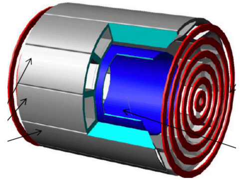
International
MUON Collider
Collaboration

Magnetic Field Configurations for Detectors

John Hauptman, Iowa State University, 12 October 2022


Iron-free, 8 Tesla

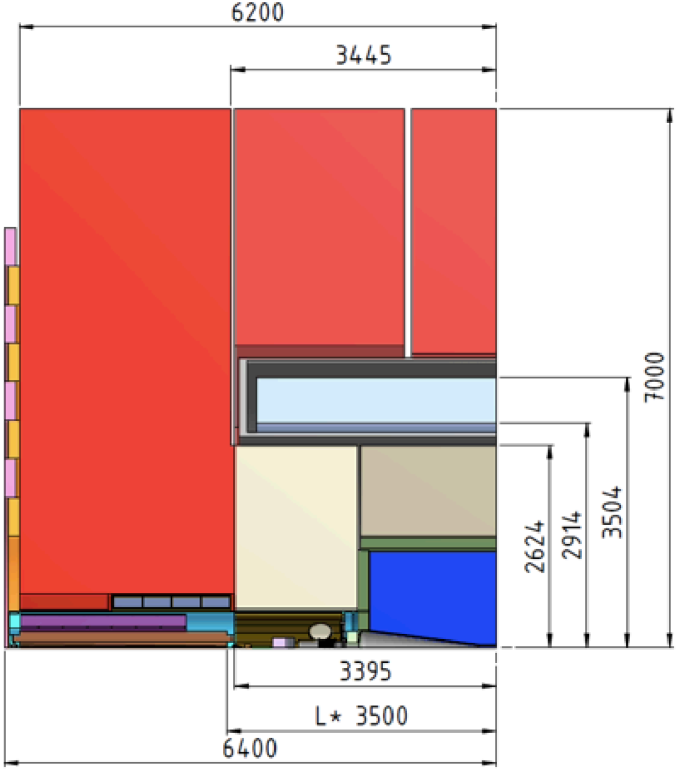
Given these early days and the uniqueness of a Muon Collider, we can explore large deviations from the current detector paradigm. I have watched "concept" detectors from 2004 through 2022 (e.g., ILC —> CLIC —> MuCol) and the main features are rather similar, in fact, similar to the "Magnetic Detector" *circa* 1972.

- Iron-free detector (return the flux of the tracking solenoid with outer solenoids)
- High-field tracking solenoid (~8T, about twice current state-of-the-art)

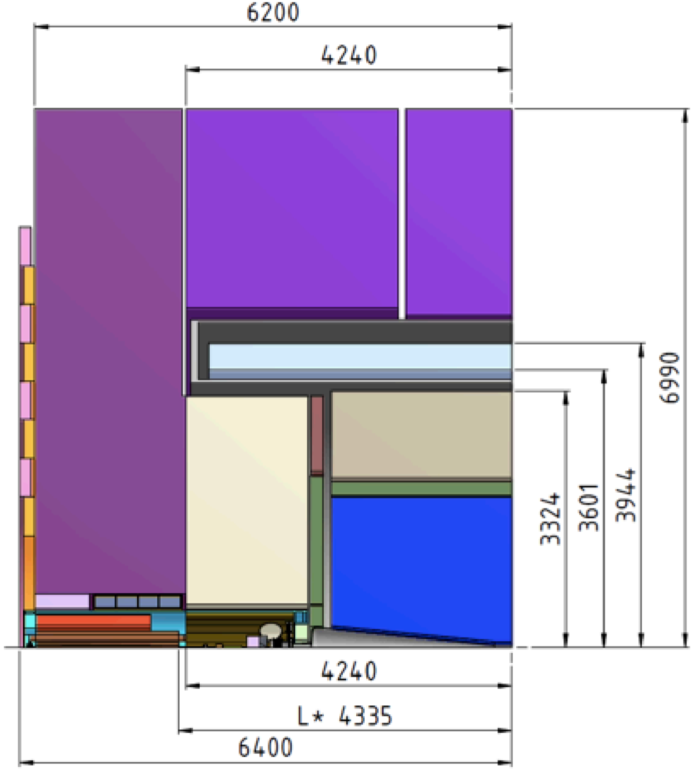
Note bene: "Superconducting Magnet with Minimum Steel Yoke for the Hadron Future Circular Collider Detector," *J. Superconductivity and Novel Magnetism*, 30 (8) Aug. 2017, V. Klyukhin, A. Herve, A. Ball, A. Dudarev, A. Gaddi, H. Gerwig, M. Mentink, H. Silva, G. Rolando, H. Ten Kate, C.P. Berriaud. (3 designs)

A huge volume is devoted to flux return and filtering out hadrons. Are there other solutions?

CLIC_SiD [5T]



CLIC_ILD [4T]

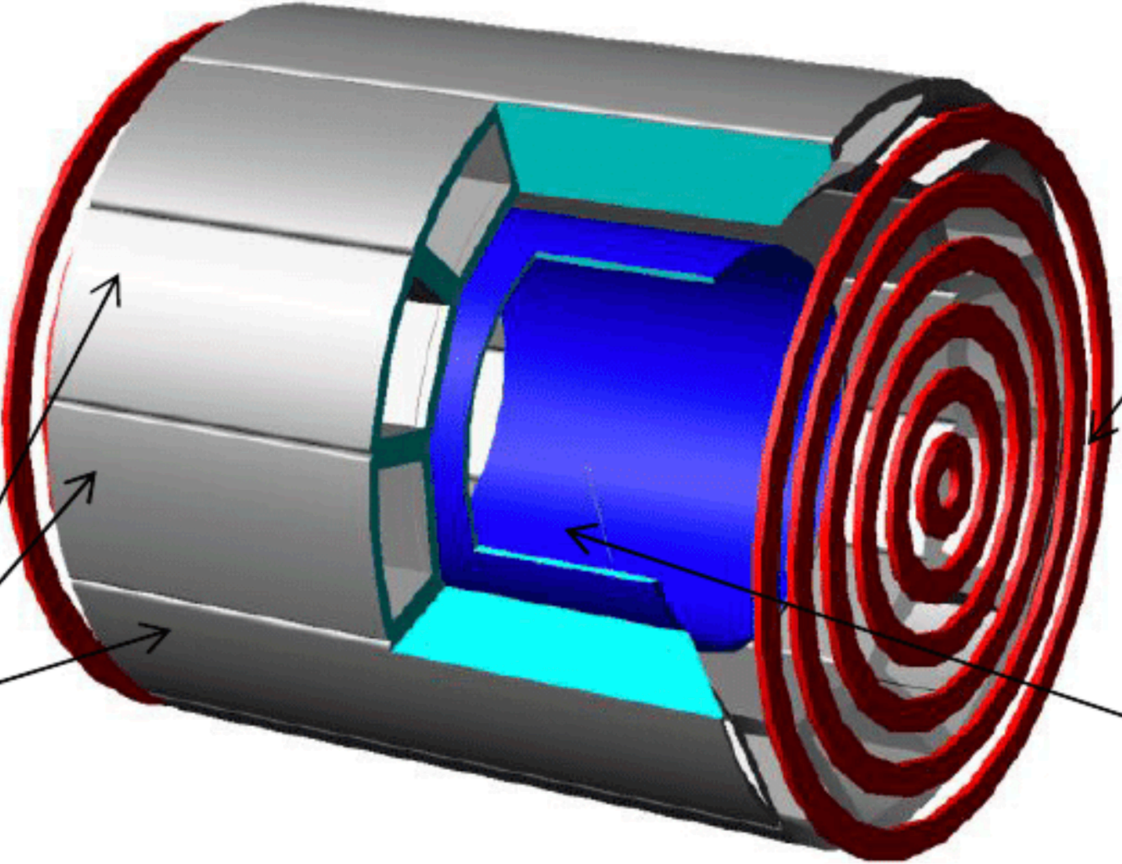


	CLIC_SiD [5T]	CLIC_ILD [4T]
Percent iron:	86.3%	80.0%
Detector mass	10,800 t	8,900 t

CLIC-CDR: Apr 2011,
Sec. 13 “Interaction Region and Detector Integration,”
H. Gerwig and M. Oriunno.

Flux return by 12 smaller solenoids

(A. Mikailichenko, Cornell LNS)



Wall of coils

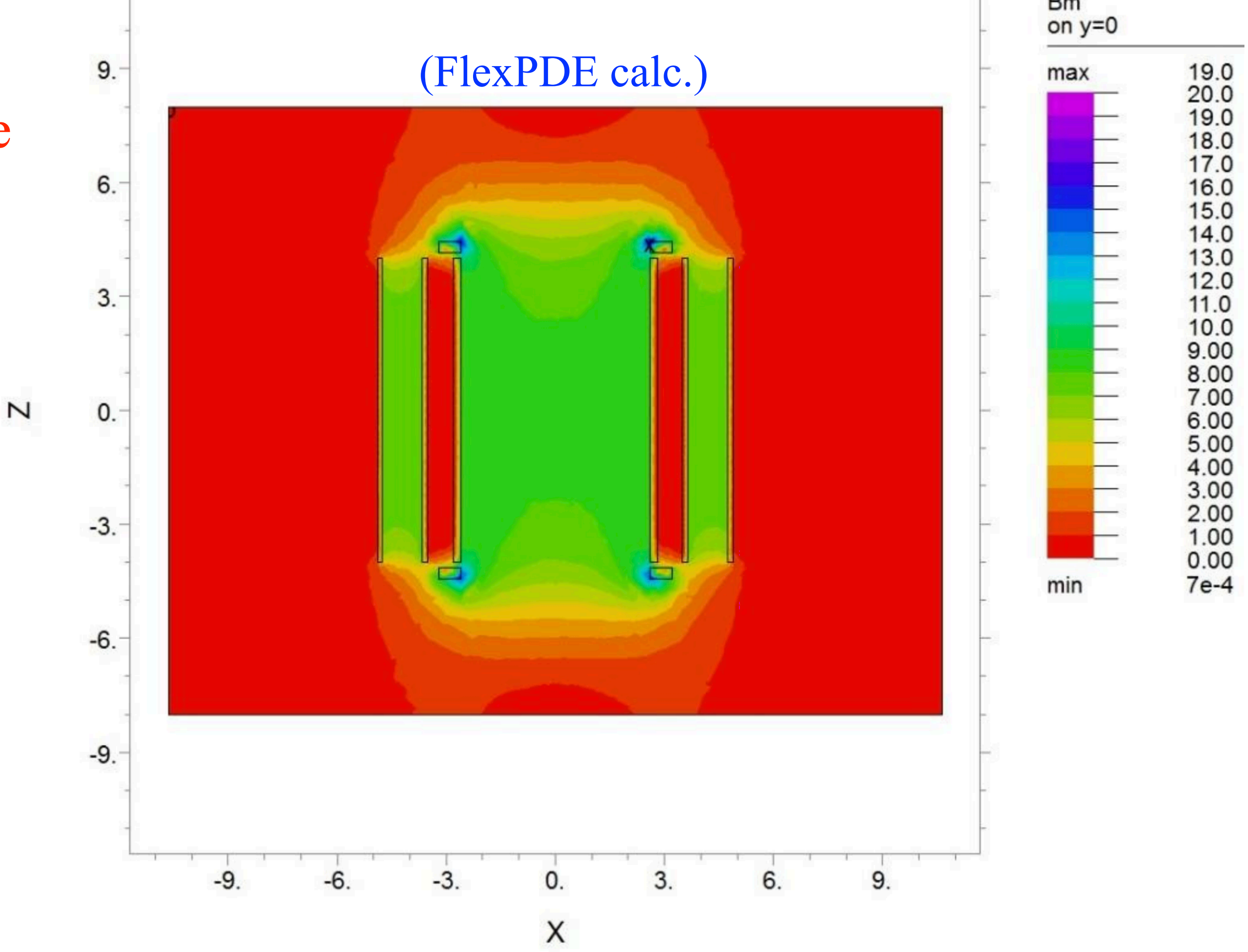
Segmented Flux-return solenoids

Main solenoid (blue)

B field magnitude

High-field is confined to the volume of the main solenoid and the 12 return solenoids:

No ‘wall of coils’ and still small fringe field.

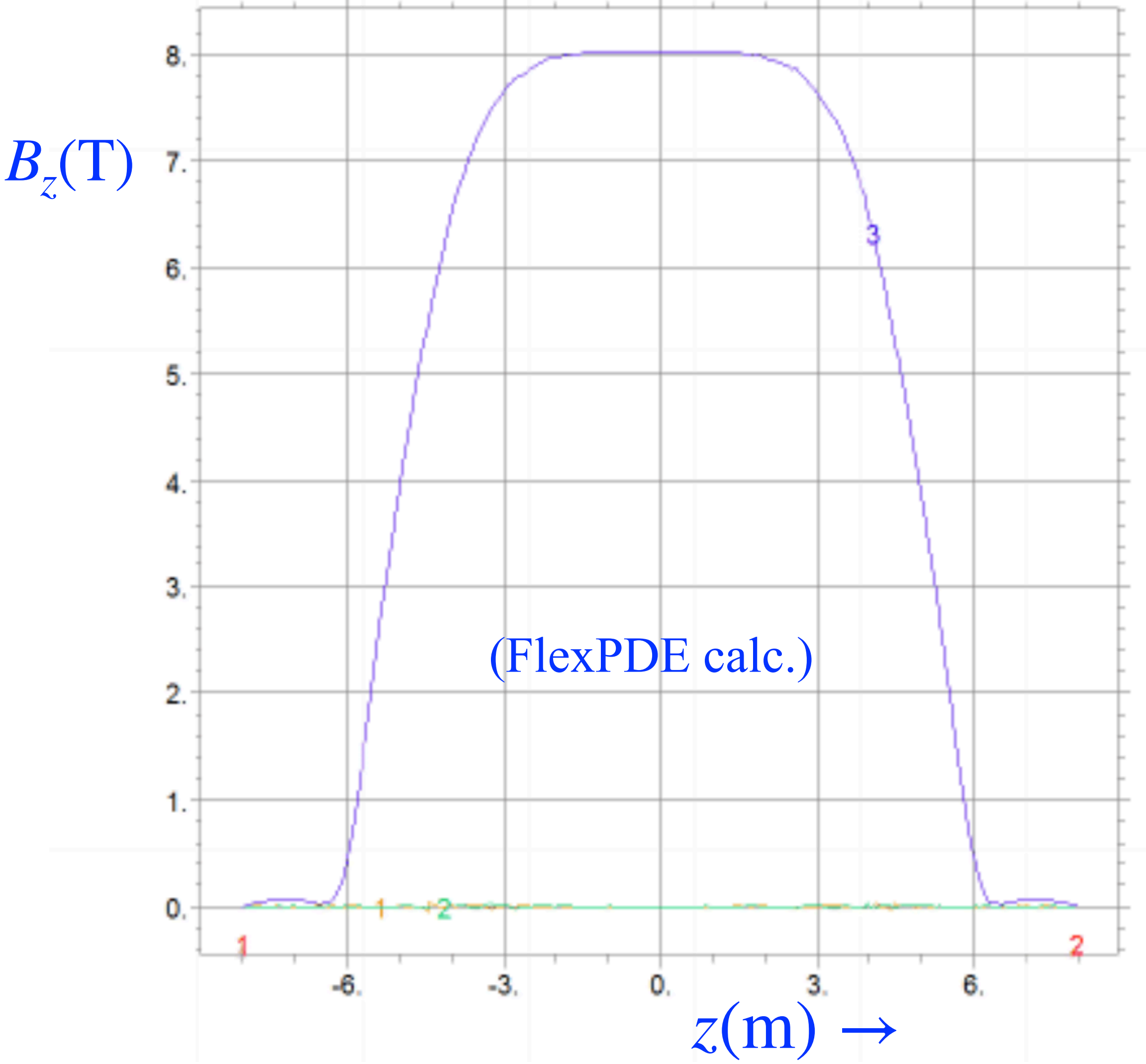

(FlexPDE calc.)

B_z field on axis

The B_z field is uniform over ±2.0 m in z, and goes to zero around ±6.0 m.

This is sufficient for a tracking field.

A "wall of coils" will extend the tracking field in z, an area of future design work.



(FlexPDE calc.)

- A high-field tracking volume suppresses the $\mu \to e$ decay electrons and e^+e^- pairs from entering the detector volume.

- Since iron saturates around 1.8T, it is not useful in a high-field environment, so better to leave it out and support the field with currents only.

Getting rid of the iron leads to many experimental and technical benefits.

Eleven benefits of an iron-free tracking field:

1. Any small stray field can be completely cancelled with trim coils (multipole-by-multipole).

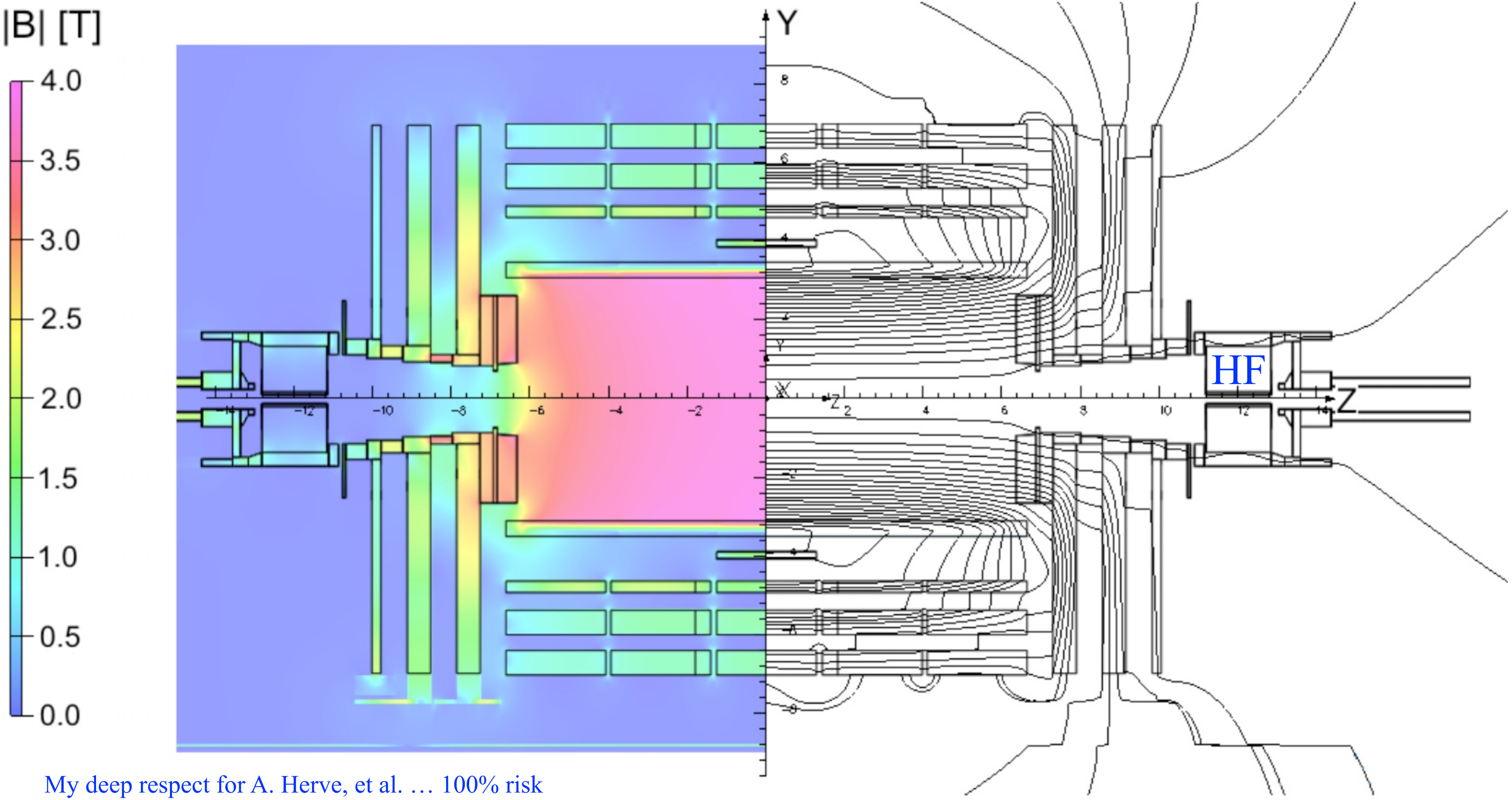
2. The **B** field can be reversed (**B** → − **B**) to cancel detector asymmetries, and can be any value between 0 and 8T.

3. Avoids the huge internal forces (~ 25 kt) on nearby iron volumes (e.g., CMS HF iron calorimeter at z=11 m moved 19 mm into the B=4T field).

4. Avoids the CMS problem of too little iron in the pole tip regions to contain the 4T flux density.

(3,4. CMS B-field)

Exercise in minimizing $\frac{1}{2\mu}\int B^2 dV$



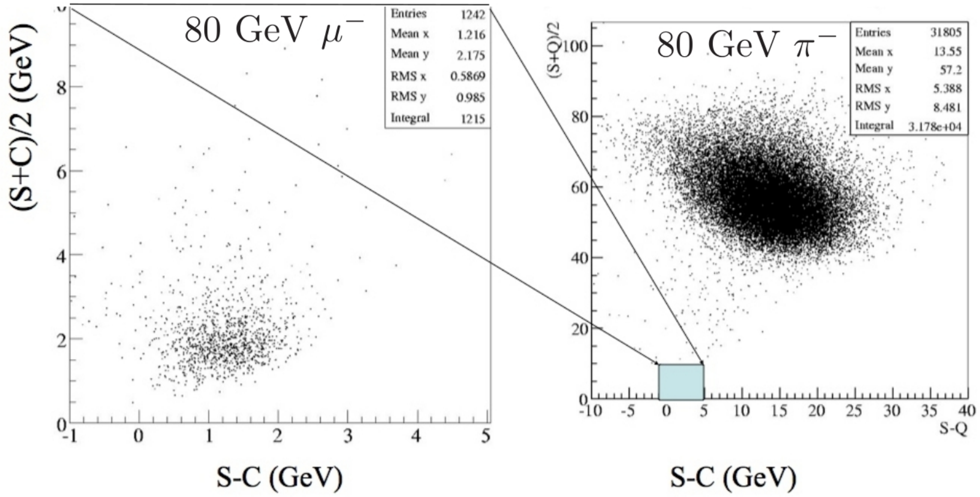
My deep respect for A. Herve, et al. … 100% risk

Benefits of an iron-free tracking field, continued:

5. CLIC_LDC and CLIC_SiD have iron volumes of 80.0% and 86.3%, respectively, of their total volume. This volume could be better used for instrumentation, maybe for long-lived WIMPs, SUSY LSPs, dark matter, etc. (e.g., the Lead Glass Wall add-on to Mark II).

6. An iron-free detector is more easily disassembled, for repairs or upgrades.

7. A dual-readout fiber calorimeter allows an excellent muon ID.



Benefits of an iron-free tracking field, continued:

8. The interiors of the 12 flux return solenoids can be instrumented, but this only covers about 1/2 the solid angle.

9. The absence of iron makes this a light-weight and open detector.

10. Almost every problem in the IR becomes easier without the 15,000-tonne iron mass, including crane capacities, platform deformation and floor loading.

Benefits of an iron-free tracking field, continued:

11. Charged momentum resolution in the TeV/c range (Gluckstern).

$$\frac{\sigma_p}{p^2} \approx \frac{\sigma_x}{0.3B\ell^2}\sqrt{\frac{720}{N+4}}$$

The CLIC_ILD design has $\ell \approx 2.0$ m. Assuming $\sigma_x \approx 50\mu$m and N=50, and for B=8T,

$$\frac{\sigma_p}{p^2} \approx 2.0 \times 10^{-5}\ (\mathrm{GeV/c})^{-1}$$

so that a 5 TeV/c $\mu^{\pm}$ can have a momentum resolution of about 10%.

(Note also: a 5 TeV $\mu^{\pm}$ loses about 1% of its energy per meter by radiation in a calorimeter.)

Problems ("challenges")

- 8T over this huge solenoid volume is hard. Magnetic stored energy, magnetic pressure and all forces scale as B^2. Unlike the 4th dual-solenoid, this has not been "engineered."

- A fail-safe procedure for bringing down all solenoids for a single quench.

- The solenoid in a big collider detector is a "100% risk" - by this we mean that if the solenoid fails, the experiment fails.

- I once talked with Alain Herve about the dual solenoids and, all I can say is, he listened. A realist like Herve knows the effort and risk involved (I do not).

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E.J. Bahng and I will submit a proposal to support university people on

* G4 simulations of BIB and e^+e^-pairs in this B-field, starting from the CLIC_ILD code.

* Assess loopers and resolutions.

* Include particle IDs with calorimeter, including new work by Sehwook Lee in the IDEA collaboration, and low-mass tracker and vertex chambers.

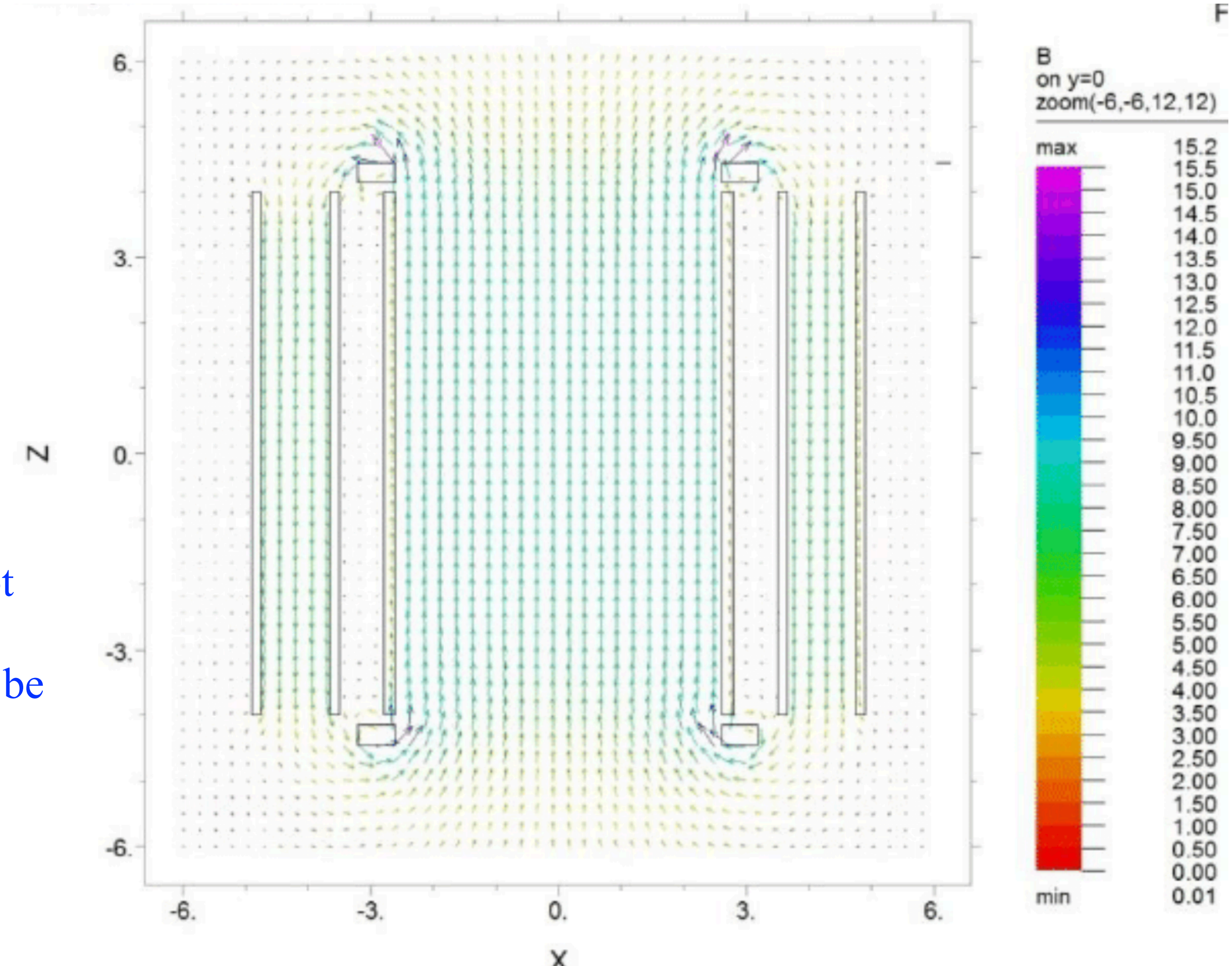
* Along the way, Bahng will write an illustrated children's book on particle physics, the muon collider, and the people who do it.

Thank you for your attention.

B vector field

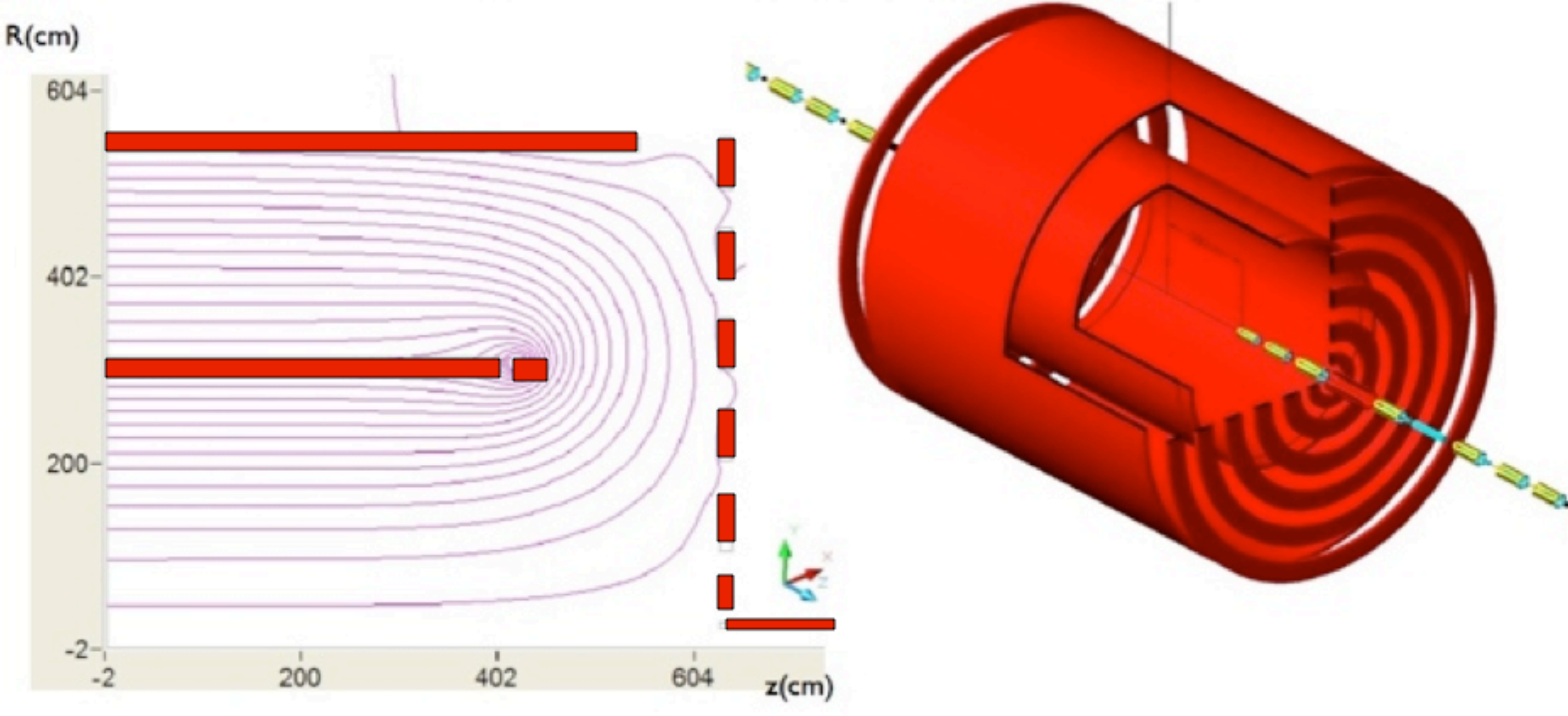
Needs more design work on high-field regions near conductors.

The end-coils are not included in this calculation, but will be added.



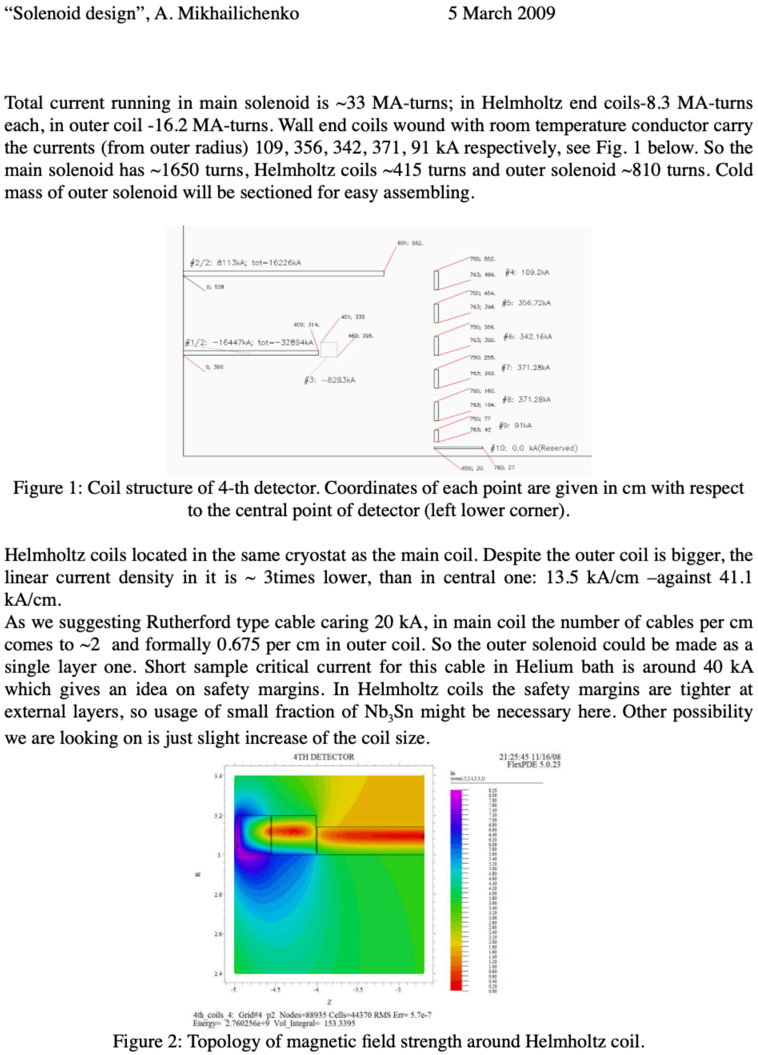
Dual-solenoid “engineering”

Magnetic field of dual solenoid and wall of coils



Alexander Mikhailichenko, Cornell LNS

(first ideas of multiple solenoids for detectors, 2001)



"Solenoid design", A. Mikhailichenko 5 March 2009

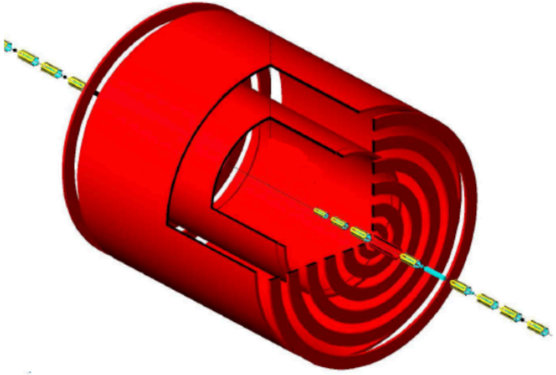
Total current running in main solenoid is ~33 MA-turns; in Helmholtz end coils-8.3 MA-turns each, in outer coil -16.2 MA-turns. Wall end coils wound with room temperature conductor carry the currents (from outer radius) 109, 356, 342, 371, 91 kA respectively, see Fig. 1 below. So the main solenoid has ~1650 turns, Helmholtz coils ~415 turns and outer solenoid ~810 turns. Cold mass of outer solenoid will be sectioned for easy assembling.

Figure 1: Coil structure of 4-th detector. Coordinates of each point are given in cm with respect to the central point of detector (left lower corner).

Helmholtz coils located in the same cryostat as the main coil. Despite the outer coil is bigger, the linear current density in it is ~ 3times lower, than in central one: 13.5 kA/cm –against 41.1 kA/cm.

As we suggesting Rutherford type cable caring 20 kA, in main coil the number of cables per cm comes to ~2 and formally 0.675 per cm in outer coil. So the outer solenoid could be made as a single layer one. Short sample critical current for this cable in Helium bath is around 40 kA which gives an idea on safety margins. In Helmholtz coils the safety margins are tighter at external layers, so usage of small fraction of Nb_3Sn might be necessary here. Other possibility we are looking on is just slight increase of the coil size.

Figure 2: Topology of magnetic field strength around Helmholtz coil.



4th Concept Detector at Fermilab
19-20 October, 2006

Fermilab
PPD/MD/Engineering Analysis Group

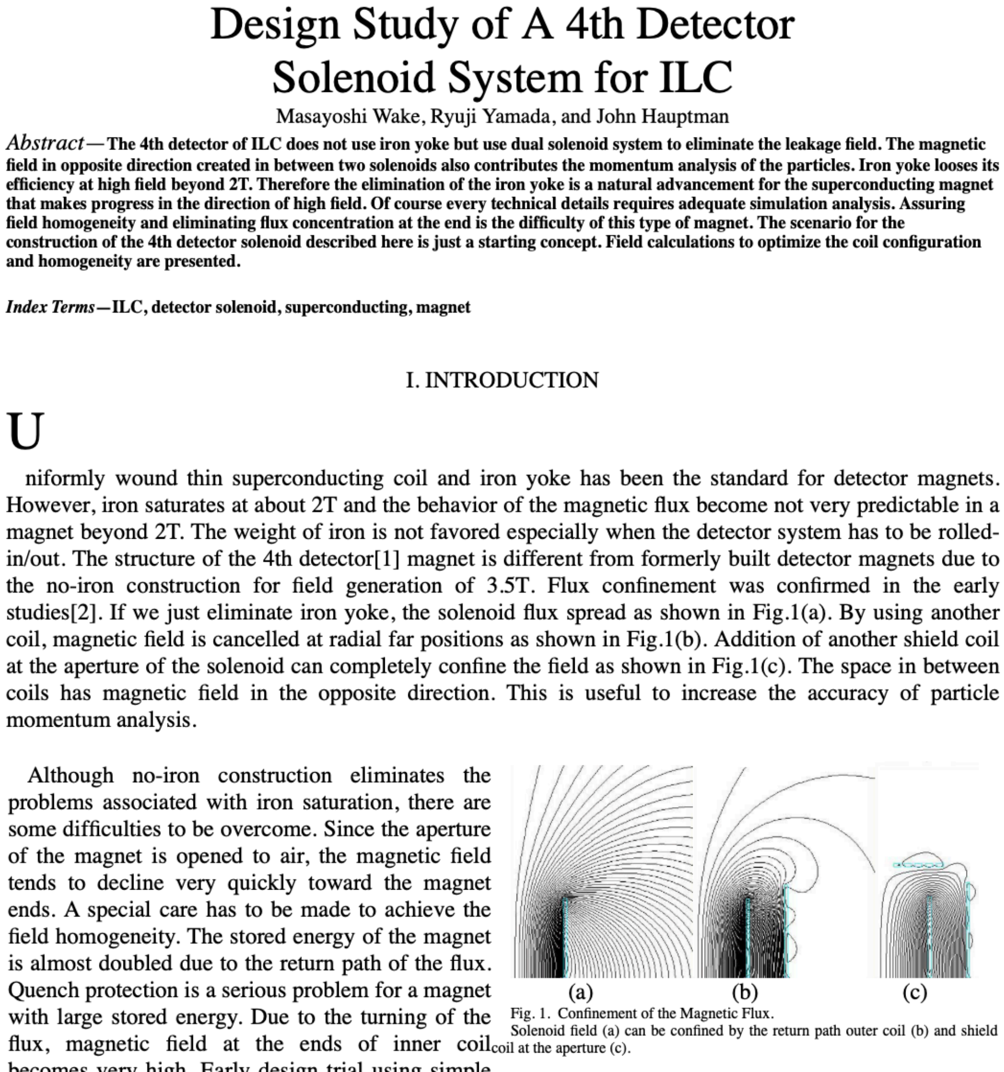
Magnets and Supports

Bob Wands

October 20, 2006

Masayoshi Wake, KEK
Ryuji Yamada, Fermilab

(novel ideas with non-rectilinear conductors)



Design Study of A 4th Detector Solenoid System for ILC

Masayoshi Wake, Ryuji Yamada, and John Hauptman

Abstract—**The 4th detector of ILC does not use iron yoke but use dual solenoid system to eliminate the leakage field. The magnetic field in opposite direction created in between two solenoids also contributes the momentum analysis of the particles. Iron yoke looses its efficiency at high field beyond 2T. Therefore the elimination of the iron yoke is a natural advancement for the superconducting magnet that makes progress in the direction of high field. Of course every technical details requires adequate simulation analysis. Assuring field homogeneity and eliminating flux concentration at the end is the difficulty of this type of magnet. The scenario for the construction of the 4th detector solenoid described here is just a starting concept. Field calculations to optimize the coil configuration and homogeneity are presented.**

***Index Terms*—ILC, detector solenoid, superconducting, magnet**

I. INTRODUCTION

Uniformly wound thin superconducting coil and iron yoke has been the standard for detector magnets. However, iron saturates at about 2T and the behavior of the magnetic flux become not very predictable in a magnet beyond 2T. The weight of iron is not favored especially when the detector system has to be rolled-in/out. The structure of the 4th detector[1] magnet is different from formerly built detector magnets due to the no-iron construction for field generation of 3.5T. Flux confinement was confirmed in the early studies[2]. If we just eliminate iron yoke, the solenoid flux spread as shown in Fig.1(a). By using another coil, magnetic field is cancelled at radial far positions as shown in Fig.1(b). Addition of another shield coil at the aperture of the solenoid can completely confine the field as shown in Fig.1(c). The space in between coils has magnetic field in the opposite direction. This is useful to increase the accuracy of particle momentum analysis.

Although no-iron construction eliminates the problems associated with iron saturation, there are some difficulties to be overcome. Since the aperture of the magnet is opened to air, the magnetic field tends to decline very quickly toward the magnet ends. A special care has to be made to achieve the field homogeneity. The stored energy of the magnet is almost doubled due to the return path of the flux. Quench protection is a serious problem for a magnet with large stored energy. Due to the turning of the flux, magnetic field at the ends of inner coil becomes very high. Early design trial using simple

(a) (b) (c)

Fig. 1. Confinement of the Magnetic Flux.
Solenoid field (a) can be confined by the return path outer coil (b) and shield coil at the aperture (c).

Alexey Bragin,
Budker Institute

(design of conductor,
overall dual-solenoid
system)

Development of the large superconducting solenoid

Aim of the work

Aim of the work is a development of the superconducting solenoid for the particle physics detector. Very large dimensions of the solenoid rise problem to develop the solenoid with a lower price than existing LHC detectors magnets. This would be done if new design will exclude the costly high purity aluminum stabilizer from SC cable and can found another ways of a protection and stabilization of the solenoid.

Parameters of the 4th detector solenoids

The layout of the magnets for the 4th detector is shown on the Fig. 1. The large solenoid considered in this report is designated on the Fig. 1 as coil#2. The parameters of the magnets are listed in the Tab. 1.

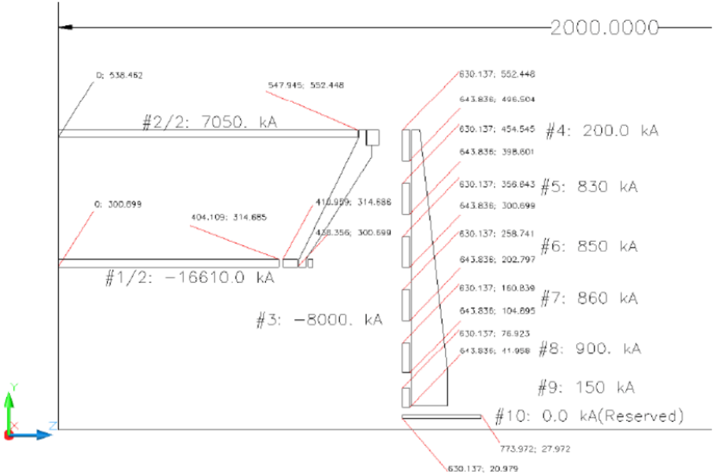


Fig. 1. Layout of magnets.

Table 1. Parameters of the detector coils.

Coil number	Dimensions: i∅ and length, m	Total current, MA	Maximal magnetic field in the coil, T	Stored energy of separately charged coil, GJ
1*	6.00×8.08	14.5	~ 5	1.75
2	10.8×11.0	33.2	1.66	0.58
3	6.00×0.27	8.0		0.44