LOW-CHARGE SIMULATIONS FOR PHASE SPACE TOMOGRAPHY DIAGNOSTICS AT THE PITZ FACILITY

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Abstract

The Photo Injector Test Facility at DESY, Zeuthen site (PITZ) aims to optimize high brightness electron sources for linac-based FELs. Since the performance of an FEL strongly depends on the transverse electron beam emittance, the electron source is studied in details at PITZ by measuring the emittance with the help of the Emittance Measurement SYstems (EMSY). The EMSY employs the slit scan technique which is optimized for 1 nC bunch charge and, therefore, it might not be an optimal choice for low charge bunches. To extend the ability of the facility for transverse phase space measurements, a module for phase-space tomography diagnostics and its matching section are installed in 2010. The basic components of the module are four screens separated by FODO cells. It is designed for operation with high charge and low energy beams. This work studies the performance of the tomography module when it is operated with low charge beams. The influence of different beam parameters is evaluated according to the requirement to match the envelope to the optics of the FODO lattice. Simulation results and phase space reconstructions are presented.

INTRODUCTION

PTTZ aims to optimize high brightness electron sources for linac-based FELs like FLASH and the future European XFEL. Since the performance of an FEL strongly depends on the transverse electron beam emittance, the last is a major point for the photo-injector optimization process done at PITZ. In the last run period only the single slit scan technique using an Emittance Measurement System - EMSY, has been used [1, 2]. EMSY consists of horizontal and vertical actuators with 10 and 50 μm slits masks and a YAG/OTR screen for beam size measurement. A new module for phase space tomographic diagnostics and its matching section, both undergoing commissioning at the moment, extends the ability of the facility to characterize the transverse phase space. At the same time the old TESLA booster cavity was replaced by a CDS booster which is expected to deliver beam momentum up to 30 MeV/c. Figure 1 shows the new schematics of the PITZ beamline - PITZ 1.8. The tomography module, situated in the second part of the beamline, consists of three FODO cells and four diagnostic screens as shown in Fig. 1. More details about the design of tomography module can be found in [3, 4]. The phase advance between the FODO cells is 45° which is expected to deliver the smallest emittance measurement error using the four screen method as shown in [4]. The FODO cells are only 0.76 m and therefore the design Twiss parameters for a periodic solution to be achieved are rather stringent - $\beta_{\mathrm{x,y}} = 0.999\ \mathrm{m}$ and $\alpha_{\mathrm{x,y}} = \pm 1.125$. In order to deliver the expected Twiss parameters up to nine quadrupole magnets upstream the tomography module can be used. In this paper simulations with 100 pC bunch charge for tomography diagnostics are presented. In the first part the emittance optimization at EMSY1, which is normally used for emittance measurements, using ASTRA [5] is presented and then matching solutions are shown. Finally, phase space reconstructions for some of the matching cases are demonstrated.

EMITTANCE OPTIMIZATION

To study the performance of the tomography module when it is operated with low charge bunches, simulations are performed using ASTRA. The beam evolution is simulated from the cathode to the EMSY1 station. The initial conditions for the simulations are shown in Table 1. The laser spot size is chosen as a compromise between small emittance at EMSY1 and bigger spot size considered as suffering less from space-charge effects. The criteria for the simulations is to optimize the emittance at the EMSY1 station for a momentum range from 15 MeV/c to 32 MeV/c. The focusing solenoid magnetic field and gun phase are optimized. Simulation results predict that the maximum emittance at EMSY1 for this momentum range is 0.185 mm mrad.

Table 1: The Initial Parameters of the Simulations

	parameter	value	units
Laser	pulse length	20	ps
	rise/fall time	2	ps
	kinetic energy	0.55	eV
	rms laser spot size	0.150	mm
	bunch charge	100	pC
RF-gun	gradient at the cathode	60	MV/m
Booster	phase	on-crest	
Tracking particles	macro particles	200000	particles

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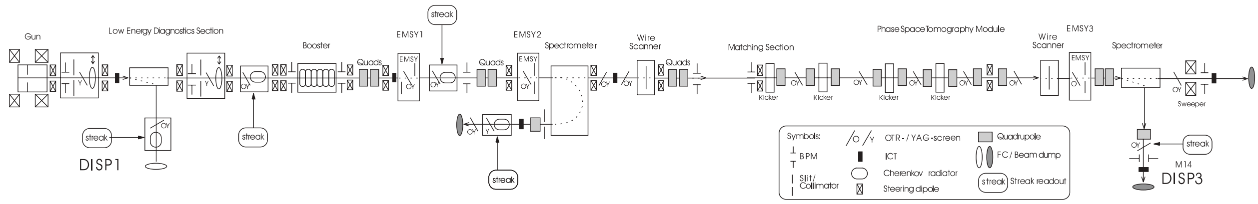


Figure 1: The new layout of PITZ beamline (PITZ 1.8).

Figure 2 shows the evolution of the normalized emittance and rms beam size along the beamline until 10 m for a beam momentum of 20.6 MeV/c. The normalized projected emittance and rms beam size on EMSY1 are correspondingly 0.183 mm mrad and 0.172 mm. Figure 3 shows the obtained slice emittance and slice β-function, at the same location. Both show alignment of the longitudinal slices and expected easier matching.

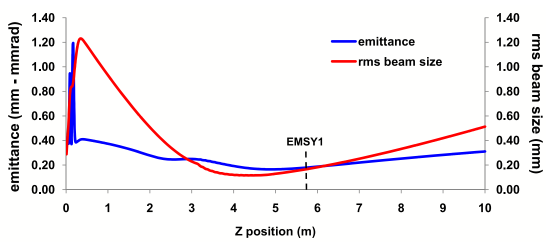


Figure 2: Simulated rms beam size and normalized emittance evaluated along the beam line for 100 pC bunch charge and 20.6 MeV/c beam momentum. The position of EMSY 1 is shown at 5.74 m downstream the cathode.

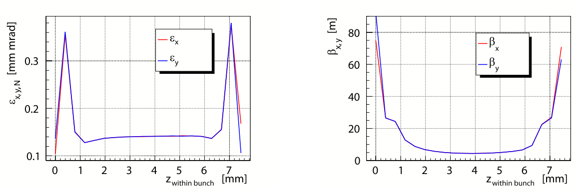
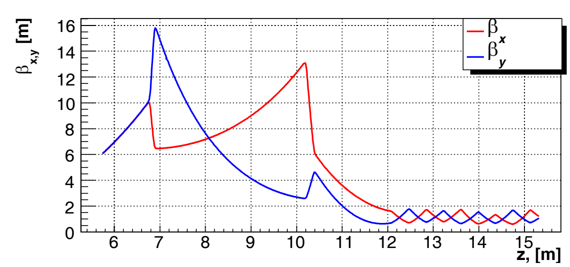


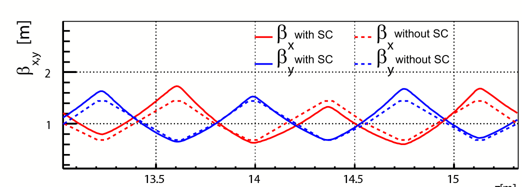
Figure 3: Slice emittance (left) and slice beta function (right) for a beam momentum of 20.6 MeV/c at EMSY1.

MATCHING SOLUTION

At the beginning of the next run period the new booster cavity will accelerate the beam momentum only up to 24 MeV/c, therefore the matching solutions were achieved for momenta from 15 to 25 MeV/c. Matching into the tomography section has been performed using the V-code [6]. The V-code is a beam dynamics simulation tool which is able to calculate the statistical moments of a bunch distribution as an input and calculate trajectories of those moments through electro-magnetic fields. The matching starts from EMSY1 to the first screen of the tomography module and uses seven quadrupoles. In practice it is desirable to use as few magnets as possible but according to simulations the four Twiss parameters cannot be matched simultaneously having a limited range of quadrupole gradients. In the simulations, the gradients of the last two quadrupoles in the matching section are kept constant and have values close to the magnets inside the module in order to make the first periodic cross in front of the first screen. This is needed because those two magnets have stronger influence on the Twiss α parameters which are harder to adjust in the presence of space charge and short quadrupoles. The other five quadrupoles are varied to match and minimize the deviation of the Twiss parameters on the first screen. The solutions from the V-code are plugged into ASTRA and tracked from EMSY1 until the end of the module. In this tracking 3D space charge and the measured quadrupole fields are included. The solutions which deliver β-mismatch $\Delta\beta$[1], both for the horizontal and vertical planes, less than 50% are evaluated. At the moment the best solution is the one that can achieve a β-mismatch of 24% in the horizontal and 17% in the vertical plane for a beam momentum of 20.6 MeV/c. The β-functions for the best solution from EMSY1 until the end of the tomography module is shown in Fig. 4(a).



(a) β -functions from EMSY1 up to the end of the tomography module.



(b) Comparison of the β-functions with- and without space charge SC effect inside the tomography module.

Figure 4: Twiss β -functions for beam momentum of 20.6 MeV/c.

[1] $\Delta\beta\,[\%] = 100\cdot \frac{\beta_{design}-\beta_{measured}}{\beta_{design}}$

Figure 4(b) shows a comparison of the β-functions along the FODO lattice for the case with- and without space charge effects. The matching is not as easy as expected for 100 pC bunch charge because these simulations for optimized emittance are in a space charge dominated regime as shown in Fig. 5. The space charge over emittance ratio

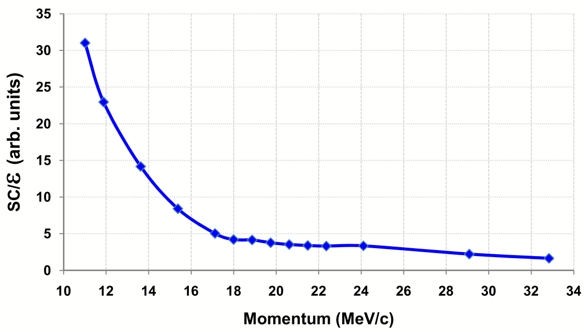


Figure 5: Space charge over emittance ratio as a function of beam momentum.

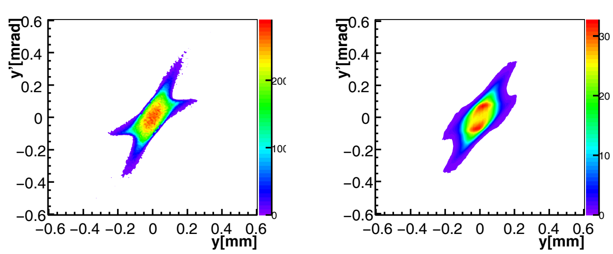
as defined in [7] and shown in Eq. (1) is higher than 1 for the whole range of momenta which corresponds to space charge dominated regime.

$$\rho = \frac{I\sigma^3}{2\beta\gamma I_0 \varepsilon_N^2}, \tag{1}$$

where I is beam peak current, I_0 = 17 kA is the Alfven current, σ - the rms beam size, and ε_N is the normalized emittance.

PHASE SPACE RECONSTRUCTION

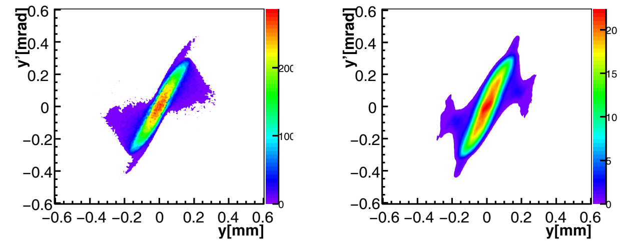
The transverse phase space of the electron beam on the first screen can be reconstructed from projections of the (x, y) distributions on the four screens of the tomography section using the **M**aximum **ENT**ropy-MENT [8] algorithm. More details about the phase space reconstruction can be found in [4]. Figure 6 shows results of the $(\mathrm{y}, \mathrm{y}')$ reconstruction using a perfectly matched solution for the case without space charge forces.



(a) Original distribution. (b) Reconstruction result.

Figure 6: Original and reconstructed vertical phase space of a perfectly matched case for a beam momentum of 20.6 MeV/c.

Figure 7 shows the result from a solution which has a β-mismatch of 17% in the vertical plane. Visually it can be concluded that in the second case the spot size is bigger and the reconstruction delivers higher density in the tails then there is. Table 2 summarises parameters of the original and reconstructed phase spaces for both cases.



(a) Original distribution. (b) Reconstruction result.

Figure 7: Original and reconstructed vertical phase space for beam momentum of 20.6 MeV/c with 17% mismatch.

Table 2: Summarized Parameters of the Original and Reconstructed Phase Spaces (subscripts case 1, 2 referred to a perfectly matched and 17% mismatched case accordingly).

Parameters	**Original**	**Reconstruction**	**Δ[%]**
$\sigma_{y,1}$	0.068	0.069	0.67
$\sigma_{yy',1}$	0.051	0.052	1.00
$\varepsilon_{y,N,1}$	0.182	0.181	0.89
$\sigma_{y,2}$	0.092	0.080	4.97
$\sigma_{yy',2}$	0.0102	0.010	1.45
$\varepsilon_{y,N,2}$	0.296	0.355	20.0

CONCLUSIONS

The simulation results show that it is not easy to match a 100 pC bunch charge optimized for minimum emittance since the beam is still in the space charge dominated regime. It is possible to achieve good solutions but it is cumbersome to do fine quadrupole gradient adjustments. Higher energy is another possibility to overcome this problem. The work continues to find a good matching with this setup. To decrease the space charge effects others parameters will be adjusted - for example laser spot size and the case which emittance is not fully optimize will be matched. Simulations with even lower charges are considered.

ACKNOWLEDGMENTS

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