Fermilab has long and successful history of SC accelerator magnet R&D:
Tevatron, Low Beta Quads, SSC dipoles, VLHC superferric transmission-line, LHC IR Quads, HFM dipoles

This is because SC magnets are an enabling technology for HE accelerators
**Why Nb₃Sn?**

Better performance at 4.2 K than NbTi at 1.8 K

**Why not yet?**

*“Why there aren’t Nb₃Sn magnets in any HE accelerator?”*

Because Nb₃Sn is a brittle material

- Degradation at longitudinal strain > 0.3-0.5%
- Degradation at transverse pressure > 120-180 MPa

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All Experimenters Meeting  
March 6, 2006

HFM/LARP Magnet R&D  
R. Flukiger et al., Intrinsic axial strain [%]
HFM and LARP goals

- **HFM program mission:** development of next generation SC accelerator magnets with operating fields above 10 T at 4.5 K
  - Presently focus on Nb$_3$Sn and Wind-and-React technology,
    - React-and-Wind was explored (3 racetrack, 1 Common Coil magnets)
  - Sufficient aperture, field quality, acceptable dynamic effects
  - Design and technology compatible with scale-up and industrialization

- **LARP goal:** provide options for future upgrades of the LHC IRs
  1$^{\text{st}}$ deadline: “Demonstrate by 2009 that Nb$_3$Sn magnets are a viable choice for an LHC IR upgrade”
  - Predictable and reproducible performance
    - SQ and TQ series (1 m, 90 mm aperture, $G_{\text{nom}} > 200$ T/m, $B_{\text{coil}} > 12$ T)
  - Long magnet fabrication
    - LR and LQ series (4 m, 90 mm aperture, $G_{\text{nom}} > 200$ T/m, $B_{\text{coil}} > 12$ T)
  - High gradient in large aperture
    - HQ series (1 m, 90 mm aperture, $G_{\text{nom}} > 250$ T/m, $B_{\text{coil}} > 15$ T)
HFM magnet designs

- Ceramic Insulation with Ceramic Binder
- No Interlayer Splice
- Spacers instead of Collars
- The yoke gap remains open
- Coil prestress by Al-clamps and skin

**DIPOLE magnet:**
- Magnet bore diameter = 43.5 mm
- Number of turns = 48
- Cable: 28 1-mm strands
- \( B_{\text{max}} = 12 \text{ T} @ J_c = 2000 \text{ A/mm}^2 \)
- \( I_{\text{max}} = 21.2 \text{ kA} \)
- Insulation thickness = 250 \( \mu \text{m} \)

**MIRROR magnet**
- Number of turns = 24
- Same cable as in dipole magnet
- \( B_{\text{max}} = 8.4 \text{ T} @ J_c = 2000 \text{ A/mm}^2 \)
- \( B_{\text{peak}} = 11.2 \text{ T} @ J_c = 2000 \text{ A/mm}^2 \)
- \( I_{\text{max}} = 25 \text{ kA} \)
HFM results - I

- Found limitation of present high-current-density $\text{Nb}_3\text{Sn}$ conductors, understood cause, presented problem to community, and successfully implemented solution.

“The tremendous accomplishments of these last two years confirm the strength of the group”

“The expertise developed in these years and the infrastructure that exists or is under procurement, constitutes a vital asset for LARP”

Jan 06 HFM review closeout (L. Rossi, chair)
HFM Results - II

- Developed a robust Nb$_3$Sn coil fabrication technology with several new features suited for length scale-up and industrialization ➔ All adopted for LARP quadrupoles
  
  Ceramic binder for insulation, water-jet technology for end-parts, reaction procedure with azimuthal and pole gaps, segmented tooling with “gentle-transfer” procedure, splice design and procedure,

- Developed Nb$_3$Sn magnet design and assembly technology allowing significant reduction in cost and assembly time, and easily scaleable to full length accelerator magnets
  
  - 4 ½ months for dipole magnet test, 3 months for dipole coil test
**HFM results - III & Work in Progress**

- **Demonstrated field quality reproducibility in Nb₃Sn accelerator magnets**, developed simple and effective **passive correction of coil magnetization effect**, and are studying **dynamic effects**
  - Measured field quality in 5 Nb₃Sn cos-theta dipoles (unprecedented)
  - and their dynamic effects (unprecedented) – **Work in progress**
  ➔ understanding and reducing largest deviations (by feedback into coil fabrication and assembly technology) – **Work in progress**

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**Iron strips**

**Passive correction effectiveness**

The passive correction has reduced the sextupole variation in the field range of 1.5-4 T during the field up-ramp from $19 \times 10^{-4}$ to $4 \times 10^{-4}$ ($R_{\text{ref}} = 10$ mm)
HFM short-term plan

GOAL: to develop fabrication technology for long Nb$_3$Sn coils

→ fabricate and test 2m and 4m long Nb$_3$Sn dipole coils
  – TD Industrial Building 3 (IB3) has been upgraded to allow the fabrication of Nb$_3$Sn coils and cold masses up to 6m
Technological Quadrupoles using collars (TQC)
Plan: 3+ by the end of FY07

- Magnet bore diameter = 90 mm
- Number of turns = 136
- Strand: Nb$_3$Sn, $\phi$ 0.7 mm,
- Cable: N=27, Keystone Angle = 1
- $J_c = 2000$ A/mm$^2$ @ 4.2K 12T
- $G_{max} = 216/233$ T/m @ 4.2/1.9 K
- $I_{max} = 12.9/14.1$ kA @ 4.2/1.9 K
- Insulation thickness = 125 µm

Can use collars, yoke, skin, tooling and infrastructure developed for the LHC-IR Quads
LONG QUADRUPOLES

- Gradient > 200 T/m
- Aperture 90 mm
- Length 4 m

- Coil design based on LARP-TQs:
  - 2 layers with 10 mm wide 0°C cable, no interlayer splice
- Two mechanical designs under investigation (TQs):
  - collars (TQC)
  - Al-shell based structure (preloaded by bladders & keys)
- Length related issues under investigation by LARP LQ
  Design Study, by LARP Long Racetrack (4m), and by FNAL
  Long Mirror magnets
- Two Long Quad models tested by end of FY 2009
Long-term Plans

• **LARP Second phase (2010-2012)**
  – New IR design and **full-size (6m) IR quadrupole prototype**

• **LHC IR upgrade project (~2013-2015)**
  – **fabrication and test of IR quads** for the LHC high luminosity upgrade

• **Magnets for future accelerators: (Muon collider/SR, future hadron colliders, …)**
  – Nb$_3$Sn: Wind-and-React vs. React-and-Wind
    ➔ cost estimate and industrialization
  – new HFM technologies based on alternative/complementary superconducting materials (HTS, MgB$_2$, …)