DESIGN OF COMPACT C-BAND STANDING-WAVE ACCELERATOR FOR MEDICAL RADIOTHERAPY*

H. R. Yang#, M. H. Cho, and W. Namkung
Pohang University of Science and Technology, Pohang 790-784, Korea
S. H. Kim, Argonne National Laboratory, Argonne, Illinois 60439, USA
J. S. Oh, National Fusion Research Institute, Daejeon 305-333, Korea

Abstract

We design a C-band standing-wave accelerator for an X-ray and electron source of medical radiotherapy. The accelerator system is operated two modes, using the X-ray and electron beams. Since two modes require different energy, the accelerator is capable of producing 6-MeV, 100-mA pulsed electron beams with peak 2-MW RF power, and 7.5-MeV, 50 mA electron beams with peak 2.5-MW RF power. The beam is focused by less than 1 mm without external magnets. The accelerating structure is a bi-periodic and on-axis-coupled structure with a built-in bunching section, which consists of 3 bunching cells, 14 normal cells and a coupling cell. It is operated with the π/2-mode standing-wave. The bunching cells are designed to enhance the RF phase focusing. Each cavity is designed by the MWS code within 3.5% inter-cell coupling. In this paper, we present design details of RF cavities and the beam dynamics.

INTRODUCTION

The electron accelerator is widely used for industrial and medical applications: a contraband detection, material processing, a medical diagnosis and therapy, sterilizing food, and environmental processing [1, 2]. For the medical applications, the electron beam with 3 ~ 15 MeV, pulsed tens mA is required. These applications require the small beam spot size at the X-ray conversion target for reducing the penumbra [3]. In order to achieve such a small beam spot size, the RF focusing effect is maximized instead of the magnetic focusing with external magnets for a compact accelerator system.

We are developing a C-band standing-wave electron accelerator for an X-ray and electrons source of medical radiotherapy. This accelerator system is operated two modes, using the X-ray and electron beams. The X-ray beam is used to irradiate the viscera, and the electron beam is used to irradiate the inner and outer layers of skin. There is energy loss by two scattering foils which are between the accelerating column and the affected area in the electron mode, as shown in Fig. 1 [4]. The beam energy at the end of column has to be higher than irradiated energy in the affected area, 6 MeV which are widely used in the medical radiotherapy [5]. For such reasons, the accelerator is designed to produce 6-MeV, pulsed 100-mA electron beam with peak 2-MW power in the X-ray mode, and 7.5-MeV, pulsed 50-mA electron beam with peak 2.5-MW power in the electron mode. It is operated with a pulse length of 4 µs and with a pulse repetition rate of 250 Hz. The bunching cells are designed with beam dynamics simulation for enhancing the RF phase focusing. We design the RF cavities in the bi-periodic and on-axis-coupled accelerating structure with the MWS code. The beam dynamics simulations are conducted with PARMELA codes.

*Work supported by POSTECH Physics BK21 Program.
#highlong@postech.ac.kr

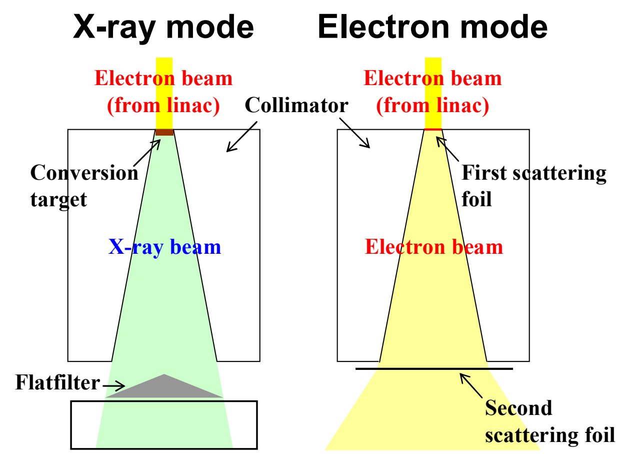

Figure 1: Schematic diagram of the X-ray and electron modes.

Table 1: The design parameters of the accelerator

Parameters	X-ray Mode	Electron mode
Operating Frequency	5712 GHz	
Input Pulsed RF Power	2.0 MW	2.5 MW
Pulse Length	4 µs	
Repetition Rate	250 Hz	
E-gun Voltage	19.0 kV	20 kV
Input Pulsed Beam Current	80 mA	180 mA
Output Beam Energy	6 MeV	7.5 MeV
Output Pulsed Beam Current	50 mA	100 mA
Type of Structure	Bi-periodic, On-axis coupled	
Operating Mode	SW π/2 mode	
Beam Aperture Diameter*	6 mm	
Average Accelerating Gradient	13.4 MV/m	16.7 MV/m
Number of Cells	18	
Inter-cell Coupling	3.5%	
Quality Factor*	9000	
Shunt Impedance*	113 MΩ/m	
Transit-time Factor*	0.84	

*Values for normal cells.

ISBN 978-3-95450-122-9

ACCELERATOR OVERVIEW

The accelerator uses a 5712-MHz magnetron as an RF source. It is capable of producing a max. 2.5 MW RF with a 4-µs pulse length and a 250-Hz repetition rate. It is supplied pulsed 2.0 MW RF in the X-ray mode, and pulsed 2.5 MW RF in the electron mode, as shown in Table 1. The RF power is transmitted to the accelerating column through the WR187 waveguide network, as shown in Fig. 2. Since there is a transient reflection during an RF filling time in the standing-wave accelerating structures, a circulator with the matched load is inserted in the waveguide network. The pulse modulator supplies a max. 65-kV and a 90-A pulsed power to the magnetron with a 4-µs pulse length. It also supplies a max. 20-kV pulsed voltage to an E-gun.

The E-gun is a diode-type thermionic DC gun with a dispenser cathode. Although the E-gun is capable of emitting electron beam of maximum 560 mA, the gun emits 80-mA electron beam with 20-kV pulse in the electron mode, and 180-mA e-beam with 19-kV pulse in the X-ray mode. The beam radius is 0.6 mm at the beam waist which is 15.2 mm from the anode. The direction of the beam is adjusted by the steering coils in the upstream and downstream of the accelerating column, as shown in Fig. 3.

The accelerating column is attached to the E-gun directly, as shown in Fig. 3. For a compact structure, it has a built-in bunching section without a pre-buncher, and any focusing magnet is not used, because the beam is focused enough by the enhanced RF phase focusing with the design of the bunching cells [6]. A bi-periodic and an on-axis coupled structure is adopted for the π/2-mode standing-wave structure [7]. The first three cells, in Fig. 3, are the bunching cells with phase velocities (βph) of 0.3, 0.5, and 0.85. The number of normal cells with βph = 1 is 14 units, and after these, the coupler cell is attached to the tapered C-band waveguide.

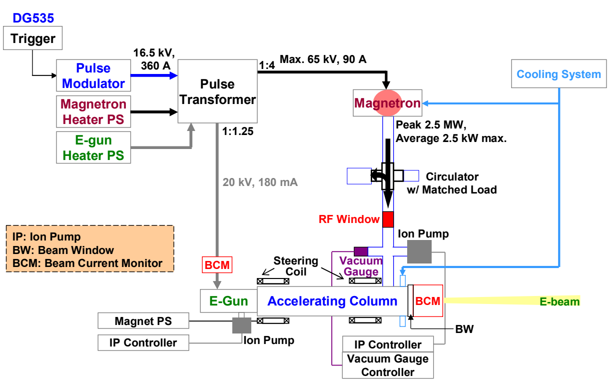

Figure 2: Schematic diagram of the accelerator system.

BEAM DYNAMICS

Beam dynamics simulations in the accelerating column are conducted by using the PARMELA code. The emittance of input beams is 20 mm-mrad and other parameters of input beams are described in the previous section. The phase velocities of bunching cells, and the asymmetric geometry of the first and second bunching cells are optimized to enhance the RF phase focusing, as shown in Fig. 3 [6]. In the electron mode, since the beam is scattered at two foils, the small beam spot is not required. Therefore, the efforts to enhance the RF phase focusing are optimized in the X-ray mode.

Fig. 4 is the phase trajectories of the X-ray and electron modes, and Fig. 5 is the beam envelopes of two modes. In the X-ray mode, the accelerating field is lower compared with that of the electron mode, because of the lower input RF power. Since the RF focusing is proportional to the square of the accelerating field, the beam is less focused in bunching cells, as shown in Fig. 5 [6]. However, since the beam is less accelerated in bunching cells, the average phase of the bunch is higher than that of the electron mode, as shown in Fig. 4. Then, the RF phase focusing is increased in normal cells [7]. Since these two effects cancel each other out, the beam spot size is almost the same in two modes. With effective RF focusing, the beam spot sizes of both are less than 1 mm at the end of column, as shown in Fig. 5.

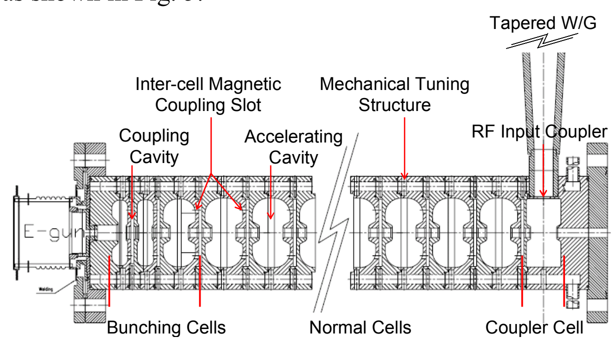

Figure 3: Cross-sectional view of the accelerator structure.

The output beam parameters of two modes are in Table 2. Since there is a lot of beam loss in the conversion target, collimator, and the flatfilter, as shown in Fig. 1, the beam current in the X-ray mode is higher than that of the electron mode, in order to obtain a lot of radiation. In the electron mode, the beam is accelerated near the crest, and more bunched, as shown in Fig. 4. Therefore, the beam energy spread is 10% less than that in the X-ray mode. It affects the increasing of the energy uniformity of beam in the electron mode.

RF CAVITY

Each cell in the accelerating column consists of the accelerating cavity and the coupling cavity, as shown in Fig. 3. Magnetic coupling slots are bored on the side wall between the accelerating cavity and the coupling cavity for the inter-cell coupling. The inter-cell coupling constant becomes 3.5%, restricted by the decrease of the shunt impedance. Due to these slots, the 3-D electro-magnetic simulation is conducted with the MWS code to obtain the resonant frequency for the π/2-mode of each cavity, as shown in Fig. 6. In the case of the coupling cavity, the transverse mid-plane can not be a symmetric boundary due to the magnetic coupling slots. To estimate an accurate resonant frequency for the coupling cavity, the end cells are detuned for the frequency of the detuned cell to be lower than 3 GHz, as in Fig. 6(b) [8]. From the simulation result, the resonant frequencies of each cavity is obtained, 5711.5±0.5 MHz.

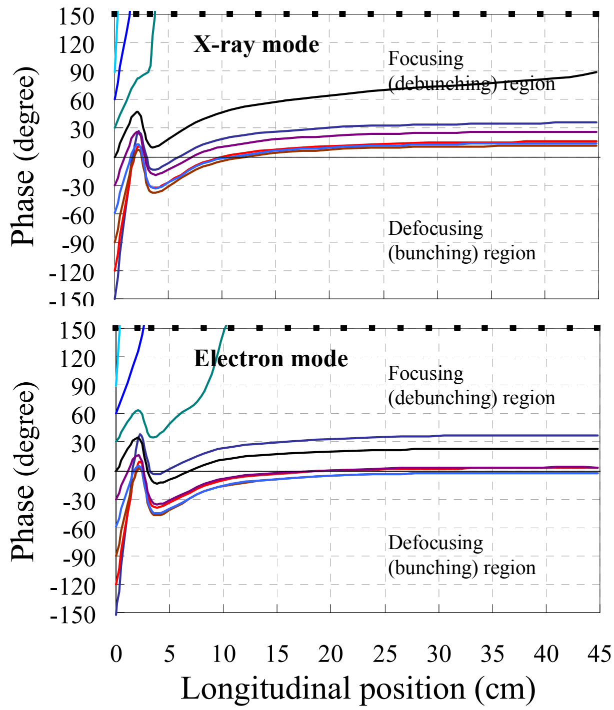

Figure 4: The phase trajectories of the X-ray and electron modes.

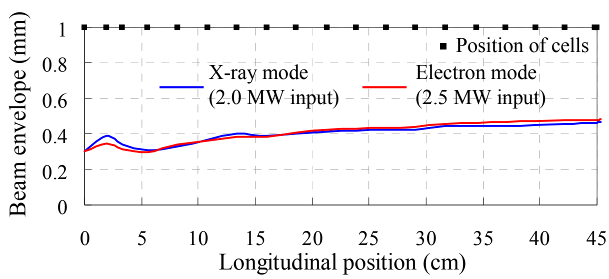

Figure 5: The beam envelopes of the X-ray and electron modes.

Table 2: The output beam parameters of the X-ray and electron modes

Beam parameters	X-ray Mode	Electron mode
Average Energy	6 MeV	7.5 MeV
Pulsed Beam Current	100 mA	50 mA
Energy spread	37%	27%
Beam spot size	~ 1 mm	~ 1 mm

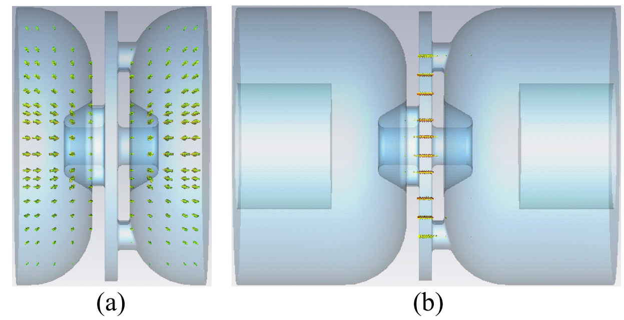

Figure 6: Simulation model to find the resonant frequency for (a): the accelerating cavity, (b): the coupling cavity.

SUMMARY

The C-band standing-wave accelerator is developed for the X-ray and electron source. This accelerator is capable of producing 6-MeV, 100-mA pulsed electron beams with an RF power of 2.0 MW for the X-ray source, and 7.5-MeV, 50-mA pulsed electron beams with an RF power of 2.5 MW for the electron source. In order to enhance the RF phase focusing, the phase velocities of bunching cells and the geometry of the first and second bunching cell are adjusted with beam dynamics simulations. Under these conditions, the beam is focused by less than 1 mm at the end of accelerating column in both of conditions. Since the beam is accelerated near the crest and more bunched in the electron mode, the beam energy spread 27% which is 10% less than that in the X-ray mode. The bi-periodic accelerating structure with on-axis coupling is designed. The cavity dimensions are determined for the π/2-mode frequency to be 5712 MHz with 3.5% inter-cell coupling by the MWS code simulation.

ACKNOWLEDGEMENT

This work is partly supported by MKE, Korea and POSTECH BK21 Program.

REFERENCES

[1] W. A. P. Calvo, et al., Rad. Phys. Chem. **81**, 1276 (2012).

[2] C. Tang, et al, "Present Status of the Accelerator Industry in Asia," in *Proc. of IPAC10* (Kyoto, Japan, May 23-28, 2010), p. 2447.

[3] L. W. Wang and K. Leszczynski, Med. Phys. **34**, No. 2, 485 (2007).

[4] G. X. Ding, et al., Med. Phys. **23**, No. 3, 361 (1996).

[5] G. A. Loew, SLAC-PUB-1830, 1 (1976).

[6] H. R. Yang, et al, "Self-focusing Effects in Compact C-band Standing-wave Accelerating Structure for X-ray Imaging Applications," in *Proc. of IPAC11* (San Sebastian, Spain, Sep. 4-9, 2011), p. 2046.

[7] H. Euteneuer, et al, "The 4.9 GHz Accelerating Structure for MAMI C," in *Proc. of EPAC 2000* (Vienna, Austria, June 26-30, 2006), p. 1954.

[8] S. H. Kim, et al, "Cold Test on C-band Standing-wave Accelerator," in *Proc. of PAC07* (Albuquerque, USA, June 25-29, 2007), p. 2823.