

TOWARDS A SEEDED HIGH REPETITION RATE FEL: CONCEPT OF SEED LASER BEAM TRANSPORT AND INCOUPLING

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Abstract

In this contribution we report the concept of seed laser beam transport and incoupling into the electron beamline to achieve the required seeding parameters for FLASH2020+ project. In our concept a defined source point inside the laser lab is imaged to the center of the modulator. This provides the possibility of controlling the delivered seed parameters at the modulators by actuators within the laser system. We illustrate how the total energy transmission is maximized while the risk of laser induced damage of optics is mitigated. The nonlinear effects of high peak power pulse propagation are studied. Considerations for the incoupling of the seed laser into the electron beamline and the concept for laser-electron timing stabilization are presented.

INTRODUCTION

FLASH2020+ is an upgrade project of the FLASH facility at Hamburg. A main goal of the project is to generate fully coherent soft X-ray FEL radiation at a high repetition rate (MHz) [1]. This will be accomplished by utilizing the well-known seeding techniques High Gain Harmonic Generation (HG) and Echo-Enhanced Harmonic Generation (EEHG), hence it requires two external seed lasers. The combination will provide seeded FEL radiation with tunable wavelength from 4 to 60 nm.

For HG, a tunable UV laser system (Seed2: 297 – 317 nm, 50 fs, < 16 μJ) will modulate the electrons inside the second modulator (Mod2). For EEHG, fixed wavelength (Seed1: 343 nm, 500 fs, < 50 μJ) laser pulses interact with the electrons inside the first modulator (Mod1) which is followed by the interaction of Seed2 and electrons inside the second modulator [2].

Details of the high energy and high repetition rate laser system for seeding are described in [3]. The laser system operates at 10 Hz burst mode with a pulse train of 6000 pulses per second with 1 MHz in a 600 μs long pulse trains. This matches the electron bunch repetition rate structure.

The femtosecond laser pulses will be transported about 28 and 35 m to the first and second modulators, respectively using dedicated transport laser beamlines and incoupling. The laser beamlines pass mainly through radiation protected area. Figure 1 illustrates the overview of the FLASH accelerator, seeding laser lab and the laser beam transport.

FLASH operates 24/7, with limited access (4 – 8 hours per month) for the maintenance and repair of components inside accelerator tunnel. Therefore, our design has to provide proper means to monitor and control the beam

parameters and at the same time minimize the required time and expenses for repair and maintenance.

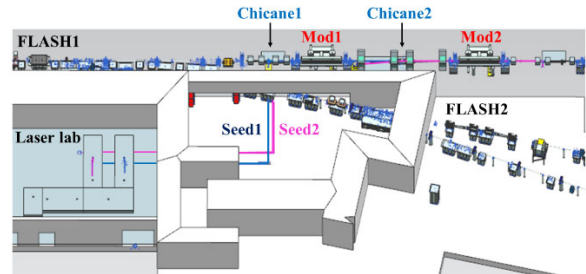


Figure 1: Overview of laser beam transport. Seed1 and Seed2 are coupled into first and second modulators via mirrors installed at the chicanes, where a transversal offset between the laser path and the electrons is presented.

Table 1: Required Seed Laser Beam Parameters Inside Modulators, Mod1 and Mod2

Parameter	Seed1	Seed2
Wavelength (nm)	343	297 – 317
Pulse duration (fs)	500	50
Pulse energy (μJ)	50	16
Peak power (MW)	1 – 100	5 – 300
Polarization	s (perpendicular)	
Beam radius (μm , $1/e^2$)	600	
Beam quality	$M^2 < 1.5$	
Position control (μm)	± 500 , 20 μm resolution	
Pointing (angle) control (μrad)	± 80 , 3 μrad resolution	
Position / pointing stability (μm , rms) / (μrad)	50 / 40	
Temporal jitter (fs, rms)	Seed1 to e-beam < 50 Seed2 to Seed1 < 50	

SEED LASER BEAM TRANSPORT

Required Parameters for Seeding

Stable overlap in time and space between seed laser and electron beam inside Mod1 and Mod2 is required to imprint an energy modulation onto the electron bunches. Each of the modulator undulators are about 2.5 m long, the electron beam size is between 100 μm and 200 μm ($1/e^2$, radius) along the modulator and the laser beam size is $\sim 600 \mu\text{m}$ ($1/e^2$, radius). This beam size ratio ensures that the electron beam is modulated by the uniform pulse energy distribution of the laser beam and providing most stable modulation.

Table 1 summarizes some of the most relevant parameters of the Seed1 and Seed2 laser pulses inside

modulators which need to be concerned by laser beam transport and incoupling.

Interface Between Seed Laser and Beam Transport

The main strategy of beam transport is to reduce the complexity. In this respect, we define an interface between seed laser and beam transport as the source point and the required parameters for seeding are controlled by the seed laser system at the interface.

Figure 2(a) illustrates the scheme of interface between seed laser and beam transport for Seed2. The beam mode matching is done in the astigmatism compensated distance constant (AC-DC) telescopes. First the beam is expanded to reduce the B-integral of propagating inside the bulk compressor (BC). The delay of BC can be used to manage the dispersion through the beam transport. In addition, adaptive optics (e.g. deformable mirror) will be used to optimize the laser wavefront distortion for best seeding performance.

Figure 2(b) shows the evolution of beam waist, pulse duration and the B-integral as the beam propagates from the laser system to the interface plane. The Kerr lensing effect varies at different pulse energies. This can be compensated by the AC-DC telescope to preserve the beam size and divergence at the interface.

Imaging System, Optical Components, Energy Efficiency and LIDT

The seed lasers have to exhibit high pointing and position stability inside modulators. To achieve this, the source point in the laser lab (“interface” in Fig. 2(b), right) is relay imaged into the modulators. A schematic view of the relay imaging for Seed1 and Seed2 with magnification factors 9x and 11x, respectively is shown in Fig. 3. The concept uses two focusing modules that consist of spherical mirrors MS1.10/11&MS1.3 for Seed1 and MS1.11/12&MS2.4 for Seed2.

The Seed2 laser output parameters show 2 μrad position and 1% pointing fluctuations in a start-to-end simulation [3]. We then simulated the transfer of laser position and angle pointing fluctuations through the relay imaging beamline considering 1 μm instability for each of the mirrors. The results show the pointing and position fluctuations of laser beam $\sim 25 \mu\text{m}$ and 2.2 μrad (rms) inside modulator.

To prevent air turbulences affecting the laser spatial pointing and arrival time, contamination of the optical components and to minimize the nonlinear effects such as B-Integral, the laser beam will be transported under ultrahigh vacuum (UHV) condition $< 10^{-6}$ mbar.

The beam transport and incoupling consist of 12 (13) high reflective (HR) dielectric coated mirrors, 2 samplers (CaF₂, uncoated) and 1 vacuum window (uncoated Z-cut UV Fused Silica). We will use HR mirrors with IBS dielectric coating. The reflectivity of these mirrors is higher than 99%, which provides a total energy transmission of about 80% for both Seed1 and Seed2. The

main loss factor in here is the uncoated vacuum window which separates laser and electron UHV beamlines.

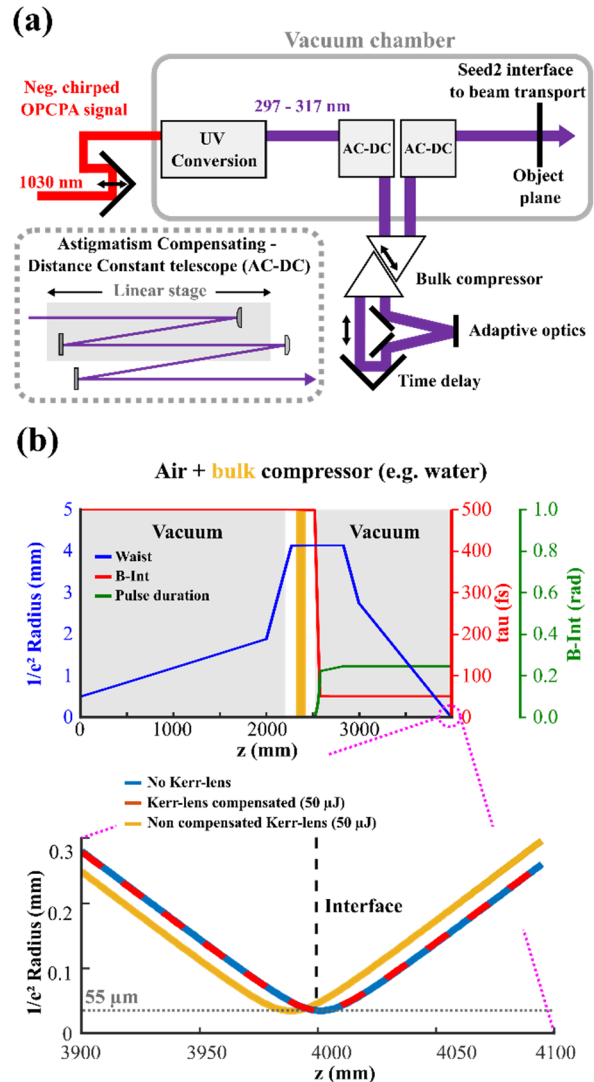


Figure 2: (a) Scheme of the interface between seed laser and beam transport. (b) Beam waist, B-Integral and pulse duration propagation from seed laser to the interface.

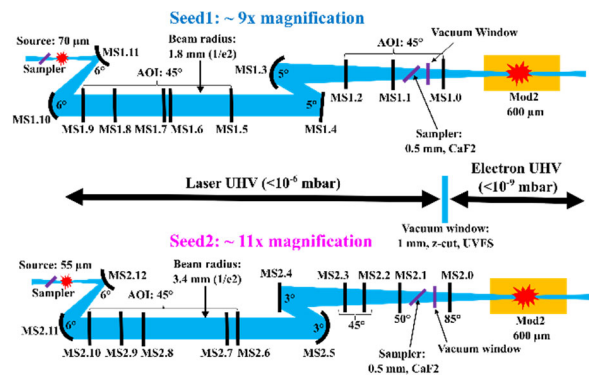


Figure 3: Relay imaging system for Seed1/2.

An important parameter which defines the total transmission and accessibility of the beam transport for seeding is the laser induced damage threshold (LIDT). The

LIDT depends on the pulse duration, wavelength and the repetition rate. As our laser system delivers pulses in special burst mode structure which affect the equilibrium conditions of the coating layers, we try to account of a safety margin in our design. The maximum fluences on the IBS coating HR mirrors for Seed1 is 4 mJ/cm^2 . This is much less than the reported LIDT values of such coating at 343 nm with, s-pol: 120 mJ/cm^2 , p-pol: 170 mJ/cm^2 .

Figure 4 shows the fluence at each mirror through the laser beam transport for Seed2. The fluence on the most of mirrors is kept below 0.25 mJ/cm^2 by increasing the beam size or the angle of incidence (AOI). At FERMI at Elettra the incoupling mirror (IBS coating, HR@ $232\text{--}267 \text{ nm}$, 50 Hz , $60\text{--}100 \text{ fs}$, out of vacuum) experiences maximum 1.4 mJ/cm^2 and no damage has been observed. The maximum fluence for Seed2 beam transport is 0.6 mJ/cm^2 , but the entire beamline is inside UHV where the coatings in general might have a lower LIDT, therefore a LIDT test for the optics of Seed2 is being planned.

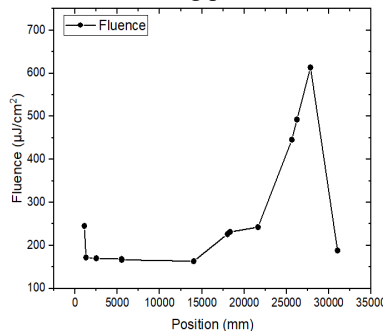


Figure 4: fluence at each mirror (filled circles) through the laser beam transport for Seed2. The fluence on the incoupling mirror (MS2.0), inside electron UHV beamline, is reduced using a grazing incidence angle, $\text{AOI} = 85^\circ$.

B-Integral

The peak intensity of the seed lasers is in the order of tens of GW/cm^2 . Thus, it is important to consider possible nonlinear effects such as Kerr lensing that can change the beam waist and position inside modulators. In Fig. 5 the B-Integral and the beam waist for different pulse energies of Seed1 and Seed2 are illustrated. The main contribution to the B-Integral is caused by the propagation through vacuum windows. For Seed2 the total B-Integral and change of beam waist and position inside the modulator is negligible. Seed1 also has a total low B-integral over the beamline. The variation of the beam waist and position for Seed1 can be adjusted and compensated by the AC-DC telescope in the laser system (see Fig. 2).

Incoupling Design

The chicane magnets deflect the electron beam and allow the incoupling and outcoupling of the seed lasers.

An important consideration for the design of the in/outcoupling chambers is the space charge effect. This effect occurs when the high energy electron bunch travels in the vicinity of dielectric substrates and accumulates charges on the surface of the substrate [4]. This effect can

cause damage of dielectric coated optics, as well as the deflection of e-beam trajectory.

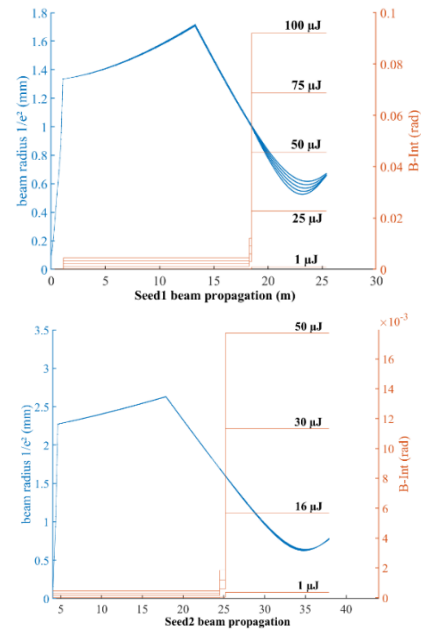


Figure 5: B-Integral and waist propagation of seed lasers for different pulse energies.

Since there is little data available, in a dedicated campaign at FLASH, this effect was studied. Dielectric coatings on glass substrates were located in the vicinity of the electron beam with an energy of 650 MeV and 970 MeV operating with one electron bunch per pulse train. We observed that in the case of 650 MeV , at distances smaller than 0.5 mm , the electron beam position monitors 7.2 m downstream of the testing station shows periodic deflection of the electron beam trajectory (see Fig. 6).

FLASH can operate at much higher electron bunch number, thus a minimum distance of 3 mm between the dielectric mirrors and the electron beam in our design will be considered to prevent the deflection of electron beam and damage of the laser incoupling mirrors.

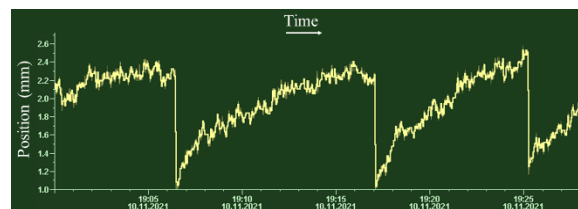


Figure 6: electron beam position after the dielectric mirror shows periodic changes of the electron trajectory.

Diagnostics and control

The design of laser beam transport is aiming to provide on-line and off-line diagnostics through the entire beamline in order to monitor the beam parameters such as position and pulse energy. In addition, at each of the incoupling sections, dedicated laser tables are considered to accommodate the diagnostics for Seed1 and Seed2. Figure 7 illustrates the diagnostic table for the Seed2 incoupling.

There, the laser pulse energy (PE), beam size and profile (CCD) can be monitored. The wavefront sensor (WFS) feedbacks to the adaptive optics (see Fig. 2) to optimize the beam quality.

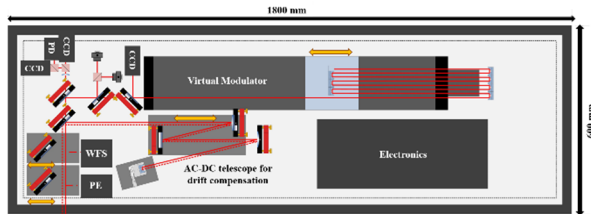


Figure 7: Seed2 diagnostic at incoupling to electron beam.

CCDs will be used to actuate the beamline motorized mirrors in order to establish the transverse overlap between laser and electron beam. A beam stabilization system that uses the beamline cameras and actuators to monitor and preserve the transverse overlap. The virtual modulator will give the possibility to scan the laser beam profile along the real modulators.

For the laser beamline, UHV compatible opto-mechanics that are free of hydrocarbons will be used. The number of movers and actuators will be minimized to reduce the system complexity. Almost all of the beam transport mirrors are selected to be standard 2-inch substrates. We are currently evaluating several choices of mirror mount designs which can be actuated with high resolution and provide low wavefront distortion and sm minimum beam pathlength variation.

Incoupling mirrors have to be compatible with electron beamline UHV requirements which forbid any actuators. Here, we will use out of vacuum actuators that manipulate the components inside vacuum using mechanical feedthroughs. This type of actuators provides only few μm resolution which is not as fine as the nm resolution of laser transport beam opto-mechanics.

To control the transverse overlap, the position of laser beam in respect to the electron beam axis needs to have the adjustment possibility of $\pm 500 \mu\text{m}$, with $20 \mu\text{m}$ resolution along the modulators. The linear manipulators of the incoupling mirrors with few mm of travel range and bellow $5 \mu\text{m}$ precision can provide the required position modification. The requirements for the laser beam angle is $\sim 80 \mu\text{rad}$ with $3 \mu\text{rad}$ resolution. To realize this, the opto-mechanics of incoupling mirrors, MS1.0 and MS2.0, will be used for coarse movements. The fine tuning of the beam position and pointing is provided by the high resolution opto-mechanics of MS1.1 and MS2.1/2.

Seed Laser and Electron Timing

The longitudinal overlap between seed lasers and electron pulses is established by the detection of the electron energy modulation and/or the seeded FEL radiation.

Stable seeding requires low (bellow 50 fs, rms) timing jitter between the two seed lasers and the seed laser and electron bunch. The seed laser system utilizes fast synchronization between the seed laser oscillator (Origami 1030 nm) and an optical fibre link (1550 nm) with timing

jitter < 30 fs based on an optical balanced cross-correlator (NIR-OSC BXC) [5].

The 28 to 35 meters of laser beam transport from laser lab to the FLASH tunnel experiences different environmental conditions, e.g., temperatures and humidity, in addition to the ground movements. These will cause changes in the laser beamline path length and consequently the arrival time of laser pulses. We expect timing drifts in the order of several picosecond which have to be compensated.

The concept for the drift compensation for Seed1 and Seed2 is illustrated in Fig. 8. A small portion of the seed laser is mode matched using an AC-DC telescope in the seed laser incoupling section and redirected towards the laser lab through the beam transport. In this way, the relay imaging for the re-directed beam is in principle preserved, which will provide pointing and position stability after the long propagation. The redirected seed laser and oscillator pulses are mixed in a DFG process in the balance cross correlator (UV-OSC BXC). For Seed1 the timing stabilization actuates the translation stage after the THG setup to compensate for the slow drifts. For Seed2 the the slow fibre delay line between oscillator and the NKT front end is actuated to stabilize the timing between laser and the electron beam.

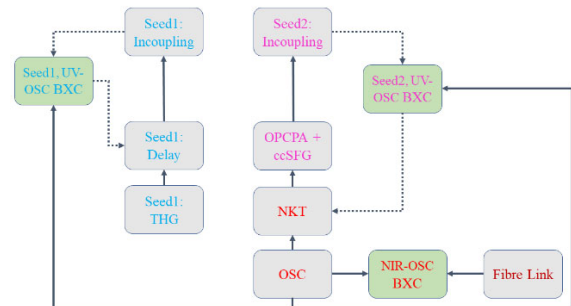


Figure 8: Scheme of the beam transport drift compensation concept.

CONCLUSION

The concept of laser beam transport and incoupling is based on imaging a defined source point from laser room to the modulators. Keeping the complexity low, this design is capable of transporting fs tunable UV pulses with $\sim 80\%$ energy transmission efficiency. The fluence on the optical components of Seed1 is significantly lower than the expected LIDT. For Seed2 further LIDT tests are required to study the risk of damaging optics. The study of nonlinear effect shows that the variation of B-Integral is low and the residual changes can be compensated by a tunable telescope in the laser system. The space charge effect was tested and measures for the incoupling design are taken. The diagnostics of the beam transport and incoupling will provide the possibility to monitor and modify seed laser parameters for optimized FEL performance. A timing stabilization concept is under development to provide low laser arrival time jitter and drift.

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