CERN-ACC-2018-200

STUDY OF THE ELECTRON BEAM TRANSFER LINE FOR THE AWAKE RUN II EXPERIMENT AT CERN*

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Abstract

Proton Beam-Driven Plasma Wakefield Accelerator (PBD-PWFA) has been actively investigated at CERN within the AWAKE experiments to study the electron beam acceleration using plasma wake fields of the order of GV/m. In the AWAKE RUN 1 experiments an electron beam with an energy of 19 MeV and a bunch length of 2.2 ps rms has been used for the first demonstration of electron beam acceleration in the plasma wake fields. It has been observed that the energy gain of the electron beam is up to 2 GeV, and electron capture efficiency is few percent. Higher capturing efficiency and emittance preservation could be achieved by making the electron beam short enough to be injected only into the acceleration and focusing phase of the plasma wake fields. The electron accelerator needs to be upgraded for AWAKE RUN 2 experiments to obtain a bunch length less than 100 fs which corresponds to a quarter of the plasma wavelength. Planned electron beam parameters for the AWAKE RUN 2 are a beam charge of 100 pC, and a beam energy larger than 50 MeV. In this paper, we show the electron beam parameters for RUN 2, and the parameters of the transfer line such as Twiss parameters, beam envelope, and emittance.

INTRODUCTION

In the first run of the AWAKE to demonstrate the acceleration of 19 MeV electron beam through the PBD-PWFA, it has been observed that the energy gain of the electron beam is in the order of GeV [1]. Furthermore, a new experimental setup is now under study for the next run of AWAKE starting from 2021 to study electron acceleration with high energy and emittance preservation. For the RUN 2 experiments, target parameters have been determined from the simulation [2]. The beam size and length are less than 50 µm and 100 fs, respectively to increase capturing efficiency to more than 90 %. In addition, while a single Rb-Vapor plasma cell has been used for both Seeded Self-Modulation (SSM) and accelerating of the electron beam In RUN 1, it is considered for RUN 2 experiment that an additionally introduced 4 m plasma cell is used only for SSM to generate the microbunches of the proton beam. Then, the modulated proton beam propagates to another 10 m of plasma to generate the plasma wake fields, which are going to be used to accelerate the electron beam. The electron beam has to be injected in between the two plasma cells.

In this paper, studies on electron beamline optimization using RUN 2 beam parameters are shown, and a new beamline is briefly proposed. For the beamline simulation, ASTRA [3], MAD-X [4] and ELEGANT [5] codes are used to simulate the beam, and for the optimization of the beam parameters along the beamline.

ELECTRON BEAMLINE AND OPTIMIZATION

The beam parameters considered for RUN 2 are obtained from a new injector combining S- and X-band electron accelerator [6]. Apart from a S-band RF gun, it consists of X-band buncher and a traveling wave structure to reduce the bunch length out of the linac section. Beam parameters at the end of the injector are shown in Table 1.

Table 1: Beam Parameters Out of the Linac Section

Parameters	Values
E_k	85 MeV
σ_E	0.33 %
σ_r	0.14 mm
σ_z	82.57 fs
$\epsilon_{nx,ny}$	0.5 mm mrad

Conventional Electron Beamline Optics

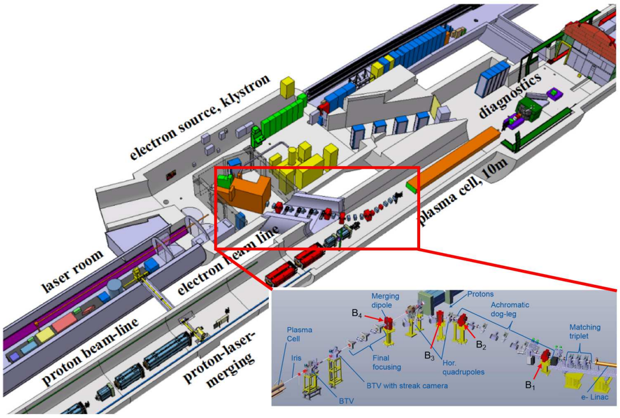

Figure 1: AWAKE tunnel and current electron beamline.

First, it has been studied whether the existing electron beamline for RUN 1 can be used also for the RUN 2 experiments with the initial beam parameters described in Table 1. The current electron beamline is depicted in Fig. 1 [7, 8].

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* Work supported by NRF
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The beamline has been built following the constraints of the existing tunnels. The beam propagates through the matching triplet, and achromatic dog-leg for zero-dispersion. Then, it goes to the merging point with the proton beam. Since the tunnel has a slope, the final dipole magnet B_4 has a tilt angle to match the beam trajectory to the slope of the tunnel.

Optimization process for β function in Twiss parameters and dispersion (η) function have been done using MAD-X simulation code. At the plasma merging point, β and dispersion are matched to 0.6 m, 0 m, respectively. Figure 2 shows β and dispersion functions along the beamline. Due to the tilt angle of B_4 magnet, derivative of dispersion value exists on the vertical plane at the plasma merge.

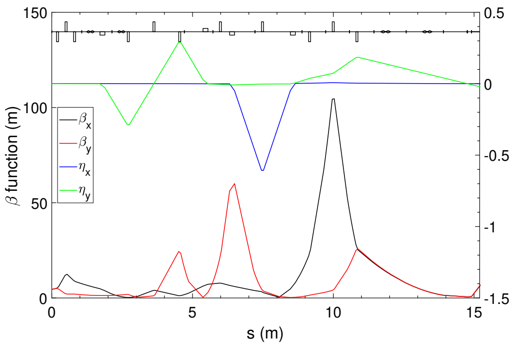

Figure 2: β and dispersion functions along the beamline.

Particle tracking has been done using ELEGANT code with given quadrupole strength obtained from MAD-X simulation. In this simulation study, space charge calculation has been ignored. In Fig. 3, beam size and normalized emittance are shown. Solid line indicates the value with considering higher order terms (chromatic effects), while dashed line is the value with consideration of both higher order terms, and coherent synchrotron radiation (CSR). The beam size $\sigma_{x,y}$, and the normalized emittance $\epsilon_{nx,ny}$ values at the plasma merge are described in Table 2.

Table 2: $\sigma_{x,y}$ and Normalized $\epsilon_{x,y}$ at the Plasma Merge

Parameters	**Higher order terms included**	**Higher order terms and CSR included**
σ_x	71.41 µm	377.01 µm
σ_y	82.31 µm	277.07 µm
ϵ_{nx}	1.03 mm mrad	6.36 mm mrad
ϵ_{nx}	2.35 mm mrad	8.98 mm mrad

When higher order terms and CSR effects are included in the simulation, the emittance value, and beam size of the merging point are rapidly increased at due to large β, η values along the beamline (e.g., β_x at 10 m), and the tilt angle at the final dipole magnet.

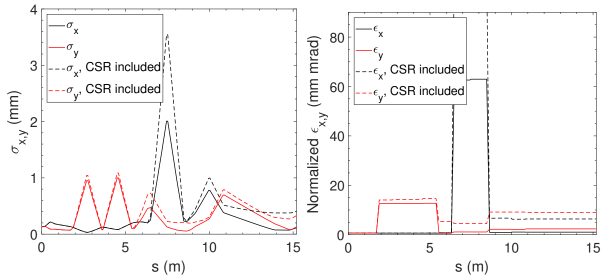

Figure 3: Beam envelope and normalized emittance.

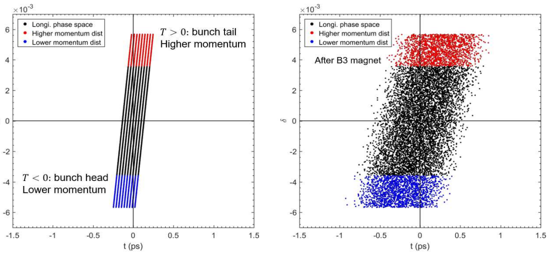

Figure 4: Longitudinal phase space before B_3 (left), and after B_3 (right).

Moreover, the bunch length σ_z at the plasma merge is about 300 fs in the conventional beamline. When the beam passes through the B_3 magnet, its length increases sharply. In the longitudinal phase space before passing through the magnet (Fig. 4), particles (red dot; hot particles) that have momentum larger than the reference momentum are mainly in the bunch tail ($t > 0$), while the cold particles (blue dot) are in the bunch head ($t < 0$). According to the transport matrix, bunch length can be calculated from Eq. (1) where R is transport matrix of the B_3 dipole magnet.

$$s_1 = R_{55}s_0 + R_{56}\delta_0 \tag{1}$$

Since the hot and cold particles are randomly distributed in the transverse phase space, we can ignore corresponding terms on calculating of the bunch length. On the bunch tail, s_1 is balanced by $s_0 + R_{56}\delta$ while on the bunch head, $s_1 = -s_0 - R_{56}\delta$. It means that the bunch head and tail have longer path length compared to the particles before entering the dipole magnet. In order to reduce the bunch length, it is needed to control R_{56}. However, since the dipole magnets are used for the tunnel constraints, we cannot modify a configuration of the dipole magnet.

New Electron Beamline Optics

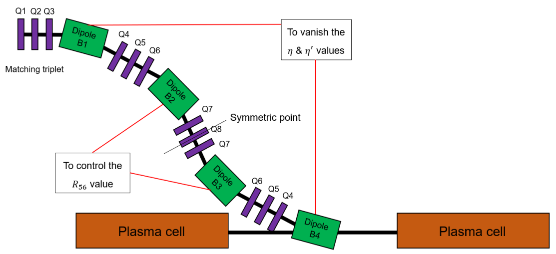

Figure 5: Schematic view of the parallel electron beamline.

In order to overcome the bunch lengthening, another type of electron beamline has been studied. In this case, a four-bend chicane [9] has been considered to control the R_{56}

component. Figure 5 shows the layout of the parallel electron beamline. Proton beamline and plasma cell for SSM are located next to the electron beamline. The bending magnets, B_1 and B_4 with respect to the central quadrupole Q_8 are placed to compensate the η and η'. In the middle of the beamline, B_2 and B_3 are for controlling the R_{56} component. In fact, such a chicane can receive a positive and negative R_{56}. The bending angle of the dipole magnets is 16°, and they bend the beam only in the horizontal plane. In addition, concerning the technical issue of the beamline, distance between two plasma cells should not exceed 1 m for the vacuum-plasma transition of the proton beam. Therefore, the distances between B_1 and Q_4, and Q_4 and B_4 are set to be 1.1 m to avoid space conflicts, and for the symmetry of the beamline.

The matched beamline optics including dispersion function are described in Fig. 6. β at the plasma entrance is 0.5 m, and η is 0 m.

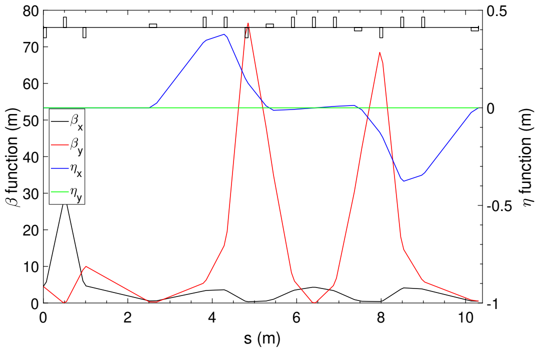

Figure 6: β and η functions along parallel beamline.

The beam envelope, emittance, and bunch length obtained including higher order terms and CSR from the ELEGANT simulations are shown in Fig. 7, and Fig. 8. The beam size and bunch length at the end are about 50 µm and 92 fs with chromatic effects only. However, when the CSR effects is included, σ_x and σ_z at the plasma entrance become 246 µm, and 120 fs, while σ_y maintains its target parameter. The large increases of the σ_x is caused by the CSR effects which is only in the horizontal plane by using only the horizontal bending dipole magnets.

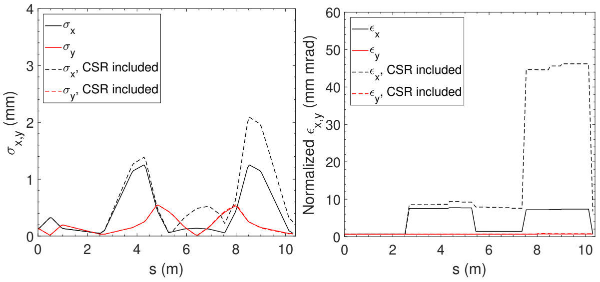

Figure 7: Beam envelope and normalized emittance.

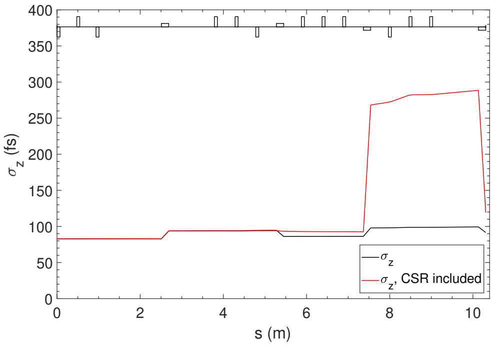

Figure 8: Bunch length along the beamline.

However, we confirmed from the simulation that a higher beam energy can minimize the CSR effects on the σ_x. In this case, 164 MeV electron beam has been used. We also considered the space charge forces on the transfer line using PARMELA [10]. It has been checked that the beam parameters at the end of the beamline are close to the target parameters using the optimized quadrupole strength under the space charge forces. From the PARMELA simulation, σ_x and σ_y at the end of the line are 54 µm, 65 µm, and the bunch length is 79 fs. When the optimized quadrupole strength is used for the ELEGANT simulation for the CSR effects, obtained beam size and bunch length are about 40 µm, and 81.40 fs.

SUMMARY AND FUTURE WORK

The newly introduced transfer line is completely flexible from the bunch length controlling point of view, and it can provide any desired value for the bunch length. However, since the space charge forces and the CSR effects has not been considered simultaneously, studies on the beamline optimization will be done with both effects for the target parameters.

ACKNOWLEDGEMENT

This work was supported by NRF (National Research Foundation of Korea) Grant funded by the Korean Government (NRF-2016-Fostering Core Leaders of the Future Basic Science Program/Global Ph.D. Fellowship Program)

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