LOW ENERGY RF ACCELERATOR FOR VARIOUS APPLICATIONS

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Abstract

Compact X-ray sources are integral parts of systems used in medical, industrial and security applications. X-ray dose rate for a particular application (5-20 cGy/min at 1 meter) mainly depends on the energy and current of the beam used to hit a target, usually made of tungsten. In applications that need higher penetration (100s of mm in steel), the beam energy needed is in the range of 1-5 MeV which can only be obtained using an RF linear accelerator. In order to reduce the size of the linac, higher RF frequencies (X-band) should be used while in order to reduce the overall bulk, RF focusing is employed instead of solenoidal focusing. Thus the main attraction of an X-band linac compared to its lower frequency version is the small amount of lead required for shielding the system, and hence less weight. For capturing and bunching the low energy dc beam, a bunching section is needed in the front end of the main linac. The bunching cavity can either be a part of the main linac cavity or an independently powered section which can be used for certain specific applications such as a shorter low energy linac. In this paper, the RF design of an X-band 1 MeV linac to be suitable for compact X-ray sources is presented.

INTRODUCTION

Compact linacs are high demand for the generation of high power beams (for cancer therapy, material processing, sterilisation etc) and high dose X-rays for radiography (cargo scanning, non-destructive testing). For the latter applications, the beam power determines the X-ray dose rate whilst the pulse rate determines the horizontal scan resolution. Primary requirements of compact X-ray sources are small size, reduced weight, long life and low cost of production. The above demands make X-band operation more suitable than C or S-band operation. A normal conducting standing wave accelerating structure driven by a 9.3 GHz pulsed magnetron is a possible solution [1] for such generic applications. Stable operation of the linac depends on both the stability of the magnetron source and the cavity. Stable magnetron oscillations could be achieved by using an Automatic Frequency Control (AFC) system.

Tight manufacturing and assembly tolerances at the X-band suggest π/2-mode as the most appropriate operating mode of the cavity. Because of its maximum separation from adjacent modes compared to any other modes, this gives more stable fields in the presence of perturbations and losses [2, 3]. This however is achieved at the cost of acceleration efficiency (R/Q). In order to avoid the use of focusing solenoids, RF focusing in the low energy section is used whereby the RF phase alternates between radial focusing and longitudinal bunching [1].

CAVITY DESIGN

When an iris loaded cavity is operated at π/2-mode, every alternate cell which is empty of field can be shrunk to form a bi-periodic cavity as shown in Figure1. This combines the high efficiency of a π-mode from the beam perspective and the field stability of the π/2-mode from the RF perspective which can't normally be achieved simultaneously in a conventional linac.

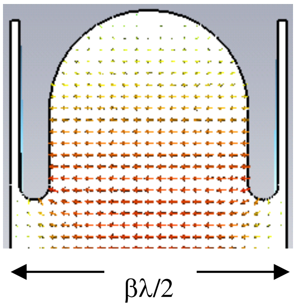

Figure 1: Single cell of a biperiodic cavity.

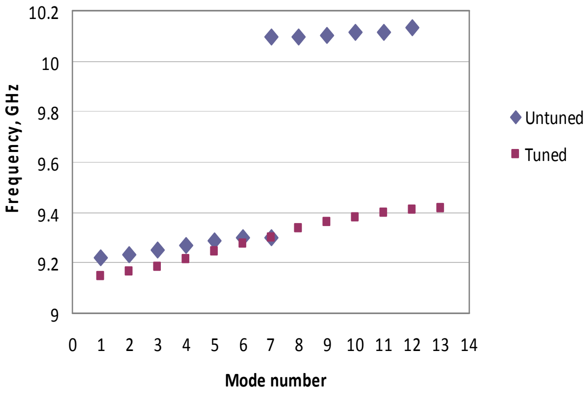

Figure 2: Dispersion diagram of finite cell biperiodic cavity.

Dispersion diagram for a 13 cell biperiodic cavity is shown in Figure 2 using CST Microwave studio. In the untuned state, there is a stop band at the operating mode which corresponds to independent π/2 excitation of accelerating and coupling cells. The stop band needs to be closed by relatively tuning the cells in order to get the π/2-mode (7th mode) in the accelerating cells only as shown in the same figure. As the power output from the magnetron is limited and losses are expected in the distribution lines, the cavity should be optimised for high shunt impedance to achieve the desired voltage over a short length. Also the cell shape should be designed so that the beam gets bunched and accelerated conforming to a small spot at the linac output as required. It is rather difficult to achieve all three functions in a single linac section and a compromise is the only solution.

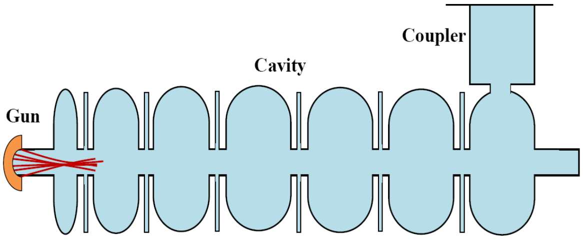

Figure 3: Schematic of the compact linac and electron gun.

Based on beam dynamics simulations using ASTRA code [4], cell lengths and number of cells have been optimised for a beampipe diameter of 5 mm as shown in the schematic in Figure 3. The wall thickness between the accelerating and coupling cells is chosen as 1.75 mm for better heat removal and mechanical strength. In contrast to inductive coupling through the walls, capacitive coupling through the beampipe is used in order to achieve better ruggedness in the absence of slotted walls. Also re-entrant cavity shapes are not preferred as the surface electric field will be much higher and the cost of surface preparation will be significant. The cell shape in Figure 1 gives a predicted shunt impedance of 116 MΩ/m, Q_0 = 6500, peak field $E_s/E_{acc} = 2.567$, $H_s/E_{acc} = 0.0027$ at $\beta = 1$ length. Figure 4 shows the transverse size of a fabricated cell.

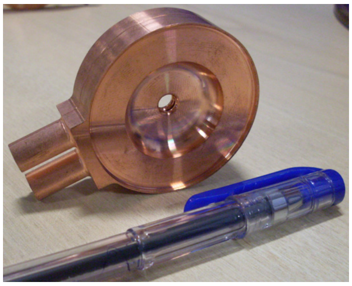

Figure 4: Half accelerating cell of the cavity.

RF POWER DISTRIBUTION

The X-band cavity shown in Figure 3 would need ~433 KW RF power including beam loading for 1 MeV acceleration. Thus the external Q required by the waveguide coupler should match the total losses which give Q_{ext} of 6378. A pulsed magnetron at 9.3 GHz (9.295 to 9.31 GHz) of 1.3 MW peak power can be used to feed the cavity. The RF output is pulsed using a modulator giving 4 μs pulses at 250 Hz. However AFC is needed to provide a stable frequency from the magnetron.

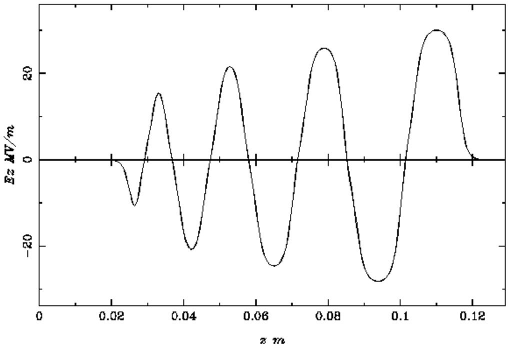

Figure 5: Computed Electric field at 9.3 GHz along the cavity axis.

As Figure 6 shows, RF output from the magnetron is fed through a circulator to provide protection from reflections. It is then split into 2 paths by a hybrid coupler with a coupling factor of -4.77 dB (providing a 1/3 split). This will provide up to ~430 kW for the linac, the remaining 860 kW can be made available for future upgrades to higher energies, however it is currently dissipated into a water cooled dummy load. Directional couplers provide diagnostics along the length of the waveguide system, which also includes an arc detection port and the waveguide is filled with pressurised (2.5 bar absolute) Sulphur Hexafluoride (SF6).

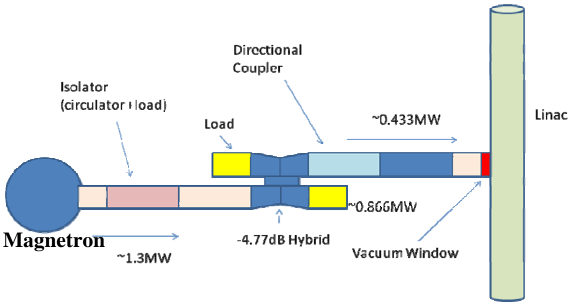

Figure 6: RF distribution for the linac.

MAGNETRON CONTROL

The magnetron AFC needs a single cell 9.3 GHz copper cavity to give a phase shift proportional to the change in magnetron frequency. This phase shift is then measured with a double balanced mixer by mixing the cavity output with the direct output from the magnetron. Phase of the cavity output varies with its input frequency and the voltage at the mixer's IF output is directly proportional to a change in frequency, as long as the magnetron frequency stays within the cavity bandwidth. A phase shifter is placed to calibrate volts/degrees at the IF as well as to null the IF when the magnetron frequency is the same as the cavity centre frequency. This technique gives high resolution for frequency drift observation during a pulse. It does however require temperature stabilisation of the cavity as the cavity centre frequency acts as the reference.

BEAM DYNAMICS

In order to simulate the beam from a basic DC gun of 17 keV, 100-200 mA, a particle distribution with the same beam properties as that of the gun output was used. About 40,000 particles spanning over about 10 RF periods was tracked using ASTRA incorporating the effects of both space charge and external RF forces. The RF field distribution used is shown in Fig. 5.

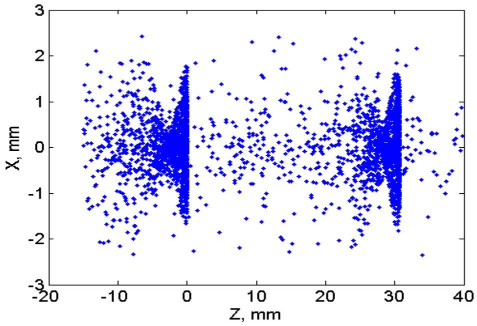

Figure 7: 1 MeV bunches in the linac output.

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. The 1 MeV bunches at the linac exit, one per RF cycle are shown in Figure 7. The RMS spot diameter is ~1.6 mm and the bunches seem to have a low energy tail which is not crucial in most industrial applications as what matters is the peak charge density. Energy of the reference particle as a function of the RF phase of the cavity is plotted in Figure 8.

A sensitivity study has been carried out to see how the variations in cavity field and gun voltage affect the output beam. Results are shown in Table 1. Changes in the gun voltage or cavity field have an identical effect but of different degree on the output beam. If the field is lower than nominal, particles will arrive late with respect to the RF in each cell. Thus they are longitudinally defocused and transversely focused causing a decrease in energy, current and spot size.

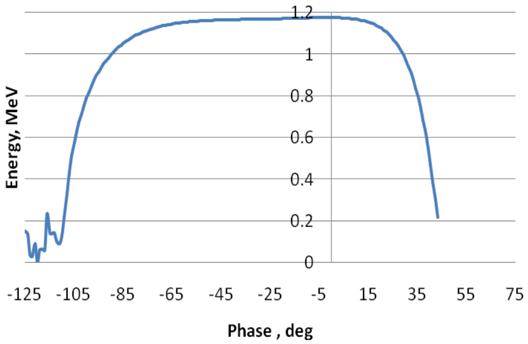

Figure 8: Energy versus cavity phase scan for the reference particle.

Table 1: Sensitivity of the Output Beam on Cavity Field and Gun Voltage

Max Field, MV/m	E, MeV	Iout, mA	Spot Size, mm
20 (nominal)	1.08	70	1.6
+10 %	+11 %	-4 %	+58 %
-10 %	-27 %	-33 %	-55 %
Gun Voltage,kV	**E, MeV**	**Iout, mA**	**Spot size, mm**
17 (nominal)	1.08	70	1.6
+10 %	+0.8 %	-3.5 %	+48 %
-10 %	-7 %	-20 %	-15 %

CONCLUSION

RF design of a low energy linac has been carried out using Microwave studio and ASTRA codes. The cavity design is a compromise among several factors such as the field stability, compactness, mechanical strength and fabrication cost. With under 0.5 MW input power, the poposed linac will accelerate a 17 keV beam to 1 MeV, 1.6 mm spot over a length of 130 mm. The structure is currently being fabricated by Shakespeare Engineering (UK) and is in the brazing stages with the high power commission anticipated to take place in the next months.

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