Superconducting RF Activities at Cornell University*

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1 - INTRODUCTION

The efforts at Cornell fall into three major categories; B-factory RF system development, SC Linear Collider studies, and Basic SC studies. This paper will outline and briefly describe the scope and status of these efforts since the last SC workshop at KEK in 1989. The order of discussion is indicative of the relative resources that have been allocated to these three areas. In addition to these activities the First TESLA workshop was held at Cornell during July 1990. The results of this activity will be mentioned.

2 - B- FACTORY EFFORT

For a future high luminosity e^+-e^- B-factory[1], the approach actively under consideration relies on many bunches that are a factor of 2 shorter than presently used in CESR. To achieve these short bunches will require a factor of 4 higher voltage. If 2 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 47 MV as compared to 7 MV presently supplied by the copper RF system for CESR. The total RF power plus refrigeration power to maintain a superconducting system at 4.2 K would be more than an order of magnitude lower than for a copper system. Use of high voltage superconducting cavities also minimizes the overall accelerating structure length, and thereby the accompanying cavity impedance. Moreover, superconducting cavities have larger beam holes and geometries more suitable for higher beam currents than copper cavities. A comparison of CESR and superconducting cells shows that the beam current induced HOM loss factor for CESR cells is 3 times higher.

The proposal includes the use of a small crossing angle (± 12 mr) for the two beams. In order to maintain luminosity and to avoid the excitation of unwanted synchrotron-betatron resonances, a crab crossing scheme will be used.[2] The present plan is that this system, which requires very large voltage but low energy transfer, would consist of superconducting cavities operating in the TM_{110} mode at 500 MHz.

3 - SYSTEM PARAMETERS

The proposed B-factory[3] will consist of a high energy ring (HER) at 8 GeV and a low energy ring (LER) at 3.5 GeV. The total beam currents would be 1 ampere and 2 amperes respectively. There would be 230 bunches in each ring. The HER, with a synchrotron radiation loss of 4.5 Mwatts, would have 12 cavities, each operating at an accelerating field of 10 MV/meter. The LER with synchrotron radiation loss of 1.5 Mwatts, would have 4 cavities, each operating again at an accelerating field of 10 MV/meter. The cavity contribution to the HOM power is of the order 5 Kwatts per cell in both rings whereas the total RF input power into each of the cavities in both rings is approximately 400 Kwatts. The frequency of operation will be 500 MHz. This system will be described in greater detail by Hasan Padamsee in an invited paper at this workshop.

4 - ACCELERATING CAVITY

A sketch of the accelerating cavity system is shown in Figure 1.[4] Because of the very large input power per cell, a waveguide input coupler has been chosen. The beam pipe on both sides of the cavity are very large (240 mm diameter) with the result that all longitudinal HOM's will propagate in the beam pipe. This allows us to absorb this power and damp these modes at room temperature outside the cavity. The complex "fluted" beam tube shape is to take care of the propagation of the TM_{110} and the TE_{111} modes which are cut off in the round beam tube. This scheme proposed by Kageyama at KEK, reduces the cutoff frequency of the transverse modes without changing the cutoff of the longitudinal modes.

SUPERFISH, URMEL and URMEL-T calculations have been made of the cell for the fundamental mode as well as the higher order modes. MAFIA calculations have been made to verify the propagation of the TM_{110} and TE_{111} modes down the fluted beam tube, the wakefield losses in the fluted beam tube, and also to calculate the electric and magnetic fields present around the tongue of the "Sceszi" input coupler.

* Supported by the National Science Foundation, with supplementary support under the U. S. -Japan Agreement.
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[1] M. Tigner, DSC4, 91 PAC, San Francisco, CA
[2] K. Oide, K. Yokoya, Phys. Rev. A 40, 315 (1989)
[3] CESR-B, Conceptual Design, CLNS 91-1050
[4] H. Padamsee et.al., HRA66, 91 PAC, San Francisco, CA

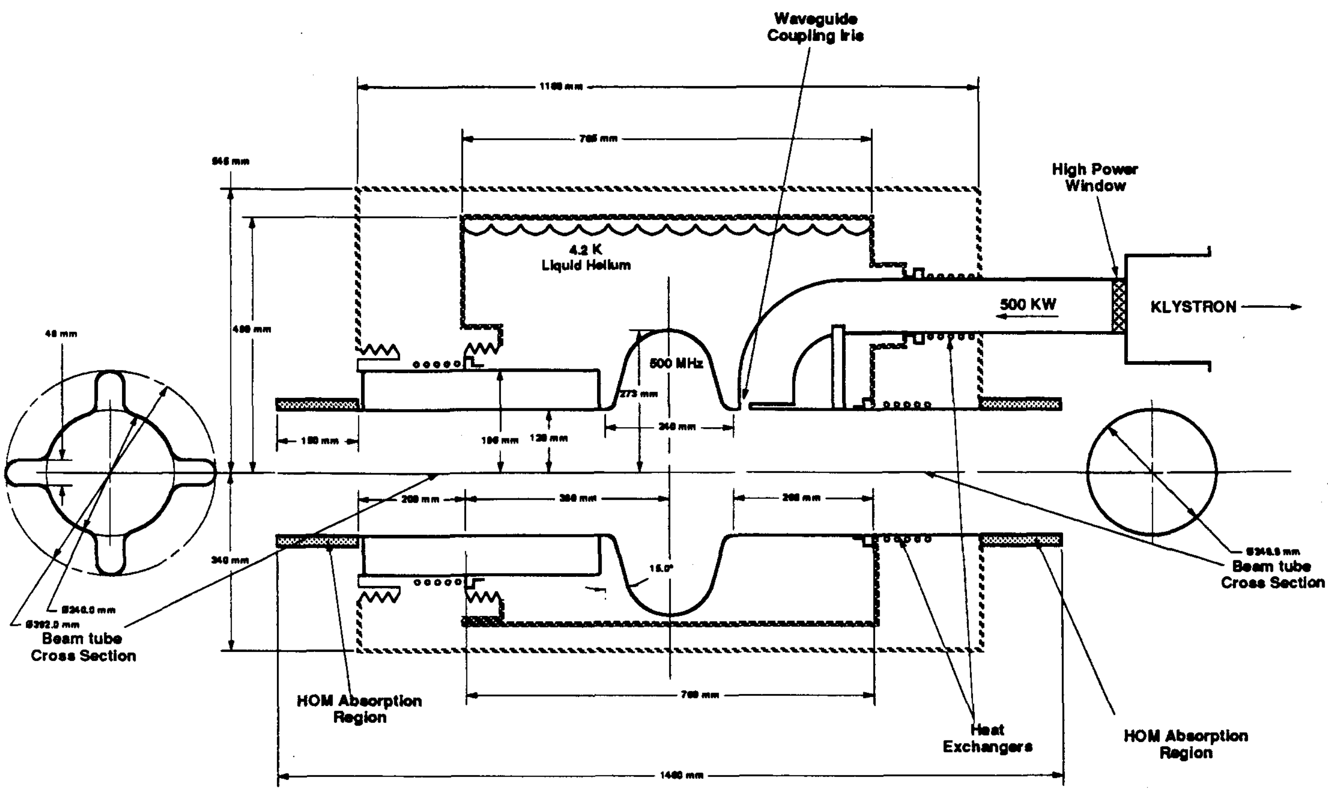

FIGURE 1

The length of the tongue has been adjusted to give a Q_{ext} for the input waveguide of 2.7×10^5. At this value and at the planned excitation level the peak surface electric field in the vicinity of the coupler will be 6.5 MV/meter and the peak surface magnetic field will be 152 Oersteds.

We have ordered one prototype niobium cavity and one copper cavity, complete with waveguide couplers. These components are being manufactured by Dornier GmbH and includes the chemical treatment of the niobium structures. The scheduled delivery for the copper parts is August, 91 and the niobium parts a month or two later. Cornell has manufactured the copper fluted beam tube which will be welded to the cavity by Dornier. The parts for the niobium fluted beam tube are complete but have yet to be welded. When the chemistry is completed at Dornier and the niobium cavity is delivered, the final assembly will take place at Cornell and the cavity will be shipped, under vacuum, to KEK for the first vertical cold tests. In a parallel effort we are upgrading chemistry and vertical cold test facilities at Cornell so that, if required, additional processing and tests can be carried out at Cornell.

In addition to this effort we are manufacturing a 1/3 scale model of this cavity to operate at 1500 MHz. The parts of this model, made of high RRR material, are all complete and welding is now taking place. This model is complete in all details including the waveguide input coupler and the fluted beam tube. It will be tested at Cornell at 2 K and should uncover any unforeseen difficulties associated with this cavity and coupler geometry.

5 - FERRITE HOM LOADS

As mentioned above, all of the higher mode power is transmitted out the beam tubes of the cavity where it may be absorbed at room temperature. This will be done with specially designed Ferrite lined beam tubes at both ends of each accelerating cavity.[5] Because the modes are propagating, these modes can be damped in a 15 cm long beam tube section of Ferrite-50[6] such that the Q's of all the higher order modes are below 200, and most are below 100. The microwave losses of Ferrite-50 have been found to be $\geq 10^4$ times higher than copper at ~ 1 GHz, and to decrease by a factor of 10 at 10 GHz. The tolerance of Ferrite-50 has been tested up to 10 watts/cm^2 in sheets 1/8 " thick. Its vacuum properties appear promising and a 200° C bake is permissible without any apparent loss of the microwave absorptive properties. Bonding techniques are under development and RF measurements have been made on 1/6 scale models. Measurements will soon be made on a full size prototype at low power.

In order to calculate the mode damping in the final cavity, detailed measurements are being made of the material properties of the ferrite, μ', μ", e' and e". These measured properties are then used in SEAFISH[7], a complex version of

[5] D. Moffat et. al., HRA11, 91 PAC, San Francisco, CA
[6] Ferrite-50 is a product of Trans-Tech, Inc., Adamstown, MD
[7] M. S. deJong and F. P. Adams, Proc. of the CEFC "90 Conf., Toronto, Ont. Canada, Oct, 1990

SUPERFISH to calculate the Q's of the various HOM's. Impedance of ferrite beam tubes are being evaluated by wire measurements at Los Alamos.[8]

6 - HIGH POWER RF WINDOW

One of the most demanding needs in the B-factory effort is the development of a window to handle the 400 Kwatts of RF power (traveling wave). In the absence of beam, the window will also have to tolerate 125 Kwatts of reflected power, and the full 400 Kwatts of reflected power for a short time interval in case of beam loss. We have received proposals from 2 RF window manufacturers for a planar waveguide window to meet these requirements and we have ordered and are testing a pair of such windows.[9] A sketch of one of the windows under test is shown in figure 2.

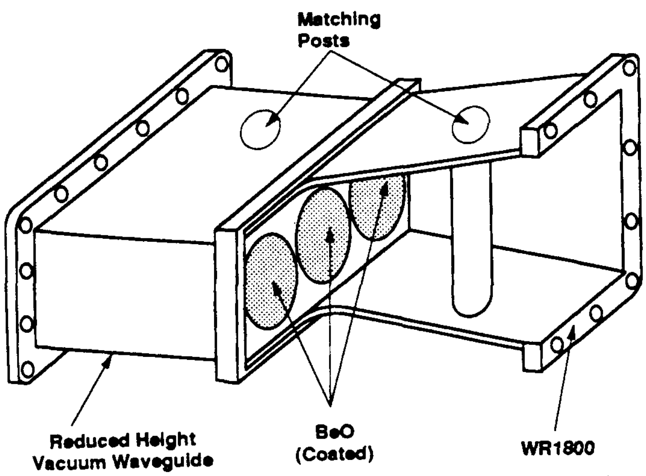

FIGURE 2

The windows have been tested at this time to a traveling wave power level of 26 Kwatts with no apparent effect. The test assembly required for higher power tests is completed and under vacuum for power tests to 500 Kwatts. Traveling wave and standing wave power tests at this level will be performed as soon as the high power transmitting equipment is available.

7 - CRYOSTAT DEVELOPMENT[10]

In order to accomplish a beam test of the B-factory accelerating cavity in CESR we are designing a horizontal test cryostat that will serve as a prototype of the final design. The design is made difficult by the very large beam tube at each end of the cavity and by the very large waveguide delivering power to the cavity. User friendly computer programs have been developed which calculate the conductive and radiative heat load to the helium. These programs allow for metal plating on the inside of the beam tubes and waveguides and are capable of taking into account dissipation in the tubes and waveguides due to input RF power, HOM output power and beam induced image currents. The incorporation of heat exchangers on the tubes and waveguides between 4.2 K and 77 K is planned and this design capability will be incorporated into the programs.

Preliminary calculations give us encouragement that we can keep the parasitic heat loss to the helium to less than 25 watts per cavity.

A design effort is underway and some but not all of the design details have been fixed. A welded helium vessel is planned, and on the prototype cavity the beam tube flanges and waveguides will be attached with indium seals. The design goal for overall cavity length including HOM dampers and a sliding joint between cavities is $\leq$ 1.7 m.

8 - CRAB CAVITY SYSTEM

The present approach to the B-factory is to divide the desired current of 1-2 amperes into a large number of low current bunches, which helps to reduce detector backgrounds. To fit 230 bunches into the CESR size ring, they need to be very closely spaced, eliminating any room for any conventional separators. Instead, a small (12 mr) crossing angle is considered, which may cause harmful coupling between synchrotron and betatron coupling motion. By rotating the bunches before collision ("crabbing") so they collide head-on, and then rotating them back, so they pass through the arcs normally, this dangerous coupling can be eliminated.

We calculate that the required transverse kick is 2 MV which can be achieved with one single cell superconducting cavity that we have designed, operating in the TM_{110} mode at 500 MHz. This shape keeps the surface electric field below 25 MV/meter to avoid excessive field emission. The cell design that has been chosen allows all modes higher in frequency than the crab mode to propagate out the beam tube and be damped outside the cryostat with ferrite beam pipe absorbers. The TM_{010} mode frequency of the cell would be 367 MHz and the TE_{111} mode would be 485 MHz.[11]

Splitting the degeneracy of the two polarizations of the TM_{110} mode as well as aligning the field in the proper orientation is accomplished by cell deformation.[12] One concern has been the possibility of multipacting when operating a cavity in this mode.

Two cavities have been successfully tested in this mode. The first, a single cell LTP shape cavity (see section 14) with the TM_{110} mode at 2010 MHz operated satisfactorily at the required fields. A single cell cavity was constructed of Niobium with a shape exactly the same as the designed Crab cavity shape with the TM_{110} mode at 1500 MHz. This cavity after overcoming one low field multipacting barrier, reached E_{pk} = 30 MV/m @ Q = 1.2×10^9 in one polarization and E_{pk} = 27.5 MV/m @ Q = 2.3×10^9 in the other polarization of the TM_{110} mode. In both cases the field limitation was field emission.

[8] Measurements made by Linda Walling at Los Alamos.
[9] J. Kirchgessner et. al., HRA18, 91 PAC, San Francisco, CA
[10] In collaboration with Horst Heinrichs, Univ. of Wuppertal
[11] H. Padamsee et. al., PTP16, 91 PAC, San Francisco, CA
[12] J. Kirchgessner et. al., page 479, 89 PAC, Chicago, IL

Dealing with adequate damping of the lower frequency TM_{010} and TE_{111} parasitic modes remains an important problem which may be approached by selective tuning.

9 - BASIC STUDIES

The Cornell effort has continued to address itself to basic problems of RF superconductivity. Both the B-factory effort and the TESLA research require the highest possible peak surface electric fields and the highest values of Q that we can obtain.

The use of a ultra high vacuum furnace to increase the onset level of field emission has been used successfully and continues to be one of the tools valuable to this effort.

Another technique more recently used with success is High Peak Power Processing. This work which has been done using single cell and multi cell S-band cavities has shown very promising results.

The "Mushroom" cavity has been used extensively to try to better understand the nature of field emission. Considerable use has been made of our SEM with EDS to observe regions that have experienced field emission and/or sparking.

High pressure rinsing has recently been tested to see if this technique might be useful in the fight to eliminate emission sites.

Many measurements were also made on niobium samples placed in the TE_{011} mode "High T_c" cavity[13] to contribute to the understanding of Q degradation due to hydrogen that several laboratories have been experiencing.[14]

10 - FURNACE TREATMENT

We continue with success to use our ultra high vacuum furnace to process cavities in order to reduce field emission.[15] The heat treatment procedure that we have adopted is to fire a niobium cavity for 4 hours at 1500 C. During this time the vacuum is usually near $1x10^{-7}$ torr measured above the heat shields. At this temperature and pressure the RRR degrades due to oxygen absorption. To prevent this the cavity is enclosed in a niobium box with a titanium liner[16]. The titanium vapor coats the outside only of the cavity and "getters" the oxygen out of the cavity via diffusion. For best performance the titanium must subsequently be chemically removed from the outside of the cavity in order to regain the heat transfer capabilities of the niobium helium interface. For 1-cell cavities this technique has resulted in a 50% increase in the maximum E_{pk} values obtained, from 40 MV/m to 60 MV/m. This increase can be seen in figure 3 which shows a collection of performance results of many 1-cell cavities.

[13]D. Moffat et. al., page 488, 89 PAC, Chicago, IL
[14]D. Moffat et al. with D. Proch (DESY), PTP13, 91 PAC, San Francisco, CA
[15]H. Padamsee et. al., PTP15, 91 PAC, San Francisco, CA
[16]Q. S. Shu et. al., page 491, 89 PAC, Chicago, IL

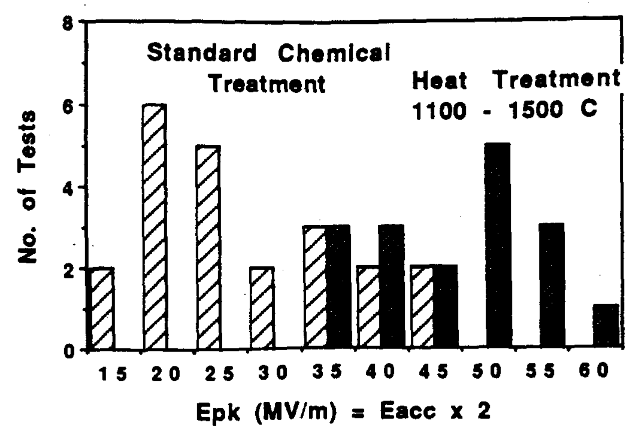

FIGURE 3

Encouraged by the success of heat treatment on single cells, application of the procedure to multicells has started. The first 6-cell cavity (LTP shape) has been heat treated twice. For simplicity the outside Ti layer was not removed in either run. After the first heat treatment E_{acc} = 16 MV/m was achieved at a Q of $6x10^9$, limited by thermal breakdown from a defect suspected to be introduced during a hole/repair operation. The Q remained above 10^{10} until E_{acc} = 14 MV/m. After a heavy etch to attempt defect removal, the second heat treatment was carried out. This time we reached E_{acc} = 20 MV/m at a Q = $3x10^9$, limited by field emission, radiation level and available RF power. Q remained above 10^{10} E_{acc} = 17 MV/m. Figure 4 shows the performance of this 6-cell, L-band cavity, after heat treatment. These are the highest accelerating field/Q values ever reached in a multicell structure at 1.5 GHz. Depending on the availability of resources, further heat treatments of this and a second (LE shaped) 6-cell cavity will continue.

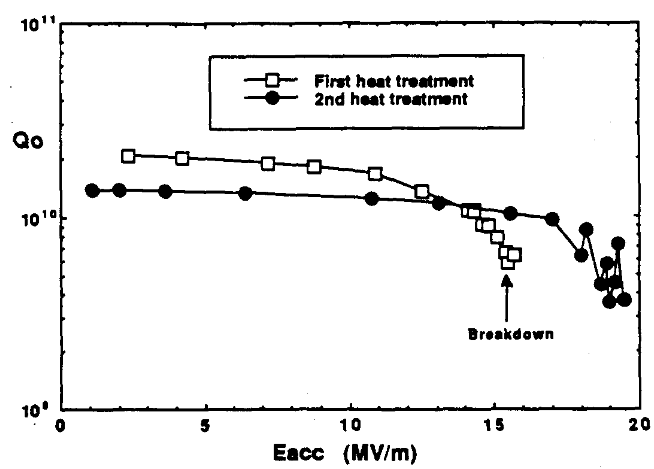

FIGURE 4

11 - HIGH PEAK POWER PROCESSING

It has long been realized that processing with RF reduces the field emission current for a given voltage. With the use of CW low power, however, this processing generally saturates after a modest improvement in the electric field levels. Equipment has been arranged to try to measure an increase in the level of this improvement by processing with a short pulse of High Peak Power processing (HPP) up to 200-Kwatts, 1 msec long pulses.[17]

Extensive tests have been carried out on single cell and multi cell 3 GHz, S-band niobium structures.

It is generally observed that during the high power processing pulse, the field will rise higher than can be achieved CW. This electric field enhancement factor during the pulse (or field degradation factor for CW) is usually about 1.5. In figure 5 is shown a series of 3 tests on a 9 cell S-band cavity. In each case the dramatic effect of the HPP can be seen. These improvements are far in excess of the improvements realized with low level processing.

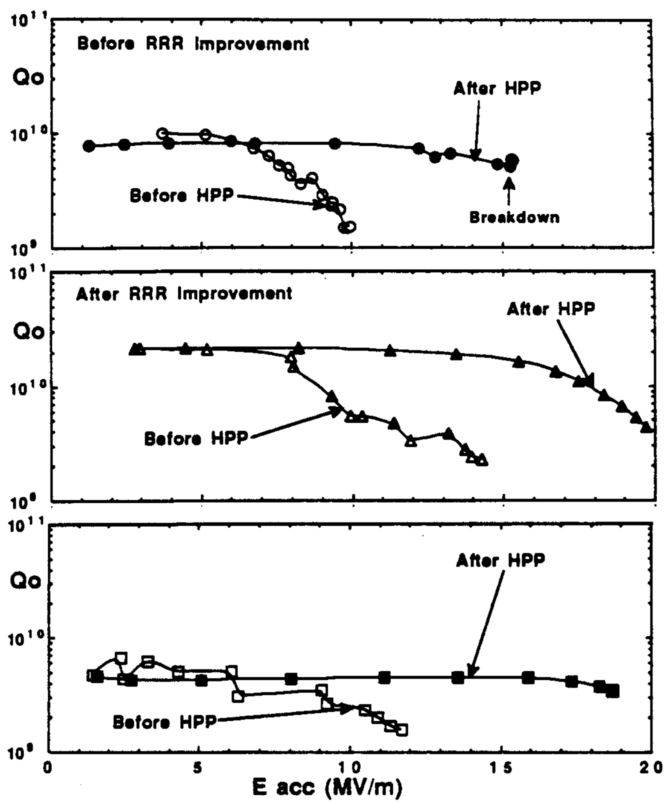

FIGURE 5

The importance of this HPP technique as a tool to increase the field emission threshold is becoming increasingly apparent. Unlike the furnace treatment, the equipment necessary to process a large accelerator is reasonable and, perhaps more important, the HPP can be repeated at any time as required without the enormous effort required for furnace treatments. It would be very interesting to see this technique applied to some other cavities at some other laboratories, particularly at lower frequencies. As more high power SC systems are operating, the equipment exists to try to use very high pulse power, which in most cases is already installed, to decrease the CW field emission levels.

A set of temperature boards have been built in order to monitor and track individual emission sites.[18] After sites have been located and then processed away using HPP, some cavities have then been cut and examined using the SEM/EDS. In some instances foreign material has been found at the site locations and in some instances there was only molten niobium.

Joel Graber will present a poster paper at this workshop giving further details and the latest results of this work.

12 - FIELD EMISSION CHARACTERIZATION

The Mushroom cavity[19] with a dimple to increase the surface electric field levels to high values has been used extensively. Field levels as high as 145 MV/m (E_{pk}) were realized by the last workshop. Field values around 100 MV/m were reproduced in several tests.

A break-apart version of this cavity now exists which allows us to examine the dimple in the SEM after operating the cavity at very high field levels.[20]

In the break-apart cavity with a choke joint, fields of 50 to 70 MV/m are routinely achieved on base plates prepared by standard chemical treatment techniques. One base plate that was heat treated at 1400 C reached 87 MV/m. After some testing and processing, in the presence of field emission, the cavity bottom plate is removed and examined in the SEM. Many new and interesting features associated with emission are always observed. Each emission site is located at the center of a "starburst" shaped region of reduced secondary emission coefficient. Typically 30 such starbursts were seen on the dimple area at E_{pk} = 70 MV/m for a chemically treated surface. In the single heat treated case only 10 starbursts were found after E_{pk} = 87 MV/m. At the center of these sites we have often found craters of molten niobium. Sometimes the sites contain features which look like ripples on a molten niobium surface. The EDS feature of the SEM is used to analyze the area for material other than niobium (Ti, Fe, In).

This same technique has also been used to examine S-band accelerating cells which have been cut in half after high field operation in order to fit them in the SEM/EDS. Similar features have been found in abundance, sometimes with foreign material at the center of the features (In, Fe, Cu).

At this conference, Dave Moffat will present a paper which gives detailed information on the field emission work and how it has been studied using the SEM/EDS system.

13 - HIGH PRESSURE RINSING

An idea that has been around for many years was recently investigated. There exists today high pressure rinsing systems using ultra pure Freon that are used for the final cleaning of components, mainly, high power laser components. We

[17] J. Kirchgessner et. al., page 482, 89 PAC, Chicago, IL

[18] J. Graber et. al., PTP12, 91 PAC, San Francisco, CA

[19] J. Kirchgessner et. al., page 37, Proc. of 4th Workshop on RF Superconductivity, KEK, Japan, 1989

[20] D. Moffat et. al., BGR2, 91 PAC, San Francisco, CA

recently rinsed several L-band cavities and several base plates for the Mushroom cavity using such a 2000 psi rinsing system.[21]

The two L-band cavities that were rinsed showed onset of field emission between 15-20 MV/m and maximum surface field Epk = 30 and 42 MV/m. These results are within the spread of 1-cell cavities that were not high pressure rinsed. Evaluation of the rinsed mushroom cavity end-plates is still in progress.

Although these first tests do not show a breakthrough, the successful experience in other fields using the high pressure rinsing warrants a continuation of this effort.

14 - TESLA EFFORT

Most of the work in this area will be reported in greater detail during the 2nd TESLA workshop which will immediately follow this workshop. During the last two years a considerable fraction of our SC effort at Cornell has gone toward the completion of the R & D work required to make a superconducting linac a viable contender for the configuration of a high energy linear collider.[22] A large part of this work is the achievement of the required fields and Q's.

To further this effort several cavity shapes were investigated. The properties that were considered were the ratios of E_{pk}/E_{acc} and H_{pk}/E_{acc}. Also the cell to cell coupling was very important as a large number of coupled cells was desired. Any tendency for a particular cell shape to trap some of the HOM's within the structure, where they could not be damped at the ends, was also significant in the cell shape choice.

A method for calculating the potential HOM damping of a multicell structure was developed. This method uses URMELT and calculates the relative Q's of HOM's as a resistive band is placed in the beam tube adjacent to the end cell. We find this to be an accurate predictor of the best that can be done with any sort of HOM coupler placed on the beam tube outside the end cells.

An L-band shape was designed and manufactured.[23] This shape designated LTP6, a six cell structure was tested several times. The best result with a chemical treatment followed by 2 hour rinsing was E_{acc} = 17 MV/m. Tests after heat treatment are reported in Section 10. All of the forementioned considerations were rather advantageous in this shape except the ratio H_{pk}/E_{acc} which was rather high.

Another 6-cell structure was built using the elliptical Cornell-CEBAF cell shape. This shape, which did not have as advantageous value of E_{pk}/E_{acc}, was tested and had E_{acc} = 15 MV/m with chemical treatment.

Several 9-cell S-band structures were also designed and manufactured as part of the HPP (high peak power processing) program and the TESLA program.[24] Three 9-cell cavities have been sent to Wuppertal for 1400 C heat treatment tests. These cavities are equipped with the same beam tubes as required for later installation in the Darmstadt accelerator for beam tests. One 9-cell was used for HPP studies reported in Section 11.

Careful records were kept of the total manufacturing cost of both the L-band and the S-band structures. These manufacturing costs were included in the 1st TESLA workshop proceedings and are < $10,000/m for the structure alone.

As part of this effort a series of test stands were developed and built which incorporated the desirable features of: remotely variable input coupling, vacuum pumping from the bottom, and RF input from the bottom. Details of this test stand with part of an LTP cavity are shown in figure 6. These test stands have been used on a wide variety of cavities and the results indicate that the test stands have not been imposing limitations on the performance of the cavities.

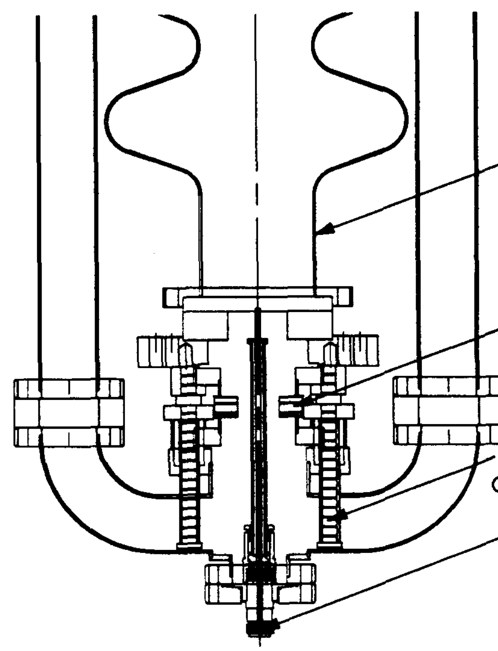

FIGURE 6

At the last TESLA workshop, we had available a spreadsheet program for generating machine parameters for various linear collider configurations.[25] Since that time we have developed a "user friendly" program for accomplishing this complex task utilizing "MathCAD" that will be presented at the TESLA workshop at the end of the week.

15 - FIRST TESLA WORKSHOP

In August, 1989, at the end of the KEK SC RF workshop, the TESLA collaboration was first formed. The name TESLA derived from "TeV Energy Superconducting Linear Collider". During the following year, working groups were formed and bilateral collaborations started. In July, 1990, Cornell, with

[21]In collaboration with D. Bardas, HEPL, Stanford Univ., Palo Alto, CA

[22]H. Padamsee, NGR2, 91 PAC, San Francisco, CA

[23]J. Kirchgessner et. al., PTP17, 91 PAC, San Francisco, CA

[24]R. Roth et. al., PTP14, 91 PAC, San Francisco, CA

[25]J. Rosenzweig, page 180, 1st TESLA Workshop Proc.'90

help and cooperation of all the other laboratories, organized and hosted the First International TESLA Workshop.

This 4-day workshop confronted the task of working on a parameter list for TESLA and exploring ideas on improving gradients and lowering cost. About 70 scientists participated from 17 laboratories around the world. The major challenges were defined to be reaching 30 MV/m Eacc and lowering the costs.

All of the material presented at the workshop, both technical and cost information were collected and published in the proceedings of that workshop. This 650 page document has been very useful as a reference source for the continuation of these working groups and for various TESLA like projects that have been proposed and studied in the ensuing year. Two days following this workshop will be dedicated to the 2nd TESLA workshop here at Hamburg and we feel that Cornell played a useful role in the use of some of our scant resources to organize the first of what will probably be a continuing effort and field of endeavor.

16 - Conclusions and the Future

In the coming years the major part of Cornell's SC resources will be dedicated to the design and testing of superconducting cavities to be used in the proposed CESR B-factory. This will include the crab cavities and the accelerating cavities. There are plans for beam tests in CESR for at least one accelerating cavity and for a pair of crab cavities.

We hope to maintain some level of effort in Basic Studies and the TESLA area. We feel that a considerable part of our work in the area of field emission will be applied to pursuing High Peak Power processing which we feel offers particular promise.