LONGITUDINAL PHASE SPACE STUDIES AT PITZ

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Abstract

The main goal of the Photo Injector Test facility at DESY in Zeuthen (PITZ) is to test and to optimize photo injectors for Free-Electron Lasers (FELs). The demands on such a photo injector are small transverse emittances, short bunches and high bunch charge. A FEL is driven by an accelerator which consists of a RF gun followed by an acceleration section and a magnetic bunch compressor. For an effective bunch compression detailed studies of the longitudinal phase space have to be performed. The correlation between the positions of the particles in the bunch and their longitudinal momenta has to be understood and the non-linearities of the longitudinal phase space have to be analysed. A special apparatus for longitudinal phase space tomography at a momentum of around 5 MeV using a dipole, a Cherenkov radiator, an optical transmission line and a streak camera was developed. Results of longitudinal phase space measurements are presented and compared with simulations and the influence of the space charge force is discussed.

INTRODUCTION AND SETUP

To measure the longitudinal phase space a correlated measurement of momentum and temporal distribution is required. In Fig. 1, a schematic of the PITZ1 setup [1] is shown. To measure the longitudinal distribution of the electron bunch a Cherenkov radiator (silica aerogel) [2] is used to transform the bunch into a light distribution at screen station 4 in the straight section (SS). This light distribution is imaged by an optical transmission line [3] onto the entrance slit of a streak camera (C5680 from Hamamatsu).

The momentum distribution is measured at screen station 5 on a YAG-screen in the dispersive arm (DA) by means of a spectrometer dipole [4]. To measure the longitudinal phase space both methods are combined. The YAG-screen in the DA can be replaced by silica aerogel using a movable actuator. The light pulse which presents the longitudinal phase space is transported to the streak camera. A description of the setup and the impact of the main components of the apparatus (as dipole magnet, streak camera and optical transmission line) on the results of the measurements of the longitudinal phase space can be found in Ref. [5].

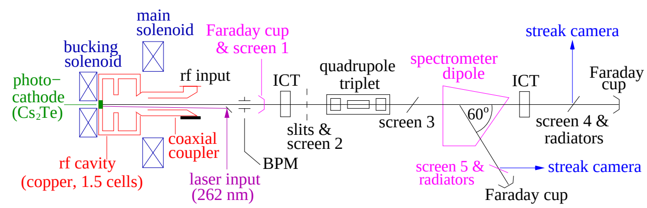

Figure 1: Schematic of PITZ1 setup.

COMPARISON OF MEASUREMENT AND SIMULATION

First measurements of the longitudinal phase space were done at the end of 2004 in order to test the method. The measurements were done for flat-top and gaussian temporal laser distribution, bunch charges of 30 pC up to 1 nC and different phases between RF and laser (launch phases). In order to avoid including dispersion effects of the optical transmission line into the measurement, a spectral transmission filter with a bandwidth of 10 nm was inserted into the optical transmission line in front of the streak camera. The disadvantage of using filters is the strong reduction of the numbers of photons, thus the number of images to be taken increases and consequently the influence of jitter increases.

Figure 2 shows a result of these measurements compared to simulations, at a distance of 3.45 m downstream from the cathode, for standard operation conditions of PITZ, i.e. 1 nC bunch charge, flat-top longitudinal laser distribution (FWHM = 20 ps; rising time = 8 ps) and the launch phase is chosen such that the momentum gain in the gun is maximum (optimum launch phase). The electrons with negative time values represent the beginning of the bunch and the higher time values its tail.

The projections of the longitudinal phase space agree in principle with the direct measured distribution and the simulations. In the longitudinal distribution measured in the dispersive arm two minima can be found. These minima are caused by the assembling of different streak images.

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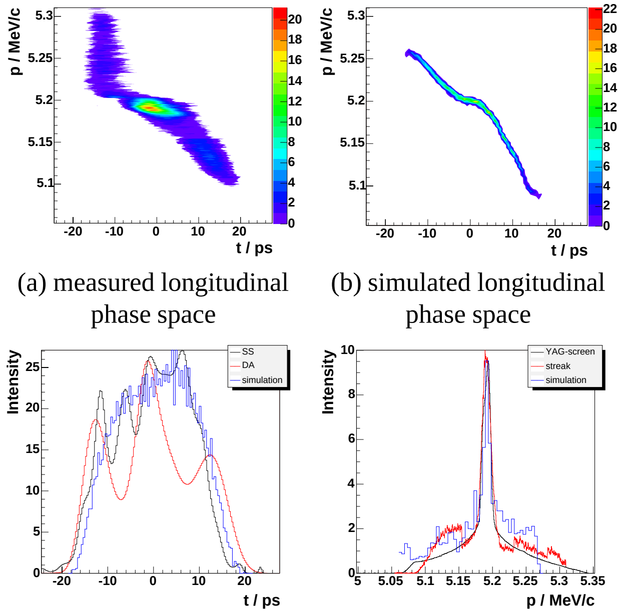


(a) measured longitudinal phase space

(b) simulated longitudinal phase space

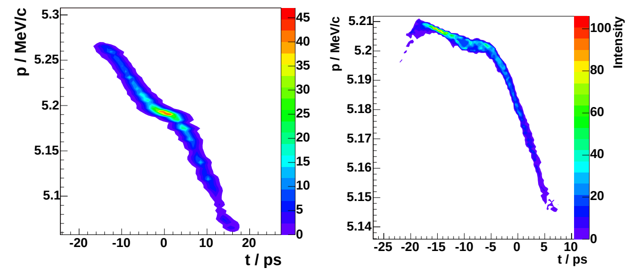
(c) longitudinal distribution

(d) momentum distribution

Figure 2: Measured (a) and simulated (b) longitudinal phase space and their projections: longitudinal (c) and momentum (d) distribution for 1 nC bunch charge, optimum launch phase and a flat-top laser distribution with about 20 ps FWHM pulse length. In (c) and (d) the black curves are direct measurements, the red ones are the projections of the measured longitudinal phase space and the blue ones are simulations.

This process has to be improved. Measured and simulated longitudinal phase space show a similar shape, but the measured one is wider than the simulated one. This is commonly observed for all used operation conditions. To estimate the impact of the resolution of the streak camera the simulated longitudinal phase space (2 (b)) was convoluted with the resolution function of the streak camera [6]. The resolution is given by the producer to be about 2 ps. In Fig. 3 (a) the convoluted distribution is shown. It bears a better resemblance to the measured one, but there is still a discrepancy due to jitter, noise and the fact that for the correction of the effects in the dipole only simulated distributions were used. For the measurement of the longitudinal distribution (bunch length) the resolution of 2 ps is sufficient, but for longitudinal phase space measurements it strongly impacts the measurement, because the longitudinal distribution of a certain energy is smaller than 2 ps. Therefore, the measured values of longitudinal emittance exceed the simulated ones.

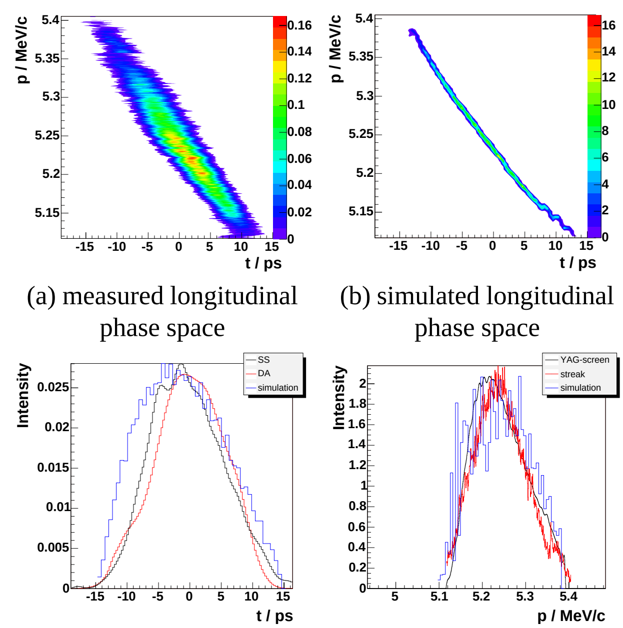
Figure 3 (b) shows the longitudinal phase space for the same initial conditions as in Fig. 2 (b), but at a position close to the exit of the gun. The particles in the center of the bunch could reach the maximum energy gain. Due to space charge forces the particles in front of the bunch are slightly accelerated and the electrons in the end are slightly decelerated.



(a) convoluted simulated longitudinal phase space

(b) simulated longitudinal phase space behind the gun

Figure 3: Simulated longitudinal phase space for optimum launch phase, flat-top laser distribution and 1 nC bunch charge (Fig. 2 (b)) convoluted with the resolution function of the streak camera (a). For studying the evolution of the longitudinal phase space the simulated longitudinal phase space for optimum launch phase, flat-top laser distribution and 1 nC bunch charge at the gun exit is shown (b).



(a) measured longitudinal phase space

(b) simulated longitudinal phase space

(c) longitudinal distribution

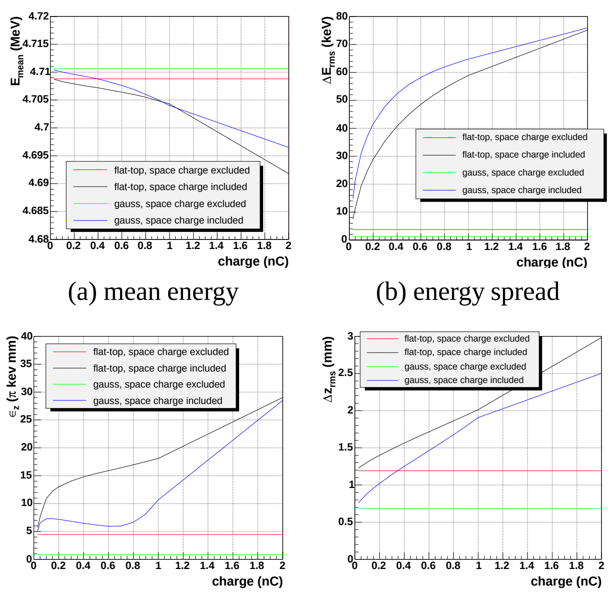
(d) momentum distribution

Figure 4: Measured (a) and simulated (b) longitudinal phase space and their projections: longitudinal (c) and momentum distribution (d) for 1 nC bunch charge, optimum launch phase and gaussian laser distribution with about 10 ps FWHM pulse length. In (c) and (d) the black curves are direct measurements, the red ones are the projections of the measured longitudinal phase space and the blue ones are simulations.

Figure 4 shows the results for optimum launch phase, 1 nC bunch charge and gaussian longitudinal laser distribution (FWHM = 10 ps). For this case the assembling of different streak images was working better, there is no minimum in the distribution visible as in Fig. 2. For longitudinal gaussian distribution the influence of the space charge force is even higher than for flat-top, because the charge density in the bunch is higher. This leads to a strong increase of the momentum spread and an almost linear longitudinal phase space, with high energetic electrons in the head and lower energetic electrons in the tail. At TTF VUV-FEL further accelerating modules follow. A third harmonic cavity can remove the curvature of the longitudinal phase space, because the longitudinal phase space of the electron bunch which enters into the bunch compressor should be linear off-crest [7]. The influence of the space charge force to the main parameters of the longitudinal phase space is shown in Fig. 5 and 6.

INFLUENCE OF THE SPACE CHARGE FORCE

Figure 5 shows the mean energy, the energy spread, the longitudinal emittance and the bunch length as a function of the bunch charge for flat-top and gaussian longitudinal laser distribution, each with and without space charge at the position of the dipole in the PITZ1 setup. When space

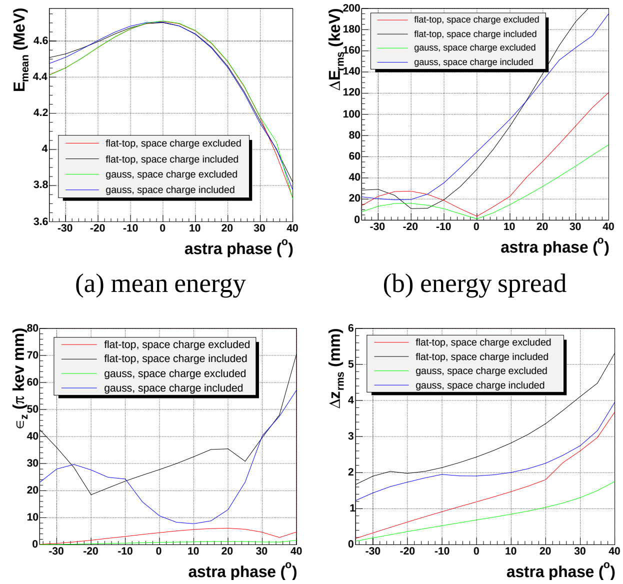


(a) mean energy (b) energy spread

(c) longitudinal emittance (d) bunch length

Figure 5: Simulated mean energy (a), energy spread (b), longitudinal emittance (c) and bunch length (d) as a function of the bunch charge.

charge effect is excluded from the simulation the longitudinal phase space does not change with the charge. Taking the space charge force into account for the simulation, charge increase signifies higher charge density for similar beam conditions. This impacts the momentum spread in the first instance but also the bunch length and consequently the longitudinal emittance. The mean momentum is decreased by about 1‰ for 1 nC bunch charge due to space charge effects. The longitudinal emittance for flat-top laser distribution increases with the charge, especially for small charges there is a strong rise. For gaussian laser distribution a minimum of the longitudinal emittance is at about 0.65 nC. In practice the solenoid current is optimized to focus the beam on the screen in the dispersive arm. For all this simulations a solenoid current of 290 A has been used. For small charges the position of the focus is shifted towards the gun and the focusing leads to increasing space charge forces behind that point.



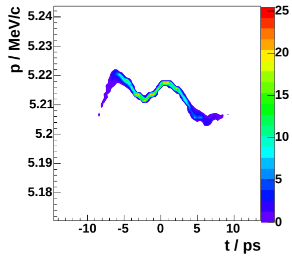
(a) mean energy (b) energy spread

(c) longitudinal emittance (d) bunch length

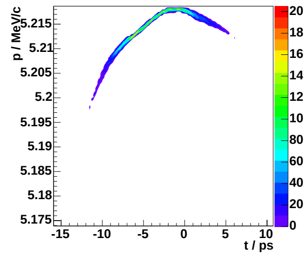
Figure 6: Simulated mean energy (a), energy spread (b), longitudinal emittance (c) and bunch length (d) as a function of the launch phase.

Figure 6 shows the same parameters but for different launch phases, for 1 nC bunch charge. Also for varying the launch phase the mean momentum is almost independent of space charge force, but the momentum spread shows a strong dependency. The launch phase of minimum momentum spread is shifted due to space charge force. The dependency of the mean momentum and the momentum spread on phase (as displayed in 6 (a) and (b)) and influence of the longitudinal laser distribution to these distributions are discussed in Ref. [8, 9, 10]. The smallest longitudinal emittance for flat-top laser distribution was reached for about the same launch phase as the smallest energy spread.

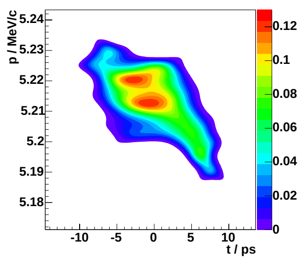
For a better understanding of the shape of the longitudinal phase space, a low bunch charge (of about 40 pC) has been used in order to reduce the influence of space charge force (Fig. 7). In Fig. 7 (c) the measurement result is shown, the result from the simulation is displayed in Fig. 7 (a) for the same position and in Fig. 7 (b) at the gun exit. Here it is visible that the electrons at the head of the bunch are accelerated due to the space charge forces, whereas the particles at the tail are slowed down. Due to



(a) simulated longitudinal phase space 3.45 m downstream from the cathode



(b) simulated longitudinal phase space at the exit of the gun



(c) measured longitudinal phase space 3.45 m downstream from the the cathode

Figure 7: Simulated longitudinal phase space for optimum launch phase, flat-top laser distribution and about 40 pC bunch charge at dipole position (a) and at the exit of the gun (b). In (c) the measurement result is displayed.

the smaller space charge force the influence is not as strong as for 1 nC.

CONCLUSION

Measurements of the longitudinal phase space for an energy around 5 MeV have been presented. The resolution of the longitudinal phase space measurement is restricted by the resolution of the streak camera. Therefore, the measured values of longitudinal emittance are in general noticeably higher than the simulated values. There is a significant influence of the space charge force to the longitudinal phase space even for charges of about 40 pC.

ACKNOWLEDGEMENTS

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