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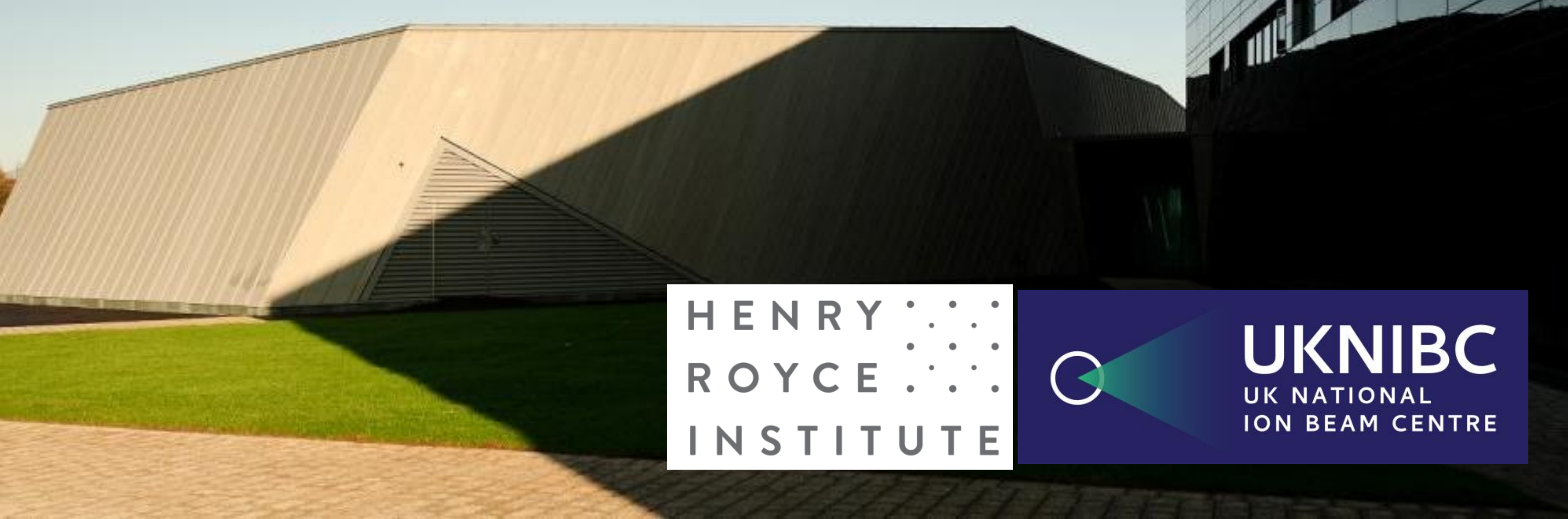
PAB 2024
Particle Accelerators and Beams Conference
11–12 June 2024 | Cumbria

Applications of ion accelerators & the Dalton Cumbrian Facility

Andy Smith, Samir Shubeita, Mel O'Leary, Aidan Milston
(University of Manchester)



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UK NATIONAL ION BEAM CENTRE

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Outline

- The nuclear problem(s)
- Role of radiation testing
- Types of radiation
- Radiation facilities at DCF
- Some examples
- Future plans

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THE NUCLEAR PROBLEM(S)

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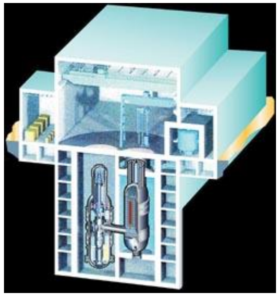
Problems for the full fuel cycle

Power production

Extending life of Existing plant



Gen IV

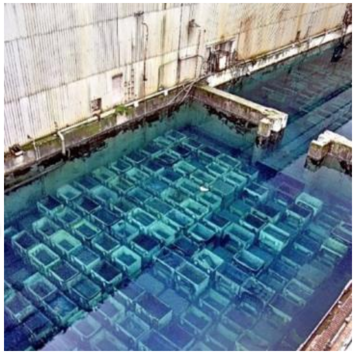
Next Generation Power Production

Fusion

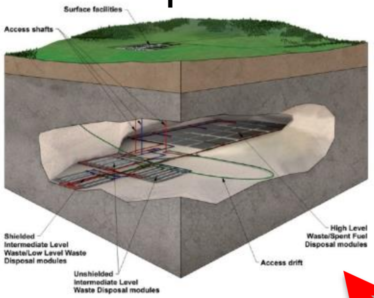
New materials for new plant

Fuels and reprocessing

Safe disposal



Geological disposal



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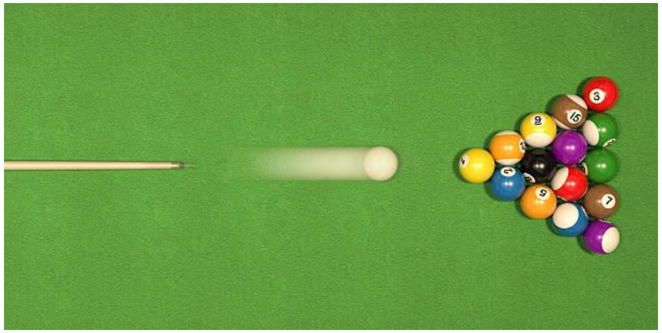
Effects of types of Radiation

Photons & electrons

- Ionisation
  - Electronic bond breaking
  - Changes to chemistry

Ions and particles

- Ionisation
  - Electronic bond breaking
- Particles also have mass and hence KE
  - Dislodge atoms from their normal lattice positions



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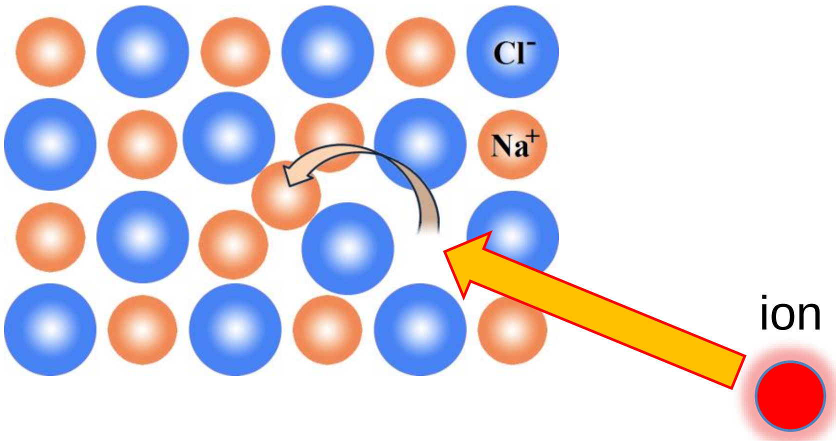
Frenkel defects



Cation dislocation in NaCl crystal (Wikipedia)

- Incoming ion dislodges target atom to form a Frenkel defect
- Atoms can exchange to from a Frenkel pair
- These form local lattice distortions
- Sufficient dislocations can migrate and coalesce to from defects in the structure
- Leading to work hardening, swelling, embrittlement and other structural failures.
- Measure of damage is *dpa* – displacements per atom

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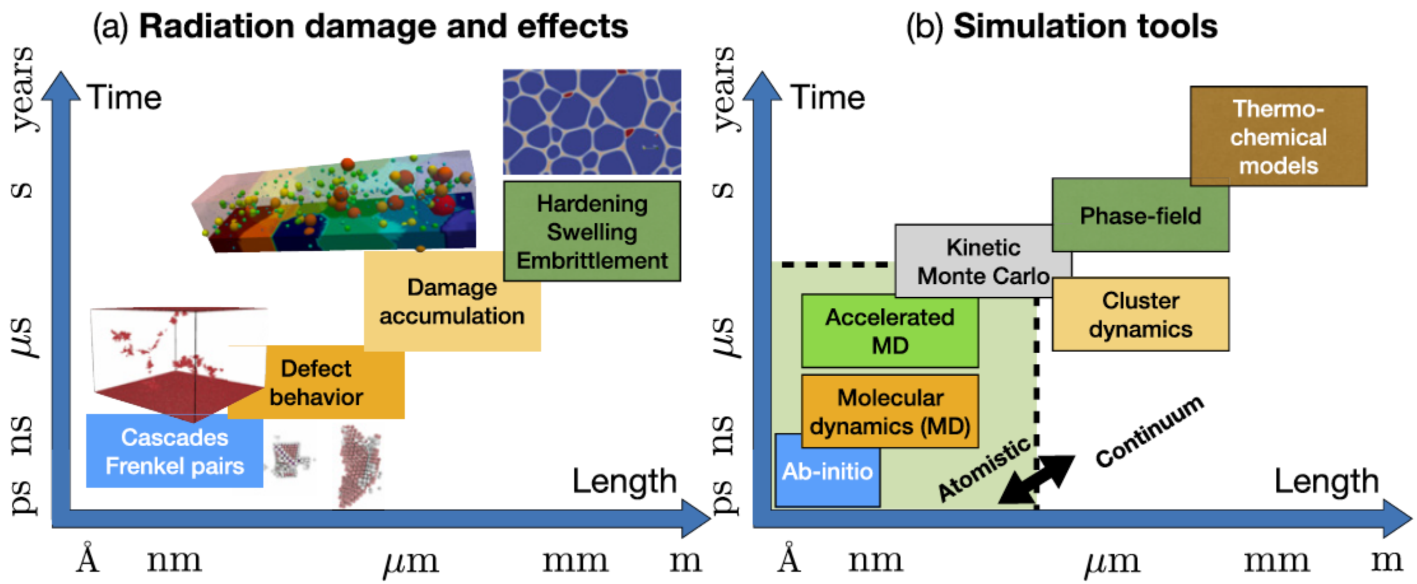
Propagation of damage



C.S. Deo et al. Modelling Simul. Mater. Sci. Eng. 30 (2022) 023001 (22pp)

- Damage accumulates over time and over a range of length scales
- Macroscopic property changes & crystal amorphisation can be attributed to ballistic effects
- Use of intense ion beams to accumulate a lot of damage in a short time

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Linear Energy Transfer (LET)

- Energy loss per unit of travel (keV/μm)
- Can be equated to the Stopping Power
- Linked to Relative Biological Effectiveness (RBE)
- For low LET, LET = RBE
- For higher LET, LET <> RBE
- Gammas, X-rays & electrons are low LET, ions have high LET

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Choice of ions ?

- Majority of particle damage in nuclear reactors (fission of fusion) is caused by *neutrons*
- Neutrons are difficult to accelerate, focus or bend
- Charged particles are much more compliant
- Protons – 'same' mass as a neutron
- Helium ions = alpha particles
- Heavy ions (Z > 2) do much more damage
  - Chemically neutral, self ion or fission product

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Particle sources

Test reactor

- ‘Gold standard’ source of neutrons
- Expensive to run
- Long time to accumulate dose (months – years)
- Activated samples

Ion beam accelerator

- Relatively cheap to buy and run
- Dose accumulated in minutes – days
- Samples not necessarily activated
- Adaptable – fluences, ion species, ion energies, sample environments

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DCF RADIATION FACILITIES

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Gamma & X-ray irradiation

High Dose Rate ^{60}Co Gamma Irradiator

- Wide range of absorbed dose rates (30 kGy/hr down to 100 Gy/hr)
- 10 litre sample chamber incorporating three turntables & two access ports for connection to external experimental rigs

X-Ray Irradiator

- Up to 350 kV
- Up to 40 Gy/min
- Turntable & access port

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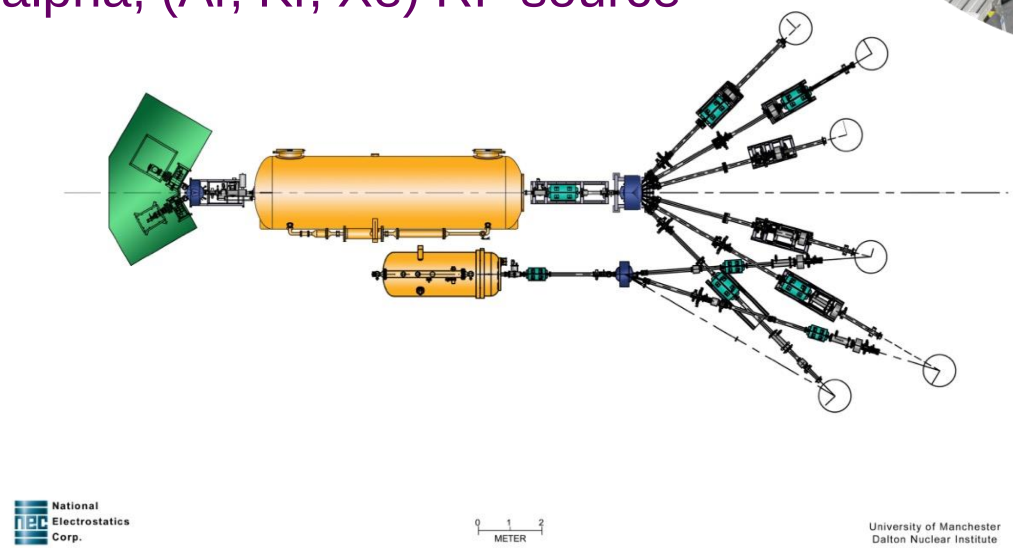
Ion Beam Accelerators

- Commercial NEC Pelletron
- 5MV Tandem
  - Proton, alpha, deuterium Torvis
  - 20 cathode heavy ion SNICS
- 2.5MV Single
  - Proton, alpha, (Ar, Kr, Xe) RF source



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Pelletron Accelerators

- Electrostatic
- Simple & robust
- Charging chains, charge a central terminal to high voltage
- Primarily *dc* beams only
- 5 MV tandem & 2.5 MV single-ended

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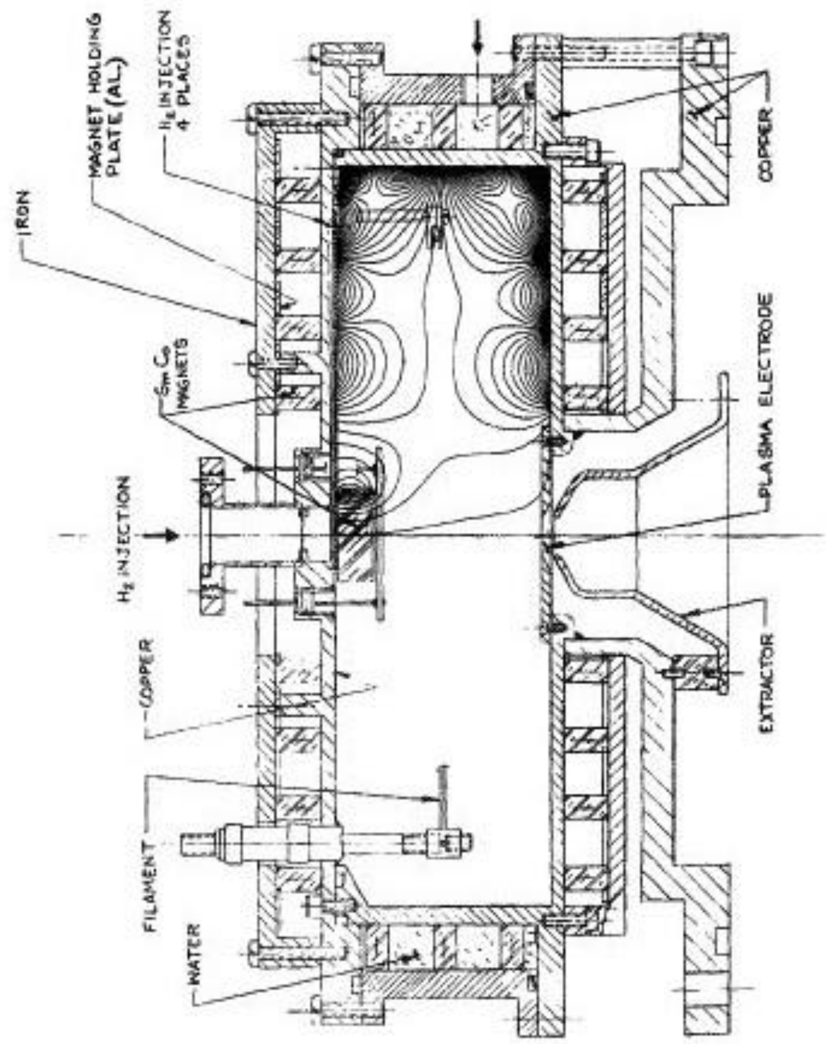
Ion Sources (1)

TORVIS

(TORoidal Volume Ion Source)

- Hot filament source
  - Negative ion source
  - High current H/He



K.Prelec (1990) *Rev.Sci.Instrum*. **61** pp.415–418

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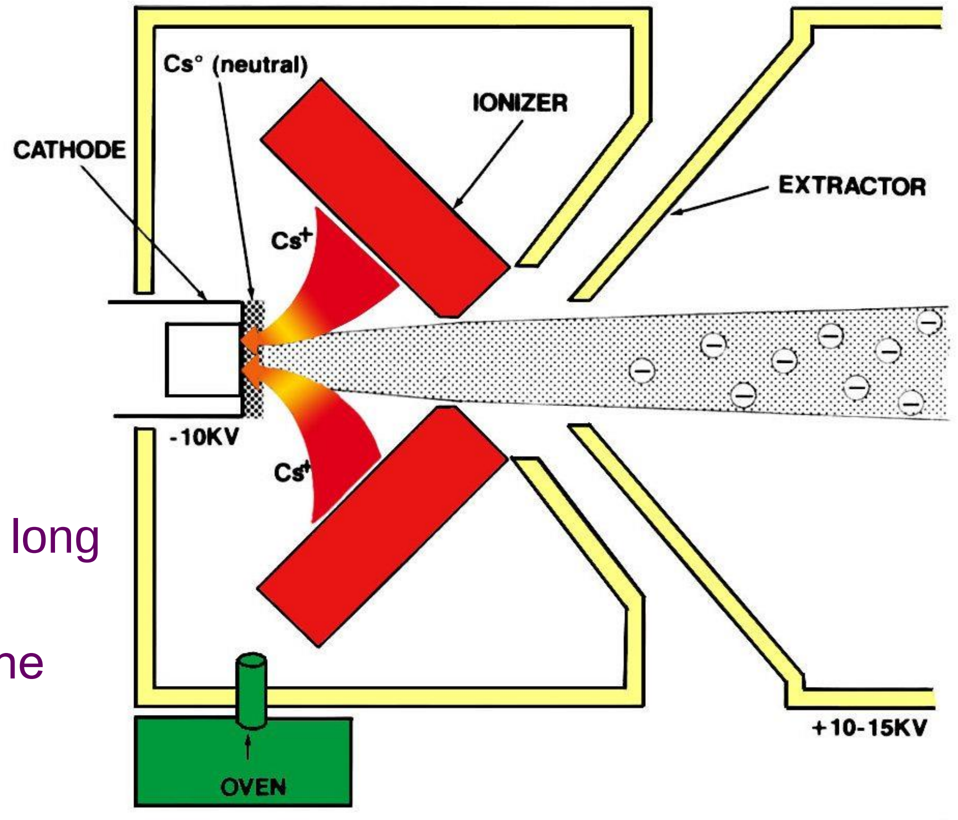
Ion Sources (2)

SNICS

(Source of Negative Ions by Caesium Sputtering)

- Cs sputtered solid cathode
  - Negative ion source
  - 20 cathode wheel
  - 'large' (6mm *Φ*) cathodes for long life
  - 'Heavy' ion source (most of the periodic table)



R.Middleton (1983) *Nucl.Instrum.Meth.* **214** pp.139–150
R.Middleton (1994) *Nucl.Instrum.Meth.* **B93** pp.39–51

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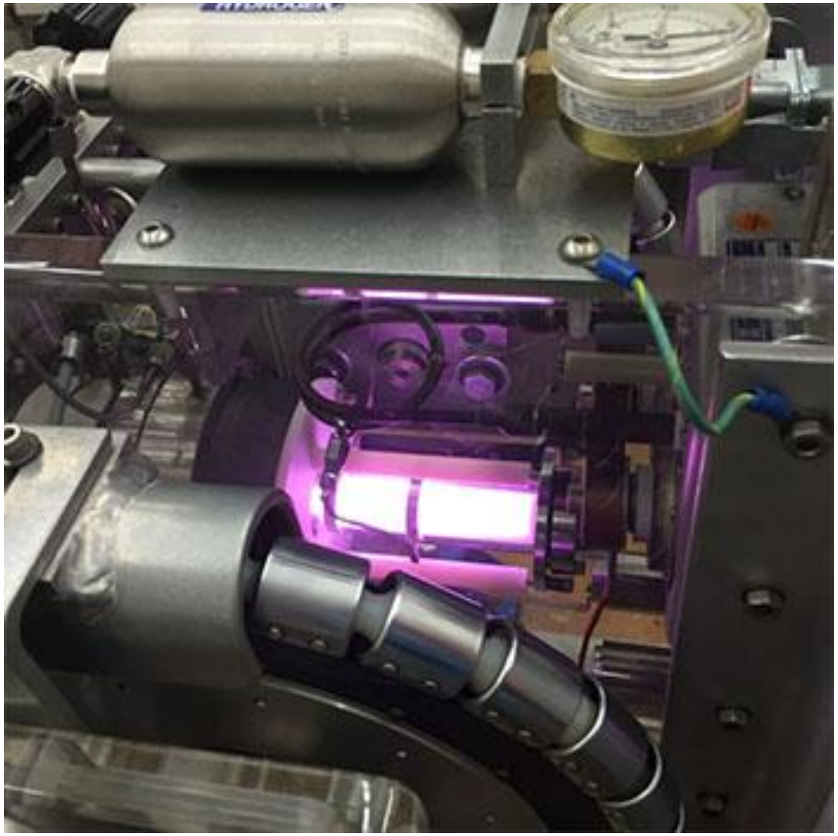
Ion Sources (3)



RF plasma

- RF discharge source
  - Positive ion source
  - 4 source bottles
  - H/He (also Ar, Kr, Xe)
  - High current (~100μA H^{+})

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EXAMPLE CASE STUDY

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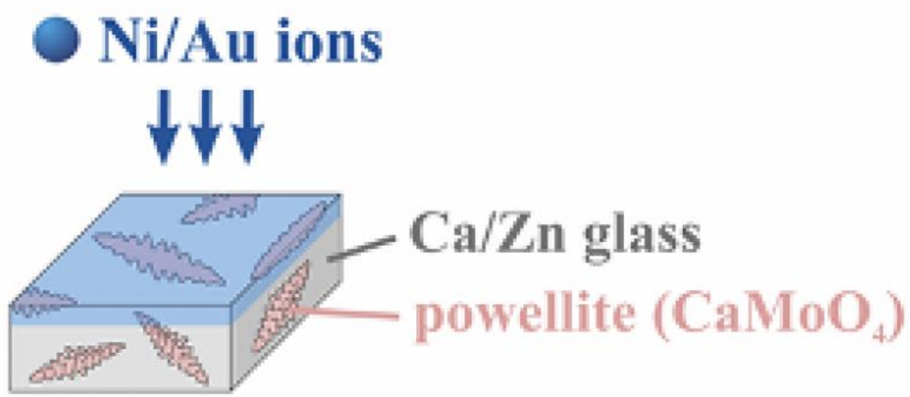
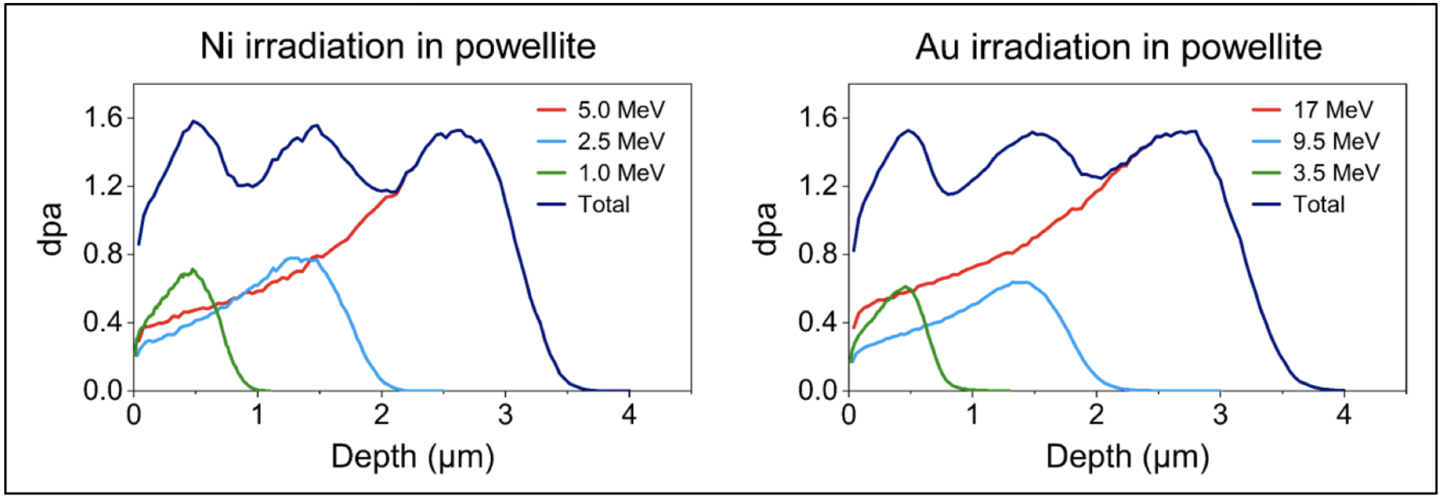
Glass composite nuclear waste forms (Tamás Zagyva)

- Encapsulation of high level active waste from nuclear fuel reprocessing in borosilicate glass
- Waste stream contains Mo rich solids
- Vitrification of Mo-rich waste streams is a significant challenge
- Low solubility in the glass leads to molybdate crystalline phases (often water soluble)
- New Ca/Zn borosilicate glass for high Mo waste streams promoting formation of powellite ($CaMoO_4$) crystals
- Radiation tolerance testing using high-Z ions (Ni & Au) to simulate accumulate the ballistic effects of α-recoil.

Accelerated damage rate using heavy ions

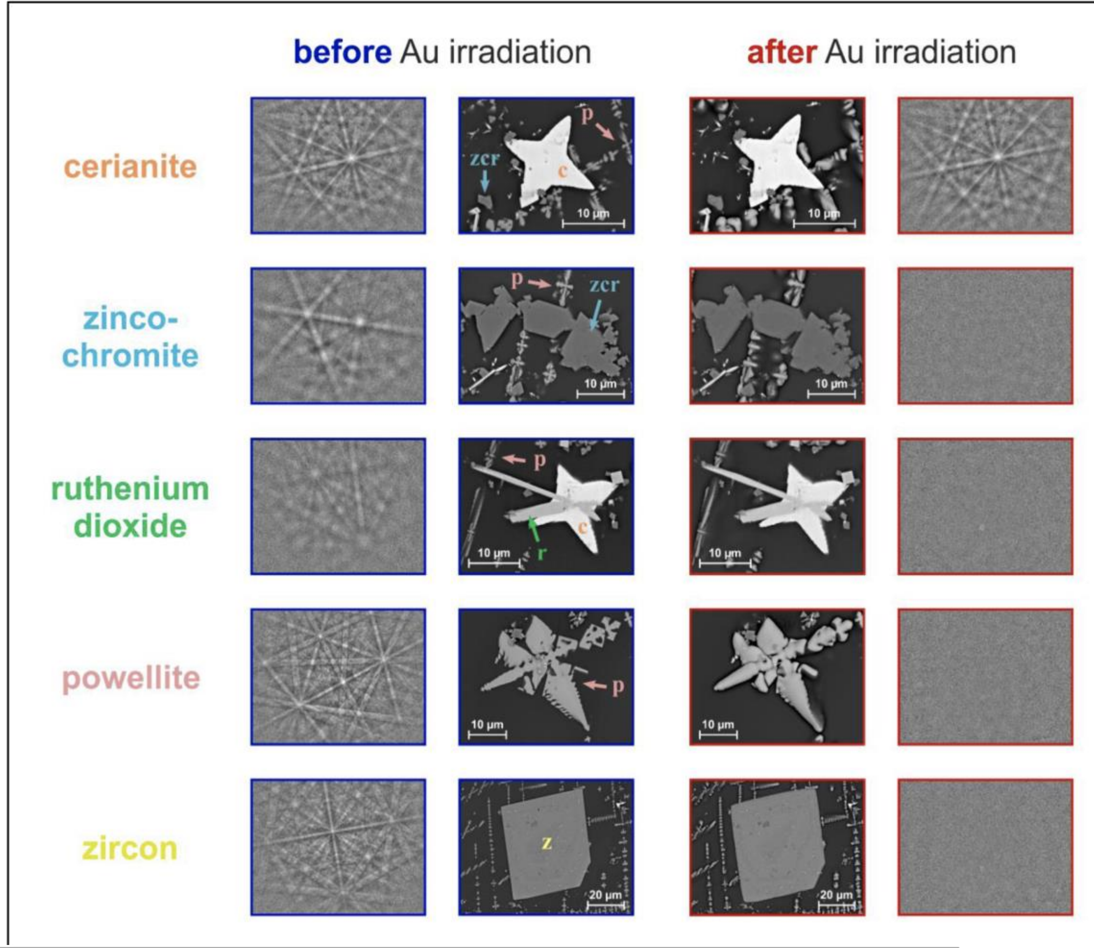
'Low' energy heavy ions to simulate ballistic damage from recoil alpha particles from decay mechanism in highly radioactive high level nuclear waste

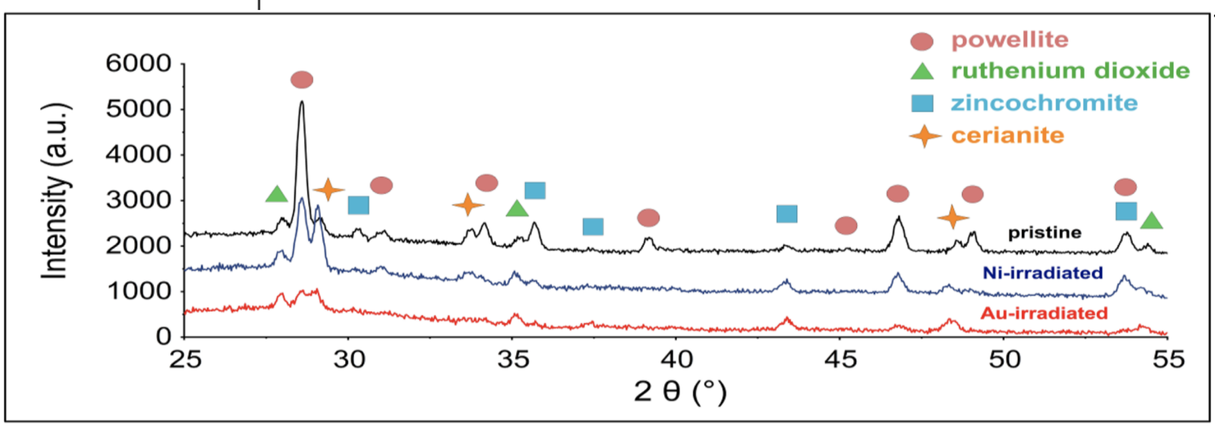




T. Zagyva *et al* J.Nucl.Mat. 585 pp.154635 (2023)

Heavy ions → Crystal amorphisation





T. Zagyva *et al* J.Nucl.Mat. **585** pp.154635 (2023)

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Conclusions

- Powellite & zircon crystals less radiation tolerant than previously thought
- Previous low dose studies may be below threshold for damage to appear
- Earlier studies using very high energy ions (100 MeV) may be misleading due to annealing effects
- Radiation induced swelling could be significant and lead to microcrack formation in the HLW glass composite material.

T. Zagyva *et al* J.Nucl.Mat. **585** pp.154635 (2023)

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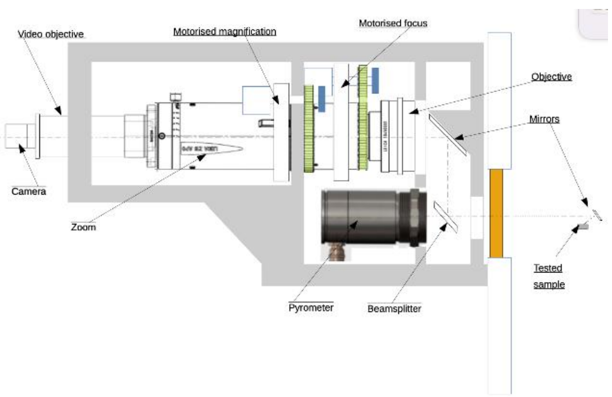
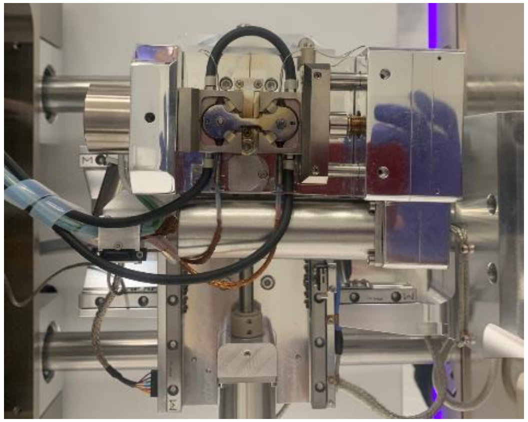
In-situ tensile test stage

- **Collaboration between University of Manchester & UKAEA**
- **To perform synergistic irradiation thermo-mechanical testing**

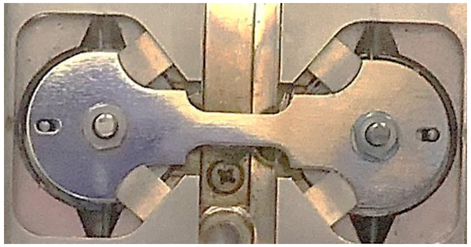
Optical microscope and pyrometer system

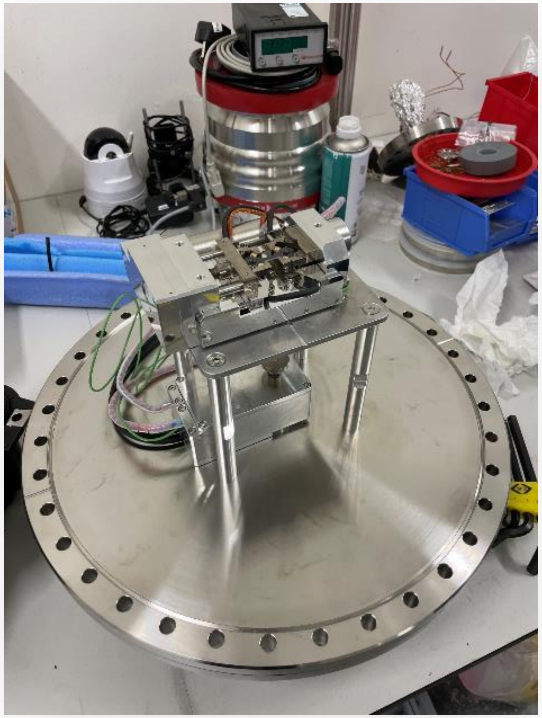


NewTec MT1000 adapted loading rig



Sample design and loading





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NEW APPLICATIONS OF ION BEAMS FOR DCF

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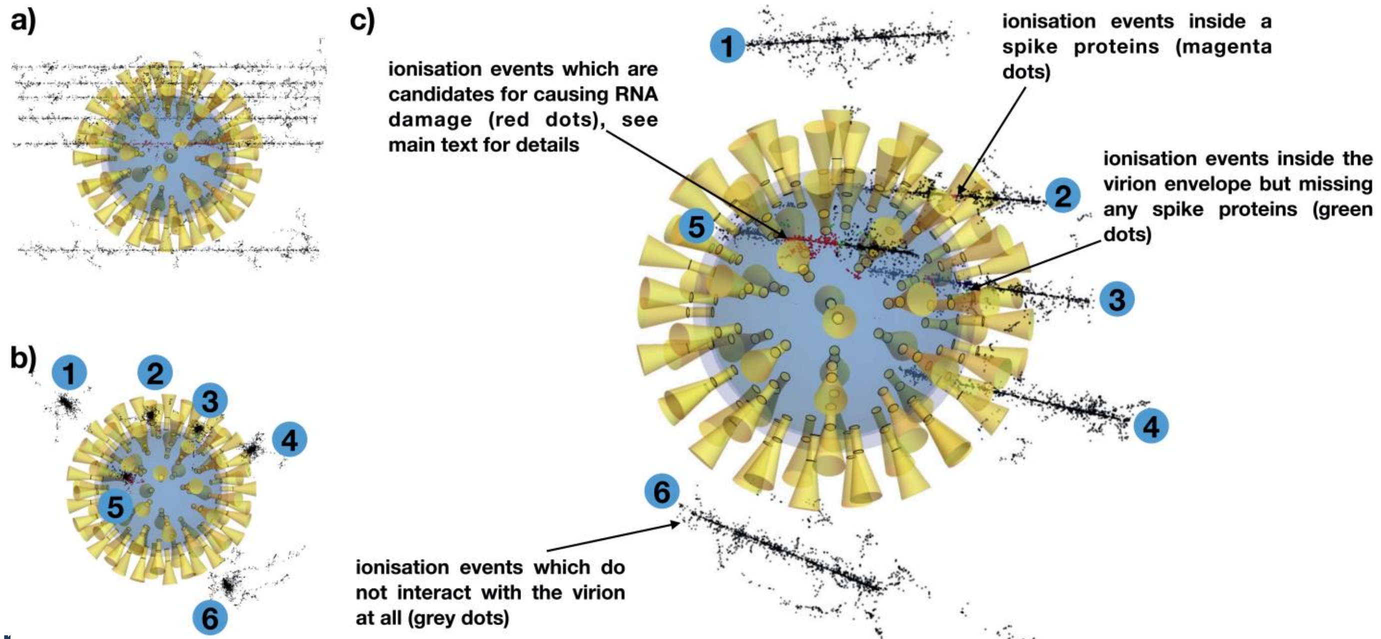
Virus in-activation by ions

- Use the high LET of ions to break RNA strands in virus particles
  - Without seriously damaging the spike proteins



B. Villagomez-Bernabe, S.W. Chan, J. A. Coulter, A.M. Roseman, F.J. Currell
Rad.Research **198** pp.68–80 (2022)

New radio-medicines

- Transmutation of materials to create new radionuclides for medicine
- New radio-isotopes – not in the current radio-medicine ‘tool box’
- For treatment & For diagnosis (scanners)
  - Transform nuclear waste into something useful
  - DCF has funded (DESNZ) project to develop a capability

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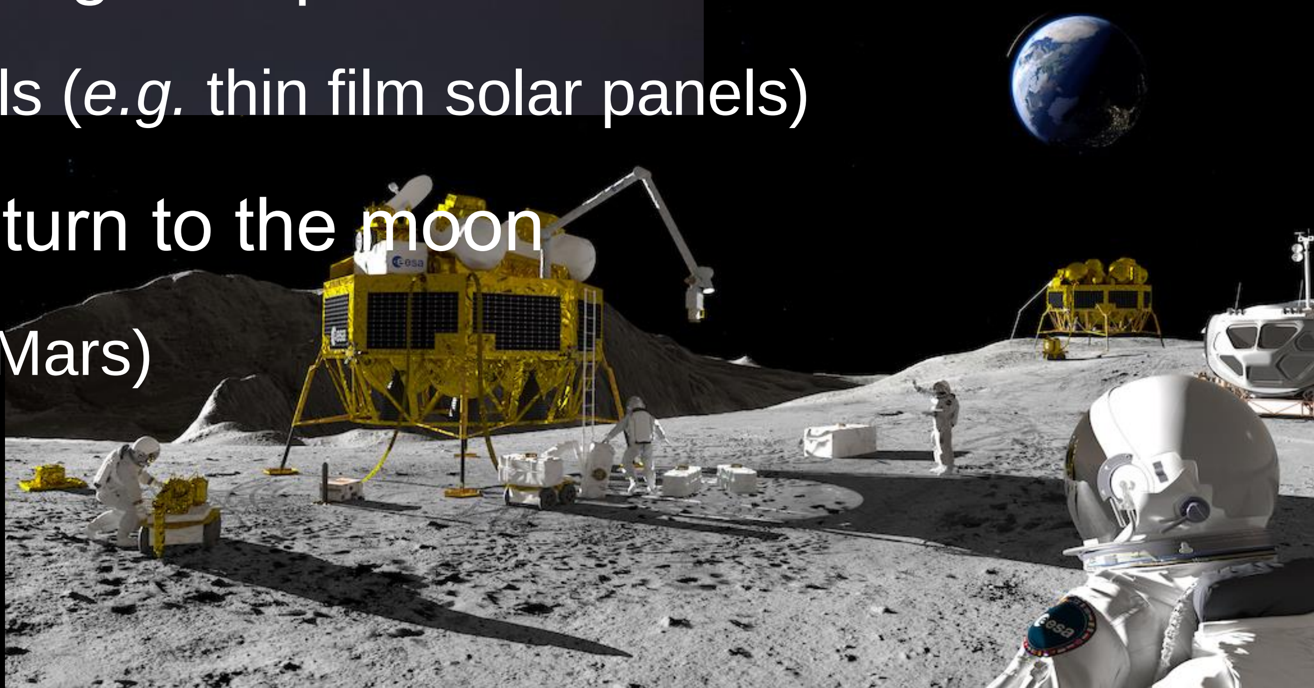
Into Space

- Astrochemistry changes in inter-planetary space
- Radiation damage to space-craft
  - new materials (*e.g.* thin film solar panels)
- Humanity's return to the moon
  - (and then to Mars)



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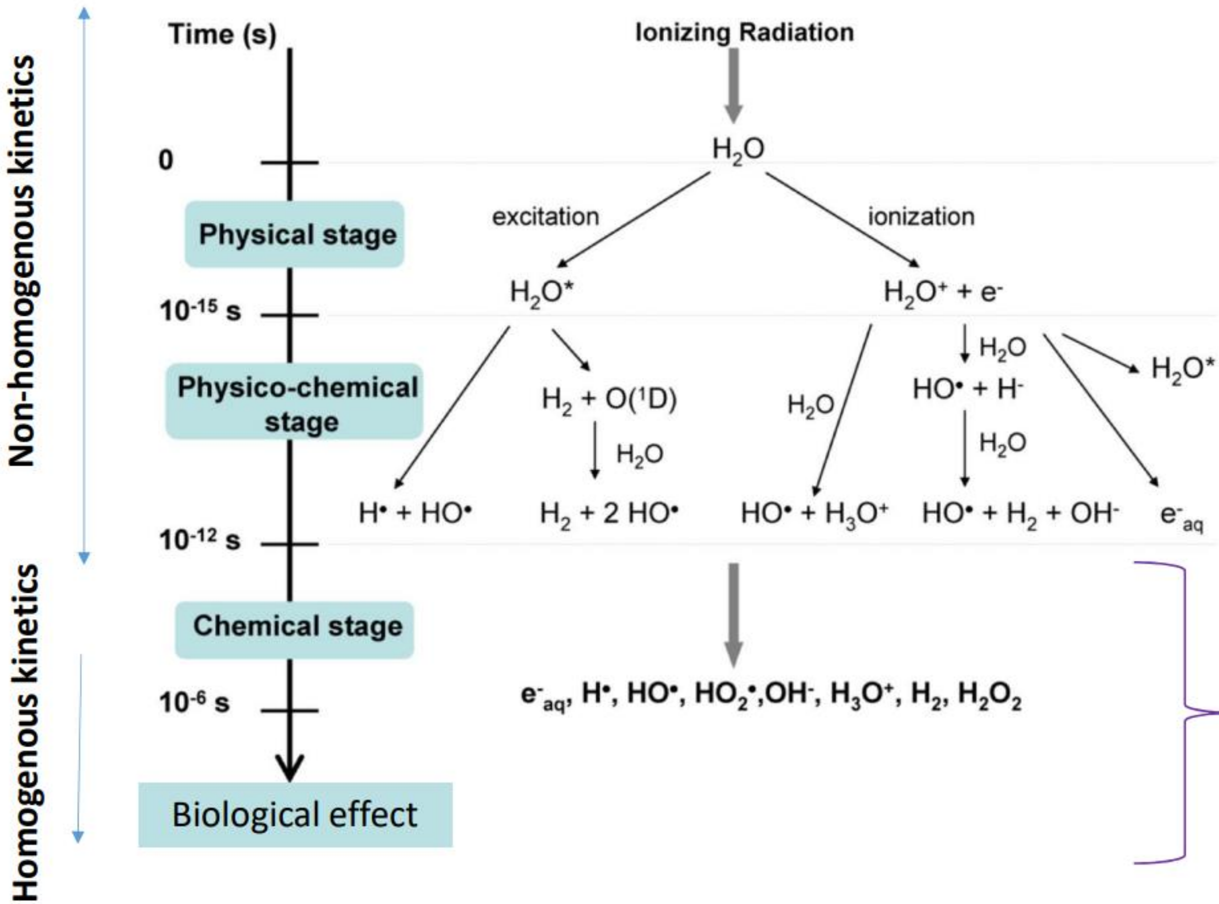
Ultra-fast kinetics



Water **2011**, *3*(1), 235-253; doi:10.3390/w3010235 Open Access

Review

Water Radiolysis: Influence of Oxide Surfaces on H_2 Production under Ionizing Radiation

Sophie Le Caër

Novel science, Domain of discovery

Useful kinetic information, well studied for electrons, still novel for ions

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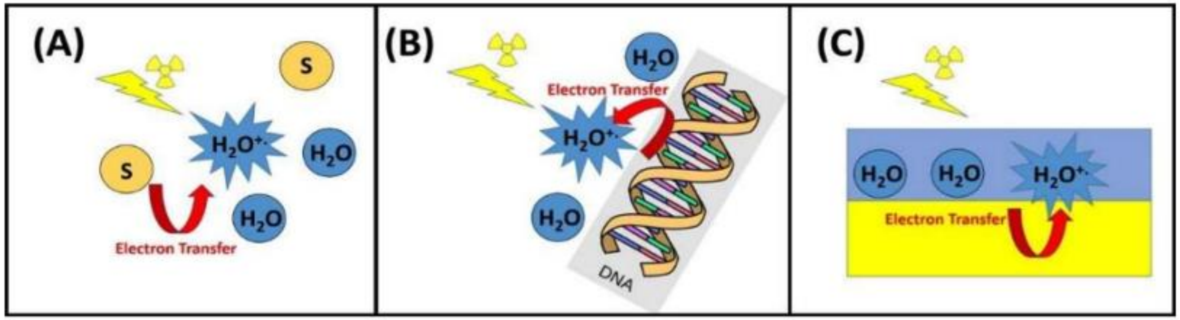
Ultra-fast processes in radiation chemistry



- Radiolysed water can form radical cations that engage in electron transfer

- Highly concentrated solutions in which the water radical cation can oxidise solute molecules directly – *e.g.* spent nuclear fuel processing (purex)
- Highly structured water layers formed in contact with biomolecules *e.g.* DNA – cancer therapy
- Water/solid interfaces – safe nuclear waste storage, Pu stewardship, corrosion in reactors & storage ponds.

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How to generate ultra-short ion pulses ?

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- Staff & students @ DCF
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Thank You!

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