STUDIES ON THE APPLICATION OF THE 3D ELLIPSOIDAL CATHODE LASER PULSES AT PITZ*

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Abstract

The Photo Injector Test facility at DESY, Zeuthen Site (PITZ) characterizes and optimizes high brightness electron sources for FLASH and the European XFEL. At nominal conditions the electron bunches are created from a photocathode laser of flat-top temporal distribution with sharp rise and fall times. Beam dynamics simulations using a 3D ellipsoidal cathode laser shape at PITZ yielded to a significant improvement of the electron beam quality compared to the traditionally used cylindrically shaped beams. The 3D ellipsoidal laser system is under development at the Institute of Applied Physics (IAP) and will be used at PITZ soon, to create high quality electron beams. The recent studies of electron beam simulations at PITZ have been devoted to the position optimization of the second accelerating cavity for the 3D ellipsoidal laser profile. Electron beam properties were compared for cylindrical and 3D ellipsoidal beams applying default and optimized booster positions. Beam tolerance studies revealed much better injector performance for the 3D ellipsoidal laser profile case with the optimized booster position. The outcome of such investigations is presented and discussed in this contribution.

INTRODUCTON

High quality electron beams are generated and optimized at the Photo Injector Test facility at DESY, Zeuthen Site (PITZ) for detailed study of photoinjector physics for linac based free electron laser (FEL) machines such as the European XFEL. At PITZ high brightness electron beams are generated by the photo effect using a Cs_2Te cathode and are accelerated in an L-band RF gun cavity up to 7 MeV electron beam energy. At nominal conditions a cathode laser with a flat-top temporal profile is applied to create photoelectrons. The gun is surrounded by the main solenoid to suppress the electron beam transverse blow up due to strong space charge forces at low energies. The bucking coil is used to compensate the longitudinal component of the magnetic field at the cathode. The electron beam gets its final momentum of about 25 MeV/c, after passing through the so called CDS (cut disc structure) booster cavity which is starting at a position of ~ 3.1 m downstream the cathode. Transverse phase space and transverse projected emittance of the electron beam are usually measured by the single slit method [1] using the first emittance measurement system (EMSY1), which is located at 5.74 m downstream the cathode. A more detailed description of the PITZ injector setup can be found elsewhere [2]. PITZ is well known as a producer of extremely high quality electron bunches of different charges [3]. However, the beam quality can be further improved if cylindrically shaped electron bunches are replaced with a uniformly filled 3D ellipsoidal distributions. The phase space distribution of the electron bunches with such a shape is linear due to the linear nature of space charge forces [4].

A few years ago experimental studies have been performed at the PITZ photoinjector to study the possibility of creation of ellipsoidal beams via so called blow-out regime [5] at 750pC bunch charge by using the shortest available Gaussian temporal laser profile with ~1 ps rms duration [6]. As a result, the ellipsoidal character of the electron beam was distorted due to strong image charge forces. Additionally the laser pulse duration was not short enough to explore the possible limitations coming from the relatively slow response time of the Cs2Te cathodes [7].

Recent measurements using an L-band injector at Fermilab, where the Cs_2Te photocathode was illuminated by a short (~200 fs rms) laser pulse have confirmed the possibility of creating the 3D ellipsoidal bunches with charges up to 500 pC [8]. Nonetheless, the measured transverse emittance of the electron beam was high even though compared to the results with cylindrically shaped beams [3]. For that reason, direct shaping of the laser profile to a quasi 3D ellipsoidal distribution would be the best way to generate high brightness electron beams at high bunch charges such as 1 nC.

The first beam dynamics simulations performed at Stanford Linear Accelerator Center (SLAC) resulted in a better electron beam quality for the 3D ellipsoidal laser beams when compared to the traditional cylindrically shaped ones [9]. Simulation studies have been continued in the same direction using the PITZ injector setup. Again better quality of the 1 nC beam was achieved when the cylindrically shaped beams are replaced with the beams from 3D ellipsoidal laser distributions [10]. The next step towards the practical beam quality improvement is the installation and characterization of a 3D ellipsoidal laser system at PITZ, which is being developed at the IAP within the frame of German-Russian collaboration project [11].

In this work the PITZ injector optimization using a 3D ellipsoidal laser shape is presented including the position optimization of the second accelerating cavity. Moreover, the results of beam tolerance studies comparing different booster positions and different laser beam shapes are also discussed.

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OPIMIZATION OF CDS BOOSTER POSITION FOR THE PITZ LINAC

ASTRA [12] simulations for the PITZ injector have shown a significant improvement (~ 30 %) of the transverse normalized emittance of a 1 nC beam when 3D ellipsoidal cathode laser is used to create photoelectrons instead of laser shape with longitudinally flat-top and transversely radial homogeneous distribution [10]. In Fig.1, the evolution of the electron beam transverse size and transverse emittance is shown for the case of the 3D ellipsoidal laser shape at the optimized machine settings (best transverse emittance at EMSY1) for the current facility layout. One can see from the figure that the electron bunch enters the booster cavity after passing through its waist. In this case the rf focusing from the booster is not applied properly, since the different (mismatched) slices of the bunch experience different focusing conditions. It was discussed in the past, how important is the position optimization of the booster cavity during emittance optimization process, especially for the space charge dominated beams [13]. For that reason, fine transverse emittance optimization was performed for the PITZ setup including variation of CDS booster position together with other machine parameters. During the optimization the following parameters were kept constant: The gun peak electric field at the cathode to 60.58 MV/m, gun lunching phase to the phase of maximum acceleration and bunch charge was fixed to 1 nC. The longitudinal size of the laser of different profiles was also fixed (flat-top: 21.5 ps FWHM length with 2 ps rise and fall times, 3D ellipsoidal: initial bunch length to the rms value of 6.1 ps, which, according to the previous studies, should result in a comparable rms bunch length at EMSY1 as for the flat-top case). The laser rms spot size on the cathode, main solenoid current, the initial Z position of the CDS booster and the amplitude of the booster accelerating field have been varied in order to find the best matching conditions. The result of the optimization is summarized in Fig.2, where the emittance growth at EMSY1 (relative to the best values obtained for flat-top and 3D ellipsoidal laser cases with the optimum position of the booster) as a function of booster position is shown for two different laser profiles. In order to estimate how strong is the influence of each optimized machine parameter on the transverse emittance, beam tolerance studies have been performed, where the emittance dependence on one of the optimized machine parameters was observed while the others are kept constant. The beam tolerances were studied for different laser profiles, comparing current booster position (Z=3.1 m) and the optimum positions for flat-top (Z=2.9 m) and 3D ellipsoidal (Z=2.7 m) laser profiles. The results were found to be not strongly sensitive to the booster position for the flat-top case, whereas the beam performance was more strongly dependent on the booster settings for the 3D ellipsoidal laser case. In Fig.3 the outcome of such studies is shown assuming different laser profiles and two booster positions Z=2.7 m (optimum for 3D ellipsoidal case) and Z=3.1 m (the current one). In the same figure the empty circles and filled triangles correspond to the case of 3D ellipsoidal beam with default and optimized (Z=2.7 m) booster settings, while the empty squares and filled rhombi represent the points for the case of the flat-top laser profile. As always, the blue and the red colours indicate the results for the 3D ellipsoidal and the flat-top laser profiles, respectively. Since the results are not strongly dependent on the booster position for the case of the flat-top laser profile, the points corresponding to Z=2.9 m booster position were not included in the figure in order to not overload it. As can be seen from Fig. 3, for the 3D ellipsoidal laser case with optimized booster position, the dependence of the transverse emittance on the machine parameters is remarkably less (compared to the current position), especially the emittance dependence on the solenoid peak field which is one of the main parameters during emittance optimization. The results on beam tolerances are comparable for the flat-top laser case, except the emittance dependence on the gun phase, which

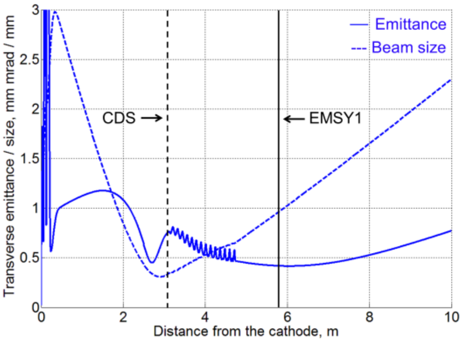

Figure 1: Transverse beam properties along the PITZ beamline. The positions of CDS booster (dashed line) and EMSY1 (solid line) are marked on the picture. Solid and dashed curves in the graph represent the transverse rms emittance and the transverse rms beam size, respectively.

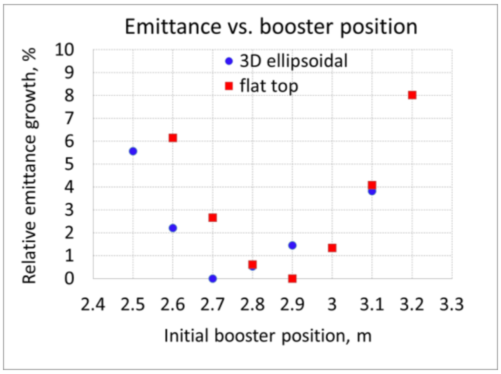

Figure 2: Relative growth of transverse emittance (at EMSY1) for different booster positions. Blue circles and red squares represent the values for the 3D ellipsoidal and flat-top laser shapes correspondingly.

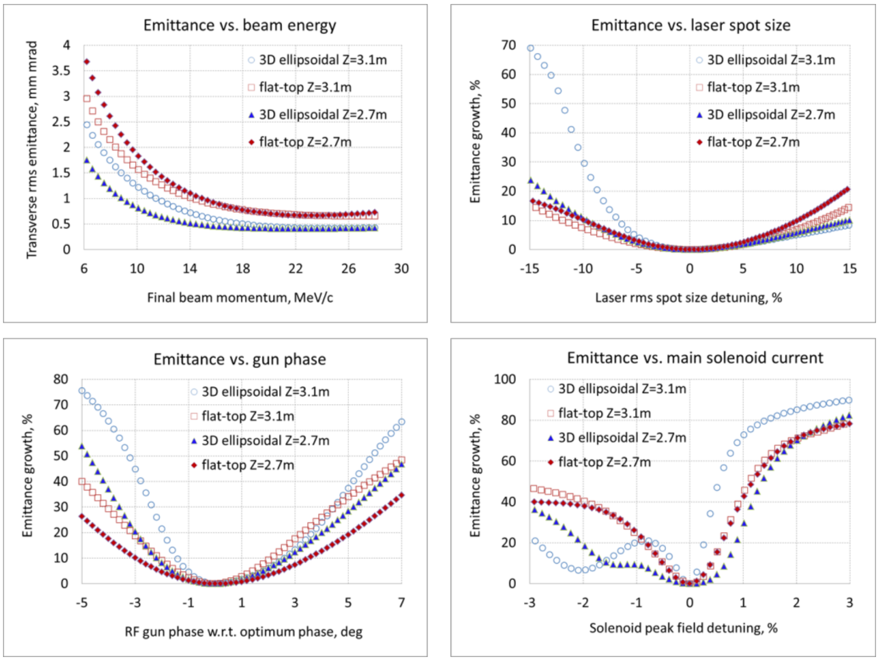

Figure 3: Summary of beam tolerance studies for two different laser profiles for default (Z=3.1m) and optimized (Z=2.7m) booster positions. The blue colour indicates the 3D ellipsoidal laser case, while the red one specifies the case of the flat-top laser profile.

Table 1: Optimized parameters of 1nC beam at EMSY1 for the cases of flat-top and 3D ellipsoidal laser profiles at default and optimized booster positions.

Parameter	3D ellipse	Flat top	3D ellipse	Flat top
Booster starting position, m	3.1	3.1	2.7	2.7
Projected emittance, mm mrad	0.419	0.639	0.406	0.637
Peak current, A	46.8	43.2	50	45.7
Thermal/final emittance, %	79	53	90	64
Average slice emittance, mm mrad	0.392	0.57	0.394	0.54

is significantly improved for the new settings (Z=2.7 m) due to originally bigger laser spot size at the cathode. The optimized 24 MeV electron beam properties at EMSY1 for different laser profiles and booster positions are summarized in Tab.1, proving that besides the improved beam stability against machine parameter variations, the beam quality is at least as good with the shifted booster position. One should mention a small difference (-7 %) in the electron bunch rms lengths at default and optimized booster settings (flat-top and 3D ellipsoidal), as for the fixed size of the flat-top longitudinal laser profile the optimized booster settings required initially bigger laser spot size to be applied at the cathode. The longitudinal laser size for 3D ellipsoidal case was, therefore, adjusted accordingly to have the same electron bunch rms values for two laser profiles at optimum booster conditions.

CONCLUSION

The PITZ linac was optimized to obtain the smallest transverse emittance of 1 nC beam, including position optimization of the second accelerating cavity. 50 A beam peak current and 90% contribution of thermal emittance to the final one was achieved for the 3D ellipsoidal laser case with the optimized booster position. In addition beam tolerance studies were performed for flat-top and 3D ellipsoidal laser profiles comparing different booster positions. The results were found to be not very sensitive to the booster position for the flat-top case. Strong dependence of the injector performance on the booster position was observed for the 3D ellipsoidal laser case. Much better injector performance (beam parameters at EMSY1 as well as tolerances) was achieved for the latter laser shape with the optimized booster conditions.

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REFERENCES

[1] L. Staykov, Characterization of transverse phase space at the Photo Injector Test Facility in DESY, Zeuthen site, PhD thesis, Hamburg University, 2012.

[2] F. Stephan et al., "Detailed characterization of electron sources yielding first demonstration of European X-ray Free-Electron Laser beam quality." PRST-AB 13, 020704 (2010).

[3] M. Krasilnikov et al., "Experimentally minimized beam emittance from an L-band photoinjector". PRST-AB 15, 100701 (2012).

[4] I.M. Kapchinskij, V.V. Vladimirskij, Conference on High Energy Accelerators and Instrumentation, CERN, Geneva, 1959, p. 274.

[5] J. Rosenzweig et al., "Emittance compensation with dynamically optimized electron beam profiles". Nuclear Instruments and Methods in Physics Research, A557, (2006), pp. 87-93.

[6] B.O. Shea et al., "Measurement of self-shaped ellipsoidal bunches from a photoinjector with postacceleration". PRST-AB, 14, 012801 (2011).

[7] G. Ferrini et al., "A Monte Carlo simulation of low energy photoelectron scattering in Cs_2Te". Solid State Commun. 106, 21 (1998).

[8] P. Piot at el., "Formation and acceleration of uniformly filled ellipsoidal electron bunches obtained via space-charge-driven expansion from a cesium-telluride photocathode". PRST-AB, 16, 010102 (2013).

[9] C. Limborg-Deprey, P.R. Bolton "Optimum electron distributions for space charge dominated beams in photoinjectors". Nuclear Instruments and Methods in Physics Research, A557, (2006), pp. 106-116.

[10] M. Khojoyan et al., "Beam dynamics optimization for the high brightness PITZ photo injector using 3D ellipsoidal cathode laser pulses", TUPSO36, Proceedings of the 35th International Free Electron Laser Conference, Manhattan, USA, 2013.

[11] M. Krasilnikov et al., "Development of a photo cathode laser system for quasi ellipsoidal bunches at PITZ", TUPSO39, Proceedings of the 35th International Free Electron Laser Conference, Manhattan, USA, 2013.

[12] K. Flöttmann, ASTRA, http://www.desy.de/~mpyflo

[13] M. Ferrario et al, "New Design Study and Related Experimental Program for the LCLS RF Photoinjector", Contributed to the 7th European Particle Accelerator Conference, Vienna, 2000.