# STATUS AND ISSUES OF SUPERCONDUCTING RF TECHNOLOGY*

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## Abstract

Superconducting rf technology is today considered mature enough to make significant and wide-ranging contributions to accelerators for particle physics, nuclear physics and free electron lasers. Industrial involvement is growing to fulfill important needs for aggressive application of the technology. The foundations for this progress have been steady improvements in the understanding of field limitations of the past and invention of methods to control them. These efforts continue to address the challenge of bringing the technology closer to the full potential of rf superconductivity. Success in this endeavour will entail devotion of significant resources and could result in performance levels more than one order of magnitude higher than the modest levels upon which present applications are envisaged.

## Overview of Current Status

The last 5 years have seen substantial worldwide progress in the field of rf superconductivity. Superconducting heavy ion-accelerators at Argonne and SUNY at Stony Brook have been commissioned.[1] Eight separate tests[2] of electron storage ring prototypical structures have been carried out by Cornell U. KFK, CERN, KEK and DESY in high energy electron-positron rings, CESR, PETRA, and TAR (accumulation ring for TRISTAN). Two major accelerator projects planning medium energy electrons for nuclear physics have switched to SRF technology, one in the United States (CEBAF[3]) and the other in France (ALS-II[4]). In W. Germany, a Darmstadt/Wuppertal collaboration is continuing construction of a superconducting recirculating linac[5] At HEPL, the first and largest superconducting recirculating linac in the world has been operated for free electron laser (FEL) experiments, recently surpassing the milestones of visible (0.5 $\mu$m) radiation and the first energy recovery experiment with a superconducting linac[6].

Advances in SRF technology aspects have taken place on several fronts: increased understanding of long-standing limitations, implementation of successful remedies and resulting improvements in performance. Improved higher order mode coupling devices for controlling beam-cavity interaction have been perfected[7]. New quater-wave, half-wave and interdigital structures with improved mechanical stability for accelerating low velocity heavy-ions have been developed[7]. In over a dozen full scale accelerating structures for electron accelerators, spanning the frequency range from 350 Mhz to 3000 Mhz, gradients between 5 and 15 Mev/m have been achieved in laboratory tests, with an average value of 8 Mev/m. $Q_0$ values over $3\times10^9$ at 5 Mev/m are regularly observed. In over 100 tests on a large number of simpler, single cell cavities spanning the same frequency range, accelerating fields between 8 and 23 Mev/m have been achieved, with an average of 10 Mev/m[8]. Accelerating fields between 4 - 10 Mev/m are achieved in the new resonators for heavy ions[7,9] United States, European and Japanese firms have acquired the advanced technology of fabricating superconducting cavities[10]. Full scale structures built by these firms have consistently exceeded performance goals.

For application to electron accelerators, expectations are that this technology is now capable of achieving, on the average, 5 Mev/m at Q's > $3\times10^9$. The sustained progress have given impetus to wide-ranging applications in electron storage rings for high energy physics (TRISTAN[11], LEP[11] and HERA[12]), recirculating electron linacs for nuclear physics (CEBAF[3] and ALS-II SUPRA[4]) and linacs for free electron lasers (HEPL[6], TRW[13] and INFN-Frascatti[14]). Successful heavy-ion accelerator projects[15] at Argonne and Stony Brook have stimulated similar projects at the U. of Washington, Florida State U., Kansas State U., Australian National U., Daresbury, and the Weizman Institute. In all over 1 Km of superconducting structures are now contemplated for installation by the mid 1990's.

Superconducting cavity technology continues to offer attractive opportunities for further advances in achievable voltage at reasonable cost for future accelerators. For niobium, the full potential implies an order of magnitude increase over current capabilities. Substantial R&D is in progress aimed towards advancing the technology so that it may continue to serve in the current and succeeding generation of accelerators. Success in these projects could promote SRF technology as an attractive candidate for TeV scale electron-positron linear colliders for the turn of the century. Two excellent reviews of this field have recently been given by H. Lengeler[7,11]. We will discuss the foundations for the advances registered and glimpse into research activities that seek to further the capabilities of this promising technology.

## Applications in progress

Table 1 summarizes the current status and plans for application of SRF technology to electron accelerators. Comparable information for heavy-ion accelerators is covered in a review at this conference by L. Bollinger[1]. Prototype SRF structures have been developed by CERN (see Figure 1) for increasing LEP energies towards 100 GeV, by DESY for increasing HERA energies to 33 - 35 GeV and by KEK (see Figure 2) for increasing TRISTAN energies to 33 - 35 GeV. For medium energy nuclear physics electron linacs, the original designs were based on normal conducting rf technology, with recirculating beams followed by a storage ring to stretch the pulses to a nearly (80%) continuous beam. Both machines will now be recirculated superconducting linacs providing a 100% continuous beam of electrons at energies between 0.5 and 4 GeV. The timely switch to SRF technology is based on a recognition of the maturity of rf superconductivity, the superior beam quality that would result, the substantial reduction in operating costs and the prospects of upgradability of beam energy as the technology continues to advance[16].

CEBAF will be built from 220 meters of SRF cavities (see Figure 3) of the type developed by Cornell University LNS, originally for storage ring application. The Cornell cavity was chosen because of the advanced state of the design that virtually eliminated the need for further laboratory scale R&D, because of successful prototypes built and tested at Cornell, and because of beam tests carried out in CESR (Cornell Electron Storage Ring[2]).

*Supported by NSF with supplementary support from the US-Japan collaboration.



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PAC 1987

TABLE 1: SRF Technology for Electron Accelerators

| LABORATORY | APPLICATIONS | MACHINE PARAMETERS | STRUCTURE PROPERTIES: Freq. Mhz | No. of cells | Active Length (meters) | LONG TERM PLANS | DESIRED PERFORMANCE: Eacc MeV/m | Q ($10^9$) | Temp (K) |
|---|---|---|---|---|---|---|---|---|---|
| HIGH ENGERGY PHYSICS | | | | | | | | | |
| CERN | Long Period SPS Test of LEP Prototype | Increase LEP energy to 100 GeV | 350 | 4 | 1.71 | 4 Cavities/LEP I $\geqslant$ 192 Cavities /LEP II | 5-7 | 3 | 4.2 |
| DESY | Test HERA prototypes in PETRA | Increase HERA energy from 27 to 32 GeV | 500 | 4 | 1.2 | 16 Cavities/HERA | 5 | 2 | 4.2 |
| KEK | Test TRISTAN Prototypes in TAR (accumulation ring) | Increase TRISTAN energy to 33 GeV | 508 | 5 | 1.5 | 32 Cavities/ TRISTAN | 5 | 3 | 4.2 |
| NUCLEAR PHYSICS | | | | | | | | | |
| Darmstadt/ Wuppertal | 10 MeV Injector Test 1x5 cell + 2 x 20 cells | 130 MeV recirculating Linac, 3 passes, 20 μA 100% duty cycle | 3000 | 20 | 1 | Complete Recyclotron cavities completed | 3-5 | 3 | 1.8 |
| CEBAF | Cryomodule Test with 8 cavities | 4 GeV Recirculating Linac, 4 passes 200 μA, 100% duty cycle | 1497 CORNELL DESIGN | 5 | 0.5 | 440 cavities | 5 | 2.4 | 2.0 |
| SACLAY | Develop Prototype for ALS-II | 1.5 - 2 GeV Recyclotron 100μA, 100% duty cycle | 1500 | ←----------Design in Progress----------→ | | | | | |
| FREE ELECTRON LASERS | | | | | | | | | |
| Stanford U. HEPL | High Brightness Injector for SCA | 6 MeV, 300μA average 50 A peak | 1300 | 2 | 0.23 | 4x2 cells + 2x1 cell Harmonic cavities | 7.5 | ~$10^9$ | ~2 |
| Stanford U. | Operation of existing SCA for FEL experiments | Up to 140 MeV in 3 passes, visible and near UV FEL | | | | | | | |
| TRW | Test 2 cavities in one cryostat produced by Interatom. | ~ 130 MeV Linac, visible FEL | 500 | 1 | 0.3 | 60 cavities | 7 | 0.8 | 4.2 |
| INFN Frascatti | Infra-Red FEL | 40 MeV Linac, 200 μA, 2 MeV S-band injector | 500 | ←----------Under Development----------→ | | | | | |

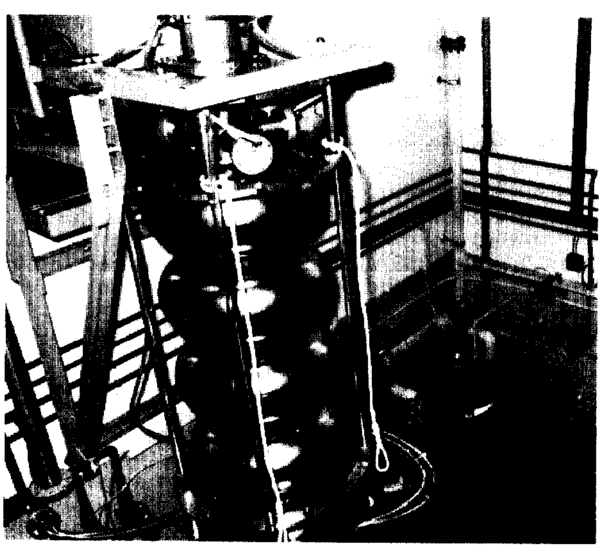

Figure 1. 4-cell LEP prototype cavity under preparation for chemical etching.

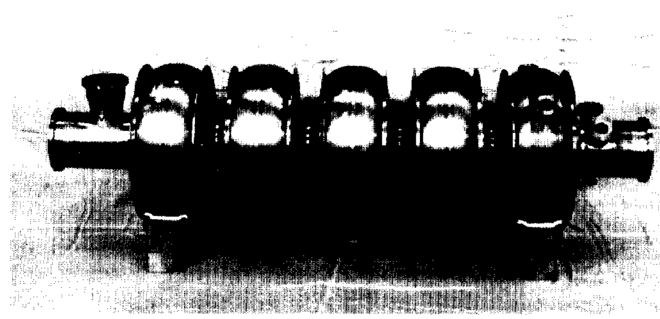

Figure 2. 5-cell TRISTAN prototype cavity

## Foundations of Progress in SRF Technology

Limitations in performance of superconducting cavities have been overcome through detailed understanding of the underlying mechanisms. Achievable field levels in superconducting cavities have been steadily upgraded with the inhibition of multipacting and subsequently with the suppression of breakdown.

Figure 3. CEBAF/Cornell cavity pair.

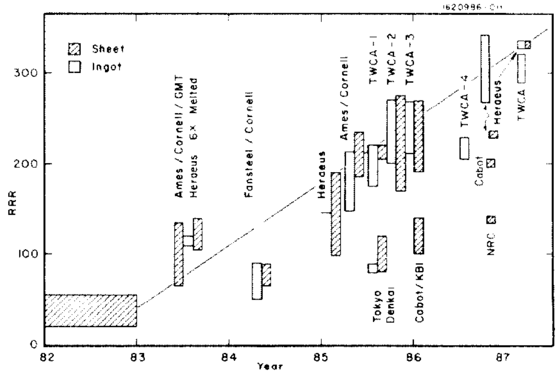


Figure 4. Progress in electron beam melted high purity commercial niobium.

## Multipacting

By means of thermometric measurements and theoretical calculations on superconducting cavity geometries used for electron acceleration, it was determined that multipacting, the persistent performance limitation before 1980 was of the one-surface variety, revealing resonant electron generation at the equatorial (large diameter) cavity wall[17]. Several solutions were proposed and explored before it was recognized that the spherical cavity shape provided the definitive cure by destroying the stability of the resonant electron trajectories[18]. The elliptical shape is a variation that enhances mechanical stability and facilitates cleaning[19]. Since then these shapes have been universally adopted and multipacting is no longer a serious problem.

## Thermal Breakdown

With the elimination of multipacting, breakdown of superconductivity at localized spots took over as the dominant limitation. The thermal nature of this phenomenon was clearly established by mode-mixing experiments[20] and detailed low temperature thermography of the cavity[21]. A computer code based on iterative solution of heat flow equations was developed to simulate the onset of thermal breakdown at small defects and resulted in the key prediction[22]:

$$E_{acc} = \sqrt{k}/(\sqrt{d}\ \sqrt{R})$$

where k is the thermal conductivity, d is the diameter and R is the surface resistance. Improvements in manufacturing techniques and processing cleanliness have reduced the frequency of major defects and allowed field levels to increase. Occasionally the starting Nb material has been found to contain foreign inclusions. Low temperature thermometry diagnostics systems are used to locate defective areas on the surface and ways to repair them have been developed[23]. The most promising approach to elimination of thermal breakdown has been to improve the thermal conductivity of Nb by removing the light interstitial impurities O, N, C and H[24]. The residual resistivity ratio (RRR) at 4.2 K in the normal state provides a convenient guage of the total Nb impurity content.

Collaboration between the Nb producing industry and the rf superconductivity community has led to intense efforts to remove the relatively large quantities of interstitial impurities contained in the normal commercial product. Before 1983 a RRR of 30 - 40 was typical for commerical Nb used for cavities. Today over 8 tons of Nb with RRR > 100 and over 5 tons with RRR >200 have been produced. Nb with RRR= 300 is becoming available[8] (see Figure 4). A new method of further improving the thermal conductvity of Nb for rf cavities has been developed[25]. This method is based on the principle of solid state gettering using purifying agents Yttrium and Titanium[26]. High purity commercial material can be improved to a RRR of 400 - 600[8].

## Performance of Superconducting Cavities

Cavities have been manufactured from high purity Nb from most major suppliers, as well as after further purification with solid state gettering. Both single cell cavities as well as full-scale structures equipped with ports or devices for coupling microwave power have been tested at various laboratories. Figure 5 summarizes the results from over 20 tests in a dozen structures fabricated from high purity Nb. These cavities regularly exceed 5 Mev/m without the need to painstakingly locate and repair defects. Better results are achieved in single-cell cavities. These cavities rarely breakdown and achievable field levels scale with √RRR until field emission loading sets in. 121 test results over a large number of single cell cavities are summarized in Figure 6, and show the expected improvement with RRR.

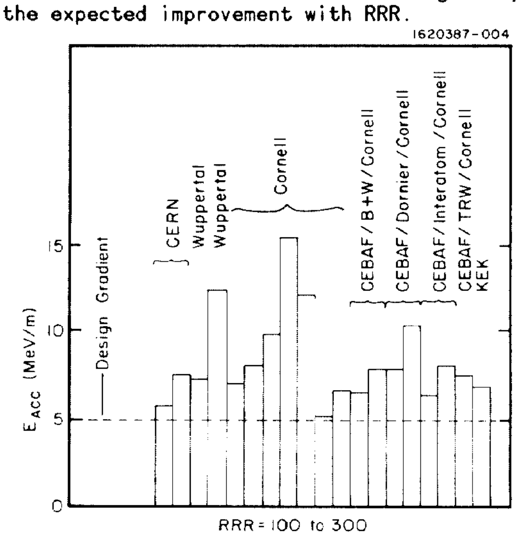


Figure 5. Recent laboratory test results on multi-cell accelerating structures out of high purity Nb.

## R&D in Progress Towards Advancing SRF Technology

Potential capabilities, both technical and economic make rf superconductivity one of the important advanced accelerator research candidates to develop for future high energy electron machines.. While the above review of the current state of the art shows that considerable progress has been made, much more will be needed before the full potential of rf superconductivity can be approached and put to service for the generation of electron-positron colliders in the TeV energy domain. The recent progress convinces us that, with an intense effort, the capabilites of SRF technology can be substantially advanced. Achievement of the rf critical magnetic field implies

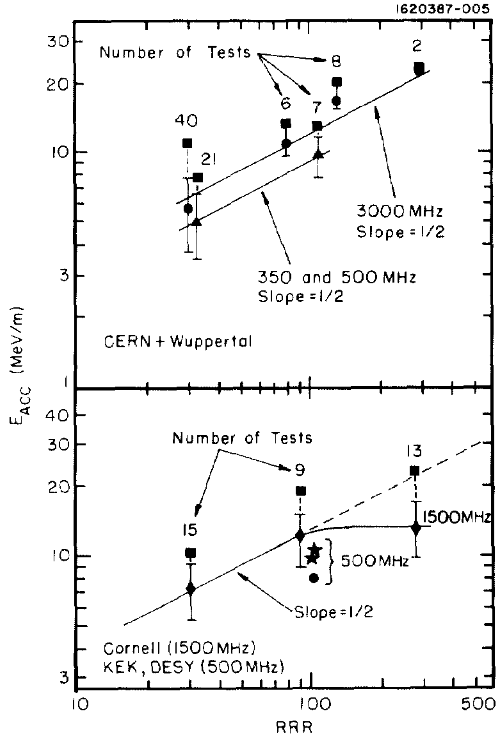


Figure 6. Compilation of single cell cavity results from various laboratories, showing improvement with Nb purity.

gradients as high as 75 Mev/m in Nb for suitably designed linac structures[27], and the theoretically predicted surface losses imply Q's as high as $7 \times 10^{10}$ $*(3/f\text{-Ghz})^2$ at 1.5 K[28]. The capital and power costs of TeV-scale cw linacs using SRF technology have been investigated as a function of performance levels[28]. Cost optimization studies have been made for a 2 TeV scale superconducting linac with $10^{33}$ luminosity (cgs units) in which the rf is operated with a pulsed duty cycle[29]. Here it is shown that the cost of such a linac decreases steeply as gradients approach 30 Mev/m. With Q's of $10^{10}$, and a short duty cycle, capital costs for refrigeration form a small fraction of the overall costs. This is one avenue of research that could conceivably lead to an economically practical linear collider. It offers real advantages with respect to peak and average power requirements because long rf pulses and multiple bunches can be used.

Advances towards the needed capabilities will only be realized if efforts already in progress continue their quest to deepen understanding of the behavior of superconducting surfaces in rf fields, and seek ways of upgrading the performance and reliability of cavities. Currently the dominant problems may be categorized in two broad groups: field emission (FE) and surface resistance. Several studies are in progress to characterize the sources of field emission and enhanced losses.

## Field Emission Studies

### DC Studies

Recent studies in which field (FE) emission sites are located by a dc probe and subsequently examined by secondary electron microscopy, show conslusively that FE is associated with anomalous particles or inclusions on the surface[30]. Such features have geometrical shapes that could only sustain field enhancement ($\beta$) factors of order 10. Complementary studies of the emitted electron energy spectra show a shift below the Fermi energy level, and a field dependent width[30]. The emission current is also subject to instabilities, namely switching and noise. The time to initiate a switch is observed to be current dependent. All these features imply that FE involves semiconductors or insulators. The physical mechanisms at work are still in the range of speculation.

Progress has continued at the U. of Geneva[31] in empirical characterization of field emitters on Nb surfaces, and a method has been found to drastically reduce their numbers up to 100 MV/m. More than 200 sites have been studied over a total Nb surface area of 200 $cm^2$. There is no correlation between location of sites and grain boundaries. $\beta$ values range from 10 - 600 with 100 as the most probable value, emissive areas range from $10^{-15}$ to $10^{-5}$ $cm^2$, with $10^{-9}$ $cm^2$ as most frequent; particle sizes range from 0.5 $\mu$m upto 20 $\mu$m, with the most probable size between 0.5 and 1 $\mu$m. Typically half a dozen emission spots/$cm^2$ are seen at field levels up to 40 MV/m. The density of sites increases exponentially with electric field.

With heat treatment the density of field emitters first increases upto 850 C then decreases sharply. Surfaces of $cm^2$ size which do not emit upto 100 MV/m have been repeatedly obtained by heat treatments above 1400 C. 1600 C heating makes both particle and emission disappear.

### Rf Studies

To improve our understanding of field emission behavior in rf fields from cold surfaces there is a need to substantially augment the data available on the density of emitters, on their FN characteristics and on their processing characteristics. Recently, an improved, high speed superfluid He thermometry has been developed for systematic studies of emitter distribution and properties[32]. Temperature maps can be obtained within a few seconds. Maps can be taken in rapid succession at increasing field levels or at 20 msec intervals, so that field level dependent and time dependent phenomena such as switching and processing can be tracked. In another study, arrays of Si X-ray detectors are being used to track emission sites[21,33].

In recent experiments with single cell 3000 Mhz cavities made out of high purity Nb, it was observed that a bakeout of several hours at temperatures between 850 and 1100 C strongly reduced emission as compared to tests on the same cavity after standard surface treatment. Only a few such experiments have been completed and plans are underway to thoroughly explore heat treatment as a potential cure for FE using high purity Nb 1500 Mhz and 3000 Mhz cavities[33].

## Surface Resistance

The histogram in Figure 7 summarizes the low field residual resistance obtained in 23 tests on several single cell 1500 Mhz cavities. The mean value corresponds to a Q of 1 - 2 $\times 10^{10}$. The spread shows that we do yet not control the important variables. Comparable values have been obtained for similarly processed cavities at other frequencies from 350 - 3000 Mhz.

For a long time there has been speculation regarding the importance of residual lossses caused by natural oxides of Nb. Recently, a lower limit of 1 -2 nano-ohms has been ascertained for this contribution to the residual resistance[34]. 8.6 Ghz Nb cavities have been fired at 1400 C to dissolve the oxide layer into the bulk, as confirmed by companion Auger studies on similarly treated Nb samples. Rf tests in the oxide free state show a residual resistance level of 5 -10 nano ohms. Oxide layers subsequently grown on these "clean" surfaces by controlled exposure to 0.1 torr oxygen for two days do not show any increase

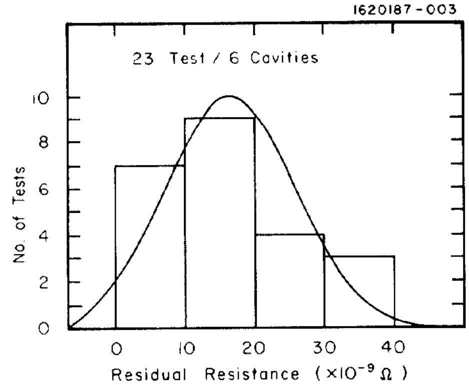


Figure 7. Residual resistance obtained in 23 tests on 6 single-cell cavities at 1500 Mhz (Cornell).

above 1 - 2 nano-ohms in residual losses.

Improvements in the sensitivity of spatially resolved thermometry, together with availability of scanning surface analytic tools indicate that the time is ripe for a direct understanding of mechanisms that cause losses in SRF cavities. For these studies, a test cavity with a 100 $cm^2$ demountable end plate scanned by very sensitive thermometers has been developed[35]. Micro-kelvin temperature increments are measurable, so that nano-ohm residual losses are discernable. To study the lossy areas detected by thermometry system, scanning electron microscopy, energy dispersive X-ray elemental analysis and the use of other surface analytic instrumentation is envisioned. UHV heating as a final surface treatment for reducing residual losses is also envisioned.

## Alternate Materials

$Nb_3Sn$ surfaces bave been produced on low frequency (500 Mhz[36] and 1 Ghz[37]) cavities with $Q_0$ values over $10^{10}$ at 4.2 K. Maximum accelerating field levels remain in the 5 - 7 Mev/m range, below those achievable with comparable high purity Nb cavities. Work is in progress to locate the breakdown areas by thermometry and to study the frequency dependence of the residual losses. The promise of higher Q's at 4.2 K and the higher intrinsic thermodynamic critical field of $Nb_3Sn$ continues to motivate efforts on this material.

Sputtered Nb surfaces on copper substrates are now produced by a magnetron system to increase the deposition speed and quality of layers[38]. The best results are comparable to high purity Nb cavities, but reproducibility is a problem due to local blistering. The residual losses of sputtered Nb surfaces are some of the lowest on record (4 nano-ohms) for non heated surfaces and the sensitivity to the ambient residual dc magnetic field is markedly lower than for bulk Nb cavities. The potential pay-offs in material cost reduction, pipe cooling and stability against breakdown remain strong incentives to master these problems.

## Conclusions

Rf superconductivity has become an important technology for particle accelerators. Experience with existing machines has shown that the alluring features of high accelerating fields with low rf losses can be maintained for operationally significant lengths of time. Practical structures with attractive performance levels have been developed for a variety of forthcoming applications. In the next five years, realization of the current plans will depend on the successful extrapolation of past efforts that have produced, installed and operated several 10's of meters of superconducting structures to scale of several 100 meters. Steady progress in the discovery and invention of ideas, techniques and materials have brought SRF devices to the stage where 5 Mev/m at Q's $> 3x10^9$ are expected on a reliable basis and chosen for the design of forthcoming machines. These levels are modest by comparison with the full potential of rf superconductivity.

Future advances will depend on a continuation and expansion of efforts currently underway to improve our understanding of field emission, surface resistance and material properties of promising superconductors. By realization of the full potential, this technology may eventually play a parallel role for electron accelerators as superconducting magnets do for proton accelerators.

## Acknowledgements

Compilation of information for this review has been made possible by information kindly provided by Y. Kojima (KEK), H. Lengeler (CERN), H. Piel, G. Mueller and M. Pienegar (Wuppertal), K. Shepard (Argonne), A. Schwettman and T. I. Smith (Stanford HEPL), D. Proch (DESY), S. Fornaca (TRW), and S. Tazzari (Frascatti). I am also grateful to my colleagues from Cornell and CEBAF for many helpful discussions.

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