High Field Quadrupole (HQ) Program

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Presentation Outline

1. Status of the HQ program
   - Main design goals and parameters
   - Progress since the last DOE review
   - Impact of the HQ results on HiLumi and LARP

2. HQ Plans in the context of the Risk Reduction Strategy for the Construction Project
   - HQ Schedule
   - Goals and status of the HQ02b test at CERN
   - Goals and status of HQ03

HQ Design

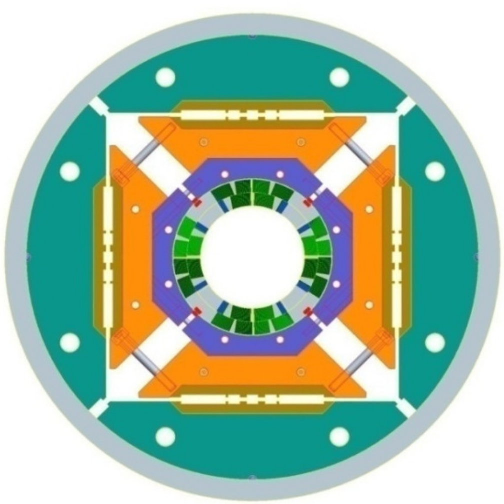
Goal: **demonstrate all performance requirements for Nb_3Sn IR Quads** *in the range of interest for HiLumi* (magnetic, mechanical, quench protection etc.)

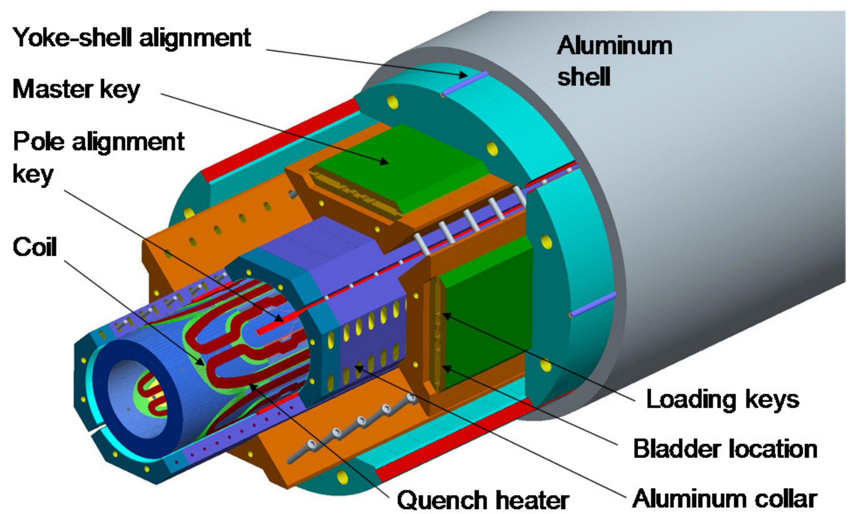
Main parameters: 120 mm aperture, 15 T peak field at 220 T/m (1.9K)

- *Three times the energy and force levels compared to 90 mm*

First LARP design incorporating all provisions for accelerator field quality:

- *Control of geometric, saturation, magnetization, eddy currents*
- *Alignment at all stages of coil fabrication, assembly & powering*





HQ Program Contributions

• Cable design and fabrication	LBNL
• Magnetic design & analysis	FNAL, LBNL
• Mechanical design & analysis	LBNL
• Coil parts design and procurement	FNAL
• Instrumentation & quench protection	LBNL
• Winding and curing tooling design	LBNL, FNAL
• Reaction and potting tooling design	BNL
• Coil winding and curing	LBNL
• Coil reaction and potting	BNL, (LBNL)
• Coil handling and shipping tooling	BNL
• Structures (quadrupole & mirror)	LBNL, FNAL, BNL
• Assembly (quadrupole & mirror)	LBNL, FNAL, (CERN)
• Magnet test	LBNL, CERN, FNAL
• Accelerator Integration	BNL, LBNL, FNAL, CERN

HQ status at the last DOE review

- HQ01 models: despite high failure rates in first-generation coils, a high performing set was selected in 3 cycles of assembly and test
  - April 2012: HQ01e-2 tested at CERN, **reached 184 T/m (1.9K)**
  - Above linear scaling from TQ (240/120*90=180 T/m) – *supporting a further increase to 150 mm, with significant benefits to HL-LHC*
  - **Very promising results in many areas**: simultaneous control of pre-load and alignment, training, field quality, quench protection
- Strong indications that design flaws leading to coil failures had been understood and corrected in second generation coils
  - June 2012: HQM04, tested at Fermilab, **reached 97% SSL at 4.6K and 94% at 2.2K**
  - Successful **demonstration of revised coil design**
  - No issues with new cable process including a core

From HQ01 to HQ02

Changes in coil design and fabrication to prevent conductor damage and insulation failures observed in first-generation coils:

- **Decreased axial coil strain** by progressively increasing pole gaps to 4 mm/m
- **Decreased azimuthal compaction** during reaction using smaller strand/cable
- **Aluminum oxide insulating coatings** for coil parts to prevent shorts
- **Increased insulation thickness** under protection heaters and between coil layers
- **New coil parts design** to account for extra insulation and winding experience
- **More refined/stringent electrical QA** at all stages: coil fabrication, assembly, test

Additional changes implemented to address field quality and production issues:

- **Cored cable** to control eddy currents (for field quality and quench performance)
- **1-pass cable** for more efficient cabling process (also driven by core)
- **Braided insulation** replacing fiberglass sleeve for long unit lengths
- **Ti-doped conductor** to confirm performance for future procurements

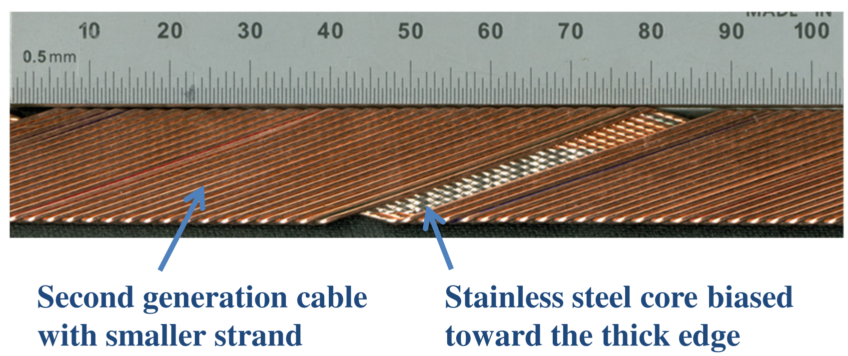
Improved features and processes of HQ coils are now the baseline for QXF coils

New cable with core

- Large dynamic effects were observed in previous LARP quadrupoles
  - Due to low inter-strand resistance (R_c) after coil reaction
  - Affects critical performance requirements: field quality, fast discharge
- A 25 μm stainless steel core was introduced in coil 12 for a first mirror test
- The development of second-generation HQ cable with reduced dimensions incorporated a 25 μm stainless steel core as the baseline
  - Partial coverage (8 mm, about 60% of the available width)
  - Biased toward the thick edge for mechanical stability

Parameter	Unit	HQ01e	HQ02a
Core material	-	-	SS316L
Strand diameter	mm	0.80	0.778
Cable width	mm	15.15	14.77
Cable mid thickness	mm	1.437	1.376

D. Dietderich

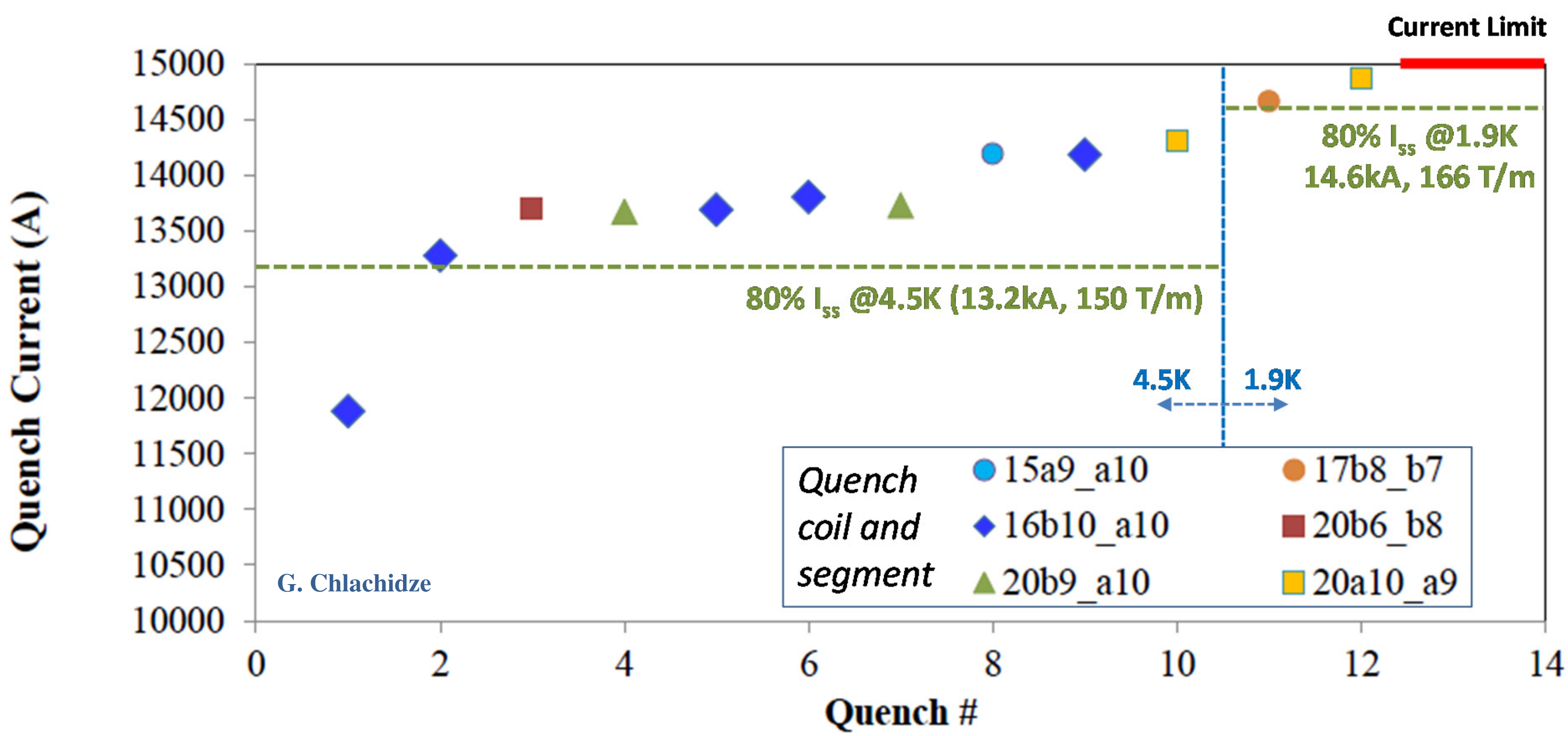


Note: second generation cable proved more difficult to wind, requiring the development of new tools and more refined procedures

HQ02a Quench Performance

Test conditions: temperature range 1.9-4.6K, but with a current limit of 15kA

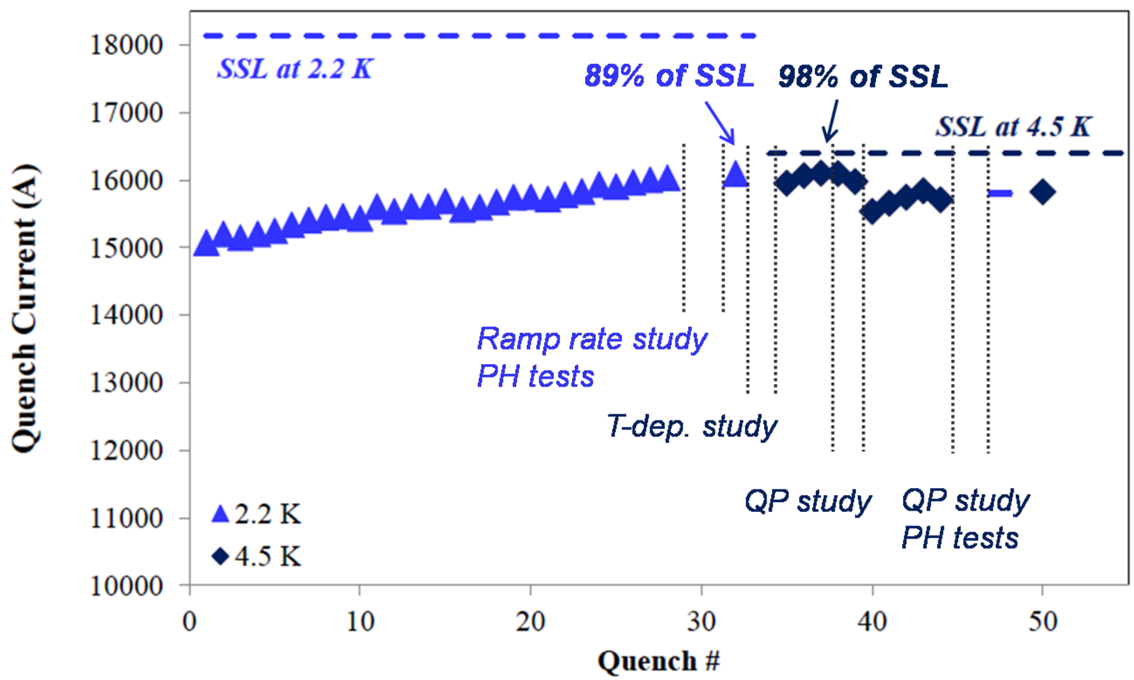
Results:
- 1-2 quenches to nominal operating point (80% SSL) at 4.5K and 1.9K
- 15kA, 166 T/m limit quickly reached at 1.9K and retained at 4.5K
- Quenches in high-field pole area of all coils, no specific limitations



HQ02a-2 Quench Performance

Test Conditions: magnet was mounted on a different header that removed the current limitation, but with a minimum temperature limitation of 2.2K

Results:
- **No detraining after thermal cycle**: first quench above 15 kA
- **Slow training** at 2.2K, up to 16.2kA, T/m (89% SSL)
- Quench current fully retained at 4.5K, corresponding to **98% of SSL**
- Quenches in high-field pole area with no localized limitation

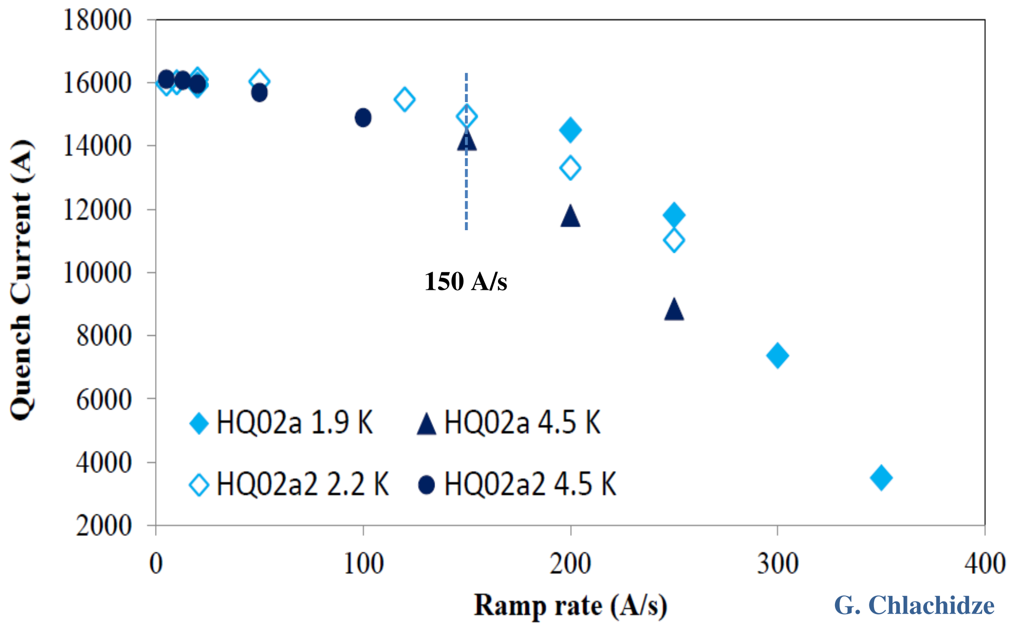


G. Chlachidze

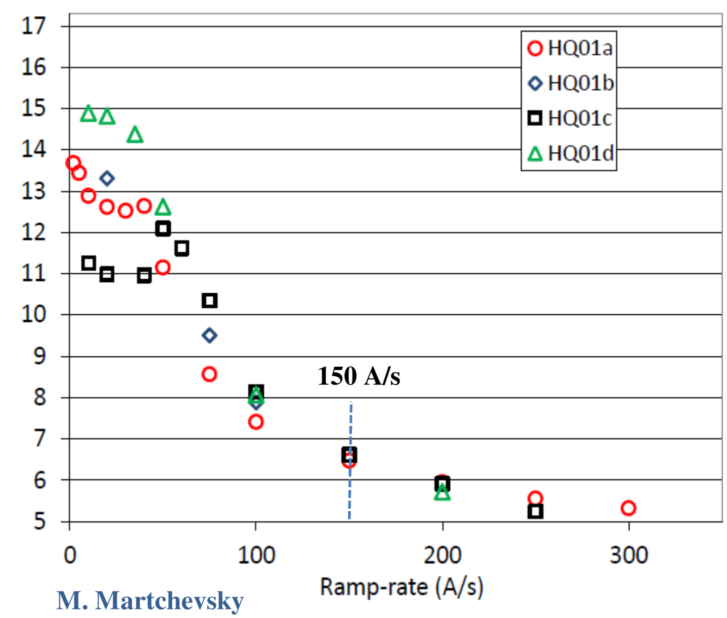
HQ02a Ramp Rate Dependence

- Dramatic reduction of ramp rate dependence with cored cable
  - Reached nominal 14.6 kA (80% SSL) with **ramp rates up to 150 A/s** (1.9K)
  - Safe discharge from nominal level with **ramp rates up to 300 A/s**
- Partial core coverage is sufficient to control eddy currents while maintaining sufficient current sharing and stable performance

HQ02: 15kA @ 150 A/s

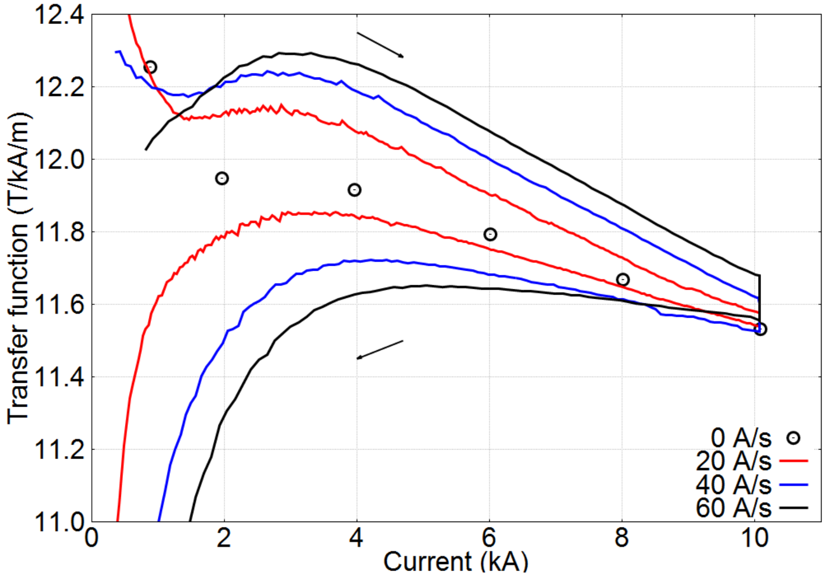


HQ01: 6.5 kA @150 A/s



Eddy current harmonics

- Cored cable increased the effective R_c from 0.1-0.4 μΩ (HQ01) to 2-4 μΩ (HQ02) with a corresponding reduction of the errors by a factor 10-20
- Increased R_c also results in lower variability of the effect from coil to coil, allowing more accurate prediction and correction of the residual errors
- HQ modeling and measurements will be applied to optimize core design for QXF

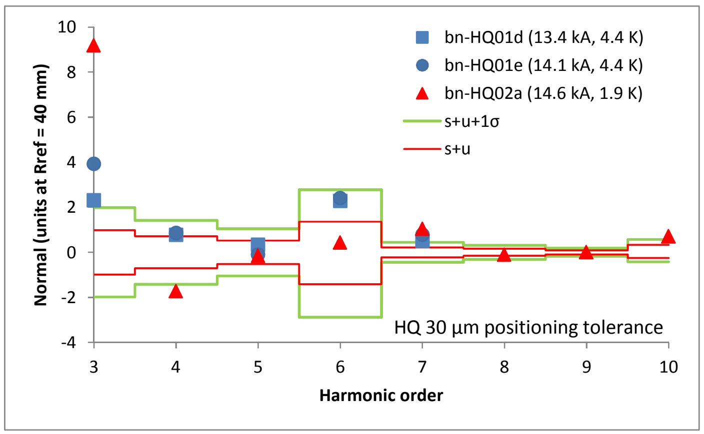


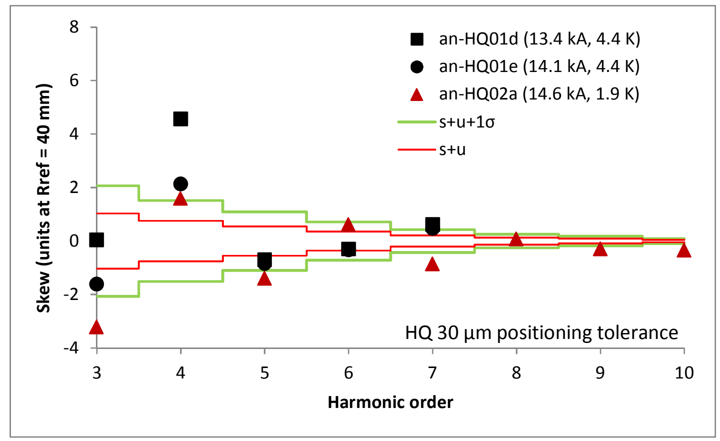
Harmonics	HQ01e	HQ02a	Reduction (%)
b_2	14.60	0.85	94
b_3	1.56	-0.12	92
b_4	0.43	0.04	90
b_5	0.21	0.00	98
b_6	2.09	0.10	95
a_3	4.73	0.44	91
a_4	0.18	-0.14	25
a_5	0.52	0.12	77
a_6	-0.26	-0.04	84

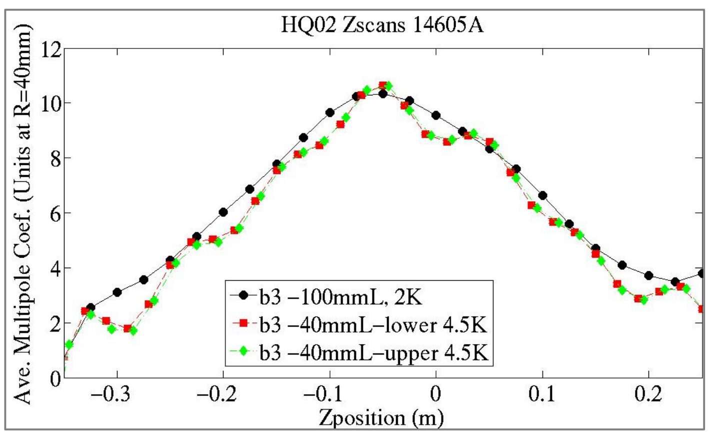
J. DiMarco, X. Wang

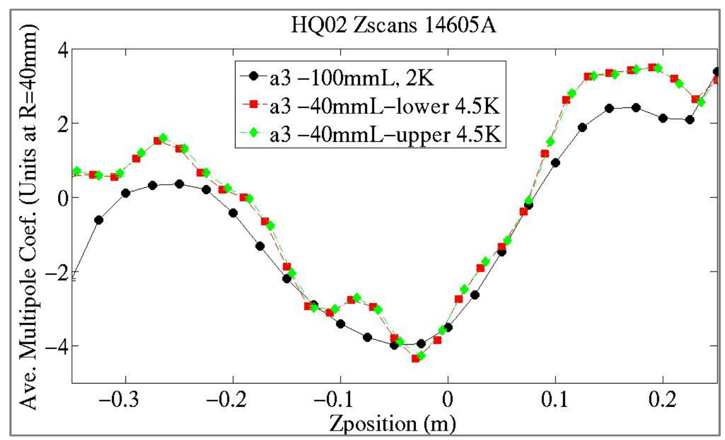
HQ02a Geometric Field Quality

- Higher order harmonics (n>4) consistent with 30 μm positioning tolerances
  - ✓ *Comparable with NbTi technology*
- However, lower orders (n=3,4) show larger errors requiring better uniformity of coils production and/or correction capabilities (to be assessed in HQ03)









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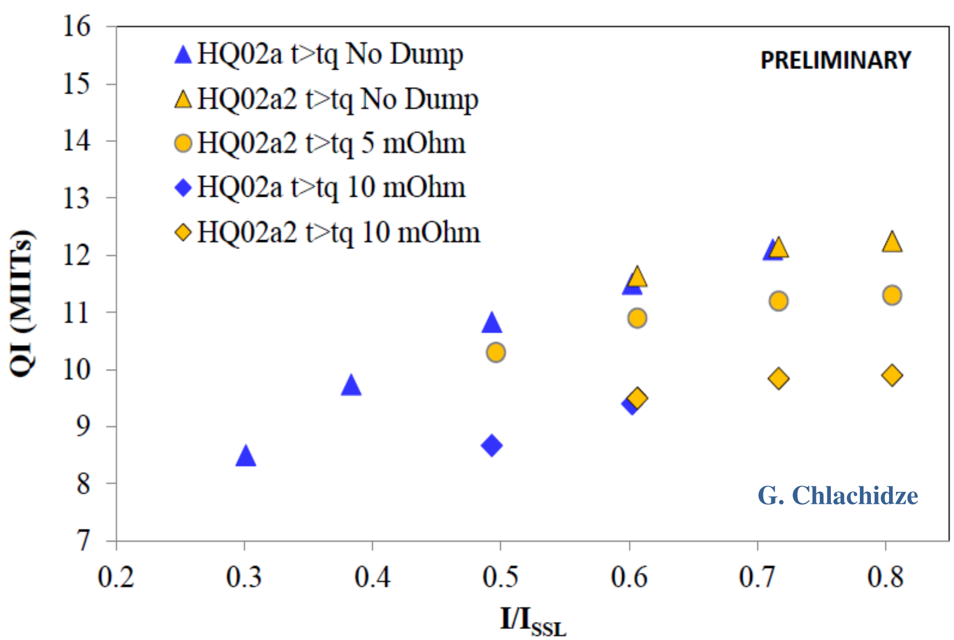
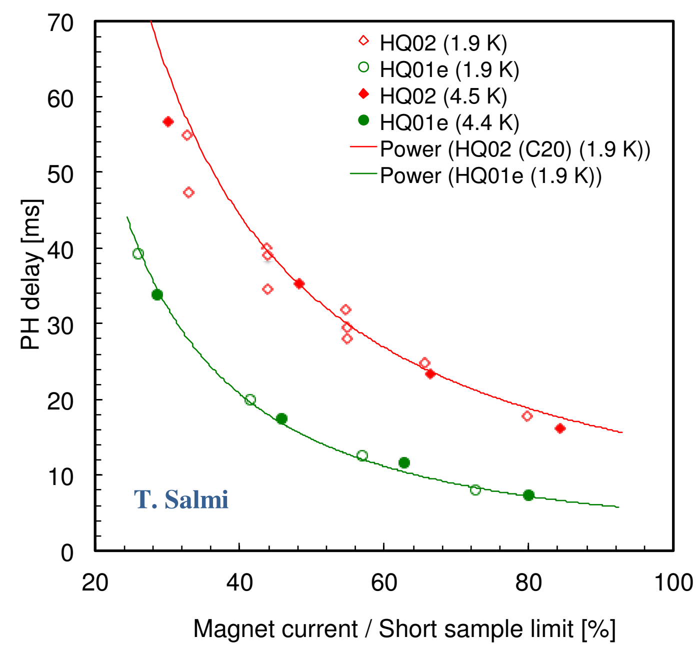
HQ02a Protection Studies

- Quench integral measurements in relevant conditions for operation in the accelerator
  - Partial heater coverage to facilitate heat transfer and assess failure modes
  - (Lack of) efficacy of a smaller external resistor to accelerate current decay
- Detailed characterization of quench heater performance to validate calculations and support the design of QXF heaters
  - Significant increase of the heater delay with the increased thickness of the kapton insulation in HQ02 (75µm vs. 25 µm) → input for QXF





Summary of HQ02a Results

- Fast training to nominal, no retraining after thermal cycle, and robust electrical performance with 4 new coils
  - Demonstrates key requirements for production and accelerator operation
  - Ramp rate dependence: large margins in up ramps, and safe fast discharge
  - Structure can simultaneously provide required pre-load and alignment
- Achieved short sample performance at 4.5K
  - No damage to the conductor during fabrication, assembly and operation
  - Allows accurate characterization of quench protection limits in HQ02b
- Field quality
  - Significant reduction of eddy current harmonics achieved, as was required
  - Need to decrease the low order geometric harmonics through better fabrication tolerances and/or correction methods
- Quench protection
  - Detailed performance characterization for different heater/extraction settings
  - However, studies of protection limits and alternative protection methods (e.g. coupling loss induced quench) had to be postponed to HQ02b/03

HQ in the Risk Reduction Phase

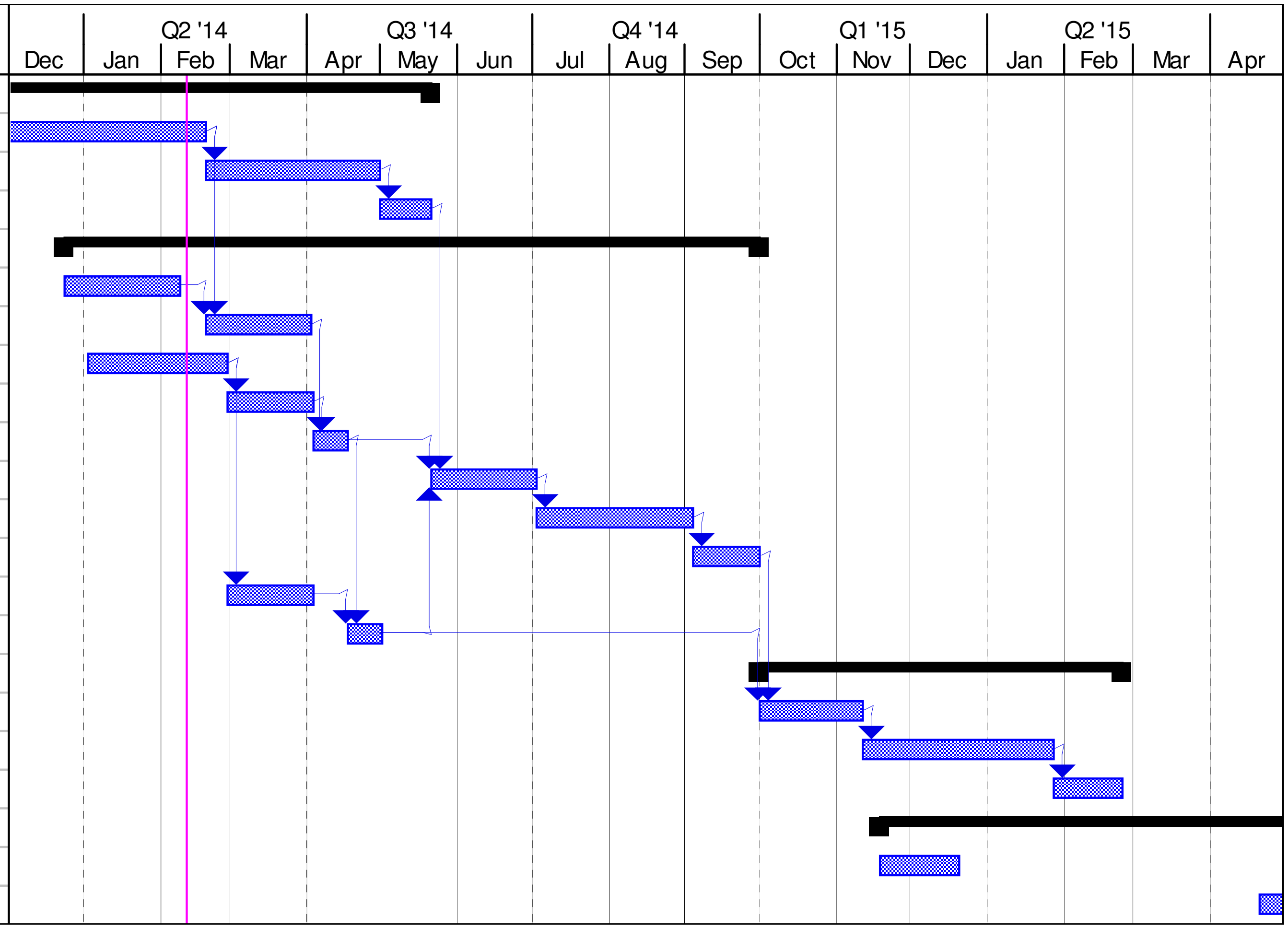
- HQ has been used as the baseline for QXF design in many key areas
  - Cored cable, coil design and fabrication, mechanical structure
- HQ is presently the best platform available to get experimental feedback on issues of critical importance for HiLumi design and QXF development, in a fast and cost-effective manner
  - Quench Performance: design/operating margins, pre-load windows
  - Field Quality: assessment of random field errors with more uniform coil process; correction based on warm measurements; injection errors
  - Quench Protection: limits for performance degradation; optimized heater design; new quench protection tools
- The above issues also have significant impact on HL-LHC machine design and production planning
  - Machine: IR layout, corrector strength, powering and protection systems
  - Project: QXF specifications, tooling design, test capabilities/cost

LARP

HQ Schedule

High Luminosity LHC

ID	Task Name
1	**HQ02b**
2	HQ02b assembly
3	HQ02b test incl. shipping
4	HQ02b disassembly
5	**HQ03a**
6	SG analysis/test
7	Coil 22-24 instrum
8	New trace design/fab
9	Coil 25 potting
10	Coil 25 instrum
11	HQ03a assembly
12	HQ03a test incl. shipping
13	HQ03a disassembly
14	Coil 26 potting
15	Coil 26 instrum
16	**HQ03a2 or 3b (option/CERN)**
17	Assembly
18	Test incl. shipping
19	Disassembly
20	**SQXF Models**
21	SQXM1 (LARP mirror) test
22	SQXF1 (LARP quad) test



HQ02b Test Goals

1. Complete quench training at 1.9K
   - Increased pre-load to support faster training at the higher current levels
   - Feedback on mechanical design windows for optimal performance
2. Assess performance of CLIQ system for magnet protection
   - Wish list includes provoked, natural and reference quenches
   - Opportunities for optimization are being discussed
3. Study of quench protection limits
   - MIITS budget before start of permanent degradation
   - Additional degradation down to minimum performance requirements

Additional goals:

- Incorporate/characterize new instrumentation (QA, acoustics etc.)
- Demonstrate/validate methods to incorporate magnetic shims

Not included in this test (due to schedule/resource/infrastructure constraints)

- Robustness studies: large number of cycles, full accelerator cycle
- Cold magnetic measurements (warm measurements are included)

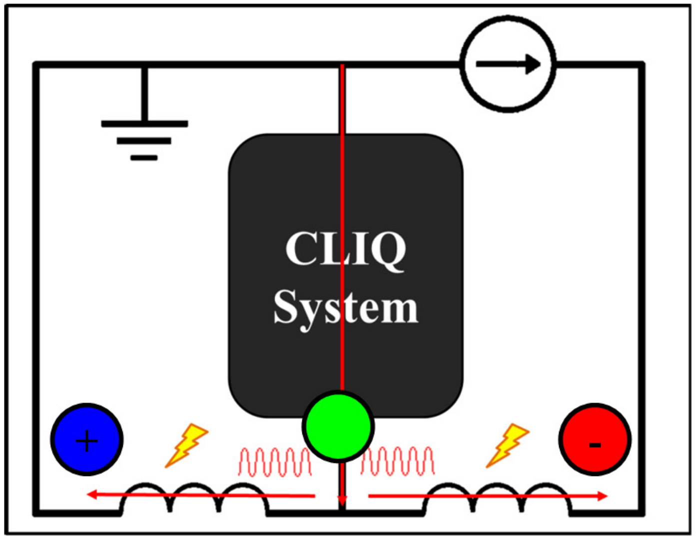
CLIQ Protection System Tests

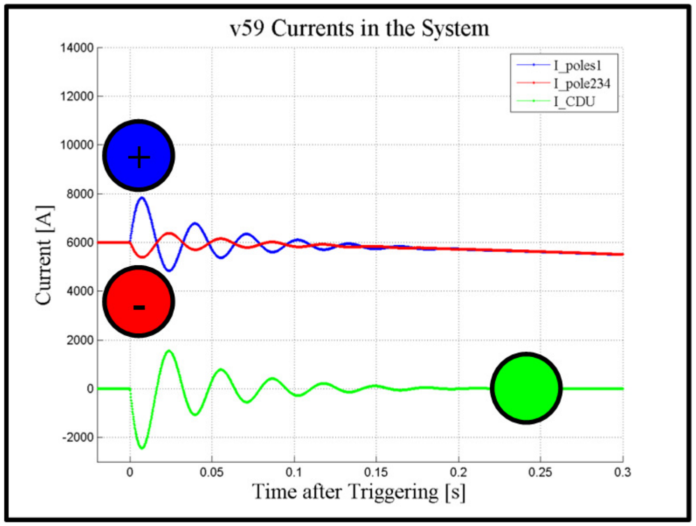
Concept:

- CLIQ = Coupling Loss Induced Quench system under development by CERN
- Capacitive discharge to induce fast oscillations of the transport current (ref: IEEE Trans. Appl. Superconductivity 24 (3) June 2014)
- May be required for QXF to complement traditional approaches based on quench heaters and energy extraction

Goals for HQ02b:

- First test of CLIQ on a Nb_3Sn magnet
  - Higher energy density required to provoke and propagate a quench in the coil
- Comparison with heater performance: quench integral, hot-spot temperature, development of quench resistance

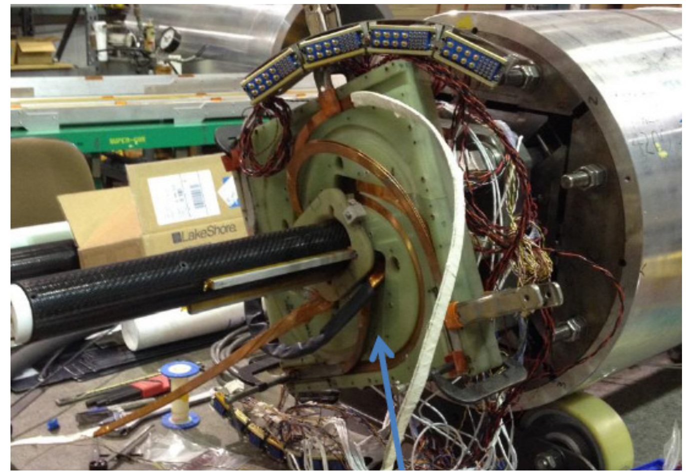




E. Ravaioli

HQ02b Warm Measurements

- Fermilab FERRET system successfully tested at LBNL during HQ02b assembly
- Demonstrated good accuracy and warm-cold correlation
- HQ03 assembly will include field quality correction based on warm measurements
- Impact on machine design and production cost



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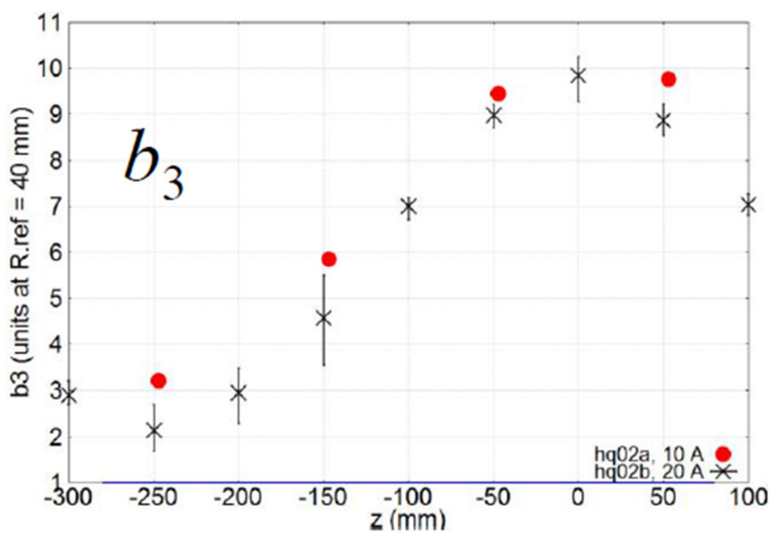
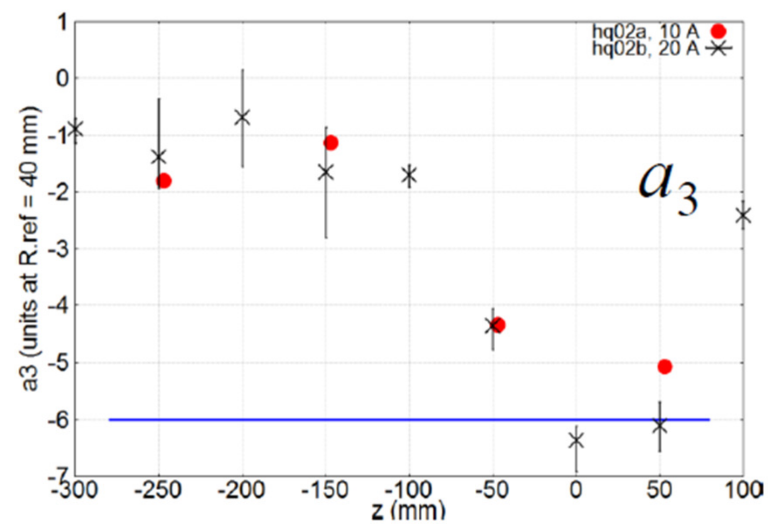
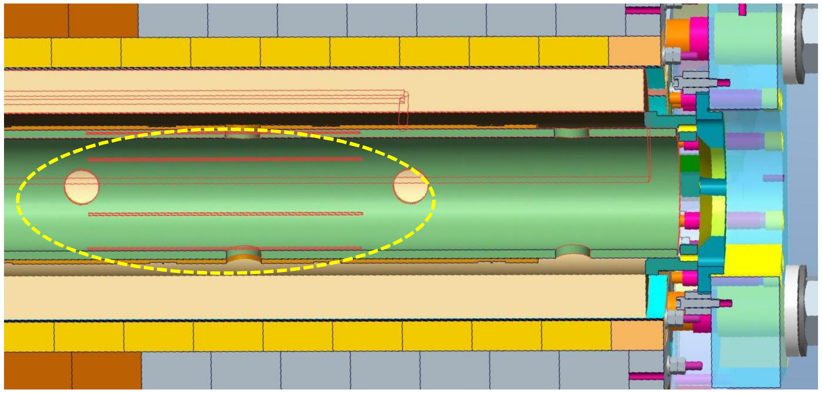




Control of Injection Field Quality

- Thin iron strips at selected angular locations can compensate for persistent current effects
- HQ02b will include shims to evaluate the mechanical assembly and perform warm measurements
- Full test and cold measurements in HQ03



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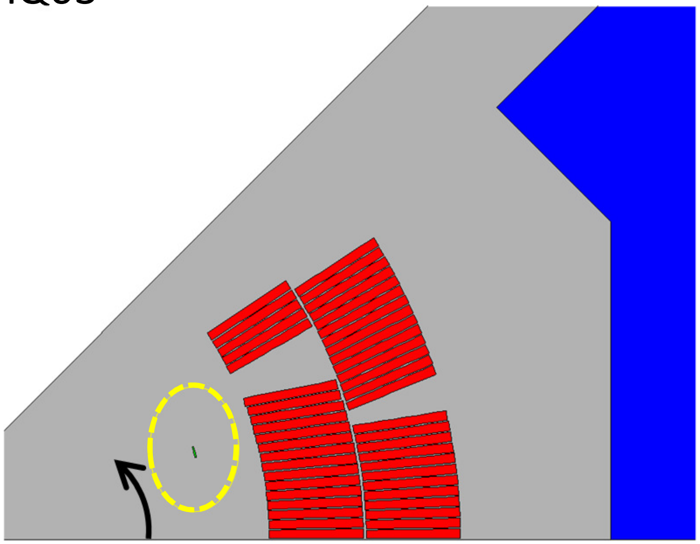
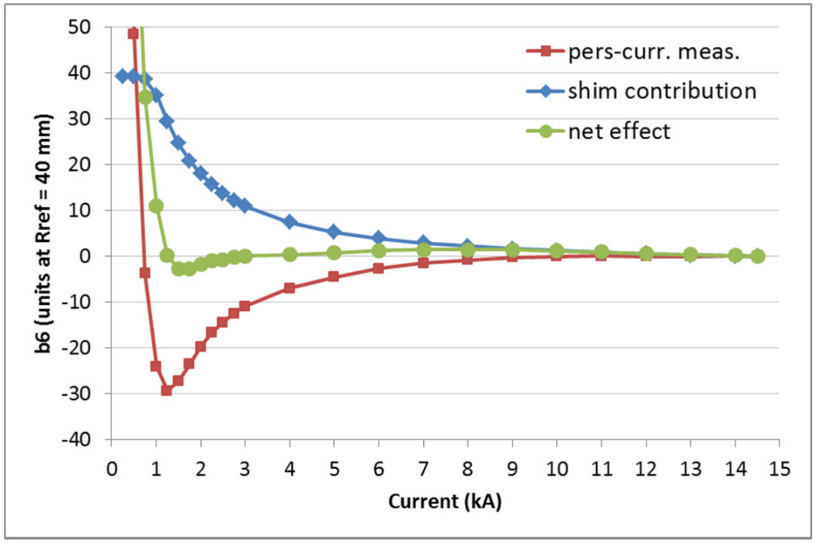




HQ03 Goals and Status

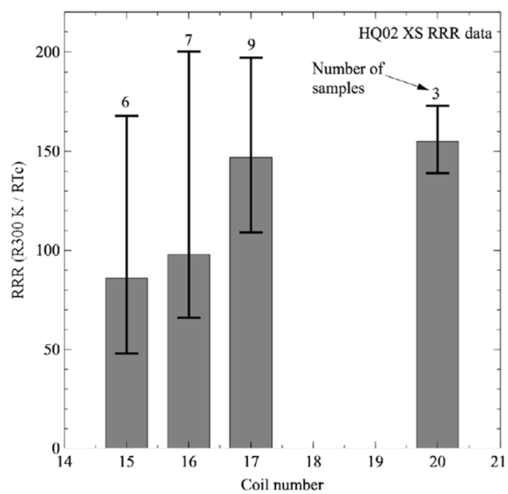
Launched after the Napa collaboration meeting (4/13) with strong interest by HiLumi

Main goals:

- Reproduce HQ02 results: quench performance, cored cable, protection studies
- Demonstrate better uniformity of coil dimensions and properties
    - Despite a significant improvement from HQ01, the HQ02 coils still show differences that reflect ongoing optimization of design and fabrication processes, and variability of components (conductor, parts)

Status: three coils impregnated and awaiting SG installation, two coils reacted

Average RRR, detected range, and number of samples

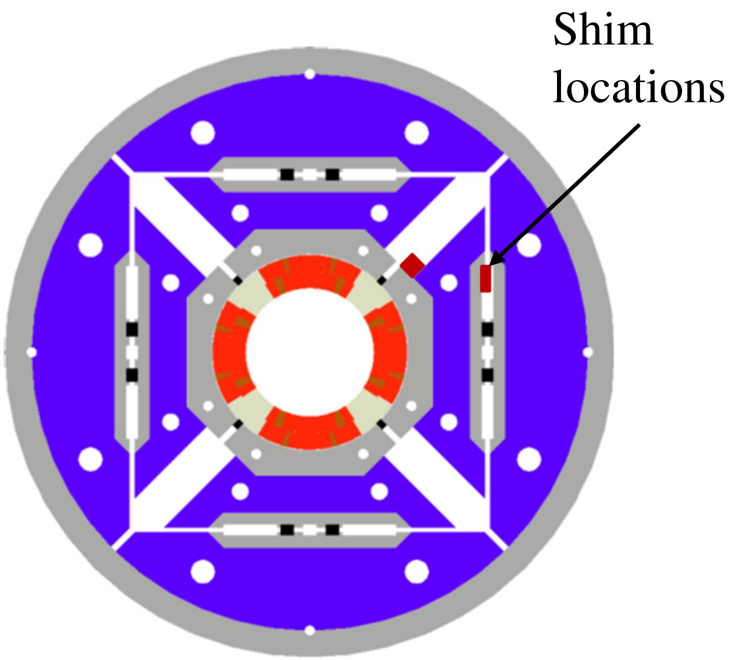


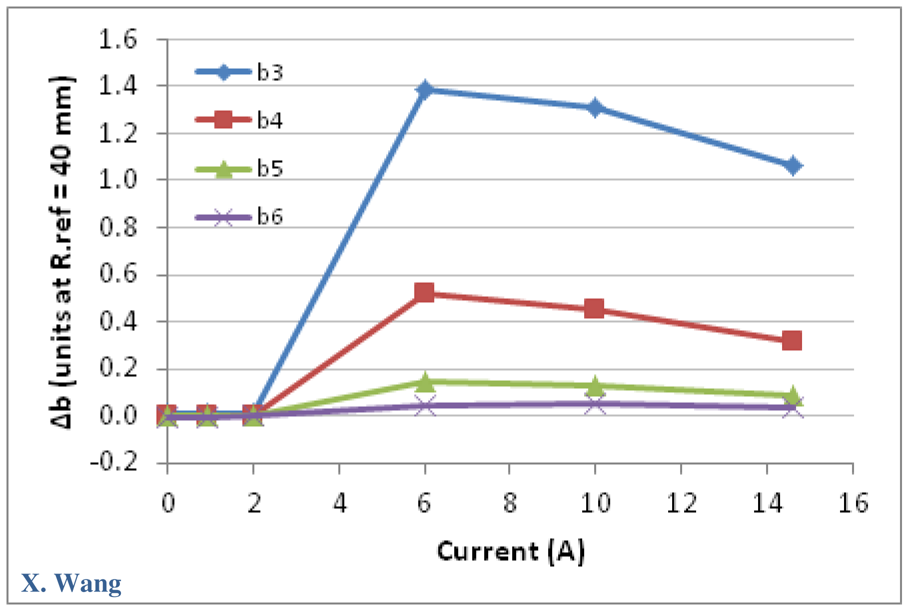
A. Godeke. A. Ghosh

Coil #	Design/process changes introduced
HQ02 coil series	
15	Increased heater insulation to 75 mm
17	Applied coatings to selected end parts/surfaces Decreased reaction temperature to increase RRR
20	Applied coating to Ti pole
21	Tested/corrected issues with new set of parts
HQ03 coil series	
22	New design of end parts and fully coated

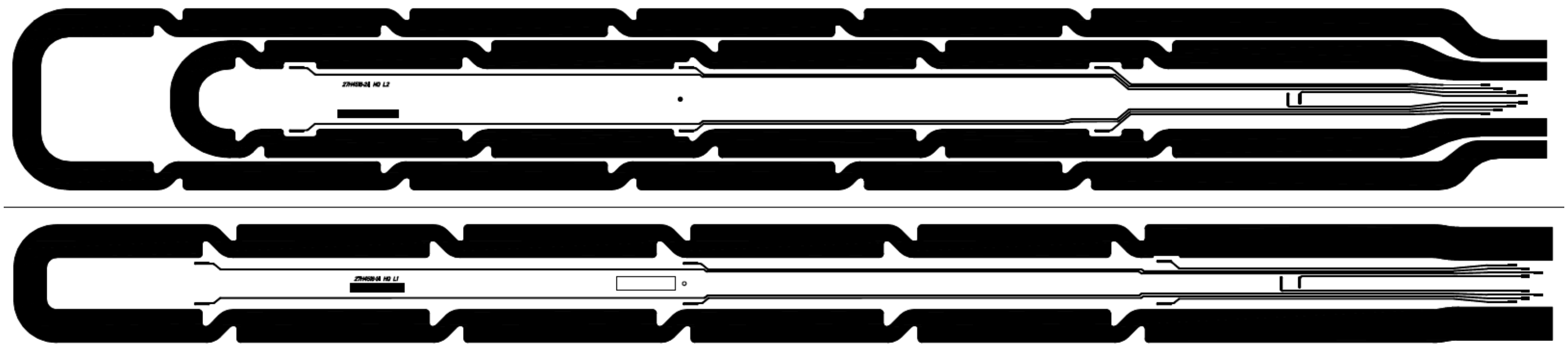
Control of Collision Field Quality

- Several past studies including test/application in magnets (RHIC, MQXB)
  - *Typically relying on 8 independent shims at quad-symmetric locations*
- Design goal: sufficient correction strength at high field, minimal saturation
- Correction will be attempted in HQ03 based on magnetic measurements, and results used to assess/revise the QXF field error tables





QXF Heater Design Evaluation



New HQ heaters for coil 25-26

M. Martchevsky, D. Cheng

- The main design features of the QXF heaters were selected in December
    - Key parameters: voltage, power, distance between stations etc.
    - OL: independent heaters for mid-plane and pole blocks for redundancy
    - IL: leave 50% of available surface free to allow heat transfer to cold bore
- In order to evaluate the performance of this approach, the HQ heaters were redesigned using the same concepts and are currently being fabricated
- Impregnation of the last two coils #25 and #26 was postponed in order to incorporate these heaters
- No delay to the HQ03 assembly and test (schedule driven by HQ02b test)

Summary

1. Accomplishments and implications for LARP and the HiLumi LHC Project
   – HQ demonstrated that Nb_3Sn IR Quadrupoles can meet all key requirements for the HiLumi LHC
   – HQ results provided a **technical foundation for HiLumi LHC,** leading to the **successful completion of the LARP R&D phase,** and the start of the **transition toward a construction project**
2. Goals and Plans in the context of the Risk Reduction Strategy for the Construction Project
   – Main experimental reference to **set the QXF specifications that are driving the new IR design** (HiLumi LHC Design Study)
   – Best experimental platform to **support a range of critical decisions for QXF** development in the near term