TWO CHARGES IN THE SAME BUNCH TRAIN AT THE EUROPEAN XFEL

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Abstract

The European XFEL has been initially designed for the operation with bunch charge of 1 nC [1] which was later extended down to 20 pC [2]. An important upgrade of this extension might be the ability to operate different bunch charges in the same RF pulse. In this paper we assume the nominal design of the XFEL injector which means in particular that both charges in the same RF pulse experience the same solenoid field and are generated by the laser of the same rms size. We discuss the requirements which the combined working points of the injector have to fulfil and show the results of the complete start to end (S2E) and SASE simulations for the simultaneous operation of 250 pC and 500 pC bunch charges.

INTRODUCTION

We report about the simulations on the operation of two different bunch charges at the European XFEL. From the beam dynamics point of view the most essential issue there is to achieve the similarity of the beam optical functions keeping emittance growth of the bunches reasonably low. In the next section we give an overview about the XFEL injector with respect to the beam optical functions which is followed by the presentation of the combined working points for the solenoid field and laser beam profile if the injector is operated with two charges in the same RF pulse. Finally we discuss the results of the S2E and SASE simulations for the bunch pair of 250/500 pC.

BEAM OPTICS ISSUES OF THE XFEL INJECTOR

The injector of the European XFEL may be divided into three sections from the beam optical functions point of view. The first section begins at the cathode and is 14.48 m long. Since it doesn't contain quadrupole magnets manipulation of the beam optical functions is achieved here indirectly by the choice of the solenoid field strength as well as gun gradient, RF focussing effects in ACC1 or laser beam size at the cathode.

The next (matching) section begins right after the first accelerating module which is followed by the first quadrupole. It contains six quadrupoles which are used for the matching of the beam optical functions.

The third part of the injector begins after the matching point at 29.51 m where the beam optics is expected to be the same for any bunch charge and any initial settings of the gun.

Since both bunches in the train experience the same magnetic field in the quadrupoles one has to guarantee that they arrive the matching section with similar twiss functions in order to avoid effects of the beam optics distortion like beta beat downstream the matching point.

The ability of the XFEL injector to obtain two different charges in the same RF train with similar beam optical functions has been discussed in [3]. It was shown that it is possible on cost of emittance growth of lower charge if the difference between charges is not too large. Once the suitable value of the peak solenoid field has been found the choice of the laser beam size should be then on the ascending branch for higher charge and on the descending branch for lower charge (see Fig. 1).

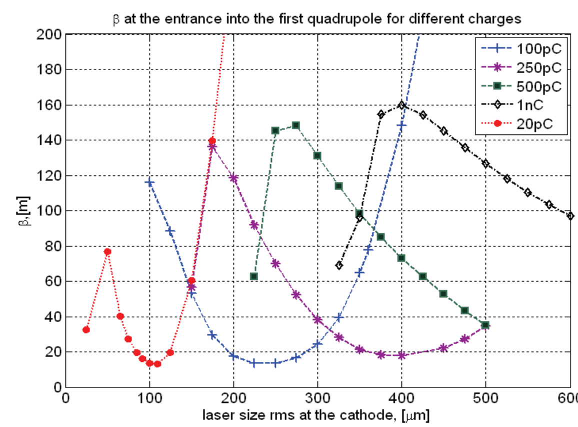

Figure 1: Dependence of the β-function at the beginning of the matching section on laser beam rms size for different bunch charges. Simulations are done for the peak solenoid field of 0.2220 T.

COMBINED WORKING POINTS FOR TWO CHARGES IN THE SAME TRAIN

Under combined working points we define the choice of the settings of the solenoid peak field and rms laser beam size at the cathode. These settings are valid for each particular RF pulse so that they can't be adjusted separately for any bunch in the same RF pulse.

The determination of the combined working points has been also performed under the assumption of the same parameters of the gun and longitudinal gun laser profile for both bunches. These parameters are summarized in the Table 1. The energy of the beam has been fixed to 150 MeV at the exit of the first accelerating module ACC1 and to 130 MeV after the third harmonic module

Table 1: Gun Parameters

Peak Gun Gradient, [MV/m]	Gun Phase	Laser Pulse and Form
60	-1.9	Flat Top 20 ps, rise and fall time 2 ps

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ACC39. In order to make use of the computed working points for the later start to end simulations a compression scenario with the phase of 17.8 degrees of the ACC1 was assumed.

In order to find the combined working points we have analysed the intersections of the operation windows for bunch charges of 20, 100, 250, 500 and 1000 pC. Except of the bunch charge pair of 250/500 pC a combined operation appeared possible also for pairs 100/250 pC and 500/1000 pC. It is also possible to find settings which provide similar beam optical functions for some other bunch pairs though, but the match of the twiss functions by means of the quadrupoles which are foreseen in the matching section is no longer feasible.

As mentioned in the previous section the condition of similarity of the beam optical functions can be fulfilled on cost of the emittance growth of the lower bunch charge. For example, the comparison of the scans for 250 pC and 500 pC bunch charges has shown a perfect agreement of beam optical functions for peak solenoid field of MaxB=0.2235 T and rms laser beam size at the cathode of XY=0.325 mm but the emittance growth of the 250 pC bunch compared to the possible minimum has achieved already 160% which reduces significantly the SASE generation with this bunch.

On the other hand recent tests at FLASH [4] related to the operation of the two bunch charges in the same RF train have shown that the distortion of the beam optical functions which has been introduced by the change of the energy gain by 5% and keeping at the same time the currents in the quadrupole magnets unchanged leads though to a SASE drop of 10-20% but operation and generation of SASE remain acceptable.

In order to find a suitable combined working point we introduce the penalty function which takes into account not only the mismatch between beam optical functions $\xi_{1\to2}$ but also the relative emittance growth of both charges:

$$pen = \frac{\Delta\epsilon_1}{\epsilon_{10}} + \frac{\Delta\epsilon_2}{\epsilon_{20}} + 2(\xi_{1\to2} - 1)$$

Detailed description of the two dimensional scans over the combined working points can be found in [3]. The combined working points which minimize the penalty function and resulting relative emittance growth of the corresponding bunches are summarized in the Table 2.

Table 2: Combined Working Points for Different Bunch Charge Pairs

Bunch Charges Q_1/Q_2, [pC]	Combined WP MaxB, [T]	XY, [mm]	Emittance Growth $\frac{\Delta\epsilon_1}{\epsilon_{10}}$, %	$\frac{\Delta\epsilon_2}{\epsilon_{20}}$, %	Pen
100/250	0.2220	0.205	74.8	1.7	1.487
250/500	0.2224	0.285	50.1	0.0	0.887
500/1000	0.2226	0.400	51.7	4.1	0.957

OPERATION WITH 250/500 pC BUNCH CHARGES WITHIN THE SAME TRAIN

RF Rough Adjustment

We consider an operation of 250 pC and 500 pC bunches within the same RF pulse for the nominal design of the XFEL injector.

The first rough definition of the RF settings has been accomplished by means of RF tweak tool [5]. The tool simulates the dynamics of the particle distribution mainly in the longitudinal phase space, takes into account some collective effects like the longitudinal space charge and CSR and gives also a simple approximation of transverse dynamics. It is based on the semi analytical approach which has been described in [6]. This way it becomes possible to find the first guess of the proper RF settings which would provide the chosen compression scheme.

The input parameters which make possible to achieve this way a Gaussian-like profiles with the peak current of several kA for each charge are shown in the Table 3.

Table 3: Input Parameters for the Compression Scheme

R_{56} at Bunch Compressors, [m]			Energy at Bunch Compressors, [GeV]		
R_{56_0}	R_{56_1}	R_{56_2}	E_0	E_1	E_2
0.065	0.043	0.020	0.13	0.65	2.3

RF Fine Adjustment

Once the "first guess" for the RF settings was found the expected reference distributions after each bunch compression stage have been saved and a start to end run has been performed for each bunch charge from the first quadrupole at s=14.48 m up to the end of the linac 3 at s=1629 m. Since the longitudinal particle distributions after the start to end run normally differ from the reference distributions due to more accurate calculation of the collective effects and taking into account of the wake fields an additional RF adjustment was performed to provide the required longitudinal distributions. In the Table 4 the results for the final RF settings are shown which lead to reasonable 6D distributions with a peak current of 7.75 kA for 250 pC and 5.34 kA for 500 pC bunch charges.

Table 4: RF Settings for the Simultaneous Compression of 250 pC and 500 pC Bunch Charges

	ACC1	ACC39	L1	L2	L3
ΔE_{max}, [GeV]	0.157	0.026	0.657	1.667	11.76
Phase, [deg]	17.79	186.1	37.69	6.57	0.00

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Bunch Parameters after S2E Simulations

The results for the main bunch parameters at the beginning and at the end of the S2E simulations are summarized in the Tables 5a and 5b.

Table 5a: Projected Emittance of the 250 pC and 500 pC Bunches Operated at the Combined WP at the Beginning and at the End of S2E Section

	250 pC		**500 pC**	
	$\varepsilon_{x,pr}$ [μm]	$\varepsilon_{y,pr}$ [μm]	$\varepsilon_{x,pr}$ [μm]	$\varepsilon_{y,pr}$ [μm]
Start	0.336	0.325	0.424	0.422
End	0.391	0.509	0.486	1.367

Table 5b: Rms Energy Spread, Peak Current, FWHM Bunch Length and Total Compression at the Beginning and at the End of S2E Section for 250 pC and 500 pC Bunches Operated at the Combined WP

	250 pC			
	$\delta_{E,rms}$ [MeV]	**I_p, [A]**	**τ,[fs]**	**C**
Start	2.74e-4	16.12	11225	196
End	0.765	7.75e+3	19	
	500 pC			
Start	7.58e-4	26.14	13890	136
End	0.553	5.34e+3	78	

SASE SIMULATIONS FOR THE BUNCH CHARGE PAIR 250/500 pC

Lasing simulations for the SASE 1 section of the European XFEL has been performed by means of the Genesis tracking code [7]. The beam input files have been generated from the output files of the S2E simulations while the evolution of the beam optical functions between Linac 3 and undulator section has been approximated by formulas of the linear optics using the XFEL lattice file.

The results of the simulations indicate the resulting SASE pulse energy of 618 μJ for 250 pC and 708 μJ for 500 pC bunch charge. Though both bunch charges demonstrate comparably equal pulse energy they differ at the same time in pulse length and average laser power. The part of the bunch which contributes to the SASE process is three times longer for 500 pC bunch than that for 250 pC bunch (approximately 30 μm compared to 10 μm). On the other side the 500 pC bunch has smaller peak current and also significantly smaller maximum averaged power (12.5 GW compared to 31 GW for 250 pC bunch). Moreover it is to mention that the 250 pC bunch demonstrates not only high peak current but also a double horn longitudinal structure while 500 pC bunch retains a stable "flat top" pulse with moderate laser power over the entire length of 30 μm (see Fig. 2 and 3).

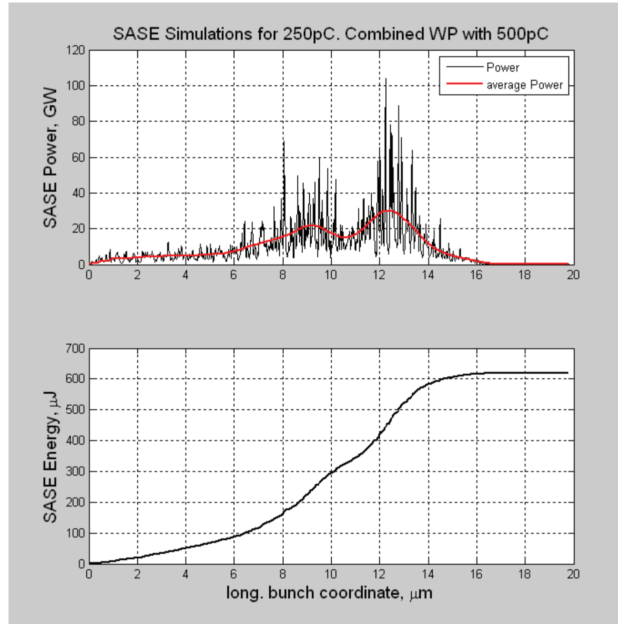

Figure 2: SASE Simulations for 250 pC Bunch.

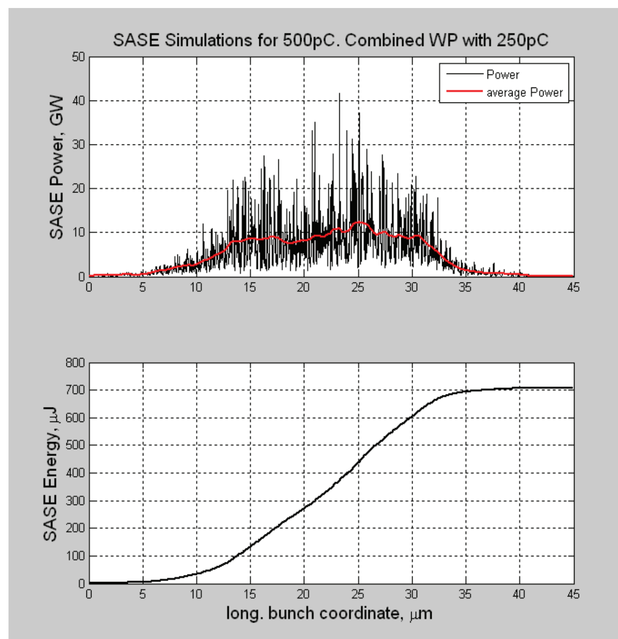

Figure 3: SASE Simulations for 500 pC Bunch.

SUMMARY AND DISCUSSION

Crucial point for the simultaneous operation of the European XFEL with two different bunch charges is the ability to achieve similar beam optical functions of both bunches after the first accelerating module. Simulations have shown that it is possible for nominal design of the XFEL injector on cost of the emittance growth of the bunch with smaller charge. In order to get suitable bunch parameters it is reasonable however to look for a compromise between emittance growth and mismatch of

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the beam optical functions between bunches. Combined working points have been derived by means of the simulations with ASTRA code as ones which minimize the penalty function proposed in this paper.

A complete S2E simulations consisting of the particle tracking from the cathode to the undulator section has been performed for 250/500 pC bunch pair. It was shown that it is possible to find combined working points for the operation of the solenoid, injector laser and RF settings of the accelerating modules which lead to suitable for lasing 6D particle distributions of both charges.

Subsequent SASE simulations with Genesis code revealed that both charges deliver laser pulses of similar energy but different longitudinal structure, length and average power.

A very tempting upgrade of the nominal design of the XFEL injector with respect to the simultaneous operation of two different bunch charges can be an installation of an additional laser system at the cathode. The benefit of it would be more flexibility by the choice of the combined working points since the rms laser beam size becomes adjustable for each bunch separately and only solenoid field remains the same for both bunches. Detailed analysis of this case can be found in [3]. Another promising improvement could be the ability to change the RF settings during the RF pulse which has been already successful tested at FLASH [4].

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