Innovations in Heavy Ion Fusion

by

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SUMMARY

• A new science campaign has been launched to explore the limits of compression of heavy ion beams to very high intensities

• This science campaign can lead to nearterm applications for high energy density physics

• The same campaign provides the science base for modular Heavy Ion Fusion drivers with significant advantages in development path
A Robust Point Design study established a baseline for a multiple-beam quadrupole induction linac HIF driver.
Integration of target, chamber, and accelerator requirements led to the self-consistent point design.

Ion: Bi\(^+\) (A=209)
Main pulse: 4 GeV
Foot pulse: 3.3 GeV
120 beams total (72 main, 48 foot)
Pulse energy: 7 MJ
Final spot radius: 2.2 mm

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3 D neutronics calculations
Length: 2.7 km; Efficiency 28%
Total cost: 2.8 B$

Chamber dynamics
Mechanical engineering

Final beam optics
+ target physics + chamber propagation
Neutralized Chamber Transport: 
Electrons from external source are entrained by the beam and neutralize the space charge sufficiently that the pulse focuses on the target in a nearly ballistic manner to “make small spots.”
The Neutralized Transport Experiment

Gated Camera

400 kV Marx generator
pinhole diagnostic
glass-scintillator diagnostic
injector
four magnetic quadrupoles
rf source ("target plasma")
cathode-arc source ("plasma plug")

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NTX Linear Beam Dynamics

Final focus lattice prepares beam for ballistic neutralized drift
Reduction of Spot Size Using *Plasma* Plug & Volume Plasma (24 mA beam, 20 mm initial radius)

Non-neutralized transport

Effect of plasma plug on spot size

Effect of plasma plug and volume plasma on spot size

FWHM: 2.71 cm

FWHM: 2.83 mm

FWHM: 2.14 mm

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Beam profile at focal plane for three neutralization methods (6 mA beam, 10mm initial radius)

**MEASUREMENT**

**SIMULATIONS**
How can heavy-ion beams be compressed to intensities required for high energy density matter?

Science campaigns (Thrust areas) described in the FWP:

♣ **High brightness beam transport**, to determine the technical requirements for preserving high beam brightness during transport of intense high-current ion beams

♣ **Focusing onto targets**, to develop a basic understanding of magnetic lens aberrations and of how beam-plasma interactions can be used to optimize the transverse focusing of intense ion beams

♣ **Longitudinal beam compression**, to determine the conditions under which the shortest pulse lengths are achievable for future HEDP and IFE targets

♣ **Advanced theory and simulation tools**, to model the physics in the experiments, and to explore brightness degradation due to non-ideal effects.

♣ **Beam target interaction** 10% incremental funding would expedite diagnostic development to determine how uniformly matter can be heated with tailored short-pulse ion beams.
Opportunity: innovations (new or resurrected) can help us address this top-level question

• Neutralized drift compression ◊ much shorter pulses (can test with inexpensive modifications to current hardware)

• Simulations show solenoid and adiabatic plasma lens can focus a beam having the velocity spread associated with neutralized compression ◊ higher focus intensity

• Upstream time-dependent focusing is also tolerant of large velocity “tilt” (using solenoids or quadrupoles)

• Injectors incorporating deceleration after acceleration and / or higher voltage gradient ◊ shorter initial bunches, better match to applications

Both IFE and HEDP can benefit from these ideas
## Timescales for Heavy Ion Beam Science

<table>
<thead>
<tr>
<th>Year</th>
<th>Goal Description</th>
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| 2006     | **2.5 year goal**  
“Assess scientific limits of neutralized ion beam compression to short pulses” (use existing 400 kV, 25 mA, 2 ms K+ beam source) |
| 2009     | **~ 5 year goal**  
“Integrated experiments to assess neutralized beam compression and focusing onto targets” (1 A He, acceleration to 700 kV) |
| 2014     | **OMB/OFES 10 year goal for IFE/HEDP**  
“With the help of experimentally validated theoretical and computer models, determine the physics limits that constrain the use of IFE drivers in future key integrated experiments needed to resolve the scientific issues for inertial fusion energy and high energy density physics” (IBX) |
Intermediate experiments (~FY06) to assess physics limits of neutralized ion beam compression to short pulses (before FY09 upgrades)

First neutralized drift experiment using existing equipment

Existing LBNL 400 kV injector, focusing magnets and induction core

Neutralized Drift Compression Experiment using PPPL large plasma source delivered FY04

2nd step: Accel-Decel Bunching & Solenoid Transport Experiments using existing solenoids and pulsers

1.4 m drift section

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Preliminary LSP-PIC simulations of proposed NTX experiment show dramatically larger compressions of tailored-velocity ion beams *inside a plasma column* (Welch, Henestroza, Yu 3-11-04)

Snapshots of a beam ion bunch at different times shown superimposed

- Velocity chirp amplifies beam power analogous to frequency chirp in CPA lasers
- Solenoids and/or adiabatic plasma lens can focus compressed bunches *in plasma*
- Instabilities may be controlled with \( n_p >> n_b \) and \( B_z \) field (Welch, Rose, Kaganovich)
Solenoids can transport high line charged density at beam low energies

Maximum transportable line charge density has a different scaling than quadrupoles on key quantities:

\[
\lambda \approx \left(10 \frac{\mu C}{m}\right) \left(\frac{B}{10T}\right)^2 \left(\frac{r_p}{10\text{cm}}\right)^2 \left(\frac{133}{A/q}\right) \left(\frac{\eta}{1.0}\right) \left(\frac{a/r_p}{1.0}\right)^2
\]

Advantage for large \( B, r_p \),
Advantage for small \( A/q \) (cf. extensive experience with e⁻ induction linacs)

Note \( \lambda \) is independent of energy, so very low energy transport is possible

For magnetic quadrupoles,
\( \lambda \sim (q/A)^{1/2} \beta r_p \), favoring small beams and high energy.

For electric quadrupoles,
\( \lambda \sim \) independent of \( q/A, r_p, \) and \( \beta \) (except at very low energy when \( \lambda \sim \beta^2 \)),
favoring small beams and low (but not too low) ion energy and heavy ions
Solenoidal Transport Experiment Layout
Solenoidal Transport Experiment

STX EXPERIMENT (NTX-SOLENOID)

K beam @ 300 kV, apertured to 25 mA

- S1: 787 kA-turns
- S2: 630 kA-turns
- S3: 630 kA-turns
- S4: 630 kA-turns

20cm 40cm

Trajectories

Bz/100(T)

GUN
Accel-Decel Injector Provides Beam Compression $\lambda$

Front-End

HIGH LAMBDA INJECTOR (NTX-EINZEL)

K beam @ 300 keV ---> 12 keV

$\lambda=0.02$ ---> 0.1 $\mu$C/m

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LOAD AND FIRE

Injected a 2µs parabolic pulse, 25 mA, 10 keV, K beam
Accelerated by a constant e-field @ 200 kV/m (0 to 1.5 m)
Further preliminary simulations show neutralized compression and focusing may extend to regimes of interest to HEDP/IFE\(^1\)

Example for FY09 integrated exp. (NDCX-II) for neutralized compression and focusing

\[\downarrow\] 1.5-meter long plasma column
Beam: He\(^+\); Pulse energy: 0.7 J
Energy ramp: 500 - 1000 keV
Current: 10 → 750 A,
Pulse duration: 100 → 1 ns,
Beam radius: 20 → < 1 mm
Final Energy density: \(>10^{11}\) J/m\(^3\)

Possible modular driver example for IFE:

\[\downarrow\] 100 m long plasma column
Beam: Ne\(^+\); Pulse energy: 140 kJ
Energy ramp: 200 - 240 MeV
Current: 3 → 140 kA
Beam radius: 10 cm → < 5 mm
Pulse duration: 210 → 5 ns
shows filamentation but still 92% of beam falls within 5 mm spot for a hybrid-distributed radiator target

1. Welch, et.al. MRC
FY09 integrated beam experiments combine neutralized compression and focusing onto target (NDCX-II)

*Needs ~1 A Helium beam injector instead of present 25 mA K⁺, and stronger solenoid*

- Short Pulse accel-decel Injector: $885 K
- Short acceleration and compression tilt section to 700 keV (use existing cores): $1,160 K
- 1.4 m long Neutralized Drift: $380 K
- Solenoid and Z-Pinch focus: $500 K

+ 30% contingency ($878 K) => Total hardware systems $3.8M beyond NDCX-I
**NDCX-III**

**EXISTING BUILDING 58**

**600kV ACCEL-DECEL INJECTOR**

**2-3 MV INDUCTION BUNCHER 200 ns**

**High gradient short pulse ACCELERATOR 30 MV @ 3MV/m**

**UNNEUTRALIZED DRIFT COMPRESSION to 20 ns**

**PLASMA-NEUTRALIZED DRIFT COMPRESSION AND FOCUS**

**TARGET CHAMBER**

1 to 10 eV warm dense matter physics

**Parameters at Target:**
- 30 MeV Ne+ / 60 MeV Ar++
- 20-40 J Beam Energy
- 1-2 kA peak Current
- 0.5 to 1 ns Pulse Length

**NDCX-III High Energy Density User Facility Layout (FY 2015)**
Example: A 16 module, 1 beam/module solenoid focus option

**Pulse energy ~ 6.7 MJ**

**V ~ 200-300 MV: T ~ 2.5 GeV Xe^{+8} ions or T ~ 200 MeV for Ne^{+1}**

Chamber options

Vortices with liquid FLiNaBe or FLiBe serving as wall protection, and heat absorbing fluid, may be well suited for cusp or solenoidal focusing options (upper left).

Hi-life-like chamber protections schemes (as in the RPD design, lower right) may be extendable to assisted pinch designs (lower left).
An integrated PIC Simulation (LSP) from Accelerator Exit to Target Demonstrates 92% energy deposition within required 5mm spot

Ion beam in Brillouin flow equil. Neutralized drift compression region Neutralized focusing region Chamber first wall

Immersed Plasma

Solenoids

Adiabatic section

~100 m 50 kA channel current

50 kA channel current

B_θ

Hybrid target

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147 J beam energy transport design with 105 m drift length

- 3.35-kA, 10-cm, 8-mm-mrad, 231-MeV, 210 ns Ne$^{+1}$ beam (147 kJ) with a 20% perfect energy tilt to axially focus at L=104.5 m
- Injected Billouin Flow equilibrium into 10 T
- Transition to neutralized drift (σ=10$^{12}$ s$^{-1}$) with .14 T at z = 2.4 m
  - $n_p/n_b = 10$, $r_L/\lambda_{sd} \approx 0.01 << 1$ (no self fields)
- 5 kG dipole field at 2.2 m, no plasma electron transport
- Focusing solenoid at 90-100 m (2.7 T)
- 50-kA, discharge channel z>101 m: 2-0.5 cm radius in 1.5 m adiabatic channel; 3-m long, .5-cm radius straight channel

Envelope solution
Good energy transport to target

- 92% of 147 kJ energy strikes target within 5 mm radius
- Halo forms from lack of “ears” and due to filamentation (σ model dependent)

Well matched radius except for ends

Emittance remains small until focus

Current rises to 140 kA at discharge

Peaked distribution at target
A new science campaign has been launched to explore the limits of compression of heavy ion beams to very high intensities.

This science campaign can lead to nearterm applications for high energy density physics.

The same campaign provides the science base for modular Heavy Ion Fusion drivers with significant advantages in development path.
Backup
Additional preliminary simulations show neutralized compression and focusing may extend to higher energy regimes of interest to HEDP/IFE (Welch, et.al. MRC)

Potential example for FY09 integrated exp.

Ramped 500-1000 keV, 10 A, 100 ns, 0.7 J He$^+$ ion beam injected into a 1.5-m-long plasma column compresses to 750 A @ <1 mm focus and ~ 1 ns\(>10^{11} \text{ J/m}^3\)

Possible modular driver example for IFE

Ramped 200-240 MeV, 3 kA, 210 ns, 140 kJ Ne$^+$ ion beam injected into a 100-m-long plasma column shows filamentation but still compresses nicely to 140 kA, 5ns <5 mm focal spot radius for a hybrid-distributed radiator target.
A solenoid-based final focus system for a modular driver has attractive features

- Large cone angle $\theta \sim 100$ mr produces a small spot ($\sim 5$ mm) on target for $\varepsilon \sim 4 \times 10^{-4}$ m-rad
- Moderate fields allow normal magnets
- Highly stripped ions (200-300 MeV Ne$^{+10}$)
- Fringe field aberrations minor
A Modular HIF Driver Point Design

Pulse energy ~ 6.7 MJ

$V \sim 200-300\,\text{MV}$: $T \sim 2.5\,\text{GeV}$ $\text{Xe}^{+8}$ ions or $T \sim 200\,\text{MeV}$ for $\text{Ne}^{+1}$

High $\lambda$ injector
Merging beamlet source/injector
or
accel/decel injector

Induction linac
single beams
$r_p \sim 15\,\text{cm}$
$B_s \sim 9\,\text{T}$
$I \sim 6.7\,\text{kA}$
$T \sim 2.5\,\text{GeV}$
$\Delta t \sim 100\,\text{ns}$
double pulsed for foot and main pulses

cusp focusing
with axisymmetric vortex flow

or

adiabatic plasma lense assisted
pinch with cross-jet flow. liquid walls

Neutralized drift compression
$\Delta v/v \sim 0.01$
(no space charge stagnation)

Solenoid focusing leads to a significantly different driver architecture

Low $A/q \Rightarrow$ Low cumulative voltage $V$ (ion energy/q)

High $\lambda$, large $r_p \Rightarrow$ Few beams ($\sim 20$), separate cores
  $\Rightarrow$ Short, parallel linacs
  $\Rightarrow$ Modularity

High $\lambda \Rightarrow$ High line charge injector required

Few beams $\Rightarrow$ High space charge in each beam
  $\Rightarrow$ Aggressive use of neutralization
  $\Rightarrow$ Neutralized drift compression (no space charge to remove velocity tilt)

Neutralized final focus (with velocity tilt)
  $\Rightarrow$ Cusp focus, or,
  $\Rightarrow$ Adiabatic plasma lens, assisted pinch final focus
Representative schematic of FY09 Integrated beam experiments on compression and focusing to targets

Needs ~1 A Helium beam injector instead of present 25 mA K+, and larger B-a solenoid

First beamline might be used for quadrupole gas/electron experiments

Short Pulse accel-decel Injector

Short acceleration and compression tilt section to 700 keV (use existing ETA and DARHT Cores)

1.4 m long Neutralized Drift

Solenoid and Z-Pinch focus

Target focus diagnostics
Beam diagnostics requirements for neutralized pulse compression experiments

• Large axial compression requires accurate measurement of $\Delta p/p$. Improved Electrostatic Energy Analyzer now under development.

• Fast diagnostic developments required include
  – Improved scintillators for high speed/long life
  – Modify existing diagnostics (Faraday cup, slit scanner) for high speed

• As beam intensity increases, migrate to nonperturbing diagnostics where possible
  – E.g. active probe beams: electron, optical probes
  – Passive: capacitive, inductive, RF pickups
Neutralized Transport Experiment (NTX-operating at LBNL)

- 400 kV Marx / injector
- Focusing magnets
- Pulsed arc plasma source
- Drift tube
- Scintillating glass
- Envelope simulation of NTX focusing with and without plasma

Space charge blow-up causes large 1-2 cm focal spots without plasma.

Smaller 1 to 2 mm focal spot sizes with plasma are consistent with WARP/LSP PIC simulations.

(Submitted for publication in Physical Review Special Topics- Accelerator and Beam Physics)
Example of critical physics issue: drift compression of bunch length by factors of 10 to 30

Induction acceleration is most efficient at $\tau_{\text{pulse}} \sim 100$ to 300 ns

Bunch tail has a few percent higher velocity than the head to allow compression in a drift line

The beam must be confined radially and compressed longitudinally against its space-charge forces

Issues that need more study and experiments:

1. Matching beam focusing and space-charge forces during compression.
2. Beam heating due to compression (conservation of longitudinal invariant)
3. Chromatic focus aberrations due to velocity spread
Our new strategy centers on ion beam experiments and modeling to address a top-level scientific question *central* to both HEDP and IFE:

**How can heavy-ion beams be compressed to intensities required for high energy density physics and IFE?**

- Two experimental science campaigns:
  1. Longitudinal beam compression and focusing onto targets, to determine the shortest pulse lengths and smallest spots achievable for future HEDP and IFE targets.
     Plasma neutralization is a key element
  2. High brightness transport of non-neutral beams, including electron cloud effects

- Two supporting areas:
  - Advanced theory and simulation, to model experiments, and to explore non-ideal effects
  - Enabling injector and source development, to provide required beams
Final focus options

Cusp focusing

Magnetic field lines
Ion beams

Solenoidal focusing

Laser channels
Adiabatic plasma lens (z-pinch)

Assisted Pinch Focusing

z-pinch transport

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Movable Pinhole Measurement of 4-D Phase Space at Entrance to Neutralization Pipe (6 mA beam, 15 mm initial radius, Ne \( \sim 2 \times 10^{11}/\text{cm}^3 \))

Image taken after pinhole sample has drifted 1 meter

Vertical Pinhole Scan

Plasma density \( \sim 2 \times 10^{11}/\text{cm}^3 \)

Full 2-D Pinhole Scan

rms size \( \sim 1.0 \text{ mm} \)

Neutralized beam

rms size \( \sim 1.4 \text{ mm} \)
STX - 4 solenoid transport

- Beam should be measured inside solenoid
- Primarily \( n_b(x, y, z) \)

**Accel-Decel / Load-fire diagnostics**

- \( E(t) \), \( I(t) \) very near exit end and/or inside the magnet
- Beam measurement inside the solenoid will be highly desirable
NDC-I

At pulser location

\[ E = \begin{cases} 
1.25V & \text{voltage} \\
0.75V & \text{current}
\end{cases} \]

\[ K^2 - 300 \text{keV} \]

\[ V_0, E_0 \]

\[ K - 500 \text{ns} \rightarrow K \]

\[ 1 \text{ m downstream} \]

\[ \begin{align*}
\text{Current} & \rightarrow 25 \text{mA} \\
\text{Time} & \rightarrow 5 \text{ns}
\end{align*} \]

Necessary hardware and diagnostics

1. 1-m long volume plasma (ferro-electric)
2. Pulsed (\(< 1\%\) accuracy)
3. Energy analyzer (\(< 1\%\))
4. Beam measurement:
   - Time resolution (\(~\text{ns}\))
   - Spatial resolution (\(~\text{mm}\))
   - The final beam is a "blob" (~2 mm radius; 5 mm long)