DESIGN AND MEASUREMENT OF DOUBLE GAP BUNCHER CAVITY PROPOSED FOR REDUCTION OF X-RAY RADIATION

Ki R. Shin[1], Yoon W. Kang, Aly E. Fathy[1], and Mark S. Champion
ORNL, Oak Ridge, TN 37831, [1]University of Tennessee, Knoxville, TN 37996, U. S. A.

Abstract

X-ray radiation from accelerating cavities can be serious problem not only in high energy section but also in certain low energy system including beam matching section with buncher cavity. In this paper we propose a double gap buncher cavity design for low energy part of H- ion accelerators which can reduce X-ray radiation. The cavity utilizes Transverse Magnetic (TM) mode at about 400MHz as the operating mode. A drift tube supported by a stem in the cavity can form two gaps that can divide the required gap voltage to a half per each gap. Lower peak field can be realized since this double gap cavity can avoid sharp geometry. 3D simulation is utilized to address the analysis of non-axisymmetric structure. An Aluminum scaled model is built and tested with low power measurement. The measured results are in good agreement with simulations.

INTRODUCTION

For safety, radiation shielding is an important part of a high energy accelerator design [1]. Concrete material surrounds accelerator system in a tunnel to shield any hazardous radiations. Often bunching cavities in low energy section of ion accelerator < 3MeV are placed outside the tunnel only with fundamental radiation shield. X-radiation with non-negligible level can occur, however, if cavities are not under good vacuum condition [2]. Therefore, more conservative design to prevent X-radiation can help to improve system operability.

Assuming a constant vacuum level, X-radiation intensity is related to the cavity gap voltage and discharge current [3][4]. Ref. [3][4] expects that the radiation intensity has quadratic to cubic relation with gap voltage. The radiation wavelength is inversely related to the gap voltage as well [4]. Consequently, lower gap voltage may decrease a radiation dose and hard X-ray generation.

The mechanism of discharge current is rather complex, but in general it is relevant to the field emission and explosive emission mechanism [5]. The electric field in cavity determines the discharge current, and lower electric field is expected. In other words, lower electric peak field with smooth gap geometry may help to minimize discharge current and radiation intensity.

With regarding these voltage and peak field requirements, a double gap buncher cavity design is proposed and its lab type measurement is presented in this paper. This design is aimed to fit the requirement of the cavity 4 with 30mm bore diameter in medium energy beam transport (MEBT) section in the Spallation Neutron Source (SNS) [6]. The cavity length and particle speed are about 13cm and 0.073 v/c, respectively.

X-RADIATION BY VACUUM DISCHARGE

At cavity gap, the X-ray radiation dose D_X is determined by the integration of the radiation intensity J_X over the particle commutation time t_c (1) [3][5].

$$D_X \cong \int_0^{t_c} J_X(t)dt \qquad (1)$$

$$J_X \propto i(t) \cdot V^n(t) \qquad (2)$$

The radiation intensity J_X is related to the discharge current $i(t)$ at cavity gap and the gap voltage $V(t)$ likewise (2) [3][5]. The variable n commonly has values in range of 1.8~3.0 [3-5]. As a result, $V(t)$ becomes an important parameter to determine J_X. The maximum X-radiation frequency also rises as the gap potential energy increases. This may induce a generation of hard X-ray. Therefore, low cavity gap voltage is desired to decrease X-radiation.

In accelerating cavities with high electric field intensity, the discharge current is generally formed by Fowler-Nordheim field emission mechanism [5]. Fig. 1 describes the field emission process at cavity gap (between cathode and anode), and the current density definition.

In field emission mechanism, some cathode electrons are stripped by strong electric field and collide to the anode. The emission current is a function of electric field; hence smaller electric field is desirable to decrease X-radiation by discharge current.

Most RF cavities are designed to have enough design margins until to reach the field breakdown limit, however, some micropoints on cathode and anode surface (Fig. 1) may lower the barrier of discharging. These micropoints can generate plasma around cathode, and as a result the discharging process starts earlier than as expected. This mechanism is called as explosive electron emission [5]. The anode part can also suffer from extra heating, evaporation, and ionization.
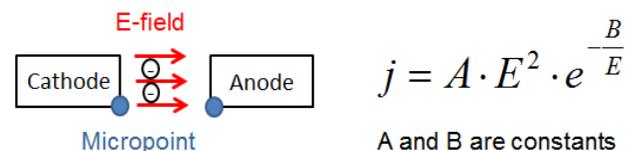

Figure 1: Field emission at cavity gap and Fowler-Nordheim current density.

The sharp gap shape in low energy ion accelerator section can be more vulnerable to explosive electron

emission mechanism; because the geometry would have more chance to contain micropoints than flat shape.

Regarding all considerations above, we propose a double gap cavity design which can help to relieve X-radiation problem. This design decreases gap voltage and peak electric field that is directly related to X-radiation. The voltage is reduced to a half by using double gap, and the peak electric field can be decreased with flat gap geometry.

DOUBLE-GAP TM MODE CAVITY

Buncher cavity operates with -90º phase from the RF electric field maximum, as a result the average particle speed does not change. For that reason, the multi gap cavity geometry can be symmetrical. The transverse magnetic (TM) electromagnetic mode can be more reliable from the multipacting issues than transverse electromagnetic (TEM) cavity design [7]. The benefit of higher R/Q in TEM cavity diminishes at higher frequency about 400MHz [8] because of very low Q. The TEM cavity efficiency further decreases for the requirement of SNS MEBT buncher cavity, which has a large bore diameter about 30mm. Therefore, TM mode is adopted as the operating mode.

The design of double gap cavity requires 3D RF analysis because of rotational asymmetry. The CST Microwave Studio [9] is utilized in the cavity design and parameter study.

Fig. 2 shows the electric field formation of the single and double gap cavities. About a half voltage of single gap cavity is formed in each gap of the double gap cavity. Each double gap cavity gap dimension is slightly bigger than the single gap cavity to decrease the electric peak field. Each gap field has the same RF phase in the double gap cavity and matched to the particle velocity.

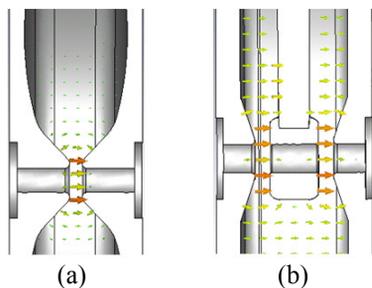

(a)   (b)

Figure 2: Electric field and cavity geometry around on axis- (a) single gap, (b) double gap.

A summary of the cavity parameters are shown in Table 1. The double gap design obviously can decrease peak electric field by 55% and generate half voltage per each gap, which can help to decrease X-radiation intensity. Although this design gives slightly lower power efficiency and may become mechanically slightly bigger due to additional gap spacing. The power efficiency can be improved further by optimizing the cavity gap geometry.

Table 1: Parameter Comparison (3.0cm bore/ 28.2kW rms)

	Single Gap	Double Gap
Frequency (MHz)	401.9	400.1
Gap size (mm)	12.30	14.23 14.23
Q (unloaded, Copper)	21413	20903
r/Q	29.35	27.83
R_s/L (Mohm/m)	5.48	4.47
V_0 (kV)	119.08	57.28 57.28 (Total : 114.45)
T	0.447	0.452
E_0 (MV/m)	2.32	1.93
E_{pk} (MV/m)	29.9	13.26
H_{pk} (A/m)	6565	8644

½ SCALED MODEL FABRICATION

A scaled prototype model of half size is built with Solidworks [10] to verify the design. AL 6061 T6 material with 42% of copper conductivity is used as a cavity material. As shown in Fig. 3, the drift tube assembly is attached on the equator of the cavity main body. Next, the minor piece is mounted to the main piece to complete the assembly. This prototype model is designed for low power measurement; hence does not include the design of cooling channel.
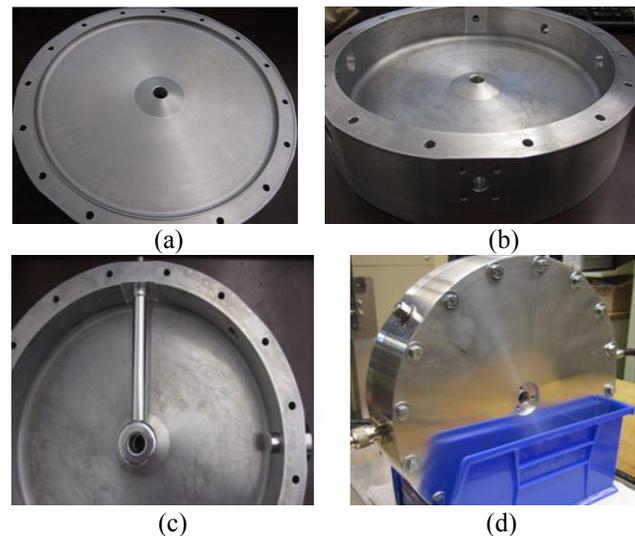

(a)   (b)

(c)   (d)

Figure 3. Fabricated ½ scale double gap cavity (a) minor piece, (b) major piece, (c) major piece with tube, (d) final assembly with 2 ports.

FREQUENCY AND Q MEASUREMENT

Table 2 shows the comparison of the simulated and measured TM010 mode frequency and Q value. S21 parameter is measured with a two port vector network analyser (VNA). The simulation and the measurement showed an excellent agreement in frequency. The 12%

07 Accelerator Technology

T06 - Room Temperature RF

difference in Q measurement comes from extra power loss on the cavity seam plane and coupler ports.

Table 2: Simulation vs. Measurement – Frequency and Q

	Simulation	Measurement
Frequency	800.49	800.56
Q	9286	8179

R/Q MEASUREMENT

One of the cavity figures of merit, shunt impedance, is both RF loss and frequency dependent. Hence R/Q [11], which is independent of the loss and frequency is measured and compared.

Fig. 4 shows a beadpull system setup for R/Q measurement. A spherical metallic bead was used. We try the phase shift measurement to find R/Q since this method is rather simple and accurate [12].

The measured phase shift results in Fig. 5 are all integrated on the cavity beam axis to calculate R/Q. The reference phase outside of the cavity gap is set to zero, and two shifting curves are shown due to the double gap. The same method used in Ref. [13] is utilized to calculate R/Q.
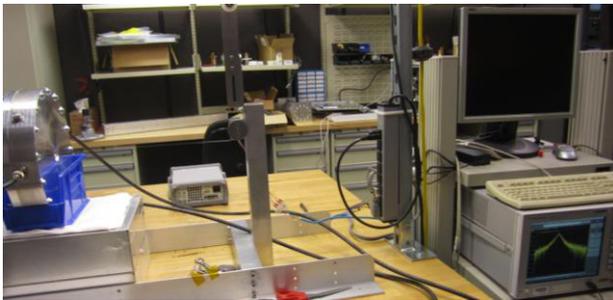

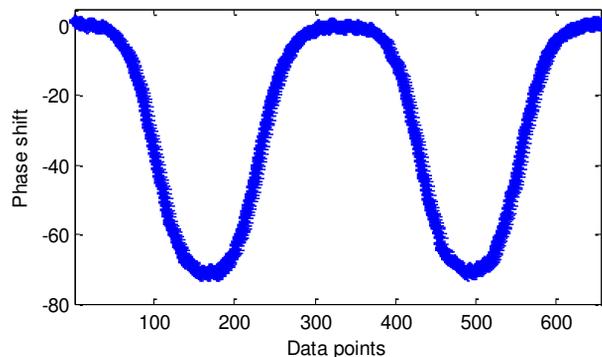Figure 4: R/Q measurement system.

Figure 5: Measured phased shift by perturbation method.

The measured R/Q is in good agreement with the simulation with 94% accuracy as shown in Table 3. The estimated shunt impedance Rs is lower in accuracy with about 83%, because of 12% Q discrepancy already

discussed in Table 2. R/Q value will be the same for 400MHz as well.

Table 3: Simulation vs. Measurement – R/Q

	Simulation	Measurement
R/Q	27.83	26.12
Rs (Mohm)	0.258	0.213

CONCLUSIONS

A buncher cavity design to reduce X-ray radiation for better operability is proposed for the low energy ion accelerator section with SNS MEBT cavity example. Gap voltage and peak electric field drastically decreases with this double gap design. Measurement results with scaled model are in good agreement with simulations.

ACKNOWLEDGMENT

REFERENCES

[1] J. Cossairt, "Radiation Physics for Personal and Environmental Protection", FNAL Report TM-1834.

[2] A. Aleksandrov, "The SNS beam diagnotics experience and lessons learned", Proceeding of the 2010 Beam Instrumentation Workshop.

[3] J. Haimson, "Some Aspects of Electron Beam Optics and X-Ray Production with the Linear Accelerator", IRE Trans. On Nuc. Sci. Vol. 9, Issue 2, April 1962.

[4] A. Oppelt, "Imaging systems for medical diagnostics", J. Wiley and Sons, 2006.

[5] G. Mesyats et. al., "Pulsed Electrical Discharge in Vacuum", Springer-Verlag, 2012.

[6] J. Staples et al., "Design of the SNS MEBT", XX International Linac Conference, California.

[7] A. Millich et al., "Comparison of Three Buncher Structure Designs for the 3MeV SPL Chopping Line", CERN PS/RF/Note 2002-028.

[8] T. Enegren, "The SSC RFQ-DTL Matching Section Buncher Cavities", 15th Particle Accelerator Conference, May. 1993.

[9] CST Microwave Studio, www.cst.com

[10] Solidworks, www.solidworks.com

[11] L. Maier et. al., "Field Strength Measurements in Resonant Cavities", J. Appl. Phys. 23, 68, 1952.

[12] J. Slater, "Microwave Electronics", Van Nostrand, 1950.

[13] P. Matthews et. al., "Electromagnetic Field Measurements on a Millimeter Wave Linear Accelerator", IEEE Trans. on Micro. Theory and Tech. Aug. 1996.