LONGITUDINAL PHASE SPACE DISRUPTION IN MAGNETIC BUNCH COMPRESSORS

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Abstract

It is now well-established [2, 3] that high-charge ultra-short bunches can radiate coherently on curved trajectories (coherent synchrotron radiation). The two main consequences of such an effect are (1) an energy redistribution within the bunch, (2) a potential transverse emittance dilution in the bending plane. This effect is especially important in the foreseen next generation of free-electron laser driver linacs and linear colliders. In this paper after briefly discussing the general aspects of coherent synchrotron radiation (CSR), we report on recent experimental results obtained at the Tesla Test Facility I and compare them with numerical simulations. Schemes for reducing the impact of CSR on the beam dynamics are also discussed in the frame of the TESLA X-ray FEL project.

1 INTRODUCTION

When electrons travel on curved trajectory, e.g. in bending magnets, they emit synchrotron radiation. Radiation emitted at a retarded time can overtake the bunch on a straight line and interact with electrons ahead in the bunch. 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 $(24\sigma_s\rho^2)^{1/3}$, where σ_s is the rms bunch length and ρ the bending radius. This is the regime of coherent synchrotron radiation (CSR) – the power radiated [1] is $\propto N^2$ (N being the number of electrons in the bunch). This effect is favored in magnetic bunch compressors employed in FEL's and linear colliders, where short (ps-level) and highly charged ($Q \simeq 1$ nC) bunches travel through magnets with small bending radii ($\rho \sim 1$ m). The CSR longitudinal wake function scales as [2]

$$\widehat{W}_{||} = \frac{Q}{\epsilon_0 (2\pi)^{3/2} 3^{1/3} \sigma_s^{4/3} \rho^{2/3}}, \quad (1)$$

ϵ_0 being the electric permittivity for vacuum. Eqn (1) assumes the bunch has a Gaussian charge density. For the bending radius of the bunch compressor dipoles used at the Tesla Test Facility (TTF I), $\rho = 1.6$ m, we have $\widehat{W}_{||} \simeq 3.64 \times \sigma_s^{-4/3}$ [eV/nC/m].

2 RECENT EXPERIMENT AT TTF I

The TTF I [4] driver-accelerator (see Fig. 1) consists of a superconducting RF-linac capable of accelerating electron bunches up to 300 MeV. A 17 MeV photoinjector produces bunches of σ_s $\simeq$2.7 mm that are compressed down to σ_s $\simeq$750 μm by the mean of a magnetic bunch compressor installed downstream of the first accelerating TESLA-module (module 1), at an energy of approximately 135 MeV. The beam is then accelerated in a second TESLA-module (module 2). Further downstream, in a spectrometer transport line, a beam profile monitor (OTR) provides a beam energy measurement. The rate of compression is tuned by adjusting the RF-phase of module 1, thus adjusting the amount of correlated energy spread. Module 2 is always operated for maximum energy gain. The magnetic compressor consists of a four-dipole achromatic chicane, the deflection angle of the dipoles being ± 18 deg yielding a momentum compaction $R_{56} = (\partial s)/(\partial \delta) = -18.04$ cm. Preliminary experiment on bunch compression were performed [5] and it was reproducibly observed that the energy profile fragments in the vicinity of maximum compression. A typical energy profile measurement for maximum compression is presented in Fig. 2 (top): the energy distribution splits into principally two main peaks, the characteristic energy separation being $\simeq$3 MeV. To understand such phenomenon we considered several effects: geometric wake in TESLA-cavity, possible charge modulation due to imperfection in the photocathode drive laser, bunch self-interaction via CSR effect within the compressor. Only the latter of these considerations produces effects that are comparable to those observed (see Fig. 2 (bottom)) while both former effects could not yield any fragmentation of the energy profile. The CSR-induced effects were calculated using the tracking program `TraFiC`^{4} [6] which incorporates bunch self-interaction due to retardation effects. The simulations include both the compressor and the spectrometer dipoles [7]. The latter, which has a bending angle comparable to the compressor dipoles can locally over-compress the beam so that CSR-induced effects are not negligible as shown in Fig. 2 (bottom).

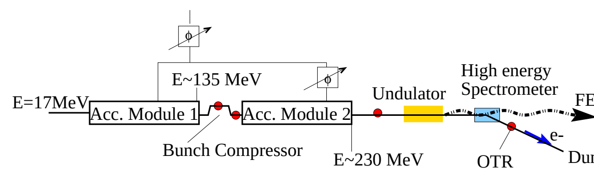

Figure 1: Overview of the TTF I experiment (the red solid circle represents locations of beam profile monitors).

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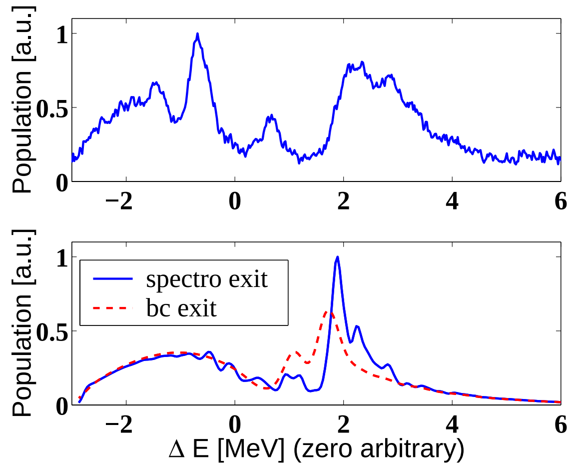

Figure 2: Example of measured (**top**) and simulated (**bottom**) energy profiles. The simulations correspond to the energy profiles downstream of the compressor (dashed lines) and at the measurement location (solid lines). The measurements are presented in Ref. [5].

3 LESSONS FROM TTF I AND IMPLICATIONS ON TESLA X-FEL

It was pointed out [8] that local charge concentration within the bunch can significantly enhance the CSR-wake function. In our case such a charge concentration originates from the nonlinear distortion of the longitudinal phase space at the compressor entrance: the bunch, being rather long at the entrance of module 1, accumulates some RF-curvature during its acceleration in module 1. The compression of such distorted longitudinal phase space (see Fig. 3), produces a local peak of $25\ \mu$m (rms) containing approximately half of the bunch charge (i.e. 0.5 nC). Simple estimates of the CSR-wake amplitude using Eqn (1) gives 2.5 MeV/m, a number close to (supposing a self-interaction length of 1 m) the measurement value. The longitudinal phase space and charge density downstream of the compressor obtained with `TraFiC`[4] are presented in Fig. 4 with and without CSR. It is worthwhile to note that the CSR effect, in this example, enhances the peak current. This leads to an increase in the energy disruption in the spectrometer magnet (see Fig. 2 (bottom)). CSR-induced gradient would lengthen the bunch if it passes through a simple four-dipole chicane as in TTF I ($R_{56} < 0$). However, if the energy gradient is generated inside the chicane, and a single spectrometer magnet follows downstream, the effective R_{56} now results from the dipoles and quadrupoles magnets between the point where the energy correlation was induced and the point of observation. For instance, the effective R_{56} between the third dipole of the chicane in TTF 1, where the CSR-effect is expected to be the strongest, and the end of the spectrometer is $\simeq +0.40$ cm. This has the proper sign and magnitude to even over-compress the bunch locally, i.e. in region of the phase space where the CSR-induced gradient is significant. In the case of TTF I, the incoming pulse is essentially given by the photocathode drive-laser (a Gaussian pulse of 8 ps), and is not easy to reduce.

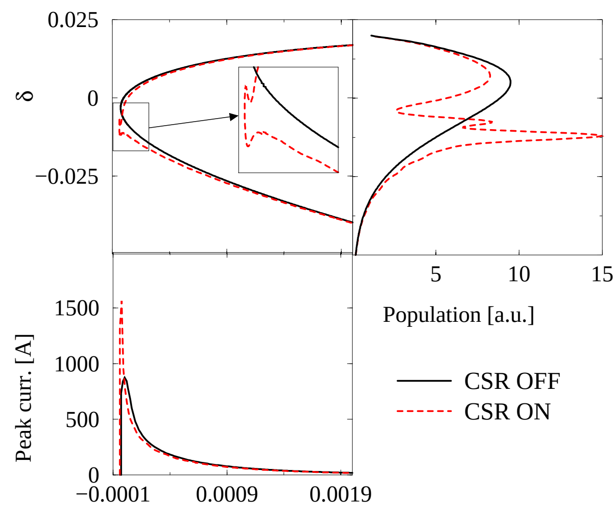

Figure 3: Impact of CSR effect on the longitudinal phase space downstream of the bunch compressor. The simulation corresponds to the TTF I compressor of Fig. 2.

We have studied how to reduce the impact of CSR-driven effects in for the TESLA X-ray FEL [10] injector [11]. In the driver-accelerator, the bunch is compressed in three stages to reach a final peak current, at the undulator entrance, of 5 kA. The injector is required to deliver bunch with peak current of approximately 400-500 A. Optimization of the photoinjector parameters yields a minimum tolerable bunch length at the gun exit of $\simeq$ 1.7 mm (to minimize the transverse emittance). Thus the first stage compression has to reduce the bunch from 1.7 mm down to approximately 0.250 mm – the adopted compressor consists of a chicane similar to TTF I with a lower momentum compaction of $R_{56} = -10.0$ cm. We have investigated the impact of two types of incoming distributions: Gaussian and Uniform (both with the same rms value of 1.7 mm). In Fig. 4, we present the charge density and longitudinal phase space for these two cases. For both cases, the upstream linac is operated so that the shortest bunch length is obtained. The Gaussian density yields a higher charge concentration that the Uniform one, which results in stronger CSR-effects in particular on the energy profile. This dependence on the incoming profile suggests that tailoring an incoming longitudinal distribution might be a way of reducing the CSR impact. Practically this is not an easy task: the longitudinal density is generally chosen to be as close as possible to a uniform distribution in order to reduce nonlinear space charge forces at low energy.

Another mechanism for reducing the impact of CSR wake field is to correct for the longitudinal phase space nonlinear distortions. The principal advantages of this scheme are that (1) the bunch shape does not change and

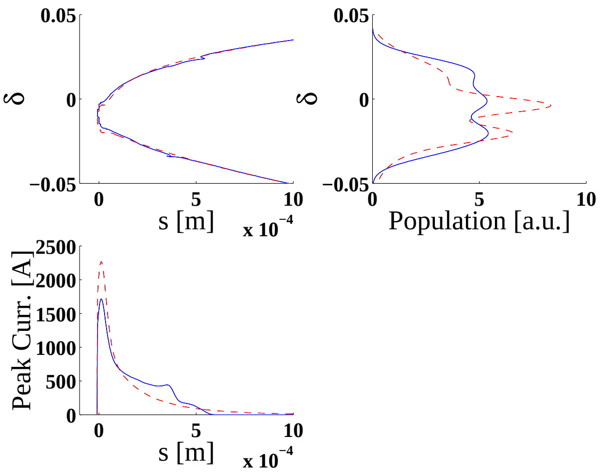

Figure 4: Comparison of magnetic compression impact on the beam for a Uniform (solid) and Gaussian (dashed) incoming charge density.

the generation of highly charged peaks is avoided, and (2) maximum compression is not required anymore to achieve bunch length of $\simeq 250\ \mu$m. Such technique is indeed foreseen for the TESLA X-ray FEL. The photoinjector is foreseen to incorporate a 3.9 GHz RF accelerating section [12] whose purpose is to "linearize" the longitudinal phase space. This 3.9 GHz section has to be operated in a decelerating mode. As a consequence the beam looses about 10% of its energy during this correction mechanism. In Fig. 5 we compare the phase space upstream and downstream of the compressor. In this example the incoming longitudinal phase space is obtained from multi-particle simulations of the photoinjector and includes the correction using TESLA cavities scaled to 3.9 GHz. It can be seen that the compression process does not significantly impact the shape of the beam profiles.

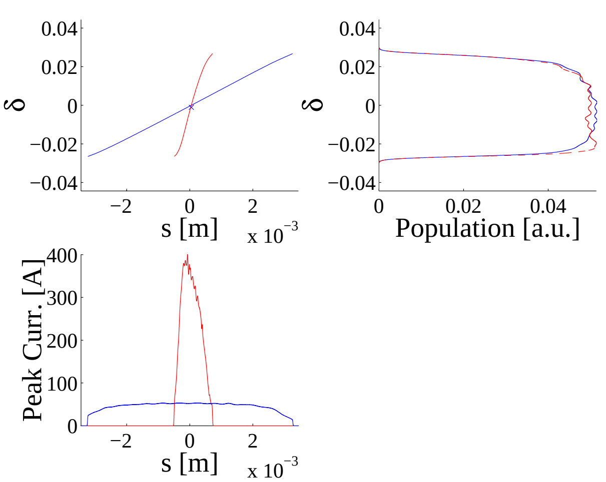

Figure 5: Phase space before (solid) and after (dash) the 1^{st} stage compression stage in the TESLA X-ray FEL.

Finally, avoiding the CSR-field to propagate is also a way of reducing the impact of CSR on the beam dynamics. Because the vacuum chamber acts as an electromagnetic waveguide, only frequency components of the radiation spectrum beyond the cut off frequency, $\omega \sim \pi c/\rho \times (2\rho/h)^{3/2}$ (h being the vacuum chamber height), can propagate. Simulations were performed with `TraFiC`[4], using metallic plates separated by $h = 8$ mm. In Fig. 6 we present the impact of shielding on the longitudinal emittance development along the chicane compared to the free-space case.

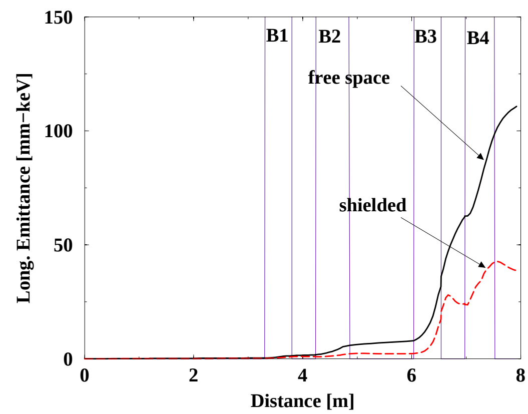

Figure 6: Effect of shielding with 8 mm parallel plates vacuum chamber on the longitudinal emittance growth along the compressor beamline. The labels B1,...,B4 correspond to the location of the chicane dipoles.

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