# Magnet System Designs for A Lower Cost Hadron Collider

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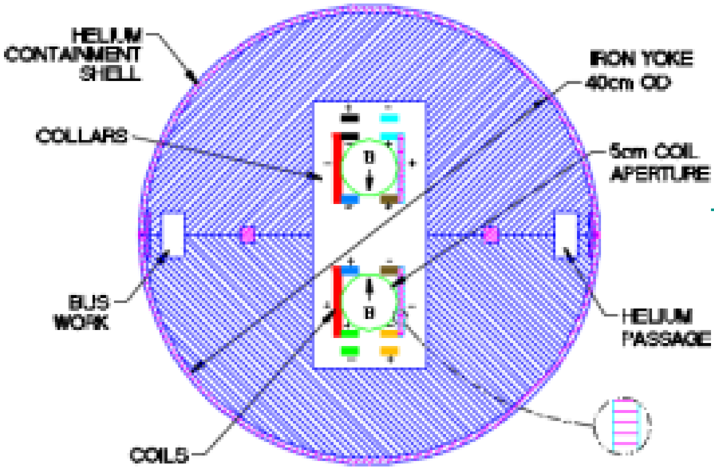
# VLHC: The Challenge is the Cost

- To change it substantially, we have to do things differently.

- Superconducting dipoles are the cost driver. *"Cosine Theta Niobium Titanium Magnet Technology"* has been around for decades; the cost is unlikely to change significantly. We need to explore alternate designs & manufacturing techniques.

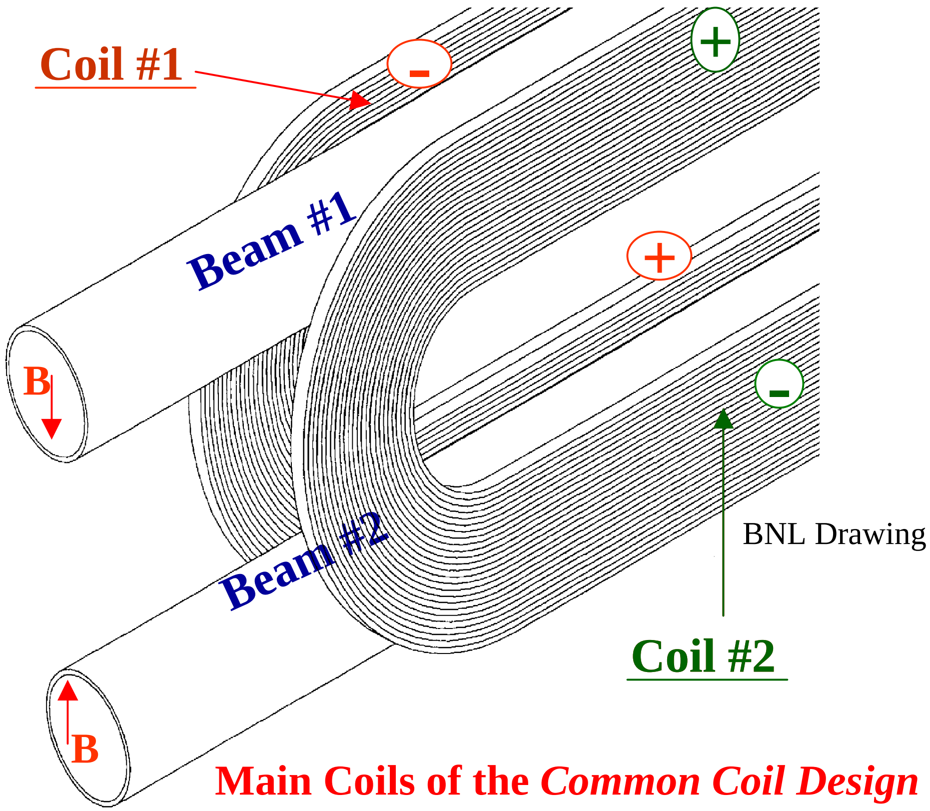
- A unique window of opportunity to explore innovative magnet designs as VLHC is ~15 years away. We are pursuing high field frontier. However, a number of benefits of this approach may be applicable to the medium field option as well.

- While the superconducting dipole magnets (~1/4 of the machine cost) remain the major thrust of cost reduction strategies, to alter overall VLHC cost significantly we need to go beyond magnets. Examine all major sub-systems (components) and see if they can be made cheaper or if some can be eliminated all together.



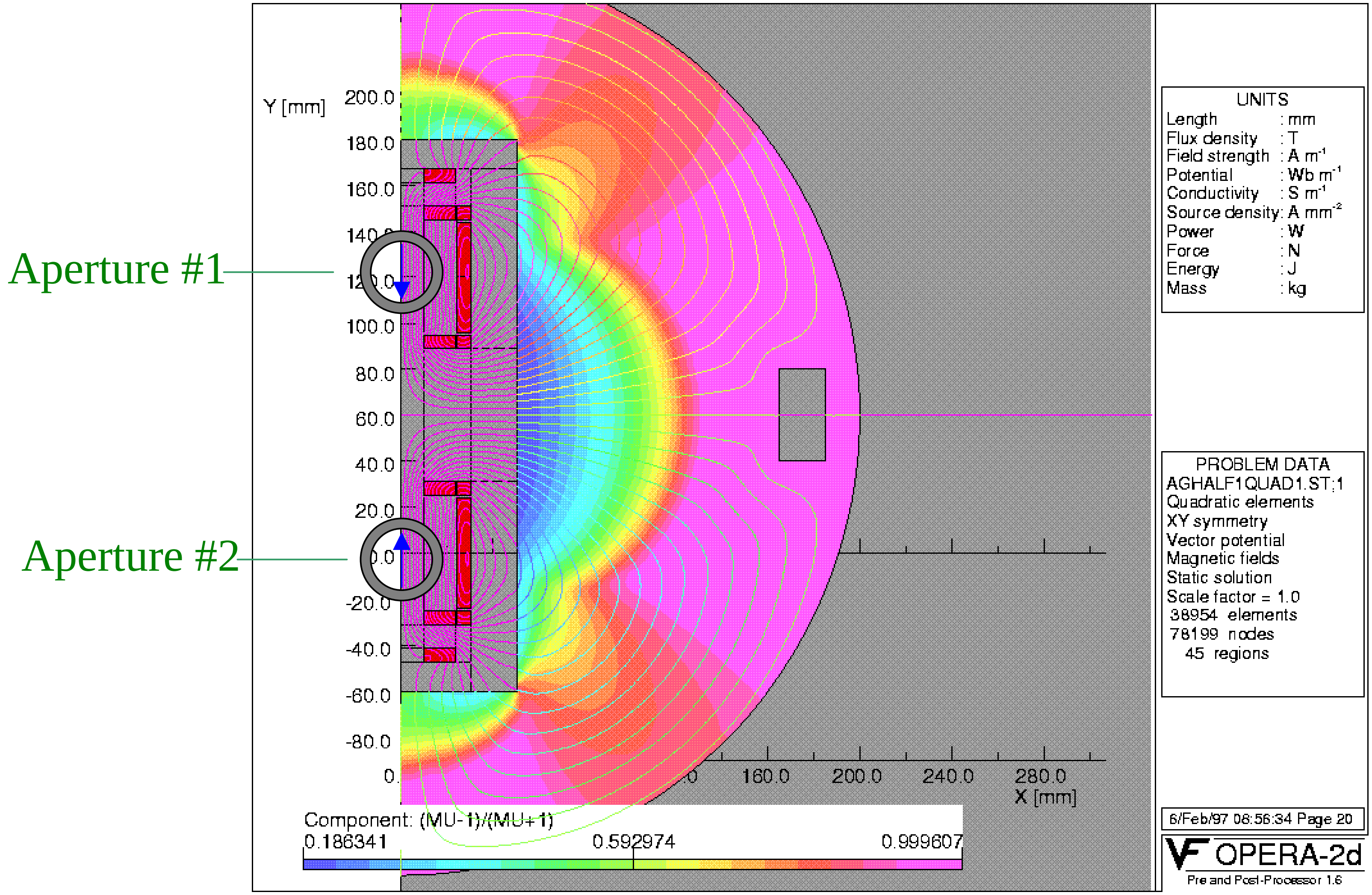

# Common Coil Design

- **Simple 2-d geometry with large bend radius (no complex 3-d ends)**
- **Conductor friendly suitable for brittle materials ($Nb_3Sn$, HTS, etc.) and React & Wind coils**
- **Compact (compared to single aperture D20 magnet, half the yoke mass 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***




**Main Coils of the *Common Coil Design***

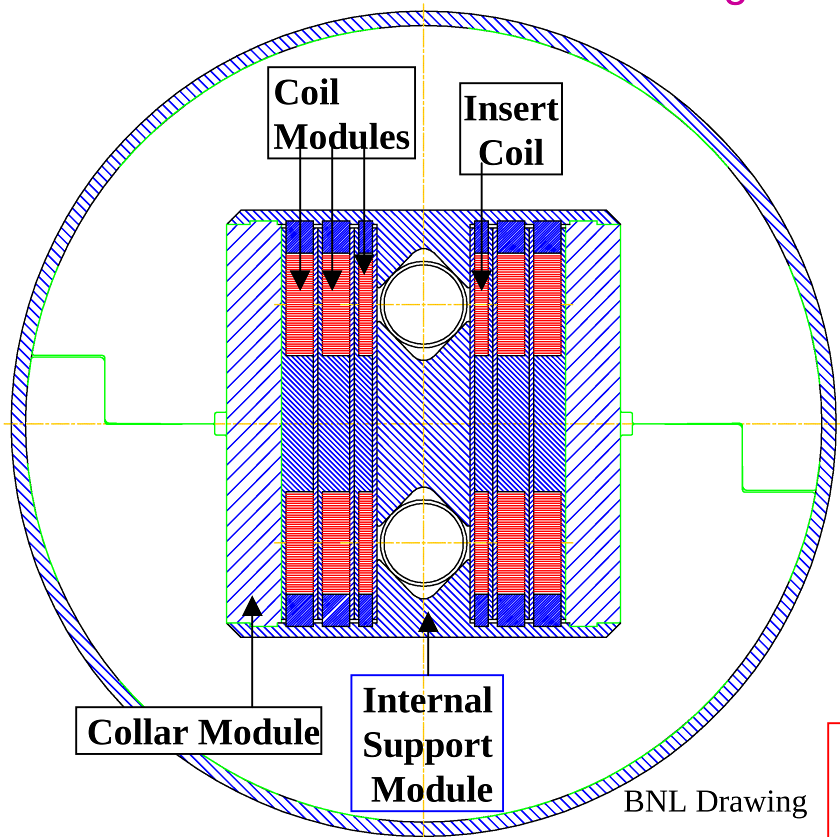
# Field Lines at 15 T in a Common Coil Design Magnet



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

Another challenge:

A limited R&D funding.




We must learn how to do magnet research cheaper that will lead to cheaper magnets. This is the time to undertake an innovative R&D program. Once the machine is funded, we are unlikely to take chances. This design provides a low-cost, systematic R&D facility.

- **Replaceable only a single coil module by one made with different conductor, insulation, cable (may have different width), React&Wind, etc.**
- **Reduce magnet aperture for higher test fields.**
- **Study support structure, stress management.**

**Traditionally such changes required building a new magnet - expensive, takes time, limits amount of R&D**

**The left and right sides need not be identical.**
**Combined function magnets possible.**
**A potential for major cost savings ===>**

***This could be a Magnet R&D Factory***

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

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

TABLE 1

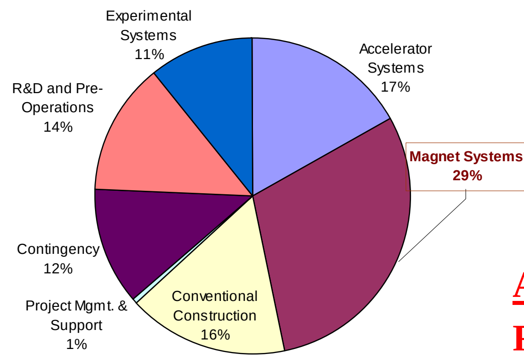
(1990 Estimates in US$)

Superconducting Super Collider
Cost Estimate Summary

(Table used to get rough estimates)

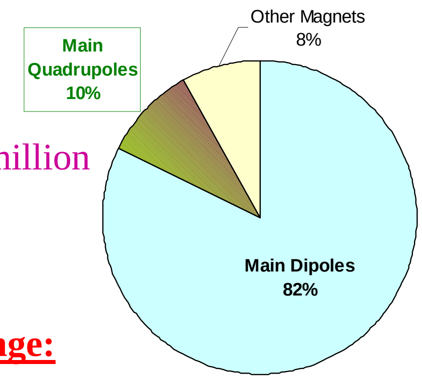
| Project Component | | Costs in $M |
|---|---|---|
| 1.1 Accelerator Systems | | 1322 |
| 1.1.1 Management and Support | 37 | |
| 1.1.2 Linac | 45 | |
| 1.1.3 LEB | 52 | |
| 1.1.4 MEB | 137 | |
| 1.1.5 HEB | 190 | |
| 1.1.6 Collider | 777 | |
| 1.1.7 Test Beams | 14 | |
| 1.1.8 Global Systems | 70 | |
| 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 |

**SSC Project Cost Distribution**
(Reference SSC Cost: 1990 US $7,837 million)




**Collider Ring Magnet Cost Distribution**

Total: $2,037 million




## AP Challenge:

**Retaining benefits of Synchrotron Damping**

SSC Main Quads: ~$200 million; VLHC: ~$400 million (x2 not 2.5)

Additional savings also from tunnel, interconnect, contingency, etc.

Estimated savings by eliminating main quads: ~$500 million (1990)

## Another Major Sub-system: HEB

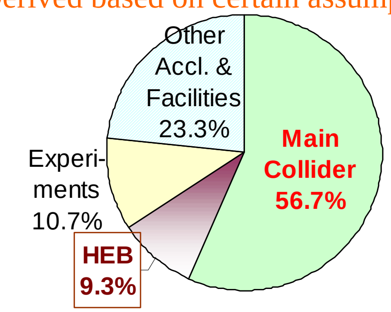
2 TeV HEB Cost in SSC (derived):
$700-800 million

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

A possibility to save 70-80% of it follows.

Cost savings in equivalent 20xx $?

**Cost Distribution of Major Systems**
(Reference SSC Cost: 1990 US $7,837 million)
(Derived based on certain assumptions)



# Field Quality in Common Coil Design

- Geometric harmonics
  - an inherent up-down asymmetry both in the body and in the ends
    - A proof of principle solution that overcomes this asymmetry.

**=> A field quality comparable to cosine theta designs by using a similar amount of conductor.**

Should remove the age-old conventional wisdom that "block designs" use more conductor than the "cosine theta magnets".

* We just have to optimize the design a bit more carefully! *

- Saturation induced harmonics
- Persistent current induced harmonics

  - could be a serious problem in $Nb_3Sn$ magnets.
    - The proposed solution brings major savings as a bonus.

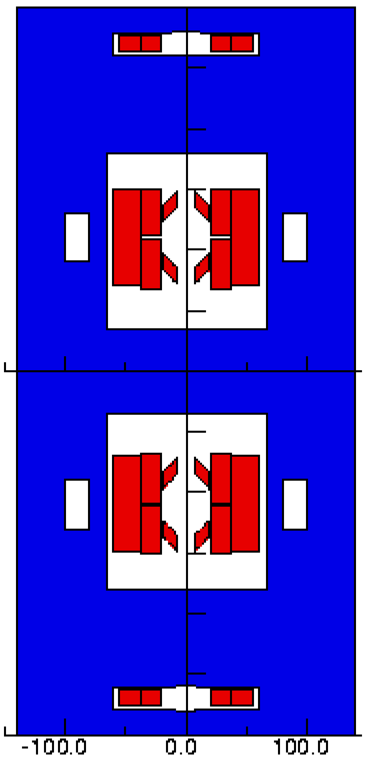
# Field Quality Optimization in the Common Coil Design (Magnet Body)

## A Proof of Principle Design

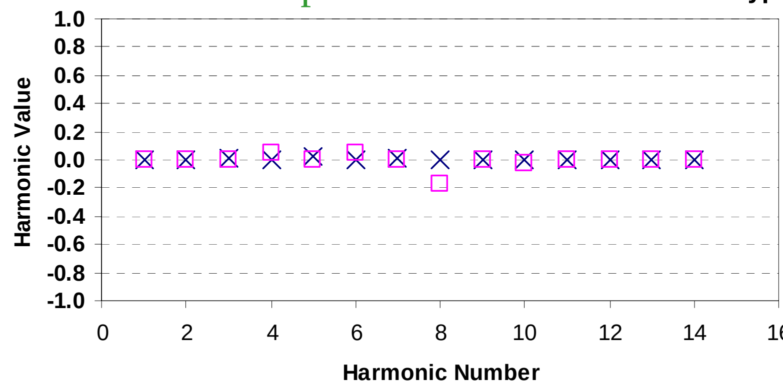
(still comparable or better than similar cosine theta designs)

**ROXIE for real optimizations**

A Compact Design (lower cost) 15 T 4-in-1 dipole.
2.4 times smaller than single aperture 13.5 T D20;
1.4 times smaller than dual aperture 9-10 T LHC

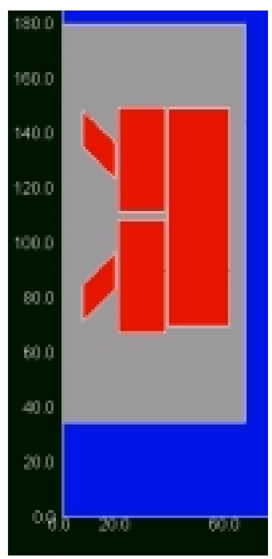



A preliminary cross-section: geometric harmonics < 0.2 parts in $10^4$ at 10 mm.



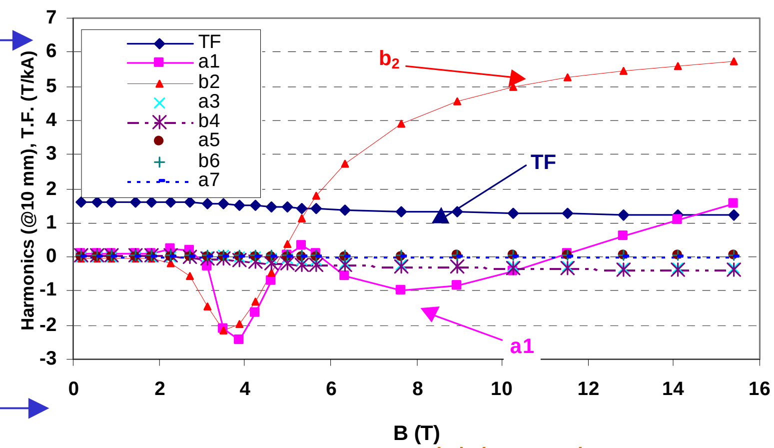

**Harmonics at 10 mm at 1.8 T in $10^{-4}$ units**
**(b2 is sextupole)**
**Typical accelerator requirements: ~ $10^{-4}$**

| N | SKEW($a_n$) | NORMAL($b_n$) |
|---|---|---|
| 1 | -0.01 | 0.00 |
| 2 | 0.00 | 0.00 |
| 3 | 0.01 | 0.00 |
| 4 | 0.00 | 0.04 |
| 5 | 0.02 | 0.00 |
| 6 | 0.00 | 0.05 |
| 7 | 0.01 | 0.00 |
| 8 | 0.00 | -0.17 |
| 9 | 0.00 | 0.00 |
| 10 | 0.00 | -0.03 |
| 11 | 0.00 | 0.00 |
| 12 | 0.00 | 0.00 |
| 13 | 0.00 | 0.00 |
| 14 | 0.00 | 0.00 |



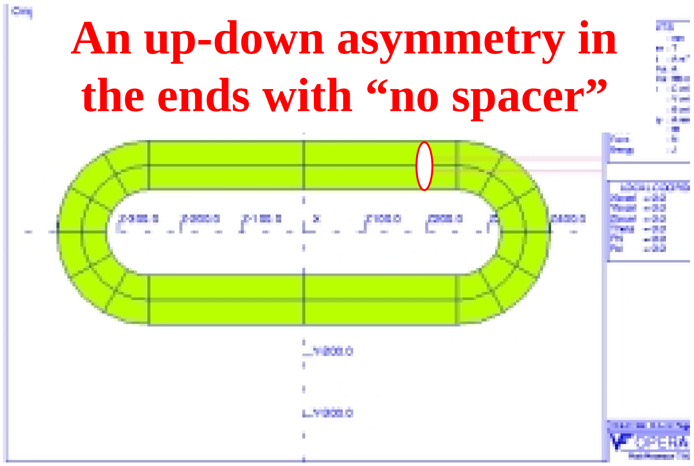
**Computed Quench Field: 15 T**
**(4.2K and no cable degradation)**

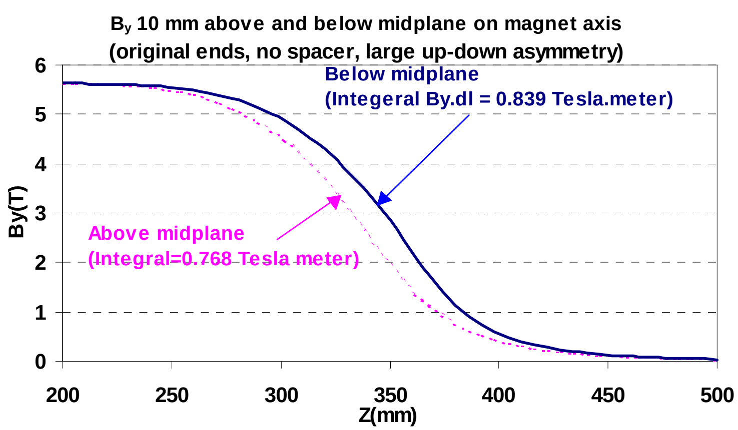
Iron saturation (comparable to cosine theta designs)



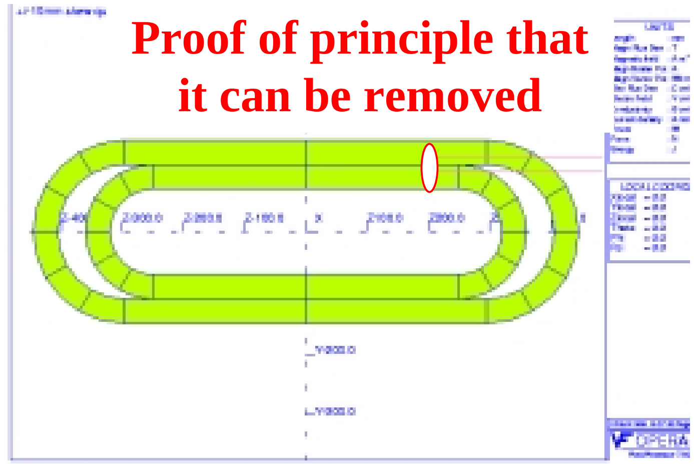
# Field Quality Optimization in the Common Coil Design (Magnet Ends)

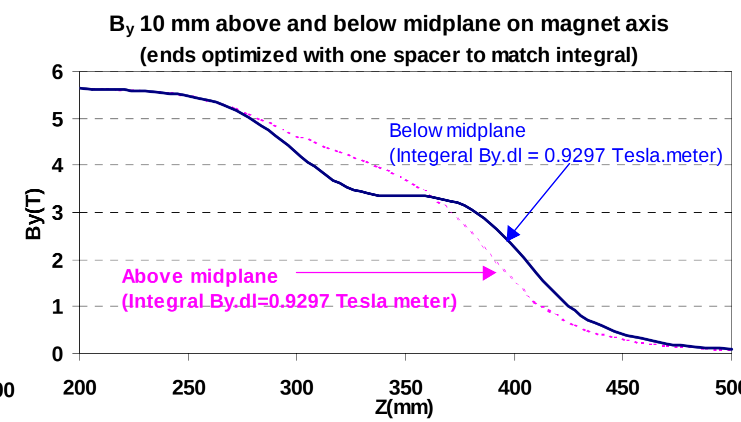
Up-down asymmetry gives large skew harmonics if done nothing. Integrate By.dl 10 mm above and 10 mm below midplane.




Up-down asymmetry can be compensated with end spacers. One spacer is used below to match integral By.dl 10 mm above & below midplane.




Computer code ROXIE (developed at CERN) will be used to efficiently optimize accelerator quality magnet design.

Young Post-doc (Suitbert Ramberger).

A large Bz.dl in two ends (~1 T.m in 15 T magnet).

- Is it a problem?
- Examine AP issues.
- Zero integral.
- Lead end of one magnet + Return of the next magnet will make it cancel in about ~1meter (cell length ~200 meters).
- Small v X B.

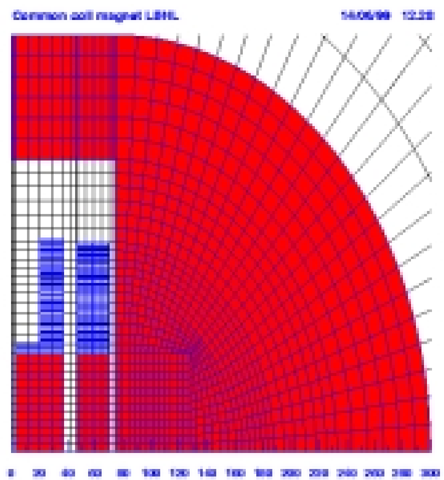
# Magnetic Design of 14 T Dipole (the magnet under development)

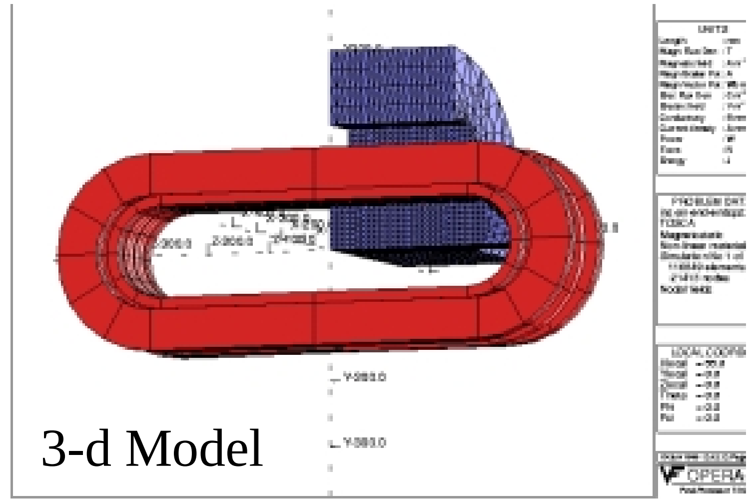
- **40 mm aperture, 2-in-1 common coil magnet design, 220 mm bore spacing**
- **Uses the high performance, the best available, $Nb_3Sn$ conductor**
  - **$J_{sc}$(12T, 4.2K) ~2000 A/mm$^2$, Cu/Sc Ratio = 0.7, 1.7**
- **70 mm bend radius (in ends), one end spacer in outer coils to reduce peak field**
- **Iron insert & iron yoke in magnet body; no iron over ends to reduce peak field**
- **Three full (plus one partial) layers to give a computed 14.3 T field at 4.2 K**
  - **assumes no degradation (either due to stress or in cabling)**
  - **13.7 T with Oxford cable (has less SC) and single power supply**
- **Uses unconventional cable grading**
  - **graded in width (NOT in thickness) for better efficiency and flexibility**
- **Field quality**
  - **not a field quality design yet, but some components of it may be used in a field quality magnet.**

# Magnetic Field Calculations

The design is optimized for obtaining maximum field and not for field quality.

2-d Model with ROXIE

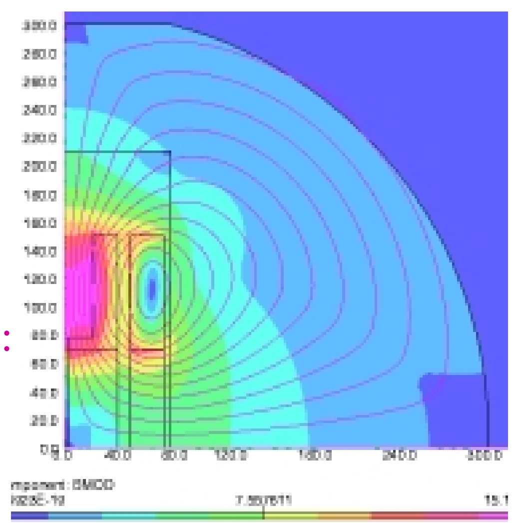




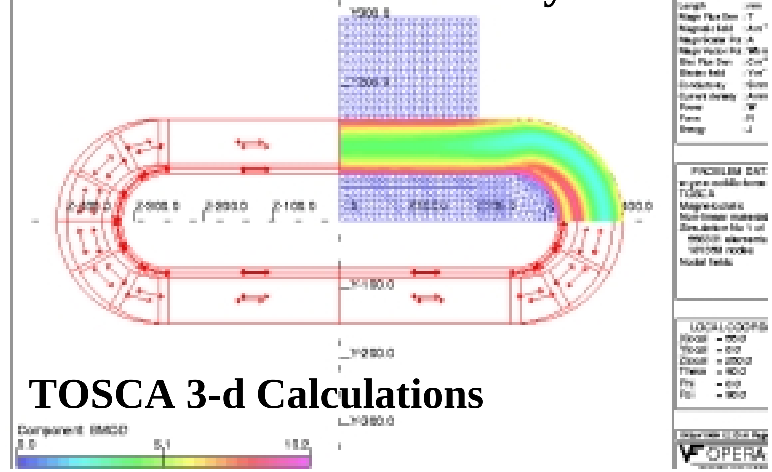
3-d Model

Field and Field lines as computed by OPERA 2-d

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



Peak field in the outer layer



TOSCA 3-d Calculations

# 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 (13.7 for oxford wire) |
| Peak Fields, inner & outer layers (T) | 15.1 & 10.5 |
| 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) | 17.4, 11.6 |
| Cu/Non-Cu ratio, inner & outer | 0.7, 1.7 |
| No. of turns in magnet half (total) | 5+50+49+49 (153) |
| Height of 4 layers (mm) | 8.06, 80.59, 79.98, 79.98 |
| Bore spacing (mm) | 220 |
| Minimum coil bend radius (mm) | 70 |
| Yoke outer radius (mm) | 300 |
| Coil straight section length (mm) | 500 |
| Yoke length (mm) | 400 |

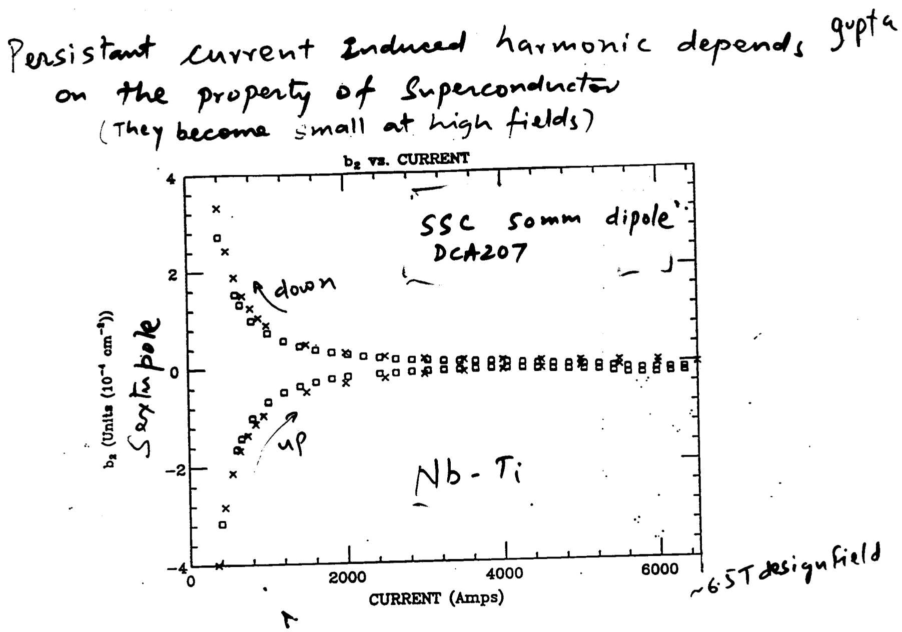
# Persistent Current-induced Harmonics

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

$Nb_3Sn$ 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).

Measured sextupole harmonic in Nb-Ti magnet




Measured sextupole harmonic in $Nb_3Sn$ magnet

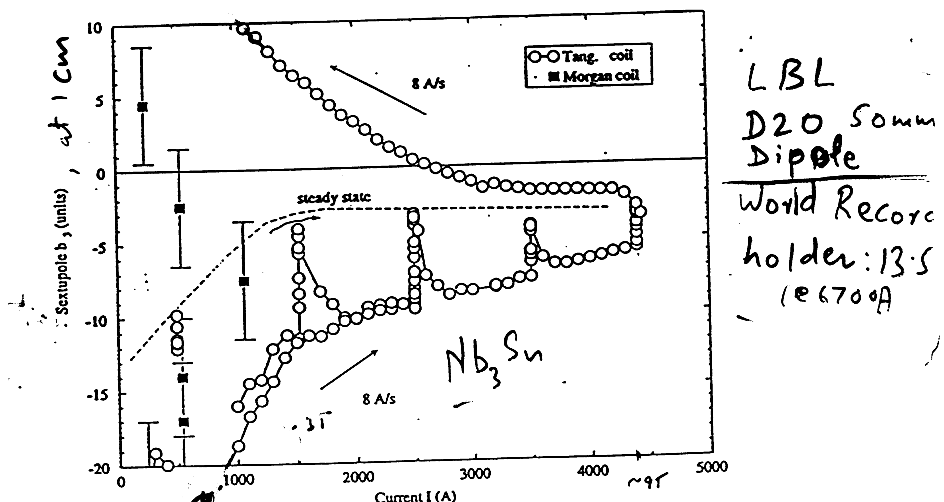



Fig. 6. Measured sextupole at low field (direction of arrow indicates up or down current).

# Persistent Current-induced Harmonics

## Traditional solution: work on the superconductor

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

$\nu$ , VOL. FRACTION OF NbTi

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

Problem in $Nb_3Sn$ Magnets because

(a) Jc is higher by several times

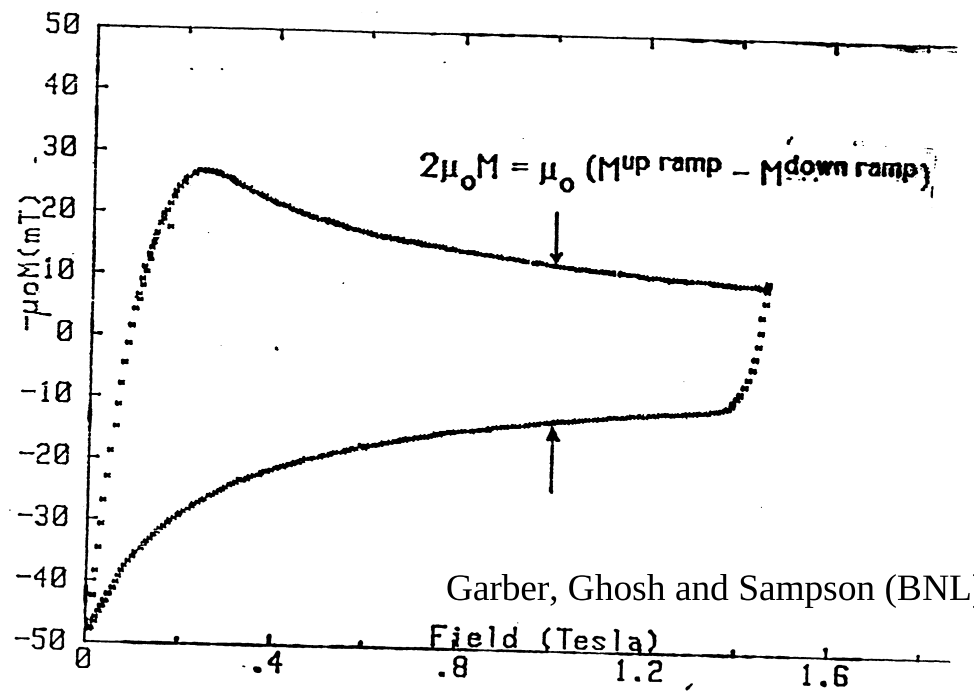
(b) Effective filament diameter is larger by about an order of magnitude

**Conductor solution:**

Reduce effective filament diameter.

A challenge; in some cases it also reduces $J_c$.

Measured magnetization




Garber, Ghosh and Sampson (BNL)

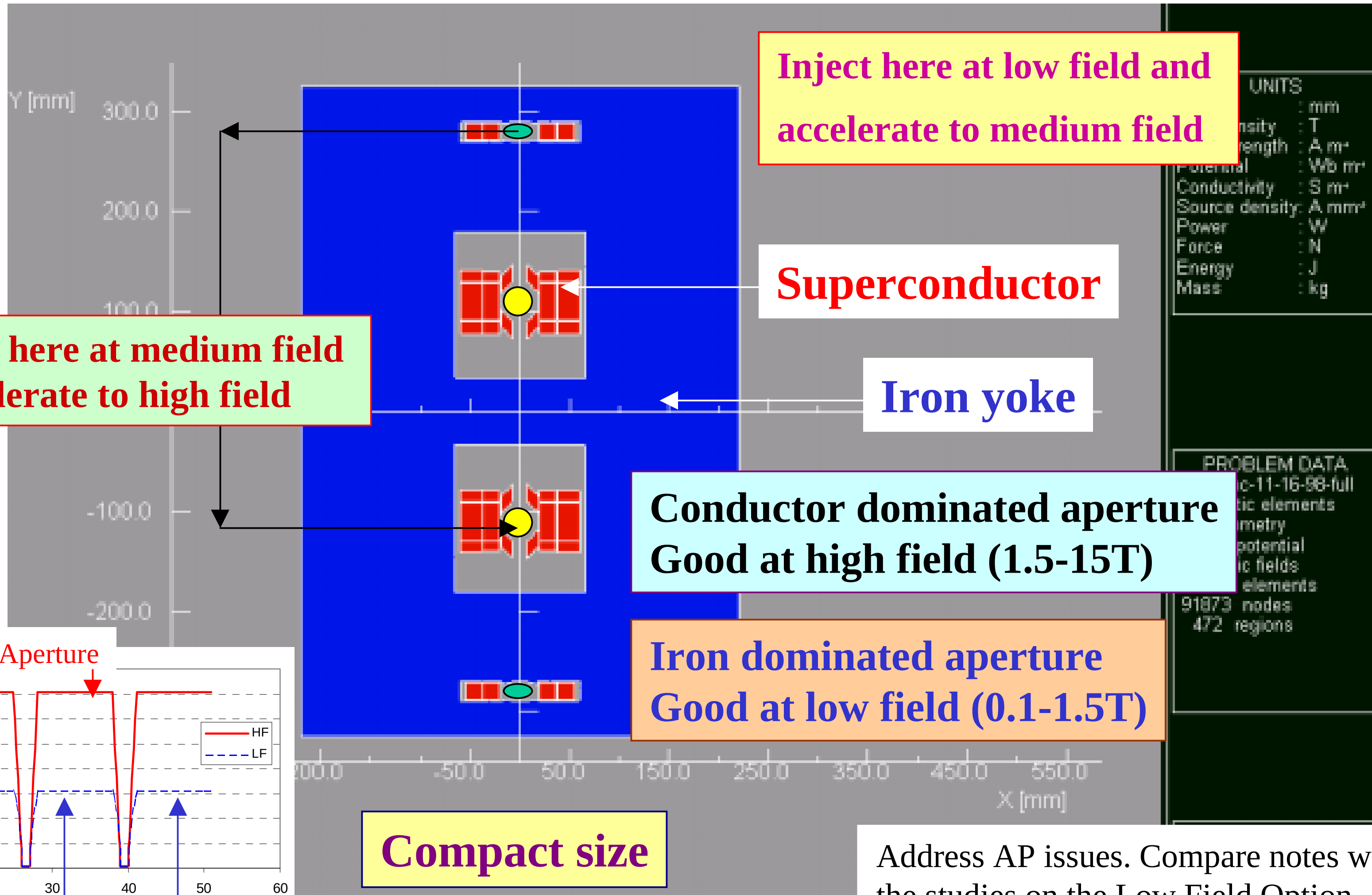
Fig. of a typical magnetization loop.

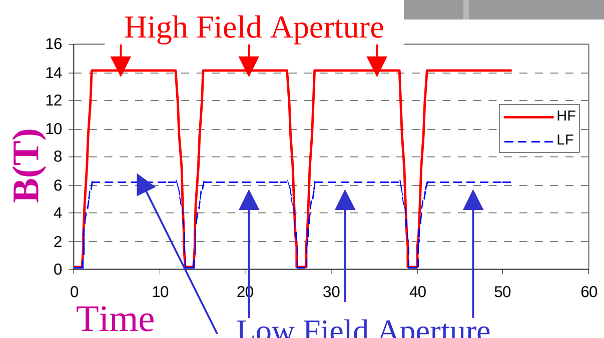
**Note: Iron dominated magnets don't have this problem.**

# A Common Coil Magnet System for VLHC

## Alternate solution: work on the magnet design

**A 4-in-1 magnet for a 2-in-1 machine**

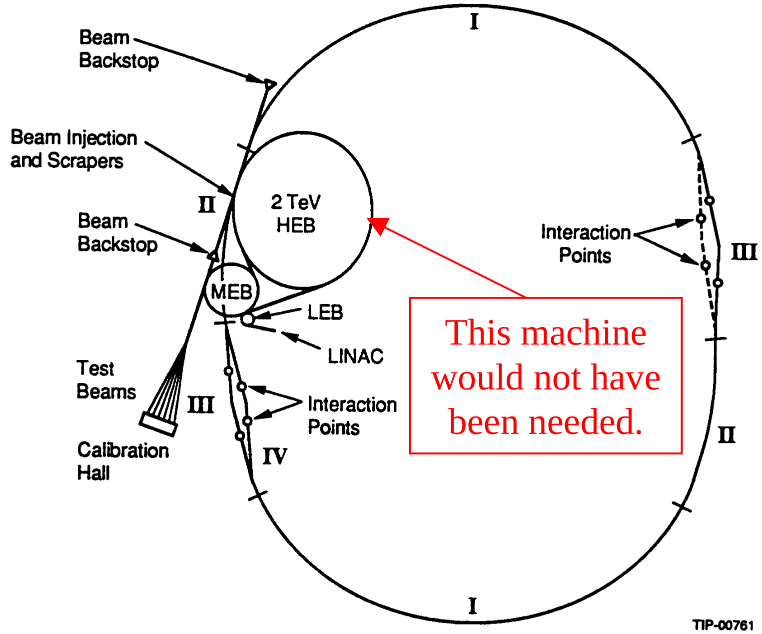



Address AP issues. Compare notes with the studies on the Low Field Option.

# The Proposed Solution to Large Persistent Current Problem in $Nb_3Sn$ Magnets that, as a Bonus, Eliminates HEB

Funny that the side benefit is more attractive than the original reason.




This machine would not have been needed.

**Figure 4.1.1.1-4.** Schematic layout of SSC.

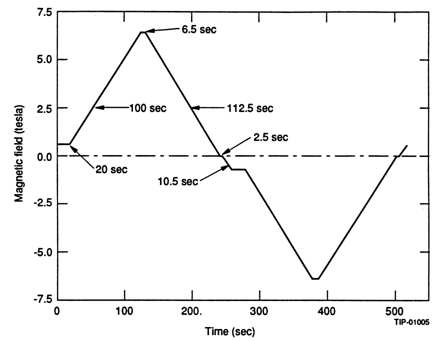



**Figure 4.1.2.4-1.** The suggested slow, alternating ramp scenario of the HEB.

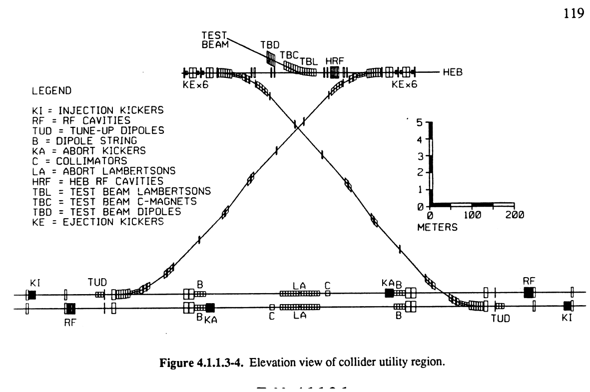



**Figure 4.1.1.3-4.** Elevation view of collider utility region.

Savings for VLHC may be *over one billion dollars* for an equivalent HEB with 5 TeV design energy

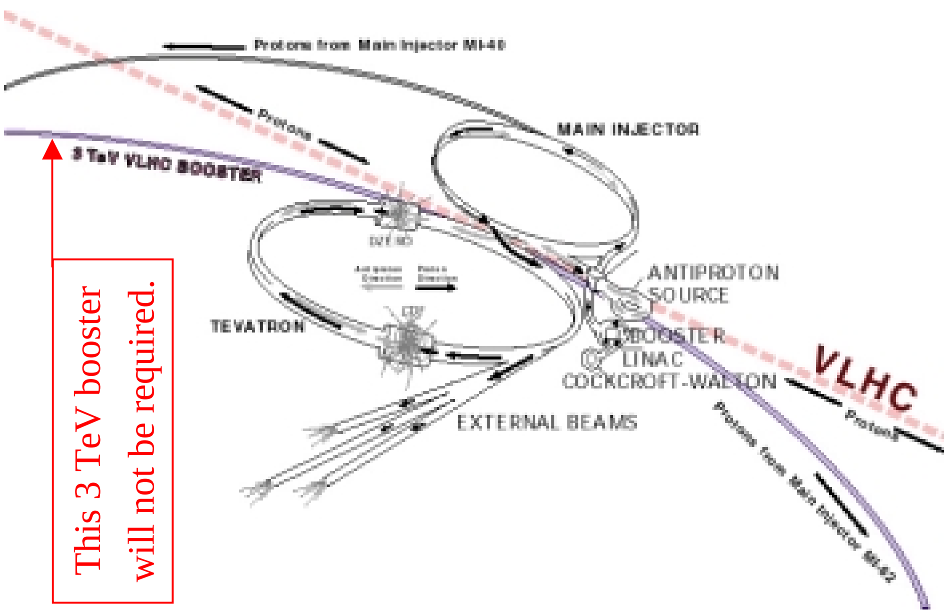
(SSC: 2-20 TeV, VLHC 5-50 TeV)

- 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.

# Case Studies for VLHC at/near Fermilab Site

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

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




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

**Fermilab machine chain as VLHC injector:**

**Main Injector: 150 GeV (ejection energy)**

**Tevatron: 150-800 GeV (20% margin)**

All options have a dynamic range 10 or less for vlhc.

<u>Option 1</u>:

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

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

<u>Option 2</u>:

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

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

<u>Option 3</u>:

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.

# 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.*

- **Compact Magnet System**

*As compared to single aperture D20, 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 cost.*

# 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

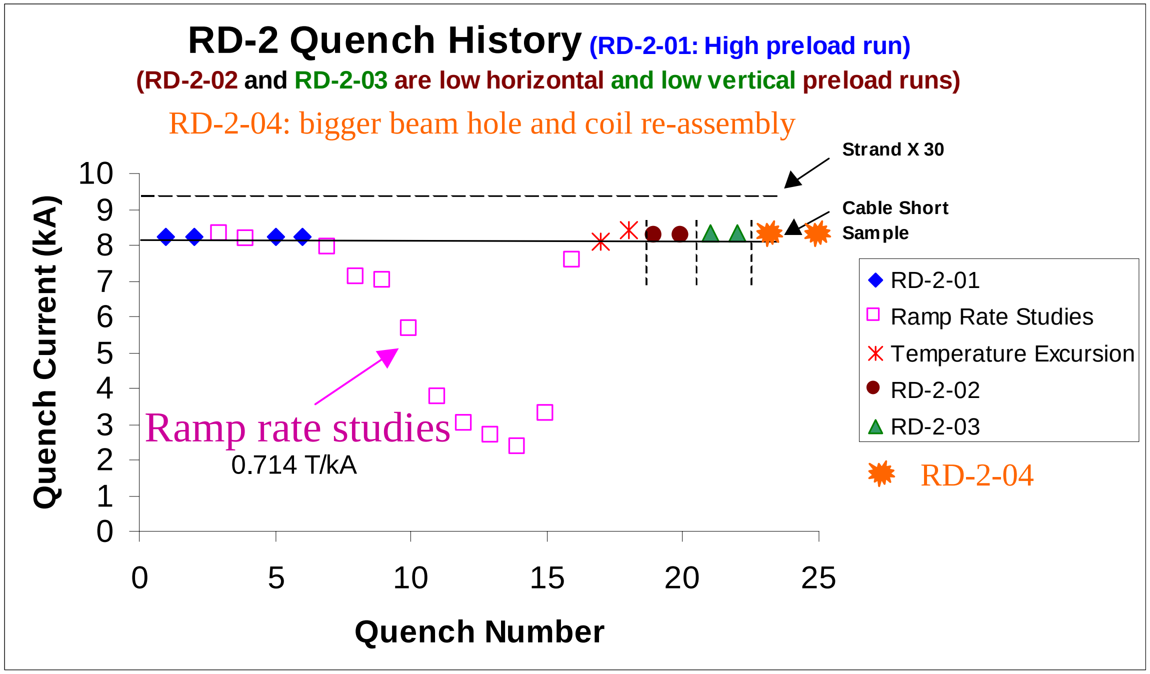
The conventional cosine theta magnets are hard to build below certain aperture as the bend radius and the end geometry would limit the magnet performance. In the common coil design, the magnet aperture and magnet ends are completely de-coupled. The situation is even better than that in the conventional 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.

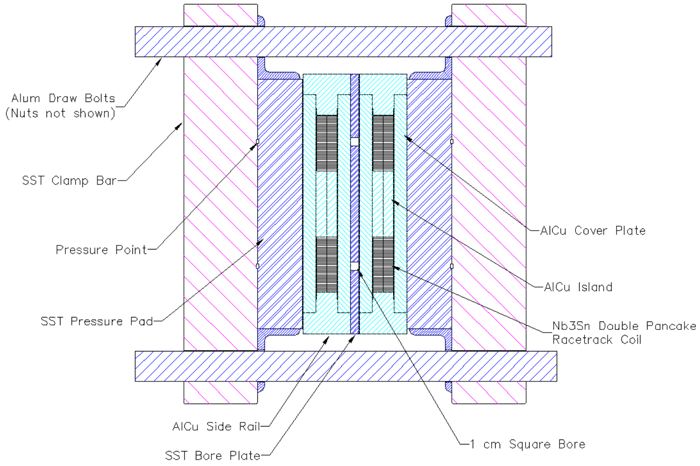
## Accelerator Physics Issues

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. There 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.

# Experimental Investigations for support structure design in ultimate magnet

Support structure is expansive and the cost grows rapidly in high field magnets. The cost may be lowered and the magnet may be made simpler if we can prove that full pre-stress is not essential. (LHC magnet experiments).




1. The magnet reached plateau performance right away (plateau seems to be on the cable short sample, not wire short sample).

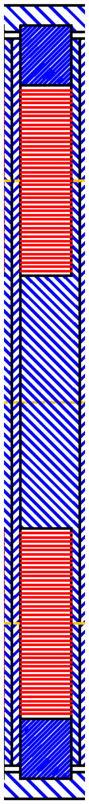
2. Didn't degrade for a low horizontal pre-load (must for this design).

3. Didn't degrade for a low vertical pre-load (highly desirable).

4. Didn't degrade for a bigger hole (real magnets).

# 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)**

# Recap on Cost Saving Possibilities for VLHC

## A multi-pronged approach:

- 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 design.
- Possibility of removing the high energy booster (the second largest machine) in the proposed system.
- Possibility of removing main quadrupoles (the second most expansive magnet order) in the proposed combined function magnet design.

Need to examine the viability of these proposals further; need to continue the process of exploring more new ideas and re-examine old ones (they may be attractive now due to advances in technology, etc.); need to keep focus on the bigger picture…

VLHC cost reduction may also come from other advances: cheaper tunneling, development in superconductor technology, etc.

# Conclusions and Summary

**VLHC based on the common coil magnet system**

(large savings are unlikely if we continue the same way of doing things)

- **A new magnet and system design**
  - May significantly reduce the cost of building and operating machine with several technical advantages.
- **A systematic magnet R&D approach for encouraging innovative designs and technologies**
  - **Faster turn-around time; this is the time to explore.**