

# DEVELOPMENT OF SUPERCONDUCTING MAGNETS FOR HEAVY-ION FUSION

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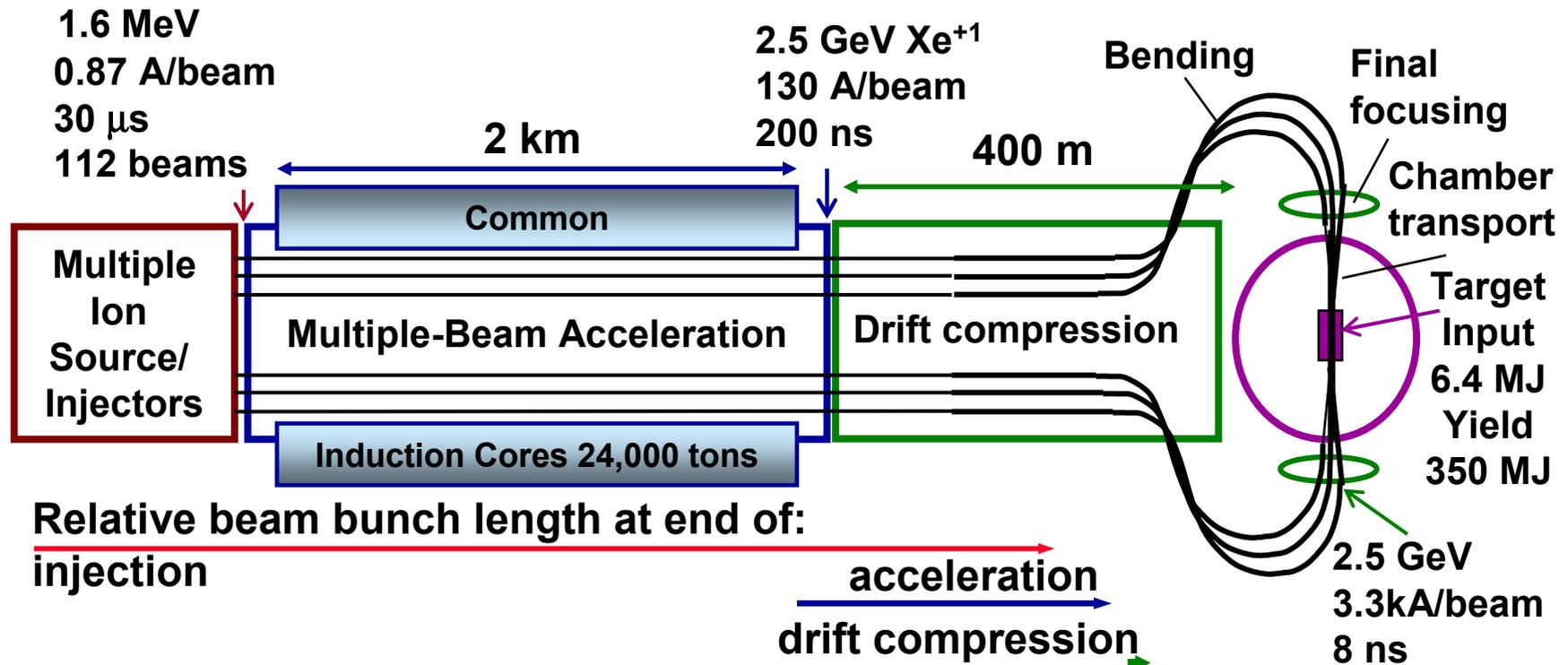
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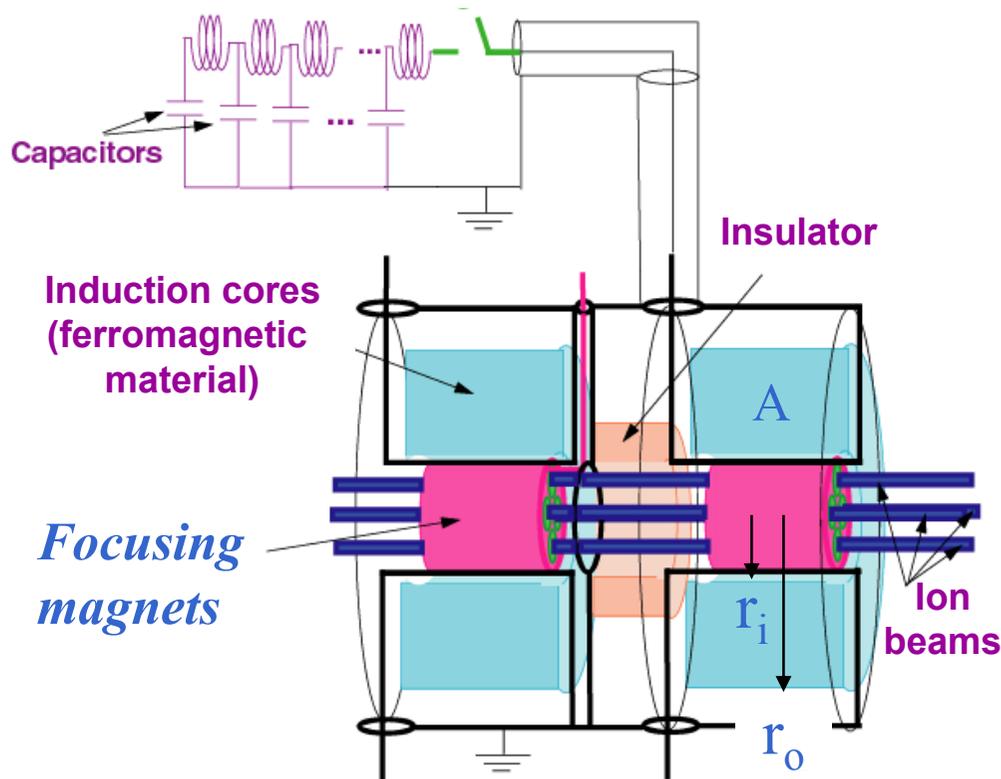
# HIF Driver Concept



Superconducting magnets are required for efficient beam transport

# Compact Magnets for Efficient Acceleration

## Pulse forming network



- Accelerating voltage:

$$\Delta V = A \Delta B / \tau$$

- Cross-sectional area  $A$  is proportional to

$$r_o - r_i$$

- Mass/cost of ferromagnetic material is proportional to

$$r_o^2 - r_i^2$$

Minimize  $r_i$  i.e. the transverse size of the quad array & cryostat

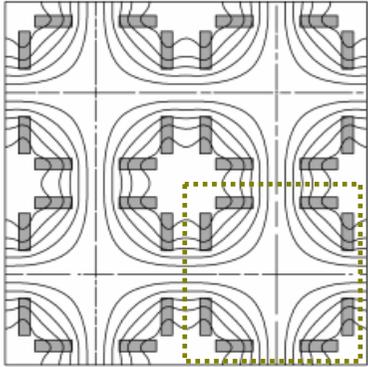
# HIF - Magnet Development

**HIF Magnet Designs Focus on Following Challenges:**

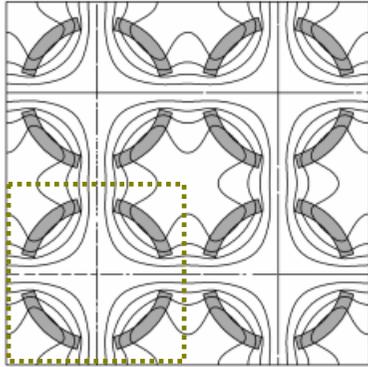
- **Minimal Radial Build-Up**
- **Most Cost Effective Design**
- **Highest Field Gradients**

# Quad Arrays for Multiple Beam Transport

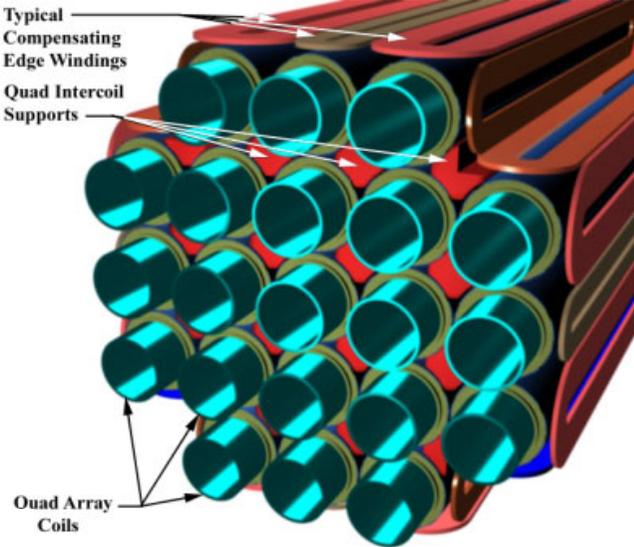
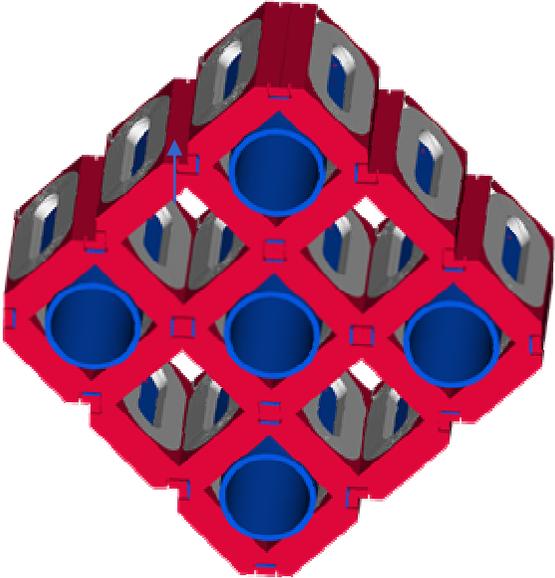
Racetrack coils:  
better mechanical  
properties



Square unit cells



Shell-type coils:  
better magnetic  
properties



Alternating polarity for optimal magnetic efficiency

# #1 Priority : Cost-effective Magnets

## Magnetic transport:

- Number of channels ~ **100**
- Number of hlp's ~ **1000**
- Number of quads ~ you do the math...

## Some good news, too:

- Gradient and field quality requirements are moderate
- Short magnetic length

Conventional  $\cos 2\theta$  windings are magnetically efficient, but not suitable for **inexpensive production of many thousands of coils**  
(complex end geometries, winding and assembly techniques)

Explore alternative design concepts

# Coil Design Concepts



Simple double-pancake **racetrack** coils  
SS/Al coil holders with iron inserts  
Rutherford cable or monolith with **APC**

Martovetsky et al., ASC 00



Concentric support cylinders, each supports one layer of conductor in machined **grooves** (circular or **rectangular** cross-section).

Meinke et al., PAC01



37-strand round cable

Multiple layer round cable, **automatically wound** in pockets machined in the support structure.

The program continues to explore new ideas

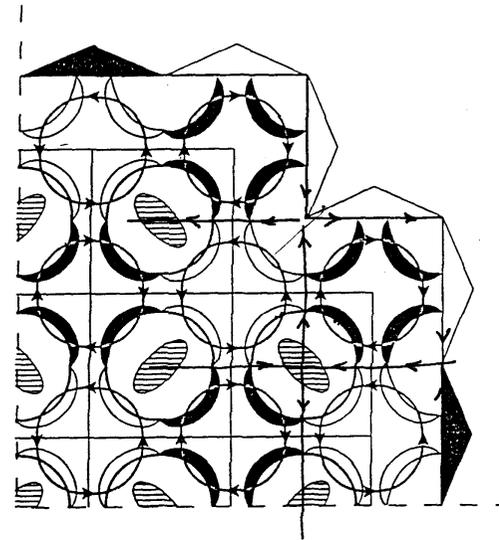
# Flux Termination

Edge coils are required in boundary cells to obtain same field and field quality as in the inner cells.

Magnetic coupling between quads and induction cores results in:

- Loss of core efficiency
- Field errors in the array
- Power dissipation at 4.2 K

Termination of the magnetic flux within the **shortest radial distance** is also required (compactness)



A current sheet at the edge with **linearly increasing density** provides desired B.C. (flux normal)

Faltens et al., SOFE 99

# From Scaled Experiments to an HIF Power Plant

## SBTE:

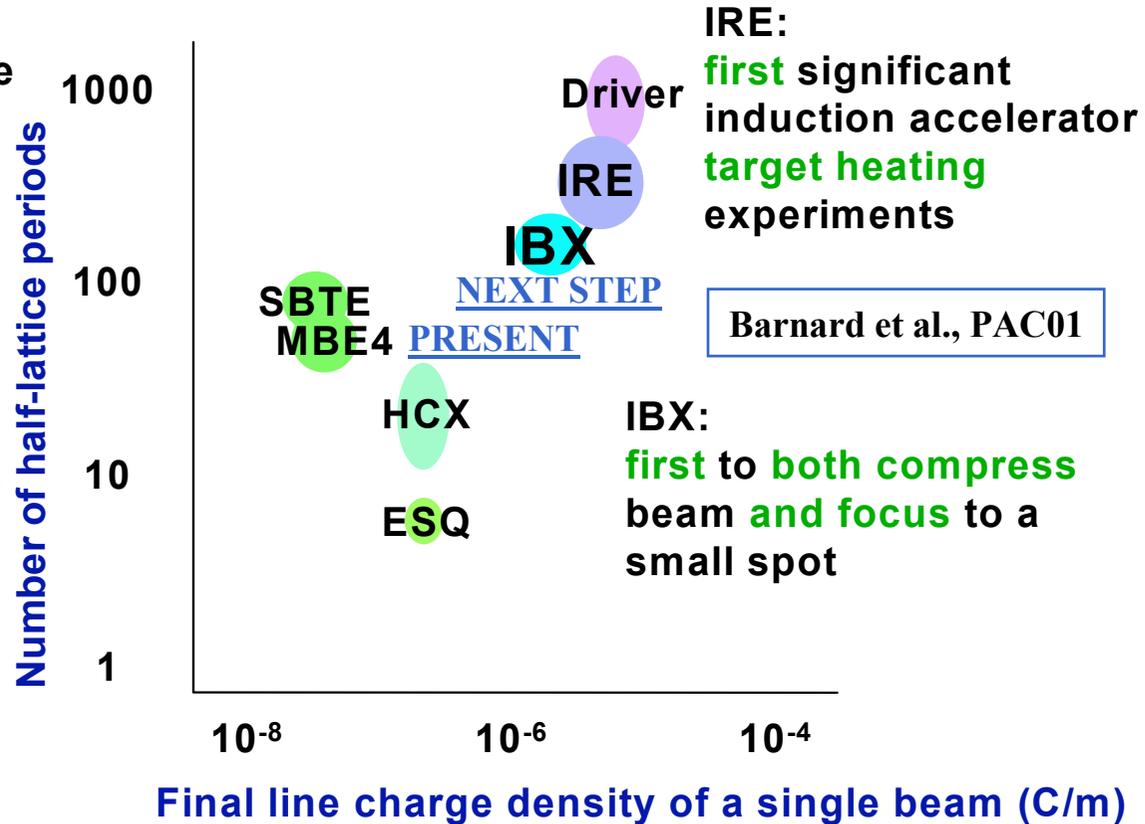
**stability** of space-charge dominated beams

## MBE-4:

**multiple beams** and **simple pulse compression**

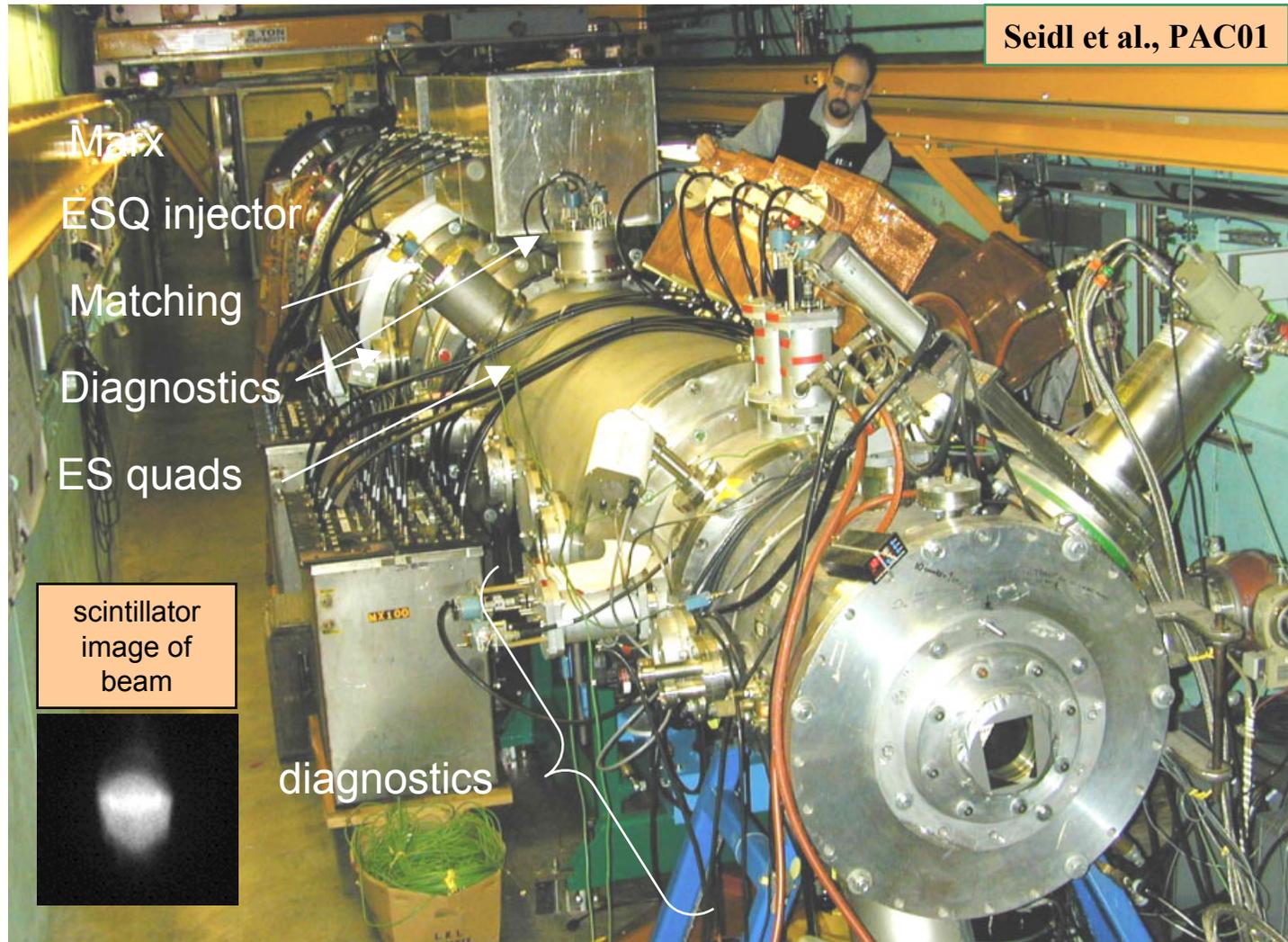
## HCX and ESQ:

line charge comparable to **initial line charge in driver**; **electron effects**



Magnet development is presently focused on HCX and IBX parameters, but takes into account long term requirements

# High Current Experiment (HCX)



# HCX: Physics at large fill factor for electrostatic and magnetic transport lattices (single beam)

$K^+$ , 1-1.8 MeV, 0.2-0.6 A

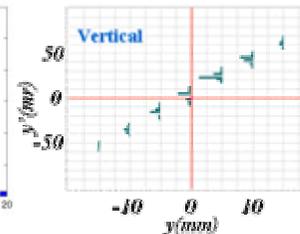
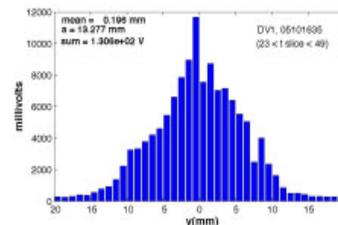
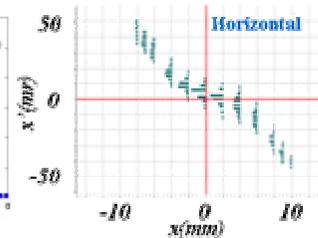
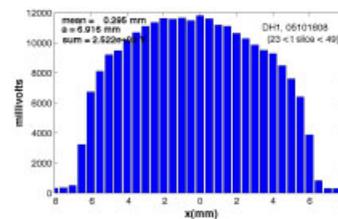
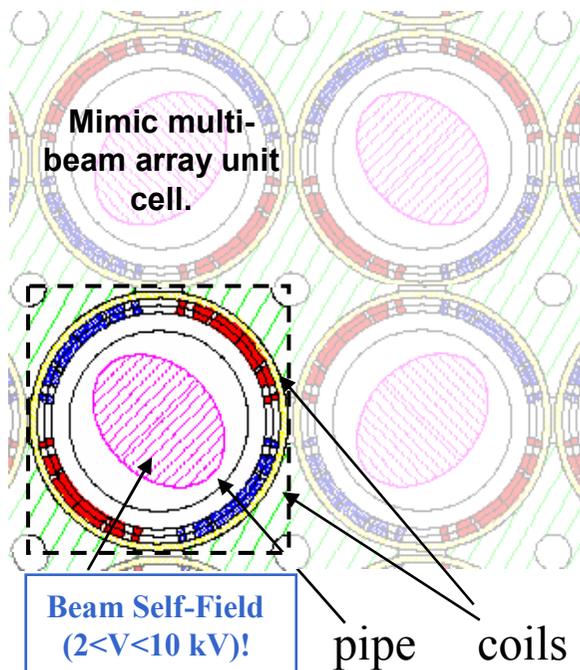
$\tau_{\text{pulse}} \approx 4 \mu\text{s}$

$\lambda \approx 0.1\text{-}0.2 \mu\text{C/m}$

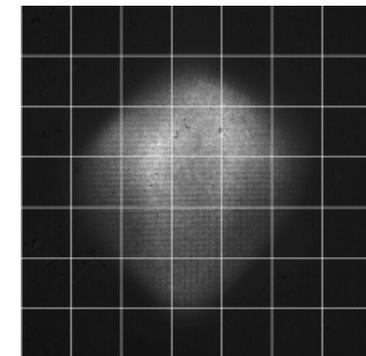
~5x previous experiments

## Main goals:

- transport (without acceleration) through 30-40 electrostatic quadrupoles
- Determine sensitivity to secondary  $e^-$  effects in magnetic quadrupoles



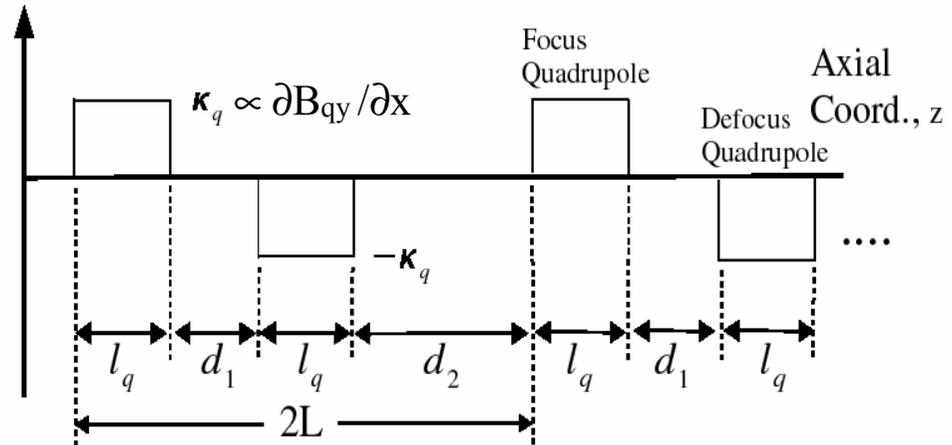
Seidl et al., PAC01



# HCX Lattice Parameters

## DEFINITIONS

|                                    |                      |
|------------------------------------|----------------------|
| $2L$                               | - Lattice Period     |
| $\eta$ ( $0 < \eta < 1$ )          | - Quad occupancy     |
| $l_q = \eta L$                     | - Magnetic Length    |
| $G = \partial B_{qy} / \partial x$ | - Focusing gradient  |
| $\alpha$ ( $0 < \alpha < 1$ )      | - Syncopation factor |
| $d_1 = \alpha(1-\eta)2L$           | - Short Drift        |
| $d_2 = (1-\alpha)(1-\eta)2L$       | - Long Drift         |



## HCX Parameters for SC Transport

|                      |                         |               |
|----------------------|-------------------------|---------------|
| $2L = 45 \text{ cm}$ |                         |               |
| $\eta = 0.4489$      | $G = 84.2 \text{ T/m}$  | $d_1 = 6.219$ |
| $\alpha = 0.2508$    | $l_q = 10.1 \text{ cm}$ | $d_2 = 18.58$ |



# HCX Magnet Specification

## Axial Geometry:

$$L_{\text{coil}} = 125 \text{ mm}$$

$$L_{\text{mat}} \leq 155 \text{ mm}$$

## Transverse Geometry:

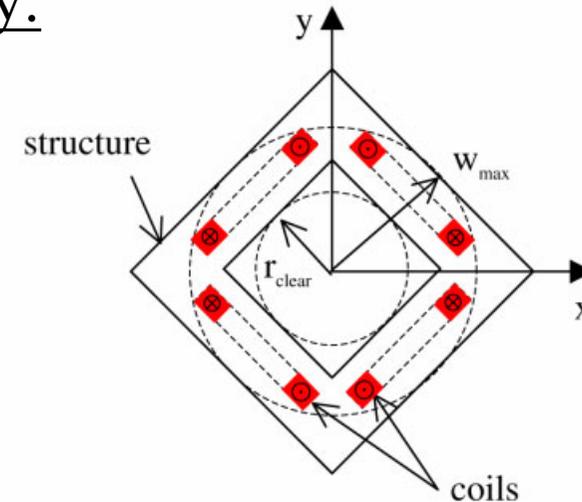
$$r_{\text{clear}} = 35 \text{ mm}$$

$$W_{\text{max}} \leq 64 \text{ mm}$$

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

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

Integrated Gradient:  $\int_{-\infty}^{\infty} B'_q dz \geq 8.5 \text{ T @ } I_{\text{op}}$



Geometric spec is given in terms of the array cell size

# HCX Field Quality Specification

Definitions:

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

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

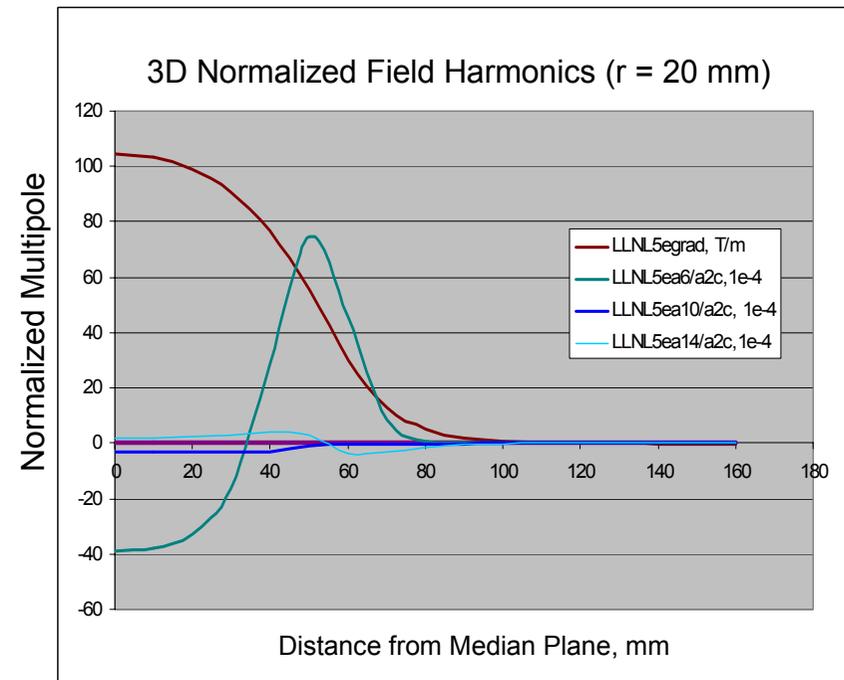
$$\bar{B}^* = \hat{B}_y + i\hat{B}_x = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{\bar{z}}{r_0}\right)^{n-1} = \sum_{n=1}^{\infty} \bar{C}_n \left(\frac{\bar{z}}{r_0}\right)^{n-1}$$

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

Requirement:

$$\delta F \leq 50 (10^{-4} \text{ units}) @ r_g = 25 \text{ mm}$$

Allows body-end compensation to simplify and shorten the coil



# AML Design Features

Round cable, 6x1 strands (SSC outer)

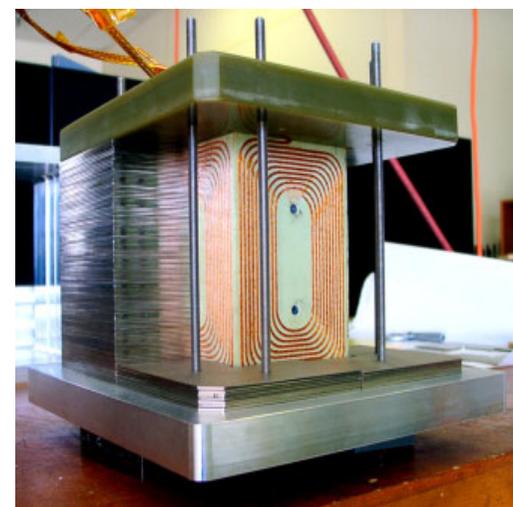
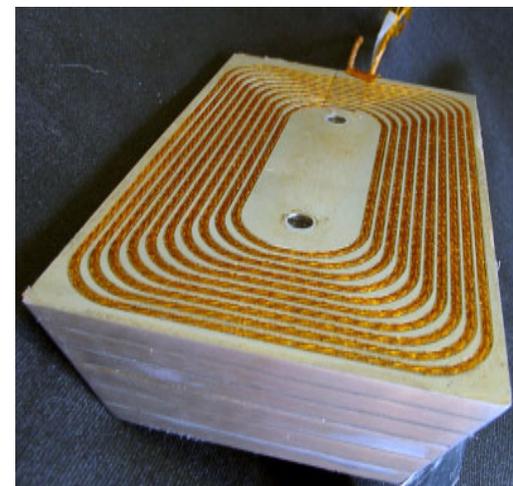
Grooved plates define conductor position in each layer (flat coil geometry)

Coil module: 6-layers wound in double pancakes

Continuous winding - no joints

Outer Al frame provides preload from differential thermal contraction with yoke

Field quality: *separately optimized* for magnet body and ends



Meinke et al., PAC01

# LLNL Design Features

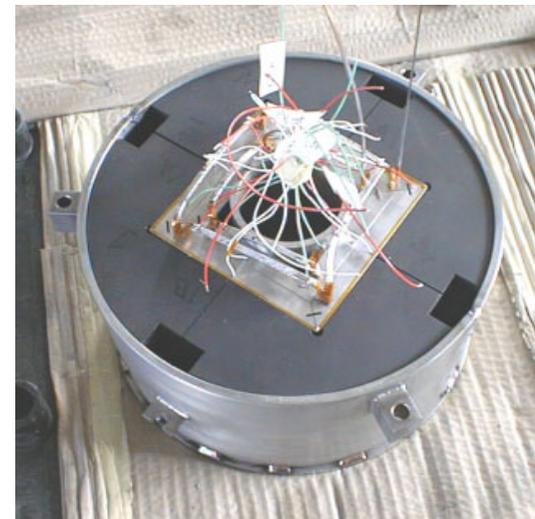
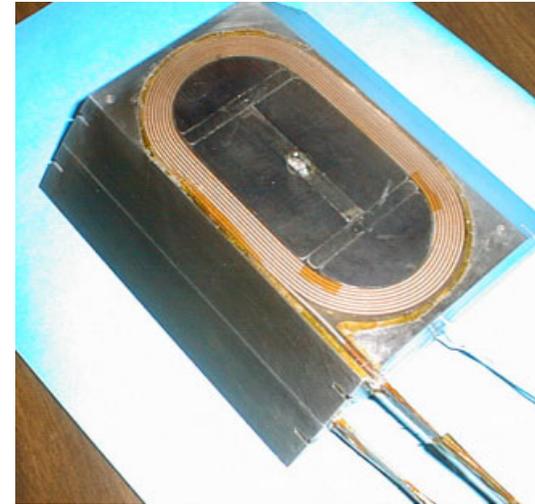
Cable: #1: Monolithic APC  
#2: 13-strand Rutherford cable

Coil module: 2 (double-pancake) layers  
(flat geometry)

Mech. support: windings are placed in SS holder and prestressed with steel core pieces and wedges.

Coil modules are supported by SS outer shell through yoke

Field quality: body-end compensation for compact design (no spacers)



Martovetsky et al., MT-17

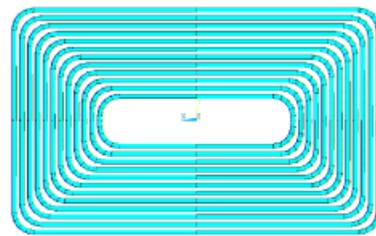
# Optimized HCX Prototype

- LLNL design selected as **baseline**
- Design optimization:
  - **New end geometry**: improved integrated gradient and field quality
  - **Al support plates**: improved mechanical support and cost reduction
- An **optimized prototype** is being fabricated by AML
- Prototype will be tested at LBNL (**w/magnetic measurements**)

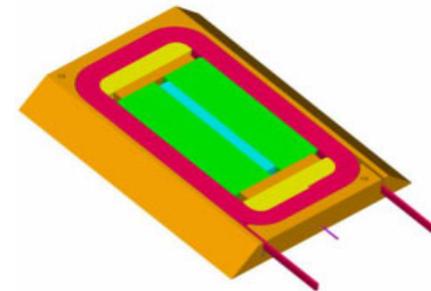
Concentric Turns (LLNL)



Min. Radius Turns (AML)



Optimized coil module



# IBX (Short Pulse, RT) COMPONENTS:

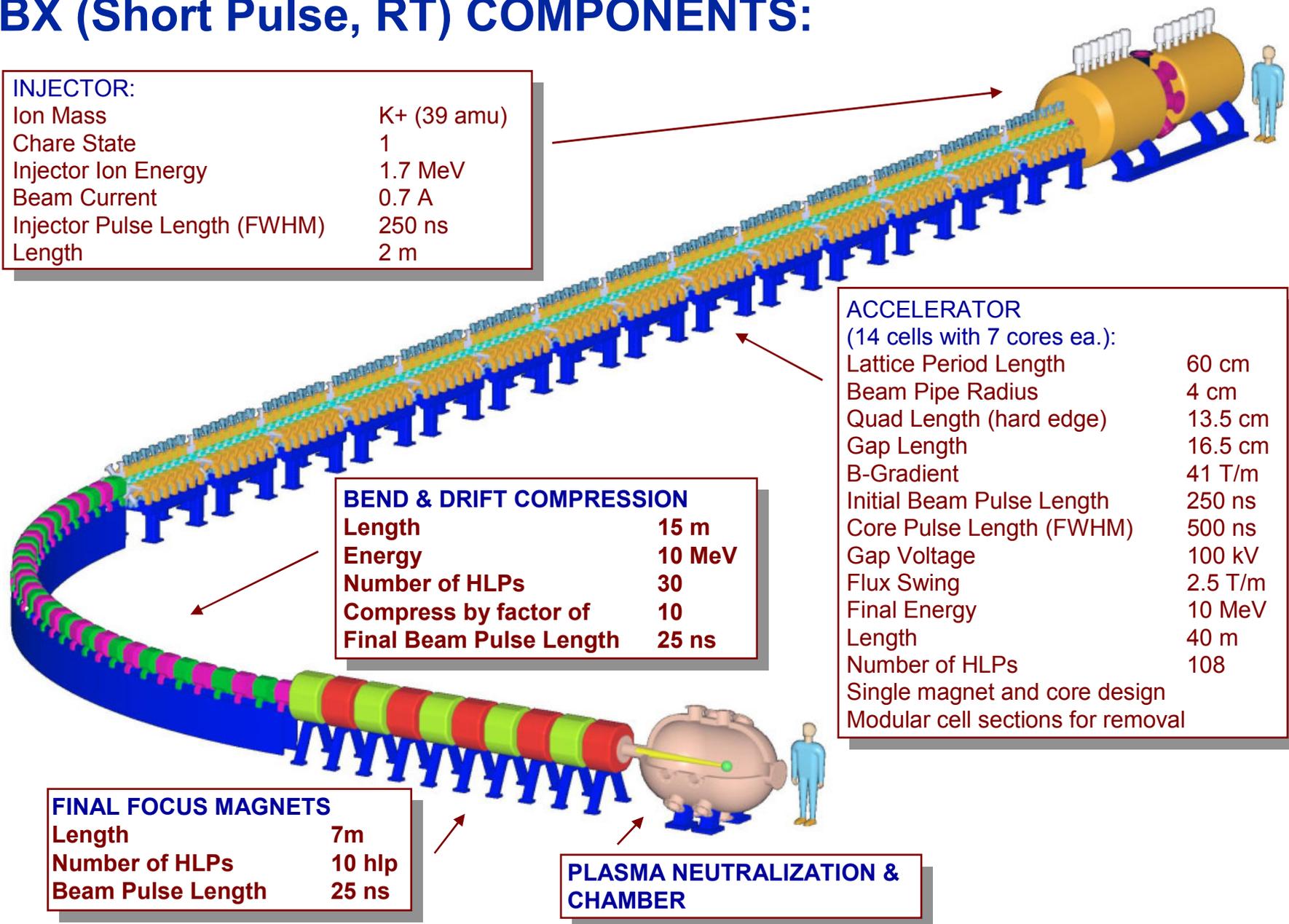
| INJECTOR:                    |                         |
|------------------------------|-------------------------|
| Ion Mass                     | K <sup>+</sup> (39 amu) |
| Chare State                  | 1                       |
| Injector Ion Energy          | 1.7 MeV                 |
| Beam Current                 | 0.7 A                   |
| Injector Pulse Length (FWHM) | 250 ns                  |
| Length                       | 2 m                     |

| ACCELERATOR                       |         |
|-----------------------------------|---------|
| (14 cells with 7 cores ea.):      |         |
| Lattice Period Length             | 60 cm   |
| Beam Pipe Radius                  | 4 cm    |
| Quad Length (hard edge)           | 13.5 cm |
| Gap Length                        | 16.5 cm |
| B-Gradient                        | 41 T/m  |
| Initial Beam Pulse Length         | 250 ns  |
| Core Pulse Length (FWHM)          | 500 ns  |
| Gap Voltage                       | 100 kV  |
| Flux Swing                        | 2.5 T/m |
| Final Energy                      | 10 MeV  |
| Length                            | 40 m    |
| Number of HLPs                    | 108     |
| Single magnet and core design     |         |
| Modular cell sections for removal |         |

| BEND & DRIFT COMPRESSION |        |
|--------------------------|--------|
| Length                   | 15 m   |
| Energy                   | 10 MeV |
| Number of HLPs           | 30     |
| Compress by factor of    | 10     |
| Final Beam Pulse Length  | 25 ns  |

| FINAL FOCUS MAGNETS |        |
|---------------------|--------|
| Length              | 7m     |
| Number of HLPs      | 10 hlp |
| Beam Pulse Length   | 25 ns  |

**PLASMA NEUTRALIZATION & CHAMBER**



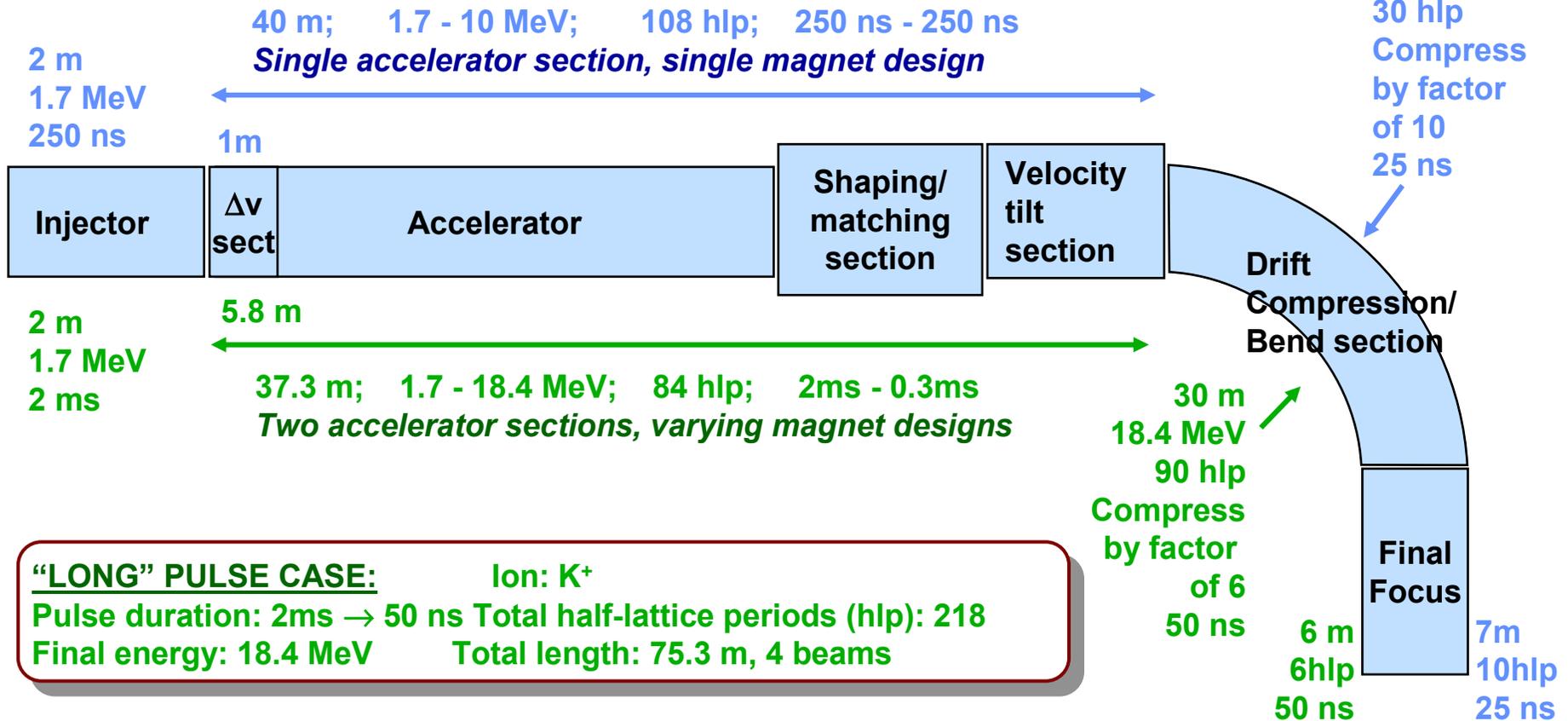
# IBX Design

## “SHORT” PULSE CASE:

Pulse duration: 250 ns → 25 ns  
Final energy: 10 MeV

Ion: K<sup>+</sup>

Total half-lattice periods (hlp): 148  
Total length: 64 m, 1 beam



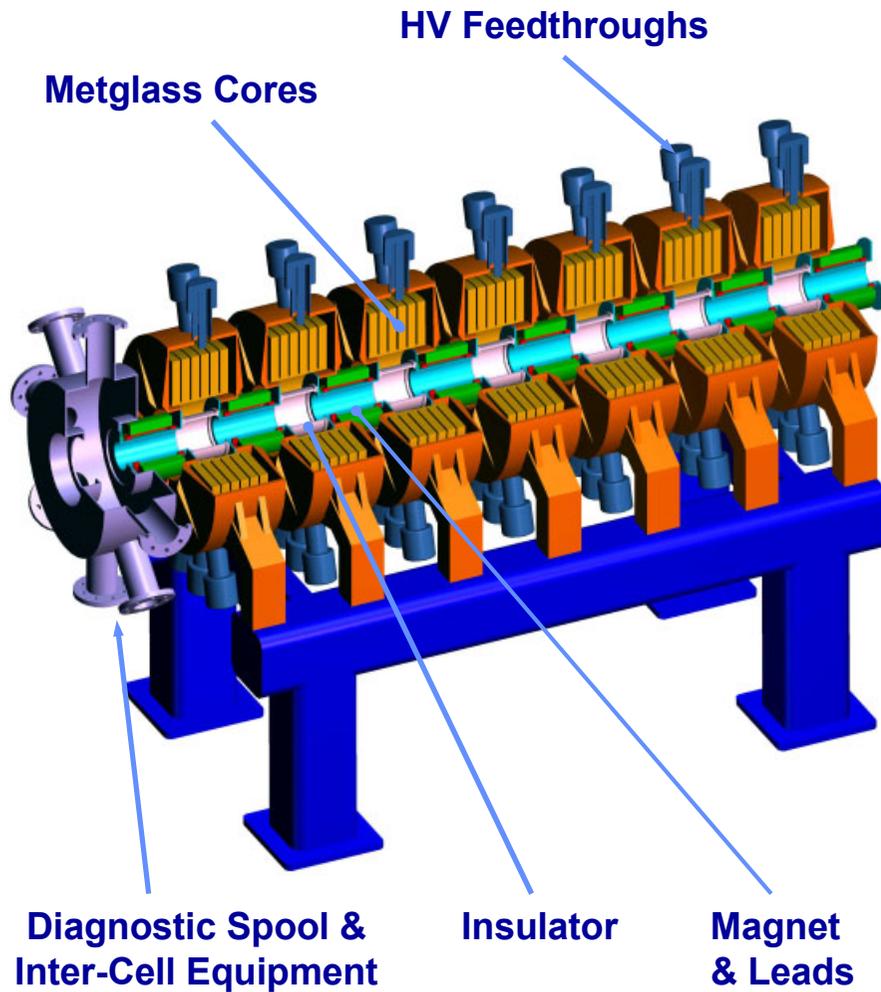
## “LONG” PULSE CASE:

Pulse duration: 2ms → 50 ns  
Final energy: 18.4 MeV

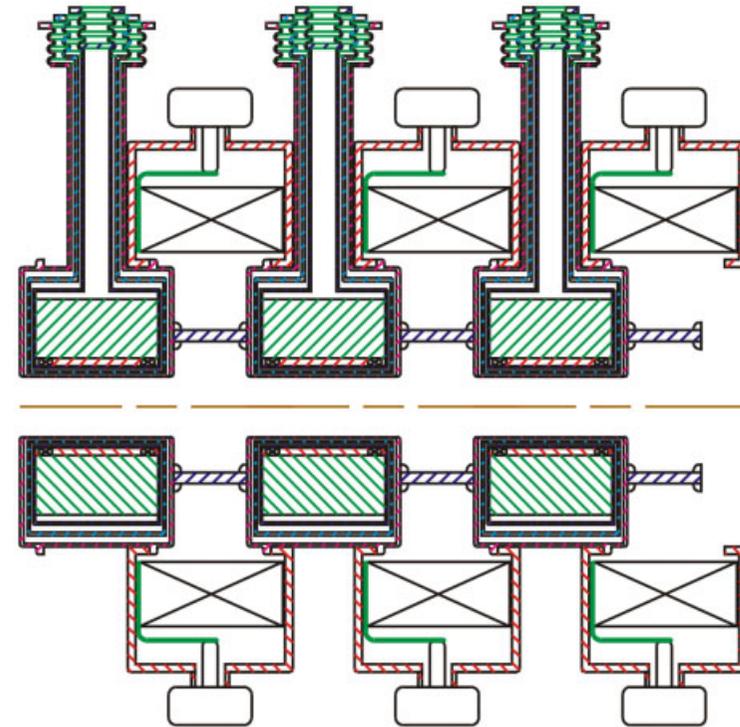
Ion: K<sup>+</sup>

Total half-lattice periods (hlp): 218  
Total length: 75.3 m, 4 beams

# IBX: Integrated Transport /Acceleration Modules



## COLD BORE DESIGN



HCX cryostat design  
meets IBX requirements

# Summary

HIF Magnet Designs Focus on Following Challenges:

- Minimal Radial Build-Up
- Most Cost Effective Design
- Highest Field Gradients

Collaboration between VNL (LBNL, LLNL) and external partners (MIT, AML).

Four superconducting quadrupole prototypes of two different designs (LLNL, AML) have been tested at LBNL and MIT.

All four prototypes have reached the minimum performance requirements for operation in HCX.

Present effort centers on the development of a cryostat housing two superconducting quadrupoles. A prototype focusing unit is being fabricated using existing magnets, and will be installed in HCX.

One additional quadrupole with optimized parameters is being fabricated and tested.

Array designs for IBX & IRE developed by LBNL, LLNL and MIT (Phase I SBIR grant awarded to AML.)



# Quadrupole Array Development

Array designs for IBX & IRE developed by LBNL, LLNL and MIT

Phase I SBIR grant awarded to AML. Major objectives are:

- Optimization of **magnet aperture** for max current
- Analysis of coil configurations
- Development of **mechanical support** structure
- Analysis of **cryogenics** and **vacuum** issues
- Conceptual design of a four-channel array



# Conclusions

- HIF requires **cost-effective** quadrupoles of new designs
- Good progress on **array cell** development
- Well positioned to meet the needs of near term **experiments**
- Need to progress to **multi-channel** array prototypes
- Many opportunities for **innovation**
- Projects have the **right scale** for SBIR grants

# Summary

Collaboration between VNL (LBNL, LLNL) and external partners (MIT, AML).

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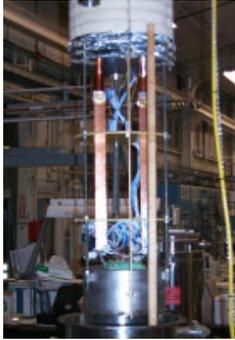
All four prototypes have reached the minimum performance requirements for operation in HCX.

The LLNL design was selected for further development, having demonstrated higher gradient and better training performance.

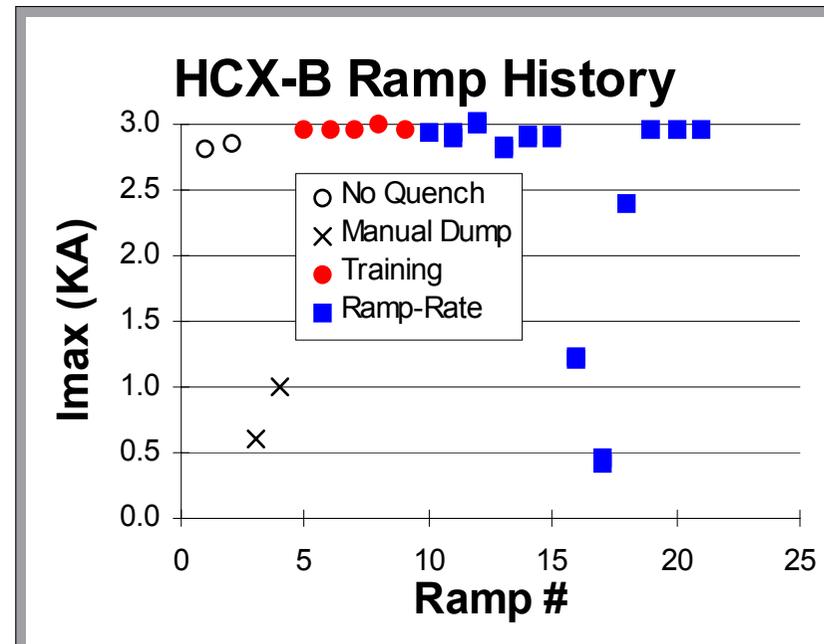
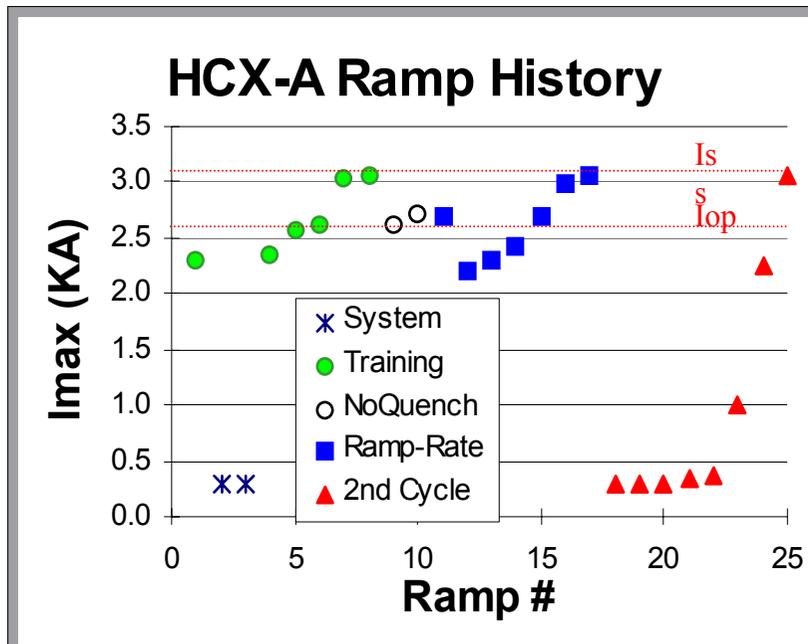
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# LLNL Test Results

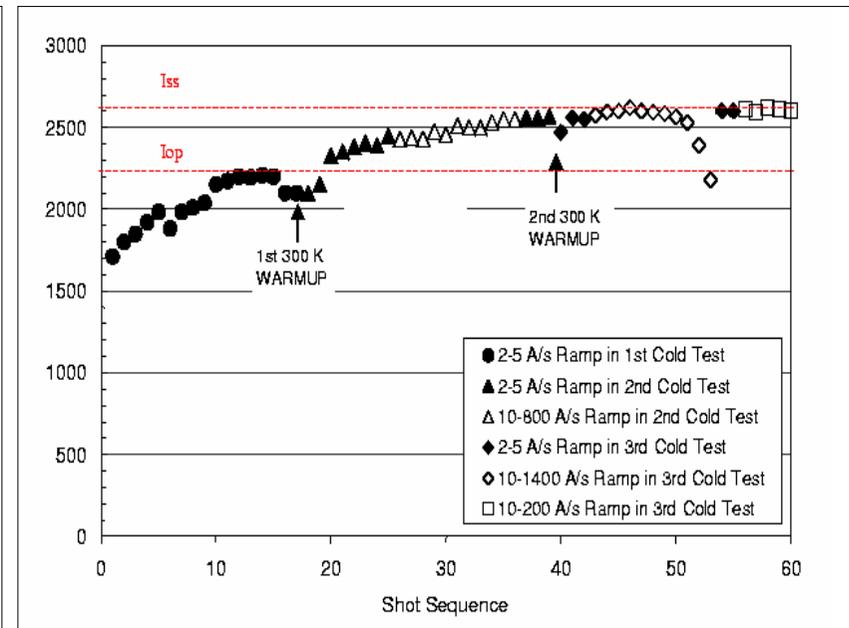
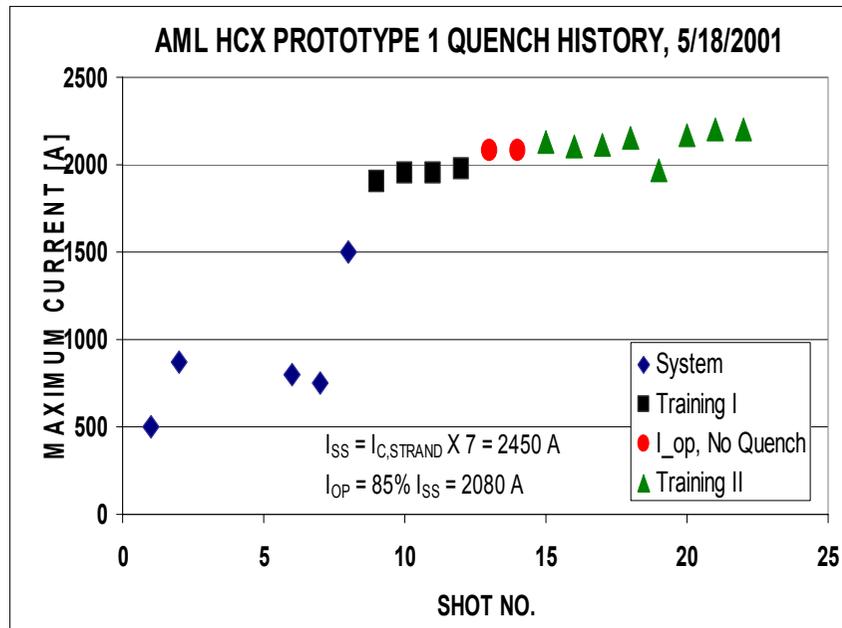


- Two prototypes tested at LLNL
- HCX-A: low first quench, fast training to short sample
- HCX-B: short sample at first quench

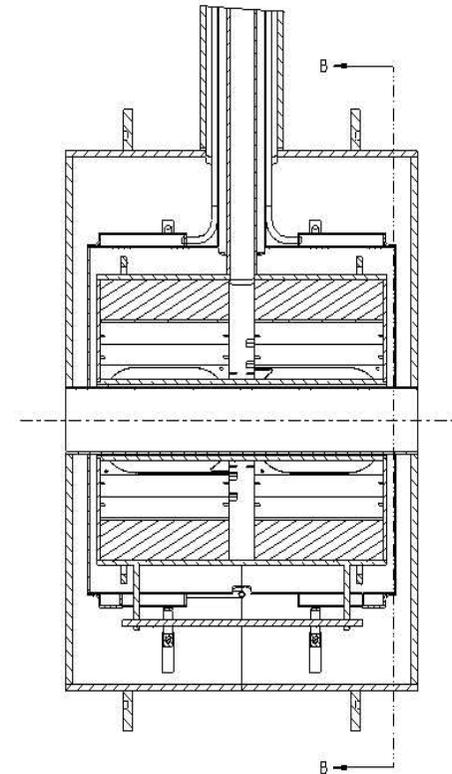
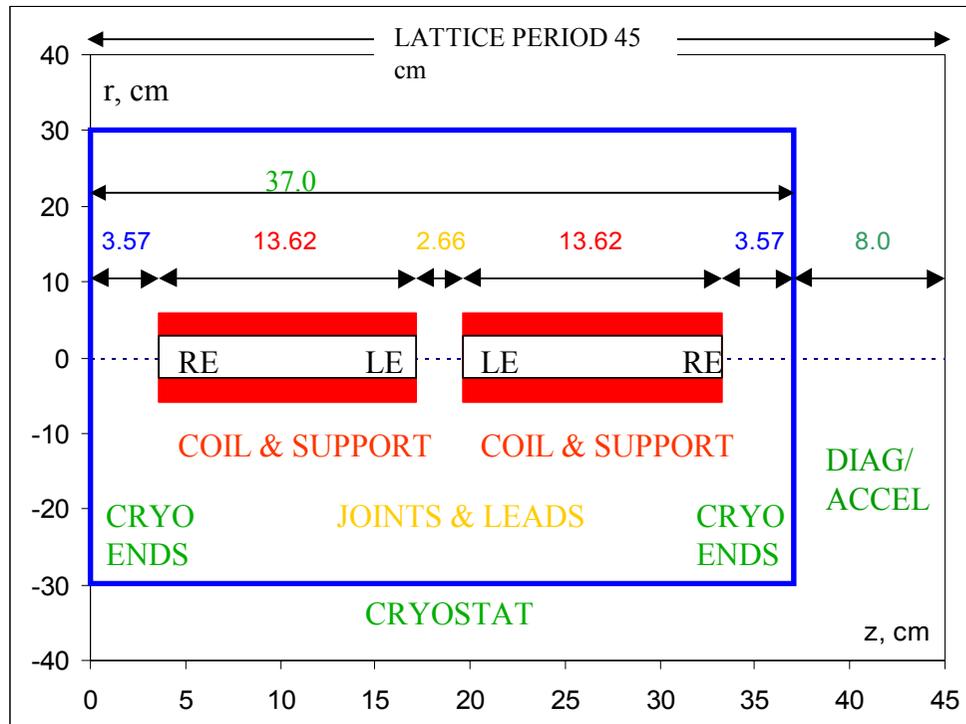


# AML Test Results

- Two prototypes were tested at MIT
- AML#1: 4 quenches to operating gradient
- AML#2: 12 quenches to operating gradient



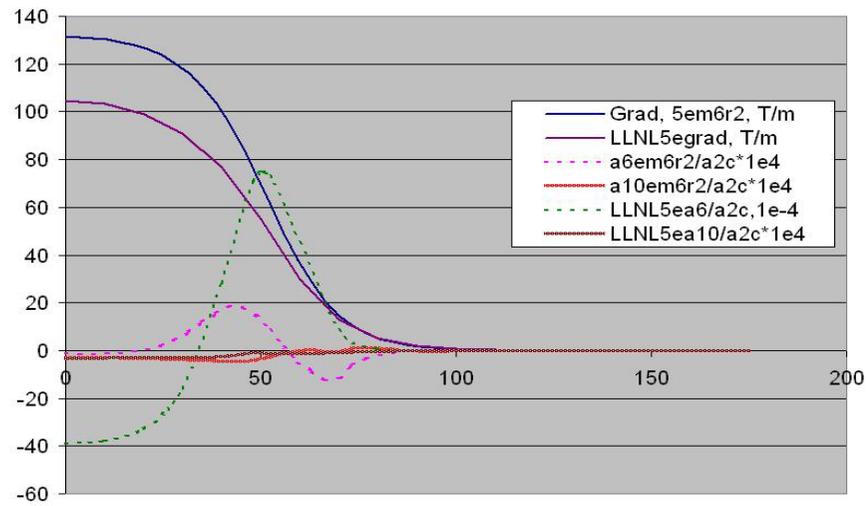
# HCX / IBX Cryostat Design



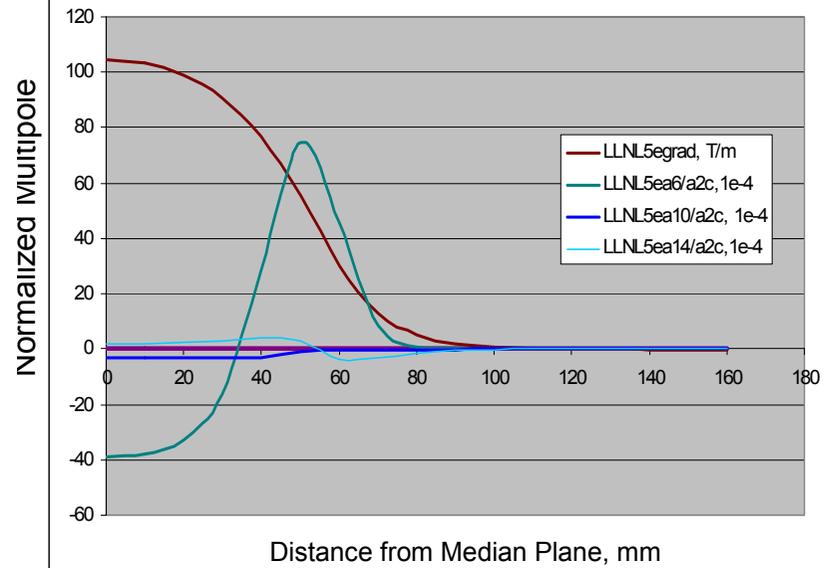
Short terminations & short high-gradient magnets enables exploring low energy magnetic transport while allowing axial space for acceleration modules/gaps.

First focusing unit is being fabricated, using existing quadrupole prototypes.

**LLNL6r2 vs LLNL5e design**  
at 500 A/mm<sup>2</sup> in winding pack



**3D Normalized Field Harmonics (r = 20 mm)**



# HCX Magnet Development

HCX provides an opportunity to address key magnet design issues:

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

Several design concepts analyzed and compared

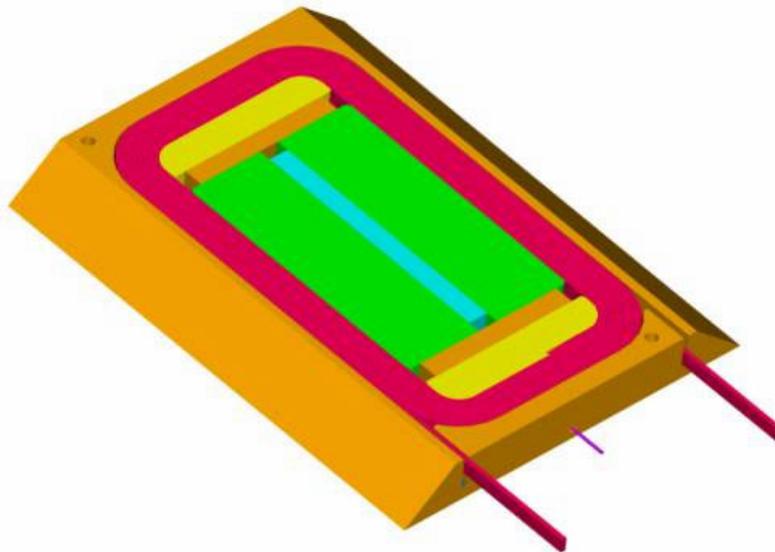
Two designs (by AML and LLNL) selected for prototyping

Two prototypes of each type fabricated and tested

# Magnet Optimization

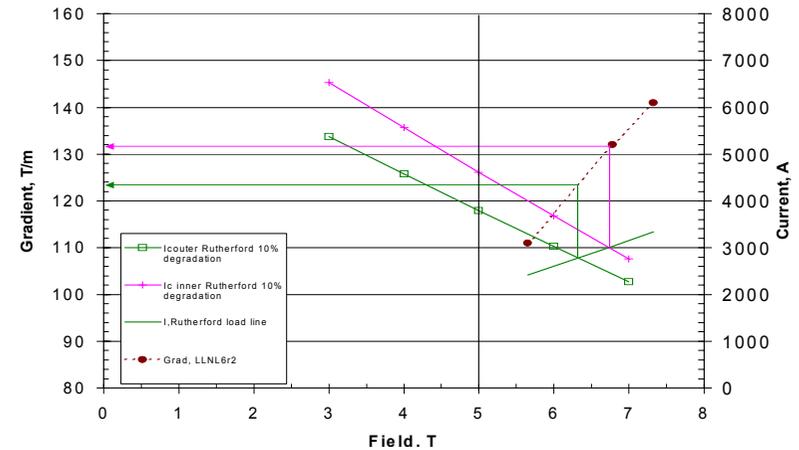
*Significant improvement in integrated gradient, field quality, mechanical support and cost:*

- New coil geometry (from continuous bend to tight bend and straight segments) leads to 20% increase in gradient and better field quality.
- Aluminum coil holders for higher pre-load, lower shear stress and lower cost.
- Rutherford cable for a more flexible design using available strand.
- SSC inner wire, Cu/Sc=1.3:1



*Short sample parameters:*

$$G_{SS}=132 \text{ T/m}, L_{\text{mag}}=10.5 \text{ cm}$$



*Field quality:  $b_6=-7.3$ ,  $b_{10}=-19.9$   
( $10^{-4}$  units,  $R_{\text{ref}}=25 \text{ mm}$ )*

