DESIGN AND OPERATION OF A COMPACT 1 MeV X-BAND LINAC

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Abstract

A compact 1 MeV linac has been produced at the Cockcroft Institute using X-band RF technology. The linac is powered by a high power X-band magnetron and has a 17 keV 200 mA thermionic gun with a focus electrode for pulsing. A bi-periodic structure with on-axis coupling is used to minimise the radial size of the linac and to reduce the surface electric fields.

INTRODUCTION

Small, low-energy linacs are required by industry for the production of X-rays to be utilised in security applications and for non-destructive testing. Mobile cargo scanning systems used in the security industry typically use S-band (3 GHz) RF linacs to accelerate electrons produced from a pulsed electron gun to the required energy (typically 1-5 MeV depending on the type and thickness of the material to be scanned) [1]. Typically all the power supplies, control electronics and water cooling are placed on the back of a truck along with a robotic arm which will have the linac cavity, electron gun and target attached, along with a substantial amount of lead shielding. For mobile security applications the weight of the linac is critical to the mobility of the linac. Using higher frequency linacs reduces the cavity radius and hence the weight of the lead shielding required. For this reason an ultra-compact 9.3 GHz, 1 MeV linac has been designed at the Cockcroft Institute.

LINAC DESIGN

The linac is to be driven from a 1 MW e2v magnetron. As magnetrons are not very frequency stable the structure must be tolerant to changes in frequency. This is made more difficult by the requirement to have a small iris to have the maximum possible R/Q. In order to increase stability the structure was chosen to work in a $\pi/2$ mode. As every 2nd cell is empty there are two options to keep the R/Q high, to use a side coupled structure or an on-axis coupled bi-periodic structure. As we also want to keep the structure diameter small it was decided to use the latter. The structure is electrically coupled through the iris, this doesn't have as much coupling as magnetic coupling through slots in the wall, but is simpler to manufacture and operate. A 5 mm iris diameter was chosen to give sufficient coupling between the cells.

Although the electron gun is pulsed it has a pulse width that is several thousand RF periods hence it is necessary to bunch the electron beam within the linac cavity before acceleration. The electron beam is injected into the cavity from the gun at a relatively low energy (17 keV) and the electron velocity will not become close to the speed of light until after several cells of the cavity. This requires the length of each cell to be carefully optimised using beam dynamics codes to track each electron through the cavity such that the synchronous phase varies along the structure. As the electron velocity is dependent on the accelerating gradient, the electric field amplitude must be chosen before optimising the cavity. A peak accelerating gradient of 30 MV/m was chosen as a compromise between structure length and peak surface electric field, and this resulted in a structure with 8 accelerating cells.

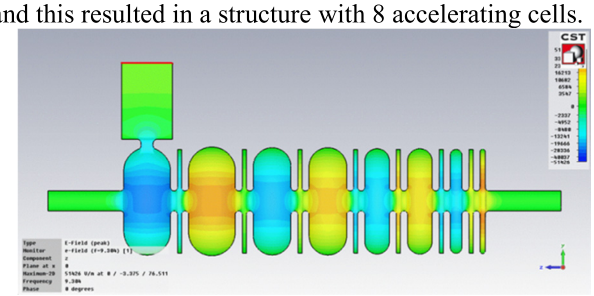

Figure 1: Compact Linac Cavity modelled in CST [4].

Particle tracking including space charge has been performed in ASTRA[2] as well as full PIC simulations in VORPAL [3], shown in Figure 2 and 3. It is observed that space charge forces are quite large in the front end of the linac where the cavity field is very low, resulting in particles spreading and hitting the cavity walls. This however is not expected to cause much heating or radiation as the impact energy is low. As the particles travel further downstream, they get bunched and transversely focused and at the exit of the linac reach 1 MeV and 50 to70 mA on average which is sufficient to produce the desired range of X-ray dose for many applications.

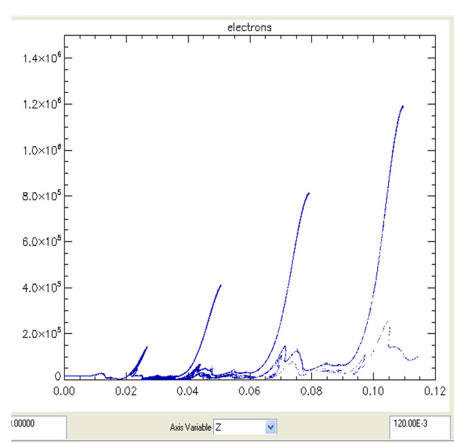

Figure 2: Electron energy, in eV, as a function of longitudinal position in the linac, in metres.

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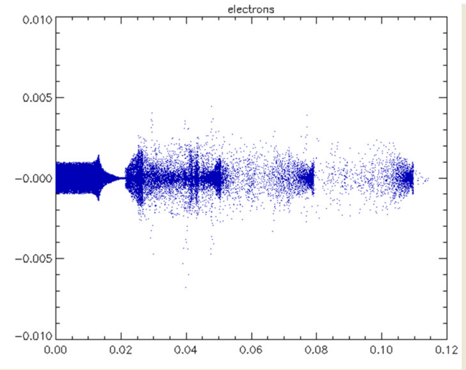

Figure 3: Electron horizontal offset plotted against longitudinal position in metres.

After optimising the basic cell shape and the length of each cell, it is necessary to model the full cavity in an RF simulation code, design an RF waveguide input coupler and to adjust the cell dimensions to account for the perturbation due to the ohmic losses. This was performed in CST Microwave Studio [4].

CAVITY MANUFACTURE

The linac cavity has been manufactured by Shakespeare Engineering, a UK precision Engineering company. The cavities were delivered to Daresbury Laboratories for final tuning and RF measurement. The cavity frequencies were measured using a vector network analyser and a resonant perturbation technique is employed to measure the field profile of the cavity. Both processes are performed in a clean laminar flow environment.

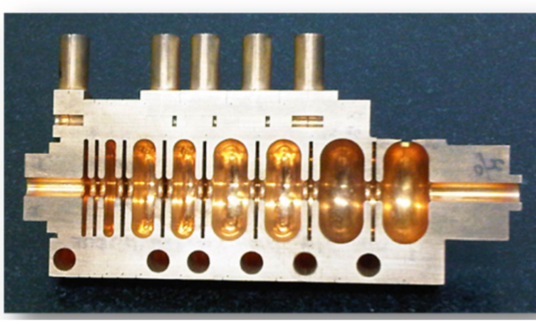

Figure 4: Cross-section of the manufactured cavity.

It was found that the manufacturing tolerances on the cavity manufacture had not been met resulting in the field only being present in some of the cells. This was confirmed by cutting a cavity in half with wire EDM, as shown in Figure 4. A new cavity is currently being manufactured to resolve some of the issues in the first cavity.

The cavity was then connected to the electron gun and pumped down. The installed cavity is shown in Figure 5.

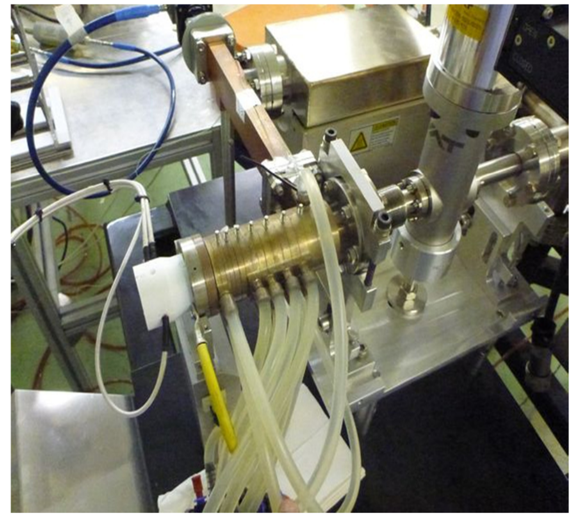

Figure 5: Compact linac cavity and gun installed.

DIAGNOSTICS LINE

In order to accurately measure the energy, current and spot size of the accelerated electron bunch a diagnostics line was constructed at the end of the linac. Integrating current transformers were placed on the cathode supply of the electron gun and in between the linac and the tungsten target for the measurement of beam current. A movable stepper drive section allowed the tungsten target to be removed from the beamline and replaced with either a straight section or a slit.

To measure the beam energy an ex-SRS dipole magnet was placed to deflect the beam down an angled beamline terminated in a Faraday Cup. The electrons energy can be calculated from the magnetic field required to deflect the beam to the Faraday cup. The magnet had previously been calibrated by the magnet group in ASTeC Department, STFC and hence the magnetic field could reliably be worked out from the magnet supply current.

In addition a radiation monitor was used to measure the X-ray production when the target is placed in the beamline.

The full diagnostics line is shown in Figure. 6.

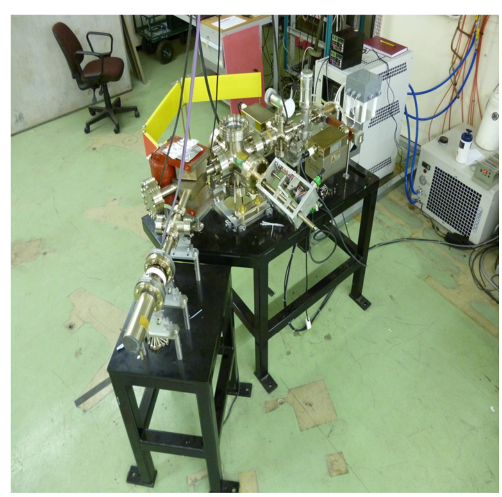

Figure 6: Compact linac Diagnostics Line.

LINAC TESTING

The linac was fully assembled in July 2011, and commissioning started with testing of the electron gun. The electron gun was found to produce 160 mA as measured by an ICT on the cathode input.

A 1.3 MW, e2v magnetron and modulator is used as the RF power source. The cavity was then tested at high power, and was found to operate well up to an input power of 800 kW, well above the design power of 450 kW. However as the field profile is not as expected it is difficult to work out what gradient this is.

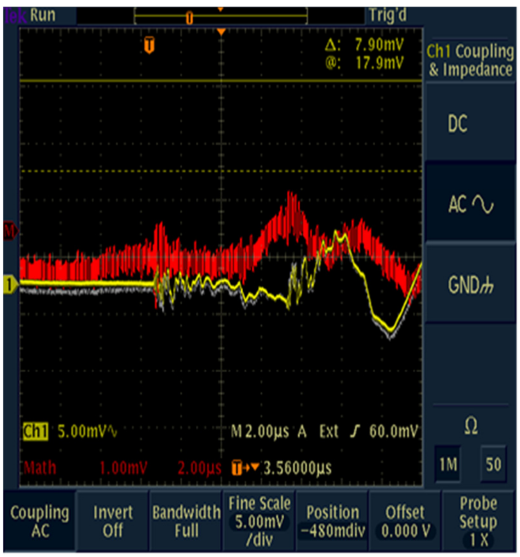

Figure 7: Faraday cup signal after the spectrometer magnet at 610 keV.

The electrons were then injected into the cavity. As there is no field in the first few cells the beam is not effectively bunched, hence a higher power is required to reach high energy. With an input power of 800 kW the maximum electron energy was measured on the spectrometer to be 610 keV. However it should be noted that due to the lack of bunching some electrons may reach a higher energy but with too low a current to be measured on the Faraday Cup. The signal from the Faraday cup is shown in Figure 7.

CONCLUSION

A compact linac has been designed and tested. Due to the cavity manufacture not meeting the design tolerances the field profile was far from ideal and field was only measured in the last 5 cells. This resulted in a lack of bunching and a lower beam energy at the output of 610 keV. A new cavity that better matches the design specification is currently being manufactured by Shakespeare Engineering and commissioning is expected to restart in the near future.

ACKNOWLEDGEMENTS

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