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SIMULATIONS OF THE SUITABILITY OF A DC ELECTRON PHOTOGUN AND S-BAND ACCELERATING STRUCTURE AS INPUT TO AN X-BAND LINAC

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Abstract

Work has been underway for some time to design a compact electron beamline utilising X-band linear accelerating structures in the new Melbourne X-band Laboratory for Accelerators and Beams (X-LAB). The original design utilised an S-band RF photogun as an input to a pair of high gradient X-band linear accelerating structures, but we have been motivated to investigate an alternative starting section to allow for initial testing. This will utilise a DC photogun and S-band accelerating structure similar to those used at the Australian Synchrotron. Simulation results incorporating space charge of a beamline composed of a DC photogun, S-band accelerating structures, and two high gradient X-band structures will be presented. These simulation results will be optimised for minimum emittance at the end of the beamline.

INTRODUCTION

As part of the arrival of the X-Box test stand at the University of Melbourne we have been planning a beamline that can be installed in the University of Melbourne X-LAB accelerator hall utilising X-band RF accelerating cavities of a similar design to the structures used by the compact linear collider [1, 2].

For optimal beam capture and acceleration an RF photogun is planned as an injector, but in this document we investigate the possibility of integrating a relatively low-cost alternative for use during commissioning, that is a 100 keV DC photogun. However, the use of non-relativistic electrons ($\beta \approx 0.55$) will cause acceptance, capture, and acceleration issues as the X-band structures are matched to $\beta \approx 1$.

To alleviate this, we have investigated the possibility of using an S-band RF buncher available locally to increase the energy of the bunch to an satisfactory level for acceptance.

X-BAND RF ACCELERATING STRUCTURE ACCEPTANCE

The X-band structure in question is a TW X-band structure operating at 11.9942 GHz similar to the CLIC T24 structure [3]. Following simulation in CST Microwave Studio [4] its fieldmap is exported for further use in simulations, and can be seen in Figure 1. At this stage in Melbourne X-LAB planning it is estimated to be fed 20 MW of RF power, yielding an average accelerating gradient of 70 MW m^{-1}, with a maximum gain per structure of approximately 17.5 MeV.

To demonstrate the acceptance issues we shall show results from single particle tracking simulations using the code ASTRA [5]. We use single particle simulations for this section due to their simplicity, and ease of cross checking by numerical integration. Although we neglect whole bunch dynamics at this stage it is very unlikely for a whole bunch to pass through without issues if it a single particle can't.

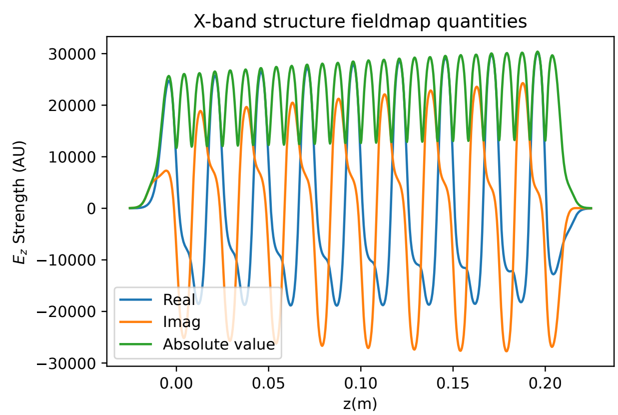

Figure 1: X-band structure fieldmap used.

To investigate acceptance we simulate a single on axis electron multiple times, for different initial Kinetic Energies (KE) and structure phases in increments of 1°. A particle is deemed to have passed though if it reaches the other end of the accelerating structure, and its longitudinal momentum p_z has not dropped below 200 keV c^{-1} (KE 37.75 keV). This threshold was chosen after inspection of multiple simulations to give good separation between simulations where the particle passes through or is brought to near halt.

In Figure 2 we present a combined plot showing the number of simulations deemed to have passed according the previous criteria for a given initial KE, and the maximum energy gain for a given initial KE. The range of phase acceptance (acceptable starting phases), in blue, is calculated by counting the number of simulations where a particle is transmitted for the given initial energy. We see that we need an initial energy of approximately 150 keV to have any phase range acceptable for transmission, and then as KE increases the entire phase range is allowed for transmission. We specifically note that this is for transmission only, not acceleration;

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a 1 GeV particle would be able to pass through for all phases, but only roughly half would result in any nett energy gain. The orange scatter plot demonstrates the maximum energy gain, out of all phases, for a given initial KE, and we see we can achieve near maximal energy gain above initial KEs of 500 keV.

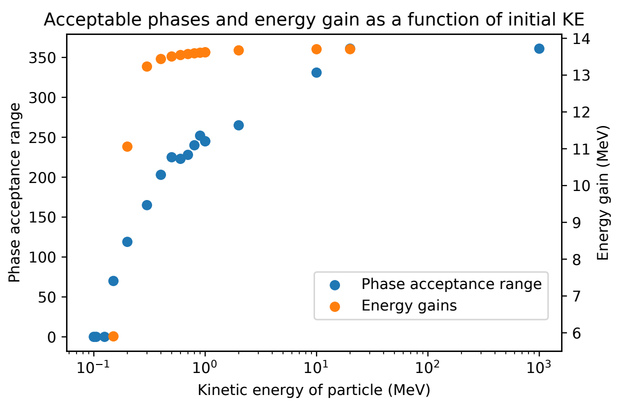

Figure 2: Acceptable for transmission phase range, and maximum energy gain for a given initial kinetic energy.

In Figure 3 we show the momentum change of a single particle just as it enters the accelerating structure for different initial KE, where the phasing of the X-band structures has been set for maximum energy gain or greatest depth for the KE=0.1 MeV case. We see that for an initial KE less than or equal to 0.5 MeV there is a initial decrease in momentum the particles are accelerated, whereas for the case of KE=1000 MeV acceleration starts almost immediately. For less than KE<0.5 MeV we view this as a case of phase slippage, where the particles arrive ahead of the accelerating crest in the non-beta matched first cell.

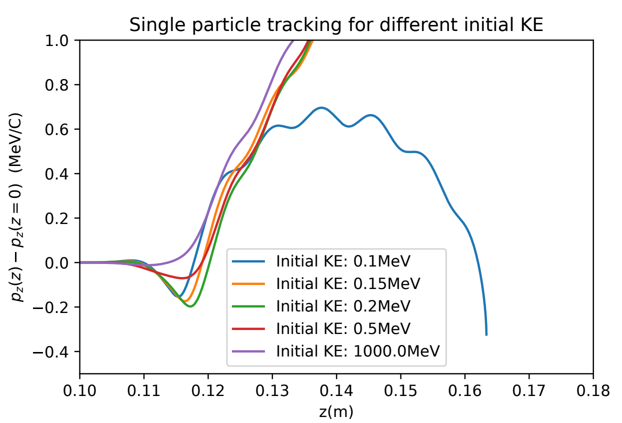

Figure 3: Trajectory of single particles for different initial energies.

To summarise; if we were to use a 100 keV DC photogun we would need an extra energy boost to at least 500 keV, thus motivating the use of an additional accelerating section before the X-band structures. Additionally, concerns about bunch lengthening also motivate the use of that section to also re-bunch the beam.

Table 1: Initial Conditions and Simulations Parameters

Parameter	Value
Bunch charge	1 pC
Number of macro particles	10000
Transverse shape	2D Gaussian cutoff at $2\sigma_x$
Transverse dimension (σ_x)	0.25 mm
Longitudinal shape	Gaussian in time
Pulse Length (σ_t)	100 fs

DC PHOTOGUN SIMULATION

In the following simulations we consider a 100 keV DC photogun with a focusing solenoid magnet with peak field 0.042 T. We note in contrast to the first section we will now be considering multi-particle simulations with space charge effects present. The magnetic field has been optimised to minimise the transverse emittance of the bunch downstream of the gun. The initial bunch has the parameters in Table 1:

Plots of how the beam size and emittance develops can be seen in Figure 4, and were generated by the code ASTRA.

We note that although this configuration results in low transverse emittance bunches that focuses to an RMS size of 100 µm, we have a growing Z RMS. Also, the Z RMS at the focal point of approximately 1 mm would correspond to a phase difference of 14.4° at X-band wavelengths, strongly motivating rebunching the beam.

S-BAND BUNCHER

To provide the energy boost required for acceptance of the bunch into the X-band accelerating structures we investigate the use of an S-band buncher similar to those already present at the Australian Synchrotron. This was remodelled using CST Microwave Studio and the fieldmap exported for use in the code ASTRA. The CST model can be seen in Figure 5.

This is a four cell constant impedance S-band (2.9979 GHz) travelling wave operating in $\frac{2\pi}{3}$ mode with an average gradient of 7 MV m^{-1} and a total cell length of 80 mm. This structure has a design phase velocity of 0.6 c, and and is thus adequately matched to a kinetic energy 100 keV ($\beta \approx 0.55\,c$).

PROPOSED BEAMLINE CONFIGURATION

We present a configuration of the DC photogun, S-band buncher, and two X-band accelerating structures in Figure 6 that produces a low and stable emittance bunch with kinetic energy of approximately 27.29 MeV. This configuration was found by iterative optimisation of the position and phase of the buncher and X-band accelerating structures through successive simulations in ASTRA with space charge effects present.

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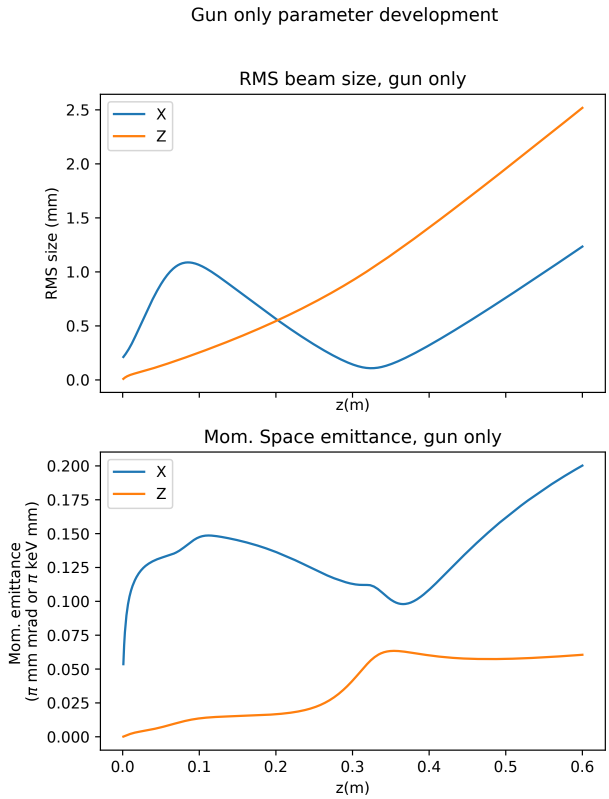

Figure 4: Gun only RMS and emittance development.

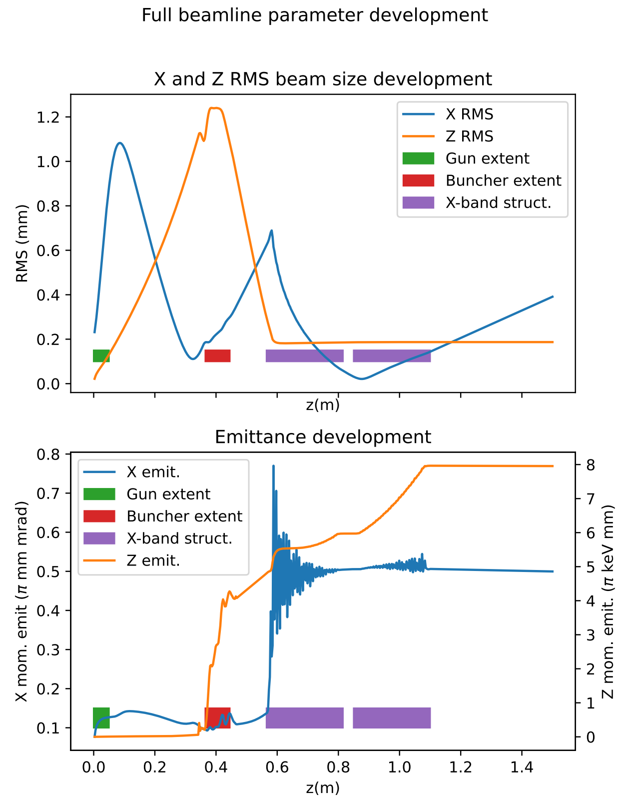

Figure 6: Development of bunch RMS and emittance through beamline.

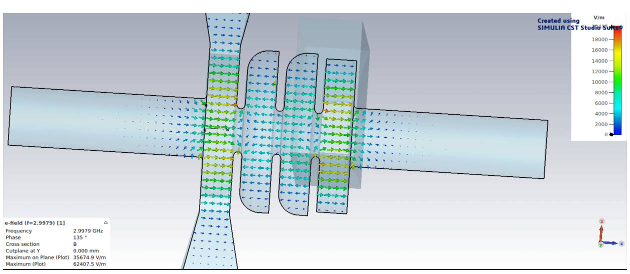

Figure 5: 3D model of buncher.

DISCUSSION

We have been able to demonstrate that the addition of the S-band buncher to the DC photogun is able to boost the energy of the bunch to the point where it can be accepted and accelerated by the X-band structures.

With regards to the suitability of this beamline, two future applications have been discussed so far; one is for dosimetry studies involving biological, and industrial samples, and other was as an electron source for an Inverse Compton Scattering light source. In the first case, as long as the beam size is amenable to the sample, the main performance characteristics are energy, bunch charge, and repetition rate. Although we will not discuss the repetition rate of the entire line, the beamline presented here would be appropriate for accelerating bunches.

With regards to using the beamline as an electron source suitable for an Inverse Compton Scattering light source, one of the design goals is to minimise the transverse emittance so that we may focus the bunch to a small interaction point, thus maximising scattering. The transverse emittance here of approximately 0.5 π mm mrad is comparable to what may have been achieved with an RF photogun, but with a smaller bunch charge (1 pC here, compared to 100 pC elsewhere).

In both cases this would be sufficient to commission the beamline, to test downstream diagnostics and feedback systems, systems for laser alignment, and to perform early test experiments.

We also note that this investigation has not considered the practical implications of two separate devices versus a single one, nor of working with two separate frequencies and klystron feeds. A possible future development here is to investigate the use of a custom designed and appropriately matched X-band boost cavity instead of the S-band buncher presented here.

CONCLUSION

We have been able to demonstrate issues with the X-band structures in accepting 100 keV electrons. Although far from ideal, we have also shown that the addition of an extra bunching cavity gives an extra energy boost that allows for acceptance. Although the bunch charge will be low it is possible to generate and preserve low emittance bunches for early commissioning and testing.

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