DESIGN OF A COMPACT X-BAND LINAC STRUCTURE FOR KAERI-RTX-ISU MEDICAL CYBERKNIFE PROJECT

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Abstract

Recently, the Advanced Accelerator and Ultrafast beam Lab (AAUL) at Idaho State University (ISU), has been developing an X-band linac for the medical CyberKnife project by collaborating with Korean Atomic Energy Research Institute (KAERI) and Radiation Technology eXcellence (RTX) [1–3]. The medical CyberKnife is essentially an X-band linac, which is attached to a robotic arm for precise cancer treatment. The X-band linac has considerable advantages in cancer treatment over C-band or other RF linacs, partly due to its compact size and light weight. These qualities make the X-band linac easier to attach to a robotic arm, thus making it more maneuverable. Other advantages include a higher accelerating gradient and a higher shunt impedance. Since high mobility is necessary for precise cancer treatment, the compact X-band RF linac was selected for the CyberKnife project. This paper describes detailed design processes of the X-band linac structure, which was done with 2D SUPERFISH and 3D CST MICROWAVE STUDIO (CST MWS) electromagnetic simulation programs.

INTRODUCTION

Recently, ISU AAUL, KAERI, and RTX have been developing an X-band Standing Wave (SW) RF linac for the CyberKnife robotic radiosurgery system. CyberKnife is a non-invasive cancer treatment technique, which can be used for a multitude of cancers or tumors in the human body [4]. By adjusting a robotic arm housing the X-band linac precisely, CyberKnife can target with pinpoint accuracy. The X-band linac is used to deliver high doses of radiation directly to the cancer or tumorous areas. This process is a major improvement over older and harsher cancer treatment techniques and has the potential to save thousands of lives. The expected parameters of the X-band linac for the CyberKnife project is summarized in Table 1. The X-band linac consists of a π-mode SW linac structure with 15 cells and a coupler as shown in Fig. 1. By using the π-mode, a higher shunt impedance and a higher gradient can be obtained [5]. For the RF power source of the linac, an X-band coaxial pulsed magnetron manufactured by L-3 Communications was selected [6]. Therefore, the linac was optimized to make an RF resonance at 9.3 GHz.

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Table 1: Parameters of an Optimized X-band Linac

Parameter	Value	Unit
length of the linac	0.25	m
initial beam energy from gun	20	keV
maximum beam energy at linac exit	6	MeV
RF frequency	9.3	GHz
maximum RF input power	2.36	MW
shunt impedance	78	MΩ/m
maximum energy gain per cell	400	keV
unloaded quality factor	8306	·
external quality factor	7099	·

By knowing the RF resonant frequency, the cell lengths and cell radii of the linac structure can be calculated in advance. The cell length l of the π-mode SW linac structure is given by

$$l = \beta \frac{\lambda_{RF}}{2}, \quad (1)$$

where β is the relativistic velocity of electrons, and λ_{RF} is the RF wavelength of the linac structure [1]. In our linac design, the bunching cells in the linac structure correspond to the cells where β is smaller than 0.95. All these initial conditions were used in 2D SUPERFISH simulation to find a basic geometry of the linac structure. A MATLAB program was developed to work in conjunction with the 2D SUPERFISH program to design basic geometries of each bunching cell and nominal accelerating cell. These individual cells are then combined in series to form a full linac structure with good electric field symmetry. Therefore, we can save our working time to find full geometry of the X-band linac structure with good electric field symmetry by using the homemade MATLAB and SUPERFISH combined program. Then, 3D CST MWS was used to optimize the linac structure and coupler by starting with the full geometry generated by the MATLAB and SUPERFISH combined program. Once the design is completed with CST MWS, it will serve as a blueprint for an actual working model.

2D SUPERFISH SIMULATION

SUPERFISH is a 2D electromagnetic field solver created and distributed by the Los Alamos National Laboratory to evaluate cylindrically symmetric RF accelerator cavities [7]. The cells in the X-band SW RF linac structure

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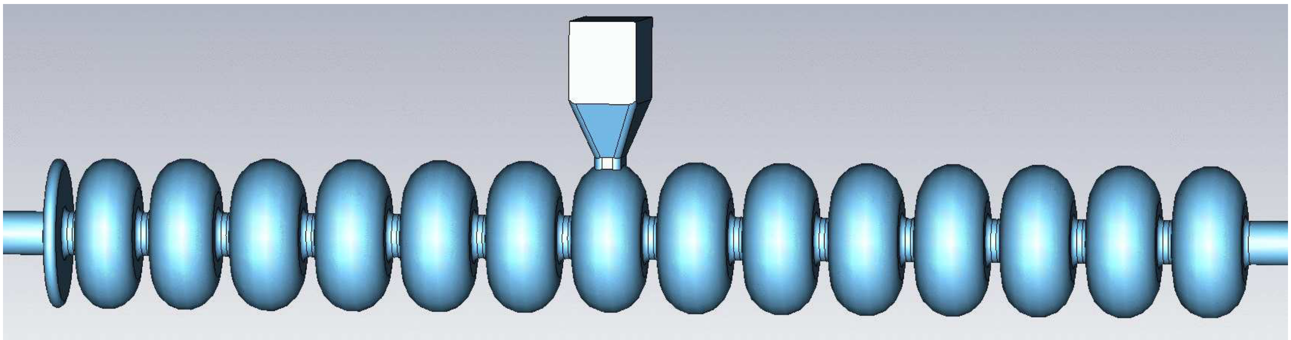

Figure 1: 3D CST MWS simulation result for an X-band linac structure with 15 cells summarized in Table 2.

were individually modeled using the SUPERFISH elliptical cavity tuning program ELLFISH. ELLFISH tunes an elliptical cell for explicit beam parameters and geometric constraints by making slight adjustments in the geometry of the cell. The geometric constraints are determined by the parameters of the electron beam. In this case, unbunched electron beam enters the linac structure with kinetic energy of 20 keV from the electron gun. Then, the bunching will be developed at bunching cells in the linac structure. The linac accelerates the electron beam through each cell in the structure and exits with a total energy of 6 MeV.

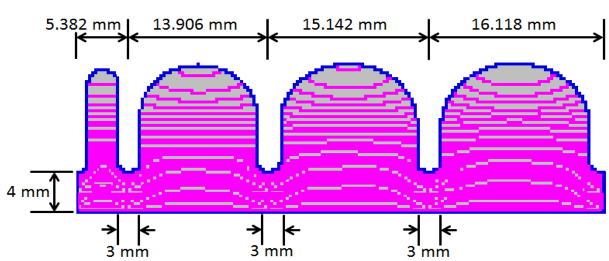

Figure 2: 2D SUPERFISH simulation result for a linac structure with four bunching cells.

The field symmetry along the linac cells is dependent upon the radius of the linac cells as summarized in Table 2. The semi-major and semi-minor ellipses of the elliptical cells can be calculated from the cell length, cell radius, and the desired septum thickness and iris radius. ISU AAUL has developed a MATLAB program to expedite the modeling of the linac structure with several bunching and nominal accelerating cells. The boundary constraints for the SW π-mode in the linac are hard coded into the program. The program allows for the user to input a desired frequency, the β values for the bunching cells and nominal cells with $\beta = 1$, and the desired iris radius. The program also offers an option to specify the mesh size and to add an extended beamline to the structure. The MATLAB program writes the geometrical parameters, calculated from the data input by the user, to several ELLFISH control files. ELLFISH executes each control file, optimizes the geometry for each cell, and writes the optimized geometries to a set of output files. The MATLAB program splices the individually optimized cell geometries, writes the multi-cell geometry to a single control file, and executes the control file in Autofish. Autofish performs an electromagnetic analysis of the multi-cell linac structure as shown in Fig. 2. WSFplot displays the longitudinal electric field. The shunt impedance, power dissipation, and transit-time factor are located in the PMI output files for the multi-cell linac structure.

Table 2: Detailed Geometry of the X-band Linac Cells

Cavity	Radius (mm)	Length (mm)
1^{st} bunching cell	13.680	5.382
2^{nd} bunching cell	13.850	13.906
3^{rd} bunching cell	13.906	15.142
4^{th} cell	13.949	16.118
5^{th} cell	13.950	16.118
6^{th} cell	13.950	16.118
7^{th} cell	13.951	16.118
8^{th} coupling cell	13.790	16.118
9^{th} cell	13.950	16.118
10^{th} cell	13.951	16.118
11^{th} cell	13.950	16.118
12^{th} cell	13.950	16.118
13^{th} cell	13.949	16.118
14^{th} cell	13.949	16.118
15^{th} cell	13.929	16.118

DESIGN OF RF COUPLER

The RF input is channeled through a WR-112 waveguide with an inside dimension of 28.4988 mm $\times$ 12.6238 mm with an allowable frequency range of 7.05 GHz to 10.0 GHz. Using these waveguide dimensions, the coupler design could be developed for the structure. Placing the coupler in the central location in the accelerating structure provides greater separation of modes [8]. The waveguide dimensions needed to be reduced to an appropriate size to couple with the X-band structure. This was accomplished by tapering the X-band waveguide to the RF power input window of the 8th coupling cell as shown in Fig. 1. The RF power input window to the coupling cell has the di-

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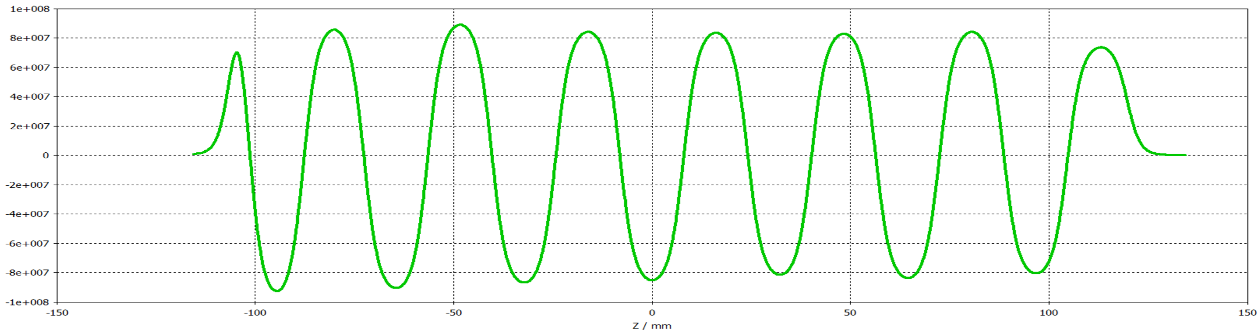

Figure 3: Electric field along the axis of the X-band linac structure summarized in Tables 1 and 2.

mensions of 10.7 mm × 5.0 mm and comes straight up out of the cell 1.0 mm. The waveguide, tapered area, coupler window and the coupling cell were tuned as a single cell, apart from the full structure. This single cell was given the proper boundary conditions in CST MWS as shown in Fig. 1. The dimensions of cell radius and coupler window have been tuned to obtain a coupler coefficient $\beta = 15$, which is the same as the total number of cells at the resonance frequency of 9.3 GHz. This coupling coefficient of $\beta = 15$ provides the maximum RF power coupling to each of the 15 cells in the full structure [8]. After this coupler is tuned individually, it is then placed into the full structure and tested once more. Experience shows that this coupler still will need an adjustment before it will work properly in the full linac structure.

3D CST MWS SIMULATION

CST MWS provides 3D manipulation and a more in-depth testing ground for the X-band structure [9]. To get a higher shunt impedance, generally, we may choose cell geometries with the nosecones. However, as shown in Figs. 1 and 2, all cells of the X-band linac structure have the bell shapes instead of the nosecone ones for easy fabrication. To obtain the symmetric electric field for the whole linac structure, the radius of each cell was individually modified by small increments [5]. These small increments were determined by the physical machining tolerances, which are ± 2 μm. Even small changes in the cell radius generate big impacts on the symmetry of the electric field. The cavity radius and the iris radius of each cell are inversely proportionally to the global frequency and the local electric field strength. Since the iris radius is directly related to the frequency separation between electromagnetic modes, we chose 4 mm for the iris radius of the linac structure to keep the mode separation larger than 5 MHz. Any shape made in CST MWS is carved from a default background of uniform conducting solid material and the carved shape is assumed to be vacuum. Once the cells, irises, and a coupler are connected into one solid structure, the electric fields can be optimized. The electric field was optimized for π-mode in CST MWS using the *Eigenmode Solver Parameters* tool to produce the desired field as shown in Fig. 3. This tool uses one of two solvers: the Advanced Krylov Subspace method (AKS) and the Jacobi-Davidson method (JDM). AKS measures modes with the lowest resonant frequencies, whereas the JDM measures modes at arbitrary positions specified by user input; this X-band structure used JDM [9]. The specifications of *Eigenmode Solver Parameters* tool were shown to be the first five modes above the frequency of 9.295 GHz. To help alleviate the calculation time, the *Boundary Conditions* toolbox has an option under the *Symmetry Planes* tab to cut the structure into symmetrical sections for calculation purposes. This process of optimizing the electric field was the most time consuming part of the X-band linac design.

SUMMARY

An X-band SW linac structure was successfully designed with SUPERFISH and CST MWS. The linac will be operated in π-mode to generate 6 MeV electron beam for the CyberKnife. The central RF coupler was designed and optimized to produce a symmetric electric field for the X-band structure as shown in Fig. 3. The final optimized geometry of the X-band linac structure is shown in Fig. 1 and its parameters are summarized in Tables 1 and 2. The next steps in the process are to simulate the X-band linac with a copper shell and design the heat dissipation method for the structure. Then it will be built and tested as an electron beam source for the medical CyberKnife project. Independently, we also have been optimizing a longer X-band linac structure with 25 cells.

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