⟨S|P|S⟩ swiss physical society

Nr. 59
Oktober 2019

SPG MITTEILUNGEN
COMMUNICATIONS DE LA SSP

AUSZUG - EXTRAIT

PT 3/2019

First Electron Acceleration in AWAKE

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The potential of reaching high accelerating gradients up to three orders of magnitude stronger than conventional methods has been successfully demonstrated with plasma wakefield acceleration in the last decades; electrons were accelerated to energies up to ~8 GeV using short, PW laser pulses to drive wakefields in 20 cm long plasma cell [1]. Using a short high-charge electron bunch driver an energy gain of 42 GeV in 85 cm, corresponding to 52 GV/m accelerating gradient has been achieved [2].

However, the energy carried by a laser or electron drive beam is only at the order of ~10s Joules limiting the maximum energy gain of electrons accelerated in a single stage. In order to accelerate electrons to TeV energies (equivalent to 2 kJ in 2×10^{11} electrons) several stages are required in both laser- and electron driver beam experiments.

Proton drive beams available today carry much higher energies (typically 10s to 100s of kJ) and could therefore accelerate electrons to the energy frontier in a single plasma stage, simplifying and shortening the accelerator.

The maximum field of plasma wake scales with the plasma electron density; at least 10^{14} cm^{-3} are required to reach accelerating gradients of GV/m and above. Typically, large amplitude wakefields are produced by short bunches at the order of the plasma wavelength and at these densities the plasma wavelength is of the order of a millimeter or smaller. However, proton beams today are 3 – 12 cm.

Long proton bunches can nevertheless drive strong wakefields taking advantage of the self-modulation [3] of the proton bunch; the process of seeded self-modulation starts from a seeding wakefield in the plasma whose transverse field acts on the proton beam and modulates its radius. The wakefield's amplitude grows exponentially from head to tail of the bunch and along the propagation distance. At saturation, the initially long and smooth beam is split into a train of micro-bunches near the axis, with periodicity equal to the electron plasma frequency. The micro-bunches resonantly excite a strong plasma wave.

The ***A****dvanced* ***WAKE****field* Experiment, AWAKE, is a proton driven plasma wakefield acceleration experiment and was approved in 2013. In 2016/17 AWAKE observed the strong modulation of high-energy proton bunches in a 10 m long plasma; the results represent the first ever demonstration of strong plasma wakes generated by proton beams. In 2018 AWAKE demonstrated for the first time the acceleration of externally injected electrons to multi-GeV energy levels in the proton driven plasma wakefields [4].

Figure 1 shows a schematic drawing of the AWAKE experimental facility. A proton bunch with intensity on the order of 3×10^{11} protons, energy of 400 GeV/c (19.2 kJ) and a length of 6 - 12 cm is extracted from the CERN SPS towards the AWAKE experimental area. The bunch is focused at the entrance of the plasma to a transverse beam rms size of $\sigma_r = 0.2$ mm. The AWAKE plasma is 10 m long, has a radius

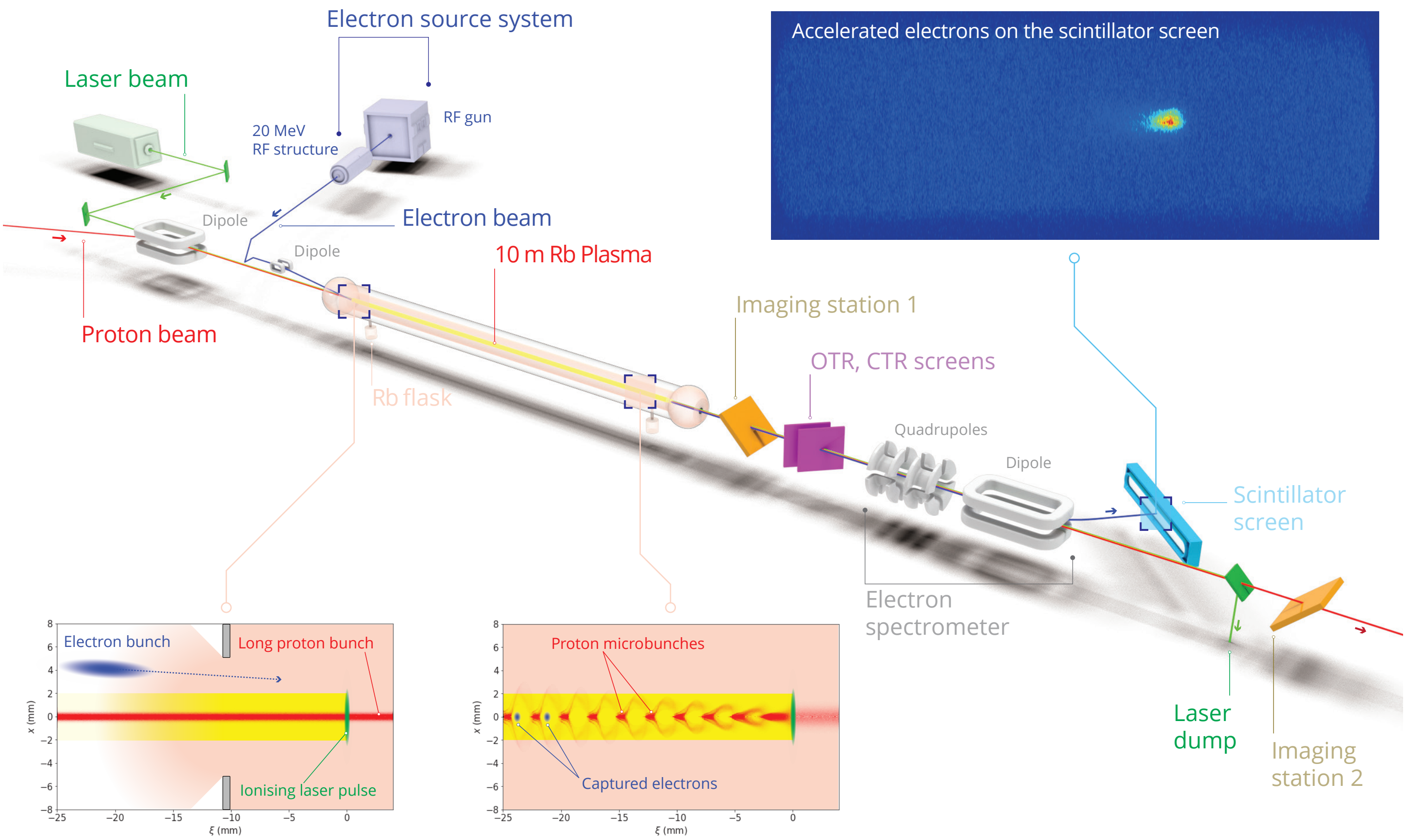

Fig. 1: Schematic layout of the AWAKE experiment.

of approximately 1 mm and density uniformity better than 0.1%.

To create the plasma a heat exchanger evaporates rubidium and a 4.5 TW laser pulse ionizes the outermost electrons of the rubidium atoms. The vapor (and therefore the plasma density) is adjustable between 0.5 – 10 × 10^{14} atoms/cm^3.

The laser (100 fs pulse length, 450 mJ energy) is overlapped in space and time with the proton beam, which allows for seeding the proton self-modulation by creating a sharp ionization front inside the proton bunch. The protons ahead of the laser pulse propagate in rubidium vapor, the ones after in the plasma self-modulate to micro-bunches, as seen in the left lower pictures of Fig. 1.

20 MeV electrons are externally injected into the plasma to probe the wakefields and demonstrate electron acceleration. The electrons are produced in an S-band photo-injector system and transported to the plasma entrance. The beam diagnostics systems and the electron spectrometer measuring the energy of the accelerated electrons on a scintillator screen (see upper right figure in Fig 1.) are installed downstream the plasma.

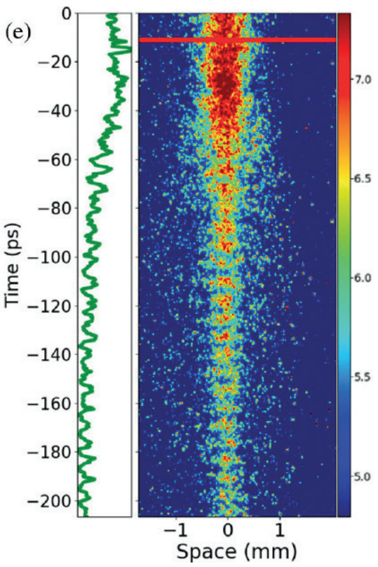

Fig. 2: Streak camera measurement of the self-modulated proton micro-bunches beam after the ionizing laser pulse (red line) and the start of the plasma

Fig 2. shows results of the streak camera measurement of the self-modulated proton micro-bunches beam after the ionizing laser pulse and the start of the plasma [5]. The micro-bunch periodicity is equal to the electron plasma period.

The measurements showed that during the self-modulation process the wakefield amplitude grows from the initial seed value according to the self-modulations growth rate until saturation both along the bunch and along the plasma [6], as also predicted by simulations. In addition by seeding the self-modulation with sufficient wakefield amplitude the process is reproducible and stable. This is particularly important since the witness electron bunch is injected several micro-bunches (usually 30-100) behind the seed point, where the controlled phase and wakefield period keeps the electrons in the accelerating and focusing phase.

Fig. 3 shows the energy of the accelerated electrons after the 10 m plasma as a function of the plasma density without and with a positive plasma density gradient (~2.2% over 10 m) [6]. The measurements demonstrated that the energy gain increases with plasma density. Electron acceleration

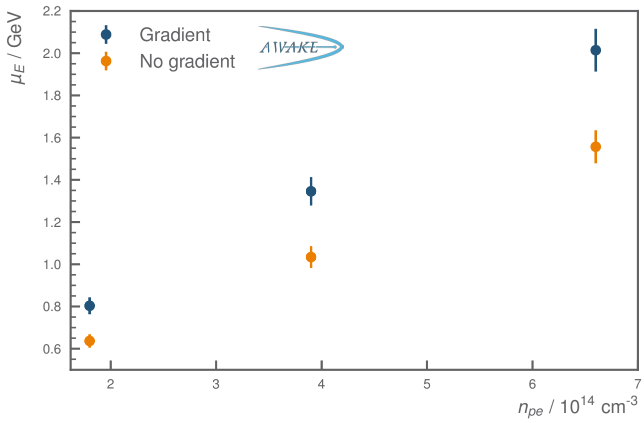

Fig. 3: Accelerated electron energy for different plasma densities with (blue) and without (orange) gradient in the plasma density.

up to 2 GeV in the plasma wakefield driven by the self-modulated proton beam has been observed.

AWAKE Run 1 was a proof-of-concept experiment [7]. The goals for AWAKE Run 2 are to bring the R&D development of proton-driven plasma wakefield acceleration to a point where particle physics applications can be proposed and realized. Therefore AWAKE Run 2 starting in 2021 after CERN Long Shutdown 2 aims to achieve high-charge bunches of electrons accelerated to high energy, about 10 GeV, while maintaining beam quality through the plasma and showing that the concept is scalable to long acceleration distance scales. In order to achieve acceleration with low energy spread and emittance preservation, the electron beam injected in the plasma needs higher energy (165 MeV) and much shorter electron bunches (~200 fs). X-band technology will be used for the new electron source system. Two plasma sources are proposed in Run 2; in the first plasma source the proton bunch self-modulates until saturation is reached. A density step will be introduced to freeze the modulation process and allow for much higher final electron energies over long acceleration distances. The electron bunch will be injected into the stable wakefields driven by the micro-bunch trains in the second plasma.

By the successful end of AWAKE Run 2 the AWAKE scheme could be used for first high-energy physics applications already in the intermediate time-scale; first high energy experiments are seizable, where proton driven plasma wakefield acceleration technology could be used for fixed target experiments for dark photon searches and also for future electron-proton or electron-ion colliders, where low luminosity is acceptable.

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