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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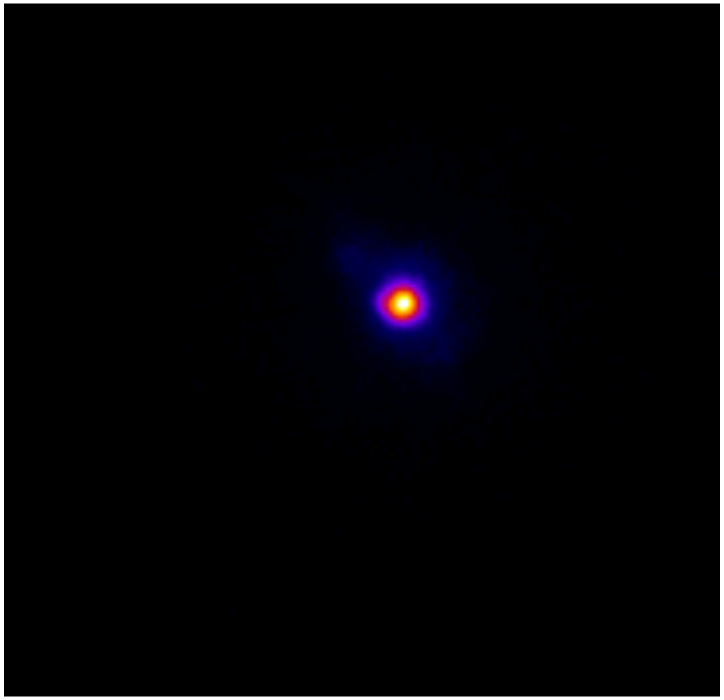
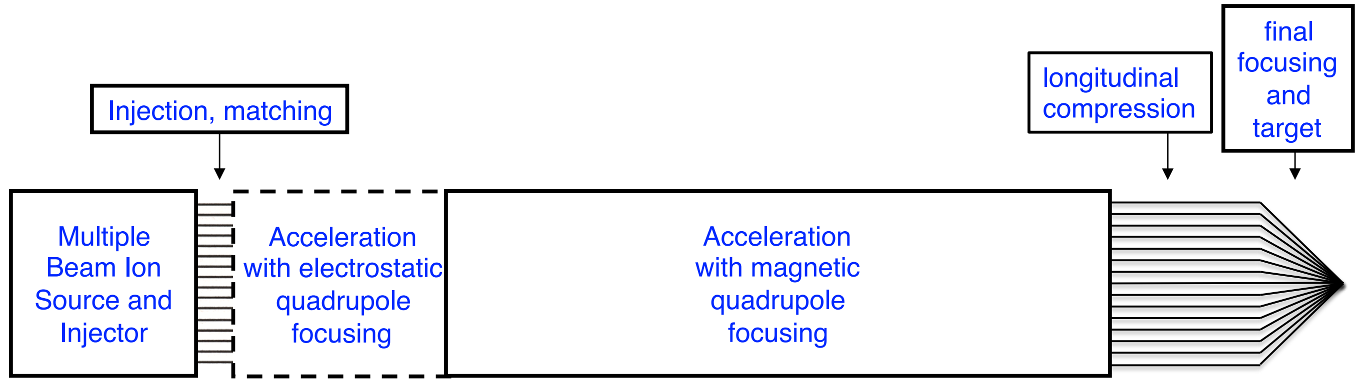
Outline

- 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:

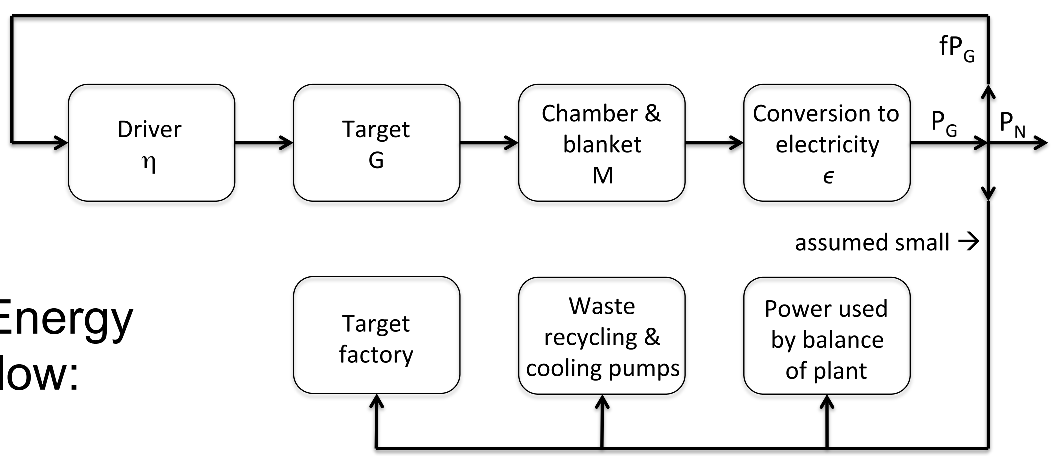


~ 2-3 MeV
~1 A/beam
~ 20 μs, A ≥ 133, q = 1

~ 3-10 GeV
I ~ 200 A/beam
~ 200 ns

~ 3-10 GeV
at target:
~ 4000 A/beam
~ 10 ns

Energy flow:



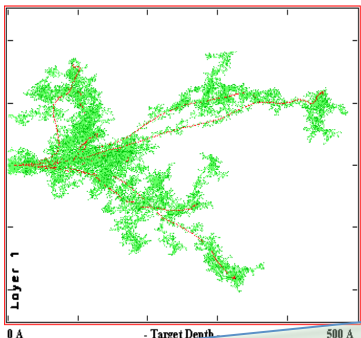
P_G = gross electrical power
P_N = net electrical power
Assume f < 0.2, $P_N \approx P_G(1-f)$

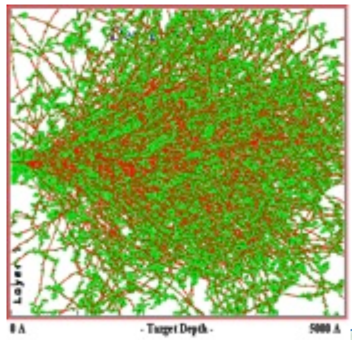
$\eta G > 10$, G = 50 - 150
η = 0.2 – 0.4
M = 1.1 - 1.3
ε = 0.3 - 0.5

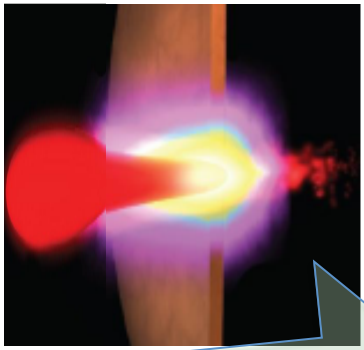
NDCX-II provides uniquely intense, short ion pulses with high degree of flexibility and tunability

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

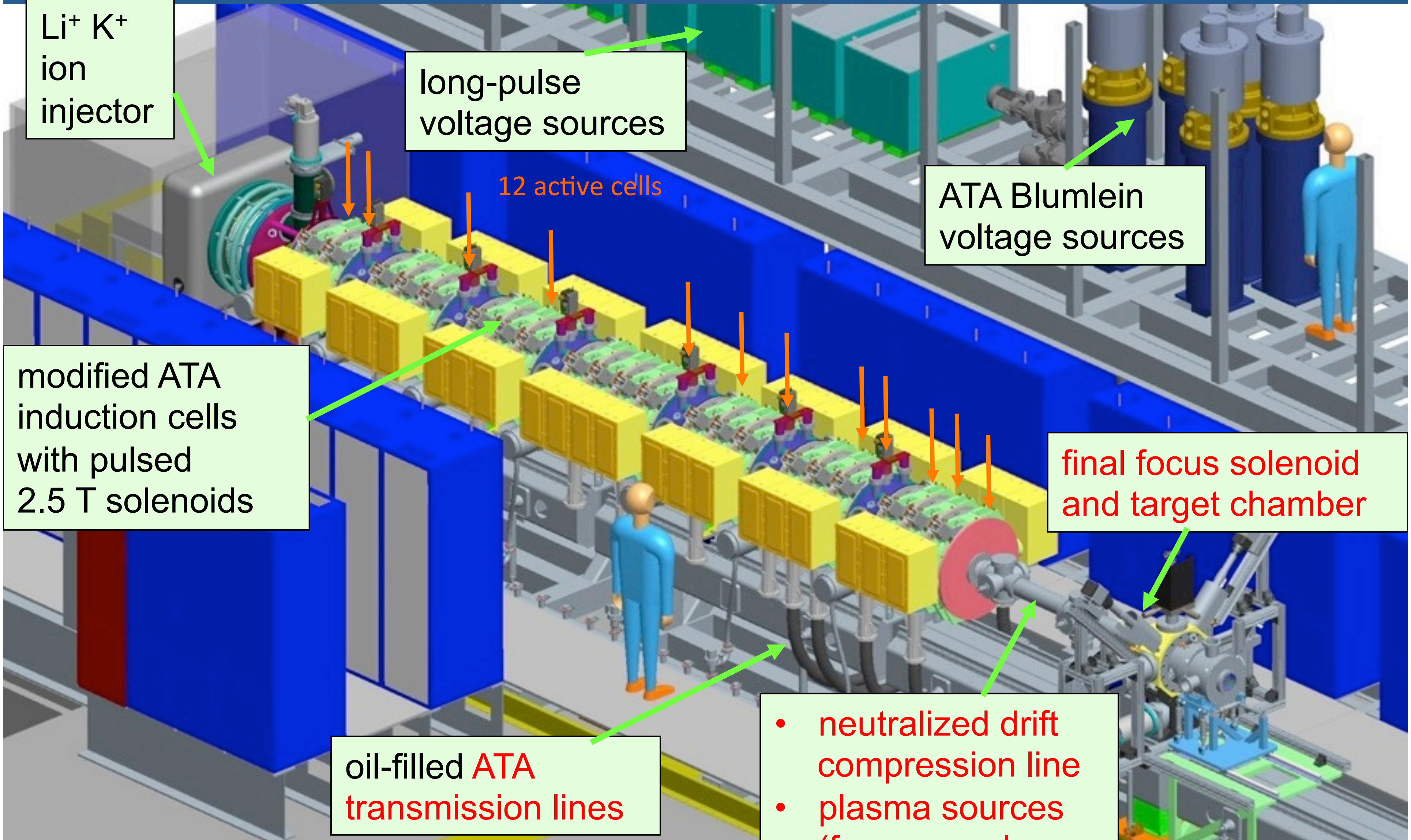
1-30 nC, 0.3 -1.2 MeV, few mm^2, ~1-20 ns

~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



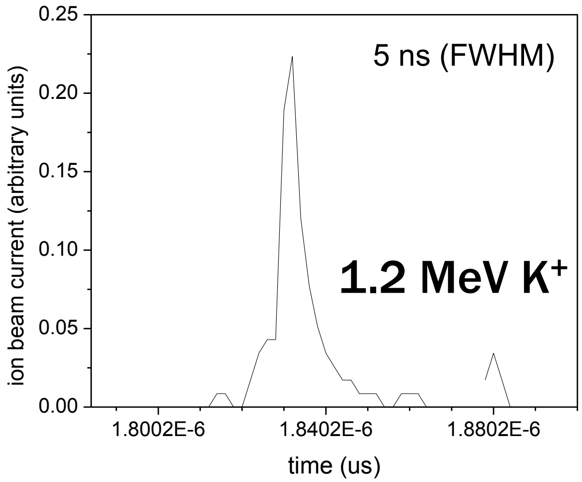
NDCX-II time line in 2014

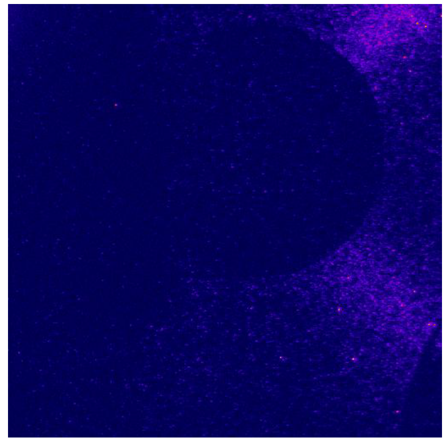
- March 6, review of science with NDCX-II
  - physics of warm dense matter
  - dynamics of radiation effects in materials
  - physics of intense beams
  - Reviewers: Farhat Beg (UCSD), Mike Campbell (SNL), Ron Davidson (PPPL), Roger Falcone (UCB, LBNL), Peter Hosemann (UCB)

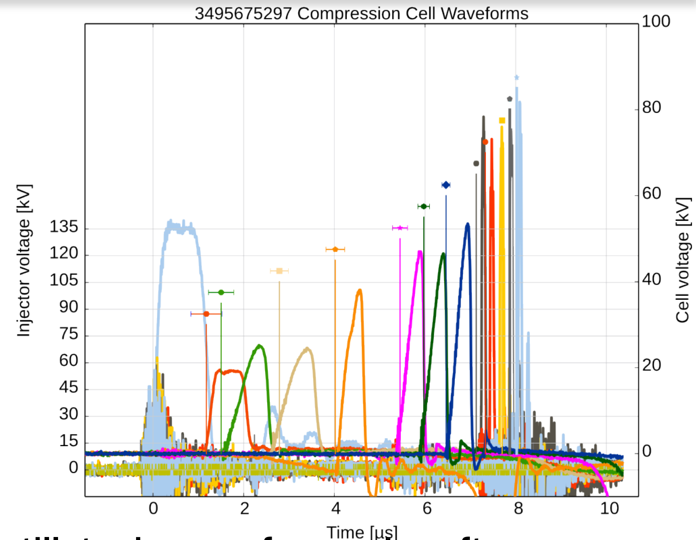
- March 17, engineering review of effort to reach 1.2 MeV and to commence neutralized drift compression experiments

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

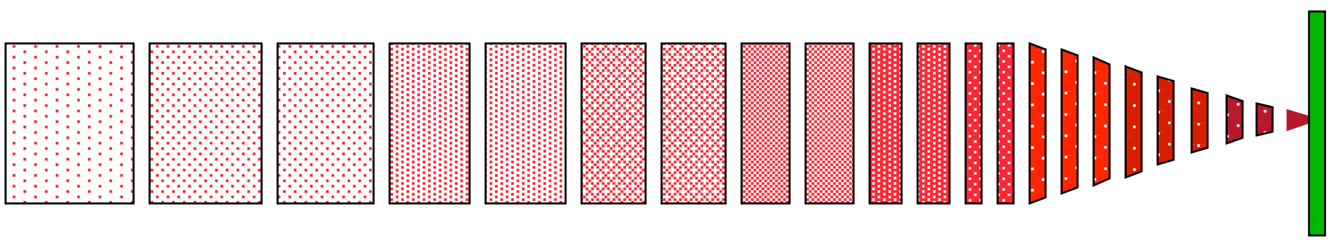
We are running neutralized drift compression experiments.







- **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

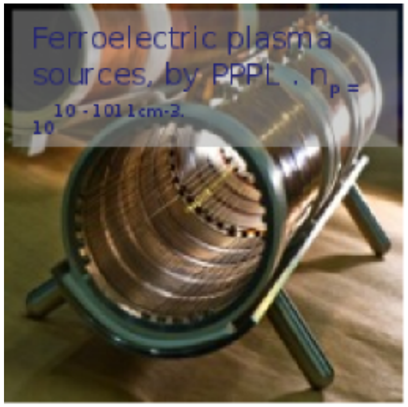
Induction linac provides custom waveforms for rapid beam compression

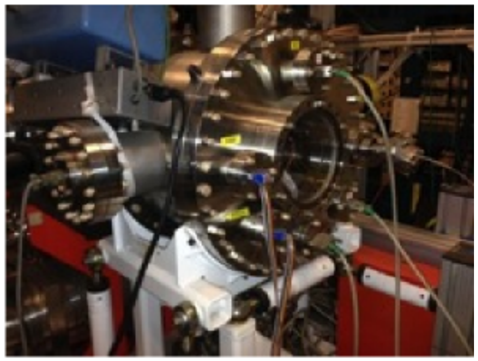
Neutralized drift compression and final focus

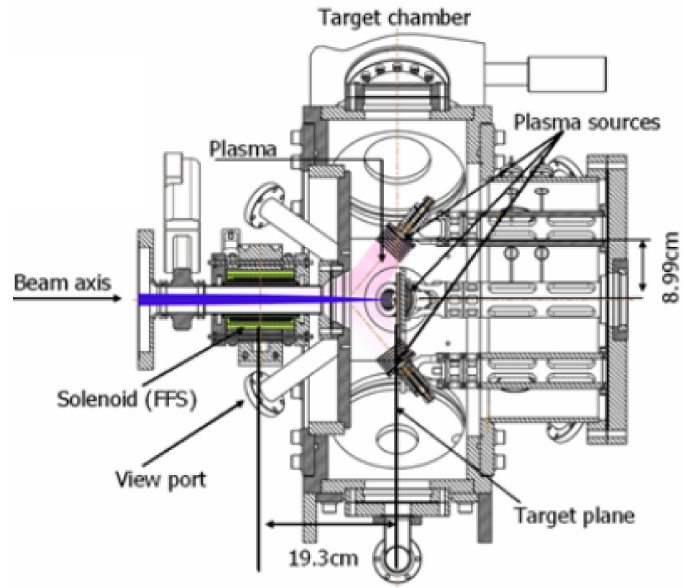
Target

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

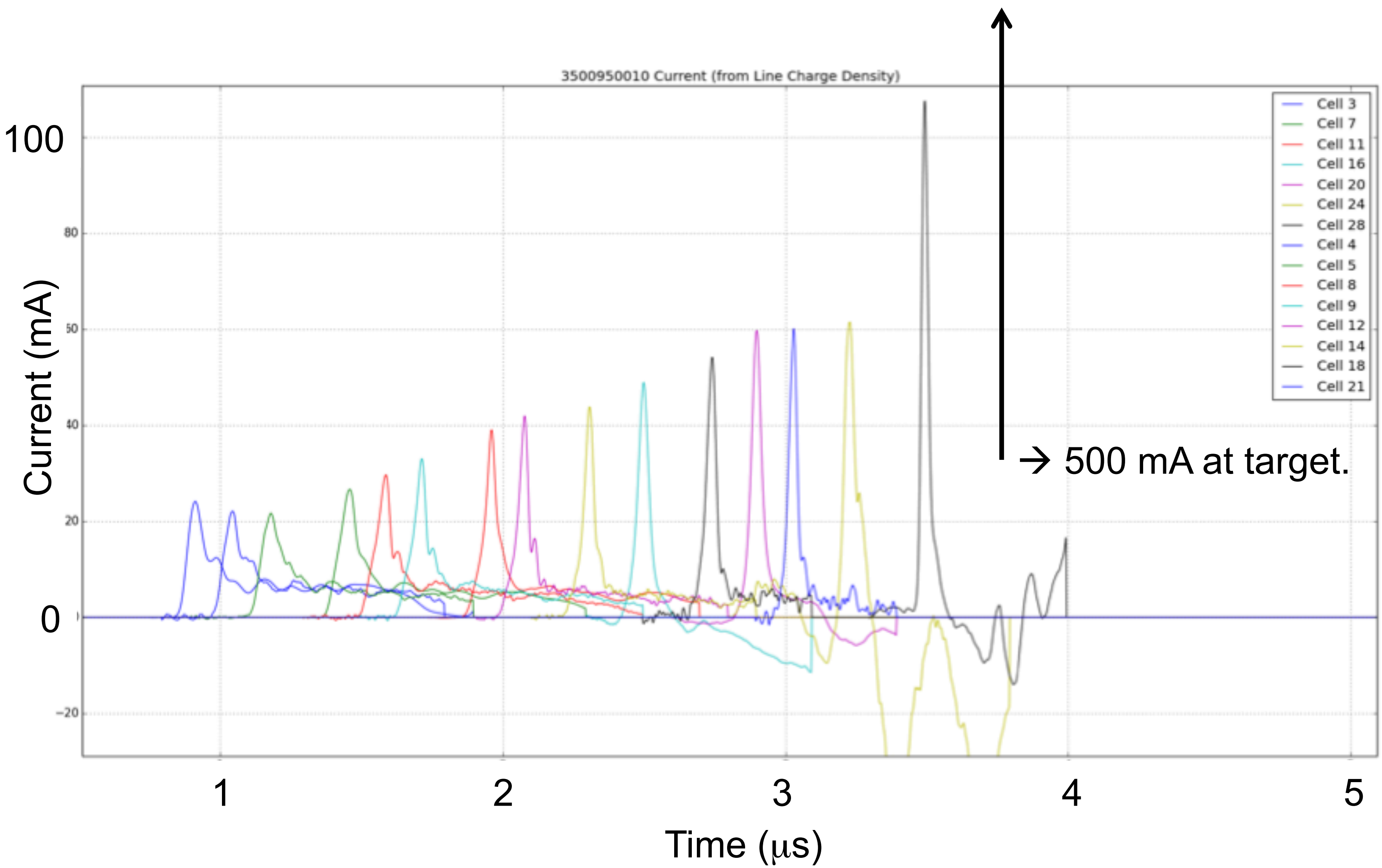




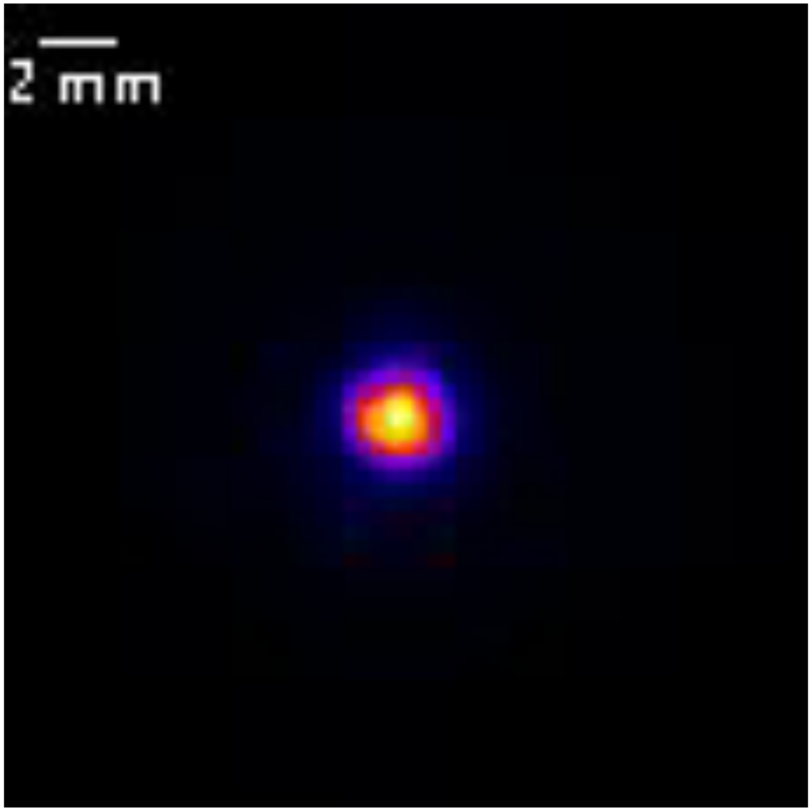


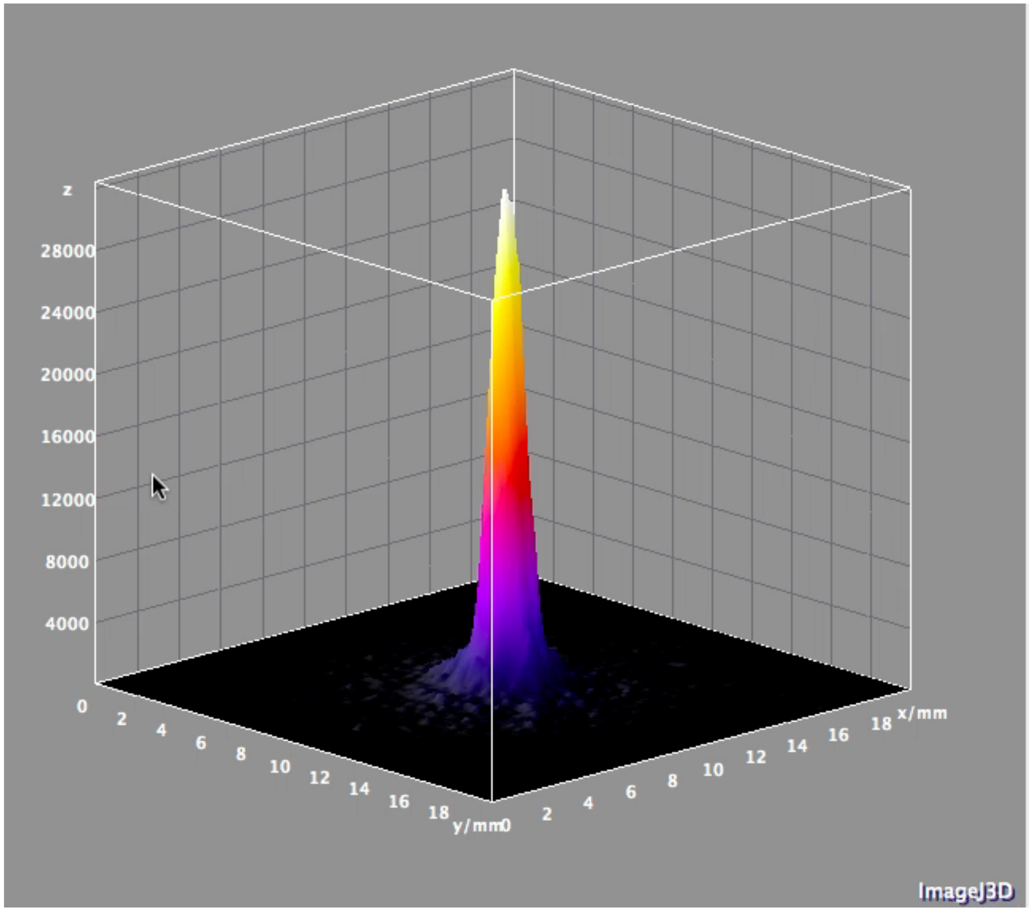
8 T solenoid, plasma sources, Target chamber

Acceleration and compression



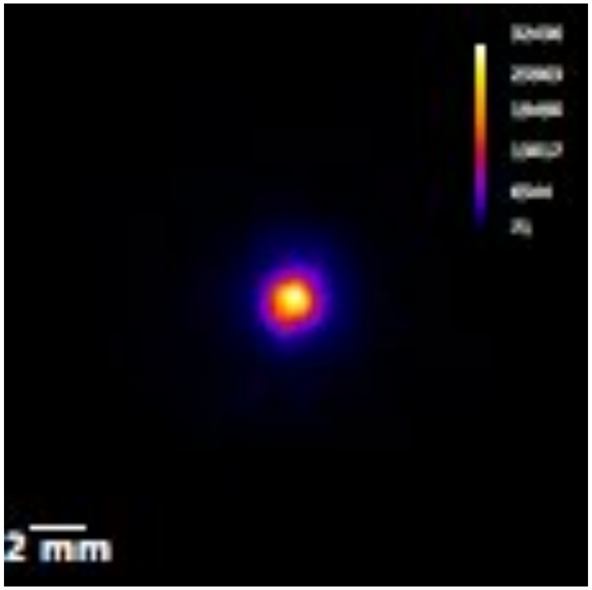
Li^+ beam parameters are stable

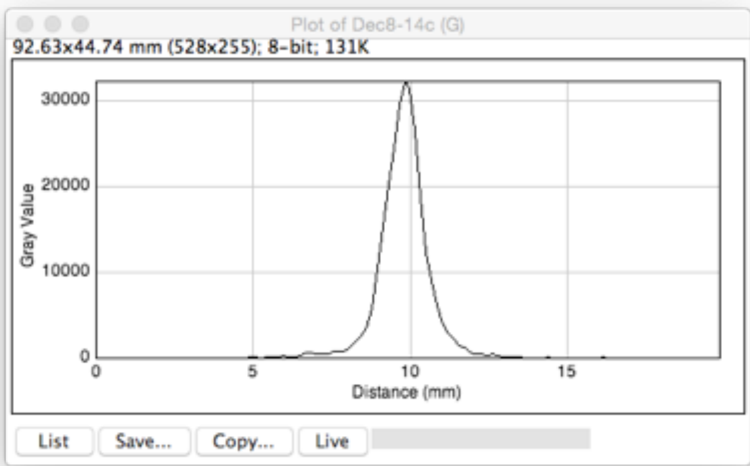




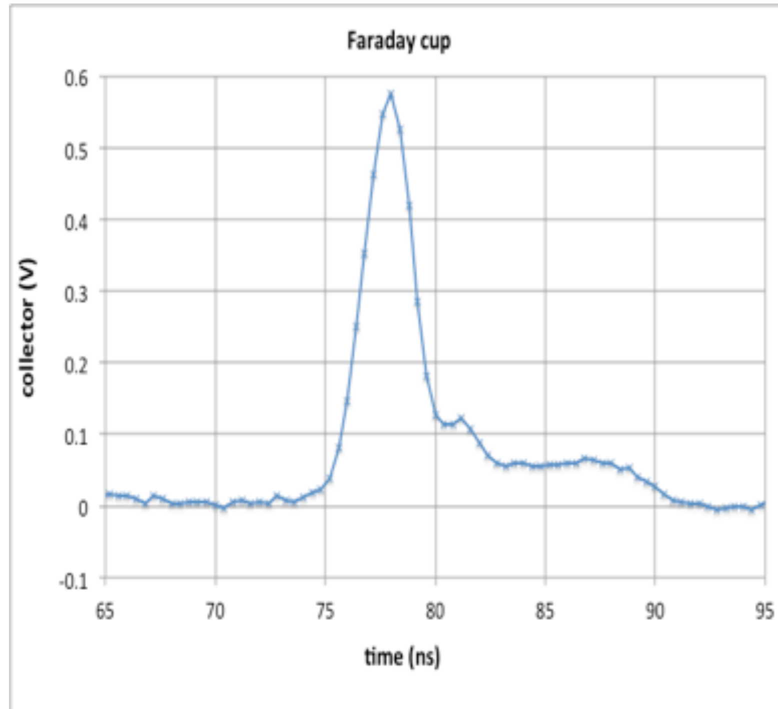
Centroid jitter: <200 microns.

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

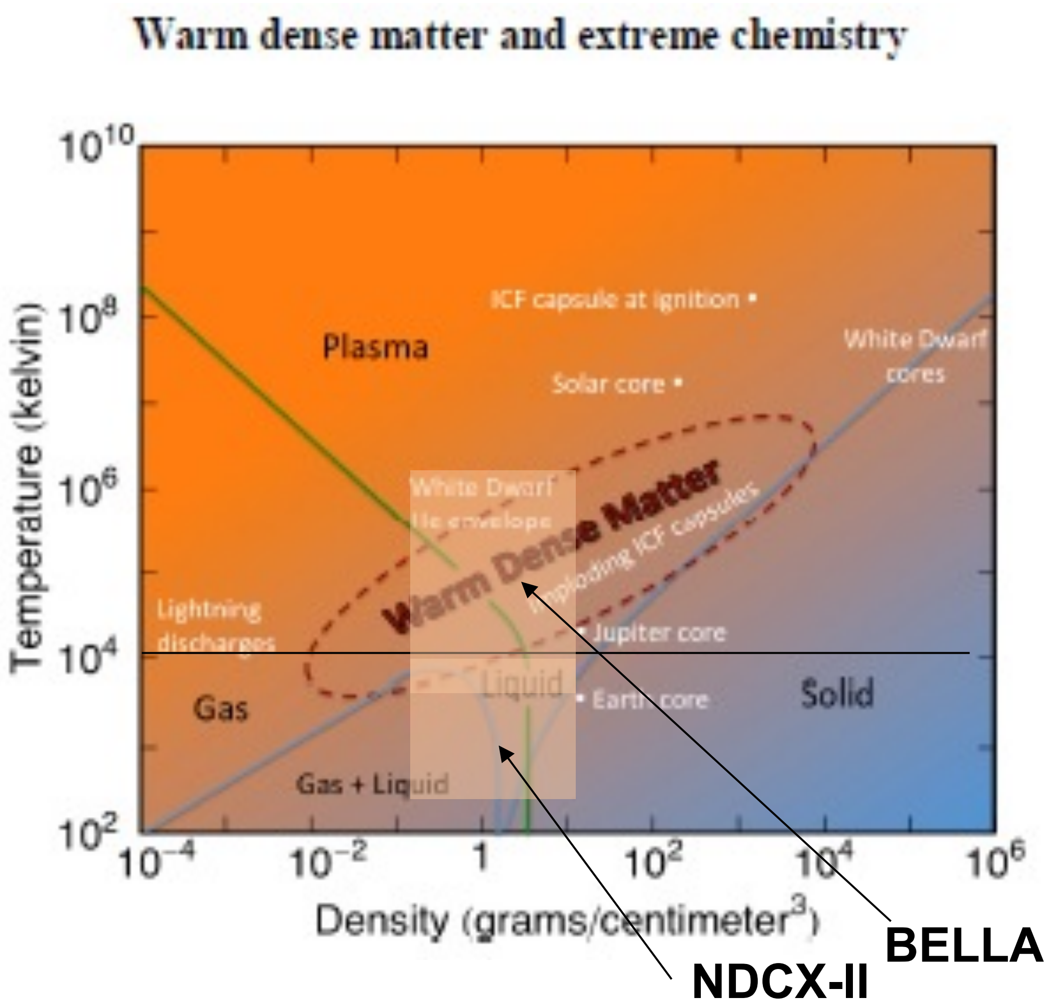
- Access to warm-dense-matter, isochoric heating of large volumes (~10^5 μm^3) to 0.5 - 1 eV
- Access to novel materials physics, defect dynamics, materials synthesis, extreme chemistry
- Access to the physics of intense, space charge dominated ion beams

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

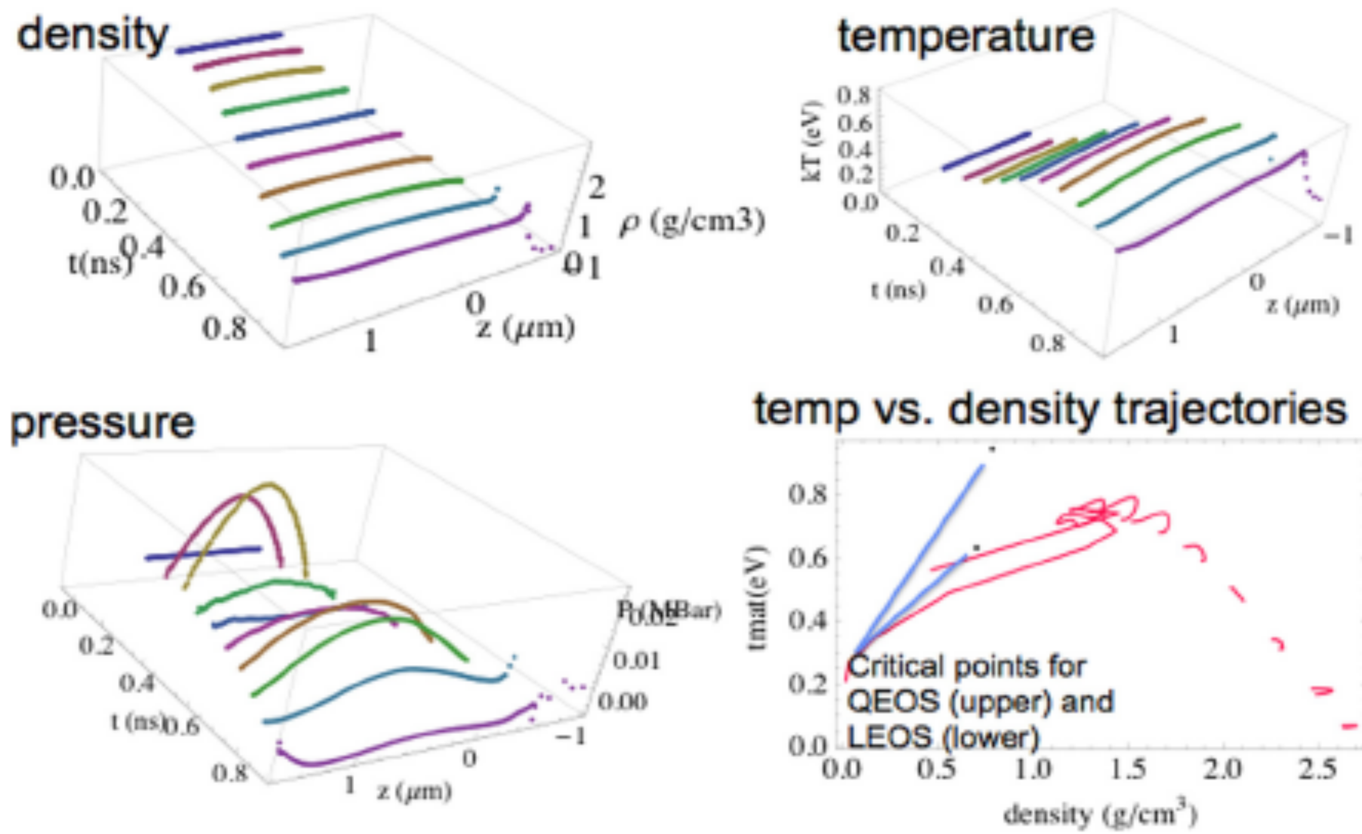
- Temperature 0.5 - 1 eV
- Uniform heating
- Large heated volume ~10^5 μm^3
- Heating by atomic collisions
- Reproducible shots at a rate of 2/min
- User access as early as summer 2015

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

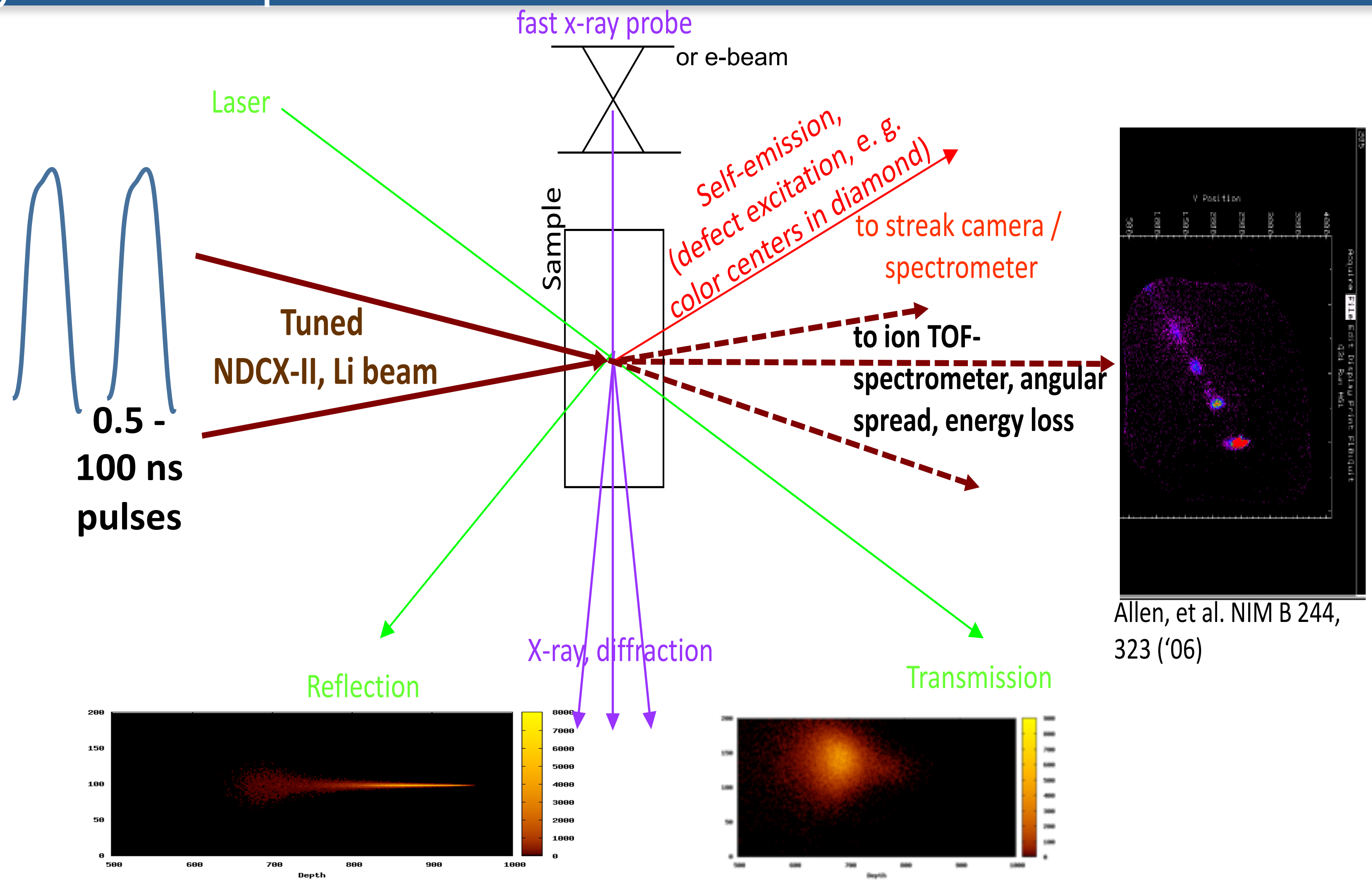
Simulations in preparation of warm dense matter experiments – Li^+



- 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

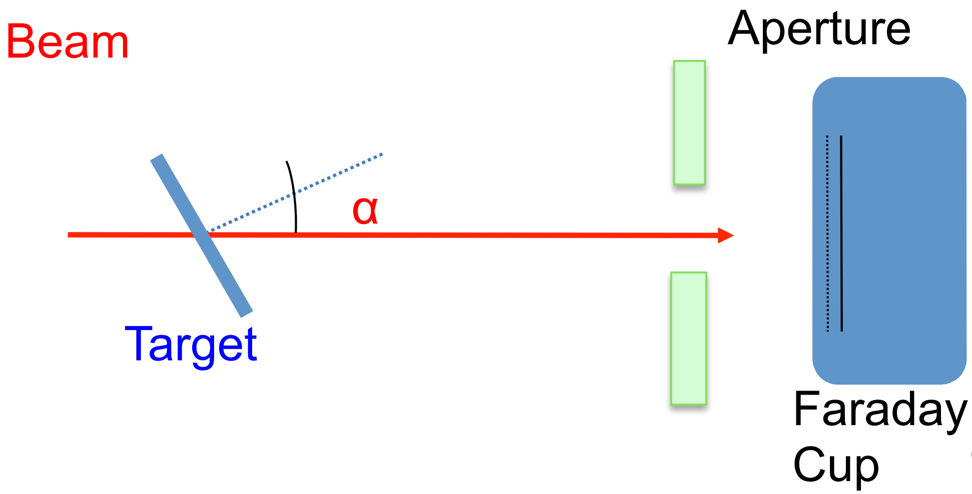
Diagnosing warm dense matter experiments and defect dynamics experiments at NDCX-II

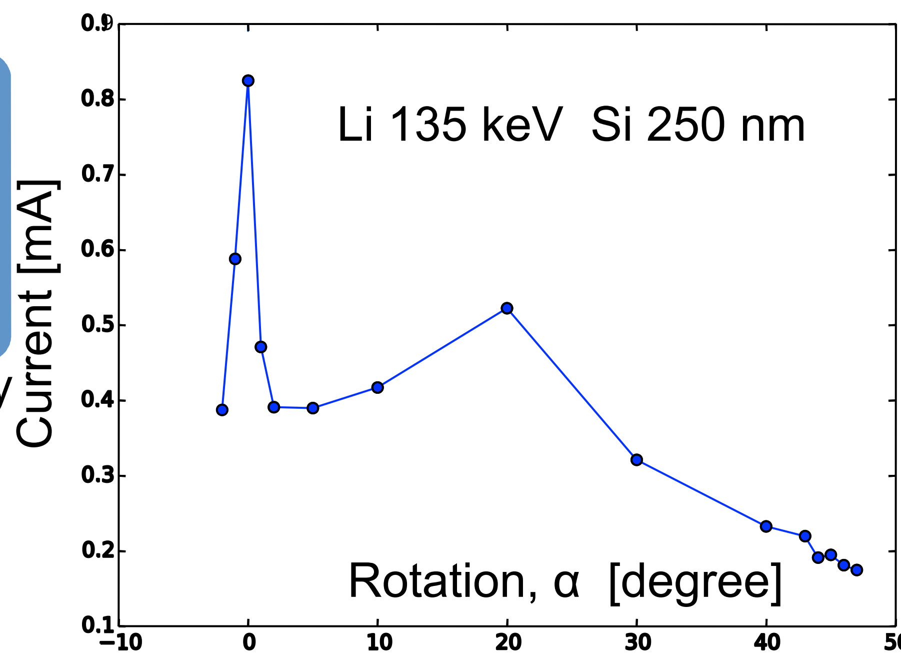


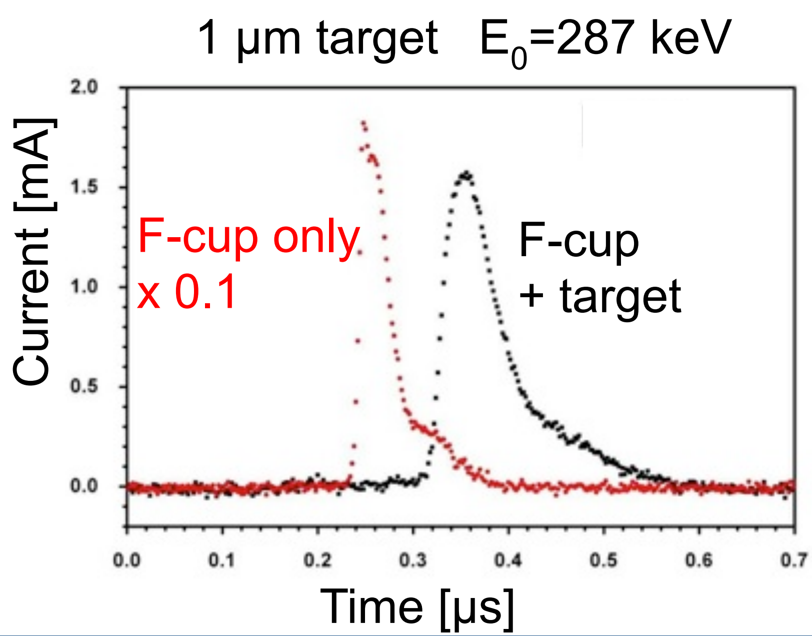
Allen, et al. NIM B 244, 323 ('06)

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

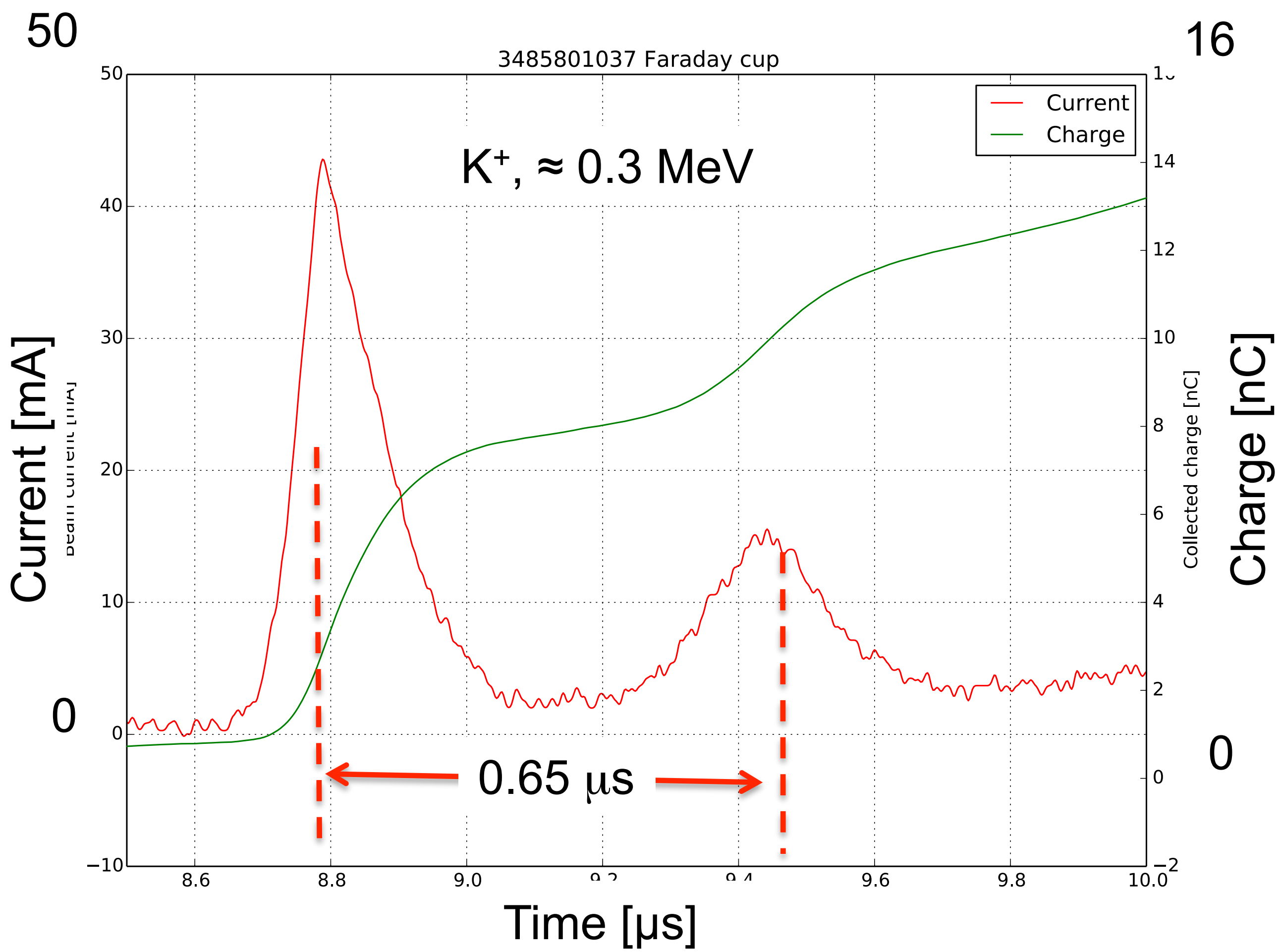
In-situ, channeling apparent with the Li beam. At higher intensity, we will look for changes in the waveform shape.







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



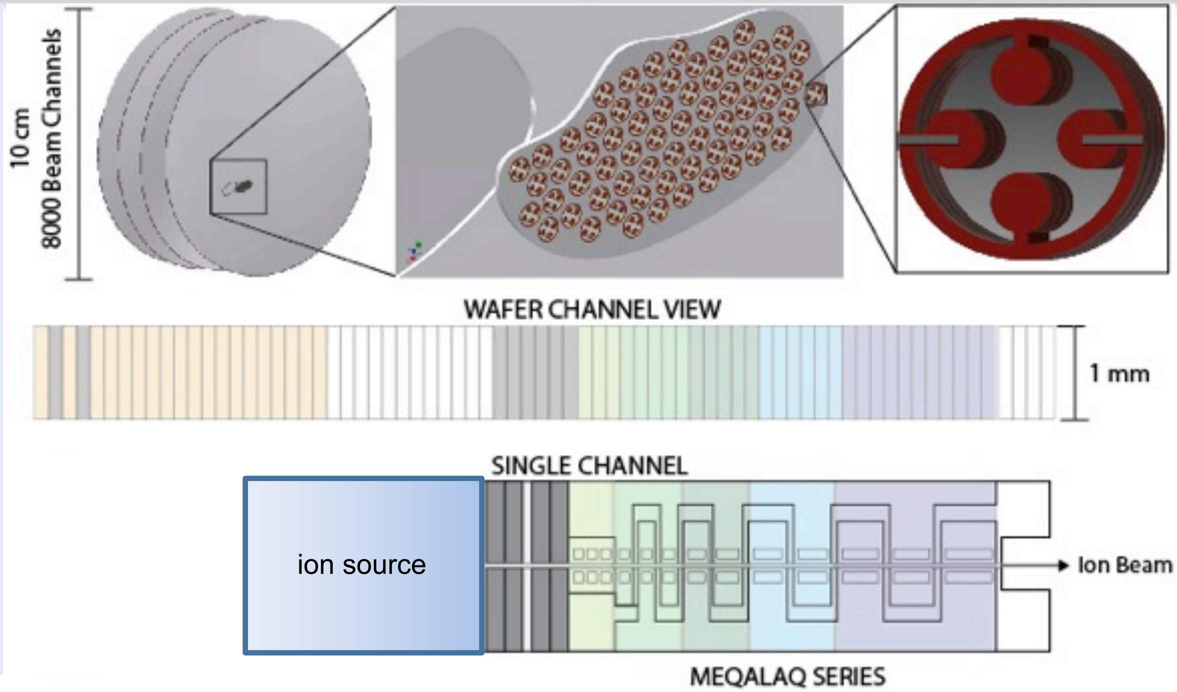
We are beginning to explore this capability.

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.

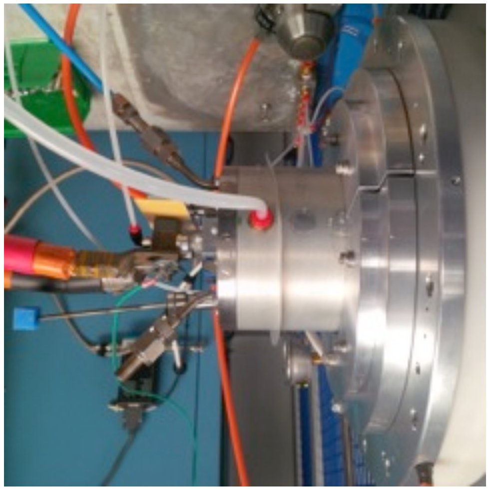
T. Schenkel (LBNL), A. Lal (Cornell) proposal to ALPHA /ARPA-e

Summary

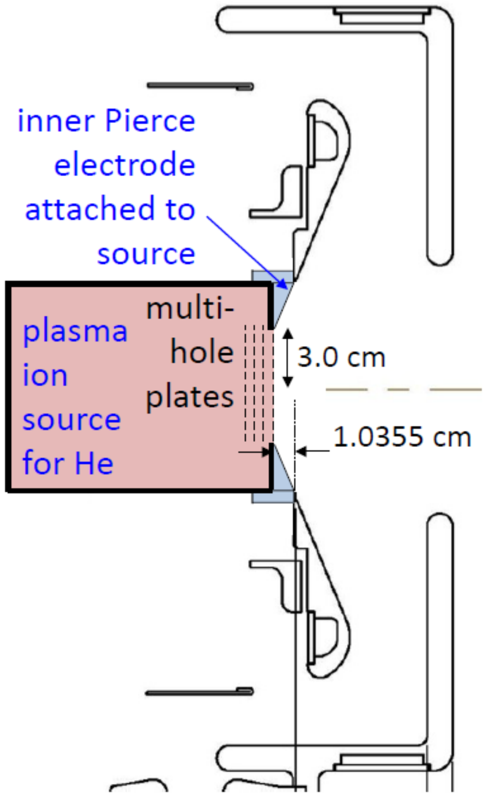
- ✓ NDCX: Increased beam energy 4x to 1.2 MeV. Added plasma neutralization channel, final focusing and target chamber.
- ✓ All components are working: plasma sources, solenoid focusing, dipole steering, pulsed power timing.
- ✓ Started neutralized drift compression experiments. We have demonstrated r<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)

Extra slides

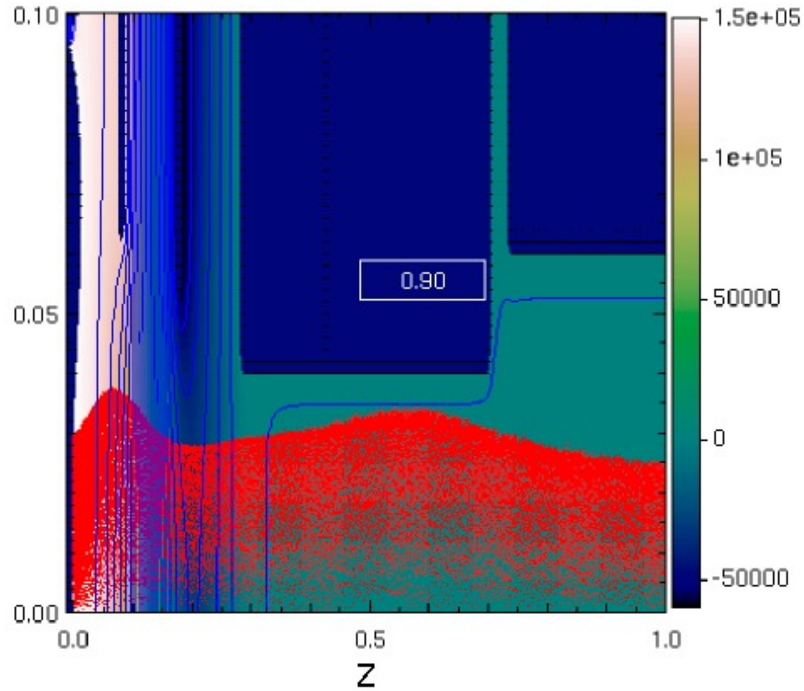
Multi-cusp, filament driven helium ion plasma source



- Photo of plasma ion source



reentrant He⁺ injector



- WARP3D simulation of He injection
- A. Friedman and D. Grote, LLNL

- We have a plasma ion source that delivers well over 60 mA/cm^2, ~5 mTorr
- The goal is to extract ~160 mA of He$^+$ ions during ~500 ns, for 80 nC per pulse
- Trade-offs between current density, emission area, number of beamlets (~100), emittance (~1.0 π-mm-mrad)
- We plan to swap the He-source in by early February 2015
- He vs. Li: more ions, more uniform heating, lower cost, more flexible (other gases)

Warm Dense Matter experiments at NDCX-II

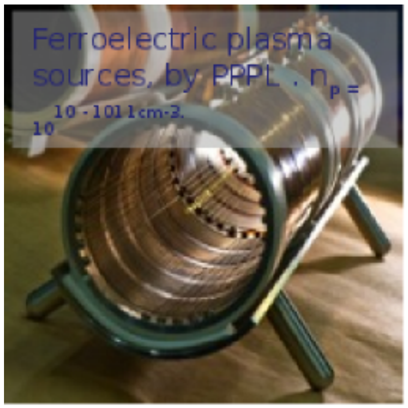
- Heat an Aluminum foil with a ~1 ns pulse and ~0.1 J (10 J/cm^2) to 0.5 - 1 eV
- Measure temperature, pressure and density for EOS

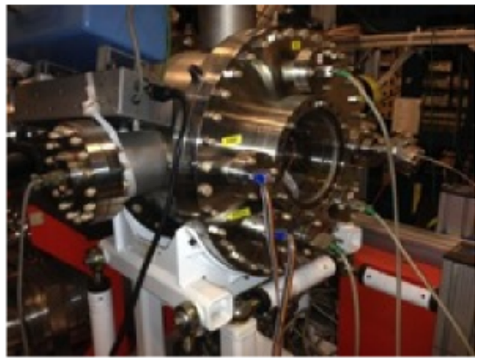
- temperature evolution from detection of black body radiation with an optical streak camera
- target expansion velocity with a fiber coupled VISAR (for pressure and density evolution)

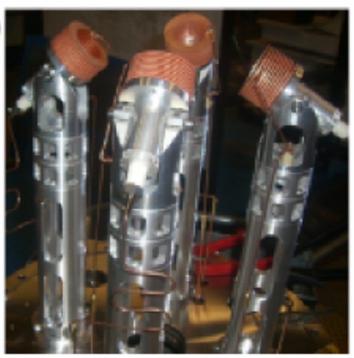
- new opportunities:
  - form an XUV pulse or a betatron pulse from a fs-laser (0.1 J for XUV, ~1 J for betatron x-rays) for precision radiography
  - with the same laser, implement chirped pulsed Fourier domain interferometry to imaging expansion
  - measure ion induced x-ray emission during the pulse (x-ray streak, spectrometer)
  - with a larger target chamber we can implement experiments with greater flexibility for users

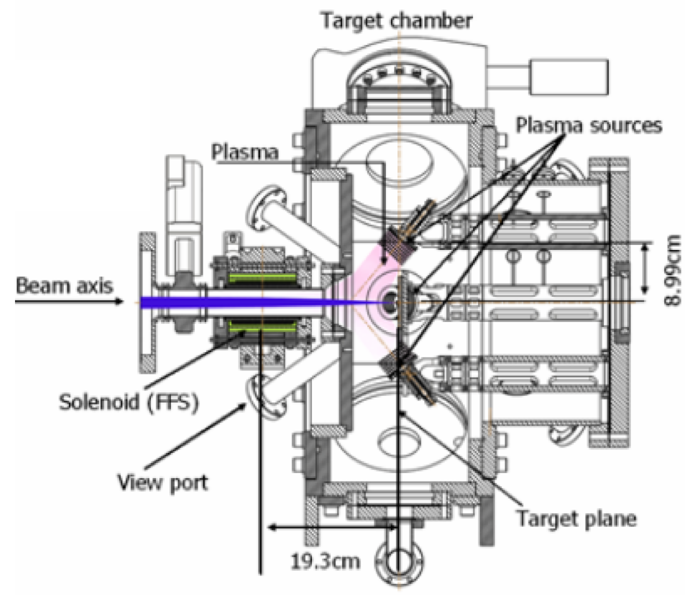
Ions enter a neutralizing plasma where transverse and longitudinal defocusing due to space charge are cancelled

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





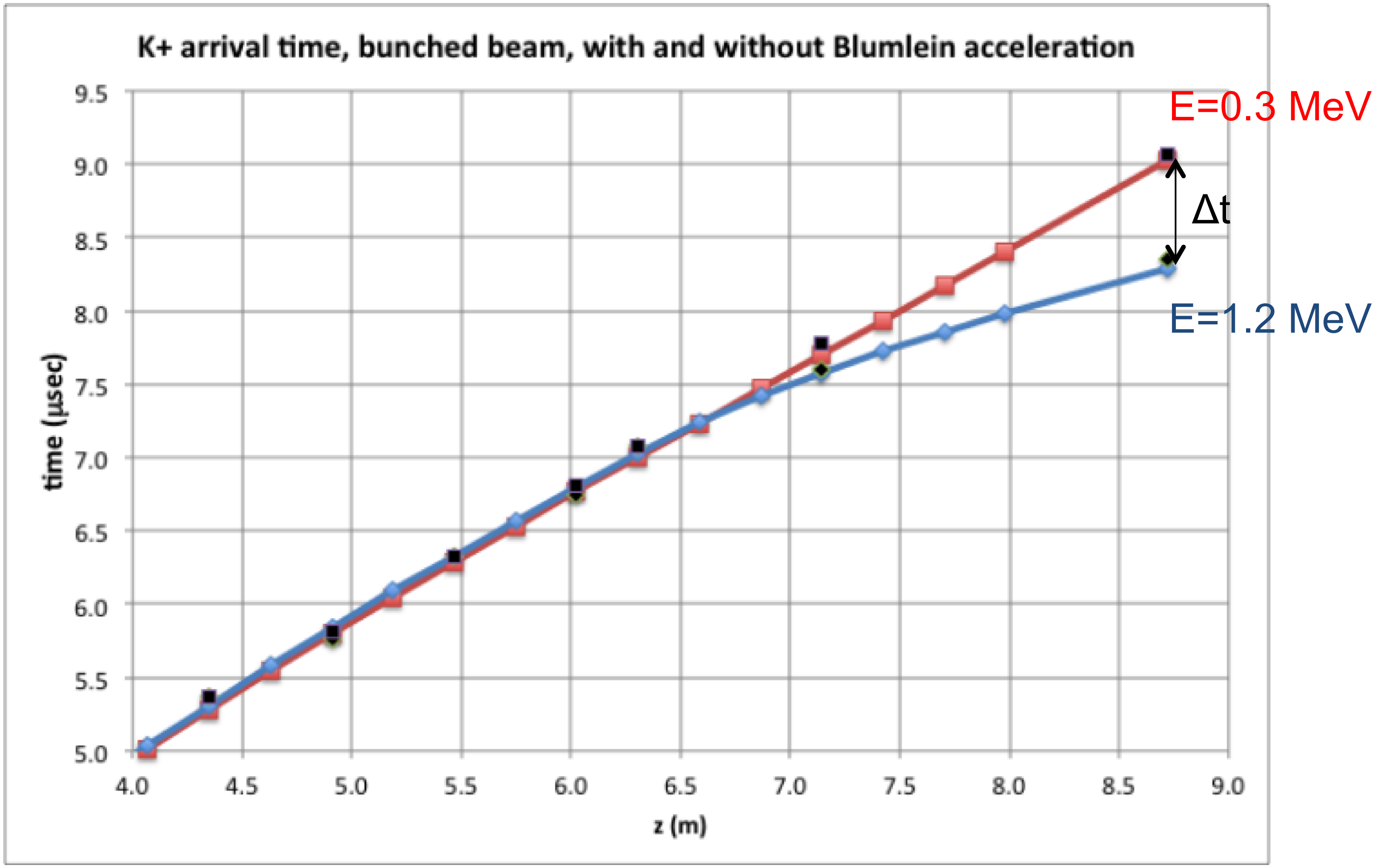




8 T solenoid, plasma sources, Target chamber

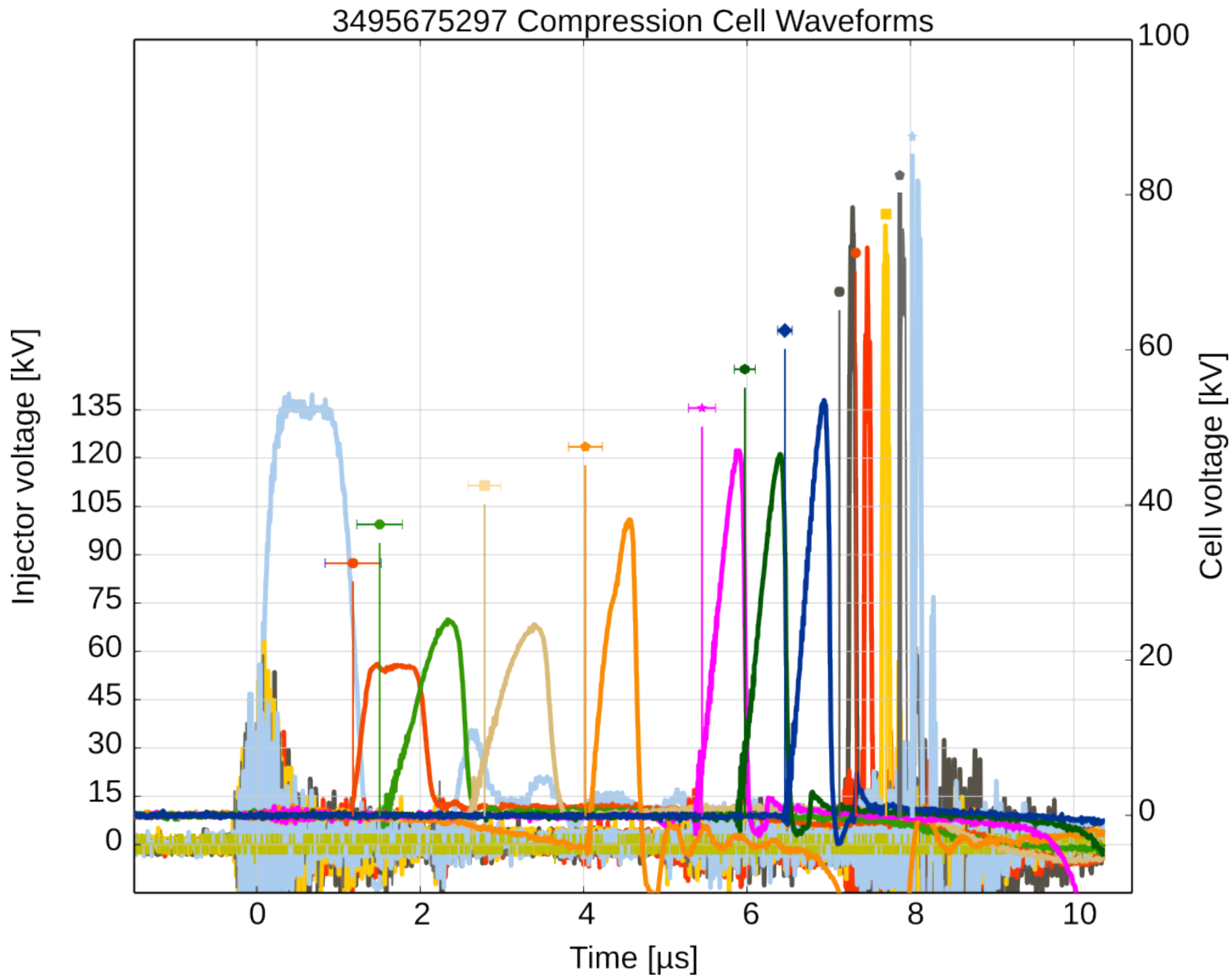
Neutralized drift compression and focusing Components are being installed today

Estimate final energy of 1.2 MeV from the arrival time at several beamline diagnostics

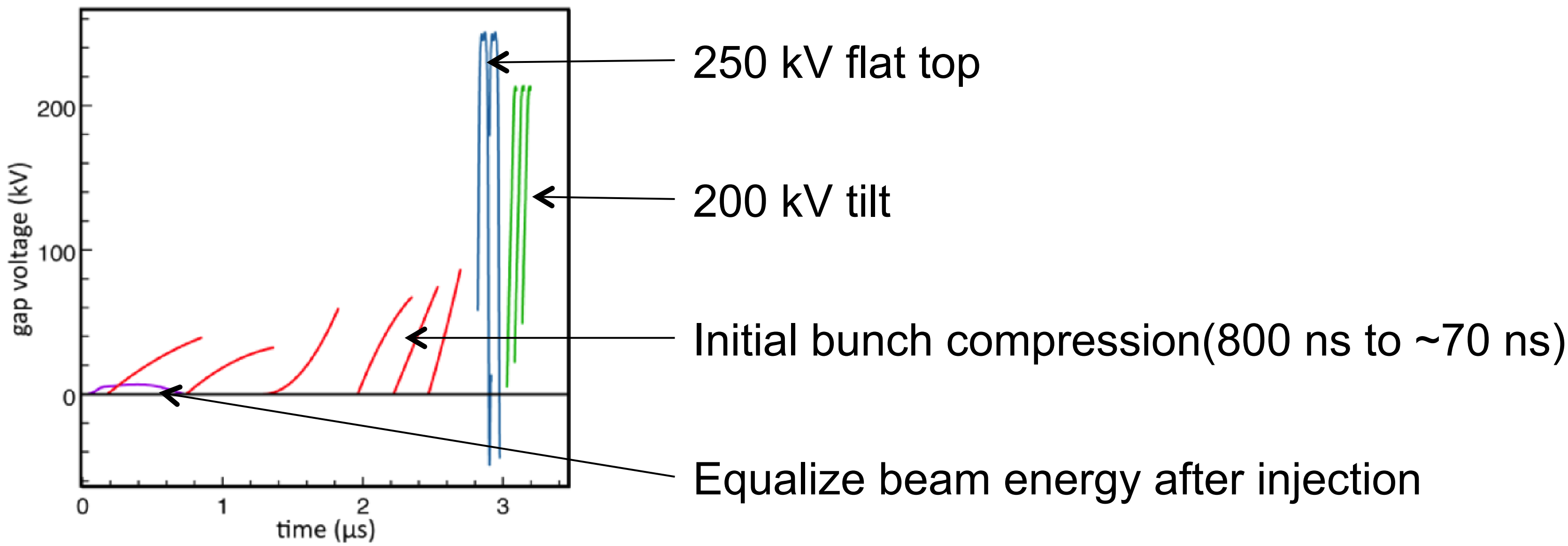


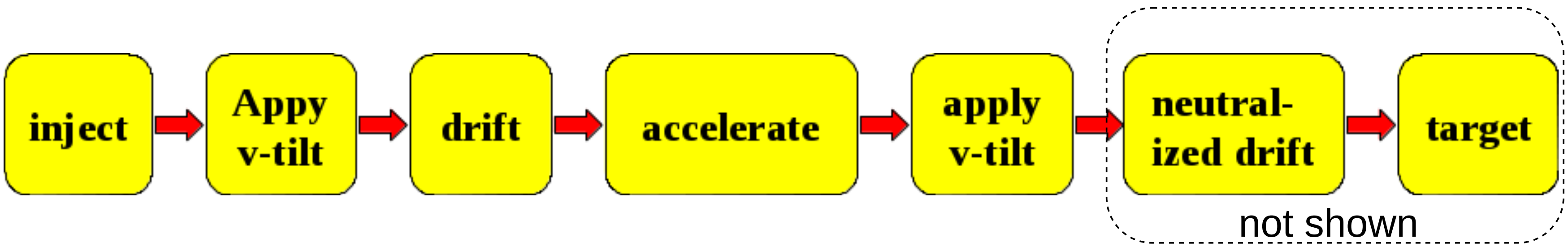
Empirical model: Δt (Faraday Cup) = 0.73 μs, 0.72 μs observed

Cell Waveforms and arrival time of 1.2 MeV shot

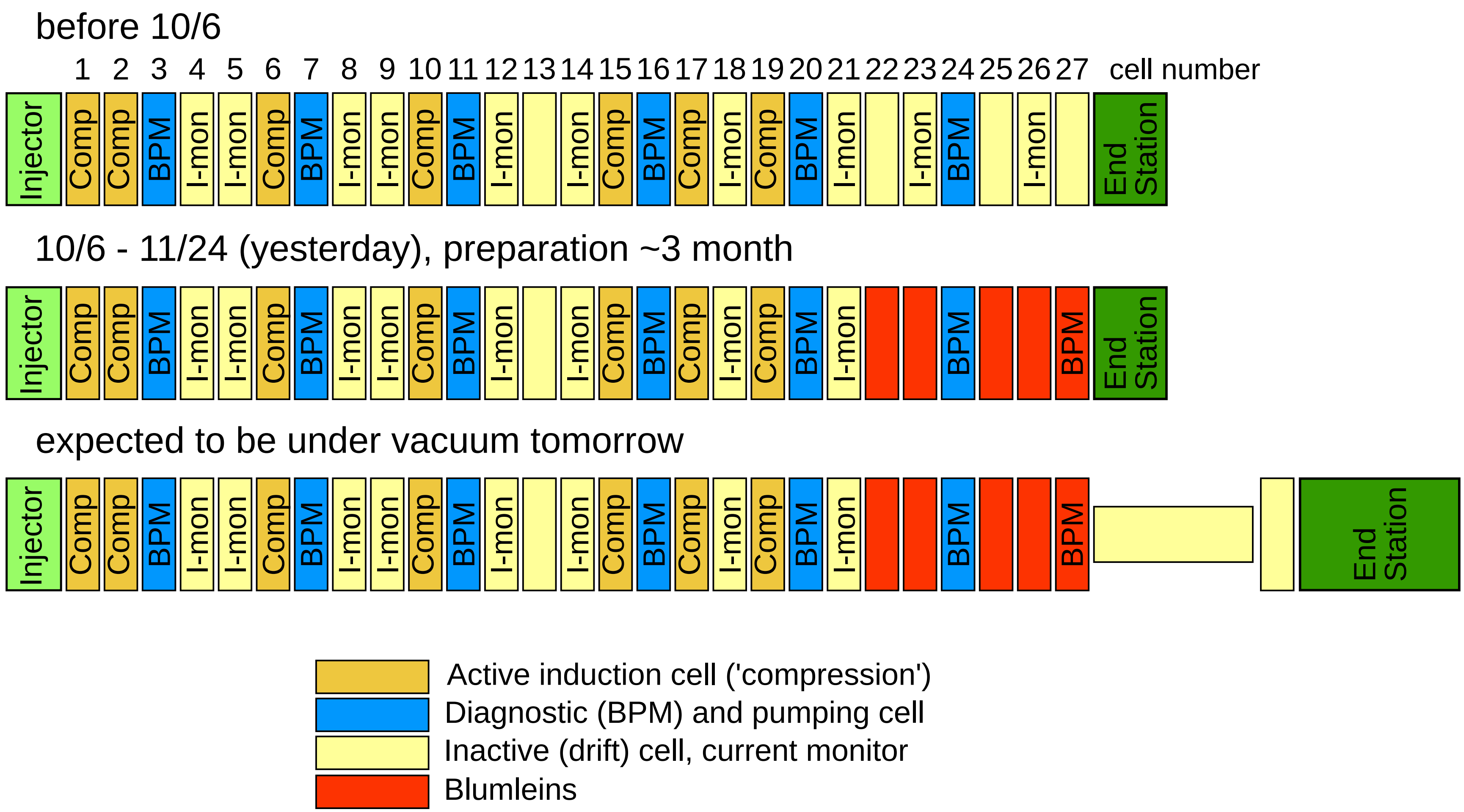


We accelerate and bunch the ion beam with tunable voltage waveforms

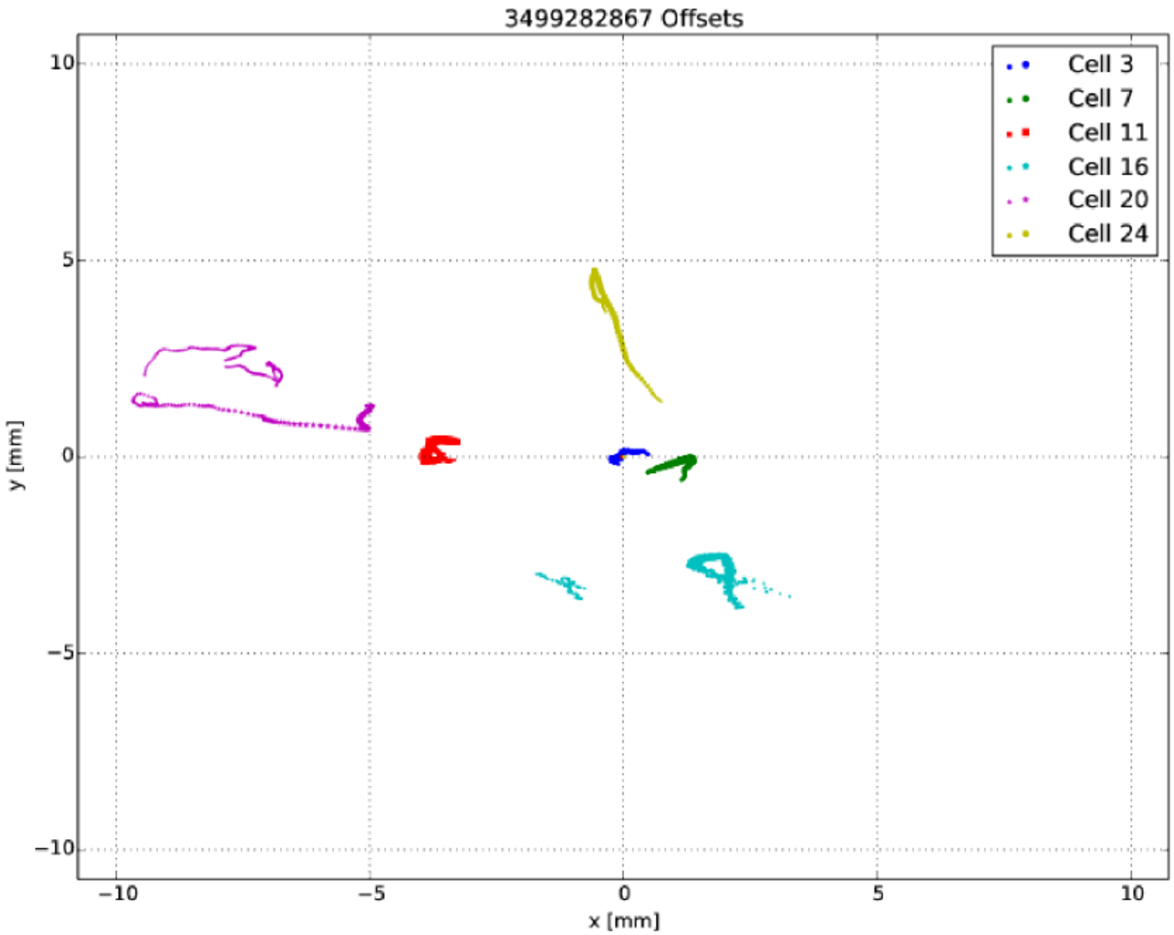




3 build-out phases at NDCX-II during this year



First test of beam steering using dipole magnets was successful



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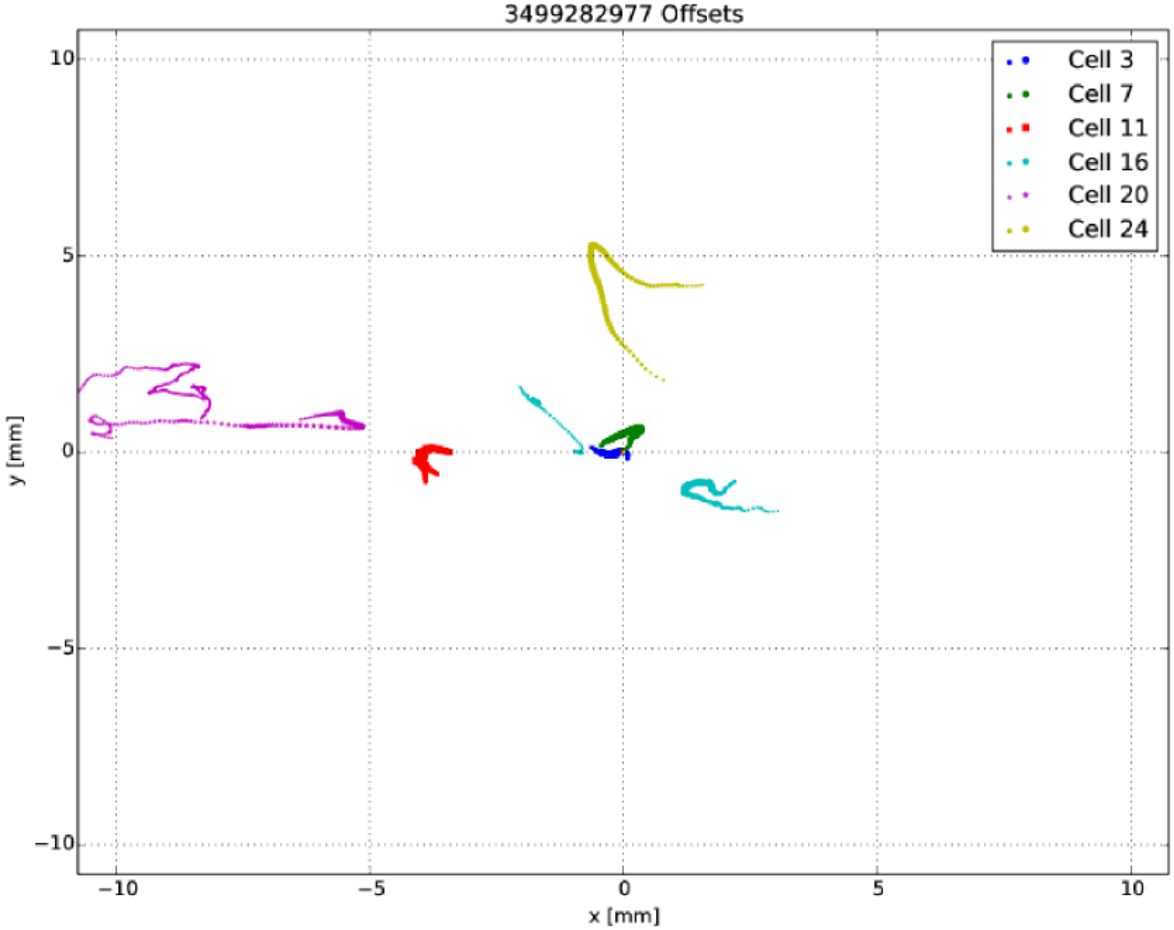

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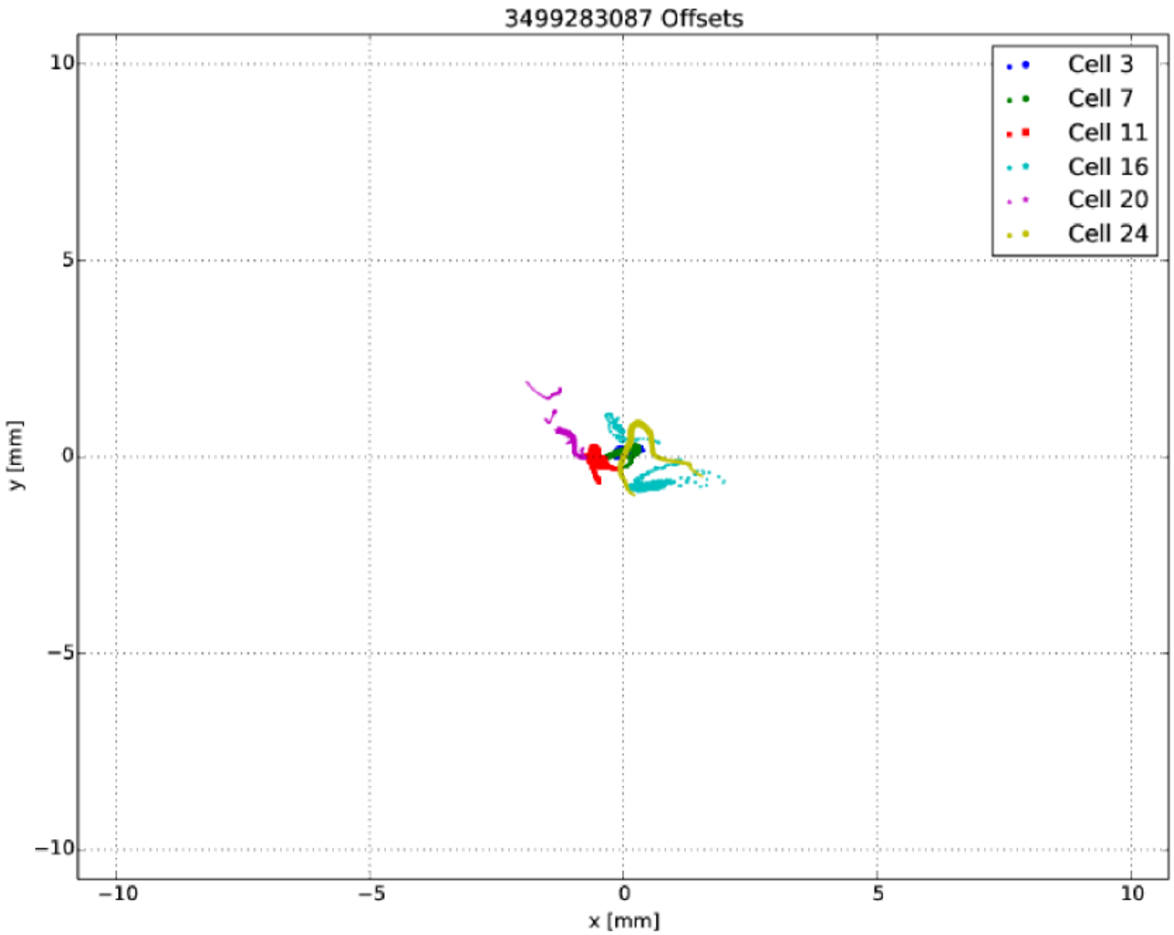
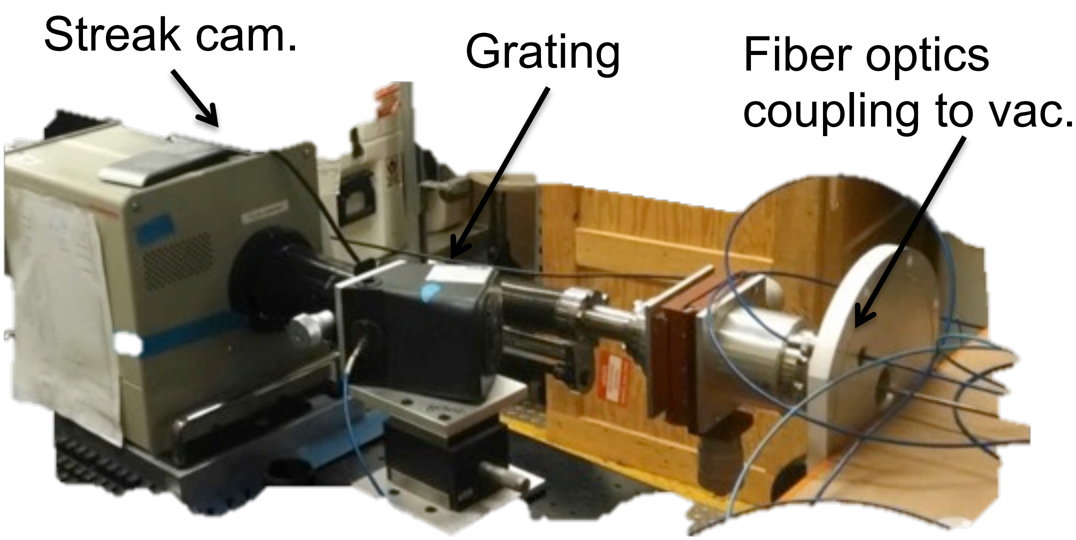


Experiments recording luminescence using a fast camera and a streak camera are being prepared



Streak camera coupled to a spectrometer grating

→ ps resolution

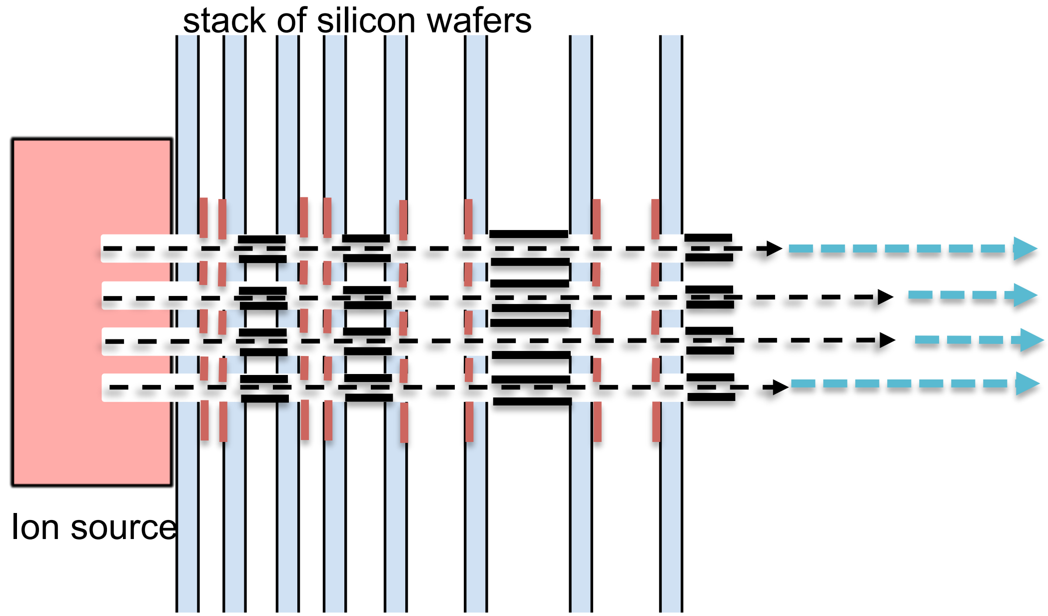
Enables study of target materials with fast optical centers.

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

We are considering:

- Ionoluminescence
- X-ray diffraction probes
- Electron diffraction
- Backscatter; RBS, Raman?

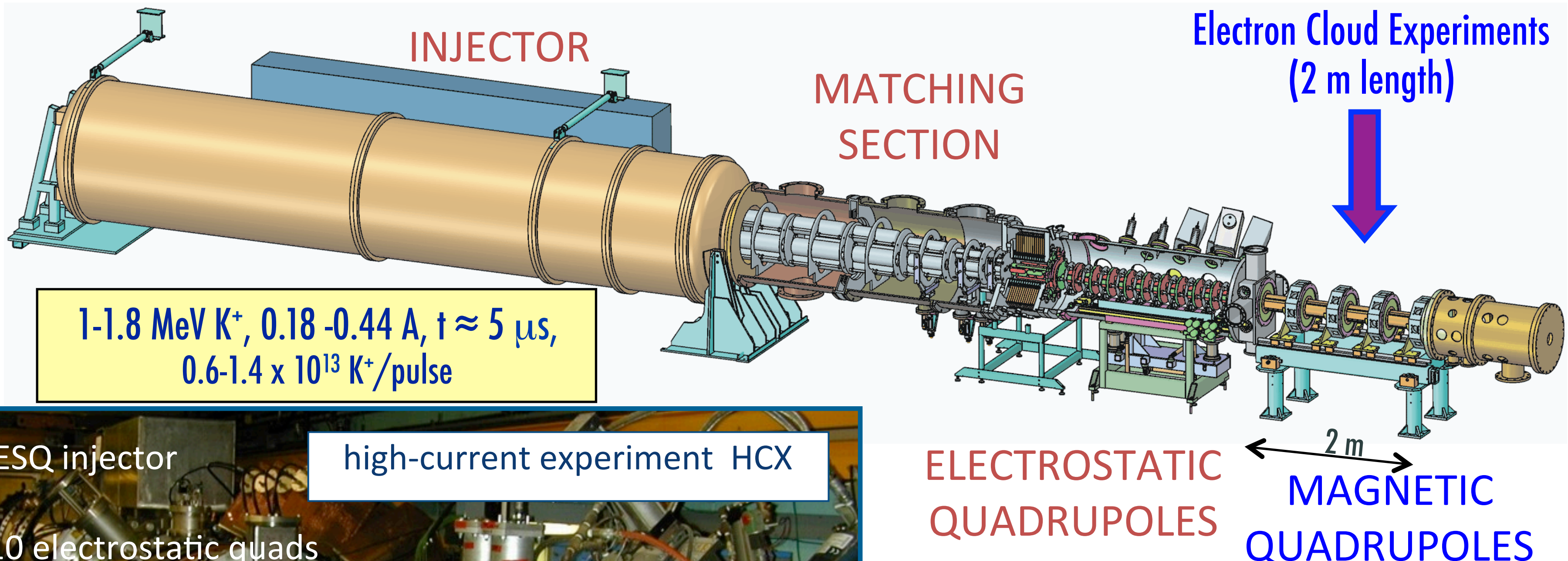
MEMS based Ion Beam Drivers for Fusion

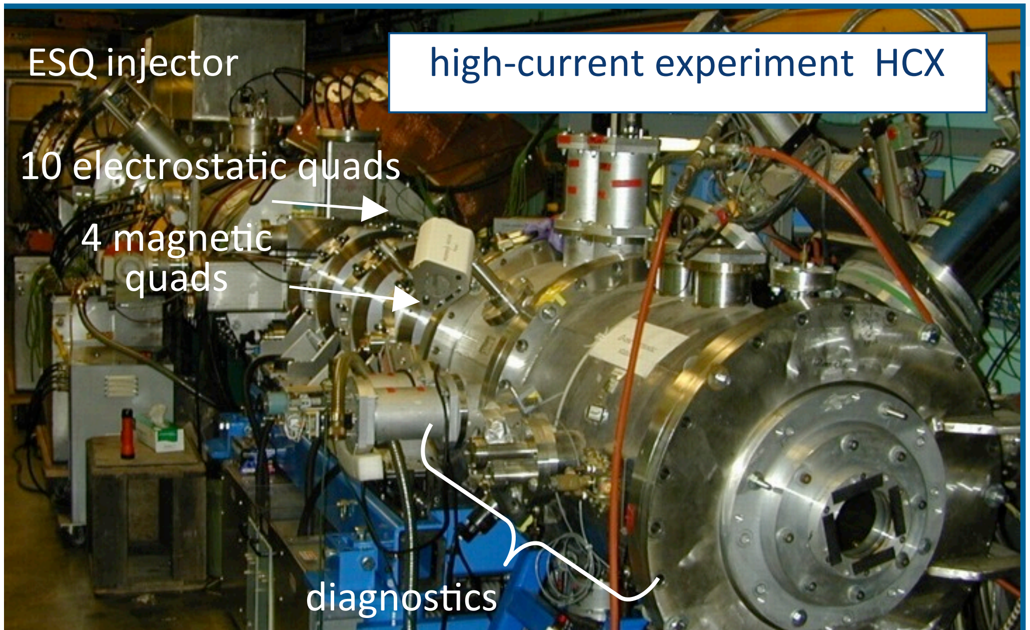


Gap electrodes are driven to high RF voltage for synchronous acceleration of ions. Beamlet holes and electrodes are formed by MEMS processing.

Ions travel through ~1 mm holes in wafer stacks

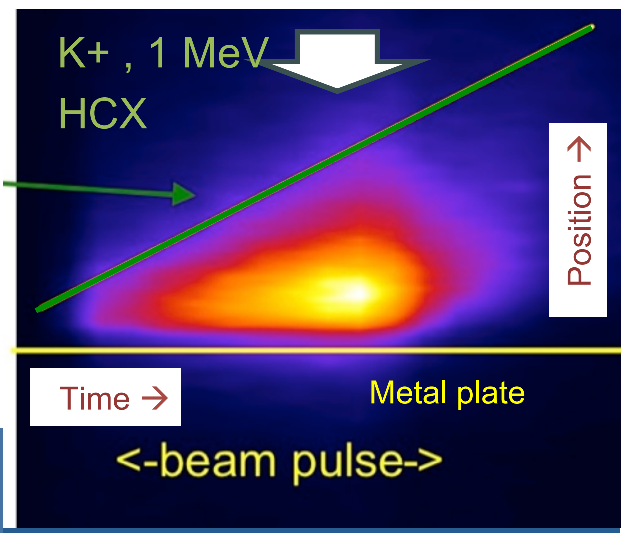
Driver scale beam transport experiments for HIF *(conclusion 2-8, Nat. Academy, 2013)*





Ions, e-, particle loss, desorption:

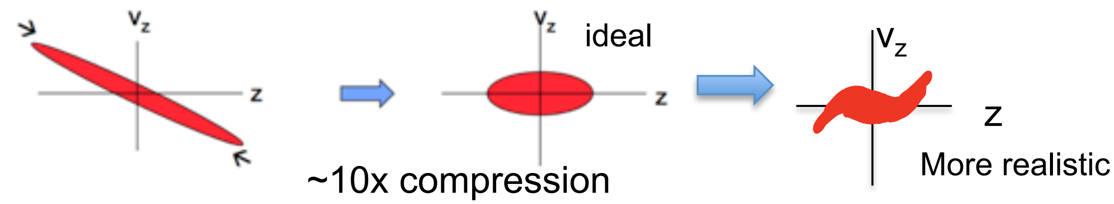
$v_{cloud} \approx 1.5$ mm/μs, mostly H_2

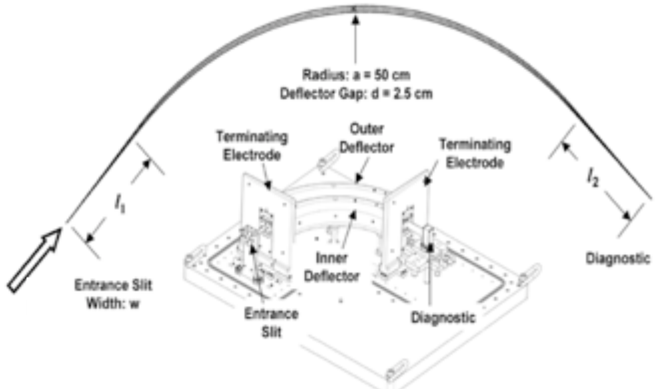


Kireeff-Covo, PRL (2006), Prost, PRST-AB (2005)

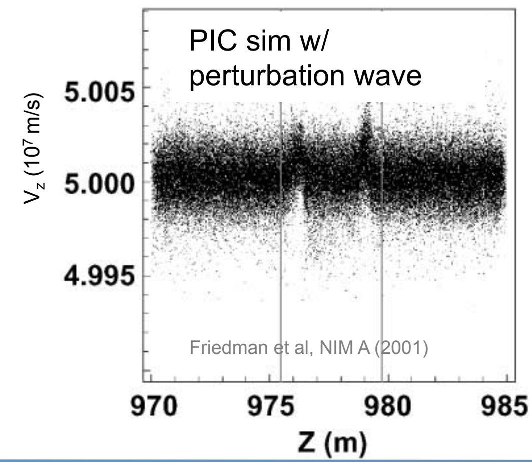
Demonstrate removing a large velocity spread from a high space charge beam via drift compression. Reduces chromatic aberrations in the final focusing elements.

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





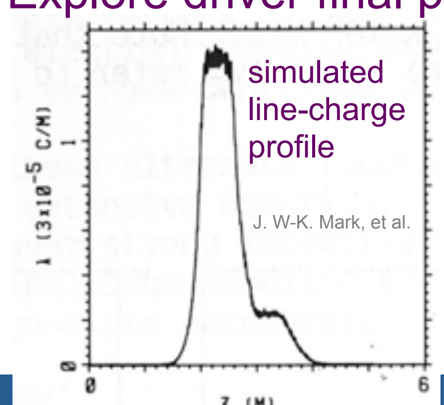
Waveform errors can launch space charge waves, and degrade the final energy spread and may cause particle loss. Detailed initial conditions must be included in simulations.

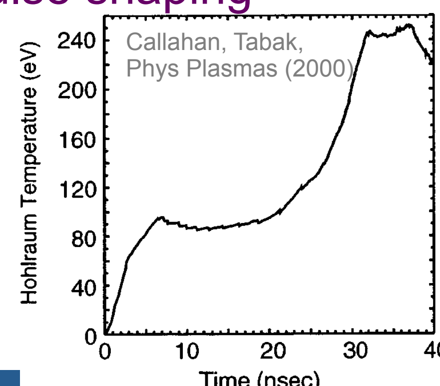


Pulse shaping: pump-probe for materials studies

Double pulsing @ NDCX-II (preliminary)

Explore driver final pulse shaping

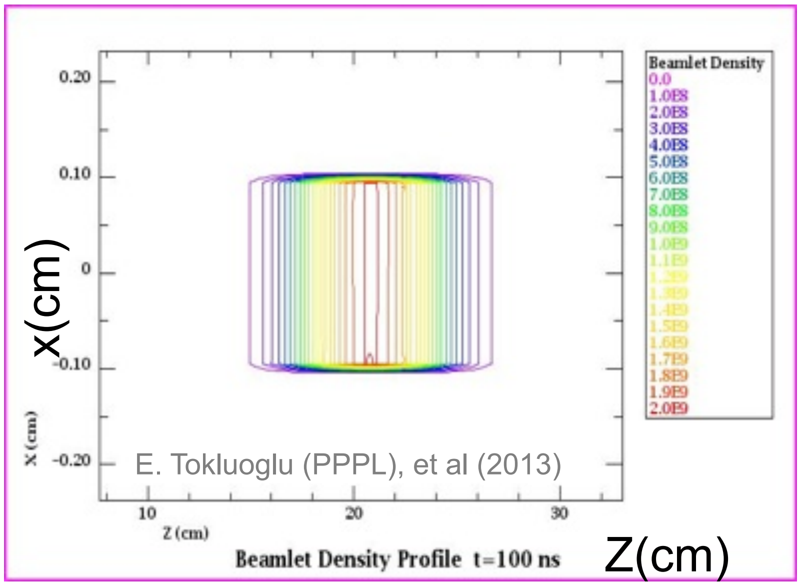




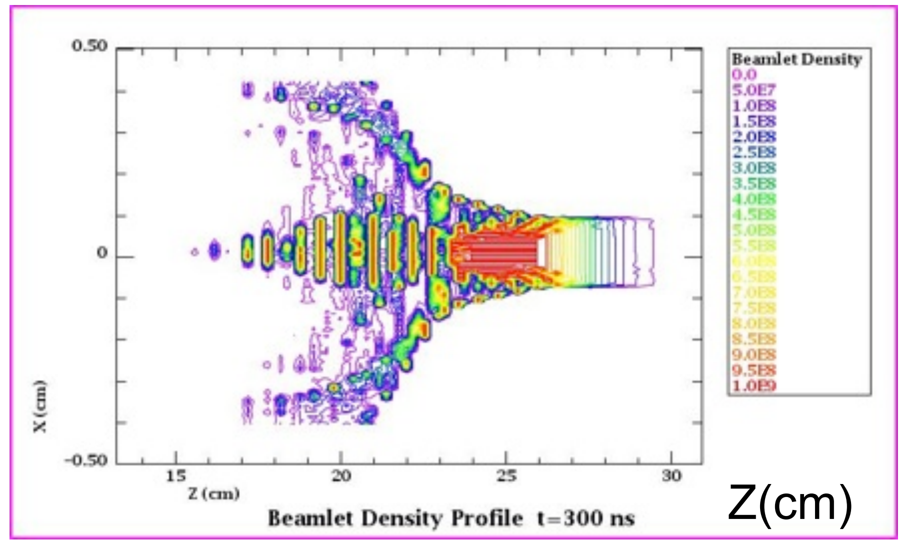
Exp connect to HIF parameters: Perveance, "tune depression", compression ratio) ~ a fusion driver.

Beam-plasma interaction: We will explore the transverse defocusing of the beam due to the two-stream instability

<u>Discovery science opportunity:</u> This has not been observed in high current ion beams.
<u>IFE science opportunity:</u> May be an issue for reactor chambers, depending on n_b and the background e^- /gas density.



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



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

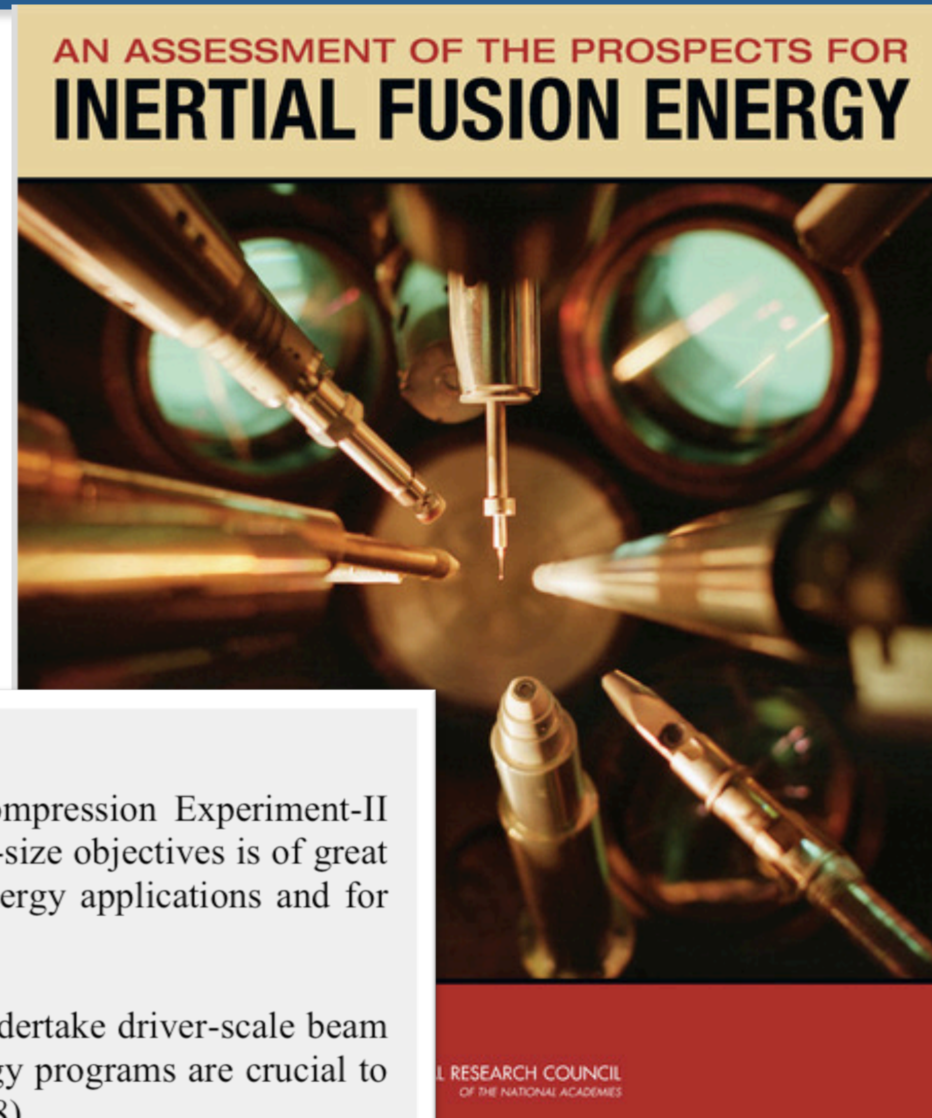
NDCX-II beam parameters for apertured beam r_b=1 mm.

Defocusing for small $\Delta v/v$.

But the defocusing effect is absent when the velocity spread is increased to ≈ few %.

Heavy ion driven inertial fusion energy research

- DOE FES waiting for NIF ignition
- US commitment to ITER
- NRC report (2013) is supportive of the HIF approach to IFE.



from the NRC report:

Heavy-Ion-Beam Drivers

Conclusion: Demonstrating that the Neutralized Drift Compression Experiment-II (NDCX-II) meets its energy, current, pulse length, and spot-size objectives is of great technical importance, both for heavy-ion inertial fusion energy applications and for high-energy-density physics. (Conclusion 2-7)

Conclusion: Restarting the High-Current Experiment to undertake driver-scale beam transport experiments, and restarting the enabling technology programs are crucial to re-establishing a heavy-ion fusion program. (Conclusion 2-8)

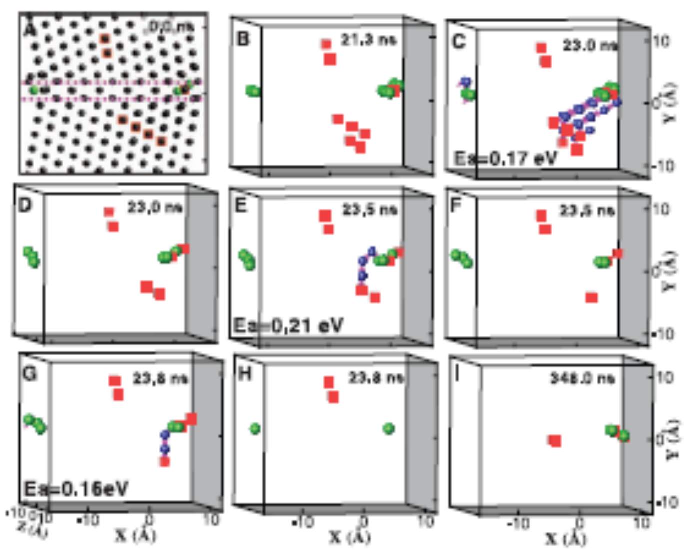
Efficient Annealing of Radiation Damage Near Grain Boundaries via Interstitial Emission
Xian-Ming Bai *et al.*
Science **327**, 1631 (2010);
DOI: 10.1126/science.1183723

(Los Alamos group)

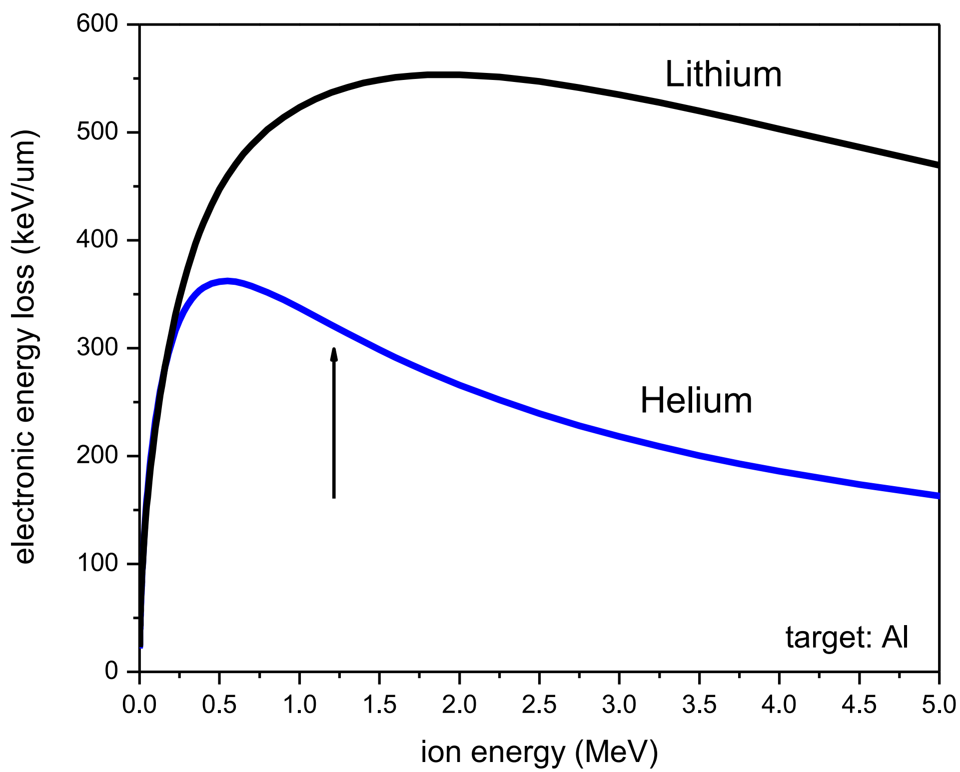
"Radiation damage spans from the atomic (nanometer, picosecond) to the macroscopic (meter, year) length and time scales.

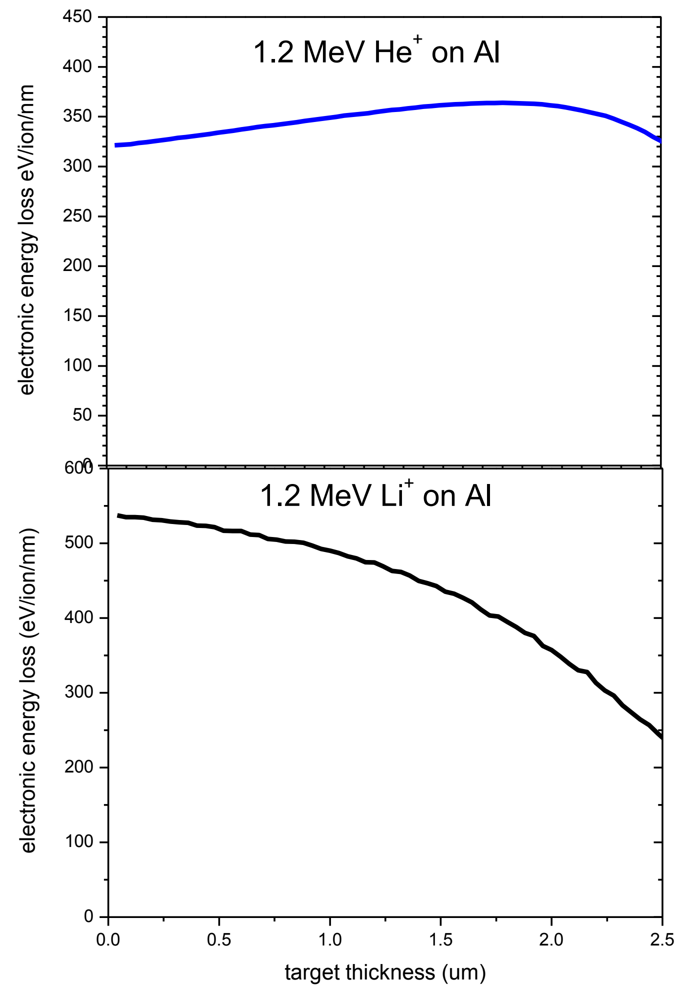
Critical processes involving individual point-defect migration are difficult to observe experimentally.

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



Very uniform heating over ~2 microns with 1.2 MeV He⁺ ions





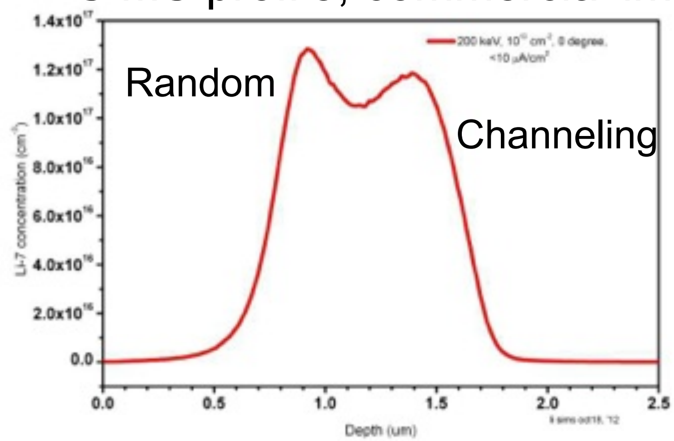
- Electronic energy loss as a function of ion kinetic energy in aluminum for He and Li ions (from SRIM)
- With 1.2 MeV He$^+$, we can neatly hug the Bragg peak

- Energy deposition as a function of depth in aluminum for He and Li ions
- Heating with 1.2 MeV He$^+$ is very uniform

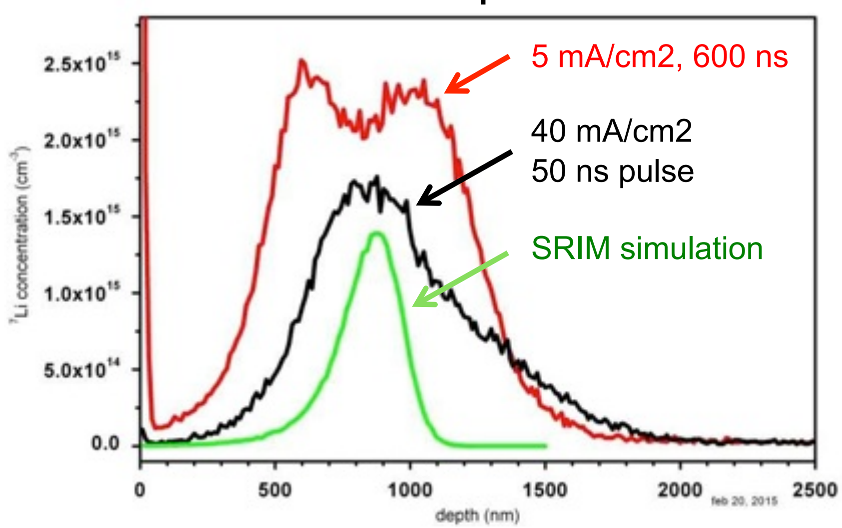
After bombarding with a few shots, ex-situ SIMS profiles show a dependence of the Li deposition range with the fluence

"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, $n(\theta, t)$

Ideas for soft x-ray spectroscopy for GF and NDCX-II

Goals:

- Time resolved
- Spectral info
- 100 eV to a few keV
- Broad band plasma emission from hot electrons maps to plasma temperature
- But need to resolve contributions from characteristic lines from e. g. from heavy impurities
- Line emission makes accurate temperature measurements using x-ray diodes with filter foils difficult and unreliable, thus the interest in a better solution

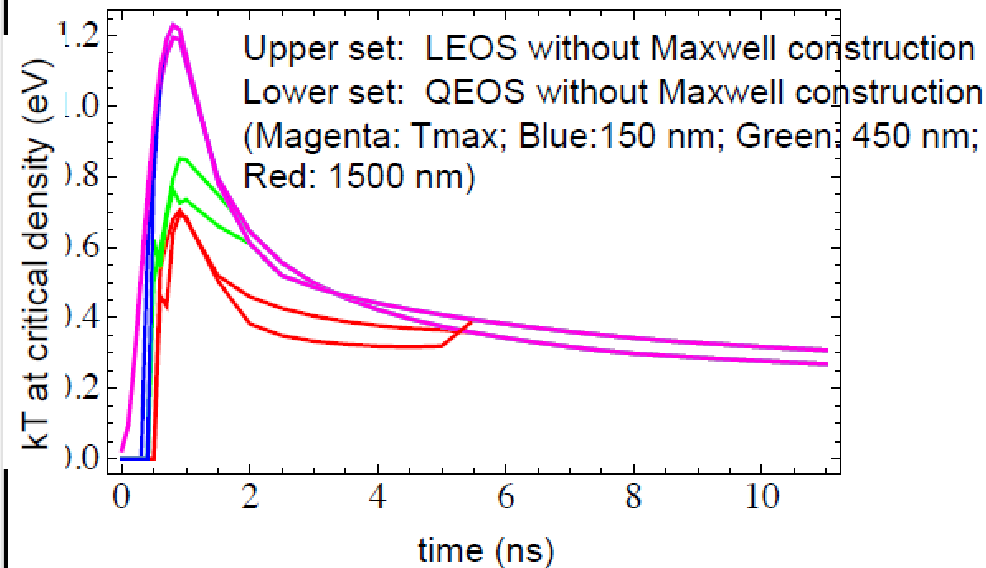
GF: accurate measurements of time dependent plasma temperature
x-ray source is compressing plasma torroid and plasma lifetime is a few hundred micro s

NDCX: 1 ns

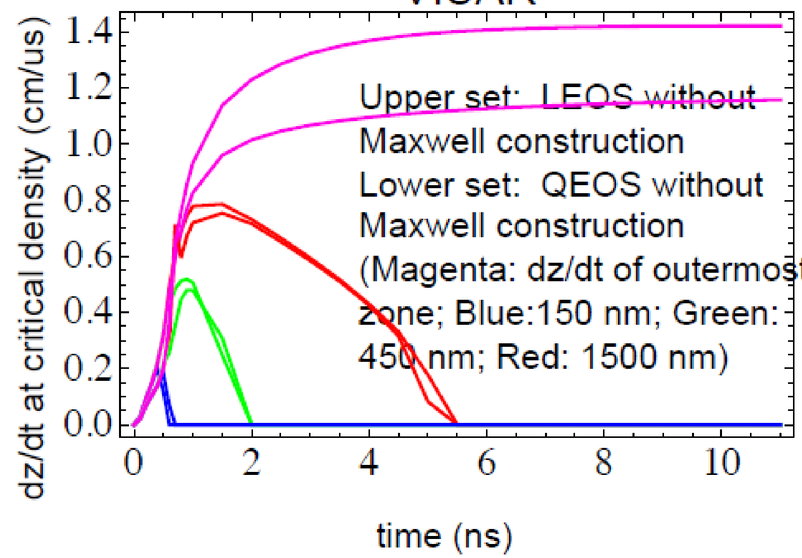
- grating spectrometer to disperse x-rays
- detect time resolved with x-ray streak camera (~400K from Hamamatsu)
- cheaper detectors?
- diodes are fast and could use arrays of diodes to assemble a spectrum
- issues: cost, robustness (mechanical and electrical noise when pistons are fired, …)

Diagnostics for temperature, velocity, and density can be compared to simulated diagnostics to distinguish between candidate EOS

Pyrometry



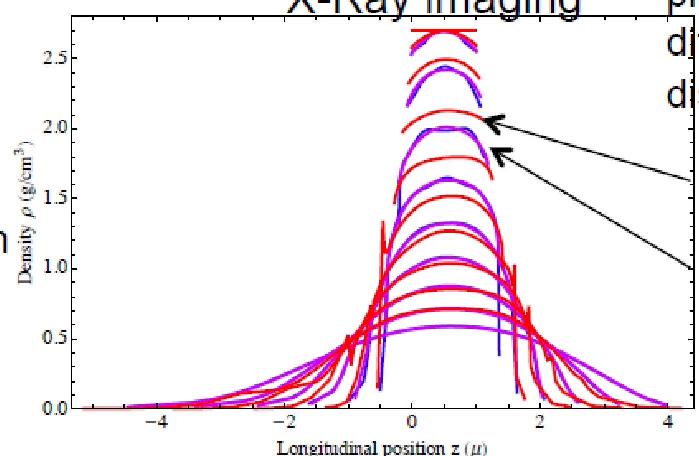
VISAR



X-ray imaging of density profile (lower, shown at 10 different snapshots) can distinguish between EOS

Multi-frequency (upper left) and multi-angle pyrometry measurements, together with multi-frequency Visar measurements (upper right) can distinguish between EOS candidates.

X-Ray imaging



Upper (in each pair): QEOS without Maxwell construction
Lower (in each pair): LEOS without and **with** Maxwell construction

(1.2 MeV, 12 J/cm^2, 1 ns Li$^+$ ion beam on Al target)

(Snapshots separated by 0.1 ns