GENERATION OF SHORT PROTON BUNCHES IN THE CERN ACCELERATOR COMPLEX

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Abstract

Short high-energy proton bunches have been proposed as efficient drivers for single-stage electron-beam plasma accelerators. We discuss some very preliminary ideas if and how the desired proton bunches could be obtained in the CERN accelerator complex, considering various bunch-shortening schemes, such as a fast non-adiabatic lattice change prior to extraction from a storage ring or the use of transversely deflecting cavities, as well as the possibility of introducing, in a longer bunch, a microstructure that might resonantly excite a plasma wake field.

MOTIVATION

Recently a scheme was suggested to use high-energy proton bunches as drivers of a plasma wake field that could accelerate electrons to hundreds of GeV or even TeV energies in a single stage [1]. In beam-driven plasma acceleration, the energy gain of a particle in the accelerated witness bunch cannot exceed twice the energy of the particles in the bunch exciting the plasma. The two are linked through the "transformer ratio" [1, 2], $\Delta E_{\rm witness}/E_{\rm drive} \leq 2 - N_{\rm witness}/N_{\rm drive}$, which shows that the highest gain can be reached in the limit that the witness bunch population $N_{\rm witness}$ is much smaller than the drive-bunch charge $N_{\rm drive}$.

Presently available electron beams have maximum energies of tens of GeV. If one wants to use a beam-driven plasma wake field for accelerating other electrons to 100s of GeV, many stages would be required. The staging is challenging. By contrast proton bunches are available at much higher energy than electron bunches. Therefore, a single proton bunch passing through a plasma could accelerate a bunch of trailing electrons to a TeV-scale energy [1].

In order to efficiently excite the plasma the driving proton bunch must have an rms length of order 100 μm or less. This is much shorter than the typical length of proton bunches in operating accelerators. In this paper we discuss if and how the desired short proton bunches could be obtained in the present or upgraded CERN accelerator complex for a possible demonstration experiment.

PROTON BEAMS AT CERN

The present CERN proton accelerator chain starts with Linac-2, which is followed by the PS Booster (PSB), the CERN Proton Synchrotron (PS), the Super Proton Synchrotron (SPS) and, at highest energy, the Large Hadron Collider (LHC). Any plasma demonstration experiment would most likely use the beams from the PS or SPS, which are of sufficiently high energy, and more readily available as well as more easily extracted than the beam of the LHC. In 2012/13 the role of Linac-2 will be taken over by the new Linac-4 (now under construction) improving the beam quality throughout the complex. It is planned to replace the PS Booster and the PS by a 4–5 GeV Superconducting Proton Linac (SPL) linac and a new synchrotron, the PS2, around 2018. Linac-4 will serve as frontend for the SPL.

Table 1 compiles parameters of typical "LHC-type" beams that could be readily available from the present and near-future machines at CERN. Recalling that 100 μm corresponds to 0.3 ps, it is evident that most protons bunches naturally available at CERN are too long by three to four orders of magnitude.

The only proton bunches which are naturally "short" are those from the SPL, with an rms length of about 60 μm. The SPL beam has only about 2.5×10^7 protons per bunch and would be available at the earliest in 2017.

All other beams, e.g. the one from the SPS, would need to be compressed or shortened by about a factor 3,000 to obtain rms bunch lengths of 100–200 μm. The energy spread would increase by the same factor and it would be larger than 100% for all example cases considered here. This appears to rule out a full compression of the entire bunch to the desired short length. However, a partial compression could already be helpful.

At the CERN PS, beams can be fast extracted into several beam lines. After "bunch rotation" at extraction from the PS, the typical full bunch length (4 σ) is 5 ns (> 30 cm rms), and the relative rms energy spread about 5×10^{-4}, for a beam momentum of 26 GeV/c. Options for generating about 30% shorter single bunches exist [3]. Bunch intensities from a few 10^9 to 10^{11} protons would be available. The beams are 'LHC like', with normalized transverse rms emittance around 2 micron. At a moderate beta of 10 m this would correspond to an rms size around 1 mm. Not only a short bunch, but also a transversely matched bunch would be required for precise diagnostics of energy loss and gain along the bunch (i.e. matched to the plasma focusing).

Presently, there is no fast extraction from the SPS, except for the CNGS beam, and the beam for LHC. A new facility, 'HiRadMat', is being proposed that could possibly also accommodate a plasma experiment. The beam here has an energy of 450 GeV, the rms normalized emittance is 3.5 micron, and the transverse spot size 0.2–2.0 mm depending on the focusing. The total number of protons per pulse can be as high as 3×10^{13}, delivered in 288 bunches, each with 1.15×10^{11} protons.

Table 1: Parameters for an LHC-Type Beam in the Existing and Upgraded CERN Accelerator Chains

accelerator	PSB	PS	SPS	LHC	SPL	PS2
final momentum [GeV/c]	2.1	26	450	7000	5	50
protons / bunch [10^{11}]	17	1.3	1.15	1.15	2.5×10^{-4}	4
rms longit. emittance [eVs]	0.11	0.03	0.06	0.2 (0.08*)	7.3×10^{-7}	0.05
rms bunch length [ns]	143	1	< 0.5	0.25 (0.16*)	1.9×10^{-4}	1
rms relative energy spread [10^{-3}]	0.32	1	0.3	0.11 (0.07*)	0.18	1
rms transverse emittance [μm]	2.5	3.0	3.5	3.75	0.35	3.0
bunch spacing [ns]	N/A	25	25	25	2.8	25
#bunches/cycle	4 (1/ring)	72	288	2808	200,000	168
cycle time	1.2 s	3.6 s	$\sim$ 22 s	5–10 h?	20 ms	2.4 s

*The LHC numbers in parentheses would be obtained without (intentional) longitudinal blowup on the ramp.

BUNCH SHORTENING SCHEMES

As stated above, after extracting the presently available beam from the PS or SPS, a bunch shortening by a factor 3000 would be needed. Standard RF bunch compression in the extraction line is one option [4].

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 slippage factor $\eta \equiv (\alpha_c - 1/\gamma^2)$. Therefore, adiabatically increasing the RF voltage or adiabatically reducing the momentum compaction α_c prior to extraction would not appear to be efficient.

Other possibilities 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 extraction; (2) the use of a transversely deflecting crab cavity followed by a suitable beam line that "exchanges" the sizes in the longitudinal and transverse dimensions; (3) coherent electron cooling; or (4) creating a longitudinal microstructure inside a partially shortened bunch to resonantly drive the plasma wave.

Bunch Compression after Extraction

A standard scheme for single-pass bunch compression sends the beam through an RF cavity close to the zero crossing of the RF wave, that introduces a position dependent energy, which is followed by a region with nonzero momentum compaction factor. Aspects of such compressor for proton plasma acceleration have been analyzed by G. Xia and A. Caldwell [4]. The RF voltage required is substantial and scales with the proton beam momentum.

Fast Bunch Rotation with Pulsed Change of RF Voltage and Lattice

In a storage ring, a rapid change to the momentum compaction factor α_c along with a quick rise of the RF voltage $V_{\rm RF}$ can mismatch the RF bucket, so that the initial bunch length becomes too long for the new bucket shape. The bunch will start to execute bunch-length oscillations around a new equilibrium. After a quarter period of synchrotron oscillation, the bunch assumes a minimum length and can be extracted. The scheme is sketched in Fig. 1. A more sophisticated variant, yielding even shorter bunches, consists in applying a series of similar fast up and down changes at twice the synchrotron frequency over one or two synchrotron periods [5].

This type of "bunch rotation" prior to extraction is a standard operation when transferring beams between synchrotrons (e.g. PETRA to HERA, PS to SPS), but it is normally realized only by RF changes. Rapidly changing the momentum compaction factor so that the slippage factor assumes a value near zero could create a larger mismatch at lower cost. Similar changes of the momentum compaction factor are routinely used in transition-crossing schemes. In the current CERN PS machine the transition crossing is performed in such a way that the effective crossing speed is fifty times the nominal one [6, 7, 8]. The transition jump changes γ_t $(= 1/\sqrt{\alpha_c})$ by -1.2 units in 0.5 ms. For the PS2 a transition jump changing γ_t by 1.5 units, also within 0.5 ms, had been considered for an earlier PS2 optics based on a FODO lattice [9]. A transition "jump" of this magnitude and speed would be adequate for initiating a fast bunch rotation at extraction energy. The latter could be realized, e.g., by adding pulsed jump quadrupoles to the presently foreseen flexible momentum-compaction lattice of the PS2.

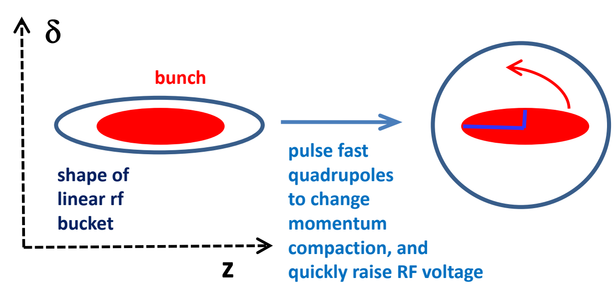

Figure 1: Schematic of fast bunch rotation in a storage ring.

In analogy to the case of transverse mismatch [10], the minimum bunch length during fast bunch rotation in a storage ring is

$$\sigma_{z,{\rm min}} \approx \sqrt{\frac{V_{\rm RF,initial}\eta_{c,{\rm new}}}{V_{\rm RF,new}\eta_{c,{\rm initial}}}}\sigma_{z,{\rm initial}} \, . \qquad (1)$$

For large relative changes, the bunch length scales with the square root of the ratio between the new and old RF voltage and of the inverse ratio between the two momentum compaction factors. For example, consider an initial 50-GeV/c slippage factor $\eta_{c,\mathrm{initial}}$ of about -0.0004 (PS2 design), and a pulsed value $\eta_{c,\mathrm{new}}$ as low as 10^{-6}. Further suppose that the RF voltage can be increased 10 times, e.g. from 300 kV to 3 MV. According to (1), this may compress the bunch by a factor $\sqrt{8000} \approx 90$, which could lower the bunch length from 20 cm to about 2 mm. At the same time the rms energy spread would increase from 0.1% to more than 10%, complicating further beam manipulation.

Transversely Deflecting Cavities

Transversely deflecting (or "crab") cavities are being developed worldwide for producing ultra-short synchrotron-light pulses at light sources [11]. Such cavities could conceivably be applied with the similar purpose of shortening the proton bunch length by effectively "converting" the smaller horizontal beam size into a longitudinal one, or by exchanging the horizontal and longitudinal emittances. A conceptual sketch of such scheme is shown in the left picture of Fig. 2. An alternative might be to employ a transversely deflecting cavity followed by a "slit", which would however lower the bunch intensity.

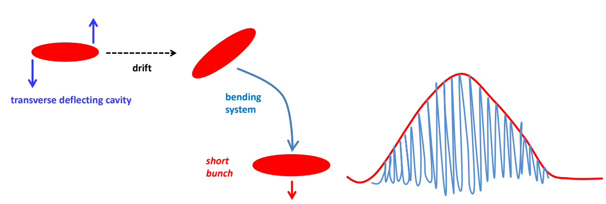

Figure 2: The combination of a transversely deflecting cavity and a bending system with suitable optics could reduce the effective bunch length at a downstream plasma — the crab cavity also induces an x-dependent energy change (left). Schematic of a bunch with longitudinal microstructure [blue] superimposed on an original smooth bunch shape [red] — the horizontal axis is time; the vertical shows the charge density (right).

Coherent Electron Cooling

Another approach would be to reduce or cool the (longitudinal) beam emittance. Cooling techniques include coherent electron cooling, an advanced technique which would remain efficient even at high beam energies (the LHC damping time would be 1 hour at 7 TeV), and which will be demonstrated in a proof-of-principle experiment at RHIC in 2012 [12]. Presently, on the contrary, in the PS, SPS and LHC the longitudinal emittance is intentionally blown up during acceleration, typically by a factor of about 3 in each machine, to combat various types of instabilities. Such instabilities may recur if cooling is applied.

Generating Longitudinal Microstructure

A new approach that does not aim for a short bunch per se, would be a microstructure with a period which coincides with the plasma wavelength, as sketched in the right picture of Fig. 2.

The small "bunchlets" inside the bunch would then excite the plasma wake resonantly. The frequency for this microstructure is daunting, around 3000 GHz. It is clear that innovative technology is required to generate such a microstructure. Three possibilities are considered: (1) The fine structure inside the bunch could be created by exciting a microwave instability introducing a high-Q impedance at the relevant high frequency. (2) An energy modulation at the right frequency could be self-induced in a first plasma serving as "conditioner". This energy modulation can then be converted into a spatial (or temporal) density modulation via bending magnets. Similar plasma-induced modulation and resulting beam slicing have been proposed and simulated for electron bunches passing through a plasma [13]. (3) Or the microstructure could be created by a rapidly rotating (1000s of rotations per second) nano-structured "chopper," essentially a wheel that rotates through the beam while it passes. A small transverse spot size is beneficial. The total bunch intensity would be decreased.

CONCLUSIONS

From 2018 onward the SPL will provide small 5-GeV proton bunches with rms lengths below 100 μm. To obtain short proton bunches of higher energy or higher charge that could drive plasma acceleration from the existing or upgraded CERN complex, no single-step approach is available, but it appears possible to reach the goal by combining two or three of the following methods: (1) bunch rotation prior to extraction, e.g. via lattice manipulation and RF voltage changes, (2) bunch compression after extraction, (3) 4-D or 6-D emittance exchange transformations, possibly involving crab cavities, and (4) the creation of an internal bunch microstructure.

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