Review of the Development of RF Cavities for High Currents*

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Abstract

To fulfill the need for ever higher luminosities, the magnitude of the beam currents continues to increase. This is true for the electron-positron rings, the hadron colliders, and the synchrotron light sources. These high currents bring a set of new and difficult challenges. Both normal conducting and superconducting cavity[1,2,3] structures will be considered. While these two alternatives have significant differences, the challenges addressed are rather similar.

RF cavities present an impedance to the beam by virtue of the wakefields left behind in the cavity cells. This energy extracted from the beam and left behind has an adverse effect on other particles encountering these fields. The broadband impedance presents current stability thresholds for the beam bunches, both due to the longitudinal and transverse impedance of the cavities.

The broad band impedance is characterized in a simple way by the Kloss factor of the cavity. For a given bunch length and cavity shape Kloss tells us the HOM beam power loss and the threshold of single bunch instabilities.

The current threshold for beam instabilities depends on the total Kloss for the whole machine which includes all other components in the machine as well. But the highest Kloss factors are generally in the RF cavities. The total loss factor of the RF system is essentially the Kloss per cavity multiplied by the number of cavities. Therefore there is advantage in having as high a cavity voltage as possible in order to reduce the number of cavities and therefore the total Kloss. SC cavities typically provide 3-5 times higher the voltage than copper cavities used for CW operation, as in high current storage rings

Figure 1 shows the shape of two accelerating cells. The CESR NRF cavity shape is typical of the shape used for copper cavities. The shunt impedance is made as high as is possible in order to maximize the accelerating field, E_{acc}, for a given amount of dissipation in the cell. The two factors leading to this high value of R/Q is the small beam hole size and the reentrant noses on the cell. Both these factors unfortunately lead to high values of Kloss. All of the NRF cavities that are listed in Table 1 have a cavity shape similar to the left hand picture in Figure 1.

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At the other extreme, the shape on the right in Figure 1 approximates the shape used for the SRF cavities for KEK-B, CESR-B and the LHC cavity. The shape is similar to that used in LEP II, HERA and TRISTAN, all SRF, but the beam hole is larger still. R/Q of the fundamental and HOMs are substantially lower with great benefits to the multibunch stability of the beam as discussed below. The very large beam hole size is important in damping all of the cavity HOMs in order to avoid resonant buildup of the fields that would cause multibunch instabilities at high currents.

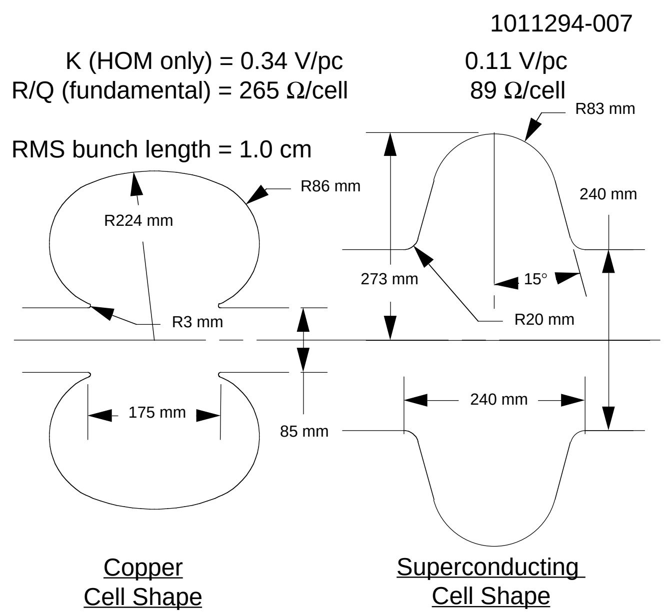

Figure 1: Comparison of Cell Shapes

CONSEQUENCES OF VOLTAGE GRADIENT

In high current systems the 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:

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

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

For NRF cavities, Δf could approach or even exceed the revolution frequency of the beam. In this case, the dangerous

Location	Type	Freq. MHz	Particles	Current Amperes	# of Cav.	E_{acc}/Cav MV	Wall Diss.	Qloaded	Q_o	In Pwr/ Coupler	HOM Q
LEP II[4]	SRF(O)	352	$e^+ e^-$	0.01	168 x 4	10.3	.036 kW	$2\ 10^6$	$2\ 10^9$	60 kW	10^4
TRISTAN	SRF(O)	508	$e^+ e^-$	0.01	32 x 5	7.5	.036 kW	10^6	$2\ 10^9$	100 kW	10^4
HERA[5]	SRF(O)	500	e^-	0.06	16 x 4	6	.044 kW	$2.4\ 10^5$	10^9	100 kW	10^3
CESR-II[6]	NRF(O)	500	$e^+ e^-$	0.25	4 x 5	1.5	70 kW	$8\ 10^3$	$3.2\ 10^4$	280 kW	10^3
APS[7]	NRF	352	e^+	0.3	16	0.75	90 kW	$1.5\ 10^4$	$4.8\ 10^4$	248 kW	10^2-10^3
PEP II (LER)[8]	NRF	476	e^+	2.25	10	.59	50 kW	$6.5\ 10^3$	$3\ 10^4$	393 kW	10^2
PEP II (HER)	NRF	476	e^-	1.03	24	.77	85 kW	$6.5\ 10^3$	$3\ 10^4$	245 kW	10^2
KEK B (LER)[9]	NRF	508	e^+	2.6	20	.6	160 kW	$6\ 10^3$	$3.3\ 10^4$	400 kW	10^2
KEK B (HER)[10]	SRF	508	e^-	1.1	13	1.5	.02 kW	$2\ 10^5$	$2\ 10^9$	400 kW	10^2
CESR-III[11]	SRF(*)	500	$e^+ e^-$	1	4	2	.05 kW	$2\ 10^5$	10^9	325 kW	10^2
LHC[12]	SRF	400	p p	1.6	8	2	.05 kW		10^9	150 kW	

(O) - Operating, the rest are at various stages of design or construction.
(*) - This design is also intended to be used on the Syn. Light Source at Orsay.

Table 1: Comparison of Various Medium and High Current Cavities

multibunch longitudinal instability is excited by the high impedance of the fundamental (accelerating) mode. One solution is to use multiple levels of sophisticated feedback circuits around the klystron-cavity-beam system.

With an SRF cavity the detuning frequency is substantially reduced by virtue of the lower R/Q from the cell shape, and the higher cell voltage made possible by the higher gradient with SRF cavities. Consequently, the values for $\Delta f/f_{rev}$ are low and, therefore, safe.

In the case of p-p colliders such as the LHC, transient beam loading effects are very important. High beam current, high RF frequency and a long revolution period along with the lack of synchrotron radiation damping make the effect of transient beam loading extremely important. 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, in a manner as above, cause a phase modulation of the beam. The maximum phase excursion is given by: $\Delta Ø=(R/Q)\ (2\pi f_o/2V)\ I_b\ \Delta t$ 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 $\Delta Ø$ 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 $\Delta Ø$ are both an order of magnitude lower in a superconducting system as compared to a normal conducting system.

HOM RESONANT BUILDUP

The effects of the cavity impedance on the beam can be drastic even at low currents if there is a resonant buildup of electric field in the cavity. In Figure 2 is shown a plot of R/Q versus frequency for the lower frequency HOMs of typical NRF and SRF cavity shapes.

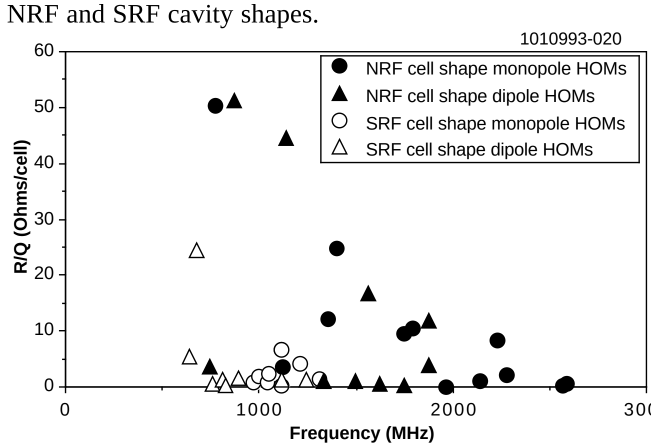

Figure 2: R/Q vs. Frequency for NRF and SRF Cavity Shapes

As can be seen the R/Q values for the NRF shapes are higher in general and therefore, to attain equally low impedances, NRF structures must be damped to correspondingly lower Q values. If any of the Fourier components of the multibunch beam bunch train coincide with the multitude of higher order resonances of the cavity then the voltage in the cavity continues to build up limited only by the Q of that mode in the cavity. One may be so fortunate as to not have any of the cavity resonances lie directly on one of these beam Fourier frequencies but the only safe solution is to damp all of these cavity resonant modes to a Q value sufficiently low to prevent the exponential growth of the HOM field in the cavity that will destroy the beam.

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

Comparison of Various Systems

In Table 1 are listed parameters of some of the systems that are operating or are being constructed. A range of currents is shown but this list does not mention all of the systems that might have been considered. Of the systems listed, the four cavities with the highest planned current, namely PEP II (NRF), KEK B-LER (NRF), KEK B-HER (SRF), and CESR B (SRF) will be examined in greater detail and comparisons will be made.

PEP II

The first system to be considered is the accelerating cavities planned to be used with the PEP II B Factory. This is an NRF cavity that has been specifically designed to encounter the challenges of very high electron currents. As can be seen in Table 1, the gradients are as high as 0.8 MV/cell. This value has required careful engineering of the water cooling of the cavity to prevent overheating of the inside copper surface.

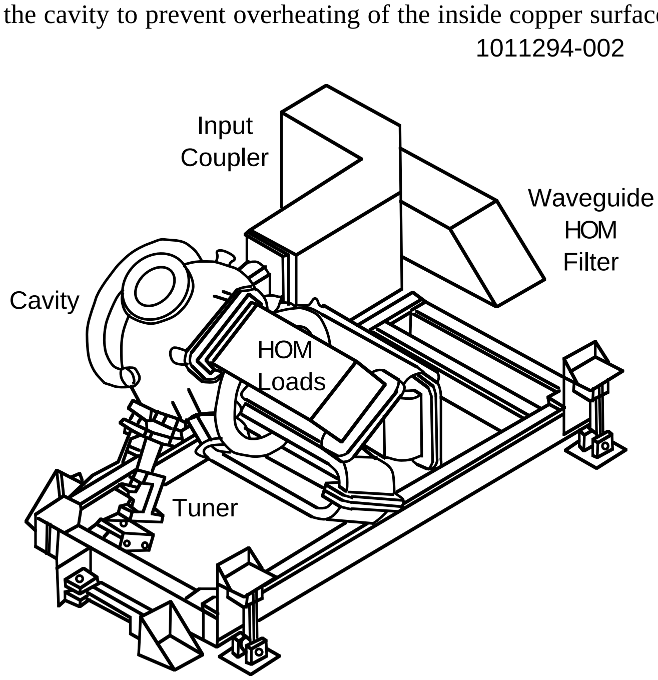

Figure 3: PEP II RF Accelerating Station

The input power per cell, up to 400 kWatts, is coupled in through a planar waveguide window[13], then into the cell with either a loop or an iris.[14] Some of the HOM power (TM_{021} mode) will be coupled out through the input coupler. The damping of the rest of the HOMs with significant R/Q is accomplished with three waveguide coupling slots. The insertion of these three slots, unfortunately, further increase the peak dissipation density of the fundamental mode to as high as 70 W/cm^2.

A drawing of the Accelerating station "Raft" that would be used in both the LER and the HER rings is shown in Figure 3. As can be seen, the damping Waveguides are folded back along the beam line to make as compact a package as possible that could be preassembled and tested and then placed in the rings. It is expected that the overall system, consisting of 34 cavities damped to Q values of 100 or less[15], will require a rather high power longitudinal multibunch feedback system in order to prevent any instabilities.

KEK LER Accelerating Cavity

This cavity (Figure 4) is rather unique in all the high current cavities. It is made of three separate cavities coupled together in a way to give special advantages in the acceleration of high currents. The one cell is for acceleration, the second cell is for coupling and the third cell is for energy storage.

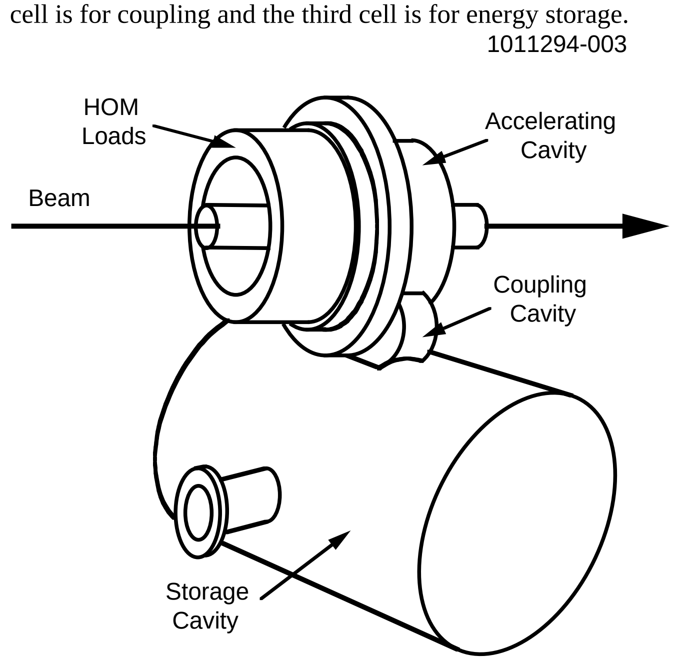

Figure 4: KEK B LER Accelerating Cavity System

Three cells give rise to three resonant frequencies in the TM010 accelerating mode. The π/2 mode is used for acceleration. In this mode there is little energy in the coupling cell so the cell is heavily damped. In the 0 and π modes, the coupling cell has energy and are therefore heavily damped.

The damping of the HOMs is done in the accelerating cell.[16] There is a choke joint at the equator of this cell. The accelerating mode is stopped and little energy is lost. All other modes are transmitted by the choke joint and heavily damped by the load. This arrangement is shown in Figure 5.

These features give the following results. The HOMs are heavily damped in the accelerating cavity and the energy of the system has been increased without adding to cavity dissipation. The effective fundamental mode R/Q of this three cavity system is only 10-15 Ω. The increase in the stored energy has, of course, decreased the negative effects usually encountered in NRF cavities associated with reactive beam detuning without increasing the wall dissipation in the accelerating cell.

The usual challenges associated with the high power input coupler are essentially the same as in the PEP II cavity. The one advantage is that the input coupler can be located on the storage cell.

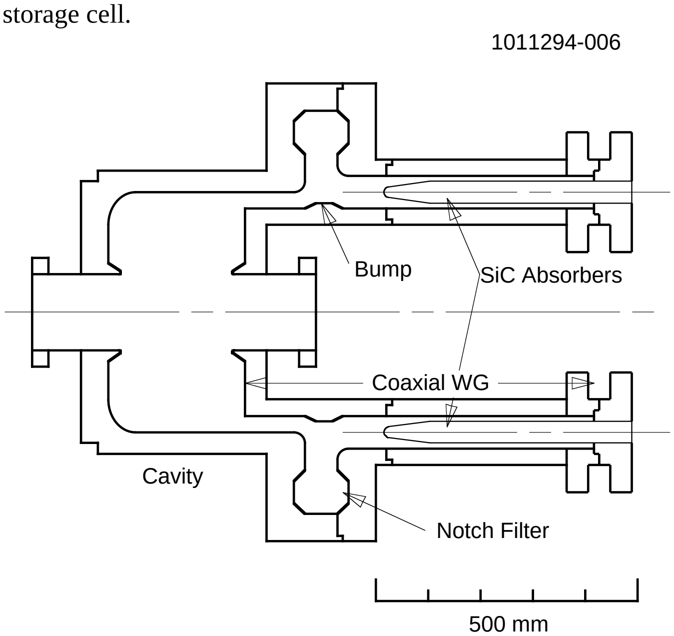

Figure 5: KEK B LER Accelerating Cavity Damping

SRF CAVITIES

There are two cavities that have been manufactured and tested that are of the so called "single mode" type. These cavities are the KEK B SRF cavity and the CESR B cavity.

The basic concept for both of these is to have the beam tube on one or both ends of the cell of adequate diameter such that all cavity modes above the fundamental, both longitudinal and transverse, propagate in a waveguide mode through the beam tube. The only mode trapped in the cell is the TM_{010} accelerating mode. A sketch of these two cavities is shown in Figure 6 and Figure 7.

All of the longitudinal modes except the fundamental mode propagate out both ends of the cavity but this 120 m radius size will not pass the two lowest dipole modes, the TE_{111} and the TM_{110}. The solution adapted by KEK is to make the beam tube large enough on one end to pass these transverse modes. The method used by Cornell is to use a fluted shape[17] which has a lower cutoff frequency for the transverse modes without affecting the decay rate of the trapped TM_{010} mode. This allows the length of the beam tube on both ends to be equal, giving a shorter overall length.

The method employed for damping the HOMs in the KEK[18] and the Cornell B Factory cavity designs[19] are to line a section of the beam pipe at room temperature at the large diameter with a lossy ferrite. With this damping material the HOM Q values have been measured on the CESR B cell and all fall within the limit of Q <= 100 for all modes.[20]

A possible problem with this type of HOM damping is that the beam pipe, lined with ferrite or other lossy material, is subject to the fields generated by the beam directly. This will increase the broad band impedance of overall system due to the lossy beam pipe. This effect has been examined and measured and found to cause no difficulty to the beam even though the HOM loads must be able to handle a few extra kWatts of power deposited directly by the beam at beam current levels of 1 Ampere.[21]

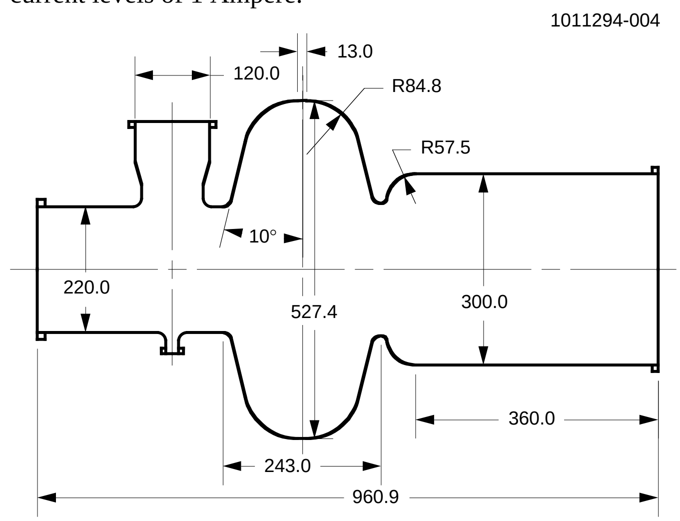

Figure 6: KEK B HER (SRF) Cavity

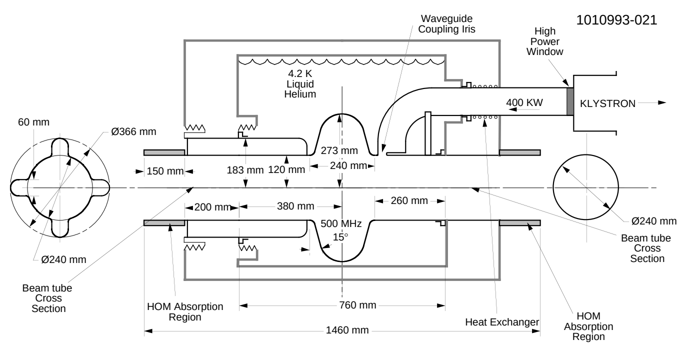

Figure 7: CESR B Cell

RF Power Input Couplers

All of the high current cavities share the challenge of very high input power (300-400 kW/cell). This is true of both NRF and SRF designs. As we have seen, the PEP II design is undecided as to whether they will use an aperture coupler or a loop coupler but they have decided upon a planar waveguide window. They are presently manufacturing such a window. The KEK NRF design will use a coaxial window input with antenna into the storage cavity. Likewise with the KEK SRF design they have chosen the type of coupler with which they have experience, a coaxial window with antenna into the beam pipe.

In the CESR B design a planar waveguide window is chosen followed by a resonant aperture between the waveguide and the beam tube. A prototype of such a window has been made and tested. 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.[22] A new window of a different design has been procured and the results of this test will be reported.[23]

During the vertical 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. A weakly coupled probe was used to drive this waveguide resonator up to full cavity field levels.[24]

TEST RESULTS

A prototype PEP II cavity at low power has been built and tested. The HOMs have been measured and all modes are damped to the desired amount. High power feedback will however be required. A high power test cavity and high power window are under construction.

The KEK NRF cavity is in the design stage with a low power prototype under construction. The KEK SRF cavity has been built and tested in a vertical dewar. In these tests the cavity achieved the desired field of 10 MV/m at a Qo value of $1\ 10^9$. Measurements have been made at low level of all the HOM damping and found to be satisfactory.

The CESR B cavity was tested in a vertical dewar and achieved 10 MV/m at a Qo value of $1\ 10^9$.[25] A beam test has been made in CESR with the CESR B cell cavity.[26][27] Beam currents as high as 220 mA with 27 bunches and single bunch currents to 41 mA were accelerated by the cavity with no beam instabilities. This current value was not limited by the cavity but was limited by beam induced heating of other components in CESR. This beam current limit was unaltered by the presence of the SRF cavity. The HOM power extracted from the cavity and absorbed by the HOM loads was as high as 2 kWatts. Experiments were also performed with the TM_{010} cavity mode detuned and with no RF drive to see if a resonant buildup of RF fields could be measured as the cavity frequency was scanned by as much as 100 kHz. The Q of all the modes was low enough to prevent significant field buildup in the cavity or beam instabilities.

Experiments were also made to measure the maximum power that could be transferred to the beam. 155 kW was achieved. This value was limited not by cavity or coupler behavior but by electronic driven vacuum deterioration at the window. As mentioned, a new window design will be tested.[28] A second cavity and cryostat will be placed in CESR for a long term beam test.

CONCLUSIONS

The first generation of cavities, both NRF and SRF, operating at currents up to several hundred mA have been successful. They have operated much as predicted and the reliability has been satisfactory. The next step has yet to take place, namely, the cavities operating at currents of 1-2 amperes.

At ever higher currents the problems associated with RF windows and input couplers become increasingly challenging and the differences between SRF and NRF become less significant as the voltage per cavity is limited by the power input capabilities.

The ultimate 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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