Design of the PERLE injector

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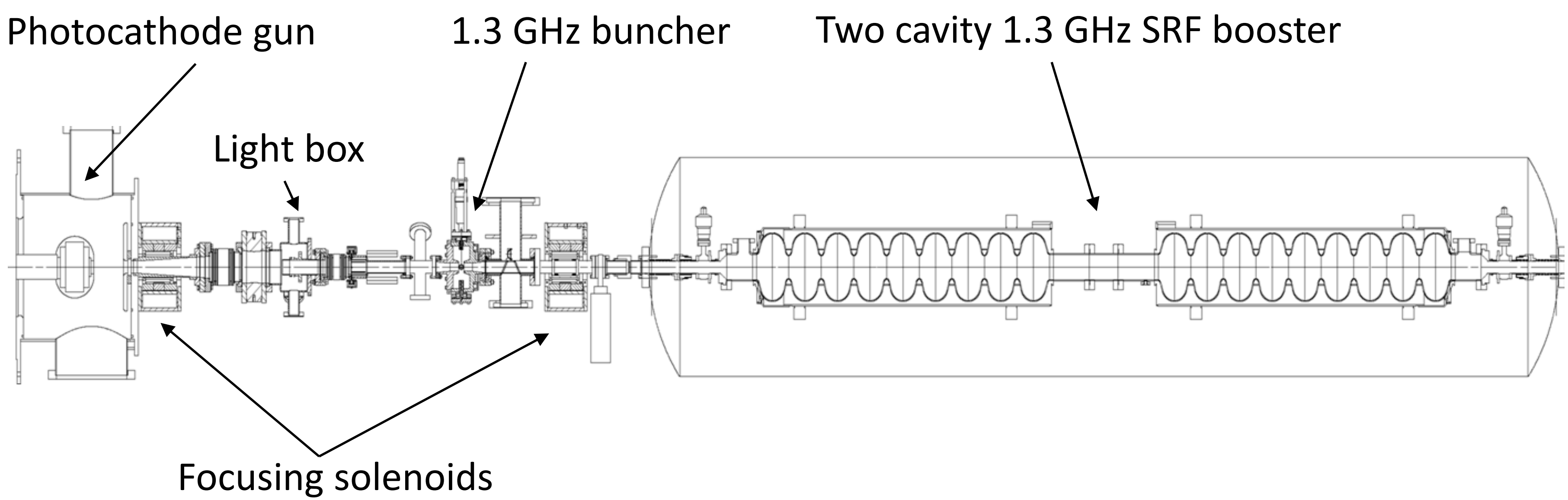
PERLE injector specification

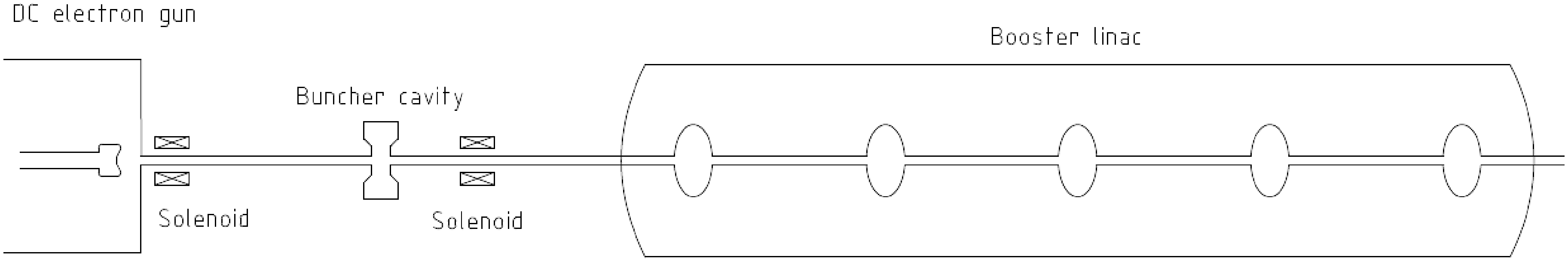
Parameters	
Injection energy	7 MeV
Bunch charge	500 pC
Current	20 mA
RMS bunch length	3 mm
Emittance	< 6 π·mm·mrad
Uncorrelated energy spread	< 10 keV

ALICE Injector layout



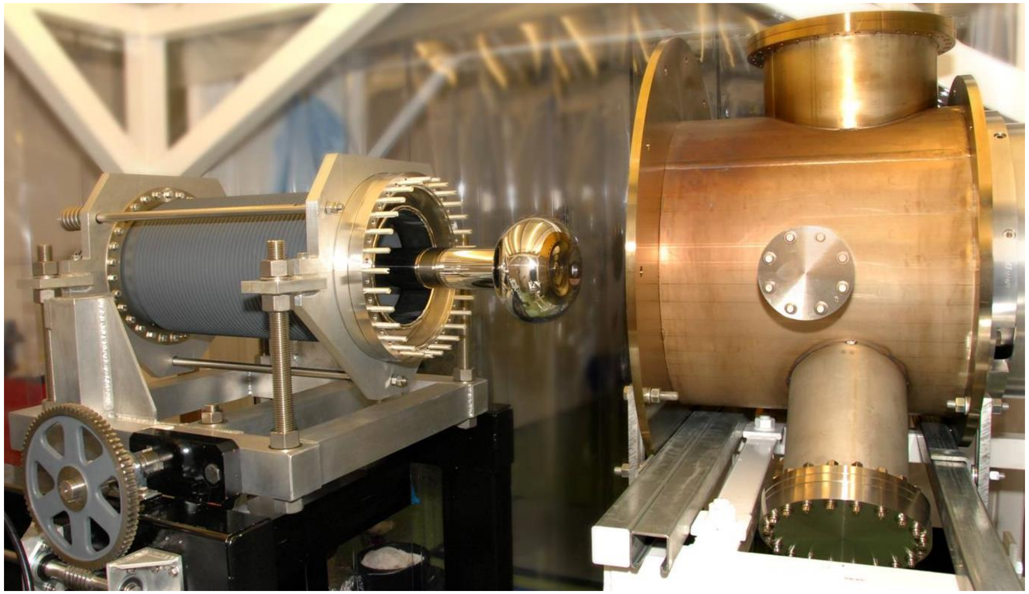
PERLE injector layout

- The PERLE injector consists of:
    - An upgrade of ALICE DC photoemission electron gun.
    - A bunching and focusing section consisting of a solenoid, 802 MHz normal conducting buncher cavity and then another solenoid.
    - A superconducting booster with 5 single cell 802 MHz cavities with individual control of the amplitudes and phases.
- Other elements such as Beam diagnostic must be placed between the components. This sets the lower limit on the size of the gaps. For the PERLE injector these values were determined based on the existing ALICE injector components.



ALICE photocathode gun

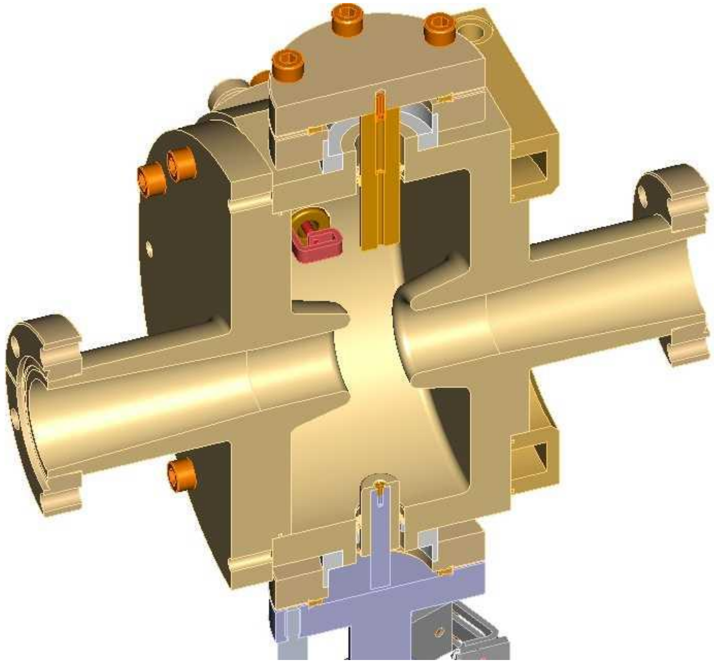
- The ALICE electron source was based on a 350 kV DC photocathode electron gun.
- The PERLE gun is based off a modified version of the ALICE gun and will also operate at 350 kV.
- The ALICE gun used a GaAs photocathode.



- It is currently being assumed that the PERLE gun will use a Sb-based photocathode.
- The ALICE laser system consisted of a 532 nm green laser which produced 7 ps pulses which could be stacked to deliver longer pulse lengths. In this work it is currently assumed that the laser pulse length for PERLE is also 28 ps.

Buncher

- The buncher cavity is an 802 MHz normal conducting cavity.
- The field map used for the beam dynamics simulations is a scaled version of the 1.3 GHz ALICE buncher.
- For the next iteration a more realistic buncher cavity design will be needed.
- The possibility of a 401 MHz cavity will be investigated and may help reduce the curvature of the longitudinal phase space.



1.3 GHz ALICE buncher

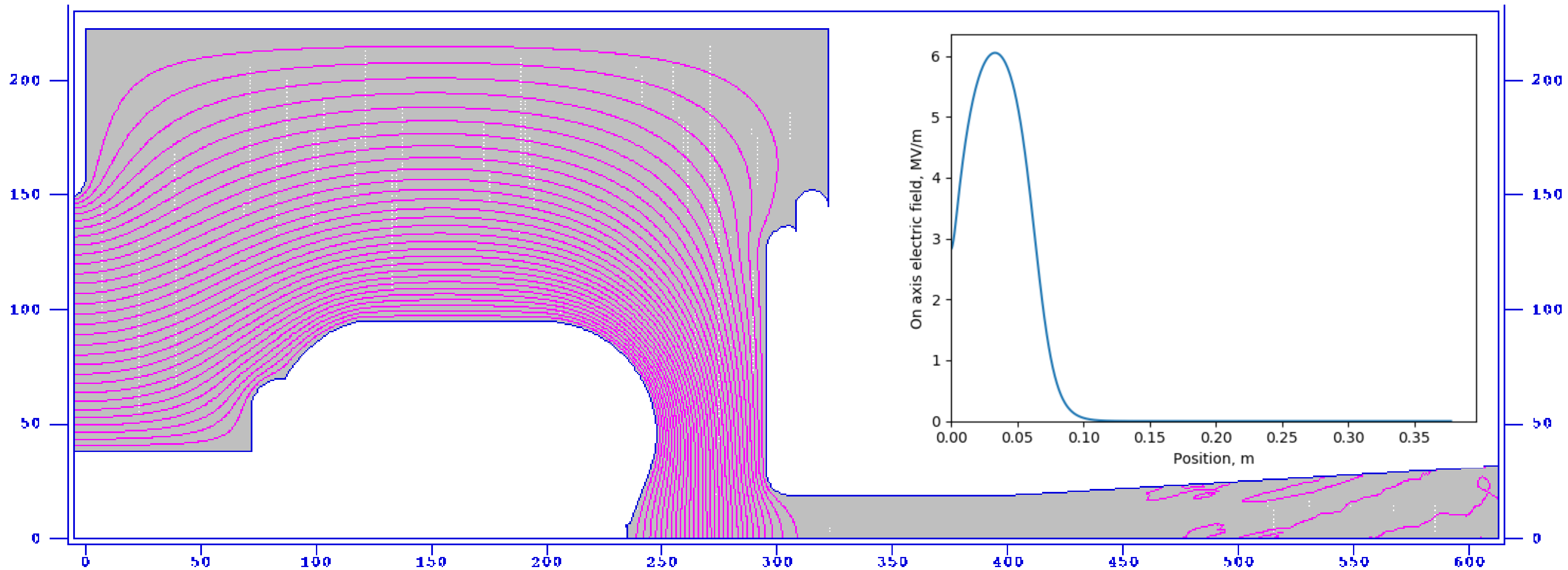
Booster

- Uses 5 individually controllable single cell superconducting 802 MHz cavities.
- Two options are considered for the cavities. An option with all β = 1 cavities and an option with all β = 0.8 cavities.
- The fieldmaps used in the simulation were provides by from TJNAF.
- The cryomodule design has not yet been completed so the positions used in the simulation are estimates.

ALICE upgrade gun

- The ALICE upgrade gun was designed for 80 pC with very modest emittance requirements. The PERLE injector requires a 500 pC bunch charge with more stringent emittance requirements. This means modifications are required.
- To increase the cathode field. The cathode-anode gap was closed until the maximum surface field on the electrode was just under 10 MV/m.
- This was done by moving the anode close to the cathode. While the cathode remained stationary.
- Eight variants with focusing electrode angles in the range 18°-25° were created.
- This angle was used as one of the variables in the optimisation.

Electric field in optimum gun electrode profile



Injector optimisation

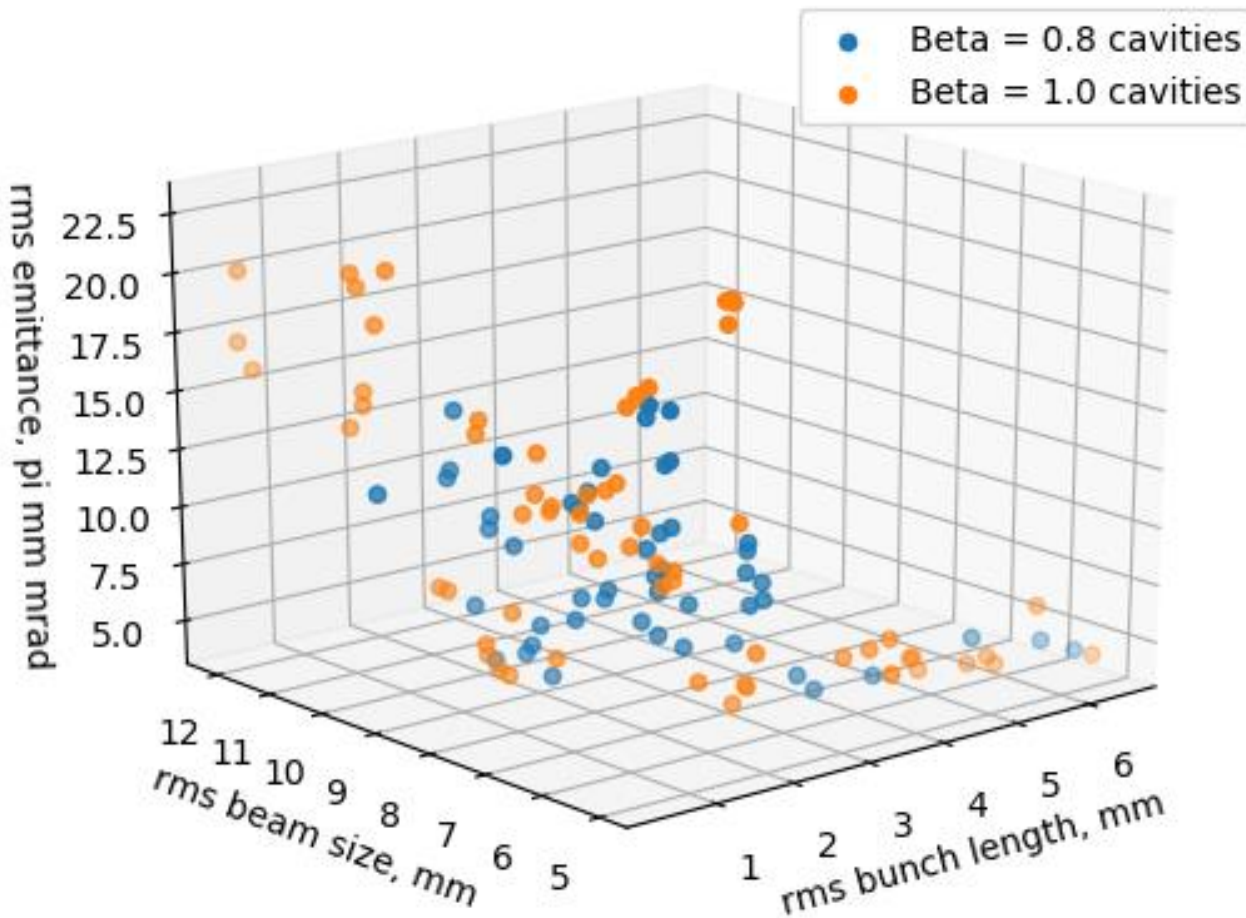
- The injector optimisation was carried out using NSGAII a widely used multi-objective genetic algorithm.
- The individual simulations were carried out with ASTRA. The particle count was set to 4096. The low particle counts kept the time required for the optimisation reasonable.
- A population of 100 individuals was used and the optimisation carried out for 250 generations.
- Three objectives:
  - Minimise rms transverse emittance
  - Minimise rms bunch length
  - Minimise transverse rms beam size at all points along the injector
- One constraint:
  - Final beam energy between 5-10 MeV

Optimisation parameters

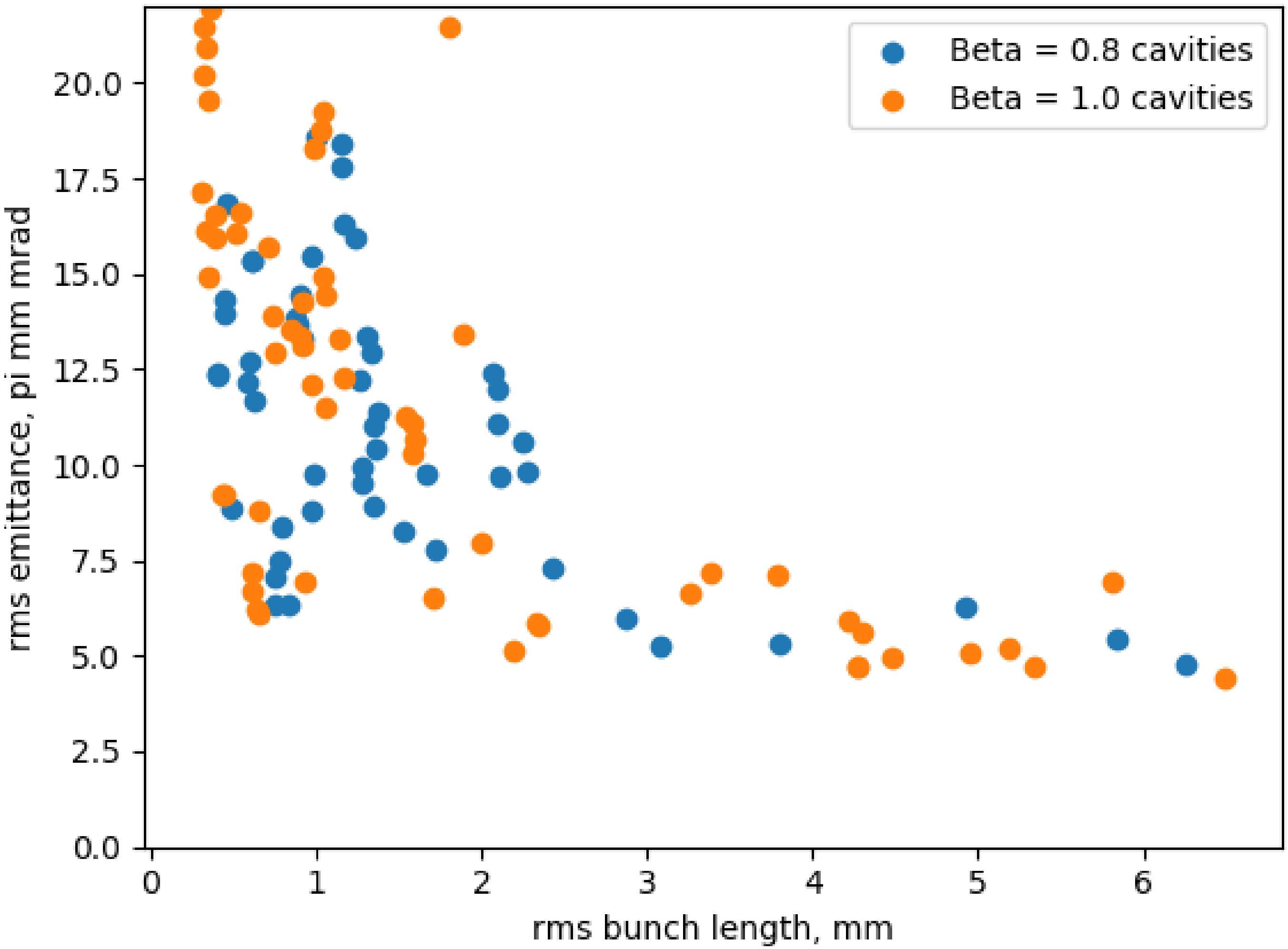
- The optimisation algorithm varies the parameters in the table within the ranges shown.
- In addition it varies the sizes of the gaps between the element.
- In total there are 19 variables in the optimisation.
- Multi-objective optimisation allows the trade offs between the different objectives to be visualised.

Parameter	Range
Laser spot size	6 mm – 10 mm
Focusing electrode angle	18°-25°
Solenoid 1 field	0.033 T – 0.038 T
Buncher cavity amplitude	0.8 MV/m – 2.0 MV/m
Buncher cavity phase	-70 °- -110°
Solenoid 2 field	0.01 – 0.04 T
Booster cavity 1 amplitude	0 MV/m – 25 MV/m
Booster cavity 1 phase	-40° - 40°
Booster cavity 2 amplitude	0 MV/m – 25 MV/m
Booster cavity 2 phase	-40° - 40°
Booster cavity 3 amplitude	0 MV/m – 25 MV/m
Booster cavity 3 phase	-40° - 40°
Booster cavity 4 amplitude	0 MV/m – 25 MV/m
Booster cavity 4 phase	-40° - 40°
Booster cavity 5 amplitude	0 MV/m – 25 MV/m
Booster cavity 5 phase	-40° - 40°

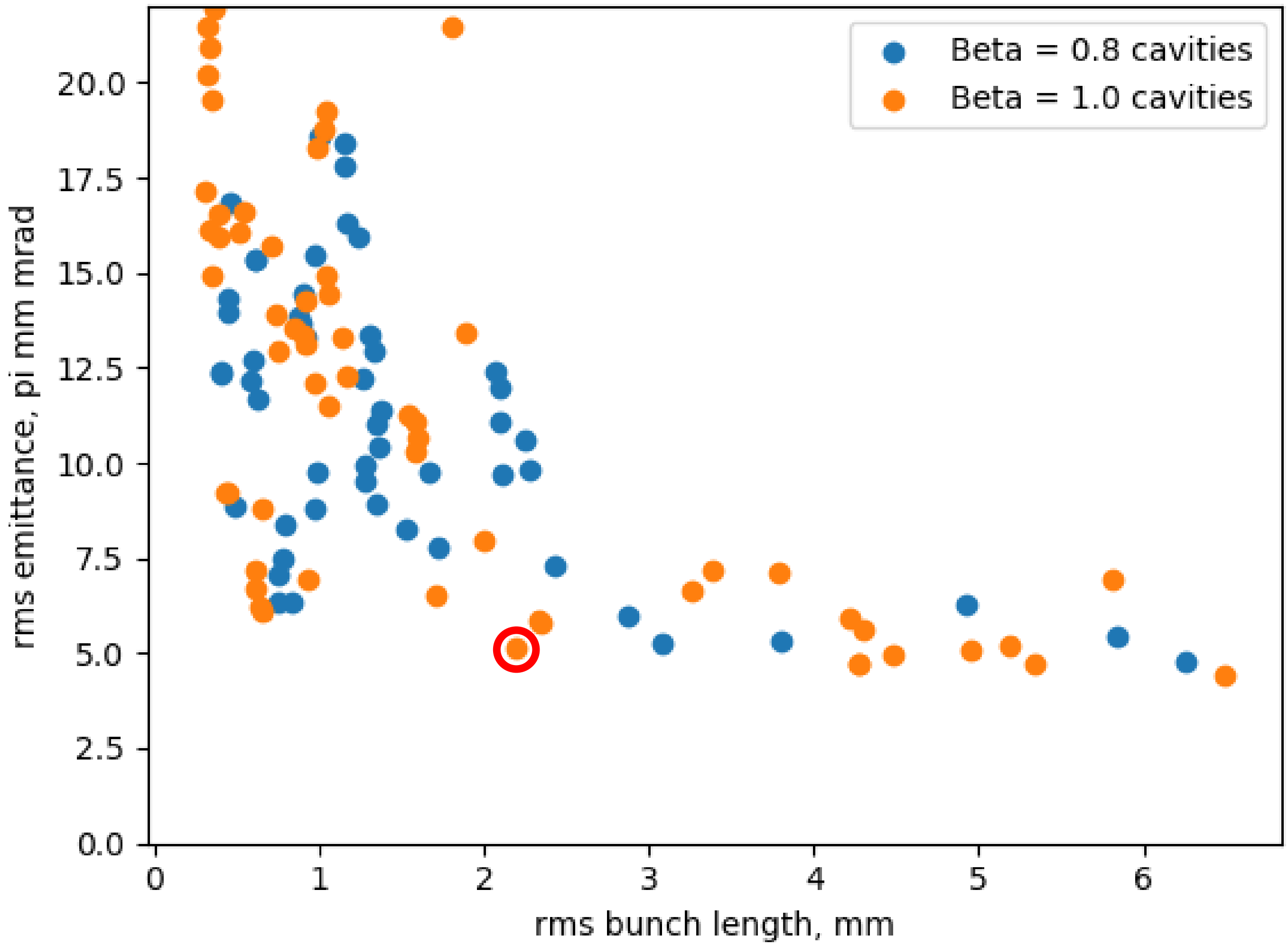
3d plot of optimisation results



2d projection of emittance vs rms bunch length



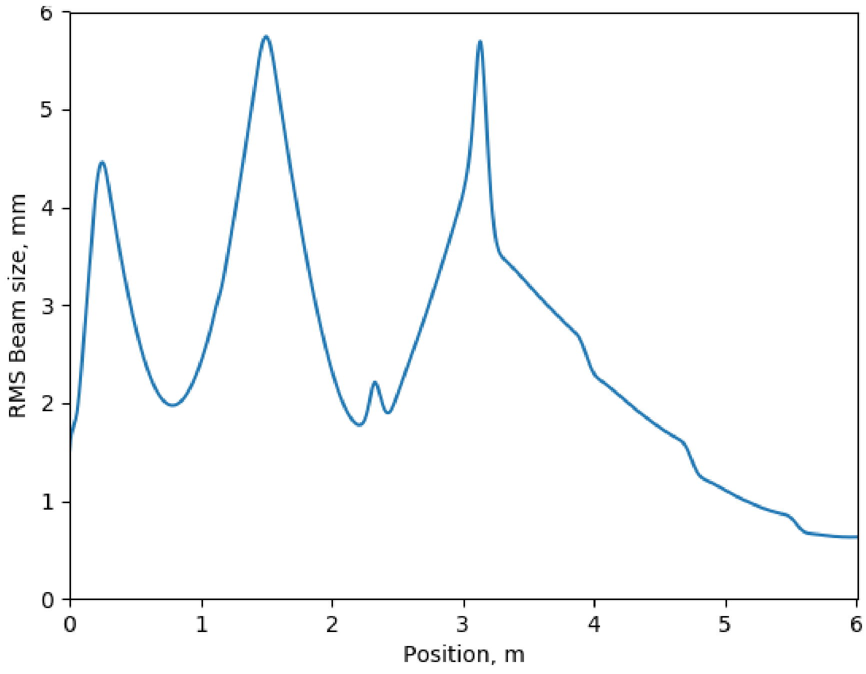
Emittance vs rms bunch length

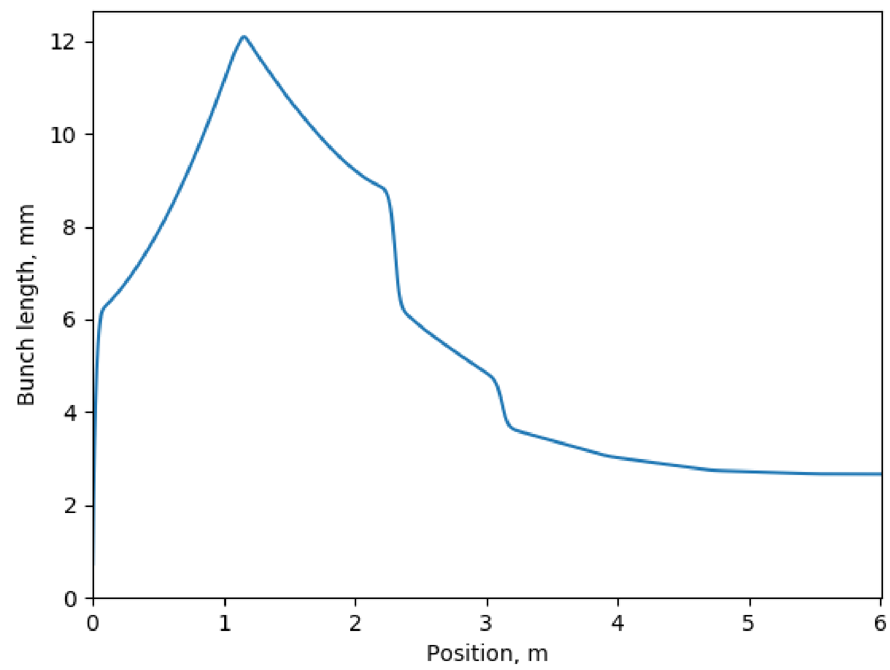


Fine tuning of the solution

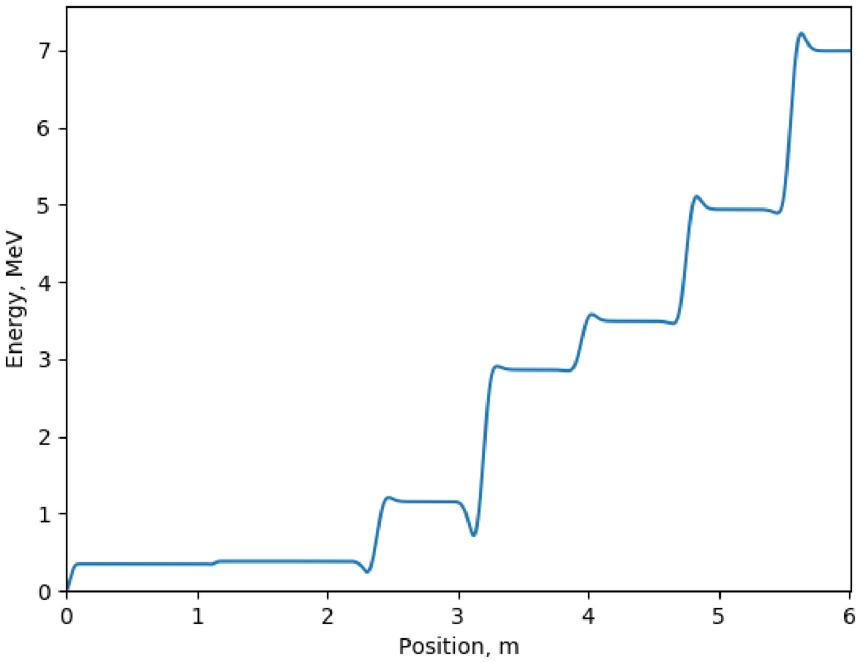
- The multi-objective optimiser only cares about the objectives and constraints. However there are other aspects of the final beam which are important.
- The last three cavities were further optimised with three new objectives:
  - Minimise transverse emittance
  - Minimise rms energy spread
  - Minimise absolute deviation from 7 MeV final beam energy
- This optimisation was carried out for 55 generations.
- The simulation was then run with 32768 particles. This also led to a change in the parameters.

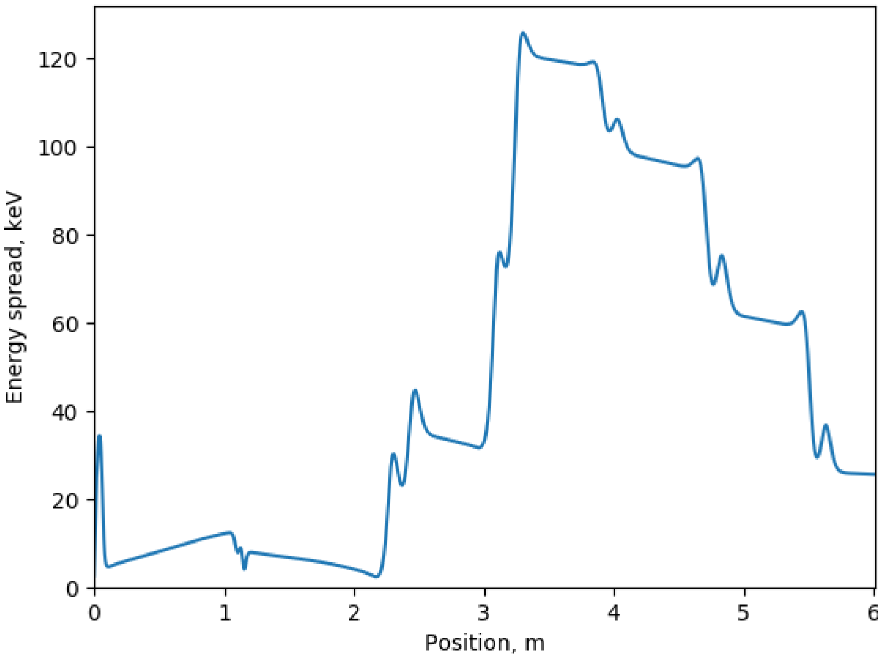
Optimisation results: RMS beam size & Bunch length



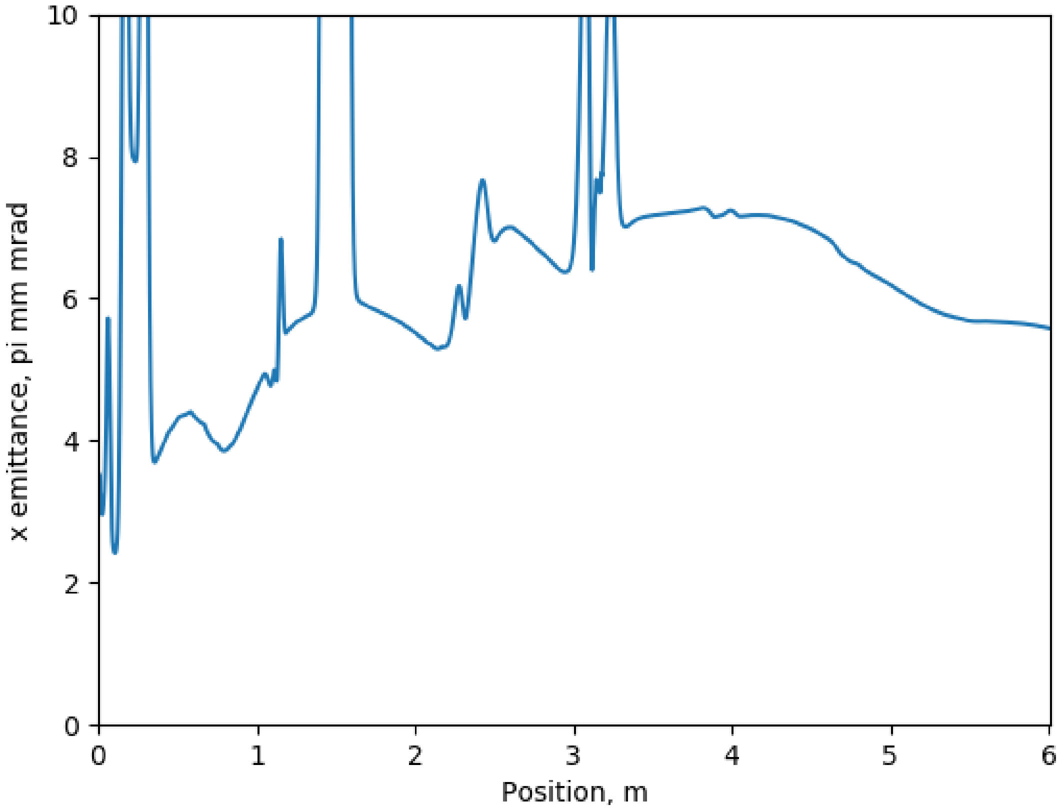


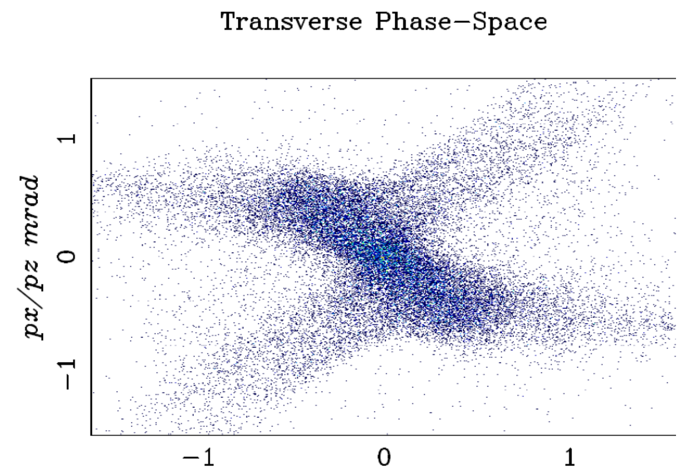
Optimisation results: Energy & rms energy spread

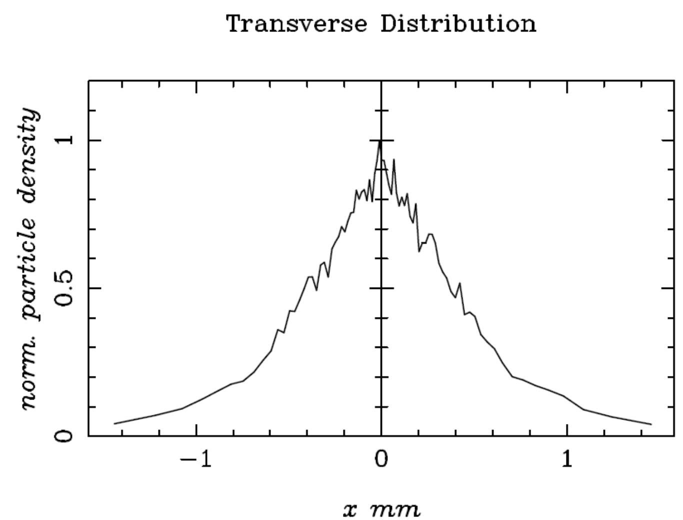




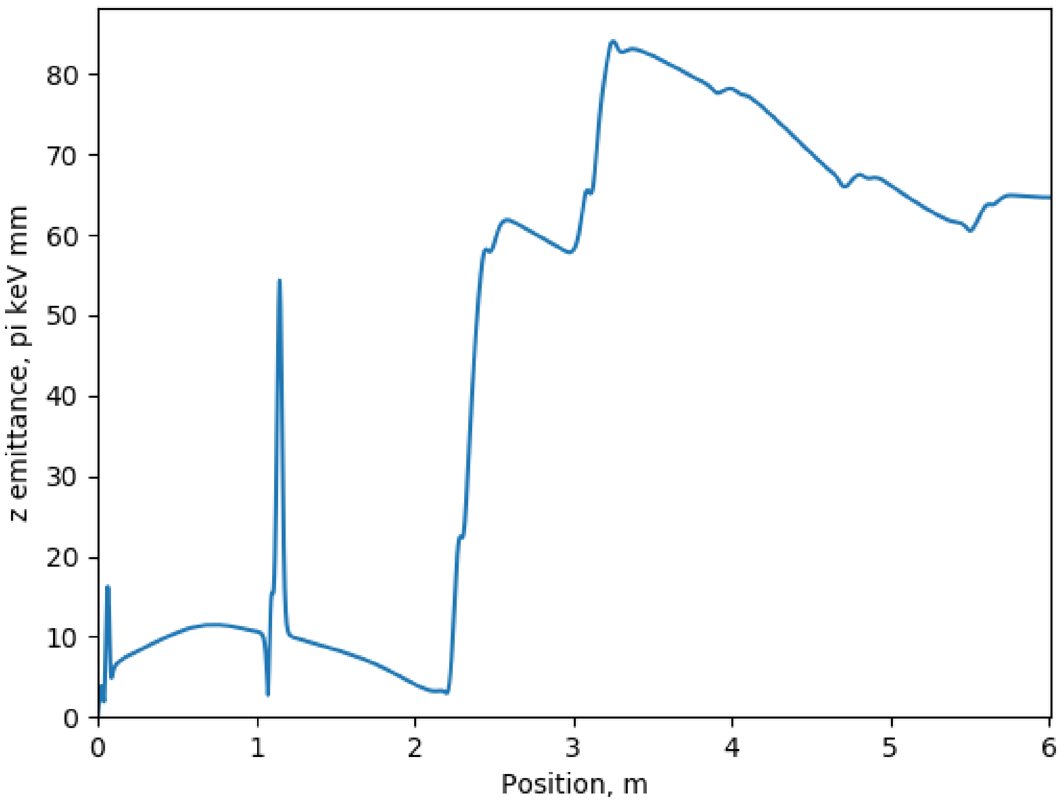
Optimisation results: Transverse emittance & phase space

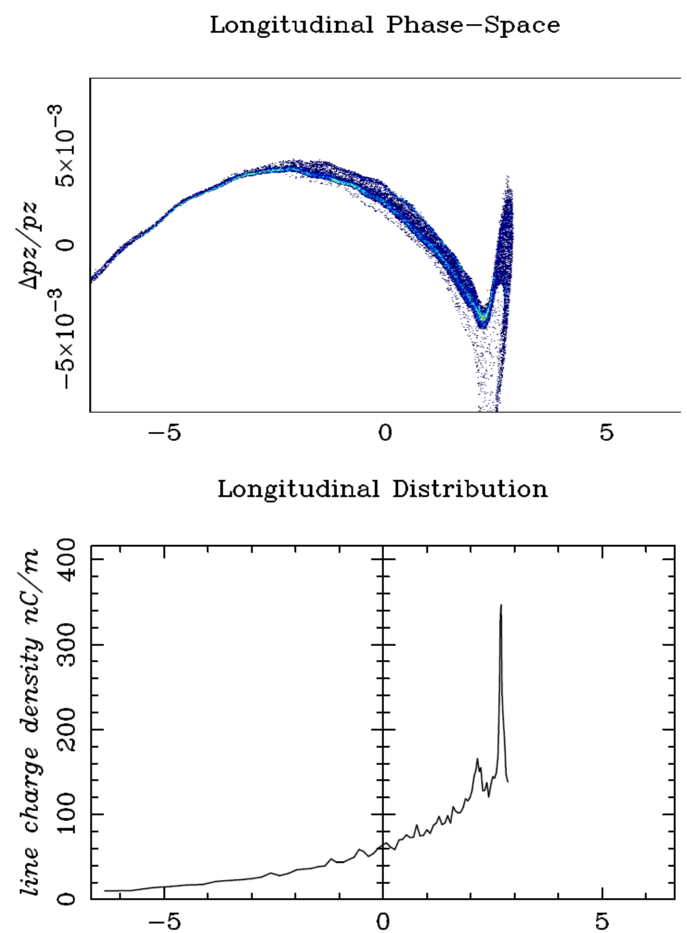






Optimisation results: Longitudinal emittance & phase space





Current best optimisation parameters

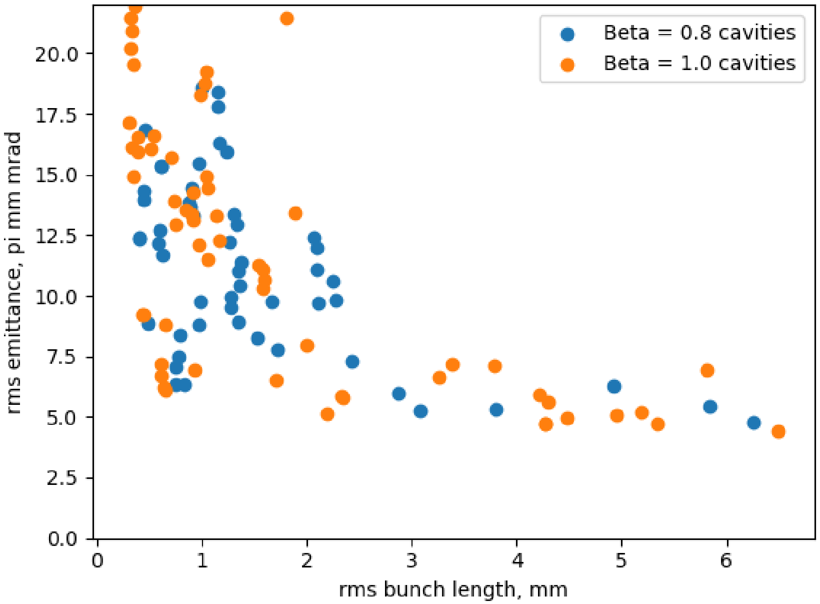
Parameters	Goal	Achieved
Injection energy	7 MeV	6.99 MeV
Bunch charge	500 pC	500 pC
Transverse emittance	< 6 π mm mrad	5.60 π mm mrad
Max RMS beam size		5.74 mm
Longitudinal emittance		64.66 π keV mm
RMS bunch length	3 mm	2.66 mm
RMS energy spread		25.70 keV
Uncorrelated energy spread	10 keV	

Table of injector parameters

Parameter	Optimised value	Range
Laser spot diameter	6.08 mm	6 mm – 10 mm
Focusing electrode angle	20°	18°-25°
Solenoid 1 field	0.0367 T	0.033 T – 0.038 T
Buncher cavity field	1.99 MV/m	0.8 MV/m – 2.0 MV/m
Buncher cavity phase	-74.85°	-70 °- -110°
Solenoid 2 field	0.0276 T	0.01 – 0.04
Booster cavity 1 field	10.29 MV/m	0 MV/m – 25 MV/m
Booster cavity 1 phase	-21.60°	-40° - 40°
Booster cavity 2 field	24.13 MV/m	0 MV/m – 25 MV/m
Booster cavity 2 phase	-39.93°	-40° - 40°
Booster cavity 3 field	8.02 MV/m	0 MV/m – 25 MV/m
Booster cavity 3 phase	29.50°	-40° - 40°
Booster cavity 4 field	17.61 MV/m	0 MV/m – 25 MV/m
Booster cavity 4 phase	25.49°	-40° - 40°
Booster cavity 5 field	24.74 MV/m	0 MV/m – 25 MV/m
Booster cavity 5 phase	24.60°	-40° - 40°

Merger considerations

- Detailed study of the merger has not yet been carried out.
- A review of the mergers in the literature has been carried out and some options identified.
- Some basic consideration are:
  - At 500 pC space charge will be a significant effect. This provides an incentive to keep the length of the merger as short as possible.
  - From the multi-objective optimisation there does not seem to be much incentive from an emittance perspective to bunch less prior to the merger and then compress in the merger.



Future work

- Refine the optimisation
  - Optimise with larger particle counts. Using the final populations from the low particle count optimisations as the initial populations for the larger particle count optimisations.
  - Reduce the energy spread
  - Use realistic buncher cavity design and booster cavity positions.
  - Expand some of the variable ranges
- Detailed merger study
- Polarised injector

Summary

- Optimisation of the injector until just after the exit of the booster has been carried out.
- Controlling the transverse beam size is challenging at 500 pC.
- The emittance at the exit of the booster is below the required value of < 6 mm mrad but there will be some emittance growth in the merger.
- The rms energy spread is still higher than the target value.
- The bunch distributions and longitudinal phase spaces need further work.
- The optimiser selected the extreme values for a number of the injector parameters so in expanding the possible range there may be room for further improvement.

Acknowledgements

- Max Klein
- Boris Militsyn
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- Peter Williams

Questions?