SUPERCONDUCTING RF ACTIVITIES AT CORNELL UNIVERSITY

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Introduction

This paper will outline the RF Superconductivity research and development work that has taken place at Cornell Laboratory of Nuclear Studies over the past years. The work that has been performed since the last RF Superconductivity workshop will be emphasized together with a discussion of the direction of our future efforts.

Past Work

Research and development activities in the area of RF Superconductivity have been carried out at Cornell Laboratory of Nuclear Studies for more than 20 years. This work, for the most part, has been concentrated on the development of better accelerating structures for particle beams using the state of the art techniques available at that time. In general these projects have been divided into large scale development efforts centered around the particular structure needed. During the course of these developments, the state of the art has been considerably advanced over the years.

The first full scale structure that was developed was an 11-cell S-Band "Muffin Tin" cavity that was tested in the Cornell Electron Synchrotron in 1975 [1]. This structure, machined from solid Niobium, operated at an accelerating field of 4 MV/meter with a Q of $1x10^9$. A picture of 1/2 of this structure is shown in Figure 1.

Several years later when CESR, the electron positron storage ring, was built at Cornell [2], the direction of the Superconducting RF effort changed to storage ring acceleration.

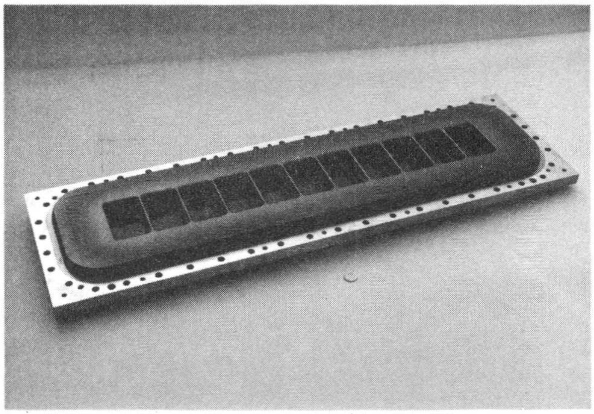


Figure 1

The first major effort in this era was the development and test of a pair of 5 cell "Muffin Tin" structures operating at 1500 MHz [3]. These structures incorporated HOM (higher order mode) waveguide output couplers and there were grooves in the cup bottoms to eliminate multipacting [4]. These structures operated in CESR with 12 ma of current at a field of 1.8 MV/meter and a Q of $1x10^9$. One of these 5 cell structures is shown in Figure 2.

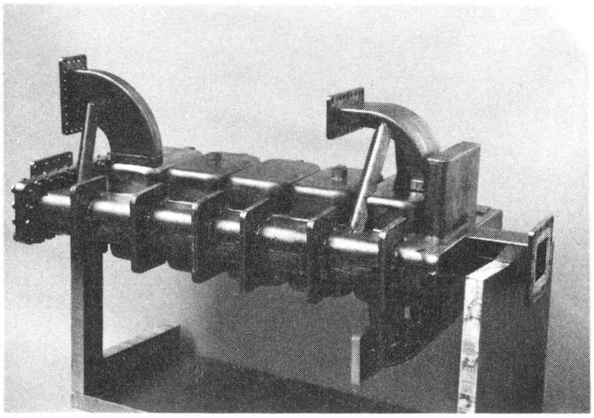


Figure 2

Both of these tests were "firsts' for the operation of Superconducting RF structures in circular accelerators and storage rings.

In 1982 the Cornell effort changed over from "Muffin Tin" structures to "Elliptical" structures with cylindrical symmetry due to their multipacting free behavior. A pair of such 5 cell circular structures was tested in CESR in 1984 [5]. The better of the two cavities reached 6.5 MV/meter at a Q of 5×10^9 and 22 ma of beam current was accelerated.

These structures, which incorporated wave guide type fundamental and HOM coupling, were made of high RRR material for increased thermal conductivity. The desire was , of course, to increase the stabilization of the thermal defects [6].

Several of these structures were manufactured at Cornell and this design was subsequently adopted by CEBAF for use in the recirculating superconducting electron linac being constructed in Newport News, VA. Several hundred of these cavities will be manufactured by industry in the next few years[7]. Cornell transferred the technology to industry to allow this. A picture one of these cavities is shown in Figure 3.

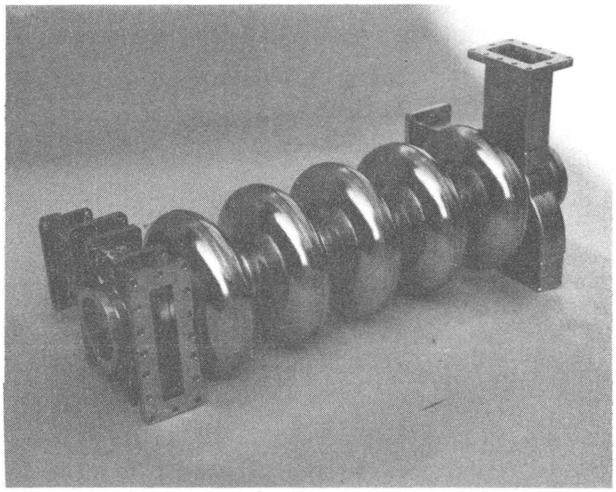


Figure 3

During the course of development and testing of these varied structures, Cornell has contributed to the technology pool available to the superconducting community on many fronts [8],[9]. Table 1 lists some of these areas.

Table 1

- Muffin Tin Cavity Shape Development.
- Niobium Sheet Metal Technology, Deep Drawing, etc.
- Niobium Hydroforming, (multicell cavities)
- Electron Beam Welding of Niobium.
- Electropolishing of Niobium.
- Chemical polishing of Niobium.
- Stabilization of Defects with High RRR Niobium.
- Solid State Gettering to Enhance Commercial Nb. RRR.
- Production of High RRR Materials.
- Waveguide Coupler Designs.
- Niobium Waveguide and Bellows Manufacture.
- Thermometry Diagnostic Techniques, Including Superfluid He. Operation.
- Cavity Tuners and Cold Drive Motors
- Horizontal Beam Test Cryostat Design.
- Basic Field Emission studies.
- Residual Losses.
- Characterization of Defects and Emitters.
- Cavity Manufacturing Technology Transfer to Industry.

Superconducting TEV Linear Collider

Since the last workshop the main thrust of our effort has been to attack the research and development effort required to successfully apply superconducting RF to a future TEV linear collider [10].

Very briefly, the inherent advantages offered by a superconducting acceleration system for a TeV linear collider are:

a)long filling times eliminate the need for ultra-high peak power sources. TeV colliders based on normal conducting linacs require peak powers of

500 to 1000 Megawatts per meter of structure, as compared to 100-200 Kilowatts per meter for a superconducting linac.

b)long RF pulses allow trains of 100's of well separated bunches for efficient conversion of RF to beam power, and

c) efficient storage of RF structure energy allow a low RF frequency, highly desirable for limiting long and short range wakefields and their adverse effects which exact extremely tight tolerances on the alignment and jitter in the linac. normal conducting linac proponents are considering RF frequencies of 20-30 GHz. A superconducting linac would use 3 GHz.

In the first version of a fully superconducting collider, we consider a C.M. energy of 2 TeV with a luminosity of 10^{33} $cm^{-2}sec^{-1}$. The source emittance, damping ring parameters, final focus and bunch length used are chosen as typical of values obtained in the SLC. This approach eliminates the need for technological development beyond SLC on these fronts. The mode of operation of the superconducting linac is to pulse the RF, accelerate a train of bunches and then dump the stored energy. Between pulses a fresh train of bunches is cooled in the damping rings. Because of the long RF pulse (0.5 msec) suitable to a superconducting linac, a large number (≈60 x 2) of damping rings are required. With a duty cycle of 1% and Q values of 10^{10}, it was shown that the capital costs of the refrigeration system become very small in comparison to the structure cost and injection system. The overall capital costs decrease sharply as gradients approach 30 MV/meter.

Recently, considerations for a TLC by SLAC and others have led to damping ring designs superior to the SLC damping rings. Such rings could yield horizontal emittances a factor of 10 lower, vertical emittances a factor of 1000 lower, and can store 100 bunches. Main improvements stem from the use of wigglers, and very low impedances in the ring. Similarly, improvements in the final focus systems are projected. Use of very small aperture quadrupole magnets are considered to reduce β^*_y's by a factor of 25. We have started to explore versions of a superconducting linear collider that incorporates these conceptual advances under exploration for a TLC.

Using a set of self consistent parameters developed for a TLC (E=1 TeV C.M., L=$10^{34}$$cm^{-2}sec^{-1}$) we considered the simple substitution of a low frequency (3 GHz) superconducting linac in the place of the room temperature TLC structure. This parameter set is for 1 TeV C.M. energy, and yields a luminosity of $10^{34}$$cm^{-2}sec^{-1}$. Several improvements are realized over the previous superconducting TeV collider version aside from the factor of 10 higher luminosity. A substantial reduction is possible in the number of injector damping ring pairs, i.e. from ≈60 to 2. With a factor of 4.5 lower beam power and a factor of 2.5 lower dumped stored energy, the total wall plug power demand (including the refrigerator) is reduced by a factor of 2 in the new version, to below 100 Mwatts. Incidentally, the normal conducting TLC version is based on 200 Mwatts total AC demand.

The major challenge for the superconducting TeV linac is to improve the gradients beyond the current capabilities, while at the same time reducing unit costs.

Linear Collider Structure Development

We have continued our efforts towards

development of a simpler (and thereby cheaper) structure for a TeV linear collider. The thrust of this effort has been to improve the couplers. Beam stability calculations completed (see below) suggest that the HOM damping requirements for a TeV collider structure are significantly relaxed over that needed for a storage ring, encouraging our quest for more than 5 cells per cavity module.

A key issue in the design of an accelerating structure for a superconducting TeV linac is the degree of damping required for higher order modes. Bunches at the head of the bunch train excite parasitic cavity modes that interact destructively with trailing bunches. The effect of the longitudinal modes is to introduce energy spread from one bunch to the next and from head to tail,within one bunch. Dipole modes are excited by bunches that are displaced transversely and these cause emittance growth of the beam.

Simulations were carried out to establish stability limits. In the simulations, the minimum spacing between bunches is determined by the shunt impedances and damping times ($\approx Q_{ext}$) for various higher order modes, the charge in the bunch and the spread in the frequencies of the modes from one structure to the next. For the distribution of modes, impedances and loaded Q's we used the measured values in a 5 cell structure developed for CESR II (now adopted by CEBAF). A spread in the frequencies, $\Delta f/f=2x10^{-5}$, was used for each of the HOM's considered. For a bunch charge of a few 10^{10} particles it was found that the loading typical of multicell superconducting cavities for storage rings permits stable acceleration for bunches spaced within as few as 10 nsec of each other. Equivalently, less damping (higher Qext) is tolerable if the bunches are spaced further apart. In the superconducting linac with TLC beam parameters presently under consideration, a bunch spacing of 1 μsec is used, so that the density of higher mode loads per unit length of linac can be reduced, translating to the possibility for increasing the number of cells per structure. Storage ring type structures have typically 4-5 cells per unit with two HOM couplers located at the beam pipe past one end cell. Units with 10 cells per HOM coupler would greatly reduce structure cost, the dominant capital component for the fully superconducting linear collider. Encouraged by these results we are investigating how much damping is lost for the dangerous modes by going from 5 to 10 cells.

Progress has been registered toward development of a simpler and thereby cheaper accelerating structure design than the Cornell 5-cell, elliptical cavity (LE-5). Current experience with fabricating these cavities shows that a large fraction of the structure cost is associated with the complex Higher Order Mode (HOM) couplers and the Fundamental Power Coupler (FPC) ports. The HOM coupler has three waveguide arms in a Y-shape configuration,with two arms serving as ports and the third as a matching stub. The FPC is a larger waveguide with a matching stub, and a stub-on stub section to assist in coupling out 8 of the lowest frequency HOM's. In developing a new design, we reduced the number of HOM ports at the end of the structure from two to one by controlling the mode polarizations in the individual cells. Without this control, one polarization of each deflecting mode has negligible coupling. Measurements on 5-cell copper model cavities with polarized cells showed that both polarizations of dangerous dipole modes can be coupled out of a single arm [12]. Of the first 20 dipole modes studied, all had Q_{ext} between $1x10^4$ and $1x10^5$, except for 2 which had Q_{ext} of $5x10^5$. One of these had sufficiently high impedance that the coupling needs to be further improved. For the most dangerous monopole HOM family, very satisfactory Q valuesof $2x10^3$ to $1.4x10^4$ were obtained with the single coupler.

Another refinement of the single-arm HOM coupler allows a major simplification of the FPC port, through removal of the stub on stub, previously necessary for extracting 8 of the lowest frequency higher order modes. These modes now couple effectively through the single HOM port. Apart from reducing Nb structure cost, these improvements will also lower the cryostat cost by reducing the number of penetrations and through a reduction in the overall diameter of the structure and the liquid He vessel. Elimination of couplers also reduces the overall heat leak.

Further savings are realized by introducing a battery of simplifications in fabrication procedures. the elliptical profile is replaced by a geometry that can be specified more simply by two circles and a straight segment, allowing less complex numerical milling machine codes used for cutting the dies. The machined step at the mating surfaces between the cavity parts is eliminated. Beam welding parameters are developed that allow all cylindrically symmetric welds to be carried out in a single pump-down of the weld chamber, i.e. all equator and iris welds can now be done from the outside in one step. Grinding of iris welds and cavity surfaces is left out. This eliminates labor intensive interruptions for repeated inspections, and chemistry during the fasbrication sequence.

A cold testing program for 2.8 GHz, 1-cell and 3-cell Nb polarized cavities has been started. Commercial high purity Nb with RRR =250-300 is used as a starting material and improved to RRR=450-500 with yttrification. All Nb cavities are fabricated by simplified techniques discussed above. Tests on companion unpolarized Nb cavities are also started. At low field, best Q values of $2x10^{10}$ and $1x10^{10}$ were reached in 1-cell and 3-cell polarized cavities. After standard chemical treatment, the highest surface electric (magnetic) fields reached were 31 MV/meter (610 Oe) and 25 MV/meter (490 Oe) in a 1-cell and 3-cell, limited by heavy field emissinn in both cases. These surface field values are comparable to those obtained after standard chemical surface treatment with 1500 MHz cavities.

Shape distortions necessary for polarization did not regenerate any multipacting problems, which settles a key question regarding the suitability of polarized cells for superconducting cavities. It is planned to continue these tests with efforts to reduce field emission using heat treatment and to increase field levels.

B Factory With Superconducting RF

Recent developments have intensified the laboratory's efforts to formulate a conceptual design for a B-factory. There are important reasons for considering a superconducting RF system for a B-factory. Many of the issues that are being addressed to advance RF superconductivity for linear colliders overlap the research necessary to bring superconducting cavities into service for a B-factory. Accordingly our efforts at improving the performance of Nb cavities will benefit both B-factory and linear collider applications.

For a future high luminosity B-factory, one approach that is actively under consideration relies on bunches that are a factor of two shorter than used in CESR. To achieve the short bunches will require a factor of 4 higher voltage. If two rings are used, as seems likely to optimize the conditions to push for the highest possible luminosity, the total voltage demand for a B-factory will be 56 MV as compared to 7 MV presently supplied by the copper RF system for CESR. Superconducting cavities can economically provide this high voltage. The total RF power (including higher order mode losses) consumed by a copper cavity system similar to the CESR RF will be 23 Mwatts. By comparison, the total RF plus refrigerator power to maintain a superconducting system at 4.2 K will be 1.4 Mwatts, more than an order of magnitude lower. This does not include the power into the beam in either case. These estimates are based on a preliminary parameter list which assumes 500 MHz for the RF system [13].

Among other factors, the maximum current in storage rings is limited by disruptive beam cavity interactions. A key feature essential to achieving high luminosity is to lower the impedance presented to the beam by the cavity and other components. Use of high voltage superconducting cavities minimizes the overall accelerating structure length, and thereby the accompanying cavity impedance. Moreover, copper cavities have small beam holes to provide the maximum voltage for the RF power expended, thereby intensifying the disrupting wakefields. Superconducting cavities can have large beam holes and geometries more suitable for higher beam currents. A comparison of CESR and superconducting cells indicates that the total beam induced HOM loss factor for CESR is 3 times higher.

A superconducting RF system for a B-factory poses severe challenges in several arenas. To minimize the overall cavity impedance it is desirable to operate at the highest possible gradient. Today, 5-cell superconducting cavities are operated in the storage ring TRISTAN at accelerating gradients of 5 MV/meter. Without beam, the average gradient reachable by the system is 7.5 MV/meter. Prior to installation into the ring, off-line tests showed that individual structures are capable of 10-12 MV/meter. Relying on continuing technology advancements forthcoming over the next several years, we may (optimistically) expect to operate a B-factory SRF system at accelerating gradients of 10 MV/meter. Our efforts to understand and suppress field emission will continue to remain of highest importance if we are to be successful in this regard.

B-factory Structure Development

A major challenge lies in advancing the capability of sc cavities to carry beam currents of several amperes necessary for a high luminosity storage ring. The maximum current handled by sc cavities to date was ≈ 30 mA. New fundamental and HOM couplers with substantially enhanced power capability will need to be invented to safely couple in the required beam (plus HOM power) of nearly 1.5 Mwatt/meter, and to safely couple out the beam induced HOM power at the level of 200 Kwatts/meter. These are heavy demands over the capability of components presently used in sc cavities, which can handle 100 Kwatts/input coupler and 10-100 watts/output coupler. To improve our chances of success, it will be necessary to distribute the input and output powers over a large number of couplers. A convenient approach under consideration is the use of single cell cavities with individual input and output couplers per cell.

Several initiatives are under way to address these challenges. Our immediate objective is to study those issues that will help us make basic design choices for a cavity/coupler unit suitable for service in a B-factory. A specific design will follow as the logical,next step. Depending on the availability of additional resources, we aim to complete the design so that we may place an order for prototype Nb cavity fabrication to industry in the next year. Initial planning for a chemical treatment and cold test facility will also be started.

Initial considerations are being given to the degree of mode damping necessary to ensure beam stability, the fate of HOM power that travels freely down the beam pipe, as well as the development of a power window with 1/2 Megawatt capability.

Other structure development issues are also being addressed. The shape of cells will be optimized to provide the lowest HOM loss factor for the best fundamental shunt impedance. Careful attention is being paid to the need to minimize the additional impedance associated with the holes presented by the couplers. Preliminary calculations using the BCI code indicate this to be a serious consideration, but the restriction of cylindrical symmetry characteristic of the BCI code necessitated examination of a much larger disturbance than a coupler hole. To make a realistic evaluation, we have installed the 3D MAFIA code, which will allow us to calculate the loss factor for coupling holes on the beam tube. This code will also help us with other design features such as the optimal shape and location of coupling holes. An RF bench modeling effort is already underway to determine the minimum hole size necessary to provide the needed external Q ($2x10^5$) with a waveguide type input coupler. Model measurements are also underway to determine the extent of damping that a single waveguide type HOM coupler will provide in a one cell cavity.

We plan to carry out straightforward calculations to determine the HOM power deposited by the beam in modes with frequency below cut-off of the beam-pipe. This power will have to extracted from the cavity. Longitudinal and transverse modes will have to be damped sufficiently to avoid instabilities.

Towards Higher Gradients

The key to the realization of a high energy superconducting linac or a superconducting RF B-factory is high gradients in practical accelerating structures. At present electron field emission limits the peak surface field that can be supported in superconducting cavities.

In the last year our efforts to increase the field capabilities of Nb cavities using furnace treatment in the final stages of surface preparation have been very successful [14]. This treatment reduces the number of field emitters present on the surface of a sc cavity. We have now completed a total of 12 separate heat treatments between 1100 and 1350 C on several 1-cell, 1500 MHz high purity Nb cavities and compared their performance with 15 tests conducted in the past on the same cavities, but with the standard chemical surface treatment (CT). On the average,the peak surface electric field achieved with heat treatment (HT) was 40 MV/meter, with 53 MV/meter as the new record. Without heat treatment, the average is 22 MV/meter, consistent with the current capability of the structures built today for application to electron accelerators. Therefore, the new final surface treatment procedures provide an 80% increase in gradient capability, a substantial step towards making the superconducting cavity approach an attractive choice for a TeV collider. Figure 4 shows the vacuum furnace built for this purpose.

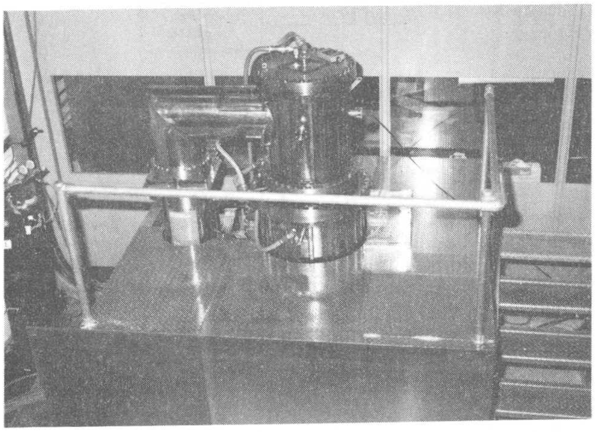


Figure 4

In the first 9 heat treatments, an important problem we faced was that the RRR of high purity NB drops due to absorption of oxygen into the bulk from the residual gases in the furnace, decreasing the bulk thermal conductivity of the cavity wall and increasing the probability of thermal breakdown at minor surface imperfections. To minimize this effect we restricted the treatment time and temperatures, i.e. 1250 C for 2-5 hours or 1350 C for only 10 minutes. Among these tests, the more recent showed increased relief from field emission with higher temperature and longer times. To continue to push in this direction, we devised a technique that allows 1350 C heat treatments for 4 hours (or longer) without decreasing Nb purity (RRR). In the new procedure, Ti sheets surround the outside of the cavity. Evaporated Ti forms a protective film against gases striking the outside of the cavity. Gases striking the inside (RF surface) diffuse rapidly to the outer wall and are removed from the Nb by the solid-state gettering process at the Nb-Ti interface. To prevent Ti vapors from reaching the interior of the cavity, the Ti sheets are surrounded by an outer can of Nb. After the heat treatment, the Ti rich layer on the outside is chemically removed while the cavity which is filled with class 100 clean room air is sealed so that the heat treated RF surface is not exposed to acids. The removal of this Ti rich layer is necessary in order to achieve adequate heat transfer from the cavity to the surrounding liquid helium. RF test results following this procedure are very encouraging. Figure 5 shows a histogram which summarises these results.

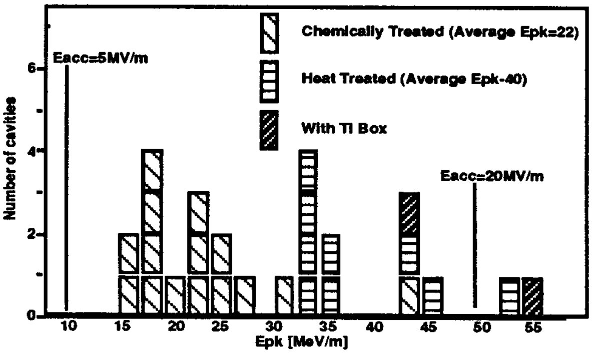


Figure 5

Without the use of He processing, 41 and 45 MV/meter were reached in two separate tests with Q values over $2x10^9$: both results surpassed the 36 MV/meter maximum achievable field with RF processing alone. With He processing, fields could be further increased to 43 an 53 MV/meter (current record). Figure 6 shows schematically the vacuum furnace with the Titanium box containing a cavity.

While heat treatment is beneficial in reducing the number of emitters present on the surface, we find that RF processing, especially in the presence of He gas is very effective in further reducing emission. Our studies show that the benefits of processing at a fixed RF power level diminish after a short period, but further gains are possible as the RF power is increased.For continued exploration with this approach we have installed a 3 GHz pulsed high power RF source with the capability to provide 2.5 msec wide pulses of 200 Kwatt peak power at a repetition rate of 1 Hz. For this source, the Klystron and socket were obtained gratis from Rome Air Force Base.

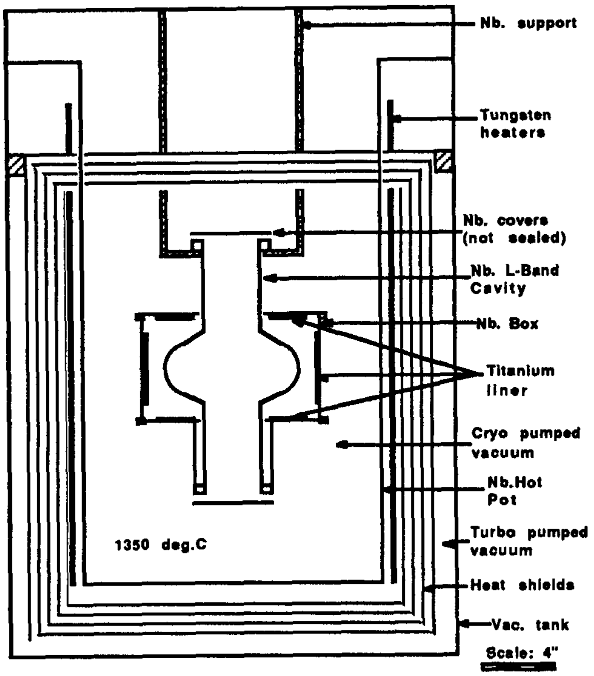


Figure 6

The Klystron is equipped with a modulating anode which will permit a variable pulse length to study the effect of increasing the cavity fields very rapidly. We have installed a high voltage power supply, capacitor energy storage, a mod anode driver, RF distribution, cooling, controls and safety systems. The power supply has been operated with pulsed DC current to a peak power of 400 Kwatts and an average power of 2 Kwatts with a pulse width of 2 msec. The Klystron has been operated at full emission current and full voltage [15]. RF tests have started and the peak power from the Klystron has been raised to 100 Kwatts. A schematic of the transmitter is shown in figure 7.

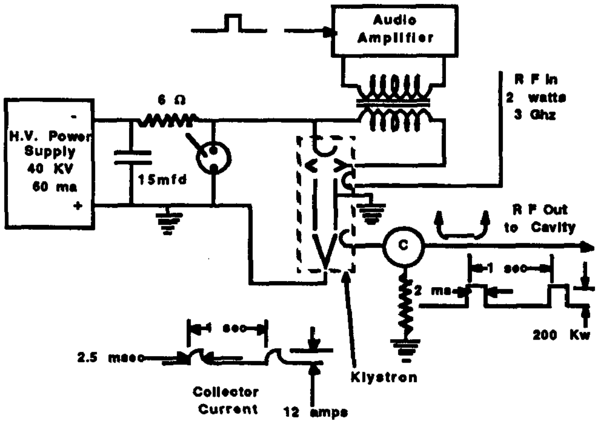


Figure 7

A cold test set-up for 3 GHz Nb cavities with high power input coupler is designed, modeled for RF properties on the bench, constructed and presently undergoing cold tests at low power. The input coupling can be varied from a Q_{ext} of 10^5 to 10^{10} without breaking vacuum. In the strong coupling extreme, 200 Kwatt peak power provides the capability to raise the peak surface field to 70 MV/meter within a 10 µsec (1-cell) cavity fill time. Higher fields can be reached with longer fill times at reduced coupling, depending on the progress of processing. After completion of high power processing, with or without He, it will be possible to withdraw the coupling to a Q_{ext} of $1x10^{10}$ to evaluate whether the ensuing benefits will allow a high field with the standard low RF power source and long fill time. A drawing of this test stand is shown in Figure 8. Further details are presented in a contributed paper at this workshop.

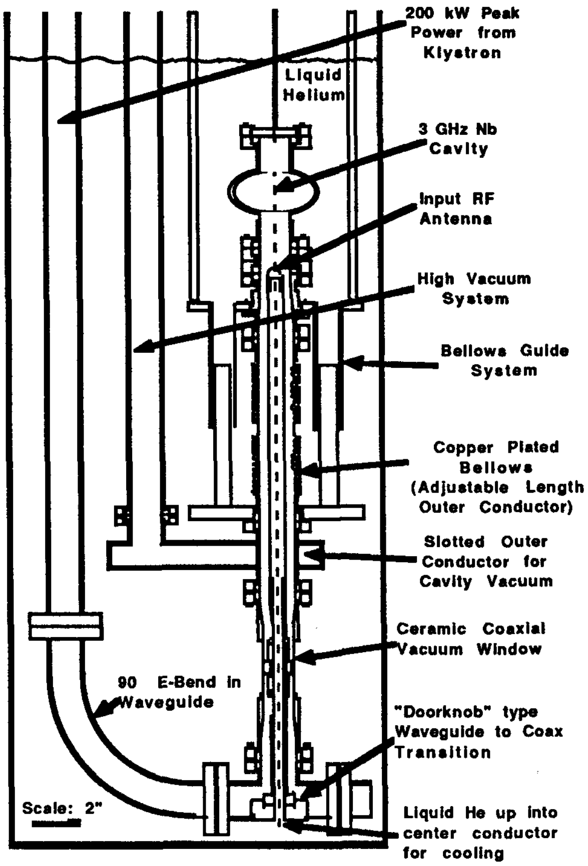


Figure 8

Basic Understanding of RF Superconductivity

Among the most basic questions pertaining to the high field capability of Nb cavities is whether a Nb surface under any condition will tolerate the needed surface electric fields. DC electric fields as high as 200 MV/meter have been achieved over cm^2 Nb surfaces.However, the highest RF surface field ever achieved with a Nb cavity was 70 MV/meter. A Nb cavity operating near the theoretical limit set by critical magnetic field(2000 Oersted) needs to support a surface electric field of $\approx$100 MV/meter. Heat treated 1.5 GHz single cell cavities in our laboratory now frequently reach 40-50 MV/meter. These cavities have large areas simultaneously exposed to high electric fields, so that emission from a few spots limits application of higher fields elsewhere, even though other areas may have the higher intrinsic capability.

A new "mushroom" cavity [16] was designed to determine the intrinsic capability of Nb surfaces with regard to high RF electric fields. A standard S-band accelerator cavity half cell was closed off at the equator with a Nb plate. We have experimented with non-accelerating higher modes, in which the cavity has a very small area exposed to electric fields that are 4-6 times higher than anywhere else on the surface, depending on the mode. The cavity also has a very favorable ratio of peak surface electric to peak surface magnetic field. At 100 MV/meter, the highest surface magnetic field is 1300 Oersted, well below the theoretical limit.

Several Nb mushroom cavities have been constructed, both of a closed and of an open design.These closed and open designs are shown in Figure 9 and Figure 10.

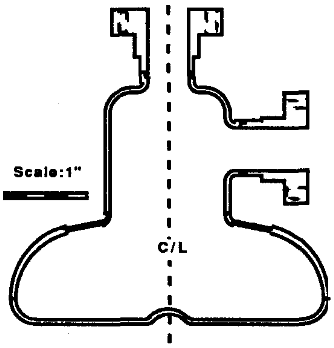


Figure 9

In the closed design, after some initial difficulties with low Q values, as well as some early problems in identifying the desired modes from neighboring unwanted ones, we have had two very successful tests. After reaching a Q value of 3x10^9 at low fields, we were able to apply the available RF power

(20 watts). Peak surface electric field values of 80 MV/meter and 145 MV/meter were achieved at the maximum field region. There were several multipacting barriers that successfully processed away. We did observe emission but we suspect that it originated from a lower field region around 30 MV/meter, where the area and probability of encountering emitters is significantly greater. These results established that there are no fundamental limits to reaching the desired RF electric fields on Nb surfaces.

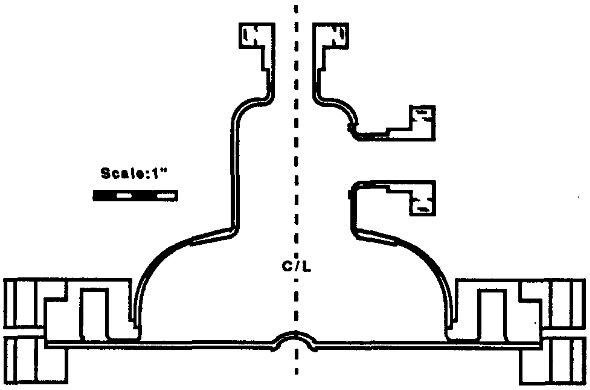


Figure 10

The open design of the mushroom cavity has also been tested. The concept of this design is that, a demountable bottom plate, including the high field region, can be removed and the details of emitter sites can be characterized with SEM and EDX surface analysis techniques. This flat bottom plate is sealed at the equator to the rest of the cell with a circular choke joint and an indium seal. While this open design has not yet reached high fields, the Q, including the choke joint, has been measured at 9 x10^9. Further details of this work are presented in a contributed paper at this workshop.

Our search for the sources of emitters that contaminate RF cavities continues. We have exposed RF surfaces which can sustain high electric fields (30-50 MV/meter) to various mediums with which a cavity comes into contact in the course of surface preparation. At present we have excluded Class 10-100 clean air and the clean methanol routinely used for final rinsing. Remarkably, we were able to reach 53 MV/meter both after exposure to clean air followed by rinsing with clean methanol. Two separate tests showed that the rinsing water we use is richer in emission sites, but He processing was found effective against these sites, so that original performance was eventually recoverable. We addressed the question of whether a heat treated cavity will retain its superior performance if the surface is reprocessed by standard chemical treatment. Three tests on this question have shown that the performance falls back to the level of cavities without heat treatment, so there is no memory of the benefits of heat treatment. Tentatively, these results suggest that chemical residues and/or inclusions within the Nb material are dominant sources.

We have established the presence of dormant emission sites that can be activated by condensed gases even from the vacuum system at the test set-up. Such sites appear to be present independent of specific surface treatment. Perhaps condensed gas is the active culprit in many sites. Unfortunately the presence of dormant sites implies RF or He processing has to be repeated to some degree each time a cavity is cycled to room temperature. Till now we have always been able to re-establish maximum fields after cycling to room temperature by additional RF or He processing.

High Tc superconductors (HTS)

Our main effort was devoted to characterizing the RF behavior of material provided by our collaborators, AT&T Bell Labs, Bellcore, GE

Research & Development, Superconducting Technology Inc. Most of our samples were YBaCuO, and a few thin films of TlSrCaCuO.

The best RF properties were observed on a batch of crystals (total area 20mm^2) from AT&T. 6 GHz measurements showed a narrow RF transition with 89 K onset and more than two orders of magnitude drop in RF surface resistance between Tc and 0.9Tc. In separate runs individual platelets showed Rs<5x10$^{-4}\Omega$ at 77 K. These values are considered an upper limit as the Q of the test vehicle was still affected by the sample holder. With a higher sensitivity calorimetric technique developed for this purpose, we know that the resistance is 2x10$^{-5}\Omega$ at 3 K. The response of the crystals to higher RF magnetic fields was also superior to other forms of HTS studied. Below 20 K, the surface resistance remained below 5x10$^{-4}\Omega$ up to 90 Oe.

Significant improvements over the past year were observed with polycrystalline and thin film material that we have measured [17].

One possible reason for the previously observed inferior properties in randomly oriented polycrystalline HTS ceramics could be related to the anisotropy of the superconducting properties; crystals aligned unfavorably with the sampling RF field could be responsible for the high resistance. another possibility is related to the difficulty of carrying current across the grain boundaries due to weak links arising from wrong phases, impurities, etc. known to be present at the boundaries. To elucidate the contribution from these two potential problem sources, we measured the RF properties at 6 GHz of an oriented polycrystalline ceramic pellet prepared by General Electric, Schenectady, from a suspension of high purity powder in a 4 Tesla magnetic field. At liquid He temperature, the surface resistance was 18 times lower when the c-axis is perpendicular to the plane in which RF currents flow, than when the c-axis is in the plane. At 77 K, the surface resistance was 3 mΩ, a substantial improvement over the properties of the best randomly oriented material reported (10 mΩ). At 4 K the resistance improved to 0.3 mΩ. These values were all taken below 10 Oersted, as in the polycrystalline material. Our results at 10 Oersted indicate that while the low field RF behavior is strongly improved by orientation, the high field behavior is dominated by poor current carrying capacity across weak links. These results are shown in Figure 11a and Figure 11b.

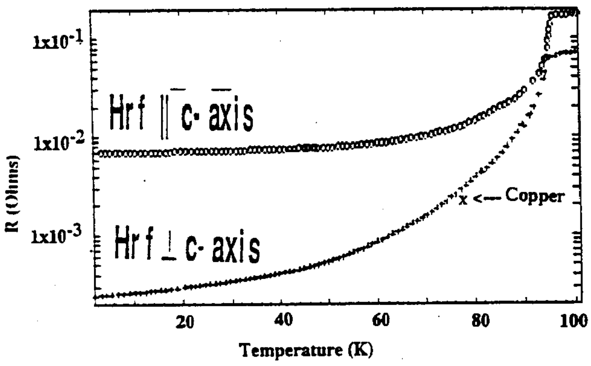


Figure 11a

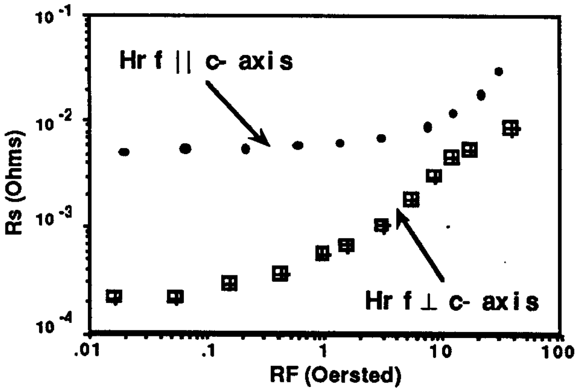
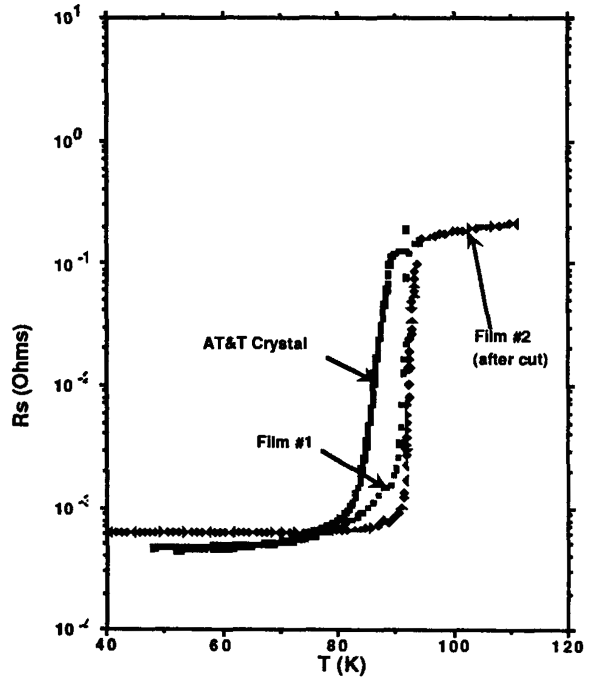


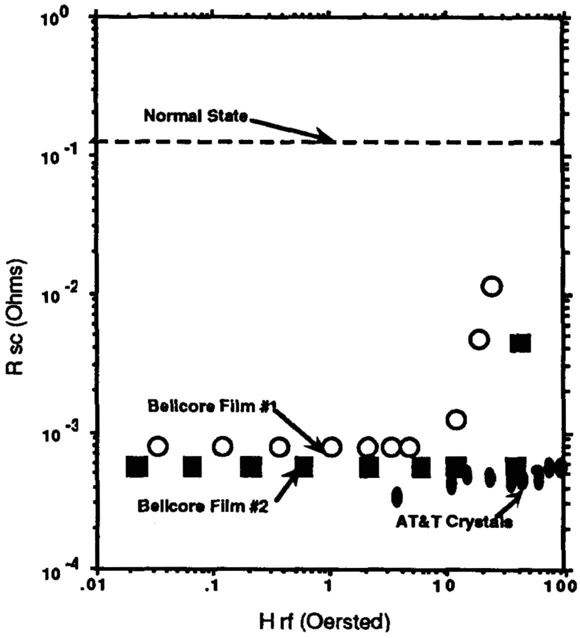
Figure 11b

A high quality, highly oriented thin film of YBaCuO has been received from Bellcore. The film was deposited by Laser ablation on a 25 mm^2 substrate of Lanthanum Aluminate. Bellcore and others have successfully used laser ablation to produce films over 1 cm^2 in area. RF measurements at 6 GHz showed the surface resistance at 77 K is as good as that of the best material we have measured to date (crystals from ATT Bell Labs), i.e., $R_S < 5 \times 10^{-4} \Omega$, an order of magnitude better than copper at the same temperature and frequency. The transition was sharper than the crystals and the onset was 5 K higher, at 93 K. A naked substrate of the same material was separately measured and losses found to be below our measurement sensitivity. The new substrate material is reputed to be comparable to strontium titanate, which up to now has proved the best for YBaCuO. However strontium titanate has extremely high RF losses.

The high RF field behavior of the film was also superior to any film or bulk ceramic we have measured so far, but not as good as the ATT crystals. The surface resistance was insensitive to increase in the RF field up to 10 Oersted, as compared for 90 Oersted for the crystals. We also received a laser ablated Tl-compound HTS film on an MgO substrate from STI , Santa Barbara, CA. With a transition at 120 K, the surface resistance of this film was below 1 mΩ at 77 K. At 4.2 K, the high field resistance remained below 1 mΩ up to 10 Oersted. Both thin film results bode well for laser ablation as a technique for deposition of near crystal quality HTS films. However, it is still a long way before we can expect to apply HTS materials to cavities for particle accelerators. The results of this measurement as well as the single crystal AT&T results are shown in Figure 12a and Figure 12b.



Fugure 12a



Fugure 12b

Summary

We are attempting to address a variety of issues, mostly as they pertain to the application of RF superconductivity to TeV linear colliders and B-factories with superconducting RF systems. In conjunction with this we are continuing to attack the basic issue of field emission.

We feel that we are beginning to understand how satisfactory structure designs might be achieved at a minimum cost.

We have increased our peak surface field capability by various techniques and have not yet exhausted the methods at hand.

We find our group generally has more ideas than we have resources. This is at least a necessary, if not sufficient, requirement for further advancement of the utilization of RF superconductivity.

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