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Radio Frequency Study of S-band Side Coupled Accelerating Structure

A. Aleem*, M.A. Khan, R. Khalid and I. Mahmood

RF Acceleration Group, LINAC Project, Islamabad, Pakistan

ABSTRACT

Currently, PINSTECH is developing S-band electron linear accelerator (LINAC) for medical applications. The side coupled accelerating structure (SCAS) was selected for electron acceleration process in the LINAC due to its compactness and high efficiency. The basic concept of SCAS was derived from the design of biperiodic chain of coupled cavities already published in the literature. This study focuses on the conceptual design realization and optimization of the structure through radio frequency (RF) simulations. COMSOL electromagnetic solver was used for the RF simulation work. The working frequency and excitation mode were selected as 2998 MHz and π/2, respectively. The design process of SCAS is stepwise explained starting from unit section to the complete stack of unit sections. The coupling iris was optimized to transfer maximum RF power to the structure. The electric field profile on the axis of SCAS was successfully optimized to achieve the field flatness. Subsequently, the characteristic parameters were derived directly through post processing of the simulation results.

Keywords: *Accelerating structure, Biperiodic chain, Magnetic coupling, Shunt impedance, Quality factor, Coupling iris*

1. Introduction

Electron linear accelerators were originally developed for scientific research studies. With growing need of the low energy LINACs in recent years, they are widely used in radiation therapy, proton imaging, flaw detection and industrial radiation applications. In medical domain, electron LINACs are used both in direct electron and secondary X-ray therapy [1-3]. For the development of an electron LINAC, the side coupled accelerating structure (SCAS) is a very popular choice, which is widely used in the accelerators around the world for different applications. The SCAS is one of the most famous biperiodic coupled cavity structure which was first developed in Los Alamos Scientific Laboratory few decades ago [4, 5].

The SCAS looks quite promising as it may deliver highest accelerating gradient to electron beams [6]. It is shorter and compact in size as compared to the usual LINACs that makes it suitable for accelerating proton beams for deep tumor cancer therapy (proton therapy) in hospitals [7, 8]. The fabrication tolerances play a crucial role in the performances of these devices because of the extremely high frequency. The fabrication errors produce deviations from the nominal design values of the most relevant parameters. In this regard, SCAS is the best option because the dimensional variations have less effect on the operating mode during the high power operation. Nevertheless, it is imperative to undergo a parametric analysis to measure the sensitivity of different geometrical dimensions.

Pakistan is facing continuous challenge of growing number of cancer patients apart from the follow-ups. Electron beam or X-ray therapy is essentially required at some stage of the treatment to cure the cancer patients. Therefore, to meet the requirement of cancer hospitals in Pakistan, the development of electron linear accelerator is under progress at LINAC project PINSTECH. Emulating the varian 600C LINAC, the S-band SCAS was selected for the electron acceleration to produce 6 MV X-rays.

The dimensions of a single accelerating cavity published by Roy and Shanker in 1993 [9] and Aubin et al. in 2010 [10] are redesigned for the SCAS in the LINAC project. The present study is focused on RF design simulation where all necessary steps are explained. In simulations, the SCAS was optimized for π/2 mode working at nominal frequency of 2998 MHz.

2. Conceptual design and simulation of the unit section

The design of the SCAS can be described as a chain of biperiodic coupled cavities. Theoretical basis and conceptual realization of the SCAS are given in detail in previous studies [4, 5]. The chain can be divided into a set of unit sections, where each section consists of three coupled cavities. Actually complete unit section comprises of two on axis accelerating cavities and one side coupled cavity as shown in Fig. 1. RF power coupling between the cavities was achieved by introducing a coupling slot through penetration of the side cavity into the main accelerating cavities. Some of the proposed geometry parameters are marked inside Fig. 1 and others are given in Table. 1.

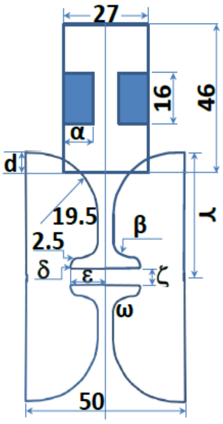

Fig. 1: 2D cross-sectional view of the unit section marked with the dimensional details.

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*Corresponding author: abi_aleem@yahoo.com

Table 1: Geometry parameters.

Parameter	Measurement (mm)
α	9.5
β	5.5
γ	38.47
ε	10.88
ζ	5
δ	1
ω	2.5
d	6

After conceptual realization, deciding the working frequency and design parameters, a simulation model of the unit section was prepared. Pro-engineer software was used to prepare a mechanical model of the unit section as well as the whole SCAS as shown in Fig. 2 (a) and (b). After preparation of the model, COMSOL software [11] was used for electromagnetic solutions. According to the resonant coupled theory, three normal modes (0, π/2 and π) essentially appear in Eigen mode simulation. The unit section design was optimized for π/2 mode working at frequency of 2998 MHz.

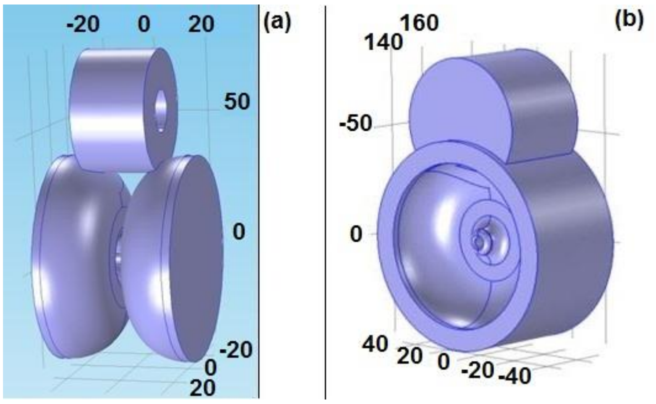

Fig. 2: Simulated model of (a) vacuum part and (b) solid part of the unit section.

The electric and magnetic field configurations of the unit section are shown in Fig. 3 (a) and (b), respectively.

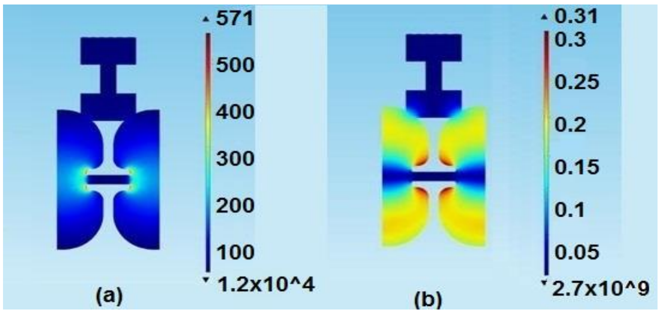

Fig. 3: (a) Electric field and (b) Magnetic field configuration of the side-coupled unit section.

The color coding of the bar shows that electric field is intense at a point on the nose cones. Therefore, nose cones are more sensitive towards the electrical breakdown. The side cavity does not contain electrical field at all. The magnetic field is also not strong mostly along the side cavity except around the coupling irises between the side cavity and main accelerating cavities. Presence of magnetic field on irises shows that the type of coupling between the side and main cavities is magnetic. Magnetic field in the main accelerating cavities is stronger near the round surfaces.

Electric field profile of π/2 mode along the axis of the unit section is shown in Fig. 4. Shape of the field profile is symmetric and phase change is 180° between the two consecutive accelerating cavities.

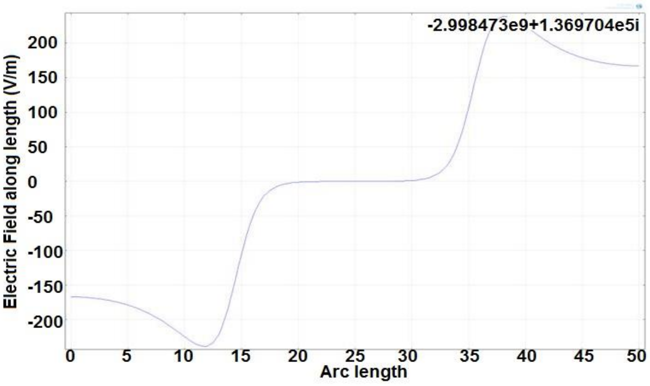

Fig. 4: Electric field profile along the axis of the unit section.

RF accelerating structures are defined with some specific characteristic parameters. Characteristic parameters of the instant SCAS are derived directly through simulation of the unit section or through post processing as shown in Table 2. The most important parameter of RF structure used for acceleration process is the shunt impedance. The shunt impedance of the SCAS is of very promising value that shows high acceleration efficiency.

Table 2: Characteristic parameters of the side-coupled structure.

Parameter	Measurement
Frequency resonant	2998 MHz
Mode	π/2
Bandwidth	50 MHz
Minimum frequency	2976 MHz
Maximum frequency	3026 MHz
Side to main coupling	0.01%
Accelerating gradient	40 MV/m
Shunt Impedance	160 MΩ/m
Q (unloaded)	17648
Energy	6 MeV

The frequency defining parameter is the radius or diameter of the on axis accelerating cavities of the unit section. Nevertheless, all other dimensions of the section have effect on the frequency variation. It is very crucial to measure the dimensional sensitivity of the accelerating structures. Parametric analysis was performed on the unit section to measure the dimensional tolerances and the results are given in Table 3. It is observed that frequency of

Table 3: Sensitivity of the critical dimensions of the unit section.

Parameter	Sensitivity (MHz/10μm)
ω	0.190
β	0.022
d	-0.036
ε	-0.587
γ	-0.338

the RF structure is certainly dependent on each dimension of the unit section.

Measured dimensional tolerances are essentially required to mechanically design the accelerating structure. Mechanical engineers are unable to make manufacturing drawings for fabrication of these structures without knowing the sensitivity of the particular dimension.

3. Stacking of the unit sections

Individually designed five unit sections are stacked together to completely design 6 MV side coupled accelerating structure. By this arrangement, there are 6 main accelerating cavities and 5 side coupling cavities as shown in Fig. 5.

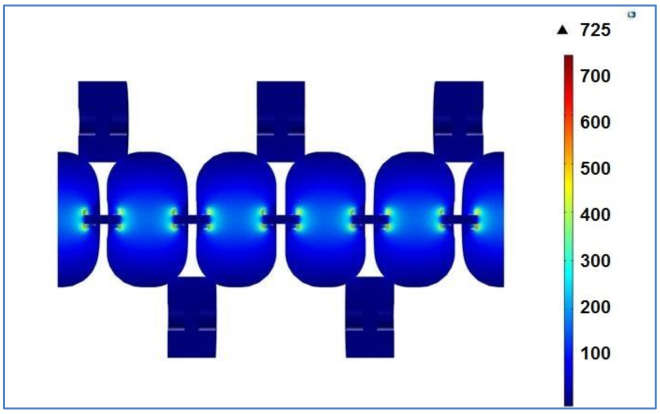

Fig. 5: Electromagnetic field configuration of the 5 unit section stack.

Eigen mode solution was obtained for the whole stacked sections and it was tuned at the frequency of 2988 MHz for the excitation of π/2 mode. It is seen that the electric field configuration of the whole stack is similar to the unit section that confirms the continuity and uniformity in sections of the stack as shown in Fig. 5. The most important thing in eigen mode solution is the electric field flatness along the axis of accelerating structure. The accelerating structure was optimized to obtain uniform electric field profile in all cavities as shown in Fig. 6. Apart from the field flatness in the tuned structure, a phase difference between the two consecutive accelerating and one side coupled cavity must be π/2 with respect to each other. However, the phase difference between the two consecutive accelerating cavities must be π.

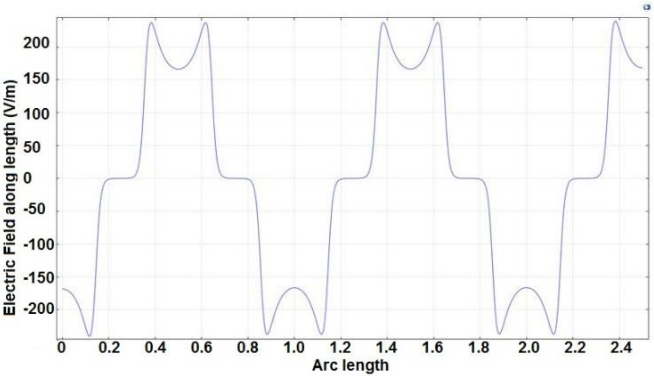

Fig. 6: Electric field profile along the axis of the 5 unit section stack.

As we are emulating the geometry of SCAS used in the Varian medical LINAC, the last section of the stack must have a full cavity instead of half-cell. The geometry of the stack was modified to obtain the full end cavity as shown in Fig. 7. Eigen mode simulation was repeated to tune the stack again for π/2 mode at a frequency of 2998MHz.

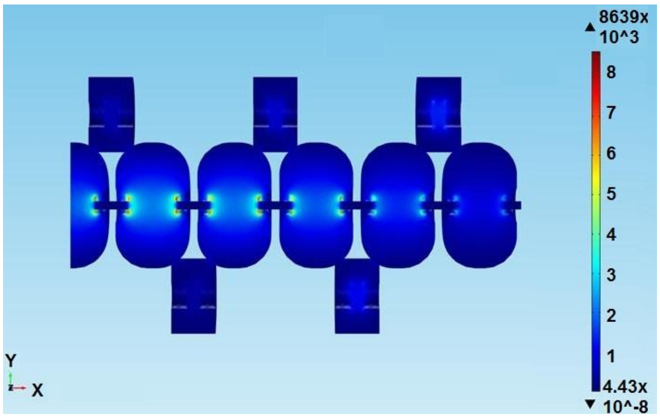

Fig. 7: Electromagnetic field configuration of the modified stack before tuning.

In first step of the simulation, the electric field does not remain uniform anymore in the accelerating cavities as shown in Fig. 8. The electric field flatness depends upon the resonant frequency and stored energy in the respective cavities.

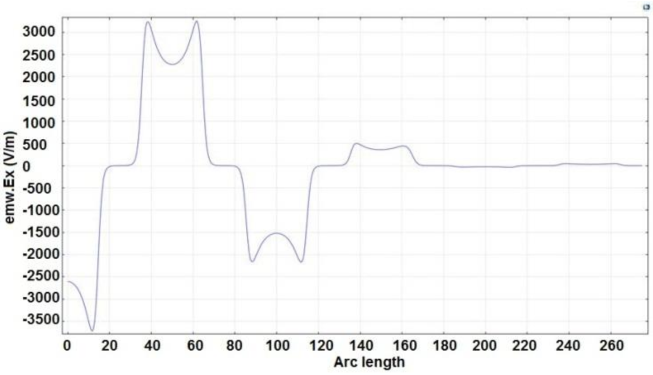

Fig. 8: Electric field profile of the modified stack before tuning.

The diameter of the last full cavity, nose cone diameter and nose cone distance ‘ε’ are required to modify to accommodate the change occurred after making a full end cavity. Modification in dimensions is done iteratively to bring the resonant frequency back to 2998 MHz for the stack. In this process the electric field amplitude becomes uniform again in the accelerating cavities as shown in Fig. 9.

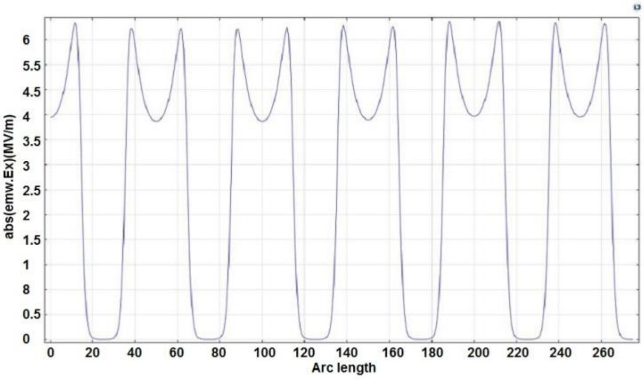

Fig. 9: Electric field profile along the axis of the stack after tuning.

4. Wave guide coupling with SCAS

High frequency power from RF source (magnetron/klystron) is coupled through waveguide to any accelerating structure. The coupling of power from waveguide to the accelerating structure is normally obtained through irises. In principal, power can be coupled to any accelerating cavity of the stack. It is normally preferred to couple a power in accelerating cavity sufficiently away from the electron gun (particle source) in order to avoid asymmetries in electromagnetic field excitations. Asymmetry in the field affects the longitudinal and transverse dynamics of the electron beam in the structure. In the present study, WR284 was coupled on the fourth cavity of the stack through a rectangular iris. Initially, the iris was designed with approximate dimensions and placed between the waveguide and fourth accelerating cavity.

Maximum power transfer into the structure is measured by the reflection co-efficient at the input of the waveguide. According to the resonant coupling theory, the longitudinal and transverse dimensions of the rectangular iris are adjusted to optimize the reflection co-efficient. The electromagnetic field configuration and shape of the coupling iris on the waveguide coupler are shown in Fig. 10 (a) and (b), respectively.

The dimensions of theiris are carefully optimized and given in Table 4. Frequency of the coupling cavity was reduced by making an opening in the wall. Electric field profile on-axis of the structure also did not remain uniform due to opening up of the iris. This deviation of the field profile occurred due to the change in individual frequency of the coupling cavity and in turn the resonant frequency of π/2 mode of the stack. Diameter of the coupling cavity was adjusted to achieve the resonant frequency of the stack back to 2998 MHz. The process of setting up the right frequency of coupling cavity also makes the field profile uniform on the axis of the structure as shown in Fig. 11.

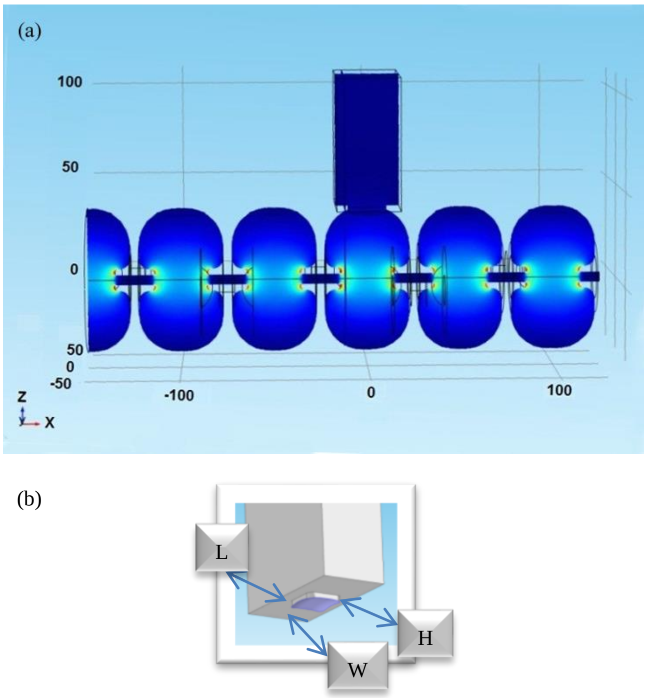

Fig. 10: (a) Electric field configuration of the waveguide coupled structure and (b) Geometrical shape of the iris.

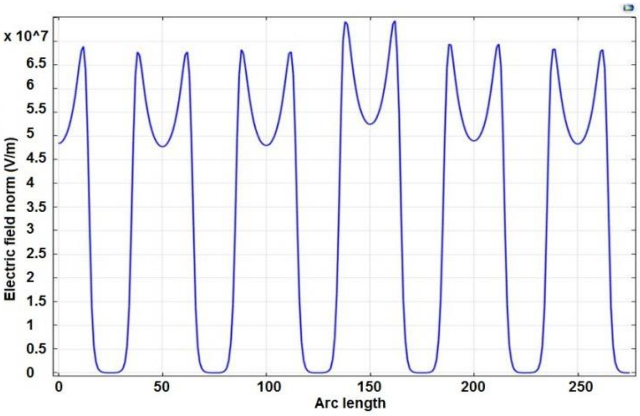

Fig. 11: Electric field profile along the axis of the structure after inserting the RF power coupler.

Table 4: Optimized dimensions of the iris.

Sr. No.	Parameter	Measurement (mm)
1	Length of iris (L)	23
2	Width of iris (W)	14
3	Height of iris (H)	1

The s-parameter (reflection) was measured at the input of the waveguide against the narrow band around the resonant frequency of 2998 MHz as shown in Fig. 12. The analysis shows that RF power was sufficiently coupled to SCAS as the s-parameter was approaching to almost -30dB.

Maximizing the input power means that the reflected power towards RF source has been accordingly reduced.

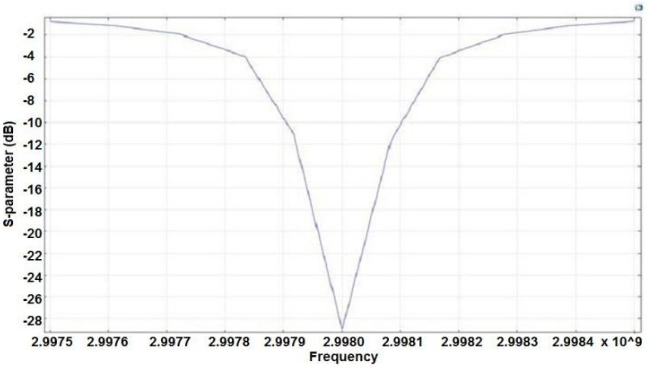

Fig. 12: S-parameter analysis of the SCAS.

5. Dispersion Diagram

Dispersion diagram of the coupled cavity structure, in general, is a relationship between the frequency and wave number. In case of SCAS, we have used the eigen mode simulations in COMSOL to calculate the frequency of the possibly excited normal modes. The dispersion diagram of the SCAS is then obtained by plotting the frequency against the mode numbers. It certainly describes the behavior of the SCAS as shown in Table. 5 and Fig. 13. Normal modes in any periodic structure are different possible excitation patterns of the electromagnetic field. In periodic coupled cavity structure as many modes are excited as the number of coupled cavities are present in the structure.

Table 5: Possible number of modes in the structure.

Normal Mode	Frequency (MHz)
0	2976.4
$\pi/10$	2977.4
$\pi/5$	2979.5
$3\pi/10$	2982.2
$2\pi/5$	2984.8
$\pi/2$	2998
$3\pi/5$	3017.4
$7\pi/10$	3020.2
$4\pi/5$	3023.1
$9\pi/10$	3025.3
π	3026.7

In this simulated design of the SCAS, there are 6 accelerating and 5 side coupling cavities (see Fig. 5).

Therefore, in total 11 modes are excited at slightly different frequencies within the bandwidth of 43 MHz. SCAS was designed to essentially resonate at $\pi/2$ mode at 2998 MHz. Design optimization of the structure requires that the neighboring modes of $\pi/2$ mode are far away on the frequency scale. In this optimized structure the neighboring $2\pi/5$ mode was 13.2 MHz and $3\pi/5$ was 19.4 MHz away from the resonant $\pi/2$ mode.

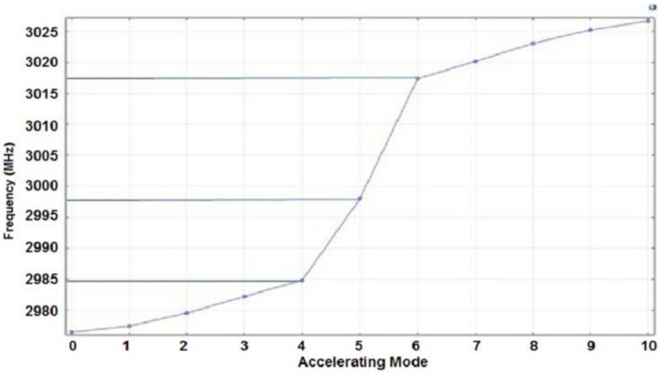

Fig. 13: Dispersion diagram of the SCAS.

RF power source for this SCAS would be magnetron. The resonant frequency of the magnetron is 2998 MHz and has a band width of 10 MHz. The relative distance of the neighboring modes of the structure is larger than the bandwidth of the magnetron. There is no fear of mode mixing or mode switching during operation of the designed structure at 2998 MHz.

6. Summary

At PINSTECH we have successfully optimized a physical design of the S-band side couple accelerating structure. Electromagnetic solver COMSOL software was used stepwise for the simulation of the complete design. In the first step, a unit section was defined that consists of two accelerating and one side cavities. Coupling between the cavities was achieved with penetration of the side cavity into the two main on axis accelerating cavities. The characteristic parameters of the SCAS were derived from eigen mode solution of the unit section. Shunt impedance was optimized to obtain maximum acceleration efficiency and minimize the possibility of any electrical breakdown in the structure. Furthermore, five unit sections are stacked together to form a complete accelerating structure and on axis electric field profile was optimized in the simulation. Dimensional sensitivities were also measured to decide about the mechanical tolerances in fabrication process. RF power was coupled from WR284 waveguide through a rectangular iris into the structure. S-parameter analysis at the input of the waveguide showed that maximum RF power was transmitted to the structure with minimum reflection back towards the power source. Design specifications of the structure safely allow excitation of 2.5 MW power into the structure to achieve the electron acceleration of 6 MeV. SCAS is now under development to practically achieve the designed specifications.

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