MAX-IV LINAC INJECTOR SIMULATIONS INCLUDING TOLERANCE AND JITTER ANALYSIS

J.W. McKenzie*, B.L. Militsyn, STFC Daresbury Laboratory, ASTeC & Cockcroft Institute, UK
S. Thorin, S. Werin, MAX-Lab, Lund, Sweden

Abstract

The MAX-IV linac will be used both for injection and top up into two storage rings, and as a high brightness injector for a Short Pulse Facility (SPF) and an FEL (in phase 2). 100 pC bunches of electrons are created from a 1.5 cell S-band photocathode gun and subsequently accelerated up to 3 GeV by S-band linac sections. Simulations of the dynamics of the space-charge dominated beam up to 100 MeV are presented including an analysis of the tolerances required and the effects of jitter sources.

MAX-IV

The MAX IV project [1] at MAX-lab has been funded, and construction has started, to build two storage rings, a full energy injection linac and a Short Pulse Facility (SPF) [2]. An FEL will be added in phase 2.

The rings will be operated at 1.5 and 3 GeV. One option for injection and top up into the storage rings, is the production of triple pulse from the injector, i.e. three 100 pC electron bunches in consecutive RF buckets. The triple bunches will be extracted to each ring at 10 Hz for injection and top up. In between each top up period the beam will be delivered to the SPF.

The SPF will be a single pass spontaneous light source, producing sub-ps X-ray pulses. In SPF operation mode the linac will deliver single 100 pC bunches at a repetition rate of 100 Hz. The electrons are then accelerated off crest prior to bunch compression and the resulting short bunches are delivered at 3 GeV to the SPF beamline.

THE MAX-IV LINAC

The MAX-IV linac is based on normal conducting S-band technology and is shown in Fig. 1 and presented in [3]. The beam is kicked out for injection into the rings at 1.5 and 3 GeV. Bunch compression is done in double achromats [4] at 260 MeV and 3 GeV.

This paper will show the design and beam dynamics simulations, using ASTRA, of the electron gun and first accelerating module, up to a beam energy of 100 MeV. Detailed simulations and tolerance studies from 100 MeV to 3 GeV are presented in [5].

INJECTOR COMPONENTS

The photocathode RF gun is based on the FERMI@*elettra* design [6]. This is a 1.6 cell copper cavity operated at 2998 MHz. A solenoid encompasses this cavity, however, there is no bucking coil as the solenoid field is close to zero at the cathode, as shown in Fig. 2. It is assumed that this gun can operate at a gradient of 100 MV/m, however, a case with a reduced gradient of 80 MV/m has also been investigated as a back-up option.

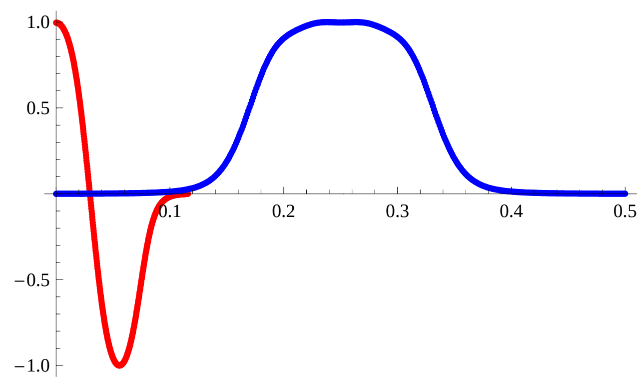

Figure 2: Normalised on-axis field maps for the gun (red) and solenoid (blue).

The drive laser will deliver Gaussian pulses with a FWHM of 5 ps to a copper photocathode. An initial thermal emittance of 0.9 mm mrad per mm rms has been assumed, as per LCLS measurements [7]. A flat top laser spot with diameter of 1 mm was chosen as simulations have shown that further reduction of spot size increases the final bunch length and energy spread to an extent that outweighs the emittance decrease.

The first linac section is a 5 m long S-band structure fed by a SLED which accelerates the beam to 100 MeV. As the amplitude of the RF pulse from the SLED is decreasing in time, the gradient throughout the linac section is modelled as being increasing throughout the structure, giving a non-linear energy gain.

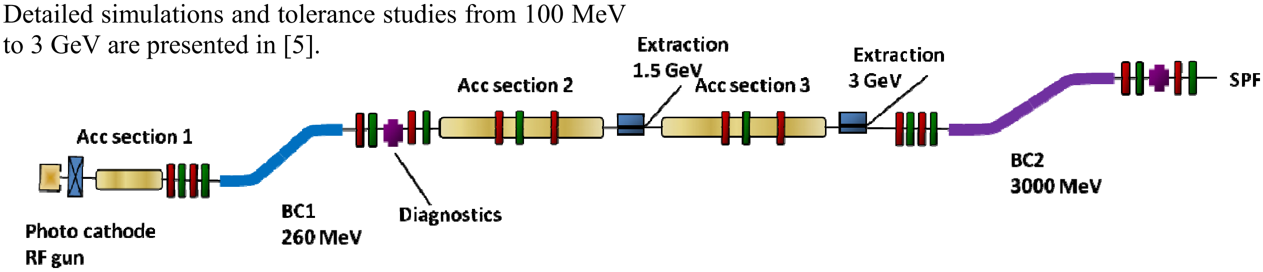

Figure 1: Overall schematic layout of the MAX-IV linac.

*julian.mckenzie@stfc.ac.uk

INVARIANT AMPLITUDE MATCHING

In order to achieve a constant transverse beam size and low emittance throughout the linac structure, without a surrounding solenoid, the invariant amplitude condition,

$$\sigma_i = \frac{2}{\gamma'}\sqrt{\frac{I}{3I_0\gamma_i}} \quad (1)$$

should be met [8]. This relates the beam size σ_i at the linac entrance to an accelerating gradient γ' for a beam of current I and initial energy γ_i. For a beam with initial energy of 4.5 MeV, linac gradient of 26.25 MV/m, current of 15 A, this condition is met with $\sigma_i = 0.21$ mm.

The beam should also enter the linac with zero divergence. This occurs when the position of the beam size minimum and the position of the local emittance maximum (between the two minima) meet. Fig. 3 shows that such a case can be met by adjusting the gun phase and solenoid strength. The linac is then placed in the position described.

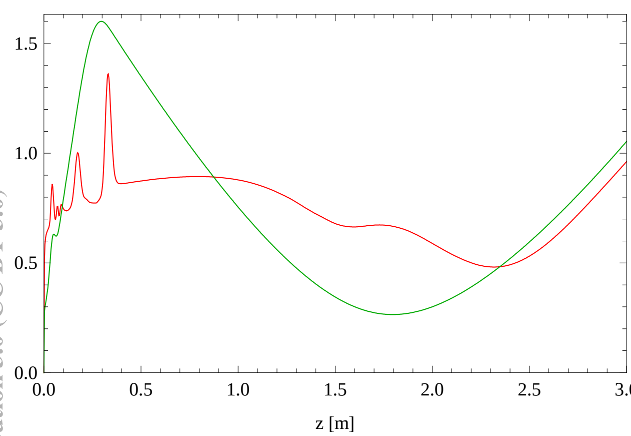

Figure 3: Evolution of rms beam size [mm] (green) and transverse emittance [mm mrad] (red).

SIMULATION RESULTS

Fig. 4 shows the evolution of the beam size and emittance along injector with the linac placed at the optimum position described above. The beamline parameters are described in Table 1. Final beam parameters are summarised in Table 2. Each simulation used 100,000 macroparticles.

Table 1: Beam line parameters used in simulations

Parameter		Units
Bunch charge	100	pC
Laser spot diameter	1	mm
Laser pulse width (FWHM Gaussian)	5	ps
Initial thermal emittance	0.225	mm mrad
Gun peak field	100	MV/m
Gun phase	- 5	°
Solenoid peak field	0.190	T
Linac entrance position	1.85	m
Linac peak field	40.3	MV/m
Linac field flatness	0.58	
Linac phase	+ 5	°

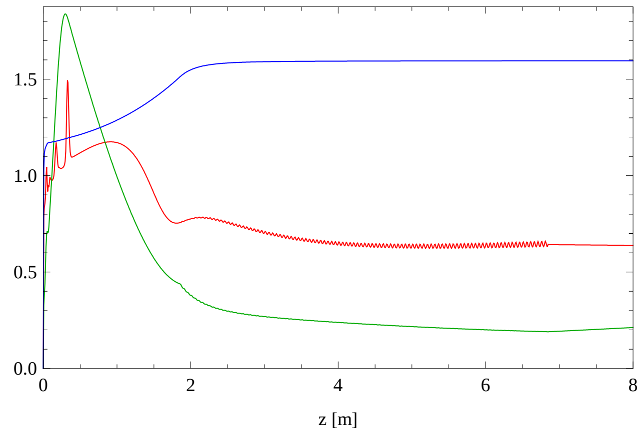

Figure 4: Evolution of rms beam size [mm] (green), transverse emittance [mm mrad] (red), and rms bunch length [ps] (blue).

For a reduced gun gradient of 80 MV/m, similar matching conditions were found by reducing the solenoid peak field to 0.155 T. Fig. 5 shows the final current and emittance profiles at both gun gradients.

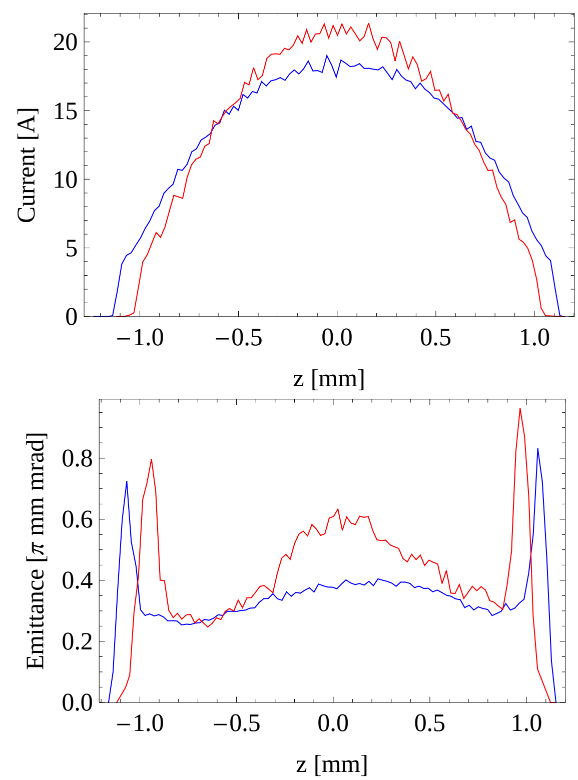

Figure 5: Current and emittance profiles for gun peak fields of 100 MV/m (blue) and 80 MV/m (red).

Table 2: Beam parameters for different gun gradients

Gun gradient	100	80	MV/m
Beam size (rms)	0.212	0.209	mm
Projected emittance	0.638	0.654	mm mrad
Peak current	21	17	A
Bunch length (rms)	1.60	2.05	ps
Bunch length (full)	7.38	8.79	ps

JITTER AND TOLERANCES

Using the 100 MV/m setup as described in Table 1 as the basis, jitter studies were carried out to determine what the effect of random errors are on the bunch to bunch parameters and beam stability. Table 3 summarises the jitter sources considered. The standard deviations were taken as best cases from other laboratories.

Table 3: Jitter sources

Parameter	Standard deviation	Unit	Label
Bunch charge	1	pC	Q
Laser x position	0.02	mm	L1
Laser y position	0.02	mm	L2
Laser arrival time	300	fs	L3
Gun gradient	0.1	%	G1
Gun phase	0.1	°	G2
Solenoid strength	0.1	%	S1
Linac gradient	0.1	%	A1
Linac phase	0.1	°	A2

To determine the most sensitive sources of error, each source of jitter was varied individually, with the results shown for difference from the nominal emittance and bunch length in Figs. 6 and 7 respectively.

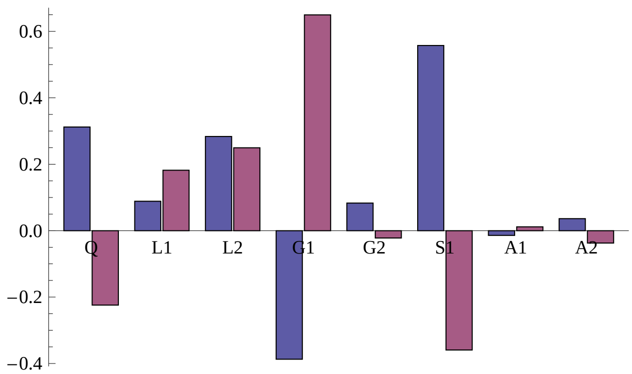

Figure 6: Percentage change in emittance for +/- errors as shown in Table 3.

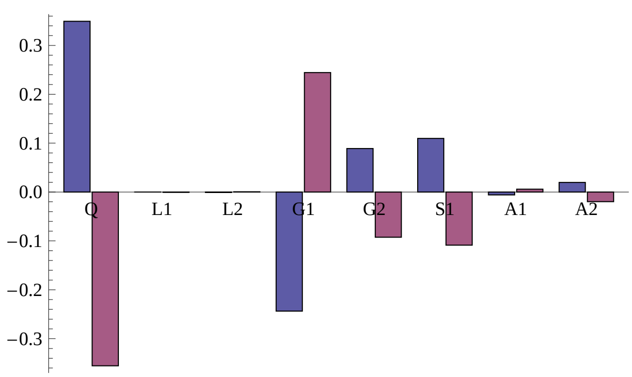

Figure 7: Percentage change in bunch length for +/- errors as shown in Table 3.

To investigate the jitter which can be expected during machine operations, 1000 simulations, each of 10,000 macroparticles, were performed. For each simulation, errors on each jitter source were sampled randomly according to a Gaussian distribution, truncated at three standard deviations as per Table 3.

All jitters are defined by varying one beam line parameter from the nominal, apart from the arrival time of the laser pulse which is emulated by changing the phase of the gun and linac simultaneously. Figure 8 summarises the distributions of emittance, bunch length, arrival time and energy when all random jitters are applied.

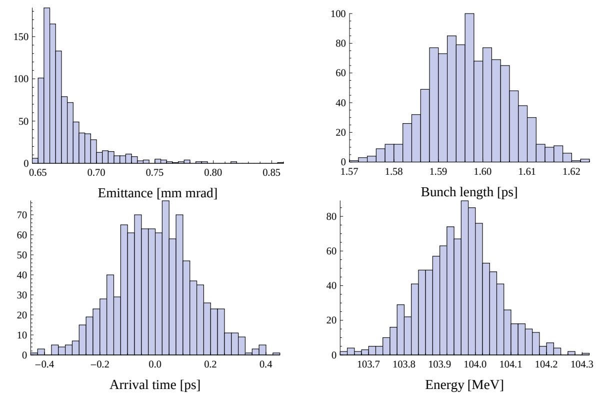

Figure 8: Histograms of beam parameters after 1000 simulations with random jitters applied.

These jitter simulations show that beam parameters can be expected to vary with standard deviations of 0.8% for projected emittance, 0.6% for bunch length, 0.14 ps for bunch arrival time and 0.1% for beam energy.

SUMMARY

The beam dynamics simulations of the MAX-IV gun have been presented. It has been shown that emittance of less than 0.7 mm mrad can be achieved, for both the nominal 100 MV/m accelerating gradient of the S-band RF gun, and the reduced 80 MV/m accelerating gradient. Given the set of tight tolerances shown, jitter studies have shown that operational beam parameters should not vary by more than 1 %.

REFERENCES

[1] MAX IV conceptual design report (2006). URL http://www.maxlab.lu.se/maxlab/publications/max4/MAX-IV-CDR.pdf.
[2] S. Werin et al., Nuclear Instruments and Methods in Physics Research A 601 (2009) 98–107.
[3] S. Thorin et al., "Design of the MAX IV Ring Injector and SPF/FEL Driver", proceedings of PAC 2011.
[4] S. Thorin et al., "Bunch Compression by Linearising Achromats for the MAX IV Injector", proceedings of FEL 2010.
[5] P.H. Williams et al., "Optics Design and Tolerance Studies of the Max-IV Linac", these proceedings, THPC067.
[6] G. D'Auria et al., "The New Photoinjector for the Fermi Project", proceedings of PAC 2007.
[7] D. Dowell, "The Limits of Beam Brightness from Photocathode RF Guns", FEL 2010.
[8] L. Serafini & J.B. Rosenzweig, Phys. Rev. E, 55 (6) p7565-7590 (1997)