# BEAM POSITION MONITOR WITHIN THE CORNELL ENERGY RECOVERY LINAC CAVITY ASSEMBLY*

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## *Abstract*

In an energy recovery Linac (ERL) the low energy beam is very sensitive to deflections due to the RF fields as it passes through the accelerator cavities. Therefore, to avoid the possible effects of beam breakup, it will be important to determine the optimum transverse position for the beam within the first several sets of cavity cells in the cryostat assembly and to maintain this position over long periods. As a result a beam position monitor (BPM) has been designed to be located between the higher-order modes (HOM) loads and the seven-cell RF structures. This BPM's design reduces the coupling of RF power from the fundamental mode and HOMs into the BPM, while maintaining acceptable position sensitivity and resolution. We analyzed the coupling of the probe to the HOMs of realistically shaped cavities by generating geometries for hundreds of cavities having small shape variations from the nominal dimensions consistent with present machining tolerances, and solved for their monopole and dipole spectra. Our results show that the peak, dissipated power within BPM cables, which pass through the cryostat, is well within the permissible levels.

## REQUIREMENTS FOR CAVITY BPMS

In energy recovery mode the Cornell ERL RF cavities [1] are designed to operate with 77 pC bunches spaced with a frequency of 2.6 GHz, having subsequent bunches alternating between being accelerated and decelerated. In the initial commissioning and later recovery periods after accelerator down periods, the beam utilized in a non-energy recovery mode for tune-up will have 7.7 pC bunches with a 50 MHz spacing. In this tune-up phase of operation the design for the BPM requires a position sensitivity of ±150 μm in the 55 mm-radius beam pipe, connecting the 7-cell superconducting RF (SRF) structures to the coaxial HOM loads, which are integrated into the beam pipe. It is expected with this requirement the BPM electronics need a dynamic range of a 10-fold increase in charge per bunch and more than a 25-fold increase in the bunch frequency, allowing their sensitivity to approach ±2 μm in full current operation.

For example with top and bottom pickups of the BPM in the beam pipe of radius $R_{pipe}$ (55 mm) the BPM position sensitivity δy will be

$$\delta y = \frac{R_{pipe}}{2}\left(\frac{S_{top}-S_{bottom}}{S_{top}+S_{bottom}}\right) \qquad (1)$$

where $S_{top}$ and $S_{bottom}$ are the RF signal amplitudes from the respective pickups. Thus to achieve the desired BPM sensitivity each electrode needs to have a signal-to-noise (S/N) ratio of at least 46 dB. Assuming 50 Ω input impedance-BPM electronics operating at 300°K and having a processing bandwidth of 1 MHz, the thermal noise level at the input of the electronics will be -138 dBW. This requires a signal level from the pickup through cables to exceed -92 dBW at the BPM processor.

Another requirement is that the BPM must not couple more than -3 dBW of total power from the fundamental mode and HOMs into each signal line, a small coaxial cable of length about 2.3 m connecting the pickup's port to the outside of the cryostat. The small diameter cable is utilized to minimize heat flow to the cryogens, however the cable incurs a minimum of 4 dB loss at 1.3 GHz (the loss rises about 3 dB every octave) causing most of the signal power to be dissipated in this cable.

The frequency chosen for signal analysis is of less importance for an accelerated beam alone, however when both accelerated and decelerated beams are present, we wish to measure the position for the two individual beams. This is achieved by analyzing the pickup signal amplitudes at different carrier frequencies (even and odd harmonics of 1.3 GHz) requiring these frequencies be outside of HOM pass-bands.

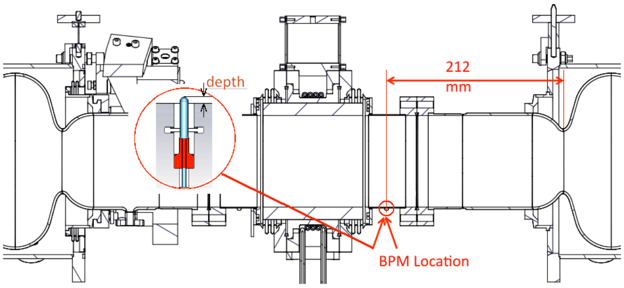

Figure 1: Cryostat assembly in the region between seven cell RF structures, including the BPM and an inset defining the probe's depth.

## DESIGN CONCEPT

As shown in Figure 1 the cryostat geometry has the HOM loads placed equidistant between ends of pairs of 7 cell-RF structures since the 55 mm-radius beam pipe is cutoff for the 1.3 GHz fundamental frequency. To minimize the coupling to the fundamental RF power, the BPM needs to be located remotely from the last coupling iris of the RF structure. In the present cryostat's design this places the BPM 212 mm from the last coupling iris. A number of different BPM geometries were considered and their frequency responses were modeled using Microwave Studio [2]. The "button" BPM-structure coupled high levels of RF power from the fundamental RF mode with a non-uniform frequency response for the detected signal.

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The geometry, selected for more detailed study, is a coupling post, extending a (positive) depth into the cross section of the beam pipe or retracted below the pipe's surface (for a negative depth.) The post, connected to a coaxial line with the same inner diameter, gives uniform frequency response for signals coupled onto the post. This geometry also allows for the possibility of an additional notch filter for the fundamental mode as part of the coaxial line.

## MODELING

Detailed modeling of the BPM was undertaken using Microwave Studio [2] and of the HOMs in the RF structure using CLANS, a simulation code from the SLANS family of software that is capable of modeling the losses in the dielectric material in the HOM loads [3].

### *Fundamental Power Coupling*

To narrow the range of possible depths that the BPM post might extend into the beam pipe a sequence of studies were made with two 7 cell-structures and their intervening beam pipe. The calculation yielded the power coupled into the coaxial line at the RF fundamental frequency as a function of distance from the nearest iris and for the depth of the post, assuming the design 16.1 MV/m accelerating field. The results are given in Table 1 for a probe at a distance of 212 mm along the pipe indicating a depth of the post up to 10 mm is acceptable.

Table 1: Upper Limit for the Power Coupled from the Fundamental Mode at Distance of 212 mm from the Nearest Cavity Iris vs. Depth of the Post

| Depth (mm) | 10 | 7.5 | 5 | 2.5 | 0 | -2.5 | -5 |
|---|---|---|---|---|---|---|---|
| Power (dBW) | -11 | -15 | -20 | -26 | -36 | -48 | -65 |

### *BPM Pickup Sensitivity*

The BPM pickup sensitivity was simulated by using a simplified post geometry coupled to a coaxial line with a small center conductor down the length of the beam pipe. The simulation yielded the coupling from the TEM mode into the pickup as a function of frequency. Table 2 contains the results vs. probe depth for the lowest harmonics of the beam's repetition frequency.

Table 2: RF Signal Level (in dBW) for 7.7 pC Bunches at 50 MHz Repetition Frequency at Different Beam Harmonics vs. Depth of the BPM Post

| Depth (mm) | 10 | 7.5 | 5 | 2.5 | 0 | -2.5 |
|---|---|---|---|---|---|---|
| 2.6 GHz | -31 | -33 | -38 | -44 | -55 | -75 |
| 3.9 GHz | -34 | -39 | -44 | -50 | -68 | -78 |
| 5.2 GHz | -33 | -33 | -39 | -47 | -68 | -80 |

### *HOM Power Coupling*

HOMs pose two challenges for the BPM design. First, the power transferred from the beam to the cavities and then coupled into the BPM needs remain low to prevent heating in the cryostat. Then the pass-band frequencies of the HOMs cannot overlap those, which the BPMs will utilize to detect the beam position signals, i.e. two of the harmonics of 1.3 GHz.

Monopole and dipole modes were computed for RF cavities, HOM loads and attached beam pipes for an ensemble of different geometries, where the dimensions of the structures were allowed to vary by ±0.5 mm to account for construction variations. The sets of frequencies, R/Q's and Q's for each HOM were employed to compute the power spectrum for two different beam conditions, 1) a single 100 mA accelerated beam and 2) 200 mA for the combined accelerated and decelerated beams. Examples of the spectra may be seen in figures 2 and 3 for monopole modes in each beam condition, respectively. The power transfer into the BPM from the beam pipe vs. frequency was simulated for post depths of 2.5, 0, and -2.5 mm. The integrated HOM power was computed for each post depth out to 10 GHz assuming a worst case of a total of 400 W of HOM power being coupled from the two 100 mA beams into the HOM loads. For this case the coupling factor and total HOM power coupled into each BPM is given in first two lines of Table 3 for the three post depths. Due the total coupled HOM power it is clear that the BPM may not protrude into the beam pipe.

Table 3: The Coupling Factor, the Upper Limit for the Total RF Cavity Monopole HOM Power at Full Two Beam Currents and the HOM Spectral Components for the Two Beams Scaled to 7.7 pC Bunches at 50 MHz Repetition Rate after Coupling into the BPM vs. Depth of the BPM Post

| Depth of Post (mm) | 2.5 | 0 | -2.5 |
|---|---|---|---|
| Coupling Factor (dB) | -28 | -37 | -47 |
| Total HOM Power (dBW) | -2 | -11 | -21 |
| HOM Components at | | | |
| 2.6 GHz (dBW) | -69 | -79 | -89 |
| 3.9 GHz (dBW) | -84 | -94 | -104 |
| 5.2 GHz (dBW) | -40 | -49 | -60 |

### *BPM Signal Levels*

The spectral components at the first three beam harmonics above the fundamental are also presented in Table 3 for single beam currents in the beam-tuning mode of operation. In this mode of operation (accelerated bunches only at 50 MHz repetition frequency) any harmonic of 1.3 GHz would work sufficiently for CW processing of the BPM signals. Comparing Tables 2 and 3 suggests that a probe with the depth of 0 mm (i.e. a probe that is flush with the surface of the beam pipe's wall) would couple into the BPM signal 24-26 dB above the worst case interference signal from monopole HOMs. As the design criterion is to have a S/N ratio of 46 dB, this would seem to be a failure. However, since the monopole modes create a common-mode signal in the BPM, as is seen in the numerator of equation (1) this signal subtracts out, leaving only approximately a 5% error in the denominator. This effect alone would create a 5% systematic gain error in the position determination, however the nominal electrical center of the BPM would remain a fixed point. If in addition to this, the common mode signal was unbalanced at the few percent level, then the presence of the HOM signal would shift the electrical center of the BPM by a few percent of 28 mm. To the extent that HOM contributions remain constant over time, these systematic errors would also remain constant, making the determination of the preferred trajectory repeatable at a level slightly better than the design, ±100 μm. However, since the HOM and BPM signals scale proportional to beam current, there will be no improvement in position resolution as the current increases. Since this effect is essentially the same for 2.6, 3.9 and 5.2 GHz, any one of this frequencies could be used equally well for CW signal processing. This also implies that one of the even and one of the odd harmonics can be used to determine the relative positions and relative amplitudes of the accelerated and decelerated beams with approximately the same resolution as for a single accelerated beam.

What we have discussed above is the worst-case situation if the HOM pass-bands overlap all even and odd harmonics of 1.3 GHz. In practice the situation may be less severe. Generally to reduce resonant excitation, SRF cavities tend to avoid HOM pass-bands at harmonics of the highest beam repetition frequency. Measurements of a prototype accelerator structure at Cornell indicates that the lowest of these harmonics are outside of the pass-bands implying that 2.6 and 3.9 GHz would be good choices for signal processing for this structure. In addition since the ERL bunch length is 2 ps or less, the beam harmonics extend to quite high frequencies. One would expect that the R/Q's and Q's will fall as we look at higher 1.3 GHz harmonics. So if we are able to process the CW signals at high enough frequencies, it is likely that there will be higher harmonics of 1.3 GHz where the signal-to-HOM ratio improves and below where the skin effect losses in the cable become too severe. So although the worst-case situation yields poorer resolution than the design criterion, it is likely that this may be relatively easy to improve with some care.

## FINAL DESIGN

A coaxial coupling port, flush with the beam pipe wall, is the selected design for ERL SRF cryostat BPM, which meets the design criteria for power dissipation less than -3 dBW within the cryostat. In the worst case where the HOM pass-bands completely overlap all of the lowest harmonics of 1.3 GHz, the design is close to achieving the ±150 μm at all beam currents. In the more likely situation where there are some harmonics free of HOM pass-bands or if CW processing can be designed at much higher harmonic numbers, then it may be possible to substantially exceed the desired position resolution.

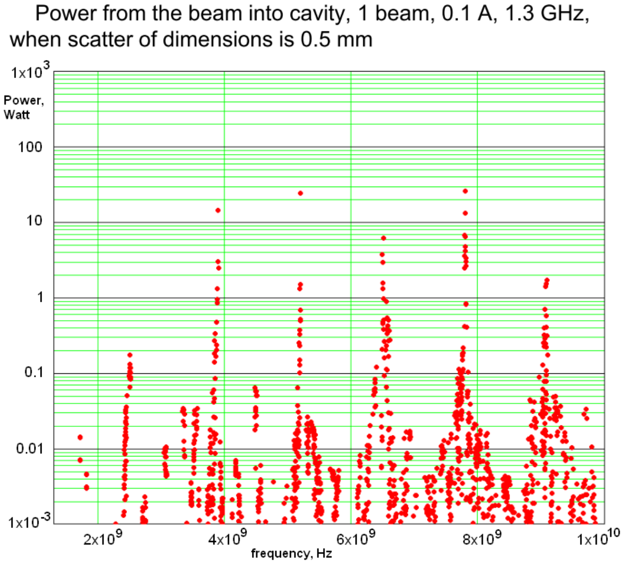

Figure 2: Beam power in monopole modes for a single accelerated ERL beam.

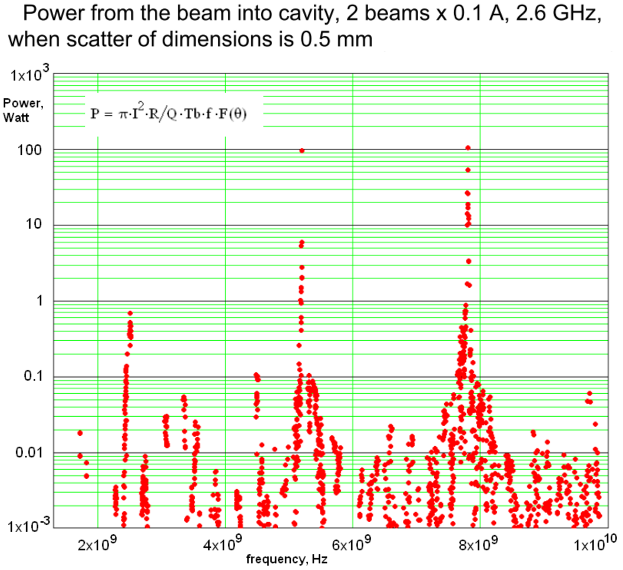

Figure 3: Beam power in monopole modes for a both accelerated and decelerated ERL beams.

## REFERENCES

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