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9/6 MeV EUROPEAN S-BAND LINAC STRUCTURE FOR CONTAINER INSPECTION SYSTEM AT RTX AND KAERI

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Abstract

Recently, demands on low energy electron linear accelerators (linacs) for industrial applications are rapidly growing. Their beam energies are lower than 20 MeV, and they require a compact, cheap, and stable accelerator system. For the Container Inspection System (CIS), KAERI successfully developed a 9/6 MeV American S-band (= 2856 MHz) linac with a 5 MW klystron in 2013. To reduce the cost of the RF source, recently, KAERI and RTX also have been developing another 9/6 MeV European S-band (= 2998 MHz) linac by using a magnetron with a lower RF power of about 3.1 MW. Its accelerating structure is designed to be operated in the $\pi/2$ mode by coupling 13 accelerating cells together through 12 side-coupling cells. The CST Microwave Studio is used for electromagnetic simulations and optimization of the accelerating structure. After various optimizations, a shunt impedance of 84 MΩ/m is obtained at the $\pi/2$ mode frequency of 2998.31 MHz. In this paper, we describe design concept, optimization, and RF measurement of the new 9/6 MeV European S-band linac structure. Then, we compare it with our old American S-band linac structure.

INTRODUCTION

Since Roentgen discovered that the X-rays could pass through the human tissue leaving the bones and metal visible in 1895, X-rays have been developed to identify the inner structure for medical imaging and nondestructive testing (NDT). Now, NDT with X-rays is a technique widely used in many industrial applications such as analysis of food products, screening of luggages as well as container inspection system (CIS) [1, 2]. With the rapidly growing of international trade, container inspection became more and more important [3]. X-rays CIS has been used to detect the possible presence of contrabands in cargoes or truck containers. Generally, a CIS consists of a dual energy linear accelerator (linac) to generate electron beam, a collimator, an X-ray target to generate Bremsstrahlung X-rays, and an X-ray detector array. The X-rays CIS system based on 9/6 MeV S-band linac can generate MeV-energy X-ray with the maximum dose rate of 30 Gy/min at 1 m away from the X-ray target. This X-ray is capable of scanning cargo inside a container.

In 2013, Korea Atomic Energy Research Institute (KAERI) successfully developed the X-ray CIS based on 9/6 MeV S-band (= 2856 MHz) linac with the maximum X-ray dose rate of 30 Gy/min at 1 m [4]. The RF power source of this CIS is a 5 MW klystron which makes this system big and expensive. To reduce the cost of the RF source, recently, KAERI and Radiation Technology eXcellence (RTX) also have been developing another 9/6 MeV European S-band (= 2998 MHz) linac by using a magnetron [5]. The CST Microwave Studio (CST-MWS) is used for electromagnetic simulations and optimization of the accelerating structure [6]. Then, the beam dynamics is simulated in the CST Particle Studio (CST-PS). In this paper, we describe design concept, optimization, and RF measurement of the new 9/6 MeV European S-band linac structure. Then, we compare it with our old American S-band linac structure. Finally, the beam dynamics simulation is also described.

ELECTRON GUN AND MAGNETRON

The 9/6 MeV S-band (= 2998 MHz) linac for container inspection system consists of a DC electron gun, a side-coupled accelerating structure, and an RF magnetron. The Altair Technologies A102414 electron gun is used and can be applied a gap voltage up to 25 kV [7]. It is connected directly to the accelerating structure, so that the first cell wall of the accelerating structure acts as the anode. The magnetron that we have chosen for the container inspection systems is an MG7095 tunable magnetron for switched energy applications made by Teledyne e2v [8]. It can generate RF power at an RF frequency of 2998 MHz with the peak power of 3.1 MW, and it is also tunable over the range of 10 MHz with a specified duty factor of 0.1%. The RF power from magnetron is fed using a tapered waveguide matched to the rectangular-shaped WR284 waveguide with an internal dimension of 72.14 mm × 34.04 mm.

ACCELERATING STRUCTURE

The 6/9 MeV S-band side-coupled linac is designed to be operated in two modes: low-energy mode (6 MeV) and high-energy mode (9 MeV) with the maximum X-ray dose rate of 30 Gy/min at 1 m. It consists of three bunching cells, ten accelerating cells, and twelve side-coupling cells. To continuously accelerate electrons, the length of each cell must be $\beta\lambda/2$ where $\beta = v/c$ is the electron speed over the light speed, and λ is the RF wavelength.

Bunching Cell

In bunching cell design, the main goal is to obtain a high electron capturing. When electron beam from electron gun enters the bunching cell, some electrons start moving backward to electron gun or hit the cavity wall, and finally get lost.

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However, some electrons can maintain a positive velocity throughout their motion. It depends on the choice of RF phases velocity in the bunching cell, β_w. To determined the RF phase velocity, the captured electron fraction for different values of β_w is estimated with the following equation [9]:

$$F_\mathrm{cap} = \frac{1}{\pi}\cos^{-1}\left[1 + \frac{2\pi m_0 c^2}{\lambda_\mathrm{RF}\beta_\mathrm{w} e E_z}\left(-1 + \sqrt{p_e^2 + 1} - \beta_\mathrm{w} p_e\right)\right]. \quad (1)$$

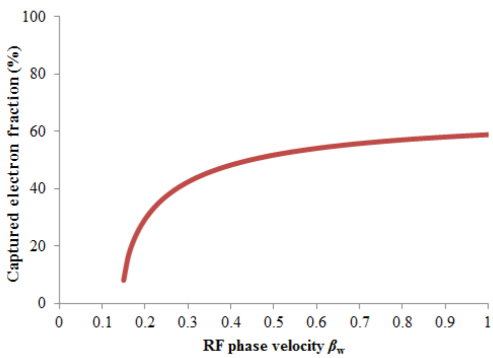

Figure 1: Variation of electron capture fraction with different RF phase velocity for the first bunching cell.

Electrons are injected into bunching cell from electron gun with a gun potential V_gun of 25 kV and a normalized momentum $p_e = \gamma_e m_0 v_e / m_0 c$ where γ_e is the relativistic velocity of electron, and v_e is the speed of electron. Here, m_0 is the electron rest mass, λ_RF is the RF wavelength, c is the speed of light, E_z is the accelerating gradient, and e is the electron charge. The F_cap plot with β_w for fixed electron velocity β_e of 0.29 and accelerating gradient E_z of 20 MV/m is shown in Fig. 1. It is found that F_cap increases with the value of β_w until it shows saturation. We chose $\beta_\mathrm{w} = 0.5$ for the first bunching cell, where F_cap is around 51.8%. As the electrons are accelerated, the β_w for the next cells should be increased. Therefore, all electrons which are captured in the first bunching cell can maintain to move toward the next accelerating cell with bigger F_cap. The best RF phase velocities which gave the high captured electron for three bunching cells are 0.5, 0.82, and 0.94.

Accelerating Cell

Each accelerating cell is an Ω-shape with a nose cone angle of 20° to obtain a higher shunt impedance. The accelerating cell aperture is 4 mm in radius. To meet the requirement of mechanical strength, the thickness between cells is 3 mm. To get high shunt impedance and Q factor, the nose cone gap is optimized. The accelerating structure is designed to be resonated at 2998 MHz in both the side-coupling cell and the accelerating cell by adjusting the cell radius R and the side-coupling gap t.

In the dispersion curve of the side-coupled accelerating structure, the stop band is introduced at $\pi/2$ mode due to different frequencies in the accelerating cell (red line) and the side-coupling cell (blue line) as seen in Fig. 2. The

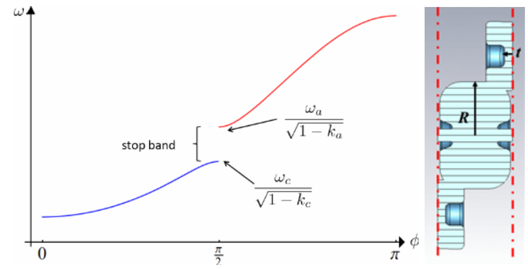

Figure 2: The SAS periodic unit and the dispersion curve of SAS unit.

frequency of the $\pi/2$ mode can be calculated as:

$$\omega_{\frac{\pi}{2}} = \begin{cases} \dfrac{\omega_\mathrm{a}}{\sqrt{1-k_\mathrm{a}}} & \text{for accelerating cell} \\ \dfrac{\omega_\mathrm{c}}{\sqrt{1-k_\mathrm{c}}} & \text{for side-coupling cell} \end{cases} \quad (2)$$

where, ω_a and ω_c are the resonant frequency of a single accelerating cell and a single side-coupling cell, respectively. k_a and k_c are the coupling factor between two accelerating cells and two side-coupling cells, respectively. Figure 2 also shows the SAS periodic basic unit in the accelerating structure (A denotes the accelerating cell and S denotes the side-coupling cell) with two different longitudinal boundary conditions: the perfect electric boundary condition for simulating $\pi/2$ mode frequency of the accelerating cell, and the perfect magnetic boundary condition for simulating $\pi/2$ mode frequency of the side-coupling cell. To close the stop band at the $\pi/2$ mode, the geometries of SAS unit must be adjusted to reduce the frequency gap less than 1 MHz. The resonant frequencies of optimized accelerating and side-coupling cells are 2997.8939 MHz and 2997.8943 MHz, respectively, with a coupling between accelerating and side-coupling cells of 3.1%.

Whole Accelerating Structure

After optimization of individual cells, three bunching cells, and ten accelerating cells are coupled together with twelve side-coupling cells to accelerate the electron beam to 9/6 MeV with an input RF power of 3 MW. The important component of an accelerating structure is the input coupler. The last accelerating cell is used as the input coupler cell by having a slot in the coupler cell. Thus the diameter of the coupler cell needs be slightly modified.

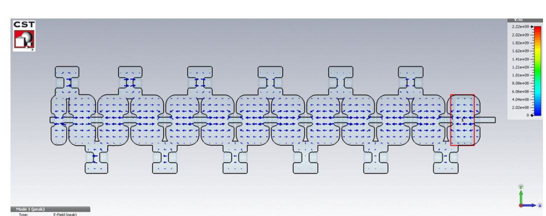

Figure 3: Electric field of the $\pi/2$ mode for the whole accelerating structure.

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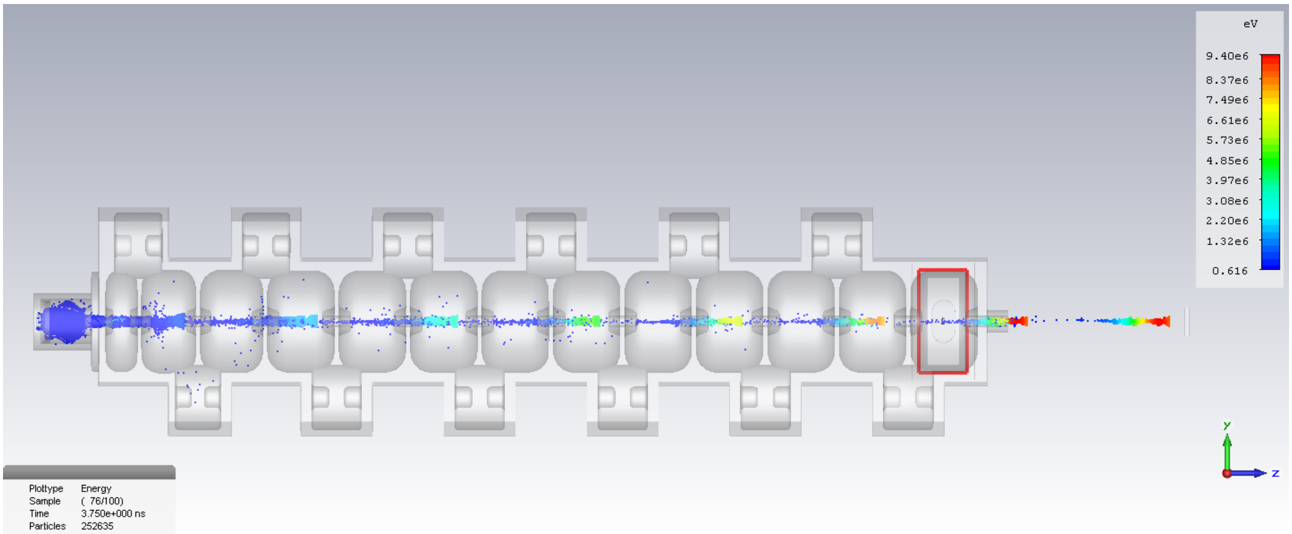

Figure 4: Beam dynamics simulation of the accelerating structure.

The three-dimensional electromagnetic simulation of the whole structure with the input coupler was performed using CST-MWS code. Figure 3 shows the electric field distribution at the $\pi/2$ mode frequency of 2998.306 MHz. For this structure, the shunt impedance is about 84 MΩ/m, and the external beta coupling is 1.94. Main accelerator parameters of 9/6 MeV European S-band accelerator are summarized in Table 1. This European S-band (= 2998 MHz) linac is derived from American S-band (= 2856 MHz) standing wave linac developed by KAERI in 2013. For the European linac structure, the number of accelerating cell is increased from 11 to 13. This increasing results in a lower RF power requirement from 5 MW to 3 MW. Thus, it causes the lower cost and compact of CIS by changing RF source to a magnetron instead of a klystron.

Table 1: Accelerator Parameters

Parameters	EU S-band	US S-band
Frequency (MHz)	2998.31	2855.73
No. of accelerating cells	13	11
Structure length (m)	0.63	0.57
Beam energy (MeV)	9/6	9/6
Shunt impedance (MΩ/m)	84	72
Peak current (mA)	100/150	150/200
Peak power (MW)	3	5
Repetition rate (Hz)	250	150
External beta coupling	1.94	1.02
Unloaded Q factor	15153	16362

BEAM DYNAMICS

CST-PS code was carried out the beam dynamics simulations from the cathode up to the tungsten target. The electrons were tracked their motion through the accelerating structure by taking into account the space charge force. The simulation model consists of a 25 kV DC electron gun, an accelerating structure with the maximum field gradient of 30 MV/m, and two solenoids. To calculate the beam dynamics, we imported the accelerating field calculated by CST-MWS, electron gun field, and solenoid field calculated by CST EM Studio (CST-EMS) into CST-PS.

A frame from beam dynamics simulation of the accelerating structure, including the electron gun and tungsten target is shown in Fig. 4. At the DC electron gun, the electron beam with peak current of 375 mA was assumed to be generated from cathode with a diameter of 11 mm. This electron beam, then, is focused into the first accelerating cell. When electron beam is injected into accelerator, some of electrons are bunched and can be accelerated along the structure as shown in Fig. 4. At the tungsten target, electron beam with a proper RF phase can gain energy to reach 9/6 MeV. Captured electron fraction at the target is about 40% while the rms energy spread of the electron beam is about 9.3%. The optimized transverse rms emittance and electron beam size are 18 µm and 1.6 mm (FW), respectively.

CONCLUSION

We have designed a compact European S-band (= 2998 MHz) side-coupled linac structure operating in two modes (6 Mev and 9 MeV) with a prescribed dose rate for X-ray container inspection system at RTX and KAERI. The shunt impedance of 84 MΩ/m and the unloaded quality factor of 15200 are obtained at the $\pi/2$ mode frequency of 2998.31 MHz. At the external coupling coefficient of 1.94, the 9 MeV mode requires an RF power of 2.5 MW with a peak current of 100 mA, but the 6 MeV mode needs an RF power of 1.6 MW with a peak current of 150 mA. The continuous electron beam emitted from cathode is bunched in the first three cells and gained the energy along the structure. By using the solenoids, The desired beam spot size of 2 mm (FW) can be achieved at the X-ray target.

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