Design of a Proof of Principle
High Current Transport Experiment


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Abstract

Preliminary designs of an intense heavy-ion beam transport experiment to test issues for Heavy Ion Fusion (HIF) are presented. This transport channel will represent a single high current density beam at full driver scale and will evaluate practical issues such as aperture filling factors, electrons, halo, imperfect vacuum, etc., that cannot be fully tested using scaled experiments. Various machine configurations are evaluated in the context of the range of physics and technology issues that can be explored in a manner relevant to a full scale driver. It is anticipated that results from this experiment will allow confident construction of next generation “Integrated Research Experiments” leading to a full scale driver for energy production.
An Integrated Research Experiment (IRE) is being planned to test most remaining issues for Heavy-ion Fusion (HIF)

K\(^+\) ions at 200 MeV, \(E_{\text{tot}} \sim 30 \text{ kJ}\), intensity goal \(\geq 3 \times 10^{12} \text{ W/cm}^2\)

\(\tau \sim 7 \mu\text{s}\)

- Injector & match (6 m)
- Electric focusing accel (50 m) to 9.4 MeV
- Magnetic focusing accel (205 m)
- Drift line (60 m)
- Chamber (r \sim 2 m)
- Final focus magnets

- Ferromagnetic core
  - \(r_{\text{inner}} \sim 0.4 \text{ m}\)
  - \(r_{\text{outer}} \sim 0.67 \text{ m}\)

- Beam bore \(r_{\text{beam}} \sim 1.8 \text{ cm}\)
- Half-lattice period 0.2 - 1.7 m

- 32-beam quadrupole magnet array
Transport Understood in Scaled Experiment

Simulation

Experiment

- \( \lambda = 5.6 \times 10^{-3} \, \mu \text{C/m}, \ K = 6.3 \times 10^{-4}, \ \varepsilon_n = 0.025 \, \text{mm-mrad measured} \)

- \( \varepsilon^2/(2K\langle r_x \rangle) \sim 10^{-2} \rightarrow \) strong relative space charge (driver like)
  But absolute strength weak relative to a driver
Transport Understood In Ideal Theory and in Simulations

WARP transverse “slice” simulations [D.P. Grote] of a single-beam of an unoptimized IRE design with acceleration, electric and magnetic fringe fields, lattice structures, etc.

- Various quadrupole alignment and field errors simulated
- Each color represents an overlay of five simulations with different sets of errors (random “seeds”)

<table>
<thead>
<tr>
<th>pseudo-octopole included</th>
<th>RMS quad offset</th>
<th>RMS quad strength error</th>
<th>RMS quad angle error</th>
</tr>
</thead>
<tbody>
<tr>
<td>no</td>
<td>25μ</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>yes</td>
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<td>0.1°</td>
</tr>
<tr>
<td>yes</td>
<td>25μ</td>
<td>0.1%</td>
<td>0.2°</td>
</tr>
</tbody>
</table>

Normalized RMS Edge Emittance

RMS emittance growth due to expected machine errors is consistent with maintaining beam focusability on target
A High Current Transport Experiment (HCX) Is Needed

Next-step IRE/Driver machines will be expensive.
For confident design:

- Non-scalable issues in transport need to be explored experimentally at driver scale line-charge density
- "Dirty" physics issues must be better understood
- Technological components need to be engineered, prototyped, and tested

This program is being carried out with present group resources in the Virtual National Laboratory (VNL, an LBNL LLNL collaboration) by:

- Developing and prototyping technology for multi-beam transport, eg. arrays of quadrupole magnets for beam focusing, etc.
- Verify transport and needed machine aperture clearances at full scale in beam self-fields with a single-beam transport experiment

A single-beam High Current Transport Experiment is being designed to verify transport at full driver scale line-charge density and pulse duration. This experiment will explore physics and technology issues associated with high current transport and will enable confident design of next-step IRE/Driver experiments.
HCX Philosophy

Test transport issues not addressed by scaled experiments and idealized simulations

- Purpose not to validate present thinking, but to find where it may be wrong
- Understanding will help select a more optimal beam size and thus downselect from the large range of beam number (4 to thousands) presently being considered

Test transport limits to failure for confident IRE/driver design

- Find and improve limits at full driver scale space-charge ($\lambda \sim 0.25 \, \mu C$) and pulse duration ($\Delta t \sim 20 \, \mu s$ and less)
- Maximize average beam current density $J$ and aperture fill factor

Push Technology to Limit

- Transport limits are inextricably linked to technology
- Experiment should be assembled from hardware designed for the purpose
HCX: Physics Issues

Transport Limits at High Aperture Fill Factors
- Imperfect alignment and focusing fields
- Image charges from beam proximity to conducting pipe

Electrons
- Production from lost halo particles and beam proximity to structures/apertures
  - Self field potential $\sim 6 \text{ kV}$ on-axis and a long pulse $\sim 20 \text{ µs}$ can allow electron trapping
  - Magnetic quadrupole focusing lacks intrinsic electron sweeping
- Streaming instabilities can rapidly degrade beam quality

Beam Halo
- Halo particles can be lost resulting in electron production and liberation of desorbed gases
  - Possible degradation of transport limits

Matching Bunch Head, Transverse/Longitudinal Equilibration Instability, Space-Charge Waves, etc.
Electric Quadrupoles Inhibit Electron Trapping Whereas Magnetic Quadrupoles Do Not

Total electrostatic potential at the point of max beam envelope excursion in an x-focusing quadrupole

Electric Focusing
Potential Contours

Magnetic Focusing

Grounded Beam Pipe
$r_p = 2.47$ cm

Hyperbolic Electrodes

X (cm)
Y (cm)

Clear Aperture
$r_p = 2.05$ cm

Edge Radius of Beam Envelope

75.9 kV

Potential (kV)

6.6 kV
Superconducting Quadrupole Focusing Magnets

- Develop compact, high-field quadrupoles
  Wire radius $r_w \sim 2-4 \text{ cm}$, Field $B_q \sim 3-6 \text{ Tesla}$
  Employ mass production techniques for cheap construction
  Winding geometries for acceptable field quality
  Minimize axial and radial dead space in cryostats
  Employ features of array magnets to the extent economical

- Gain experience with
  Cryo-systems
  Superconducting magnet power supplies
  Quench protection

Diagnostics

- Must measure detailed distribution
  accurate time dependent measures of mismatch, misalignments, electrons, halo, etc, needed to understand transport limits

- Must be compact for eventual use in IRE/driver
HCX: Technology Issues (2)

Alignment, Matching, and Steering
- Systems (possibly automatic) needed for beam
  - Matching
  - Steering
  - Electron sweeping
  - Trim/prevent halos

Vacuum
- Driver-like high vacuum systems
  - Use liquid He in quadrupole cryostats for combined function cryo-pumping
Alternating Gradient Focusing Lattice

**x-Focusing Strength,** $\kappa_x$  \quad  (\kappa_x = -\kappa_y)

- **F-Quad**
- **Drift**
- **D-Quad**
- **Drift**

\[ d_1 = \alpha (1 - \eta) 2L \]
\[ d_2 = (1 - \alpha)(1 - \eta) 2L \]

**Focusing Strength:**

\[ \kappa_q = \begin{cases} 
\frac{1}{[B\rho]} \frac{dB_x}{dy} \\
\frac{1}{[B\rho]V_b} \frac{dE_x}{dx} 
\end{cases} \]

- **Q** = Quadrupole Occupancy \quad (0 < \eta < 1)
- **\alpha** = Syncopation Factor \quad (0 < \alpha < 1)
- $\alpha = 1/2 \Rightarrow$ Symmetric FODO, $d_1 = d_2$
- $\alpha = 0, 1 \Rightarrow$ F touches D

**Magnetic Quadrupole**

\[ [B\rho] = m\gamma V_b / q \]

**Electric Quadrupole**
Transport Limits: Transverse RMS Envelope Equations

Neglecting image charges, centroid offsets, and nonlinear self-fields (emittance constant) to calculate the beam envelope radii in a lattice period

\[
\frac{d^2 r_x}{ds^2} + \kappa_x r_x - \frac{2K}{r_x + r_y} - \frac{\varepsilon_x^2}{r_x^3} = 0
\]

\[
\frac{d^2 r_y}{ds^2} - \kappa_y r_y - \frac{2K}{r_x + r_y} - \frac{\varepsilon_y^2}{r_y^3} = 0
\]

\[
K = \frac{qI}{2\pi \varepsilon_0 mc^3 \gamma_s \beta_s^3}
\]

\[
\varepsilon_x = 4\left[ \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2 \right]^{1/2}
\]

\[
( \varepsilon_{xn} = \gamma_b \beta_b \varepsilon_x \text{ normalized})
\]

The matched beam solution together with parametric constraints from engineering, higher-order theory, and simulations are used to design the lattice
Transport Limits:

Introduce $\sigma$ and $\sigma_0$ the phase advance of particle oscillations per lattice period ($2L$) in the presence and absence ($I = 0$) of space-charge

$$\cos \sigma_0 \approx 1 - \frac{(\eta \kappa q L^2)^2}{2} \left[ \left(1 - \frac{2}{3} \eta \right) - 4 \left(\alpha - \frac{1}{2}\right)^2 \left(1 - \eta \right)^2 \right]$$

For maximum current transport ($\sigma \to 0$), the matched envelope equations can be approximately solved to obtain [E.P. Lee, Particle Accel. 52, 115 (1996)].

Scaling of Solutions

average force balance

$$\frac{L}{r_x} \approx \sqrt{\frac{1 - \cos \sigma_0}{2K}}$$

$$\bar{r_x} = \frac{2L}{r_x} r_x = \int_0^{2L} \frac{r_x}{2L} ds$$

envelope excursion

$$\frac{Max[r_x]}{r_x} \approx 1 + \frac{(\eta \kappa q L^2)}{4} \left(1 - \frac{\eta}{2}\right) \left[1 - 4 \left(\alpha - \frac{1}{2}\right)^2 \left(1 - \eta \right)^2 \right]$$
Transport Limits (2):

Lattice parameters must be chosen consistent with stability restrictions, materials limits, practical engineering tolerances and rules of thumb that account for detailed effects, “dirty” physics, etc. For example:

- $\sigma_0 < 80^\circ$ to account for envelope and space-charge instabilities
- Field limits in magnetic materials, superconductors, voltage breakdown limits, materials strengths, source technology, etc.
- Aspect ratios and geometries to limit undesirable nonlinear applied focusing fields
- Machine alignments tolerances

An important choice is the machine aperture or “pipe radius.” Practical experience with scaled experiments and simulations shows:

For $\sigma/\sigma_0 << 1$

$$r_p = 1.25 \times \text{Max}[r_x] + \Delta$$

Typical $\Delta = 1 \text{ cm to } 0.5 \text{ cm}$

Depending on details of lattice, steering, etc.
Transport Limits (3):

A systems code incorporating numerous constraints was written to design lattices that minimize the aperture needed to transport a given current $I$:

$$I \approx \frac{\pi \varepsilon_0 c^2}{\sqrt{2}} \left[ \left(1 - \frac{2}{3} \eta \right) - 4 \left( \alpha - \frac{1}{2} \right)^2 (1 - \eta)^2 \right] \left(1 - \cos \sigma_0 \right)^{\frac{1}{2}}$$

$$ \times \beta_b^2 \left( \frac{r_x}{r_p} \right)^2 \eta \left( \frac{B_p r_p}{2 V_q / (c \beta_b)} \right) ; \text{Magnetic Focusing}$$

$$B_p = \text{Quadrupole Field at } r_p \quad V_q = \text{Rod-to-Ground Voltage of Quadrupole Rod}$$

$$B_w = B_p \left( \frac{r_w}{r_p} \right) = \text{Field at } r_w = \text{inner wire radius of magnet coil}$$

Potassium ($K^+$) with $I \sim 1 \text{ A ( } \lambda \sim 0.25 \text{ } \mu \text{C/m) most attractive:}$

- Consistent with driver-like injector technology
- Practical and economical electric and magnetic focusing quadrupoles
- Allows more viable acceleration and pulse compression experiments in a continued series of experiments
**HCX: Lattice Options with $\sigma_0 = 80^\circ$**

### Potassium
(38.96 amu, singly ionized)

\[ E = 2.0 \text{ MeV}, \ I = 810 \text{ mA}, \ K = 0.00116, \ \varepsilon_n = 0.346 \text{ mm-mr} \]

<table>
<thead>
<tr>
<th>Case</th>
<th>$L$ cm</th>
<th>$\eta$</th>
<th>$\alpha$</th>
<th>Avg $[r_x]$ cm</th>
<th>Max $[r_x]$ cm</th>
<th>$r_p$ cm</th>
<th>$r_w$ cm</th>
<th>$B_w$ T</th>
<th>$V_q$ kV</th>
<th>$\sigma/\sigma_0$</th>
<th>$d_f$ cm</th>
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</thead>
<tbody>
<tr>
<td>* Sync, Mag</td>
<td>17</td>
<td>0.55</td>
<td>0.15</td>
<td>0.90</td>
<td>1.18</td>
<td>2.47</td>
<td>2.87</td>
<td>4.05</td>
<td>-</td>
<td>0.11</td>
<td>7.8</td>
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<td>Sync, Elec</td>
<td>18</td>
<td>0.60</td>
<td>0.20</td>
<td>0.95</td>
<td>1.24</td>
<td>2.05</td>
<td>-</td>
<td>-</td>
<td>75.9</td>
<td>0.11</td>
<td>6.8</td>
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<tr>
<td>FODO, Mag</td>
<td>21</td>
<td>0.50</td>
<td>0.50</td>
<td>1.11</td>
<td>1.46</td>
<td>2.82</td>
<td>3.22</td>
<td>2.93</td>
<td>-</td>
<td>0.09</td>
<td>5.1</td>
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<tr>
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<td>20</td>
<td>0.55</td>
<td>0.50</td>
<td>1.06</td>
<td>1.38</td>
<td>2.23</td>
<td>-</td>
<td>-</td>
<td>73.2</td>
<td>0.10</td>
<td>4.3</td>
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</tbody>
</table>

### Cesium
(132.9 amu, singly ionized)

\[ E = 2.0 \text{ MeV}, \ I = 430 \text{ mA}, \ K = 0.00113, \ \varepsilon_n = 0.187 \text{ mm-mr} \]

<table>
<thead>
<tr>
<th>Case</th>
<th>$L$ cm</th>
<th>$\eta$</th>
<th>$\alpha$</th>
<th>Avg $[r_x]$ cm</th>
<th>Max $[r_x]$ cm</th>
<th>$r_p$ cm</th>
<th>$r_w$ cm</th>
<th>$B_w$ T</th>
<th>$V_q$ kV</th>
<th>$\sigma/\sigma_0$</th>
<th>$d_f$ cm</th>
</tr>
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<tbody>
<tr>
<td>Sync, Mag</td>
<td>26</td>
<td>0.50</td>
<td>0.40</td>
<td>1.36</td>
<td>1.78</td>
<td>3.23</td>
<td>3.63</td>
<td>4.00</td>
<td>-</td>
<td>0.07</td>
<td>10.0</td>
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<tr>
<td>Sync, Elec</td>
<td>26</td>
<td>0.50</td>
<td>0.40</td>
<td>1.36</td>
<td>1.78</td>
<td>2.73</td>
<td>-</td>
<td>-</td>
<td>70.0</td>
<td>0.07</td>
<td>10.9</td>
</tr>
</tbody>
</table>

**Cesium, Existing Pulsed Magnets**
(132.9 amu, singly ionized)

\[ E = 1.6 \text{ MeV}, \ I = 310 \text{ mA}, \ K = 0.00114, \ \varepsilon_n = 0.187 \text{ mm-mr} \]

<table>
<thead>
<tr>
<th>Case</th>
<th>$L$ cm</th>
<th>$\eta$</th>
<th>$\alpha$</th>
<th>Avg $[r_x]$ cm</th>
<th>Max $[r_x]$ cm</th>
<th>$r_p$ cm</th>
<th>$r_w$ cm</th>
<th>$B_w$ T</th>
<th>$\sigma/\sigma_0$</th>
<th>$d_f$ cm</th>
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<tr>
<td>FODO, Mag</td>
<td>50</td>
<td>0.62</td>
<td>0.50</td>
<td>2.62</td>
<td>3.41</td>
<td>5.0</td>
<td>5.4</td>
<td>1.23</td>
<td>0.04</td>
<td>12.5</td>
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</tbody>
</table>
Matched Envelope --- 2MeV, 810 mA, K⁺ Beam

\[
\overline{r_x} = \overline{r_y} = 0.896 \text{ cm}
\]

Max[\(r_x\)] = Max[\(r_y\)] = 1.175 cm \quad \text{Max}[r_x'] = -\text{Min}[r_y'] = 41.1 \text{ mr}

Min[\(r_x\)] = Min[\(r_y\)] = 0.648 cm \quad \text{Max}[r_y'] = -\text{Min}[r_x'] = 63.8 \text{ mr}
Lattice Schematic --- 2MeV, 810 mA, K⁺ Beam

R-Z Cross-Section
(2 quadrupole cryostat)

X-Y Cross-Section
(in magnet)

- Cryostat
- Coils
- Free Space (Diagnostics, Pump, etc)
- Bellows
- Beam Pipe
- Insulation
- Coils
- Collar/Yoke
- Pipe
3x3 array, $\cos(2\theta)$, circular cross section

$G_{\text{oper}} = 50 \text{T/m}, B_w = 3.74 \text{T}, r_p = 7 \text{ cm}$

$L_{\text{eff}} = 320 \text{mm}$

"A Superconducting Quadrupole Magnet Array for a Heavy Ion Fusion Driver", S. Caspi et al. (1998).

"Vector Potential and Stored Energy of a Quadrupole Magnet Array", S. Caspi (PAC99).
3x3 array, pancake design [Caspi, Hinkins, and Martovetsky (LLNL)]

**G=47 T/m**
**I= 6295 A**
harmonics, forces

26 strand
Rutherford cable
23 turns.

Advanced Magnet Labs (AML) is constructing prototype superconducting magnets for HCX.

- AML winds magnet coils with robots, using round, flexible cables.

- Two prototype magnets near completion:
  1: \( r_p = 2.3 \text{ cm}, L_{\text{eff}} = 15 \text{ cm}, \) \( B_w = 3-4 \text{ Tesla} \)
  2: \( r_p = 6.0 \text{ cm}, L_{\text{eff}} = 50 \text{ cm}, \) \( B_w = 4 \text{ Tesla} \)

- LBNL/SC program is developing and supplying the cable (H. Higley), and will test the finished quadrupoles.
Electrostatic Quadrupoles

4-beam quadrupole arrays already developed induction linacs can be readily adapted to meet HCX needs

Clear Aperture Radius, \( r_p = 2.3 \text{ cm} \)

Breakdown Voltage, \( V_{q,\text{max}} \sim 150 \text{ kV} \) (Rod-to-Ground)

Total Axial Length, \( L_{\text{tot}} = 28 \text{ cm} \)

Effective Axial Length, \( L_{\text{eff}} \sim 25 \text{ cm} \)
HCX Injector -- Near Term

An existing injector system is based on a diode with a surface-ionization source, a biased column of electrostatic quadrupoles (for acceleration with focusing), and a Marx-based pulser [S.S. Yu et al, Fusion Eng Design, 32, p 309 (1996)]

- Alumino-silicate sources up to 17 cm diameter
  \[ \text{K}^+ (38.96 \text{ amu}) \text{ and Cs}^+ (132.91 \text{ amu}) \text{ sources tested} \]
- Marx presently 2 \(\mu s\) upgrading to 4 \(\mu s\) (possibly \(\sim 7 \mu s\))
- Beam uniformity emerging from diode poor (optics and/or vacuum?) but is being fixed for HCX

\[
\begin{align*}
\text{K}^+: & \quad E = 2 \text{ MeV} \quad I = 800 \text{ mA} \quad \varepsilon_n > 0.6 \text{ mm-mr} \\
\text{Cs}^+: & \quad E = 2 \text{ MeV} \quad I = 430 \text{ mA} \quad \varepsilon_n > 0.3 \text{ mm-mr}
\end{align*}
\]

This injector is adequate for early stages of the experiment and improved K\(^+\) and Cs\(^+\) injector systems with long duration pulsers (20 \(\mu s\)) are under development
HCX Injector -- Planned

Improved $K^+$ single-beam injector systems are under development with:

- $E = 2$ MeV  
  Kinetic Energy
- $I > 800$ mA  
  Current
- $\varepsilon_n < 1$ mm-mr  
  Normalized RMS Edge Emittance
- $\tau_p \geq 20$ $\mu$s  
  Pulse Duration

- Will allow intense beam experiments over full driver scale pulse durations

Issues:
- Beam uniformity must be addressed

<table>
<thead>
<tr>
<th>Source</th>
<th>Alumino-Silicate</th>
<th>Vapor Ionizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Uniformity</td>
<td>Less</td>
<td>More</td>
</tr>
</tbody>
</table>
| Neutral Flux         | Low              | High $K^+$ too large?  
                       |                  | $Cs^+$ acceptable |
Bevatron Building at LBNL a Possible Site for HCX

100+ meters of straight axial length available
- ~20 meters needed initially -- should not interfere with present site uses
- If needed: Sufficient for extended experiments on focusing, compression, and chamber transport
- Possible to use for early stages of IRE or (with extensions) a full IRE

Facilities present and conveniently located to AFRD group

Possible Beamline Layout
Possible Phase II of the High Current Experiment

Design should be flexible to allow progress in the event of any IRE delays

- Capable of reconfiguration to exploring a wide range of issues for IRE/Driver
- Choose site to allow a wide range of experiments to be carried out

Issues addressable in an expanded program:

- Beam acceleration to ~ 20-100 MeV (short pulse for economy)
- Bunch compression (short pulse)
- Longitudinal space-charge waves
- Final focus systems
- Unneutralized, partially neutralized, and channel transport from final focus lenses to the focal spot
Conclusions

We are designing a High Current Transport Experiment (HCX) to test full-scale intense heavy-ion beam transport and enable high confidence next-step Integrated Research Experiments (IRE) and Driver designs for Heavy Ion Fusion (HIF)

- Test non-scalable issues
  -- Electron effects with magnetic focusing and strong self-fields
  -- Halo and lost particles
  -- Imperfect vacuum, materials, etc.

- Develop technology needed for next-step experiments
  -- Superconducting quadrupole magnets:
    Small aperture \( (r_p = 2-4 \text{ cm}) \), high-field \( (B_p = 3-6 \text{ Tesla}) \)
  -- Injectors: High current \( (~1 \text{ A}) \), long-pulse \( (~20 \mu \text{s}) \), uniform charge \( (\rho) \)
  -- Diagnostics: Compact flexible for beam position and phase space

Status

- Preliminary design work has begun
  -- Options in machine parameters are being analyzed, simulated
  -- Component development and prototype
  -- Teams of engineers and scientists are being assembled

- Timescales consistent with programmatic needs
  -- Early assembly work is expected by mid-year 2000
  -- Main program 2-3 years
  -- If needed: Machine upgrades for acceleration, compression, etc.