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# Superconducting Superferric Dipole Magnet with Cold Iron Core for the VLHC

G. W. Foster, V.S. Kashikhin

[1]*Abstract*-- **The magnet system of the Very Large Hadron Collider (VLHC) Stage I is based on a superconducting 2 Tesla magnetic field combined function magnets. These magnets will have a room temperature iron core with two 20 mm air gaps. Magnetic field in both horizontally separated air gaps is excited by a single turn 100 kA superconducting transmission line.**

**The alternative design with cold iron core, horizontally or vertically separated air gaps is under investigation. The cold iron option with horizontally separated air gaps reduces the amount of iron, which is one of the main cost driver for 233 km length magnet system of the future accelerator. The vertical beam separation decreases volume superconductor, heat load from synchrotron radiation and eliminates fringing field from a return bus. But the horizontal beam separation has lowest volume of iron core and as a result lower heat load for cryosystem during cooling down. All these options are discussed and comparison is made. Superconducting correction system, combined with the magnet, allowing to increase the maximum field is also under discussion. Preliminary cost analysis are made for all options.**

***Index Terms*—Accelerator magnets, Cold Iron, Cost, Superconducting magnets, Superferric, VLHC.**

## I. Introduction

THE Very Large Hadron Collider (VLHC) Design Study was performed in Fermilab [1]. The staged scenario of this machine decreases the total project cost and provides a shallower funding profile. The major cost driver for collider is the civil construction cost. Magnet system is the second cost driver. The Stage I VLHC is based on the superconducting 2 Tesla transmission line magnets [2]. These combined function superconducting magnets cost only 900 $/T-m [1] and provides essential cost savings.

It is well known other types of superconducting magnets generating magnetic fields in the range of 2 – 6 Tesla with very high efficiency [3] – [5]. Most of them have the cold iron ferromagnetic screen with superconducting NbTi winding placed into cryostat. The goal of this paper is to investigate the possibility of design superconducting transmission line magnet with cold ferromagnetic screen and compare it with warm iron deign.

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G. W. Foster is with the Fermi National Accelerator Laboratory, Batavia, IL 60510 , USA (telephone: 630-840-3906, e-mail: GWF@fnal.gov).

V. S. Kashikhin is with the Fermi National Accelerator Laboratory, Batavia, IL 60510, MS 314, USA (telephone: 630-840-2899, e-mail: kash@fnal.gov).

## II. Warm Iron Magnet with Horizontal Apertures Separation

The 2 Tesla transmission line magnet [2] has horizontal beam separation and warm iron, Fig. 1. The 100 kA superconducting transmission line made from NbTi superconductor incorporated into a very compact (80 mm OD) cryostat. The return bus of transmission line has separate 300 mm diameter cryostat, which also includes all cryolines. The main advantages of this magnet are: simple construction, warm iron, open from both sides air gaps, easy magnetic measurements and beam pipe installation, low cold mass, low heat load and cost per Tesla-meter. There are also disadvantages: useless return bus only to reduce fringing field, weak mechanical connections between half-cores, strong iron saturation effects, which is difficult to correct.

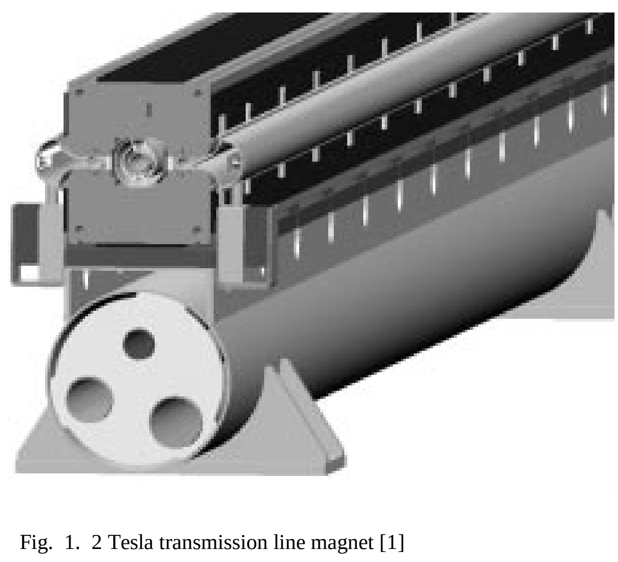

Fig. 1. 2 Tesla transmission line magnet [1]

## III. Cold Iron Magnet with Horizontal Apertures Separation

The cold iron option of this magnet can be made without transmission line cryostat. It reduces apertures separation distance and as a result the quantity of needed ampere-turns.

The volume of superconductor will depend on the maximum applied field, which will be higher for this option. The cross-section of this magnet is shown on Fig.2. Magnet has

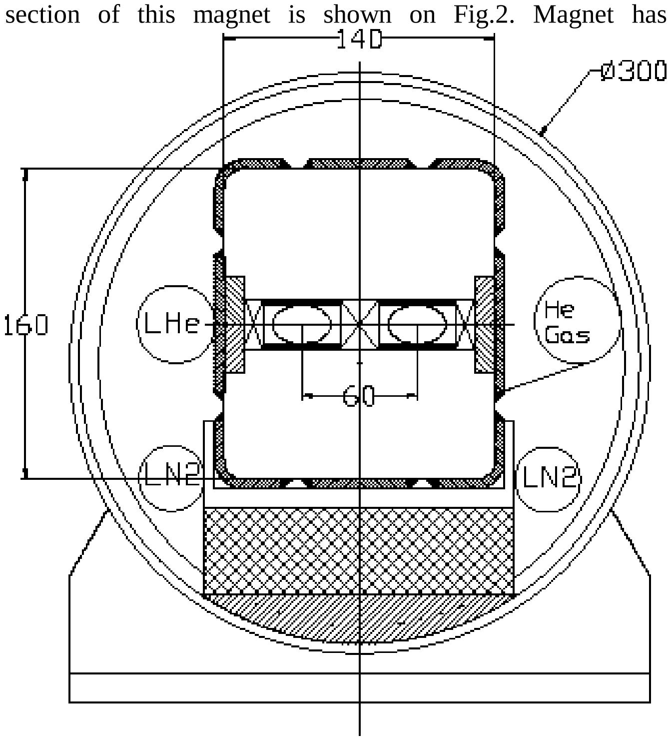


Fig. 2 Transmission line magnet with cold iron and horizontal beams separation

rectangular transmission line cable (cable in conduit) with direct or indirect LHe cooling. The superconducting pole windings produce positive or negative gradient field and correct an iron saturation effect. The air gap should be increased from 20 mm up to 26 mm to provide an extra space for pole correction windings. As a result winding ampere-turns will be higher and for 3 Tesla field the total current should be 162 kA . Both beam pipes are also cold and do not need big ante-chamber as in warm iron variant. It also helps to provide better mechanical stability using side spacer bars and connecting plates. The return bus can be splitted and placed on both sides of air gaps. Magnet in this case has only one common cryostat of ~ 300 mm diameter. The weight of iron is also lower for cold iron design, because influence of larger air gaps compensated by very short path for magnetic flux in an iron core. The pole profile is optimized for maximum magnet field to generate field with negative or positive gradient. In this case correction coil current is zero at nominal field. The return buses position should be also optimized to reduce distortions of magnetic field in air gaps because of iron saturation effects. Magnetic forces are not a problem for this design, because whole cold mass does not have decentering magnetic forces and only small fringing fields go outside the magnet .

## IV. Cold Iron Magnet with Vertical Beams Separation

The vertical beams separation has several advantages for the future collider magnets. This option was investigated for SSC 3 Tesla superferric magnets and other applications [4]-[5]. Such type of magnet has more mechanically stable structure but more iron core weight and as a result larger cryostat and heat load. The window frame magnets [4] – [5] generate only dipole field, and separate system of focusing and defocusing quadrupoles should be incorporated in the ring magnet system during accelerator lattice design. Fig. 3 shows cross-section of C-shaped combined function magnet with vertical beams separation.

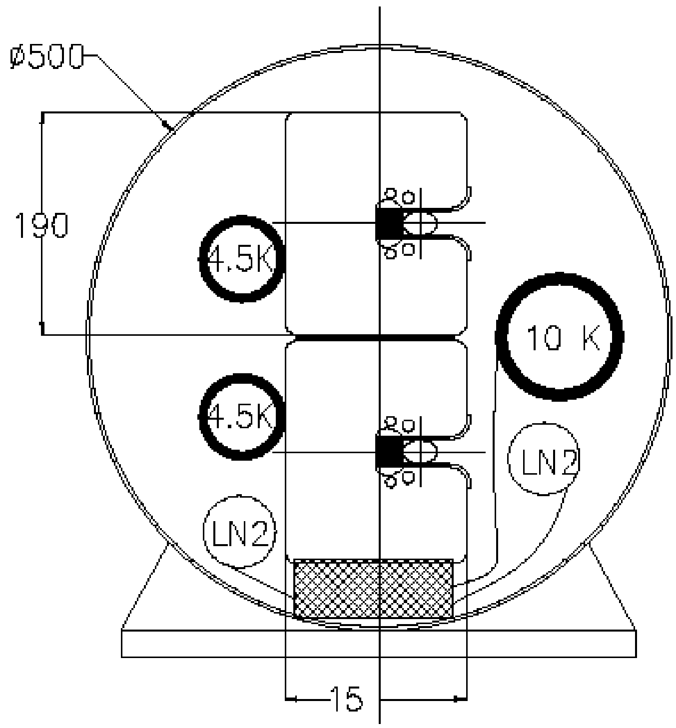


Fig. 3 Transmission line magnet with cold iron and vertical beams separation

It is rather attractive to use a nature of C-shaped magnets, which have gradient field caused by an iron core saturation effect, as a combined function magnet. Pole profiles could be optimized for maximum field and needed negative gradient 4 - 5 %/cm. The superconducting pole winding correct field distortions at low and medium field levels. The open on outer ring side air gaps give the exit for a synchrotron radiation and simplify the beam pipes installation. It is possible for one turn winding eliminate transmission line electrical insulation and place G10 spacers between both C-cores. But in this case voltage breakers should be installed on all vacuum pumps outlets. The magnet with positive gradient can be obtained by magnet rotation on 180º with corresponding transmission lines interconnection in the space between focusing and defocusing magnets.

## V. MAGNETS COMPARISON

The preliminary cost analysis and comparison various types of magnets can be made using FNAL VLHC Design Study [1] and experience of RHIC magnets production [6].

The main cost driver for VLHC Stage I is the tunnel cost. It is obvious that at lower tunnel cost magnet system of collider moves to the lower magnetic field. The main magnet system cost drivers are the cost of iron core, cost of superconductor and cryostat. Magnet parameters for 2T and 3T magnetic fields are presented in Table 1.

TABLE I
MAIN MAGNET PARAMETERS

| Parameter | Warm iron | Cold iron horizontal | Cold iron vertical |
|---|---|---|---|
| Max field, Tesla | 2 | 3 | 3 |
| Gradient, %/cm | 4.75 | 4.75 | 4.75 |
| Air gaps, mm | 20 | 26 | 26 |
| Transmission line ampere-turns, kA | 100 | 160 | 160 |
| Pole winding ampere-turns (max), kA | 0 | 8 | 8 |
| Max SC cable field, Tesla | 1 | 3 | 3 |
| Width, mm | 242 | 140 | 150 |
| Height, mm | 290 | 160 | 380 |
| Iron core weight, kg/m | 460 | 150 | 410 |
| NbTi superconductor weight, kg/m | 1.1 | 2.2 | 2.2 |
| Cryostat outer diameter, mm | 80 | 300 | 500 |

The main difference between various magnet configurations is defined by total quantity of ampere-turns needed to generate specified magnetic field. Fig. 4 shows this difference for warm and cold iron core options with horizontal beams separation.

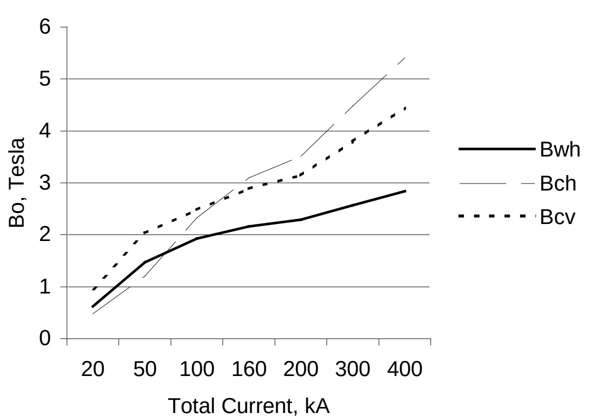


Fig. 4 Magnetic field in the air gap center at different currents. Bwh – magnet with warm iron Fig. 1, Bch – magnet with cold iron Fig. 2, Bcv – magnet with cold iron Fig.. 3.

The warm iron option has comparable ampere-turns up to 2 Tesla magnetic field. It should be noted that at the same central field in warm iron variant transmission line has lower field on the superconducting cable surface and as a result can carry larger current. The same type of graph shown on Fig.5 for window-frame superferric magnet.

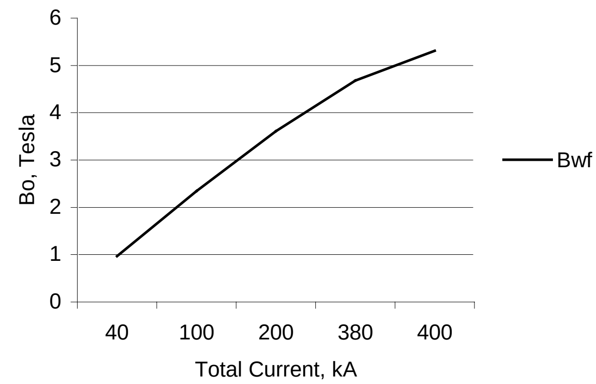


Fig. 5 Magnetic field in the air gap center at different currents in window-frame magnet with cold iron and verical beams separation (type of SSC superferric magnet [4]).

The most effective magnet configuration with lowest ampere-turns for field range 3-5 Tesla is the magnet with cold iron core and horizontal beams separation. The iron core weight is also ~ 3 times lower than for other options shown in Table 1. The disadvantage of this cost effective configuration is apertures coupling problem. Nevertheless it is useful investigate parameters of cost effective configuration to clarify the directions of future magnet system optimization.

## VI. PRELIMINARY COST ANALYSIS OF MAGNET SYSTEM

Preliminary cost analysis based on the following assumptions:

- magnet configuration Fig. 2
- magnetic field range 1 – 5 Tesla
- magnet air gaps (each) 26 mm
- superconductor NbTi
- max superconductor field is equal the field in an air gap
- iron core saturation is the same for different central fields
- tunnel length -total magnets length plus straight sections
- heat load decrease for shorter tunnel variants is compensated by an extra load for larger cryostat diameters
- cost of cryostat is proportional the RHIC magnet cryostat scaled to outer cryostat diameter and inflation
- costs of correction and other accelerator systems are the same for all variants.

The main cost driver for this analysis is the tunnel cost. Several attempts were made to estimate the tunnel underground construction closer to the reality. The Fermilab

VLHC Design Study [1] based on 4000 $/m tunnel cost. The total underground constructions cost is ~2 times more per meter length, which includes shafts, beam transport lines, detector halls, etc. The tunnel cost extremely depends on the type of tunneling technique, automation and in future can be decreased. That is why it is interesting to estimate how the tunnel cost may influence on magnet system optimization. Fig, 6 shows the result of cost analysis as a function of the main magnets magnetic field.

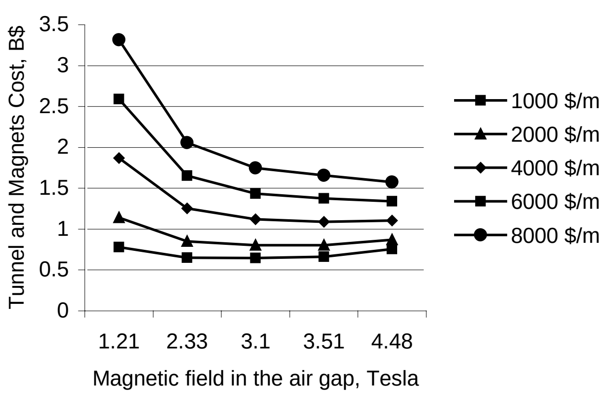


Fig. 6 The magnet system and accelerator tunnel cost as a function of magnetic field.

First of all the lower tunnel cost the more shallow dependence of total cost from the magnetic field in the magnets. The cost minimum shifts to the higher field levels at higher tunnel cost per meter length. Fig. 7 shows this dependence.

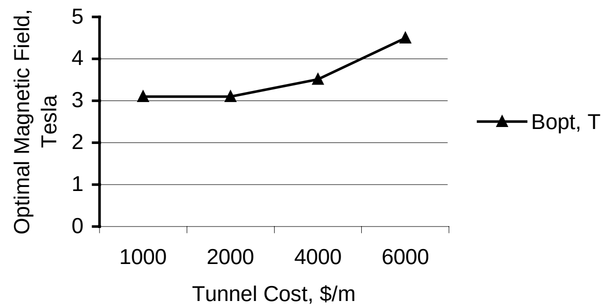


Fig. 7 The optimal magnetic field versus of tunnel cost per meter length

| | |
|---|---|
| - iron core height | 160 - 200 mm |
| - iron core weight | 140 - 200 kg/m |
| - magnet cost | ~1000 $/T-m |
| - cryostat outer diameter | 300 - 400 mm |
| - superconductor NbTi | 2.5 - 3.5 kg/m |
| - iron core width | 140 - 160 mm |

## VII. Conclusion

The goal of presented preliminary analysis is to start a discussion relatively basic parameters of superferric magnet systems. The superferric magnet options with cold iron core should be investigated as a possible candidate for the VLHC Stage I. The staged scenario of the VLHC, when the final energy and the tunnel perimeter are fixed, limits the magnets optimization for the VLHC Stage I. There are two possibilities. The first is a magnet optimization for the minimum cost at fixed tunnel length and fixed final energy of Stage I. The second is to fill in the ring by magnets with lowest cost per T-m at fixed only tunnel length.

The presented in this paper analysis showed a strong influence of tunnel cost on the optimal magnetic field and the collider magnets design.

## VIII. Acknowledgment

The authors express their warm thanks to all the members of VLHC Design Study team and Snowmass 2001 magnet technology working group.

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The optimal magnetic field for a cold iron approach Fig. 2 is in the range of 3 - 4.5 Tesla magnetic fields. The higher field levels can be provided by very strong pole windings to compensate the iron saturation effects and in this case superconducting winding configuration moves to the shell type windings, which were widely investigated for SSC, RHIC, HERA and other accelerators.

So, close to the optimum magnet should have the following parameters:

| | |
|---|---|
| - maximum magnetic field | 3.0 - 3.5 Tesla |
| - total current | 150 - 200 kA |