DESIGN OF COMPACT C-BAND STANDING-WAVE ACCELERATING STRUCTURE ENHANCING RF PHASE FOCUSING*

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Abstract

We design a C-band standing-wave accelerating structure for an X-ray source of the imaging and medical applications. It is capable of producing 6-MeV, 100-mA pulsed electron beams which is focused by less than 1.5 mm without external magnets. As an RF source, we use a peak 1.5-MW magnetron with a duty factor of 0.08%. The accelerating structure is a bi-periodic and on-axis-coupled structure with a built-in bunching section, which consists of 3 bunching cells, 13 normal cells and a coupling cell. It is operated with the π/2-mode standing-wave. The bunching section is designed to enhance the RF phase focusing in order to achieve 1.2-mm beam spot size. Each cavity is designed with the MWS code to maximize the effective shunt impedance within 3.5% inter-cell coupling. In this paper, we present design details of RF cavities and the beam dynamics simulation by the PARMELA code.

INTRODUCTION

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

We are developing an electron accelerator for industrial X-ray sources. It is capable of producing 6-MeV electron beams with a pulsed beam current of 100 mA, which is powered by a pulsed 1.5-MW C-band magnetron. 6-MeV electron beams are widely used in the commercial applications for the radiography and radiotherapy [4]. It is operated with a pulse length of 4 μs and with a pulse repetition rate of 200 Hz. The bunching section is 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.

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Table 1: The Design Parameters of the Accelerator

Operating Frequency	5 GHz
Input Pulsed RF Power	1.5 MW
Pulse Length	4 μs
Repetition Rate	200 Hz
E-gun Voltage	20 kV
Input Pulsed Beam Current	180 mA
Output Beam Energy	6 MeV
Output Pulsed Beam Current	100 mA
Type of Structure	Bi-periodic, On-axis coupled
Operating Mode	SW π/2 mode
Beam Aperture Diameter*	6 mm
Average Accelerating Gradient	13.3 MV/m
Number of Cells	17
Inter-cell Coupling	3.5%
Quality Factor*	8500
Shunt Impedance*	110 MΩ/m
Transit-time Factor*	0.85

*Values for normal cells.

ACCELERATOR OVERVIEW

The accelerator uses a 5-GHz magnetron as an RF source. It is capable of producing 1.5-MW RF with a 4-μs pulse length and a 200-Hz repetition rate. The RF power is transmitted to the accelerating structure through the WR187 waveguide network, as shown in Fig. 1. 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 40-kV and a 90-A pulsed power to the magnetron with a 4-μs pulse length [5]. It also supplies a 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 180-mA electron beam with 20-kV pulse in the nominal operation. The beam radius is 0.6 mm at the beam waist which is 15.2 mm from the anode. The direction of the initial beam is adjusted by the steering coils in the forepart of the accelerating structure, as shown in Fig. 1.

The accelerating structure is attached to the E-gun directly, as shown in Fig. 2. For a compact structure, it has a built-in bunching section without a pre-buncher section. Furthermore, any focusing magnet is not used, because the beam is focused enough by the enhanced RF

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phase focusing with the design of the bunching section [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. 2, are the bunching cells with phase velocities (β_{ph}) of 0.3, 0.5, and 0.9. The normal section consists of normal cells of 14 units with β_{ph} = 1, and after these, the coupler cell is attached to the tapered C-band waveguide.

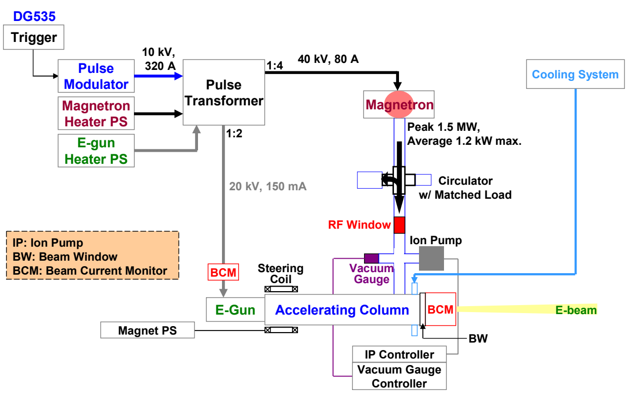

Figure 1: Schematic diagram of the accelerator system.

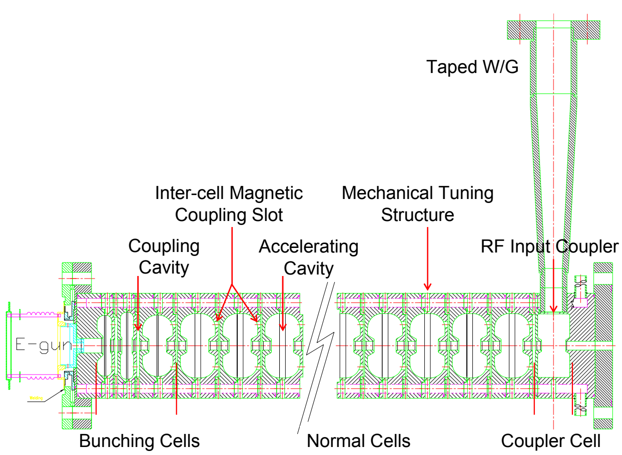

Figure 2: Cross-sectional view of the accelerator structure.

ENHANCING OF RF PHASE FOCUSING

Beam dynamics in the accelerating structure is investigated 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 beam parameters on the configuration of phase velocities of bunching cells are simulated in order to investigate the enhancement of the RF phase focusing. The configuration is modified by changing of β_{ph} of the last bunching cell, as shown in Fig. 3. Also, the beam parameters on the first bunching cell with longitudinal asymmetric geometry are simulated to reduce the beam spot size. The simulation is conducted on the iris radius of the upstream which is varied 3 − 6 mm with 4-mm iris radius of the downstream, as shown in Fig. 4. Considering of these results, the configuration of phase velocities of bunching cells with 0.3, 0.5, and 0.9 is adopted, and the first bunching cell is designed as shown in Fig. 2 and 4 [6]. Under this condition, the beam energy is 6.4 MeV with pulsed 100 mA, and the beam spot size is less than 1.2 mm, as shown in Fig. 5.

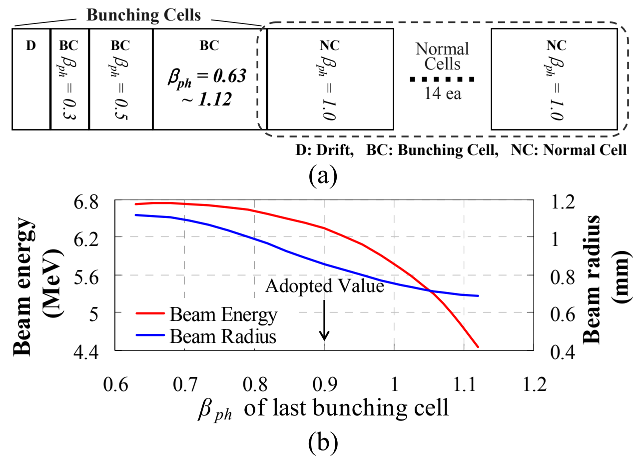

Figure 3: (a) Schematic diagram of the beam dynamics simulation setup for optimizing the configurations of phase velocities in the bunching cells. (b) Variation of beam parameters on β_{ph} of the last bunching cell.

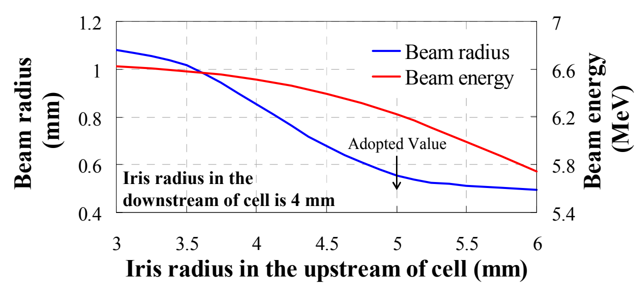

Figure 4: The beam radius and the average beam energy on the iris radius in the upstream of the first bunching cell.

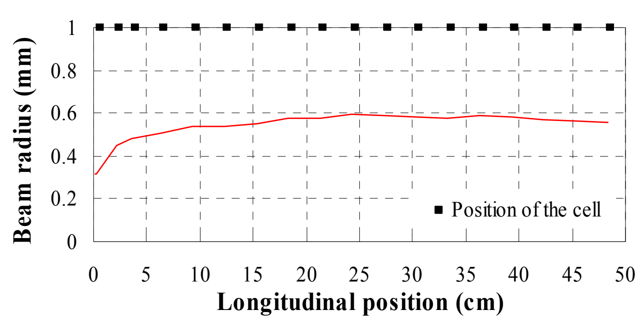

Figure 5: The beam envelop in the accelerating structure.

RF CAVITY

Each cell in the accelerating structure consists of the accelerating cavity and the coupling cavity, as shown in Fig. 1. The general dispersion relation of the bi-periodic structure is defined by

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$$k^2 \cos^2 \varphi = [1-(\omega_A^2/\omega^2)+k_{AA}\cos 2\varphi] \times [1-(\omega_C^2/\omega^2)+k_{CC}\cos 2\varphi], \quad (1)$$

where ω is the resonance frequency of the coupled cavities at the φ mode, ω_A and ω_C are the resonance frequency of the accelerating cavity and the coupling cavity, and k is the coupling coefficient between the accelerating cavity and the nearest coupling cavity, while k_{AA} between two neighbouring accelerating cavities and k_{CC} between coupling cavities [8]. With negligible k_{AA} and k_{CC}, this dispersion relation has a stop band between ω_A and ω_C at π/2-mode. To avoid field attenuations due to the stop band, the coupling cavity should be also designed for its frequency to be equal to the accelerating cavity and the RF frequency.

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 electromagnetic simulation is conducted with the MWS code to obtain the resonant frequency 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]. When more cells are added up to the model in Fig. 6 periodically, it is confirmed that the dispersion relation from (a) is almost same to (b), as shown in Fig. 7.

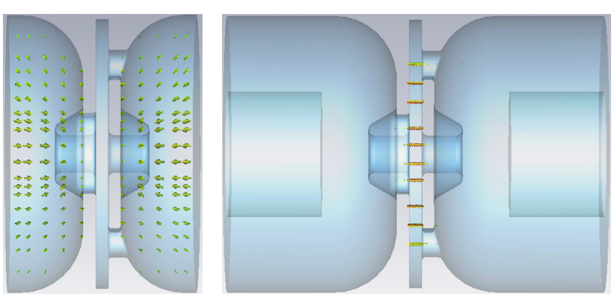
(a) (b)

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

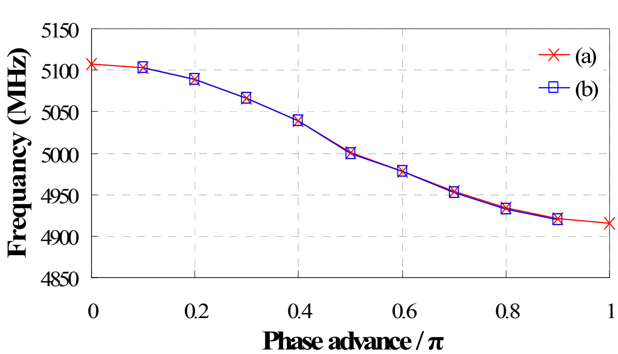

Figure 7: The dispersion relation from Fig 6 (a) and (b).

SUMMARY

The C-band accelerating structure is designed. It is capable of producing 6-MeV, 100-mA pulsed electron beams with an RF power of 1.5 MW. In order to enhance the RF phase focusing, the configuration of phase velocities of bunching section and the geometry of the first bunching cell are adopted with beam dynamics simulation. Under this condition, the beam is focused by less than 1.2 mm at the conversion target. The bi-periodic accelerating structure with on-axis coupling is designed. With the MWS code simulation, the cavity dimensions are determined for the π/2-mode frequency to be 5 GHz with 3.5% inter-cell coupling.

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