SHUNT IMPEDANCE MEASUREMENT OF THE APS BBC GUN*

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Abstract

The injector test stand (ITS) at Advanced Photon Source (APS) presently incorporates a ballistic bunch compression (BBC) gun, and it is used as a beam source for a number of experiments, including THz generation, beam position monitor testing for the Linac Coherent Light Source (LCLS), novel cathode testing, and radiation therapy source development. The BBC gun uses three independently powered and phased rf cavities, one cathode cell, and two full cells to provide beam energies from 2 to 10 MeV with variable energy spread, energy chirp, and, to an extent, bunch duration.

The shunt impedance of an rf accelerator determines how effectively the accelerator can convert supplied rf power to accelerating gradient. The calculation of the shunt impedance can be complicated if the beam energy changes substantially during its transit through a cavity, such as in a cathode cell. We present the results of direct measurements of the shunt impedance of the APS BBC gun on an individual cavity basis, including the cathode cell, and report on achieved gradients. We also present a comparison of the measured shunt impedance with theoretical values calculated from the rf models of the cavities.

DEFINITIONS

The shunt impedance serves as a figure of merit for the accelerating efficiency: the larger the accelerating field per unit supplied rf power, the more efficient the accelerator. For an accelerating cavity, the shunt impedance is defined, such as in the code Superfish [1], as

$$Z_f = \frac{\left(\int_{z_i}^{z_f} E_z(z)dz\right)^2}{LP_T} = \frac{V_{ins}^2}{LP_T}, \quad (1)$$

where z_i is the entrance of the cavity field on z-axis and z_f is the exit, $L = z_f - z_i$ is the length of the cavity, P_T is the total power loss in the absence of beam, $E_z(z) = E_z(r = 0, z)$ is the axial longitudinal electric field, and $V_{ins} = \int_{z_i}^{z_f} E_z(z)dz$.

Alternatively, one can define the shunt impedance as

$$Z_b = \frac{V_g^2}{LP_T}, \quad (2)$$

where V_g is the voltage gain of an electron passing through the cavity. The latter definition is well suited for beam-based measurement of the shunt impedance as described in the next section. For a normal conducting cavity with close to critical coupling, we can assume that all the forward power P_{FWD} is lost in the cavity so that $P_T \approx P_{FWD}$.

Generally speaking, the two definitions of the shunt impedance, Z_f and Z_b, do not agree since the beam-based definition implicitly includes all transit-time and velocity-change-related effects via the voltage gain V_g. These are explicitly absent in the definition of Z_f.

EXPERIMENT

Experimental Setup

The BBC gun is a 2+1/2 cell rf cavity. Each cell has a separate rf feed which allows its field amplitude and phase to be independently controlled. A photo of the gun before installation is shown in Fig. 1.

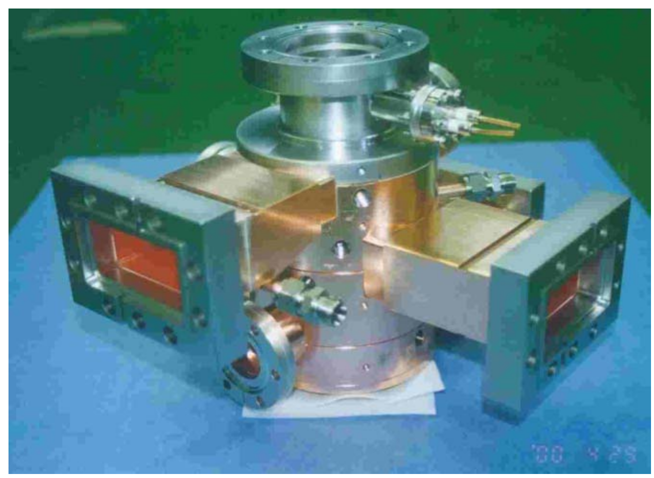

Figure 1: The BBC gun before installation in the beamline.

A dispenser photocathode mounted on the back plate of the half-cell cavity can produce electron bunches with charges exceeding 1 nC [2]. The beam's final energy ranges from approximately 2 to 10 MeV. Downstream of the gun the beamline includes quadrupoles, magnetic steerers, and a dipole spectrometer.

Measurement of Full-Cell Shunt Impedance

By keeping the power into the cathode cell constant and measuring the beam energy as the first full cell forward power is varied, we can obtain the shunt impedance of the first full cell via Eq. (2). The result of the measurements is shown in Fig. 2. A linear regression of the data yields a shunt impedance value of approximately $Z_b^{fc} = 79 \pm 6$ MΩ/m. The maximum average accelerating gradient reached in this set of measurements is about 75 MV/m.

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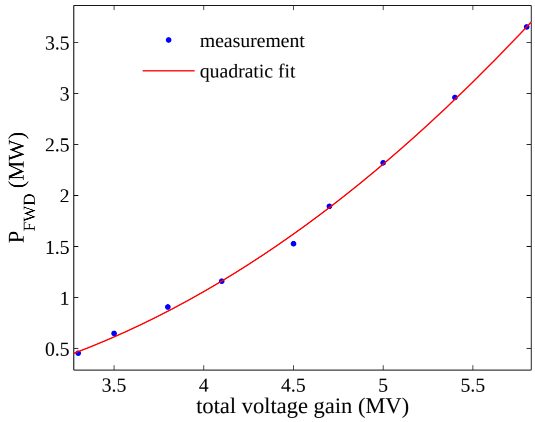

Figure 2: The forward power of the first full cell versus the total voltage gain from the cathode cell and the first full cell.

The shunt impedance of the second full cell is approximately the same as the first full cell by observing that the beam energy is about the same when powering either (1) the cathode cell and the first cell or (2) the cathode cell and the second full cell at the same power level. Both cells are operated for maximum energy gain in this measurement.

Measurement of Cathode-Cell Shunt Impedance

With the two full cells downstream of the cathode cell turned off, the cathode cell forward power is set to about $P_{FWD} = 1.8$ MW. The corresponding maximum beam voltage gain is measured to be $V_g = 2.8$ MV, indicating a shunt impedance of approximately $Z_b^{cc} \approx 135$ MΩ/m for the 3.22-cm-long cathode cell. The average accelerating gradient is about 87 MV/m, corresponding to a peak field of $\sim$ 125 MV/m.

THEORETICAL MODEL

Full Cell

The ratio of two shunt impedances given by Eq. (1) and Eq. (2) is

$$\frac{Z_b}{Z_f} = \left(\frac{\int_{z_i}^{z_f} E_z(z)\cos(kz+\phi_0)\,dz}{\int_{z_i}^{z_f} E_z(z)dz} \right)^2, \quad (3)$$

where ϕ_0 is the launching phase and k=$\frac{2\pi}{\lambda}$ is the wave number. Let's consider a beam with normalized velocity $\beta = 1$. To evaluate the numerator integrand in Eq. (3), we chose ϕ_0 to provide the maximum energy gain; see Fig. 3 for a plot of the two integrands. A numerical integration using the on-axis field profile obtained from Superfish gives $\int_{z_i}^{z_f} E_z(z)dz = 40.47$ kV and $\int_{z_i}^{z_f} E_z(z)\cos(kz+\phi_0)\,dz = 30.40$ kV, resulting in a ratio $Z_b^{fc}/Z_f^{fc} \approx 0.56$. The shunt impedance given by Superfish for the full cell is Z_f^{fc}=148 MΩ/m, therefore the expected Z_b^{fc} = 83 MΩ/m. This agrees very well with our measurement result 79 ± 6 MΩ/m as reported in the last section, given that any real cavity generally has imperfections that lower the shunt impedance, such as the pumping ports, power feeds, etc.

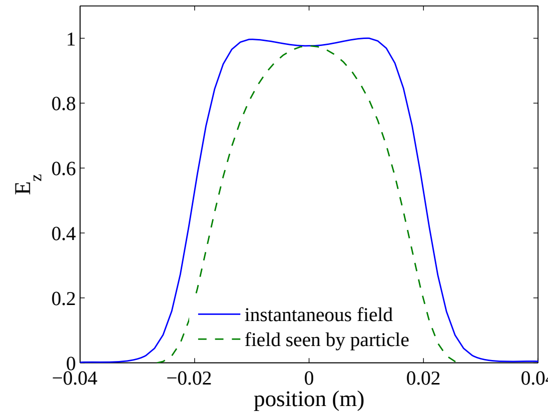

Figure 3: The instantaneous longitudinal electric field and the field seen by the particle inside the full cell.

Cathode Cell

Analysis of the cathode cell is somewhat more complicated compared to the full cells because the beam velocity changes drastically during the transit of the cathode cell. Effects such as phase slippage need to be incorporated; this can be done by numerically integrating the longitudinal equations of motion. Consider an electron in an rf standing wave accelerating structure that experiences the following longitudinal electric field

$$E_z(z,t) = E_0\cos(kz)\sin(\omega t+\phi_0). \quad (4)$$

Let $\psi(z,t) = \omega t - kz + \phi_0$ be the relative phase of the electron w.r.t the wave. The evolution of $\psi(z,t)$ can be expressed as a function of z solely:

$$\frac{d\psi}{dz} = \omega\frac{dt}{dz} - k = \frac{\omega}{\beta c} - k = k\left(\frac{\gamma}{\sqrt{\gamma^2-1}} - 1\right), \quad (5)$$

where γ is the Lorentz factor. The energy gradient can be written as [3]:

$$\frac{d\gamma}{dz} = 2\alpha k E_z \sin(\psi + kz), \quad (6)$$

where $\alpha = \frac{eE_0}{2kmc^2}$ is the normalized accelerating field. The system of coupled ordinary differential equations, Eq. (5) and Eq. (6), describes the longitudinal motion of an electron in the rf structure and is numerically integrated. For a peak accelerating gradient E_0 = 120 MV/m, the beam energy gain as a function of the launching phase is shown in Fig. 4.

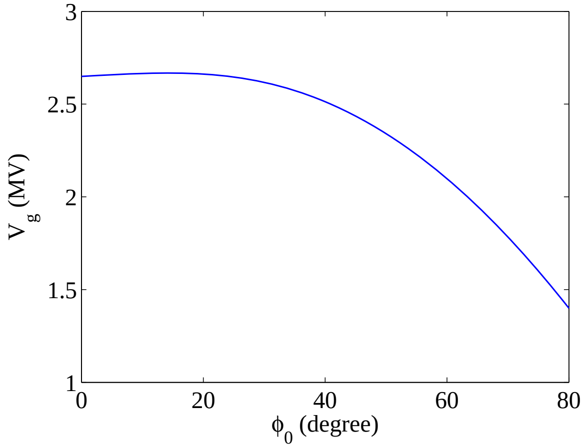

Figure 4: Beam voltage gain in the cathode cell as a function of launch phase.

The actual cathode-cell field is close to, but not a true sine wave; we therefore numerically calculate both the beam voltage gain V_g and the instantaneous voltage gain V_{ins}. The ratio of the corresponding impedances Z_b/Z_f is equal to $(V_g/V_{ins})^2$ and is plotted in Fig. 5.

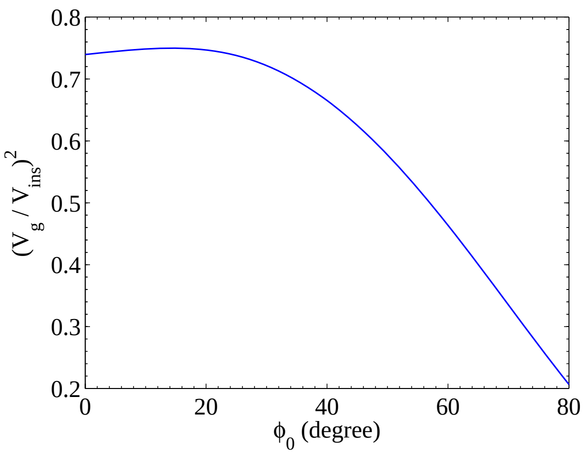

Figure 5: The ratio of the cathode-cell impedances defined by Eq. (2) and Eq. (1) as a function of launch phase.

From Superfish, the shunt impedance of the cathode cell is Z_f^{cc}= 100 MΩ/m. From Fig. 5, we are expecting a measured shunt impedance $Z_b^{cc} \approx 75$ MΩ/m. However, the measured value is much higher, at around 135 MΩ/m. This might be due to some residual power (P_{resid}) existing in the first full cell. The corresponding voltage gain in the first full cell is given by

$$\Delta V_g = \sqrt{Z_b^{fc} \cdot L^{fc} \cdot P_{resid}}\,, \qquad (7)$$

where $L^{fc} = 0.0525$ m is the full-cell length. The apparent impedance ratio is given by

$$\frac{Z_b^{cc}}{Z_f^{cc}} = \left(\frac{V_g + \Delta V_g}{V_{ins}}\right)^2 \qquad (8)$$

and is plotted in Fig. 6 using the measured Z_b^{fc} = 79 MΩ/m.

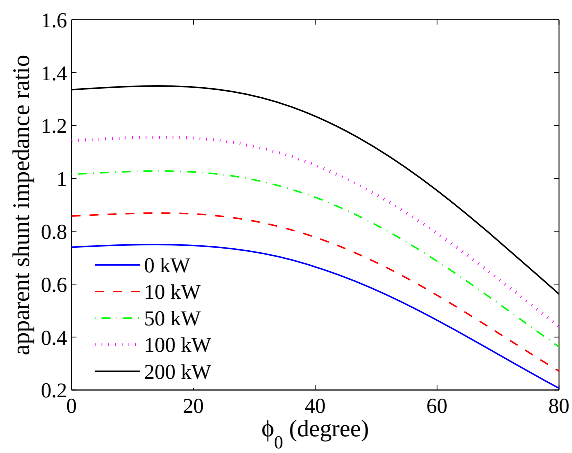

Figure 6: The apparent shunt impedance ratio at different full-cell residual power levels.

As a result of the high shunt impedance of the first full cell, a small amount of residual power can increase the beam energy significantly. Therefore the apparent acceleration from the cathode cell could be measured much higher than it actually is, leading to a higher apparent shunt impedance ratio. For example, at 200-kW residual power, the ratio is about 1.35; therefore the apparent $Z_b^{cc} = 1.35 Z_f^{cc}$ =135 MΩ/m, which is the measured value.

SUMMARY

The BBC gun is very efficient in terms of converting rf power into accelerating power, as indicated by its high impedance, which is above 75 MΩ/m for any one of its three cells. The maximum peak accelerating gradient of about 125 MV/m has been achieved in the cathode cell, and average accelerating gradient of 75 MV/m is observed in the full cells. There is still the potential for higher gradient of the gun, as the current measurable energy limit is set by what the spectrometer can measure and not by what the gun can produce.

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