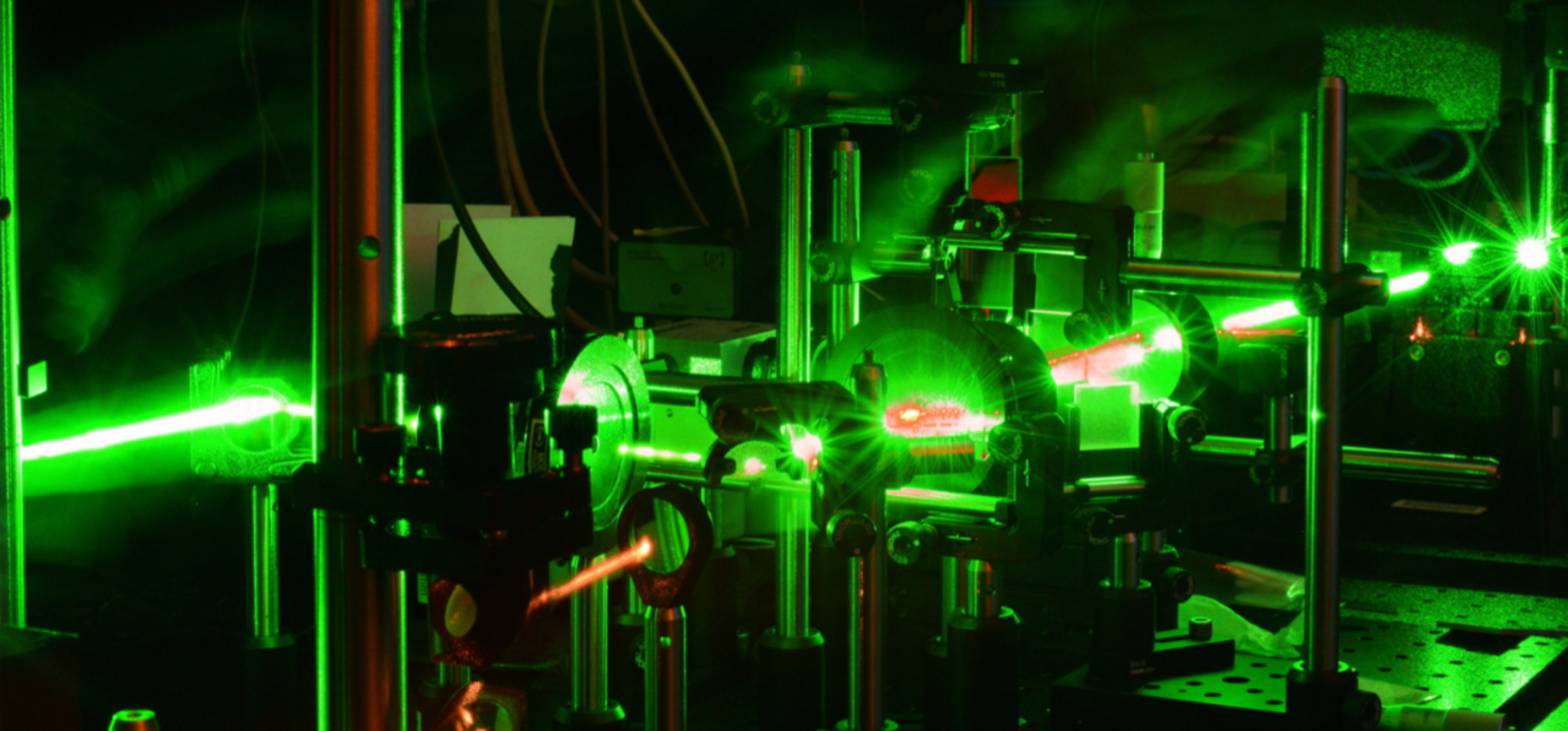
Irradiation-induced void swelling in pure copper characterized using transient grating spectroscopy

SAND2017-12014C

Innovation in Nuclear Technology R&D Awards

ANS Winter Meeting, 2017



Cody A. Dennett

Kangpyo So

Akihiro Kushima

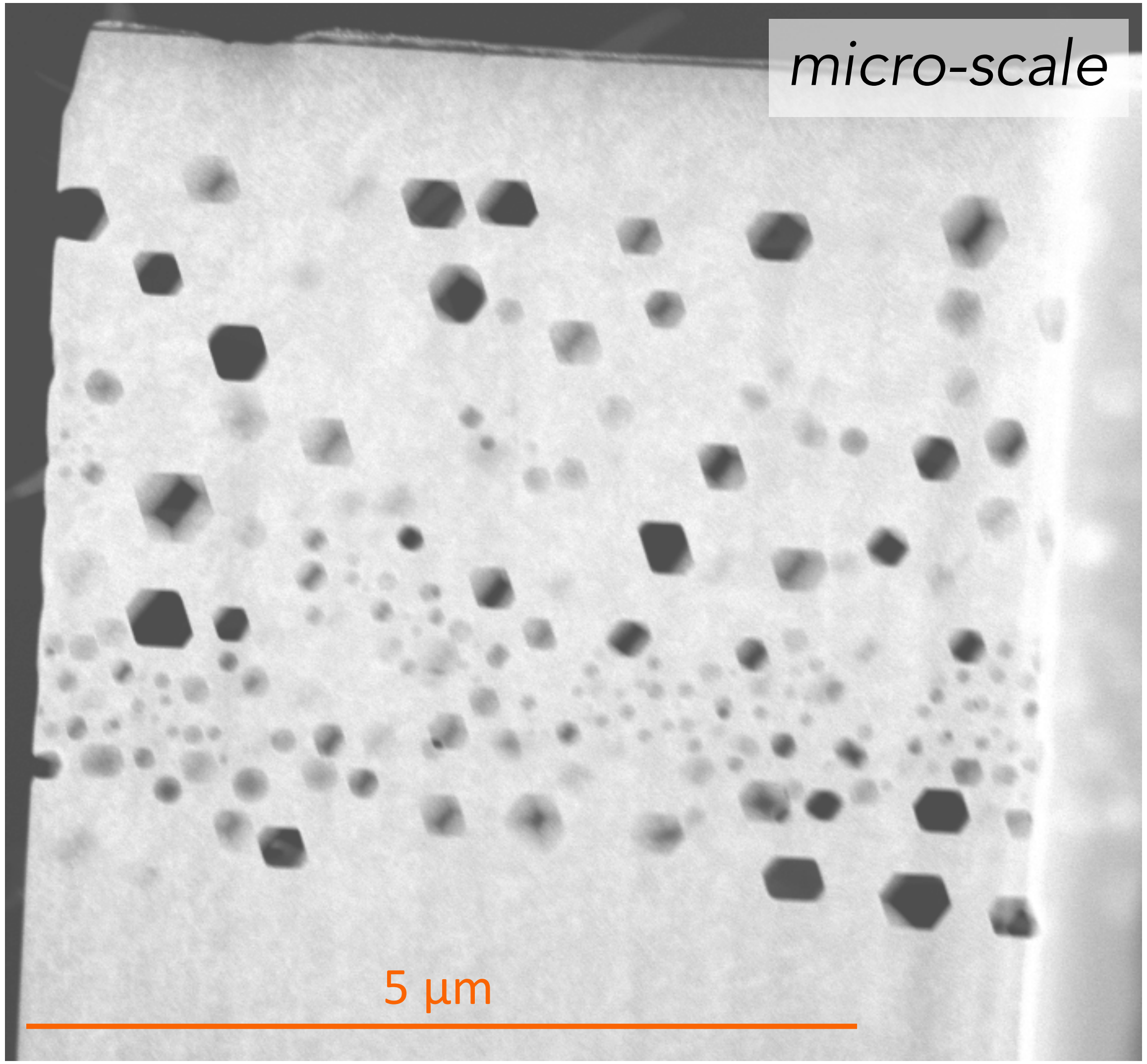
Khalid Hattar

Michael P. Short

Nuclear materials development has a two-fold problem

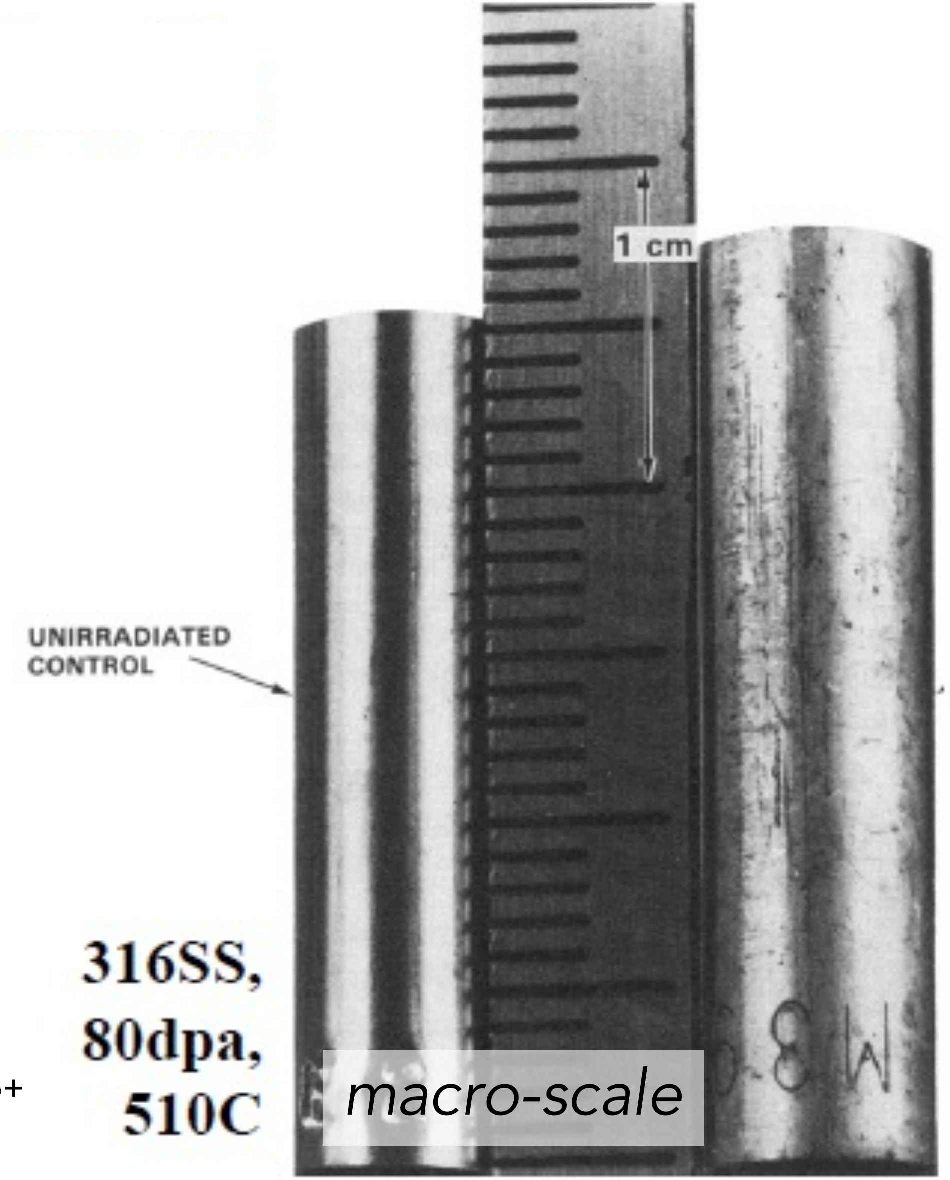
Radiation-enhanced material degradation

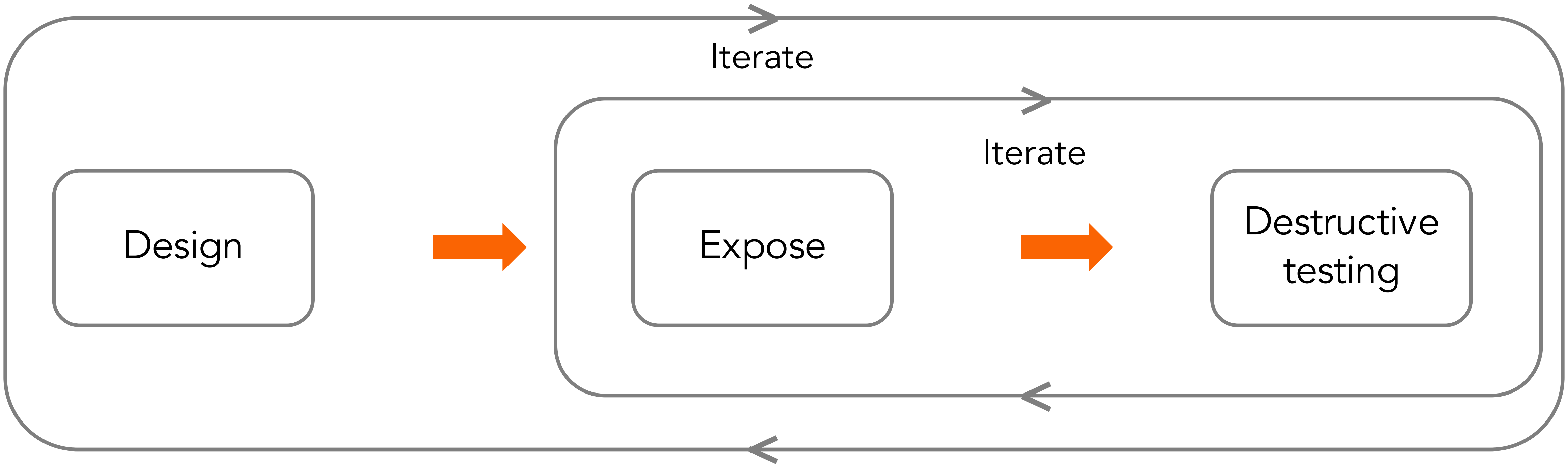
Design process and time scale



Pure Cu
35 MeV Cu^{6+}
400°C

316SS,
80dpa,
510C





- Time
- Temperature
- Radiation
- (Corrosive conditions)

- Electron microscopy
- Fracture analysis
- Impact testing

Reactor irradiations

maximum of

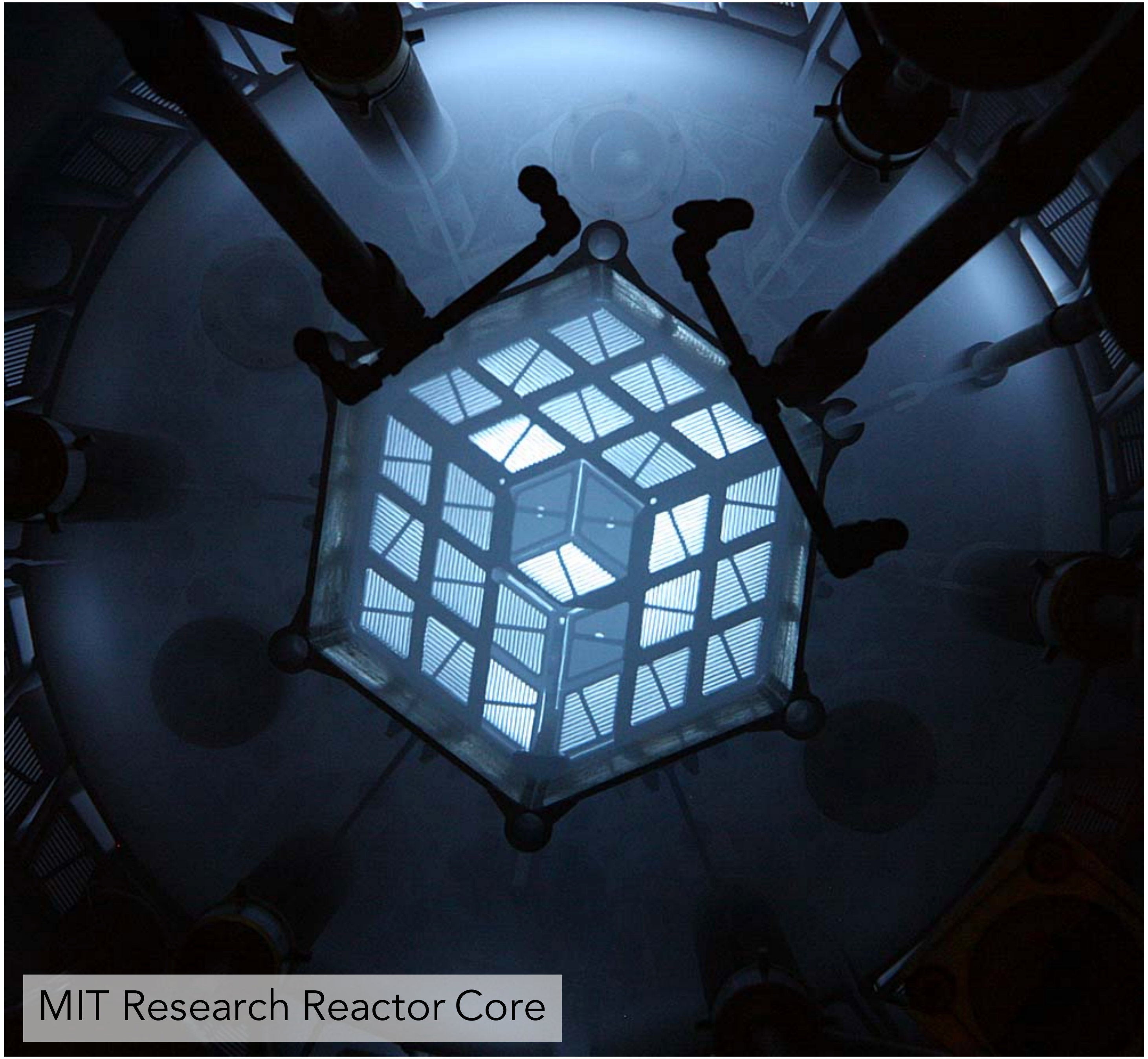
~1 dpa/year

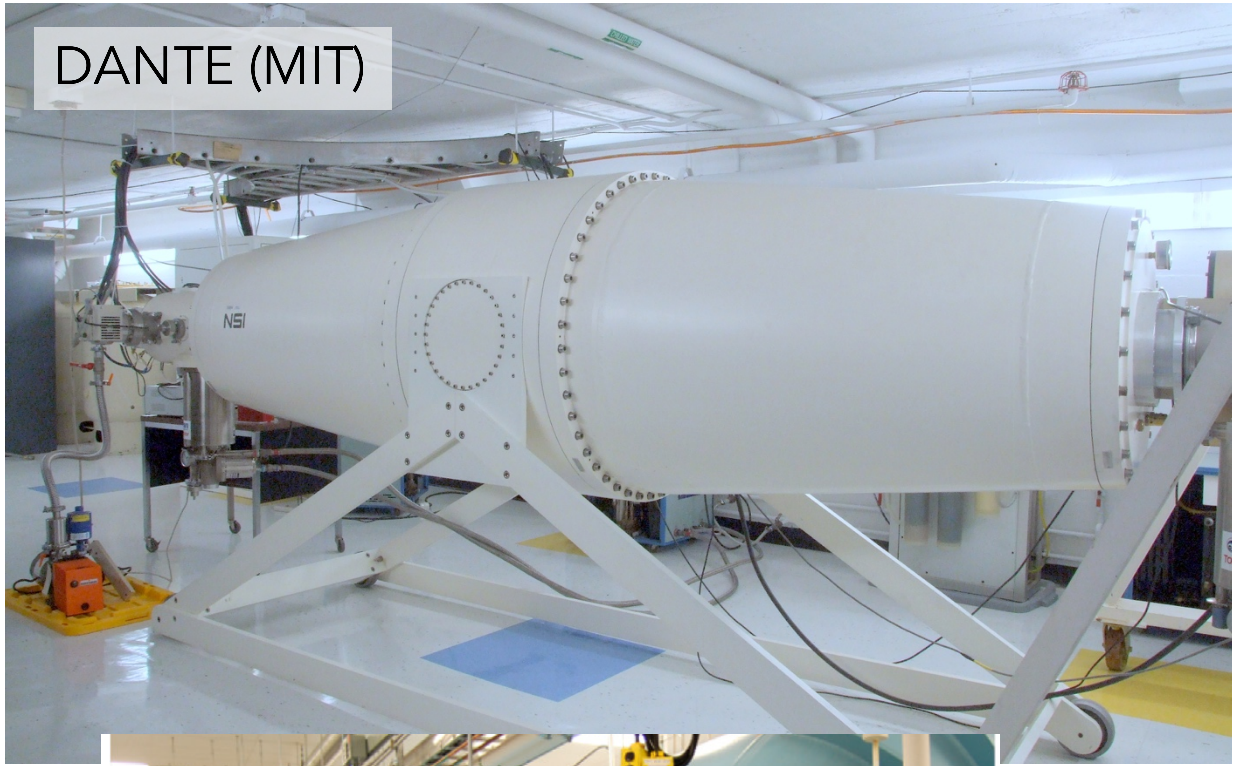
(MITR)

maximum of

~25 dpa/year

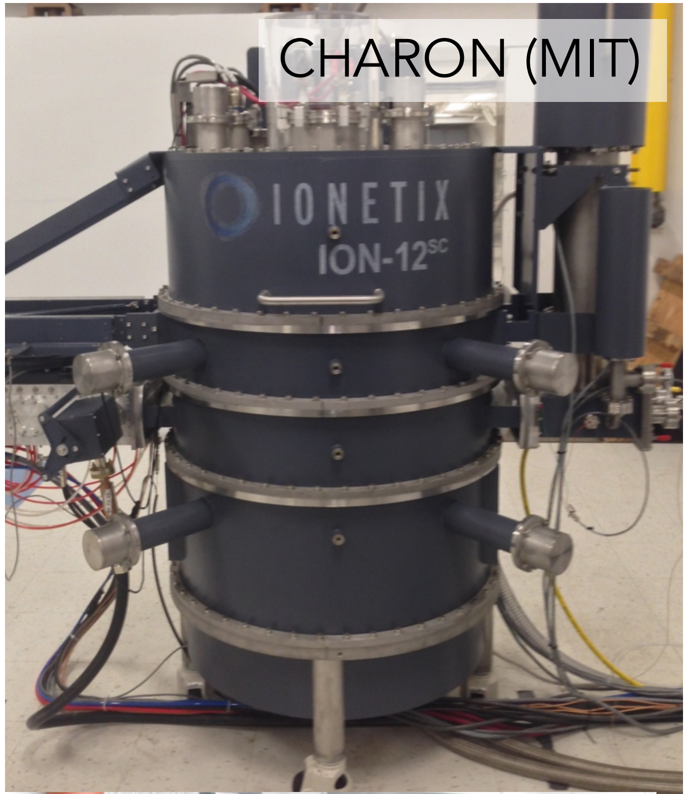
(BOR-60)

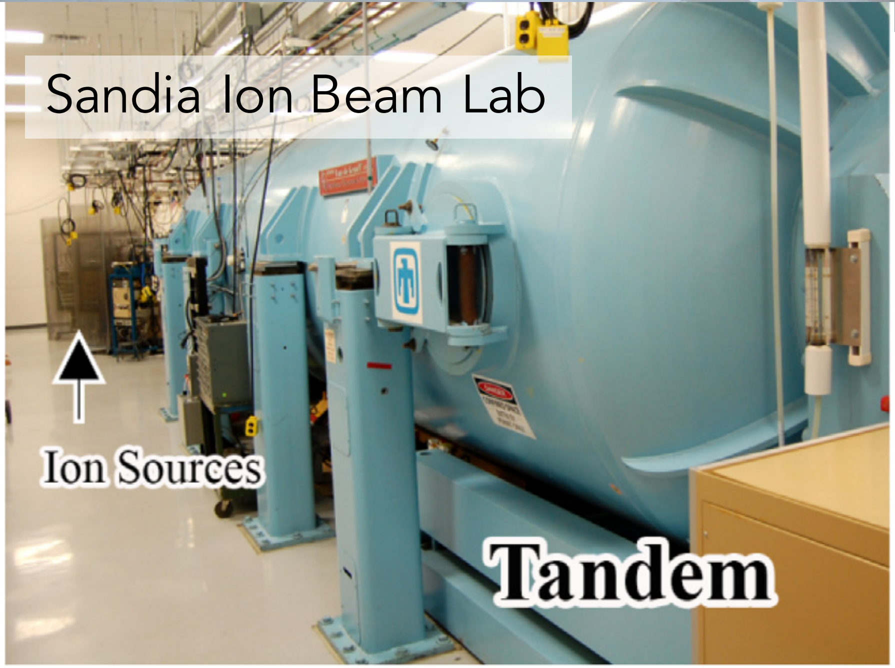


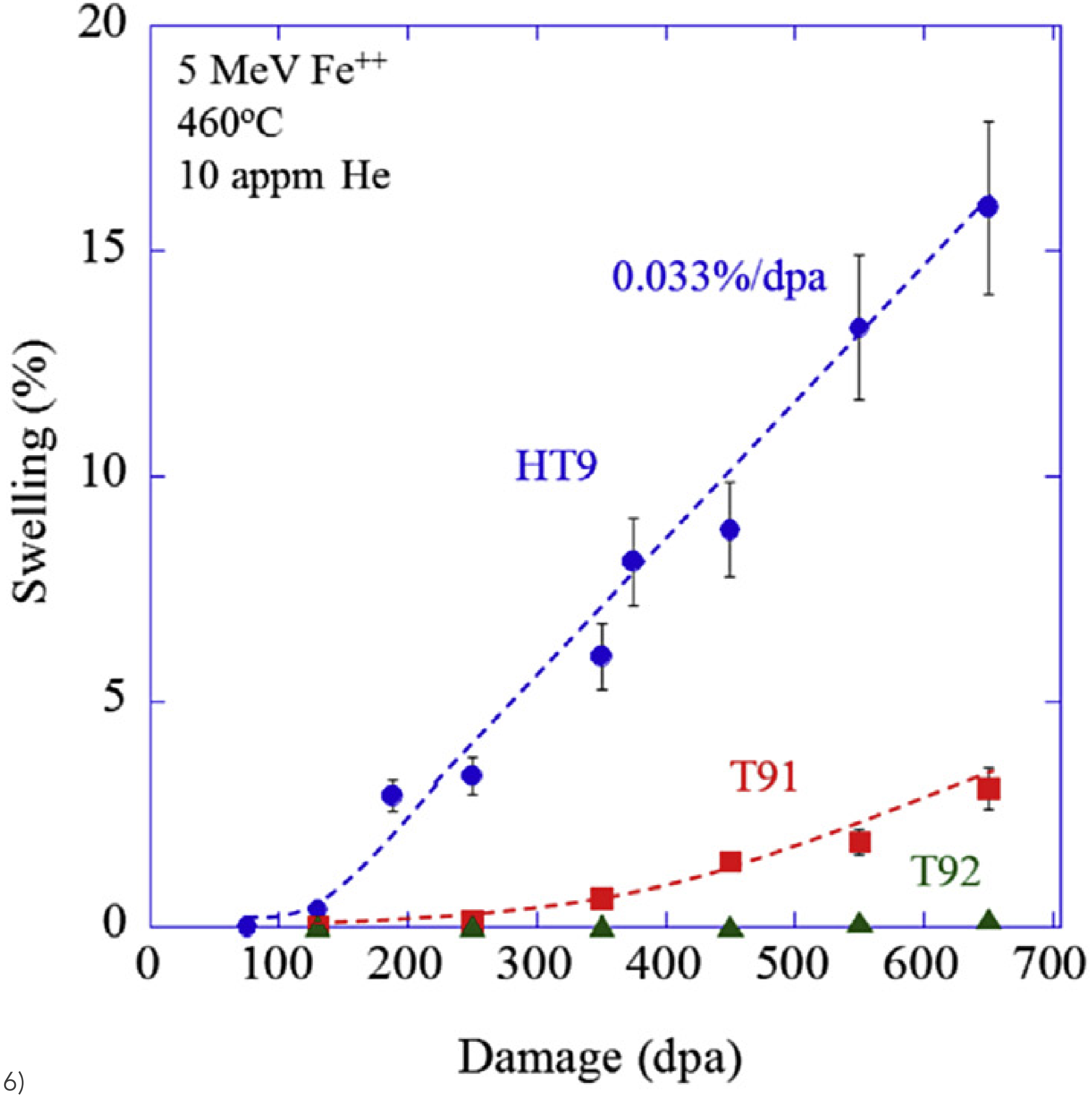


Ion beam irradiations

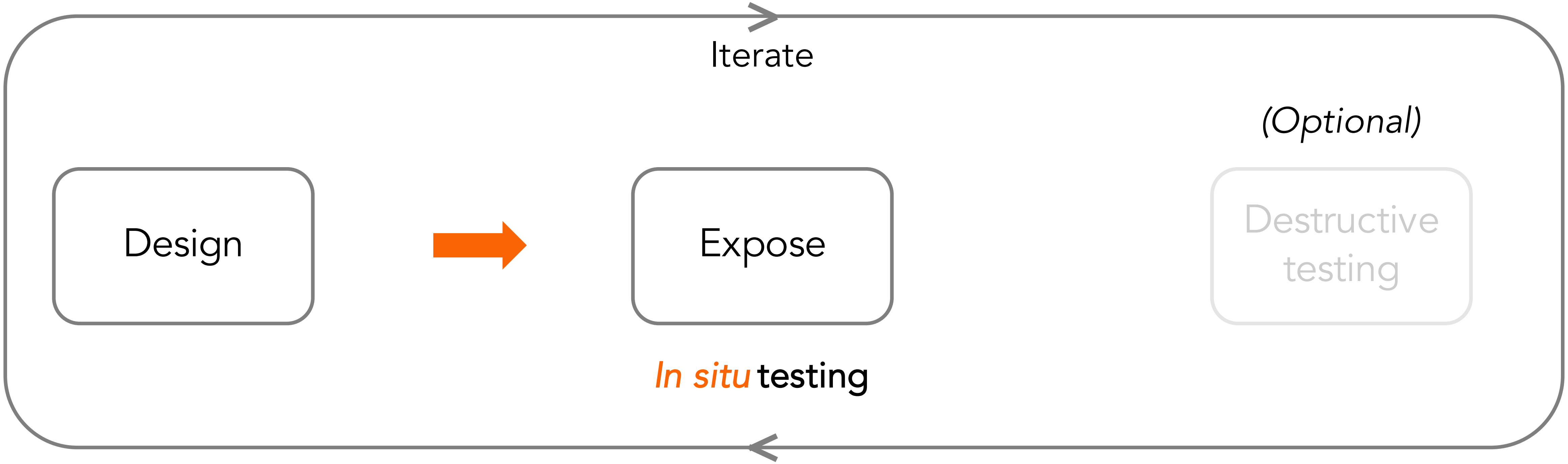
up to
5 dpa/hr







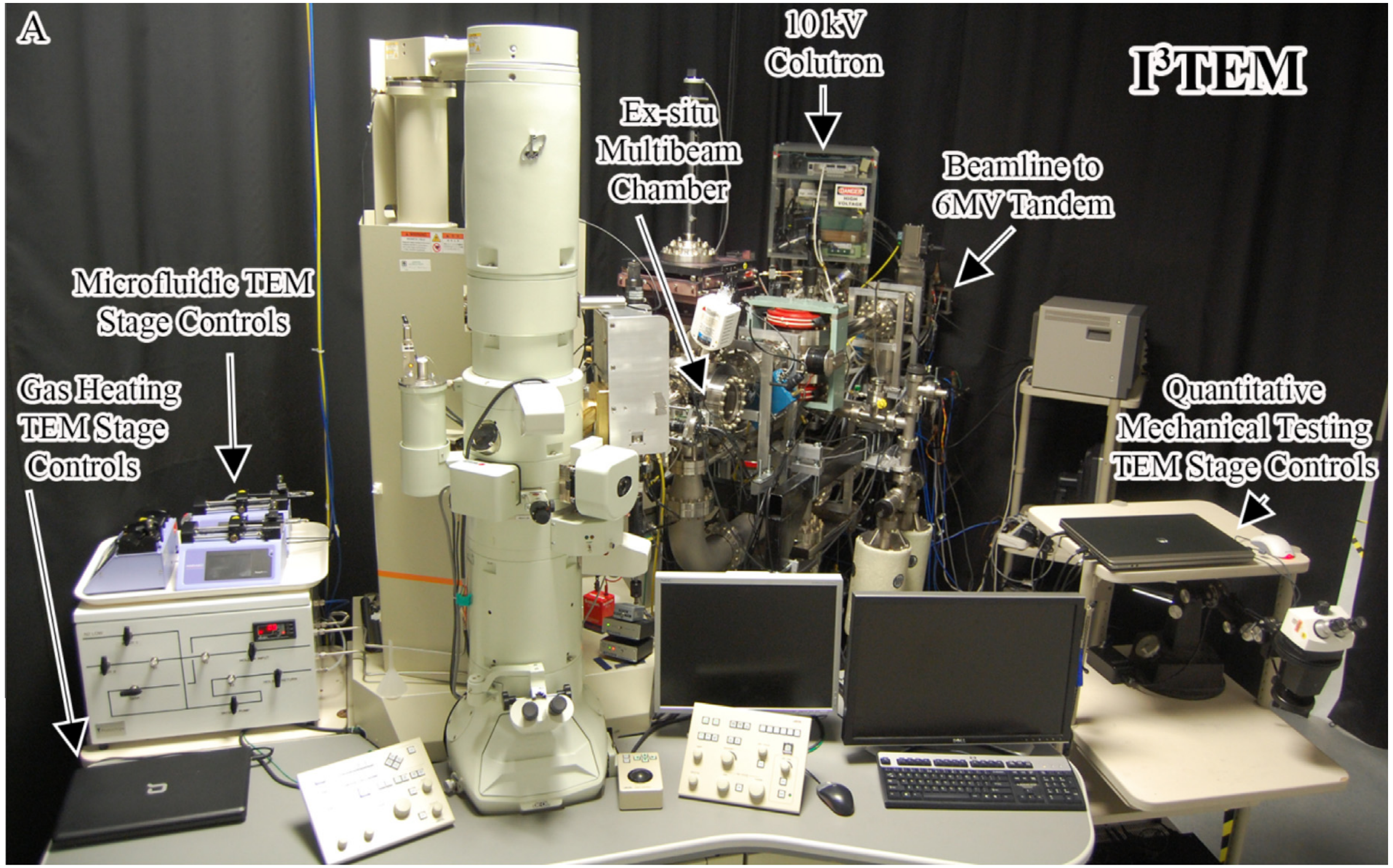
Getto et. al., *J. Nucl. Mater.,* 480 (2016)



- Time
- Temperature
- Radiation
- (Corrosive conditions)

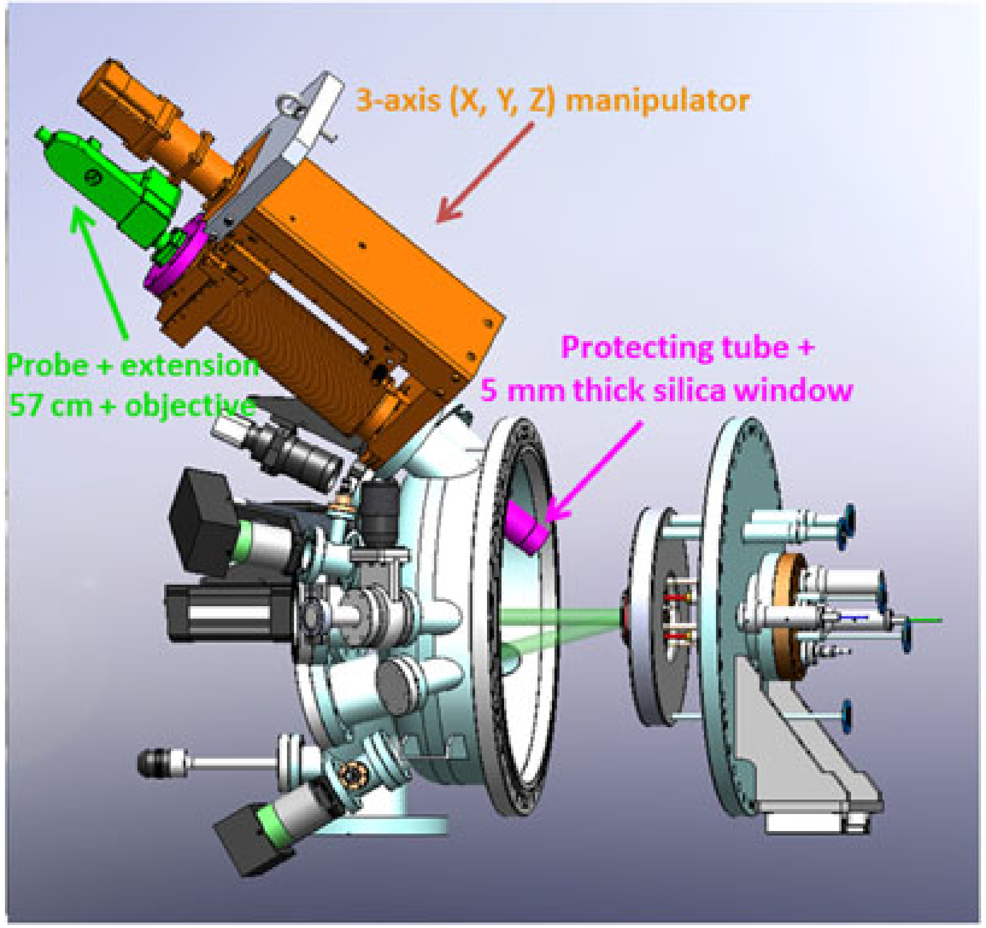
- Electron microscopy
- Fracture analysis
- Impact testing

In situ TEM
Sandia Ion Beam Lab



K. Hattar et al., *Nucl. Instr. Meth. Phys. Res. B*, **338** (2014)

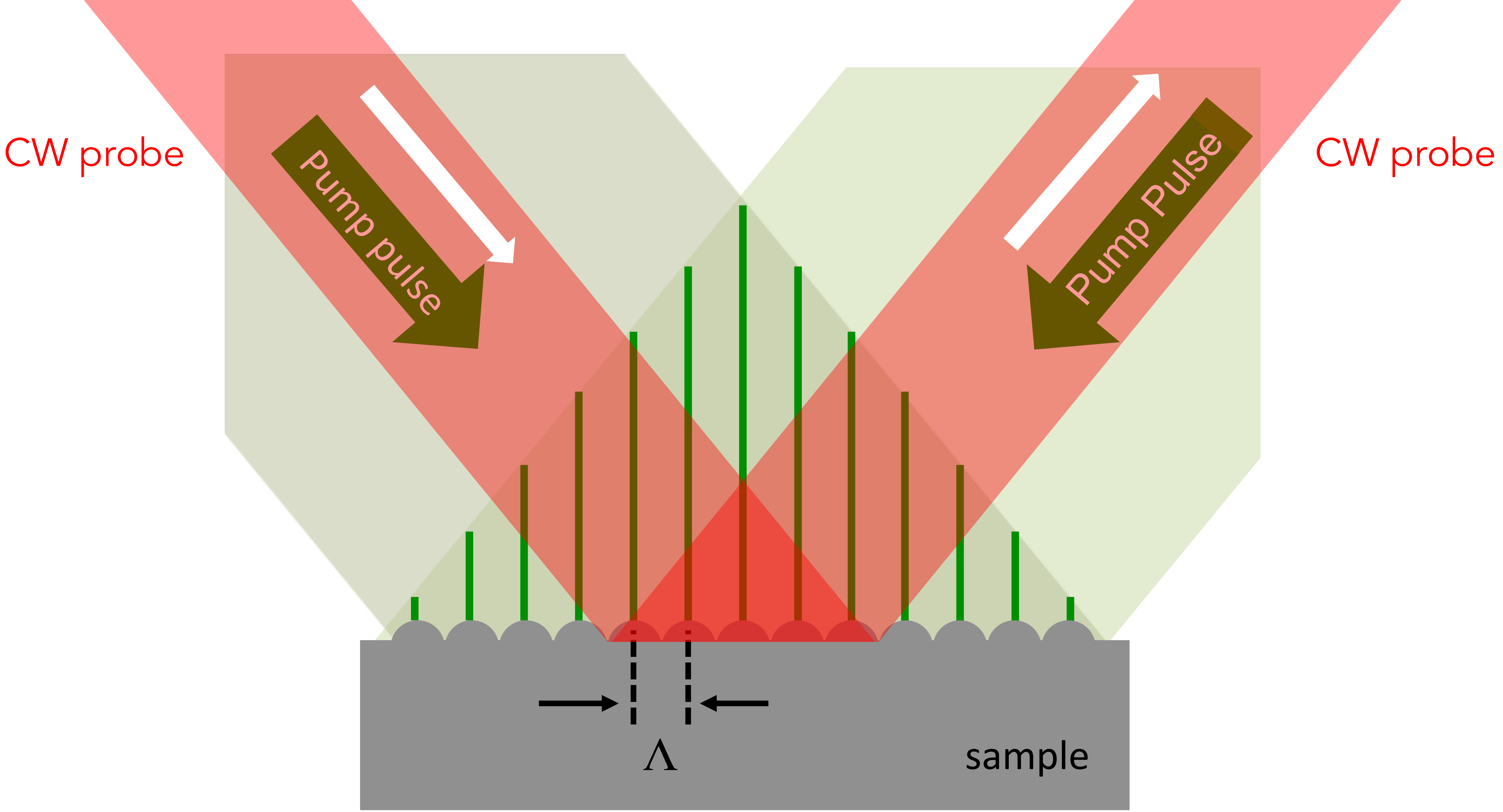
In situ Raman Spectroscopy
JANUUS-Saclay



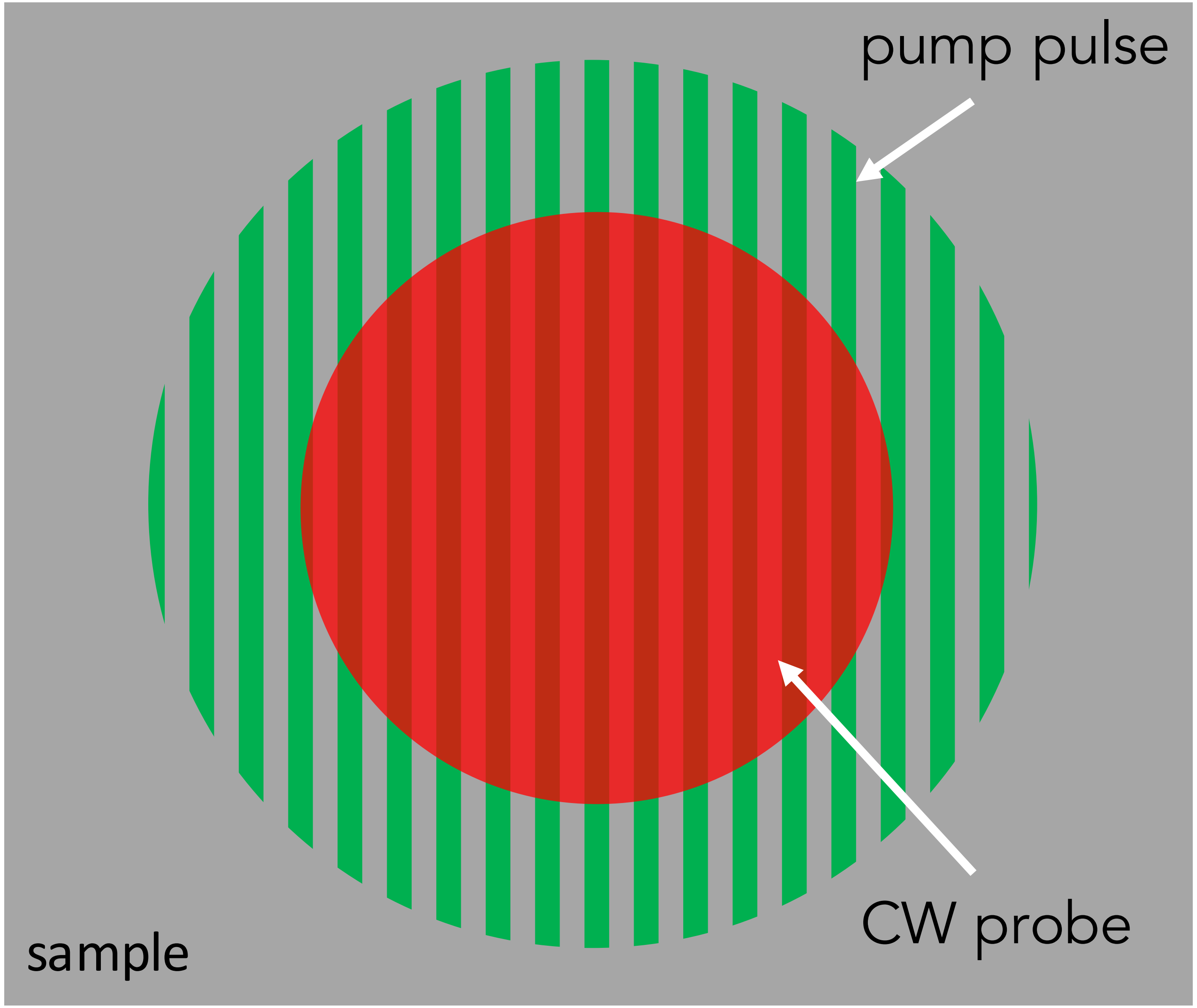
S. Miro et al., *J. Raman Spectrosc.*, **47** (2016)

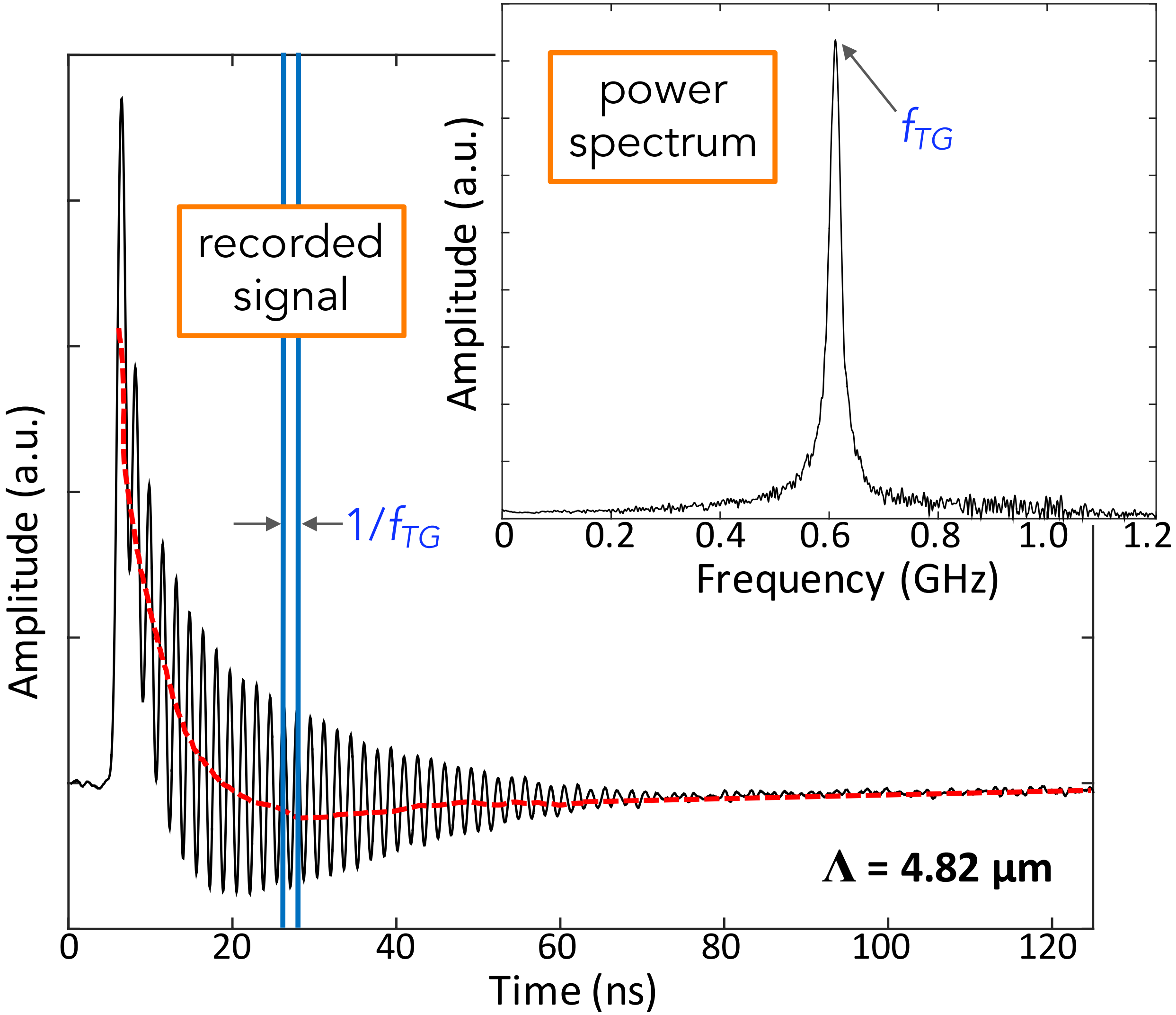
Transient Grating Spectroscopy (TGS)

(image from title slide here)



Dennett et. al., *Phys. Rev. B*, **94** (2016)


pump pulse
CW probe
sample

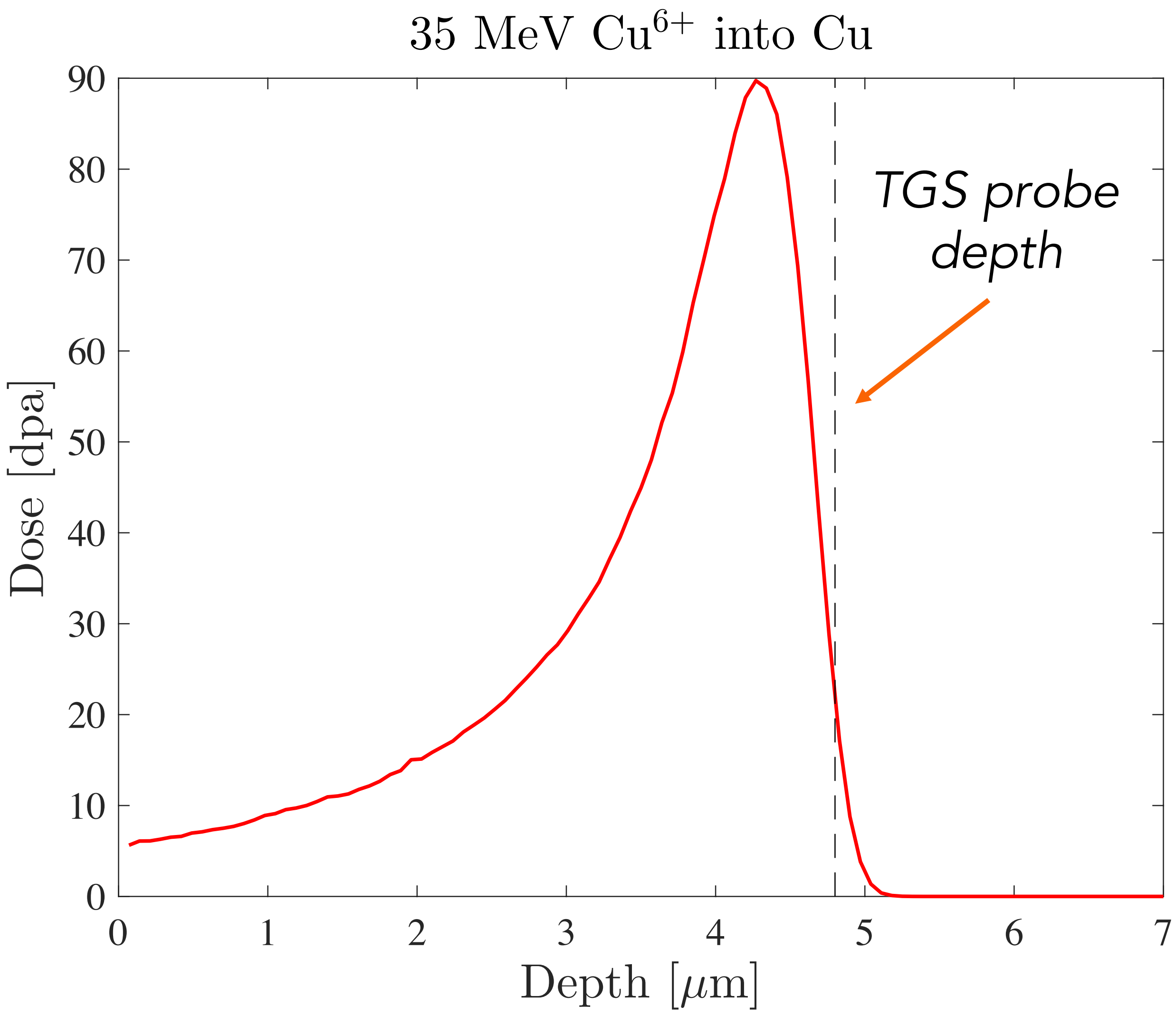


Acoustic oscillations return **elastic mechanical** properties

Grating decay returns **thermal transport** properties

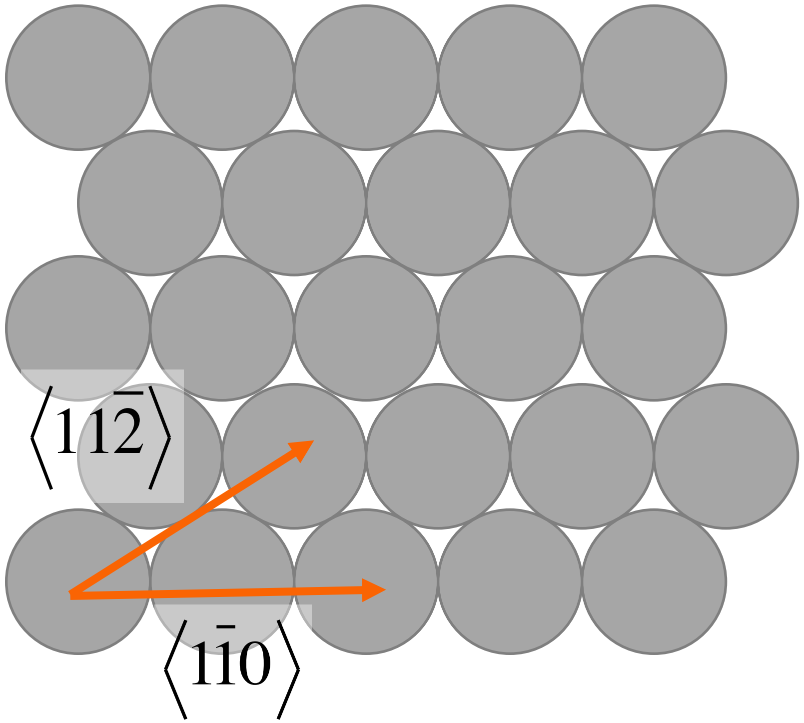
Dennett et. al., *Phys. Rev. B*, **94** (2016)

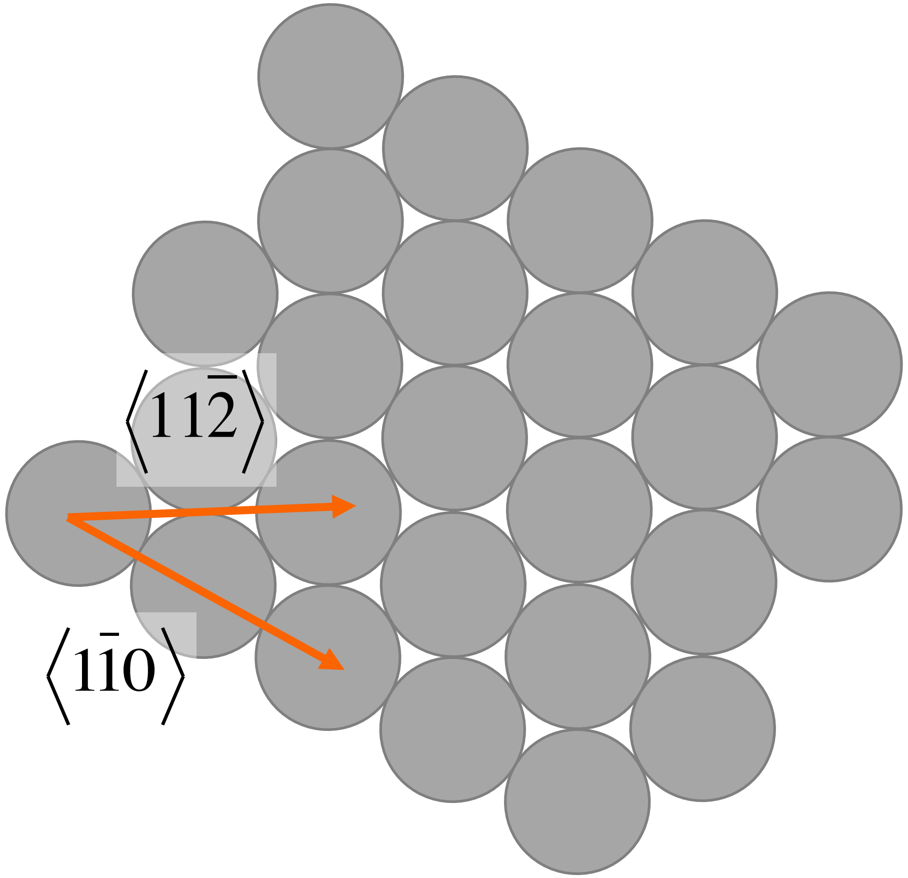
Material	Single crystal {111} Cu
Ion Species	Cu^{6+}
Ion Energy	35 MeV
Temperature	400˚C
Spot Size	0.19 cm^2
Beam Current	100-250 nA
Target Doses	[0, 5, 10, 30, 50, 100] dpa



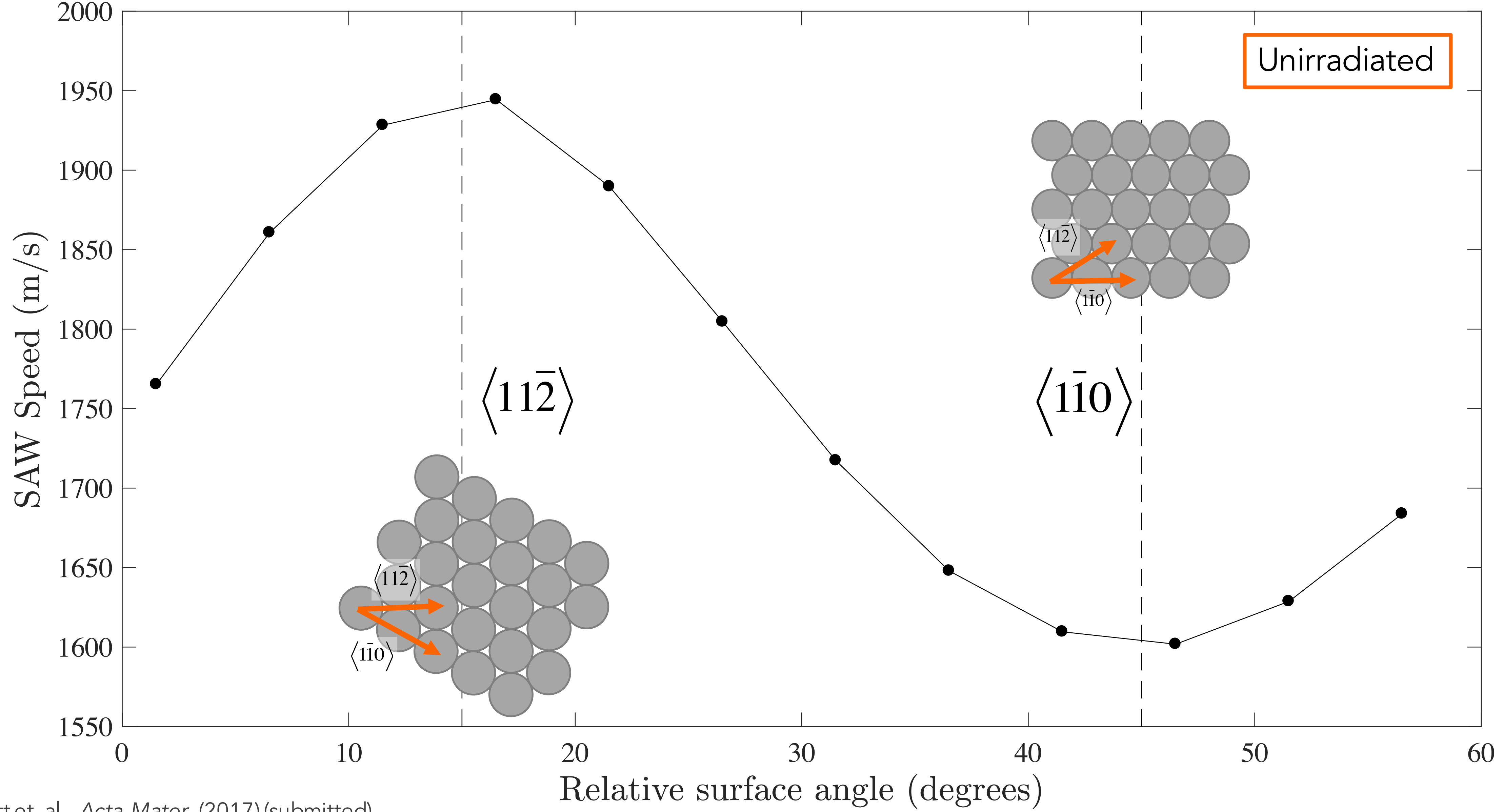
Dennett et. al., *Acta Mater.* (2017) (submitted)

{111} *plane – face centered cubic*



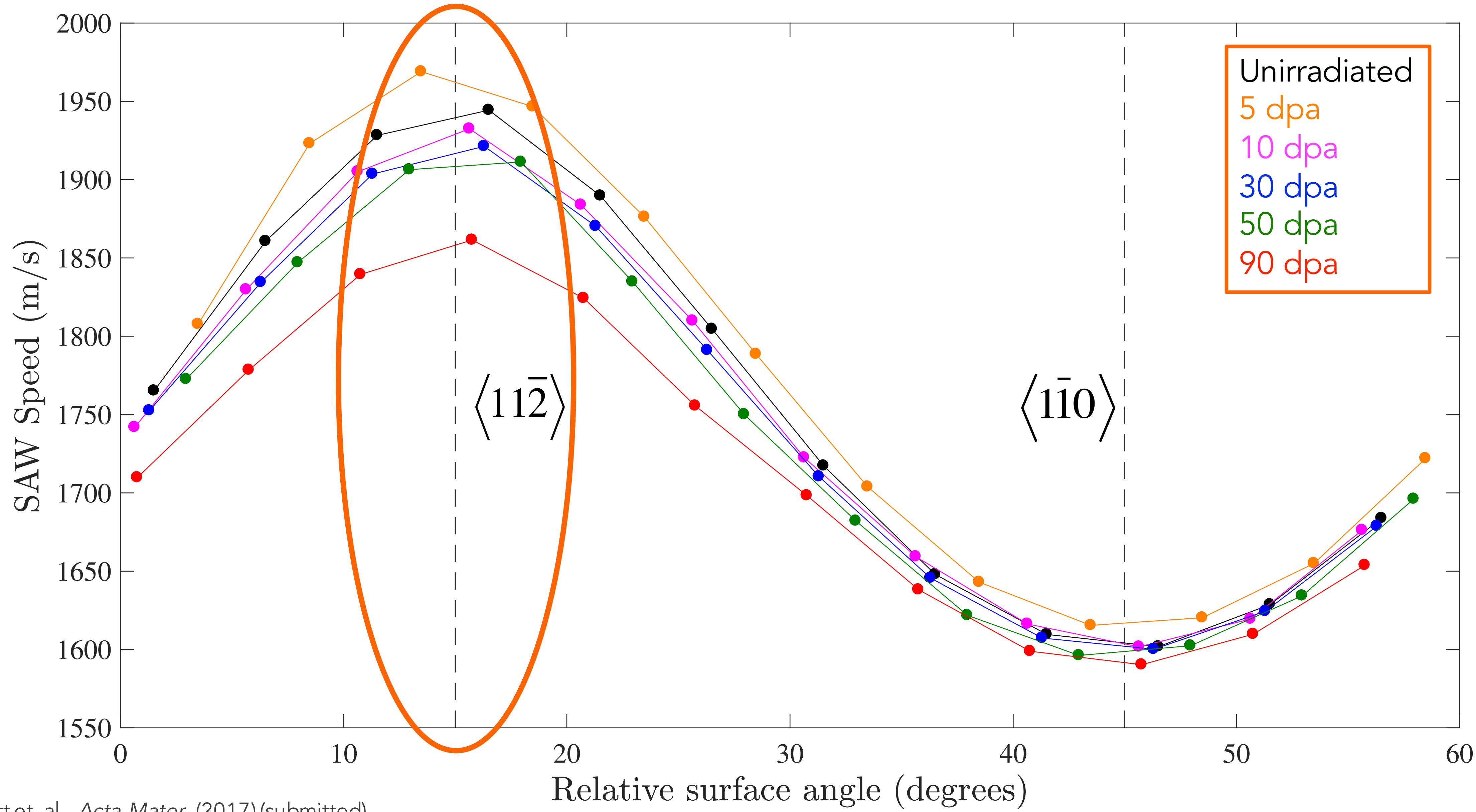


Surface acoustic wave (SAW) response of irradiated Cu

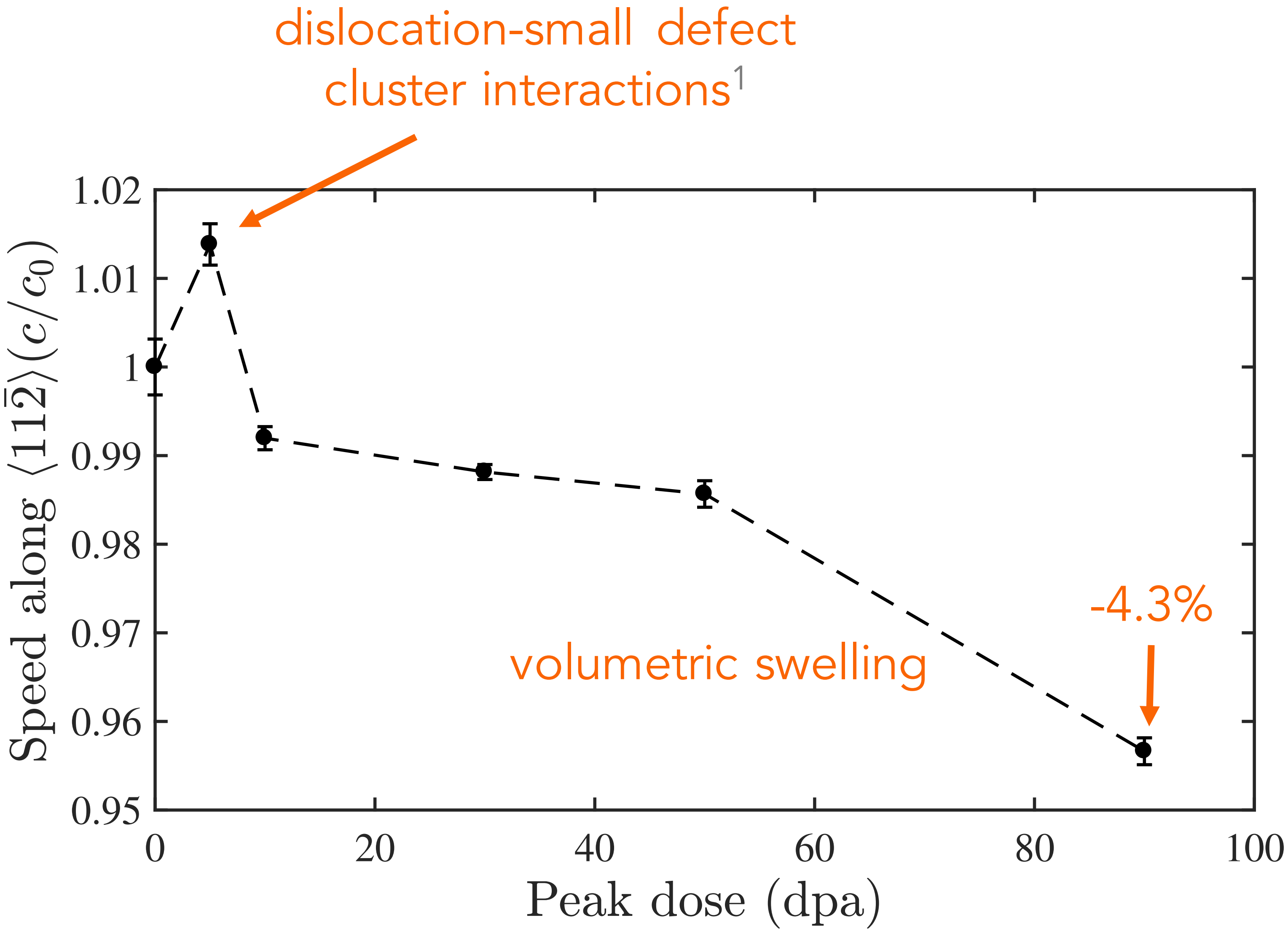


Dennett et. al., *Acta Mater.* (2017) (submitted)

Surface acoustic wave (SAW) response of irradiated Cu



Dennett et. al., *Acta Mater.* (2017) (submitted)



Dennett et. al., *Acta Mater.* (2017) (submitted)

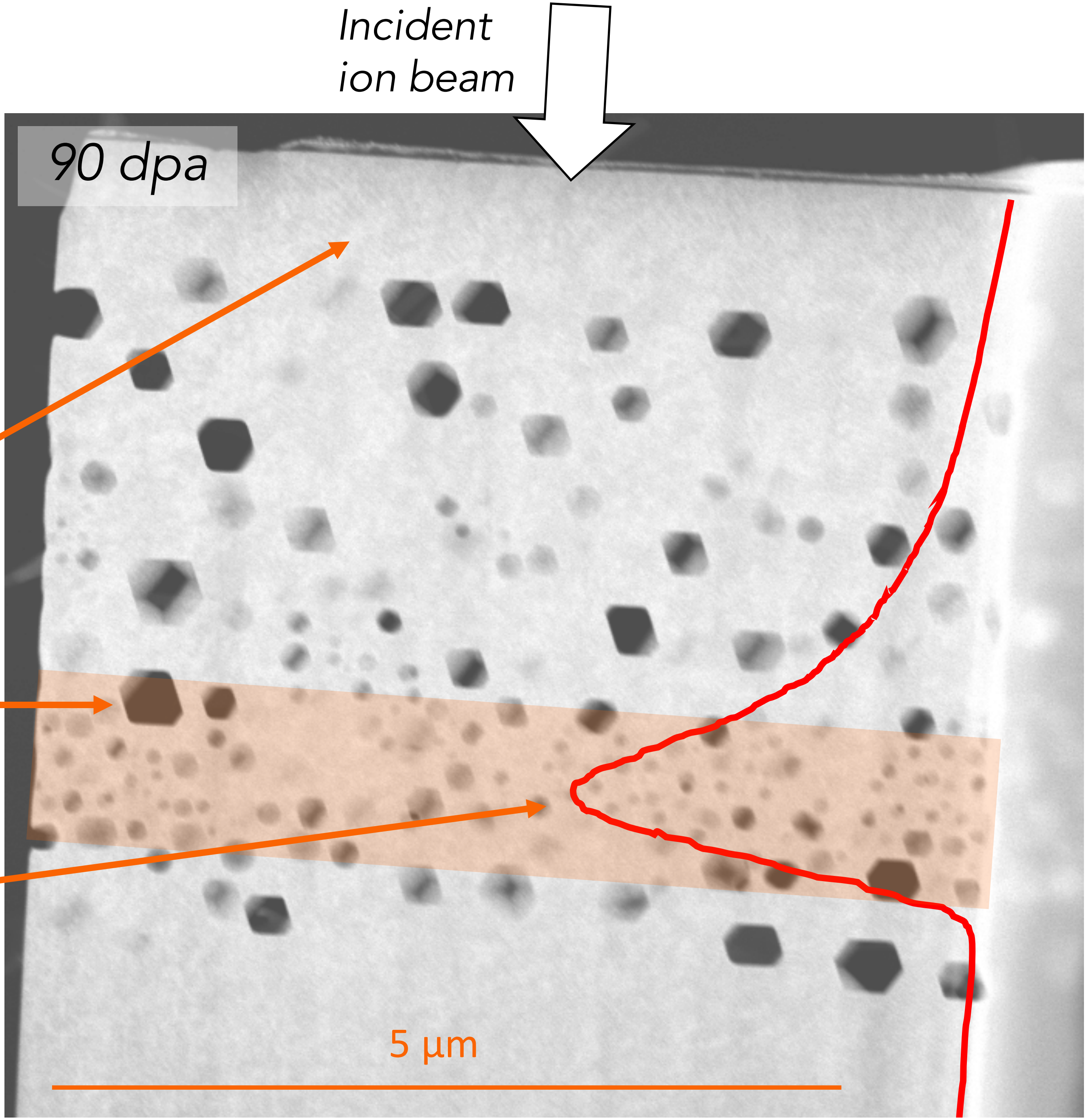
[1]Parkin et. al., *J. Phys. F: Met. Phys.*, **17** (1987)

High angle annular dark field scanning transmission electron micrograph (HAADF-STEM)

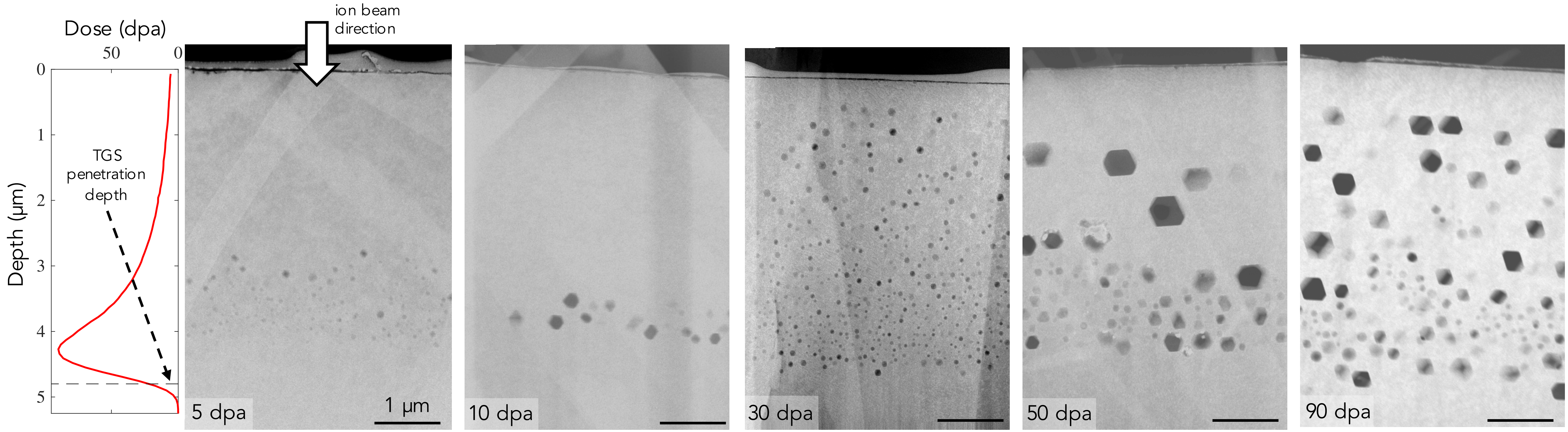
Void denuded zone

Large, crystallographic voids

High density, small size near damage peak



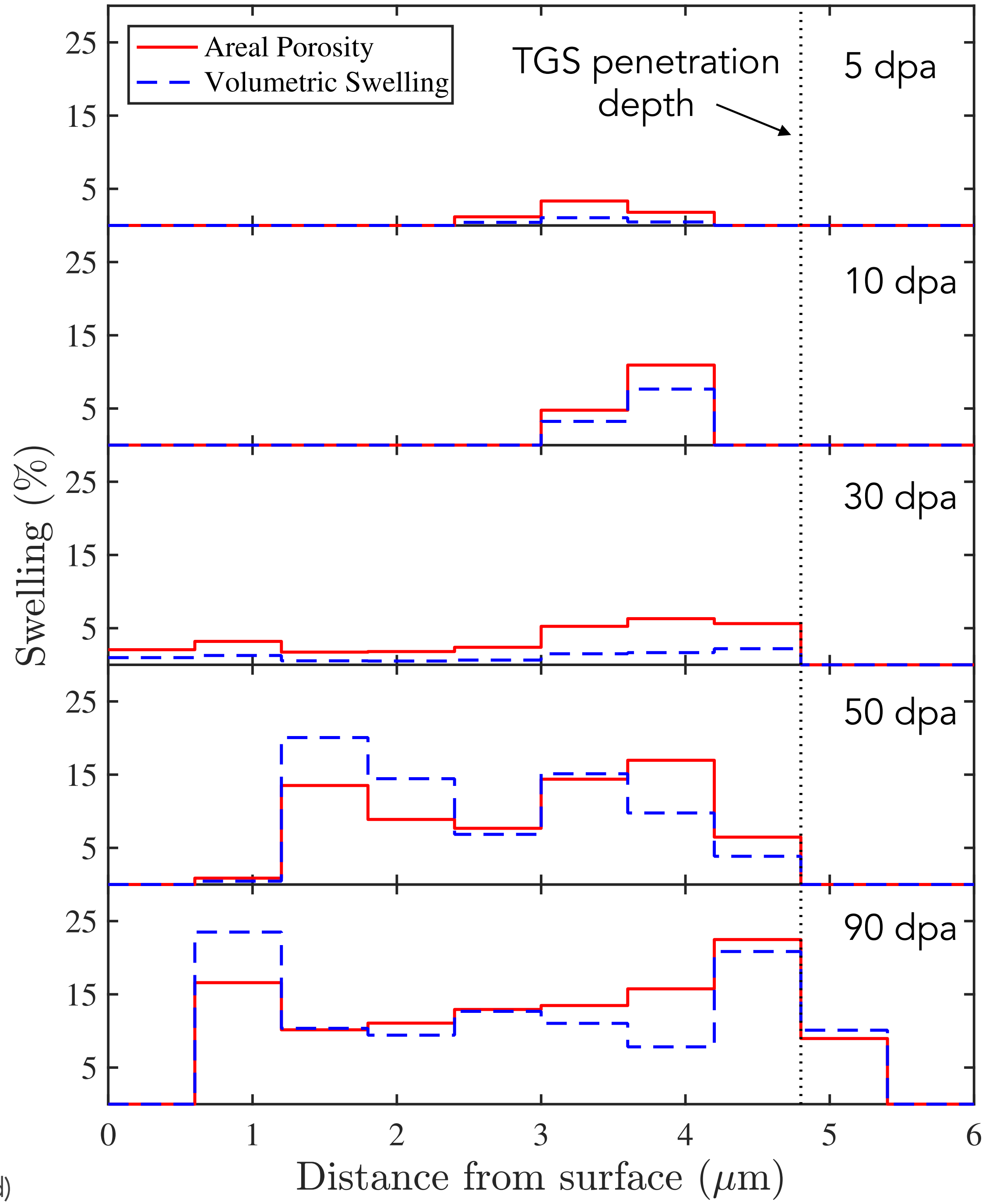
Dennett et. al., *Acta Mater.* (2017) (submitted)



1.9×10^{-3} dpa/s

0.85×10^{-3} dpa/s

Dennett et. al., *Acta Mater.* (2017) (submitted)

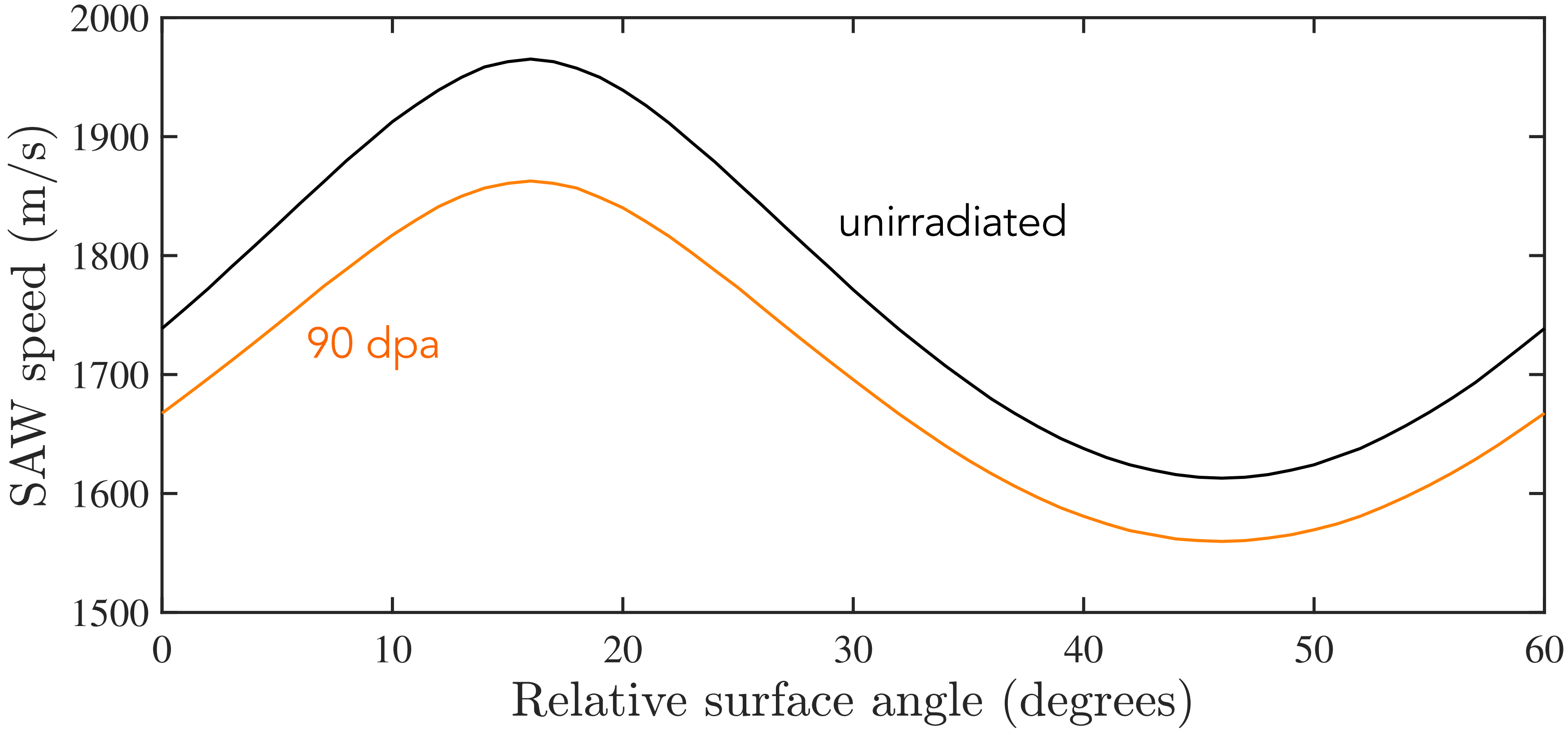


Dennett et. al., *Acta Mater.* (2017) (submitted)

Peak dose at 4.25 um (dpa)	Intermediate dose at 2.4 um (dpa)	Peak dose rate ($\times 10^{-3}$ dpa/s)	$\Delta c/c_0$ along $\langle 11\bar{2} \rangle$ (%)	Areal porosity (%)	Volumetric swelling (%)
5.0	1.1	1.5	1.38	0.79	0.24
10	2.1	1.9	-0.80	1.96	1.36
30	6.3	0.85	-1.19	3.55	1.17
50	11	1.0	-1.43	8.59	8.82
90	19	1.7	-4.34	12.8	12.0

Dennett et. al., *Acta Mater.* (2017) (submitted)

Elastic theory predicts the expected SAW speed on single crystal surfaces



minimize best-fit elastic constants based on TGS data

Zener anisotropy ratio

	ρ (g/cm^3)	C_{11} (GPa)	C_{12} (GPa)	C_{44} (GPa)	A	Speed along $\langle 11\bar{2} \rangle$ (m/s)	Speed along $\langle 1\bar{1}0 \rangle$ (m/s)
Unirradiated	8.96	165.9	119.6	73.51	3.18	1945	1601
90 dpa	7.81	137.7	99.35	56.24	2.93	1861	1559
% change	-12.8%	-17.0%	-17.0%	-23.5%	-7.9%	-4.35%	-0.75%

Dennett et. al., *Acta Mater.* (2017) (submitted)

To be a useful *in situ* diagnostic a new method must

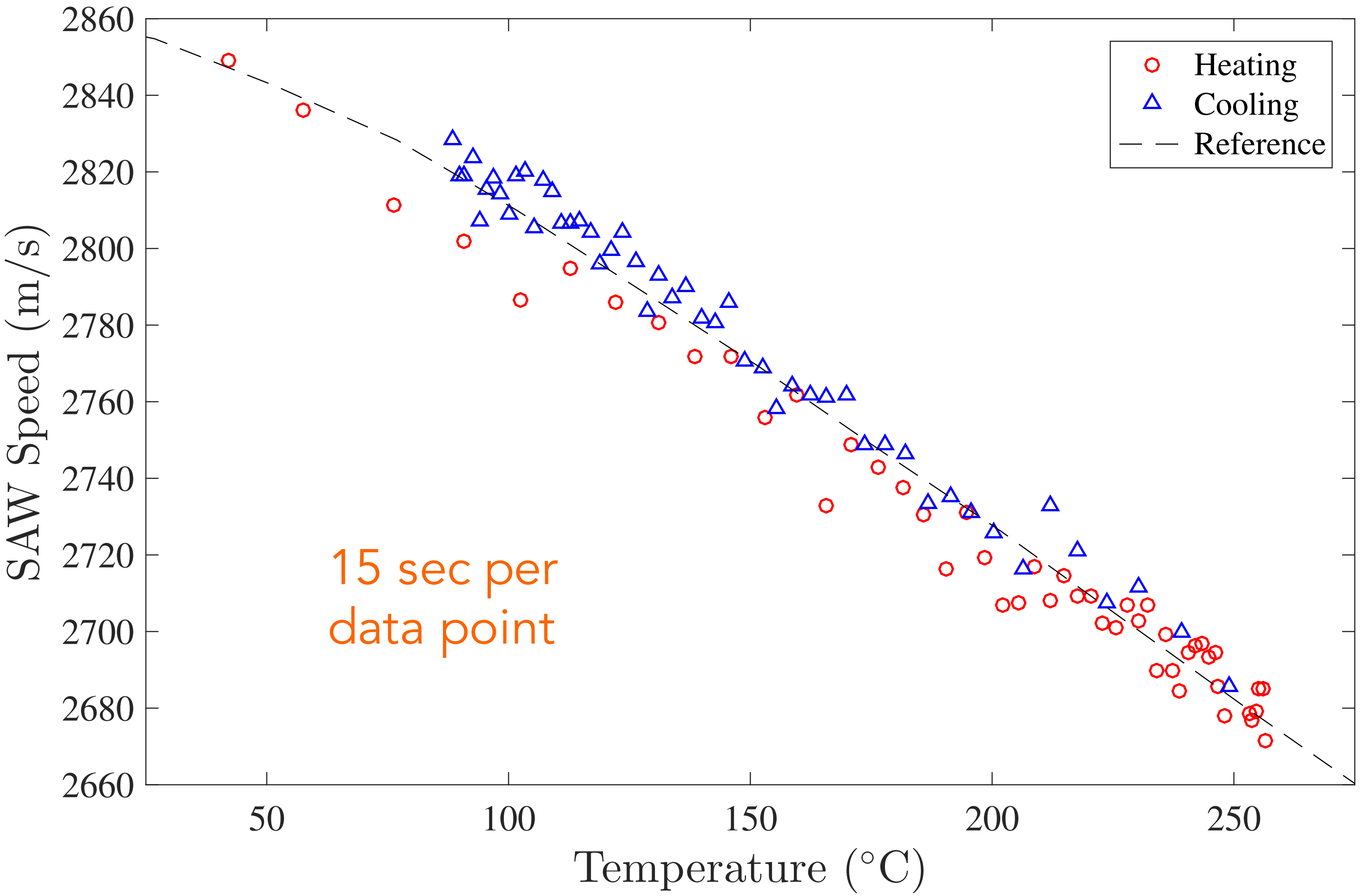
be non-destructive

be non-contact

measure appropriate physical quantities

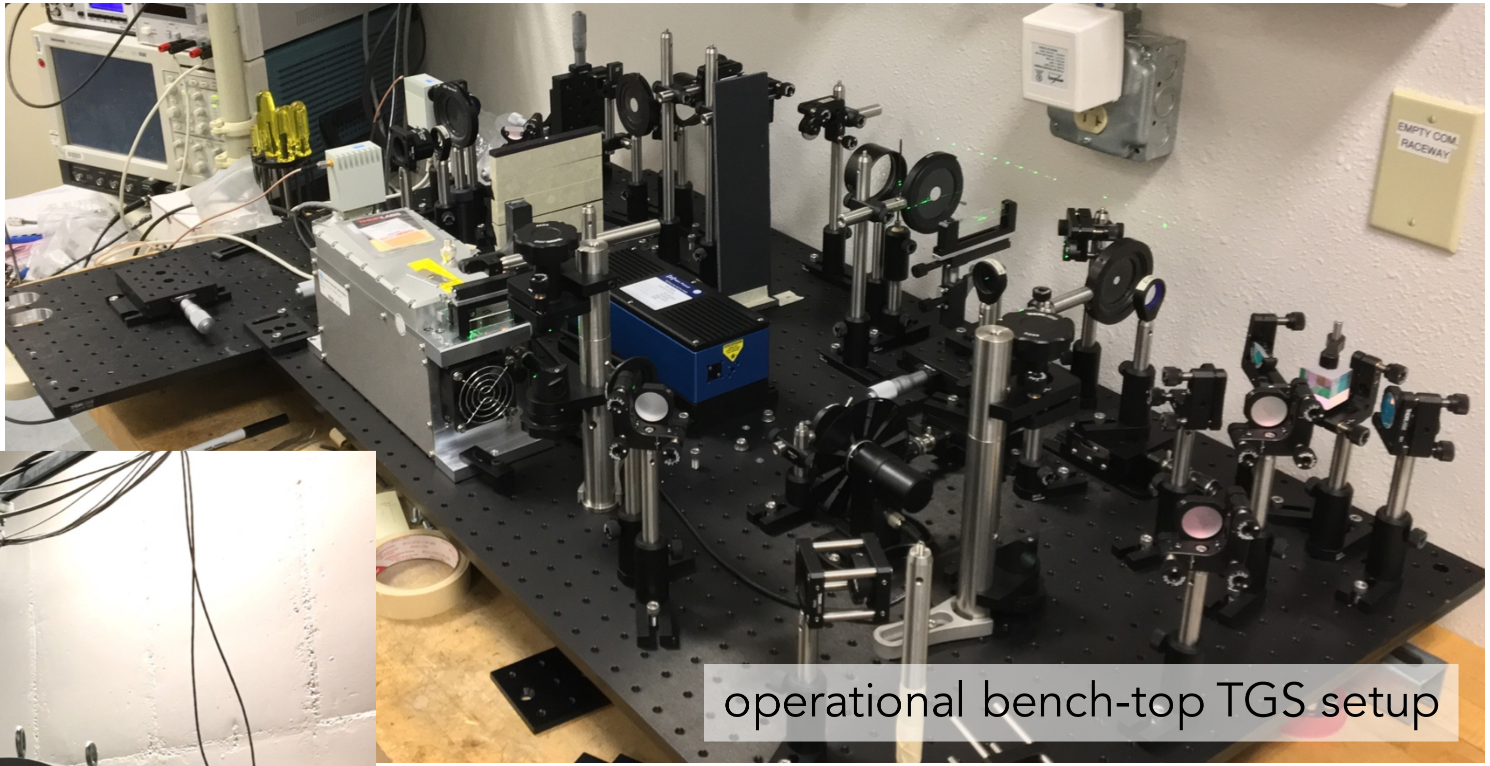
have sufficient time resolution

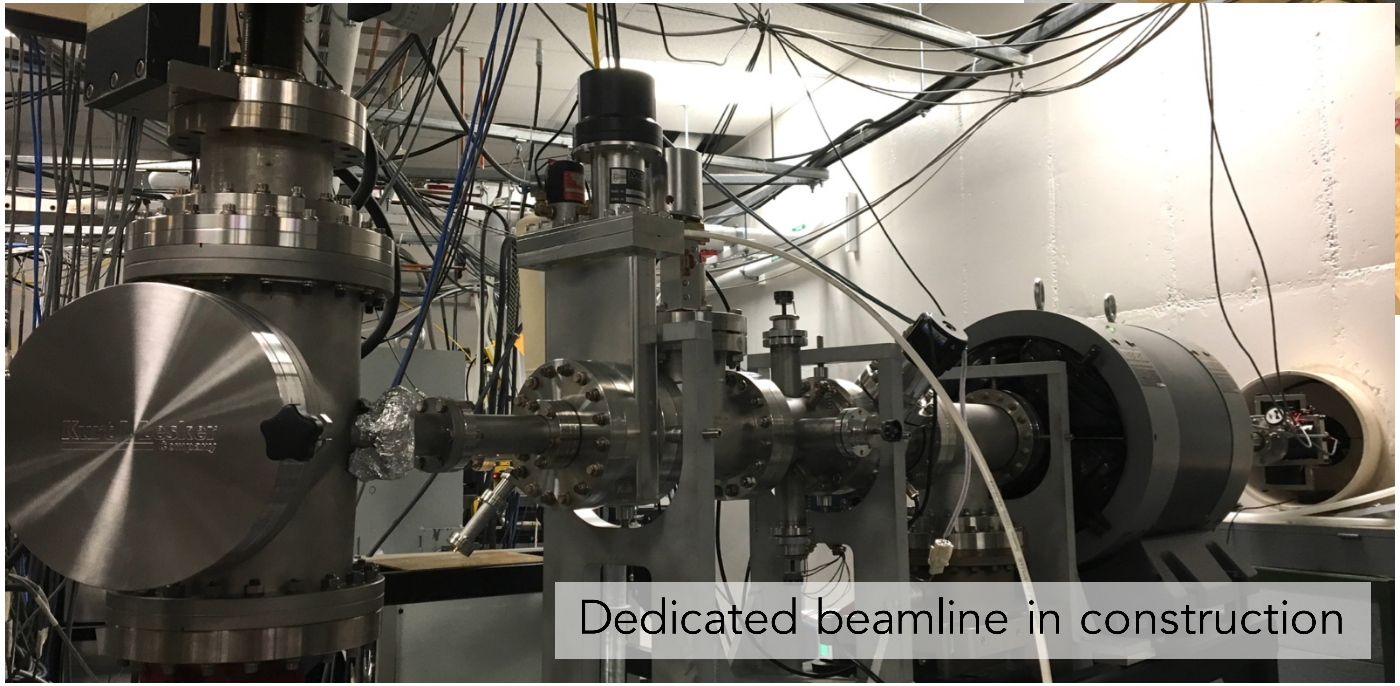
Aluminum single crystal on a 30min heating and cooling cycle



Dennett and Short, *Appl. Phys. Let.*, **110** (2017)

In situ TGS beamline experiment currently under development for Sandia Ion Beam Lab 6 MV tandem accelerator


operational bench-top TGS setup


Dedicated beamline in construction

U.S. DEPARTMENT OF ENERGY

Sandia National Laboratories

NNSA
National Nuclear Security Administration

SUTD-MIT INTERNATIONAL DESIGN CENTRE (IDC)

SSGF
STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP

MNM
Mesoscale Nuclear Materials