BEAM DYNAMICS OPTIMIZATION FOR THE HIGH BRIGHTNESS PITZ PHOTO INJECTOR USING 3D ELLIPSOIDAL CATHODE LASER PULSES*

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Abstract

The Photo Injector Test facility at DESY, Zeuthen Site (PITZ) is one of the leading producers of high brightness electron beams for linac based Free Electron Lasers (FELs) with a specific focus on the requirements of FLASH and the European XFEL. The main activities at PITZ are devoted to the detailed characterization and optimization of electron sources yielding to an extremely small transverse beam emittance. The cathode laser pulse shaping is considered as one of the key issues for the high brightness photo injector. Beam dynamics simulations show that the injector performance could be further improved by replacing the typical cylindrically shaped PITZ bunches by uniformly filled 3D ellipsoidal shaped electron beams. A set of numerical simulations were performed to study the beam dynamics of uniformly filled 3D ellipsoidal bunches with 1 nC charge in order to find an optimum PITZ machine setup which will yield the best transverse emittance. Simulation results comparing both options of cylindrical and 3D ellipsoidal beams are also presented and discussed.

INTRODUCTION

The X-ray free electron lasers (XFELs) require excellent electron beam quality in terms of high peak current, small transverse emittance and energy spread. Production of such high quality beams is obligatory to perform a single pass beam transport through hundreds of meters long undulators with a gap size of a few millimetres. The ideal beam distribution for the best transverse and longitudinal bunch compression is a three-dimensional uniformly filled ellipsoid, in which the space charge force fields inside the bunch are linear [1]. Such distributions, also called 3D Kapchinskij and Vladimirskij distribution [2], will allow a full emittance compensation scheme [3] with proper arrangement of the beam optics. One possibility to create such beams is to use a uniform ellipsoid photocathode laser pulse [4], which is a challenging task due to the difficulty of simultaneous spatiotemporal control of the photon distribution at the photocathodes.

Recently many investigations have been carried out into creation of quasi ellipsoidal electron bunches relying on the beam expansion due to strong longitudinal / transverse space charge forces. In the first case, (longitudinal beam expansion, also called blow up regime) the studies were performed for a pancake shape (transverse bunch size much bigger compared to longitudinal one) electron beams initialized from an ultra-short (~30 fs) laser pulse [5]. As the formation of the ellipsoidal beam shape is also sensitive to the radial laser profile the idea was further improved later on by the suggestion of using a surface charge density with a "half-circle" radial profile [6]. In the second case, (transverse beam expansion) a "cigar-like" beam (longitudinal size much bigger compared to transverse one) with a parabolic longitudinal profile was applied by using a very small (~30 μm) transverse laser spot size on the cathode. An electron beam with quasi ellipsoidal shape was formed after the emission due to strong space charge driven transverse expansion [7]. In the former cases the transverse emittance is limited by the thermal emittance which is comparably high due to a big laser spot size on the cathode. The latter case could cause difficulties to transport ultralow charge (0.1-1pC) beams and to measure the beam properties though a nanometer transverse emittance out of such investigations (measurements and simulations) was reported.

The Photo Injector Test facility at DESY, Zeuthen Site (PITZ) is well-known for developing of high brightness electron sources for linac based, single pass multi user FEL facilities such as Free electron LASer in Hamburg (FLASH) and the European XFEL. The PITZ facility was already utilized to establish the injector requirements of the high quality electron beam for the European XFEL [8]. A schematic layout of the current PITZ beamline is shown in Fig. 1. The electron bunches are created in an L-band RF gun cavity using a Cs_2Te cathode and accelerated up to ~6.2 MeV energy. Typically electron beams with 1 nC charge are formed with a longitudinally flat-top and transversely radial homogenous photo-cathode laser profile. The RF 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 transverse emittance of the 25 MeV electron beam (after post acceleration through the booster cavity) along the linac is measured by the emittance measurement systems (EMSY), using a single slit scan technique [9]. Additionally, there are many diagnostics devices available for full characterization of high brightness electron beams. More detailed description of the PITZ setup can be found elsewhere [10]. Recent measurements of the transverse emittance for different bunch charges yielded worldwide record low values where the photocathode laser with a flat-top temporal profile was used to create the electron bunches [11]. To further improve the electron beam quality, a 3D ellipsoidal photocathode laser system

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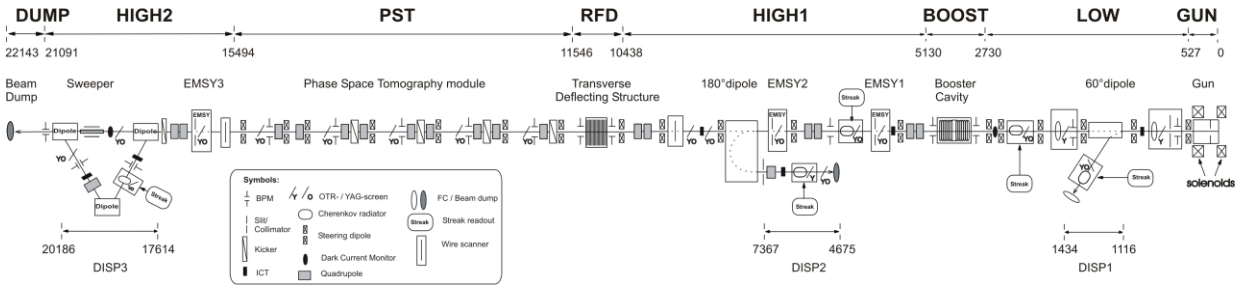

Figure 1: Current PITZ beamline with the electron beam propagation direction from the right to the left.

will be installed at PITZ for generation and characterization of 3D quasi ellipsoidal electron bunches. Such an advanced laser system is currently under development at the Institute of Applied Physics (IAP) in Nizhny Novgorod. The project is being realized in the frame of a Joint German-Russian Research Group including PITZ (DESY), IAP and the Joint Institute for Nuclear Research (JINR). The aim of this contribution is to study the beam dynamics of cylindrical and 3D ellipsoidal beams with 1 nC charge for the PITZ injector setup. Advantages of using the uniformly filled 3D ellipsoidal laser beams are expressed in comparison to the traditional cylindrically shaped pulses. The impact of non-perfectly shaped 3D ellipsoidal laser profile on the electron beam transverse emittance is also considered.

SIMULATION SETUP: COMPARISON OF 3 DIFFERENT LASER SHAPES

A space charge tracking algorithm [12] (ASTRA) has been used for transverse emittance optimization at the position of EMSY1, located at 5.74 m downstream the cathode. Three different laser shapes have been considered during the simulations: Gaussian and flat-top temporal profiles with radially homogenous transverse distribution on the cathode and a 3D ellipsoidal distribution. The goal was to compare the transverse emittance for the three cases with the same electron rms bunch length at EMSY1. The reference bunch rms length (~ 2 mm) was chosen from the simulation results of the flat-top temporal laser profile with 21.5 ps FWHM length and 2 ps rise and fall times, which yielded the smallest transverse emittance at EMSY1 for 1 nC bunch charge [9]. The gun peak electric field at the cathode was fixed to 60.58 MV/m, which corresponds to the experimentally obtained beam momentum of 6.7 MeV/c at the phase of maximum acceleration. A fixed final electron beam momentum (by setting the booster accelerating gradient to 19.76 MV/m) of ~24 MeV/c was applied during the calculations for three different cases of laser shapes. In all cases the length and the transverse size of the cathode laser distributions were tuned together with the main solenoid current to achieve the best transverse emittance of an electron beam with the same rms length at the position of EMSY1. The space-charge settings in ASTRA were optimized for all cases in order to minimize the impact of numerical errors on the emittance values. The result is shown in Fig. 2, where the optimized normalized transverse projected normalized emittances (rms values) are plotted for the cases of 3 different laser profiles: Gaussian (blue triangle), flat-top (red square) and 3D ellipsoidal (green circle). The 100 % value on the graph corresponds to the transverse emittance for the flat-top temporal laser profile.

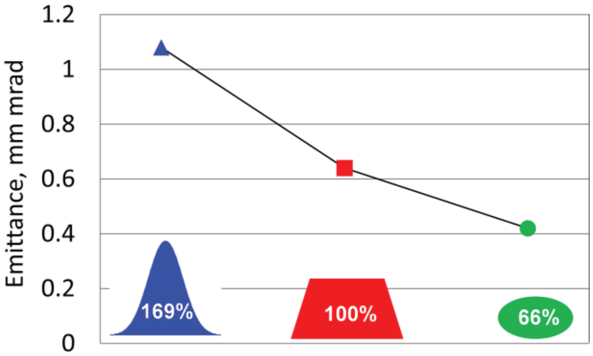

Figure 2: Transverse rms normalized emittance optimized for 3 different laser shapes with the same electron beam rms length at EMSY1.

The picture above shows that the electron beam quality is further improved when the flat-top laser profile is replaced by the 3D ellipsoidal profile. The electron beam transverse projected normalized emittances and rms sizes

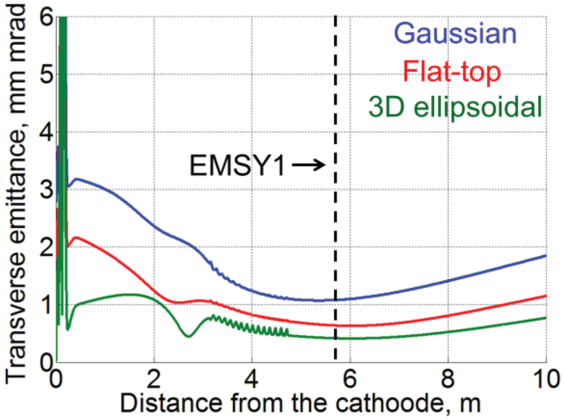

Figure 3: Transverse projected rms emittance along the PITZ beamline for three cases of laser profiles. The position of EMSY1 is marked in the graph.

(3 different laser shapes) along the PITZ beamline up to 10 m are shown in Fig. 3 and Fig. 4 respectively. The position of the first emittance measurement system (EMSY1) is marked with a dashed line in the graphs. As can be seen from Fig. 4 the optimized (best emittance at EMSY1) beam size evolution is different in the case of the 3D ellipsoidal laser profile. The beam is focused (passing through the waist) before entering the booster, whereas the focus in the Gaussian and flat-top cases is located inside the booster. One of the explanations is a non-proper position of the booster cavity in the 3D ellipsoidal laser profile case.

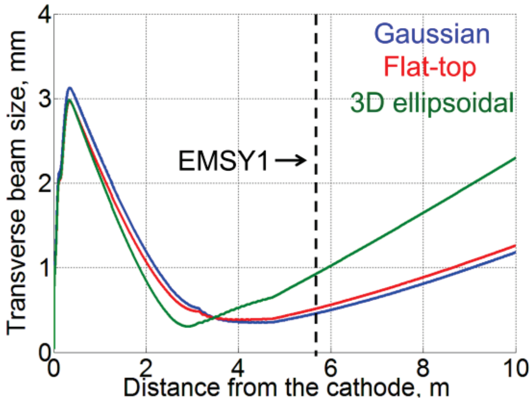

Figure 4: Transverse rms beam size along the PITZ beamline for three cases of laser profiles. The position of EMSY1 is marked in the graph.

Additional beam dynamics studies (including position optimization of the booster cavity) are still necessary for a more precise analysis of the beam evolution of quasi-ellipsoidal electron bunches. Electron beam current and transverse slice emittance distributions within the bunch (at the position of EMSY1) are presented in Fig. 5, by dashed and solid lines, respectively.

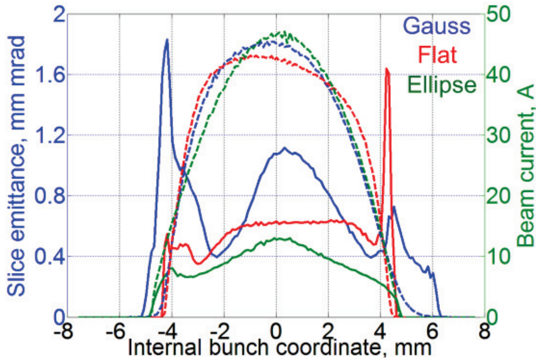

Figure 5: Beam current (dashed curves) and transverse emittance distribution within the bunch at the location of the EMSY1 for three cases of laser profiles.

Despite the comparable peak current values, there is a huge bump on the slice emittance in the middle part of the bunch for the case of the Gaussian profile. Peaks in the emittance distributions for the Gaussian and flat-top temporal laser profiles are correlated with the non-linear space charge forces, as different longitudinal parts (slices) of the electron bunch experience different focusing conditions. Electron beam longitudinal phase spaces for different laser profiles are compared in Fig. 6. One of the advantages of applying the 3D ellipsoidal laser profile is expressed in less nonlinearity and more regular shape of the longitudinal phase space.

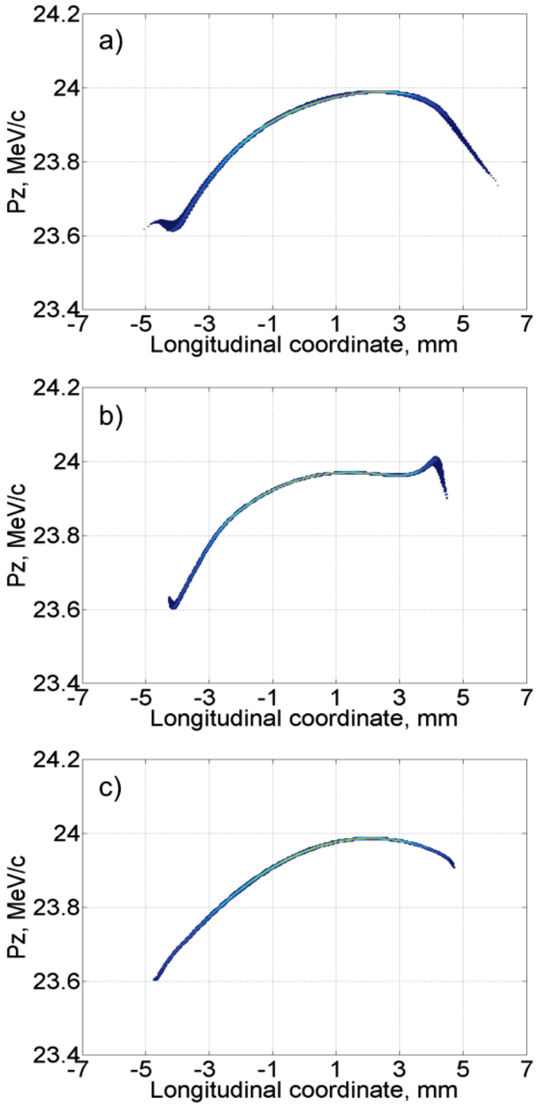

Figure 6: Electron beam longitudinal phase spaces for a) Gaussian, b) flat-top and c) 3D ellipsoidal laser profiles.

For that reason a better longitudinal beam compression after the injector is expected, assuming linearization of the longitudinal phase space by applying a 3^{rd} harmonic cavity. Simulated electron beam parameters at the location of EMSY1 are summarized in Tab. 1. In the case of 3D ellipsoidal laser shape ~80 % contribution on the optimized transverse emittance is attained from the thermal emittance (0.55 eV initial kinetic energy of the electrons was assumed in the simulations [13]).

Table 1: Electron Beam Parameters with 1 nC Charge at the Position of EMSY1 for Three cases of Laser Profiles

Parameter	Gaussian	Flat-top	3D ellipsoidal
Peak current, A	45.4	43.2	46.8
Projected emittance, mm mrad	1.1	0.64	0.42
Longitudinal emittance, keV mm	107	98	88
Thermal/final transverse emittance, %	30	53	79
Average slice emittance, mm mrad	0.78	0.57	0.39

The average slice emittance values shown in Table 1 are weighted by the beam current. As a conclusion one can see that for the case of the 3D ellipsoidal laser shape the average slice emittance is improved compared to cylindrically shaped beams. For the same case the thermal to projected emittance ratio is also increased, which means that the emittance compensation is more efficient when the electron bunches are created with the 3D ellipsoidal laser shape.

INFLUENCE OF CATHODE LASER IMPERFECTIONS ON THE ELECTRON BEAM TRANSVERSE EMITTANCE

The laser system for generating 3D pulses is a complex system consisting of a diode pumped Yb:KGW disk amplifier, a 3D pulse shaper and frequency conversion crystals for second and fourth harmonic generation [14]. The new laser system capable to produce 3D ellipsoidal pulses is currently under development at IAP, in Nizhny Novgorod. Recent measurements of the laser pulse energy after the KGW amplifier have shown a significant disturbance in the energy spectrum influenced by amplified spontaneous radiation (ASR). Filtering of the high frequency spatial harmonics (installing an opaque mask with holes) resulted in a pulse amplification without any significant ASR effects. However a less sharp border of the 3D ellipsoidal pulse was observed [14]. In order to study tolerances of a non-perfect ellipsoidal cathode laser shape impacts on the electron beam transverse emittance, temporal (δ_r) and radial (δ_t) border sharpness parameters were introduced into the laser intensity distribution modelling for the beam dynamics simulations. In Fig.7 one can see the intensity distribution of an initially homogenous 3D laser pulse, which is modified depending on bounded sharpness of ellipsoid edges. δ_r, δ_t are given in percentages related to the 3D ellipsoid semi axis. δ=0 % corresponds to a sharp border, while δ=50 % means the border width is half of the semi axis. The ttransverse emittance growth due to non-perfectness of 3D ellipsoidal laser shape was simulated at the position of EMSY1. In Fig. 8 the result of two parameter scan is shown, where the numbers on the graph represent the corresponding emittance growth in percentage as a function of temporal and radial border sharpness parameters. The optimum perfect case described in the previous section was regarded as a reference. During the tolerance studies, the parameters in ASTRA which are responsible for the rms emission time of the bunch (Trms) and the 3D laser beam transverse projection onto the z axis (XYrms) were kept unchanged.

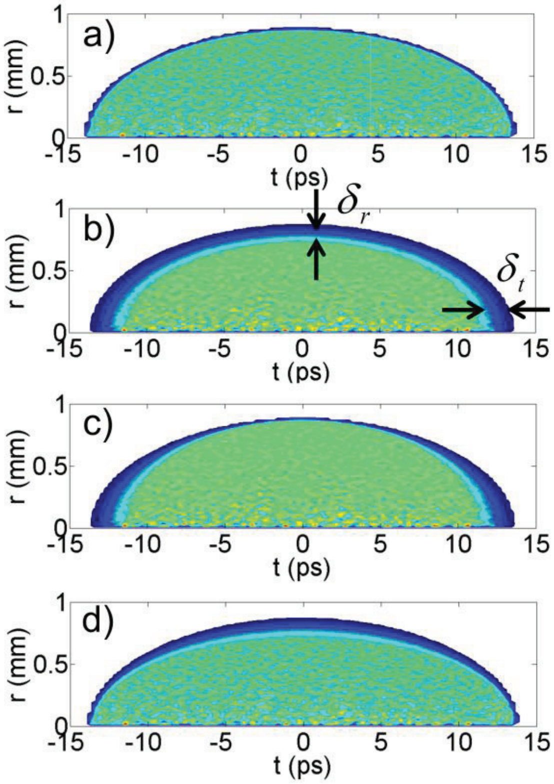

Figure 7: Border sharpness modelling in ASTRA. a) Perfect 3D shape, b) 20 % distortion in temporal and radial directions, c) 20 % distortion only in the temporal direction, d) 20 % distortion only in the radial direction.

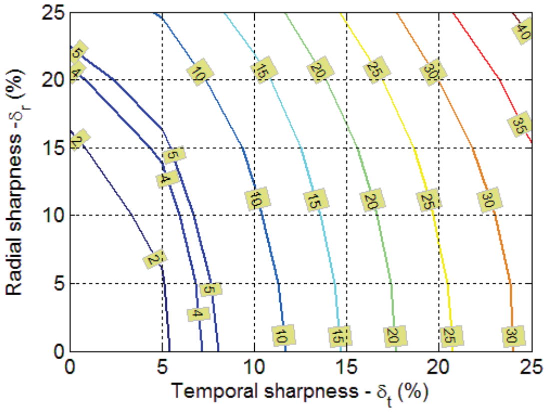

Figure 8: Simulated emittance growth (in %) versus temporal (δ_t) and radial (δ_r) border sharpness parameters.

Relative growth of transverse emittance as a function of border sharpness ($\delta_r = \delta_t$) is presented in Fig. 9. The same figure also displays the comparison of the transverse phase spaces for the ideal 3D laser pulse and the pulse with 20 % border sharpness ($\delta_r = \delta_t = 20$ %) in temporal and radial directions. It can be seen from Fig. 8, that the imperfections in temporal direction have bigger effect on the transverse emittance compared to radial ones. Another conclusion is made that 10 % non-perfections in 3D ellipsoidal laser shape are still acceptable in terms of measurable beam transverse emittance compared to the flat-top profile.

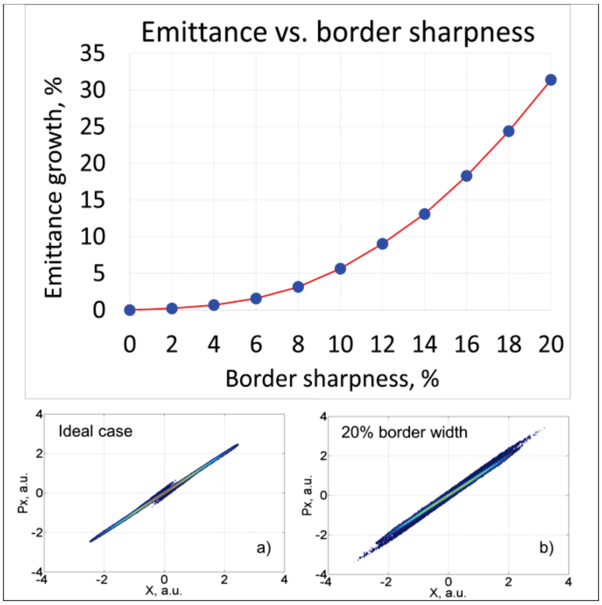

Figure 9: Relative emittance growth for $\delta_t = \delta_r = \delta$ and transverse phase spaces for the cases of a) ideal 3D laser pulse and b) the pulse with 20% border width. The coordinates of the transverse phase spaces are shown in arbitrary units.

SUMMARY

Beam dynamics simulation results have shown a further improvement of electron beam quality by using a 3D ellipsoidal laser beam instead of conventional cylindrically shaped beams. As compared to the flat-top temporal laser shape more than 30 % reduction in transverse projected emittance at 1 nC bunch charge was seen in simulation for the 3D ellipsoidal laser case. The transverse beam emittance has been simulated for more realistic conditions, in which the 3D ellipsoidal laser pulse doesn't have perfect borders in spatial and temporal directions. A model of a non-perfect border of a 3D ellipsoid was introduced, where both radial and temporal sharpness parameters were implemented. Two parameter scan of border sharpness showed overall 10 % acceptability in terms of transverse emittance. Further studies including different bunch charges are still necessary for a more explicit overview of beam dynamics of the quasi-ellipsoidal beams at the PITZ injector.

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