RF DESIGN OF THE DEFLECTING CAVITY FOR BEAM DIAGNOSTICS IN ERL INJECTOR*

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Abstract

A 1300 MHz deflecting cavity will be used for beam slice emittance measurements and to study the temporal response of negative electron affinity photocathodes in the ERL injector currently under construction at Cornell University. A single-cell TM110-mode cavity was designed to deflect the beam vertically. The paper describes the cavity shape optimization.

INTRODUCTION

An injector for the Energy Recovery Linac (ERL), where a high average current beam will be accelerated to energy of several MeV, is being constructed at Cornell University [1] and a suite of sophisticated methods to measure low-emittance beam parameters is under development. Some of the proposed techniques use a deflecting cavity. These include: photoemission response time measurement and temporal profile of the initial electron distribution after the gun, bunch temporal profile determination at 5 to 15 MeV, and reconstruction of an unprojected (temporal slices) emittance both after the gun and after the injector.

While multi-cell deflectors are used at higher beam energies (see [2], for example), available space limited our choice to a single-cell cavity. A relatively low beam energy and use of an optimized cavity shape allowed us to design such a cavity with a TM110-like mode. In our design we utilized an approach similar to one of the CEBAF RF deflector [3], where four rods are used to concentrate electromagnetic field near the axis. In our case the relative beam pipe opening is much larger than that of the CEBAF deflector, so simple rods become less effective. We have used protrusions of a more elaborate shape to reach our design goals. The protrusions make the cavity azimuthally asymmetric thus splitting resonant frequencies of two usually degenerative TM110 modes far apart. The cavity was designed to deflect the beam vertically.

ERL deflecting cavity will be used for experiments at different energies from 750 keV ($\beta = 0.914$) after the gun to 15 MeV after the injector. A deflecting angle of 12 mrad is required for all energies. At low energy the cavity will operate in CW mode with the available RF power of 200 W from a TWT amplifier. At high energies, after the injector, it will operate in pulsed mode from a high-power klystron transmitter with the pulse length of 18 μs and repetition rate of 1 kHz. As the latter case is more challenging, the deflector was optimized for $\beta = 1$. The paper describes the cavity shape optimization procedure and presents the optimization results.

GEOMETRY FOR OPTIMIZATION

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

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

where $B_\perp(z)$ 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 circular frequency of the RF field.

Alternatively, one can use the Panofsky-Wenzel theorem to integrate only the longitudinal component of the electric field at some distance a from the axis:

$$V_\perp = \left| \frac{1}{\beta\cdot ka}\cdot\int_{-\infty}^{\infty} E_z(z)\cdot e^{ikz/\beta}dz \right|. \quad (2)$$

The transverse shunt impedance, defined as

$$Z_\perp = \frac{V_\perp^2}{2P} = \frac{V_\perp^2 Q}{2\omega U}, \quad (3)$$

is the measure of deflector efficiency. The higher the transverse impedance value, the less power is required to deflect the beam at a certain angle. 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 when we add beam pipes, e.g., for the beam pipe ID of $1\frac{3}{8}$ inches $Z_\perp$ = 1.08 MOhm. An ~~I~~increase of ID by one inch decreases this value to 0.96 MOhm.

Figure 1 illustrates electric and magnetic field patterns of the TM110 mode in a simple pill-box cavity. One can see that the electric field is zero on the cavity axis and its maxima are located at some distance from the axis, while the maximum of the magnetic field is on axis. Shifting the electric field maxima closer to each other would increase the maximum value of the magnetic field and hence improve the deflecting efficiency. By introducing two protrusions near the beam pipe iris on each side of the cavity (Figure 2), one can concentrate electromagnetic fields on axis. The transverse electric field that appears on axis of a modified shape enhances the beam deflection. This idea was used in developing an optimized deflecting cavity.

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RESULTS OF OPTIMIZATION

The shape optimization procedure consisted in searching the cavity dimensions to maximize $Z_\perp$. While the ERL deflecting cavity has some features similar to the CEBAF 0.5 GHz cavity [3], its shape is quite different. The relative aperture, which determines the distance between the protrusions and hence the distance between the electric field maxima, is six times larger (see Figure 3), therefore we used protrusions of a more complicated shape. The conical shape of the protrusions and a proper radius of the cavity shell help increase the Q factor. The cavity length is 5.5% shorter than half wavelength to compensate negative influence of fields propagating into the beam pipe.

Most of our efforts were dedicated to finding optimal dimensions of the protrusions. The following constraints were observed: the maximum surface electric field was limited to 3 MV/m and the maximum dissipated power density was limited to 5 – 10 W/cm^2 for the total dissipated power of 200 W. In spite of a relatively big beam pipe diameter, we have obtained high value of the transverse impedance, 5.3 MOhm.

Distributions of electric and magnetic fields in the most strained area are shown in Figure 4. For the input power of 200 W the maximal electric field is 2.8 MV/m, and the maximal power density is 5.8 W/cm^2. For this calculation it was assumed that the Q factor of a copper cavity will decrease by 20% from its ideal value and is equal to 11,500. Bigger rounding radius of the beam pipe iris (R = 10 mm), as compared to that of the protrusion edges (R = 3.5 mm), decreases current density at the most heated place, Figure 4, thus decreasing maximal power density and further increasing the Q.

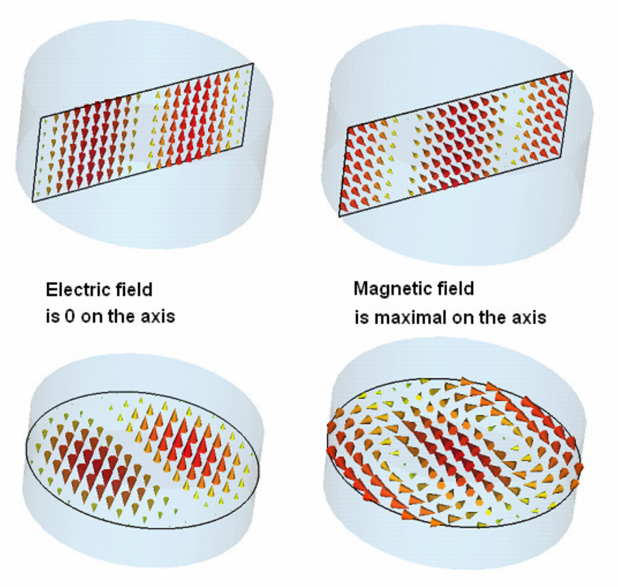

Figure 1: TM110 mode in a pill-box cavity.

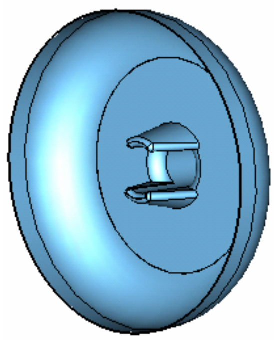

Figure 2: Optimized shape of the ERL deflecting cavity.

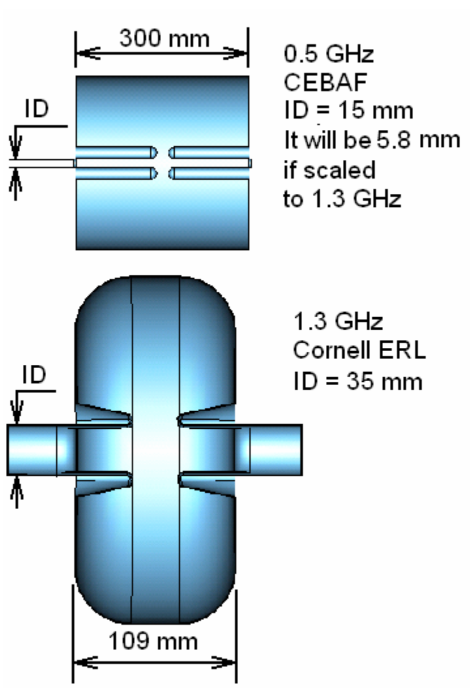

Figure 3: Comparison of the CEBAF and Cornell ERL deflecting cavity shapes.

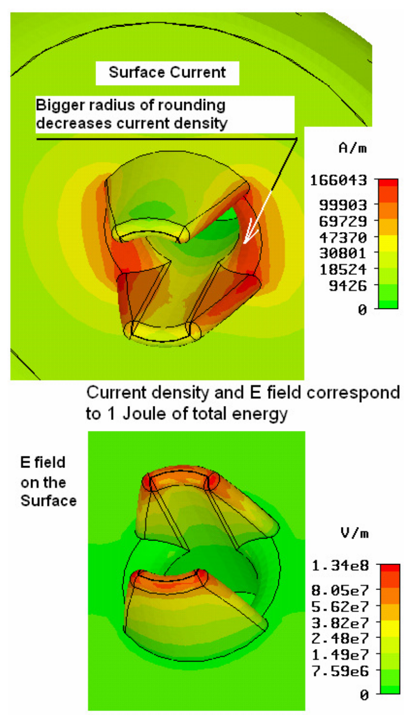

Figure 4: Current density and electric field in the most strained area.

Cavity fields and Q factor were calculated using CST MICROWAVE STUDIO® (MWS) [4] for a given stored energy U of 1 Joule. Values of $V_{\perp}$, and $Z_{\perp}$ were then found using equations (1) – (3). The results of the calculations are presented in Table 1. The "round" geometry in the table is the geometry without auxiliary elements (tuner, input coupler, etc.) as used during the cavity shape optimization. Accurate calculation of the quality factor and the deflecting voltage is key for optimization. However, accuracy of Q calculations by MWS strongly depends on the mesh density. In the table, N is the mesh parameter defined as $s = \lambda/2N$, where s is the size of the mesh cell and λ is the wavelength of the calculated mode. Although higher values of N improve accuracy, they also rapidly increase calculation time. Three conditions of symmetry were used for the round model, but the final model with added auxiliary elements (described in the following section) has only 1 symmetry plane, and so requires more calculation time. This is why the optimization was done without additional elements, which were added at the final design stage.

To perform the optimization in a reasonable time the mesh used was not very dense. This made the Q factor fluctuate from one program run to another and it was sometimes hard to say whether the given change of a parameter improves/worsens the value of $Z_{\perp}$ or the change in $Z_{\perp}$ is a result of the fluctuating Q. The influence of the mesh density on accuracy of calculations is discussed in the Appendix.

In the calculation of the final model we used $N = 20$. However, for calculation of the external Q factor the mesh was used with an increased density in the coaxial line areas, and for calculation of E_{max} the mesh size was less than 1 mm in a 24 mm vicinity of the axis.

FINAL RF DESIGN

The final design of the cavity includes a coupler, a frequency tuner, a pumping port, and an RF probe. These elements are shown in Figure 5. To better distribute RF currents near the pumping port, the port is divided by a partition. Positions of the coupler and the RF probe are chosen so that the ratio between electric and magnetic RF fields is equal to 377 Ohm (impedance of free space). In this case the tuning of the coupler or of the probe does not disturb the cavity frequency.

The tuner is of a plunger type, similar to that designed for the buncher cavity [5]. The tuner should compensate thermal shift of the cavity frequency and fabrication errors. The thermal expansion coefficient of copper is $\Delta L/L = 3.32\times10^{-4}$, hence one calculates $\Delta f = -0.43$ MHz for the cavity temperature changes of 20°C. This can be compensated if the initial position is -3.5 mm from the line of maximal circumference. The total stroke of ±10 mm from the initial position will secure the total tuning range of more than 2 MHz, see Figure 6.

The input coupler is a coaxial antenna type coupler. Calculations of the external Q factors determine the position of the input coupler for optimal coupling and the length of the RF probe tip to get the required output power of 1 W in the probe cable (for 200 W of RF power applied to the cavity). Figure 7 shows that the end of the probe should be withdrawn by about 2.5 mm into the probe port. The antenna tip of the input coupler tuned for the optimal coupling sticks inside the cavity by 6.5 mm.

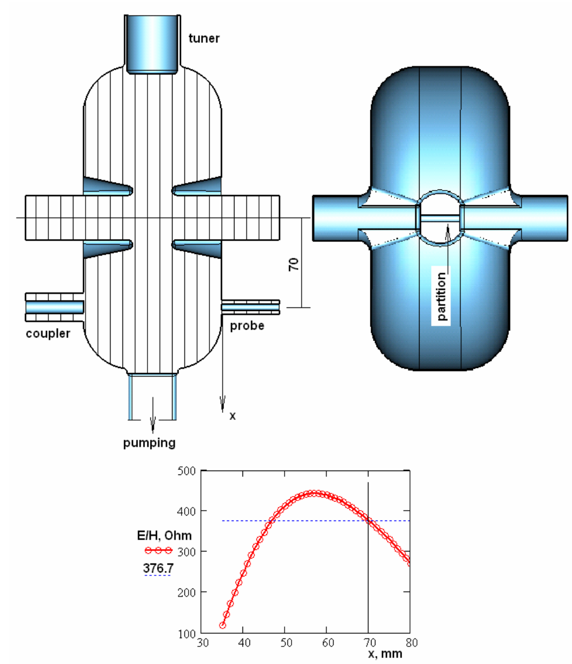

Figure 5: Elements of the cavity and choice of the coupler/probe position.

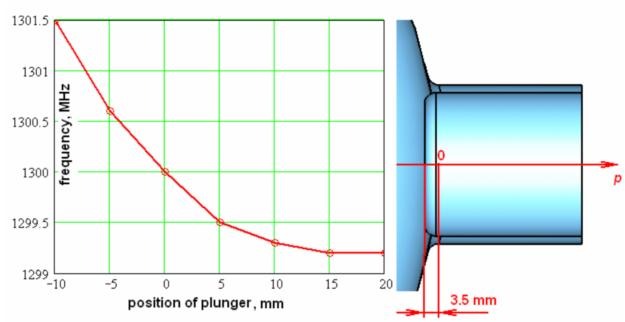

Figure 6: Resonant frequency tuning.

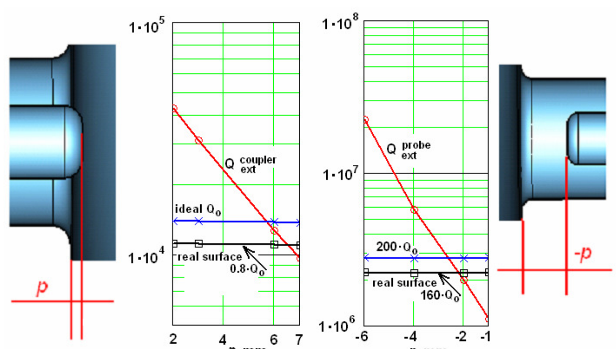

Figure 7: External Q versus position of the input power coupler (left) and the RF probe.

Table 1: Results of calculation with Microwave Studio.

Parameter	Model id_138_ptcp (Geometry with pump, tuner, coupler, and probe)	Model id_138_slot (Round geometry)		units
Mesh parameter N	20 (mesh step s < 1 mm for R < 24 mm)	20	40	-
Resonant frequency, f	1297.22	1295.26	1299.99	MHz
Quality factor, Q	1.405×10^4	1.374×10^4	1.441×10^4	-
Transverse shunt impedance $Z_\perp$	5.27	4.62	5.09	MOhm
Peak surface electric field E_{max}	1.546×10^8	1.517×10^8	1.407×10^8	V/m
Peak surface magnetic field H_{max}	1.963×10^5	1.839×10^5	1.831×10^5	A/m
Peak electric field at 200 W	2.82	2.78	2.64	MV/m
Maximum dissipated power density at 200 W total power	5.80	5.35	5.56	W/cm^2
Number of mesh cells, M	466,240	33,600	187,880	-
Calculation time, t	$6^h\ 19'$	$1'\ 00''$	$6'\ 34''$	hrs., min., sec.

Table 2: Resonant frequencies of several deflecting cavity modes.

Frequency [MHz]	Mode
797.4	TM010, fundamental, Figure 8a
1300	TM110, working mode, Figure 8b
1550	TE101, dipole, pipe region, Figure 8c
1677	TM110, orthogonal to the working mode, Figure 8d
1678	Dipole mode strongly interacting with the tuner, Figure 8e

Finally, resonant frequencies of the operating mode and the dipole mode orthogonal to it should be well separated. Higher order modes resonant frequencies should not be multiples of the operating one. Results for some modes are presented in Table 2 and Figure 8.

CONCLUSION

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.

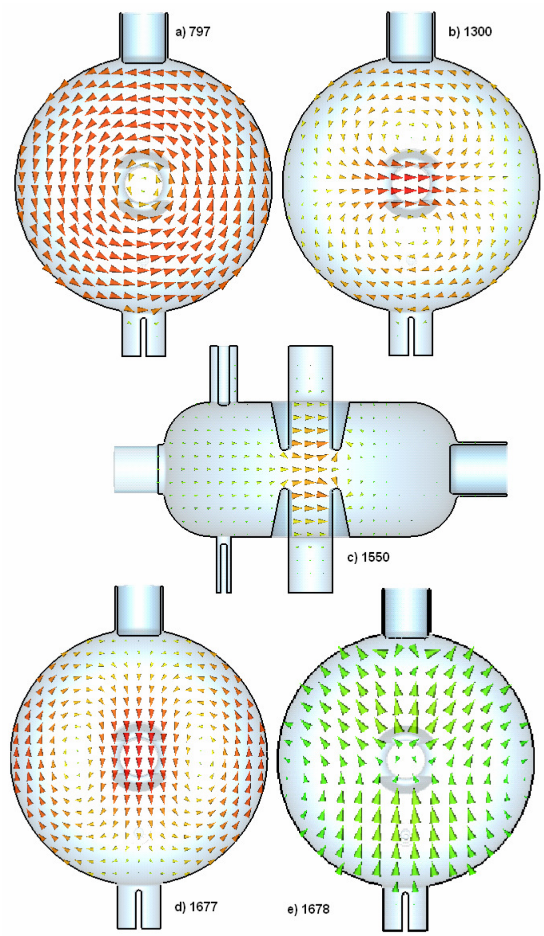

Figure 8: Field patterns for modes from Table 2.

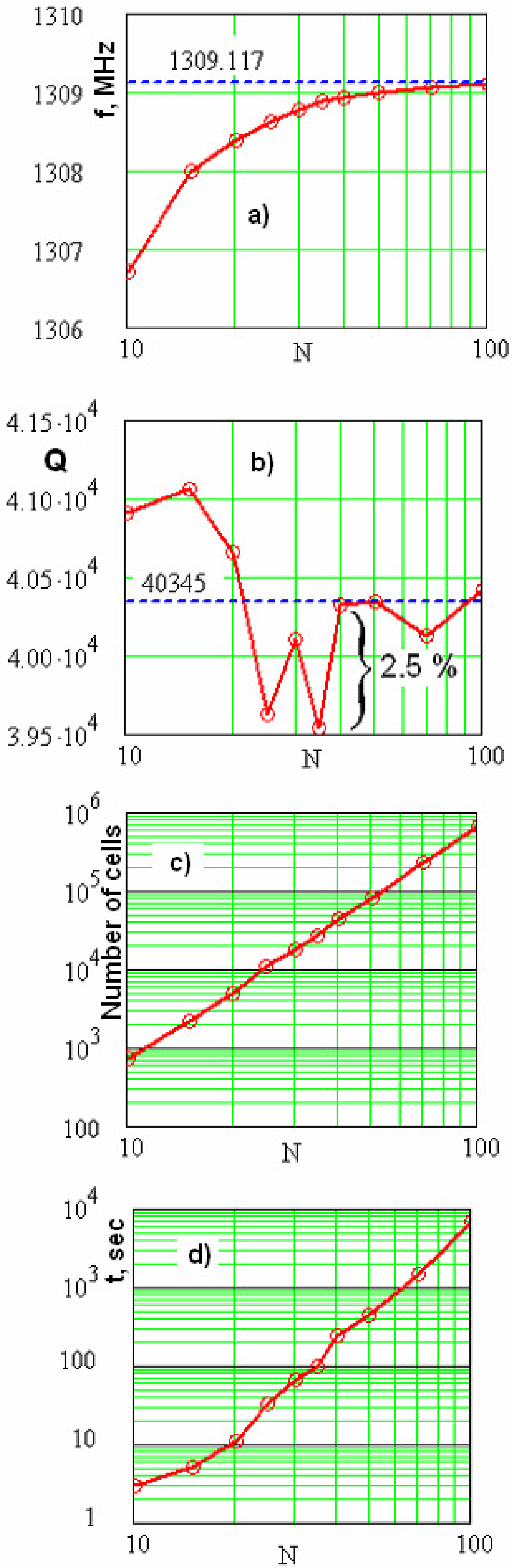

Figure 10: Dependences of the frequency (a), quality factor (b) number of cells (c), and calculation time (d) on the mesh parameter *N*.

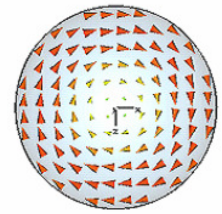

Figure 9: Magnetic field of the TM010 mode in a spherical cavity.

APPENDIX: CALCULATIONS OF A SPHERICAL CAVITY

In the process of optimization it is important for values of $Z_\perp$ to change smoothly with the change of the optimization parameter. For a reasonable optimization we need to have an accuracy of $Z_\perp$ better than 1–2-% for each step. This accuracy is mainly determined by calculations of Q.

A spherical cavity is a good model for understanding what the mesh density should be, since we can calculate its quality factor and frequency analytically, and compare these theoretical values with the MWS results. It is not as simple as a pill-box cavity and invokes curvilinear elements like the optimized cavity. Such a comparison was done for other codes [6] and a choice of a spherical shape for this purpose proved useful. The spherical cavity is not an ideal model for our problem because the deflector has some small details that the sphere does not have. Thus the real situation is even more complicated.

Magnetic field of the TM010 mode in the spherical cavity is shown in Figure 9. Dependencies of the frequency, Q, number of mesh cells and calculation time on the mesh parameter N are presented in Figure 10. The cell size is defined as $\lambda/2N$, where $\lambda = 230$ mm is the wavelength. Theoretical values of f and Q for a sphere of radius 100 mm are shown on the graphs as dashed lines.

To calculate Q with accuracy better than 2% one has to use $N \geq 40$. This corresponds to calculation time of ≥ 4 minutes. Three planes of symmetry were used for these calculations. In the case of a single symmetry plane, which we have for the deflecting cavity, this time will be four times longer. As a trade-off between the calculation time and the required accuracy, we chose the mesh parameter $N = 40$.

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