Magnetic Resonance Imaging: Its 20th Century Origins and 21st Century Opportunities

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Superconductivity and the concept of the nuclear atom were both introduced in 1911 and the word proton was proposed for the hydrogen nucleus around 1920. The possibility of a proton magnetic moment was suggested in 1924 but the associated magnetic fields were was far too feeble to be observed macroscopically. The Dutch physicist C. J. Gorter suggested a resonant technique for detecting nuclear magnetism in bulk materials in 1936 but this was not demonstrated successfully until just after World War 2. This led to the standard chemistry technique of nuclear magnetic resonance (NMR). The possibility of scaling up this test-tube technology to permit magnetic resonance imaging (MRI) of human beings was suggested the early 1970s and was demonstrated in human beings beginning in 1976 using low fields (roughly 0.1 tesla) and non-superconducting magnets. The field was revolutionized by the 1982 introduction of whole-body superconducting magnets operating at 1.5 tesla. Scanners operating at this field strength have dominated this new imaging modality until the present time. Between the early 1980s and 2011 approximately 0.5 billion clinical MRI studies, mainly using signals originating in the protons of water and fat molecules, have been performed worldwide. MRI has become a major practical application of superconductivity and cryogenic technology. In 2001 a panel of practicing physicians selected MRI, along with computed tomography, as the most significant technical innovation in patient care during the previous 25 years. MRI continues to generate intense clinical research activity, including the introduction of whole-body magnets operating up to and well above 7 tesla and promises to be a continuing source of new medical capabilities.

Superconductivity
Yesterday – Today – Tomorrow

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2011 witnesses the 100th and 25th anniversaries of the discoveries of low- and high-temperature superconductivity, respectively[1], which arguably rank amongst the ultimate in elegance and profundity, experimentally and theoretically, of all condensed matter physics advances in the 20th century. Indeed, the BCS framework that underlies all known present superconductors appears to reach deep into the interior of neutron stars as well.

Steady progress in the application of superconducting materials to power and electronics devices has aided in the exploration of physics beyond the Standard Model, the search for the origin of Dark Matter, and will play an important role in providing energy technologies for adaptation to Climate Change. Best known to the general public has been the development of a number of vital medical imaging techniques which only superconductivity could have enabled.

Our title…Yesterday, Today and Tomorrow…has been "borrowed" from the landmark 2000 review paper by the late Nobel Laureate, Vitaly Lazarevich Ginzburg. In this talk, we will very briefly outline the Story of Superconductivity…materials, theory and its application, past and present, and especially speculate on the possibility of finding future materials that operate at room temperature and beyond.

[1]An extensive literature anthology on major developments in superconductivity to date can be found at http://www.w2agz.com/SuperWiki.htm.

Cryogenics for Superconductors: Refrigeration, Delivery, and Preservation of the Cold

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Applications in superconductivity have become widespread due to advancements in cryogenic engineering. In this paper, the history of cryogenic refrigeration, its delivery, its preservation and the important scientific and engineering advancements in these areas in the last 100 years will be reviewed, beginning with small laboratory dewars to very large scale systems. The key technological advancements in these areas that enabled the development of superconducting applications at temperatures from 4 to 77 K are identified. Included are advancements in the components used up to the present state-of-the-art in refrigeration systems design. Viewpoints as both an equipment supplier and the end-user with regard to the equipment design and operations will be presented. Some of the present and future challenges in these areas will be outlined.

How superconductors became practical: A walk through the history and science of flux pinning.

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Since the investigation of flux pinning in superconductors in the early sixties, a considerable amount of work has been accumulated in this field to understand the underlying principles of fundamental interaction mechanisms of flux lines with pinning defects as well as the summation problem for a well characterized arrangement of flux lines. Pinning is and remains one of the essential problems to tailor and optimize the current carrying capability of practical low-T_c or MgB_2 superconductors and to make them viable for application. For high-temperature superconductors it is even more challenging because now one has to deal with highly anisotropic superconductors with complex flux and flux line structures which strongly govern the essential irreversibility fields and with a pinning landscape which can be tailored to a large extent to improve engineering critical currents. The challenge is to understand the mechanisms which govern current limitation and to further increase flux pinning and critical current densities in the presently known HTS materials at the operating fields and temperatures, e.g. for devices in electrical and power engineering, to pave the way for a widespread application.

A Century of Superconducting Technology

Martin N Wilson

Although it may seem like pure serendipity, the discovery of superconductivity by Heike Kammerlingh Onnes in 1911 was actually the culmination of his systematic work over many years on the essential technology of cryogenics. In 1894 he liquefied air in the laboratory at Leiden, followed by hydrogen in 1906 and helium in 1908. The behaviour of resistivity at very low temperatures was a topic of great scientific interest at the time and superconductivity soon emerged from those measurements – an early example of basic science being fundamentally changed by the development of an enabling technology. Shortly afterwards, Kammerlingh Onnes speculated on the possibility of building a superconducting magnet, but was disappointed to find that superconductivity in the metals he had measured: mercury, tin and lead, was quenched by quite modest fields. Despite many advances in the theory, it was to be another 50 years before superconducting technology really got off the ground with the discovery, largely in the USA, of a new class of hard 'type 2' superconductors which could retain their superconductivity up to very high magnetic fields. Starting with small solenoids for laboratory use, a new industry was borne, which then expanded into larger scale applications like NMR spectroscopy, clinical MRI and large particle accelerators. The discovery of High Temperature Superconductivity, just ¾ of a century after Leiden, promised a further expansion of the industry into new application areas, but this hope has yet to be fulfilled. Recently however the performance of HTS conductors has dramatically improved with the advent of oriented thin film YBCO tapes. There are good reasons for hoping that these new conductors will open up new applications for superconductivity – perhaps in that most obvious area for the abolition of Ohm's law: electrical power engineering.

Electric Power Applications of Superconductivity

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From the initial discovery of superconductivity in 1911, electrical engineers have sought to take advantage of special features superconducting materials such as zero resistance and high current density. The expectation has been that these devices will be lighter, smaller, and more efficient than conventional equipment. In concept replacing wires made of a conventional conductor such as copper with superconductors is straightforward. In practice, there are many hurdles to be overcome in developing practical superconductive power applications. In this paper we will discuss two specific challenges. The first has to do with maintaining an operating temperature at or below the temperature of liquid nitrogen. Because cryogenic systems are always an addition to the power applications themselves, these systems must meet reliability and availability requirements that are better than those of conventional power equipment. In addition, since reducing cost and improving overall system efficiency are major goals, the cryogenic system must be both inexpensive and as efficient as possible. The second is the need for the superconducting materials to meet special requirements, such as very low ac losses, stability against a transition to the normal state, resistance to large and cyclical stresses, etc. Cryogenic and material requirements and practical solutions for several power applications including cables, fault current limiters, motors, generators, and SMES are discussed.

Research sponsored by Advanced Energy Analysis and by the U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, Advanced Cables and Conductors Program, under contract No. DE-AC05-00OR22725 with UT-Battelle, LLC, and.

Superconducting generators for large wind turbine: design trade-off and challenges

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As the wind power generation industry goes towards more off-shore wind farms, larger turbines generating 10 MW or more are needed to keep the cost of electricity competitive. Such large turbines located in remote areas must exhibit outstanding reliability in order to limit the cost of maintenance and therefore should not rely on gearboxes. Because of the poor scaling of conventional direct drive generators, they cannot be deployed cost effectively in large power turbines leaving superconducting generators as the only viable option. Using a superconducting generator in a direct drive 10 MW wind turbine can reduce the mass of the nacelle by a 2 to 4-fold compared to state-of-the art permanent magnet generators, depending on the type of generator configuration. Wind generators represent an ideal application for superconducting machines; the very large torques and low speed taking full advantage of their unmatched specific torque scaling. However, some critical technological trade-offs need to be performed in order to obtain a reliable and cost effective system. This paper presents a review of the ongoing superconducting generators for large wind turbine development efforts and gives an overview of the major design challenges including the choice of generator topology, conductor and associated cryo-cooling system. The different trade-offs related to technological choices, engineering and cost are also discussed.

High Temperature Superconductors Realizing Systems

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After the industrial materialization of high temperature superconducting (HTS) wire in 2004, a variety of HTS application projects for constructing and evaluating real-sized prototypes started. Annual production of HTS wire is reaching to 1,000 km/year level. Also, the product of critical current by unit length of wire, which means application probability, reached 300,000 Am at the mass production level. HTS application is mainly in five fields; cables/energy field, transportation, ICT field, manufacturing and, medical/ analysis. Current leads and magnetic billet heaters are already commercial products. Also, cables, motors, MRI, NMR and fault current limiters are fabricated and are under evaluation at their real-sized system. Present status of these application systems and future perspective are introduced.

Cryogenic Measurement Foibles

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Failures are sometimes more instructive (and entertaining) than successes. Usually these do not get publicized, and, as a result, they are often repeated. In that spirit, I share a few of my prime examples, as well as the lessons learned. Based on the text Experimental Techniques for Low Temperature Measurements,[1] a brief overview is given of how (and how not) to design a measurement cryostat, as well a few of the obvious (and less obvious) experimental pitfalls to be avoided. Materials selection is one of the more critical elements, and in that vein, a free website (www.ResearchMeasurements.com) has been created with over ten thousand annotated cryogenic materials data entries that can help simplify this task.

[1]Oxford University Press 2006, 2007

The Use of Cryogenics in Space Transportation

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Cryogenics plays a large role in our access to and utilization of space. The high efficiency of cryogenic propulsion is critical to enabling space missions, in particular missions beyond low Earth orbit. Liquid Oxygen/Hydrogen propulsion has been used by Apollo to send Astronauts to the moon, by the Space Shuttle to enable on-orbit servicing, by Delta IV to deliver critical national security payloads and by Atlas launching nearly every American deep space exploration probe, including the Pluto New Horizon mission, the fastest object to leave Earth's gravity well. The cold temperatures of cryogens make them the ideal coolant for scientific mission such as Spitzer and Gravity Probe B so critical in enhancing our knowledge of the Universe.

From the beginning space pioneers recognized the need to enhance our ability to handle cryogenic propellants in space. Early rocket scientists utilized the Saturn S4B and Centaur stages to enable on-orbit experimentation with cryogenic propellants learning about low acceleration propellant handling and heating. Despite 40 years of experience using cryogens in-space, on-orbit cryogenic fluid management is still in its infancy. To support the demanding missions planned for the future we will need to be able to efficiently store vast quantities of cryogens for month's to years, transfer these cryogens into cryogenic propulsion stages, design lighter and more efficient cryogenic systems as well as manufacture cryogens at the moon, Mars and other locations through the solar system. Experimenting with on-going cryogenic launches as well as proposed ground and flight experiments will enhance our ability to work with cryogens to support a very exciting future in space promising new discoveries and renewed human exploration.