Laser-Plasma Doping as A Tool for Material Research: From Quantum Emitters to Superconducting Diamond

JLF user meeting   February 12, 2025

Arun Persaud[1], Kaushalya Jhuria[1], Xinran Li[2], Amanda F. Hebert[1], Sajid Husain[4], Wei Liu[1], Edward Barnard[3], Boubacar Kante[2], Liang Z.Tan[3] and Thomas Schenkel[1]

[1]Accelerator Technology & Applied Physics Division, Lawrence Berkeley National Laboratory

[2]Physics Division, Lawrence Berkeley National Laboratory

[3]The Molecular Foundry, Lawrence Berkeley National Laboratory

[4]University of California, Berkeley

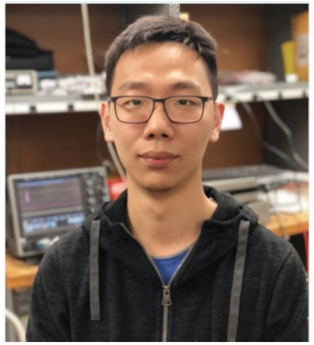
Team

BERKELEY LAB


Arun Persaud


Kaushalya Jhuria


Wei Liu


Xinran Li


Amanda Hebert


Thomas Schenkel

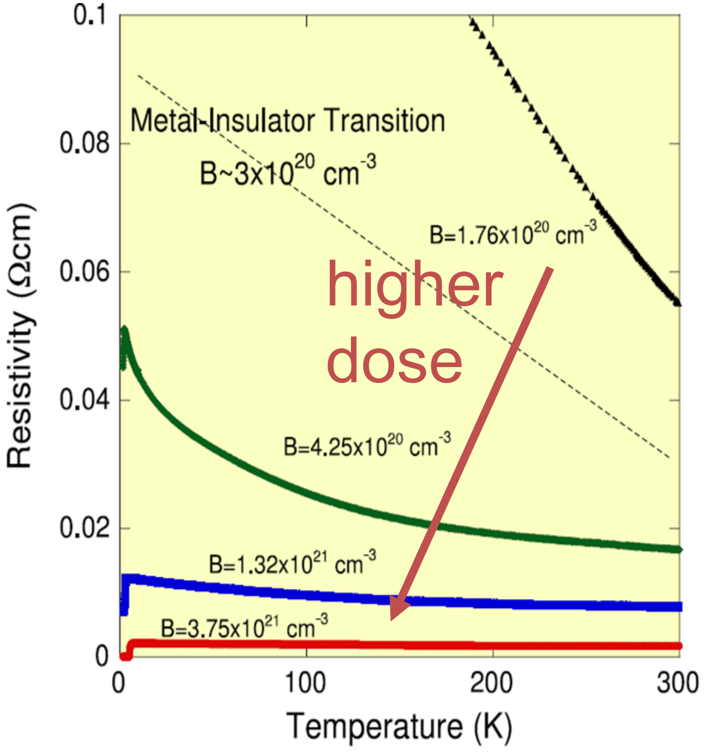
ATAP
ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

https://atap.lbl.gov

Fusion Science and
Ion Beam Technology Group

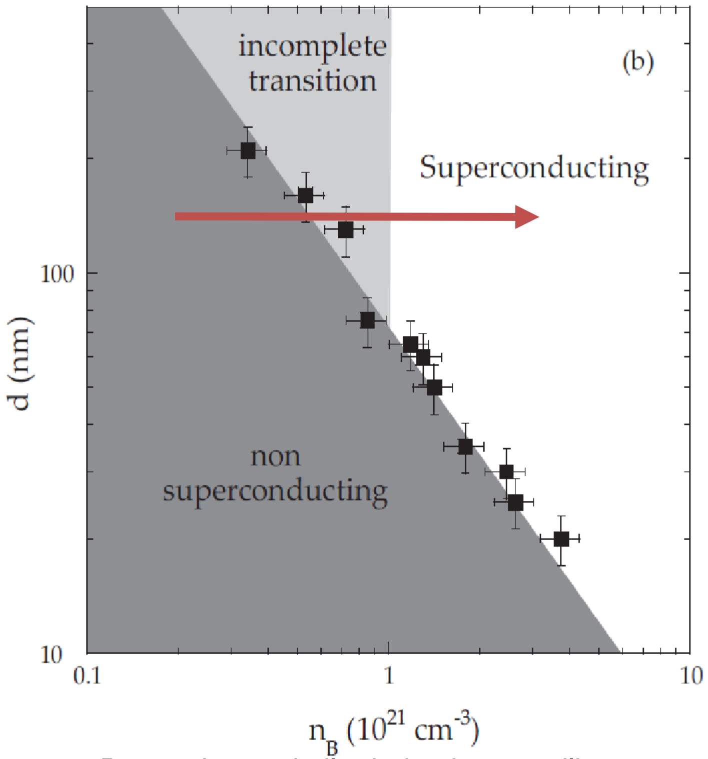
Superconductivity in boron-doped diamond

Y. Takano, J. Phys. Condens. Matter **21** 253201 (2009)



Temperature versus resistivity of Diamond at different Boron concentrations

A. Grockowiak, *et al.*, Phys. Rev. B **88**, 064508 (2013)



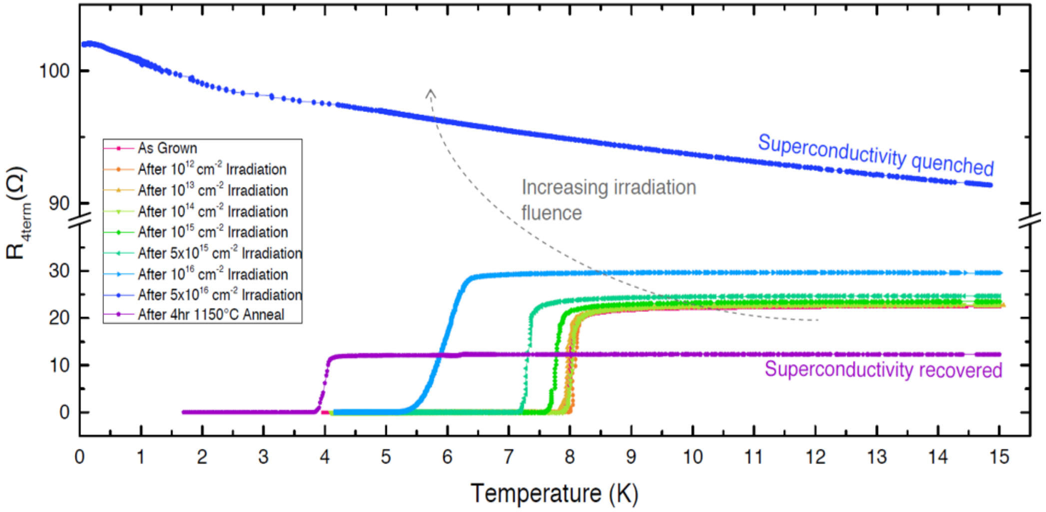
Boron shows similar behaviour as silicon

Critical temperature Tc of up to 50K is theoretically predicted for boron-doped diamond

Moussa, Cohen, Phys. Rev. B Condens. Matter Mater. Phys. **77**, 064518 (2008)

Tc of **~10K** for diamond has been reported with boron incorporation from growth.

D. L. Creedon, et al., Phys. Rev. Applied **10**, 044016



Superconductivity is hindered and quenched post-conventional ion implantation due to the high crystal damage

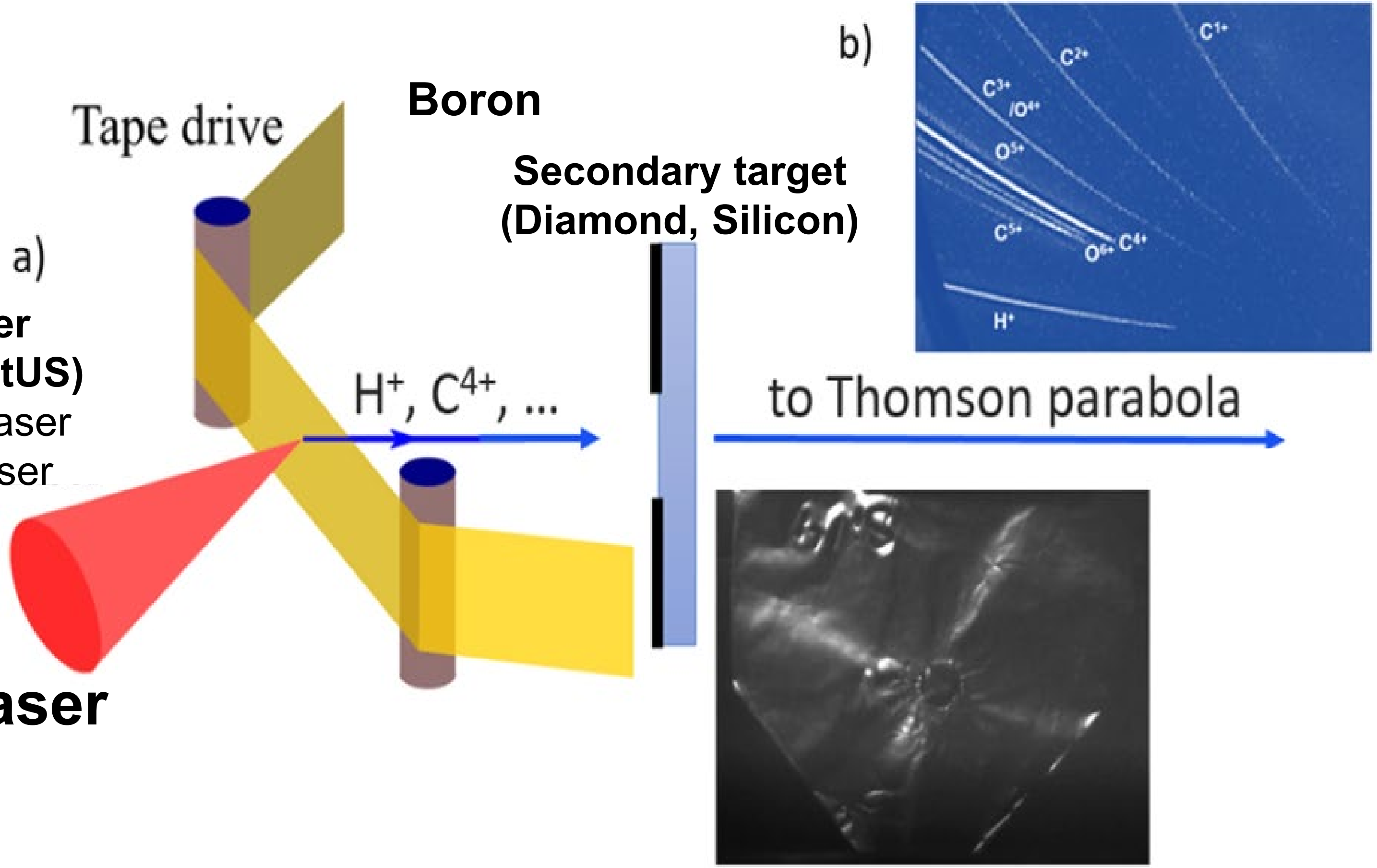
We use laser-driven ion acceleration to create intense ion beams

Titan laser
(LaserNetUS)
PHELIX laser
BELLA laser

PW laser

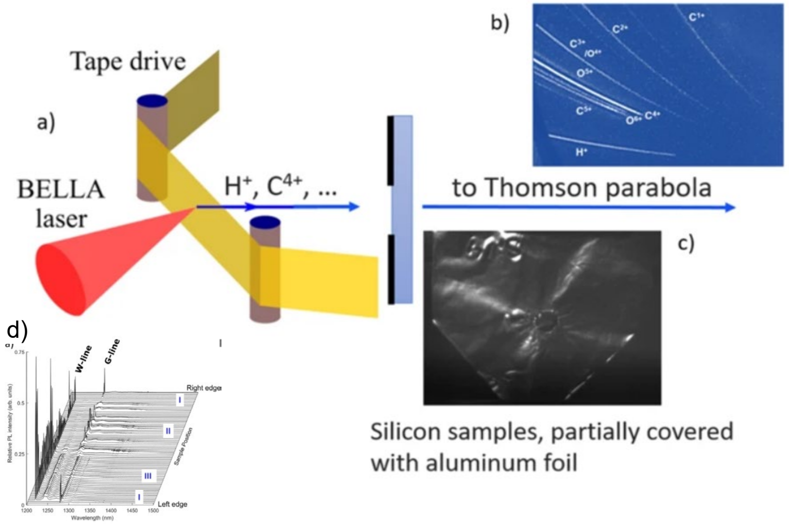
Boron

Secondary target
(Diamond, Silicon)



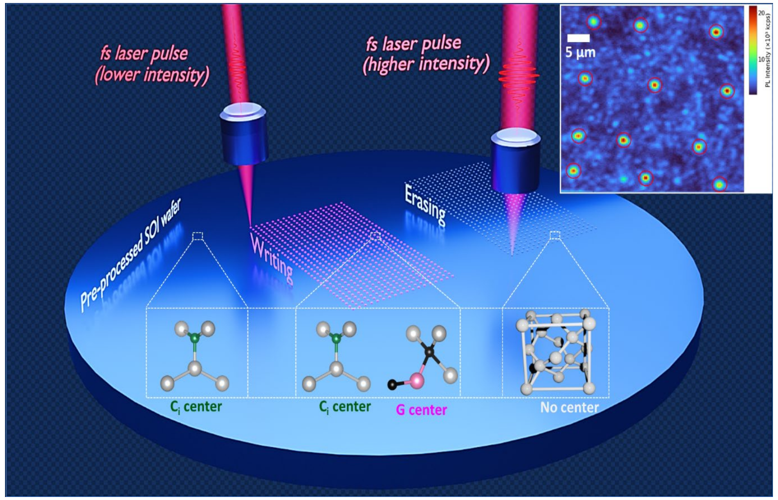
Redjem, W., *et al.*, Defect engineering of silicon with ion pulses from laser acceleration. *Comm. Mater.* **4**, 22 (2023)

We also make high-quality spin-photon qubits using conventional and non-conventional methods



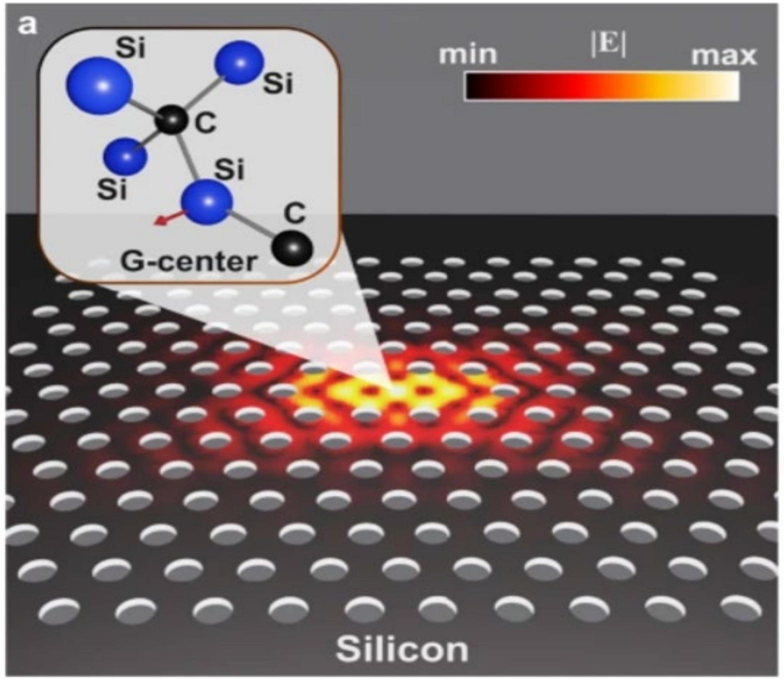
Schematic of the tape drive and ion target assembly with the secondary target to implant hydrocarbons into silicon and form telecom band color centers

Redjem, W., *et al.* Defect engineering of silicon with ion pulses from laser acceleration. ***Comm. Mater.*** **4**, 22 (2023)



Artistic representation of the fs laser irradiation approach to locally write and erase G, and C_i centers in SOI.

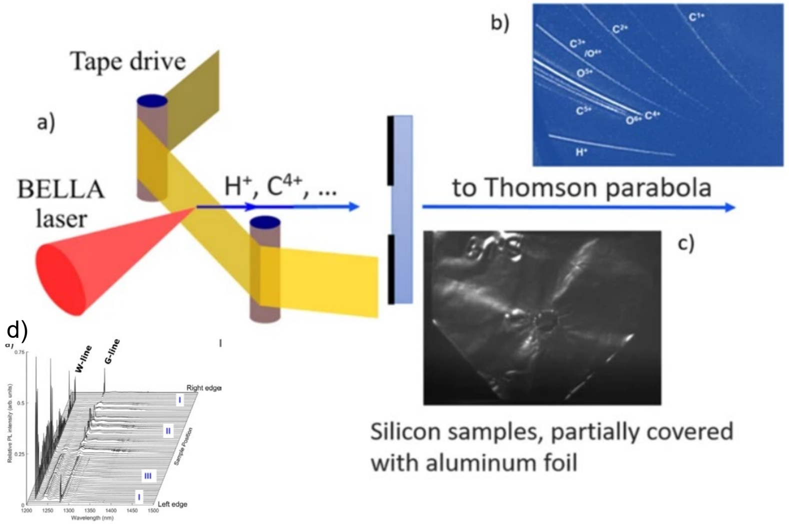
Jhuria, K., Ivanov, V., Polley, D. *et al.* Programmable quantum emitter formation in silicon. ***Nat. Comm.*** **15**, 4497 (2024)



A single atomic emissive center embedded in a silicon-photonic cavity.

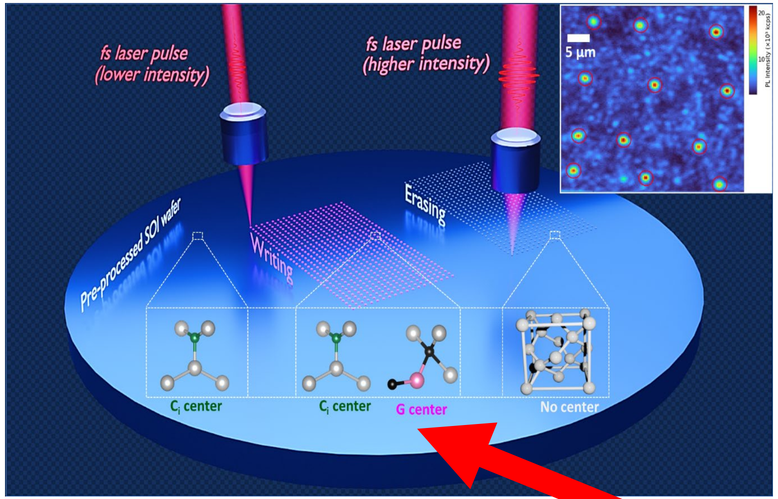
Redjem, W., K.Jhuria, *et al.* All-silicon quantum light source by embedding an atomic emissive center in a nanophotonic cavity. ***Nat. Comm.*** **14**, 3321 (2023).

We also make high-quality spin-photon qubits using conventional and non-conventional methods



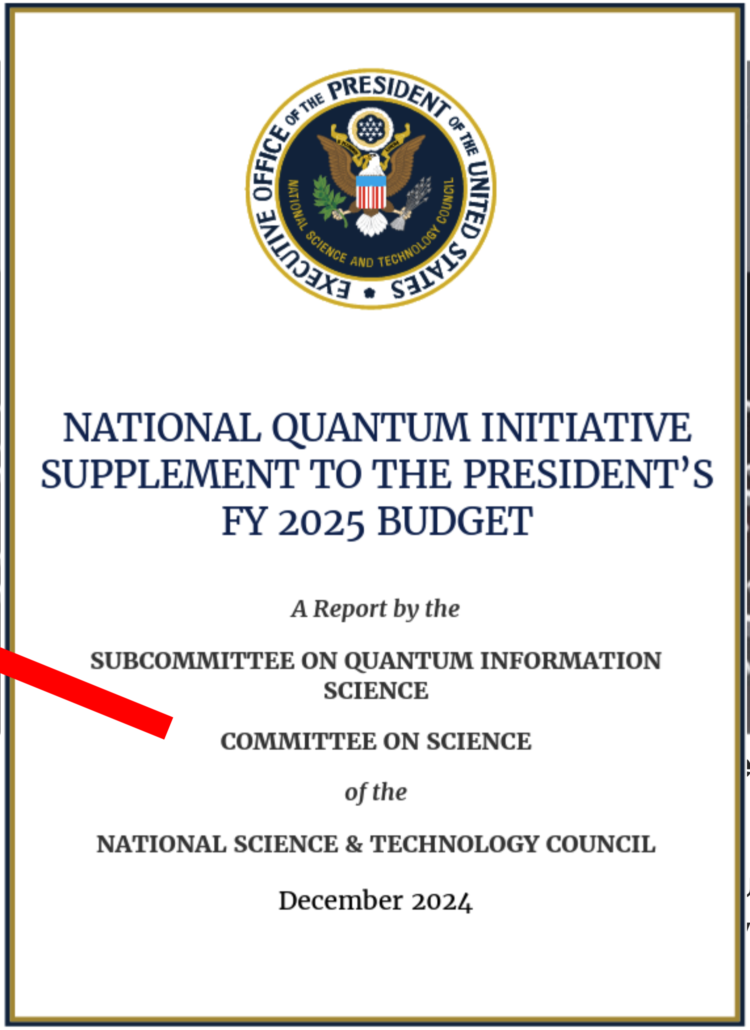
Schematic of the tape drive and ion target assembly with the secondary target to implant hydrocarbons into silicon and form telecom band color centers

Redjem, W., *et al.* Defect engineering of silicon with ion pulses from laser acceleration. ***Comm. Mater.*** **4**, 22 (2023)



Artistic representation of the fs laser irradiation approach to locally write and erase G, and C_i centers in SOI.

Jhuria, K., Ivanov, V., Polley, D. *et al.* Programmable quantum emitter formation in silicon. ***Nat. Comm.*** **15**, 4497 (2024)



NATIONAL QUANTUM INITIATIVE SUPPLEMENT TO THE PRESIDENT'S FY 2025 BUDGET

A Report by the

SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

COMMITTEE ON SCIENCE

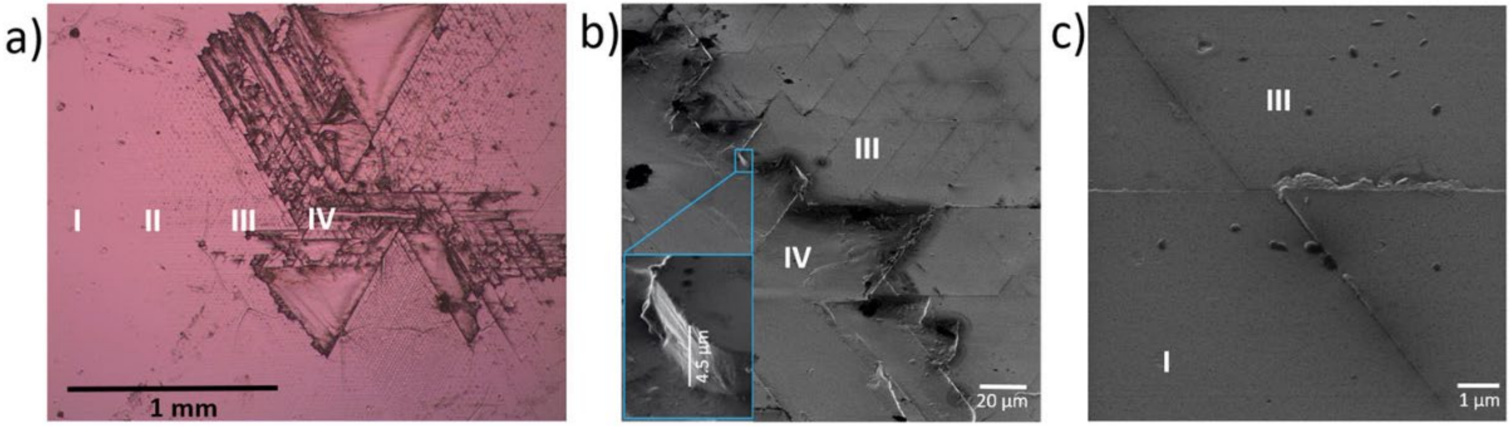
of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

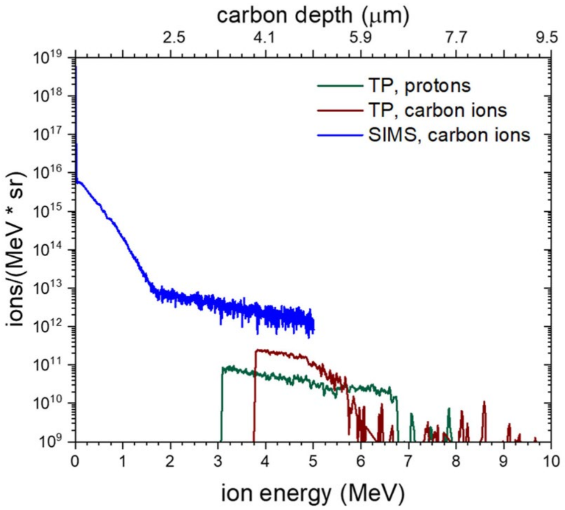
December 2024

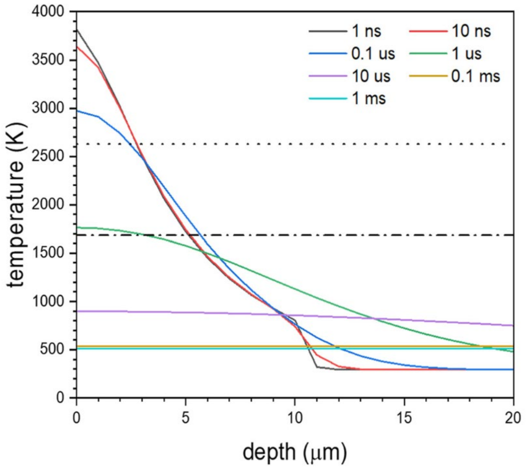
Laser ion implantation is a unique tool to provide high fluxes and high temperatures

Microscope images of ion beam hits (images from Si sample)



Ion energy distribution from TP and SIMS





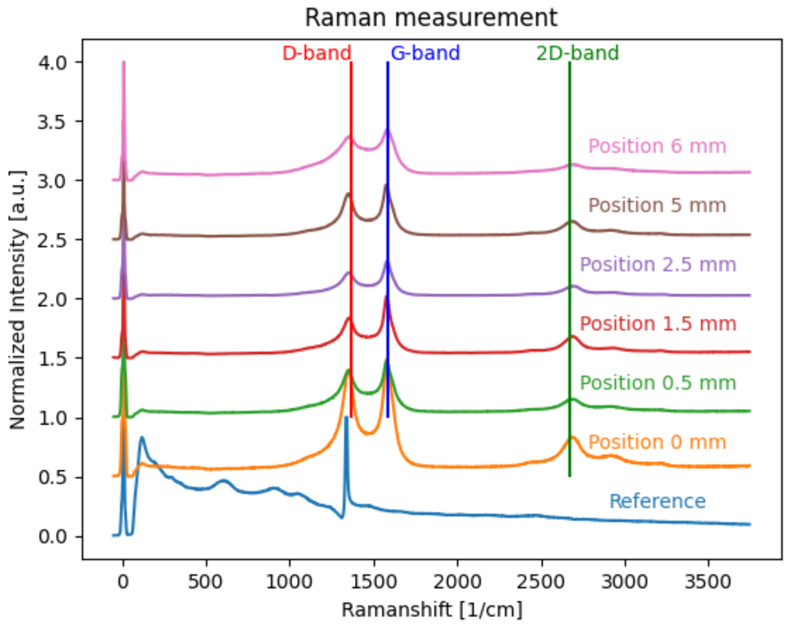
Simulated temperature distribution as a function of time

Redjem, W., *et al.*, Defect engineering of silicon with ion pulses from laser acceleration. *Commun. Mater.* **4**, 22 (2023)

Ex-situ material characterization for electrical and structural properties of boron-doped diamond

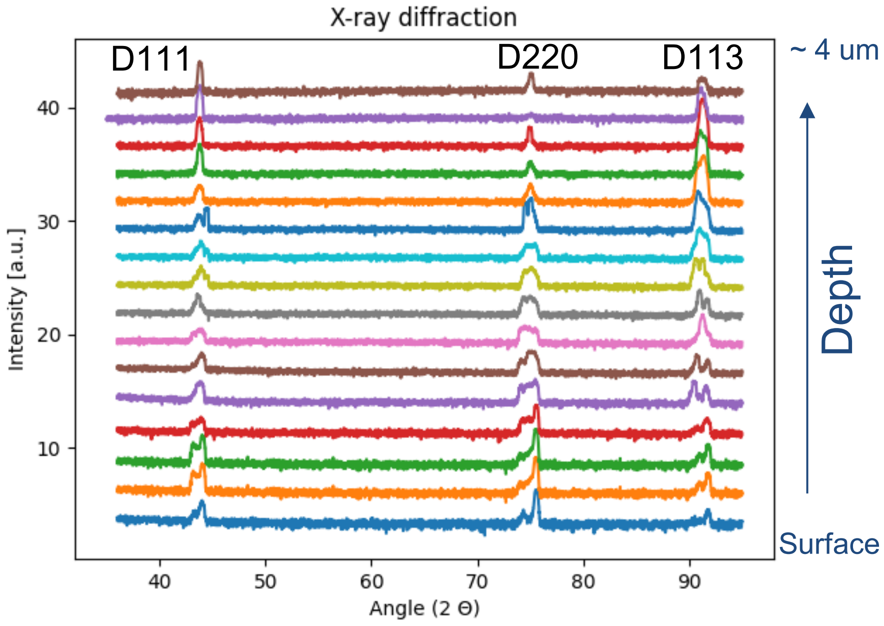
Raman spectroscopy

Raman spectroscopy helps us understand the structural properties of boron doped diamond and their impact on the superconducting phase



X-Ray diffraction

Depth-resolved X-ray diffraction analysis helps us understand the structural properties of diamond post laser-ion doping



Hall effect

Hall measurement measures RT mobility and carrier concentration.

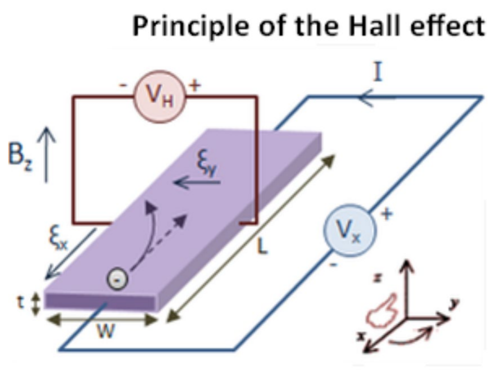
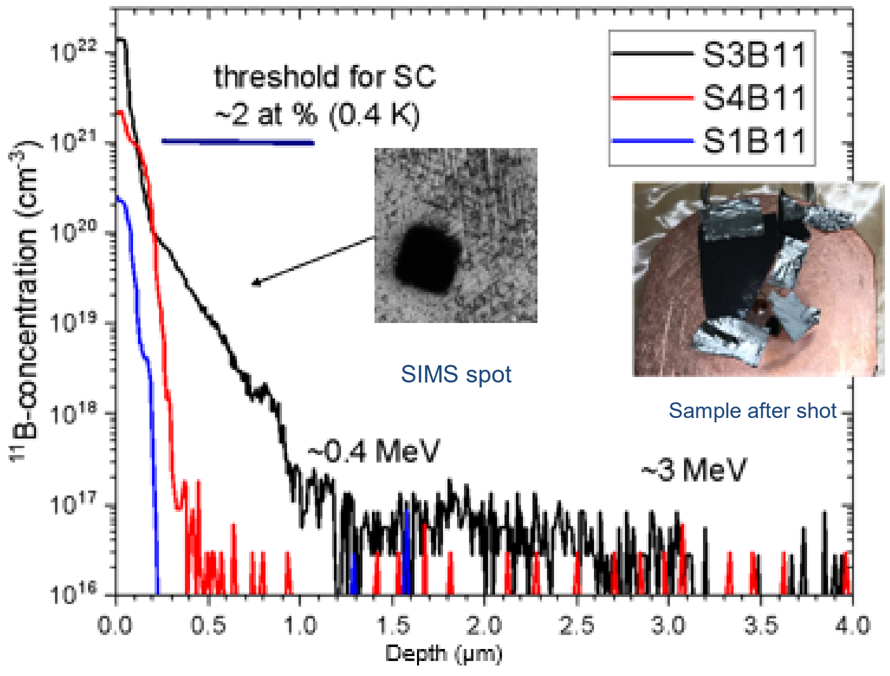


Image taken from https://www.testandmeasurementtips.com/measuring-the-hall-effect-faq/

(Measurements done at RT)

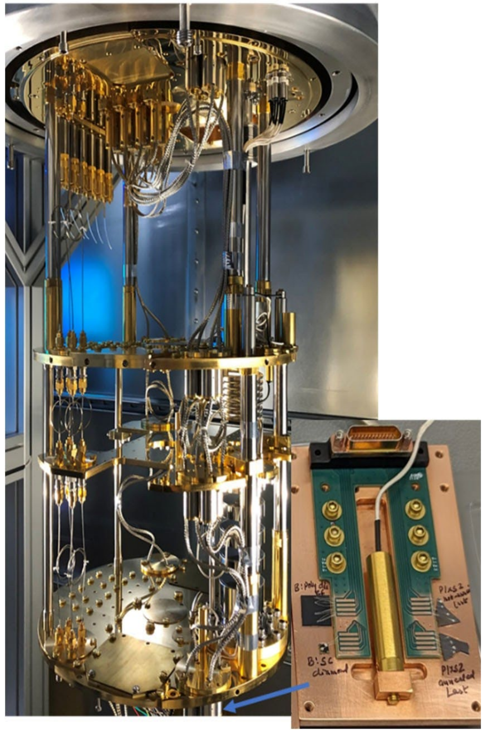
First demonstration of superconductivity in boron-doped diamond post ion implantation

Doping profile shows high concentrations

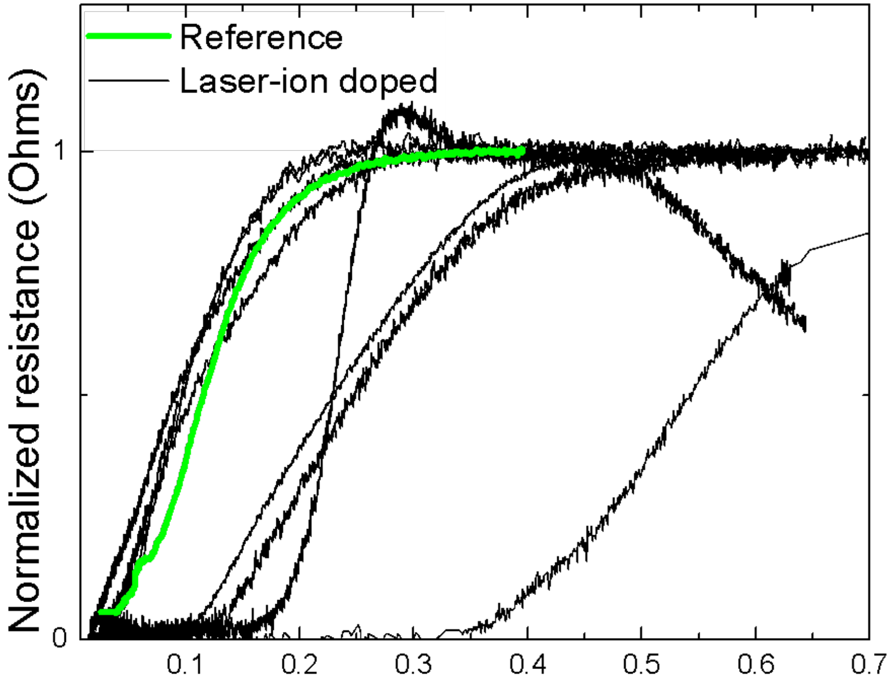


SIMS profile shows concentration well above metal-insulator transition post laser ion doping
(data from Si sample)

Low-temperature transport measurement show superconductivity



Cryostat used for SC measurements



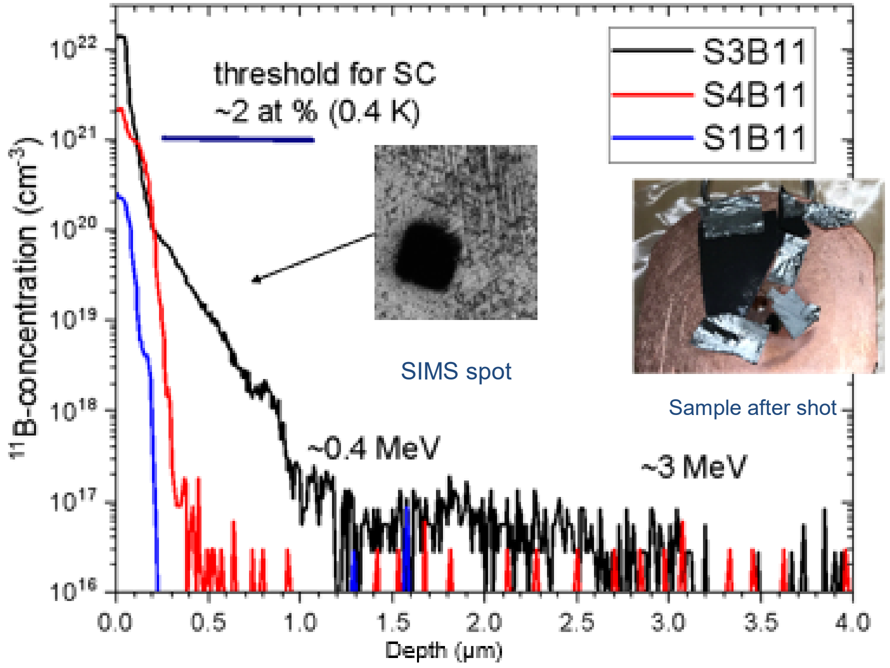
Note: no B-Field

(Reference sample is boron doped diamond sample where 2e20 B/cm2 was introduced during growth showing partial transition to superconductivity)

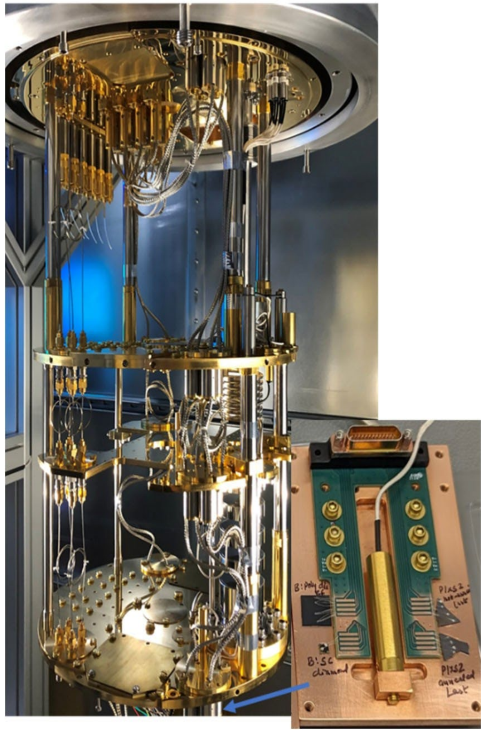
K. Jhuria, *et al.*, Non-trivial superconducting phase in Boron doped polycrystalline diamond (manuscript under preparation)

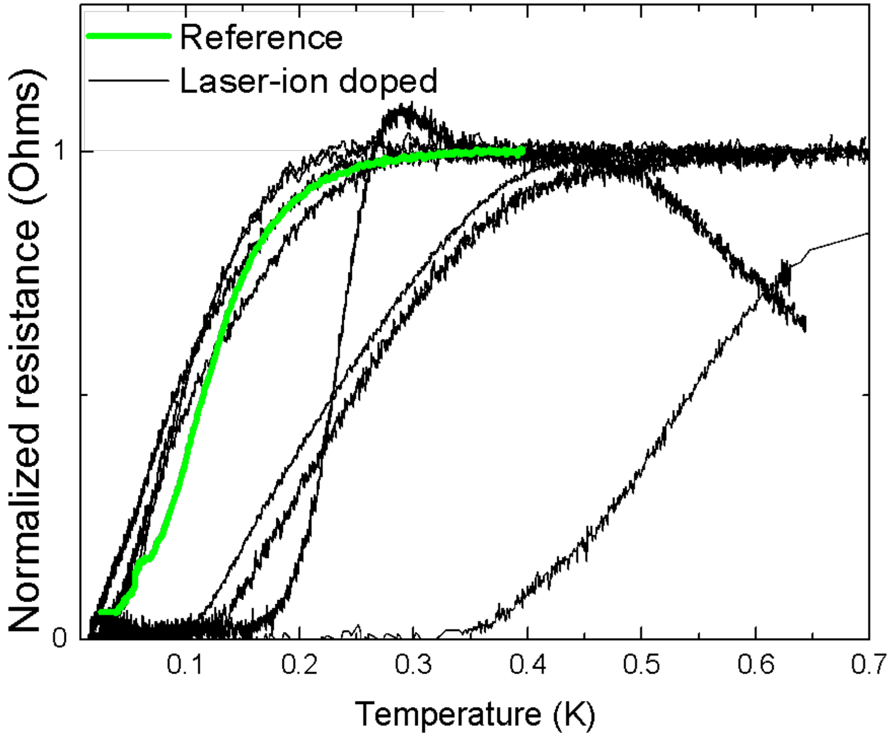
First demonstration of superconductivity in boron-doped diamond post ion implantation

Doping profile shows high concentrations



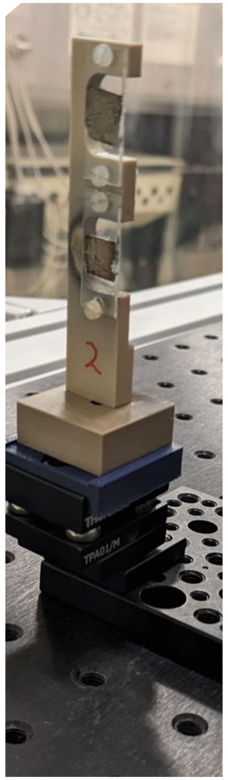
Low-temperature transport measurement show superconductivity



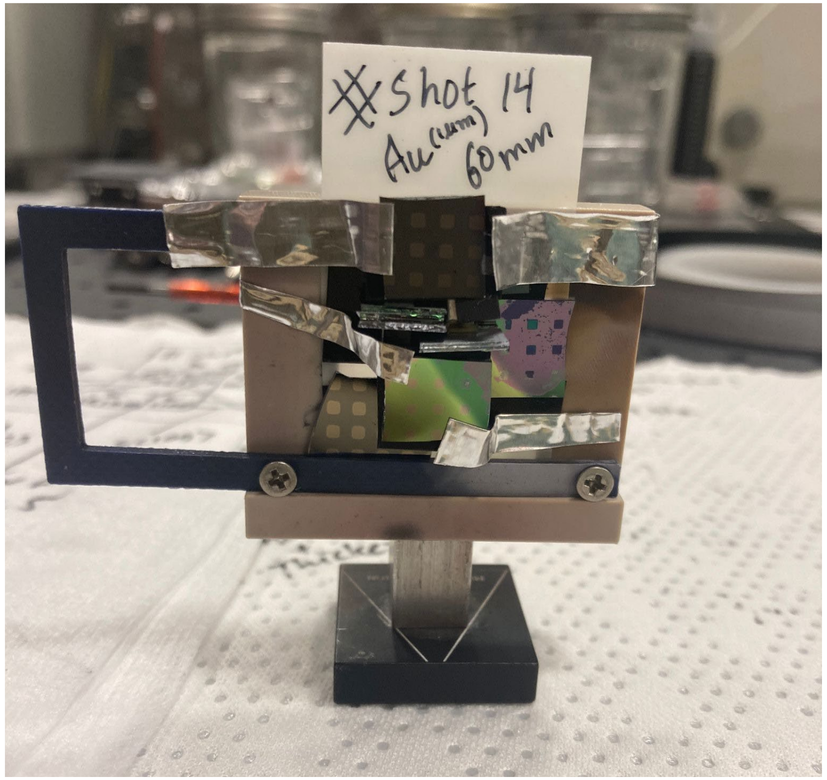


Summary: Unique beam qualities of laser accelerated ions allows us to create material properties that cannot be achieved using standard implantation techniques

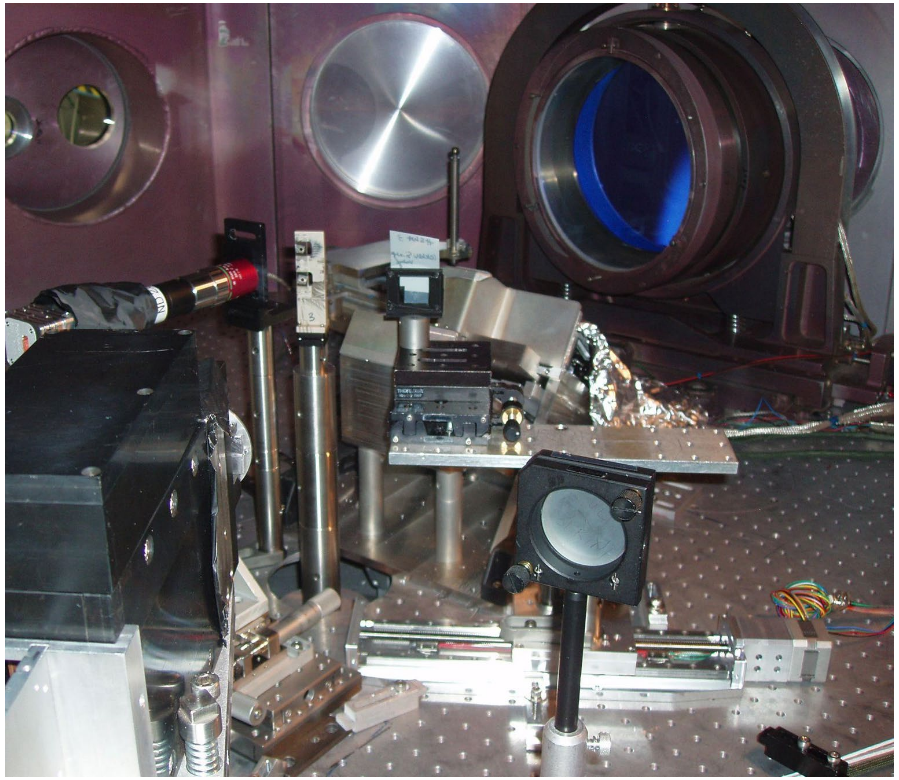
Typical setup for our laser-plasma ion-doping experiments



Sample holder for laser target foils

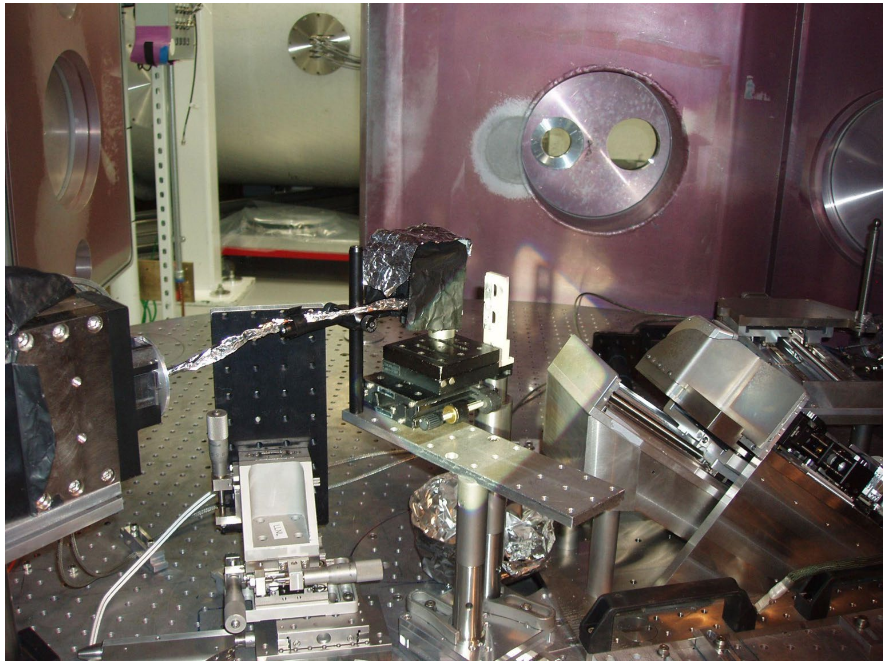


Sample holder for implantation targets

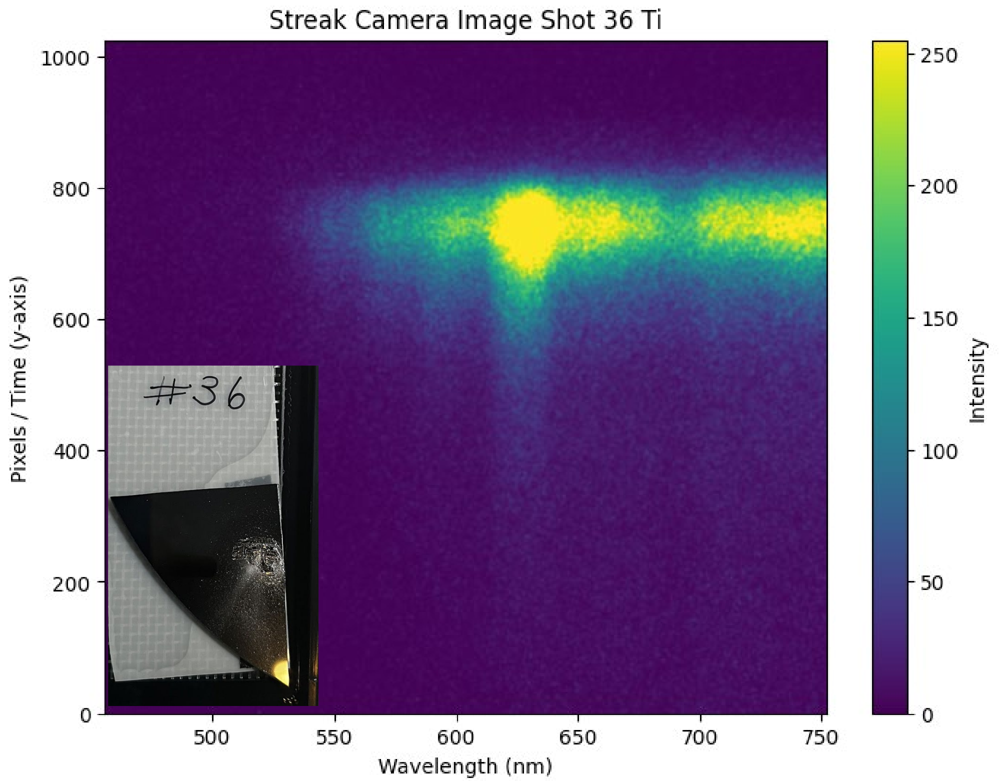


Target chamber at Titan

Started to test streak camera images for in-situ diagnostics

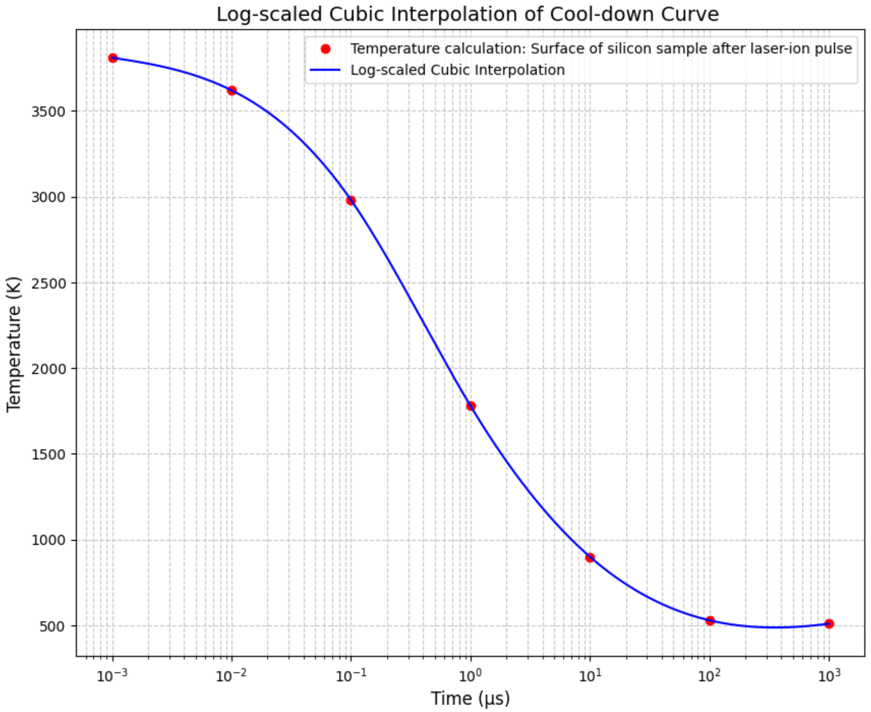


Streak camera setup in the chamber. Here, the fiber is pointed at the backside of the secondary target.



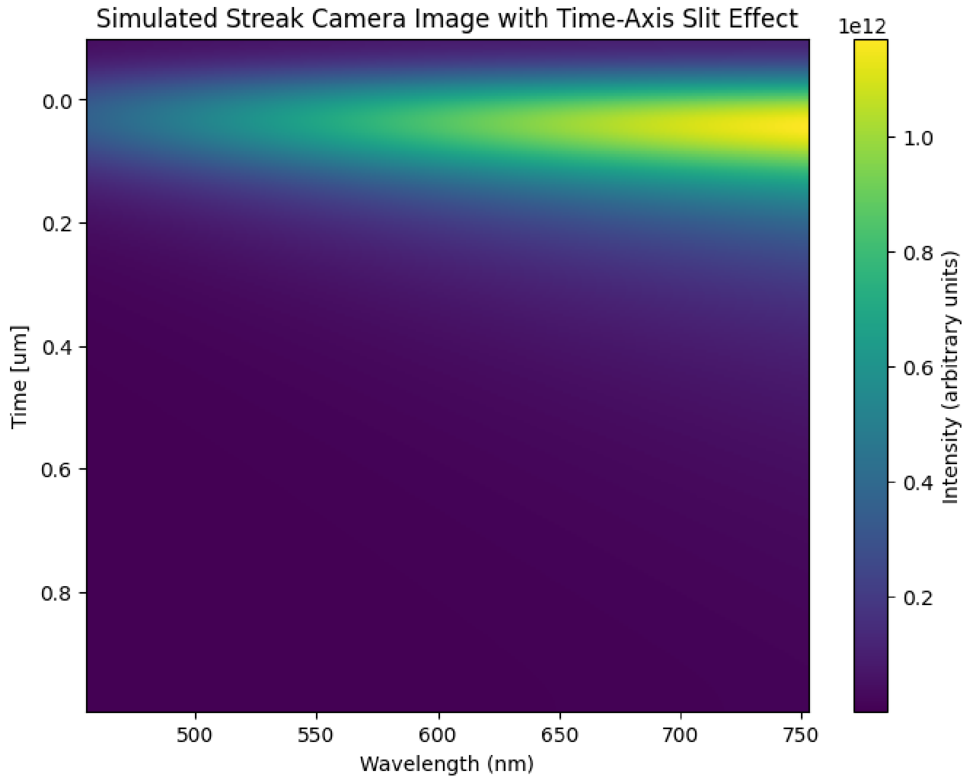
Streak camera image taken of front of intrinsic silicon (secondary target) for a titanium shot (primary target). Time delays were adjusted using the 5 Hz laser and a delay generator relative to the main trigger. (dt: 2 μs)

First Streak Camera images to measure temperature profiles



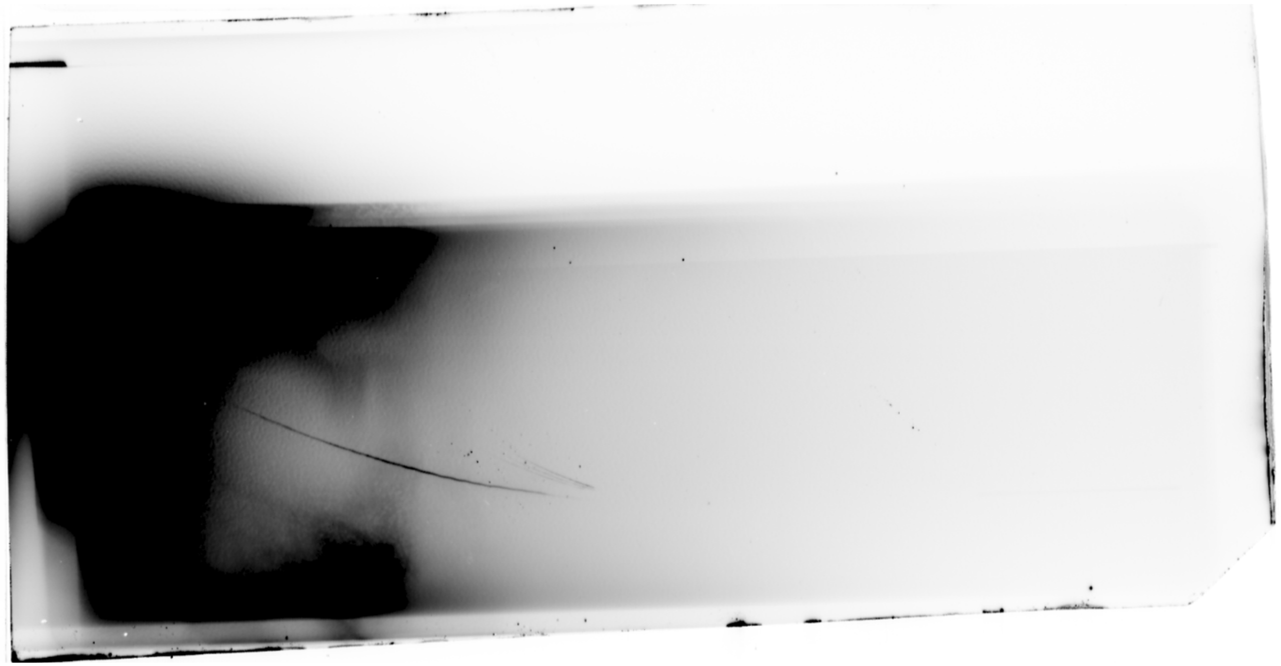
Simulated temperature profile using energy deposition during laser-plasma implantation.

Redjem, W., Amsellem, A.J., Allen, F.I. *et al.* Defect engineering of silicon with ion pulses from laser acceleration. *Commun Mater* **4**, 22 (2023). https://doi.org/10.1038/s43246-023-00349-4



Preliminary simulation of black body radiation using the temperature profile on the left shows reasonable agreement.

Mixed results from Thomson Parabola shots taken during Titan run

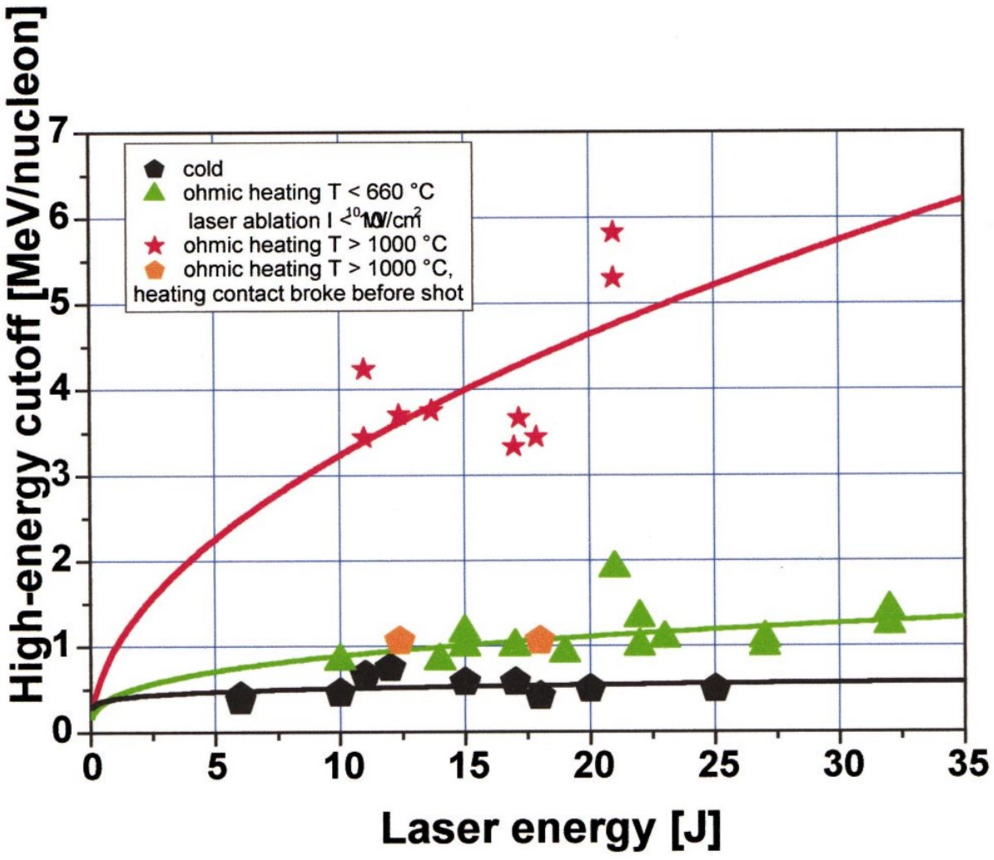


Thomsen parabola from Al shot left and Cu/Ni right. (Shot 8 and 21) show separate parabolas from different ion species and charge states.
However, the right shot shows also typical noise that we have seen in many shots. Sometimes the noise covers the whole region of interest.

Outlook: Pre-cleaning the target foil is an interesting option for us to reduce implantation of unwanted species

Pre-clean of foil to reduce H, C, and O ions.
Several option to achieve pre-cleaning:

- **Radiative heating**
- **CW laser heating** (attempted with defocused CW last beamtime)
- Ohmic/resistive heating
- Short pulse laser ablation
- Ion etching



B. M. Hegelich, et al.; *Phys. Plasmas* 1 May 2005; 12 (5): 056314. https://doi.org/10.1063/1.1915350

Outlook

- Data analysis ongoing from a successful LaserNet US beamtime
- More measurements at LaserNet Us facilities planned
- Working on better ion beam diagnostics to correlate beam conditions with samples conditions (including Thomson parabola and Streak cameras)
- Move to thinner diamond films, for improved superconductivity measurements
- *In-situ* cleaning of foils before laser shot to remove O, C, H contaminants
- Preparing structures on samples, e.g., for single photon detector (detect change from SC to non-SC when a photon hit)

Thank you for your attention!

Questions?

APersaud@lbl.gov
Kaushalya@lbl.gov

The presented results are based on experiments conducted at the Jupiter Laser Facility (LLNL, Livermore, USA) through LaserNetUS and at the PHELIX facility (GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany).

This work at Berkeley Lab received support from the Office of Science, Office of Fusion Energy Sciences, U.S. Department of Energy, under Contract No. DE-AC02-05CH11231. Work at the Molecular Foundry was supported by the Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.The use of the Jupiter Laser Facility was supported by the U.S. Department of Energy, Lawrence Livermore National Laboratory, under Contract No. DE-AC52-07NA27344.