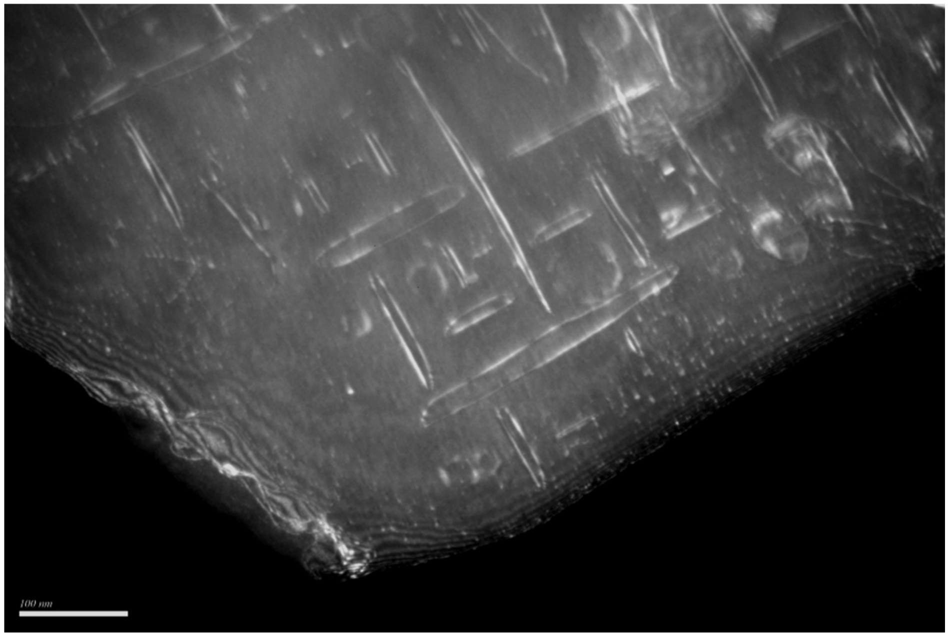




Iron, ion-irradiated to 2.5 dpa at 300°C

Dislocation loops in Fe irradiated at 500˚C





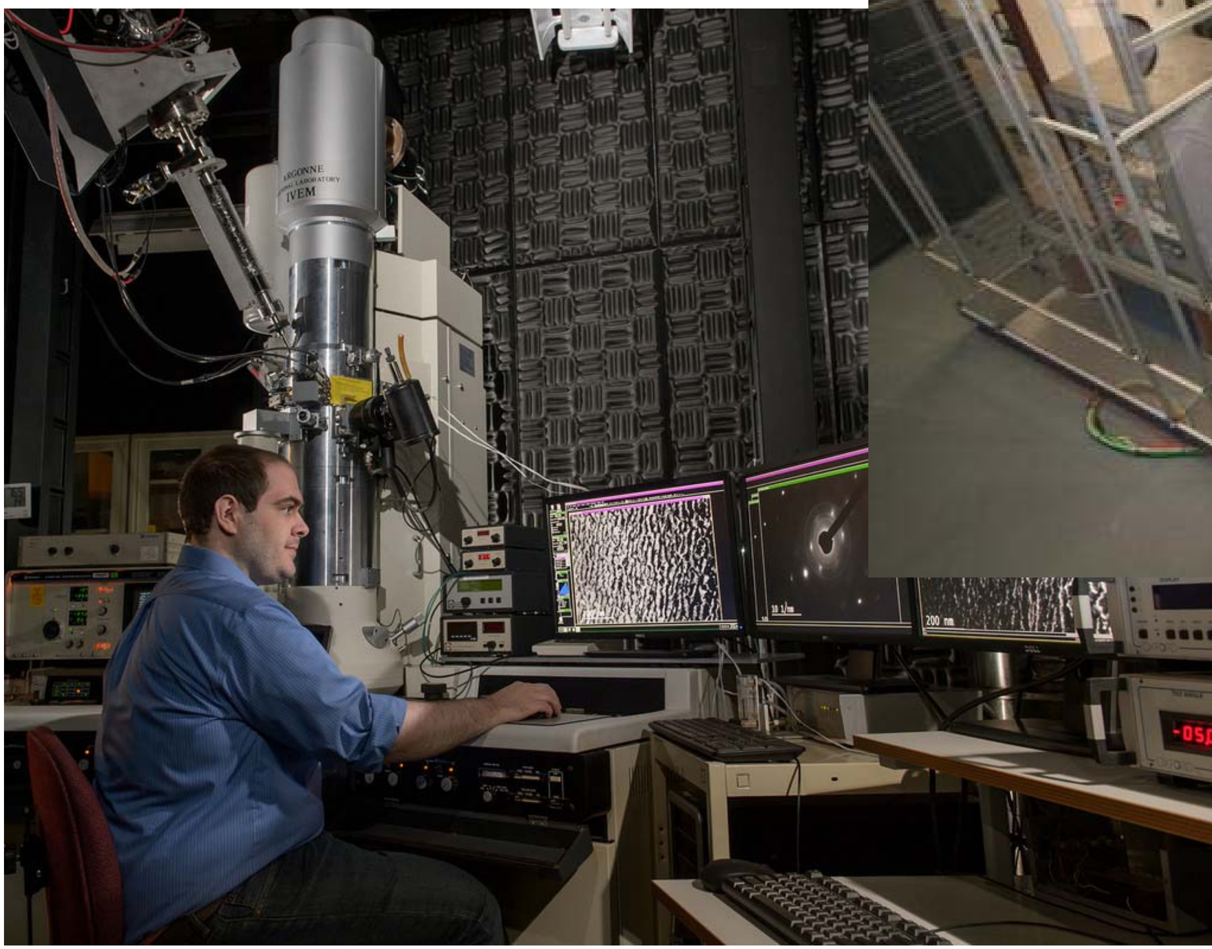
Dose: **$3x10^{18}$** ions m^{-2},

Dose: **$1x10^{19}$** ions m^{-2}

UHP-Fe irradiated at 500^{o}C with 150 keV Fe^{+} ions
- loops are of <100> type.
- loops are of *interstitial* type

Radiation Damage as it happens…

IVEM – Argonne NL



MIAMI – U. Huddersfield

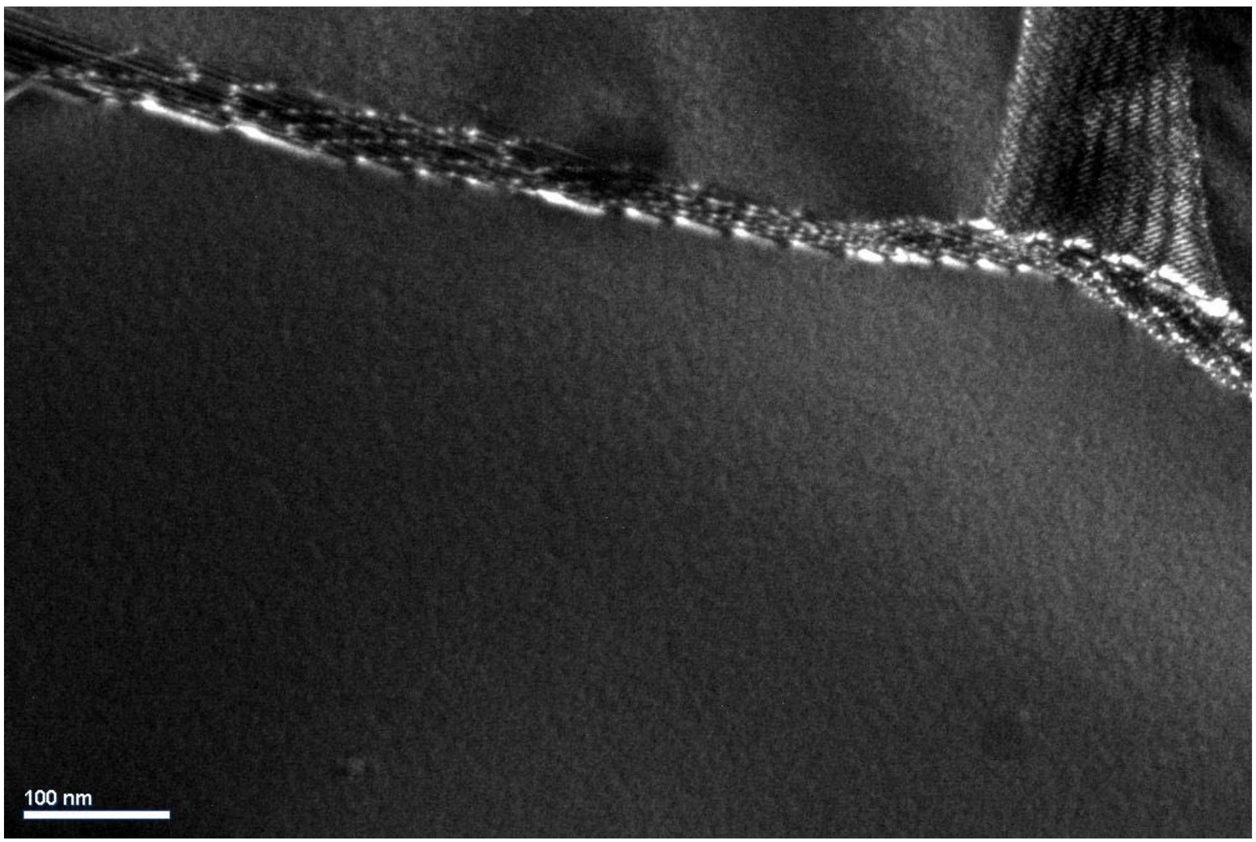
Damage accumulation; Fe, 300°C , high dose

Loop density vs dose: W-5%Re

g=200

0

Unit: $10^{13}W^{+}/cm^{2}$

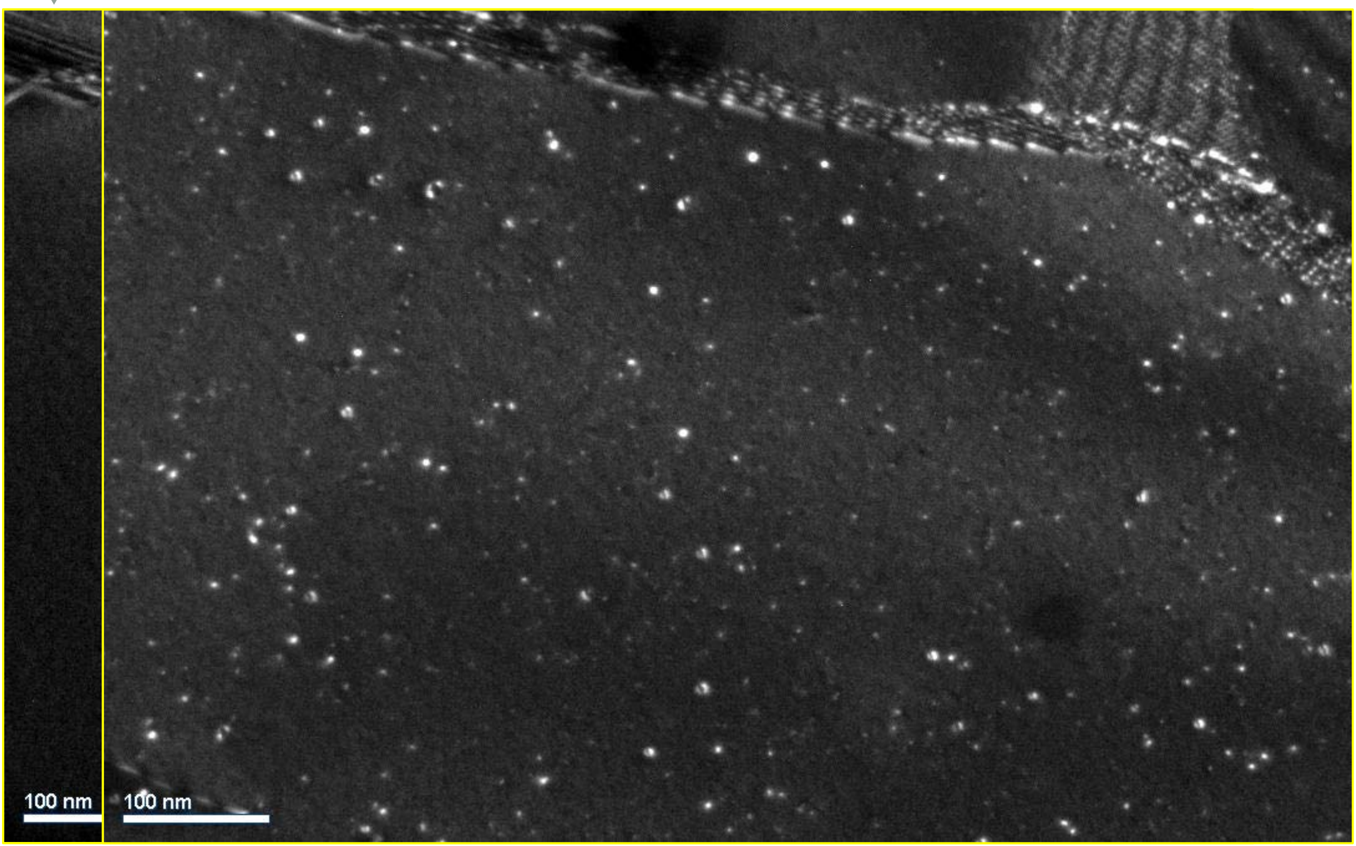


Loop density vs dose: W-5%Re

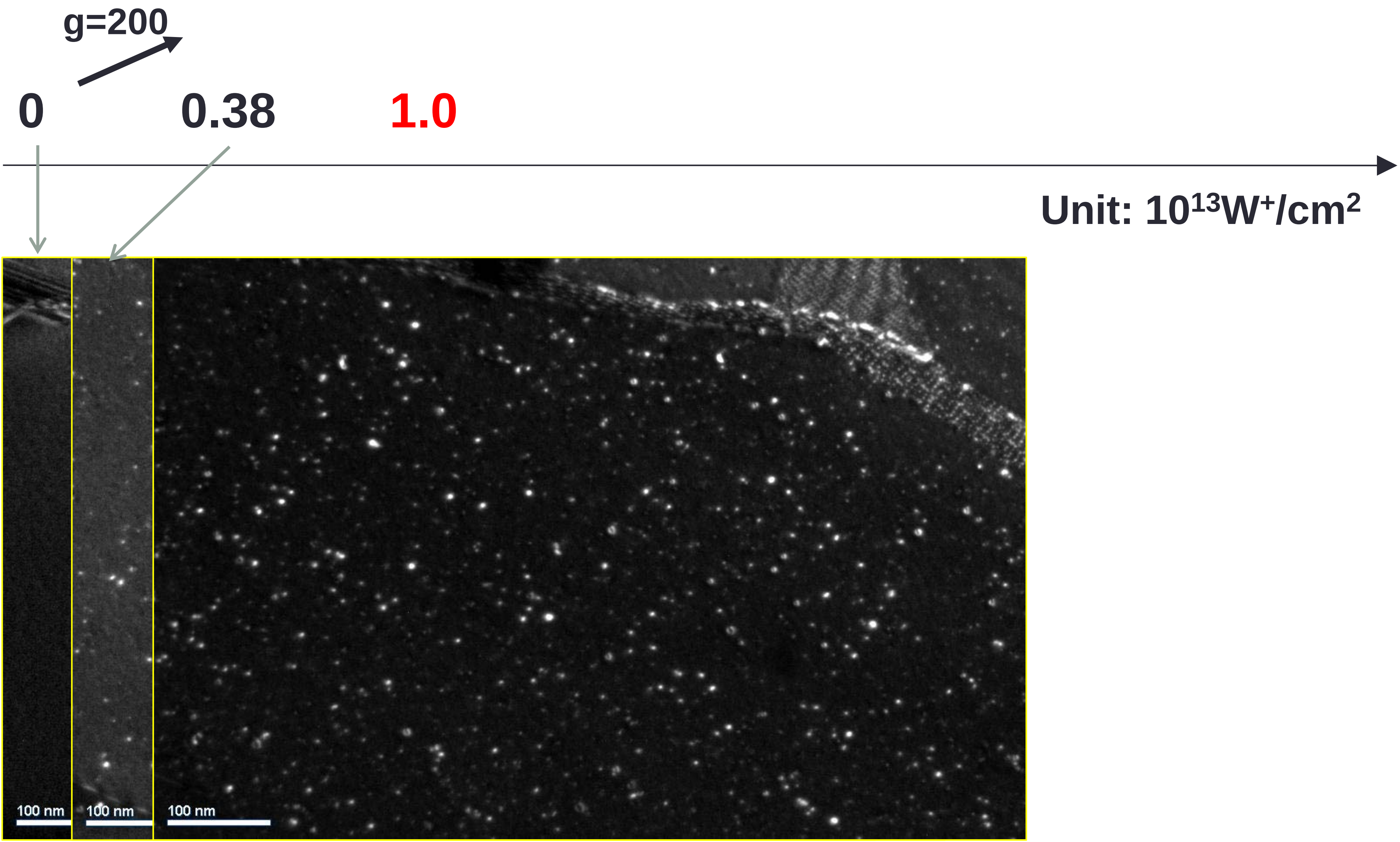
g=200

0 **0.38**

Unit: $10^{13} W^{+}/cm^{2}$



Loop density vs dose: W-5%Re



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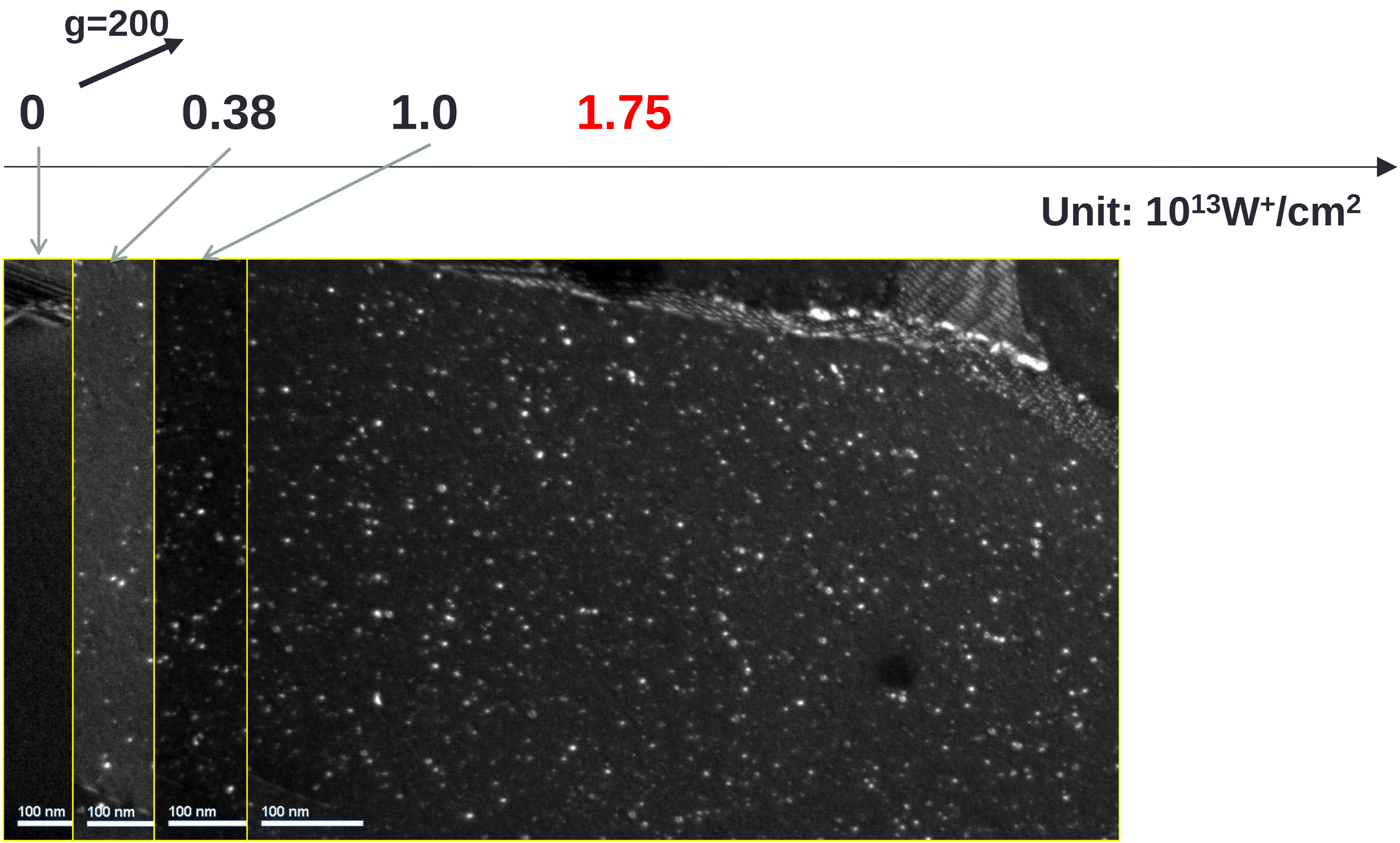

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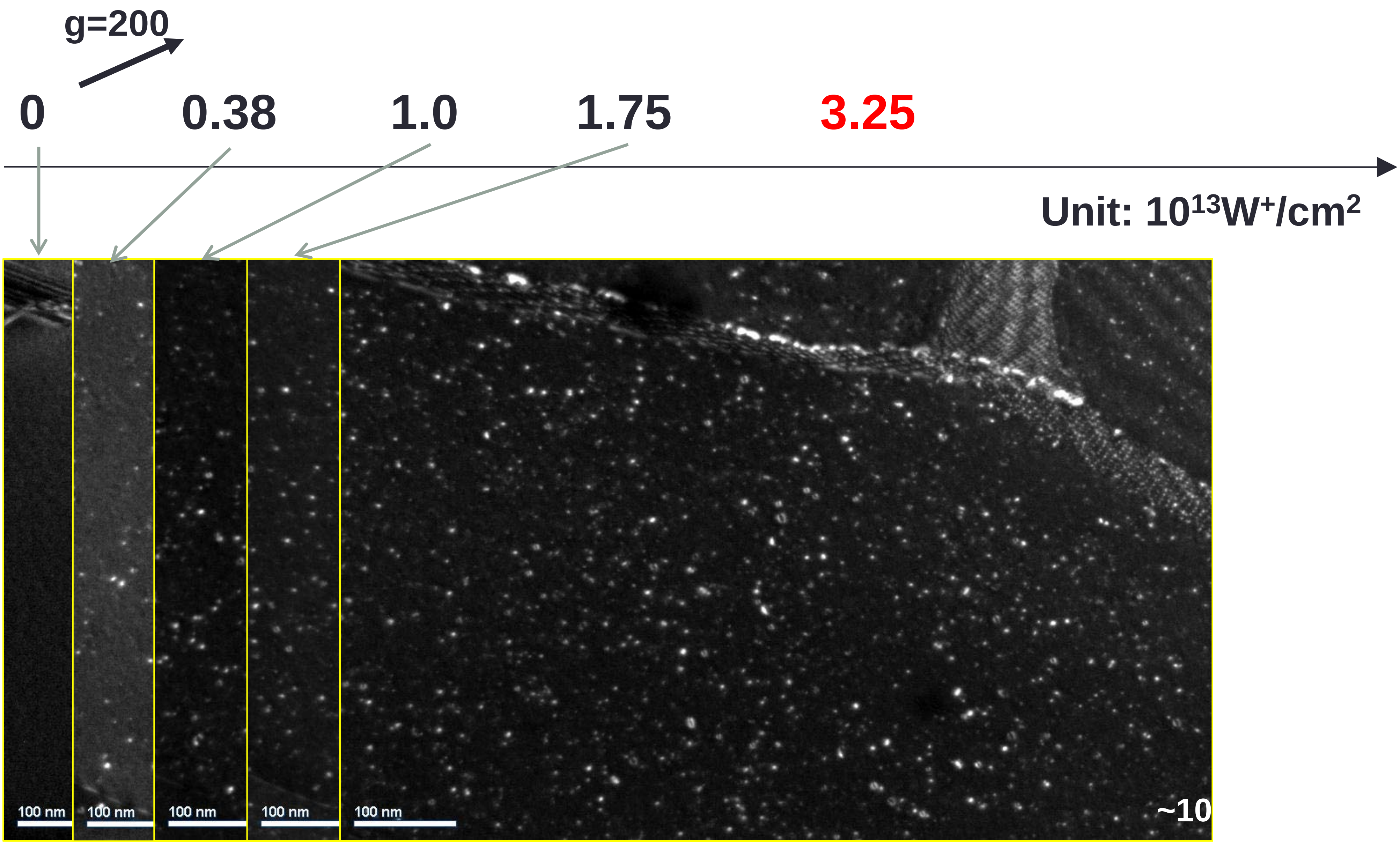
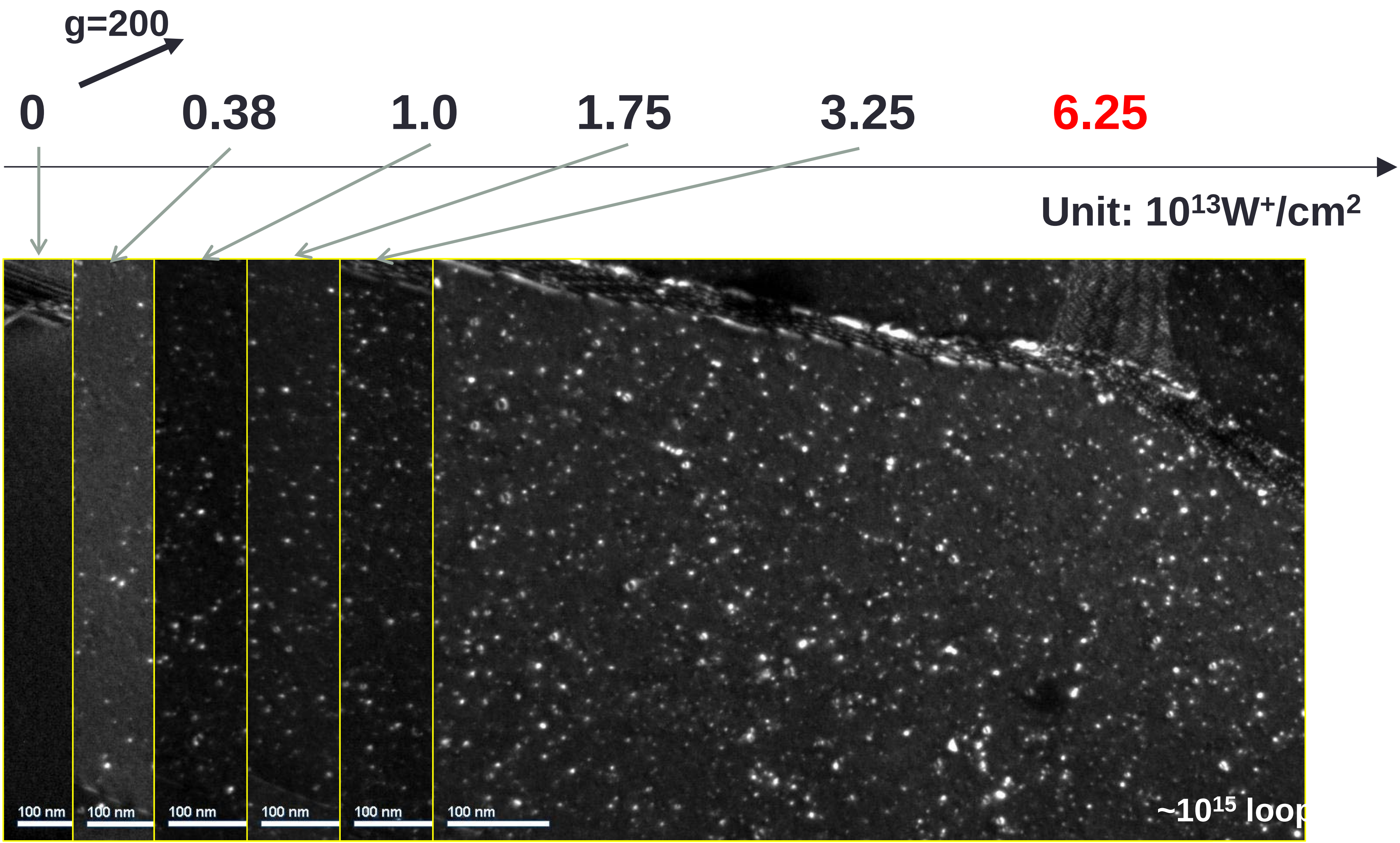
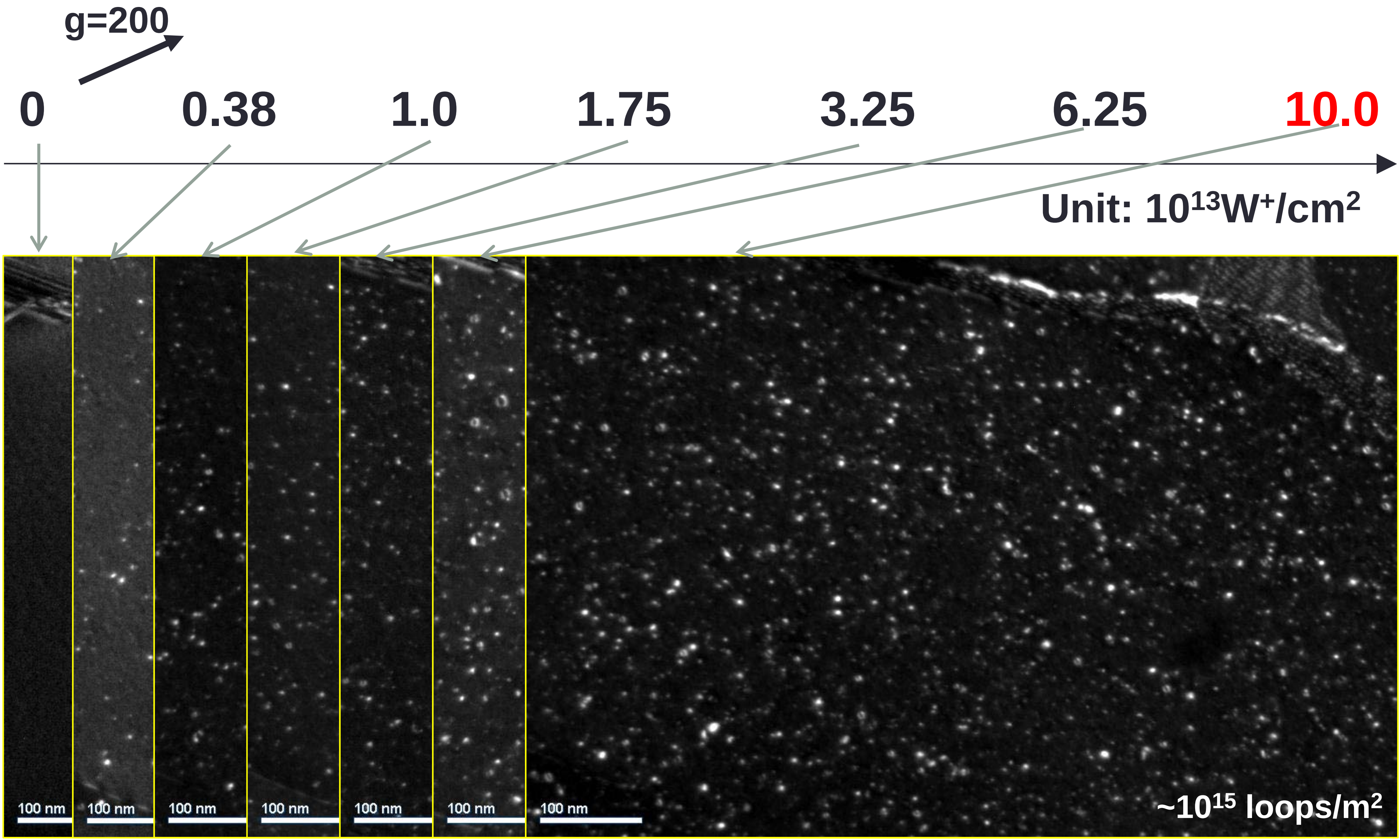


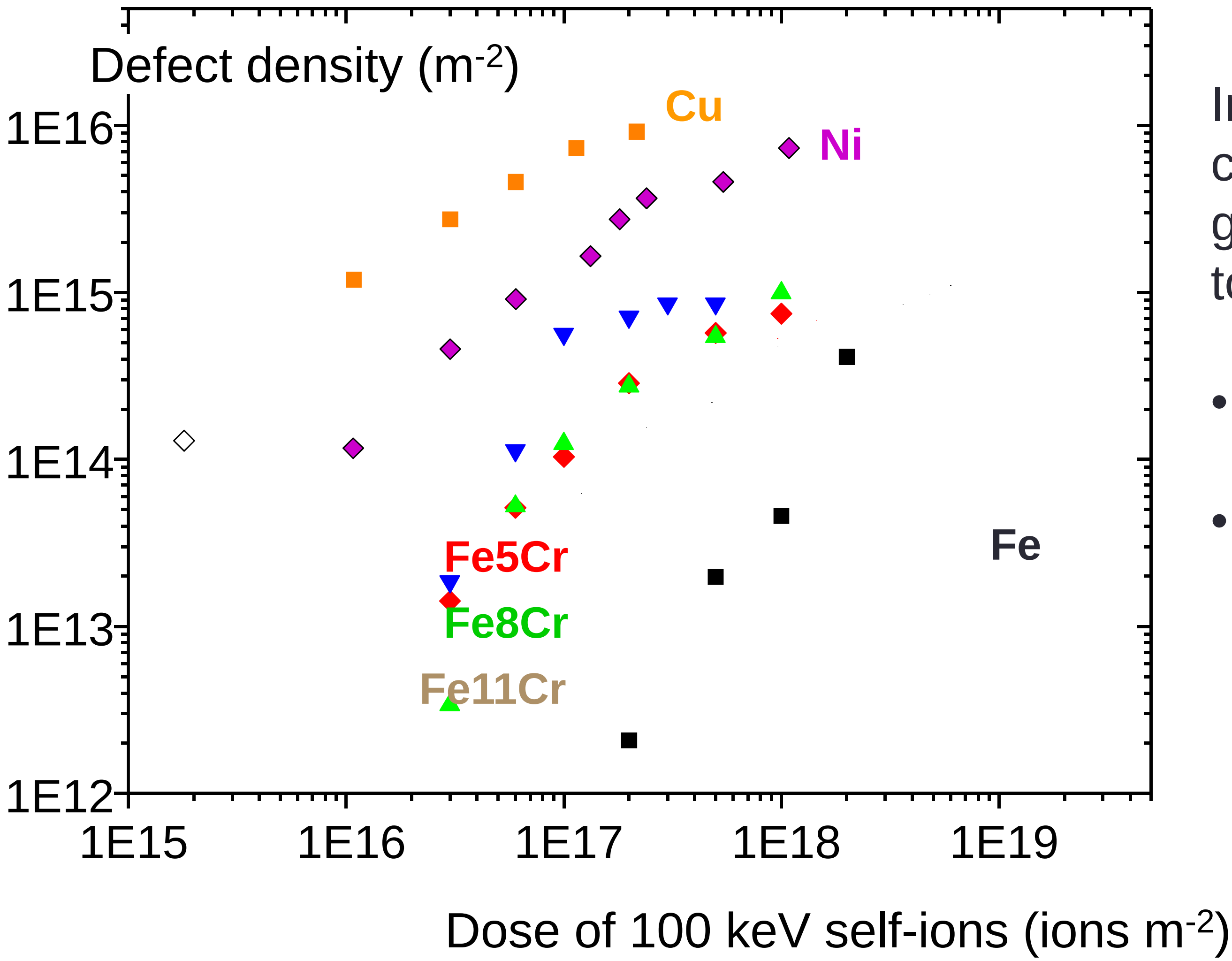
Loop density vs dose: W-5%Re



Loop density vs dose: W-5%Re



Self-ion irradiations of pure materials and FeCr alloys - 100keV room temperature irradiations



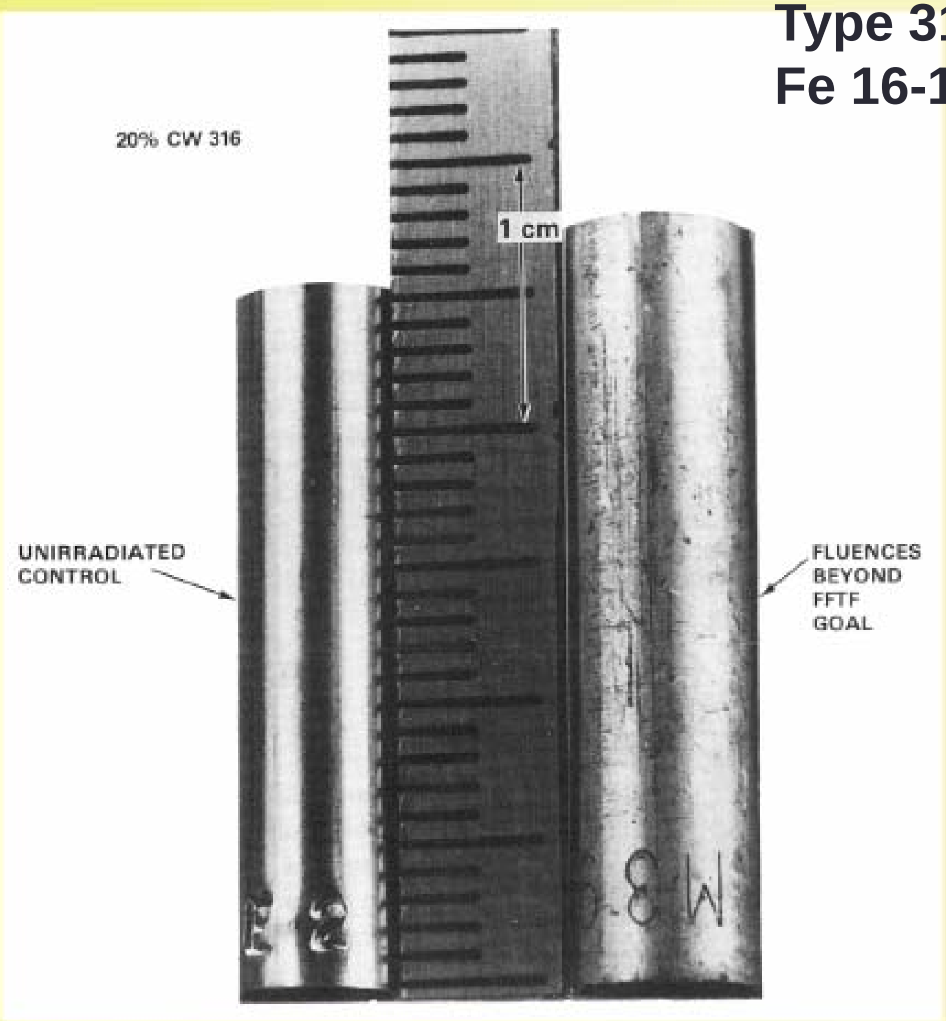
Iron-based metals (Body centred cubic metals in general?) are more resistant to radiation damage.

- Fewer defects
- Threshold dose

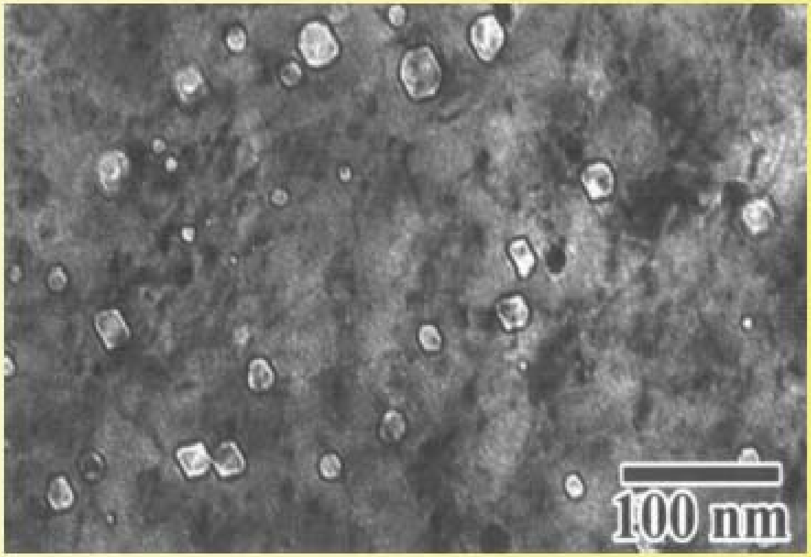
Effects of radiation damage on materials

1. **Sputtering**
2. **Stored energy**
   a) "Wigner energy" release
3. **Point defect accumulation**
   a) Swelling, dislocation loops, nano-voids
   b) Changes in thermal & electrical conductivity
4. **Enhanced diffusion**
   a) Radiation-enhanced creep
   b) Faster kinetics of phase transitions
   c) Radiation-enhanced grain-boundary segregation
5. **Gas from transmutation**
   a) Bubbles, swelling (with 2)
6. **Soluble and insoluble transmutation products**
   a) Hardening, precipitation
7. **Knock-on randomisation of structure**
8. **Non-equilibrium microstructures?** (related to 3. 6)
9. **Hardening** (from 2, 4, 5)
10. **Embrittlement** (from 7, 3c, 4)
11. **Radiation-enhanced corrosion** (related to 3a, maybe 5)

Radiation-induced swelling

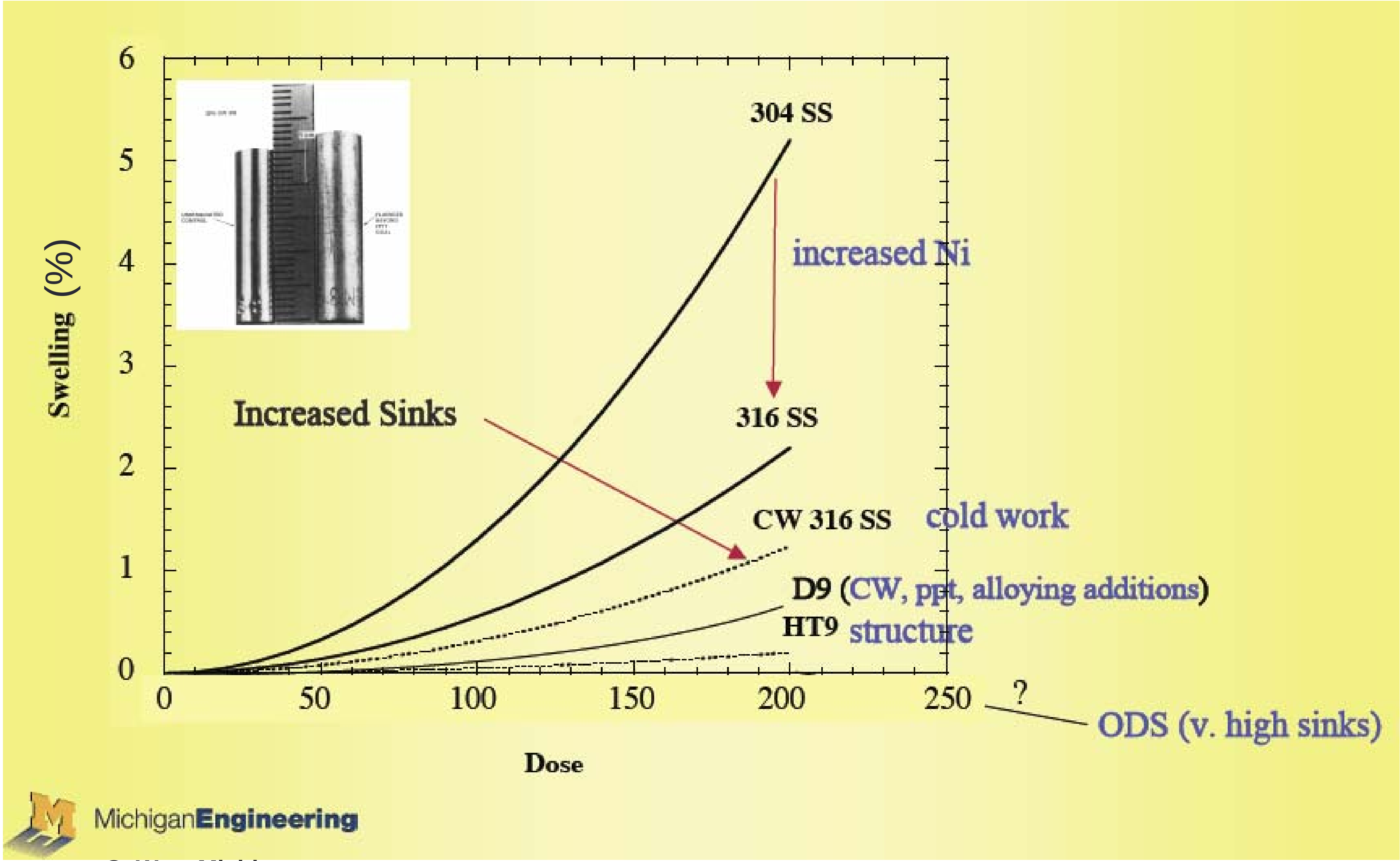


Type 316 stainless steel:
Fe 16-18%Cr, 10-14%Ni, 2%Mo, <0.08%C



Straalsund, 1982, and F. Garner

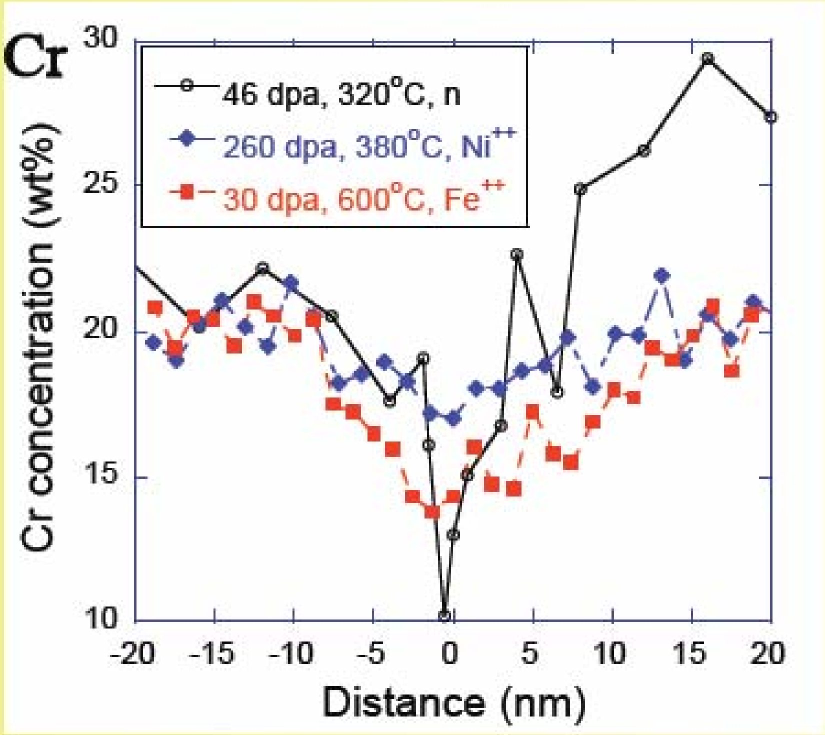
Radiation-induced swelling

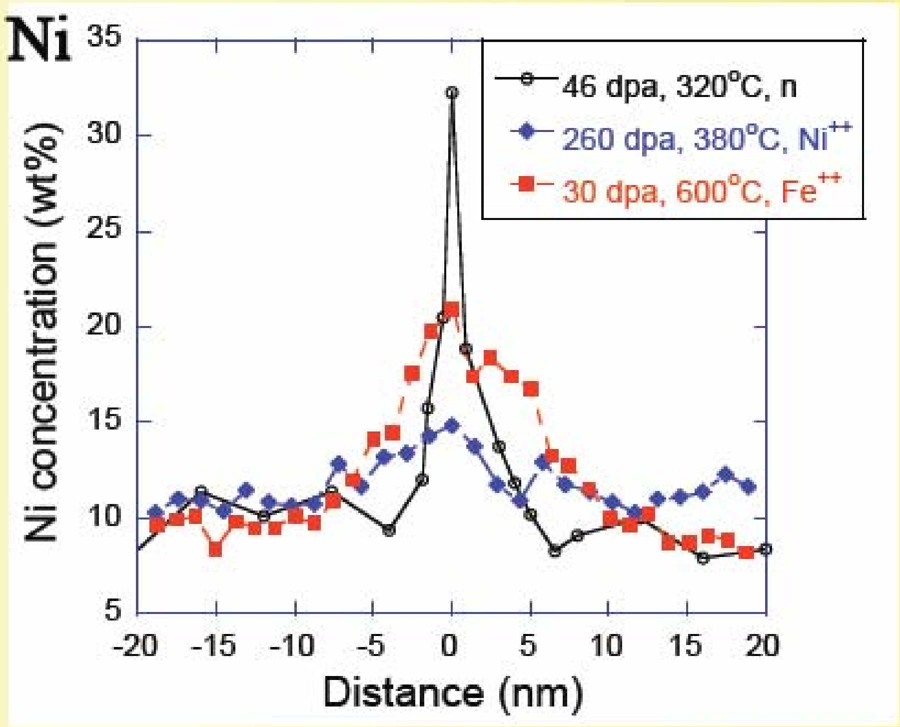


G. Was, Michigan

Radiation-induced grain boundary segregation

Type 304L stainless steel: Fe 18-20%Cr, 8-12%Ni, <0.03%C



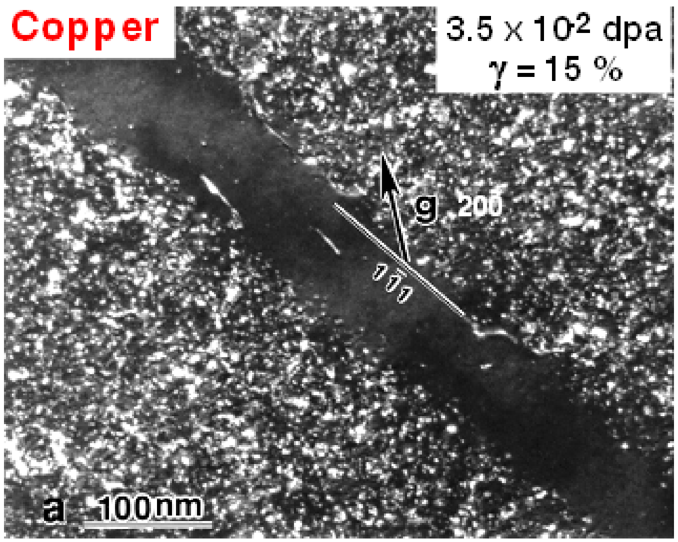


- Depletion of Cr and enrichment of Ni are consistent among all the irradiations.
- Self-ion irradiations produced wider and shallower segregation profiles compared to those by neutron irradiations

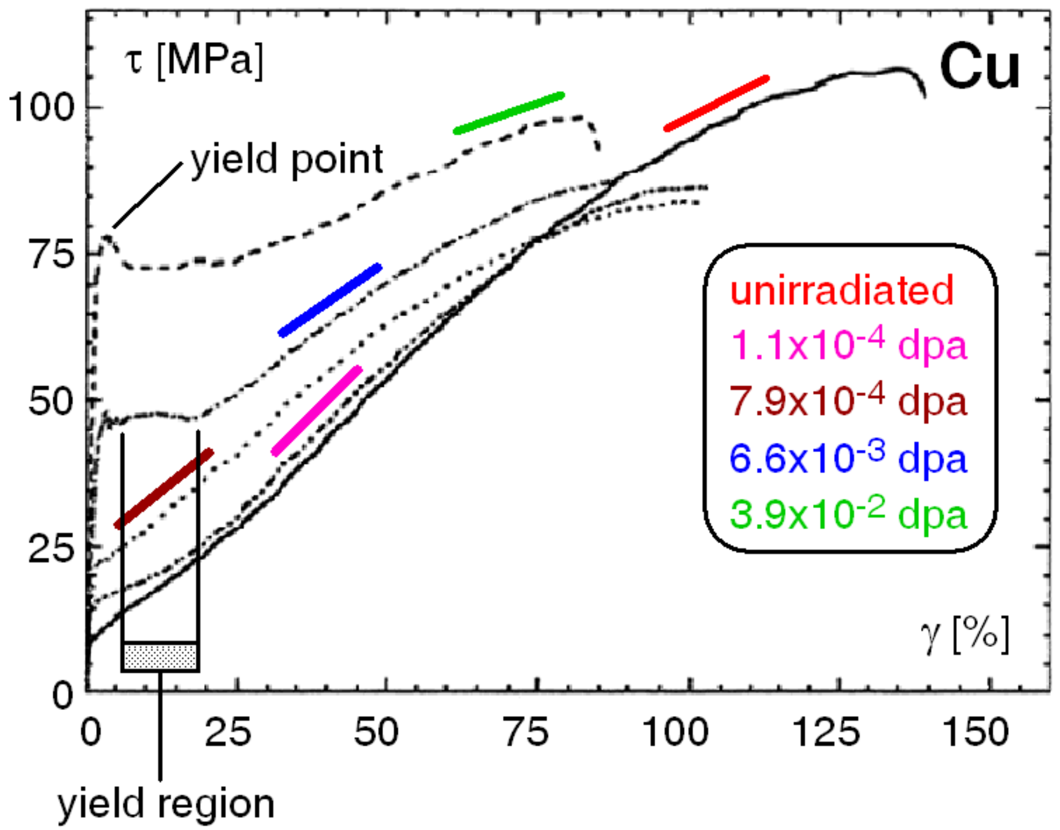
MichiganEngineering

G. Was, Michigan

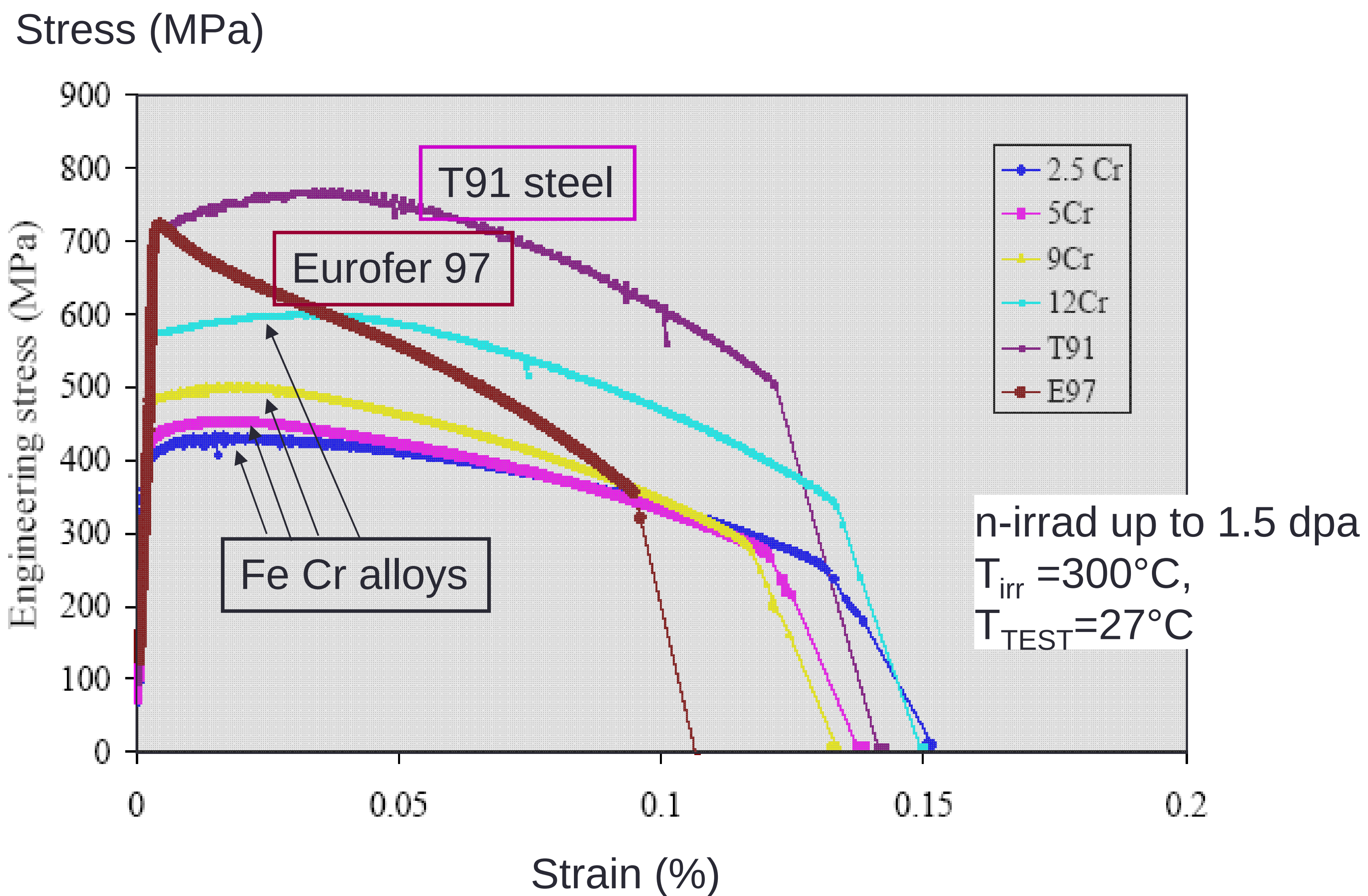
Radiation-induced dislocation loops: effects on mechanical properties



"Strain localisation"



Stress-strain curves: Iron alloys

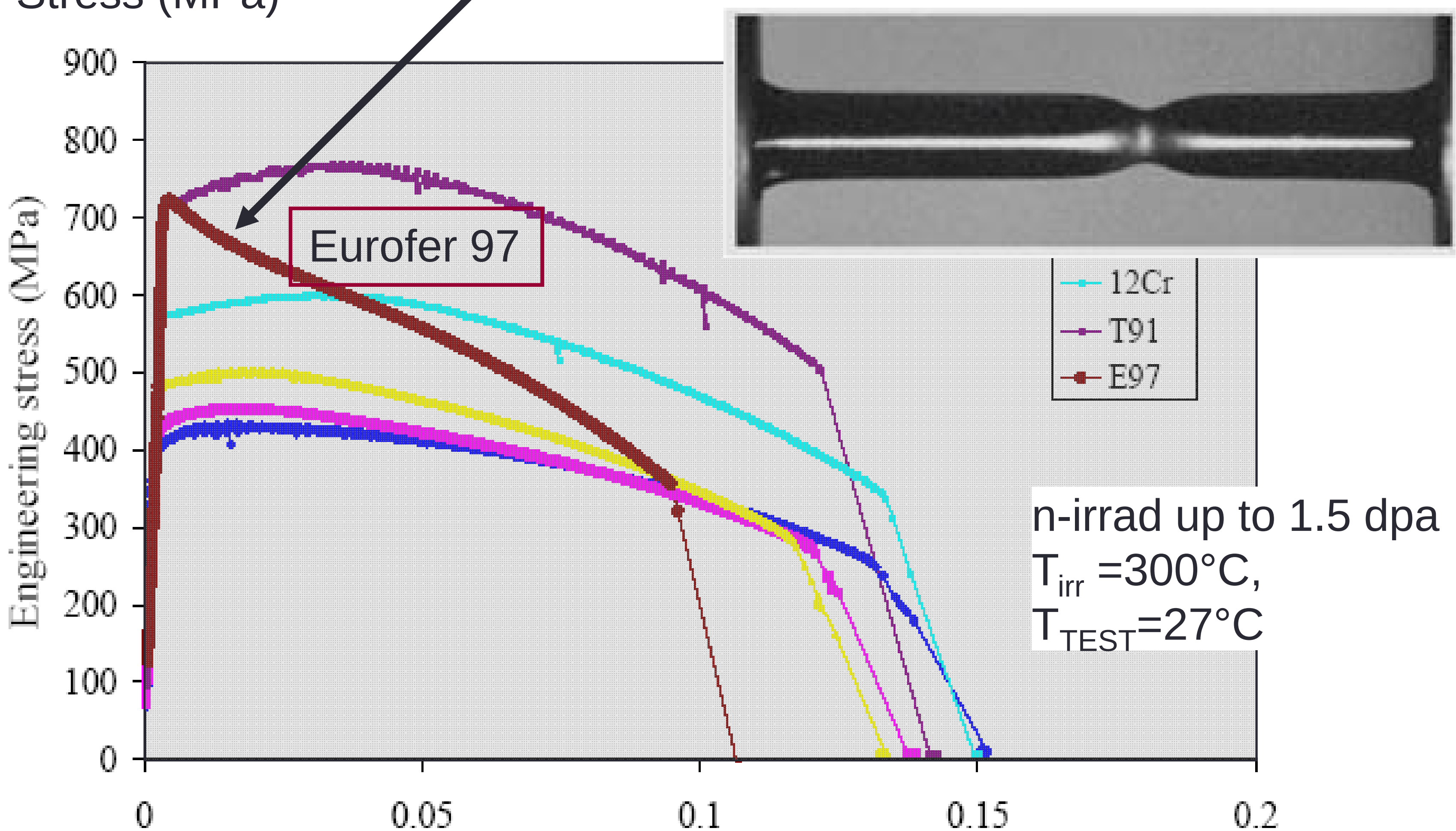


Eurofer 97: **Fe - 8.9%Cr – 1%W - 0.2%V - 0.14%Ta - 0.12%C**

T91: **Fe - 8.3%Cr – 0.4%Mn - 1%Mo - 0.2%V - 0.08% Nb - 0.1%C**

Stress-strain curves: Iron alloys

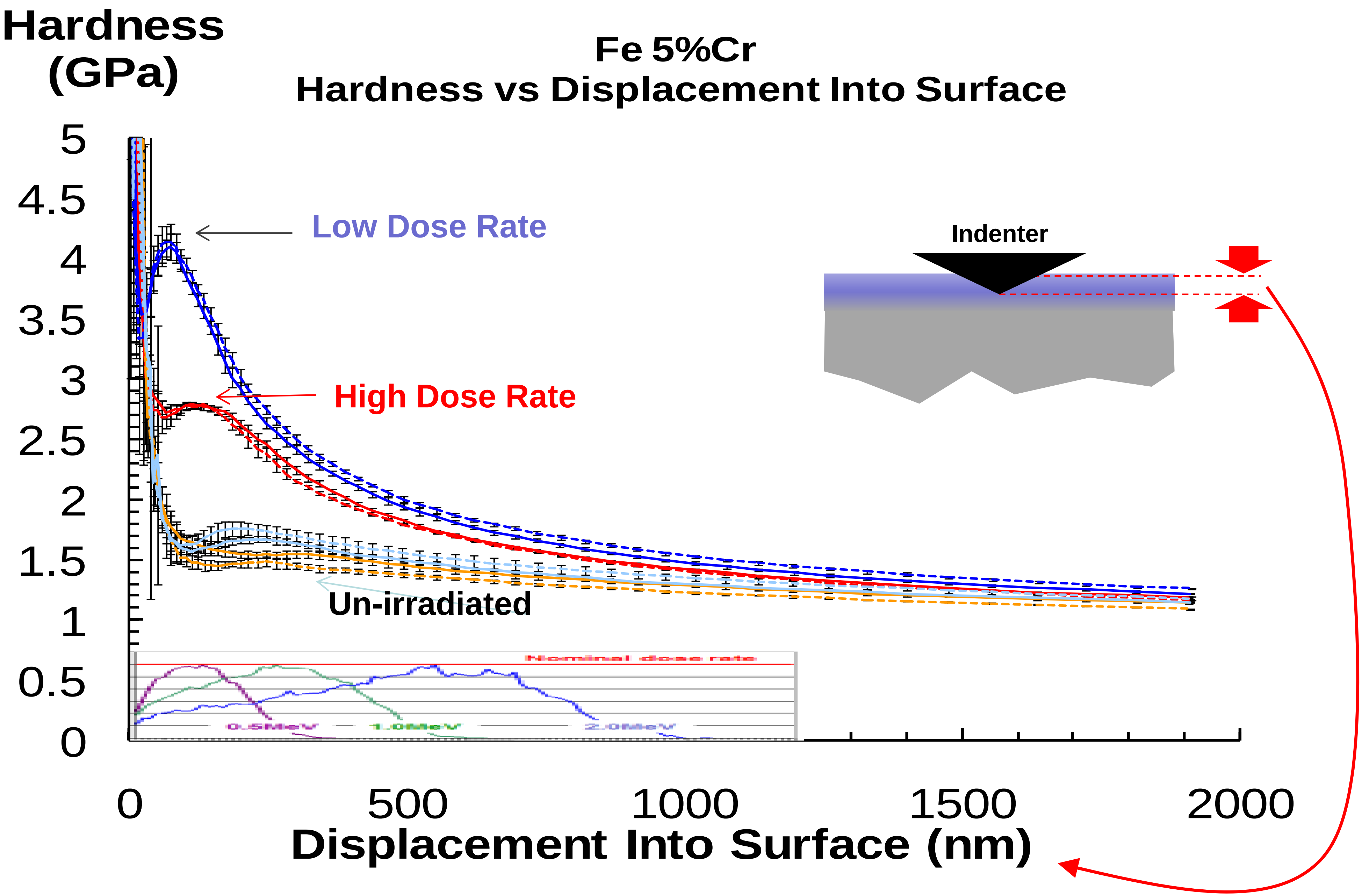
Plastic instability after yield



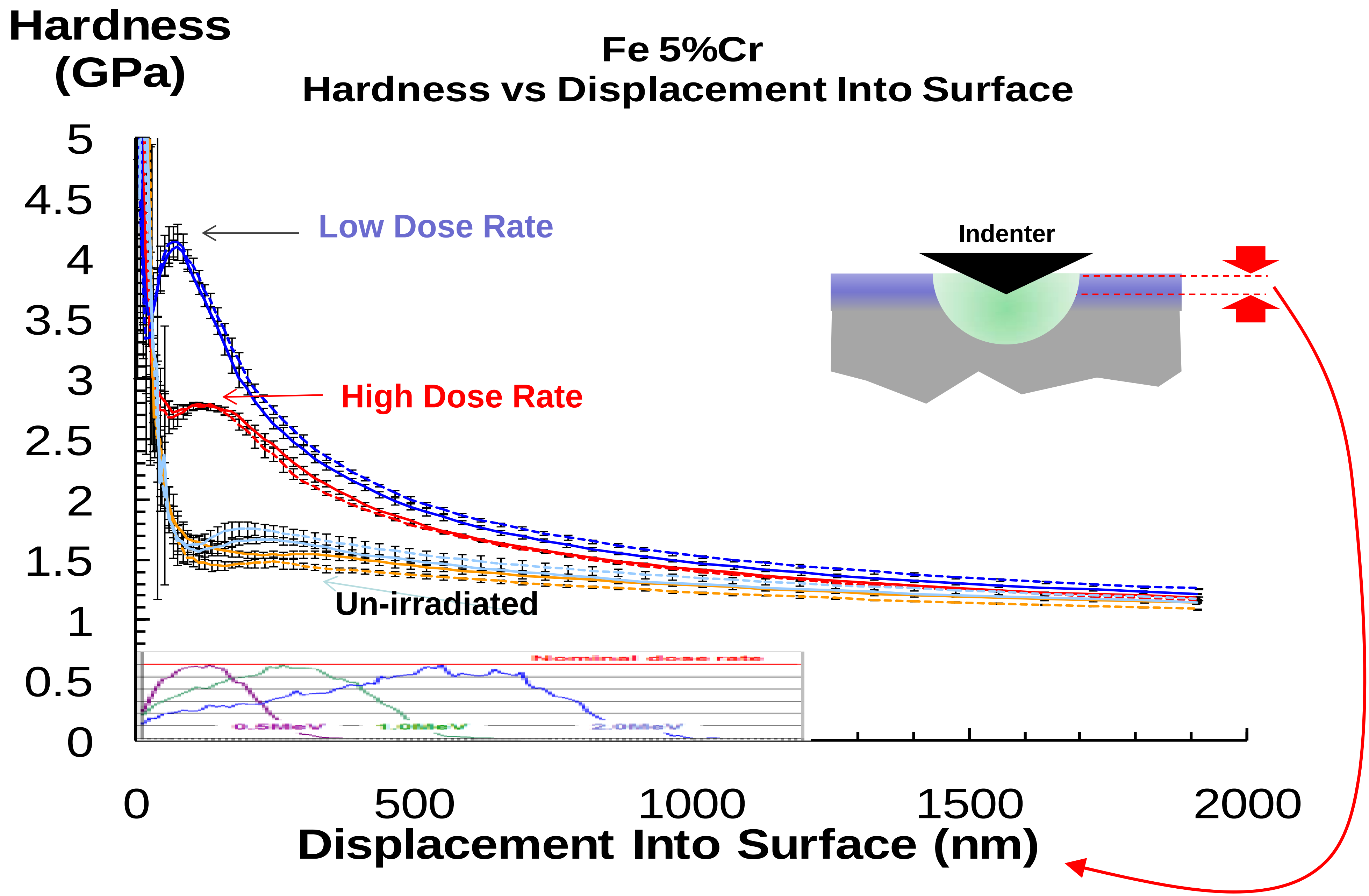
Dose Rates

Radiation Source	Dose Rate (dpa / s) in Iron-based Alloys
Fission Reactor Pressure Vessels (RPV)	~ 10^{-12} – 10^{-11}
Rotating Target Neutron Source (RNTS-II)	~ 10^{-10}
Fast Flux Test Facility (FFTF)/DEMO Fusion Reactor	~ 10^{-8} – 10^{-6}
Ion Implantation – Low Dose Rate	3×10^{-5}
Ion Implantation – High Dose Rate	6×10^{-4}
HVEM Irradiation	~ 10^{-3}

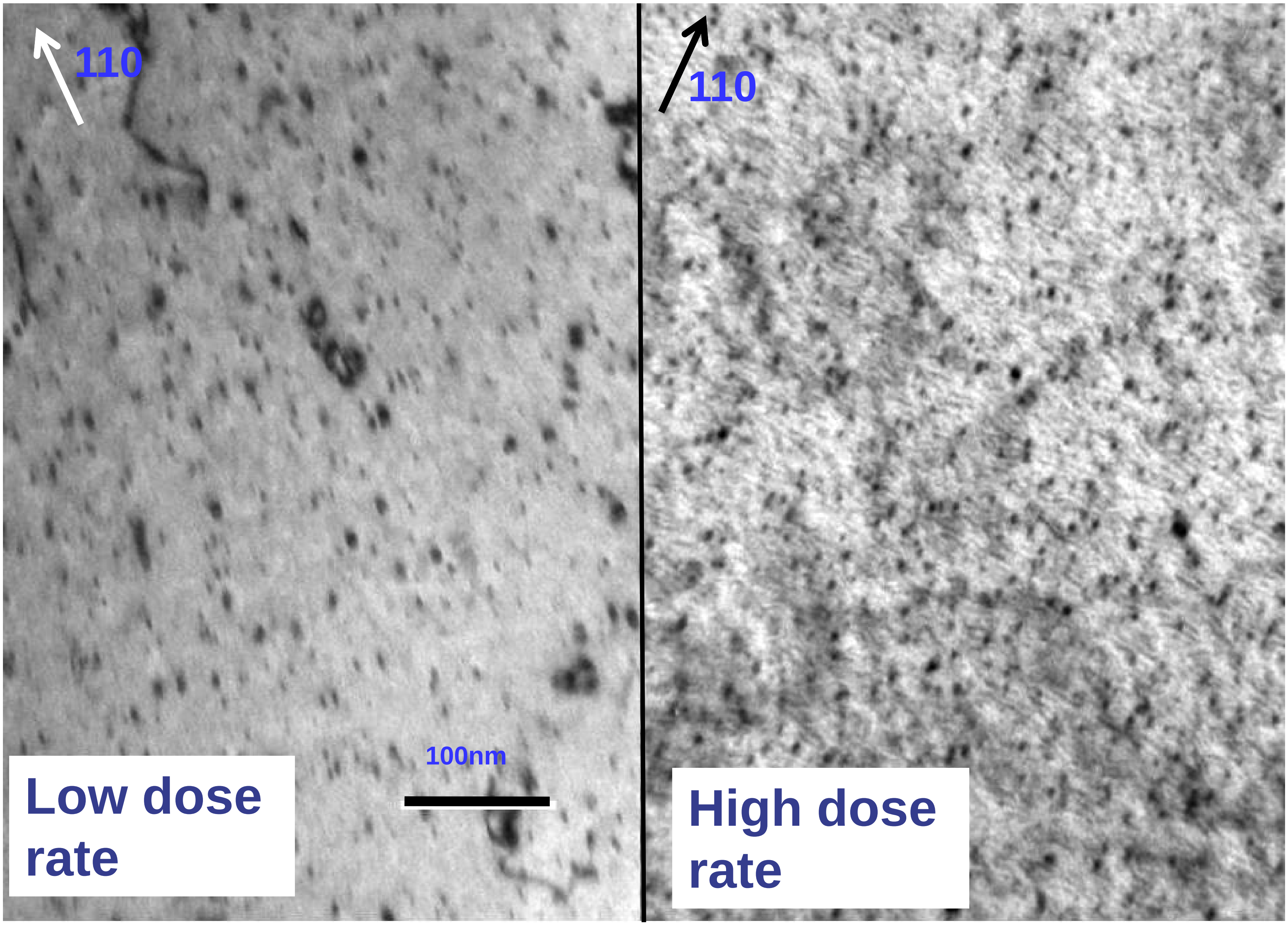
Nanoindentation hardness: Fe 5%Cr 0.6dpa



Nanoindentation hardness: Fe 5%Cr 0.6dpa

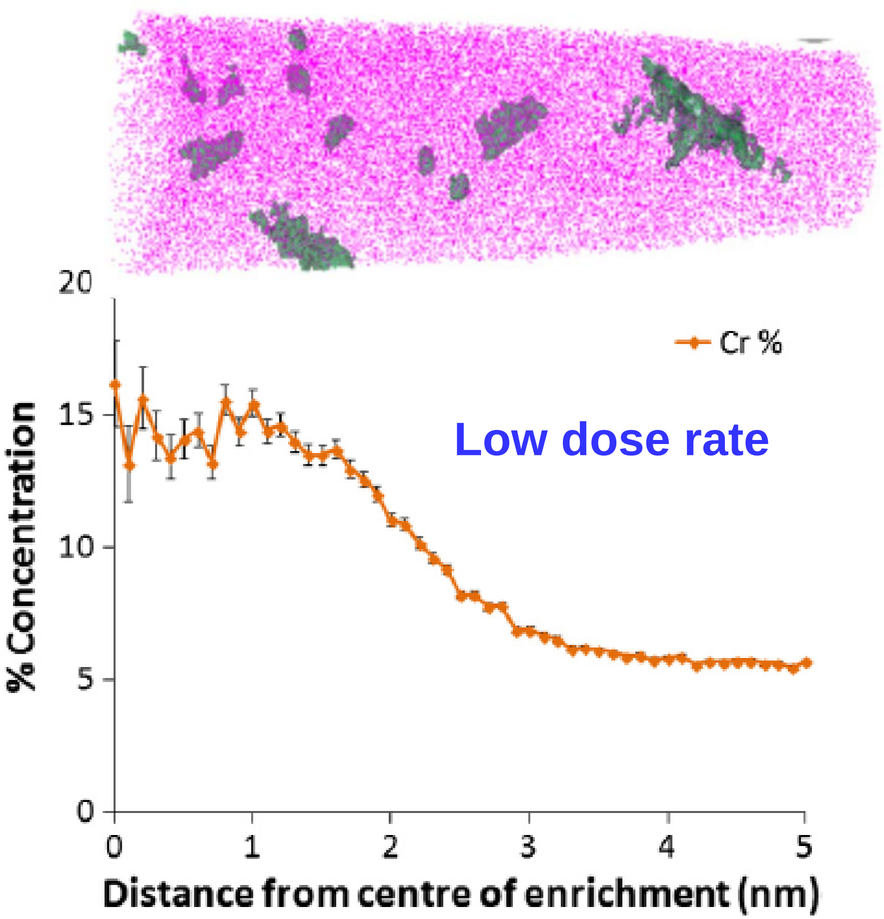


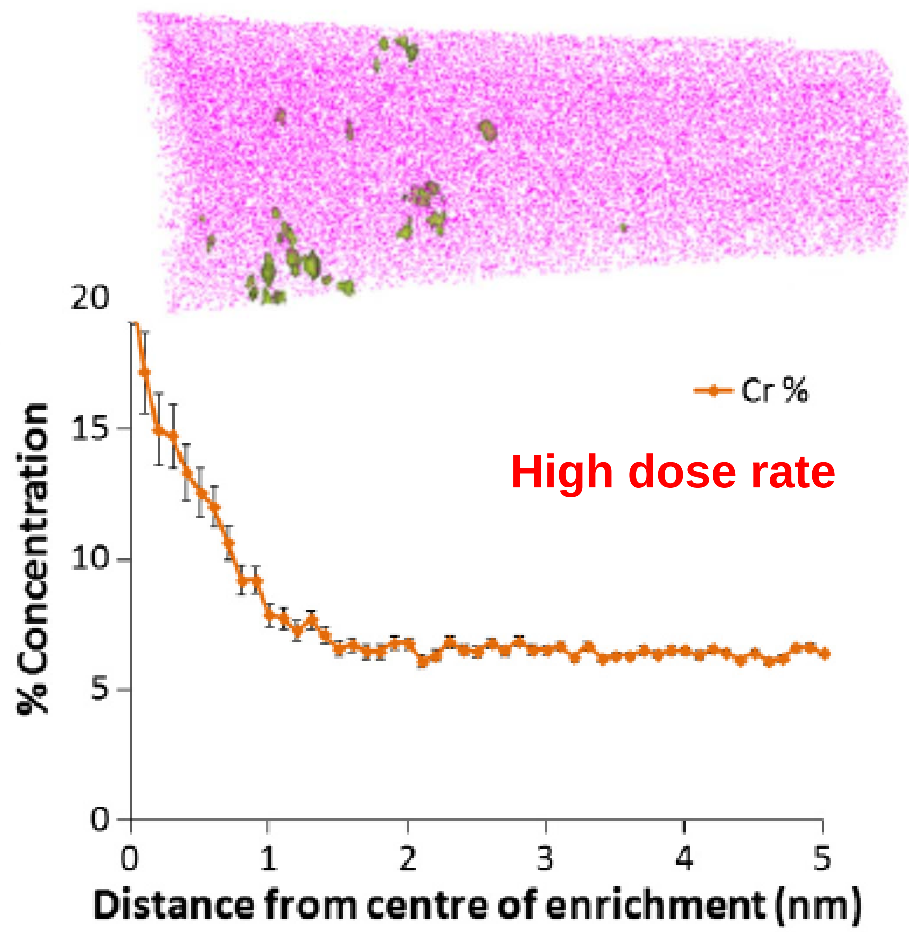
TEM of ion irradiation damage Fe 5%Cr 300ºC



S. Xu 2012

APT of ion irradiation damage Fe 5%Cr 400ºC

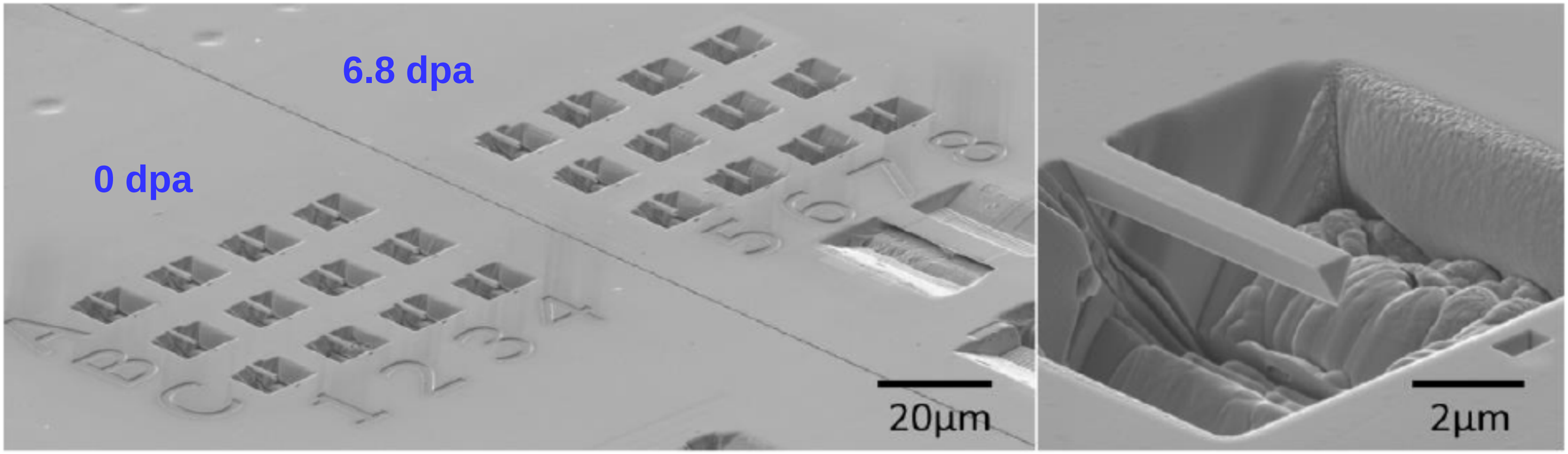




APT data for the Fe 5%Cr alloy irradiated at 400 Cwith the low dose rate (a)and high dose rate.(b)The figureincludes an atom map showing Fe atoms and a0.5 at.%CrN isoconcentration surface (i)and proximity histograms showing the variation in composition from the centre of enrichment outwards into the matrix (ii).Centre of enrichment is definedas the region of highest CrN concentration.

C.D. Hardie et al. J Nuclear Materials 439 (2013) 33–40

Micro-mechanical Testing

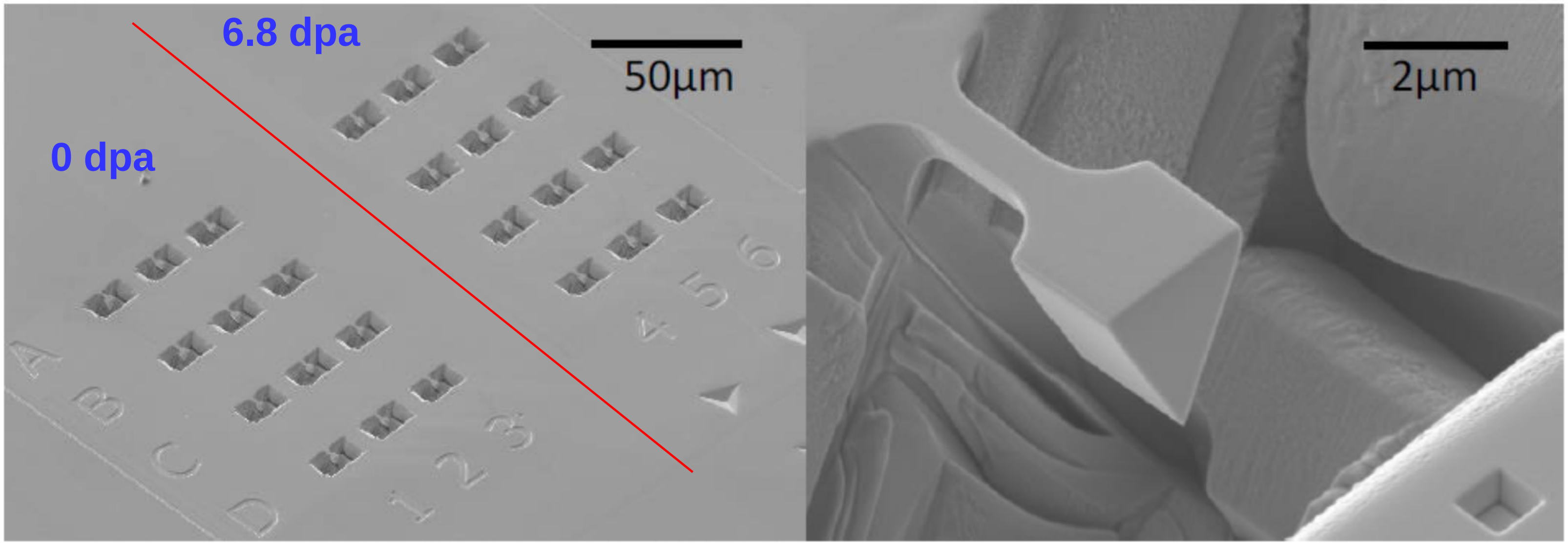


Fe-12%Cr

Ion – irradiated
Fe^{+}
0.5MeV & 2MeV
320°C

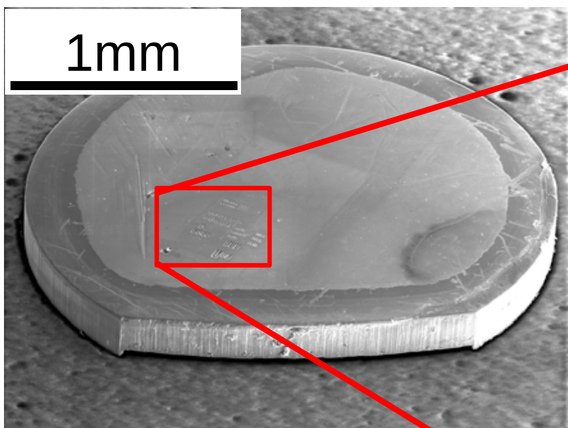
Chris Hardie, D.Phil Thesis, Oxford, 2013

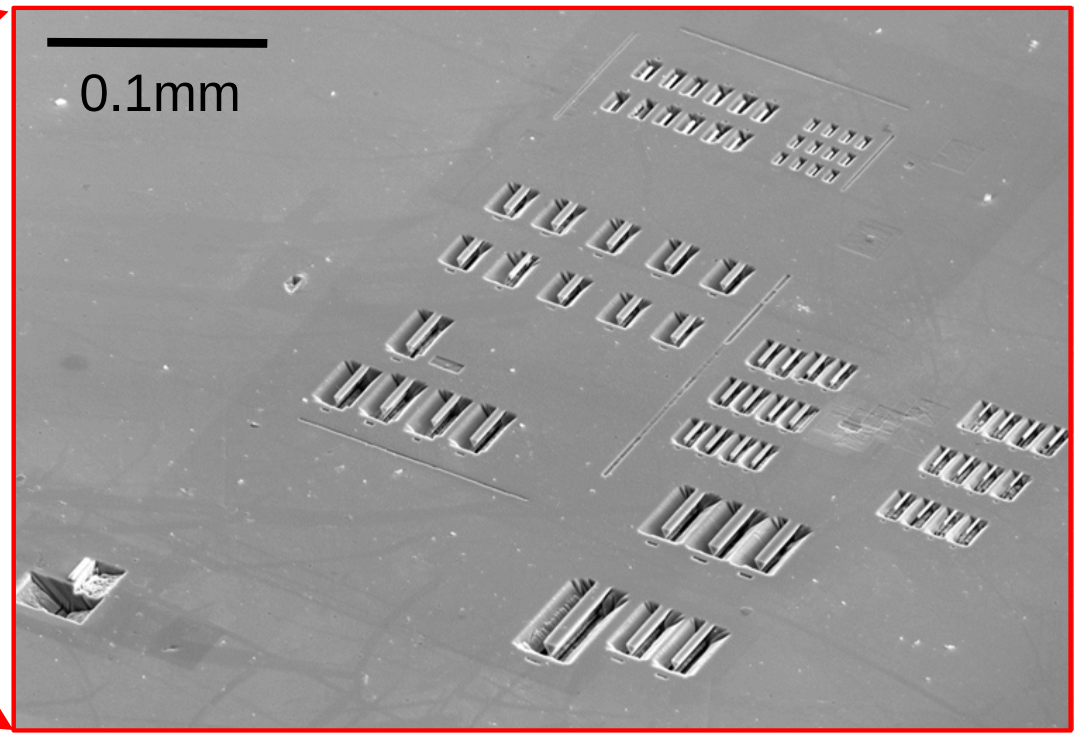
Micro-mechanical Testing



Fe-12%Cr

Ion – irradiated
Fe^{+}
0.5MeV & 2MeV
320°C



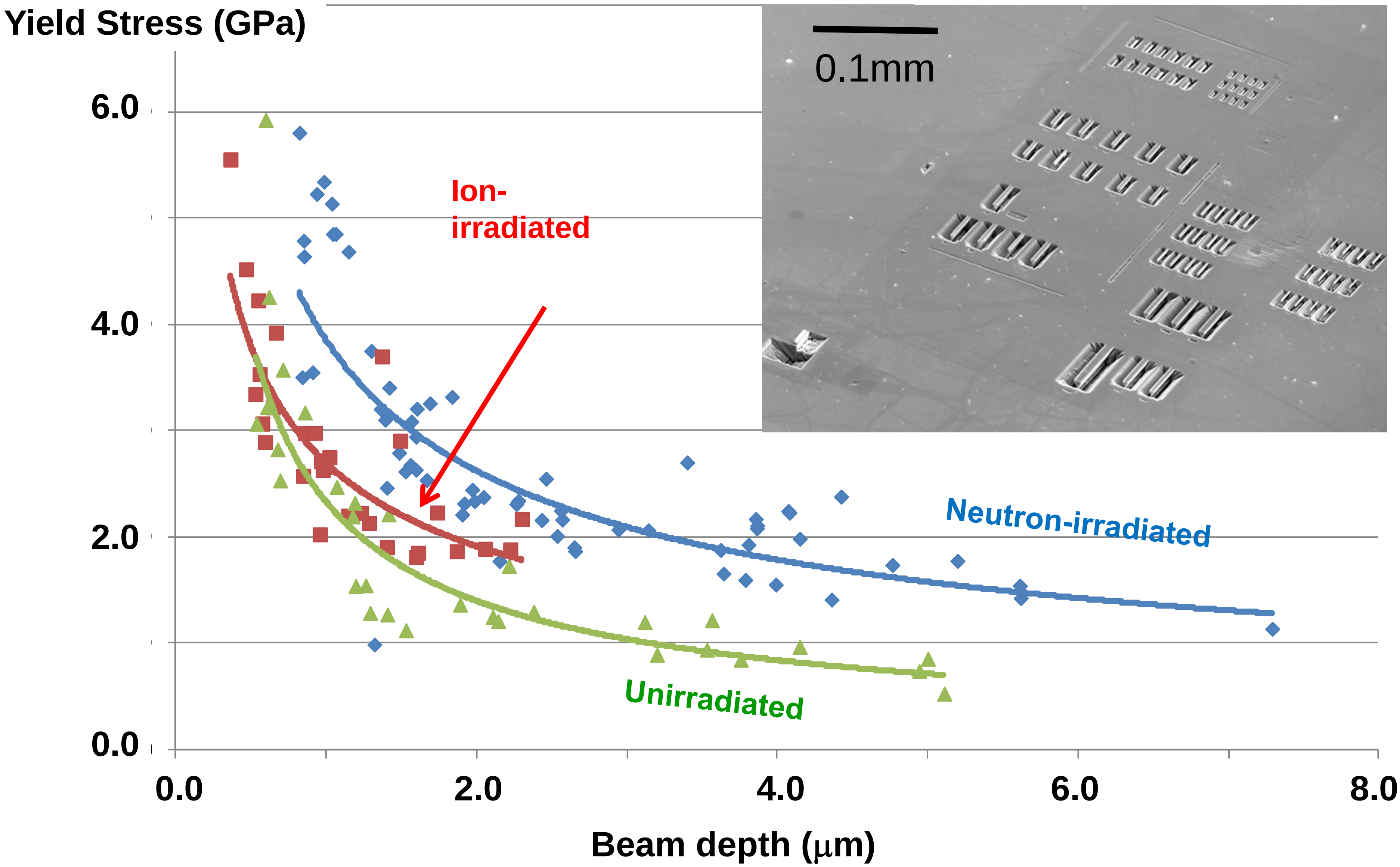


Fe-6%Cr

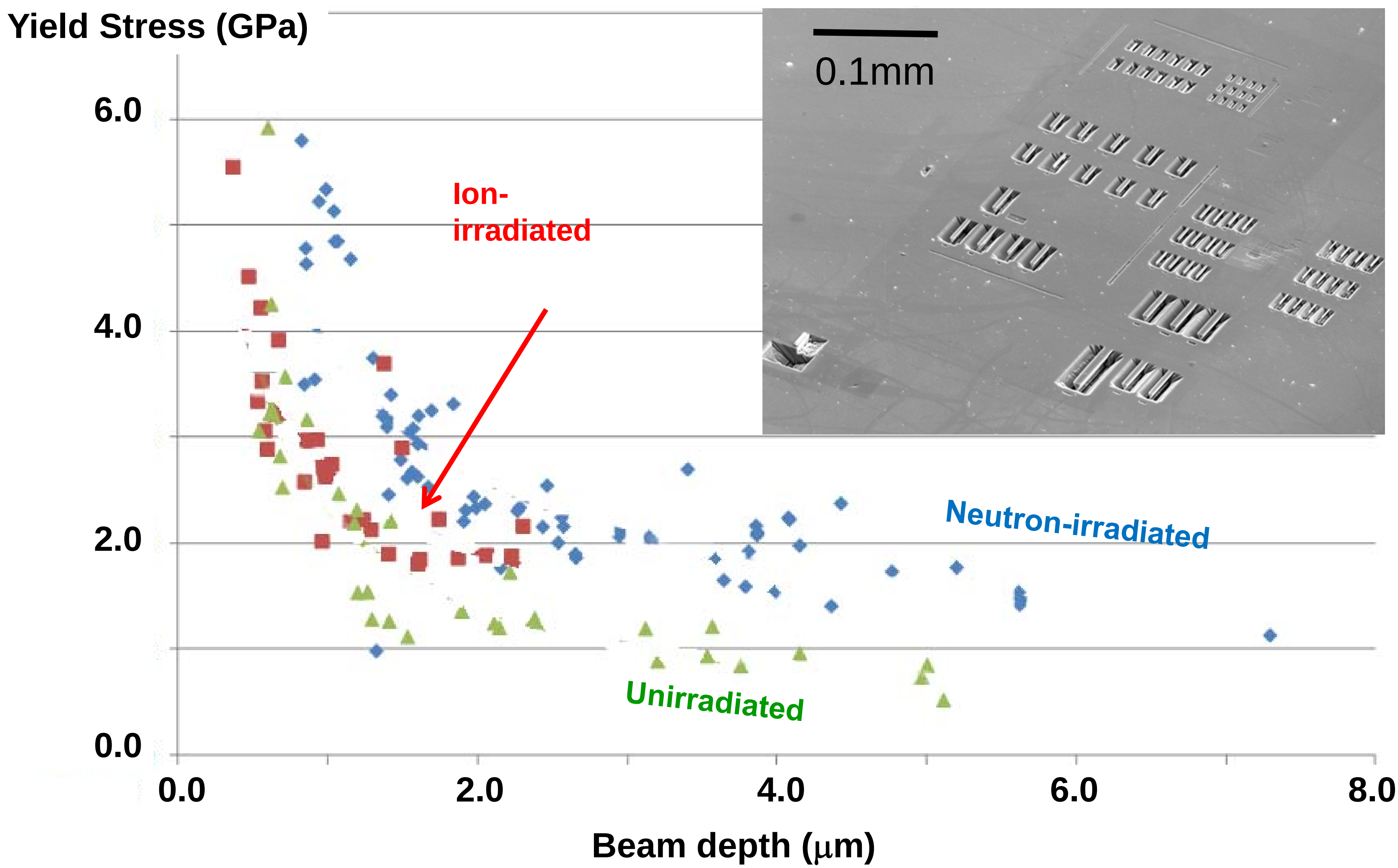
neutron – irradiated
288°C
1.7 dpa

Chris Hardie, D.Phil Thesis, Oxford, 2013

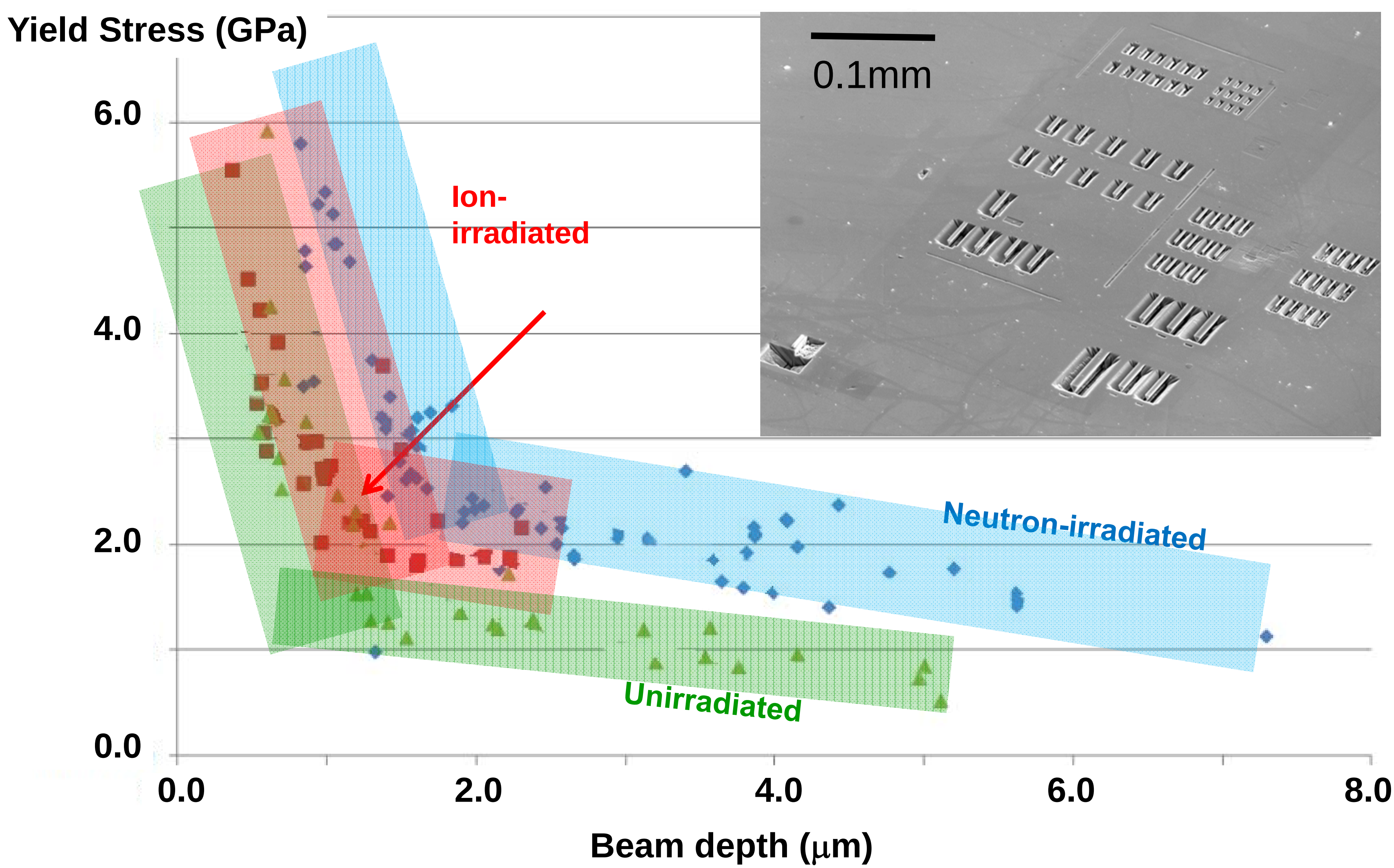
Micromechanical testing Fe-6%Cr – Size effects



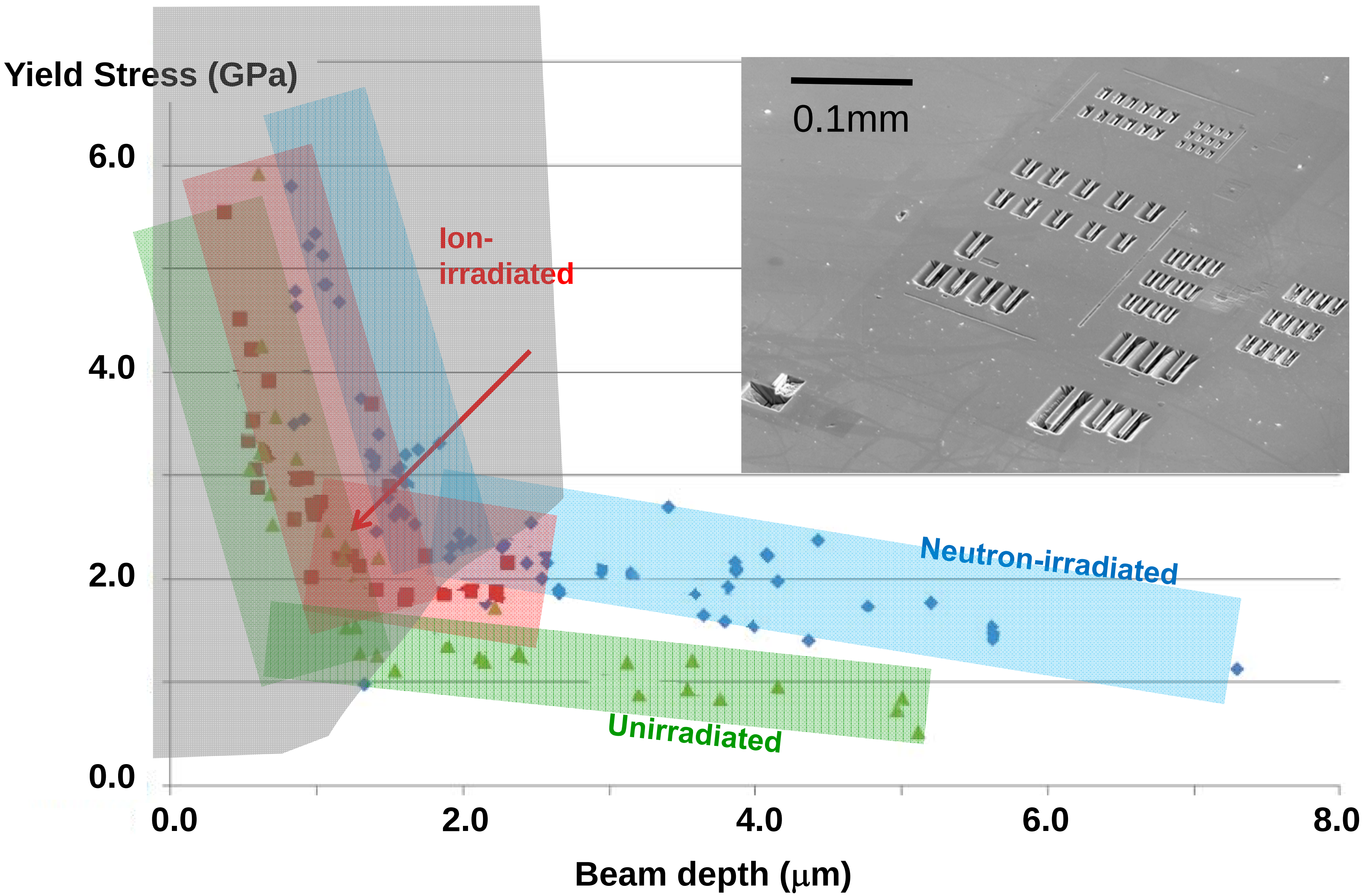
Micromechanical testing Fe-6%Cr – Size effects



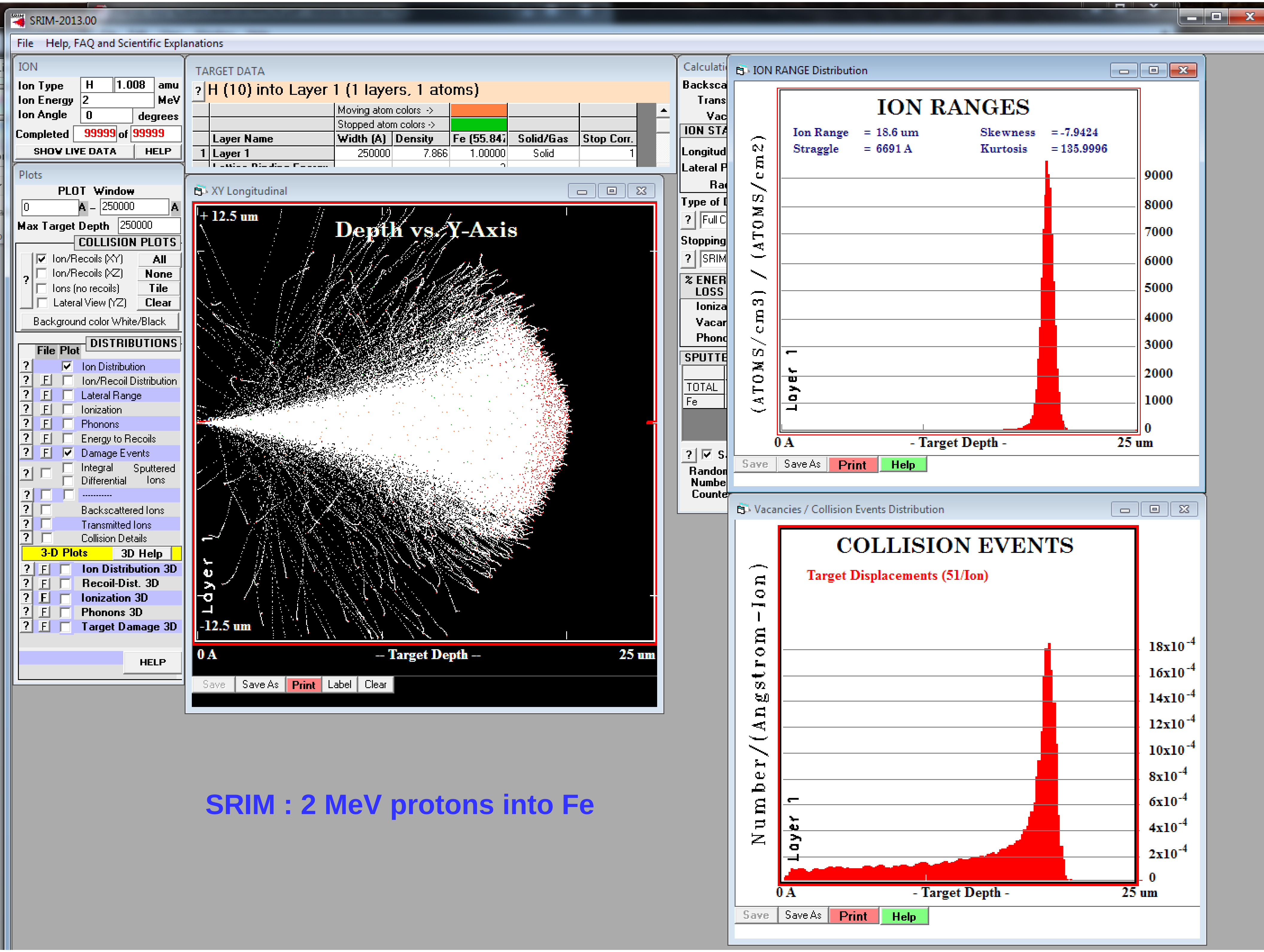
Micromechanical testing Fe-6%Cr – Size effects



Micromechanical testing Fe-6%Cr – Size effects



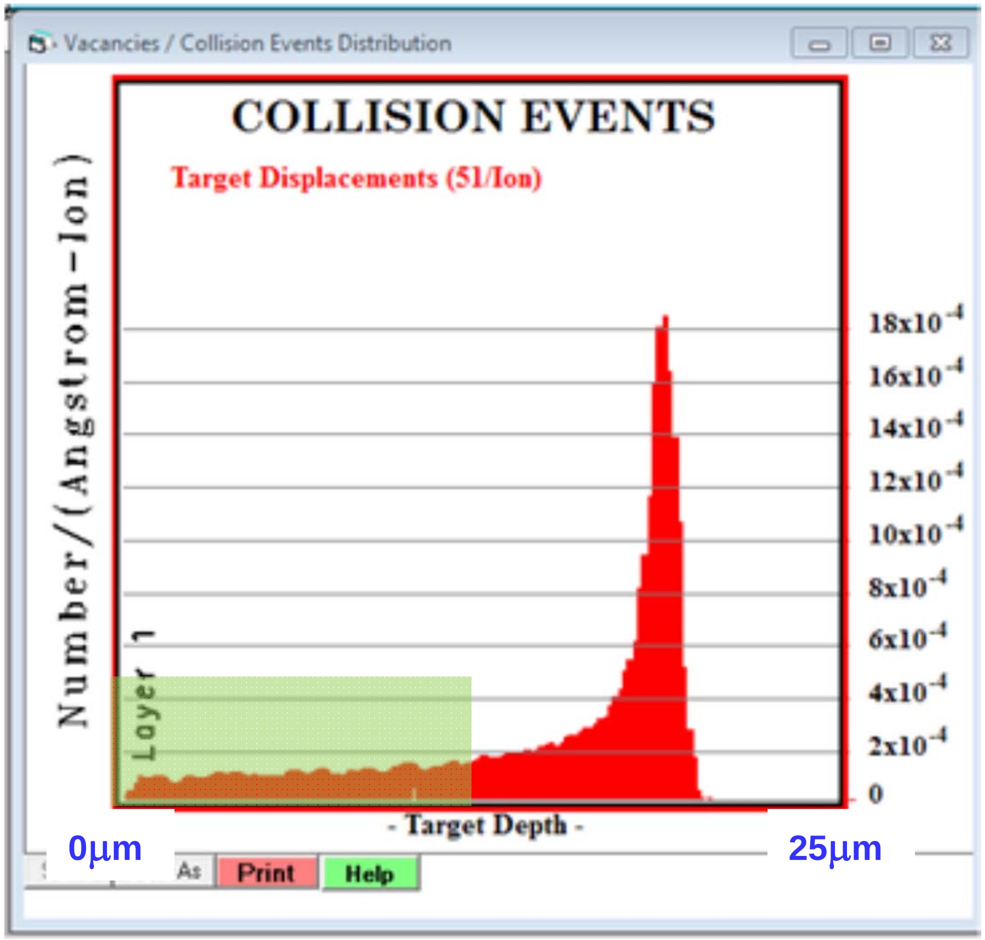
Protons ?

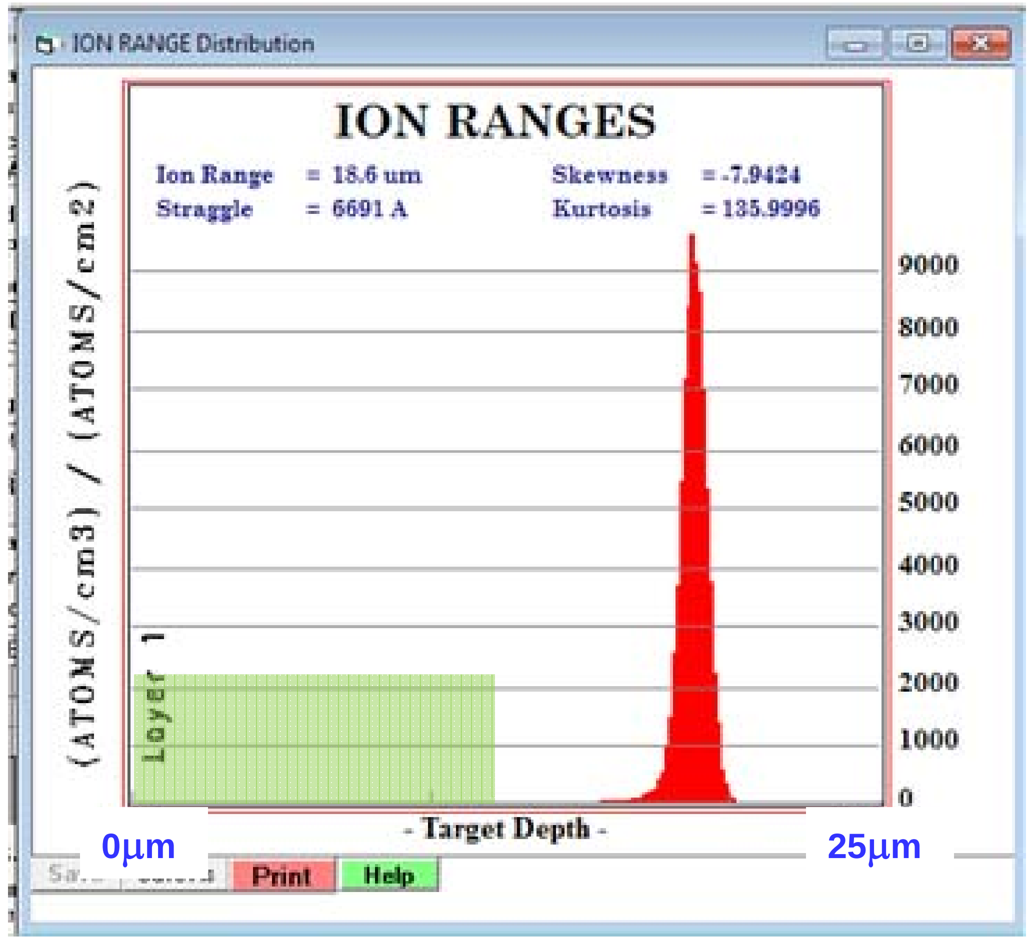


SRIM : 2 MeV protons into Fe

Proton irradiation for (micro) mechanics?

SRIM : 2 MeV protons into Fe

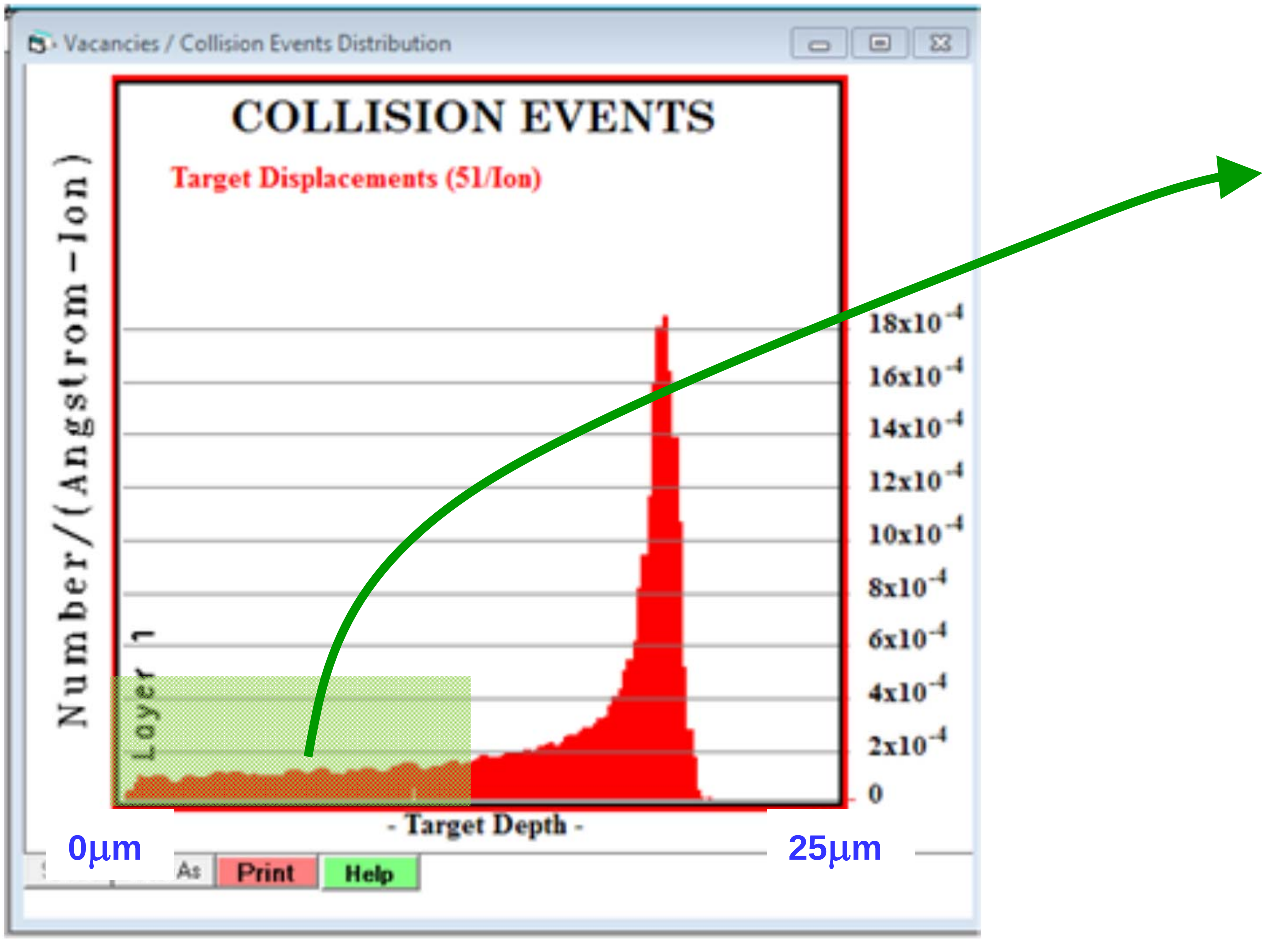




Could use specimens 10 – 12 µm thick – well beyond the size-dependent mechanics regime

Proton irradiation for (micro) mechanics?

SRIM : 2 MeV protons into Fe



For 2MeV H^+ into Fe:

Total damage:

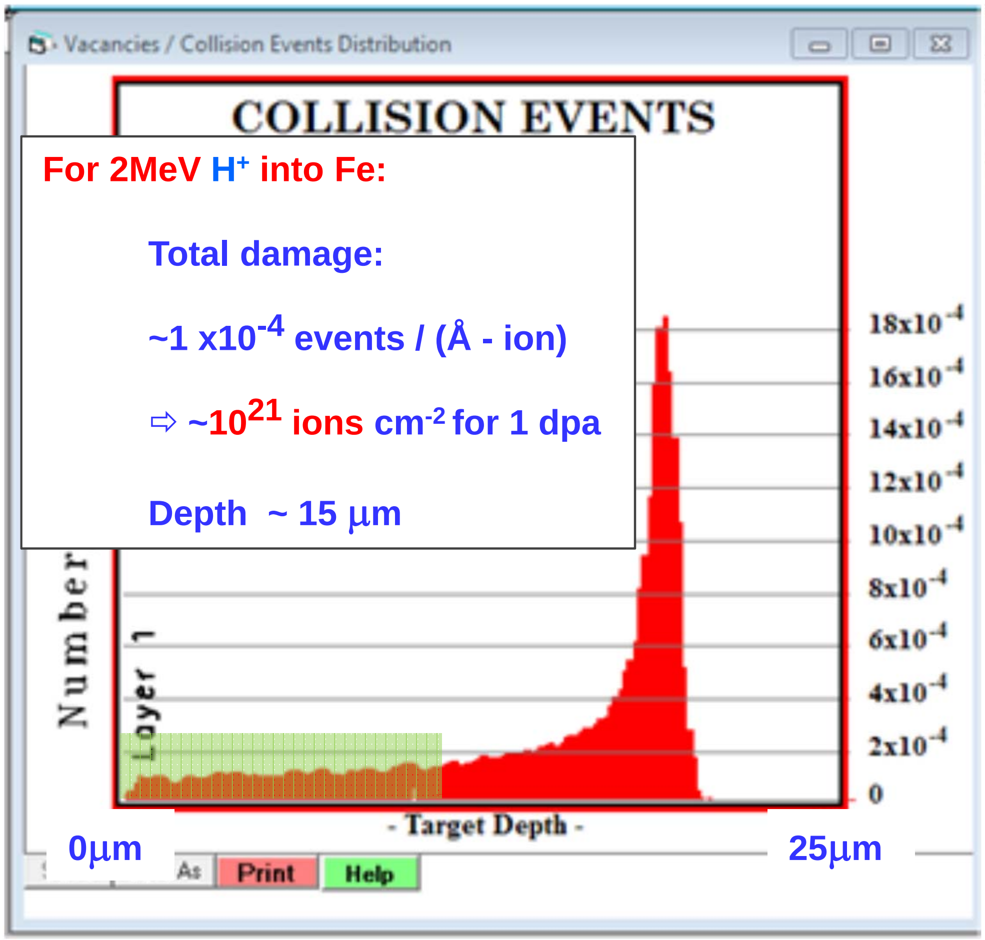
~1 $x10^{-4}$ events / (Å - ion)

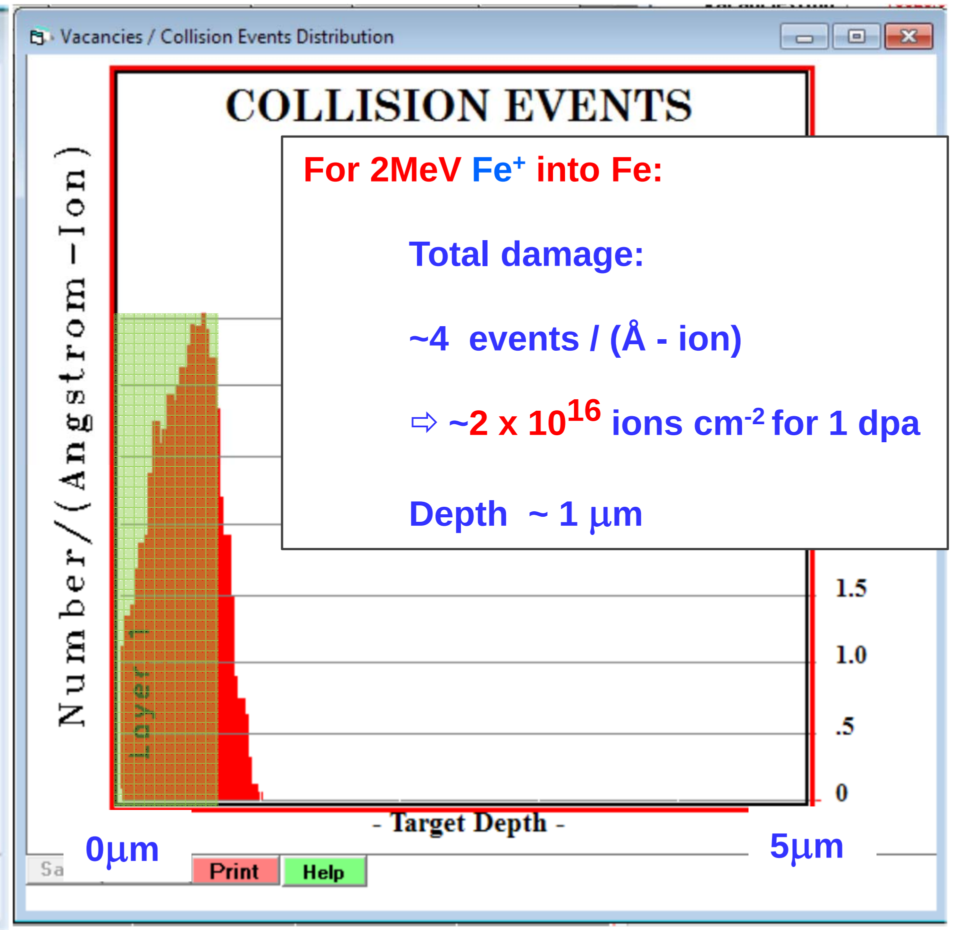
⇨ ~10^{21} ions cm^{-2} for 1 dpa

Depth ~ 15 µm

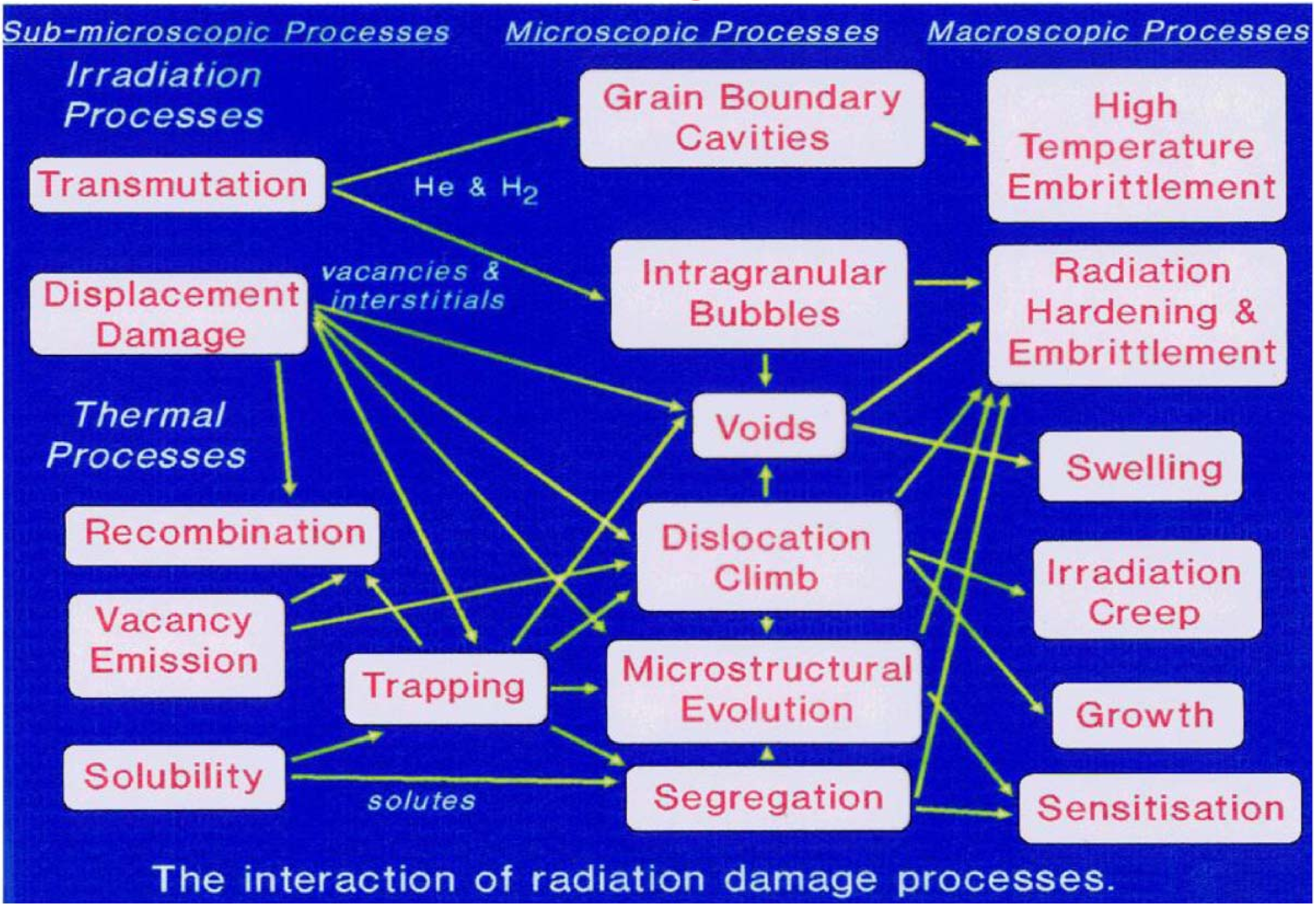
Proton irradiation for (micro) mechanics?

SRIM : 2 MeV protons into Fe





Radiation damage in Materials



C.A. English (2011)