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PROTON ELECTRON ACCELERATOR AT CERN*

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Abstract

AWAKE is a proton driven plasma-wakefield acceleration experiment at CERN that uses proton bunches from the SPS. In a dense plasma, a long proton bunch ($\sigma_{tb} \sim 400$ ps) is subject to micro-bunching at the plasma period due to the self-modulation instability. The self-modulated proton bunch generates large amplitude charge separation in the plasma through resonant wakefield excitation. We briefly summarise the physics of self-modulation instability, the AWAKE experiment layout, the plasma source under study and the diagnostics plan for bunch modulation measurement using transition radiation.

INTRODUCTION

Plasma-based accelerators are of great interest because of their capability to sustain large acceleration gradients. It has been shown that a drive beam (either laser or electron beam) produces a plasma wave (wakefield) that can accelerate charged particles with gradient of up to 100 GV/m [1–4]. Afterwards a new plasma-based acceleration scheme using a high-energy proton bunch was proposed by Caldwell et al. [5]. Proton bunches produced in conventional accelerators, such as the CERN complex, can carry energy of many tens of kilojoules. The proton bunches from the Super Proton Synchrotron (SPS) with 3×10^{11} particles per bunch (400 GeV per particle) carry 19.2 kJ of energy. These bunches can excite the wakefield and accelerate externally injected electrons with gradient of several GV/m. To effectively excite the wakefield, the proton bunch must be short when compared to the plasma period. But the existing proton bunches are long when compared to the plasma period: $\sigma_{zb} \sim 100\lambda_{pe} \propto n_{pe}^{-1/2}$, for $\sigma_{zb} = 12\,cm$ and plasma density $n_{pe} = 7 \times 10^{14}/cc$ and λ_{pe} is the plasma wavelength.

In 2010 Kumar et al. showed that a long proton bunch traversing a dense plasma undergoes a transverse self-modulation instability (SMI) that modulates the bunch radius and density and drives the wakefields to large amplitude [6]. Numerical simulations show that when seeded the SMI can grow and saturate over 4 m in a plasma with density in the (1–10) $\times 10^{14}$ /cc range. Seeding also allows for deterministic injection of a witness electron bunch in the focusing and accelerating phase of the wakefields. In the planned experiment, seeding is achieved by a short and intense laser pulse that co-propagates with the proton bunch and creates the plasma. The AWAKE collaboration[1] was formed to perform the first proton-driven plasma wakefield acceleration experiment in the world.

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SELF-MODULATION INSTABILITY

The 12 cm long proton bunch must be split into micro bunches to drive the high amplitude wakefields. The longitudinal wakefield does not lead to modulation in the propagation direction due to relativistic energy of the particles. In contrast, the radius of a long proton bunch is modulated at the plasma period by the transverse focusing/defocusing field that further develops the SMI until it reaches saturation.

In simulation studies a half-cut bunch was considered to seed the instability with a sharp edge that drives the wakefield not from the noise level but from ~ 6.5 V/m [7]. A half cut bunch creates high-frequency components (when compared to c/σ_{zb}) that can seed the wakefields more effectively.

The electron bunch is externally injected on-axis into the plasma from the beginning. Simulation studies show that some of the electrons are trapped from the very beginning by the wakefield of seed perturbation and move with the wave phase velocity while the beam self-modulates. They reach >1 GeV energies.

The possible experimental parameters are explored through numerical simulations with codes such as VLPL [8], OSIRIS [9] and LCODE [10]. The AWAKE baseline parameters used in simulations are listed in Table. 1.

Table 1: AWAKE Baseline Parameters

Parameter, Notation	Value
Plasma density, n_0	7×10^{14} cm^{-3}
Length, $L_{\max}$	10 m
Skin depth, $c/\omega_{pe} \equiv k_p^{-1}$,	0.2 mm
Radius, r_1,	> 1 mm
Wavebreaking field, $E_0 = mc\omega_{pe}/e$,	2.54 GV/m
Proton bunch population, N_b	3×10^{11}
Length, σ_{zb}	12 cm
Radius, σ_{rb}	0.2 mm
Energy, W_b	400 GeV
Energy spread, δW_b	0.35%
Normalized emittance, ϵ_{nb}	3.6 mm mrad
Initial density, n_{b0}	4×10^{12} cm^{-3}
Electron bunch population, N_e	1.25×10^9
Length, σ_{ze}	1.2 mm
Radius, σ_{re}	0.25 mm
Energy, W_e	16 MeV
Energy spread, δW_e	0.5%
Normalized emittance, ϵ_{ne}	2 mm mrad
Injection delay, ξ_e	16.4 cm

Numerical simulations using baseline parameters show that the electron bunch with initial energy of 16 MeV can be used to probe the wakefield driven by the self-modulated proton bunch. The capture efficiency for an electron bunch that spans a few plasma wavelength is about 14 %. These

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captured electrons are accelerated to 1.3 GeV after 10 m of propagation, see Fig. 1.

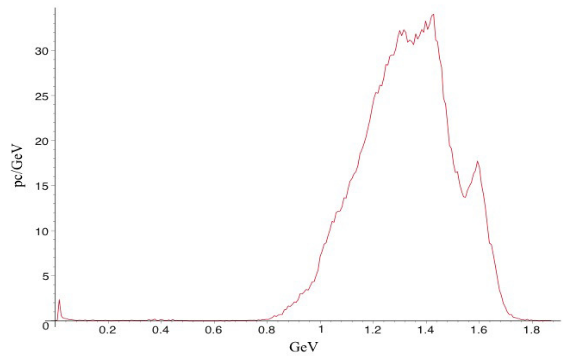

Figure 1: Energy spectrum of accelerated electrons, obtained from an LCODE simulation with the parameters of Table 1. The mean energy is ≈ 1.3 GeV and the relative energy spread ≈ 10%.

AWAKE EXPERIMENT FACILITY

The AWAKE experiment at CERN [11] was approved in 2013. The proposed experiment is aiming for:

- phase 1: measurement of proton bunch self-modulation (planned for late 2016)
- phase 2: acceleration of externally injected electrons to GeV level (planned for late 2017)

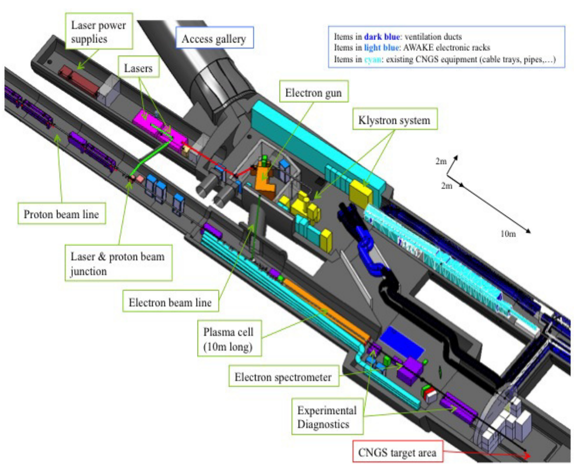

Figure 2: Schematic layout of the AWAKE experiment facility.

The schematic layout of the facility is shown in Fig. 2. A proton bunch ($\sigma_{zb} = 12\,cm, N_b = 3 \times 10^{11}$) is extracted from the SPS and transported over more than 800 m of beam-line into the experimental area. The bunch is focused to $\sigma_{rb} = 200\,\mu m$. To avoid the current filamentaion instability the plasma skin depth should be kept larger than the bunch transverse size ($c/\omega_{pe} > \sigma_{rb}$), which is a limiting factor for the nominal plasma density ($c/\omega_{pe} \propto n_{pe}^{-1/2}$). Therefore the plasma density is kept in the $10^{14} - 10^{15}/cc$ range.The plasma source is a 10 m-long Rubidium (Rb) vapour source with a low ionisation potential (4.2 eV for the first electron) [12]. The vapour is ionised using a laser pulse with an intensity exceeding the ionisation threshold of $1.7 \times 10^{12} W/cm^2$. The electron bunch (16 MeV, Q = 0.2 nC) is produced by an RF-gun and is injected on-axis into the plasma, collinear with the proton bunch with an optimum delay relative to the seed laser pulse.

The energies of accelerated electrons are monitored with a magnetic spectrometer located a few meters downstream from the plasma. In addition, three diagnostic stations are foreseen to measure and study the physics of self-modulation, see next section.

For more information on the design of the experimental area, electron injection studies, and electron spectrometer, refer to AWAKE publications in this proceeding [13–15].

SMI DIAGNOSTICS

For a clear understanding of the modulation process due to the SMI, the characteristics of the drive bunch after propagation through the plasma source have to be extracted. For this purpose, different measurement techniques are planned and are under study. These techniques should satisfy the following criteria:

- Single shot measurement due to possible large time jitter and shot-to-shot variation of the proton bunch.
- A broad bandwidth of at least 500 GHz. The plasma electron frequency at nominal density is 237.5 GHz.
- A short sampling window of about 100 ps to extract information from different longitudinal bunch positions ($\sigma_{tb} = 400\,ps$).

As was mentioned previously, the proton bunch becomes *radially* modulated at the plasma frequency and the current per cross-section does not change during the modulation process. We briefly describe different diagnostics that will be implemented in the AWAKE experiment.

OTR and Streak Camera

Optical transition radiation (OTR) is prompt and can be directly time-resolved using a streak camera [16]. Unlike in single short-pulse measurements the OTR from the proton bunch lasts ∼ 400 ps and has a modulation period of ∼ 4 ps. Test measurements using laser light with the same time structure as the expected OTR have shown that modulation frequencies up to 290 GHz within a 50 ps window can be measured. These results will be published elsewhere. The challenge with OTR is light collection from the central part of the bunch with a transverse size smaller than the outer modulation radius (∼ 1 mm near the middle of the bunch where proton beam density is the highest). The whole beam

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radius is about 5 mm. This diagnostic can also be used to measure the relative phasing of the laser pulse, the proton bunch, and the electron bunch at sub-picosecond level.

CTR and TCTR

Coherent transition radiation (CTR) is conventionally used to determine bunch envelope structures by measuring the particle number per cross-section. Recently it has been shown that charged particles traversing a metal-vacuum boundary also emit transverse coherent transition radiation (TCTR) [17]. The emission has a dipole-like pattern and propagates along the surface of the boundary, radially around the exit point of the particles (see Fig. 3). The electric field vector is normal to the boundary. The radially modulated density of a particle bunch should be imprinted to the TCTR amplitude variations.

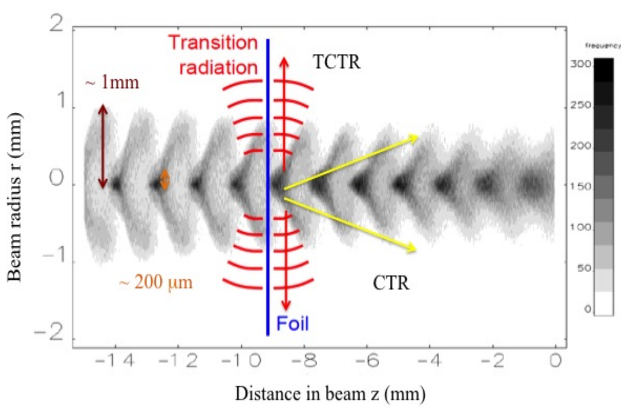

Figure 3: Charge density distribution of the radially modulated proton bunch obtained with LCODE. Schematic of the CTR and TCTR generation by a modulated particle bunch are shown in yellow and red, respectively.

Modules with integrated waveguides and pickup antennas are under design to collect the TCTR/CTR radiation effectively. The collected radiation will be detected using the following methods:

Schottky diode. A Schottky diode with a detection bandwidth of 50 GHz to 2 THz will be used to measure the envelope of the modulated bunch with bandwidth of 4 GHz using an oscilloscope.

Heterodyne measurements. The coherent radiation at frequency f_{RF} equal to the plasma frequency will be mixed with a local oscillator frequency f_{LO} to bring the signal to an intermediate frequency $f_{IF} < 10\,GHz$ that can be directly measured with a Fourier analyser. This yields the frequency and amplitude of the self-modulation.

DFT electro-optic sampling. Electro optic sampling in the frequency domain using a dispersive Fourier transform (DFT) technique will be used to detect the coherent radiation. Using this method, the phase of an optical pulse centred around a wavelength of 1550 nm and with a width of 100 ps FWHM is modulated due to the time varying electric field of the radiation in an electro-optical crystal. The phase-modulated optical pulse is stretched in time in a highly dispersive fibre and can be detected using a fast photodetector and a standard digitiser. Raman amplification of the signal is planned to increase the sensitivity of the setup. The simple and robust fibre-based system is very attractive for multiple measurement stations [18].

A Smith-Purcell radiation diagnostic could be considered to obtain the spectrum of the coherent radiation on a single-shot basis with a peak at the modulation period.

In addition photon acceleration is also considered as an independent diagnostic for measuring plasma density perturbation corresponding to the proton bunch density modulation.

CONCLUSION

The AWAKE experiment is the first proton driven plasma wakefield experiment and is planned for late 2016 at CERN using SPS proton bunches. The design and construction of the Rubidium vapour plasma source, diagnostics for proton bunch self-modulation measurements and transport beamlines have started. The first phase of the experiment will be dedicated to the proton bunch self-modulation physics. In the second phase, acceleration of externally injected electrons from MeV to GeV energies over a 10 m-long plasma will be demonstrated.

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