

HIGH-ENERGY MICRO-BUNCHER BASED ON THE MM-WAVELENGTH DIELECTRIC STRUCTURE

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Abstract

The proton-driven plasma wakefield acceleration is a recently proposed technique promising a GeV/m rate of acceleration to a TeV-scale energy in a single plasma stage. In order to excite high-amplitude plasma wakefields a long proton bunch from a synchrotron should be broken into a sequence of sub-mm long micro-bunches which can drive the plasma oscillations resonantly. We suggest a novel approach to produce the required train of micro-bunches using collinear wakefield acceleration in a dielectric-loaded structures. First the energy modulation is introduced into the proton beam with the help of the mm-wavelength dielectric accelerating structure. Then the energy modulation is transformed into the longitudinal micro-bunching using proton beamline with magnetic dipoles. Beam dynamics simulations were used to find the appropriate parameters of the dielectric accelerating structure, driving electron bunch and the beam focusing system.

INTRODUCTION

Hadron beams in high-energy synchrotrons provide the highest-energy particles available in laboratories today. Synchrotrons also hold the record for the maximum total energy stored in the beam. For example, both rings of the Large Hadron Collider currently operate at 6.5 TeV with 2200 bunches of $1.1 \cdot 10^{11}$ protons each. This beam has the total energy of 250 MJ which is equivalent to the kinetic energy of a typical fully-loaded airliner (80 t) at the take-off speed of 300 km/h (280 MJ). Even the single bunch ($3 \cdot 10^{11}$ protons at 400 GeV) in the 40 year old Super Proton Synchrotron (SPS) at CERN carries an order of magnitude more energy than the single bunch in the proposed International Linear Collider ($2 \cdot 10^{10}$ electrons or positrons at 250 GeV). Several techniques have been suggested to transfer a fraction of the proton beam energy to other particles which cannot be accelerated in a circular machine either because of the prohibitively high energy loss due to the synchrotron radiation (electrons/positrons) or because of the short life-time of the unstable particles (muons, pions) [1–3]. Such accelerated particles can be used for instance in the collider experiments which do not require high luminosity [4]. The proton-driven plasma wakefield acceleration [3] is the recently proposed method promising a GeV/m rate of acceleration to a TeV-scale energy in a single plasma stage. GV/m plasma wakefields correspond to the plasma wavelength of around 1 mm, while proton bunch in a typical synchrotron is several tens of cm long. In order to excite high-amplitude plasma wakefields the proton bunch should

be either compressed longitudinally by a large factor [2, 3] (which is technically very challenging) or the single proton bunch should be broken into the sequence of sub-mm long micro-bunches which can drive the plasma oscillations resonantly. The Self-Modulation Instability (SMI) of a long proton beam in plasma has been suggested as a convenient way to create such a resonant sequence of micro-bunches [5]. The feasibility of this technique will be tested in the forthcoming AWAKE experiment at CERN [6]. However the efficiency of the SMI is low since the majority of protons are lost from the beam during the development of this instability. In this article we propose a more efficient alternative approach to create the sequence of sub-mm long proton micro-bunches via the longitudinal bunching process first described in the “proton klystron” proposal [1]. We rescale it down to the mm-wavelength using the collinear wakefield acceleration in the dielectric-loaded structures. A resulting train of sub-mm proton micro-bunches could be useful not only for the plasma wakefield acceleration but also as a powerful source of mm-wavelength radiation or as a driver for the similar dielectric accelerator.

GENERAL DESCRIPTION OF THE METHOD

The basic idea of the proposed scheme is shown in Figure 1 [7]. First the energy modulation is introduced into the proton beam with the help of a mm-wavelength accelerating structure. Then the energy modulation is transformed into the longitudinal micro-bunching using the beamline with magnetic dipoles. Proton path length inside the dipoles linearly depends on the proton momentum therefore the energy modulation is transformed into the longitudinal micro-bunching. The 400 GeV SPS proton beam used here as an example has the energy spread $\sigma_{\Delta E} = 120$ MeV (the relative value $\sigma_{\Delta E/E} = 0.03\%$). In order to produce micro-bunching suitable for the plasma wakefield acceleration the energy modulation introduced by the mm-wavelength accelerating structure should be several times larger than the uncorrelated energy spread of the incoming proton beam, — we take ± 500 MeV as a typical value. The dielectric wakefield acceleration is based on excitation of electromagnetic wave with a longitudinal component of electric field by a high-current electron bunch in the vacuum channel of a dielectric wave guide. The proton beam will pass the dielectric channel behind the electron bunch. At a typical field of 100–150 MV/m the required ± 500 MeV energy modulation can be obtained in 3–5 m. Since the length of the proton beam is much larger than the wavelength the wakefield should be excited in a single mode. It’s important to note that the

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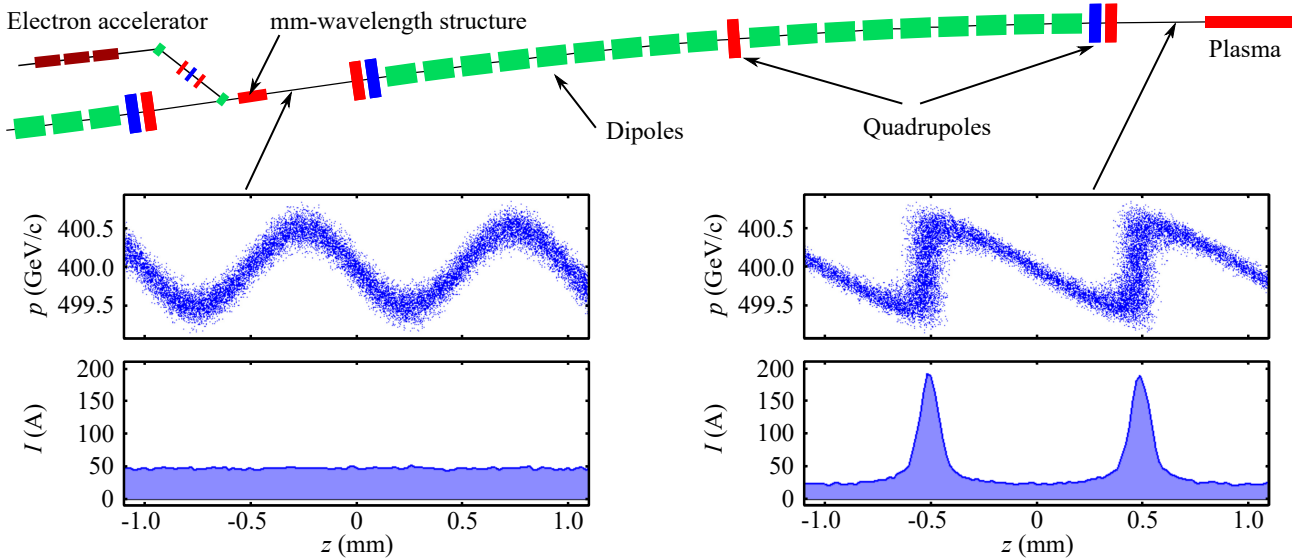


Figure 1: General layout of the proposed micro-bunching system. Proton beam current and proton momentum modulation along the beam are shown before and after the achromat. The realistic proton beam is much longer ($\sigma_z = 5 - 10$ cm) and it can produce around 100 of such micro-bunches.

proton beam does not extract energy from the wakefield in our case (i.e the wakefield is not loaded) – the energy is just redistributed within the proton beam.

THE DIELECTRIC ACCELERATING STRUCTURE

Waveguide parameters and self-consistent beam dynamics calculations were carried out in the DynPart code [9, 10]. For creation of a wakefield with the required parameters (the basic frequency of 300 GHz, electric field above 100 MV/m, we use a dielectric waveguide with an internal radius of vacuum channel $R_c = 1$ mm, dielectric permittivity $\epsilon = 3.75$ (quartz). The external radius of dielectric $R_w = 1.061$ mm, thickness of dielectric $d = 0.061$ mm. Dielectric thickness with the given frequency depends on waveguide radius (in case of $R_c = 2$ mm $d = 0.0334$ mm). Radius of the waveguide defines the amplitude of the wakefield in case of the given value of electron bunch charge and its length. We will consider a Gaussian electron bunch. Length of the bunch defines the spectrum of the excited field. Increase in bunch length leads to lower generated wakefield and, at the same time, to exponential suppression of high-frequency modes of the waveguide. Reduction of the bunch length leads to higher generated wakefield, but, at the same time, to increase in quantity of the excited waveguide modes. As a result, character of the field becomes non-uniform in amplitude. In this regard, we will select such a minimum length of the bunch which provides the maximum amplitude, but excites almost pure single-mode of the wakefield. Achieving 100 MV/m amplitude wakefield in the waveguide with $R_c = 1$ mm and length $L = 5$ m requires electron beam charge $Q = 5$ nC and energy $W_0 = 600$ MeV. The mean squared length of the bunch which meets the requirements described above is $\sigma_z = 0.1$ mm.

The initial transverse parameters of electron bunch are defined by its transverse dynamics in the dielectric waveguide. The field generated by the electron bunch affects both electron and proton beams. If electron bunch is slightly shifted from the waveguide axis the transverse component of the wakefield can reach significant values, leading to electron beam defocusing and loss due to the beam break-up instability. To keep the intense electron bunch on-axis the strong quadrupole focusing is required. The value of the focusing magnetic field for not superconducting (“warm”) magnets on waveguide border, as a rule, doesn’t exceed $B_0 = 1.5$ T, which we will use in these calculations. For the fixed magnetic field gradient inside the quadrupoles the maximum travel distance for the electron bunch is determined by the initial shift of the bunch from the axis as well as the length of the focusing section. There is an optimum length of the focusing section (i.e. the optimum average beta-function of the quadrupole channel). We will select the transverse size of the electron bunch $\sigma_x = \sigma_y = 0.05$ mm. The typical required beta-function of the quadrupole focusing channel is ~ 10 cm meaning that the maximum normalized emittance of the matched beam $\epsilon_{nx} = \gamma\sigma_x^2/\beta_x \sim 1200 \cdot (0.05 \text{ mm})^2 / 100 \text{ mm} = 30 \text{ mm} \cdot \text{mrad}$ which is around 10 times higher than the typical electron beam emittance produced by photo-injectors. This means that significant emittance blow-up in the electron bunch compression system can be tolerated.

The best electron beam transfer is achieved in our simulations with 11 cm long FODO period, while the length of every quadrupole is 4.7 cm. The magnetic field at the pole of the first quadrupole is 1.5 T. The strength of the following quadrupoles is decreasing proportional to the energy of electrons in the middle of the bunch.

The simulation is terminated as soon as the first electron beam macro-particle reaches the waveguide wall. The 5 m propagation of the driver bunch was reached for the initial 0.03 mm offset of the electron beam with respect to the waveguide axis. In this case electrons from the middle part of the drive bunch are decelerated by 450 MeV down from the initial energy of 600 MeV. In this case the maximum energy modulation is ± 670 MeV in the proton beam. The initial transverse offset of 0.1 mm limits the electron beam propagation distance to 2.4 m with a corresponding energy spread in the proton beam reaching ± 340 MeV.

It's important to note that the proton beam emittance is not distorted significantly by the transverse wakefields excited in the dielectric channel due to initial electron beam offset from the axis. The normalized proton beam emittance increases only by 0.2 mm · mrad (10% of the typical ϵ_n) after the dielectric section.

THE PROTON BEAMLINER

The typical normalized emittance of the proton beam extracted from the SPS is around 2 mm · mrad [8]. Taking a typical value of the proton beam beta-function equal to the length of the dielectric section (5 m) this corresponds to the transverse beam size $\sigma_x = \sqrt{\beta_x \epsilon_{nx} / \gamma} = \sqrt{5000 \text{ mm} \cdot 2 \text{ mm} \cdot \text{mrad} / 400} = 0.16 \text{ mm}$ which gives us a 6 sigma aperture for the proton beam transport through the dielectric channel.

In order to transform the proton beam energy modulation into the micro-bunching and focus the beam before plasma some kind of achromatic bending system can be used. The path length difference of particles with momentum spread Δp is given by

$$\Delta z = \frac{\Delta p}{p} \int_L \frac{D(s)}{\rho(s)} ds, \quad (1)$$

where D is the dispersion function, ρ is the bending radius. Therefore the required length of the achromat L is defined only by the value of dispersion function inside the dipoles. This value can't be too high since the dispersion-induced beam size $D\Delta p/p$ is limited by the aperture of quadrupoles and dipoles. The required energy modulation is around ± 500 MeV and for the 400 GeV beam this corresponds to $\Delta p/p = \pm 1.3 \cdot 10^{-3}$. The aperture of quadrupoles used in the SPS-AWAKE transport line TT41 is 4 cm. In this case the dispersion function can't be larger than $2 \text{ cm} / 1.3 \cdot 10^{-3} = 15 \text{ m}$.

Consider the simplest symmetric achromat with one quadrupole in the middle (as shown in Figure 1). The dispersion function before the quadrupole grows as $D(s) = [1 - \cos(s/\rho)]\rho$. The integral in Eq. 1

$$\int_L \frac{D}{\rho} ds = 2 \int_0^{L_d} \left[1 - \cos\left(\frac{s}{\rho}\right) \right] ds \approx \frac{\rho}{3} \left(\frac{L_d}{\rho}\right)^3, \quad (2)$$

where L_d is the length of each of the two dipoles in this achromat ($L_d \ll \rho$). Assuming the momentum modulation

along the proton beam after the dielectric section

$$p(z) = p_0 + \Delta p \sin(2\pi z / \lambda_{rf}), \quad (3)$$

Eq. 1 and Eq. 2 can be used to find the required L_d :

$$\begin{aligned} L_d &\approx \rho \sqrt[3]{\frac{3p}{\rho} \left(\frac{dp}{dz}\right)^{-1}_{\max}} = \rho \sqrt[3]{\frac{3p}{\rho} \left(2\pi \frac{\Delta p}{\lambda_{rf}}\right)^{-1}} \approx \\ &\approx (790 \text{ m}) \sqrt[3]{\frac{3}{790 \text{ m}} \left(2\pi \frac{1.3 \cdot 10^{-3}}{1 \text{ mm}}\right)^{-1}} \approx 60 \text{ m}. \end{aligned} \quad (4)$$

And the full length of the achromat will be close to $2L_d = 120 \text{ m}$ (15% of the TT41 beamline total length). The maximum value of the dispersion function

$$D_{\max} = \left[1 - \cos\left(\frac{L_d}{\rho}\right) \right] \rho \approx \frac{\rho}{2} \left(\frac{L_d}{\rho}\right)^2 \approx 2.2 \text{ m}, \quad (5)$$

which is below the maximum dispersion function (3 m) in the existing beamline and well below the aperture defined limit of 15 m (i.e. with more complicated achromat optics its length can be reduced). The required proton optics with low-beta insertion followed by the achromat seems possible to implement by rearranging dipoles and quadrupoles in the existing beamline.

CONCLUSIONS

We suggested a novel approach to produce the long train of high-energy proton micro-bunches using the mm-wavelength dielectric-loaded structure.

For the considered example case of the 400 GeV proton beam from the CERN SPS the requirements on electron drive beam parameters seem to be rather challenging. Such electron beams are normally produced for the soft X-ray Free Electron Lasers and require too much infrastructure investment to be considered for the AWAKE experiment now. Still such option can be very interesting for some eventual application of the proton-driven acceleration using the LHC proton beam for example.

The efficiency of electron driver can probably be improved significantly. The mm-wavelength accelerator parameters obtained in our studies are very similar to the Argonne proposal of the dielectric-based high-repetition FEL [11, 12]. However the transverse electron beam dynamics in our case is more relaxed since the required propagation length of the electron beam is many times shorter. Using the drive beam shaped similar to the FEL proposal it should be possible to reduce the electron beam energy well below 600 MeV assumed in this article.

Some kind of longitudinal proton beam cooling at high-energy (e.g. optical stochastic cooling) can reduce the random energy spread in the proton beam, so that the required mm-wavelength energy modulation can be reduced also.

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