STATE-OF-THE-ART ELECTRON BUNCH COMPRESSION

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Abstract

Many accelerator applications such as advanced accelerator R&D, free-electron laser drivers and linear colliders, require high peak current electron bunches. The bunch is generally shortened via magnetic compression. In the present paper we review various bunch compression schemes and discuss their limitations.

INTRODUCTION

There is a growing demand for generating and transporting very bright electron bunches. Applications range from linac-based light sources (both free-electron laser (FEL) and spontaneous emission-based), future linear colliders, to novel electron beam-driven acceleration schemes (e.g. plasma wake-field acceleration). The generation of bright electron bunches directly out of an electron sources is generally not an easy task. Instead it is preferred to create relatively low peak current bunches at the source. Beam manipulations are subsequently implemented in the downstream transport in order to obtain short electron bunches. Several proposed projects [1, 2] call for peak current in the multi-kiloamps regime resulting in bunch length of as low as $\sim$20μm (corresponding to a duration of $\sim$ 70 fs). The process of manipulating an electron beam so to enhance its peak current is called bunch compression. Many other schemes aimed to produce short bunches have been proposed, either with special design of electron source [4] or by selecting only one part of the bunch, e.g. via dispersive collimation or spoiling. These latter "selective" techniques are not addressed in the present paper and a review in the context of light source short radiation pulse production is given in Reference [3]).

MAGNETIC COMPRESSION SCHEMES

Principle

A magnetic bunch compressor, in its simplest form, consists of two elements: an energy "modulator" and a non-isochronous achromatic sections. The energy modulator provides a time-energy correlation (or chirp) along the bunch length, the non-isochronous section introduces an energy-dependent path length. Thus a proper tuning of the modulator parameters to impart the needed chirp along the bunch results in compression as the bunch propagates in the non- isochronous section.

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Let's first discuss the magnetic compression scheme by considering a single particle linear model. Consider an electron with longitudinal phase space coordinate (z_0, δ_0) w.r.t. the bunch center upstream of the energy modulator (δ denotes the fractional energy offset of the electron with respect to the bunch center). Downstream of the modulator, the longitudinal phase space coordinate, (z_m, δ_m), are

$$z_m = z_0, \text{ (assuming } \gamma \gg 1) \quad (1)$$
$$\delta_m = \frac{eV_{rf}}{\mathcal{E}_m}(\cos(kz_0+\varphi)-\cos\varphi) \doteq \kappa z_0 + \mathcal{O}(z^2)$$

wherein e is the electron charge, V_{rf} and φ are the accelerating voltage and operating phase of the energy modulator section, k is the rf wavenumber ($k = 2\pi/\lambda_{rf}$, λ_{rf} being the rf-wavelength), and $\mathcal{E}_m \doteq \mathcal{E}_0 + eV_{rf}\cos(\varphi)$ ($\mathcal{E}_0$ being the initial electron energy). After passing through a non-isochronous section characterized by its first order momentum compaction, R_{56}, the electron coordinates are mapped, to first order, to the following:

$$z_c = z_0 + R_{56}\delta_m, \text{ and } \delta_c = \delta_m. \quad (2)$$

Thus the final electron position with the bunch, z_c, is related to the initial position, z_0, via $z_c = (1+\kappa R_{56})z_0$ which gives the longitudinal matching condition $\kappa = -1/R_{56}$ for minimizing the bunch length in a single stage magnetic compressor. The constant κ is the bunch chirp and can be tuned via V_{rf} and/or φ variable. If one consider rms quantities, the final rms bunch length downstream of the compressor is:

$$\sigma_{z,c} = \left((1+\kappa R_{56})^2\sigma_{z,0}^2 + (R_{56}\sigma_{\delta,0}\mathcal{E}_0/\mathcal{E}_m)^2\right)^{1/2}. \quad (3)$$

When the longitudinal matching condition is satisfied, we have $\sigma_{z,c} = R_{56}\sigma_{\delta,0}\mathcal{E}_0/\mathcal{E}_m$. Therefore compression at higher energy ($\mathcal{E}_m \to \infty$) would results in shorter minimum bunch length. The above linear theory holds under the condition (i.e. $k\sigma_z \ll 1$). In a real accelerator such a condition is not a fortiori satisfied: e.g. in a photo-injector it is common [5] to generate a long bunch length so to properly compensate transverse emittance growth. The bunch compression is then performed once this bunch has been accelerated to high enough energy to sufficiently damp space charge forces. As the bunch is accelerated in the structure, the longitudinal phase space accumulates some curvature due to the cos-like time dependence of the rf-field and the fractional energy spread downstream of the accelerating structure is expanded as $\delta_m = \kappa z_0 + \mu z_0^2 + \mathcal{O}(z_0^3)$ instead of Eq. 1. In turn the bunch compressor needs to be treated to second order in energy (we consider the bunch as a line charge and ignore transverse effects for the sake of simplicity), and the electron longitudinal coordinate downstream of a bunch compressor now writes:

$$z_c = z_i + R_{56}\delta_m + T_{566}\delta_m^2, \quad (4)$$

wherein the constant T_{566} is the second order momentum compaction of the bunch compressor. Expression of momentum compactions (R_{56}, and T_{566}) for various bunch compressors can be found in Reference [6]. Similar to the linear case we can calculate the rms bunch length downstream of the compressor:

$$\begin{aligned}\sigma_{z,c}^2 \;=\;& (1+\kappa R_{56})^2\sigma_{z,0}^2 + \langle z^4\rangle(\mu R_{56}+\kappa^2 T_{566})^2 \\ & +2\langle z^3\rangle(1+\kappa R_{56})(\mu R_{56}+\kappa^2 T_{566}) + \\ & R_{56}\sigma_\delta^2 + T_{566}\langle\delta^4\rangle, \quad (5)\end{aligned}$$

wherein $\langle A^n\rangle$ is the n-th order centered moment of A. The minimum bunch length is no more achieved for the aforementioned "linear" matching condition. A way to correct for the second order aberration in Eq. 5 is either to (1) design a bunch compressor with the proper ratio R_{56}/T_{566} or (2) to include higher frequency accelerating section(s) in order to render the accelerating potential constant over the bunch length [7, 8]. The use of an higher harmonic rf-field provides an independent control of μ and κ parameters and it has been preferred in recent designs (e.g. [10]) because it does not introduce coupling between longitudinal and transverse phase spaces contrary to a bunch compressor designed to have the proper R_{56}/T_{566} ratio. This higher harmonic compensation scheme is integrated in the LCLS and TESLA X-ray FEL designs [9, 10]. The results of linearizing the longitudinal phase space along with its impact downstream of the compressor are illustrated in Fig. 1. Theoretically, it is conceivable to synthesize an arbitrary pulse shape by introducing an arbitrary number of rf harmonics.

In the spirit of trying to tailor the bunch distribution, it is planned at Neptune Lab (UCLA) to use a dogleg type non-isochronous system to compress and shape the beam current distribution as a linear ramp [11]. Such a ramped current profile has applications in plasma-wakefield acceleration to maximize the so-called transformer ratio, i.e. the accelerating over decelerating longitudinal field excited as the beam passes through the plasma. The dog-leg, which has a positive R_{56} in our convention, incorporates sextupoles to tune the values of T_{566} given the R_{56}.

We have, up to now, considered the modulator wavelength to be much longer than the incoming bunch length ($\lambda_{rf} \gg \sigma_z$) so that the modulator effectively introduces a chirp along the bunch. Recently the use of an inverse free-electron laser (IFEL) as a modulator was studied, and simulations showed the possibility to reach bunch durations in the sub-femtosecond regime [13]. In such a proposal, a laser with wavelength $\lambda = 0.8$ μm interacts via an undulator with a 100 MeV electron bunch. The thereby imparted energy modulation along the bunch allows to compress the bunch in a subsequent magnetic compressor; the

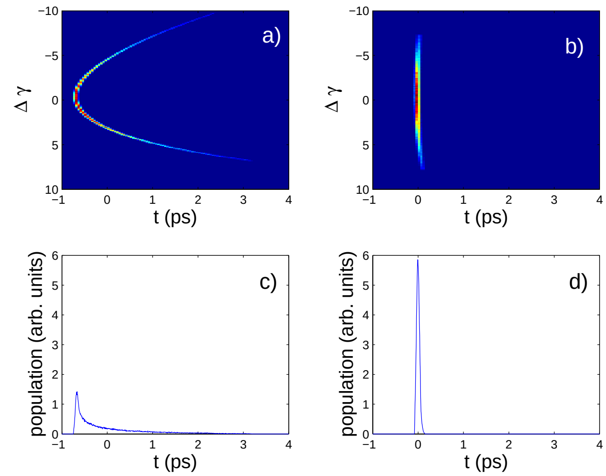

Figure 1: longitudinal phase spaces downstream of a bunch compressor (top plots) and corresponding time-distribution (bottom plots) with (right plots) and without (left plots) an harmonic rf-section to linearize the phase space upstream of the compressor.

bunch then consists of a train of microbunches with width of ~ 200 attoseconds.

Finally, the energy chirp along the bunch can also be introduced by the beam self-field, for instance by resistive or geometric wakefields. The use of these latter effects to chirp the bunch prior to a compressor was proposed as a last (optional) stage bunch compression for the TESLA X-ray FEL [14] and has recently been realized at the SPPS facility at SLAC (see below).

Limiting Effects

The main limitation associated to magnetic bunch compression comes from synchrotron radiation: as an electron travels on a curved trajectory, e.g. in bending magnets, it emits radiation due to centrifugal acceleration. This emission process causes the electron to loose energy as $\propto \gamma^4 I_2$, and the corresponding fractional energy spread dilution and bend-plane emittance growth for a bunch of electrons are respectively proportional to $\propto \gamma^6 I_5$ and $\propto \gamma^5 I_3$ wherein the I_n's stand for the n-th synchrotron integrals [15]. Radiation emitted by a collection of electrons have two regimes: coherent and incoherent as illustrated in Fig. 2(a). The coherent radiation results in a significant self-interaction: at a retarded time the radiation can overtake the bunch on a straight line and interact with electrons ahead in the bunch. This bunch self-interaction is relevant when the path length in the bend is comparable to the so-called overtaking length, $(24\sigma_z\rho^2)^{1/3}$, where ρ the curvature radius. This is the regime of coherent synchrotron radiation (CSR) – the power radiated [16] 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

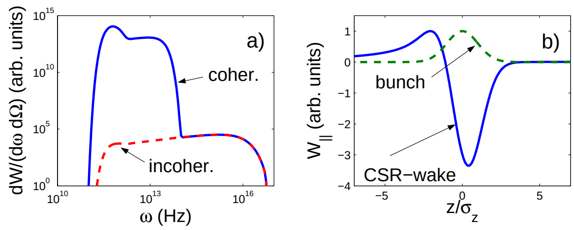

Figure 2: Synchrotron radiation spectrum associated to a Gaussian bunch **a)**, and corresponding coherent synchrotron radiation overtake function as the bunch orbit on a curved trajectory with radius of 1.6 m **b)**. The bunch energy is 140 MeV, its charge 1 nC and rms length $\sigma_z = 250$ μm.

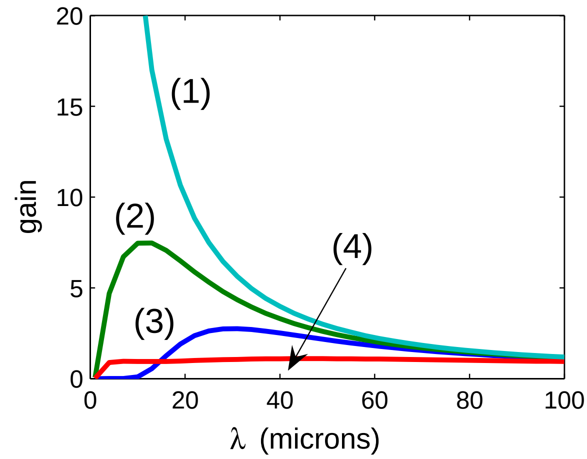

Figure 3: Microbunching gain calculation for a bunch compressor located at 5 GeV, with a $R_{56} = 25$ mm. The bunch is not compressed and its peak current is kept to 6 kA. The four cases presented are: (1) $\tilde{\varepsilon} = 1 \times 10^{-3}$ mm-mrad, $\sigma_\delta = 2 \times 10^{-6}$, (2) $\tilde{\varepsilon} = 1$ mm-mrad, $\sigma_\delta = 2 \times 10^{-6}$, (3) $\tilde{\varepsilon} = 1$ mm-mrad, $\sigma_\delta = 2 \times 10^{-5}$, and (4) $\tilde{\varepsilon} = 20$ mm-mrad, $\sigma_\delta = 2 \times 10^{-6}$.

($\rho \sim 1$ m). The magnitude of CSR longitudinal wake function scales as [17]:

$$\widehat{W}_{||} = \frac{Q}{\epsilon_0 (2\pi)^{3/2} 3^{1/3} \sigma_z^{4/3} \rho^{2/3}}, \qquad (6)$$

ϵ_0 being the electric permittivity for vacuum. Eq. 6 assumes the bunch has a Gaussian charge density. The CSR overtake function is presented in Fig. 2. Although CSR-induced beam degradation is a major limitation, scheme to neutralize the deleterious impact on bend-plane emittance dilution have been proposed: possible solutions include split chicane or periodic F0D0 arcs with proper betatron phase advance [18, 19].

CSR studies via simulation unveiled a micro-bunching instability [20] that was analyzed in References [21, 22, 23]. Such an instability is deleterious for FEL performances, since it affects the beam parameters on time scale comparable to the so-called cooperation length. It was later realized that any energy or density modulations in the longitudinal phase space can be amplified in a magnetic bunch compressor system [24, 25]. In Fig. 3 we present an example of gain calculation for the CSR microbunching instability [23]. Although the gain can be substantial, it can be significantly reduced via Landau damping, e.g. by introducing energy spread via the IFEL process [24, 26].

Example of Experimental Results

The Tesla Test Facility - phase 1 (TTF1), at DESY, has driven a FEL in the saturation regime in the vacuum ultraviolet (VUV) spectrum. A key parameter for achieving such a results was the peak current. During commissioning, the longitudinal phase space was measured [27] and the expected banana shape of the phase space (see Fig. 1) was observed as depicted in Fig. 4. However due to resolution limit of the measurement, it was not possible to obtain a precise value for the peak current. From the achieved FEL performances (gain length, number of mode, etc...) a posteriori simulations were used to reconstruct the bunch profile, and the peak current was estimated to be $\simeq$2.5-3 kA [28].

The sub-picosecond photon pulse source (SPPS) [29], at SLAC, currently holds the record in achieved peak current. The compression occurs in three stages and the final current reaches up to $\sim$30 kA. First the bunch out of the damping ring is compressed by a factor 6, down to 1.2 mm in the ring-to-linac transfer line. The bunch is then accelerated off-crest to 9 GeV and compressed through a four-bend chicane [30] down to $\sigma_z \simeq 50$ μm. Finally the bunch is accelerated to 28.5 GeV and the geometric wakefield of the S-band linac provides a chirp than allows further compression down to $\sim$12 μm in the FFTB dog-leg.

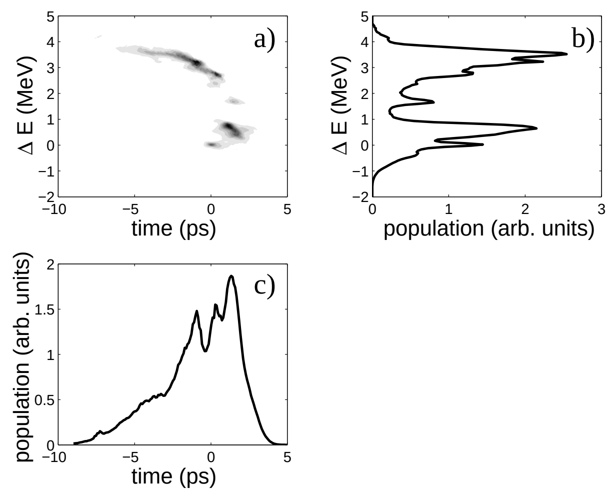

Figure 4: Measured longitudinal phase space at the TTF-1 accelerator **a)** with corresponding energy **b)** and density **c)** profiles. Note positive time corresponds to bunch head.

VELOCITY AND BALLISTIC COMPRESSION SCHEMES

Principle

In this section we elaborate a simple model that describes how the velocity bunching works. A more detailed discussion is given in Reference [31]. An electron in an rf traveling wave accelerating structure experiences the longitudinal electric field: $E_z(z,t) = E_o \sin(\omega t - kz + \psi_o)$, where E_o is the peak field, k the rf wavenumber and ψ_o the injection phase of the electron with respect to the rf wave. Let $\psi(z,t) = \omega t - kz + \psi_o$ be the relative phase of the electron w.r.t the wave. The evolution of $\psi(t,z)$ can be expressed as a function of z solely:

$$\frac{d\psi}{dz} = \omega\frac{dt}{dz} - k = \frac{\omega}{\beta c} - k = k\left(\frac{\gamma}{\sqrt{\gamma^2-1}} - 1\right). \quad (7)$$

Introducing the parameter $\alpha \doteq \frac{eE_o}{kmc^2}$, we write for the energy gradient [32]:

$$\frac{d\gamma}{dz} = \alpha k \sin(\psi). \quad (8)$$

The system of coupled differential equations (7) and (8) with the initial conditions $\gamma(z=0) = \gamma_o$ and $\psi(z=0) = \psi_o$ describes the longitudinal motion of an electron in the rf structure. Such a system is solved using the variable separation technique to yield:

$$\alpha\cos\psi + \gamma - \sqrt{\gamma^2-1} = \mathcal{C}. \quad (9)$$

Here the constant of integration is set by the initial conditions of the problem: $\mathcal{C} = \alpha\cos\psi_o + \gamma_o - \sqrt{\gamma_o^2-1}$. The latter equation gives insights on the underlying mechanism that provides compression. In order to get a simpler model, we consider the limit: $\psi_\infty \doteq \lim_{\gamma\to\infty}\psi(\gamma) = \arccos\left(\cos(\psi_o) + \frac{1}{2\alpha\gamma_o}\right)$; we have assumed $\gamma_o \gg 1$. After differentiation of Eq. 9, given an initial phase $d\psi_o$ and energy $d\gamma_o$ extents we have for the final phase extent:

$$d\psi_\infty = \frac{\sin(\psi_o)}{\sin(\psi_\infty)}d\psi_o + \frac{1}{2\alpha\gamma_o^2\sin(\psi_\infty)}d\gamma_o. \quad (10)$$

Hence depending upon the incoming energy and phase extents, the phase of injection in the rf structure ψ_o can be tuned to minimize the phase extent after extraction, i.e. to ideally (under single-particle dynamics) make $d\psi_\infty \to 0$. We note that there are two contributions to $d\psi_\infty$: the first term $\partial\psi_\infty/\partial\psi_o$ comes from the phase slippage (the injection and extraction phases are generally different). The second term $\partial\psi_\infty/\partial\gamma_o$ is the contribution coming from the initial energy spread. To illustrate the compression mechanism we consider a two macro-particles model. In Figure 5 we present results obtained by numerically integrating the equation of motion for two non-interacting macro-particles injected into a 3 m long traveling wave structure. Given the incoming phase $\Delta\psi_o$ and energy $\Delta\gamma_o$ spreads between the two macro-particles, and the accelerating gradient of the structure (taken to be 20 MV/m), we can optimize the injection phase to minimize the bunch length at the structure exit.

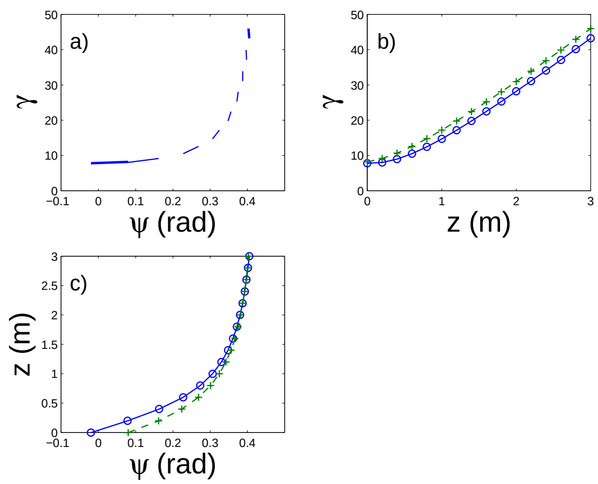

Figure 5: Simple two-macropaticle illustration of the velocity bunching scheme. Snapshots of the longitudinal phase space **a)**, and energy **b)** and phase **c)** spread evolutions as the two macroparticle are transported in a 3 m long traveling wave structure operated with an accelerating gradient of 20 MV/m. The initial energy of ∼4.5 MeV corresponds to the beam energy upon exit from an rf-gun.

Similarly to velocity bunching, ballistic bunching occurs for non-ultra-relativistic electron bunches. In such a scheme, an energy chirp is imparted along the bunch and the compression occurs in the downstream drift (the momentum compaction of a drift of length L is $R_{56} = -L/\gamma^2$). Ballistic bunching is of common use in conjunction with DC-gun electron sources e.g. as planned for the production of polarized electron beam for linear colliders [33], or for CW high power FELs [34].

Limiting Effects

Velocity and ballistic bunching have to occur at low energy, downstream of the electron source. In the case of rf-gun, the accelerating structure, located immediately downstream of the gun, plays also an important role in the so-called transverse emittance compensation process [35]: it needs to be operated to provide acceleration as prescribed by the so-called invariant envelope matching condition [36]. Such a requirement is, at first, incompatible with operating this first structure far off-crest. This limitation was taken into account for the design of SPARC-FEL [37] and a magnetic field superimposed on the first accelerating structure was proposed to prevent significant transverse emittance growth [38]. This technique is however not applicable for a superconducting linacs.

Recent Experimental Results

To date a series of experimental results have been obtained at several facilities.

At the deep ultraviolet FEL (DUVFEL) in Brookhaven [39], a 3 m long S-band (f=2.856 GHz) linac located immediately downstream of an rf-gun was used to bunch the beam [40]. The bunch was injected at various phases, and the bunch length was measured, after being accelerated to ∼70 MeV, via the zero-crossing method [41, 42]. An example of measurement of bunch length compared to the expectation is presented in Fig. 6 – sub-picosecond bunch length were achieved with a bunch charge of ∼ 0.5 nC.

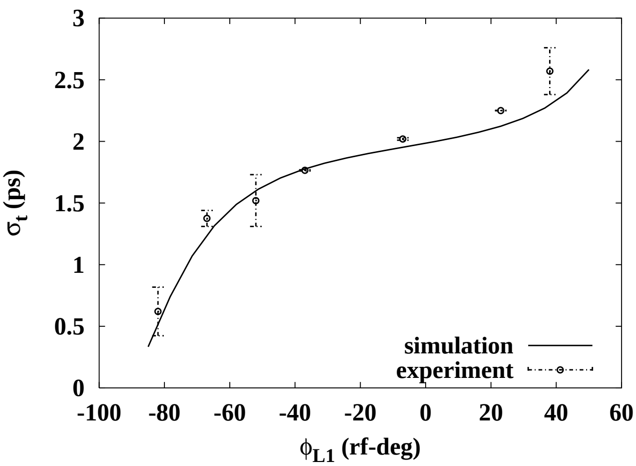

Figure 6: Measured bunch length variation as the phase of the linac located downstream of the rf-gun is varied. The measurements were performed at the DUVFEL in BNL.

At the Neptune Lab [43] of UCLA, a similar experiment was performed and the transverse emittance growth as the rf-section far operated far off-crest was also measured [44].

CONCLUSION

We reviewed two types of compression either employed in currently operating linear accelerators or included in the design of foreseen accelerators. We have not however addressed the integration of such compression schemes in an accelerator complex. In present designs [1, 2, 12], it is common to compress the bunch in a staged fashion. Such a staged compression is needed to (i) avoid driving the beam back into the space-charge dominated regime, (ii) to be less sensitive to time/energy jitter, (iii) to mitigate coherent synchrotron radiation effects. Among the two compression schemes we discussed, magnetic bunch compression, despite its limitations, seems well mastered and most of the current state-of-art accelerators (either operating or under design study) rely on this type of compression.

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