HIF Driver Point Designs

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Summary

• An HIF driver point design must be an integrated system that is self-consistent from injector to target

• The Robust Point Design (RPD) is an integrated system based on a single accelerator with multiple beams

• Ongoing Modular Point Design (MPD) study seeks a self-consistent integrated solution based on 10-20 accelerator modules with single beam/module
A Robust Point Design study established a baseline for a multiple-beam quadrupole induction linac HIF driver.

1.6 MeV
0.63 A/beam
30 μs
120 beams

3 km

4 GeV Bi^{+1}
94 A/beam
200 ns

400 m

Relative beam bunch length at end of:
- injection
- acceleration
- drift compression

Multiple Ion Source/Injectors

Multipe-beam acceleration

Common

Induction cores

Drift compression

Bending

Final focusing

Chamber transport

Target
Input 7 MJ
Yield 400 MJ

4 GeV
1.9 kA/beam
9.3 ns

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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

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

Chamber dynamics
Mechanical engineering
+ target physics +
chamber propagation

Final beam optics
Target design is a variation of the distributed radiator target (DRT)

- This new design allows beams to come in from a larger angle, up to 24 degrees off axis.
- Yield = 400 MJ, Gain = 57 at $E_{\text{driver}} = 7$ MJ
A building block pulse shape is used

Beam and Pulse Shape Requirements

<table>
<thead>
<tr>
<th>Block</th>
<th>No. of Beams</th>
<th>Power, TW</th>
<th>Pulse width, ns</th>
<th>Energy, MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Foot)</td>
<td>16</td>
<td>70</td>
<td>6.5</td>
<td>0.46</td>
</tr>
<tr>
<td>B (Foot)</td>
<td>16</td>
<td>20</td>
<td>38.3</td>
<td>0.77</td>
</tr>
<tr>
<td>C (Foot)</td>
<td>16</td>
<td>53</td>
<td>10.1</td>
<td>0.54</td>
</tr>
<tr>
<td>D (Main)</td>
<td>24</td>
<td>120</td>
<td>13.7</td>
<td>1.64</td>
</tr>
<tr>
<td>E (Main)</td>
<td>48</td>
<td>388</td>
<td>9.3</td>
<td>3.61</td>
</tr>
</tbody>
</table>

48 foot pulse beams:
\[ T = 3.3 \text{ GeV}, \ E_F = 1.76 \text{ MJ} \]

72 main pulse beams:
\[ T = 4.0 \text{ GeV}, \ E_M = 5.25 \text{ MJ} \]

120 total beams:
\[ E_D = 7.0 \text{ MJ} \]
The Robust Point Design (RPD) beam line
Neutralization is required for small spot sizes

Results for standard Xe main pulse
• time histories of rms radius at selected axial positions
• plasma is electrically connected to wall by images and emission

- 2.5 mm waist is close to value needed by distributed-radiator target
- Bi is easier to focus and meets spot requirement
Beam envelop in final focus region

x- and y- envelopes for the Block E main pulse beams in the final focus system. The target is to the right.
Final focus configuration uses four magnets
Magnet Lifetime: Sufficient material has been added to make the shielding & activation results very robust

Magnet lifetimes, which are limited by dose to the insulators and neutron fluence to the superconductor, exceed the plant lifetime; Insulator & superconductor lifetimes (in years) are:

- Last magnet: 230/260
- 2nd magnet: 410/1580
- 3rd magnet: 100/610

- Waste disposal ratings are significantly reduced from previous work: 1.7, 0.5, 0.4 (\(^{94}\)Nb)

- Increasing liquid stand-off distance in vortices (from 1→5 mm) will reduce lifetimes by ~2x

- Optimizing shielding to increase neutron effectiveness (at cost of gamma-ray shielding effectiveness) should enable all magnets to qualify for disposal as low-level waste; adequate margin exists for magnet lifetime to exceed plant life.
Illustration of final focus arrays is a real eye opener

From Tom Brown, PPPL

Grant Logan
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

Target capsule implosion times require beam drive pulses $\sim 10$ ns

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

The beam must be confined radially and compressed longitudinally against its space-charge forces
Modular Point Design 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}

High λ injector
Merging beamlet source/injector
or
accel/decel injector
Induction linac single beams
r_p ~ 15 cm
B_s ~ 9T
I ~ 6.7 kA
T ~ 2.5 GeV
Δt ~ 100 ns
double pulsed for foot and main pulses

Cusp focusing with axisymmetric vortex flow
or
adiabatic plasma lens assisted pinch with cross-jet flow. liquid walls

Neutralized drift compression
Δv/v ~ 0.01
(no space charge stagnation)

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:

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

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,
$$\lambda \sim \text{independent of } q/A, r_p, \text{ and } \beta \text{ (except at very low energy when } \lambda \sim \beta^2),$$ favoring small beams and low (but not too low) ion energy and heavy ions
RPD and MPD accelerators have different scalings

One 120-beam x 3 km
= 3 km total length of linac

<table>
<thead>
<tr>
<th>RPD Accelerator</th>
<th>MPD Accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta R_c = 0.47,m$</td>
<td>$\Delta R_c = 0.3,m$</td>
</tr>
<tr>
<td>$R_{ci} = 0.74,m$</td>
<td>$R_{ci} = 0.27,m$</td>
</tr>
</tbody>
</table>

39,200 tons of induction cores
220,000 quadrupoles
$0.63\,V\cdot s/m$ cores

7,000 tons of induction cores
4000 solenoids
$0.4\,V\cdot s/m$ cores

16 single-beam modules x 200 m
= 3.2 km total length of linacs

$3.2\,km$ total length of linacs

$750\,M$ total capital cost

$2.8\,B$ total capital cost

49,200 tons of induction cores
220,000 quadrupoles
$0.63\,V\cdot s/m$ cores

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Injectors Options

Three injector options have been suggested so far:

1. Standard injector with aggressive bunch compression within the accelerator. \( \lambda \sim 0.25 \, \mu \text{C/m} \) compressed to \( \sim 25-60 \, \mu \text{C/m} \) requires large initial pulse duration. (May require high gradient to increase initial \( \lambda \) and minimize initial pulse duration.)

2. Accel/decel injector: Use high voltage diode to obtain large current; immediately decelerate, to reduce bunch length; use load-and-fire acceleration to rapidly decrease pulse duration and minimize core volume.

3. \( \beta = 0 \) injector: Inject plasma into solenoid. Apply a longitudinal electric field to separate ions from electrons. Utilize velocity independence of solenoids to confine low velocity beam.
Target will be “hybrid” design, allowing larger focal spots\(^1\)

“Hybrid design” for Modular Point Design:

<table>
<thead>
<tr>
<th>Hybrid target: Large beam spot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spot radius: (~5.0) mm round (or (~5.4 \times 3.8) mm elliptical)</td>
</tr>
<tr>
<td>Pulse energy: 6.7 MJ</td>
</tr>
<tr>
<td>Minimum 8 beams per side</td>
</tr>
<tr>
<td>Ion range equivalent to 4.5 GeV Pb (main) and 3 GeV Pb (foot)</td>
</tr>
</tbody>
</table>

**New task:** define the allowable velocity spread that maintains high target performance

In contrast, Robust Point Design used “Distributed radiator design”

<table>
<thead>
<tr>
<th>Distributed radiator: “Baseline” target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spot radius: 1.8 mm (\times) 4.2 mm (main)</td>
</tr>
<tr>
<td>Pulse energy: 6.5 MJ</td>
</tr>
<tr>
<td>Ion range equivalent to 4 GeV Pb (main) and 3.3 GeV (foot)</td>
</tr>
</tbody>
</table>

The drift length for NDC is determined by how much velocity tilt the target can accommodate.

<table>
<thead>
<tr>
<th>Drift length</th>
<th>$\Delta v_1 / v_1$</th>
<th>$\Delta v_m / v_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>134 m</td>
<td>.037</td>
<td>.256</td>
</tr>
<tr>
<td>268 m</td>
<td>.0188</td>
<td>.128</td>
</tr>
<tr>
<td>536 m</td>
<td>.0095</td>
<td>.0638</td>
</tr>
<tr>
<td>1032 m</td>
<td>.0048</td>
<td>.0319</td>
</tr>
</tbody>
</table>
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).
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 $\epsilon \sim 4\times10^{-4}$ m-rad
- Moderate fields allow normal magnets
- Highly stripped ions (200-300 MeV Ne$^{+10}$)
- Fringe field aberrations minor

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### Self-consistent target / chamber / drift compression: an example

<table>
<thead>
<tr>
<th>Hybrid Target</th>
<th>Solenoid / NDC</th>
<th>Assisted Pinch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse shape</td>
<td>Controlled by initial velocity shaping at entrance to NDC</td>
<td>Independent of Beam current</td>
</tr>
<tr>
<td>Range shortening</td>
<td>Beam at exit of NDC maintains initial velocity tilt</td>
<td>Can accommodate large energy variations</td>
</tr>
<tr>
<td>Spot size (~5mm radius)</td>
<td>Driver optimized with high Q/M</td>
<td>Tighter focusing with high Q/M</td>
</tr>
<tr>
<td></td>
<td>Some stripping can occur in NDC</td>
<td>Insensitive to Z-variation</td>
</tr>
<tr>
<td>Symmetry</td>
<td>Few beam driver</td>
<td>Anharmonic focusing in Z-pinch symmetries</td>
</tr>
<tr>
<td>Shallow entrance angle</td>
<td>Nearly parallel beamlines</td>
<td>Beam merging in adiabatic lens</td>
</tr>
</tbody>
</table>
An integrated PIC Simulation (LSP) from Accelerator Exit to Target Demonstrates 92% energy deposition within required 5mm spot.
The RPD and MPD have distinctly different architectures

<table>
<thead>
<tr>
<th>Driver components</th>
<th>RPD (M beams M=120)</th>
<th>MPD (N modules N=10-20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator/Pulse Power System (PPS)</td>
<td>1 accelerator/1PPS</td>
<td>N accelerators/1PPS</td>
</tr>
<tr>
<td>Ion species</td>
<td>Heavy - Bi (Xe possible)</td>
<td>Medium (Ne to Ar)</td>
</tr>
<tr>
<td>Injector</td>
<td>M compact injectors</td>
<td>N high λ injectors</td>
</tr>
<tr>
<td>Transport</td>
<td>Multiple quad array for M beams</td>
<td>Solenoid/hybrid (1 solenoid/module)</td>
</tr>
<tr>
<td>Drift Compression</td>
<td>M vacuum drift compression beamlines</td>
<td>1 Neutralized drift compression beamlines/module</td>
</tr>
<tr>
<td>Final focus / chamber transport</td>
<td>Quad focusing / neutralized ballistic transport</td>
<td>Solenoid in plasma or assisted pinch</td>
</tr>
<tr>
<td>Chamber</td>
<td>HYLIFE II</td>
<td>Vortex chamber or modified HYLIFE</td>
</tr>
<tr>
<td>Target</td>
<td>Distributed Radiator Target With Large Angle</td>
<td>Hybrid Target</td>
</tr>
</tbody>
</table>
Summary

• An HIF driver point design must be an integrated system that is self-consistent from injector to target

• The Robust Point Design (RPD) is an integrated system based on a single accelerator with multiple beams

• Ongoing Modular Point Design (MPD) study seeks a self-consistent integrated solution based on 10-20 accelerator modules with single beam/module
BACKUP
A 7 MJ induction linac driver using Bi+ is the baseline

Accelerator parameters at:
- Injector
- Foot pulse final energy (3.3 GeV)
- Main pulse final energy (4.0 GeV)
- Ion = Bi+ (A = 209 amu)
- Length = 2.9 km
- Driver efficiency = 38%
- Total cost = $2.8B

<table>
<thead>
<tr>
<th>Along Accelerator</th>
<th>Injector Exit</th>
<th>Ti - 3.3 GeV</th>
<th>Ti - 4.0 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion energy, GeV</td>
<td>0.0016</td>
<td>3.3</td>
<td>4.0</td>
</tr>
<tr>
<td>Pulse duration, µs</td>
<td>30</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Ion speed/light speed</td>
<td>0.004</td>
<td>0.18</td>
<td>0.20</td>
</tr>
<tr>
<td>Pulse length, m</td>
<td>36.5</td>
<td>10.9</td>
<td>12.0</td>
</tr>
<tr>
<td>Beam current, A*</td>
<td>0.63</td>
<td>94</td>
<td>94</td>
</tr>
<tr>
<td>Beam radius, cm*</td>
<td>3.8</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Bore radius, cm</td>
<td>5.3</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Field gradient, T/m</td>
<td>62</td>
<td>106</td>
<td>106</td>
</tr>
<tr>
<td>Core inner radius, m</td>
<td>1.29</td>
<td>0.77</td>
<td>0.62</td>
</tr>
<tr>
<td>Core build, m</td>
<td>0.48</td>
<td>0.47</td>
<td>0.47</td>
</tr>
<tr>
<td>Quad Occupancy, %</td>
<td>0.75</td>
<td>0.090</td>
<td>0.075</td>
</tr>
<tr>
<td>Half lattice period, m</td>
<td>0.30</td>
<td>3.83</td>
<td>4.43</td>
</tr>
<tr>
<td>Acc. gradient, MV/m</td>
<td>0.026</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Dist. from injector, km</td>
<td>0</td>
<td>2.39</td>
<td>2.86</td>
</tr>
</tbody>
</table>

*For max current beams (Block E)
147 J beam energy transport design with 105 m drift length

- 3.35-kA, 10-cm, 8-mm-mrad, 231-MeV, 210 ns Ne\textsuperscript{+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 (\(\sigma=10^{12} \text{s}^{-1}\)) with .14 T at z = 2.4 m
  - \(n_p/n_b = 10\), \(r_L/\lambda_{sd} \approx 0.01 \ll 1\) (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
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 (s model dependent)

Well matched radius except for ends

Emittance remains small until focus

Current rises to 140 kA at discharge

Peaked distribution at target
Neutralization of beam space charge in fusion chamber is critical to focusing of driver beams.

Plots show 3.2-kA beam of singly charged 2.5-GeV xenon ions. Beam radius vs time is shown at selected points over a 6-m focal length.

Without plasma neutralization, the ion kinetic energy would have to triple to recover the 2-mm focal spot for the target, increasing the linac voltage, length, and cost.