BEAM DYNAMICS STUDY OF AN RF BUNCH COMPRESSOR FOR HIGH BRIGHTNESS BEAM INJECTORS

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Abstract

A new method based on a rectilinear compressor scheme, utilizing the bunching properties of slow RF waves, has been recently proposed as an alternative to magnetic compressors in order to avoid beam quality degradation due to Coherent Synchrotron Radiation effects. We present here a theoretical and numerical study of the beam dynamics in an S-band photoinjector with rectilinear compressor, as proposed for the SPARC project.

1 TRANSVERSE BEAM DYNAMICS IN RADIO-FREQUENCY COMPRESSORS

Whenever a beam is injected into an RF structure at the zero acceleration phase and slips back up to the peak acceleration phase undergoing a quarter of synchrotron oscillation, it can be compressed [1].

In this section we present the theoretical description of transverse beam dynamics in RF compressors, and, in particular, the theoretical explanation on how the emittance correction process can be implemented in these devices. The analytical model is basically an extension of the invariant envelope theory [2], applicable to quasi-laminar beams carrying a constant current, to the case of currents variable along the beam line (i.e. growing together with energy along the RF compressor).

It is known that the invariant envelope is given by $\sigma_{INV} = \frac{1}{\gamma'}\sqrt{\frac{2I}{I_A\left(1+4\Omega^2\right)\gamma}}$, where the normalized beam kinetic energy is $\gamma = 1 + T/mc^2$ while the normalized accelerating gradient is defined by $\gamma = \gamma_0 + \gamma' z$ and $\gamma' \equiv \frac{E_{acc}}{mc^2}$, I is the beam peak current in the bunch, and the normalized focusing gradient is $\Omega^2 = \left(\frac{eB_{sol}}{mc\gamma'}\right)^2 + \left\{\begin{matrix}\approx 1/8\ SW \\ \approx 0\ \ TW\end{matrix}\right\}$ for a superposition of magnetic field of solenoids and RF ponderomotive focusing by Standing Wave or Traveling Wave sections. σ_{INV} is an exact analytical solution of the rms envelope equation for laminar beams

$$\sigma'' + \sigma'\frac{\gamma'}{\gamma} + \sigma\frac{\Omega^2\gamma'^2}{\gamma^2} - \frac{I}{2I_A\sigma\gamma^3} = \frac{\varepsilon_{n,sl}^2}{\sigma^3\gamma^2} \approx 0$$

where the emittance term (r.h.s.) is considered negligible (this is true in standard photo-injectors up to relevant energies, higher than 100 MeV): it corresponds to an equilibrium beam condition that assures emittance correction, i.e. a control of emittance oscillations associated to envelope oscillations such that the final emittance at the photoinjector exit is reduced to an absolute minimum. In order to assure this condition is necessary to match two types of flow along the photoinjector: the invariant envelope inside accelerating sections and Brillouin flow, given by $\sigma_{BRI} = \frac{mc}{eB_{sol}}\sqrt{\frac{I}{2I_A\gamma}}$, in intermediate drift spaces.

This analysis is valid only for beams carrying constant peak current I, as usual in photoinjectors when no compression mechanism is applied (or space charge debunching is negligible). In order to extend the model to the case of RF compression (where I grows by large factors) we have assumed that the current grows in the compressor at the same rate as the energy, i.e. $I = \frac{I_0\gamma}{\gamma_0}$, where I_0 and γ_0 are the initial values for the current and the energy, respectively, at injection into the compressor. This assumption is derived by observations performed in several simulations of the RF compressor, indicating that best results in terms of final beam brightness are achieved under this condition of adiabaticity, which indeed gives rise to a new beam equilibrium.

In fact, the rms envelope equation becomes in this case:

$$\sigma'' + \sigma'\frac{\gamma'}{\gamma} + \sigma\frac{\Omega^2\gamma'^2}{\gamma^2} - \frac{I_0}{2I_A\sigma\gamma_0\gamma^2} = 0$$

whose new exact analytical solution is $\sigma_{RFC} = \frac{1}{\Omega\gamma'}\sqrt{\frac{I_0}{2I_A\gamma_0}}$, i.e. a beam flow at constant envelope (instead of $1/\sqrt{\gamma}$ as for the invariant envelope). This is dictated by a new equilibrium between the space charge defocusing term (decreasing now as $1/\gamma^2$) and the focusing and acceleration terms (imparting restoring forces to the beam): while for the invariant envelope equilibrium is achieved even in absence of external focusing , i.e. at $\Omega = 0$, in this case we need to provide external focusing.

Just for sake of comparison we notice that the solution for Brillouin flow (i.e. drifting beam at constant energy and constant current undergoing a rigid rotation in the solenoid field B_{sol}) becomes $\sigma_{BRI}^{BAC} = \frac{mc}{eB_0}\sqrt{\frac{I_0}{2I_A\gamma_0}}$ in the case of current increasing linearly along the drift ($I = (\mu z)I_0$) for a corresponding growing solenoid field of the type $B_{sol} = \sqrt{\mu z} B_0$ (also in this case we obtain a constant envelope matched beam through the system, like for the case of RF compression). σ_{BRI}^{BAC} describes what typically happens in ballistic bunching to the beam envelope, which needs to be taken under control by providing a ramped solenoid field to avoid envelope instability.

What is relevant for the emittance correction process is the behavior of the envelope and associated emittance oscillations due to envelope mismatches at injection: let us assume that the injecting envelope is mismatched with respect to the equilibriuum condition such that $\delta\sigma_{INV0} = \sigma_{INV} - \sigma_0$, or $\delta\sigma_{RFC0} = \sigma_{RFC} - \sigma_0$, or $\delta\sigma_{BRI0}^{BAC} = \sigma_{BRI}^{BAC} - \sigma_0$, depending on the type of equilibrium flow that the beam has to be matched on. A perturbative linear analysis of the rms envelope equations reported above (together with $\sigma'' + \sigma\left(\frac{eB_0\sqrt{\mu z}}{mc\gamma_0}\right)^2 - \frac{(\mu z)I_0}{2I_A\sigma\gamma_0^3} = 0$ for the ballistic bunching case) brings to these solutions for the evelope mismatches:

$$\delta\sigma_{INV} = \delta\sigma_{INV0}\cos\left[\sqrt{1/4+2\Omega^2}\,\ln\left(\frac{\gamma}{\gamma_0}\right)+\psi_0\right]$$

for the invariant envelope,

$$\delta\sigma_{RFC} = \delta\sigma_{RFC0}\cos\left[\Omega\ln\left(\frac{\gamma}{\gamma_0}\right)+\psi_0\right]$$

for its generalization in RF compressors, and

$$\delta\sigma_{BRI}^{BAC} = \delta\sigma_{BRI0}^{BAC}\cos\left[\left(\frac{eB_0\sqrt{\mu z}}{mc\gamma}\right)z+\psi_0\right]$$

for the ballistic bunching case.

These envelope mismatches produce emittance oscillations in laminar beams because of the spread in initial mismatches due to different slice currents [2]. The emittance behaviors for the three flow conditions come out to be

$$\varepsilon_n^{INV}(z) \approx \sqrt{\varepsilon_{off}^2 + \frac{I\left\langle\delta\sigma_{INV}^2\right\rangle}{\left(\frac{1}{4}+\Omega^2\right)\gamma'^2\gamma}}$$

$$\varepsilon_n^{RFC}(z) \approx \sqrt{\varepsilon_{off}^2 + \frac{I_0\left\langle\delta\sigma_{RFC}^2\right\rangle}{\Omega^2\gamma'^2\gamma_0}}$$

$$\varepsilon_n^{BAC}(z) \propto \sqrt{\varepsilon_{off}^2 + \frac{I_0\left\langle\delta\sigma_{BRI0}^{BAC\,2}\cos^2\left[\left(\frac{eB_0\sqrt{\mu z}}{mc\gamma}\right)z+\psi_0\right]\right\rangle}{B_0^2\gamma_0}}$$

where the average $\left\langle\delta\sigma^2\right\rangle$ is performed over the initial spread of mismatches in different bunch slices and ε_{off} accounts for the non linear and thermal contributions.

While the rms normalized emittance oscillates and adiabatically damps as $1/\sqrt{\gamma}$ in the invariant envelope case (ε_n^{INV} , constant current), it oscillates at constant amplitude along the RF compressor (ε_n^{RFC}), and with a frequency scaling like the invariant envelope case, i.e. $\frac{\Omega}{z}\ln\left(1+\frac{\gamma' z}{\gamma_0}\right)$ compared to $\frac{\sqrt{1/4+2\Omega^2}}{z}\ln\left(1+\frac{\gamma' z}{\gamma_0}\right)$. In the case of ballistic bunching the emittance ε_n^{BAC} exhibits on the other hand a completely different scaling, with constant amplitude but an increasing frequency like $\left(\frac{eB_0\sqrt{\mu z}}{mc\gamma}\right)$. This the basis why the transverse emittance can be corrected succesfully in the RF compressor: by connecting the two types of flow carefully (proper matching) we can make the emittance oscillates at constant amplitude in the RF compressor and connect adiabatically these oscillations to a damped oscillatory behavior in the accelerating sections following the RF compressor, where the beam is propagated under invariant envelope conditions - this is possible because of the similar frequency behavior of the two flows. It seems hardly achievable in the ballistic bunching, where the increase of the emittance oscillation frequency prevents a good matching to the invariant envelope regime, and induces the onset of non-linear space charge effects that prevent the emittance oscillations to be fully reversible (each minimum in the oscillations is slightly larger than the previous ones).

2 AN RF COMPRESSOR FOR SPARC

The SPARC [3] design assumes a 1.6-cell S-band RF gun of the same type of the BNL-UCLA one equipped with an emittance compensating solenoid and followed by three standard SLAC 3-m TW each one embedded in a solenoid. The preliminary results of the first simulations show that with a proper setting of accelerating sections phase and solenoids strength it is possible, applying the compression method described above, to increase the peak current preserving the beam transverse emittance. An optimized parameters set is shown in table 1.

In order to get a slow bunching of the beam (the current grows about at the same rate of the energy) and to increase the focusing magnetic field with the current during the compression process, we used the first two sections as compressor stages.

Table 1: RF compressor parameters

TW Section	**I**	**II**	**III**
Gradient (MV/m)	15	25	25
Phase (Deg)	-88.5	-64.3	0 (on crest)
Solenoid field (Gauss)	1120	1400	0

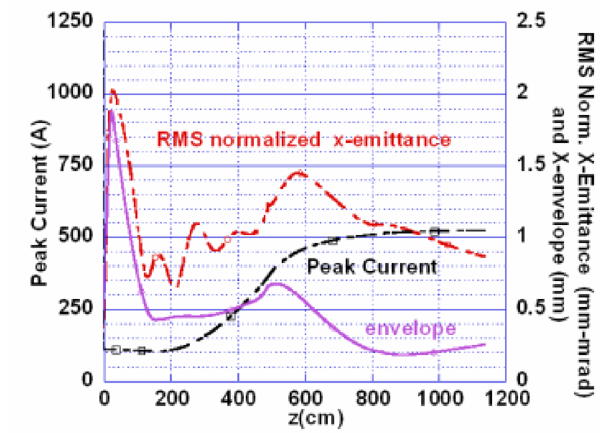

Figure 1: RMS normalized emittance, beam envelope and peak current vs the distance from the cathode.

The plots in fig. 1 of the peak current and the transverse normalized rms emittance (a thermal emittance of 0.3 mm mrad is included) as a function of the distance from the cathode computed by PARMELA for 10K particles show that a peak current of 510 A can be reached with a transverse rms normalized emittance of 0.9 mm mrad. The final beam energy is 120 MeV. The plots of figures 2 and 3 show the evolution of the bunch during the compression as derived from PARMELA computations. One can see that the bunch temporal distribution that is uniform at the beginning tends to a triangular shape: so the value of the peak current in the plot of fig.1, that is simply scaled with the rms bunch length, in reality is an average current in the bunch corresponding to a larger value in the peak (almost doubled respect to the average).

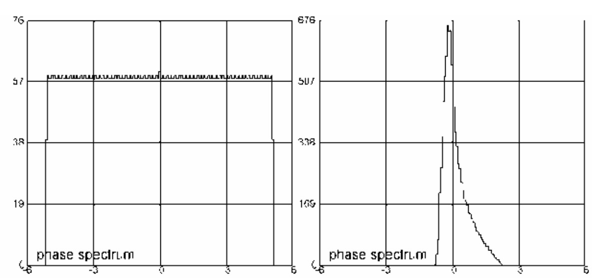

Figure 2: initial and final phase spectrum.

From the point of view of the beam transverse dynamics, during the compression slices with different longitudinal position within the bunch undergo different focusing strengths: in particular the head of the bunch which contains the maximum charge is defocused, while the tail tends to be focused or overfocused, as it shown in figure 3 which shows the plot x-phi in different points of the compressor line.

According to PARMELA convention in the plots of figure 3 and figure 4 the head of the bunch is on the left.

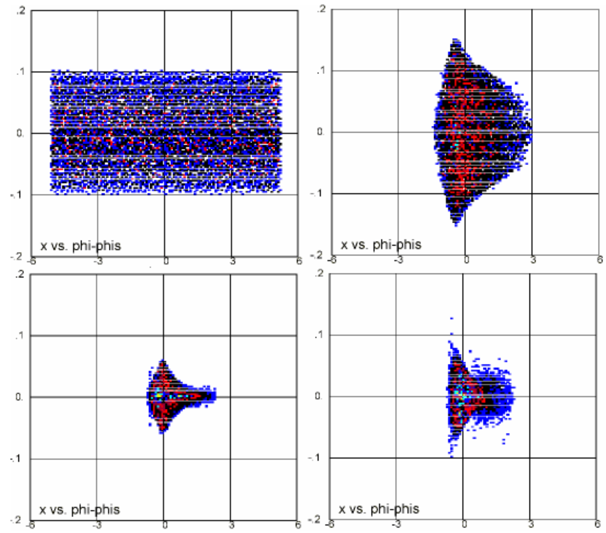

Figure 3: x-phi plot Top: left plot: initial RF gun, right plot: output Section 1, Bottom: right plot: output Section 2, left plot: output Section 3.

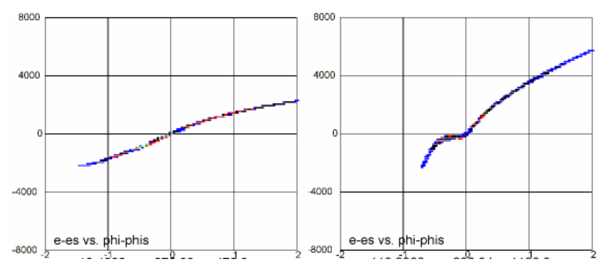

Figure 4: Energy-phase space: left: output Section 1 I=330 A, left: output Section 3 I=510 A.

From the point of view of the longitudinal phase space, as it can be seen in Figure 4, when the current becomes greater than 400 A the bunch head tends to loose the energy-phase correlation differently from the tail that contains less charge, which could be a problem for a further compression of the bunch at higher energy. This point will be investigated more carefully in the future.

3 REFERENCES

[1] L. Serafini, A. Bacci, M. Ferrario , “Ultra-short electron bunch generation with a rectilinear compressor,” PAC2001, Chicago, June 2001.

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[3] The SPARC study group, “An R&D Program for a High Brightness Electron Beam Source at LNF”, These proceedings