Radiation Damage Calculations for the Rare Isotope Accelerator

Susana Reyes, Brian D. Wirth,[1] L. E. Ahle, W. Stein
and our RIA target area R&D collaborators

Lawrence Livermore National Laboratory
[1] University of California, Berkeley

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Presentation overview

- Motivation: need to address radiation damage of components in high power accelerator facilities such as RIA
- Overview: ion interactions with materials, radiation damage and a review of irradiation effects in Cu and Al
- Radiation damage simulations for RIA beam dump concepts
- ATLAS simulations and experiments
- Summary & suggested future directions

Introduction

- **In the context of high power accelerator facilities such as RIA, high priority is given to optimization of component lifetime, so as development of remote handling/maintenance systems required for radiation damaged and activated components**

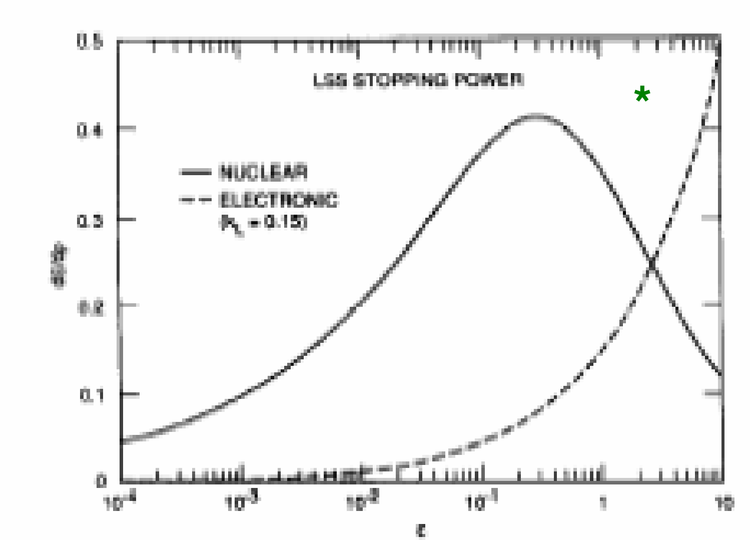
- **Radiation damage is a critical issue for those components with structural, electrical, and magnetic functions (i.e. target structures, beam dumps, beam windows, catchers, magnets, insulators and seals)**

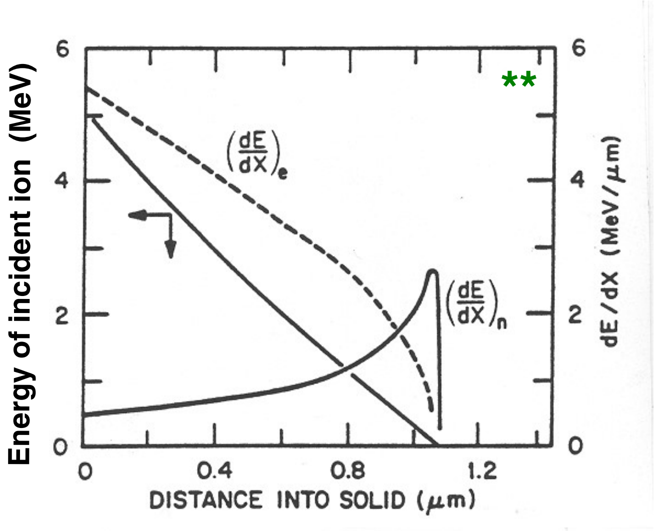
- **Experimental data and previous operating experience are extremely useful when available, however for next-generation facilities, simulations become essential to predict material behavior under irradiation**

Overview of ion interaction with materials

- **Energy loss (slowing down) of energetic ions in a solid is characterized by the linear energy transfer rate or stopping power, S(E) = dE/dx; commonly divided into energy lost in electronic excitation and through atomic collisions (nuclear interactions)**

$$S(E) = \frac{dE}{dx} = \left.\frac{dE}{dx}\right|_{elec} + \left.\frac{dE}{dx}\right|_{nuclear}$$





- **Except for large electronic energy loss rates (dE/dx|elec >~ 10keV/nm), this energy dissipates as heat with no lasting damage production**

* M.T. Robinson, *JNucMat* **216** (1994) 1.
** D.R. Olander, <u>Fundamental Aspects of Nuclear Reactor Fuel Elements.</u>

Overview of ion interaction with materials (cont)

- **Nuclear interactions, predominately as binary elastic collisions, produce permanent atomic displacements - in the form of vacancy + self-interstitial atom = Frenkel pair. The number of displacements depends on the kinetic energy transfer in the collision, T, the displacement energy, E_d, of the solid, and the particle flux, Φ**

$$\frac{dpa}{s} = \int_{E_d/\Lambda}^{\infty} \sigma_d(E)\phi(E)dE$$

$$\Lambda = \frac{4m_1m_2}{(m_1+m_2)^2}$$

$$\sigma_d(E) = \int_{E_d}^{\Lambda E} \sigma(E,T)\nu(T)dT$$

$$\nu(T) \equiv \#\ \text{of displacements produced by recoil of energy } T$$

$$= \xi(T,Z)\frac{T}{2E_d}$$

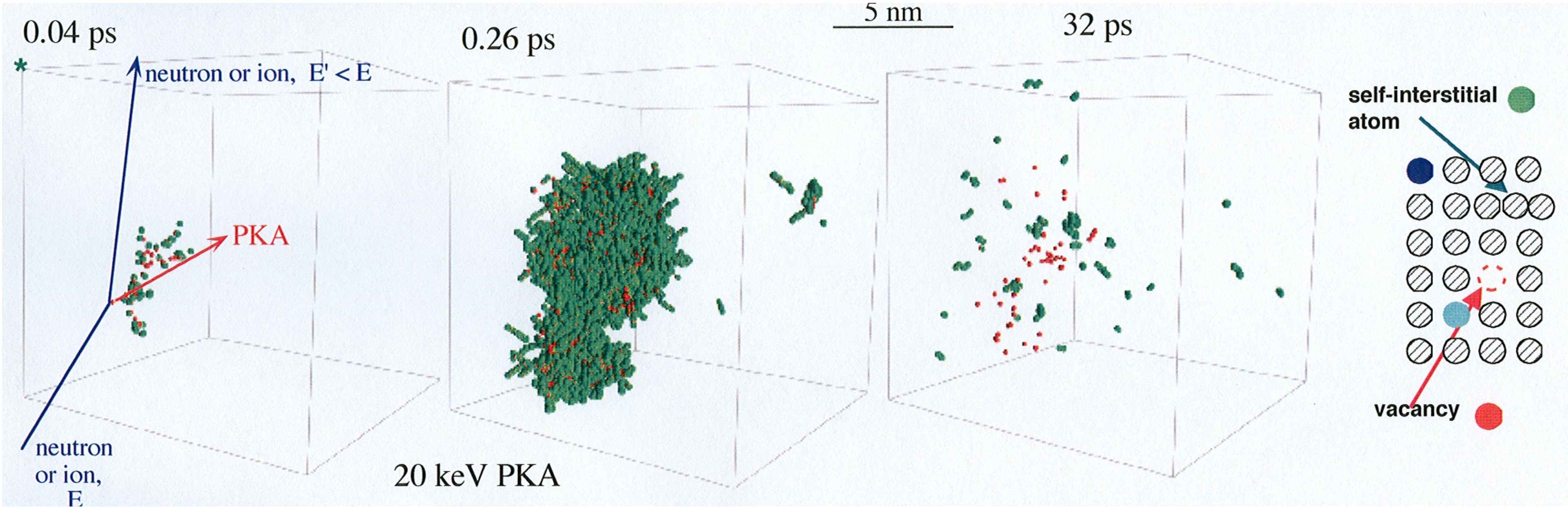
- **The high-energy particle transport codes, including SPECTER, PHITS & MARS, use these expressions to calculate displacements - accuracy depends on the differential scattering cross-sections and treatment of energy partitioning (ξ) between electronic & nuclear stopping**

* M.T. Robinson, *JNucMat* **216** (1994) 1.

** D.R. Olander, Fundamental Aspects of Nuclear Reactor Fuel Elements.

Radiation damage of materials

- Radiation damage is inititated by Frenkel pair production in collisional cascades



- Defect diffusion, clustering and solute enhanced diffusion, precipitation and segregation (in alloys) responsible for microstructural evolution

- Defect clusters and microstructural defects impede dislocation motion (increased strength and decreased ductility) and scatter phonons (increased electrical resistivity, decreased thermal conductivity)

* R.E. Stoller, personal communication.

Microstructure of irradiated Cu

- **Large number density of nanometer-sized defect clusters commonly observed in irradiated metals. In Cu, these defect clusters are predominately small (≈ 2.5 nm) stacking fault tetrahedra (SFT) and dislocation loops. Measurements of Cu irradiated at T≈100°C indicate saturation of defect cluster density with increasing fluence**

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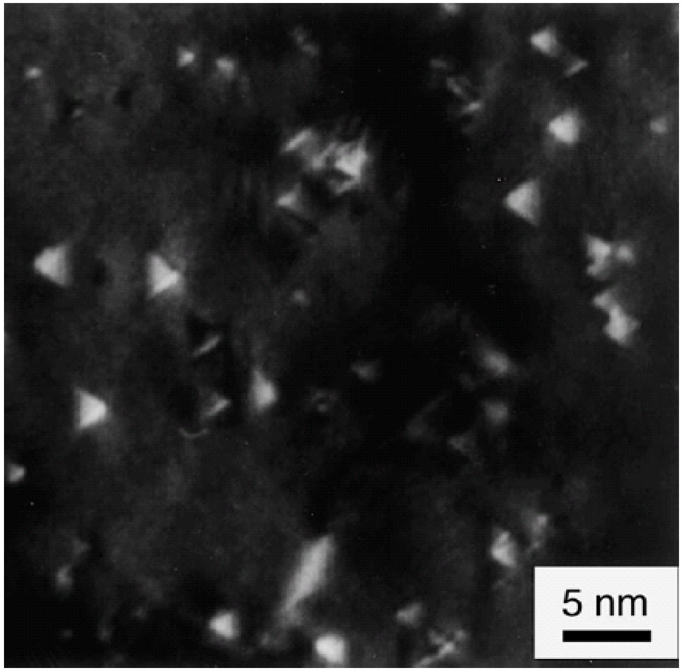

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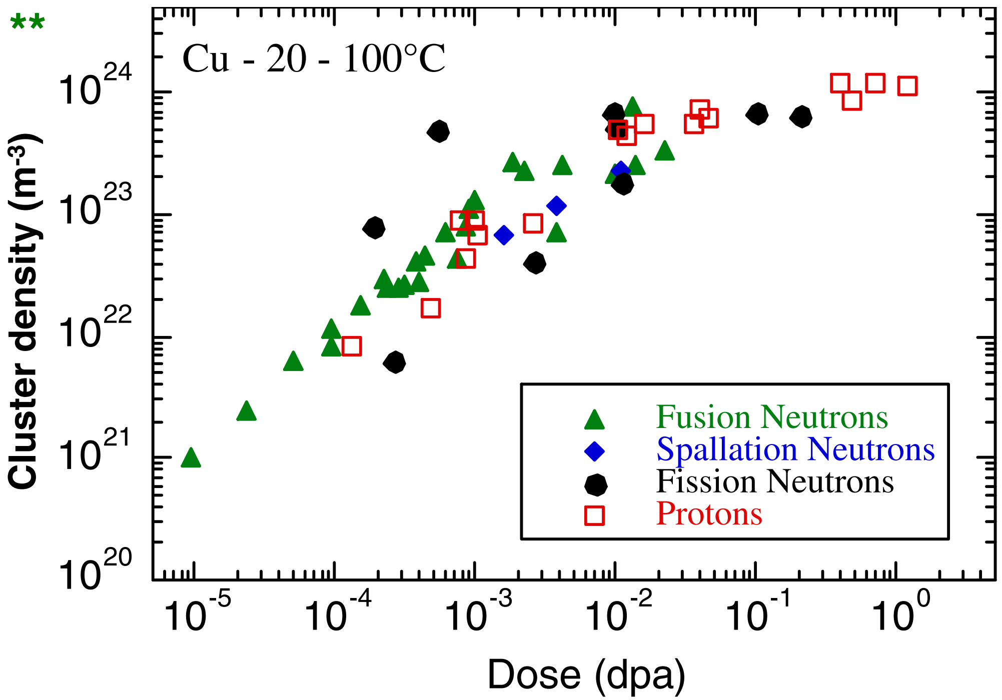
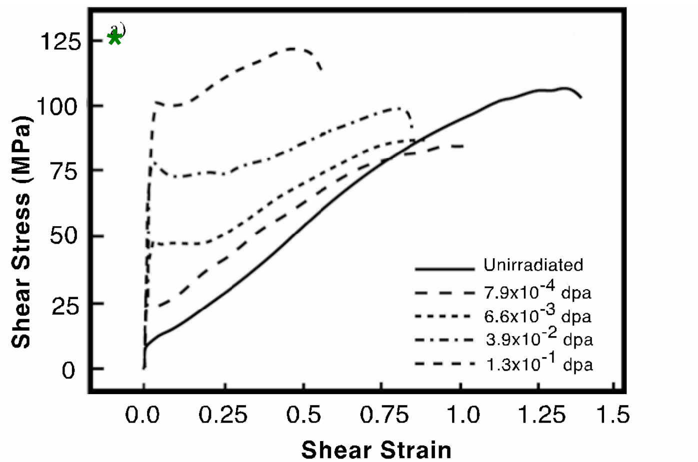


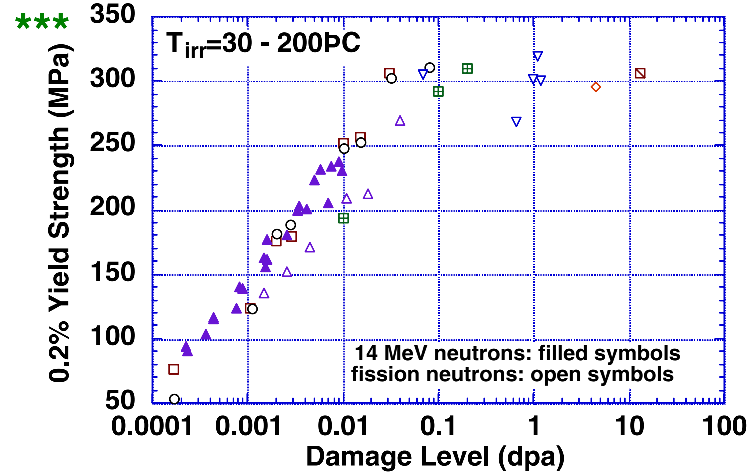
TEM observations of SFT cluster density indicate saturation of defect density by about 1 dpa

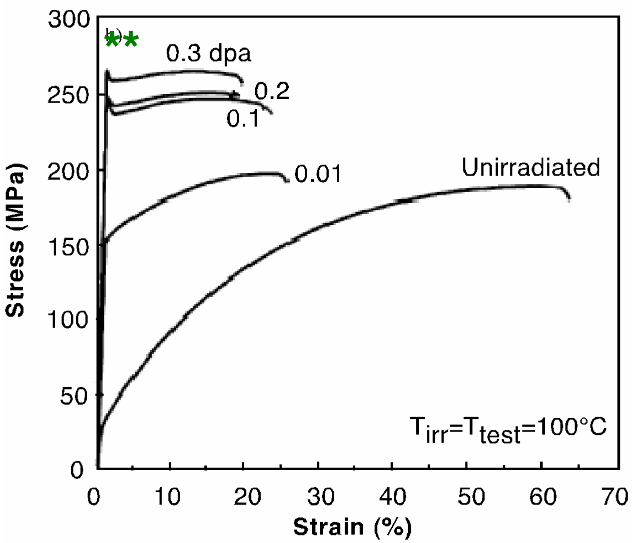
* R. Schaublin et al, *Journal of Nuclear Materials*, **276** (2000) 251. ** S.J. Zinkle, and Y.Dai and M. Victoria, personal communication.,

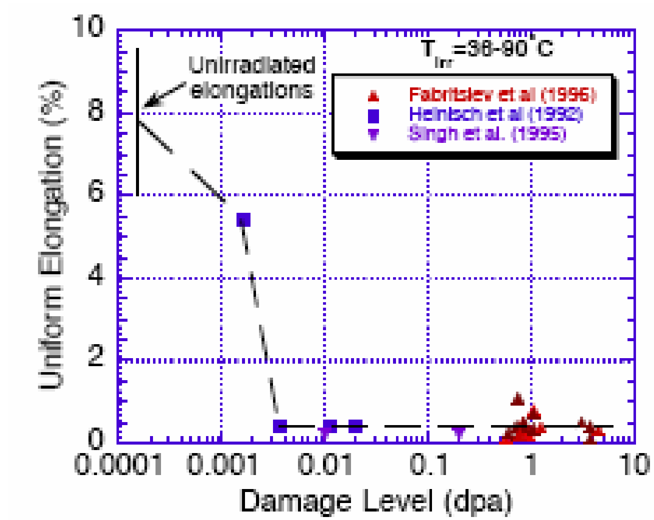
Mechanical behavior of irradiated Cu ($T_{irr} \approx 100°C$)

- **Radiation-induced defect clusters serve as obstacles to dislocation motion, thereby strengthening the material, but also decrease strain to failure in tensile test**







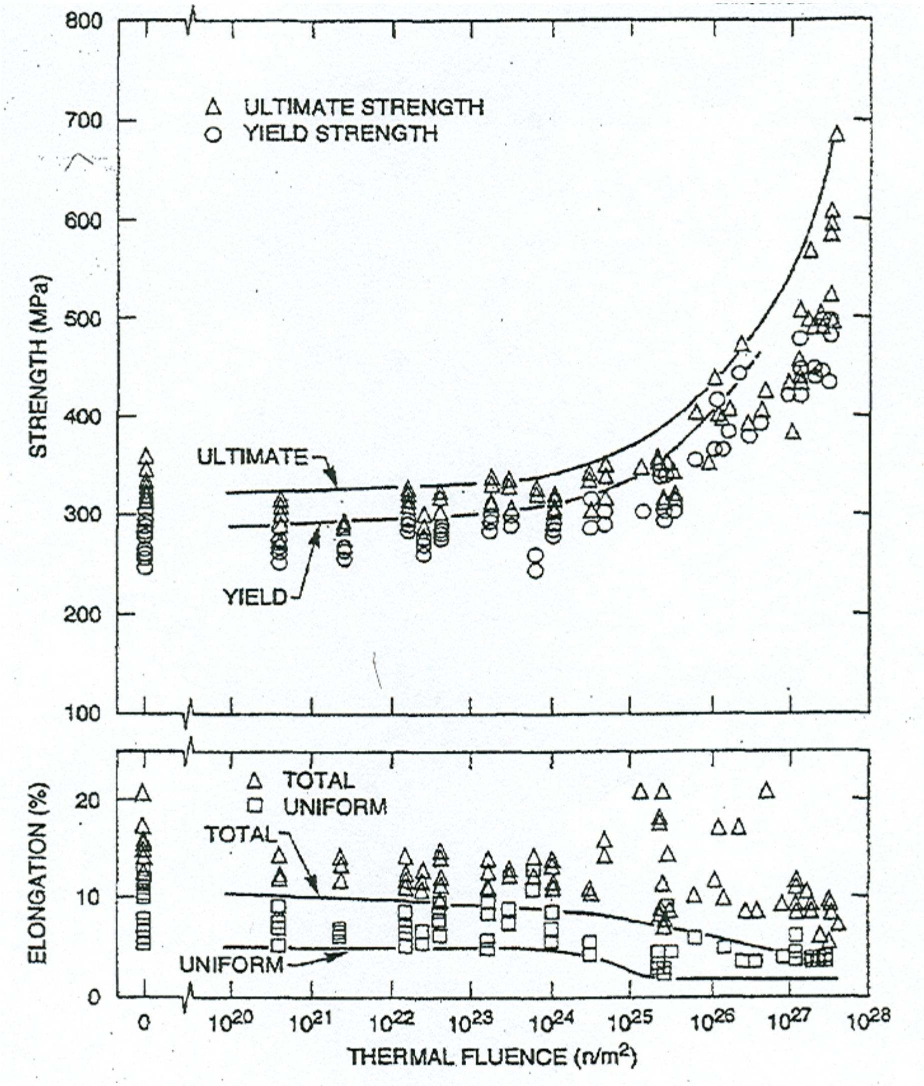


* Y. Dai, et al., *J. Nucl. Mat.*, **212-215** (1994) 393.,

** B.N. Singh, D.J. Edwards, and P. Toft, *J Nucl Mat*, **299** (2001) 205, *** S.J. Zinkle, personal communication.

Mechanical behavior of irradiated Al ($T_{irr} \approx 100°C$)*

- **Similar effects observed in pure Al and aluminum alloys. While the total elongation (ductility) approaches saturation, the strength does not.**



* K. Farrell, ORNL-TM-99/208.

Swift Heavy Ion effects

- **Numerous studies* have shown strong effects on damage production (# defects produced and defected microstructure) by *Swift Heavy Ion* (SHI) irradiation when $(dE/dx)_{elec}$ >≈ 10 keV/nm.**
  - **Effects vary from damage annealing (reduced defect densities) at lower $(dE/dx)_{elec}$ to additional damage creation and more rapid radiation enhanced precipitation kinetics at higher $(dE/dx)_{elec}$.**

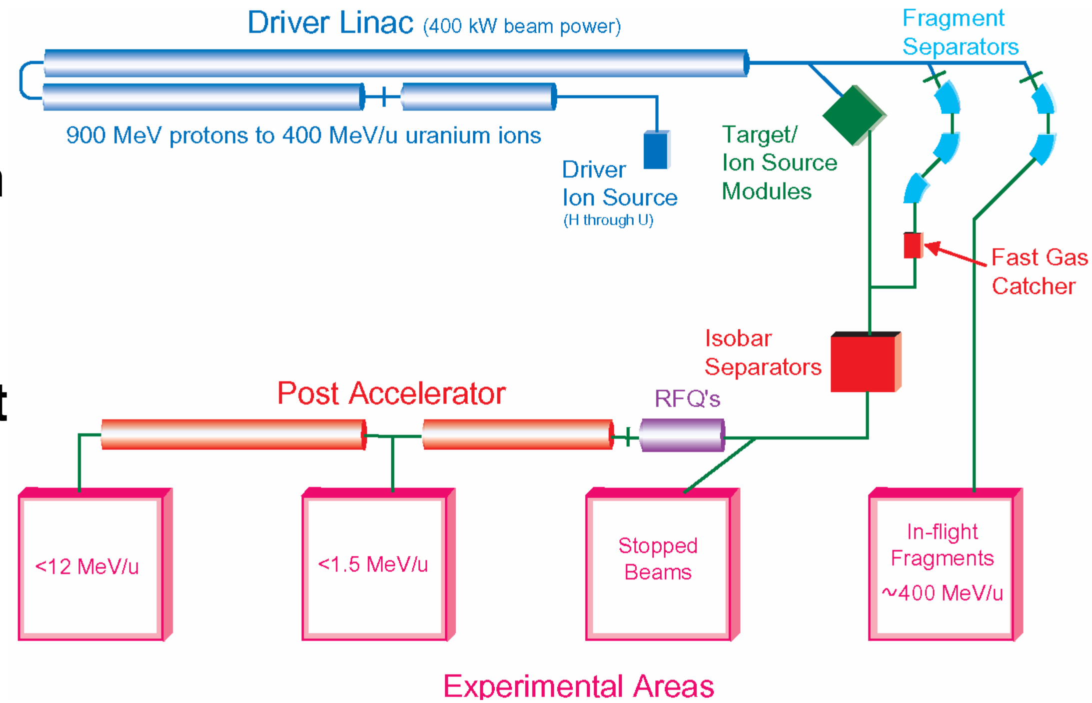
- **Detailed SHI mechanisms are not well established. Two main models:**
  - ***Thermal spike model*: excited electrons rapidly transfer energy to phonons. Very large energy (heat) deposition leading to localized melting & rapid cooling → high defect densities or amorphization.**
  - ***Coulomb explosion model:* large positive space charge resulting from electronic excitation leads to strong atomic repulsion, atomic displacements and a cylindrical shock wave.**

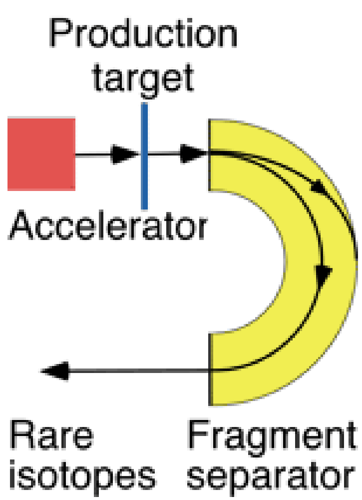
- **Experimental irradiations with high-energy U ions needed to resolve SHI concerns.**

* e.g., A. Dunlop, D. Lesueur, and A. Barbu, *J. Nucl. Mat.* **205** (1993) 426., A. Dunlop et al., *Nuc. Inst. Meth. B.* **90** (1994) 330., H. Dammak et al., *Phys Rev Let* 74 (1995) 1135., Z.G. Wang et al., *Nuc. Inst. Meth. B.* **115** (1996) 577.

RIA overview

- **RIA is the next-generation national user facility for basic and applied research with radioactive beams**
- **RIA will have one or more fragmentation stations that will accept up to 400 kW beams of heavy ions**

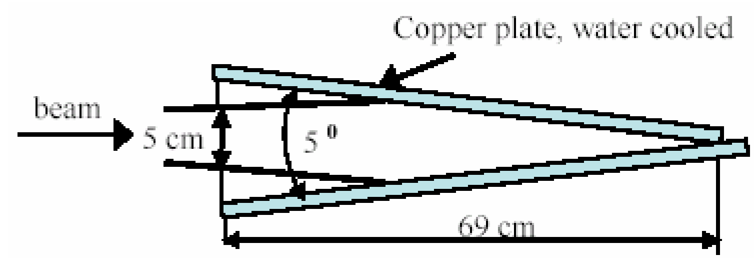




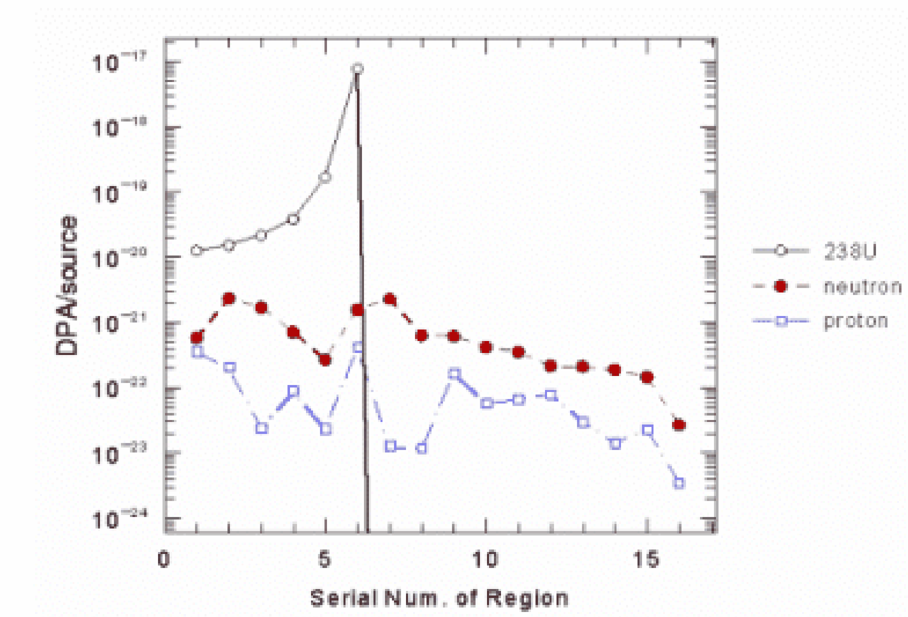
- **Designing a fragmentation beam dump for RIA is a critical challenge:**
  - must be compact to reduce optical aberrations
  - must survive deposition of hundreds kWs of power
  - mechanically simple to facilitate remote handling
  - must survive radiation damage by primary beam

Simulations for RIA beam dump

- **Developed static water-cooled wedge-shaped beam dump for a 320 MeV/A U beam at 400 pnA/cm², 5 cm² spot**

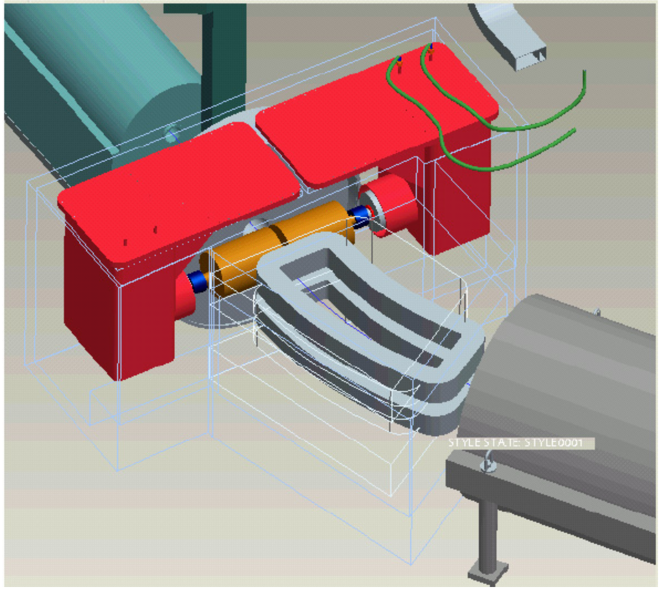


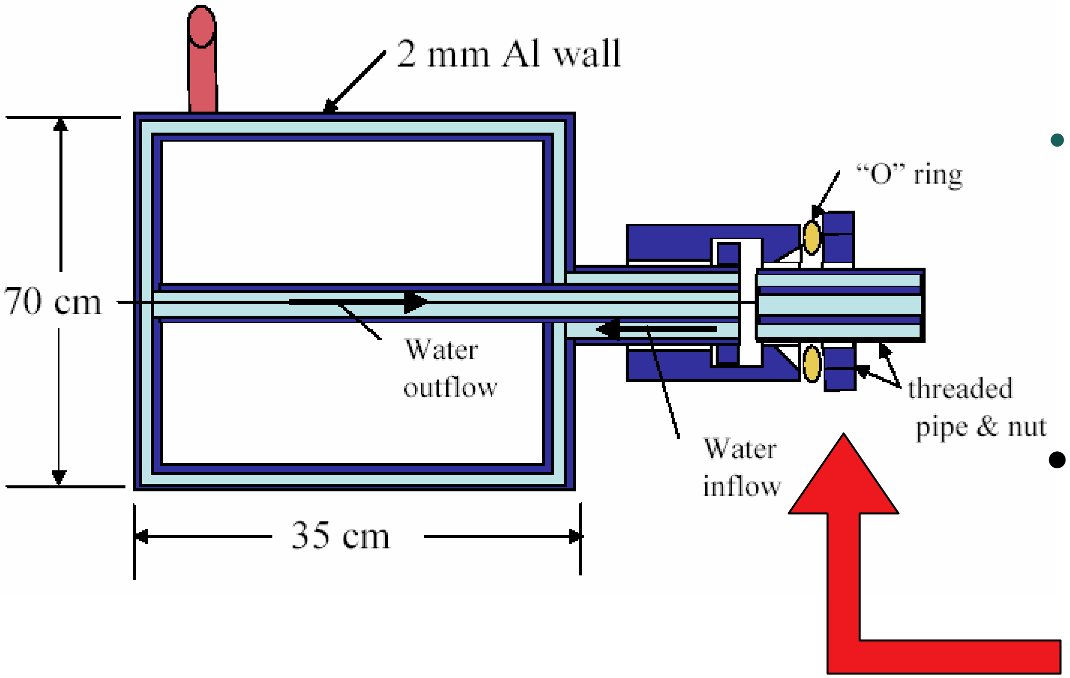
- **Beam sputtering was shown not to be significant**
- **However, radiation damage predictions using PHITS transport code indicated very high levels of DPA and gas transmutants in copper:**
  - maximum DPA ~25 DPA per full power day
  - several hundreds appm H and He gas transmutants
  - **effects of SHI irradiation and relationship between DPA and properties degradation needs to be addressed**



Advanced beam dump design

- **To mitigate radiation damage, rotating beam dump concepts are being considered**
- **In particular, a rotating barrel-shaped dump has been designed capable of withstanding a 1cm-diameter beam spot**

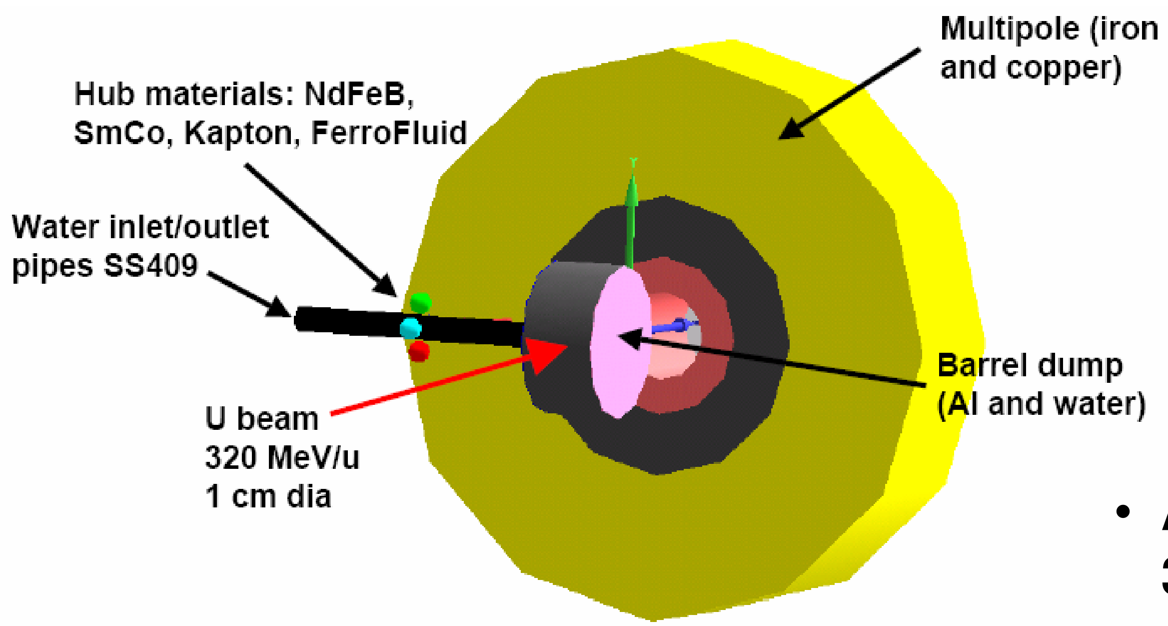




- **U beam slows down in cooling water, avoiding high DPA values in structural material**
- **Lifetime increases significantly, however more complex design (i.e. rotating vacuum seal)**

PHITS simulations for rotating beam dump

- **The heavy ion transport code PHITS to simulate particle transport in pre-separator area**
- **Model includes barrel beam dump, steel water inlet/outlet pipes, rotating vacuum seal with representative materials, and downstream multipole magnet**



- **Assumed operation with a 320 MeV U beam with 1 cm-diameter spot size at a current of 3×10^{13} pps**

PHITS results

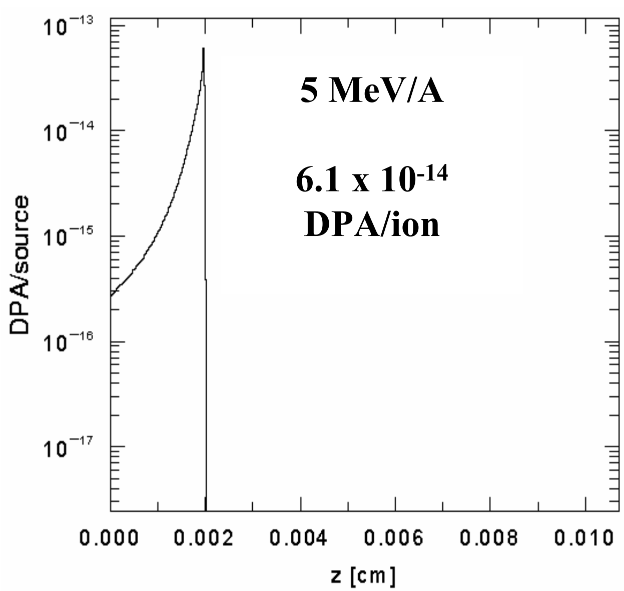
Material	Density (g/cc)	Effective dose (MGy/yr*)	Dose limit (MGy)	DPA/yr*
NdFeB	6	0.29	0.1	4.5E-06
SmCo	8.82	0.15	100	5.9E-06
Kapton	1.42	0.74	10	7.6E-07
FerroFluid	1.42	1.08	>1?	7.1E-07

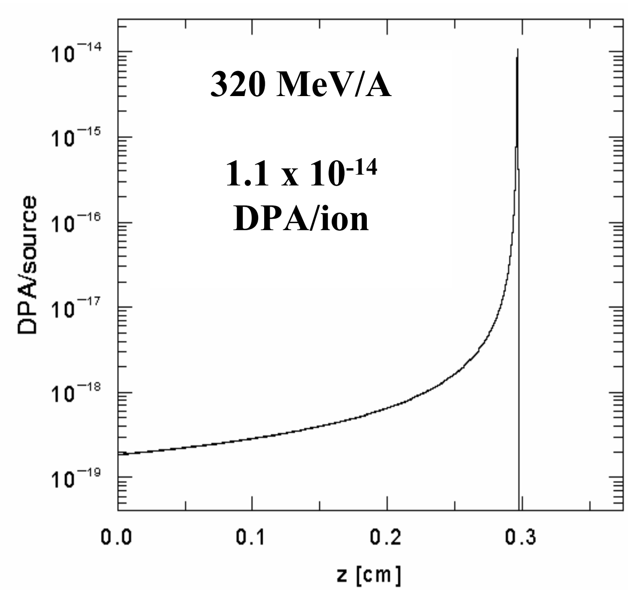
*Assumed that fragmentation line is operating at full power for one-third of the calendar year

- **DPA in the rotating seal materials found to be negligible**
- **Maximum DPA rate in the Al barrel ~0.03 DPA/yr (most of the primary beam stops in water); maximum DPA in multipole ~5x10^{-4} DPA/yr**
- **Gas production in Al barrel is not an issue**
- **However, with expected large electronic energy loss rates (dE/dx|elec >~ 10keV/nm), SHI effects still need to de addressed**

ATLAS Experiments

- **Results from PHITS show DPA unacceptable for static beam dump, but allowable for the rotating beam dump case**
- **Some issues still not addressed by PHITS simulations:**
  - **What is the impact of SHI effects?**
  - **How does DPA value translate into effects on material properties?**
- **Recent experimental campaign at ATLAS (6 MeV/A) to help find these answers (see J. Nolen's presentation)**





Summary

- **High-energy particle irradiation of Cu at low (≈ 100°C) temperatures, produces significant radiation damage, with yield stress increases of ≈ 300 MPa, uniform elongations < 1% and thermal k decreases of 5 - 10%**
- **Radiation effects in Cu saturate at doses of ≈ 1 dpa (*limited high-dose (>10 dpa) data, behavior may change with high gas levels)***
- **Preliminary analyses show high DPA levels in RIA Cu beam dump: experimental data under RIA conditions is needed**
- **A rotating beam dump design has been proposed that mitigates the problem of radiation damage from static design**
- **However, concerns specifically related to the RIA irradiation environment require additional research:**
  - **benchmarking of PHITS simulations with experiments/models**
  - ***swift heavy ion (SHI) irradiation effects***
  - **underestimates of radiation doses due to limited cross-section data for high-energy electronic losses, nuclear scattering and inelastic collision processes**