Lawrence Berkeley National Laboratory

Recent Work

Title

Nb₃Sn Magnet Development at LBNL

Permalink

<https://escholarship.org/uc/item/6tq632s9>

Author

Sabbi, G

Publication Date

2003-03-17

Peer reviewed

Nb_3Sn Magnet Development at LBNL

Advanced Accelerator Magnet Workshop
Archamps, March 17-18, 2003

Gian Luca Sabbi

BERKELEY LAB

March 17-18, 2003

Superconducting Magnet Program

Gian Luca Sabbi

LBL 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.*

BERKELEY LAB

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

LBL 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)

LBNL Prototype Highlights

RT1 - 12 Tesla

RD2 - 6 Tesla

D20 - 13.5 Tesla

RD3-b - 14.7 Tesla

RD3-c - 10 Tesla

BERKELEY LAB

March 17-18, 2003

Superconducting Magnet Program

Gian Luca Sabbi

Prototype Objectives and Features

<u>Magnet</u>	<u>Year</u>	<u>Field</u>	<u>Type</u>	<u>Design Features</u>
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

BERKELEY LAB

Accelerator Quality in $\cos\theta$ Magnets

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

BERKELEY LAB

March 17-18, 2003

Superconducting Magnet Program

Gian Luca Sabbi

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 Magnet Assembly and Cooldown

Pressurized Bladders

RD Series: Conductor Limits

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

BERKELEY LAB

March 17-18, 2003

Superconducting Magnet Program

Gian Luca Sabbi

RD Series: Accelerator Quality

	RD3C	RD3D	RD4	RD5
Geometric field quality				
Bore support, coil deflections				
Physical Aperture at coil ends				
Magnetic efficiency				
High field				
Saturation/Magnetization				
End optimization				

BERKELEY LAB

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

BERKELEY LAB

RD3c Magnetic Design

Coil geometry

Field at the probe

BERKELEY LAB

March 17-18, 2003

Superconducting Magnet Program

Gian Luca Sabbi

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

Nb₃Sn Strand Design

Ore 130
(RD3b outer)

Ore 88-90-103
(RD3a outer)

End Field

BERKELEY LAB

March 17-18, 2003

Superconducting Magnet Program

Gian Luca Sabbi

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

BERKELEY LAB

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

BERKELEY LAB

March 17-18, 2003

Superconducting Magnet Program

Gian Luca Sabbi

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)	I _{ss} (kA)
HD1 reference	16.2	10.5
RD3B conductor	15.3	10.0
Nb ₃ Sn 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

BERKELEY LAB

HD Series: Conductor Limits

HD1 Dipole - Design field 16.5 T

Lorentz forces per quadrant:

$$F_x = 4750 \text{ N/mm} \rightarrow \sigma_{x\text{coil}} = 153 \text{ MPa}$$

$$F_y = 1550 \text{ N/mm} \rightarrow \sigma_{y\text{coil}} = 30 \text{ MPa}$$

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

BERKELEY LAB

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

BERKELEY LAB

March 17-18, 2003

Superconducting Magnet Program

Gian Luca Sabbi

SM Magnet Features

Two layer coil

Assembled Magnet

BERKELEY LAB

March 17-18, 2003

Superconducting Magnet Program

Gian Luca Sabbi

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

Phase I : improve performance

Phase II : Scale-up, cost issues

J_c vs. Time
 Nb_3Sn

J_c (A/mm²) @ 12 T, 4.2 K

Year

Project	Year	J_c (A/mm ²)
D10 IGC I.T.	1984	~750
ITER IGC I.T.	1990	~650
D20 MUR	1992	~1400
MSUT PIT	1992	~1250
D20 IGC I.T.	1993	~1000
UTD1 PIT	1998	~1600
RCB OST MUR	2000	~2200
UTD1 PIT	2001	~2350
IGC I.T.	2001	~2450
OST MUR	2002	~2600

Nb₃Sn Critical Current Density

Nb₃Sn wires for High Field Dipoles, 1996-2002

BERKELEY LAB

March 17-18, 2003

Superconducting Magnet Program

Gian Luca Sabbi

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

MM02 Fast Flux Changes vs. I_{mag}

LBL Cable R&D

Keystoned, w/core

Flat, low compaction

Mixed-strand

React-and-Wind

BERKELEY LAB

March 17-18, 2003

Superconducting Magnet Program

Gian Luca Sabbi

Summary

Three prototype series to pursue the Program Goals:

- **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*

Superconducting Magnet Group

Scott Bartlett, Paul Bish, Sharon Buckley, Shlomo Caspi,
Luisa Chiesa, Daniel Dietderich, Paolo Ferracin, Steve Gourlay,
Modeste Goli, Aurelio Hafalia Jr, Charles Hannaford, Hugh Higley,
Alan Lietzke, Nate Liggins, Sara Mattafirri, Al McInturff,
Kelly Molnar, Mark Nyman, GianLuca Sabbi, Ronald Scanlan,
Jim Smithwick, James Swanson, Kathleen Weber

BERKELEY LAB

March 17-18, 2003

Superconducting Magnet Program

Gian Luca Sabbi