Fusion Research at Berkeley Lab

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Fusion Science & Ion Beam Technology

Accelerator Technology & Applied Physics Division

December 17, 2014

http://atap.lbl.gov/

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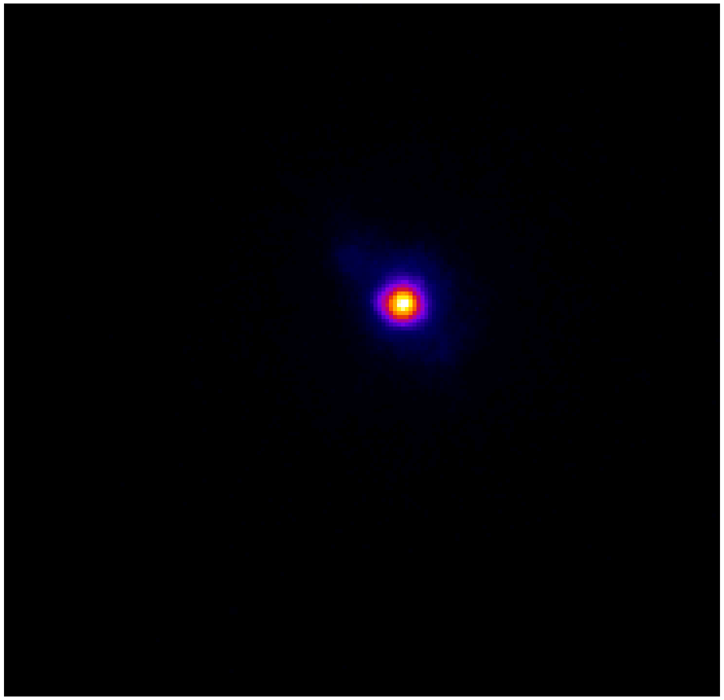
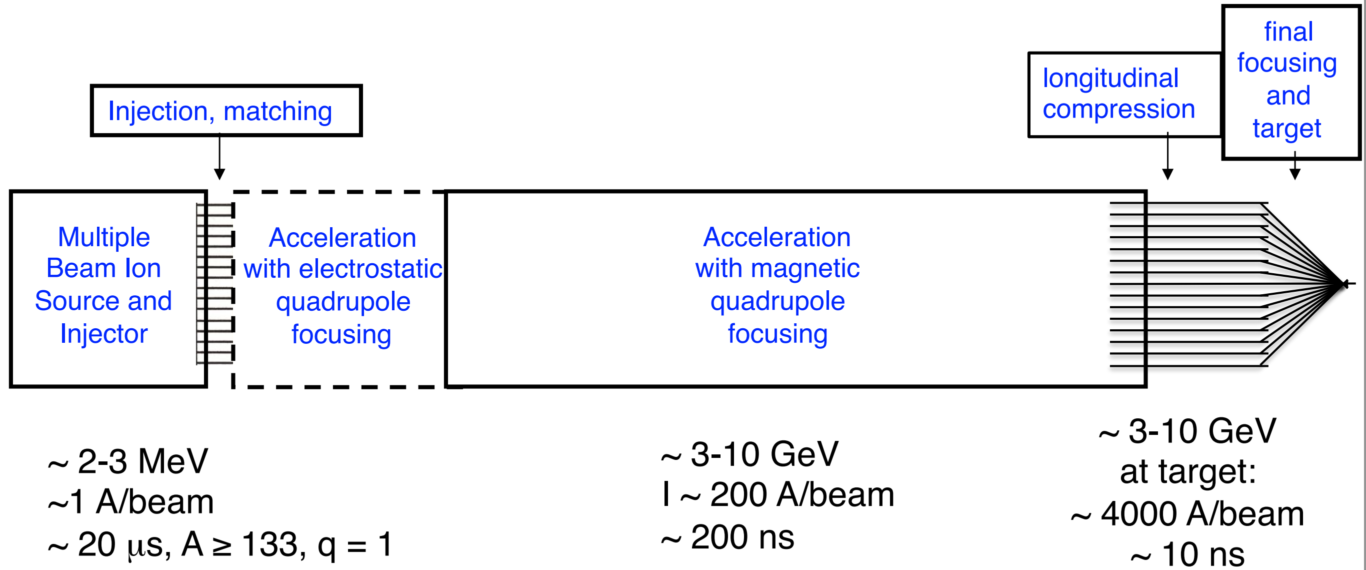
Outline

- Status of the Neutralized Drift Compression Experiment (NDCX-II)
- Discovery Plasma Science
- Fusion energy research

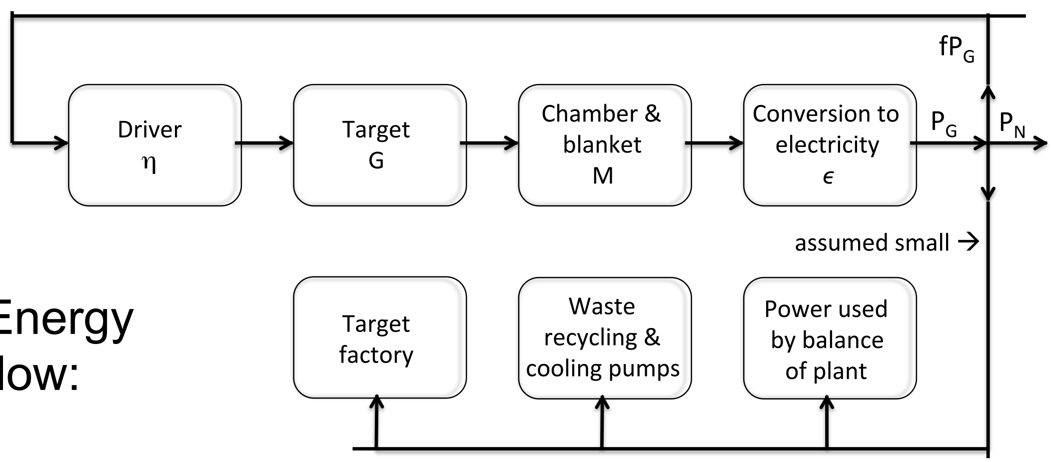


Heavy ion driven fusion remains an attractive approach.

Induction linear accelerator driver for HIF:



Energy flow:



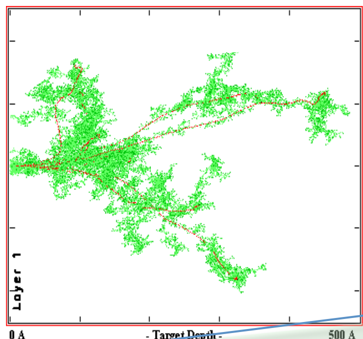
P_G = gross electrical power
P_N = net electrical power
Assume $f < 0.2$, $P_N \approx P_G(1-f)$

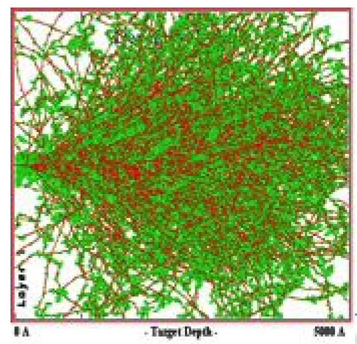
$\eta G > 10$, $G = 50 - 150$
$\eta = 0.2 – 0.4$
$M = 1.1 - 1.3$
$\varepsilon\ = 0.3 - 0.5$

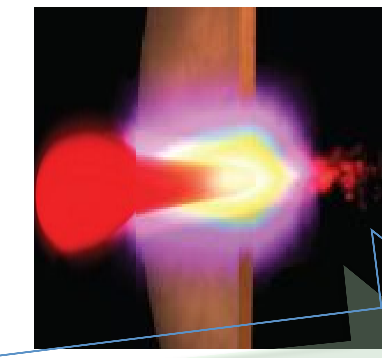
NDCX-II provides uniquely intense, short ion pulses with high degree of flexibility and tunability

Lower intensities:
defect dynamics in materials
→ fusion materials

Higher intensities:
isochoric heating, warm dense matter, extreme chemistry







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

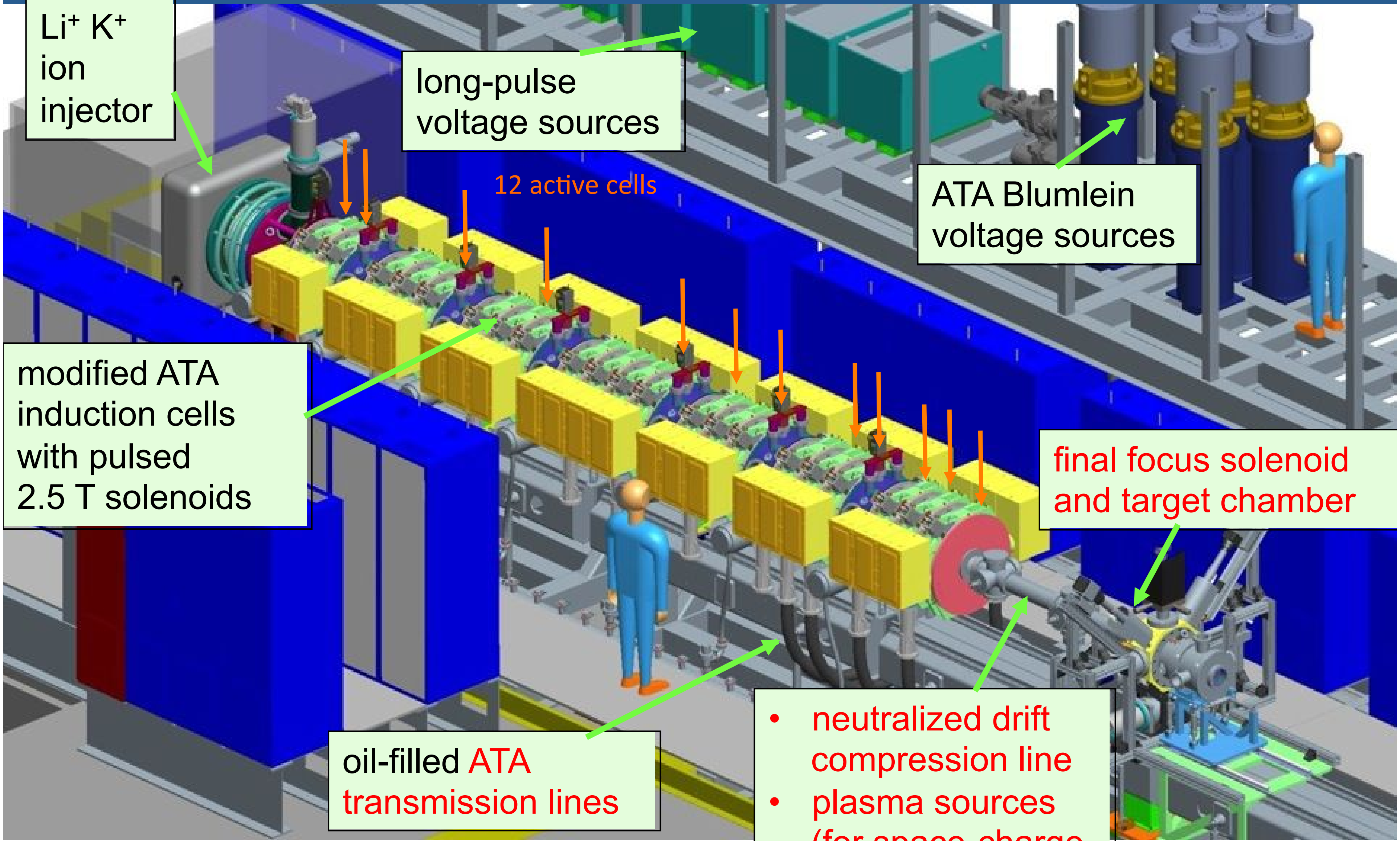
1-30 nC, 0.3 -1.2 MeV, few mm^2, ~1-20 ns

~50 nC, 1.2 MeV, ~1 mm^2, ~1 ns

- Ions deposit energy via collisions with target electrons and nuclei
- Ion driven heating is uniform for ion energies near the Bragg peak in stopping power

Fusion relevance
- Ion heating of matter in the WDM range
- Materials studies for fusion reactors
- Driver beam physics

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



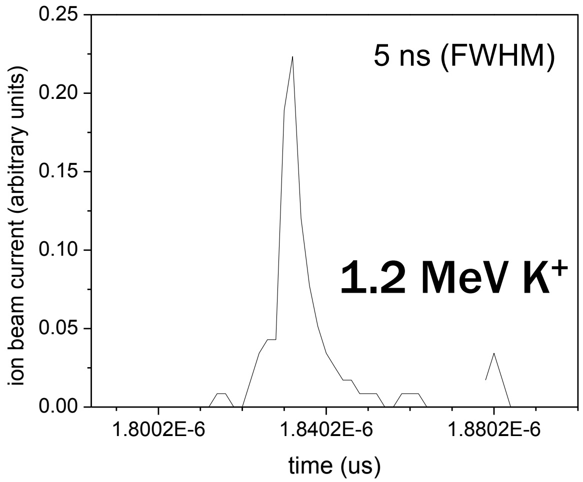
NDCX-II time line in 2014

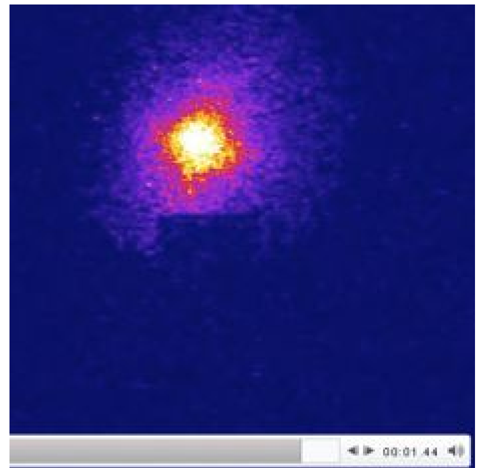
- March 6, review of science with NDCX-II
  - physics of warm dense matter
  - dynamics of radiation effects in materials
  - physics of intense beams
  - Reviewers: Farhat Beg (UCSD), Mike Campbell (SNL), Ron Davidson (PPPL), Roger Falcone (UCB, LBNL), Peter Hosemann (UCB)

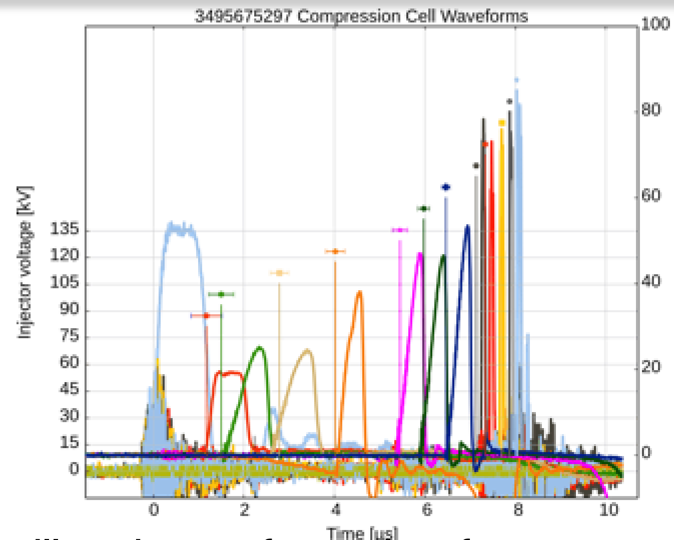
- March 17, engineering review of effort to reach 1.2 MeV and to commence neutralized drift compression experiments

- May: Build-out commences
- Oct. 9: reached the energy goal of 1.2 MeV
- Dec. 3: commenced neutralized drift compression experiments.

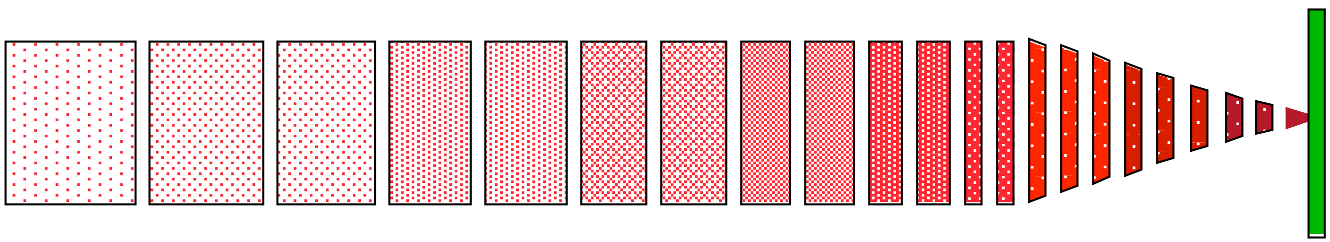
We are running neutralized drift compression experiments.







- Time trace of a shot with neutralized drift compression (right) and scintillator images for a pulse after neutralized drift compression and focusing (left).
- First runs were with K^+; we are now running with Li^+ (Dec. 6) and have achieved drift compression to ~2.5 ns (Dec. 8).
- All modules are working and we have not run into any show stoppers.



Ion source and injector, 500ns

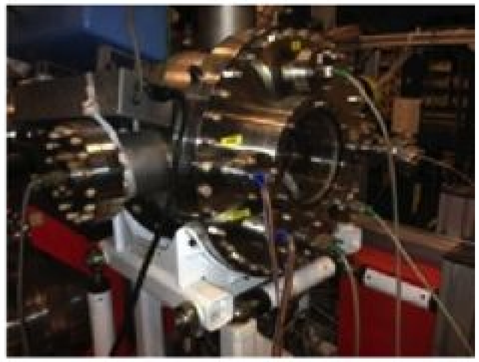
Induction linac provides custom waveforms for rapid beam compression

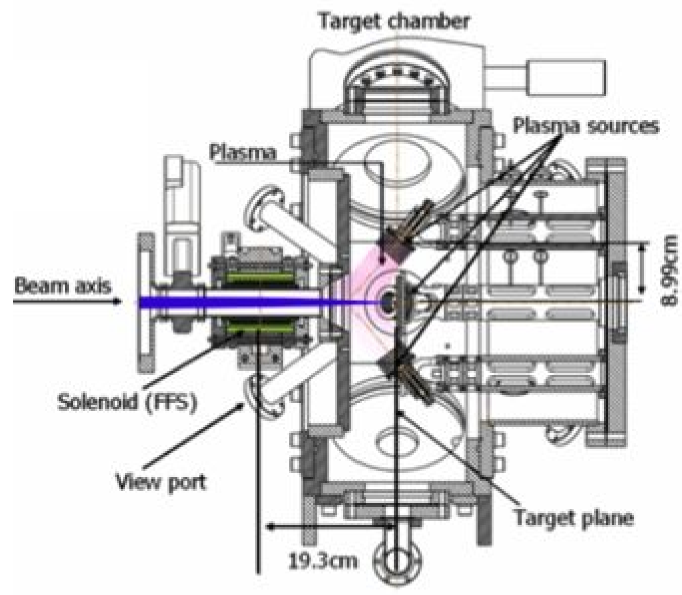
Neutralized drift compression and final focus

Target

Ions enter a neutralizing plasma where transverse and longitudinal defocusing due to space charge are cancelled

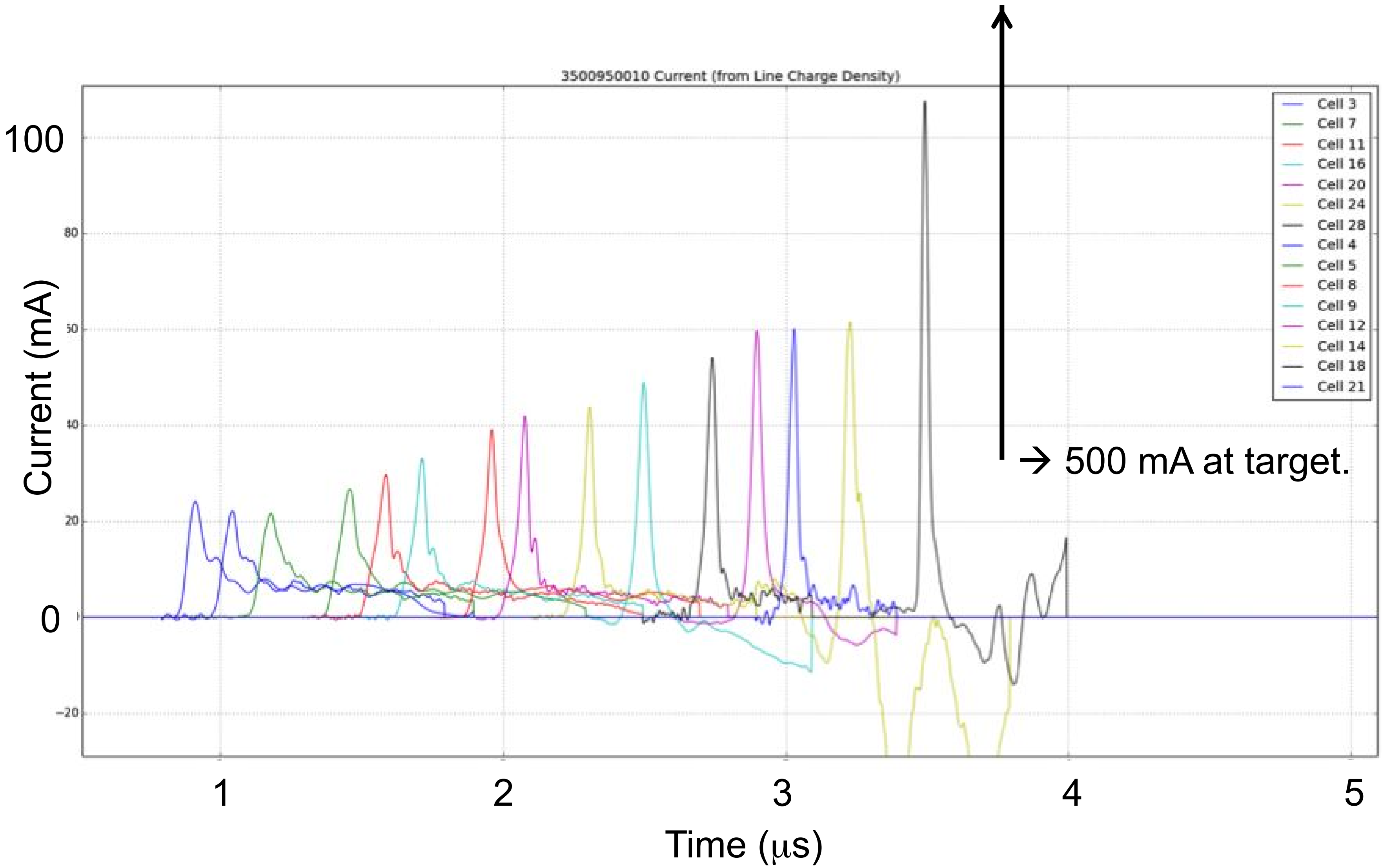
Using Ferro-electric volumetric plasma sources and an 8 T focusing solenoid, plus cathodic arc plasma sources in the target chamber



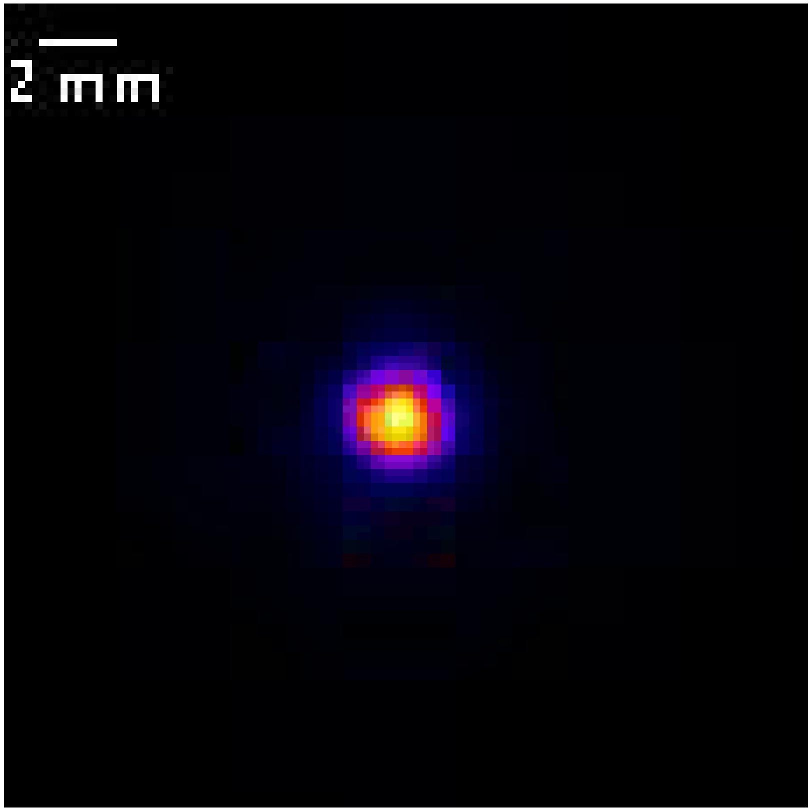


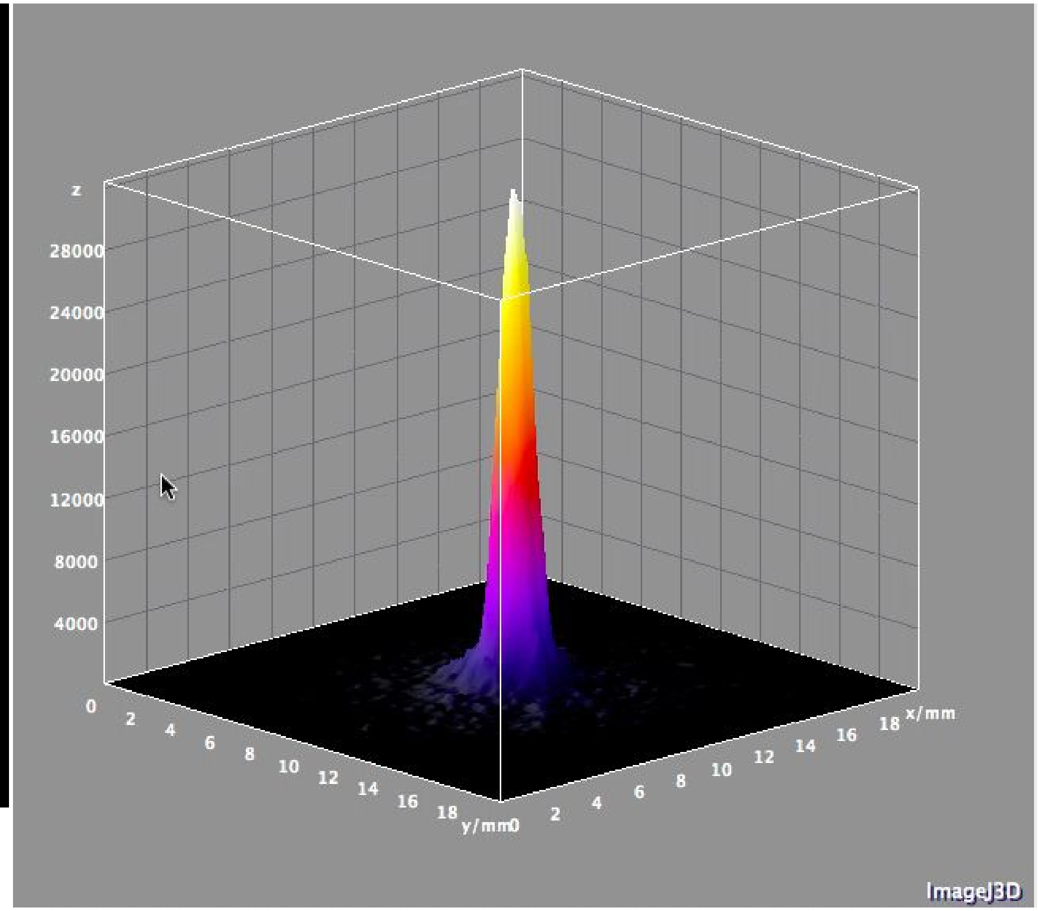
8 T solenoid, plasma sources, Target chamber

Acceleration and compression



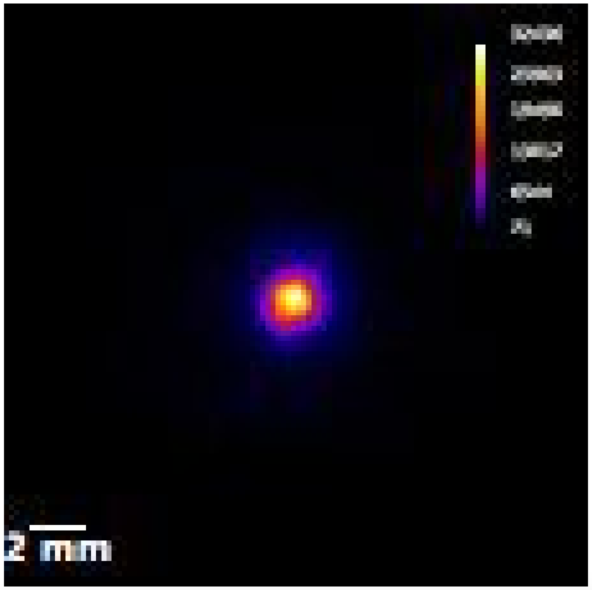
Li$^+$ beam parameters are stable

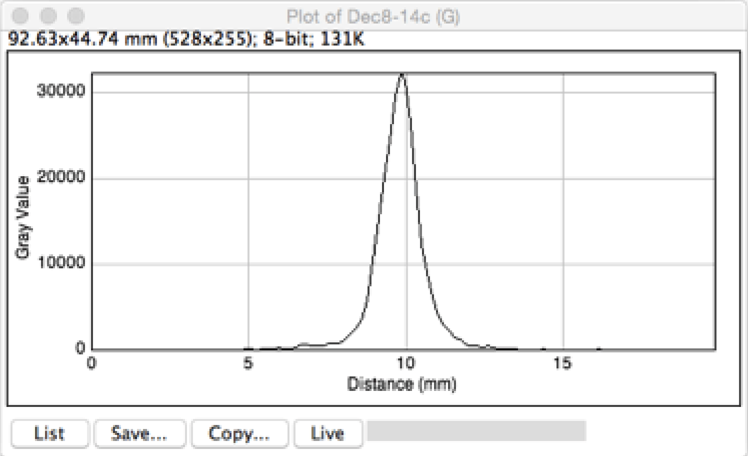




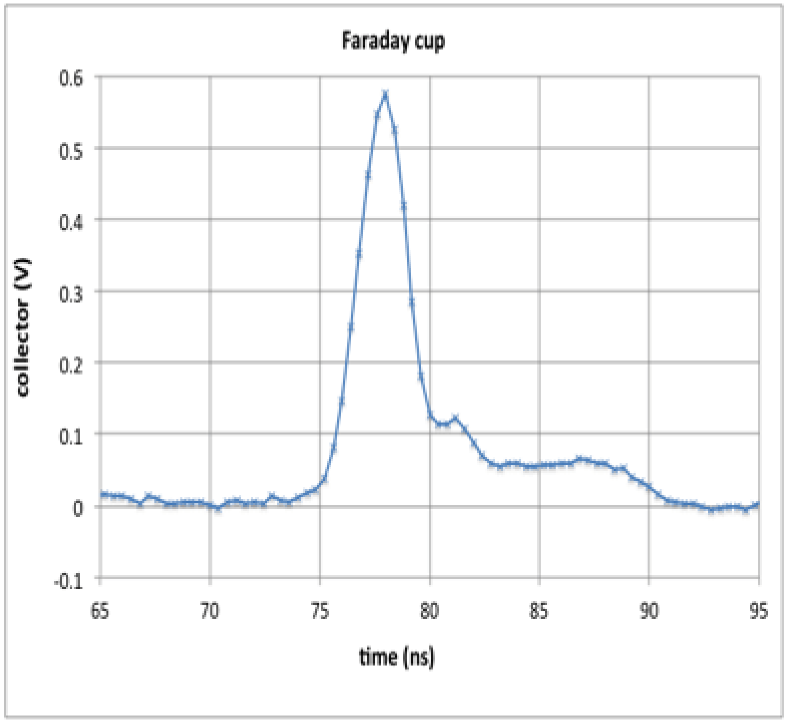
Centroid jitter: <200 microns.

NDCX-II run, 2nd day with Li^+ source, Dec 08, 2014





Scintillator image, lineout FWHM ≈ 1.4 mm



Fast Faraday cup, FWHM ≈ 2.5 ns

- So far only 0.5 A at the peak as the Li source was still conditioning
- shots centroids are stable to <0.2 mm
- 80% of charge is within 0.8 mm

→ Drift compression is working
→ Lateral focusing is working

NDCX-II produces intense, pulsed ion beams for Discovery Plasma Science

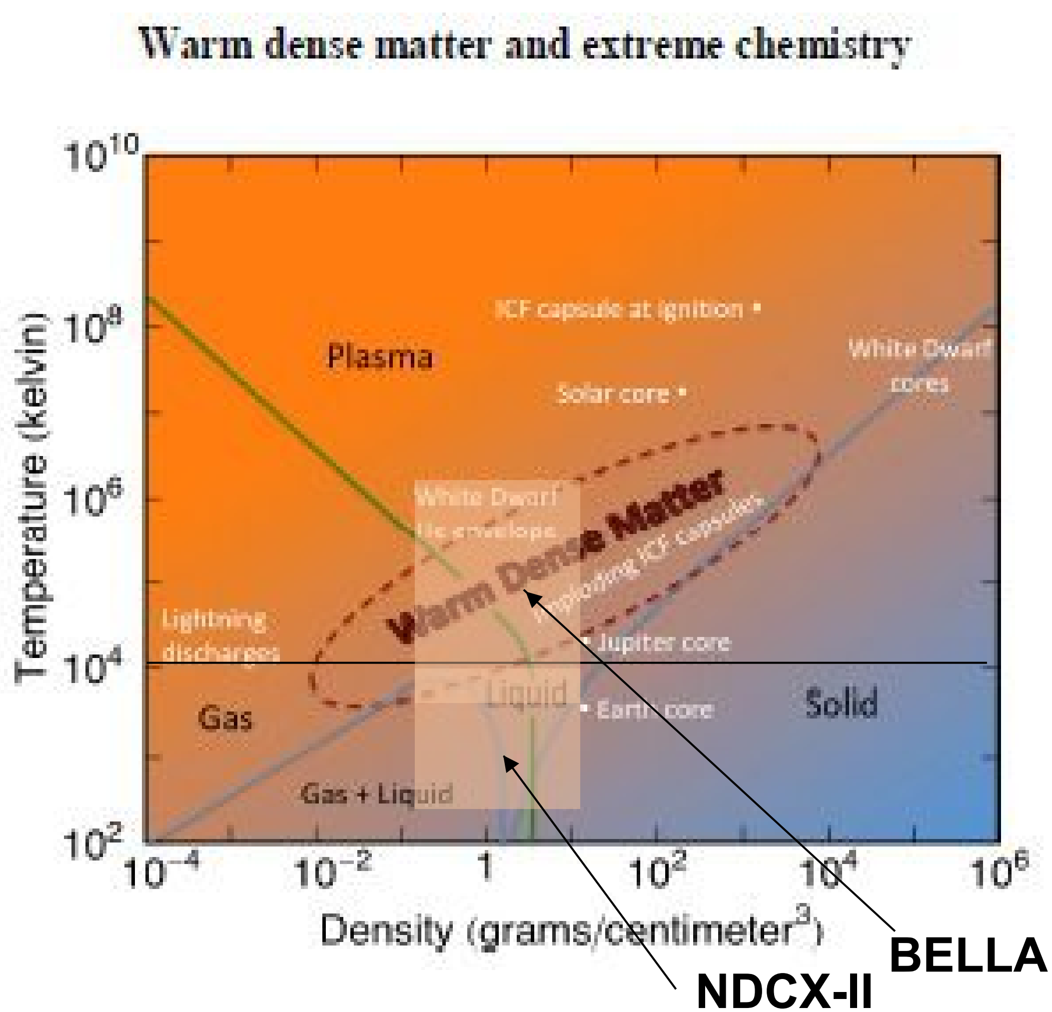
- Access to warm-dense-matter, isochoric heating of large volumes (~10^5 μm^3) to 0.5 - 1 eV
- Access to novel materials physics, defect dynamics, materials synthesis, extreme chemistry
- Access to the physics of intense, space charge dominated ion beams

Ion beam parameter	NDCX-II, 1st beam, Fall 2014*	NDCX-II goals	Path to reaching design goals
Pulse length	2.5 ns	0.6 to 1 ns	Neutralized drift compression
Kinetic energy	1.2 MeV	1.2 MeV	Well timed induction cells
Ions per pulse	10^{11}	5×10^{11} , I_{peak}~60 A	He^+ plasma source being tested
Spot size (FWHM)	7 mm	0.6 to 1 mm	Focusing solenoid, plasma sources (PPPL)
Energy fluence	~60 mJ/cm^2	5 to 10 J/cm^2	**80 nC * 1.2 MeV in a 1 mm spot**
Repetition rate	~2 shots/min	~2 shots/min	Solenoid cooling
Ion species	Li, K	He, Li, K, Ar, …	plasma source for gas ions being tested

*best result for each parameter, not all achieved in one shot

We are adapting a He^+ plasma ion source for more uniform target heating, lower cost and flexibility.

HEDLP parameter space to be explored



NDCX-II

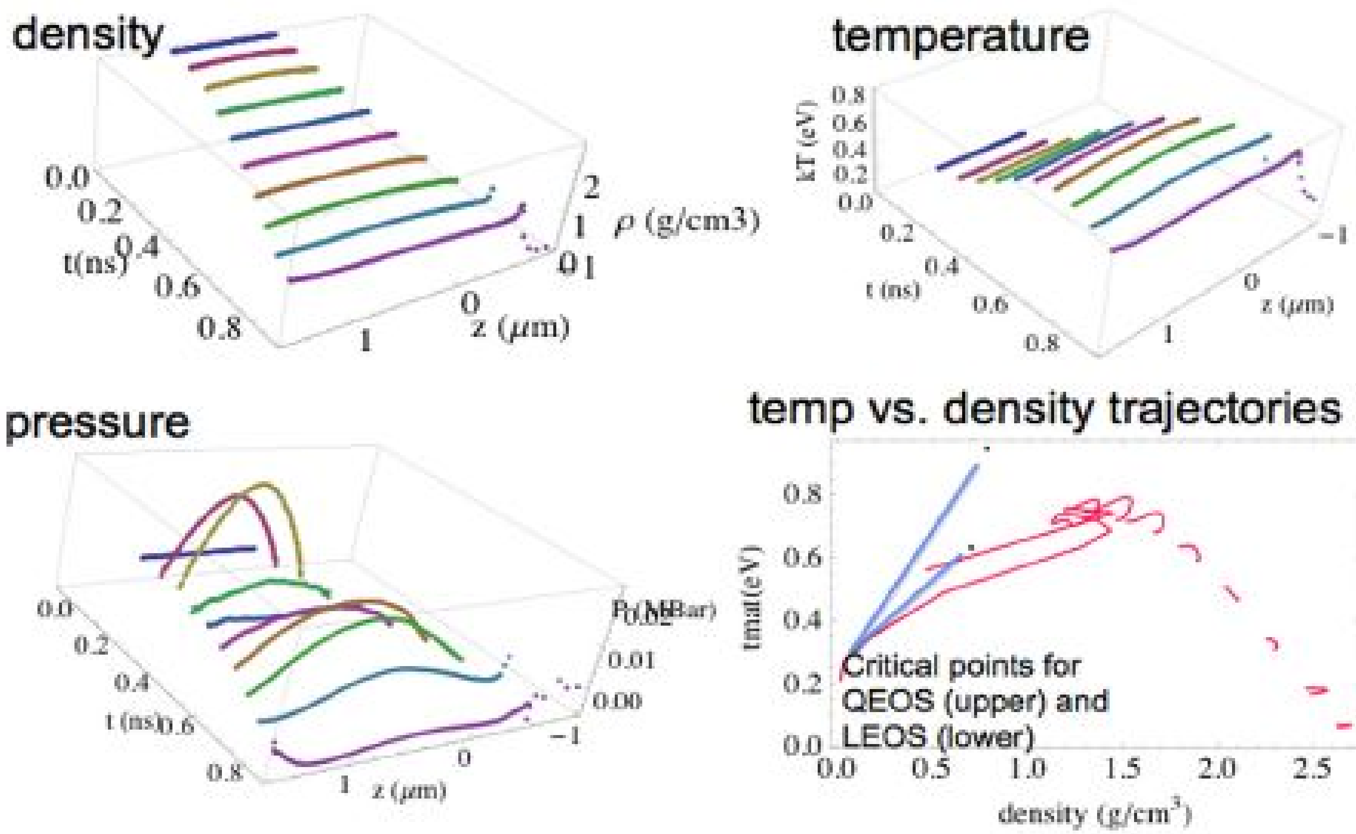
- Temperature 0.5 - 1 eV
- Uniform heating
- Large heated volume ~10^5 μm^3
- Heating by atomic collisions
- Reproducible shots at a rate of 2/min
- User access as early as summer 2015

BELLA (Berkeley Lab Laser Accelerator)

- Temperature 10 to ~100 eV
- Very high power, ≥10^{21} W/cm^2
- High repetition rate, 1 Hz

- Synergies:
  - cross fertilization and development of ideas, diagnostics, theory and simulation tools
- Close connection to MEC-SLAC and Jupiter for a Bay Area cluster of excellence in HEDLP

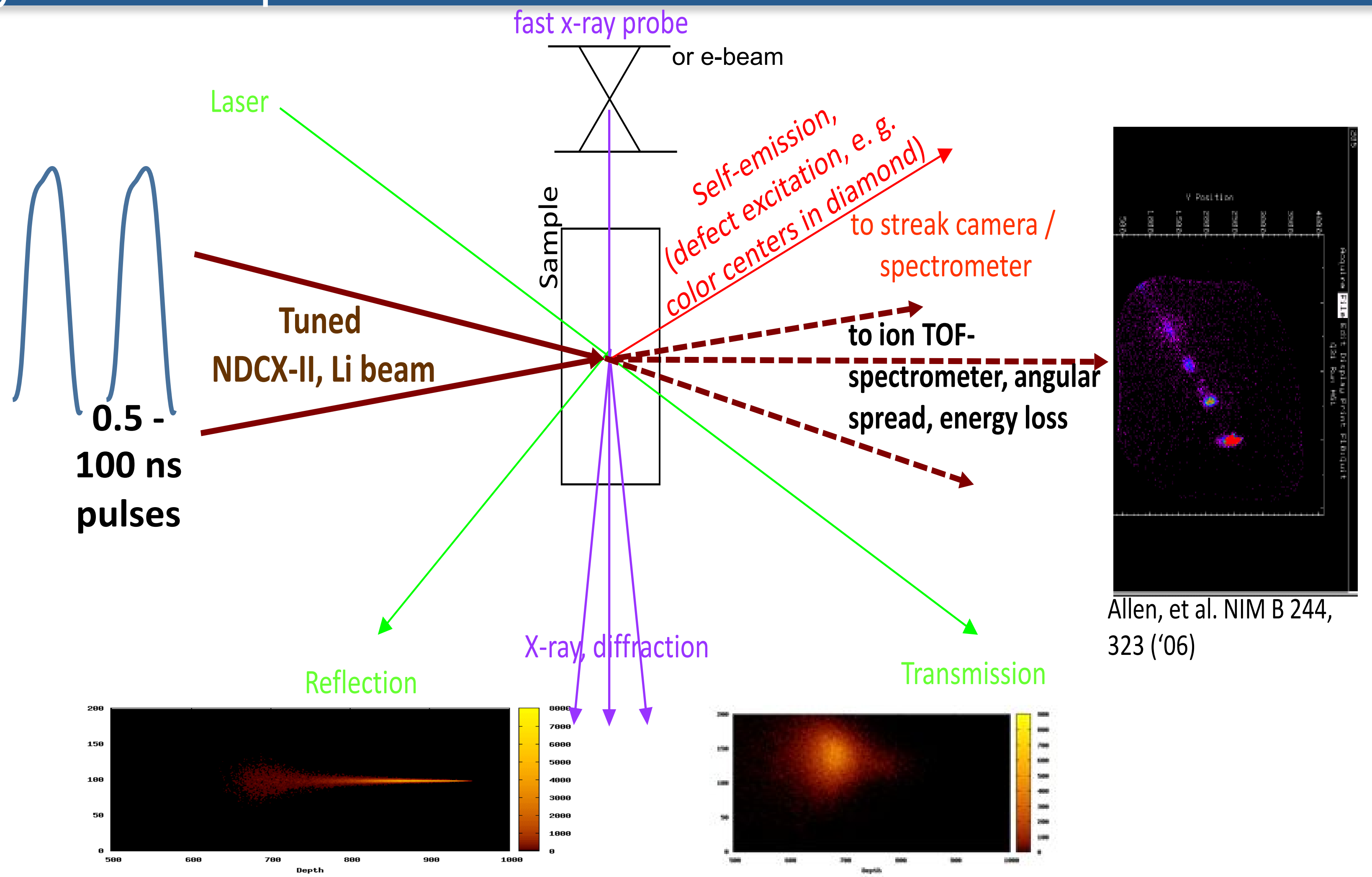
Simulations in preparation of warm dense matter experiments – Li^+



- HYDRA simulations of a 1.2MeV Li^+ pulse on a 1 μm Al foil using the QEOS equation of state. Fluence: 8.4J/cm^2, in 0.85 ns. Upper left: density ρ at the center of the foil vs. longitudinal position z, for ten snapshots in time. Upper right: temperature kT vs. z and t. Lower left: pressure vs. z and t. Lower right: temperature vs. density for each of the snap shots. The two points are the critical points for QEOS and LEOS, two commonly used Equations of State models,

  J. Barnard, et al., Nucl. Instr.. Meth. A, 2014

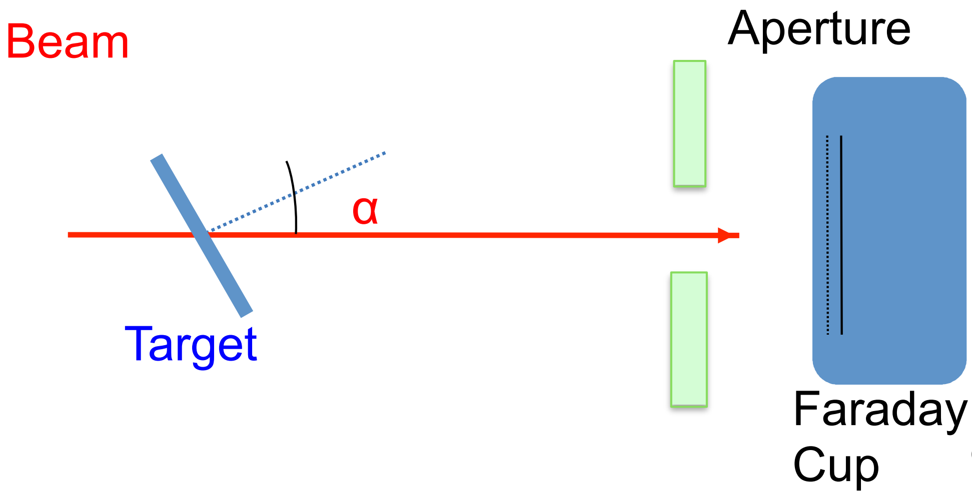
Diagnosing warm dense matter experiments and defect dynamics experiments at NDCX-II

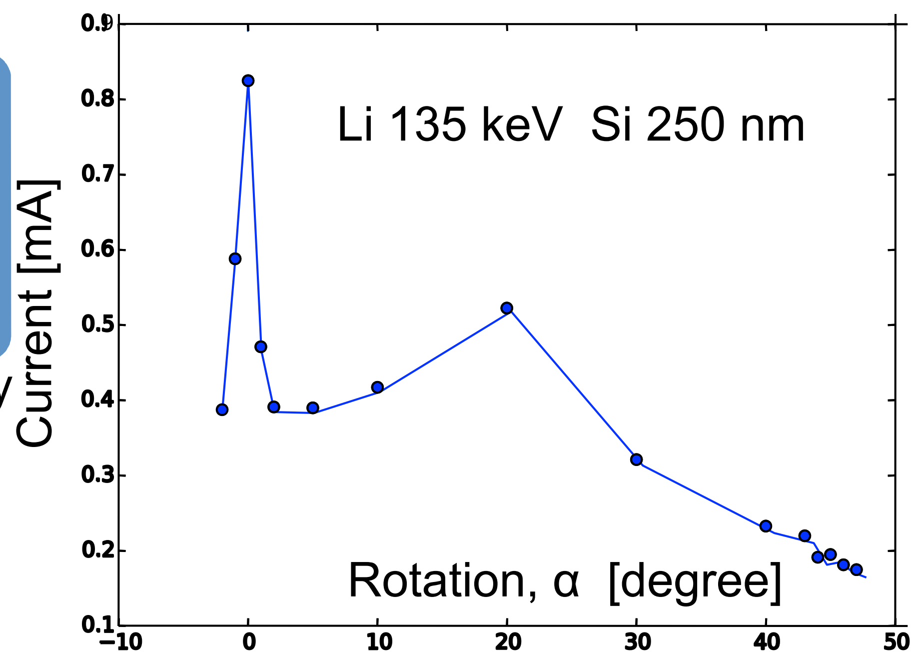


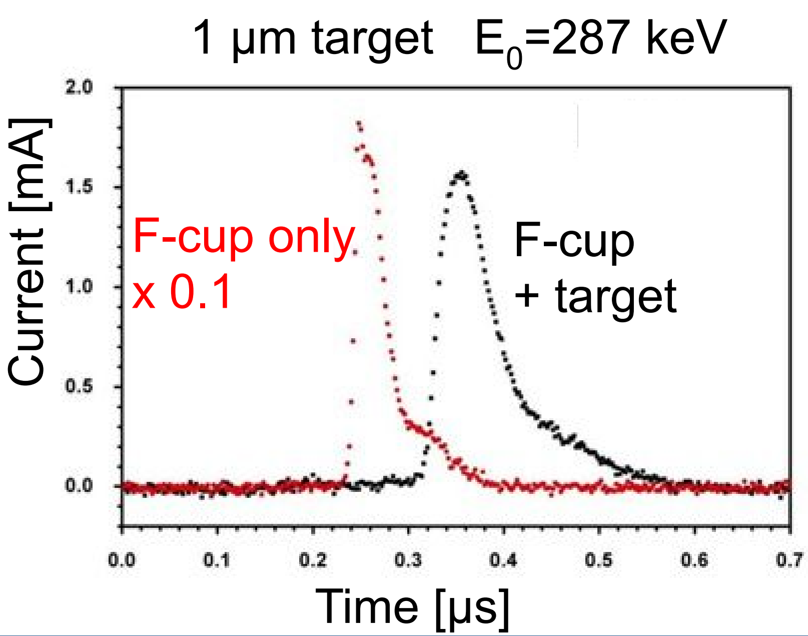
Allen, et al. NIM B 244, 323 ('06)

- Now: beam derived diagnostics: ion channeling, ionoluminescence, pyrometry
- Next: auxiliary probe(s), time resolved electron and/or x-ray diffraction, laser scattering, …

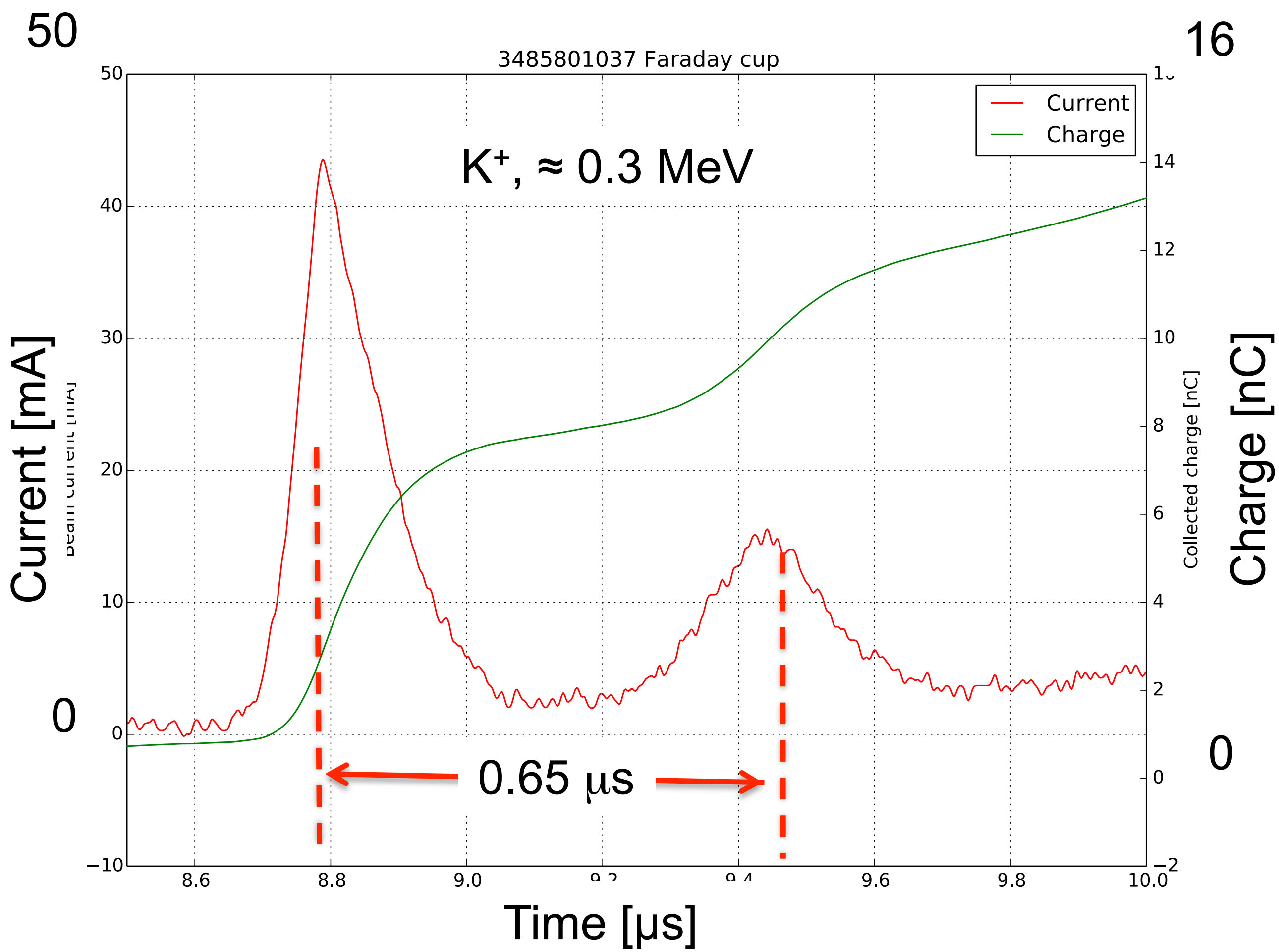
In-situ, channeling apparent with the Li beam.
At higher intensity, we will look for changes in the waveform shape.







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



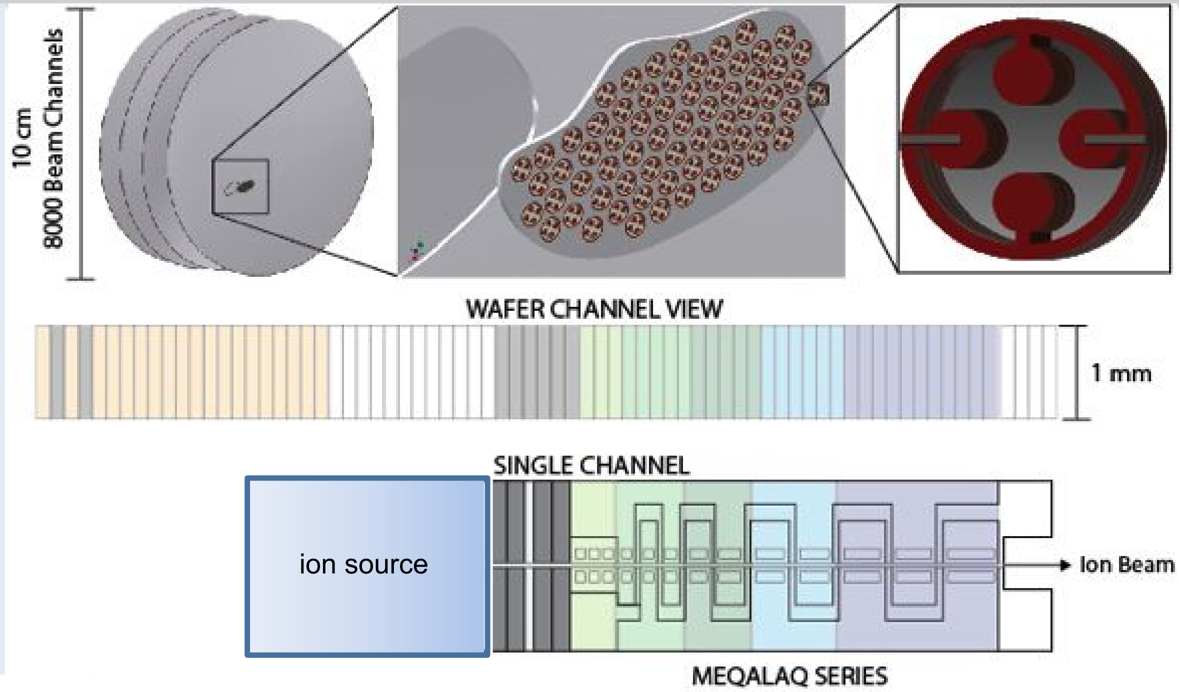
We are beginning to explore this capability.

MEMS based Ion Beam Drivers for Fusion (MTF)

Goals:

- *develop massively parallel ion beam drivers based on MEMS technology*
- *adapt the MEQALAC concept for RF acceleration of ions in MEMS structures, coupled to efficient ion sources*

➢ *scalable ion beam driver technology for plasma liner formation and target compression*



Metric	State of the Art	Proposed
Ion acceleration in a RF driven MEMS structure	Basic electron acceleration, no data for RF and ions in MEMS	Accelerate ions (>1 mA/beamlet) to >100 keV
Multi beamlet transport	No experimental data for MEMS	Transport multiple ion beams
Quantify ion acceleration and transport efficiency	No experimental data for MEMS	>30% efficient acceleration and transport

Proposed multi-beamlet MEMS based MEQALAC **(Multiple Electrostatic Quadrupole Array Linear ACcelerator)**. Aggressive scaling → thousands of beamlets on a 4-6" wafer. Ions are injected from a high efficiency ion source, accelerated across RF gaps, powered from wafer integrated solid state microwave amplifiers, and transported by quadrupole lenses. Beams from bundles of beamlets can be focused into cm-scale plasma targets in the center of a reactor chamber.

T. Schenkel (LBNL), A. Lal (Cornell) proposal to ALPHA /ARPA-e

Summary

- ✓ NDCX: Increased beam energy 4x to 1.2 MeV. Added plasma neutralization channel, final focusing and target chamber.
- ✓ All components are working: plasma sources, solenoid focusing, dipole steering, pulsed power timing.
- ✓ Started neutralized drift compression experiments. We have demonstrated r<1 mm focal spots, and t<2.5 ns bunches with Li^+.
- Designing He^+ source → More uniform heating, higher charge, flexible.
- Spring 2015: achieve target heating, 0.5 to 1 eV, conduct WDM experiments.
- Spring 2015: tentative plans for a workshop on Discovery Plasma Science to engage a vibrant user community.
- Research toward magnetized target fusion (ARPA-e):
  - Explore scaling of multiple beams to mm-scale with massively parallel MEMS technology.
  - Development of x-ray diagnostic for MTF plasmas (with GF)