Multiple Beam Transport

Quadrupole array configuration

- Square unit cells
- Shell-type coils: better magnetic properties
- Racetrack coils: better mechanical properties

Superconducting magnets are required for efficiency in the HIF driver
Classroom Exercise

$$HIF2004$$

$$\eta = 0.4489$$  $$\alpha = 0.2508$$

$$\frac{\partial B_q}{\partial x} \bigg|_{I_{op}} = 0.4489$$  
$$\alpha = 0.2508$$

$$G = 84.2 \text{ T/m}$$  
$$l_q = 10.1 \text{ cm}$$  
$$d_1 = 6.219$$  
$$d_2 = 18.58$$

**HCX Quadrupole Specification**

**Axial Geometry:**

$$L_{coll} = 125 \text{ mm}$$  
$$L_{mat} \leq 155 \text{ mm}$$

**Transverse Geometry:**

$$r_{clear} = 35 \text{ mm}$$  
$$w_{\text{max}} \leq 64 \text{ mm}$$

**Conductor:**

$$J_c (5T,4.5K) = 2.55 \text{ kA/mm}^2$$

**Operating Point:**

$$I_{op} = 0.85 I_{ss}$$  
$$J_{cu}(I_{ss}) \leq 1.3 \text{ kA/mm}^2$$

**Integrated Gradient:**

$$\int_{-\infty}^{\infty} B_q' dz \geq 8.5 \text{ T} \quad @ \quad I_{op} \quad \Leftrightarrow \quad G \approx 100 \text{ T/m}$$

Opportunity to address key R&D issues for HIF superconducting magnets:

- Cost-effectiveness
- Compactness
- Reliability
- Performance trade-offs

...while serving the near term program needs:

- Advance beam science
- Progress on IBX design

**Beam Physics Experiments**

*High Current Experiment (HCX)*

Axial Geometry:

$$l_q = 10.1 \text{ cm}$$  
$$d_1 = 6.219$$  
$$d_2 = 18.58$$

Focus Quadrupole

Defocus Quadrupole

Transverse Geometry:

$$r_{clear} = 35 \text{ mm}$$  
$$w_{\text{max}} \leq 64 \text{ mm}$$

**Conductor:**

$$J_c (5T,4.5K) = 2.55 \text{ kA/mm}^2$$

**Operating Point:**

$$I_{op} = 0.85 I_{ss}$$  
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**Integrated Gradient:**

$$\int_{-\infty}^{\infty} B_q' dz \geq 8.5 \text{ T} \quad @ \quad I_{op} \quad \Leftrightarrow \quad G \approx 100 \text{ T/m}$$
HCX Field Quality Specification

Definitions:

\[ \hat{B}_y(x, y) = \int \frac{\partial B_y}{\partial x} \, dz \]

\[ \hat{B}_z(x, y) = \int \frac{\partial B_z}{\partial y} \, dz \]

\[ \delta \beta = \hat{B}_y + i \hat{B}_z = \sum_n \left( B_y + iA \left( \frac{2}{n} \right) \right) = \sum_n \left( \frac{2}{n^2} \right) \]

\[ \delta F = \frac{\max \left| \beta \left( r, \theta \right) - B_y(r, \theta) \mathcal{e}^{\mathcal{i} \theta} \right|}{B_y(r, \theta)} \]

Requirement (50 periods):

\[ \delta F \leq 50 \times 10^{-4} \text{ "units"} @ r_g = 25 \text{ mm} \]

A factor of ~10 improvement may be needed for beam transport in HIF driver

Magnet Design Concepts

Coil layout

**Shell-type (cosθ)**
- magnetically more efficient
- radially more compact
- complex geometry, fabrication

**Block-type**
- simpler tooling and parts
- mechanical support/assembly
- compatible with brittle SC

Fabrication and assembly

Racetrack coils
Conductor in groove (cylinder, plate)
Baseline Design

Magnet design:
- Block-coil (square) geometry
- 8 double-pancake racetracks

Coil fabrication and support:
- Pre-load by split-pole and wedges
- Epoxy-impregnation in holders
- Modules supported by yoke/shell

Test results (2 pre-series models):
- Rutherford cable or monolith
- Fast training to short sample
- No retraining after th. cycle

Design Optimization (HCX-C)

New design features:
- “square” ends for magnetic efficiency
- Aluminum coil holders for lower cost
- Rutherford cable for flexible design
- SSC inner wire, Cu/Sc=1.3:1.

Fabrication experience:
- Some difficulties due to tight bends
  ⇒ winding radius must be increased
- Larger than expected cable size
- Higher deflections of Al holders
  ⇒ deviations from design geometry
HCX-C Test

- Achieved conductor-limited gradient (132 T/m) in 2 quenches (stable after Q4)
- No retraining after thermal cycle & no significant dependence on ramp rate.

![HCX-C Quench History](image)

### HCX-C Magnetic Measurements

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Temp (K)</th>
<th>Data type</th>
<th>Gradient B2/r0 (T)</th>
<th>12-pole</th>
<th>20-pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5</td>
<td>300</td>
<td>Meas. (*)</td>
<td>0.0674</td>
<td>109</td>
<td>15.5</td>
</tr>
<tr>
<td>9.5</td>
<td></td>
<td>Calc.</td>
<td>0.0726</td>
<td>121</td>
<td>19.1</td>
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<tr>
<td>2500</td>
<td>4.2</td>
<td>Meas.</td>
<td>11.03</td>
<td>5.8</td>
<td>8.5</td>
</tr>
<tr>
<td>2500</td>
<td></td>
<td>Calc.</td>
<td>11.63</td>
<td>8.1</td>
<td>8.7</td>
</tr>
</tbody>
</table>

(*) Averages for ±9.5 A current and clockwise/counterclockwise probe rotation.

### INTEGRATED HARMONICS

<table>
<thead>
<tr>
<th>Order</th>
<th>Measured</th>
<th>Random-Block</th>
<th>Random-Quad</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>5.3</td>
<td>2.7</td>
<td>6.5</td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>5</td>
<td>7.0</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>7</td>
<td>0.6</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>1.0</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>9</td>
<td>2.8</td>
<td>0.05</td>
<td>0.1</td>
</tr>
</tbody>
</table>

(8) Random displacements in a ±100µm interval, flat distribution.
Magnetic Field Optimization (HCX-D)

- 3 turns /layer removed from inner coil, 1 turn /layer removed from outer coil
- Two rectangular pockets introduced in the inner pole-island, facing the bore

All design harmonics within 1 unit at the reference radius (22 mm)

New Coil Fabrication Procedure (HCX-D)

Monolithic pole; coils are impregnated separately, then inserted in holder
Goals: accurate and reproducible geometry; reduction of labor and parts
**HCX Quadrupole Cost**

Cost basis:
- Experience with prototype fabrication
- Cost of parts for the prototypes
- Quotes for larger sets of parts
- Comparison with other accelerators

Assumptions:
- Production of 100 quads (HCX “Phase II”)
- Conductor/cable procured by project
- Other parts procured by manufacturer
- Overhead/fees at 40% of labor and parts
- Project costs are not included

Estimated cost for each quad: 9 k$

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand</td>
<td>0.5 k$</td>
</tr>
<tr>
<td>Cabling</td>
<td>0.15 k$</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.2 k$</td>
</tr>
<tr>
<td><strong>Total conductor</strong></td>
<td><strong>0.85 k</strong></td>
</tr>
<tr>
<td>Coil holders (Al)</td>
<td>1 k$</td>
</tr>
<tr>
<td>Inserts/wedges</td>
<td>0.65 k$</td>
</tr>
<tr>
<td>Insulators/spacers</td>
<td>0.26 k$</td>
</tr>
<tr>
<td>Yokes/shell</td>
<td>1.25 k$</td>
</tr>
<tr>
<td><strong>Total parts</strong></td>
<td><strong>3.16 k</strong></td>
</tr>
<tr>
<td>Coil winding</td>
<td>16 hrs</td>
</tr>
<tr>
<td>Coil loading</td>
<td>12 hrs</td>
</tr>
<tr>
<td>VPI</td>
<td>6 hrs</td>
</tr>
<tr>
<td>Splices</td>
<td>6 hrs</td>
</tr>
<tr>
<td>Alignment</td>
<td>8 hrs</td>
</tr>
<tr>
<td>Shell welding</td>
<td>2 hrs</td>
</tr>
<tr>
<td><strong>Total assembly</strong></td>
<td><strong>50 hrs</strong> (at 50$/h)</td>
</tr>
<tr>
<td><strong>Total/quad</strong></td>
<td><strong>9 k</strong></td>
</tr>
<tr>
<td><strong>Overhead/fees</strong></td>
<td>2.5 k$</td>
</tr>
</tbody>
</table>

**Prototype Focusing Doublet**

- Compatible with the HCX short lattice period of 45 cm
- Warm axial gap between cryostat tanks as (acceleration, diagnostics, pumping)
- Leads & cryogen supplies provided through central chimney (max. core efficiency)
Cryostat Test Results

**First cool-down:**
- thermal short in the beam tube region
- unacceptable heat loads
- magnets close to short sample (-3%)
- no training

**Second cool-down:**
- thermal short repaired
- Heat loads ~ 1W in quad+chimney
- magnets at the short sample limit
- low ramp-rate dependence

Will be published at the 2004 Applied Supercond. Conference

IBX Magnet System

**IBX**
- *Single-layer Quad Design*
- Cost: 6 k$/unit

* Cryostat is magnet cost driver (single channel, accel. gaps)
* HCX doublet: 35 k$

**IBX Magnet Cost Distribution by Category**
- Overhead/fees: 28%
- Labor: 24%
- M&S (Lab): 10%
- M&S (company): 38%

**RHIC Magnet Cost Distribution by Category**
- Overhead/fees: 29%
- Labor: 11%
- M&S (Lab): 22%
- M&S (company): 38%
**Advanced Superconductors**

**Superconducting wires:**

- **NbTi:**
  - well developed
  - performance limitations

- **Nb$_3$Sn:**
  - Substantial progress
  - New baseline for HEP

- **HTS:**
  - Very good potential
  - Practical challenges

_Hb$_3$Sn Quads (including racetrack) are presently being developed for the LHC_

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**Summary**

**HCX/IBX:** opportunity to address key magnet design issues:

- Design simplicity and cost-effectiveness
- Aperture, Gradient and Field Quality tradeoffs
- Optimization of the conductor parameters
- Modularity
- Compact cryostats compatible with induction acceleration

*Prototypes tested with excellent results*

*Cryostated doublet successfully fabricated and tested*

*Further optimization in progress*

*Cost estimates generated in support of the IBX design*
Lab Credits

LBNL: Program coordination; specs; magnet design and test
LLNL: Magnet design and fabrication; cryostat design
AML: Magnet design and fabrication; value engineering
MIT: Magnet design and test; cryostat fabrication and test