Review of Quench Limits

Nikolai Mokhov

Fermilab

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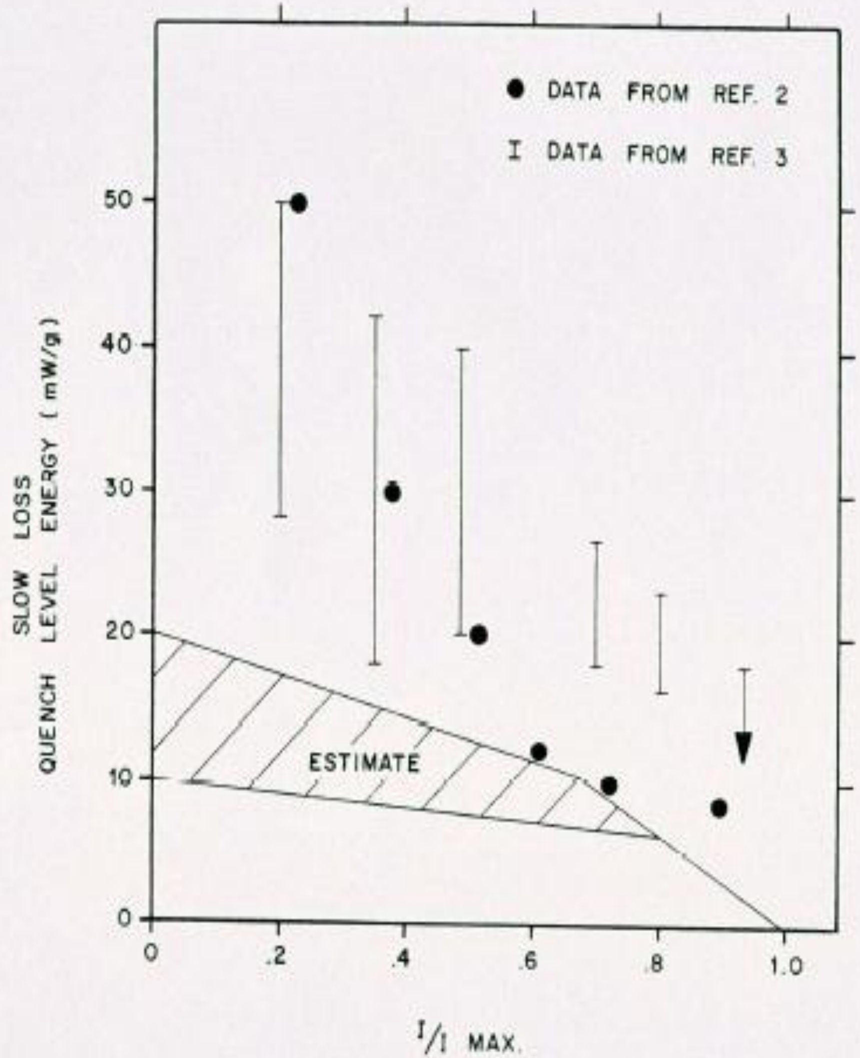
OUTLINE

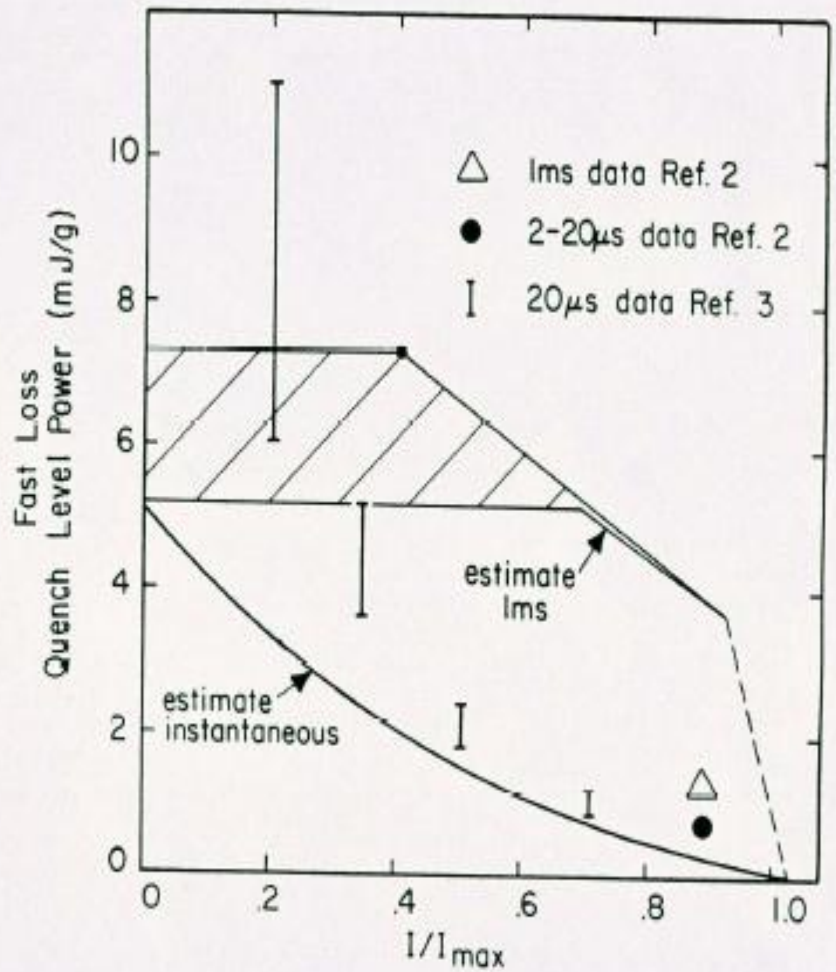
1. Tevatron Experience
2. NbTi and Nb_3Sn LHC IR Quads
3. IR Design

RADIATION CONSTRAINTS AT COLLIDERS

- Sustain favorable background conditions in experiments.
- **Maintain operational reliability in stores: quench stability (this talk)** and dynamic heat loads on cryogenics.
- Prevent quenching SC magnets and damage of machine and detector components at unsynchronized beam aborts.
- Minimize radiation damage to components, maximize their lifetime.
- Minimize impact of radiation on personnel and environment: prompt and residual radiation (hands-on maintenance).

Slow and Fast LOCAL Quench Levels in Tevatron Magnets





Tevatron Quench Limits

Tevatron: Based on measurements and analyses by H. Edwards et al (1977-1978), the following **LOCAL** energy deposition design limits for the Tevatron **NbTi SC dipole** magnets (4.4 T, I/I_c=0.9, 4.6 K) have been chosen in the Tevatron design report (1979):

1. Slow loss (DC) 8 mW/g (~2 mW/g w/cryo) = 56 mW/cm^3
2. Fast loss (1 ms) 1 mJ/g = 7 mJ/cm^3
3. Fast loss (20 μs) 0.5 mJ/g = 3.5 mJ/cm^3

Proven in 25-year Tevatron operation and numerous studies, calculations and machine improvements over that period.

Justification of QL in 1979-1980 Beam Tests

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Oct 25, 2011

Farewell to the Tevatron

Installation of the world's first superconducting synchrotron began at Fermilab 30 years ago, but now the Tevatron has finally seen its last beam. Roger Dixon looks back at the intriguing story of this pioneering machine.

Towards construction

In 1979, energy-deposition studies were carried out to measure the quench behaviour of two Energy Doubler dipoles in 350 GeV and 400 GeV beam extracted from the Main Ring. These measurements provided an early opportunity to use the MARS Monte Carlo shower simulation software that Nikolai Mokhov wrote at the Institute of High Energy Physics, Protvino, in 1974 and is now widely used for many accelerator and beam-related applications. Mokhov began visiting Fermilab with MARS in 1979. He helped to collect the data from the tests and used his software to determine that a superconducting collider should be feasible. A fixed-target machine was more uncertain; the extraction

LHC Cable Composition and Density

NbTi cable: 90% (0.6 Cu + 0.4 NbTi) + 10% Kapton, density ρ = 7.0 g/cm^3

quench limit (mW/cm^3) = 7×quench limit (mW/g)

Nb3Sn cable: 15.3% Nb3Sn + 15.3% Bronze + 36.7% Cu + 1.2% StSt + 24.4% Ceramic Insulation + 7.1% Epoxy, density ρ = 6.8 g/cm^3

quench limit (mW/cm^3) = 6.8×quench limit (mW/g)

LHC IR Quad Design: Local Quench Limits at $I/I_c=0.8$

LHC IR quads (NbTi):

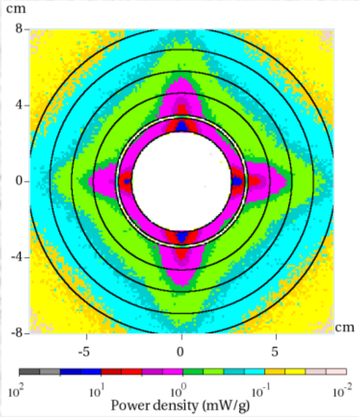
1.41 mW/g (~10 mW/cm^3) DC; design goal 0.47 mW/g (3.3 mW/cm^3)

Used since 10 years ago in design of LHC inner triplets

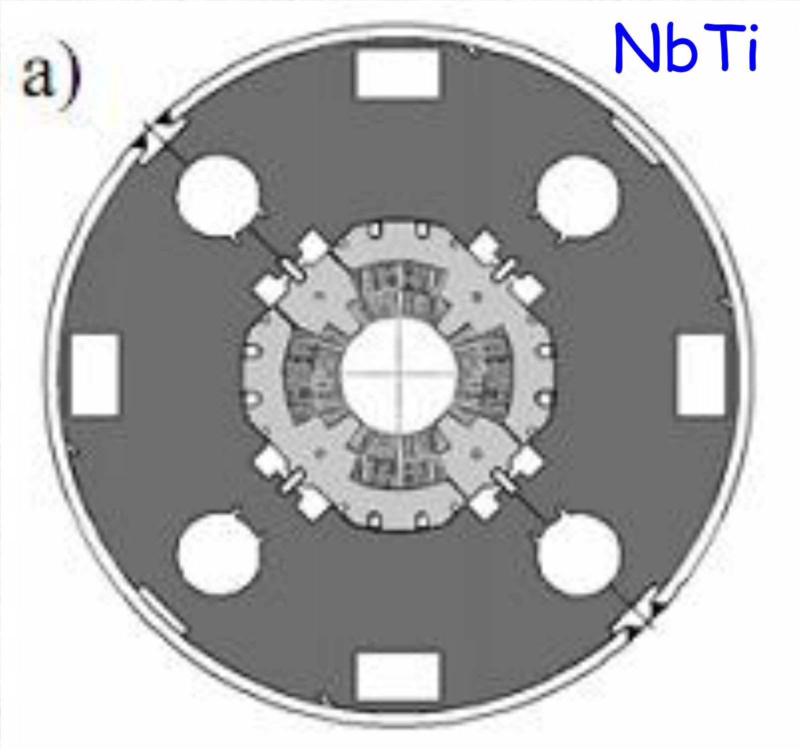
Nb_3Sn IR quads (Nb_3Sn):

5.9 mW/g (40 mW/cm^3) DC; design goal 1.9 mW/g (13.3 mW/cm^3)

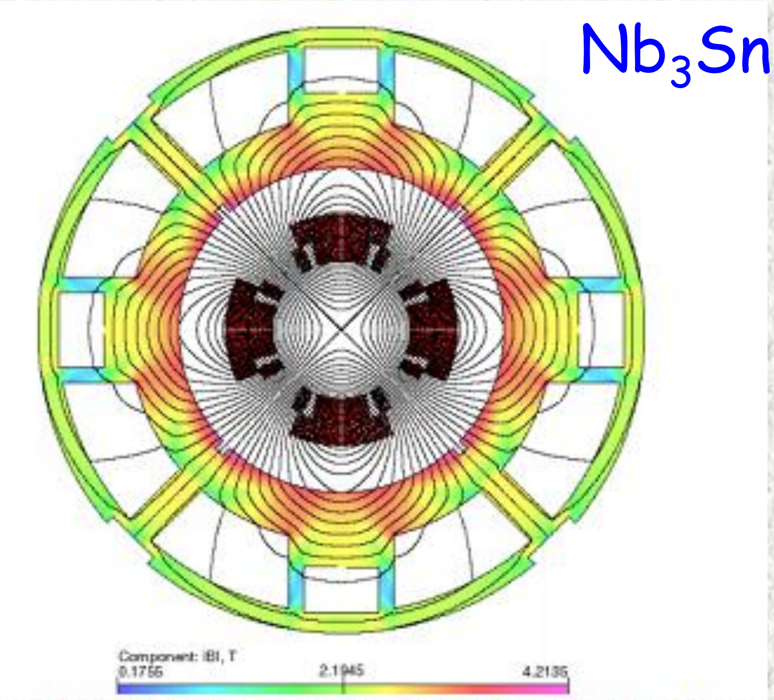
Used currently in our analysis for HL-LHC



FNAL 250 T/m IR Quad Designs (A. Zlobin et al)



70-mm bore, 15-mm wide graded cable insulated with kapton (MQXB).



: Optimized 90-mm quadrupole cross-section.

90-mm bore, 15-mm wide cable insulated with thick S-2 glass epoxy.

In both designs, magnet cold mass (coil, collar and yoke) is cooled with He-II at 1.9K.

MARS15/ANSYS Temperature Profiles

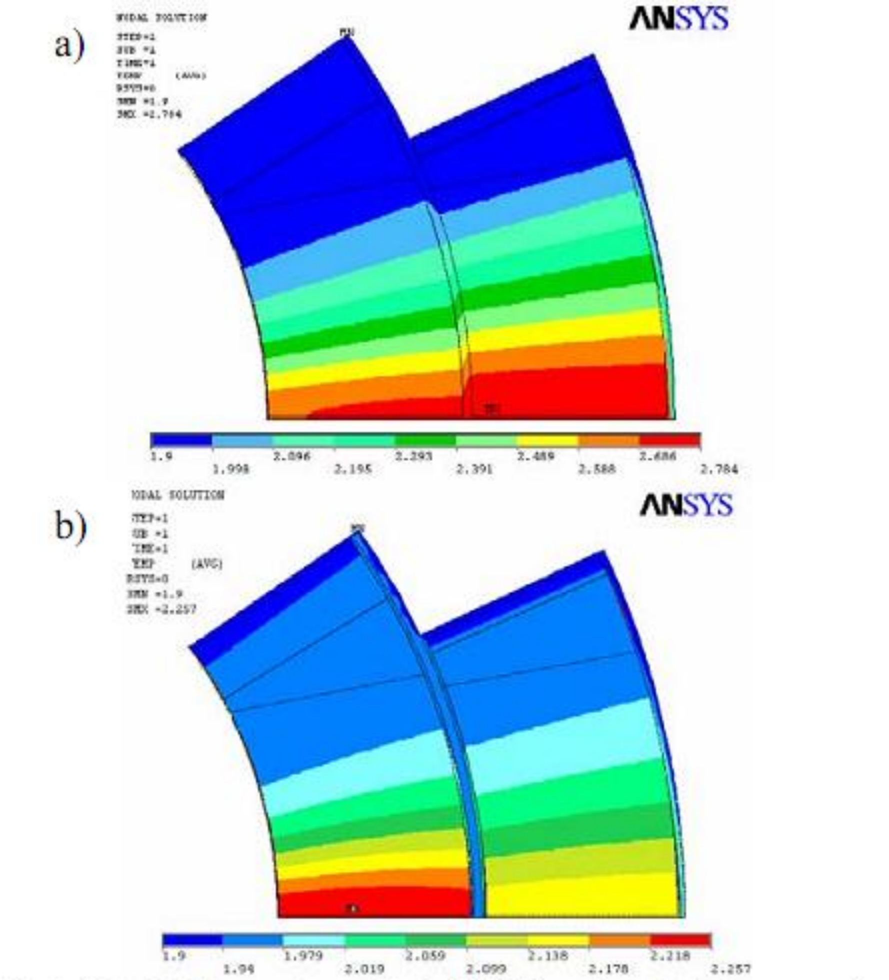


Fig.3. Calculated temperature profile in NbTi IR quadrupole for two cases: a) without and b) with the inter-layer HeII channel. In both cases it is assumed that HeII penetrates inside the collar blocks reaching the coil outer surface.

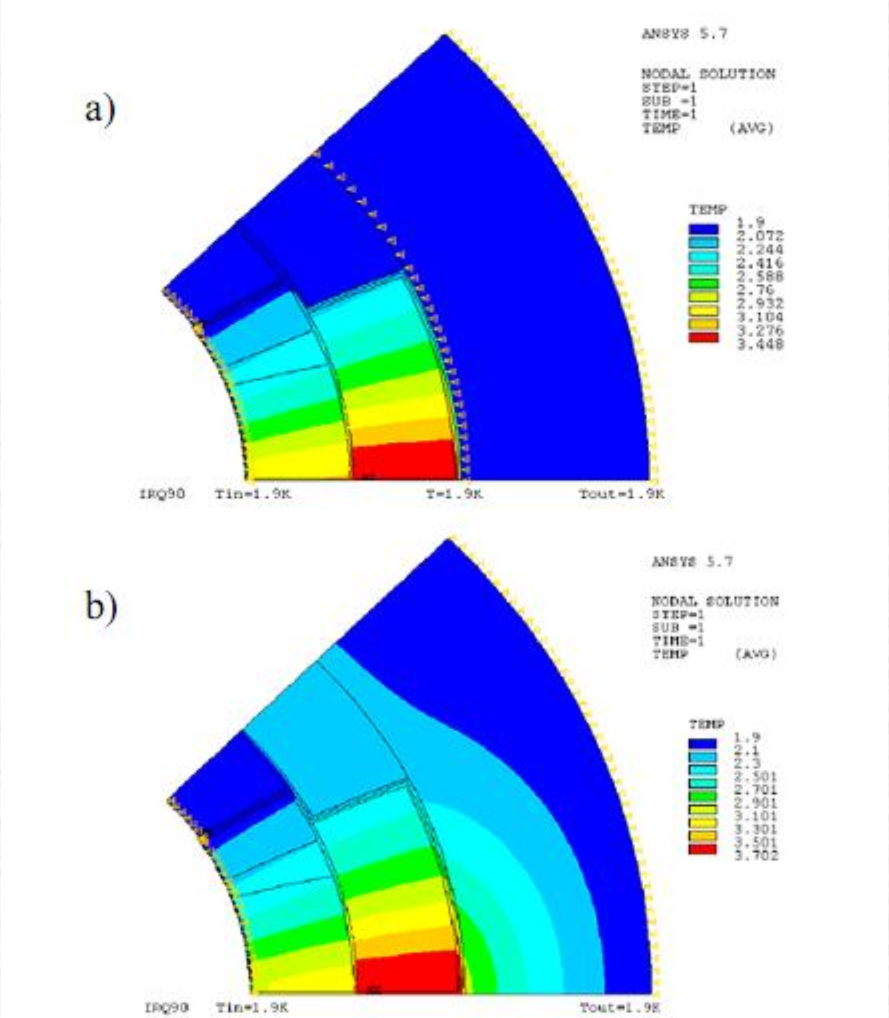
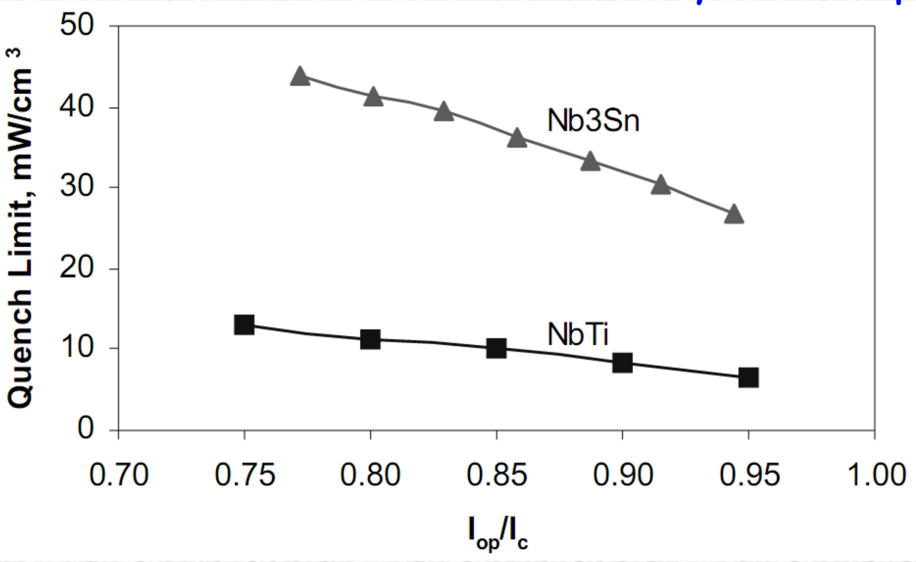
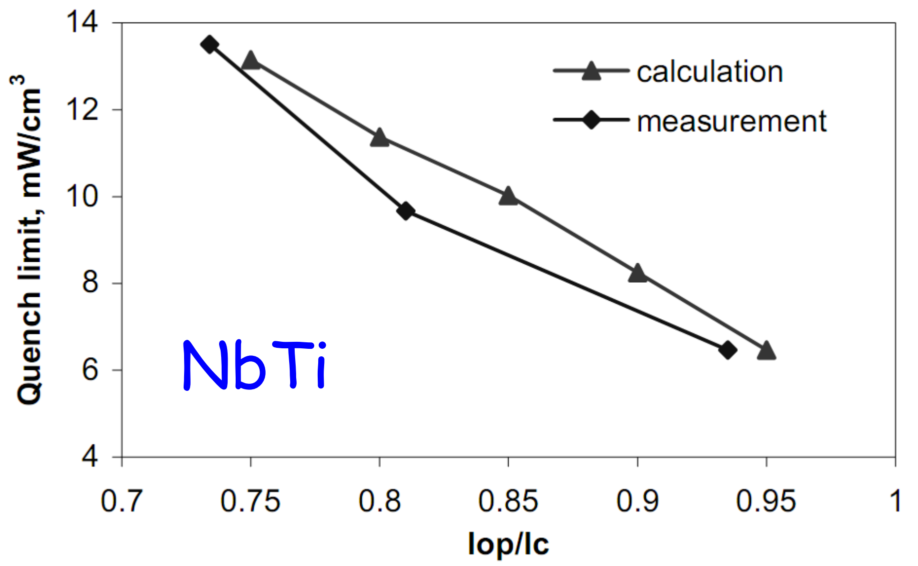


Fig.4. Calculated temperature profile in Nb_3Sn IR quadrupole without the inter-layer channel for two cases: a) HeII penetrates between collars reaching the coil outer surface; and b) HeII does not penetrate inside collar blocks.

Quench Limits at 1.9K in NbTi & Nb_3Sn IR Quads

Inner layer, mid-plane turns





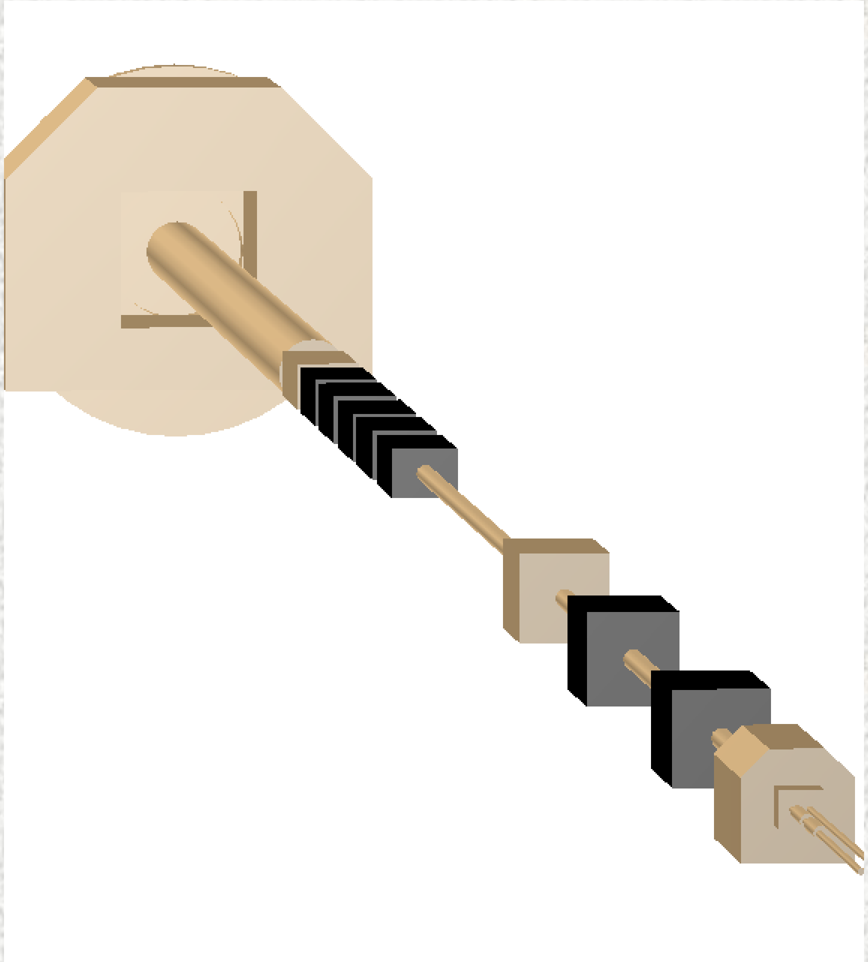
Quench limit (and corresponding magnet operation margin) for Nb_3Sn is ~4 times larger than for NbTi

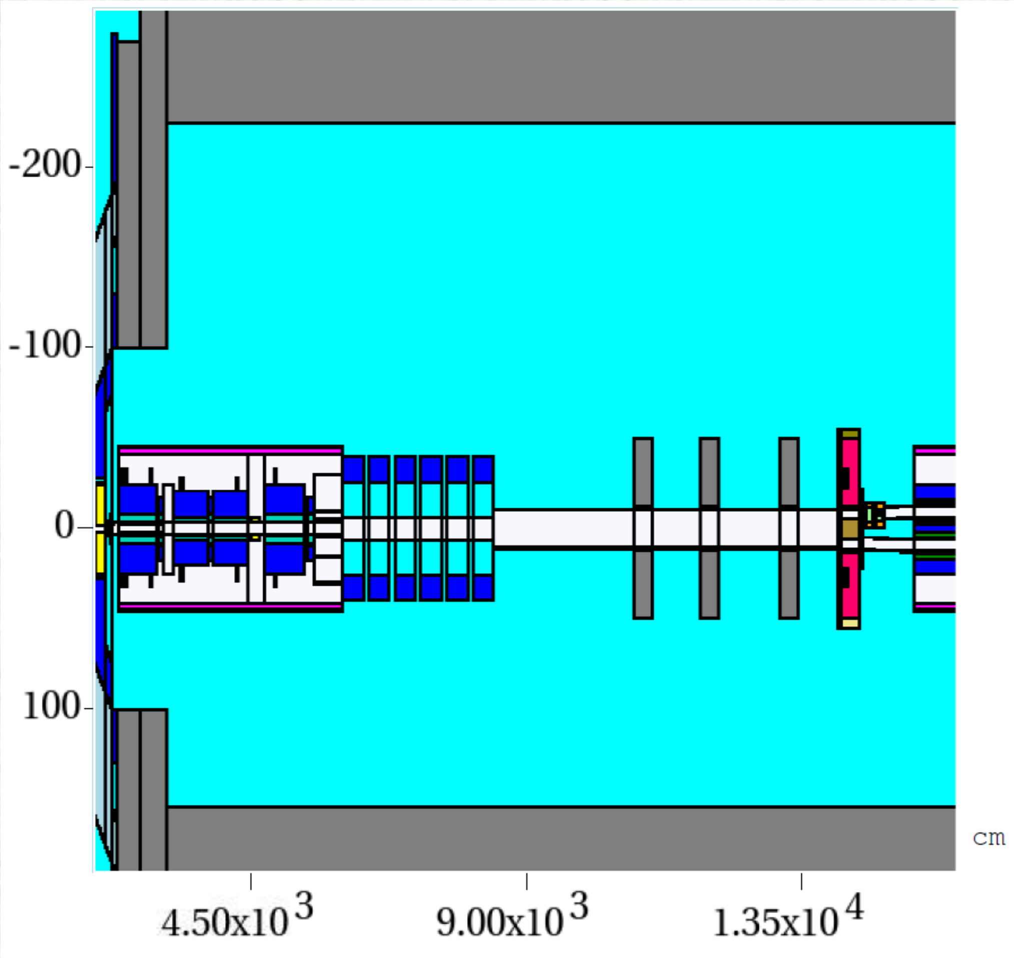
FNAL measurements with special 2-m long **NbTi** quad designed to provide AC loss level and radial profile similar to those calculated for LHC IR quads. Similar measurements were performed with 90-mm **Nb_3Sn** TQ LARP 1-m long quad with mid-plane heaters: same level of agreement between thermal model and data.

LHC IR Protection: Design Constraints

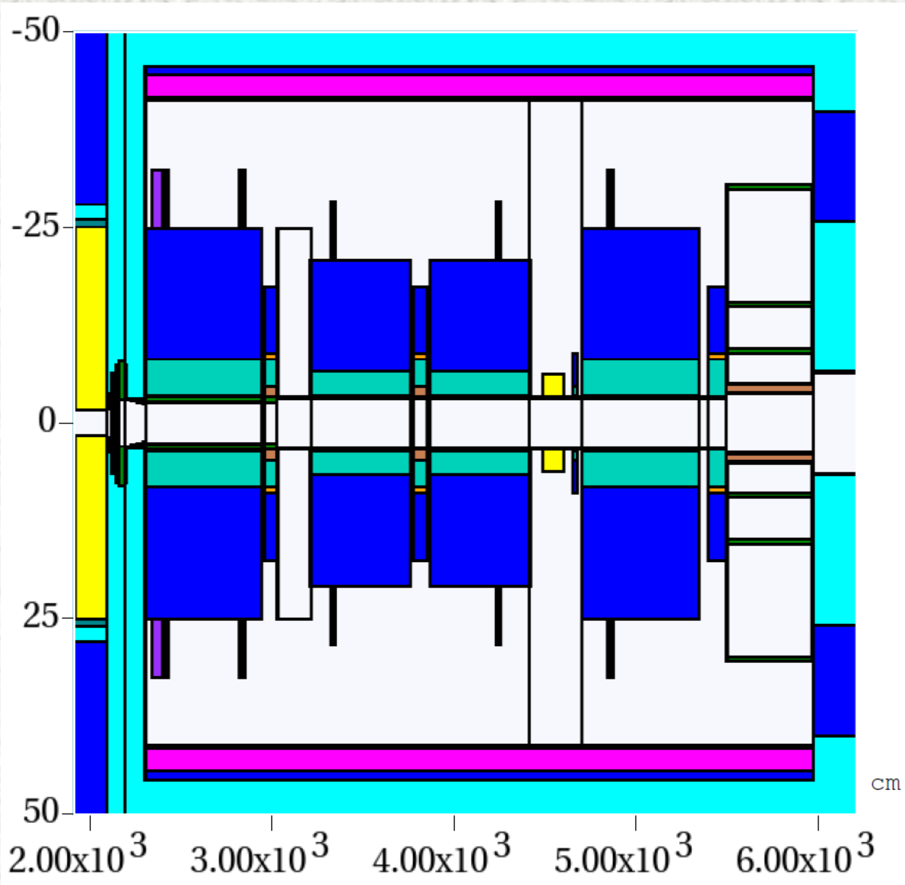
1. LHC: Nominal luminosity of 10^{34} cm^{-2} s^{-1}; HL-LHC: 5×10^{34} cm^{-2} s^{-1}.
2. Geometrical aperture: keep it larger than "n1 = 7" for injection and collision optics, including closed orbit and mechanical tolerances.
3. Quench stability: **keep peak power density ε_{max} (local one in mW/g, never linear loss density in p/m/s or W/m) which can be as much as an order of magnitude larger than the azimuthal average, below the quench limit with a safety margin of a factor of 3.**
4. Quench limit: 1.41 mW/g = 10 mW/cm^3 (NbTi) and 5.9 mW/g = 40 mW/cm^3 (Nb_3Sn).
5. Radiation damage: with the above levels, the estimated lifetime at hottest spots exceeds 7 years (LHC) and TBD (HL-LHC with Nb_3Sn).
6. Most efficient protection is inner absorbers (liners), e.g. with high-Z segments at horizontal and vertical planes, with enlarged coil aperture as a price. Other measures (absorbers in interconnect regions, low-Z inserts in the coils) might be needed, but effect on ε_{max} is modest.
7. Dynamic heat load: keep it below ~20 W/m.
8. Hands-on maintenance: keep residual dose rates on component outer surfaces below 0.1 mSv/hr.
9. Engineering constraints must always be obeyed.

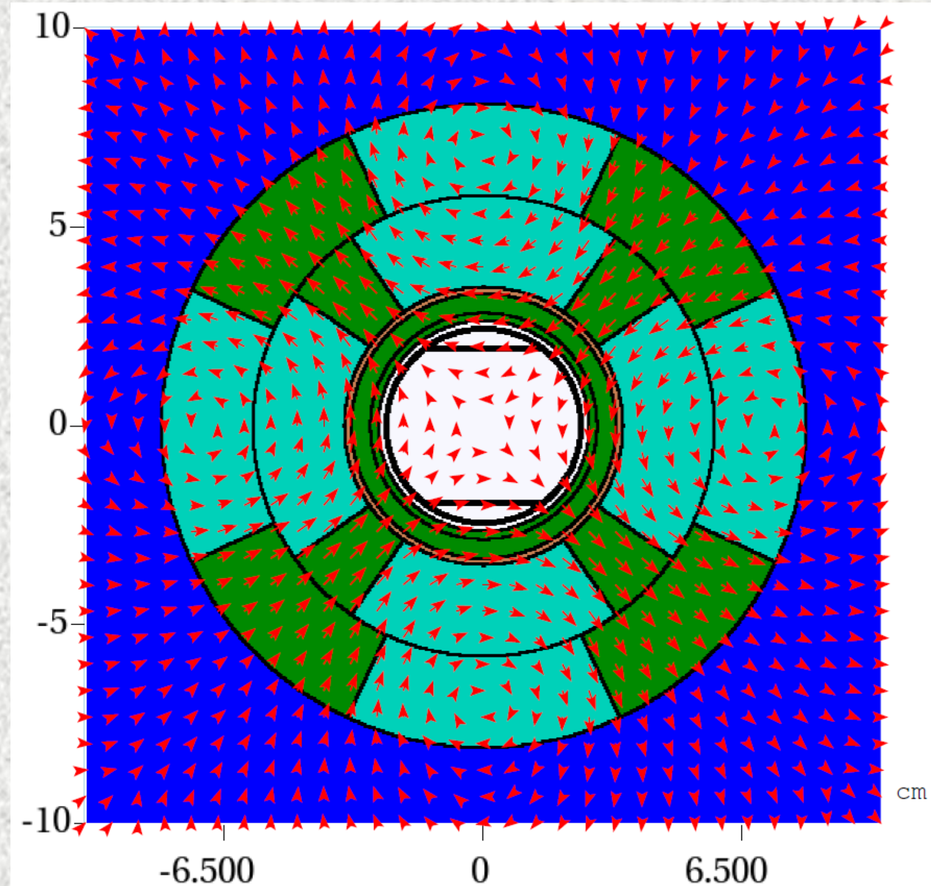
LHC IR5 MARS15 Model





Triplet MARS15 Model

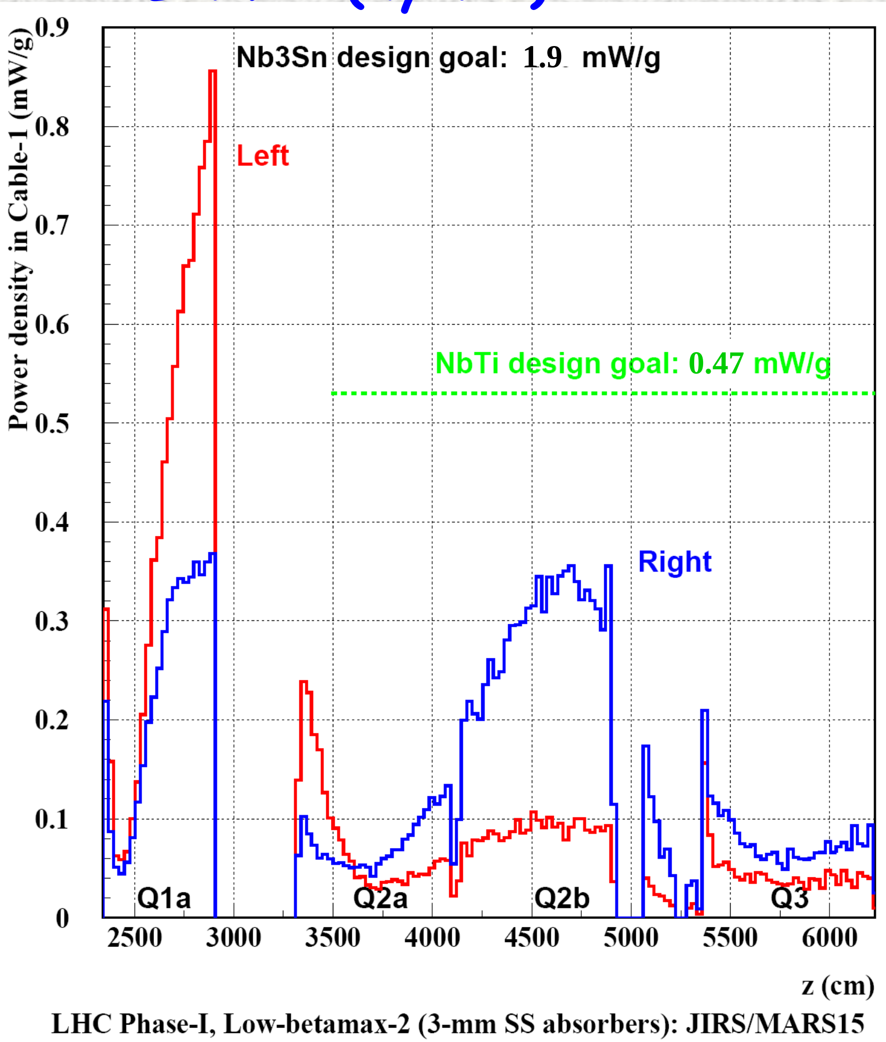




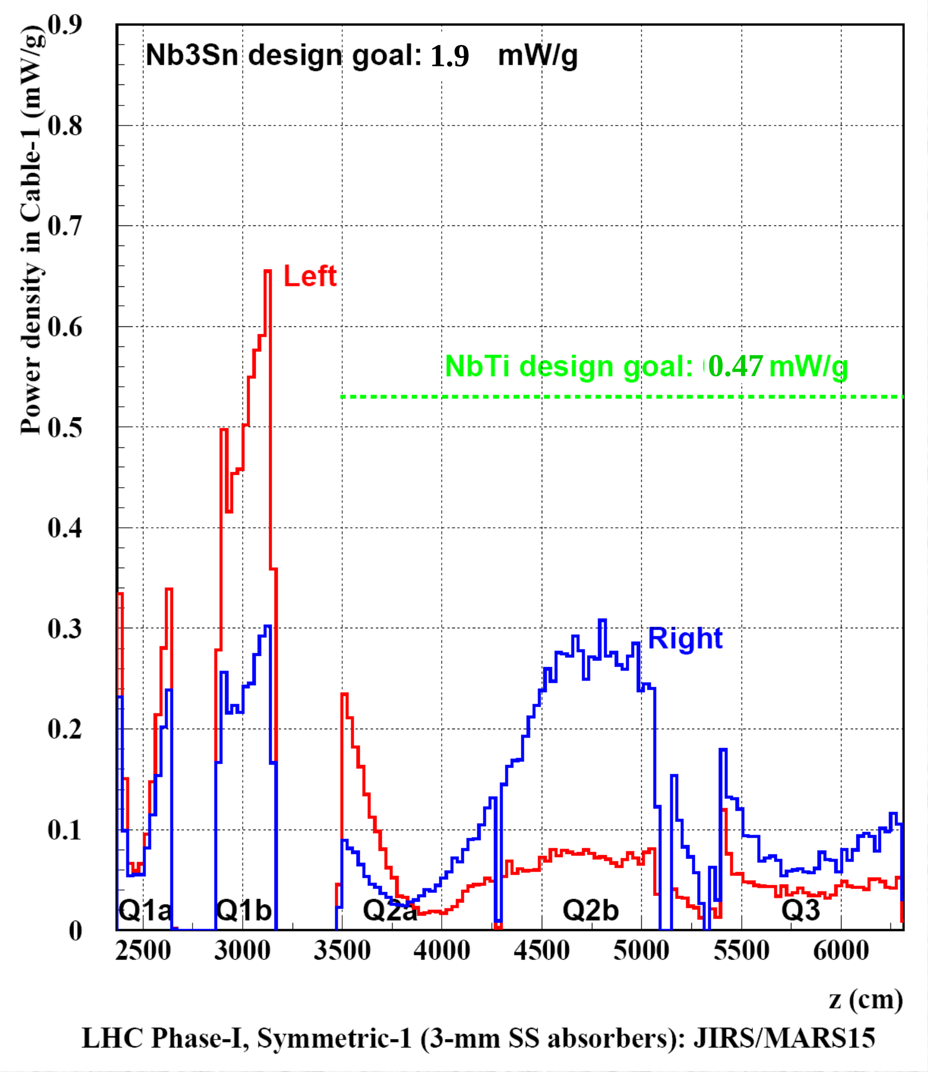
Example of MARS Studies: Peak Power Density in Cable-1 at 2.5×10^{34} cm^{-2} s^{-1}

55-mm aperture TAS

LBM-2 (hybrid)



SYM-1 (hybrid)



Summary

- Local quench limit (QL) approach and values have been proven in 25-year Tevatron operation and numerous studies, calculations and machine improvements over that period.

- QL for **NbTi of 1.41 mW/g** (~10 mW/cm^3) DC, with design goal of 0.47 mW/g (3.3 mW/cm^3) were derived in calculations and measurements with FNAL quads and are used since 10 years ago in design and construction of inner triplet IRs of LHC.

- QL for **Nb_3Sn of 5.9 mW/g** (40 mW/cm^3) DC, with design goal of 1.9 mW/g (13.3 mW/cm^3) were derived on the basis of thermal analysis of LARP IR quads and are currently used in our studies for HL-LHC.