INJECTOR OPERATION WITH LOW CHARGE BUNCHES

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Abstract

The three stage bunch compression system proposed for the European XFEL will be able to achieve overall compression of about 100. This would lead to the reduction of the bunch length up to 2.5 10^{-5} m for the designed bunch charge of 1nC. It is anticipated that the final compression would be limited here mainly by rf tolerances (jitter) which are determined by technical specifications of the manufacturer. For a large variety of experiments it could be however desirable to go to shorter bunches even on cost of less radiation power. A good possibility to achieve this might be to operate the injector at lower than 1nC bunch charge. In this paper the possibility of the operation of the injector with low charge bunches was investigated. On this issue simulations with ASTRA code have been done in order to find suitable working points for the low charge regimes and to figure out the dependence of the bunch parameters on the initial bunch charge at the cathode. The results of these simulations are presented.

INTRODUCTION

The injector of the European XFEL foresees three stage bunch compression system. Linearization of the longitudinal phase space distribution will be achieved by means of the third harmonic system similar to one installed at FLASH during the shutdown 2009-2010. This way the bunch compression is no longer limited by the nonlinearities in the longitudinal phase space distribution but by the limits given by rf tolerances. It is expected that the overall bunch compression of about 100 will be possible. For the design bunch charge of 1nC this would lead to the bunch length of 2.5 10^{-5} m after the compression. Further bunch length reduction is only achievable if the injector will be operated with lower bunch charges. Possibility to operate the injector with low charges would extend the flexibility of the European XFEL also over the experiments which require short bunch length rather than higher SASE radiation level.

Simulations with ASTRA code have been done in order to find out the working points for the operation of the XFEL injector with bunch charges in the range of 20-500pC. The results of these simulations as well as sensitivity scans with respect to the solenoid peak field are discussed in this paper.

XFEL INJECTOR

The design of the XFEL injector is based on the injector which is currently used at FLASH [1]. The main improvements which are foreseen for the XFEL injector are:

- the laser system will deliver a 20ps flat top pulse with 2ps rise time instead of 4.4ps Gaussian profile laser pulse at FLASH injector.
- the 1.5cell cavity gun will be powered by 10MW klystron and will be able to produce peak electric field of max. 60MV/m

Similarly to the FLASH injector an accelerating module of 8 nine-sell cavities (booster) beginning 3.3m downstream the cathode and a system of two solenoids for the emittance compensation are foreseen for the XFEL injector.

OPTIMIZATION PROCEDURE

The optimization procedure which has been used for the simulations is based on the code written by M. Krasilnikov [2]. Originally it foresees two loops. In the main loop the parameters of the gun, both solenoids and laser are adjusted. Then for each choice of these parameters the second internal loop is carried out which looks for the best solution for the position, gradient and phase of the booster. The choice of the parameter to optimize is arbitrary. In this work the transverse emittance of the bunch at the end of the booster was optimized to its minimum for each working point.

This procedure has been applied to find the working point for the operation with the design bunch charge of 1nC first. This has established the best position for the components like the booster and main solenoid. For the simulations with lower bunch charges these parameters has been chose then as fixed. Also it has been assumed that the gun is operating at its maximum since this provides the best conditions for the prevention of the emittance blow up due to longitudinal space charge forces. These and other assumed fixed parameters in the simulations are shown in the table 1.

Table 1: Assumed fixed parameters in the simulations

Parameter	Value
Laser pulse length	20.00 ps
Laser shape	Flat top, rise time 2ps
Gun gradient	60.00 MeV/m
Gun Phase	-0.9
Booster position	3.300 m
Booster gradient	40.00 MeV/m
Booster Phase	0.0

WORKING POINTS FOR LOW CHARGES

The results for the calculated working points for the on-crest operation with the bunch charges between 20 and 500 pC are shown in the table 2.

Table 2: Working points for XFEL injector operation with low bunch charge

Bunch Charge, pC	Laser Spot Size rms, mm	Max. Solenoid Field, T
20	0.0725	0.2203
100	0.167	0.2211
250	0.230	0.2224
500	0.290	0.2227

The main bunch parameters which one expects if the injector is operated at these working points for bunch charges 20, 100, 250 and 500pC are summarized in the table 3. This can be compared with 2.0mm bunch length, 0.99mm mrad emittance and 46A peak current which are valid for the operation with the design bunch charge of 1nC. In general shorter bunches with tighter emittance are possible on cost of the peak current. However the dependence of the bunch length on the bunch charge is not linear. For instance the reduction of the bunch charge from 1nC to 500pC leads to smaller emittance though, but doesn't change the bunch length significantly.

Table 3: Expected bunch parameters at the end of the booster for the XFEL injector

Bunch Charge, pC	Normalised emittance, mm mrad	Slice emittance, mm mrad	Bunch length, mm rms	Peak current, A
20	0.1029	0.0858	1.494	1.203
100	0.2517	0.2129	1.580	5.727
250	0.3620	0.3256	1.715	13.360
500	0.5088	0.4797	1.941	23.774
1000	0.985	0.852	2.010	46.171

For the comparison the expected bunch parameters for the operation of the FLASH injector with low charges are shown in the table 4 [3]. One can see that the predicted emittance for the XFEL injector is almost two times smaller than that at the FLASH injector. Also one may expect slightly shorter bunches with higher peak current for the operation with the design bunch charge. However for extremely low charges (20-100pC) one gets the same bunch length and peak current in both injectors.

Table 4: Expected bunch parameters at the end of the booster for the FLASH injector

Bunch Charge, pC	Normalised emittance, mm mrad	Slice emittance, mm mrad	Bunch length, mm rms	Peak current, A
20	0.202	0.113	1.498	1.444
100	0.495	0.296	1.697	6.063
250	0.738	0.501	1.968	12.584
500	1.056	0.775	2.381	20.202
1000	1.832	1.355	2.5	41.7

MATCHING THE OPTICS AFTER THE BOOSTER

There are four quadrupoles foreseen for the matching of the optics at the XFEL injector. Two of them are placed between the booster and the third harmonic system and the other before the laser heater. It has been found that for the design charge of 1nC the matching is possible for the initial beta which is smaller than 100 and alfa is near zero [4]. The values of the twiss parameters after the booster which follow from the simulations are shown in the table 5. They satisfy the conditions for the matching and give apparently enough space for the tuning.

Table 5: Expected values of the twiss parameters at the end of the booster (entrance to the first matching quadrupole)

Bunch Charge, pC	beta	Alfa
20	44.25	-3.017
100	21.27	-1.834
250	27.58	-2.864
500	11.28	-0.855

SENSITIVITY WITH RESPECT TO THE SOLENOID CURRENT

Emittance compensation mechanism as it described for instance at [5] implements for each set of values for gun gradient and laser beam size an appropriate solenoid field in order to minimize the transverse beam emittance.

In the table 6 the results of the sensitivity scan of the beam emittance with respect to the solenoid peak field are shown. The accuracy of the solenoid current adjustment has been assumed to be 0.1A which corresponds to approximately 0.03% for the operation with 0.22T solenoid field. This assumption is based on the given accuracy of the solenoid which is currently used at the

FLASH injector. The sensitivity scan has shown that this accuracy should be good enough to control the emittance within 2% for all bunch charges from the range of 20-500pC.

Table 6: Sensitivity of the emittance with respect to the solenoid field strength

	20pC	100pC	250pC	500pC
0.1A	0.3%	0.7%	1.6%	0.7%
1%	17.7%	42.2%	59.9%	101.5%

ALTERNATIVE WORKING POINTS

Similar to [3] the simulations have shown that the emittance doesn't go up at the same rate for the solenoid field above or below this optimal value also for the XFEL injector. Moreover the working point which guarantees the smallest beam emittance doesn't assure that the beta function at the end of the booster will have its minimum for the same injector settings. This means that though the emittance at the calculated working points seems to be insensitive enough with respect to the main machine parameters like solenoid current or laser spot size, the twiss functions will have a high sensitivity there (table 7) so that the matching of the optics may become a tedious problem.

Table 7: Sensitivity of the beta function with respect to the solenoid field strength for the nominal working points

	20pC	100pC	250pC	500pC
–0.1A	+7.8%	+10.9%	+15.5%	+9.7%
+0.1A	-2.2%	-1.8%	-4.1%	+2.4%

A set of alternative working points has been calculated which guarantees low sensitivity of both emittance and twiss functions (table 8). The results of the bunch parameters if the XFEL injector is operated at the alternative working points are summarized ion the table 9. Compared to the nominal working points emittance growth could be kept within 10% for all bunch charges except of 500pC. For this case the emittance growth makes 33.5%. On the other side the sensitivity of the twiss functions could be reduced significantly which would allow stable operational conditions (tables 10 and 11).

Table 8: Alternative working points

	20pC	100pC	250pC	500pC
Laser spot size rms	0.0725	0.167	0.230	0.290
Max solenoid field	0.2215	0.2220	0.2230	0.2240

Table 9: Bunch parameters for alternative wp

	20pC	100pC	250pC	500pC
emittance	0.114	0.268	0.389	0.679
Emittance 90%	0.088	0.219	0.239	0.487
Emittance increase, %	10.3	6.5	7.5	33.5
Beta	30.1	16.0	11.7	17.4
alfa	-1.132	-0.628	-0.593	-0.113

Table 10: Emittance sensitivity for the alternative wp

	20pC	100pC	250pC	500pC
+0.1A	+1.3%	+2.3%	+3.4%	+3.6%
–0.1A	-0.9%	-0.4%	-0.5%	-1.8%

Table 11: Beta sensitivity for the alternative wp

	20pC	100pC	250pC	500pC
+0.1A	-1.4%	+1.9%	+2.4%	+3.6%
–0.1A	+0.2%	+2.3%	+0.5%	-2.5%

SUMMARY

The working points for the operation of the XFEL injector with low charges have been calculated. Scans over the working points with respect to the solenoid field have shown low sensitivity of the bunch emittance but higher sensitivity of the twiss functions after the injector. Alternative working points are proposed which would guarantee low sensitivity of both emittance and twiss functions.

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