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# RF DELECTING CAVITY DESIGN FOR BERKELEY ULTRAFAST X RAY SOURCE *

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## *Abstract*

Our proposed source for production of ultra-short (less than 100 fs FWHM) x-ray pulses utilizes a scheme for manipulation of the relatively long (~ 2 ps) electron bunch in transverse phase-space, followed by compression of the emitted x-ray pulse in crystal optics [1]. In order to compress the x-ray pulses, RF cavities operating in a dipole mode ($TM_{110}$-like) are required to deflect the head and tail of a 2.5 GeV bunch in opposite directions. For a 2 ps duration electron bunch, an 8.5 MV deflecting voltage is required at a RF frequency of 3.9 GHz. In this paper, we will present a preliminary cavity design based on numerical simulations performed by MAFIA and URMEL codes.

Seven-cell superconducting π mode dipole RF cavities are proposed to provide the necessary deflecting voltage. Due to the presence of beam iris, the cavities operate in a hybrid mode where TM and TE like modes co-exist. Even on the beam axis, both magnetic and electric fields contribute to the transverse kick.

Lower order monopole modes (LOMs) in the cavities may cause energy spread of the electron beam and need to be damped. The effects of the LOMs on beam dynamics are estimated. Possible damping schemes will be discussed.

## 1 INTRODUCTION

Driven by scientific demands and a strong local femto-second x-ray science research community, Lawrence Berkeley National Laboratory (LBNL) has begun a design study for a facility dedicated to the production of x-ray pulses with ultra-short duration [2]. The design produces x-ray pulses of ~ 60 fs FWHM to study very fast dynamics, high flux of approximately $10^{11}$ photons /sec/0.1%BW to study weakly scattering systems, and tunability of over 1-10 keV photon energy. The 10 kHz repetition rate is chosen to match the requirements of the experimental sample or attendant pump laser systems for the structural dynamics experiments. The proposed machine consists of a photocathode RF gun at 10 kHz repetition rate, a superconducting (SC) 100 MeV linear pre-accelerator, a 600 MeV SC main linac, magnetic arcs and straight sections, **deflecting cavities** and photon beam production sections [3]. Electron pulses generated at the photocathode have 1 nC charge and 20 ps duration. A solenoidal magnetic field is applied on the cathode to generate angular moment in the beam, which allows for production of flat beams with small vertical emittance in a specially configured skew-quadrupole channel [4]. The electron pulses are compressed to approximately 2 ps duration, and pass the main linac four times to be accelerated up to 2.5 GeV, before reaching the deflecting cavities. The cavities deflect the beam vertically to create a temporal correlation between longitudinal and transverse positions and angular momentum within the electron bunches. X-rays are generated in bending magnets and undulators, and are compressed by specially designed asymmetrically cut silicon crystal mirrors [1,2].

## 2 THE DEFLECTING CAVITIES

To produce sufficient deflection in the electron bunches to allow x-ray compression to < 100 fs requires up to 8.5 MV transverse voltage at 3.9 GHz for a 2.5 GeV electron bunch of 2 ps duration. Production of this voltage is most efficiently achieved through multi-cell RF cavities. We find that for a given electron bunch length, the required deflecting voltage is independent of the number of cavity cells simply because the effective deflecting voltage is inversely proportional to the cavity frequency. This is true only for a given fixed deflecting gradient because the effective voltage per cell reduces linearly with the RF frequency. On the other hand, the effective voltage increases linearly with the RF frequency for a given bunch length and a given fixed peak voltage. These two effects cancel out for a given bunch length and a given deflecting gradient. To minimize RF power requirements, reduce short-range wake-field effects, and increase the cavity efficiency at higher frequencies, 3.9 GHz CW superconducting multi-cell dipole RF cavities are chosen for this application.

### *2.1 Shunt Impedance*

For the TM dipole mode of an ideal closed cylindrical pillbox cavity, there is no electric field on-axis. Beam going through such a cavity on-axis should experience a transverse force from the magnetic fields only. Once beam irises are introduced, as necessary for a real cavity, TE-like modes are mixed in. The deflecting mode is no longer a pure $TM_{110}$, it instead becomes a hybrid of $TM_{110}$ and $TE_{111}$ modes in order to satisfy the new boundary conditions introduced by the irises. A beam passing through the cavity on-axis will not just experience transverse forces from the magnetic fields, but also from the transverse electric fields near the irises. It is worth noting that for a cavity with π phase advance, these two transverse forces add. To characterize the dipole cavity properties, one typically defines the shunt impedance as follows,

$$\left(\frac{R}{Q}\right)^{*} = \frac{\left|\int E_z\,(r=r_0)e^{jkz}\,dz\right|^2}{(kr_0)^2\,wU} = \frac{{V_T}^2}{wU}.$$

Where the Panofsky-Wenzel theorem has been applied to obtain the deflecting voltage, $V_T$ using the longitudinal electric fields off-axis. $V_T$ is the transverse voltage; $\omega = 2\pi f$ with $f$ as the resonant frequency; U the stored energy of the mode at the resonant frequency; $E_z$ the longitudinal electric field, $k$ is the RF wavenumber, and $r_o$ is the radius at which the longitudinal electric field is integrated.

## *2.2 Preliminary Cavity Design*

The deflecting cavity requirements for the Berkeley x-ray source are similar to ones proposed and actively under development at Fermi National Accelerator Laboratory (FNAL) for the Kaon Separation [5]. Taking advantage of the FNAL SC RF cavity development and the crab cavity designs for KEK-B developed at KEK and Cornell University [6], we started our design study by scaling the KEK-B crab cavity geometry and then extended it into a 7-cell structure. To identify and understand key issues relevant to us, we did not optimize the cavity geometry for highest possible $(R/Q)^*$. Nevertheless a reasonable $(R/Q)^*$ of 50 Ω/cell was easily achieved for a 7-cell 3.9 GHz cavity. We believe $(R/Q)^*$ can be further increased by about 20% with a more careful cavity geometry optimization. Two computer codes, MAFIA and URMEL are used for the cavity simulations. Most of the simulations were performed using the 2D MAFIA code while the ratio of deflecting voltage to peak surface field were studied using the URMEL code. The main cavity parameters are listed in Table 1.

Table 1. The cavity parameters

| | | |
|---|---|---|
| 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 |

## *2.3 Simulation Results of a 7-cell Cavity*

The electric field distribution of the deflecting mode for a 7-cell 3.9 GHz cavity is shown in Figure 1. The simulations were conducted in 2D (RZ geometry) using the MAFIA code. The beam pipe radius at the end cell is enlarged to allow for RF coupler to be added later. The end-cell geometry was adjusted (the cavity gap was shortened, and radius was enlarged) in order to obtain good field flatness. This same MAFIA model has also been used for higher- and lower-order mode calculations. Following the state of the art of the superconducting RF cavity technology, a modest 5 MV/m gradient is chosen by limiting critical magnetic fields to be around 80 mT, which corresponding to a 25 MV/m gradient for the TESLA SC cavities. This is due to the different values for the ratios of $V_{acc}/H_{peak}$ and $V_T/H_{peak}$ between the TESLA and the deflecting cavities. We conservatively assume achievable $Q_0$ to be $2\times10^9$.

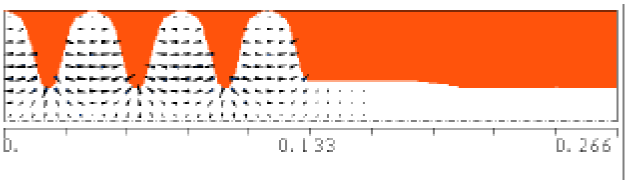

Figure 1. Electric field distribution of the deflecting mode for a 7-cell cavity

We summarize the simulation results and requirements for a 7-cell SC deflecting RF cavity in Table 2.

Table 2. Parameters for one 7-cell SC cavity

| | | |
|---|---|---|
| $(R/Q)^*$ | 350 | Ω |
| $Q_0$ | $2\times10^9$ | |
| 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 |

To obtain 8.5 MV voltage, we need seven 7-cell cavities with total RF power dissipation of about 20 watts at 2 K. RF source power requirements will depend on the coupler, achievable $Q_{ext}$ and control of microphonics.

## *2.4 Polarization of the Cavity*

For a perfectly cylindrical RF cavity, there are a pair of degenerate dipole modes. In order to obtain the needed polarization, the cavity geometry has to be perturbed to push up the frequency of the unwanted polarization mode, and align the required mode in a selected orientation. We plan to adopt the technique of deforming the cavity in one plane to get select the needed polarization.

## *2.5 Higher Order Modes (HOMs) and Lower Order Modes (LOMs)*

MAFIA simulations have been carried out on the 7-cell cavity to study the higher and lower order modes. To simulate all modes below beam pipe cut-off frequencies, we performed the MAFIA 2D simulations with different combinations of the symmetry and boundary conditions. Loss factors and shunt impedance of these modes are then calculated in the MAFIA post processor. Table 3 and 4 list the simulation results of all the dipole and monopole modes below cut-off frequencies of the adjacent beam pipes. For a conservative estimation, we have assumed $Q_0$ of $10^{10}$ for all modes. As indicated in Table 4, two LOMs dominate the total loss factor. Electric field distributions of these two modes are plotted in Figures 2 and 3. A steady state voltage, $V_{induce}$ induced by 1 nC beam bunch at 10 kHz repetition rate for each monopole mode is estimated and listed in Table 4.

Table 3. Higher order dipole modes of the 7-cell cavity

| Frequency | $(R/Q)^*$ | *k*-loss | $Q_0$ | $R_T$ |
|---|---|---|---|---|
| [GHz] | [Ω] | [V/pC/m] | | [MΩ/m] |
| 3.9112 | 0.3 | 0.1 | $10^{10}$ | 0.000205852 |
| 3.9212 | 3.0 | 1.5 | $10^{10}$ | 0.002430867 |
| 3.9390 | 0.2 | 0.1 | $10^{10}$ | 0.000201667 |
| 3.9662 | 0.3 | 0.1 | $10^{10}$ | 0.00022897 |
| 4.0045 | 0.3 | 0.2 | $10^{10}$ | 0.000287811 |
| 4.0523 | 0.0 | 0.0 | $10^{10}$ | 5.8875E-07 |
| 4.2213 | 0.2 | 0.1 | $10^{10}$ | 0.000196049 |
| 4.2939 | 1.2 | 0.7 | $10^{10}$ | 0.001046349 |
| 4.4175 | 0.0 | 0.0 | $10^{10}$ | 5.0746E-06 |
| 4.5725 | 1.7 | 1.2 | $10^{10}$ | 0.001637706 |
| 4.7488 | 2.7 | 2.0 | $10^{10}$ | 0.002657887 |
| 4.9336 | 7.8 | 6.3 | $10^{10}$ | 0.008085616 |
| 5.1024 | 1.2 | 1.0 | $10^{10}$ | 0.00124523 |
| 5.3002 | 0.3 | 0.2 | $10^{10}$ | 0.000291165 |
| 5.3058 | 0.1 | 0.1 | $10^{10}$ | 9.78527E-05 |
| | Sum k: | 13.7 | | |

Table 4. Monopole LOMs and HOMs of the 7-cell cavity

| Frequency | $Q_0$ | (R/Q) | *k*-loss | R | $V_{Induce}$ |
|---|---|---|---|---|---|
| [GHz] | [SC] | [Ω] | [V/pC] | [MΩ] | [MV] |
| 2.8132 | $10^{10}$ | 1 | 0.0038 | 8,656 | 0.0866 |
| 2.8208 | $10^{10}$ | 1 | 0.0056 | 12,537 | 0.1254 |
| 2.8321 | $10^{10}$ | 13 | 0.0597 | 134,150 | 1.3415 |
| 2.8453 | $10^{10}$ | 10 | 0.0427 | 95,534 | 0.9553 |
| 2.8581 | $10^{10}$ | 284 | 1.2742 | 2,838,100 | 28.3810 |
| 2.8685 | $10^{10}$ | 411 | 1.8515 | 4,109,100 | 41.0913 |
| 2.8750 | $10^{10}$ | 56 | 0.2546 | 563,800 | 5.6380 |
| 5.7836 | $10^{10}$ | 0 | 0.0017 | 1,892 | 0.0189 |
| 5.8026 | $10^{10}$ | 0 | 0.0002 | 265 | 0.0026 |
| 5.8348 | $10^{10}$ | 4 | 0.0357 | 38,914 | 0.3891 |
| 5.8797 | $10^{10}$ | 12 | 0.1105 | 119,610 | 1.1961 |
| 5.9343 | $10^{10}$ | 5 | 0.0498 | 53,467 | 0.5347 |
| 5.9912 | $10^{10}$ | 0 | 0.0002 | 164 | 0.0016 |
| 6.0377 | $10^{10}$ | 0 | 0.0013 | 1,357 | 0.0136 |
| 6.6123 | $10^{10}$ | 2 | 0.0233 | 22,481 | 0.2248 |
| 6.6135 | $10^{10}$ | 0 | 0.0033 | 3,164 | 0.0316 |
| 6.7391 | $10^{10}$ | 0 | 0.0010 | 926 | 0.0093 |
| 6.8025 | $10^{10}$ | 2 | 0.0227 | 21,218 | 0.2122 |
| 6.8722 | $10^{10}$ | 0 | 0.0037 | 3,390 | 0.0339 |
| 6.9377 | $10^{10}$ | 0 | 0.0048 | 4,372 | 0.0437 |
| 7.0615 | $10^{10}$ | 32 | 0.3507 | 316,200 | 3.1620 |
| 7.5036 | $10^{10}$ | 10 | 0.1124 | 95,385 | 0.9538 |
| 7.5093 | $10^{10}$ | 0 | 0.0014 | 1,214 | 0.0121 |
| SUM | | | 4.2147 | | 84.4594 |

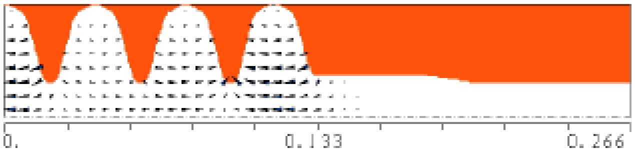

Figure 2. E-field of monopole LOM at 2.8581 GHz

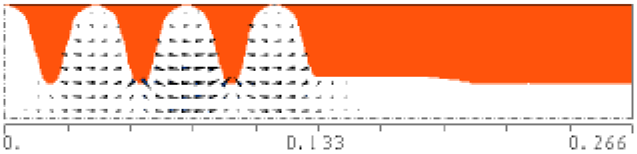

Figure 3. E-field of monopole LOM at 2.8685 GHz

Impedance of higher order dipole modes is small and has little effect on the beam. As much as 84 MV could be induced in the monopole modes in one cavity, and the two dominant lower order monopole modes must be damped. Their $Q_0$s need to be damped below $10^5$-$10^6$ in order to maintain a small energy spread of $10^{-4}$ for 2.5 GeV beam energy. It is worth pointing out that both the HOMs and the LOMs will be damped in some extent by the main RF coupler. Further investigation will be conducted once a 3D MAFIA model is established for the study of the RF coupler. A coaxial type LOM damper through beam pipe, proposed for the KEK-B factory, may be adopted if necessary, but this may increase the complexity and cost of the cavity.

## 3 SUMMARY

A preliminary design for a 7-cell dipole cavity has been completed. HOMs and LOMs need to be damped to minimize the beam energy spread. A 3D model will be established to study RF coupler and its effects on the LOMs and HOMs.

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