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Superconducting Magnet Division

Magnet Note

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Topic: Common Coil Design

Title: Superconducting Magnets for Future Colliders and Storage Rings
`http://magnets.rhic.bnl.gov/gupta`

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Superconducting Magnet Division

Superconducting Magnets for Future Colliders and Storage Rings

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BNL

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Overview of the Presentation

Our initiatives for future machines:

- A new magnet design for VLHC
  - with a possible application to a future RHIC upgrade
- Alternate designs for muon collider and storage ring magnets
- A cost effective magnet R&D program for developing innovative concepts and technologies in a systematic way

Not elaborated in this talk : Magnet work based on matured technologies (where most of our resources go)

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VLHC
Very Large Hadron Collider

Very Large Hadron Collider
Steering Committee for a Future Very Large Hadron Collider
p-p collider: 50 Tev + 50 TeV

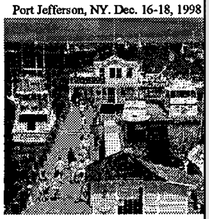
Mission Statement

The steering committee for a future very large hadron collider coordinates efforts in the United States to achieve a superconducting proton-proton collider with approximately 100 TeV cm and approximately 10^{34} $cm^{-2}sec^{-1}$ luminosity.

The charge from VLHC Steering Committee:

... *explore and develop innovative concepts that will result in significant cost reductions.*

Magnet Technology Workshop
Port Jefferson, NY. Dec. 16-18, 1998



Magnet Technology Working Group
P. Wanderer (BNL), Organizer, Foster (FNAL), R. Scanlan (LBL)

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VLHC: The Challenge is the Cost

VLHC can be built with the present technology.
But the cost may be too high.

To change the cost substantially, we have to do things differently.

- Superconducting dipoles are the cost and technology driver and require a large lead time for magnet R&D.
- Their cost is significant (~1/4 of the total machine cost).
- Critically examine all major components and sub-systems See if some of them can be elimiited. Alternate "magnet system design" can be spring-board for bringing additional savings in the overall machine cost

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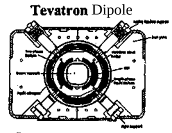
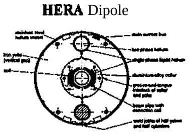
Present Magnet Design and Technology

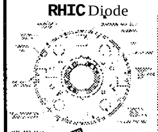
Tevatron Dipole



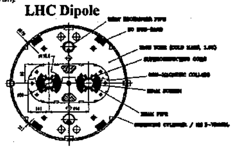
HERA Dipole



RHIC Dipole



LHC Dipole



- All magnets use Nb-Ti Superconductor
- All designs use cosine theta wil geometry
- The technology has been in use for decades.
- The wst is unlikely to reduce significantly.

RHIC magnet production sets new standards based on cost and performance (field quality and quench performance).

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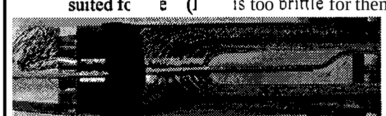
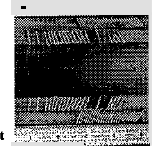
High Temperature Superconductors (HTS) in Accelerator Magnets

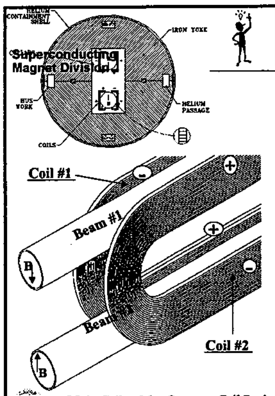
- HTS in accelerator magnets: *An* exciting possibility, BNL is leading this initiative
- Applications: vlhc & muon colliders/storage rings
- May allow higher fields, higher operating temperature, higher heat loads and less stringent operating conditions
- However, the conventional magnet designs are not well suited fc e (I ıs too brittle for them)





End of a conventional magnet

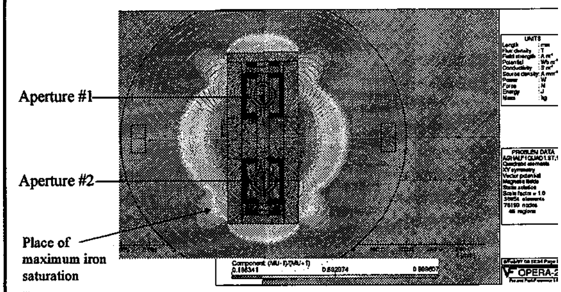
Common Coil Design (The Basic Concept)



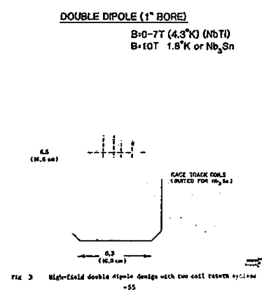
Main Coils of the *Common Coil Design*

- Simple 2-d geometry with large bend radius (no complex 3-d ends)
- Conductor friendly (suitable for brittle materials - most are - Nb_3Sn, HTS tapes and HTS cables)
- Compact (compared to single aperture LBL's D20 magnet, half the yoke size for two apertures)
- Block design (for large Lorentz forces at high fields)
- Efficient and methodical R&D due to simple & modular design
- Minimum requirements on big expensive tooling and labor
- **Lower cost magnets expected**

Field Lines at 15 T in a Common Coil Magnet Design



Earlier Designs: Double Dipole, Danby, BNL (1983)



A good idea never dies, it gets re-invented in one or other form

Danby A person ahead of his time

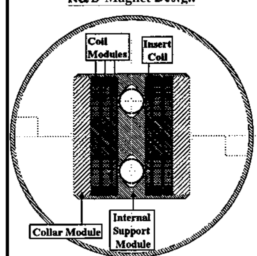
Common coil design is similar to double dipole design, except that at no place cable bends in a tight radius

A "conductor friendly" geometry is important since all high field superconductors (HTS, Nb_3Sn, etc) are brittle

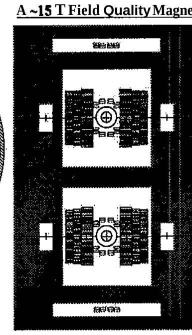
Other features of common coil design modularity, and easy-to-fabricate structure, etc

How Does a Common Coil Magnet Look?

R&D Magnet Design



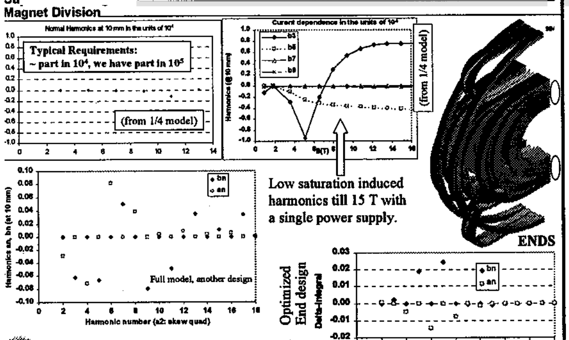
A ~15 T Field Quality Magnetic Design



RHIC: 3.5 T
SSC: 6.6 T
LHC 8.4 T
(forces go as B^2)

15 T is based on the best available Nb_3Sn conductor available today: $J_c = 2200$ A/mm² (12T,4.3K). Goal: $J_c = 3000$ A/mm².

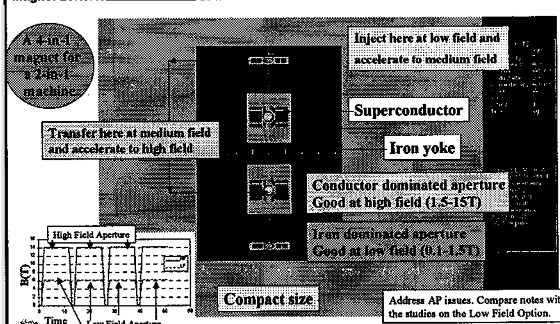
Field Quality in a 15 T Common Coil Design



As good field quality as in present day magnets (geometric, saturation & end harmonics).

A Common Coil Magnet System for VLHC

May eliminate the need of a High Energy Booster (HEB)



Address AP issues. Compare notes with the studies on the Low Field Option.

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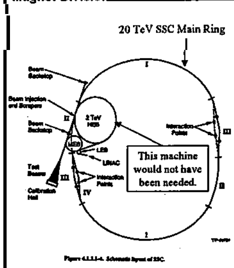
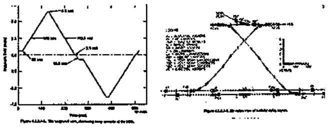
Possibility of Removing the Second Largest Machine (HEB) from the vlhc complex





- In the proposed system, the High Energy Booster (HEB) - the entire machine complex - will not be needed. Significant saving in the cost of construction and operation.
- Many consider that HEB, in some ways was quite challenging machine: superconductor (*2.5* μ instead of *6* μ filaments), bipolar magnets, etc.

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SSC: 20+20 TeV;
VLHC: 50+50 TeV

(1990 Estimates in US$)

This table has been used to obtain rough estimates in 1990 US$ in deriving cost savings from various proposals

Superconducting Super Collider
Cost Estimate Summary

Project Component		Costs in $M
1.1 Accelerator Systems		1322
1.1.1 Management and Support	37	
1.1.2 Linac	45	
1.1.3 LEB	52	
1.1.4 MEB	137	
1.1.5 HEB	190	
1.1.6 Collider	777	
1.1.7 Test Beams	14	
1.1.8 Global Systems	70	
1.2 Magnet Systems		2326
1.2.1 Management and Support	33	
1.2.2 HEB Magnet Production	209	
1.2.3 Collider Magnet Production	2037	
1.2.4 SSCL Test Facilities	47	
2.0 Conventional construction		1285
2.1 Accelerator Facilities	777	
2.2 Experimental Areas	155	
2.3 Site and Infrastructure	135	
2.4 Campus	67	
2.5 Design & Construction Mgmt.	151	
3.0 Project Management & Support		59
Contingency		921
Construction Project Subtotal		5913
4.0 R&D and Pre-Operations		1082
5.0 Experimental Systems		842
R&D, Pre-Operations and Expt'l Systems Subtotal		1942
Total Project Costs		7837

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Common Coil Magnet System
(Estimated cost savings by eliminating HEB)

SSC 20+20 TeV;
VLHC 50+50 TeV

Based on 1990 cost in US$

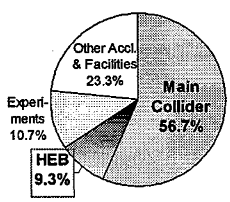
2 TeV HEB Cost in SSC (derived):
$700-800 million

Estimated for 5 TeV (5-50 TeV vlhc):
~$1,500 million (in 1990 US$)

A part of this saving (say ~20-30%) may be used towards two extra apertures, etc. in main tunnel. Estimated savings ~ $1 billion.

Cost savings in equivalent 20xx $?

Cost Distribution of Major Systems
(Reference SSC *Cost* 1990 **US $7,837 million**)



(Derived based on certain assumptions)

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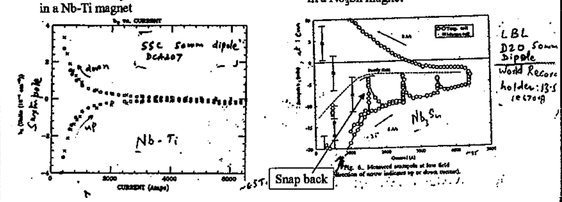
Persistent Current-induced Harmonics
(may be a problem in Nb_3Sn magnets, if done nothing)

Nb_3Sn superconductor, with the technology under use *now*, is expected to generate persistent current-induced harmonics which are **a factor of** 10-100 worse than those measured in Nb-Ti magnets

In addition, a snap-back problem is observed when the acceleration starts (ramp-up) after injection at steady state (constant field)



The iron dominated aperture in a common coil magnet system overcomes the major problem associated with magnets using Nb3Sn superconductor.

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Advantages of Common Coil Magnet System with 4 Apertures (2-in-1 Accelerator)

- **Large Dynamic Range**

  ~150 instead of usual 8-20

May eliminate the need of the second largest ring. Significant saving in the cost of VLHC accelerator complex

- **Good Field Quality (throughout)**

  Low Field Iron Dominated
  High Field Conductor Dominated

Good field quality from injection to highest field with a single power supply.

- **Compact Magnet System**

  As compared to single aperture DZO, 4 apertures in less than half the yoke.

- **Possible Reduction in High Field Aperture**

  Beam is transferred, not injected
  - **no** wait, **no snap-back.**
  Minimum field seen by high field aperture is ~1.5 T and not ~0.5 T.

The basic machine criteria are changed!
Can high field aperture be reduced?

Reduction in high field aperture => reduction in conductor & magnet cmt.

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Magnet Aperture: MT and AP Issues

Main magnet aperture has an appreciable impact on the machine cost. The minimum requirements are governed by the following two issues:

Magnet Technology Issues

The conventional cosine theta magnets are hard to build below certain aperture as the bend radius and the end geometry would limit the magnet performance. In the common coil design, the magnet aperture and magnet ends are completely de-coupled. The situation is even better than that in the conventional block designs as not only that the ends are 2 d but the bend radius is much larger, as it is determined by the spacing between the two apertures rather than the aperture itself. This means that the magnet technology will not limit the dipole aperture.

Accelerator Physics Issues

The proposed common coil system should have a favorable impact. The aperture is generally decided by the injection conditions. In the proposed system, the beam is transferred (not injected) in a single turn, on the fly, and the transfer takes place at a higher field. The magnets continue to ramp-up during beam transfer and thus the "snap-back" problem is bypassed. Then is a significant difference at the injection from the conventional injection case. This and other progress in the field (feed-back system, etc.) should encourage us to re-visit the aperture issue.

A Combined Function Common Coil Magnet System for Lower Cost VLHC

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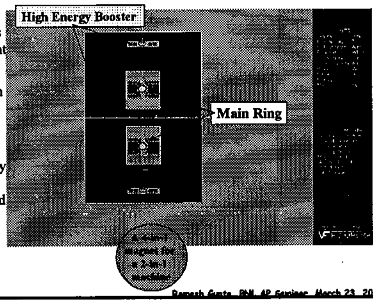
n ε ɔo ıeı c ü ;ɪ ıa design, the gl side of the coil return on the l(

- A combined magnet design is possible as the coils on the right and left sides are different.
- Therefore, combined function magnets are possible for both low and high field apertures.
- Note: Only the layouts of the higher energy and lower energy machines are same. The "Lattice" of the two rings could be different.



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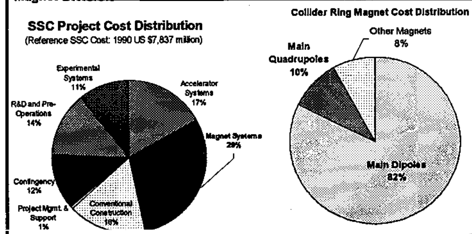
A Combined Function Magnet Option (Estimated cost savings for VLHC)

Division



Total: $2,037 millio

AP Challenge: Retaining the benefits of the *Synchrotron Damping* in the *High Field Magnet* vlhc option.

SSC (20 TeV) Main Quads ~$200 million, VL[redacted]
Main Quads ~$400 million (x2 **not** *2 5)*
Additional savings from tunnel, **interconnect, e**[redacted]
Estimated potential savings ~$0.3-0.5 billion [redacted] US$)

Cost savings in equivalent 20xx $?

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A Possible Low-cost Magnet Manufacturing Process

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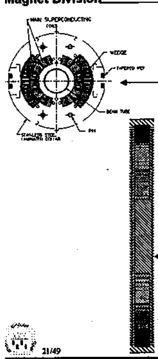

- Reduce steps and bring more automation in magnet manufacturing
- Current procedure: make cable from Nb-Ti wires => insulate cable => wind coils from cable => cure coils => make collared coil assembly
- Possible procedure: Cabling to coil module, all in one automated step - insulate the cable as it comes out of cabling machine and wind it directly on to a bobbin (module)

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Recap on Cost Saving Possibilities in VLHC

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- Lower cost magnets expected from a simpler geometry
- Possibilities of applying new construction techniques in reducing magnet manufacturing costs.
- Possibilities of reducing aperture due to more favorable injection scenario in the proposed common coil magnet system i
- Possibility of removing the high energy ste t hi d sy
- Possibility of removing main quadrupoles (the second most expansive magnet order) in the proposed combined function magnet design

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y also come from other advances: cheaper t
development in superconductor technology, etc

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Performance of the First magnet Based on the Common Coil Design

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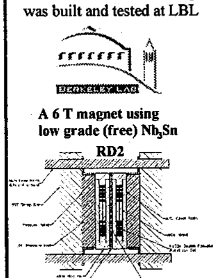
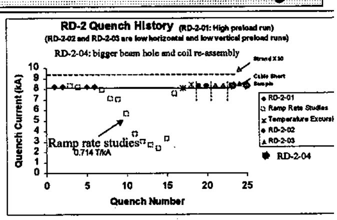
The first common coil magnet was built and tested at LBL

A 6 T magnet using low grade (free) Nb_3Sn

RD2





1. The magnet reached plateau performance right away (plateau seems to be on the cable short sample, not wire short sample).
2. Didn't degrade for a low horizontal pre-load (must for this desig
3. Didn't degrade for a low vertical pre-load (highly desirable).
4. Didn't degrade for a bigger hole (real magnets).

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On To A High Field Common Coil Magnet

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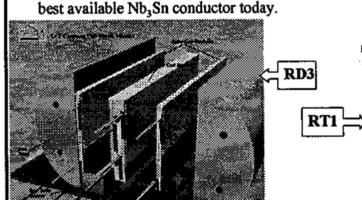
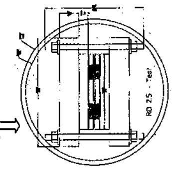
Now under construction at LBL

~14 T common coil design with the best available Nb_3Sn conductor today.



The first step towards high field common coi magnet: test outer coils with minimum gap.



Bss ~12.3 T

The magnet reached the short sample field (~12 3 T) with only a few quenches

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Common Coil Work at BNL- Phase I

Charge:

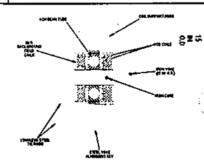
Build and Test a common coil magnet with NbTi

Purpose

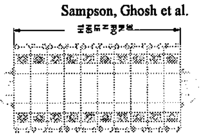
Validate "Common Coil Design" and provide a simple and efficient background field test facility for **HTS coils**

Resources

None (almost)



Sampson, Ghosh et al.



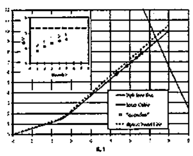
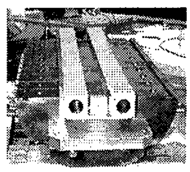


Figure 4. The training behaviour of the main winding of the common coil magnet.



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Common Coil Work at BNL- Phase II

Charge:

Continue Innovative Magnet Research

Design Field : 12.5 T

Conductor: Nb_3Sn (HTS in future magnets)

Technology: React and Wind

Challenges:

High Field A Good Engineering Design is Critical

Resources: Limited

Strengths:

Demonstrated skills in designing and building cost effective high quality magnets

History in carrying out innovative magnet research that defines the field

The Team:

M. Anerella
J. Cozzolino
J. Escallier
G. Ganetis
A. Ghosh
R. Gupta
M. Harrison
G. Morgan
B. Parker
W. Sampson
P. Wanderer

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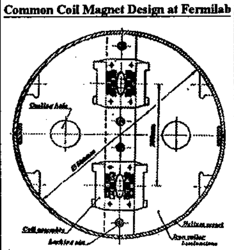
Summary of Common Coil Magnet Work at Various National Labs

Common Coil Magnet Design at Fermilab



Fermilab

BNL

Invented it.

Phase I: Built and commissioned NbTi magnet with Nb_3Sn insert coils. Built and tested HTS insert coil in low field common coil mode. HTS coils are now ready to go as a part of a hybrid design with common coil magnet as a background field test facility.

Phase 2: High Field –12.5 T, "React and Wind", Nb_3Sn dipole, R&D Magnet Factory, HTS insert coils

Got maximum support for building it.

Built and tested 6 T, "Wind and React", Nb3Sn magnet. Tested high performance coils in common co mode for 12 T field. Both had excellent performance.

Next step ~14 T magnet with third coil.

FNAL

Design and support work for an initial ~11 T magnet.

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A Possible Application of High Field Magnet Program
URHIC: Ultra Relativistic Heavy Ion Collider in RHIC Tunnel

URHIC

Heavy Ions 500 GeV + 500 GeV (1 TeV center of mass)
Protons 1 25 TeV + 1 25 TeV (2 5 TeV center of mass)

	RHIC	URHIC
Energy (GeV/u)	100 GeV + 100 GeV	500 GeV + 500 GeV
Injector	AGS	RHIC
Lattice	Separated Function	Combined Function
Dipole Fill Factor	65 % (+quad)	~85-90% (no quad)
Dipole Design	Cosine Theta	Common Coil
Operating Field	3 5 T	– 13 T

Physics Potential?

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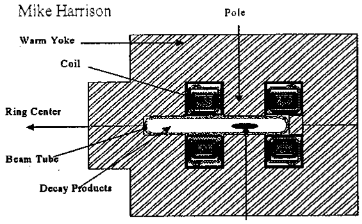
Dipole for V Storage Ring

Mike Harrison

With Nb-Ti, Bo ~ 5 T muon beam



A Conceptual Design

In neutrino storage ring ~10% energy deposition may be acceptabl

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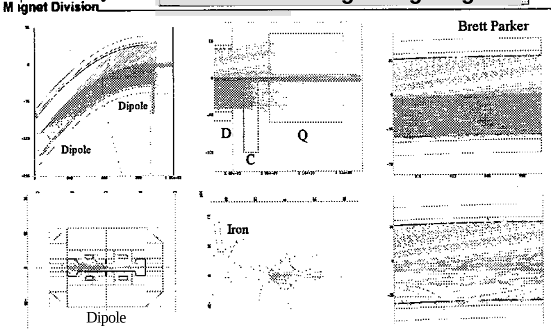
Particle Tracking with MARS for Neutrino Storage Ring Magnet

Brett Parker



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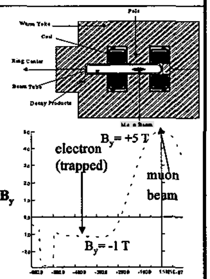
Possible Extension of Neutrino Storage Ring Dipole for Higher Energy Muon Collider Storage Ring

Nb_3Sn Version, B_o ~ 8-9 T (for higher energy ring)

Another Possibility HTS - higher field higher temperature



Challenge:

- A higher field magnet is required for higher luminosity.
- A much lower energy deposition will be tolerated.

Possible scenarios for manipulating energy deposition:

- **Make reverse field much higher that 1 T with additional coils to trap higher energy electrons**
- **Extend positive field region much further out by adding conventional coils on one side.**

This will make decay particles hit metal further out and away from superconducting coils.

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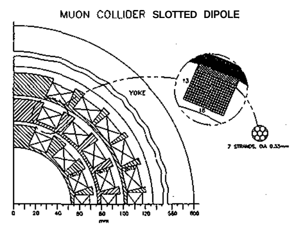
Dipole Magnet for the Muon Collider

- Field on midplane is above 13 Tesla
  Superconductor is currently available Nb_3Sn---could also use HTS material
  Coils made as "react-and-wind"
- The cable needs to be optimized larger diameter with smaller strands is probably better
- The Lorentz forces are contained in the individual blocks and do not pile up on the midplane as in conventional cos θ magnets
- **High gradient quadrupoles can be** made with a similar design



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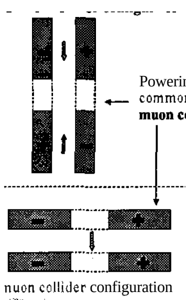
Muon Collider Racetrack Dipole Design (15 T, Nb_3Sn and 10^{-5} Field Quality)



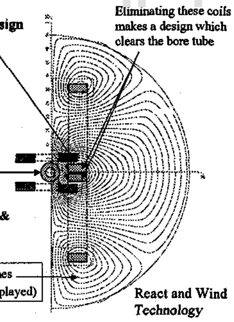
coils
the bore in this **design**

Eliminating these coils makes a design which clears the bore tube

Powering differently changes common coil design test to **muon collider design test**

Tungsten & bore tube

Iron yoke with field lines (only half model is displayed)



muon collider configuration

Note : A high stress test is created here

React and Wind Technology

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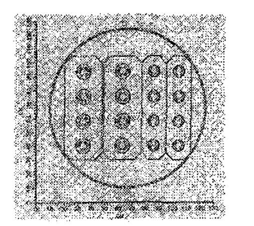
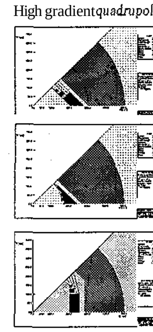
Other Muon Collider Magnet Designs

Multi aperture dipole (Morgan, Kahn, et al.)



High gradient *quadrupoles*



High field racetrack coil Nb_3Sn quadrupoles for muon collider (didn't look much advantageous over cosine theta at that time)

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BNL Contribution to LHC Magnet Requirements

Cable testing for LHC magnets: Arup Ghosh
Insertion region magnets based on RHIC coils: Erich Willen

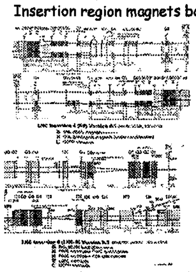

Table 1 Dipole magnets to be built by Brookhaven for the LHC. The coil aperture is 80 mm. The overall length of the magnets is approximately 10 meters.

Name	Style	Number (Spares)	Aperture Separation (cold), mm	Operating Temperature, K
D1	Single Aperture	4(1)	---	1.9
D2	2-in-1	8(1)	188	4.5
D3a	Dual 1-in-1	2(1)	420	4.5
D3b	Dual 1-in-1	2(1)	382	4.5
D4a	2-in-1	2(1)	232	1.9
D4b	2-in-1	2(1)	194	1.9

Table 2 Position parameters and fields required in the magnets at injection energy, nominal energy, and 8% above nominal energy. The numbers listed for the bend center-to-center distance and the deflection are those specified in Version 6.1 of the LHC lattice. The magnetic length of the magnets is 9.45 m.

Magnet	IR Location	Bend Center-to-Center Distance, m	Deflection, m	Field (T) for E (TeV) 0.45	7.0	7.56
D1/D2	1 & 5	87.424	0.097	0.176	2.742	2.954
D1/D2	2 & 8	63.116	0.097	0.244	3.797	4.091
D3/D4	4 left	41.766	0.097	0.215	3.343	3.602
D3/D4	4 right	40.884	0.113	0.220	3.415	3.679

Note: Above figures don't include all magnets that are being contributed by BNL.

BNL Contribution

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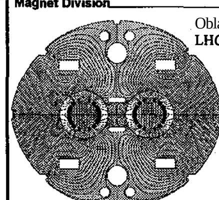
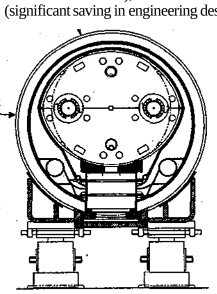
LHC Insertion Magnets

Oblate yoke (instead of conventional circular), allowed us to use LHC cryostat, post, etc. (significant saving in engineering design)



Animesh Jain

CERN cryostat



LHC magnets use RHIC coils. They use SS collars i ste d of phenolic spacers. Oth r d s changes as ll.

The **first** model magnet **has** been recently tested. It reaches the design field.

CRYOSTATED MAGNET

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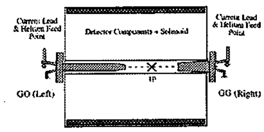
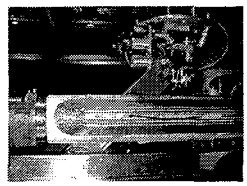
HERA Upgrades Magnets at BNL

Brett Parker



- Magnets go inside HERA experimental detectors.
- Multilayer coils with dipole, quadrupole, skew quadrupole, skew dipole and sextupole windings.
- For GG, a short tapered magnet, we achieved 5×10^{-5} field uniformity out to 75% coil radius!



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The Basic Guiding Principles for An Innovative R&D Program

Remember the next machine is 10+ years away

In addition to maintaining the expertise we have acquired, this is also a unique time to explore

- ❒ **Explore alternate concepts and technologies**
- ☑ **Explore new conductors (HTS) for high fields**
- ❒ **Use the "Magnet R&D Factory" approach:**
  - faster turn-around is important to try ideas outside the "comfort zone"

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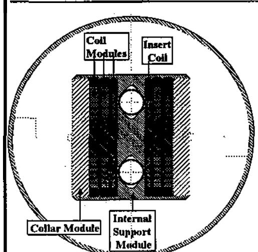
A Modular Design for a New and Low-cost Magnet R&D Approach

"A Cost-effective Magnet R&D Factory"



Not only that we must learn how to make magnets cheaper, we must also learn (due to limited funding), how to do magnet research cheaper which will lead to **eventually making the magnets cheaper.**

- Replaceable coil module.
- Change cable width or type.
- Combined function magnets.
- Vary magnet aperture for higher fields.
- Study support structure
- Traditionally such changes required building a new magnet.
- One can also can test modules off-line.

This is the time to explore and carry out an aggressive R&D program. Once the machine is funded, we are unlikely to take chances. The above facility allows that.

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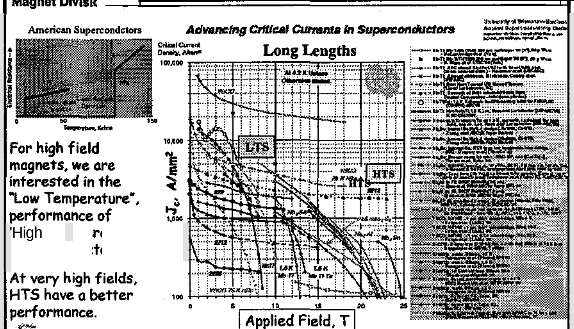
High Field Magnets and High Temperature Superconductors (HTS)



For high field magnets, we are interested in the "Low Temperature", performance of 'High ...

At very high fields, HTS have a better performance.

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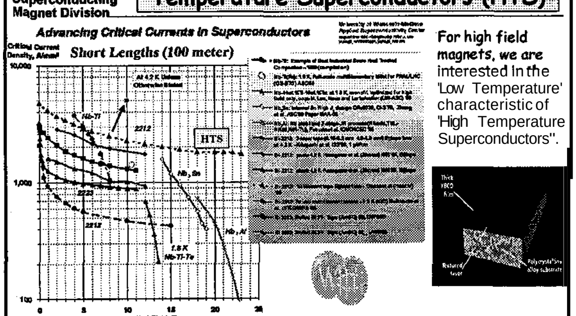
High Field Magnets and High Temperature Superconductors (HTS)



For high field magnets, we are interested in the 'Low Temperature' characteristic of 'High Temperature Superconductors".

But what really matters is the engineering current density (J_e)

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Advantages of HTS

significant efforts by Sampson & Ghosh at BNL on HTS cables (tapes), coils and magnets

Advantage of HTS: A slow transition to non-superconducting stage.
If them is a degradation or if the operating conditions become such that a part of the magnet can no longer remain in an ideal superconducting stage, then there is only a modest temperature rise locally. If the local temperature rise can be tolerated and if the heat can be removed, the magnet will continue to operate in superconducting stage.

This is in contrast to a sharp transition to "normal zone" in conventional low temperature superconductors where the whole magnet must be switched to normal stage for protection

This implies a more relax design and operating conditions for a magnet built with HTS.

The cost and performance issues still remain.

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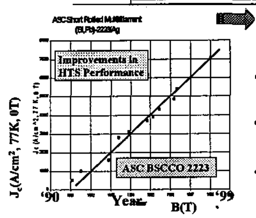
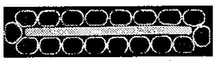
Improvements in HTS Technology And Challenges for Magnet Design



- HTS have made significant progress, enough to make R&D magnets
- To he shown that it's practical for large production (cost & technology)
- It takes long time to do magnet R&D (many technical questions remain)
- Start magnet R&D now, so that if the wst situation improves and if it can he made technologically feasible, we can use it in the next machine



KAmp Rutherford cable : LBL-industry collaboration

Stainless steel reinforcement

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HTS in a Hybrid Magnet

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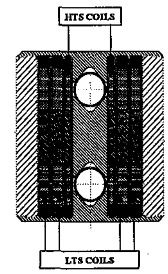

- **Perfect for R&D magnets now.** **HTS is subjected to the similar forces that would be present in an all HTS magnet. Therefore, several technical issues will be addressed.**
- **Also a good design for specialty magnets where the performance, not the cost is an issue. Also future possibilities for main dipoles.**
- **Field in outer layers is ~2/3 of that in the 1st layer. Use HTS in the 1st layer (high field region) and LTS in the other layers (low field regions).**

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Hybrid Common Coil Magnet at BNL

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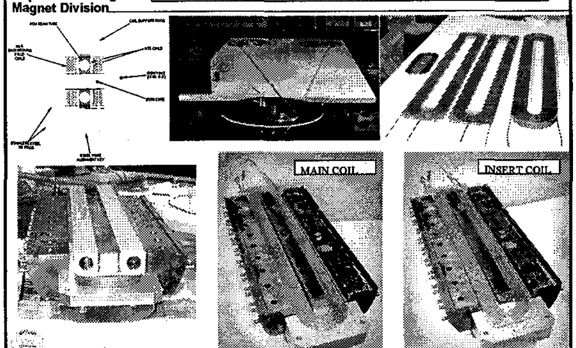

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Initial R&D For Phase II Common Coil Magnet Program

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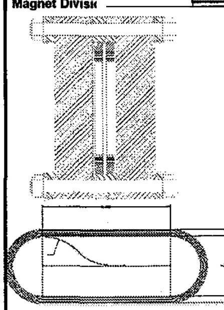

- Make several 10-turn coils (mini-coils) in their own modular structure
- Test a pair of these mini-coils in a common coil geometry with a simple and compact external structure that can be directly put in a helium vessel for a faster turn-around
- A pair of 10-turn coils made from the cable obtained from Berkeley gives ~8 T field for a minimum spacing
- This "Magnet R&D Factory Approach" would provide us guidance in dealing with various issues related to this design and technology in time and cost effective manner and encourage innovative magnet R&D

This also becomes a magnet R&D test factory.

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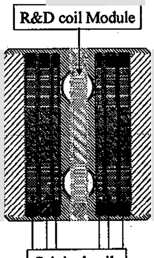
Uses of Smaller R&D Funding to Labs and Industries for a Collaborative and Innovative Magnet Research

Magnet Division

R&D coil Module



Original coils

- A M[illegible] a dynamic **R&D that was not possible before**
- **An important part of this high field magnet research is the coil module – be it conductor manufacturing, coil manufacturing, insulation,** stress [illegible]men or whatever.

  The [illegible] is to test these [illegible] **in a "magnet like" situation to avoid surprises/unknowns.**
- **The critical module has a relatively m[illegible]ate price tag.** [illegible] **ideas, i[illegible] R&D by small labs (or big labs) and industries.**
- ***Make*** this [illegible] ***ere and test it in*** the [illegible] in a future all **HTS** magnet.
- Use the positive results in the next magnet

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What can one *study* with these modules

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A few examples of systematic studies in a modular approach

- Different technologies
  - Wind & React Vs React & Wind
- Different conductors
  - Nb_3Al, HTS, *etc*
- Different insulation
- Different geometry's
  - Tape, cable
- Stress management/High stress configuration
- Coil winding and Splicing

and a vanety of other things that are not mcluded (especially those that are not mcluded)

*** A Dynamic Program with fast turn-around time for exploring new frontiers/ideas ***

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Summary

- An exciting program for developing innovative magnet designs and technologies
  - » This is the need of the hour (year) to bring a large reduction in cost
- A new magnet system design for a possible lower cost VLHC and RHIC upgrade (URHIC)
- A conductor friendly approach for using ***"brittle"*** conductors (HTS, Nb_3Sn, etc.) in a competitive way