High Field Dipole Studies at FNAL

Alexander Zlobin
Fermilab

Outline

- FNAL Program Mission and Goals
- R&D Summary (focus on Nb_3Sn D and Q work)
- 11 T dipole for LHC collimation system upgrade
- Work status
- Conclusions

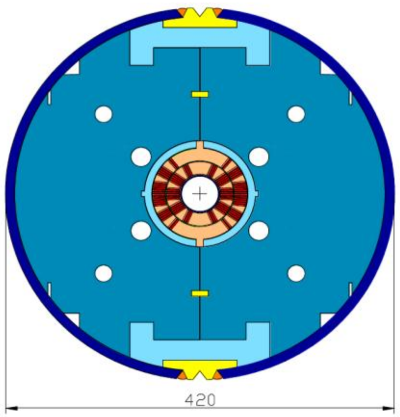
FNAL Program Mission and Goals

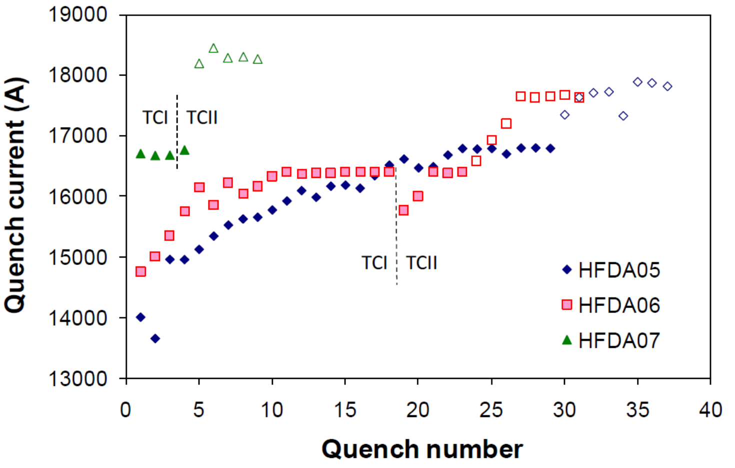
- **Magnet technology a key enabling technology for particle accelerators.**
- ***Main goal at Fermilab is*** **the development of advanced SC** ***accelerator*** **magnets and baseline technologies for present and future particle accelerators.**
- ***Present focus*** **is on the development of high-field accelerator magnets with operating fields up to 15 T based and Nb_3Sn superconductor.**
- ***In the longer term*** **the program will support the development of accelerator magnets with operating fields above 20 T based on HTS/LTS hybrid coils.**
- ***SC materials R&D*** **is a key part of this program.**
- ***This program supports also*** **the improvements of magnet design and analysis methods and tools, fabrication and test infrastructure, instrumentation, training of young scientists and engineers.**

R&D Summary

- ❖ **HFM Program started in 1998**
- ❖ **Program major R&D results:**
  - o **43.5 mm Nb_3Sn dipoles for VLHC with operation fields up to 10-11 T (1998-2007)**
  - o **90-mm Nb_3Sn quadrupoles for LHC IRs with operation gradients up to 200 T/m (2005-2011)**
  - o **Nb_3Sn magnet technology scale up (2007-2011)**
  - o **Rutherford cables based on Nb_3Sn, Nb_3Al and Bi-2212 strands (since 2000)**
  - o **Solenoidal and helical coils based on YBCO tape (2009-2011)**
  - o **Contributed to VLHC, LARP, MCTF-MAP, CDP, VHMFC, etc. studies**

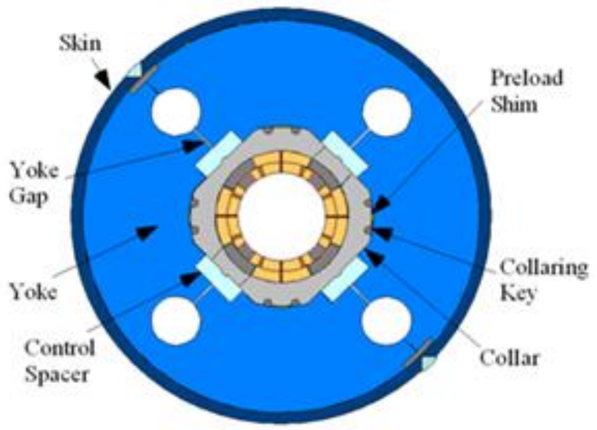
Dipole Magnets for Hadron Colliders

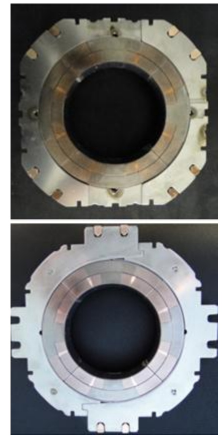


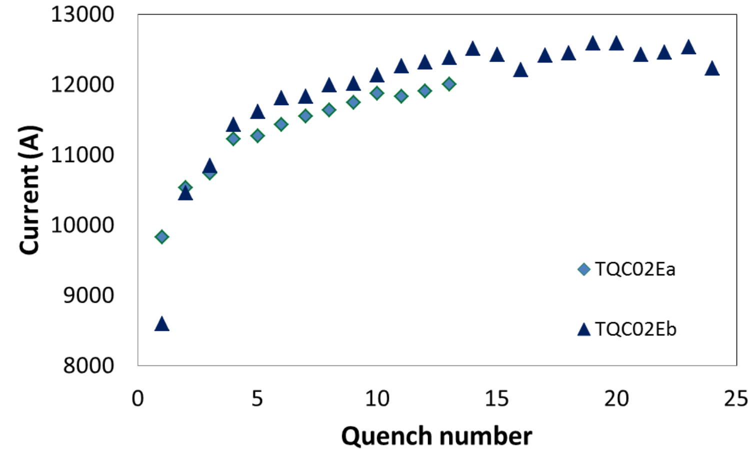


- **Development a series of 43.5-mm Nb_3Sn dipoles with B_{nom}~10 T based on collar-free structure**
- **First demonstration of the quench performance and field quality reproducibility for Nb_3Sn accelerator magnets**
- **Development and demonstration of effective passive correction scheme based on iron strips**

Quadrupole Magnets for Hadron Colliders

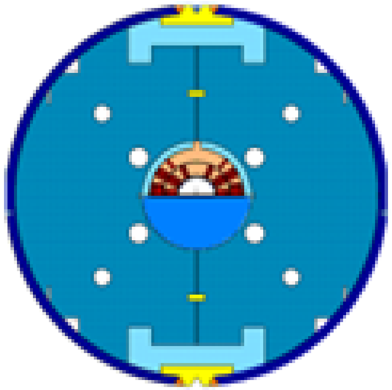
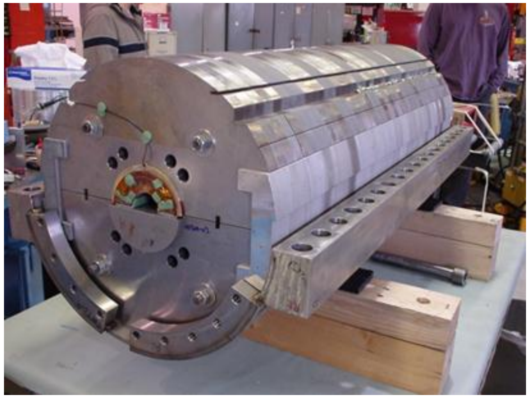


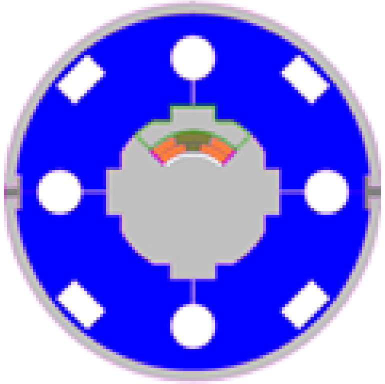




- Development a series of 90-mm Nb_3Sn quadrupole with G_{max}~217 T/m based on modified MQXB structure
- First demonstration of the traditional collar-based mechanical structure with brittle coils
  - two collaring techniques for Nb_3Sn coils - quadrupole-style and dipole-style collar
- Quench performance and field quality reproducibility for Nb_3Sn quadrupoles

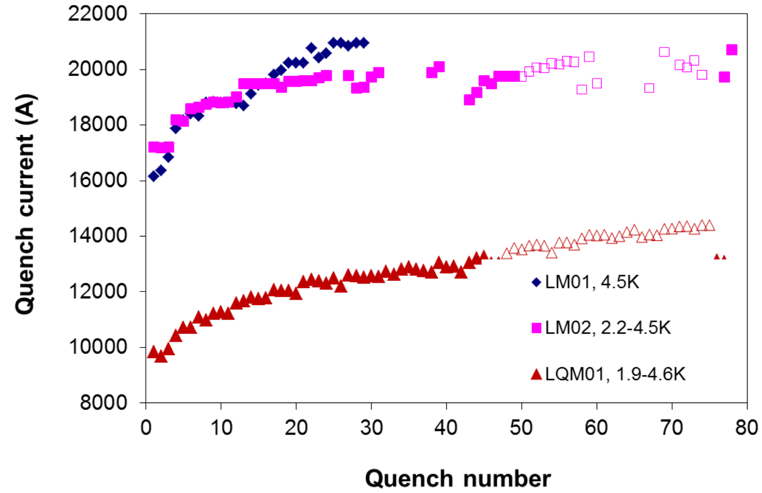
Technology Development



- **Development of Coil Test Structure for single short and long dipole and quadrupole coils**
  - **lower cost, shorter turnaround time, advanced instrumentation**
- **Experimental studies:**
  - **Nb_3Sn strand (PIT, MJR, RRP) performance at 1.9-4.5 K**
  - **cable with SS core to suppress eddy currents**
  - **cable insulation based on ceramic, E-glass and S2-glass tapes**
  - **coil structural materials (bronze vs Ti poles) and processing**
  - **the effect of coil pre-stress on its quench performance**

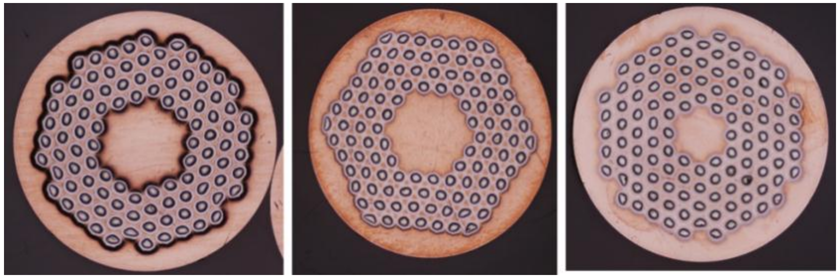
Nb_3Sn Magnet Technology Scale Up



4-m long Nb_3Sn dipole (left) and quadrupole

4-m long coil test structure

Nb_3Sn Strands & Rutherford Cables

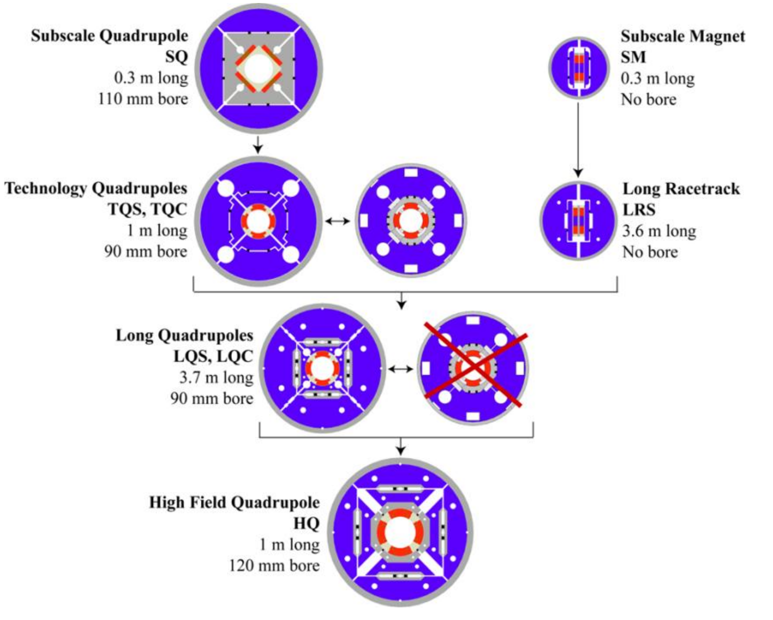


RRP-102/127 RRP-108/127 RRP-114/127

- **RRP strand design improvement in collaboration with OST by increasing the number of subelements and subelement spacing in the strand cross-section**
  - **Better stability, lower magnetization**
  - **Lower damage during cabling**
- **Rod-in-Tube Technology with Hyper Tech Research**
  - **Smaller Deff, alternative vendor**
- **PIT Technology with SMI and SupraMagnetics, Inc.**
- **Cables made with and without stainless steel cores had low (<5%) critical current degradation in magnets**

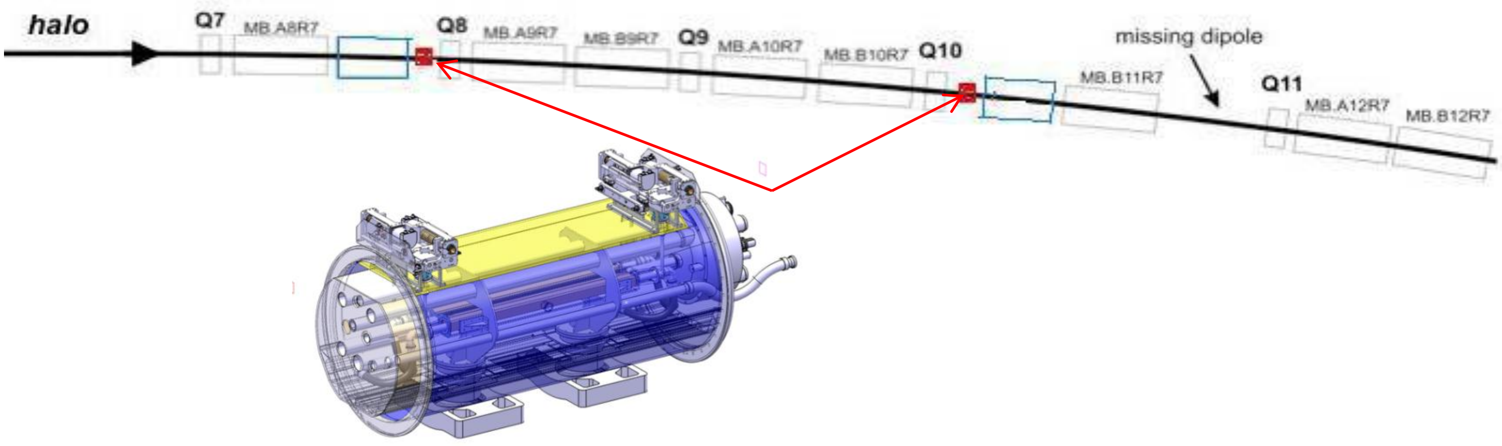
Contribution to LARP and Plans

- ❖ **FNAL contributions to US-LARP**
  - o **90-mm technology quadrupoles (TQ series)**
  - o **3.6 m long quadrupoles (LQ series)**
  - o **120-mm quadrupoles (HQ and LHQ series)**
  - o **Materials study**
  - o **IR and Magnet Design studies**



- ❖ **Mid-term goal: Implement Nb_3Sn magnets with magnetic fields up to 13 T into existing machines (HL-LHC)**
- ❖ **Long-term goal: Start exploratory accelerator magnet R&D to achieve magnetic field up to 20 T based on HTS/LTS for energy frontier machines (HE-LHC, MC)**

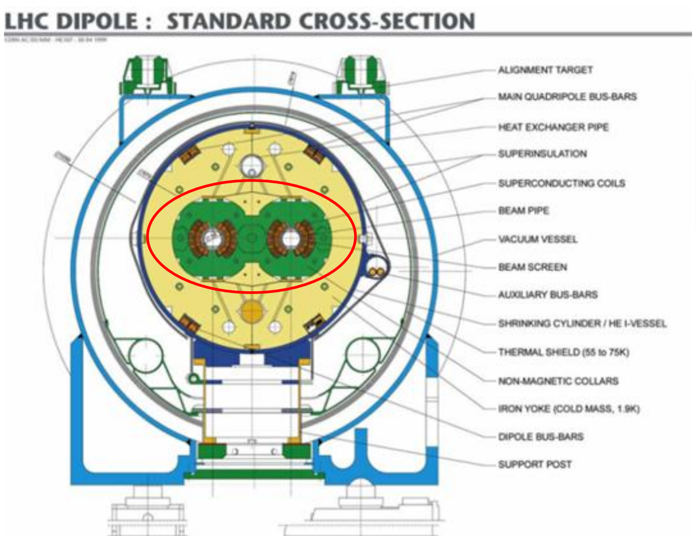
LHC Collimation Upgrade

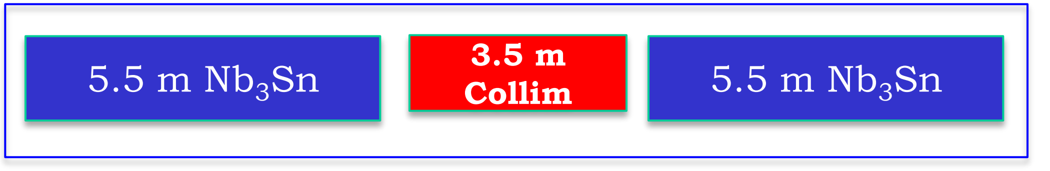


- **CERN is planning to upgrade the LHC collimation system**
  - **additional collimators in DS regions around points 2, 3, and 7**
  - **IR 1 and 5 as part of the HL-LHC**
- **The required space ~3.5 m can provide stronger and shorter dipoles**
  - **These dipoles will be operated at 1.9 K, powered in series with the main dipoles and deliver the same integrated strength at 11.85 kA**
  - **MB: B_{nom}=8.35 T, L_{mag}=14.3 m, $\int BdL$ = 119.2 Tm @ I_{nom} = 11.85 kA**
  - **L_{mag}=14.3-3.5=10.8 m, B_{nom}=11 T => *Nb_3Sn technology***

General Design Approach

- **Coil aperture 60 mm**
    - **accommodate the beam sagitta and avoid the additional complication of curved Nb_3Sn coils**
- **Coil length 5.5 m**
    - **present tooling length limitations at Fermilab**
- **Modified 550 mm iron yoke from the LHC main dipole**
    - **compatibility with LHC main systems**
- **11 m long cold mass combines two 5.5 m long cold masses**
    - **arrangement flexibility**





Magnet Development Plan

- **CERN and FNAL have started in October 2010 a joint development program to demonstrate feasibility of twin-aperture 11 T, 5.5 m long Nb_3Sn dipoles by 2014.**
- **R&D Phases**

Date	Description	Length	Remarks	Goals
End-2011	1-in-1 Demonstrator Magnet	2 m	Construction at FNAL	Cable technology Coil Technology Quench performance Magnetization effects
End-2012	2-in-1 Demonstrator Magnet 1	2 m	FNAL collared coils CM-Assembly at CERN	2-in-1 structure Field quality: - iron saturation - cross-talk - Magnetization effects Quench performance Reproducibility
Mid-2013	2-in-1 Demonstrator Magnet 2	2 m	CERN collared coils CM-Assembly at CERN	
End-2014	2-in-1 Prototype Cold Mass	5.5 m	Aperture 1 by FNAL Aperture 2 by CERN CM assembly at CERN	Scale-up Long tooling Fabrication of long coils CM assembly Magnetic performance

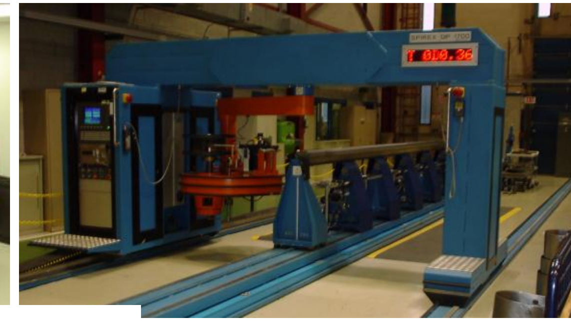
Possible Production Phase 2014-17

CERN & FNAL:

- Cable & coil production
- Coil collaring

CERN:

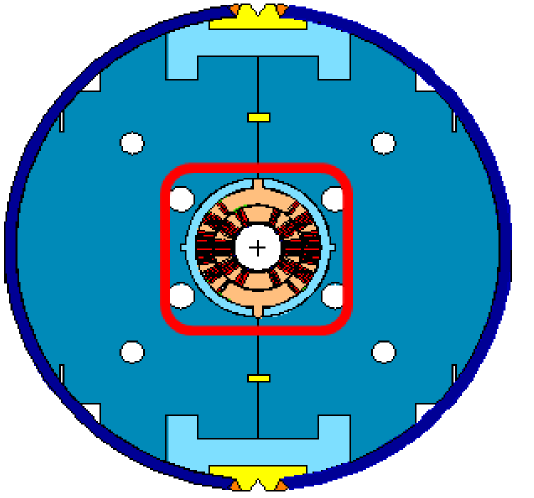
- Cold mass assembly
- Cryostat integration
- Testing
- Installation in the tunnel



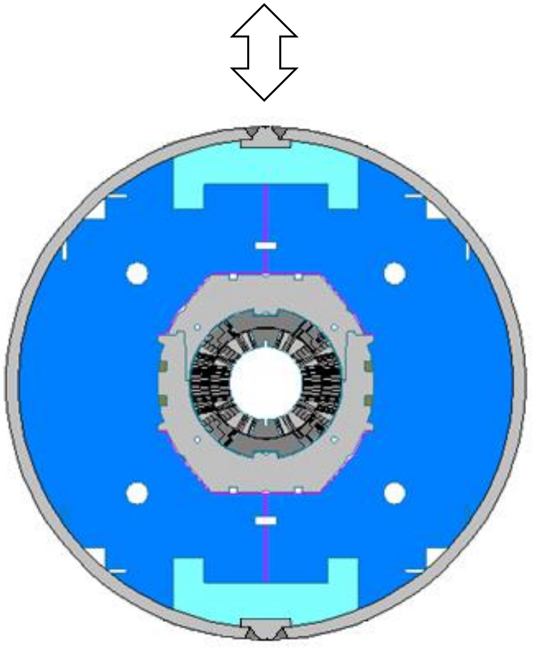
FNAL

Single-Aperture Demonstrator

- Modified structure of HFDA dipole.
- Two-layer 6-block coil design
- Stainless steel collar
- 400 mm vertically split iron yoke
- Al clamps to control yoke gap
- 12 mm thick stainless steel skin
- 50-mm thick end plates

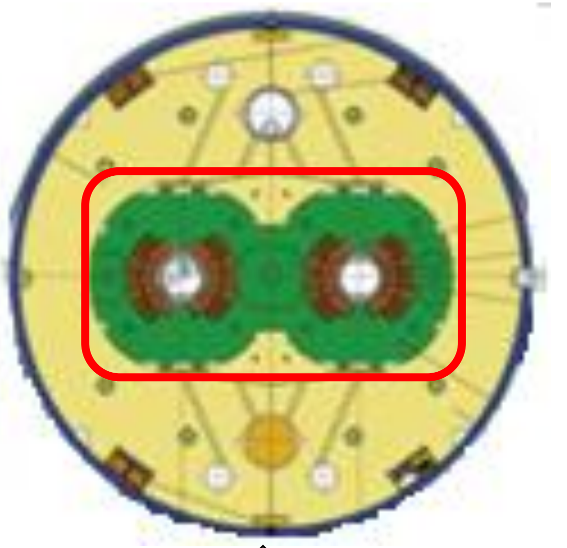


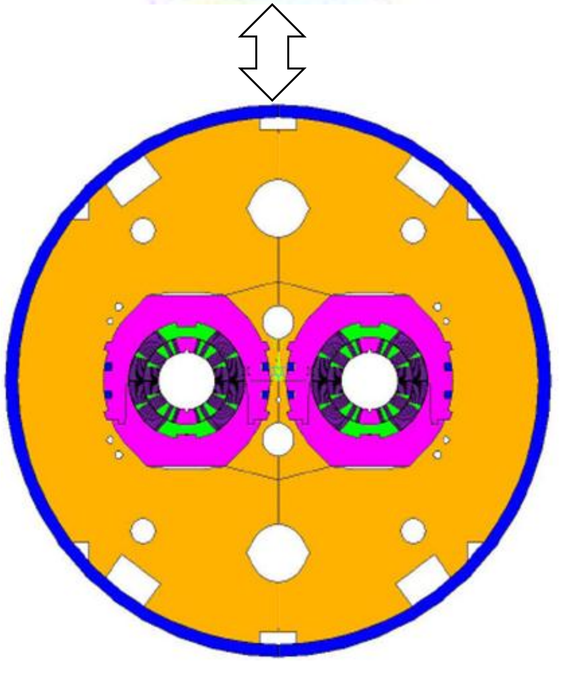
- Maximum stress during assembly ~130 MPa to keep coil under compression up to 12 T bore field
- Mechanical structure optimized to maintain the coil stress below 165 MPa - safe for brittle Nb_3Sn coils



Twin-Aperture Design Studies

- **Modified MB structure with separate collared coils - to simplify the process and reduce the press force during collaring**
- **Electromagnetic design challenges**
  - **matching the MB transfer function**
  - **control the magnetic cross-talk between apertures**
  - **minimization of the unwanted multipoles in the current cycle**
- **Mechanical design challenges**
  - **first twin-aperture Nb_3Sn dipole**
  - **Lorentz force management**
  - **Poles under compression and coil stress <165 MPa**



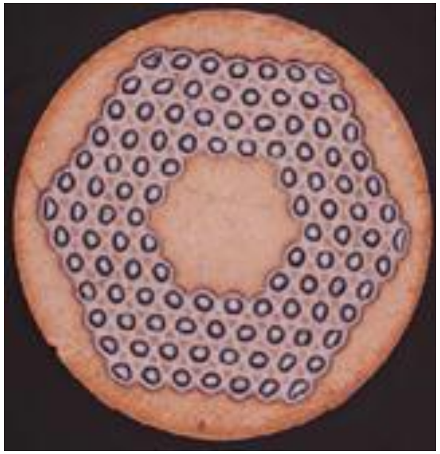


Demonstrator Dipole Parameters

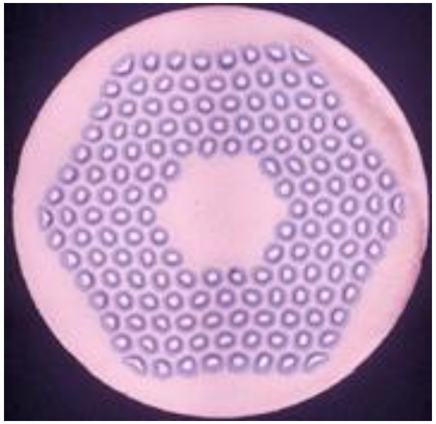
Parameter	Single-aperture	Twin-aperture
Aperture [m]	60	
Nominal current I_{nom} [A]	11850	
Yoke outer diameter [mm]	400	550
Nominal bore field [T]	10.86	11.25
Short-sample bore field at 1.9 K [T]	13.6	13.9
Margin B_{nom}/B_{max} at 1.9 K [%]	80	81
Maximum design field [T]	12.0	12.0
Inductance at I_{nom} [mH/m]	5.6	11.98
Stored energy at I_{nom} [kJ/m]	473	969
F_x per quadrant at I_{nom} [MN/m]	2.89	3.16
F_y per quadrant at I_{nom} [MN/m]	-1.57	-1.59
Coil length [m]	1.9	1.9
Magnetic length [m]	1.79	1.68

RRP Strands for 11 T Dipole

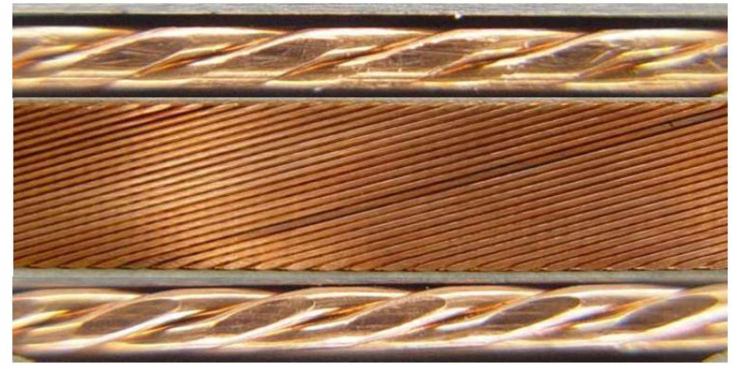
- **Strand design parameters**
  - **Diameter 0.7 mm**
  - **J_c(12, 4.2 K)>2650 A/mm^2**
- **Baseline strand – RRP-108/127 (OST)**
  - **High-J_c, stable at 1.9-4.6 K**
  - **Produced in long length**
  - **Performance demonstrated in several short and long coils**
  - **Could be used for production magnets**



- **R&D strand – RRP-150/169 (OST)**
  - **promising performance**
  - **Production - 60 kg in 2011**
  - **Performance demonstration in magnet – summer 2012**

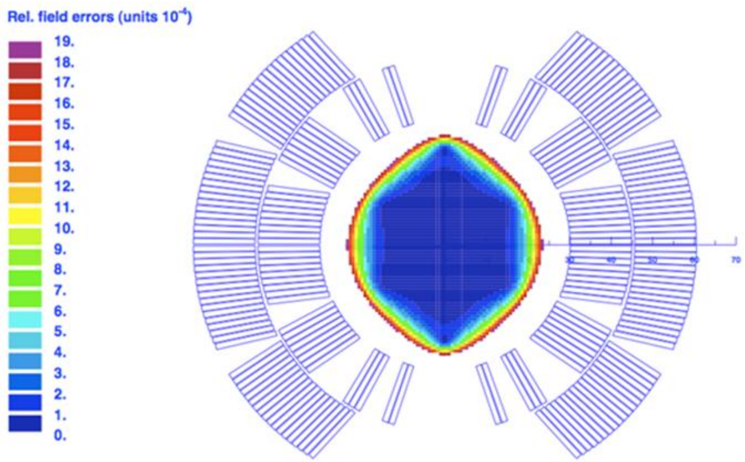


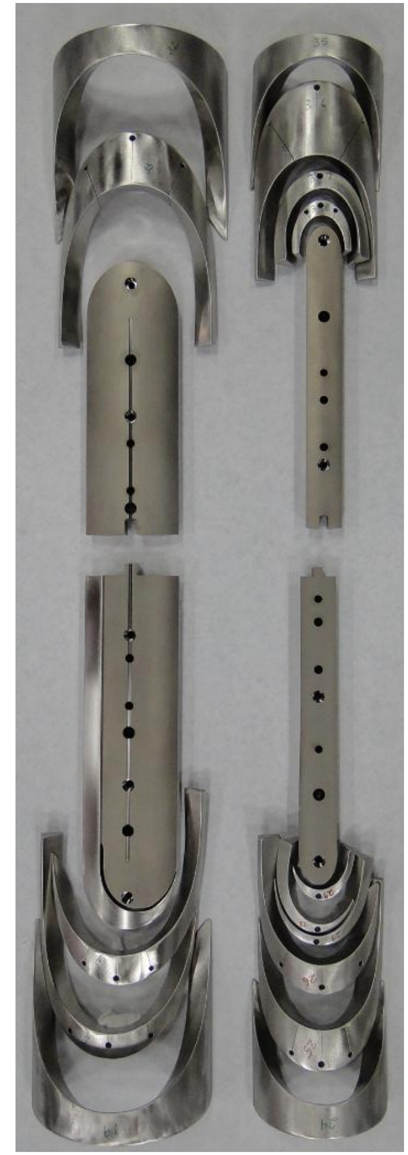
Cable Development and Fabrication



- **Baseline cable for demonstrator magnets**
  - **40 strands based on RRP-108/127 0.7 mm strand w/o core**
  - **Unit length 210 m**
- **Cable R&D and production**
  - **250 m – practice coil**
  - **234 m + 167 m – practice cable**
  - **440 m piece – 2 ULs for demonstrator model + ~20 m for samples**
  - **230 m - CERN for coil #3**
- **Cable for production magnets**
  - **RRP-150/169 strand with 25 um SS core**
  - **60 m + 120 m + 230 m**

Coil Design and Fabrication





- ❖ **60 mm ID, 2-layer**
- ❖ **PC#1 – rectangular Cu cable**
  - o **two types of end parts**
- ❖ **PC#2 – Nb_3Sn cable (RRP-114/127)**
  - o **will be used for mechanical model**
- ❖ **Coil #1 – wound, prepared for impregnation**
- ❖ **Coil #2 – wound, prepared for reaction**
- ❖ **Coil #3 – winding starts in January (CERN cable)**

Coil Technology

Coil winding

Reacted coil

Cured coil

Coil after epoxy impregnation

Conclusions

- Magnet technology a key enabling technology for accelerators
  - High Field Magnet Program is a key R&D effort at Fermilab
  - Good progress and excellent results
- Present focus on 11 T Nb_3Sn dipole magnets for the LHC upgrades in collaboration with CERN
  - additional cold collimators
  - other applications in LHC, VLHC
- The fabrication of single-aperture demonstrator dipole is in progress - model test in April 2012
- The twin-aperture 11 T dipole design have started
- Nb_3Sn technology is also fundamental for accelerator magnets with fields ~20 T
  - Nb_3Sn coil will generate ~70% of the total field and play an important role in quench protection and cost reduction
- Mb_3Sn technology will provide excellent opportunities for LHC upgrades and Muon Collider