Field Emission Suppression in High-Gradient SRF Cavity Systems

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Introduction

The superconducting radio frequency (SRF) technology that is flourishing today has broad applications worldwide for current and future accelerator-based sciences. These include nuclear physics (for example ATLAS at ANL, CEBAF at TJNAF, FRIB at MSU, EIC at BNL), elementary particle physics (for example BEPC at IHEP, Super-KEKB at KEK, LHC at CERN, PIP-II at FNAL, ILC in Japan, CEPC in China, FCC at CERN), neutron sciences (for example SNS at ORNL, ESS in Europe), as well as photon-based material sciences (for example E-XFEL at DESY, LCLS-II at SLAC, SHINE at SARI). Given this current and emerging accelerator facility landscape, the well-being of many fields undoubtedly depends on the SRF technology, which has been increasingly recognized by the fields and funding agencies nationwide and worldwide. The recent history has witnessed rapid growth in SRF science and technology. In turn, it has led to plans of adopting the SRF technology at much larger scale such as ILC and ultimately transferring it for industrial applications.

A key challenge the SRF field is facing today is how to reliably control and cure the long-standing problem of field emission from particulate contamination. The current technology has been optimized over time and individual cavities can be qualified to high gradient of 35 MV/m with 90% yield in laboratory environments [1]. European industry delivered 800 test-ready cavities for the X-FEL project, providing a strong hint that these tricky procedures can be ultimately transferred from laboratory to industry. But the problem is that a final state cleaning technique does not exist. As a result, particulates generated from steps connecting individual cavities into a cavity string are left behind and carried over from the SRF cryomodule production line to the cryomodule test facility and ultimately to the site of SRF system operation. These particulates may then become field emitters if deposited directly onto the cavity surface, degrading the cavity gradient performance. Even remote particulates may be transported over to the cavity surface causing further loss in usable cavity gradient to below the specified operational value of the SRF system. For the 80 cavities installed in CEBAF for its energy upgrade, the field emission onset gradient degraded on average by 8 MV/m going from their vertical qualification testing to cryomodule commissioning in the tunnel. Lessons learned from CEBAF 12 GeV upgrade were applied for the most recent cryomodule production run at JLab for the LCLS-II project, resulting in clear improvement, but still 23% cavities were loaded by field emission at the specified operation gradient during cryomodule qualification testing, despite rigorous control in releasing only field-emission free individual cavities for cavity string assembly [2]. It is evident that even with today’s best available practice for cavity string and cryomodule assembly, there is still a large chance of introducing particulates onto the final cavity surfaces causing significant penalty in the usable gradient. Therefore, a new technique is needed for the final cleaning of the cavity string in a completed cryomodule. Interests of raising the operation SRF gradients above 40 MV/m [3] motivates well the need for field emission suppression.

Advanced Field Emission and Dark Current Measurements

Field emission instrumentation development at Kyoto University

Knowing the distribution of X-rays generated by field emissions is useful to locate suspicious cells or cavities in cryomodules. A handy instrumentation tool which should be helpful for this purpose is under development [4]. The multiplexing technology and flexible printed circuit enable easy cabling with less wires and easy installation. In addition to X-rays, temperatures on cavity surfaces and other parameters such as magnetic field and second sound detection are also under investigation.

Development of field-emission and dark current instrumentation at SLAC

For the LCLS-II project, SLAC is now installing a 4-GeV, 120-kW superconducting linac driven by continuous RF at 1.3 GHz. A laser and a normal-conducting photocathode gun produce photocurrent bunches at variable rates of up to 1 MHz. Rapid response to beam loss is essential to protect against damage both from this photocurrent and from field emission in the high-gradient SRF cavities. Long beam-loss monitors using radiation-hard quartz optical fibers [5] are being installed in 200-m segments along the full length of the machine, from the gun to the beam dumps. As a beam-loss shower passes through a fiber, a portion of the resulting Cherenkov emission is captured in a fiber mode and transmitted to a photomultiplier at one end. A test at JLab of a fiber running just outside a CEBAF cryomodule showed sensitivity to field emission along the fiber's length. For photocurrent, loss locations can be identified by the signal arrival time, but for field emission, localization takes advantage of the signal's sensitivity to changes in cavity gradients.

The SLAC S30XL project will also be able to extract dark current that is captured in RF buckets between the primary LCLS-II FEL bunches which are separated by 1,400 1.3 GHz RF buckets after the beam has been accelerated to 4 GeV. This will allow a 6-D reconstruction of the dark current phase space and may provide additional information to understand the scaling and dependence of the dark current capture [6].

New Field Emission Suppression Technologies

Wiping technology development at KEK

It has been observed that many small particles emerge on the electropolished niobium surface. Those particles, typically a few microns in size, are made of sulfur and fluorine elements and niobium oxide. Ultra-sonic treatment and high-pressure-water-rinsing are the tools to remove them, but sometimes not perfectly. Ultra-sonic treatment should be re-considered to optimize its power, process time and geometrical arrangement [7]. Additional treatment after electropolishing process is proposed to use direct wiping by fine-fiber cloth with surface-active agent (detergent). For a 9-cell cavity, end group regions can be easily wiped by hands. As for the iris region of inner cells, a special tool is under development at KEK to reach every iris and to wipe them by motor-driven rotating fine-fiber clothes.

Snow cleaning at DESY

Another promising technology for suppressing field emission is CO2 snow cleaning. DESY is operating a respective facility since long. During the last decade it was extensively used for normal-conducting RF gun resonators and other RF devices like transverse deflecting cavities used close to superconducting accelerator modules. In general, there is large interest to further develop cleaning techniques usable for all components which are installed in direct neighborhood of superconducting accelerator structures. Cleaning of SRF structures itself has been tried but requires further action. Of large interest is the cleaning of SRF gun cavities. DESY intends to define a respective program.

Liquid nitrogen cleaning development at JLab

JLab will develop the high pressure liquid nitrogen jet cleaning [8]. The work will significantly advance the state-of-the art accelerator capabilities, including new facilities and, as a test bed, most immediately improving the performance of CEBAF. This research and development will take a novel high pressure liquid nitrogen cleaning technique from conceptual design to a full scale prototype device and process applied to a CEBAF cryomodule over 2 years. The prototype aims to recover a contaminated cryomodule to meet its original gradient specification, without the need for tearing it down and then reassembly. Ultimately, we anticipate introducing a transformative final cleaning tool for cryomodule production so as to make an immediate impact in the field. Jefferson Lab will form partnership with Conco Services LLC, which wishes to become a licensee of such a tool and process for the treatment of cryomodules in national labs, as well as in the industry in the future.

Dust Particle Mitigation in SRF Components Assembly and SRF Accelerator Systems

Field emitter particulates generated during the SRF cavity and cryomodule assembly procedures are so tiny that they cannot be seen by naked eyes. This makes the cleanliness control a challenge. KEK is filling this gap by using vacuum particle counting technology to visualize the movement of harmful particulates inside vacuum components, such that the assembly equipment (for example the slow pumping/venting system) and procedures to be well defined for repeatable cleanliness results. As a result, we expect it will become possible in the future that the dust contamination problem is significantly reduced and field emission free superconducting cavity systems are installed for beam acceleration.

A major gap exists in understanding of field emitter particulate movement in long SRF linacs, such as in CEBAF where a slow loss of the machine energy reach is observed due to particulate field emitters. Insights are needed toward the preservation of the cavity operational gradient. This is a problem of interest for the field as we stand at the current junction of time with several SRF machines being constructed or planned including LCLS-II, EIC in the US and ILC in Japan. JLab is pursuing the design, test and field implementation of a novel particle counter at CEBAF SRF linacs for real-time and non-interruptive monitoring of particulate movement.

References

1. R. L. Geng and A. C. Crawford, "Standard Procedures of ILC High Gradient Cavity Processing at Jefferson Lab", in Proc. 15th Int. Conf. RF Superconductivity (SRF'11), Chicago, IL, USA, Jul. 2011, paper TUPO015, pp. 391-393.
2. M. Drury, LCLS-II Cryomodule Acceptance Testing – Results, SRF Hot and Cold Topics, 20 Apr 2020, unpublished.
3. A. Grassellino et al., "Perspectives on International Superconducting Linear Colliers (ILC) to the Next Century Part B: ILC Energy Upgrades to 3 TeV and Beyond," Snowmass 2021 LoI, SNOWMASS21-AF4_AF0_Hasan_Padamsee-054.pdf
4. Z. A. Conway, M. Ge, and Y. Iwashita, "Instrumentation for localized superconducting cavity diagnostics", Superconductor Science and Technology, 30, 034002 (2017).
5. A.S. Fisher et al., "Beam-loss detection for the high-rate superconducting upgrade to the SLAC Linac Coherent Light Source," Phys. Rev. Accelerators and Beams 23, 082802 (2020).
6. N. Toro, T. Raubenheimer, et al., "Sector 30 Transfer Line and Linac to End Station A: Community Statements on Science Opportunities," SLAC-Report-1147 (2020).
7. V. Chouhan, et.al., "Chemical analysis and field emission study of electropolished niobium surface with numerous synthesized niobium oxide particles", submitted to Applied Surface Science, Aug. 2020.
8. Provisional patent pending. "Method and Apparatus for Removal of Microscopic Contaminant Particulates by High Pressure Liquid Nitrogen Jet Cleaning from Superconducting Radio Frequency Cavities and Cavity Strings", application submitted Jan. 2020.