Field Quality Optimization
in a
Common Coil Magnet Design

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Challenge for the Next Collider

One major challenge for the next collider

(whatever it is)

- electron collider
- muon collider
- hadron collider

is the cost.

... and it can't be reduced by a large amount by extrapolating the present technology.

We have to look for alternate designs and technologies.
Perhaps, it's not a choice; it's a requirement.

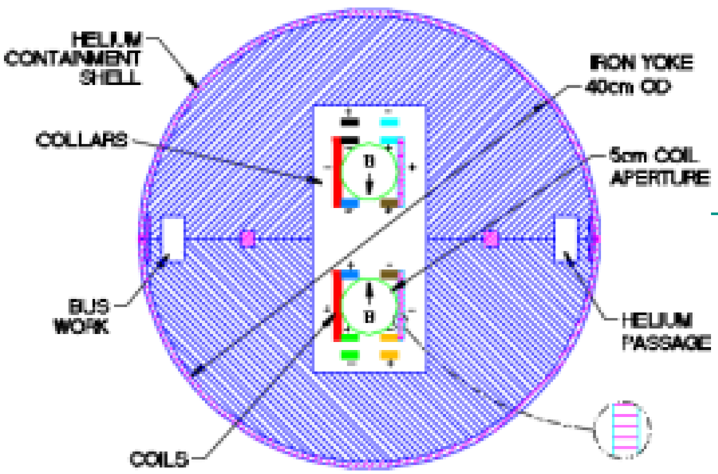
Very Large Hadron Collider (VLHC)

- For VLHC, the biggest challenge is not that whether it can be built with the present day technology or not but that it will cost too much if built that way.

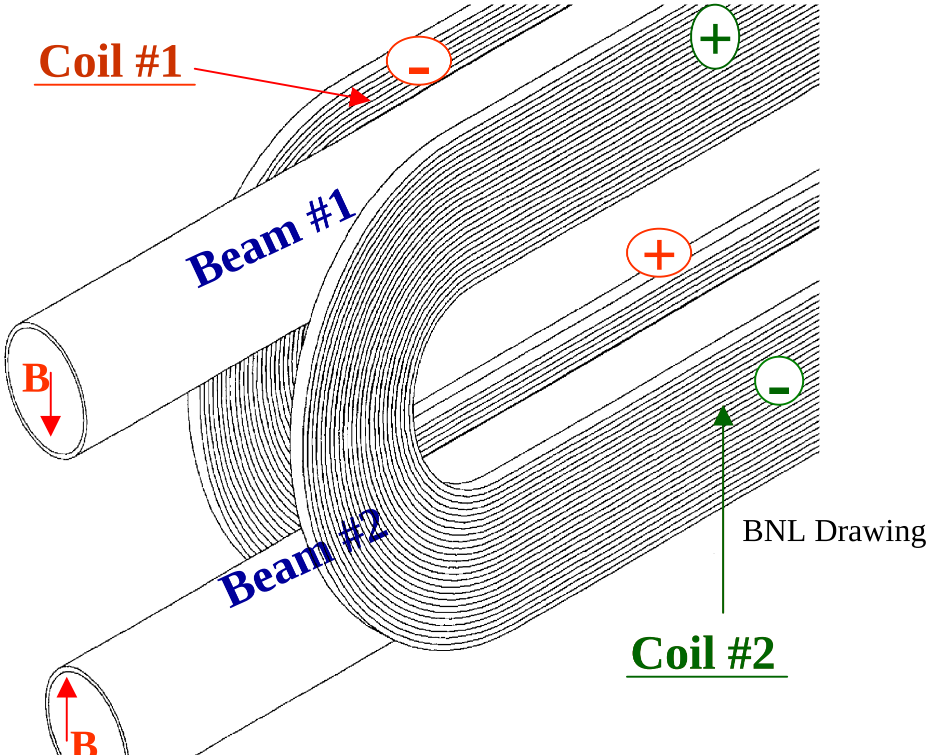
- Superconducting dipoles are the cost driver. *"Cosine Theta Niobium Titanium Magnet Technology"* has been around for decades; the cost is unlikely to change significantly. We need to explore alternate designs & manufacturing techniques.

- A unique window of opportunity to explore innovative magnet designs as VLHC is ~15 years away. The common coil design is primarily developed for high field magnets. However, a number of benefits of this may be applicable to the low and 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
(The Original Concept)



BNL Drawing

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**

Why Don't We Have More Racetrack Coil Magnets?

- If racetrack coil magnets are really so nice, why don't we have more of them?
- Why *"cosine theta"* has been the standard design for high field superconducting accelerator magnets for decades?

Possible reasons --- the general perception(?):

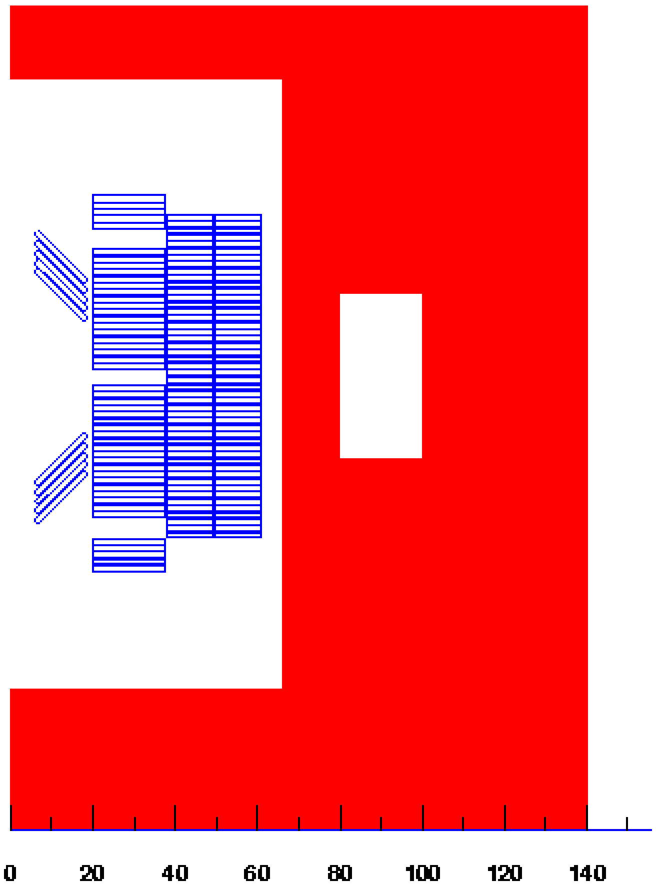
- that one can't obtain a *"good field quality"* in a racetrack coil magnet design.
- that the conductor requirement for good field quality in a racetrack coil design will be *"much more"* than that in a *"cosine theta"* design. So much so that the additional cost of conductor would out-run the cost savings from a simpler design.

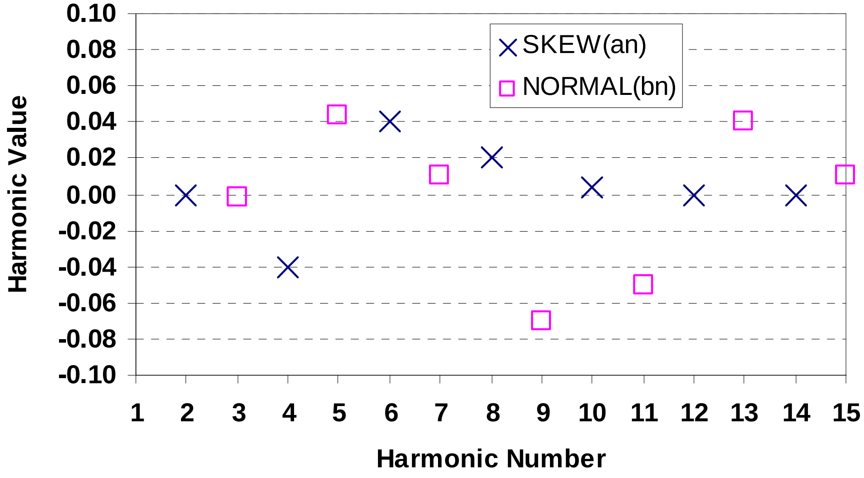
Above has been the general impression for decades.

- The results presented here (see McIntyre paper also) shows that one can get a good field quality in magnets built with racetrack coils. And it uses a similar amount of conductor.
- One just has to be a bit more careful in designing.

  Strategy: Simulate elliptical coil geometry with conductor blocks.

Geometric Harmonics

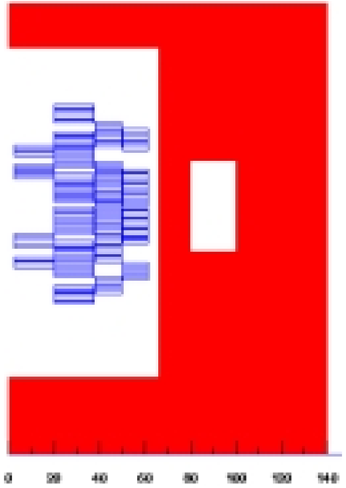




All harmonics are <10^{-5} (<0.1 unit)

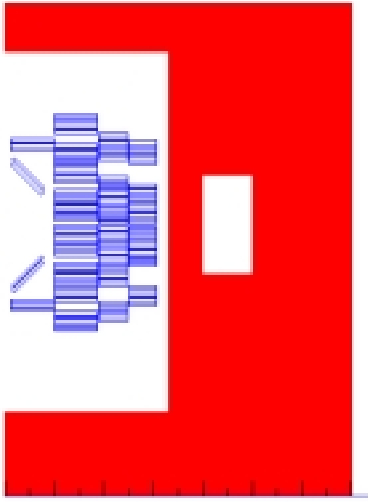
n	SKEW(a_n)	NORMAL(b_n)
2	0.00	
3		0.00
4	-0.04	
5		0.04
6	0.04	
7		0.01
8	0.02	
9		-0.07
10	0.00	
11		-0.05
12	0.00	
13		0.04
14	0.00	
15		0.01

A Few Possible Configurations for Auxiliary Coils

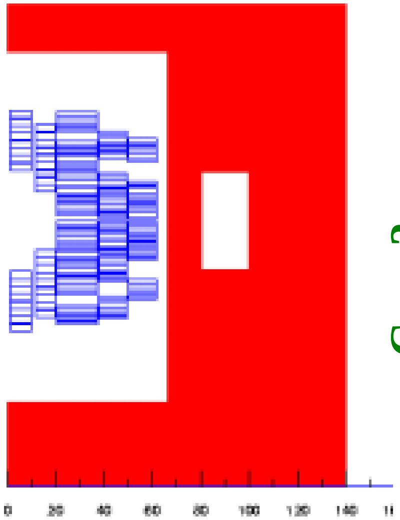


Case 1a

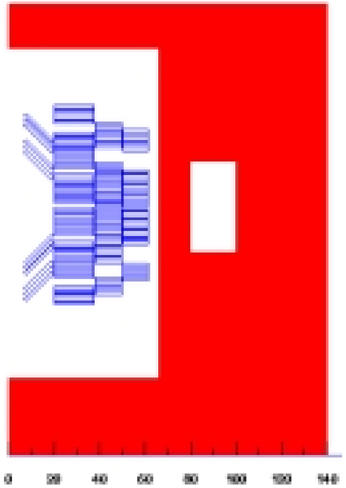
FEM$_{2D}$ * ROXIE$_{7.0}$



Case 1c



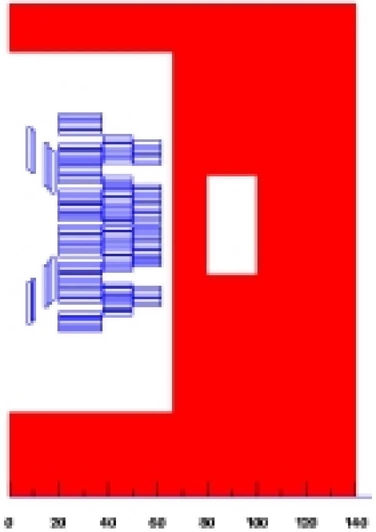
Case 2



Case 1b

Possibility of Case 1a Type ends in Case 1c

Case 1c is better from field quality point

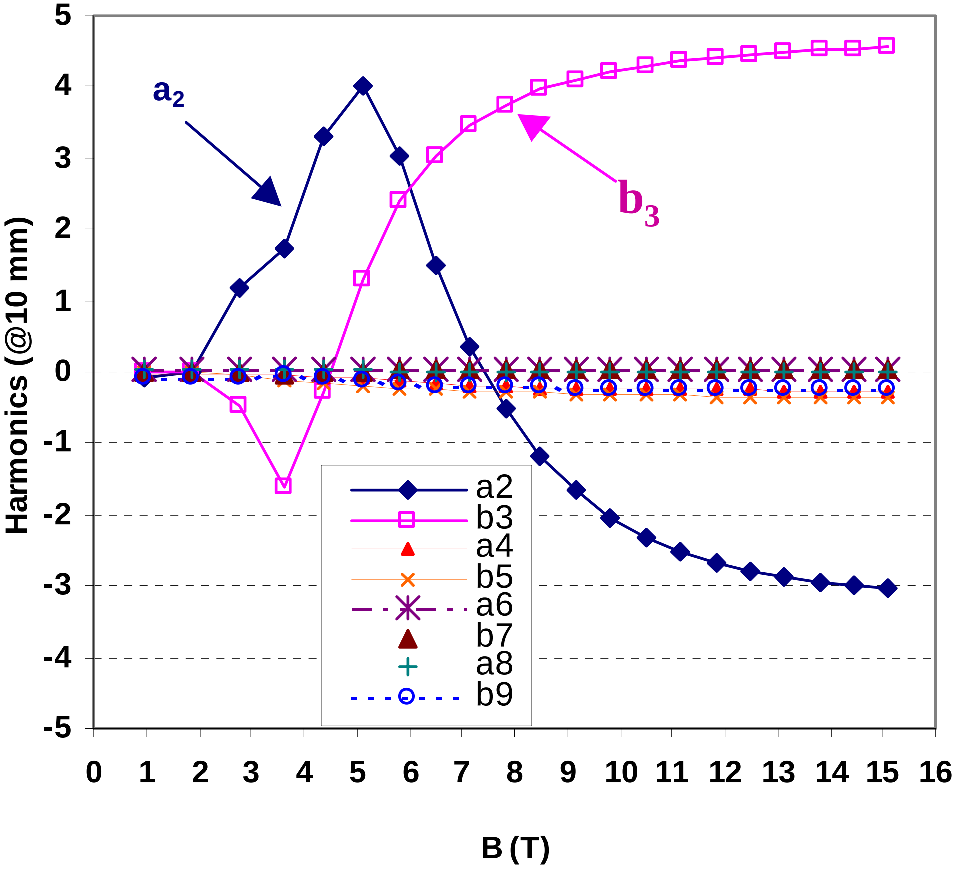


Case 3

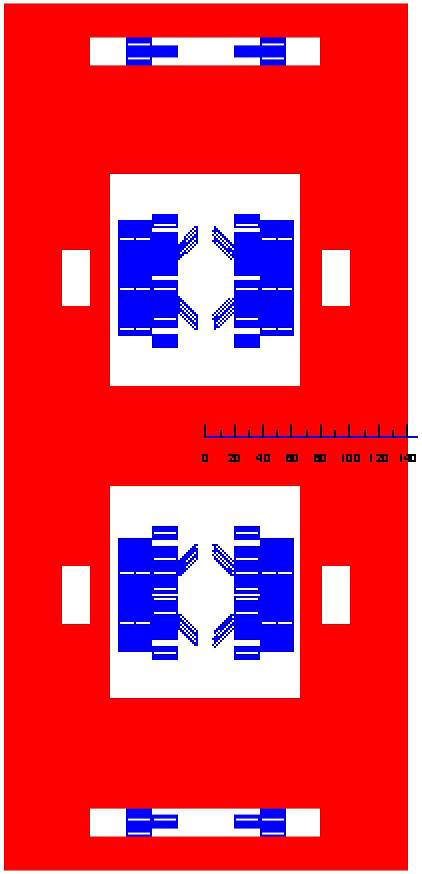
Saturation Induced Harmonics

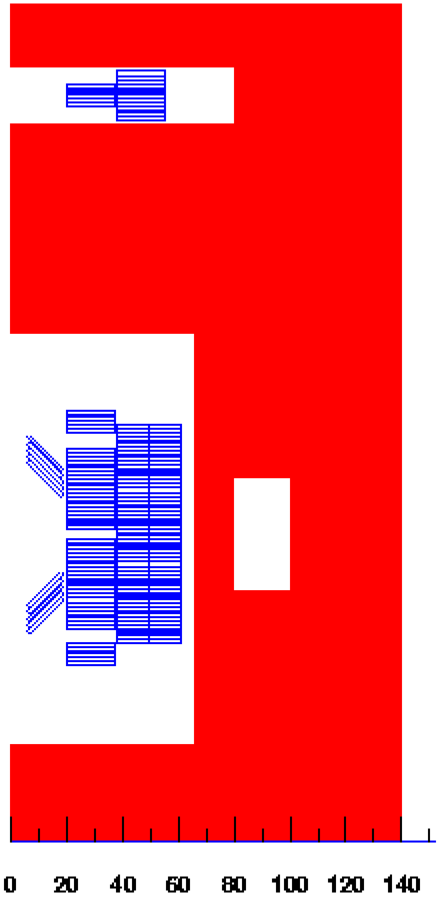
Yoke optimization for small saturation induced harmonics (a single power supply solution)

B(T)	a2	b3	a4	b5	a6	b7	a8	b9
0.94	-0.09	0.01	-0.04	0.00	0.04	0.01	0.02	-0.07
1.88	0.00	0.00	-0.04	0.00	0.04	0.01	0.02	-0.07
2.80	1.19	-0.48	-0.04	-0.03	0.04	0.00	0.02	-0.06
3.61	1.73	-1.63	-0.04	-0.12	0.04	-0.03	0.02	-0.05
4.37	3.30	-0.28	-0.06	-0.17	0.04	-0.01	0.02	-0.09
5.10	4.00	1.31	-0.09	-0.21	0.04	0.02	0.02	-0.14
5.80	3.02	2.39	-0.13	-0.23	0.03	0.03	0.02	-0.17
6.48	1.50	3.03	-0.16	-0.24	0.03	0.04	0.01	-0.19
7.16	0.37	3.46	-0.19	-0.26	0.03	0.05	0.01	-0.20
7.83	-0.52	3.75	-0.21	-0.27	0.03	0.05	0.01	-0.21
8.50	-1.17	3.96	-0.22	-0.28	0.02	0.05	0.01	-0.22
9.16	-1.67	4.11	-0.23	-0.30	0.02	0.06	0.01	-0.22
9.83	-2.04	4.22	-0.24	-0.31	0.02	0.06	0.00	-0.23
10.49	-2.30	4.31	-0.24	-0.32	0.02	0.06	0.00	-0.23
11.15	-2.51	4.37	-0.25	-0.33	0.02	0.06	0.00	-0.23
11.81	-2.67	4.42	-0.25	-0.34	0.02	0.06	0.00	-0.24
12.48	-2.79	4.46	-0.26	-0.34	0.02	0.06	0.00	-0.24
13.14	-2.87	4.50	-0.26	-0.35	0.02	0.06	0.00	-0.24
13.80	-2.94	4.52	-0.26	-0.36	0.02	0.06	0.00	-0.24
14.46	-3.00	4.54	-0.26	-0.36	0.02	0.06	0.00	-0.24
15.12	-3.05	4.56	-0.26	-0.37	0.02	0.06	0.00	-0.25



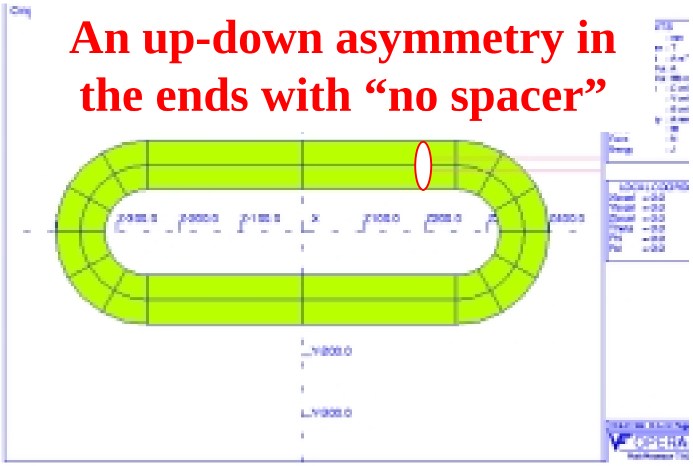
Optimized Yoke



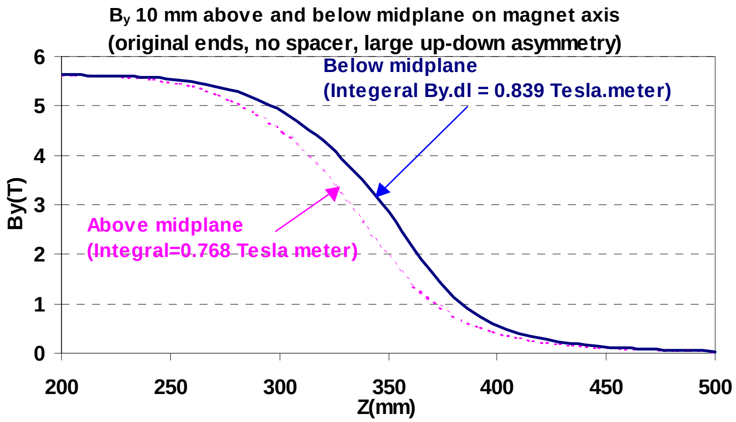


Field Quality Optimization in the Common Coil Design (Magnet Ends)

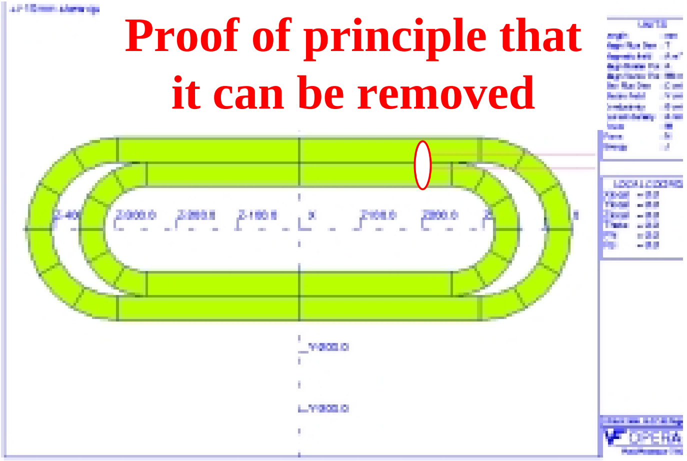
Up-down asymmetry gives large skew harmonics if done nothing. Integrate By.dl 10 mm above and 10 mm below midplane.



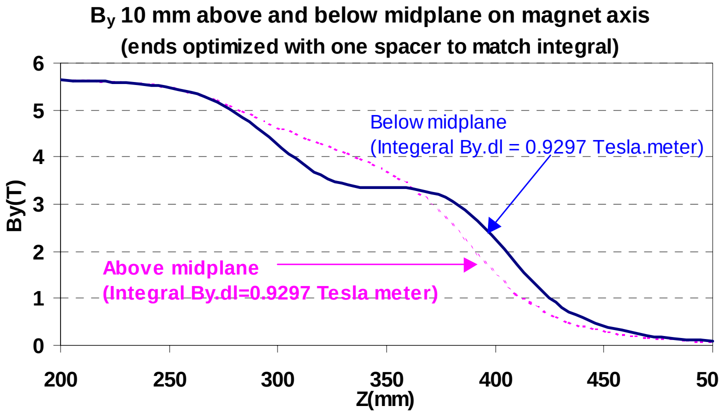
An up-down asymmetry in the ends with “no spacer”



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



Proof of principle that it can be removed



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.

Design Optimization Strategies for End Harmonics (3-d)

The top-bottom symmetry is highly violated in the ends (example:RD3). In a design with “no end-spacers”, it creates very large skew harmonics in addition to normal sextupole.

Compare this to early cosine theta designs which had large sextupole in the ends.

- Must do some thing to reduce them qualitatively.

Strategy:

- Use spacers to reduce peak field and to minimize field harmonics (as done in a typical cosine theta design, but do it here for both normal and skew harmonics). As usual, the field harmonics are minimized in an integral sense.
- Make coils above the midplane (in the upper aperture) go further out in the ends to compensate for the higher conductor volume below the midplane.

B_z is not zero locally in an individual end. But is zero in integral sense.

B_z in the ends of two nearby magnets cancel each other. AP issues?

An Example of End Optimization with ROXIE (iron not included)

Proof:

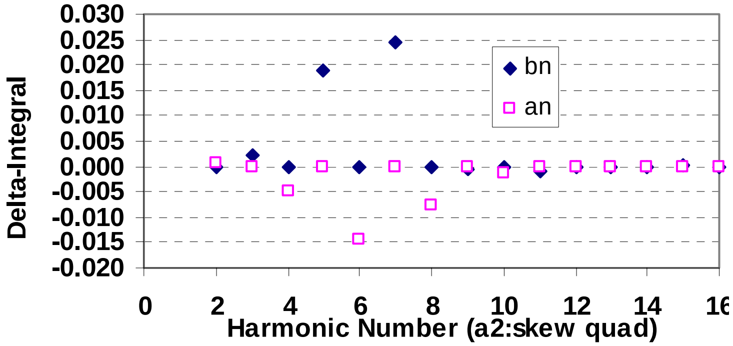
End harmonics can be made small in a common coil design.

End harmonics in Unit-m

n	Bn	An
2	0.00	0.00
3	0.01	0.00
4	0.00	-0.03
5	0.13	0.00
6	0.00	-0.10
7	0.17	0.00
8	0.00	-0.05
9	0.00	0.00
10	0.00	-0.01
11	-0.01	0.00
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00
15	0.00	0.00
16	0.00	0.00
17	0.00	0.00
18	0.00	0.00

Contribution to integral (a_n,b_n) in a 14 m long dipole ($<10^{-6}$)

n	bn	an
2	0.000	0.001
3	0.002	0.000
4	0.000	-0.005
5	0.019	0.000
6	0.000	-0.014
7	0.025	0.000
8	0.000	-0.008
9	-0.001	0.000
10	0.000	-0.001
11	-0.001	0.000
12	0.000	0.000



The additional influence of iron in a re-optimization will be included later with the help of TOSCA. The influence of iron can also be included using the CERN version of ROXIE.

Persistent Current-induced Harmonics

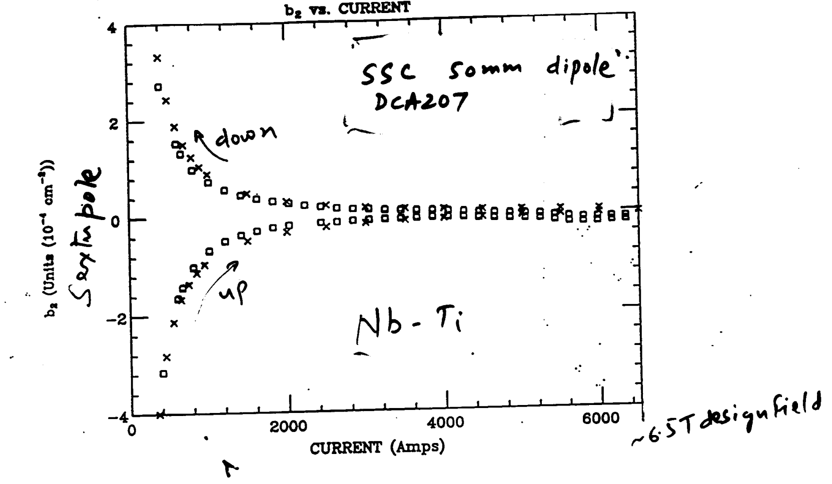
(may be a problem in Nb_3Sn magnets, if nothing is done)

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

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



Measured sextupole harmonic in Nb_3Sn magnet

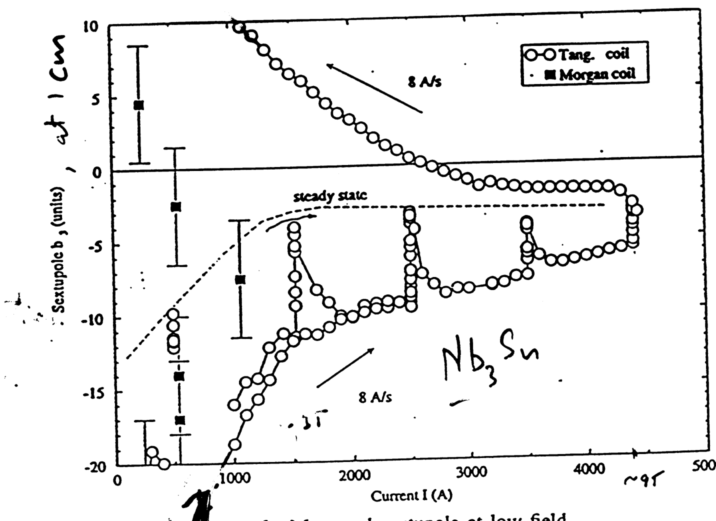


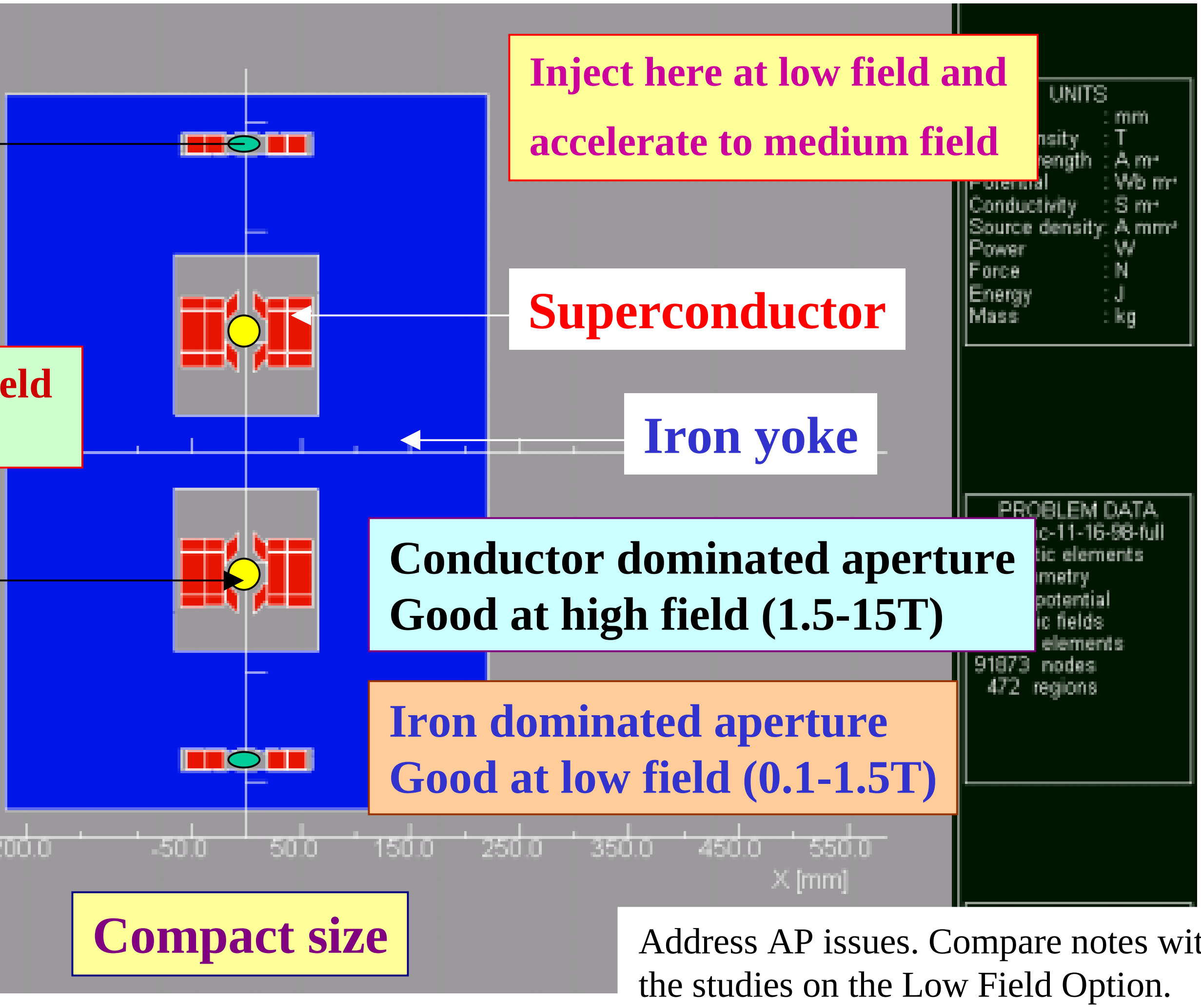
Fig. 6. Measured sextupole at low field (direction of arrow indicates up or down current).

LBL
D20 50mm
Dipole
World Record
holder: 13.5
(@ 6700A

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



Inject here at low field and accelerate to medium field

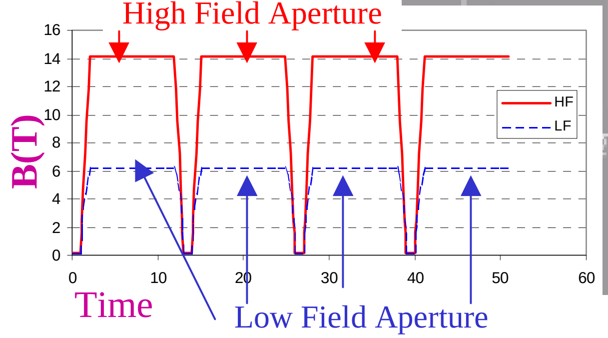
Superconductor

Transfer here at medium field and accelerate to high field

Iron yoke

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

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



Compact size

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

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

Common Coil Design can produce

- **Small geometric harmonics**
- **Small saturation induced harmonics**
- **Small end harmonics**
- **Small persistent current induced harmonics**