IAEA 60 Years
Atoms for Peace and Development

Accelerated Irradiation with Ion Beams

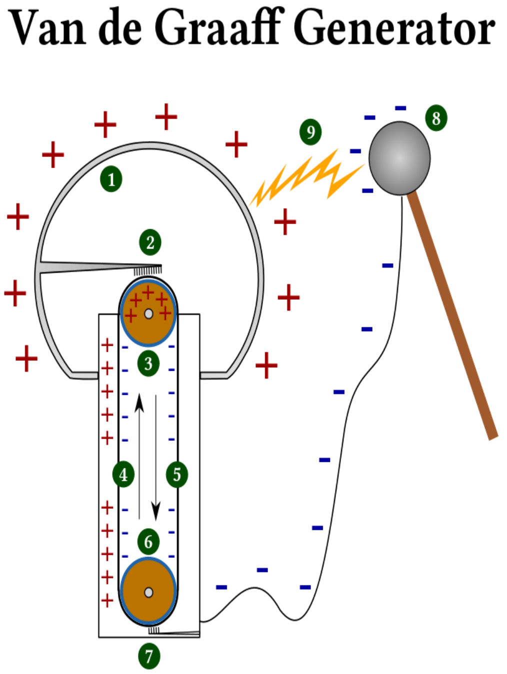
Ian Swainson
IAEA-Physics Section

With special thanks to Gary Was, University of Michigan for provision of slides and material

Electrostatic accelerators

- Use electrostatic field to accelerate an ion

SF$_6$ insulator gas enables higher terminal potential: 25-30MV

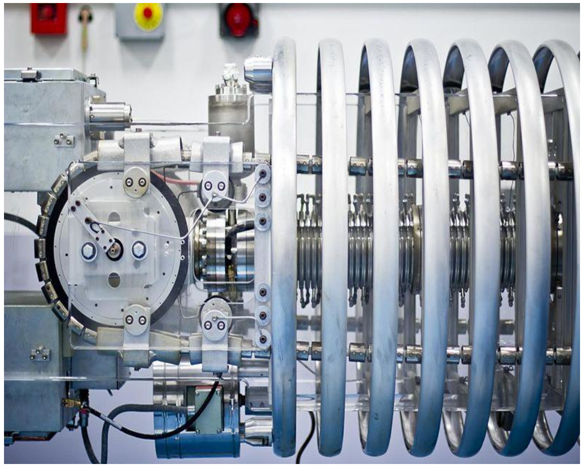


1. hollow metal sphere
2. upper electrode
3. upper roller (for example an acrylic glass)
4. side of the belt with positive charges
5. opposite side of belt, with negative charges
6. lower roller (metal)
7. lower electrode (ground)
8. spherical device with negative charges
9. spark produced by the difference of potentials

By Omphalosskeptic - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=33070240

van der Graaff accelerator

Pelletron: chain of pellets replaces belt

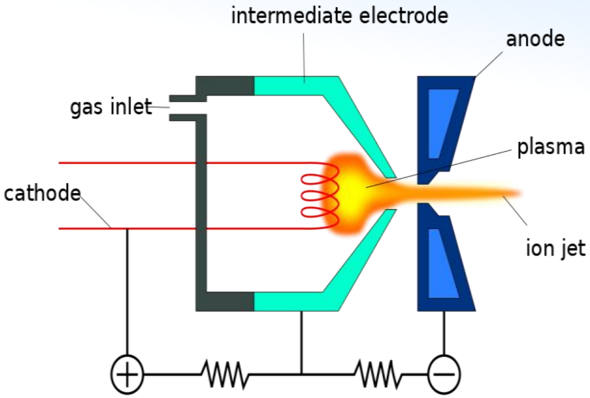


2.5 MeV Pelletron accelerator SIRIUS at the École polytechnique.

Other common method is C-W multiplier

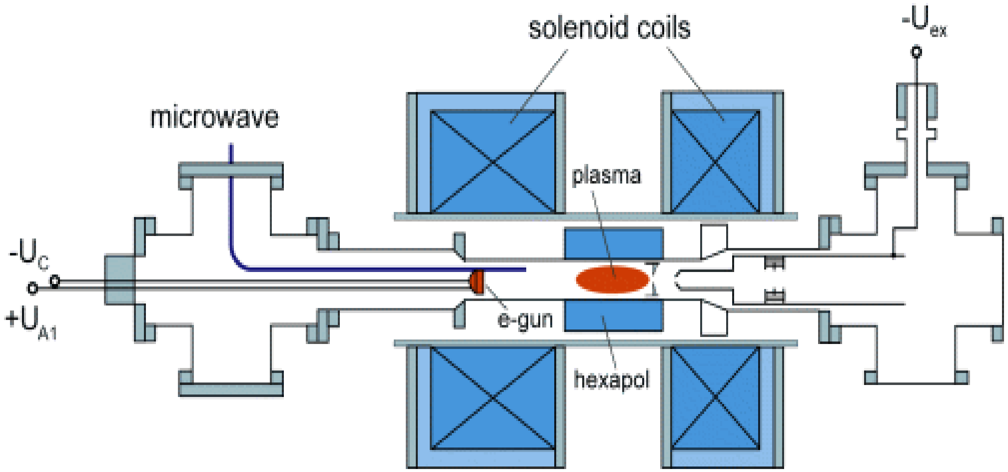
Ion source

duoplasmatron: low-pressure gas ionized via electrons



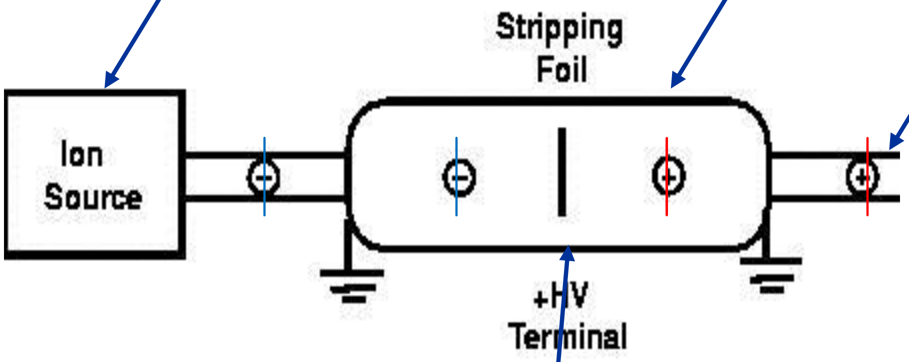
By Evan Mason - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=49972388

Electron cyclotron resonance: microwaves tuned to the gyration frequency of electrons around the imposed magnetic fields



http://www.casetechnology.com/source.html

Tandem accelerator



External negative ion source

SF_6 tank

positive ion beam of energy (N+1)V

Conductive “stripper foil” removes N electrons and converts beam to positive ions

An H^- beam would generate a proton beam of energy 2qV.

q=e ⇒ MeV is the convenient energy measure

Ions

- Interactions involve electron-electron; electron-nucleus; nucleus-nucleus
- By definition charged, wide mass and charge ranges:

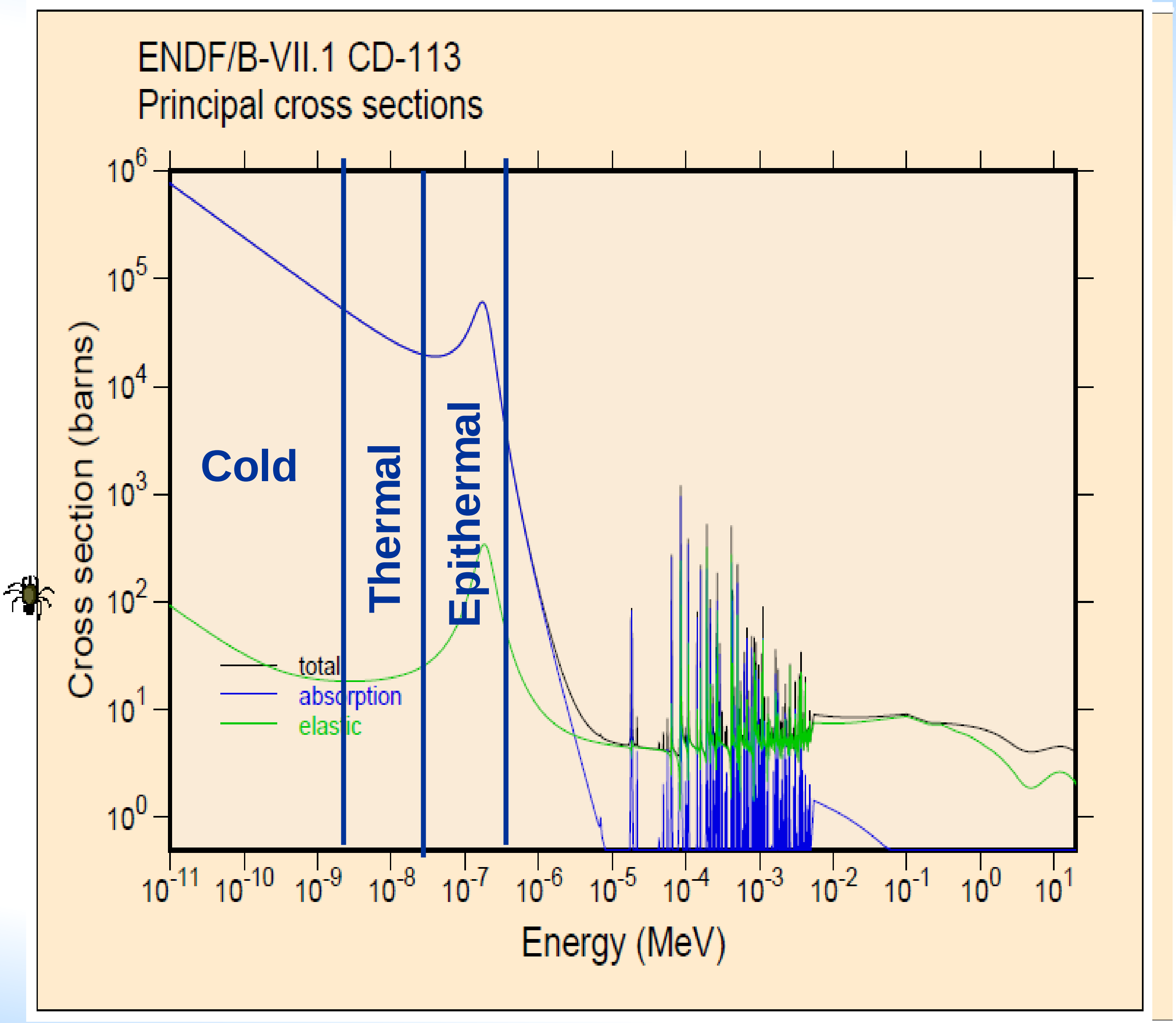
Particle	**amu**	**q(e)**
neutron	**1**	**0**
electron	1/1840	-1
proton	1	+1
U	238	≤+92

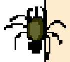
- Ion energy generally quoted as the specific energy MeV/amu
- Energy loss on travelling through matter can be divided into parts:
  - elastic (nuclear stopping power, $\mathbf{S_n}$)
  - electronic stopping power, $\mathbf{S_e}$
  - [radiation]
- S is often measured in MeV/μm

Neutron interaction with nuclei

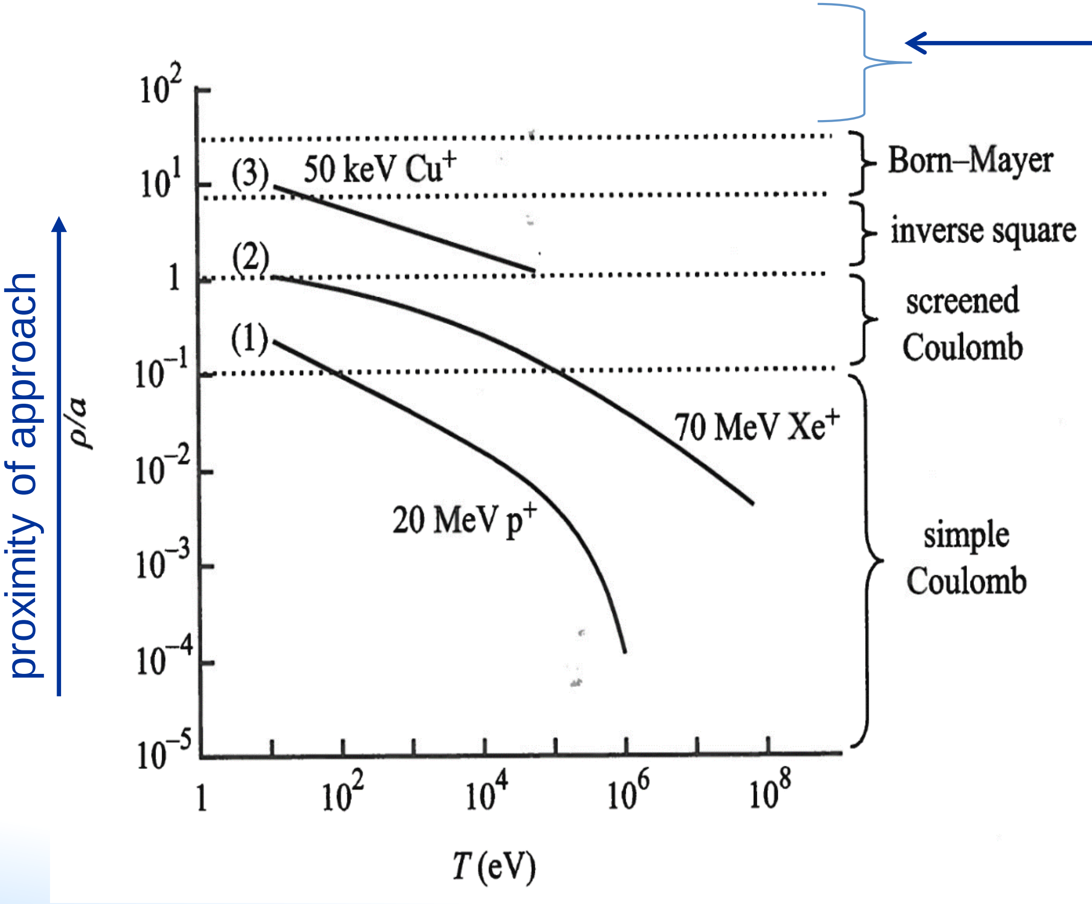
- Neutrons are neutral particles, *mostly* insensitive to the electron clouds,. Interaction therefore weak, with the nucleus. Interactions include
- elastic: kinetic energy transferred from neutron to target nucleus
- $\sigma_S(E_i, T) = {}^{\sigma_S(E_i)}/_{\gamma E_i}$ [Note RHS independent of *T*], where
  - $\bar{T} = \frac{\gamma E_i}{2}, \gamma = \frac{4mM}{(M+m)^2}$
  - 1 MeV neutron ($m = 1$) ⇒
  - $\bar{T} = 0.14$ MeV ^{12}C:
  - $\bar{T} = 0.069$ MeV ^{56}Fe;
  - $\bar{T} = 0.009$ MeV U
  - absorption (n,γ). *T* may also be sufficient to displace a recoiling atom.

all bigger than E_d (~30-40 eV)


ENDF/B-VII.1 CD-113
Principal cross sections
Cross section (barns)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Cold
Thermal
Epithermal
total
absorption
elastic
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
Energy (MeV)



A variety of potentials are required



Hard-sphere E<50 keV

Closed shell electron repulsion

Some screening via inner electrons of the nuclei

Direct interaction of nuclei
Light ions at MeV energies.
Basis of Rutherford scattering.

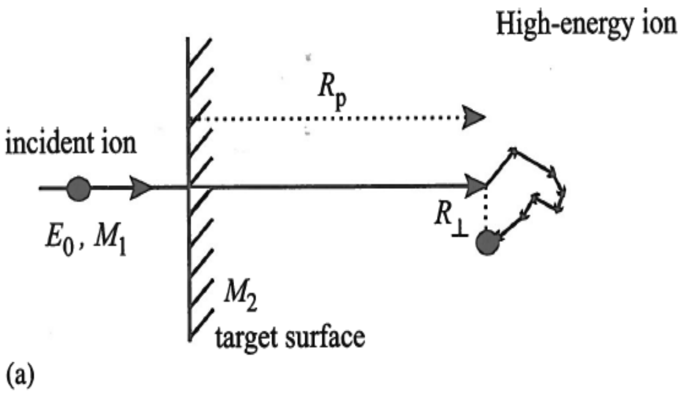
a = Bohr radius of H ~ 0.5Å.

Energy Loss: S = -dE/dx

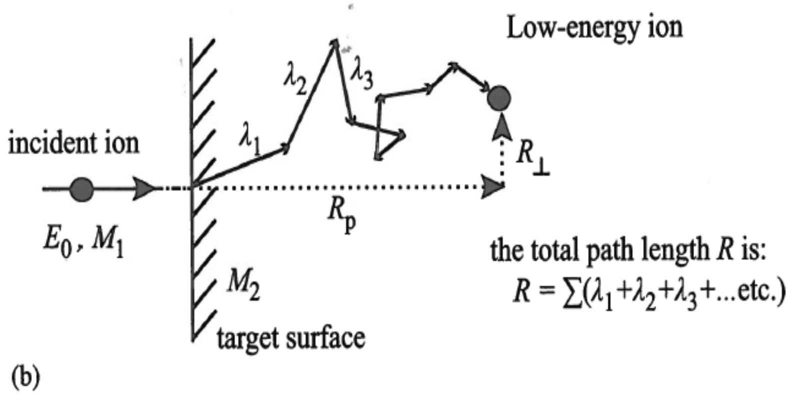
- High energies: $S_e \gg S_n$.
  - Can be visualized as “drag”/friction of electrons braking the ions
  - Chiefly inelastic (loss of energy due to electron cloud interaction)
  - For 1 MeV protons, $S_e \sim 2000\ S_n$
- Low energies: $S_n > S_e$
  - It is in the low energy range in which the displacement damage peaks via the nuclear interaction
  - At very low energies, $S(E_i,T)$ for atom-atom interactions is ca. 10^8 stronger than the neutron-nucleus interaction: PKA and KA
  - S_n generally increases with the mass (#n,p) of the ion

Trajectory form

- High energy ion:
  - S_e dominates the range and trajectory quasilinear,
  - S_n grows at the end where the beam straggles

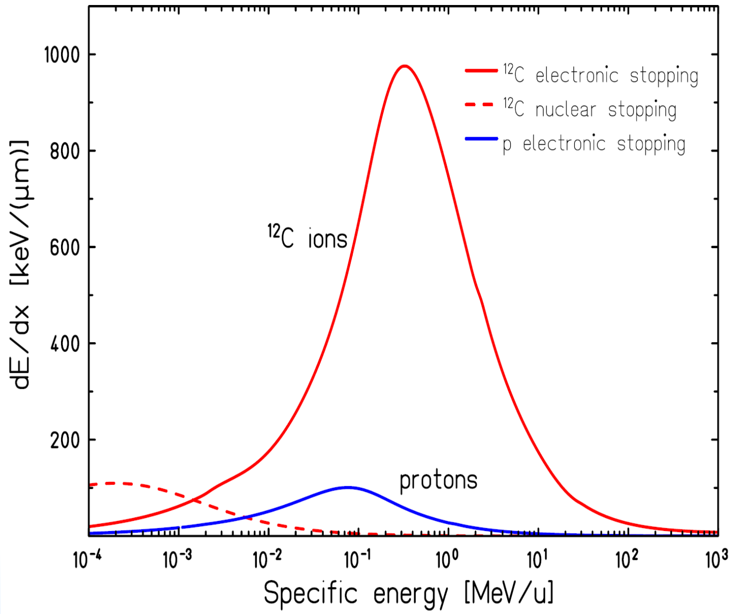


- Low energy ions entering a solid immediately have a closer balance of S_e and S_n
  - pathway straggles earlier



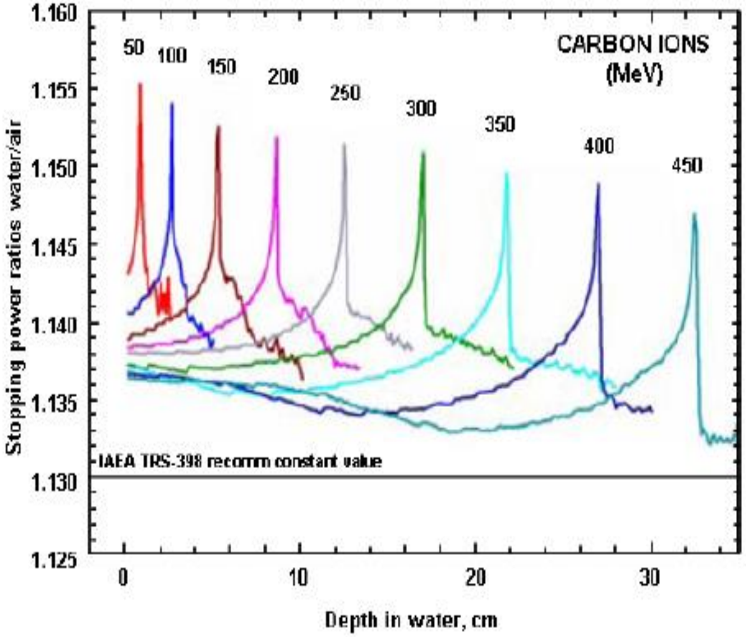
Bragg peak

- Cross-section increases as particle slows ($S_e \to S_n$).
- Causes rapid deposition of energy (dose) as the particle comes towards end of travel: Bragg peak



http://brenthuisman.net/msc/images/stopping-power.png

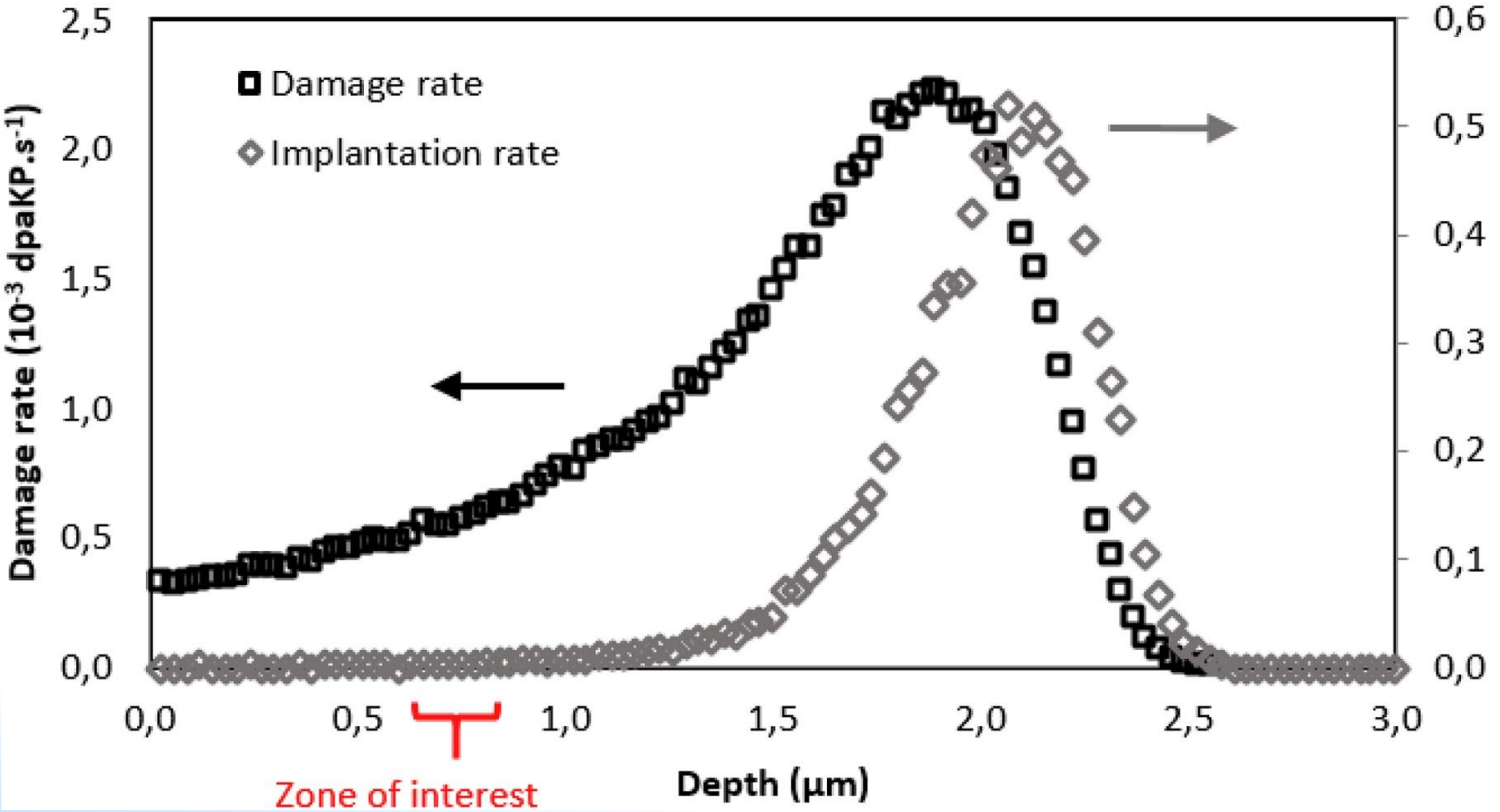
Note logarithmic horizontal scale



Bragg peak profile as a function of E_i: example from ion beam therapy

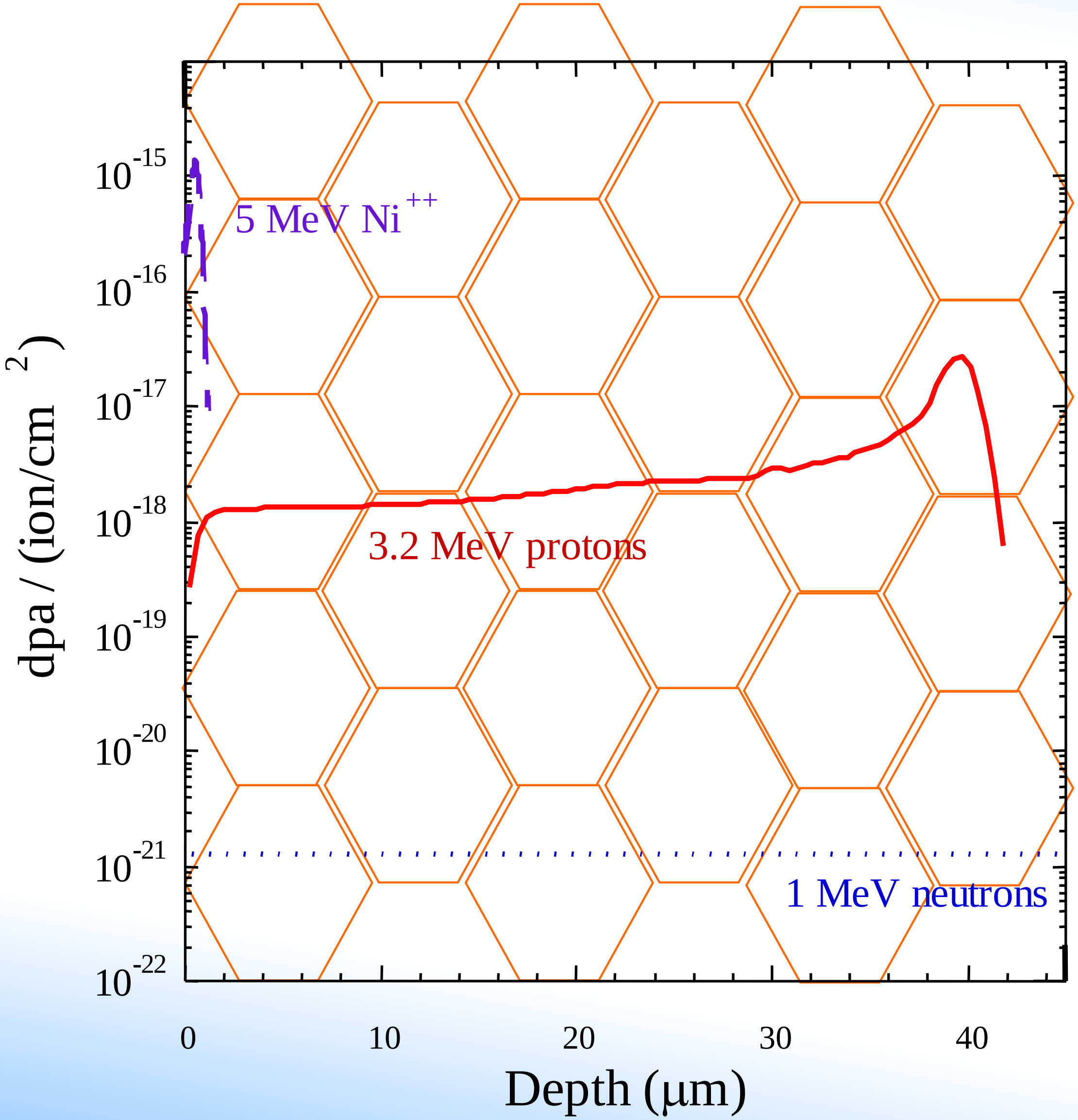
Injected interstitials

Often use “self-ions”=major alloying components; choose energies appropriately to separate damage at suitable depth from ii.
Need to overlay H, He injection at the right depth (energy control) and in the right proportion (current control)



10 Mev Fe^{5+} in 316 ss

Penetration depth for light and self-ions in steel



10 μm grain structure.

3.2 MeV Protons 100-1000 times faster than 1 MeV neutrons

Smaller mass (cf Ni2+) gives more lower recoil energy

Numerous grain boundaries can be irradiated with this proton energy.

Kinchin-Pease: displaced atoms in the cascade

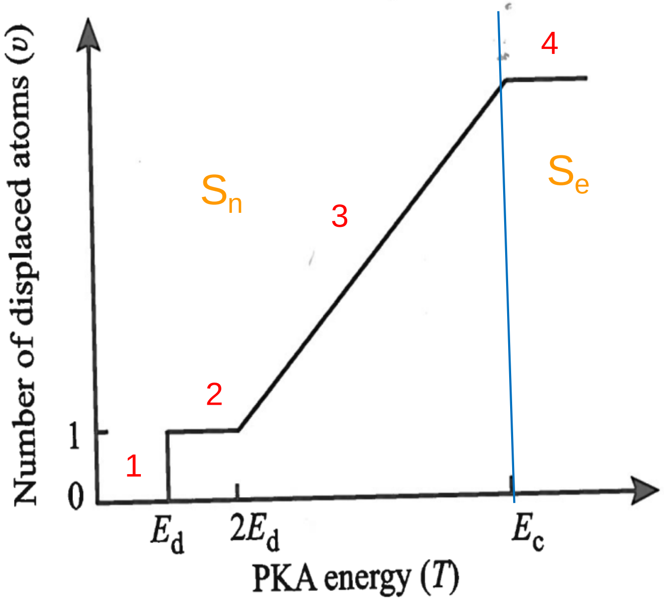
- Assume that for $E_i > E_c$: loss is only S_e – no displacive collision – a cutoff
- Once $E_i<E_c$, only atomic collisions via hard-sphere potential ~(0,∞)

Kinchin Pease produces a simple four domain result for the number of displacements per PKA as a function of PKA energy, T.

1. $N_d(T) = 0 \quad T < E_d$
2. $N_d(T) = 1 \quad E_d < T < 2E_d$
3. $N_d(T) = T/2E_d \quad 2E_d<T$

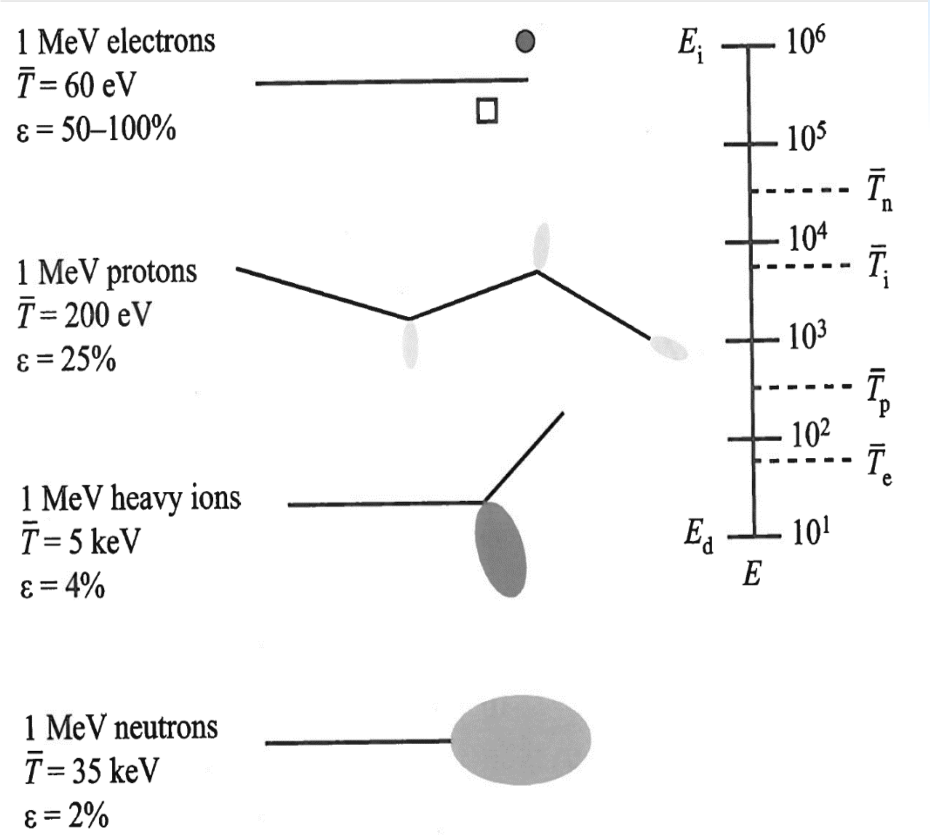
with a maximum above:

4. $N_d(T) = E_c/2E_d \quad T \geq E_c$



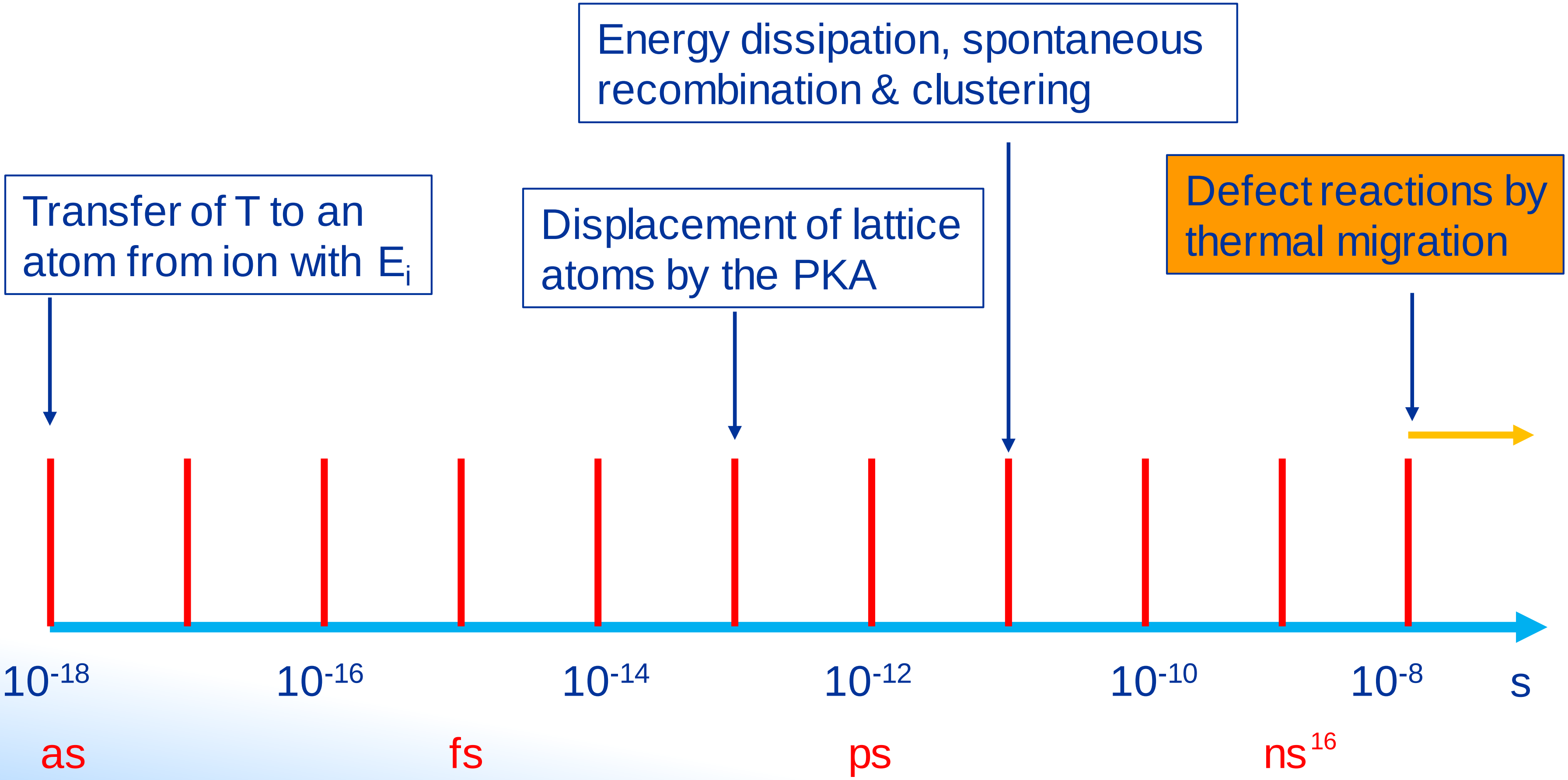
Different types of cascades

- light ions give
  - isolated Frenkel pairs (electrons) or
  - small disperse clusters (protons)
- heavy ions and neutrons give
  - fewer denser cascades



E_d ~ threshold displacement energy
E_i ~ initial incoming particle energy
T ~ energy transferred to PKA

Time frames of events



Transfer of T to an atom from ion with E_i

Displacement of lattice atoms by the PKA

Energy dissipation, spontaneous recombination & clustering

Defect reactions by thermal migration

Modification to the NRT-dpa to damage

We recognise that the current NRT-dpa standard is fully valid in the sense of a scaled radiation exposure measure, as it is essentially proportional to the radiation energy deposited per volume. As such, it is highly recommended to be used in reporting neutron damage results to enable comparison between different nuclear reactor environments and ion irradiations.

$$N_d(T_d) = \left[\begin{array}{ccc} 0 & , & T_d < E_d \\ 1 & , & E_d < T_d < 2E_d/0.8 \\ \dfrac{0.8T_d}{2E_d} & , & 2E_d/0.8 < T_d < \infty \end{array}\right]$$

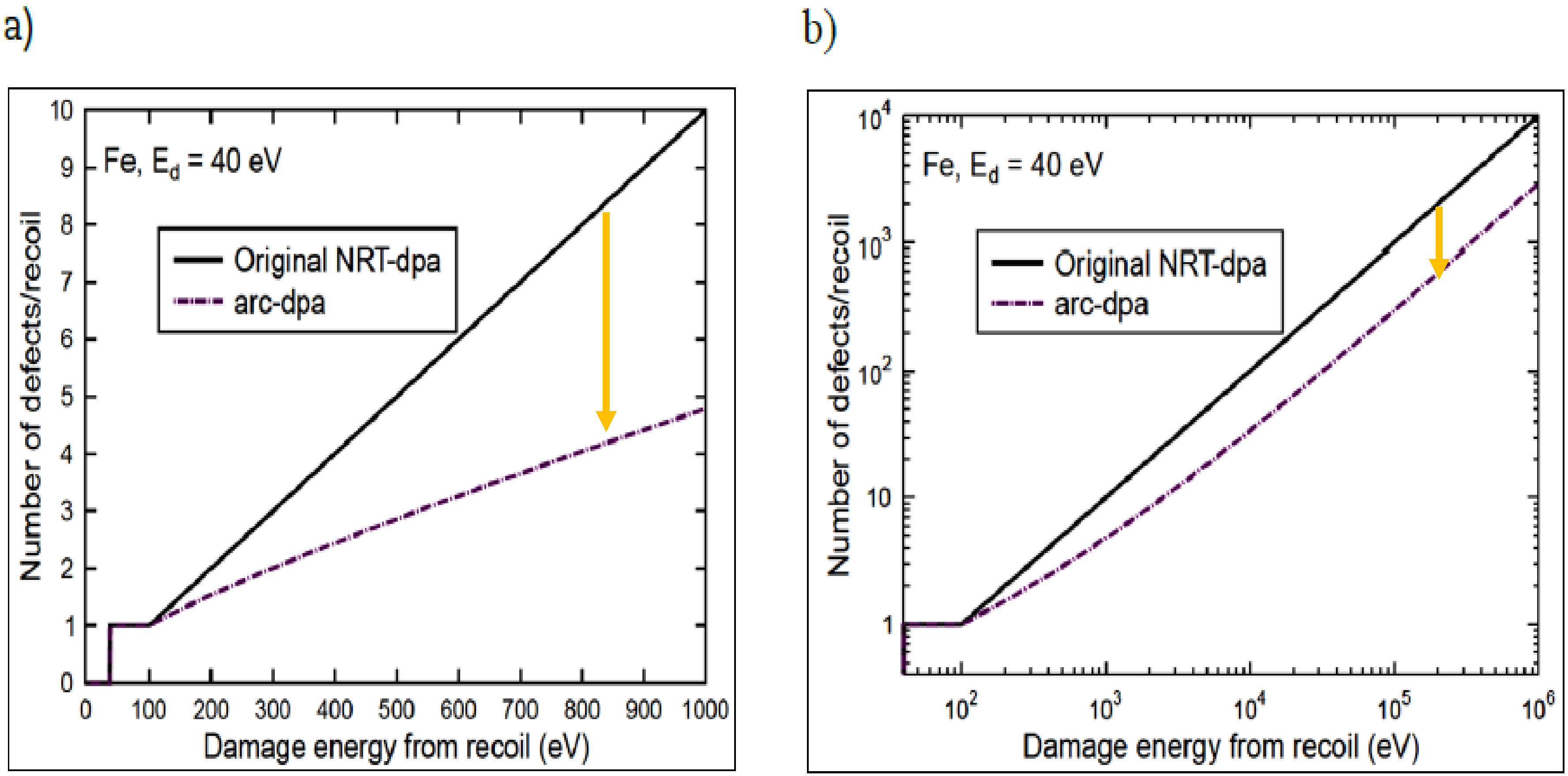
$$N_{d,arcdpa}(E) = \left[\begin{array}{ccc} 0 & \text{when} & E < E_d \\ 1 & \text{when} & E_d < E < 2E_d/0.8 \\ \dfrac{0.8E}{2E_d}\xi(E) & \text{when} & 2E_d/0.8 < E < \infty \end{array}\right]$$

To partially start to alleviate these problems, for the case of metals we present an "athermal recombination-corrected dpa" (arc-dpa) equation that accounts in a relatively simple functional for the well-known issue that the dpa overestimates damage production in metals under energetic displacement cascade conditions.

Primary Radiation Damage in Materials: OECD NEA/NSC/DOC(2015)9

arc-dpa as a corrected measure of "displacive dose"

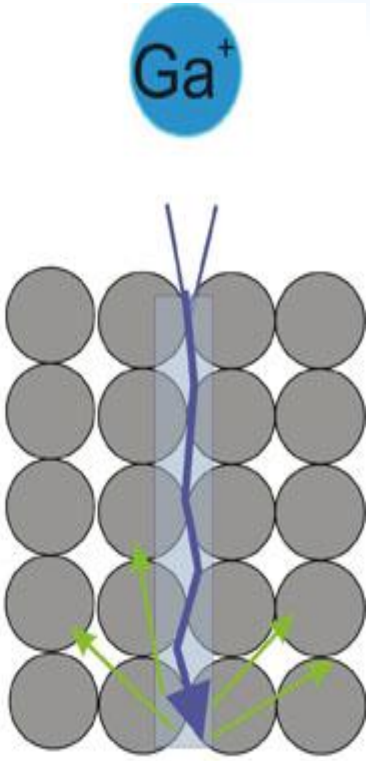
Figure 2.13. Illustration of the original NRT damage function for dpa calculations and the new function that accounts for athermal recombination (arc-dpa)



DIRECTIONAL TRANSPORT OF ENERGY AND IONS AWAY FROM THE CASCADE

Channeling

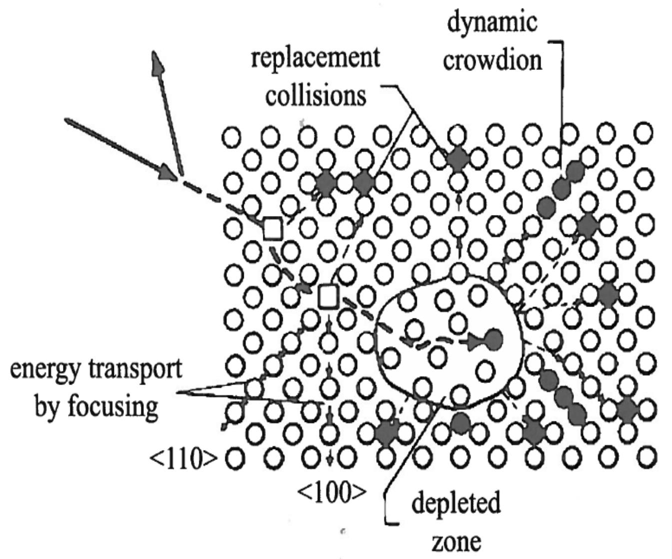
- Along high-symmetry directions in a crystalline solid there can be channels that ease the direction of the ion beam or of KAs
- For fast ions Se dominates
  - little straggling (Sn, displacement)
- Long distance displacement away from the cascade
- Glancing interactions with the walls tend to keep the ion within the walls



Ion beam channeling

Focusing

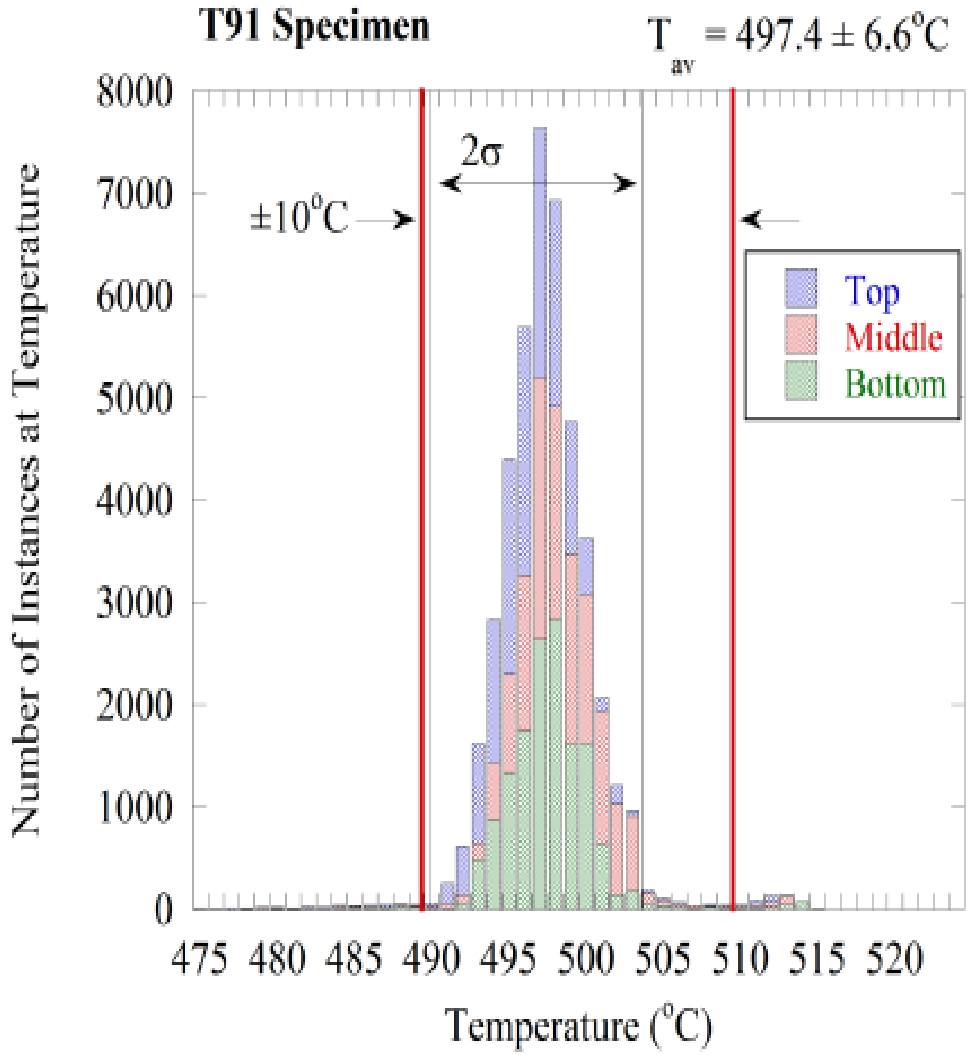
- Along high-symmetry directions in a crystalline solid there are rows of atoms, e.g. cp directions in metals
- Neighbouring rows tend to keep the momentum transfer focused in the same direction
- Displacive, therefore mostly nuclear collisions, therefore for low energy KAs
- Long distance displacement away from the cascade

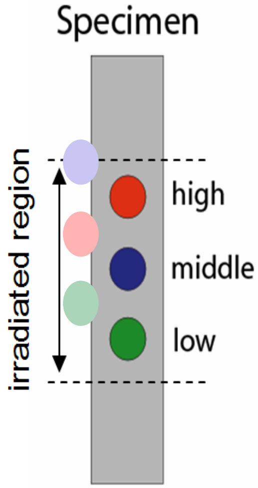


Advantages of ion irradiation

- Extremely well-controlled irradiations (temperature, dose, dose rate)

Histogram of a proton irradiation of T91 at 500°C





Advantages of ion irradiation

- Extremely well-controlled irradiations (temperature, dose, dose rate)
- High doses are easily achievable
    - 1dpa/day for protons
    - 100 dpa/day for heavy ions

Advantages of ion irradiation

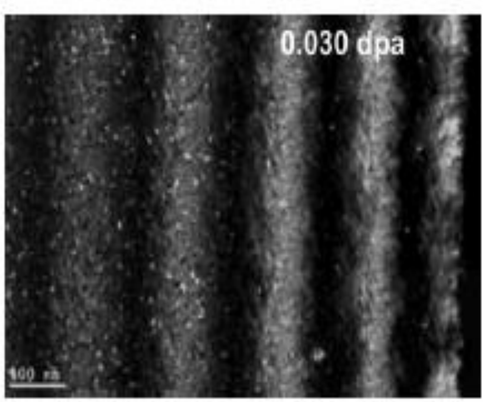
- Extremely well-controlled irradiations (temperature, dose, dose rate)

- High doses are easily achievable
  - 1dpa/day for protons
  - 100 dpa/day for heavy ions

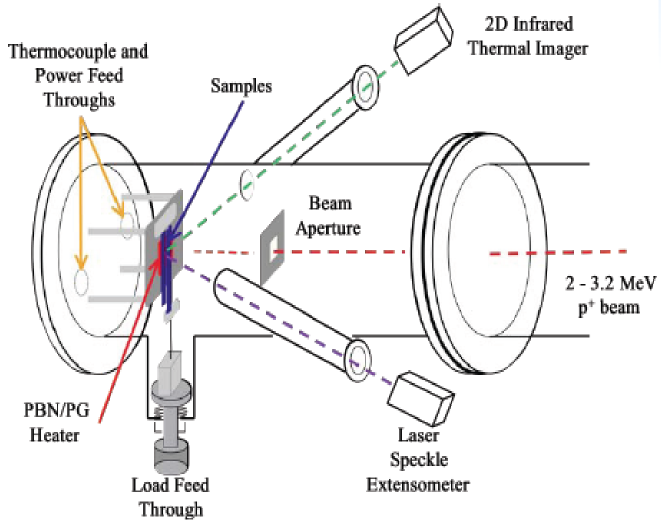
- Can address multiple components of the "extreme environment" and more easily employ in-situ analysis

Multiple components of the “extreme environment”

In-situ 1 MeV Kr irradiation (ANL)

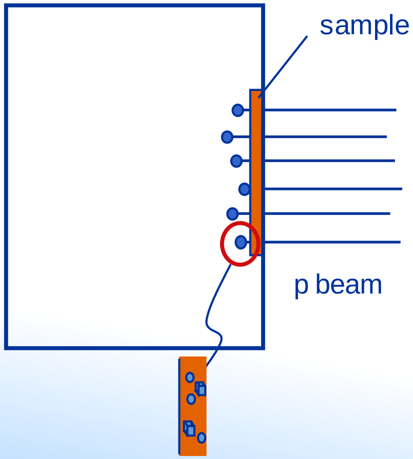


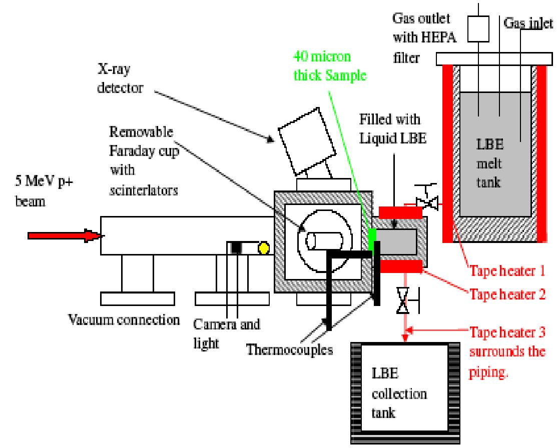
Irradiation creep of F-M alloys, SiC and PyC (UM)



In-situ corrosion and irradiation

Water-UM





LBE-LANL

Advantages of ion irradiation

- Extremely well-controlled irradiations (temperature, dose, dose rate)
- High doses are easily achievable
  - 1dpa/day for protons
  - 100 dpa/day for heavy ions
- Can address multiple components of the “extreme environment” and more easily employ in-situ analysis
- Low sample activation
- Cheap

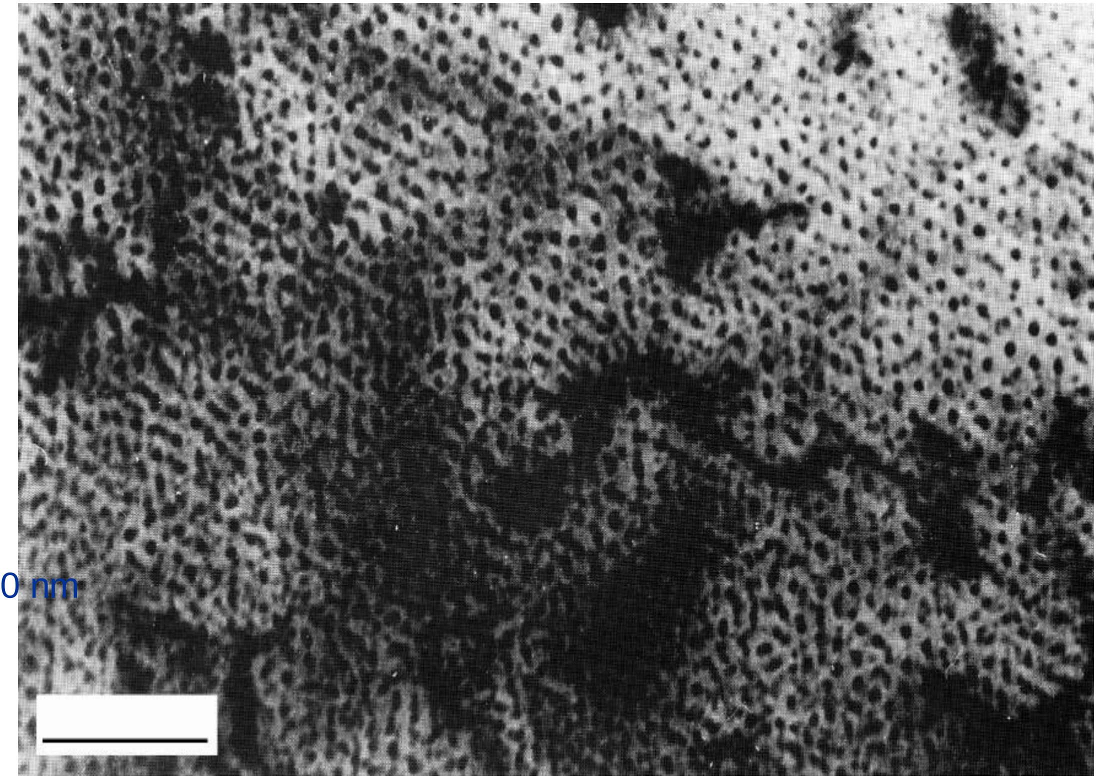
More than displacement..

- There is ingrowth of hydrogen and helium gas even in structural alloys from (n,α) and (n,p) reactions.

Remember:

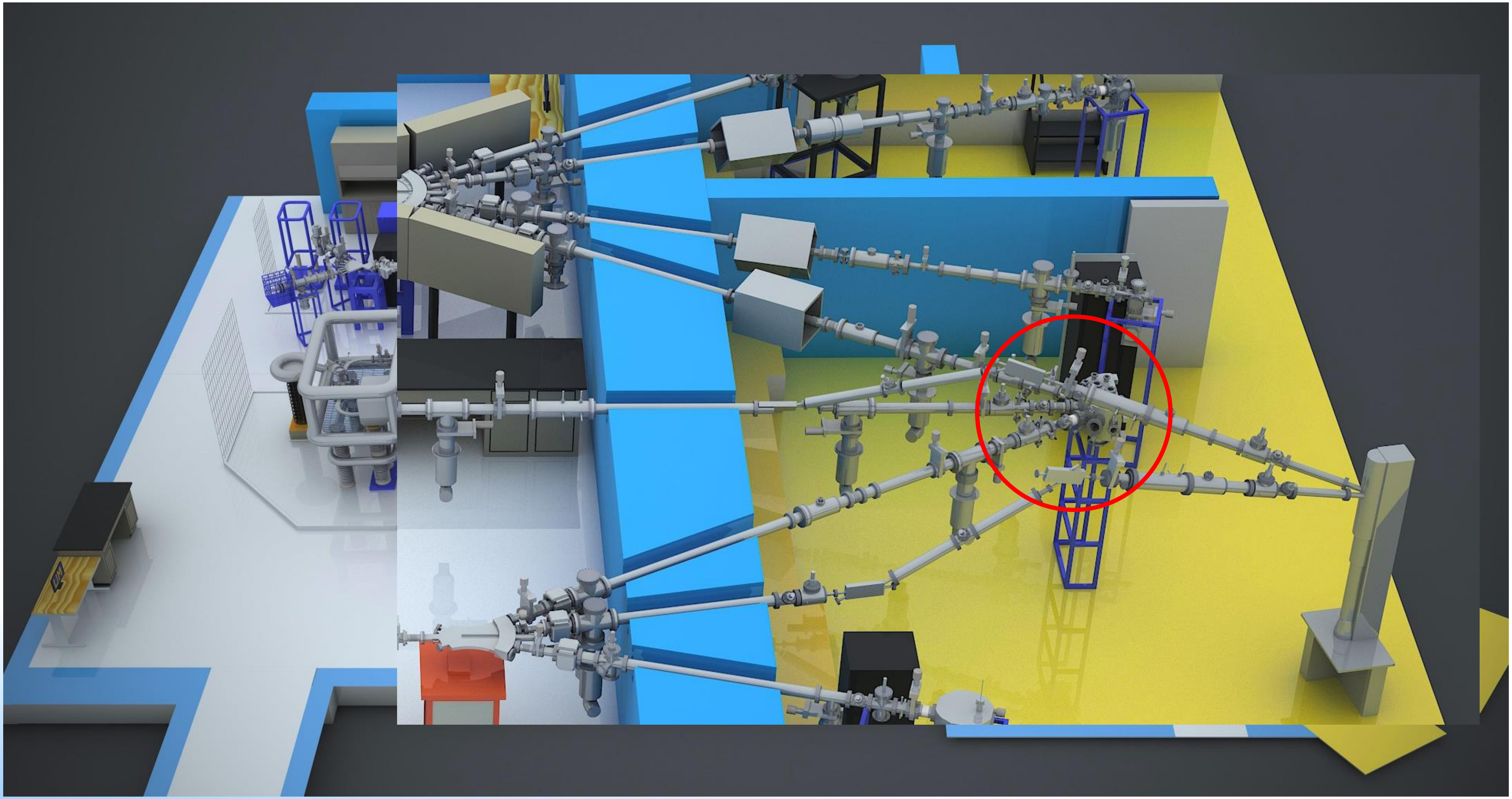
$$
\begin{aligned}
&{}^{58}\mathrm{Ni} + \mathrm{n} \rightarrow {}^{59}\mathrm{Ni} + \gamma \\
&{}^{59}\mathrm{Ni} + \mathrm{n} \rightarrow {}^{56}\mathrm{Fe} + {}^{4}\mathrm{He} \\
&{}^{59}\mathrm{Ni} + \mathrm{n} \rightarrow {}^{59}\mathrm{Co} + \mathrm{H} \\
&{}^{59}\mathrm{Ni} + \mathrm{n} \rightarrow {}^{60}\mathrm{Ni} + \gamma
\end{aligned}
$$

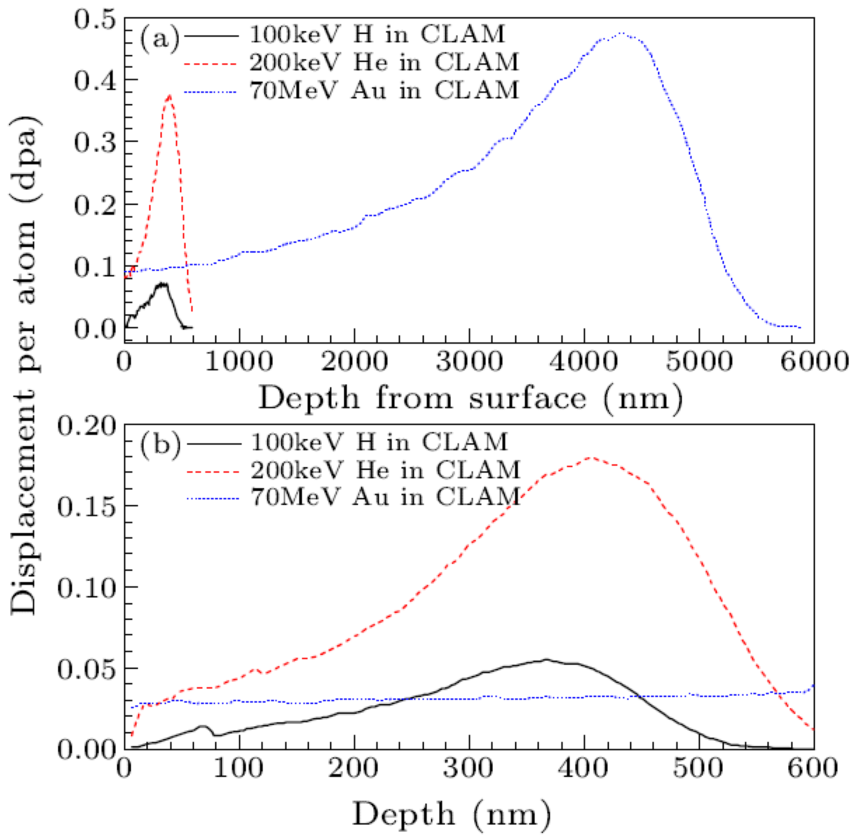
Bubbles - clusters of vacancies with He gas atoms



N.M. Ghoniem, et al, 2002

Michigan Ion Beam Lab





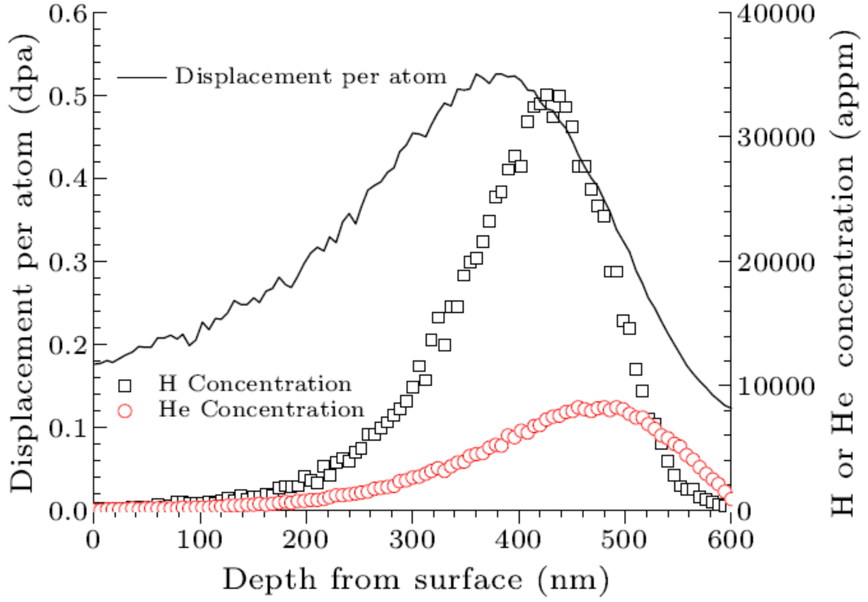
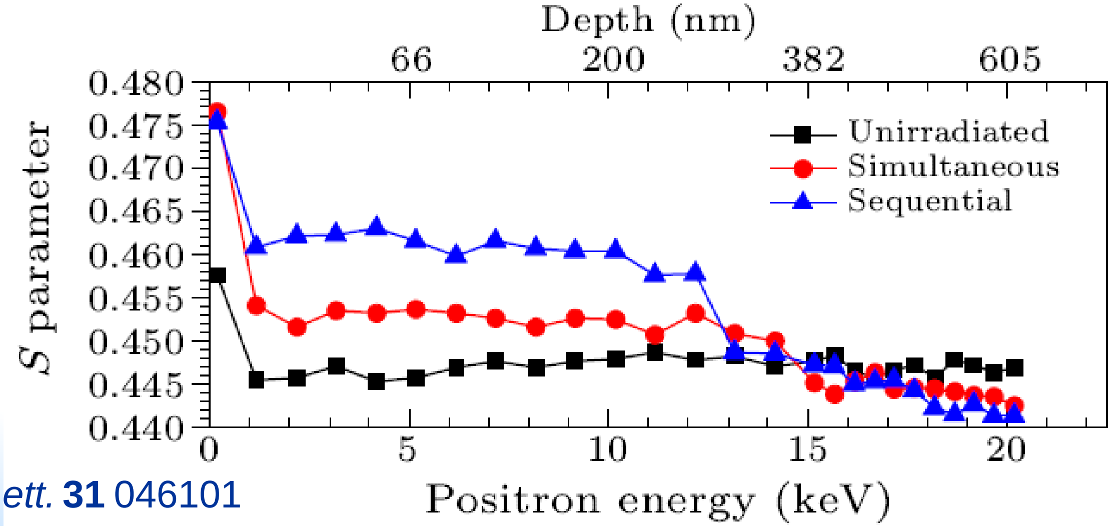


Fig. 3. Depth profiling of displacement for Au and concentrations for H and He.

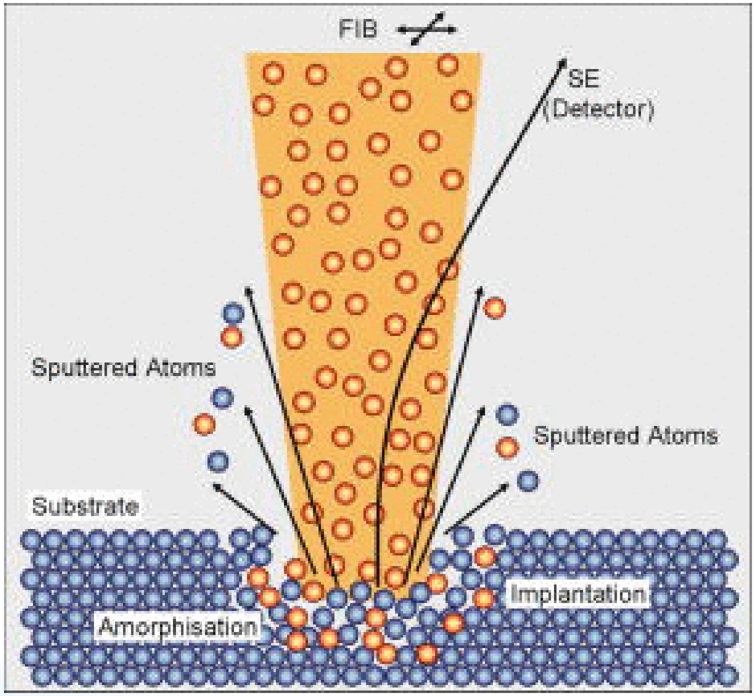
Above: dpa H, He, Au profile
Top right: dpa-Au, [H, He]
Right: PAS: unirradiated, simultaneous, sequential



Yuan Da-Qing *et al* 2014 *Chinese Phys. Lett.* **31** 046101

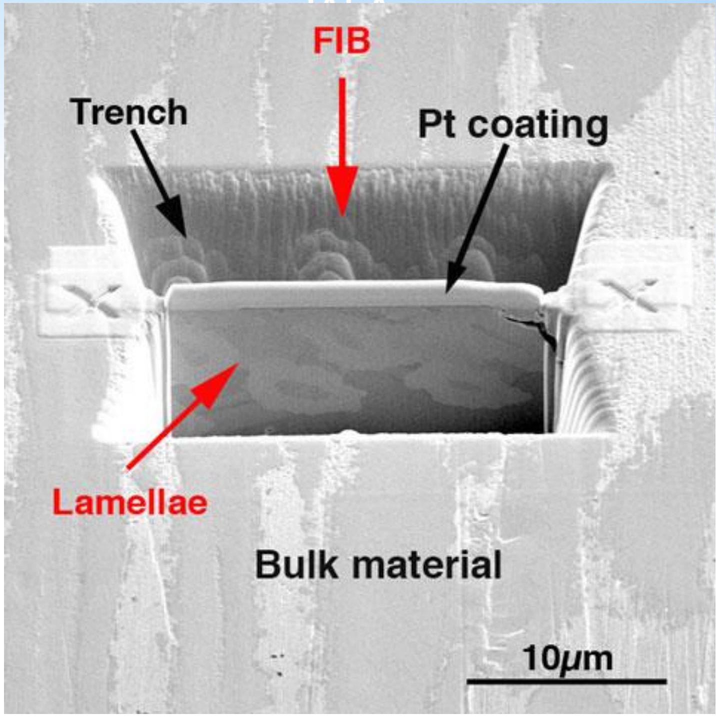
PIE: Focussed Ion Beam Milling

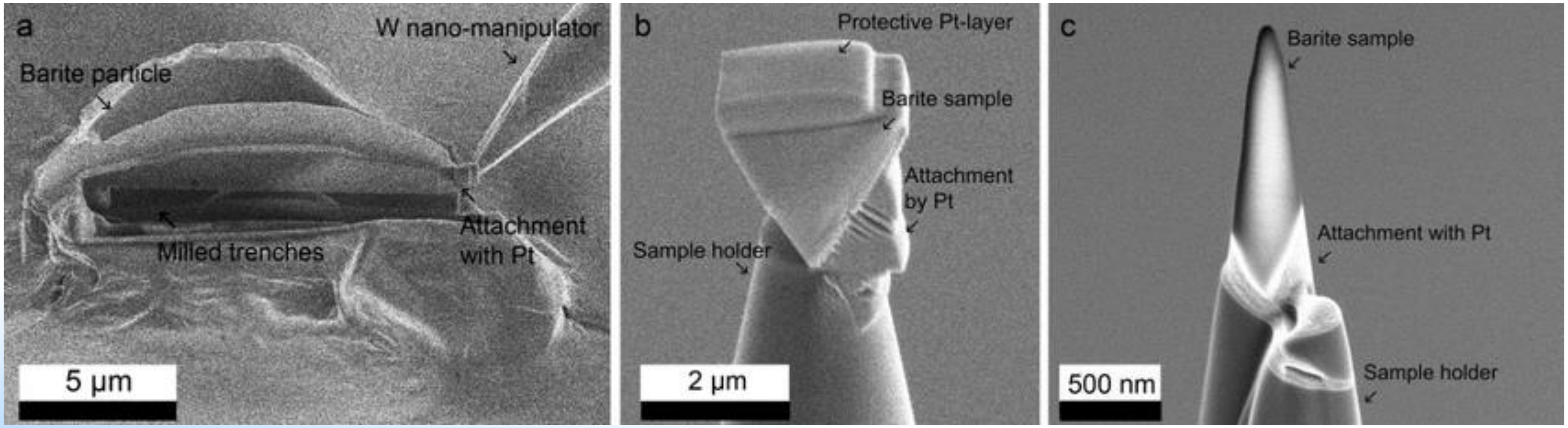
- Need to extract very thin sections from IB-irradiated materials.
- TEM foils can be cut using FIB cutting at the right depth



PIE

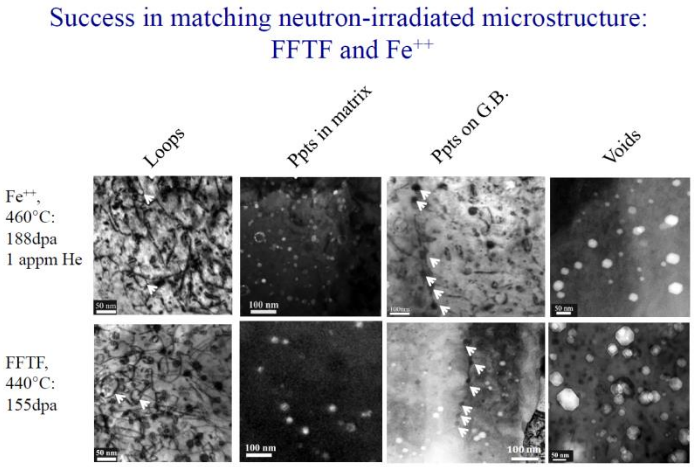
- Need to extract very thin sections from IB-irradiated materials.
- TEM foils can be cut using FIB cutting at the right depth





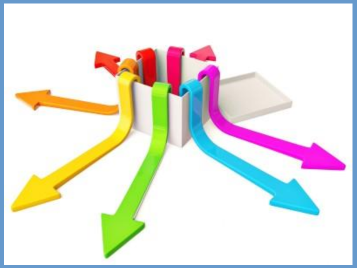
SMoRE-II Nutshell: Ion beam irradiation as a proxy for accelerated reactor testing

The idea is well known and long standing. But, very few well-controlled tests around.



Need Round Robin intercomparison under controlled testing of various parameters to determine best practices for (i) study of radiation damage (ii) reactor irradiation emulation

Success has been achieved, but is this a one-off or reproducible at multiple sites around the world?



For every selected material there is one distribution source

Every material is irradiated at multiple different sites around the world

For every selected PIE technique, there is one laboratory

Resume

- Electrostatic acceleration, ion source
- Interatomic potentials and particles
- Energy loss
- Bragg Peak, injected interstitials
- NRT-dpa; arc-dpa; vs. damage
- Advantages of ion beams
- H, He, dpa; simultaneous vs. alternating
- PIE and FIBbing.

IAEA

60 Years

Atoms for Peace and Development

Thank you!