RF SUPERCONDUCTIVITY: ENABLING TECHNOLOGY FOR THE FUTURE

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Abstract

It has been my good fortune to work for two directors, Bob Wilson and Bjoern Wiik, who had vision on directions of future accelerator technology. In 1992, Bjoern Wiik, soon to become Director of DESY, organized an international effort dedicated to a dramatic improvement in performance and cost of accelerating structures based on RF superconductivity. In this paper I will discuss the degree to which this goal has been achieved and the accompanying technology advances. Today, RF superconductivity is the technology of choice for high duty factor, high beam brightness applications and a serious competitor for use in a linear collider.

INTRODUCTION

This paper is a review of superconducting cavity development and is divided into three sections:

- first a history of the development of superconducting rf systems prior to the start of the TESLA R&D program and through the 90's [1],
- then the evolution of the TESLA 1.3GHz cavity development [2],
- and finally an overview of other superconducting cavity R&D, and future applications that are being proposed.

This talk is dedicated to Robert Wilson and Bjoern Wiik, two leaders of outstanding talent and vision, for whom it has been my great fortune to work.

RF SUPERCONDUCTIVITY BRIEF HISTORY

Ideas for the possibility of using superconducting materials for RF cavity structures first blossomed in the 1960's. P. Wilson, Schwettman, and Fairbanks at Stanford proposed an electron linac of 20 GeV, 10% duty factor, with cavity gradients of 10 MV/m. At Harwell, Banford and Stafford proposed a proton linac. Montague at CERN proposed a superconducting cavity separated beamline, and Susini began surface studies at 300MHz on lead and Niobium. At Stanford studies began at S band.

It is interesting to note that the Stanford proposed electron linac parameters are not unlike those of the present TESLA FEL project, that a proton linac (SNS) is now being built, that CERN went on to build a Kaon separated beam and that Fermilab (CKM) plans such a beam. Stanford went on to build HEPL, one of the first superconducting RF (srf) accelerators, which has recently been upgraded with TESLA cavities.

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Twenty years later by the '80's prototype cavities were beginning to be built with gradients up to ~7MV/m. Active programs were underway at Cornell (which produced the CEBAF cavity design), KEK, CERN, and Wuppertal. At this time Padamsee at Cornell developed the 1400C Titanization process that led to better residual resistance ratio (RRR) and higher thermal conductivity in the niobium material and less sensitivity to quench.

By '92 before the start of the TESLA R&D program, a number of laboratories had significant superconducting RF installations with cavity gradients of 3 to 7 MV/m. These installations are listed in Fig 1. The TRISTAN ring at KEK was the largest installation. CEBAF construction was proceeding at 16 cavities per month, and LEP cavity production had started. By 2000 there would be over 5 GV and over one km of superconducting structures that had been installed for electron or heavy ion acceleration.

	Nbr. of cav.		MHz	m	MV/m	MV
MACSE	5	5-cell	1500	2.5	6.5	16
S-DALINAC	10	20-cell	3000	10.0	5.9	59
HERA	16	4-cell	500	19.2	3.6	69
HEPL				30.8	3.0	92
TRISTAN	32	5-cell	508	47.2	6.6	310
CEBAF	106	5-cell	1497	53.0	7.6	400
LEP	12	4-cell	352	20.4	3.7	75

Figure 1: Status of SRF installations in 1992 [1].

Two Projects of the '90's

Two major projects of the '90's were CEBAF recirculating linac at Jefferson Laboratory and the LEP electron positron collider energy upgrade to 200 GeV cm.

Both systems are (or were) operated well above design gradients. Achieved operational gradients are (were) limited by cavity trip rates that could be tolerated by the experimental program in a tradeoff with beam energy delivered. There has been a steady evolution of energy with time, and in both installations the superconducting systems have been very reliable.

CEBAF [3] was completed in 1993, and was designed for 4 GeV beam and 5 MV/m cavity gradient at 1.5 GHz frequency. There are 338 5 cell, 1/2 m cavities in 42 modules. Today it operates at 5.8 GeV with 5 passes, and an average gradient of 6.9 MV/m (45% above design). The active cavity length is 169 m and the total accelerating voltage is about 1160 MV. The major limitation to gradient is the RF cold window location close to the cavity. Field emission from the cavity leads to arcing of the cold window. This is a design limitation that can be addressed in any future design. In operation, gradient is set to limit RF trips to 100/day (with ~45 sec recovery). Thus trips are a major source of unavailability, typically of order 3.5%, whereas failures of the SRF installation is very low (~0.2% of operating time) and cryogenics is ~0.9%. An upgrade for CEBAF to 12 GeV is underway.

The LEP-2000 collider [4] achieved up to 209 GeV cm energy operation before decommissioning to make way for LHC. LEP had 288 1.7m 350 MHz superconducting cavities, for a total active length of 490 m. These cavities were driven by 36 1 MW cw klystrons. The design gradient was 6 MV/m, however 7.2 MV/m average gradient was achieved (20% above design) for a total accelerating voltage of 3600 MV. Because of the demands of the experimental program search for the Higgs, the gradient was pushed higher and higher, requiring considerable processing during maintenance times and a sophisticated operating strategy. By 2000, the last year of operation, this strategy included increasing the acceleration voltage during a beam store so that by the end of a store all klystron systems were required to hold the beams. At the beginning of a store one klystron system was held as margin (2.7%) in case of a trip, after reduction of lumonsity to some level the energy was increased and all systems were required. Mean time before trip was about 14 minutes, with RF recovery of 2 min. Trips were generally due to field emission leading to excessive helium usage and helium interlock trips. Fig. 2 illustrates the evolution of available RF voltage and beam energy at LEP over the 5 years of operation ending in 2000.

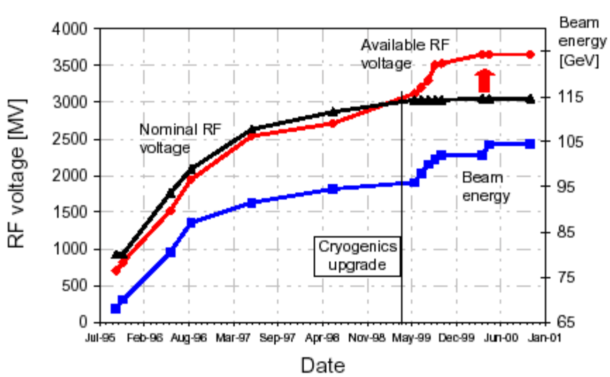

Figure 2: LEP operation showing the increase in available rf voltage over nominal design voltage, and resulting increased beam energy. [4]

These two examples of major accelerators that have used superconducting RF illustrate ability to push the cavities to levels where operation is limited by trips due to field emission at gradients well beyond design. System reliability exclusive of trip rates was excellent.

THE TESLA R&D PROGRAM

In 1992 Bjoern Wiik organized a collaboration to undertake SRF cavity R&D with focus toward its use for linear colliders (LC). The large aperture of the superconducting 1.3 GHz cavities leads to low wake fields, relaxed alignment tolerances, and less emittance dilution with the possibility of long bunch trains, bunch to bunch feedback and emergency turnoff within a fraction of a bunch train pulse. Potential benefits have been acknowledged since the beginning of LC R&D but projected costs were considered too high. The TESLA R&D program had the goal of a cost reduction of a factor of 20 per MV. This could be accomplished by an increase of a factor of 5 in gradient from the then typical 5 MV/m to 25 MV/m and a cost reduction per unit length over existing installations of a factor of 4. This cost reduction could be realized by long continuous module strings with many cavities without warm-cold transitions. The initial gradient goal set for realization in the TESLA Test Facility (TTF) was 15 MV/m with a clear path toward 25 MV/m for a LC. Now the goal for TESLA 800 (800 GeV cm) is 35 MV/m and cavity R&D is focused to that end.

The R&D for cavity improvement has concentrated on a number of areas with care toward careful, high quality manufacturing, processing, preparation, and testing. There has been no one specific most important improvement area but rather careful attention in many areas that has led to success. Many of these procedures had been developed through international R&D efforts prior to TESLA.

The cavity improvement efforts included [2, 5]:

- High RRR Niobium for better thermal conductivity.
- Scanning sheet Nb material for defects and inclusions of non-Niobium material using eddy current scanning devices (and more recently squid scanners as well).
- Care in preparation for e-beam welding and good vacuum during welding.
- High temperature heat treatment (HT) of the finished cavity at 800 C (to remove H and prevent Q disease), or the more effective treatment with Titanium at 1400 C to getter O_2 and increase the thermal conductivity by about a factor of 2 above that of the high RRR sheet.
- Cavity tuning for field flatness.
- Buffered chemical polishing (BCP) followed by ultra pure water (UPW) rinsing.
- High pressure water rinse (HPR) to remove particles and eliminate field emission.
- Clean room assembly in class 10-100 cleanrooms.

The fabrication and preparation is followed by a series of tests of cavity gradient and Q performance:

- Vertical dewar test of the "bare" cavity (without helium vessel, tuner or input coupler).
- Horizontal dewar test of the "dressed" cavity (with helium vessel, tuner, input coupler).
- Module assemblies of 8 cavities per module.
- TTF installation and test of the 8 cavity module, and operation for beam acceleration.

Performance limitations can be caused by inclusions, dust particles, resistive regions, high surface resistance, or bad thermal conductivity and ultimately by the theoretical Hc limit. The limitations are:

- Cavity quench or thermal breakdown
- Field emission
- Multipacting
- Q slope (drop in Q at high gradient)

Early in the program a very significant set of tests was carried out at Cornell. These tests performed on three 1.3 GHz 5 cell cavities fabricated at Cornell showed that greater than 25 MV/m at Q of $5x10^9$ was indeed achievable. A technique of high peak power processing (HPP) was used to achieve these results.

The Cavity Program with BCP

The TESLA program has involved fabrication of the 9 cell 1.3 GHz cavities by industry from the very beginning. Four different vendors have produced cavities. In time there have been 3 production runs. The fourth is underway presently. In total over 80 cavities have been produced. The processing, tuning, assembly, and testing is all done at DESY. Results of the first 3 production runs, and the modules assembled from these cavities are illustrated in Fig. 3 [2]. One sees the improvement in quality and reproducibility as the productions have proceeded. Much of this improvement has been due to improved welding, better niobium control, better overall quality control, and the learning curve associated with the production of a number of cavities. In Fig. 4 [2], a comparison of test results is given for those obtained in the vertical test dewar of bare cavities with cw RF, against those obtained in the horizontal test dewar of fully dressed cavities with pulsed RF (1.3ms). Though the scatter in correlation is large it is important that there is no obvious deterioration of gradient after the cavities are fully dressed. In fact some cavities perform better in the horizontal cryostat after being "dressed ", probably because of thermal heating differences between cw and pulsed operation. It is interesting to note that already in this data set some are achieving gradients of 33 to 35 MV/m.

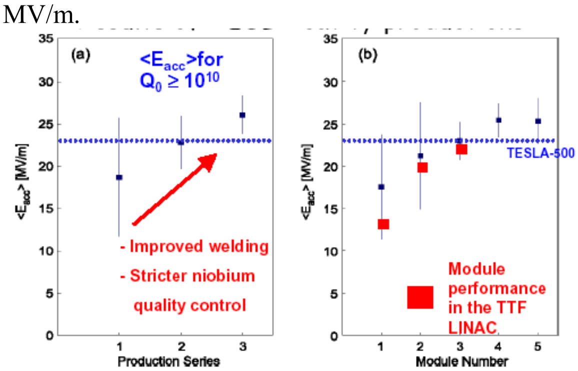

Figure 3: Cavity performance results from a) successive production runs, and b) when installed in TTF modules.

Fig. 5 shows the good reproducibility of vertical results (cw) from cavities of the 3rd production run prepared with BCP surface chemistry. However it is clear the there is a rapid drop in Q ("Q slope") above about 25MV/m. Some of these same cavities show higher gradient operation in the horizontal pulsed tests as illustrated in Fig. 6. Many are at or near the required 35MV/m @ Q of $5x10^9$. However the Q slope indicates that cavities prepared in this manner are reaching their performance limitations.

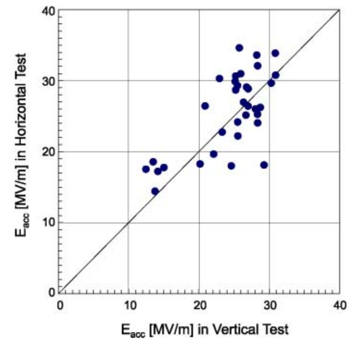

Figure 4: Reproducibility of results in the horizontal test of dressed cavities vs. in the vertical test of bare cavities.

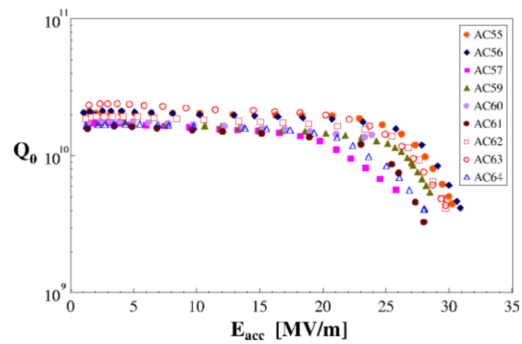

Figure 5: Vertical dewar results for cavities from the 3rd production processed with BCP [2].

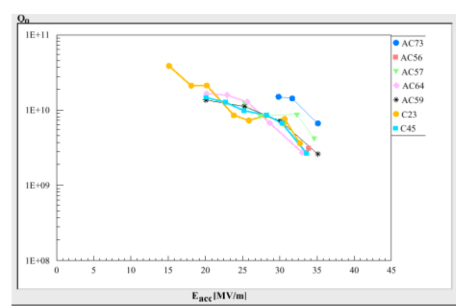

Figure 6: Horizontal pulsed test results of TESLA cavities. AC73 is electropolished, the rest have BCP treatment.

Electropolishing

The development and refinement of the electropolishing (EP) process has been successfully pursued by a broad international collaboration of laboratories working on srf R&D (CERN, DESY, JLab, KEK, Saclay). The effort is an excellent example of the power of international collaboration.

One cell cavities have been electropolished at CERN and measured at DESY as part of studies carried out in a CERN-DESY collaboration [5]. KEK (with Nomura

Plating) has developed the electropolishing process so that it can be used with good results on multicell cavities [6]. KEK has electropolished a number of multicell cavities for DESY and JLab. DESY and JLab are both bringing on their own EP facilities based on the KEK development.

The EP process is usually done after heat treatment (HT) at 1400 or 800C, and BCP etching as greater of 100 microns of niobium must be removed and the EP rate of removal is ~ 1/2 micron/min. Whereas the BCP process makes for differential etching of the different crystal grains and surface discontinuities at the grain boundaries, the EP process concentrates electric current on surface high points and removes them. The result is a very smooth surface. The rough surface produced by BCP can lead to local field enhancement that could be detrimental especially as local H fields approach the theoretical Hc limit [6,7].

Results from single cell cavities with EP preparation showed very interesting results [5]. The cavities did not show remarkably better results than BCP prepared cavities until a 120C bake was performed as a final step. Before the 120C bake a strong Q slope was observed at gradients above 25MV/m as with the BCP preparation. There was no field emission associated with the Q slope. (Emission is a usual explanation.) After the bake, the Q slope was much reduced and gradients in excess of 40 MV/m were observed.

Initial vertical dewar results from 4 TESLA 9 cell cavities (out of 9) electropolished at KEK then shipped to DESY for final HPR and 120 bake are shown in Fig. 7. Test results of one of these cavities in the horizontal dewar before and after being "dressed" is illustrated in Fig. 8. This cavity has achieved gradients of 37 MV/m in 10 Hz, 1.3 ms pulsed mode. [5]

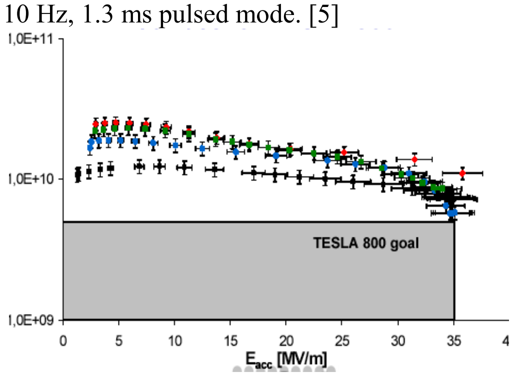

Figure 7: First results of EP processing on four cavities.

Clearly the 120C bake has some very important influence on the superconducting properties of the cavities. There is evidence that oxygen from the oxide surface layer diffuses into the first ~100 microns of material and effects the superconducting surface resistance by changing the electron mean free path. (Other changes to the superconducting properties may be going on as well.) [6]

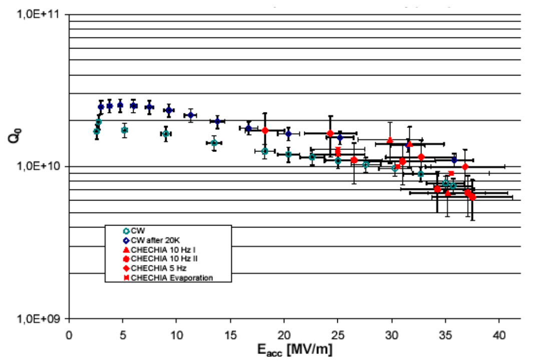

Figure 8: Horizontal pulsed test of EP cavity AC73.

It is still early to know just what the best preparation with EP will be and further understanding of the modification of the surface layer is needed. One outstanding question relevant to cavity production processing is whether heat treatment at 1400C will be required or if the easier 800C treatment will be adequate.

ACTIVITIES IN OTHER R&D AREAS & NEW APPLICATIONS OR POSSIBLE PROJECTS

Other SRF R&D

Superconducting cavity R&D efforts are going on in a number of other areas. Only some of these can be mentioned here [8]. In some cases the motivation is directed toward future potential projects, in other cases the motivation is driven by possible cost reduction through the use of less niobium material or simplified fabrication processes.

Sputtered cavity development (as was done for LEP) continues for low frequency applications where cavity size makes use of solid Nb prohibitive. LHC will use 16 400 Mhz single cell cavities with specification of 5 MV/m and Q $2x10^9$ at 4.5 K. These cavities have been produced by industry and operate above specification. They typically reach ~9MV/m and Q~$1x10^9$ at 4.5K, and up to 14MV/m at 2.5K. As with other sputtered cavities, the Q slope is large and continuous from low Eacc. Understanding and curing this is an important area of R&D that would make it possible to push the use of sputtered cavities to higher gradient.

Cornell and CERN have a collaboration to fabricate and test 200 MHz single cell cavities for muon acceleration [8]. First cavity tests have reached Eacc ~11 MV/m (goal is ~17 MV/m). Here again Q slope is very evident.

A different approach is being pursued at DESY in collaboration with Jlab. Nb/Cu clad single cell cavities are produced by hydroforming without an equator weld. Tests of one of these cavities have achieved 40 MV/m and Q ~ $9x10^9$, with almost no Q slope. Interestingly, preparation was BCP, 800C HT, HPR, and 140C bake.

A completely different area where there has been good success is the low beta spoke cavity effort at Argonne and

LANL. It shows great promise for application in RIA (Rare Isotope Accelerator) for β~0.3-0.4 structures [8].

Ongoing and Potential Projects

The prominent ongoing accelerator project using srf is SNS . The change to superconducting cavities took place relatively late in the planning. However this application of srf is natural because of the need to minimize beam loss, large aperture of the cavities and their potential to provide further beam energy increases. The ability to use the srf technology at SNS was a direct spinoff from the TESLA R&D. SNS linac uses 81 800 MHz srf cavities of 2 β types from 186 to 1000 MeV. Cavity production overseen by JLab is well underway. Fig. 9 shows first tests of high beta cavities with BCP and EP processing. Performance is well above specification (including the increased high β specification that was changed when EP was adapted for processing of the high β cavities) [8].

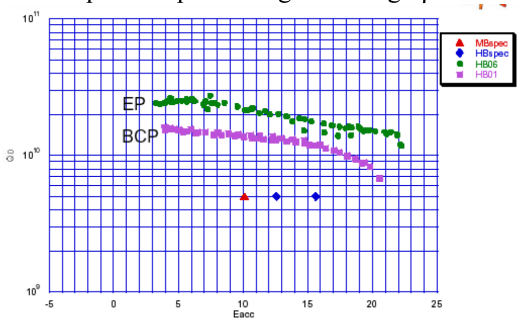

Figure 9: First results from Jlab on SNS high β structures prepared with BCP or the new EP setup [9].

JLab is also working on an upgrade of CEBAF to 12GeV, and work is underway on the ERL FEL Upgrade to 10kW. EP cavities have been tested to 19 MV/m [8].

TESLA TTF II linac is being assembled. It will have energy to 1 GeV and use cavities of more recent production series. It will produce SASE FEL radiation to 6 nm. The TESLA GeV XFEL project (10 to 20 GeV linac) has been approved by the German government at 50% funding support. The remaining support will come from collaborating countries. [8]

It is interesting to review the reports submitted to DoE for development of its 20 road map plan. Though many of the ideas, doubtless will not survive to the project level, it is striking to note just how many rely on srf technology. Listed by DoE Science Divisions, these include:

Basic Energy Sciences (BES)

- SNS- power upgrade to 3MW
- "Greenfield" XFEL (beyond LCLS)
- LUX- Linac based Ultra-fast Xrays (LBL srf recirculating linac)
- ACNS- Acc based Continuous Neutron Source (BNL 10MW)
- Crosscutting issues- investigation of Energy Recovery Linac (ERL) applications

Nuclear Physics (NP)

- RIA-Rare Isotope Accelerator (400MeV/nucleon)
- CEBAF 12 GeV Upgrade

High Energy Physics (HEP)

- Linear Collider- cold or warm
- CKM- Charged Kaons at Main Injector (FNAL separated beamline)
- Neutrino Super Beam- Proton Driver (warm or cold, BNL or FNAL)
- Neutrino Factory

There are also proposals to NSF:

- Cornell ERL
- MIT-Bates X-ray laser (4 GeV linac)

And finally BNL is discussing a high current electron linac for electron cooling at RHIC.

CONCLUSIONS

Superconducting RF systems of the 90's have demonstrated remarkable reliability, and operability at limits considerably in excess of design.

The TESLA R&D program has been a model of concerted R&D. It has been dramatically successful at pushing the gradient of superconducting cavities to a level required for Linear Collider application. The improvements in cavity performance have made it possible to use the superconducting technology in projects such as SNS.

There still remains more work, and more to understand in order to achieve high performance, reliable and cost effective cavities. But the TESLA R&D program clearly shows how well planned R&D with a major commitment can succeed in making real progress.

Superconducting RF has become a major enabling technology for accelerator projects of the future.

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REFERENCES

[1] H. Weise, LINAC 98, p. 674, Aug. 1998, ANL-98/28.
[2] TESLA Technical Design Report, DESY 2001-011, ISBN: 3-935702-06-X, March 2001.
[3] C. Reece, et al, Proc. 2001 PAC, p. 1186, IEEE: 01CH37268C, ISBN: 0-7803-7193-3, 2001.
[4] P. Brown, et al, Proc. 2001 PAC, p. 1059, IEEE: 01CH37268C, ISBN: 0-7803-7193-3, 2001.
[5] L. Lilje, DESY-Thesis-2001-034, July 2001, ISSN 1435-8085; L. Lilje, private communication.
[6] K. Saito & P. Kneisel, TUP031, Proc. 9th SRF Workshop, LA-13782-C, LANL, 1999;
K. Saito, ROAA002, this conference.
[7] J. Knoblock et al, TUA005, Proc. 9th SRF Workshop, LA-13782-C, LANL, 1999.
[8] See a number of papers this conference.
[9] C. Rode, private communication.