IR QUAD Status and Plans

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Outline

IR Designs and Magnet Requirements

Challenges

RD questions and issues

IRQ design study summary

Model Magnet R&D Strategy

FY05-FY07 goals and plans

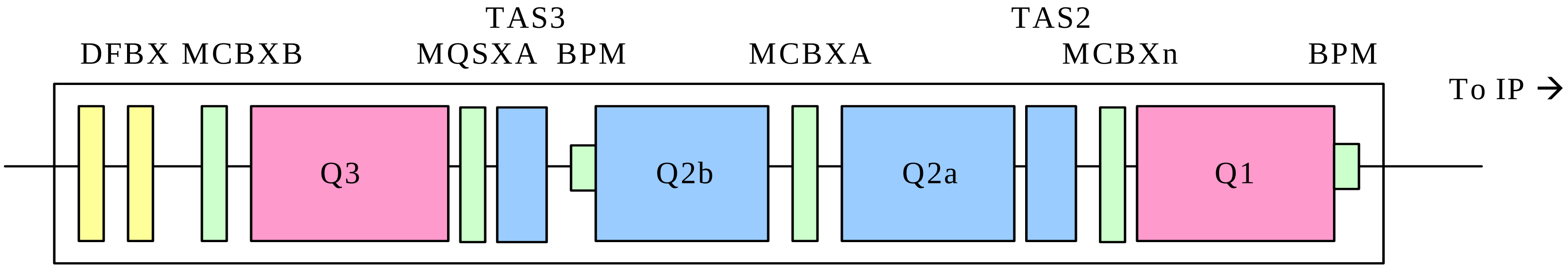
Conclusions

1st Generation LHC IRs

Baseline LHC inner triplets consist of single-bore, high-gradient quads based on NbTi superconductor.

Quadrupole parameters:

- 70 mm coil aperture
- 205 T/m nominal gradient with 20% margin
- 1.9 K operating temperature



2^{nd} generation Inner Triplet Design Options

Two fundamental inner triplet design approaches (both need large-aperture quadrupoles):

a) single-bore design

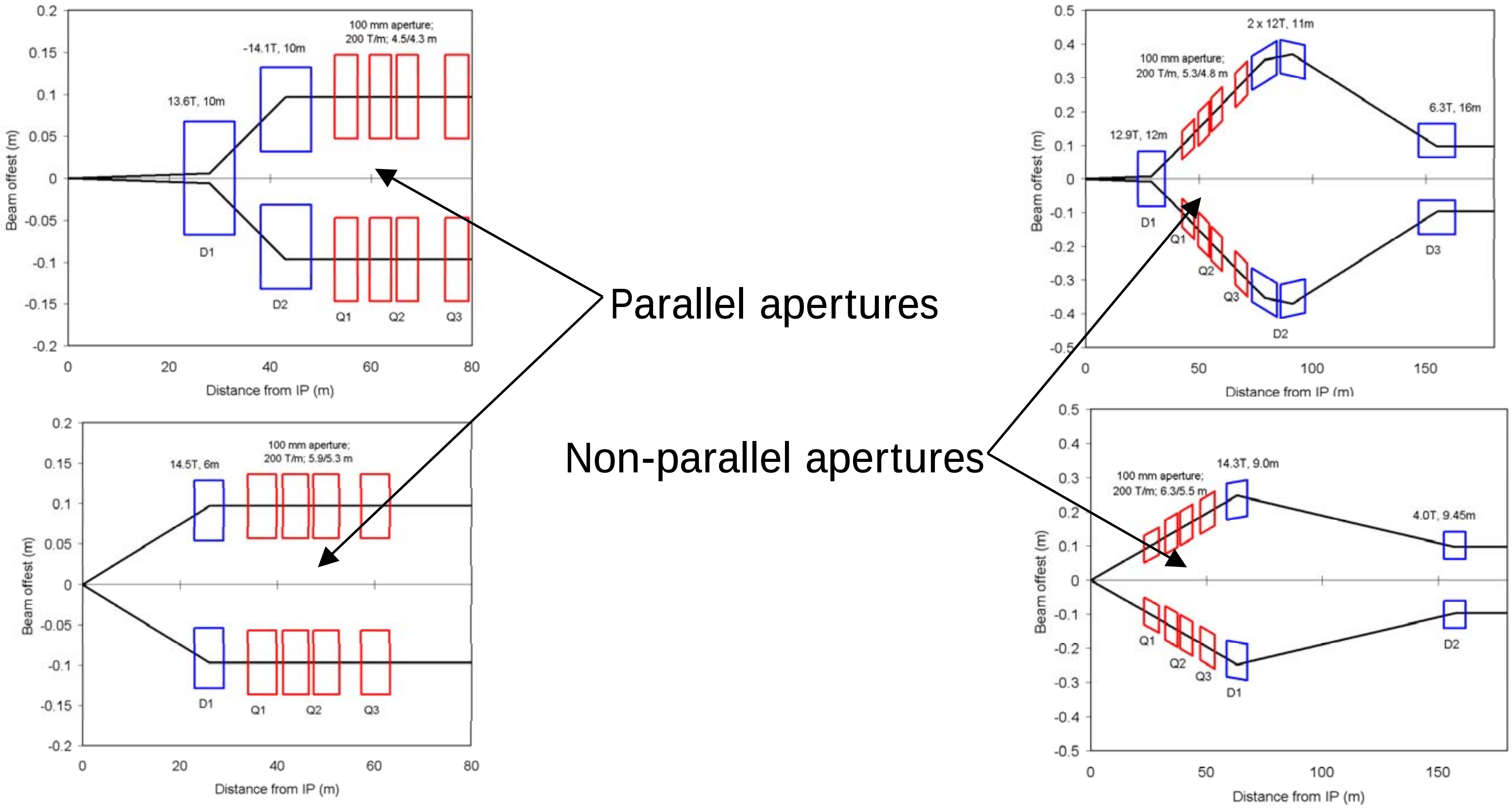
Quadrupoles with largest possible aperture are required, to provide largest beam separation and accommodate the large β-max.

b) dipole-first designs with double-bore quadrupoles

For these IR designs there are two contradictory requirements for IR quads:

- Large β-max requires largest possible aperture
- Twin-bore configuration limits aperture

Double-bore Inner Triplet Designs



Parallel apertures

Non-parallel apertures

Examples of 2^{nd} generation LHC IR optics based on double-bore inner triplet with 100 mm quads.

Challenges

At present time the IRQ R&D program is focused on the large-aperture quadrupoles based on Nb3Sn superconductor for the single-bore inner triplet and double-bore inner triplet with parallel apertures.

Why Nb3Sn?

- Nb_3Sn critical parameters (B_{c2}, T_c and J_c) are much higher than NbTi parameters
- High-performance Nb_3Sn strands are commercially available in long lengths at affordable price

Challenges:

Nb_3Sn is brittle => new technologies for accelerator magnets.

The operating gradient of 205 T/m => G_{max} = 250 T/m, in magnet bore 100-110 mm, push magnet parameters above the present state-of-the-art:

- Jc(12T,4.2K)>3 kA/mm^2 in the coil
- the B_{max} in the coil at quench >15 T exceeding the level reached in Nb_3Sn accelerator magnets to date
- the maximum stress in the coil, induced by Lorentz forces, approaches to the level which may cause significant degradation or even damage of brittle Nb_3Sn conductor

R&D Questions

Some important R&D questions:

- What is the optimum aperture for single-bore and double-bore quads? What are the major limiting factors?
- What is the optimal magnetic and mechanical design for large-aperture Nb_3Sn quads?
- What are appropriate materials for operational conditions?
- Can magnets provide adequate margins necessary for operation in the extreme radiation environment at very high luminosity?
- Can good field quality be maintained in magnets over the full operating range?
- How can the large heat deposition (few kW) be removed from the magnet cold mass for a tolerable cost?
- Are non-parallel axis double-bore quadrupoles feasible?
- Can we provide reliable magnet quench protection for these magnets?

IRQ R&D Phases

Program starts with Conceptual Design Studies of IR and magnet designs.

A series of short models has to address the issues of magnet quench performance, field quality, mechanics, quench protection, reproducibility, long term performance, etc.

Length dependent effects will be studied with 4-m long coils, as soon as we achieve acceptable quench performance on short models.

Model R&D will be followed by the construction of one or more prototypes containing all of the features required for use in the LHC.

Summary of IRQ design studies

IRQ conceptual design studies and preparation to the short model R&D were started few years ago at Fermilab and LBNL.

They included:

- magnetic analysis on different IRQ designs
- mechanical analysis of different IRQ mechanical structures
- Nb3Sn quarupole thermal analysis
- IRQ quench protection
- Analysis of structural materials

These results will be presented and discussed at this meeting in different presentations.

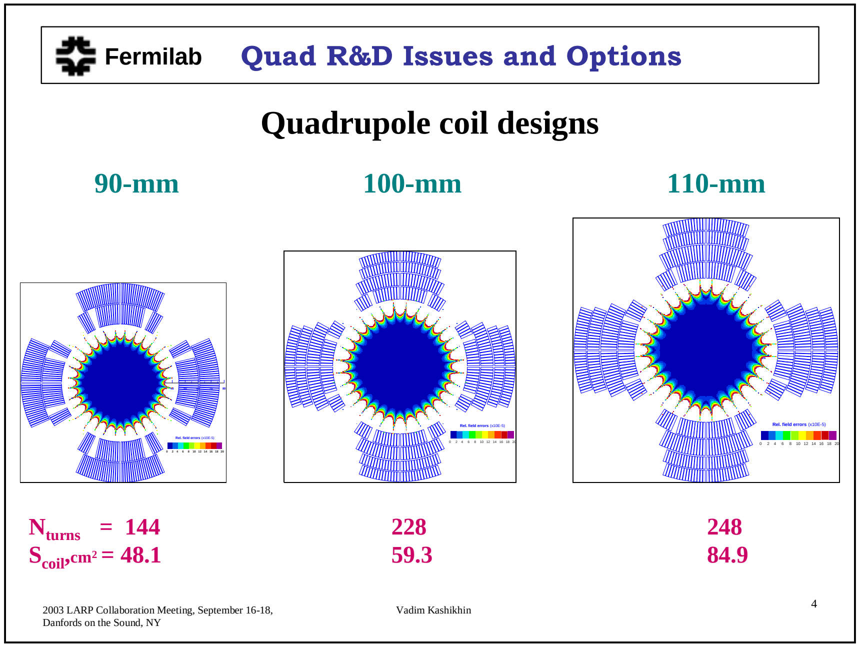
Preliminary answers on some of the R&D questions have been already obtained. However, the final answers on most of these questions can be provided only by model magnet R&D.

Major structural materials

- What are appropriate materials for operational conditions?
  - Superconductor: Nb3Sn, major requirements are high-Jc and stability
  - Structural materials: metallic parts everywhere where possible
  - Insulation: TBD, major requirements are radiation life time and compatibility with Nb3Sn magnet technology

Aperture limitations

- What is the optimum aperture for single-bore and double-bore quads?
  - TBD, the limit is 100 mm (superconductor Jc, mechanics)



Fermilab Quad R&D Issues and Options

Quadrupole coil designs

	90-mm	100-mm	110-mm
N_{turns} =	144	228	248
S_{coil}, cm^2 =	48.1	59.3	84.9

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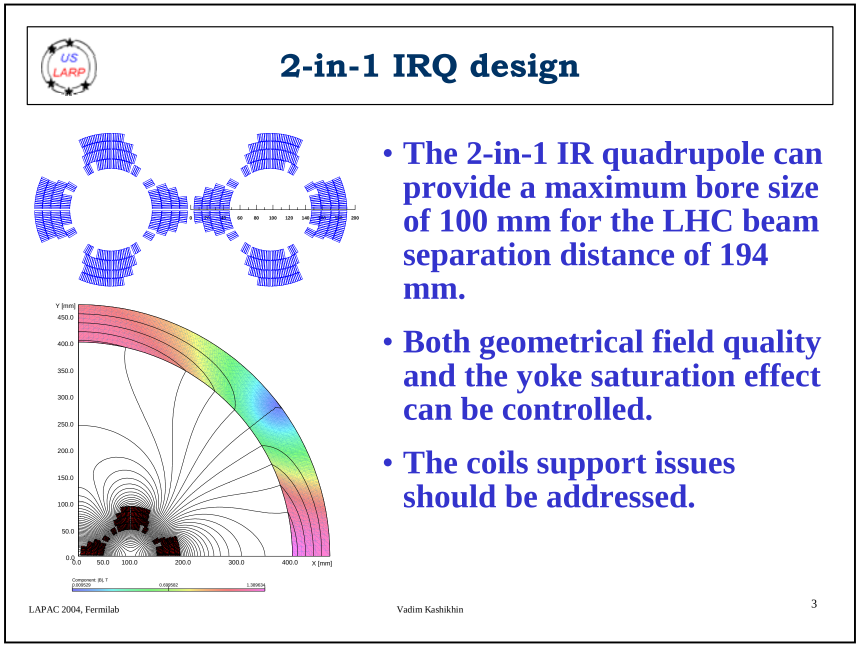

2-in-1 IRQ design

- The 2-in-1 IR quadrupole can provide a maximum bore size of 100 mm for the LHC beam separation distance of 194 mm.
- Both geometrical field quality and the yoke saturation effect can be controlled.
- The coils support issues should be addressed.

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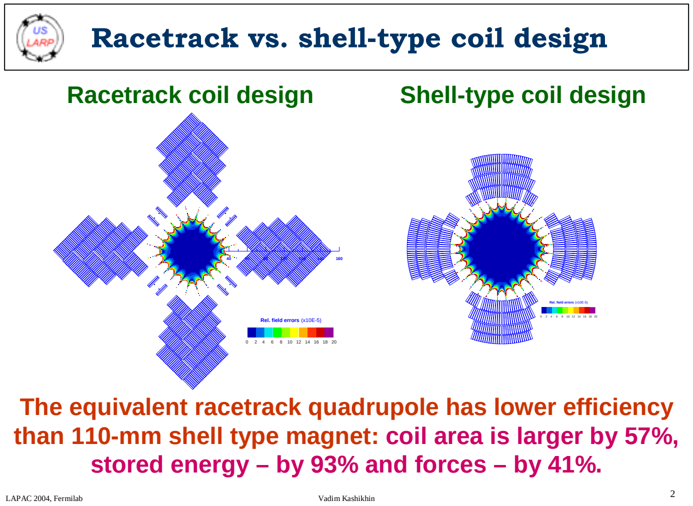
Design options

- What is the optimal design for large-aperture Nb_3Sn quads?
  - Shell-type vs. block-type ⇒ shell-type more efficient based on analysis
  - 2-layers vs. 4-layers coil ⇒ need experimental study and evaluation
  - Al shell with bladders vs. traditional collar/yoke/skin support structure ⇒ need experimental study and evaluation
  - Yoke: cold vs. warm – depend on mechanical structure and heat load



Racetrack vs. shell-type coil design

Racetrack coil design

Shell-type coil design

The equivalent racetrack quadrupole has lower efficiency than 110-mm shell type magnet: coil area is larger by 57%, stored energy – by 93% and forces – by 41%.

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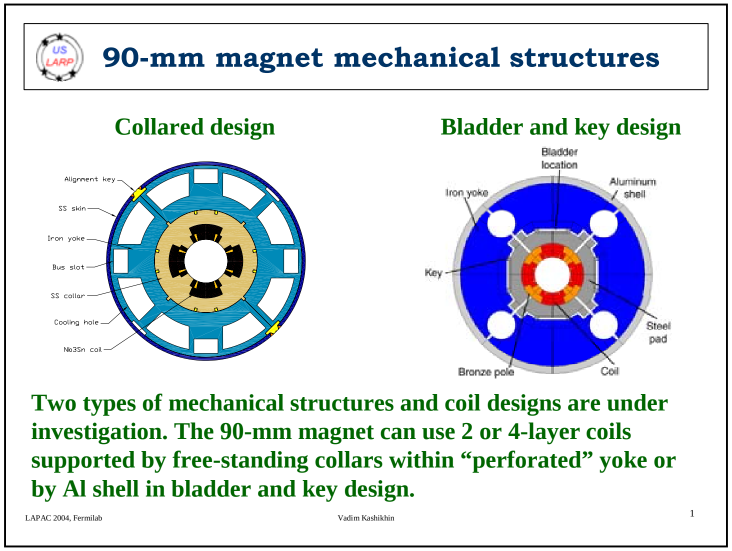

90-mm magnet mechanical structures

Collared design

Bladder and key design

Two types of mechanical structures and coil designs are under investigation. The 90-mm magnet can use 2 or 4-layer coils supported by free-standing collars within “perforated” yoke or by Al shell in bladder and key design.

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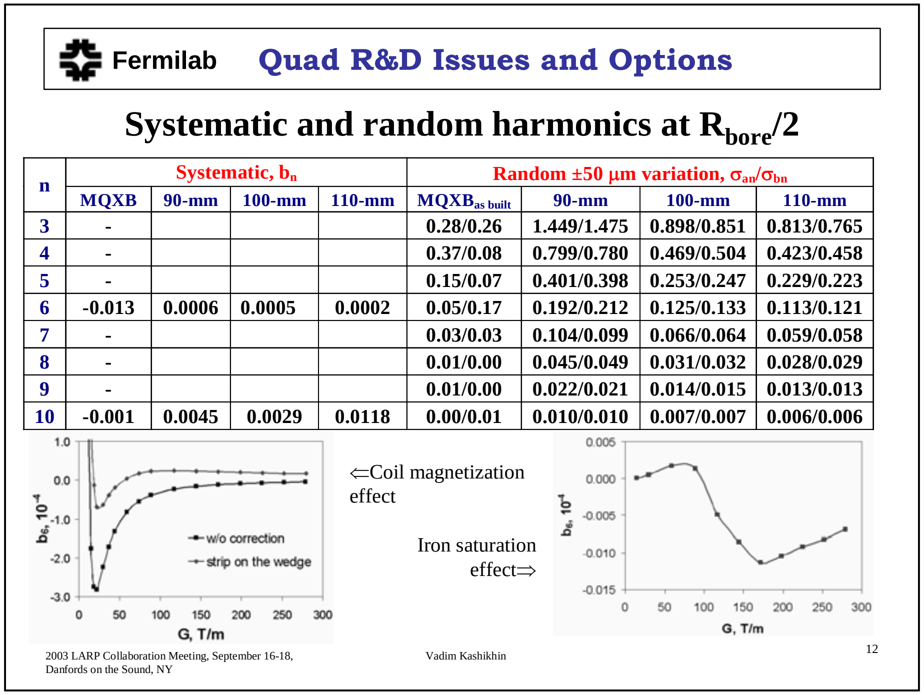
Field quality

- Can good field quality be maintained in magnets over the full operating range?

•Yes, based on simulation

•Need experimental studies to understand real field quality and its reproducibility



Fermilab **Quad R&D Issues and Options**

Systematic and random harmonics at $R_{bore}/2$

n	Systematic, b_n				Random ±50 μm variation, σ_{an}/σ_{bn}			
	MQXB	90-mm	100-mm	110-mm	$MQXB_{as\ built}$	90-mm	100-mm	110-mm
3	-				0.28/0.26	1.449/1.475	0.898/0.851	0.813/0.765
4	-				0.37/0.08	0.799/0.780	0.469/0.504	0.423/0.458
5	-				0.15/0.07	0.401/0.398	0.253/0.247	0.229/0.223
6	-0.013	0.0006	0.0005	0.0002	0.05/0.17	0.192/0.212	0.125/0.133	0.113/0.121
7	-				0.03/0.03	0.104/0.099	0.066/0.064	0.059/0.058
8	-				0.01/0.00	0.045/0.049	0.031/0.032	0.028/0.029
9	-				0.01/0.00	0.022/0.021	0.014/0.015	0.013/0.013
10	-0.001	0.0045	0.0029	0.0118	0.00/0.01	0.010/0.010	0.007/0.007	0.006/0.006

⇐Coil magnetization effect

Iron saturation effect⇒

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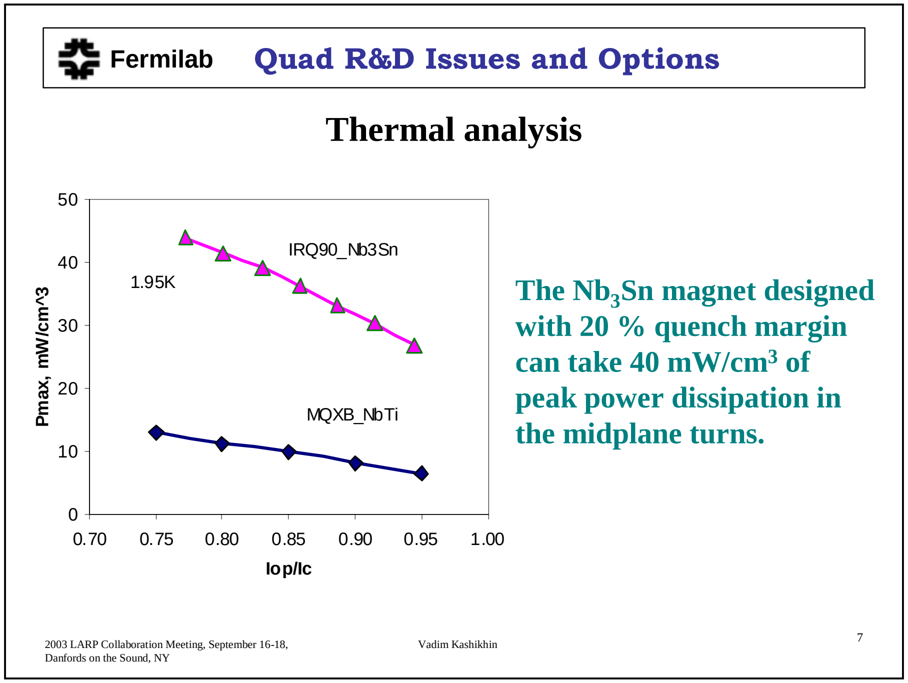
Quench margin

- Can magnets provide nominal field gradient of 205 T/m in the extreme radiation environment at very high luminosity?
  - Operation margin 10(5) at 1.9K (4.2K) and 20% current margin for Tc=18K.
  - Analysis has to be updated for the high-Jc Nb3Sn strands with Tc~16K



Fermilab **Quad R&D Issues and Options**

Thermal analysis

The Nb_3Sn magnet designed with 20 % quench margin can take 40 mW/cm^3 of peak power dissipation in the midplane turns.

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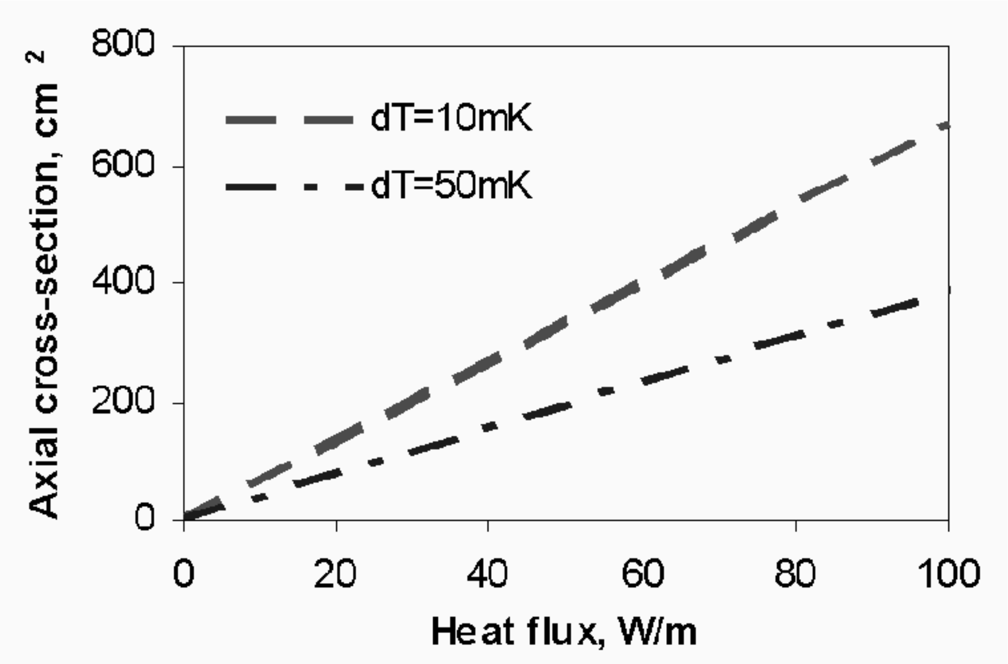
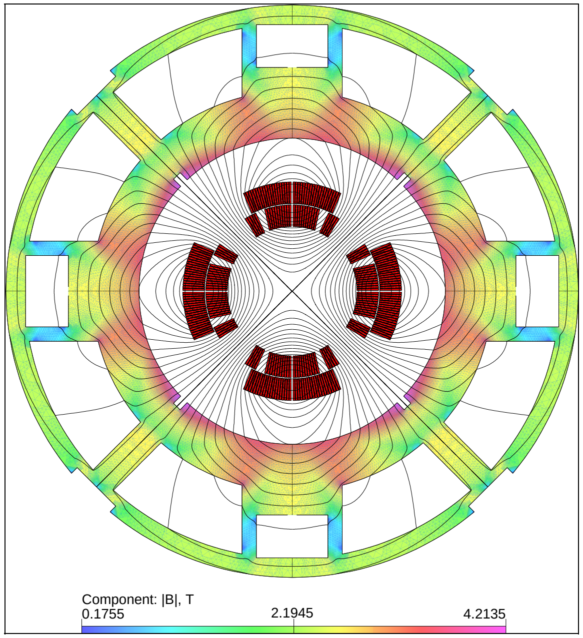
Cold mass heat transfer

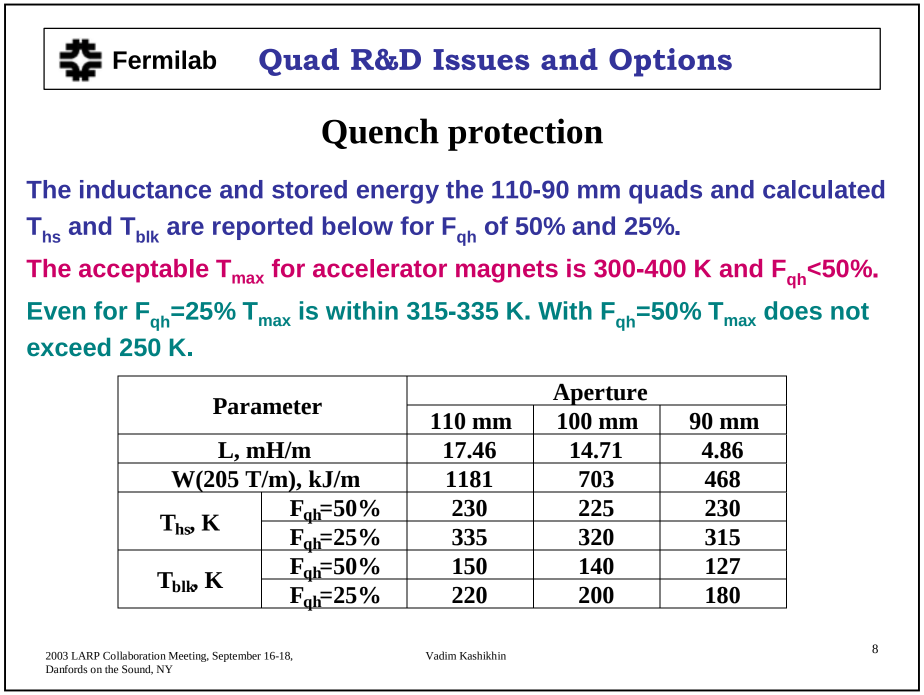
- How can the large heat deposition be removed from the magnet cold mass for a tolerable cost?
  - – Yes in case of superfluid He, radial+longitudinal channels.
  - – Holes with total area of 400 cm^2 will restrict the HeII temperature rise inside the cold mass by 10 mK for heat flux up to 60 W/m.
  - – Need more studies if magnets will work at 4.5 K





Quench protection

- Can magnets be protected in case of quench?
  - – Yes, using an active quench protection



Fermilab **Quad R&D Issues and Options**

Quench protection

The inductance and stored energy the 110-90 mm quads and calculated T_{hs} and T_{blk} are reported below for F_{qh} of 50% and 25%.

The acceptable T_{max} for accelerator magnets is 300-400 K and F_{qh}<50%.

Even for F_{qh}=25% T_{max} is within 315-335 K. With F_{qh}=50% T_{max} does not exceed 250 K.

Parameter		Aperture		
		110 mm	100 mm	90 mm
L, mH/m		17.46	14.71	4.86
W(205 T/m), kJ/m		1181	703	468
T_{hs}, K	F_{qh}=50%	230	225	230
	F_{qh}=25%	335	320	315
T_{blk}, K	F_{qh}=50%	150	140	127
	F_{qh}=25%	220	200	180

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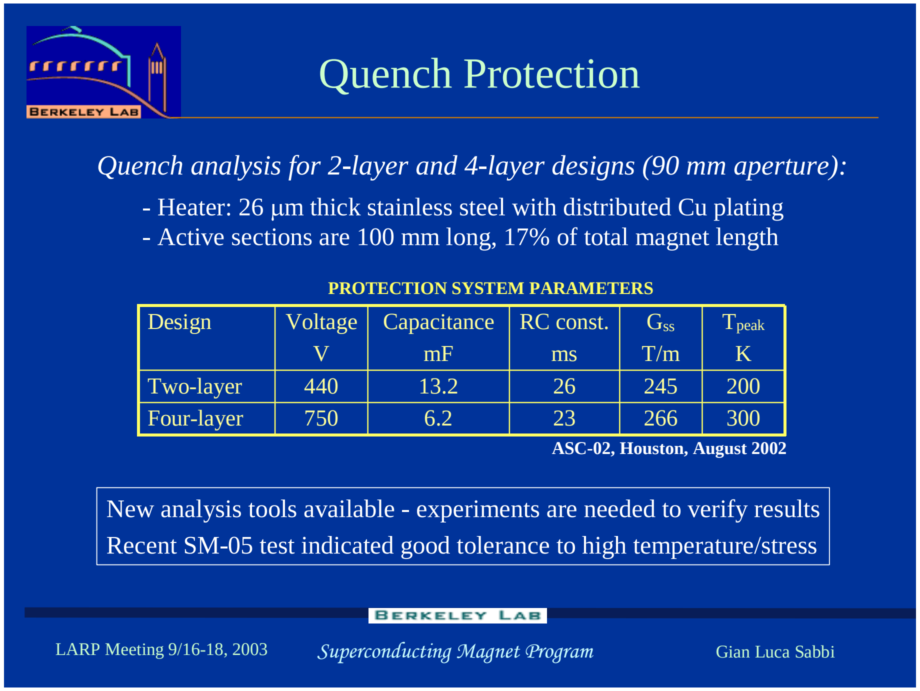

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Quench Protection

Quench analysis for 2-layer and 4-layer designs (90 mm aperture):

- Heater: 26 μm thick stainless steel with distributed Cu plating
- Active sections are 100 mm long, 17% of total magnet length

PROTECTION SYSTEM PARAMETERS

Design	Voltage V	Capacitance mF	RC const. ms	G_{ss} T/m	T_{peak} K
Two-layer	440	13.2	26	245	200
Four-layer	750	6.2	23	266	300

ASC-02, Houston, August 2002

New analysis tools available - experiments are needed to verify results
Recent SM-05 test indicated good tolerance to high temperature/stress

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LARP Meeting 9/16-18, 2003 *Superconducting Magnet Program* Gian Luca Sabbi

IRQ Magnet R&D Strategy

A success of 2nd generation IR quadrupole development program is the key to any of the future LHC IR designs.

The parameters of the new IR quads have to be pushed to their extremes to provide the best performance of the new generation IRs.

However, the design and parameters of IR quadrupoles have to be realistic to accomplish the R&D in a finite time and be ready to replace the IR magnets in 2015.

Balance of these two requirements determines the strategy of the quadrupole model R&D program.

The progress made in the IRQ design studies allows us more aggressive, early start of the IRQ short model R&D.

First phase of IRQ short model R&D

Based on the performed magnet design studies, LARP program goals, status of the Nb3Sn strand R&D we are planning to focus the first 3-year phase of the short model R&D program on the 90 mm shell-type technological quadrupoles (TQ).

TQ models will serve as a tool for both quadrupole technology development and magnet performance studies:

- possibility of 2- and 4-layer coil designs and fabrication technologies (*fully keystone cable in 4-layer design, simultaneous coil reaction/impregnation, etc.)*
- possibility of different mechanical designs (*free-standing collar, warm yoke, helium vessel, etc.)*
- possibilities of different assembly techniques

This choice, in addition to the technical considerations, reduces cost and risks of this important phase of the program.

In the future based on the results of this phase and program needs we could increase the magnet aperture size.

FY2005-FY2007 goals

The main goals of the first 3-year IRQ R&D phase are:

- fabricate, test and evaluate two shell-type coil designs: 2-layers and 4-layers
- fabricate, test and evaluate two alternative mechanical structures based on *bladder-Al shell* or *collar-yoke-skin*
- develop and study narrow and wide cables for both coil designs
- study and optimize strand parameters for quarupole models
- develop and evaluate coil fabrication technologies
- develop and build tooling to perform short model (1-m long) R&D
- develop infrastructure for fabrication and test of long (up to 4-m long) coils

By the end of this phase we are planning to choose the optimal conductor, coil aperture and design and mechanical structure for the next phase of the short model R&D which will have to address the *field quality* and *reproducibility* issues.

TQ design considerations

In order to provide internal consistency and compatibility of this phase of the program, optimize program cost and reduce the development time we need to:

- unify as much as possible the coil fabrication tooling
- distribute responsibilities among the groups for
  - tooling development and procurement
  - coil and magnet component design and procurement
  - magnet fabrication and test

In particular, it is planned that the coil innermost and outermost diameters for 2-layer and 4-layer designs will be the same, compatible with different mechanical structures.

This phase of IRQ R&D program in FY04-FY07 will be performed mainly by Fermilab and LBNL groups (with some help from BNL group).

FY2005 tasks

The following tasks are planned for FY2005:

- develop engineering design of TQ4L1a (simplified 2-layer version of TQ4L) and TQ4L1b (complete 4-layer version of TQ4L)
- procure TQ4L1a coil components
- develop and procure coil fabrication tooling for TQ4L1a
- develop and test strand and cable samples for TQ4L1a (small racetrack)
- fabricate coils for TQ4L1a and assemble coils with mechanical structure
- test TQ4L1a and analyze the data
- develop engineering design of TQ2L1
- develop strand and cable samples for TQ2L1 (small racetrack)
- continue conceptual design studies of single- and double-aperture IRQ

The primary goal of FY2005 is fabrication and test of first simplified quadrupole technological model TQ4L1a by collaborative efforts of 3 Labs – start technology and magnet performance studies.

FY2004 tasks

To achieve FY2005 goals the following work has to be finished in FY2004:

- accomplish conceptual designs and determine major performance parameters and goals for TQ2L (2-layer quadrupole model) and TQ4L (4-layer quadrupole model)
- define parameters of major magnet components including strand, cable, cable insulation, coil cross-section, coil ends
- define coil and magnet length
- accomplish conceptual design and 2D mechanical analysis of mechanical structures for TQ2L and TQ4L
- determine major steps of coil fabrication technologies for 2-layer and 4-layer design and prepare list of major tooling required for both coil designs
- determine and coordinate major tooling dimensions and parameters

FY2006 tasks

The following tasks are planned for FY2006:

- fabricate coil tooling for TQ4L1b
- develop and test strand and cable samples for TQ4L1b (2 small racetracks)
- fabricate coils for TQ4L1b and assemble coils with mechanical structure
- test TQ4L1b
- develop and fabricate tooling for TQ2L1
- procure components and fabricate coils for TQ2L1
- assemble coils with mechanical structure and test TQ2L1
- procure strands in support of IRQ magnet R&D in FY05, FY06 and FY07
- continue conceptual design studies of single- and double-aperture IRQ

Starting from FY2006 two coil designs and two mechanical structures will be studied, one at Fermilab and another one at LBNL – compare technologies and magnet performance.

We will also start working on the infrastructure plan for long quadrupole coils.

FY2007 tasks

The following tasks are planned for FY2007:

- design and procure components for TQ4L2 and fabricate new coils for TQ4L2
- assemble coils with mechanical structure and test TQ4L2
- design and procure components and fabricate coils for TQ2L2
- assemble coils with mechanical structure and test TQ2L2
- re-assemble 2-layer or 4-layer coils with alternative mechanical structures and test them
- procure strands in support of IRQ magnet R&D in FY07 and FY08
- develop and test strand and cable samples for FY08 models (2 small racetracks)
- continue conceptual design studies of single- and double-aperture IRQ

By the end of FY2007 we are planning to choose the optimal conductor, coil aperture and design and mechanical structure for the next phase of the short model R&D based on the model technologies and performances.

In FY2007 we are also planning to start infrastructure preparations for 4-m long coil fabrication.

Conclusions

The LARP IRQ R&D program technically is very challenging.

Additional risks are related to the limited resources and the time available.

Proposed 3-year plan is goal-oriented and realistic.

It is designed to minimize program risks and reach our short-term and long-term objectives mobilizing all available resources of LARP collaboration.