WORLD-WIDE EXPERIENCE WITH SRF FACILITIES

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Abstract

The speaker will review and analyze the performance of existing SRF facilities in the world, addressing issues of usage and availability for different customers (HEP research, material sciences, ADS). Lessons learned should be summarized for proposed future facilities (ILC, Project X, Muon Collider).

INTRODUCTION

The first use of superconducting cavities for accelerating beams was at HEPL, Stanford University in the early sixties. Rather quickly, other laboratories followed suit, notably the University of Illinois at Champagne, Urbana and Cornell University. There were two main uses, which still persist today. The first is to provide accelerated particles as an injector or for fixed target experiments. The second is to maintain circulating beams, either for synchrotron light sources or for colliding beam experiments. Given the differing requirements, these two uses led to rather different implementations and, in particular, different average operating gradients.

A second difference in the implementation is the speed of the particle being accelerated. Electrons are sufficiently relativistic at low beam energies (>~5 MeV) that cavities designed for relativistic beams can also function acceptably at low energy. This is not the case for protons or ion accelerators so, until recently, copper cavities were used to cover the first ~100 MeV. Superconducting cavities are now also being proposed to cover this energy range as well using a series of superconducting cavities, each of which is matched to the particle velocity.

PERFORMANCE

The early cavities could only be operated at a gradient of a few MeV/m, while the recent cavities produced for the International Linear Collider (ILC) are able to operate above 30 MeV/m. Figure 1 (courtesy of Rong-Li Geng, Jefferson Lab) shows the evolution of the cavity gradient as a function of time. SRF cavities are further differentiated between CW cavities and pulsed cavities. Higher gradients can be achieved in routine pulsed operation than CW operation for two reasons. Some of the gradient-limiting phenomena can take a finite time to

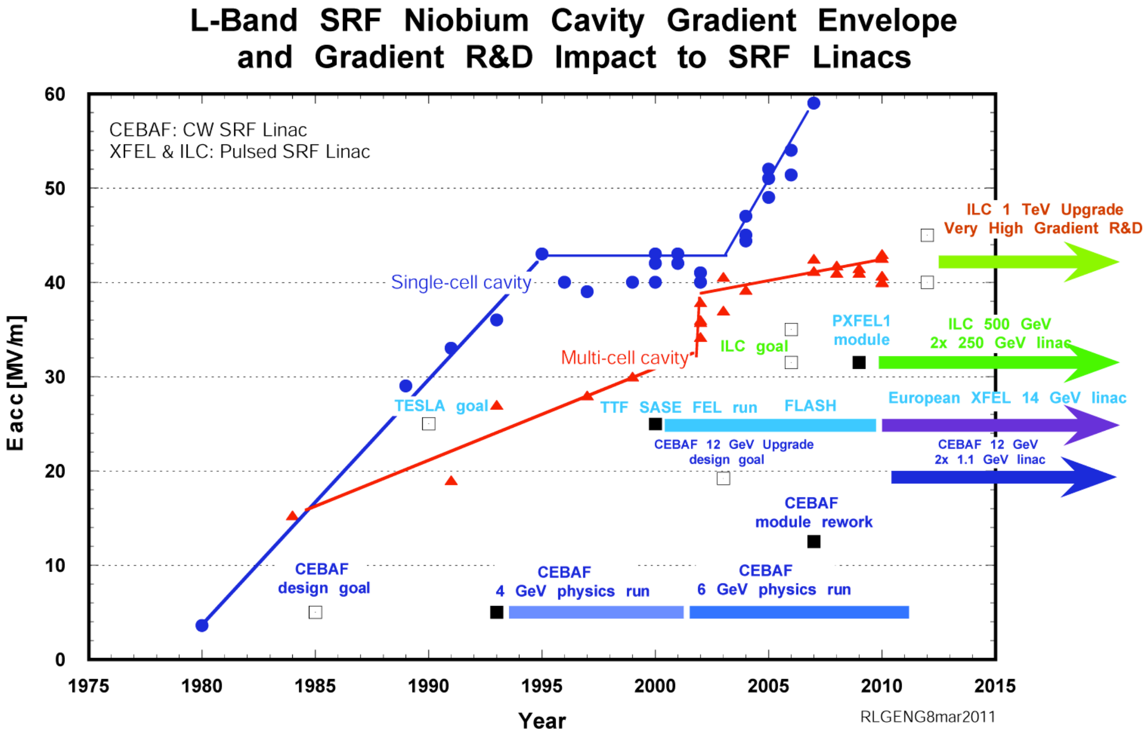

Figure 1: History of accelerating gradient in SRF cavities.

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develop, but this is now rarely the case. However, the cryogenic power required to maintain the cavity at superconducting temperatures increases as the square of the gradient. Cost-optimization exercises show the optimum operating gradient for the new generation of pulsed accelerators is a broad minimum at around 25-35 MeV/m, while for CW operation the optimum is around 15-20 MeV/m.

OPERATING EXPERIENCE

Integrated SRF operating experience can be measured using the “cryomodule century", or CC. Ten cryomodules operating for a decade, or 50 of them operating for two years, yield 1 CC. In the past, Tristan at KEK and HERA at DESY each accumulated more than 1 CC, and LEP-II accumulated nearly 4 CC. KEK-B, Cornell, and the Tesla Test Facility/FLASH have each accumulated a large fraction of 1 CC.

Over half of the world’s SRF operating experience has been accumulated at two US Department of Energy nuclear-physics facilities: ATLAS at Argonne National Laboratory and the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab. ATLAS, with nine cryomodules, has operated continuously since 1978, accumulating 3 CC of operating experience. Jefferson Lab, after more than 15 years of operating 42 cryomodules in CEBAF and a decade of operating the FEL, has accumulated about 6 CC of operating experience.

In Hamburg, the European XFEL project will yield more than 10 CC in its first decade, about half of today’s combined world total. The main linacs of the International Linear Collider (ILC), however, will require around 2,000 cryomodules. The first decade of ILC operation will yield some 186 CC – about an order of magnitude greater than the world’s present total.

SRF USER TYPES

Linacs

In all linacs, the over-riding concern has been to increase gradient, often at the expense of availability. In CEBAF, the requirements of the experiments are to keep the RF trip rate below 15 per hour, and the operating energy is adjusted accordingly.

Rings

Most modern storage rings, either for colliding beam experiments or synchrotron light sources, operate in top-up mode with continuous injection to maintain the beam current constant. An RF trip leads to a loss of the stored beam and re-injection leads to a significant loss of operating time. With these constraints, the optimum average operating gradient is much lower than in linacs to keep the trip rate at an acceptable level.

SRF SURVEY

In preparation for this paper, an SRF Survey was prepared to gather information on the current state of worldwide SRF technology use. The primary focus of the survey was on the availability and reliability of the main SRF technology, e.g., SRF cavities and cryomodules, as well as the supporting technologies, e.g., cryogenics, RF, vacuum, protection systems, with secondary focus on the performance and pervasiveness of this technology.

The survey itself was split into two separate questionnaires, one brief and one in-depth. The brief questionnaire was designed to assess the use of SRF technology in laboratories around the world. The in-depth questionnaire focused on information from laboratories that use SRF (e.g., number of cryomodules, installation date, particles accelerated), performance information (e.g., average gradient achieved, annual scheduled beam time) and reliability information (e.g. number of beam interruptions of a given severity, downtime by SRF system).

While the overall response has been encouraging, more data is required for an in-depth study of SRF. Sixty-seven labs were invited to participate; as of this writing, eighteen labs have responded to the brief questionnaire and four have responded to the in-depth questionnaire, one of which is still in the development stage. The respondent data shows that a small, but consequential number of accelerator sites are using SRF and that some are planning to install new SRF technology (Figure 2). While this is only a limited (and possibly biased) sample, it shows that SRF is still a vibrant technology in the accelerator community.

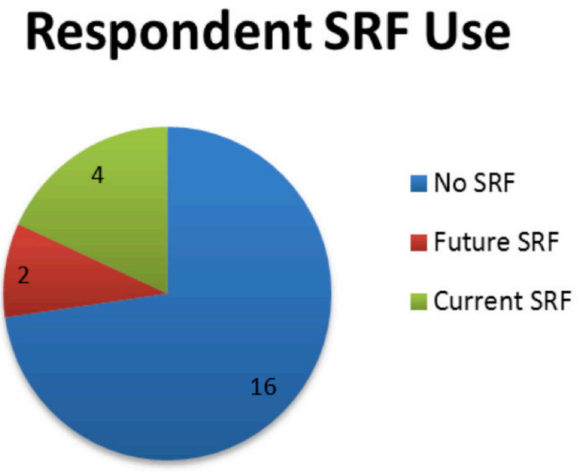

Figure 2: Breakdown of survey results.

The in-depth survey revealed some interesting data. In general SRF and related support technologies account for a relatively small amount of downtime. The average down time reported by the laboratories was equivalent to 3.7 percent of the time that the accelerator was in operation. CEBAF reported the largest downtime, equivalent to 7.5 percent of operational time, but it also operates the largest number of SRF cavities, 335 compared to SNS's eighty and CESR's four. This is remarkable in that it shows the scalability of SRF technology. A facility with eighty times as many cavities only increases its lost time by a factor less then ten.

Additionally, most of the time lost is due to the supporting technologies. Respondents reported several similar failure types. The high-voltage modulators that supply power proved to be a common issue, which results in downtimes from less than a week to less than an hour. RF control instabilities, vacuum valve and pump failures, and a range of cryogenics issues from failed turbines to unstable cryogenic liquid levels appear to be pervasive problems causing downtimes of similar magnitude to the power supply problems. Fast shut down or protection interlock trips represent another class of lost beam time that will be examined more closely below, using data from CEBAF. Focusing on improving these supporting systems can yield improvements in reliability that may be much larger than the total time lost due to failures with the cavities and cryomodules and may represent the next major increase in availability for SRF based accelerators.

The PAC '11 SRF Survey is still open for laboratories to participate (on the Web at https://cebaf.jlab.org/srf-survey/main_survey (for the SRF survey) or https://cebaf.jlab.org/srf-survey/home (for links to all data and surveys).). Additional data will allow for more detailed analysis of the reliability of SRF technology in accelerator environments. Further study will hopefully determine specific SRF-related systems across the accelerator community where improvements can be made. However, the survey already demonstrates the overall reliability of SRF across a wide swath of accelerator installations.

RF TRIPS, CAUSES, PROTECTION SYSTEMS

A detailed evaluation of one aspect of SRF availability, RF trips, was carried out on the extensive data set available at CEBAF. The number and recorded cause of the automated RF trips, which cause a fast shut down of the accelerator, were evaluated for a one-year period from August 2009 to September 2010. In this period, CEBAF was being operated with 29 of the original cryomodules (called C-20 modules as they were designed to produce a total acceleration of 20 MV) and 9 C-50 cryomodules (producing 50 MV). The C-50 cryomodules had undergone an extensive rework to increase the average accelerating gradient and to modify the input power waveguides to prevent field-emitted electrons from hitting the RF window. The analysis was designed to evaluate the effectiveness of these trip reduction measures when operating the accelerator at an energy 50% higher than design.

The data was analyzed for the presence of outliers; cryomodules with unusual or irregular circumstances that would inflate the number of trips for reasons not relevant to this study. Trips on a given cryomodule were defined as outliers if they were at least twice as frequent as the average value for that category of trip and cryomodule type. These outliers were removed to form a trimmed dataset. The following analysis notes when a significant qualitative or quantitative difference is observed in the trends, based on the exclusion of data. Unless otherwise stated, statistics are presented on the trimmed dataset.

Many of the conclusions drawn from, and possible explanations for, the following statistics have not been examined or tested using external data and may be incorrect. They represent plausible hypotheses supported by this set of data.

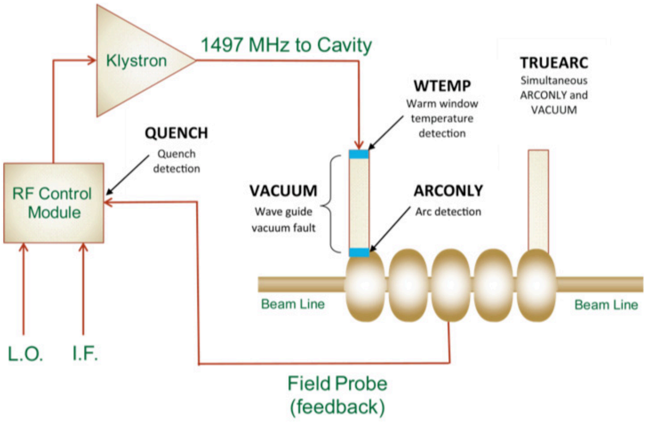

Figure 3: Fast shut down (FSD) inputs that protect the SRF cavities from arc damage.

Like most SRF installations, CEBAF has a complex machine protection system (MPS) to protect the SRF cavities during operation (Figure 3). The MPS includes a suite of automated fast shut down (FSD) procedures, which are designed to detect the presence of an arc and to remove RF power and the electron beam before the cavity is damaged (both of these sources can supply enough energy to the cavity to maintain an arc indefinitely).

However, FSD trips accounted for a significant amount of downtime, equivalent to 0.5% to 1% of the annual scheduled uptime. FSDs are generated by a number of different systems, which detect fault conditions that could be caused by an arc; these include ARCONLY, VACUUM, QUENCH, WTEMP, and TRUEARC faults.

QUENCH faults are triggered by a sudden increase in resistance of the SRF cavities implying a loss of superconductivity. WTEMP faults are triggered by increases in the cryomodule window temperature. ARCONLY faults are generated by a photodiode, designed to detect an arc flash at the cryomodule window. VACUUM faults are triggered by increases in pressure in the RF waveguides. TRUEARC faults are those that have triggered both ARCONLY and VACUUM faults simultaneously.

A major source of RF FSD trips in these modules is due to internal electrical arcing registered as ARCONLY or VACUUM faults, and if both are present, as TRUEARC. Since TRUEARCs require two totally independent systems to detect an anomalous condition, it is believed that these are truly arcs. However, the corollary is not true; it is not obvious that the other arcs are false positives and they may indeed be real trips that escape detection by the other detectors.

The original C-20 cryomodules used at CEBAF operate at an average gradient of 9.4 MV/m, while the C-50s operate at around 12.1 MV/m. Under these conditions, the new C-50s experienced a higher RF FSD trip rate than C-20s. On average, the C-50s tripped 579 times per cavity over the one-year period, while the C-20s tripped 516.3 times (not a statistically significant difference). This behavior should not be taken to mean that the C-50s are a less reliable design. Our environment is geared towards performance, pushing equipment to an acceptable threshold, so the cavities are pushed to the gradient limit. Driving the C-50s at a higher gradient than the C-20s also stresses the equipment supporting the C-50s even more. Additionally the C-50s have not received the years of fine-tuning that the C-20s have. For example, filters were designed for the C-20s to reduce the number of false-positive ARCONLY fault readings due to scintillation, an inconsequential, random sparking near the ARCONLY sensor. These filters are in use on the C-50s, but were not redesigned or thoroughly reevaluated for use in the newer modules.

Due to the redesign, the C-50s experience many fewer TRUEARC and ARCONLY faults. For the average C-50, TRUEARC and ARCONLY faults represented 4.3 and 3.5 percent of all trips, respectively. This should be compared to the average C-20, where TRUEARC and ARCONLY faults represented 53.9 and 15.8 percent of all trips, respectively. This means that the C-20s were 12.6 times as likely to generate a TRUEARC fault and 4.6 times as likely to generate an ARCONLY fault as were the newer C50s. This trend is only slightly modified by inclusion of all the data points.

The fact that the C-50s displayed a much greater reduction in TRUEARC faults than in ARCONLY faults may be due to a number of causes. A significant number of ARCONLY faults may be false-positives due to sub-optimal sensor filtering and calibration, as mentioned above. In addition, changes in arc behavior or a reduction in arc strength could cause the associated pressure increase to be small enough to avoid triggering a VACUUM fault. While unlikely, it is also possible that sensor malfunction is a contributing factor.

Not unexpectedly, the C-50s displayed a higher percentage of VACUUM and QUENCH faults than the C-20s. Since there are fewer arc-related faults, these two categories have risen to be the primary source of FSDs, with VACUUM and QUENCH faults accounting for 28.7 percent and 62.2 percent of all C-50 trips, respectively. In comparison, these categories only accounted for 13.2 and 20.0 percent of all C-20 trips. These two categories now constitute the primary causes of RF FSDs and will be further investigated for future reliability and performance enhancements.

Since the maximum gradient in the cavities is limited to 1 MV/m below the gradient at which each cavity quenches, as recorded during commissioning, it is quenches. The increased QUENCH faults are likely due to the greater stress placed on the equipment supporting the C-50 cryomodules. Since the C-50s are being driven at a higher gradient, the supporting electrical equipment experiences greater strain and may have instabilities that register as QUENCH faults. QUENCH faults are essentially the result of voltage irregularities at the cavities and cryomodules, so the original source of the fault may be unrelated to the cavities. For example, a malfunctioning klystron pre-amplifier could cause irregular voltage readings and would be interpreted as a QUENCH fault. Future effort will be directed at a detailed evaluation of the performance of this equipment to determine if they are a source of this fault. as well as a re-evaluation of the detection algorithm.

The increased VACUUM faults are, on the other hand, a bit of a mystery. The implication is that some new behavior may be present, e.g. arcing that is not registered by the ARCONLY sensor, erroneous readings, or something else altogether. Finally, it is worth noting that WTEMP faults remained relatively constant and represent only a minor amount of all faults.

These are examples of how improving reliability of one system in a performance-focused environment invariably reveals another system that also needs to be upgraded. The arc faults are a prime example of system that was upgraded and subsequently revealed another system in need of improvement (quench fault detection). In this environment, increasing reliability is more of an ever-expanding frontier than some static goal to be achieved.

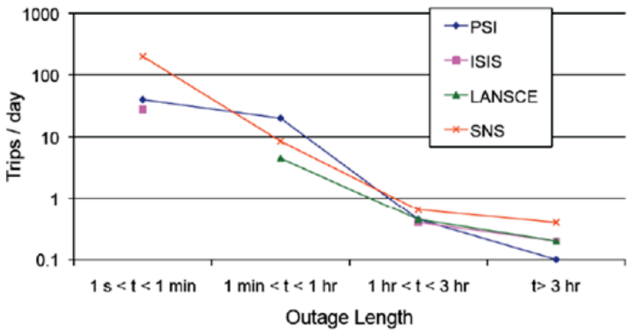

Figure 4: Beam trip frequency for operating high-power proton accelerators.

RF Trip Requirements for ADS

In a recent White Paper [1] which evaluates the readiness of superconducting RF technology for accelerator-driven transmutation and energy production, goals for the RF trip rate were developed for four different cases (Table 1). An analysis of the state of the art in superconducting proton accelerators was also presented (Figure 4), which is rather similar to the CEBAF data. Two strategies are possible to achieve the required goal; reduce the frequency of the trips (notably by improving the support hardware and fine-tuning the arc detection algorithms) and reducing the duration of the trips. In practice, both of these approaches will needed, although reducing the trip frequency appears likely to be easier, at least initially.

Table 1: Range of Parameters for Accelerator Driven Systems

	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam Power	1-2 MW	10-75 MW	10-75 MW	10-75 MW
Beam Energy	0.5-3 GeV	1-2 GeV	1-2 GeV	1-2 GeV
Beam Time Structure	CW/pulsed (?)	CW	CW	CW
Beam trips (t < 1 sec)	N/A	< 25000/year	<25000/year	<25000/year
Beam trips (1 < t < 10 sec)	< 2500/year	< 2500/year	<2500/year	<2500/year
Beam trips (10 s < t < 5 min)	< 2500/year	< 2500/year	< 2500/year	< 250/year
Beam trips (t > 5 min)	< 50/year	< 50/year	< 50/year	< 3/year
Availability	> 50%	> 70%	> 80%	> 85%

SUMMARY

What challenges will confront those who seek to operate the ILC and other future machines over long periods?

The order-of-magnitude scale-up for ILC is reminiscent of the SRF installation at CEBAF, which was an order-of-magnitude scale-up from the SRF R&D that had been conducted mainly at Cornell, KEK, DESY, and earlier at Stanford University. In the effort to minimize operational difficulties, CEBAF's scale-up challenges included higher-order modes, and overall reliability in a many-cryomodule system. Yet, even though these and countless other pre-operational questions were addressed, actual practice, year in and year out, has turned up much that was simply unforeseen, and was probably unforeseeable. As a result, in CEBAF's decade and a half of operating, about 1.5 refurbishments have been necessary per CC; extrapolated, that would imply about 30 per year for the ILC.

Of course, extrapolations about the ILC and other future SRF machines are inevitably subject to errors. For one thing, experience to date involves operating gradients significantly lower than those planned for the ILC (and for the XFEL, as well). And at CEBAF and other operating SRF machines, most of the post-construction problems have already been corrected. For example, in SRF cavity processing, future accelerator builders won't have to re-learn the value of high-pressure rinsing, which removes the performance limitation of field emission – and which is helping the ILC high-gradient R&D program to achieve significantly higher accelerating gradients than past machines have reached.

But the XFEL, the ILC and future SRF accelerators for ADS will push the (current) state of the art just as CEBAF pushed the (then) state of the art. So it is certain that the problems that these future SRF machines are sure to encounter will be new and different. Nevertheless, past experience is all that we have, and we should try to learn from it. Despite the uncertainties, strategies for spares will need to be developed. To maintain the operating gradient, failure rates will need to be estimated. CEBAF had one cryomodule failure per CC, but the failures appeared only after the first 7 years, or the first 3 CC. The failures exposed flaws but new problems are surely coming. CEBAF has also had gradient degradation of 1% per year from new field-emission sites caused by particulates inside the vacuum system. In sum, from CEBAF experience, any SRF machine needs to plan for refurbishments at a rate of 1–2 per CC.

In current SRF accelerators, cryomodules are independent, standalone entities that can (with some difficulty) be pulled out for refurbishment. In future SRF accelerators, the need to minimize static heat losses pushes the design toward more integrated accelerator systems, even at the cost of making replacement harder. Yet if extrapolation from current operating experience is valid, it will be important to have the ability to refurbish, which means that it will be necessary to avoid having cryomodules that are difficult to extract. It is the continuation of a longstanding design conflict: tight integration of systems improves performance, but makes repair harder.

SRF operating experience now has a long standing – many cryomodule centuries of it, in fact. This experience base constitutes an imperfect yet vital tool. And for all of us, there's profit in looking back in order to see forward.

ACKNOWLEDGEMENTS

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