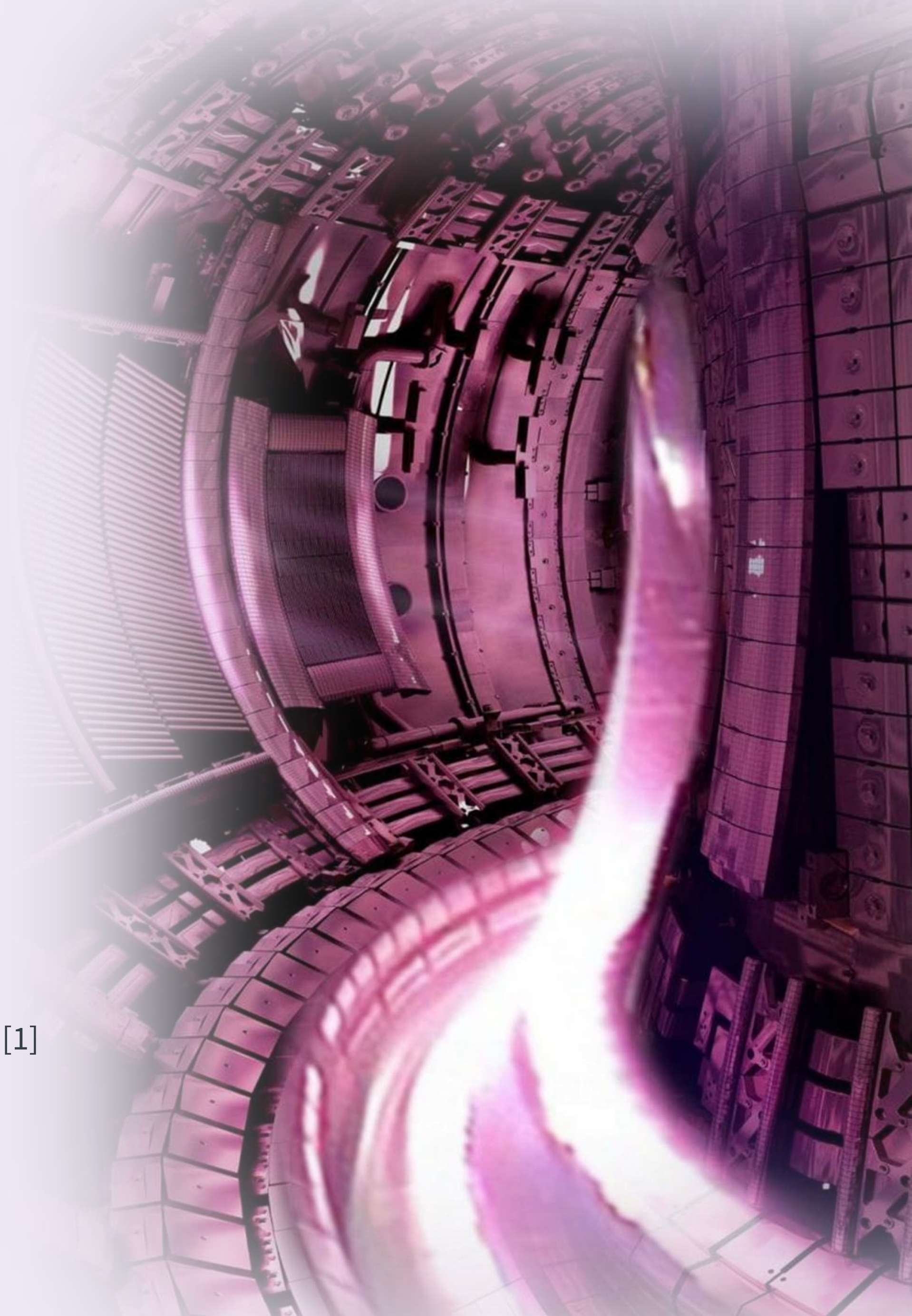
University of Sheffield

MPI 8th Postgraduate Research Symposium on Ferrous Metallurgy

Exploration of the use of ferrous alloys as radiation damage resistant materials for fusion

Sophie Barwick [1], Jack Haley [2], Samir de Moraes Shubeita [3], Katerina Christofidou [1], Chris Race [1], Amy Gandy [2], Russell Goodall [1]

[1] University of Sheffield
[2] UK Atomic Energy Authority
[3] Dalton Cumbria Facility

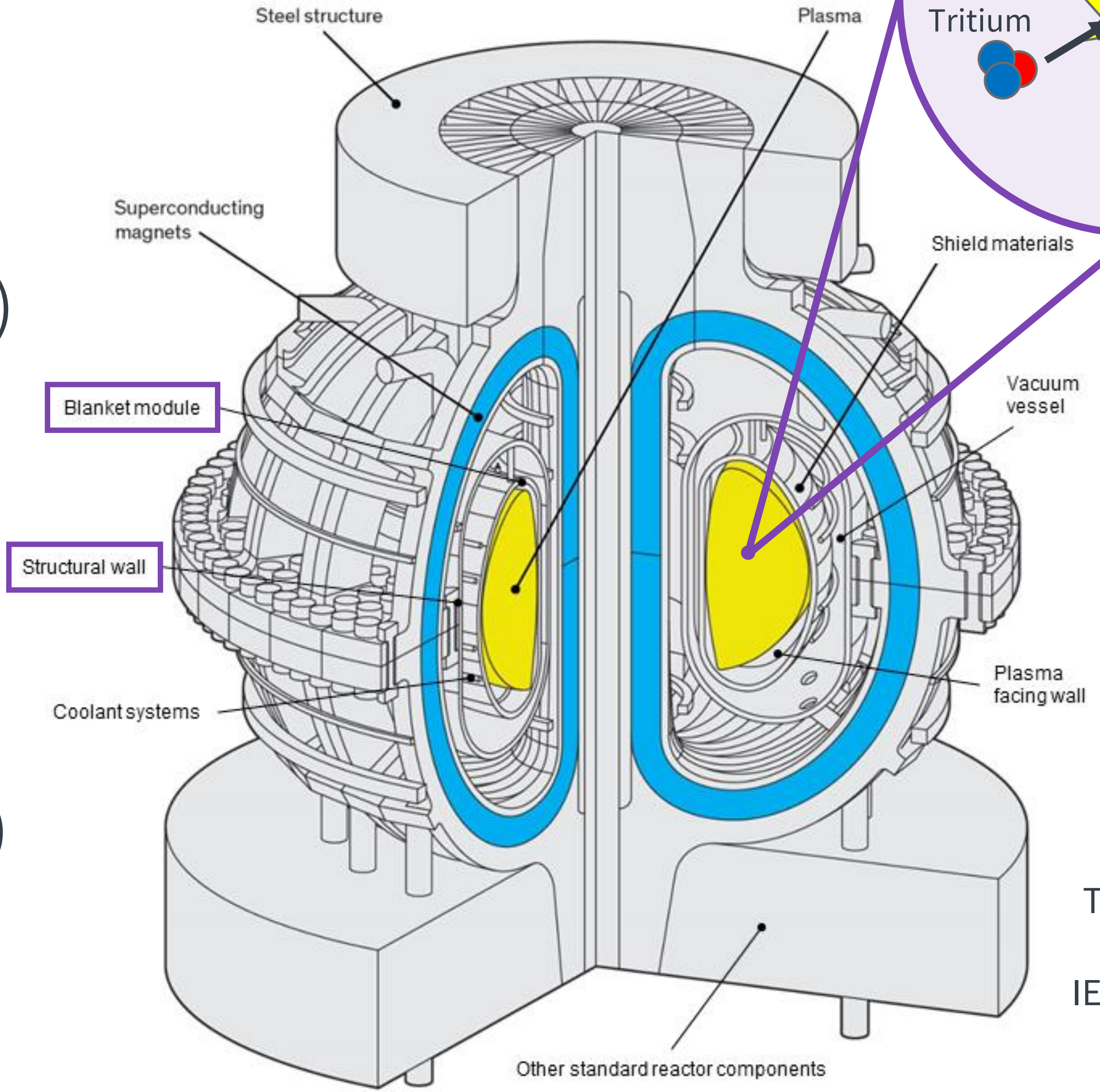


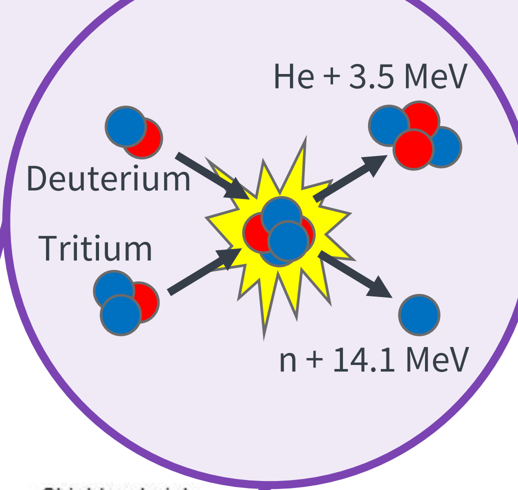
UK Atomic Energy Authority

Background

Nuclear Fusion

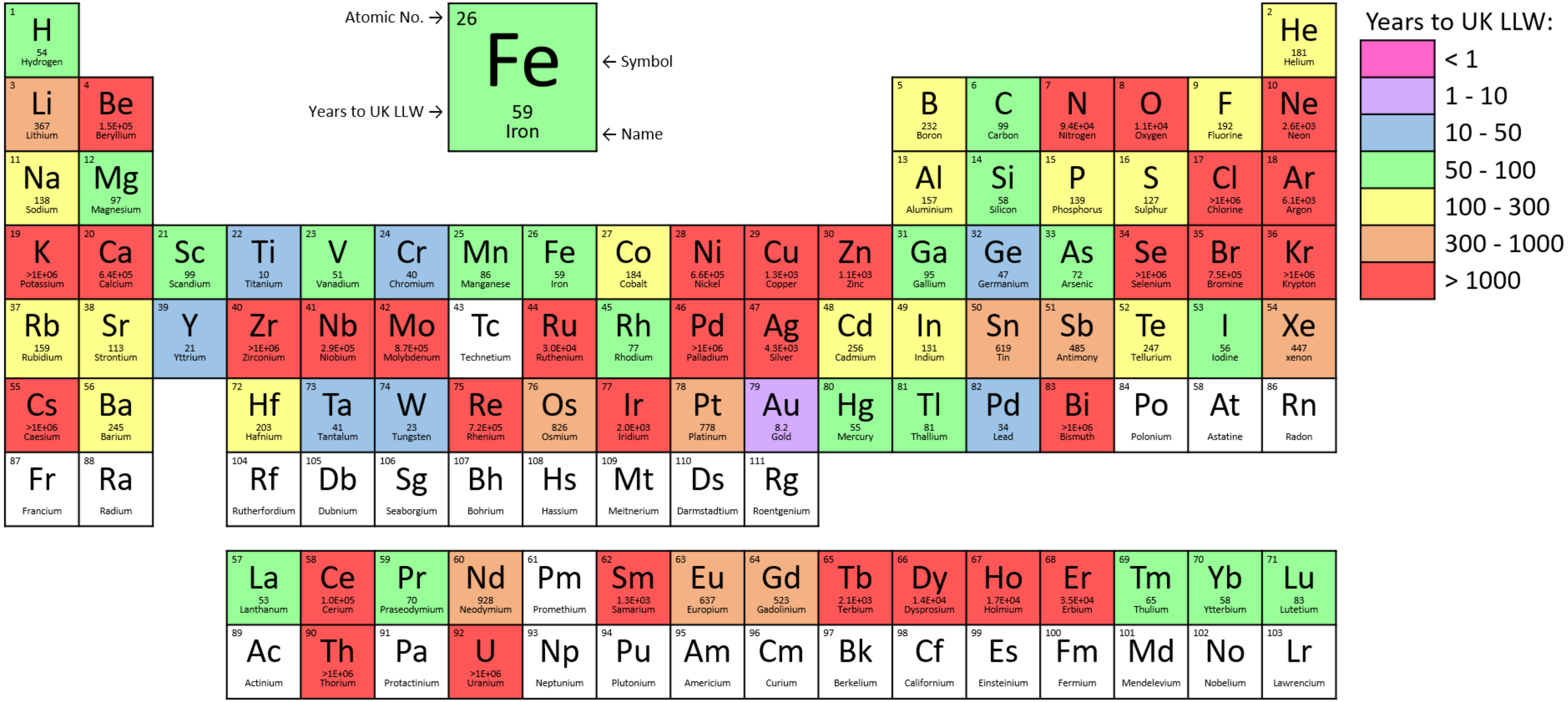
- ~ 4 million times energy from burning coal, oil, or gas (at equal mass of fuel)
- 4x the energy from nuclear fission reactions (at equal mass of fuel)
- Magnetic confinement reactor – tokamak
- Spherical Tokamak for Energy Production (STEP) due to be built in 2040





T. Clynes and C. Philpot / IEEE Spectrum (2020)

Low Level Waste Element Restrictions



M.R. Gilbert et al. / Nucl. Fusion 59 (2019) 076015

Materials Development

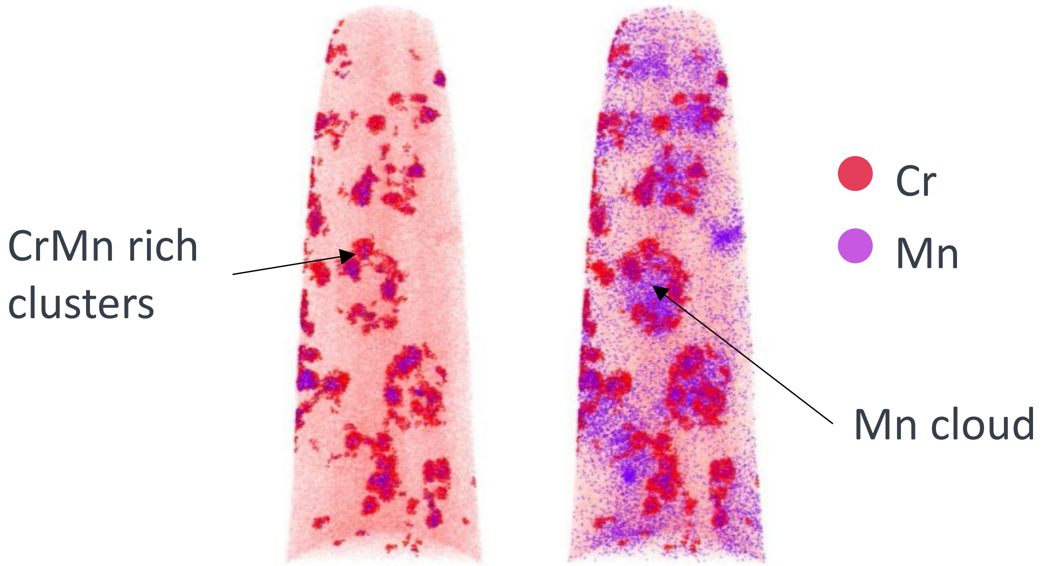
Current Materials

- Reduced Activation Ferritic Martensitic (RAFM) steels
- EUROFER97

Issues

- Clustering
- Embrittlement
- Swelling
- Activation
- Bubble formation
- Irradiation induced creep

EUROFER97 15dpa neutrons/330°C

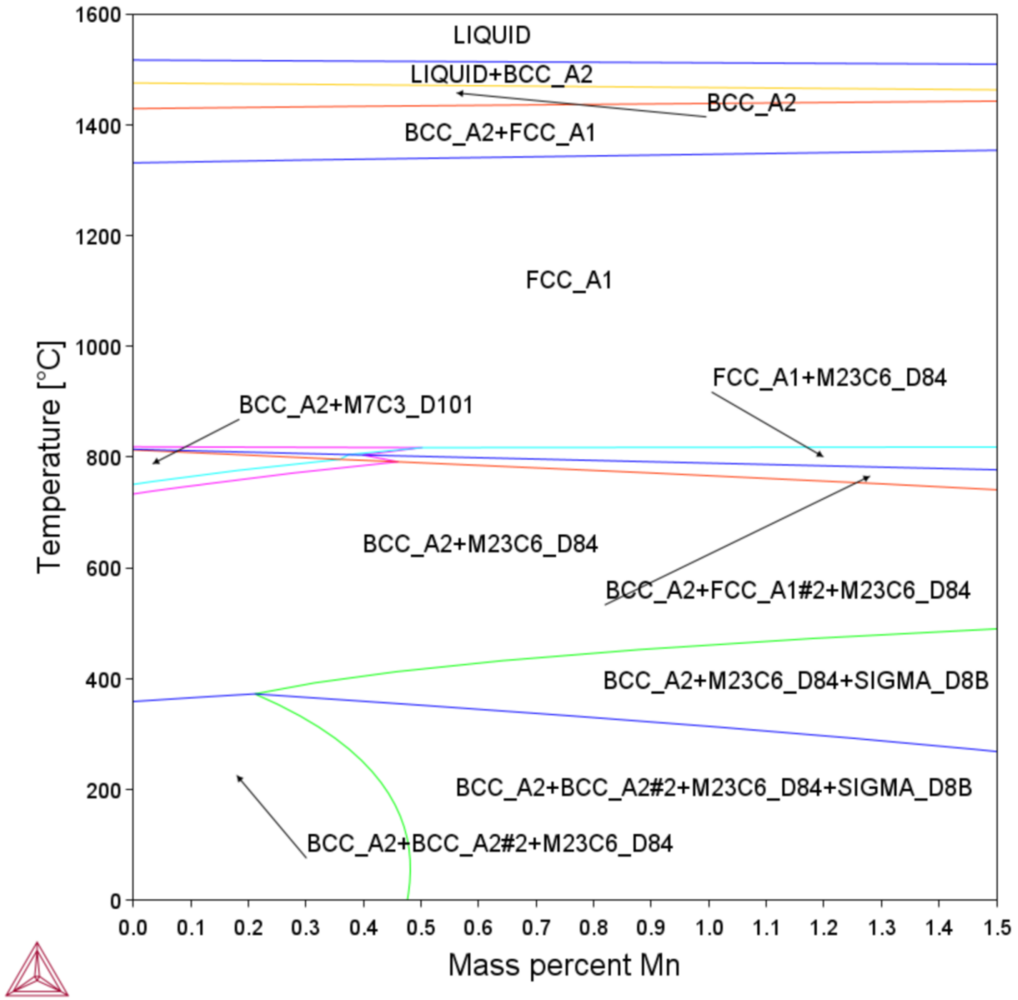


B. Gomez-Ferrer et al. / Journal of Nuclear Materials 537 (2020) 152228

Alloy development

Alloys

Fe8Cr0.11C(0-1.5)Mn



Alloy name	Fe	Cr	C	Mn	HT
	[wt%]				°C
Fe8Cr	Bal	8	0.11	-	980
Fe8Cr0.4Mn				0.4	980
Fe8Cr0.4Mn				0.4	1150
Fe8Cr1Mn				1.0	980
Eurofer-97	*89.14*	*9*	*0.11*	*0.4*	*+ W, V, Ta, N2*

Heat Treatment Route:
Normalise at HT -> Water Quench -> Temper at 760°C -> Air Cool

E. Gaganidze et al. / UKAEA-CCFE-PR(18)63

Methodology

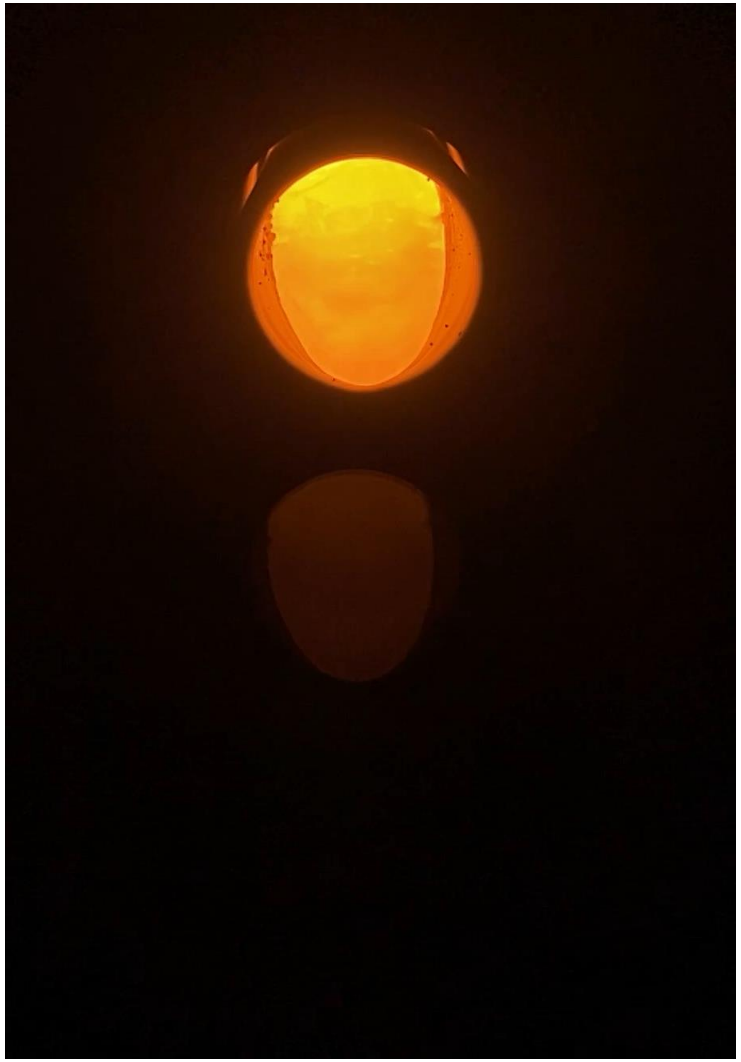
Vacuum Induction Melt (VIM) samples

Sample preparation of surface

Pre-irradiation analysis:

- Optical microscopy
- Scanning Electron Microscopy (SEM)
- Energy Dispersive X-ray (EDX) Spectroscopy
- Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)
- Dilatometry vs ThermoCalc
- Grazing Incidence X-Ray Diffraction (GIXRD)
- Nano-indentation
- Laser Flash Analysis (LFA)

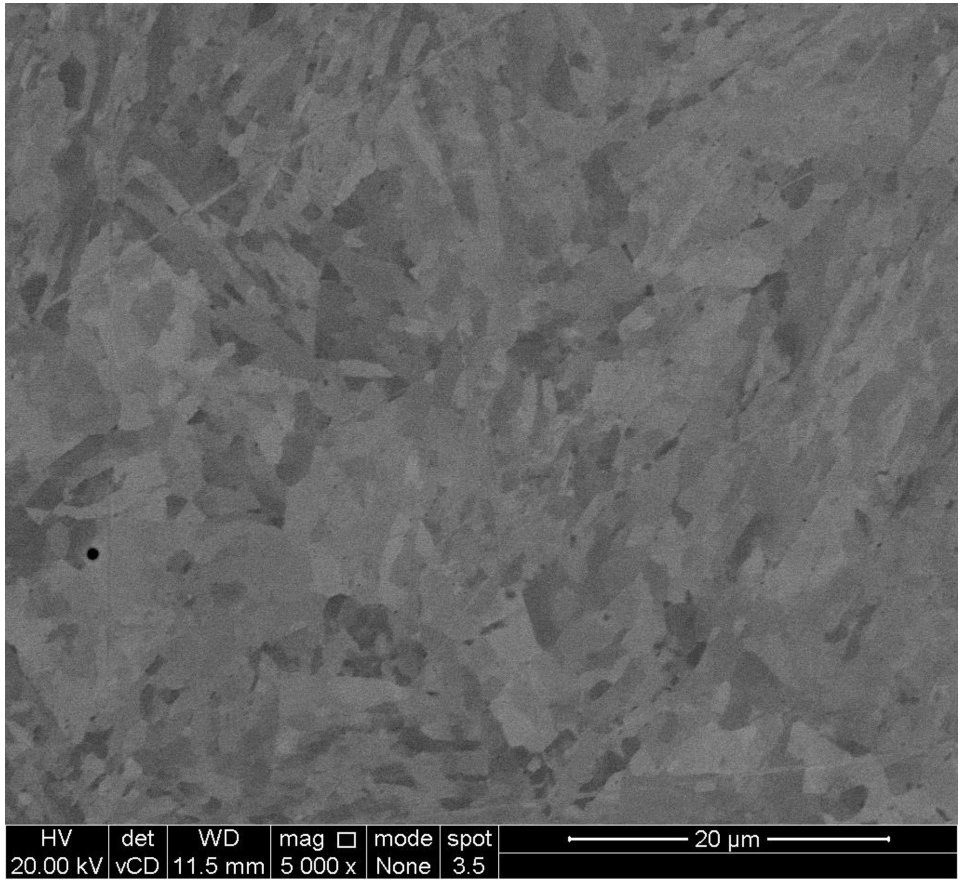
Irradiation planning

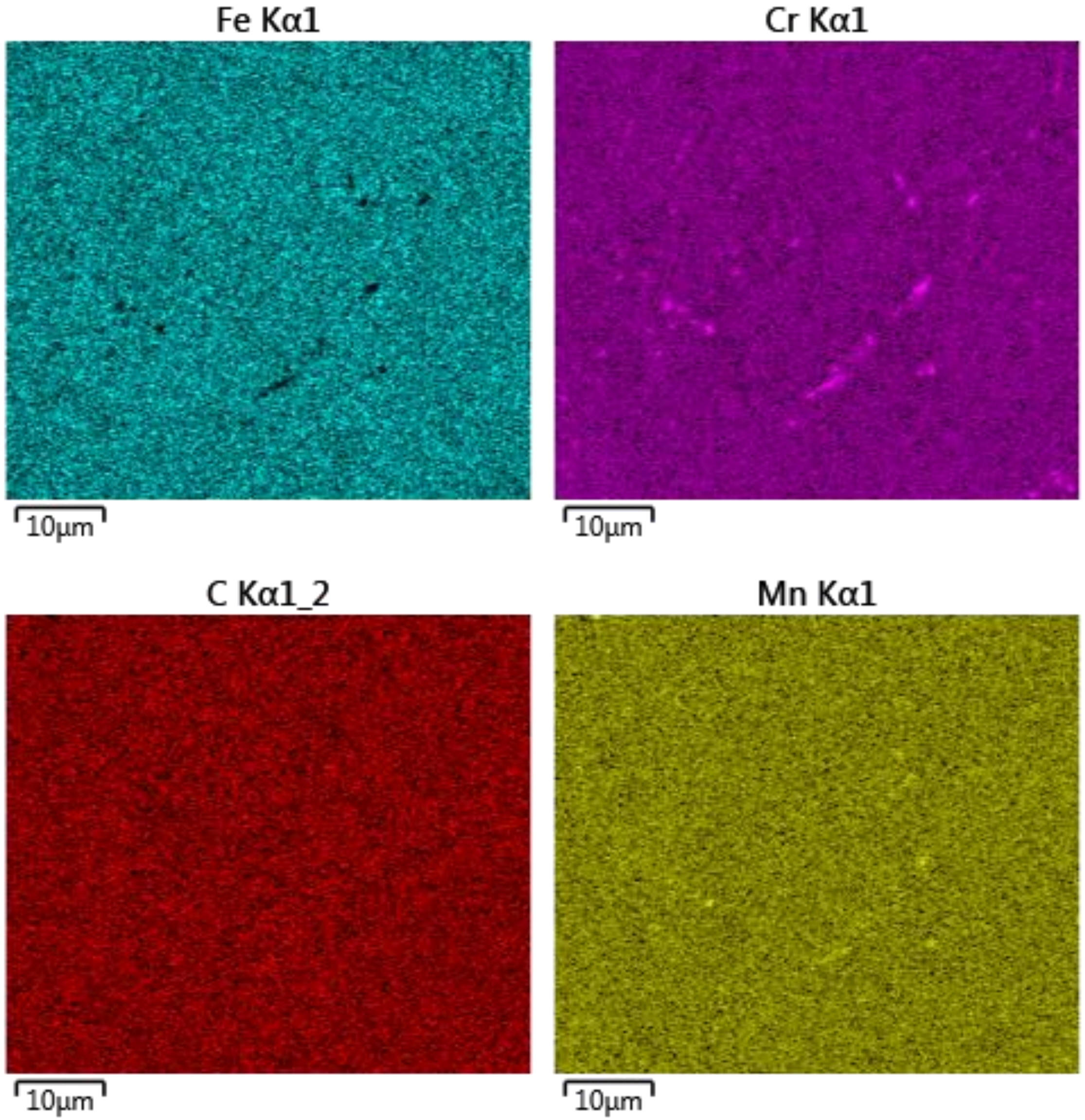


Pre-irradiation analysis

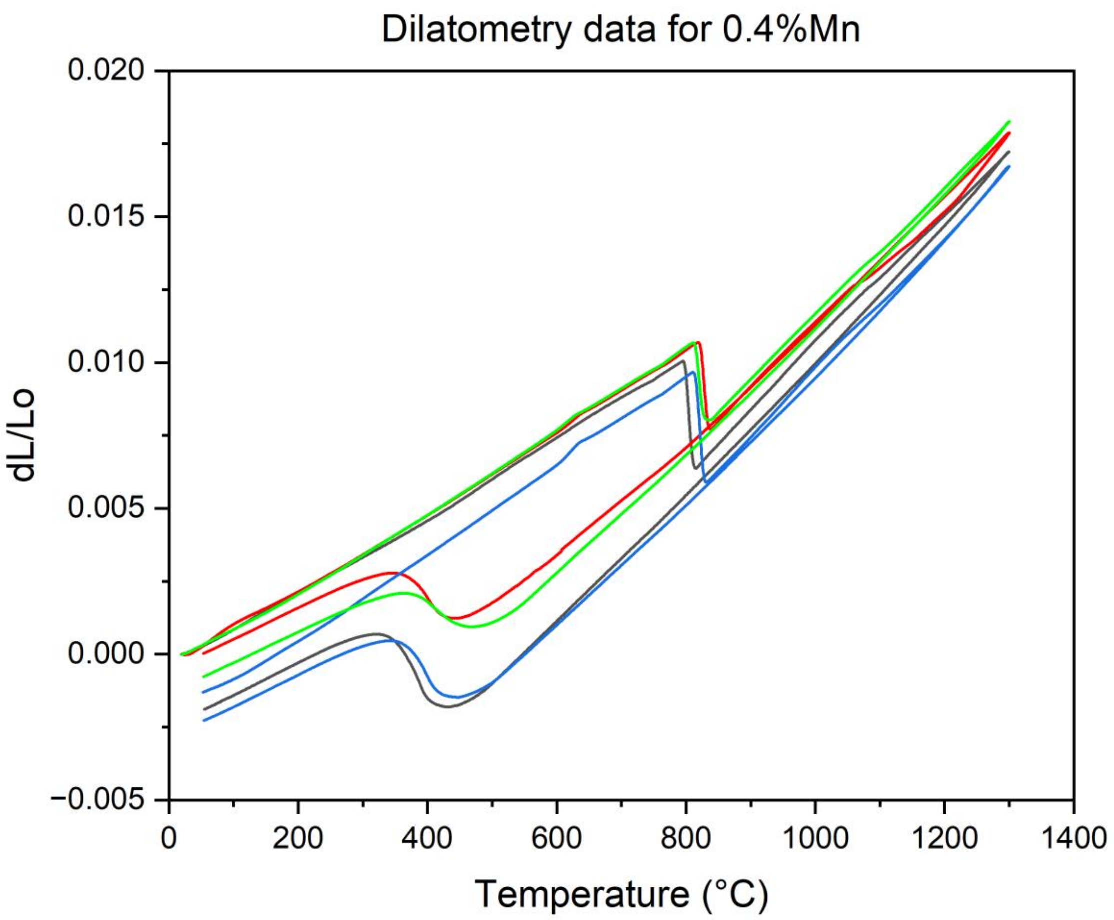
Energy Dispersive X-Ray Spectroscopy (EDX)

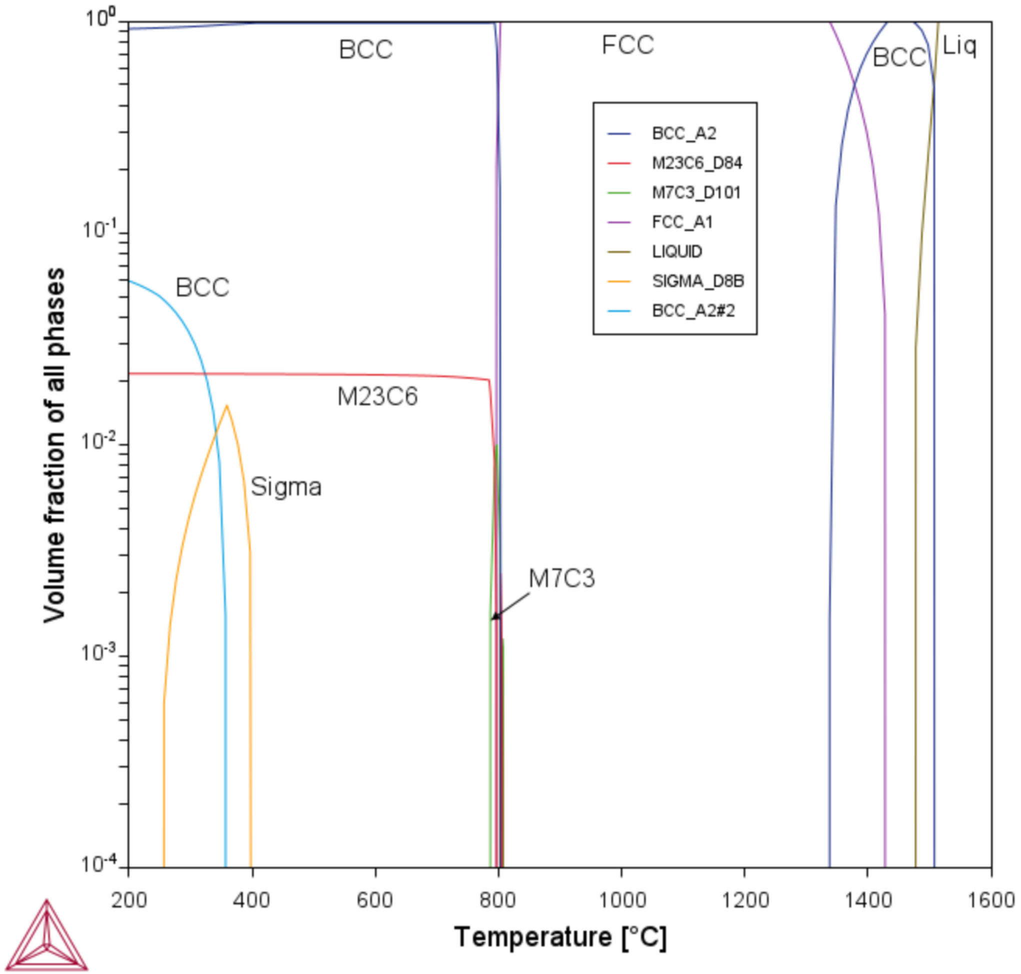
Fe8Cr0.11C0.4Mn HT980





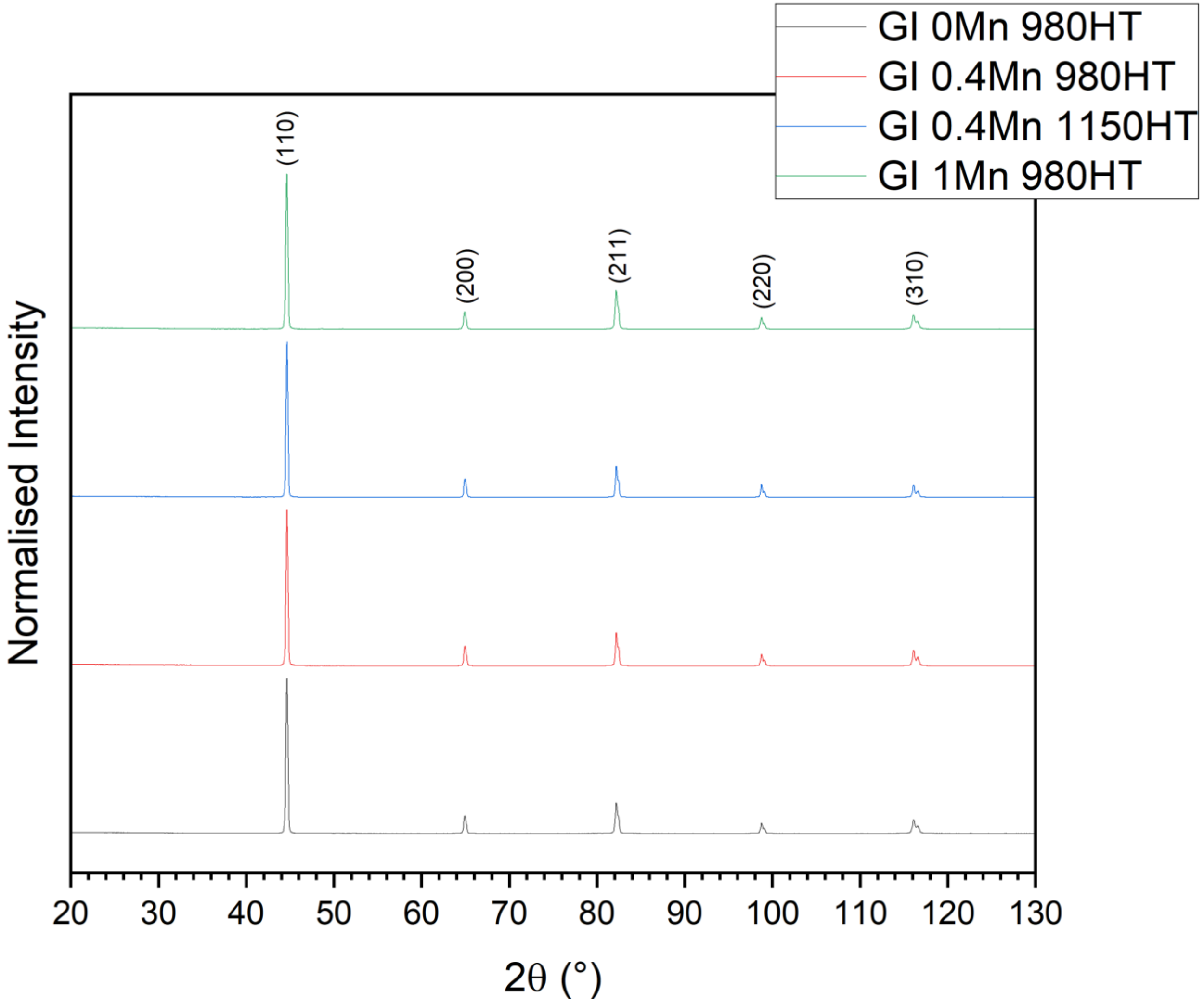
Dilatometry





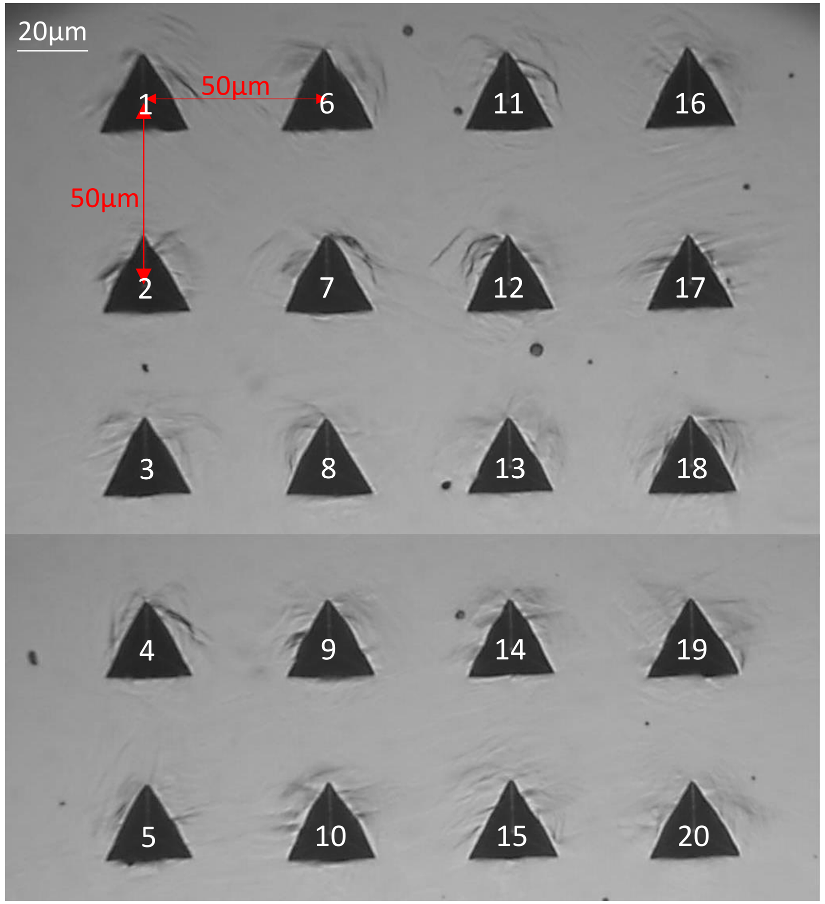
Grazing Incidence X-Ray Diffraction (GIXRD)

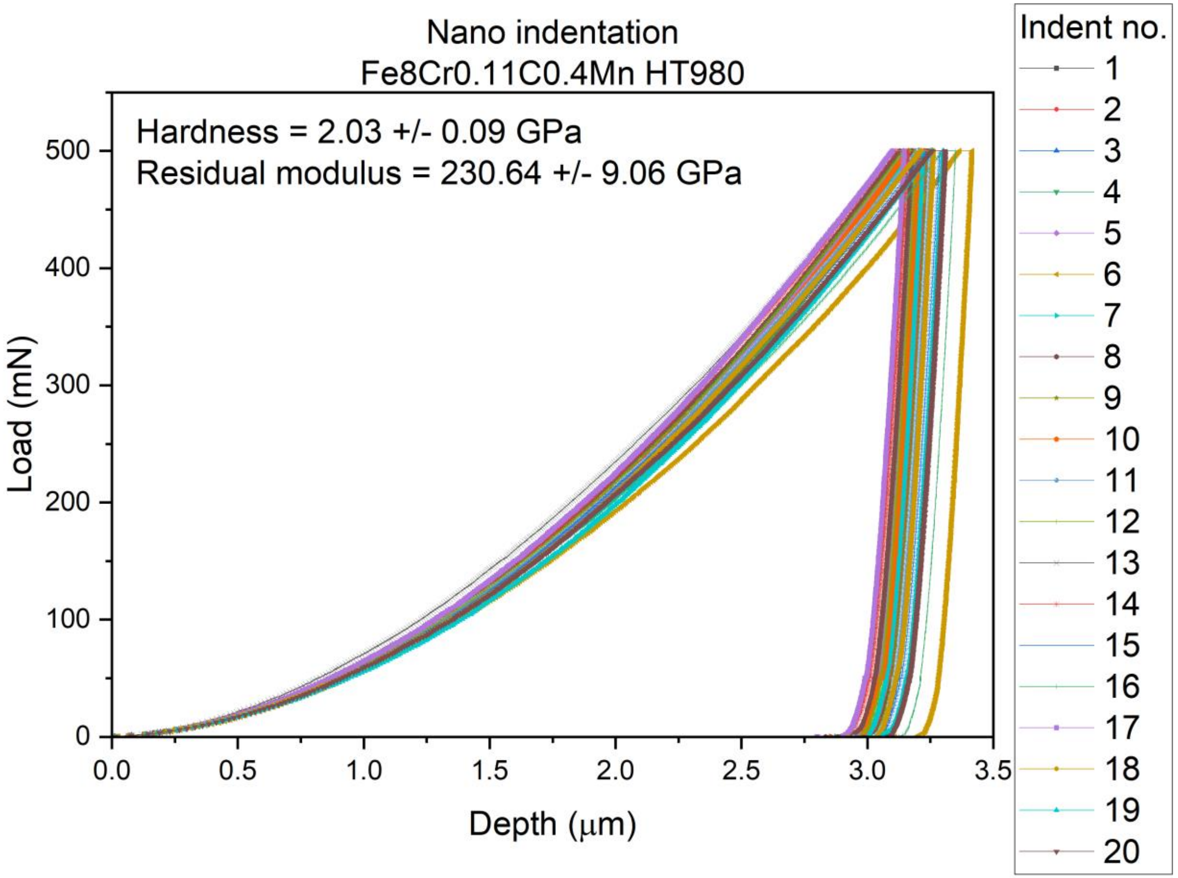
3.5 µm
- Fe8Cr0.11C: 15.603°
- Fe8Cr0.11C0.4Mn: 15.593°
- Fe8Cr0.11C1Mn: 15.578°



Nano Indentation

Force: 500mN
Rate: 20mN/s
20 indents per sample





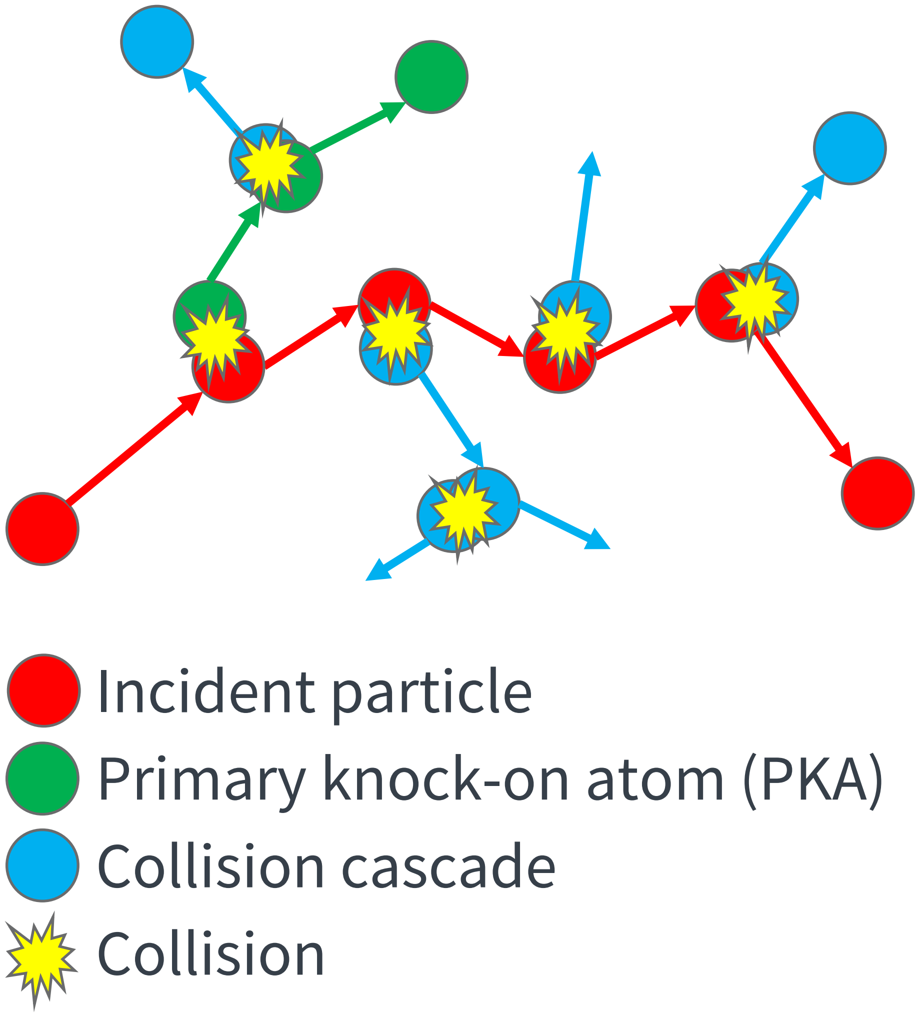
	0Mn	0.4Mn (980HT)	0.4Mn (1150HT)	1Mn
Hardness [GPa]	1.88 +/- 0.10	2.03 +/- 0.09	1.91 +/- 0.07	2.19 +/- 0.08

Irradiation theory

Radiation Damage

Type and amount of damage produced depends on:

- Nature of particle
- Mass of particle
- Energy of particle
- Nature of material

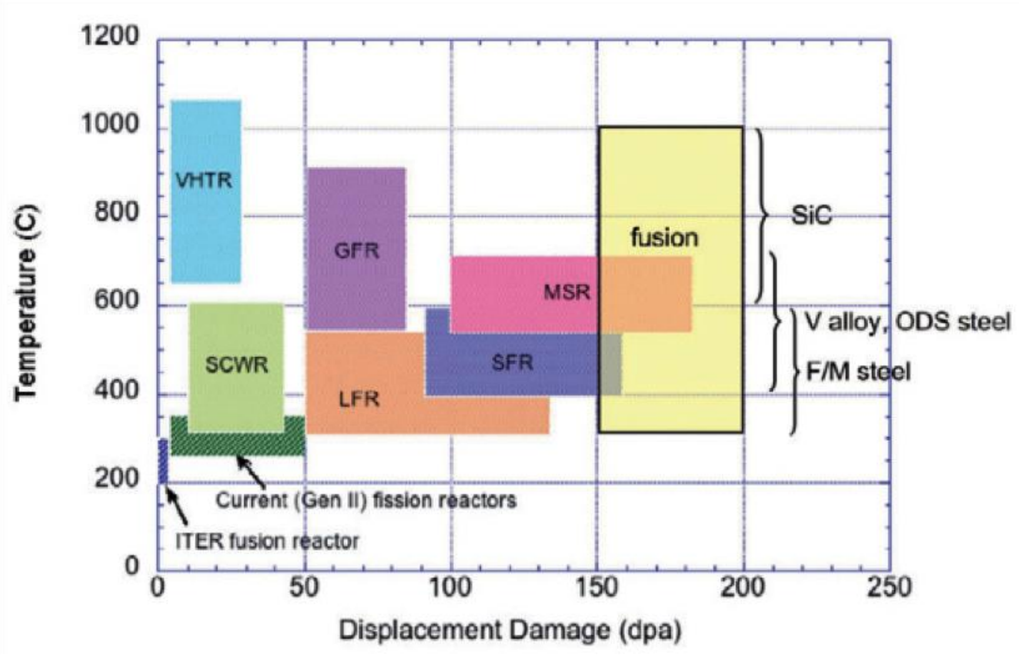


Displacements per Atom (dpa)

Displacements per atom: number of times that an atom is displaced for a given fluence

Fluence: total number of particles that intersect a unit area over a specific time interval

dpa is used to normalise the amount of radiation damage that different reactors produce

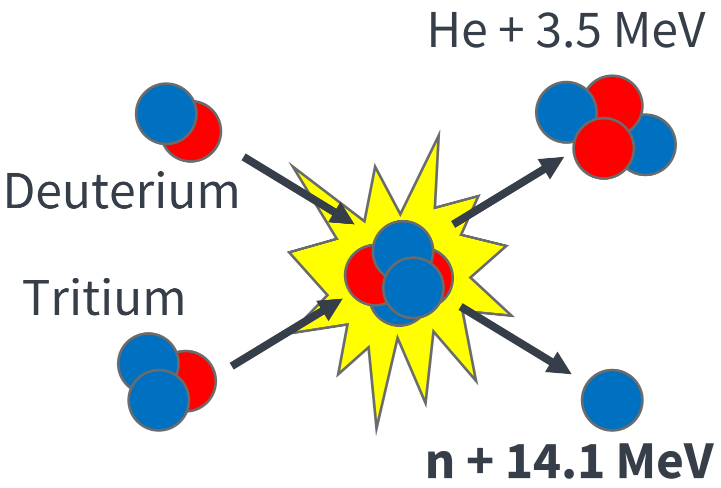


S.J. Zinkle & J.T. Busby / Mater. Today 12 (2009) 12

Neutrons

Cause significant levels of damage:

A single 1 MeV neutron creating a PKA in an iron lattice will produce approximately 1100 Frenkel pairs

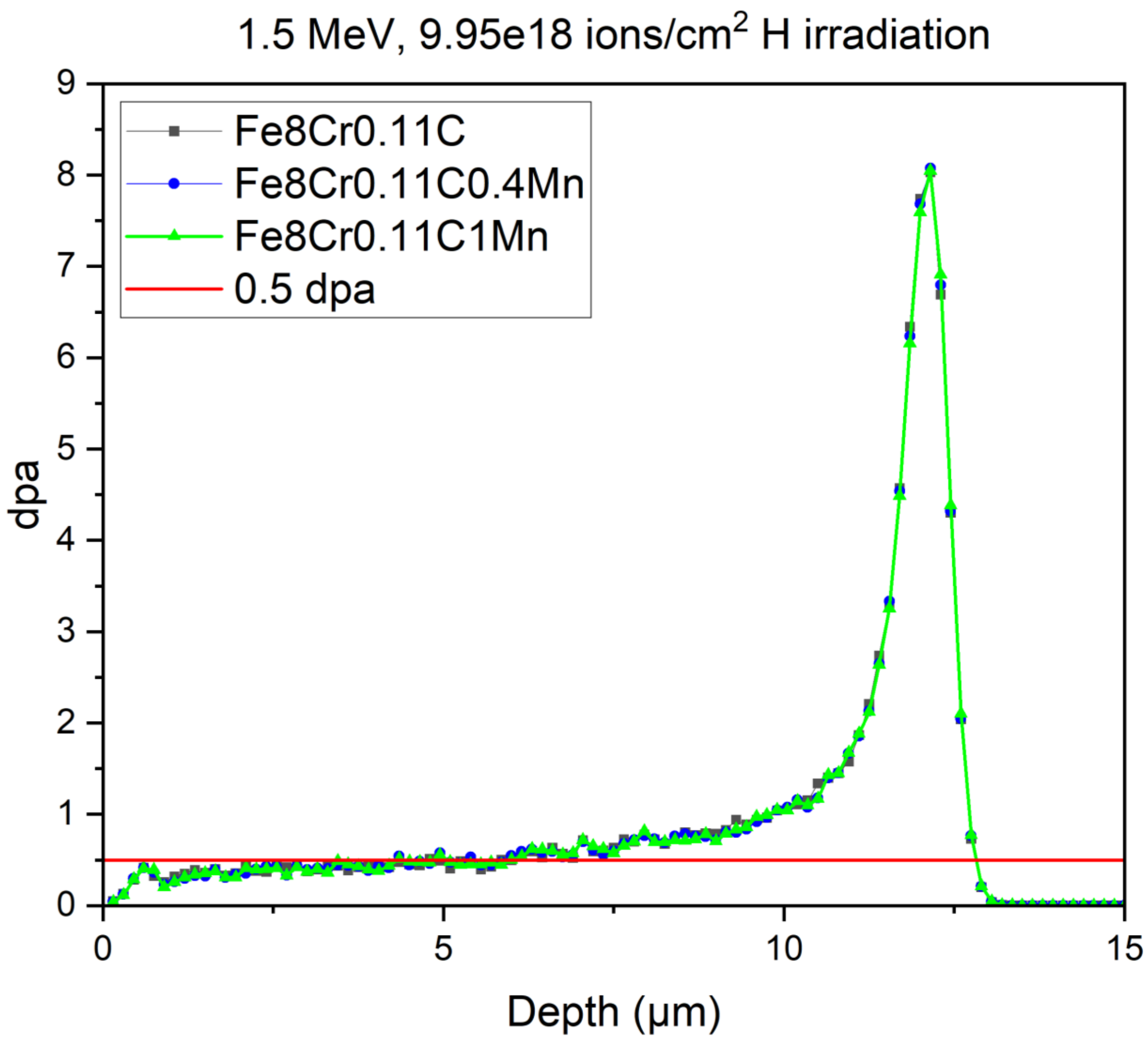


Induce other effects:

- Induce collision cascades - scattering
- Absorption to induce fission
- Absorption – producing γ radiation, or β^- particle:

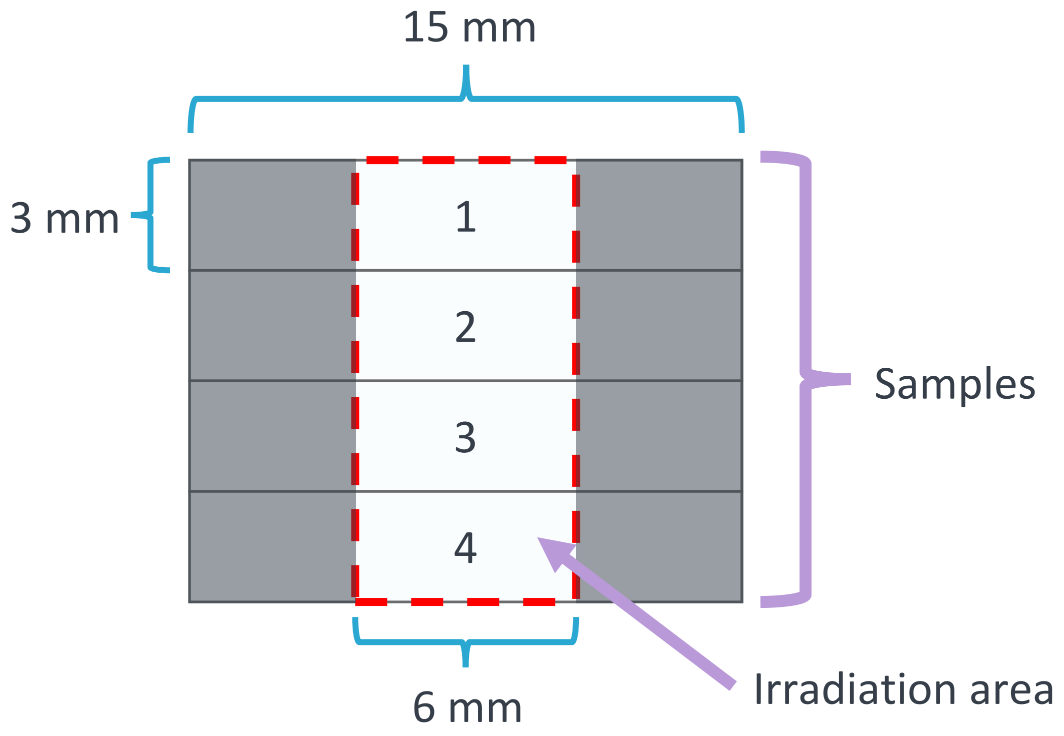
Irradiation planning

Stopping and Range of Ions in Matter (SRIM)



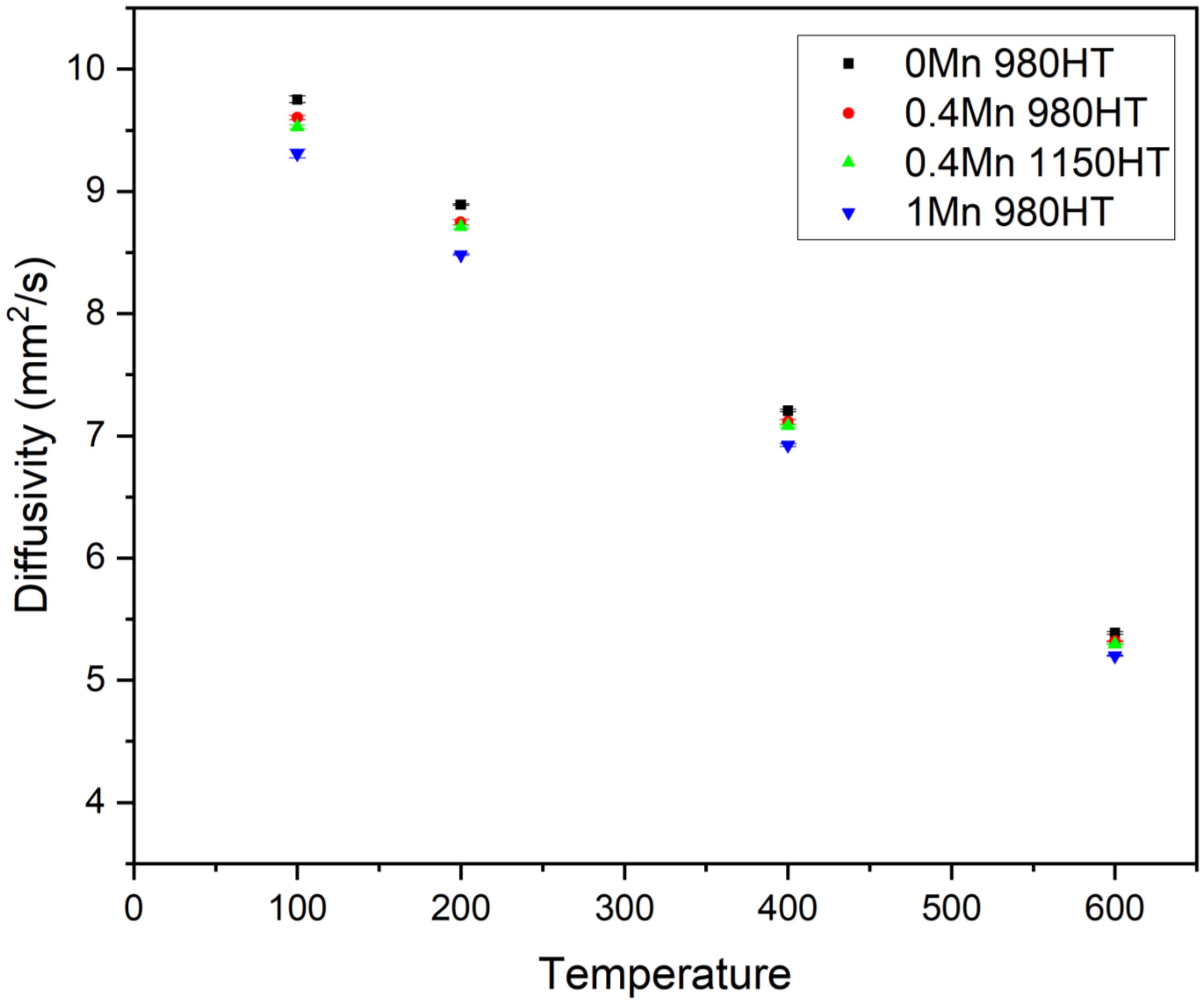
Original Irradiation Experiment at Dalton Cumbria Facility (DCF)

- **Proton** irradiation
- Energy: **1.5 MeV**
- Fluence: **9.95 x 10^{18} ions/cm^2**
- Damage: **0.5 dpa** in plateau
- Temperature:
    a. Low temp hardening embrittlement: **300 °C**
    b. Transition at 350 °C (DBTT), out of transition: **400 °C**
  - (Upper limit: 500 °C)



1. Fe8Cr0.11C (HT at 980/760 degC)
2. Fe8Cr0.11C0.4Mn (HT at 980/760 degC)
3. Fe8Cr0.11C0.4Mn (HT at 1150/760 degC)
4. Fe8Cr0.11C1Mn (HT at 980/760 degC)

Laser Flash Analysis (LFA)



Revised Irradiation Experiment (for 104 hours)

Irradiate each sample individually in order of priority:

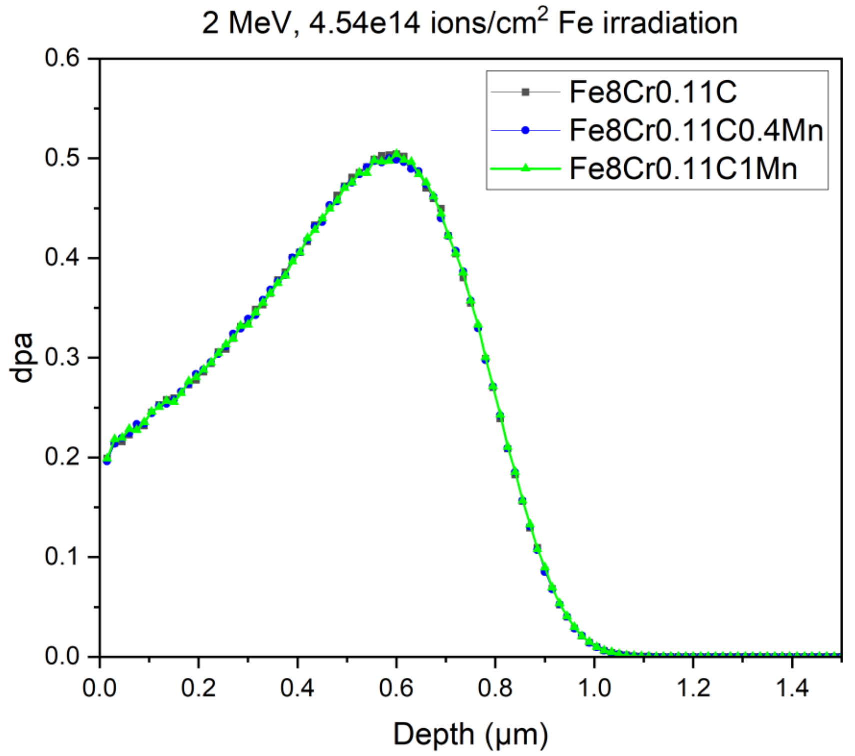
1. 1Mn 980HT 400°C
2. 0.4Mn 980HT 400°C
3. 0Mn 980HT 400°C

Options after those 3:

- 0.4Mn 1150HT 400°C to same dose/dose rate would give a full set
- Not enough time to complete full sample: possibly both 0.4Mn HTs at 400°C to a lower dose or at higher dose rate
- Test thicker/larger samples plates

Heavy ion irradiation at Surrey Ion Beam Centre

- **Fe heavy-ion** irradiation
- Energy: **2 MeV** (max at Surrey)
- Fluence: **4.54 x 10^{14} ions/cm^2**
- Damage: **0.5 dpa** at Bragg peak (to align with proton irradiation plateau)
- Temperature: **400 °C** (same as proton)
- Area: same as original proton plan – beam heating will be undetectable, so all 4 matchstick samples at once



Post-irradiation analysis at Materials Research Facility (MRF), UKAEA

- SEM
- EDX
- Transmission electron microscopy (TEM) prepared using Focussed Ion Beam (FIB) and/or electropolishing
- Atom Probe Tomography (APT) prepared FIB
- GIXRD
- Nano-indentation

Thank you

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