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HTS Accelerator Magnets Conceptual Design for Future Lepton Colliders

Vladimir Kashikhin

***Abstract*—There is an interest in designing superconducting magnet systems for future lepton circular colliders. This application requires many low-field iron-dominated dipole and quadrupole magnets. Conventional room-temperature magnets are often used because of their low field, low total current, and low power losses. However, high electricity bills for large accelerators drive magnet design to superconductivity. High-temperature superconducting (HTS) magnets can substantially reduce energy losses in magnet systems. The present study investigated the conceptual design of HTS dipole and quadrupole magnets operating in persistent current mode. Energy is transferred into the magnet from an external detachable power source. A continuously circulating current generates a stable magnetic field. The iron-dominated magnet system concept was investigated using OPERA3D code, and the results confirmed the proposed approach's validity.**

Keywords*— Accelerator, Design, Dipole, High-Temperature Superconductor, Magnet, Magnetic field, Quadrupole, Simulations, Superconducting.

I. INTRODUCTION

Circular accelerators with electron beams have a long history. The most well-known and giant machine of this type is the Large Electron–Positron Collider (LEP) [1]. The LEP at CERN consisted of 5,800 iron-dominated electromagnets. The CERN future lepton collider [2] will be built in the new 98-km-circumference tunnel. At BNL, the started Electron Ion Collider project [3] is also based on relatively low-field iron-dominated magnets for an electron beam. The study's main goal is to show the possibility of using HTS magnets instead of resistive magnets to reduce electricity consumption for future accelerators substantially. Recent advances in the HTS magnets technology [4]-[16] open the way to replace resistive magnets by superconducting working at elevated temperatures. The most critical issue is the cost of superconducting magnets which is usually higher than resistive magnets. But if the magnet should generate a stationary magnetic field, it could be used an operation in a persistent current mode when the main current in the HTS coil induced by the resistive coil works only for a short time. It substantially reduces the cost of HTS magnets and makes them competitive with resistive magnets. Several magnet models were successfully built and tested at Fermilab [8]-[10] at the liquid nitrogen temperature 77 K. This temperature level substantially reduces the cost of the accelerator cryogenic system.

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II. HTS MAGNETS CONCEPTUAL DESIGN

The main goal of this study is to show that HTS magnets could replace the resistive magnets at lower cost. Conceptual design of HTS magnets was performed using the resistive magnet specifications from the FCC-ee [2] project. The magnet specifications are shown in Table 1. These are double-aperture dipoles and quadrupole magnets. Iron poles shape the required magnetic field. Magnets work in DC mode and, in this case, can be used HTS magnets [4]–[8] working in a persistent current mode. Because of the large number of magnets and high operational costs, dipoles with a relatively low 0.79 A/mm^2 current density were chosen [2], allowing for the use of air-cooled, relatively cheap resistive aluminum coils. However, even in this case, the power loss for all dipoles will be 13.3 MW. A 1-m-long magnet prototype with a Cu coil was thus built and successfully tested at CERN [2]. Quadrupoles with a 2.1 A/mm^2 current density require water cooling because of a significant 22.6 MW power loss. To substantially reduce the 35.9 MW electricity bill, a variant of magnets with HTS coils is proposed and discussed in this paper.

TABLE I
MAGNETS SPECIFICATION

Parameters	Units	Dipole	Quadrupole
Electron Beam Energy	GeV	45.6 ÷ 182.5	
Dipole field	mT	57	-
Quadrupole gradient	T/m	-	10
Number of magnets		2900	
Magnet aperture diameter	mm	84	
Magnet length	m	24	3.1
Beams separation	mm	300	
Field quality in Ø 20 mm	%	± 0.01	
Winding ampere-turns	A	3800	28440
Al coil current density	A/mm^2	0.79	2.1
Maximum total power	MW	13.3	22.6
Outer dimension height	mm	136	500
Outer dimension width	mm	450	500

A. HTS Dipole Magnet Concept

Recent advances in HTS magnets [9]–[15] allow us to propose the concept of an HTS double-aperture dipole magnet operating in persistent current mode, as shown in Fig. 1. This magnet has the exact iron core dimensions of the dipole magnet in [2], but the aluminum coil was replaced with a single-turn, short-circuited HTS coil, which was mounted inside a cryostat and cooled by LN_2. The main drive behind this concept idea is to eliminate 13.3 MW of continuous electrical power. This represents a large portion of the operational costs of the accelerator complex.

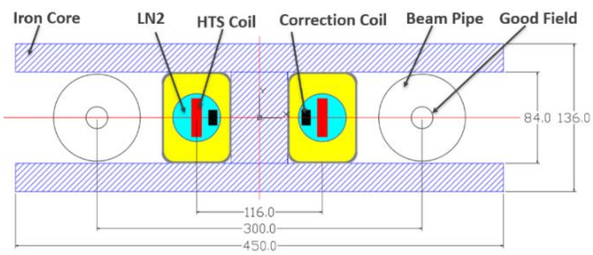

Fig. 1. HTS dipole magnet concept view.

The HTS coil is energized by a primary (correction) resistive coil, which works for only 2-3 minutes. A heater was placed at the end of the HTS coil to reduce or eliminate induced current. The magnetic field simulation model is shown in Fig. 2.

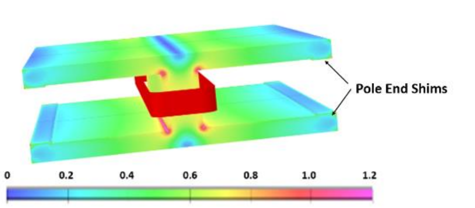

Fig. 2. HTS dipole flux density in Tesla at a 3800 A coil total current.

The iron yoke is not saturated with a peak of 1.2 T flux density in the corners. Simple rectangular shims at the poles provide field homogeneity ± 4 units (1 unit = 10^{-4}), as shown in Fig. 3. Further improvement can be achieved with further shim form optimization.

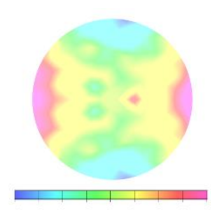

Fig. 3. Field homogeneity in units(1 unit = 10^{-4}) for a good field area of Ø 20 mm.

The HTS coil was assembled from a stack of HTS 12-mm-wide tapes slit in the middle beside the ends, forming the short-circuited loops of the superconducting coil (see Fig. 4).

Fig. 4. Model of HTS coil assembled from 100 tape loops.

The critical current of the 12-mm-wide HTS tape at 77 K is 550 A. At least 14 of 6-mm-wide loops are needed to carry a 3800 A coil total current. The peak field on the coil is only 0.1 T. The number of loops was increased to 20 for reliability, to have a sufficient margin. The magnet parameters are shown in Table 2.

TABLE II
DIPOLE MAGNET

Parameters	Units	Values
Dipole peak field	mT	57
Dipole length	m	24
HTS coil ampere-turns	A	3800
HTS REBCO 12 mm, Ic at 77K	A	550
Number of HTS 6 mm wide loops		20
HTS 12 mm tape length/magnet	m	480
Primary Cu conductor #12 dimensions	mm	2.05 x 2.05
Primary Cu coil current	A	100
Primary Cu coil number of turns		38
Primary coil resistance at 77 K	Ohm	0.22
Primary coil power losses at RRR=10	kW	1.2
Outer dimension height	mm	136
Outer dimension width	mm	450

B. HTS Quadrupole Magnet Concept

The parameters shown in Table 1 were used for the conceptual design of the double-aperture HTS quadrupole magnet. The magnet's main difference from the dipole magnet is that it needs a 10 T/m magnetic field gradient with a 0.42 T pole tip field and a large total winding current of 28.44 kA. The HTS double-aperture quadrupole magnet concept operating in persistent current mode is shown in Fig. 5.

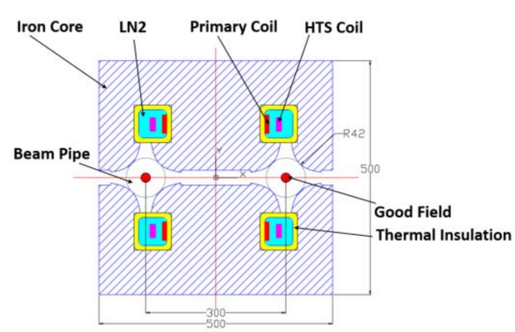

Fig. 5. HTS quadrupole magnet concept view.

The double aperture Figure-8 quadrupole magnet has two Cu and two HTS coils. The gap in the magnet center is filled with non-magnetic material to direct magnetic flux through apertures and mechanically support upper and lower magnet sub-assemblies. The result of the magnetic field simulation is shown in Fig. 6. The peak magnetic flux density reaches 1.7 T in the iron core, which is close to steel saturation and can be reduced by increasing the magnet yoke thickness.

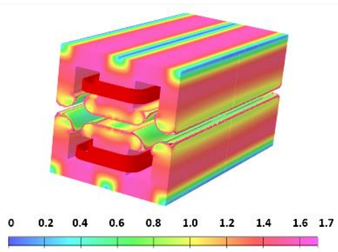

Fig. 6. Flux density in Tesla for the iron yoke (Bmax = 1.7 T).

Fig. 7 shows the quadrupole field gradient in the magnet aperture at a 10 mm radius. The gradient homogeneity is 4.2 units (1 unit = 10^{-4}).

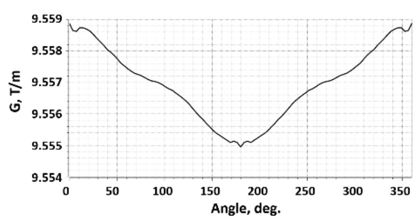

Fig. 7. Quadrupole field gradient in the aperture.

Further field quality improvement can be achieved by better pole tip shims optimization. The HTS quadrupole magnet must have more Cu primary winding turns and HTS loops relative to the HTS dipole, but the HTS quadrupole version will provide 22.6 MW power savings relatively resistive magnets. Table 3 shows the main HTS quadrupole magnet parameters.

TABLE III
QUADRUPOLE MAGNET

Parameters	Units	Values
Quadrupole peak gradient	T/m	10
Quadrupole length	m	3.1
Number of magnets		2900
HTS winding ampere-turns (2 coils)	A	28440
HTS REBCO 12 mm, Ic at 77K	A	550
Number of HTS 6 mm wide loops		104
HTS 12 mm tape length/magnet	m	322
Primary Cu conductor #12 dimensions	mm	2.05x 2.05
Primary coil current	A	100
Cu winding total number of turns		284
Primary coils resistance at RRR=10	Ohm	0.78
Primary winding power losses	kW	7.8
Outer dimension height/width	mm	500/500

III. HTS Magnet Operation

Finding the most optimal way to energize the HTS coil for the HTS magnet is critical. There are two options: (1) use a primary magnetization coil fully coupled with the HTS coil and with the same total current as the HTS coil, and (2) use a detachable magnetizer forming a closed ferromagnetic path for the magnetization flux. Both options were successfully investigated in the dipole magnet models [8]–[10] and [14], [15]. The first option is to use the copper coil shown in Fig. 1 as a correction coil because it works quickly to energize the HTS coil and is initially cooled to the LN_2 temperature. Later, it can be used as a ±1.2% field correction coil due to the particle energy decay caused by synchrotron radiation [1]. The second option uses a detachable magnetizer. This approach uses very low magnetizer coil ampere-turns to generate the magnetic flux in the closed ferromagnetic core. Much of the energy transferred into the HTS coil comes from the mechanical energy produced by removing the magnetizer. In [14] and [15], it was shown that the optimal way to remove magnetizers is to slide them vertically. In this case, the peak force will be an order of magnitude lower than when magnetizers are pulled out horizontally. This paper discusses only the first option, but a version with a magnetizer is also possible.

The magnet has a primary conventional winding that is strongly magnetically coupled through a common magnetic core with an HTS secondary coil. The HTS coil is initially non-superconducting (heater activated), but when the primary coil is energized, the needed magnetic flux fully penetrates the HTS coil area. Because the HTS coil currently is non-superconducting, no current is generated. After that, the HTS coil is cooled down to a superconducting state, and the magnetic flux is frozen in the coil area. At that time, the current in the primary coil is reduced to 0, generating the opposite current in the HTS coil, in agreement with Lentz's law. The first option will be the final current in the HTS coil, equal to the primary coil ampere-turns. For the second option, a magnetizer must be detached to transfer mechanical energy into the magnetic field energy. The HTS magnet schematic diagram is shown in Fig. 8.

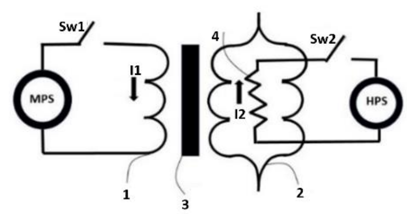

Fig. 8. Magnet system schematic. MPS and HPS, main and heater power supplies, respectively; 1, primary winding; 2, secondary HTS coil; 3, magnet core; 4, heater; and Sw, switches.

The HTS magnet tests [8]–[10] and [14]–[15] in LN_2 showed fast HTS coil heating and cooling, which defined the ~2 min time of the current transformer operation.

Fermilab investigated the HTS dipole magnet model [10] shown in Fig. 9, which could be used to verify the proposed magnet concept.

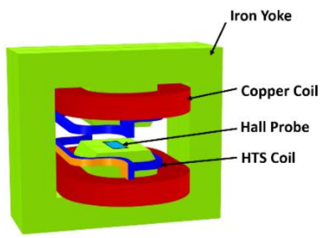

Fig. 9. HTS dipole magnet with Cu primary coil and HTS secondary coil.

The magnet primary coil was energized only for 2 min, enough to transfer in the HTS secondary coil 4.47 kA current, generating a stable 0.5 T magnetic field in the 20 mm dipole magnet gap (see Fig. 10).

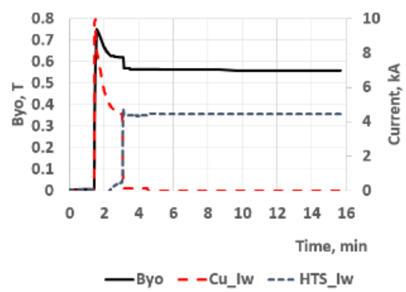

Fig. 10. HTS dipole operational test result. Byo – magnet center field, Cu_Iw – primary Cu coil total current, HTS_Iw – HTS coil total current.

During the long-term test, a persistent HTS coil current circulated for 10 hours without decay until all the liquid nitrogen was evaporated.

In the tunnel, magnets are usually connected in series, forming a string of magnets. An individual power supply powers each string. Fig. 11 shows the variant of primary coils connections to the power supply.

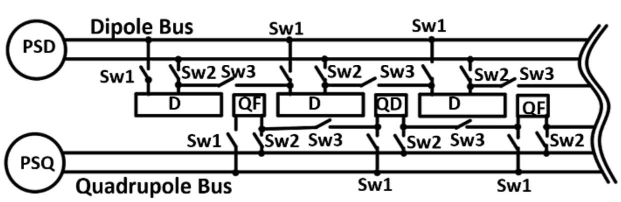

Fig. 11. Magnets primary coils powering diagram. PSD, PSQ, dipole, and quadrupole power supplies, D, dipole; QF and QD, focusing and defocusing quadrupoles, respectively; and Sw, switches.

In this case, magnets can be powered individually by closing any SW1-SW2 switches, and in strings by closing SW1-SW3-SW3-SW3 to SW3-SW2 switches. The number of closed SW3 switches defines the number of magnets in the series. The power supply voltage is proportional to the number of magnets in the string and will be low because the cold primary coils have low resistance. Finally, when persistent currents are excited in all ring magnets, all switches are open, and power supplies are disconnected.

IV. Possible Cost Saving

For the proposed HTS magnet concepts, it is critical to estimate the possible cost savings. In Switzerland, the cost of electricity in August 2023 was \$101/MWh. The cost of electricity has risen 2 times over the years 2019 – 2023. For dipoles, the cost of continuous operation will be \$11.8M/year. The optimized balance between the capital cost and operational expenses for magnet systems must be even for ~10 years of operation [17]. This means that a proper balance is \$118M for each of them. The extra costs for the HTS version are those for superconductor and liquid nitrogen (LN_2) cooling. The cost of LN_2 for 10 years of operation is \$11M. The cost of the iron core is the same for resistive and superconducting versions, and the cost of the HTS magnet cryostat is less than resistive magnet coils and cabling in the tunnel and large power supplies for room-temperature magnets. Thus, the cost driver difference between resistive and HTS magnets is the cost of the HTS superconductor. In the future, an HTS superconductor cost reduction could be expected from fusion energy systems [16]. For the HTS 12 mm ReBCO tape with a cost of \$80/m and with a critical current of 550 A at 77 K, the total superconductor cost for the dipoles will be ~\$83.5M. The total cost of a superconductor with LN_2 will be \$94.5M, which is 20% lower than the electricity bill of \$118M for conventional room-temperature dipole magnets. For quadrupoles, the electricity bill increases quadratically with the current density. However, the cost of the superconductor increases only linearly with the total current. Thus, the cost savings will be even more significant. Of course, this operational cost can be reduced by an accelerator accessibility factor or funding limitations.

V. Conclusion

The HTS magnet conceptual design described in this paper meets the required resistive magnet specifications. Because of its superconductivity, the estimated electricity bill could be 20 % lower than for resistive magnets. It can have the same iron core as room-temperature magnets. HTS coils assembled from short-circuited superconducting loops operate in persistent current mode, generating a very stable magnetic field in magnet apertures. In magnets, correction coils can be added to provide uncoupled field variations in both gaps.

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References

[1] "The Large Electron-Positron Collider," 1989-2000, CERN, https://home.cern/science/accelerators/large-electron-positron-collider.

[2] M. Benedikt, A. Blondel, O. Brunner, *et al.*, "FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2," Eur. Phys. J. Special Topics 228, (2019) 261-623.

[3] 'Electron-Ion Collider," BNL, https://www.bnl.gov/eic/.

[4] A. Ageev, *et al.*, "Test Results of HTS Dipole," *IEEE Trans. on Applied Superconductivity*, 2002, vol. 12, pp. 125-128, 2002.

[5] D. Pooke, *et al.*, "HTS 5 Tesla Synchrotron and Neutron Beamline Magnets", *IEEE Trans. on Applied Superconductivity*, 2009, vol. 19, no. 3, June 2009, pp. 1372-1375.

[6] J. Muratore *et al*., "Magnetic field measurements of an HTS retrofit synchrotron dipole," *IEEE Trans. Appl. Superconductivity*, vol. 21, Issue 3, pp. 1653–1656, 2011.

[7] T. Huang, *et al*., "A Commercial HTS Dipole Magnet for X-Ray Magnetic Circular Dichroism (XMCD) Experiments", *IEEE Trans. Appl. Superconductivity*, vol. 22, no. 3, 2012, 4203504.

[8] V. Kashikhin, J. DiMarco, A. Makarov, Z. Mendelson, S. Rabbani, S. Solovyov, D. Turrioni, "High Temperature Superconducting Quadrupole Magnets with Circular Coils," *IEEE Trans. on Applied Superconductivity*, 2019, vol. 29, Issue 5, 4002404.

[9] V. Kashikhin, D. Turrioni, "HTS Quadrupole Magnet for the Persistent Current Mode Operation," *IEEE Trans. on Applied Superconductivity*, vol. 30, NO. 4, JUNE 2020, 4602104.

[10] V. Kashikhin, D. Turrioni, "HTS Dipole Magnet Model for the Persistent Current Operation," *IEEE Trans. on Applied Superconductivity*, vol. 32, Issue: 6, February 2022, 21643599.

[11] J. Kosa, I. Vajda, A. Gyore, "Application Possibilities with Continuous YBCO Loops Made of HTS Wire," *Journal of Physics-Conference Series*, 234:(3), Paper 032030.

[12] R. Schauwecker, R. Herzog, R. Tediosi, M. Alessandrini, "Method for Manufacturing a Magnet Coil Configuration Using a Split Band-Shaped Conductor," US Patent 8712489 B2, April 29, 2014.

[13] H. Lee, *et al*., "Design and Fabrication of Permanent Mode Magnet by using Coated Conductor," *Physica C: Superconductivity and its Applications*, vol. 445-448, 2006, pp. 1099-1102.

[14] V. Kashikhin, "Superconducting Magnet System Concept with a Mechanical Energy Transfer in the Magnetic Field," *IEEE Trans. on Applied Superconductivity*, vol. 33, no. 5, August 2023, 3800305.

[15] V. Kashikhin, D. Turrioni, "HTS Dipole Magnet with Mechanical Energy Transfer in the Magnetic Field," *IEEE Trans. on Applied Superconductivity*, vol. 33, Issue: 5, April 2023, 4003404.

[16] Y. Zhai, A. Otto, M. Zarnstorff, "Low Cost, Simpler HTS Cable Conductors for Fusion Energy Systems," ICMC 2021, 1241 (2022) 012023.

[17] G. Bianti, M. Gabriel, "Basic Expression for Evaluating Iron Core Magnets a Possible Procedure to Minimize their Cost," CERN/SI/Int. DL/70-10, 1970, 40 p.