Superconducting Superferric Dipole Magnet with Cold Iron Core for the VLHC

G. W. Foster and V. S. Kashikhin

***Abstract*—Magnetic system of the Stage I Very Large Hadron Collider (VLHC) is based on 2 Tesla superconducting magnets with combined functions. These magnets have a room temperature iron yoke with two 20 mm air gaps. Magnetic field in both horizontally separated air gaps is generated by a single, 100 kA superconducting transmission line.**

An alternative design with a cold iron yoke, 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 major cost drivers for the 233-km magnet system of future accelerator. The vertical beam separation decreases the superconductor volume, heat load from the synchrotron radiation and eliminates fringe field from the return bus. Nevertheless, the horizontal beam separation provides lowest volume of the iron yoke and, therefore, smaller heat load on the cryogenic system during cooling down. All these options are discussed and compared in the paper. Superconducting correction system combined with the magnet that allows increasing the maximum field is also discussed. Preliminary cost analysis is performed for all these options.

***Index Terms*—Accelerator magnets, cold iron, cost, superconducting magnets, superferric, VLHC.**

I. INTRODUCTION

DESIGN Study of the Very Large Hadron Collider (VLHC) 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 the collider is a civil construction cost. Superconducting magnet system is the second cost driver. The Stage I VLHC is based on the superconducting, 2 Tesla transmission line magnets [2]. These superconducting magnets with combined functions cost only 900\$/T·m [1] and provide essential cost savings.

Other types of superconducting magnets, generating magnetic fields in the range of 2 to 6 Tesla with a very high efficiency [3]–[5] are well known. Most of them utilize the cold iron ferromagnetic screen with superconducting NbTi winding mounted into a cryostat. The goal of this paper was investigation of the transmission line magnet design with the cold iron yoke and comparison it with the warm iron design.

Manuscript received September 24, 2001.

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Publisher Item Identifier S 1051-8223(02)03440-1.

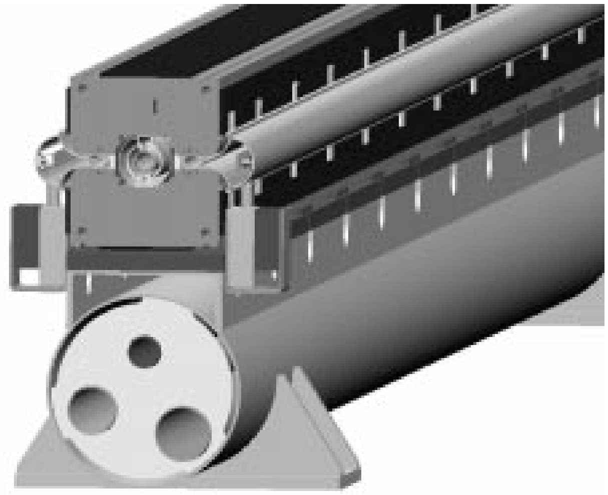

Fig. 1. 2 Tesla transmission line magnet [1].

II. WARM IRON MAGNET WITH HORIZONTAL APERTURE SEPARATION

The 2 Tesla transmission line magnet [2] has horizontal beam separation and warm iron, shown in Fig. 1. The 100 kA superconducting transmission line is made from NbTi superconductor, incorporated into a very compact (80 mm OD) cryostat. The return bus of the transmission line has a separate cryostat, 300 mm in diameter, 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, like: useless return bus, serving for reduction of the fringe field only, weak mechanical connections between half-cores, strong iron saturation effects, difficult to correct.

III. COLD IRON MAGNET WITH HORIZONTAL APERTURE SEPARATION

The cold iron option of this magnet can be made without the transmission line cryostat. It reduces the aperture separation distance and therefore the quantity of needed ampere-turns. The volume of superconductor, depending on the maximum applied field, will be higher for this option. The cross-section of this magnet is shown in Fig. 2. The magnet has a rectangular transmission line cable (cable in conduit), cooled with LHe. Superconducting pole windings produce positive or negative field gradient and correct the iron saturation effect. The magnet air gap

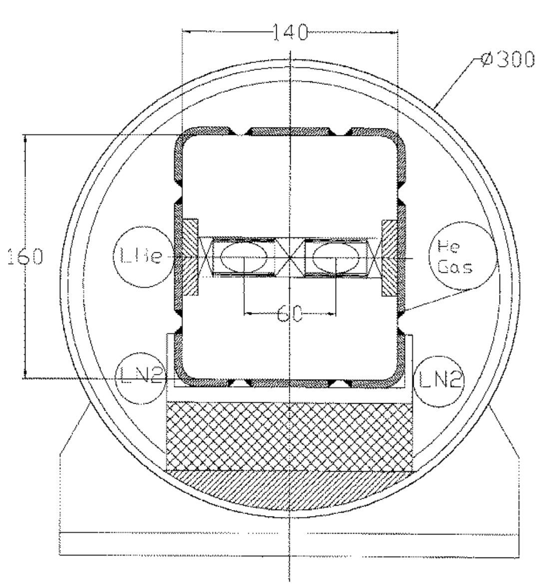

Fig. 2. Transmission line magnet with the cold iron and horizontal beam separation.

should be increased from 20 mm to 26 mm to provide space needed for the pole correction windings. As a result, the winding ampere-turns will be higher, thus for a 3 Tesla field the total current should be 162 kA. The beam pipes are cold and do not need big anti-chambers as in the warm iron design. It also helps providing a better mechanical stability, using the side spacer bars and connecting plates. The return bus can be split and placed on both sides of air gaps. In this case, the magnet has only one common cryostat of $\sim$300 mm diameter. Weight of the iron is lower for the cold iron design, since influence of the larger air gaps is compensated by a very short path for the magnetic flux in the iron yoke. The pole profile is optimized for the maximum magnet field and generation of the negative or positive gradient. In this case, current in the correction coil is zero at the nominal field. The return bus position should also be optimized to reduce distortions of magnetic field in the air gaps due to the iron saturation effect. Magnetic forces do not make a problem in this design, since the cold mass is not exposed to decentering magnetic forces and only a small fringe field goes outside of the magnet.

IV. Cold Iron Magnet With Vertical Beam Separation

The vertical beam 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 larger iron core weight and consequently larger cryostat and heat load. The window frame magnets [4], [5] generate only a dipole field, and a separate system of focusing and defocusing quadrupoles should be incorporated in the ring magnet system. Fig. 3 shows cross-section of a C-shaped combined function magnet with the vertical beam separation.

It is rather attractive to use nature of the C-shaped magnets, generating a gradient field caused by the iron saturation effect, in a combined function magnet. Pole profiles could be optimized for a maximum field and the needed negative gradient of

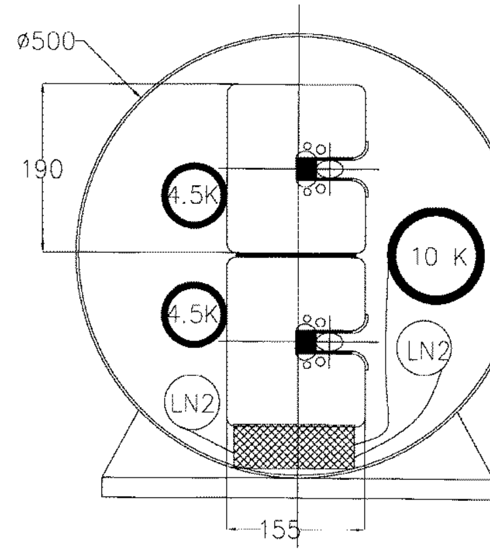

Fig. 3. Transmission line magnet with the cold iron and vertical beam separation.

TABLE I
Main Magnet Parameters

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

4–5%/cm. The superconducting pole windings correct the field distortions at low and medium field levels. The open air gaps on the outer ring side provide exit for the synchrotron radiation and simplify the beam pipes installation. It is possible for one turn winding to eliminate the transmission line electrical insulation and place G10 spacers between both C-cores. In this case, the voltage breakers should be installed on all vacuum pump outlets. The positive gradient magnet can be obtained by the magnet rotation on 180° with corresponding transmission lines interconnections in the space between focusing and defocusing magnets.

V. Magnets Comparison

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

The main cost driver for the VLHC Stage I is a tunnel cost. It is obvious that at a lower tunnel cost the magnet system of

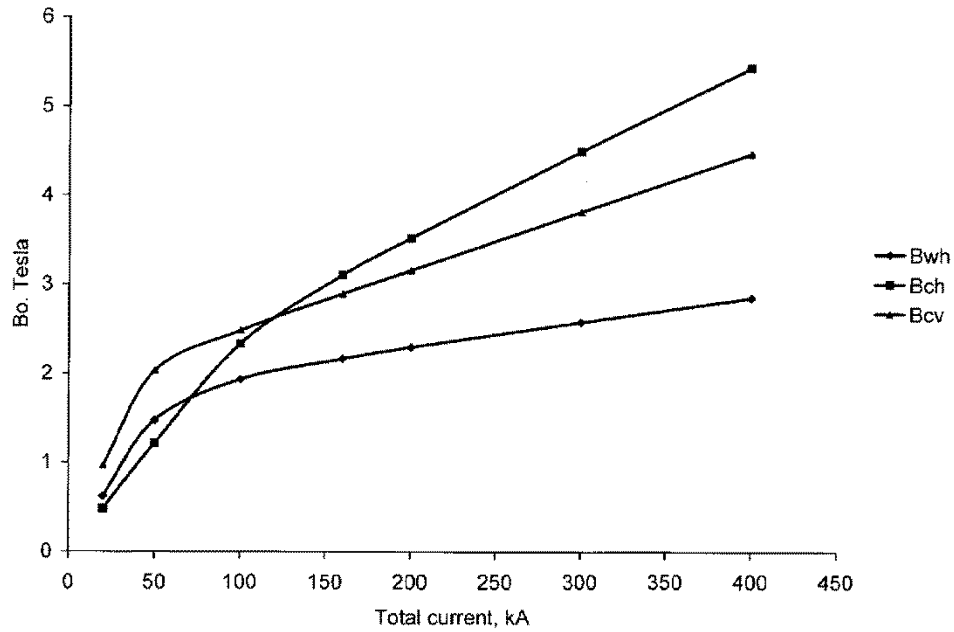

Fig. 4. Magnetic field in the air gap center at different currents. Bwh - magnet with warm iron Fig. 1, Bch—magnet with cold iron Fig. 2, Bcv—magnet with cold iron Fig. 3.

the collider moves to a lower magnetic field. The cost drivers of magnet system are: cost of iron core, cost of superconductor and cryostat. Parameters for the 2T and 3T magnets are presented in Table I. The main difference between various magnet configurations is defined by the total quantity of ampere-turns needed to generate a specified magnetic field. Fig. 4 shows this difference for the warm and cold iron core options with the horizontal beam separation.

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

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

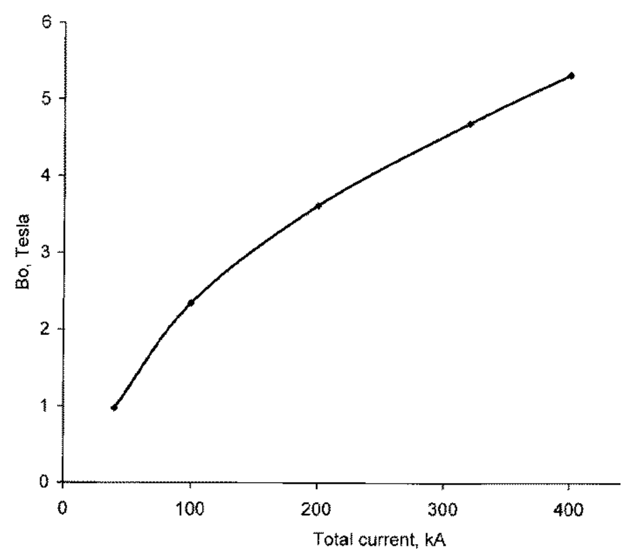

Fig. 5. Magnetic field in the air gap center at different currents in the window-frame magnet with the cold iron and the vertical beams separation (type of SSC superferric magnet [4]).

VI. Preliminary Cost Analysis of Magnet System

Preliminary cost analysis was based on the following assumptions:

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

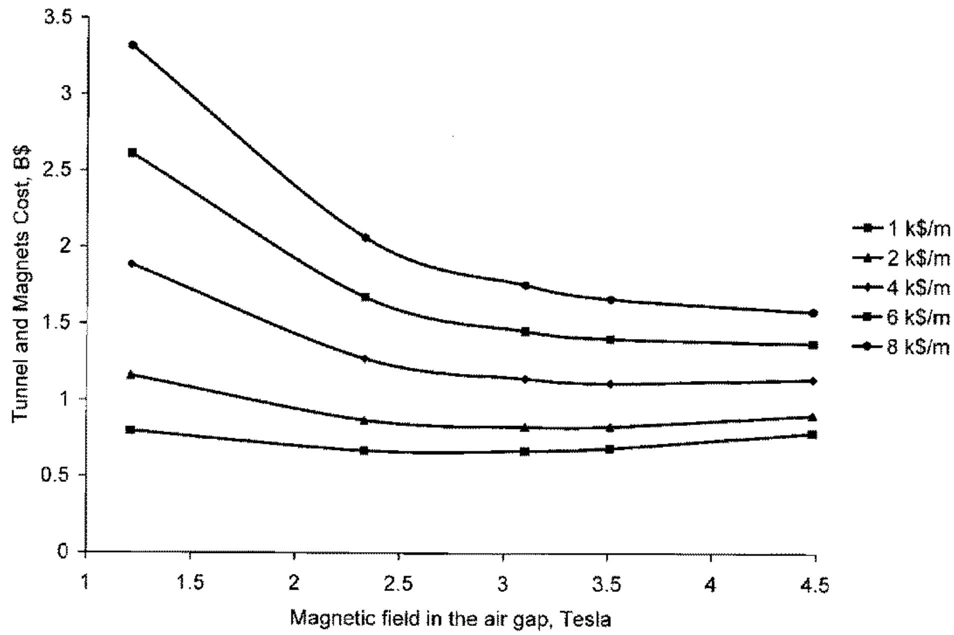

Fig. 6. The magnet system and accelerator tunnel cost as a function of magnetic field.

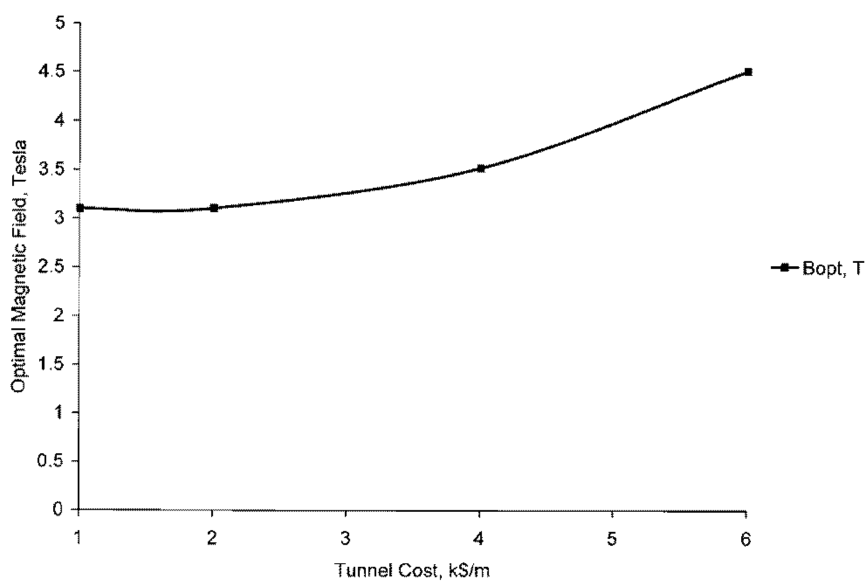

Fig. 7. The optimal magnetic field versus of tunnel cost per meter length.

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 VLHC Design Study [1] cost estimation is based on the 4000$/m tunnel cost. The total value is $\sim$2 times more, which includes shafts, beam transport lines, detector halls, etc. The tunnel cost depends extremely on the type of tunneling technique, automation and can be decreased in future. That is why it is interesting to estimate how the tunnel cost may influence on the magnet system optimization. Fig. 6 shows the result of cost analysis as a function of the main magnets magnetic field. First, the lower tunnel cost means the more shallow dependence of the total cost on 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. The optimum magnetic field for a cold iron approach in Fig. 2 is in the range of 3 to 4.5 Tesla. The higher field levels can be provided by the very strong pole windings to compensate the iron saturation effects and in this case the 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 to 3.5 Tesla
- total current	150 to 200 kA
- iron core height	160 to 200 mm
- iron core width	140 to 160 mm
- iron core weight	140 to 200 kg/m
- cryostat outer diameter	300 to 400 mm
- superconductor NbTi	2.5 to 3.5 kg/m
- magnet cost	∼1000$/T-m

VII. Conclusion

The goal of presented preliminary analysis is to start a discussion on the basic parameters of superferric magnet systems. The superferric magnet options with the 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. There are two possibilities. The first is a magnet optimization for the minimum cost at the fixed tunnel length and final energy of Stage I. The second is to fill in the ring by magnets with lowest cost per T·m at the fixed tunnel length only.

Presented in this paper analysis has shown a strong influence of the tunnel cost on the optimal magnetic field and the collider magnets design.

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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