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FOLLOW-UP ON TECHNICAL DIVISION R&D RETREAT

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Abstract:

The Technical Division R&D Retreat of January 26, 2016 was a welcome initiative, and a venue to inform our organization of its various areas of research and development for future strategic planning. Themes focused on ongoing R&D efforts and plans for the next few years, including alignment of the research efforts with the P5 and HEPAP Accelerator R&D subpanel recommendations, and adequacy of the research efforts towards future Intensity Frontier HEP facilities at Fermilab, as well as future high energy colliders worldwide.

INTRODUCTION

In the following, we briefly describe what is research in the high field accelerator magnet area, and whenever helpful, making some simple comparisons with SRF.

1. What is "R" in superconducting magnets and conductors? A comparison with SRF cavities

Nb_3Sn and other high field accelerator magnets (HFAM) are very complex objects. It takes months, when well-equipped, to make a 2 m short model with one aperture. It takes one year to make one with two apertures. As a comparison, it takes a few days to make a Nb SRF cavity (at least that what it takes at JLab, whose facilities I was touring last year when visiting for a Lehman's review). The physics science that goes into a HFAM comes from several different disciplines, of which Superconductivity is only but one.

- **Conductor:** High field magnets use Composite materials, i.e. wires made of a number of components, of which the superconductor is only but one. The Nb_3Sn round composite is made of several subelements, each of which include Nb filaments which surround a Tin rod. Each subelement is enclosed within a surrounding barrier (of either SC or non-SC material). Finally, these dozen of subelements are encased within a Cu matrix. Nb_3Al round composites are similarly made, with different materials. The same holds true for round Bi-2212 wires, where however the matrix is made of Silver rather than Cu, i.e. the cost is ~10 times larger. Second generation YBCO is a multi-layered tape 4-12 mm wide and 0.1-0.2 mm thick. It has a dozen layers, of which the superconducting (SC) one is among the thinnest, at 1 μm thick. The round composites Nb_3Sn, Nb_3Al and Bi-2212 all require high temperature reaction in inert atmosphere or oxygen to form their respective superconducting phases. Once formed, these wires are highly sensitive to strain, i.e. their SC properties depend on strain.

Round wires are made into Rutherford cables, which reduce coil inductance. Rutherford-type cables, out of which HFAM are wound, are developed, designed, and fabricated in-house and optimized according to their component wires. The development and test of the cables to be used in magnets aim at reducing degradation of transport current properties, and at quantifying the effect of the transverse pressure conveyed to the cable during magnet fabrication and operation. Short samples of different cables are designed and fabricated within a range of packing factors to compare results of critical current measurements made on round virgin strands with those made on extracted strands and on cables. These studies allow further advances in strand development from industry, and producing the most appropriate cables to be used in magnets. Cables were also designed and produced for a number of Nb_3Sn and Nb_3Al small racetracks, cos-theta dipoles, short and long dipole mirrors, and quadrupole mirrors. Magnets short sample limits are predicted based on witness samples results. Rutherford and 6 around 1 cables were also designed and produced out of Bi-2212 and MgB_2 round wires.

⇨ The science that goes into the conductor is in principle unlimited based on the number of existing parameters. It is therefore important, not to disperse resources, to focus on those conductor aspects that have useful impact on HFAM applications.

- Rutherford cable development requires knowledge of cabling machine tooling design and operation, stress-strain theory coupled to finite element modeling to optimize engineering current density by a careful balance of cable compaction and SC properties, ability to fabricate cables in long lengths, study and optimization of the high temperature heat treatment cycles, study of appropriate cable insulation materials that have to withstand both high temperature and potentially corrosive environments, i.e. study of chemical compatibility among the various component materials, etc.
- Systematic cable degradation studies were performed on Modified Jelly-Roll, Internal Tin and Powder-in-Tube Nb_3Sn Rutherford-type and round cables, as well as Bi-2212 cables. An experimental method was developed to simulate the plastic process undergone by brittle superconducting wires when becoming part of a Rutherford cable, and this process was then extended to finding correlations of intrinsic superconducting properties between cables and experiment.
- A finite element model of composite Nb-Sn wires under plastic deformation was produced and extended to modeling a Rutherford cable. Systematic comparisons between experimental data and model allowed identifying a critical criterion. The model now allows evaluating for each considered cable geometry what is the plastic strain seen by the strands during fabrication, what are the most critical strand locations, and predicting local damage whenever the failure mechanisms of a specific strand technology are known.
- Wire development towards conductor specs needed for HFAM requires sufficient billet processing knowledge to profitably interact with the companies which make the wires. To go further and possibly contribute to wire development, study and characterization of the wires' SC and non-SC properties is paramount to identity useful correlations among the parameters into play. This includes the design what are often unique experimental setups to perform measurements of these important properties, i.e. knowledge of physics, mechanics, electrical and electromagnetic properties, cryogenics, sophisticated DAQ and analysis systems, some more physics to interpret the data, etc. Examples of these setups are in Appendix A.

- The kinetics of phase growth in the Cu-Sn system was measured to provide diffusion coefficients and activation energies of Cu-Sn phases in an ampler temperature range than originally found in literature. The effect of heat treatment on superconducting properties was studied and heat treatment schedules of Nb_3Sn were optimized, obtaining a reduction of heat treatment durations of Internal Tin by 2 to 4 times.
- The highest ambition in this field is to understand the flux pinning mechanisms in the superconductor itself, to possibly control and improve them, i.e. solid state physics and materials engineering/nano engineering. In the last 20 years, a couple of experiments (not models) have been done on thin films. However, any imagined solution has to be implemented in billet manufacturing, which has been so far a practical obstacle.

- **Magnets:** In a sound magnet R&D program, the set of functional specifications (i.e. magnet aperture and length, operating field range and field quality, alignment tolerances, cryogenic and power requirements, magnet quench protection, etc.) for an accelerator magnet are prepared in tight conjunction with accelerator experts. Conceptual design studies of magnets that meet the agreed specifications are then performed. This step goes hand in hand with studies and optimization of the superconductor and cable properties, and evolves and changes along with superconductor progress.

⇨ The science that goes into the magnet is amply multi-disciplinary, and includes applied superconductivity, electro-magnetism, mechanics, cryogenics, heat transfer, power engineering, sophisticated instrumentation, sensors and electronics, etc.

2. Can "R" be measured? It can and it should

We list below examples of breakthroughs and achievements in the HFAM program.

- **Conductor:**

⇨ The development with industry of Nb_3Sn wires that solved the magnet instability problem and are now adopted by CERN and by LARP. Only 10 years ago, none of the existing Nb_3Sn technologies met all of the specifications required for accelerator magnets on the minimum critical current density, J_c, the maximum (effective) size of the subelements, D_{eff}; and the capability to withstand the plastic strains produced by the cabling process. When plastically strained during the cabling process, the subelements deformed and merged together, creating even larger flux jumps instabilities in magnets. This kind of damage in the superconductor causes the magnet to quench before reaching its operation current. In collaboration with Oxford Superconducting Technology (OST), new and better Nb_3Sn wires of the Restacked-Rod Process (RRP) were developed and produced. Eventually 10 T small racetracks and dipoles were able to reach their nominal current both at 4.2 K and at 1.9 K, where stability is further challenged by higher critical currents.

This was done by pioneering studies of "flux-jump" instability that reinstated the role of large D_{eff} in making superconducting wires thermo-magnetically unstable and easy to quench to the normal state, by identifying the process by which magnetic instabilities worsen in cables, and by understanding the importance of providing adequate spacing between filaments to prevent their merging under deformation.

- The impact of this work has been all encompassing for HFAM, i.e. the wire developed by FNAL with OST is the only commercially available Nb_3Sn wire in the world with the appropriate specifications for HFAM.

⇨ The development with Japanese colleagues from NIMS, KEK and industry of Nb_3Al wires, cables and small racetrack coils that established the use of this conductor in magnets for the first time. Nb_3Al is more resistant to strain than any other high field conductor, but requires heat treatment at very high temperatures (1900°C) to become superconducting. This had prevented to make it in a wire with Cu as stabilizer, and this obstacle had slowed down progress in the US. Then in 2005 in Japan, Dr. Akihiro Kikuchi at NIMS developed a method to coat the superconducting precursors with Cu. This stimulated new research and, in collaboration with a Japanese team, we were able to produce Rutherford cables and small magnet coils in excess of 10 Tesla. This was the first time that the Nb_3Al conductor was shown to work in a magnet.

- The impact of this work has been that now the Nb_3Al technology is available for applications where conductor strain is a limiting factor, for instance for fusion magnets. This achievement was recognized by the Japanese "Superconductor Science and Technology Prize".

⇨ The development of an YBCO solenoid that produced a maximum field on the conductor, and record field at FNAL, of 21.5 Tesla. This result came from core program research on High Temperature Superconductors (HTS) towards superconducting accelerator magnets above 20 T for possible Muon colliders. Studies included conductor procurement and characterization, splice studies, magnetic and mechanical coil design, impregnation and insulation studies, instrumentation and testing. Following the result on a single HTS double pancake coil, which had produced a maximum field on the conductor of 18.1 T at 4.2 K (17 T in the bore) when tested up to 13.5 T, a coil made of four double pancakes wound from 4 mm wide YBCO tape with spiral wrap insulation was assembled and tested. A maximum field of 21.5 T (21.2 T in the bore) was produced at 4.2 K on the conductor by testing the 7.5 T coil package at 14 T background field. This corresponded to 92% of the expected short sample limit.

⇨ Co-authoring a flux pinning model for J_c in granular A15 superconductors based on Josephson-coupled arrays and anisotropic flux pinning by grain boundaries, where it is shown that a single mechanism can account for both NbTi and Nb_3Sn scaling laws. This model is a noticeable improvement with respect to the classic 1974 Kramer model in reproducing many of the features seen experimentally and also suggests that the critical current of these materials could be largely improved by nano-engineering.

- This work has led to the development in the last few years of two different electro-chemical deposition techniques, both under US Patent Application No. 62/190, 199, to produce Nb_3Sn coatings on Nb and on Cu substrates respectively, in collaboration with Politecnico di Milano. For the latter technique on Cu substrates, Nb_3Sn is obtained by direct electrodeposition from ionic liquids at 130°C and no heat treatment whatsoever is necessary. Both methods are cost-effectively scalable to complex 3D shapes, which is typical of electrochemical techniques. Whereas the second technique still requires research to optimize film homogeneity, the first technique has applications for:
  * Superconducting Nb_3Sn wires – use thin films to test flux pinning properties of additional elements inexpensively and with fast turnaround;
  * SRF cavities;
  * Multi-layer superconducting magnetic shields.

- **Magnets:** FNAL's role in the US National Magnet Collaboration is perfectly aligned with the latest P5 report, which invokes a very high-energy proton-proton collider as the most powerful future tool for direct discovery in the future of HEP. The P5 recognizes the U.S. as the world leader in R&D on the critically enabling high field SC magnet technology. The HEPAP Accelerator R&D subpanel reiterated to "Aggressively pursue the development of Nb_3Sn magnets suitable for use in a very high-energy proton-proton collider.".

As outlined above, meeting all the necessary specs is required for machine operation. This is a formidable challenge for Nb_3Sn magnets, which so far still have to be used in an actual accelerator. <u>Surpassing the 14 T brick wall is presently considered a crucial goal and inherent demonstration of innovation</u>.

⇨ [2002-2006] The design, development and production of 6 short dipoles of 40-44 mm aperture and 6 mirror dipoles for a VHLC.

- While generating the first reproducible series of 10 T Nb_3Sn magnets in the world, including quench performance and field quality data, the <u>impact</u> of this work has also been to reinstate the role of flux jumps instabilities in magnets.

⇨ [2007-2010] The design, development and production for the LHC upgrades of 7 quadrupoles of 90 mm aperture and 6 quadrupole mirrors with a collar based mechanical structure.

- A nominal gradient of 200 T/m was achieved with accelerator quality field.

⇨ [2007-2011] The technology scale-up and production of 2 m and 4 m long dipole and quadrupole coils in mirror structures.

- The 4 m long quadrupole coil reached short sample limit.

⇨ [2011-2015] The design, development and production of 11 T dipole models, including single-aperture and double-aperture models, which reached a maximum field of 11.7 T.

- This magnet is the world's first twin-aperture accelerator dipole made of Nb_3Sn. Its successful test is an additional demonstration of the maturity of the Nb_3Sn accelerator magnet technology and an important milestone on the way to using Nb_3Sn accelerator magnets in the LHC and in future hadron colliders. The 11 T dipole technology was transferred to CERN, which recently successfully tested a 2 m long double-aperture dipole.

⇨ The development of important tools and materials for use in the Nb_3Sn technology, including cored cables, ceramic, S2 and E-glass insulation, ceramic binder, CTD101K and Matrimid-type impregnations, water-jet and laser-sintering techniques for coil end parts, dipole and quadrupole mirror test structures, etc.

- Mirror test structures operate in similar mechanical and assembly conditions to those of the magnets, and therefore allow advanced instrumentation to be used and reduce the turnaround time of coil fabrication and evaluation, as well as material and labor costs.

- **<u>Other measureables for "R"</u>**:

⇨ HFMA presentations at the biennial Applied Superconductivity Conferences, the biennial Magnet Technology Conferences, the biennial Cryogenic Engineering Conference & International Cryogenic Materials Conference, at the biennial Particle Accelerator Conferences, at the European Particle

Accelerator Conferences, the International Particle Accelerator Conferences, the biennial European Conference on Applied Superconductivity, etc.

⇨ Since 1998, ~200 peer-reviewed publications in Materials Letters, Superconductor Science and Technology, IEEE Transactions on Applied Superconductivity and on Nuclear Science, Advances in Cryogenic Engineering, Nuclear Instruments and Methods in Physics Research, as well as one book chapter, 3000+ citations, h-indexes in our group up to 27. To be compared in the magnet business with: 24 at LBNL, 22 at BNL, 16 at CERN, and 16 at MIT. To be compared in the superconductor business with: 22 at LBNL, 19 at FSU, 18 at BNL, 14 at NIMS, 13 at NIST, and 11 at CERN.

⇨ Since 1998, training of 34 graduate students in physics and engineering during summer internships or Masters and PhD theses.

⇨ Two APS Fellowships in the HFMA program.

⇨ Founding of a new Plenary Special Session on "Applied Superconductivity in HEP" at the "Frontier Detectors for Frontier Physics" (FDFP) Pisa Meeting, 24-30 May 2015, at La Biodola, Isola d'Elba (Italy). A 2-page editorial titled "Frontier detectors for the future" has appeared on this HEP Conference, which takes place only every three years, on the July/August 2015 CERN COURIER.

⇨ Invitations to organize Special Sessions at International Conferences. See for instance the Special Session on "Superconducting Sensors and Instrumentation" organized and chaired at the IEEE International Instrumentation and Technology Conference – I2MTC in Pisa, Italy, May 11-14, 2015, where FNAL Director gave the keynote speech.

⇨ Memberships in prestigious committees (APS Fellowship Committee, Lehman's Reviews, the International Advisory Committee (IAC) of an ICFA Mini-Workshop on High Field Magnets for Future pp Colliders, etc.).

⇨ Requests for plenary and invited talks at International Conferences. The latest was a plenary talk titled "15 Years of R&D on Superconducting Accelerator Magnets at Fermilab or An Example of Education and Innovation in Global Science" at the CAM Graduate Student Physics Conference, 9-12 September 2015, Oaxaca, Oaxaca, Mexico, organized by the APS and co-funded by NSF.

⇨ Invited as Partners by European colleagues to participate to European Projects within the Marie Curie program. A "Research and Innovation Staff Exchange" Project was submitted, and an "Innovative Training Network – European Training Network" Project is under preparation.

⇨ An invited review paper titled "Research and Development of Nb_3Sn Wires and Cables for High-Field Accelerator Magnets" will appear in the spring in the special issue of the IEEE Transactions on Nuclear Science (TNS) in commemoration of the 50^{th} anniversary of the original Particle Accelerator Conference.

3. Where funds are needed for HFAM? A comparison with SRF cavities

In magnet R&D, quality design and also quality control of each of the dozens of delicate steps required during development and fabrication are of paramount importance for the success of magnet models. Both design and quality control require sufficient personnel with adequate qualifications.

Presently, performing R&D on conductor, designing and fabricating cable, and developing, procuring parts and fabricating magnets, all has to be done on the same yearly budget that the SRF R&D receives just on materials R&D. Unlike SRF, magnet funding does not include any money from LDRD's. A growth in funding for magnet R&D is clearly consistent with recommendation 5f of the HEPAP Accelerator R&D subpanel, i.e. "Significantly increase funding for superconducting accelerator magnet R&D in order to support aggressive development of new conductor and magnet technologies.".

4. The lesson learned from SRF cavities on the strategic importance of internal support of R&D achievements

Based on how profitable FNAL strong support of the SRF materials R&D has proven to be with both DOE and outside institutions, we believe that part of the problem has been that our program had not gotten sufficient attention from the lab before. For example, we never heard for magnets anything like Erk Jensen's public statement during his FNAL colloquium that he knew that FNAL has SRF cavities with larger gradients. We feel confident that with our new Director and Division Management, stronger support will make a difference in how our program is perceived, both at CERN and at DOE.

CONCLUSIONS

The world revival that we are witnessing for Nb_3Sn, both in SC magnets and SRF cavities, is offering the US an immense opportunity. After investing millions of $ in this technology for the last decade and more, we should want to preserve and cultivate our well-deserved leadership. This would, among other things, also leverage CERN monopoly in HEP and make the US as relevant as possible in critical technologies.

On the other hand, present HTS materials like Bi-2212 and REBCO are still in the prehistory for applications. This should not be surprising when one thinks that it took decades to make NbTi – a simple, ductile, binary alloy – work for magnets. Bi-2212 is the least advanced of the two HTS conductors mentioned above, with the strongest strain sensitivity of any other high field superconductor. Other examples of lack of results for Bi-2212 is the still unproven capability of oxygen reaction forming the superconducting phase in cable packages, and the lack of a well-proven insulation for cables with adequate properties for magnets, including chemical compatibility with the Bi-2212.

APPENDIX A - INNOVATIVE SETUPS DESIGNED FOR RESEARCH

- [1997-1998] Design and commissioning of probes and sample holders for critical current strand tests in liquid Helium, after developing and solving a physical model for high current copper leads, to be operated up to 17 T in the first OST magneto-cryostat.
- [1998-1999] Supervision of graduate student in the design and commissioning of a balanced coil magnetometer to measure superconductor magnetization.
- [2000-2001] Supervision of graduate student in the design of a device to test critical current sensitivity of superconducting cables to transverse pressure, commissioning it and optimizing

sample impregnation fixtures and techniques.

- [2002-2003] Supervision of graduate student in the design and commissioning of low resistance probes and sample holders for instability studies in superfluid Helium.
- [2002-2004] Design and commissioning of a superconducting transformer for Nb_3Sn cable splice testing, and design upgrade from 21 kA to 28 kA in secondary current for Rutherford cable tests at self-field.
- [2005-2006] Design of a variable temperature insert and implementation of a fast data acquisition system for the second OST magneto-cryostat.
- [2005-2007] Development of sample holders to measure critical current of High Temperature Superconducting wires. Design and commissioning of sample holder to measure the angular dependence of the critical current with respect to magnetic field for anisotropic 2G YBCO wires.
- [2006-2007] Automation of the data analysis and acquisition of both magneto-cryostats of the Superconducting R&D Lab.
- [2007-2010] Design, assembly, commissioning and calibration of a 14 T/ 16 T Rutherford cable test facility with bi-filar sample and a SC transformer, which provides sample currents up to 30 kA. A sample impregnation technique was developed, and Nb_3Sn impregnated and non-impregnated cables were successfully tested up to 14 T.
- [2009-2010] Design, assembly, commissioning and calibration of a Walters' Spring type probe for strain sensitivity studies of critical current densities in superconducting wires.
- [1998-2015] Design, assembly and commissioning of a number of RRR probes for wire and bulk samples.
- [2014-2015] Design, assembly and commissioning of Hall probe system to measure magnetic shielding capabilities of superconducting tubes.
- [2001-to date] Commissioning of a Rutherford cabling machine, supervision of its electronic synchronization to produce cables within ample lay angle range, commissioning of upgraded cable turk-heads to improve cable quality, and design of mandrels to optimize cable performance.