WITNESS BEAM PRODUCTION WITH AN RF GUN AND A TRAVELLING WAVE BOOSTER LINAC FOR AWAKE EXPERIMENT AT CERN

Oznur Mete Apsimon*†, Robert Apsimon†, Graeme Burt†, Lancaster University, Lancaster, UK
Guoxing Xia†, The University of Manchester, Manchester, UK †
Steffen Doebert, CERN, Geneva, Switzerland

Abstract

AWAKE [1] is a unique experiment that aims to demonstrate the proton driven plasma wakefield acceleration. In this experiment, proton bunches from the SPS accelerator will be injected into a 10 m long pre-formed plasma section to form wakefields of hundreds MV/m to several GV/m. A second beam, e.g., the witness beam, will be injected after the protons in an appropriate phase to gain energy from the wakefields. A photo-injector will be utilised to deliver this second beam. It consists of an S-band RF gun followed by a meter long accelerating travelling wave structure (ATS). The RF gun was recuperated from existing PHIN photo-injector. A 3D RF design of the ATS was done by using the CST code and the field maps produced were used to characterise the electron beam dynamics under space charge effect by using the PARMELA code. The impact of the mechanical errors on the beam dynamics were investigated.

INTRODUCTION

The AWAKE experiment consists of a 10 m long plasma cell to study the production of proton driven plasma wakefields and acceleration of an externally injected electron beam by these wakefields. 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 [2, 3]. Commissioning of the experiment and data taking will take place in 2016-2017 with protons during the so called "Phase I" [4, 5].

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.

* o.mete@lancaster.ac.uk
† and The Cockcroft Institute, Sci-Tech Daresbury, Warrington, UK

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 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.

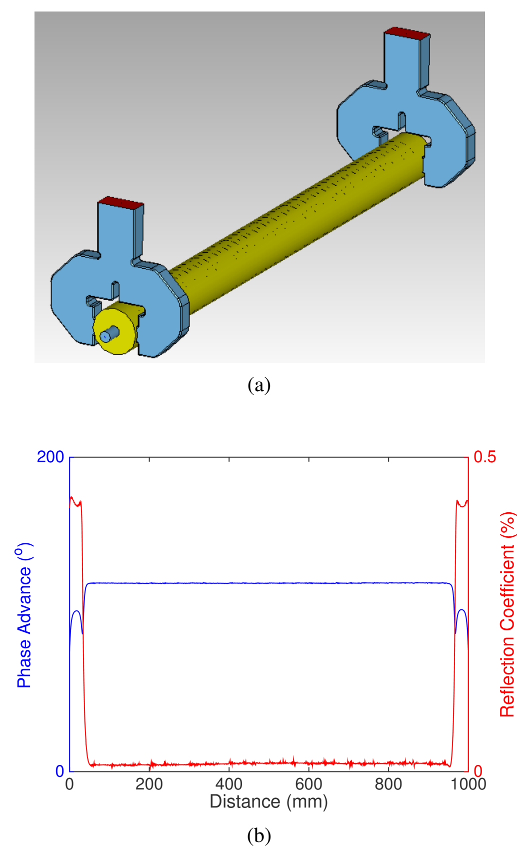

Figure 1: a) A CST drawing of the 30 cell linac with couplers. b) Evolution of phase advance and the reflection coefficient along the linac.

In PARMELA, 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.

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 [6], 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.

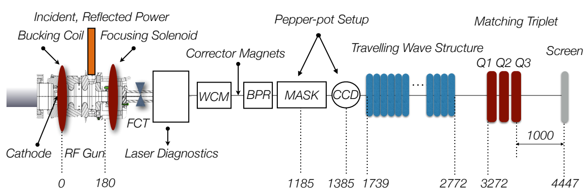

Figure 2: Layout with AWAKE e$^-$ injector.

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.

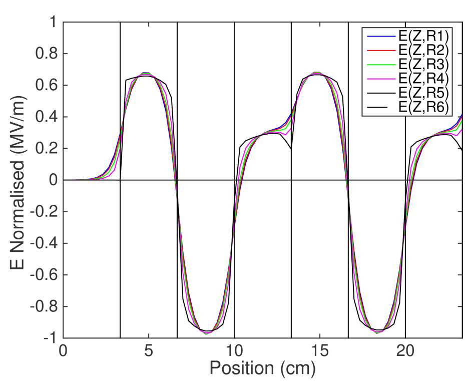

Figure 3: Longitudinal fields at subsequent radii cross the bore tube and first six cells.

Beam dynamics across the beamline and through the booster linac was studies using Parmela [7]. 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 [8], an alternative code which also features the space charge. Results agree within 0.5 mm mrad.

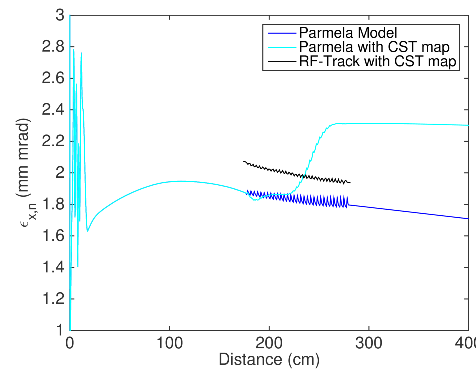

Figure 4: Tracking results for emittance evolution along the beamline.

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.

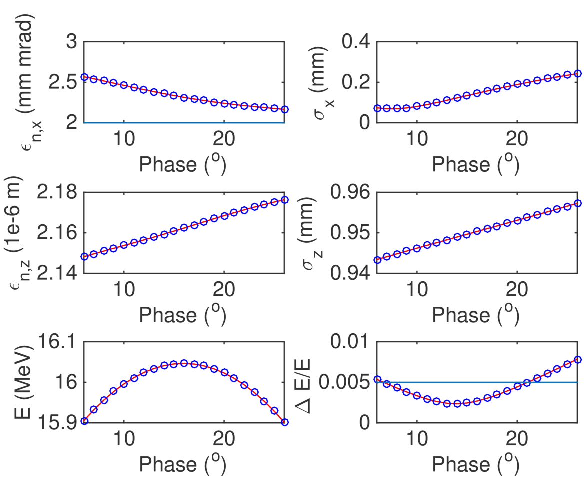

Figure 5: Variation of observables around the on-crest phase.

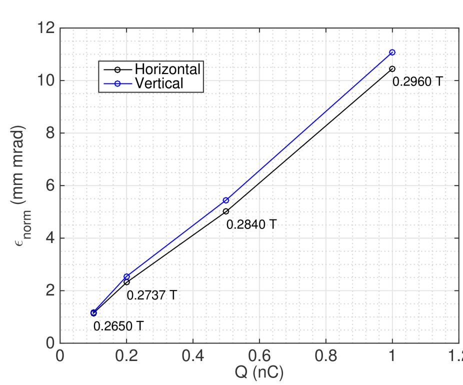

Figure 6: Beam emittance as a function of the charge per bunch.

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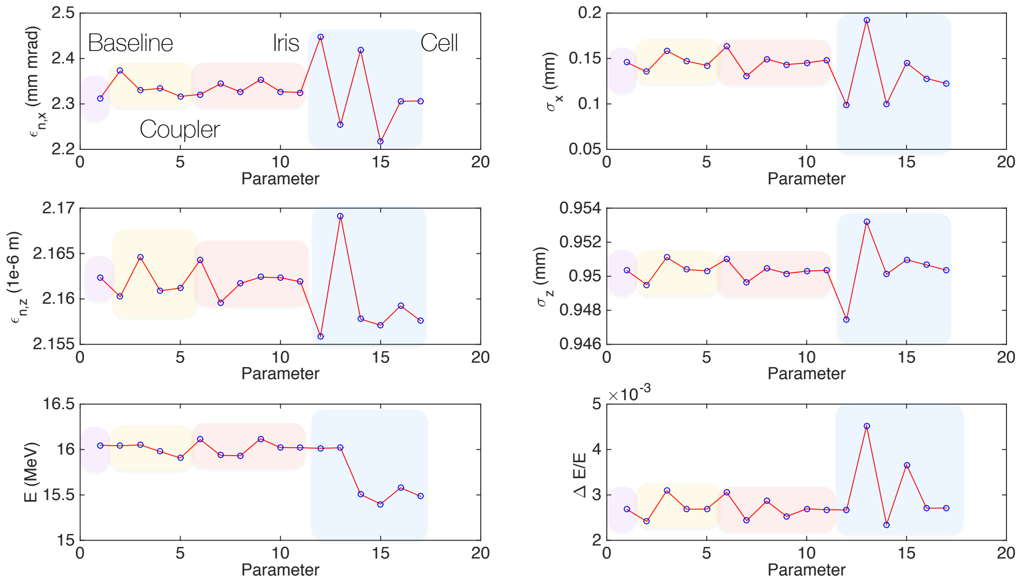

Figure 7: Various beam dynamics observables as a function of geometric modifications on the linac cells.

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.

ERROR STUDIES

Error studies were conducted in three groups; a) coupler cell radius (for cells: 1^{st}, 30^{th}); b) iris aperture (for cells: 1^{st}, 15^{th}, 29^{th}); and c) cell radius (for cells: 1^{st}, 15^{th}, 30^{th}) were modified systematically to investigate the effect on the beam. Each dimension was adjusted ±20 μm. For each case, particles were tracked using the field maps extracted from CST and the effects on the beam dynamics observables were recorded.

Table 1: Definition of Data Points in the Error Studies Plots

Parameter	Radius Type	Cell number	Modification
1 - 4	Coupler cell	1, 30	∓20 μm
5 - 10	Iris aparture	1, 15, 29	∓20 μm
11 - 16	Cell radius	1, 15, 30	∓20 μm
17	Baseline	All	None

Table 1 summarises the data points presented in Figure 7 corresponding to the aforementioned three groups. The largest impact on all observables was caused by the change in the radius of the first cell.

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 presented. 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.

ACKNOWLEDGEMENTS

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