Toward pump-probe experiments of defect dynamics with pulsed ion beams

Peter Seidl, Accelerator and Fusion Research Division, LBNL
Hua Guo[1], Peter Hosemann[1,2] , Andrew Minor[1,2] , Arun Persaud[1], Thomas Schenkel[1], William Waldron[1] , John Barnard[3]
[1]LBNL and [2]Univ. of California, Berkeley, [3]LLNL

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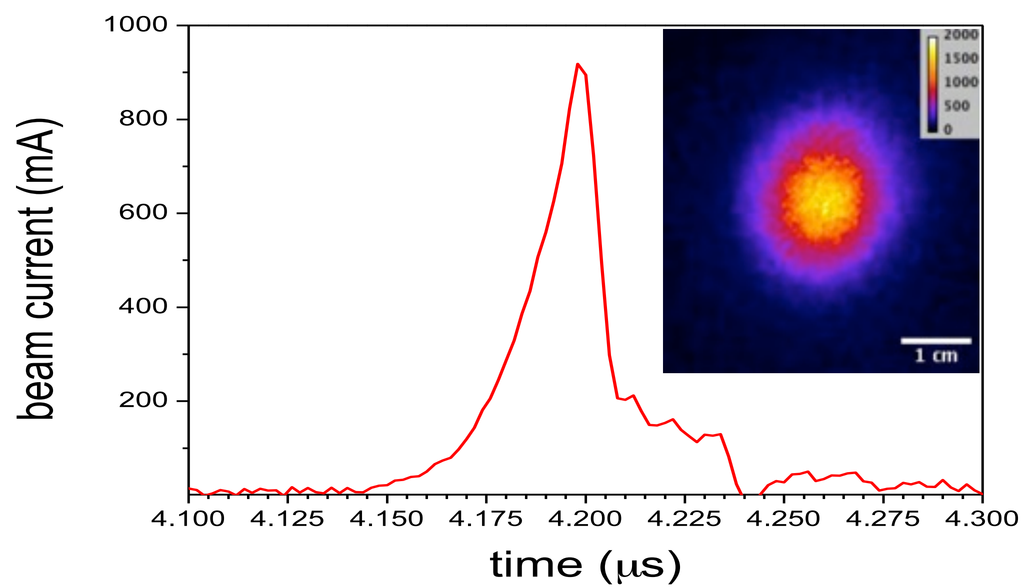
We have formed ~16 ns long pulses with peak currents up to 1 A, (r ≈ 5 mm) with Lithium ions, and have begun experiments with K+ ions.

We are preparing shorter pulses (~1 ns) and smaller focal spots 30-nC bunches.

Such pulses can give access to defect dynamics on a 1 to 600 ns times scale.



Current trace for a single ion pulse compressed to 16 ns (FWHM) (Li^+, 280 keV, 25 nC), T. Schenkel, et al., Nucl. Instr. Meth B 315, 350 (2013)

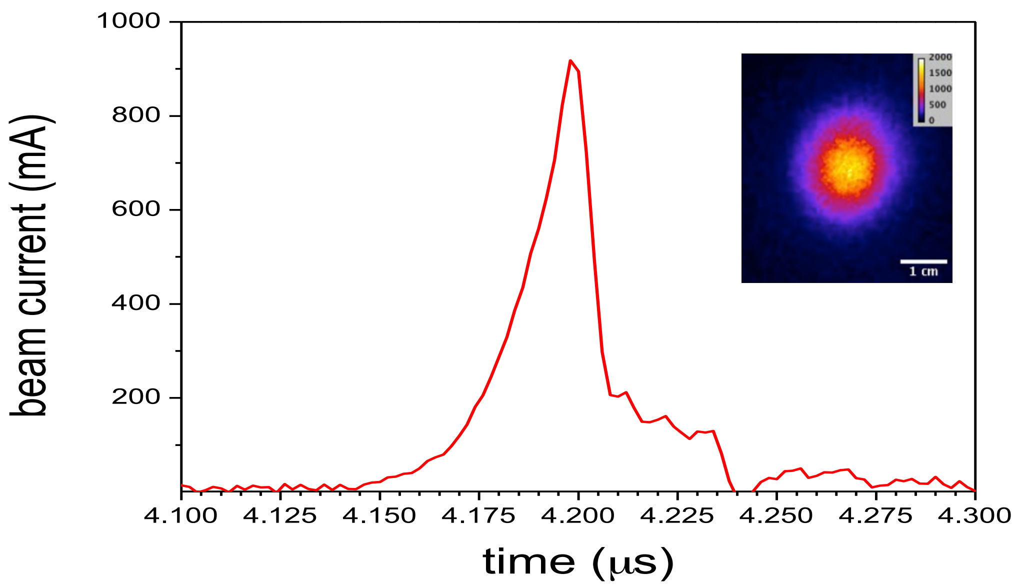
NDCX-II is a unique facility for discovery science with intense, pulsed ion beams

Our goals:

- Short, intense ion pulses for isochoric heating of solids to Warm Dense Matter states
- Access to defect dynamics in pump-probe type experiments with ion beam as pump
- With NDCX-II we can access to the physics of very intense ion beams and non-neutral plasmas. Relevant to accelerator physics and fusion research

Beam parameters

- Pulse length 0.6 ns (currently ~20 ns) with 2 shots/min.
- ~10 to 50 nC ($3x10^{11}$ ions/pulse)
- Beam spot r ~1 mm (currently ~5 mm)
- 1.2 - 3 MeV (currently 0.3 MeV)
- Ions: Li, K… (He, other noble gases in progress)

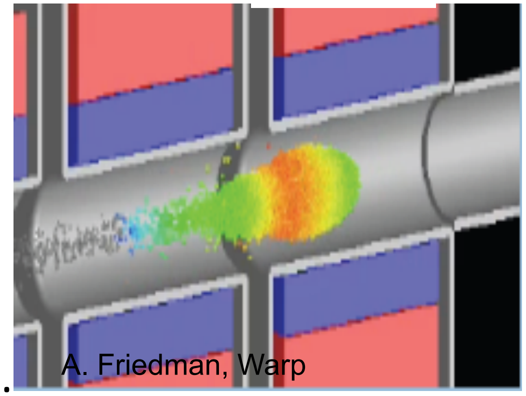


Current trace for a single ion pulse compressed to 16 ns (FWHM) (Li^+, 280 keV, 25 nC), T. Schenkel, et al., Nucl. Instr. Meth B 315, 350 (2013)

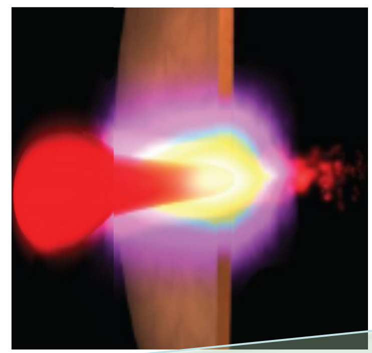
<u>NDCX-II</u>, the **Neutralized Drift Compression Experiment**, a short pulse ion accelerator at Berkeley Lab

NDCX-II provides uniquely intense, short ion pulses with high reproducibility and tunability

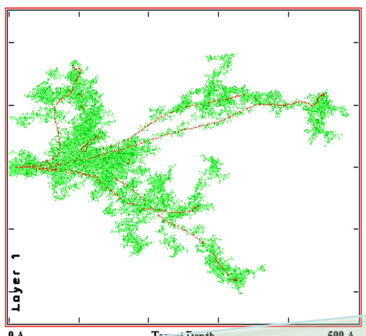
Nano-second ion pulses ("pump")

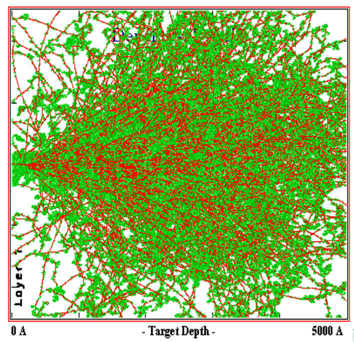


Higher intensities:
Warm Dense Matter, isochoric heating



Lower intensities:
defect dynamics in materials





isolated cascades

overlapping cascades

amorphization and melting

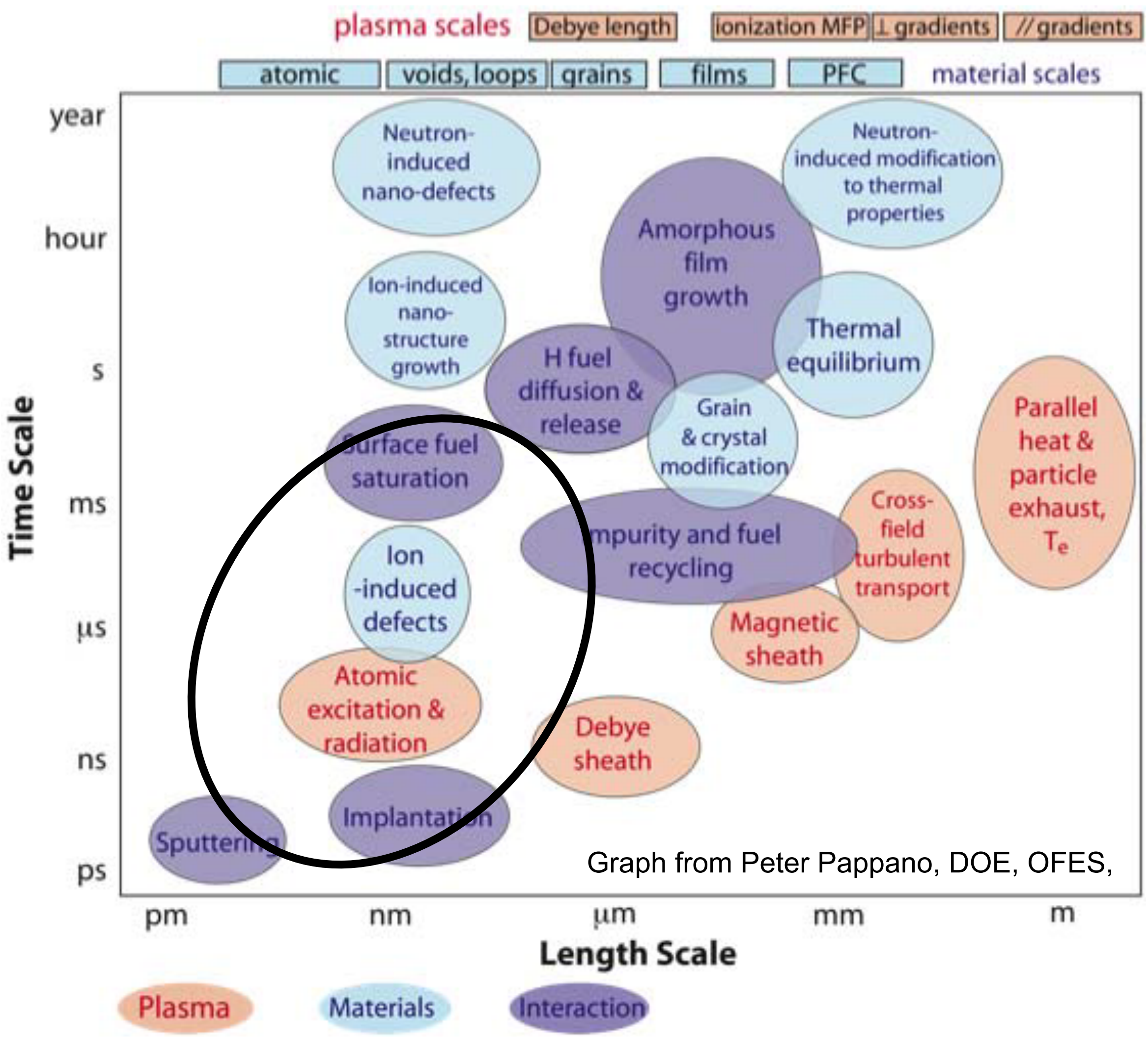
warm (~1 eV), dense matter

~40 nC, 1.2 MeV, ~1 mm^2, ~1 ns

1-30 nC, 0.3 MeV, ~10 mm^2, ~20 ns

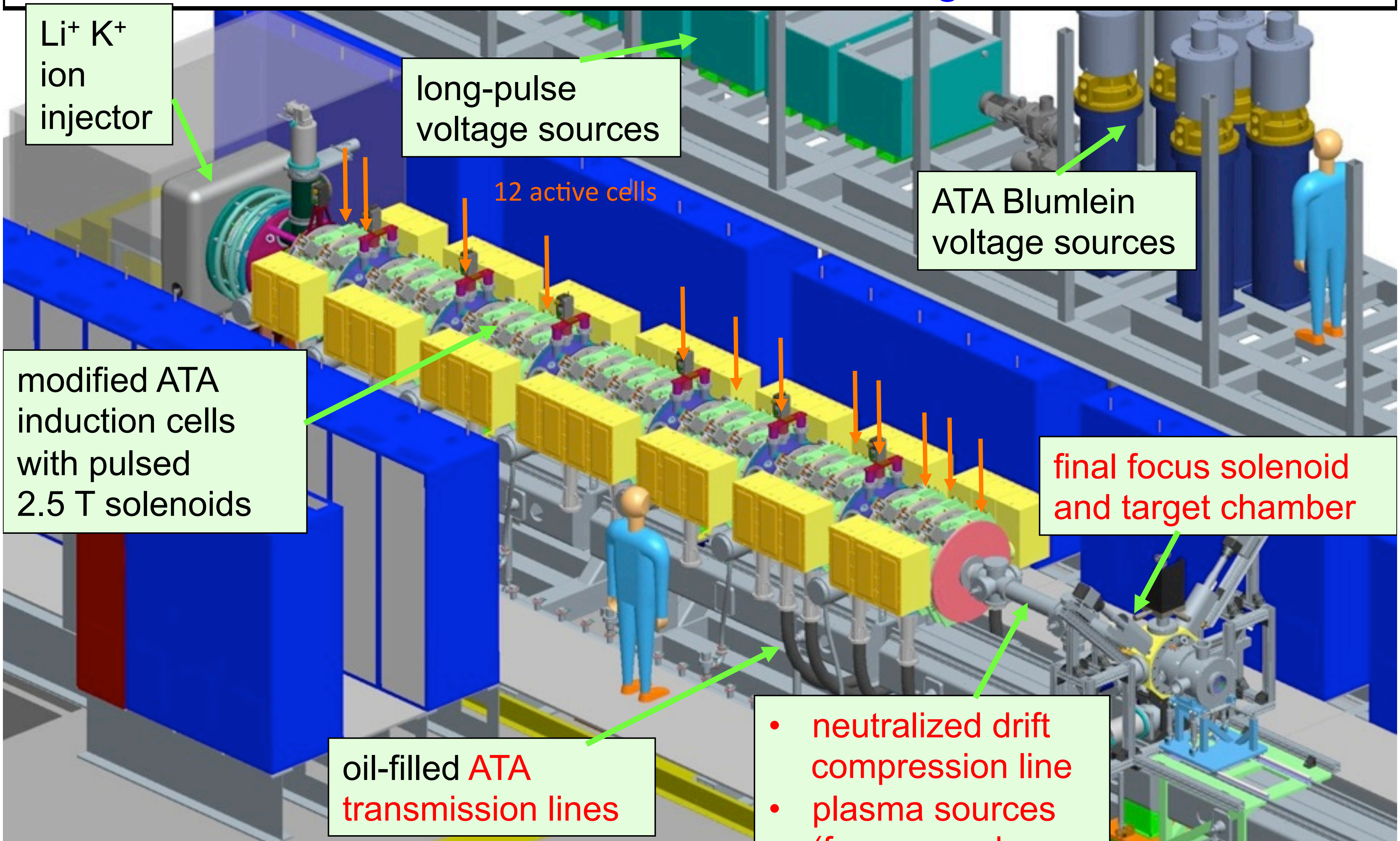
Ions deposit energy via elastic and inelastic collisions with target electrons and nuclei
Ions can couple to atoms directly via elastic collisions, complementary to laser heating

With ion pump-probe experiments we can access the dynamics of radiation induced damage in materials from ps to second time scales and nm to ~μm length scales



Understanding the multi-scale dynamics of radiation induced defects is of fundamental interest and it is important to benchmark simulations codes and to **engineer fusion materials for the burning plasma era**

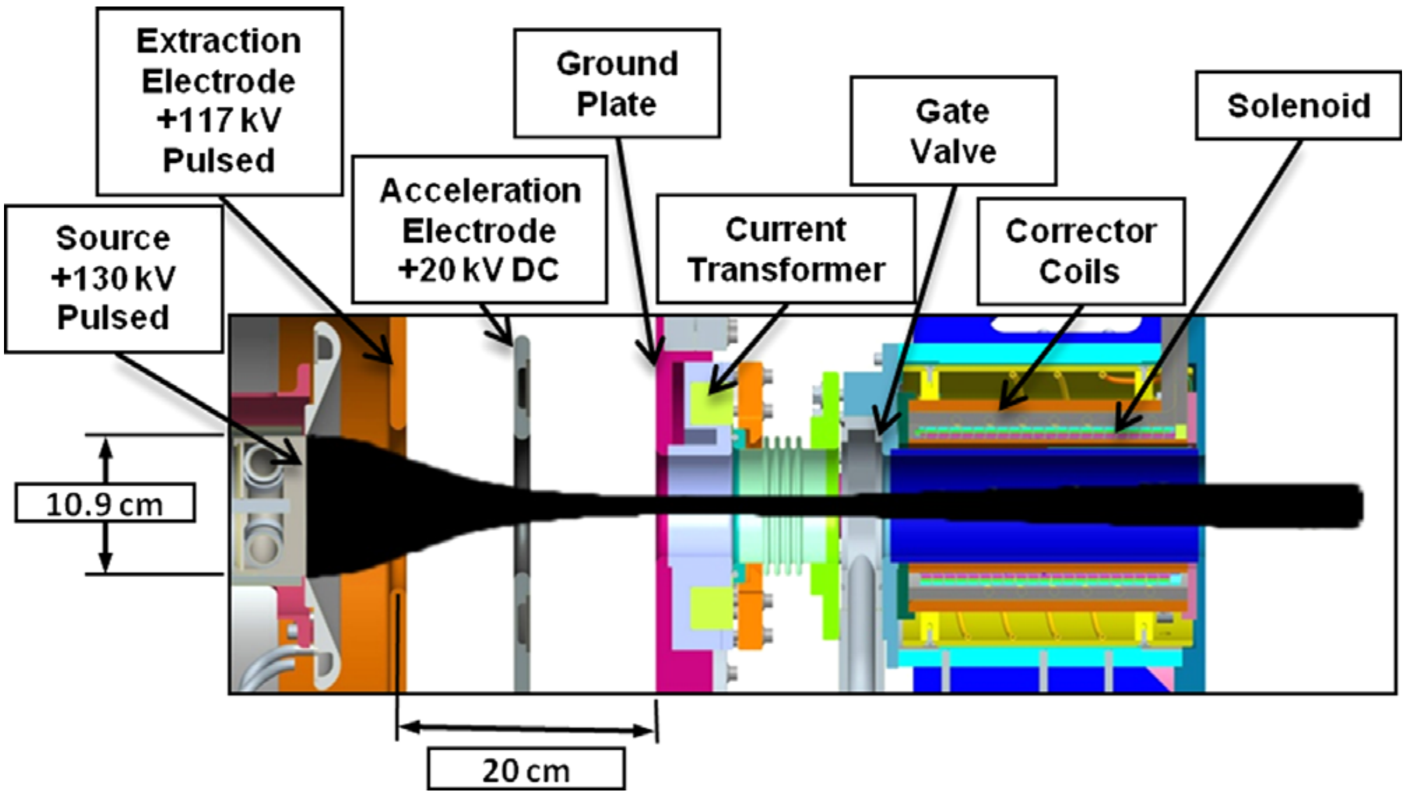
NDCX-II has 27 cells (7 powered now, 12 soon), a neutralized drift section, a final focus lens, and a target chamber



The ion source and injector supplies a ~ 1 μs beam to the front end of the accelerator

Extraction from a hot-plate (thermionic) 11-cm diameter emitter at 1000-1250C.

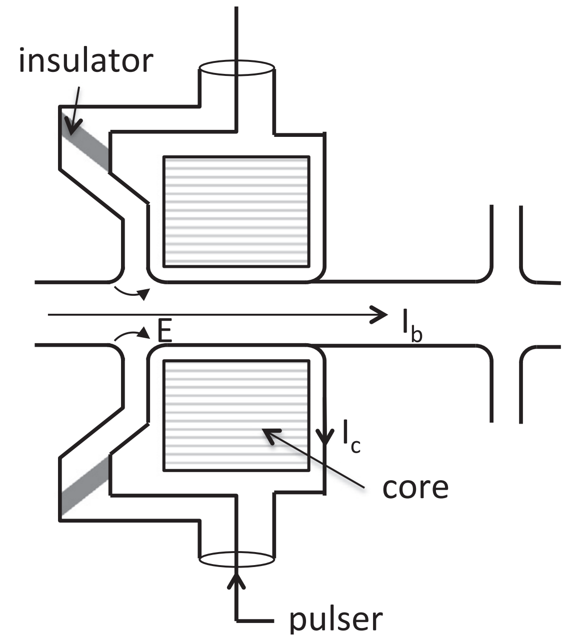
Eg: 50 mA Li^+, 40 mA K^+ at 135 kV.



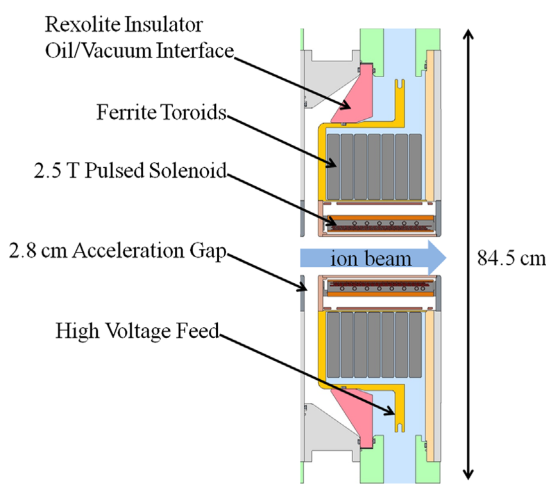
Seidl et al., Phys. Rev. ST Accel. Beams 15, 040101

<u>Induction accelerator:</u> A non-resonant (low-Q) structure in which the acceleration field is established by a high voltage pulse across the gap. The induction core presents a high impedance to prevent the pulser from seeing a short circuit. Have high (>20%) electrical efficiency at high I_{beam} (>100 A)

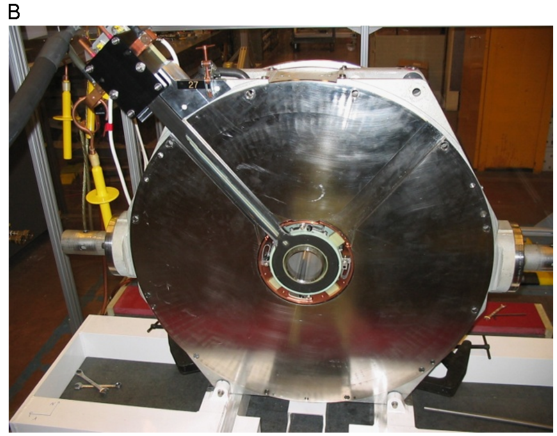
- Gap voltage and the pulse duration are related to the magnetic flux swing via Faraday's law: $\Delta B \bullet A = \Delta V \bullet \Delta t$.
- NDCX-II cells: "Compression cells" are shaped 30–90 kV and the ramp duration is 300–700 ns. Followed by 200 kV, 70 ns Blumlein driven cells.



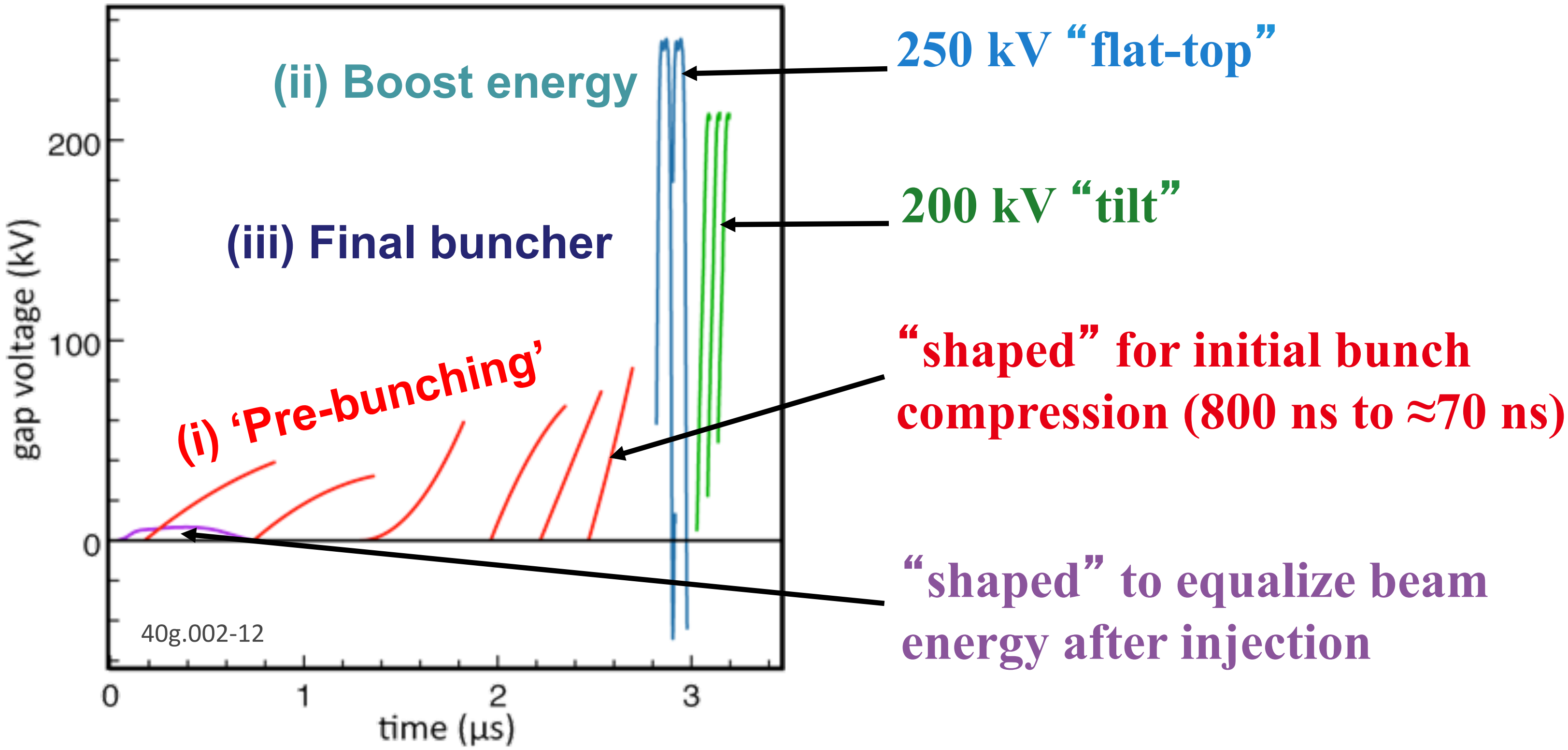
<u>Focusing:</u> $B_{solenoid}$ = 3T, L_{eff} = 19 cm, R_{ap} ≈ 4 cm, pulsed, 2/min,d I_c = 7.7 kA.



B

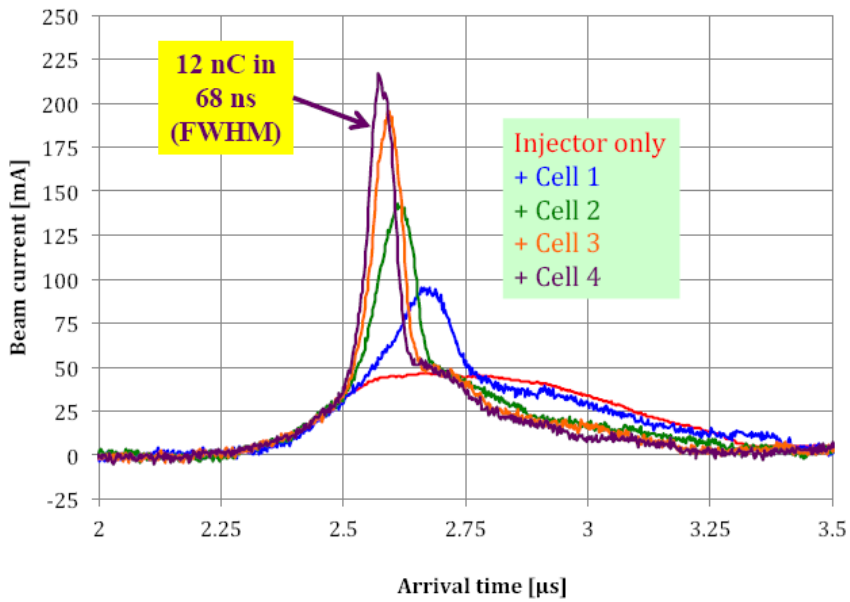


A variety of acceleration waveforms accelerate and bunch the beam



Tailored waveforms in our models use measured shapes for both long-pulse (moderate-voltage) or short-pulse (high-voltage Blumleins)

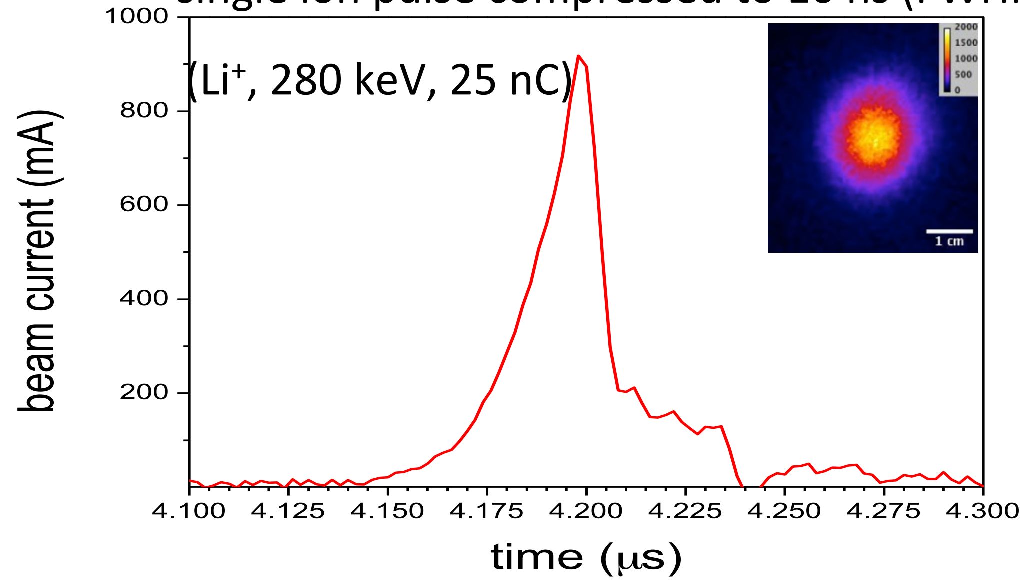
Beam compression from ~600 ns to 100, 50, and 16 ns



Beam diagnostics:

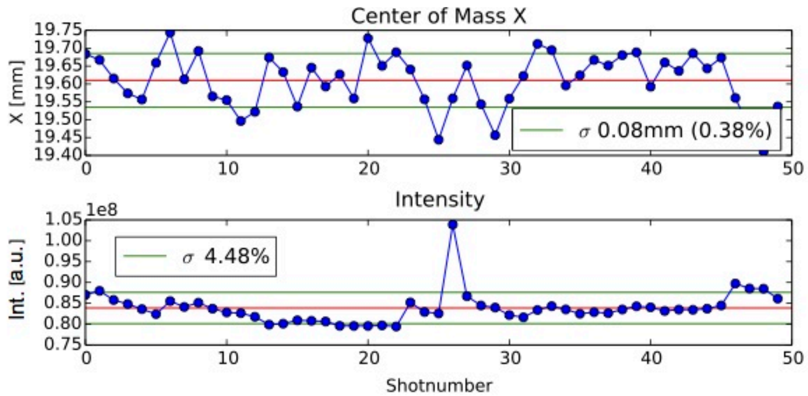
- Faraday cups
- Inductive current monitors (inactive acceleration cells)
- Capacitive beam position monitors
- Scintillator and II-CCD camera (~ns)

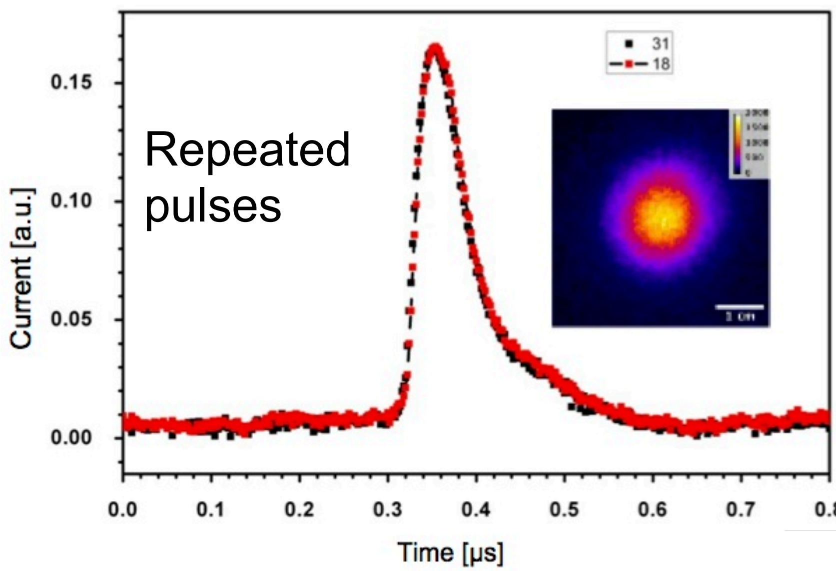
single ion pulse compressed to 16 ns (FWHM)

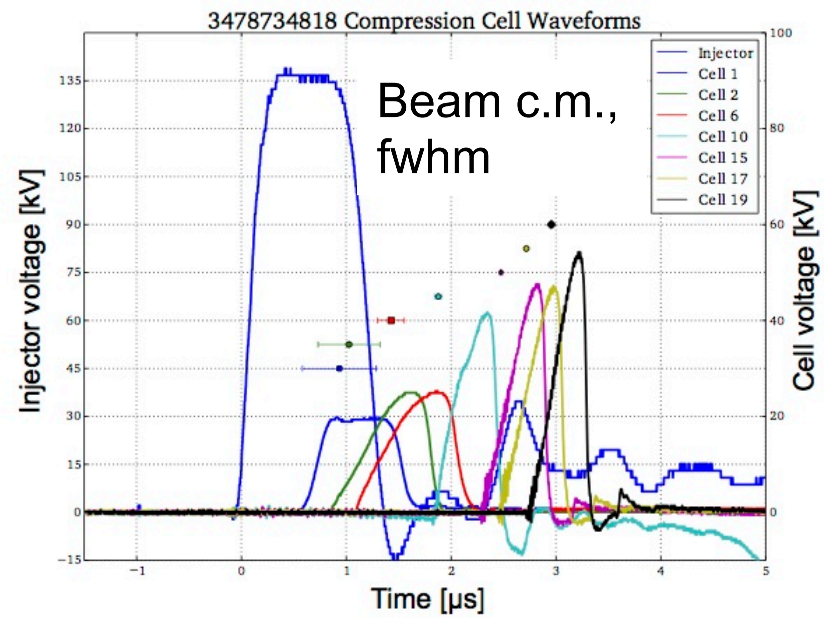


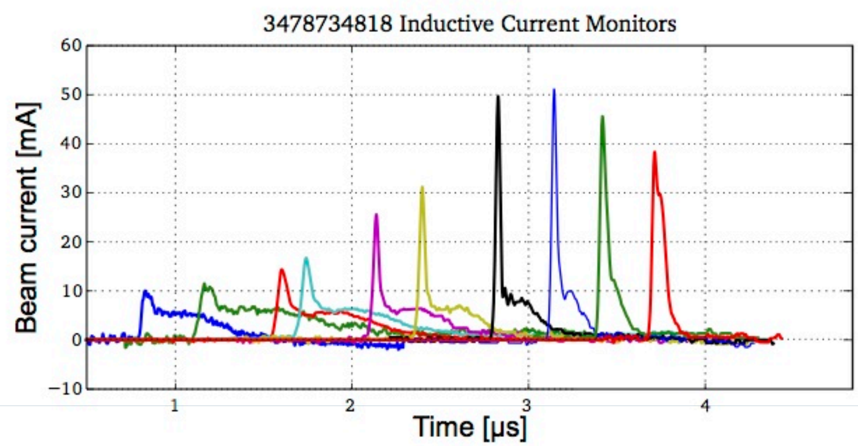
The ion beam is reproducible in time and space

Transverse jitter: σ_x < 0.1 mm
Intensity jitter < 5%









NDCX-II enables studying WDM, material defects and fundamental driver beam questions.

Control dose rate over six orders of magnitude through control of charge/pulse, pulse length and spot size.

New results: defect dynamics in materials, Schenkel et al., NIM B 2014.

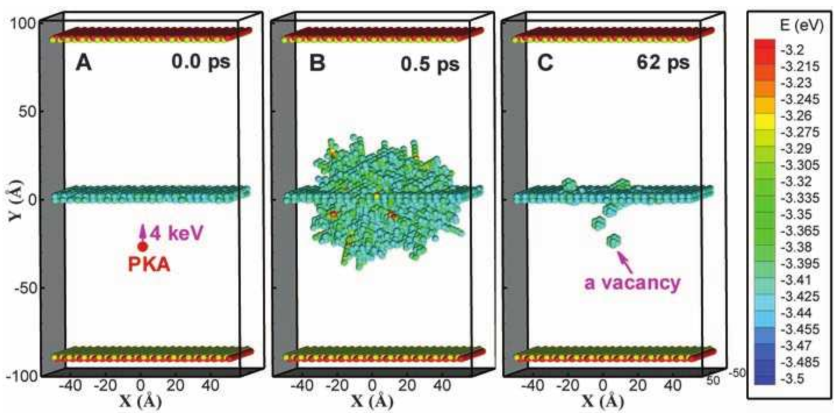
	Now	Goal (y1)	Goal (y2+)
Ion species	Li^+ (A=7) , new: K^+ (space charge limited) also exploring Na^+,...		
Total charge / pulse (nC) **# ions / pulse**	25 2×10^{11}	30 2×10^{11}	50
Ion kinetic energy (MeV)	0.3	1.2	1.2
Focal radius (50% of beam) (mm)	~10	~2	<1
Pulse duration (FWHM, ns)	20 - ~600	2 - ~600	<1
Peak current (A)	0.8	15	45
Peak fluence (time integrated) (J/cm^2)	~0.01	0.5 - 1	5-10

In 2014: increasing the operating energy and focal spot intensity.

7 papers on design and science with NDCX-II, Proc. 19th Int'l. Symp. on Heavy Ion Inertial Fusion, NIM A V733 (2014).

Motivation: Gain in-situ access to the relaxation dynamics of radiation induced defects

Multi-scale problem -- picoseconds to years
Most defects are created and self anneal within tens of picoseconds
Important for better understanding of materials, e.g. verification of theoretical models and simulations



Xian-Ming Bai *et al.* Science **327**, 1631 (2010)

A pump-probe experiment can be sensitive to these time constants.

Science AAAS

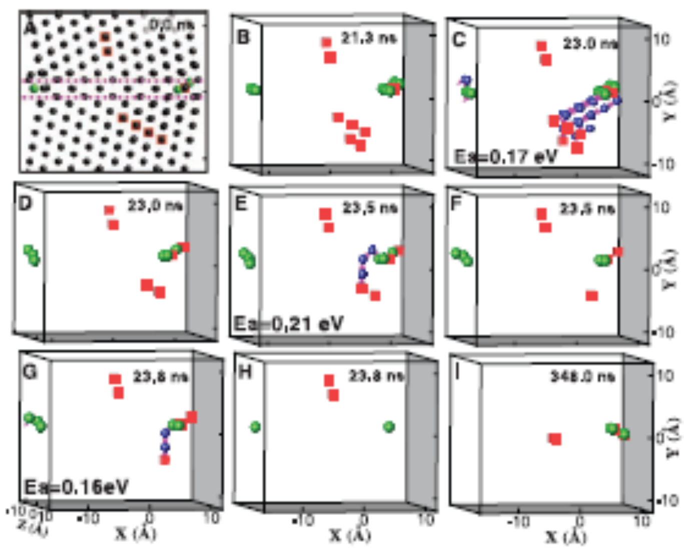
Efficient Annealing of Radiation Damage Near Grain Boundaries via Interstitial Emission
Xian-Ming Bai *et al.*
Science 327, 1631 (2010);
DOI: 10.1126/science.1183723

(Los Alamos group)

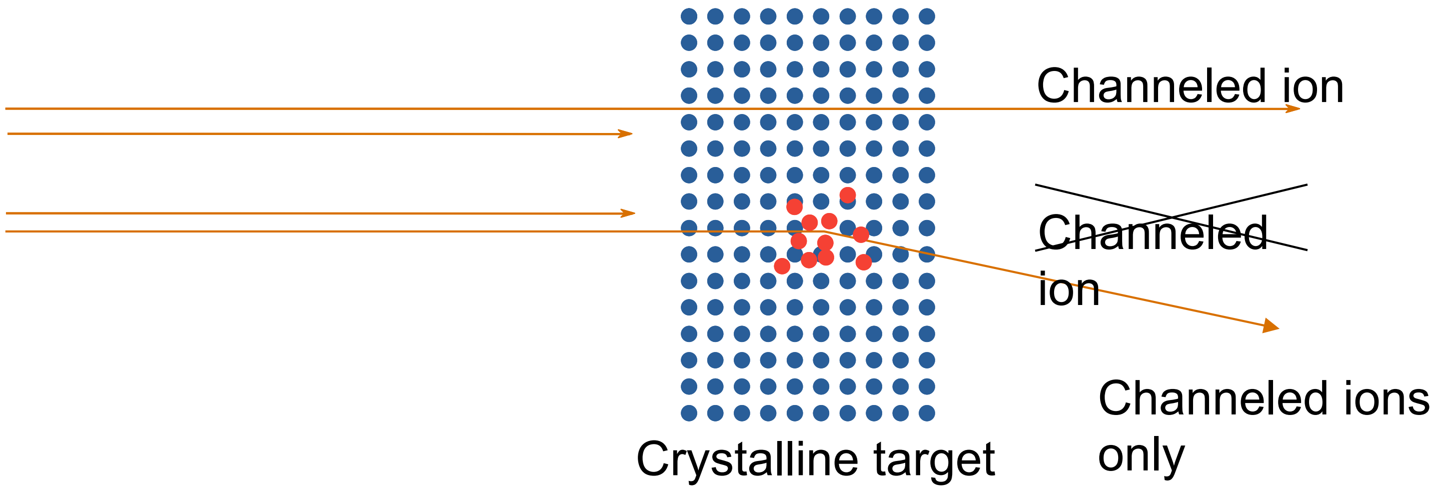
"Radiation damage spans from the atomic (nanometer, picosecond) to the macroscopic (meter, year) length and time scales.

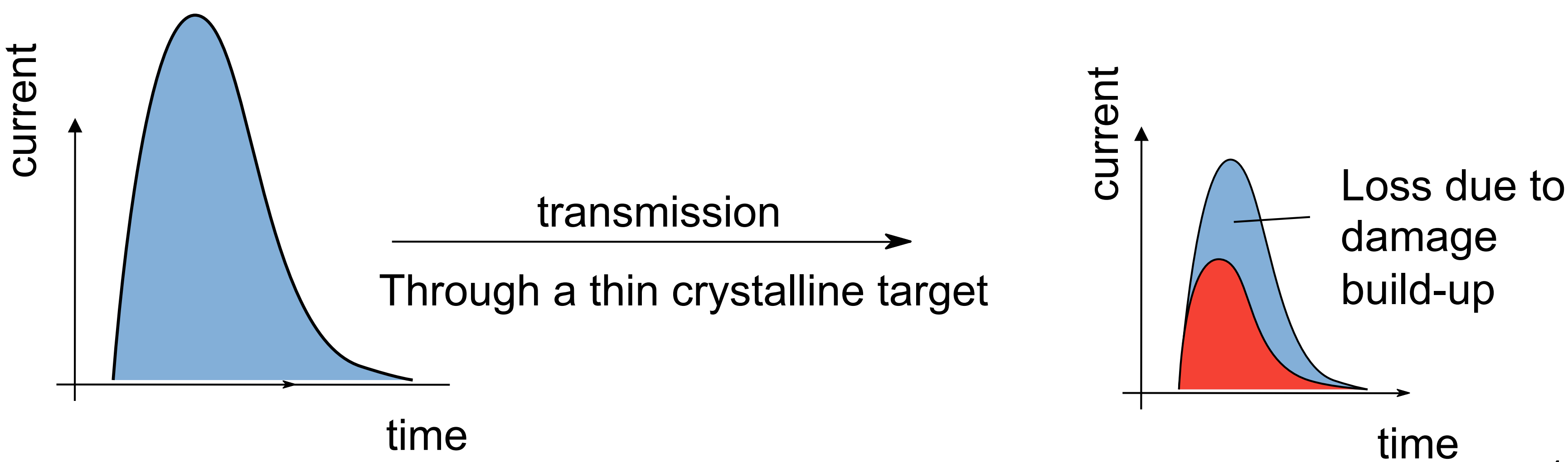
Critical processes involving individual point-defect migration are difficult to observe experimentally.

Molecular dynamics (MD) simulations are widely used for simulating defect production."

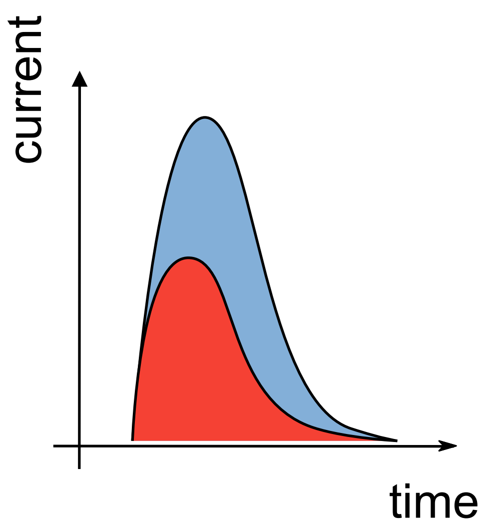


Measurement of channeled ions allows using the ion beam pump as its own probe for in-situ, single shot experiments





Considerations for using channeling as a sensitive probe for overlapping damage cascades



Intensity of the beam needs to be high enough for overlapping damage cascades

Good time resolution

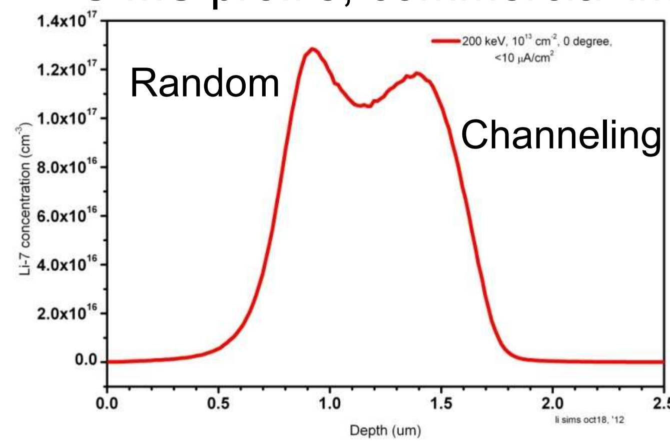
Beam properties need to be well understood (angular distribution, energy spread, ...)

Only measure channeled ions

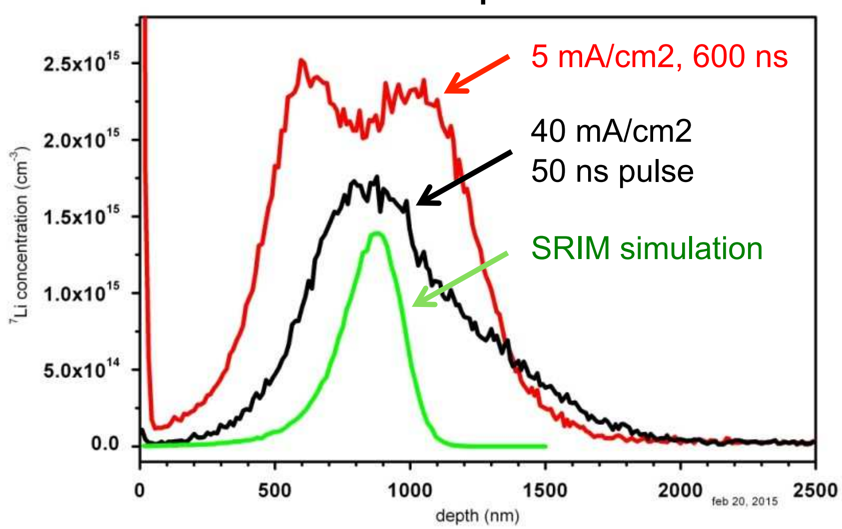
After bombarding with a few shots, ex-situ SIMS profiles show a dependence of the Li deposition range with the fluence

"Coasting beam" – 135 keV, ~600 ns.
"Bunched beam" – 250-300 keV, 16-50 ns.

SIMS profile, commercial implant

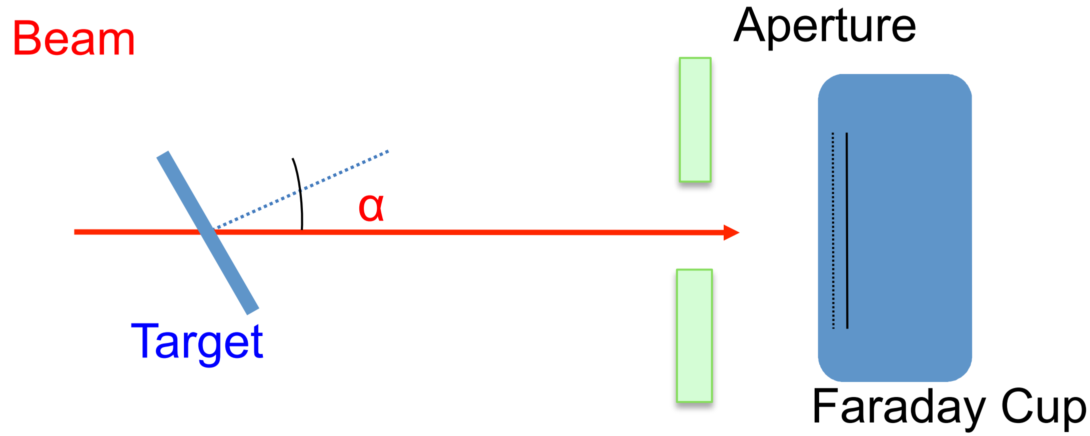


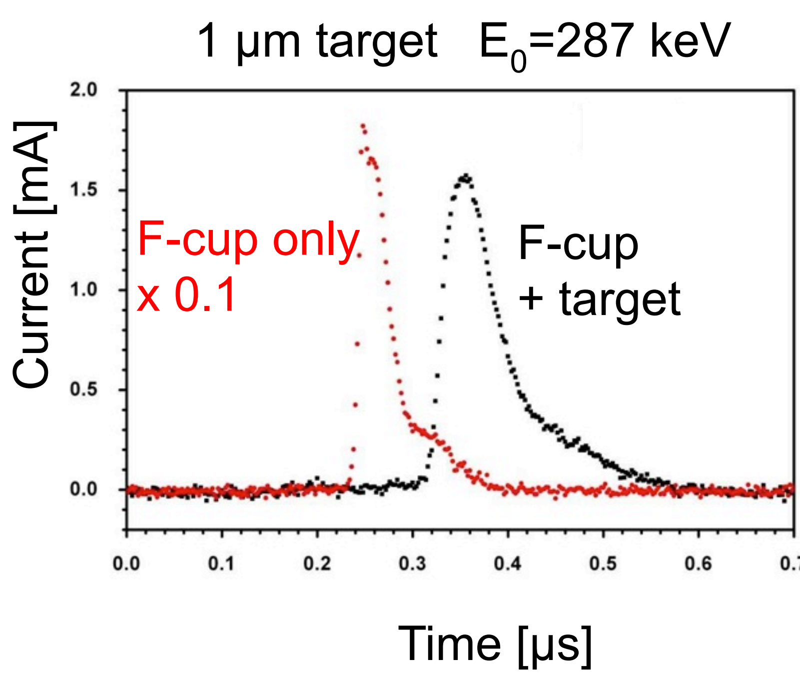
SIMS profile

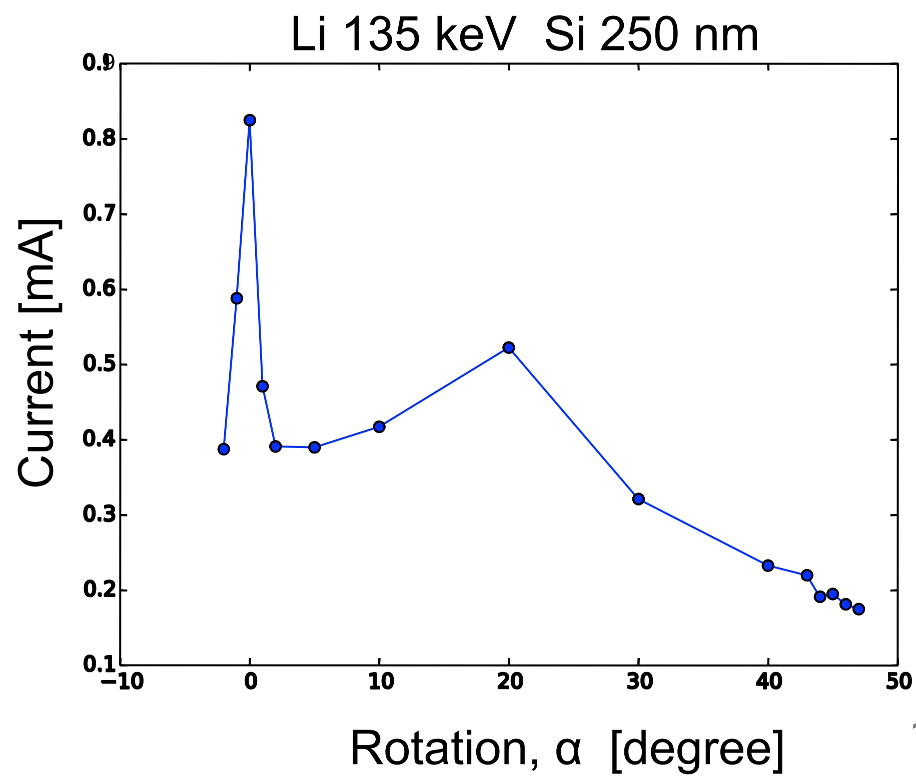


Convoluted with beam properties, such as angular dependence over time of the beam pulse, n(θ, t)

In-situ, channeling was apparent with the Li beam, but a change in the waveform shape was not detected

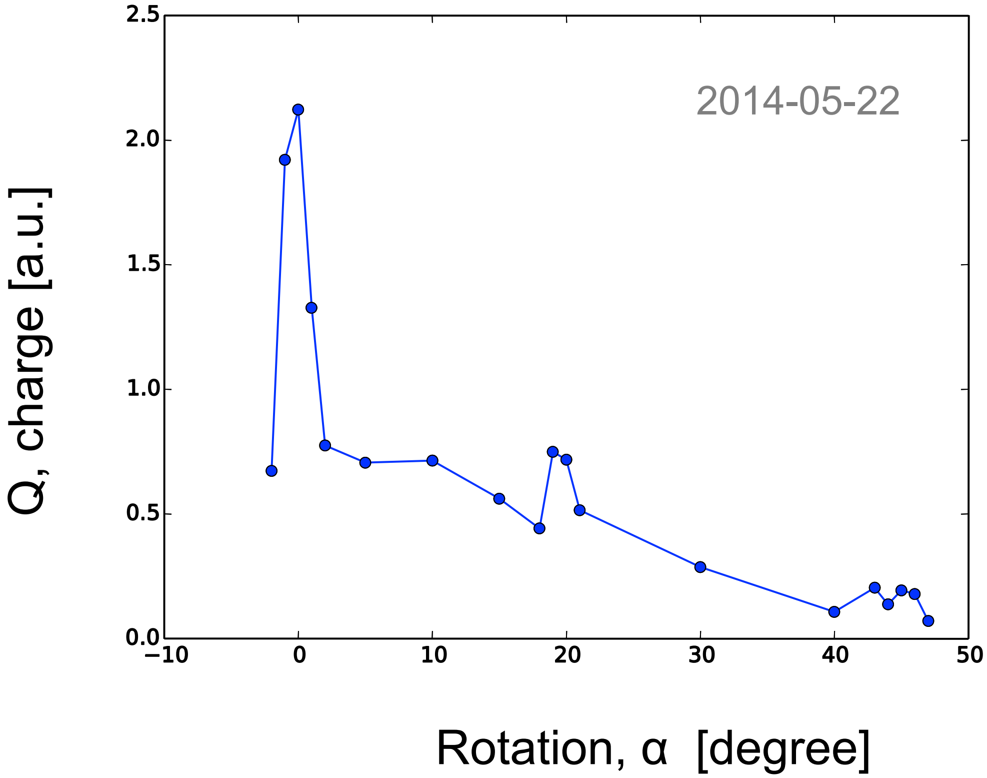






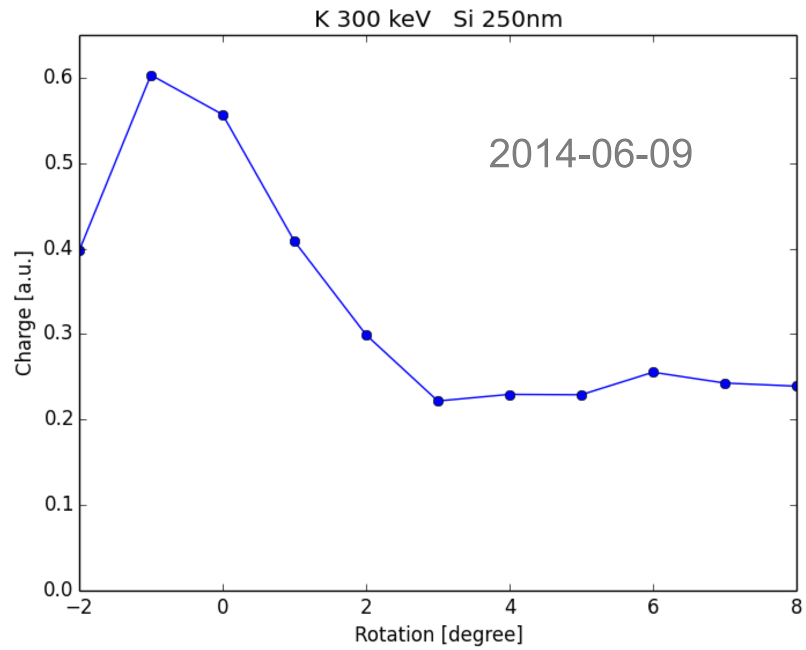
A potassium (K+) beam is expected to create more damage due to higher nuclear stopping

K+, 135 keV, Si 250 nm



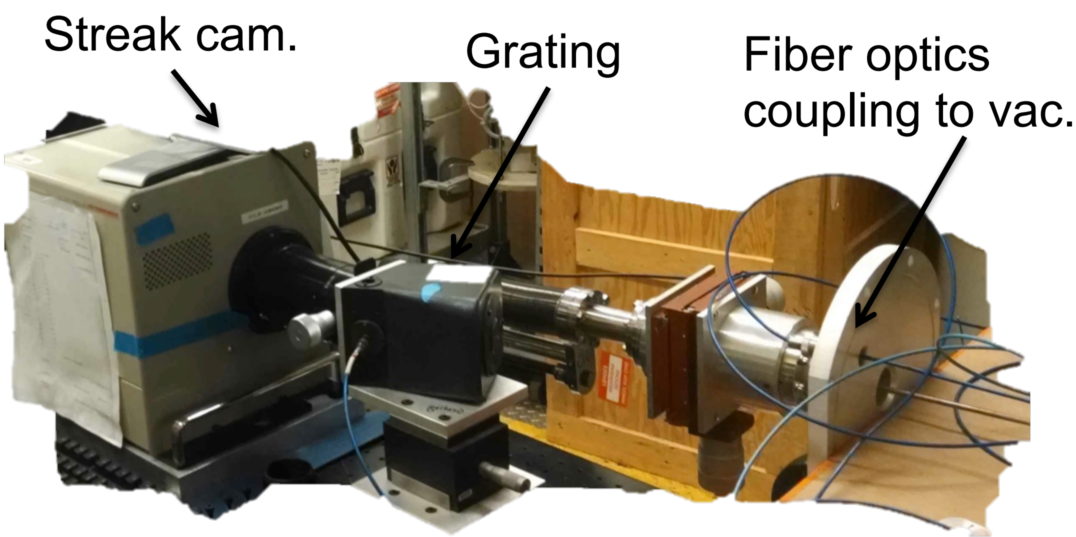
Observed channeling

For the bunched beam
we Q(0°)/Q(8°) ≈ 3



Data analysis ongoing

Experiments recording luminescence using a fast camera and a streak camera are being prepared



Streak camera coupled to a spectrometer grating

→ ps resolution

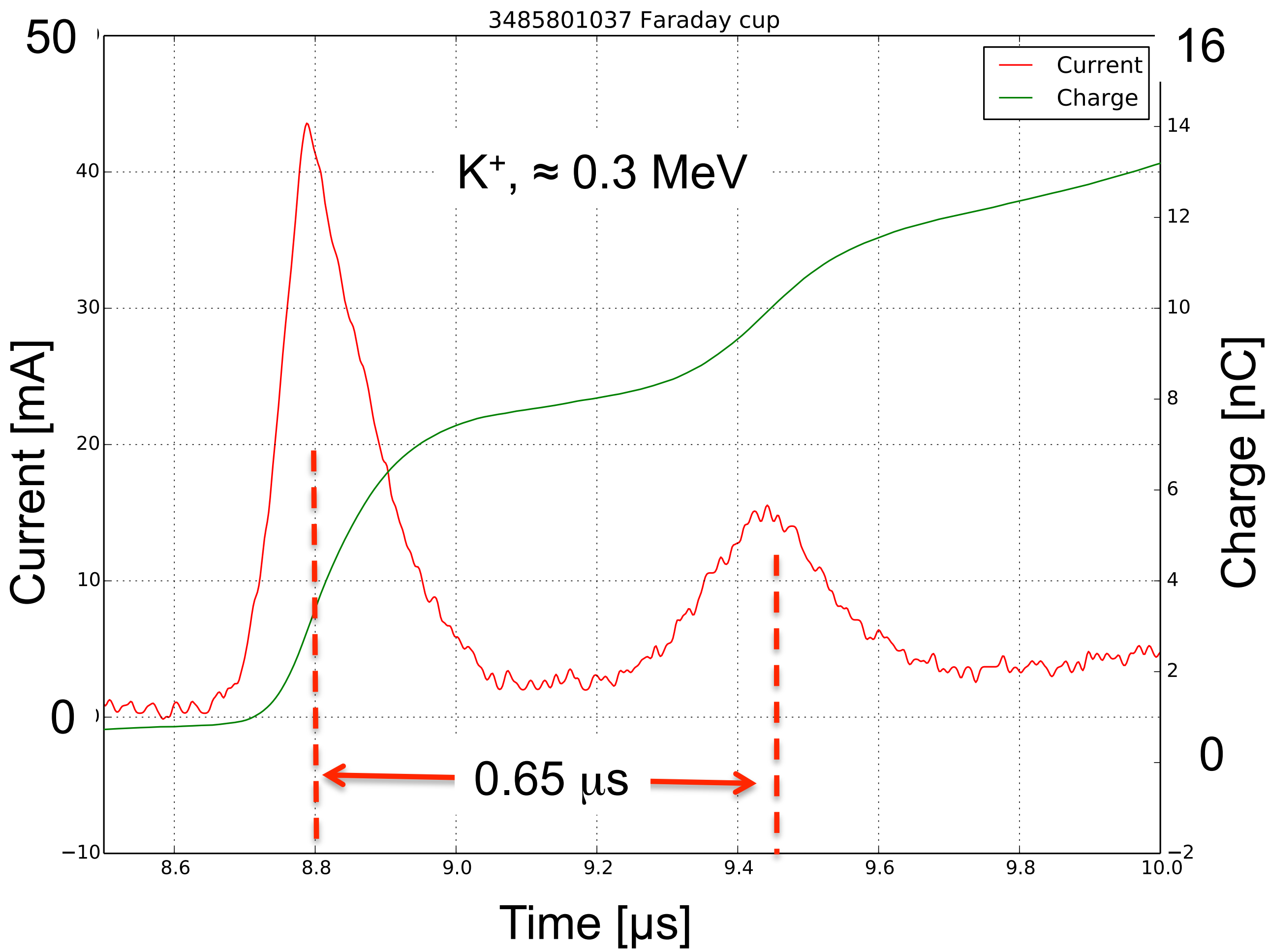
II-CCD camera with 2 ns exposure time directly images beam distribution

Enables study of target materials with fast optical centers.

We are considering:

- Ionoluminescence
- X-ray probes
- electrons

Double pulses with adjustable delay can be tailored for separating the pump and the probe.



We are beginning to explore this capability.

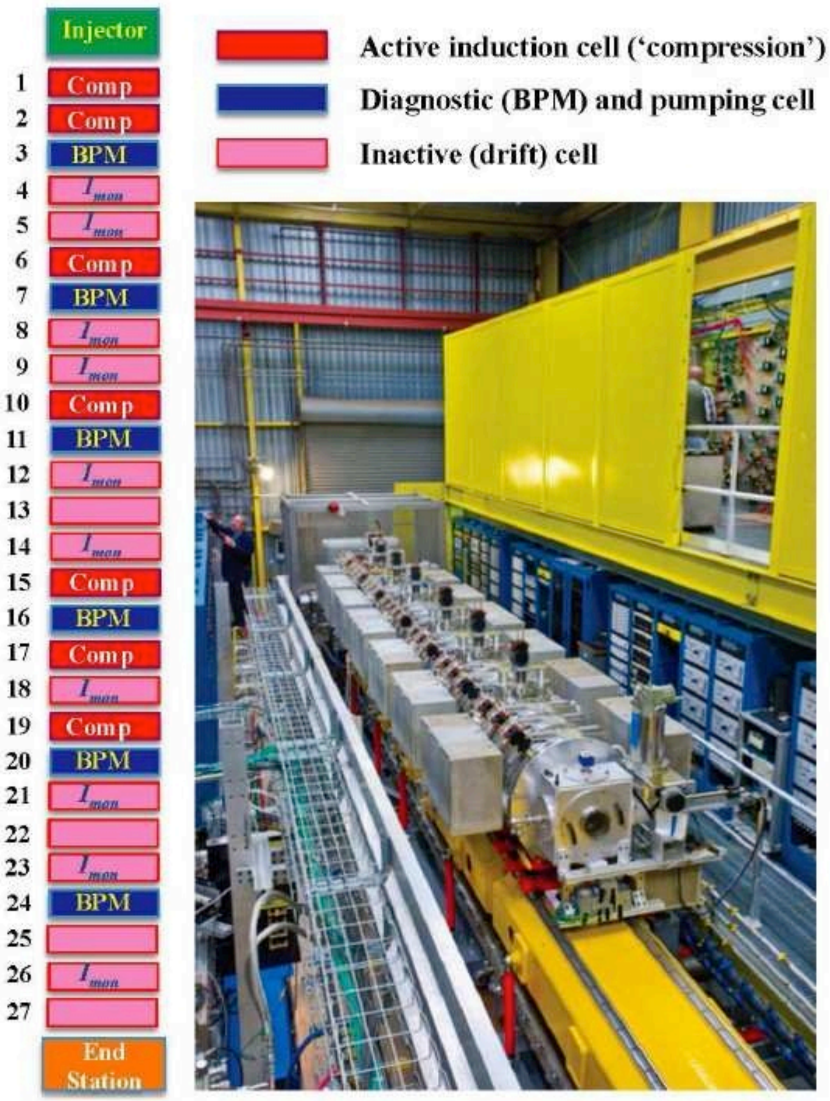
We are adding components to extend to higher energy, smaller focal spots, shorter pulse duration

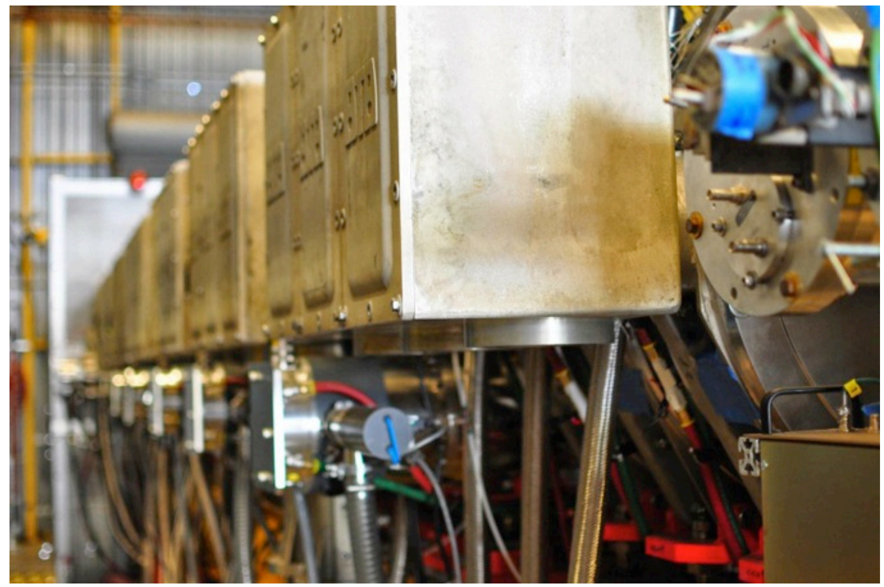
Total charge/pulse: 30-50 nC

Beam energy: 1.2 MeV

Pulse width: 1 ns

Spot size: 1-2 mm





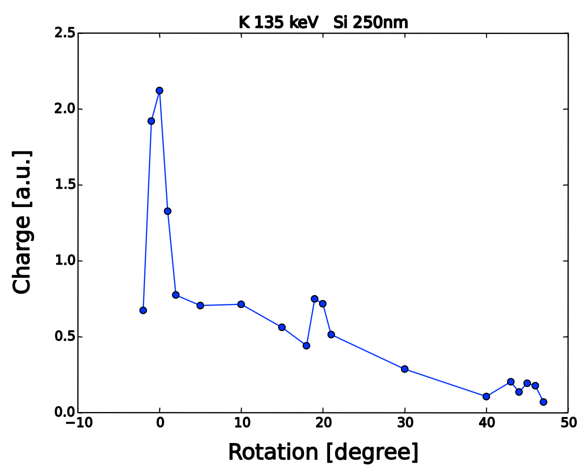
Neutralized drift compression will give access to beam-plasma experiments. Higher intensity and energy will allow a wider range of defect dynamics studies and then to warm dense matter (1 eV) experiments.

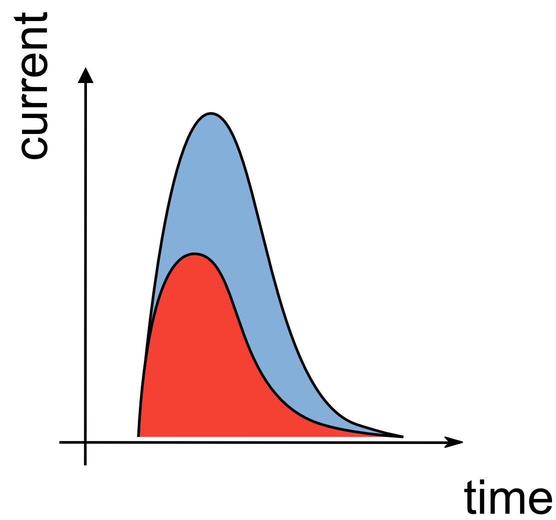
Summary:

Unique high-intensity beam facility
Allows access to defect dynamics using pump-probe type experiments

Outlook:

Higher energy, shorter pulses, and smaller beam spots
Wider range of target materials with new diagnostics





We welcome collaborations. Come visit us!