INVESTIGATIONS OF THE LONGITUDINAL BEAM PROPERTIES AT THE PHOTOINJECTOR TEST FACILITY IN ZEUTHEN*

J. Rönsch†, J. Rossbach, Hamburg University, 22761 Hamburg, Germany
G. Asova, J. Bähr, H.-J. Grabosch, S. Khodyachykh, S. Korepanov, M. Krasilnikov,
A. Oppelt, B. Petrosyan, S. Riemann, L. Staykov, F. Stephan, DESY, 15738 Zeuthen, Germany
D. Lipka, D. Richter, F. Marhauser BESSY, 12489 Berlin, Germany
A. Onuchin, Budker Institut of Nuclear Physics, Novosibirsk 630090, Russia.

Abstract

The goal of the Photoinjector Test Facility at DESY in Zeuthen (PITZ) is to test and optimise electron guns for FELs like FLASH and X-FEL at DESY in Hamburg. In 2005 the setup was extended by a booster cavity. In order to measure longitudinal and transverse properties of the beam with a momentum in the range between 4 to 40 MeV/c, a viewport after the booster cavity has been developed. It contains several radiators. One of them is Silica aerogel used as Cherenkov radiator for the measurement of the longitudinal electron distribution with a streak camera. Design considerations are presented in this paper.

INTRODUCTION

The main goal of PITZ is the test and optimization of L-Band RF photo injectors for Free-Electron Lasers (FELs). The demands on this photo injector are long bunch trains with short bunches, a charge of about 1 nC and small emittances. The linac based FEL at FLASH incorporates a 1.5 cell RF gun capable of producing a high charge density, followed by an acceleration section and a magnetic bunch compressor. For an effective bunch compression detailed studies of the longitudinal phase space after the gun and its evolution behind the booster cavity have to be performed. The new screen station (HIGH1.Scr2) is planed to be placed about 5 m downstream of the photocathode and about 1.5 m downstream of the exit of the booster cavity in the PITZ2 setup [1] as shown in Figure1.

In the past, PITZ made good experience by using the full cone of a Cherenkov radiator for bunch length measurements after the gun [2]. It will be discussed whether a copy of screen station LOW.Scr3 can be used and which modifications are necessary.

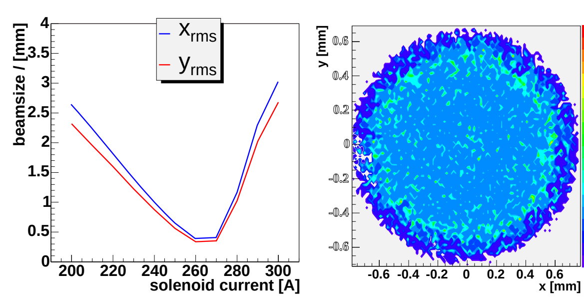
SCREEN STATION FOR BUNCH LENGTH MEASUREMENTS

Screen station LOW.Scr3 was designed for an electron energy of about 5 MeV. It contains a YAG screen to determine transverse properties using a TV camera, three radiators (aerogel, an optical transition radiator (OTR), quartz), whose light is transported to the streak camera [3] and a tapered empty tube, for beam passage without wakefield production. The Silica aerogel (refractive index $n = 1.03$, thickness $th = 2$ mm) is used as a Cherenkov radiator and the pulse length is measured using an optical transmission line [4] and a streak camera.

The new screen station (HIGH1.Scr2) and its elements should be designed for electron energies in the range of 4 up to 40 MeV, so it can be used even if the booster cavity is off. Planed elements are: a YAG-screen and an OTR for the determination of the transverse beam size and position of the electron beam using a TV camera, Silica aerogel and a further OTR for bunch length measurements as well as an empty tube.

Screen Dimensions

For higher energies the beam size becomes smaller, but when the booster cavity is turned off the beam size increases. Simulations of transverse beam size at the position of HIGH1.Scr2 were made to clarify the needed dimensions. Figure 2 (a) shows the simulated transverse beam size at a gun and booster phase with maximum energy gain for different solenoid currents, when the booster is turned on. The smallest transverse beam size could be reached for about 260 A. In Figure 2 (b) the simulated transverse beam



(a) (b)

Figure 2: Simulations of the electron beam size as a function of the solenoid current (a) and transverse beam properties at the screen station (b) for a gun and booster phase with maximum energy gain and a flat-top longitudinal laser distribution at 1 nC.

distribution are shown for 260 A and a gun and booster phase with maximum energy gain.

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† jroensch@ifh.de

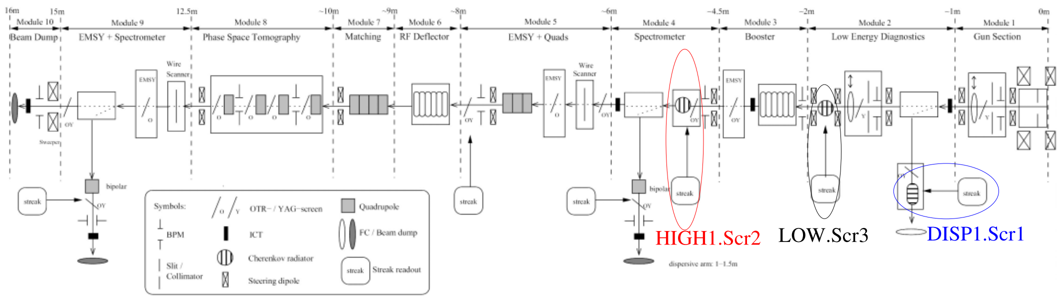
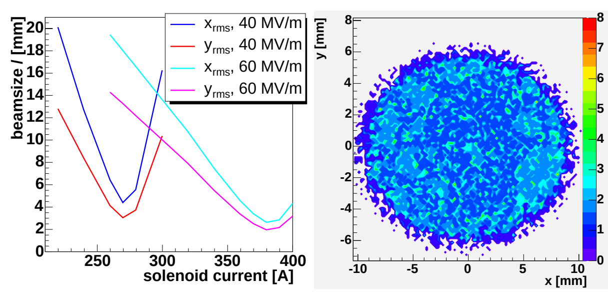


Figure 1: Planed setup of PITZ2. The screen station HIGH1.Scr2, LOW.Scr3 and DISP1.Scr1 are marked.

Results of simulations of the beam dynamics, when the booster is off are shown in Figure 3. In this case the beam size is almost 10 times higher than with the booster cavity turned on.



(a) (b)

Figure 3: Simulated transverse electron beam size as a function of the solenoid current for 40MV/m and 60MV/m gradient (a) and transverse beam properties at the screen station (b) for a gradient of 40MV/m in the gun and a phase with maximum energy gain, a flat-top longitudinal laser distribution at 1 nC, when the booster is turned off.

For measurements using the booster the beam size could be very small, therefore both OTRs will have an effective size of 20 mm $\times$ 20 mm. Using an OTR at an angle of 45° with respect to the beam direction, backward radiation is emitted at 90° regarding the beam direction. A thin plate (about 300 μm) will be used as OTR, because of its better optical quality and resistance compared to a thin foil. Two different types of OTR screens are in use at FLASH [5]:

- 350 um thick polished silicon (Si)
- 350 um thick Si with an aluminium (Al) coating

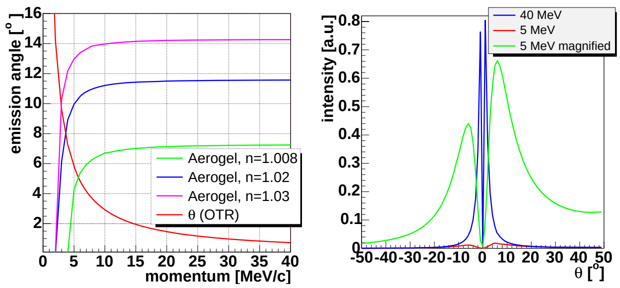
The Si has a better thermal resistance than Al, and therefore the pure Si screen stands a higher charge density (i.e small beam with high charge) than Si coated with Al. On the other hand the Al emits about 2-3 times more photons than polished Si, i.e. the light yield is much better. That is why we decided to use the Al coated Si plates.

Since there are no quadrupoles planed before this screen station there is no possibility to reduce the beam size in the case the booster is off. To catch the whole beam even when the booster is off the effective size of the YAG screen should have the dimension size as the beam tube (diameter = 35 mm).

Bunch Length Measurement

The temporal resolution of the Silica aerogel used at LOW.Scr3 was calculated to be 0.12 ps at a beam momentum of 4.5 MeV/c [6]. This value is very small compared to the resolution of the optical transmission line. The temporal resolution of the optical transmission line was determined with 1.15 ps when using an optical transmission filter of 550 nm with a bandwidth of 10 nm [7]. The bunch length measurements were typically done for a streak camera slit width of 100 μm. The temporal resolution of a 100 μm slit was determined with about 1.75 ps for the streak camera used at PITZ [2]. The resolution of the streak camera C5680 is denoted by the producer with 2 ps FWHM [3]. Therefore it is useful to increase the thickness of the Silica aerogel in order to increase the number of photons, so one could reduce the slit width or the number of pulses used for a measurement. The initial idea was to use Silica aerogel with an index of refraction $n = 1.03$ and a thickness of 5 mm. Cherenkov light is emitted under a certain angle depending on the average refractive index of the radiator (n) and the electron energy. It leaves the radiator following Snells law. Figure 4(a) shows the emission angle of Cherenkov radiators with three different indices of refraction. For low energies the angle changes strongly with the energy, but at higher energies it stays constant. Aerogel with $n = 1.03$ has an emission angle of up to 14.3° at an electron beam momentum of 40 MeV/c, but the acceptance angle of the optical system from the screen station to the streak camera is only $\pm 11.8^\circ$. Using an aerogel with $n = 1.03$ it is impossible to collected the whole Cherenkov cone.

In contrast to Cherenkov radiator the optical transition radiator emits the light within a certain angular distribution. The angular distribution of transition radiation depends on the particle energy and the angle of incident [8]. In Figure 4,(b) the angular distribution for a beam momentum of 40 MeV/c and 5 MeV/c electrons are shown. At 40 MeV/c beam momentum most of the light is emitted within a small angle. At smaller energies it becomes impossible to collect

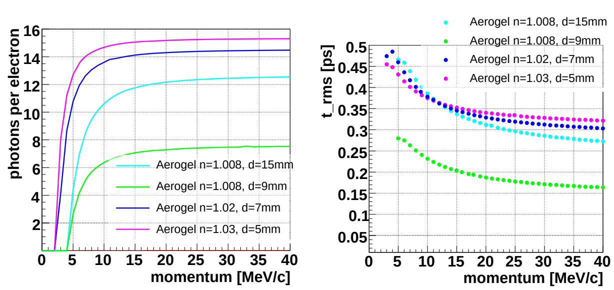


(a) (b)

Figure 4: The emission angle of OTR and the Silica aerogel radiators with different reflective indices as a function of the electron momentum (a) and the angular distribution of optical transition radiation produced by 40 MeV and 5 MeV electrons (b).

all the light by the used optical system. The red curve in Figure 4 (a) shows the angle with the highest number of emitted photons.

An aerogel with $n = 1.02$ and $th = 7$ mm (as well as $n = 1.008$ and $th = 15$ mm) would lead to about the same temporal resolution as an aerogel with $n = 1.03$ and a thickness of $th = 5$mm, but the number of photons is lower, as shown in Figure 5.



(a) (b)

Figure 5: Number of photons (a) and resolution (b) of Silica aerogels with different indices of refraction and thickness's as a function of the energy.

By mechanical reason the maximum usable thickness is 9 mm. The Budker Institut of Nuclear Physics (Novosibirsk) is producing Silica aerogel for PITZ, but only Silica aerogel with $n = 1.008$, 1.03 and 1.05 are produced by default. A production of Silica aerogel with $n = 1.02$ would take a lot of effort. So we will start to use aerogel with n = 1.008 and 9 mm, which can be replaced later. The main disadvantage of the refractive index $n = 1.008$ is that the lower limit for the production of Cherenkov light is at about 4 MeV/c and the photon yield changes strongly within the beam momentum range from 4 to 6 MeV/c. The advantage is that the Cherenkov light of bigger transverse distributions can be transported and small misalignments of the optical transmission line does not lead to losses. The number of photons produced by aerogel at 40 MeV/c is still a factor of a few hundred higher compared to OTR.

LONGITUDINAL PHASE SPACE MEASUREMENTS

The longitudinal phase space after the gun at DISP1.Scr1 (shown in Figure1) and its projection were measured for different phases of the gun. In order to compare simulated (Fig.6 second row) and measured (Fig.6 first row) longitudinal phase space the simulated one was tracked through the dipole using matrix formalism. The vertical scale was converted into momentum scale after the correction of M_{56} [9] by shearing the distribution (Fig.6 third row). Matrix element M_{56} describes the influence of the dipole on the longitudinal distribution due to different particle momenta. The measured momentum distribution fits very well with the distribution traced through the dipole (Fig.6 fourth row). Also the longitudinal distribution (Fig.6 fifth row) shows a rather good agreement. It is difficult to find similarities with in the longitudinal phase space. The longitudinal phase space changes completely after tracing the particle though the dipole. In [10] it will be shown, how to design a dipole magnet in order to minimize this problem. Beside the influence of the dipole magnet the optical transmission line and the streak camera itself have an influence onto the resolution as described in [7].

CONCLUSION

A screen station to measure longitudinal and transverse beam properties in the momentum range from 4 to 40 MeV/c was designed. One of the radiator is Silica aerogel used as Cherenkov radiator for the measurement of the longitudinal electron distribution with a streak camera. Even at 40 MeV/c Silica aerogel produces a higher photon yield than OTR. Longitudinal phase space studies and improvements of the system are ongoing.

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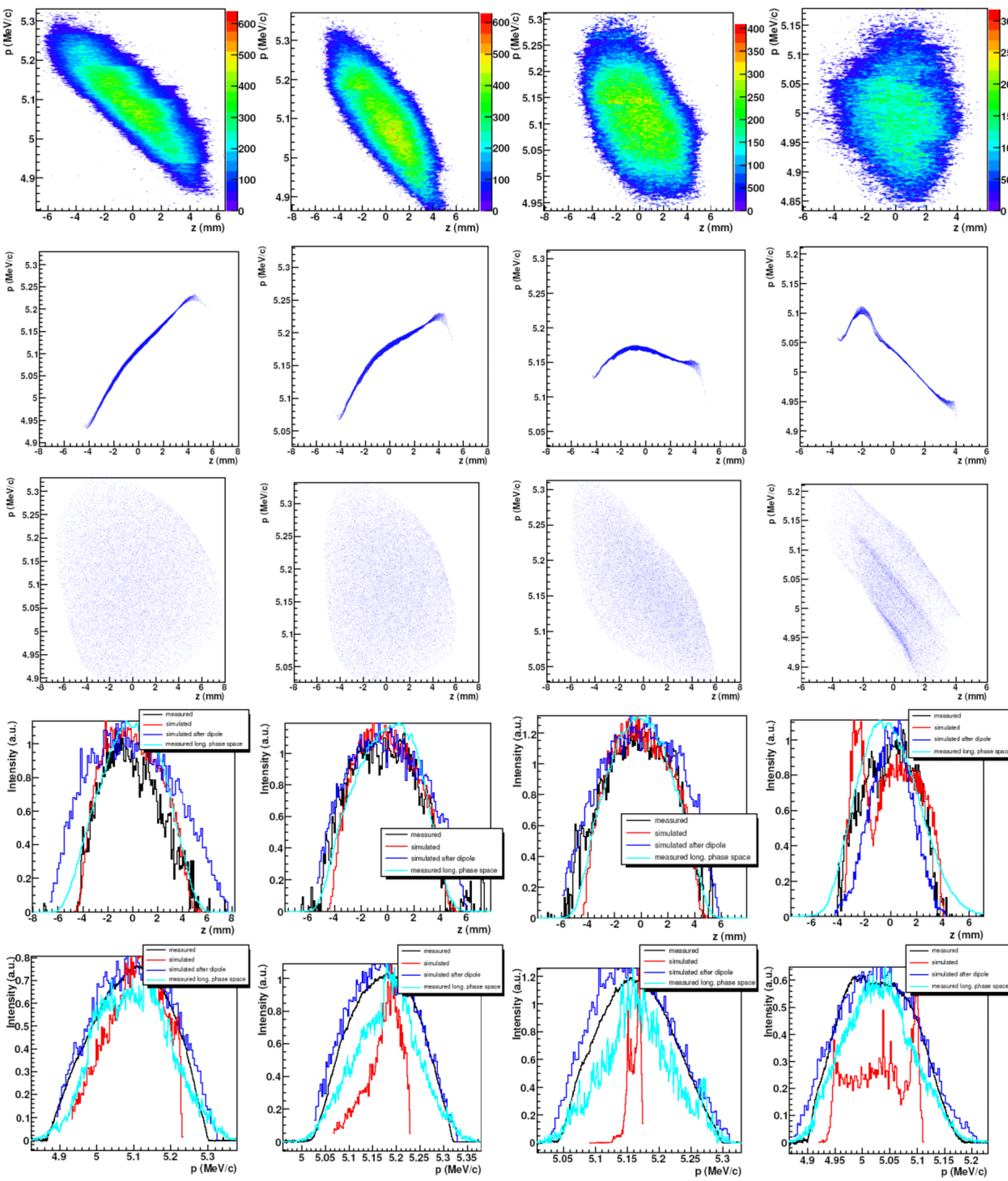

Figure 6: Measurement (1st row) and simulation (2nd row) of the longitudinal phase space. The simulation was traced through the dipole to show the expected distribution. The projections of the three distributions were compared to the direct bunch length measurement (4th row) and momentum measurement (5th row). Black line is direct measurement, red simulation, cyan projection of the phase space measurement and blue projection of the traced distribution. The results were shown for gun phase with maximum energy gain +10 °, +0°, -10° and -25° (from left to right).

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