Intense, pulsed ion beams for studies of defect dynamics and materials processing very far from equilibrium

Thomas Schenkel, Jianhui Bin, Sven Steinke, Qing Ji, Stepan Bulanov, Jaehong Park, Arun Persaud

Accelerator Technology & Applied Physics Division, Lawrence Berkeley National Laboratory

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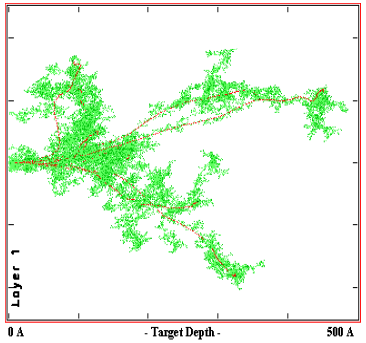
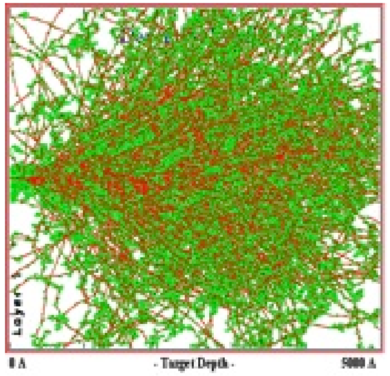
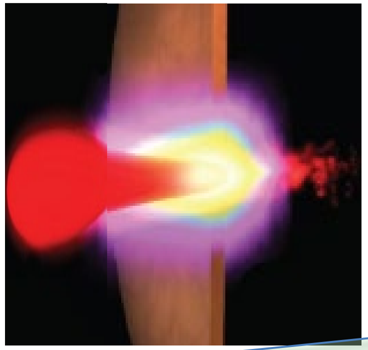
Intense, short ion pulses are a unique tools for (bio)-materials science, studies of phase-transitions and warm-dense matter research

Lower intensities:
defect dynamics in materials

Higher intensities:
phase transitions and warm dense matter







isolated cascades → overlapping cascades → amorphization and melting → warm ($\gtrsim$1 eV), dense matter

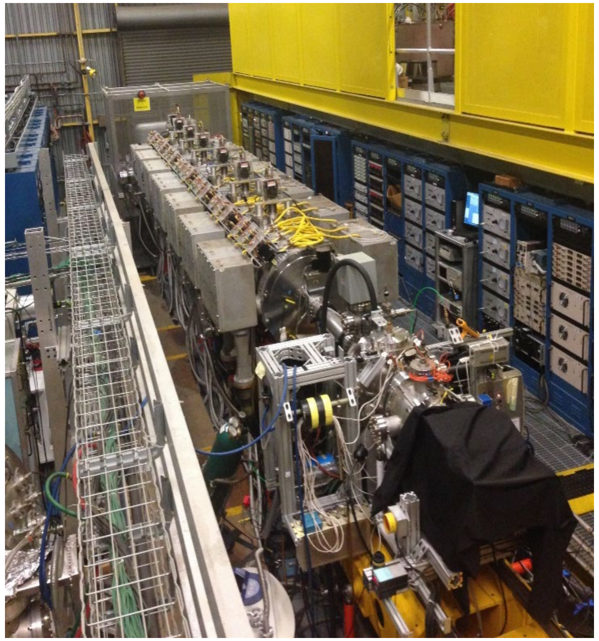
- Short ion pulses enable access to dynamics of rad effects experiments
- Intense ion pulses enable access to phase transitions, materials processing far from equilibrium and warm dense matter with uniformly heated materials

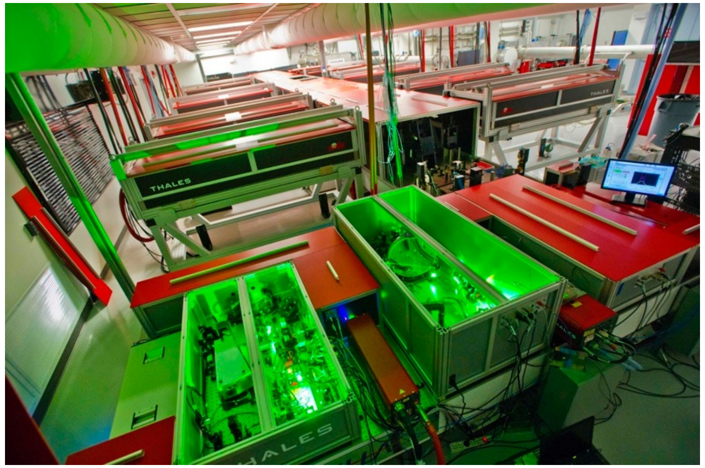
- J. H. Bin, et al. Rev. Sci. Instr., in press (2019)
- P. A. Seidl, et al. Laser and Particle Beams 35, 373 (2017)
- J. J. Barnard, T. Schenkel, J. Appl. Phys. 122, 195901 (2017)
- A. Persaud, et al., Physics Procedia 66, 604 (2015)
- P. A. Seidl, et al., Nucl. Instr. Meth. B 800, 98 (2015)
- J. Schwartz et al., J. Appl. Phys. 116, 214107 (2014)

Outline

1. **Accelerators for intense, short ion pulses**
    1. Induction linac, NDCX-II
    2. Laser-plasma acceleration, BELLA

2. **Experiments with ion pulses at Berkeley Lab**
    1. Defect dynamics
    2. Materials processing and color center synthesis
    3. Phase transitions





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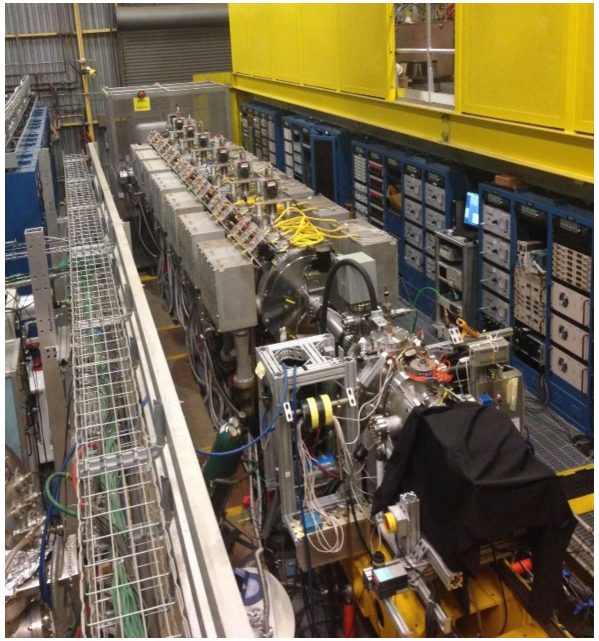
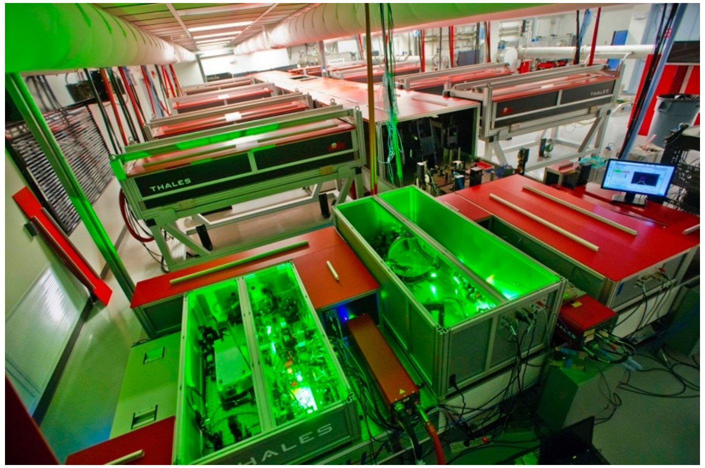
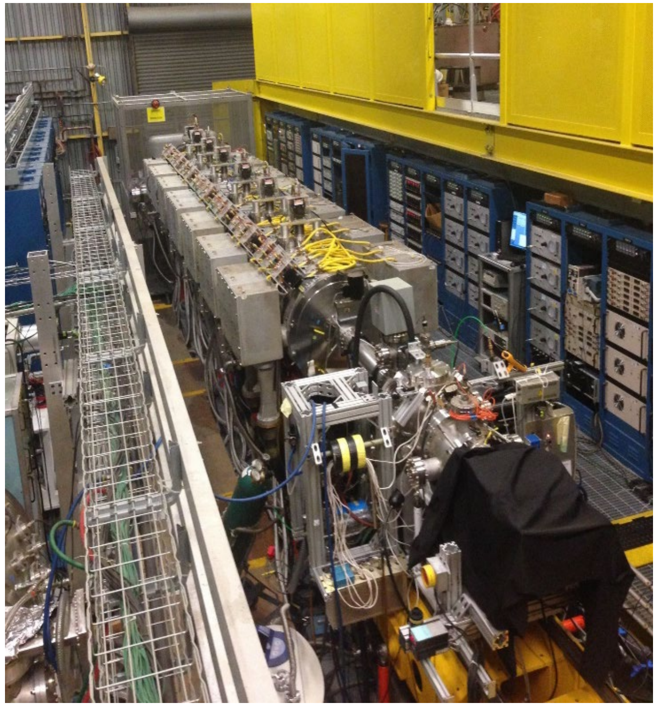
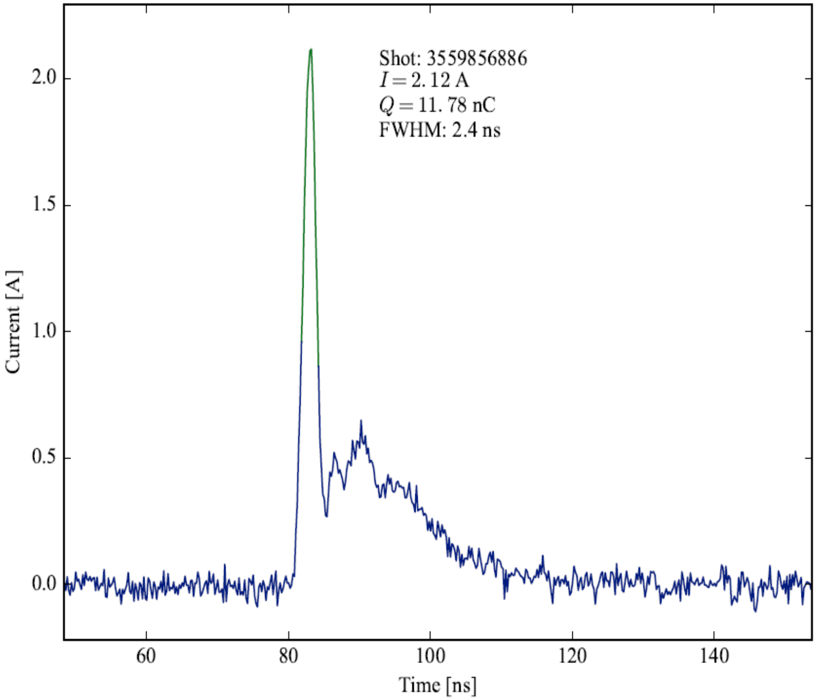


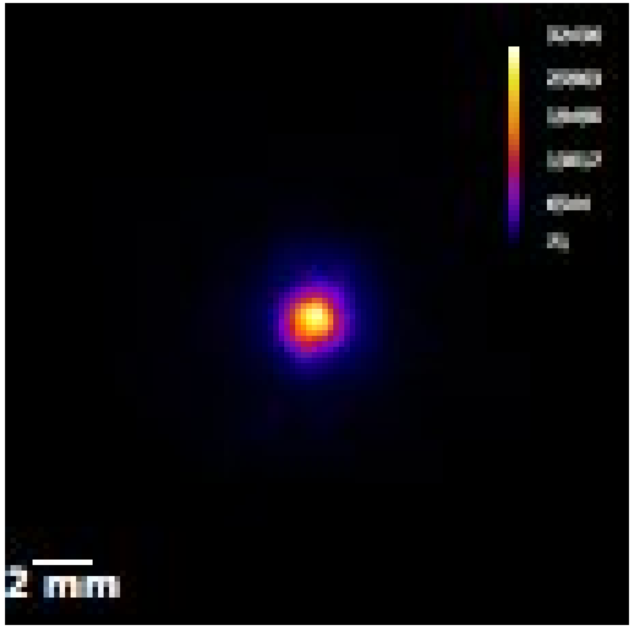


Intense, pulsed ion beams by neutralized drift compression in an induction linac – NDCX-II



- NDCX-II at Berkeley Lab



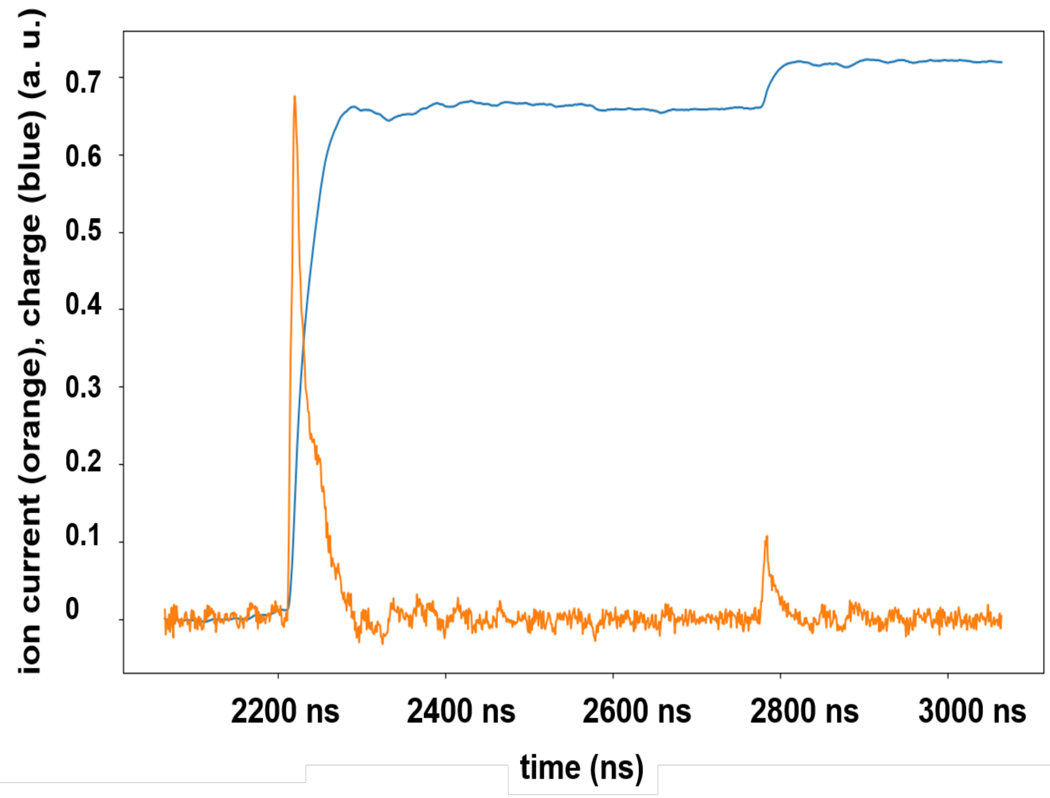


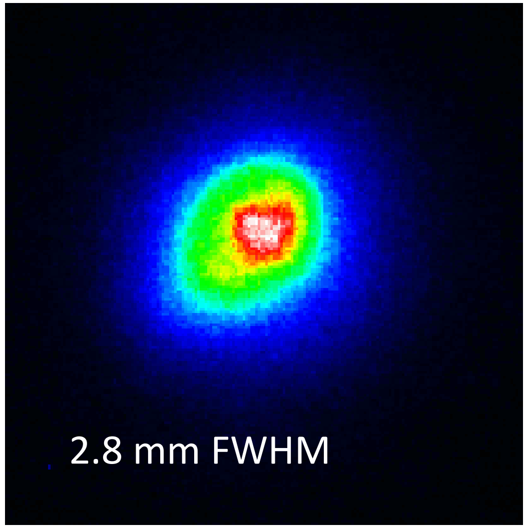
- 1.1 MeV (He^+), 12 nC (7.5×10^{10} ions), 13 mJ
- Routinely ~5×10^{11} ions/cm^2/pulse

- Pulse length: 2 to 10 ns, spot size ~1 to 5 mm radius, 1 MeV protons, He^+, Li^+, …
- Peak current: ~0.1 to 2 A
- Repetition rate ~1 shot / minute

- **P. A. Seidl, et al., NIM A (2015)**

Pulses of 1 MeV protons from NDCX-II





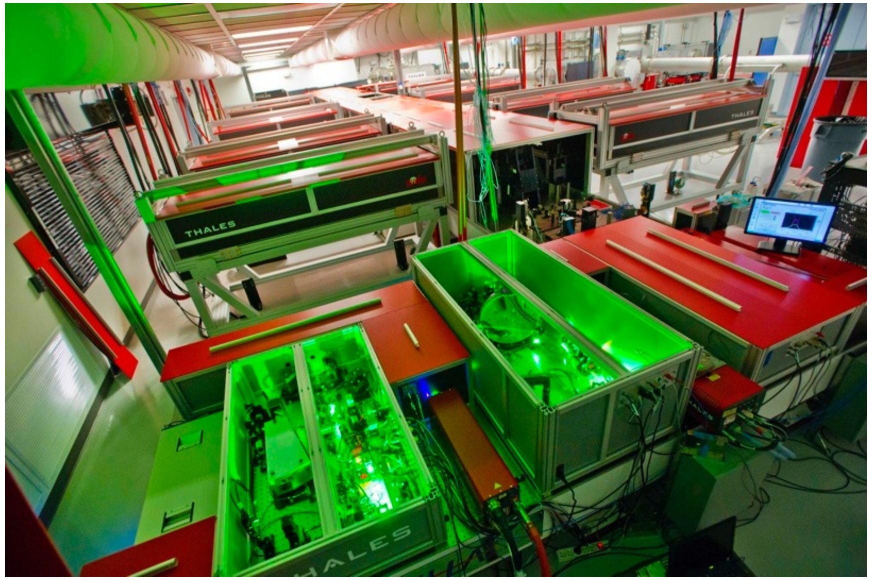
- Proton pulses with peak currents of 0.1 to 1 A, 10 to 20 ns FWHM, ~1 to 5E10 protons/pulse (to date)
- The proton energy is 1 MeV with a range in silicon of 16 um.
- J-H Bin, et al., Rev. Sci. Instr., in press (2019)

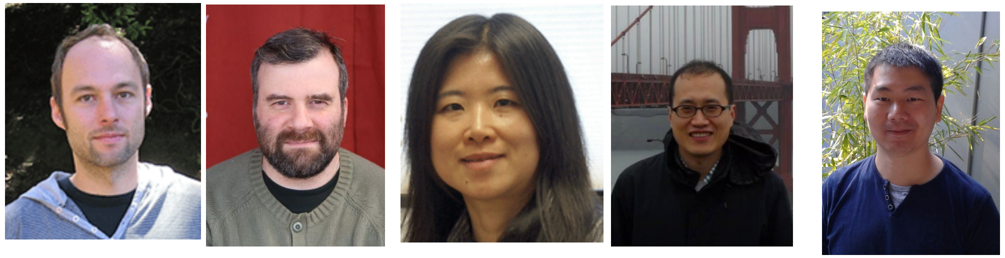
We use the BELLA PW laser to form pulses of high energy electrons (GeV) and ions (MeV)

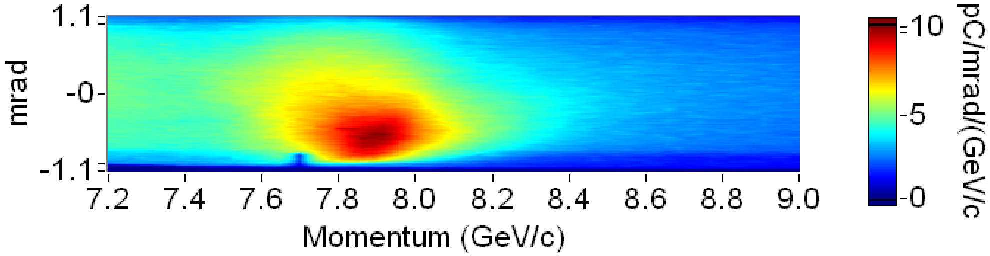
- BELLA – 1 PW at 1 Hz
- 40 J, 33 fs, ~2×10^{19} W/cm^2

- **The BELLA Center is part of a network of collaborative user facilities, LaserNetUS (www.LaserNetUS.org)**

- Contacts:
  - T_Schenkel@LBL.gov
  - CGRGeddes@lbl.gov



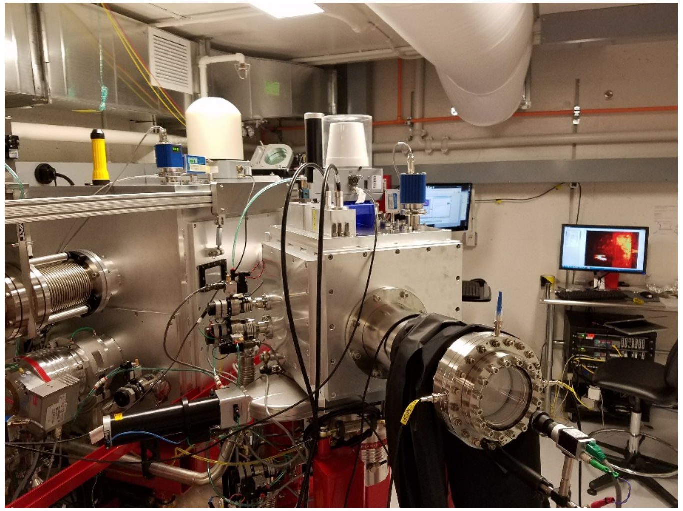


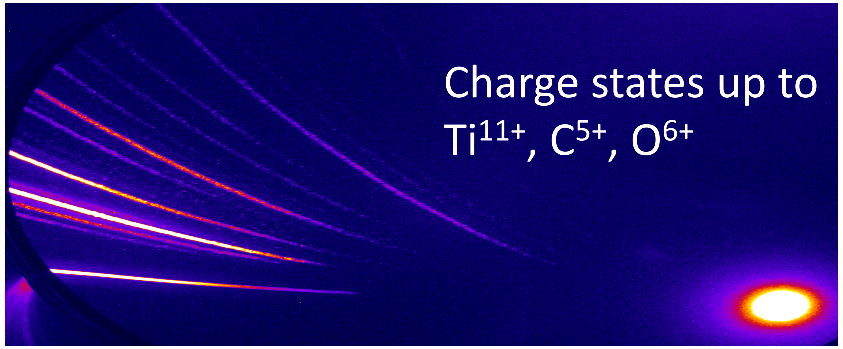


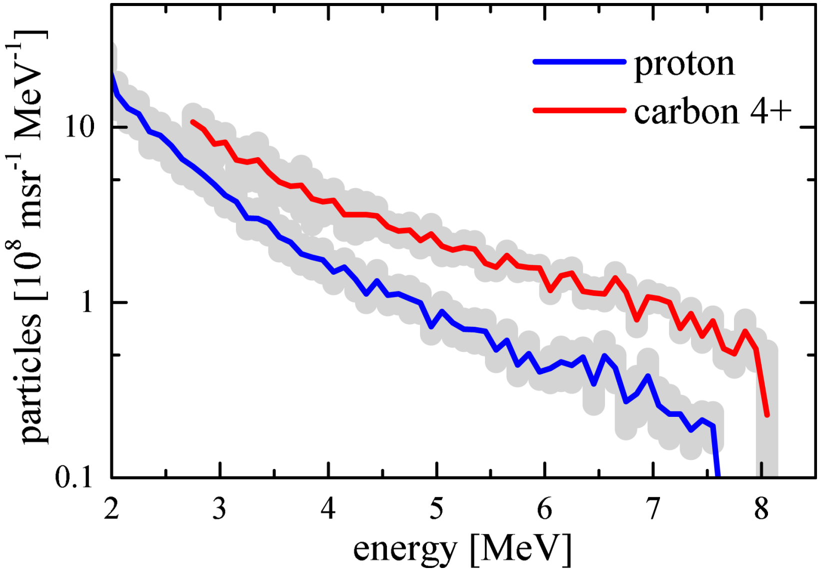
BELLA overview:
K. Nakamura et al., IEEE J. Quant. Electr. 53, 1200121 (2017)

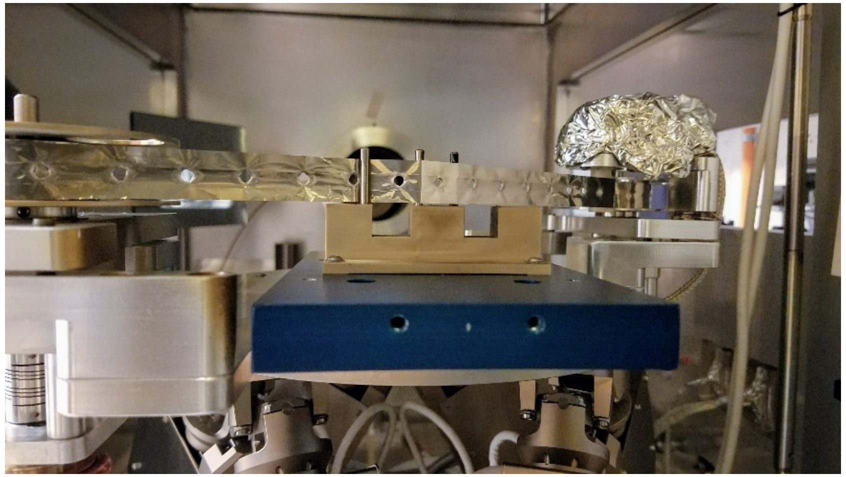
A. J. Gonsalves, et al. Phys. Rev. Lett. 122, 084801 (2019)

Ion acceleration at BELLA-i



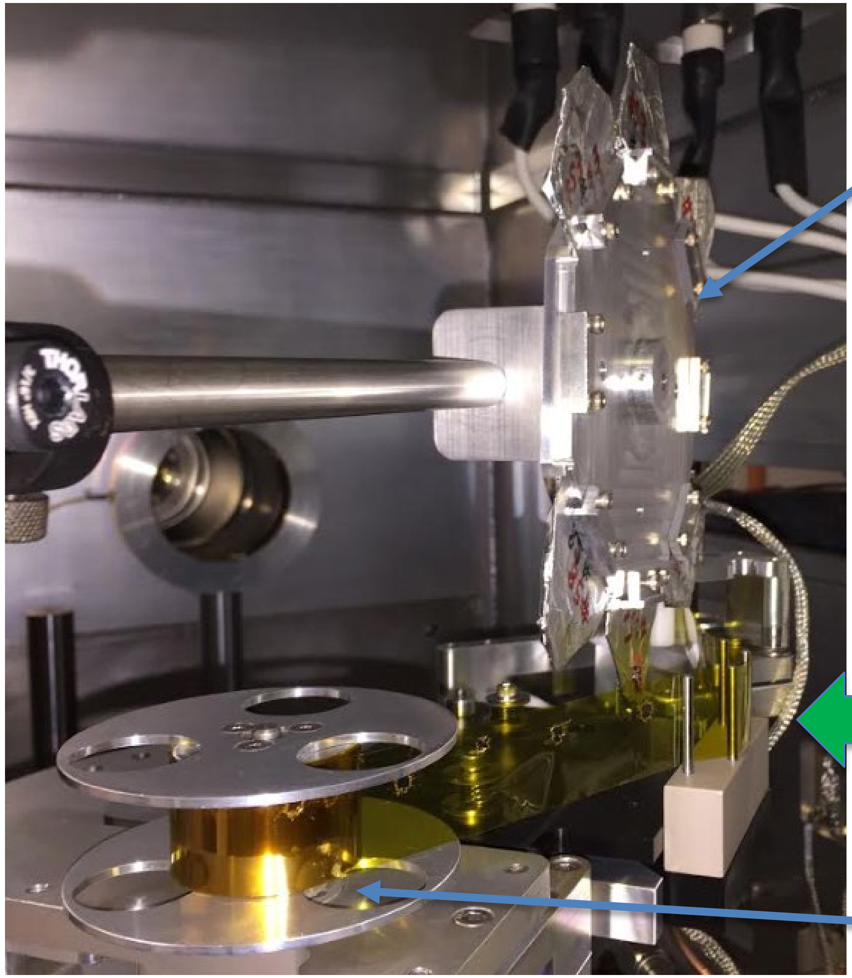






- ~10^{12} total number of MeV ions (from Thomson parabola) and >10^{13} lower energy ions (from ex situ sample analysis by Secondary Ion Mass Spectrometry, SIMS)
- Ti tape drive target for extended 1 Hz operation
- Bin et al. Rev. Sci. Instr., in press (2019); Steinke et al, in preparation

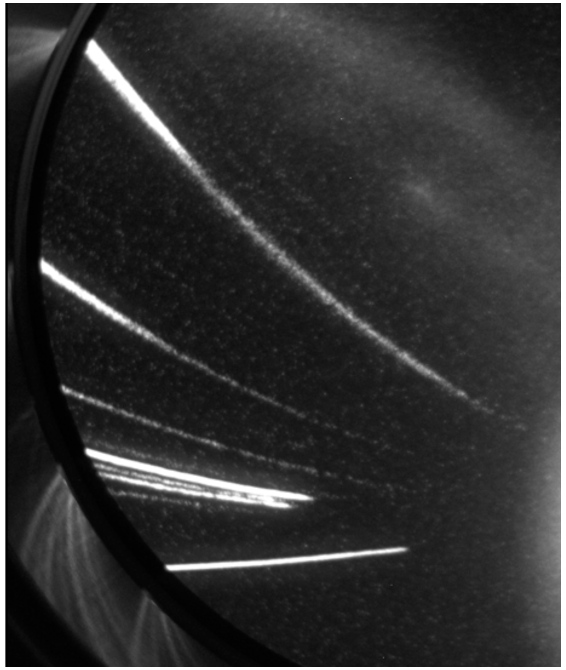
Setup for laser ion acceleration at 1 Hz with samples 3 cm from the laser target



Target wheel for samples to be hit by ions

Laser pulse

Tape drive for laser targets, e. g. Kapton (shown) or titanium, ~2 – 10 micron thick



Thomson parabola spectra of protons and carbon ions from a Kapton tape laser target

- Distance of laser-target to ion-target now 3 cm for proton fluences of 5 to 10 J/cm^2/shot with sub-ns pulses

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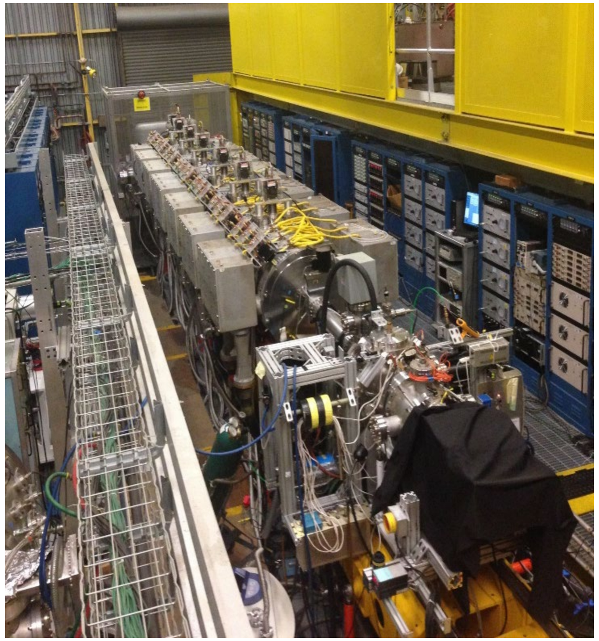
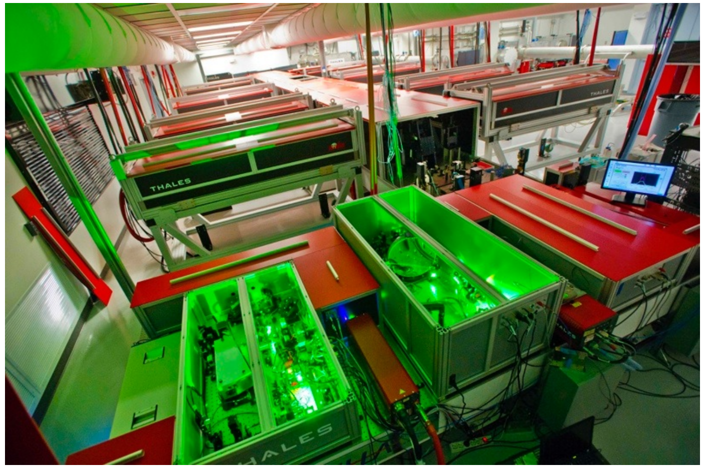
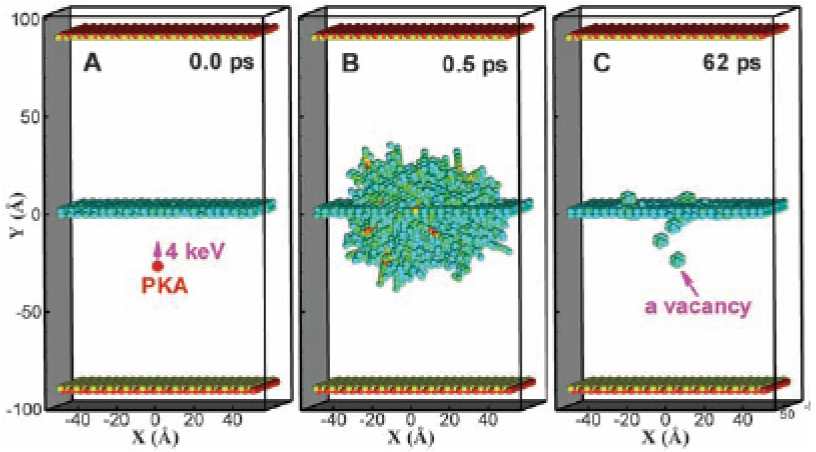


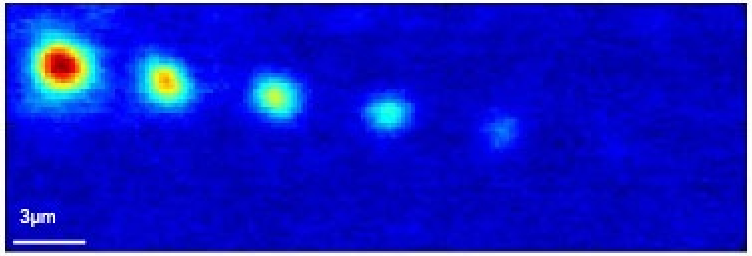


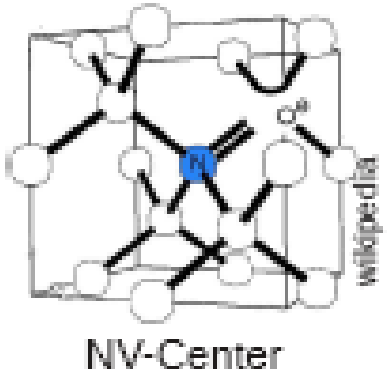
Motivation: Understanding the dynamics of radiation induced defects in solids

- Defects affect materials properties
  - Desired properties (e. g. optical, electrical, …)
  - Undesired properties (e. g. mechanical failure, …)
- Defect dynamics is a multi-scale problem (ps to years)
- Probes of defect dynamics on different time scales can inform the development of optimized materials and benchmark simulation models



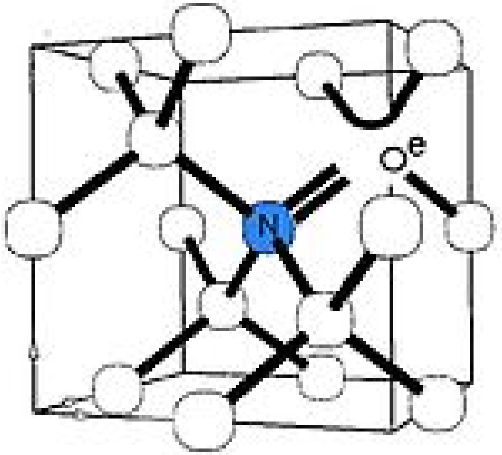
Efficient Annealing of Radiation Damage Near Grain Boundaries via Interstitial Emission
X.-M. Bai, A. F. Voter, R. G. Hoagland, M. Nastasi, B. P. Uberuaga, Science 327, 1631 (2010)



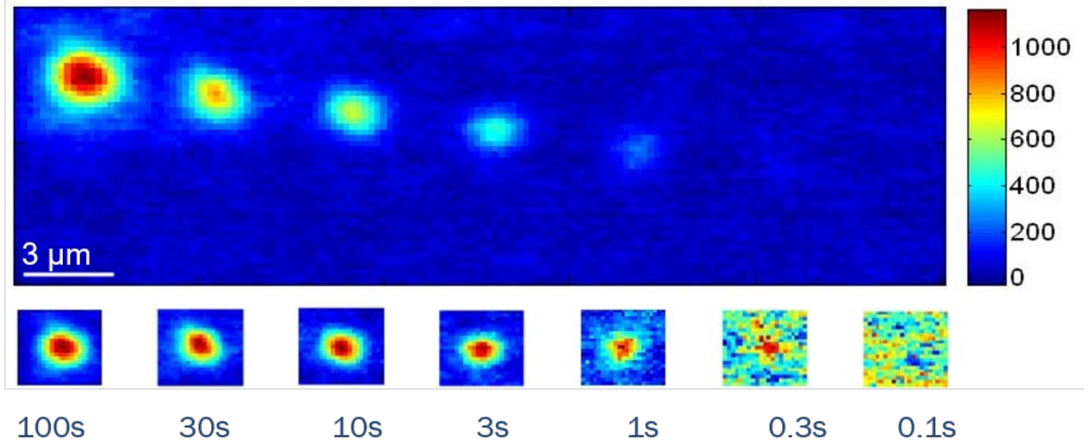


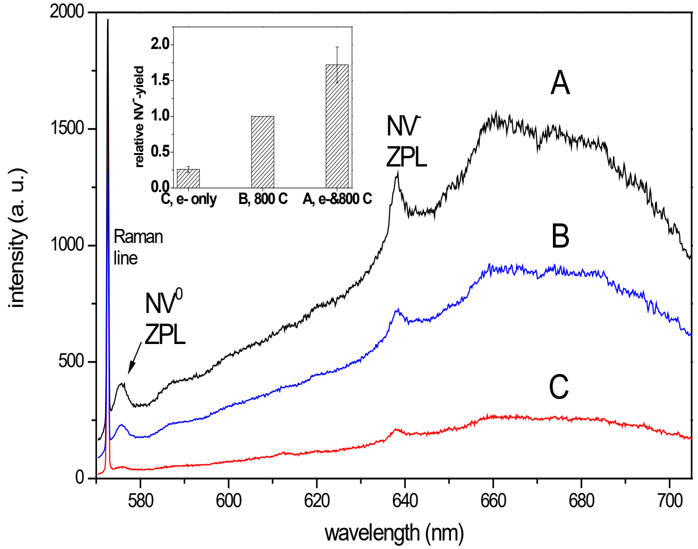
Effects of low-energy electron irradiation on formation of nitrogen–vacancy centers in single crystal diamond
J. Schwartz, S. Aloni, F. Ogletree, T. Schenkel, New J. Phys. 14 043024 (2012)

NV-centers form during local exposure to low energy electrons at room temperature



https://en.wikipedia.org/wiki/nitrogen-vacancy center





- confocal PL image of NV⁻ centers (635–642 nm) at room temperature, recorded following exposure of 1 µm squares to a 9 pA, 2 keV electron beam. Insets show locally auto-scaled spots.

- **local activation enables iterative formation of NV^- in arrays**

- Note: activation of NV^0 centers in diamond by low energy electrons and high energy ions was reported already in the 70s and 80s (see A. M. Zaitsev, 2001)
- J. Schwartz, S. Aloni, D. F. Ogletree and T. Schenkel, “Effects of low-energy electron irradiation on formation of nitrogen–vacancy centers in single-crystal diamond”, New J. Phys. 14, 043024 (2012)

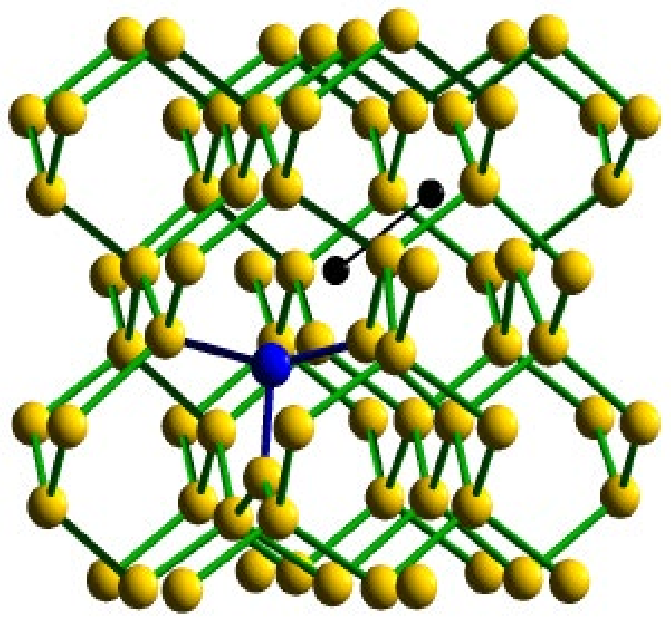
What are mechanisms of NV-formation?

$N_{substitutional} + V \rightarrow NV^{0,-}$

vs.

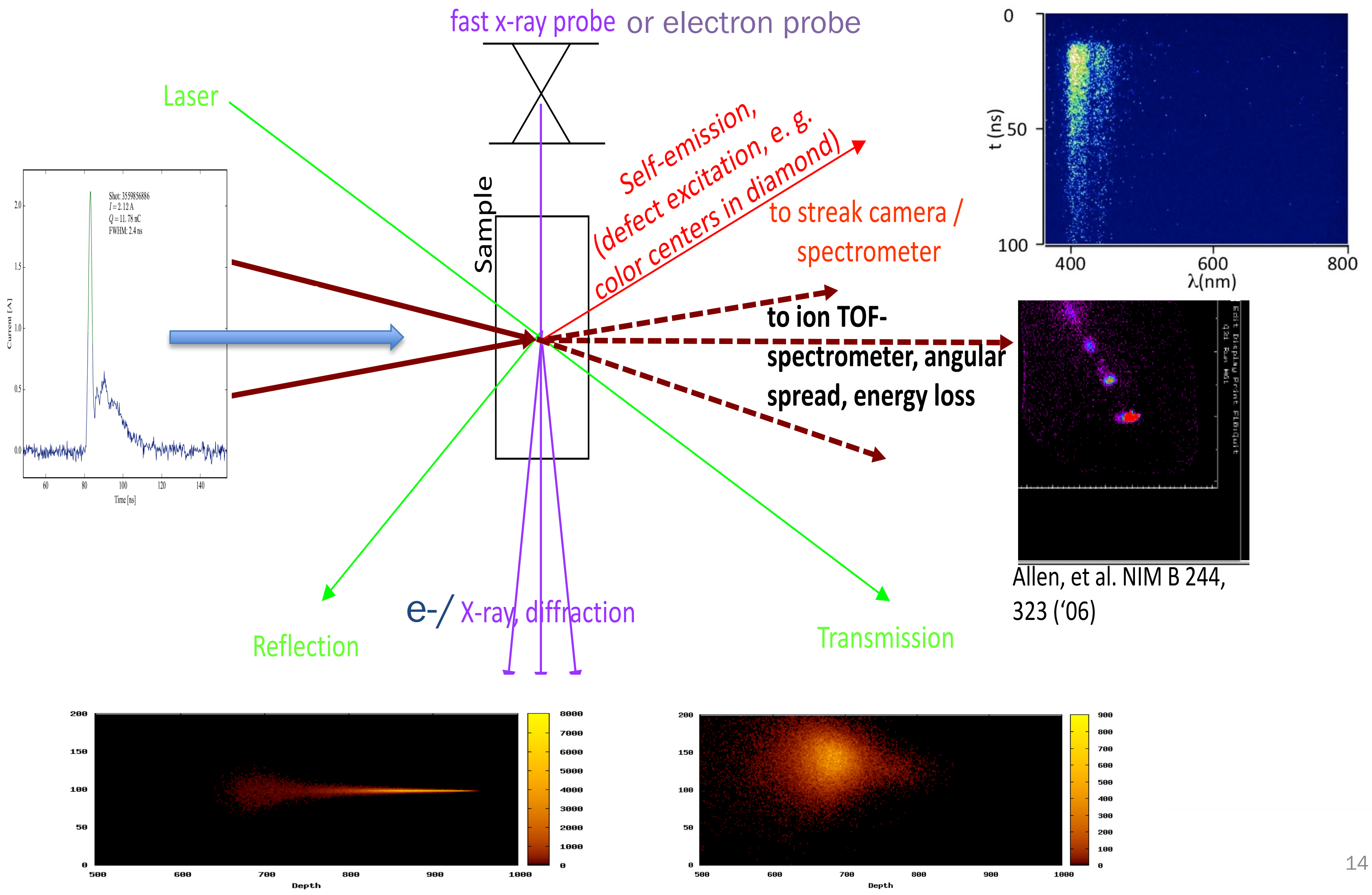
$N_{interstitial} + V_n \rightarrow NV^{0,-}$

J. Schwartz, et al., NJP 2012, JAP 2014

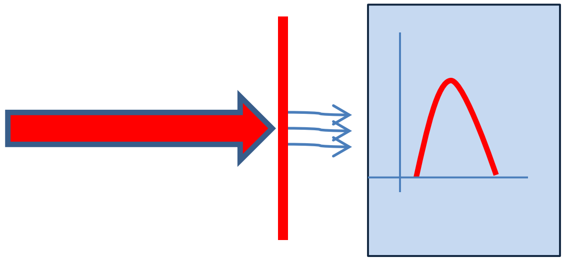


- A nitrogen atom on a split interstitial site (blue), close to two vacancies (black). Carbon atoms in yellow. NV's form during annealing at >300°C
  - J. Adler, R. Kalish, et al., J. of Physics, 2014
- P. Deak et al. PRB 2014: di-vacancy formation favored over NV formation during annealing of N rich diamond after vacancy producing irradiation

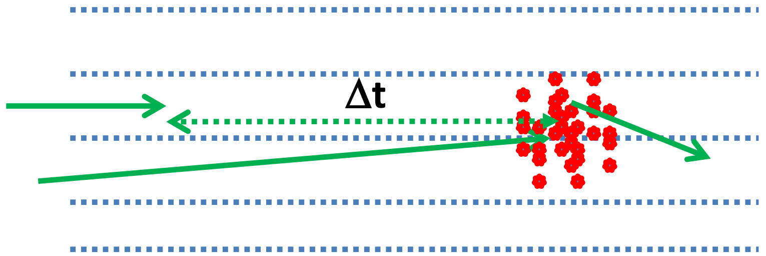
Short ion pulses enable access to the dynamics of radiation effects in pump-probe type experiments



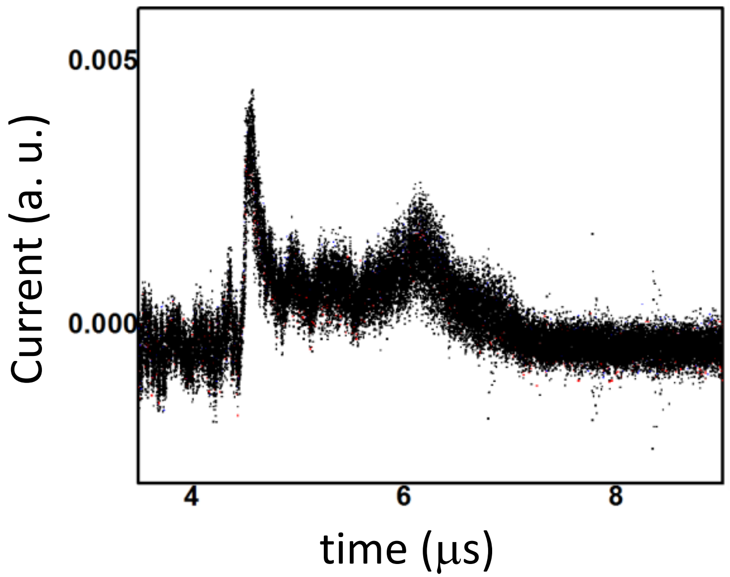
Time resolved detection of ion transmission through single crystal silicon membranes

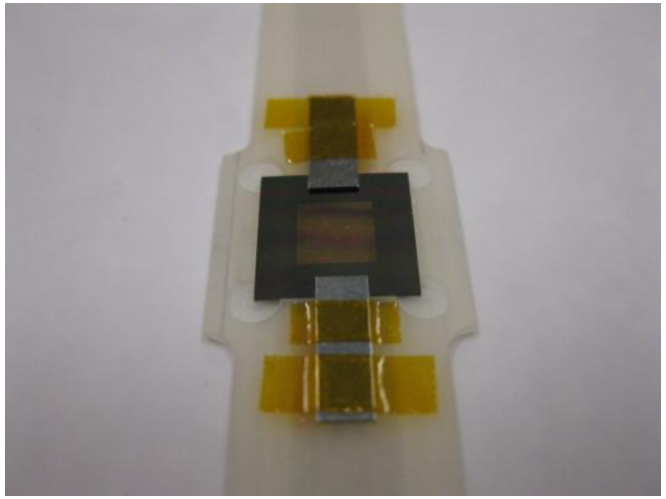


Faraday Cup,
~2 ns time resolution



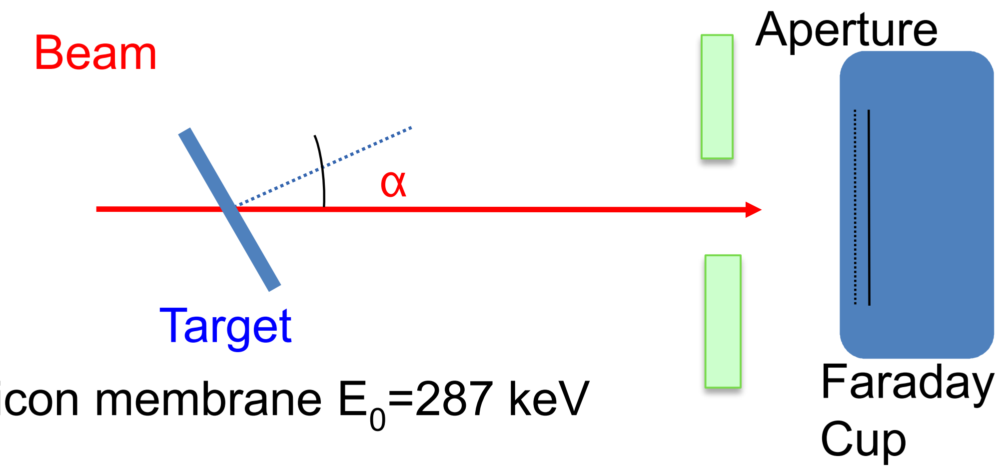
Δt: time between damage event and arrival of the next channeled ion in the same region



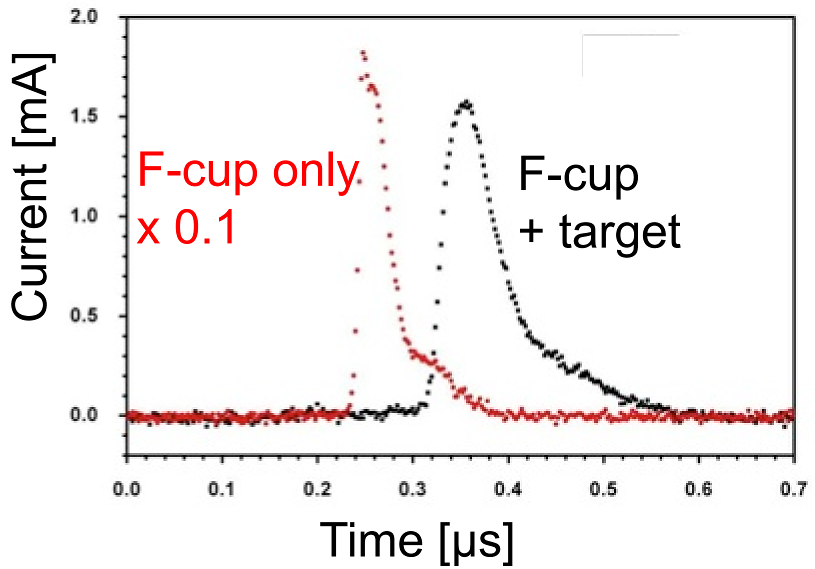


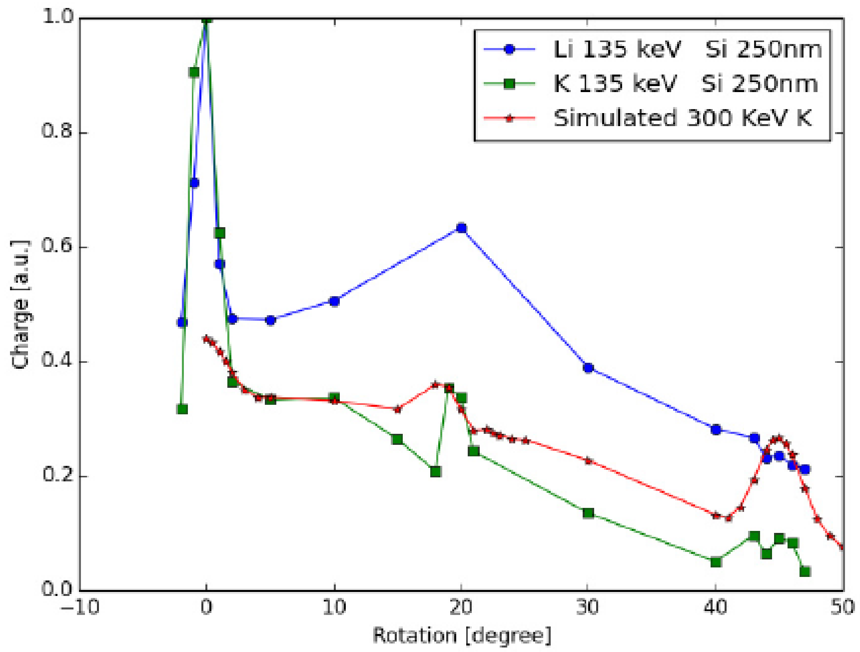
- 1 μm thick, Si (100)

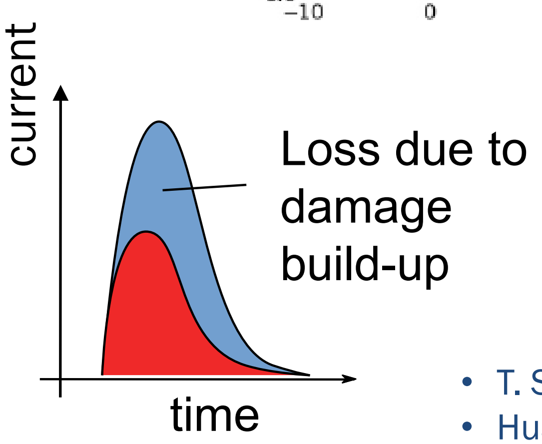
Order-disorder transition can be tracked *in situ* with ion channeling during short ion pulses



1 μm Silicon membrane E_0=287 keV







- T. Schenkel et al., NIM B 315 (2013) 350
- Hua Guo, et al., Mater. Res. Soc. Symp. Proc. Vol. 1712, DOI: 10.1557/opl.2014.856

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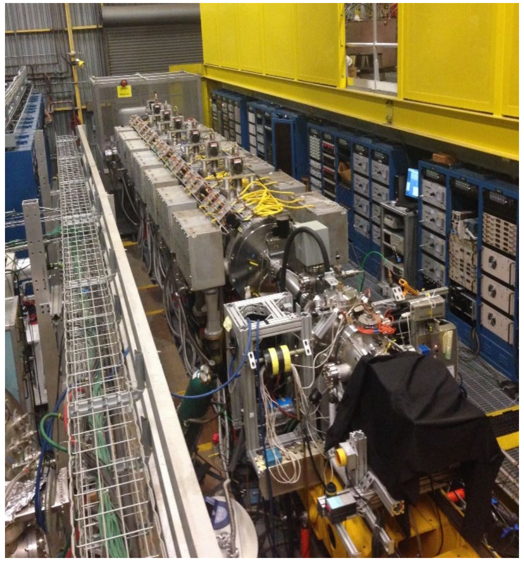
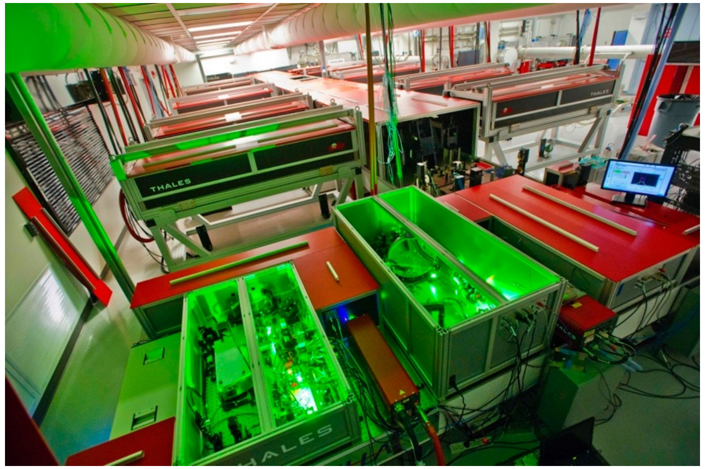
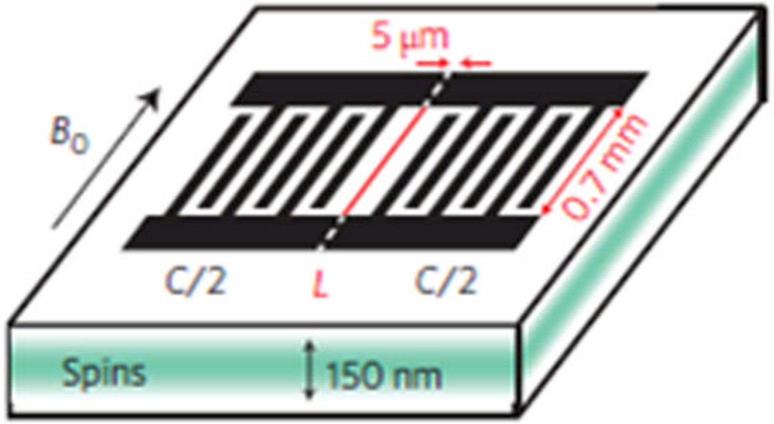
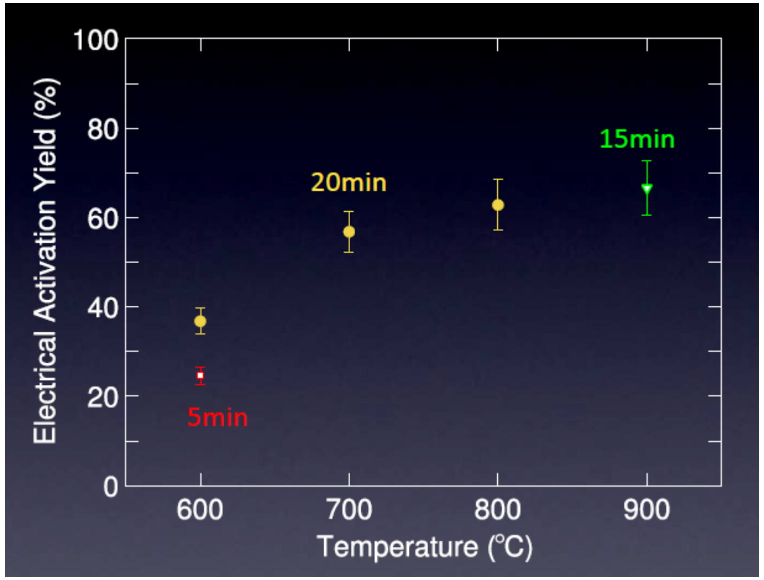




Materials processing – limits of conventional annealing



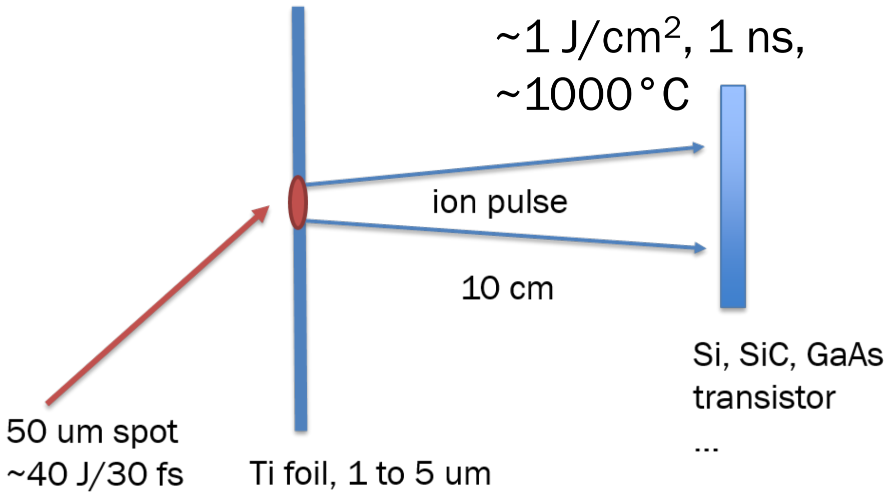


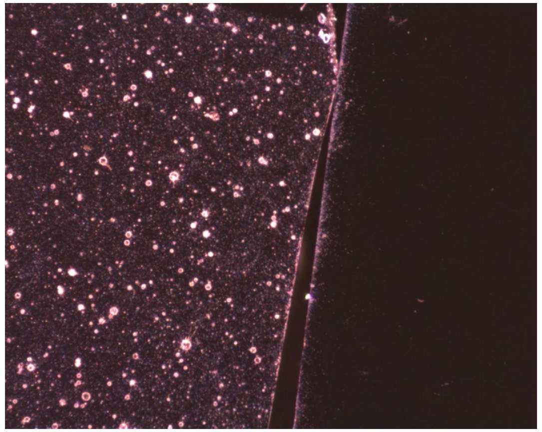
- Bismuth doped ^{28}Si enabled the recent demonstrations of the Purcell effect with spins
- But only ~60% of the bismuth atoms were electrically active after conventional processing

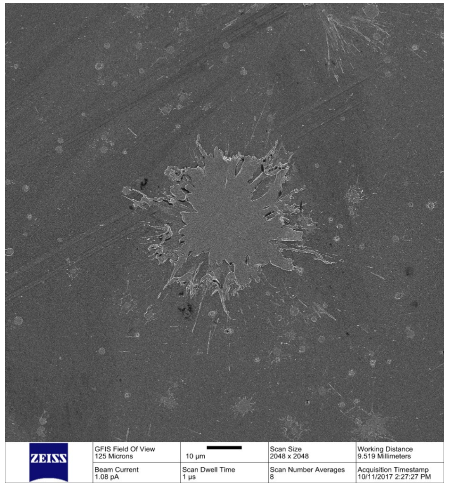
→ Excite materials locally with intense, pulsed ion beams and rapidly quench to stabilize the novel phase

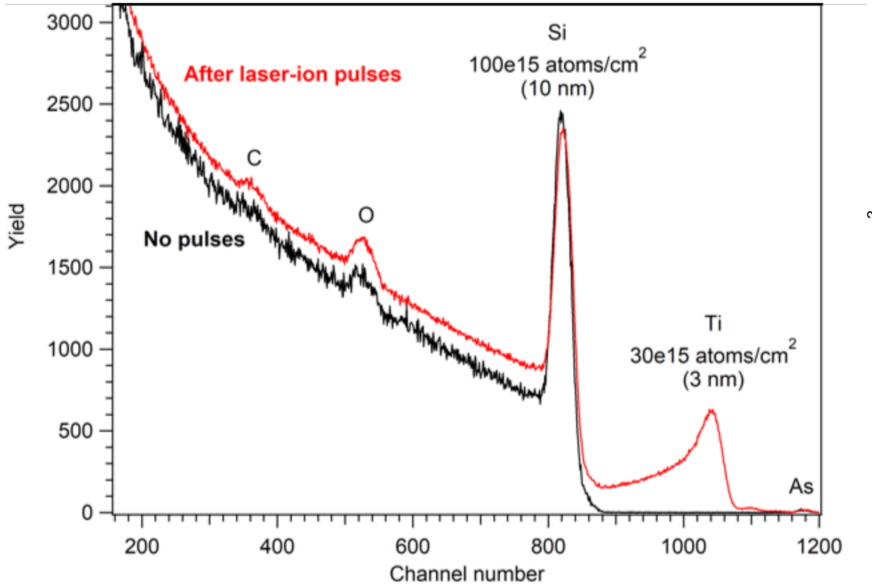
- *"Controlling spin relaxation with a cavity", 2. A. Bienfait, J. J. Pla, Y. Kubo, X. Zhou, M. Stern, C. C. Lo, C. D. Weis, T. Schenkel, D. Vion, D. Esteve, J. J. L. Morton, P. Bertet, Nature 531, 74 (2016)*

First pulsed implantation of SiC with ion pulses from BELLA-i

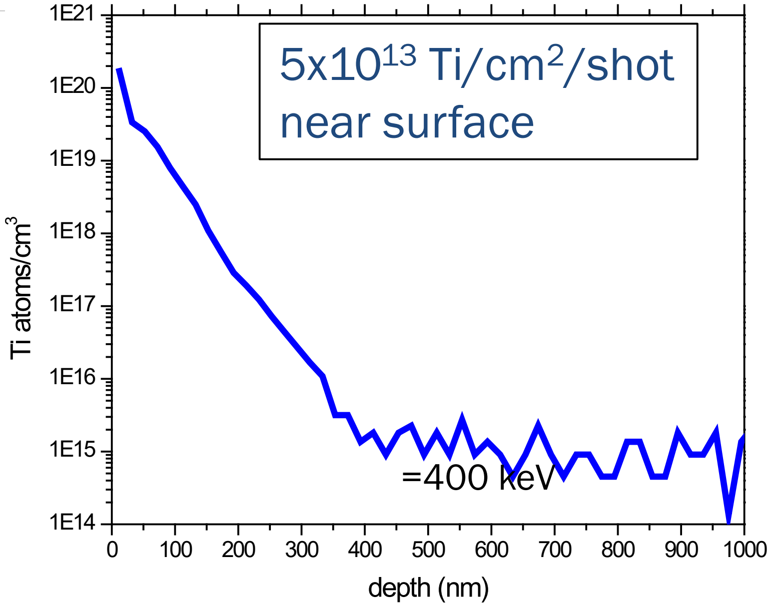




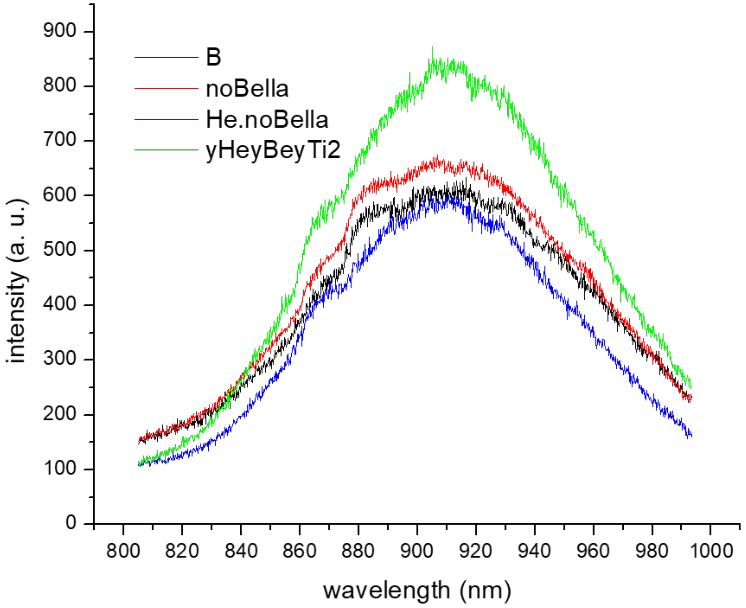




Channeling - RBS, Ryan Thorpe, Rutgers

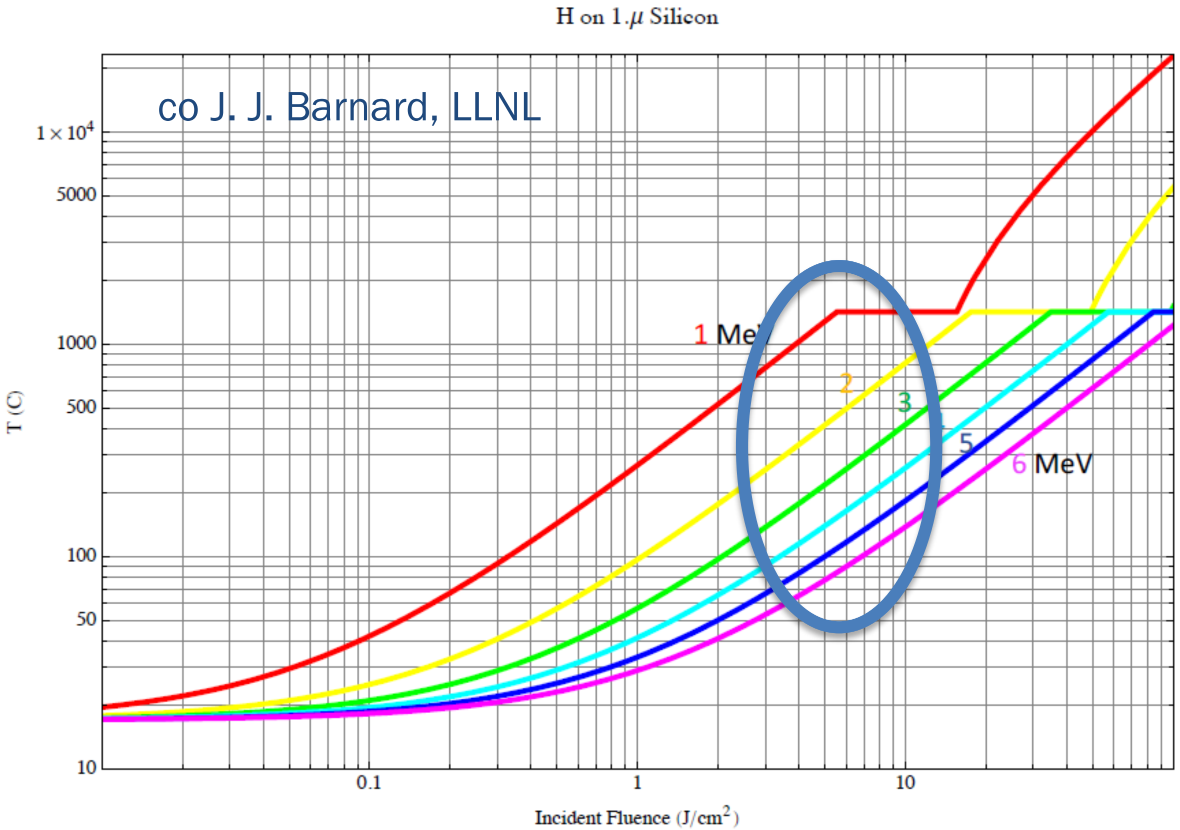


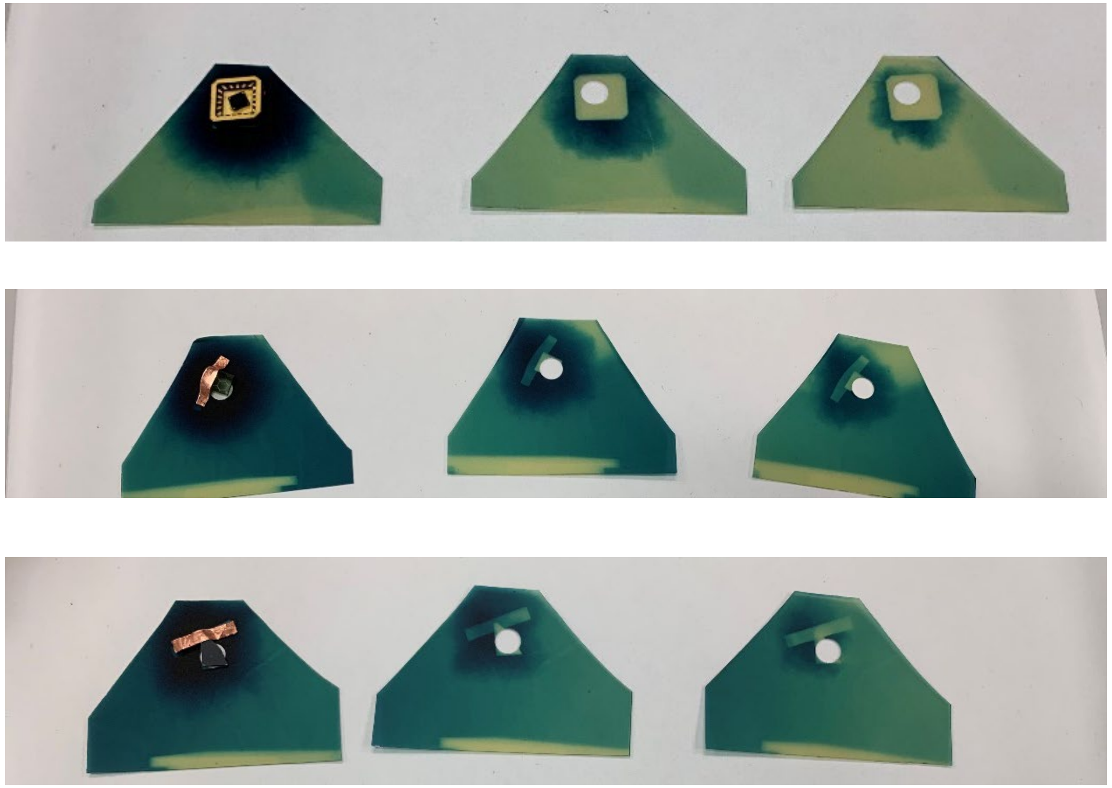
SIMS



Photoluminescence

Exposure of semiconductor samples to proton pulses with ~1 to 10 J/cm² and PW laser shot rates up to 0.2 Hz – analysis in progress





- next step - focusing of ions onto a second target with a plasma lens - in progress

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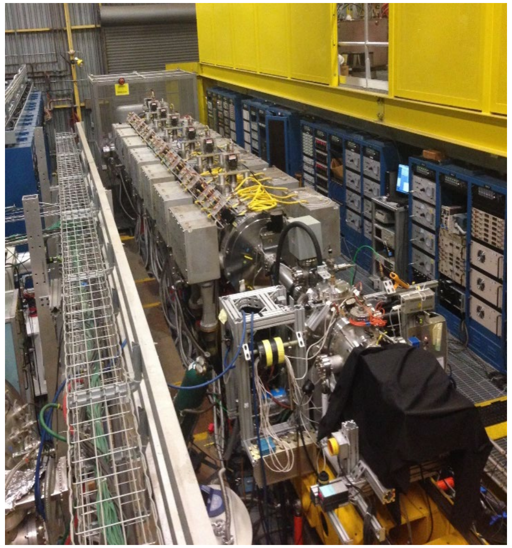
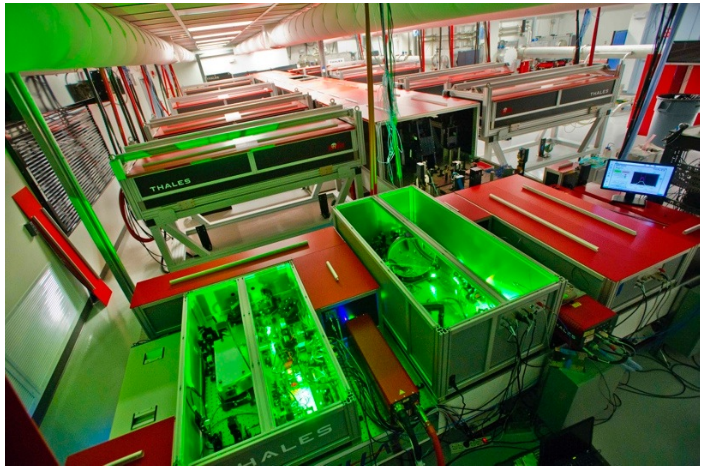
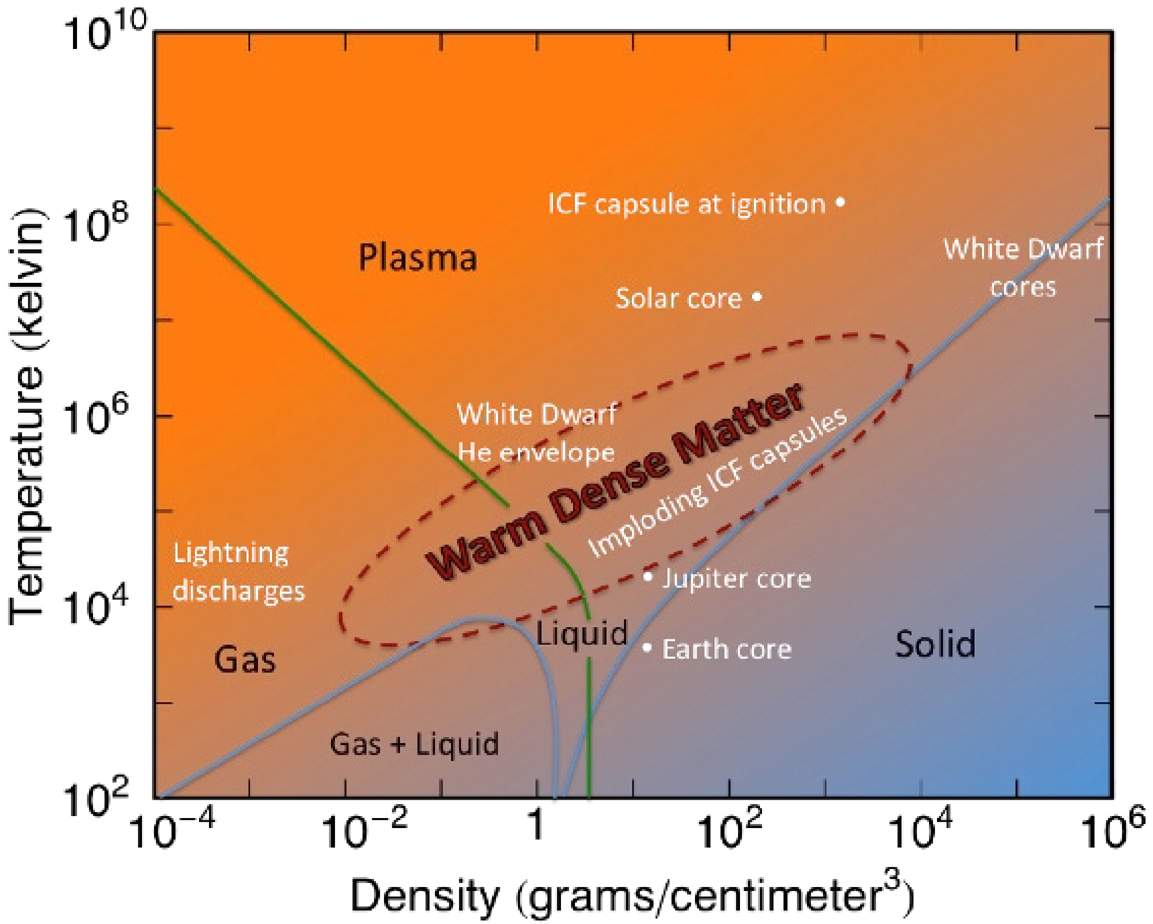


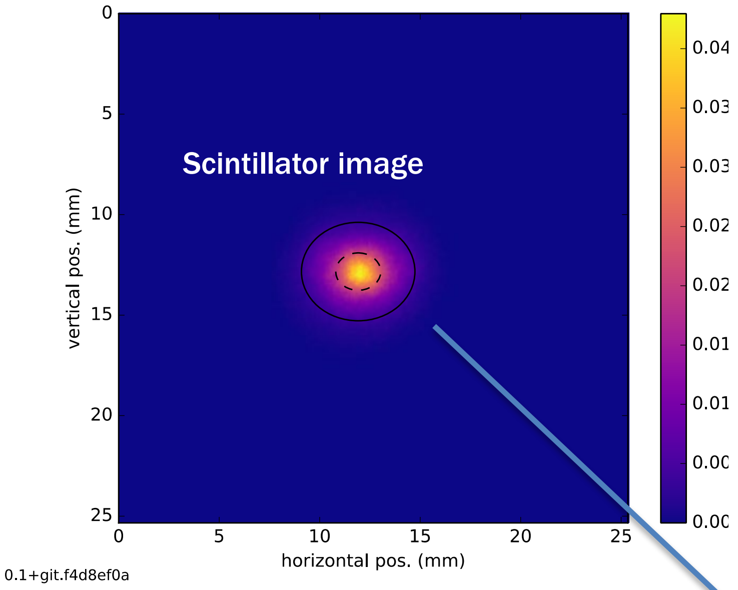


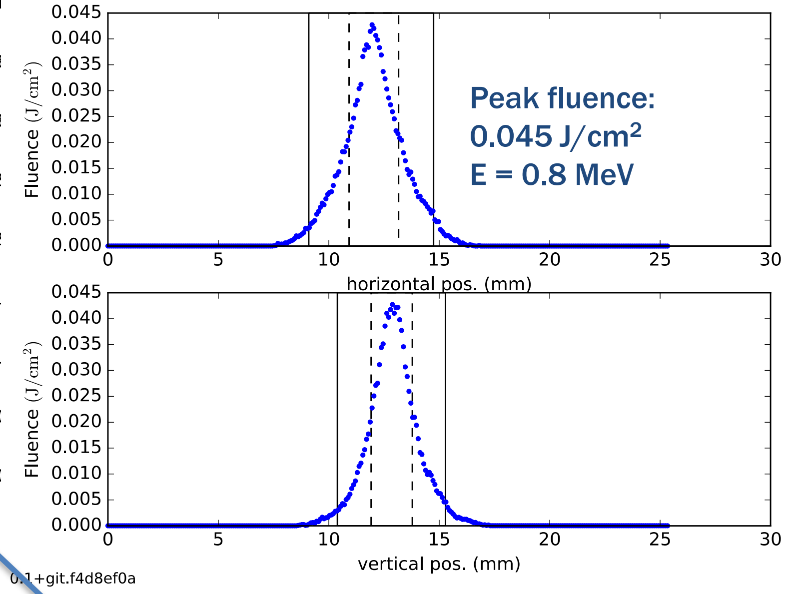
Intense ion pulses enable isochoric heating of materials for studies of warm dense matter

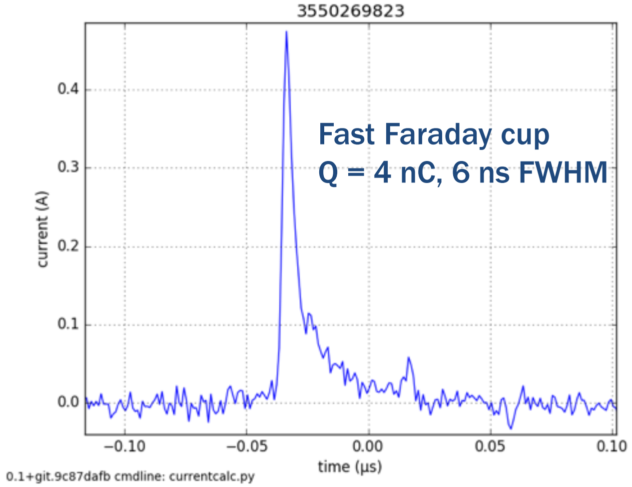


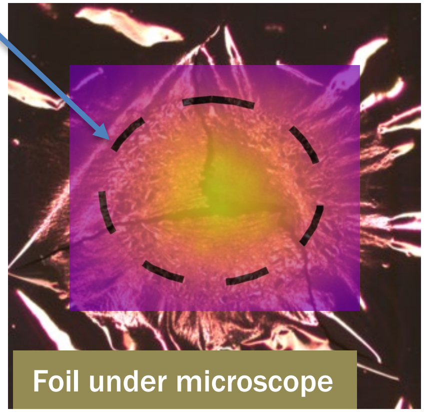
https://www.lanl.gov/projects/dense-plasma-theory/background/warm-dense-matter.php

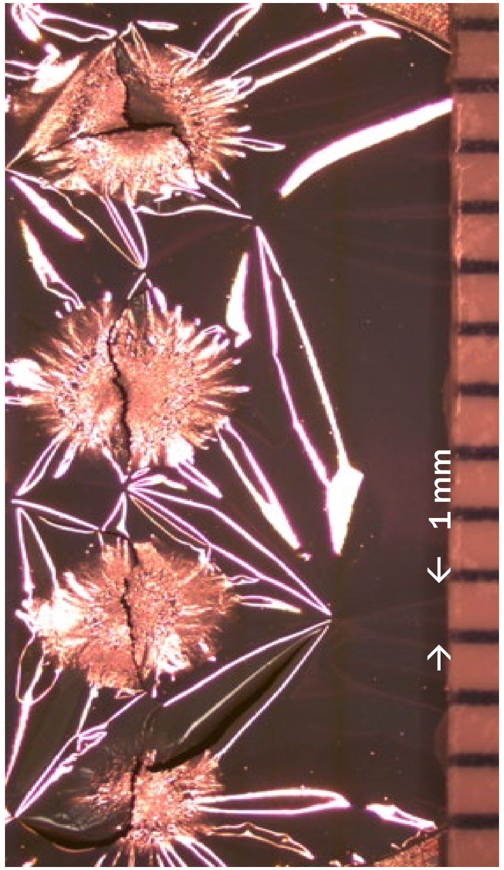
Heating of thin tin foils (300 nm) with a short-pulse helium beam





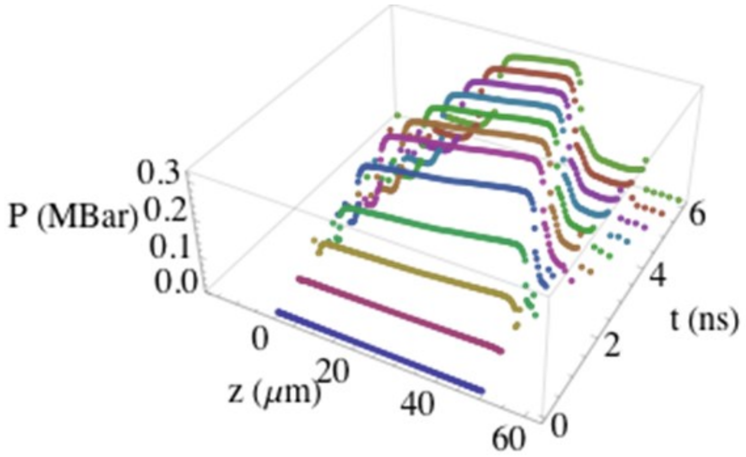




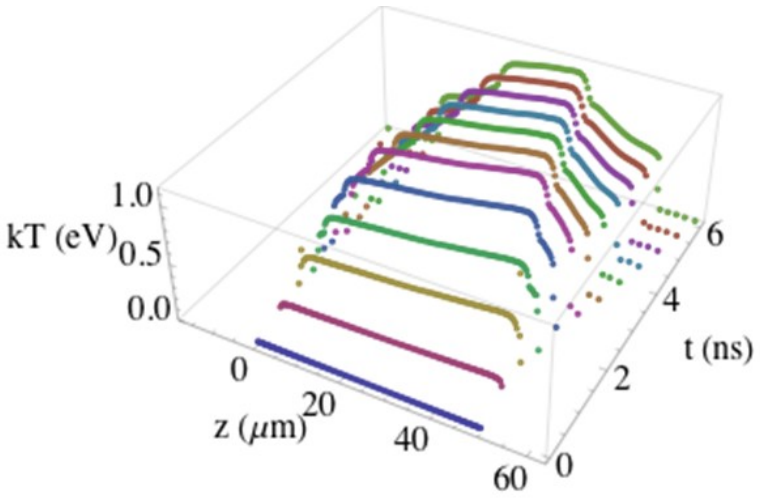


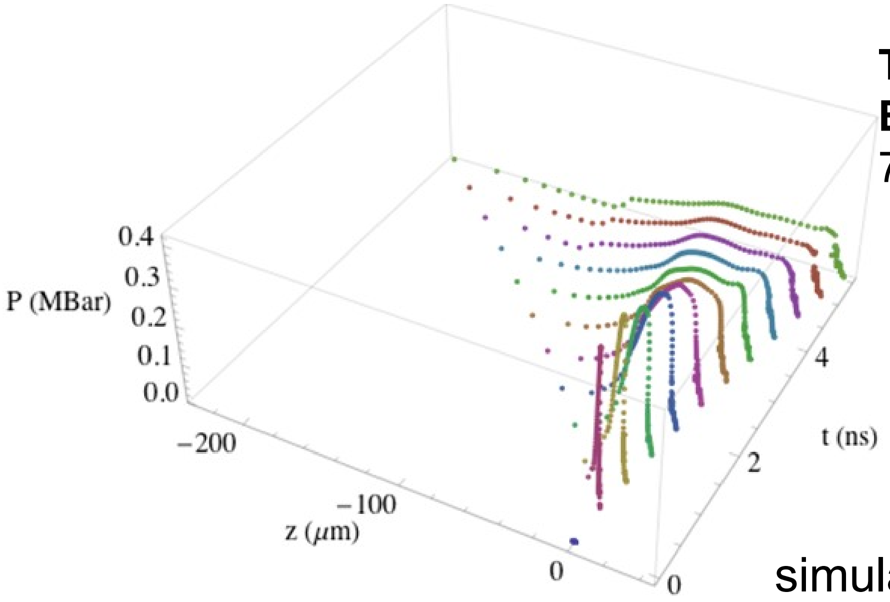
P. A. Seidl, et al., Laser and Particle Beams (2017), 35, 373–378

HYDRA simulations show heating to warm dense matter by protons and carbon ions with ion pulse parameters in reach at BELLA

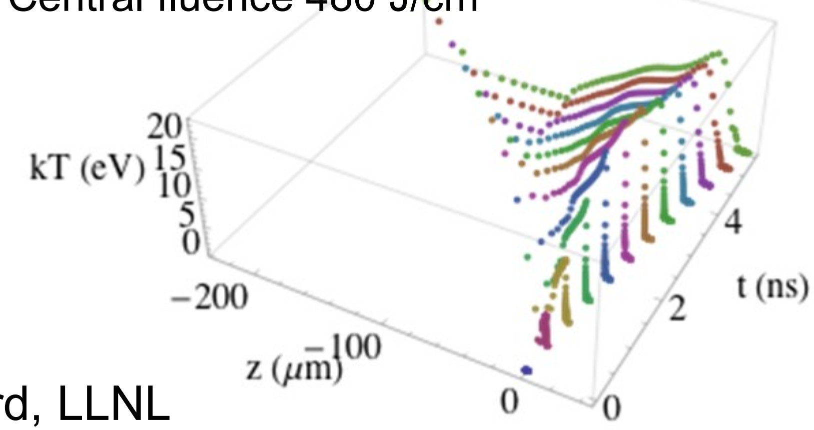


Target: 50 μm Au foil
Beam: 0.25 mm radius (Gaussian); 3 ns full width
7.5 MeV **proton** beam, Central fluence 480 J/cm^2





Target: 1.5 μm Au foil
Beam: 0.25 mm radius (Gaussian); 3 ns full width
7.5 MeV **Carbon** beam, Central fluence 480 J/cm^2

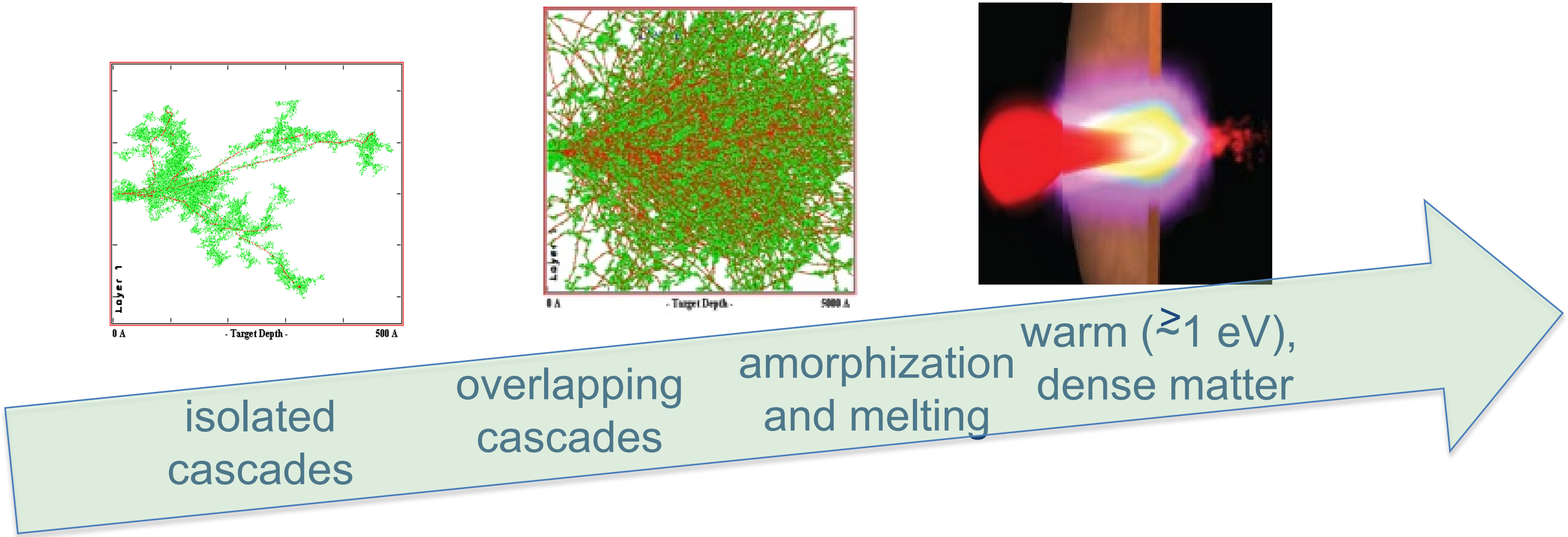


simulations by J. J. Barnard, LLNL

Intense, short ion pulses are a unique tool for (bio)-materials science, studies of phase-transitions and warm-dense matter research

Lower intensities:
defect dynamics in materials

Higher intensities:
phase transitions and warm dense matter



- Short ion pulses enable access to dynamics of rad effects
- Intense ion pulses enable access to phase transitions, materials processing far from equilibrium and warm dense matter with uniformly heated materials

- J. H. Bin, et al. Rev. Sci. Instr., in press (2019)
- P. A. Seidl, et al. Laser and Particle Beams 35, 373 (2017)
- J. J. Barnard, T. Schenkel, J. Appl. Phys. 122, 195901 (2017)
- A. Persaud, et al., Physics Procedia 66, 604 (2015)
- P. A. Seidl, et al., Nucl. Instr. Meth. B 800, 98 (2015)
- J. Schwartz et al., J. Appl. Phys. 116, 214107 (2014)