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The role of grain boundary migration on irradiation-fatigue

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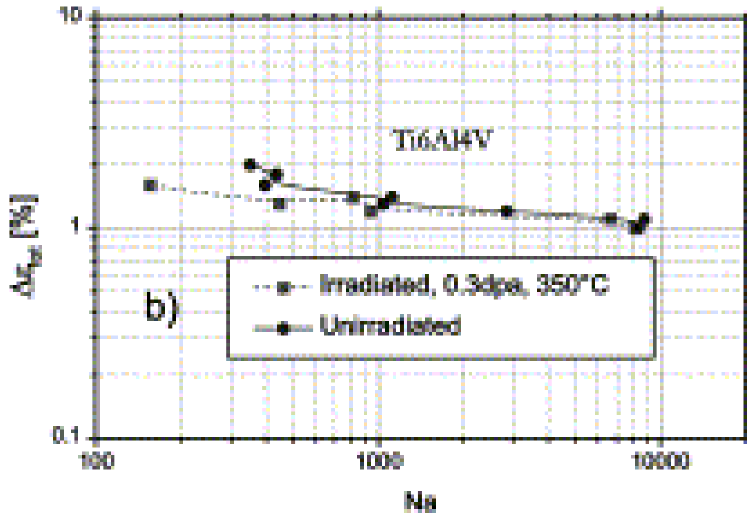
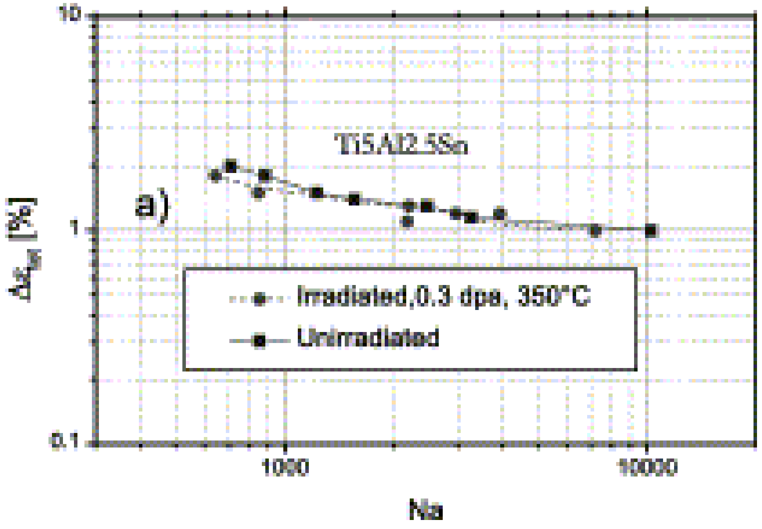
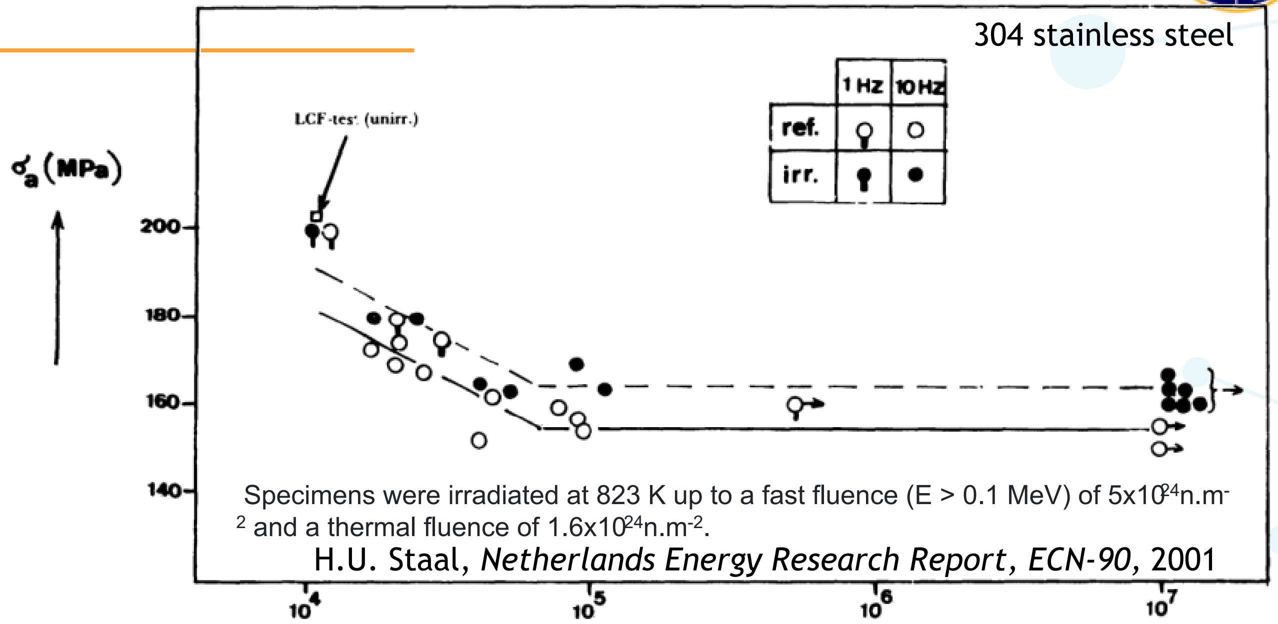
What do we know about high-cycle fatigue resistance during or after irradiation?



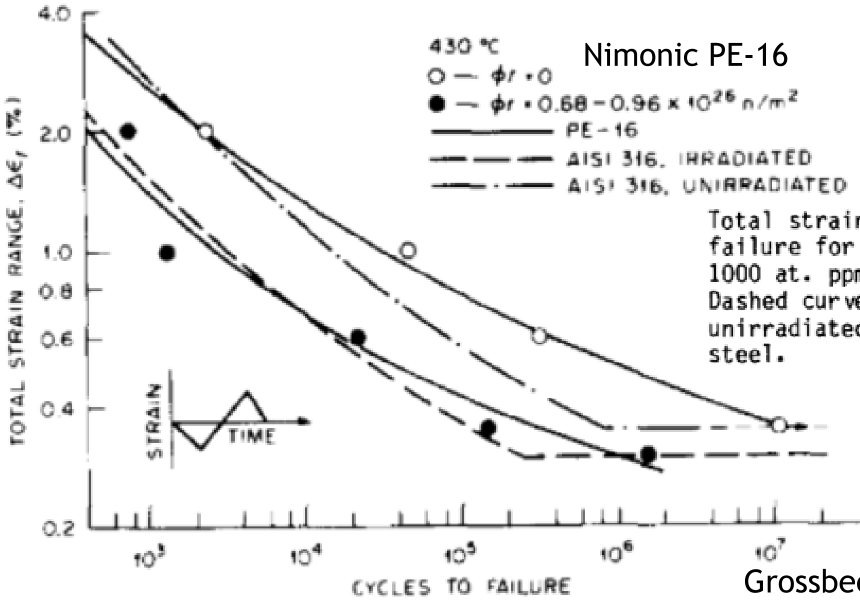


Marmy and Leguey, *J. Nucl. Mater.*, 2001



Specimens were irradiated at 823 K up to a fast fluence (E > 0.1 MeV) of 5×10^{24} n.m^{-2} and a thermal fluence of 1.6×10^{24} n.m^{-2}.

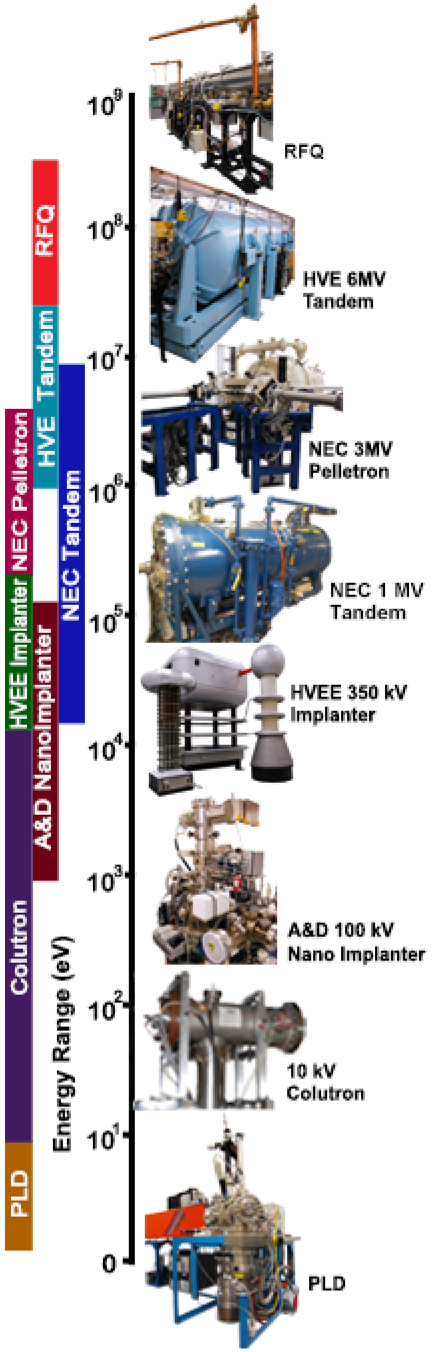
H.U. Staal, *Netherlands Energy Research Report, ECN-90*, 2001

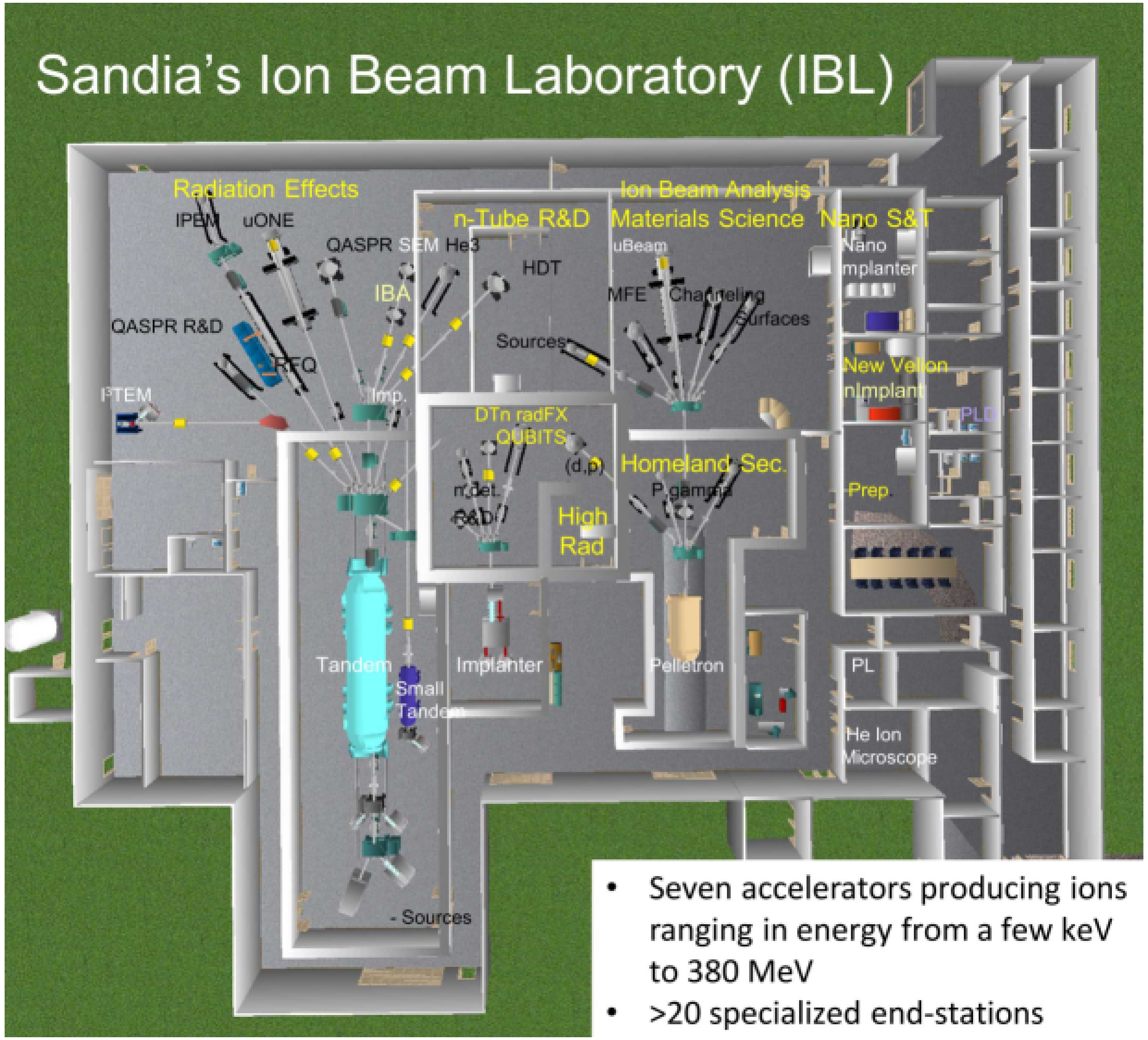


Total strain range as a function of cycles to failure for HFIR-irradiated (6–9 dpa, 560–1000 at. ppm He) and unirradiated Nimonic PE-16. Dashed curves are for similarly irradiated and unirradiated 20%-cold-worked type 316 stainless steel.

Grossbeck and Liu, *J. Nucl. Mater.*, 1984

Sandia's Ion Beam Laborato



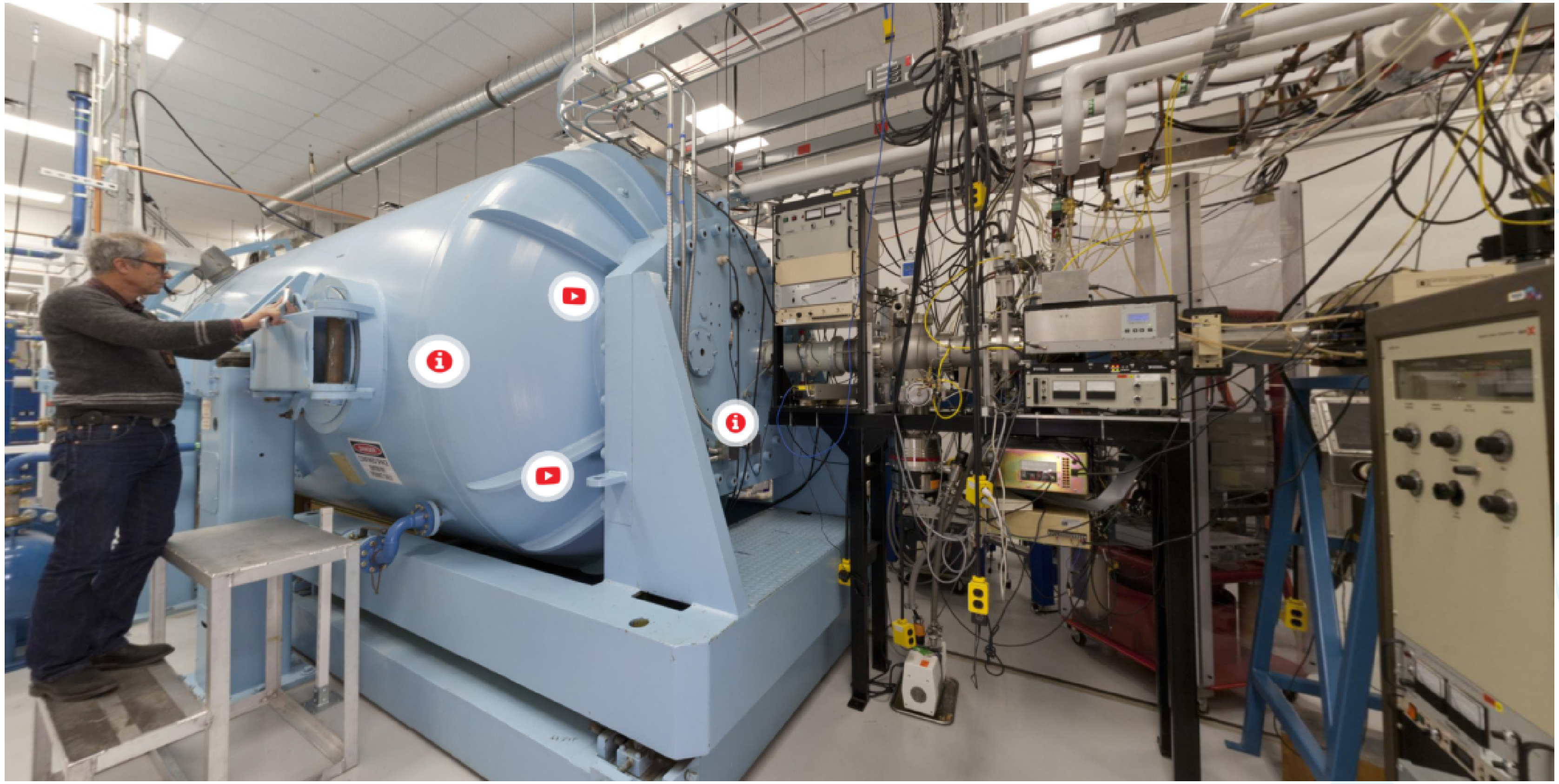


- Seven accelerators producing ions ranging in energy from a few keV to 380 MeV
- >20 specialized end-stations

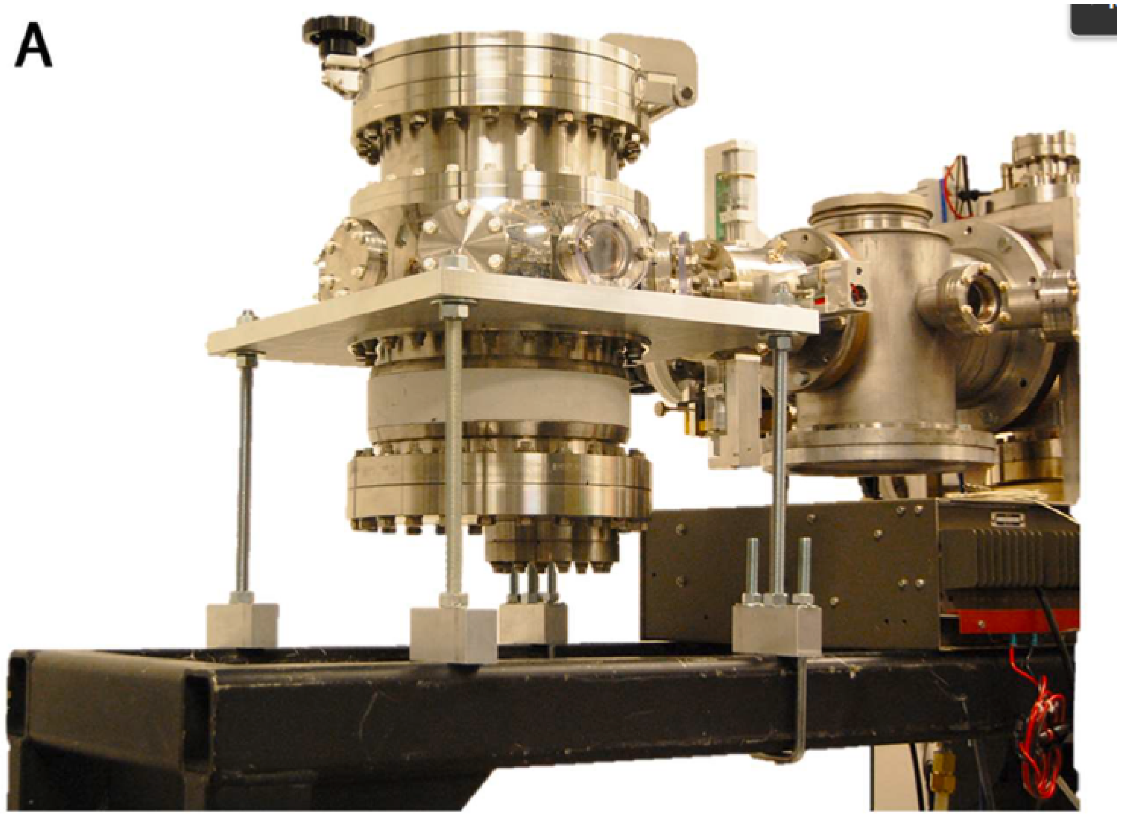
6 MeV Tandem Accelerator @ Sandia's Ion Beam Lab

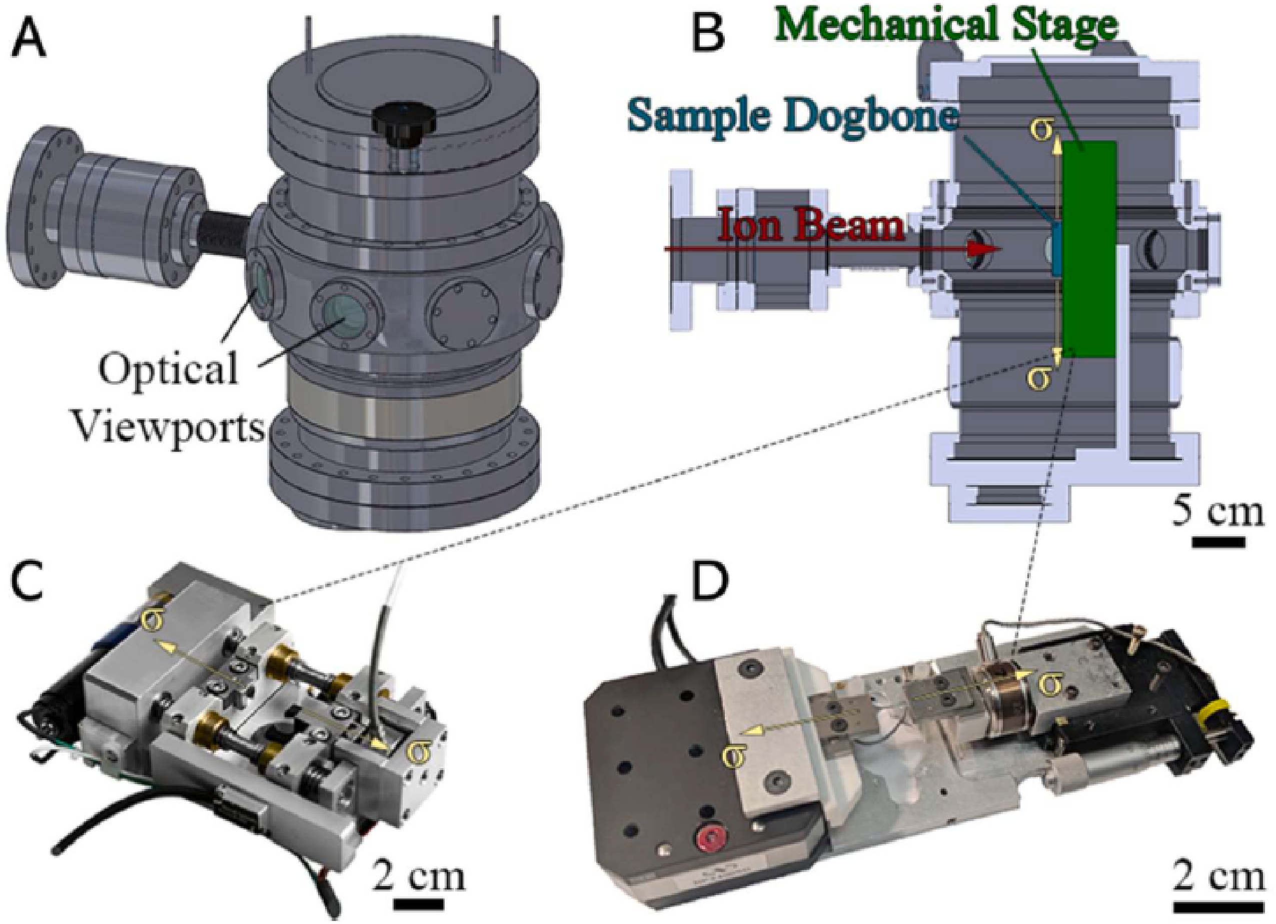
Ions from protons to Au

Energy:
10-100 keV; 800 keV-100 MeV.

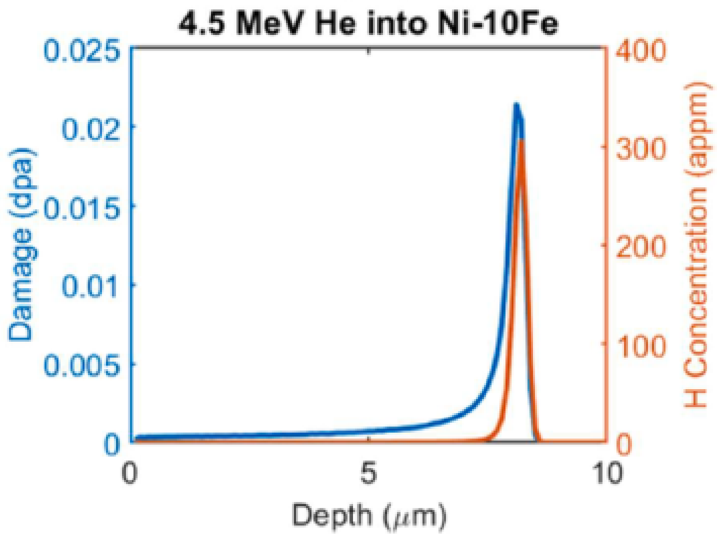


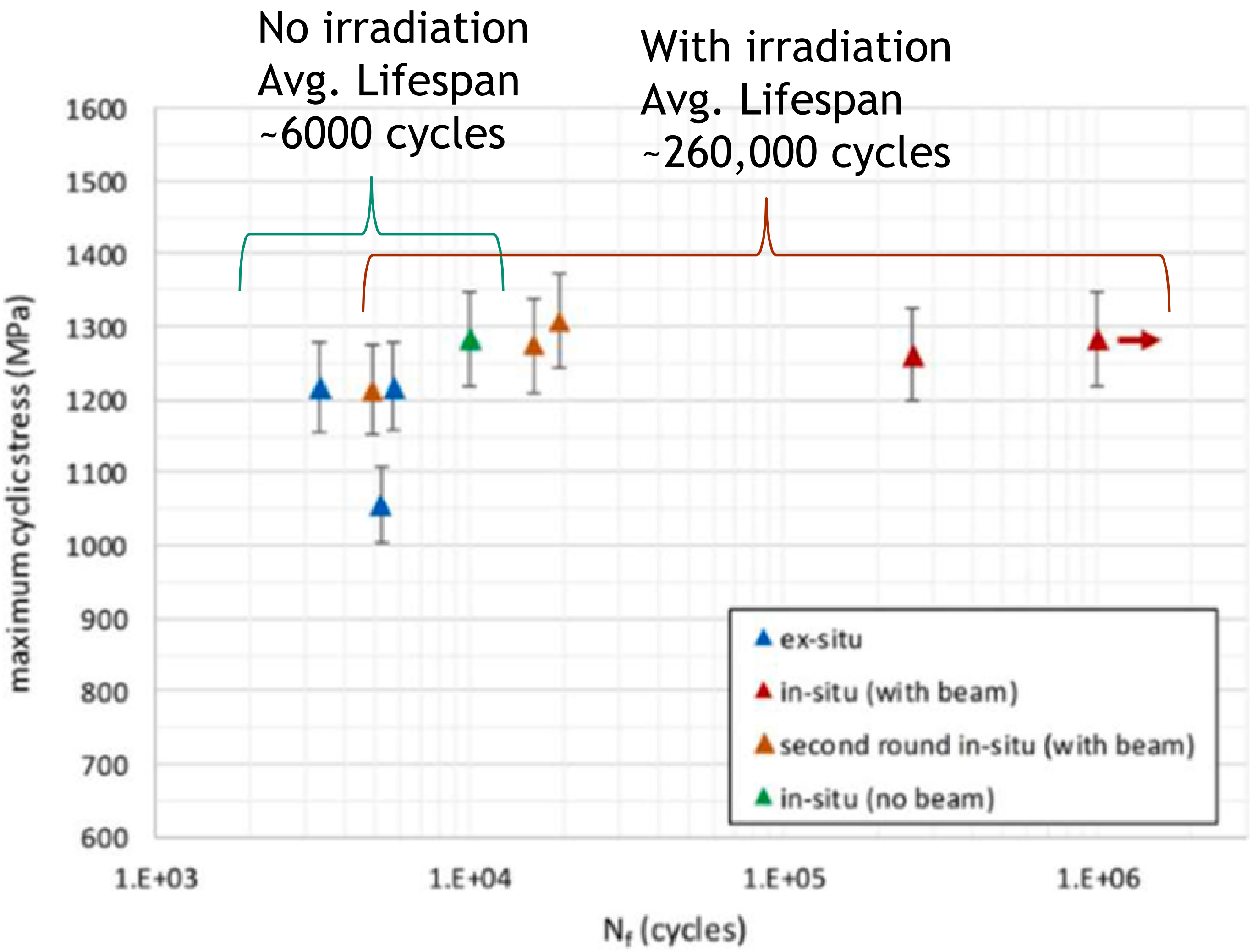
Sandia Ion Beam Lab's thermomechanical end station





Bottom line up front:
enhanced fatigue resistance under irradiation?

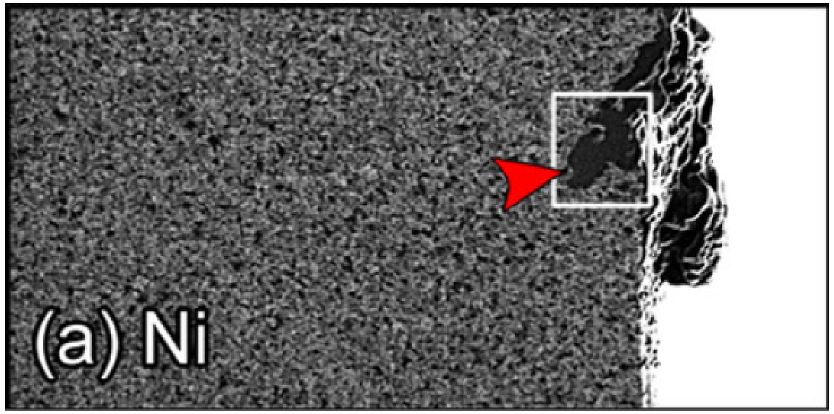


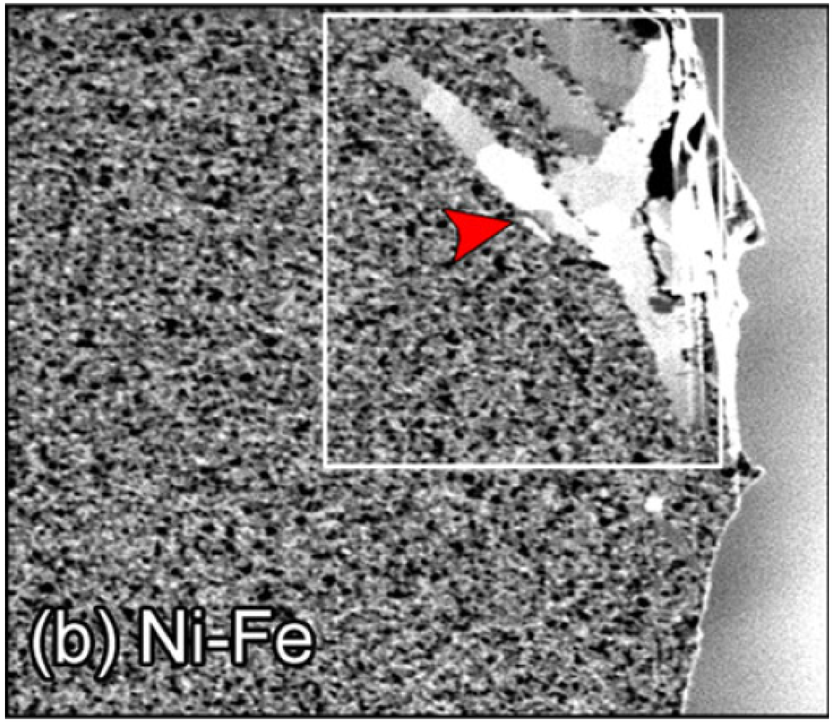


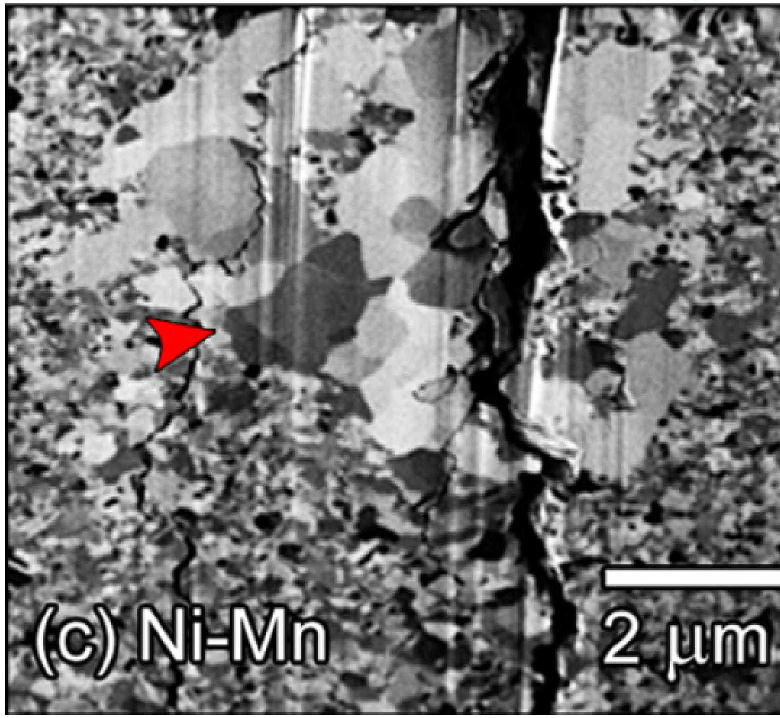
Briggs et al., *Nucl Inst. Meth. Phys. Res.*, 2021

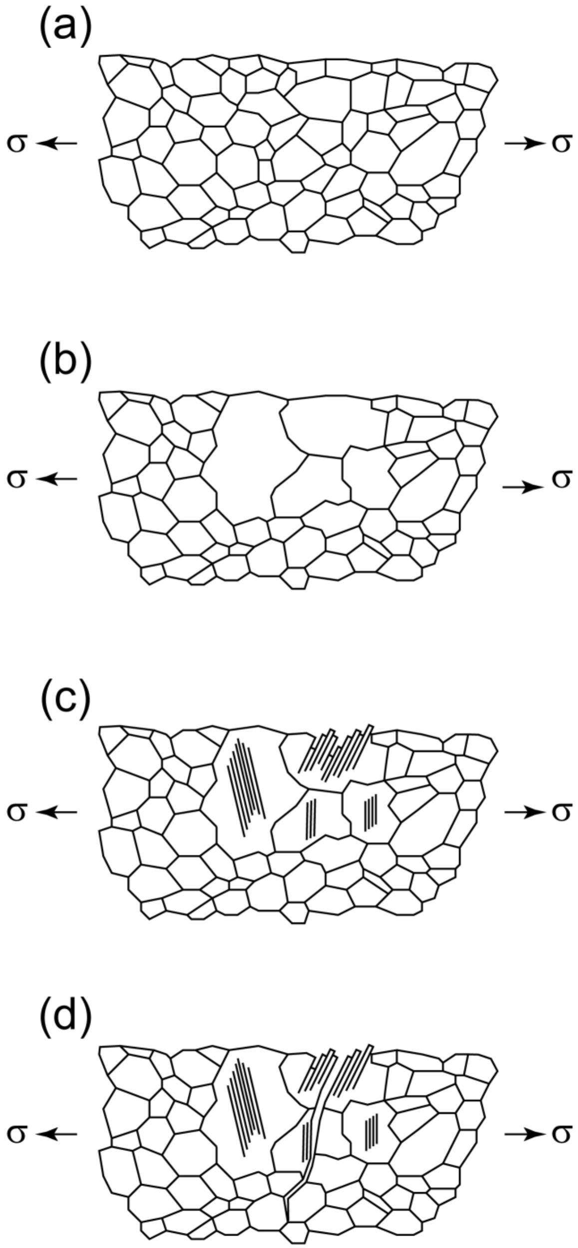
What do we know about the high-cycle fatigue process in nanocrystalline metals?

Localized grain growth precedes fatigue-crack initiation









We posulate that in nanocrystalline metals (d_{gb} < ~70 nm), the fatigue process induces grain growth as a precursor to gross slip and eventual crack initiation

Important questions

a. Can fatigue really cause grain growth? **YES**

b. Does the grain growth precede crack initiation? **YES**

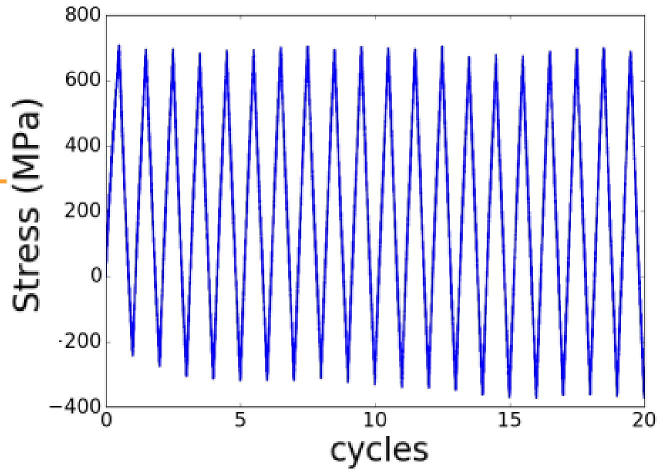
c. Does the crack initiate at the site of grain growth? **YES**

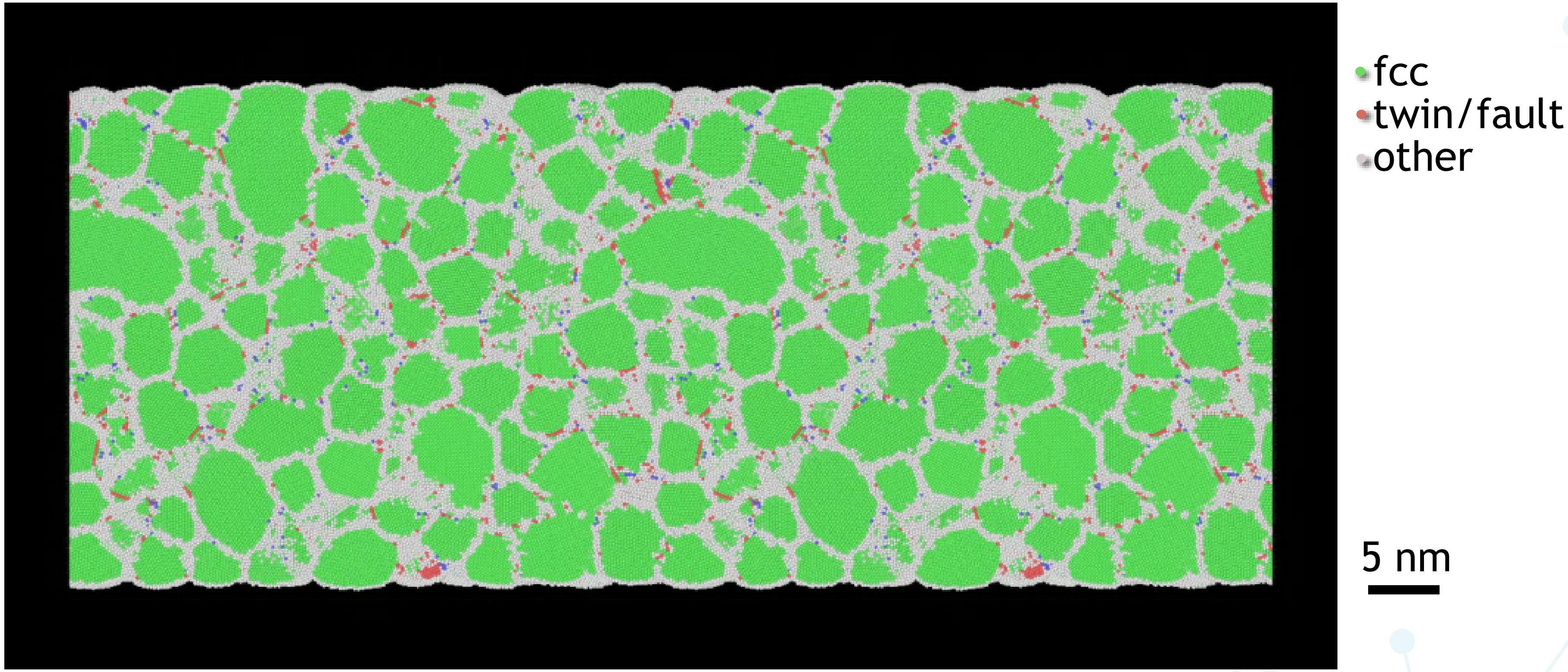
For more details, our work:
Padilla and Boyce, *Exper. Mech.*, 2010
Boyce and Padilla, *Metall. Trans. A*, 2011
Bufford et al., *Nano Letters*, 2016
Furnish et al., *J. Mater. Sci.*, 2017
Furnish et al., *Scripta Mater.*, 2018
Foiles et al., *Model. Sim. Mater. Sci. Eng.*, 2019
Heckman et al., *Int. J. Fatigue*, 2020
Heckman et al., *Acta Mater.*, 2022

Others as well, e.g.,
Luo, Zhu, Zhang, *Nature Comm*, 2014
Kobayashi, Kamata, Watanabe, *Acta Mater*, 2015
Kapp, Renk, Leitner, Ghosh, Yang, Pippan, *J. Mater. Res.* 2017
Goswami, Feng, Qadri, Pande, *Sci. Reports*, 2017
Zhao, Chen, Kelleher, Yuan, Guan, Zhang, Tu, *Acta Mater*, 2019
Zheng, Luo, Zhang, *J. Mater. Res.*, 2020
Zhang, Zeng, Cheng, Wang, *J. Mater. Sci. Tech.*, 2021

Molecular dynamics simulation of fatigue-induced grain growth

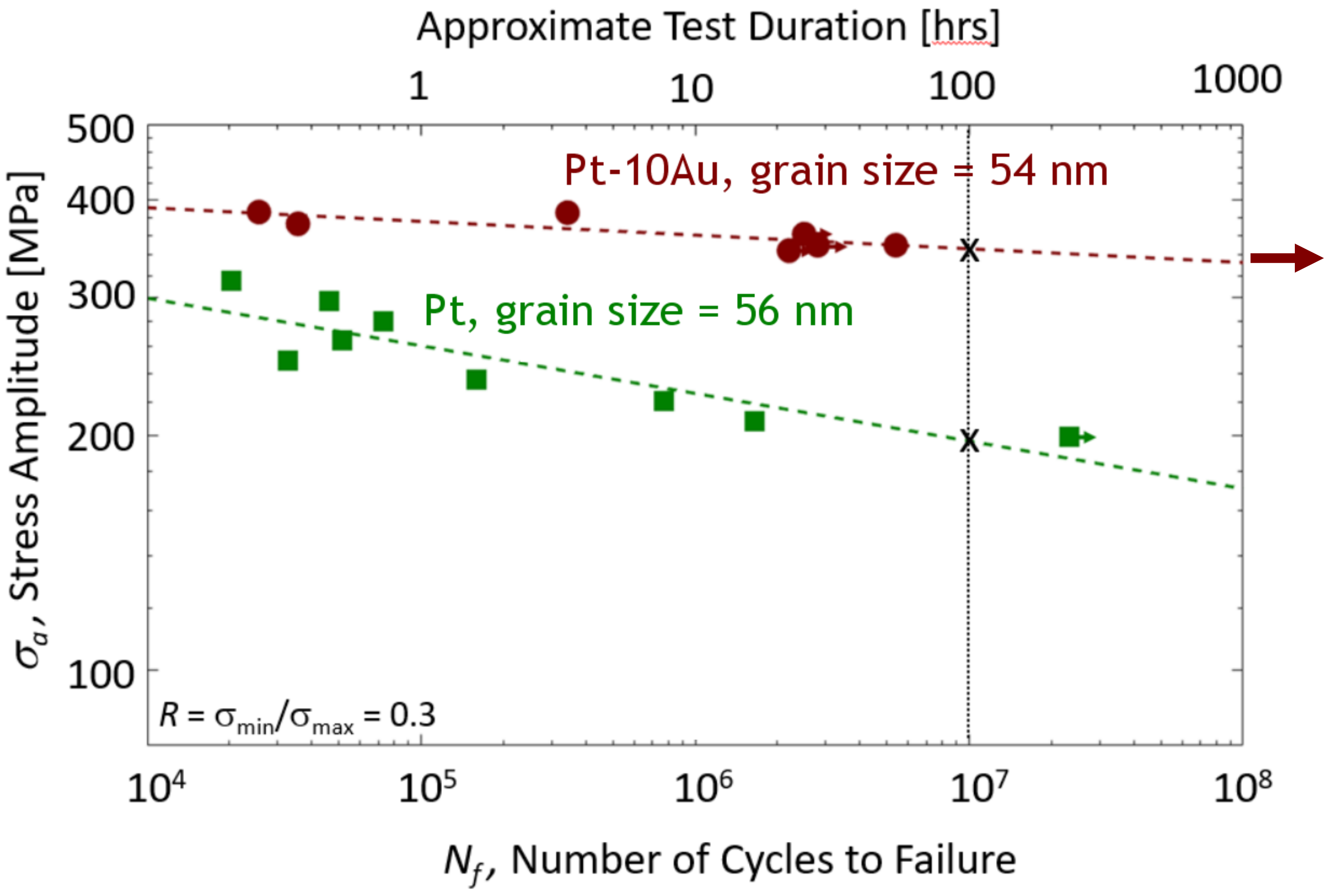
20 cycles, 2 ns/cycle, 1% strain
Simulation: 110,000 cpu-hours

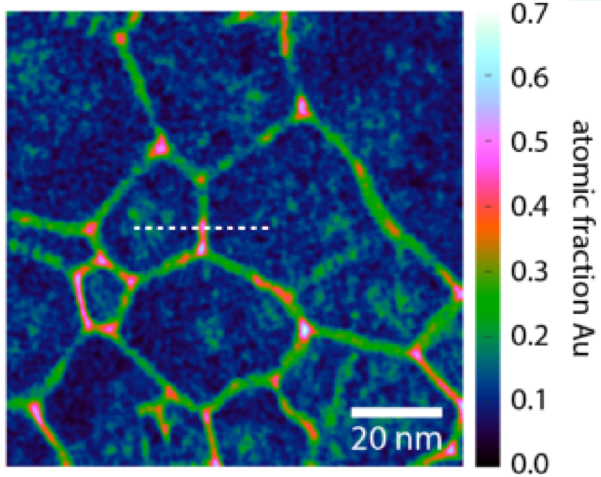




Foiles…Boyce, *Model. Sim. Mat. Sci. and Eng.*, 2019

Ok, so is stabilized Pt-Au more fatigue resistant?





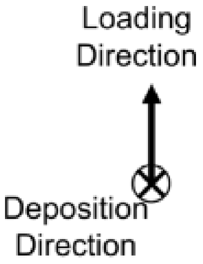
Heckman, et al., *Acta Mater*, 2022

Did the Pt-Au actually resist fatigue-induced grain growth?

Pt

$N_f = 8.5\times10^5$ cycles

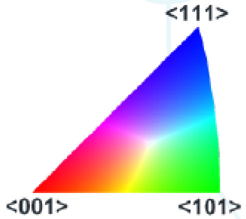
$\sigma_a = 104$ MPa

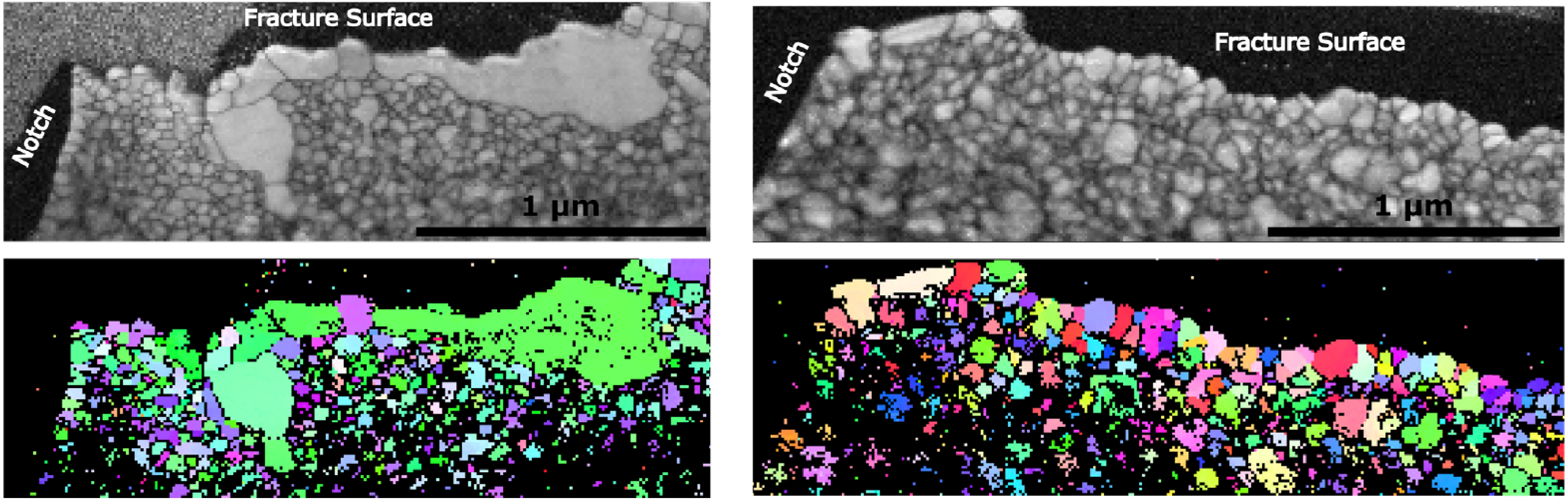


Pt-10Au

$N_f = 7.1\times10^5$ cycles

$\sigma_a = 126$ MPa



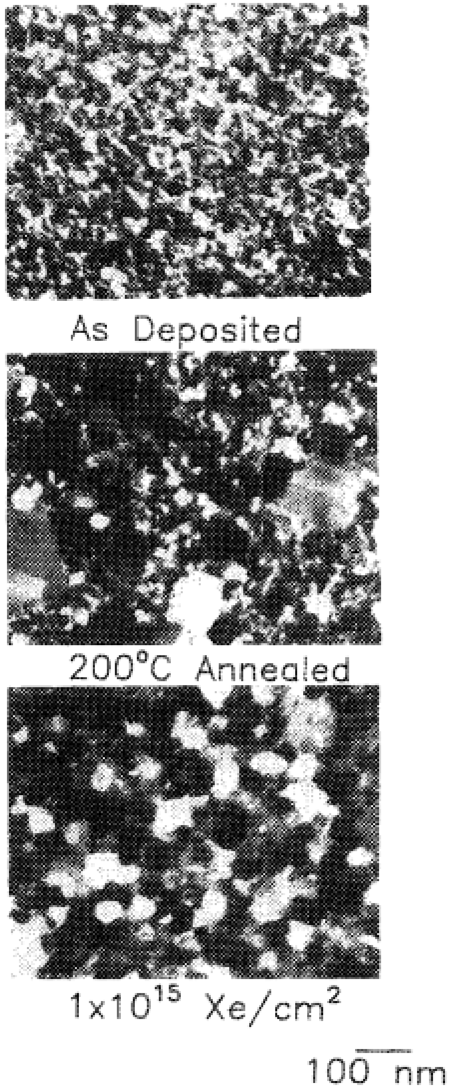


Heckman, et al., *Acta Mater*, 2022

How do grain boundaries respond to irradiation???

Radiation-enhanced grain growth in metals…

560-keV Xe^{+2} into nanocrystalline Pd



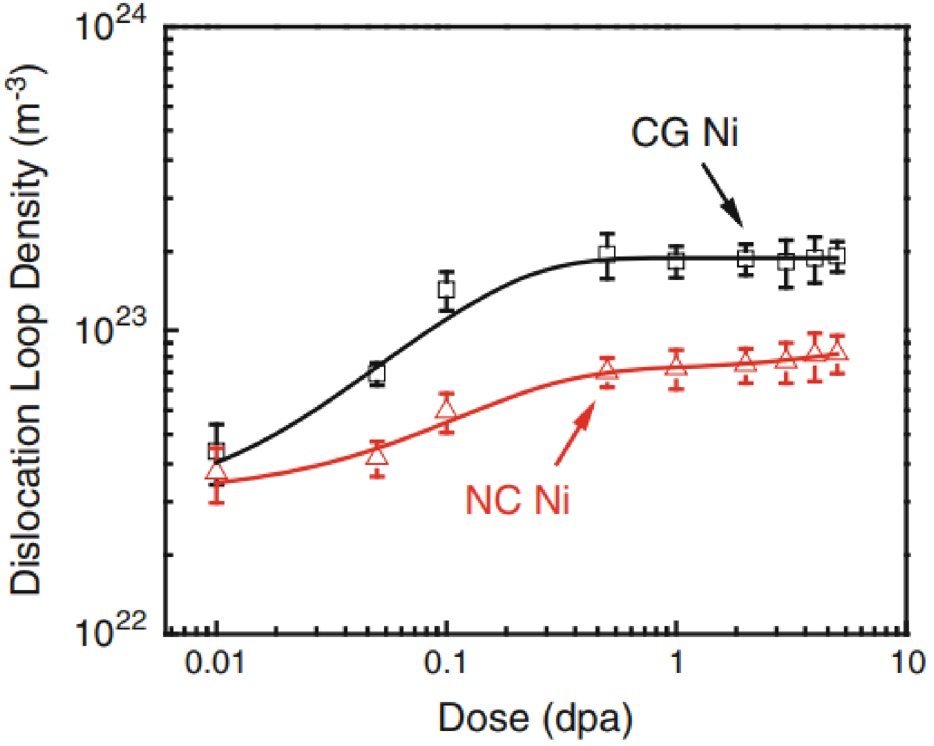
Liu, Nastasi and Mayer, *J. Appl. Phys.*, 1987

Some studies rationalize the grain growth on the basis of thermal spikes alone:

Liu, Li, and Mayer, *J. Appl. Phys.*, 1989
Kaoumi, Motta, Birtcher, *J. Appl. Phys.*, 2008

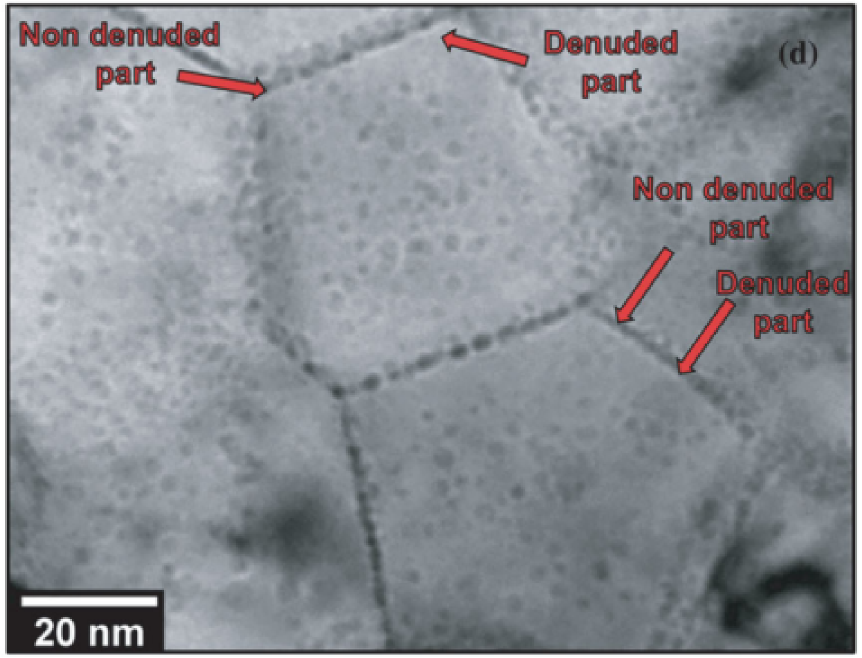
Generally, GBs are thought of radiation defect sinks

1 MeV Kr^{+2} ions through Ni films (CG and NC)



C. Sun et al., *Metall. Mater. Trans A*, 2013

Denuded zone of He bubbles near GBs

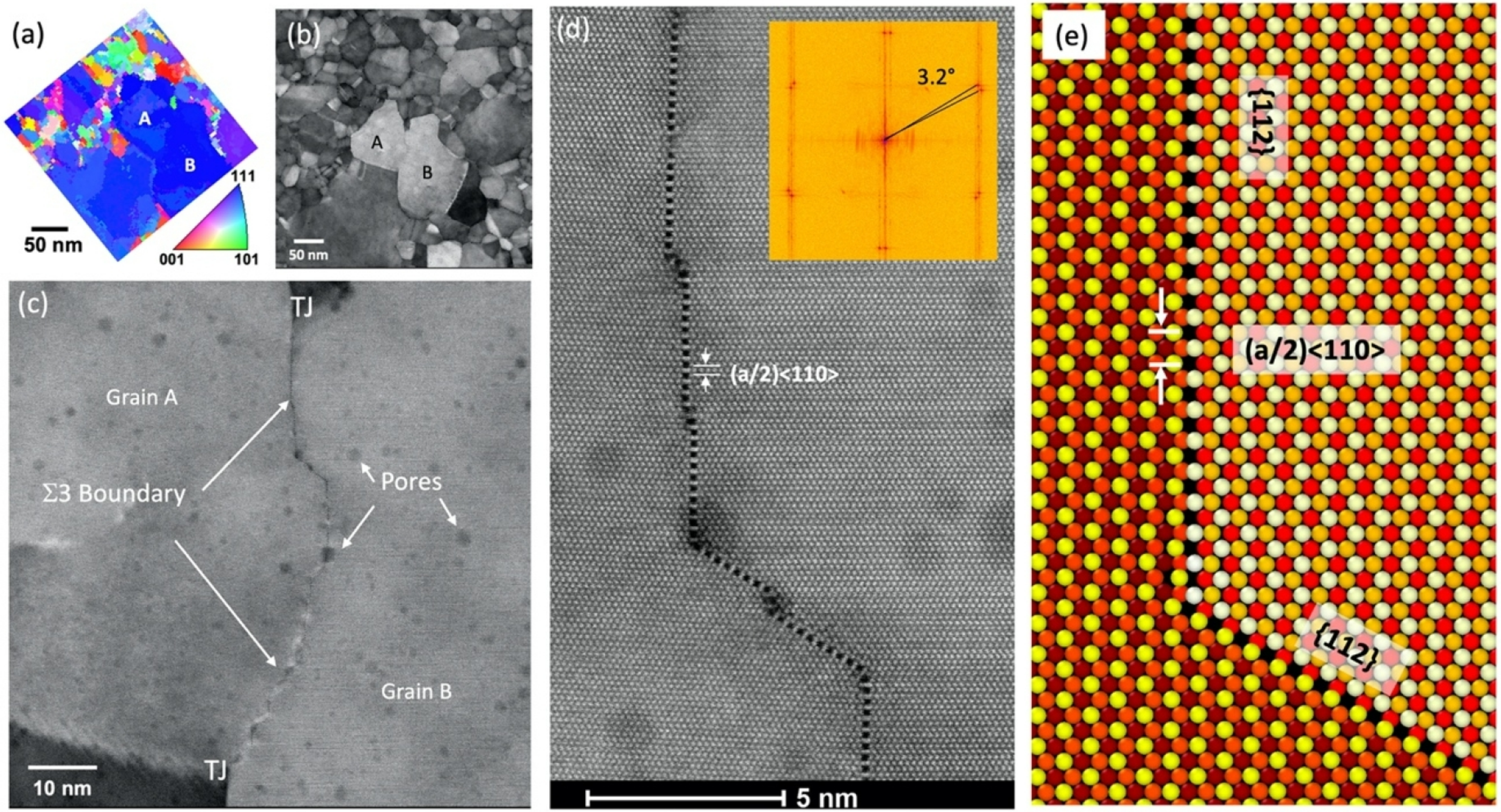


10 keV helium ions into nanocrystalline Fe

El-Atwani et al., *Mater. Res. Lett.*, 2017

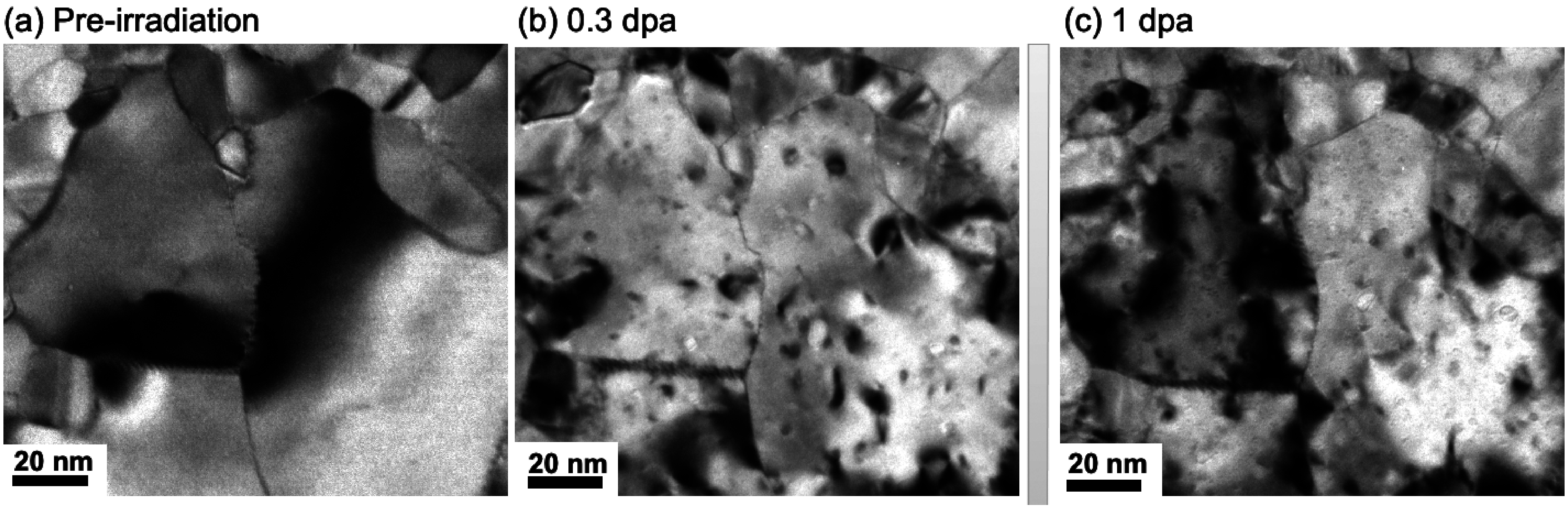
Radiation response of a faceted Σ3 {112} boundary w/ 120° junctions

Pt polycrystal



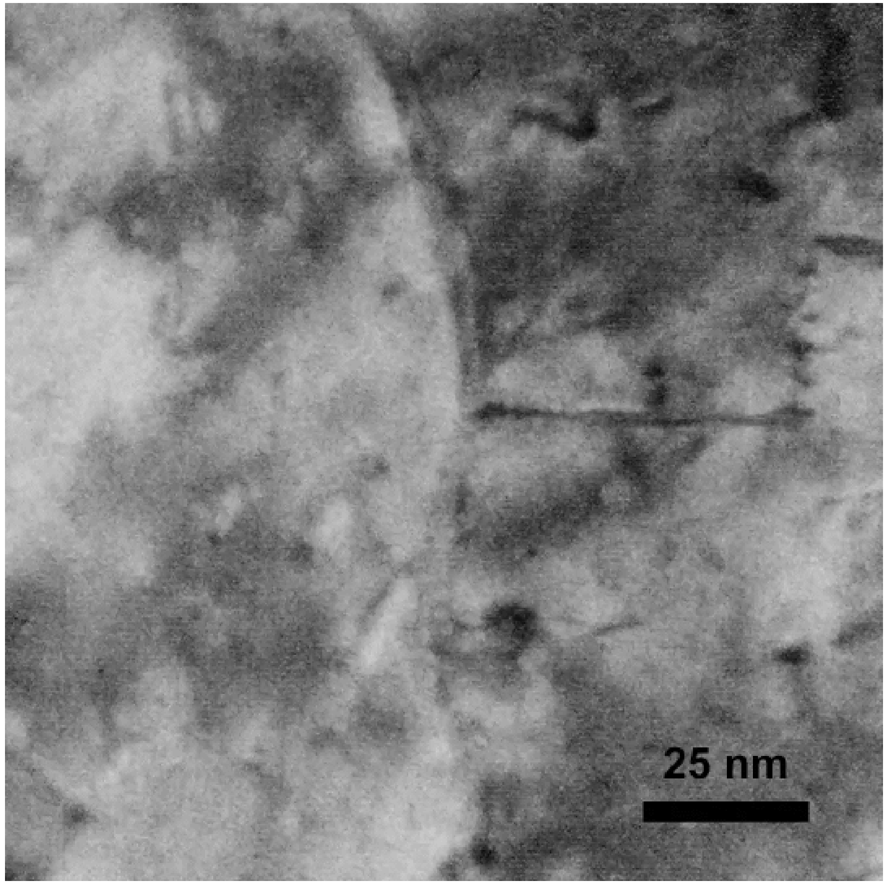
C.M. Barr, et al., *Science Advances*, in press

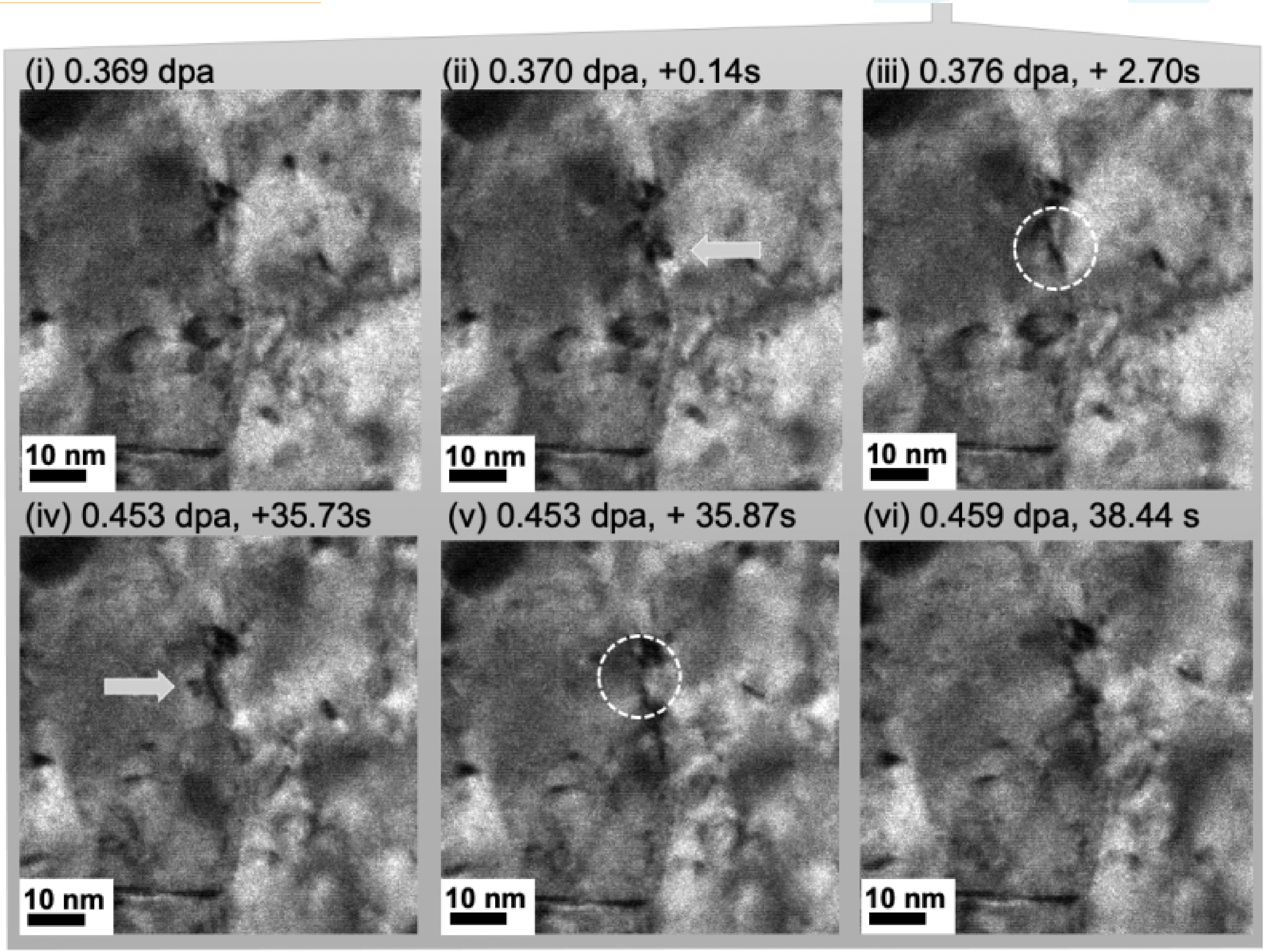
Irradiated with 2.8 MeV Au^{4+}



C.M. Barr, et al., *Science Advances*, in press

Watching the evolution *in situ*

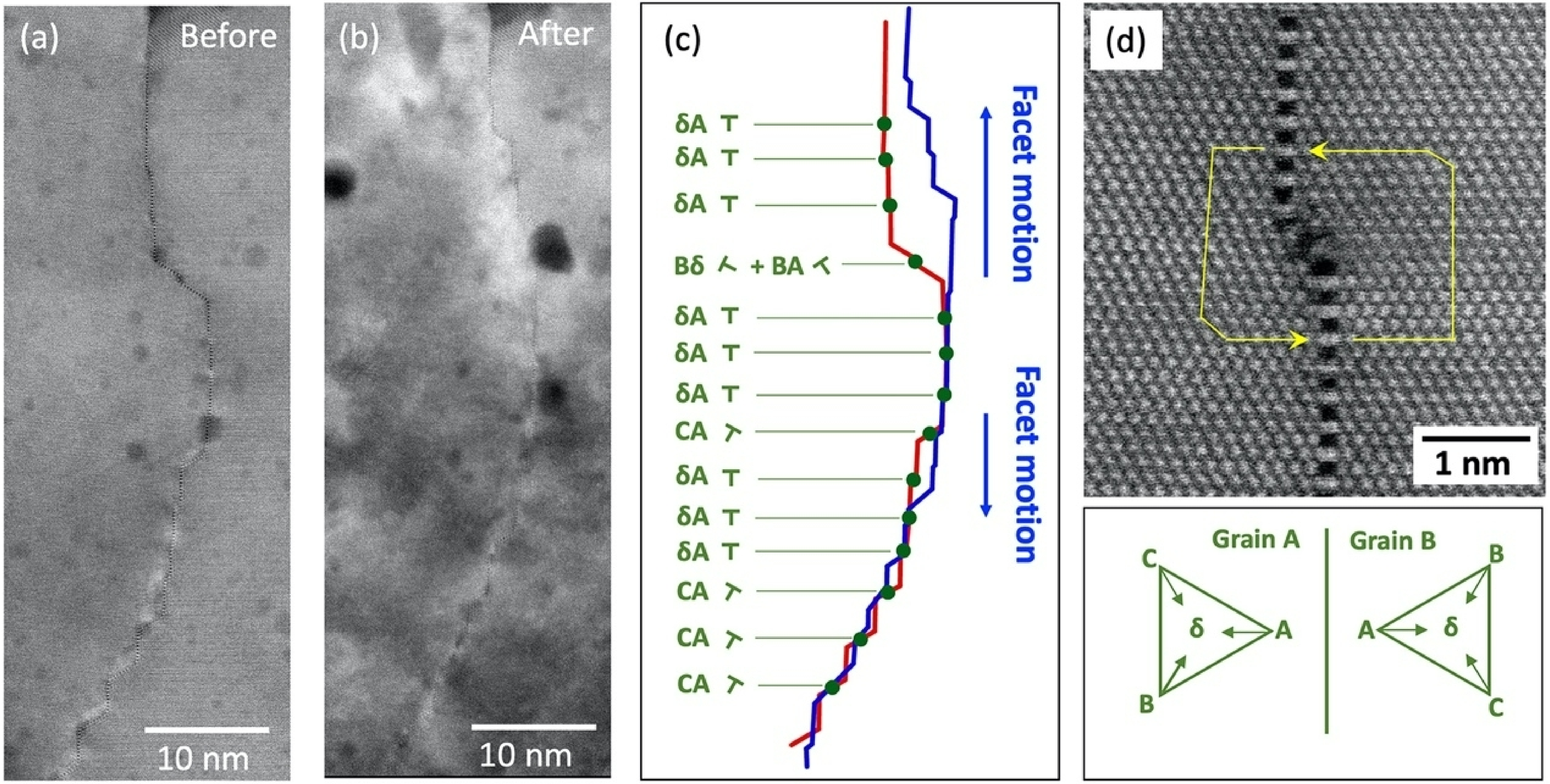




C.M. Barr, et al., *Science Advances*, in press

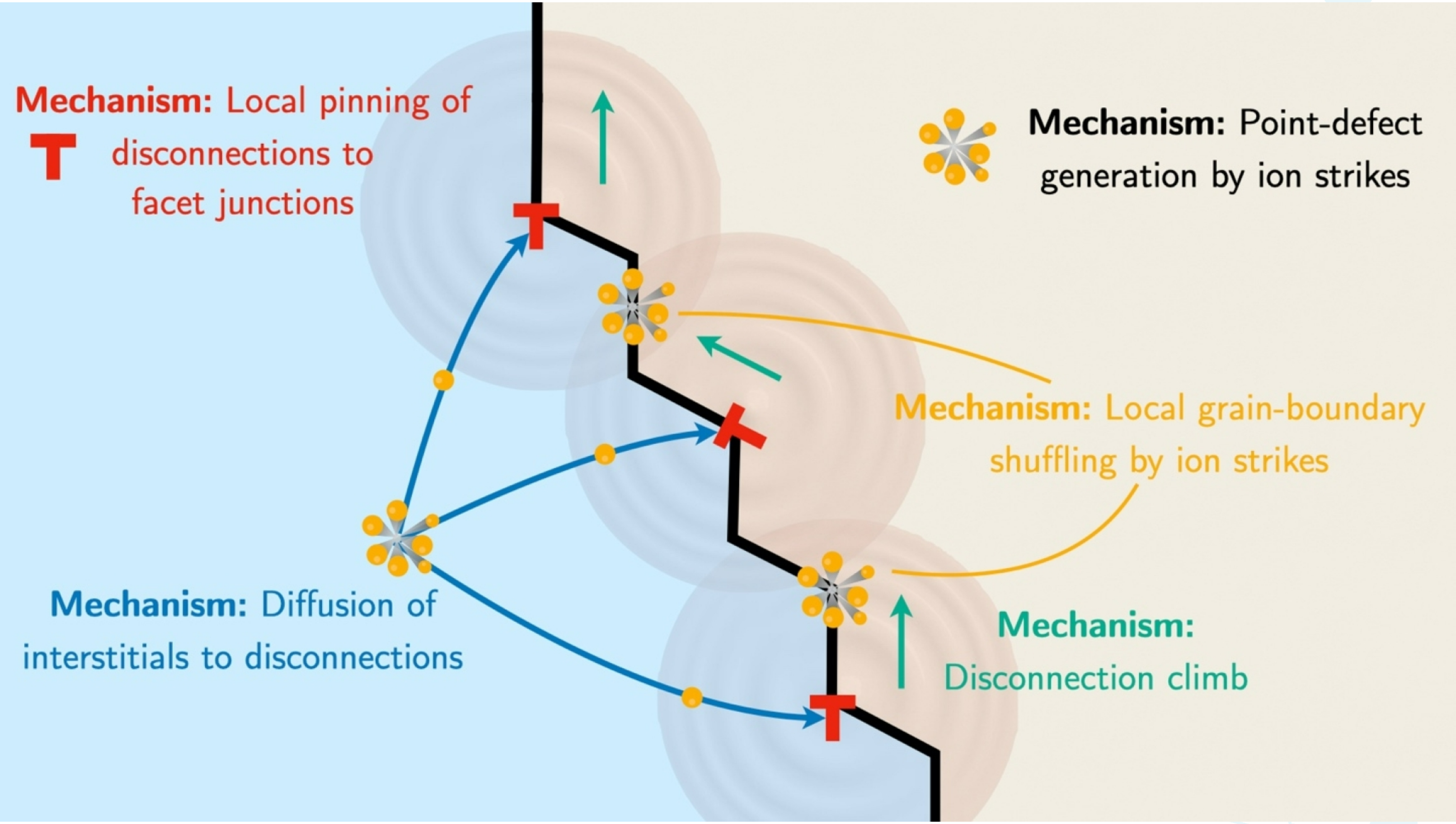
Detailed analysis of facet junction character & facet motion

$\mathbf{b} = (a/6)[1\bar{2}1] = \delta\mathbf{A}$



C.M. Barr, et al., *Science Advances*, in press

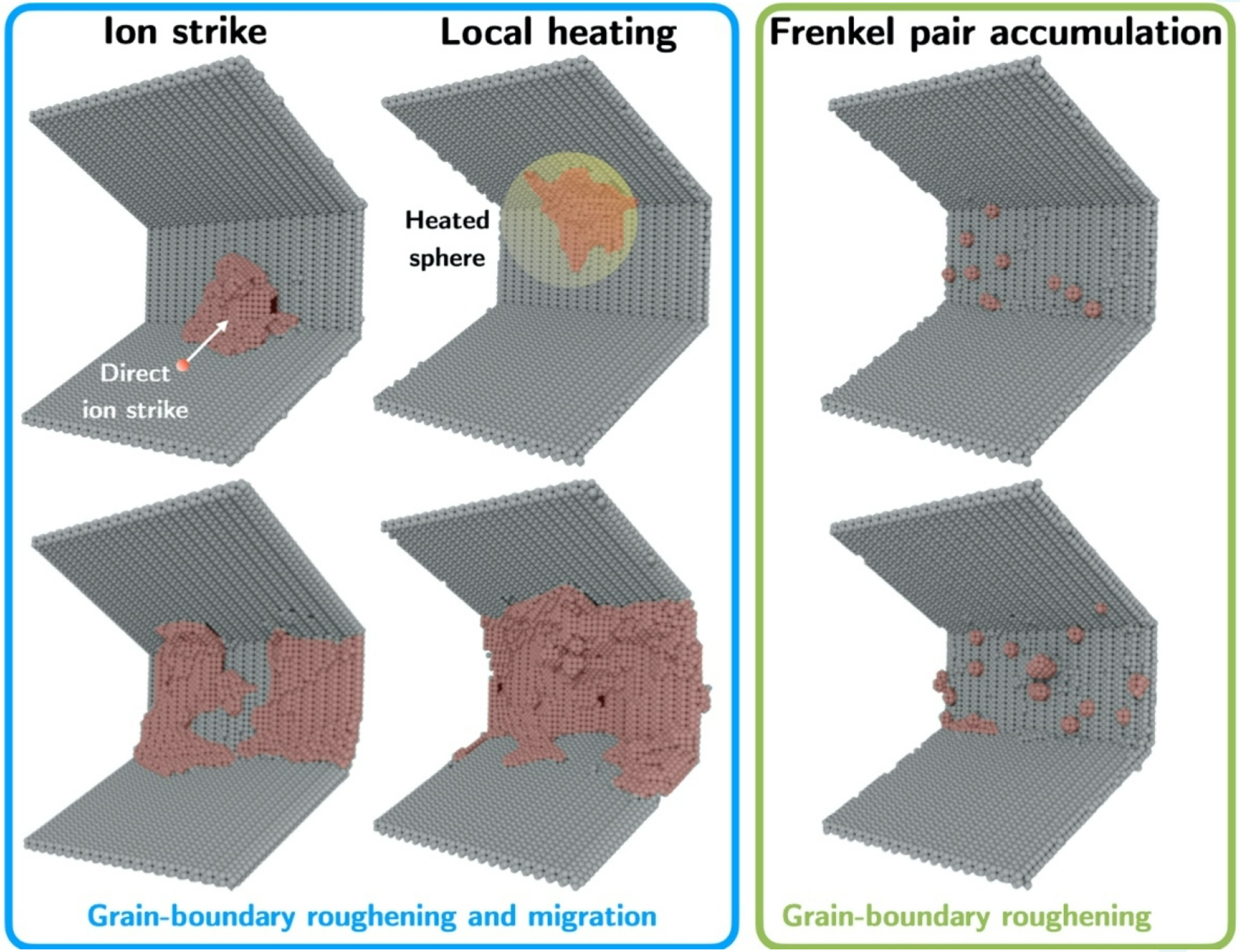
What unit mechanism(s) cause migration?



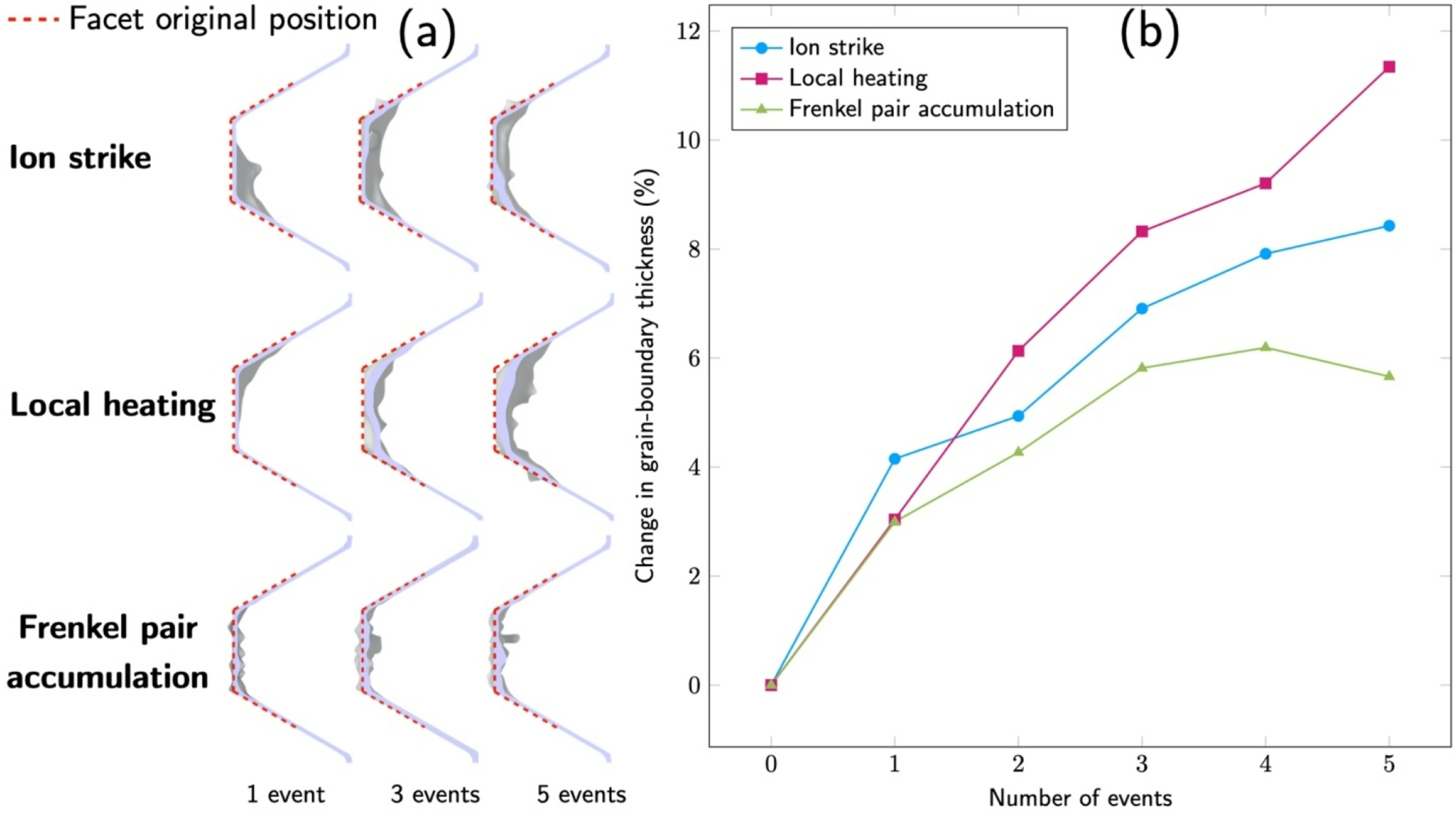
Atomistic simulation

After 1 event

After 5 events



Atomistic simulation

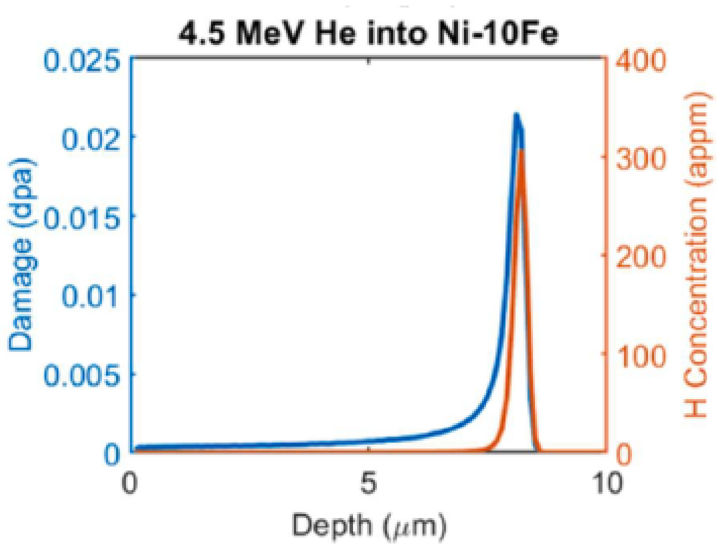


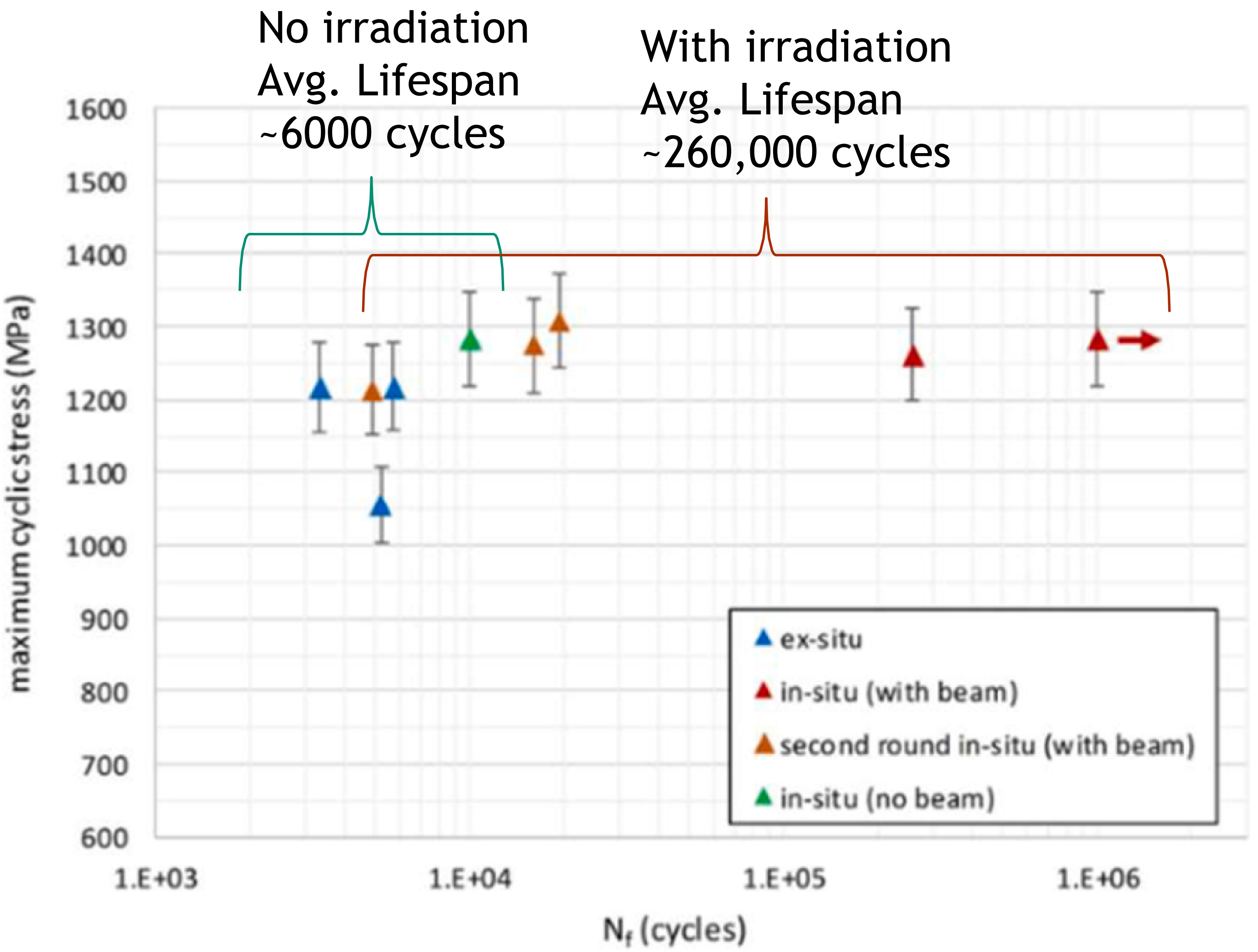
Summary…

High-cycle fatigue, and in particular crack initiation, of nanocrystalline metals seems to be facilitated by grain growth

In general, non-depositing radiation damage serves to heat a GB and induce defects, seemingly stimulating boundary motion and grain growth

Bottom line up front:
enhanced fatigue resistance under irradiation?





What else?
Compressive residual stress?
Radiation-induced strengthening?
Complex defect-interactions?

Briggs et al., *Nucl Inst. Meth. Phys. Res.*, 2021