Development of Superconducting Magnet Systems for HIF Experiments

G. Sabbi[1], L. Chiesa[3], A. Faltens[1], C. Goodzeit, C. Gung[3], W. Hinson[4],
P. Hwang, M. Leitner[1], A . Lietzke[1], S. Lund[2], N. Martovetsky[2],
R. Meinke[4], J. Minervini[3], J. Schultz[3], P. Seidl[1]

(1) Lawrence Berkeley National Laboratory, Berkeley, CA
(2) Lawrence Livermore National Laboratory, Livermore, CA
(3) MIT Plasma Science and Fusion Center, Cambridge, MA
(4) Advanced Magnet Lab, Palm Bay, FL

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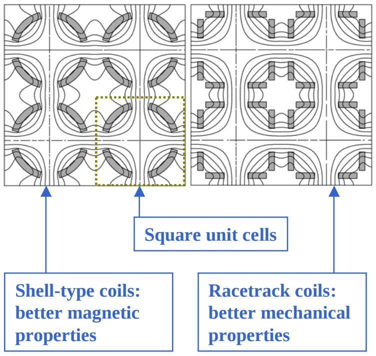
Princeton, June 7-11, 2004

Multiple Beam Transport

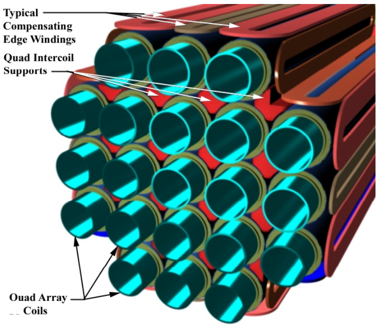
Quadrupole array configuration



Square unit cells

Shell-type coils: better magnetic properties

Racetrack coils: better mechanical properties

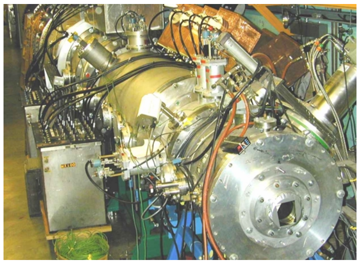


MIT Quadrupole Array Design for IRE

Superconducting magnets are required for efficiency in the HIF driver

Beam Physics Experiments

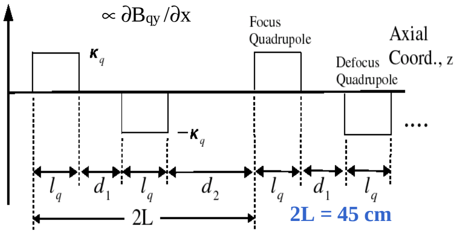
High Current Experiment (HCX)



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

$G = 84.2$ T/m
$l_q = 10.1$ cm

$d_1 = 6.219$
$d_2 = 18.58$



2L = 45 cm

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

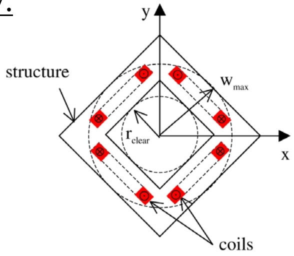
HCX Quadrupole Specification

Axial Geometry:

$L_{coil} = 125$ mm
$L_{mat} \leq 155$ mm

Transverse Geometry:

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



Geometric spec is given in terms of the array cell size

Conductor: J_c (5T,4.5K) = 2.55 kA/mm^2

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

Integrated Gradient: $\boxed{\int_{-\infty}^{\infty} B'_q dz \geq 8.5\ \text{T} \quad @\ I_{op}}$ $\Leftrightarrow$ *G ≈ 100 T/m*

HCX Field Quality Specification

Definitions:

$$\hat{B}_x(x,y)=\int_{-\infty}^{\infty} B_x(x,y,z)dz$$

$$\hat{B}_y(x,y)=\int_{-\infty}^{\infty} B_y(x,y,z)dz$$

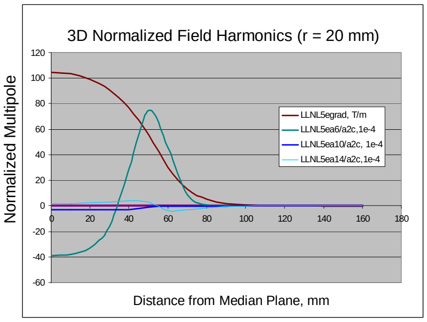
$$\overline{B}^* = \hat{B}_y + i\hat{B}_x = \sum_{n=1}^{\infty}(B_n + iA_n)\left(\frac{\bar{z}}{r_0}\right)^{n-1} = \sum_{n=1}^{\infty}\overline{C}_n\left(\frac{\bar{z}}{r_0}\right)^{n-1}$$

$$\delta F = \frac{Max_\theta\left|\overline{B}^*(r=r_g,\theta) - B_2(r_g/r_0)e^{i\theta}\right|}{B_2(r_g/r_0)}\cdot 10^4$$

Requirement (50 periods):

δF $\leq$ 50 (10^{-4} “units”) @ r_g = 25 mm

Allows body-end compensation
to simplify and shorten the coil



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

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Magnet Design Concepts

Coil layout

<u>Shell-type (cosθ)</u>

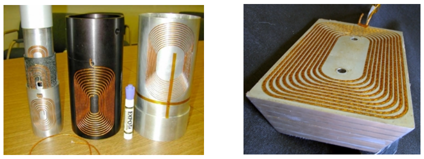
- magnetically more efficient
- radially more compact
- complex geometry, fabrication

<u>Block-type</u>

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

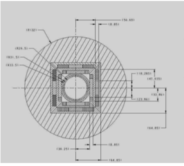
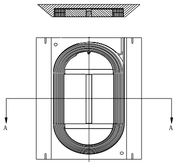
Fabrication and assembly

Racetrack coils



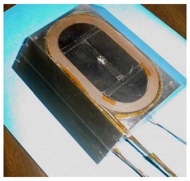
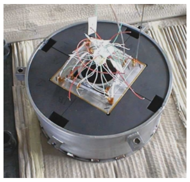
Conductor in groove (cylinder, plate)

Baseline Design

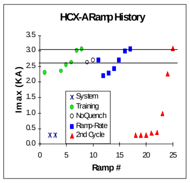
Magnet design:

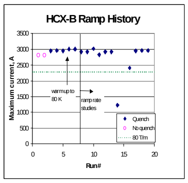
- Block-coil (square) geometry
- 8 double-pancake racetracks

Coil fabrication and support:

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





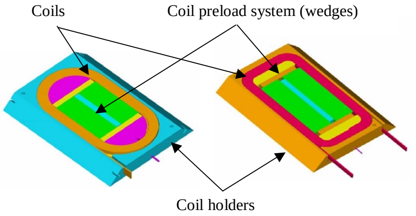
Test results (2 pre-series models):

- Rutherford cable or monolith
- Fast training to short sample
- No retraining after th. cycle

Design Optimization (HCX-C)

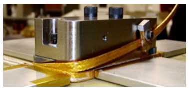
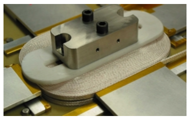
New design features:

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



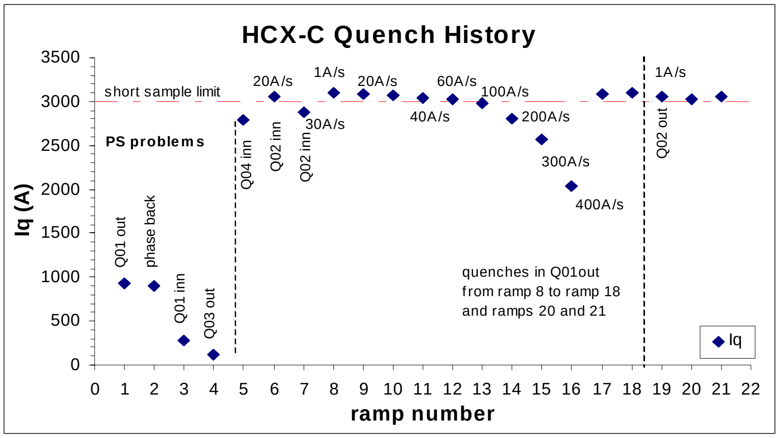
Fabrication experience:

- *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

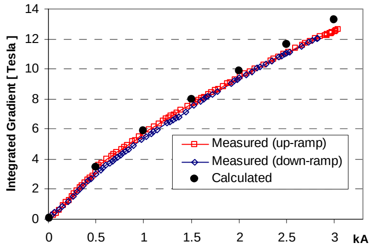



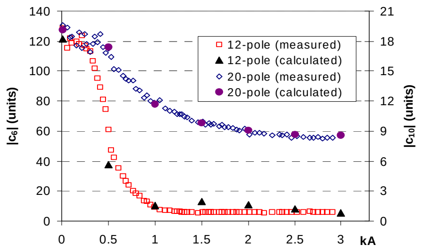

HCX-C Test

- 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 Magnetic Measurements





INTEGRATED HARMONICS

Current (A)	Temp (K)	Data type	Gradient B_2/r_0 (T)	12-pole $\lvert c_6\rvert$ (units)	20-pole $\lvert c_{10}\rvert$ (units)
9.5	300	Meas. (*)	0.0674	109	15.5
9.5	-	Calc.	0.0726	121	19.1
2500	4.2	Meas.	11.03	5.8	8.5
2500	-	Calc.	11.63	8.1	8.7

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

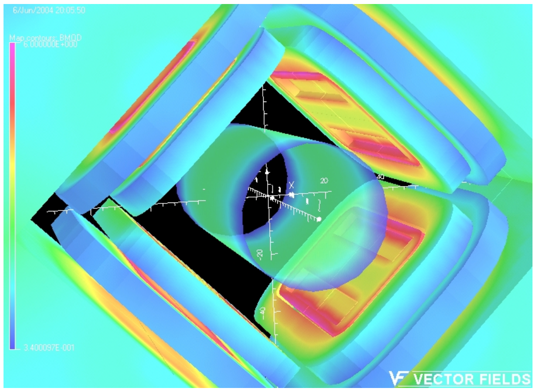
NON-ALLOWED HARMONICS VS RANDOM ERRORS (ONE SIGMA)

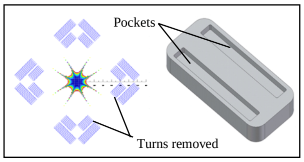
Order n	Measured $\lvert c_n\rvert$ (units)	Random- Block(#) $\lvert c_n\rvert$ (units)	Random-Quadr.(#) $\lvert c_n\rvert$ (units)
3	5.3	2.7	6.5
4	2.5	1.8	1.8
5	7.0	0.8	0.3
7	0.6	0.2	0.5
8	1.0	0.1	0.3
9	2.8	0.05	0.1

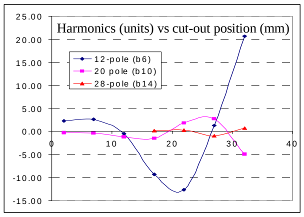
(#) Random displacements in a ±100 µm interval, flat distribution

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*



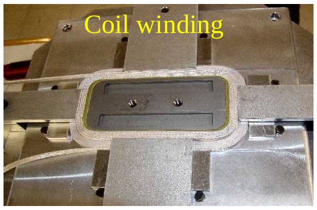


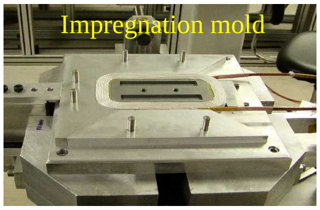


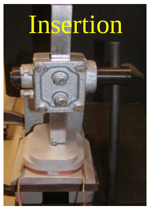
All design harmonics within 1 unit at the reference radius (22 mm)

New Coil Fabrication Procedure (HCX-D)

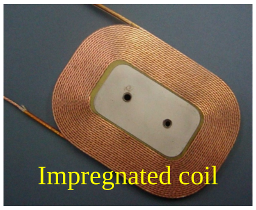
Monolithic pole; coils are impregnated separately, then inserted in holder
Goals: accurate and reproducible geometry; reduction of labor and parts

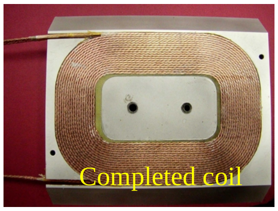

Coil winding


Impregnation mold


Insertion


Coil holder


Impregnated coil


Completed coil

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:

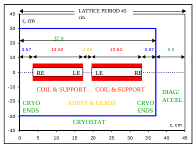
- *Production of 100 quads (HCX "Phase II")*
- *Conductor/cable procured by project*
- *Other parts procured by manufacturer*
- *Overhead/fees at 40% of labor and parts*
- *Project costs are not included*

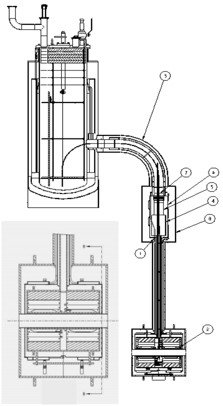
Estimated cost for each quad: 9 k$

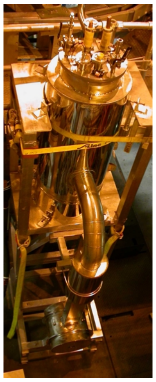
Strand	0.5	k$
Cabling	0.15	k$
Insulation	0.2	k$
Total conductor	**0.85**	**k$**
Coil holders (Al)	1	k$
Inserts/wedges	0.65	k$
Insulators/spacers	0.26	k$
Yoke/shell	1.25	k$
Total parts	**3.16**	**k$**
Coil winding	16	hrs
Coil loading	12	hrs
VPI	6	hrs
Splices	6	hrs
Alignment,	8	hrs
Shell welding	2	hrs
Total assembly	**50**	**hrs**
(at 50$/h)	2.5	k$
Overhead/fees	**2.5**	**k$**
Total/quad	**9**	**k$**

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:

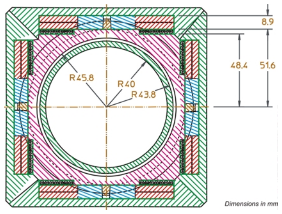
- thermal short repaired
- Heat loads ~ 1W in quad+chimney
- magnets at the short sample limit
- low ramp-rate dependence

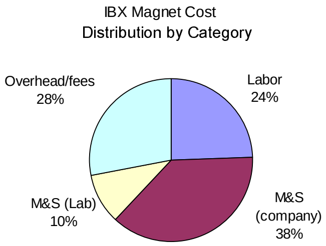
Will be published at the 2004 Applied Supercond. Conference

IBX Magnet System

IBX
Single-layer
Quad Design

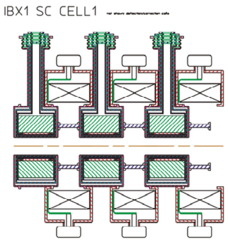
Cost:
6 k$/unit

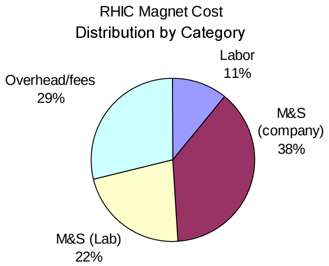




Cryostat is
magnet cost driver
(single channel,
accel. gaps)

HCX doublet:
35 k$





Advanced Superconductors

Superconducting wires:

NbTi:

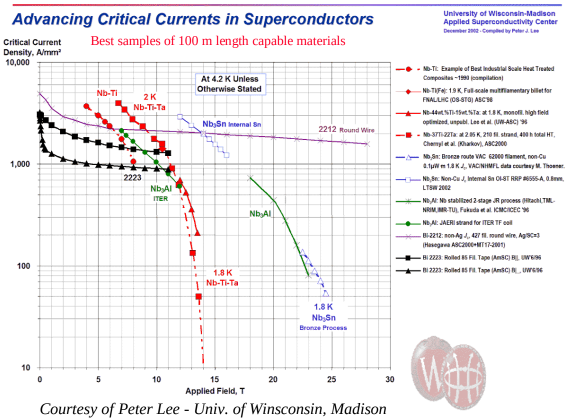
- *- well developed*
- *- perfomance limitations*

Nb_3Sn:

- *- Substantial progress*
- *- New baseline for HEP*

HTS:

- *- Very good potential*
- *- Practical challenges*



Courtesy of Peter Lee - Univ. of Winsconsin, Madison

Nb_3Sn Quads (including racetrack) are presently being developed for the LHC

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