

DEVELOPMENT OF 6 MeV EUROPEAN S-BAND SIDE-COUPLED INDUSTRIAL ELECTRON LINEAR ACCELERATOR AT RTX & KAERI

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Abstract

There are growing demands on low energy electron linear accelerator (linac) for industrial applications. Most of industrial electron linacs require a compact structure and limited undesirable neutron production to avoid huge lead shielding. Radiation Technology eXcellence (RTX) and Korea Atomic Energy Research Institute (KAERI) have developed a 6 MeV compact side-coupled linac by using 2998 MHz European S-band RF technology to meet those requirements. To design the linac structure, the 3D CST MICROWAVE STUDIO (CST-MWS) was used for various electromagnetic simulations, and ASTRA code was used for particle beam dynamics simulations. After various optimizations, the shunt impedance of 61 M Ω /m is obtained at 2998.38 MHz. With a peak RF power of 2.2 MW and a 47 cm-long structure, electron beam with a peak current of 150 mA can be accelerated from 25 keV to 6 MeV. For the industrial linac, the electron beam spotsize at an X-ray target, located 5 cm downstream of the linac structure exit should be smaller than 2 mm (FW). In addition, it can supply an X-ray dose rate of 8 Gy/min at 1 m after the X-ray target. In this paper, we describe the design concepts and optimization of the 2998 MHz side-coupled industrial linac structure.

INTRODUCTION

The Non-Destructive Testing (NDT) is an analysis technique widely used in industry to evaluate the properties of materials, components without causing any damage [1]. Generally, the NDT method uses ultrasonic, X-ray, gamma, neutron, or eddy-current to examine a sample. However, the X-ray NDT can inspect materials with a higher resolution [2, 3]. Recently, the X-ray NDT systems based on low energy S-band electron linear accelerator (linac) have been playing more and more important roles in industrial applications [4]. Therefore, the demands of low energy electron linac for industrial activities have been increasing rapidly. The industrial electron linacs are required a self-shielding system and reasonably compact for easy system relocation [1].

As shown in Fig. 1, for the NDT system, recently, Radiation Technology eXcellence (RTX) [5] and Korea Atomic Energy Research Institute (KAERI) have been developing an industrial electron linac with a nominal energy of 6 MeV and an X-ray radiation dose rate of 8 Gy/min at 1 m. Our linac

is a 47 cm-long standing wave accelerating structure, which uses the side-coupled coupling technology. It is primarily aimed to be operated in the $\pi/2$ mode, and it can accelerate electrons up to 6 MeV. This electron energy can give a sufficiently high yield of the X-ray to penetrate a 30 cm-thick steel [1]. This paper describes the design of electron linac with a side-coupled structure, and the beam dynamics of electrons in the linac structure.

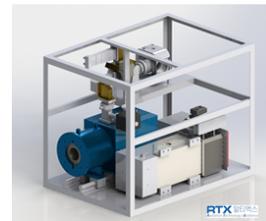


Figure 1: The compact industrial NDT system based on the European S-band electron linac.

AN INDUSTRIAL ELECTRON LINAC

The main components of the European S-band industrial electron linac are a DC electron gun, a 2998 MHz RF accelerating structure based on the side-coupled coupling, and an RF magnetron. The ALTAIR A102414 electron gun is used as its electron source, and it can be applied the maximum gap voltage of 25 kV. This electron gun is connected directly to the accelerating structure, so the wall of its first cell acts as the anode of the electron gun. The accelerating structure is designed by coupling 9.5 cells together through side-coupled cells. The first 2.5 cells are bunching ones where their relativistic speeds are less than 0.98. The first half cell plays an important part of the accelerating structure. When the DC-injected electron beam from the gun enters the half cell, it is confronted with the maximum electric field and receives energy gain effectively. The magnetron that we have chosen for the NDT systems is an MG6090 tunable S-band magnetron made by e2v technologies. It can supply a 3.1 MW RF power at an RF frequency from 2993 MHz up to 3002 MHz for an RF pulse length of 5 μ s and an RF pulse repetition rate of 200 Hz. The RF output power is coupled to the WR-284 type waveguide with internal dimensions of 72.14 mm \times 34.04 mm.

DOSE RATE OF X-RAY RADIATION

The compact industrial electron linac as the X-ray source works in a pulsed mode, and the dose rate of the X-ray pulses

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should be stable [6]. The X-ray radiation is produced by bremsstrahlung radiation when electron beam from electron linac hits a tungsten target at the end of linac. Normally, the dose rate is proportional to the duty factor, beam current, and electron beam energy as given by [6]

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

where C is the beam capture coefficient, η is the photon conversion efficiency, n is the electron energy factor, $D \cdot I_p$ is the average beam current at the 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 from the X-ray target.

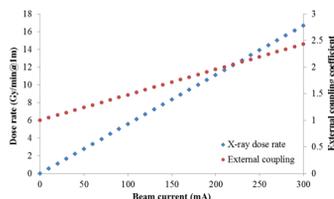


Figure 2: The X-ray dose rate and external coupling coefficient for different beam currents.

Our 6 MeV compact European S-band industrial linac is designed to generate an X-ray dose rate of 8 Gy/min at 1 m away from a target. Figure 2 shows that the desired dose rate can be achieved at a beam current of 150 mA with a beam capturing rate of 50%.

ACCELERATING STRUCTURE

Our linac is the standing wave structure with the side-coupled coupling, and it is made of 9.5 accelerating cells and 9 side-coupling cells. The accelerating cell has the Ω -shaped cross section with a nose cone angle of 20° . Since the nose cone concentrates the electric field toward the center of the accelerating cell to create a stronger field and better acceleration on the beam axis [6], the electric field at the nose cone is slightly higher than that in the middle of the accelerating cell. Each single cell is designed to be resonated at 2998 MHz in both side-coupled cell and accelerating cell. To achieve the desired resonant frequency, the magnetic and electric mirror boundary conditions on the symmetry planes are applied to the single cell as shown in Fig. 3 [7]. By adjusting the accelerating cell radius R and the side coupling gap t , both accelerating and side-coupled cells are resonated at the same frequency.

After various tunings with each single cell, the RF power coupler is introduced to couple the RF power from the magnetron to the accelerating structure at the last accelerating cell. This RF power coupler increases the accelerating structure volume, thus its resonant frequency is changed. It is necessary to tune both the radius of the last accelerating cell and the window of its RF power coupler finely. The goal of the tuning is obtaining the desired RF field distribution along the structure, removing RF fields from the side-coupled cells while keeping the desired $\pi/2$ mode frequency of 2998 MHz

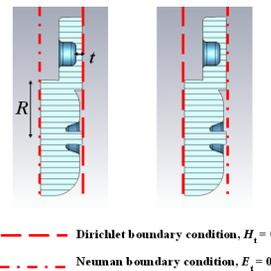


Figure 3: The $\pi/2$ mode configuration to tune the accelerating and coupling cells.

and optimizing the external coupling coefficient. The external coupling coefficient β_{ext} of the accelerating structure can be optimized by reducing the reflected RF power to zero, and it is given by

$$\beta_{\text{ext}} = 1 + \frac{P_b}{P_d} = 1 + \frac{I_p R_{\text{sh}} l}{V_{\text{acc}}}, \quad (2)$$

where P_b is the beam power, P_d is the power dissipated in the cavity wall, I_p is the beam peak current at the target, R_{sh} is the shunt impedance, l is the linac length, and V_{acc} is the electron energy. Figure 2 shows the optimized external coupling as a function of the beam peak current.

To calculate the RF input power, the beam loading effect should be considered. As described in [6], the energy gain V_{acc} is given by

$$V_{\text{acc}} = \frac{2\beta_{\text{ext}}}{1 + \beta_{\text{ext}}} \sqrt{R_{\text{sh}} l P_0} + \frac{1}{1 + \beta_{\text{ext}}} I_p R_{\text{sh}} l, \quad (3)$$

where P_0 is the RF input power. All these properties can be calculated conveniently using the eigenmode solver in the CST-MWS code with the tetrahedral mesh of four million elements. Figure 4 shows the electric field distribution inside the accelerating structure at the $\pi/2$ mode with a coupler window size of 25.82 mm \times 10 mm. The RF parameters of the designed accelerating structure at the resonance frequency are summarized in Table 1.

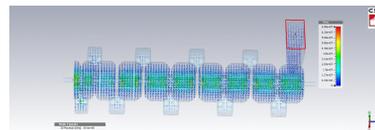


Figure 4: Distribution of electromagnetic fields along the structure.

After its RF design, dimensions to fabricate linac structure can be obtained from CST code. The industrial electron linac has been carefully machined and brazed including the cooling channel brazed to the accelerating structure as shown in Fig. 5.

BEAM DYNAMICS

ASTRA code is carried out the beam dynamics simulations from the cathode up to the end of European S-band

Table 1: The RF Parameters of the Optimized Linac Structure

RF parameters	Value	Unit
Frequency	2998.38	MHz
Electron energy	6	MeV
Linac length	0.47	m
Shunt impedance	61	MΩ/m
Unloaded quality factor	14954	
External quality factor	8699	
Loaded quality factor	5500	
External coupling coefficient	1.72	
Filling time of structure	0.584	μs
Beam current	150	mA
X-ray dose rate at 1 m from target	8.33	Gy/min
RF input power for 6 MeV	2.20	MW

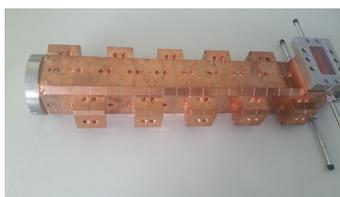


Figure 5: The fabricated European S-band accelerating structure.

electron linac with the total length of 0.6 m. To consider the space charge forces, ASTRA code was used along the linac structure. The beamline consists of a 25 kV electron gun, a 2998 MHz side-coupled industrial electron linac with the maximum field gradient of 37.5 MV/m, and two solenoids. Their normalized electric and magnetic field maps are shown in Fig. 6. The first solenoid with a magnetic field of 9 G immediately follows the DC gun, and it is used to compensate the transverse emittance due to the space charge force. The second solenoid with a magnetic field of 730 G is located at 0.165 m after the cathode. This solenoid is used to reach spotsize of 2 mm (FW) and to compensate the emittance at higher energies.

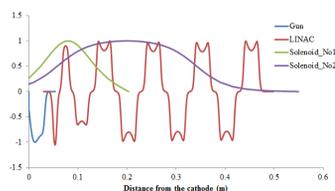


Figure 6: The normalized on-axis field maps as a function of distance from the cathode.

For ASTRA simulations, we assumed that the initial electron distribution at the cathode has a longitudinal flat-top shape with a rise and fall time of 1.5 ps and a full width (FW) of 1002 ps, corresponding 3 times of the RF period to simulate the DC gun. A transverse distribution is radially uniform with a beam size of 2.75 mm (rms) for the cathode diameter of 11 mm. For a bunch charge of 0.15 nC, the DC electron

beam from the cathode is bunched in the first two cells of the RF accelerating structure. Then the electron bunch gains accelerating energy from accelerating cells. At the X-ray target, the optimized transverse rms emittance and core part of beam size are 18 μm and 1.6 mm (FW), respectively. The beam transverse profile and phase space distribution at the X-ray target are shown in Fig. 7. The energy spread at the end of the electron linac is also simulated, and it is about 10.8%.

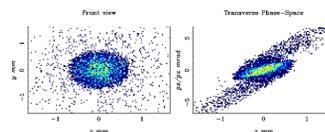


Figure 7: The beam transverse profile and phase space distribution at the X-ray target.

CONCLUSION

We have designed and fabricated a compact European S-band side-coupled industrial electron linac operating in the $\pi/2$ mode with an X-ray dose rate of 8 Gy/min for a NDT system. The shunt impedance of 61 MΩ/m and the unloaded quality factor of 14954 are obtained at the $\pi/2$ mode frequency of 2998.38 MHz. At the external coupling coefficient of 1.72, the industrial electron linac for a nominal electron energy of 6 MeV requires an RF input power of 2.2 MW for a peak current of 150 mA. The continuous electron beam emitted from the cathode is bunched in the first 2.5 cells and gained the energy along the structure. By using two solenoids, The desired beam spotsize of 2 mm (FW) can be achieved at the X-ray target. The fabrication and tuning processes of the European S-band industrial electron linac as well as the cold RF power measurement will be reported later.

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