

# RF Systems<sup>★</sup>

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## Introduction

Storage ring B factories are characterized by high current beams ( $\sim 3A$ ) of short bunches ( $\sigma_L \sim 1cm$ ) that radiate high power ( $\sim 3MW$ ). The RF system is required to supply the power and sustain a voltage adequate for the strong longitudinal focusing. The beam cavity interaction limits the stability of single and multiple bunch beams. The optimized RF system therefore has low impedance and heavy damping of parasitic modes.

The task at hand is to develop an RF system that can meet these extraordinary requirements. To that end it is useful to review the character and especially the limitations of existing technology, including those imposed by input power window and cavity accelerating gradient. In view of these limits we find that single cell cavities are a logical alternative to the multicell structures common to operating storage rings. We then proceed to an optimization of the cell shape for such a single cell structure that minimizes higher order mode impedance and facilitates the coupling of HOM power out of the cell and into loads. The conceptual design of an associated fundamental power coupler and waveguide window suitable for a superconducting single cell cavity are described. The relative virtues of superconducting and room temperature structures are reviewed.

## Single Cell Cavities

### 1. POWER WINDOW

The fundamental power that is coupled by the RF cavity from klystron to beam must pass through an RF window. The power through the window is limited by heating of the ceramic, sparking due to high fields associated with standing waves, multipacting, etc. Local field levels and vacuum conditions are all critical to the window performance but generally peculiar to the detailed design of the window and its mounting hardware. The power handling ability of a few cavity windows is summarized in Table I.<sup>[1][2]</sup> The tabulated power corresponds to the level at which the cavity was operated to accelerate beams.

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Table I. RF Windows		
Machine	Power	Type
CESR	350kW	Cylindrical
TRISTAN	225kW	Coaxial disc
PETRA	120kW	Coaxial disc
PEP	$\leq 150$ kW	

Note that the PETRA window is adapted from a klystron design. As a cavity window it can not be operated reliably above 120kW. In the klystron it operates reliably up to 1MW<sup>[3]</sup>. Cavity and klystron window environments are very different. The klystron window is isolated from reflected power whereas the cavity window is exposed to full reflections at the driving frequency as well as at higher mode frequencies. In addition the klystron vacuum environment is generally superior to that of the cavity coupler.

It is clear that barring a major breakthrough in window cavity technology a B-Factory storage ring RF system will require at least 10 windows.

## 2. ACCELERATING GRADIENT

The accelerating gradient is limited by RF dissipation in a copper cavity and electron field emission in a superconducting structure at levels corresponding to  $\leq 1.5$  MV/m and  $5 - 10$  MV/m respectively. The gradients of several normal conducting RF systems are summarized in Table II. Note that in the design of all such systems the fundamental ( $\frac{R}{Q}$ ) is maximized in order to minimize power consumption. We will find that high fundamental ( $\frac{R}{Q}$ ) corresponds to high impedances in parasitic modes.

Table II. Normal Conducting RF Systems					
Machine	frequency	$(\frac{R}{Q})$	Gradient	$P_{diss}$	Number
	MHz	$\Omega/cell$	MV/cell	kW/cell	cells
LEP	350			< 25	640
TRISTAN <sup>[1]</sup>	500	220	0.4	< 26	936
LEP SPS INJ	200	216	1	< 60	32
PEP <sup>[2]</sup>	350	291	0.37	17	120
CESR	500	256	0.35	14	28
HERA	500		0.33	< 14	$\sim 500$

TRISTAN is the only storage ring with a significant complement of superconducting RF cavities. The gradients achieved in the operation of 16 5-cell, 500MHz cavities to accelerate beam average 4.4MV/m.<sup>[4]</sup> Shuichi Noguchi et. al., Particle Accelerators, Proceedings of the 14th International Conference on High Energy Accelerators, August 22-26, 1989, pp. 719-724. The TRISTAN superconducting cavities have  $(\frac{R}{Q}) = 120\Omega/cell$ .<sup>[5]</sup> In horizontal tests of 32, 5-cell TRISTAN cavities the average gradient is over 7MV/m<sup>[6]</sup>

The peak accelerating voltage for a B factory storage ring is anticipated to be about 5 to 30 MV.<sup>[7]</sup> If the resonant frequency of the accelerating cavities is 500MHz then the active length of the cell is about 0.3m. Because the accelerating gradient of a copper system is limited to 1.5MV/m then 22 cells are required to establish a peak voltage of 10MV. A superconducting system with gradient of 7.5MV/m might be based on 5 to 15 cells. As noted above the minimum number of windows for the RF system is about ten. The numerology suggests for both copper and superconducting systems that the power to each cell be coupled by a dedicated window. The number of cells necessary to sustain the voltage is about the same as the number of windows required to deliver the power.

Typically the impedance of the storage ring is dominated by the RF cavities. The short range wake generated by the passage of the bunch through the cavities can result in bunch lengthening. The wake generated by the head of the bunch introduces a voltage that is destabilizing if its variation over the length of the bunch is comparable to that of the accelerating voltage. The instability threshold depends only on the loss parameter of each cell and the total number of cells. The optimized system has a minimum number of cells.

Multibunch stability thresholds are determined by the impedance of parasitic cavity modes and the decay time of energy stored in those modes. The impedances of the parasitic modes are the frequency domain decomposition of the loss parameter and so are a characteristic of the cell geometry. And the ring impedance is proportional to the total number of cells. Again the optimized system has as few cells as possible.

Damping is achieved by coupling higher order mode energy out of the cavities and into loads. The damping required to store high current beams in a B factory ( $Q_{ext} < 100$ )<sup>[8]</sup> can only be achieved if HOM couplers are located in each and every cell of the RF system. Since the multibunch threshold scales inversely with the mode shunt impedance, the loading in each cell necessarily increases with the total number of cells. The demand for heavy damping is conveniently addressed in single cells each with dedicated higher order mode loads.

Single cell cavities have some application in existing machines and are clearly practical devices. Thirty-two single cell copper cavities in the LEP injector operate at 200MHz and a gradient of 1.5MV/m. The power dissipated per cell is about 60kW. The shunt impedance is  $R_s = 11.5M\Omega$  at  $Q_0 = 53000$ , and  $(\frac{R}{Q}) = 217\Omega/cell$ .<sup>[9]</sup> A 500MHz single cell superconducting cavity tested in DORIS coupled 50kW to the electron beam.<sup>[3]</sup> We proceed with the notion of single cell cavities as the basis of the RF system, each cell with a complement of fundamental and HOM couplers.

## Cavity Geometry

The optimization of the shape of the single cell is constrained by the requirements of fundamental and higher order mode shunt impedance and tolerable loss parameter. For superconducting cavities in which the effective accelerating gradient is limited by field emission, it is advantageous to choose a geometry that minimizes the ratio of peak surface to effective accelerating field. It is traditional to couple fundamental power into a superconducting cavity via an aperture in the beam tube. Good coupling then depends on a cell geometry in which a relatively large amount of energy is stored in the vicinity of the coupling hole.

Our strategy is to begin with a cavity geometry that is known to be free of multipacting when superconducting and that has a low ratio of peak surface to effective accelerating gradient. Geometries with reentrant noses are therefore excluded from consideration. We then proceed to optimize the geometry with respect to the defining parameters, namely the beam tube radius, the nose(iris) radius and the cell length.<sup>[10]</sup> While the exercise leads to solutions that differ in detail for superconducting and copper cavities, there are nevertheless many similarities, and in any event we are educated as to the tradeoffs in any design.

In terms of the cavity resonant modes we seek to maximize the  $(\frac{R}{Q})$  of the fundamental and minimize the  $(\frac{R}{Q})$  of all higher order modes. Furthermore it is attractive to locate couplers, both input and output along the beam tube where magnetic fields are relatively low, rather than inside the cell. (For a copper cavity it may be advantageous to couple to resonant modes through the main body of the cavity). For all modes we prefer to obtain strong coupling via a minimal discontinuity in the beam tube in order to minimize the overall loss parameter. It is therefore desirable to maximize the stored energy of the relevant modes at the coupling holes along the beam tube.

The  $(\frac{R}{Q})$  is computed directly with cavity codes URMEL<sup>[11]</sup> U. Laustroer, U. van Rienen, T. Weiland, DESY M-87-03 or SUPERFISH. The relative  $Q_{ext}$  of a mode from one geometry to the next is estimated by computing the fraction of the power dissipated in a band on the beam tube.<sup>[10]</sup> In summary we find that increasing the radius of the beam tube reduces the  $(\frac{R}{Q})$  of all longitudinal modes and increases the fraction of stored energy of all such modes in the beam tube. Upon reducing the cell length the impedance of the fundamental is increased and the higher order longitudinal modes begin to propagate into the beam tube. For a particular combination of cell length, iris radius and beam tube radius, the only remaining cavity modes with frequencies below the beam tube cutoff frequency are the fundamental accelerating mode, the TE111(644MHz) and TM110(680MHz) deflecting modes. For details of the optimization see H. Padamsee et. al.<sup>[10]</sup>

The resulting cell geometry that is the basis for further study is indicated in Figure 1. The cell length is 24cm, the beam tube radius is 12cm and the nose radius is 2cm. Its RF properties are summarized in Table III.  $(\frac{R}{Q})_{max}$  corresponds to the largest  $(\frac{R}{Q})$  of all of the many longitudinal modes that propagate out of the cell and into the beam tube but remain trapped within the boundaries of the tapered transition (see Figure 3.)

Table III. RF Properties of Optimized Cell	
frequency	500MHz
$\frac{R}{Q}$	89 $\Omega$ /cell
$E_{peak}/E_{acc}$	2.5
$H_{peak}/E_{acc}$	55.8Oe/MV/m
$E_{surface}$ for 3MV/cell	25MV/m
$H_{surface}$ for 3MV/cell	558 Oersted
$k_L(\sigma_L = 1cm)$	0.11V/pico-C
$(\frac{R}{Q})_{max}$ (propogating HOM)	4 $\Omega$ /cell

## Couplers

Since we have supposed that the power window can transmit 500kW the fundamental coupler must be designed to match a 500kW load. The external Q associated with the coupler is chosen so that at the operating voltage, the full power is extracted by the beam and/or is dissipated in the cavity walls. Then the loaded  $Q_L = \frac{P_{tot}}{\omega U}$  where  $P_{tot} = P_{beam} + P_{walls}$  and the stored energy  $U = \frac{V_{acc}^2}{(\frac{R}{Q})\omega}$ . If the full forward power is matched into the beam and cavity walls then

$$Q_{ext} = Q_L = \frac{V_{acc}^2}{P_{tot}(\frac{R}{Q})}.$$

The total power and  $(\frac{R}{Q})$  will not be very different for superconducting and normal conducting designs. But the accelerating voltage will be several times (3-7) greater for the superconducting cavity. Therefore, the copper cavity requires at least an order of magnitude stronger coupling and consequently a larger coupling aperture or more intrusive loop. If  $V_{acc} = 3MV/cell(\sim 10MV/m)$ ,  $P_{tot} = 500kW$ , and  $(\frac{R}{Q}) = 89\Omega/cell$  we find that  $Q_{ext} \sim 2 \times 10^5$ . Of course if  $V_{acc} = 1MV/m$  then  $Q_{ext} = 2 \times 10^4$ .

Strong coupling is achieved in a copper cavity through an aperture or loop in the high magnetic field region of the cell near the equator. An advantage of such a configuration is that the discontinuities associated with the coupler are far from the beam. In superconducting operation departures from uniform curvature in the vicinity of the equator can induce multipacting and as a result in most SRF applications the hole is located on the beam tube. Because of the relative proximity to the beam, losses associated with the beam tube coupling iris can be significant and care must be taken to minimize the interference of the coupler with the wall currents.

**Fig. 1.** At the left is a cross section of the CESR copper cell. The LEP superconducting cavity cell is shown in the center. The optimized B Factory superconducting cell is shown at the right. All three are scaled to 500 MHz. Loss parameter and fundamental ( $\frac{R}{Q}$ ) are indicated.

A program of RF modeling, measurements, and computation has resulted in a conceptual design of a beam tube coupler for the B-factory single cell cavity described above. The coupling is achieved by way of a slot in the shorted end of a half height 500MHz waveguide that feeds power through a matching slot in the beam tube. The length (parallel to the beam axis) of the slot is equal to the height of the waveguide (10.2cm) and the width is 9.1cm. The waveguide is oriented so that electric fields propagating in the TE01 waveguide mode are parallel to the accelerating fields in the cavity. A tongue of width 3.7cm extends 8.3 cm into the slot. The tongue decreases the cutoff frequency of the simple rectangular opening and enhances the coupling. The geometry yields good coupling to the fundamental and the dipole modes trapped in the cell.

Mode	Frequency(MHz)	$Q_{ext}$
TM010	500	$5 \times 10^4$
TE111	644	$2 \times 10^3$
TM110	680	$9 \times 10^3$

The waveguide coupling is expected to have high power handling capability. Unlike coaxial couplers there is no center conductor to be cooled or supported. In the case of the superconducting scenario, the waveguide can simply penetrate the cryostat via a transition similar to that of the beam tube penetrations. The transition to atmospheric waveguide is through a flat window that is matched to standard waveguide. The conceptual design of such a window and specifications are shown in Figure 2. The window is maintained at room temperature. The higher order modes are presumably directed to a load, also outside of the cryostat as shown in Figure 3.

**Fig. 2.** 500 MHz high power window.

**Fig. 3.** Superconducting accelerating cavity.

Wall currents generate wake voltages due to the interaction with the break in the beam wall associated with the coupling hole. The losses are computed with the MAFIA<sup>[12]</sup> cavity code. The loss parameter for the cell not including the transition to a 5cm radius beam tube, is  $k_L = 0.11V/pico - C$  exclusive of the coupler and losses to the fundamental. The loss parameter increases to  $k_L = 0.113V/pico - C$  when the coupler (waveguide, slot, and tongue) is included (not quite 3%). The transverse wake voltage for the cell with coupler is given by  $k_{\perp} = 0.37V/pico - C/m$ . The contribution to the wake voltages due to the coupler are quite small.

## Single Bunch Stability

An estimate of the bunch lengthening threshold for a machine in which the longitudinal wake is dominated by the RF system follows from our knowledge of the longitudinal wake voltage and the peak accelerating voltage. The longitudinal wake generated by the passage of the bunch through the cell is decelerating. If the magnitude of the rate of change of the wake voltage over the length of the bunch approaches the time derivative of the externally applied accelerating voltage the bunch is likely to rearrange itself. The rate of change of the wake voltage over the length of the bunch is  $\frac{1}{c} \frac{\partial V_{wake}}{\partial t} \sim \frac{qk_L}{\sigma_L}$ , where  $k_L$  is the loss parameter per cell,  $q$  the bunch charge, and  $\sigma_L$  the bunch length. The rate of change of the accelerating voltage is  $\frac{1}{c} \frac{\partial V_{acc}}{\partial t} = \omega V_{cell}/c$ . If the ratio

$$\epsilon_w = \frac{\frac{\partial V_{wake}}{\partial t}}{\frac{\partial V_{acc}}{\partial t}} = \frac{qk_L c}{\sigma_L \omega_{RF} V_{cell}}$$

is greater than unity the charges are no longer an incoherent conglomeration. Then the charge threshold can be written as

$$q_{max} \leq \frac{\sigma_L \omega_{RF} V_{cell}}{k_L c}.$$

For  $\sigma_L = 1cm$ ,  $\omega_{RF} = 2\pi \times 500MHz$ ,  $V_{cell} = 1MV (\sim 3MV/m)$ , and  $k_L = 0.113V/pico - C/cell$ ,  $q_{max} \leq 9.1 \times 10^{-7}C = 5.6 \times 10^{12}$  electrons, at least an order of magnitude larger than is likely in a storage ring. The threshold for the head tail instability due to the transverse wake is estimated<sup>[13]</sup> to be more than an order of magnitude higher than the bunch lengthening threshold. Of course the RF cavities with couplers are not the only source of longitudinal or transverse wakes. Indeed the taper transitions from large to small beam tubes in general contribute more to the loss than the cell itself. We can however be fairly confident that the proposed cell geometry does not constrain our choice of single bunch parameters.

## Higher Order Mode Power

The beam power lost per cell to nonresonant wake fields is given by:  $P = I_{avg}^2 k_L / f$  where  $I_{avg}$  is the average beam current and  $f$  the bunch frequency. For  $I_{avg} = 3A$ ,  $k_L = 0.116V/pico - C/cell$ , and  $f = 40MHz$ ,  $P_{cell} = 26kW$ . This substantial higher mode dissipation is a strong incentive to minimize the loss parameter of the cell and the total number of cells and to maximize the number of bunches in the beam. Note that the loss parameter of the cell in our conceptual design is relatively low (about 1/3 of that of the high shunt impedance version), due mostly to the large beam tube radius. The comparison with other geometries is indicated in Figure 1.

In addition to the losses associated with the single bunch passage there can be resonant buildup of stored energy in parasitic modes. Unless the modes are heavily damped,

destabilizing voltages will rapidly accumulate.<sup>[10]</sup> For the highest impedance longitudinal mode in the optimized geometry,  $(\frac{R}{Q}) \sim 4\Omega/cell$ (including tapers). Then if  $Q_{ext} \sim 100$ , the power extracted from the beam and stored in the TM011 like parasitic mode is  $P_{TM011} \sim 3kW/cell$  and for  $Q_{ext} \sim 1000$ ,  $P_{TM011} \sim 30kW/cell$  for  $I_{avg} = 3A$ . (For  $Q_{ext} > 100$  the extracted power depends only on the average current.) The dense spectrum<sup>[10]</sup> of such modes essentially guarantees that some will interact resonantly with the beam. Heavy loading is therefore required simply to limit power consumption. Multibunch stability imposes additional constraints.

As noted above, all longitudinal modes propagate into the beam tube and outside the cooling vessel permitting relatively easy access to those modes. The possibility of lining the beam tube with an absorbing material such as a ferrite is under investigation. It offers the promise of broad banded loading of any modes with stored energy in the beam tube, which includes all longitudinal modes. Such a scheme precludes the need for additional coupling holes or loops to capture higher mode energy. There is a resistive wall loss associated with the absorber that for typical parameters is of the same magnitude as the wall loss of the entire remainder of the ring. The resistivity of the particular ferrite under study has a strong frequency dependence that peaks at about 2GHz and falls by an order of magnitude as the frequency increases to 12GHz as shown in Figure 4.

The general frequency dependence is a good match to machine requirements in so far as the modes trapped in the large radius beam tube are in the 1-3GHz range whereas a substantial fraction of the bunch power spectrum is above 12GHz. For the indicated absorption spectrum, the resistive wall heating of a 15cm long, 12cm radius ferrite 50 beam tube amounts to about 3.5kW for  $I_{avg} = 3A, f = 40MHz$ , and  $\sigma_L = 1cm$ . The effective resistance of the ferrite, averaged over the bunch power spectrum is about 800 times that of a copper tube of same dimensions.

The vacuum characteristics of the ferrite have been established by experiment to be adequate for the storage ring environment. Thermal properties and fabrication techniques are being investigated.

## Superconducting or Copper RF Systems

Superconducting structures are attractive because they can sustain an accelerating voltage several times higher than the copper counterpart. Therefore fewer cells are required to provide the necessary longitudinal focusing. Higher mode losses increase linearly with the number of cells (of given geometry) and single and multibunch instability thresholds decrease inversely with the number of cells. Of course the relative merit of the superconducting system depends on the voltages that can be achieved. Table II summarizes the characteristics of some copper RF systems. Note that the peak gradient corresponds to about 1.3MV/m(at 500MHz the cell length is taken to be 0.3m). All of the cavities are designed with high fundamental  $(\frac{R}{Q})$ , about 2.5 times greater than that of the cell optimized for B-factory parameters. The existing systems are presumably dissipation limited (either

**Fig. 4.** Surface resistance of ferrite 50 as a function of frequency.

by the economics of power or the technical difficulty of removing it). But similar gradients in the cell optimized for low HOM impedance and heavy HOM loading are attained only by a corresponding increase in dissipated power by a factor 2.5 to compensate for the deterioration of the  $(\frac{R}{Q})$  in the fundamental.

The power dissipated in 4.2K Helium at  $V_{acc} = 7MV/m, (\frac{R}{Q}) = 89\Omega/cell, Q_0 = 2 \times 10^9$  is 25W/cell corresponding to about 9.3 kW/cell of refrigerator power. The superconducting system is therefore capable of sustaining a much higher voltage at a fraction of the cost of the copper system both in terms of power and ring impedance. If on the other hand the number of cells (input windows) is determined by beam power rather than voltage requirements the advantage of superconducting RF is diminished.

## Conclusions

The conceptual design of a B-Factory RF system consists of single cell cavities. The cell shape is optimized to:

1. Minimize  $(\frac{R}{Q})$  of parasitic modes,
2. Force all longitudinal higher modes to propagate into the beam tube,
3. Yield strong coupling to the fundamental through an aperture in the beam tube,
4. Preserve fundamental  $(\frac{R}{Q})$  at a level compatible with a superconducting system,
5. Minimize  $E_{peak}/E_{acc}$ .

Each cavity has a dedicated fundamental power feed. The waveguide coupler transmits power into the accelerating mode through a slot in the beam tube. The same slot couples to the only two parasitic modes that are trapped in the cell. The wake fields generated by the slot geometry are negligibly small. A ferrite absorber is perhaps the basis of a broad band higher order mode load if distributed along the large radius beam tube beyond the cutoff length of the fundamental. A 500kW RF window unit with impedance matched to standard waveguide is designed. The window is maintained at room temperature.

A system optimized for normal conducting operation is likely to have somewhat higher  $(\frac{R}{Q})$  to reduce dissipation. Higher fundamental shunt impedance probably implies longitudinal parasitic modes that are trapped in the cell. Couplers are necessarily located near the equator of the cell. The ring HOM impedance and the AC power of the normal conducting system are higher than that of the superconducting system.

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