DEFLECTING RF CAVITY DESIGN FOR A RECIRCULATING LINAC BASED FACILITY FOR ULTRAFAST X-RAY SCIENCE (LUX)*

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Abstract

We report on superconducting deflecting RF cavity designs for a Recirculating **L**inac Based Facility for **U**ltrafast **X**-ray Science (LUX) at Lawrence Berkeley National Laboratory. The deflecting cavities operate in the lowest dipole mode and are required to produce a temporal correlation within flat electron bunches, as needed for x-ray compression in crystal optics. Deflecting voltage of up to 8.5 MV is required at 3.9 GHz. We present a 7-cell cavity design in this paper. Seven such cavities are required to generate the 8.5 MV deflecting voltage. Longitudinal and transverse impedance from LOM's (lower order mode) and HOM's (higher order mode) are simulated using the MAFIA code. Short-range and long-range wakefields excited through these impedances are calculated. Beam loading effects of the deflecting mode and parasitic modes are estimated. *Q* values of the LOM monopole modes in the cavity need to be damped to be below 10^4-10^5 levels in order to maintain the required energy spread.

INTRODUCTION

Figure 1 shows a layout of the LUX machine at LBNL. The SC deflecting cavities (highlighted with yellow color) are required at the last turn of the flat electron bunch at energy of ~ 3 GeV. More information on the LUX machine can be found in [1].

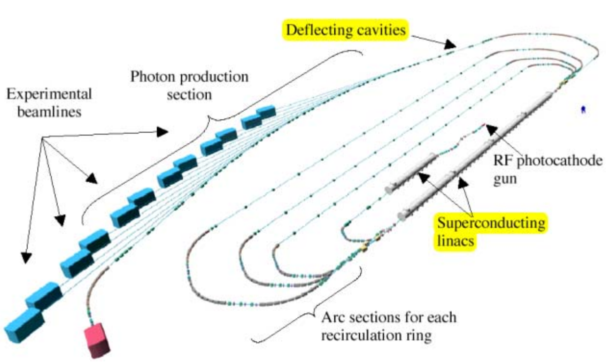

Figure 1: The layout of the proposed LUX machine

RF cavities operating in the lowest dipole mode (TM_{110}-like) deflect the head and tail of ~ 3 GeV flat electron bunches to allow for compression of the x-ray pulse in x-ray optics. The center of the electron bunch passes the cavities at *zero* phase of the RF field such that the head and tail are deflected in opposite directions, and the center of the bunch experiences no deflection. This introduces a correctable divergence into the electrons within a bunch that is much greater than the opening angle of hard x-ray radiation (the radiation opening angle is 7 µrad at 1 Å), and the angular divergence of the electrons (~ 6.4 µrad) in the undulators. The required deflecting voltage is 8 MV at 3.9 GHz for ~ 3GeV beam energy, but we aim at the cavity design for 8.5 MV to allow some head room. Superconducting cavities are a natural choice in obtaining such a high voltage, and the design of a multi-cell structure with large transverse shunt impedance has been developed. A 7-cell π-mode cavity design has been selected. This choice represents a compromise between a large number of cells to increase transverse shunt impedance and reduce the number of cavities required, and smaller number of cells to minimize the number of cavity modes and potential mode coupling. The cavity design is similar to a multi-cell deflecting cavity design for the kaon separation project at Fermilab [2].

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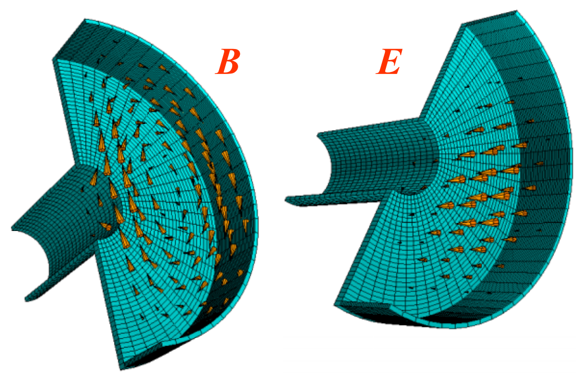
THE DEFLECTING CAVITY

The deflecting cavity operates at the lowest dipole mode, or TM_{110}-like mode. The field distribution of this mode is



shown in Figure 2 using a single cylindrical pillbox cavity with beam pipe as an example.

Figure 2: Electric (right) and magnetic (left) field distribution of the lowest dipole mode in a cylindrical pillbox cavity. This mode is used for deflecting electron bunches to generate a temporal correlation for x-ray compression.

For cylindrical cavities, dipole modes are degenerate, and two dipole modes have the same field distribution, but with different orientations. In order to obtain the needed polarization, the cavity geometry needs to be perturbed in one plane. Figure 3 shows a concept proposed for KEK-B crab cavity which splits the mode degeneracy and orients the required mode by using a non-cylindrical geometry [4]. The Fermilab multi-cell deflecting cavity used the similar technique [2].

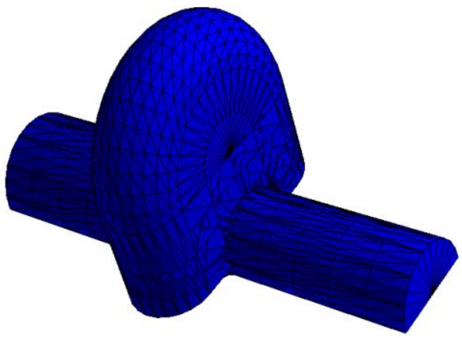


Figure 3: KEK-B Crab cavity with asymmetry to obtain the polarization of the crabbing mode

Electron bunches passing through the deflecting cavity experience transverse forces from both electric and magnetic fields. The cavity shunt impedance definition then has to take this into account.

Shunt Impedance of the Dipole Mode

For the TM dipole mode of an ideal closed cylindrical pillbox cavity, there is no electric field on-axis. Beam passing through such a cavity on-axis would not exchange energy with the cavity and experience a transverse force from the magnetic fields only. However once beam irises are introduced, as it is necessary for a practical cavity, TE-like modes are introduced and mixed with TM modes in the iris (or between cells) and beam-pipe regions. The deflecting mode is no longer a pure TM_{110} mode, but a hybrid of TM_{110} and TE_{111} modes, which is the result of Maxwell equations in order to satisfy the new boundary conditions introduced by the irises and beam- pipes. Even the beam traversing the cavity on-axis, it will not just experience transverse force from the magnetic fields, but also from the transverse electric field. For a cavity with a π phase advance, these two transverse forces add. To calculate the shunt impedance of the deflecting mode, we define the transverse shunt impedance as follows,

$$\left(\frac{R}{Q}\right)_{\perp} = \frac{\left|\int E_Z(r_0)e^{j\kappa z}dz\right|^2}{\omega U(\kappa r_0)^2}$$

where the Panofsky-Wenzel theorem is applied to obtain the deflecting voltage using the off-axis longitudinal electric fields only. $\omega=2\pi f$ with f as the resonant frequency; U the stored energy of the mode at the resonant frequency; $E(r_0)$ the longitudinal electric field at r_0 over which the longitudinal electric field is integrated along variable z over the cavity length. Note that the unit of this definition for transverse shunt impedance is in Ω, and it implies that the deflecting kick is independent of the beam transverse position within the cavity.

Design of the Multi-Cell Cavity

A 3-D MAFIA model, as shown in Figure 4, was established to simulate the deflecting cavity and the main RF coupler in addition to 2-D simulations reported previously [3]. A 7-cell design is chosen for field flatness, and to avoid mode overlaps and possible trapped modes from large number of cells.

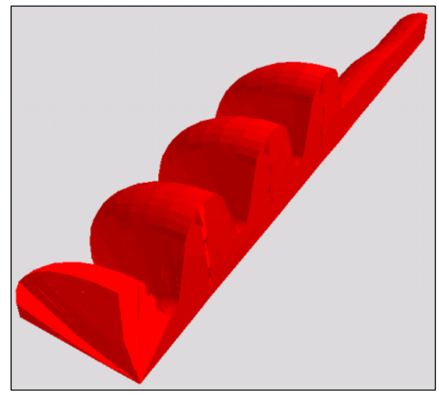


Figure 4: 3-D MAFIA model for the 7-cell deflecting cavity (1/4 of the structure shown here)

One-quarter of the cavity was used for the simulations, combinations of boundary conditions and the geometry symmetry allow us to compute all LOM and HOM modes up to the beam-pipe cut-off frequencies. Table 1 and Table 2 list the dimensions of cavity and performance parameters.

Table 1: Main dimensions of the deflecting cavity

Cavity frequency	3.9	GHz
Phase Advance per cell	180^o	Degree
Cavity Equator Curvature	1.027	cm
Cavity Radius	4.795	cm
Cell length	3.846	cm
Iris Radius	1.500	cm
Beam pipe radius	1.500	cm
TM mode cut-off frequency	7.634	GHz
TE mode cut-off frequency	5.865	GHz

Table 2: Main cavity parameters

(R/Q)	350	Ω
Q_0	2×10^9	
Active length/cavity	26.92	cm
Deflecting gradient	5	MV/m
Transverse voltage	1.346	MV
RF power loss at 2 K	2.6	Watts

The 5-MV/m gradient was chosen and determined by limiting critical magnetic fields to be ~ 80 mT, which corresponds to a 25 MV/m accelerating gradient for the TESLA SC cavities.

BEAM LOADING

Beam traversing the deflecting cavity interacts with all of the cavity modes, and the beam may lose energy, and induce a voltage in the cavity. This voltage then acts back on the beam, and may cause energy spread or perturb the deflection along the bunch.

Beam Loading in the Deflecting Mode

The beam induced transverse voltage in the deflecting mode may be written as,

$$V_{\perp} = \left(\frac{R}{Q}\right)_{\perp} \frac{Q_0}{1+\beta} (\kappa \Delta r) I \approx 1.1\,\text{kV}$$

where I, κ, Δr and β are beam current, cavity RF wave number, displacement from cavity axis and RF coupling constant, respectively. For the above calculation, we have used κ = 82, Δr = 0.1 mm and $\beta \approx 50$ assuming an achievable bandwidth of 100 Hz which corresponds to an external Q of 3.9×10^7. This bandwidth is determined from the requirements for synchronization, microphonics detuning (25 Hz peak). With 2.5 MHz band limited phase noise spectra of mode-locked laser master oscillator at optimum coupling condition, the peak RF power required is less than 200 Watts per 7-cell cavity. Beam current of 10 μA (1 nC charge at 10 kHz repetition rate) was assumed for the above calculation.

Power induced in the deflecting mode is then given by,

$$P_{\text{induced}} = \tfrac{1}{2} f_{\text{rep.}}^2 q^2 \left(\frac{R}{Q}\right)_{\perp}^{*} \frac{Q_0}{1+\beta} (\kappa \Delta r) \approx 5.3\,\text{mW}$$

This is considered to be quite small in comparison with power loss of 2.6 Watts in the cavity.

Beam Loading from Monopole Modes

Longitudinal voltages may be induced by beam through interaction with monopole LOM and HOM modes. It was found that two LOM monopole modes at 2.8581 GHz and 2.8685 GHz contribute ~ 85 % of the total impedance. At steady state the beam induced voltage per cavity can be calculated by,

$$V(\infty) = \sum_{n=1}^{n_c} 2 k_n q \left(\frac{2 Q_{n,0}}{\omega_n T}\right) \approx 17\ \text{MV}$$

Assuming $q = 1$ nC, 10 kHz repetition rate

and $Q_0 = 2\times10^9$ for all the modes

In order to maintain beam energy spread of 10^{-4} at ~ 3 GeV, these modes need to be damped. Their Q values have to be below 10^4-10^5 levels. It is worthy of noting that main RF coupler may provide certain damping to all the HOM and LOM modes, but has not been evaluated yet. Nevertheless a coaxial insert in the beam pipe (proposed for KEK-B crab cavity) may be couple to these monopole modes only and provide required damping [4], but this may add complexity to the cavity.

HOM Dipole Modes

Loss factors of HOM dipole modes were calculated by,

$$k_{\perp} = \frac{\omega}{4} \left(\frac{R}{Q}\right)_{\perp} \kappa.$$

Again assuming $2\text{x}10^9$ of Q for all HOM modes, the total loss factor is only 14 V/(pC-m), compared to 176 V/pC-m) for the deflecting mode. The overall HOM impedance is considered not to be excessive.

CONCLUSION

A 7-cell SC deflecting cavity design has been presented. To provide 8.5 MV deflecting voltage, seven 7-cell cavities are required. LOM monopole modes need to be damped to minimize beam energy spread. Impedance from the HOM dipole modes is not excessive. The main RF coupler may provide extra damping to LOM and HOM modes and will need to be evaluated in the future. RF power requirement is estimated to be less than 200 Watts per 7-cell cavity at optimum coupling (β ≈ 50), a solid state RF power amplifier may be used at this power level. Synchronization requirements may demand increased cavity bandwith, and will be investigated further with the development of the project.

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