SUPERCONDUCTING RF ACTIVITIES AT CORNELL UNIVERSITY*

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1. History

Work on Superconducting RF has been going on at Cornell since 1969. This paragraph is a brief account of early activities which are still of current importance. An 11-cell, 2856 MHz Nb muffin-tin cavity was installed in the Cornell 12 GeV electron synchrotron for 1 year in 1974-1975.[1,2,3] This cavity was anodized to 400 Å, and operated at an accelerating gradient of 4 MeV/m at a Q_0 of $1 \cdot 10^9$. The lessons learned from this test were: (1) the magnet ring contains dust; (2) this dust apparently becomes charged and moves around due to electric fields; (3) electrostatic precipitators are reasonably effective in stopping this dust from entering the cavity; (4) the cavity was operated periodically for six months without degradation of field or Q_0; (5) the cavity tolerated $2 \cdot 10^{-9}$ Torr-years of gas exposure while cold without significant degradation; (6) dust which does get into the cavity severely degrades its performance but can be removed by detergent, water, and solvents, but no acids, thereby restoring the original performance; (7) weakly attached particles can reach incandescence; and (8) the cavity tolerated at least 123 kRad of ionizing radiation without degradation of its performance.

2. Work Completed Since the 1980 Karlsruhe Workshop on RF Superconductivity

A beam test was conducted simultaneously on two 5-cell, 1500 MHz Nb muffin-tin cavities in the Cornell 8 GeV e^+e^- storage ring, CESR.[4,5] It was demonstrated that these cavities are suitable for use in a 50 GeV/beam

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e^+e^- storage ring optimized for the use of superconducting cavities. Advantages of the muffin-tin structure are that all high-field regions are accessible for welding, inspection, grinding, and chemical treatment. Disadvantages are that there are an excessive number of edges to machine and weld per meter of structure; there is field curvature which causes beam dynamics problems unless compensated by rotating alternate modules; the structure is mechanically weak; higher order mode (HOM) extraction through the cell walls induces local multipacting; and the structure requires use of an excessive amount of Nb.

Since the muffin-tin structure is intrinsically subject to multipacting, a method of grooving the cup bottoms by electro-discharge machining (EDM) was developed.[6] These grooves were found to be effective in suppressing the multipacting which normally occurs in the cup bottoms.

A standard electron beam weld generates a vapor column which penetrates the material at the weld. Such welds require surface grinding, high temperature outgassing, and additional grinding to equal the RF performance of unwelded material. By scanning the welder beam in one direction at 4 kHz, and in the other direction at a mixture of 4 and (5 + epsilon) kHz, a rhombic raster is generated which penetrates the material by less than 10 microns. Nb in a rhombic raster weld has been found to be at least as good as the surrounding Nb, with no grinding or other special treatment.

"Bubble cavities" have been made in one and multiple cells, copper and Nb, and S-band and L-band. These cavities were hydroformed from pipe of suitable grain size. Seven die sizes and two anneals per cell are required.[6]

Nb having a residual resistivity ratio (RRR) of 12,000 was made by heating electrodeposited Nb to 2200°C in an UHV furnace without heat shields. Unfortunately, the RF surface resistance of this material was not acceptable without remelting it.[7]

Several improvements have been made in cavity preparation. It was found that the best solvents we can buy contain about 100 particles of more than 1 micron diameter per cc. Filtering is difficult because additional particles are dislodged from the filter unless the filtration is done extremely slowly. Better filtration, polishing, and recirculation have been added to our demineralized water supply. Although a clean room has long been used for final rinsing of our cavities, clean rooms or clean areas for attachment of cavities to the test stands was recently implemented.

Increased sensitivity of our cryogenic thermometers has been achieved by improving the thermal conduction from the cavity to the resistor, and by improving the thermal insulation from the bath to the resistor (using epoxy, vacuum, or exchange gas). A lock-in amplifier, a differential bridge, and a reduced thermometer read-out power have been used when high sensitivity (about 10 micro-degrees) is desired.

A thermometer multiplexing scheme which avoids cold multiplexers (which have caused difficulties in the past) and avoids a huge number of wires emerging from the cryostat has been implemented. Imagine a number of horizontal wires and a number of vertical wires crossing, but not touching, the horizontal ones. Now connect all horizontal-vertical pairs which cross each other on the principal diagonal of this array. Connect thermometers (resistors) between horizontal and vertical wires where they cross if they cross to the right of the principal diagonal. Make no external connection to the horizontal wires, but bring leads from each of the vertical wires out of the cryostat. Apply a voltage to one wire, connect a pseudo-ground current-measuring circuit to another, and ground the remainder. By changing the wire to which the voltage is connected and the wire which measures the current, any thermometer can be read out.

An improved method for measuring ZT^2/Q (where Z is the impedance per unit length for infinite velocity particles, and T is the transit time factor) has been devised using three metallic beads of equal length but different diameters. A computer code extracts the longitudinal electric field from the perturbations caused at each location by each of the three beads.

Scaling laws have been derived to permit a known Q, frequency, and ZT^2/Q to be transformed into a different Q, frequency, and ZT^2/Q which would yield the same beam instability threshold.

The possibility of using passive damping cavities to suppress instabilities caused by ensembles of other cavities has been explored.[8] Controlled frequency, single mode high impedances in undriven cavities can be used to stabilize the instabilities driven by other damped cavity modes whose frequencies are not controlled. Limitations of this method are that (1) one such cavity mode must be used for each potential beam instability mode and (2) the effectiveness of this method climbs with increasing Q until the Q becomes so high that the oscillation "energy" is traded back and forth between the beam and cavity; above this Q, further Q increases decrease the damping effectiveness.

Cavity shapes which deviate slightly from cylindrical symmetry and which lock the 1, 2, and 3 θ mode polarizations so that both polarizations of each mode would couple equally well out a single coupler have been developed.

Imaginary thin irises within actual cell irises have been used computationally to explore passband behavior as a function of the thin iris diameter. As the thin iris diameter is increased from zero, it was found that the passband developed in the canonical fashion until the passband being studied and the one above it approached each other. As members of the two passbands approached each other (with increasing iris diameter), the members of the first passband closest to the second started to converge. Based on this behavior, the greatest separation between modes occurred at intermediate diameters of the thin iris diameter.

It has been recognized and computationally verified that field emitted electrons in an elliptical cavity can bombard their own emission site only if the emission site is sufficiently close to the plane of the iris.

Breakdown field has been calculated as a function of thermal conductivity, defect size, defect R_s, frequency, bath temperature, Nb thickness, and thermal impedance between the Nb and the bath.

3. Current Activities

Our principal activity at the present time is the preparation of two superconducting 1500 MHz 5-cell elliptical cavities for a beam test (see Fig. 1 and Fig. 2.)

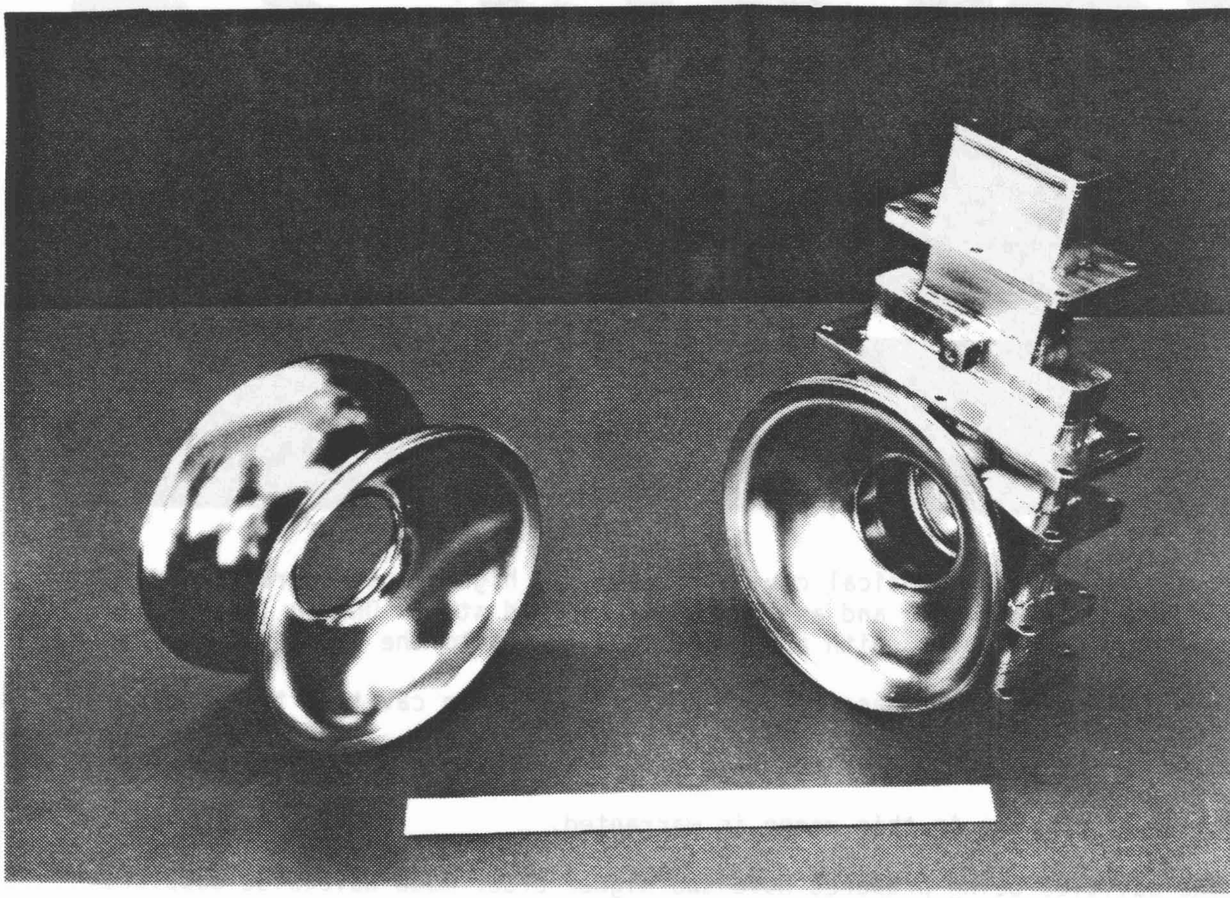

FIGURE 1. Pair of iris-welded elliptical cups and cup with fundamental coupler.

Although the 1982 beam test showed that muffin-tins are suitable for use in a 50 GeV e^+e^- storage ring, we believe that elliptical cavities will prove more suitable for this purpose. There are no plans to build an e^+e^- storage ring of higher energy than PEP in the United States, but we believe that it is important

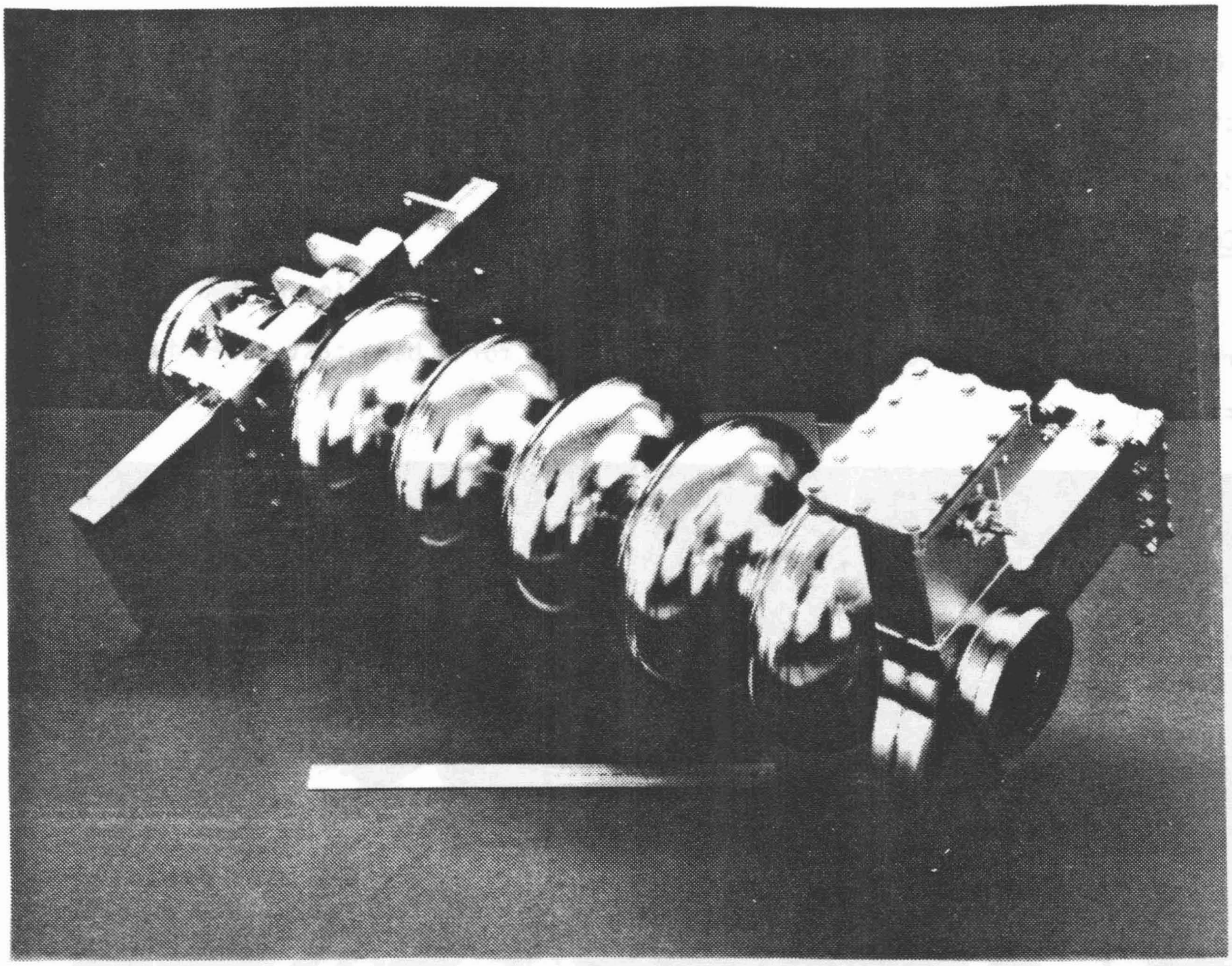

FIGURE 2. Five cell elliptical cavity showing two higher mode extraction couplers at the right (blanked off) and an associated shorted stub. On the left is the fundamental power coupler, with a shorted stub bolted to the input flange.

to establish a technology base for using superconducting cavities to build such a machine in the 25 to 300 GeV per beam range should the physics indicate that an additional machine in this range is warranted.

The cavities being prepared have two higher order mode waveguide couplers at right angles intersecting the beam pipe at one end of the cavity, and a fundamental power coupling waveguide intersecting the beam pipe at the other end of the cavity.

The HOM ZT^2/Q's have been measured extensively and studied computationally. The Q_{ext} values of these modes have been measured. The geometry of the HOM couplers has been optimized to maximize the damping of the most dangerous modes, while preserving adequate damping of other modes.

Several nominally identical copper models were built, their fundamental modes were tuned to the proper frequency, and the spread in their HOM frequencies was then measured. This information, together with the ZT^2/Q and Q_{ext} values, was used to compute instability thresholds for both the planned test in CESR and for use in an e^+e^- storage ring optimized for 50 GeV/beam operation. Calculations done to date indicate that full current beam stability in such a machine would be assured down to injection energies as low as 25 GeV.

The fundamental power coupler is conceptually similar to the one used on the muffin-tin. Coupling to the four unwanted passband members is enhanced by virtue of their different frequencies. A shorted narrow waveguide stub extending from the fundamental waveguide short enhances coupling to some low frequency HOM's.

Although we have neither calculations nor measurements showing that it is necessary, the severe problems with the "fast head-tail instability" in PETRA and PEP led us to use a design which preserves the rotational symmetry of the wakefield seen by the tail of the bunch and generated by the head and center of the bunch on the same pass through the cavity. Causality and "light cones" are used to establish the region within which cylindrical symmetry must be preserved. With cylindrical symmetry preserved, calculations have been done which show that this cavity design would not cause the "fast head-tail instability" to occur in an optimized 50 GeV per beam e^+e^- storage ring.

Tuning of the cavities is accomplished by changing the spacing between two rings, clamped to grooves in the equators of cells 1 and 5, respectively. The mechanism is driven by stepping motors immersed in the liquid helium, as was done with the muffin-tins. Stepping motors are also used on coupling adjusters mounted on the fundamental power couplers.

Five five-cell elliptical cavities have been built to date, the last three of these cavities being equipped with integral fundamental and higher order mode couplers. The last two of these cavities have had their cups (Fig. 2) treated with yttrium, approximately tripling their thermal conductivity. The cavities are cleaned with buffered chemical polish (Fig. 3), water, hydrogen peroxide, and methanol.

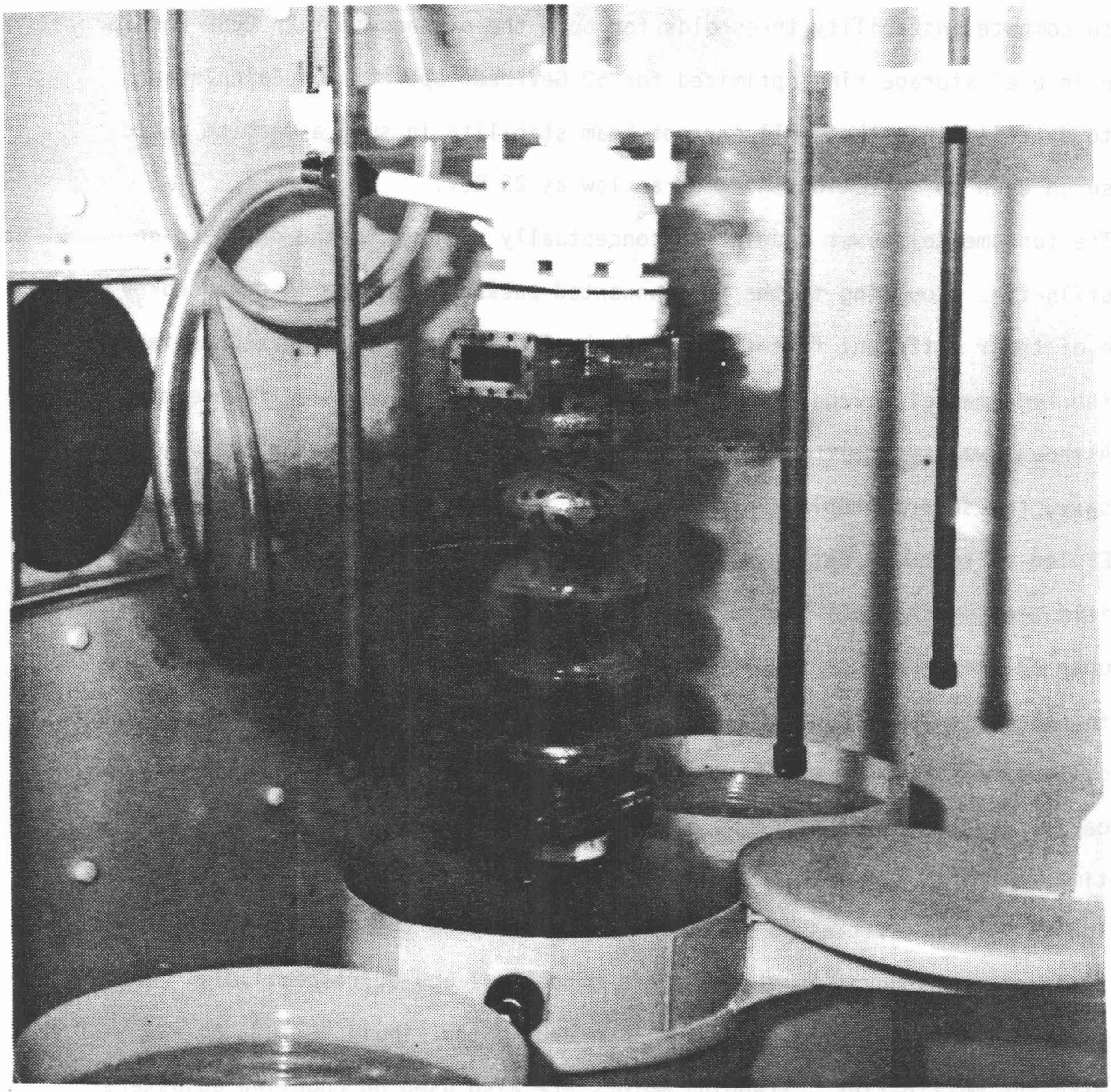

FIGURE 3. A five-cell cavity emerging from the buffered chemical polish.

The results achieved with the three cavities with couplers are listed in Table I.

TABLE I

Cavity	Q_0, low field	Q_0, at E_{max}	B_p, mT	E_p, MV/m	E_{acc}, MV/m	Field limit
LE5-3	$9 \cdot 10^9$	$7 \cdot 10^9$	41.6	23	8.9	Thermal-magnetic.
LE5-4	-	$3 \cdot 10^9$	37.4	20	8.0	Defect, cell 3, 2.5 cm from equator.
LE5-5	$4.2 \cdot 10^9$	$2 \cdot 10^9$	71.5	39	15.3	Cell 1, near but not at an iris. Defect or field emission.

Present plans call for the use of LE5-4 and LE5-5 in the beam test. LE5-4 was chosen in preference to LE5-3 because LE5-3 does not have improved thermal conductivity, and would be more adversely affected by dust.

Several problems related to the couplers occurred during development of the elliptical cavities. One problem was that a 90^0 inside corner was inadvertently left at a low field location inside the fundamental power coupler; when it was realized that the magnetic field at this corner diverges as $r^{-1/3}$, where r is the distance from the corner, and that this divergence was causing breakdown, the corner was radiussed. A second problem was that, in the process of deep drawing some coupler parts, some Nb was scraped off the sides of the parts and coined into the bottom; this problem was not visible by inspection until considerable chemistry had been done, but the weak RF currents in the region were immediately aware of the problem. A third problem was that there is a mode trapped in the HOM coupler at the beam pipe. This mode is adequately damped by the fundamental coupler, but the field reference probe had to have its coupling weakened to avoid coupling out too much HOM power through this probe.

Other current work includes testing of one-cell 1500 MHz cavities, primarily to study field emission and evaluate benefits of higher RRR at L-band. In nine different tests on one of these cavities, an yttrium-treated reactor grade cavity, low field Q_0's have ranged from $1\cdot10^{10}$ to $5.8\cdot10^{10}$, peak surface magnetic fields ranged from 40 mT to 85 mT, and peak surface electric fields ranged from 16 MV/m to 34 MV/m (note that the peak magnetic to peak electric ratio is different than for the five-cell units).

Collaboration with industry (Fansteel) and another laboratory (Ames) to produce high RRR Nb continues. Material produced to date has a typical RRR of 80, but most of the residual impurity can be removed with yttrium or titanium, as RRR's between 300 and 700 have been achieved this way. Many RRR measurements are routinely made in conjunction with this work. Two precautions should be kept in mind when using the yttrium or titanium purification procedures. One is that the yield strength of the material is greatly reduced; the second is that the BCS losses are increased.

Work with reabsorption of surface oxygen into deoxidized Nb is in progress. This method offers the promise of a possible method to eliminate surface oxides from an installed cavity.

Following earlier work in which we hand-ground defects whose locations were identified by thermometers, we are now using motorized grinders patterned after ones built at Wuppertal[9] and DESY. A computer program selects the proper grinding wheel and provides instructions for setting dials to get the grinder to the selected location without any unwanted collisions with the walls of the cavity.

Following A. Septier's report at the 1980 Karlsruhe Workshop[10] and the recent discovery at CERN that thick anodized layers can suppress RF field emission,[11] we have also started exploring the effects of various anodization thicknesses.

Work is in progress to equip our electron beam welder with computer controls and to explore the feasibility of controlling the weld puddle temperature by measuring the ratio of 2500 Å light to 7000 Å light.

Work is also in progress to improve the degree of automation of the cryogenics used for the beam test, and of the apparatus used for the routine testing of cavities.

A computer simulation is being developed to explore the reason that transverse bunch dipole modes are commonly seen in electron storage rings, but quadrupole and higher multipole modes are not. It is hypothesized that the curvature of the RF restoring force with longitudinal particle position provides Landau damping for internal bunch modes, but not for the rigid bunch mode.

4. Future Activities

When the beam test and enhanced thermal conductivity work are completed, we expect to have the technology base in hand to build elliptical cavities for an e^+e^- storage ring of energy up to 300 GeV/beam. It is our opinion, however, that the next e^+e^- collider of interest is likely to have 1 TeV/beam, and that linear colliders would be more economical at this energy than storage rings.

In order to make the cost of such a machine attractive, superconducting cavities operating at fields appreciably above values presently achieved for storage ring cavities are needed.

A first objective is to explore the phase spaces of collider parameters (such as emittance, bunch charge, bunch length, bunch spacing, beamstrahlung, and CW vs. pulsed) and of cavity parameters (such as field, Q, HOM damping, intercell coupling, number of cells per cavity, frequency, and CW vs. pulsed) to find optimum combinations.

Insofar as the Q is an important parameter, and needs to increase as E_{max}^2, work will be undertaken to explore the nature of surface resistance. Measurements will be made to determine what fraction of the losses are due to distributed sources and what fraction to discrete sources.

Pillbox TE and nearly hemispherical TM cavities will be used with flat test plates to determine whether the losses are predominantly electric or magnetic, and to provide removeable test plates whose surfaces can be studied to look for correlations between surface losses and surface properties. Such cavities will be used in conjunction with sensitive thermometry. Efforts will be made to understand and eliminate the source of the losses.

Field emission studies using flat plates and micro-positioned needles will be used to study field emission causes. Surface analysis instruments will be used to try to understand the nature, source, and means of suppression of the emitters. Close cooperation with other laboratories engaged in similar work is envisioned.

If pulsed RF looks attractive, either for use in an accelerator or for diagnostic purposes, apparatus suitable for this purpose will be built.

Cavities similar to those used for surface resistance studies will also be used for thermal breakdown studies, again in conjunction with thermometry and surface analysis instruments. In addition to suppressing the breakdown caused by defects (by using high thermal conductivity Nb), efforts to eliminate the source of the defects will be made.

Improvements made by the preceding methods will be verified by tests on single cell elliptical cavities, and later incorporated in structures optimized for linear collider use.

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