Electron-Positron Collider Design- simulations from long proton driven beam to 125GeV witness electron and positron bunches

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Abstract

In this paper, the feasibility of the electron-positron collider based on plasma accelerator is proved by simulation experiments. Starting from the 17.612cm proton beam provided by SPS (super proton synchrotron), the simulation shows that the long proton beam can form several high quality proton bunches through seeded self-modulation in the first half of the long proton beam in a uniform plasma. Then we use these high-quality bunches to excite the wakefield in a uniform plasma and accelerate witness positrons and witness electrons. The simulation results show that the average energy of witness bunches after about 90 meters acceleration is about 125 GeV, and the average acceleration gradient is about 1.3 GeV/m. The center-of-mass (CoM) energy of positron-electron collision is about 125 GeV. The energy spread, witness particle survival rate, emittances and luminosity of the output witness bunches are also discussed.

INTRODUCTION

CERN first measured the mass of the Higgs boson at about 125GeV through the Proton Collider in 2012, but the internal structure of the protons makes them produce a lot of background particles after the collision, which makes the mass measurements have a big error. Electrons as elementary particles do not have internal structure, so people hope to re-measure the mass of the Higgs boson through electron-positron collisions to reduce errors. Because high-energy electrons will lose a lot of energy due to synchrotron radiation when accelerating in the cyclotron, electrons can only be accelerated by the linear accelerator, but the acceleration cavity of the traditional RF accelerator will also be breakdown when it produces a strong acceleration field. In theory, the maximum acceleration gradient of a RF accelerator is about 100 MeV/m, which is far from enough to accelerate electrons to 125 GeV [1]. The plasma accelerator proposed by Toshiki Tajima can easily produce GeV/m-level acceleration gradients, which can accelerate electrons to 125GeV in about 100 m. The economical and efficient of plasma accelerator makes it be a very potential research field.

Existing research has proved that a series of short proton bunches can excite the wakefield in a 150 meter hollow plasma and accelerate the energy of the witness electron bunch from 10 GeV to 470 GeV, which can also ensure that the witness electron beam has high qualities when output. Which meets the requirements of high-energy physics research [3]. However, long proton beams produced by SPS cannot be converted into short proton beams through self-modulation in hollow plasma, and short proton beams that complete self-modulation in a uniform plasma cannot be used in hollow plasma, because the proton beam spacing and the wavelength of wakefield in hollow plasma mismatch causes the excited wakefield to be very weak. The most important problem is that the current technology cannot build a 150 meter hollow plasma channel. This paper proposes a long proton beam that completes the seeded self-modulation in uniform plasma can excite high-quality wakefield in uniform plasma and accelerate witness positron bunch and electron bunch to 125 GeV, respectively, while ensuring that the output witness bunches have good qualities.
BASIC DESIGN

This electron-positron collider is composed of SPS, an electron accelerator and plasma channels. A seed electron bunch with an average energy of 1 GeV is injected into the first plasma channel with length of 3.57 m, and a 17.612 cm proton beam (generated by SPS with average energy of 400 GeV) is injected behind a phase difference of $3/2\pi$ from this electron beam. The long proton beam is partially self-modulated in the first plasma channel with the help of a seed electron beam. When these short proton bunches and seed electron beams are output from the first plasma channel, the seed electron beam is filtered out and proton bunches are injected into the second plasma channel, while the witness electron beam with an average energy of 5 GeV is also injected into the second plasma channel and placed on the acceleration phase of the wakefield. Figure 1 and 2 shows the basic structure of the electron-positron collider with 125 GeV CoM energy.

SIMULATIONS

All the simulations in this paper are carried out in plane geometry of LCODE, which is a two dimensional quasi-static approximate simulation software developed based on particle-in-cell [4].

Existing research proves that placing a seed electron bunch in front of a long proton beam and changing the longitudinal density of the plasma during seeded self-modulation can obtain high-quality proton bunches [5]. In the simulations presented in this paper, seeded self-modulation is also used to process 17.612 cm proton beams. Because LCODE does not provide a Gaussian distributed beam current, we use beam current distribution with shifted cosine shape. The parameters of long proton beam, seed electron bunch are shown in Table 1. The change in longitudinal plasma density with plasma length $z$ is shown in Table 2.

| Parameter          | Value | Unit |
|--------------------|-------|------|
| **Long Proton Beam** |       |      |
| Energy, $E$        | 400   | GeV  |
| Energy Spread, $\delta E/E$ | 0.1   | %    |
| Normalized Emittance, $\epsilon_n$ | 2.38  | $\mu$m |
| Number of Protons, $N_p$ | $6.24 \times 10^{11}$ | /    |
| Longitudinal Beam Length, $\sigma_Z$ | 17.612 | cm   |
| Beam Radius, $\sigma_r$ | 238   | $\mu$m |
| **Seeded Electron Bunch** |       |      |
| Energy, $E$        | 1     | GeV  |
| Number of Electrons, $N_e$ | $9.30 \times 10^9$ | /    |
| Longitudinal Beam Length, $\sigma_Z$ | 750   | $\mu$m |
| Beam Radius, $\sigma_r$ | 238   | $\mu$m |
| **Witness Bunch**   |       |      |
| Energy, $E$        | 5     | GeV  |
| Energy Spread, $\delta E/E$ | 0.1   | %    |
| Normalized Emittance, $\epsilon_n$ | 1.21  | $\mu$m |
| Number of Electrons, $N_e$ | $8.43 \times 10^7$ | /    |
| Longitudinal Beam Length, $\sigma_Z$ | 23.8  | $\mu$m |
| Beam Radius, $\sigma_r$ | 71.4  | $\mu$m |
| **Rectangular External Focusing** |       |      |
| Magnetic Field Gradient, $S$ | 3000  | T/m  |

Table 1: The table shows the parameters of the long proton beam and the seed electron bunch used in the first plasma channel. It also shows the parameters of witness electron bunch and external magnetic field used in the second plasma channel.
The simulation results show that the first 6 cm of the long proton beam can become high-quality proton bunches under seeded self-modulation, but the qualities of the second half of the bunches are very low. This is because the slight changes in the wakefield in the first half will greatly change the wakefield in the second half, and this change cannot be adjusted by changing the longitudinal plasma density. Fortunately, there are 10 to 15 consecutive bunches with best qualities in the first 6 cm that can be selected for exciting a stronger wakefield in the second plasma channel for accelerating the witness electron bunch. From Figure 3, it can be seen that the intervals between the selected bunches are approximately equal to \( \lambda_p = \sqrt{\frac{\pi e^2 m_e}{n_p e^2}} \), and their beam current distributions are relatively similar, which makes each bunch can make enough contribution to the wakefield to generate a relatively high acceleration gradient.

If we continue to use the 17.612 cm proton beam as the driving beam to simulate a 100 meter plasma accelerator, the simulation time will be too long because the simulation window is too long. Fortunately, the charge distribution of proton beam at the time of incidence is almost uniform, so we use a uniform charge distribution proton beam of 2.14 cm instead of the proton beam of 17.612 cm as the driving beam in the next simulation stage. We used the same seed electron parameters and plasma parameters to make the 2.14 cm proton beam complete the seeded self-modulation to obtain the simulation result of Figure 3b. By comparing Figure 3a and 3b, it can be seen that the distribution of the last few bunches selected from the 17.612 cm beam and the last few bunches of the 2.14 cm beam in the real plane geometry are different, but their charge density distributions are very similar. This makes them excite similar wavefields in the plasma, so we can replace the 17.612 cm proton beam with a 2.14 cm proton beam to accelerate the witness electron bunch in next simulation step in the second plasma channel.

In the next simulation, 15 short proton bunches obtained after the seeded self-modulation of 2.14 cm proton beams are conducted into the second plasma channel. At the same time, an witness electron bunch is placed in the acceleration region of the wakefield excited by the proton bunches. As shown in Table 1, during the acceleration, both the electron bunch and the proton bunches are applied with additional focusing force to prevent them from being defocused by the transverse wakefield. It is worth noting that the initial plasma density \( (z = 0) \) in the second plasma channel is smaller than the final plasma density \( (z = 3.57) \) in the first plasma channel. This is because the mass of the electron is 1836 times smaller than the mass of the proton. Although the energy of the electron is always lower than the energy of the proton during the acceleration, its velocity is far greater than that of the proton. This will make the electron bunch slowly approach the proton bunch in front of it and leave the acceleration region of the wakefield causes phase slippage. Although the maximum dephasing length of the witness electron bunch is more than one hundred meters under the simulation parameters used in this article, the relative motion between the witness electron bunch and the acceleration region of the wakefield will affect the acceleration gradient [6]. One way to solve the phase slippage is to linearly increase the
longitudinal plasma density in the second plasma channel, so that the wavelength of the wakefield is reduced, and the peak value of the target wakefield slowly approaches the proton bunch in front of the electron bunch. This method allows the witness electron beam to always be located at the maximum acceleration gradient in the acceleration region, but excessively reducing the wavelength of the wakefield will also cause the peak of the wakefield to significantly decrease due to the mismatch between the last proton bunch and the wakefield, thereby reducing acceleration gradient. Through simulation, we find that the more the last proton bunch overlaps with the positive part of the target wakefield, the more obvious the peak drop caused by the phase mismatch. In order to prevent this phenomenon, we use a lower plasma density in the early stage of self-modulation stage than in the end of self-modulation stage, as shown in Figure 3. In this way, there will be a short distance between the last proton bunch and the positive part of the wakefield, even if the wavelength of the wakefield shrinks during the acceleration, there will not be much overlap between the positive wakefield and the last proton bunch.

As shown in figure 5, the average energy of the witnessed electron bunch and the witnessed positron bunch reached 125.5 GeV and 126.6 GeV, after 90 m and 95 m acceleration, respectively, with an average acceleration gradient of 1.34 GeV/m and 1.27 GeV/m. The energy distribution of electron bunch and positron bunch is shown in figure 6, and their energy spread are about 4.8% and 10.3%. The positron bunch has a larger energy spread because its longitudinal bunch length increases more than that of the electron bunch in the later stage of acceleration, resulting in greater differences in acceleration gradients at different positions of the positron bunch. The energy distribution of electrons is decreasing part of Gaussian, while the energy distribution of positrons is Gaussian, which is related to the position where the witness bunch is placed at the beginning of acceleration. The emittances of positron bunch and positron bunch when they are output are 2.98 mm and 7.66 mm, respectively. The CoM energy of the electron-positron collision is 125 GeV and the luminosity is $3.33 \times 10^{17} \text{cm}^{-2}\text{s}^{-1}$ (assuming the collision frequence is 1 Hz).
Figure 4: 4a and 4b show the variation of the average energy of the witness bunch and the number of witness particles with the acceleration distance.

CONCLUSIONS

In this paper, we simulate the complete process of accelerating electrons and positrons to about 125-GeV by plasma accelerators based on SPS. The simulation results show that the 17.612 cm long proton beam produced by SPS can be transformed into several high quality protons bunches by seeded self-modulation. These protons bunches can excite strong wakefields in uniform plasma to accelerate witness bunches. The energy and quality of the witness bunches accelerated about 100m can meet the scientific research requirements of exploring the Higgs boson. To sum up, the design of the electron-positron collider is successful, which proves that the plasma accelerator is a very potential field.

Reference

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