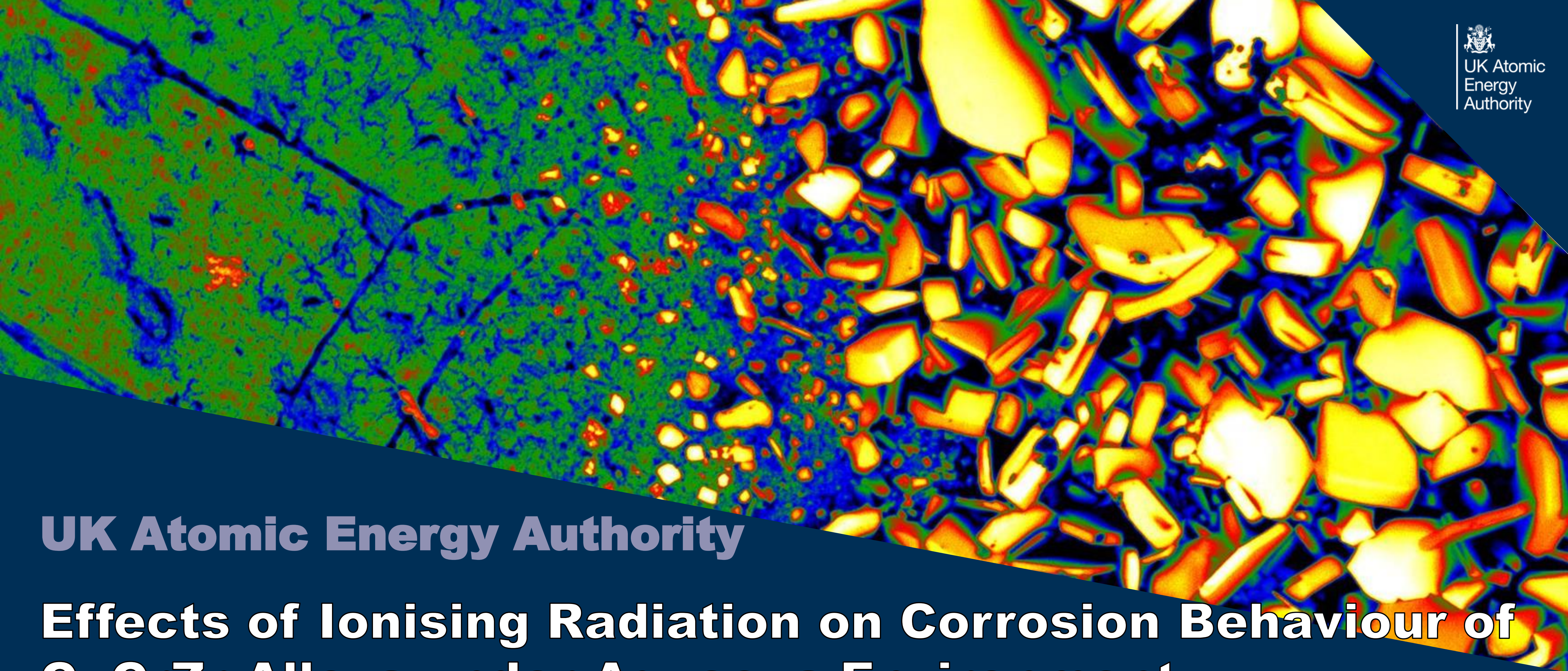

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Effects of Ionising Radiation on Corrosion Behaviour of CuCrZr Alloys under Aqueous Environment

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IAEA Technical Meeting on Compatibility Between Coolants and Materials for Fusion Facilities and Advanced Fission reactors (30 Oct-3 Nov 2023, Vienna)

Content

1. Current understanding of radiation impact on corrosion & materials
2. Simulation of in-vessel component environments
3. Impact of irradiation &/or radiolysis
4. Summary: Learnings, & Its application on liquid metals & molten salts

1. Current understanding of radiation impact on corrosion & materials

Corrosion

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Common

Destructive attack of a material by reaction with its environment.

Up to US$ 875 billion

Can be saved annually on a global basis with existing corrosion control practices [1]

US$ 2.5 Trillion

Annual global cost of corrosion [1]

44%

Piping & Piping component failure in Fission industry [2]

References:
[1] International measures of prevention, application, and economics of corrosion technologies study, NACE international, 2016
[2] Simonen, F.A. et al., 'Life prediction and monitoring of nuclear power plant components for service-related degradation', Transactions of ASME 2001, p.58

Corrosion

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- Corrosion affects structural integrity of components by
  - Material being remove via oxidation/erosion
  - Changing the local chemistry of the material

(e.g. forming surface oxides and preferential oxidation along the grain boundary)

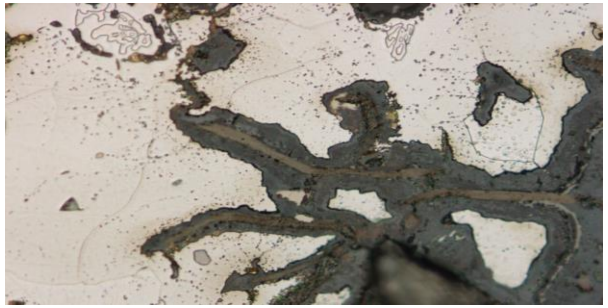
Uniform (general) attack

Localised
(pitting, crevice, filiform)

Galvanic
(two-metal corrosion)

Intergranular corrosion

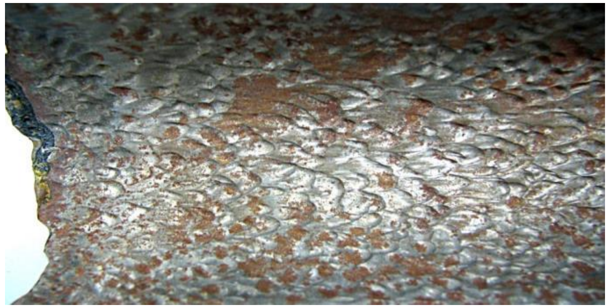
Selective leaching



Environmental corrosion cracking

Fretting

Flow-assisted (erosion) corrosion

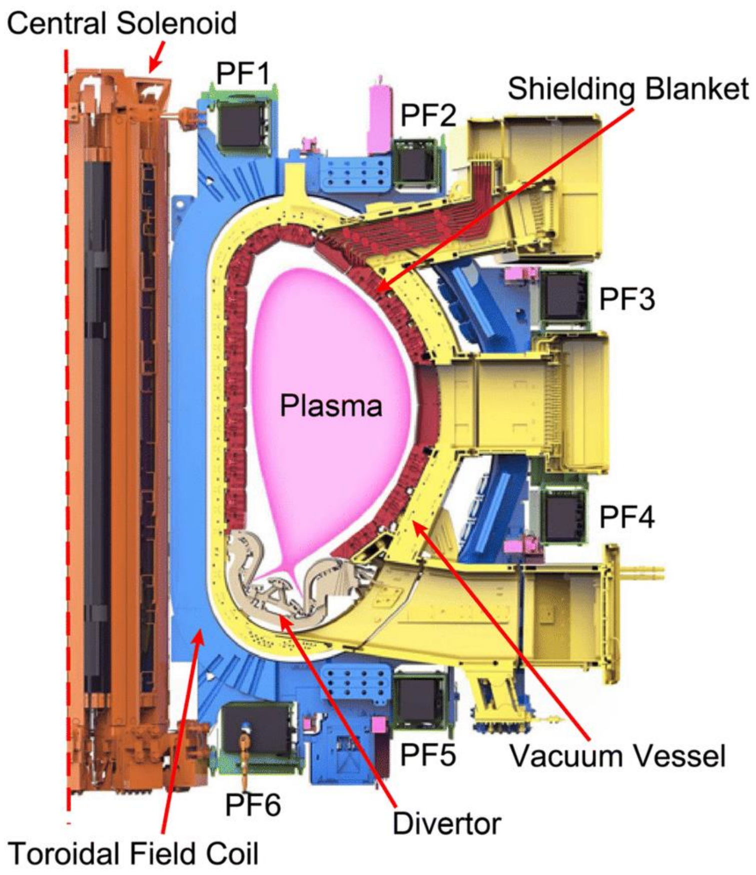


Commonalities between Next Generation Fusion & Fission PPs (Choice of Coolants)

	Fission	**Fusion**
	Small Modular Light Water Reactor, Supercritical-Water-Cooled Reactor, Very High Temperature Gas-cooled Fast Reactor, Sodium-cooled Fast Reactor, Lead-cooled Fast Reactor, & Molten Salt Reactor	*Magnetic confinement, Inertial confinement, Magneto-inertial, Electrostatic Hybrid, & Muon-catalysed fusion*
Common Coolants:	Water (H_2O & D_2O), Gas (He & CO_2), & Molten Salts (FLiBe)	
Uncommon Coolants:	Liquid Metals (Na, Pb, PbBi), Molten Salts (FLiNaK), & etc.	Liquid Metals (Li, PbLi), Molten Salts (FLiPb), & etc.

Do you know that Fusion PPs could have more than 3 cooling/breeder loops with each using different coolant?

Potential corrosion issues in a Tokamak

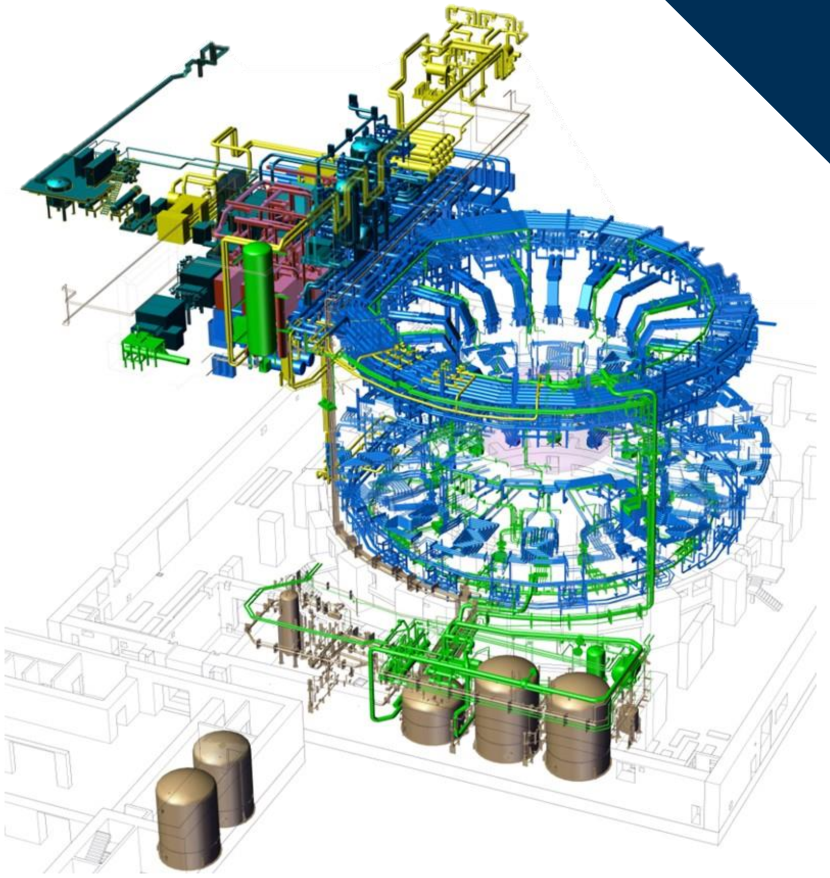


Poloidal cross-section of the ITER tokamak highlighting the major tokamak components (PF1–PF6 are the poloidal field coils) [3]

Components:

- Inboard first wall & shielding
- Outboard first wall & blanket
- Divertor
- Vacuum vessel

ITER cooling water system will have ~ 35km length of pipes & 3000 valves



ITER cooling water system for heat management [4]

Any modules/ components in contact with liquid (flowing or static) &/or connection of dissimilar materials, especially in in-vessel components due to the presence of radiation

References:
[3] DOI: 10.1007/s10894-018-0187-9
[4] https://www.iter.org/mach/coolingwater

Corrosion issues in a Tokamak reactor

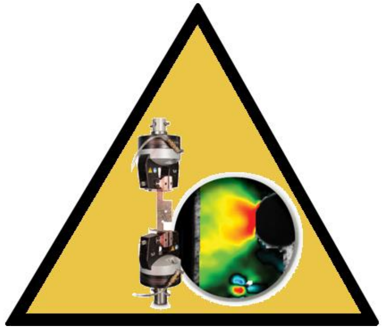
Environmental-induced cracking

will be the main concern.

<u>Environmental factors to consider</u>

Coolant
(Type, flow regime, rate & pressure)

Temperature
(Thermal loading profile)



Stress
(Type, Cyclic or static; internal or external; by design)

Radiation
(Type, energy range, & Transmutation)

Magnetic field
(Cyclic or static)

Impact on our daily life →

Impact on nuclear reactors & accelerators →

Impact on Magnetic confinement fusion reactors →

Effects of corrosion on component's lifetime-governing materials properties

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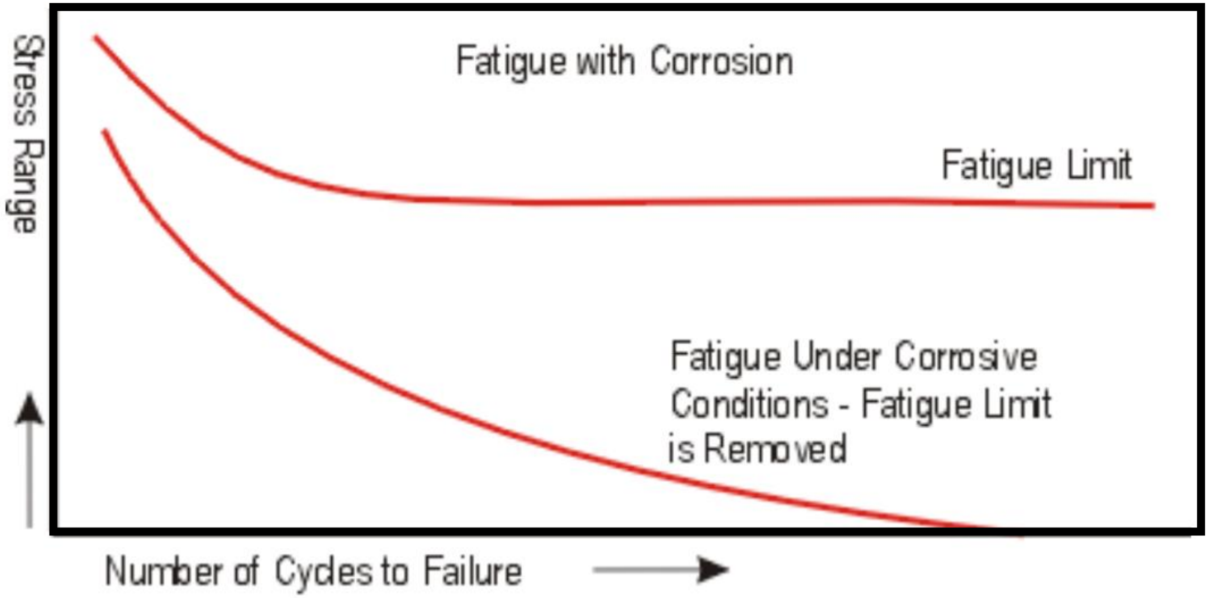
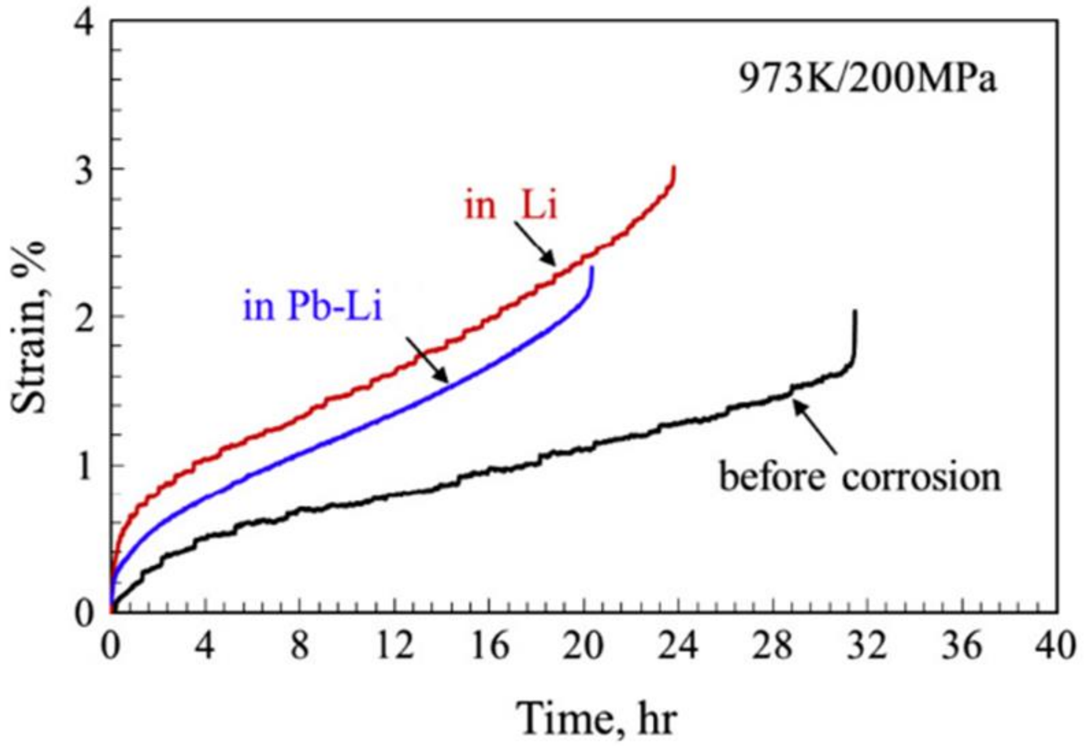
Fatigue



Stress-No. of cycles to failure (S-N) curve in corrosion fatigue
[Courtesy of Azom.com]

Creep



Strain-time curves of 9Cr-ODS Ferritic/Martensitic steels before and after exposure to static Li and PbLi
[Courtesy of NIFS, Japan]

Impact of energetic radiation on materials

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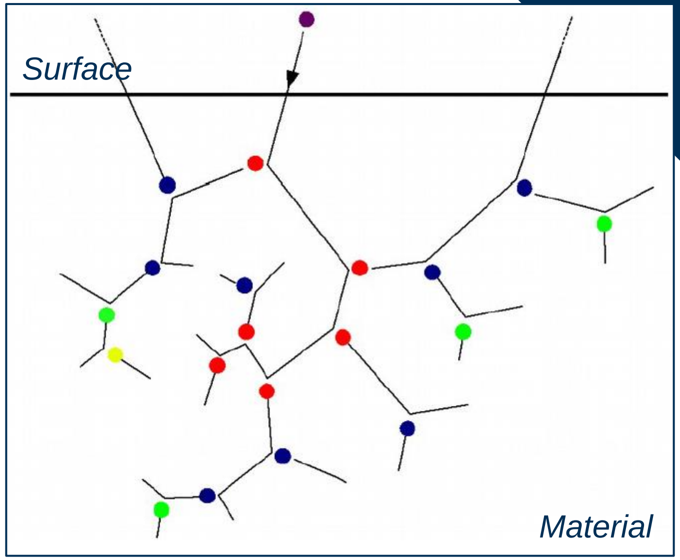
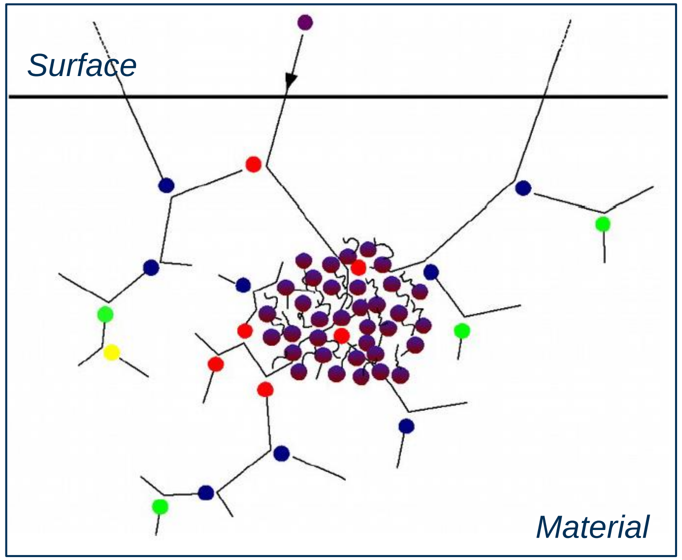
Cascade Damage & Dynamic

<u>Simple picture (Top):</u>
Neutron (or ion) collides with target atom (Primary Knock-on Atom (PKA)), setting off a sequence of collision events (secondary, tertiary, etc. recoills)

Actually (Bottom):
Interactions with surrounding atoms give rise to localised, highly disordered ‘melted’ volume; especially with high PKA energies & dense materials.





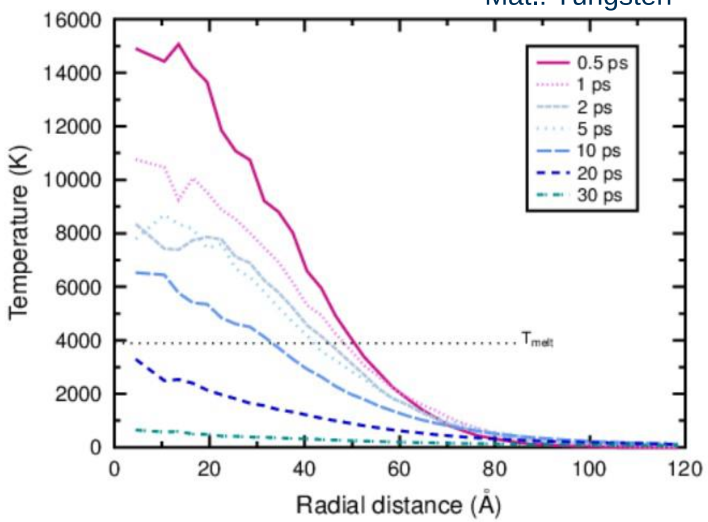
[*Courtesy of A. Sand*]

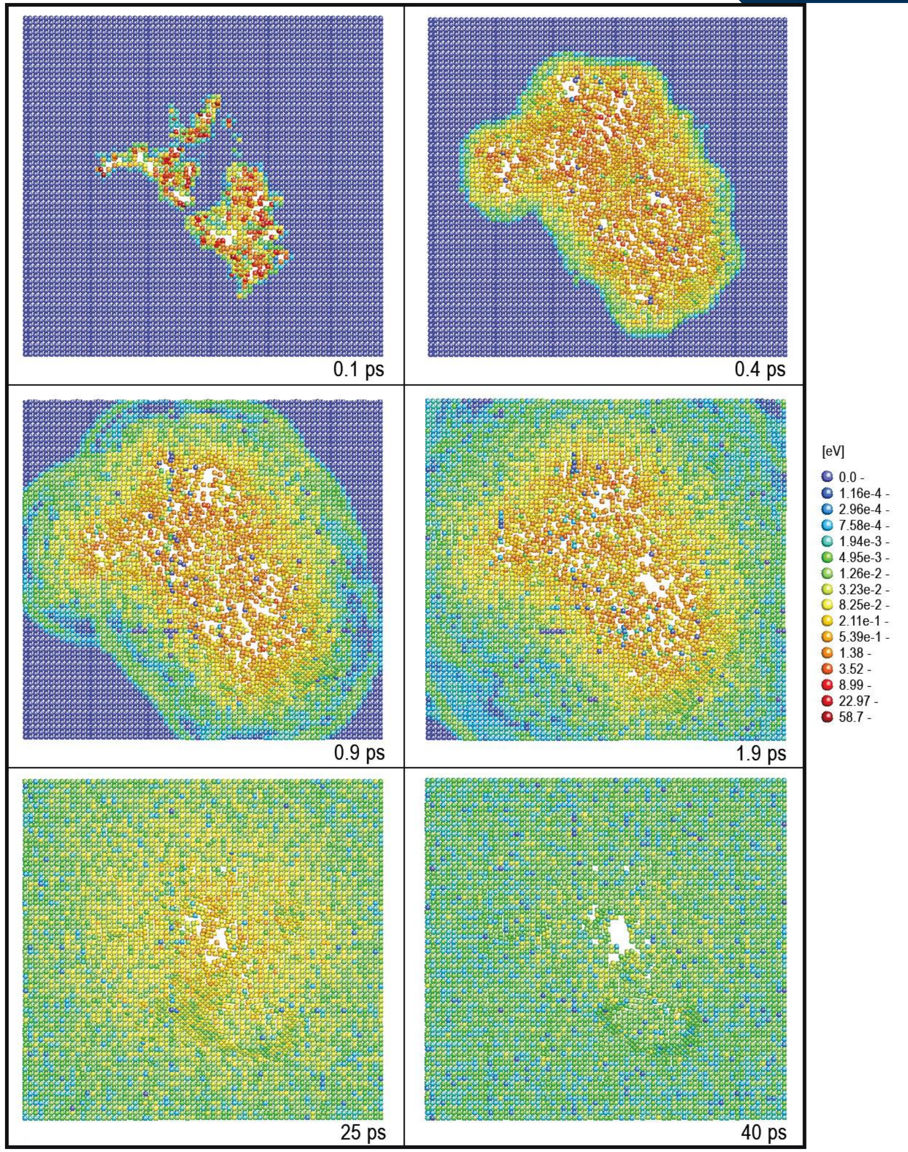
Impact of energetic radiation on materials

Heat spikes:

- The highly disordered ‘melted’ volume has the characterisatics of liquid
- It cools in picosecond time scale
- Facilitates recombination of point defects, but also results in formation of extended defects, including nano-sized vacancy clusters & dislocation loops.

Mat.: Tungsten





[*Courtesy of A. Sand*]

Impact of energetic radiation on materials

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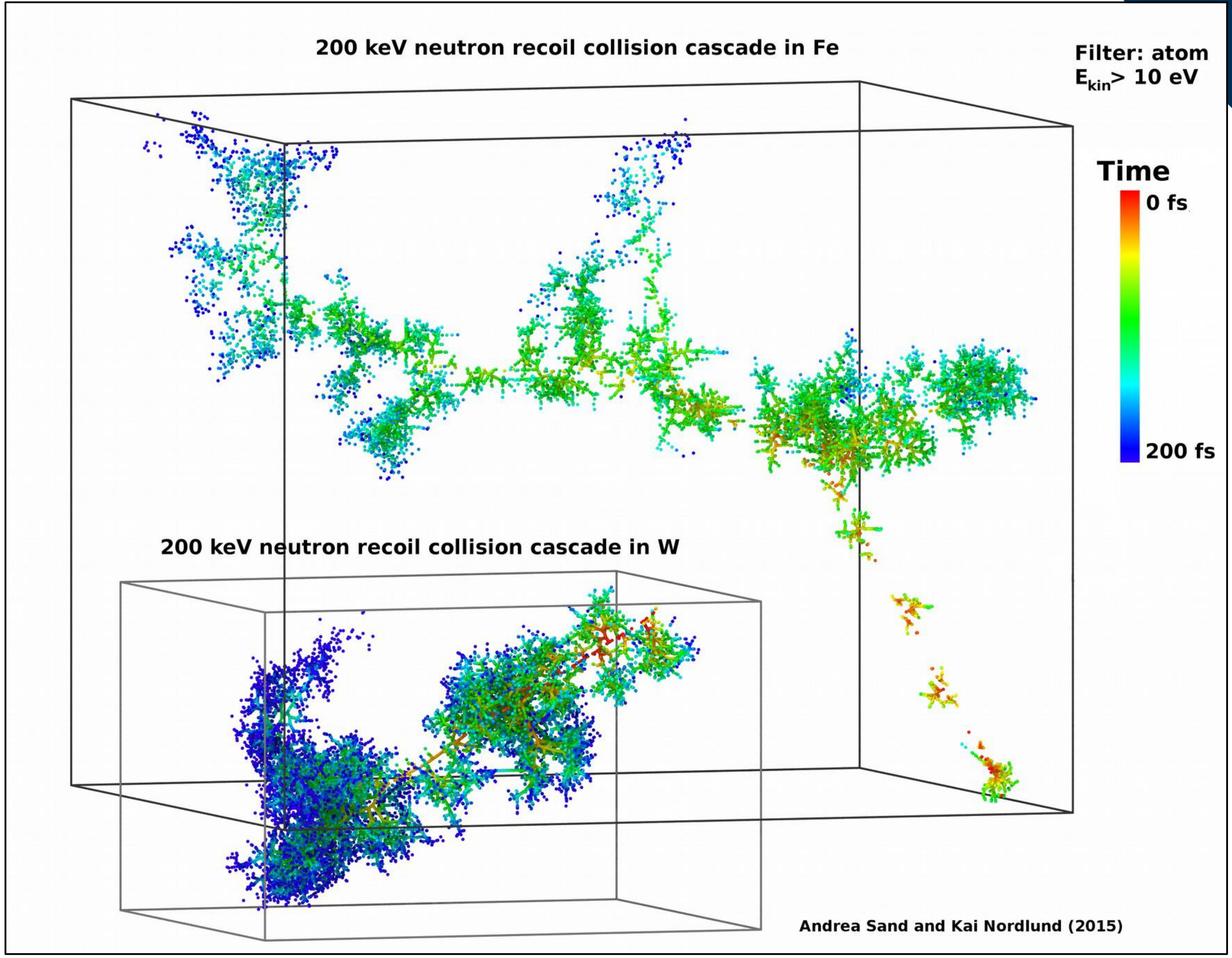
Sub-cascades splitting

- Cascades in different materials develop differently
  - More compact in denser materials

E.g. in tungsten:

  - Sub-cascades slitting sets in for around 150 keV PKAs



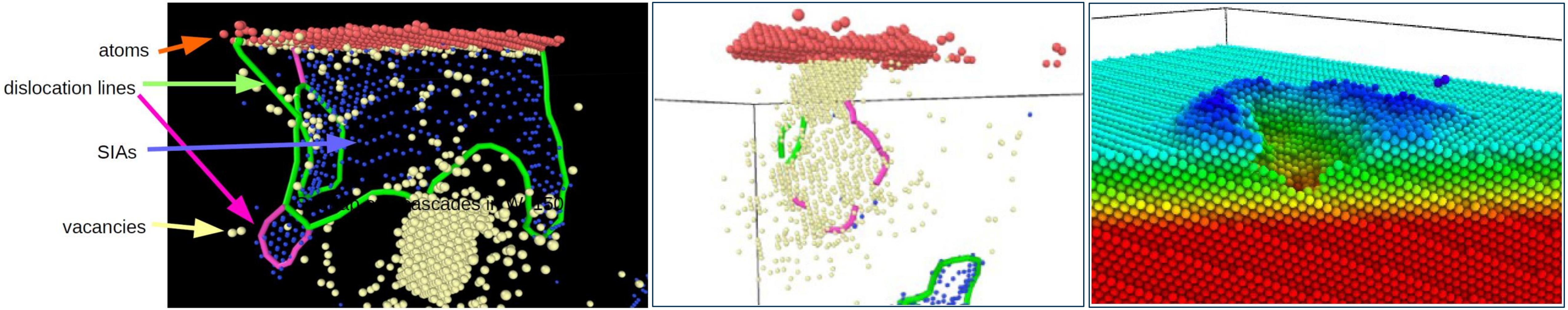
[*Courtesy of A. Sand & Kai Nordlund*]

Effects of energetic radiation on materials @ Surface

Surface effects

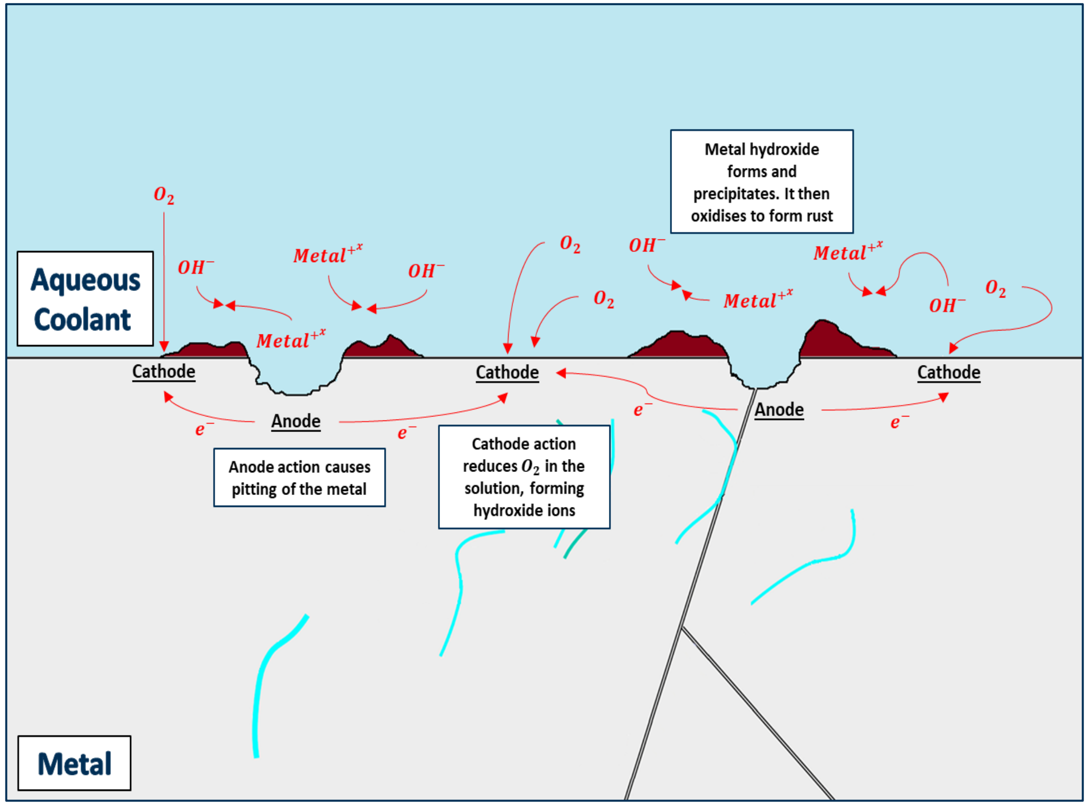
- Craters, excess of vacancy defects, & dislocations terminating at surface
- Cascades near/ at the surface will
  1. Modify material's surface conditions/properties locally
  2. Promotes exchange of atoms between materials and local environment
  3. Increase defects at subsurface of the material

Mat.: Tungsten; Cascades splitting in 150 keV PKAs

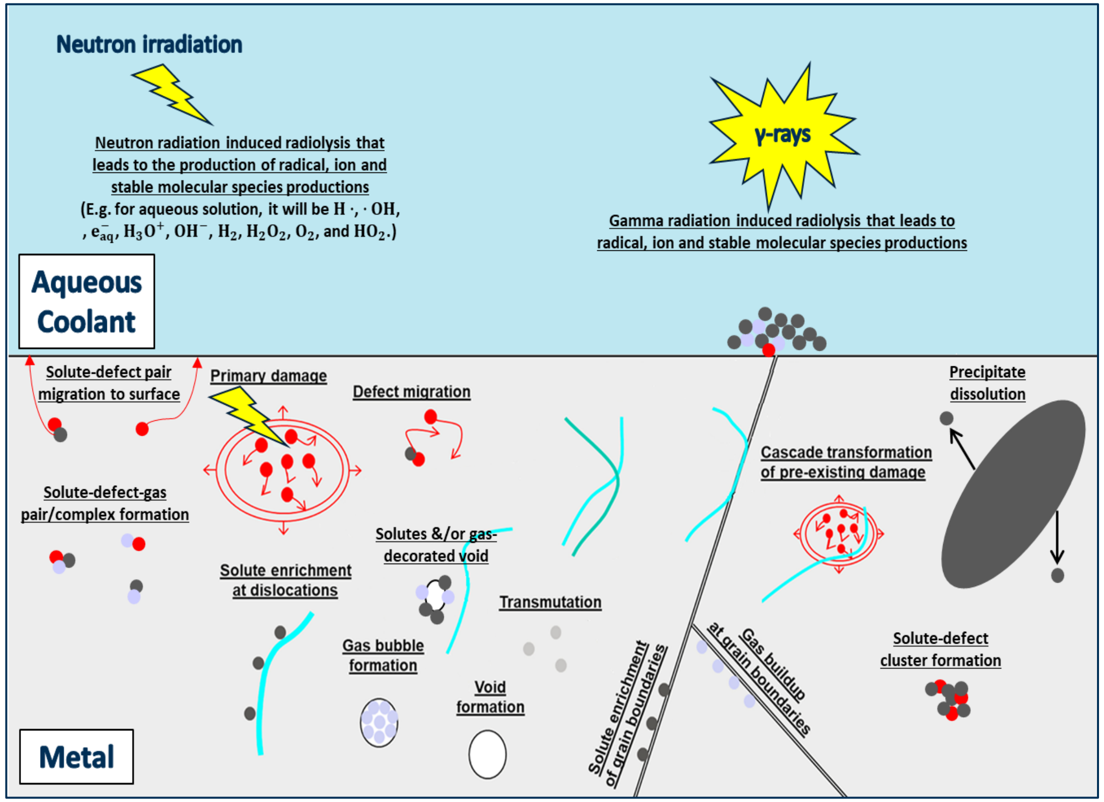


[*Courtesy of A. Sand*]

Overview of the impact of ionising radiation on corrosion and materials



Schematic diagram showing the common/ simplified localised corrosion events that occur in metal under aqueous coolant under **no radiation** scenario.



Schematic diagram showing general events that occur in a metal and in an aqueous coolant **under irradiation environment** that were missing in Figure left.

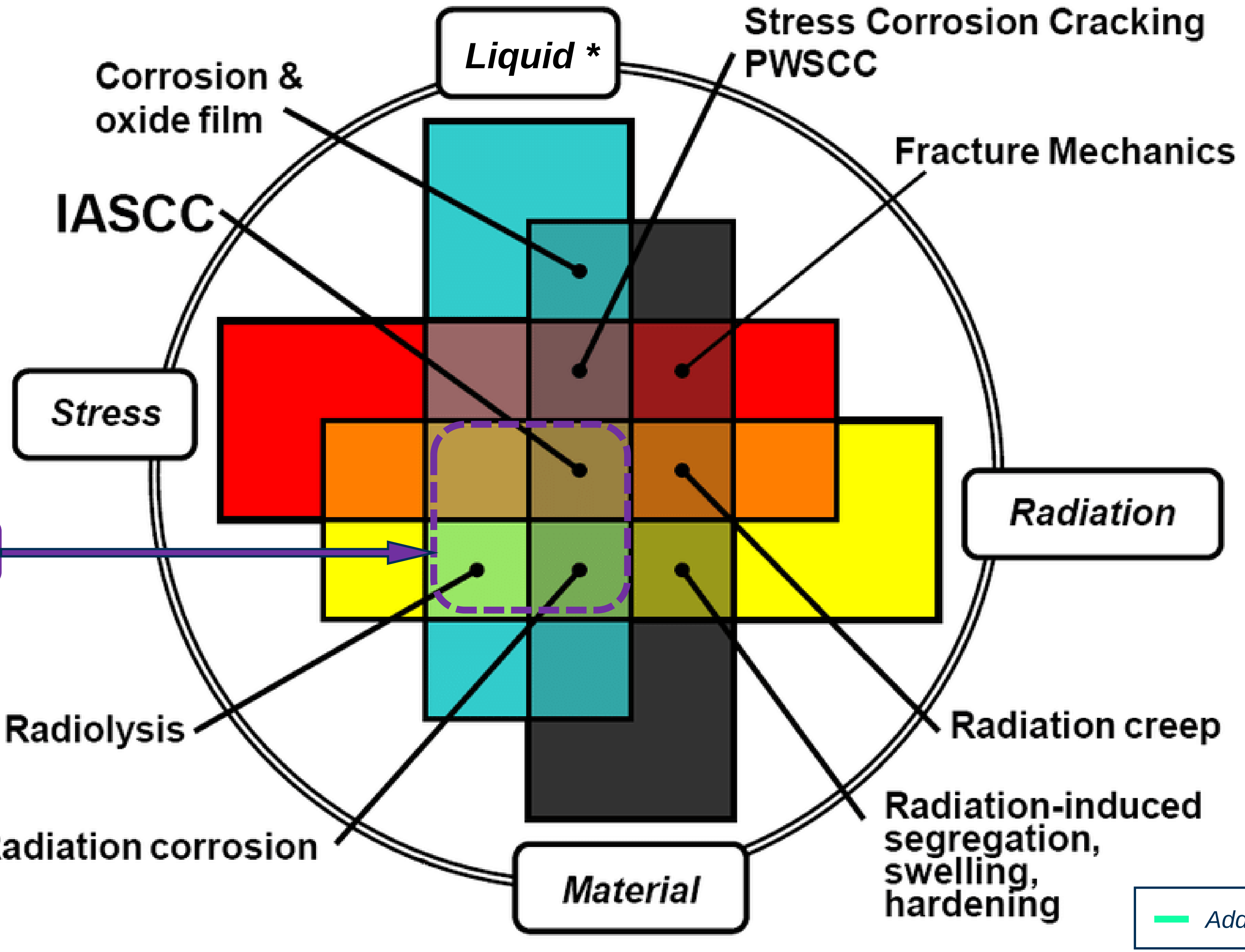
Note that other events might be occurred in specific condition/s or other coolant/s that have not been able to capture in this schematic, e.g. transmutation will occur in coolant and are particularly important for molten salt and liquid metal coolants that also act as 'fuel'. Also, the synergistic effects of irradiation with another environmental factor/s is not included, e.g. magnetic field.

Lessons learnt from Fission

Column out of the screen

Magnetic field

e.g. MHD effects



* Coolant or Breeder

Additional environmental factor/s from Fusion

Schematic diagram showing different processes involved in radiation induced stress corrosion cracking

2. Materials testing under simulated in-vessel component environments

Designing Experimental method:
Matching PKA spectrum + Transmutation + Radiolysis

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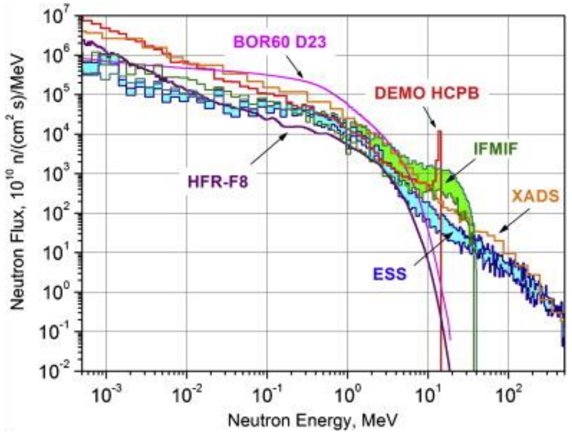
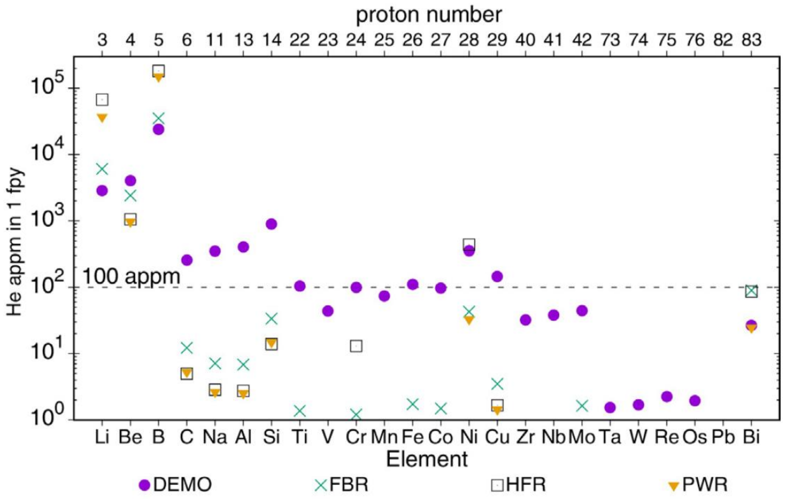
Neu. Spectrums from various source



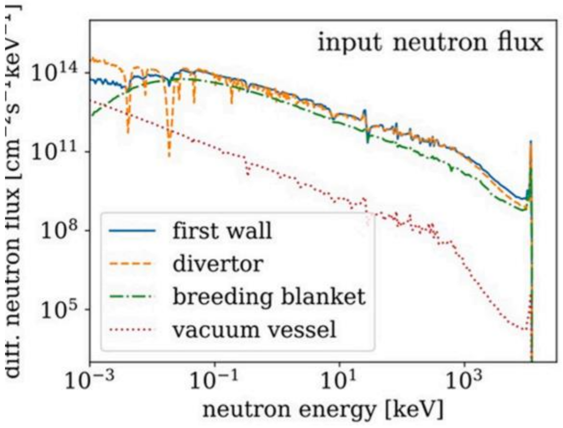
Comparison of the neutron spectra of the helium cooled pebble bed (HCPB) blanket of a fusion DEMO reactor, with different planned or existing neutron sources including IFMIF
(P. Vladimirov, A. Möslang – KIT)

He productions from various Neu. Spectrum



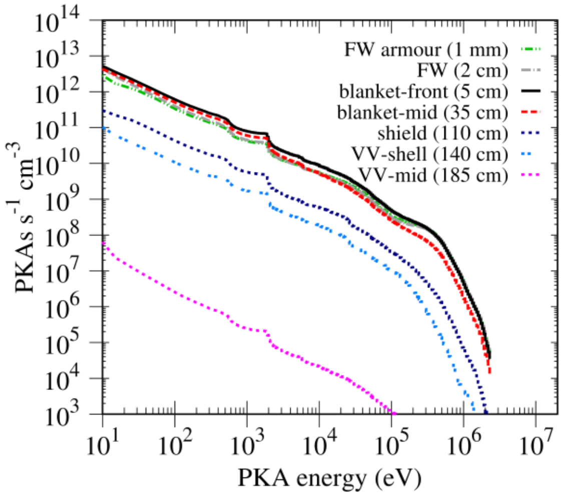
Variation in He production per FPY as a function of element and irradiation environment
(M Gilbert et al.)

Neu. Spectrums within DEMO



Simulated neutron spectrums of various components for DEMO
(L Reali, M Gilbert et al.)

PKA spectrums within DEMO



Variation in Fe PKAs with depth into a fusion reactor wall
(M Gilbert et al.)

Designing Experimental method:
Triggering relevant degradation mechanisms

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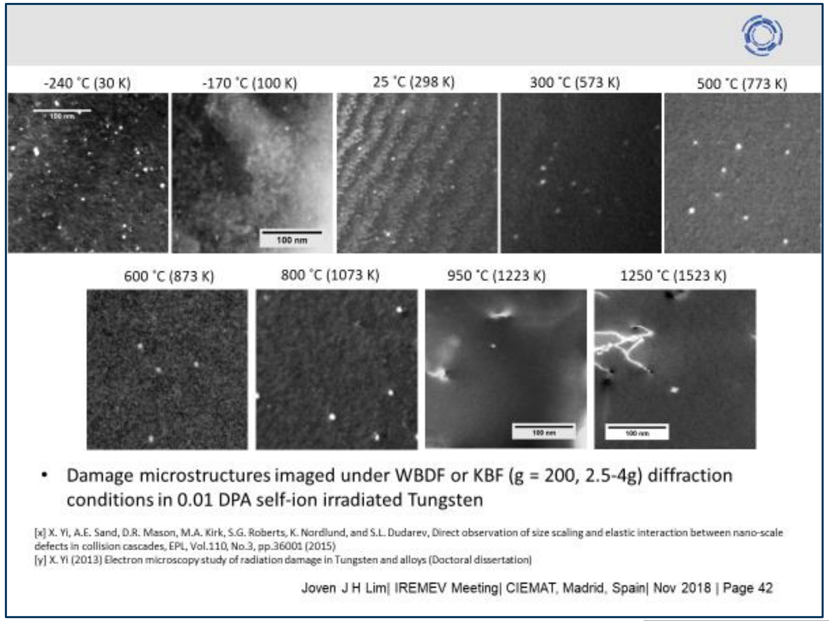
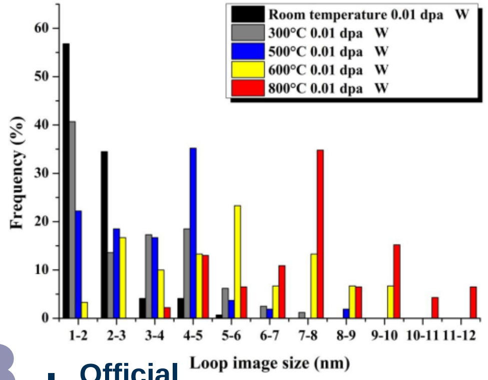
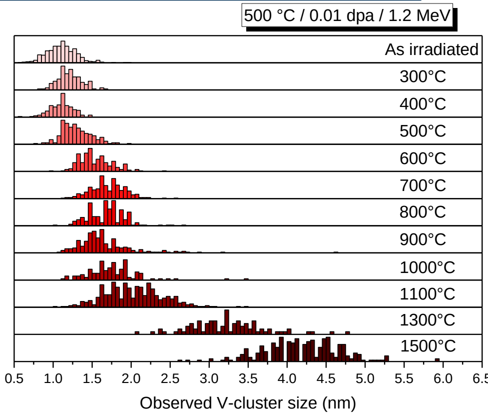
Effects of Temp. on Radiation Damage Stability

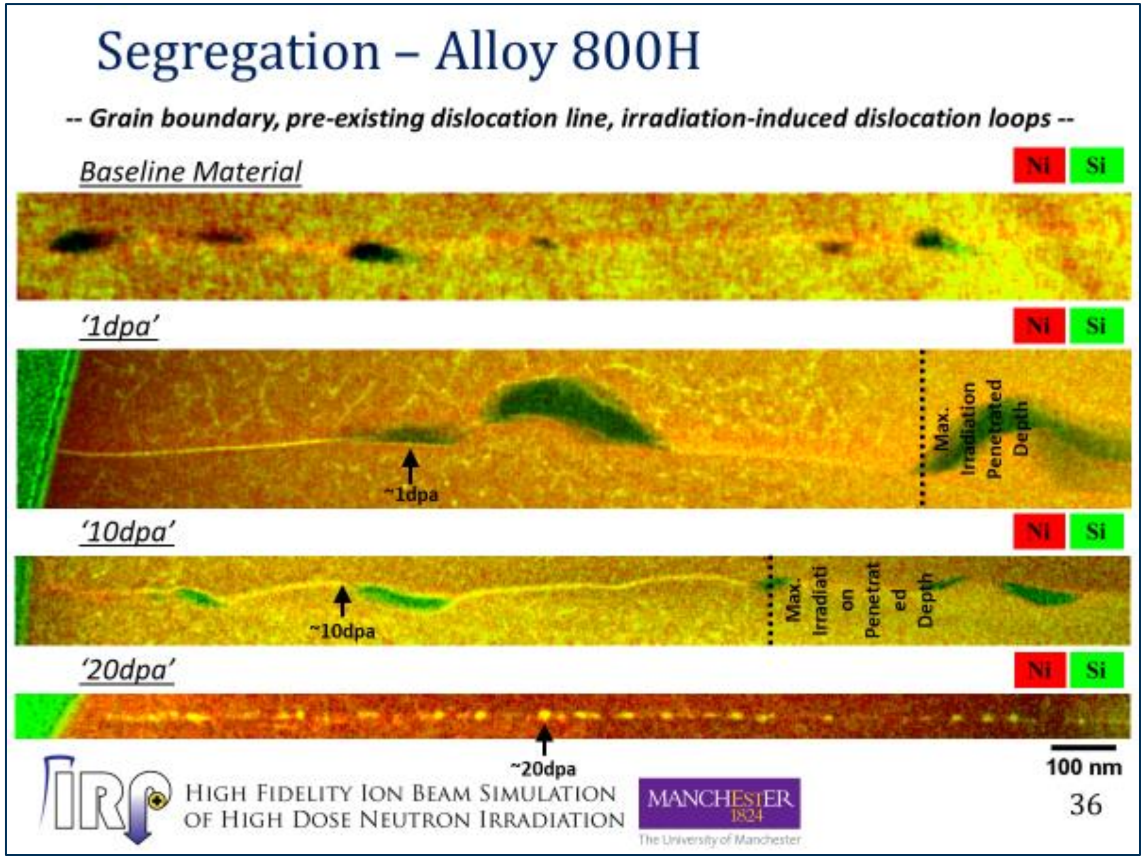






[Courtesy of M.F.Barthe et al.]

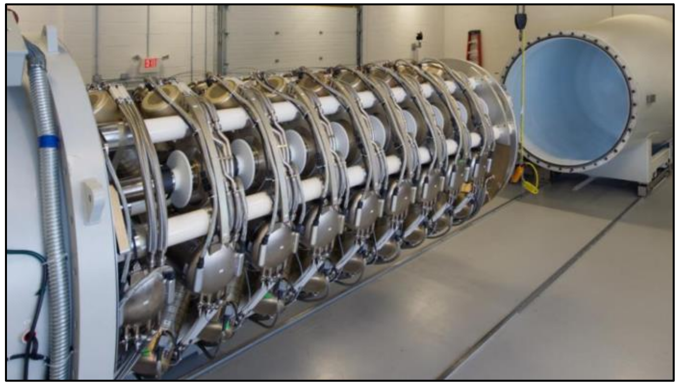
Radiation-induced chemical diffusion (+ impact of Temp.)



Irradiation-Corrosion experimental set-up

(1) Source of ionising radiation

(Surrogate to neutron)



[*Courtesy of Birmingham University, UK*]

Radiation

(2) Source of coolant

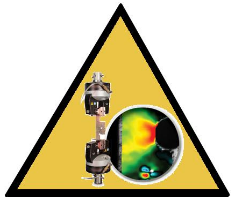
[*Courtesy of CORMET, Finland*]

Coolant

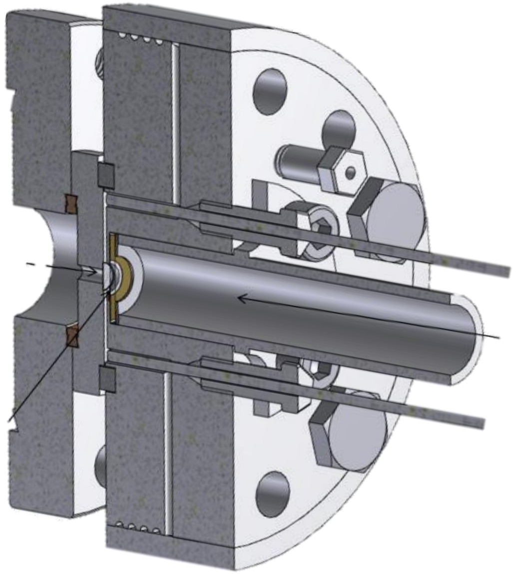
Temp.

Synergistic effects

(3) Testing chambers to introduce various environmental factors on sample



Stress



[*Courtesy of Michigan Ion Beam Laboratory, USA*]

Missing:

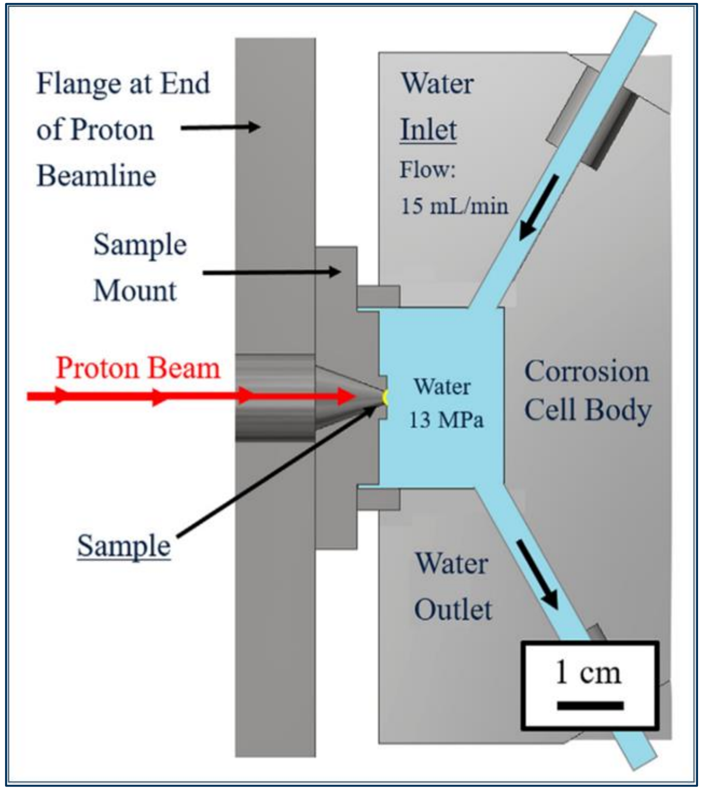
Magnetic field

Rad.-Transmutation

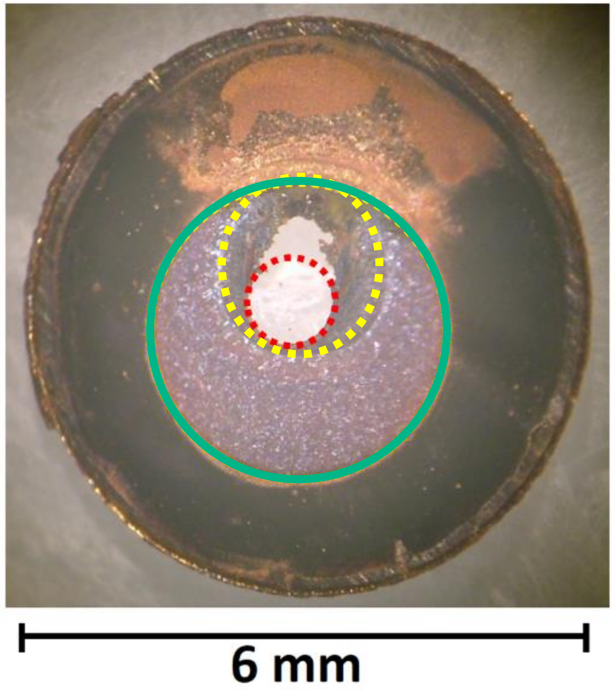
Advantages:

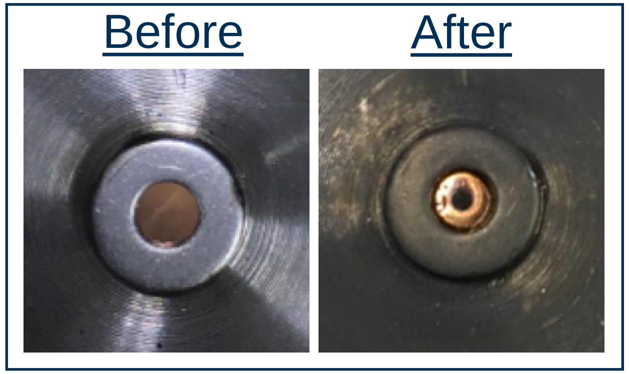
- Well calibrated and controlled environment to study the degradation behaviour of materials
- High through-put & less expensive

Typical sample geometry & type of information can be obtained



Experimental set-up to study impact of radiation on material under aqueous environment in MIBL, USA





Typical sample shape and size

- **Region within red dotted circle** is area exposed to radiation, radiolysis and coolant at temperature simultaneously.
- **Region between the yellow dotted circle** and **red dotted circle** is area exposed radiolysis and coolant at temperature simultaneously.
- **Region between green solid circle** and **yellow dotted circle** is area exposed to just the coolant at temperature simultaneously.

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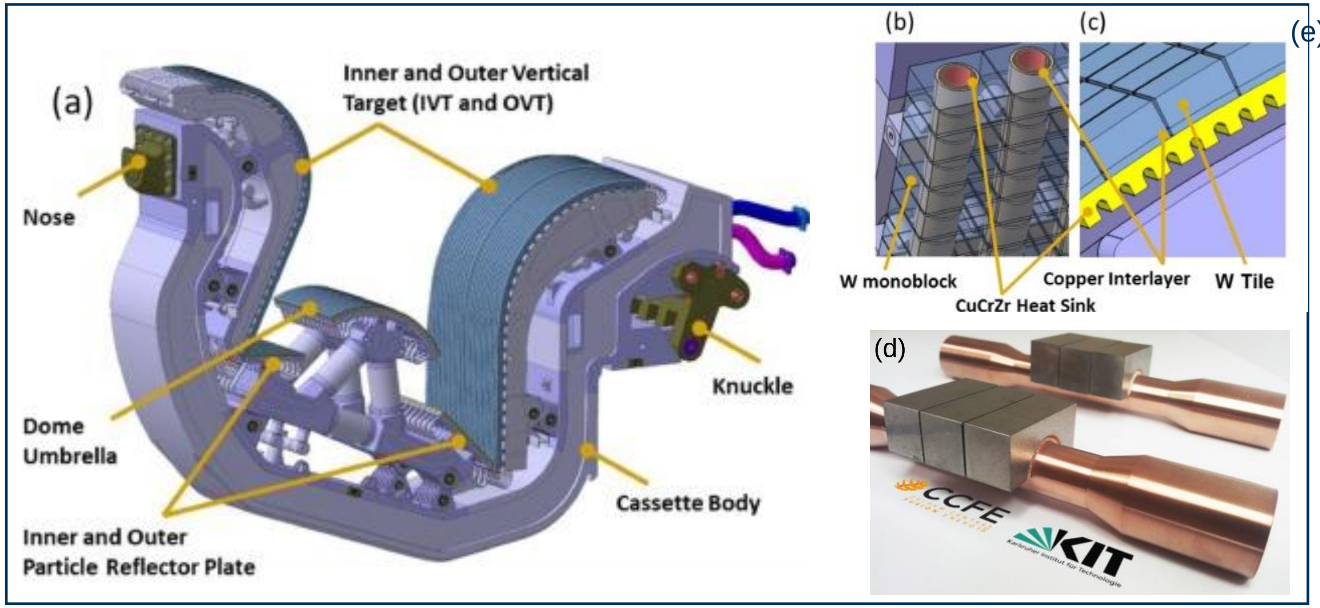
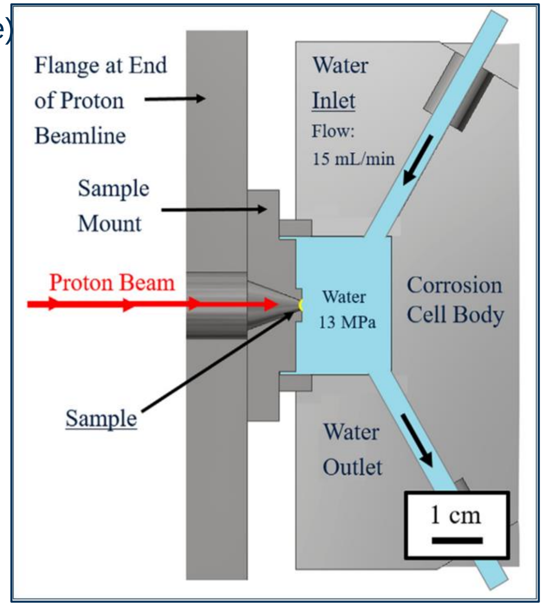
3. Impact of irradiation & radiolysis

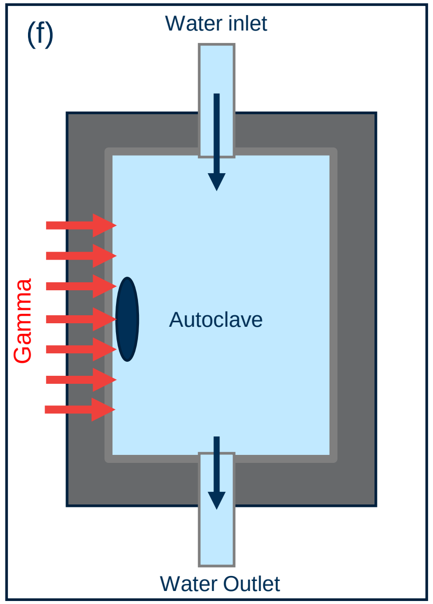
Case studied:
CuCrZr alloy in light water reactor condition

Experiment details (Proton):

Damage (dose) rate on sample:	0.15 (± 0.01) dpa/day
Ionisation dose rate on water:	1151 (± 10) kGy/hr
Total damage investigated:	0.1 & 0.3 (± 0.02) dpa (close to design end-of-life for ITER)
Temp. investigated:	35, 150 & 325 (± 25) °C
Coolant condition:	Deaerated (~1psig Ar) water with 15 mL/min of flow rate; local pH become acidic due to injection of H^+







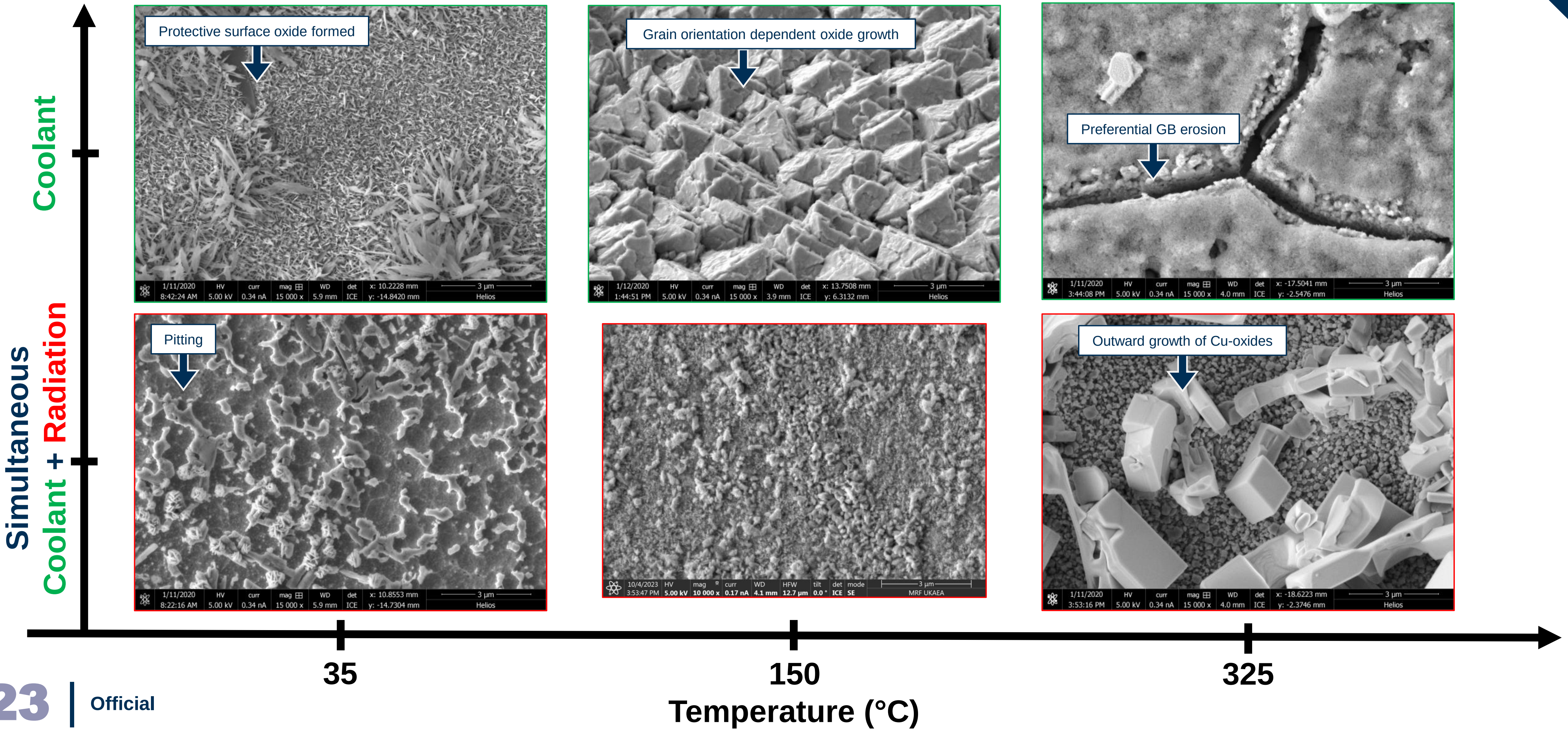
Schematic view of ITER divertor consisting of inner and outer vertical targets, dome umbrella, dome particle reflector plates and cassette body; (b) monoblock geometry at the inner and outer vertical targets; (c) flat tile geometry at the dome umbrellas and particle reflector plates; [5] (d) divertor target mock-ups manufactured at UKAEA, in collaboration with KIT in Germany; and (e) experimental set-up to study impact of radiation on material under aqueous environment in MIBL, USA [6]; (f) Experimental set-up to study impact of radiolysis on materials.

References:
[5] https://doi.org/10.1016/j.nme.2016.07.003
[6] https://doi.org/10.1016/j.jnucmat.2019.05.039

Irradiated-Corroded CuCrZr: Surface

Analytical Method: Scanning Electron Microscopy – Secondary Electron Micrographs
Irra. Type: Proton
Dose: 0.3 dpa [Expected end-of-life dpa for ITER divertor – CuCrZr material]
Irra. Temp.: 35, 150, 325°C

Highlights:
- Surface oxides formed are clearly differences between area exposed to ‘coolant’ and ‘radiation & coolant’.
- Corrosion/Erosion becomes significant for area exposed to ‘radiation & coolant’ simultaneously.

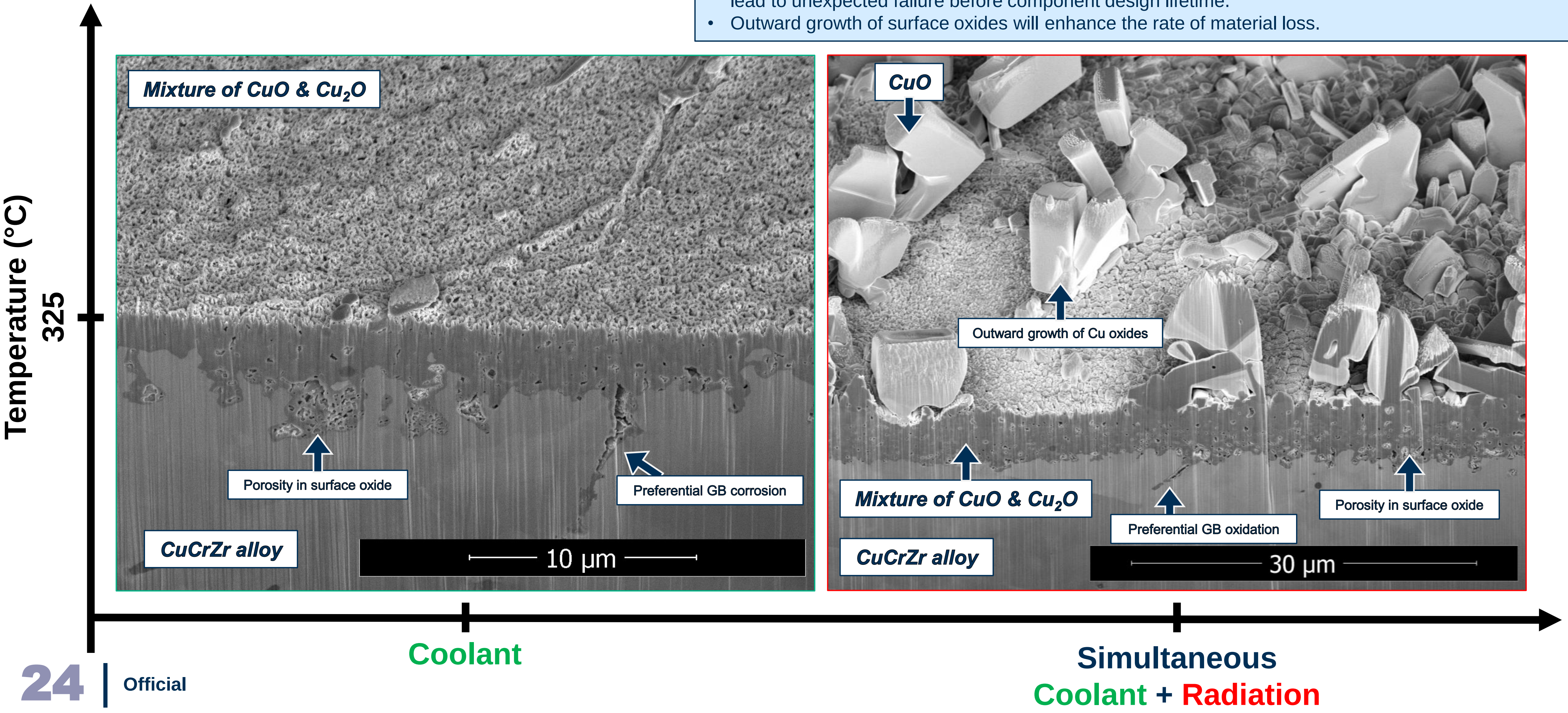


Irradiated-Corroded CuCrZr: Cross section

Analytical Method: Scanning Electron Microscopy – Secondary Electron Micrographs
Irra. Type: Proton
Dose: 0.3 dpa [Expected end-of-life dpa for ITER divertor – CuCrZr material]
Irra. Temp.: 325°C

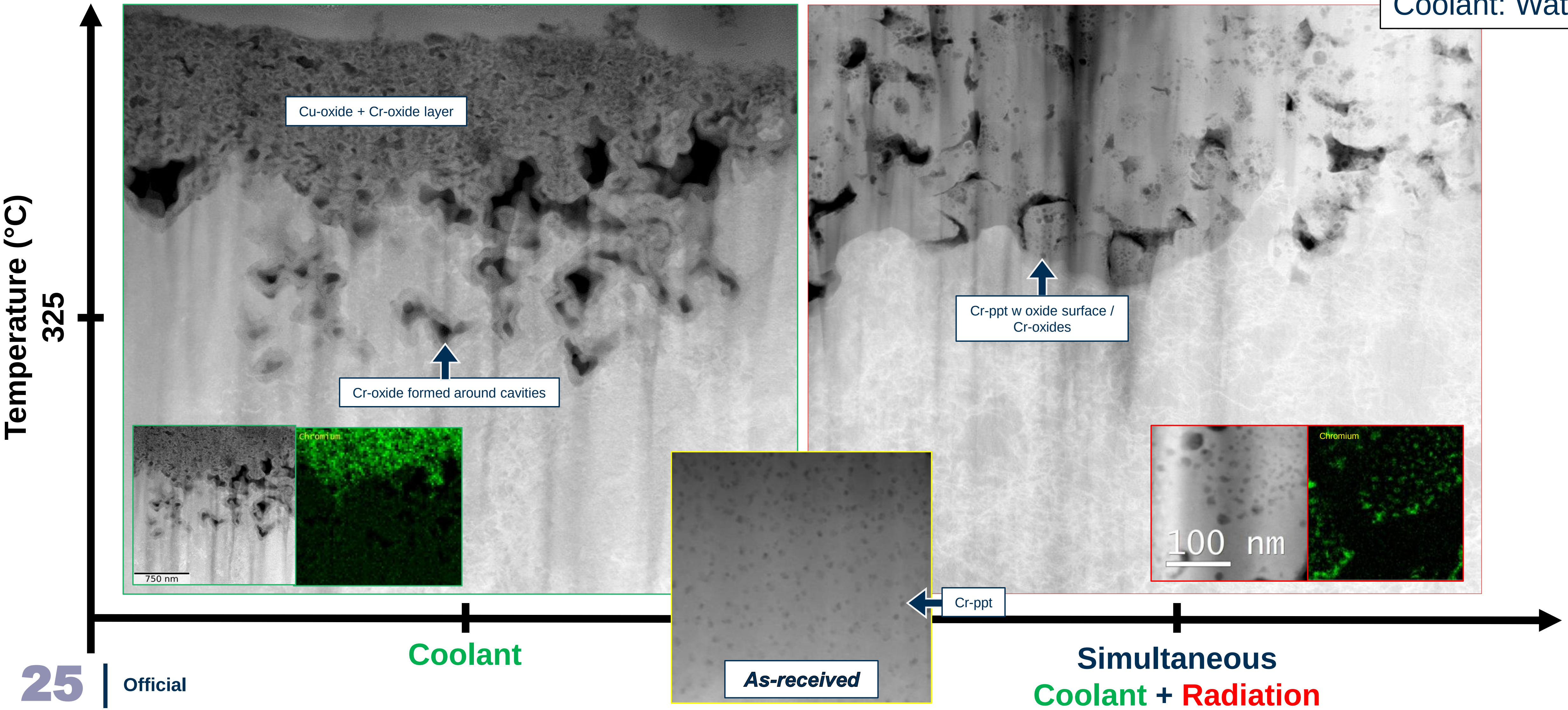
Highlights:

- High porosity in the surface oxide provide an easier pathways for oxygen to diffuse thru the surface oxide layer to encourage further in-ward growth of oxides
- Preferential grain boundary corrosion/oxidation will impose non-hardening embrittlement, that could lead to unexpected failure before component design lifetime.
- Outward growth of surface oxides will enhance the rate of material loss.



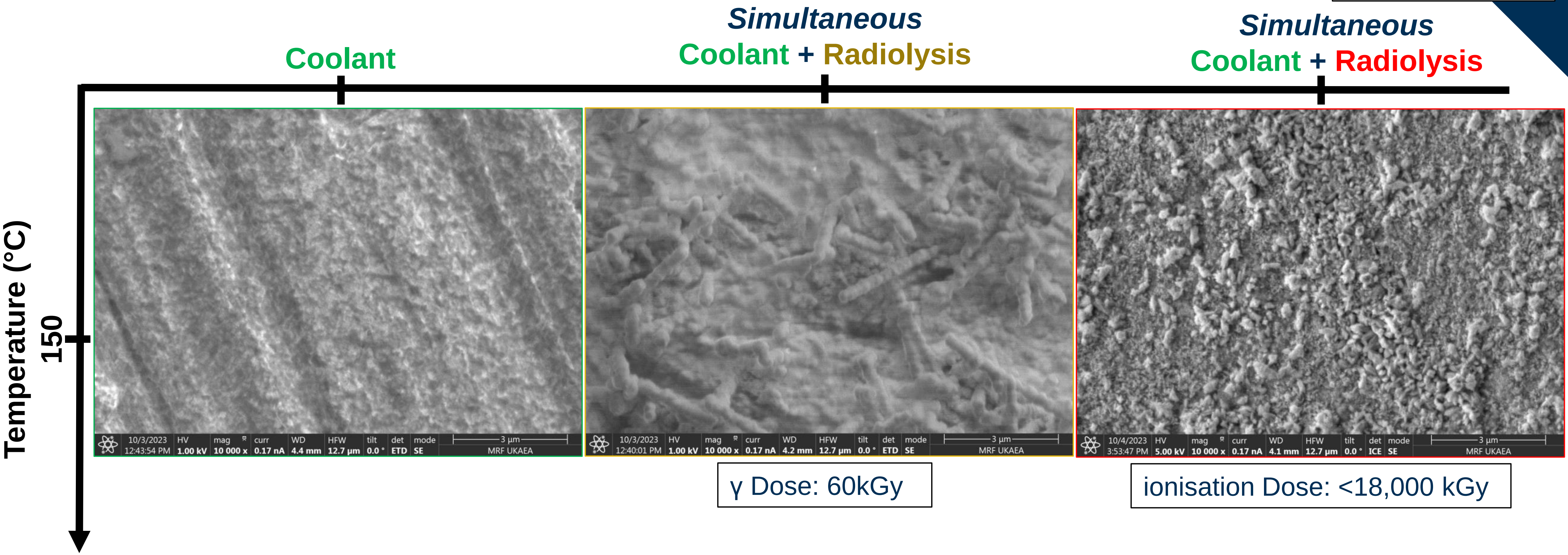
Effects of irradiation on corrosion behaviour: Surface oxides density

Dose: 0.3 dpa
Coolant: Water



Effects of Radiolysis on Corrosion Behaviour: <u>Surface</u>

Coolant: Water



Summary

☑ Simulating the synergistic effects of radiation and environmental factors relevant for Fusion

Corrosion behaviour

Radiation environment ≠ Without radiation

Oxides growth rate

Radiation environment > Without radiation

Type of surface oxides

Radiation environment ≠ Without radiation

Density of Oxide/s layer

Radiation environment ≠ Without radiation

Note that other studies had indicated that radiation could enhance the formation of a protective oxide layer to prevent corrosion [7].

! Mitigation strategy such as (1) using material compatible with the coolant/environment, (2) coolant chemistry engineering, and (3) corrosion & aging management are crucial for plant safety.

Reference:
[7] DOI: 10.1038/s41467-020-17244-y

4. Learnings, & Its application on liquid metals & molten salts

Effects of Ionisation Radiation on Liquid Metals and Molten Salt

UK Atomic Energy Authority

Liquid Metal for Fusion

[Li, LiPb, & etc.]

Molten Salt for Fusion

[FLiBe. FLiPb, & etc.]

Alloying & impurities elements*:
O, N, H, C, Al, Si, Ti, V, Cr, Mn, Fe, Ni, Y, Mo, Ta, W, Er, & etc

Transmutation elements**:
H3, He6, Li8, Be10, N13, C14, N16, O19,Na22, Na24, Al26, Mg27, Al28, Al29, Si31, P32, Ar39, Ca41, Ar42, K42, Ti45, Sc49, V49, Cr51, V52, V53, Mn 53, Mn54, Mn56, Fe55, Co60 & etc

* Based on breeder facing materials, i.e. structural and coatings
** Based on potential radioisotopes expected from chemical elements in cooling systems

Thank you for listening!

Email: Joven.lim@ukaea.uk

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EPSRC, EUROfusion, Henry Royce Institute,
UK's National Nuclear User Facility, & US Nuclear Science User Facility.

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