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DESIGN, FABRICATION AND VARIFICATION OF A 3 MeV S-BAND MEDICAL LINEAR ACCELERATOR

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Abstract

ZAP-X is an innovative stereotactic radiosurgery platform that is self-shielded, using gyroscopic motion to allow precision neurosurgical treatment. It requires a compact linac with lower than typical energy for medical applications. A 3 MeV S-band linac is designed and fabricated for this purpose. Thorough, clinical style testing was performed to verify the performance. The characteristics of photon beam, which is generated by the linac, are compared with the design goal, as well as Monte Carlo simulations.

INTRODUCTION

The ZAP-X is an innovative, self-shielded radiosurgery system specifically for head and neck treatment. The gyroscope structure rotating around dual-axes gimbals provides 2π solid angle access. A compact 3 MeV linac is required to deliver high dose rate for the system [1].

The LINAC developed to meet ZAP-X requirement and fit in the system. This on-axis coupled S-band linac has advantage of being light weight, easier to fabricate and low cost. It is designed to generate high dose rate and exceptional photon beam quality inside the ZAP-X.

The linac is fully tested in ZAP-X environment to verify the performance. As a compact medical linac, it lacks electron beam monitors. Most measurements are made on the photon beam. Measurements are performed to verify Monte Carlo simulations.

LINAC DESIGN

The S-band 3MeV linac is developed by Elekom technical team, which consists of a triode electron gun, RF window, waveguide, ion pump, standing wave (SW) accelerating cavities and an insulated target. All components except triode gun are manufactured by Elekom.

The triode gun generates about 600 mA electron current, which can be adjusted by grid control voltage. Electrons are injected into linac cavities with a 10.5-12 keV energy. The linac has a stable capture ratio according to the SW linac physics [2]. The linac cavities adopt on-axis coupled SW structure, which has 2 bunching cavities and 3 normal cavities. 2MW RF power is fed into the structure to generate high accelerating field to accelerate electron beam from 10.5-12 keV to 3 MeV which bombards a tungsten target to generate X-rays. To monitor the target current, an insulated target is adopted. The linac is shown in Figure 1. After beam dynamic optimization simulation, the accelerated electrons results are shown in Figure 2. The beam spot size is 1.0 mm (FWHM), and the mean beam energy is 3 MeV. The main design parameters are shown in Table 1.

Table 1: 3MeV SW Linac Main Design Parameters

Parameter	Value
Energy	3 MeV
Structure	On-axis Coupled
RF Frequency	2998 ± 1 MHz
Gun Type	Triode
High Voltage	10.5 - 12kV
Dose Rate	1500 cGy/min@450mm
Capture Ratio	38.3%
Beam Spot Size	1.0 mm (FWHM)
Beam Current	230 mA
Input Power	2 MW
Target	Insulated
Length	354 mm

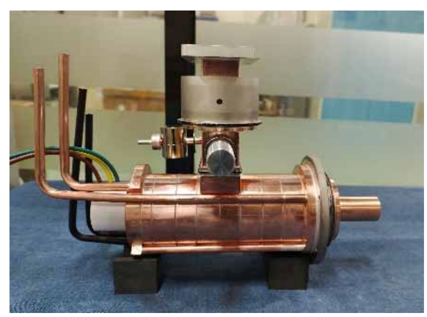

Figure 1: S-band 3 MeV linac.

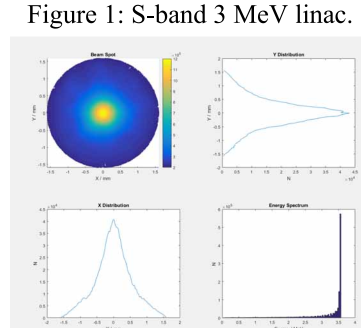

Figure 2: Beam size and energy spectrum at end of linac.

FABRICATION AND INITIAL TEST

The most important components of the linac are the accelerating cavities, which must be machining precisely and with a high quality of surface smoothness. The material of the cavities is Oxygen Free High Conductivity Copper

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(OFHC), due to it has characteristics of high electrical conductivity, thermal conductivity and low outgassing. The cavities are fabricated by CNC turning using diamond cutting tool producing dimensional precision and surface smoothness are better than 2 µm, 0.1 µm respectively, preventing the cavities from break down. After machining, the cavities are brazed and frequency tuned. RF window and target are brazed by hydrogen furnace to produce a single structure. The main components are shown in Figure 3 and Figure 4.

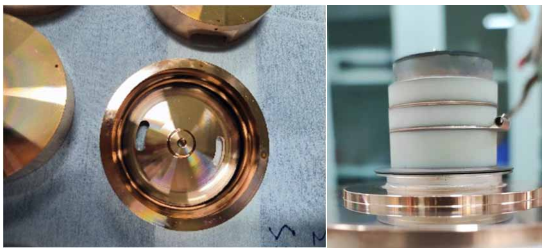

Figure 3 RF cavities and triode gun.

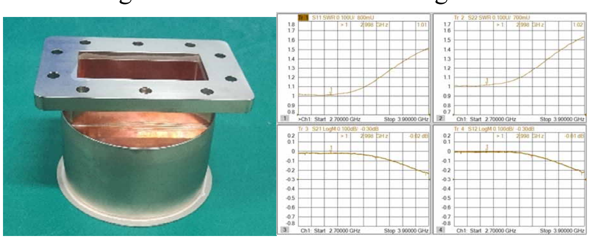

Figure 4: RF window picture.

All components are sealed by welding and the linac starts thermal outgassing (bake-out). This process bakes out the gas in the material inner surface of the linac and makes sure the linac maintains a high vacuum (about 2e-8 Pa) capable of establishing a high electric field without arcing or break down. The final S parameter of linac is shown in Figure 5.

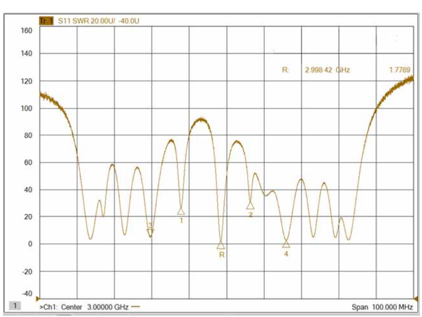

Figure 5: S11 parameter of 3 MeV linac.

Before the linac is sent out from Elekom, the linac is processed by high power RF conditioning, and basic beam on tests including gun emission, X-ray energy, dose rate and vacuum etc.

LINAC PERFORMANCE TESTS

The linac is fully evaluated in the ZAP-X environment, including same RF power chain, primary and secondary collimators, and on-board ion chambers. The system set up is shown in Figure 6:

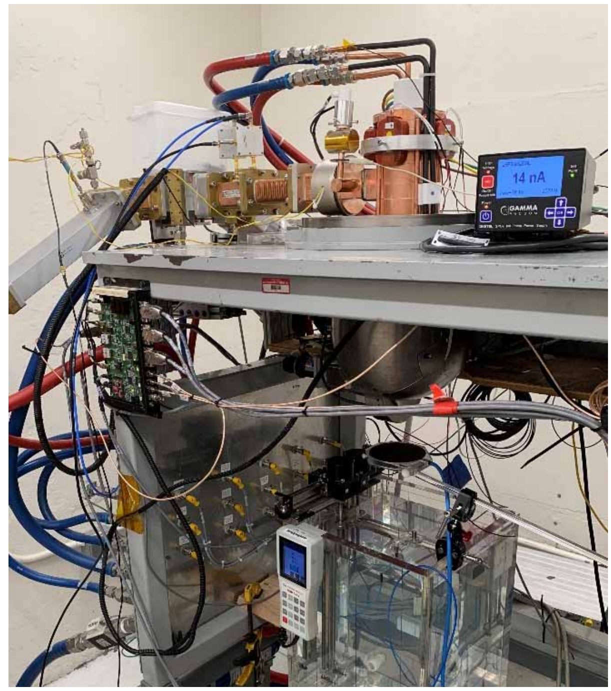

Figure 6: Linac testing setup.

The testing validates all performance specifications of the photon beam required for clinical treatment procedures.

Gun Emission

The emission curve is measured with and without RF on. The results are plotted in Figure 7 (a). The back heating is moderate so that it won't cause too much extra load for the gun and does not require heater cut back. Figure 7 (b) shows the oscilloscope traces of gun emission current (red) and target current (green), measured 630 mA and 230 mA respectively. They are well within the design values.

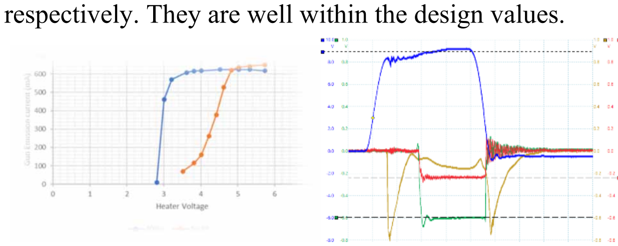

Figure 7: (a) Emission curves; (b) Gun & target current.

High Power Performance and Dose Rate

The most important parameter is to deliver the dose rate required at the isocenter. For ZAP-X, the isocenter is 450 mm from the target. There is primary collimator, secondary collimator and ion chamber in the beam line. The ion chamber has considerable amount of dose rate attenuation. With that included, the linac delivers over 1500 cGy/min dose rate to the isocenter, measured by external PTW ion chamber and electrometer. It meets the design goal.

Beam Spot Size Measurement

Direct measurement of electron beam spot is not available as the linac is sealed without beam monitors. However, measuring the photon spot size just outside of the target

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gives a close approximation of the electron spot. The spot is measured with a sweeping slit-collimator device [3]. The data is shown in Figure 8 with double Gaussian fit. The measured FWHM spot size is very close to the design value.

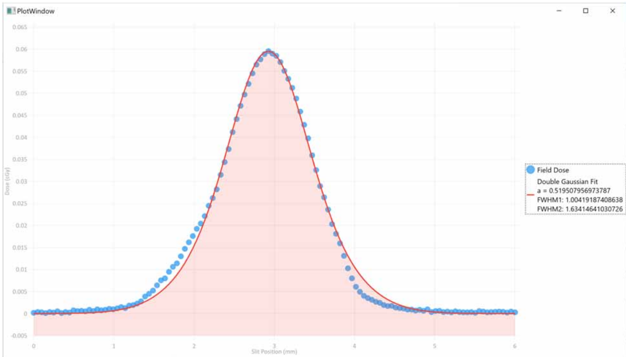

Figure 8: Measured beam spot.

Dark Current

This linac exhibits exceptionally low dark current. The dose rate with full RF power, without turning on the gun, is below the instrument detection limit. By extending the integration of dose, we estimate the dark current (in photon) is in 0.0002% range.

PHOTON BEAM CHARACTERIZATION

While the linac is verified, it is more important for medical linacs to deliver proper photon beam quality that is required for treatment.

Percentage Depth Dose

The photon energy generated by the electrons accelerated in the linac is typically determined by the percentage depth dose (PDD), measured by scanning in water along the beam axis. The dose rate ratio of 100 mm depth and maximum value, typically at 7 mm depth for 3 MV beam, is used as the energy measurement. For ZAP-X, this ratio is set at 40% ± 2%. Figure 9 shows the measured PDD curve and the D_{100}/D_{max} ratio is 40.3%.

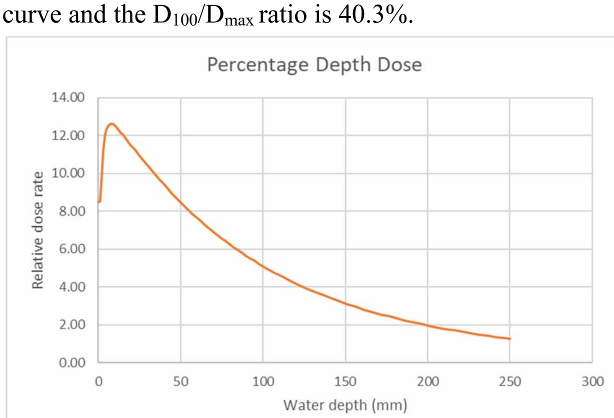

Figure 9: Measured PDD by water tank.

Beam Profile

Clinical treatment requires the photon beam to have good symmetry and expected beam size after collimation. The photon beam profile is measured by scanning inside a water tank. The plot in Figure 10 shows the profile measured under 25 mm collimator at the depth of 7 mm, 50 mm, 100 mm and 200 mm. The results show good symmetry and alignment that meet the system specification.

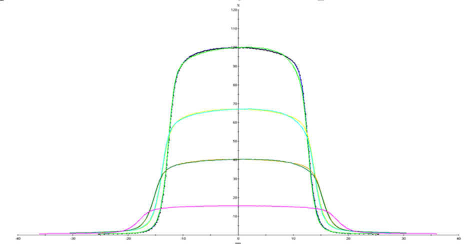

Figure 10: Beam profile measured with 25 mm collimator.

MONTE CARLO SIMULATION AND COMPARISON

As one can see, medical linacs are designed to deliver electrons while verified with photon beams, the best way to relate them is through Monte Carlo simulation. We use a well-established program, PENELOPE [4], to simulate the beam line. The result is validated with measurement. Figure 11 plots the PDD data from measurement and simulation. It demonstrates good agreement between the two. It gives confidence for the Monte Carlo simulation to be used as research and design guidance.

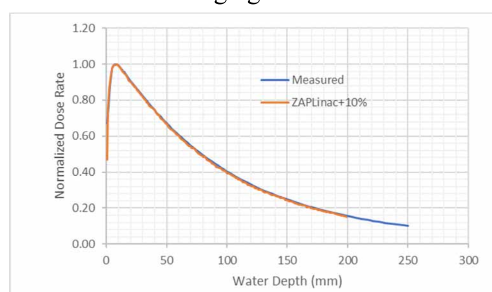

Figure 11: Comparison of simulation and measurement PDD results.

CONCLUSION

The compact S-band, on-axis coupled linac is designed and fabricated for precision radiosurgery system. The linac is fully characterized in the ZAP-X environment. It demonstrates the capability to provide photon beams with the required dose rate with high quality beam profiles.

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