DIAGNOSTICS AT THE MAX IV 3 GeV STORAGE RING DURING COMMISSIONING

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Abstract

The MAX IV 3 GeV storage ring based on a multibend achromat lattice allows for horizontal emittances from 330 pm rad down to 180 pm rad, depending on the number of insertion devices. The diagnostics used during commissioning will be described, with emphasis on the emittance diagnostics. This will involve two diagnostic beam lines to image the electron beam with infrared and ultraviolet synchrotron radiation from bending magnets, in order to determine also beam energy spread. The scheme for horizontal emittance measurements looks promising also for an order of magnitude lower emittance. Bunch lengthening with harmonic cavities is essential for the low emittance machine performance. We have used a radiation-based sampling technique to verify individual bunch distributions.

THE MAX IV FACILITY

The MAX accelerator facility is shown in Fig. 1. A more detailed description can be found in [1]. As an injector, a 3 GeV S-band linac has been chosen. Admittedly, a booster synchrotron is a more economical choice as a ring injector, but a linac injector opens up for Short-Pulse Facility (SPF) operation [2] and also paves the way for possible Free-Electron Laser operation [3]. A smaller ring at 1.5 GeV, MAX V, was also introduced at the laboratory to increase the spectral range of high-quality undulator radiation. This ring has just started (fall 2016) to be commissioned.

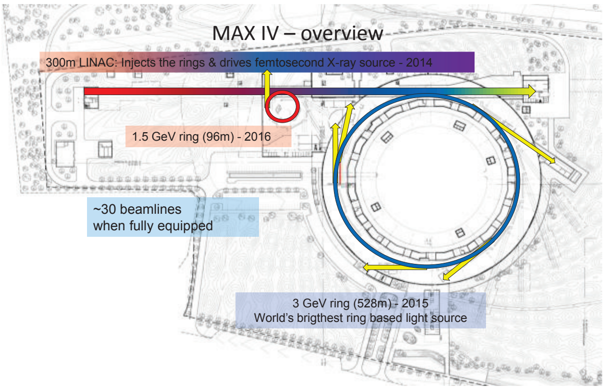

Figure 1: The MAX IV facility.

THE LINAC INJECTOR AND ITS MAIN DIAGNOSTICS FOR INJECTION

The 3 GeV injector linac is described in more detail in [1] and [4]. Two electron guns are used; one thermionic RF gun used for injections into the rings and one photo-cathode RF gun for short pulse operation for the SPF. Our experience with the former is positive regarding robustness and long cathode lifetime. However, recent experience with the photo-cathode gun operation exceeds the expectations, and in future it might be used as injector gun as well. In this paper we limit the description to the diagnostics relevant for ring injections.

Linac commissioning started in August 2014 when the installation of the MAX IV 3 GeV ring started. After one year the linac commissioning was completed and the 3 GeV ring commissioning started. Some parameters for the MAX IV linac can be found in Table 1.

Table 1: Injector Linac Parameter Values

End energy	3 GeV
RF	2.9985 GHz
Field gradient	17 MV/m
Acc cell length	5.2 m
No of structures	39
Bunch compressors	Double achromats

Current Transformers

The beam current and the electron bunch train envelope are resolved by twelve current transformers (CTs). Three of them are strategically placed after the RF thermionic gun, just after the chopper system [5], and just after an energy filter designed to cut away the low energy tail of the emitted pulse. Examples of these pulses are shown in Fig. 2. The chopper system efficiently creates a 100 MHz time structure, matching the ring RF, or a 500 MHz structure for maximum ring BPM sensitivity. Further, two CTs surround each bunch compressor achromats, and two CTs are placed at the beginning and at the end of each transfer line going up to the two rings. The CT signals are used continuously by the radiation protection system generating alarms in case of non-acceptable losses.

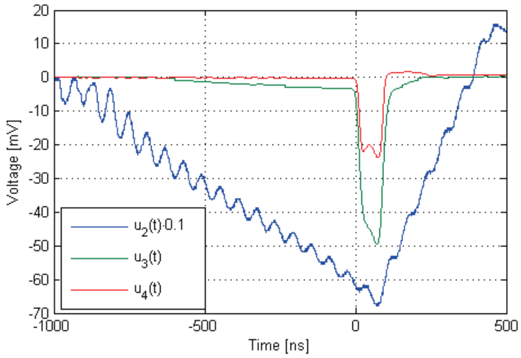

Figure 2: CT signals (Z=1 Ω) after thermionic gun (blue), chopper system (green) and energy filter (orange).

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Beam Position Monitors (BPMs)

The BPMs are of quarter wave strip-line type in order to have a good sensitivity to beam displacement even at low currents. The read out is performed with Libera Brilliance "Single pass" commercial electronics (without channel equalization). The standard deviation in position determination is of the order 0.1 mm at a few pC. The BPM offset values were determined with beam based calibration methods, and seldom the offset values exceeded 1 mm, which point on an acceptable alignment and cable phase length determination. BPMs located either in the bunch compressors, or in the transfer lines are used for energy measurements of the linac beam.

Screens

Screens are placed in the vicinity of the chopper system and after the energy filter, in transfer lines and in the bunch compressors. The screens are of YAG-type with thickness 100 microns, in order to keep the depth-of-field contribution sufficiently small. Some YAG screens, especially those at low energy, are covered with a thin conducting layer, to avoid charge build-up. A YAG screen at maximum dispersion, in the transfer line up to the 3 GeV ring, has capability to resolve individual S-band bunches. The most important screen regarding ring injection has shown to be the one situated just after the septum magnet in the ring. If something is largely detuned in the linac and/or the transfer line, it is usually seen on this screen. The thermionic RF gun delivers a transverse normalized beam emittance that has been measured to be in the order of 10 mm*mrad. This was achieved with quadrupole scans before the first bunch compressor at 260 MeV. Thus, the beam size that should be resolved at the screen position in the 3 GeV ring is in the order of 150 microns. However, this measurement is still to be confirmed.

THE MAX IV STORAGE RING AND ITS MAIN DIAGNOSTICS

The 3 GeV storage ring is described in detail in [1], [6] and [7]. In short, the 3 GeV storage ring was designed to meet the requirements of state-of-the-art insertion devices (IDs) for the generation of high-brightness hard x-rays. Its lattice was therefore based on a novel compact multibend achromat (MBA) delivering 328 pm rad bare lattice emittance in a circumference of 528 m [5-7]. 20 MBAs provide 19 long straights (4.6 m) for IDs and 40 short straights (1.3 m) for RF and diagnostics. The MAX IV achromat is a 7-bend achromat with 5 unit cells (3º) and 2 matching cells (1.5º). All bends contain a transverse gradient for vertical focusing. The matching cell dipoles have a longitudinal gradient as well. Since the vertical focusing is performed by the gradient bends, only horizontally focusing quadrupoles are contained in the unit cells. The optics for one achromat is displayed in Fig.3 and storage ring parameters are given in Table 2.

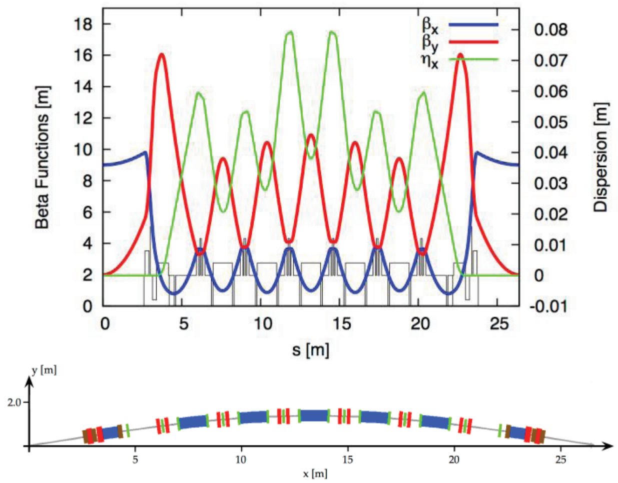

Figure 3: MAX IV 3 GeV achromat and optics.

Table 2: MAX IV 3 GeV Storage Ring Parameters

Operating energy	3 GeV
Circulating current	500 mA
Circumference	528 m
Horizontal emittance (bare lattice)	328 pm rad
Horizontal emittance (incl. IDs)	179 pm rad
Vertical emittance	2 – 8 pm rad
Total beam lifetime at 500 mA	>10 h
Q_x, Q_y	42.20, 16.28
ξ_x, ξ_y (natural)	-50.0, -50.2
Momentum compaction factor	3.06×10^{-4}
Required momentum acceptance	>4.5 %

Beam Position Monitors

The ring BPMs, amounting to 200 units (10/achromat), constitutes the backbone of the ring diagnostics. Here, the Libera Brilliance "+" units are used, which allow read-out in either single pass mode (injected beam) or integrating mode (stored beam). However, for initial commissioning, the BPMs are not used as indication of beam position, but rather they are the first diagnostic tool used to detect any (tiny) charge finding its way into the storage ring. Actually, in our case, we used the combined sum signal from all four buttons of the first BPM unit after the injection point. After verifying one or two turns, the buffer size in the read-out was enlarged, making it easy to adjust carefully some corrector magnets and follow the increasing number of turns achieved.

Once a beam is stored, the BPMs can be calibrated in positon relative to magnet centres, with help of a beam based technique [8]. In our case, we have introduced what we call "trim coils" in every sextupole and octupole magnets. For BPM calibration these coils are one by one excited in an upright quadrupole mode of quite tiny strength. The beam is displaced horizontally and vertically, and for each position the trim coil is excited. Observing the beam position readout in the nearby BPM for which the excitation has minimum influence on the beam closed orbit, gives the x and y offset values for that BPM. The novelty in our scheme is that the beam is centred in the non-linear magnetic elements, while traditionally the centring was towards the quadrupoles.

The BPM units are clamped into the magnetic blocks, with a bellow on one side in order to relax material stress. Seven magnetic blocks, encompassing several individual magnets, constitutes the entire achromat. BPM physical movements will follow the magnet blocks. Therefore, in long time scales, we are not monitoring the physical BPMs, but rather we will monitor the magnetic blocks. In short time scales, the resolution of the vertical beam positions enclosing the straight sections are the most critical. The goal is less movement than 10% of the rms beam size, which corresponds to 0.4 microns initially, and eventually 0.2 microns. A major monitor campaign has started to analyse the short term data in order to track any vibration sources.

Strip-lines for Tune Measurements

Considering our commercial BPM read-out system, one could contemplate measuring the machine betatron tunes with turn-by-turn data from a single BPM unit, by exciting the beam with an extra (in our case) vertical pinger magnet, and the horizontal injection kicker magnet. However, we found so far higher accuracy in tune measurements where a spectrum analyser (SA) is exciting a pair of strip-lines, inducing a tiny beam displacement, which is detected at an ordinary BPM in integration mode, connected to the SA.

Monitoring Machine Functions

With the equipment mentioned above, there are two ways of monitoring possible. Using the well-known LOCO approach [9], where the response matrix, 200 times 200 horizontal and vertical beam movements are measured for 200*190 horizontal and vertical corrector kicks. This huge amount of data is processed in an adequate model of the ring magnets, and the outcome is the horizontal and vertical beta functions. The dispersion function is monitored by RF changes, resulting in off-energy orbits. However, we have additionally used our trim coils (see above), and monitored induced tune shifts. This gives the beta function values in the non-linear magnets in which the trim coils are situated. Looking at Figure 3, where those are indicated with green and brown colours, we see that quite a dense sampling of the beta functions is possible. However, so far not all our trim coils are equipped with its own power supply. Additionally, we must admit that more commissioning work is needed, since the two methods still have discrepancies sometimes over 20 %, which is not acceptable. Both a LOCO model not converging properly, and an uncertainty in trim coil settings, are investigated as possible error sources.

Bunch-by-bunch Feedback System

At currents up to 120 mA, the 3 GeV ring has been operated stably, with a bunch-by-bunch feedback system with signal processors delivered by Dimtel [10]. Two 30 cm long strip-line pairs are used as transverse actuators, and a standard button BPM chamber is used as the detector. Figure 4 shows the vertical strip-line pair. One of the strip-line pairs is simultaneously used as a weak longitudinal kicker by feeding a common mode signal to its two electrodes. A waveguide overloaded cavity that will be dedicated for longitudinal feedback is currently being developed. This cavity is operating at 625 MHz ±25 MHz and will probably be installed in early 2017. The relatively low centre frequency is chosen since the form factor of the ring bunches drop rapidly at higher frequencies due to the long bunches.

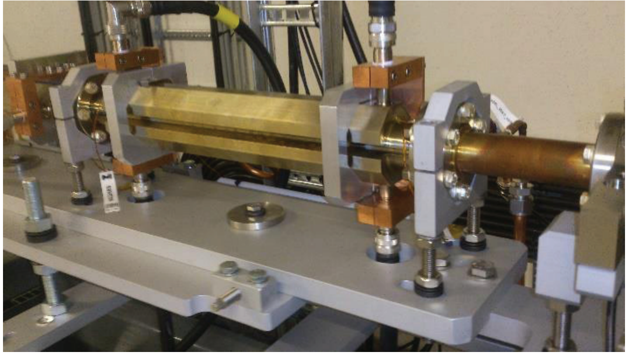

Figure 4: A 30 cm vertical strip-line pair. The horizontal pair is at left side, and the BPM is at right side.

The bunch-by-bunch system provides an efficient way to diagnose the potentially dangerous coupled bunch mode instabilities (CBI), so far mainly driven by higher order modes in the cavities. When aiming for higher currents, we use the system for instability growth rate measurements, which guides us in the temperature tuning of the individual cavities.

Vacuum Diagnostics and Scrapers

Because of the small radius vacuum chamber, r = 11 mm, almost the whole ring vacuum system is NEG-coated. Ion pumps and vacuum gauges are only placed in the short straights, and in the long straights not yet equipped with insertion devices (ID). Thus their read-out values only represent a minor part of the whole rest-gas volume encountered by the beam. It therefore becomes extra interesting to evaluate the pressure encountered by the beam, with help of scraper measurements. A vertical scraper scan, while observing the total lifetime, is shown in Fig. 5.

With the aid of in total five rest gas analyzers in the ring, capable to read-out also with beam in the ring, a fairly good estimate of the rest-gas composition could be made at around 100 mA: H_2 79 %, CO 12%, CH_4 (and dissociates) 5%, O_2 0.6% and CO_2 0.5%. Assuming this is also the composition experienced by the beam, the total pressure has been estimated at different current values, where scraper scans were performed. The result after

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several scans in the region up to 100 mA (at roughly 40 Ah integrated dose) was:

$P\,[\mathrm{nTorr}] = 1.156 + 0.028{*}I[\mathrm{mA}]$

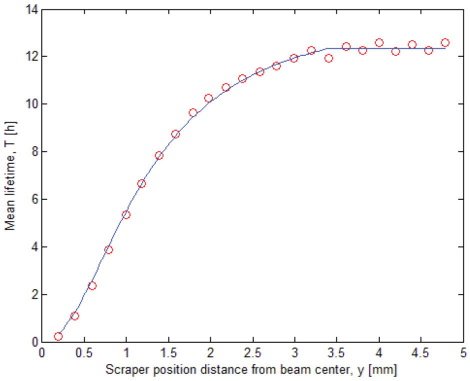

Figure 5: A vertical scraper scan. Rings are measurements and line is fitted curve.

At 50 mA both the elastic and inelastic scattering lifetimes are measured to be around 100 h. Rest gas compositions and vertical scraper scans are planned to continue for increasingly higher integrated doses. So far, these derived pressures tend to be higher than the gauge readouts, but lower than the ion-pump read-outs.

Emittance Diagnostics

The emittance diagnostic at the MAX IV storage rings is based on imaging the beam with synchrotron radiation (SR) in the near-visible spectral range from dipoles [11]. Employing two beam lines for each ring with source points at different horizontal dispersions will enable measurements also of the beam energy spread. In the 3 GeV storage ring a diagnostic beam line imaging the beam in the first dipole at horizontal dispersion close to zero has been installed and is under commissioning. Installations for another beam line in the sixth dipole (though in another achromat), where the dispersion is roughly 27 mm, is scheduled for 2017. The source points can be imagined in Fig. 3, where the dipoles are indicated in blue. These beam lines are for the moment the only dipole source beam lines in the entire 3 GeV ring, the reason being that it is quite difficult to guide the light out through the magnet blocks, which can be seen in Fig. 6.

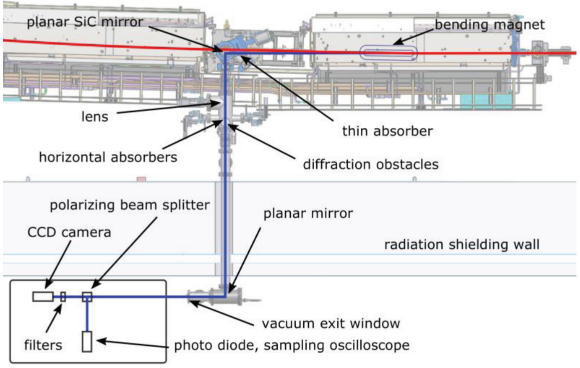

Figure 6: Schematic beam line layout. Electron path in red and SR path in blue. The distance from the center of the dipole to the first mirror is 1.85 m.

Images of the electron beam at near-visible wavelengths are dominated by diffraction that is inherent to the synchrotron radiation emitted into a narrow cone around the particle trajectory. In the MAX IV 3 GeV ring diagnostic beam lines, however, we make use of these diffraction effects by deriving both transverse beam sizes from the fringe contrast of the diffraction dominated images. Numerical simulations from a beam line modeled in the Synchrotron Radiation Workshop (SRW) [12], [13], thereby provide the relation between the fringe contrast and the horizontal and vertical beam size. SRW provides an accurate treatment of the synchrotron radiation emission process along the curved trajectory of the ultra-relativistic beam in a dipole magnet in the near-field regime as well as the propagation of SR through optical components like apertures and a thin lens.

Vertical Beam Size Measurements Established at the Swiss Light Source for resolving low vertical emittance beams, the imaging of pi-polarized SR in the near-UV [14] will be applied, as well as the obstacle diffractometer method, in which a fringe pattern is intensified in a predictable way by a horizontal obstacle in the path of the SR beam [15], (see Fig. 7).

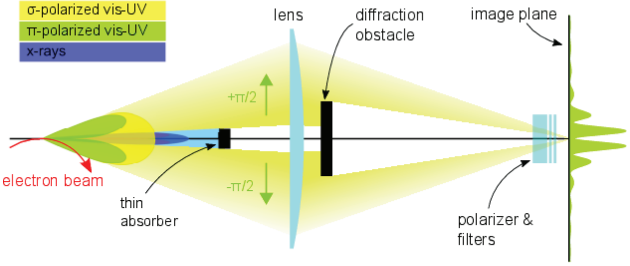

Figure 7: Schematic side-view of the obstacle diffractometer technique.

Measurements on an uncorrected beam in the 3 GeV storage ring at a vertical beam size of approximately 11.5 µm, corresponding to a vertical emittance of approximately 6.4 pm rad have been achieved to study the imaging quality of the first operational diagnostic beam line. In Fig. 8, a vertical profile of pi-polarized SR is shown with a diffraction pattern intensified by an inserted diffraction obstacle.

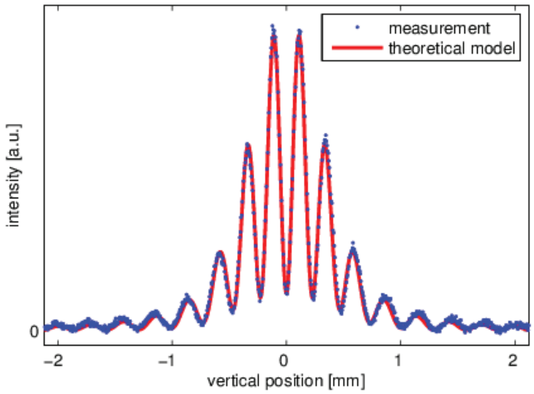

Figure 8: Vertical profile of imaged pi-polarized SR with a 9 mm diffraction obstacle at 488 nm wavelength. The measured profile (blue) is compared to a SRW calculated profile of the same fringe contrast.

For vertical beam sizes in the 10 μm range the utilized imaging wavelength of 488 nm is sufficient. A reduction in vertical emittance and beam size to the 0.3 pm rad and 2.2 μm level, respectively, (corresponding to an emittance ratio of 1 ‰) will require shorter wavelengths down to 266 nm, for which the beam lines have been designed.

Horizontal Beam Size Measurements In the 3 GeV storage ring the expected horizontal beam sizes of approximately 22 to 24 μm are resolved by imaging SR in the near infrared. We make use of an interference effect originating in the longitudinally extended source of SR, emitted by the electron beam along its trajectory in the dipole magnet. For a wide horizontal acceptance angle of up to 18 mrad enabled by the design of the beam lines, an asymmetric fringe pattern is formed in the image plane from which, by evaluation of the fringe contrast, the horizontal beam size is derived. In Fig. 9 the sensitivity of the diffraction pattern is demonstrated. Preliminary measurements indicate a horizontal beam size of 24.5±1.5 μm. The betax is still to be determined (see sub-section on machine functions), but using the design betax places the horizontal emittance at 400 pm rad. Further improvement of the experimental condition as well as the numerical model are, however, necessary.

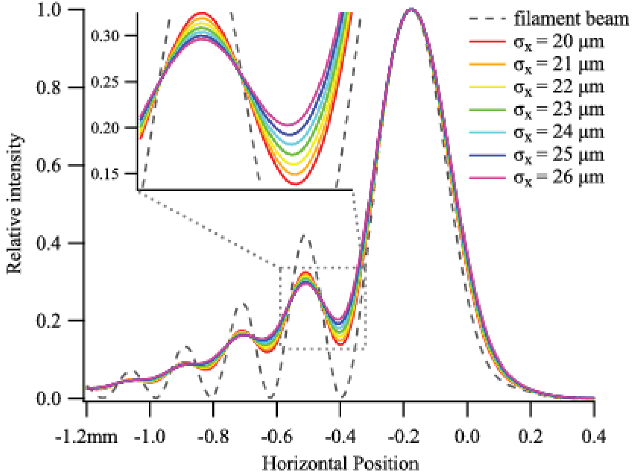

Figure 9: Horizontal profiles of sigma polarized SR calculated in SRW. The wavelength is 930 nm and the horizontal acceptance angle of the beam line is 15 mrad.

We would like to emphasize that introducing a double slit scheme, could have a beneficial effect on the resolution in this region of beam size. However, Fig. 9 indicates clearly that for future planned storage ring light sources with horizontal emittances for example at 50 pm rad, and a horizontal beta-function around a few meters, the resolution possibilities are actually higher than in the present case. In such case, or for even lower horizontal emittances, one would simply go to visible wavelengths, and image the beam without obstacles similar, in principle, to the pi-polarization method in the vertical case.

Longitudinal Bunch Shape Measurements In the same diagnostic beam line as described above, we use a Glan-Tayler polarizer for choosing the desired polarization. The discarded polarization we guide to an optical sampling oscilloscope. We have performed bunch shape measurements up to 8 mA in single bunch, verifying at low currents the natural bunch length and at increasing currents the potential well distortion. Studies to reveal the Intra Beam Scattering (IBS) onset are planned. In multi-bunch mode the bunch-by-bunch feedback system must be used in parallel with the measurements, to ensure the longitudinal stability.

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