EMITTANCE IMPROVEMENTS IN THE MAX IV PHOTOCATHODE INJECTOR

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Abstract

The MAX IV injector design predicts a beam with 100 pC of charge and an emittance lower than 1 mm mrad. The photocathode pre-injector is based on the now close to standard 1.6-cell gun adapted to 2.9985 GHz, in combination with a Ti:Sapphire laser system. This system reaches the requirements of the injector operation for the SPF, but can be tuned beyond specifications to open up new operation modes. During 2016 and 2017 several aspects where investigated to improve the emittance from the current gun, the goal was to meet the SPF specifications. In this paper we report on the progress, discuss the steps taken leading to a final emittance of 1 mm mrad and beyond.

INTRODUCTION

MAX IV [1] is a facility for the production of synchrotron radiation. The facility has two storage rings, one at 1.5 GeV and one at 3 GeV. There is also a short pulse facility [2] (SPF), where short pulses of radiation are produced in vacuum undulators. Both storage rings are operated with full energy injection, and there is a normal conducting S-Band linac [3] to provide electrons both for ring injections and for the SPF. The LINAC consist of 39 5.2 m S-Band structures at 2.9985 GHz providing a total energy gain of 3 GeV. The user operation of the 3 GeV storage ring has started, and commissioning of the SPF and 1.5 GeV ring are ongoing, and a plan for a future soft x-ray free electron laser (SXL) is under initial investigation [4].

There are two separate pre-injectors, one based on a thermionic source and one based on a photocathode source. The photocathode pre-injector is based on LBL/SLAC 1.6 cell gun adapted to 2.9985 GHz for Fermi@Elettra [5], with a finely machined, but not polished, copper cathode followed by an emittance compensating solenoid. The electric field amplitude in the gun is currently relatively low, 80 - 90 MV/m. The laser system for the photocathode pre-injector is a KM Labs Dragon with cryogenic cooled Ti:Sapphire crystals and the oscillator is at 76.9 MHz, and the pulses are amplified and frequency tripled to a wavelength of 263 nm. More details on the laser system can be found in [6]. Pulse stacking is currently used for creating longer pulses, but there is a new pulse shaper being commissioned, for details see [7]. Laser pulse lengths of 3 and 6 ps FWHM are currently in use, the spot size at the cathode is approx. 1.5 mm FWHM and typically electron pulse charges between 50 and 200 pC are used.

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The LINAC can be seen in Fig. 1. The beam is injected into the first of three s-band structures before reaching the first bunch compressor (BC1). After the first compression, the beam is accelerated in the main linac to the final energy of 3 GeV. Half-way through the linac there is the transport to the 1.5 GeV ring and by the end of the linac, just before the second bunch compressor, the transport to the 3 GeV ring. After the end of the linac the beam passes through the second bunch compressor before being delivered to the SPF.

During previous commissioning [8] the achieved emittance for a pulse charge of 100 pC at 260 MeV was approx. 1.6 mm mrad. During the 1.5 year period since then work has been ongoing to improve the the emittance and stability of the beam. Slice diagnostics of the vertical emittance was made possible using the first dispersive section in the first bunch compressor, and using this new diagnostic possibility it was possible to investigate and improve the emittance to 1 mm mrad.

SLICE DIAGNOSTICS

During 2016 there was a suggestion to use the existing first dispersive section in the first bunch compressor to investigate the possibility to resolve longitudinal properties of the beam. These methods are well known, see for example references [9], [10] and [11]. There are two different methods that are being implemented, which both uses an introduced time-energy correlation from running a linac structure off-crest. The first method makes it possible to measure the vertical emittance in the dispersive section with the single-quad scan method, using a quadrupole in the matching section before the bunch compressor. The second method uses a skew quad in the first dispersive section to introduce a correlation between the transverse planes, thus enabling the measurement of the horizontal emittance after the dispersion is closed. Different time slices will be at different vertical positions on the screen due to the correlation between time and energy of the beam in the dispersive section, that is turned into a correlated vertical displacement on the screen. In this paper a short overview of the first method is given and the preliminary results from the measurements are used for emittance improvements.

The pre-injector in combination with the first linac structure (L0), has a final energy of around 100 MeV, and at this energy the emittance oscillations are strongly suppressed. Before the beam enters the first bunch compressor, it is accelerated in two additional linac structures (L01a and L01b) to a final energy of approx. 260 MeV. These two linac structures are controlled as a pair, the phase can only be set for both structures at the same time. By running L01a and L01b

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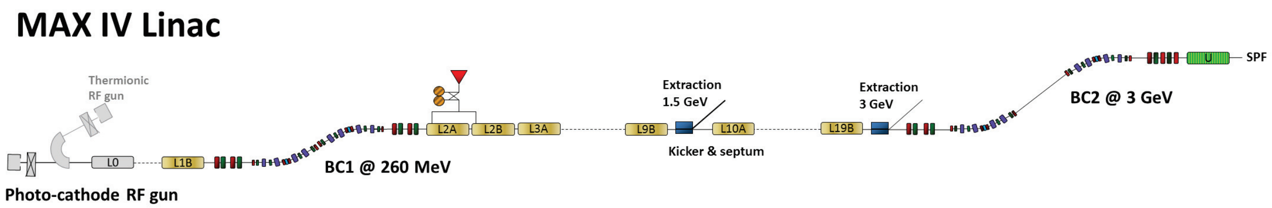

Figure 1: Overview of the MAX IV linac with both pre-injectors to the left, extractions to the 1.5 and 3 GeV rings marked and the SPF.

off-crest, a correlation between longitudinal position and energy is introduced. The beam then passes through matching section 1 (MS1), where there are four quadrupoles available for beam manipulation. The bunch compressor can be seen in Fig. 2, and the relevant parts for this measurement method is the first two dipole magnets and the first screen. These are the only elements that are being used, all other quadrupoles and sextupoles are turned off. The introduced time-energy correlation will in the dispersive section be translated into a horizontal spread on the screen. The screen is a YAG crystal, followed by a mirror and camera to capture images. The visible crystal size is approx. 18 mm and the optical resolution is 15 µm per pixel.

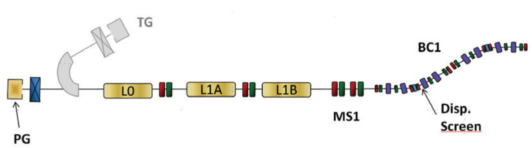

Figure 2: Closeup of BC1, L1A and B are set at an off crest phase, and one off the quadrupoles in MS1 are used to perform a single quad scan using the screen at maximum dispersion after the two first bending dipoles in BC1.

The vertical emittance is then measured using a single-quad scan. One of the quadrupoles in the matching section (MS1) is used to scan the beam size, so that the vertical focus is passed for all horizontal parts of the beam, and the vertical emittance is then found from a standard fitting of the measured beam size to the k parameter. Any quadrupoles following the scan quadrupole are switched off during the measurement. The horizontal beam is divided into slices at the post-processing stage of the captured images, i.e. simply by selecting of a suitable ROI width for each slice. For each captured image in a scan, the center of gravity of the beam is found, and the horizontal beam size extracted. The same percentage of the beam is then divided into the selected number of slices. The horizontal beam size changes slightly during a scan, and by approximating the beam size for each captured image before dividing it into slices this effect should be minimized. However, this only works as long the horizontal beam size doesn't change too much during the scan, so for each scan settings the horizontal beam size is verified before a measurement is done. When calculating the emittance based on the fit parameters, the beam effects from the dipoles are taken into account in the transfer matrix between the scanning quad and the screen.

The resolution of the system has been investigated using simulations with ASTRA and Elegant. The resolution is in part dependent on the energy spread of the slices, the time-energy correlation and the horizontal beam size at the measurement point. The horizontal rms beam size at the dispersive screen is 0.2 mm, and with 28 ° off-crest it seems possible to resolve 15 slices over the available screen size, which for a 6 ps pulse gives a resolution of about 0.4 ps. Preliminary indications are an obtainable resolution below 0.5 ps for different cases, but further investigations are ongoing to find out a more precise number for the resolution, and how general this resolution is.

RESULTS

Figure 3 shows the result from a slice emittance measurement at 6 ps pulse length and 100 pC charge. For this measurement the lowest projected emittance was found at a solenoid setting of 91.5 A. From the result in the figure it can be seen that the slice emittance for the core of the bunch (the part of the bunch with the highest charge) is lower for the solenoid setting at 91.5 A.

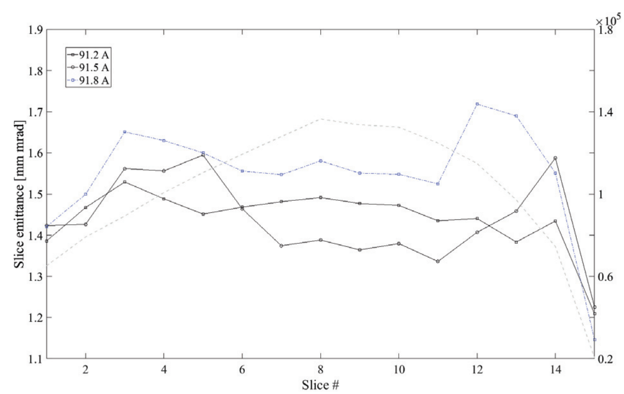

Figure 3: Result for vertical slice emittance of a 6 ps long pulse with 100 pC of charge. Charge intensity is the gray curve in arbitrary units. A solenoid current of 91.5A corresponds to the lowest measured vertical projected emittance.

The slice emittance diagnostics was used to measure the effect of different settings. The parameters that were varied in these experiments were the solenoid strength, injection phase, charge and pulse length. In agreement with simulations, it was possible to lower the emittance by using an earlier injection phase (the injection phase was changed from 30 ° to 23 °). Using this injection phase in combination with the best solenoid setting found using the slice emittance measurement (the solenoid current corresponding to the lowest and best aligned slice emittances) was then used as a base point for further optimization, where the reason for the large projected emittance was suspected to be alignment.

EMITTANCE IMPROVEMENTS

The indication at an early point from the slice diagnostics was that the slice emittance in a number of measurements was well below the measured projected emittance. All following emittances are referring to vertical emittance, unless otherwise specified. In some measurements the slice emittance was around 1.2 - 1.6 mm mrad but the measured projected emittance as high as 6 mm mrad using single-quad scan measurements in MS1.

A series of measurements were done with L01 turned off, as well as all quadrupoles following the quadrupole pair after L00. The single-quad scan was made using the same quadrupole as before in MS1 and these measurements indicated a lower emittance with only the first linac structure active. The alignment for each component was then systematically checked with the beam, and using very small corrections at the beginning of the injector, the emittance could be successfully lowered. The lowest measured projected vertical emittance for 100 pC at 100 MeV was 0.91 mm mrad and for 100 pC at 260 MeV it was 1.08 mm mrad.. The lowest found emittances for different settings are shown in Table 1.

CONCLUSIONS AND FUTURE WORK

Using well known principles, we have implemented a method for measuring vertical slice emittance at the first dispersive section in the first bunch compressor of the MAX IV linac. The first measurements indicates a resolution around 0.5 ps for the setup due to the use of two LINAC sections off crest, and investigations are ongoing to further characterize the resolution.

With help from this diagnostic tool it has been possible to decrease the vertical projected emittance of the injector to 1.08 mm mrad at 100 pC at the entrance to the first bunch compressor. The lowest measured projected emittances for different energies, charges and pulse lengths are shown in Table 1. The lowest emittance at 0.75 mm mrad with 40 pC is suspected to be close to the current limit in the system due to the relatively low electric field amplitude in the gun and the non-polished cathode, but further characterization of this is planned.

Once the slice diagnostics using the skew quad in the first bunch compressor has been commissioned, the horizontal slice emittance will be measured. There are also a number of future improvements to the setup planned. The current cathode in operation is non-polished, and the change to a polished cathode is being planned. New polished cathodes have been delivered to MAX IV, and it is investigated how

Table 1: The current lowest measured projected vertical emittance values for different charge and pulse lengths. 100 MeV measurements are made with L01a and b off.

Energy	Pulse length	Charge	Vertical emittance
100 MeV	3 ps	100 pC	0.92 mm mrad
100 MeV	3 ps	150 pC	1.1 mm mrad
100 MeV	6 ps	40 pC	0.75 mm mrad
100 MeV	6 ps	50 pC	0.8 mm mrad
100 MeV	6 ps	100 pC	0.91 mm mrad
260 MeV	6 ps	100 pC	1.08 mm mrad

to best prepare these for operations. The MAX IV gun test facility [12] will be used to condition and characterize the new cathode before installation into the current gun in operation. During the summer shutdown of 2017 the power divider for the RF power to the gun will be changes, enabling higher power to the gun. The gun will be conditioned at higher and higher fields during the autumn of 2017 and the higher fields will enable lower emittance from more rapid acceleration as well as the possibility to go to higher bunch charges.

There is also ongoing work on the laser system to replace the current longitudinal bunch manipulation with pulse stacking, to a pulse shaper with better control of both longitudinal and transverse laser pulse properties and the current progress of this work is reported in these proceedings [7].

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