Beamline simulations for the University of Melbourne X-LAB

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The University of Melbourne

Collaborators

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University of Melbourne X-LAB

- The University of Melbourne X-band Laboratory for Accelerators and Beams (X-LAB) is a new facility based at the University of Melbourne planning to condition and conduct research into X-band accelerating structures.
- For further information see the previous talk by M. Volpi *Commissioning of X-LAB: a very high-capacity X-band RF test stand facility at the University of Melbourne* at 2023-04-12 14:00.
- One of the long term goals of the group is to design and install a compact low emittance beamline based around high gradient X-band linear accelerating structures.

The X-LAB beamline hall and X-LAB compact beamline

Some quick specifications of the beamline and simulations:

- Total beamline length must be less than 8 m.
- Repetition rate of X-band infrastructure is 400 Hz.
- 40 MW total power expected to be allocated between up to two X-band RF accelerating structures, similar in design to CLIC T24. Average gradient of approximately 70 $\mathrm{MV\,m^{-1}}$ expected.
- Overall goal of the beamline is the consistent production of low transverse emittance bunches, with bunch charge and energy to be maximised as appropriate
- Eventual applications of the beamline are as an electron source for a possible Inverse Compton Scattering (ICS) light source or for dosimetry studies.

University of Melbourne X-lab - Future beamline hall

Figure 1: Beamline hall, a little over 8 m long

General beamline layout

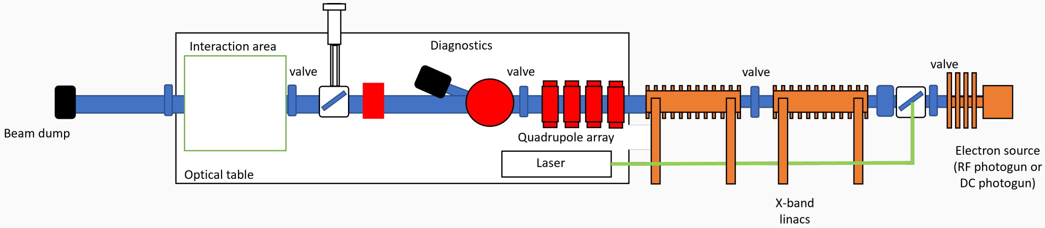


Figure 2: General beamline layout

Simulation pipeline

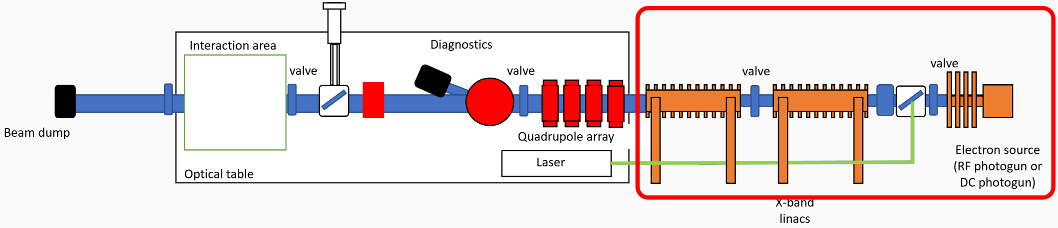
Simulation inputs Fieldmaps for focusing solenoid and accelerating cavities simulated in CST Microwave Studio and exported or provided by supplier..

Preinjector stage Macroparticle tracking simulated in ASTRA (A Space Charge Tracking Algorithm) using exported fieldmaps, full 3D space charge used. Python and associated libraries used to batch multiple runs and carry out parameter optimisation. Multiple configurations have been simulated.

Focusing stage Particle distributions converted for use in ELEGANT (ELEctron Generation ANd Tracking), a (mostly) ray optics based tracker. Quadrupole strengths optimised to minimise transverse bunch size at interaction point.

ICS/user area stage ICS simulations carried out using the Particle In Cell (PIC) code CAIN.

Preinjector configurations



Preinjector configurations

Three preinjector configurations with different initial electron sources have been investigated so far, with different tradeoffs

S-band RF photogun A conventional choice for a low emittance beamline, but would require additional high power S-band RF infrastructure. Simulated with bunch charge of 100 pC

100 keV **DC photogun with additional S-band bunching section** An additional configuration that was investigated that would require less extensive S-band RF infrastructure. Simulated with 1 pC

100 keV **DC photogun with modified X-band accelerating cavities** Another configuration investigated that would not require additional RF infrastructure. Simulated with various bunch charges and initial laser spot sizes.

Preinjector config 1 - S-band RF photogun

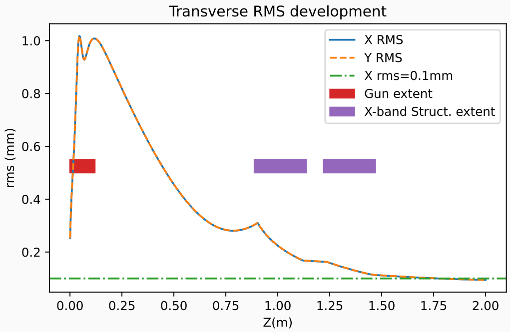


Figure 3: Bunch transverse size development.

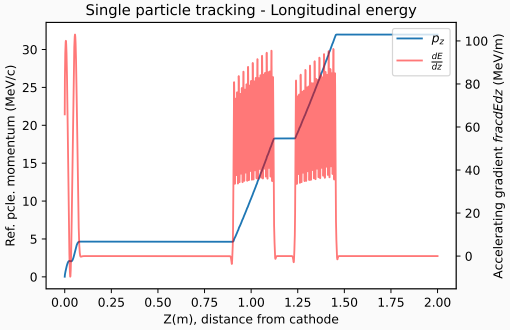


Figure 4: Results of single particle tracking, indicating energy gain and gradient

Preinjector config 1 - S-band RF photogun

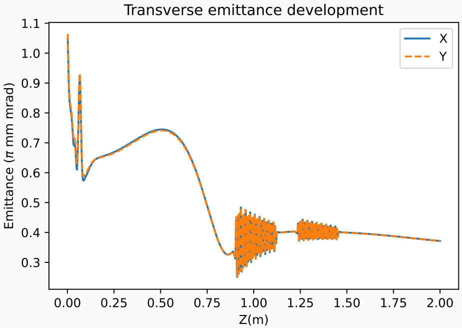


Figure 5: Bunch trans. emit. development.

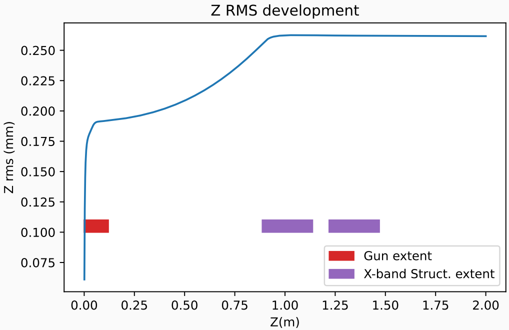


Figure 6: Bunch long. size development.

This configuration represents a conventional configuration of a low emittance beamline, but would require significant additional infrastructure procurement.

Preinjector config 2 - DC photogun with S-band buncher

- S-band buncher used for small energy gain for acceptance into X-band structures.
- Simulations initially carried out for 1 pC bunch charge as a proof of concept. Increasing bunch charge would be a goal of further simulations.
- This configuration was initially investigated to check for alternatives for S-band photogun that would allow for swift commissioning of X-LAB beamline.

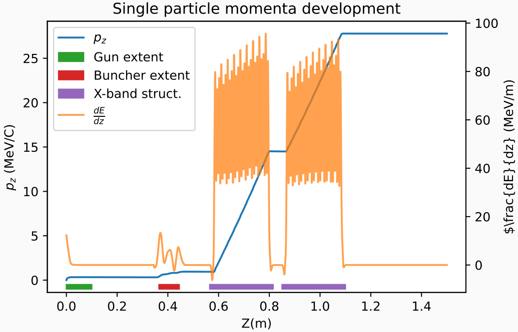


Figure 7: Results of single particle tracking, indicating energy gain and gradient.

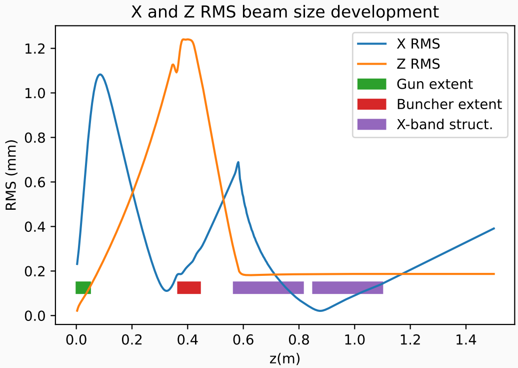


Figure 8: Bunch transverse size development.

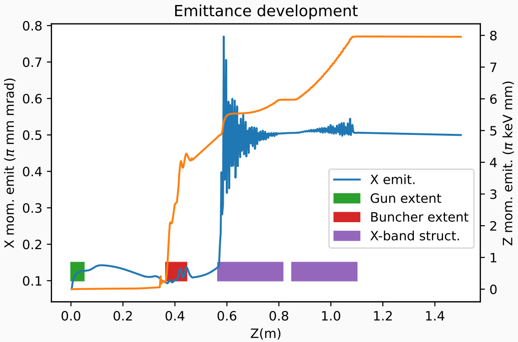


Figure 9: Bunch emittance development.

Preinjector config 3 - DC photogun with modified X-band accelerating structure

- The goal of this configuration was to check if we could design a beamline based around only two X-band accelerating structures to minimise required infrastructure.
- Key difference is that the first X-band accelerating structure has the first few cells modified for low β particle acceptance.
- Other sites taking a similar approach use an extra X-band RF buncher between the DC photogun and low β acceptance X-band structure. We have investigated performance without an extra buncher, but this can cause issues where space charge causes longitudinal extension of the bunch over too large a phase range.
- Multiple simulations have been run with different initial parameters to analyze the tradeoffs between bunch charge and final transverse emittance.
- Two approaches made - limiting bunch charge and keeping laser spot size small, and defocusing the laser to reduce effect of space charge allowing for larger bunch charges

Preinjector config 3 - DC photogun with modified X-band accelerating structure

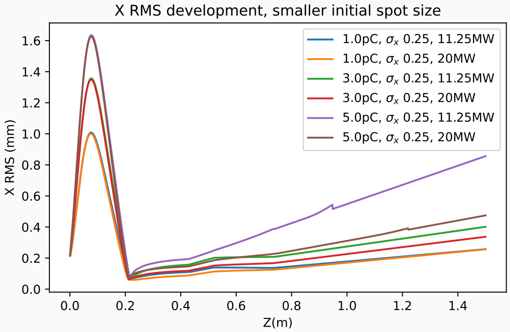


Figure 10: Legend colours are similar for all small initial spot size plots

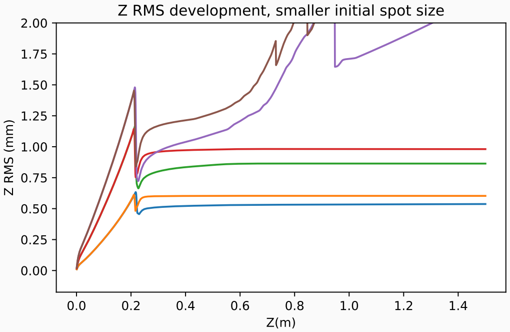


Figure 11: 5 pC simulations included to show bunch is becoming unsuitable for acceleration

Preinjector config 3 - DC photogun with modified X-band accelerating structure

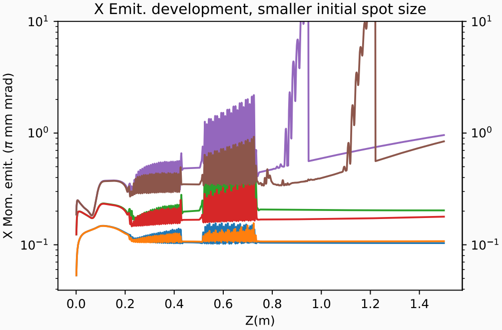


Figure 12:

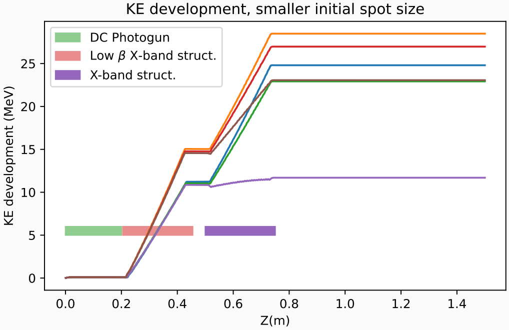


Figure 13:

Preinjector config 3 - DC photogun with modified X-band accelerating structure

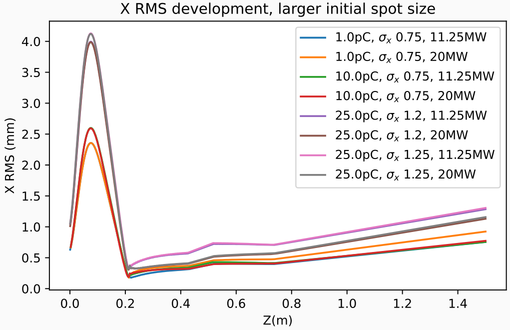


Figure 14: Legend colours are similar for all larger spot size simulations

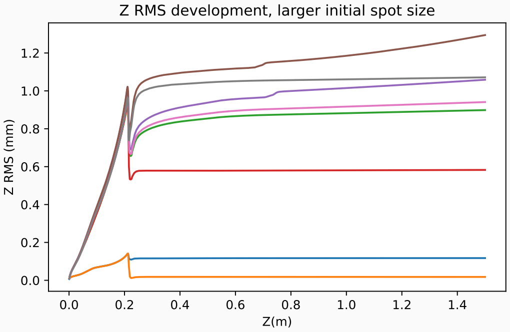


Figure 15: 25 pC simulations are on edge of acceptance, due to transverse size considerations.

Preinjector config 3 - DC photogun with modified X-band accelerating structure

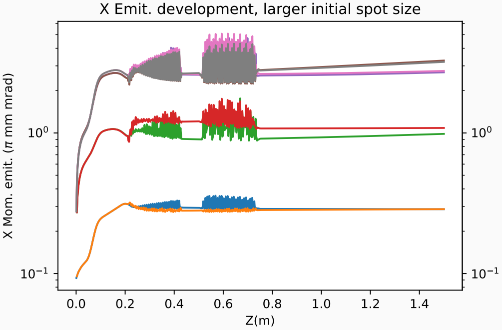


Figure 16:

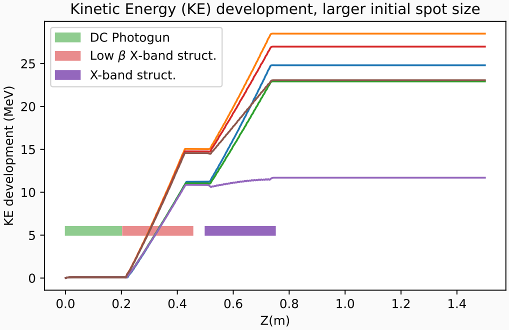
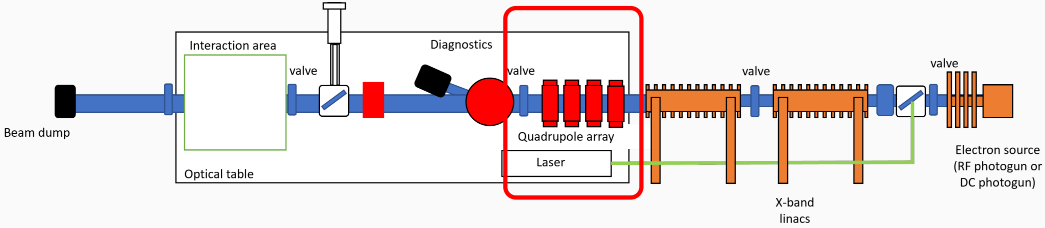


Figure 17:

Preinjector configurations

- Three different configurations with different tradeoffs have been investigated.
- These simulations will inform the final layout of the X-LAB compact beamline.
- Currently investigating using the third configuration, while the possibility of later including an RF photogun is assessed.

Focusing section



Focusing section

- Using 'ELEGANT', our approach is to find a configuration(s) of quadrupole strengths that minimise the transverse size of the bunch at some position. We'll then use this/these configuration(s) to inform a mechanical specification later.
- The Scipy implementation of the differential evolution optimisation method to minimise the transverse beam size at a given distance from the array.
- We use some Python code to wrap up the process of generating new input files (via Jinja2), running each simulation, and return the RMS size at the focus as a float. Calls to the standard multiprocessing library also allow us to parallelise this across multiple CPU cores.

Focusing section

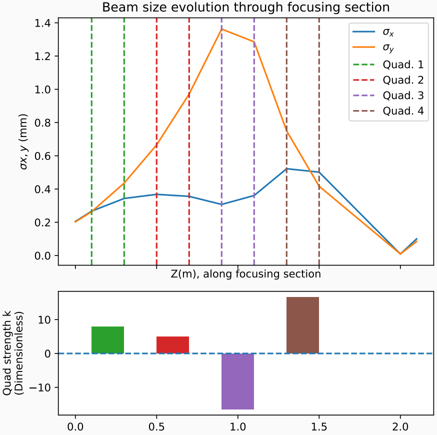
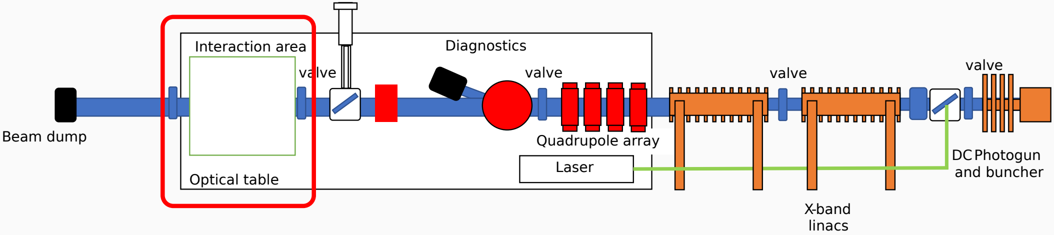


Figure 18: Transverse beam RMS size through focusing array for preinjector configuration 2

ICS section



Interaction area
Diagnostics
valve
valve
valve
valve
Beam dump
Quadrupole array
Laser
Optical table
DC Photogun
and buncher
X-band
linacs

ICS simulations

- Overall design conceptual at this stage; no long commitments made towards laser.
- For these photon production simulations we consider a laser similar to that used by the ThomX project to establish an optimistic estimate of the photons that could be produced.
- Used as a performance characteristic so that we can evalute the tradeoffs of different designs; eg. the tradeoff between a tight focus (for enhanced photon production) versus a less divergent beam.
- Preliminary plots shown for preinjector configuration 2.

ICS simulations - Single crossing energy distribution

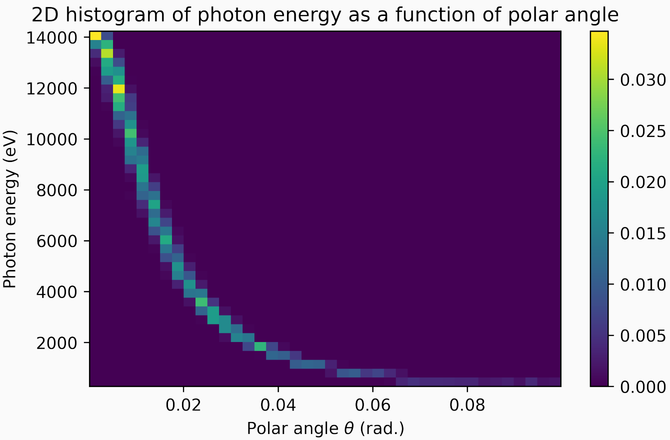


Figure 19: Expected energy and polar angle distribution for configuration 2. Color indicates probability density. Expected photons per crossing at 1 pC approximately 14000.

ICS simulations - photon production vs transverse bunch size at focus

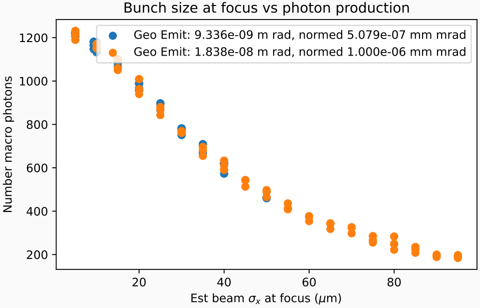


Figure 20: Photon production versus transverse bunch size at IP (macro particles)

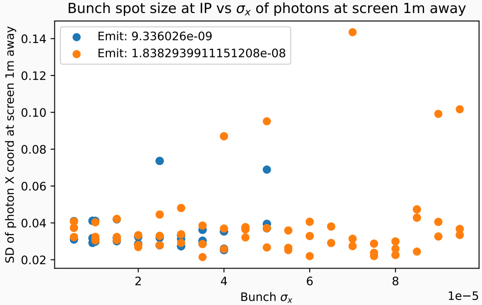


Figure 21: σ_x of photons at screen 1m away

Although preinjector configurations have been designed to minimise transverse emittance, we will need to investigate the effect on photon production and divergence.

Conclusion

- Proposed beamline for the University of Melbourne X-LAB is being simulated, simulations beyond the preinjector stage are maturing as we speak.
- Various electron preinjector configurations have been simulated, each with different tradeoffs.
- These simulations will inform the final design plan of the University of Melbourne X-LAB compact X-band beamline.