Fusion Energy Science at LBNL

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PPPL PRINCETON PLASMA PHYSICS LABORATORY

CORNELL UNIVERSITY FOUNDED A.D. 1865

TECHNISCHE UNIVERSITÄT DARMSTADT

FUSION POWER ASSOCIATES

37th Annual Meeting & Symposium

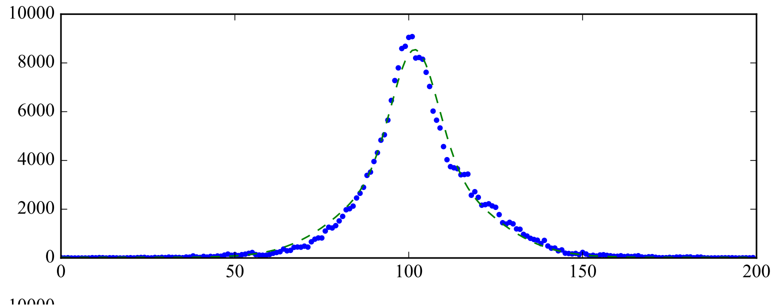
Washington, DC

December 13-14, 2016

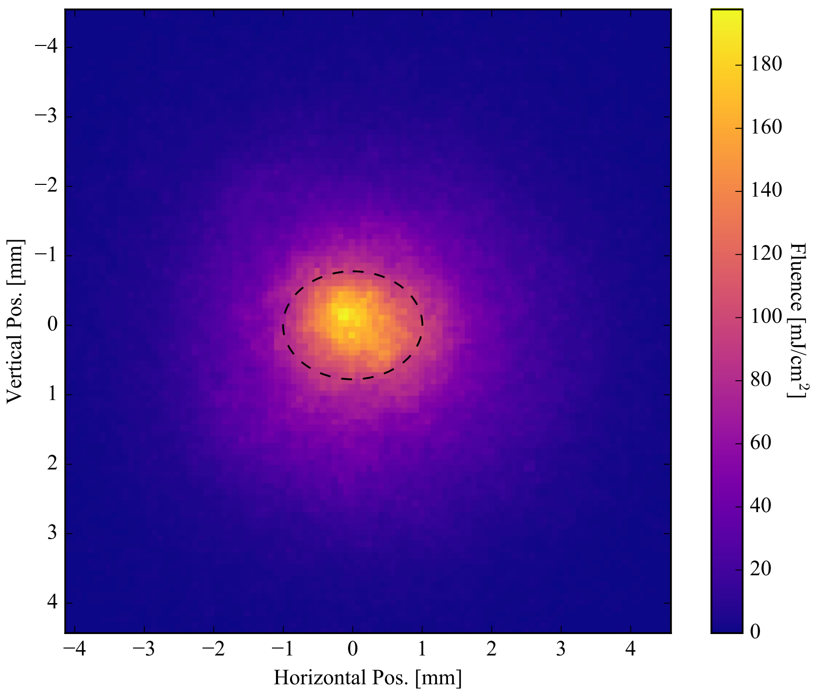
1. **Intense ion beams @ NDCX-II**
2. **Intense ion beams @ Bella-i**
3. **Scalable and compact accelerators**

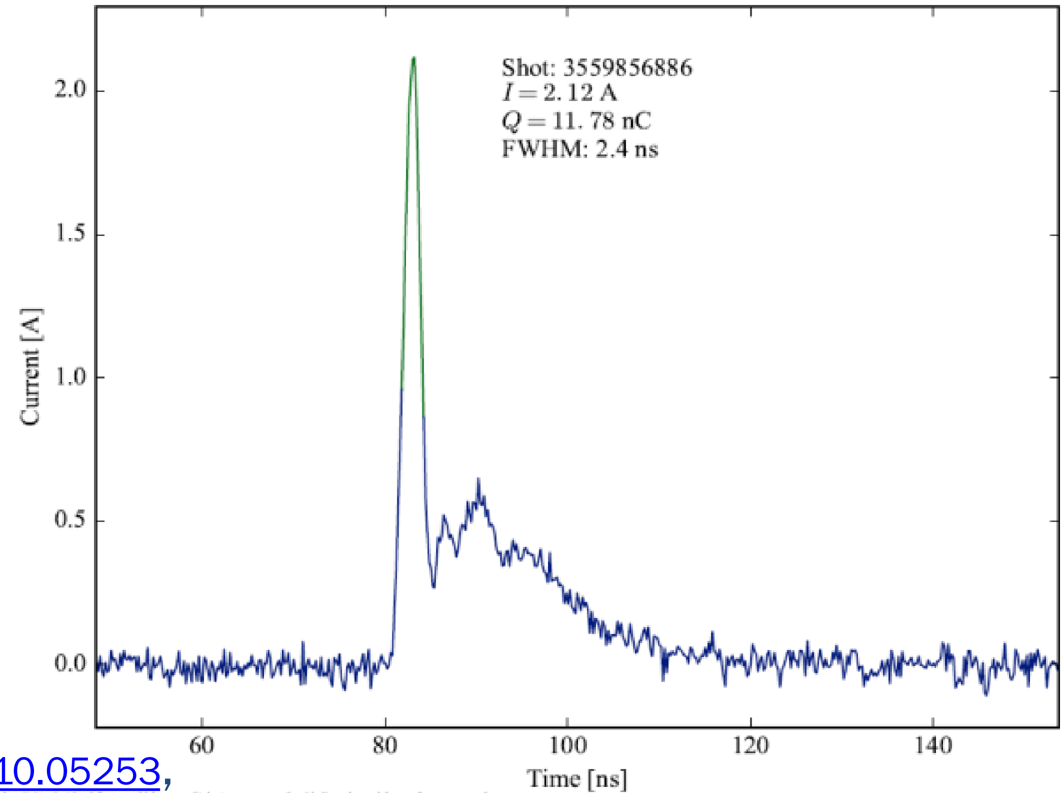
This work was supported by the Office of Science, FES and by ARPA-E, US Department of Energy.

1. With NDCX-II, we have achieved 2 A peak currents for ns pulses of 1 MeV He^+ ions



- 1.1 MeV (He^+), 12 nC in whole bunch (7.5×10^{10} ions) → 13 mJ
- ~100 mJ/cm^2 @ peak, 2 mm FWHM
- Uniform energy deposition into a 2 micron silicon foil with ~ 6×10^3 J/cm^3

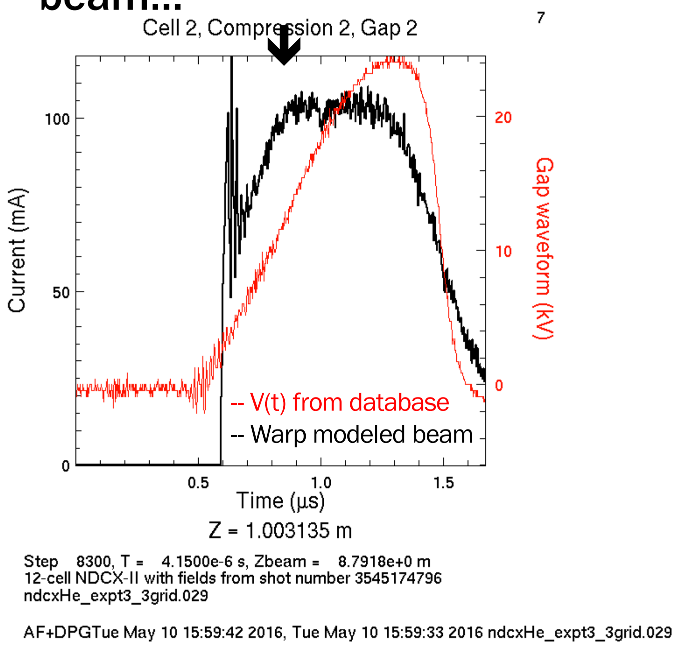




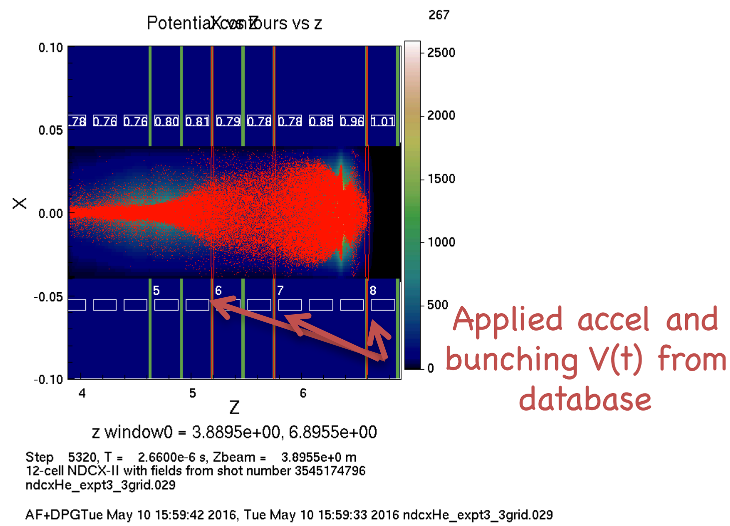
Seidl, et al., NAPAC'16 https://arxiv.org/abs/1610.05253,
IFSA'15 http://iopscience.iop.org/article/10.1088/1742-6596/717/1/012079

Particle-in-cell simulations validate our understanding of the high intensity beam physics and help optimize the performance of the accelerator for target experiments

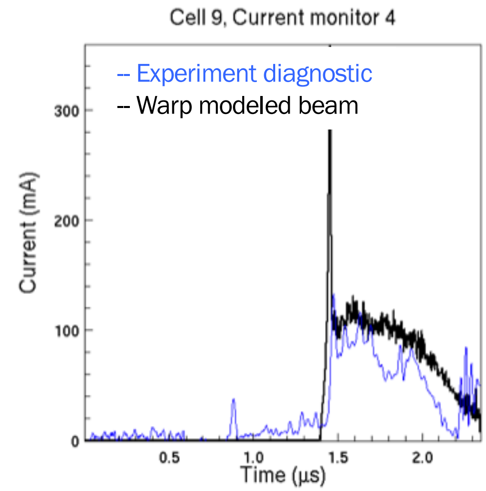
1. Beginning with model of plasma ion (He+) source injection, the experiment voltage waveforms are imported from DAQ database & applied to the 2D Warp simulated beam...

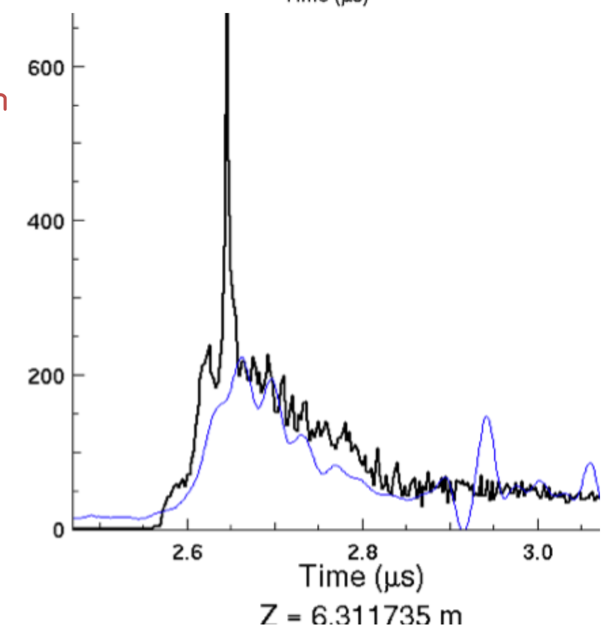


2. Snapshot of the X-Z projection shows rms properties & halo particle loss... ↓



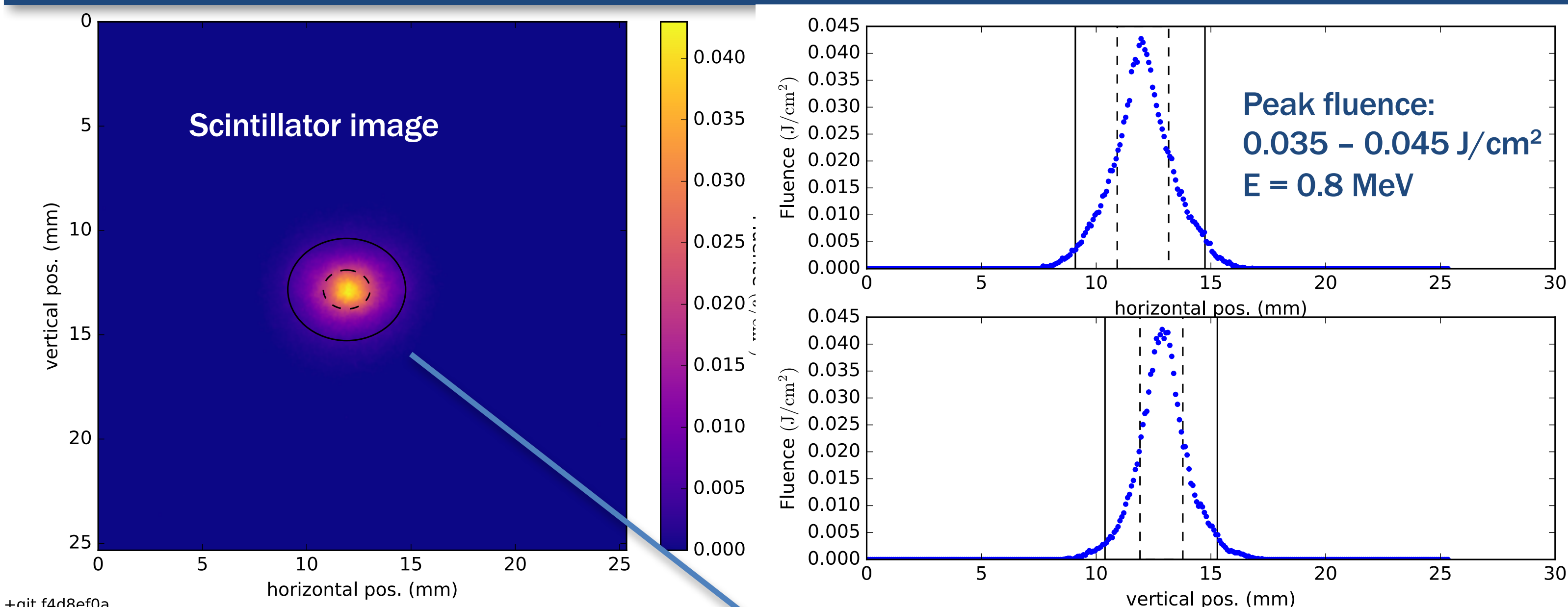
3. Results are directly compared to the experiment beam diagnostics. From these, adjust focusing, waveforms, timing, then go to #1. →

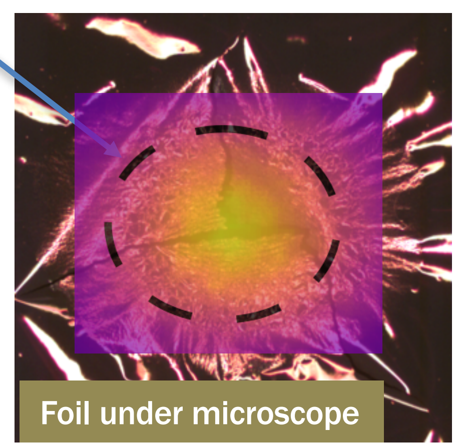


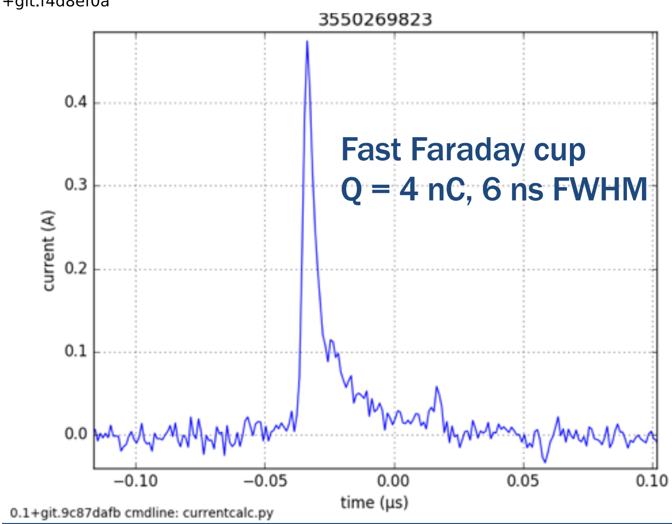


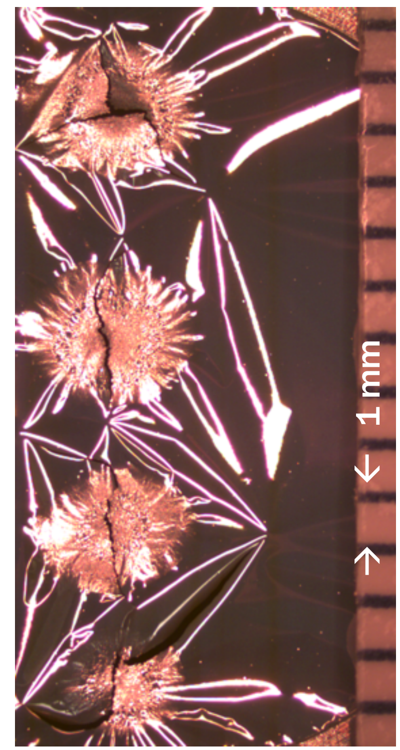
≈10 min/run/processor, we do ≈10 parallel simulations, vs 1 shot/min in the experiment

Heating 0.3-μm foil Tin with a short-pulse helium beam shows the onset to the melting phase



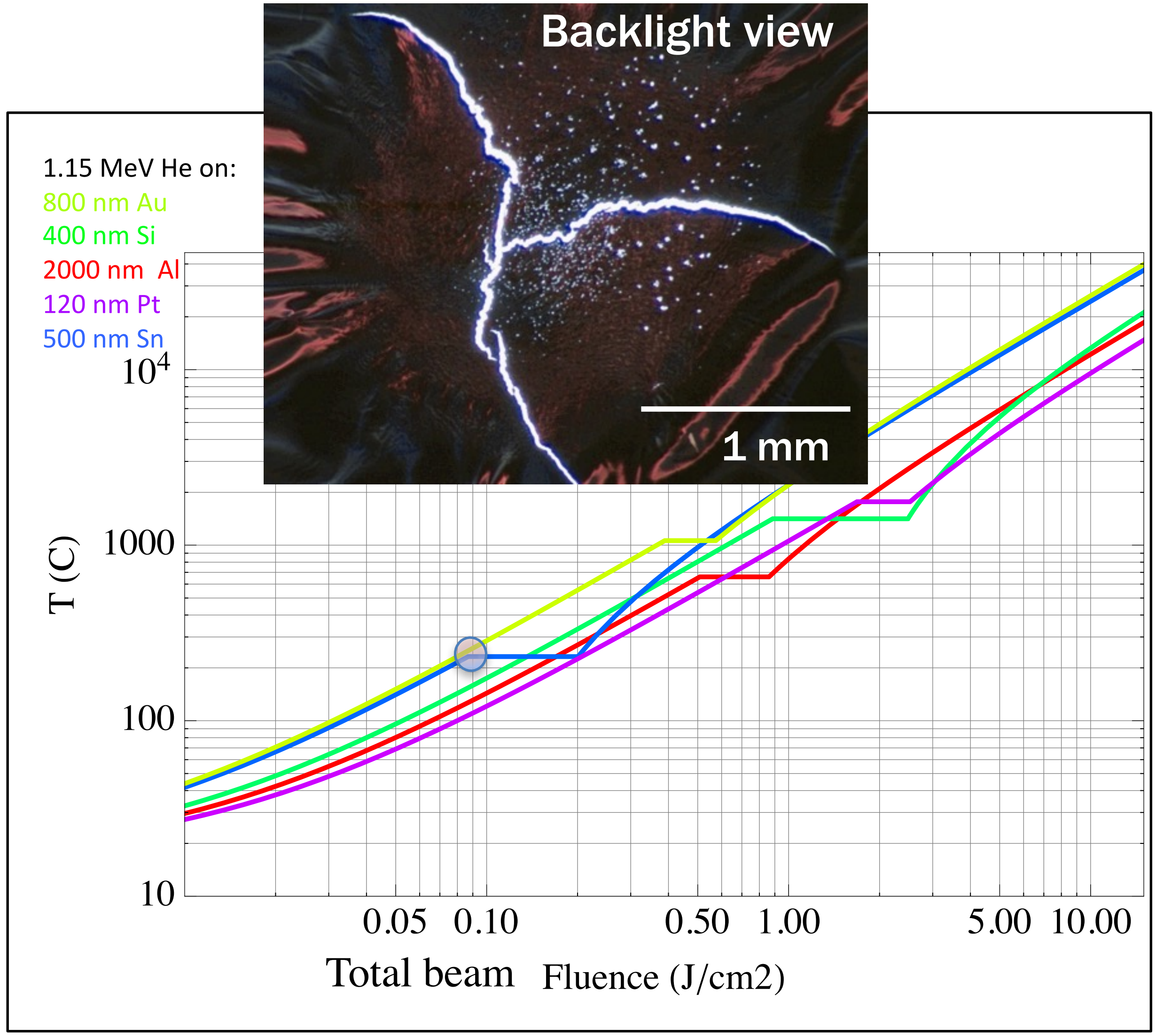




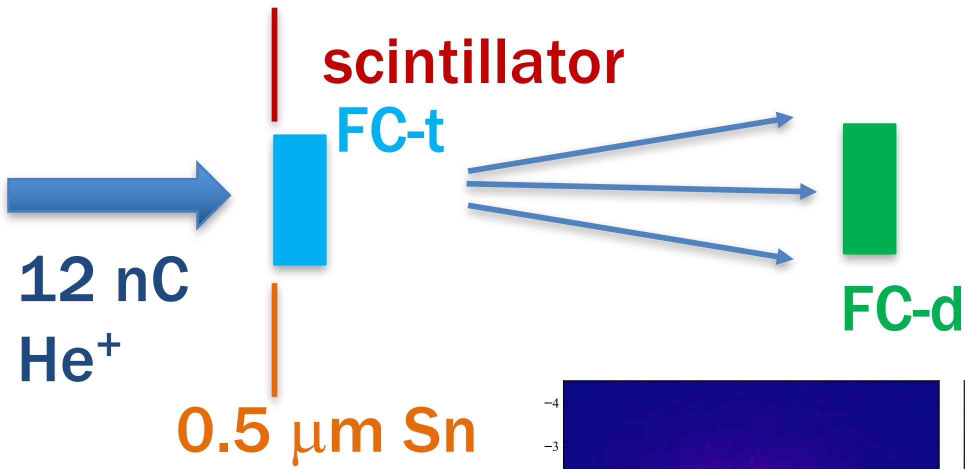


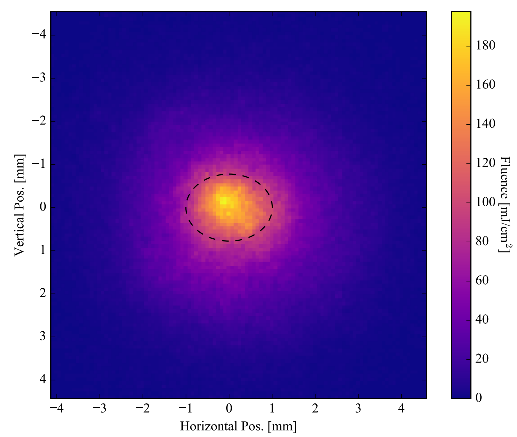
Structural changes , holes in Sn foil (0.5 μm) after uniform heating with Q_{tot} = 12-nC/beam pulse

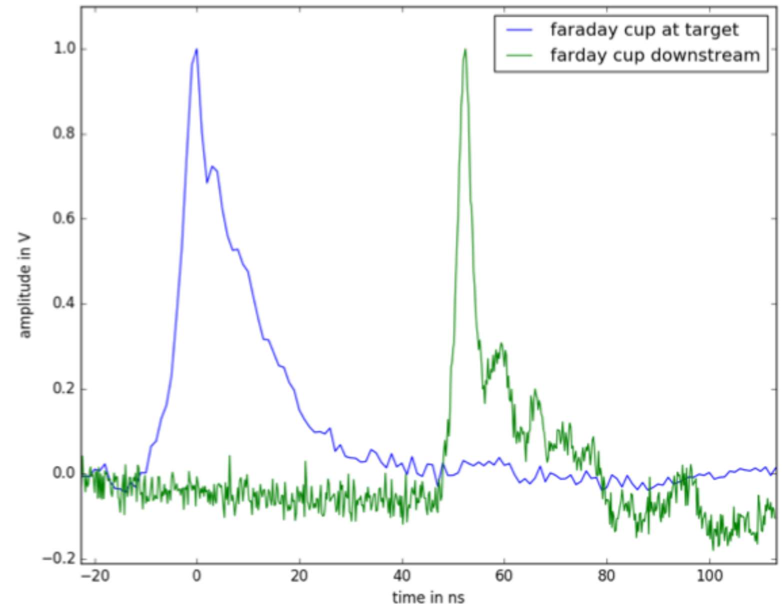
- <u>Multiphysics modeling</u> with *arbitrary Lagrangian Eulerian hydrodynamics with adaptive mesh refinement* (ALE-AMR), Koniges, et al, Plasma Sci. Tech., 17 (2) 2015
- Sensitive to solid-solid and solid-liquid phase transitions.
- Ion interactions with liquid films → plasma facing components.
- Up next: Sn phase transitions, Si membrane, energy loss in band-gap materials, streak spectroscopy, channeling…

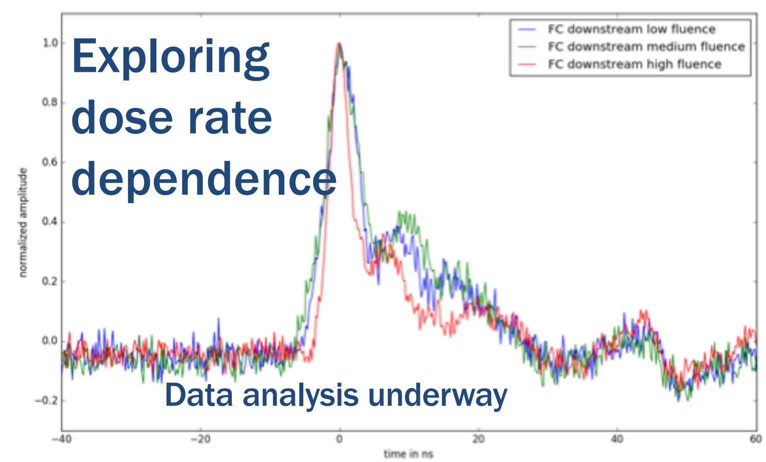


We now measure energy loss of transmitted ions in heated foils via time-of-flight







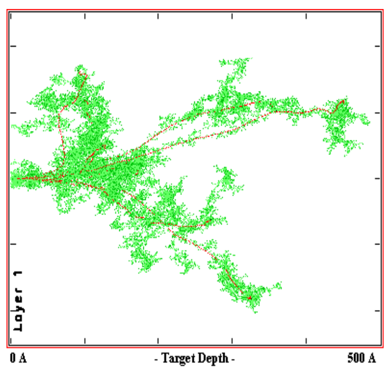


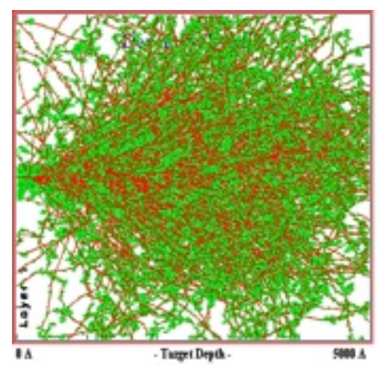
Opportunity to probe material response to short-pulse ionizing radiation (t, λ), **e.g., channeling** of ions in crystals

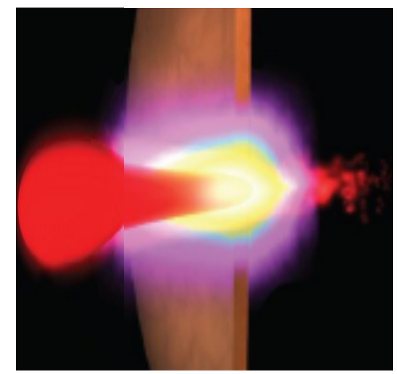
Intense, Short Ion Pulses are Unique Tools for Materials Science, Studies of Phase-Transitions and Warm-Dense Matter Research

Lower intensities:
defect dynamics in materials

Higher intensities:
processing, phase transitions and warm dense matter





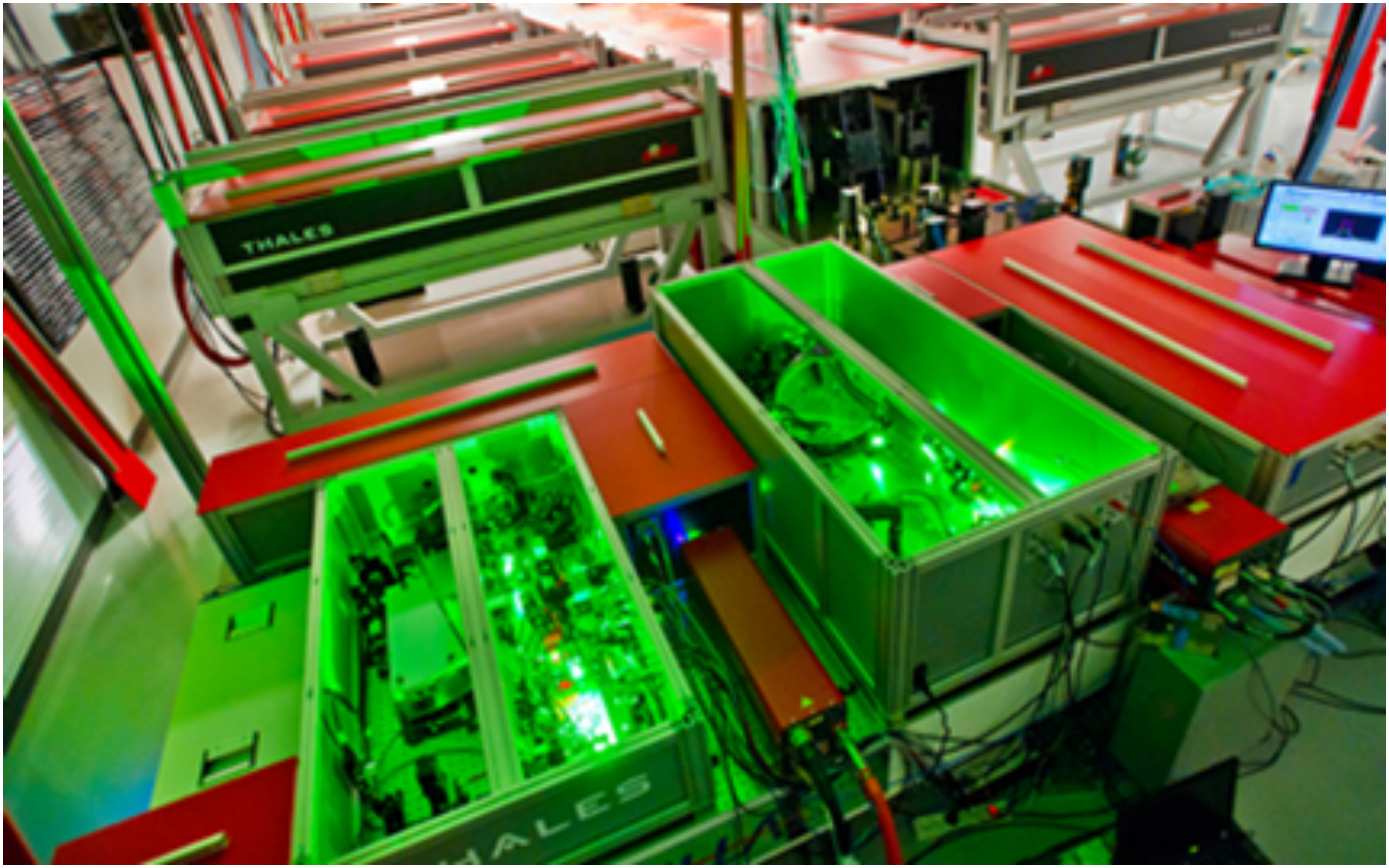


NDCX-II – now

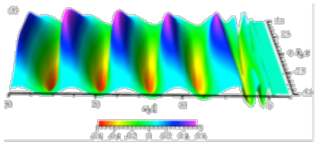
BELLA-i – soon

- Ions deposit energy via collisions with target electrons and nuclei
- Uniform, volumetric heating with ion energies near the Bragg peak in electronic stopping

2. With Bella-i we are expanding science at the Bella petawatt laser to ion acceleration and high energy density physics



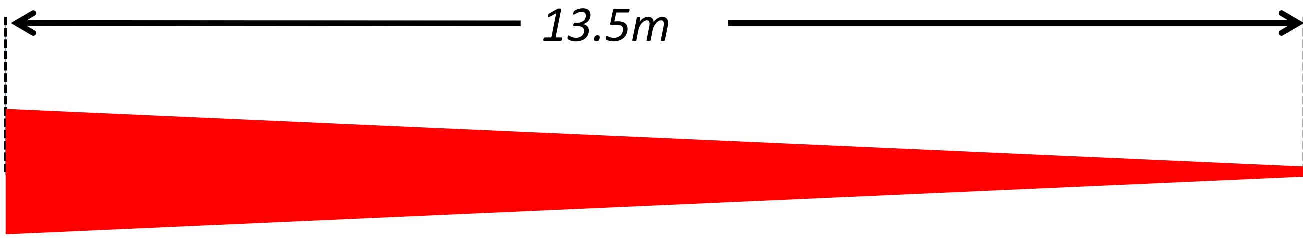
For BELLA-i, Phase 1, we will use the existing long focal length beamline at BELLA and run experiments with solid targets

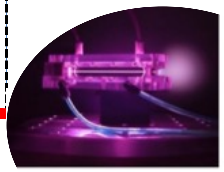


Electron acceleration

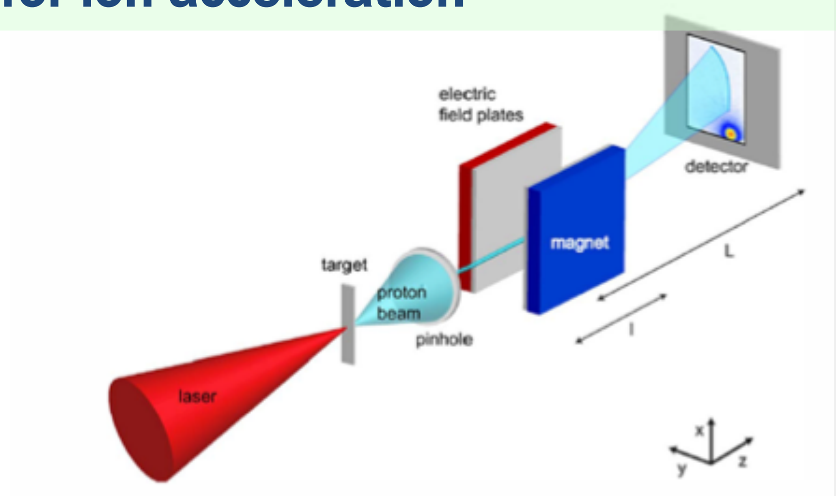
Intensity ~10^{19} W/cm^2

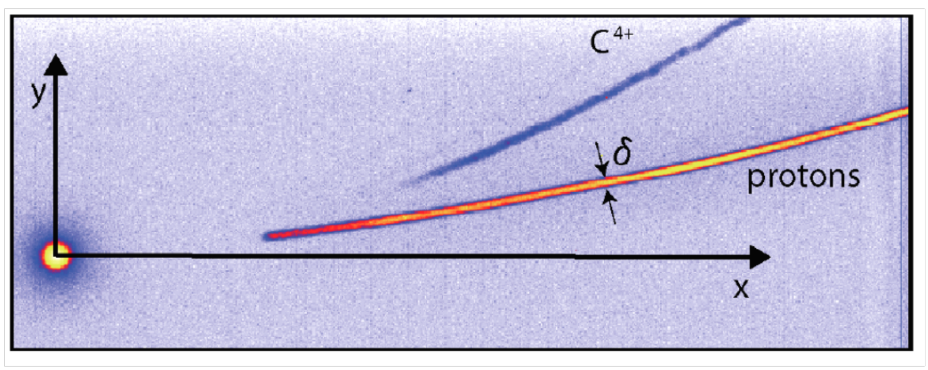
55 micron spot, 40 J, 1 Hz



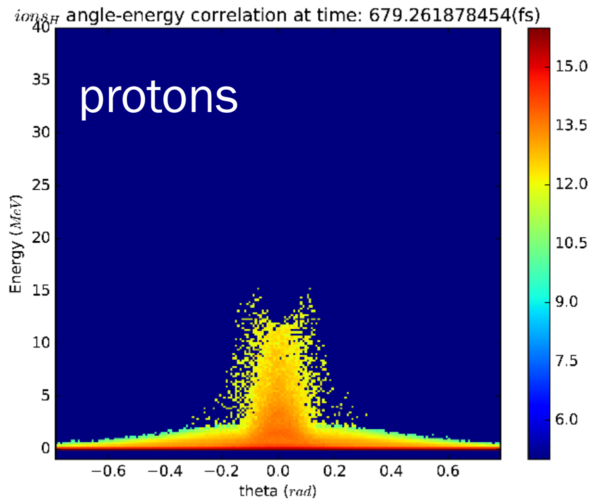


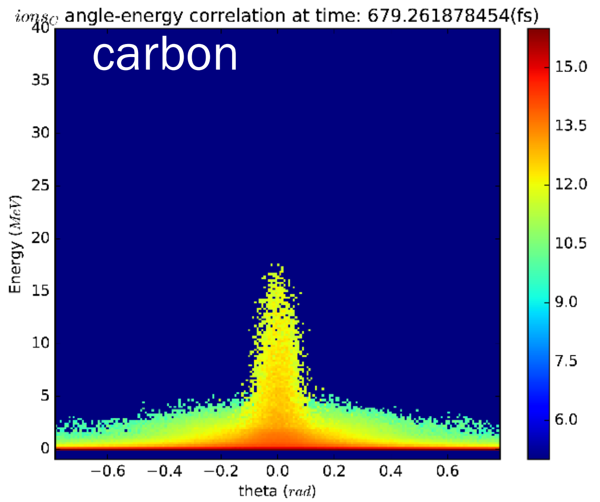
For BELLA-i, Phase 1, we will use the long focal length beamline also for ion acceleration

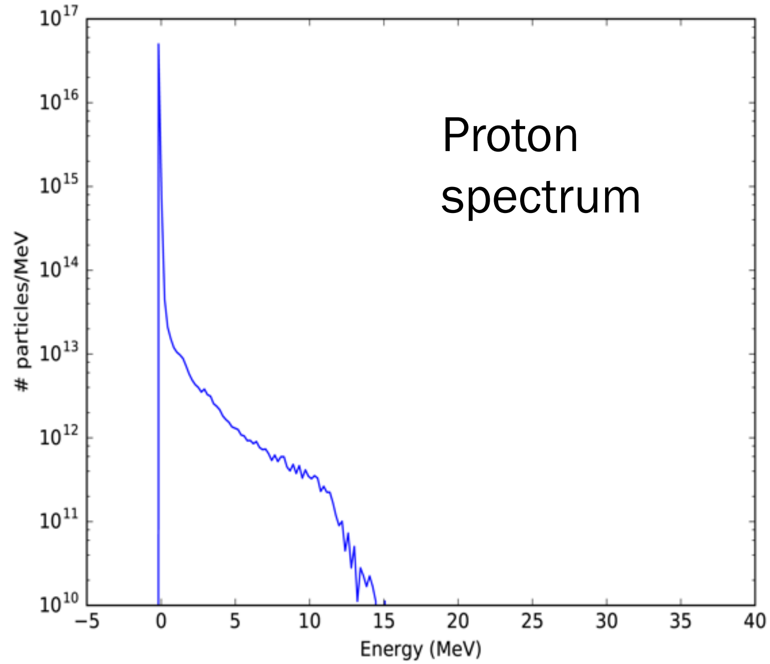




PIC simulations show directed, high charge ion pulses with energies up 15 MeV



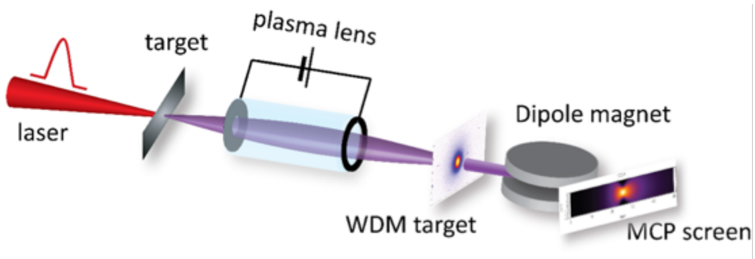




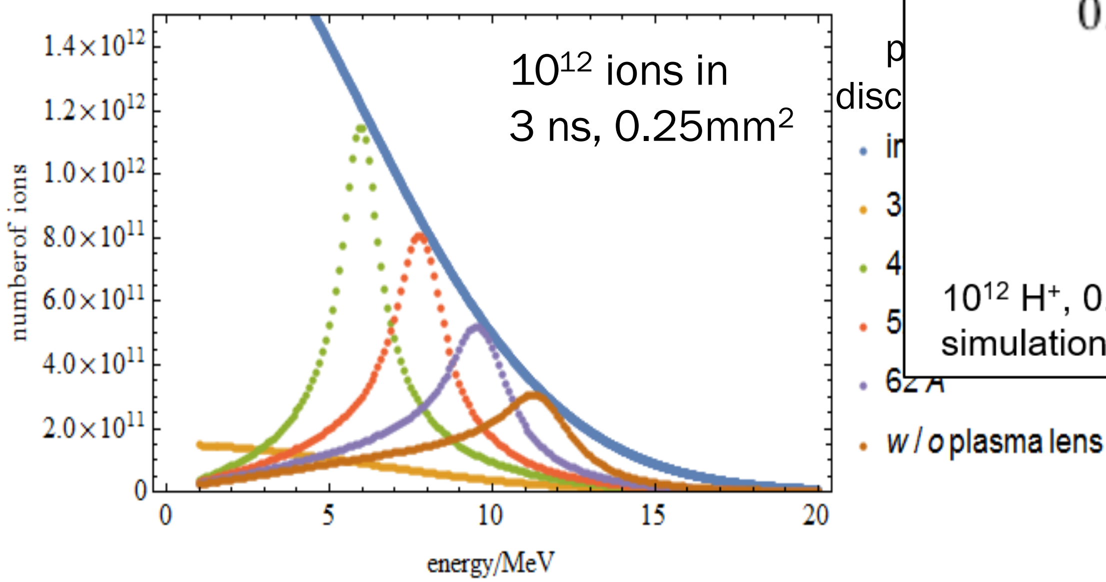
- BELLA-i, Phase 1:
  - Target normal sheath acceleration (TNSA)
  - up to 1 Hz
  - Transport ions to a second target
    - Secondary focusing, bunching for applications

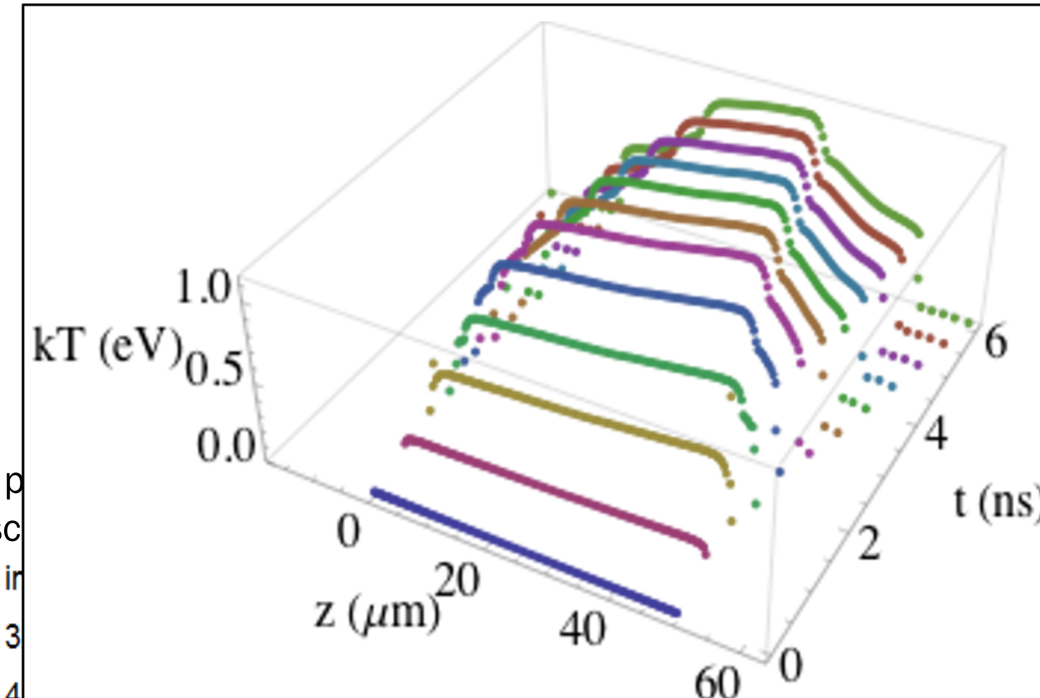
We can control the pulsed ion flux with a plasma lens from low flux to very high flux and heating to >10,000 K

Active plasma lens to focus an ion beam to a 500 μm spot 1 m downstream of laser-target interaction:

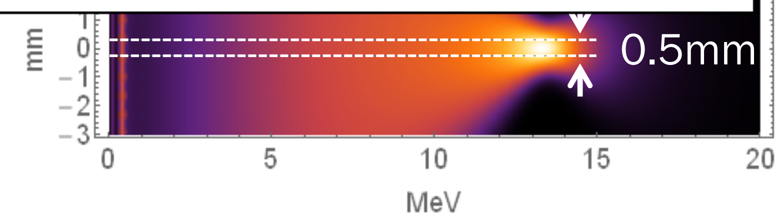


Ion distribution at WDM target:



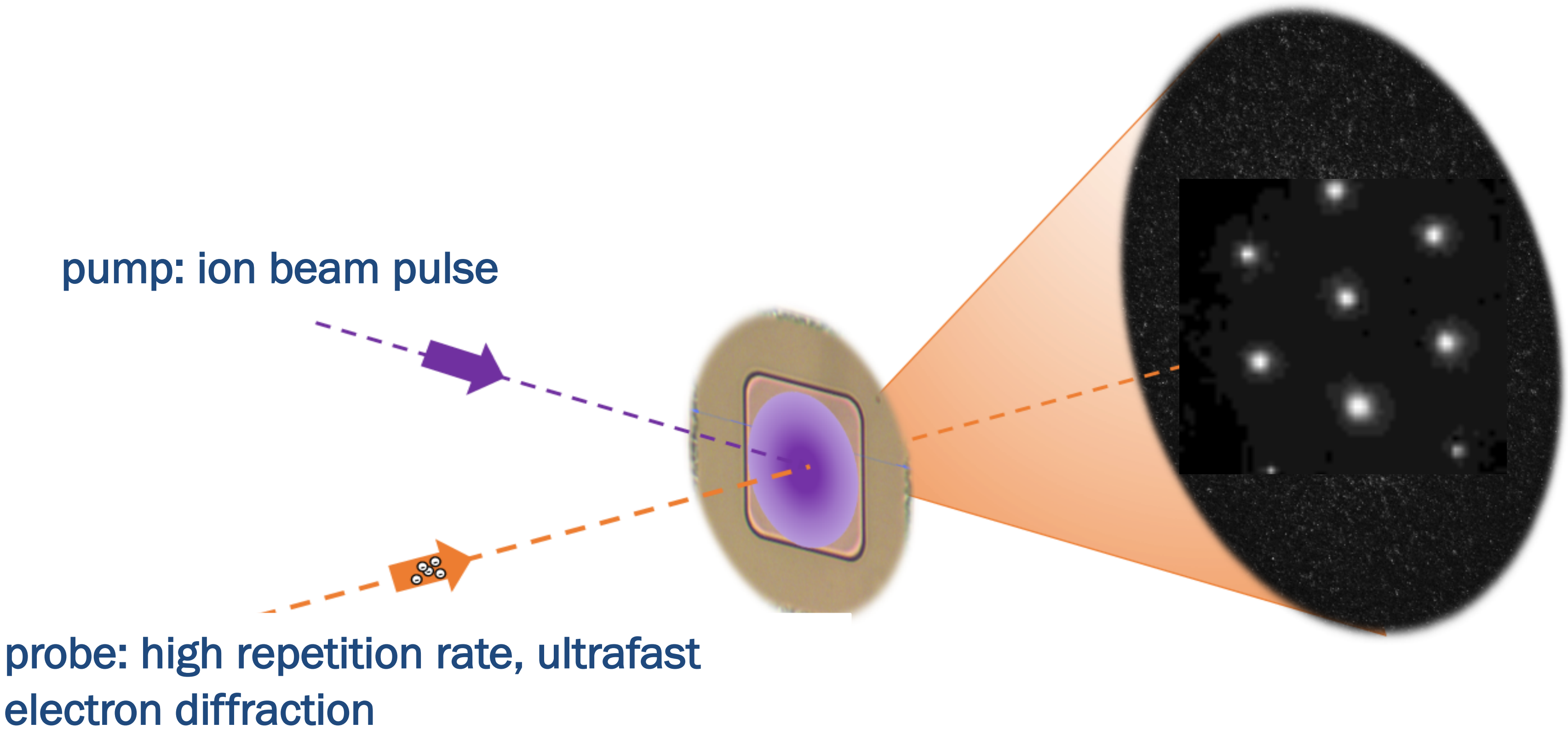


10^{12} H^+, 0.25 mm^2 , 3 ns, 7.5 MeV, 50 um Au, HYDRA simulation by J. Barnard, LLNL



van Tilborg, Steinke, Leemans, et al. PRL 115, 184802 (2015)

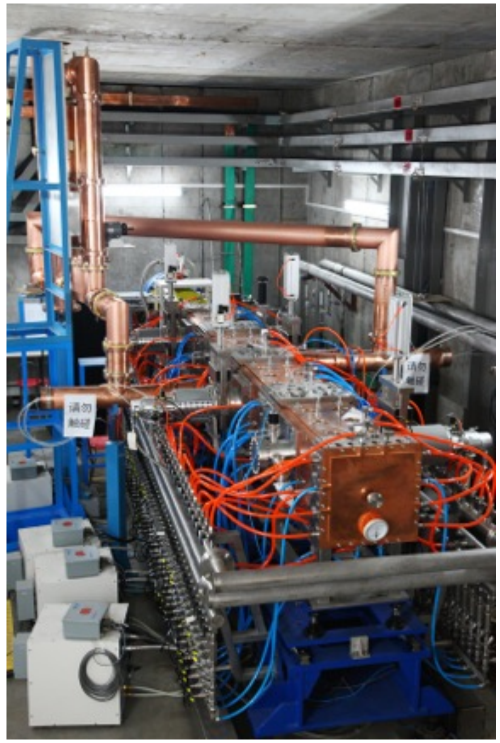
We can access the structural evolution of materials under fusion relevant conditions by pairing an ion or plasma gun with fast structural probes, e. g. ultrafast electron diffraction



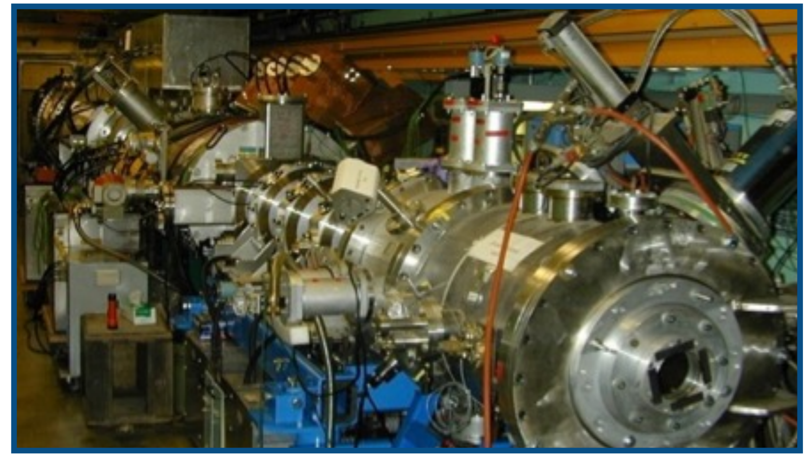
- *in situ* access to structural evolution of thin tungsten foils (~50 nm)
  - vs. ion fluence (up ~10^{20} ions/cm^2 over a few hours), ion energy, temperature, H or He, …
- UED with up to 1 MHz at Berkeley Lab, Daniele Filippetto, dfilippetto@lbl.gov

3. We are developing scalable and compact ion beam accelerator technology for fusion and other applications

- Pulsed induction linac (12 m)
- 1 MeV, 2 ns, mm, 2 A peak
- 200x drift compression
- P. A. Seidl et al. NIM A (2015)



- Radio frequency quadrupole (RFQ)
- 2 MeV, 0.01 A, cw
- 4 m long, 0.4 m cross section
- Z. Zouhli, D. Li et al. IPAC2014



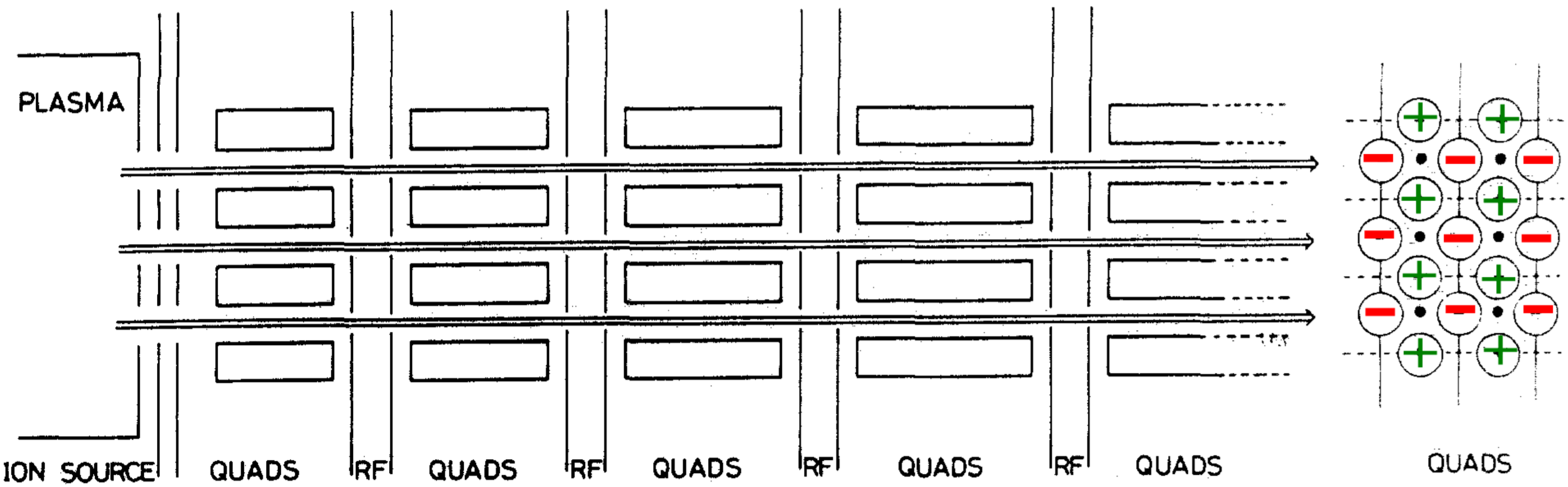
- High Current Experiment (~12 m)
- injection, matching and transport at HIF driver scale
- 1 MeV, 0.2 A, 5 μs, ~12 m
- 0.4 m cross section
- Kireeff-Covo, PRL (2006)

How can we scale ion beam drivers to >1 MJ in μs pulses at low enough cost for MTF ? (ARPA-E, α)

The MEQALAC concept (ca., 1980) exploited the multiple-beam concept for IFE.

Maschke, BNL-51022 (1979)

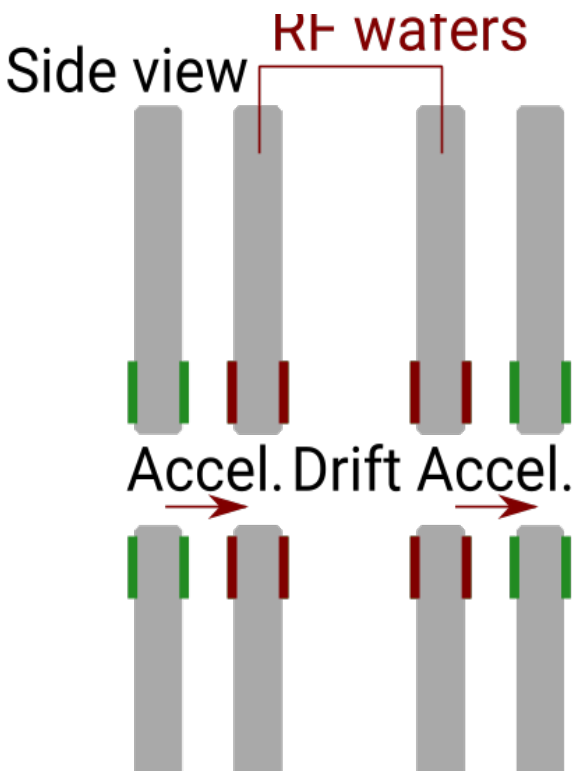
Multiple-Electrostatic-Quadrupole-Array Linear Accelerator

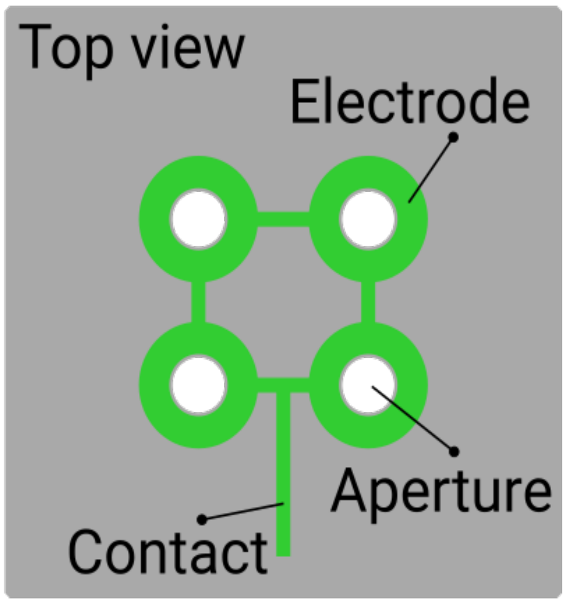


1980 Dimensions: ~ 1cm beam aperture, Quads length : ~cm

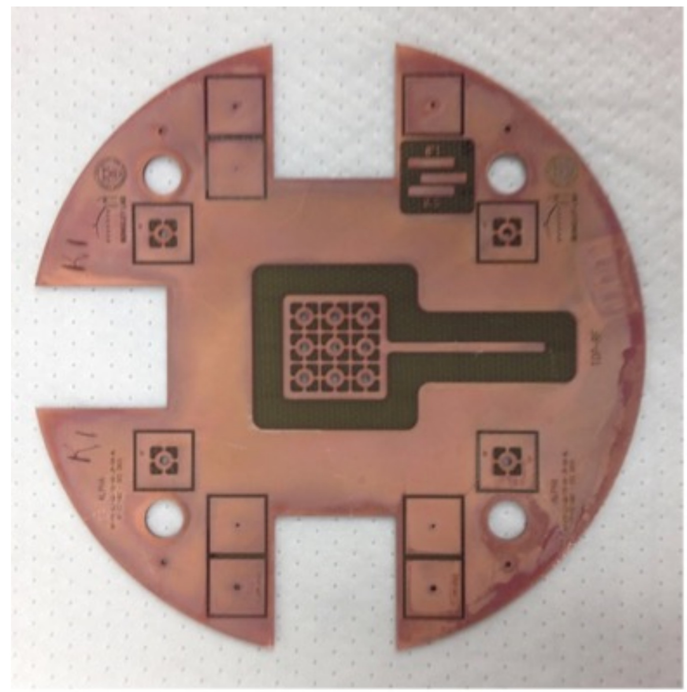
Thomae *et al.*, Mat. Science & Eng., B2, 231 (1989)

Accelerators with MEMS technology? Wafer-based RF acceleration uses a field-free drift region between wafers.





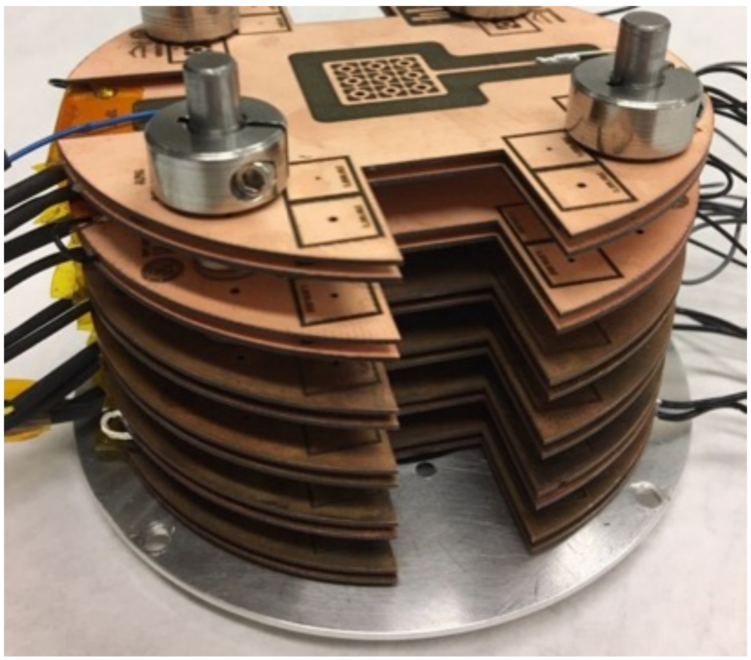
PC board implementation using a 3x3 array for first experiments

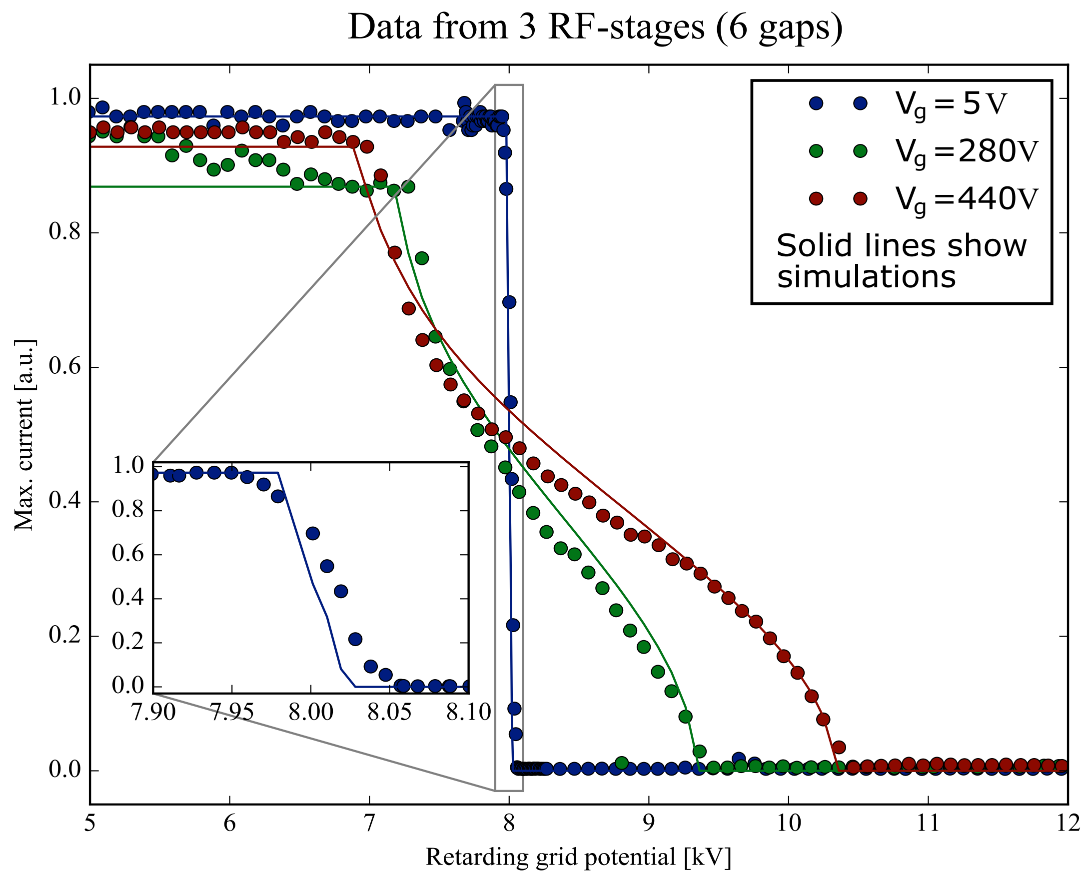


Acceleration condition:

Drift = $\beta\ \lambda/2$

Results from three stages of RF units agree well with simulations

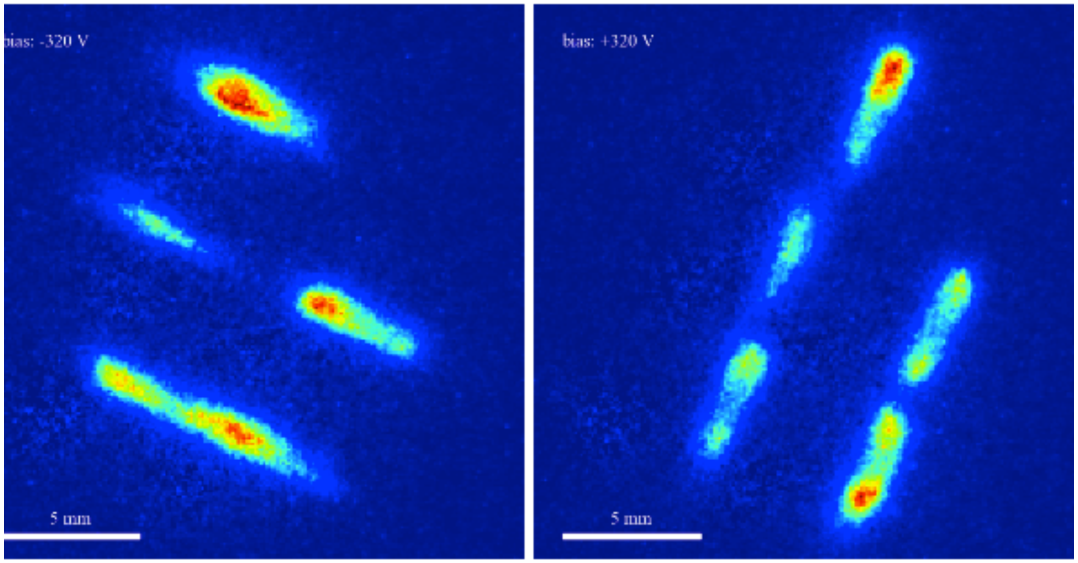




He$^+$ beam, 40 μA in a 3x3 array, r_o = 0.5 mm beam @ source.

Developing Si-wafer quadrupoles, 3D-printed quadrupoles, on-board RF-generation (coplanar waveguides)

Exciting opportunity for fusion drivers and also non-fusion applications



Single PC board **electrostatic quadrupoles show expected focusing behavior**

Many beamlets and high beam power for plasma heating or fusion target heating.

There are many applications for this technology.

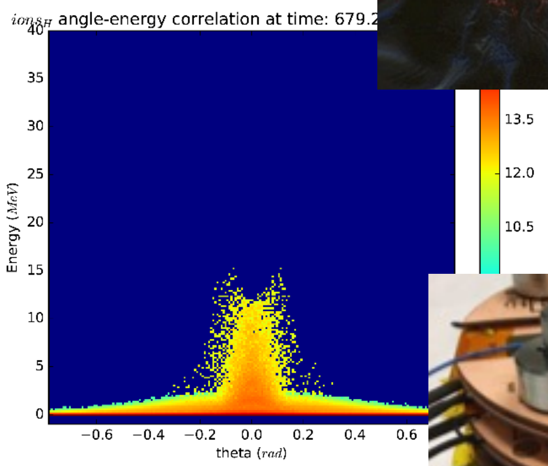
10μA-100mA, 1 to tens of MeV ions produced with low voltages (~kV) in a few meter long structure could be used for:

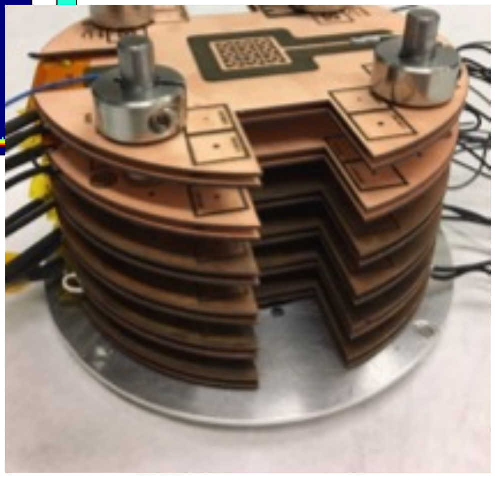
- **Ion beam analysis in material sciences**
- **Ion implantation**
- **High yield neutron generators**

Ion acceleration in a scalable MEMS RF-structure for a compact linear accelerator, A. Persaud, et al., arXiv (2016)

We are using accelerators to address fusion energy challenges

1. With intense ion beams @ NDCX-II we are exploring:
   - Dynamics of radiation effects, benchmark codes
   - Phase transitions
   - Fusion materials and plasma material interactions (PMI)
2. Laser generated ion beams @ Bella-i will explore (1st shots Jan. 2017):
   - PMI
   - Warm dense matter and HEDP
   - Novel laser generated ion beam mechanisms
3. Multi-beam, scalable and compact accelerators (ARPA-E, α) for fusion and other applications





Workshop on the

Dynamics of radiation effects in materials

WHEN

Dec. 15 - 16, 2016

WHERE

Berkeley Lab

https://conferences.lbl.gov/event/72/

BELLA i

NDCX II

BERKELEY LAB

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Remote video available.
Email PASeidl@lbl.gov