High Current, High Intensity Beams
&
New Accelerator Concepts at Berkeley Lab

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Fusion and Ion Beam Technology Group

Lawrence Berkeley National Laboratory

Proton Accelerators for Science and Innovation,
Fermilab, 2015-11-12

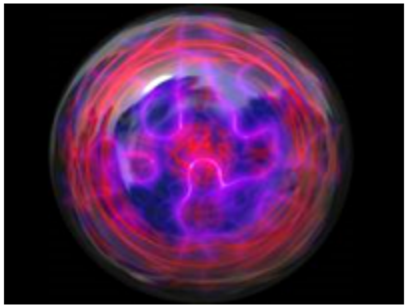
Outline

Present two ongoing projects at LBNL with connection to proton beams and high power outputs.

- MEMS based compact RF accelerators
- Neutralized Drift Compression Experiment II

Novel Accelerator Concept for Fusion Experiments funded by ALPHA project at ARPA-E

- ARPA-E ALPHA (Accelerating Low-Cost Plasma Heating and Assembly)
  - Exploration of magnetized target fusion and fusion at intermediate densities
- Ion beam drivers for fusion
  - Heavy ion fusion (HIF): ~GeV, ~10^2 A/beam
  - Magnetized target fusion (MTF): ~MeV, kA-MA
  - …

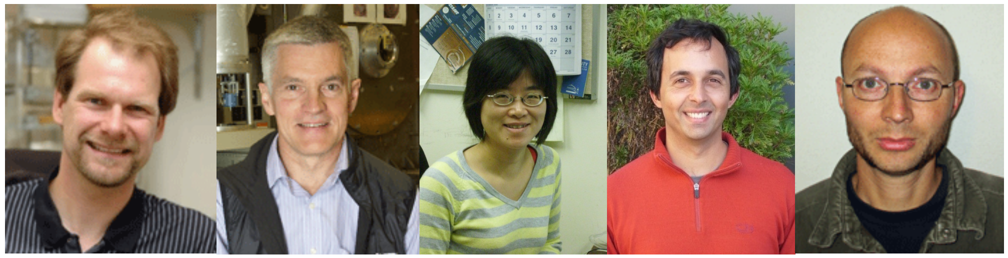


"This program seeks to develop and demonstrate low-cost tools to aid in the development of fusion power, with a focus on approaches to produce thermonuclear plasmas in the final density range of 10^{18}-10^{23} ions/cm^3."

- http://www.arpa-e.energy.gov/?q=arpa-e-programs/alpha

Projects is a collaboration between LBNL and Cornell

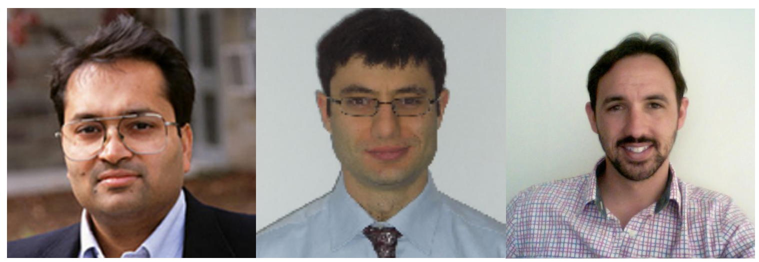
Accelerator Technology and Applied Physics Division @ LBNL:



Thomas Schenkel, Peter Seidl, Qing Ji, Arun Persaud, Will Waldron

http://ibt.lbl.gov

Sonicmems @ Cornell:

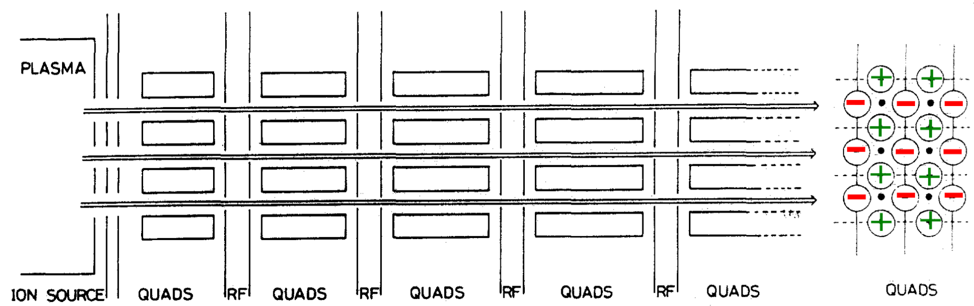


Amit Lal (Co-PI), Serhan Ardanuc, Joseph Miller

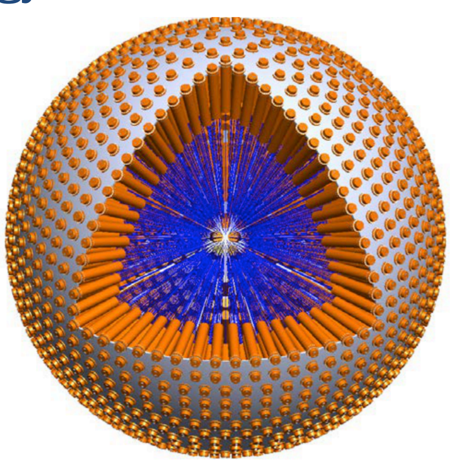
http://www.sonicmems.ece.cornell.edu/

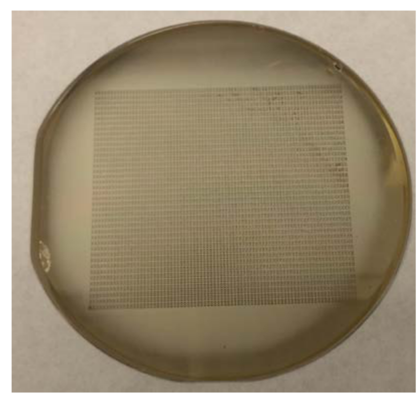
MEMS based ion beam drivers for magnetized target fusion

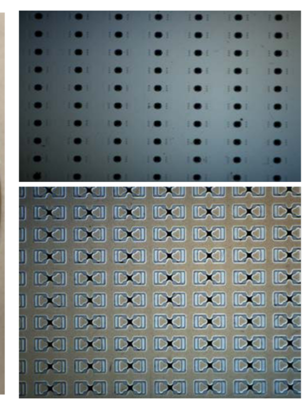
- We aim at a proof of concept with ~100 beamlets and mA's of ion currents at ~100 keV and at establishing a scaling path for MTF drivers
- We envision that there will be many applications for this technology



MEQALAC, Thomae et al., 1989





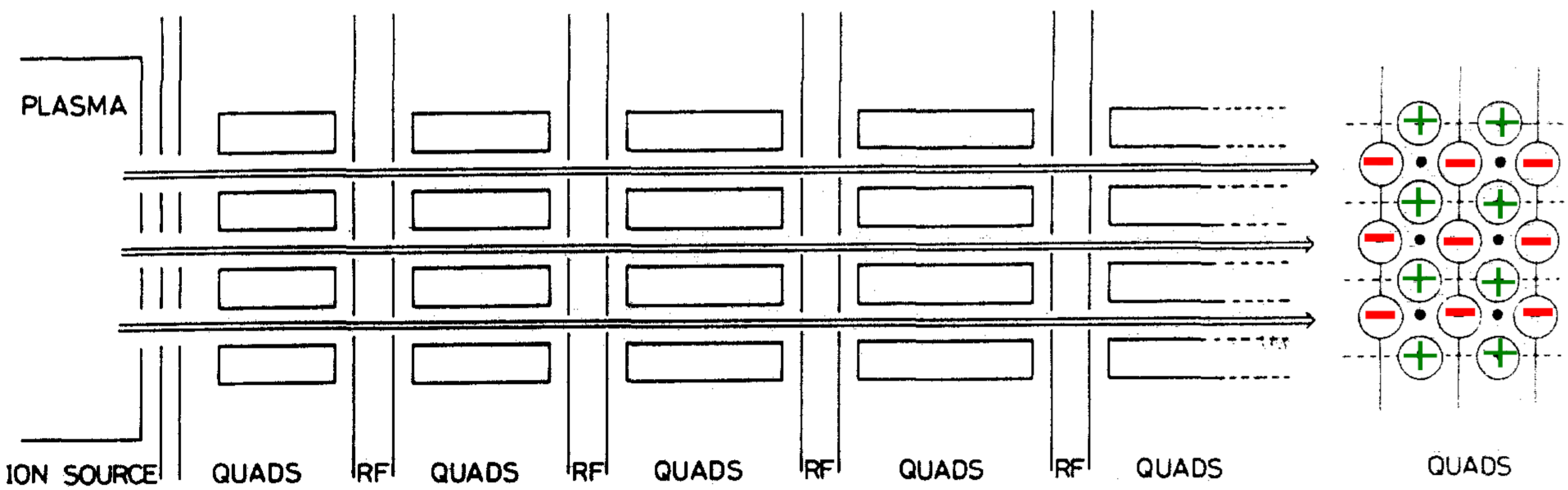


Bottom View

Top View

MEQALAC concept from 1980s exploits the many beamlets idea

Multiple-Electrostatic-Quadrupole-Array Linear Accelerator



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

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

Space charge limits can be beaten by dividing the beam into many beamlets

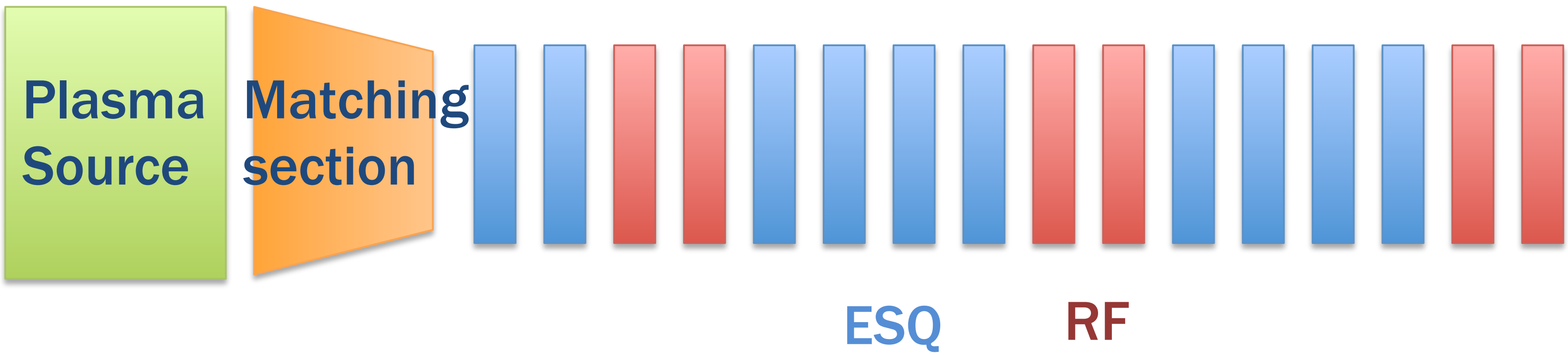
- Transport of very intense ion beams is strongly affected by space charge forces that can lead to beam divergence

- 6D – phase space density ~ f^2/β^3 A/Z (f=frequency, β=velocity)
- Max current (long.) for quadrupole focusing ~ $(\beta\gamma)^3$ A/Z
- Max current (trans.) for quadrupole focusing ~ β^2 E/f
- Current not depending on beam parameters (e.g. bore size)

- To get bright beams, start with low β → low current
- Electrostatic quadrupoles can be scaled down (no dependency on bore diameter)
- Use many, smaller-diameter beamlets to get desired current

Maschke, BNL-51022 (1979)

Basic design consist of a lattice of ESQs and RF accelerator sections

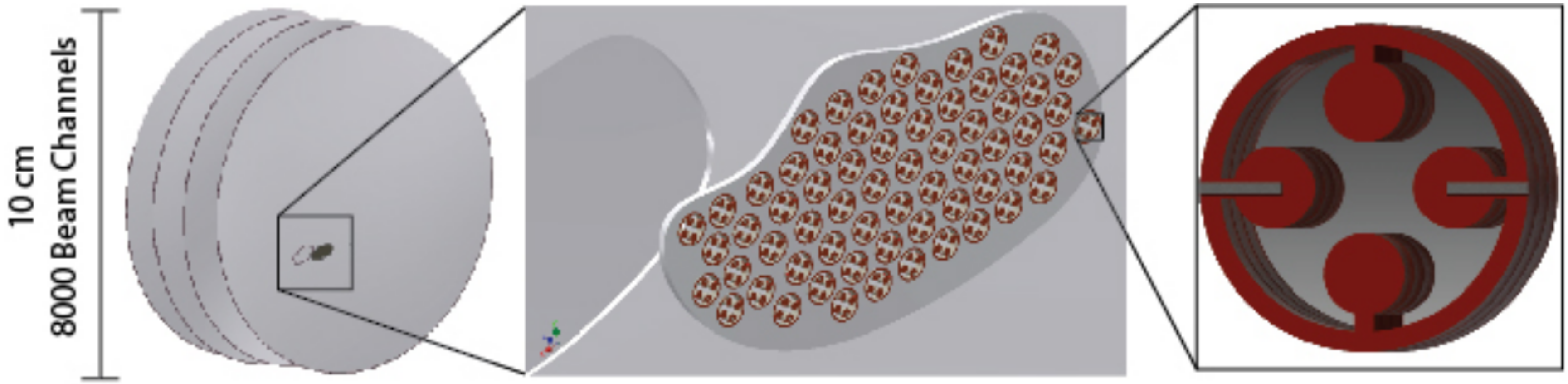


A matching section will guide the beam from a plasma source into a lattice structure.

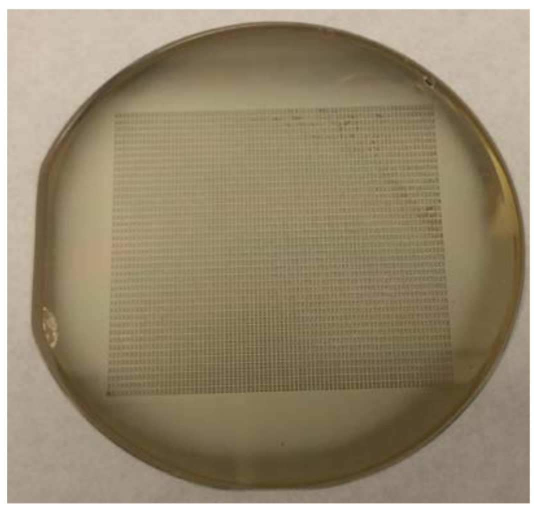
Goals:

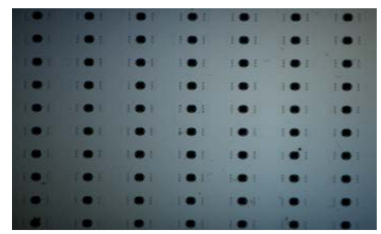
- **Show transport and acceleration**
- **Show scalability**

Arrays of electrostatic quadrupoles can be produced in silicon wafers with unit cells of the order of 1 mm

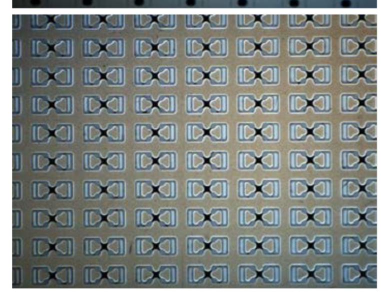


Prototype





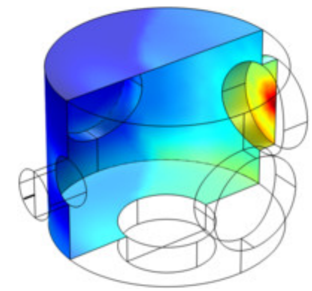
Bottom View



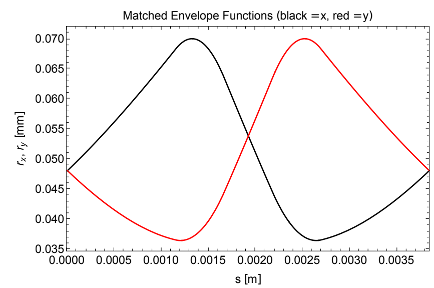
Top View

Current design phase relies on simulations and initial experiments using single test structures

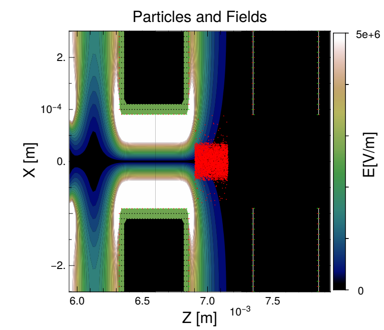
- Comsol Multiphysics for gas flow simulations
  - Input to estimate particle loss, desorption, and beam-gas interaction



- Envelope codes for fast beam transport simulations

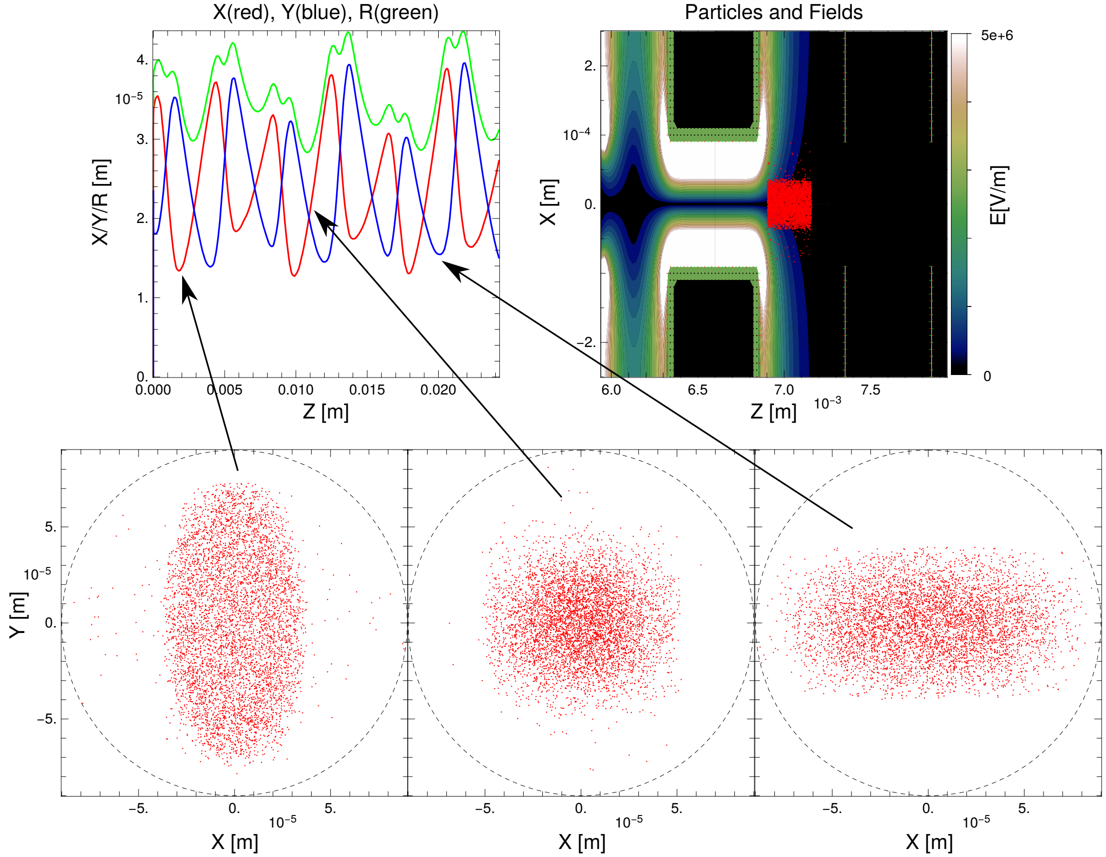


- Warp3D for full particle trajectories, for example, full space charge simulation, pulsed beam, emittance growth



- IGUN for beam extraction from plasma

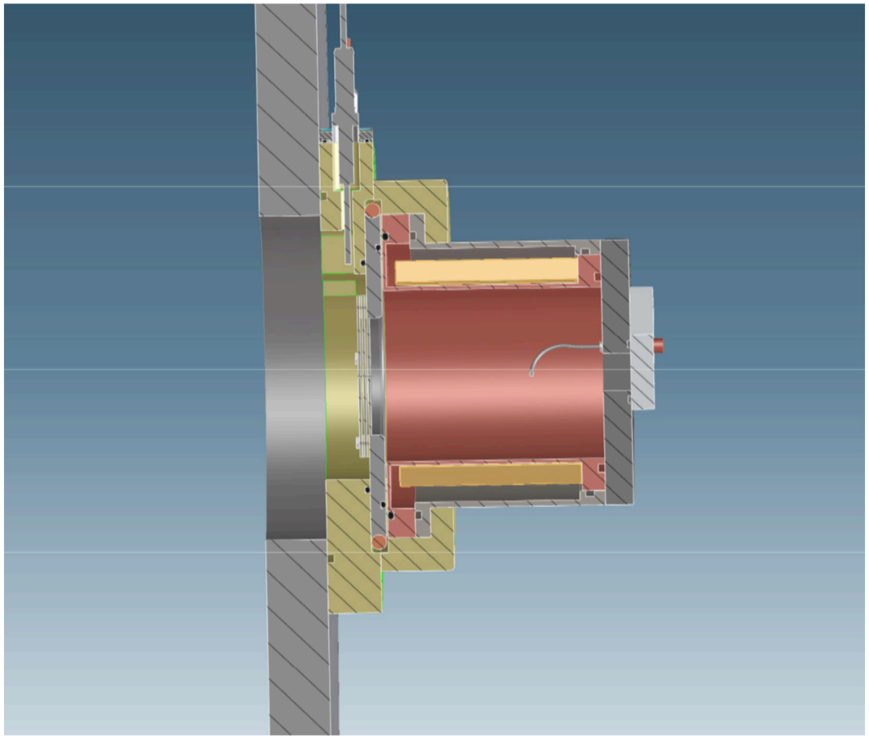
Particle-in-Cell simulations give more details: full 6D phase-space



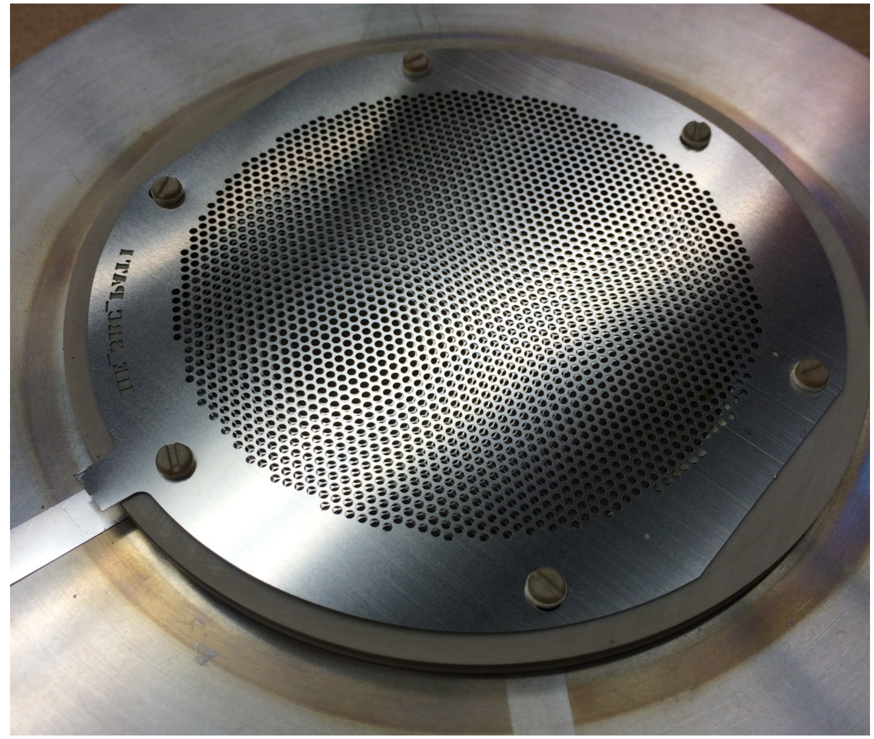
Warp3D (warp.lbl.gov)

- Correct handling of space charge effects
- Background gas interaction
- Secondary electrons
- Emittance growth and particle loss
- Longer runtimes (tens of minutes)
- Access to LBL clusters

Multicusp plasma ion source with multigrid extraction for uniform plasma extraction over several cm



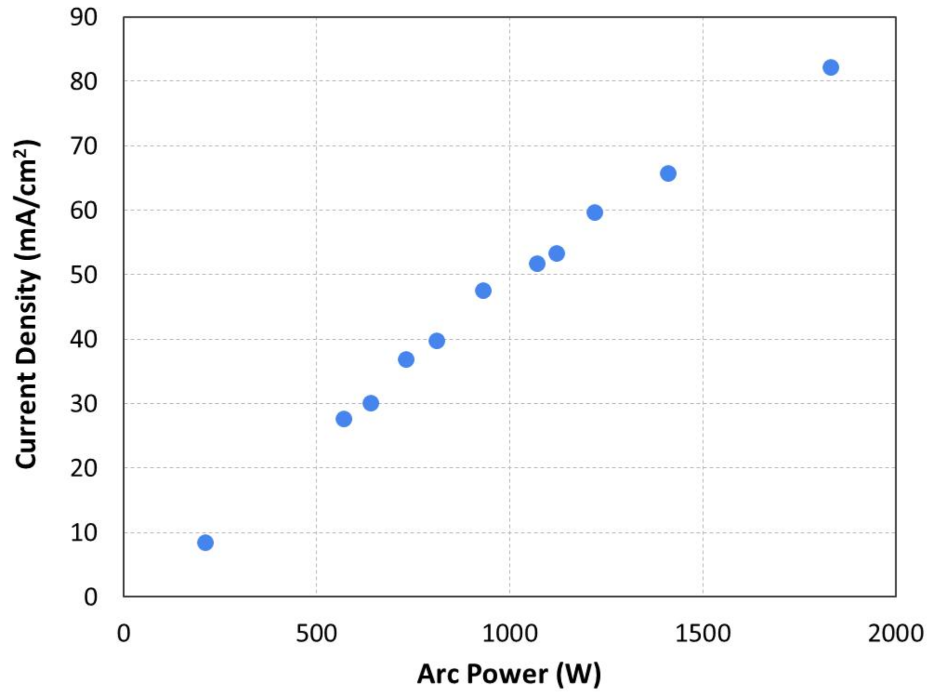
Filament driven gas ion source with multicusp magnets for plasma confinement



Multigrid extraction grids to extract multiple beamlets

Current levels achieved with multi-grid plasma source

Measured He^+ current density



The expected Xe^+ current density is $\geq$ 10 mA/cm^2

Exciting opportunity with applications outside of fusion drivers

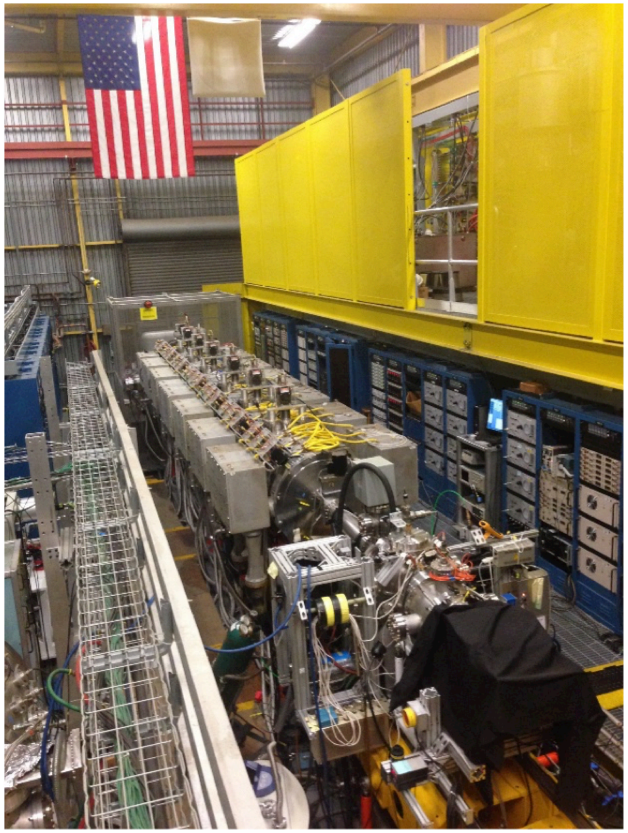
- There are many applications for this technology
- Not all need multi-beamlet approach
- 10μA-100mA, 1 to tens of MeV ions produced with low voltages (~kV) in a few meter long structure could be used for:
  - Ion beam analysis in material sciences
  - Ion implantation
  - High yield neutron generators (for example for national security applications)
  - …

Outline

- MEMS based compact RF accelerators
- Neutralized Drift Compression Experiment II

The Neutralized Drift Compression Experiment II

- Scientific goals
- The accelerator
- Current status



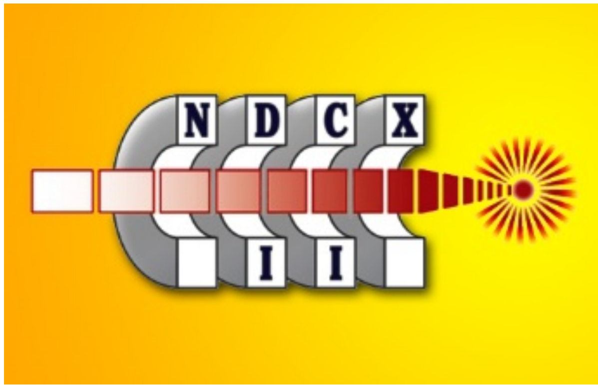
Collaboration between LBNL, LLNL, PPNL

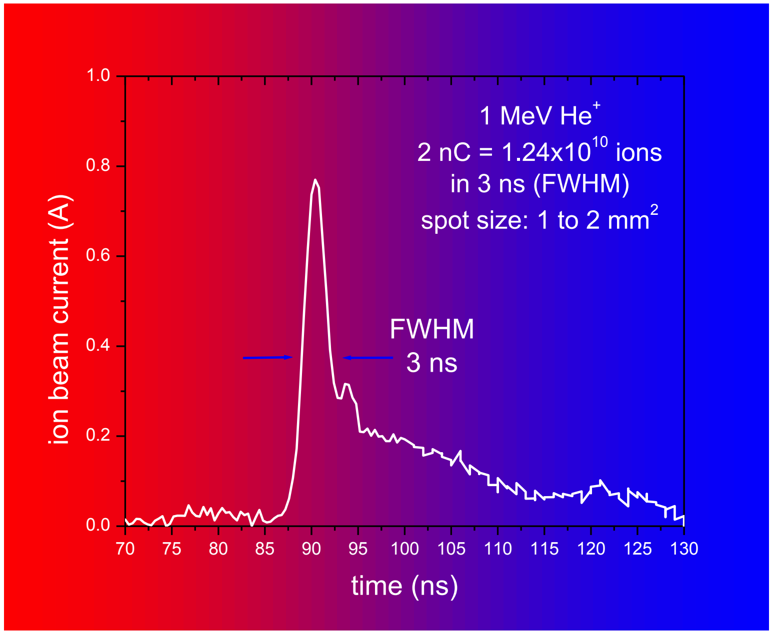
Funded by DOE-FES

The Neutralized Drift Compression Experiment II

Beam Characteristics:

- 1.2 MeV
- He, Li, K
- Several nC
- Short pulses (2-3 ns)
- Spot size 1-2 mm

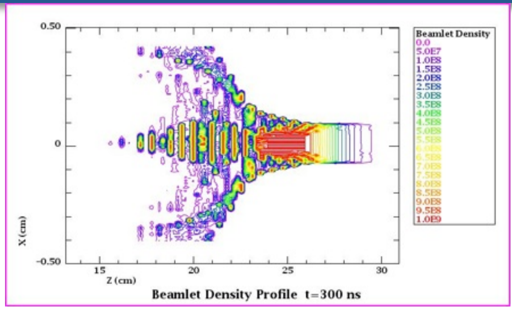


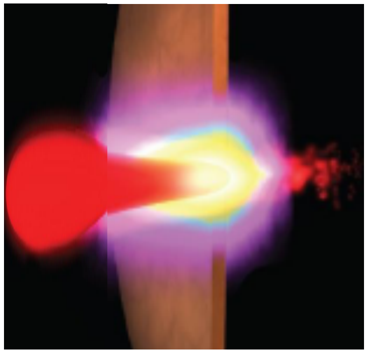


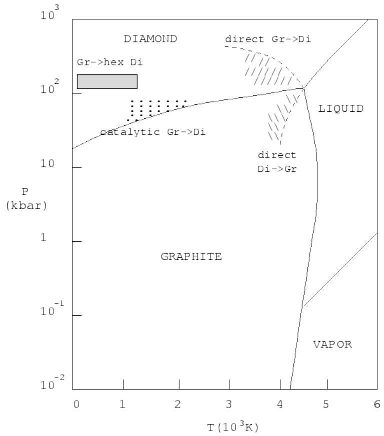
Possible to H, D, Ne, etc.
Possible to upgrade to 3 MeV

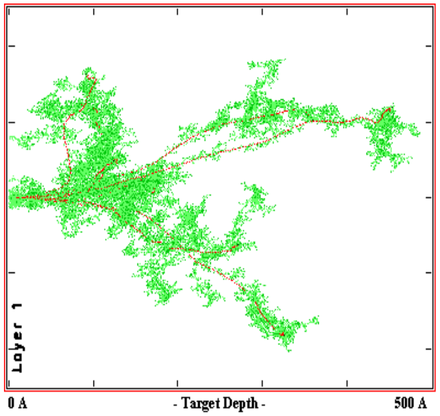
Short, intense ion pulses for current science drivers

- Beam Physics
- Warm Dense Matter Physics
- Defect Dynamics
- Extreme Chemistry



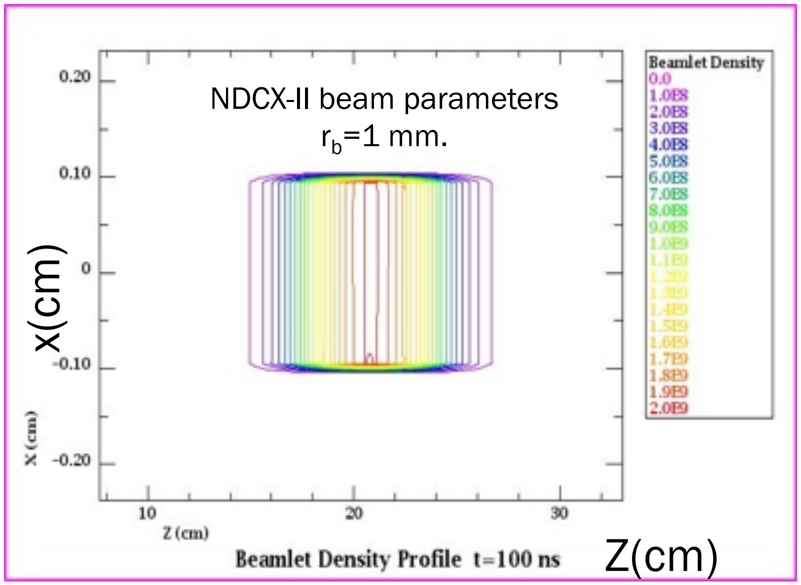




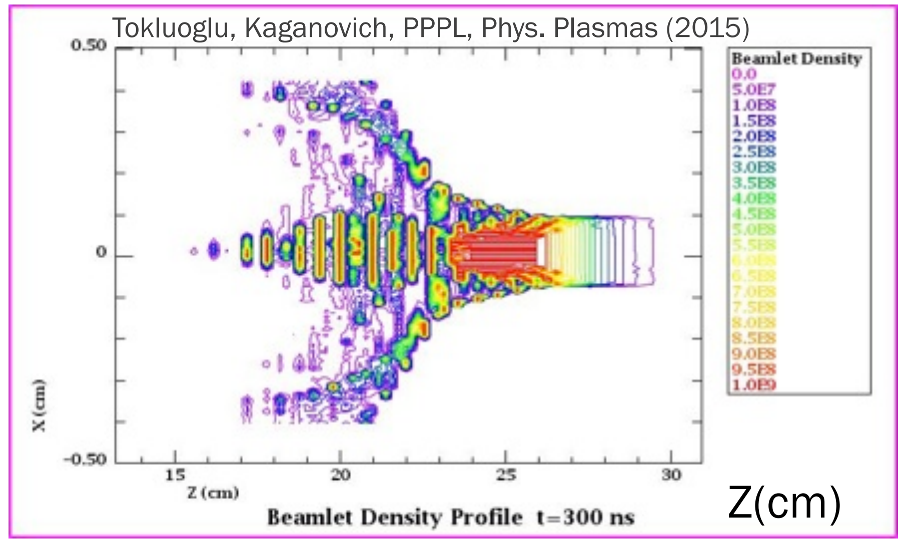


Two-stream instability of an ion beam propagating in background plasma predicted

- **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.**



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



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

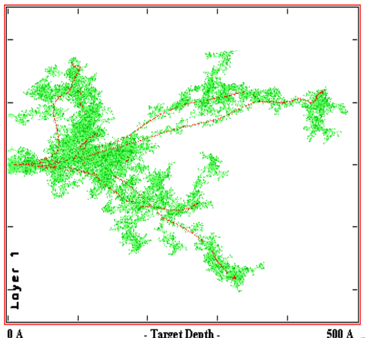
Defocusing when Δv/v is small.

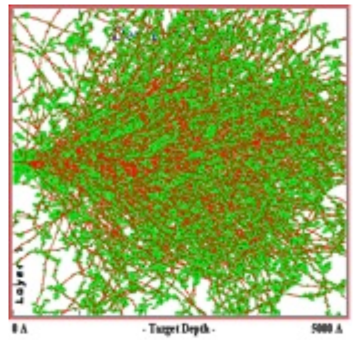
Goal: observe transverse defocusing and longitudinal self-bunching of beam

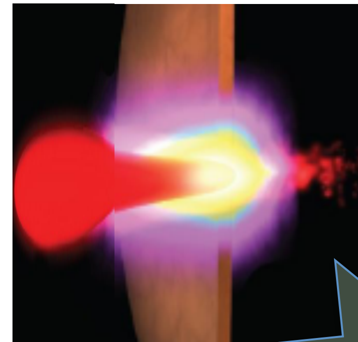
NDCX-II provides uniquely intense, short ion pulses for materials and warm-dense matter research

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

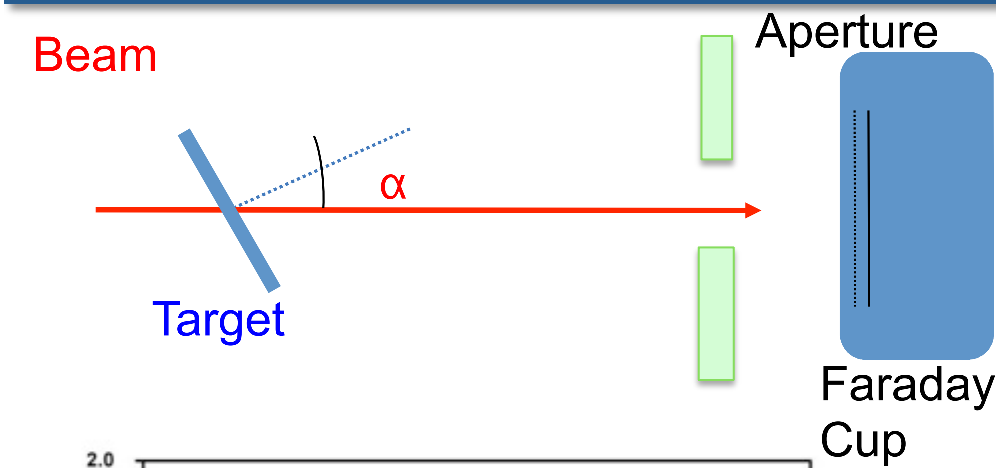
~50 nC, 1.2 MeV, ~1 mm^2, ~1 ns

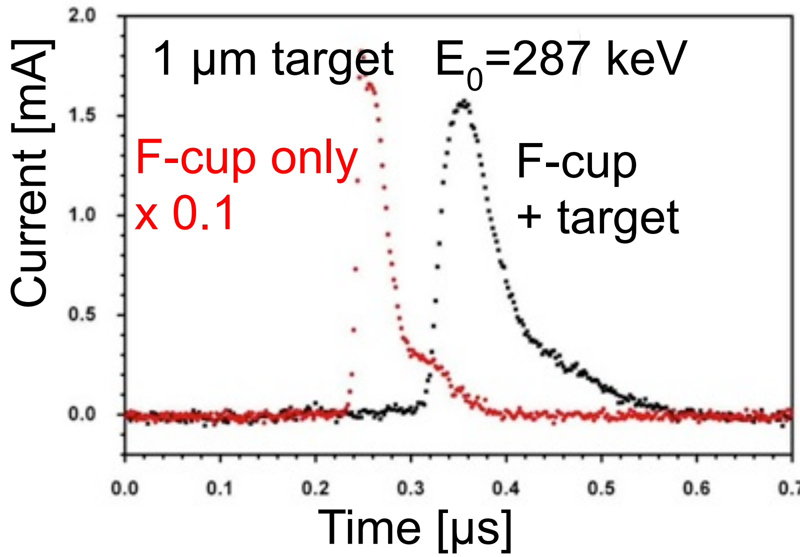
1-30 nC, 0.3 -1.2 MeV, few mm^2, ~1-20 ns

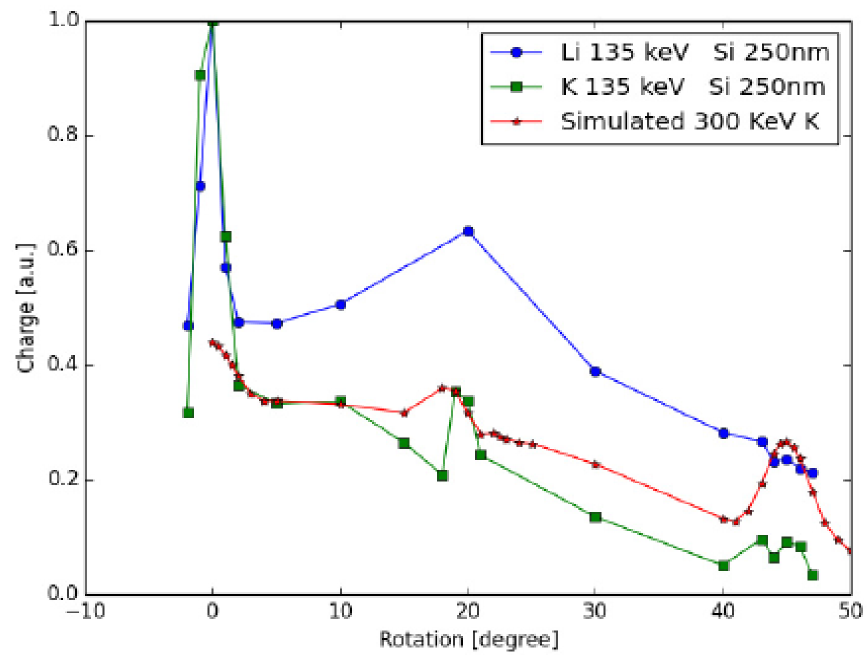
- Ions deposit energy via collisions with target electrons and nuclei
- Ion driven heating is uniform for ion energies near the Bragg peak in stopping power

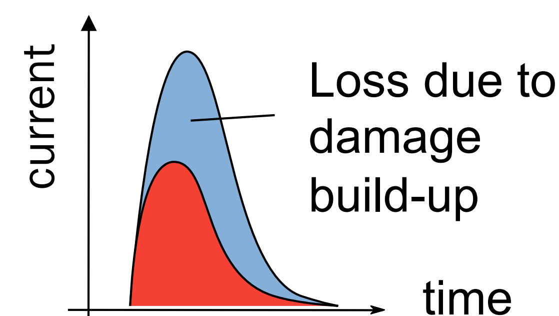
Fusion relevance
- Intense beams and beam-plasma physics
- Materials studies for fusion reactors
- Ion heating of matter (WDM)

Opportunity to probe materials response to ionizing radiation (t, λ), e.g., channeling of ions in crystals





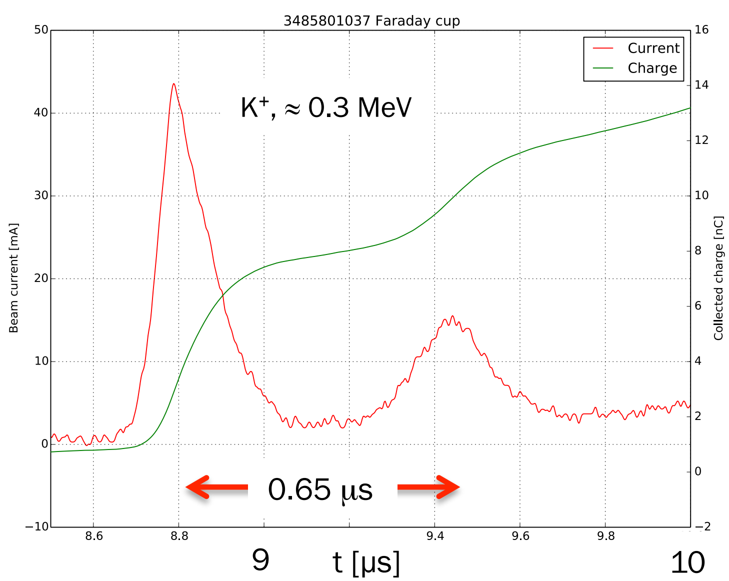


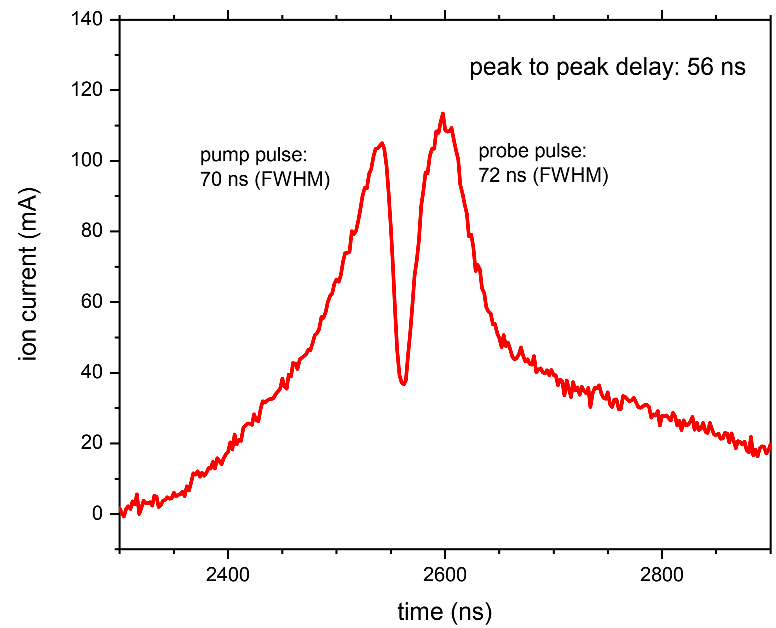


T. Schenkel et al., *Towards pump–probe experiments of defect dynamics with short ion beam pulses*, NIM B 315 (2013) 350

Towards pump-probe experiments of defect dynamics in solids with short ion beam pulses

Pulse shaping, double bunches: Probe for materials studies

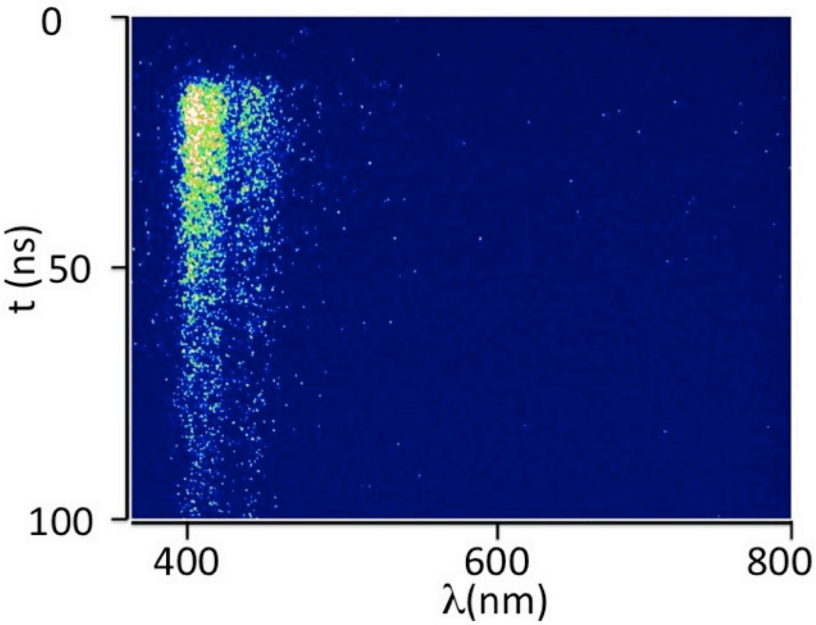




Our pulsed ion beam accelerator might allow formation of well separated, narrow pulses with variable delay for pump-probe experiments with two ion pulses (in progress)

With pulsed ion beams we can access extreme chemistry, the materials physics of radiation and warm dense matter research

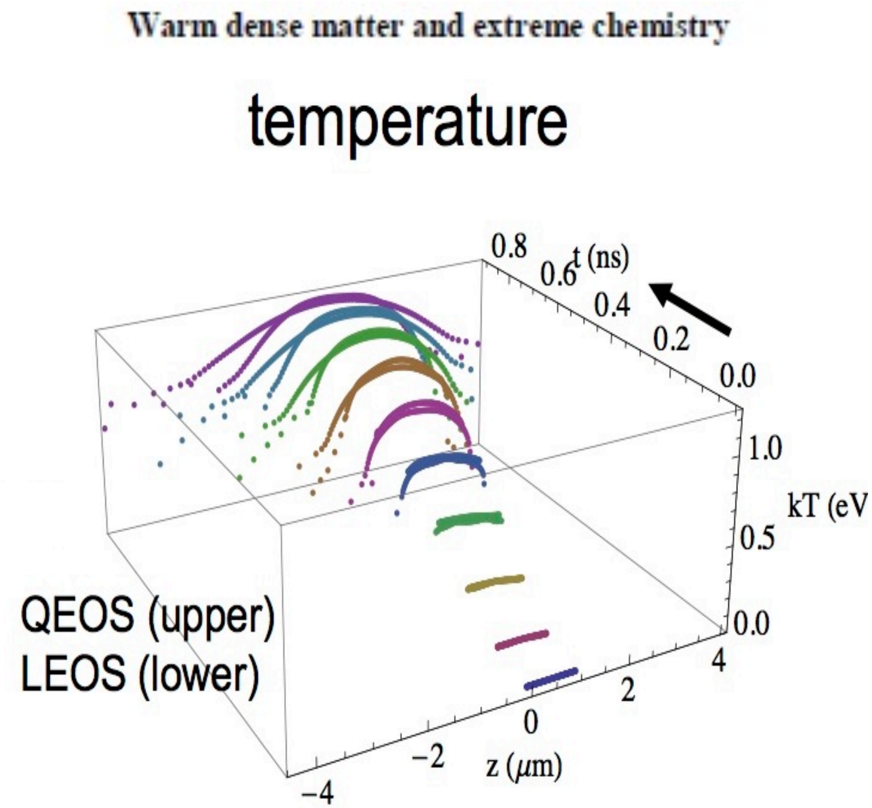
Novel opportunities with short, intense pulses to probe defect dynamics



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

Seidl, et al., NIM A, **800**, 98 (2015)
http://arxiv.org/abs/1506.05839

NDCX creates WDM with ions, complementing laser driver research.

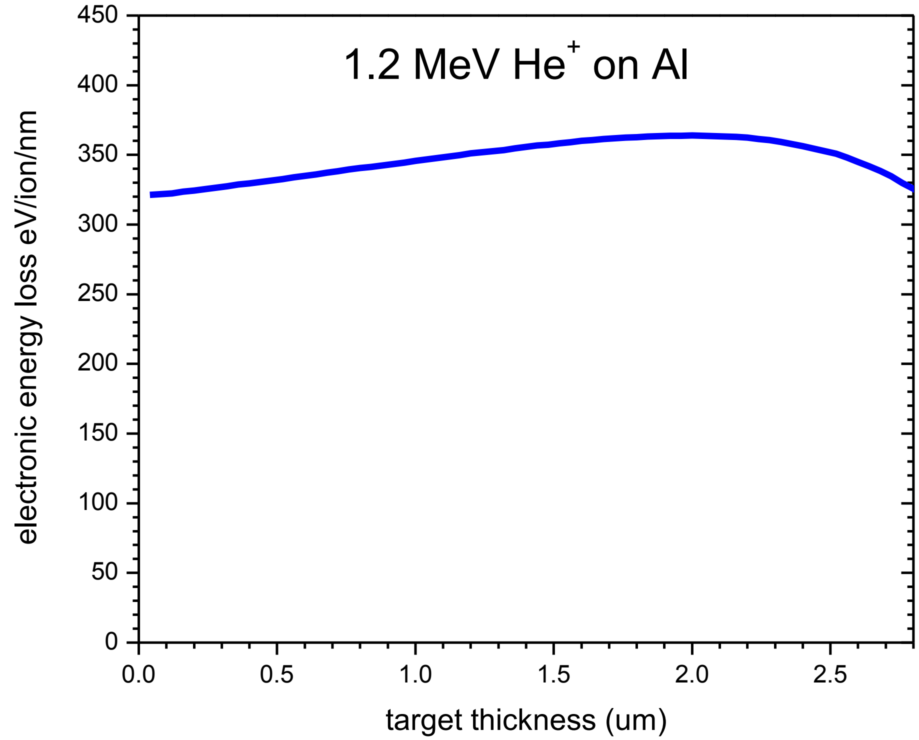


Assumed fluence: 12 J/cm^2;
1.2 MeV Li → Al target (1 ns)

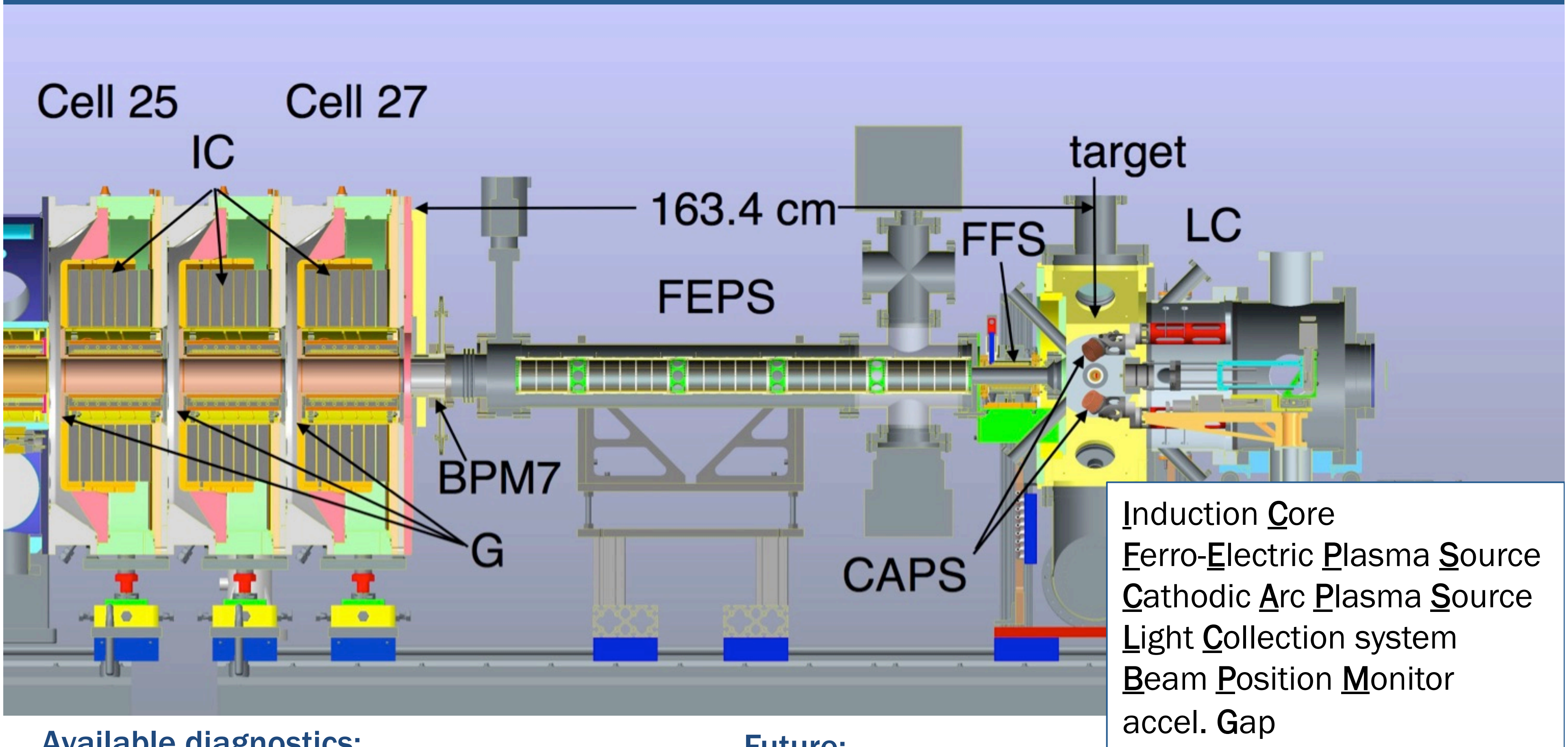
NDCX-II allows for uniform heating of materials

	NDCX-II (goal)
Ions/pulse (total)	10^{10} ($3x10^{11}$)
Pulse length	2 ns (~1 ns)
Typical spot size	1 mm^2
Ion species	He, (H, d, …)
E_{kin}	0.12 - 1.2 MeV
Energy spread	~10%
Repetition rate	2/min
Target temperature	<0.1 eV (~1 eV)
Radiation environment at the target	Benign, no shielding required
Heated volume	~1 mm^2 x 5μm =$5x10^6$ μm^3

Energy loss



Diagnostics include fiber coupled streak spectrometer (~10 ps), II-CCD. Considering laser or x-ray probes.



Available diagnostics:

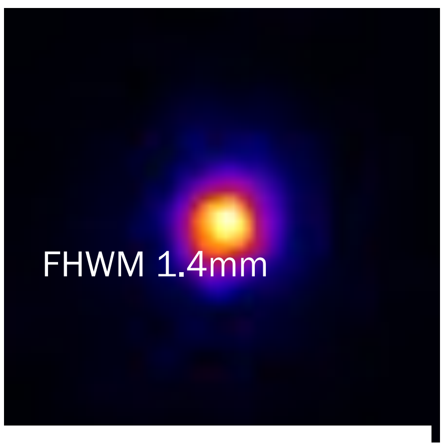
- Streaked optical spectrometry
- Ion scattering
- VISAR-interferometry

Future:

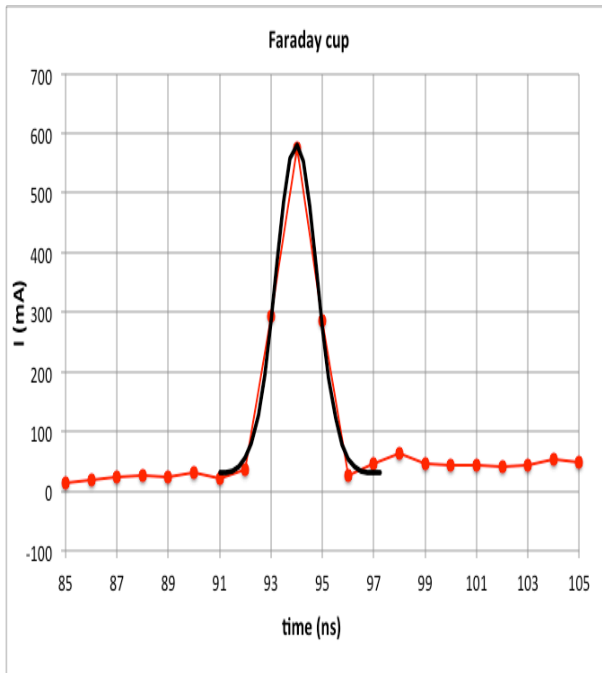
- Auxiliary ps probes (e. g. laser based XUV, ...)

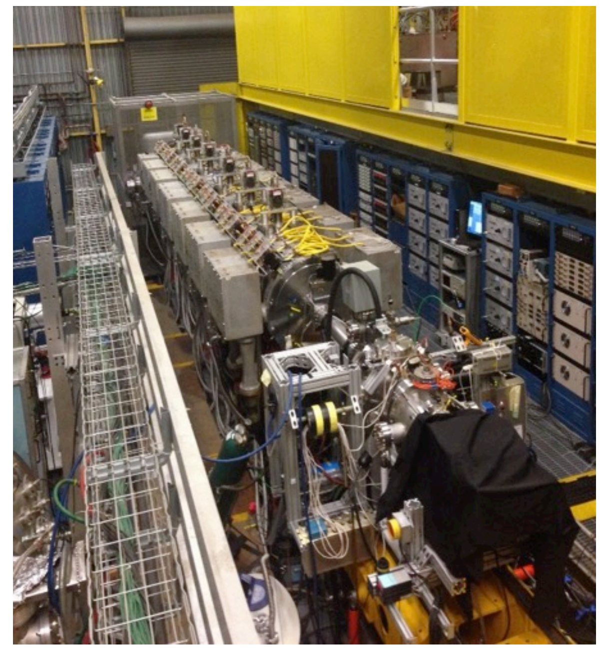
The Neutralized Drift Compression Experiment is operating

- Since June 2014, we have brought NDCX-II to full operation
- Pulse length: 2 ns, spot size 1.4 mm, 1.2 MeV, Li^+
- Now: He^+, Peak currents: ~0.6 A (~40 A/cm^2)
- We are now tuning to reach the design goals: 1 ns, 1 mm, >50 A, for volumetric heating up to 1 eV

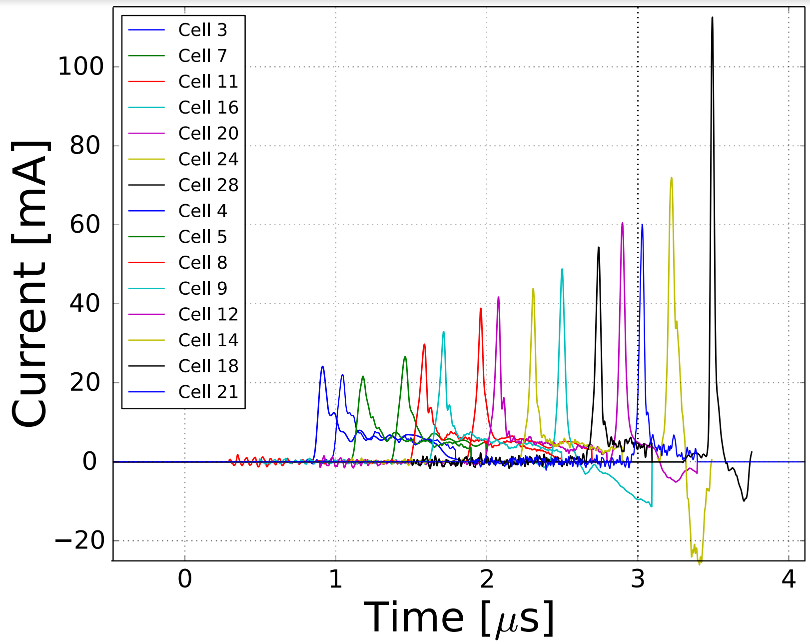


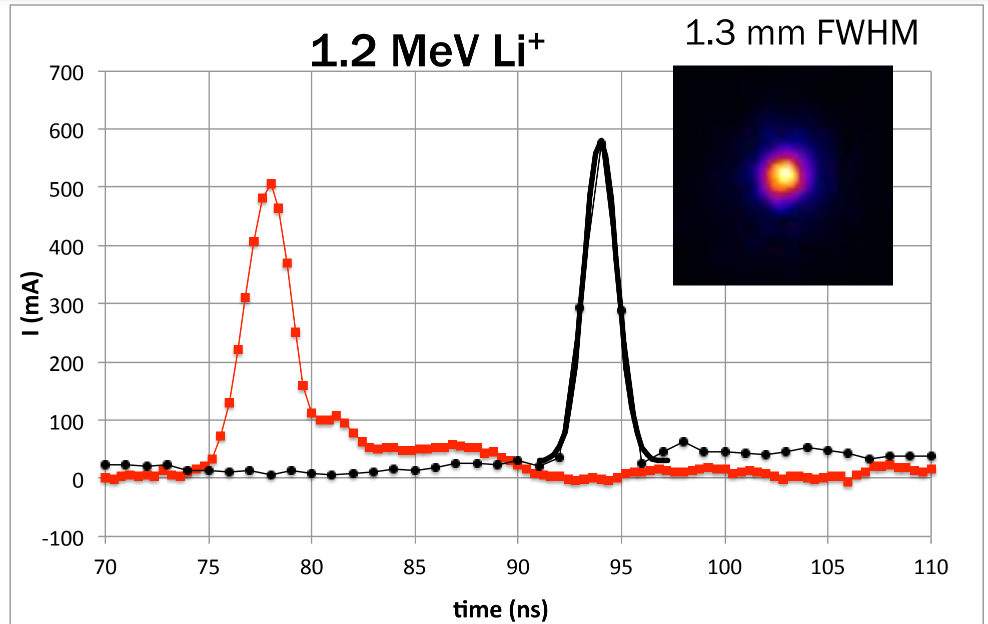
Jitter: $\sigma_{x,y} < 0.1$ mm
Intensity $\sigma_A/A < 7\%$





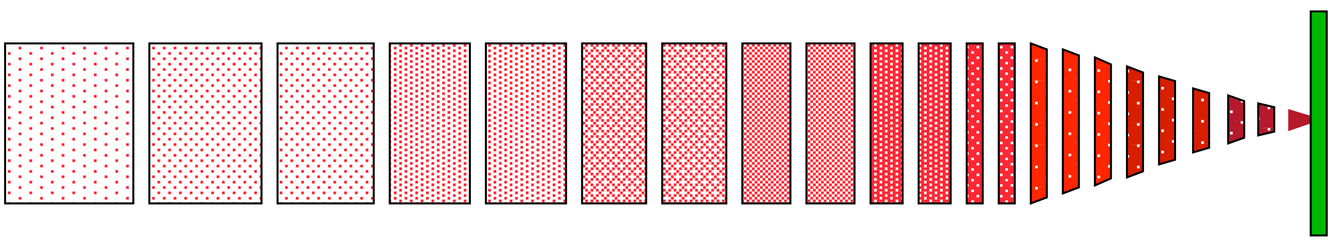
The NDCX-II induction accelerator compresses beam to ns and mm bunches on target.





- beam spots size with radius r < 1 mm within 2 ns FWHM and approximately 10^{10} ions/pulse.
- 0.02 A → 0.1 mA → 0.6 A

P.A. Seidl et al, NIM A 800 (2015) 98



Ion source and injector, 500ns

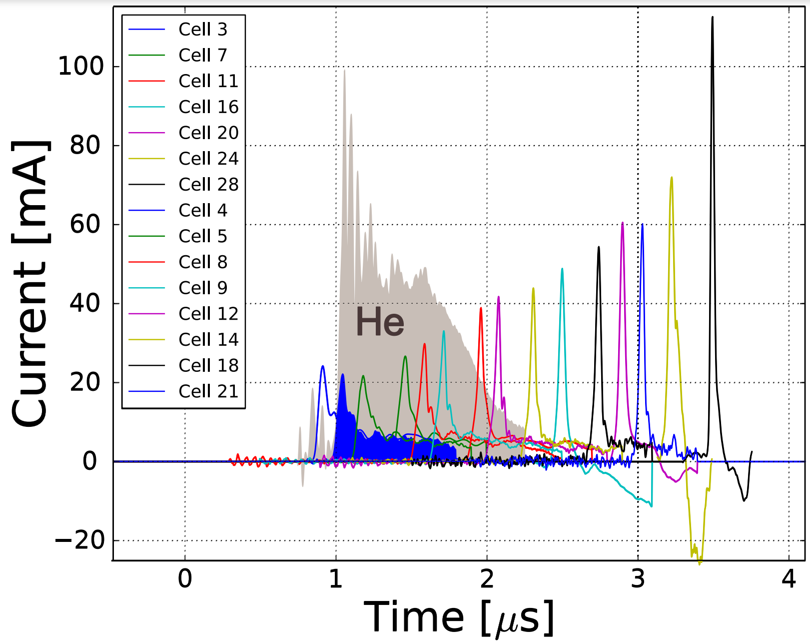
Linac custom waveforms for rapid beam compression

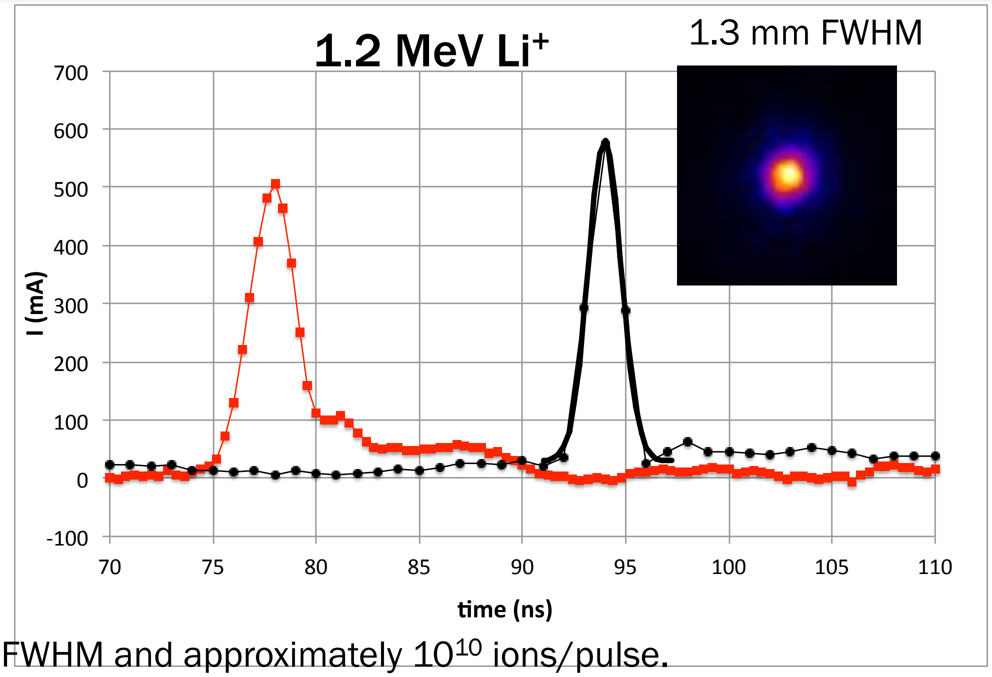
Neutralized drift compression and final focus

Z=10 m

Target

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





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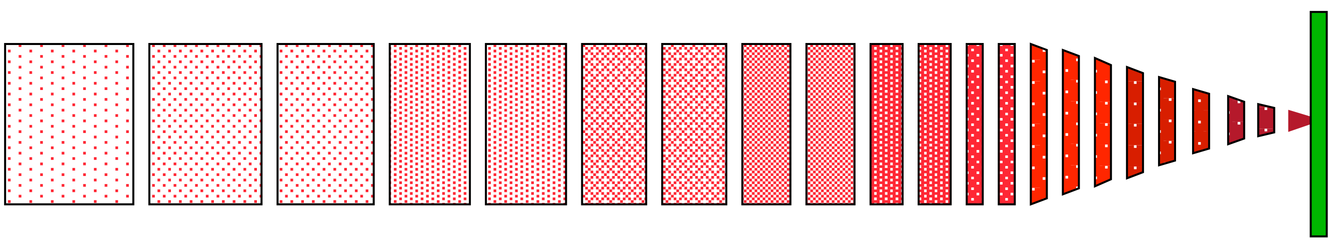
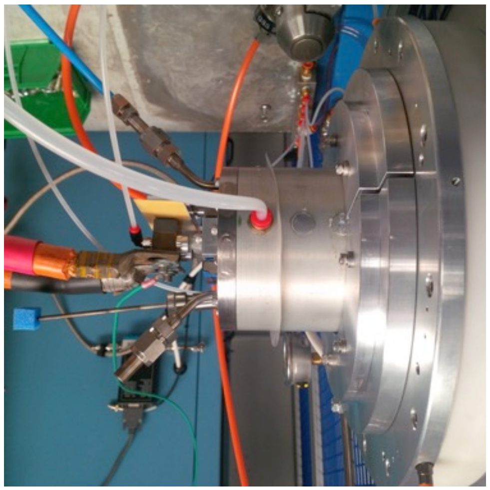
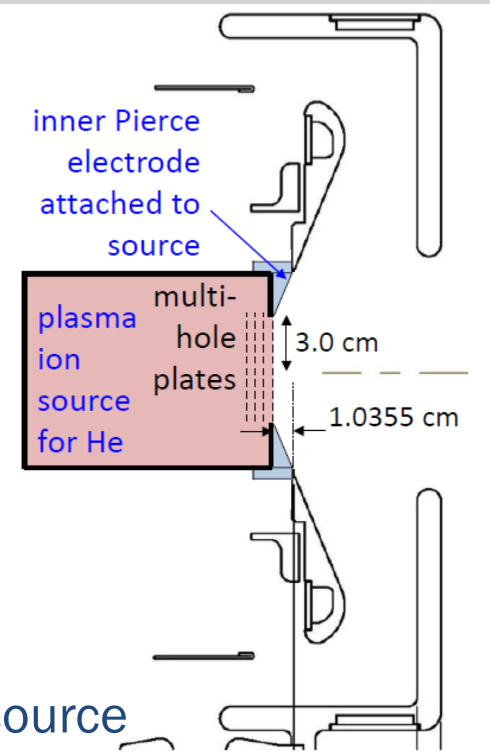


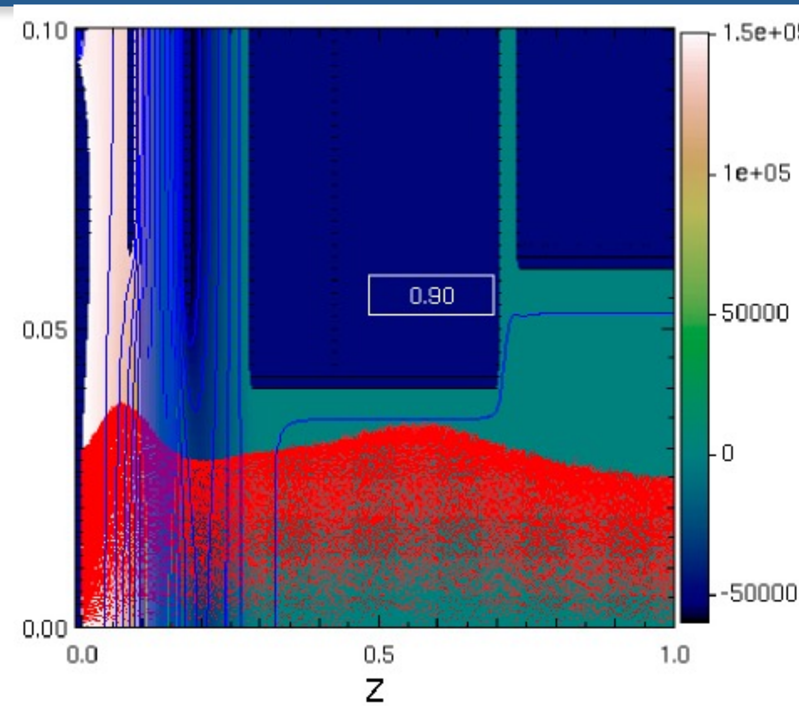
We are running NDCX-II with a multi-aperture, multi-cusp helium plasma source



- Photo of plasma ion source



reentrant He⁺ injector



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

- **We have a plasma ion source that delivers well over 80 mA/cm^2**
- **The goal is to extract ~160 mA of He$^+$ ions during ~1 us, for 80 nC / pulse, achieved 50 mA to date**
- **Trade-offs: current density, emission area, # of beamlets, emittance (~1.0 π-mm-mrad)**

Outlook & Summary

- **Planning to run protons, deuterium in near future. Other gases are possible**
- **Current focus: target heating experiment**

Thank you for your attention!

	NDCX-II (goal)
Ions/pulse (total)	10^{10} (3×10^{11})
Pulse length	2 ns (~1 ns)
Typical spot size	1 mm^2
Ion species	He, (H, d, …)
E_{kin}	0.12 - 1.2 MeV
Energy spread	~10%
Repetition rate	2/min
Target temperature	<0.1 eV (~1 eV)
Radiation environment at the target	Benign, no shielding required
Heated volume	~1 mm^2 x 5µm =5×10^6 μm^3