LARP

Nb3Sn Accelerator Magnet R&D and LHC Luminosity Upgrades

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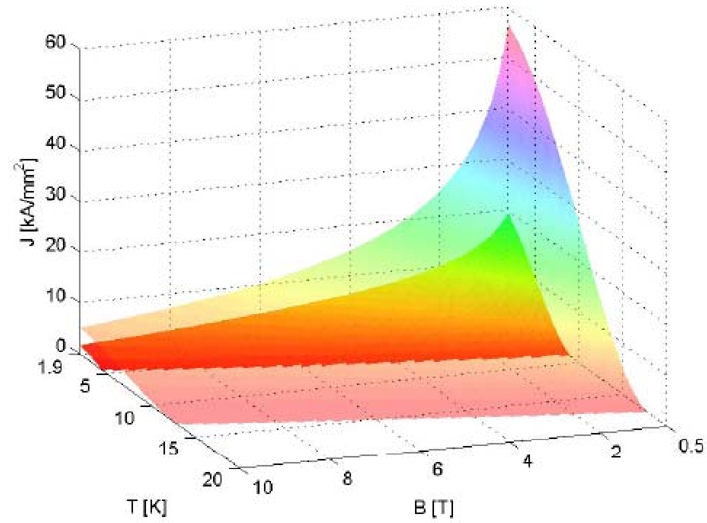
Fermilab

Introduction

- **Nb3Sn magnets provide**
  - **higher fields – Bc2~27 T**
  - **Higher temperature margin – Tc~18 K**
  - **More efficient coil – high Jc**
- **Possible applications:**
  - **LHC upgrades, critical ILC components, MC magnet systems, future HC, etc.**



- **During past 15 years Nb3Sn accelerator magnet R&D was centered in U.S.**
  - **since 2003 it is coordinated by US-LARP**
- **Nb3Sn is brittle material => new coil fabrication techniques**
  - **special attention to coil handling, assembly and operation.**
- **Fermilab's Nb3Sn Program focuses on shell-type coils, the W&R method, new and traditional mechanical structures.**
- **The primary goal - new generation IR quadrupoles for the planned LHC luminosity upgrades**

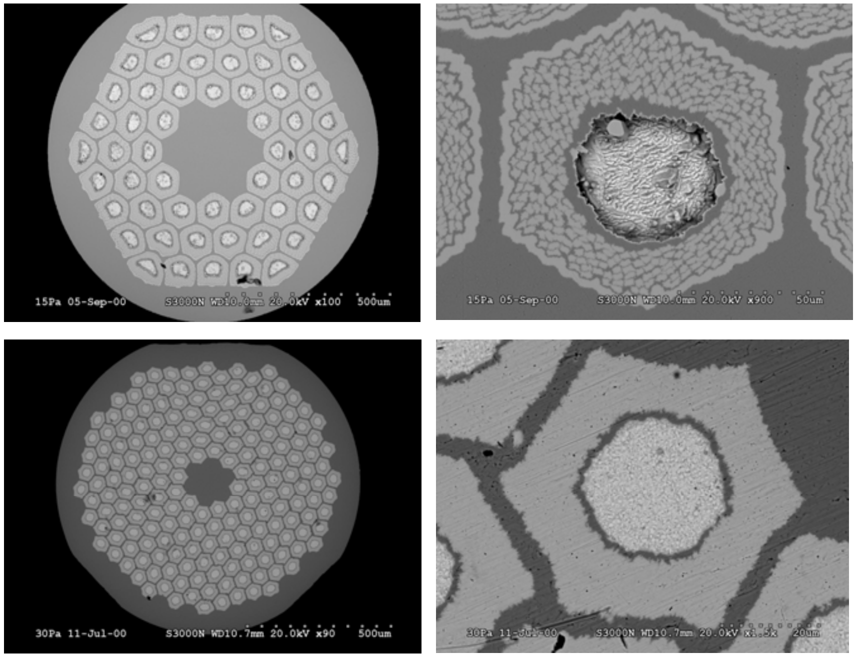
Outlines

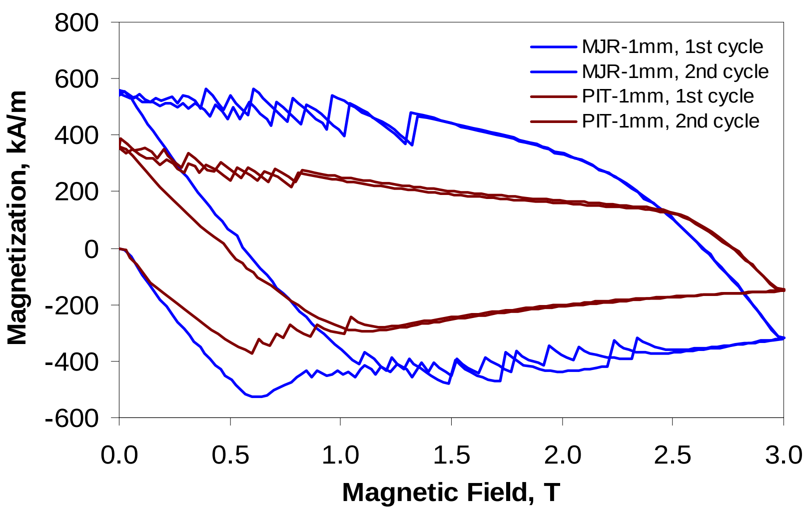
- **Nb3Sn Accelerator magnets**
  - **Strands and cable**
  - **Coils**
  - **Mechanical structures**
  - **R&D issues**

- **Technology development and demonstration**
  - **Short model R&D**
  - **Nb3Sn technology scale up**
  - **Issues and next steps**

- **Nb3Sn IRQ for the LHC upgrade**
  - **Phase I and Phase II**

Nb3Sn Strands





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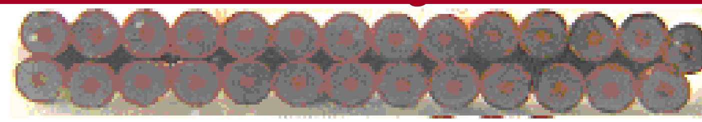
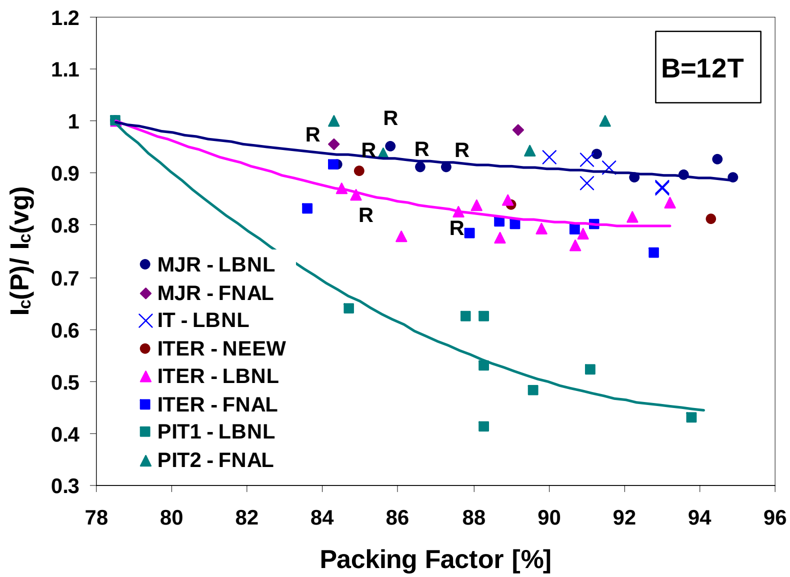
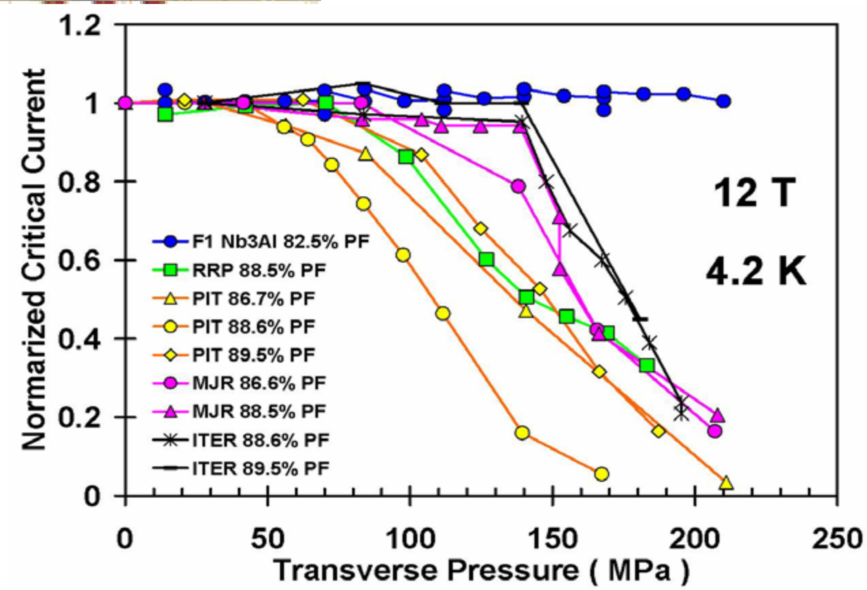
- **Two basic technologies of high-Jc strands**
  - **IT – MJR, RRP (OST, U.S.)**
  - **PIT – (ESC, EU)**
- **Strand properties**
  - **High Jc**
  - **Relatively large deff**
- **Issues**
  - **Large magnetization**
  - **Flux jumps**
- **Effect on magnet performance**
  - **quench performance**
  - **field quality**

Nb3Sn Rutherford Cable





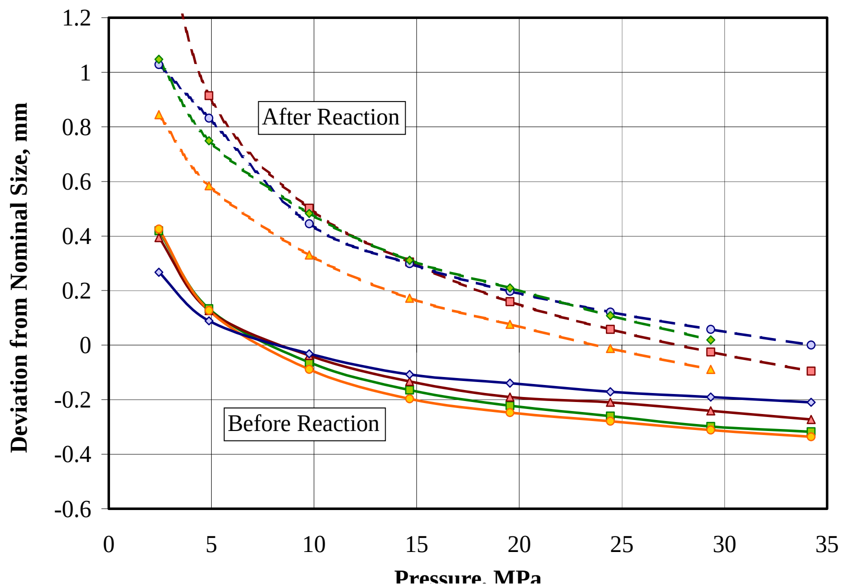


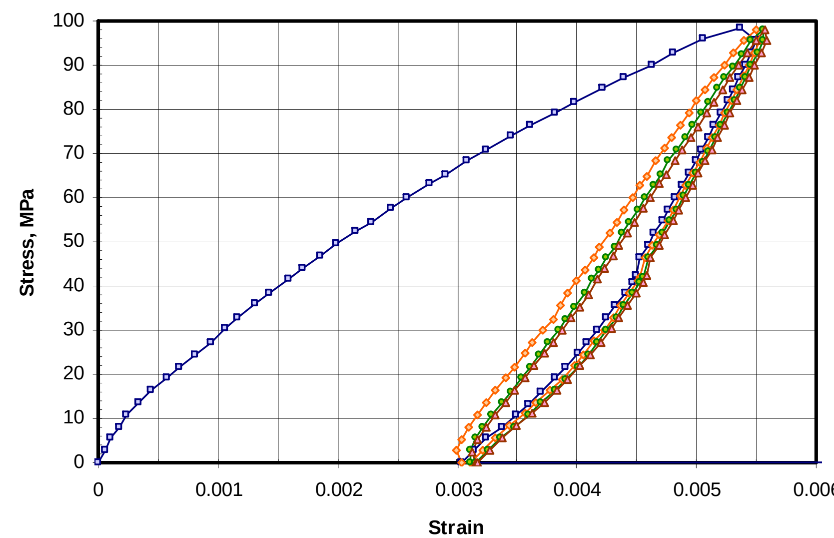
Nb3Sn Rutherford cable issues:

- Ic degradation due to plastic deformation=>low packing factor=>cable mechanical stability=>coil winding
- Sub-element deformation/breakage/merging during cabling=>deff and RRR=>flux jump instabilities
- Ic degradation due to transverse pressure=>coil pre-stress limit
- Strand sintering during reacting=>low interstrand resistance=>field quality, quench performance

Nb3Sn Coils

- **Coil fabrication technology**
  - W&R method
  - special high-temperature insulation
  - metallic coil components
  - ceramic binder
  - coil vacuum impregnation with epoxy
- **Issues**
  - Conductor expansion after reaction=>coil geometry
  - Coil plasticity=>coil size measurement, coil pre-stress
- **Impact=>magnet geometry and pre-stress**
  - Quench performance
  - Field quality
  - Scale up

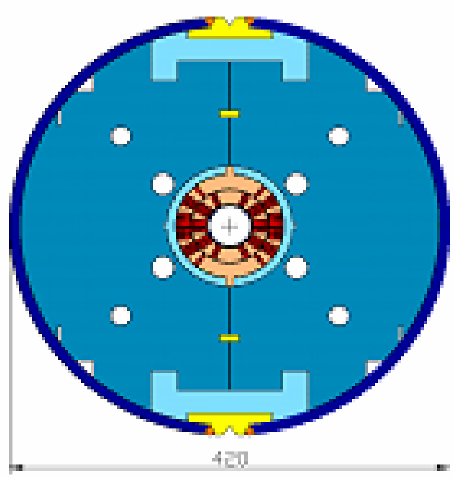


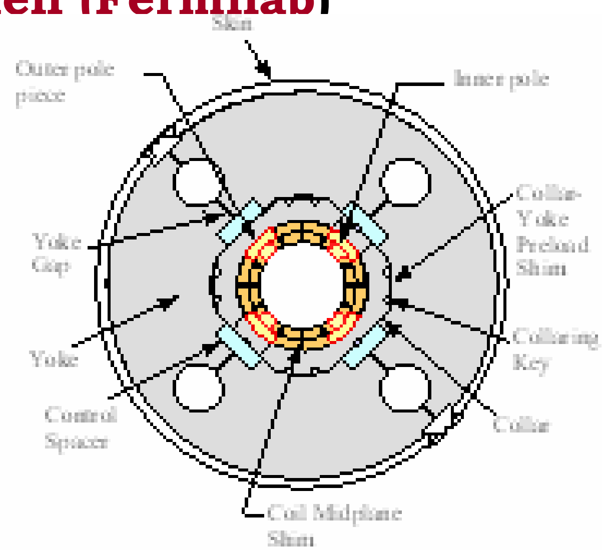


Mechanical Structures

- **Structures**
  - **The traditional collar-based structure**
  - **Shell-type structures - SS or Al shells**
  - **Hybrid**
- **Issues**
  - **safe coil pre-stress up to high stress (~150 MPa)**
  - **radial and axial support**
  - **precise geometry and alignment**

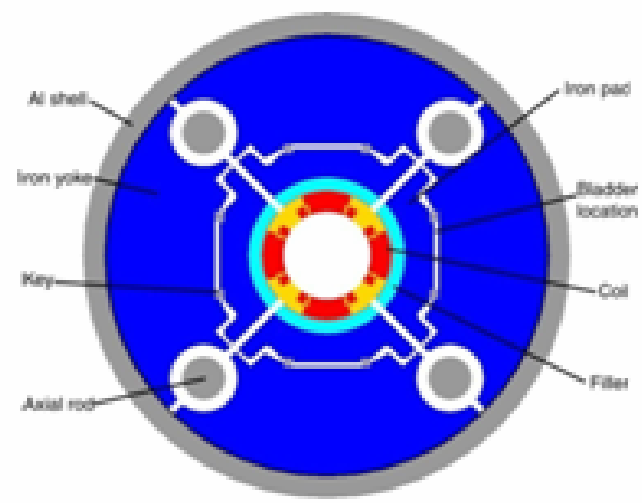
Stainless Steel Shell (Fermilab)





Hybrid - SS collar and Shell

Aluminum Shell (LBNL)



R&D Issues

- **Strand Jc, magnetization, stability**

- **Sub-element deformation/breakage/merging during cabling**
- **Ic degradation due to transverse pressure**
- **Interstrand resistance control**

- **Coil fabrication, geometry control, mechanical properties**

- **Coil pre-stress and support with mechanical structure**

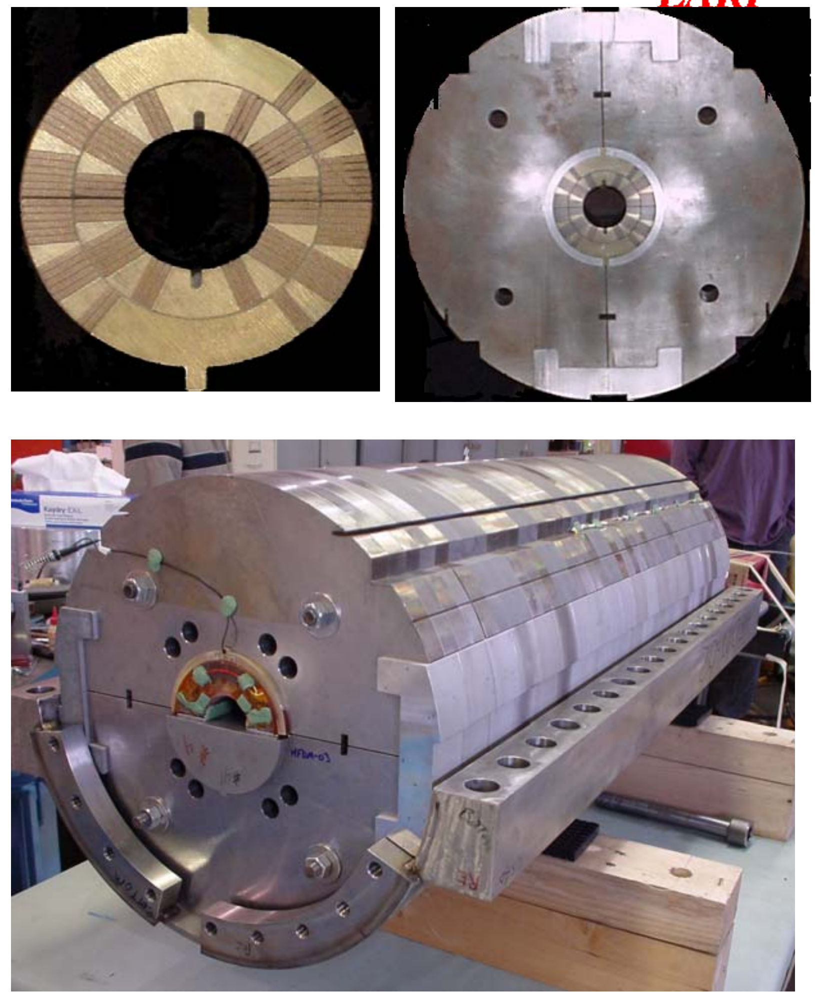
Dipole Models

Nb_3Sn dipole models (HFDA):

- **Compact mechanical structure**
- **High-J_c 1-mm Nb_3Sn strand**
- **27-28 strand cable**
- **2-layer coil**
- **43.5-mm diameter bore**
- **Maximum field ~12 T at 4.5 K**

Magnetic mirror (HFDM):

- **The same mechanical structure and assembly procedure**
- **Advanced instrumentation**
- **Shorter turnaround time**
- **Lower cost**



HFDA dipole & HFDM mirror

Technology Quadrupoles (TQ)

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LARP Technology quadrupole (TQ):

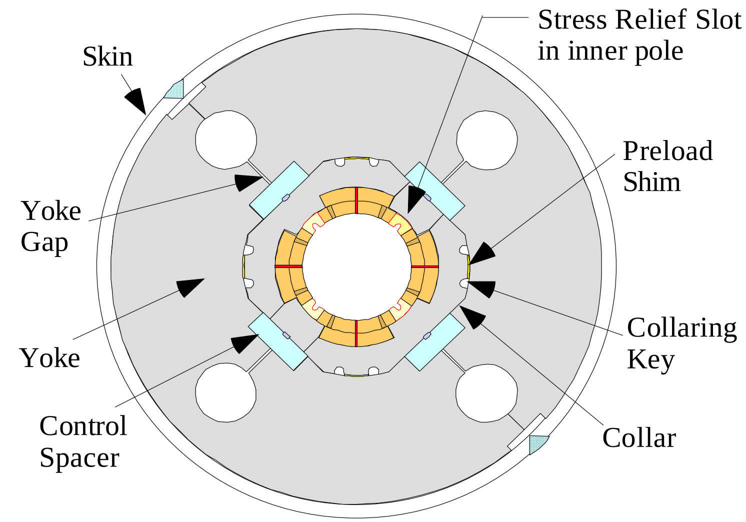
- **TQC - Hybrid mechanical structure (collar, yoke, SS skin)**
- **TQS – Al shell based structure**

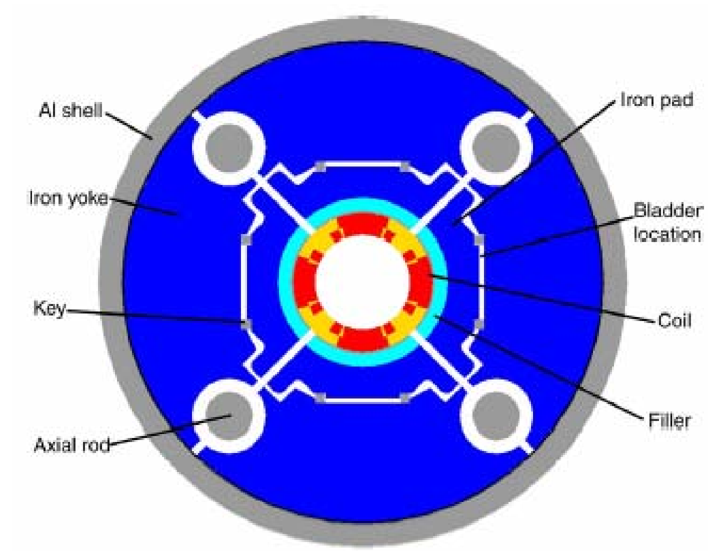
❖ Design features:

- **same two-layer coil design and technology**
- **same Nb3Sn strand and cable**
- **High-J_c 0.7-mm Nb_3Sn strand**
- **27 strand cable**
- **2-layer coil**
- **90-mm diameter bore**

❖ Design parameters

- **Gmax~230/250 T/m at 4.5/1.9 K (Bmax~12-13 T)**

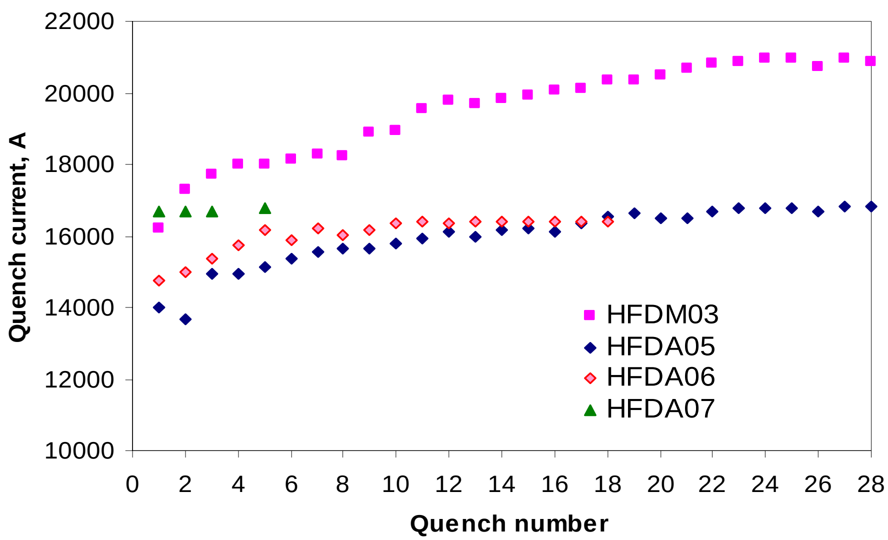


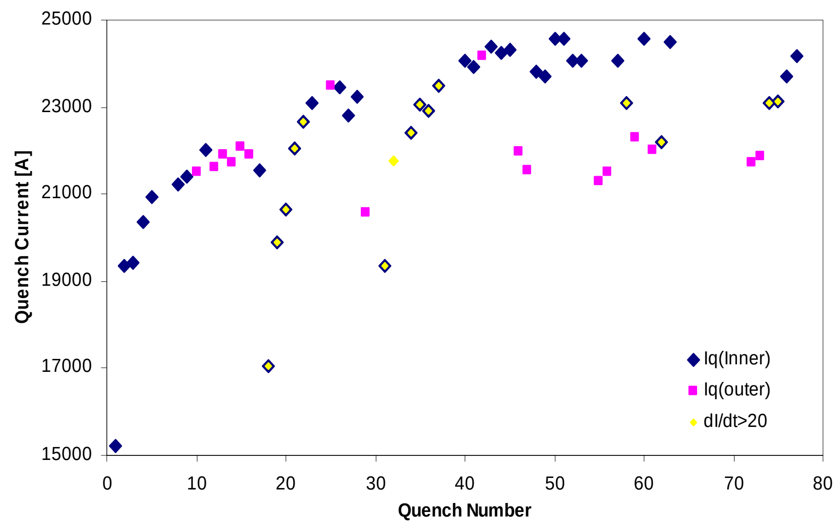


Dipole Model Quench Performance

6 short dipole and 6 mirror models were fabricated and tested

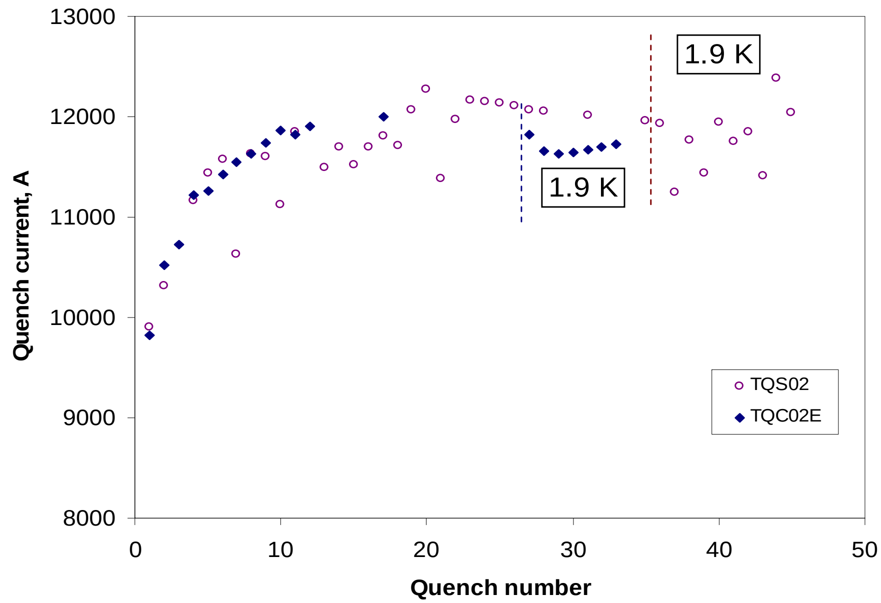
- **Models with 1-mm MJR-54/61 strand => flux jump limitations.**
- **Models with 1-mm PIT-196 strand, reached 9.4 T @4.5K and ~10.2 T @2.2K (100% of PIT strand SSL).**
- **Dipole mirror model with 1-mm RRP 108/127 strand, reached ~11.4 T at 4.5 K (97% of SSL)**
  - **instabilities at ~21kA**
- **General features**
  - **Training starts at ~80% of magnet Short Sample Limit (SSL)**
  - **Quite long training**

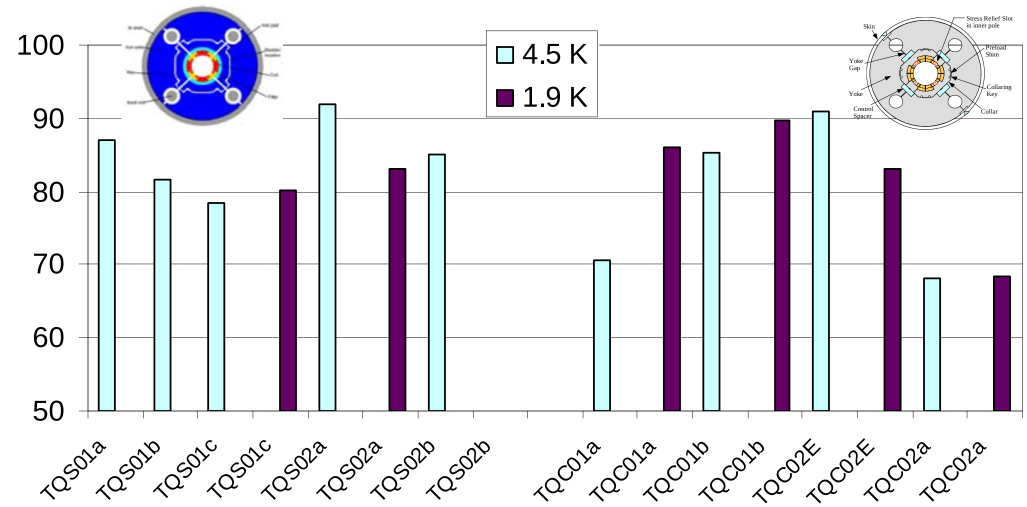




TQC Quench Performance

- 4 TQC and 5 TQS models
  - MJR 54/61 - low Jc strand
  - RRP 54/61 - high-Jc strand
- Performance
  - MJR models: Gmax~200 T/m at 1.9 K
  - RRP models: Gmax~200-215 T/m at 4.5 K
- TQC and TQS comparison:
  - Quite long training (similar to dipole models)
  - ~10% or higher degradation at 4.5K
  - Flux jumps in models made of high-Jc RRP strands

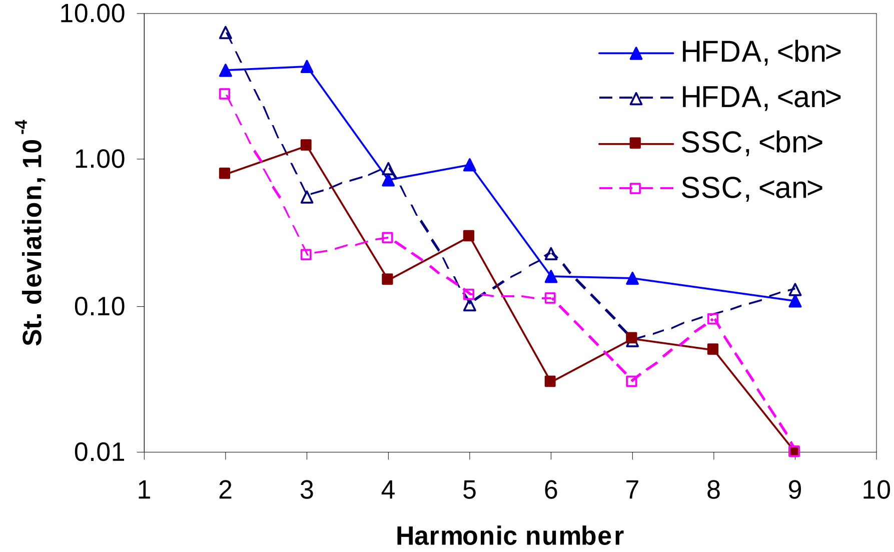


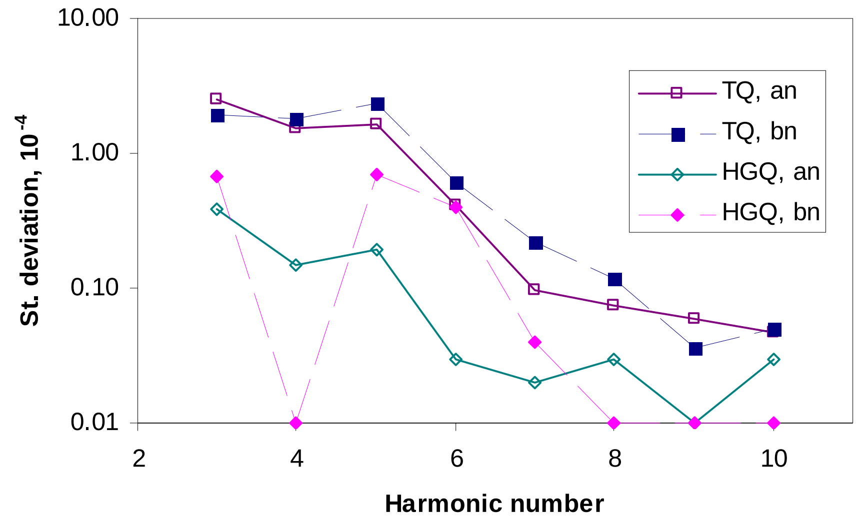


Field Quality

- **6 HFDA models vs. first 6 40-mm SSC dipole models**
- **4 Nb3Sn TQ (TQC and TQS) models vs. NbTi HGQ models.**
- **Field harmonics are still larger in Nb3Sn models**

  <= new technology
- **The geometry and alignment of Nb3Sn magnets need to be improved**





Coil Magnetization Effects

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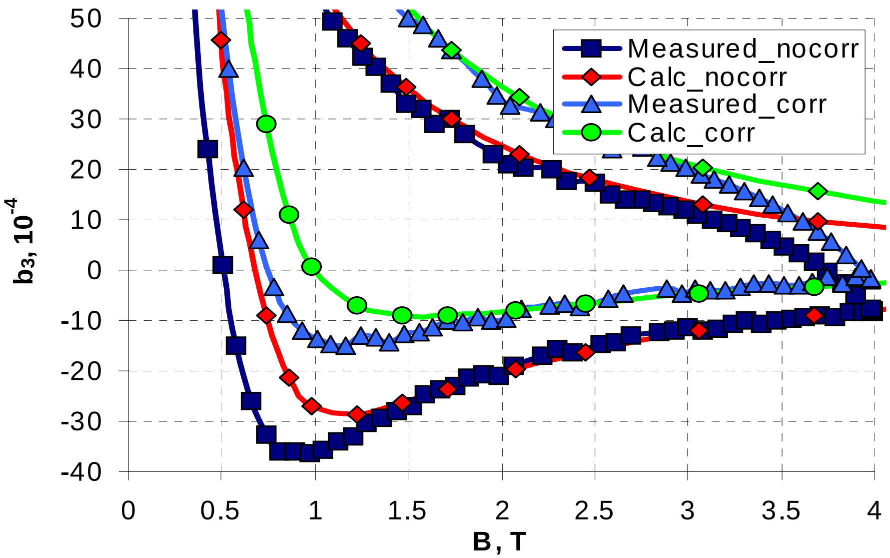
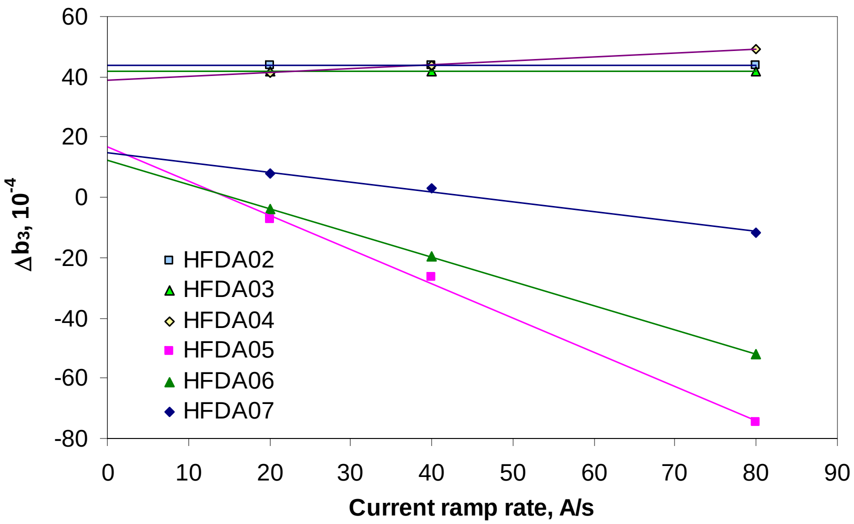
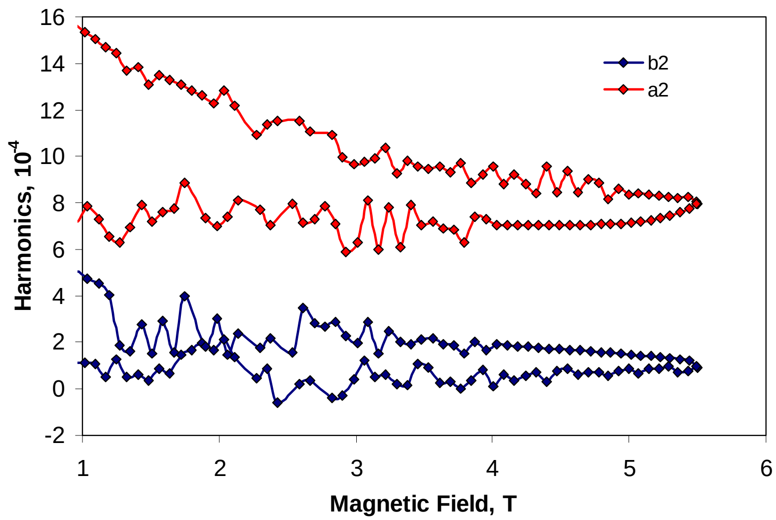
- **The persistent current effect is large but reproducible**
- **flux jumps in low order harmonics in dipole models**

  => smaller Deff
- **Passive correction to reduce the persistent current effect**
- **Large variations of the eddy current components**

  => cable with a SS core







Short Model R&D Summary

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- **Coil production:**
  - **20 dipole and 29 quadrupole 1-m long coils**
    - Good size reproducibility
    - Short fabrication time (comparable with NbTi technology)
- **Robust mechanical structures**
- **Handling and testing:**
  - **6 dipole models, 6 dipole mirror models, and 9 LARP TQ models based on different mechanical structures**
  - **Multiple reassembly without degradation**
  - **Coil and magnet transportation across the country**
- **The possibilities and present limitations of accelerator field quality in Nb_3Sn dipoles and quadrupoles were demonstrated**
- **Issues => quite long training, degradation, reproducibility**
- **Solution => improve or provide larger margin (10%degradation+20%training)**

Nb3Sn Technology Scale Up

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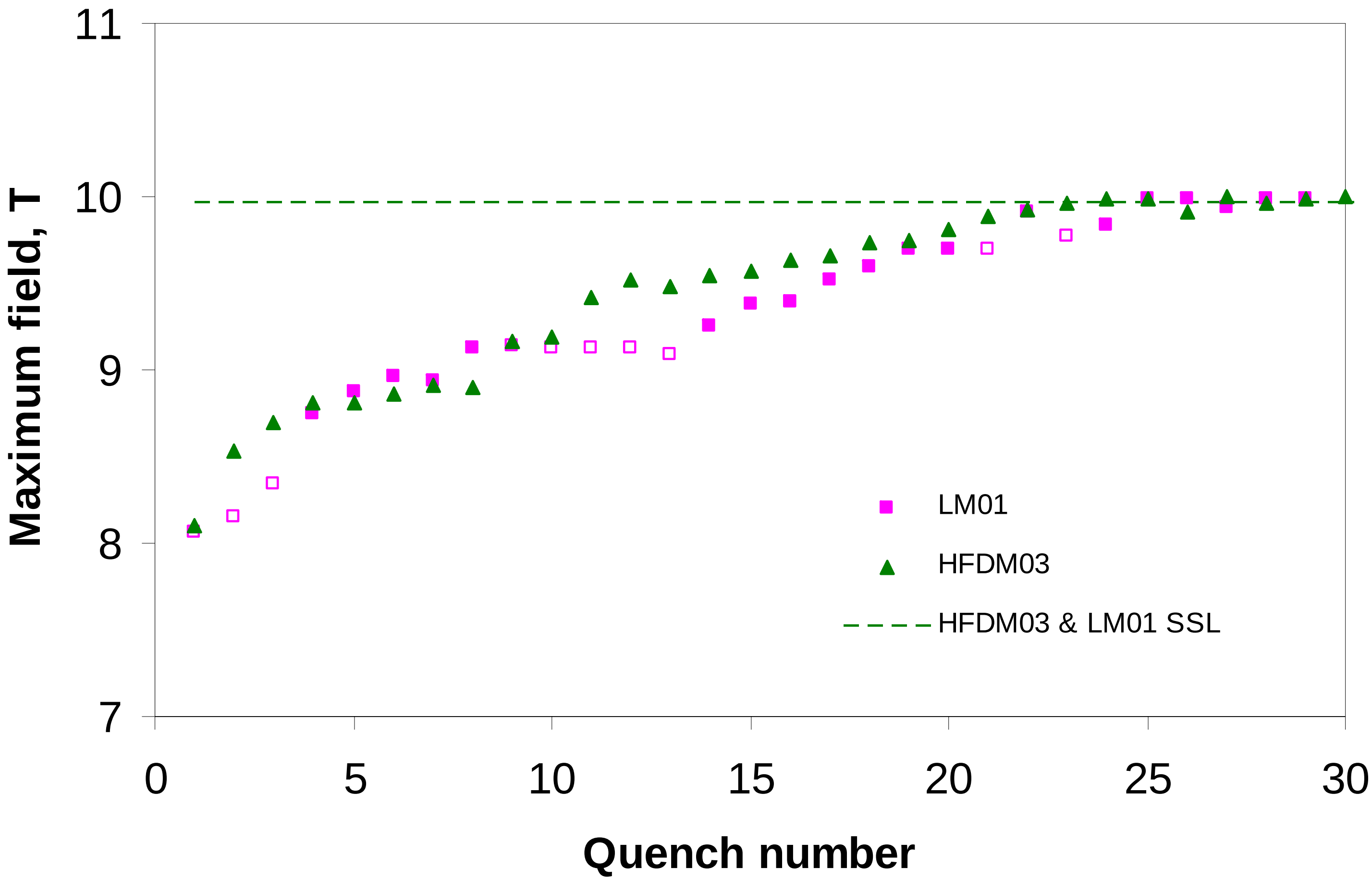
- **Nb3Sn accelerator magnet technology scale up was successfully started**
- **Goals:**
  - **Long Nb3Sn coil winding, curing, reaction, impregnation, handling, magnet assembly and testing procedures**
  - **Infrastructure for LARP and future LHC upgrade project**
  - **Long coil performance**
- **Stages:**
  - **2-m long cos-theta coil (Fermilab, June 2007)**
  - **4-m long racetrack coils (BNL/LBNL, July 2007-February 2008).**
  - **4-m long cos-theta coil (Fermilab, December-January 2008)**
- **Next step:**
  - **LARP 4-m long quadrupoles of TQ series (BNL/FNAL/LBNL, 2009).**

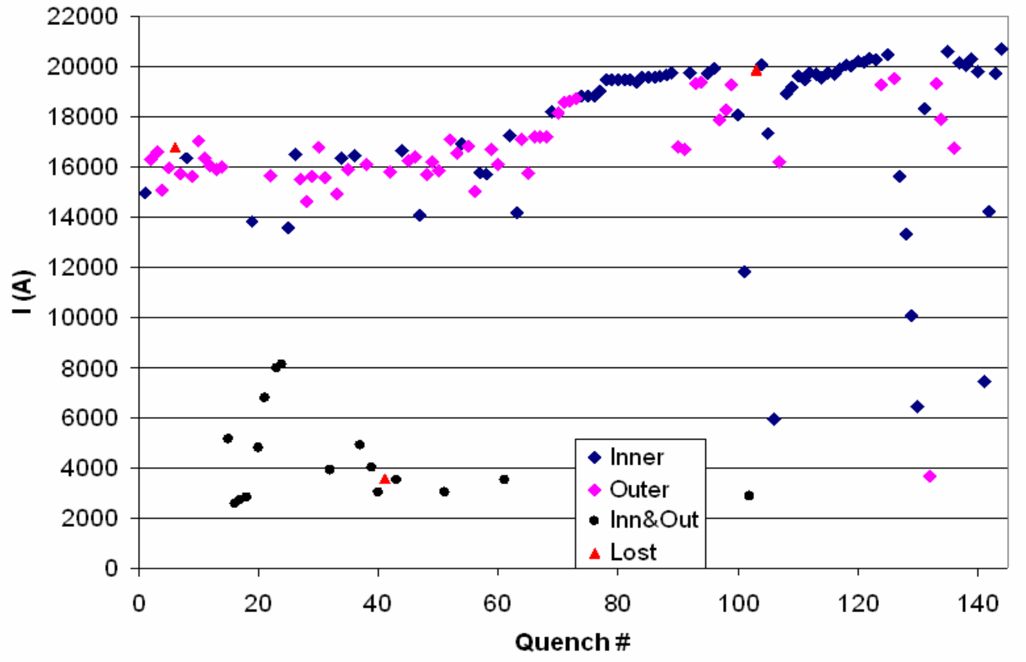
2-m Long Nb3Sn Coil Performance (PIT)

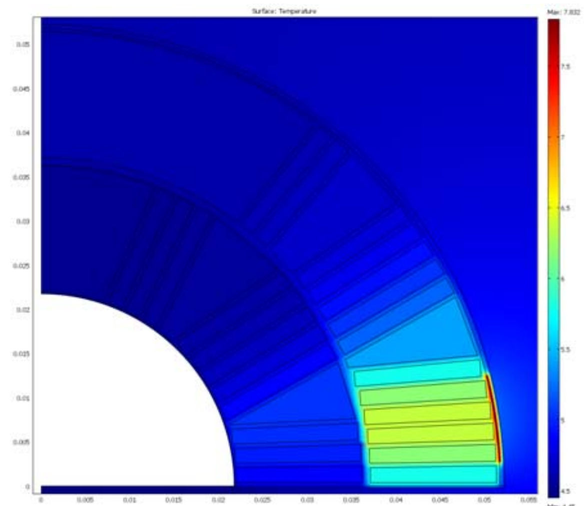


- **1-m and 2-m long PIT mirror models reached their SSL**
  - **identical quench performance typical for Nb3Sn magnets**

4-m Long Nb3Sn Coil Performance (RRP)

LARP





- ❖ **4-m long RRP mirror:**
  - o **Flux jump instabilities at I~16kA (comp. with ~21kA in short mirror)**
  - o **Imax~90% of SSL at 4.5 K (97% in short mirror)**
    - ▪ training was not finished
- ❖ **4-m long RRP racetrack (BNL):**
  - o **Imax~96% of SSL at 4.5 K <= simpler mechanics, low coil pre-stress**
  - o **Flux jumps caused few low-current quenches**

Scale Up Summary

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- All coils survived the quite complicate fabrication process and assembly with long mechanical structures
- Possibilities and present limitations of the long coil quench performance were demonstrated
- Issues
  - long training, some degradation similar to short models => Flux jump limitations
- Solution
  - improve or provide larger margin (10% degradation + 20% training)
- The optimization and use of more stable high-Jc RRP strand is critical for magnet performance improvement.
- Next steps:
  - Field quality and alignment
  - Long term performance

Nb3Sn Strand Improvement (OST)

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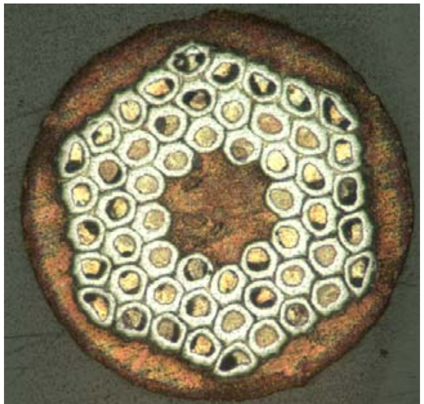
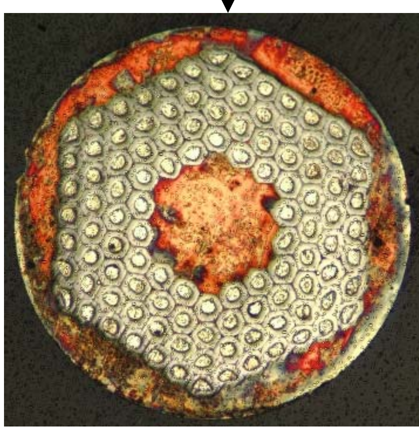
- Increase sub-element number without losing Jc, RRR
  - o improve stability
- Sub-element number and layout optimization
  - o reduce SE deformation and damage
  - o increase Cu/nonCu ratio



61 stack

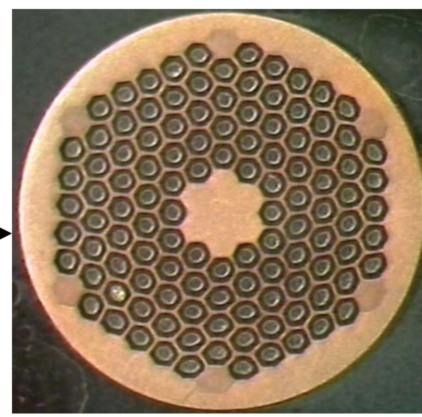
Increase SE Number

127 stack

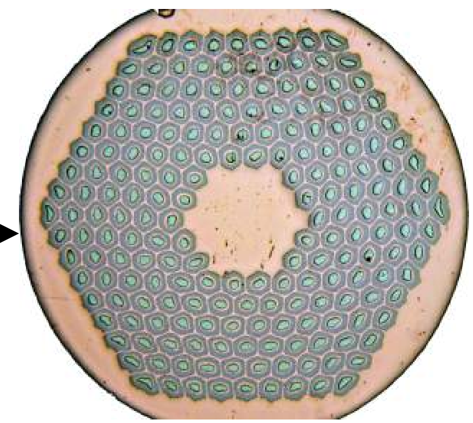


Increase SE Spacing

127 stack, spaced



217 stack, spaced



LHC Upgrade phases

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❖ Baseline LHC inner triplets:

- Lnom=10^{34} cm^{-2} s^{-1}
- β^*=0.5 m
- 70 mm NbTi IR quadrupoles
- 205 T/m nominal gradient with 20% margin
- 1.9 K operating temperature
- Limitations: aperture, operation margin, lifetime

❖ Phase I (~2012-2013):

- L~2.5×10^{34} cm^{-2} s^{-1}

❖ Phase II (TBD, ~2018?):

- L~10×10^{34} cm^{-2} s^{-1}

Phase II

- **Phase II: L~10×10^{34} cm^{-2} s^{-1}**
  - **Stronger focusing**
  - **Higher beam intensity**
  - **Crab cavities or D0 to reduce effect of crossing angle**
  - **=>Large aperture strong Nb_3Sn quadrupoles**
- **LARP studies (2002-2006):**
  - **100-mm quads with a tungsten liner are compatible with β^*~0.25 m and L~10×10^{34} cm^{-2} s^{-1}**
    - T. Sen, N. Mokhov et al.
  - **coil bore limit for Nb3Sn quadrupoles for Gnom=205 T/m + 20% margin is 110 mm**
    - V. Kashikhin, A. Zlobin et al.
  - **110 mm quadrupoles may be sufficient to achieve Phase II goals (to be confirmed)**
- **Studies will continue by JIRS group**

Phase I

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- **Phase I (~2012-2013): L~2.5×10^{34} cm^{-2} s^{-1}**
  - **Stronger focusing (β^*=0.25 m)**
  - **Reduce some limitations on intensity due to collimators**
  - **Large aperture Nb-Ti quadrupoles with available LHC cable.**
- **Two preferable optics:**
  - **Lowbetamax (LBM) and Symmetric**
    - R. de Maria, J-P. Koutchouck, E. Todesco et al.

	Lowbetamax			Symmetric		
	Q1	Q2	Q3	Q1	Q2	Q3
Aperture, mm	90	130		130		
Magnetic length, m	7.4	17.1	9.8	9.2	15.6	9.2
Nominal gradient, T/m	168	122		122		
Margin, %	20					
Nominal current, kA	12.5					
Field quality at Gnom, 10^{-4}	<1					

Nb3Sn Magnet Options

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Nb3Sn magnets: slot and operation current compatibility

Larger aperture => more complicate magnet => larger risk => …

- **TQ: insufficient margin, difficulties with quench protection**
- **130-mm options: complicate magnets with limited technical benefits for LHC performance**
- **IRQ-90 with 15 mm cable: Q1 option for Phase I with LBM optics**
  - **A. Zlobin et al., EPAC'2002, ASC'2002**
- **IRQ-110 options: Q1 or Q3 in Phase I with both LBM or Symmetric optics, consistent with Phase II magnet parameters**

	TQC-90	IRQ-90	IRQ-110	IRQ-130	HQ-130
Strand OD, mm	0.7				0.8
Coil ID, mm	90	90	110	130	134
Bare cable width, mm	10	15			
Strand Jc(12T, 4.2K), kA/mm^2	2.5				
Bmax(1.9K), T	12.9	13.8	14.4	14.5	14.5
Gmax(1.9K), T/m	248	268	229	193	190
Gnom(12.5kA)	208	186	180	156	136
W(12.5kA), kJ/m	358	**384**	674	**923**	**702**
Fx (12.5kA), kN/m	1.13	**1.23**	1.98	2.40	**2**
Fy (12.5kA), kN/m	-1.65	**-1.54**	-2.38	-**2.90**	**-2.3**
Gmax/Gnom	**1.19**	**1.44**	**1.28**	**1.24**	**1.43**
Jcu, A/mm^2	**2407**	1546	1585	1585	1345

LBM Optics with 90-mm Nb3Sn Q1

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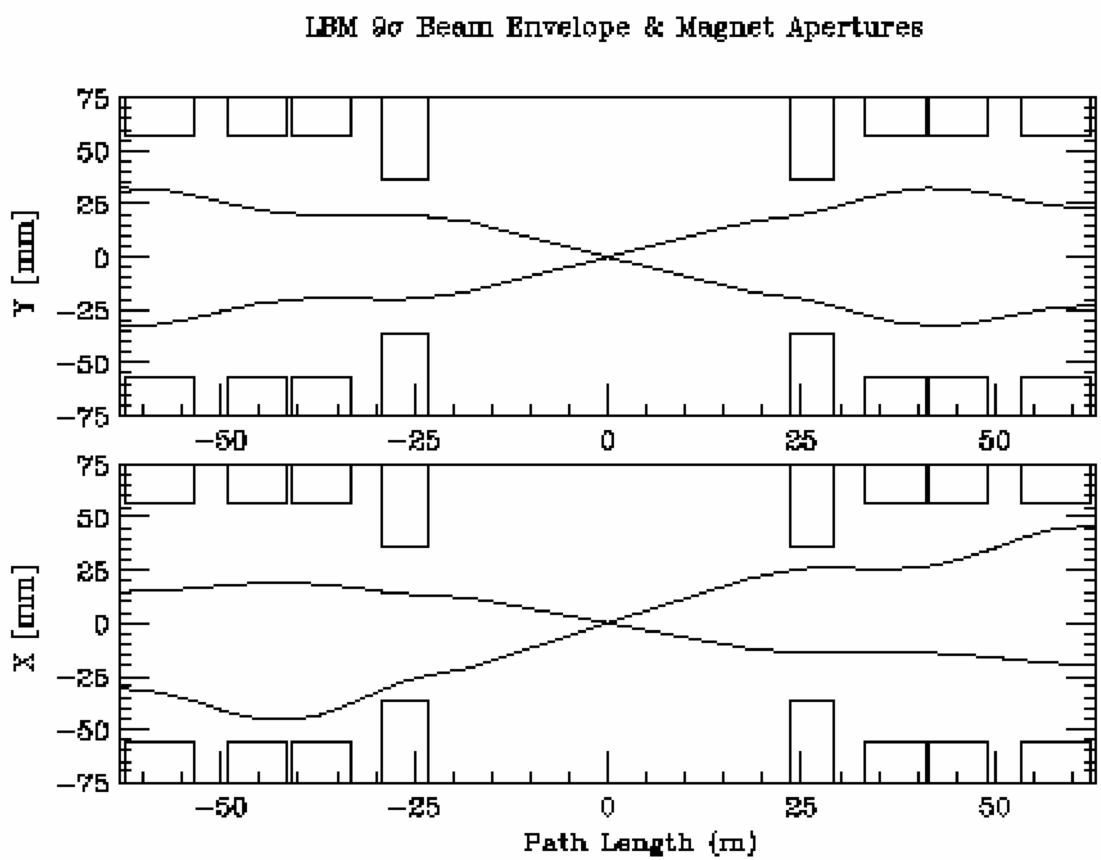

Magnet apertures includes the beam pipe, He channel, and beam screen 2*(3 + 4.5 + 1) mm.
The 9sigma beam envelope includes a 10% increase in the beam size and beam separation, plus a 2*8.6mm orbit error correction.

Optimized LBM optics (J. Johnstone, 2008):

- **Q1=90 mm**

NbTi:

- **G=167.21 T/m**
- **L=7.025 m**

Nb3Sn:

- **G=186 T/m**
- **L=6.315 m**
- **Shorter Q1 is shifted towards IP => space for additional absorber**

LBM Optics with 110-mm Nb3Sn Q3

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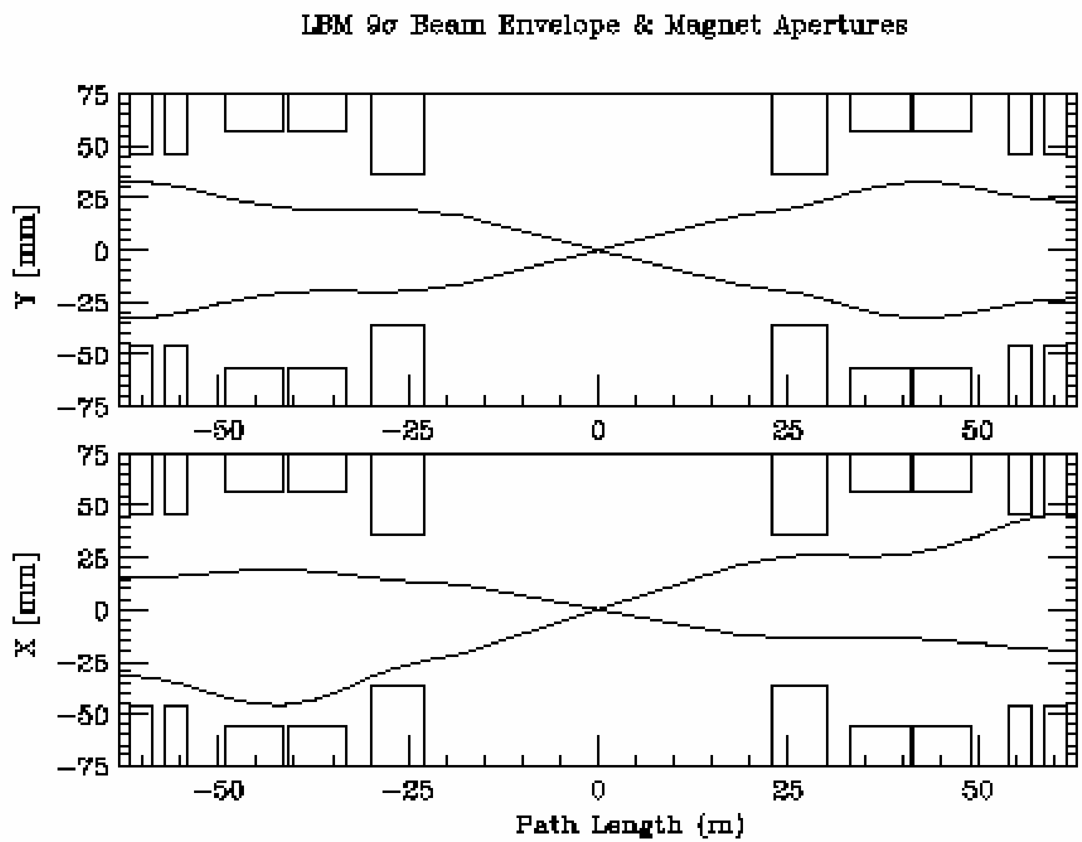

Magnet apertures includes the beam pipe, He channel, and beam screen 2*(3 + 4.5 + 1)mm.
The 9sigma beam envelope includes a 10% increase in the beam size and beam separation, plus a 2*8.6mm orbit error correction.

- **Optimized LBM optics (J. Johnstone, 2008):**

NbTi:

- **ID=130 mm**
- **G=121.37 T/m**
- **L=8.711 m**

Nb3Sn:

- **ID=110 mm**
- **G=176.21 T/m**
- **L=3 m**
  - **2 modules separated by 1.8 m in the same slot.**

Next Steps

Symmetric optics studies (J. Johnstone et al.):

- **Q3:**
  - **130 mm, ~130 T/m , ~9.5 m (2 modules)**
- **Q1:**
  - **90-110 mm, ~180 T/m, ~8 m (2 modules)**

- **Operation margin studies (N. Mokhov et al.)**
  - **90-mm NbTi Q1 + 130-mm NbTi Q2 and 110-mm Nb3Sn Q3.**
  - **90-mm Nb3Sn Q1 + 130-mm NbTi Q2 and 130-mm NbTi Q3.**
  - **Symmetric option with Nb3Sn Q1**

- **Tracking studies (G. Robert-Demilaize et al.)**
  - **Effect of field quality**

Conclusions

- Nb3Sn accelerator magnet R&D has made a good progress
  - robust coil W&R technology
  - robust mechanical structures
- The possibilities and present limitations of quench performance and accelerator field quality in Nb_3Sn dipoles and quadrupoles were demonstrated
  - performance improvement is possible
  - model magnet R&D need to continue
- The first results of Nb3Sn accelerator magnet technology scale up are quite encouraging
  - more work ahead
- The optimization and use of more stable high-Jc RRP strand is critical for magnet performance improvement

Conclusins (cont.)

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- **The ultimate goal of this program is LHC Phase II upgrade (LARP QB quadrupoles)**
  - **Nb3Sn magnet parameters and performance need to be better understood and improved**
    - **6-8 years for R&D**
- **Nb3Sn magnets (LARP QA quadrupoles) could be also considered for Phase I upgrade to improve LHC performance and also to learn more and demonstrate Nb3Sn technology in a real machine**
  - **Limited number (Q1 or Q3)**
  - **Conservative design and parameters – large margins (~30-40% to compensate for present performance limitations)**
  - **Improve the magnet performance during next 2-3 years**
- **Staged LHC upgrade strategy adopted by CERN needs to be taken into account choosing QA and QB design parameters.**

Acknowledgement

❖ **US-LARP Magnet groups at BNL, FNAL and LBNL**

❖ **US-LARP JIRS group**

❖ **CERN LIUWG**