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CONCEPT OF A HYBRID (NORMAL AND SUPERCONDUCTING) BENDING MAGNET BASED ON IRON MAGNETIZATION FOR 80-100 KM LEPTON / HADRON COLLIDERS

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Abstract

We present a concept of twin aperture iron dominated bending magnets. These compact "transmission line" dipoles are meant to be installed in the same 80-100 km tunnel of the Future Circular Colliders (FCC) currently being studied at CERN, where they shall be used for the high energy injector synchrotrons. The main feature is the coupling of a resistive cable (for first use in a leptons machine) with a superconducting one (for hadrons operation, presumably in a second phase of FCC). The main challenges in terms of operating field range are commented in the light of similar magnets already built.

INTRODUCTION AND SCOPE

The Future Circular Collider (FCC) design study is exploring different energy frontier machines in a tunnel of 80-100 km circumference in the CERN area. Several options are being considered in light of their physics potential, their technological challenges, and ultimately their cost. This applies also to the injectors' chain.

The FCC-hh [1] is the hadron collider within the FCC study, a proton-proton machine of 100 TeV centre-of-mass energy, with 16 T (100 km) or 20 T (80 km) dipoles. The field quality achievable at low excitation with these magnets is closely related to the FCC-hh injection energy. Among the possible options for a high energy injector, we consider here a new synchrotron hosted in the same tunnel of the collider and we provide a description of its possible superferric transmission line dipoles.

The FCC-ee [2] is the lepton counterpart, providing electron-positron collisions in an energy from 91 GeV (Z-pole) to 350 GeV (t-tbar threshold), passing through the Higgs resonance at around 240 GeV. Given the short beam lifetimes – of the order of 10 minutes, due to radiative Bhabha scattering – the FCC-ee shall operate at constant energy and be refilled on the go by a full energy booster. Here we show how the same transmission line magnets of the hadron high energy injector, operated at a much lower current in a resistive mode, could be used for a full energy lepton booster. This may lead to savings in capital and installation costs.

At this conceptual phase, we proceed with tentative parameters, in particular for the strength and aperture of the magnets. This is enough also to underline possible synergies for the magnets of the FCC-hh / FCC-ee high energy injectors. For many technological aspects – such as, in particular, the actual superconductor used – several options are discussed, though any choice would be rather premature at this stage.

TRANSMISSION LINE MAGNETS

For our purposes, a "transmission line magnet" is a current carrying cable (or a few ones) surrounded by an iron yoke. The current magnetizes the iron, which is to a large extent the only responsible for accelerator quality field in the gap. The design is intrinsically simple and economically attractive. No actual coils are needed; then, the yoke and the cable(s) can be manufactured separately and put together almost *in situ*. In this way long magnets can be assembled with fewer connections, which are often vulnerable zones.

The LEP dipoles [3] can be considered in a sense as transmission line magnets, with their four water cooled aluminium bars providing excitation for the 0.11 T of magnetic field in the beam aperture (top energy).

On the superconducting front, the concept of similar magnets for large hadron machines has been around since at least a 1982 paper by R. R. Wilson [4]. This was then considered in 1996 for a Really Large Hadron Collider [5-6]. In 2001 a technical design of the transmission line magnet for the Stage-1 Very Large Hadron Collider was presented [7]. These proposals originated in the US and they soon attracted supporters from other continents and for other projects, for example KEK – with a prototype Nb_3Al cable [8] – and CERN, in view of a possible injector in the 27 km tunnel [9-10]. More recently this idea has been expanded to cycled magnets with HTS superconductors, to be used for example in Project X [11] and the Muon Collider [12].

At the end of this brief historical perspective, to give a reference design based on well-established technology, we report in Table 1 the main parameters of a transmission line magnet which has been built and tested [13]. This was actually a combined function magnet, with a dipole and quadrupolar gradient, developed by FNAL in the framework of the Stage-1 VLHC [7].

Table 1: Main Parameters of a Nb-Ti Transmission Line Bending Magnet Built Around 2005 at Fermilab

Geometry	double C, 2 side apertures
Peak central field in the gap [T]	2.0
Peak current [kA]	100
Vertical full gap [mm]	2 × 20
Superconductor	16 × SSC Nb-Ti cables
Cable cryostat dimension [mm]	80 (outer diameter)
Peak operating temperature [K]	6.5 - 7

BENDING MAGNETS FOR A HIGH ENERGY HADRON INJECTOR

Superferric transmission line dipoles proposed in the past for large machines often involved two apertures side by side in the horizontal plane, with reversed polarities for counter-rotating colliding protons. We retain here the idea of a twin aperture bending magnet also for a high energy hadron injector, but we propose to stack the apertures vertically. In this way we keep the reversed field configuration, though we avoid having the magnetic reluctances of the two gaps in series, while exploiting the field generated by the current return line at the same time. In practice, for the same gap and field we halve the current needed. Then, this geometry allows the opening of the C to be on the outside for both rings, in such a way that the emitted synchrotron radiation can be dealt with more conveniently. Finally, this configuration provides the same length for both synchrotrons, avoiding the need for crossing in case synchronization of the two beams would be needed for simultaneous injection.

As for the maximum field level in the gaps, we prefer to remain in an intermediate range: large enough to inject at a “comfortably” high beam energy, though low enough to: i) reasonably limit the excitation current; ii) make the overall yoke compact, and iii) avoid field distortions in the whole dynamic range due to iron saturation.

The size constraints are particularly relevant: they impact on the cost, plus most of the new tunnel shall be reserved to the high field magnets and related systems. As a preliminary working hypothesis, we take 1.1 T in a twin (full) aperture of 50 mm. This corresponds to a current of 43.7 kA for the ideal case of an infinite permeability iron with infinitely wide poles.

We take a pole width of 100 mm, which at these field levels and with a proper design shall provide a uniformity in the $\pm 5\cdot 10^{-4}$ level in ±20 mm on the midplane.

A conceptual cross section design of such bending magnets is shown in Figure 1; the main parameters are listed in Table 2. For the core BH characteristics we use a standard high saturation low Si electrical steel. For the dimensions of the 50 kA cable, we consider an external diameter of the cryostat of 100 mm. This is conservative with respect to the 80 mm / 100 kA cable of Table 1; however, in this design the overall size of the cable has a limited impact on the size of the magnet, since the dimensions of the yoke are dictated by the pole width (related to the extent of the good field region) and the amount of saturation allowed in the return legs (related also to the field in the aperture). Here we propose a rather compact cross section and we allow 2.1 T in the yoke for 1.1 T in the gap(s). The field on the superconductor is of the order of 1.0 T. The field distribution in the aperture is the same from injection to extraction energy, as the iron saturation is rather constant across the return legs.

For the bending radius and arc filling factor, we take respectively 10.4 km and 0.79, as in the 100 km option of [1]. Taking 450 GeV as injection energy from SPS, these dipoles would have a dynamic range of about 8.

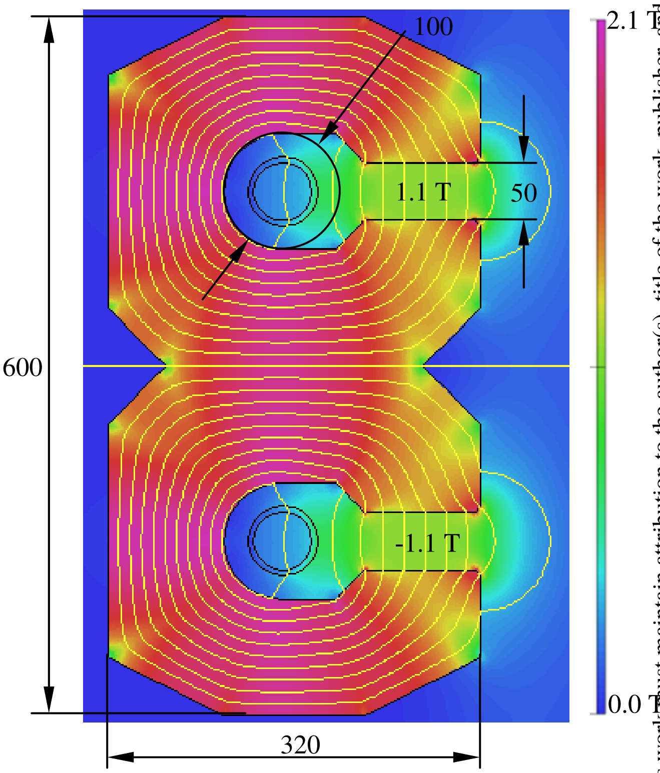

Figure 1. Cross section of the bending magnet, with dimensions in mm.

The lengths of the dipoles can be chosen as to optimize the arc filling factor and according to the optics. At given integrated strength, we favour not to increase the field – which would require a higher current and a wider iron core – but rather to lengthen the magnets, since anyway we would have 50 kA class busbars to screen in between dipoles. Also it could be convenient to have combined function magnets to reduce the number of quadrupoles, to increase the arc filling factor, and to avoid excessive bends of the cable to make room for other magnetic elements, as already proposed for example in [6-7].

If we were to make these magnets normal conducting, taking for example a rather low $1\ \mathrm{A/mm^2}$ as current density in the copper conductor, we would end up with a peak resistive power – in the magnets only – of 100 MW. This makes the resistive option hard to consider.

Table 2: Main Parameters of the Bending Magnets for a High Energy Hadron injector

Vertical full gap [mm]	2 × 50
Good field region on midplane [mm]	±20
Pole width [mm]	100
Inter-beam distance [mm]	300
Outer diameter of cable cryostat [mm]	100
Overall dimensions [mm]	320 × 600
Iron weight per unit length [t/m]	1.2
Injection energy [TeV]	0.450
Injection field [T]	0.14
Current at injection energy [kA]	6.5
Extraction energy [TeV]	3.4
Extraction field [T]	1.1
Current at extraction energy [kA]	50

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BENDING MAGNETS FOR A FULL ENERGY LEPTON BOOSTER

The lepton booster works in a much different energy range, with an injection around 10-40 GeV [2] and a top energy according to the excited resonance. A possible challenge for the dipoles will be the low injection field, where the coercive force and the low permeability of the steel can impact the field quality and magnet-to-magnet reproducibility [14-15]. The operation mode would also be different, with magnets ramped fast and frequently.

A natural design is a one aperture transmission line resistive C dipole. Besides simplicity and low cost, this has also the advantage of a minimum inductive voltage for a given dB/dt. Keeping the gap fixed at 50 mm, the top excitation current is around 5 kA.

Can the same dipoles of the previous section be a solution? The two apertures can be used one at a time with a bipolar power supply to inject electrons and positrons. For the conductor it is tempting to use the stabilizer of the superconducting cable itself, though cooling compatibility between demineralized water and, at a later stage, a cryogenic fluid shall be properly handled. A more classical solution could be to use a 5 kA resistive busbar during lepton operations. The magnets would then be designed to allow an easy replacement of the resistive busbars with the 50 kA class superconducting cable in an upgrade for hadrons configuration.

The yokes themselves could be re-used, if the injection energy allows so in terms of field level and aperture. The compact design of Figure 1 involves concentration of flux lines in the return legs, which can be beneficial at low field. This can be compared to a prototype LEP dipole, with an all iron (no dilution) yoke, where the measured field uniformity [14] suggested that down to about 14 mT in the gap the field quality remained satisfactory, with variations in the quadrupole and sextupole terms of a few units (which could be addressed by the lattice multipoles). Incidentally, no advantage in terms of field quality for a prototype steel-concrete LEP yoke – with an iron filling factor of 0.27 – was measured [14]. For the lepton booster here we expect the field quality to be less constraining than for a collider. Then, the above results were obtained with a low carbon steel with a coercitivity of the order of 50 A/m (after full saturation). Therefore, with possibly some forgiveness on field quality and a material with better performances, we can expect to work down to about 10 mT in the gap. This corresponds to an injection at 31 GeV, close to the tentative range given in [2].

Now, 1.1 T (hadron extraction) over 10 mT (lepton injection) makes an overall dynamic range seen by these yokes just slightly above 100. This looks doable compared to the 129 ratio of the SPS dipoles between 450 GeV (hadron extraction LHC era) and 3.5 GeV (lepton injection LEP era).

OPTIONS FOR SUPERCONDUCTOR

The choice of the superconducting material for the transmission line cable shall be based on many factors, such as large volume availability and form (wire, tape), operating temperature, capital cost (material, cable manufacturing and the cryogenic system), running cost (mostly for the cryogenic system), protection issues. Here we briefly comment on three main options.

- Nb-Ti: this is the cheapest and most available material, it is easy to handle, though requires a low operating temperature, possibly with supercritical He.
- HTS, bismuth or rare earth based: the main advantage is the higher operating temperature; their cost will likely decrease in the future. FNAL already built and tested [11] a 80 kA cable with YBCO tapes.
- MgB_2: this material is promising in terms of cost and – although requiring a He based cryogenics – it would allow a higher operating temperature than Nb-Ti. Recently CERN developed with industry MgB_2 round wires and manufactured a 40-m long cable. This was successfully tested up to 20 kA at 24 K [16].

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