LBNL is advancing these topics for fusion energy sciences

1. High dose-rate irradiation of materials with pulsed ion beams at NDCX-II (LLNL, PPPL, SNL, TU-Darmstadt, Lanzhou U., U. Washington)

2. High intensity laser-generated ion beams with Bella-i for materials research and warm, dense matter / HEDP

3. MEMS-based accelerators for plasma heating (Cornell)

4. High Tc superconducting magnets for high-field tokamaks (U. Houston, Tufts, Advanced Conductor Technologies)
Intense, short ion pulses for materials studies and fusion science

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 mm², ~1-30 ns

NDCX — Bella-i
NDCX and Bella-i advance intense beams, beam-plasma physics, materials, warm dense matter science

- At NDCX, we have generated ns ion pulses with **peak dose rates of \(>10^{20}\) ions/cm\(^2\)/s** with high reproducibility. **Repetition rate is \(<1/\text{minute}.\) Beam \(r = 1\) mm, \(t = 2\) ns**
- We have achieved **2 A peak currents** for ns pulses of 1 MeV He\(^+\) ions, focused to **0.1 J/cm\(^2\)**.
- We are measuring **ion energy loss in heated foils**
- Radiation effects on semiconductor transistors.

**Synergy: NDCX & Bella-i laser generated ion beams**
1. NDCX: Exploring the dynamics of the disruptions due to rapid heating using the 3D multi-physics, multi-material code ALE-AMR

Opportunity to understand materials dynamics through a solid-liquid phase transition with rapid, uniform heating.

- Work in progress, adding surface tension model to the simulation

We have explored the effects of high ion flux, short pulse irradiation on the Messenger-Spratt damage factor using Microsemi 2N2907 pnp transistors. We have applied an ion flux of $10^{18} - 10^{19}$ ions/cm$^2$/s per ~10 ns long helium ion pulse (1 MeV). We have measured late-time gain degradation as a function of ion fluence for a series of shots up to $2.5 \times 10^{11}$ ions/cm$^2$.

Ion pulses simulate pulsed neutron irradiation*. NDCX delivers dose equivalent $10^4 X$ n/cm$^2$/s vs IBL @ SNL. End-of-range ion energy loss at the base-emitter junction, where damage leads to gain degradation.

Funded by NNSA via SNL


2. BELLA-i can have transformative impact in High Energy Density Physics due to the 1 Hz rep rate and superb laser quality

- (ultra)-relativistic plasma science at 1 Hz
- fundamentals of laser ion acceleration
- laser based ion beams and neutron pulses as a tool for discovery plasma science and applications
- collaborative research facility
We have commenced ion acceleration experiments at BELLA-i

Thomson parabola

Charge states up to Ti$^{11+}$, C$^5+$, O$^6+$

- Ti tape drive target for extended 1 Hz operation
- Low ion pulse divergence, high ion number,
  publication in preparation, S. Steinke, Q. Ji, J. Bin, S. Bulanov, and BELLA team
Transport of $10^{12}$ ions at 5-10 MeV to EMP-free environment possible with plasma lens

Active plasma lens to focus an ion beam to a 500µm spot 1m downstream of plasma lens:

Charge distribution at WDM target:

$10^{12}$ ions in 3ns, 0.25mm$^2$

van Tilborg et al., PRL 184802 (2015);
3. In the first two years we have developed the first MEMS based multi-beam accelerator

Funded by the ARPA-e alpha program

We demonstrated electrostatic quadrupoles (ESQ) to re-focus the ion beams for efficient transport both in PC board and silicon.
We now operate a multi-beam accelerator formed from a stack of PC boards:

- Next step is scaling to higher beam current (from 50 µA to >1 mA) and higher beam energy (10 keV to >100 keV).
- This will be highly competitive/disruptive for mass spectrometry, neutron-generators, surface treatment, ion implantation, plasma diagnostics, …
- Scaling to ~1 MeV/m and >1 A for plasma heating will follow
  - e.g., Neutral beam injectors for MFE, where electrostatic MV holdoff is challenging.
4. LBNL magnet development for high field tokamaks: quench protection, electromechanical performance, and feedback to industrial manufacturers

Tapes → fusion scale cables: A curvature-based method for cable and magnet designs based on CORC® cable & stacked tapes


Characterize the electromechanical performance of REBCO conductors

- First results on the $I_c$-strain dependence on the latest 2-mm wide, 30 µm thick substrate commercial REBCO samples.
- Observed 8% reduction in $I_c$ with 0.46% tensile strain (data shown is reversible)

Collaborate with the community to characterize the transport performance of advanced REBCO tapes and cable prototypes

Leverage the HEP programs to develop and evaluate advanced concepts for quench detection

Thermo-acoustic quench detection

- M. Marchevsky et al., EUCAS, 2017
- M. Marchevsky S. A. Gourlay, doi:10.1063/1.4973466
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4. High Tc superconducting magnets for high-field tokamaks (Houston, Tufts, ACT)
The team

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X. Kong, Lanzhou University, China
Univ. of Houston
Tufts Univ.
Thank you!
We envision that the compact RF accelerators fit in the footprint of the DEMO NBI system.

Definition of DEMO NBI requirements

The envisaged requirements of the DEMO NBI, agreed within the EUROfusion working group on heating and current drive after several discussions, are reported in table 1, where a comparison with the ITER NBI ones is also reported.

These requirements refer to the case 'advanced DEMO NBI', while the requirements for an 'ITER-like DEMO NBI' are close to those of ITER, except for the duration of the beam on time (two hours instead of one). In fact, in this last case the DEMO NBI would be an improved version of the ITER NBI, taking into account the DEMO operating scenario and an energy recovery system for the residual ions. It can be noted that the requirements of the advanced DEMO NBI are similar, but not identical to the ones of the ITER NBI. Namely, it can be observed that:

• A value of 800 keV has been chosen for the present conceptual design of the DEMO NBI. This value is slightly decreased compared to the ITER one (1 MeV) to improve the overall reliability of the NBI system integrated into the reactor. In fact, there is currently no official beam energy value specified in the DEMO requirements. On the other hand, the voltage holding of 1 MV DC potential in presence of magnetic fields can be obtained only with optimal conditions of the electrode surfaces, in terms of smoothness and vacuum conditions.

• The maximum ion source filling pressure has been decreased from 0.3 to 0.2 Pa, to increase efficiency. In fact, the beam losses in the accelerator are strictly linked to the gas density in the accelerator, that in turn is proportional to the pressure in the ion source.

• The maximum divergence of the beamlets must be very small (less than 7 mrad for each beamlet) in both cases, allowing a large fraction of the particles to reach the plasma inside the main chamber.

• The required total accelerated current has been decreased by about 15%, to increase availability of the NBI. In fact, high values of accelerated currents are currently obtainable only in the case of a perfect set up of the ion source, that is likely to be obtained only in particularly optimized conditions.

Figure 2.
Overview of the DEMO NBI with the main components and a sketch of the grids of the modular extraction acceleration system.

modular: 2x10 RF sources and injectors
Assume 60 Amps total current, 1 MeV D-, 3 NBI ports on tokamak. Each NBI has:

- **46 accelerators, two rows per injector system**
- **Accelerator components:**
  - 6-inch square wafers, 2 cm border on wafer.
  - 1080 beamlets/wafer, total current 0.43 A.
- **Room for pumping/conductance**
  - 4 cm gap between accelerators
- **Accelerators can be angled to achieve overall convergence to match port area at tokamak wall**
- **Assume injector J = 20 mA/cm²**
  - Beam-beam pitch = 3 mm
  - 2x margin for losses: Plasma source aperture dia = 1 mm, inject 0.62 mA/beamlet (@ 20 mA/cm²), but need 0.32 mA/beamlet
Accelerator array for NBI system is a converging group of beams injected into neutralization system. 1 MeV, 20 A

2 rows, 23 accel/row

2-4 m

3.5 m

Neutralization section

Residual ion dump

Neutron-dump
Accelerator array for NBI system is a converging group of beams injected into neutralization system. 1 MeV, 20 A
NDCX and Bella-i advance intense beams, beam-plasma physics, materials, warm dense matter science

- We have generated ns ion pulses with **peak dose rates of >$10^{20}$ ions/cm$^2$/s** with high reproducibility. **Repetition rate is <1/minute. Beam r = 1mm, t = 2 ns**

- We have achieved **2 A peak currents** for ns pulses of 1 MeV He$^+$ ions, focused to **0.1 J/cm$^2$**.

- We are **measuring ion energy loss in heated foils**

- Based on new results, we will:
  - **Push the limits and testing the understanding of intense beam physics** for inertial fusion and other applications.
  - **Dynamics of radiation effects** and fusion materials science
  - **Radiation effects on semiconductor transistors.**
  - **Workshop on Dynamics of Radiation Effects, Dec 15-16, 2016, Berkeley Lab**
    - Theory and simulations of the dynamics of radiation effects in materials;
    - Excitation sources such as pulsed plasmas and pulsed ion beams paired with in situ probes such as Ultrafast Electron Diffraction, pulsed x-rays, optical and ion scattering techniques
  - **Synergistic: Bella-i laser generated ion beams**
First commissioning shots show narrow divergence beams at expected ion energies

13um Al target

2 cm

RCF film stack

1 MeV
250 mrad

4.7 MeV
250 mrad

Experiment Parameters

12J on target, $5 \times 10^{18} \, \text{Wcm}^{-2}$
13um Aluminum
Ion energies up to 4.5 MeV
Divergence (FWHM) 150mrad
The NDCX-II induction accelerator compresses beam to ns and mm bunches on target.

- Beam spots size with radius $r < 1 \text{ mm}$ within 2 ns FWHM and approximately $10^{10}$ ions/pulse.

- Ion source and injector, 500ns

Target Linac custom waveforms for rapid beam compression

Neutralized drift compression and final focus

$Z=10 \text{ m}$

Unique opportunity to study intense beam and beam plasma physics.


Extensive integration of PIC simulations: Snapshot of the X-Z projection shows rms properties & halo particle loss...

Applied accel and bunching $V(t)$ from database

Within 2 ns FWHM and approximately $10^{10}$ ions/pulse.
With a Thomson Parabola spectrometer we measure the transmitted particle energy distribution and species identification.

1.1 MeV He\(^+\) on 1 µm SiN

\[ \Delta E \approx 0.54 \text{ MeV} \]

\[ \Delta E \approx 0.32 \text{ MeV} \]

B field deflection

E field deflection

Pixel resolution \( \partial E \approx 10 \text{ keV} \)

Exploring intensity and dose rate effects

F. Treffert, TU-D, Masters thesis
Scintillator luminescence shows dose effect from intense helium ion bunches

polyvinyltoluene (PVT)

Focused and defocused beam to explore dose rate effect.

- Lifetime loss from increased temperature ($\Delta T \approx 60 \, \text{C}$).
- Bond breaking (C-H) $\rightarrow$ color centers decrease transparency.
- Thermal annealing of color centers, restoring transparency.

Zimmer, et al, “Dose rate effects ... PVT”, in preparation
Helium pulses with 100 mJ/cm²/shot @ edge of tin melting plateau

1.15 MeV He on:
800 nm Au
400 nm Si
2000 nm Al
120 nm Pt
500 nm Sn

0.5 µm Sn experiment

J. Barnard
Heating 0.3-\(\mu\)m foil Tin with a short-pulse helium beam

- Fast Faraday cup
  - \(Q = 4\) nC, 6 ns FWHM

- Scintillator image

- Peak fluence: 0.035 – 0.045 J/cm\(^2\)
  - \(E = 0.8\) MeV

- Foil under microscope

- Heating 0.3-\(\mu\)m foil Tin with a short-pulse helium beam
Inspection of 0.5 µm Sn foil after $Q_{\text{tot}} = 12$-nC/beam pulse

1 shot/target position
>1 shot/target position

Backlight view shows tiny holes
We measure the energy loss of transmitted ions in heated targets via TOF, Thomson Parabola spectrometer.

12 nC He$^+$

0.5 µm Sn

scintillator

FC-t

FC-d

Exploring dose rate dependence

Opportunity to probe material response to short-pulse ionizing radiation ($t, \lambda$), e.g., channeling of ions in crystals
We welcome visitors and collaborations!

- We are doing target experiments with >10 nC/pulse, 2-40 ns, r ≈ 1mm, >1/minute.
- We have developed a close coupling of particle-in-cell modeling to the experiment.
- These intense pulsed ion beams now open opportunities in the materials physics of radiation with *in situ* access to multi-scale defect dynamics, radiation effects in semiconductors, intense beam and bam-plasma physics
- Synergistic: Bella-i laser generated ion beams – Park TP11.47, Steinke YP11.65
We have achieved 2 A peak currents for ns pulses of 1 MeV He\(^+\) ions

- 1.1 MeV (He\(^+\)), 12 nC (7.5x10\(^{10}\) ions) \(\rightarrow\) 13 mJ
- \(~180\) mJ/cm\(^2\) @ peak, 2 mm FWHM
- Uniform energy deposition into a 2 micron silicon foil with \(~6\times10^3\) J/cm\(^3\)

Highest fluence achieved 0.7 J/cm\(^2\) for longer pulse duration.
Diagnostics include fiber-coupled streak spectrometer, II-CCD, Fast detectors for TOF, channeling and energy loss experiments.

Target chamber available diagnostics:
- Scintillator + CCD camera, Fast Faraday cup (FFC)
- Streaked optical spectrometry (10 ps)

Induction Core
Ferro-Electric Plasma Source
Cathodic Arc Plasma Source
Light Collection system
Beam Position Monitor
accel. Gap

New: Thomson parabola
NDCX advances intense beams, beam-plasma physics, materials science and radiation effects

• We have generated ns ion pulses with **peak dose rates of $>10^{20}$ ions/cm$^2$/s** with high reproducibility. **Repetition rate is $>1$/minute. Beam $r = 1$mm, $t \approx 2$ ns**

• Injecting $\sim 100$ mA of He$^+$, we have achieved 2 A peak current for ns pulses of 1 MeV He$^+$ ions, focused to **0.1 J/cm$^2$**.
  o (0.7 J/cm$^2$ for longer pulse)
  o Next experiments with proton beam.

• We are measuring **ion energy loss in heated foils, Sn, Si, SiN**

• **radiation dose and dose rate effects on transistors and diodes**

• Based on new results, we will:
  • **Push the limits and testing the understanding of intense beam physics** for inertial fusion and other applications.
  • **Radiation effects testing** and fusion materials science
  • **Phase transitions and extreme chemistry** and materials synthesis far from equilibrium (e.g. nitrogen vacancy centers, novel alloys, ...)

[Jitter: $\sigma_{x,y} < 0.1$ mm]
Routinely use particle-in-cell simulations to validate our understanding of the high intensity beam physics and to help optimize the performance of the accelerator, compression and focusing for target experiments.

1. Beginning with model of plasma ion (He+) source injection, the experiment voltage waveforms are imported from DAQ database & applied to the 2D Warp simulated beam...

2. Snapshot of the X-Z projection shows rms properties & halo particle loss...

3. Results are directly compared to the experiment beam diagnostics. From these, adjust focusing, waveforms, timing, then go to #1.

≈10 min/run/processor, we do ≈10 parallel simulations, vs 1 shot/min in the experiment.
To determine the kinetic energy distribution for each shot, we have simulated each shot with Warp PIC.

Low energy ions do not reach the sensitive layer. Analysis will separate range effects from possible dose rate effects.
Opportunity to probe material response to short-pulse ionizing radiation ($t, \lambda$), e.g., channeling of ions in crystals.

The neutralization of the beam space charge defocusing is essential for obtaining higher focused intensity.
With pulsed ion beams we can probe the radiation effects on materials and warm dense matter research.

Novel opportunities with short, intense pulses to probe material response to radiation in the time domain.

- e.g., single shot ionoluminescence of YAP:Ce measured with a streaked optical spectrometer. P.A. Seidl, et al., NIM A800 (2015)
Strong collective focusing of an ion beam in a plasma and a weak magnetic field

- Most pronounced when the beam radius is small compared to the collisionless plasma electron skin depth $r_b < c/\omega_{pe}$
- Applied $B$ can be reduced by a factor $(m_e/m_i)^{1/2} \sim 10$ Tesla $\rightarrow \sim 10^2$ Gauss

Can this be used to great advantage in high intensity ion beams?

Particle-in-cell (LSP) simulation using the collective focusing effect to focus the high intensity beam using a weak magnetic field and a plasma.

Dorf, Davidson, Kaganovich, Startsev, Phys. Plasmas (2012)
Complementary aspects of intense, pulsed ion beams from accelerators

<table>
<thead>
<tr>
<th></th>
<th>Fair</th>
<th>NDCX-II (goal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ions/pulse (total)</td>
<td>$\sim 10^{10} - 10^{12}$</td>
<td>$10^{10} (3\times10^{11})$</td>
</tr>
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<td>Pulse length</td>
<td>40-100 ns</td>
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<td>Typical spot size</td>
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<td>He (also H and higher Z)</td>
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<td>$E_{\text{kin}}$</td>
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<td>Heated volume</td>
<td>$&gt; \text{mm}^3$</td>
<td>$\sim 1$ mm$^2 \times 5\mu\text{m} =5\times10^{-3}$ mm$^3$</td>
</tr>
</tbody>
</table>

1.2 MeV He$^+$ on Al

**Diagram:**
- Electronic energy loss eV/ion/nm
- Target thickness (um)

**Table:**
- Ions/pulse (total): $\sim 10^{10} - 10^{12}$ vs $10^{10} (3\times10^{11})$
- Pulse length: 40-100 ns vs 2 ns (~1 ns)
- Typical spot size: $\sim 1$ mm$^2$ vs 1 mm$^2$
- Ion species: H, C, ..., Au vs He (also H and higher Z)
- $E_{\text{kin}}$: 0.4 – 1 GeV/u vs 0.12 - 1.2 MeV
- Energy spread: low vs $\sim 10\%$
- Repetition rate: fast vs 2/min
- Target temp.: few eV, to $\sim 100$ eV vs $<0.1$ eV ($\sim 1$ eV)
- Radiation environment at the target: Intense, requires shielding vs Benign, no shielding required
- Heated volume: $> \text{mm}^3$ vs $\sim 1$ mm$^2 \times 5\mu\text{m} =5\times10^{-3}$ mm$^3$
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.

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

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

Simulated line-charge profile

J. W-K. Mark, et al.

Hohlraum Temperature (eV)

Callahan, Tabak, Phys Plasmas (2000)

Exp connect to HIF parameters: Perveance, "tune depression," compression ratio ~ a fusion driver.
We can probe the materials physics of radiation damage *in situ* on short time scales with pulsed ion beams at NDCX-II.

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)