An *Open Lab* for the Development of Technical Superconductors

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Abstract

Superconductivity is a core technology that has fueled the progress in high-energy physics (HEP) accelerators, from the Tevatron of the early 1980's to the Large Hadron Collider of the late 2010's [1,2,3,4]. The engineering knowledge of superconducting materials in the form of composite wires, tapes, or thin layers finds application in high-field accelerator magnets [5], very large detectors magnets [6] and high-gradient/low-loss RF cavities [7]. The progress witnessed in the past years has been remarkable. Comparable progress will be required to meet a number of HEP challenges in the close future, and mainly:

- Realize ultimate performance in Nb_3Sn, as it has been specified for the realization of the main magnets of a Future Circular Collider in a new (FCC) or existing (HE-LHC) tunnel [8];
- Demonstrate the potential of HTS materials to surpass LTS accelerator magnet technology, providing efficient very-high-field or high operating margin options for specific locations in existing and future colliders, and eventually to extend the energy reach of circular synchrotrons [9].

This success was possible so far thanks to a *virtuous circle* of applied superconductivity, encompassing fundamental science, applied research and industrial production. Due to several factors, we observe that this virtuous circle is losing its effectiveness. This is perceived as a serious threat to the future of a robust applied superconductivity program for HEP and is the main justification for this proposal. In short, we propose to secure this technology by founding an Open Laboratory for Applied Superconductivity that will work as a bridge between academia and industry. This proposal is driven by an identified need, and at this stage the implementation is not localized in a specific institute.

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1. Introduction: the virtuous circle of applied superconductivity

The virtuous circle of applied superconductivity has resulted since the inception of applications for HEP from the following elements:

- The challenging performance demands driven by the specific application to HEP, and generally bound to a specific project or laboratory. This has provided a focused and consistent drive, motivated by a definite final use, and substantiated by a reality check of the viability of a given superconductor technology. We refer to this force as the *pull*;
- The first response to the above challenge is naturally provided by the R&D potential of universities and research institutes, referred to as *academia*. These hubs host personnel and expertise in the various disciplines of material science and engineering, necessary to go from the initial discovery of a superconductor to a technical material. We refer to this actor as the *scout*, exploring new venues for opportunities, and taking first steps towards its application.
- Discovery of a superconductor is only the starting point of the process that leads to a successful application. Experience has shown that the lead time from material science to the first use can be several years (e.g. Nb-Ti) to several tens of years (e.g. HTS). Work in academia has been a natural way to overcome a part of this gap, by extending its research work from fundamental aspects to applied science and engineering. At the same time, industrial partners have been traditionally involved in these early aspects of material science, complementing the work of academia with its own research. This part of the process is the *bridge* between a discovery of a material and the large-scale industrial production described next;
- Finally, industrial partners are most effective in devising production routes, including considerations on architecture, work-ability, production processes, the choice of material sources, scale, quality and cost. In addition, industry can exploit opportunities beyond the specific project, and profit from the associated *market*. This is an important step that provides long term support to the technology. Industry is the agent of the realization of the technology, responding to the demand both immediately, and on the longer term. We refer to this phase as the *run*.

Though a rather simple representation of the process, the above description is sufficiently close to reality and provides a speaking image, see Fig. 1. The key element in the circle is that the *bridge* has been effectively shared between academia and industry, whereby the boundary between technology demonstration and industrial production remained rather fluid.

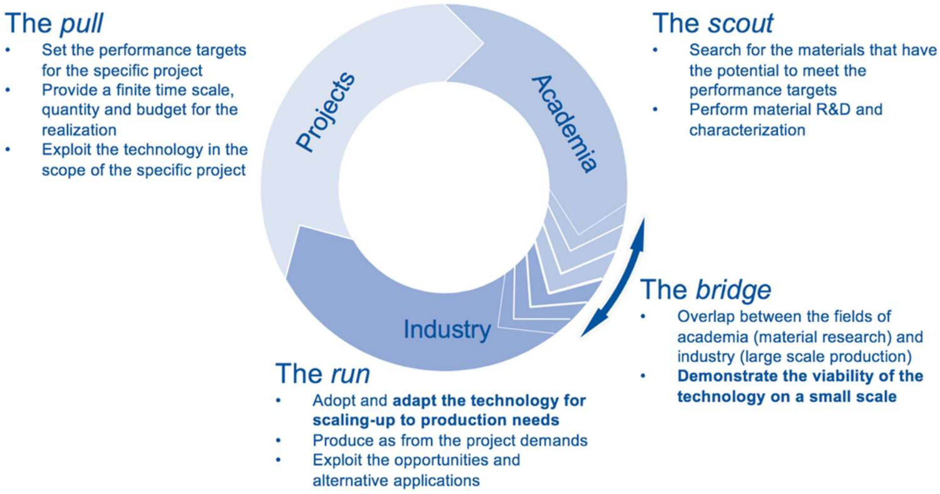

Figure 1. A schematic view of the *virtuous circle* of development of technical materials for superconducting applications, as it has been established and has been effectively working in the past. Note the overlap between academia and industry in the *bridge* area.

2. The results of the virtuous circle of applied superconductivity and its evolution

This *virtuous circle* has brought the developmental material Nb-Ti to its peak performance and industrial maturity. Originally used in modest quantities in the 1960's to the 1970's for large scale detectors such as the Argonne Bubble Chamber at ANL [10], or the Big European Bubble Chamber (BEBC) at CERN [11], and the first superconducting synchrotron, the Tevatron [1], Nb-Ti has nearly doubled its critical current density J_C during the years of intense development for the Superconducting Super-Collider (SSC) in the late 1980's [12], mainly funded by the US-DOE. The result of this work was the so-called *High-Homogeneity* (or Hi-Ho) Nb-Ti [13], which was then produced in considerable quantity (1300 tons) for the LHC [14]. Hi-Ho Nb-Ti is presently an industrial commodity, with a yearly production of the order of 600 tons, mainly for the market of Magnetic Resonance Imaging (MRI, see later).

On a smaller scale, the present need of high fields driven by the High-Luminosity Upgrade of the LHC (HL-LHC) [15] has been instrumental to the development of high J_C Nb_3Sn. This HEP-grade Nb_3Sn, originally developed in independent R&D efforts in the early 2000's in the US [16] and EU [17], has undergone the industrialization required to achieve the multi-tons production presently demanded by HL-LHC [18]. Besides its use for the HL-LHC magnets, HEP-grade Nb_3Sn is now displacing previous generation material in ultra-high-field Nuclear Magnetic Resonance (NMR) magnets [19]. This has led to commercial NMR systems with much-reduced magnet dimension, and significantly smaller foot-print when compared to previous technology. Ultra-high-field NMR is a niche application for research and laboratory work, hence Nb_3Sn production remains limited to typically a few tons per year.

These success stories are a clear example of the benefits provided by the companionship of HEP and applied superconductivity [20]. Also, they show that the loop described above can be very effective in fostering targeted progress with considerable direct and indirect return.

The past years have witnessed a considerable shift in the structure, mode of operation and priorities of research institutions, funding agencies and industry, in particular for what regards fundamental and applied superconductivity. In the new landscape, the above model of a virtuous loop appears to be much less likely to operate as witnessed in the past. More specifically, applied superconductivity no longer appears in high-priority research objectives of leading academia, thus receiving much reduced funding from government agencies with respect to the past. Also, the market of superconductivity is highly competitive, albeit for a very limited number of well-established applications, mostly in the healthcare sector. In this field, superconductors are considered as a commodity, no longer a high-technology. The profit margins have reduced considerably, leaving little space for industry to develop new technologies. Finally, while the interest in the sector of energy production and transmission is still significant for developmental HTS, there is clearly no more interest for the established LTS materials. In summary, while the *pull* remains strong, and the *scouting* for new materials continues at a fundamental level, the link to a successful and profitable industrialization *run* has weakened. We start lacking a solid *bridge* to connect basic materials, that have the potential to respond to project demands, to industrial grade technical superconductors. In the next section we expand on this change, based on market analysis, scientific indicators, and trends in governmental funding.

3. A view to the applied superconductivity landscape

The market of superconductors

Applied superconductivity is customarily subdivided in small-scale applications, large-scale applications and materials. Accelerator magnets and RF cavities fall in the field of large-scale applications, which is by far dominating in terms of production and revenues. Here we limit our analysis to this field of applications.

The largest share of production of superconductors is driven by MRI, a 5.5 BUSD/year market steadily growing at a rate close to 5 %/year, mainly following the penetration of medical diagnostics in emerging countries[1]. The other commercial large-scale production of superconductors is associated with magnets for NMR and other science, a 1 BUSD/year market driven mainly by innovation in instruments and diagnostic techniques. Production for large science projects, such as the LHC and ITER, come as highly disruptive events, but considering the average value over several years, they do not represent significant deviations from this steady business (see also later example of superconductors production). The LHC magnet system, with

[1] It is important to remark at this point that market projections tend to consistently and grossly overestimate the growth of novel technologies (HTS) to alternative fields (electronics, energy and transportation). Business reports consistently predict market expansions that have not realized so far, and lack objective credibility when comparing the predicted time scales of growth to the inherent lead times of production infrastructure.

an evaluated cost of approximately 2 BUSD over 5 years, represented on average a +10 % variation with respect to the commercial MRI and NMR market quoted earlier. The same is true for the production of the ITER magnets, evaluated at 1.4 BUSD total value over a comparable period of 5 years. Figure 2 gives a summary view of the market shares among the largest applications of superconductivity. MRI systems represent 80 % of the market share, other applications for science and research are worth 18 % of the total market. Electronic and new applications for large scale only represent a total of 2 % of the total market.

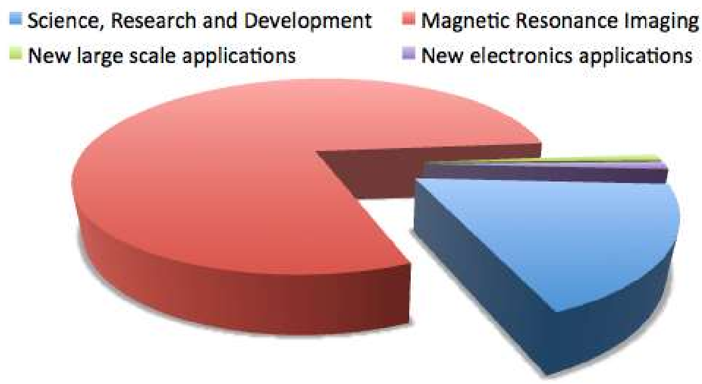

Figure 2. Pie chart of market value for the main applications of superconductivity. MRI systems, NMR and magnets for science and research account for 98 % of the total value.

The superconductor required for the magnet productions quoted above is mainly Nb-Ti. The estimated yearly production for commercial purposes, worldwide, is 600 tons/year, which corresponds to a total value of 200 MUSD/year. This provides enough leeway to sustain the industrial infrastructure required. Still, margin is minimal: Nb-Ti production follows very tight schedule and quality constraints to respond to the demands of medical applications, it is subjected to considerable competition and pricing pressure, and yields small profit margins, typically in the range of 5 %. As an indication of the maturity of the process, the sale price for standard Nb-Ti wires is about three times the cost of the raw material [21]. As to development, there is no push from the healthcare sector to innovate in more advanced materials, as this does not result in more value for the end customer. Most of the R&D goes into maintaining competitiveness.

The other technical superconductor for large scale applications is Nb_3Sn, used for the high-field grades of NMR and laboratory solenoid magnets, crystal growth, and more recently for proton therapy cyclotrons. Excluding Big Science, the yearly production for commercial purposes is estimated at 10 tons/year, corresponding to a total value of 15 MUSD/year. In spite of the small scale, production of Nb_3Sn can be profitable because it tends to use the same industrial infrastructure as for Nb-Ti. Indeed, all successful producers of Nb_3Sn are also producers of Nb-Ti. It is however clear that this market is not sufficient to self-sustain and can exist only in symbiosis with the much larger Nb-Ti production, or at net loss and only for strategic purposes (e.g. the control of a specific wire technology for a profitable application).

Finally, MgB_2 and HTS materials (mainly BSCCO and REBCO, and the emerging Fe-based superconductors), are produced for niche applications, in much smaller quantities. The main lever arm is the promise of growth in the fields of power generation, regulation and transmission, that would require large material quantities. In contrast, ultra-high magnetic field only requires very small quantities of these advanced materials. The estimated combined production is below 1 ton/year. Specifically, in the case of HTS, the technology is much more complex than for LTS, the infrastructure represents a large capital expense (in the range of few tens of MEUR) and requires highly qualified labor. The production of the quoted range of material is only possible thanks to subsidies (funded by national and international programs), or again at net loss because of strategic interest. HTS superconductor cannot be considered a *market* in the strict sense.

Figure 3 reports the split of the value of the LTS and HTS commercial applications and shows the clear predominance of LTS. HTS sales and applications count for less than 1 % of the total market value.

In summary, LTS for medical application is a sustainable and established industrial production, but due to its focus on profitability it has a relatively high resistance to the change and innovation inherent with new materials and manufacturing routes. Other industrial endeavors in advanced LTS and HTS would be suitable to respond to R&D challenges, but they are not sustainable. This results in high volatility of return, unless external institutional or government funding is secured for the full development

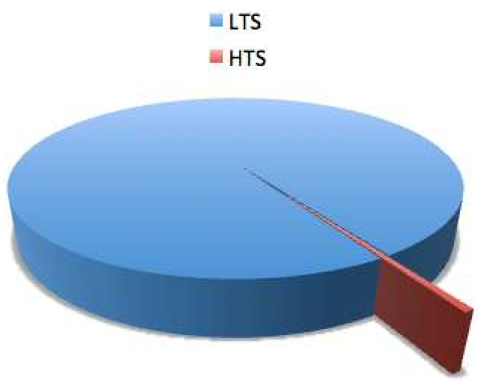

Figure 3. Pie chart of market value of large scale superconducting applications based either on LTS or HTS materials. LTS-based applications account for more than 99 % of the total market value.

The role of Big Science

The need of superconductors for Big Science, materials, cables, magnets, devices and RF, is typically a one-off enterprise, very far from a sustainable industrial production. A representative example is shown in Fig. 4, from [22], reporting the value of superconductor production for Big Science projects of the past twenty years at a selected producer that participated to the major projects LHC, ITER and HL-LHC. The value of the produced material fluctuates with a ten-year periodicity, increasing and decreasing by orders of magnitude over a time scale of two years. Sizeable projects have long lead times, driven by design and funding, during which industry cannot survive in a *waiting mode*. Once funded, the required production scale-up needs to be fast (one to two years), for a relatively short production time (a few years). This climax is typically followed by a dramatic reduction of demand that leads to unavoidable loss of personnel, associated knowledge, and infrastructure. Production forecast is very difficult in such environment, and the process of up-scaling and down-sizing are significant challenges both for the installations (tooling and machines) and personnel. In fact, industry has recently declared the expectation that Big Science should bear long-term cost and risk of R&D.

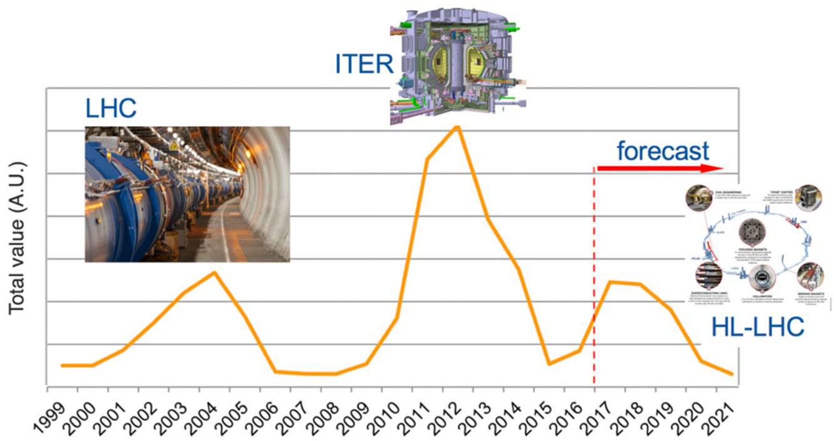

Figure 4. Value of produced superconducting wires for Big Science projects in the past 20 years, and forecast for the coming years. Plotted in arbitrary units, adapted from [22], and based on data of 2017.

The role of academia

Drawn by the scientific challenge of superconductivity, academia (universities and research institutes) is highly interested in the fundamental properties of superconducting materials. The broad focus of present work of leading academic entities is on:

- Discovery of new materials, in the direction of increased critical temperature, with the ideal aim of room-temperature superconductivity;
- Measurement of the fundamental properties of superconductors, in an attempt to understand the underlying physics, such as a closed theory for High Temperature Superconductors (HTS) which is still missing.

This research is naturally biased towards aspects of solid-state physics, whereby superconductivity is often a means to study anomalous electronic properties. Often, in addition, superconductivity is a desirable feature for a specific research domain, such as quantum computing, or advanced detectors for physics. The material quantities involved in this research is typically what is required for microscopy or other analytical techniques. The main research focus is on HTS materials, the most exciting from the point of view of solid-state physics, thus the tools that are available in laboratories are typically for material deposition and analysis of thin layers and small samples. Only a few institutes worldwide have some remaining capability for the realization of demonstration LTS conductors, on the scale of the order of a kg. Indeed, interest in this work, covering metallurgy, has strongly reduced in the past years. The main reason is that seen from the academic point of view this type of work is too applied and production oriented, offering only a modest resonance in terms of scientific production. The institutes with remaining capabilities, mostly because of historical reasons, are the Applied Superconductivity Center of the NHMFL at FSU (Tallahassee, FL, USA), KIT (Karlsruhe, DE), University of Geneva (Geneva, CH), and the Texas Center for Superconductivity at the University of Houston (Houston, TX, US).

4. Adapting to the evolution of the virtuous circle of applied superconductivity: The SC Open Lab proposal

The description of the situation outlined above indicates, in the terms of the virtuous circle of Fig. 1, that academia and industry are retracting their domains of activity: the *bridge* becomes increasingly narrow and difficult to pass. Indeed, we can identify two main risks to the long-term future of superconductors for HEP, namely:

- With the lack of an effective *bridge* between academia and industry, it may not be possible to respond to the continuous advances in the performances of LTS and HTS demanded by HEP, or such a response may be possible only through an exceedingly large funding effort to cover the full cost of the R&D in academia and industry;
- In a market that is not self-sustained, and with the high volatility identified earlier, know-how critical to the realization of high-performance superconductors specific to HEP may be lost.

In this situation, it is mandatory to develop a new mechanism to secure the long-term future of the technology of superconducting materials, wires, tapes and cables for accelerator magnets, and in particular LTS. This is obviously mandatory for the future, where a missing development link would effectively throttle the evolution of superconducting devices beyond the present state-of-the-art. It may be less evident, but these considerations also concern the maintenance and upgrade of the existing installations based on technical superconductors such as Nb-Ti and, in the near future, Nb_3Sn. Clearly, the sought mechanism should not be just limited to LTS materials, but also span the field and include HTS materials so to anticipate on future demands. The proposed solution is to create an *institutional bridge*, founding a laboratory for applied superconductivity that would host critical technology on long term, and act as a perennial connection of academia and industry. We refer to this new actor as an Open Laboratory for R&D on Applied Superconductivity (SC Open Lab), shown schematically in Fig. 5.

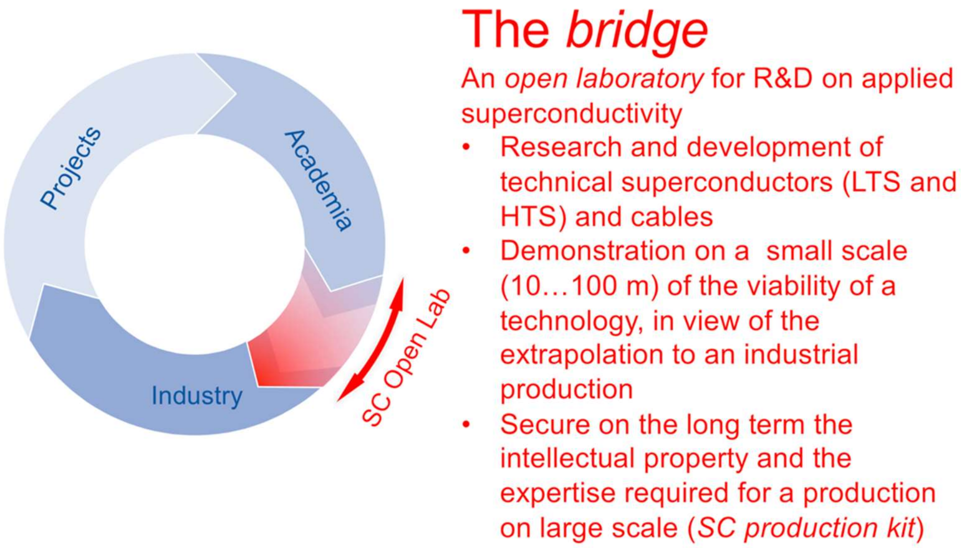

Figure 5. The present state of the *virtuous circle* of applied superconductivity, with retracting academic and industrial participation, and the proposed solution of an Open Laboratory for R&D in Applied Superconductivity that should take the function of the *bridge* (described later).

The SC Open Lab would be devoted to research on technical superconducting materials, conductors and cables. It would provide a facility to try out novel ides, develop architectures, test manufacturing processes on a reduced scale and effective cost, without the overheads of the infrastructure necessary for production on large scale. The small-scale production of LTS technical superconductors and cables would be limited to a few hundred-meter length, as required for demonstration of cables. HTS, once included, would be limited to more modest few ten-meter length due to their inherent complexity. The SC Open Lab would need to be supported by facilities for characterization, measurements and test of technical superconducting materials, conductors and cables.

Besides the main aim of acting as the *bridge* between material R&D and industrial scale production, a SC Open Lab would unite and secure on the long-term the competences and the critical intellectual property in applied superconductivity, as required by HEP (and other large-scale science programs, see later), from material inception to production. At the same time, one such laboratory would be the ideal hub to train the new generation of applied physicists and engineers in applied superconducting material science and technology.

The practical activities of the SC Open Lab would be:

- R&D on compositions and architectures of LTS and HTS wires, tapes and cables, receiving relevant input from the basic material science performed in academia, and realizing demonstration lengths of technical superconductors (e.g. from mono-filaments to final wire and tape demonstrators);

- LTS billet preparation, assembly and processing (chemistry, vacuum, mechanical deformation) for unit lengths up to 100-m scale, relevant for validation as part of a short cable length;
- HTS sample preparation and processing to explore the potential of new materials for HEP applications, for unit lengths up to 10-m scale.

The required infrastructure would resemble the typical set-up of a mechanical workshop in terms of services and general tooling. LTS material processing would require a chemical cleaning facility and clean area for composite billet assembly, including fine powder processing and preparation. The largest tooling would consist of hydrostatic extrusion press and drawing stages (straight bench and bull-block) for mechanical deformation. HTS material processing would require substrate preparation and physical deposition machines. Heat treatment ovens would be required for annealing and reaction steps. The activity of the SC Open Lab should extend to cabling in various forms, as relevant to the application of the superconductors to magnets and other devices. Finally, the SC Open Lab would require supporting material analysis and suitable cryogenic test facilities.

As to the localization of the SC Open Lab, it is important to recall what already mentioned earlier, i.e. that some of the installations, services and supporting activities are already available in the HEP community. While some steps in the material R&D described above do require a dedicated site, existing capability can be integrated and effectively exploited through close coordination. Finally, governance will also require the definition of a suitable and practical method for the most effective operation of the SC Open Lab.

5. The SC Open Lab as an opportunity for collaborations

The need identified in this proposal is not exclusive to HEP. We postulate, rather logically, that other Big Science projects such as thermonuclear fusion (DEMO), or magnet technology for medical applications such as ultra-high-field MRI will benefit from the existence and results of a SC Open Lab. In fact, one such institutionally funded center may in last analysis also benefit industry. Indeed, in several cases industry has difficulties in justifying development when existing technology is sufficient to satisfy present needs (e.g. power applications). A SC Open Lab could provide sufficient advancement and momentum to justify a business case, so that industry would eventually jump on a high-technology avenue parallel to established product. This possible collateral effect may lead to societal impact beyond the science that a SC Open Lab would serve and should not be neglected.

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