BEAM DYNAMICS SIMULATION FOR THE UPGRADED PITZ PHOTO INJECTOR APPLYING VARIOUS PHOTOCATHODE LASER PULSES

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Abstract

Production of electron bunches with extremely small transverse emittance is the focus of the PITZ (Photo Injector Test facility at DESY in Zeuthen) scientific program. PITZ is one of the leading laboratories on generation and optimization of high brightness electron bunches with different charges for free electron laser (FEL) machines such as FLASH and the European XFEL. In 2011 using a photocathode laser with a flattop temporal profile, PITZ has revealed record low transverse properties emittance values at different bunch charges. However, further improvement of beam quality with smaller emittance is foreseen using a cathode laser system, capable of producing 3D ellipsoidal bunches. Numerical simulations were performed to study and compare the beam dynamics of electron beams produced with 3D ellipsoidal and flattop laser profiles. Different bunch charges from 20 pC up to 4 nC are considered in the simulation, in order to find an optimum PITZ machine setup which yields the lowest transverse emittance. In the present paper, the simulation setup, conditions, and results of the comparison are presented and discussed.

INTRODUCTION

The handiness of a high brightness electron source is one of the key issues for successful operation of linac-based free electron lasers like, FLASH [1] and the European XFEL [2]. The self-amplified spontaneous emission (SASE) of the FELs process requires an extremely high space charge density of the radiating electron bunches implying high peak current, low energy spread and small transverse emittance of the electron beam. Such high quality beams are mandatory for efficient SASE generation in a single pass through long undulators with narrow gaps [3]. However, the above-mentioned properties are hard to be improved in a linac and thus the emittance has to be minimized already in the photocathode injector.

The Photo Injector Test facility at DESY, Zeuthen site (PITZ), aims to produce electron bunches with extremely small transverse emittance. A flattop temporal profile of the cylindrical pulses has been used at PITZ to reduce the transverse emittance of space charge dominated beams compared to the Gaussian pulse shape previously used [4]. The lower beam emittances reported from PITZ were obtained with a flattop temporal laser profile from Cs_2Te cathodes. The photocathode laser pulse shaping is considered as a powerful tool to optimize the photo injector performance. Thus, a further improvement is foreseen from the cathode laser pulse shaping. The overall brightness of a photo injector can be further improved by using an ideal electron bunch profile, which, according to simulations, is 3D ellipsoidal (hereinafter ellipsoidal) in space and time [5]. Because of the fact that the space charge force fields inside the bunch are linear, the ellipsoidal beam distribution is an ideal beam distribution for high brightness charged beam applications with the best transverse and longitudinal bunch compression. Such electron bunches not only have lower emittance, but are also less sensitive to jitter of machine parameters, thus allowing more stable and reliable operation, which is a key requirement for SASE-FELs facilities like FLASH and the European XFEL.

Simulations have been performed at PITZ to study the feasibility of using an ellipsoidal laser shape instead of flattop and Gaussian laser profiles [6]. The results have revealed a better injector performance when using the ellipsoidal laser profile. Further improvement was expected when shifting the second accelerating cavity (CDS booster) and the first emittance measurement screen (EMSY1) by ~40 cm upstream. Moreover, simulations for the imperfections of the ellipsoidal laser shape for 1 nC showed that the transverse emittance value is still smaller than the optimized emittance value for the flattop laser shape [7]. Recently, a new photocathode laser system capable of producing ellipsoidal pulses has been installed at PITZ [8]. It is foreseen to operate the new system in parallel to the nominal one that generates cylindrical pulses with various temporal profiles. First electrons were already generated by the new laser system; however, emittance measurements are not yet performed.

A schematic layout of the current PITZ setup is shown in Fig. 1. The PITZ photocathode RF gun delivers electron bunches up to several nC with a maximum mean momentum of up to 7 MeV/c generated from a Cs_2Te cathode. The gun is surrounded by two solenoids: main and bucking. The main solenoid is used for the transverse beam focusing, while the bucking solenoid is meant to compensate the remaining longitudinal magnetic field at the cathode. The final maximum momentum after the booster is up to 25 MeV/c. The transverse emittance of the electron beam is measured by the emittance measurement system, (EMSY1 located at 5.27 m downstream the cathode), using a single slit scan technique [9]. Additionally, there are many diagnostics devices available for the full characterization of electron beams. A detailed description of the PITZ setup can be found elsewhere [10].

The aim of this contribution is to check the feasibility of using the ellipsoidal laser beams in comparison to the flattop shaped pulses by means of the lowest transverse

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ISBN 978-3-95450-134-2

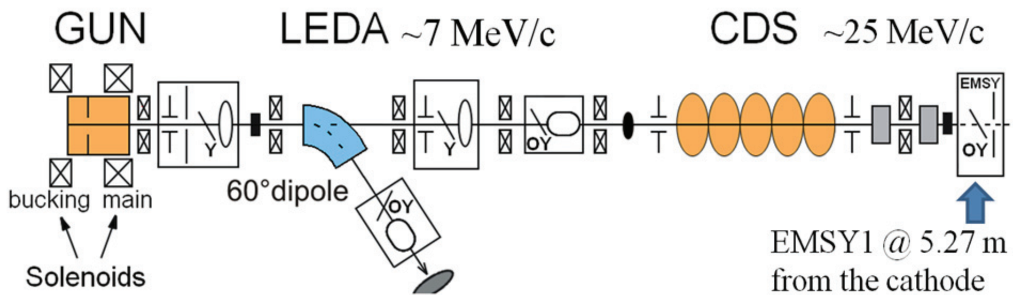

Figure 1: Schematic layout of the current PITZ beamline used in ASTRA simulations up to EMSY1.

emittance at EMSY1. This will be done by studying and comparing the beam dynamics of ellipsoidal and flattop beams with different bunch charges, from 20 pC up to 4 nC, for the actual PITZ setup.

SIMULATION SETUP AND CONDITIONS

Two different laser shapes, flattop temporal profile and an ellipsoidal distribution on the cathode, have been compared by tracking the generated electron beam using A Space charge Tracking Algorithm (ASTRA) [11]. For each of the profiles, the transverse emittance at the position of EMSY1 was optimized. Different bunch charges from 20 pC up to 4 nC are considered in the simulation, each was assumed to have 200000 macro particles with initial average kinetic energy of 0.55 eV [12]. In the simulation, the gun and booster peak electric fields were fixed at the phase of maximum mean momentum gain to 58.8 and 17.6 MV/m, which correspond to respectively beam momenta of 6.7 and 22 MeV/c downstream of gun and booster. This corresponds to the actual run conditions at PITZ [13]. The beam length of the ellipsoidal laser was chosen so that the produced electron beam has the same rms length at EMSY1 as the electron beam produced by the flattop laser with 2/21.5/2 ps rise, FWHM length and fall times respectively. A perfect ellipsoidal laser shape was considered in this simulation. For all bunch charges, the rms laser spot was simultaneously tuned with the main solenoid current and the gun phase to achieve the best transverse emittance of the electron beam at the position of EMSY1. The CDS booster phase was always tuned to deliver the maximum mean momentum of the electron beam. The space charge settings in ASTRA were optimized in order to minimize the impact of numerical errors on the emittance values.

RESULTS AND DISCUSSION

Results for 2 nC Bunch Charge

In the first part of this section, the results of 2 nC bunch charge with the two laser profiles are determined and presented as an example of the simulations in Figs. 2-4. The electron beam transverse projected emittances and rms beam sizes along the PITZ beamline up to EMSY1 are depicted in Fig. 2. The electron beam current and transverse slice emittance distributions within the bunch

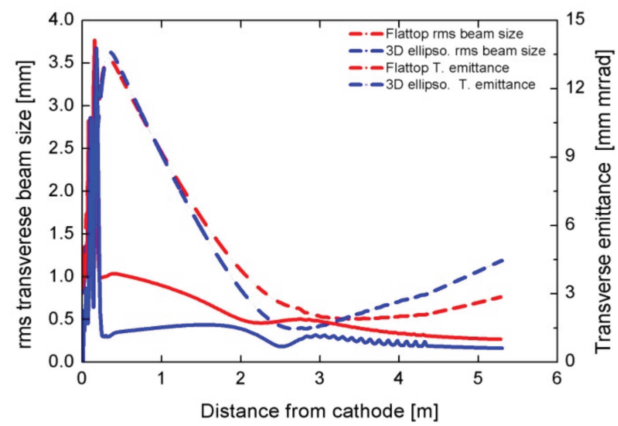

Figure 2: Transverse projected emittance and rms beam size for 2 nC bunch charge along the beamline up to EMSY1.

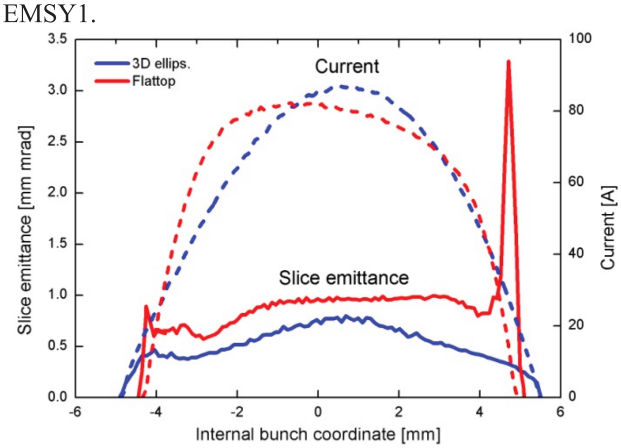

Figure 3: Beam current and slice transverse emittance distribution within the bunch for 2 nC bunch charge at EMSY1.

are plotted in Fig. 3. In addition, the electron beam longitudinal phase spaces for the two laser profiles are compared in Fig. 4.

It can be seen from Fig. 2, the optimized (best emittance at EMSY1) beam size for the ellipsoidal beam is higher than that for the flattop one; however, the transverse projected emittance is smaller. This tendency is related to the space charge effect in the booster. The peak current for 2 nC bunch charge generated from the ellipsoidal beam is estimated to be 88 A compared to 82 A generated from flattop beams as shown from Fig. 3.

ISBN 978-3-95450-134-2

Moreover, one can observe the existence of a high peak in the slice transverse emittance distributions for the flattop beam, while, the curve is almost flat for the ellipsoidal beam. This spike originates from the halo in the head of the bunch and it starts to be even from the emission when the head of the bunch is only emitted, it corresponds to a very short bunch length and therefore to the strong nonlinear transverse space charge force resulting in the blowup of the slice emittance of the bunch head.

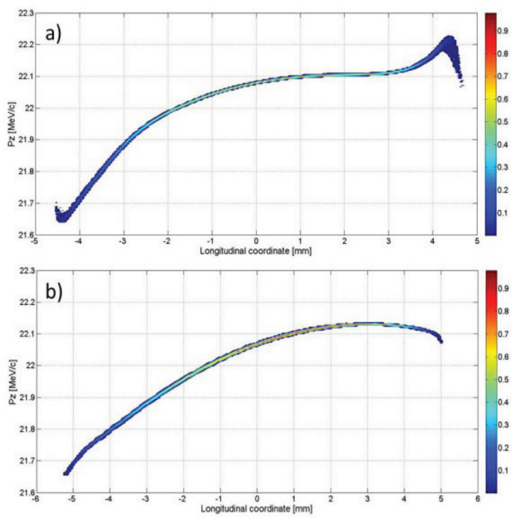

Figure 4: Electron beam longitudinal phase space for 2 nC bunch charge generated from (a) flattop and (b) ellipsoidal cathode laser pulses.

From Fig. 4 one can observe clearly the advantages of using an ellipsoidal laser profile compared to a flattop one, in terms of less nonlinearity in the longitudinal phase space and one obtains 91 mm-keV longitudinal emittance for the ellipsoidal beam compared to 114 mm-keV for the flattop one. Moreover, the ellipsoidal beam has a more regular shape without halo as compared to the flattop one. The simulated transverse emittance from the simulation at EMSY1 is 0.617 mm-mrad for the ellipsoidal beam compared to 1.008 mm-mrad for flattop one. This means ~40% improvement of the transverse emittance and 36% improvement in the average slice emittance are expected when using an ellipsoidal laser profile with respect to a flattop. Thus, the results have yielded a beam brightness for the ellipsoidal beam ~280% higher than that for the flattop beam.

Results for 20 pC to 4 nC Bunch Charges

The normalized transverse emittance and the brightness of the electron beam as a function of bunch charge from 20 pC up to 4 nC generated from the ellipsoidal and flattop laser profiles are shown in Figs. 5 and 6, respectively. The emittance gain and the brightness gain from using the ellipsoidal beams with respect to the flattop ones are also depicted in the right axis of Figs. 5 and 6 respectively. As seen from Fig. 5 there is ~30-42% improvement in transverse emittance for the case of ellipsoidal as compared to flattop profile for bunch charges higher than 100 pC. However, for bunch charge less than 100 pC the emittance gain is dramatically decreased and reaches only ~5% for 20 pC bunch charge. This behavior can be explained by the fact that at low bunch charge the contribution of the space charge in the emittance growth is very small compared to the higher bunch charge. Another reason for this degradation is that the beam emittance was optimized for the fixed laser pulse duration. Therefore the cathode laser pulse shape for the low charge case correspond to more thin linear charge column whereas the high charge case is close to the 3D cylinder with comparable transverse and longitudinal dimensions.

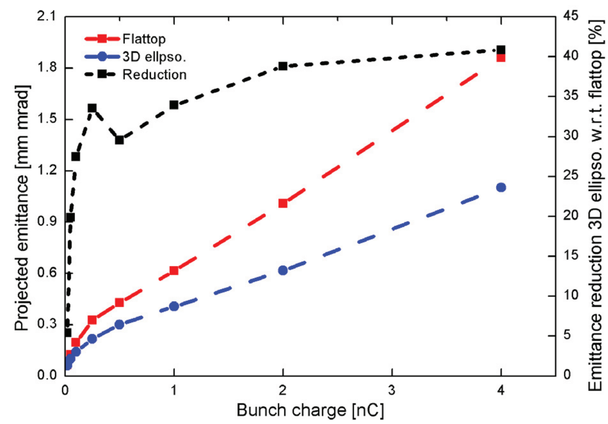

Figure 5: Electron beam transverse emittance as a function of bunch charge for flattop and ellipsoidal laser profiles at EMSY1 in the left axis, and in the right axis the emittance gain from ellipsoidal beams with respect to flattop ones.

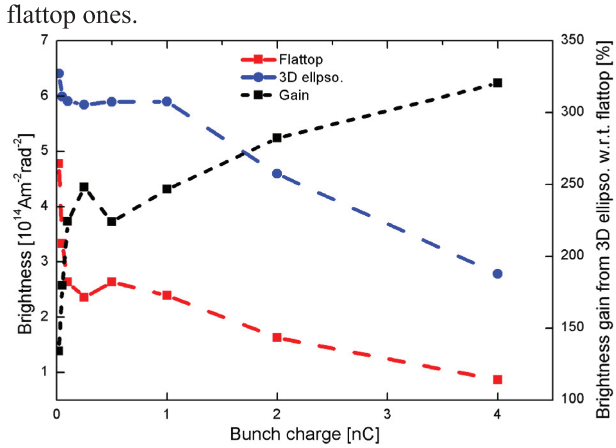

Figure 6: Brightness of the electron beam as a function of bunch charge for flattop and ellipsoidal laser profiles in the left axis, and in the right axis the brightness gain from ellipsoidal beams with respect to flattop ones.

It is well known that to increase the brightness ($b=2I/\varepsilon^2$ A mm^{-2} mrad^{-2}, where I (A) is the peak current, and ε (mm-mrad) is the transverse emittance) of an electron source it is necessary to increase its peak current while keeping a very small transverse emittance. This leads to the usage of high electric fields at the cathode to reduce

ISBN 978-3-95450-134-2

the influence of space charge forces. The peak currents for different bunch charges generated from ellipsoidal distributions are ~6-18% higher than that generated from flattop ones, however, the transverse emittances are 30-42% smaller. Moreover, the average slice emittance from the flattop pulse can be reduced by ~25-40% by using ellipsoidal laser pulses. Thus impressive increase in the beam brightness is expected. The beam brightness of the ellipsoidal beam was estimated to be ~225-320% higher than that for a flattop beam for bunch charges more than 100 pC.

As mentioned in the previous paragraph significant improvements on the electron beam brightness can be obtained by applying ellipsoidal pulses of the cathode laser. These advantages of ellipsoid laser pulses motivate experimental studies on such a cathode laser system in order to provide further improvement on emittance/ brightness from the electron sources for a extend the scientific reach of modern FEL facilities. In the near future, comparative measurements of the beam emittance with both ellipsoidal and flattop cathode laser profiles at PITZ are planned in order to verify the simulations. However, more investigations are required for the low bunch charges.

CONCLUSION

Beam dynamics simulations using ASTRA were performed for the current PITZ setup to compare the electron beam quality for the range of bunch charges from 20 pC to 4 nC generated from two different temporal shapes of the photocathode laser pulses (flattop and ellipsoidal). Emittance vs. bunch charge optimization was performed by tuning the rms laser spot size together with the main solenoid current and the gun phase to achieve the best transverse emittance of the electron beam, at the same rms bunch length for each bunch charge, at EMSY1. The simulation results yielded great improvement ~30-42%, and ~225-320% in the electron beam transverse emittance and brightness, respectively, when the flattop temporal shape is replaced by the ellipsoidal profile. Almost no beam halo and less nonlinearities of the electron beam shape in longitudinal phase space were observed for the electron beams created from the ellipsoidal laser profile. Overall, ~5-10% increase in the peak current is expected from ellipsoidal laser pulses compared to flattop pulses. The above-mentioned improvements should give sufficient headspace in the experimental realization of the ellipsoidal laser system to be able to demonstrate significant improvement with respect to the nominal flattop case.

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ISBN 978-3-95450-134-2