AN UPGRADED INJECTOR FOR THE TTF FEL-USER FACILITY

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Abstract

The Tesla Test Facility (TTF) will soon be upgraded to an FEL-user facility capable of providing SASE-FEL radiation with a wavelength down to 6 nm. In the context of this upgrade, it was recognized that the present injector needed to be rebuilt. In this paper, after discussing the short comes of the present injector in use at TTF-1, we present the new design and its performance study for various scenarii of operation.

1 OVERVIEW

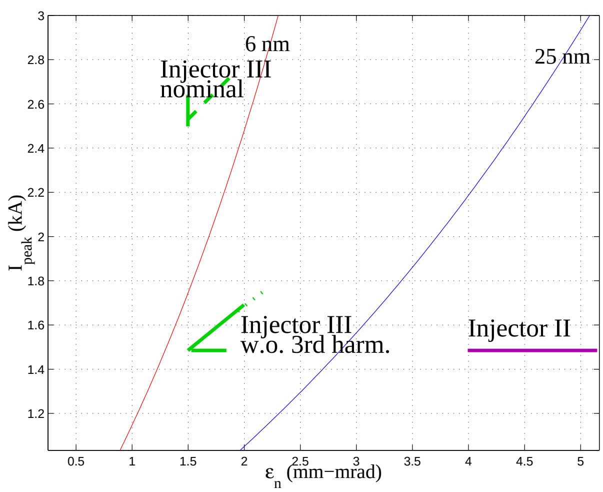

Figure 1: Required minimum peak current versus transverse emittance for 25 nm and 6 nm laser wavelength. The rms energy spread is assumed to be $\sigma_E = 1$ MeV.

The TESLA Test Facility (TTF) accelerator has driven a SASE FEL in the 100 nm regime. In the next years it will be upgraded to a user facility with the aim of providing a SASE FEL at wavelength around 6 nm. Though a first step toward this ultimate goal will be the ability of producing SASE at 25 nm in a year from now. In the context of this project, the required electron beam parameters (peak current, $\hat{I}$, normalized transverse emittance, ε, and momentum spread, σ_E) are intimately related to the undulator parameters. Especially the undulator length needs to be larger than the "saturation length" of the SASE process. In Figure 1, we present the required minimum peak current given the beam emittance and assuming σ_E=1 MeV that insures the SASE process to operate in the saturation regime [1]. At 6 nm, the required peak current to reach saturation given a realistic emittance of 2 mm-mrad at the undulator entrance, would be 2.5 kA. For the first light case (wavelength of 25 nm), the requirement on emittance and peak current are relaxed: for instance with 2 mm-mrad emittance, a peak current of 1.5 kA (similar to what as been achieved in TTF-1) would be sufficient. In the same figure, we also present the achievable parameters with the injector used during the operation at TTF-1 FEL (the so called Injector II [2]) and with the upgraded injector (Injector III) which is hereafter discussed. It is seen that the Injector II fails to meet the requirement for reaching saturation even for 25 nm.

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2 DESIGN CONSIDERATION

The injector design follows the same philosophy we adopted for the proposed TESLA XFEL injector [3]: the manipulation of the longitudinal and transverse phase spaces are decoupled. We start with an elongated photocathode drive-laser pulse (FWHM=20 ps) and manipulate the transverse phase space accordingly to the emittance compensation scheme. After acceleration through a standard TESLA module, the longitudinal phase space, which is distorted due to rf-induced curvature during the acceleration, is "linearized" using a third harmonic rf-section [4]. Though a few differences between the present and the TESLA-XFEL designs should be underscored:
Firstly the rf-gun cavity is operated to yield a peak field on the photocathode of 40 MV/m (comparable to the presently achieved 37 MV/m at TTF-1).
Secondly The design is geometrically "bounded" within the present building.

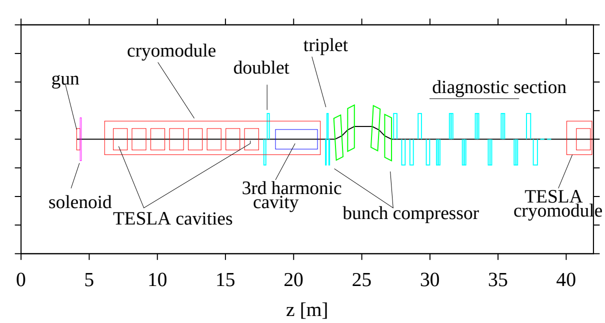

Figure 2: Overview of the TTF Injector III.

A floor plan of the proposed design is presented in Figure 2. Compared to the Injector II the main changes are: (1) removal of the so-called "capture cavity", (2) displacement of the first accelerator module, (3) installation of a 3.9 GHz rf-section to "linearize" the longitudinal phase space, (4) shortening of the bunch compressor, and (5) a diagnostic section.

3 NOMINAL OPERATING POINT

For the optimization, we assume the electric peak field on the photocathode is 40 MV/m. The laser is first supposed to be 20 ps long with a uniform distribution and a transverse radially uniform distribution. The initial photo-emitted distribution is generated taking into account the thermal effect due to kinetic energy of the electrons ($kT = 0.55$ eV). The resulting thermal emittance is approximately 0.6 mm-mrad for the nominal photocathode laser spot size ($\sigma_r = 0.75$ mm). This latter number is used for all the simulations presented hereafter. The optimized parameters are

parameter	value	units
bunch charge	1	nC
laser σ_r	0.75	mm
laser pule length (FWHM)	20	ps
solenoid $\hat{B}_z$	163	mT
φ_G	34	rf-deg
cathode E_o	40	MV/m
module ACC1 (cav 1 to 4) $\bar{G}_{rf}$	12.5	MV/m
module ACC1 (cav 5 to 8) $\bar{G}_{rf}$	20.0	MV/m
module ACC1 (cav 1 to 8) φ_{rf}	-10.80	rf-deg
module ACC39 $\bar{G}_{rf}$	14.00	rf-deg
module ACC39 φ_{rf}	183.0	rf-deg

Table 1: Optimized injector settings for the nominal operating point.

gathered in Table 1. The phase of the accelerating module and 3$^{\text{rd}}$ harmonic section were optimized, taking into account the subsequent bunch compression stages, to achieve the proper peak current with minimum longitudinal phase space distortion. The first four cavities are operated at a lower gradient to match the beam to the so-called invariant envelope [5]. At the end of the accelerating section (z=18.7 m from the photocathode), and prior to the first stage compression, the achieved beam parameter are gathered in Table 2. The beam parameters for a series of longitudinal slices are plotted in Figure 3 where the mismatch parameter is defined as:

$$\zeta = \frac{1}{2}\left(\gamma_o\beta_s - 2\alpha_o\alpha_s + \beta_o\gamma_s\right). \quad (1)$$

Here, the subscripts $_o$ and $_s$ indicates the Twiss parameters averaged over the whole bunch ensemble and over one longitudinal slice respectively. This mismatch parameter quantifies how mismatched is a given slice when one match the bunch (which is what one does experimentally). Slices with a mismatch parameter close to unity are matched when the whole bunch is matched.

A magnetic compressor located at $E \simeq 120$ MeV is used to shorten the bunch from 2.10 mm down to ~0.340 mm.

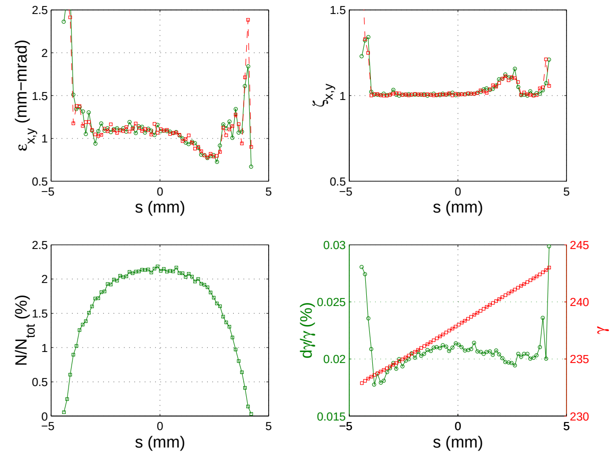

Figure 3: Beam parameter computed for a series of 60 longitudinal slices at $z = 18.70$ m.

The expected parameters downstream of the bunch compressor are gathered in Table 2.

parameter	value before compression	value after compression	units
projected ε_x	1.32	2.63	mm-mrad
projected ε_y	1.32	1.45	mm-mrad
centre-slice ε_x	1.11	1.39	mm-mrad
centre-slice ε_y	1.24	1.10	mm-mrad
σ_z	2.1	0.388	mm
$\sigma_{\delta p/p}$	1.029	0.981	%

Table 2: Beam parameters for the nominal operating point before and after the bunch compressor.

4 “FIRST LIGHT” OPERATING POINT

For the first lasing at 25 nm, the 3$^{\text{rd}}$ harmonic section will not be available; this will impact the longitudinal beam dynamics. In such a case the phase of the accelerating module is set to minimize the bunch length at the compressor exit (ϕ_{rf} is now -14° and the resulting energy increases to 136 MeV). The principal degrading effect comes from the accumulated rf-curvature as the bunch is accelerated in the first module which leads, downstream of the bunch compressor, to a local charge density concentration in the time profile of the bunch (see Figure 4). This local charge concentration enhances the bunch self-interaction via coherent synchrotron radiation (CSR) along with its associated emittance dilution (in fact the dilution essentially comes from the correlated emittance). It is also worth noting that since the compressor needs to be operated for maximum compression, the downstream compressor is not of any use.

5 ALTERNATIVE SETUP

In order to commission and use the two compressors, even in the absence of the 3rd harmonic section, we need to have a $\sim$0.8 mm (rms) long bunch in the accelerating module. This is to insure that the rf-distortion along with the nonlinearities resulting from the bunch compression process do not induce a fold-over of the longitudinal phase space such as shown in Figure 4.

A first possibility would be to shorten the photocathode drive-laser pulse length. However even if one would be able to use a 2 ps rms Gaussian laser, the bunch length at the injector front end would be of the order of 1.6 mm (due to thelongitudinal space charge force) and the transverse emittance would degrade up to $\sim$2.5 mm-mrad.

We have investigated a second way of reducing the bunch length via velocity bunching (see [6, 7]) in the first cavity of the accelerating module. The velocity bunching relies on the phase slippage that occurs between non ultra-relativistic electrons injected in an rf-accelerating field. In injector III, this scheme can be implemented by operating the first cavity of the accelerating module at zero-crossing and then tuning the gun solenoid field to control the evolution of the transverse emittance and envelope. As pictured in figure 5, the use of this technique looks very promising: the required bunch length of 0.8 mm could be achieved simultaneously with a transverse emittance smaller than 2 mm-mrad.

Though the velocity bunching is an attractive method it cannot be an alternative to the use of the 3rd harmonic section correction scheme due to the unavoidable longitudinal phase space distortions that always set a lower limit to the bunch compression (see Figure 5).

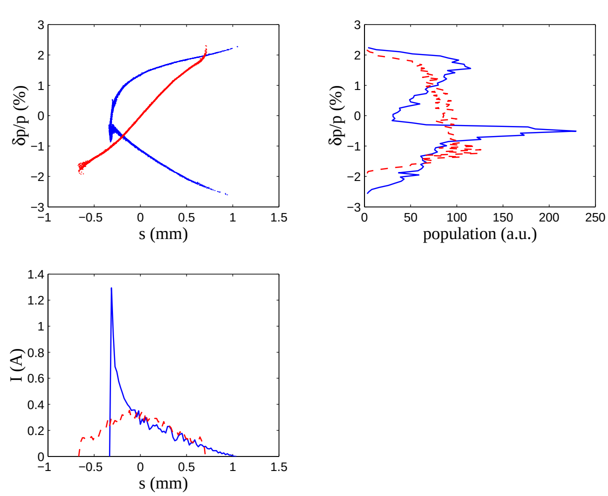

Figure 4: comparison between the longitudinal phase spaces obtained after the bunch compressor for the nominal setup (red/dashed) and "first lasing" setup (blue/solid).

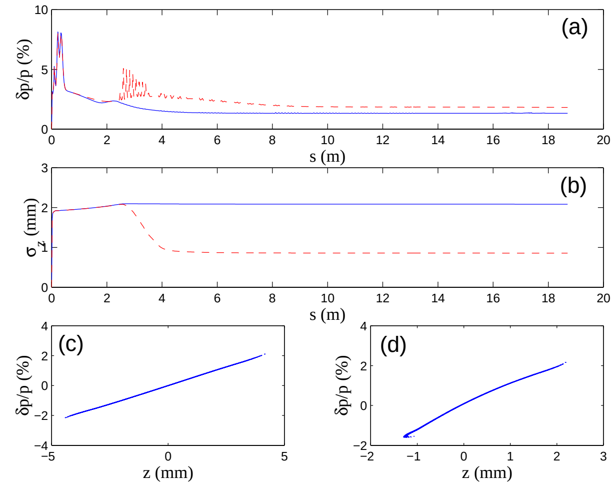

Figure 5: bunch length **(a)** and transverse emittance **(b)** evolution along the injector. The solid lines correspond to the nominal case while the dashed ones to the case when the first cavity is used as a "velocity buncher". The bottom plots **(c)** and **(d)** correspond to the longitudinal phase space for the nominal and velocity bunching cases. For the velocity bunching case, the solenoid magnetic field is 158 mT.

6 CONCLUSION

According to our numerical studies, the injector III of TTF-2 will provide the required phase space for operating the SASE FEL-user facility in the saturation regime at 6 nm. In the first phase of its upgrade, i.e. without the installation of the 3rd harmonic section, the injector should be flexible enough to support saturation of the SASE-FEL at long wavelength ($>$ 25 nm) and with tunable bunch length in the sub-picosecond regime. A detailed study of the performance of injector III is reported in Reference [8].

REFERENCES

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