Innovative Magnet Designs for Future Colliders

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Overview of the Presentation

- The Common Coil Magnet Design for VLHC
- The Common Coil Magnet System
  - Significant savings while improving the technical performance (new)
- Feedback from the last magnet
  - Impact on the future designs
  - Reality check (promise Vs. performance)
- The 14 T magnet (work-in-progress)

The Recommendations

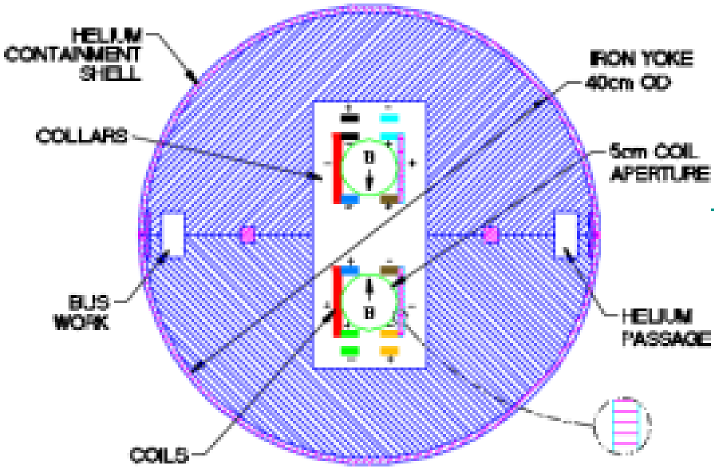
... The Gilman Subpanel recommends an expanded program of *R&D on cost reduction strategies, enabling technologies,* and accelerator physics issues for a VLHC.

... identifying *design concepts for an economically and technically viable facility.*

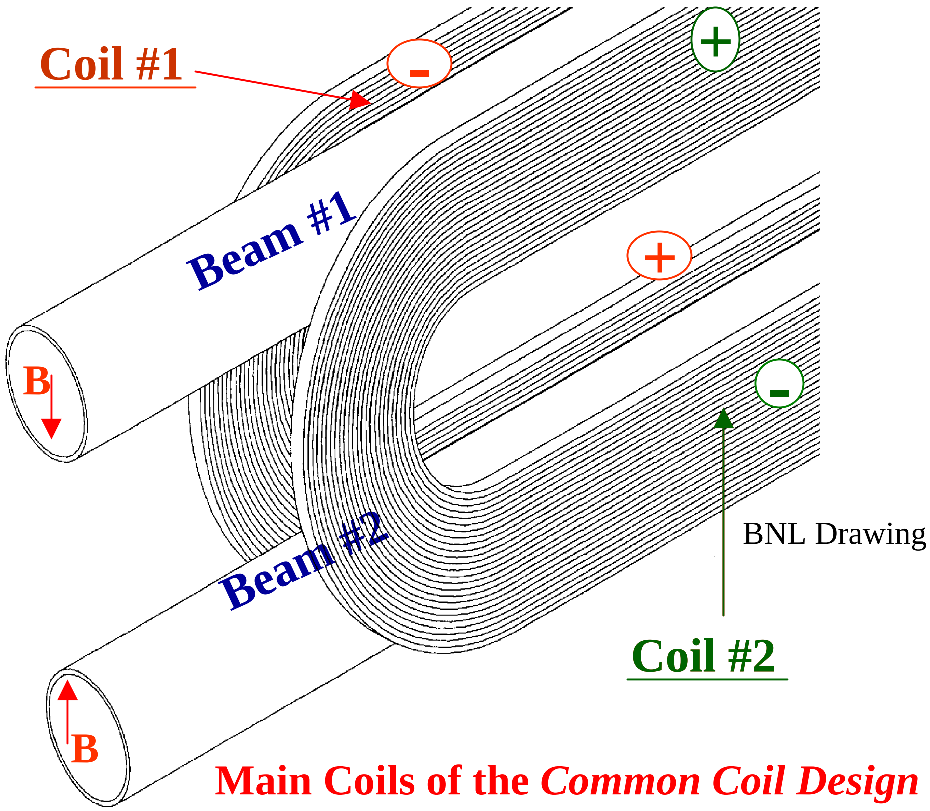
$$$ Since the cost is unlikely to come down by a large amount with the same way of doing things (i.e. making VLHC by simply scaling up SSC or LHC designs and technologies),

the charge from VLHC Steering Committee:

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



Common Coil Design
(The Original 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, including HTS tapes and cables)**
- **Compact (compared to single aperture 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**

Extension of the Common Coil Design (new since the last review)

Looking for the major cost savings, while improving the performance.

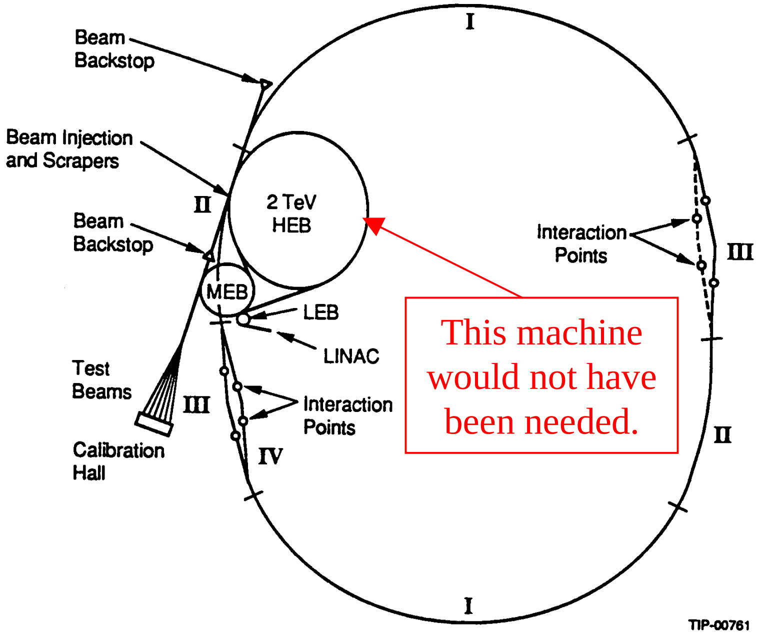


Figure 4.1.1.1-4. Schematic layout of SSC.

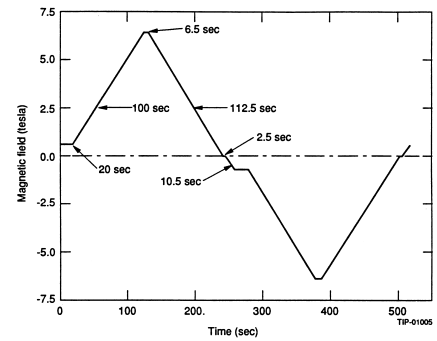


Figure 4.1.2.4-1. The suggested slow, alternating ramp scenario of the HEB.

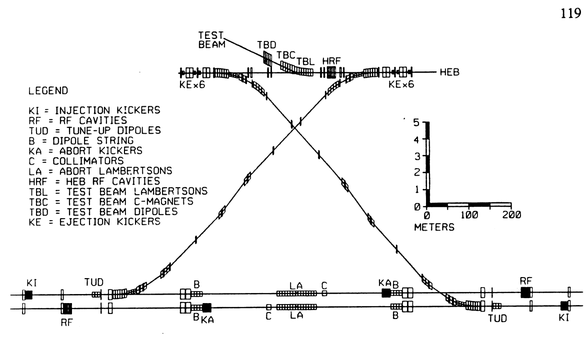


Figure 4.1.1.3-4. Elevation view of collider utility region.

(the savings in VLHC may be of the order of 0.5 billion dollars for a 3 TeV booster)

- 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 in the cost of operation.

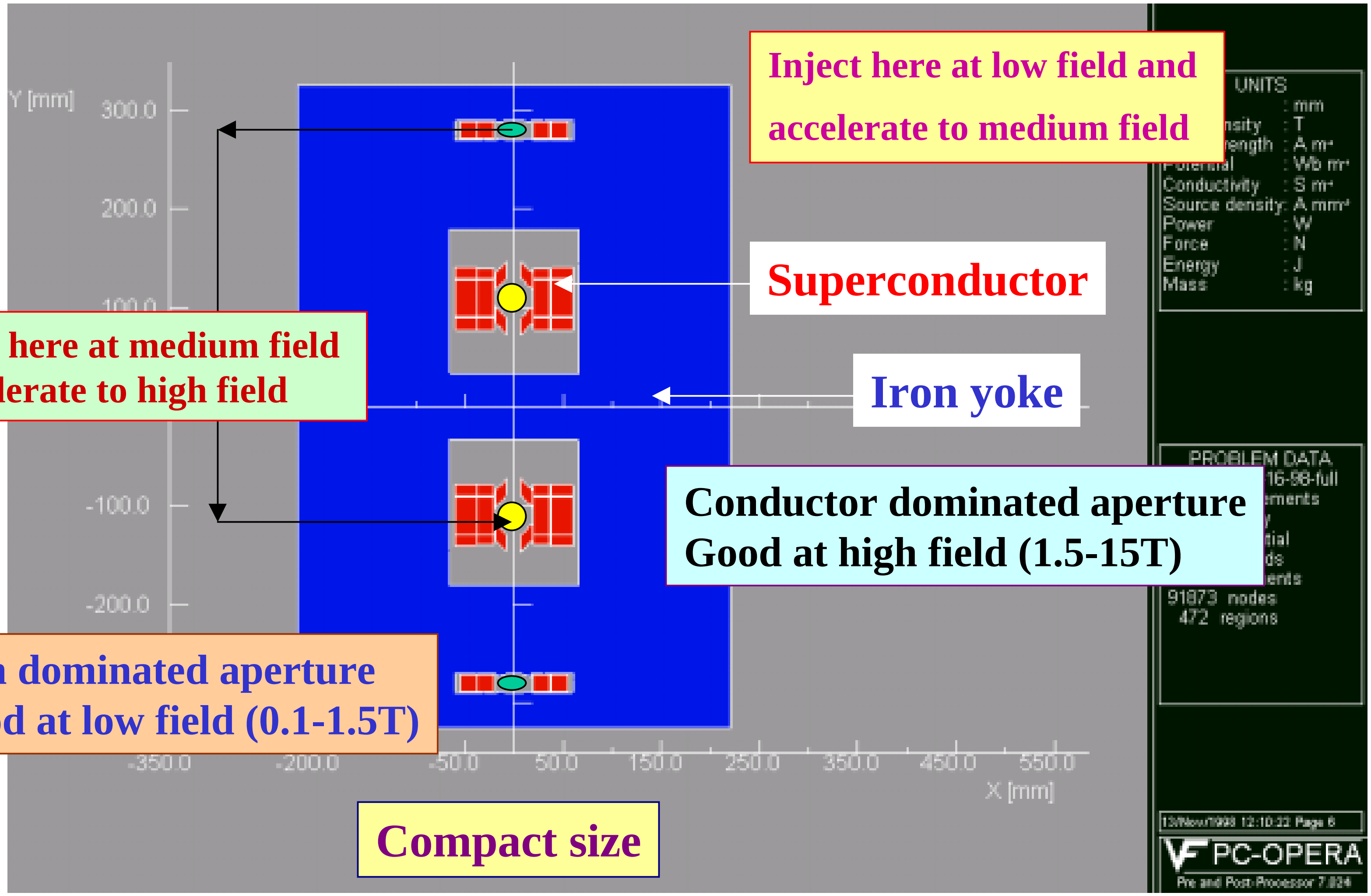
- In SSC, the cost savings could have been enough to **pay for the entire cost of the superconductor** (some say more, when every thing is accounted for).

- HEB was a technically more complex machine: superconductor (2.5 μ instead of 6 μ filaments), bipolar magnets, challenging operation and/or complex/expensive beam transfer. Many issues remain unresolved until the end.

A Common Coil Magnet System for VLHC

(May Eliminate the Need of a High Energy Booster)

A 4-in-1 magnet for a 2-in-1 ring



Inject here at low field and accelerate to medium field

Superconductor

Iron yoke

Transfer here at medium field and accelerate to high field

Conductor dominated aperture
Good at high field (1.5-15T)

Iron dominated aperture
Good at low field (0.1-1.5T)

Compact size

Common Coil Magnet System with a Large Dynamic Range
(Possible Advantages)

- **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.

- **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!
Reduce high field aperture, say to 25 mm?

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

- **Compact Magnet System**

As compared to single aperture D20, 4 apertures in ~70% of the yoke mass.

Persistent Current-induced Harmonics

(may be a problem in Nb_3Sn magnets, if nothing is done)

Exploring the unusual options for the major cost savings while improving the performance.

Magnet/machine designs to accommodate challenging superconductors.

Nb_3Sn, 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 addiction, a snap-back problem is observed when the acceleration starts after injection at steady state (constant field).

Garber, Ghosh and Sampson (BNL)

Persistent current induced magnetization :

$$2\mu_0 M = 2\mu_0 \frac{2}{3\pi} \nu J_c d \quad (1)$$

J_c , CRITICAL CURRENT DENSITY

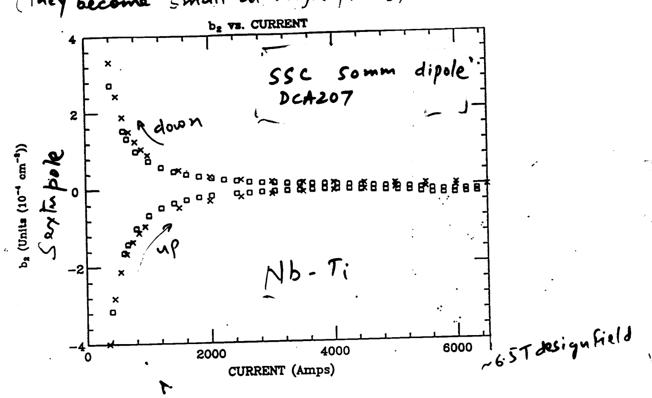
d , FILAMENT DIAMETER

ν , VOL. FRACTION OF NbTi

$$M_s = M/\nu \quad (2)$$

Measured sextupole harmonic in Nb-Ti magnet

Persistant current Induced harmonic depends on the property of Superconductor (They become small at high fields) gupta



Measured sextupole harmonic in Nb_3Sn magnet

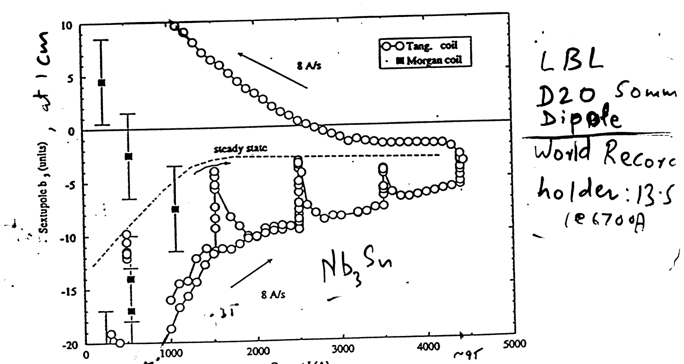


Fig. 6. Measured sextupole at low field (direction of arrow indicates up or down current).

Measured magnetization

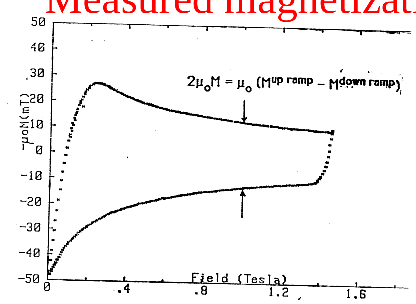
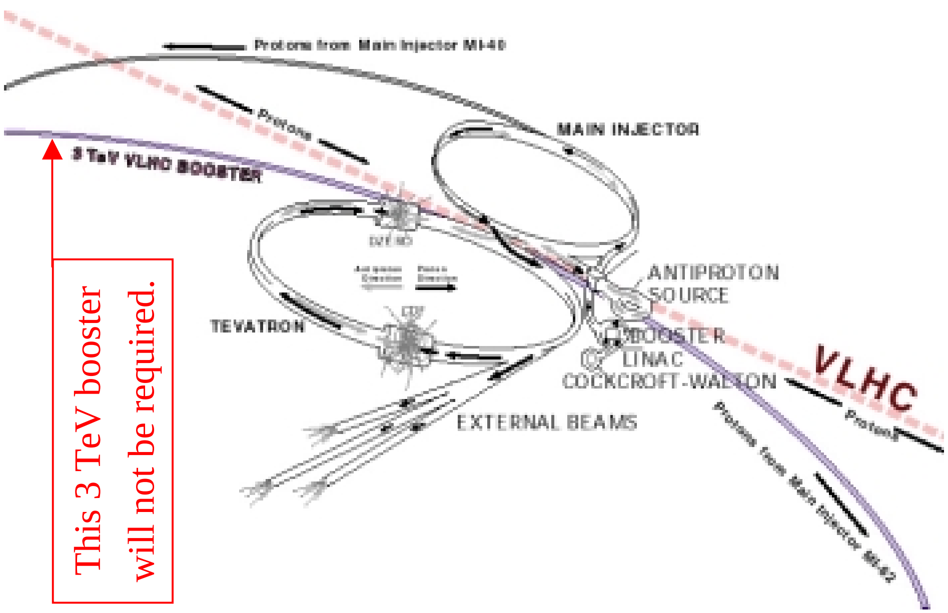


Fig. of a typical magnetization loop.

Case Studies for VLHC at/near Fermilab Site

(only one tunnel will be needed over the present infrastructure)

A schematic of the VLHC low field option using FNAL infrastructure (E. Malamud, W. Foster et al.).



The proposed common coil magnet system requires only one new complex for the center of mass energy up to 200 TeV (option 2 and 3).

Fermilab machine chain as VLHC injector:

Main Injector: 150 GeV (ejection energy)

Tevatron: 150-800 GeV (20% margin)

Option 1:

Low Field aperture: 0.8-5 TeV (0.24-1.5 T)

High Field aperture: 5-50 TeV (1.5-15 T)

Option 2:

Low Field aperture: 0.8-10 TeV (0.12-1.5 T)

High Field aperture: 10-***100 TeV*** (1.5-15 T)

Option 3:

Low Field aperture: 0.8-12 TeV (0.1-1.5 T)

High Field aperture: 12-***100 TeV*** (1.5-12.5 T)

Several other options are also possible.

Can raise the max. field in low field aperture, hence injection energy in high field aperture.

Flexibility in the Operations of Two Rings

Classical case: 2 apertures are coupled and field in the two is equal (~1.5 T) when the beam is transferred.

Flexible case: apertures de-coupled, with an extra power supply in low field aperture.

Cost of extra power supply will be recovered from the savings in the conductor cost.

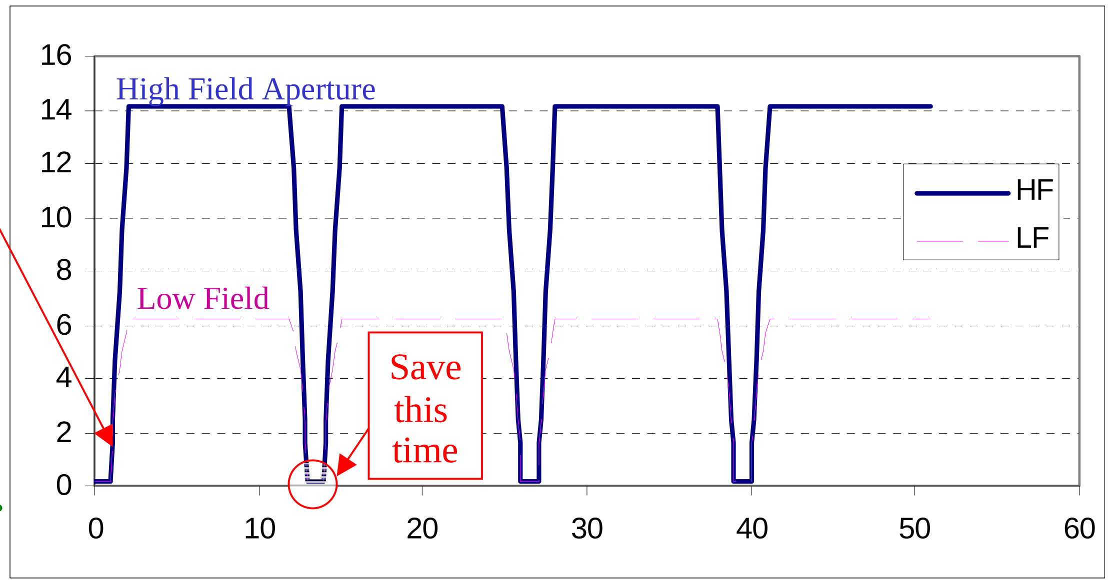
Lower energy ring can be filled while the experiments are being done in the high energy ring. This increases the duty factor to experimentalists - a more cost effective way of operating these expensive machines.

One could maintain the field quality in low field aperture to higher fields (2-3 T). It should help the beam dynamics in high field ring and hence reduce aperture (saving in the cost and size of magnet system).

The beam is transferred here (~1.5 T)

Plot between field (tesla)
in the low field and high field apertures
with time (arbitrary units).

Note: The two rings need only have the same layout-the lattice can be different.

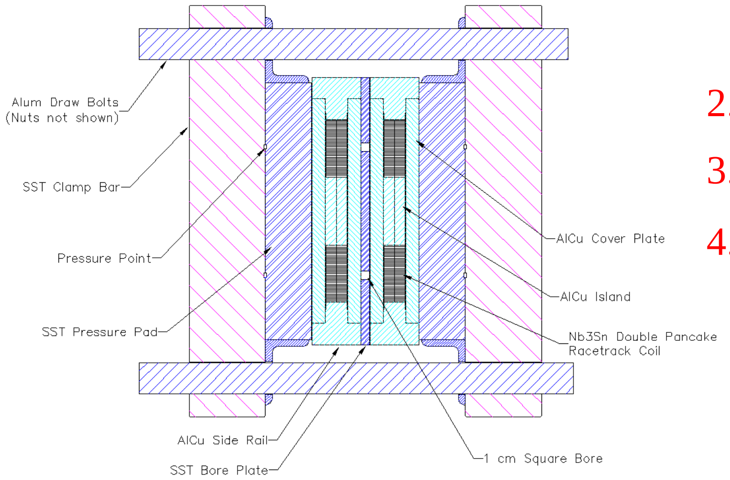


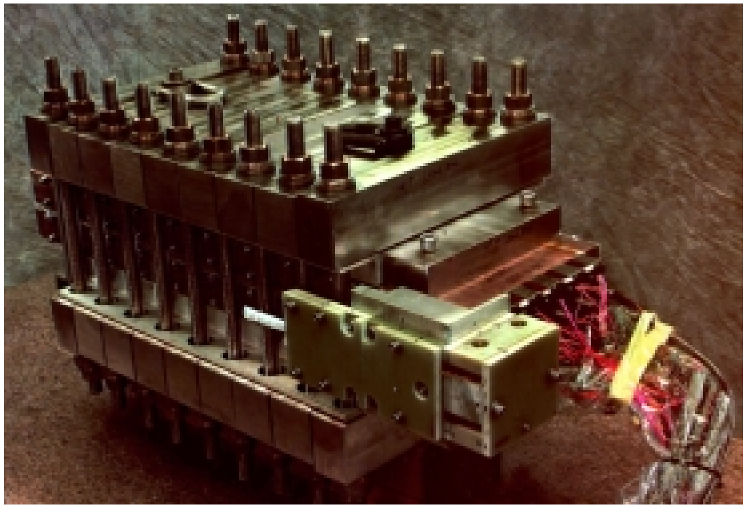
Results from the first magnet based on the common coil design

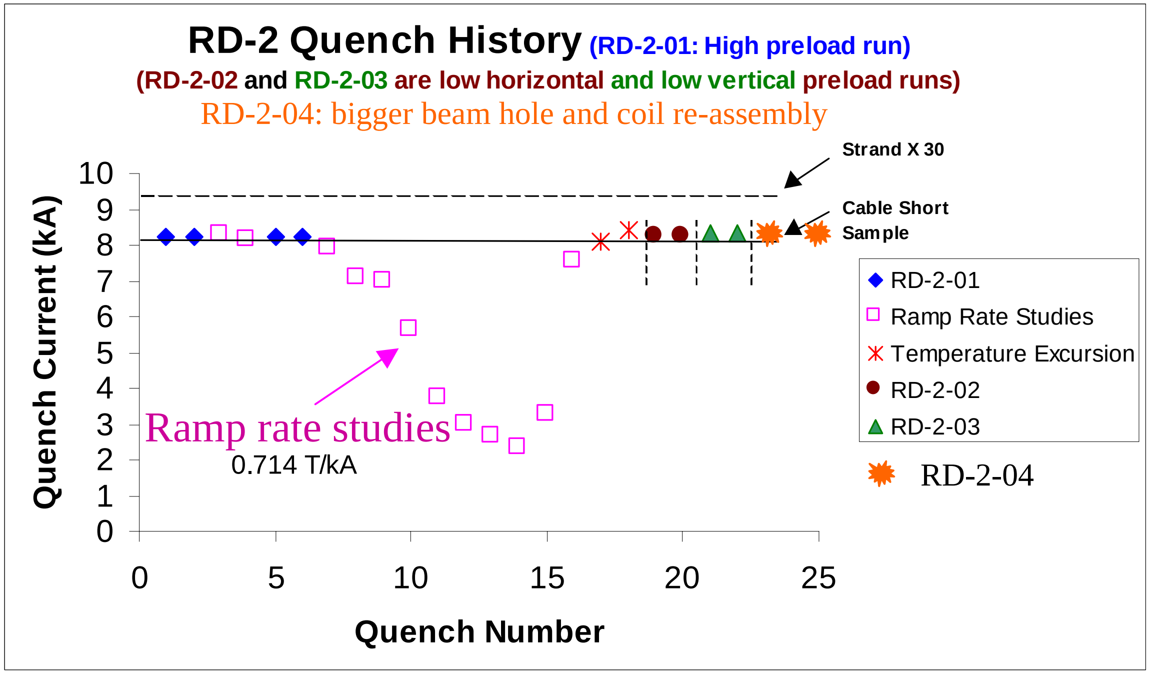
- We have built and tested the first magnet based on the common coil design
  - detailed results in the next presentation.
- It proves the viability of the concept and a job well done by the team in designing, constructing and testing this magnet.
- It also confirms the advantages that were initially identified:
    - A simple design that requires minimum tooling
    - Faster turn-around
  - A magnet built at BNL also supports the above advantages.

Quench Performance of the First Common Coil Nb_3Sn Magnet

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 design).
3. Didn't degrade for a low vertical pre-load (highly desirable).
4. Didn't degrade for a bigger hole (real magnets) and coil re-assembly.

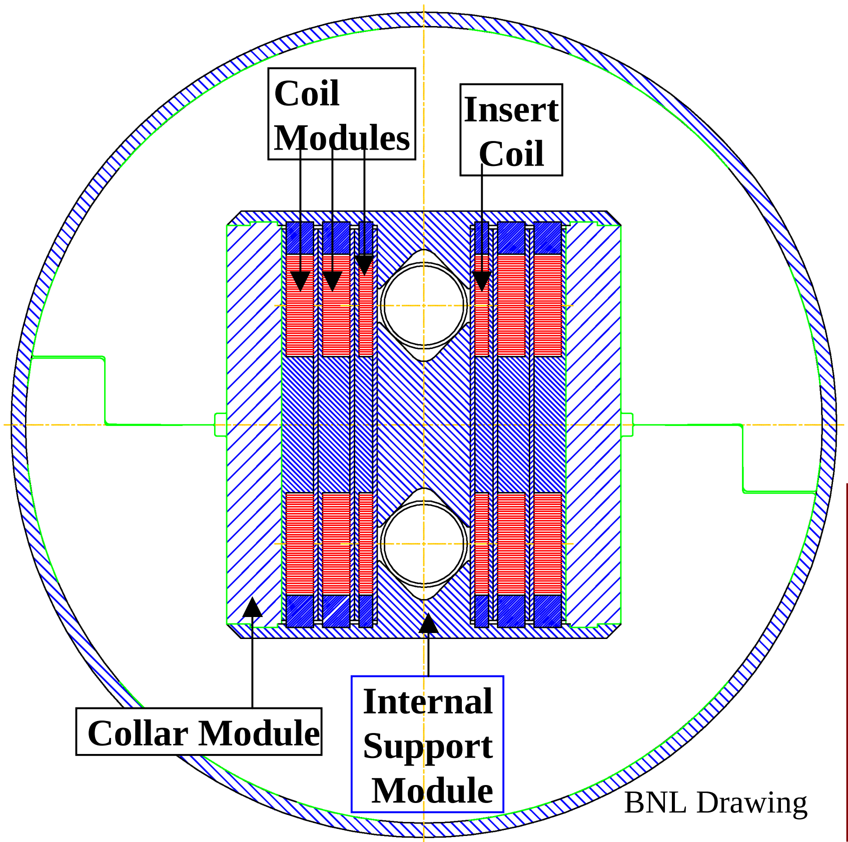






A Modular Design for a New and Low-cost Magnet R&D Approach

This could be a Magnet R&D Factory



BNL Drawing

- **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.**

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.

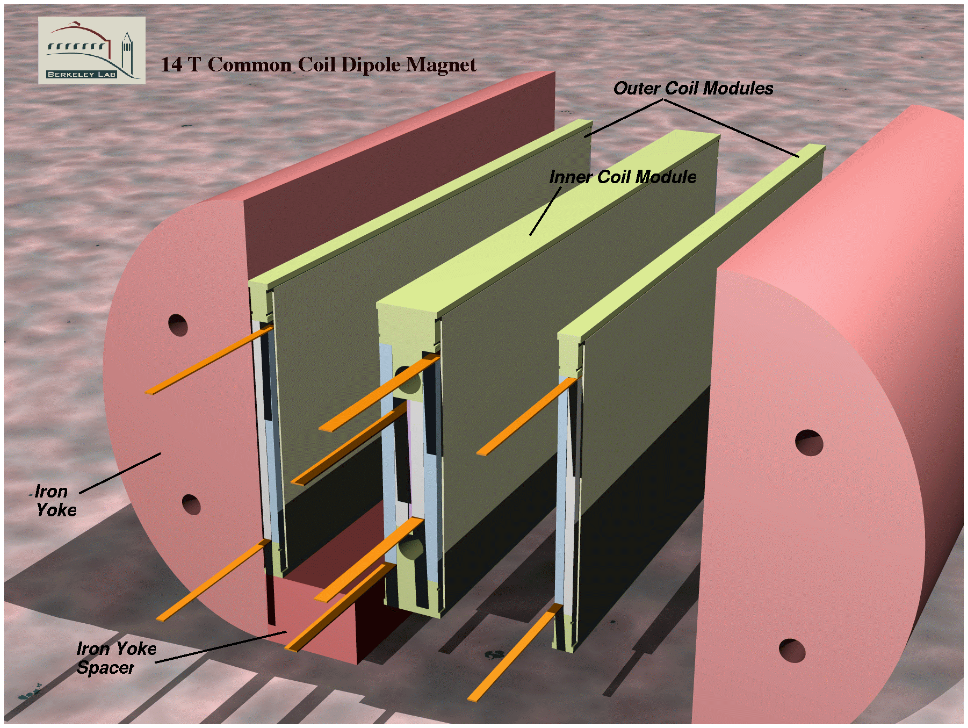
This is the time to explore and carry out an aggressive R&D program. Once the machine is funded, we are unlikely to take chances. The above facility allows that.

14 T Magnet Design Parameters (work in progress)

- Uses the high performance, the best available, Nb_3Sn conductor
  - J_{sc}(12T, 4.2K) ~2000 A/mm^2, Cu/Sc Ratio = 0.7, 1.7
- 40 mm aperture, 2-in-1 common coil magnet design
- 70 mm bend radius (in ends), 220 mm bore spacing
- Uses Iron yoke and iron insert
  - mechanically closer to an accelerator magnet
- Three layers to give a computed 14.3 T field
  - assumes no cable degradation and 4.2 k operation
- Uses unconventional cable grading
  - graded in width (NOT in thickness) for better efficiency and flexibility
- Field quality
  - not a field quality design yet, but the components of it may be used in a field quality design.

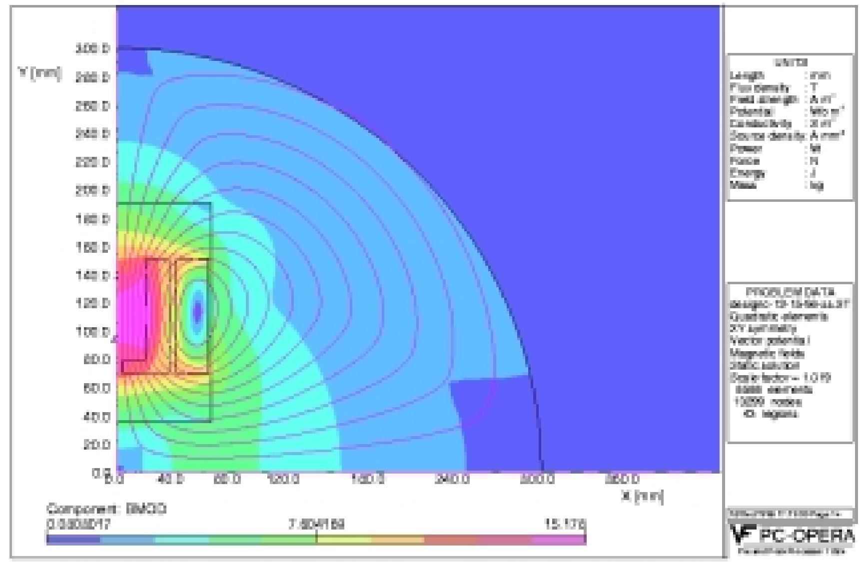
Impressions of 14 T Common Coil Magnet (now under development)

Mechanical Design and Manufacturing: Next talk (S. Gourlay)



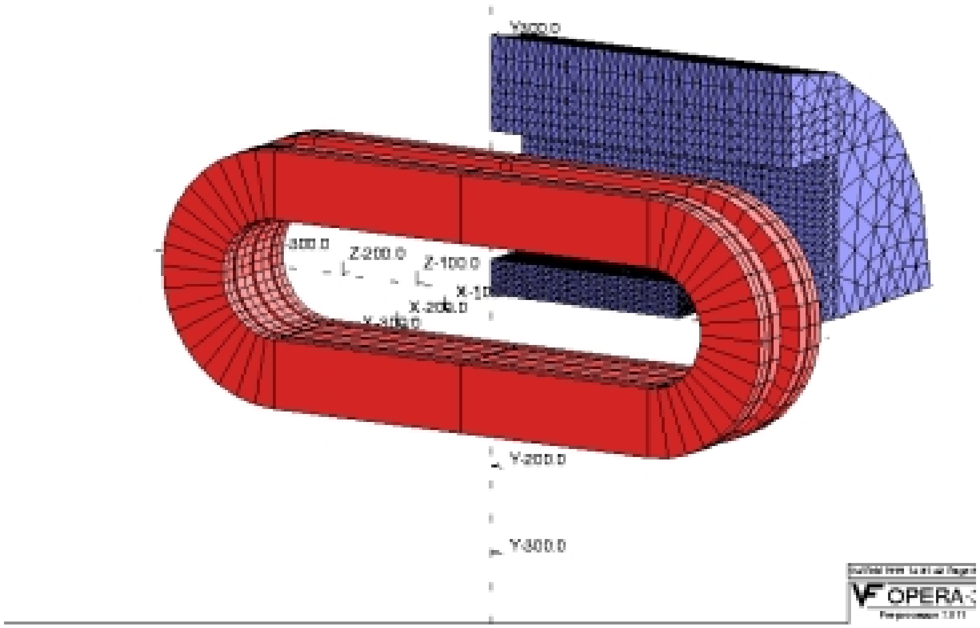
A designer (Larry Morrison) and an engineer (Ken Chow) turned into artists (good for explaining overall structure).

Magnetic Analysis of the cross-section
(1/4 of the coldmass; 1/2 of the upper aperture)



And a boring physicist (identity withheld)

Iron Yoke in the Design



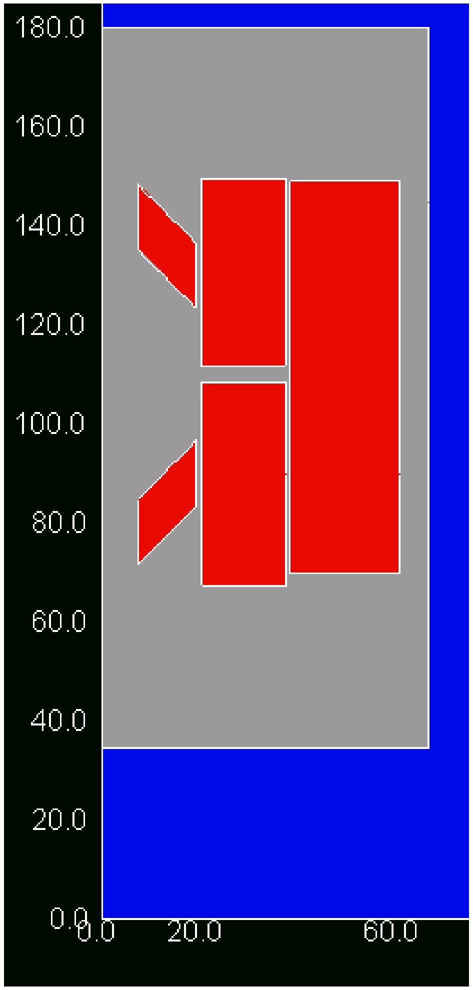
Computed Quench Performance:
~14 T at 4.2 K
(assuming no cable degradation)

- Iron yoke is placed around the coil and also in between the two apertures.
- Design appears a bit closer to the eventual machine magnet (last magnet had no iron).
- Iron and coils (in the body and ends) in this design are optimized for high quench field.
- Future designs will also be optimized for producing field quality magnets.

Parameter List of the High Field Magnet

Coil aperture (mm)	40
Number of layers	3+
Computed quench field at 4.2 K (T), zero degradation	14.3
Peak Fields, inner & outer layers (T)	15.2 & 10.6
Quench current, inner & outer layers (kA)	11.7
Wire Non-Cu J_{sc} {4.2 K, 12 T} (A/mm^2)	2000
Strand diameter (mm)	0.8
No. of strands, inner & outer layers	40, 26
Cable width, inner & outer layer (mm)	16.9, 11.1
Cu/Non-Cu ratio, inner & outer	0.7, 1.7
No. of turns in magnet half (total)	5+48+48+48 (149)
Height of 3 layers (mm)	80
Bore spacing (mm)	220
Minimum coil bend radius (mm)	70
Yoke outer radius (mm)	300

Field Quality Optimization in the Common Coil Design Magnet



One wedge and adjustments in block positions generates a cross-section where all geometric harmonics are less than 2 parts in 10^5 at 10 mm reference radius.

Saturation (current dependence) needs to be reduced in skew quad and normal sextupole (current high field value ~20).

Computed Quench Field:

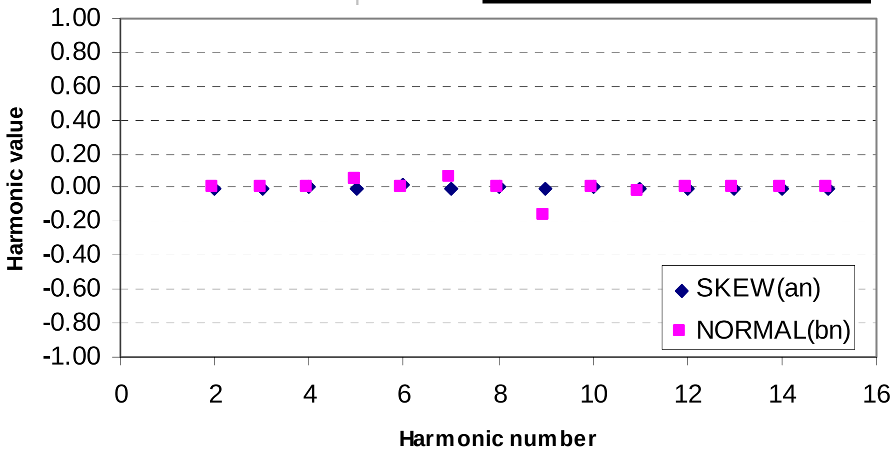
15 T (4.2 K, no degradation)

Harmonics at 10 mm at 1.8 T in 10^{-4} units

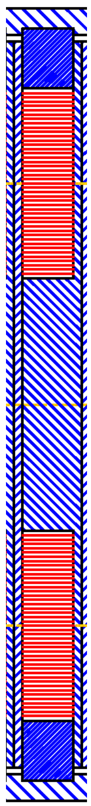
(b_3 is sextupole)

Typical accelerator requirements is 1 x 10^{-4}

N	SKEW(a_n)	NORMAL(b_n)
2	-0.01	0.00
3	0.00	0.00
4	0.01	0.00
5	0.00	0.04
6	0.02	0.00
7	0.00	0.05
8	0.01	0.00
9	0.00	-0.17
10	0.00	0.00
11	0.00	-0.03
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00
15	0.00	0.00



A Possible Low-cost Magnet Manufacturing Process



- **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)**

Conclusions and Summary

VLHC based on the common coil magnet system

- **A new magnet and system design**
  - large savings are unlikely to come with the same way of doing things.
- **A proposal that eliminates the second largest ring (and associated complex) with several technical advantages.**
- **This will significantly reduce the cost of magnets, machine and the operation.**
- **A systematic magnet R&D approach for faster turn-around.**