SIMULATIONS OF BEAM-BEAM INTERACTIONS WITH RF-TRACK FOR THE AWAKE PRIMARY BEAM LINES

J. S. Schmidt, A. Latina, CERN, Geneva, Switzerland

Abstract

The AWAKE project at CERN will use a high-energy proton beam at 400 GeV/c to drive wakefields in a plasma. The amplitude of these wakefields will be probed by injecting into the plasma a low-energy electron beam (10-20 MeV/c), which will be accelerated to several GeV. Upstream of the plasma cell the two beams will either be transported coaxially or with an offset of few millimetres for about 6 m. The interaction between the two beams in this beam line has been investigated in the past, with a dedicated simulation code tracking particles under the influence of direct space-charge effects. These simulations have recently been crosschecked with a new simulation code called RF-Track, developed at CERN to simulate low energy accelerators. RF-Track can track multiple-specie beams at arbitrary energies, taking into account the full electromagnetic particle-to-particle interaction. For its characteristics RF-Track seems an ideal tool to study the AWAKE two-beam interaction. The results of these studies are presented in this paper and compared to the previous results. The implications for the facility performance are discussed.

MOTIVATION

The plasma wakefield of AWAKE [1] (the Advanced Proton-Driven Plasma Wakefield Acceleration Experiment at CERN) is driven by a 400 GeV/c bunch of $3{\cdot}10^{11}$ protons. In the second phase of the experiment an 10-20 MeV/c electron beam will be accelerated in the plasma wakefield. The design of these two beamlines was presented in [2], the main beam parameter are shown in Table 1.

Table 1: Proton Beam Parameters

Parameter	Protons	Electrons
Particles per bunch	$3{\cdot}10^{11}$	$1.25{\cdot}10^{9}$
Charge per bunch [nC]	48	0.2
Bunch length [mm]	120	1.2
Norm. emittance [mm·mrad]	3.5	2
Momentum [MeV/c]	400 000	10-20
Momentum spread [%]	±0.035	±0.5
Bρ [Tm]	1334.25	0.03-0.07

In order to inject the electron beam into the plasma cell, it has to be merged into the same vacuum chamber as the proton beam. A merging dipole for the electron beam is located about 6 m upstream of the plasma cell. Additional magnets, like the final focussing quadrupoles and corrector magnets, are distributed over the length of this common beam line. Due to its much higher beam rigidity (Bρ), the proton beam is not effected by these magnetic fields. Figure 1 shows the integration model of the primary beam lines upstream of the plasma cell.

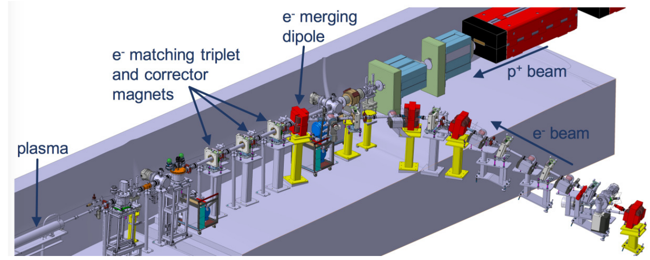

Figure 1: View of the AWAKE primary beam lines upstream of the plasma cell. The e- merging dipole bends the electron beam onto the proton beam axis. The final focussing quadrupoles of the electron beam are located between the merging dipole and the plasma cell. Additional corrector magnets can be used to introduce an offset between the two beams.

Several scenarios were studied for the injection of the electron beam into the wakefield. The baseline trajectory of the electron beam is on an identical axis as the proton beam. Optics for alternative injection schemes with an offset between the two beams in the order of a few mm (with and without an angle at the start of the plasma cell) are prepared as well. This allows to scan the capture efficiency of the electrons in the plasma wakefield according to injection parameters (see [2] for more details).

In any case, the electrons and protons will experience beam-beam forces in the common beam line. While the proton beam will not be effected by these forces, the phase space distribution of the electron beam might change. In [3] first studies based on an analytical model of these interactions were presented. As these studies are crucial for the outcome of the experiment, it was decided to cross-check the analytical results with a fully numerical code called RF-Track.

INTRODUCTION TO RF-TRACK

RF-Track [4] is a code developed for the optimisation of low energy accelerators, exhibiting some unique characteristics that make ideal for the study presented in this paper: it implements fully-relativistic tracking of multiple-specie beams, and it applies full electromagnetic interaction simultaneously including space-charge and beam-beam effects.

RF-Track solves the differential laws of electromagnetism to compute the forces acting within the beam. The electromagnetic interaction is computed, in 3d, using two independent alternative methods: *particle-to-particle* algorithm, where the electromagnetic interaction is computed between each pair of particles; or the faster *cloud-in-cell* algorithm,

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where the electric and the magnetic fields are computed solving the Maxwell equations for the scalar and the vector potentials, using a Fourier method on a grid. No approximations such as "small transverse velocities", or $\vec{B} \ll \vec{E}$ are made.

Furthermore, RF-Track is capable of integrating the equations of motion using two models: beam moving *in space*, where all particles lie on a thin sheet sharing the same longitudinal position S, and the tracking is performed integrating the equations of motion in dS; or beam moving *in time*, where the particle coordinates are kept as a six-dimensional snapshot taken at the same time t, and the tracking is performed integrating the equations of motion in dt. The effect of the space-charge force can be applied every N steps of motion integration, with N an arbitrary integer number chosen by the user. Last but not least, RF-Track offers a friendly and easy user interface through the scientific code Octave [5].

SIMULATIONS OF THE AWAKE COMMON BEAM LINE WITH RF-TRACK

A number of different aspects of space charge forces in the 6 m common beam line were simulated in the time domain of RF-Track using integration steps of dt=1 mm/c. The presented studies include space charge effects within a separate bunch, the interaction of the proton and electron bunches copropagation on the same axis and with an offset between the two bunches up to the start of the plasma cell (focal point of the electron and proton beam), as well as an additional drift of 10 m through the plasma cell under vacuum. In all simulations no effect could be observed on the proton bunch, as its momentum is factor of 20000 higher than the one of the electron bunch. Therefore the following discussions concentrate on the electron beam distribution.

Start Distributions of the Proton and Electron Bunch

The simulated lattice was chosen to start at the end of the electron merging dipole. Figure 2 gives an impression of the distributions of the proton and electron bunch at this point.

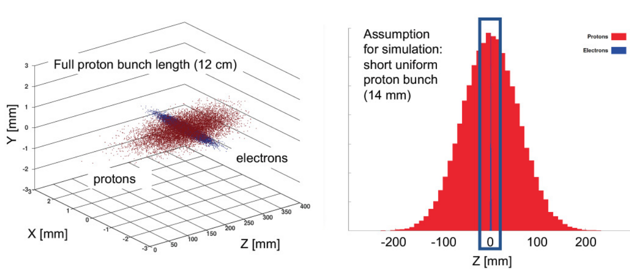

Figure 2: Starting distribution of the electron and proton bunch from the optics TWISS parameter. The long gaussian proton bunch has been reduced in the simulation model to a short one around the electron bunch with a constant particle distribution as indicated by the window in the histogram.

These distributions have been generated according to the TWISS parameter given by the optics of each beam line. The full 3d view of the two bunches is shown on in the left plot of Fig. 2, the histogram on the right shows the longitudinal relation of the 1.2 mm long electron bunch inside the 12 cm long proton bunch. In order to optimise the simulation volume, further studies were performed with a simplified model of the proton bunch. Instead of the full bunch length with a gaussian distribution in all planes, a short proton bunch with a constant particle distribution in the longitudinal plane was generated at ±7 mm around the electron bunch as indicated by the window in the histogram in Fig. 2.

Simulations With a Gaussian Electron Beam Distribution

In a first step the effect of space charge forces within the electron bunch were tested. Figure 3 shows the comparison of the tracked electron bunch phase space with and without space charge included in the simulation. The effect is not strong, but a minor beam blow-up can be seen.

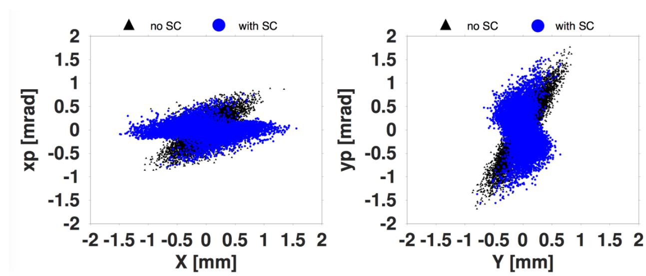

Figure 3: The electron phase space at the focal point with and without space charge included in the tracking algorithm.

In the following studies the population of the proton bunch was raised up to the full intensity of $3{\cdot}10^{11}$ protons. The electron beam phase space after tracking with the nominal proton bunch is presented in Fig. 4. The two regimes of the beam-beam force can be distinguished in these plots. The linear regime close to the proton beam axis has a quadrupole like effect on the core of the electron beam, which experiences a rotation. The non-linear regime of the beam-beam force leads to a distortion of the outer part of the electron bunch, where it experiences filamentation.

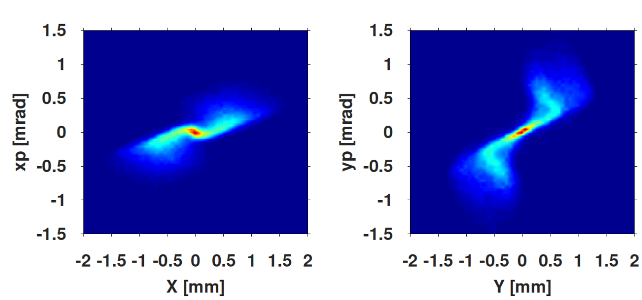

Figure 4: The electron phase space at the focal point after copropagation on axis with the $3{\cdot}10^{11}$ proton bunch.

For the same set-up, simulations were performed including an additional drift of the electron and proton bunches through the 10 m plasma cell under vacuum. This simulation of in total 16 m of coprogation shows that the beam-beam interaction can lead to a pinching effect on the electron beam core, while the outer arms are further blown out. A similar behaviour was observed as well in the simulations with the analytical model.

As mentioned before in the introduction, an offset of several mm between the proton and electron beam axis is of interested to study the dependency of the plasma wakefield capture efficiency on the electron beam parameter at injection. This kind of offset was also shown to reduce the electron beam blow-up due to the proton beam interaction in the former studies. Therefore a possible corrector configuration, which introduces a vertical offset of 3 mm from the first corrector in the common beam line up to the plasma cell, was studied with RF-Track. The transverse profiles of the tracked electron beam for the on-axis (left) and offset (right) case are presented in Fig. 5. The spot size of the electron beam in the simulation including the 3 mm offset is comparable to the one without a proton beam present, while a blow-up can be observed for the on-axis simulation.

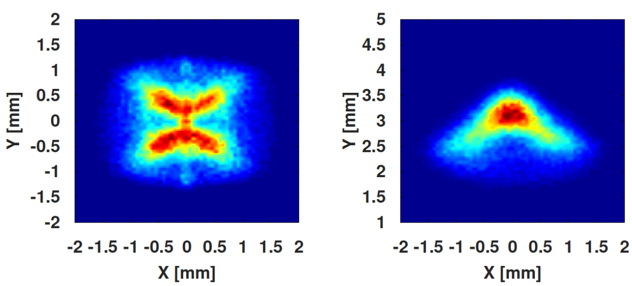

Figure 5: The transverse profiles of the electron bunch at the focal point after propagation through the common beam line on-axis (left) and with an offset of 3 mm between the electron beam axis and the proton beam axis (right).

Simulations With an Imported Transverse Electron Beam Distribution from PTC Tracking Simulations

In order to study also a more realistic transverse electron distribution, results of a PTC tracking simulation [6] were imported into RF-Track to form the starting distribution at the end of the merging dipole. The phase space for this case is shown in Fig. 6, where the chromatic effects due to a non-zero dispersion in the vertical plane are visible. Beam profile measurements and PTC tracking simulations show that the assumption of a gaussian bunch shape is valid for the proton bunch.

In this distribution the electron density at the core of the bunch is reduced compared to a gaussian bunch. As the proton bunch is located in the geometric centre of the electron bunch, this leads to a reduction of the beam-beam interaction between the proton and electron bunch. The results of this tracking simulation in Fig. 7 confirm this consideration. They show a reduced filamentation of the electron beam compared to the simulations of the gaussian

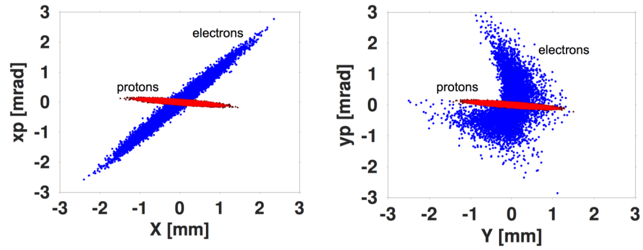

Figure 6: Transverse phase space of the imported electron bunch distribution, which was generated by PTC tracking simulations of the electron beam line.

bunch. Also a pinching effect, similar to the one which was observed in the simulation of the additional 10 m drift through the plasma cell can be identified.

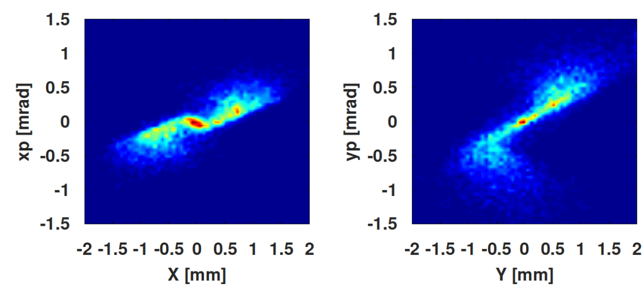

Figure 7: The tracked electron phase space of the PTC based starting distribution after copropagation on axis with the $3{\cdot}10^{11}$ proton bunch.

CONCLUSION

The characteristics of the electron bunch at the focal point are crucial for the capture efficiency of the electrons into the plasma wakefield of AWAKE. The goal of the presented studies was to use tracking simulations with the code RF-Track, which is capable to include electromagnetic interaction in combination with space-charge and beam-beam effects, to study the effect of the proton bunch onto the electron bunch for the different possible operational scenarios of the AWAKE electron beam. For all simulations, which were performed with the gaussian electron beam distribution, the results of the RF-Track studies match well with the results of former studies based on an analytical beam-beam model. Both studies lead the the conclusion that an offset in the mm-range between the proton and electron beam axis reduces the blow-up of the electron bunch due to the copropagation with the proton bunch. Additional studies were performed with more realistic transverse starting distributions of the electron bunch imported from PTC simulations. They showed that the beam-beam effect might be overestimated by simulations with gaussian distributions and that there is the possibility of a pinching effect, which creates a dense core of the electron beam.

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