Title
Nb3Sn Magnet Development at LBNL

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Advanced Accelerator Magnet Workshop

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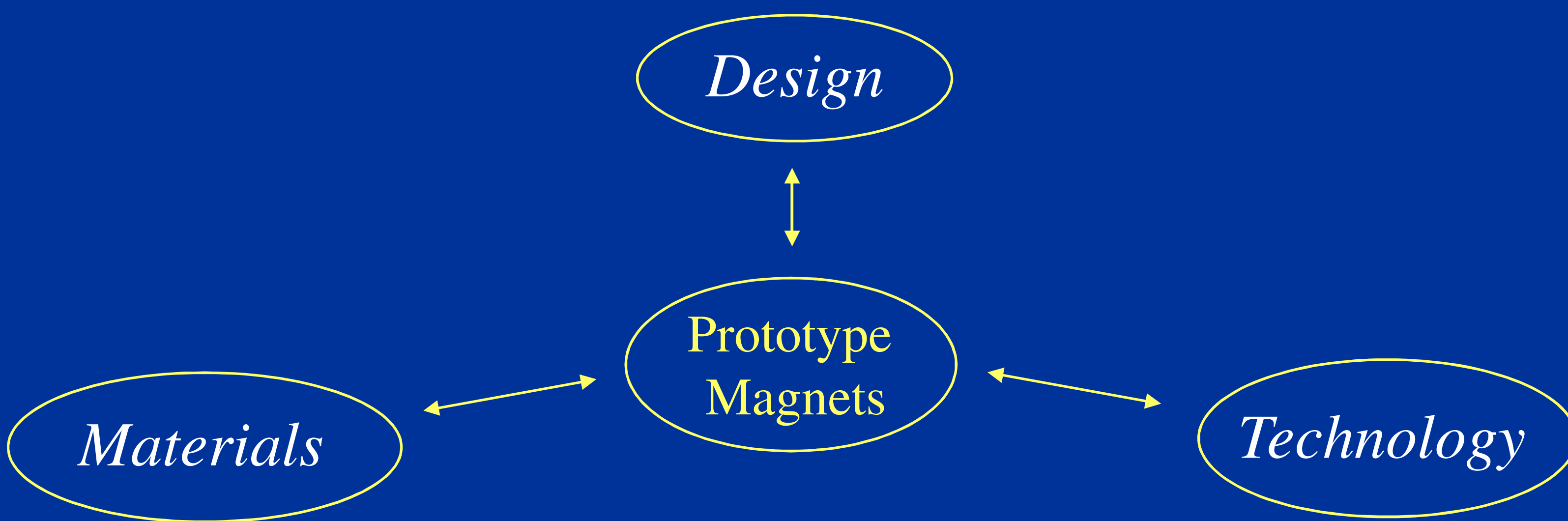
LBNL Program Goals

Develop and establish the technologies associated with high-field superconducting magnets, in order to provide cost-effective options for the next-generation high energy physics accelerators. Apply our expertise towards the goals of the HEP community.



Accelerator Magnet Requirements

1) Fundamental requirements:

- Achieve operating field
- Meet field quality specs
- Safely withstand quench

2) Efficiency/cost issues:

- Operating point near short sample limit
- Minimum/no training
- Minimize conductor & structural materials
- Simple, reliable fabrication procedures

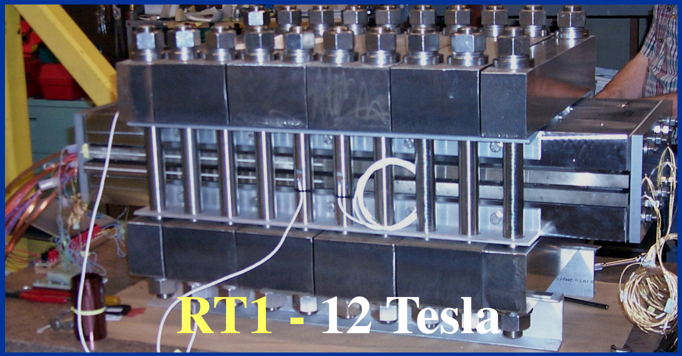
↔ Accelerator Quality Magnets

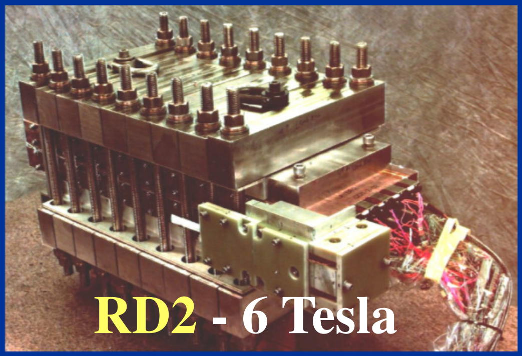
LBNL Prototype Series

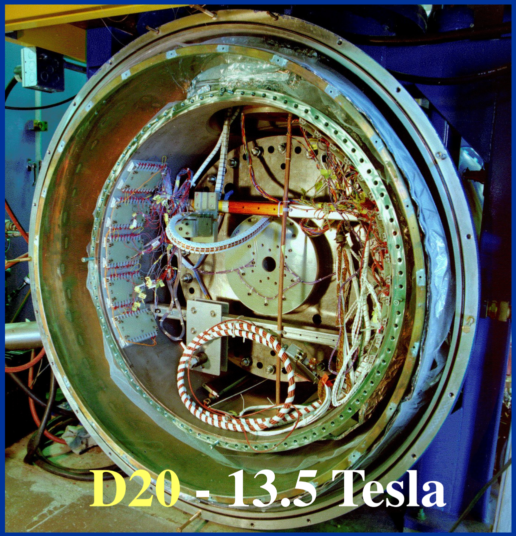
- *D:* *Single aperture, shell-type* *(1992-1997)*
- *RD:* *Twin aperture, common coil*
- *HD:* *Single aperture, block-type*
- *SM:* *Subscale (common coil)*

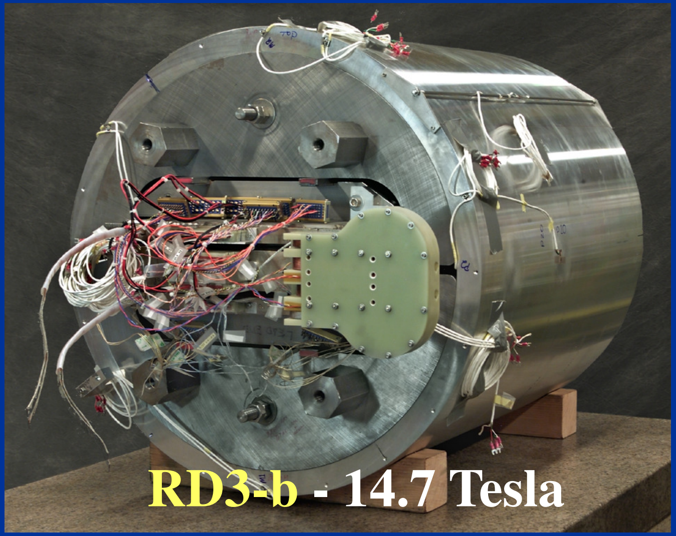
(1998-2003) (RD, HD, SM)

LBNL Prototype Highlights









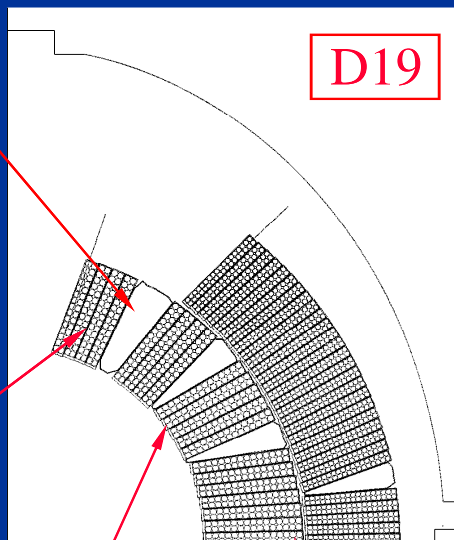
Prototype Objectives and Features

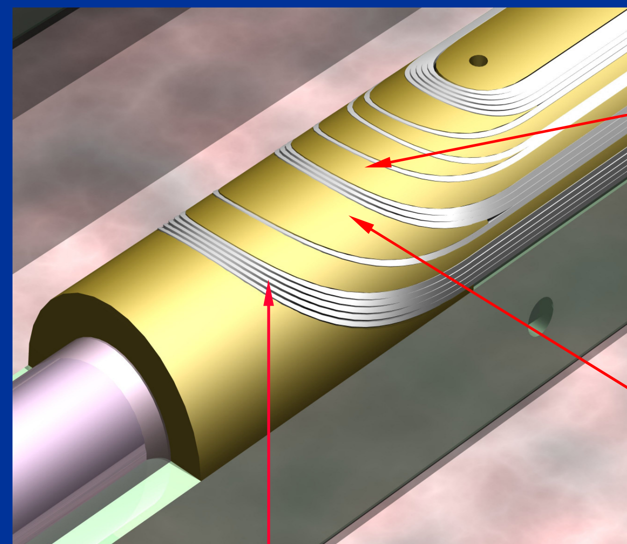
Magnet	Year	Field	Type	Design Features
D19H	1996	10.2 T	Cos θ	Coil Fabrication Process
D20	1997	13.5 T	Cos θ	Clear bore 50 mm, body/end optim.
RD2	1998	5.9 T	Comm. Coil	New "RD" configuration
RT-1	1999	12.2 T	Comm. Coil	High Field in RD configuration
RD3b	2001	14.7 T	Comm. Coil	New support structure, high stress
RD3c	2002	10.0 T	Comm. Coil	Clear bore 35 mm, auxiliary coils
HD-1	2003	(16.2 T)	Block	New "HD" configuration
RD3d	(2004)	(11.0 T)	Comm. Coil	Bore 40 mm, saturation, end field

Accelerator Quality in Cosθ Magnets

Wedges for field quality

Pole turns for field quality





End Spacers for field quality

Fillers for transitions at lead end

Keystoned cable, Roman arch for coil self-support

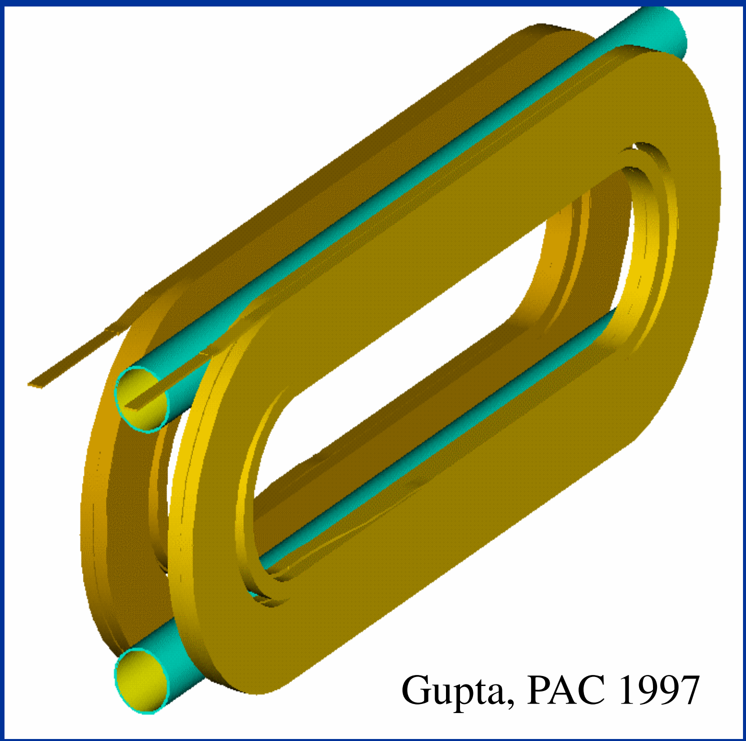
Midplane turns for magnetic efficiency

End saddle for internal bore support and physical aperture at coil ends

Main goal of D19H and D20 was to transfer these features to Nb_3Sn technology

RD Series: Common Coil Layout

A new design paradigm aiming at conductor compatibility and cost reduction



Gupta, PAC 1997

Advantages:

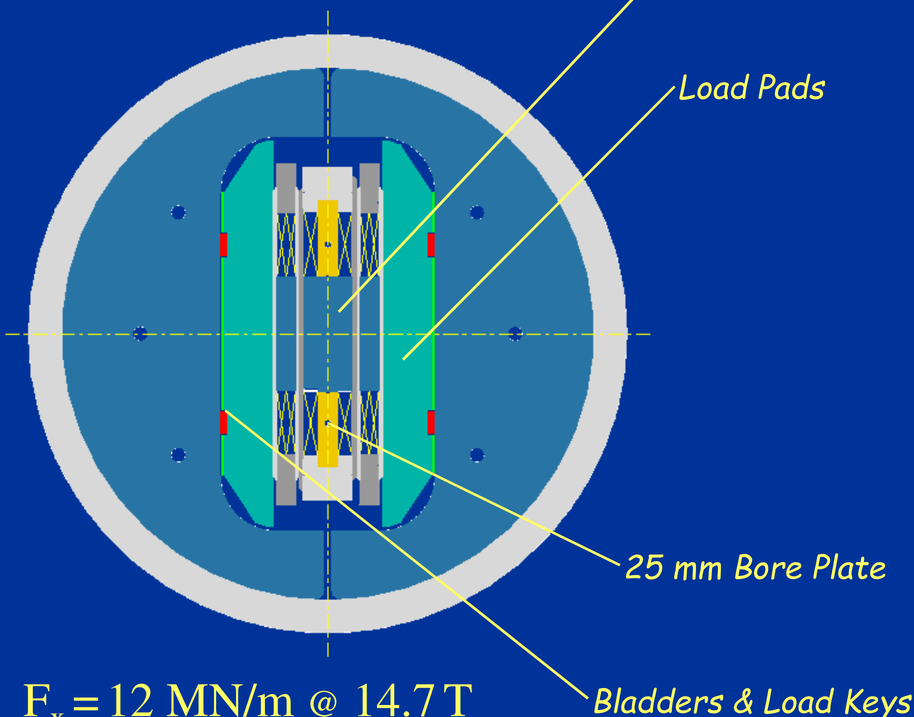
- *Large end radius (react and wind)*
- *Flat cable*
- *High packing in small aperture*
- *Simpler support structure*

Challenge:

Incorporate accelerator quality while maintaining simplicity

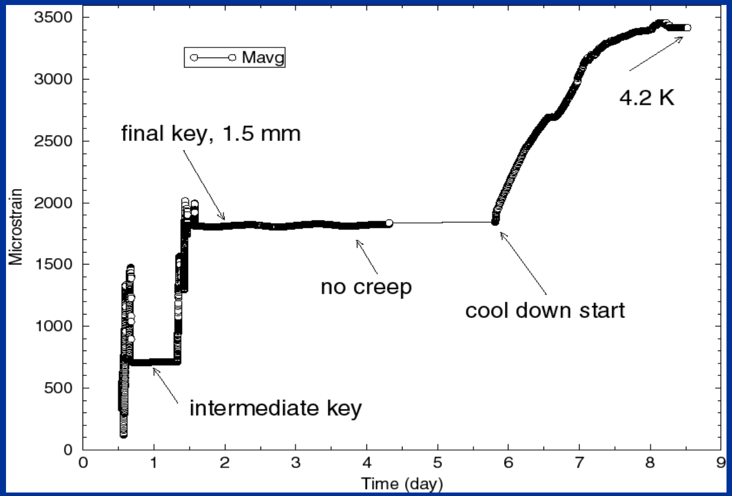
RD Series: Support Structure

RD3b Common Coil Magnet



$F_x = 12$ MN/m @ 14.7 T

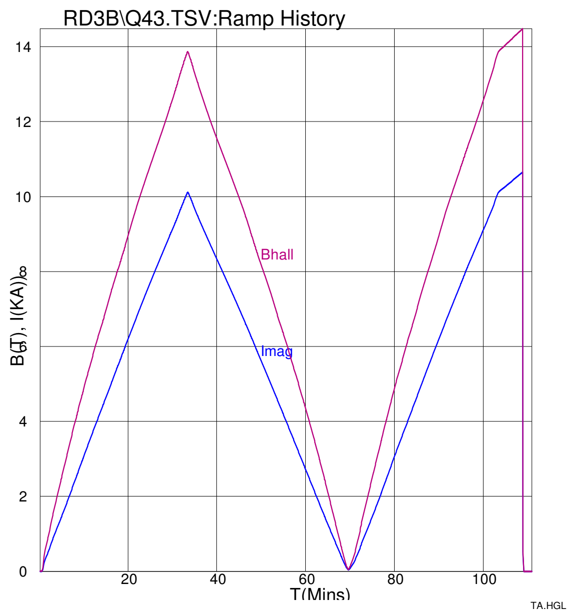
RD3b Magnet Assembly and Cooldown



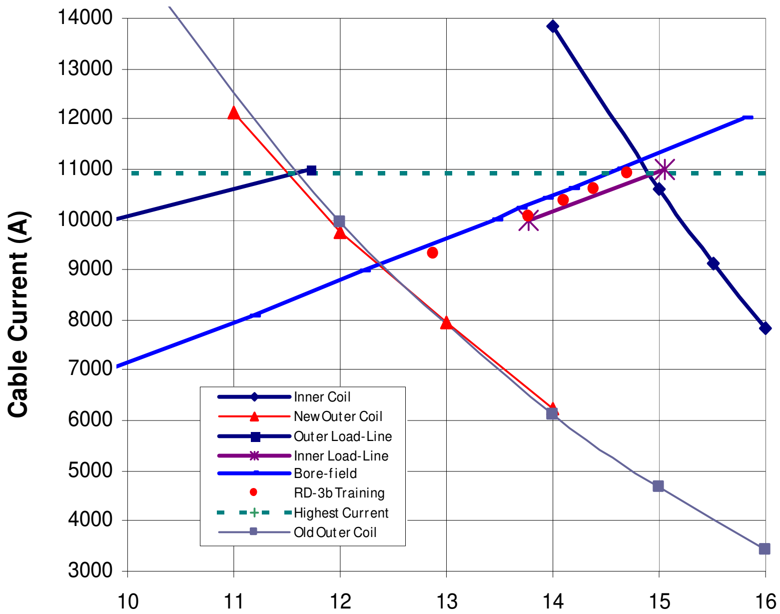
Pressurized Bladders

RD Series: Conductor Limits

RT-1, RD3B – No performance degradation up to 14.7 T, 120 MPa

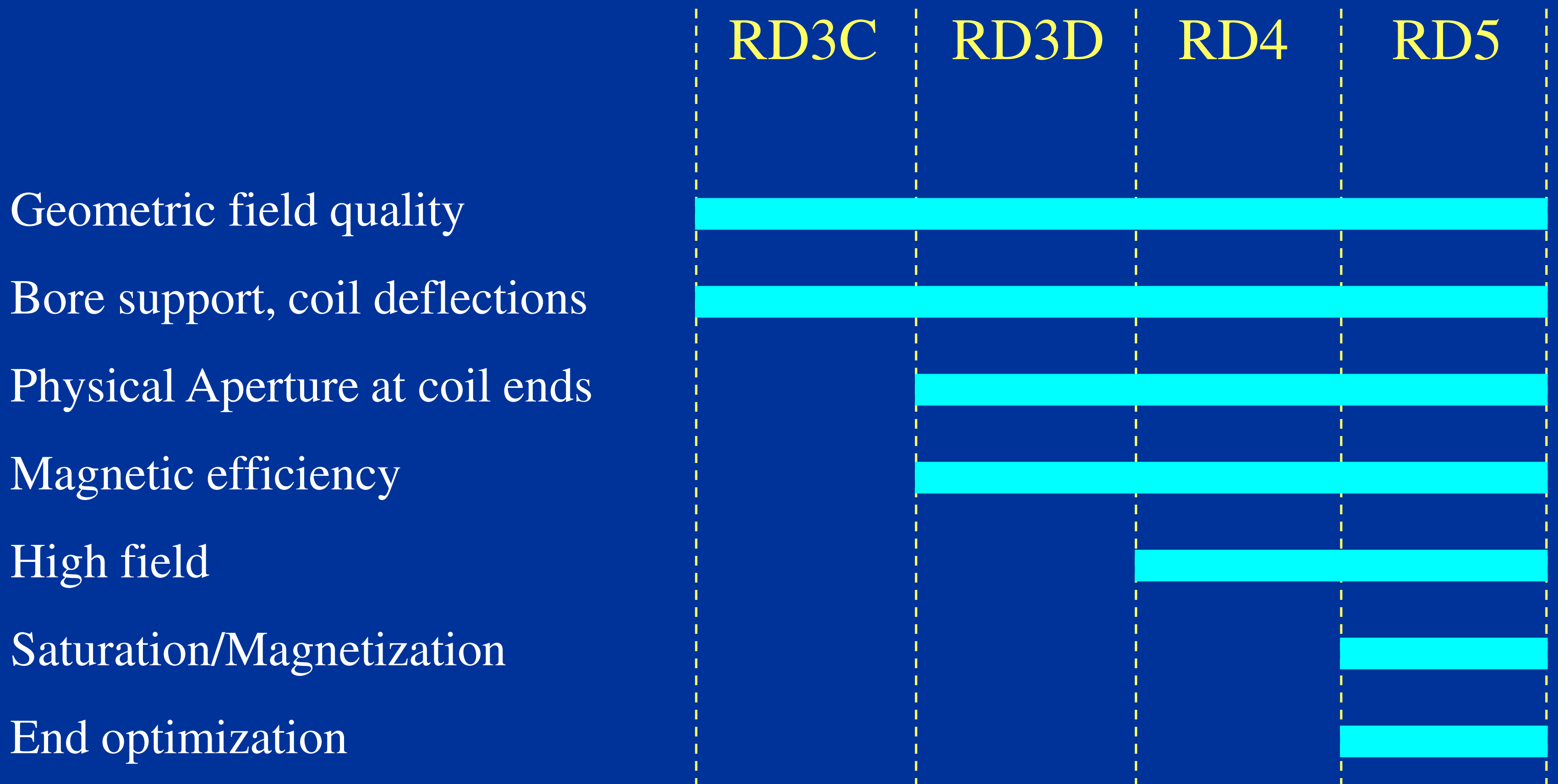


RD3B ramp cycle to quench (#43)



RD3B load lines and conductor limit **B [T]**

RD Series: Accelerator Quality



RD3c Objectives

For the first time in a common coil dipole:

1. Demonstrate central geometric harmonics at 10^{-4} level in a 35 mm bore
2. Perform measurements of other relevant geometric and dynamic effects
3. Compare experimental data with calculated values

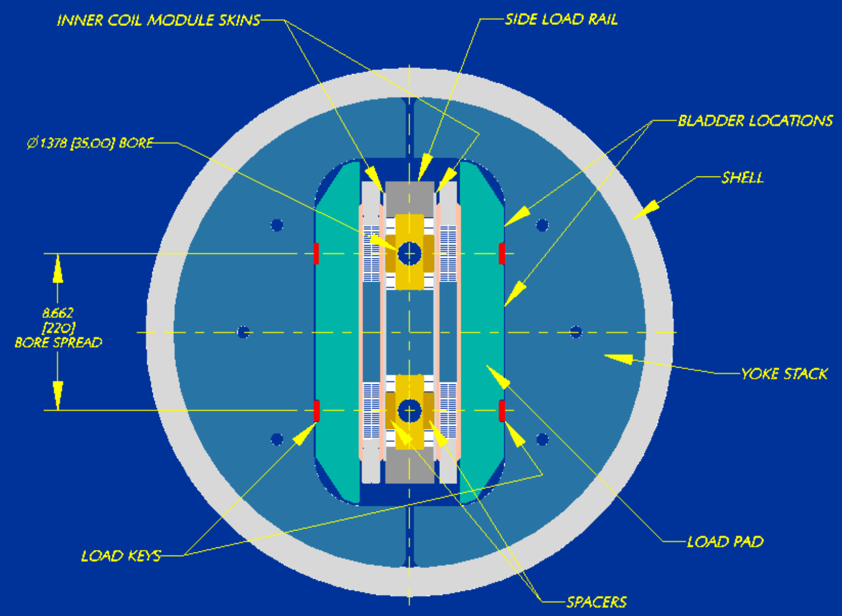
Simple coil configuration:

- RD3B Outer Modules
- New, RD3B-type inner module

Geometric field quality features:

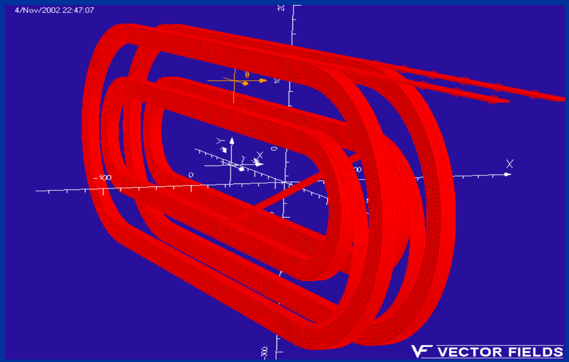
- Auxiliary (pole) turns
- Central spacer

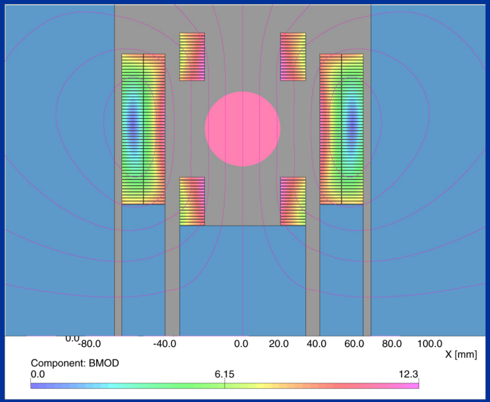
Design field: 10.9 T



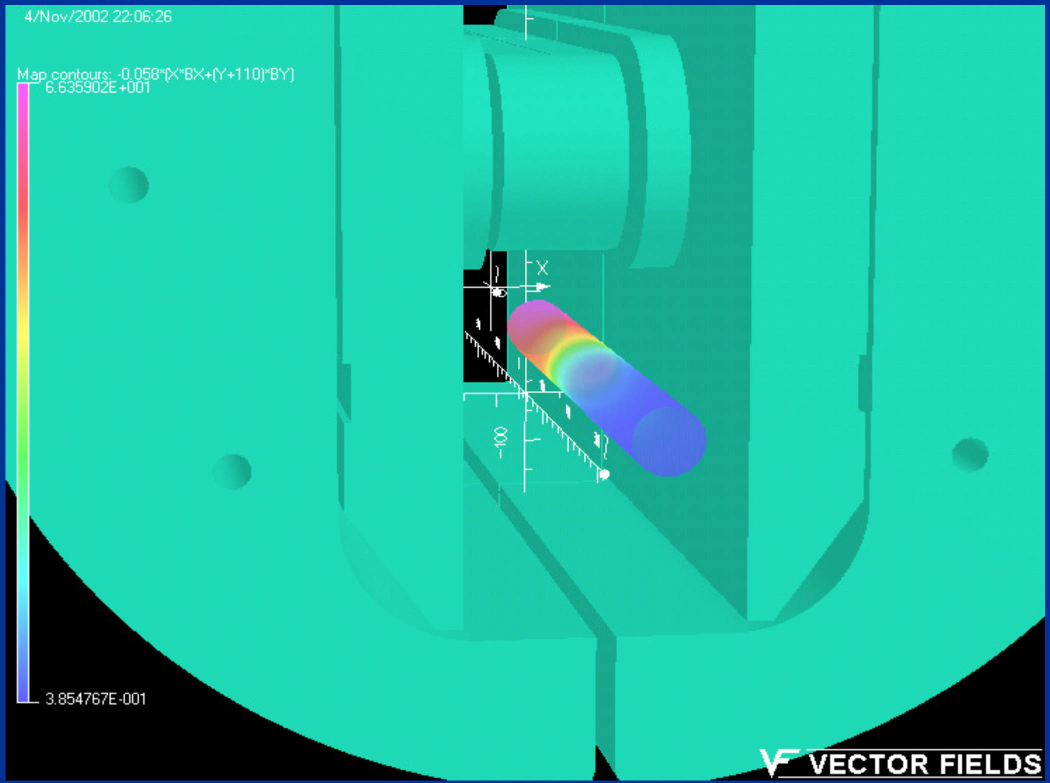
RD3c Magnetic Design

Coil geometry





Field at the probe



RD3c Integrated Harmonics

Normal	calculated	measured
b_3 (unit)	-5.44	-10.39
b_5 (unit)	-0.24	-0.02
b_7 (unit)	0.58	0.61
b_9 (unit)	<0.01	<0.01

Skew	calculated	measured
a_2 (unit)	-31.2	-15.65
a_4 (unit)	-1.56	-1.45
a_6 (unit)	0.01	-0.20
a_8 (unit)	<0.01	<0.01

I_{op}=10 kA, R_{ref}=10 mm

Integral over 43 cm is affected by coil ends, generally lower central harmonics

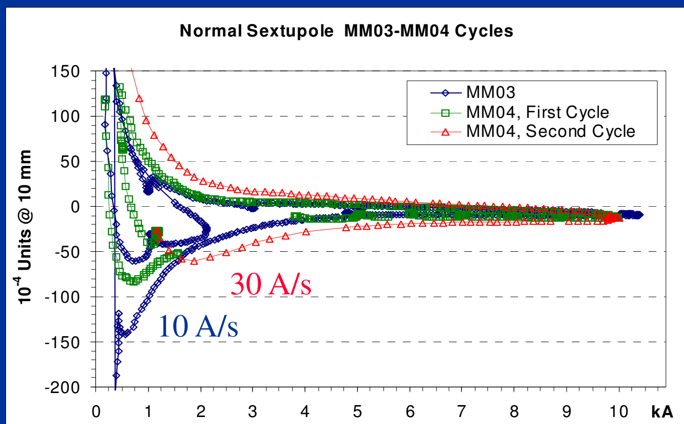
Normal sextupole: Value: saturation, ends. Discrepancy: coil geometry

Skew quadrupole: Value: saturation, ends. Discrepancy: geometry, saturation

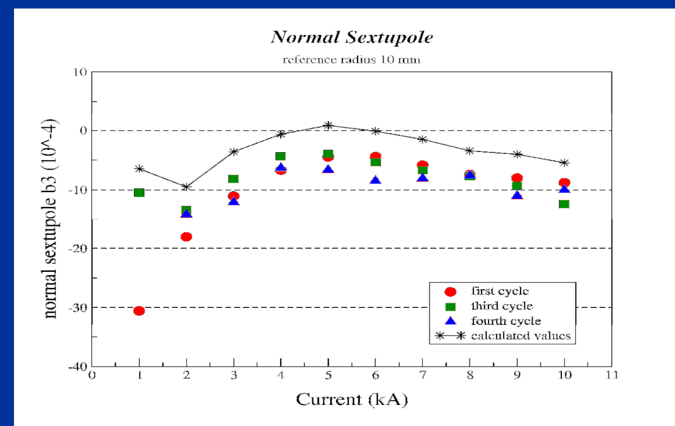
Octupole & higher: Value: small, in agreement with expectations.

RD3c Field Quality Analysis

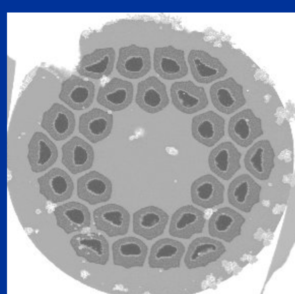
Conductor Magnetization – Eddy Currents



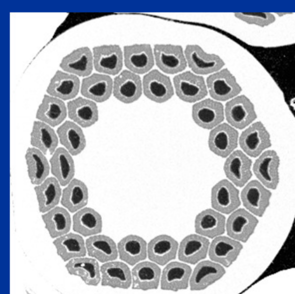
Iron Saturation



Nb_3Sn Strand Design

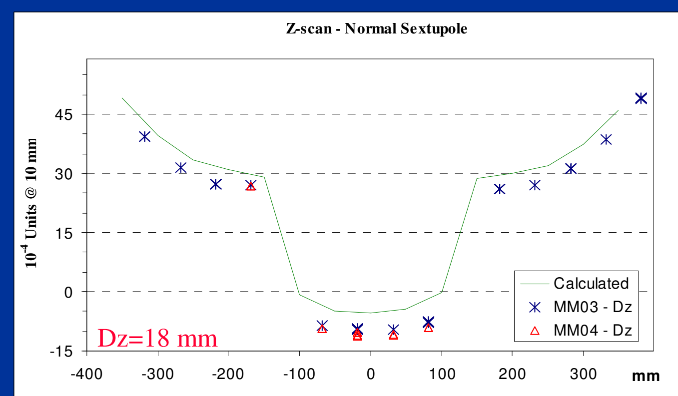


Ore 130
(RD3b outer)



Ore 88-90-103
(RD3a outer)

End Field



RD Series: Next Steps

RD3D

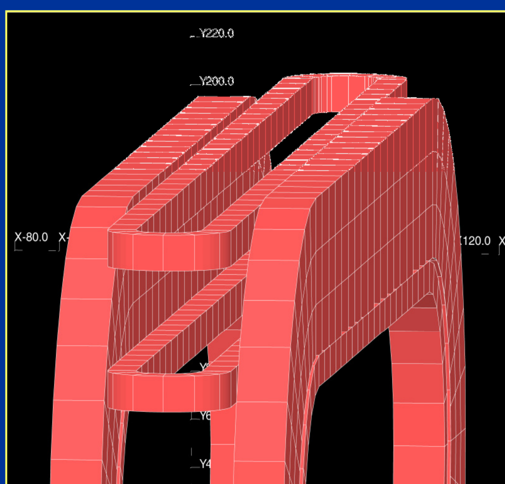
- Single layer aux. coils
- End optimization
- 10^{-4} geom. harmonics
- 11 T, 40 mm clear bore

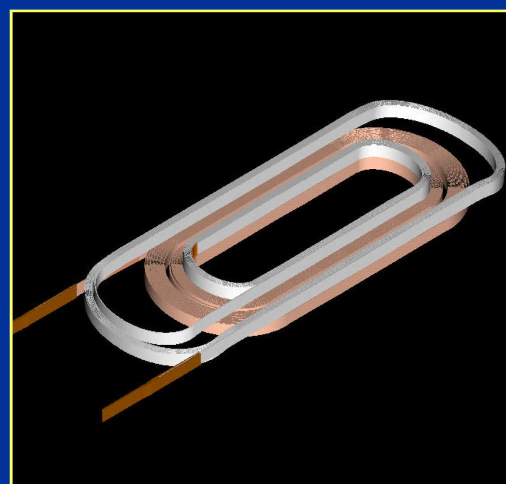
RD4

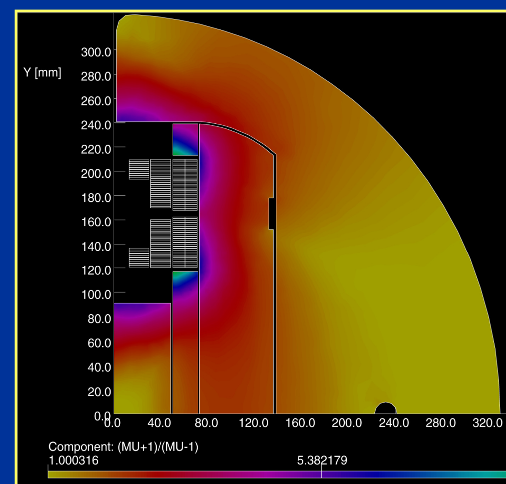
- Two-layer inner module
- Flared ends for aperture
- 10^{-4} geom. harmonics
- 13 T, 40 mm clear bore

RD5

- Four layers, flared ends
- 10^{-4} geometric, end harm.
- Saturation, magnetization
- 15 T, 40 mm clear bore





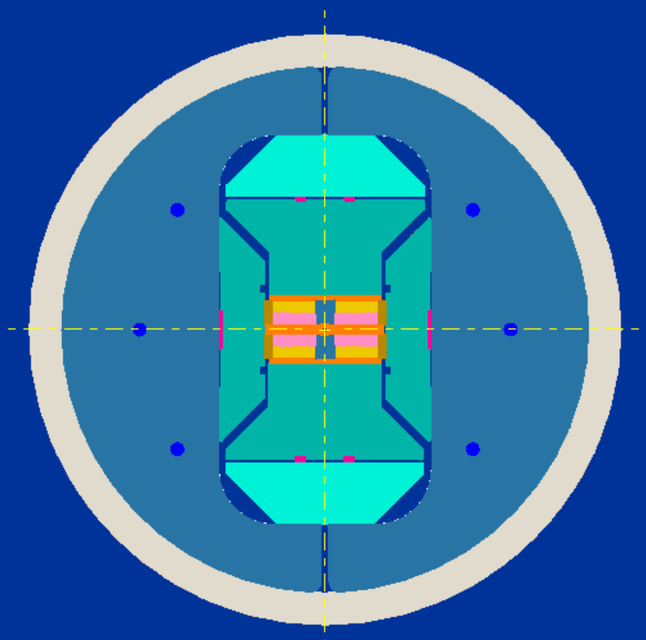


HD Series

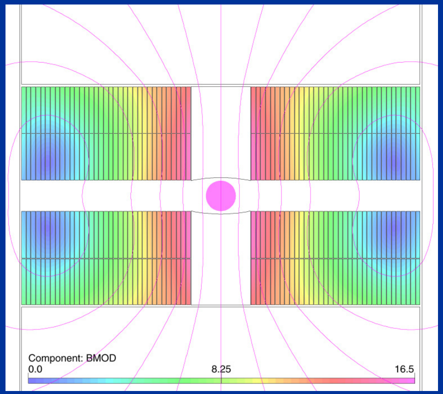
New High Field Dipole Test Configuration

Design Features:

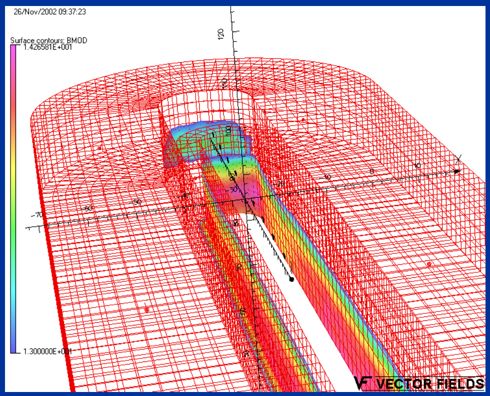
- Single bore
- Two flat double pancakes
- Horizontal configuration
- Dipole field 15-18 T



Magnet cross-section



Coil cross-section

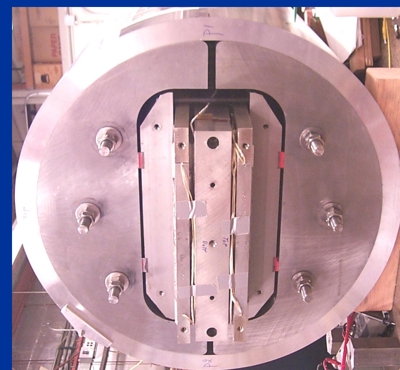


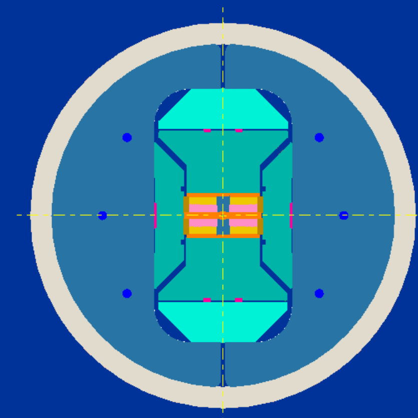
Coil end field

RD/HD Similarities

Basic features

- Block-coil
- Flat cable
- Double pancake





Fabrication

- Winding
- Reaction
- Impregnation

Magnetics

- Field profile
- Lorentz stress

Mechanics

- Force distribution
- Bore support

Assembly

- Bladders & keys
- Support structure

RD/HD Differences (1)

R&D prototype:

Parameter	RD	HD
Number of apertures	2	1
Conductor, energy, forces	2X	1X
Size (longitudinal, transverse)	Larger	Smaller

Two-in-one:

Parameter	RD	HD
Arrangement	Vertical	Horizontal
Force on structure	2X	1X
Conductor, energy, forces	Larger	Smaller
Size (longitudinal, transverse)	Larger	Smaller

RD/HD Differences (2)

Magnetics:

Parameter	RD	HD
Grading	Coil modules	Nested coils
Field/stress enhancement	Iron island	Iron pole
Symmetry	Left-right	Up-down
Central field quality	Aux. coils	Spacers
End peak field	Low	High
End Efficiency	Flared ends	End saddle

RD/HD Differences (3)

Mechanics and Fabrication:

Parameter	RD	HD
Minimum winding radius	Large	Small
React-and-wind	Yes	No
Load direction on cable	Narrow edge	Wide face
Load direction on coil	High modulus	Low modulus
End support	Iron	Non-magnetic
End compactness	Low	High
Layer transition	Low field	High field
Midplane gap	No	Maybe

HD1 Dipole

Goal (and challenge):

At one time, new coil configuration and new field record: 16+ T

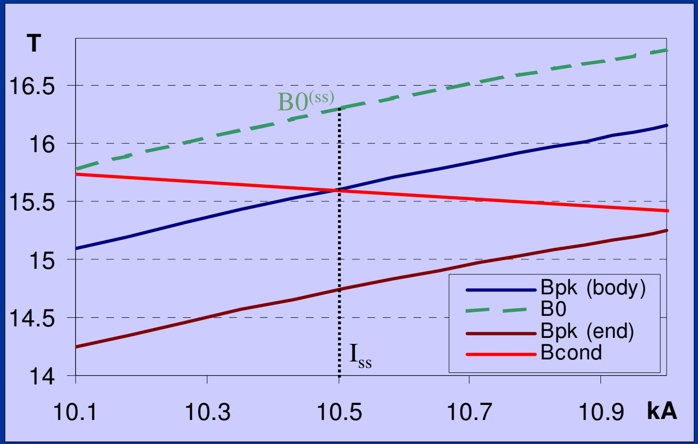
Design Features:

- Flat double-pancakes for simplicity (open midplane, less efficient)
- Magnetic pole for high field/stress (RD3B equivalent)
- Bending radius 10 mm (20 mm horizontal coil aperture)
- Midplane gap (vertical coil aperture): 10 mm

HD1 Performance Parameters

SHORT SAMPLE PARAMETERS

Parameter	Unit	HD1	RD3B
$B_0^{(ss)}$	T	16.2	14.6
$I^{(ss)}$	kA	10.5	10.8
B_{max}	T	15.6	14.8
$J_{cu}^{(ss)}$	kA/mm^2	1.2-1.4	1.1/1.5



ENERGY and FORCES

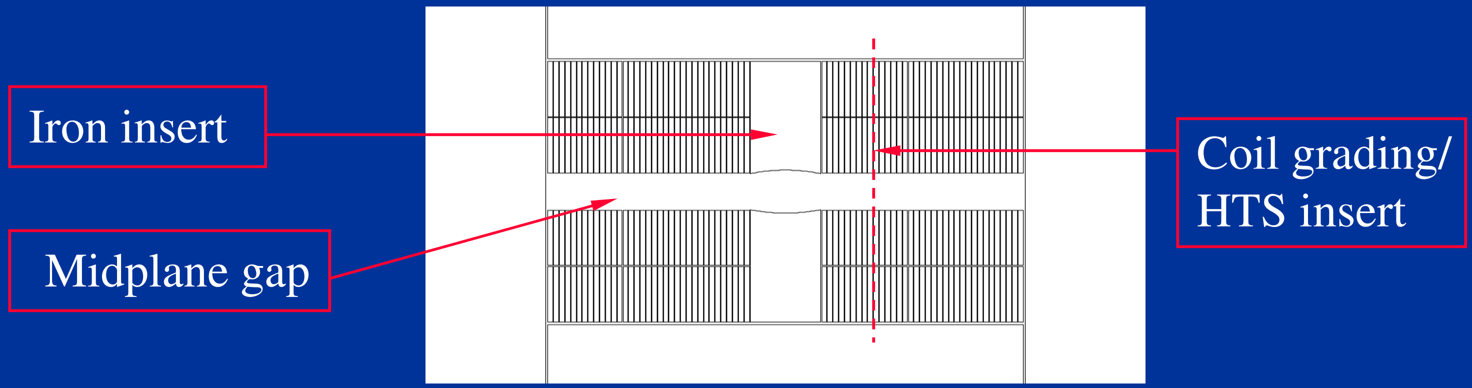
Parameter	Unit	HD1	RD3B
Stored Energy	MJ/m	0.62	1.2
Inductance	MH/m	11	21
F_x (quadrant, 1ap)	MN/m	4.1	3.7
F_y (quadrant, 1ap)	MN/m	-1.3	-2.3
Max. coil stress	MPa	150	120

CABLE PARAMETERS

Parameter	Unit	HD1	RD3B	
			Inner	Outer
Strand diameter	mm	0.8	0.8	0.8
No. strands		36	40	26
Cu/Sc		0.72-0.96	0.9	1.4
$N_t^{(quad, 1ap)}$		35+35	50	49+49

HD Series: Dipole Field

Design features	Dipole field (T)	Iss (kA)
HD1 reference	16.2	10.5
RD3B conductor	15.3	10.0
Nb_3Sn graded coil 8 turns 1/2 dens	17.5	14.0
HTS insert 7 turns 0.8 mm 361 A @ 18 T	18.6	13.0



HD Series: Conductor Limits

HD1 Dipole - Design field 16.5 T

Lorentz forces per quadrant:

$$Fx = 4750 \text{ N/mm} \rightarrow \sigma_{xcoil} = 153 \text{ MPa}$$

$$Fy = 1550 \text{ N/mm} \rightarrow \sigma_{ycoil} = 30 \text{ MPa}$$

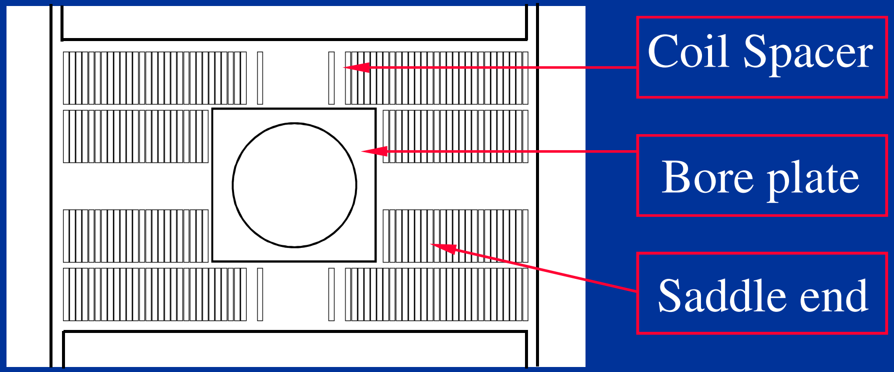
Stress Analysis	Room temp.	4.3 K	Nominal field
Shell stress (MPa)	14	115	120
Coil horiz. stress (MPa)	19	148	0 - **155**
Coil vert. stress (MPa)	5	17	5 - 40
Coil max eq. stress (MPa)	20	150	**155**

Approaching 200 MPa @ 18 T

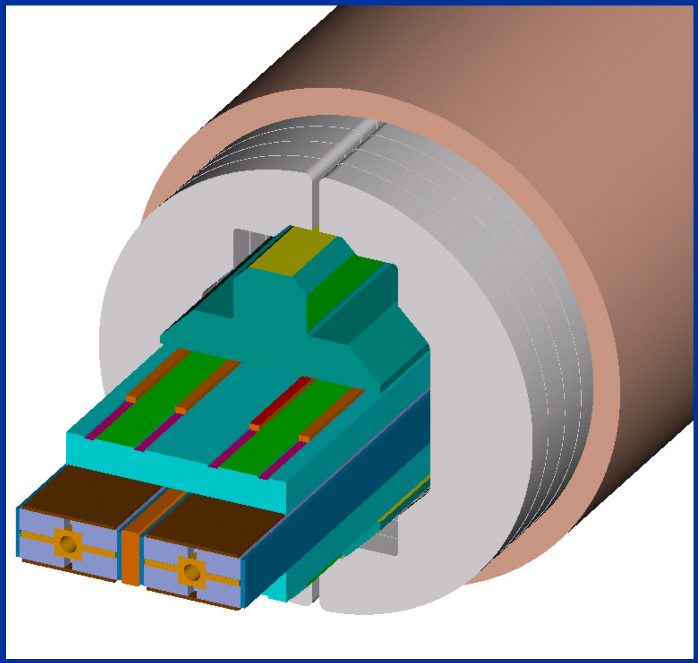
HD Series: Accelerator Quality

Design issues (and priority):

1. Saddle ends for efficiency
2. Clear bore size and support
3. Spacers & field quality



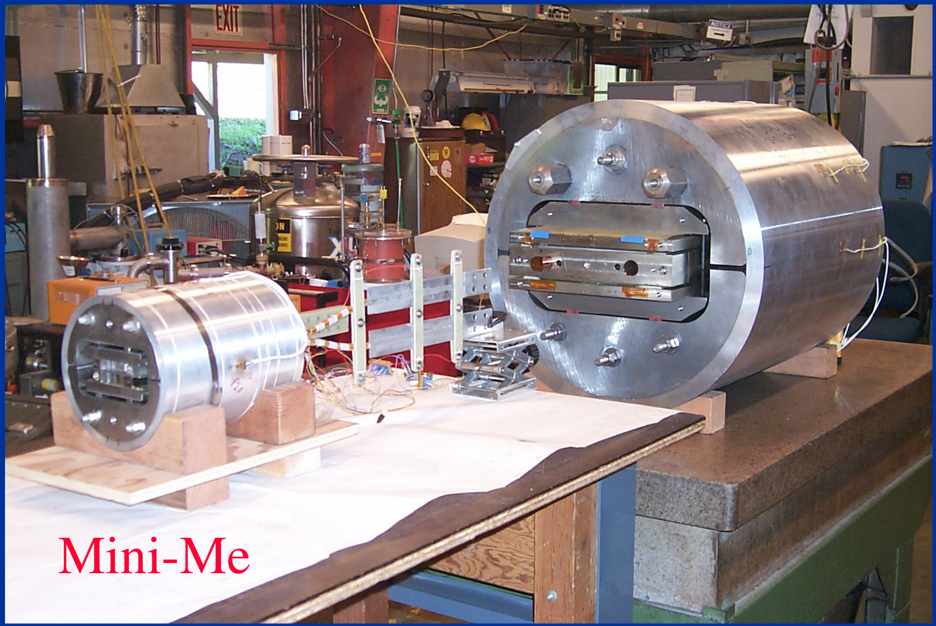
Dual bore configuration: S-LHC?



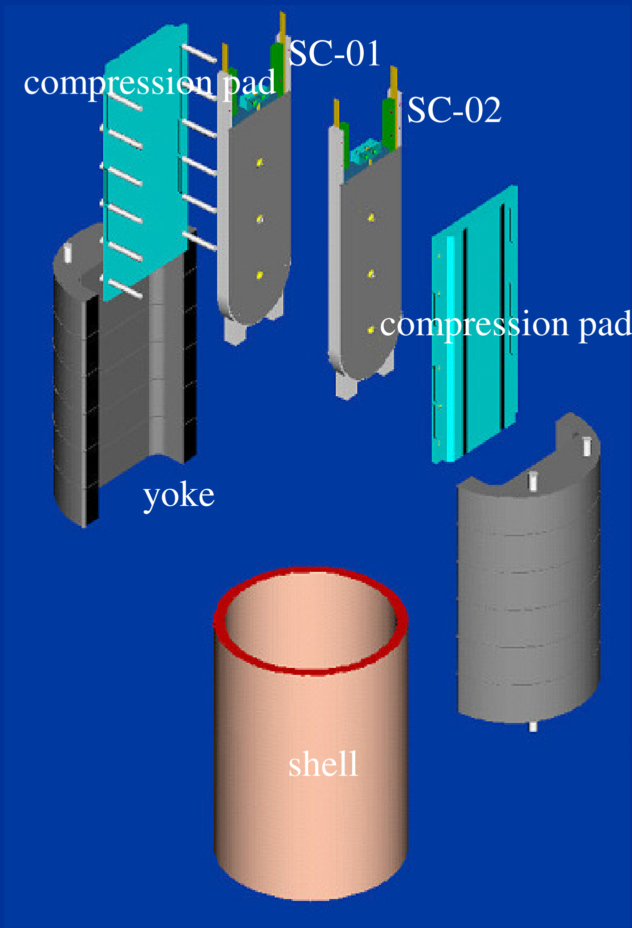
SM Series

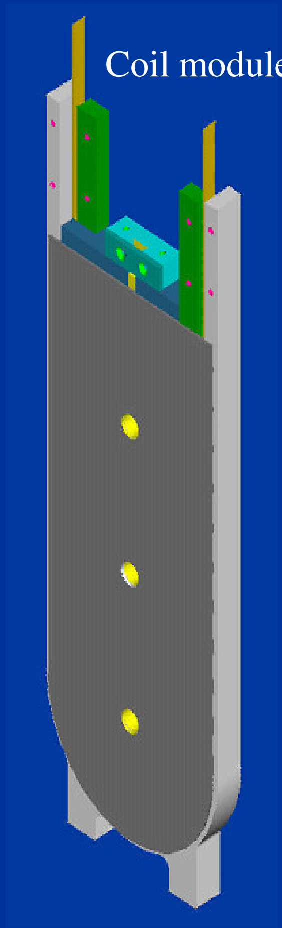
Parallel Program for Technology Development

- Scaled version of main magnet
  - Approx. 1/3 scale
- Field range of 9 – 12 Tesla
- Two-layer racetrack coils
  - 5 kg of material per coil
- Streamlined test facility
  - Small dewar
  - Basic instrumentation



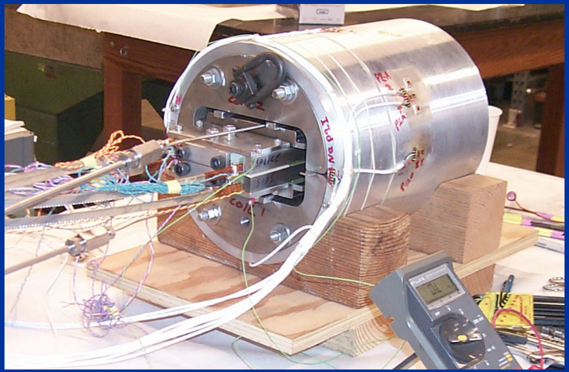
SM Magnet Features





Two layer coil

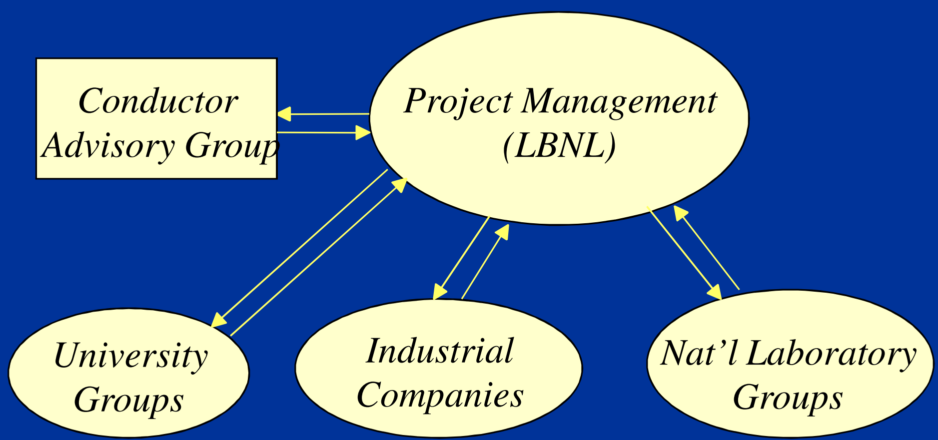
Assembled Magnet



SM Prototypes

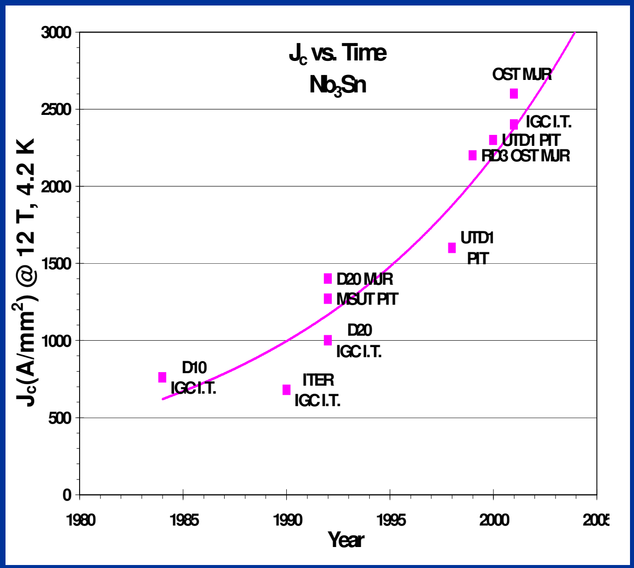
- SM-01
  - Developed the SM concept
  - Baseline "background" coils
  - Two preload configurations
  - SM-01a
    - 92 MPa horizontal preload
    - First quench at 85% short sample
  - SM-01b
    - Reduced preload to 10 MPa
    - Short sample at 11.9 Tesla
- SM-02
  - Mixed-strand
  - Low quench performance
- SM-03
  - Mixed-strand
  - Better performance than SM-02
- SM-04
  - CTD Ceramic Insulation System
  - Excellent performance
- SM-05
  - Quench protection limits
  - Analysis in progress

DOE Conductor Development Program



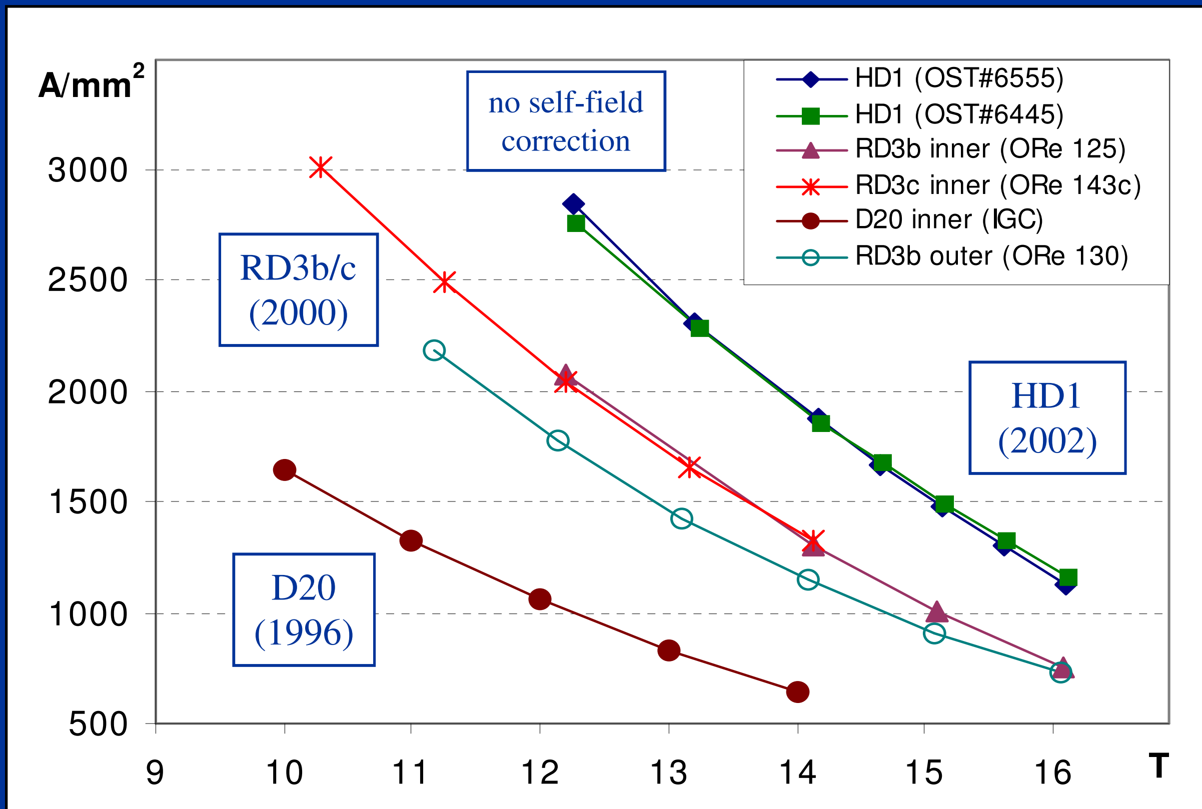
Started in 2000
Phase I : improve performance
Phase II : Scale-up, cost issues

Parameter	Unit	Goal	Progress
J_c	kA/mm^2	> 3.0	2.4-2.6
D_{eff}	µm	< 40	70-100
L_{piece}	km	> 10	1.0-1.5
H.T. time	hr	< 400	150
Cost	$/kA-m (12 T)	< 1.5	6



Nb$_3$Sn Critical Current Density

Nb$_3$Sn wires for High Field Dipoles, 1996-2002



Flux Jumps at High J_c , D_{eff}

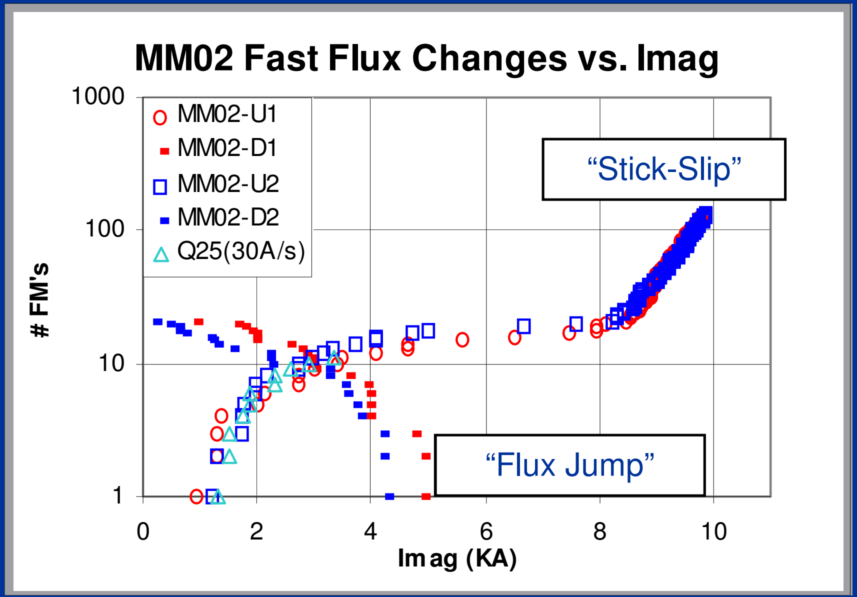
RD3C Fast Flux Changes

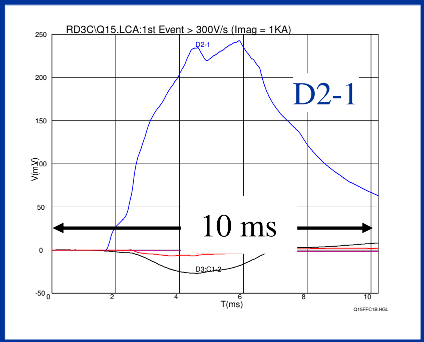
Flux Jump:
- "Slow" (10 ms)
- Low current
- No training
- Repeat at down ramp

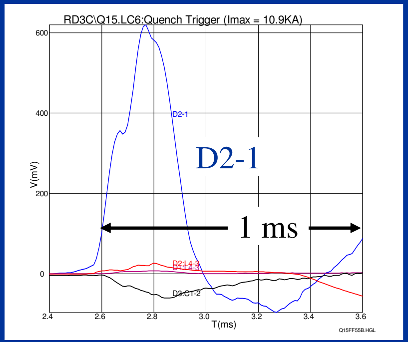
Stick-slip:
- "Fast" (0.1 ms)
- High current
- Trigger quenches
- Some training
- Not at down ramp

Flux jumps:

Can trigger quench detection system
Also observed in RT-1, RD3B

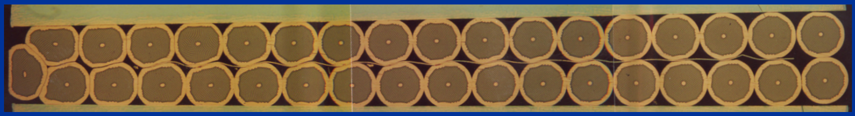






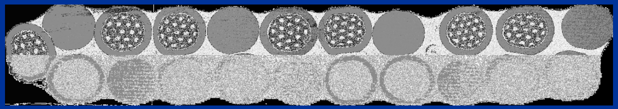
LBNL Cable R&D

Keystoned, w/core

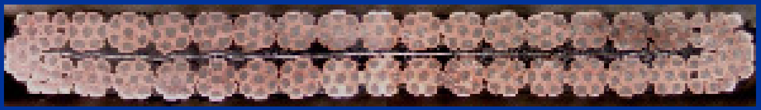


Flat, low compaction

Mixed-strand



React-and-Wind



Summary

<u>Three prototype series to pursue the Program Goals:</u>

- RD : *From high-field coil testing to accelerator quality magnets – best approach to VLHC*

- HD : *A path towards the highest fields in full-scale structures – best approach to S-LHC*

- SM : *Technology development and moderate field magnets in subscale structures*

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