S-BAND BOOSTER DESIGN AND EMITTANCE PRESERVATION FOR THE AWAKE e⁻ INJECTOR

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Abstract

AWAKE is a proton driven plasma wakefield acceleration experiment at CERN which uses the protons from the SPS. It aims to study the self modulation instability of a proton bunch and the acceleration of an externally injected electron beam in the plasma wakefields, during the so called "Phase II" until the technical stop of LHC and its injector chain (LS2) in 2019. The external electron beam of 0.1 to 1nC charge per bunch will be generated using an S band photo injector with a high QE semiconducting cathode. A booster linac was designed to allow variable electron energy for the plasma experiments from 16 to 20 MeV. For an rf gun and booster system, emittance control can be highlighted as a challenging transmission task. Once the beam emittance is compensated at the gun exit and the beam is delivered to the booster with an optimum beam envelope, fringing fields and imperfections in the linac become critical for preserving the injection emittance. This paper summarises the rf design studies in order to preserve the initial beam emittance at the entrance of the linac and alternative mitigation schemes in case of emittance growth.

INTRODUCTION

The Advanced Wakefield Accelerator (AWAKE) project offers an experimental program to study proton beam driven plasma wakefield acceleration (PDPWA). It is currently being built at CERN with the collaboration of many institutes [1]. This project aims to use the proton beam from the SPS accelerator which also serves as the LHC injector alongside with many other experiments at CERN. Plasma wakefields will be induced by the 400 GeV SPS beam and a seeding laser. After establishing the wakefields in a 10 m long plasma, a second beam, the so-called witness beam will be injected into the plasma. The witness beam, which consists of single electron bunch of 0.1 to 1 nC with energies ranging from 16 to 20 MeV, will be accelerated through the plasma [2]. An rf gun based electron injector will provide the witness beam for the AWAKE experiment. The injector system consists of a 3 GHz standing wave (SW) structure based on the existing PHIN gun and a constant gradient travelling wave structure as booster linac. Baseline beam specifications and parameter ranges for systematic plasma experiments which should be delivered by the injector system are summarised in Table 1.

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Table 1: Specifications for the Simulation Studies for the Baseline and the Parameter Range of Interest

Parameter	Baseline	Range
Beam energy (MeV)	16	10-20
Energy spread (σ, %)	0.5	-
Bunch length, (σ, ps)	4	0.3-10
Beam focus size, (σ, μm)	250	250-1000
Norm. emittance (rms, mm-mrad)	2	0.5-5
Bunch charge, (nC)	0.2	0.1-1

A photo injector is an electron source that uses laser pulses in order to extract electrons from the surface of a metallic or a semiconductor cathode (such as Cu and Cs_2Te). Electrons can escape the cathode surface if the laser pulses provide sufficient energy for electrons to overcome the potential barrier of the surface. The cathode plug is placed in one end of an RF cavity. This RF cavity is used for the rapid acceleration of the electrons after the production. Photo injectors can produce high brightness, low emittance electron beam; this is a mature technology, first implemented in the 1980s. There have been many improvements since then motivating the photo injectors as versatile and reliable electron sources. Some historical highlights and overview of photo injectors can be found in [3–5].

CERN's Super Proton Synchrotron (SPS) will provide the proton beam for the experiment, various modifications were implemented on the corresponding beamline which previously provided protons for neutrino experiments [6,7]. Commissioning of the experiment and data taking will take place in 2016-2017 with protons during the so called "Phase I" [8,9].

In Phase II of the experiment the electron beam will be injected into the plasma to be captured and accelerated by plasma wakefields. The injector consists of an S-band RF gun and traveling wave booster linac. Photoelectrons emerging from a semiconductor cathode will be accelerated to 6.6 MeV by the 2+1/2 cell RF gun with 100 MV/m accelerating gradient. Consequently, the electron beam will be transported to the constant gradient travelling wave booster linac which allows to span the energy range requested by the plasma experiments.

BOOSTER DESIGN

An S-band booster linac, ATS, was designed as a travelling wave structure with constant gradient of 15 MV/m through the entire structure (Fig. 1-a). It consists of 30 cells

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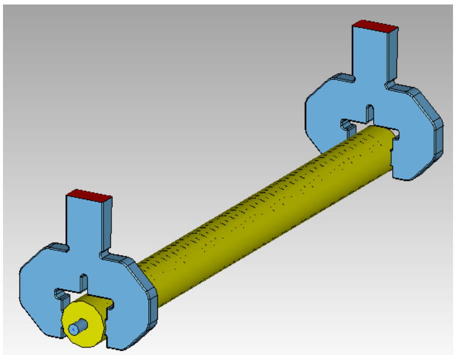
with 120° phase advance and varying radii matched to 1 µm precision. ATS was optimised for low reflection coefficient of about 2.5%. The multipole terms due to transverse RF-kicks are 9.4×10^{-7} mT, 7.8×10^{-5} mT/m and 4.9×10^{-3} mT/m^2, respectively, from dipole to sextuple terms.



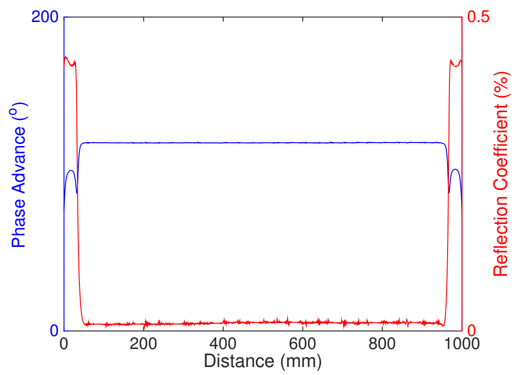


Figure 1: a) A CST drawing of the 30 cell linac with couplers. b) Evolution of phase advance and the reflection coefficient along the linac.

Evolution of the longitudinal electric field, E_z, across the linac at $t = 0$ is presented in Figure 3 at an extent covering the bore tube, where fringing occurs, and six subsequent cells. The figure shows different colours corresponding to radial locations, r, from 0 to 10 mm in steps of 2 mm, revealing a certain charge in E_z as a function of r. As implied by Panofsky-Wenzel theorem, $dE_z/dr = dE_r/dz$, a non-zero E_z' induces a radial field E_r.

In PARMELA [11], two field maps must be provided for a travelling wave structure; one produced with Neumann boundary condition (cosine map) and the other with Dirichlet boundary condition (sine map). These fields which are shifted in phase by 90° are fed into PARMELA by using the TRWCFIELD command. A single TRWAVE line is used to represent the entire ATS including the bore tubes with lengths equal to a cell length at each end of ATS to account for the fringe fields.

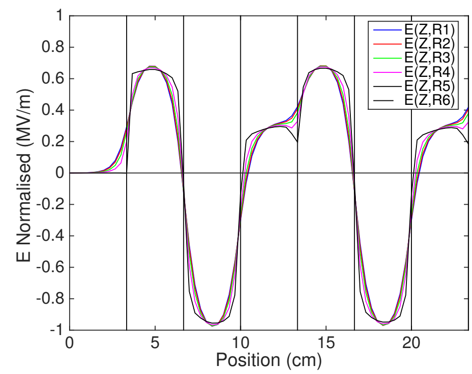


Figure 3: Longitudinal fields at subsequent radii cross the bore tube and first six cells.

BEAM TRANSPORT

In the presence of space charge force, the delivery of optimum beam envelope and emittance compensation are ensured by applying a sufficient solenoidal field at the exit of an RF gun (Figure 2). In theory [10], for a system consisting of an RF gun and a linac, beam envelope should be so that the waist of the beam occurs at the entrance of the linac. This aims to ensure beam laminarity (particle trajectories do not cross) hence a minimal emittance growth through the RF field. Aside from the space charge force, emittance can be affected by the radial fields, multipole fields and uncanceled defocusing edge effects of the fringing fields in a linac.

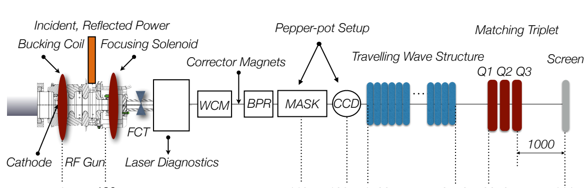


Figure 2: Layout with AWAKE e$^-$ injector.

Beam dynamics across the beamline and through the booster linac was studies using PARMELA. Parmela provides a built-in model to simulate a travelling wave structure as well as the possibility to import a field map of the real structure model. Figure 4 compares the transverse normalised emittance evolution for such two cases. In addition emittance evolution was benchmarked against RF-Track [12], an alternative code which also features the space charge. Results agree within 0.5 mm mrad. However, although the slope of the emittance curve are similar for both codes, the envelope oscillation amplitudes and the absolute initial emittances at the entrance of the structure differ. These points will be investigated further.

In order to reach the design emittance 2 mm mrad, a compromise with energy spread can be explored by adjusting the phase of the booster around the on-crest phase. In these simulations, the arbitrary on-crest phase for the booster is 16^o. Figure 5 shows the linac phase scan $\pm10^o$ around the on-crest where emittance can be reduced by 0.1 mm mrad before the energy spread budget of 0.5% is exceeded. Design emittance can be reached 21^o out of phase given that an energy spread of 1.5% can be tolerated.

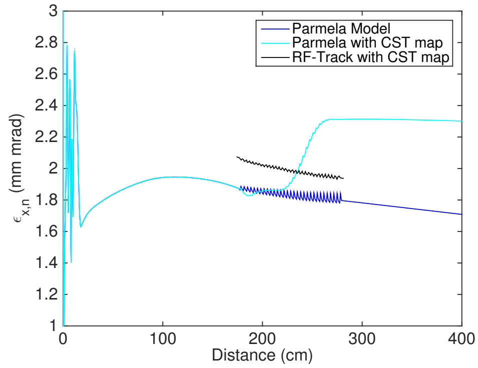


Figure 4: Tracking results for emittance evolution along the beamline.

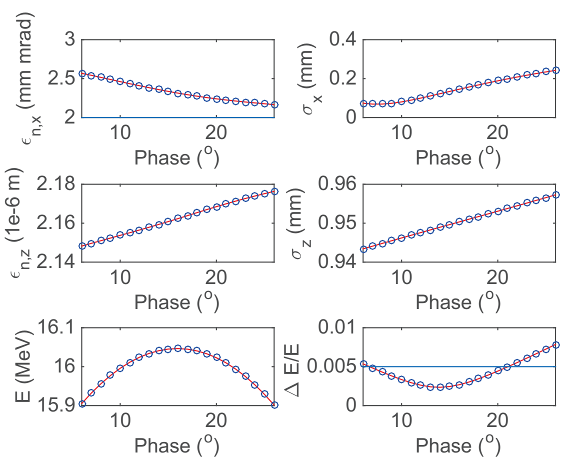


Figure 5: Variation of observables around the on-crest phase.

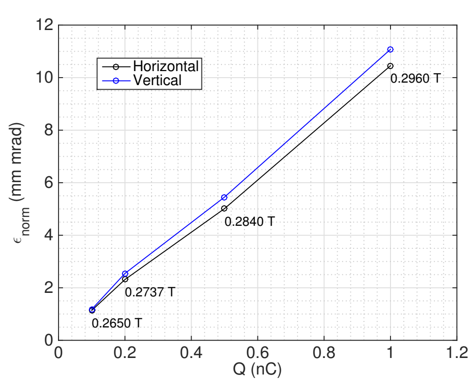


Figure 6: Beam emittance as a function of the charge per bunch.

In order to provide a wider range of witness beams for the plasma experiment the behaviour between 0.1 to 1 nC region was characterised. In Figure 6 shows the emittance as a function of charge. For each case emittance compensation was ensured by means of the two solenoids located around the RF gun.

CONCLUSIONS AND OUTLOOK

The preservation of the initial emittance through the linac of the AWAKE e^- injector was studied. Emittance compensation for the RF gun exit was performed while meeting the quasi-laminar beam condition at the linac entrance to minimise emittance growth through the structure. Consistent results were obtained after cross-checking tracking in PARMEA with field maps from CST and custom maps as well as tracking particles with RF-Track using CST field maps. Sensitivity of the beam parameters to the deviation from the on-crest phase was assessed. Given a further emittance reduction is required, a compromise between emittance and energy spread was characterised at a particular off-crest phase. Extensive analysis for the mechanical errors were carried out which are not presented in this paper. The largest impact on the beam was shown to be the errors on the radius of the first cell.

Further work will be extended to the tests with X-band RF structures, effect of phase errors, fringing fields, technicalities related to particle-in-cell tracking and different beam distributions. Those results will be soon reported elsewhere.

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