6/9 MeV S-BAND STANDING WAVE ACCELERATING STRUCTURE FOR CONTAINER X-RAY INSPECTION SYSTEM AT RTX

P. Buaphad*, Radiation Technology eXcellence, Daejeon, 34025, Korea
Advanced Radiation Technology Institute, KAERI, Jeongeup-si, Jeollobuk-do, 56212, Korea
also at University of Science and Technology, Daejeon, 34113, Korea
Y. J. Kim†, S. S. Cha, B. C. Lee, H. K. Cha, J. H. Ha,
Advanced Radiation Technology Institute, KAERI, Jeongeup-si, Jeollobuk-do, 56212, Korea
K. B. Song, H. D. Park, S. Y. Yoo. Radiation Technology eXcellence, Daejeon, 34025, Korea

Abstract

Recently, there is needs of the X-ray inspection systems around the world to combat terrorism, drug and weapons smuggling, illegal immigration, and trade fraud. A compact standing wave (SW) linear accelerator (linac) for container X-ray inspection system has been produced at Radiation Technology eXcellence (RTX) to meet this growing need. The RF accelerating structure uses SW side-coupled structure fed by a 5 MW e2v magnetron with frequency of 2856 MHz. The electrons are accelerated from DC gun with energy of 25 keV to the final energy of 6 or 9 MeV at the X-ray target and generate X-ray with the dose rate of 8 Gy/min and 30 Gy/min at 1 m after target for electron energy of 6 MeV and 9 MeV respectively. In this paper, we describe the design and optimization of side-coupled RF structure with an operating mode of $\pi/2$. The beam dynamic of particle along the RF structure is also included in this paper by using ASTRA code.

INTRODUCTION

Nowadays, there are more than half a billion container shipments around the world annually [1]. In order to conduct inspections effectively and efficiently, X-ray scanner is used to inspect cargo for nuclear materials, weapons, drugs or trade fraud, and to prevent contraband from entering their countries [2, 3]. Cargo scanning system consists of an electron accelerator, a target of bremsstrahlung radiation generation, and an array of detectors. X-rays reveal the basic shape of the cargo inside a container and recognize materials inside it [3]. The electron accelerators are required for self shielded systems and reasonably compact that can be design as a mobile systems [4].

Recently, RTX develops the compact S-band linac for inspection of containers [5]. It is primarily aimed to accelerate the electron beam to the prescribed energy and dose rate with the compact structure. With the 25 keV DC electron gun and 5 MW input RF power, we design the compact S-band SW linac using side-coupled structure operating in $\pi/2$ mode. This accelerator can accelerate electrons to 9 and/or 6 MeV. This electron energy can give a sufficiently high yield of the X-ray providing an effective depth of up to 30 cm steel penetration [4]. This paper describes the design of electron linac with side-coupled structure, and the interaction between electrons and RF fields along the linac.

ELECTRON GUN AND MAGNETRON

The compact S-band linac consists of a DC electron gun, an accelerating structure based on side-coupled structure, and an RF magnetron. The ALTAIR A102414 electron gun is used and can be applied a gap voltage to 25 kV [6]. It is connected directly to the accelerating structure, so that the first cell wall acts as the anode. The magnetron that we have chosen for the container inspection systems is a MG 6028 fast tuned magnetron made by e2v technologies [7]. It can generate RF power at an RF frequency of 2856 MHz, and it is also tunable over the range of 10 MHz with a specified 0.11 % duty factor. The magnetic field is provided by MG 6030 electromagnet. The RF output power is coupled to the rectangular-shaped waveguide with internal dimensions of 72.14×34.04 mm.

DESIGN PARAMETERS

The compact electron linac as the X-ray source in cargo inspection system usually works in a pulsed mode and needs very stable dose rate X-ray pulses [9]. The X-ray beam is produced by bremsstrahlung radiation when electron beam hits a tungsten target at the end of linac. Normally, the dose rate is in proportion to the duty factor, beam current, and electron energy as given by [8, 9]

$$J_x = C \cdot \eta \cdot D \cdot I_p \cdot V_{acc}^n. \quad (1)$$

Where C is the beam capturing coefficient, η is photon conversion efficiency, n is the electron energy factor, $D \cdot I_p$ is the average beam current at gun in unit μA, V_{acc} is the electron energy in MeV, and J_x is the dose rate in cGy/min at 1 m after the X-ray target.

Our compact S-band linac is designed to be operated in two modes: high-energy mode, HE-mode (9 MeV) and low-energy mode, LE-mode (6 MeV). The desired dose rates at 1 m after tungsten target for LE-mode is 8 Gy/min while the HE-mode requires the output dose rate of 30 Gy/min. To achieve this requirement, the beam current produced by electron gun needs to be calculated first. The parameters for the dose rate calculation of two operating modes are listed in Table 1. If the beam capturing coefficient is 50%, the peak current at the electron gun can be obtained as shown in Fig. 1.

* buappika@kaeri.re.kr
† yjkim@kaeri.re.kr

Table 1: Parameters for the Dose Rate Calculation

Operating mode	LE-mode	HE-mode
Electron energy (MeV)	6	9
RF input power (MW)	2.42	2.73
Duty factor	0.0011	0.0011
Beam peak current (mA)	200	150
Photo conversion efficiency	0.0669	0.1119
Beam capturing coefficient (%)	50	50
Electron energy factor	2.80	2.72
Dose rate (Gy/min@1m)	11.11	36.38

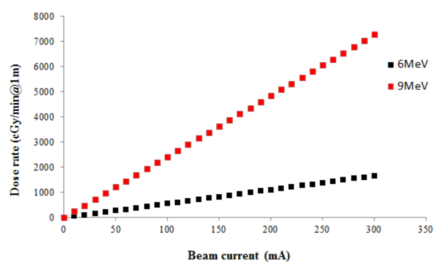

Figure 1: The dose rate for each electron energy.

ACCELERATING CAVITY

The cavity cells have a Ω-shaped cross section.The nose cone angle is about 20°. The structure is designed by coupling 11 cavities together through side-coupled cavities. The first two cavities are bunching cells where their relativistic speeds are less than 0.98. The length of each accelerating cavity must be one half the RF wavelength so that electrons which are traveling at relativistic speeds traverse the cavity in one half RF period [10, 11]. When they arrive in the next cavity as the electric field becomes negative, they can be continuously accelerated through the whole structure. The single cavity is designed to be resonated at 2856 MHz in both side-coupled cavity and accelerating cavity. However, the side-coupled structure operating on $\pi/2$ mode introduces the frequency difference in side-coupled cavity and accelerating cavity with two $\pi/2$ mode configurations (see Fig. 2) [11]. In order to fix this problem, we adjust the cavity radius (R in Fig. 2) to control the frequency in accelerating cavity. The coupling cavities are tuned by adjust the length of the posts (t in Fig. 2) until each coupling cell resonated at the same frequency as the accelerating cavities. This process is repeated for each of the accelerating cavities.

After fully tuning each cavity in the linac structure, The RF port to couple power from magnetron is placed in the last accelerating cell. This RF port increases the cavity volume, and the resonant frequency is changed. It is necessary to fine tune all cavity radii, post lengths of coupling cavities, and coupling iris window of RF port again in the whole assembly S-band linac. The goal of the tuning is to obtain the desired RF field distribution along the structure, remove RF fields from the coupling cavities, maintain the desired $\pi/2$ mode frequency, and optimize the external coupling coefficient.

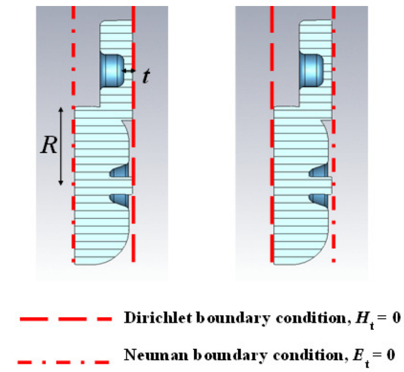

Figure 2: The $\pi/2$ mode configuration for accelerating cavity and coupling cavity.

All these properties can be calculated conveniently using eigen solver in the CST-MWS code with the tetrahedral mesh of one million elements [12]. Figure 3 shows the electric field result at the $\pi/2$ mode. The RF properties at resonance mode for the designed structure are listed in Table 2.

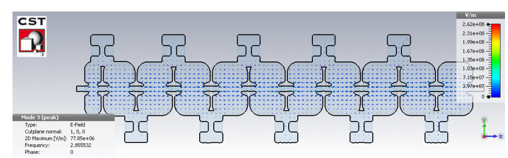

Figure 3: The simulated RF field distribution along the structure.

Table 2: The RF Properties at Resonance Mode for the designed Structure

RF property	Value	Unit
Frequency	2855.73	MHz
Linac length	0.57	m
Shunt impedance	82.45	MΩ/m
Unloaded quality factor	16362.43	
External quality factor	16078.93	
Loaded quality factor	8109.72	
External coupling coefficient	1.02	
Filling time of structure	0.91	μs

PARTICLE TRACKING

The ASTRA code is used to model the beam dynamics from the cathode up to the end of S-band linac with total length of 0.6 m. ASTRA is nominally a cylindrical symmetric code and tracks particles taking into account space charge [13]. The beam line consists of electron gun, 2856 MHz RF cavities, and a solenoid. The solenoid immediately follows the DC gun and it is responsible for transverse space charge emittance compensation. Field maps of all beam line elements are shown in Fig 4. The initial electron distribution at cathode is modeled with a longitudinal flat-top shape with a rise and fall time of 1.5 ps and a full width

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(FW) of 1050 ps, about $3T_{RF}$. The transverse distribution is radially uniform with rms beam size of 2.75 mm for cathode diameter of 11 mm. Thermal kinetic energy of emitted electrons is chosen to be 0.19 eV.

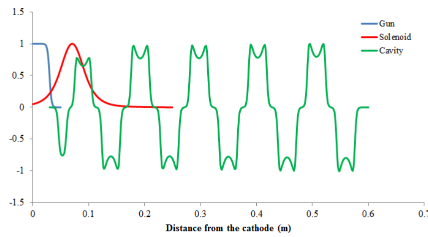

Figure 4: The on-axis field maps as a function of distance from cathode.

50000 ASTRA macroparticles are used for initial simulations, which compromise between good statistics and reasonable simulation times [14, 15]. The solenoid strength is varied to obtain the the transverse emittance and the transverse beam spot size as small as possible [15].

After scanning the all parameters, full beam dynamics simulation is carried out from the cathode to the end of RF structure with 2000000 ASTRA macroparticles . Figure 5 shows that the $3T_{RF}$ bunch length of electron beam from the cathode is bunched in the first two cells of cavity structure. Then the bunched beam gains accelerating energy from accelerating cells. The beam spot size at the exit of structure is less than 2 mm (see Fig 6). Table 3 lists the setting data and the results of ASTRA simulation for each operating mode.

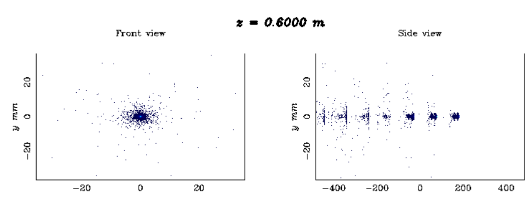

Figure 5: The particle tacking along the S-band linac.

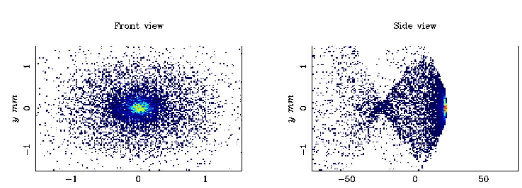

Figure 6: The beam spot size at the X-ray target.

CONCLUSION

We have designed a compact S-band side-coupled linac structure operating in two modes (6 Mev and 9 MeV) with prescribed dose rate for container X-ray inspection system at RTX. The shunt impedance per unit length of 82 MΩ/m and the unloaded quality factor of 16400 are obtained at the $\pi/2$ mode frequency of 2855.7 MHz. At the external coupling coefficient of 1.02, the 9 MeV mode requires RF power of 2.7 MW with peak current of 150 mA, but the 6 MeV mode needs RF power only 2.4 MW with peak current of 200 mA. The continuous electron beam emitted from cathode is bunched in the first two cells and gained the energy along the structure. By using the solenoid, The desired beam spot size of 2 mm can be achieved at the X-ray target.

Table 3: Specification for ASTRA Simulation

parameter	LE-mode	HE-mode
Electron initial charge (pC)	210.0	157.5
Solenoid strength (T)	0.020	0.015
Peak field gradient (MV/m)	30	45
Beam rms spot size at target (mm)	0.66	0.61
Peak current at target (mA)	200	380
Average energy energy output (MeV)	6.21	9.67
Energy spread (%)	24	15
Transverse beam emittance (μm)	13.04	27.39

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