Short Intense Ion Pulses for Materials, Warm Dense Matter and Fusion Energy Research

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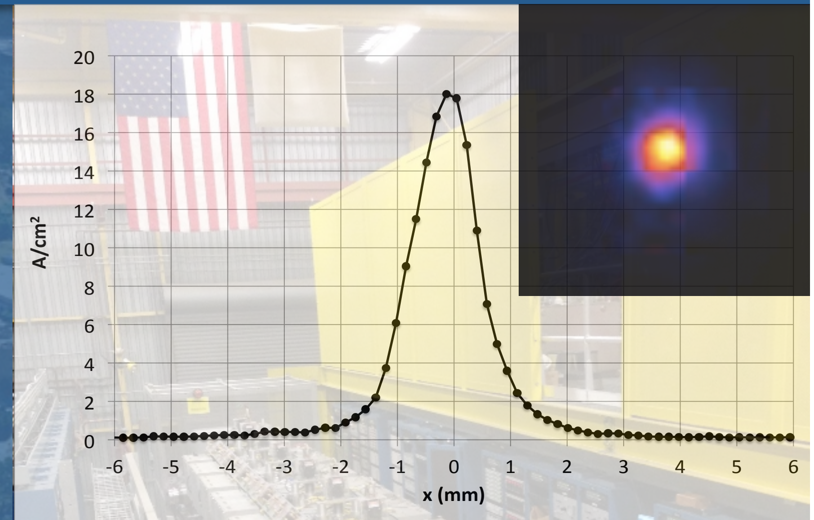
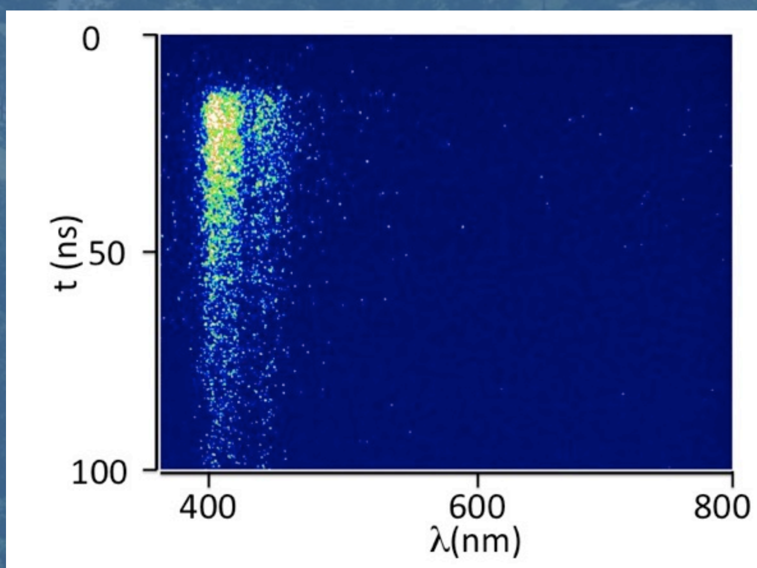
Fusion Power Associates Annual Meeting

December 17, 2015, Washington DC

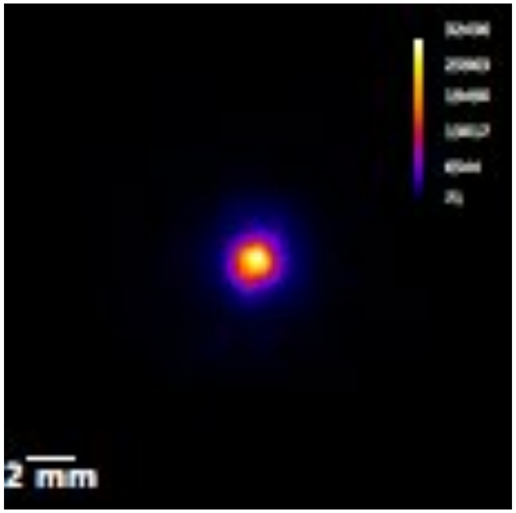




1. **Defect dynamics & extreme chemistry**
2. **Phase transitions in WDM**
3. **Intense beam and beam-plasma physics**
4. **Bella-i: HEDS @ 1 Hz**
5. **Microfabricated ion-beam drivers** (Arpa-e)

NDCX advances intense beams, beam-plasma physics, materials, warm dense matter science

- **We have integrated and commissioned all components of the Neutralized Drift Compression Experiment-II (NDCX-II).**
- We have generated ns ion pulses with **peak dose rates of 10^{20} Li^+ ions/cm^2/s** with high reproducibility.
- We are now operating with a new **plasma ion source** and have injected 50 mA of He^+, and focused to **0.7 J/cm^2**. Toward **target heating to the warm dense matter regime with He^+ and p.**
- Based on new results, we will pursue:
  - **Pushing the limits and testing the understanding of intense beam physics** for inertial fusion and other applications.
  - **Radiation effects testing** and fusion materials science
  - Precision studies of **warm dense matter and equations of state around 1 eV**
  - **Extreme chemistry** and materials synthesis far from equilibrium (e.g. nitrogen vacancy centers, novel alloys, …)
- **This is complementary to the science with lasers and laser-generated ion pulses.**

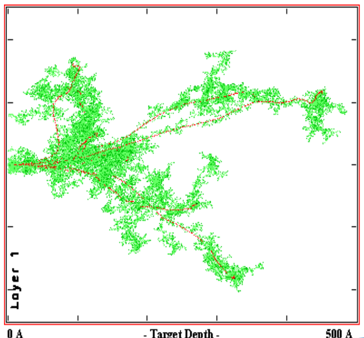


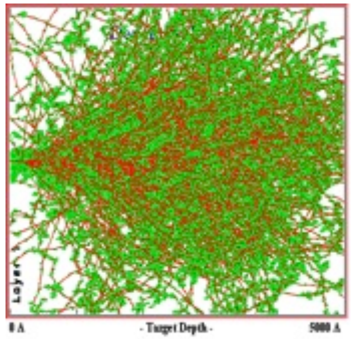
Supported by DOE-FES (LBNL, PPPL and LLNL).

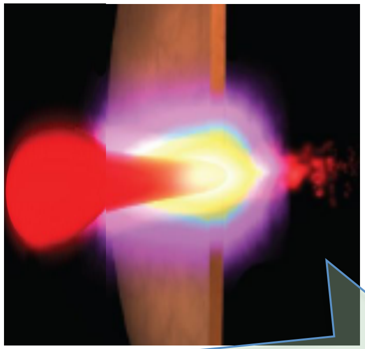
NDCX-II provides uniquely intense, short ion pulses for materials and warm-dense matter research

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

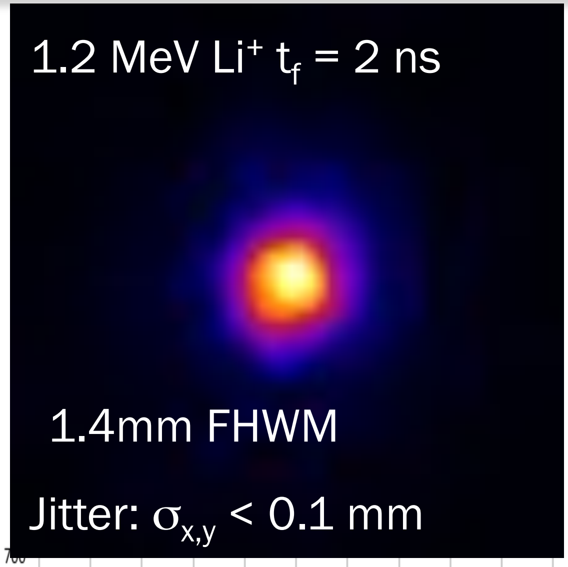
1-30 nC, 0.3 -1.2 MeV, few mm^2, ~1-20 ns

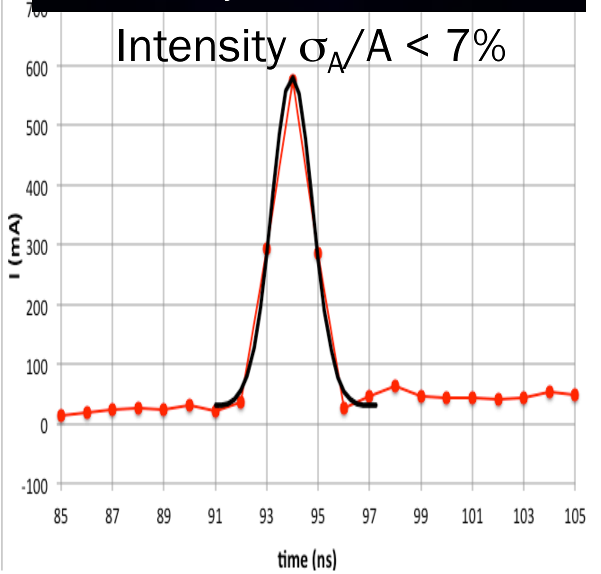
~50 nC, 1.2 MeV, ~1 mm^2, ~1 ns

- 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

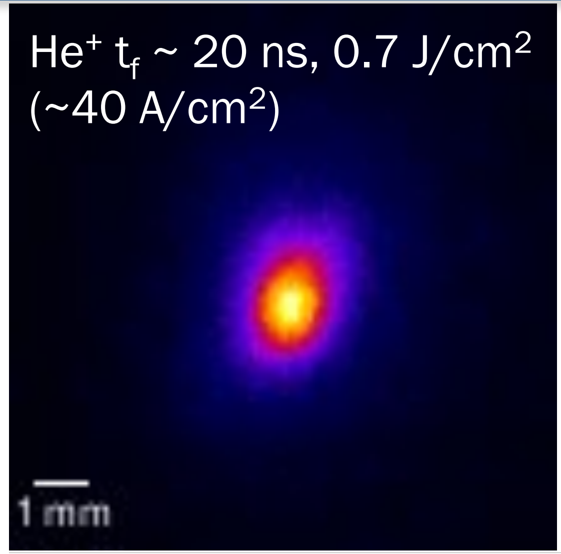
Fusion relevance
- Intense beams and beam-plasma physics
- Materials studies for fusion reactors
- Ion heating of matter (WDM)

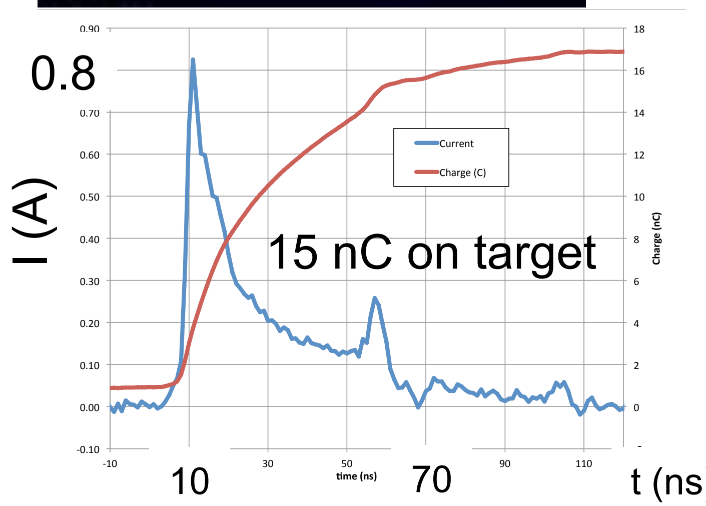
Since 2014, we have brought NDCX-II to full operation. Inject ~1 μs pulse, accelerated and compressed to ns, mm





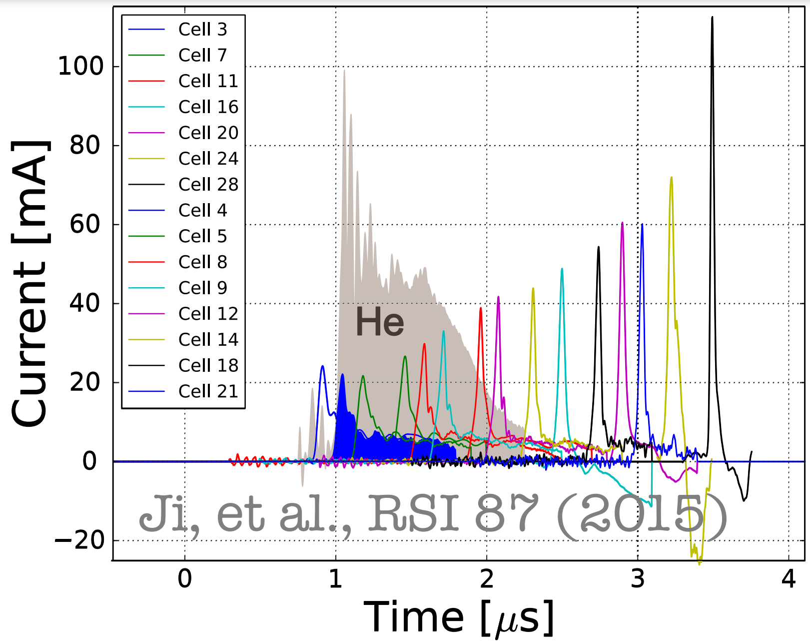
P.A. Seidl, et al., NIM A800 (2015)





We are now tuning to reach the design goals:
1 ns, 1 mm, >50 A, for volumetric heating up to 1 eV

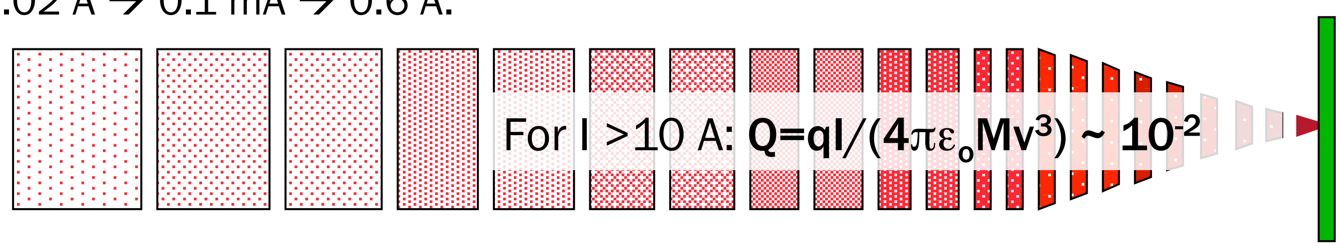
The NDCX-II induction accelerator compresses beam to ns and mm bunches on target.

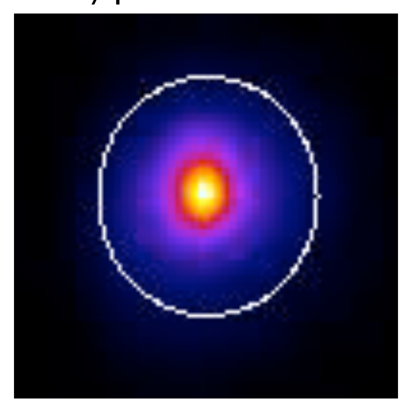


Unique opportunity to study intense beam and beam plasma physics:, e.g.:

- **2-stream instability**
- **Collective focusing of ions by electrons in a weak B-field**

- 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.





Ion source and injector, 500ns

Linac custom waveforms for rapid beam compression

Neutralized drift compression and final focus

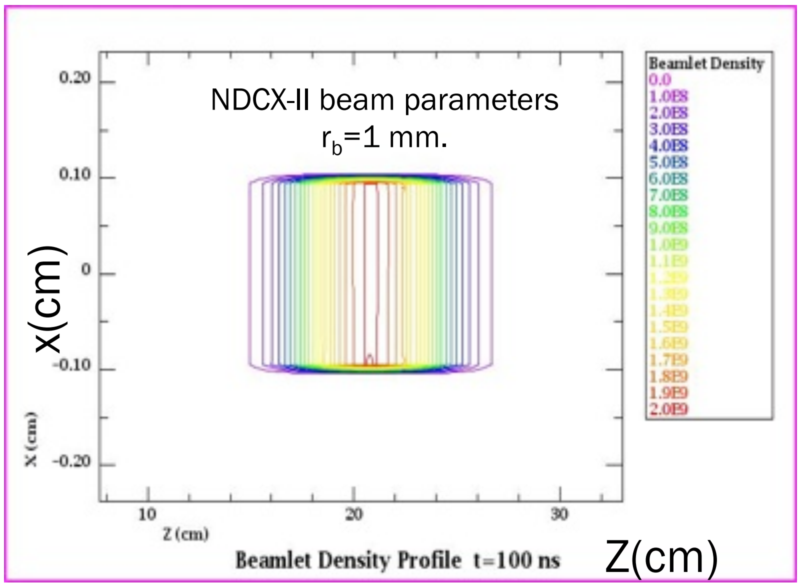
Target

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

Z=10 m

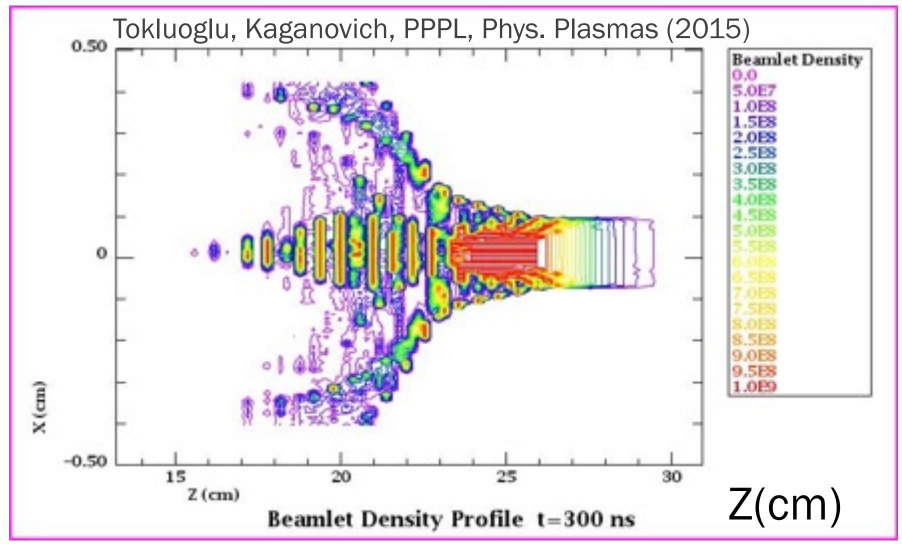
Two-stream instability of an ion beam propagating in background plasma

- 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.



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

[Kaganovich, APS-DPP invited]

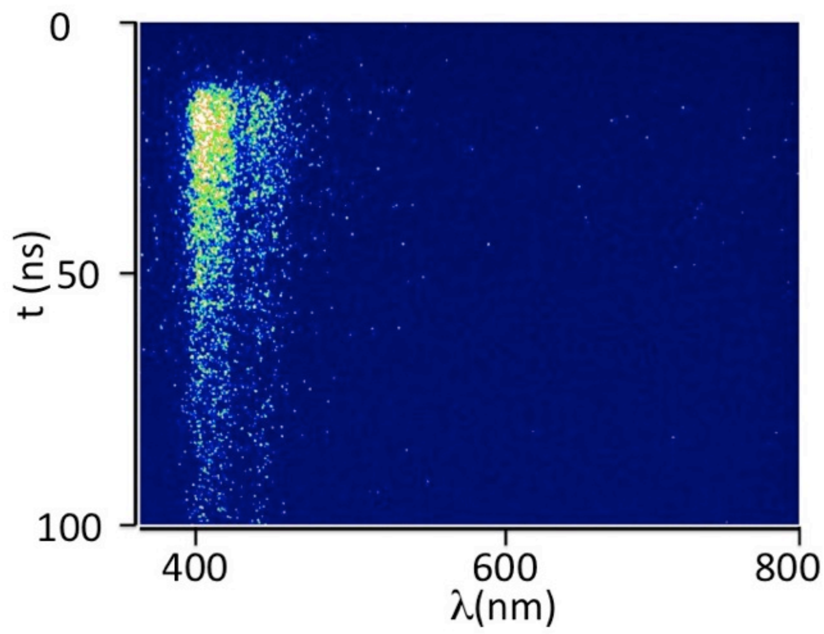


Beam density contour at t = 300 ns (3 m of propagation).

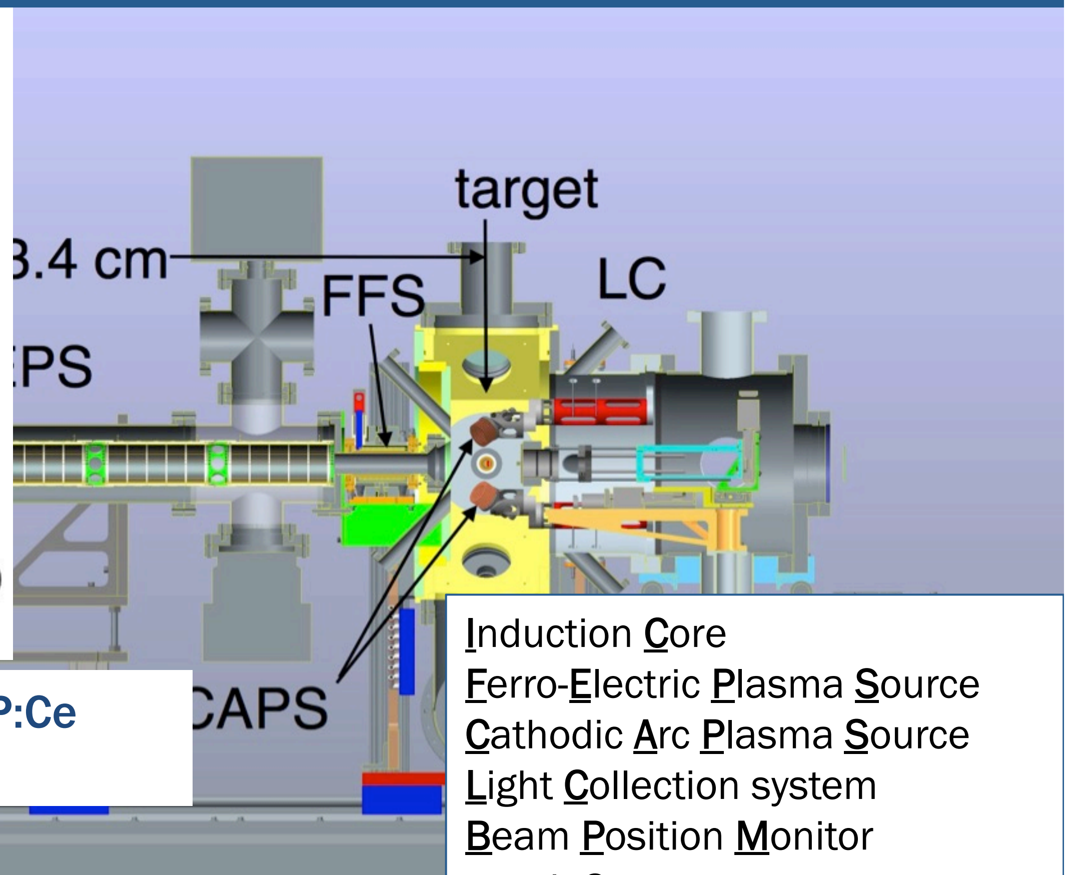
Defocusing when $\Delta v/v$ is small.

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

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



e.g., single shot ionoluminescence of YAP:Ce
(streaked optical spectrometer)



Available diagnostics:

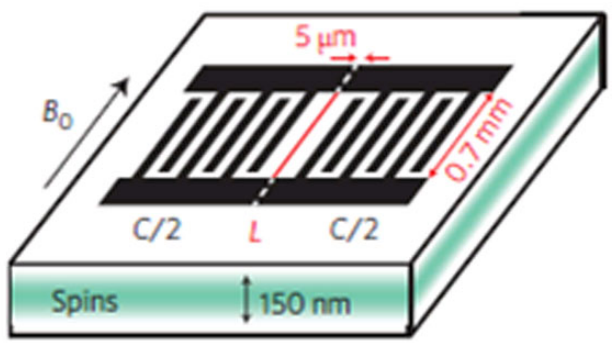
- Streaked optical spectrometry
- Ion scattering
- VISAR-interferometry

Future:

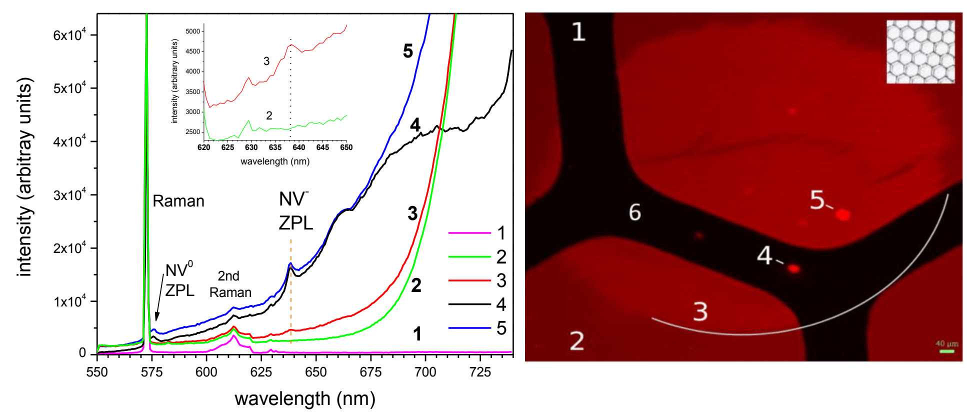
- Auxiliary ps probes (e. g. laser based XUV, ...)
- e- beam

Short ion pulses provide access to the multi-scale materials physics of radiation damage, “extreme chemistry” and phase transitions at the onset of warm dense matter

- Defects affect materials properties. The dynamics are a multi-scale problem (ps to years)
  - inform the development of optimized materials
  - benchmark models and simulation codes
- New opportunities to tailor materials properties through “extreme chemistry”
- Create new phases at the onset of warm dense matter and stabilize through rapid quenching
- Important for materials in high radiation environments, to understand effects of neutron and alpha damage on divertor plates, hydrogen release from tungsten, …



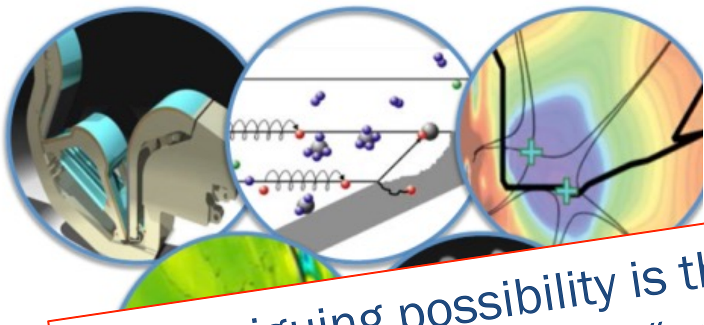
“Reaching the quantum limit of sensitivity in electron spin resonance”, A. Bienfait, J. J. Pla, Y. Kubo, M. Stern, X. Zhou, C. C. Lo, C. D. Weis, T. Schenkel, M. Thewalt, D. Vion, D. Esteve, B. Julsgaard, K. Mølmer, J. Morton, and P. Bertet, Nature Nanotechnology, Dec. 14 (2015)



“Local formation of nitrogen-vacancy centers in diamond by swift heavy ions”, J. Schwartz, S. Aloni, D. F. Ogletree, M. Tomut, M. Bender, D. Severin, C. Trautmann, I. W. Rangelow, and T. Schenkel, J. Appl. Phys. 116, 214107 (2014)

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*

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)

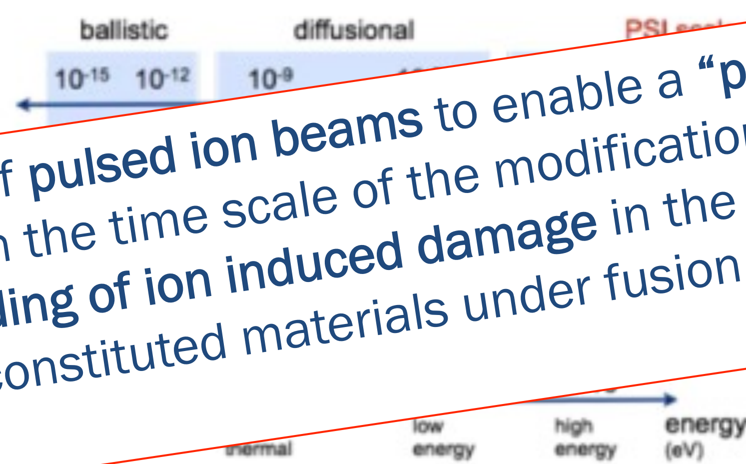
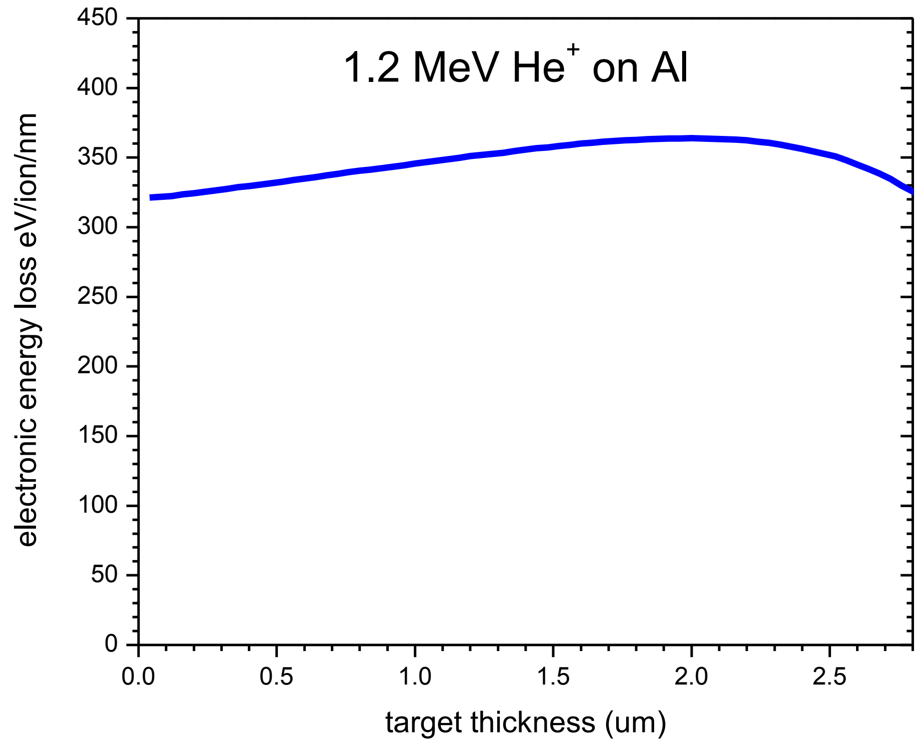


Figure VI-1: Schematic outlining the spatio-temporal physical scales involved in PSI and how experimental and computational tools access the same. For example, experimental tools could probe ballistic mechanisms with pump-probe type diagnosis. These could couple to QMD or MD type simulations tools. A 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.

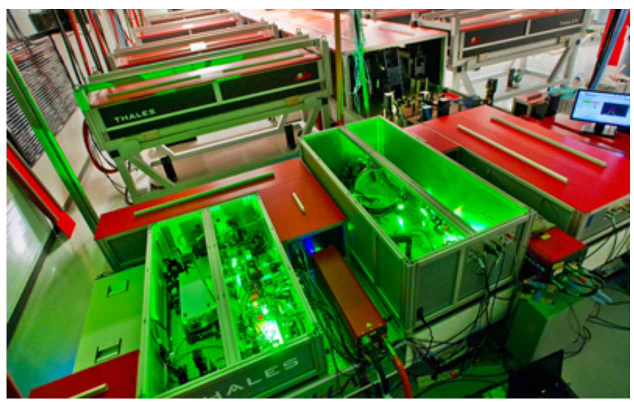
Complementary aspects of intense, pulsed ion beams from accelerators vs. laser-plasma generated ion beams

	Laser-ion	NDCX-II (goal)
Ions/pulse (total)	~10^{10} - 10^{12}	10^{10} (3×10^{11})
Pulse length	few ps	2 ns (~1 ns)
Typical spot size	~10 to 100 μm^2	1 mm^2
Ion species	H, C, …, Au	He (also H and higher Z)
E_{kin}	a few to >90 MeV	0.12 - 1.2 MeV
Energy spread	large	~10%
Repetition rate	~1 Hz to 1/day	2/min
Target temp.	few eV, to >100 eV	<0.1 eV (~1 eV)
Radiation environment at the target	Intense, requires significant shielding	Benign, no shielding required
Heated volume	~$(100\ \mu m)^3$ $=10^6\ \mu m^3$	~1 mm^2 x 5μm $=5\times10^6\ \mu m^3$



BELLA-i → high energy density science at 1 Hz

- The Berkeley Lab Laser Accelerator Center is home of the BELLA petawatt laser: 40 J, 30 fs, 1 Hz
- We propose a short focal length beamline at BELLA to enable access to High Energy Density Physics for a community of users
- Plasma science frontiers with high impact potential in our quest for fusion energy:
  - radiation effects, WDM, EOS, mixing, instabilities, …



BELLA

http://bella.lbl.gov/

BELLA-i

Workshop on High Energy Density Physics with BELLA-i

WHEN

Jan. 20-22, 2016

WHERE

Berkeley Lab

http://bella.lbl.gov/BELLAiworkshop.html/

BELLA

BERKELEY LAB

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T_Schenkel@LBL.gov

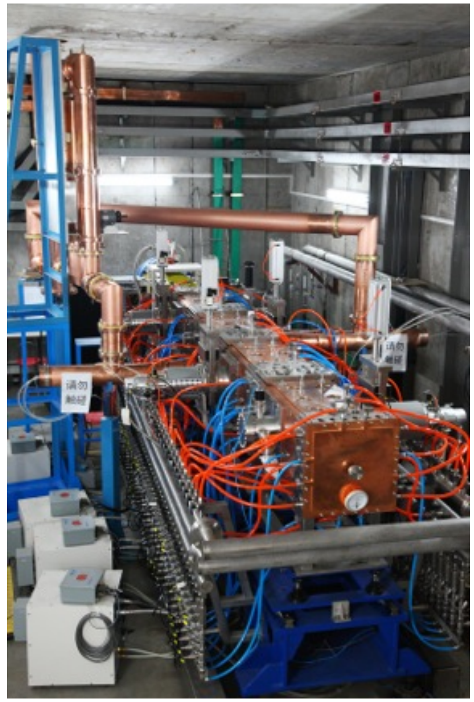
ACCELERATOR TECHNOLOGY &
APPLIED PHYSICS DIVISION

ATAP

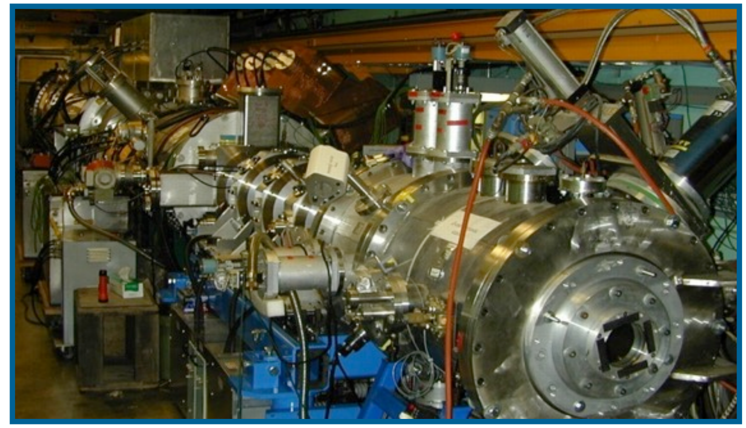
BERKELEY LAB

ARPA-e ALPHA program: Ion beam driver technology toward MTF [with Cornell Univ.]

- pulsed induction linac (12 m)
- 1 MeV, 2 ns, ≥0.8 A/mm^2 peak
- 200x drift compression
- P. S. Seidl et al. NIM A (2015)



- Radio frequency quadrupole (RFQ)
- 2 MeV, 10 mA, cw
- 4 m long, 0.4 m cross section
- Z. Zouhli, D. Li et al. IPAC2014

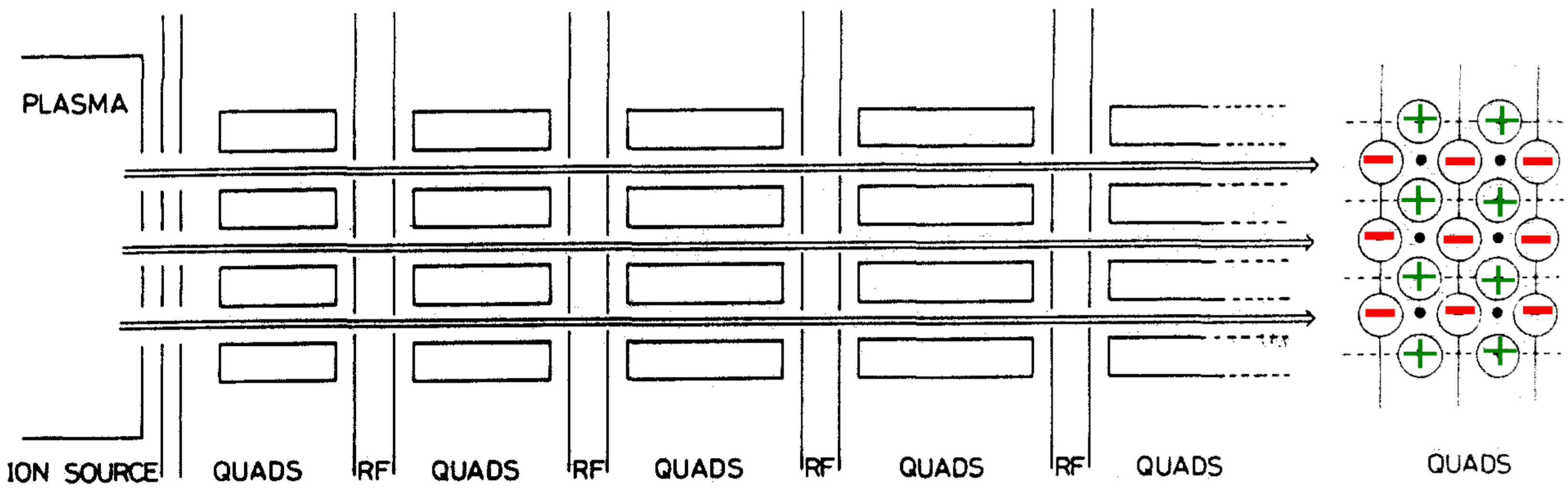


- High Current Experiment (~12 m)
- injection, matching and transport at HIF driver scale
- 1 MeV, K+, 0.2 A, 5 μs, ~12 m
- 0.4 m cross section
- Prost, et al., Phys. Rev. ST-AB 8, 020101 Molvik et al., Phys. Rev. Lett. 98, 064801

how can we scale ion beam drivers to >1 MJ at low enough cost to enable MTF ?

MEQALAC concept from 1980s
– high total currents from many beamlets

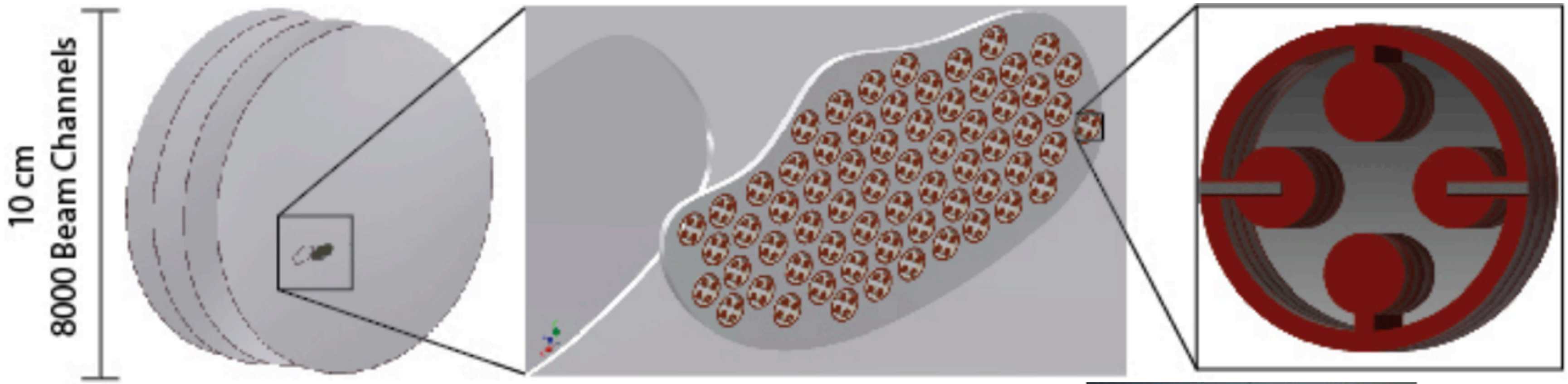
Multiple-Electrostatic-Quadrupole-Array Linear Accelerator



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

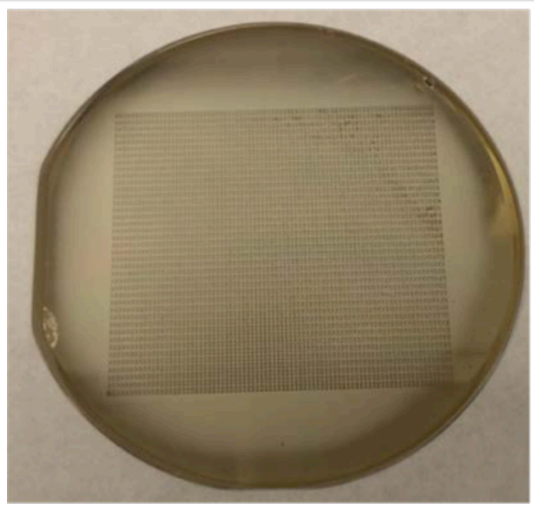
Al Maschke, BNL, late 70s; Thomae *et al.*, Mat. Science & Eng., B2, 231 (1989)

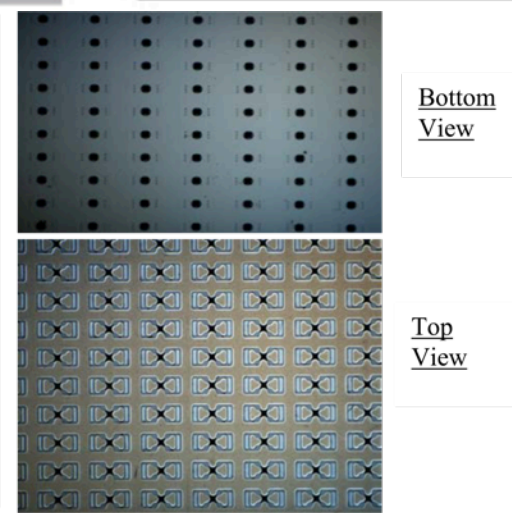
Arrays of electrostatic quadrupoles and RF elements can be produced in silicon wafers with unit cells of the order of 1 mm



Prototype

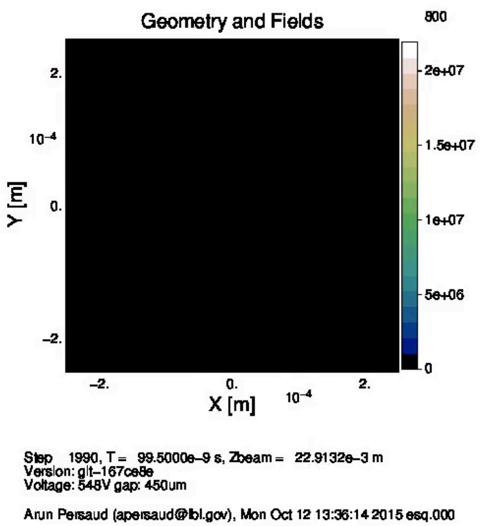
Cornell University

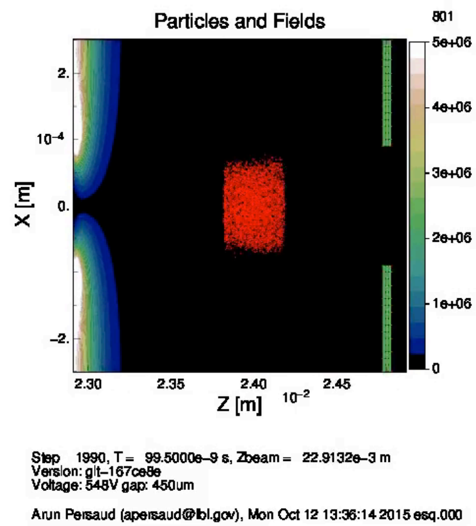


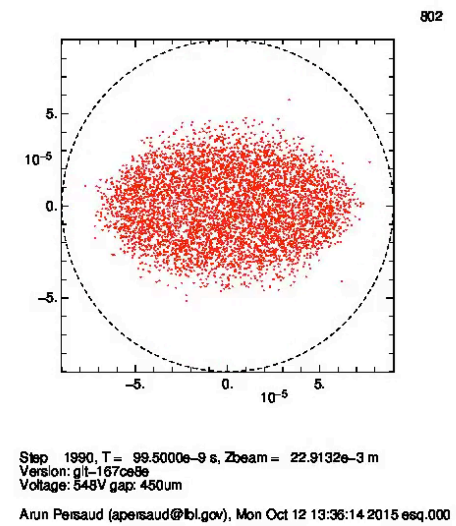


We are preparing for first beam tests in January (1,4,9,25 beams)

Simulations guide design choices



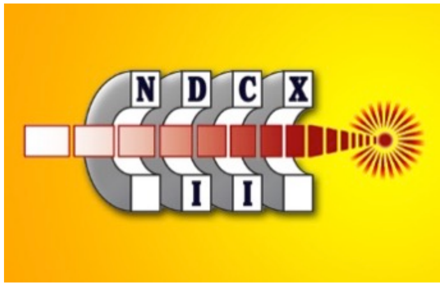


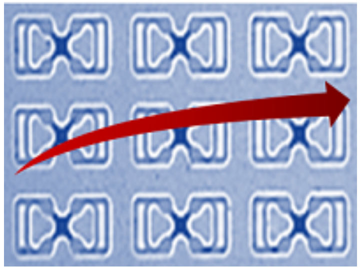


Beam transport in ESQ arrays – WARP PIC simulation

Outlook

- We contribute to the quest for fusion energy science in selected areas
  - Research towards heavy ion fusion drivers has led to intense pulsed ion beams
  - Intense pulsed ion beams now open opportunities in the materials physics of radiation with *in situ* access to multi-scale defect dynamics
  - In parallel, we are developing ion accelerators based on MEMS, a potentially disruptive driver technology
  - BELLA-i promises to be a hotbed for basic and applied high energy density physics





BELLA