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New features of the MAX IV thermionic pre-injector

J. Andersson*, D. Olsson*, F. Curbis, L. Malmgren, S. Werin

MAX IV Laboratory, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden

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ABSTRACT

The MAX IV facility in Lund, Sweden consists of two storage rings for production of synchrotron radiation. The smaller 1.5 GeV ring is presently under construction, while the larger 3 GeV ring is being commissioned. Both rings will be operating with top-up injections from a full-energy injector. During injection, the electron beam is first delivered to the main injector from a thermionic pre-injector which consists of a thermionic RF gun, a chopper system, and an energy filter. In order to reduce losses of high-energy electrons along the injector and in the rings, the electron beam provided by the thermionic pre-injector should have the correct time structure and energy distribution. In this paper, the design of the MAX IV thermionic pre-injector with all its sub components is presented. The electron beam delivered by the pre-injector and its dependence on parameters such as optics, cathode temperature, and RF power are studied. Measurements are here compared with simulation results obtained by particle tracking and electromagnetic codes. The chopper system is described in detail, and different driving schemes that optimize the injection efficiency for the two storage rings are investigated. During operation, it was discovered that the structure of the beam delivered by the gun is affected by mode beating between the accelerating and a low-order mode. This mode beating is also studied in detail. Finally, initial measurements of the electron beam delivered to the 3 GeV ring during commissioning are presented.

1. Introduction

The MAX IV facility in Lund, Sweden consists of two electron storage rings that will be operating at 3 GeV and 1.5 GeV, respectively, where the former is designed for production of high-brilliance hard X-ray synchrotron light, and the latter will produce light in the IR to the soft X-ray spectral range [1]. The 3 GeV ring is currently undergoing beam commissioning, while the 1.5 GeV ring is being constructed. MAX IV also includes a short-pulse facility (SPF) for experiments with short X-ray pulses with high peak brilliance [2]. For injection into the two storage rings, the electron beam is generated from a thermionic cathode in the thermionic pre-injector and then accelerated in the main injector. For SPF operations the electron beam is generated by photoemission from a copper cathode in the photocathode pre-injector and then accelerated in the main injector. In this paper the MAX IV thermionic pre-injector is described both from a system and from a performance perspective. The photocathode pre-injector, SPF and main injector are not covered in detail, there are only some brief references to the first LINAC section. The thermionic pre-injector is based on the design of the pre-injector at the old MAX-Lab facility [3]. The major improvement is the chopper system, explained in Section 6, used to create the correct bunch structure of the electron beam and to properly time the bunches to the two storage rings. An overview of the injector is found in Section 2, followed by a more detailed overview of the pre-injector and the requirements of the chopper system in Section 3. The sub-systems of the pre-injector are then described in Sections 4–6. Through analytical solutions and simulations the expected performance of the system is investigated with respect to the optics and emittance as well as the chopper system and bunch structure. During 2015 and early 2016, a series of measurements were made to characterize the system, both on optics, gun performance and the chopper system. These measurements are reported in Section 4.7 for the electron beam, and Section 7 covers the complete system performance. Finally, a conclusion is made on the system performance, followed by topics of interests where investigations will continue.

2. The MAX IV Injector

The two storage rings will be operating with top-up injections from the MAX IV injector, a full-energy injector which consists of 39 traveling-wave S-band LINAC structures that are fed by klystrons via SLED systems [4]. A schematic overview of the MAX IV injector can be seen in Fig. 1. There are two bunch compressors in the injector to compress bunches for SPF operations, one at 275 MeV and one at 3 GeV. The electron beam can be extracted from the injector at three different points. The first point is the extraction to the 1.5 GeV ring, it

* Corresponding authors.
E-mail addresses: joel.andersson@maxiv.lu.se (J. Andersson), david.olsson@maxiv.lu.se (D. Olsson).

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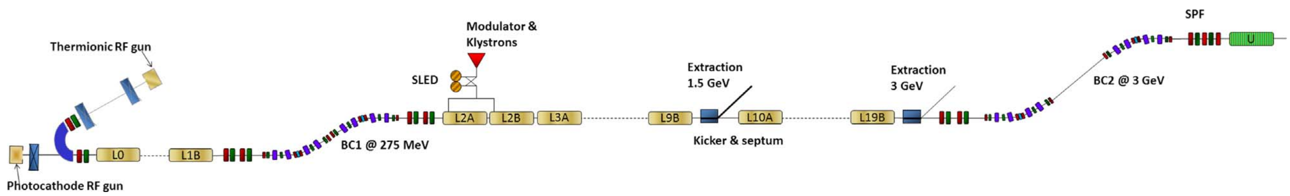

Fig. 1. Schematic overview of the MAX IV injector.

is located after 19 LINAC structures, and the two other points are the extraction to the 3 GeV ring and to the SPF, and they are both located after 39 structures. Commissioning of the injector was carried out during 2014–2015, and initial results are presented in [5]. The electron beam is delivered to the main injector by two separate pre-injectors, and the electron sources in these are a photocathode and a thermionic RF gun, respectively. For SPF operation, the photocathode pre-injector is used, where the high-charge electron bunch is accelerated in the injector in combination with the two bunch compressors. The photocathode gun might also be the electron source in a future free-electron laser (FEL) [6]. The thermionic pre-injector is solely used for ring injections, and is further described in Section 3.

3. The thermionic pre-injector system overview

For reliable operation of the injector system a thermionic RF gun system similar to the well experienced solution at MAX-lab was chosen for the thermionic pre-injector. The electrons are generated from a thermionic cathode and then accelerated and bunched in the RF gun cavities. The thermionic RF gun provides electrons at 2.5 MeV, but due to the non-triggered emission from the cathode, the bunch contains an energy tail. This tail should by preference be removed as early as possible, which is achieved in an energy filter (EF). The requirements of the temporal bunch structure of the electron bunches delivered by the thermionic pre-injector depends on several parameters, such as available RF voltage and radiation losses in the ring that is about to be filled (see Section 3.1). To create the correct temporal bunch structure and to match the 3 GHz structure of the gun and injector to the 100 MHz of the storage rings, a chopper system placed between the gun and the EF is used. It streaks the low energy beam across an aperture. There are two solenoids for focusing, one close to the gun exit used to focus the beam onto the aperture, and a second solenoid after the aperture to collimate the beam into the EF. A set of quadrupoles at the EF entrance puts a double focus at the center of the EF, and a set of quadrupoles after the EF matches the electron beam into the first LINAC section of the injector.

3.1. Injection requirements

Both storage rings will be operating with top-up injections that are as transparent to the users as possible, i.e., the perturbation of the stored beam that occurs during injection is minimized. Unlike many 3:rd generation light sources that use closed four-kicker injection bumps, pulsed nonlinear injection kickers will be used in the MAX IV storage rings [7,8].

During normal operation, the thermionic RF gun delivers a current pulse with a length of hundreds of nanoseconds that consists of S-band bunches, and most of that charge can not be accumulated in the ring buckets during injection. Therefore, a chopper system is needed to create the desired time structure of the injected current pulse. The chopper is installed in the thermionic pre-injector, and the unwanted electrons are dumped before they reach the first LINAC structure. The advantage of dumping them in the pre-injector where they have energies below 3 MeV is that the electron losses at high energies are minimized and thereby also the radiation emitted via bremsstrahlung. Apart from protecting personnel and sensitive electronic equipment from radiation, it also reduces radiation-induced demagnetization of the permanent magnets in insertion devices (IDs).

Table 1 shows the number of S-band bunches that can be accumulated in each ring bucket during an injection for different values of the RF momentum acceptance (MA) resulting from a chosen total RF cavity voltage in the two rings [9,10]. Note that Table 1 is valid when injecting with the non-linear kicker, and only for the bare lattice. The RF MA will decrease once IDs are added. As seen, the number of S-band bunches that can be accumulated in the 3 GeV ring increases when lowering the RF voltage since this results in a larger phase acceptance of the separatrix. The reasons for the much larger phase acceptance in the 1.5 GeV ring compared to the 3 GeV ring are that the former has a larger MA for injected bunches, i.e. for bunches with large amplitudes. Also note that the number of S-band bunches that can be accumulated in each ring bucket actually decreases when lowering the RF voltage in this ring. This is because the injection energy acceptance extends all the way to the maximum RF acceptance in this ring. Hence, when increasing the RF voltage, the MA increases and thereby the number of S-band bunches that can be accumulated.

The RF acceptance and the life time will vary during a typical user shift due to different ID gaps (assuming that this is not compensated for by adjusting the RF voltage). This also changes the phase acceptance and therefore the number of S-band bunches that can be accumulated in each ring bucket during an injection. In the 3 GeV ring, these variations might be considerable since the total radiation losses from IDs and damping wigglers are large compared to the losses in the bare lattice. Here, the radiation loss of the bare lattice is 364 keV/turn while the total loss in the fully equipped ring is estimated to be approximately 1 MeV/turn [10].

Since the LINAC structures are fed via SLED systems, the energy gain is a function of the electron release time. This results in an energy chirp within each LINAC shot [11]. This energy chirp limits the number of ring buckets that can be filled during each shot since the transfer lines that connect the extraction points of the injector with the two rings each have a MA of ±0.8%. It is possible to reduce the chirp by phase modulating the RF pulse to the SLED cavities, and thereby to

Table 1
The number of S-band bunches that can be accumulated during injection in the 3 GeV ring (a), and in the 1.5 GeV ring (b) for different RF MA, δ_{RF}, resulting from a chosen total cavity voltage, U_{cav}. Here, it is assumed that the electrons in the injected S-band bunches have the same momentum as the synchronous particle in the ring, and the table is only valid for the bare lattice (no added IDs).

U_{cav} [MV]	δ_{RF} [%]	# S-band bunches
1.80	± 7.1	4
1.00	± 4.4	5
0.60	± 2.4	7

(a)

U_{cav} [MV]	δ_{RF} [%]	# S-band bunches
0.56	± 4.0	19
0.37	± 3.0	18
0.28	± 2.3	16

(b)