Fusion Energy Sciences at LBNL

PETER SEIDL, LBNL

Fusion Power Associates Annual Meeting

Washington, DC December 6-7, 2017

Sandia National Laboratories

PPPL

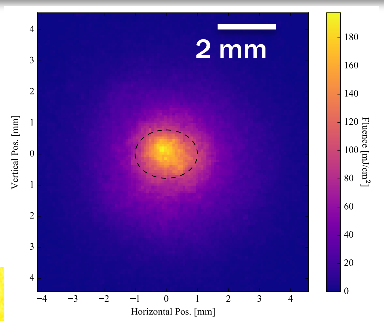
TECHNISCHE UNIVERSITÄT DARMSTADT

Tufts UNIVERSITY

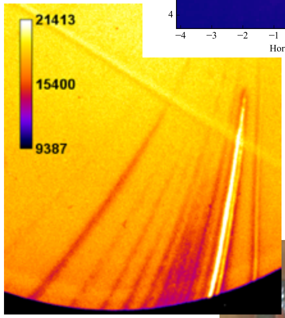
UNIVERSITY of HOUSTON

LBNL is advancing these topics for fusion energy sciences

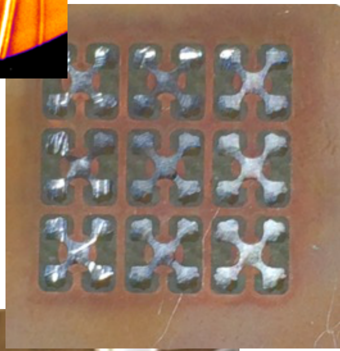
1. High dose-rate irradiation of materials with pulsed ion beams at NDCX-II (LLNL, PPPL, SNL, TU-Darmstadt, Lanzhou U., U. Washington)



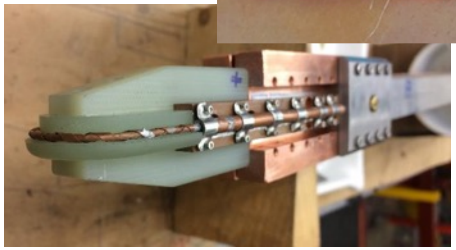
2. High intensity laser-generated ion beams with Bella-i for materials research and warm, dense matter / HEDP



3. MEMS-based accelerators for plasma heating (Cornell)



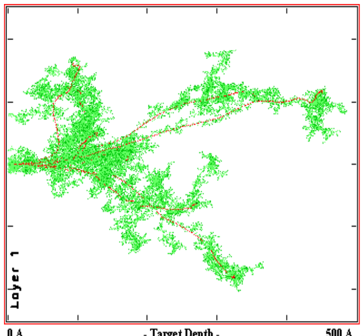
4. High Tc superconducting magnets for high-field tokamaks (U. Houston, Tufts, Advanced Conductor Technologies)

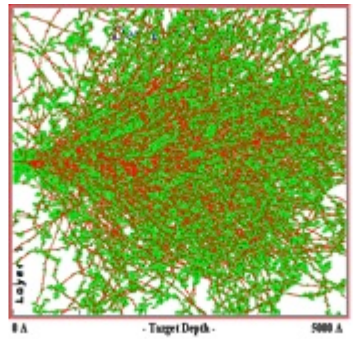


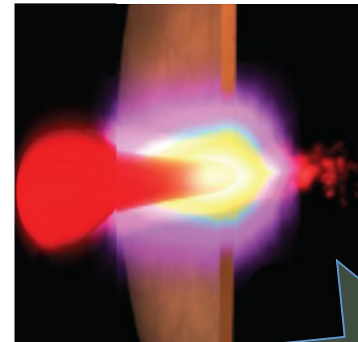
Intense, short ion pulses for materials studies and fusion science

Lower intensities:
defect dynamics in materials
→ fusion materials

Higher intensities:
extreme chemistry and warm dense matter







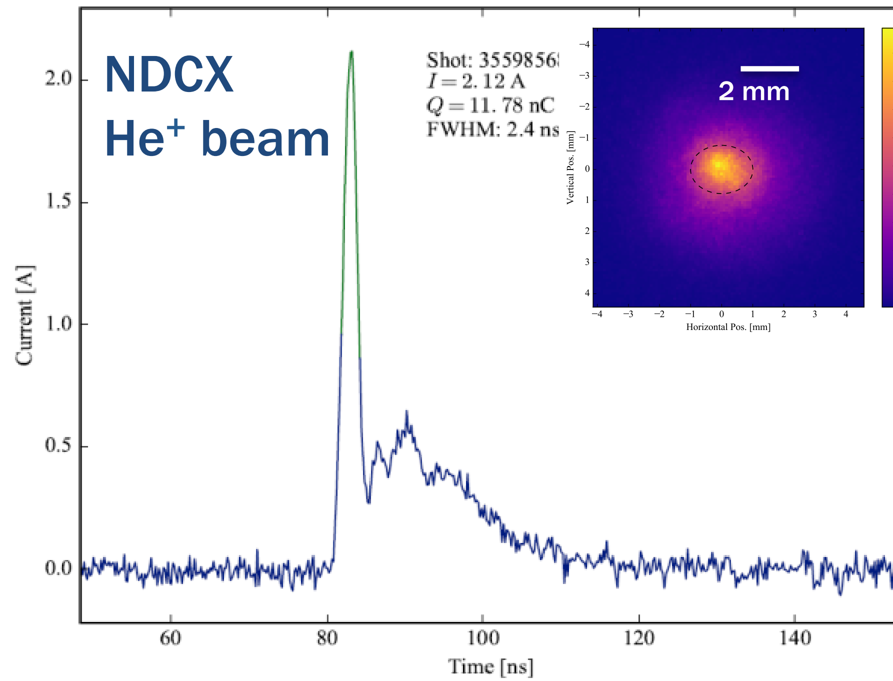
isolated cascades → overlapping cascades → amorphization and melting → warm (~1 eV), dense matter

1-30 nC, 0.3 -1.2 MeV, few mm^2, ~1-30 ns

NDCX — Bella-i

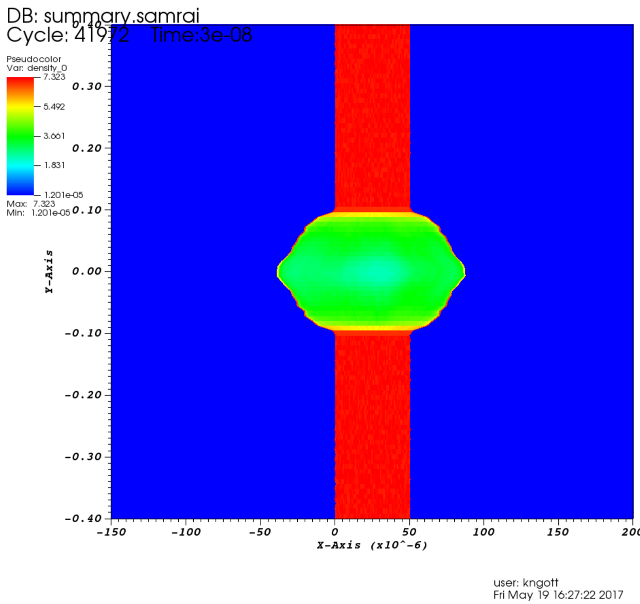
NDCX and Bella-i advance intense beams, beam-plasma physics, materials, warm dense matter science

- At NDCX, we have generated ns ion pulses with **peak dose rates of >10^{20} ions/cm^2/s** with high reproducibility. <u>Repetition rate is <1/minute. Beam r = 1mm, t = 2 ns</u>
- We have achieved <u>2 A peak currents</u> for ns pulses of 1 MeV He^+ ions, focused to **0.1 J/cm^2**.
- We are <u>measuring ion energy loss in heated foils</u>
- **Radiation effects on semiconductor transistors.**

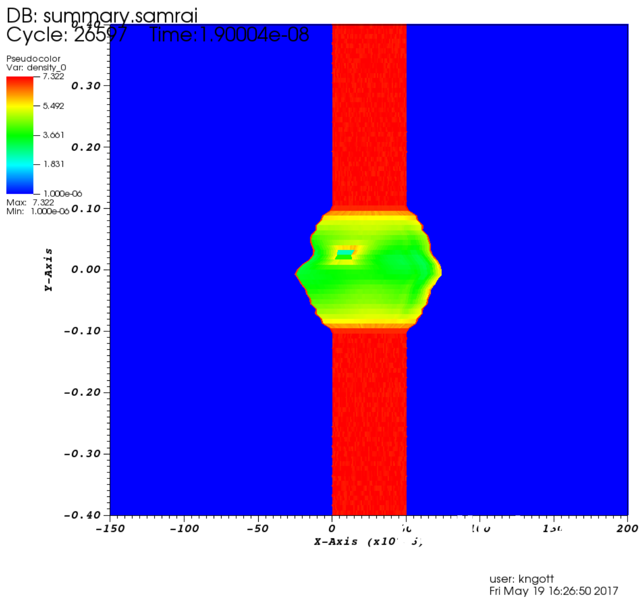


Synergy: NDCX & Bella-i laser generated ion beams

1. NDCX: Exploring the dynamics of the disruptions due to rapid heating using the 3D multi-physics, multi-material code ALE-AMR*



Pure Sn foil



...with impurity

Opportunity to understand materials dynamics through a solid-liquid phase transition with rapid, uniform heating.

- Work in progress, adding surface tension model to the simulation

*LIU, KONIGES, GOTT, et. al, *Computers and Fluids* (2017)

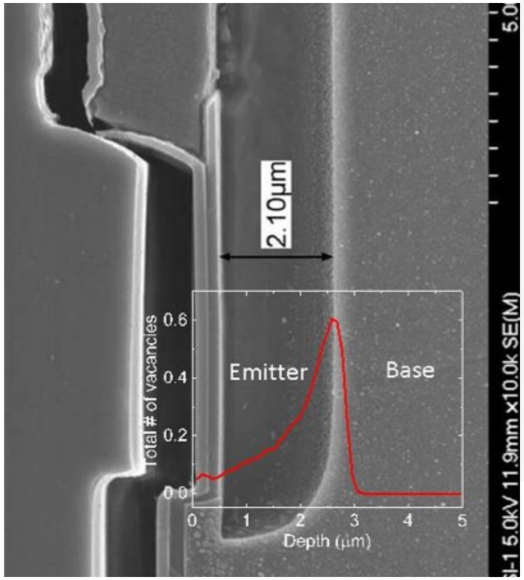
NDCX: Radiation Effects Studies with Intense Pulses of Helium Ions on transistors

E. Bielecek, SNL

We have explored the effects of high ion flux, short pulse irradiation on the Messenger-Spratt damage factor using Microsemi 2N2907 pnp transistors.

We have applied an ion flux of 10^{18} – 10^{19} ions/cm^2/s per ~10 ns long helium ion pulse (1 MeV).

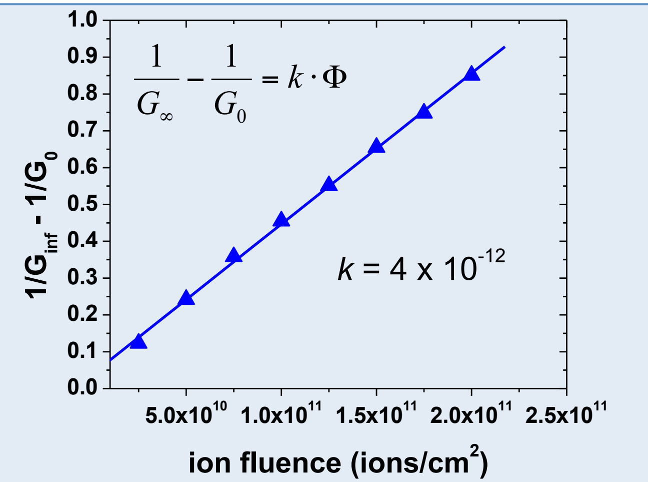
We have measured late-time gain degradation as a function of ion fluence for a series of shots up to 2.5×10^{11} ions/cm^2.



Ion pulses simulate pulsed neutron irradiation.*

NDCX delivers dose equivalent 10^4X n/cm^2/s vs IBL @ SNL.

End-of-range ion energy loss at the base-emitter junction, where damage leads to gain degradation.



Example of a measured Messenger-Spratt curve to determine the damage constant

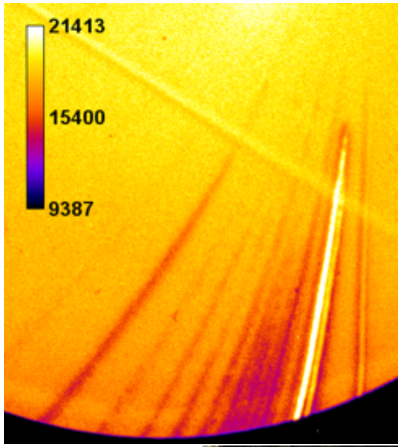
Funded by NNSA via SNL

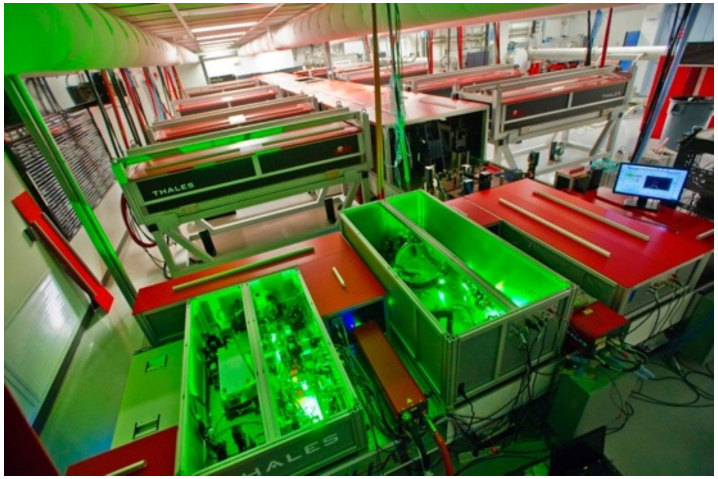
Schenkel, et al., J. Rad. Effects, Res. Eng. (2017)
Ludewigt, et al., JRERE, submitted (2017)

* Aguirre, et al., IEEE Trans. Nucl. Sci. (2017)

2. BELLA-i can have transformative impact in High Energy Density Physics due to the 1 Hz rep rate and superb laser quality

- (ultra)-relativistic plasma science at 1 Hz
- fundamentals of laser ion acceleration
- laser based ion beams and neutron pulses as a tool for discovery plasma science and applications
- collaborative research facility

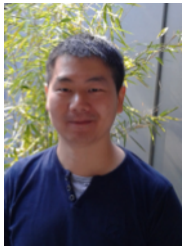





Q. Ji

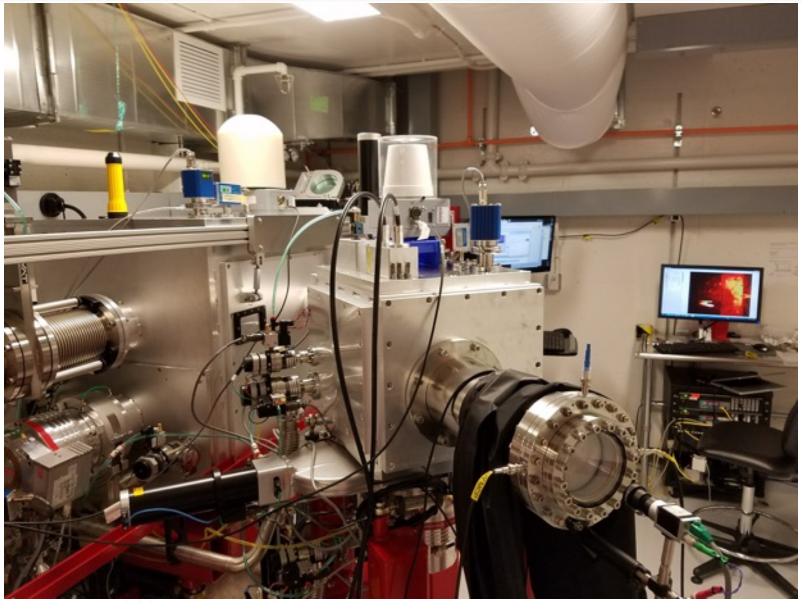

S. Bulanov

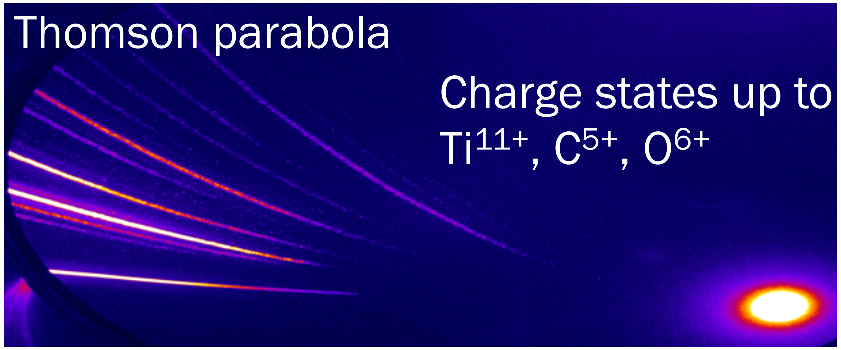

S. Steinke

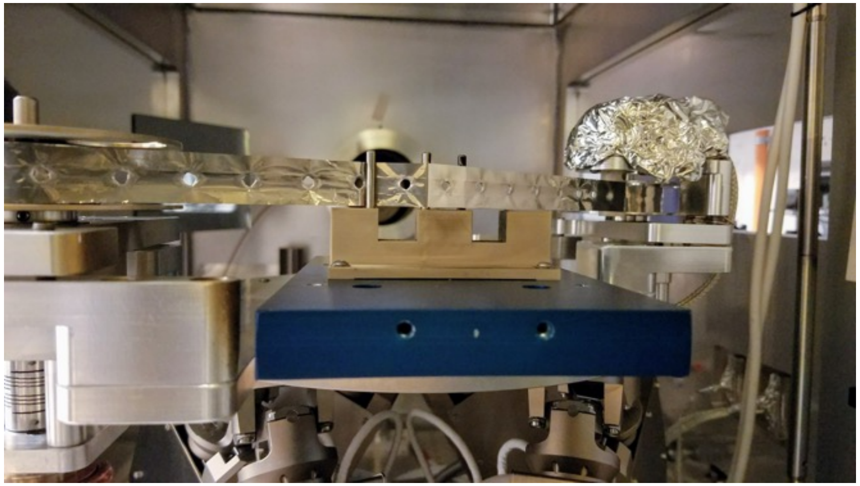

J. Bin

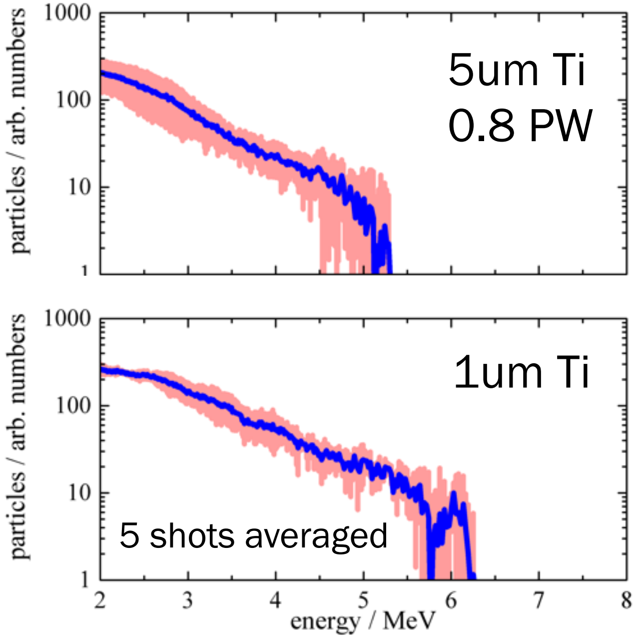

J. Park

We have commenced ion acceleration experiments at BELLA-i





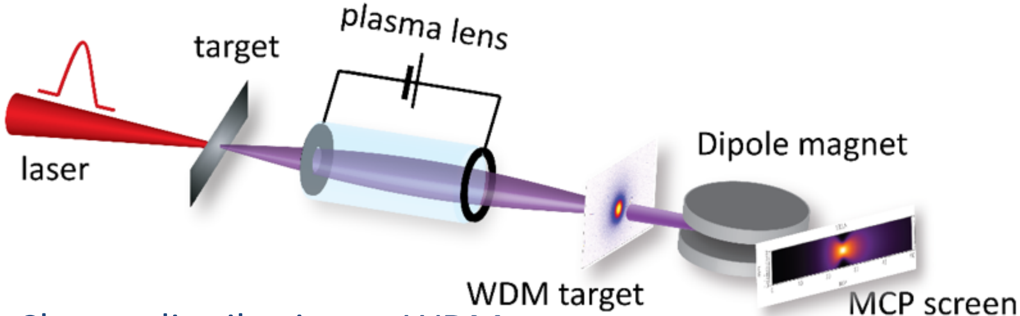


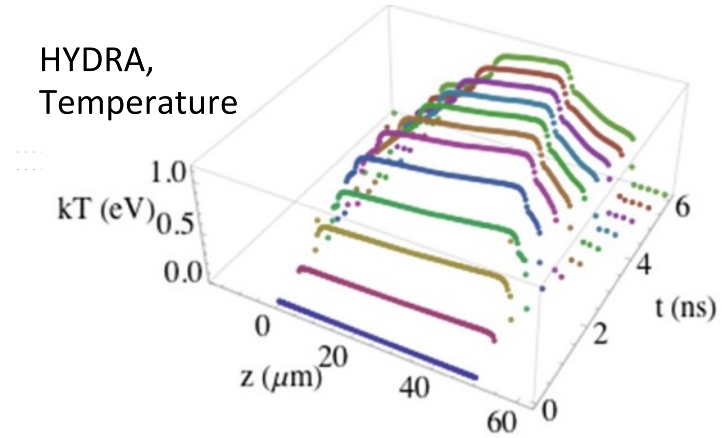


- Ti tape drive target for extended 1 Hz operation
- Low ion pulse divergence, high ion number, publication in preparation, S. Steinke, Q. Ji, J. Bin, S. Bulanov, and BELLA team

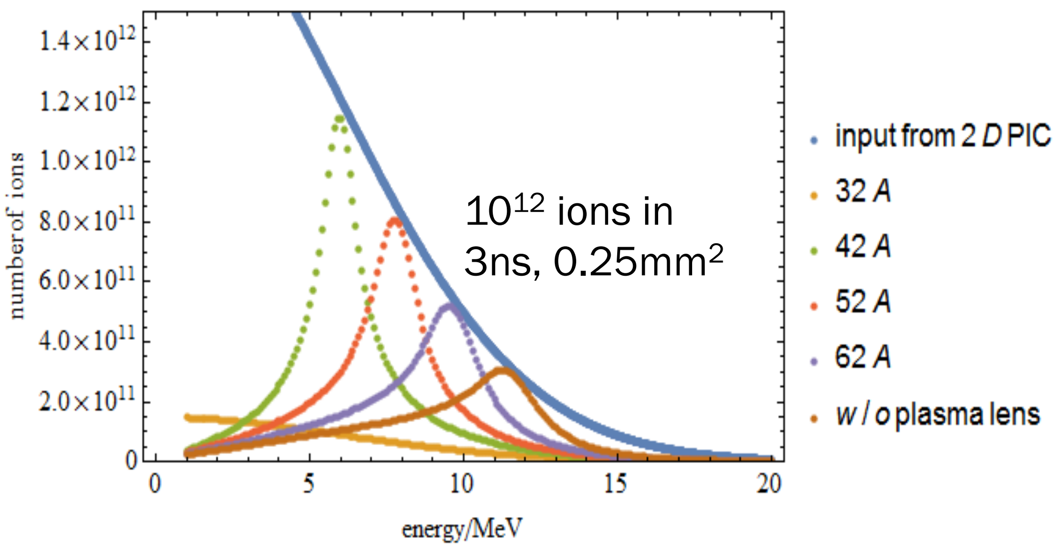
Transport of 10^{12} ions at 5-10 MeV to EMP-free environment possible with plasma lens

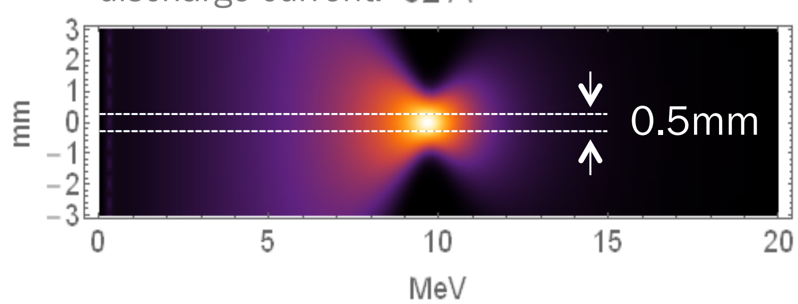
Active plasma lens to focus an ion beam to a 500µm spot 1m downstream of plasma lens:





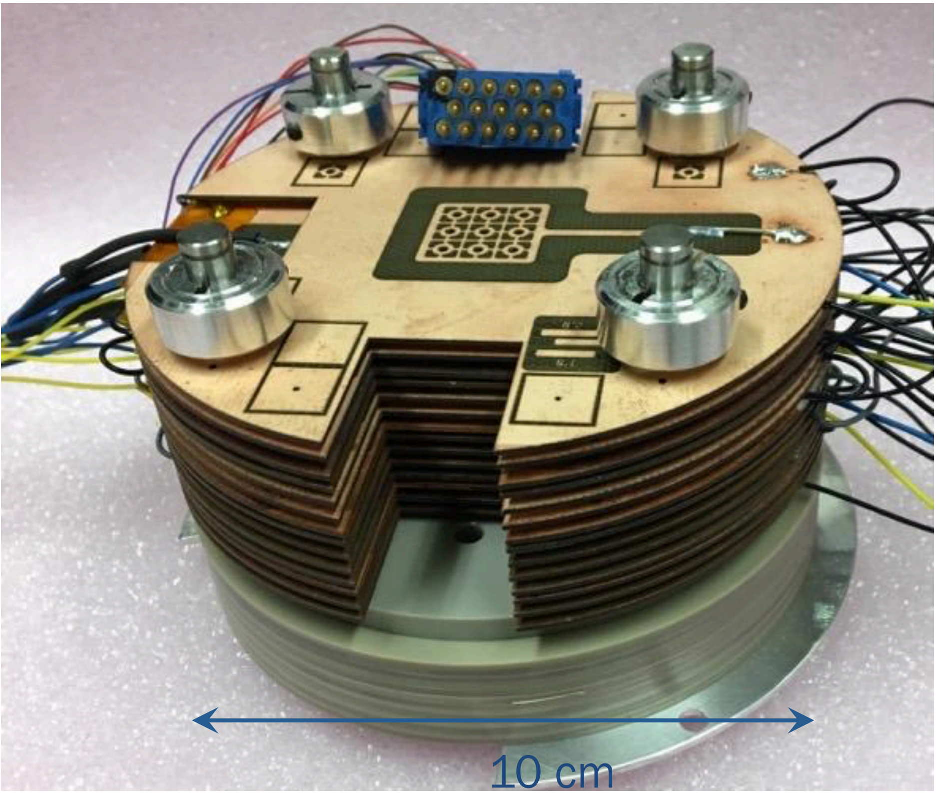
Charge distribution at WDM target:





van Tilborg et al., PRL 184802 (2015);

3. In the first two years we have developed the first MEMS based multi-beam accelerator

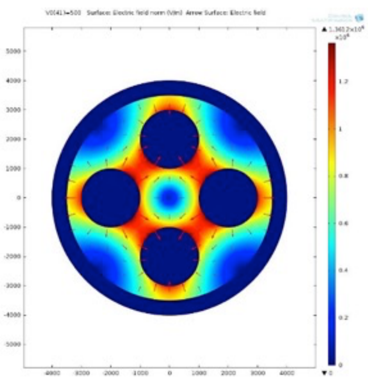


Funded by the ARPA-e alpha program

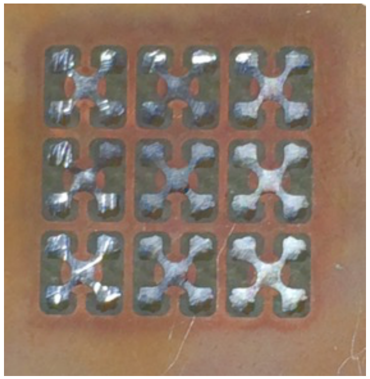
A. Persaud, Q. Ji, E. Feinberg, P. A. Seidl, W. L. Waldron, T. Schenkel, A. Lal, K. B. Vinayakumar, S. Ardanuc, D. A. Hammer, Rev. Sci. Instr. 88, 063304 (2017), http://dx.doi.org/10.1063/1.4984969, cover, June 2017

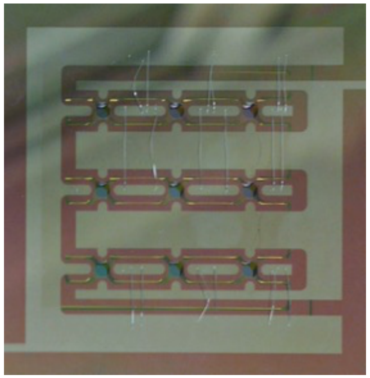
We demonstrated electrostatic quadrupoles (ESQ) to re-focus the ion beams for efficient transport both in PCboard and silicon

ESQ field distribution

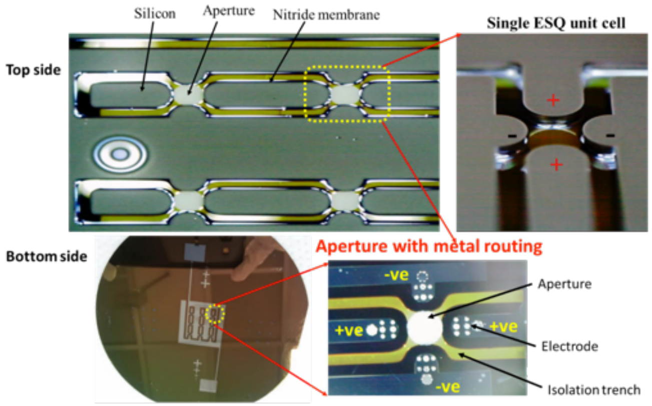


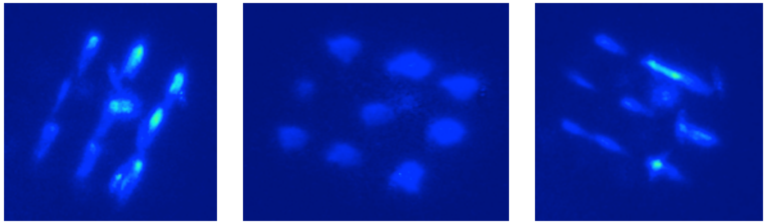
laser cut PC board

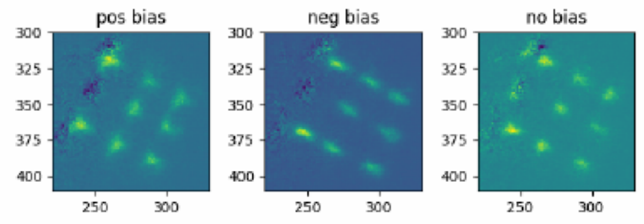




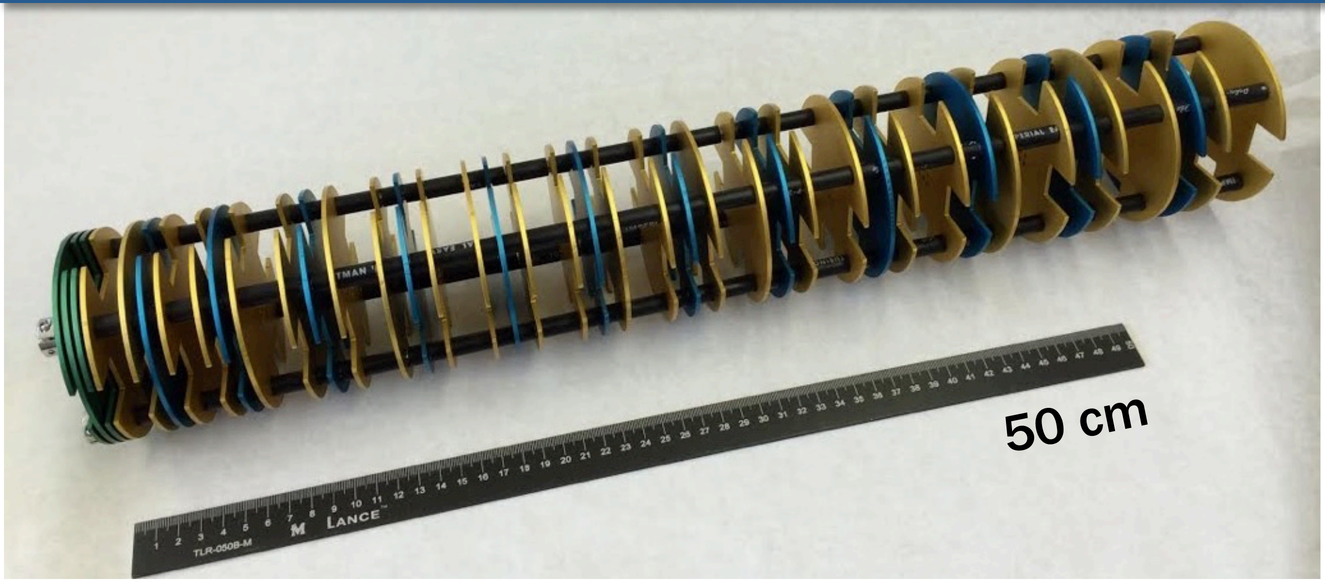
Silicon wafer







Outlook: building a 300 keV compact accelerator



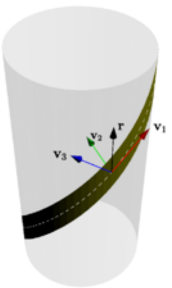
1:1 model of a
300 keV accelerator
for argon ions
at 20 MHz

We now operate a multi-beam accelerator formed from a stack of PC boards

- Next step is scaling to higher beam current (from 50 μA to >1 mA) and higher beam energy (10 keV to >100 keV)
- This will be highly competitive/disruptive for mass spectrometry, neutron-generators, surface treatment, ion implantation, plasma diagnostics, …
- Scaling to ~1 MeV/m and >1 A for plasma heating will follow
  - e.g., Neutral beam injectors for MFE, where electrostatic MV holdoff is challenging.

4. LBNL magnet development for high field tokamaks: quench protection, electromechanical performance, and feedback to industrial manufacturers

Tapes → fusion scale cables: A curvature-based method for cable and magnet designs based on CORC® cable &stacked tapes

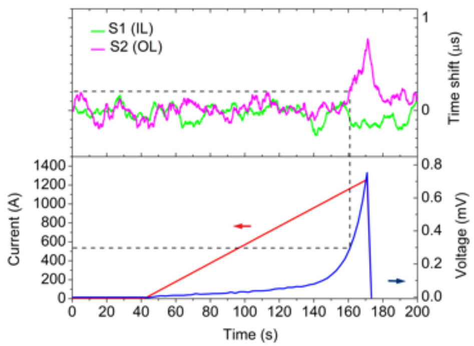


- , X. Wang et al., *IEEE Trans. Appl. Supercond.*, https://doi.org/10.1109/TASC.2017.2766132
- F. Pierro et al, presentation at MT25, September 2017, https://indico.cern.ch/event/445667/contributions/2564508/

Bending<-> performance

Leverage the HEP programs to develop and evaluate advanced concepts for quench detection

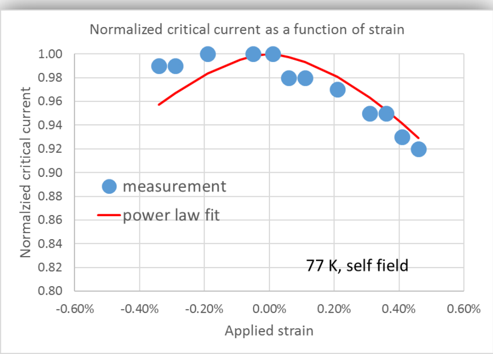
Thermo-acoustic quench detection



M. Marchevsky et al.,EUCAS, 2017
M. Marchevsky S. A. Gourlay, doi:10.1063/1.4973466

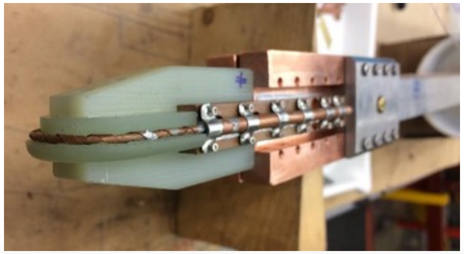
Characterize the electro-mechanical performance of REBCO conductors

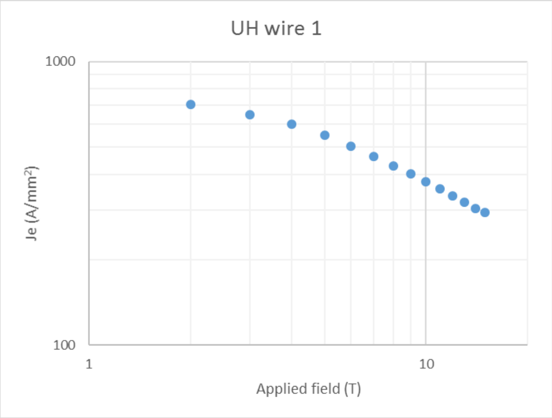
Instrumented U-spring sample holder made of Aluminum-Bronze



- First results on the I_c-strain dependence on the latest 2-mm wide, 30 μm thick substrate commercial REBCO samples.
- Observed 8% reduction in I_c with 0.46% tensile strain (data shown is *reversible*)

Collaborate with the community to characterize the transport performance of advanced REBCO tapes and cable prototypes





Wire J_e ~ 300 A/mm^2 at 15 T, 4.2 K

UNIVERSITY of HOUSTON

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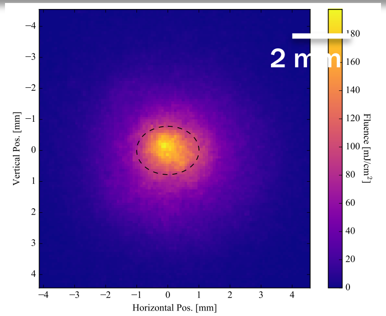

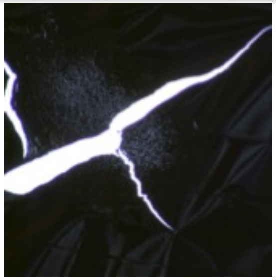

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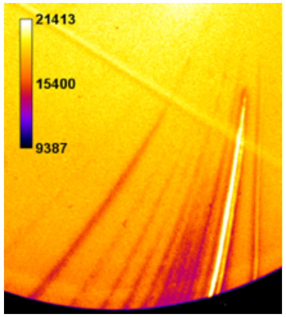

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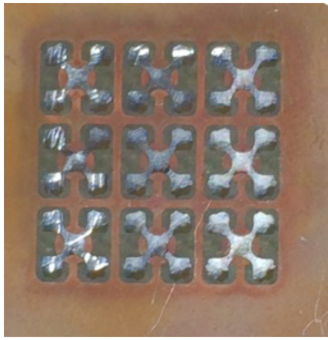
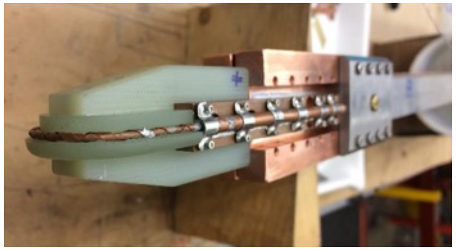


4. High Tc superconducting magnets for high-field tokamaks (Houston, Tufts, ACT)



The team

J. Bin, I. Breinyn, S. Bulanov, S. de Leon, K. Gott, Q. Ji, A. Koniges, M. Marchevsky, J. Park, A. Persaud, S. Prestemon, W.L. Waldron, D. Raftrey, P. Seidl, S. Steinke, T. Schenkel, LBNL

A. Lal, D. Ni, K.B. Vinayakumar, Cornell University

J.J. Barnard, A. Friedman, D.P. Grote, LLNL

E.P. Gilson, I.D. Kaganovich, PPPL

A. Stepanov, U. Washington

F. Treffert, TU Darmstadt, Germany

E. B. Bielejec, B. Vaandrager, Sandia Nat Lab.

X. Kong, Lanzhou University, China

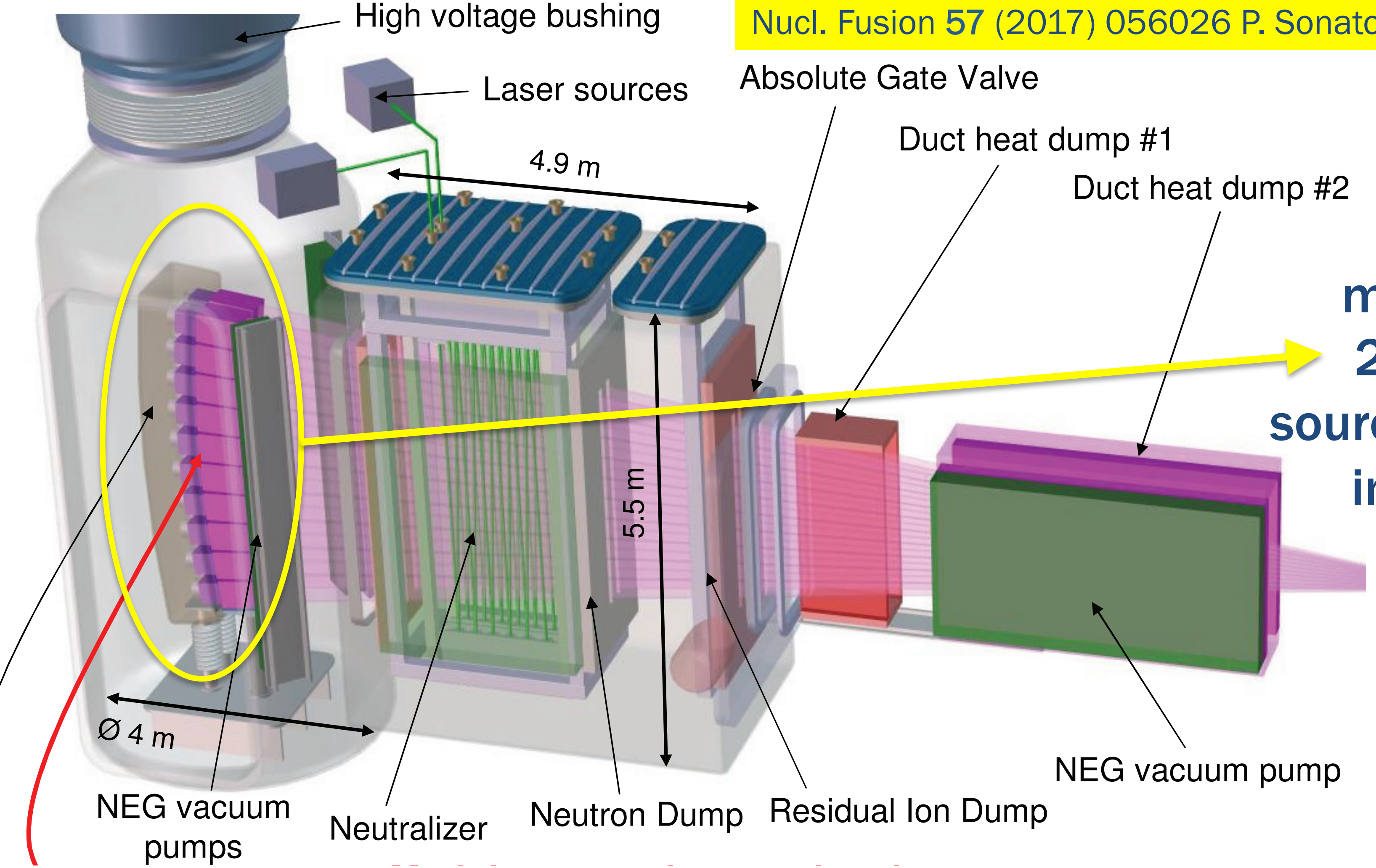
Univ. of Houston

Tufts Univ.

Thank you!

We envision that the compact RF accelerators fit in the footprint of the DEMO NBI system

Nucl. Fusion **57** (2017) 056026 P. Sonato *et al.*

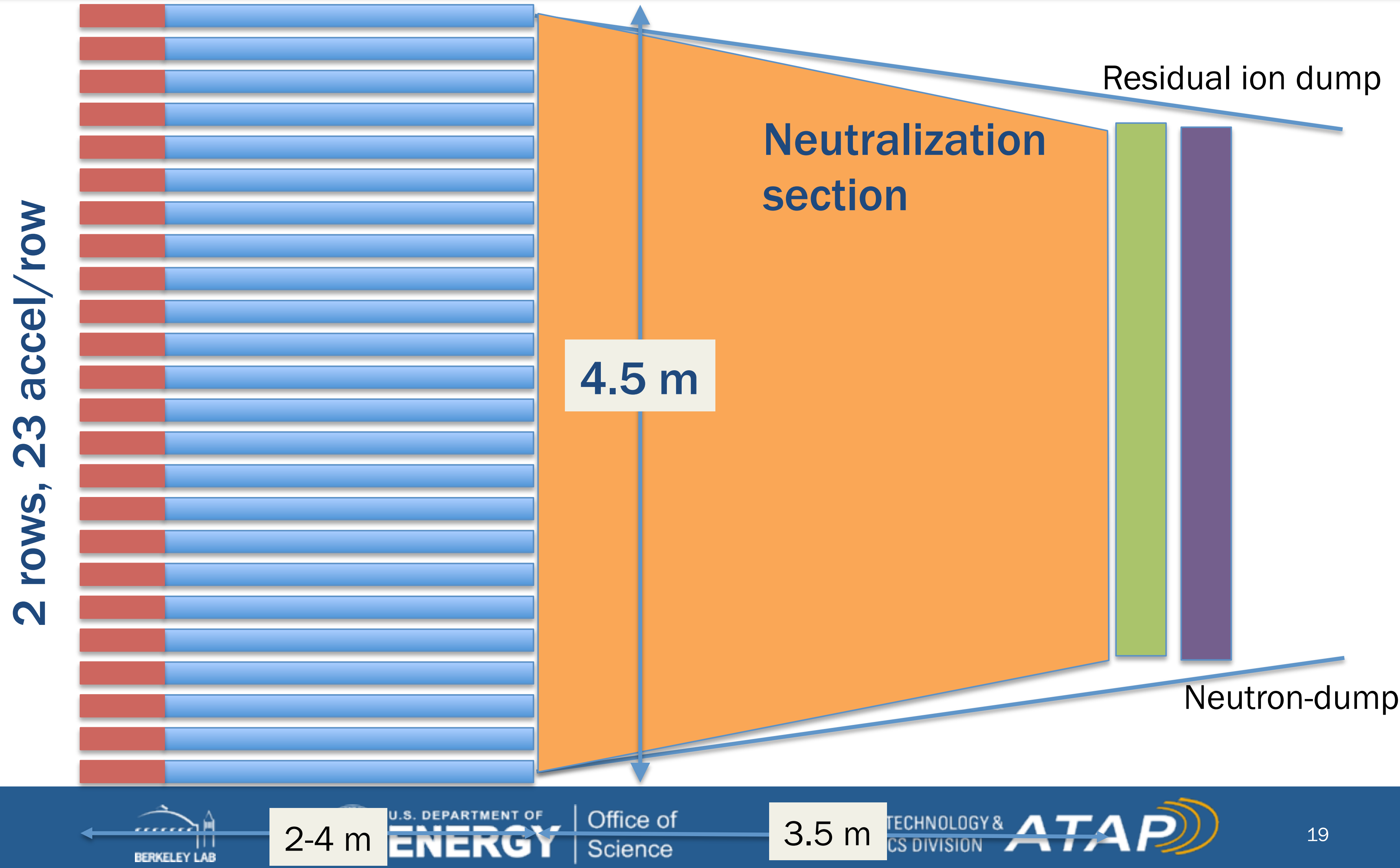


modular: 2x10 RF sources and injectors

Assume 60 Amps total current, 1 MeV D-, 3 NBI ports on tokamak. Each NBI has:

- 46 accelerators, two rows per injector system
- Accelerator components:
  - 6-inch square wafers, 2 cm border on wafer.
  - 1080 beamlets/wafer, total current 0.43 A.
- Room for pumping/conductance
  - 4 cm gap between accelerators
- Accelerators can be angled to achieve overall convergence to match port area at tokamak wall
- Assume injector J = 20 mA/cm2
  - Beam-beam pitch = 3 mm
  - 2x margin for losses: Plasma source aperture dia = 1 mm, inject 0.62 mA/beamlet (@ 20 mA/cm2), but need 0.32 mA/beamlet

Accelerator array for NBI system is a converging group of beams injected into neutralization system. 1 MeV, 20 A



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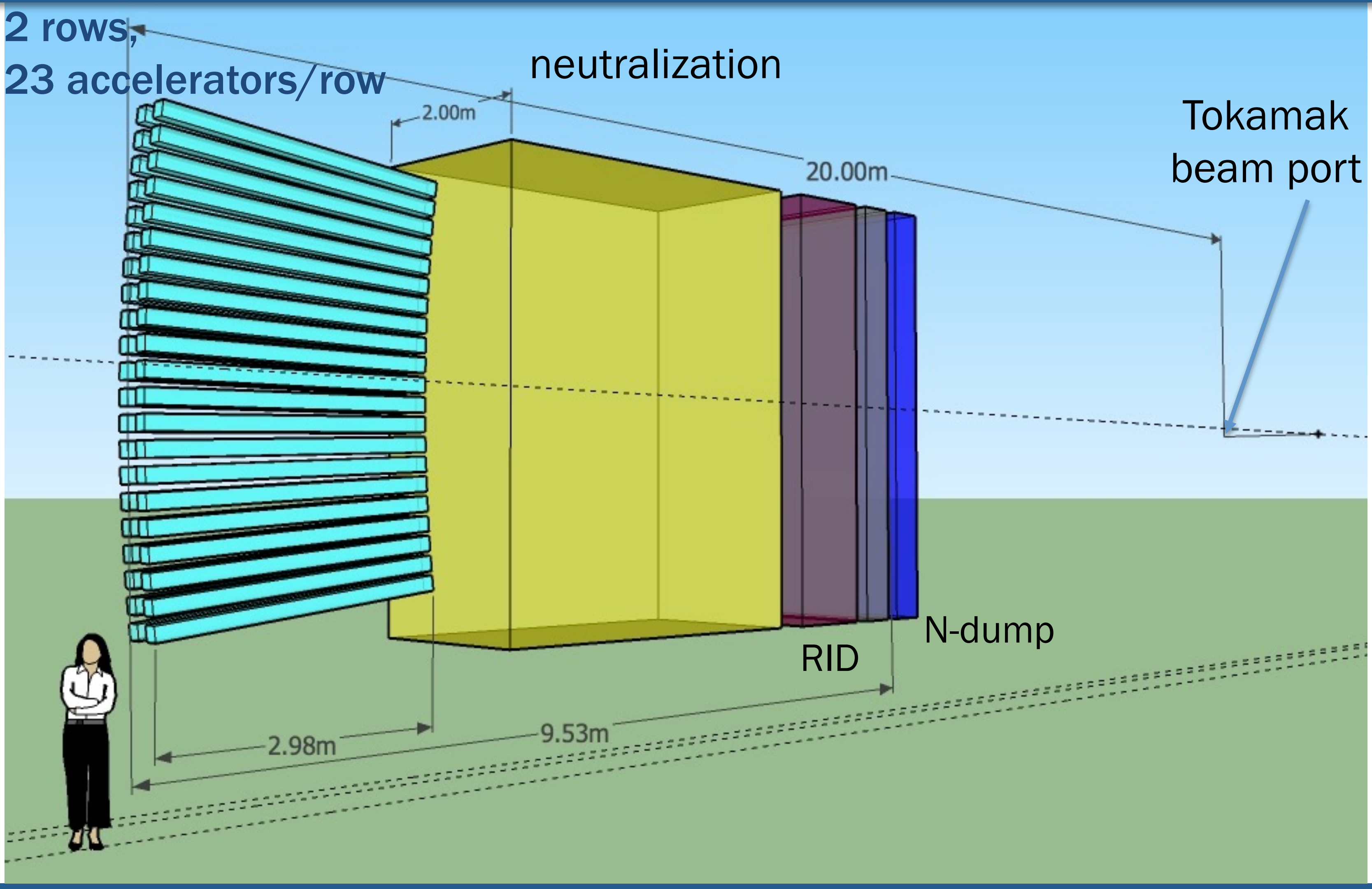
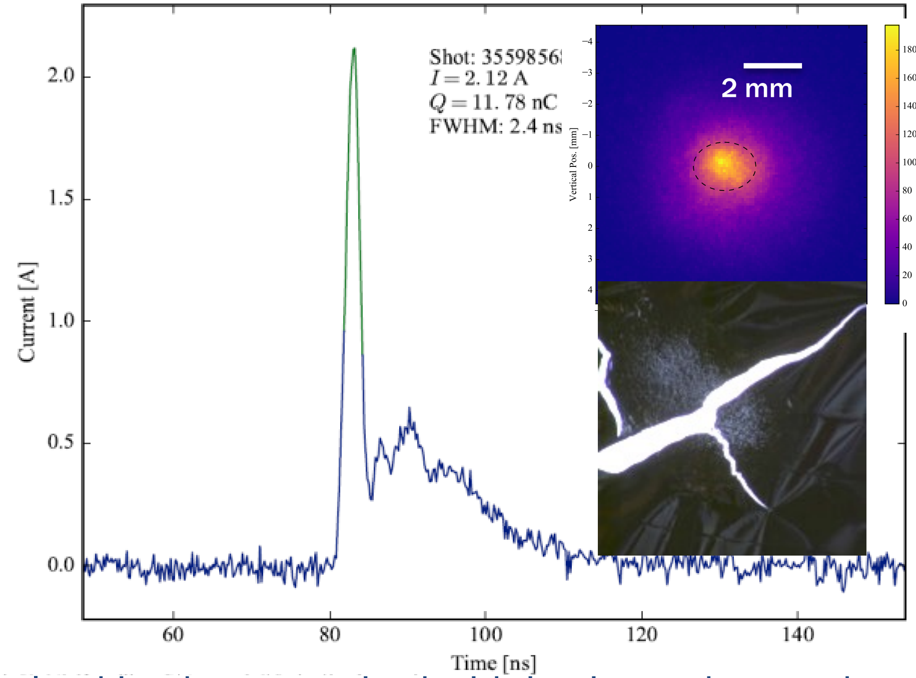
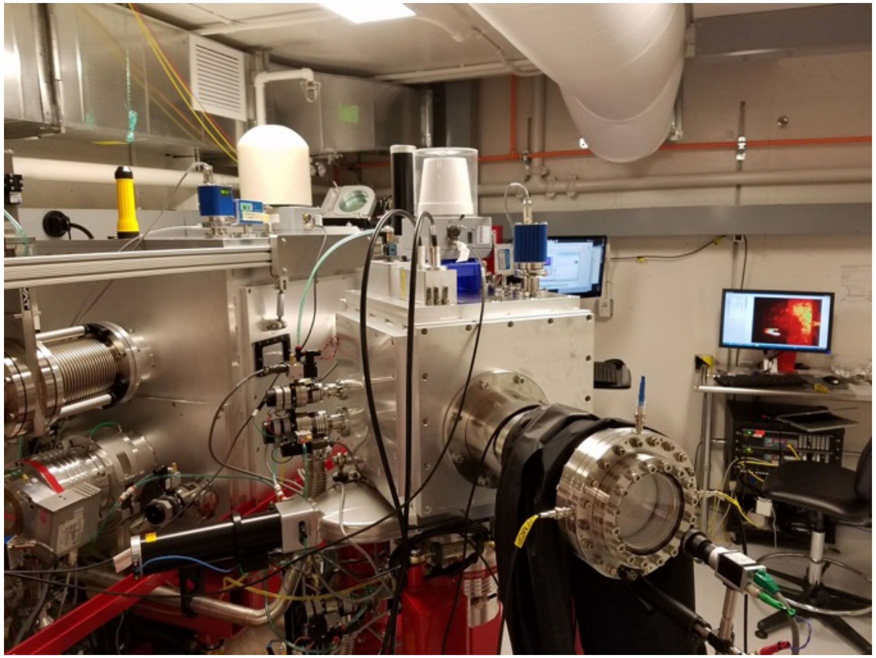


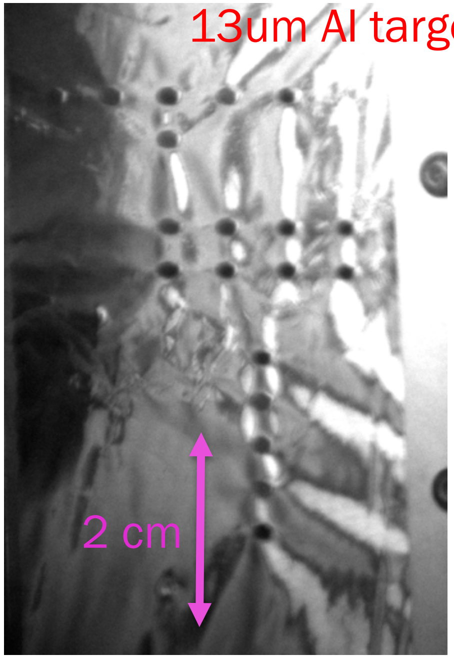
NDCX and Bella-i advance intense beams, beam-plasma physics, materials, warm dense matter science

- We have generated ns ion pulses with **peak dose rates of >10^{20} ions/cm^2/s** with high reproducibility. Repetition rate is <1/minute. Beam r = 1mm, t = 2 ns
- We have achieved 2 A peak currents for ns pulses of 1 MeV He^+ ions, focused to **0.1 J/cm^2**.
- We are measuring ion energy loss in heated foils
- Based on new results, we will:
  - **Push the limits and testing the understanding of intense beam physics** for inertial fusion and other applications.
  - **Dynamics of radiation effects** and fusion materials science
  - **Radiation effects on semiconductor transistors.**
- **Workshop on Dynamics of Radiation Effects, Dec 15-16, 2016, Berkeley Lab**
  - Theory and simulations of the dynamics of radiation effects in materials;
  - Excitation sources such as pulsed plasmas and pulsed ion beams paired with in situ probes such as Ultrafast Electron Diffraction, pulsed x-rays, optical and ion scattering techniques
- **Synergistic: Bella-i laser generated ion beams**

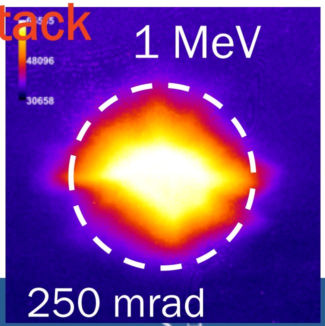


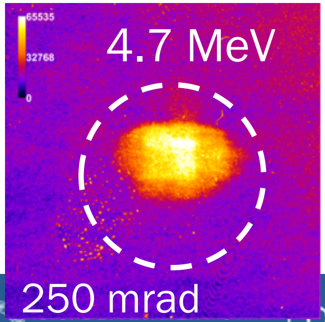
First commissioning shots show narrow divergence beams at expected ion energies





RCF film stack

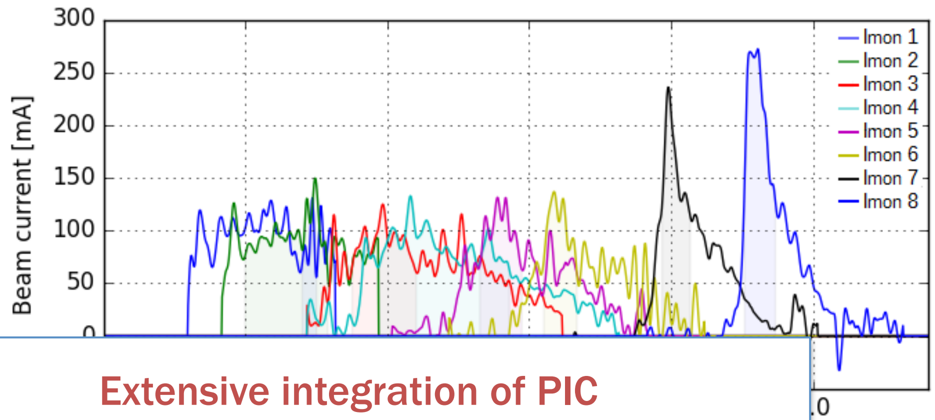




Experiment Parameters

12J on target, 5×10^{18} Wcm^{-2}
13um Aluminum
Ion energies up to 4.5 MeV
Divergence (FWHM) 150mrad

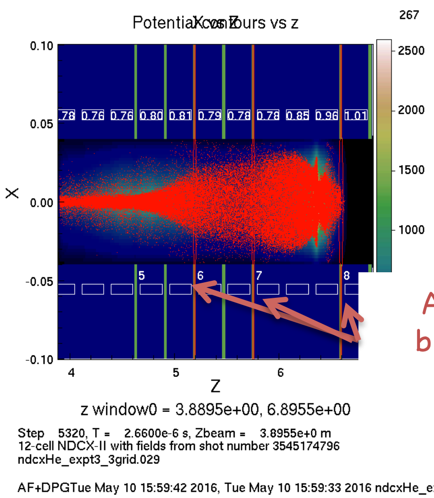
The NDCX-II induction accelerator compresses beam to ns and mm bunches on target.



Unique opportunity to study intense beam and beam plasma physics.

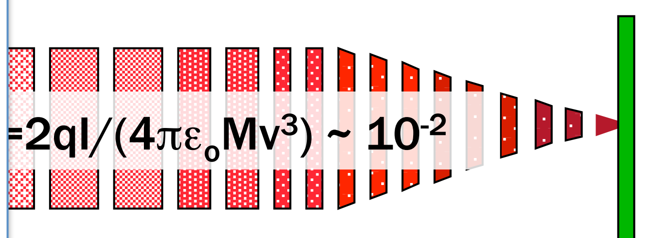
- **Stepanov, et al., "Optimizing Rapidly Compressing Beams…" MRE (2017) *submitted*.**

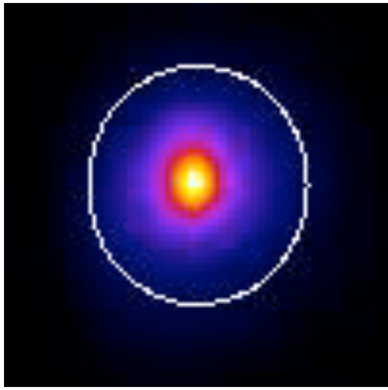
Extensive integration of PIC simulations: Snapshot of the X-Z projection shows rms properties & halo particle loss…



Applied accel and bunching V(t) from database

…thin 2 ns FWHM and approximately 10^{10} ions/pulse.





…s for
…n

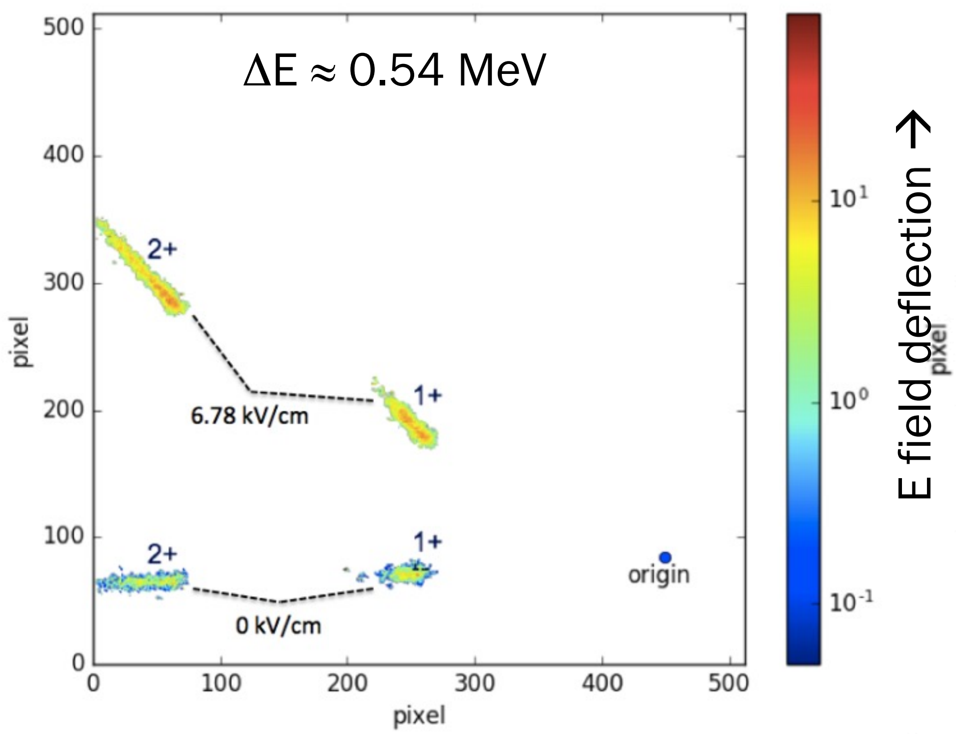
Neutralized drift compression and final focus

Target

Z=10 m

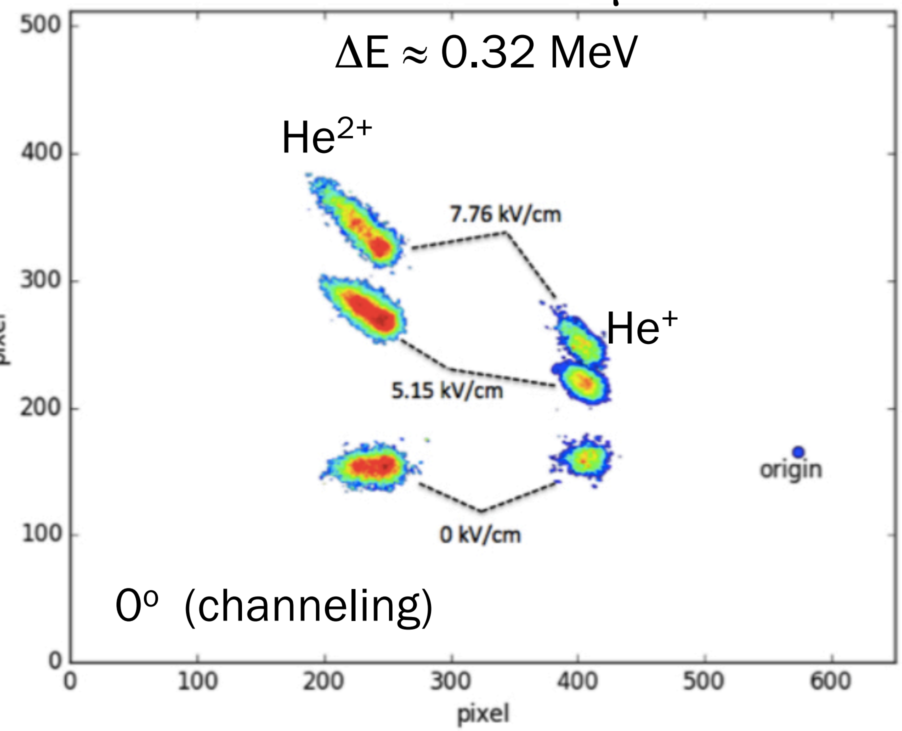
With a Thomson Parabola spectrometer we measure the transmitted particle energy distribution and species identification

1.1 MeV He^+ on 1 μm SiN



← B field deflection

1.1 MeV He^+ on 1 μm Si

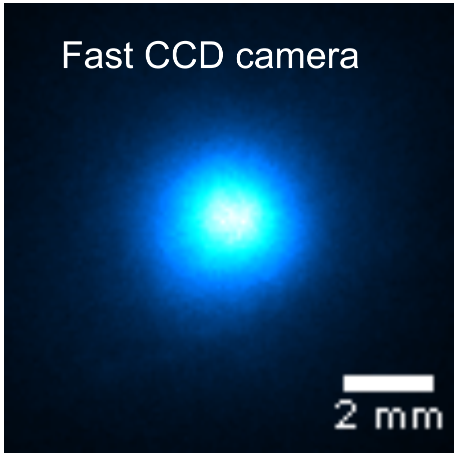


Pixel resolution ∂E ≈10 keV

Exploring intensity and dose rate effects

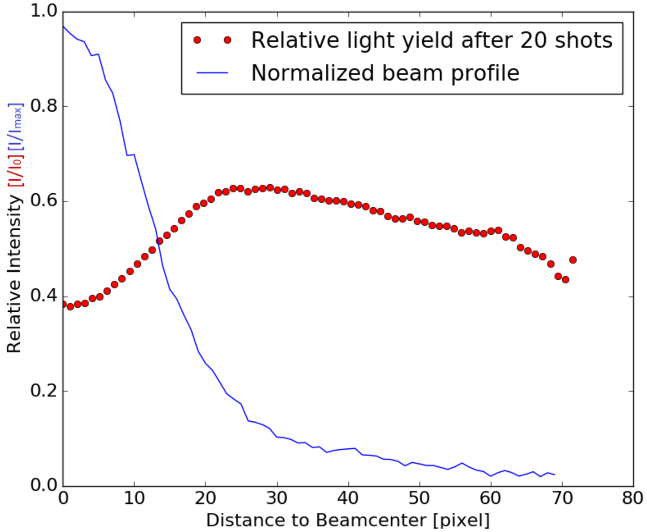
F. Treffert, TU-D, Masters thesis

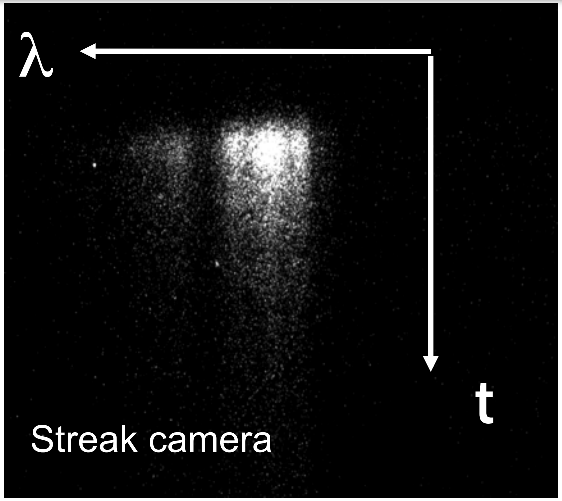
Scintillator luminescence shows dose effect from intense helium ion bunches



10^5 Gy/shot

polyvinyltoluene (PVT)



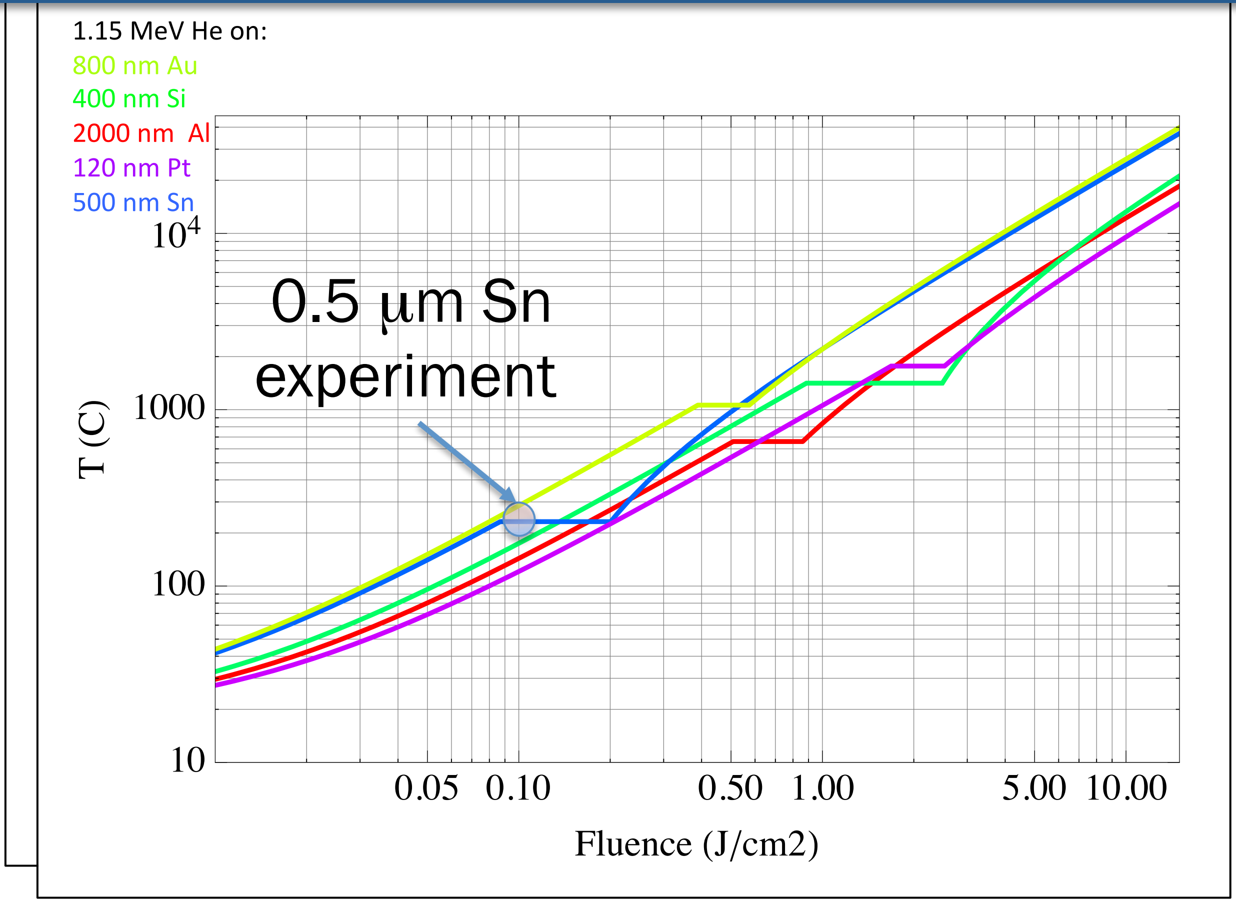


Focused and defocused beam to explore dose *rate* effect.

- Lifetime loss from increased temperature ($\Delta T \approx 60$ C).
- Bond breaking (C-H) → color centers decrease transparency.
- Thermal annealing of color centers, restoring transparency.

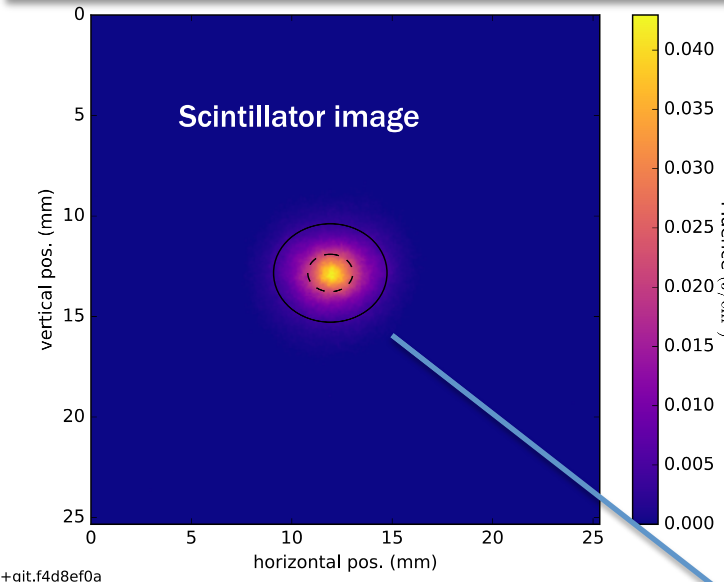
Zimmer, et al, “Dose rate effects … PVT”, in preparation

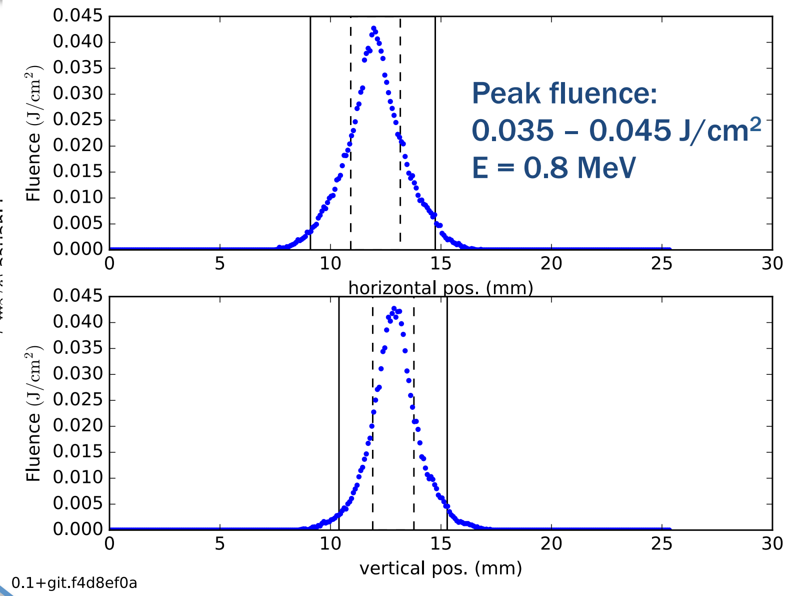
Helium pulses with 100 mJ/cm²/shot @ edge of tin melting plateau

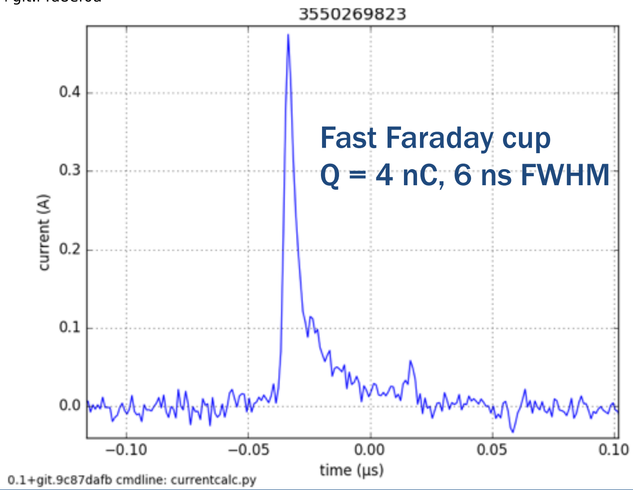


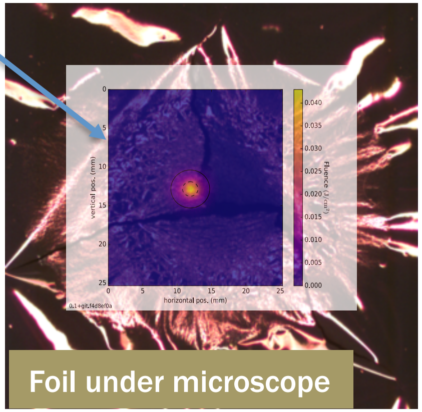
J. Barnard

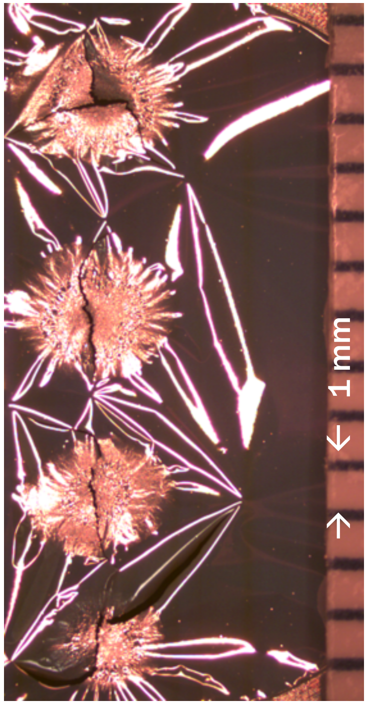
Heating 0.3-μm foil Tin with a short-pulse helium beam



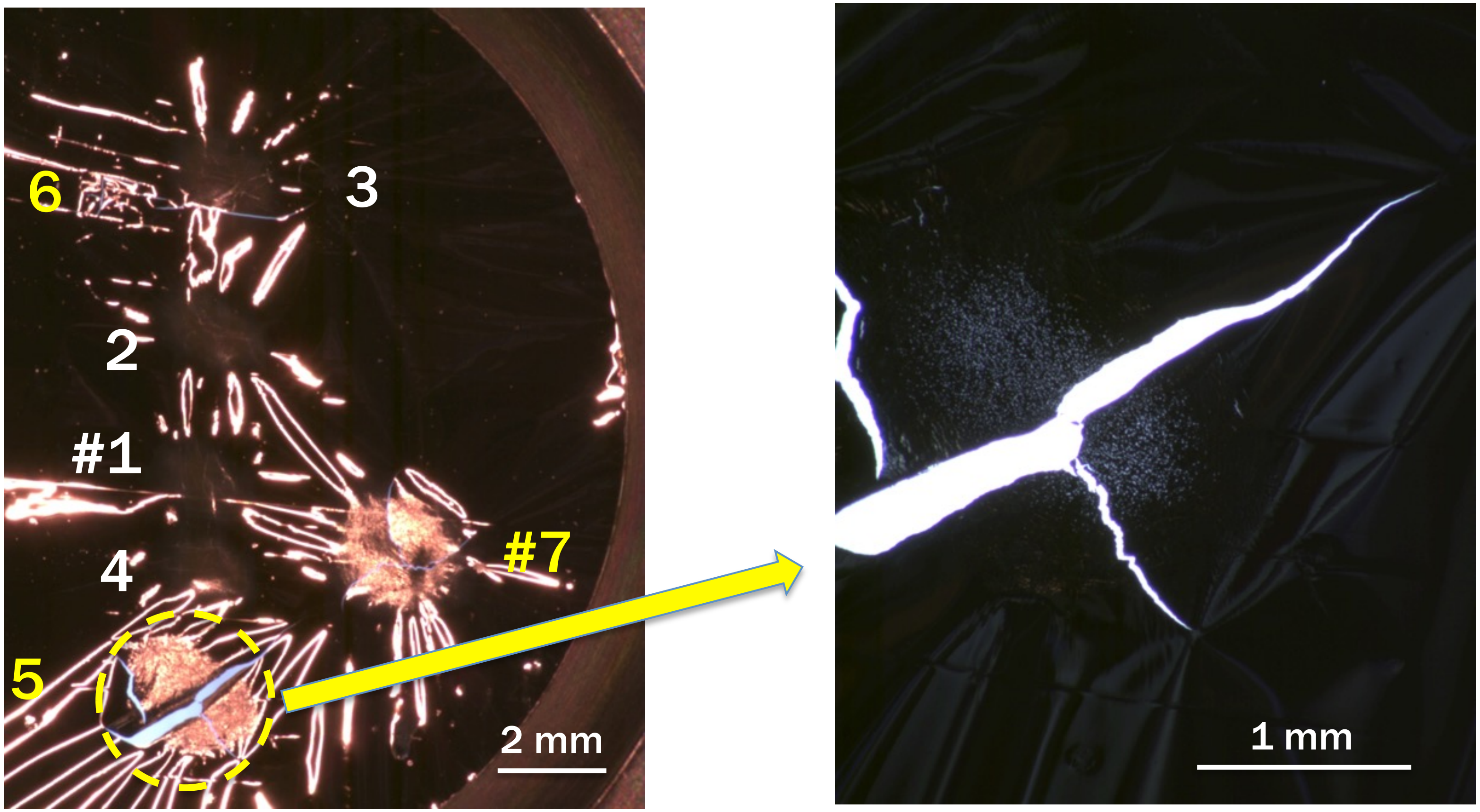








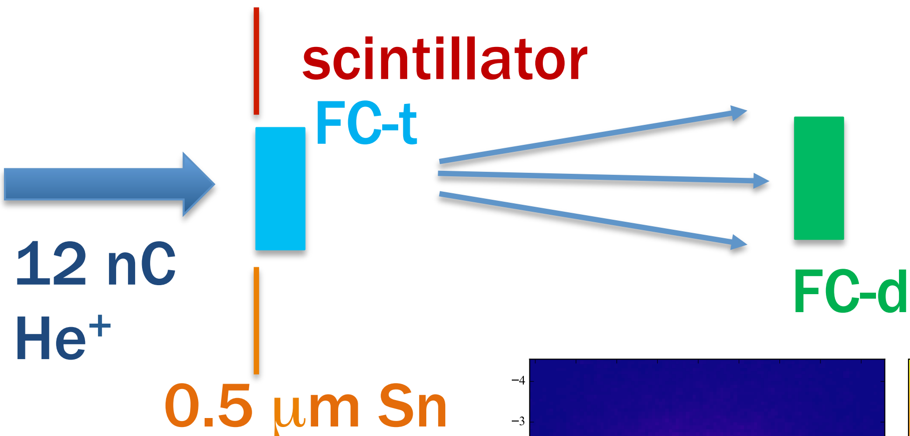
Inspection of 0.5 μm Sn foil after Q_{tot} = 12-nC/beam pulse

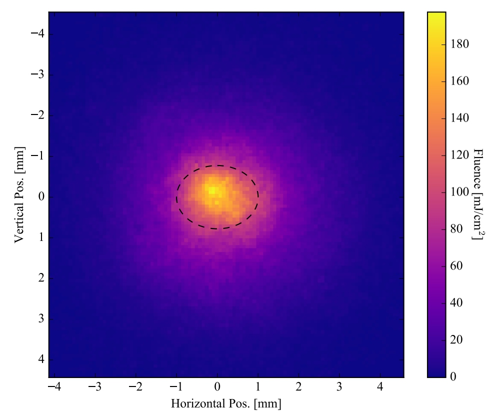


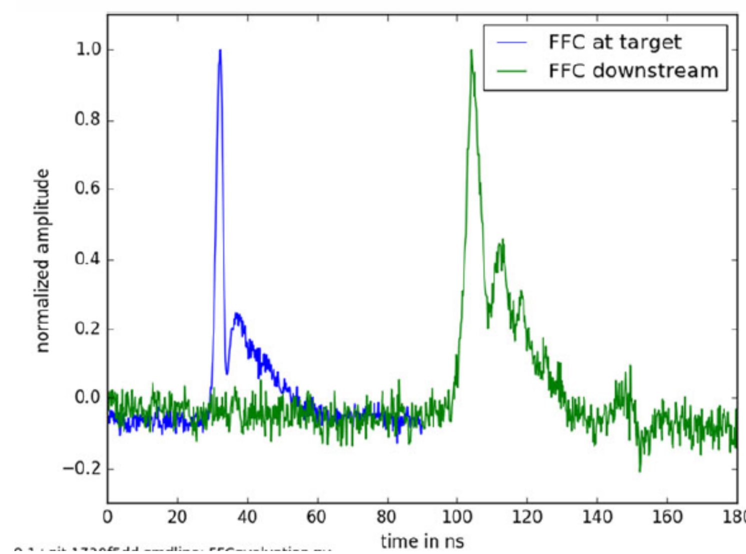
1 shot/target position
>1 shot/target position

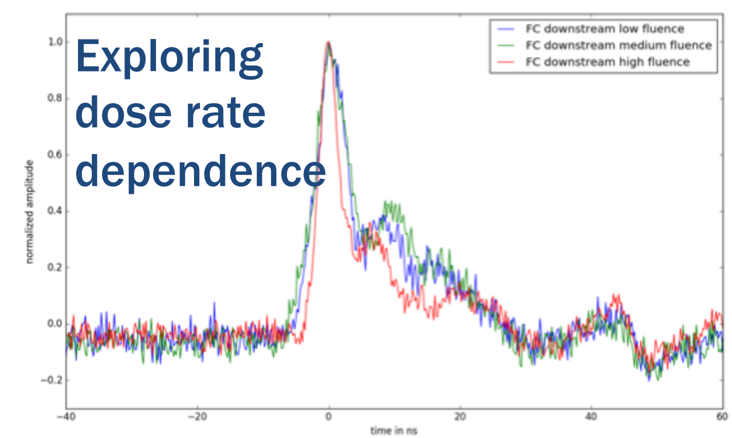
Backlight view shows tiny holes

We measure the energy loss of transmitted ions in heated targets via TOF, Thomson Parabola spectrometer



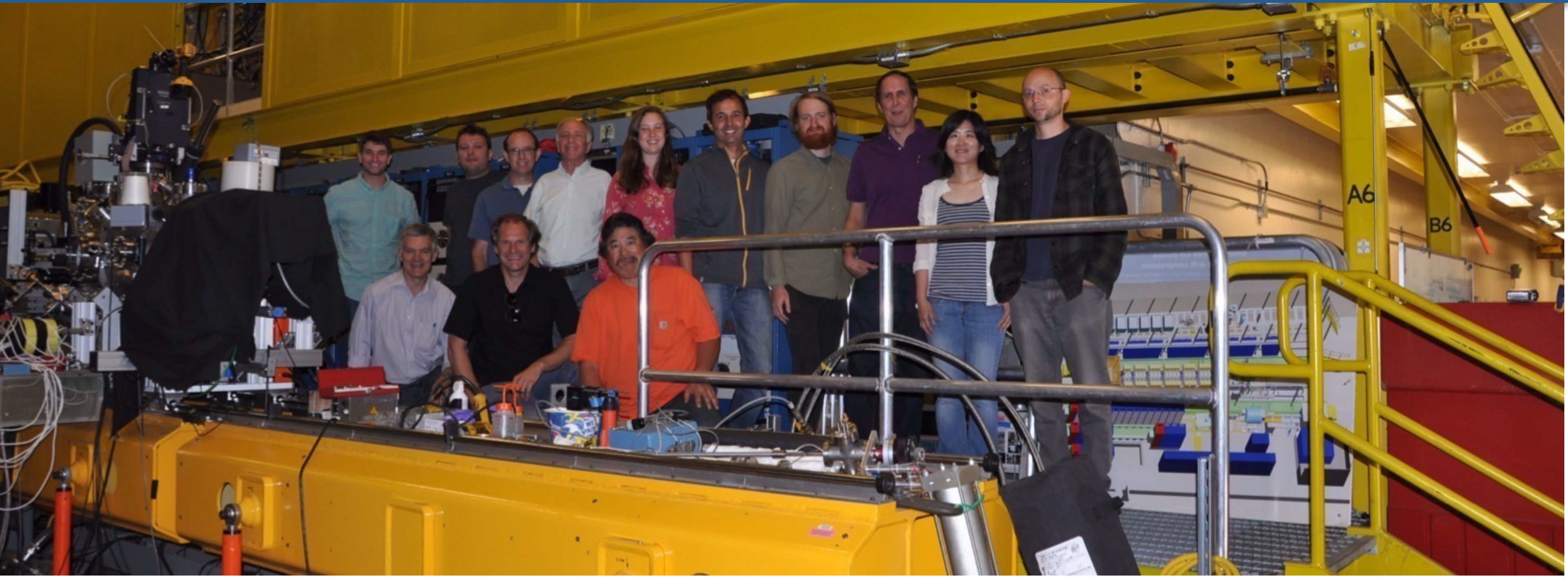






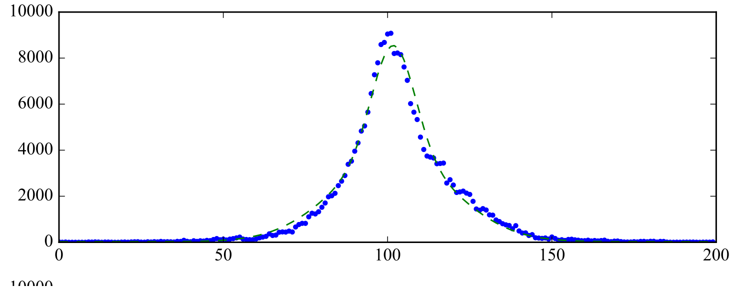
Opportunity to probe material response to short-pulse ionizing radiation (t, λ), **e.g., channeling of ions in crystals**

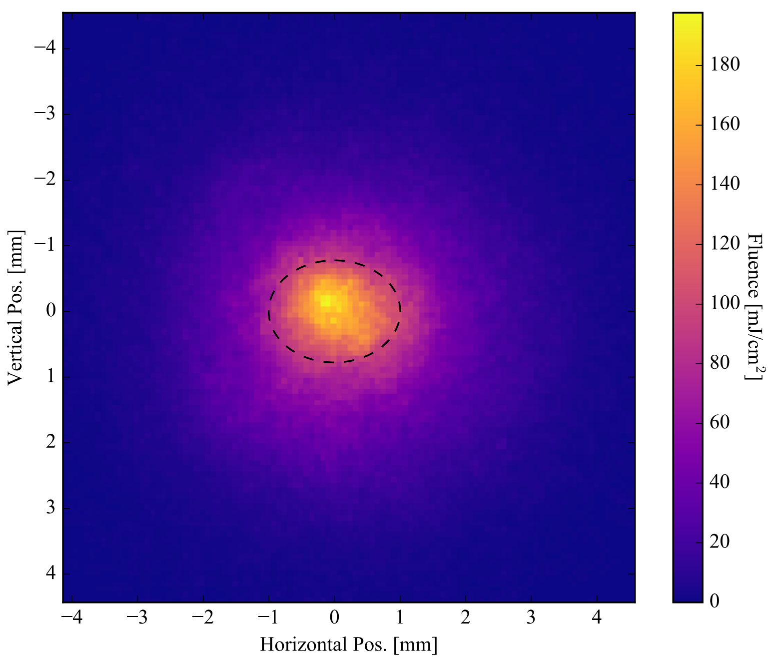
We welcome visitors and collaborations!

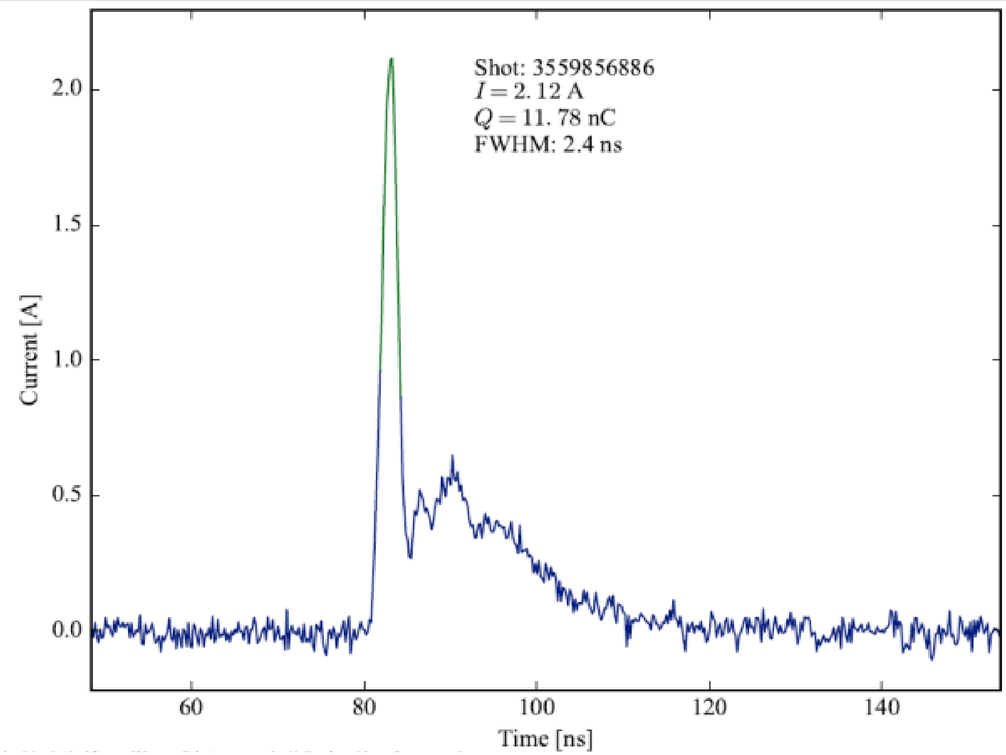


- We are doing target experiments with >10 nC/pulse, 2-40 ns, r ≈ 1mm, >1/minute.
- We have developed a close coupling of particle-in-cell modeling to the experiment.
- These intense pulsed ion beams now open opportunities in the materials physics of radiation with *in situ* access to multi-scale defect dynamics, radiation effects in semiconductors, intense beam and bam-plasma physics
- Synergistic: Bella-i laser generated ion beams – Park TP11.47, Steinke YP11.65

We have achieved 2 A peak currents for ns pulses of 1 MeV He^+ ions





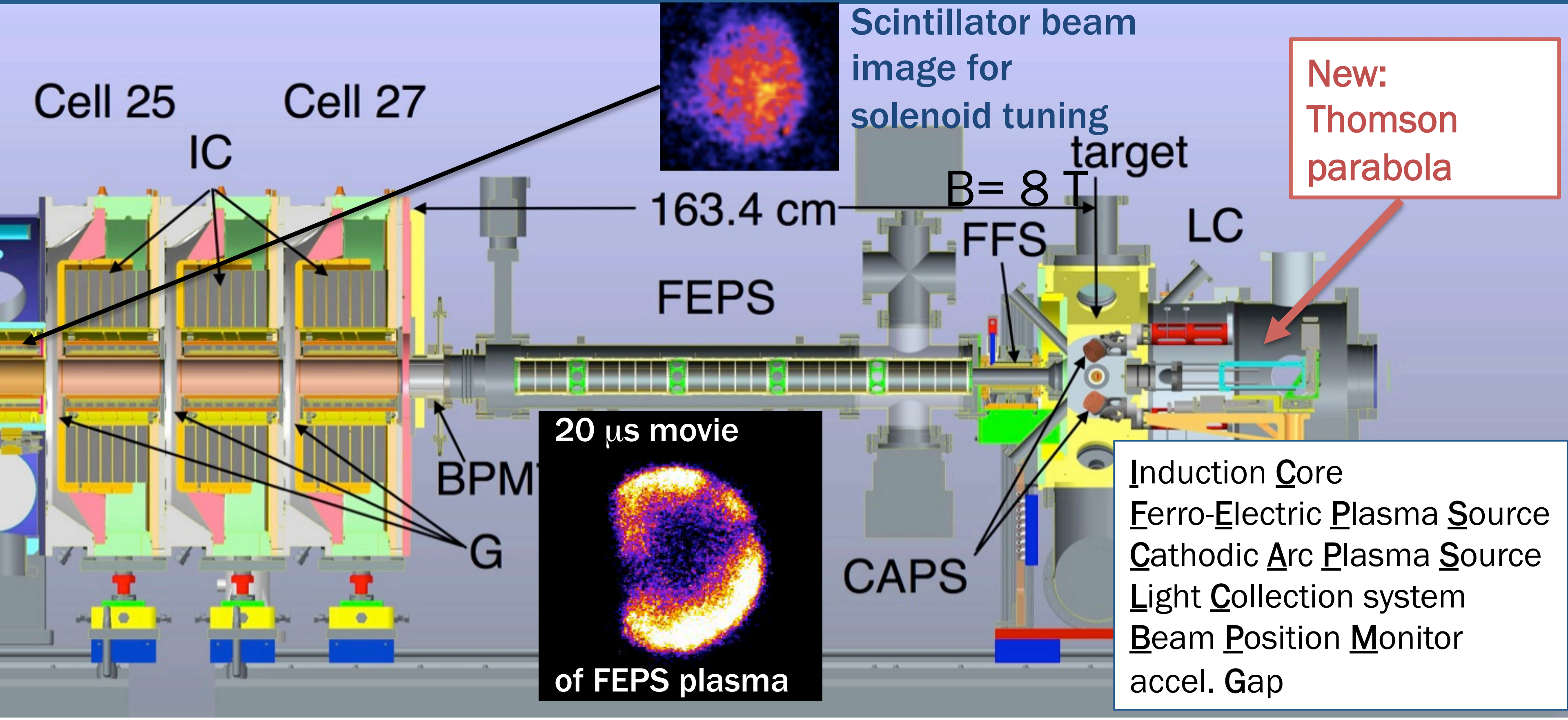


- 1.1 MeV (He^+), 12 nC (7.5×10^{10} ions) → 13 mJ
- ~180 mJ/cm^2 @ peak, 2 mm FWHM
- Uniform energy deposition into a 2 micron silicon foil with ~ 6×10^3 J/cm^3

Highest fluence achieved 0.7 J/cm^2 for longer pulse duration.

BERKELEY LAB | U.S. DEPARTMENT OF ENERGY | Office of Science | ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

Diagnostics include fiber-coupled streak spectrometer, II-CCD, Fast detectors for TOF, channeling and energy loss experiments.

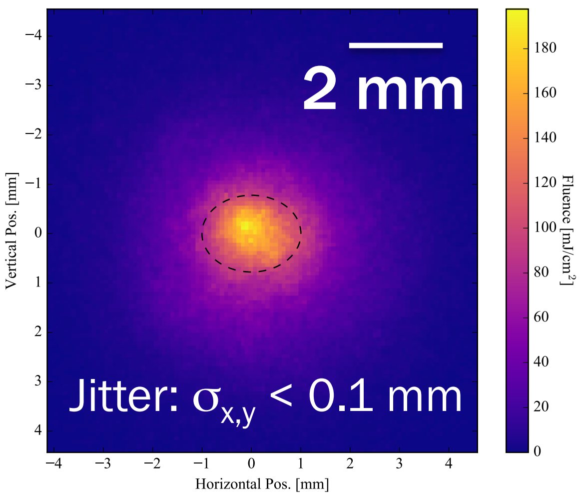


Target chamber available diagnostics:

- Scintillator + CCD camera, Fast Faraday cup (FFC)
- Streaked optical spectrometry (10 ps)

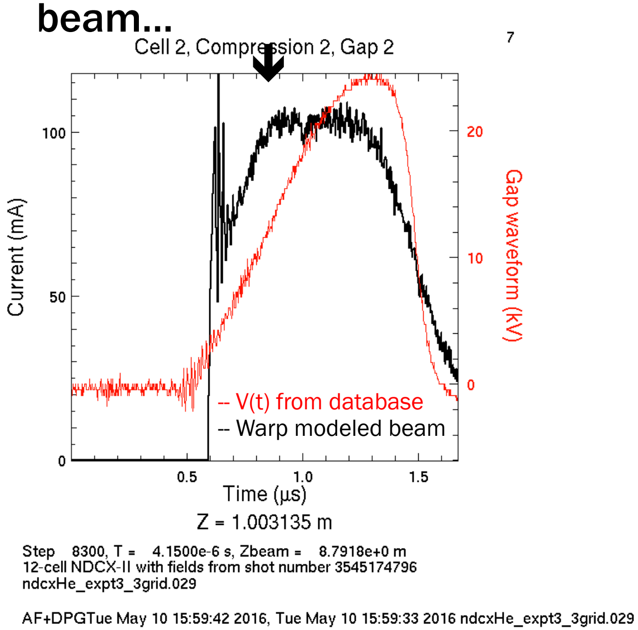
NDCX advances intense beams, beam-plasma physics, materials science and radiation effects

- We have generated ns ion pulses with **peak dose rates of >10^{20} ions/cm^2/s** with high reproducibility. Repetition rate is >1/minute. Beam r = 1mm, t ≈ 2 ns
- Injecting ~100 mA of He^+, we have achieved 2 A peak current for ns pulses of 1 MeV He^+ ions, focused to **0.1 J/cm^2**.
  - (0.7 J/cm^2 for longer pulse)
  - Next experiments with proton beam.
- We are measuring ion energy loss in heated foils, Sn, Si, SiN
- radiation dose and dose rate effects on transistors and diodes
- Based on new results, we will:
  - **Push the limits and testing the understanding of intense beam physics** for inertial fusion and other applications.
  - **Radiation effects testing** and fusion materials science
  - **Phase transitions and extreme chemistry** and materials synthesis far from equilibrium (e.g. nitrogen vacancy centers, novel alloys, ...)

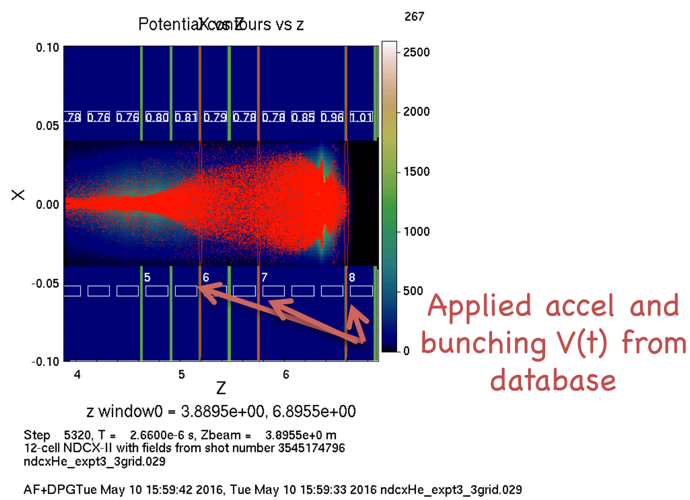


Routinely use particle-in-cell simulations to to validate our understanding of the high intensity beam physics and to help optimize the performance of the accelerator, compression and focusing for target experiments.

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…

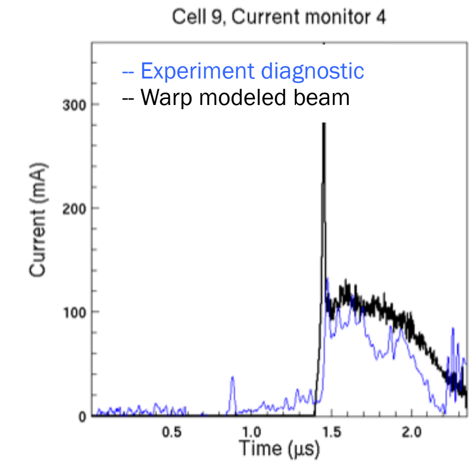


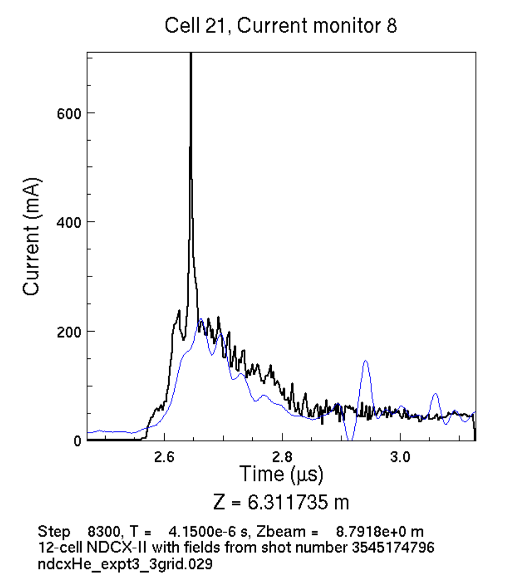
2. Snapshot of the X-Z projection shows rms properties & halo particle loss… ➜



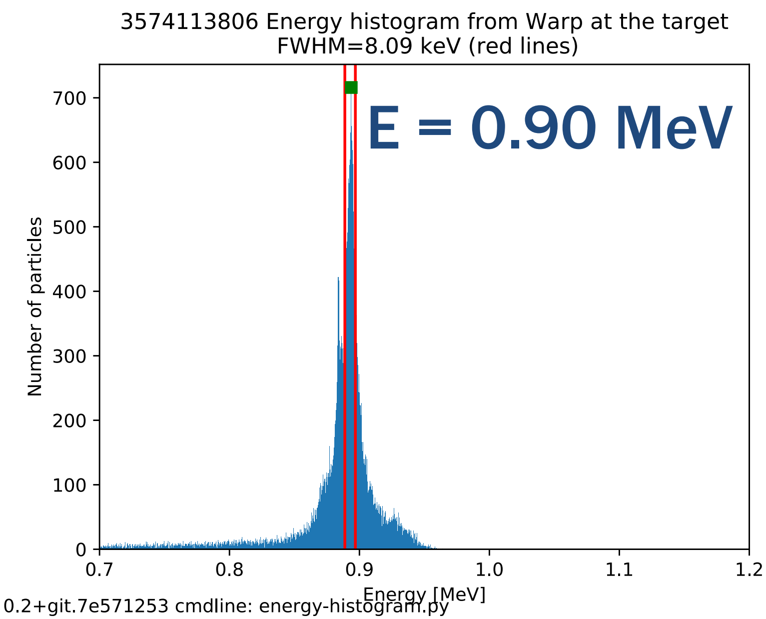
3. Results are directly compared to the experiment beam diagnostics. From these, adjust focusing, waveforms, timing, then go to #1. →

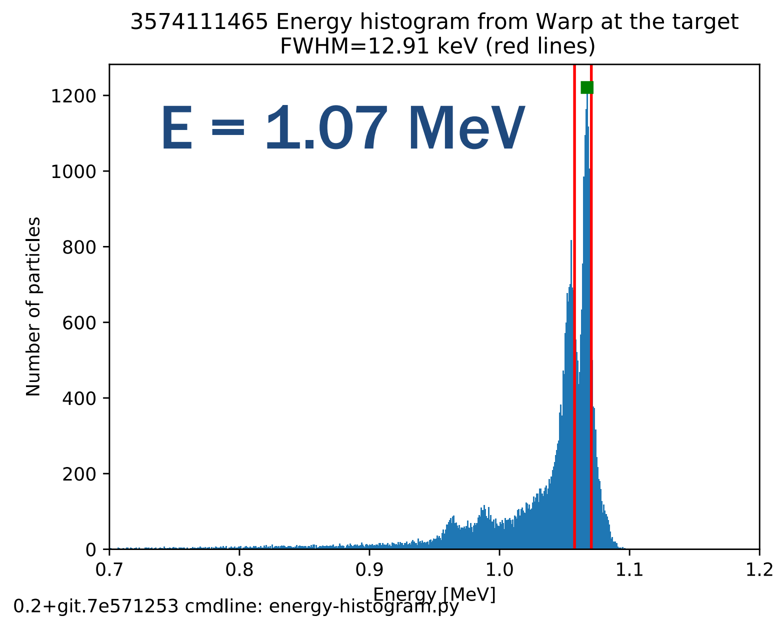
≈10 min/run/processor, we do ≈10 parralel simulations, vs 1 shot/min in the experiment





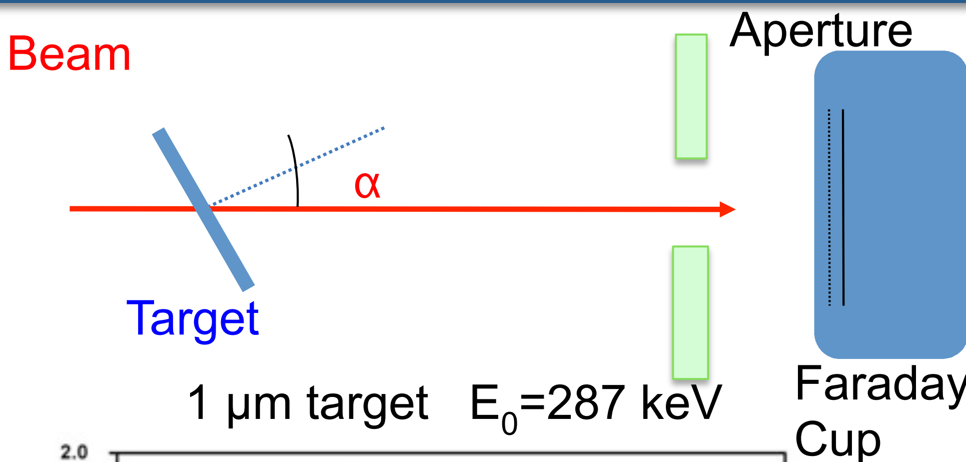
To determine the kinetic energy distribution for each shot, we have simulated each shot with Warp PIC.

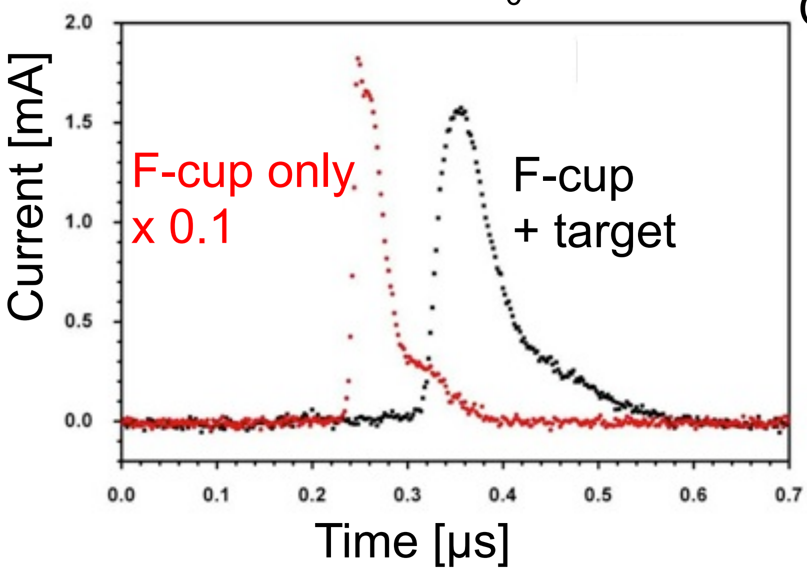


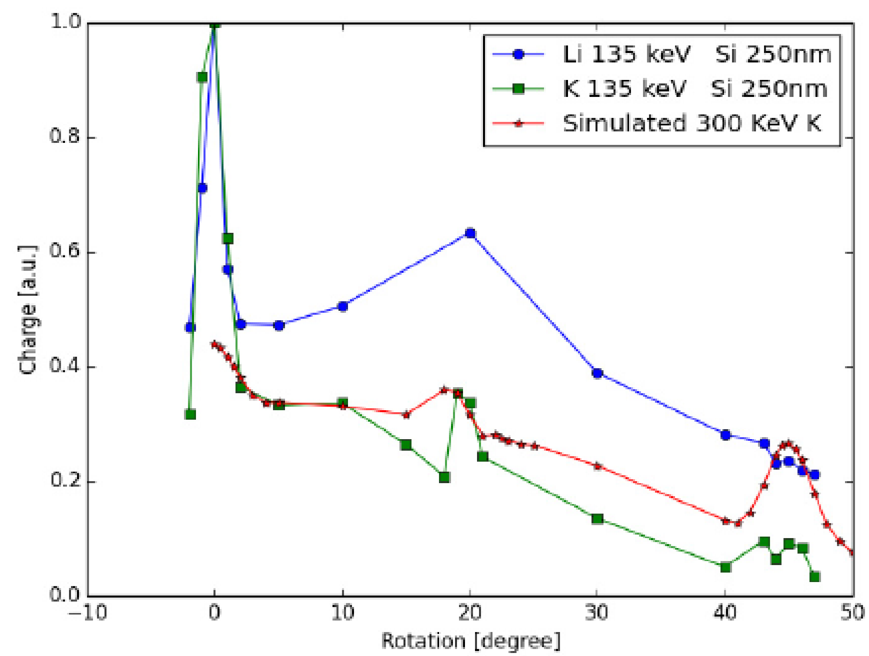


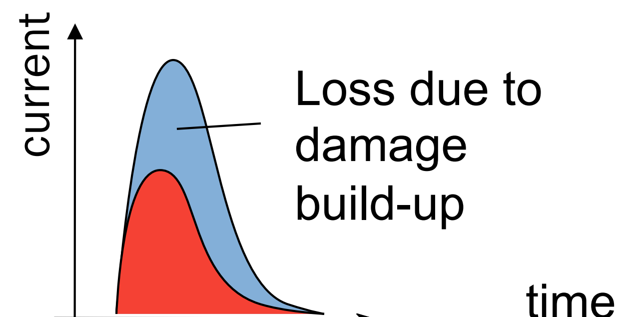
Low energy ions do not reach the sensitive layer.
Analysis will separate range effects from possible dose rate effects.

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



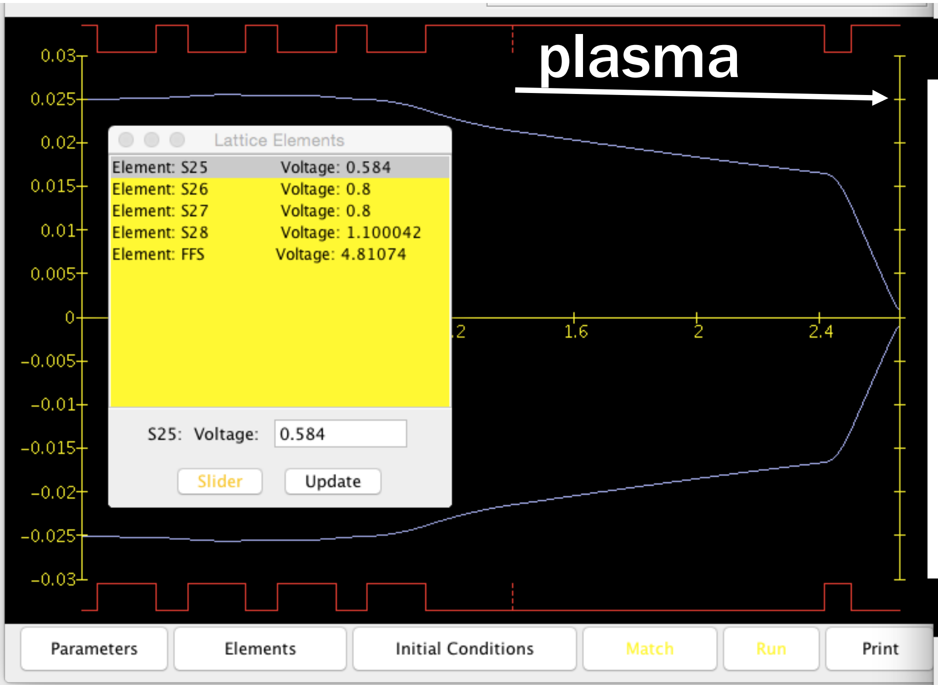


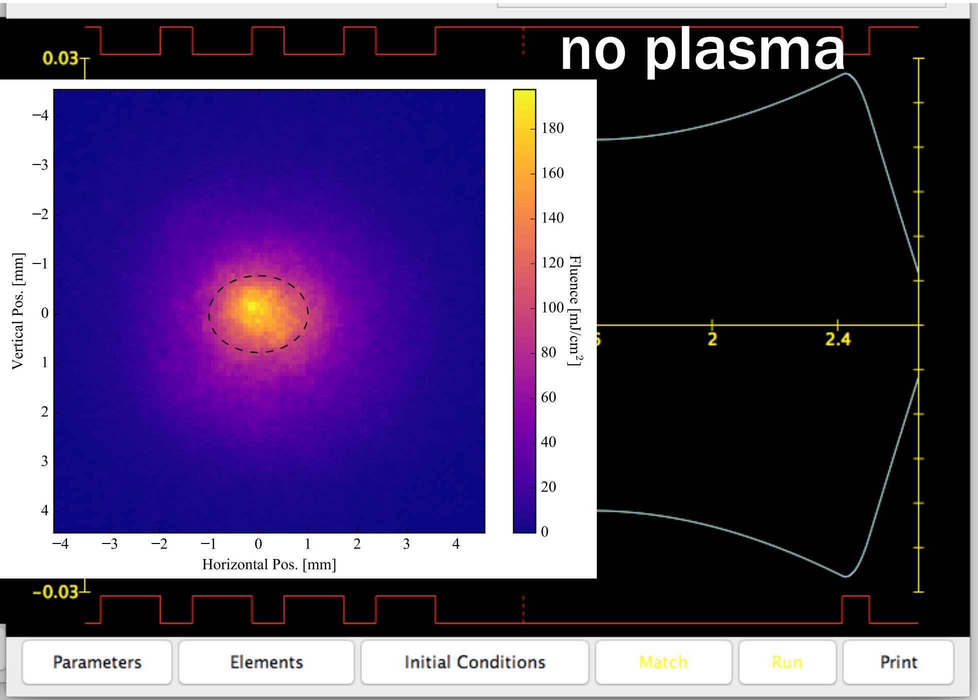




T. Schenkel et al., *Towards pump-probe experiments of defect dynamics with short ion beam pulses*, NIM B 315 (2013)

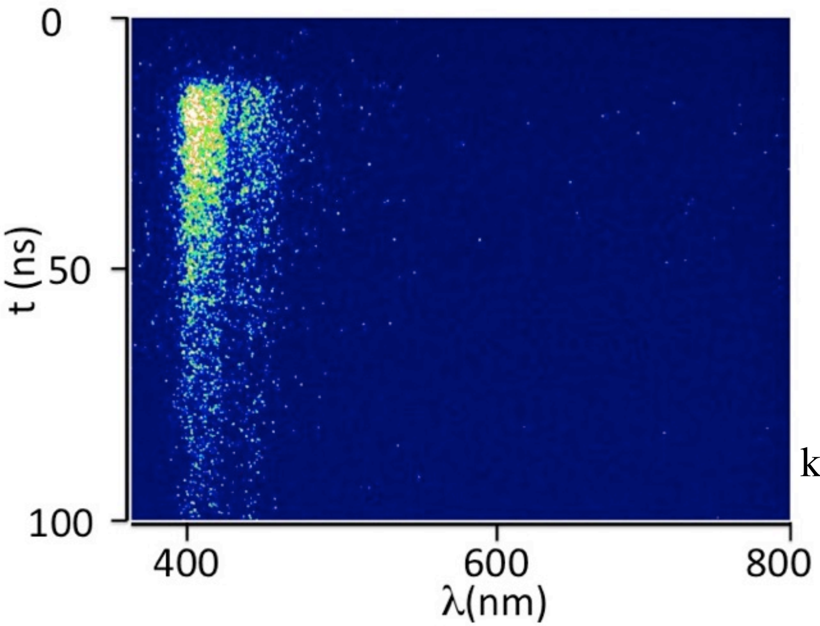
The neutralization of the beam space charge defocusing is essential for obtaining higher focused intensity





With pulsed ion beams we can probe the radiation effects on materials and warm dense matter research

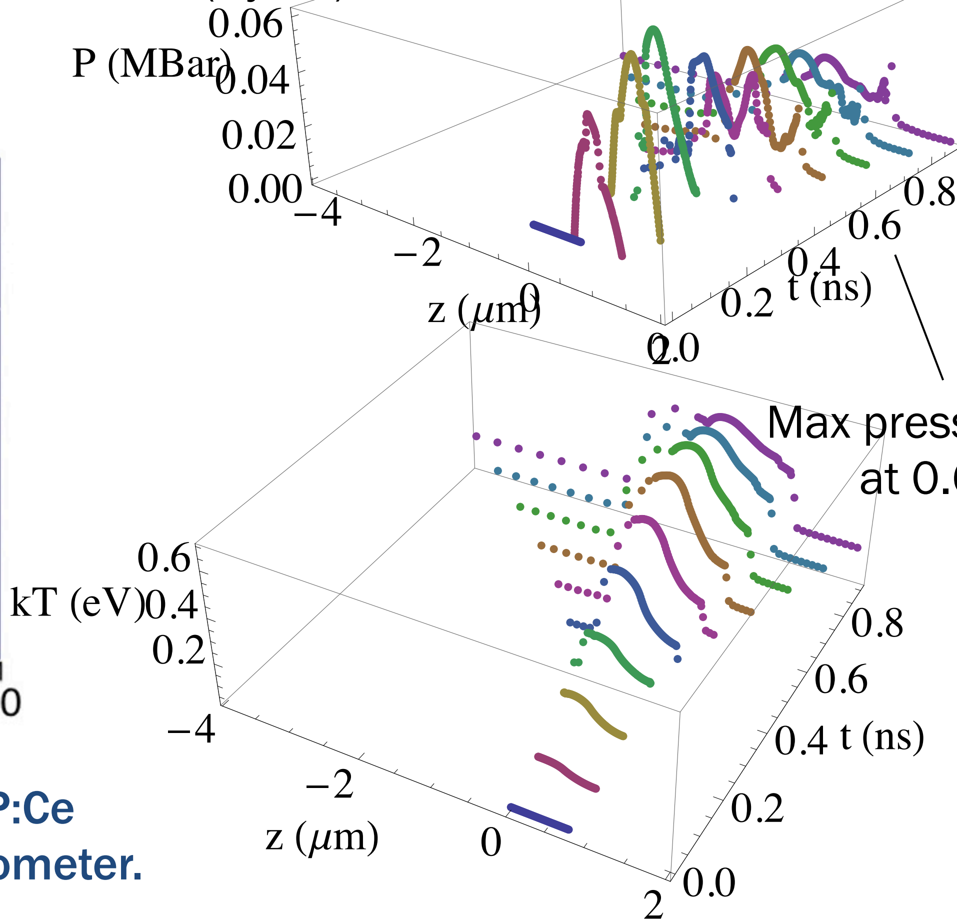
Novel opportunities with short, intense pulses to probe material response to radiation in the time domain.



e.g., single shot ionoluminescence of YAP:Ce measured with a streaked optical spectrometer.

P.A. Seidl, et al., NIM A800 (2015)

Helium beam on 0.75 μ thick gold target (Hydra), J. Barnard, LLNL.

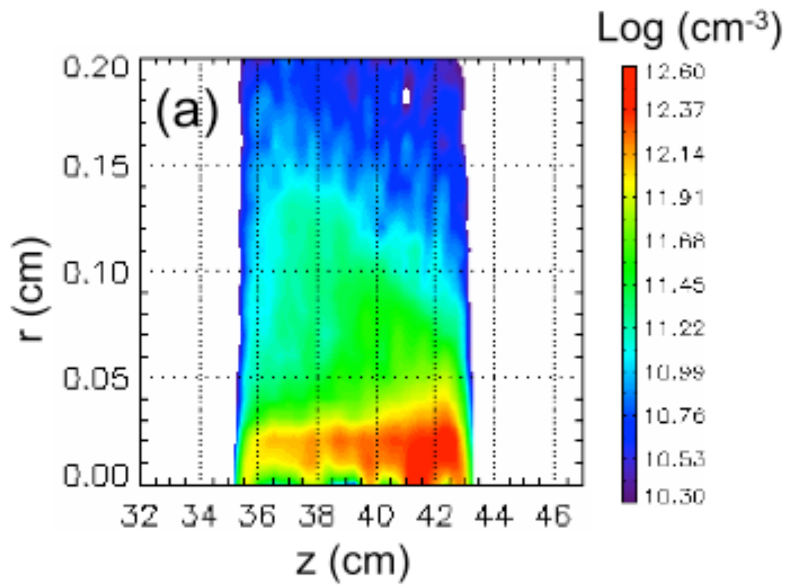


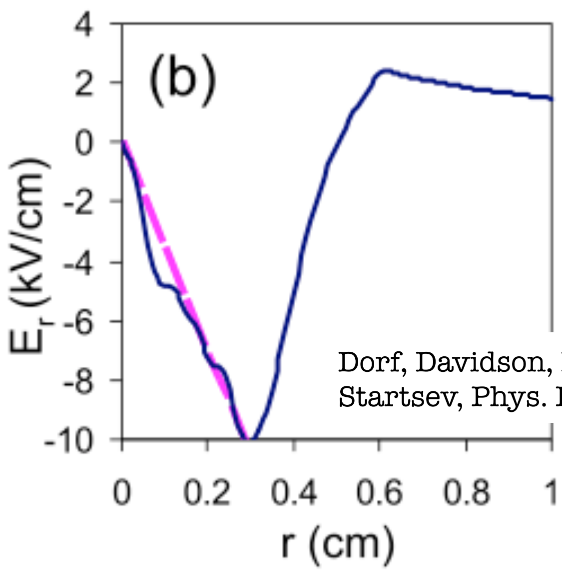
Strong collective focusing of an ion beam in a plasma and a weak magnetic field

- Most pronounced when the beam radius is small compared to the collisionless plasma electron skin depth $r_b < c/\omega_{pe}$
- Applied B can be reduced by a factor $(m_e/m_i)^{1/2}$ ~10 Tesla→ ~10^2 Gauss

Can this be used to great advantage in high intensity ion beams?

Particle-in-cell (LSP) simulation using the collective focusing effect to focus the high intensity beam using a weak magnetic field and a plasma.

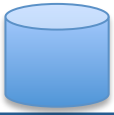


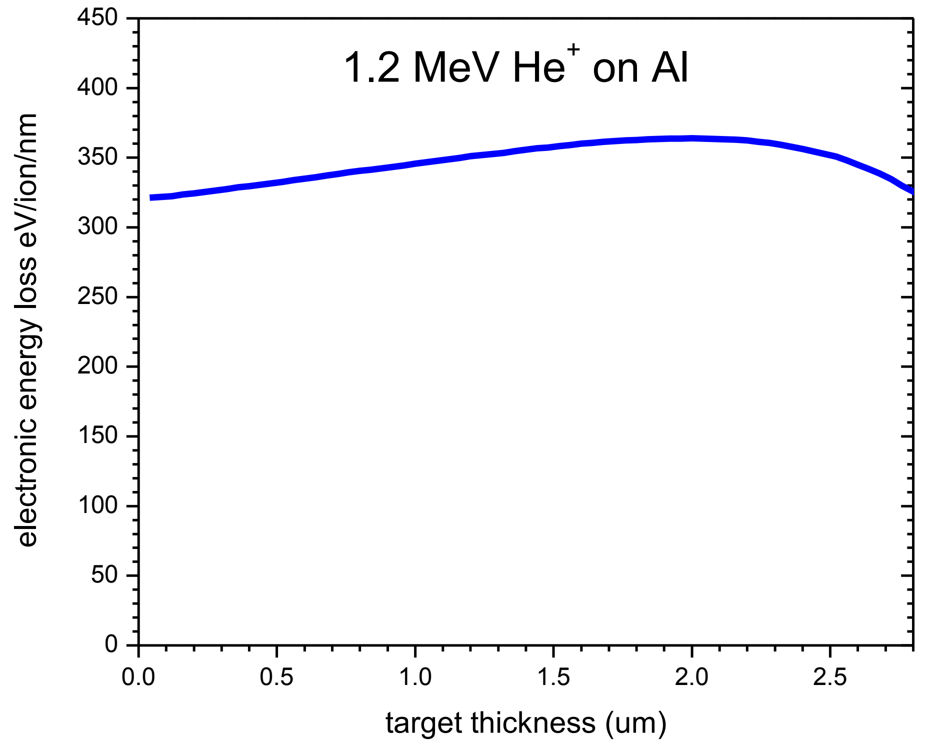


Dorf, Davidson, Kaganovich, Startsev, Phys. Plasmas (2012)

Complementary aspects of intense, pulsed ion beams from accelerators

	Fair	NDCX-II (goal)
Ions/pulse (total)	~10^{10} - 10^{12}	10^{10} ($3x10^{11}$)
Pulse length	40-100 ns	2 ns (~1 ns)
Typical spot size	~1 mm^2	1 mm^2
Ion species	H, C, …, Au	He (also H and higher Z)
E_{kin}	0.4 – 1 GeV/u	0.12 - 1.2 MeV
Energy spread	low	~10%
Repetition rate	fast	2/min
Target temp.	few eV, to ~100 eV	<0.1 eV (~1 eV)
Radiation environment at the target	Intense, requires shielding	Benign, no shielding required
Heated volume	> mm^3	~1 mm^2 x 5μm =$5x10^{-3}$ mm^3

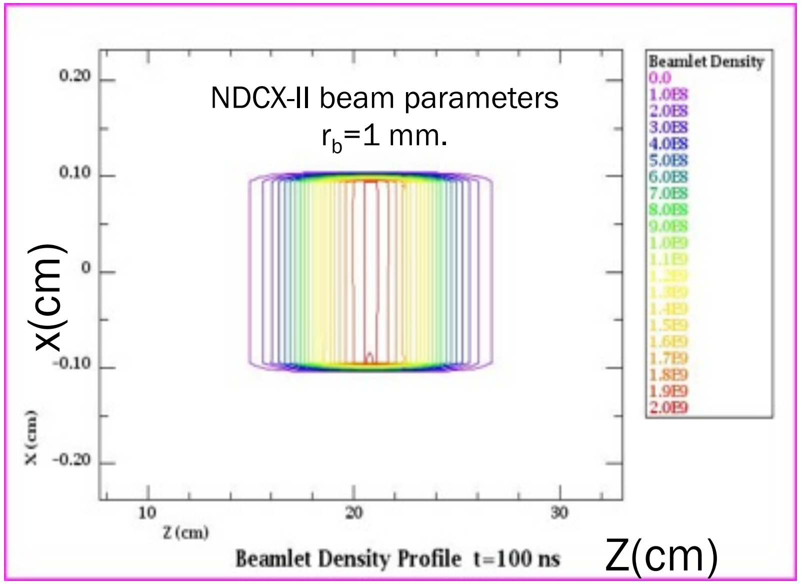


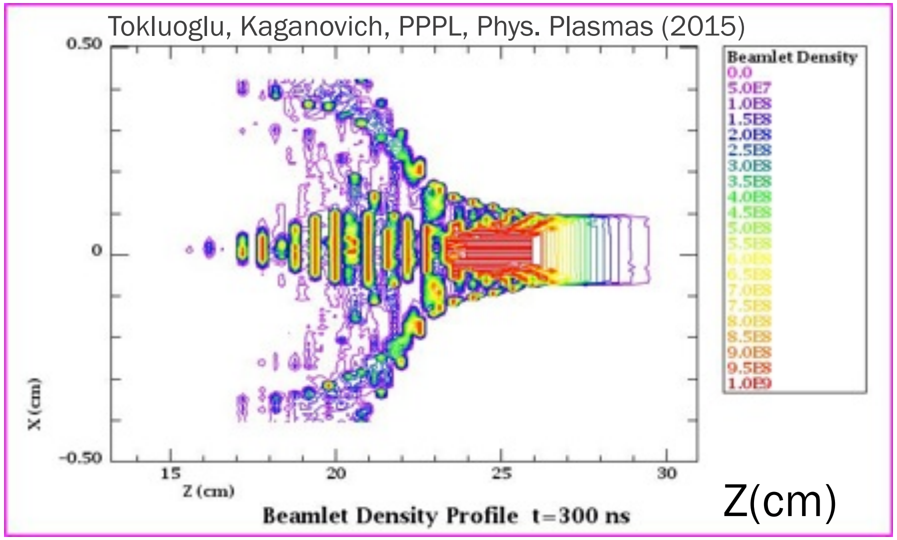


Two-stream instability of an ion beam propagating in background plasma

- In high energy accelerators: two-stream or electron cloud effects arise from stray (unwanted) electrons. → Reduce/eliminate!
- For new high-intensity ion beam systems, plasma is introduced to cancel the defocusing space charge force.

[Kaganovich, APS-DPP invited]





Beam density contour at t = 100 ns (1 m propagation).

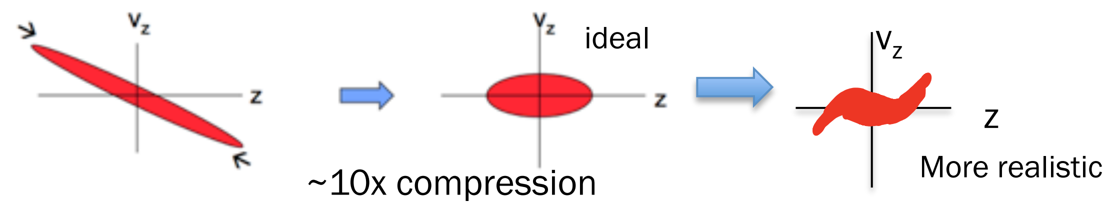
Beam density contour at t = 300 ns (3 m of propagation).

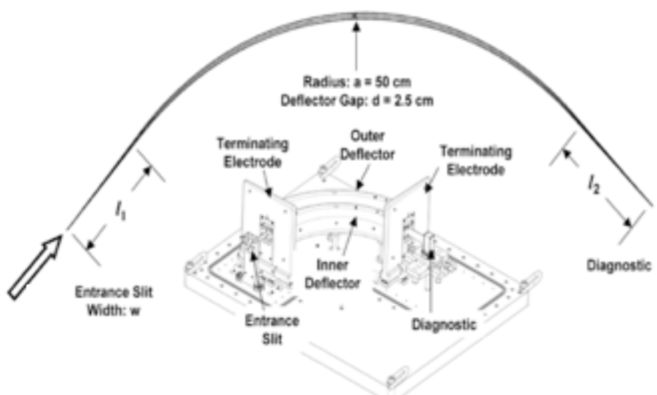
Defocusing when $\Delta v/v$ is small.

Goal: observe transverse defocusing and longitudinal self-bunching of beam

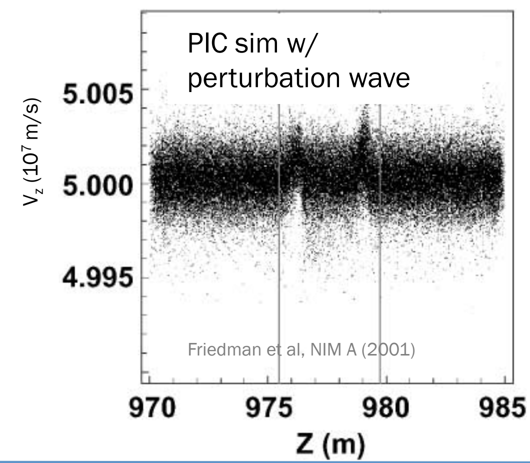
Demonstrate removing a large velocity spread from a high space charge beam via drift compression.
Reduces chromatic aberrations in the final focusing elements.

How well can space charge "stagnate" the compression to produce a "mono-energetic" beam at the final focus?

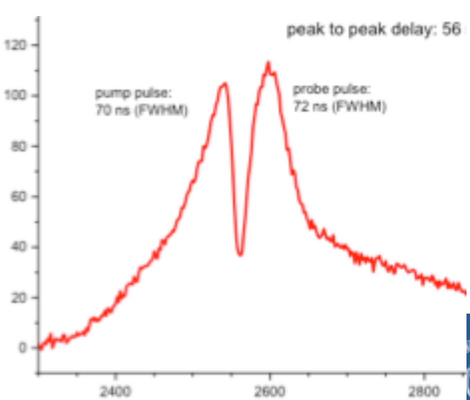




Waveform errors can launch space charge waves, and degrade the final energy spread and may cause particle loss. Detailed initial conditions must be included in simulations.

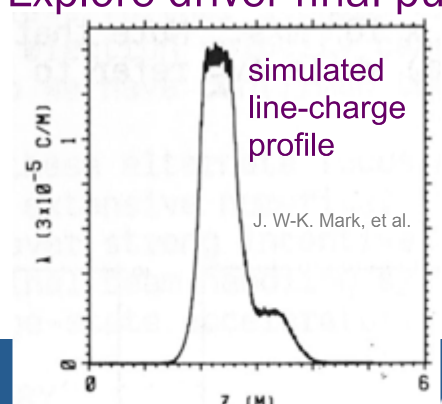


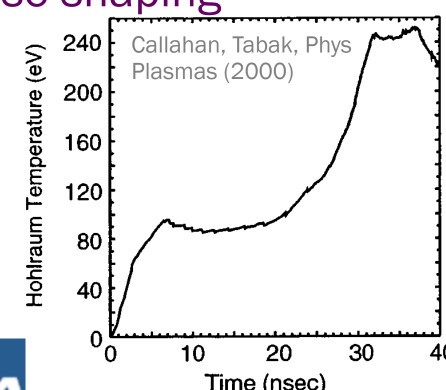
Pulse shaping: pump-probe for materials studies



Double pulsing @ NDCX-II (preliminary)

Explore driver final pulse shaping

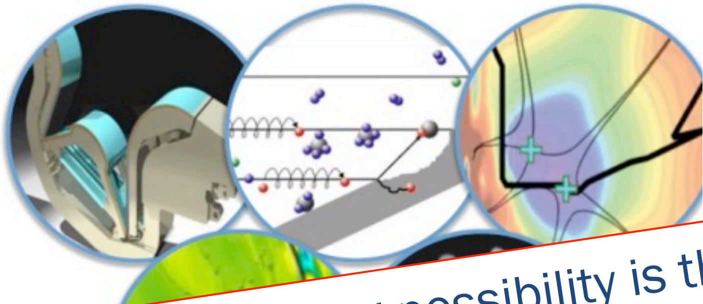




Exp connect to HIF parameters: Perveance, "tune depression," compression ratio) ~ a fusion driver.

We can probe the materials physics of radiation damage *in situ* on short time scales with pulsed ion beams at NDCX-II

FUSION ENERGY SCIENCES WORKSHOP



Report on Science Challenges and Research Opportunities in Plasma Materials Interactions

MAY 4-7, 2015

U.S. DEPARTMENT OF ENERGY | Office of Science | *Fusion Energy Sciences*

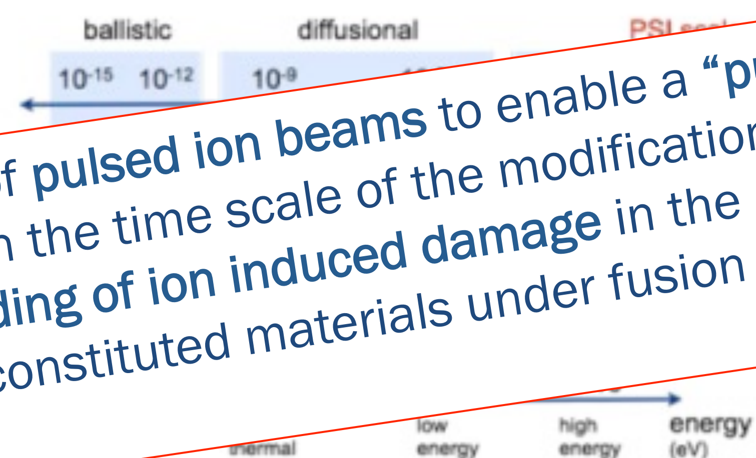


Figure VI-1: Schematic outlining the spatio-temporal physical scales involved in PSI and how experimental and computational tools access the same. For example, experimental tools could probe ballistic mechanisms with pump-probe type diagnosis. These could couple to QMD or MD type simulations tools. A third axis in the bottom depicts the energy scale relevant to PSI that one must address with the interaction of particles and the material surface.

> One intriguing possibility is the use of **pulsed ion beams** to enable a **"pump"** that could in principle be **"probed"** in the time scale of the modification. This tool **could transform our understanding of ion induced damage** in the context of the complex evolving, reconstituted materials under fusion reactor conditions. (P. 116)