DESIGN OF A QUASI-WAVEGUIDE MULTICELL DEFLECTING CAVITY FOR THE ADVANCED PHOTON SOURCE*

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Abstract

This paper reports the electromagnetic design of a 2815 MHz Quasi-waveguide Multicell Resonator (called QMiR) being considered as a transverse RF deflecting cavity for the Advanced Photon Source's (APS) Short Pulse X-ray project. QMiR forms a trapped dipole mode inside a beam vacuum chamber while High Order Modes (HOM) are heavily loaded. It results a sparse HOM spectrum, makes HOM couplers unnecessary and allows simplifying the cavity mechanical design. The form of electrodes is optimized for producing 2 MV of deflecting voltage and keeping low peak surface electric and magnetic fields of 54 MV/m and 75 mT respectively. Results of detailed EM analysis, including HOM damping at the actual geometry of beam vacuum chamber, will be presented.

INTRODUCTION

The superconducting radio frequency (SRF) multi-cell trapped mode cavity is proposed for an implementation in the Short Pulse X-ray (SPX) upgrade of Argonne APS [1]. The number of Synchrotron Radiation (SR) facilities over the world is a multiple of tenth and is growing up quickly [2]. Generating short x-ray pulses in a SR facility is in high demand for research in condensed matter physics, materials science, biology and medicine. Proposed technique is based on a beam deflection resulting a correlation between the longitudinal position of an electron within the bunch and its vertical momentum. It allows obtaining a sub-picosecond X-ray pulse without a reduction of a bunch length with existing particles accelerators.

Historically a simple pill-box type resonator with an optimized elliptical shape, operating in the dipole electric TM11 mode was used for beam deflection. Despite its simple geometry and a good surface cleaning capability, there are few major drawbacks: a) the TM11 mode is not the lowest mode in the cavity spectrum, b) number of Low Order Modes (LOM) and HOM couplers are required for damping unwanted resonances, c) such cavities have large transverse dimensions. Thus, there are difficulties with cryostat design that complicate cavity operation. Recently alternative solutions based on the transverse TE11 magnetic mode and TEM lines were proposed for the deflection of charged particles [3, 4]. Both approaches resulted in significantly smaller cavity design compared to the conventional TM11 elliptical cavity and eliminate the presence of LOM modes. However, these new conceptions are still comprised of a closed resonant volume with a dense eigenfrequency spectrum and therefore require auxiliary couplers for damping coherent HOM excitation.

Thus, there is a need for a simple and compact superconducting structure for beam manipulation applications. Such a structure has to provide a high transverse kick, have a minimum number of auxiliary couplers and must be able to operate with high beam current.

CAVITY EM DESIGN

It is known that localized imperfections in a regular waveguide will cause a so called "ghost modes" to appear [5, 6]. Ghost modes are trapped to the vicinity of imperfections, with resonant frequencies lower than a waveguide cut-off limit, and usually are treated as a parasitic factor limiting the beam intensity. Instead we try to use this phenomenon for good in our design of the QMiR cavity. Since multiple electrodes immersed into a waveguide form a trapped mode resonator, the transverse EM-field components of the TE dipole mode allow creating a kick and effectively deflecting charged particles passing through the cavity. Because such a cavity is open, i.e. has no end walls, it helps significantly in reducing the maximum quality factors of HOMs and, thus, avoiding complicate HOM couplers and simplifying a cavity mechanical design in overall.

Table 1: Design parameters for the APS deflecting cavity

Parameter	**Value**
Frequency	2.815 GHz
Optimal beta	1.00
Nominal Kick Voltage	2 MV
Beam aperture	12 mm x 30 mm
Max surface E_{pk}	54, (< 55) MV/m
Max surface B_{pk}	75, (< 80) mT
G-Factor	130 Ω
R/Q, Operating mode	1040 Ω
R_m*F, Monopole modes	<0.44 MΩ * GHz
R_t, Horizontal mode	<1.3 MΩ/m
R_t, Vertical mode	<3.9 MΩ/m

* Operated by Fermi Research Alliance, LLC, under Contract DE-AC02-07CH11359 with the U.S. DOE
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An isometric view of a three-cell 2815 MHz TE mode deflecting superconducting cavity is shown in Figure 1. The cell is composed by a pair of smooth protrusions, aka “electrodes”, in opposite walls of a square waveguide. The square shape allows minimizing a transverse space occupied by the cavity and provides a simple mechanical design simultaneously. The form of electrode is chosen to be a chain of conjugated elliptical surfaces for optimal distribution of electrical and magnetic field components. The geometry of a medium cell is illustrated in Figure 2.

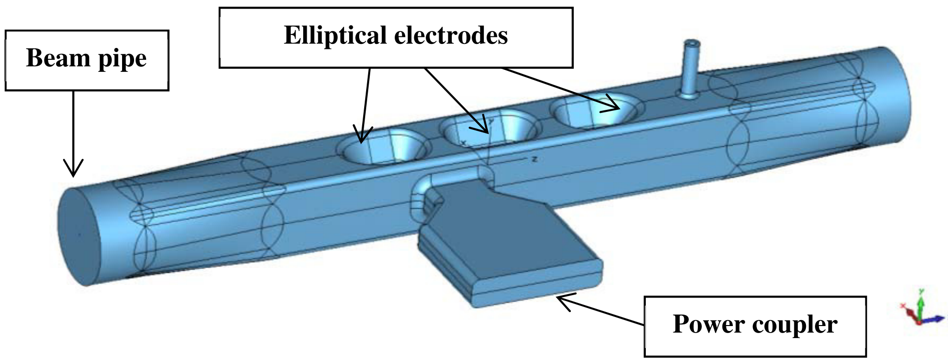

Figure 1: An isometric view of the TE mode deflecting superconducting cavity and a fundamental mode coupler.

The square waveguide is connected to a vacuum beam line by a smooth transition providing a freely radiation and damping of beam exited HOMs. The particular design of a transition has a round shape matched to the design of a vacuum chamber in the actual section of the APS circular accelerator.

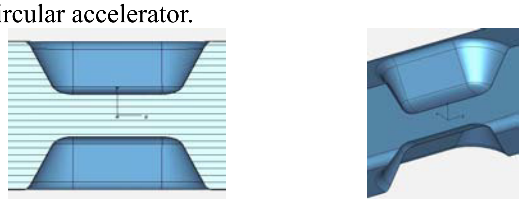

Figure 2: Geometry of the medium cell.

The rectangular lateral waveguide is attached to the cavity for feeding with RF power at operating. The waveguide position is shifted in respect to the inter-cell boundary aiming to break symmetry and provide an adequate high-Q coupling of operating mode with an external RF source in order to reduce RF power requirements. The capacitive diaphragm with rounded edges is used to control a power coupling ratio and maintain low surface magnetic field simultaneously. Distribution of electric and magnetic fields and mechanism of coupling of the cavity operating mode with external waveguide transmission line is illustrated in Figure 3. Transverse components of electromagnetic field in the cavity deflect the beam and produce a vertical kick or crabbing of the beam. Figure 4 shows transverse components of electromagnetic fields on the cavity axis normalized to 1J stored energy. The vertical kick is defined as a real part of the voltage integrated along the beam trajectory:

$$V_y = Re \int_0^L (E_y + Z_0 H_x) e^{ikz} dz \quad (1)$$

where L is the cavity length equal to distance between beam line ports, E_y and H_x are transverse electric and magnetic field components, Z_0 is the impedance of the vacuum and z is a longitudinal coordinate along the cavity axis.

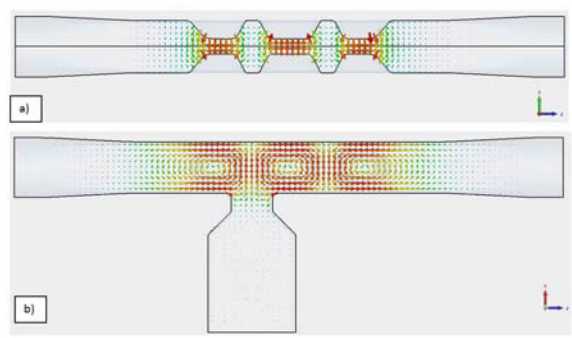

Figure 3: Vector electric (a) and magnetic (b) fields of the 2815 MHz operating dipole mode.

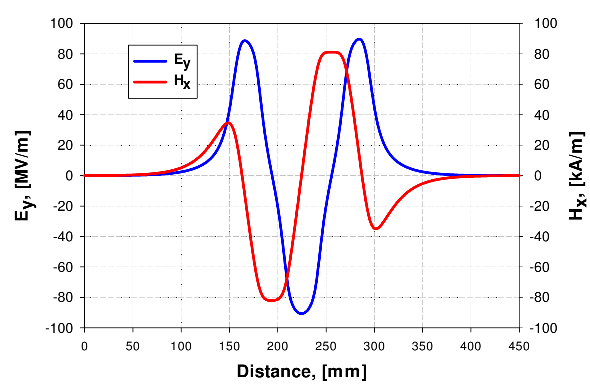

Figure 4: Operating mode transverse electric (blue) and magnetic (red) field components along the cavity axis.

The building of the vertical kick along the cavity axis is presented in Figure 5. Table 1 contains the most essential operating mode parameters including the transverse shunt impedance defined as $(R/Q)_y = V_y^2/\omega W$, where ω is the mode circular frequency and W is the electromagnetic energy stored in the cavity.

ISBN 978-3-95450-142-7

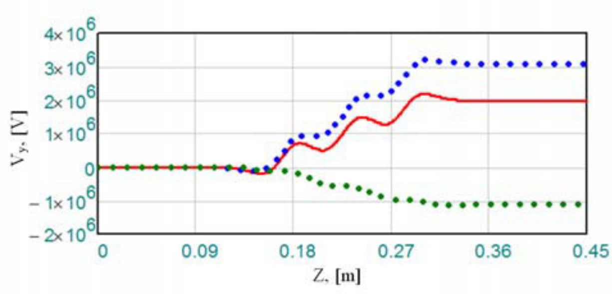

Figure 5: Integrated vertical kick along the cavity axis (solid red curve is the overall kick, dotted blue and green curves are electric and magnetic kicks).

The three protrusions have special shapes which are optimized for keeping the peak surface electric and magnetic fields below 55 MV/m and 75 mT respectively while maintaining the vertical kick at 2 MV level. The final result of the operating mode surface field optimization using ANSYS HFSS eigenmode solver is illustrated in Figure 6 [7].

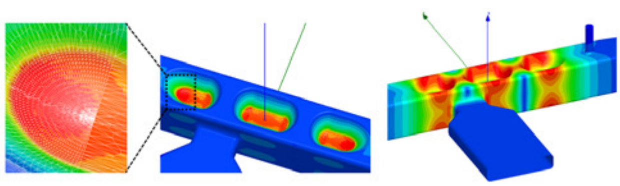

Figure 6: Operating trapped mode surface electric (right) and magnetic (left) fields.

HOM DAMPING

The lowest frequency eigenmode of the cavity is the dipole deflecting mode. Besides the operational deflecting mode, there are two other "same-order" deflecting modes whose frequencies are slightly lower. The fundamental coupler waveguide seen in Figure 1 is also used to suppress these modes and, therefore, it is purposely shifted from the cavity center in order to provide external coupling for the operating mode and damping lower frequency dipole modes simultaneously. Table 2 shows calculated transverse impedances and quality factors for these modes. The largest transverse impedance is 1.9 MΩ/m, which is below the maximum values defined as 3.9 MΩ/m. The beam pipe cutoff frequency for the transverse TE_{11} mode is 3.6 GHz and, thus, all higher frequency dipole modes freely propagate out of the cavity.

Table 2: Transverse dipole modes

Freq., [GHz]	$(R/Q)_t$, [Ω]	Q_{ext}	R_t [MΩ/m]
2.476	0.03	2400	3e-3
2.675	5.0	6800	1.9

The cavity spectrum of monopole modes is sparse and contains four modes below the beam pipe cutoff frequency of 4.7GHz and two trapped modes above. Parameters of these modes are shown in Table 3. All monopole modes are well separated from the operating mode and have a relatively low R/Q and loaded Q values.

The largest calculated longitudinal impedance is 0.26 MΩ•GHz, Thus, no multi-bunch instability is expected because the magnitude of the HOM impedances listed above are below the maximum values defined as 0.44 MΩ•GHz.

Table 3: Monopole modes

Freq., [GHz]	R/Q, [Ω]	Q_{ext}	R_m*F, [MΩ*GHz]
4.304	1.3	55	3e-4
4.409	39	530	0.09
4.471	37	400	0.07
4.530	0.35	5900	8e-3
5.080	132	390	0.26
5.114	39	108	0.02

CAVITY PERFORMANCE

It is proven by experimental data that SRF cavities can reliably operate if its surface electric field is below 75 MV/m and surface magnetic field is less than 100 mT, which gives a good safety margin to the proposed design. The first Nb prototype of QMiR cavity was recently fabricated and tested at ANL. During the preliminary 2 K vertical cold tests the bare QMiR resonator reached the deflecting voltage of 2.7 MV (~100 mT magnetic and 70 MV/m electric surface fields) without been quenched [8].

CONCLUSION

The present design of the TE-mode superconducting deflecting cavity with the open ends avoids complicated HOM couplers and creates a higher operating gradient at the same time, thereby, producing a more compact cryomodule design. The QMiR cavity has a low parasitic HOM RF losses and a higher beam instability threshold due to HOM excitation. Thus, it may be beneficially operated for various beam manipulation projects under high beam current and high repetition rate scenarios.

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