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Deflecting cavity for beam diagnostics at Cornell ERL injector

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ABSTRACT

A single-cell, 1300-MHz, TM110-like mode vertically deflecting cavity is designed and built for beam slice emittance measurements, and to study the temporal response of negative electron affinity photocathodes in the ERL injector at Cornell University. We describe the cavity shape optimization procedure, RF and mechanical design, its performance with beam.

1. Introduction

A prototype injector for the Cornell Energy Recovery Linac (ERL) is designed to accelerate high average current (up to 100 mA) of electrons to energy of several MeV [1]. A suite of sophisticated methods to measure low-emittance beam parameters has been developed. Some of the techniques utilize a deflecting cavity. These include: measurements of the photoemission response time and temporal profile of the initial electron distribution after the gun [2], bunch temporal profile determination at 5–15 MeV, including longitudinal phase space characterization in a dispersive region, and reconstruction of an unprojected (temporal slices) emittance both after the gun and after the injector.

The ERL deflecting cavity is used for experiments at different energies from 500 keV ($\beta = 0.914$) after the gun to 5–15 MeV after the injector. At low energy the cavity operates in CW mode. At high energies, after the injector, it has to operate in a pulsed mode to limit the power deposited on the viewscreen. A deflecting angle of 12 mrad allows obtaining a resolution of ≈ 100 to 400 fs on a cerium-doped YAG (YAG:Ce) view screens located approximately 4 and 1 m downstream from the cavity. RF power is provided by a high-power klystron transmitter [3]. The typical pulse length is 30 μs and the repetition rate is up to 1 kHz. The deflector was optimized for $\beta = 1$.

2. Cavity shape considerations

The amplitude of transverse deflecting voltage acting on a beam of charge e particles passing through the deflecting cavity on axis is

$$V_\perp = \frac{\Delta p_\perp c}{e} = \left| c \int_{-\infty}^{\infty} B_\perp(z) e^{ikz/\beta}\, dz - i \frac{1}{\beta} \int_{-\infty}^{\infty} E_\perp(z) e^{ikz/\beta}\, dz \right|, \tag{1}$$

where $\Delta p_\perp$ is the change of particle transverse momentum after its passing through the cavity, $B_\perp(z)$ and $E_\perp(z)$ are the transverse components (B_x and E_y in our case) of the magnetic and electric fields on the cavity axis, z is the coordinate along the axis, $k = \omega/c$ is the wave number, c is the speed of light, ω is the RF angular frequency. Then the transverse shunt impedance is

$$Z_\perp = \frac{V_\perp^2}{2P} = \frac{V_\perp^2 Q}{2\omega U}, \tag{2}$$

here P is the power dissipated in the cavity walls, Q is the quality factor of the operating mode, and U is the stored energy. For the simplest case of a TM110 mode in a $\lambda/2$- long pill-box cavity, one calculates $Z_\perp = 1.12$ MOhm. The transverse impedance drops with the addition of beam pipes, e.g., adding 35 mm diameter beam pipes reduces the impedance to $Z_\perp = 1.08$ MOhm. One can improve the transverse shunt impedance by compressing electromagnetic field toward the cavity axis. In the CEBAF RF separator [4], this was accomplished with four round rods.

At higher energies multi-cell deflecting structures are used to produce big enough transverse kick (see Ref. [5], for example). Relatively low beam energies of the Cornell ERL injector and the use of an optimized cavity shape allowed us to design a single-cell cavity with a TM110-like mode [6,7]. In our design we utilize an approach similar to the one used at CEBAF. However, in our case

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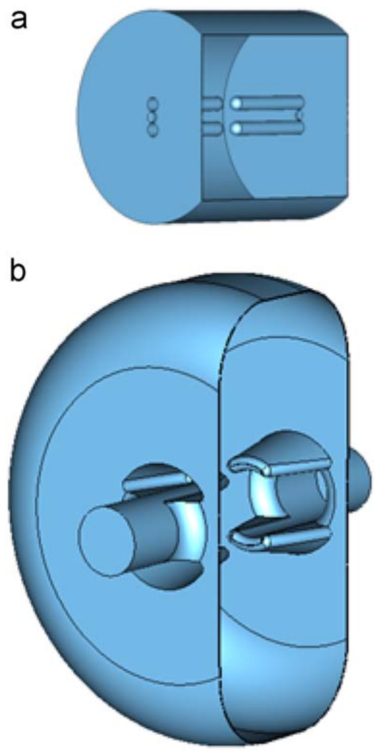

Fig. 1. Comparison of CEBAF RF separator scaled to 1.3 GHz (a) and Cornell ERL injector deflecting cavity (b).

Table 1
Calculated parameters of the deflecting cavity.

Resonance frequency, f	1300 MHz
Quality factor, Q	14,050
Transverse shunt impedance, $Z_{\perp}$	5.27 MOhm
Peak surface electric field at 200 W	2.82 MV/m
Max. dissipated power density at 200 W	5.80 W/cm^2

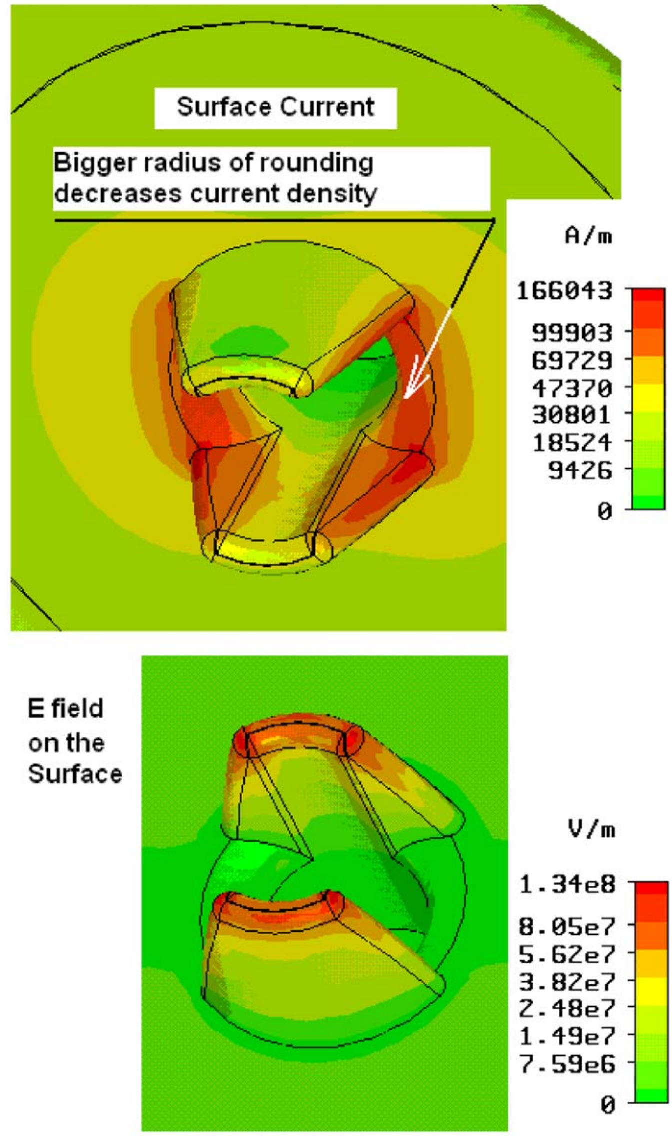

Fig. 2. Distribution of the RF current density (top) and surface electric field near the protrusions (bottom) for the stored energy of 1 J.

Table 2
Resonant frequencies of several modes.

Frequency (MHz)	Mode
797.4	TM010-like, fundamental mode
1300	TM110-like, operating mode
1550	TE101-like, dipole, beam pipe region
1677	TM110-like, polarized orthogonally to operating mode
1678	A dipole mode strongly coupled to the tuner

the relative beam pipe opening is six times larger than that of the CEBAF RF separator, so simple round rods become less effective. We have designed protrusions of a more elaborate shape to reach our goals. Fig. 1 illustrates the difference between the CEBAF and Cornell ERL deflecting cavity shapes. The protrusions make the cavity azimuthally asymmetric, providing an additional benefit of splitting resonant frequencies of two usually degenerate TM110 modes far apart.

The shape optimization procedure consisted in varying the cavity dimensions to maximize $Z_{\perp}$. The conical shape of the protrusions and a proper radius of the cavity shell (Fig. 1 b) help to increase the Q factor. The cavity length is 5.5% shorter than the half wavelength to compensate for fields leaking into the beam pipe. Table 1 summarizes results of Microwave Studio [8] calculations for the deflecting cavity equipped with auxiliary components (input power coupler, frequency tuner, pump-out port). Most of our efforts were spent on finding optimal dimensions of the protrusions. The following constraints were applied: the maximum surface electric field was limited to 3 MV/m and the maximum dissipated power density was sought to be less than 10 W/cm^2 for the total dissipated power of 200 W for CW operation at low energy. At high energy the deflector can dissipate power up to 1 kW with water cooling. In spite of a relatively big beam pipe diameter, we have obtained the transverse impedance of 5.3 MOhm. Distributions of RF current density and surface electric field in the most strained area are shown in Fig. 2. At the cavity wall

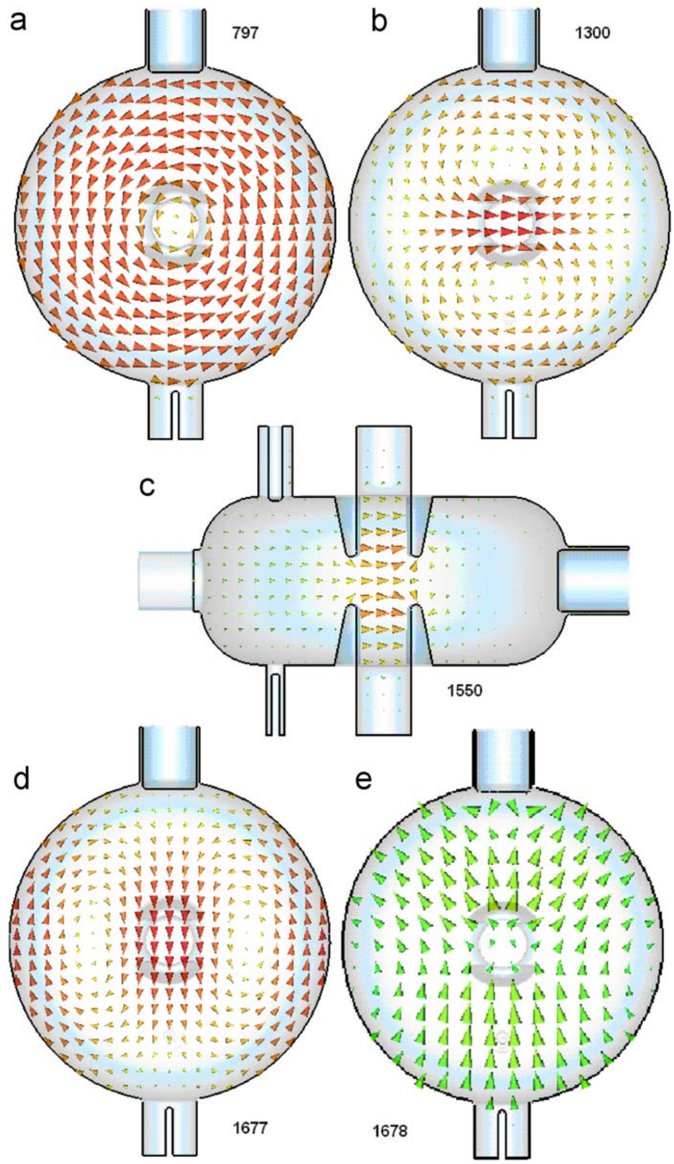

Fig. 3. Magnetic (a, b, d) and electric (c, e) field patterns for the deflector eigenmodes.

dissipation of 200 W, the maximal electric field is 2.8 MV/m, and the maximal power density is 5.8 W/cm^2. The Q factor was assumed to be 11,500 or 20% below its ideal value, taking into account surface roughness. Increasing the rounding radius of the beam pipe iris to $R=10$ mm, as compared to $R=3.5$ mm of the protrusion edges, lowers current density in this critical region.

The spectrum of cavity eigenmodes was calculated and resonant frequencies of several modes are presented in Table 2. Fig. 3 illustrates the field patterns of the modes listed in Table 2.

3. Cavity design

The body of deflecting cavity (Fig. 4) is made of three main OFHC copper parts: a central piece and two side plates. The central piece houses a 40 mm ID port for a frequency tuner at the cavity top and a pumping port at the cavity bottom. To better distribute RF currents near the pumping port, the port is divided by a partition. Two side plates accommodate conical protrusions and 35 mm ID beam pipes. A water cooling channel is machined near the base of each protrusion. One of the side plates also has a 16 mm port for a field probe and a 22.2 mm port for an input power coupler. At the first step the stainless steel ports are brazed to the individual copper pieces, and then the three subassemblies are brazed together (at a lower temperature). Finally, Conflat^{TM} flanges are welded to all ports.

The input power coupler is of a coaxial antenna type with a disk ceramic window interfaced to a $1\frac{5}{8}$ in. coaxial line. The input coupler and RF field probe are placed at locations where the ratio of electric to magnetic RF fields is equal to the impedance of free space. In this case the change in the antenna penetration does not disturb the cavity frequency. The external Q factor of the input coupler was calculated as function of the antenna penetration (Fig. 5) to determine the optimal coupling. Similar calculation was performed for the RF field probe. The frequency tuner is of a plunger type, similar to that designed for the ERL injector buncher cavity [9]. The tuner should compensate the thermal drift of the cavity frequency and fabrication errors. The total stroke of ± 10 mm from the initial position (-3.5 mm in Fig. 6) secures the total tuning range of more than 2 MHz.

4. Measurement results and operating experience

After the cavity was fabricated and assembled, a set of RF measurements was performed with an Agilent E8363 Network Analyzer. The frequency tuning range is 2.6 MHz, from 1299.1 to 1301.7 MHz, with the corresponding range of the quality factor of 9450 to 10,050, in good agreement with the predictions. The eigenmode spectrum was measured via the transmission coefficient between the input coupler and RF probe (Fig. 7). As expected, a mode at 1677 MHz, orthogonal to the working mode, was not excited.

Initially, the deflecting cavity was installed in a beam line dedicated to beam studies after a high voltage DC photoemission electron gun, where it was used to study the temporal shaping of electron distribution and the photocathode response time [2]. Upon completion of the high-current ERL injector prototype [10], the cavity was moved to one of the diagnostic beam lines there. It is used for slice emittance measurements, phasing of the superconducting accelerating cavities, etc. One can use the deflector in conjunction with a bending magnet to produce a bunch profile in the longitudinal phase space as illustrated in Fig. 8.

5. Conclusions

We have designed a 1300 MHz deflecting cavity to be used for beam diagnostics in the Cornell ERL injector. Introduction of conical protrusions allowed us to concentrate electromagnetic fields on the cavity axis and thus increase its transverse shunt impedance to approximately five times that of the pill-box cavity impedance. After fabrication, the cavity parameters were measured at low RF power level and are in good agreement with calculations. The deflector is installed in the Cornell ERL injector and is used for beam diagnostics.

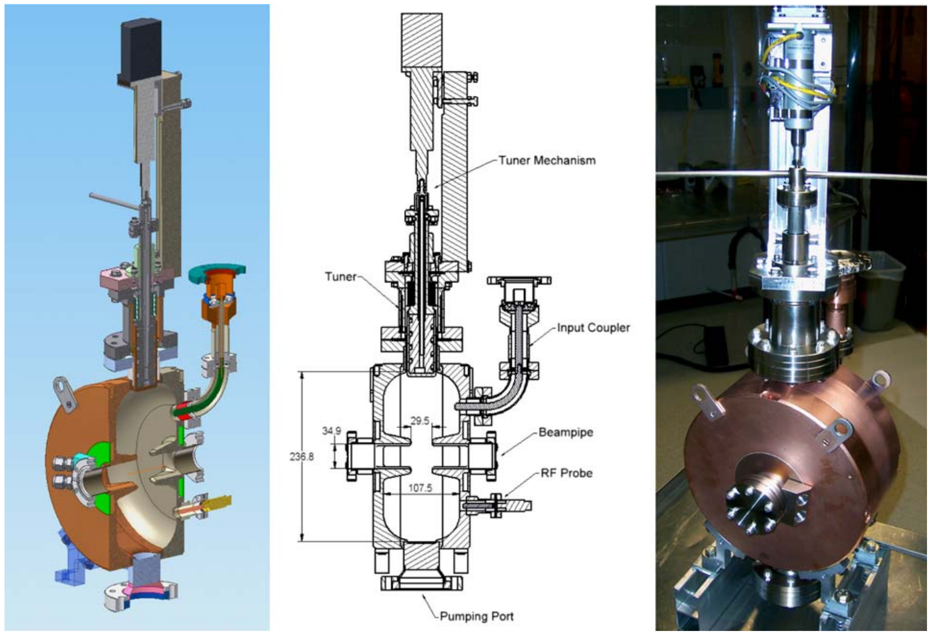

Fig. 4. Cornell ERL injector deflecting cavity.

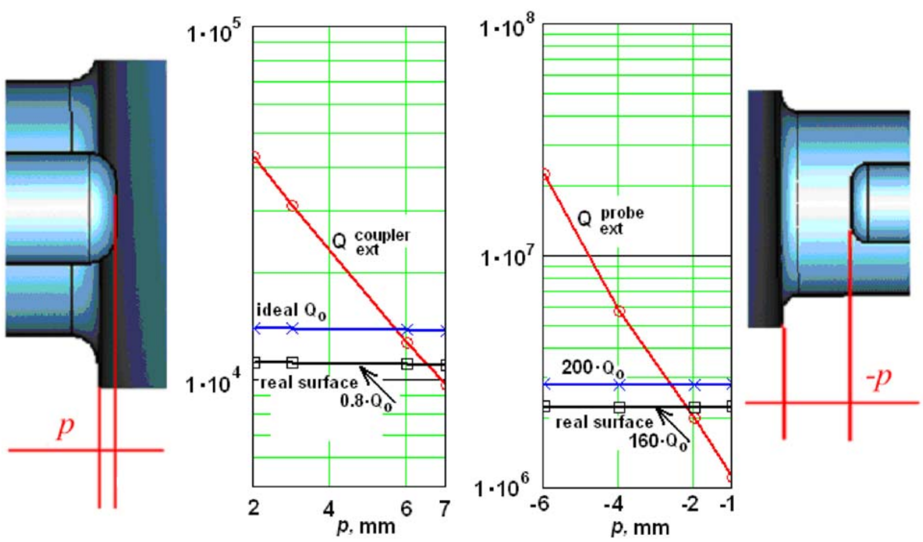

Fig. 5. External Q versus position of the input power coupler (left) and the RF probe (right).

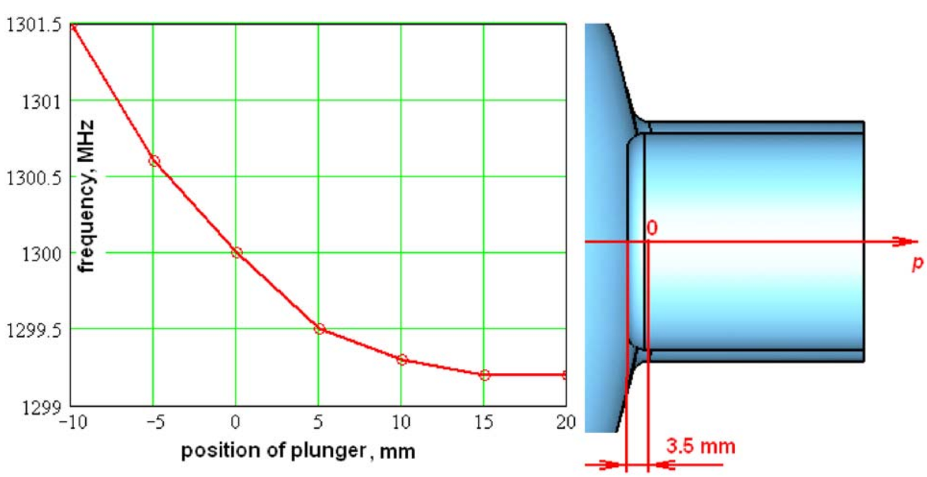

Fig. 6. Resonant frequency tuning.

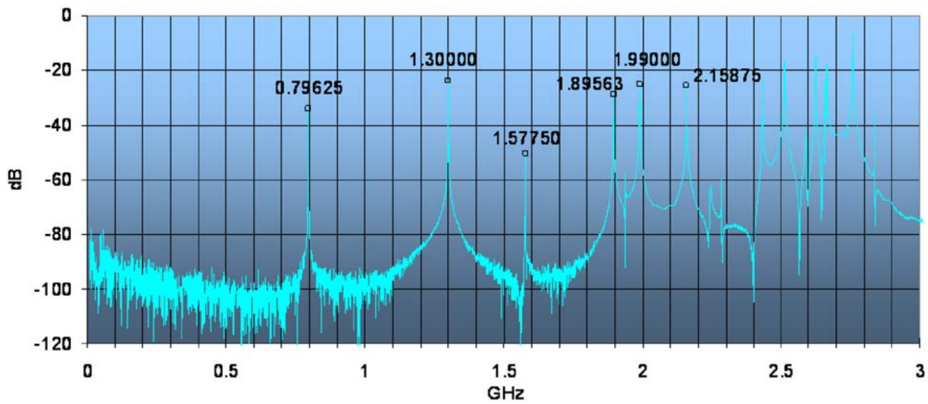

Fig. 7. Transmission coefficient between the input power coupler and RF field probe.

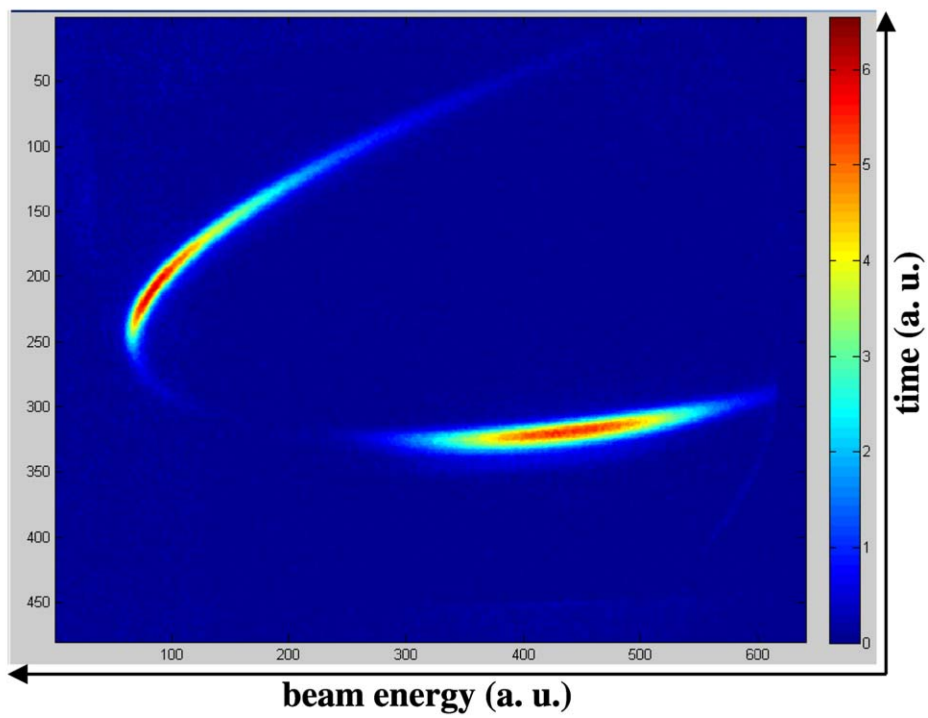

Fig. 8. Two closely spaced ($\approx$ 12 ps) bunches in the longitudinal phase space. The bunches are created in time using birefringent crystal splitting of incoming short ($\sim$ 2 ps) laser pulse [11] driving the photocathode. Beam energy is 5 MeV.

Acknowledgment

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