Accessing the High Damage Regime with Ion Irradiation in the SNAP Program

Kevin G. Field[1], Fei Gao[2], Todd R. Allen[3], Emmanuelle Marquis[4], Zhijie Jiao[5], Gary Was[6*], Brian Wirth[7], Steve Zinkle[8], & Arthur Motta[9]

[1-6] University of Michigan – Ann Arbor
[7-8] University of Tennessee – Knoxville
[9] Pennsylvania State University
*Corresponding author: gsw@umich.edu

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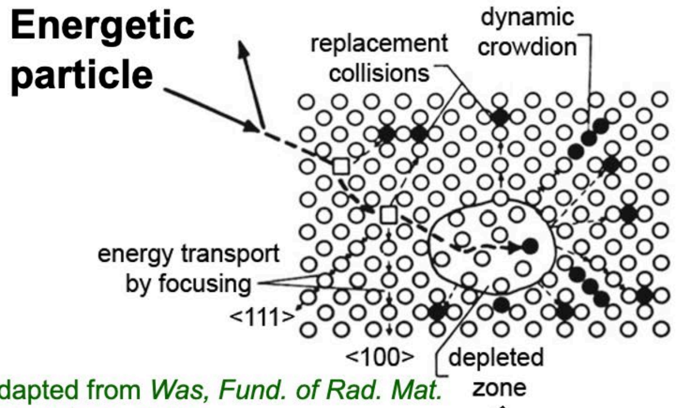
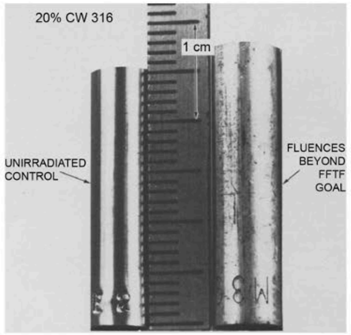
SNAP Simulating Neutrons with Accelerated Particles

High dose, fast reactor irradiation of structural materials can cause dimensional changes (e.g., swelling)



Adapted from *Was, Fund. of Rad. Mat. Sci.*, *2nd ed., 2017.*

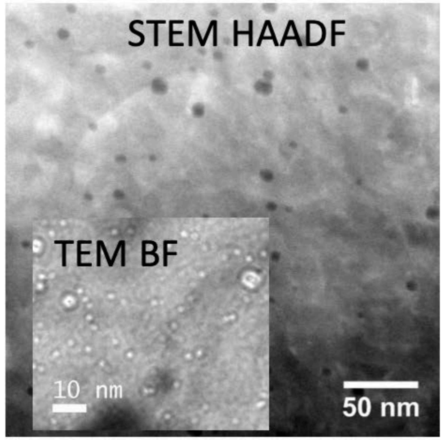


Straalsund, J.L., et.al., J. Nucl. Mater. 1982.

Swelling arises from non equal partitioning of vacancies and self-interstitials to extended defects and can be correlated to cavity (void) distribution

$$\frac{\Delta V}{V} = \frac{4}{3}\pi R^3 N$$

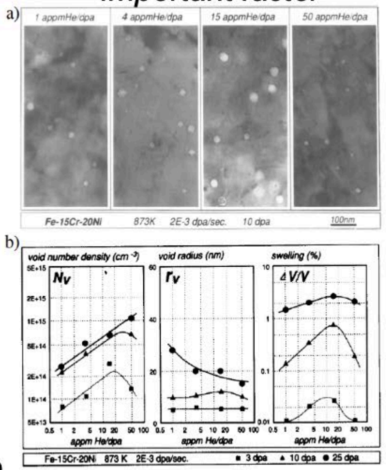
Cavities can be stabilized by helium gas atoms



T91 irradiated to 17 dpa at 376°C in BOR-60

Z. Jiao, et.al., J. Nucl. Mater. 2018

He/dpa ratio is an important factor



Katoh, et.al., J. Nucl. Mater. 1993

Complexity of radiation effects precludes empirical approach of trial and error → focus on scientifically driven investigation combining experiment & modeling

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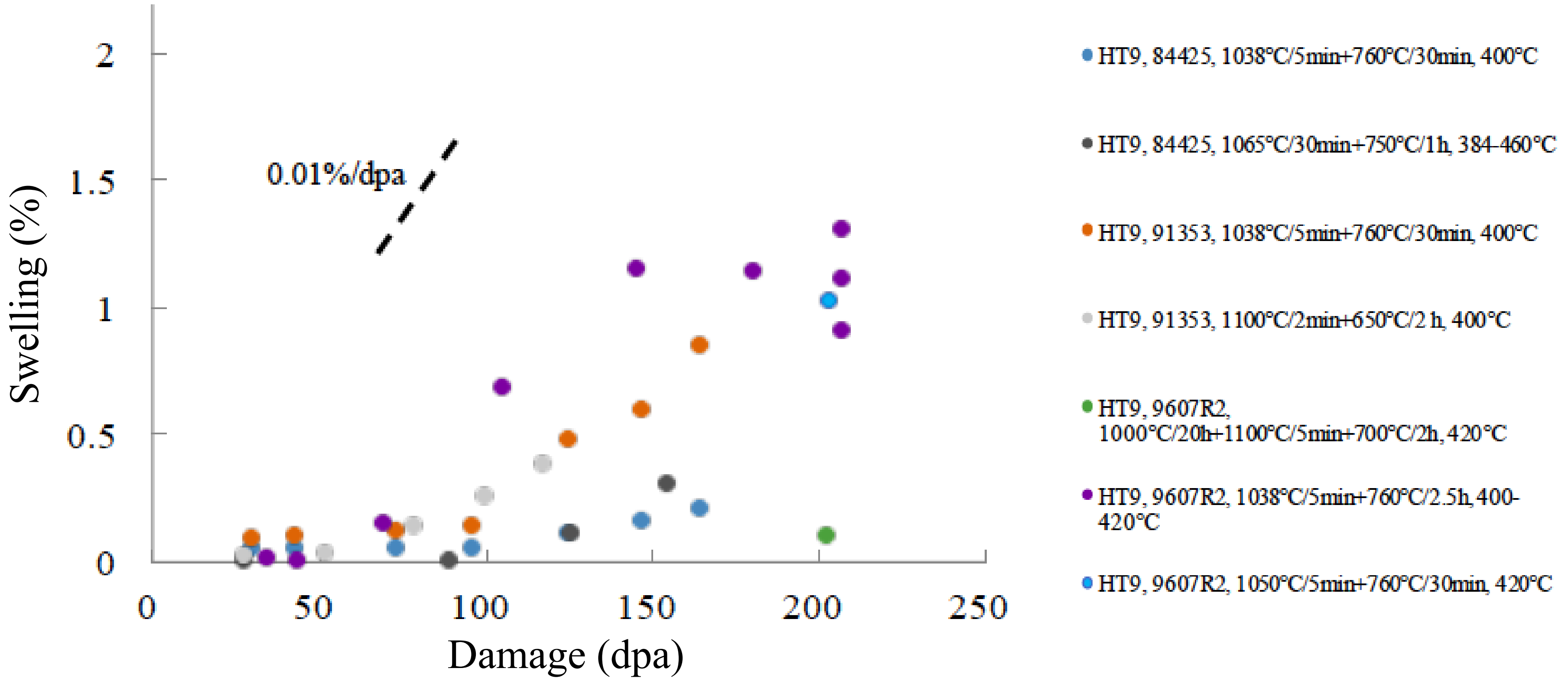
Literature data for high-dose radiation effects is commonly restricted to below 200 dpa, with most below 50 dpa



[1] D. Gelles, J. Nucl. Mater. 237 (1996) 293.
[2] M.B. Toloczko, F.A. Garner, C.R. Eiholzer, J. Nucl. Mater. 215 (1994) 604.
[3] M.B. Toloczko, F.A. Garner, Journal 237 (1996) 289.
[4] M.B. Toloczko, F.A. Garner, Eff. Radiat. Mater. ASTM STP 1325 (1999).
[5] B.H. Sencer, J.R. Kennedy, J.I. Cole, S.A. Maloy, F.A. Garner, J. Nucl. Mater. 393 (2009) 235.
[6] J.J. Kai, R.L. Klueh, J. Nucl. Mater. 230 (1996) 116.
[7] J. Van Den Bosch, O. Anderoglu, R. Dickerson, M. Hartl, P. Dickerson, J.A. Aguiar, P. Hosemann, M.B. Toloczko, S. A. Maloy, J. Nucl. Mater. 440 (2013) 91.

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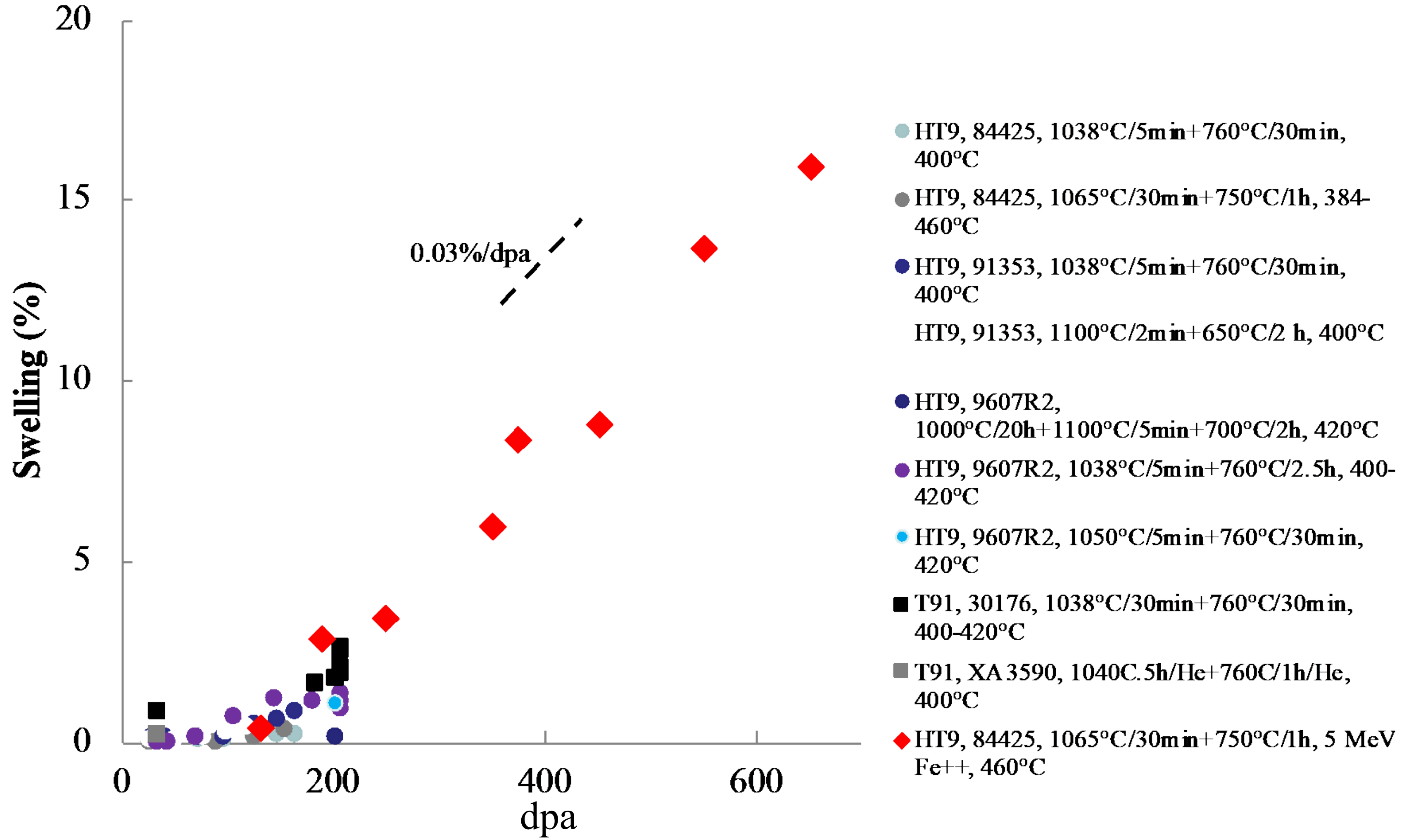
Our understanding of high dose (>50 – 100 dpa) can be extended by the use of high flux ion beams…



Getto et al., JNM 480 (2916) 159

…But, the acceleration effect must be understood

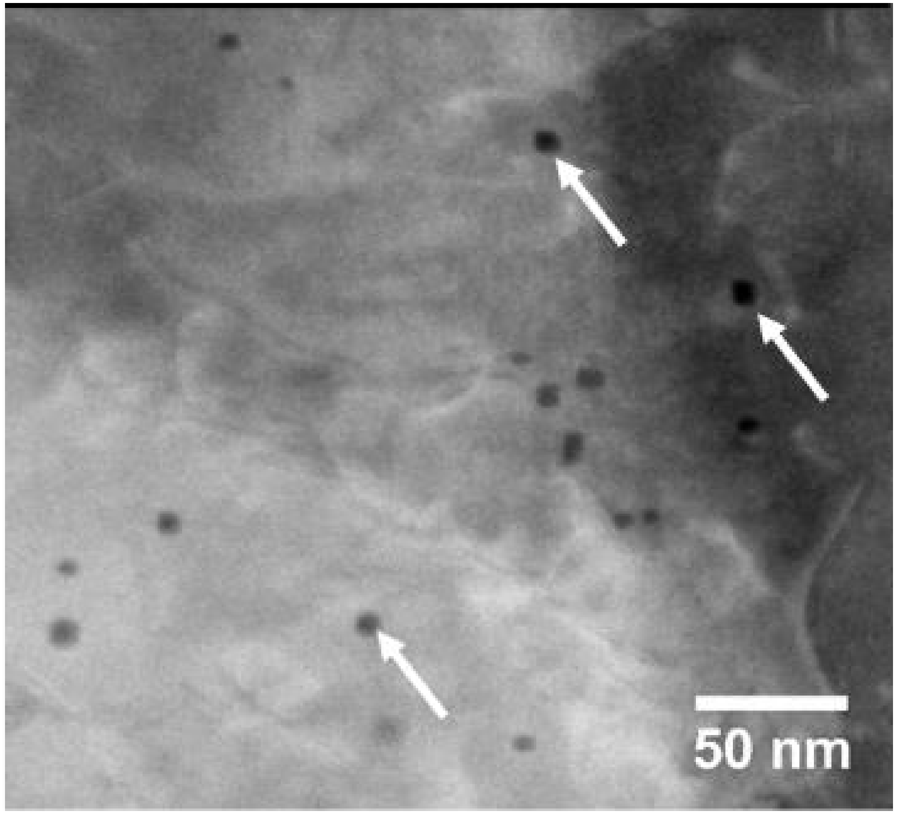
Understanding the acceleration effect at face value is akin to baking

Understanding the acceleration effect at face value is akin to baking

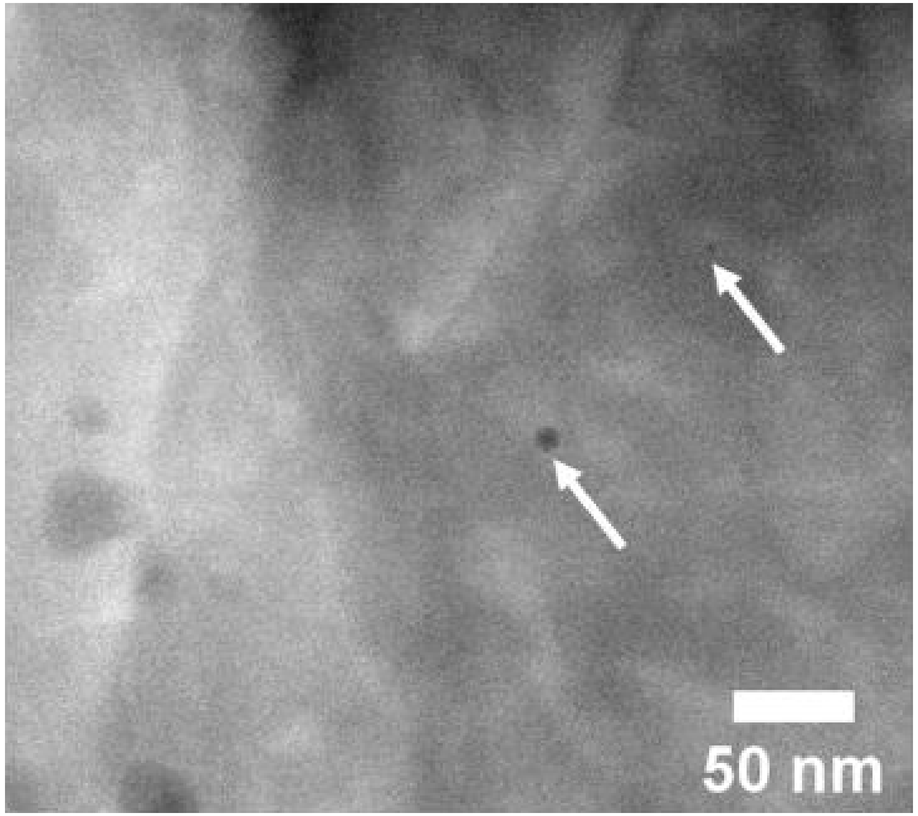
…but, it's not so simple

Traditional approach, Mansur shift, DT=120°C ***does not*** replicate microstructure

BOR-60



DI = BOR-60 + 120°C



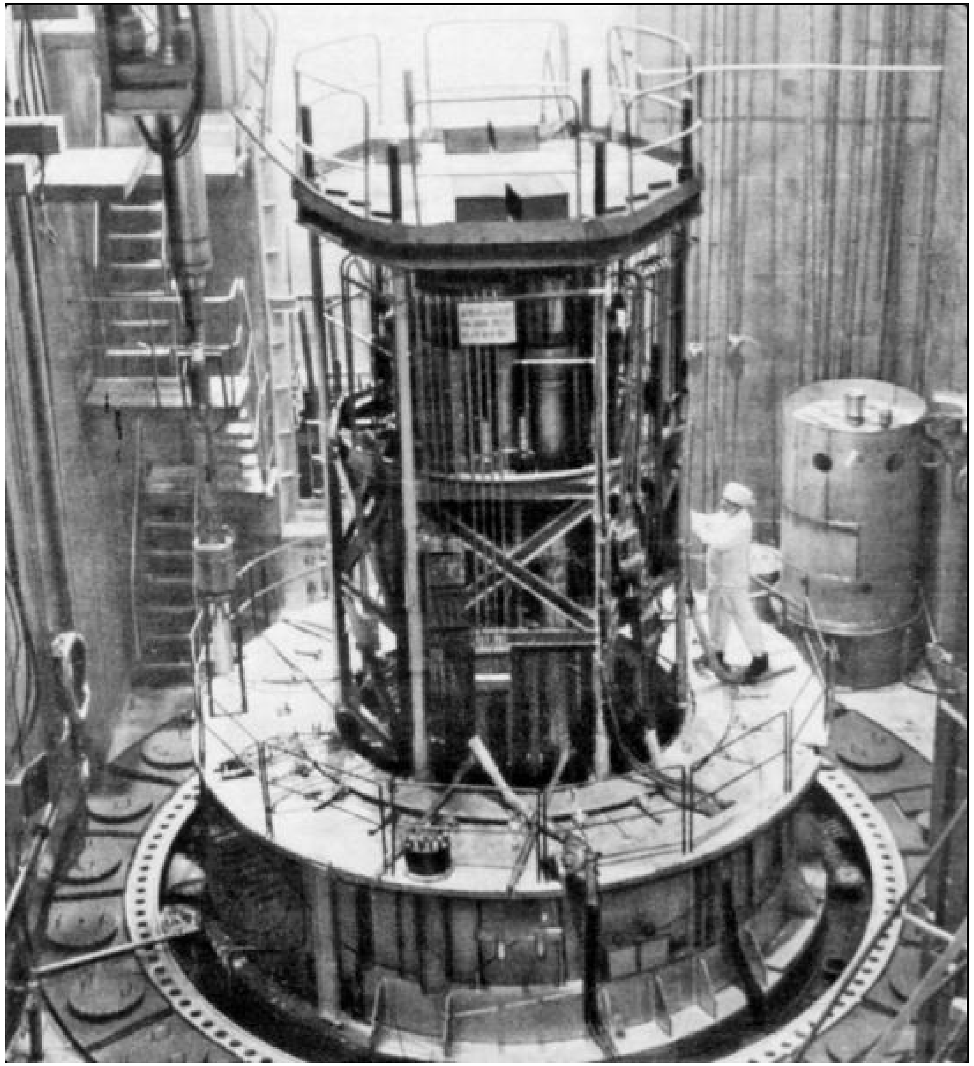
Objective

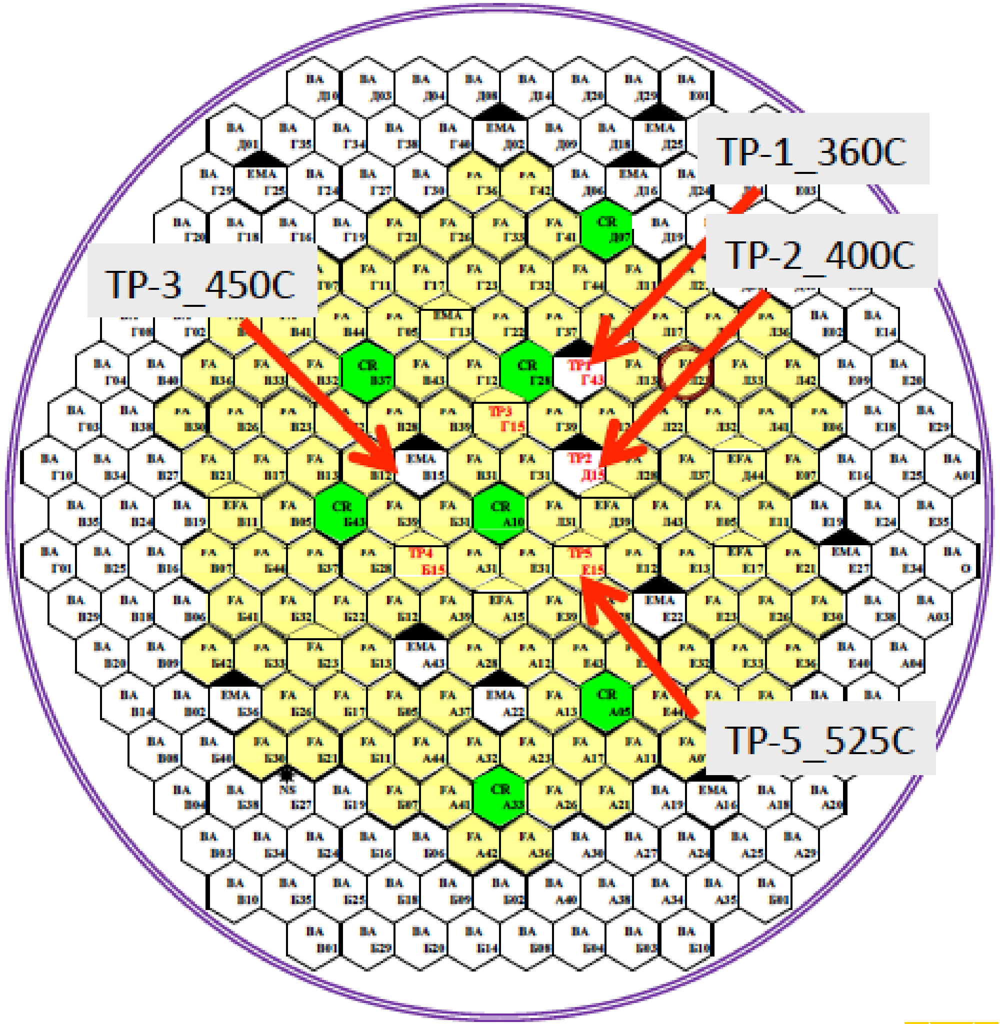
Identify the underlying processes governing cavity nucleation and early-stage growth to replicate and predict the cavity microstructure of neutron irradiated complex steels with dual ion irradiation.

Impacts of reaching the objective:

- Reduction in reliance on test reactors for data at high dpa
- Disruptive leap in speed (1000x) of assessing radiation effects, allowing rapid development of radiation resistant materials
- Reduction in cost by up to 1000x, providing resources for complementary programs
- Accelerating the licensing process

Our “reference” reactor is the BOR-60 fast reactor





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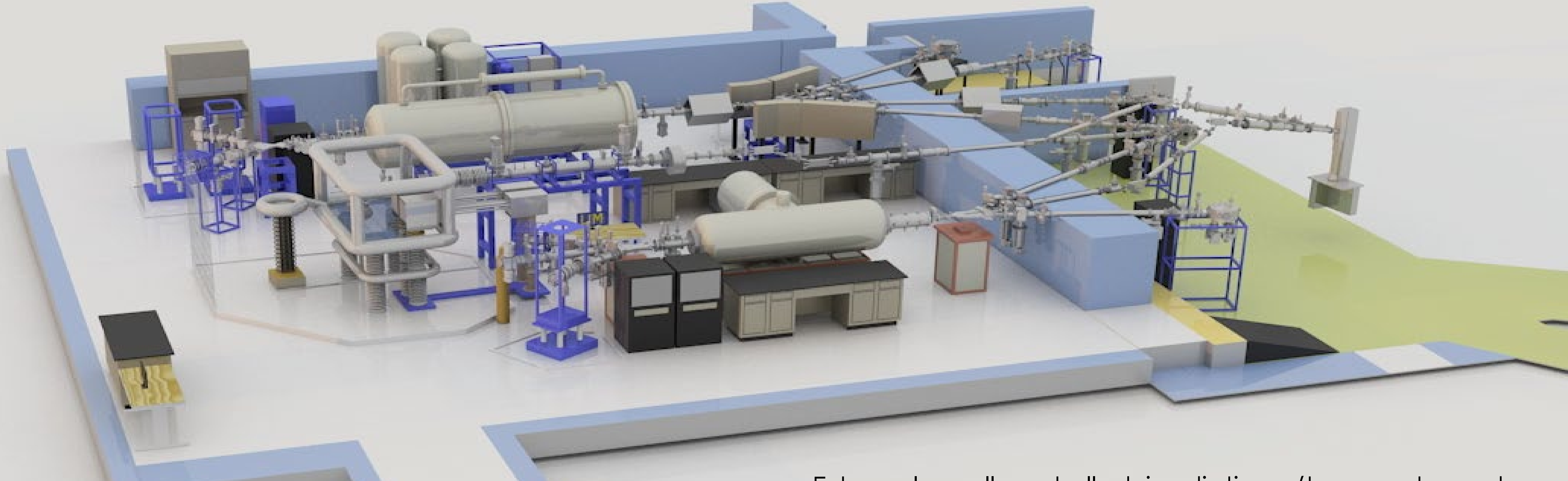
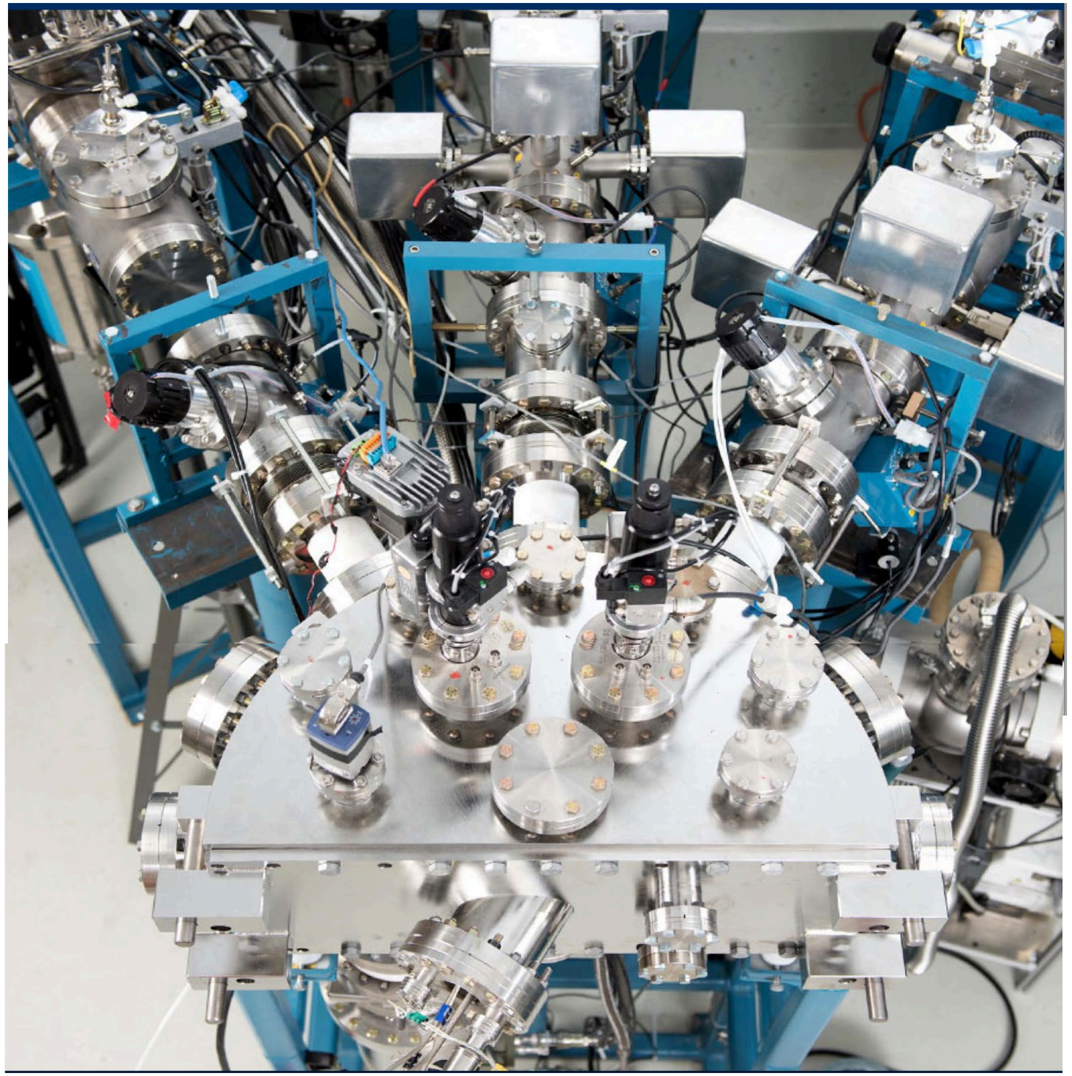
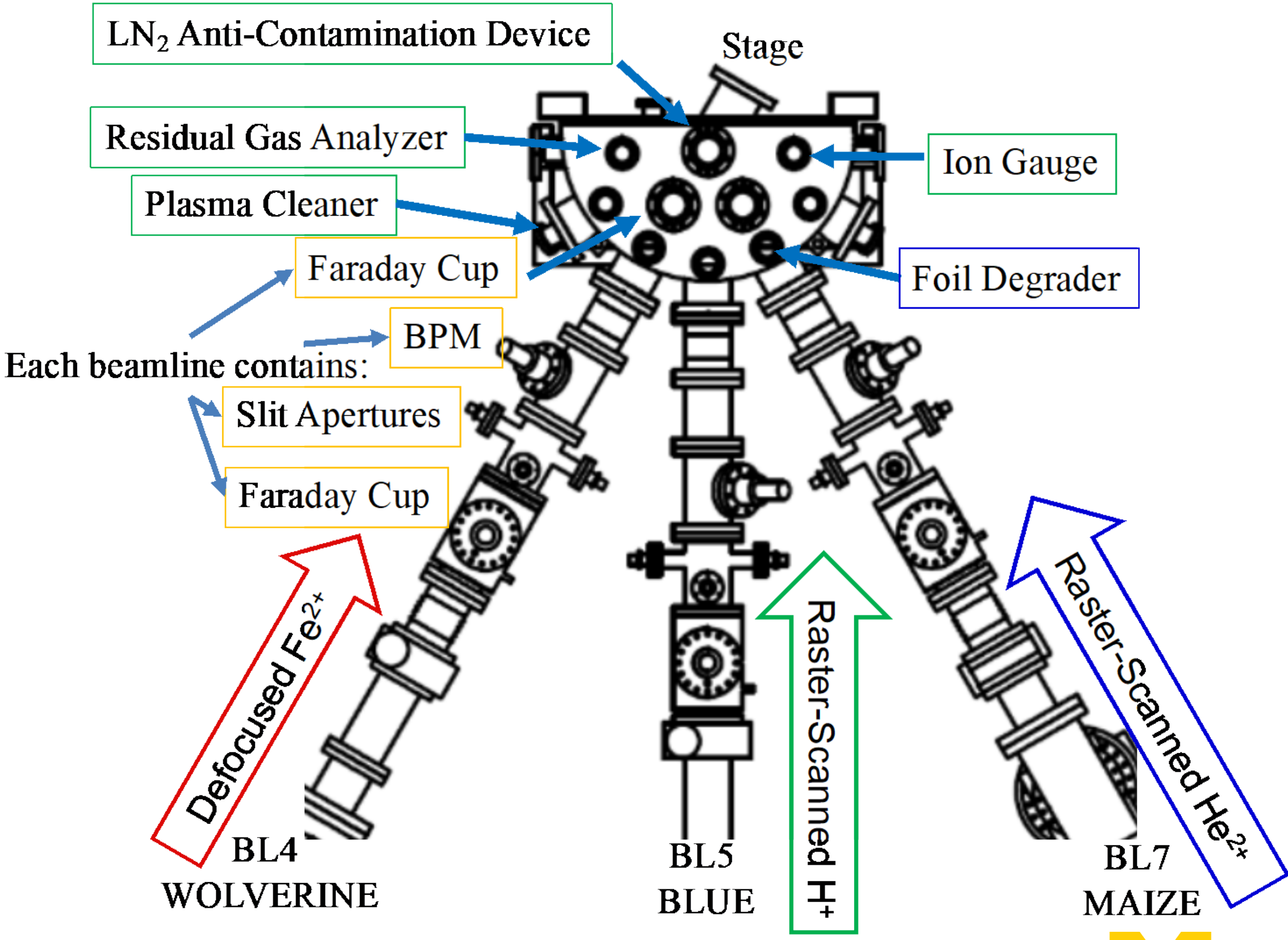
Our acceleration method is achieved using the Michigan Ion Beam Laboratory



- Extremely well-controlled irradiations (temperature, dose, dose rate)
- High doses are easily achievable
  - 1 dpa/day for protons
  - 100 dpa/day for self-ions
- Dual/Triple beam capability – to account for transmutation product
- Low sample activation
- Cheap

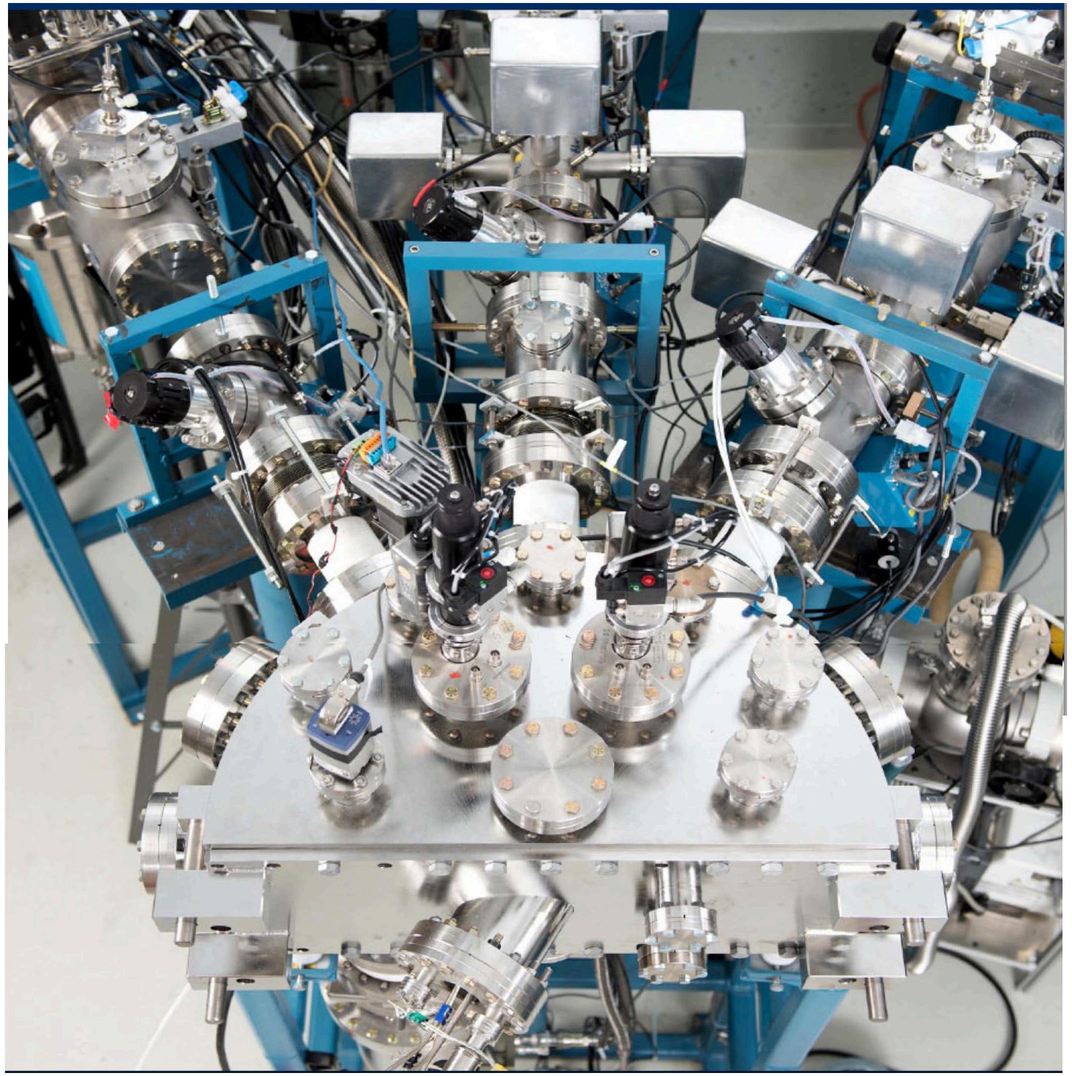
Critical to simulating neutrons using ions is the capacity for single, dual, and triple beam ion irradiations

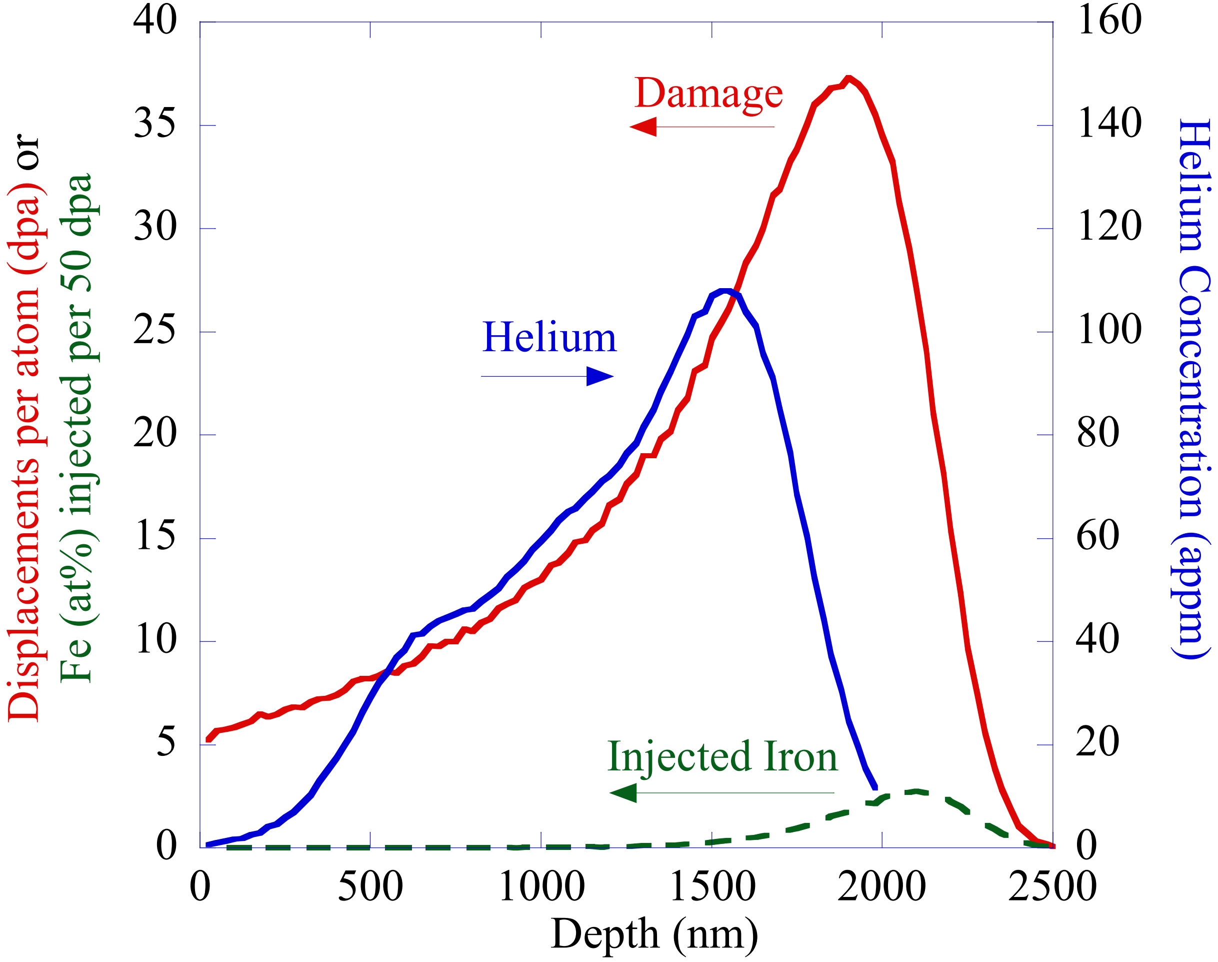




The Michigan Muli-beam Chamber (MBC) for fast reactor materials development

Critical to simulating neutrons using ions is the capacity for single, dual, and triple beam ion irradiations





The Michigan Muli-beam Chamber (MBC) for fast reactor materials development

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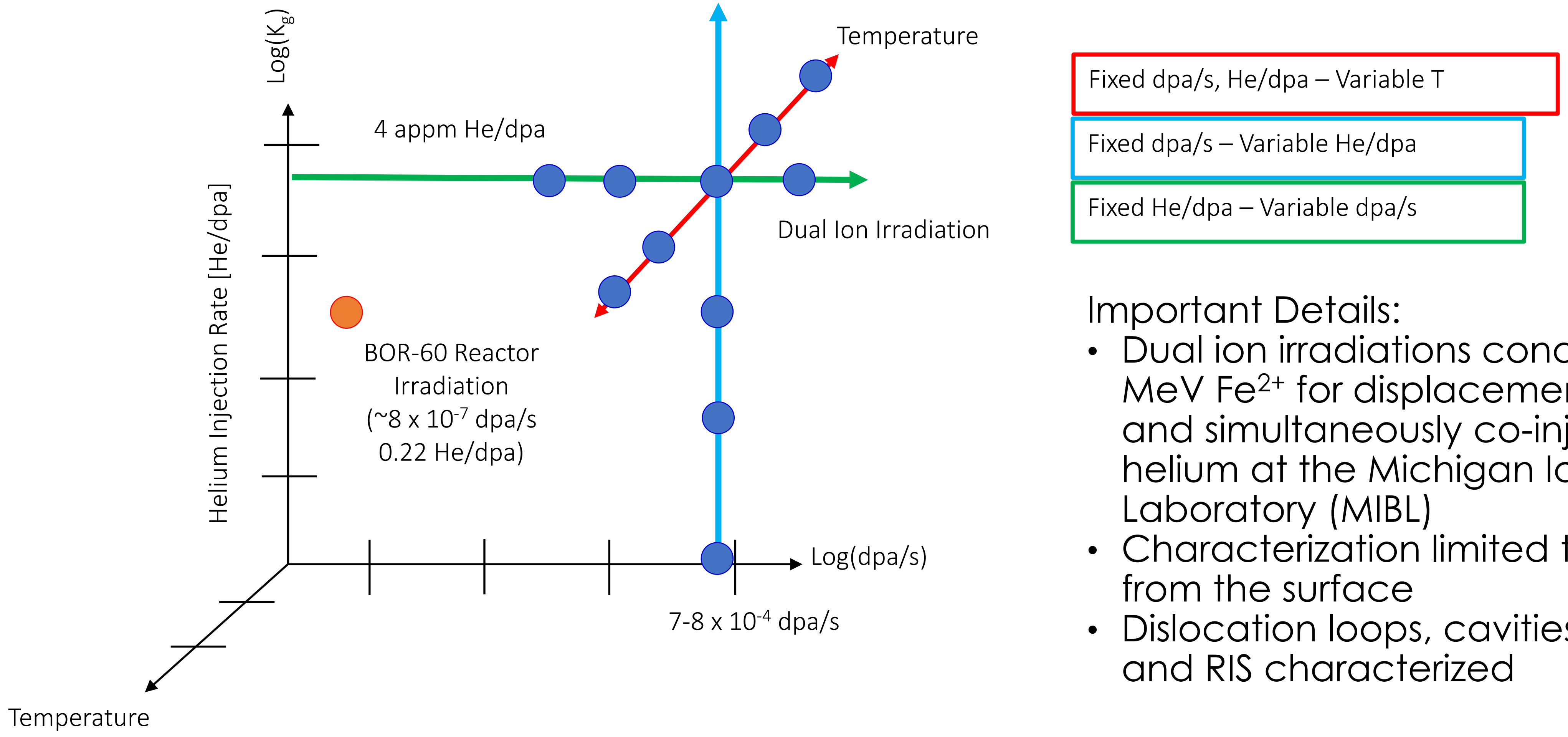
Design of experiments to meet our objective



Important Details:

- Dual ion irradiations conduced with 5 MeV Fe^{2+} for displacement damage and simultaneously co-injected with helium at the Michigan Ion Beam Laboratory (MIBL)
- Characterization limited to 500-700nm from the surface
- Dislocation loops, cavities, precipitates and RIS characterized

Alloy	Fe	Cr	Ni	Si	Mn	Mo	C	Nb	N	V
T91 heat 30176	Bal.	8.6	0.09	0.11	0.37	0.89	0.08	0.072	0.054	0.21

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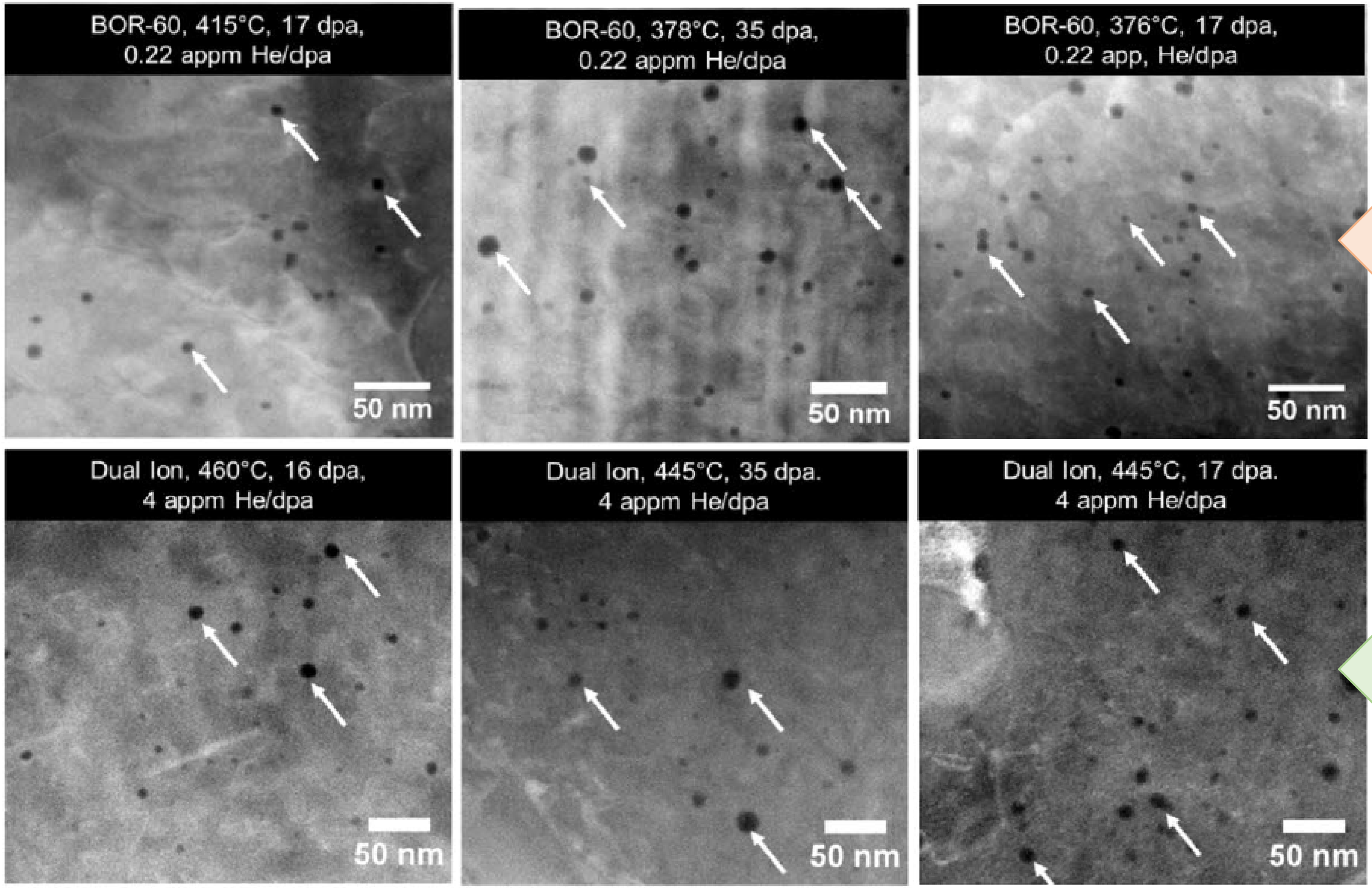
Emulation of Reactor Irradiation Using Dual Ions

Reactor

Dual Ions



484 days!

16 hours!

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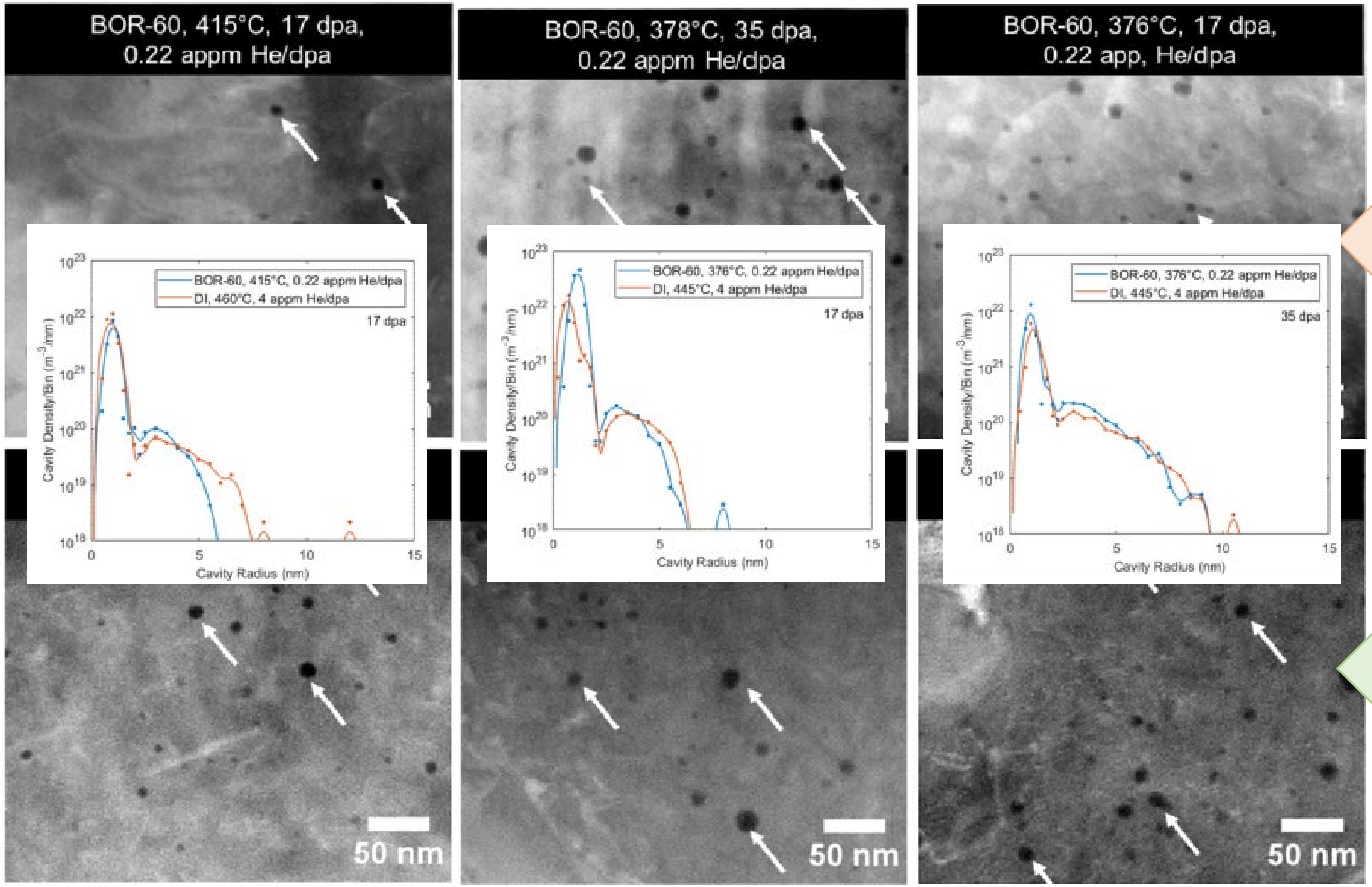
Emulation of Reactor Irradiation Using Dual Ions

Reactor

Dual Ions



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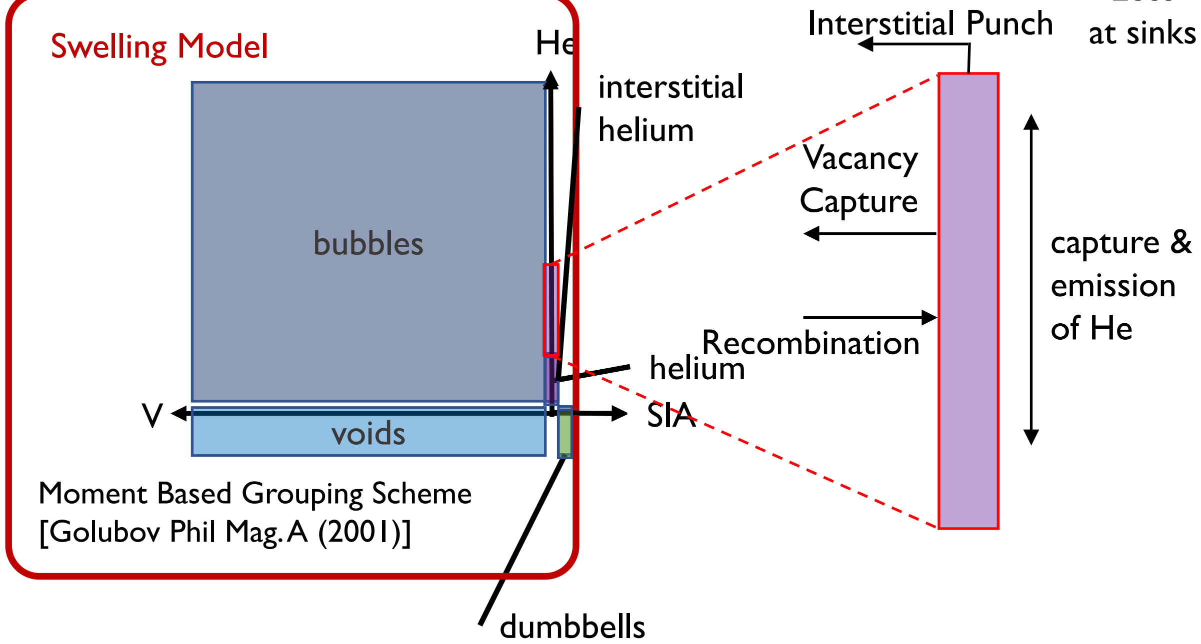
Coupling experimental results with a cluster dynamics model provides detailed insights on helium-dose rate-temperature invariances

Spatial Diffusion — Aggregation and recombination

$$\frac{dC_n}{dt} = D_n \nabla^2 C_n + R_n(C) - D_n k_n^2 C_n + g_n$$

Loss at sinks — Production in cascades



Key Parameters:

Dislocation Density (m^{-2})	3×10^{14}
Effective Bias (%)	1
Vacancy E_m (eV)	0.63
Interstitial E_m (eV)	0.22
Helium E_m (eV)	0.07

- Adds a third axis to the phase space for ‘sites’
- Only helium monomers bind to these sites with an input binding energy *(Gao JNM 418)*
- Bound helium is immobile, and can absorb incoming helium or vacancies to provide an alternative nucleation path

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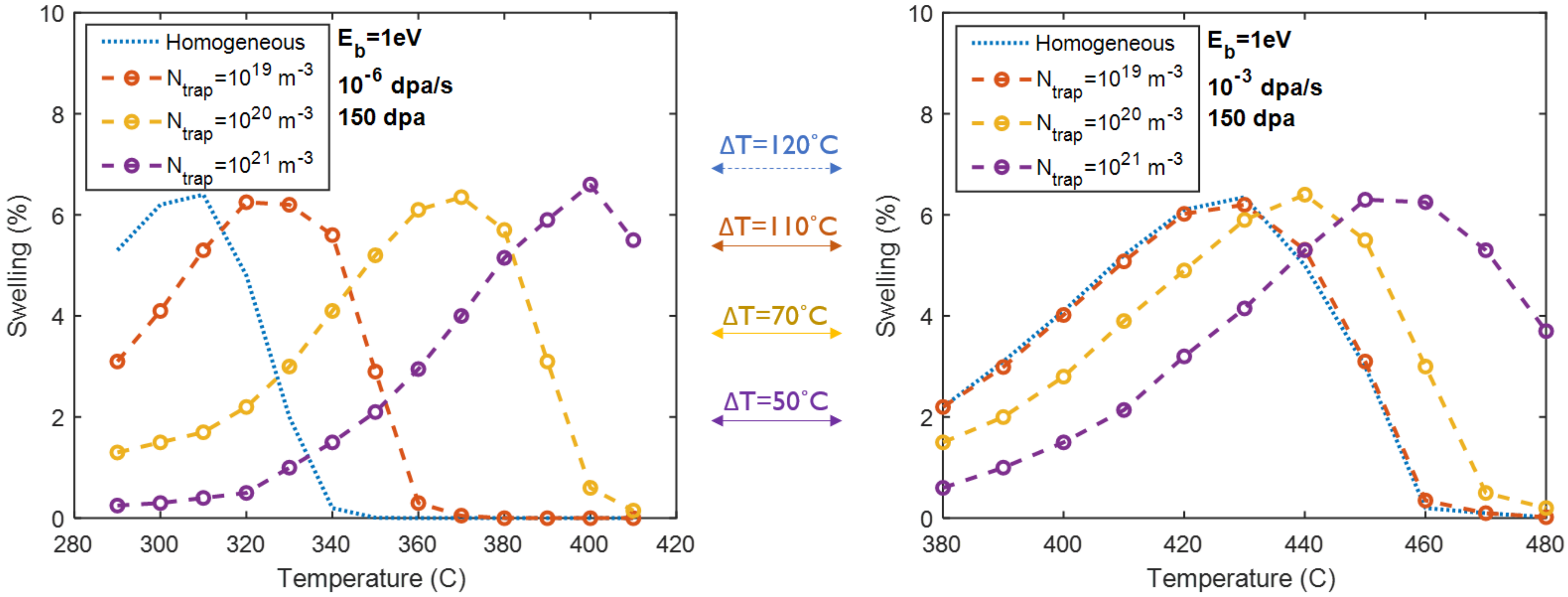
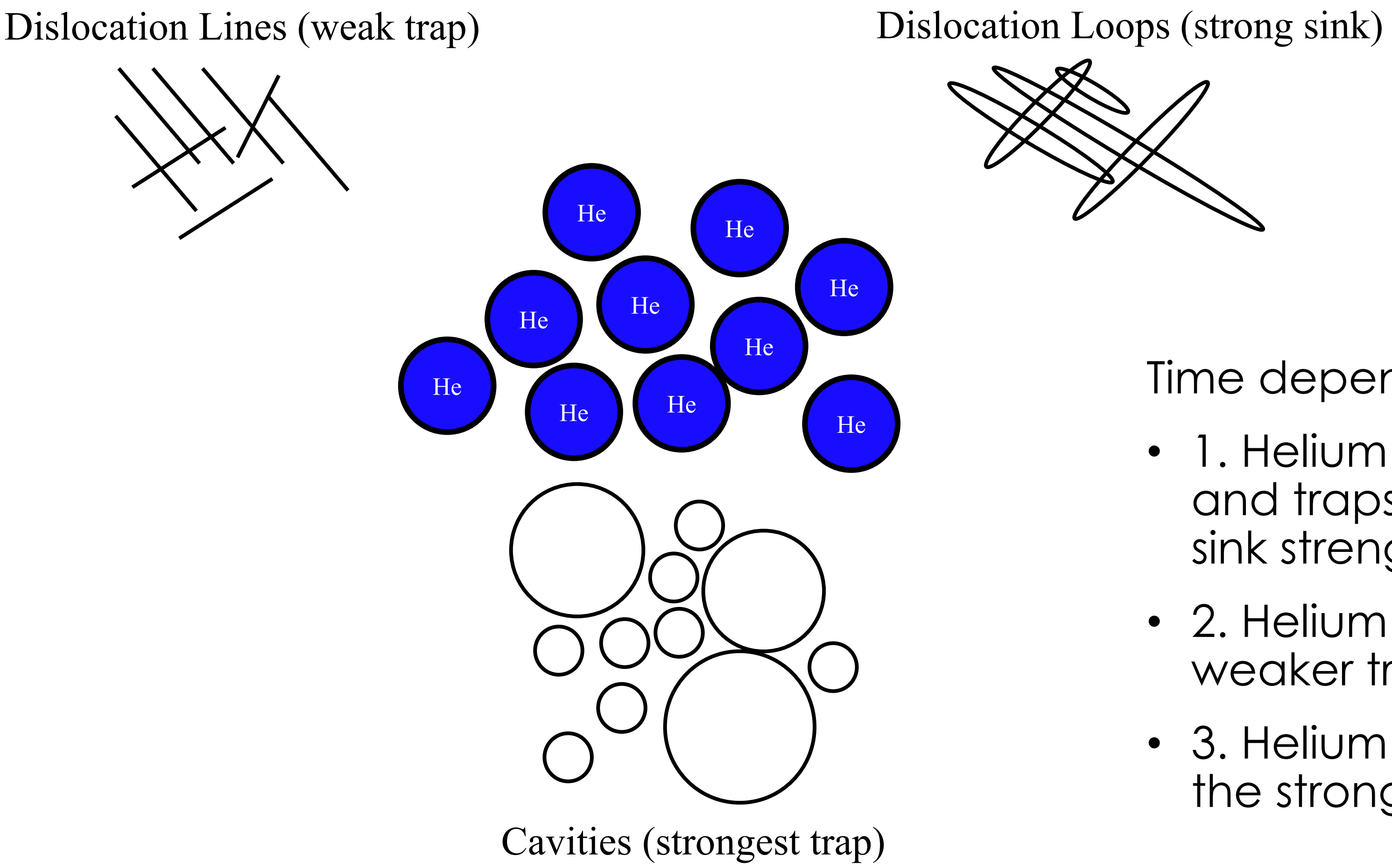
Helium trapping and detrapping must be accounted for in temperature shifts to account for dose rate



- Helium trap induced temperature shift is stronger at reactor damage rates.
- Enhanced nucleation from helium trapping results in the experimentally observed temperature shift.

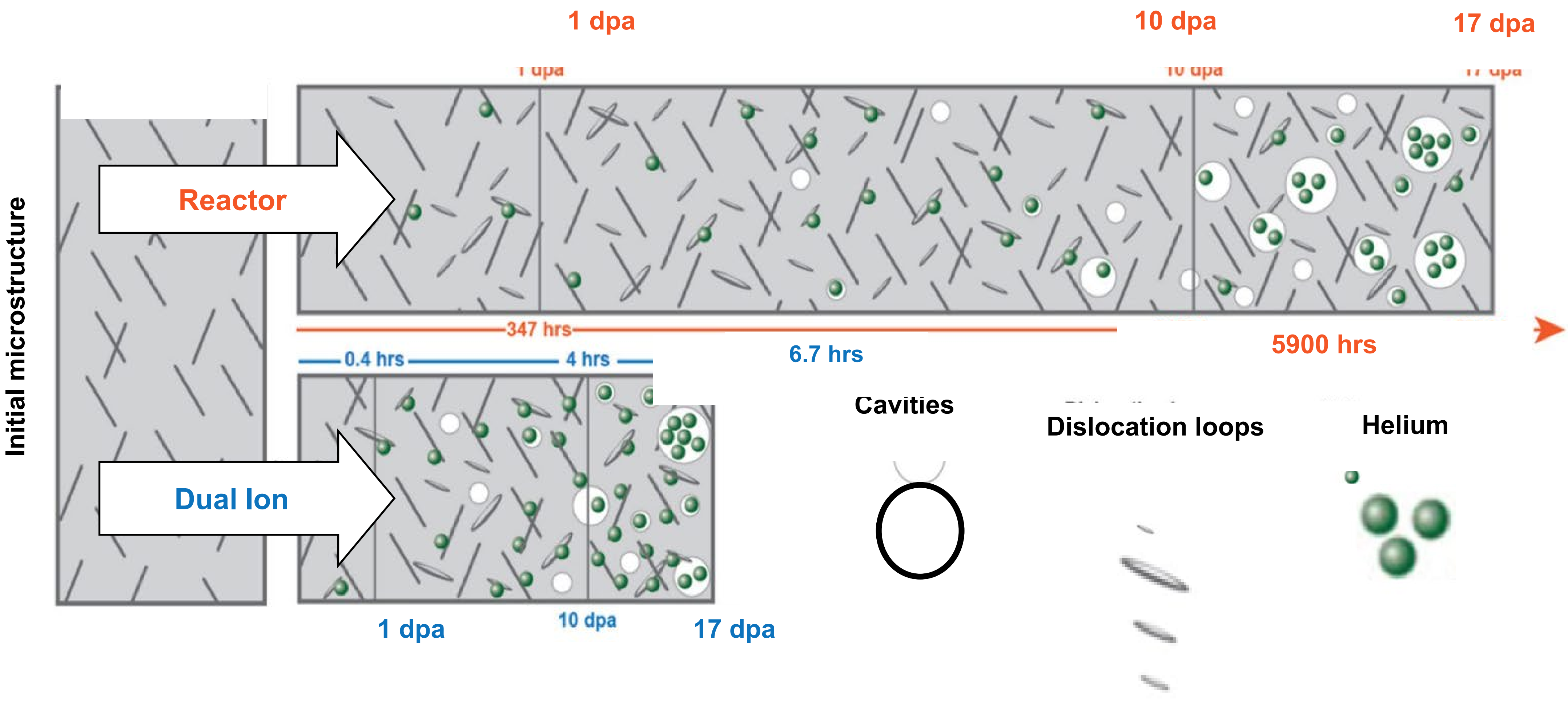
Helium “flows” from sink to sink based on binding energy



Time dependence:

- 1. Helium diffuses to sinks and traps in proportion to sink strength.
- 2. Helium releases from a weaker trap and diffuses.
- 3. Helium accumulates at the strongest trap.

Higher He injection rate to counter lack of detrapping in the short ion irradiation time



S. Taller, G. VanCoevering, B. D. Wirth, and G. S. Was, Sci. Rep. 11 (2021) 2949

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Conclusions

- Enhanced nucleation from helium trapping results in the experimentally observed temperature shift with damage rate.
- As the damage rate is increased for a fixed temperature, the amount of helium trapped at sinks other than cavities increases from the lack of time (during the short ion irradiations) to release from weaker traps and therefore the helium injection rate must be increased to compensate.
- Temperature and helium rate must be increased with damage rate to match cavity microstructure during cavity nucleation.
- At high dpa (past cavity nucleation), ion helium rate should be lowered to reactor helium generation rate.

- Acknowledgements:
  - Technical support from Michigan Ion Beam Laboratory (MIBL) and Michigan Center for Materials Characterization (MC)^2

Simulating Neutrons with Accelerated Particles

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