A proposal to study the impact of magnetic bunch compression on the beam dynamics using FNPL facility

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Abstract

We propose to perform some studies concerning the impact on the beam dynamics of low energy bunch compression. The FNPL facility incorporates a magnetic chicane that can be used to compress ~ 15 MeV bunches. Our principal motivations are:

- to perform a detailed parametric study of the impact of such a type of compression on various beam parameters (of interest are especially the transverse emittances and the energy spread),
- to gain practical experience on how low energy compression affects the beam, and use this experience at the Tesla Test Facility (TTF), which incorporates a replica of FNPL bunch compressor, to perform a multistage bunch compression experiment (TTF has two bunch compressors).

These investigations will provide experimental data for benchmarking existing numerical algorithms to simulate the dynamics of short bunch in magnetic compressors (e.g. TraFiC^4).

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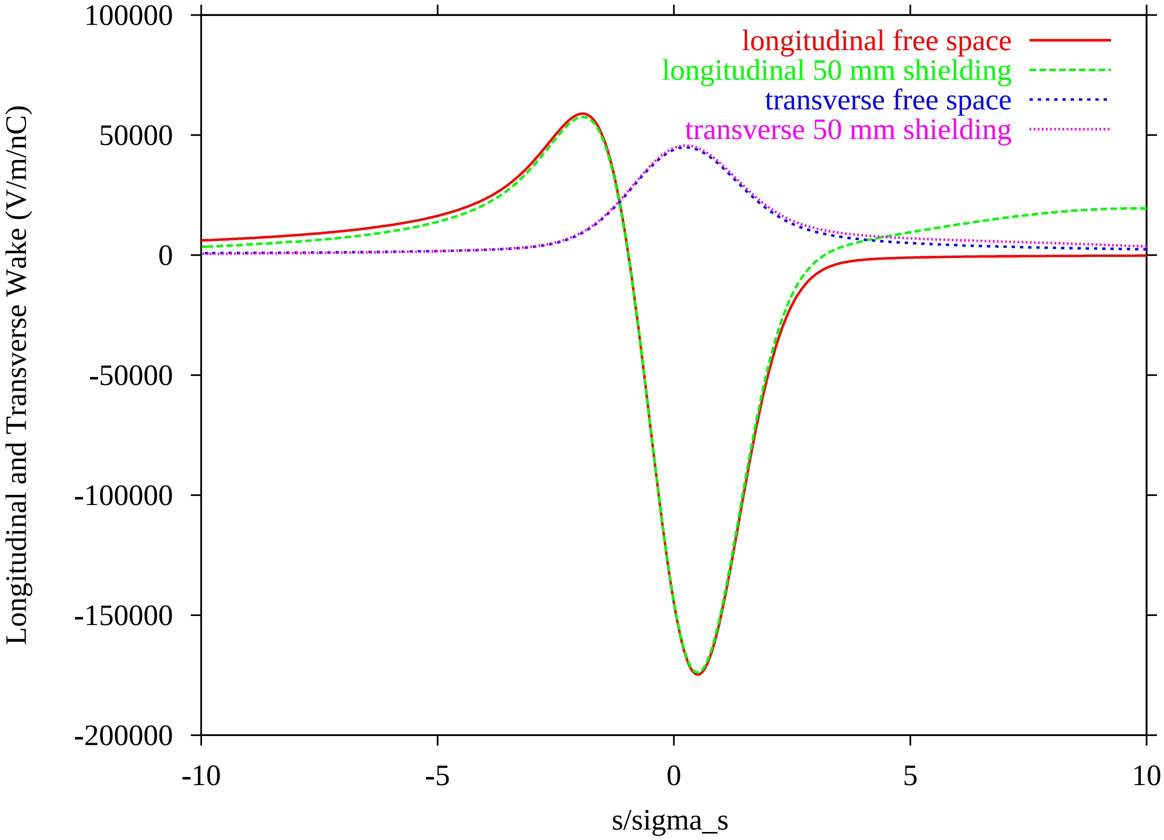

Figure 1: Steady state CSR wake potential generated by a Gaussian line charge distribution. The parameters are: $\rho = 0.75$ m, $\sigma_s = 500$ μm. ($s > 0$ corresponds to the bunch tail)

1 Introduction

At the low energy ($\simeq$ 15 MeV) of the FNPL photoinjector, two effects might impede the generation of bright beams: (1) space charge forces and (2) radiative effects due to curved trajectories in the magnetic bunch compressor.

Space charge-induced emittance growth is of two types: (1) a "correlated" emittance growth that is induced by the longitudinal dependency of linear space charge forces, and (2) an "uncorrelated" emittance growth due to nonlinear space charge forces in the generation stage of the beam (i.e. close to the photocathode). Bunch self-interaction via radiative i.e. coherent synchrotron radiation (CSR) effects may induce an emittance growth when the bunch travels on a curved trajectory (e.g. in bends such as the one employed, in a chicane arrangement, to compress the bunch). Given the rms bunch length σ_s, the bending radius ρ, one can define an overtaking length $L = (24\rho^2\sigma_s)^{1/3}$, the length a bunch needs to travel on its curved trajectory to allow particles to interact via the radiative field with others particle 1-σ_s ahead[1]. The self-interaction occurs essentially via field frequency components that are below $\sim 2\pi c/\sigma_s$, because of the frequency-dependence of the angular field distribution of the synchrotron radiation: this is the regime of coherent synchrotron radiation (a regime where the total radiated power is proportional to the squared number of electron in the bunch). This type of interaction can be reduced by avoiding the electro-magnetic field to propagate in the vacuum chamber (which acts as an electro-magnetic waveguide): only frequency components of the field that are beyond the cutoff frequency, $\omega_{cutoff} = 2\pi(c/\rho)\sqrt{h/\rho}$ propagates (the vacuum chamber is assumed to consist of two infinite parallel plates separated by the distance h).

If we consider the case of the FNPL bunch compressor [2] parameters (each bend has a magnetic length $L_{magn} = 0.60$ m, the bending radius is approximately 0.75 m, and typical bunch length measured are $\sigma_s \sim 2$ ps), the overtaking length is $L_{over} \simeq 0.2$ m, a value comparable to L_{magn}. On the other hand, taking the vacuum chamber height to be $h = 5$ cm, one finds that the ratio $(2\pi c/\sigma_s)/\omega_{cutoff} \gg 1$, implying that the vacuum chamber does not contribute in reducing the strength of the self-interaction: we are in the "free-space" case. Using the above parameters we present in Figure 1 the steady state CSR wake-potential for various cases.

In the past year there have been many groups that investigated low energy compression at energy around 10 MeV [3, 5, 6, 4]. But these experiments essentially concentrated on energy losses and induced energy spread. Only Ref.[4] reports emittance measurements and compares them with simulations. However, to date, no thorough experiment that explores the sensitivity on the incoming beam parameters have been performed in our energy/charge regime (a detailed study of CSR impact was performed at the CLIC Test Facility (CERN) for charge ranging from 1 to 4 nC at beam energy of $\sim$ 40 MeV [7]).

2 Compression of Round Beams

Under nominal operation, the FNPL injector produces round beams (i.e. $\varepsilon_x = \varepsilon_y$). An example of emittance evolution for Q=1 nC is presented in Fig. 2. This simulation assumes the photocathode drive laser parameter to be: a longitudinally uniform distribution of full width 10 ps, and a uniform radial distribution of 1.5 mm radius. Because the booster cavity, a 9-cell TESLA-type super-conducting rf-cavity, accelerates the beam up to 15 MeV only, the beam transverse phase space is not frozen and the transverse emittance, downstream of the booster cavity, does not remain constant. In the compressor region ($4.3 < z < 5.7$ m) the beam was tracked both with Astra[8] and TraFiC^4 code[9] to insure the distribution in TraFiC^4 were properly passed and able to reproduce the emittance evolution when the compressor is turned off. Since the emittance growth is expected to be dependent on the bunch length, it should be a function, when the compressor is operated, of the incoming time-energy correlation which can be varied using the phase of the booster cavity. Such a dependence is simulated in Fig. 3, both transverse emittances growth are maximum for the minimum bunch length. The transverse emittance in the plane orthogonal to the bending plane essentially results from the "standard" space-charge force. For the case of maximum compression, the expected emittance growth are gathered in Table 1. Thus if one would measure the emittance with and without operating the bunch compressor, one would expect an emittance increase of 200% (in the bending plane) and 50% for the transverse emittance.

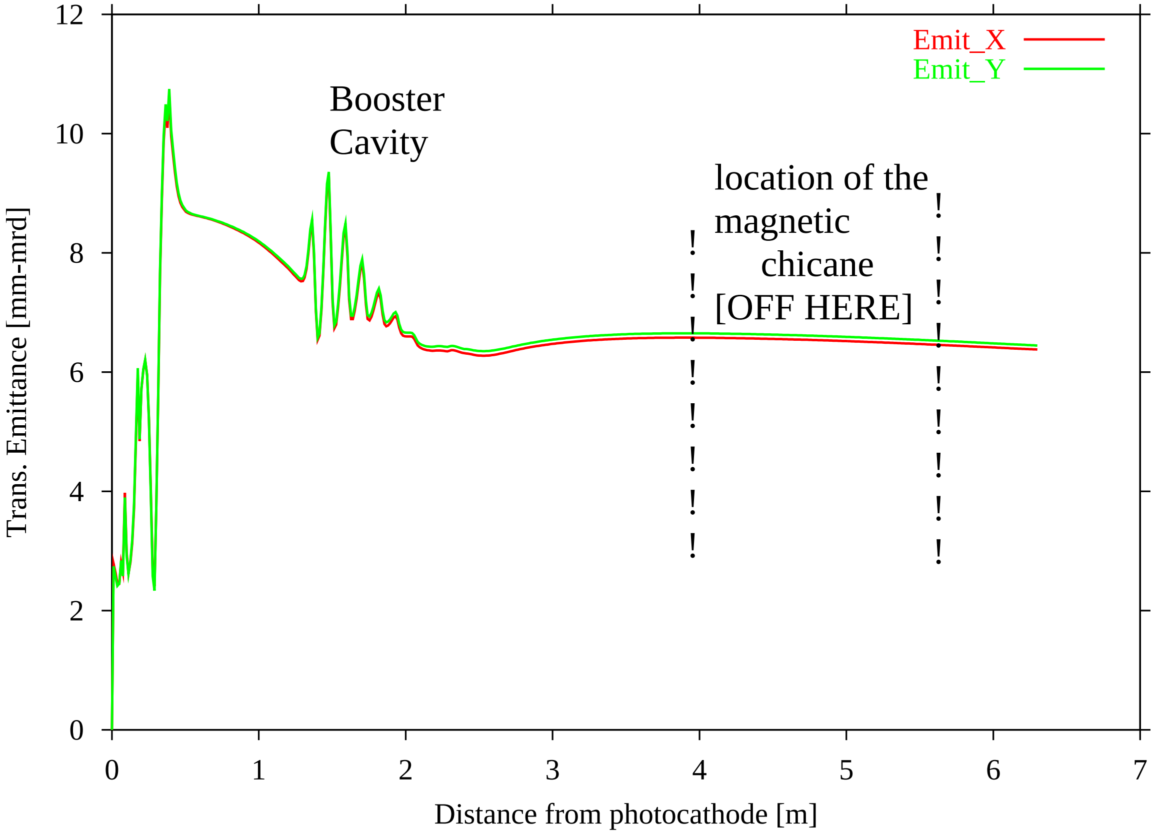

Figure 2: An example of emittance evolution along the FNPL photoinjector beamline ($Q =$ 1 nC).

	before compressor	after compressor
comp. ON	6.57 / 6.63	17.53 / 9.16
comp. OFF	6.57 / 6.63	6.34/6.40

Table 1: Expected transverse normalized emittance growth (mm-mrd).

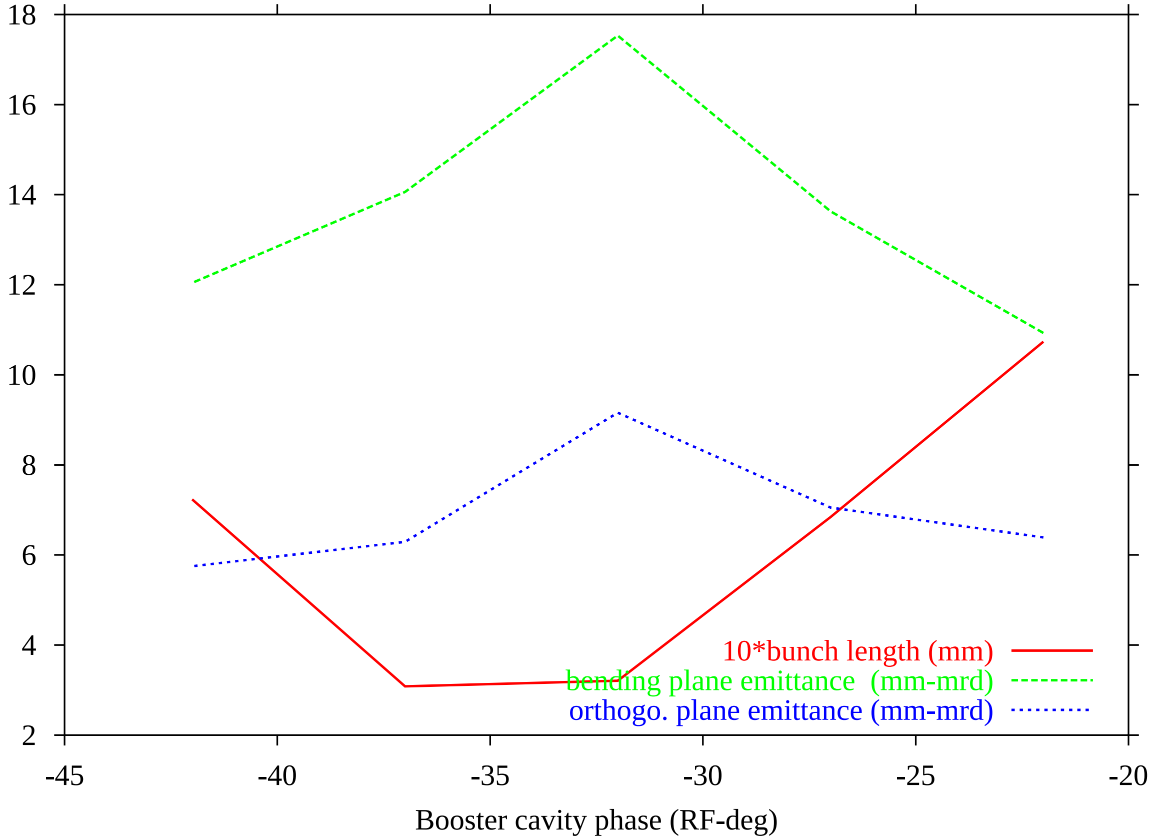

Figure 3: Emittance and bunch length versus the phase of the booster cavity.

In the longitudinal phase space, the impact of the compressor is expected to be significant. Figure 4 compares the longitudinal phase space downstream of the chicane with and without simulating the bunch self-interaction (which includes CSR and space charge): the principal impact is produced on the energy profile.

3 Compression of Flat Beams

With the use of appropriate linear transformations, developed in context of electron cooling [10], a flat beam (e.g. $\varepsilon_x \ll \varepsilon_y$) can be generated starting from a magnetized beam [11, 12]. Though the beam provides high transverse emittance ratios, the next question is how are the emittances affected during a compression performed at low energy, and whether one could

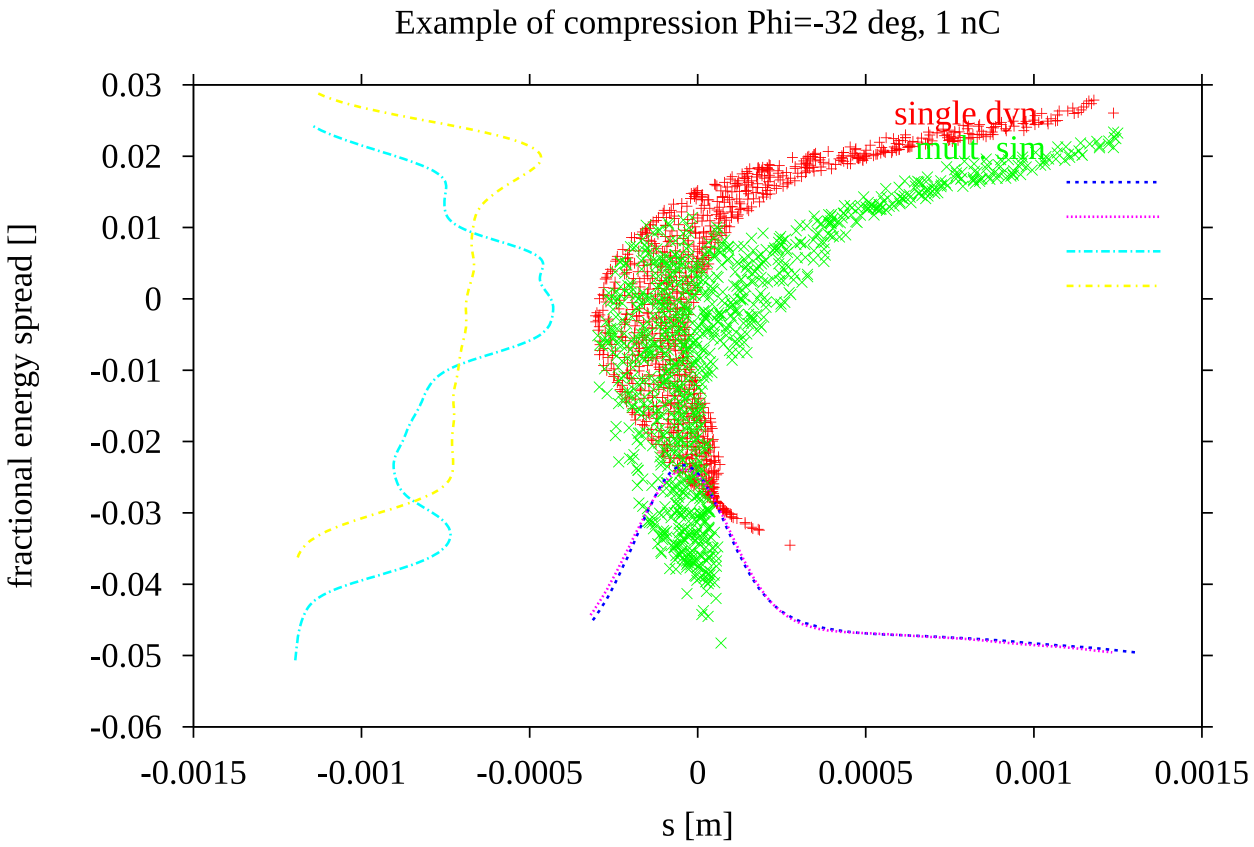

Figure 4: Comparison of the longitudinal phase space downstream of the bunch compressor with (×) and without (+) simulating the bunch self interaction.

set up the beam so that the compression process does not significantly impact the smaller emittance. We are presently engaged in further numerical studies of the compression of flat beam using the FNPL configuration. Since this facility can easily produce such type of beams [13], experiments that consist of compressing a flat beam should be straightforward.

4 Proposed Experiments

The aim of our proposal is to study the transverse emittance (and phase space) and energy spread dilution that is induced during the compression process. These quantities depend upon many "incoming" parameters, essentially:

- the incoming transverse phase space (emittance and Twiss parameters)
- the incoming bunch length
- the incoming charge

Since these parameters cannot easily be varied "orthogonally", we need to have a precise knowledge of their values at the chicane entrance (which would coincide with the starting point of our simulations).

Given a type of beam (round or flat), the following investigation are foreseen:

1. Beam parameter versus booster cavity phase: measure energy loss, energy spread and emittance for various setting of the booster cavity phase. Iterate the measurements for different charges. During these measurements, monitor the CSR power.
2. Beam parameter dependency on the chicane bending angle: the same measurements as in (1) should be performed.
3. Emittance dependency versus incoming Twiss parameters: set the phase of the booster and chicane bending angle to maximize the impact of CSR effects on the beam (per (1) and (2) experiments) and vary the quadrupole doublet located upstream of the chicane.
4. Impact of the spectrometer on the energy loss and energy spread measurement: modify the transport optics between the chicane and the spectrometer dipole and measure energy spread and energy loss.

5 Experimental Techniques

Transverse Emittance Measurement

The emittance needs to be measured downstream of the bunch compressor. The FNPL facility incorporates several multi-slit masks that enable the emittance measurement of space-charge dominated beam in both transverse planes. The multi-slit mask technique can also provide (using a few consecutive bunches) a complete picture of the phase space [14]. The expected resolution of the device is of the order of 0.5 mm-mrd but can be improved using a non-drift transformation between the multi-slit mask and profile monitor that serves for the analysis of the beamlets profiles.

Longitudinal phase space measurement

Bunch length and charge density profile

Since the rms bunch length is expected to be in the sub-mm regime, (for 1 nC the measured value is $\sigma_s \sim 0.6$ mm), a conventional streak camera should provide an accurate measurement of the bunch length. In addition, interferometry of coherent radiation (e.g. transition, or synchrotron) could be attempted and would thereby provide a "consistency check" measurement.

Energy spread and distribution

The FNPL photoinjector incorporates a spectrometer that consists of a dipole that bends the beam in the perpendicular plane w.r.t. the bunch compressor bending plane. Downstream of the spectrometer dipole, a profile monitor allows the observation of the beam density. This configuration is ideal for observing correlation that might occur between the bending plane coordinate and energy space. However because of the low energy, high charge density beam (typically $Q \sim 1$ nC and $\sigma_s \sim 0.5$ mm), and the rather long drift (6 m) between the chicane exit and spectrometer dipole, the measured energy spread might be contaminated by the space charge-induced energy spread as the beam propagates from the chicane exit to the spectrometer. A thorough analysis of this impact should be performed and we might have to use the same approach as in Ref. [3].

Coherent synchrotron radiation power spectrum measurement

The total coherent synchrotron radiation power emitted by the beam as it propagates in the fourth bend will be monitored using an insertable mirror. The radiation could then be analyzed with various techniques: (a) bolometer to measure the emitted power, (b) Michelson interferometer to get (indirectly) some information on the power spectrum of the synchrotron radiation and (c) we also would like to use a polychromator device[15]. This latter type of device would provide a direct, single shot power spectrum measurement; it consists of a diffraction grating that disperses the incoming radiation on an array of 20 cooled bolometers; the signal on each detector measures the power of the corresponding wavelength. Such an apparatus is available for loan from the Princeton Plasma Physics Lab (PPPL)[16]. Modifications of the device would be required to tailor it to the wavelength range ($0.1 \leq \lambda \leq 2$ mm) where we would like to measure the CSR power spectrum.

6 Conclusion

We believe the FNPL facility could provide an excellent platform for the experiments we propose:

1. our preliminary simulations show that CSR bunch self-interaction significantly impacts the beam parameters,
2. FNPL photoinjector incorporates an extensive suite of diagnostics and,
3. other proposed experiments, that require high peak current, would benefit from bunch compression studies.

We would propose to split the experiment into two parts.

First, using the diagnostics that are presently available, we could investigate, in the near term, the amplitude of the impact of the compressor on the beam for a given machine configuration (with a round and flat beam).

At a later stage, once some more elaborate diagnostics have been installed and further numerical studies completed, we could perform the detailed investigations mentioned in Section 4.

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