THE XFEL LASER HEATER

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Abstract

The high-brilliance photo-cathode gun foreseen for the X-FEL will provide beams with extremely small momentum spread that will make the beam susceptible to micro-bunching instabilities which will spoil SASE operation. It is therefore desirable to increase the momentum spread to a level that prevents these instabilities but still is compatible with SASE operation. The laser heater will achieve this by superimposing a transversely polarized laser and the electron beam in a properly tuned undulator, thereby producing a momentum modulation that is smeared out in a dogleg chicane to obtain the desired momentum spread increase. We present the initial design and layout of the laser heater system for the X-FEL in Hamburg.

INTRODUCTION

The need for a laser-heater comes from the fact that the electron beam from high brilliance photo-cathode guns has an extremely small energy spread which is on the order of a few keV [1]. It was realized that this causes random intensity variations can be amplified significantly due to the emission of coherent synchrotron radiation in bunch compressors [2, 3, 4] leading to a growing micro-bunching instability. Later it was noticed that at energies below 10 MeV plasma oscillations modify density fluctuations and couple to energy modulations. Even at energies much larger than 10 MeV the space charge impedance increases the energy modulation and contributes significantly to an instability. These instabilities are characterized by an impedance which translates intensity modulations into momentum modulations that can drastically increase the momentum spread way beyond the acceptable limit for SASE operation. Already in ref. [5] it was pointed out that a laser heater, where a transversely polarized infra-red laser is superimposed on the electron beam that passes through an undulator magnet, would alleviate the growth of the instability. If tuned correctly to resonance, the transversely oscillating electrons acquire a momentum modulation that is smeared out in a chicane, resulting in an increased incoherent energy spread. This will provide Landau damping to an extent that reduces the gain of the instability thereby avoiding large energy modulations whose magnitude would be much bigger than the moderate increase in incoherent energy spread caused by the laser heater. In this way the performance of the SASE FEL is not significantly affected. These papers led to a careful analysis of the implications of the micro-bunching instabilities for the linac coherent light source (LCLS) at SLAC [6] and an investigation of the reduced stability implications for the electron gun [7]. The same arguments hold true for the XFEL for which a laser heater is foreseen as well and recently the Swedish Research Council agreed to fund its construction.

Technically, the laser heater is needed to increase the energy spread from about 3 keV up to a maximum of 25 keV after the first acceleration module in the XFEL injector where the maximum beam energy is 130 MeV. Considering transverse beam sizes of about 0.2 mm and bunch length of 20 ps this requires on the order of $10\,\mu$J. Our working hypothesis is to split off part of the first harmonic at 1054 nm of the laser pulse from gun laser and transport it from the laser room to the interaction region with the undulator via a 50 m long transport line. Using part of the gun laser will automatically provide the correct number of pulses and stable timing between electron bunches and laser irrespective of the pattern in which up to 8000 bunches per macro-pulse will be delivered to experiments. The rough outline of the laser heater with all components is shown in Fig. 1 and we discuss the parts in the following sections.

LASER BEAM LINE

The relative timing between the laser and electrons will be adjusted on a laser table near the gun laser with two delay stages, one for coarse adjustment on the ns timescale and a second for ps timescale. The large distance between the laser table and the undulator of about 50 m and the vertical separation between laser table and beam level can cause convection in the vertical shaft with fluctuating refractive indices that will disturb the laser beam. In the optical replica (ORS) experiment [8] with a somewhat shorter laser beam line we observed significant wandering of the focus. To avoid these calamities it is foreseen to pass the laser pulse in an evacuated laser beam pipe with a pressure in the 10^{-7} mbar range. In order to reach a low pressure the use of large pipes is advantageous because they have large conductances and will permit using a small number

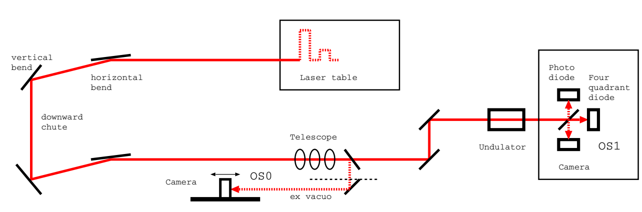

Figure 1: Conceptual layout of the laser transport system.

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of pumps. The laser pulse has to enter the evacuated beam pipe through a window that ideally has an anti-reflex coating. The same type window will be used at the end of the laser beam pipe just upstream of the telescope which will be located in air to allow permit using standard translation stages for adjusting the lens positions. The optical station 0 with the beam size diagnostic for the 'virtual' laser focus will also be located outside vacuum. A third window will be needed for the laser pulse to enter the accelerator vacuum system.

The mirrors to transport the beam from the laser table, through vertical shaft and on to OS0 and the undulator will be located in vacuo and have to be remotely controllable. We need to make sure to find remotely controlled mirrors that operate in vacuum that can work with little convective cooling and restricted lubrication. Moreover, special care must be taken with piezo-electric motors, that might not be operable in moderate pressures where they cause discharges.

Furthermore there are three movable lenses in the telescope that need to be installed in order to adjust laser beam size and waist (focus) position inside the undulator. Besides the longitudinal movement the lenses must be transversely adjustable so they can be aligned properly to prevent steering when changing their longitudinal position.

Following the telescope we need a movable mirror that allows us to deflect the laser pulse on to OS0. Putting a beam splitter on a translation stage along with a mirror will permit us to monitor the beam size parasitically during operation.

In order to see how the required rms laser beam size in the undulator can be achieved we run a simple beam tracking program that maps the rms beam sizes from one point to the next by simple transfer matrix calculations and show the result of such a simulation in Fig. 3. Here we start with a diffraction limited laser beam at longitudinal position zero. It has the diffraction limited rms emittance $\varepsilon = \lambda/4\pi = 8.4 \times 10^{-8}\mathrm{m\,rad}$ where we need to stress that this is the rms emittance that is conventionally used in accelerators, rather than the product of laser beam width and angular divergence that laser people use. We somewhat arbitrarily assume that the starting beam size is 0.1 mm and the angular divergence is 0.84 mrad. We first use a single lens with 1 m focal length and make the beam parallel in order to transport it over most of the distance to the undulator, here assumed to be located about 50 m downstream of the laser table. Due to the rather parallel beams in most of the distance the precise distance is unimportant and can be easily adapted. Similarly to what is done for the ORS experiment we use a triplet telescope with three lenses (defocusing, focusing, defocusing) each having a focal length of about 0.7 m. The triplet is located about 13 m upstream of the undulator. We then matched the positions of the second and third lens to achieve a 0.2 mm ams beam size at the focus in the undulator. The minimum is nicely visible in Fig. 3. Moving the triplet closer to the undulator should not be a problem and will be investigated soon.

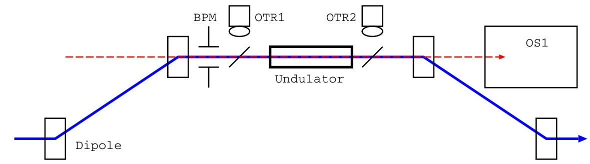

Figure 2: Chicane with diagnostics.

ELECTRON BEAM LINE

The electron beam will pass through a stainless steel vacuum beam pipe for the entire, approximately 2 m long section starting at a flange upstream of the first dipole of the chicane. The standard beam pipe radius is 40 mm and we will have to provide short sections with flanges and bellows. Special attention needs to be paid to the Y-shaped vacuum chamber in dipole 2 and 3 which need zero-degree ports to allow the laser pulse to enter and exit the section where it co-propagates with the electron beam in the undulator magnet.

We will need one BPM to monitor the arrival time of the electron beam and its transverse position. This will help in the initial setup stage to achieve synchronization as a complementary means to the method described in the section about alignment strategy with laser diode and synchrotron radiation from the undulator. During operation it will aid troubleshooting and will help to quickly identify failure modes.

The OTR screens in the ORS experiment proved absolutely essential to find transverse overlap for electrons and laser pulse and we should have a similar system in the laser heater. One OTR is installed immediately before and another immediately after the undulator. Inside the OTR housing we will need a vertically movable ladder with at least two screens, one OTR screen to find the transverse position of the electron beam and a diffuse, so-called calibration screen to observe the position of the laser pulse on the screen. The screens need to be imaged to a triggered camera.

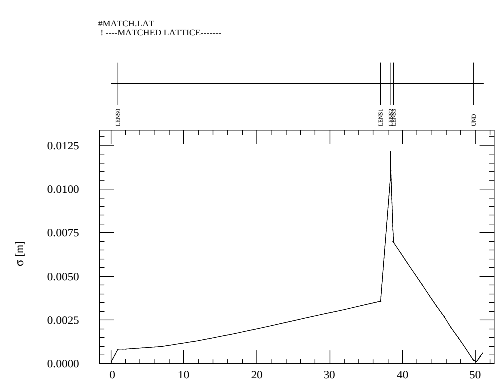

Figure 3: Laser beam optics.

The chicane consists of four, preferably air-cooled steering magnets. Possible candidates are steering dipoles from HERA which have a length of 300 mm and a gap of 48 mm. For a 7 degree deflection angle at 130 MeV we need 53 mTm which is reachable by these magnets. If this solution should prove to be impossible we need to purchase four small dipoles.

The undulator will be a hybrid magnet in which the poles are made of steel and permanent magnet material is sandwiched between the poles to pump flux-lines into the poles. These magnets have the advantage that the field quality is defined by the steel-pole geometry and can be made very high, but they can have a relatively short period length and require no power supply. We propose to use 10 periods with a period length of 60 mm which is slightly larger than that of the LCLS undulator to compensate for the larger laser wavelength used here and to keep the peak field smaller which will be advantageous and will keep the required amount of permanent magnet material reasonable. In order to be able to operate at different beam energies of up to 130 MeV we plan to adjust the magnetic field for resonance by adjusting the pole gap. In order to reach the peak field of 0.3 T we need to reduce the gap to 30 mm to simplify the design of the undulator and limit the amount of permanent magnet material.

OPERATIONAL ASPECTS

There are stringent requirements to match the electron and laser beam size in the undulator. This implies that we need good control of the laser beam position and size as well as the longitudinal waist (focus) position. A simple solution is to re-use the telescope used in the ORS experiment and locate it some distance upstream of, but as close to the undulator as possible, because that will facilitate to make small spots (0.1 mm rms) without excessive beam sizes inside the triplet lenses.

We also need a 'virtual waist' where we can verify that the laser waist is at the proper location and has the proper size. This is most easily achieved by a translation stage with mirror or beam splitter immediately following the telescope that deflects the laser out of the vacuum pipe and onto an optical table (OS0) with a triggered camera that can move longitudinally in order to scan through the waist. The nominal longitudinal position of the camera must be equal to the center of the undulator. In this way the waist-scan will give both beam size and waist position. We might need to consider to place a wheel with neutral density filters, dielectric filters, or $\lambda/2$ plate with polarizer before the camera to be able to adjust the laser intensity.

Once the beam size and waist position are fixed on the optical bench with the camera we can extract the mirror and pass the laser beam through the undulator. Mirrors before the undulator are then used to steer position and angle inside the undulator. There is an screen that will need both OTR and calibration screens to transversely align both electrons and laser in the undulator.

To verify stable operation we propose to set up a small optical table (OS1) after the undulator with a beam splitter such that the straight-ahead beam propagates to a four-quadrant diode to check steering and the other leg should go to a camera to verify that the spot size stays unchanged.

The temporal alignment is much relaxed (2 orders of magnitude) compared to the ORS experiment, because here both beams are on the order of 10 to 20 ps long rather than 0.2 ps in the ORS. We propose to use a fast laser diode on OS1 and a high bandwidth oscilloscope to observe the laser pulse and the spontaneous radiation emitted from the undulator.

We need to think about how to directly observe the effect of the laser on the electron beam. The direct increase of the momentum spread, which is the 'direct product' of the laser heater will be rather moderate and difficult to see on a downstream dispersive screen. We might consider to increase the laser power and significantly modulate the electron bunch such that we can observe coherent transition radiation from a downstream OTR screen, similarly to how we find overlap in the ORS experiment. This capability requires higher laser power levels than the 10 μJ mentioned above.

The laser operates in the infra-red regime at high power levels and is potentially harmful to humans and equipment (e.g. OTR screen). We therefore need an interlock system and also light-tight housing for the optical diagnostic stations.

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