

ULTRA-SHORT BUNCH ELECTRON INJECTOR FOR AWAKE

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Abstract

The proton driven plasma wake field acceleration experiment AWAKE at CERN will start at the end of this year. In 2017 an S-band electron injector producing bunches of a few ps in length will be added to probe the wake fields stimulated by a driving proton beam. In the future this electron injector will have to be upgraded to obtain electron bunches with a length of 100 - 200 fs in order to demonstrate injection into a single bucket of the plasma wave and therefore sustainable acceleration with low energy spread. Target bunch parameters for the study are a bunch charge of 100 pC, 100 fs bunch length, an emittance smaller than 10 mm mrad and a beam energy > 50 MeV. The status of a study to achieve these parameters using X-band accelerator hardware and velocity bunching will be presented.

INTRODCUTION

The proton driven plasma wakefield experiment at CERN called AWAKE [1,2] is about to start operation at the end of 2016. The first phase will use the 400 GeV proton beam from the SPS and a high power laser to trigger a self-modulated instability (SMI) within the roughly 1-2 ns long proton bunch. The modulated proton beam can then drive resonantly plasma wakefields in a rubidium vapour plasma. The layout of the experiment is shown in figure 1. The first phase of the experiment will focus on studying this self-modulated instability and the wakefields by observing their effects on the proton beam.

In a second phase starting at the end of 2017 an electron injector will be added to be able to directly probe the generated wakefields with an electron beam and measure its acceleration. This electron injector consists of a conventional s-band rf gun receiving a fraction of the laser energy used to generate the plasma and the SMI. The energy of the beam is boosted up to 20 MeV by an s-band accelerating structure. Beam charges between 0.1 and 1 nC can be accelerated with an emittance of the order of 2 mm mrad. Initially the bunch length of such beams will be 4 ps sigma initially and might be reduced by a factor of two by compressing the drive laser pulse length. This second phase of AWAKE should demonstrate the principle of electron acceleration with proton driven plasma wakefields. We expect electron beams accelerated up to 1-2 GeV in our 10 m long metal vapour plasma cell. The emphasis is not yet to show acceleration of high quality beams with a reasonable energy spread and emittance preservation.

The longer term goal of the AWAKE experiment however is to investigate if this novel acceleration concepts can be used for high energy physics applications. Therefore the emphasis of the next stage of the experiment named RUN

II [3] will be on demonstrating the accelerating of high quality beams and expandability of the plasma cells providing the acceleration. It is clear that the briefly described injector for phase 2 below will not be able to provide the necessary beam parameters for this purpose in particular the bunch length has to be reduced to a fraction of the plasma wavelength in our experiment. Studies are ongoing to determine the optimal parameters for RUN II in terms of bunch length and beam current.

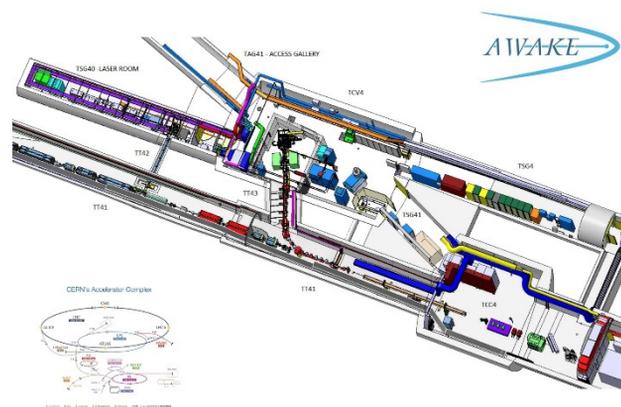


Figure 1: Overview of the AWAKE facility at CERN. A proton beam (lower left) from the SPS is sent into a 10 m long plasma cell (lower right) for interaction with a high power laser and an electron beam (central).

BASELINE INJECTOR FOR AWAKE

The electron injector for phase 2 of the AWAKE experiment has been designed taking into account numerous constraints. This part of the experiment was added relatively late to the CERN work package, which led to the choice of recycling partly existing hardware from the CLIC studies. In addition there are serious space restriction in the current setup of AWAKE that uses existing tunnels and caverns. Only about 5 m are available for the electron source, for subsequent acceleration to 20 MeV and for the associated beam line diagnostics. The layout of the injector is shown in figure 2 and is described in detail in [4]. The drive laser pulse for the rf gun is derived from the high power laser enabling the plasma and SMI generation. A custom scheme of quadrupling its frequency and pulse compression in air led naturally to a laser pulse length between 2 and 10 ps FWHM on the cathode. The rf gun is equipped with a load-lock system that allows to use copper cathodes or Cs₂Te cathodes with a higher quantum efficiency. Simulations with the tracking code ASTRA [5] predicts an emittance of 1.8 μm for a bunch charge of 0.2 nC. The gradient used in the rf gun is 100 MV/m and 15 MV/m in the 3 GHz booster

structure. The final expected bunch length is 2.6 ps rms using a 4 ps laser pulse.

The purpose of this paper is to study possibilities for much shorter bunches, possibly taking into account the existing space restrictions. Since Run II will not start before 2021 there is also the possibility to overcome some of the constraints providing more space for the injector.

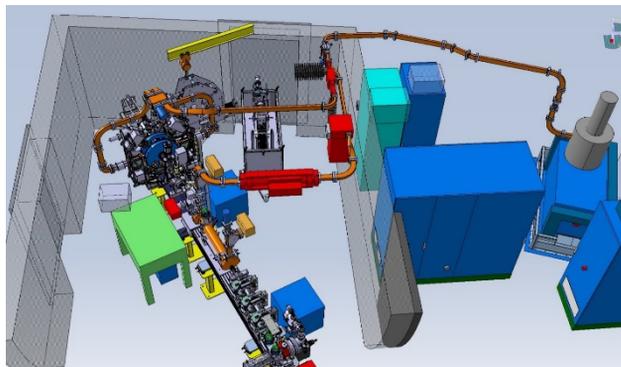


Figure 2: 3D-model of the AWAKE electron source. One can see the rf-gun in the back the 1 m booster structure in the centre of the beam line and the klystron powering the injector at the right hand side. The whole injector is about 5 m long.

REQUIREMENTS FOR AWAKE RUN II

The goal of Run II is to demonstrate sustainable plasma wakefield acceleration while preserving a reasonably good beam quality [3]. Eventually, an electron beam accelerated to ~10 GeV, suitable for high energy physics experiments would be desirable. Here we have fixed target experiments or proton-electron collisions in mind rather than a linear collider. For the study of the injector the following preliminary parameters have been chosen (see table 1).

Table 1: Tentative Beam Parameters for AWAKE RUN II

Parameter	Value
Accelerating gradient	> 0.5 GV/m
Energy gain	10 GeV
Injection Energy	> 50 MeV
Bunch length, rms	< 50 μm, 166 ns
Peak current	200 – 400 A
Bunch charge	100- 200 pC
Final energy spread, rms	few %
Final emittance	< 10 μm

The bunch charge is determined by plasma wakefield simulations aim to load the corresponding fields correctly in order to obtain a reasonable energy spread. The desired bunch length was set to about ~100 fs for the purpose of this paper in order to obtain an energy spread of ~ 10 % but of course even shorter bunches would be desirable. Bunch charges between 100 and 200 pC are required to load correctly the wake fields. The higher energy of the injected beam will help to get better through the inevitable plasma density ramp at the entrance and to reduce phase slip. As

one can see from the parameters there is not a special emphasis on emittance corresponding to the initial applications of such a beam.

SHORT PULSE INJECTOR SIMULATIONS

There are several existing or planned facilities which can achieve the requirement beam parameters described above. Examples are Sparc-Lab in Italy or SINBAD in Germany, which are accelerators dedicated to plasma wakefield acceleration providing or that will provide ultra-short bunches based on classical S-band acceleration with adiabatic bunching and final magnetic bunch compression [6,7]. Bunch lengths down to a few femtoseconds can be expected or have been achieved. These facilities are typically 40 -50 m long. A very compact all x-band approach has been studied at SLAC, in the US, using an x-band rf-gun and accelerating cavity [8]. Simulations indicated that, if an x-band bunching cavity would be added, bunch lengths below 100 fs would be accessible. However the operation of an x-band rf-gun seems to be challenging. Finally an injector based on laser plasma wakefield acceleration (LPWA) would naturally provide ultra-short bunches [9]. This option will be studied as well within the AWAKE project.

For our approach we kept the S-band rf-gun from our baseline injector that can easily provide the required bunch charge and emittance. The rf-gun is followed by a short x-band adiabatic bunching structure and subsequent high gradient x-band acceleration. With this approach we might be able to preserve the well understood operation of the s-band gun together with moderate laser parameters and benefit from the compactness of x-band accelerators and the expertise with this hardware at CERN. The schematic configuration is sketched in figure 3.

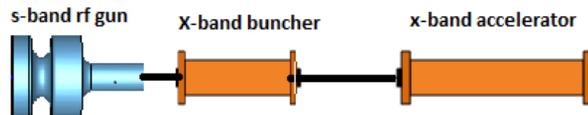


Figure 3: Simple schematic of the studied injector configuration. The electron bunches are generated in an s-band rf-gun, followed by a 30 cm long x-band structure for bunching. Finally a 1 m long high-gradient x-band accelerator is placed at the longitudinal focus (2.6 m from the cathode) for final acceleration.

The adiabatic bunching structure uses a modest gradient of 22 MV/m and has a length of ~30 cm. A CLIC prototype accelerating structure could be used for that purpose. At the longitudinal focus we use a high gradient accelerator at 80 MV/m that is able to freeze the bunch length rapidly. This structure is about 1 m long, and the beam reaches therefore more than 80 MeV at the end of this very short injector. As an example we use here an x-band structure developed as a lineariser for FEL's which is used at ELETTRA and SWISS-FEL [10].

The simulations have been done with the tracking code ASTRA. If we assume a bunch charge of 200 pC, a gaussian laser spot size of 1 mm and an initial laser pulse length of 2 ps with a uniform distribution, we can reach a rms bunch length of 116 ps at the end of the linac.

Reducing the charge to 100 pC allows for obtaining even

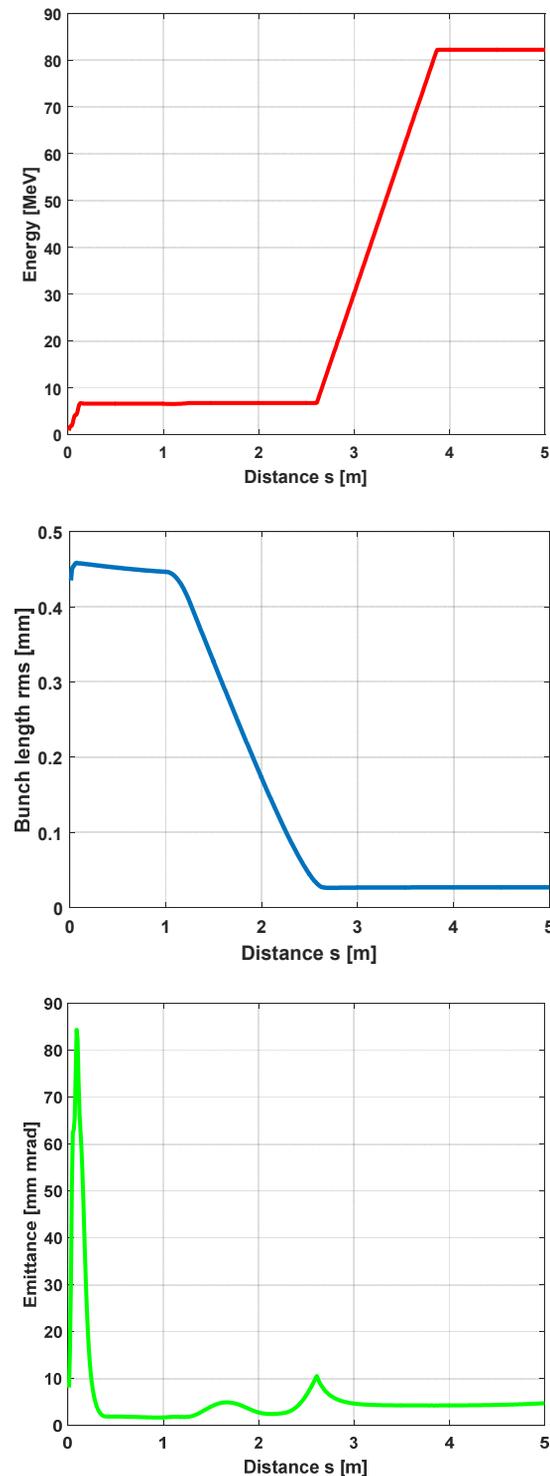


Figure 4: Energy, Bunch length and Emittance long the beam line.

shorter bunches. At the end of the injector, 5 meters from the cathode, we simulate a bunch length of 90 fs rms at an energy of 82 MeV. The energy spread is about 0.5 % rms and the emittance amounts to 5 μm . The transverse phase space has not yet been optimized. Solenoids were used to accomplish the emittance compensation in the gun area, but for simplicity the rest of the injector uses a uniform solenoidal field for the simulations.

CONCLUSION

An electron injector scheme was studied to provide electron bunches with a length of the order of 100 fs with a charge of 200 pC and an emittance below 10 mm mrad. It turns out that a combination of a s-band rf gun and x-band structures could be suitable for efficient adiabatic bunching and fast acceleration. Such a scheme would be attractive for AWAKE because of the short length of such an injector and the availability of x-band expertise and hardware from the CLIC program at CERN.

Much more detailed studies have to be done of course to provide a viable design that could be considered as an option for AWAKE Run II. In particular it will be interesting to compare such an approach with an all x-band one and with an injector based on LPWA.

ACKNOWLEDGEMENT

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REFERENCES

- [1] A. Caldwell, *et al.*, "Path to AWAKE: Evolution of the concept", Nucl. Instr. Meth. A 829 (2106)
- [2] E. Geschwendtner, *et al.*, "AWAKE, The advanced proton driven plasma wakefield acceleration experiment at CERN", Nucl. Instr. Meth. A 829 (2106)
- [3] E. Adli, *et al.*, "Towards AWAKE applications: Electron acceleration in a proton driven plasma wake", in *Proc. IPAC'16*, Busan, Korea
- [4] K. Pepitone, *et al.*, "The electron accelerator for the AWAKE experiments at CERN", Nucl. Instr. Meth. A 829 (2106)
- [5] K. Floettmann, Astra Particle Tracking Code, <http://www.desy.de/mpyflo/>
- [6] C. Vaccarezza, *et al.*, "The SPARC_LAB Thomson source", Nucl. Instr. Meth. A 829 (2106)
- [7] U. Dorda, *et al.*, "Sinbad-The accelerator R&D facility under construction at DESY", Nucl. Instr. Meth. A 829 (2106)
- [8] C. Limborg, *et al.*, "Performance of the first generation x-band photo rf gun", Phys. Rev. Accel. Beams 19, 053401, 2016
- [9] P. Muggli, *et al.*, "Injection of a LWFA electron bunch in a PWFA driven by a self-modulated proton bunch", in *Proc. IPAC'14*, Dresden, Germany
- [10] M. Dehler, "Fabrication of the CERN/PSI/ST X-band accelerating structure", in *Proc. IPAC'11*, San Sebastian, Spain.