A THREE-CELL SUPERCONDUCTING DEFLECTING CAVITY DESIGN FOR THE ALS AT LBNL

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Abstract

Deflecting RF cavities may be used to generate sub-picosecond x-rays by creating correlations between longitudinal and transverse phase space in electron bunches in radiation devices. Up to 2-MV defecting voltage at 1.5-GHz is required for 1.9-GeV electron beam at the Advanced Light Source (ALS) of Lawrence Berkeley National Laboratory (LBNL). In this paper, we present a conceptual design for a 1.5-GHz three-cell superconducting RF cavity and its couplers. The cavity geometry and its shunt impedance at the deflecting mode are optimized using MAFIA code. The cavity impedances from lower and higher order modes (LOMs and HOMs) are computed as well. Possible schemes for damping most harmful LOM and HOM modes are discussed and simulated.

INTRODUCTION

The Advanced Light Source of LBNL is a 3rd generation light source for high brightness ultraviolet and soft x-ray synchrotron radiation. The pulse structure of the radiation is an ~ 80-psec pulse (FWHM) with up to a 500-MHz repetition rate. Zholents et al. have proposed a scheme to compress the x-ray pulse down to ~1-psec [1]. This scheme uses a deflecting RF cavity to create vertical chirp along the electron bunch and subsequent x-ray optics and/or apertures to generate short x-ray pulses. More details on this scheme in the ALS can be found elsewhere in these proceedings [2]. This paper presents the initial results of a study using a deflecting cavity to achieve this.

The deflecting cavity operates at TM_{110}-like dipole mode. For the ALS, up to 2-MV deflecting voltage at 1.5-GHz is needed for 1.9-GeV electron beam. With the limitation of a few tens of kW continuous power dissipation per cell, it would require an impractical number of normal conducting cells to provide the required deflecting voltage. Therefore, we will consider only superconducting cavities inspired by the design for the KEKB crab cavity [3].

In this paper, we describe our initial simulation results for a 3-cell superconducting cavity design at π dipole mode. The cavity geometry is simulated and optimized using MAFIA code. Unlike accelerating cavities, the deflecting mode in the cavity is not the fundamental mode. There both lower and higher order modes (LOM and HOM) exist in the cavity. They need to be damped to an acceptable level. A typical field distribution of the deflecting mode in a cavity with beam iris (simulated using Microwave Studio) is shown in Figure 1.

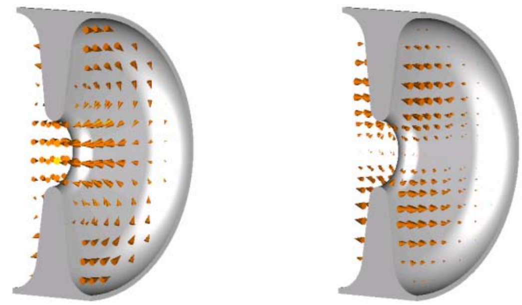

Figure 1: Magnetic (left) and electric (right) field distribution of the deflecting mode in a cavity. Transverse electric fields are introduced due to the beam iris. The deflecting mode is a hybrid mode between TM and TE.

THE DEFLECTING CAVITIES

The deflecting cavity operates at the lowest dipole mode (or TM_{110}-like mode). It is, in fact, a hybrid mode between TM_{110} and TE_{111} (induced by the iris) as shown in Figure 1.

Transverse Shunt Impedance

Since the deflecting mode is not a pure TM_{110} mode, when a charged particle passes through a deflecting cavity on axis, the particle experiences transverse forces from both electric and magnetic fields. Thus, the transverse deflecting voltage is defined by:

$$\mathbf{V}_T = \int [\mathbf{E}_T + (\mathbf{v} \times \mathbf{B})_T] dz \, , \qquad (1)$$

where **v** is the velocity of the particle; **E** and **B** are the electric and magnetic fields that the particle experiences on its path, respectively. Panofsky-Wenzel theorem can be applied directly to calculate the deflecting voltage where an off-axis line integral of E_z over the cavity length is conducted. According to Panofsky-Wenzel theorem, the relationship between transverse and longitudinal voltage can be expressed as [4].

$$\boldsymbol{V}_T = \frac{-i}{\omega / c} \nabla_T V_{//} \, , \qquad (2)$$

$$V_{//} = \int_0^L E_z e^{-i\omega z / c} dz \, . \qquad (3)$$

Following the definition of the shunt impedance for an accelerating mode in a cavity, the transverse shunt impedance of the deflecting mode is defined as:

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$$\left(\frac{R}{Q}\right)_T = \frac{{V_T}^2}{\omega U} = \frac{\left|\int_0^L E_z(r=r_0)e^{-i\kappa z}\mathrm{d}z\right|^2}{(\kappa r_0)^2\,\omega U}. \quad (4)$$

Where $\omega = 2\pi f$ as f is the frequency; κ is the wave number, which equals to ω/c; L is the cavity length; U is the stored energy of the dipole mode in the cavity. The integral is conducted at $r=r_0$ off axis is from 0 to L, the cavity length.

Optimization of the Cell Geometry

The most important parameter that limits the deflecting voltage is the critical magnetic field on the inner surface of the cavity. When the peak magnetic field is higher than the critical value, the superconducting cavity would become normal conducting and quench.

A 2D MAFIA model (see Fig. 2) is used to calculate transverse impedance of $(R/Q)_T$ for different cavity geometries and as well as for coupling factors between adjacent cavities. Different irises and equator radii are simulated to find an optimal value. When the iris radius decreases, both $(R/Q)_T$ and geometry factor, G increase while the coupling between cavities becomes weaker.

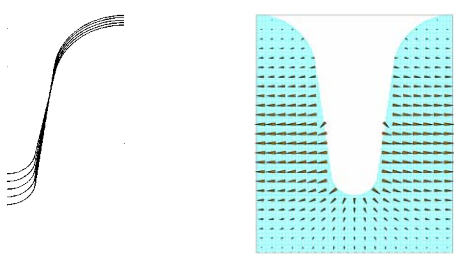

Figure 2 : MAFIA 2D model for cavity geometry design. Left: cavities with different irises. Right: typical electric field distribution of the deflecting mode.

Peak surface magnetic field is calculated using built-in macros in MAFIA code. To achieve 2MV transverse voltage, we chose a cavity design with 3 cells where the peak surface magnetic field is kept below 100 mT, which has been proved to be achievable for Nb cavities [5]. Peak electric field has also been calculated to estimate possible field emission problems. We found the peak surface electric field is ~15 MV/m, which is comfortably below most of the existing superconducting accelerating cavities, such as the TESLA cavity [6].

Table 1: Basic parameters of an optimized cell geometry

Frequency of the dipole mode	1.5	GHz
Iris radius	30	mm
Cell equator curvature	30	mm
Cell radius	126	mm
B_{peak} at 2MV deflecting voltage	85	mT
E_{peak} at 2MV deflecting voltage	14.4	MV/m
Transverse shunt impedance	64.3	Ω
G ($=R_{sur} \times Q_0$)	307	Ω

Simulation Results of the 3-Cell Cavity

Based on the optimized cell geometry, a 3-cell cavity model is generated and simulated using MAFIA code. In order to achieve the required field flatness, two end cells of the cavity have been adjusted to be slightly shorter than the central one. Beam pipes connected to the two end cells are enlarged to allow for space for coupler(s) and LOM and HOM damping. Figure 4 shows the achieved longitudinal electric field distribution plotted along z at 10-mm off axis of the deflecting π mode in the cavity. The frequency separation between the operating π mode and the nearest mode is ~ 6-MHz, which is wide enough allowing for a stable frequency control by LLRF.

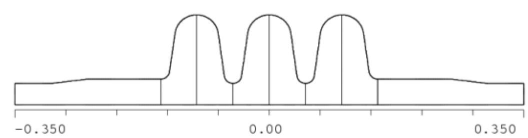

Figure 3: MAFIA 2D model of the 3-cell cavity design without couplers. The end cells are shorter than the central one and beam pipes at both ends are enlarged for couplers.

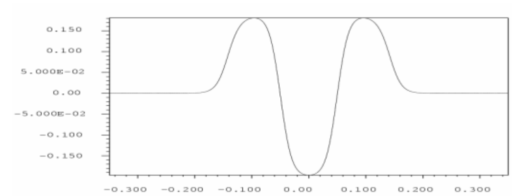

Figure 4 : Longitudinal electric field distribution of TM_{110}-like π mode, at r = 10-mm along z.

Table 2: Primary parameters of the 3-cell cavity

Central cell length	100	mm
End cell length	98	mm
Beam pipe radius	30	mm
TM mode cut-off frequency	3.825	GHz
TE mode cut-off frequency	2.928	GHz
Mode frequency	1.5005	GHz
"π-1" mode frequency	1.5064	GHz
Transverse shunt impedance	182	Ω
G ($=R_{sur} \times Q_0$)	309	Ω
R_{sur} at 2K of Nb	1.1×10^{-7}	Ω
Q_0 at R_{sur}	2.8×10^{9}	
Power dissipated at 2MV, 2K	7.8	W

Eigen-modes in the 3-cell cavity have been simulated up to beam pipe cut-off frequency using MAFIA code in frequency domain. It was found that the lower order monopole modes have very high shunt impedance that may introduce beam instability. The shunt impedance and loss factor k_{loss} of these LOM monopole modes and HOM dipole modes have been computed and analyzed. Figure 5 summarizes the simulation results by plotting the shunt impedance versus mode frequency.

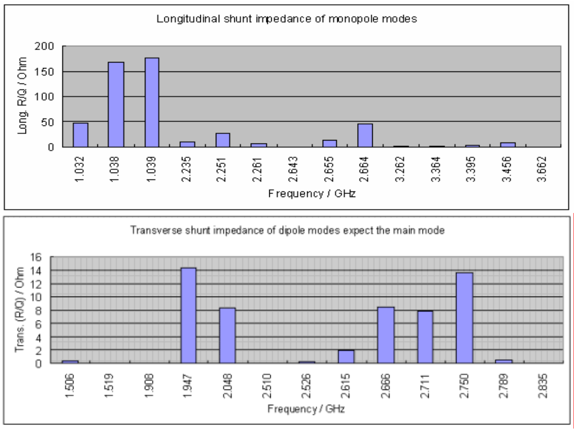

Figure 5: Shunt impedance of LOM's and HOM's

We can determine the required HOM/LOM damping by equating the longitudinal and transverse coupled bunch growth rate with the damping rate of the feedback systems. These values give us a maximum longitudinal impedance of ~ 125-kΩ/GHz and a transverse impedance of ~ 2 MΩ/m. With these constraints, the LOMs will require damping to a Q value of ~ 500. The dipole HOMs require damping to Q values of ~ 10^5.

COUPLERS DESIGN

RF coupling between couplers and the cavity is defined by a coupling constant, $\beta_C = Q_0 / Q_{ext}$, where Q_{ext} is determined by the coupler design. For superconducting cavities, Q_0 is at the order of 10^9 and Q_{ext} is typically around 10^6 to 10^7 depending on beam power, micro-phonics, cavity bandwidth and etc.

Microwave Studio (MS) Simulation

CST MS® was used to generate simulation models for coupler configurations. Voltage Standing Wave Ratio (VSWR), ρ is computed using the T-module of the MS for each configuration. Q_{ext} is then given by, (Q_0/ρ) or (ρQ_0) depending on the cavity-coupler system is over-coupled or under-coupled. Figure 6 shows preliminary designs of two couplers. The RF coupler sitting on top of the enlarged beam pipe is shown on the right-hand side of the model. A LOM coupler (damper), a co-axial insert is shown at the left-hand side of the beam pipe. The LOM coupler scheme is adopted from the design for KEK-B crab cavity [3].

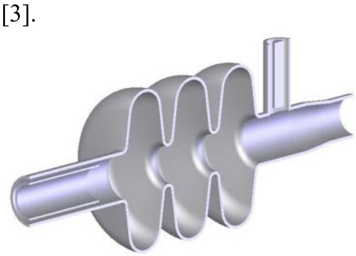

Figure 6 : Preliminary design of two couplers: a vertical coaxial line as main coupler and a beam pipe insert as LOM damper.

The Main RF Coupler and Coaxial Insert

The length of inner conductor in the coaxial line can be modified to simulate and find the relationship between Q_{ext} and the penetration of inner conductor. The simulation results are presented in Figure 7. It is convenient to adjust the length to achieve a required Q_{ext}.

Azimuthal magnetic fields of the longitudinal monopole mode in the cavity are similar to that of a TEM mode in a coaxial transmission line. Therefore the monopole modes in the cavity will couple strongly to the TEM mode in a coaxial transmission line. Our first simulation of the coaxial insert (LOM damping) indicated that it indeed coupled strongly with the longitudinal monopole modes and their external Qs have dropped down to 10^5 levels. However, a more careful simulation will be carried out later.

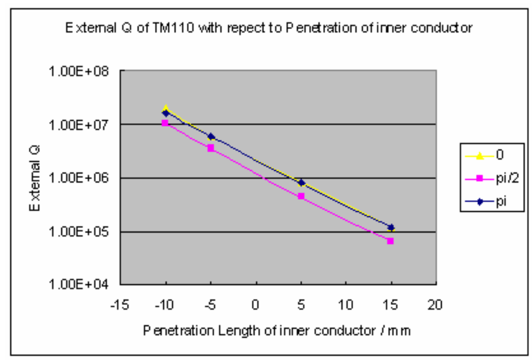

Figure 7: MS simulation results of Q_{ext}

SUMMARY

A preliminary deflecting cavity design with couplers has been simulated. Damping most harmful monopole modes is discussed while the conceptual coupler design is proposed and will be optimized later.

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