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A Possible Alternative Concept of HTS Accelerator Magnets

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***Abstract*—In this paper, we consider the advantages of an alternative design concept for HTS accelerator magnets operating at 20 K or above. The idea is primarily built on using REBCO tape as the main conductor, but may be applicable to other HTS. The key concepts are to align REBCO tapes in the most favourable field orientation and to make joints for every turn such that the tapes will not have to be wound over the saddle ends. We argue that such a concept involving resistive joints is viable at 20 K or above due to an increased cryogenic efficiency, and has multiple advantages that would more than compensate for the resistive heating cost penalty. First, the favourable tape orientation can allow a much higher current carrying capability. Second, the short unit length of tapes equal to the length of the magnet will be much more economical and can be specified at a higher performance than a long continuous piece equal to the number of turns multiplied by the length of the magnet. Third, any defective conductor can be replaced easily and at a much lower cost than an entire coil. Fourth, with each tape separately sourced and connected, efficient grading with stress management can be achieved. Fifth, the straight section of the magnet would be modular and easily scalable for production in industry. Correspondingly, the most challenging part is the end cap design and joint technology, whose geometrical constraints are well within national laboratories' capabilities, making the R&D and prototyping phases much more affordable, with a turnover time much quicker than testing full size magnets. Additional attractive potentials include conductor development (e.g. double-sided extra thick REBCO), novel diagnostics (e.g. individual tape quench detection and protection), synergy with fusion devices research (e.g. demountable joints), and other possibilities.**

***Index Terms*—High-temperature superconductors, accelerator magnets, fabrication, joining materials, high energy physics**

I. Introduction

MODERN particle accelerators for High Energy Physics (such as the SSC [1], LHC [2], HL-LHC [3], and the proposed FCC [4]) are complex machines costing billions of dollars with non-trivial technical as well as cost and schedule challenges. In recent decades, the state-of-the-art colliders have become multi-national megaproject endeavours requiring many years of planning, design, prototyping, production, and commissioning. Some, such as ISABEL [5] [6] and the SSC [7] [8] [9], encountered serious enough technical and managerial hurdles that they got cancelled. These are projects that push technologies to the limit and require many years of significant investment in research and development.

Common among them and centre to the technological challenge is the superconducting magnet, and one of the elements with the most significant cost is the superconductor. The number of iterations needed to develop the short models and refine the prototype magnet designs to maturity often means decades of sustained support of many tens of millions of dollars annually by the funding agencies is necessary. As an example, the US contribution to the HL-LHC, the so-called Accelerator Upgrade Project [10] (2016-2028) built on the US national Conductor Development Program [11] (1999-2016) and the LHC Accelerator R&D Program [12] (2003-2017). They cross almost 30 years and cost altogether nearly half a billion dollars, where the R&D phase occupied two thirds the duration and under half the budget.

High temperatures superconductors (HTS) such as REBCO [13] and Bi-2212 [14] are presently the most likely candidates for future accelerator magnets beyond the limits of Nb_3Sn. They hold promising performance that may allow very high field (16 T or 20 T) dipole magnets to be made, thereby reducing the footprint required of future colliders and thus also the civil engineering cost, or for a set length of tunnel achieving a higher centre of mass energy.

The presently pursued magnet technologies for accelerators are predominantly, in USA, the Canted Cosine Theta (CCT) design championed by LBNL [15], the Stress-Managed Cosine Theta (SMCT) design championed by FNAL [16], and the Common Coil (CC) design championed by BNL [17], as well as their variants; in Europe, the Roebel-based programs under EuCARD-2 that include the Feather coils [18], Cloverleaf [19], Cosine Theta [20]; and in China, under the Chinese Academy of Science (CAS) using iron-based superconductors (IBS) [21]. Novel design concepts such as the unilayer [22] are also being explored. In this paper, we propose another alternative design concept for HTS accelerator magnets operating at 20 K or above.

II. The Concept

A. Assumption and Design Features

A key assumption is that the thermal budget can afford many demountable joints in our accelerator magnet concept.

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The demountable joint concept was proposed first for the fusion magnets and even validated by researchers [23] [24] [25] [26]. The main feature of this magnet design is that instead of having a long piece of conductor winding a coil, we will have pieces of conductor forming the “straight sections” and joining to “end caps”.

We present our concept here using REBCO tapes and operating at 20 K for illustration purposes, but we note that the design can be applicable to other HTS materials and at other cost effective temperatures.

We also implicitly consider here the block coil design, and again we note that other coil designs may be similarly applicable, although some of the advantages and arguments for the concept presented in this manuscript may be relevant only to the block coil design and its variants.

B. Conductor

REBCO tapes are fabricated by deposition (e.g. IBAD [27], MOCVD [28], PLD [29]), and as such conductor length is a more sensitive quality limiter and cost driver than round wire produced by billet drawing. In applications such as foreseen in accelerator magnets, performance dropouts are typically not considered acceptable. To supply large amounts of high performance, long piece length REBCO tapes, the manufacturers would have to account for the material loss (and therefore reduced profit margin) due to unsellable pieces that do not meet the performance and/or length specifications. Any statistical defect that could compromise conformance or conductor acceptance would quickly drive up the loss and therefore the cost of REBCO tapes. Consider a hypothetical one-metre short model coil with 50 conductor turns, it would need a continuous piece of tape a little over 100 m. Now to scale up to a four-metre prototype coil or an LHC-style 15 m dipole coil, the conductor minimum length would leap to over 400 m and 1.5 km, and that is not a proposition that is favourable to cost reduction, despite an increase in production volume demand. One attractiveness of the proposed magnet concept using conductor pieces equal to the length of the coil rather than ~100 times its length is the cost and scalability. It retires the risk associated with conductor quality reduction when piece length and production volume increase.

Moreover, without having to wind around the beam tube, this concept removes the performance reduction due to conductor bending. The elimination of a hard-way bend may potentially save precious space that is otherwise needed to accommodate a large bend radius [18] [19]. The elimination of the easy-way bend is also beneficial, as the REBCO layer would not be under strain irrespective of whether it is in the neutral plane of the tape. This feature can significantly minimize the reduction of critical current in REBCO tapes under compressive or tensile strain. It is well-known that the critical current can reduce by 50 – 70% when the compressive strain is about 1% at 76 K [30]. This level of compressive strain on REBCO tapes is not unusual in multi-tape cable configuration such as CORC® [30]. Therefore, we expect the new magnet concept to minimize the strain impact on the transport performance of REBCO conductors, and consequently reduce the extra conductor needed to compensate the performance reduction, and thus the associated cost.

The elimination of bend also opens up the possibility of using double-sided, extra thick REBCO tapes such as proposed by [31]. The gain in performance using double-sided tapes can approximately offset the performance reduction due to operating at 20 K instead of 4.2 K. The use of extra thick REBCO layer can further boost the performance by a few times.

An additional advantage is that the REBCO tapes can always be oriented in the favourable field orientation. REBCO exhibits strong anisotropy in its current carrying capability. Current flow parallel to the Cu-O plane can be a few times to over 10 times higher than when the flow is in the perpendicular direction, depending on the field strength and temperature [32] [33]. This boost in performance by a factor of several reduces the amount of conductor required accordingly, and thus can also reduce the cost of the magnet significantly.

To illustrate the point, let us consider a comparison between the new concept and a 30-tape CORC® wire configuration that has been used in recent REBCO dipole magnets. In both cases we consider a 1 m long conductor with the same tape counts of 30 for the straight section. The new concept presented here requires a total of 30 m of REBCO tapes. A typical CORC® wire would require about 45 m of REBCO tapes due to the length reduction when a tape is in a helical shape. In addition, the new concept would allow the tapes to be oriented in parallel with the field lines and have a higher packing factor arrangement, further increasing both the total transport current per unit length of conductor and the current density in the coil pack.

Optimistically, using relatively short pieces of double-sided, extra thick REBCO tapes in the favourable field orientation without bending strain reducing performance, we believe it is a feasible goal to have 12 mm tapes carrying >5 kA at 20 T, 20 K at scale. As a comparison, the Nb_3Sn TFD cable designed to carry 14 kA at 16 T, 1.9 K has a dimension of ~26 mm x 1.9 mm [34]. In terms of engineering critical current density (over the tape or rectangular cable cross section, without insulation), assuming a thin substrate for the high-J_C REBCO tapes, that potential performance translates to >8 kA mm^{-2} at 20 T, 20 K, versus <300 A mm^{-2} at 16 T, 1.9 K for the present-day Nb_3Sn example.

C. Coil

At the coil level, there are a few obvious advantages. The first is not having any layer jump. This makes coil design and fabrication easier, especially with a tape conductor.

Furthermore, in the coil cross section, the field and stress distributions are not uniform. In a typical coil wound from a single piece of cable, the performance margin can be highly non-uniform at the pole versus at the mid-plane. In the proposed concept, every tape can be specified differently, effectively allowing near-perfect grading [35] [36]. In the low-field, low-stress regions, lower performance tapes from the conductor production batch can be used without compromising the current, temperature, or load-line margin. In high-field, low stress regions, higher performance tapes can be used to preserve the margin. In high-stress regions, reinforced tapes or a stress-managed structure can be applied to ensure there is sufficient performance margin. This is simultaneously a highly optimized coil cross section design and an efficient use of conductor.

A consequence of having individual tapes in the straight section connected by demountable joints is the hugely beneficial ability to replace defective or degraded tapes. In the high luminosity upgrade of the Large Hadron Collider's inner triplet focusing magnet MQXF series production, the successful replacement of individual faulty coils and reassembly of the magnet is hailed as a significant milestone, because of the cost saving associated with reusing the magnet structure and with the potential preservation of the other three performing coils in a quadrupole magnet. In the proposed concept, we can replace individual strips of conductor and the potential cost saving can hardly be overstated.

On the other hand, we also recognize that an optimized demountable joint technology has not yet been established for REBCO conductors or cables. There are several open issues that need to be carefully investigated. For instance, an optimal soldering material and soldering process with well-defined spatial-temporal-temperature profile that can minimize the degradation of REBCO tapes [37] [38]. Furthermore, even if the technology exists, the number of joints required in the kind of future accelerators in discussion would imply the risk of fabrication failure may be considerable and may increase the burden of engineering, necessitating appropriate management strategy.

In addition to the joint technology, the straight section reinforcement structure may present another significant technical challenge. Recent studies showed that stacks of REBCO tapes are highly compressible and that is not limited to stack of tapes [39][40] but also in magnet scale [41][42][43][44]. Compressibility of straight sections may give challenges in field homogeneity and stress concentration. Impregnation might be helpful for the conductor positioning, however, delamination would be a concern.

D. Magnet

Enabled by the high engineering current density of the conductor, the magnet can either have a more compact design or afford features that would otherwise not be possible. One such feature may be an open mid-plane design to reduce the synchrotron radiation heat load on the coils.

A key element to be much further explored is the end cap design. We accept that there are many major technical challenges, but would like to speculate a couple of features here.

To connect the two sides of the straight section electrically, the end cap will need to have some form of a bus that can carry the large current over the beam tube [26] [45]. Conveniently, as we need to make a joint, this means if tape-form conductors are to be used, we can orientate the tapes to bend over the beam tube on their broad face with a bend radius as large as the beam tube itself. Since there is no need, and possibly not practical, to make all the demountable joints within a tight space (e.g. a few tapes' width), some creative connecting methods can be perceived [26]. For example, multiple paths can be made in parallel, in order to minimize the current I and hence the power dissipation (which is proportional to I^2) at each joint. Each path may have MOSFETs to control the current distribution. Further, since the end cap can be connected at the end of the magnet instead of at the end of one coil, the current path is no longer limited to being within a coil in the conventional sense but may go from one half (assuming a dipole) to the other half [46]. This allows interesting connection schemes such as twin dipoles to add favourable longitudinal prestress during powering.

The joints are presently conceived to be Cu pressed joints and fully demountable, similar to those in [47] in terms of performance, but could also be in other forms. It is anticipated that there will be synergistic benefits from the fusion community in the development of demountable joints.

E. Cryogenics

An enabling assumption is that the superconducting magnets will be operated at ~20 K, presumably in liquid hydrogen, which has high thermal conductivity as well as high latent heat of vaporization (Latent heat of vaporization: 446 kJ/kg LH_2 vs 20.3 kJ/kg LHe) [48]. In addition to removing the risk with helium supply chain (FCC-hh would require 880 tons of He [49]) and benefiting from the so-called hydrogen economy, at 20 K, there is better cryogenics efficiency contributing to improved sustainability in terms of collider energy consumption (FCC-hh projected 580 MW[49]).

As an illustrative exercise: in LHC the cold mass (arc) cryogenic load is 170 mW/m at 1.9 K, and the resistive heating in splices is 56 mW/m at 1.9 K, and in the HL-LHC, the synchrotron radiation (arc) 310 mW/m per beam [3]. Now consider a generic hypothetical 16 T block coil Nb_3Sn dipole design with 75 turns using a 14 kA cable [50]. Assuming 5 kA REBCO tapes at 20 K connected by 1 nΩ joints, the heat load is 25 mW per joint. One 14 kA equivalent cable would require the capacity of three 5 kA tapes. Thus, 75 turns x 3 tapes x 4 joints per turn gives 22.5 W at 20 K. However, the Carnot factor at 1.9 K vs. 20 K is more efficient by about 12 times. Therefore, the equivalent heat load at 1.9 K would be less than 2 W. While this is a very rough estimate, it shows that the resistive heat load due to the joints should unlikely be a showstopper when operated at 20 K, even before accounting for the benefits of using more aggressive innovations such as liquid hydrogen cooling and open mid-plane magnet designs.

Alternatives include using helium gas and cryocoolers at other elevated temperatures [51].

III. Strategic Considerations

A. Resource Requirements

Since E. O. Lawrence's cyclotrons, HEP colliders have ever grown in size and complexity, not least because of the rule of thumb relationship that the energy of the particle beam is proportional to the size of the accelerator and the main dipole field. It is foreseen that the next hadron collider will require 10^3 to 10^4 superconducting dipole magnets similar in length to the LHC's. The development strategy beyond the present general accelerator R&D programs such as those in Europe [52] and in the U.S. [53] will possibly be a directed R&D program similar to LARP [12] to develop and demonstrate technical maturity of the key technologies. Early prototyping can perceivably be done at national laboratories, but the series production would have to be transferred to industry.

The US MDP presently receives an annual budget on the order of 10M USD, shared among the four partner laboratories, and 1M USD on conductor procurement and R&D. With the proposed FCC requiring a budget a few thousand times higher to construct and an optimistic budget of about 10B CHF to procure conductor, an intermediate budget for the directed R&D phase to develop high field magnets by a traditional strategy could potentially be seen as cost prohibitive.

The magnet concept proposed in this paper is arguably a possible and affordable path forward. In addition to the conductor cost saving and magnet technology and cryogenics advantages mentioned above, the scalability factor and technological critical path could be a game changer. The most challenging component is perceived to be the end cap, which would require much less conductor (the straight section could even be reused), much fewer resources for cold testing (the simplistic straight section implies that most of the magnet cold testing during the development phase will focus on the end cap, whose dimensions would fit within existing national laboratories' test pits), and have a much quicker turnaround than a full-size magnet would, making the R&D and prototyping phases much more affordable. The individual straight section conductors are much cheaper to replace, allowing more aggressive and faster learning by trial and error. Critically, the straight section is likely easily scalable to long length, allowing quick maturation during the most expensive phase of magnet development.

B. *Other Advantages*

The projected high engineering current density of REBCO tape even at 20 K suggests that magnets can be made more compact and that there will be increased space to afford novel ideas for auxiliaries in the coil cross section. The modular nature of the proposed design means that customs diagnostics could be implemented at each tape, allowing quench detection innovation and accelerating technology advances through better understanding of individual components. (It may be argued that customs diagnostics will have to be implemented at each tape for quench detection and protection, because of the very high current density REBCO tapes are projected to carry.)

Synergistic benefits cannot be overstated: the fusion community's stable and huge demand on HTS tape is projected to increase supply, improve production logistics (including production equipment manufacturing), and consequently reduce conductor cost, with HEP driving performance development and having a complementary demand for much shorter conductor piece lengths. The use of liquid hydrogen as a coolant is likewise beneficial: there are large scale liquefaction capabilities in the aerospace industry, ongoing investment by large automobile and aircraft manufacturers, interest among the fusion companies, as well as past experiences operating bubble chamber and detectors within HEP. All of these communities have strong incentives to develop environment, safety, and health (ES&H) protocols, and the accelerator magnet community can benefit from them.

C. *Immediate Next Steps and Further Opportunities*

Below are a few "low hanging fruits" to tackle as well as some opportunities that the authors identified, but this is by no means an exhaustive list:

- Ramp rate, AC losses, persistent current, etc. especially if non-transposed conductor is used (note that the proposed concept applies also to using transposed cables)
- Field quality near and about the end cap
- Effective magnetic length
- Mechanical support for the conductor at the transition region between the straight section and the end cap
- Magnetic forces on the edge of the tape
- How to preload the magnet
- Heat transfer limit (wattage per unit area of LH_2 at 20 K, 20 T)
- Making demountable joints with low in-field resistance in tight space
- Integration with other systems
- Additive manufacturing (3D printing) compatibility

IV. Conclusion

We presented an alternative HTS magnet concept using short individual REBCO tapes as the main conductor, requiring demountable joints such that the tapes will not have to be wound over the saddle ends. We argue that such a concept involving resistive joints is viable at 20 K or above due to an increased cryogenic efficiency, and has multiple advantages at every level from conductor, coil, magnet, to collider cryogenics and R&D program strategy that would more than compensate for the resistive heating cost penalty.

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