Characterization of the Electron Beam in the ACHIP Chamber in SwissFEL

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Abstract. We have installed an interaction chamber in the electron beam line of SwissFEL. Electrons with a particle energy of 3 GeV are focused to a few-micrometer beam size. Samples placed in this beam can be aligned to the electron beam with a hexapod. The goal of this installation is to demonstrate laser-driven acceleration inside dielectric structures. We present here the layout of this interaction chamber as well as first measurements with the electron beam.

1. Experimental Layout

The goal of the Accelerator-on-a-Chip International Program (ACHIP) is to conduct research on laser-driven acceleration inside dielectric microstructures, which integrate all necessary photonics components on a chip [1]. We have installed an interaction chamber [2] in the Athos beam line [3] of the X-ray free electron laser SwissFEL [4] at a position $z = 321$ m from the photocathode, to test the applicability of the ACHIP concepts on ultra-relativistic electron beams. These experiments will complement the research at low-energy beams [5, 6, 7]. Besides the goal of increasing particle energy, applications of laser-driven structures in conventional accelerators include electron bunch shaping [8] as well as instrumentation [9]. Given that the geometric emittance of the SwissFEL beam at a particle energy of 3 GeV can reach values down to 10 pm, we are expecting to be able to transmit the entire bunch of 1 pC through a structure with 1 µm aperture [10]. This will allow to potentially accelerate the full beam, and to to study wake fields and other collective effects in the structures. In addition, we will explore opportunities to shape the electron beam prior to sending it into the undulator of the Athos beam line of SwissFEL.

The vacuum chamber consists of a welded aluminum structure with removable walls, allowing for easy modification for future experiments. The chamber is approximately two meters long, and it houses focusing elements for the electron beam as well as the sample mount. Two turbo-molecular pumps are used to reach the required pressure for beam operation in a few hours after accessing elements inside the chamber. We are considering a load lock system to ease the

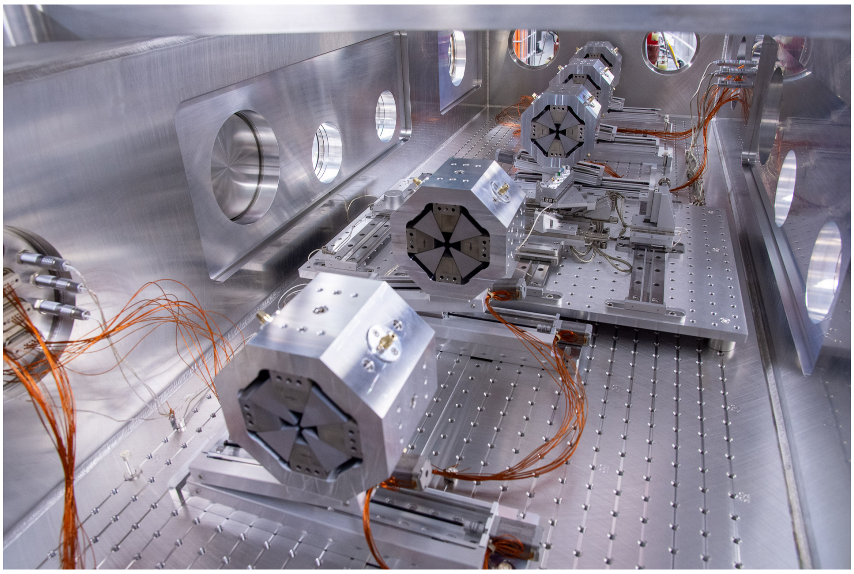

Figure 1. Inside view of the experimental chamber.

exchange of samples in the future. The chamber can be locked off the rest of the accelerator vacuum by two valves.

A hexapod is installed at the center of the chamber. Accelerating structures under test are placed on a small linear stage on top of this hexapod, allowing for a quick sample exchange. The entire system can be moved on rails along the electron beam direction. A software can be used to move the hexapod on a specified path, and to acquire data during the scan [11].

The electron beam is focused by a permanent magnet quadrupole triplet. The magnets can be moved into the beam by means of stepper-motor driven linear stages, which are also used to align the magnetic center to the beam axis. A second identical quadrupole triplet, set up symmetrically after the interaction point, matches the beam back into the accelerator lattice. A view of the inside of the chamber is given in Figure 1.

The quadrupole gradient was measured as a function of the gap (Figure 2 left). The prototype fulfilled the specifications ($G = 388$ T/m at a gap > 6 mm), but does not attend the ultimate performance predicted from RADIA simulations. We attribute this to a possibly lower remanence field of the samarium cobalt material, but did not investigate this further because the prototype achieved the necessary field gradient with a gap compatible with the experiment. The quadrupole alignment system was tested extensively before installation [12]. A test of the reproducibility of the move is shown in Figure 2 (right). The rms deviation of the alignment from the desired location is 10 µm horizontally and 6.25 µm vertically.

Since the strength of the permanent magnet quadrupole cannot be adjusted remotely, we use the electromagnetic quadrupole upstream of the interaction chamber to optimize the beam at the interaction point.

The chamber is integrated into diagnostics and control systems of SwissFEL. The electron bunch charge is measured using the monopole cavities of the beam position monitors [13], which show excellent linearity and acceptable readout noise down to charges of 100 fC. Beam losses are measured with the SwissFEL beam loss monitor system, which detects light from scintillating fibers with photomultipliers. The mean particle energy is measured with beam position monitors in dispersive sections, while the energy spectrum can be recorded on profile monitors [14].

The beam size in the focus is measured with wire scanners. Wires with sub-micrometer width,

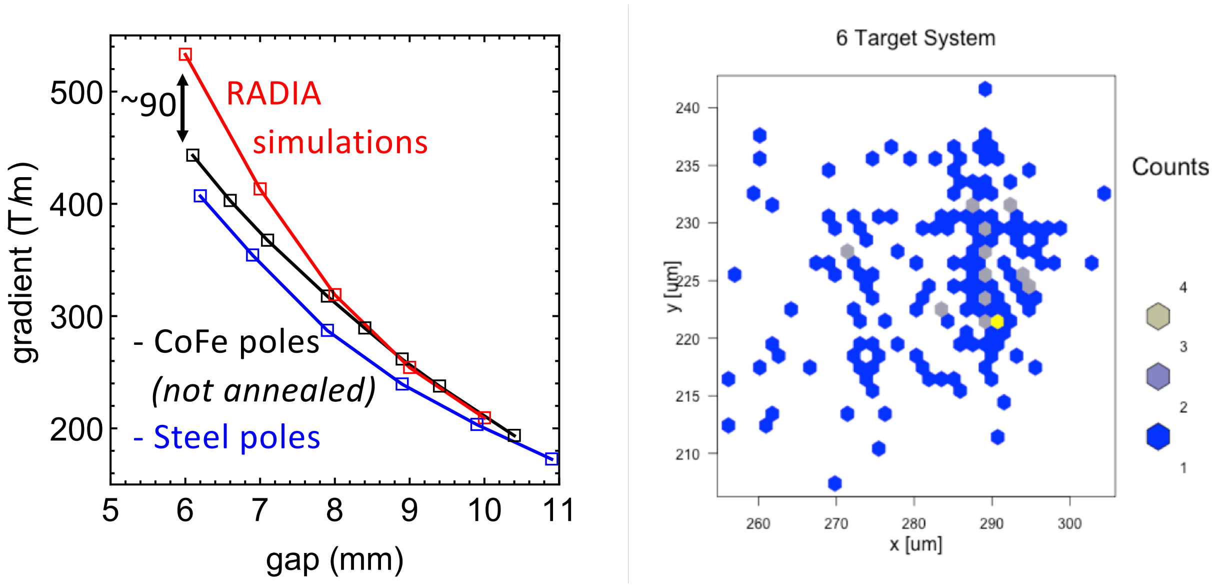

Figure 2. *Left:* Measurement of the quadrupole gradient as a function of gap. *Right:* Measurement of the reproducibility of the quadrupole alignment. The stages are moved to the home position for each iteration.

manufactured using electron beam lithography, can be positioned by the same hexapod that will hold the accelerating micro-structure. Recent developments in electron beam instrumentation [15, 16, 17] allow diagnostics of ultra-relativistic beams with sub-micrometer resolution.

2. Characterization of the Electron Beam

We characterized the electron beam during the commissioning of the Athos beam line and the ACHIP interaction chamber. We made use of the standard SwissFEL diagnostics as well as the dedicated instrumentation in the interaction chamber.

2.1. Accelerator Setup

One aspect of the ACHIP experiments in SwissFEL is the transmission of the entire electron bunch through the micrometer-sized accelerating structures. To achieve this, the design bunch charge for these experiments is 1 pC, since at these relatively low charges (the standard charge of SwissFEL is 200 pC), the emittance is naturally smaller. The optimum emittance at this charge was attained by adjusting both the laser diameter on the photocathode as well as the solenoid around the electron gun.

SwissFEL has a wide range of options regarding to the longitudinal phase space. The operators can balance between minimizing bunch length or energy spread by adjusting the phases of the radio frequency cavities before the bunch compressors. The momentum compaction factor R_{56} of the first bunch compressor can be adjusted by changing the dipole fields and moving the vacuum chamber accordingly. Non-linear compression optics can be set up by changing amplitude or phase of the harmonic cavity before the first bunch compressor. All of these adjustments take time. For the measurements presented below, the beam was compressed with close to nominal parameters, in order to spend less time on set-up and have more time available for the experiments.

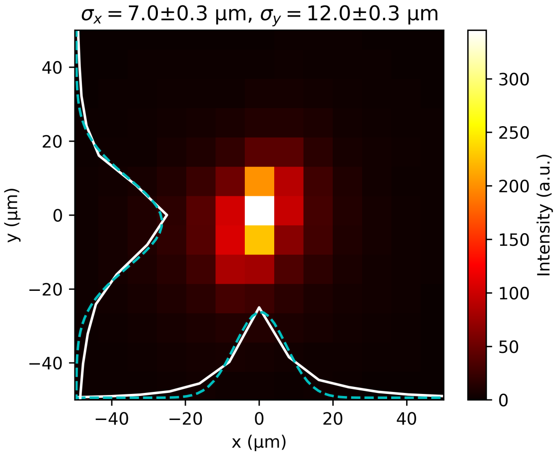

Figure 3. Beam profile measured on a scintillating screen.

2.2. Measurement of Beam Parameters

Peak current and longitudinal bunch shape were determined using the transverse deflecting cavity in the injector at $z = 85$ m. The current profile was approximately rectangular, with two horns at the beginning and end. In the core of the bunch, the electron current was 1.2 A. The rms bunch duration was determined by a Gaussian fit to be 186 fs.

The emittance was measured with a quadrupole-scan method [18] near the laser heater at a distance $z = 16$ m from the photocathode, and at a particle energy of 141 MeV. A horizontal normalized emittance of 75 nm was measured. The vertical emittance was somewhat smaller, we measured 55 nm. The measured horizontal and vertical mismatch parameters (as defined in [19] were 1.00.

This beam was then further accelerated to a particle energy of 3 GeV and focused by the permanent quadrupole magnets in the interaction chamber at $z = 321$ m. After a beam-based alignment of the quadrupole magnets, the beam spot was measured on a scintillating screen. We used a cerium-doped yttrium aluminum garnet crystal (Ce:YAG) of 100 μm thickness, mounted at a right angle to the electron beam. The crystal is observed using a mirror that intercepts the electron beam under an angle of 45°, and is imaged with a macro photo lens[1] onto a CMOS area sensor[2]. It should be noted that this setup is not immune to the coherent optical transition radiation generated on the surface of the crystal or the mirror. The performance with compressed electron beams still remains to be verified, but we do expect problems with the coherent radiation.

A Gauss fit to the projections of the profile resulted in standard deviations of 7.0 μm in the horizontal direction, and 12 μm in the vertical direction, in the same order of magnitude as the resolution of the monitor (Figure 3). A measurement using the wire scanners resulted in a beam size of 1.76×4.13 μm^2 (Figure 4). From these, we can conclude not only the beam size, but also a corresponding beam stability and alignment accuracy.

3. Conclusion

We have demonstrated the focusing of a beam from a conventional radio-frequency accelerator to few-micrometer beam sizes in both transverse dimensions. A hexapod allows for the alignment

[1] 200mm f/4D ED-IF AF Micro NIKKOR, used approximately with an imaging ratio of 1:1
[2] Basler ace acA1920-50gm, using a Sony IMX174 CMOS sensor with 1920×1200 pixels with 5.86 μm size

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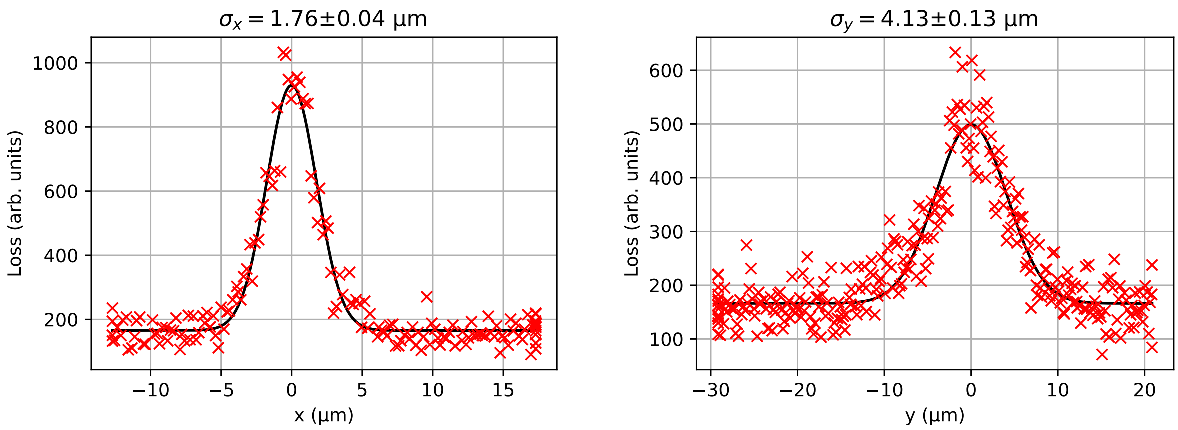

Figure 4. Result of wire scans in horizontal (left) and vertical (right) directions. A Gaussian fit results in rms beam sizes of 1.76 and 4.13 µm, respectively. Note the different vertical scale on the graphs.

of samples in the beam, and instrumentation suitable for small beams of low charge provide for studies of particle deflection and acceleration in microstructures. The beam sizes measured during the initial commissioning still need to be optimized further for the ACHIP accelerating structures, which have sub-micrometer apertures. Further studies will aim at reducing the dispersion in the beam line, while tracking down further sources of emittance growth.

Research on the effect of structures built for wavelengths of a few tens to hundreds of micrometers is possible with the present beam parameters. Available instrumentation allows for the measurement of transverse as well as longitudinal effects: a profile monitor directly behind the interaction chamber allows for a measurement of transverse forces onto the beam, a second monitor installed in a dispersive region behind the chamber allows for a measurement of acceleration.

The experimental chamber is installed upstream of the undulators of the Athos beam line in SwissFEL. This set-up can thus be used to study the effect of electron beam shaping on the generation of X-rays in a free electron laser.

Acknowledgments

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