Second Annual VLHC Meeting
October 16-18, 2000
Danfords, Port Jefferson, Long Island, NY

R&D of Cos-theta Nb3Sn High-Field Dipoles for VLHC

A.V. Zlobin, Fermilab

Outlines:

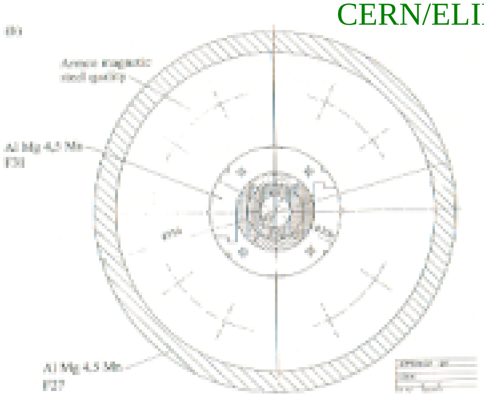
- *Research:*
  - *Magnet Designs: single/double bore, cold/warm yoke*
  - *Design Parameters: short sample limit, field quality, mechanics, quench protection, etc.*
- *Development:*
  - *Short model Design and Technology*
  - *Cable, insulation, structural materials*
  - *Short Model Fabrication Status*

First Nb3Sn Dipole Models

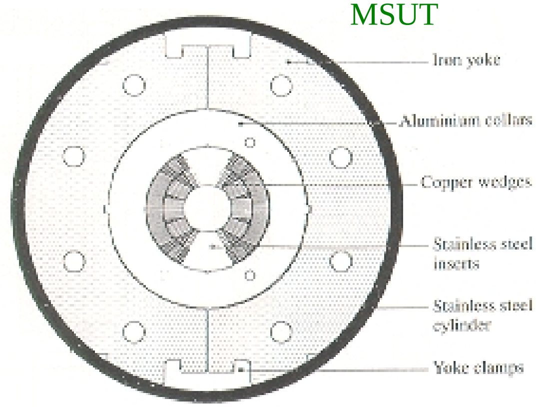
Several Nb3Sn short dipole models were fabricated and tested to demonstrate the possibility to reach the field >10 T at 4.3 K.

Laboratory	CERN	UT	LBNL
Aperture (mm)	50	50	50
Number of layers	2	2	4
Coil thickness (mm)	34	40	54
Design Bmax @4.3 K (T)	10.0	11.5	13.0
Test	1989	1995	1997

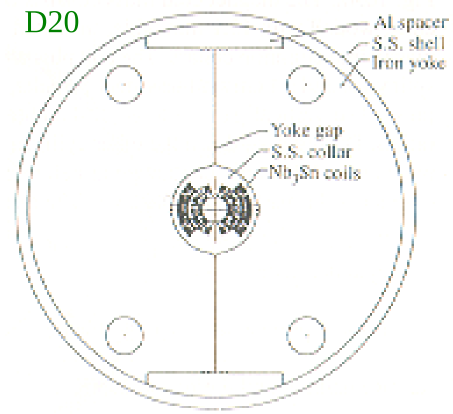
CERN/ELIN



MSUT



D20



Design Parameters and Criteria

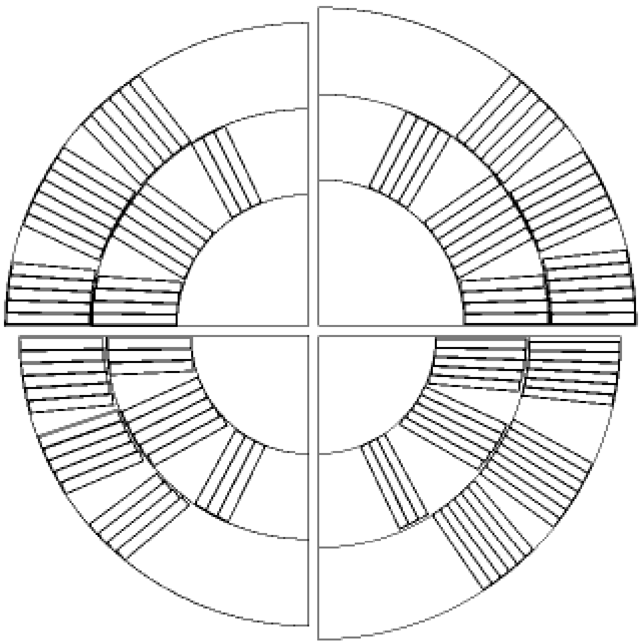
Target design parameters and requirements:

- nominal field: Bnom=10-12 T
- field range: Bnom/ Binj=50TeV/ 3TeV=17   Binj=0.6-0.7 T
- good field quality in the operation cycle: 1986 SSC specs
- sufficient physical & dynamic aperture: magnet bore >40 mm

Additional considerations:

- mechanical stability: coil support structure
- quench protection: minimal stored energy, low inductance
- low cost: small coil & magnet x-sections, simple & inexpensive technology
- applicability of design and technological solution for full-scale magnets

Magnetic Design Study



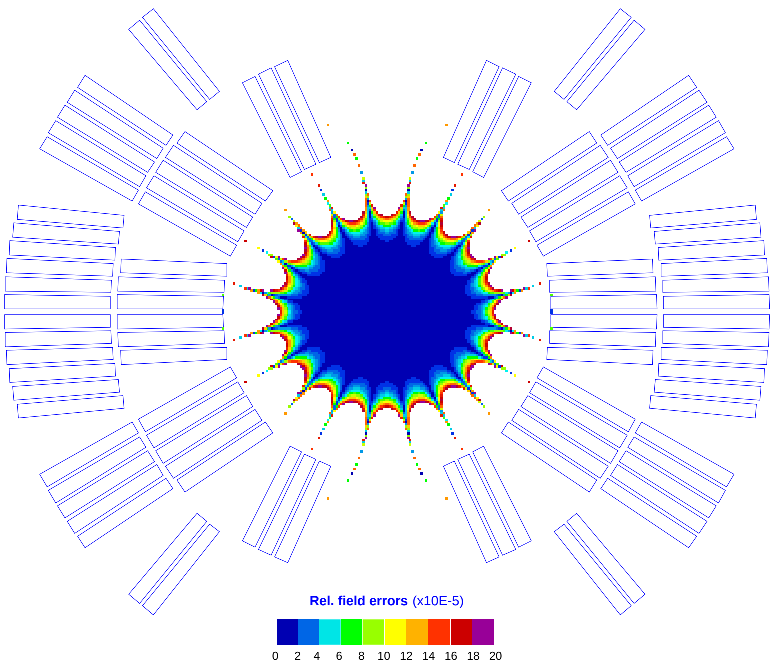
Cross-sections of coils with bore diameter of 40-50 mm

Basic parameters: 2 layers cos-theta coil
coil thickness ~30 mm

Cable	1.80x14.23mm^2			1.46x15.4mm^2
Strand diam. (mm)	1.0	1.0	1.0	0.81
Bore diam. (mm)	50	45	40	40
Bss (T)	12.4	12.4	12.5	12.5
Energy@11T (kJ/ m)	289	256	221	230
Inductance (mH/ m)	2.75	2.32	1.67	2.53
Coil area (cm^2)	33.0	30.1	26.6	28.7
Pole width (mm)	17.5	16.2	15.0	14.6

⇨ **bore diameter range 40-50 mm is OK**
⇨ **large cable is better**

Cos-theta Coil Cross-Section



Strand: Nb3Sn 1.00 mm
Cu:nonCu=0.85:1
Jc(12T, 4.2K)=2.0 kA/ mm^2

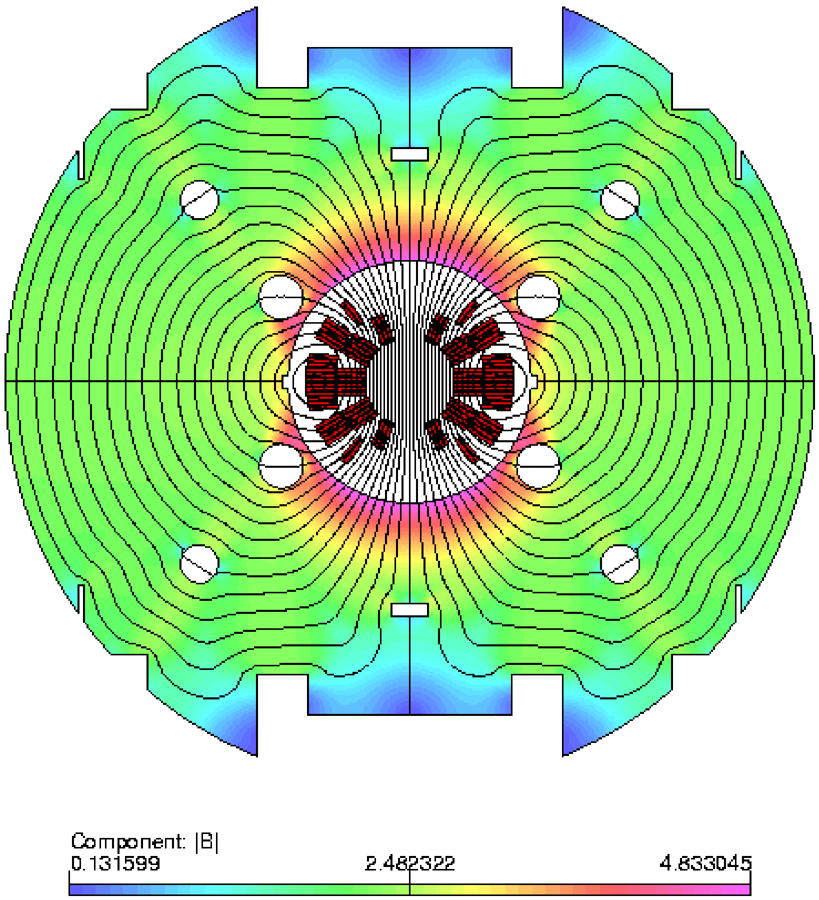
Cable: 28 strands
$14.24 \times 1.80\ mm^2$,
Keystone angle 0.9 degree
Packing factor 0.88

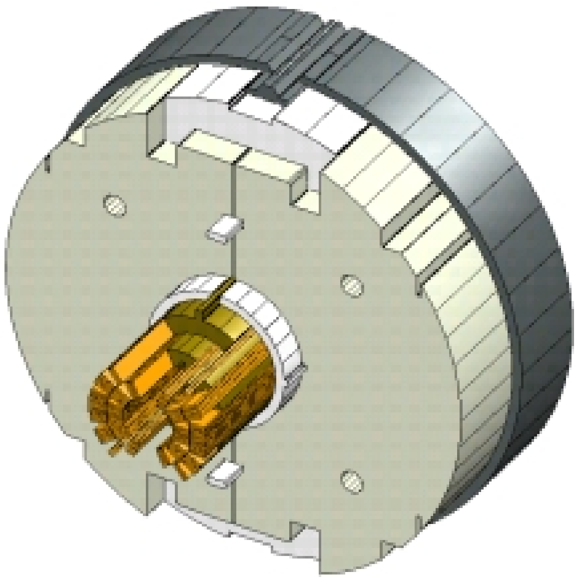
Insulation: Thick 2*0.125 mm
(20-50% overlap)

Coil: Two layers cos-theta
Bore diameter 43.5 mm
24 turns (11+13)

Technique: Wind& react

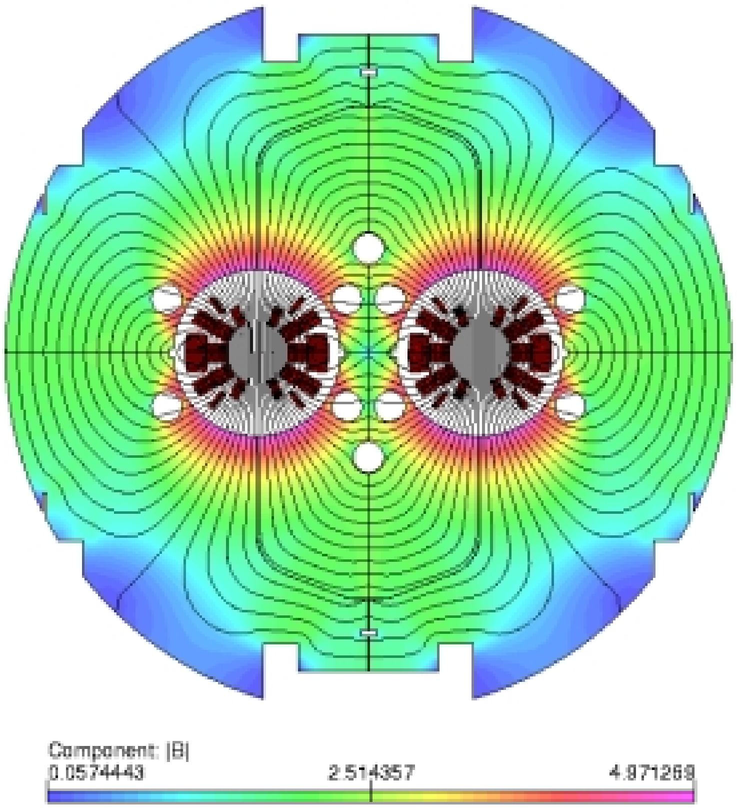
Single-Bore Cold-Yoke Design

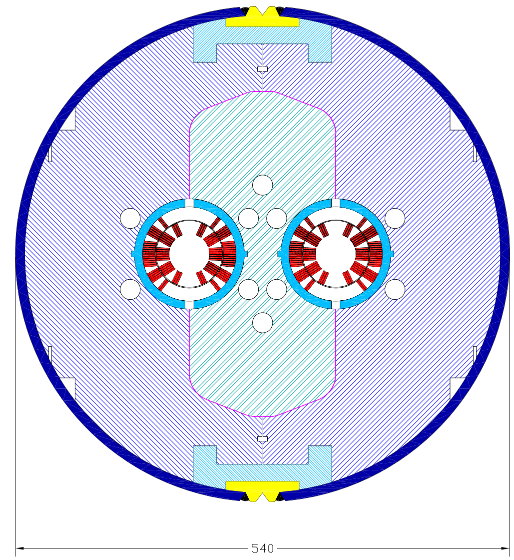




- thin coil-yoke spacers (no collars)
- 2 pieces cold yoke with open vertical gap
- Al clamps and 10 mm thick SS skin
- nominal yoke OD 440 mm

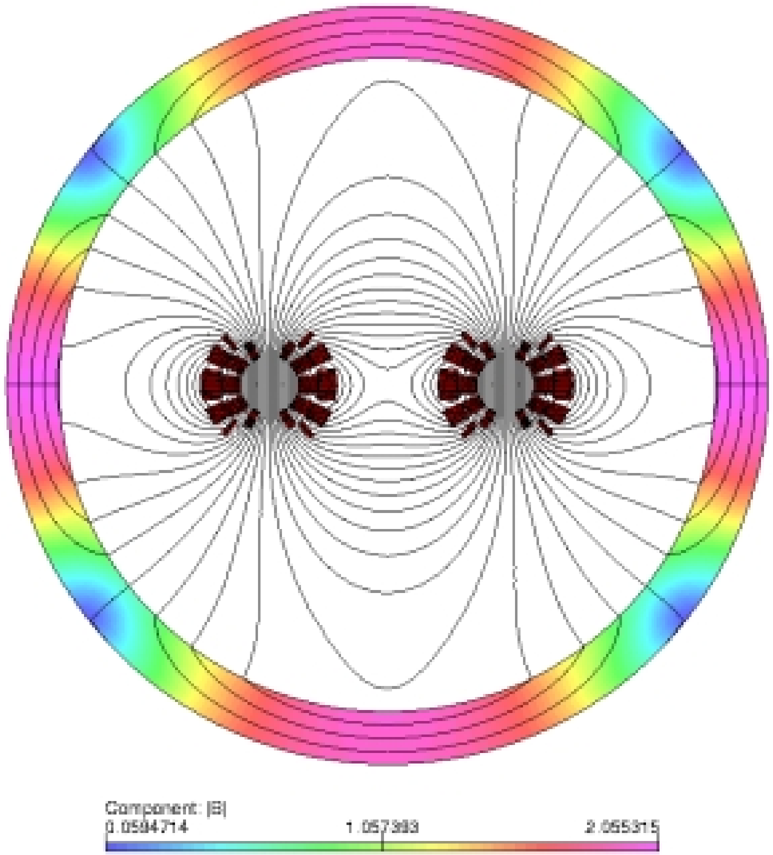
Double-Bore Cold-Yoke Design

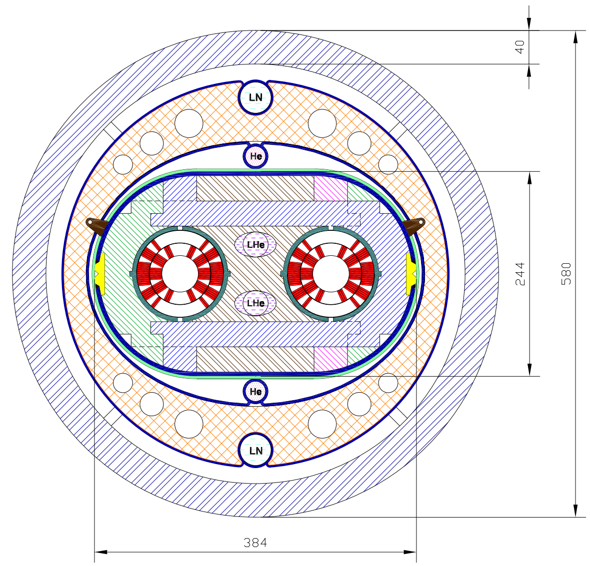




- bore diameter 43.5 mm (same coil block)
- bore separation 180 mm
- 3 piece cold yoke with vertical gap
- yoke OD 520 mm ⇨ cryostat OD ~0.8-0.9 m
- 10 mm thick SS skin
- correction holes, gap along flux lines

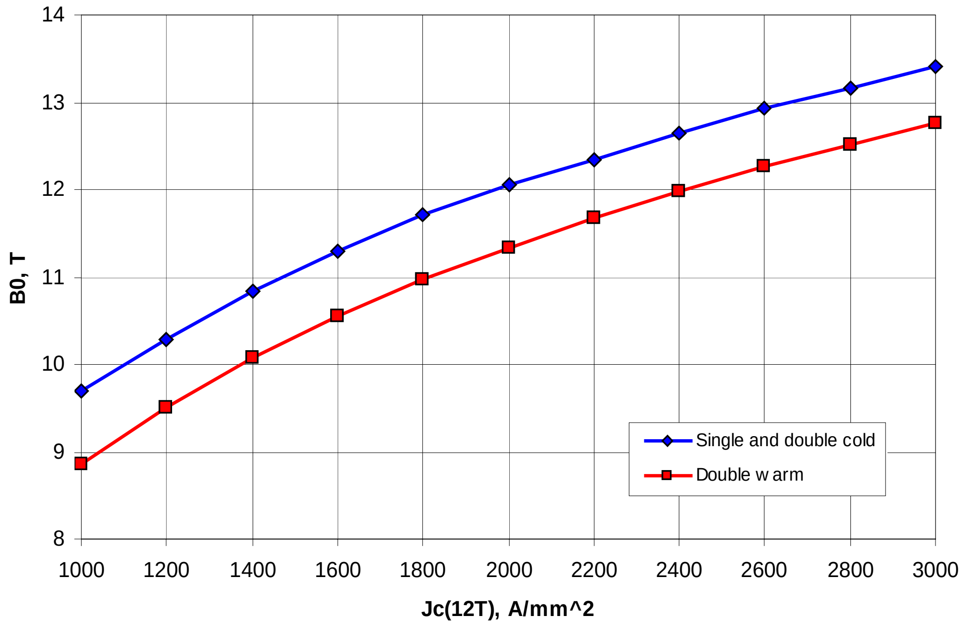
Double-Bore Warm-Yoke Design





- bore diameter 43.5 mm
- bore separation 180 mm
- cold mass size 385 mm
- thin SS skin
- yoke OD 580 mm = cryostat OD
- yoke thickness 40 mm
- asymmetric coils

Short Sample Limit & Nominal Field



Maximum field vs. Jc@12T in the coil
Cu:nonCu=0.85:1

Critical current margin - 15%

Critical current degradation - 10%

Cu:nonCu ration - 1.2:1

	Cold yoke		Warm yoke	
Jc(12T,4.2K), kA/mm^2	B_{nom}, T	B_{max}, T	B_{nom}, T	B_{max}, T
2.2	10	11.5	9.4	10.8
3.0	11	12.7	10.4	11.9

B_{nom}=11-12(cold yoke)/10-11 T(warm yoke)

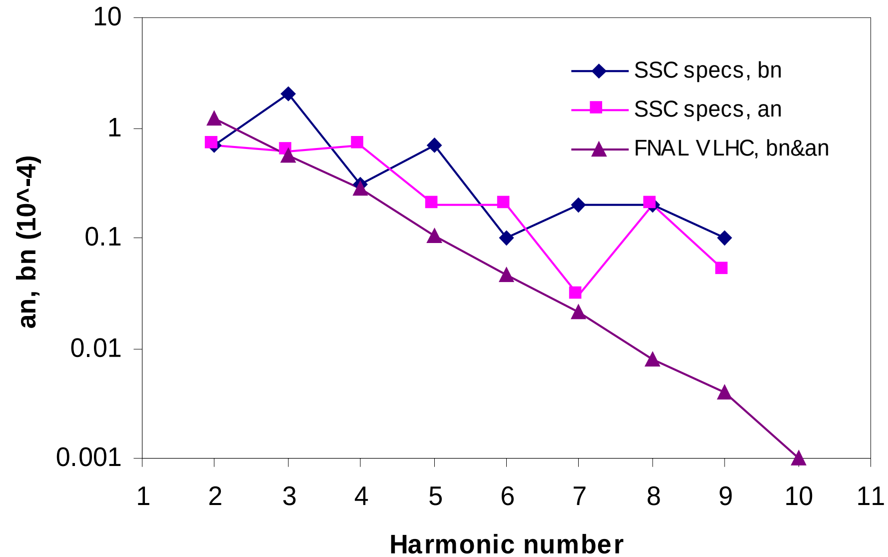
Field Quality

Systematic geometrical field errors @1 cm

Field harmonics	Cold yoke*	Warm yoke**	SSC specs
b2	-	0.000	-
b3	0.000	0.000	0.008
b4	-	0.000	-
b5	0.000	0.001	0.018
b6	-	-0.012	-
b7	0.000	-0.011	0.040
b8	-	0.031	-
b9	-0.091	-0.13	0.089
b10	-	-0.011	-

*) Symmetric coil
**) Asymmetric coil

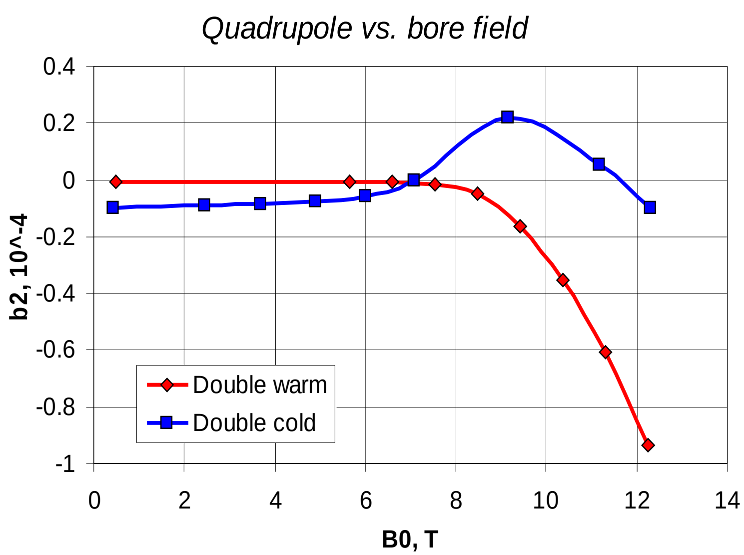
Random geometrical field errors @1 cm

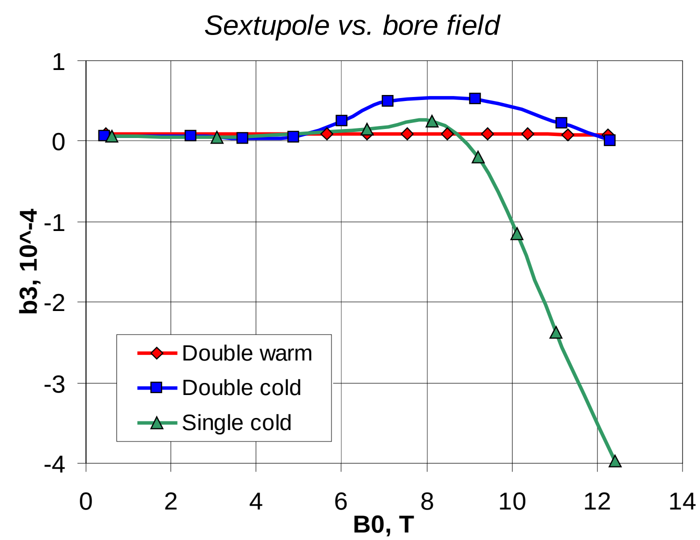


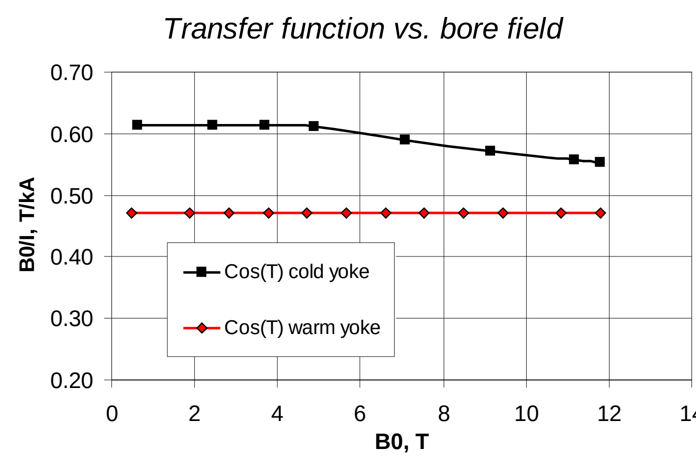
$$B_y(x,y)+iB_x(x,y)=10^{-4}\times B_1\sum_{n=1}^{\infty}(b_n+ia_n)\left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$

$B_x(x,y)$ and $B_y(x,y)$ – horizontal and vertical field components;
B_1 – dipole (main) component;
R_{ef} - reference radius (R_{ref}=1 cm);
b_n and a_n – normal and skew harmonic coefficients.

Iron Saturation Effect



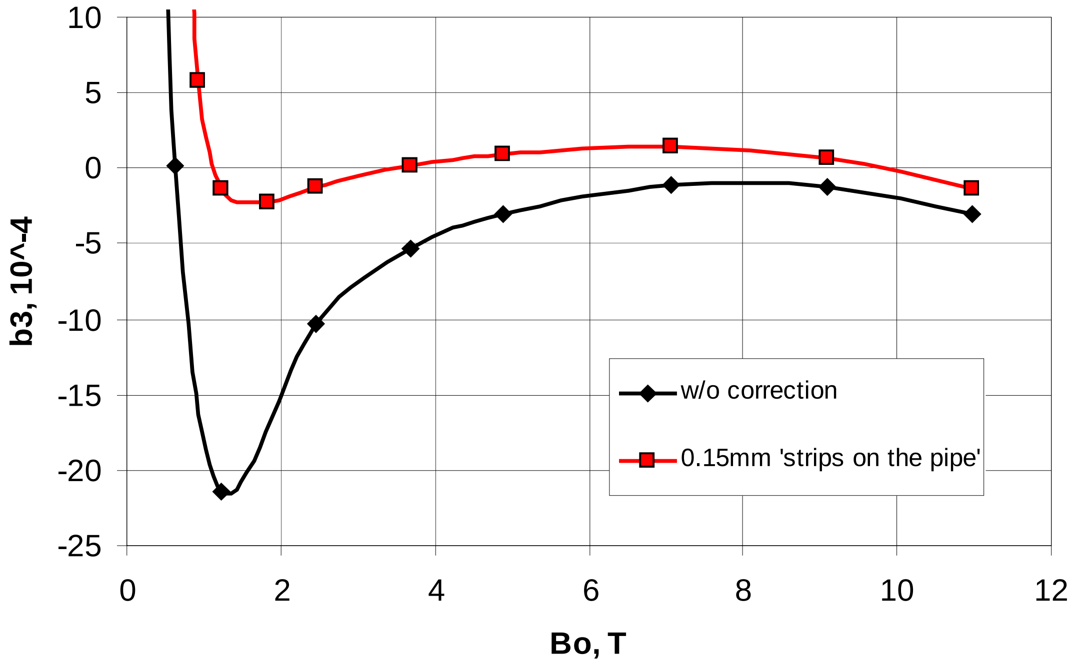




Summary:

- cold yoke design - holes, R_{out}
- warm yoke design - asymmetric coil, R_{in}

Coil Magnetization Effect



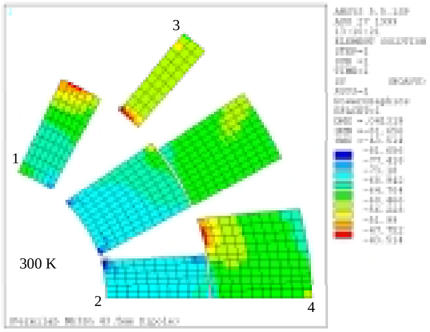
Summary:

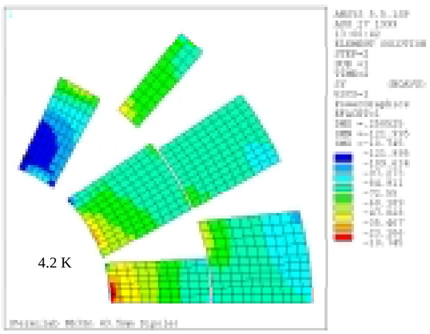
Persistent currents: - small deff<40µm, passive correction

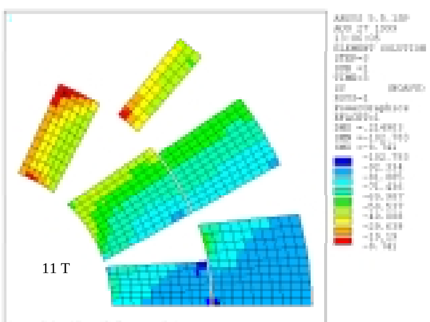
Eddy current effects: - strand: small lp~10-20 mm

- cable: large Ra (cable with SS or iron core)

Mechanical Analysis







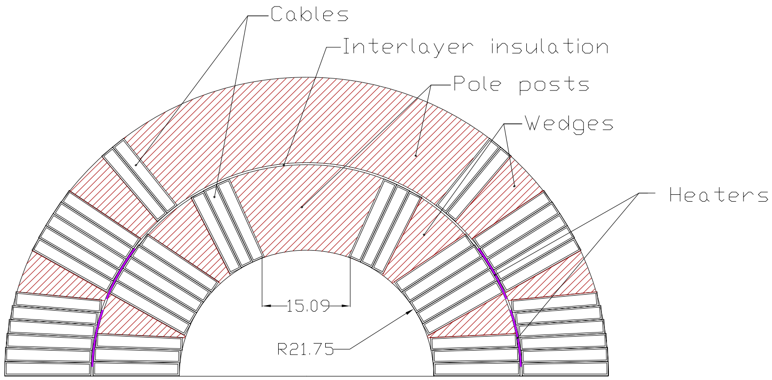
Peak equivalent stress in the coil (MPa)

Design	300K	4.2 K, 0T	4.2K, 12 T
Single cold yoke	80	121	104
Double cold yoke	120	132	125
Double warm yoke	132	118	121

Summary:

- coil stress: σ_{eq}<150 MPa and σ_{az}>0 at all conditions
- coil bore deformation is small: ΔR<100 μm
- all structural elements work in elastic regime

Quench Protection



Short model quench parameters:

Quench integral, MIIT	12
Tmax inner coil, K	180
Tmax outer coil, K	130
Vmax turn-turn, V	15
Vmax coil-ground, V	100

J_{cu}~1.8-2.0 kA/mm^2

Summary:

- For long (10-15 m) magnets ⇨ Cu:nonCu=1.2:1
- Minimum heater energy: to be studied experimentally

Research: Summary

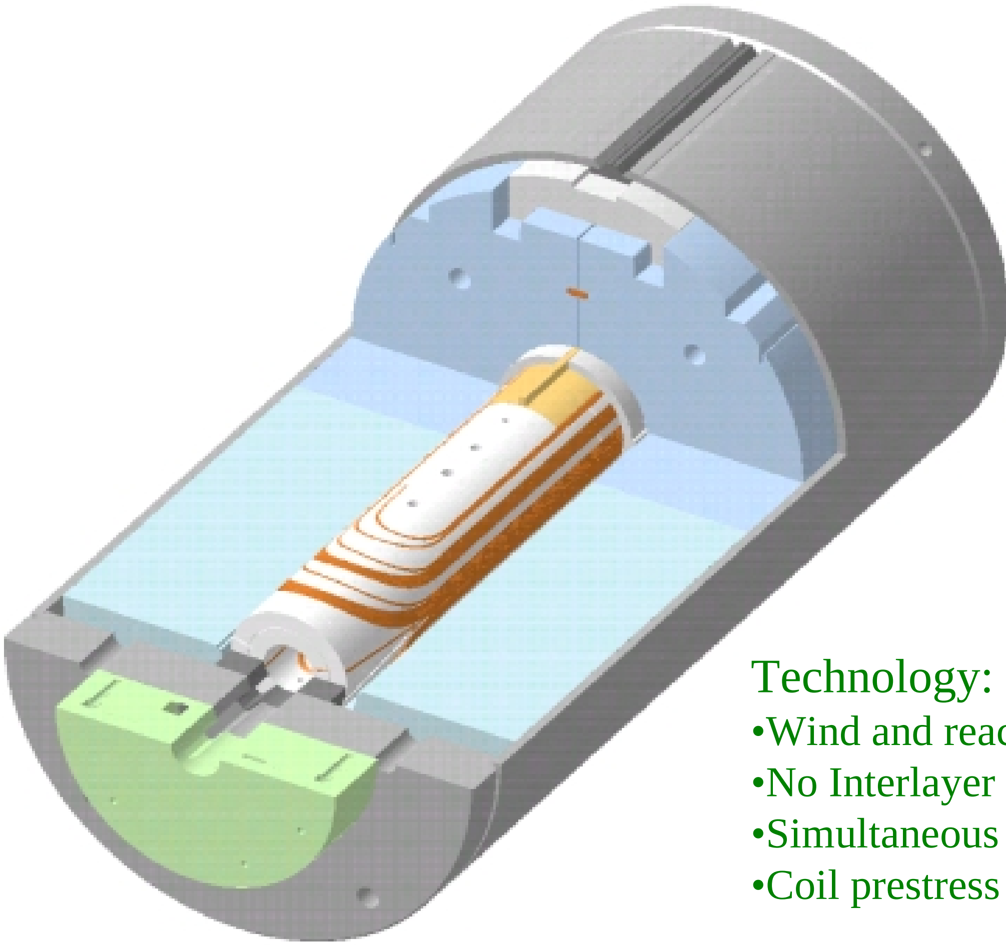
The magnetic and mechanical design of single and double aperture dipole magnets for VLHC based on the cos-theta coil geometry with cold and warm iron yoke has been developed. All magnets met the target requirements:

- B_{max}~10-11 T for commercially available Nb3Sn strands
- B_{nom}~11-12 T with 15% margin will be achieved using new R&D strands
- accelerator field quality is provided in the field range of 1-12 T. Field range can be expended by reducing d_{eff} in R&D Nb3Sn strands and using simple passive correction
- chosen mechanical designs and the coil prestress level provides the coil mechanical stability in the fields up to 11-12 T but safe for Nb3Sn strand.
- quench protection provided by the internal quench heaters. All quench parameters are on the acceptable level. Some increase of the Cu content in full-scale coils is required.

The cos-theta magnets provide higher maximum field in the same magnet bore, have lower stored energy and smaller coil volume than common coil magnets

The cos-theta design with warm yoke provides also significant reduction of magnet size without a noticeable degradation of its characteristics

Short Model Features



Design Features:

- •Nb3Sn cable
- •High temperature ceramic insulation
- •Bronze End Parts and Pole Pieces
- •Aluminum Spacers
- •400 mm Vertically Split Iron Yoke
- •Aluminum Clamps
- •8 mm thick Stainless Steel Skin
- •Stainless Steel Skin Alignment Key
- •50 mm thick SS end plates

Technology:

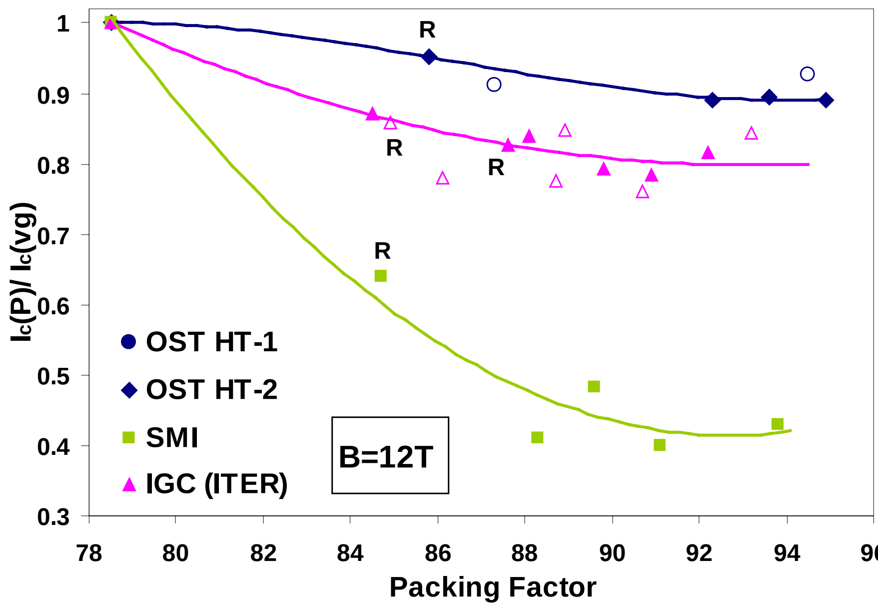
- •Wind and react technique
- •No Interlayer Splice
- •Simultaneous Reaction and Impregnation of two Half-Coils
- •Coil prestress provided by both Al clamps and SS Skin

We use some tooling and magnet parts from the HGQ project

Nb_3Sn Cable

Nb_3Sn cable optimization:

- •different strands (IT, MJR, PIT)
- •heat treatment
- •packing factor
- •inter strand resistance (SS core)



Ic degradation vs. cable packing factor @ 12 T

Insulation

S-2 Fiber Glass Tape:

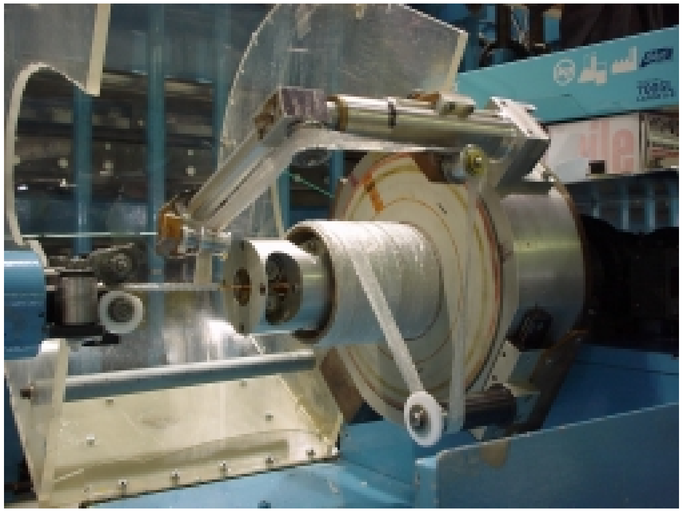
- affordable, traditionally being used to insulate Nb_3Sn cable
- involves lot of pre-processing
- was very weak to be used with an automated wrapping machine
- was improved in collaboration with a weaving company by orienting the fibers in the favorable direction
- were recently successful in using S-2 glass tape w/ o any organic binder

Ceramic Fiber Tape:

- does not contain any organic binder
- is strong enough to use for wrapping around the cable
- expensive

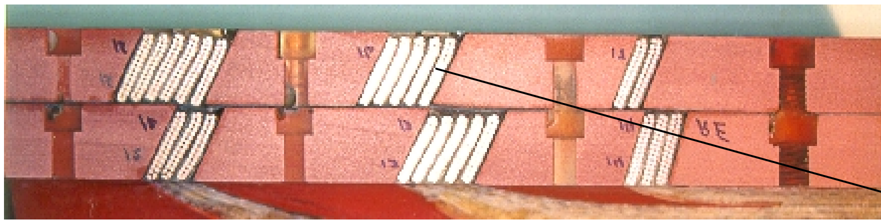
Ceramic Binder (CTD Inc.):

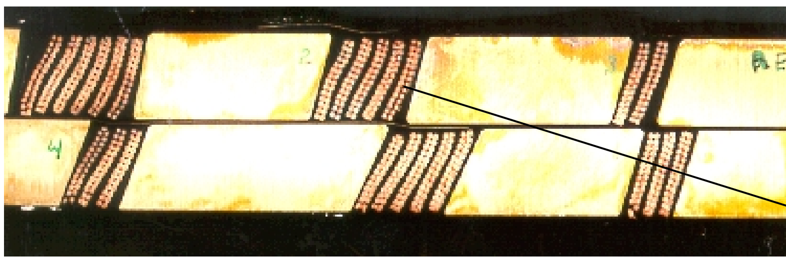
- is an inorganic adhesive
- used to improve cable insulation stiffness before coil winding and to form the coils into right shape during coil curing.



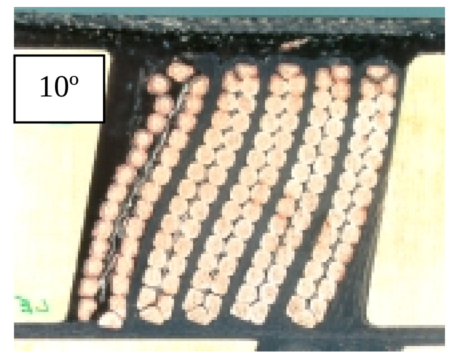
Cable insulation using the Insulation Wrapping Machine

End Part Optimization





BEND suggested angle = 43.2°



	Cost for 4 sets (84 parts)	Cost per part	Machining Time (minutes)
5-axis milling	32,000	380	60-120
5-axis waterjet machining	14,000	160	10-15

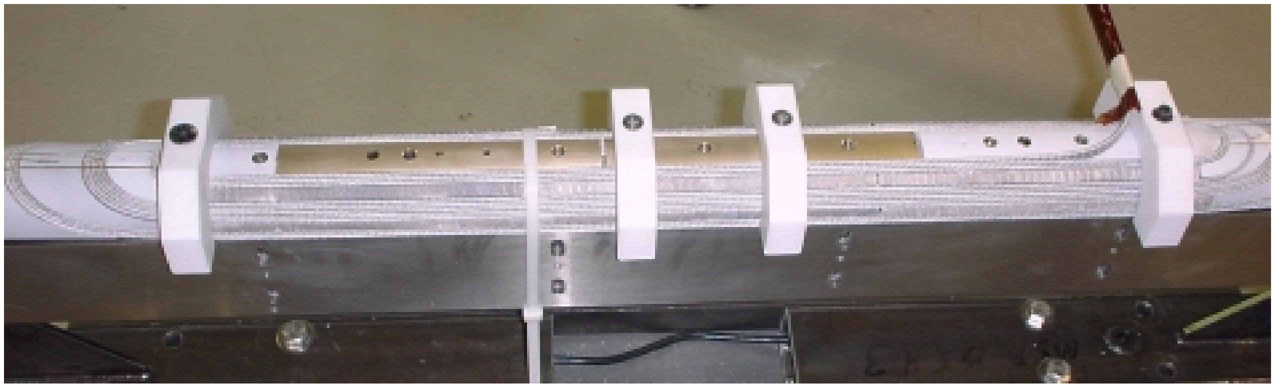
<u>Summary:</u>

•Rapid prototyping techniques reduce the time and cost of end part optimization process.

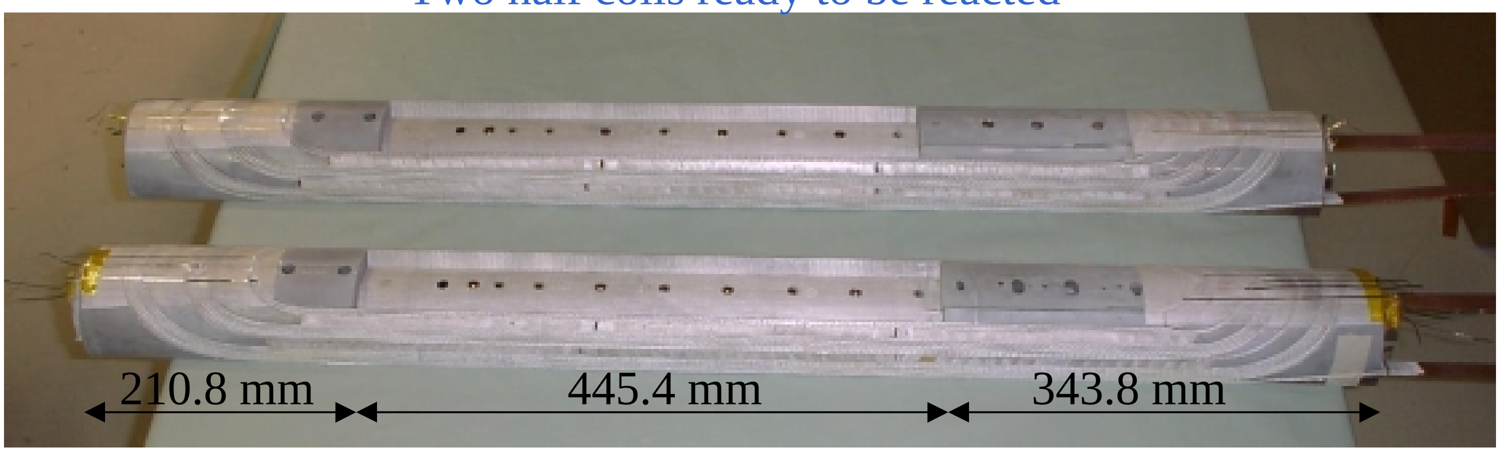
•Emerging technologies such as water jet machining promise of significant reduction of the end part fabrication cost.

Coils Winding and Curing

Inner layer winding



Two half coils ready to be reacted



Coil Reaction

Coils Assembled in the Reaction Fixture

Coil after reaction

Reaction cycle:
575 °C for 200 h followed by 700 °C for 40 h with a ramp rate of 25 °C/h

Good bonding between the turns after reaction (allows to handle the coil easily and even perform size measurements under pressure)

Epoxy Impregnation

Impregnation:

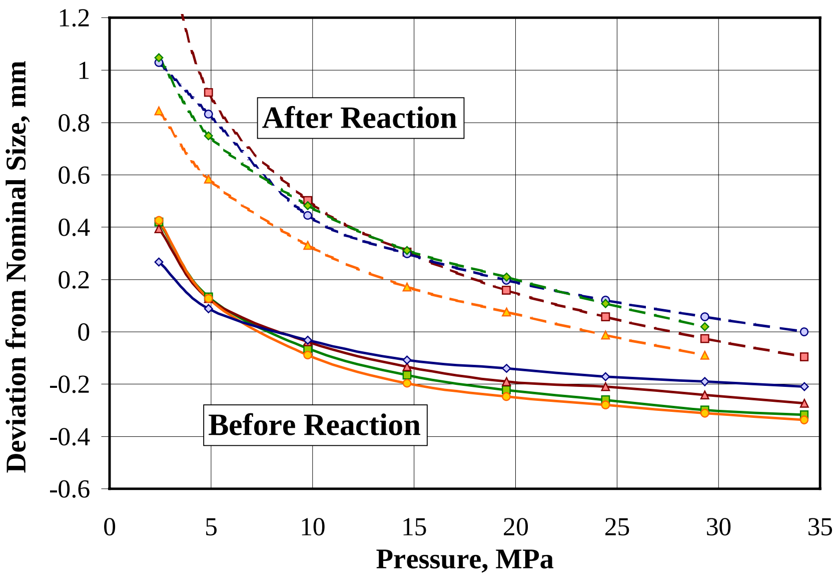
- •epoxy CTD 101K
- •time 5 h

Curing:

- •temperature 125°C
- •duration 20 h

Mechanical Measurements

Azimuthal Size Variation



Electrical Measurements

	Inductance μH	Quality Factor	Resistance mΩ
BEFORE REACTION			
First Half Coil	232.4	6.01	56.5
Second Half Coil	236.4	6.36	62.8
AFTER REACTION			
First Half Coil	94.3	0.93	78.6
Second Half Coil	200.8	2.68	81.9

Coil Azimuthal Size: increased after reaction by 0.7 mm

Coil Length Variation: increased by 9mm after reaction

Observation: - turn-to-turn shorts in the first half coil
- tin leakage in the coils.

Possible Cause: - strand/cable mechanical defects,
- removal of low temperature (200 °C) step from the reaction cycle
- high compaction of coils in the fixture before reaction.

Summary: Azimuthal size of the coils should be less than nominal

- Reduces the compaction of coils in the reaction fixture
- Coil will grow to the nominal size after reaction

Coil and Yoke Assembly

Short model assembled with iron yoke

Mechanical Model

Coil block

Yoked Mechanical Model

Azimuthal Stress Measurements (MPa)

		Coil	Spacer	
		Pole	***Mid-Plane***	***Pole***
Model				
	Under Press	154	88	152
	Under Press + Clamp	156	91	161
	After Spring back	32	40	51
Analysis				
	Under Press	145	122	156
	After Spring back	40	43	50

Mechanical calculations and measurements correlate quite well.

Development: Short Model Program Status

The developed coil design and fabrication technique resulted in a coil with good mechanical properties.

Coil size and reaction process needs to be optimized to eliminate over-sizing, tin leaks and turn-to-turn shorts.

The magnet assembly procedure and the ANSYS analysis have been verified using short model assembly and mechanical models

Fabrication of new coils for the first short model is in progress and we expect to complete the production in January 2001 and test it in February 2001.

Fabrication of cable for second and third short models is scheduled for November. Magnet fabrication will starts in December 2000.

Second model tests are expected in May 2001.

Acknowledgments

N. Andreev, G. Ambrosio, E. Barzi, P. Bauer, D. Chichili, V. Kashikhin, P.J. Limon, I. Terechkine, J.C. Tompkins, S. Yadav, R. Yamada, V. Yarba, *FNAL, Batavia, IL, USA*

S. Caspi, R. Scanlan *LBNL, Berkeley, CA, USA*

M. Wake, *KEK, Tsukuba, Japan*