DESIGN AND PERFORMANCE SIMULATION OF THE TTF-FEL II BUNCH COMPRESSION SYSTEM

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Abstract

We describe the bunch compression scheme for the TESLA Test Facility Free Electron Laser upgrade (TTF-2). The required peak current is 2.5 kA for operating the SASE-FEL within the saturation regime at a wavelength of 6 nm and with an electron beam energy of ∼1 GeV. The beam transverse slice emittance and the final energy spread should be held within the limit of 2.0 mm-mrad and ∼1 MeV respectively. We present a start-to-end simulation of the beam dynamics from the rf-gun up to the undulator entrance.

1 SINGLE PARTICLE LONGITUDINAL BEAM DYNAMICS

The TTF-2 accelerator driver for the foreseen free-electron laser (FEL) user facility is shown in fig.1. It incorporates a laser-driven rf-based injector capable of producing bunches with rms projected transverse emittances [1] of 1.3 mm-mrad [1]. The injector is then followed by a superconducting linac composed of 5 TESLA-type accelerating modules. Achieving such low transverse emittances at the injector front-end requires to start with a rather elongated (FWHM $\sim$ 20 ps) laser pulse on the photocathode. This results in an rms bunch length of 2.1 mm, a factor ∼40 larger than what is required at the undulator. The bunch is compressed using magnetic compression. In such a scheme, an accelerating section, located upstream of an arrangement of bends, is used to introduce a correlated energy chirp along the bunch. Given the incoming longitudinal coordinate of an electron within the bunch (s_o, δ_o) and the RF accelerating voltage V_{RF} and phase φ_{RF}, the induced relative momentum offset is:

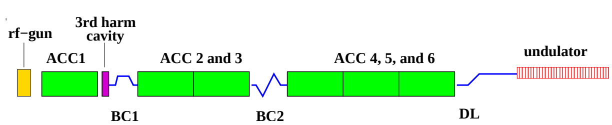

Figure 1: Overview of the TTF-2 accelerator.

$$\delta_i = \frac{\delta_o E_o + V_{RF}\left(\cos(ks+\varphi_{RF}) - \cos(\varphi_{RF})\right)}{E_o + V_{RF}\cos(\varphi_{RF})}. \quad (1)$$

Here E_o is the injection energy in the accelerating section and k is the RF-wavenumber.

The system of bends, typically arranged as a chicane, introduces an energy-dependent path length variation in such a way that the electron of coordinate (s_i, δ_i) is mapped to s_f following:

$$s_f = s_i + R_{56}\delta_i + \mathcal{O}(\delta_i^2). \quad (2)$$

Using this first order formalism and writing $\delta_i = \alpha_1 s_i + \mathcal{O}(\delta_i^2)$, we get the rms bunch length and energy spread:

$$\langle s_f^2\rangle^{1/2} = \sqrt{(1+\alpha_1 R_{56})^2\langle s_i^2\rangle + R_{56}^2\langle\delta_o^2\rangle} \text{ and,}$$
$$\langle \delta_f^2\rangle^{1/2} = \langle\delta_i^2\rangle = \sqrt{\alpha_1^2\langle s_o^2\rangle + \langle\delta_o^2\rangle}. \quad (3)$$

However, there are regimes where the approximation $\delta_i \sim \alpha_1 s_i$ is not valid, for instance when the bunch length upstream of the accelerating section does not satisfy $\langle s_i^2\rangle^{1/2} \ll 1/k$. In such a case the longitudinal phase space accumulates some curvature due to the cosine-like dependence of the RF field and one has to write $\delta_i = \alpha_1 s_i + \alpha_2 s_i^2 + \mathcal{O}(s_i^3)$, and take into account the quadratic energy-dependence of the path length in the chicane by introducing $T_{566} = 1/2\partial^2\delta/\partial s^2$. An electron of initial coordinate (s_i,δ_i) is now mapped according to:

$$s_f = s_i(1+\alpha_1 R_{56}) + s_i^2(R_{56}\alpha_2 + T_{566}\alpha_1^2) + \mathcal{O}(s_i^2). \quad (4)$$

In the latter equation one sees that the minimum bunch length is limited by the second order effect in s_i. This limitation points out that the bunch should be compressed at low energy ideally before it accumulated too much RF-curvature. On the other hand compressing the bunch at too low energy might render the beam degradation due to space charge forces significant (since space charge forces scale as $1/\gamma^2$).

To negotiate both effects while compressing the bunch to the proper bunch length for achieving the 2.5 kA peak current, TTF-2 incorporates a two stage magnetic compression scheme (labeled BC1 and BC2 in see fig. 1) and a higher harmonic ($f = 3.9$ GHz) RF-accelerating section to compensate for the RF-induced curvature during acceleration in the ACC1 linac.

In TTF-2, the 3.9 GHz accelerating section rf amplitude and phase is tuned to cancel the nonlinear quantities in Eqn. (4) after the first compressor BC1 (see Table 1 for parameters) which is located at approximately 120 MeV, in the injector area. BC1 reduces the bunch length from 2.1 to ~ 0.4 mm. The chicane is similar to the 4-bend chicane designed for TTF-1 [2] except for a slightly reduced bending angle ($15^\circ < \theta < 21^\circ$). Such a chicane has the feature to be be achromatic to all order in $\delta p/p$.

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[1] the emittance includes a thermal emittance of 0.6 mm-mrad

The second stage compression occurs downstream of the linac ACC3 at an energy of 438 MeV. The chosen chicane (BC2) is an S-type chicane [3] optimized to have a minimum emittance dilution due to coherent synchrotron radiation (see next section). Its bending angle can be varied ($1.5^\circ < \theta < 5.4^\circ$). Because of the very low momentum compaction of BC2, the linac section ACC2/ACC3 is operated at about -20° off-crest to provide the necessary correlated energy spread. However the system provides some tunability and other combination of ACC2/ACC3 phase with BC2 angle are possible.

compressors:			
parameters	BC1	BC2	
type	standard	S-chic	
Angles (°)	17.5	3.8	
R_{56} (mm)	-170	-49	
T_{566} (mm)	276	75	
E (GeV)	0.13	0.44	
final $\hat{I}$ (A)	320	2500	
Linacs:			
parameters	ACC1	ACC2-3	ACC4-5-6
aver. grad. (Mv/m)	12.5/20	20	20
RF phase (°)	-10.80	-20.0	0.0
input E (GeV)	0.005	0.12	0.44
final E (GeV)	119	438	923
final $\delta p/p$ (%)	0.93	0.55	0.18
σ_z (μm)	2100	338	68

Table 1: Bunch compressor and linac parameters for the nominal operating point.

2 MULTI-PARTICLE DYNAMICS

The simple model described in the previous section does not incorporate details such as the beam degradation that might occur via collective effect. The longitudinal phase space may be affected by essentially three effects: the bunch self interaction via wake-fields longitudinal space charge force and coherent synchrotron radiation.

The main sources of wake-fields in the TTF-2 accelerator are of geometric and resistive nature (we presently ignore the surface roughness wakes since its main impact is in the undulator vacuum chamber.). The origin of the first source of wake-field are discontinuities in the vacuum pipe whereas the resistive wake-fields come from the finite resistivity of the pipe. Assuming a transversely well-centered beam, the major impact of wake-fields on the bunch comes from the longitudinal monopole mode and its induced correlated energy spread dilution. In the TTF-2 accelerator, the vacuum chamber, starting downstream of the second bunch compressor, will be copper-coated. Thus in the simulations presented hereafter only the the wake-field generated by the TESLA cavity geometry were taken into account by using the parameterized Green delta-function derived in [4].

A major effect that can significantly degrade longitudinal and transverse phase spaces, is the bunch self-interaction via coherent synchrotron radiation (CSR). The radiated field at a retarded time can overtake the bunch and interact with electrons ahead in the bunch at a later time. This type of bunch self-interaction is relevant when the path length in the bend is comparable to the so-called "overtaking" length defined as $(24\sigma_z\rho^2)^{1/3}$, where σ_z is the rms bunch length and ρ the bending radius. Because TTF-2 incorporates two chicane-based bunch compressors; the beam degradation caused by such a "CSR effect" was carefully examined. The radiated CSR power depends on the bunch length and scales like $1/\sigma_z^{4/3}$. Therefore, especially for short bunches, CSR fields radiated on curved trajectories induce energy offsets in a necessary dispersive section; thus causing emittance growth. The optics in the bunch compressor region has to be optimized to reduce the emittance growth.

The sensitivity of the correlated transverse emittance to energy offsets is described by the function $\mathcal{H}$, defined as: [5]

$$\mathcal{H}(z) = \gamma(z)\eta^2(z) + \beta(z)\eta'^2(z) - 2\alpha(z)\eta(z)\eta'(z). \quad (5)$$

$\mathcal{H}$ depends on the magnetic lattice and becomes important in the third and the fourth bend of the magnetic bunch compressor. At these locations, where the bunch length is minimal, the CSR-driven energy offset is maximum. Eqn (5) provide guidance on how to minimize emittance growth; for instance it can be simplified by assuming a waist close to the third and fourth bending dipole, so that $\alpha \simeq 0$ and then an optimum β can be derived.

However the figure of merit for the lasing process is the slice emittance computed over a given length (typically the SASE process "cooperation" length). The slice emittance growth is generally due to the nonlinearities of the CSR fields and numerical simulations performed with the code TraFiC^4 [8] have proven, that a waist between the third and fourth dipole minimizes also the slice emittance growth.

Finally the projected emittance is also of importance because this is what is practically measured and used to match the beam and to set up the accelerator optics. Thus one should also try to match the correlated CSR-induced phase space with the slice ellipse. The beta functions, optimized with TraFiC^4 for the BC2 bunch compressor are plotted in figure 2.

3 START-TO-END SIMULATION

The set of code ASTRA [6], TraFiC^4 and ELEGANT [7] were used to simulate the beam dynamics from the photocathode gun up to undulator entrance. ASTRA, a macroparticle-based code that incorporates a space charge algorithm for a cylindrical-symmetric beam was used for the injector region (i.e. up to 119 MeV). The simulations of the bunch compressor sections were performed

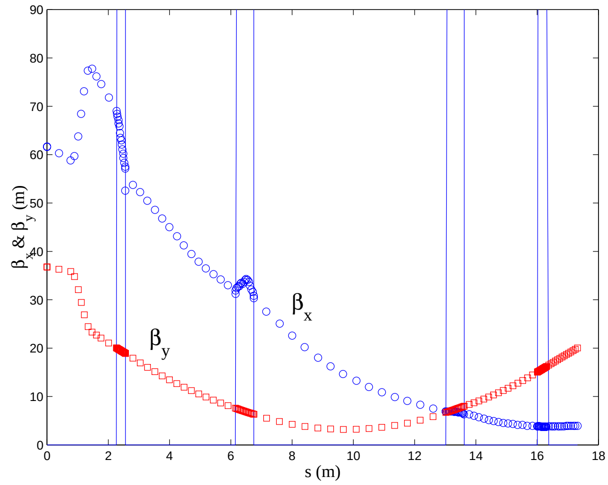

Figure 2: Betatron function evolution in the S-chicane.

with TraFiC[4], a program that properly treats all bunch self-interactions via radiative effects. In the remaining sections of the accelerator, the phase space distribution was tracked with the single particle dynamics code ELEGANT. In this latter program the geometric wake-field effects (monopole mode only) due to the TESLA cavities were taken into account.

ASTRA and ELEGANT use point-like macroparticles whereas in TraFiC[4] the phase space is distributed among weighted 3D-Gaussian macroparticles. Software have been written to properly pass the phase space between the three programs.

In the following we present the results obtained so far for the nominal operating point of the TTF-2 FEL. The longitudinal phase space upstream and downstream of the two compressors are presented in figure 3. Downstream

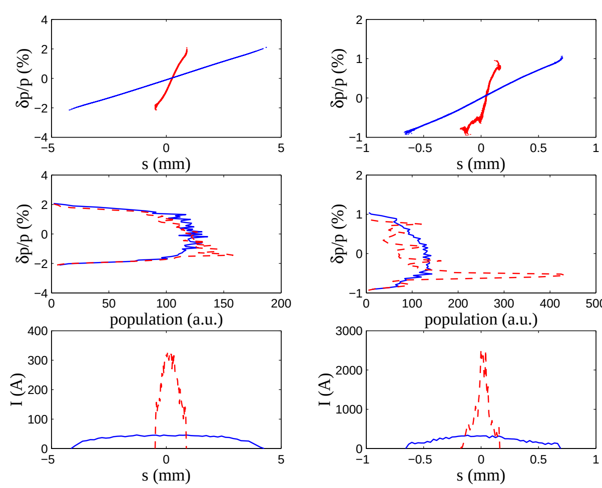

Figure 3: Longitudinal phase space before (blue) and after (red) compression through BC1 (left) and BC2 (right).

of BC2, the emittance over a $5\ \mu m$ centered slice is about 1.3 mm-mrad while the projected emittance is 3.64 mm-mrad. The beam slice parameters at the undulator entrance are shown in figure 4. The beam energy for this setup is 922.82 MeV. The slices emittances within the lasing area are below 1.5 mm-mrad, the peak current reaches the required 2.5 kA, and the full energy spread is approximately 4 MeV. In such a distribution, it is estimated that slices with peak current down to 1 kA will saturate [9]. That corresponds to 58% of the bunch charge.

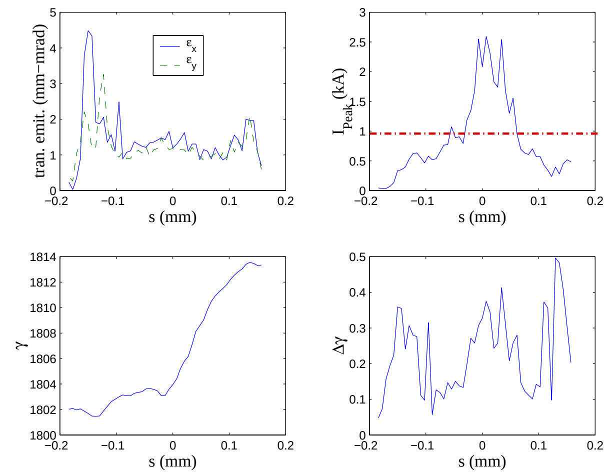

Figure 4: Peak current, transverse emittances, energy spread and mean energy of longitudinal slices along the bunch at the undulator entrance. $s > 0$ corresponds to the bunch tail.

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