The Use of Superconducting RF for High Current Applications*

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1- INTRODUCTION

As the design of future accelerators demands ever higher currents, the use of Superconducting RF accelerating cavities becomes increasingly important. This is true of Linacs as well as circular and recirculating accelerators. This paper will consider only circular accelerators. Recirculating accelerators and Linacs will be discussed elsewhere. The advantages of SRF will be discussed as well as the present limitations. Specific examples will be chosen to show the present state of the art in the use of SRF for various high current applications.

2- ADVANTAGE OF SRF FOR HIGH CURRENT

A) $e^+ e^-$

The use of superconducting RF cavities has the obvious advantage of saving the ohmic heating power required to maintain the RF fields in the cavities. This is especially true in circular machines where RF fields must be provided CW. This, however, is not the compelling argument for the use of superconducting cavities in high current machines. Here the ohmic heating power is generally less than the power required by the beam to make up for the synchrotron radiation losses.

At high beam currents the amplitude of the allowable beam current is usually limited by multibunch instabilities. This risetime is dictated by the beam impedances of the accelerator. In a well designed high current machine, the major component of this impedance is the RF cavities and proportional to the number of cavities.

The first compelling argument is that when superconducting cavities are used, the accelerating field (5-10 MV/m) can be increased well above the CW fields possible in copper cavities (1-2 MV/m). Because higher gradients per cavity can be used, the number of accelerating cavities can be decreased.[1]

Moreover, superconducting cavities can have a lower impedance because of the larger permissible beam holes. In Figure 1 is shown a comparison of typical superconducting and copper normal conducting accelerating cavity cell shapes. In Figure 2 is shown the R/Q values for the monopole and dipole HOMs for both SC and NC cavities.

Therefore, because there are fewer cavities of lower impedance, the threshold current for beam instabilities is increased. If high impedance NC cells are used, then the larger number of cells and their higher R/Q demands stronger damping for the HOMs, or a more powerful wide band bunch to bunch feedback system. [2]

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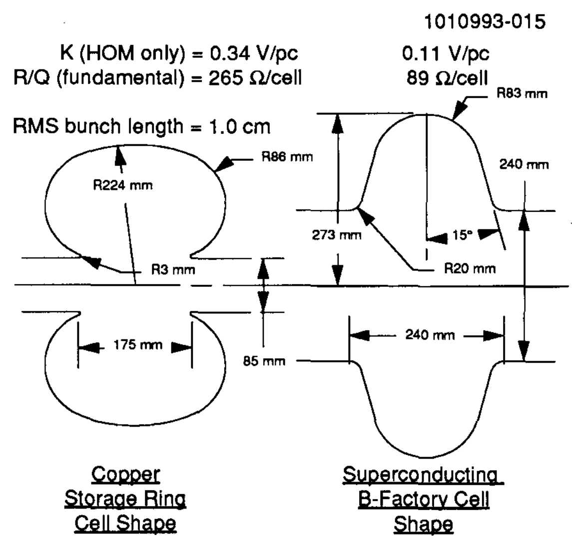

Fig. 1 Comparison of Cell Shapes

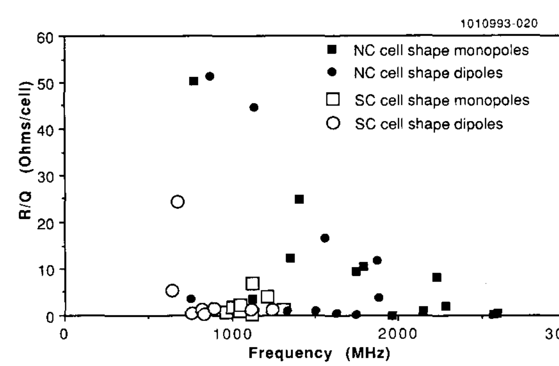

Fig. 2 R/Q vs. Frequency for NC and SC Cavity Shapes

In high current storage rings, a multibunch longitudinal instability arising from the fundamental accelerating mode can be very serious. In storage rings, beams are accelerated off the crest for phase stability. This generates reactive power into the cavity. In order to compensate for the imaginary part of the beam loading current and to minimize the required generator power, the RF cavity is operated off resonance. In a high beam current machine, the detuning frequency becomes significant:

$$\Delta f / f_{RF} = I\,(R/Q)\,\sin(\emptyset) / (2V_c)$$

where I is the total beam current, V_c is the cell voltage, and Ø is the synchronous phase.

For normal conducting cavities, Δf could approach or even exceed the revolution frequency of the beam. In this case, the dangerous multibunch longitudinal is excited by the high impedance of the fundamental (accelerating) mode, and the beam can be lost. The growth rate of the instability is quite rapid. The only practical solution to this instability appears to be multiple levels of very sophisticated feedback circuits around the klystron-cavity-beam system.

With a superconducting cavity, the detuning frequency is substantially reduced by virtue of the low R/Q from the cell shape, and the high cell voltage. Consequently, the values for $\Delta f/f_{rev}$ are low and, therefore, safe.

B) p-p Colliders

The machines in this category to be considered are the SSC and the LHC. Both are proposed or under construction. Transient beam loading effects dominate the design of these systems.[3] High beam current, high RF frequency and a long revolution period all make the effect of transient beam loading extremely important. In these cases, the synchrotron radiation is very small so that the power delivered to the beam is negligible and therefore the beam loading is almost purely reactive. The average effect of this reactive component may be compensated by detuning the cavities by an amount:

$$\delta f=(R/Q)\,(f_o/2V)\,I_{av}$$

where R/Q is the characteristic impedance of the cavity, f_o is the frequency of the cavity, V the cavity voltage and I_{av} the average RF component of the beam current. When the equilibrium of the beam is disturbed as when a new pulse is added during injection, due to the inherent slow response of the cavity tuner, the transmitter must provide the transient reactive power until the tuner settles to its new equilibrium position in order to avoid the excitation of coherent longitudinal oscillations.

Likewise any gaps in the train of bunches, such as the abort gap or the injection gaps, in a manner as above, cause a phase modulation of the beam. The maximum phase excursion is given by:

$$\Delta\text{Ø}=(R/Q)\,(2\pi f_o/2V)\,I_b\,\Delta t$$

where I_b is the maximum RF component of the beam current and Δt is the gap in the beam. As we can see both of these transient effects, δf and ΔØ depend on the quantity R/QV.

As we have pointed out, the value for R/Q for the superconducting type cells is a factor of several lower, and the quantity V is a factor of several higher than NC cells. The net result is that δf and ΔØ are both an order of magnitude lower in a superconducting system as compared to a normal conducting system.

A simple minded, qualitative way to illustrate this point is as follows. Due to the much higher energy storage in a superconducting cell, the alteration of this field by a beam bunch going through the cell is much less.

The required voltage, as we have seen, is large for bunch length control and, because there is no synchrotron radiation damping, the damping times for the beam are very long. This requires that the HOMs must be damped to a very low Q in order to avoid instabilities. The cavities that are required to meet these needs are similar to the cavities required for the B factories except that the input power coupler needs to handle <100 Kwatts. The gradients are the same, the frequencies are comparable and the required HOM damping is also the same.

Even though the bunch lengths in the p-p machines are much longer than in the e-e machines, the lack of synchrotron damping requires that the Q_{ext} values of the HOMs be about the same as in the e-e machines.

3- CHALLENGES OF SRF

Most laboratories planning to use SRF for high currents are designing for accelerating gradients between 5-10 MV/m, within the reach of present technology. At this time with most cavities being made from Niobium of RRR=300 or higher, the limit is generally imposed by field emission from the high electric field regions of the cavity surface. These field emitted electrons are accelerated by the cavity fields and impart energy to the superconducting surface. If this current is high enough, the effect can lead to thermal breakdown, but the usual case is that the Q is degraded to the point that the desired electric field cannot be achieved.

With high current cavities, in general, the power to be coupled to the beam is quite high. This power must be handled by the input coupler as well as pass through the input window and the necessary thermal transition. Consider the typical case for the CESR B Factory cavity where the total voltage required for the HER (high energy ring) is 35 MV and the total beam power that must be supplied is 4.5 Mwatts. At 10 MV/m accelerating gradient, a single cell at 500 MHz will provide 3 MV which means that 12 cells will be required. The input power into each cell is the 4.5 Mwatt/12 = 375 Kwatts/cell. In the LER (low energy ring), the higher current implies the power rises to 425 Kwatts/cell. Our research efforts include the development of RF windows and couplers at this power level. This CW power level is well within the limits for room temperature waveguide and klystrons.

Removing HOM power and damping HOMs are other significant challenges that arise from the high current and tight bunch spacing. If the Q of the HOMs is made much less than $\omega T_b/2$, then the power deposited by the beam into HOMs is given by $P_{HOM} = K\, q_b\, I$.

Here ω is the angular frequency of the HOM, T_b is the bunch spacing (eg 14 nsec), K is the loss factor (eg 0.1 V/nc), q_b is the bunch charge (eg 20 nc) and I is the average current (eg 2 A). The examples are for the LER in CESR-B. The damping requirement becomes Q < 100 and the HOM power is 4 Kwatts/cell.

In the case of cavities for Hadron colliders, the current is high but the power transferred to the beam is not high. The high voltage gradient is required for bunch shortening purposes. In this case, the input power cannot be as low as one might imagine. If the Q_{ext} of the input coupler is set at a value greater than a few 10^6, then the stability of the cavity system will be marginal due to the very narrow bandwidth and microphonics will be difficult to control. For this reason a reasonable amount of input power is required, if not by the beam, then for stability reasons, although not as much as for the e-e factories.

4- OTHER HIGH CURRENT APPLICATIONS

Another high current application that is proposed is the synchrotron light source, SOLEIL at Orsay, France. This machine will have 24 bunches, average current of 500 ma, and a beam energy of 800 MeV. A high quality synchrotron light source facility requires: a) many insertions, b) low beam emittance, and c) high current.

a) and b) tend to be contradictory. That is, the presence of many insertions make it difficult to keep the emittance low for high currents. Again, the enemy is multibunch instabilities. Thus the use of few, high gradient, low R/Q cavities that are well damped will allow one to overcome these difficulties encountered in the design when NC cavities are used.

Accelerator	Laboratory	Country	Particles	Frequency	Average I	N bunches	Total reqd. MV	Input Power/cell	Required HOM Q_{ext}
TRISTAN (O)	KEK	Japan	e+ e-	500 MHz	10 ma	4	220	20 Kwatts	10^4
LEP II (O)	CERN	Switzerland	e+ e-	352 MHz	10 ma	4	2600	15 Kwatts	10^4
HERA (O)	DESY	Germany	e p	500 MHz	60 ma	60	100	25 Kwatts	10^3
INP (P)	Novosib.	Russia	e+ e-	1000 MHz	.7-1.1 A	?	12	?	10^2
CESR-B (P)	Cornell U.	USA	e+ e-	500 MHz	1-2 A	165	50	400 Kwatts	10^2
TRISTAN II (P)	KEK	Japan	e+ e-	500 MHz	1-2 A	420	50	250 Kwatts	10^2
LHC (P)	CERN	Switzerland	p p	400 MHz	1.6 A	6000	16	150 Kwatts	?
SSC (P)	SSC	USA	p p	360 MHz	.3 A	17000	20	50 Kwatts	?

(O)- Operating
(P)- Proposed

Table 1.

5- E-E COLLIDERS TO LUMINOSITY FACTORIES

The highest current colliders now in operation as can be seen in Table 1 are TRISTAN[4], LEP II[5] and the HERA[6] electron ring. There are NC colliders in this current range such as CESR but these three from Table 1 all use superconducting RF systems. The currents are in the range of tens of ma and the accelerating gradients are all of the order of 5 MV/m. All of these cavities are fine examples of state of the art systems that are very capable of meeting their requirements in both performance and reliability. It should be pointed out that of these four systems, LEP II utilizes many cavities that, instead of being manufactured of solid Niobium, are made of copper with Niobium sputtered on all RF surfaces.

While beam loading and HOM damping due to high beam current were a consideration in the machines mentioned above, the next generation of such machines are listed in the lower part of Table 1 will have the current an order of magnitude higher than in existing machines. Cavities have been designed and tested for this purpose, one by KEK[7], one by Cornell[8], and one by CERN. All of these cavities will be described and their similarities and differences will be mentioned. Sketches of the first two of these cavities for B-Factories are shown in Figure 3 and Figure 4.

Both cavities are built at 500 MHz and both have a beam hole large enough that all the monopole modes except the fundamental mode will propagate down the beam pipe to HOM loads at room temperature. The damping of the lowest frequency dipole modes were taken care of in the same manner but special steps were taken to allow these modes to propagate in the beam pipe. KEK chose to increase the diameter of the beam tube after the iris which lowers the cutoff frequency of the beam to the HOMs. Cornell chose an idea originating at KEK, the use of a "fluted" tube that lowers the cut-off frequency of the dipole modes without altering the cut-off frequency of the monopole modes.

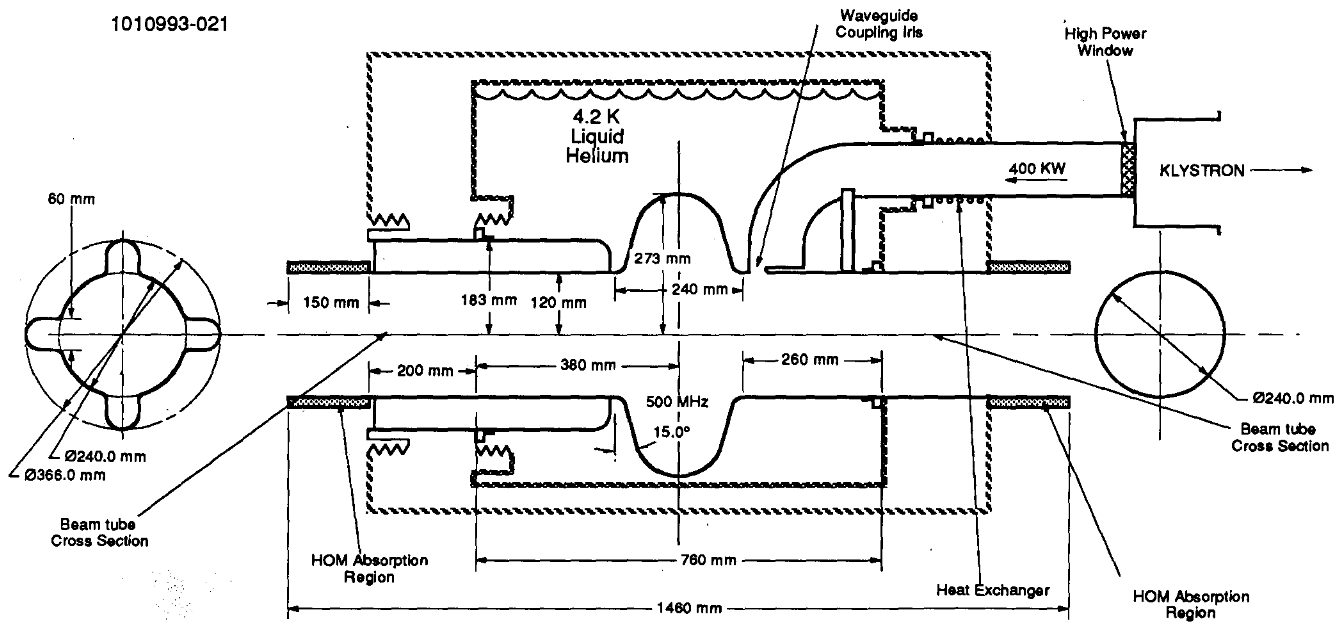

Fig. 3 Cornell B Cell

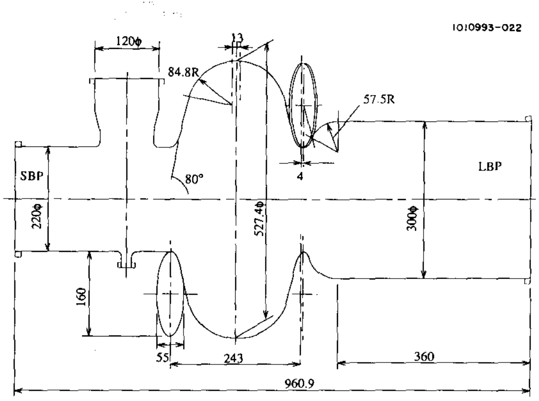

Fig. 4 KEK B Factory Cavity

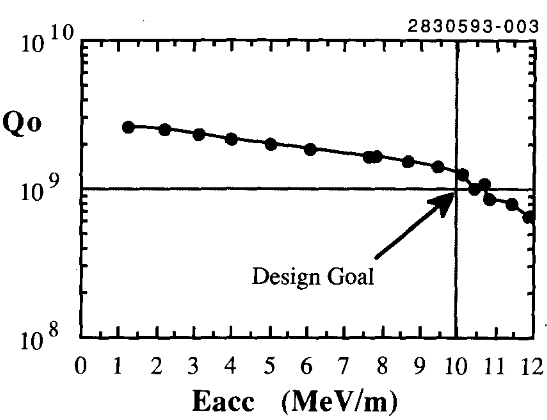

Fig. 5 Test Results of Cornell B Cell Test

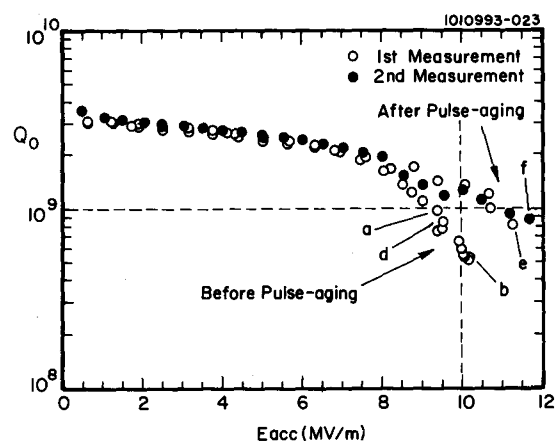

Fig. 6 Test Results of KEK B Factory Cavity

Both Nb cavities have been tested. The test results for the two cavities are shown in Figure 5 and Figure 6.

A sketch of the preliminary design of the accelerating cavity for LHC is shown in Figure 7. The single cell and the large beam tubes features are both evident, similar to the B Factory cavity designs. A prototype of this cavity has been made and tested. The cavty is Nb sputtered on Cu in its construction. Early tests gave an accelerating field of 6 MV/m at a Q of 3 x 10^9 at the 400 MHz frequency.

The cavities for both these machines, LHC and SSC[9], are presently in the design stage and this design effort is closely following and even depending upon the progress of the cavities for the B Factories.

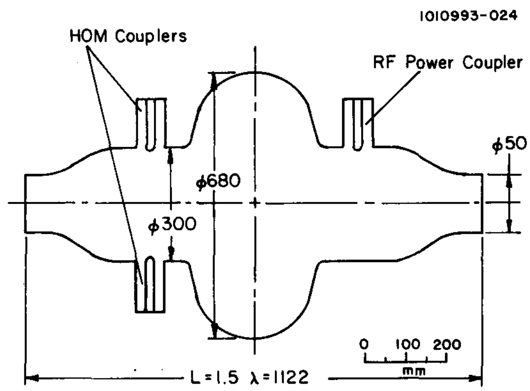

Fig. 7 Preliminary LHC Cavity design.

6- HOM DAMPING

The TRISTAN, HERA, and LEP solutions to the damping of the HOMs are similar in execution. All of these cavities required Q_{ext} values for the HOM modes of the order of 10^3-10^4-10^5. The damping system employed in all cases was to use coaxial probes on the beam lines. The amount of HOM power was in all cases was of the order of 10s of watts. These solutions have been adequate after some minor modifications.

The method employed for damping the HOMs in the KEK and the Cornell B Factory cavity designs are essentially the same. The plan is to line a section of the beam pipe with a lossy ferrite. All of the propagating HOM fields will be damped in this room temperature region. Figure 8 shows the measured values of R/Q and Q for the CESR B cavity.

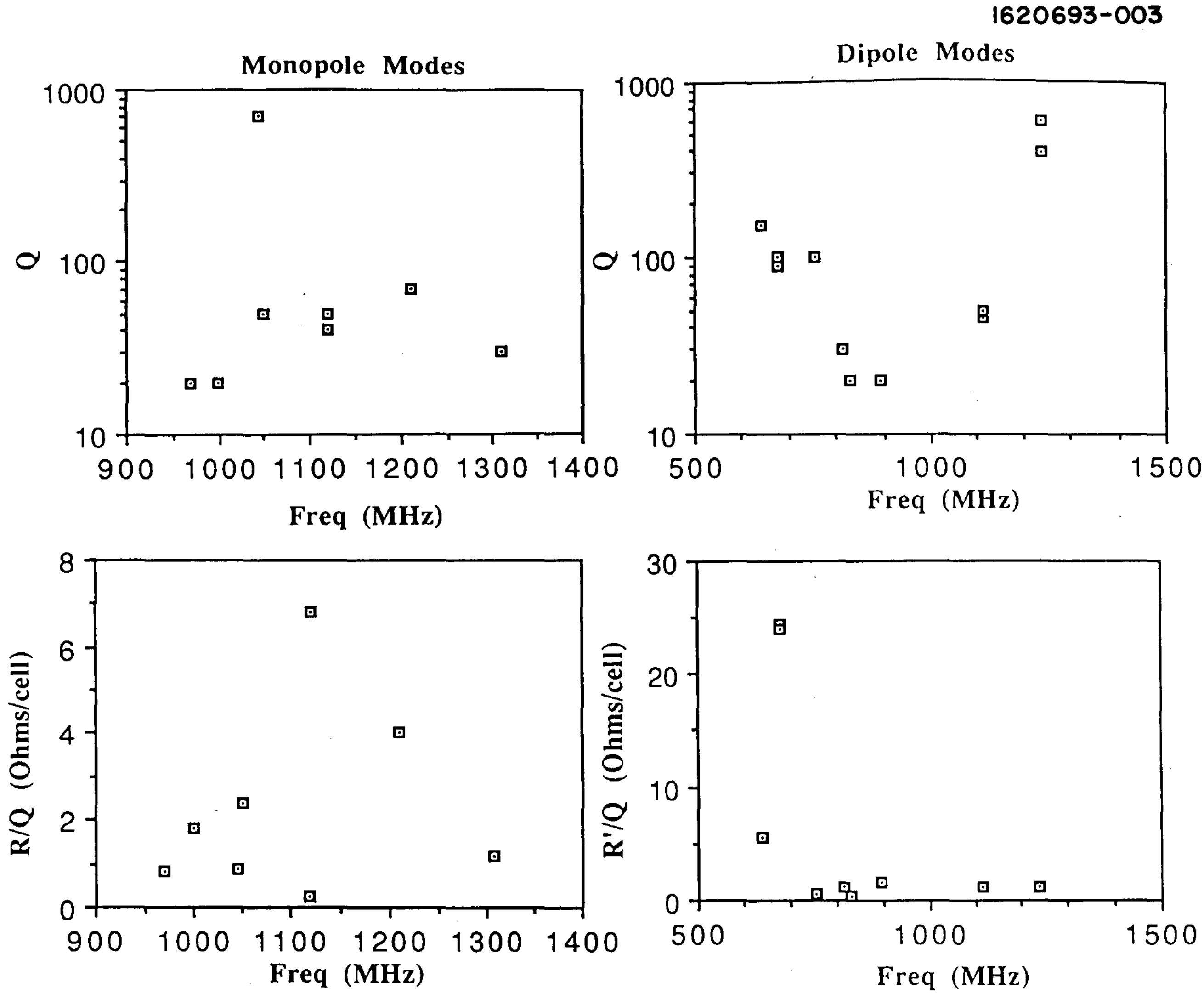

Fig. 8 R/Q and Measured Q for monopoles (left): R/Q and Measured Q for dipoles (right)

The ferrite placed in this location will, unfortunately, interact with the beam directly and add unwanted impedance. Ideally this impedance would be very low while the impedance presented to the HOMs is high enough to damp all modes to a low Q value. Room temperature measurements have been made at both Cornell[10] and at KEK[11] and the damping of all modes seems to be accomplished, in both cases, down to Q_{ext} values of 100 or so. In the case of the Cornell B Factory this degree of damping should be sufficient that no longitudinal feedback is required and, at most, a modest amount of transverse feedback will be required for beam stability.

There still remains several problems to be solved in implementation of these ferrite loads. The high power level, the vacuum properties of the ferrite , and the bonding of the ferrite to cooled beam tubes are problems that continue to be addressed.

In the p-p colliders, so far, the HOM damping method that has been considered has been the use of coaxial beam line probes. This work, however, is very preliminary and it has not yet been demonstrated that sufficient damping can be realized with this method.

All these efforts were covered in detail at the recent Workshop on Microwave-Absorbing Materials for Accelerators (MAMAs) at CEBAF in February, 1993. These proceedings will be available soon.

7- INPUT COUPLERS AND WINDOWS

In this area some of the more difficult problems associated with the use of superconducting cavities with very high current beams. The present generation of accelerators, TRISTAN, LEP II, and HERA all utilize coaxial input couplers on the beam line. Coaxial ceramic windows at room temperature couple the RF power into the vacuum. These coaxial couplers have, in general, worked without difficulty. However, a limit on the amount of permissable input power is presented by heating problems of the coaxial center conductors in the region of the thermal transition from room temperature to cryogenic temperaturres. The RF windows, some disk ceramics, some cylindrical ceramics, have all worked but with difficulty. In all window designs the input power to the cavity cannot be arbitrarily raised.

In the B Factory cavities the input power that is required for each cell is an order of magnitude higher than that presently in operation. This places very severe requirements on both the coupler and the input window. KEK has chosen a coaxial input window and coaxial ceramic window at room temperature. During the vertical cavity tests that have been done at KEK, neither the window nor the input coupler were operated at full power.

The input coupler on the Cornell B Factory cavity is a waveguide and the plan is to use a planar waveguide window. A prototype of such a window has been made and tested.[12] A pair of these windows have been tested to 250 Kwatts CW traveling wave and to a power level of 125 Kwatts of reflected standing wave, into a short.

During the vertical beam test of this cavity, the input waveguide was resonated with a superconducting short so that the energy and field levels in the coupler and input waveguide were the same in the vertical test as they will be in final operation. In fact, a weakly coupled probe was used to drive this waveguide resonator up to full cavity field levels.

Neither the window nor the thermal transition were present in this vertical test. The thermal transition problems are not insignificant for a WR1800 waveguide input. These problems as well as various other problems such as a very complicated cryostat design, RF-smooth gate valves, sliding joints, beam line tapers and the high power HOM loads will all be installed and tested in the planned beam test of this cavity in CESR.

The input couplers invisioned for the LHC and SSC cavities are of the coaxial type as well as coaxial windows. The input power levels in these p-p colliders are somewhat lower than the level required in the B factories. The final configuration of these P-P systems will undoubtedly take advantage of the experiences gained in the B factories.

8- CONCLUSIONS

The first generation of operating superconducting reasonably high current accelerators has been very successful. They have operated much as predicted and the reliability has been satisfactory. The next big step has yet to take place, namely, the B Factory type cavities. The current must be increased more than two orders of magnitude.

Many calculations have been made, room temperature measurements have been made, and vertical cavity tests have been made. Within a year a beam test will be made with one of these B Factory cavities in CESR. While the current will be 100-200 ma, not 1-2 amperes, it should still be high enough to reveal some of the difficulties that we might expect to encounter.

The design efforts for the cavities for the p-p colliders are still in the early stages and will be following closely and benefiting from the experiences with the B Factory cavities.

The true and final test for this next generation of high current superconducting cavities will take place when accelerators are operating with planned higher currents.

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