PROGRESS IN BEAM FOCUSING AND COMPRESSION FOR TARGET HEATING AND WARM DENSE MATTER EXPERIMENTS

Peter Seidl
Lawrence Berkeley National Laboratory, HIFS-VNL

...with A. Anders¹, J.J. Barnard², F.M. Bieniosek¹, R.H. Cohen², J.E. Coleman¹,³, M. Dorf⁴, E.P. Gilson⁴, D.P. Grote², J.Y. Jung¹, I. Kaganovich⁴, M. Leitner¹, S.M. Lidia¹, B.G. Logan¹, P. Ni¹, D. Ogata¹, P.K. Roy¹, A. Sefkow⁴, W.L. Waldron¹, D.R. Welch⁵

¹Lawrence Berkeley National Laboratory
²Lawrence Livermore National laboratory
³University of California, Berkeley
⁴Princeton Plasma Physics Laboratory
⁵Voss Scientific, Albuquerque

PAC 2009
May 7, 2009
Vancouver, Canada
Outline

Beam requirements
Method: bunching and transverse focusing
Beam diagnostics
Recent progress:
- longitudinal phase space measured
- simultaneous transverse focusing and longitudinal compression
- enhanced plasma density in the path of the beam
Next steps toward higher beam intensity & target experiments
- greater axial compression via a longer-duration velocity ramp
- time-dependent focusing elements to correct chromatic aberrations
Explore warm dense matter (high energy density) physics by heating targets uniformly with heavy ion beams.

Near term, NDCX-1: planar targets predicted to reach $T \approx 0.2 \text{ eV}$ for two-phase studies.

Assumptions for Hydra simulation:

- $E = 350 \text{ keV}$, $K^+$
- $I_{\text{beam}} = 1 \text{ A}$ (40X compression)
- $t_{\text{beam}} = 2 \text{ ns FWHM}$
- $r_{\text{beam}} = 0.5 \text{ mm}$, $\mathcal{E} = 0.1 \text{ J/cm}^2$
- $E_{\text{total}} = 0.8 \text{ mJ}$, $Q_{\text{beam}} = 2.3 \text{ nC}$

Later, for uniformity, experiments at the Bragg peak using Lithium ions

\[
\frac{1}{Z^2} \frac{dE}{dX} \quad \text{(MeV/mg cm}^2)\]

Energy/Ion mass (MeV/amu)

\[
\text{Li @ 0.1 - 0.4 MeV/amu = NDCX II (planned)}
\]
\[
\text{(Bragg peak)}
\]
\[
\text{K @ 0.003 - 0.009 MeV/amu = NDCX I}
\]
\[
\text{(nuclear stopping plateau)}
\]

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, A7, 233 (1970))
The Heavy Ion Fusion Virtual National Laboratory

Approach: High-intensity in a short pulse via beam bunching and transverse focusing

The time-dependent velocity ramp, $v(t)$, that compresses the beam at a downstream distance $L$.

Velocity ramp: $v(t) = \frac{v(0)}{1 - \frac{v(0)t}{L}}$

Induction bunching module (IBM) voltage waveform:
$V(t) = \frac{1}{2}mv^2(t) - \phi_o$, ($e\phi_o =$ ion kinetic energy.)

Measured $\Delta E$ of injected beam: adequate for ~ns bunches.

Energy analyzer, unbunched beam

$\sigma E = \sqrt{\frac{kT_L}{M}}$
NDCX-1 has demonstrated simultaneous transverse focusing and longitudinal compression

Objectives: Preservation of low emittance, plasma column with $n_p > n_b$, ($\varepsilon_{ni} = 0.07 \text{ mm-mrad}$, $n_{b-init} \approx 10^9 / \text{cm}^3$, $n_{b-max} \approx 10^{12} / \text{cm}^3$ now, later, $\approx 10^{13} / \text{cm}^3$)
Neutralized Drift Compression Experiment (NDCX) with new steering dipoles, target chamber, more diagnostics and upgraded plasma sources

New: steering dipoles, focusing solenoid (8T), target chamber, more diagnostics, upgraded plasma sources
Beam diagnostics - improved Fast Faraday Cup: lower noise and easier to modify

Requirements:
Fast time response (~1 ns)
Immunity from background neutralizing plasma

Design:
2 hole plates, closely spaced for fast response.
Hole pitch (1 mm) & diameter (0.23, 0.46 mm) small → blocks most of the plasma

- Metal enclosure for shielding.
- Easier alignment of front hole plate to middle (bias) hole plate.
- Design enables variation of gaps between hole plates, and hole plate transparency.
Beam diagnostics in the target chamber: Fast faraday cup

Example waveform

\[ I_{\text{beam}} = I_{\text{collector}} \times (\text{transparency})^{-1} \]

\[ = 35 \text{ mA} \times 44 \]

\[ = 1.5 \text{ A peak.} \]
Beam diagnostics in the target chamber: scintillator + CCD or streak camera, photodiode

- Biased hole plate
- $V \approx -300 \text{ V}$
- $\text{Al}_2\text{O}_3$
- $\langle Z \rangle = 1.7$
- $v_b = 1.2 \text{ mm/ns}$
- $v \approx 300 \text{ V}$

**Al$_2$O$_3$ wafer with hole plate:**
- Hole plate to reduce beam flux: less damage
- Prevent charge buildup.

Image intensified CCD camera using $2 < \Delta t < 500 \text{ ns gate}$.

- PI-MAX CCD camera
- Window
- Optical fiber
- Streak camera
- Photodiode

$10 \text{ mm}$

$10-20 \text{ pixels/mm typ.}$

$10 \text{ ns gate}$
Simultaneous longitudinal compression and transverse focusing, compared to simulation.

Net defocusing in gap due to energy change, $E_r$
Latest measurements show a smaller focused spot: $R(50\%) = 1.5 \text{ mm}$. 

Uncompressed

$\approx 10 \text{ mJ/cm}^2$ (compared to previous $4 \text{ mJ/cm}^2$)

Higher plasma density near the focal plane.
5 Tesla $\rightarrow$ 8 Tesla final focusing solenoid.
LSP simulation of drift compression

![Graph showing density (species1, cell) at Th=0.0000 with R ≈ 15 mm]
With the new bunching module, the voltage amplitude and voltage ramp duration can be increased.

12 --> 20 induction cores  
--> higher $\Delta V \Delta t$

FEPS = ferro-electric plasma source
It is advantageous to lengthen the drift compression section by 1.44 m via extension of the ferro-electric plasma source

~2x longer drift compression section (L=2.88 m), Uses additional volt-seconds for a longer ramp and to limit $\Delta V_{\text{peak}}$ & chromatic effects
Ferro-electric plasma sources for neutralized drift compression (PPPL).

Ferro-electric plasma source (FEPS)
- Generated from cylindrical surface
- Installed downstream of IBM
- \( n_e \approx 2-8 \times 10^{10} \text{ cm}^{-3} \)

New FEPS module prior to installation.
Commissioned new IBM and extended FEPS plasma source.

IBM 20 independent 50%-Ni, 50%-Fe (Astron) cores.

Waveform stacking efficiency

\[ \eta_{\text{net}} = \frac{\text{\textbf{V} \cdot s \ in \ full \ range}}{\text{\textbf{V} \cdot s \ in \ single \ core} \times N_{\text{cores}}} = 56\% \]

due to partial cancellation from cores driven with opposite polarity

In the target chamber: With the new IBM/FEPS: ~2 x more ion beam charge in a compressed pulse than the previous IBM/FEPS.

Still tuning up the system.
The improved filtered cathodic arc plasma source (FCAPS) injection has led to a higher plasma density near the target. Plasma density $> 10^{13} / \text{cm}^3$ after modifications to FCAPS: straight filters, 2 --> 4 sources, increased $I_{\text{discharge}}$.
PIC simulation of injection from Cathodic-Arc Plasma Sources confirm experiment measurements

To provide more electrons at larger R in the solenoid:

**Hexcel grid, self supporting**

**Compact FEPS**

4 cm dia.

- t = 1.0μs
- t = 2.0μs

3-D Warp simulation of plasma injection from four FCAPS.

- t = 7.5 μs

**eddy currents modify B**
Calculations support a longer IBM waveform with twice the drift compression length

Comparison of LSP, the envelope-slice model, and the simple analytic model.

(a) no final focusing solenoid.
(b) New IBM, the final focusing solenoid \((B_{\text{max}} = 8 \text{ Tesla})\) \(L_{\text{drift}} = 144 \text{ cm}\), initial setup
(c) with twice the drift compression length \((L = 288 \text{ cm})\) as the present setup.
A time dependent Einzel lens to correct the chromatic aberrations

Unipolar, 3 plates on axis pot'1

ΔV ≈ 60 kV

\[ \Delta V_r \approx -\frac{qr}{2mv^2_{zo}} \frac{dV(t)}{dt} \]

Time-dependent focusing kick (thin lens approximation.)

next: PIC modeling, pulser design, fab.
First target experiments: Prepulse heats thin foils to 3000-4000 K, additional heating by bunched beam.

Scintillator Beam Intensity Distribution

New target manipulator: target shot rep rate increased: 1/day --> several/h

碳箔目标

从快速光学光度计数据：薄金和碳箔目标被未压缩部分（1 µs）的束加热到3000-4000 K。额外加热来自束的压缩束部分已检测到。
The beam characteristics are now satisfactory for target diagnostic commissioning and first target experiments

Energy spread of initial beam is low (130 eV / 0.3 MeV = 4 x 10^{-4})
--> good for sub ns bunches.
Simultaneous axial compression (≈50x) to 1.5 A and 2.5 ns
Beam diagnostics
enhanced plasma density in the path of the beam
PIC simulations of plasma and beam dynamics
Greater axial compression via a longer velocity ramp while keeping \( \Delta v/v \) fixed.
Next steps: time-dependent focusing elements to correct considerable chromatic aberrations
backup slides
Alignment: Beam centroid corrections are required to minimize aberrations in IBM gap & for beam position control at the target plane

Alignment survey: mechanical structure aligned within 1 mm. Manufacturing imperfections (coil w.r.t support structure) not included. Observe < 5 mm, <10 mrad offsets at exit of 4 solenoid matching section without steering dipole correction. We can correct the centroid empirically with steering dipoles at the exit of the solenoid matching section.

\[ I_{\text{max}} \sim 200 \text{ A} \]
\[ B_{\text{max}} \sim 0.5 \text{ kG} \]
45 degree view -- zoomed field lines only
The WDM regime is at the meeting point of several distinct physical regimes -- a scientifically rich area of HEDP


Unknown properties:
EOS \( p(\rho, T), E(\rho, T) \)
Liquid-vapor boundary
Latent heat of evap.
Evaporation rate
Surface tension
Work function
Electrical conductivity \( \frac{dE}{dX} \) for hot targets

Phenomena:
Metal-insulator transition
Phase transitions?
Plasma composition?

Interesting phenomena at: \( 0.01 \rho_{\text{solid}} < \rho < 1.0 \rho_{\text{solid}} \) and \( 0.1 \text{ eV} < T < 10 \text{ eV} \)
Accelerators have several advantages for generating warm dense matter

**Precise control** of energy deposition and ability to measure ion beam after exit

**Sample size large** compared to diagnostic resolution volumes (~ 1's to 10's µ thick by ~ 1 mm diameter)

**Uniform** energy deposition (<~ 5%)

Able to heat **any target material** (conductors, insulators, foams, powders, ...)

A **benign environment** for diagnostics

**High repetition rates** (10/hour to 1/second)