ilc NewsLine

26 February 2009

Past successes in superconducting RF are a good omen for the ILC

Hasan Padamsee and Charles Reece highlight successes in the evolution of superconducting RF technology and look to ILC and future developments.

One of the high-value R&D programmes for the ILC is to reliably reach gradients of 35 Megavolts per metre (MV/m) in one-metre long (9-cell, 1.3-Gigahertz) niobium cavities, the heart of the main linac. More than a dozen such cavities have demonstrated gradients between 35 and 40 MV/m at DESY, and more recently at Jlab. The challenge is to hit such performance levels nearly every time, and with nearly every cavity! This means that we need to conduct some good science to understand the basic nature of the gradient limits, and clever engineering to invent methods to overcome these.

Good science and engineering are precisely the paths that the superconducting radiofrequency (SCRF) community has followed over the last few decades to steadily advance performance levels in multi-cell structures ever since the inception of the field in the 1960s. Unfortunately the early excitement abated with a first dose of reality. At the advent of SCRF, research groups at Stanford, Siemens and Cornell attained great results with available niobium, demonstrating by mid-1970 surface fields corresponding to gradients of 25-35 MV/m in single-cell cavities at X-band frequencies (8-10 GHz). However, these performance levels fell apart at the frequencies below three gigahertz. The primary roadblock was multipacting (the spontaneous resonant production of electrons), limiting the performance of 1.3-GHz cavities to 2 to 4 MV/m. Research into the physics clearly showed that multipacting field levels scale with the radio frequency, so that the X-band cavities of the early days had been fortuitously exempt of this effect.

The next three decades saw several layers of gradient problems uncovered, the underlying physics understood and solutions developed to defeat them one by one. Performance ratcheted up at a steady pace, as did accelerator applications. A watershed event was the development of a new cavity shape, the anti-multipacting spherical (and elliptical) cavity of the 1980s. The electromagnetic fields of the curved cavity wall force electrons to the equator where electron multiplication is arrested. With multipacting reliably overcome, thermal breakdown of superconductivity became the next limiting mechanism, at 4 to 6 MV/m. Local heating at surface imperfections led to thermal runaway and a quench of superconductivity. The cure was to switch to high-purity niobium – niobium with a high residual resistance ratio (RRR). With the co-operation of industry, this ratio improved by an order of magnitude and cavity gradients rose on average by a factor of three. Another cure for thermal breakdown was to sputter a film of niobium only a few microns thick onto a copper cavity substrate of high thermal conductivity, which also had the benefit of reduced material costs – especially for low-frequency (0.35 GHz) cavities.


Six modules installed in FLASH at DESY have 48 nine-cell cavities operating between 20 and 25 MV/m. The nine-cell TESLA cavities inside the module were fabricated from RRR=300 niobium and prepared by advanced methods of electropolishing and baking.

Major applications of RF superconductivity then took off and pushed the energy frontier in storage rings, with TRISTAN at KEK, HERA at DESY and LEP-II at CERN. At the cutting edge of nuclear physics, Jefferson Lab installed the recirculating linac, CEBAF, while at the luminosity frontier CESR at Cornell and KEK-B in Japan applied niobium cavities to store ampere-sized beams. Superconducting linacs powered FELs at Jefferson Lab and at JAERI in Japan. Overall, one kilometre of SCRF cavities provided a total 5 GeV of energy.

With the corresponding rise in surface electric fields, electron emission became the next significant limit to gradients, at 10-15 MV/m. Global R&D revealed microparticle contamination to be the dominant source of field emission. Micron and sub-micron sites were captured inside cavities using thermometry, and subsequently photographed with electron microscopes. The battle to defeat field emission gave rise to better preparation techniques such as powerful surface scrubbing with high-pressure water rinsing, and assembly in dust-free, Class-100 clean rooms. With these breakthroughs, cavity gradients in accelerator assemblies climbed to 20 MV/m.

But the war against quench and field emission was not completely won. For any given preparation protocol, the probability of encountering field emitters and quench-producing defects grows with cavity area, demanding strict control of processes, especially for a large ensemble of structures. Incidentally the statistical effect provided favorable conditions for the single-cell X-band cavities of the 1970s to reach high fields with areas of square centimeters compared to multicell gigahertz-accelerator cavities with surface areas in the order of square metres.

Nevertheless, the continuing gradient advance spurred new applications of accelerators for materials science, with the FLASH light source at DESY in Hamburg, operating at 20 MV/m, and the Spallation Neutron Source (SNS) in Oak Ridge, operating at about 15 MV/m, adding another 2 GV.

The quest for higher gradients continued into the new millennium. At levels above 20 MV/m, RF losses rise exponentially with the strength of the electric field. The physics of these increased losses is still under active investigation worldwide, but pragmatic countermeasures are already in place. Electropolishing has replaced standard chemical etching to obtain a smoother surface with reduced microscopic field enhancements, followed by mild baking at 120 °C for two days. Solid state and surface science research continues to understand the physics of these cures.

Niobium cavities with surface areas of square meters regularly reach 25-40 MV/m with tolerable losses. Raising the bar to hit 35 MV/m or more every time would be a great benefit for the ILC. With concerted world-wide efforts to push back on field emission and quench sources, there are already encouraging signs for higher gradient yield. Microscopic studies of surfaces show sulphur particles as the field emission culprits often left over as residue from electropolishing. The discovery generated multiple efforts for better final treatments, such as ultrasonic degreasing and ethanol rinsing. The incidents of field emission limits are coming down. Quench-producing defects on the low-performing cavities are pinned down with classical thermometry and second sound waves in superfluid helium (see readmore_20080626_ftr1.html). Advanced optical tools to examine the inner surfaces of nine-cell cavities are revealing correlated features such as "pits" and "bumps" near welds. Intense efforts are underway at many labs to trace down the origin of such features in the material or in the preparation steps. With tight control of fabrication and processing steps, the prognosis is good.

One alternative under exploration is to use large-grain niobium, cut directly from the ingot to avoid defects, combined with the simpler standard chemical etching procedure instead of electropolishing to yield comparably smooth surfaces. The final baking time can also be reduced from 48 to 12 hours. Experts around the world are working hard to validate these expectations.

These successes demonstrate how R&D in SCRF science and technology has pushed towards ever higher gradients. New applications have continued to benefit from the steady progress, as will the ILC. Beyond the 7 GV already installed, another 20 GV of SCRF cavities are foreseen for the European XFEL at DESY. A large number of new applications to high-intensity proton sources, free-electron lasers and energy recovery linacs for light sources and energy recovery linacs for nuclear physics are under study.

Beyond achieving consistent high-yield performance above 35 MV/m for the ILC, efforts continue to push the gradient frontier towards 50 MV/m – already surpassed in single-cell cavities operating at gigahertz frequencies, with innovative shapes to reduce the peak surface magnetic field. Translating the spectacular results to a nine-cell structure demands great care and dedication in parallel with the concerted effort to improve the gradient yield at 35 MV/m.

Thus the past four decades of successes in using superconducting RF technology in a variety of accelerator applications are the result of steady progress in understanding the science behind the gradient limitations and in developing effective countermeasures. It has not been a black art with progress only by trial and error, as might have been perceived from a distance. Encouraged by these successes, the worldwide SCRF community is expanding with re-invigorated efforts. Materials scientists and process engineers are joining us enthusiasts in exploring new techniques and new materials to pave the road for more powerful, compact, and efficient accelerators of the future.

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