PRODUCING SHORT PROTON BUNCH FOR DRIVING PLASMA WAKEFIELD ACCELERATION

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Abstract

A high energy, intense and short proton bunch can be employed to excite a high amplitude plasma wakefield for electron beam acceleration. In this paper, several bunch compression scenarios are analyzed. One-stage and two-stage bunch compression schemes to compress the proton bunch from the Super Proton Synchrotron (SPS) for the future experimental studies of the proton driven plasma wakefield acceleration at CERN are discussed. The simulation results of bunch compression are given.

INTRODUCTION

Particle accelerators are one of the greatest discoveries of the 20th century, and are not only used in many application areas, e.g., industry, material science, biology, medicine etc, but also used in high energy physics for exploring the fundamental questions (origin of mass, dark matter and dark energy, space and time etc.) in our universe. Since the first cyclotron operated in 1932 to nowadays, the energy of particle accelerators almost follows the famous Livingston plot, which shows that the energy of the machine increases by a factor of 10 every decade [1]. However, with the increased energies, the size of the accelerators becomes bigger and bigger. The cost of construction of such machine is also very expensive (up to billion dollars), which makes it difficult to build it by one nation. The development of modern high energy particle accelerators starts to level off in recent decade due to above-mentioned reasons.

Accelerator physicists always keep on investigating the novel ideas to increase the acceleration gradient, which in general sets the size of the linear accelerator facilities. Plasma acceleration holds promise in this aspect to reduce the machine scale significantly [2,3]. Since a plasma is already a broken-down medium, there is no breakdown limit, compared to the conventional copper or niobium RF cavities. In general plasmas can sustain thousand-time higher electric fields than that of the conventional accelerating structures; therefore, plasma accelerators can potentially minimize the sizes by a large factor and thus make the future machine more compact and cost effective.

The linear theory of plasma wakefield acceleration (PWFA) indicates that the plasma wakefield amplitude inversely scales as the bunch length squared ($E_z \propto 1/\sigma_z^2$) [4]. Therefore, a short drive beam is critical for a high field excitation. Electron bunches shorter than 20 microns rms have been achieved via magnetic bunch compressions in the Final Focus Test Beam (FFTB) at SLAC. The experiments there have shown that more than 50 GeV/m wakefields were produced and measured in an 85 cm-long Lithium plasma channel, which doubled the beam energy from the SLAC's two-mile long linear accelerator [5]. In the nonlinear regime of PWFA, in which the beam density is larger than the plasma density ($n_b > n_p$), simulation shows that this scaling law still holds [6].

Recent simulation shows that a high energy (beam energy of 1 TeV), intense (bunch intensity of 10^{11}) and short (bunch length of 100 μm) proton beam can drive a large amplitude plasma wakefield and accelerate an externally injected electron bunch (injection energy of 10 GeV) to the energy frontier (more than 600 GeV) in a single passage of plasma [7]. To verify this idea, we are now considering making a demonstration experiment by using the beam from the Super Proton Synchrotron (SPS) at CERN [8]. In order to achieve a large amplitude and stable wakefield, we prefer to reduce the bunch length so as to obtain a short and intense drive beam. In this paper, we take the proton beam from the SPS as an example to study the proton bunch compression.

SHORT BUNCH PRODUCTION SCHEMES

As mentioned above, a short drive beam (as short as the plasma wavelength) is critical for a large amplitude wakefield excitation. For the proton driven plasma wakefield acceleration, an even shorter drive beam is required to match the plasma wavelength. When a positively-charged proton beam propagates through a preformed plasma, the plasma electrons will flow-in near the beam propagation axis. This will enhances the local plasma density which means a shorter local plasma wavelength, compared to the plasma wavelength of undisturbed plasma. However, the current existing proton synchrotrons operate the proton beam with bunch length of tens of centimeters; for example, the rms bunch length in Tevatron is 50 cm and 10 cm in HERA. The LHC is expected to run 7 TeV proton beam with an rms bunch length of 7.55 cm. The reason for long beam operation is mainly because the machine operators intentionally introduce the noise within the beam (expand the beam's longitudinal phase space) for reducing the beam instability in synchrotrons so that the beam can stay long time in the rings. In addition, beam current (bunch charge divided by bunch length) related transverse instabilities also require the long beam so that the beam current can stay below the threshold of the instabilities.

In general, the equilibrium bunch length in a proton storage ring scales with the inverse fourth root of the RF voltage and with the fourth root of the momentum compaction factor. To compress the proton bunch from tens of centimetres to hundreds microns will need a formidable RF power. Therefore, adiabatically increasing the RF voltage or adiabatically reducing the momentum compaction factor prior to beam extraction would not appear to be efficient in a ring.

Other possibilities to compress the bunch include (1) a non-adiabatic rapid change of the momentum compaction factor followed by bunch rotation in the now mismatched bucket, simultaneously with a conventional bunch rotation based on a rapid RF voltage increase, prior to the beam extraction; (2) the use of a transversely deflecting cavity followed by a suitable beam line that exchanges the emittance in longitudinal and transverse dimensions [9]; (3) creating a longitudinal microstructure inside a partially shortened bunch to resonantly drive the plasma wave [10]; (4) a special designed beam lines (dogleg or chicane) combined with masks or collimators [11]; or (5) a standard magnetic bunch compression after the beam extraction [12].

Many Free Electron Laser (FEL) facilities around the world employ the standard magnetic bunch compressor for short bunch production. The mechanism of magnetic compression is well understood. Therefore this idea is also adopted in our bunch compressor design. A standard scheme for a single-pass bunch compression sends the beam through RF cavities close to the zero crossing of the RF wave that introduces a position-dependent energy, followed by a region with nonzero momentum compaction factor.

MAGNETIC BUNCH COMPRESSION

A magnetic compressor (magnetic chicane) requires RF sections to provide an energy chirp (energy modulation or position-energy correlation) within the bunch, followed by a dispersive beam line using magnets (dipoles) for the path modulation (energy-path correlation). When a proton bunch is injected off-crest into an accelerating structure (RF sections) the particle energy is modulated depending upon the actual phase of the particle in the bunch. If the bunch is injected before the field reaches its maximum the first particles in the bunch experience less acceleration than the last particles. The bunch length, however, is not affected. The amount of deflection of a charged particle in a magnetic field depends on its momentum. Therefore, the higher the energy of a proton the less it is deflected in the dipoles of a magnetic chicane. If all four deflection angles of dipoles are equal, the protons leave the chicane on the same trajectory independent of their energy. Protons of differing energy take flight paths of different length through the chicane. Protons with higher energy appear advanced, protons with lower energy delayed at the exit. This can lead to a bunch compression in time if the bunch was appropriately energy-time correlated.

Based on the SPS beam parameters shown in Table 1, we have designed a single stage bunch compressor for the SPS bunch compression. According to the linear theory of magnetic bunch compression, a high frequency RF is preferable to reduce the length of RF section (for a fixed longitudinal momentum compaction factor R_{56} of the chicane). Therefore in our design, the RF sections are assumed to operate at 720 MHz, with a gradient of 25 MV/m. Fig.1 shows the longitudinal phase space of the beam before (horizontally flat) and after (sine-like) the bunch compressor. The simulation results show that we could achieve the final bunch length of 3.6 mm, as shown in Fig.2 for a single stage of compression. In this case, the energy spread after bunch compression is about 2.6×10^{-2}. As a consequence, the density of compressed beam is around 300 times higher than the initial uncompressed beam density. The linear theory of PWFA indicates that if this compressed beam is used to drive plasma wakefield, it would excite a much higher filed amplitude. In this compression scheme, the total length of the bunch compressor is about 600 metres. It requires a long RF system (more than 500 meters) to provide energy chirp along the beam. This would increase the cost of the experiment.

Table 1: SPS beam parameters

Momentum [GeV/c]	450
Protons/bunch [10^{11}]	1.15
rms longitudinal emittance [eVs]	0.05
rms bunch length [cm]	12
Relative rms energy spread [10^{-4}]	2.8
rms transverse normalized emittance [µm]	3.5
Bunch spacing [ns]	25

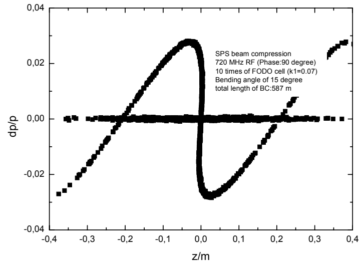

Figure 1: Beam phase space before (horizontally flat) and after (sine-like) bunch compression.

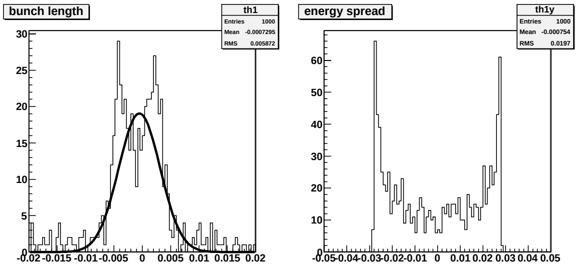

Figure 2: The bunch length and energy spread after bunch compression.

TWO-STAGE BUNCH COMPRESSION

We also investigate other bunch compression schemes. In this section, a two-stage bunch compression is taken into account.

In some electron storage rings, for example, BESSY-II [13, 14], ANKA [15], and SPEAR [16] etc, the short bunch for THz radiation production can be realized via tuning the momentum compaction factor of the machine. In this scheme, the bunch length σ_z scales as the square root of the momentum compaction factor α and inversely as the square root of the slope of RF field. It is written as following:

$$\sigma_z = \frac{\alpha c}{2\pi f_s}\sigma_\varepsilon \propto \sqrt{\frac{\alpha \gamma^3}{d V_{RF} / dz}}$$

here $\alpha = \frac{1}{L}\oint \frac{D_x}{\rho} ds$ is the momentum compaction factor of the machine, in which L is the circumference of machine, D_x is the dispersion function and ρ is the bending radius of dipole for an isochronous ring, c is the speed of light, f_s is the frequency of longitudinal oscillation, σ_ε and γ are the fractional energy spread and Lorentz factor of the beam respectively, dV_{RF}/dz is the slope of RF field applied.

It can be seen that the bunch length can be modulated via changing the momentum compaction factor and the slope of RF voltage in the machine. The final bunch length is

$$\frac{\sigma_{zf}}{\sigma_{zi}} \propto \sqrt{\frac{(dV_{RF}/dz)_i \alpha_f}{(dV_{RF}/dz)_f \alpha_i}}$$

For the two-stage bunch compression, we assume that the beam can be compressed in the ring by some factors, and then the rest can be compressed via magnetic compressor. For the SPS ring, we suppose that the momentum compaction factor can be tuned to 10^{-5}~10^{-6} (three to four orders magnitude smaller than original one) and meanwhile the slope of RF voltage can be increased by a factor of 10. In this case, it is foreseen that the SPS proton bunch can be compressed in the ring by a factor of more than 10 at least. In these cases, protons with bunch lengths of 1 cm or shorter would therefore be produced in the ring. A magnetic compressor is designed to get an even shorter bunch length.

If the bunch length is 1 cm, we use the X-band RF structures with frequency of 11.4 GHz (gradient of 70 MV/m) to provide the energy chirp along the bunch. In this case, we assume the initial beam energy spread is $1.0\text{x}10^{-3}$. Fig.3 shows the longitudinal phase space of beam before (horizontally flat) and after (sine-like) bunch compressor. The simulated bunch length after bunch compression is about 350 microns with energy spread of $3.0\text{x}10^{-2}$, as shown in Fig.4. The total length of the bunch compressor in this design is around 370 metres, which is less than the available space in the SPS tunnel (600 metres). If this compressed beam is used as the drive beam, it is expected to produce a large amplitude of plasma wakefield.

CONCLUSION

A short, intense and high energy proton bunch can drive a large amplitude plasma wakefield for electron beam acceleration. The design study shows that one-stage magnetic compressor can reduce the SPS proton bunch length to 3.6 mm within 600 metres space. If the proton bunch can be compressed in the SPS ring by a factor of 10~100, hundreds micron bunch length can be achieved. Using such compressed beam as driver beam, it is expected to excite a large amplitude plasma wakefield.

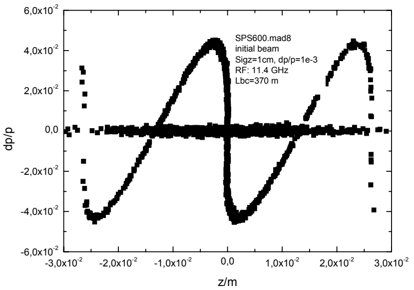

Figure 3: Beam phase space before (horizontally flat) and after (sine-like) bunch compression.

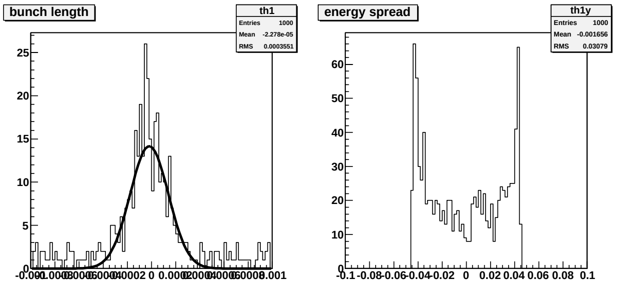

Figure 4: Bunch length & energy spread after magnetic compression (RF: 11.4 GHz). Fitting data show that the bunch length is 350 μm and energy spread is 3.0e-2.

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