Simulations and design of a compact beamline at the University of Melbourne X-lab

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October 17, 2022

Collaborators

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University of Melbourne X-lab

- The University of Melbourne X-lab is a new facility based at the University of Melbourne planning to condition and conduct research into X-band accelerating structures
- Made possible with the generous assistance of CERN and their offer of part of their surplus X-band ($11.9942\,\mathrm{GHz}$) test station infrastructure. This includes RF modulators, RF accelerating cavities, klystrons, and other associated infrastructure.
- The lab refurbishment is complete and this infrastructure is being installed and commissioned as we speak.
- For further information on the physical setup, please see the talk by M. Volpi *The southern hemisphere's first X-band radio-frequency test facility at the University of Melbourne*." at 2022-10-18 1220 (Tuesday).
- 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.

University of Melbourne X-lab - From CERN

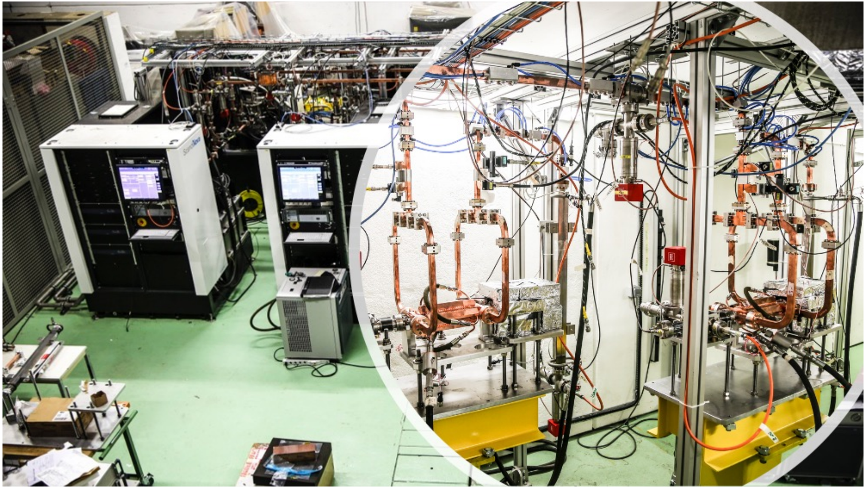


Figure 1: From in place at CERN

University of Melbourne X-lab - To Melbourne

Figure 2: To ready to unpack at the University of Melbourne

University of Melbourne X-lab - To installation

Figure 3: Installation and commissioning at the University of Melbourne

University of Melbourne X-lab - Future beamline hall

Figure 4: Beamline hall

University of Melbourne X-lab - Layout

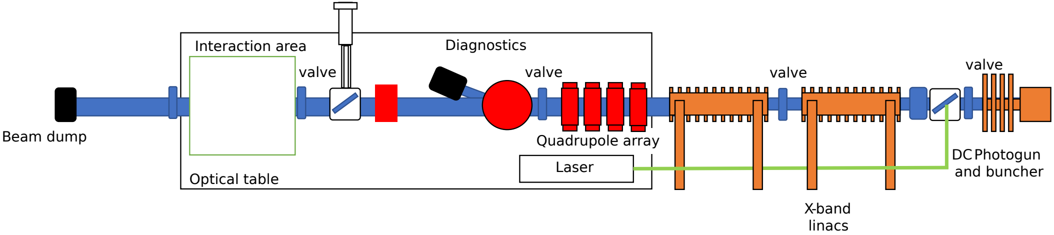


Figure 5: A simplified beamline layout, and some of the associated infrastructure we'd like to include

The proposed beamline

- We're currently in the process of creating the conceptual design report for a beamline in the hall
- Potential use cases include radiation dosimetry or a potential Inverse Compton Scattering (ICS) light source.
- The conventional approach would be to use an RF photogun, but for commissioning we will investigate the use of a DC photogun with additional bunching section.

The proposed beamline

Electron source A 100 keV DC photogun with an additional S-band buncher

- Originally the plan was to use an S-band RF photogun, but due to changed circumstances we will use this configuration for initial commissioning.
- The buncher not only compresses the beam, but also adds a small energy boost for acceptance into the X-band structures.
- The buncher investigated will be similar to and based on those at the Australian Synchrotron.

Main acclerating section Two high gradient X-band accelerating structures operating an expected average gradient around $70\,\mathrm{MV\,m^{-1}}$

A quadrupole focusing array Used to focus the beam after the initial accelerating section

User area A section for user experiments or ICS

The simulation pipeline

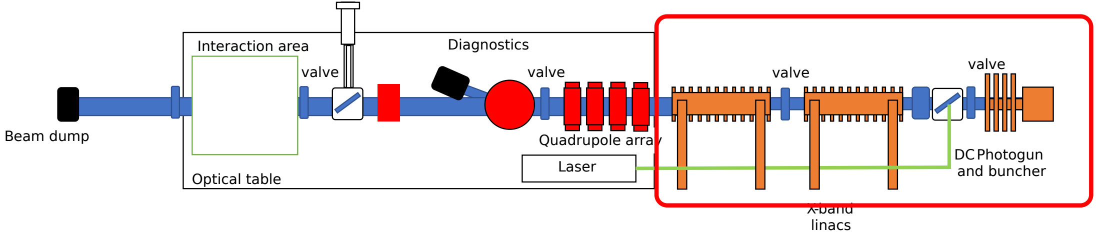
- Buncher fieldmap, accelerating structure fieldmaps
  - Buncher recreated from scale drawings, simulated in CST Studio
  - X-band structures simulated in CST Studio from original drawings/step files
- Initial particle tracking through accelerating stages performed in Astra, Opal-T used for cross check
  - Full 3D space charge simulation
- Tracking through quadrupole array performed using 'Elegant'
  - Optimisation of quadrupole array parameters using the Scipy differential evolution method, due to convergence issues with the 'Elegant' simplex method
- ICS simulations performed using 'CAIN'
  - Electron/Photon scattering code developed by Yokoya K.
  - Unsupported for many years
- Other optimisation, pipelining and automation code written in Python utilising the libraries Jinja2, numpy, scipy.

Beamline specifications

Some quick specifications for the simulations we'll be presenting

- 100 keV DC photogun, TW S-band buncher stage with average gradient of 7 $\mathrm{MV/metre}$ and length of 120 mm, two TW X-band RF accelerating structures with an average gradient of 70 $\mathrm{MV\,m^{-1}}$ and length of 250 mm
- Initial Gaussian laser spot size of 250 $\mathrm{\mu m}$ cut off at twoσ and pulse duration of 100 fs
- 1 pC bunch charge used for initial simulations, though this can be increased
- Final bunch energy of approximately 27 MeV, with transverse emittance of $0.5\pi\,\mathrm{mrad\,mm}$.
- Repitition rate of X-band infrastructure is 400 Hz
- Length of beamline must be less than 8 m

Beamline acceleration stage



Beamline acceleration stage - acceleration and momenta

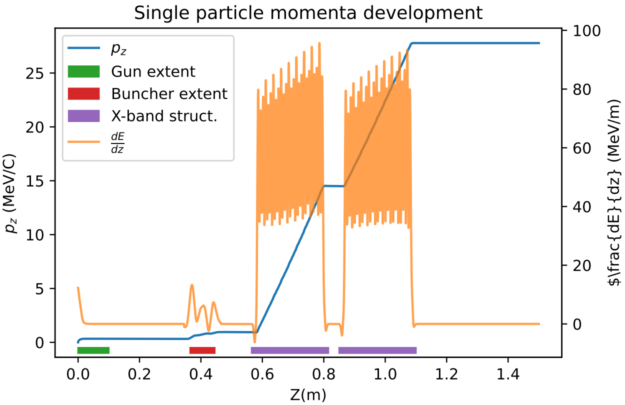


Figure 6: Accelerating gradients and partice momenta

Beamline acceleration stage - RMS size and emittance

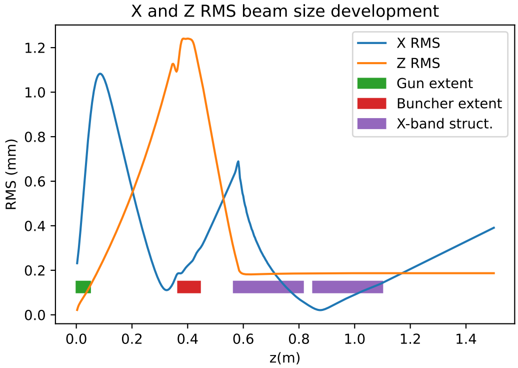


Figure 7: RMS size of bunch during the acceleration stage

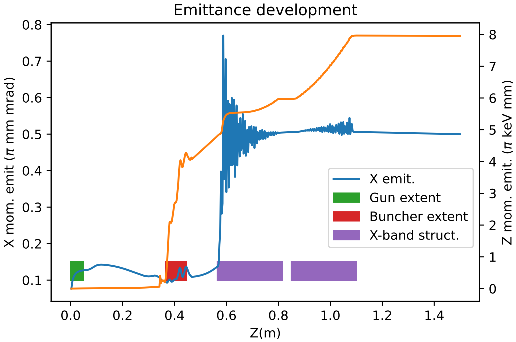
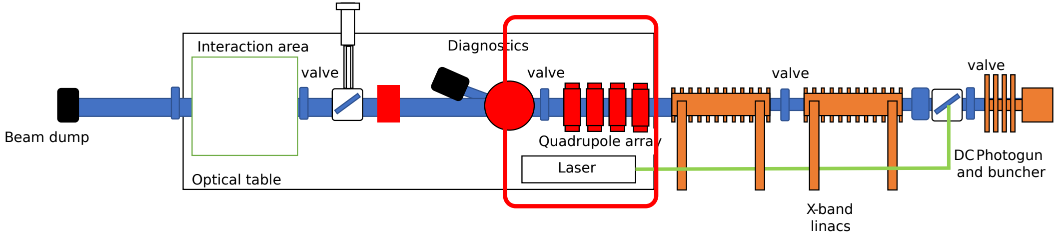


Figure 8: Emittance (normalised) of the bunch during the acceleration stage

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.
- Simplex optimiser in 'Elegant' is unsuitable for this, due to large space to sample and small sampling frequency required
- Instead, we 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

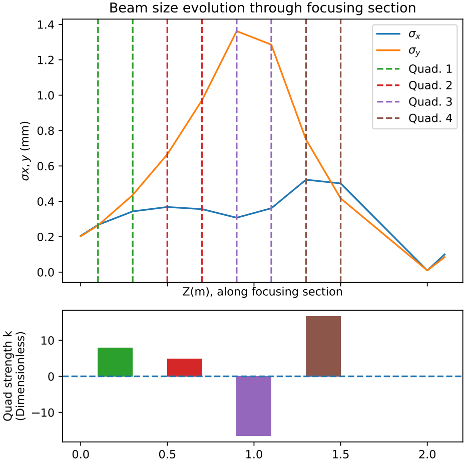
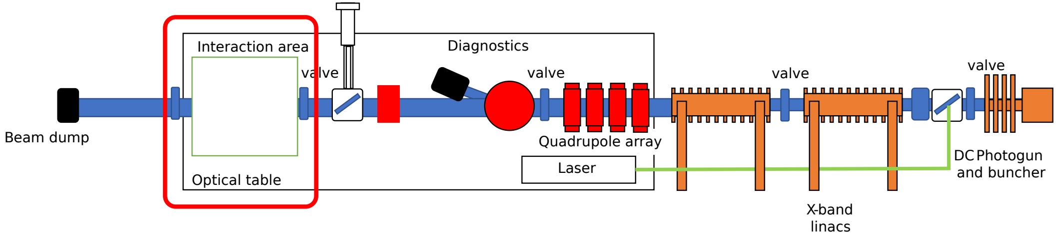


Figure 9: Transverse beam RMS size through focusing array

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

ICS simulations - photon production vs transverse bunch size at focus

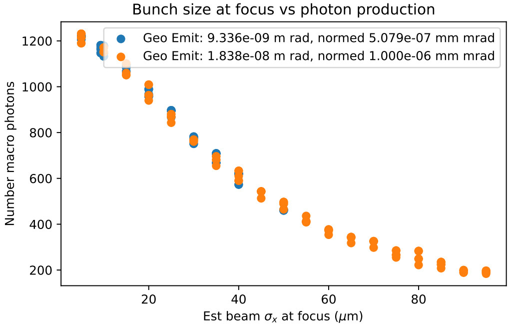


Figure 10: Photon production versus transverse bunch size at IP

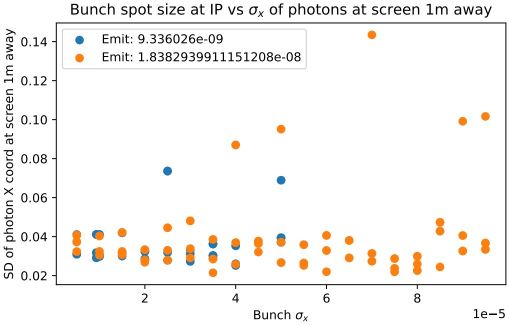


Figure 11: σ_x of photons at screen 1m away

For various beam sizes we can evaluate photon production rates, and look at how this may affect spot size of produced X-rays at a screen $1\,\mathrm{m}$ away

Beamline alternatives

We're also considering some other variations of the beamline

- Three quadrupoles instead of four.
- Instead of the S-band buncher, consider an X-band buncher or low β accepting X-band structure.
- S-band or X-band RF photoguns.

Conclusion

- Beamline simulation progressing to final stages
- Still to optimise for final ICS photon production
- Some alternative layouts being evaluated

Fin

Backup

Backup - Stability

Monte-Carlo estimate of transverse beam size for 1% error in magnet strength values.

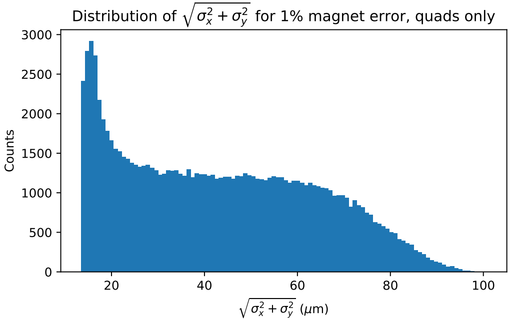


Figure 12: Distribution of size at focus

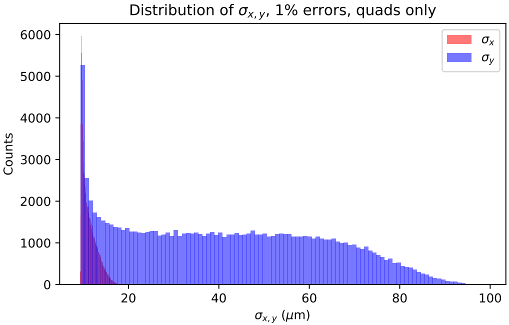


Figure 13: Distribution of σ_x, σ_y at focus

Backup - Stability

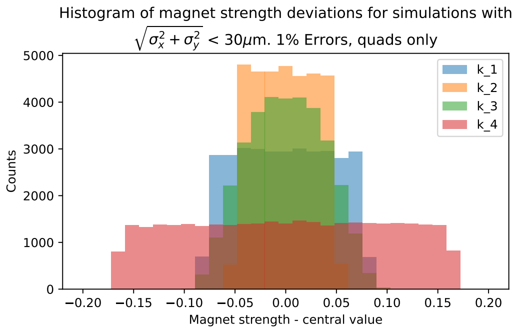


Figure 14: Distribution of magnet strengths for $\sqrt{\sigma_x^2 + \sigma_y^2} < 30\,\mu\text{m}$.

Backup - Simulation convergence, fixed IP parameters

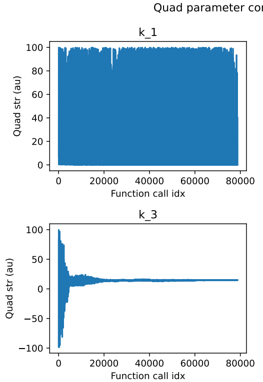


Figure 15:

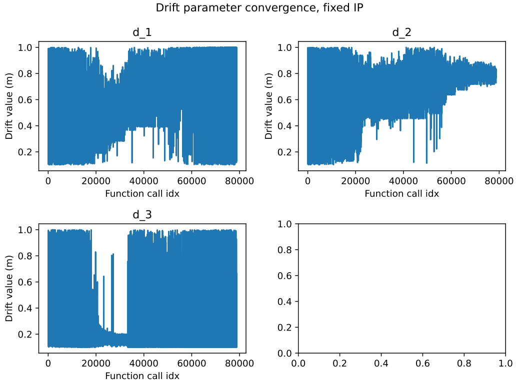


Figure 16:

By fixing one parameter we hurry along the optimiser significantly. Spends slightly less time wandering around, at least for magnet strengths, still a bit of wandering with drifts.

Backup - Simulation convergence, fixed IP parameters

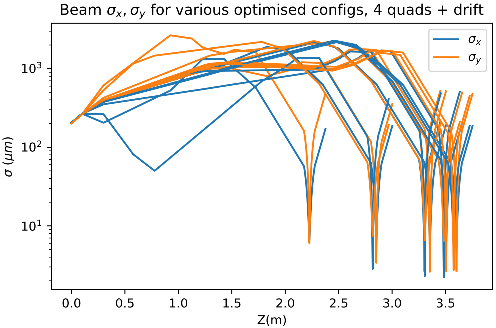


Figure 17:

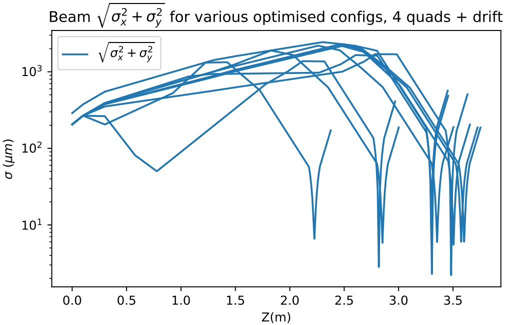


Figure 18:

For a bunch of optimised configurations, I've plotted RMS size development. Can see a couple of repeated configs.

Backup - Other beamline stats

- Total length of beamline presented here: $3.5\,\mathrm{m}$. Doesn't include diagnostics or beam dump.
- Quadrupole strength k: $k = \frac{e}{cp}\frac{\partial B_y}{\partial x} = \frac{e}{cp}\frac{\partial B_x}{\partial y}$