ARTICLE IN PRESS

Nuclear Instruments and Methods in Physics Research A ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Indirect self-modulation instability measurement concept for the AWAKE proton beam

M. Turner [a,d], A. Petrenko [a], B. Biskup [a,e], S. Burger [a], E. Gschwendtner [a], K.V. Lotov [b,c], S. Mazzoni [a], H. Vincke [a]

[a] CERN, Geneva, Switzerland
[b] Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090, Russia
[c] Novosibirsk State University, Novosibirsk 630090, Russia
[d] Graz University of Technology, Graz, Austria
[e] Czech Technical University, Prague, Czech Republic

ARTICLE INFO

Keywords:
AWAKE
Self-Modulation Instability
CERN
Proton Driven Plasma Wake Acceleration

ABSTRACT

AWAKE, the Advanced Proton-Driven Plasma Wakefield Acceleration Experiment, is a proof-of-principle R&D experiment at CERN using a 400 GeV/c proton beam from the CERN SPS (longitudinal beam size $\sigma_z = 12$ cm) which will be sent into a 10 m long plasma section with a nominal density of $\approx 7 \times 10^{14}$ atoms/cm^3 (plasma wavelength $\lambda_p = 1.2$ mm). In this paper we show that by measuring the time integrated transverse profile of the proton bunch at two locations downstream of the AWAKE plasma, information about the occurrence of the self-modulation instability (SMI) can be inferred. In particular we show that measuring defocused protons with an angle of 1 mrad corresponds to having electric fields in the order of GV/m and fully developed self-modulation of the proton bunch. Additionally, by measuring the defocused beam edge of the self-modulated bunch, information about the growth rate of the instability can be extracted. If hosing instability occurs, it could be detected by measuring a non-uniform defocused beam shape with changing radius. Using a 1 mm thick Chromox scintillation screen for imaging of the self-modulated proton bunch, an edge resolution of 0.6 mm and hence an SMI saturation point resolution of 1.2 m can be achieved.

1. Introduction

The AWAKE [1] (Advanced Proton-Driven Plasma Wakefield Acceleration Experiment) experiment currently being built at CERN intends to use a 400 GeV/c proton bunch extracted from the SPS to accelerate electrons in plasma wakefields with amplitudes up to the GV/m level.

In order to drive plasma wakefields efficiently, the length of the drive bunch has to be on the order of the plasma wavelength. Since this is not the case for this proton beam with $\sigma_z = 12$ cm, the experiment relies on the self-modulation instability (SMI) [2], which modulates the proton driver at the plasma wavelength in the first few meters of plasma. AWAKE is going to use a 10 m long rubidium vapor cell [3] filled with a density of 7×10^{14} atoms/cm^3, which corresponds to a plasma wavelength of $\lambda_p = 2\pi c/\omega_{pe} = 1.2$ mm, where c is the speed of light and $\omega_{pe} = (4\pi n_e e^2/m_e)^{1/2}$ is the electron plasma frequency being $= 1.57 \cdot 10^{12}$ s^{-1} for AWAKE, n_e is the plasma electron density and e andm_e are the electron charge and mass. A short laser pulse (100 fs, $I = 20$ TW/cm^2, $a_0 \leq 10^{-2}$) will be used to both ionize the rubidium vapor with a minimum plasma radius of $r_0 \approx 1.5$ mm and to seed the SMI of the proton bunch through a sudden onset of the plasma density. The proton drive bunch contains 3×10^{11} particles.

The SMI is a transverse two-stream instability that modulates a long drive bunch into micro-bunches with the plasma frequency [5]. The initial wakefield is created by the sudden onset of the plasma density created by laser pulse. Because of the focusing and defocusing transverse fields created by the wakefields, protons in the focusing phase of the wakefields exit the plasma close to the plasma center and appear as a narrow core on transverse profiles downstream from plasma. Protons in the defocusing phase of the wakefields appear as a halo surrounding the core. According to plasma simulations [4] these fields can be on the order of GV/m resulting in a defocusing angle on the order of 1 mrad for the 400 GeV/c protons.

The first phase of the AWAKE experiment will start in autumn 2016 and the goal is to study the SMI. In this paper we show that by measuring the transverse proton bunch profiles at two locations downstream from the plasma, it can be proved that SMI developed successfully in the plasma and hence strong transverse fields were created. Furthermore, some information about the

http://dx.doi.org/10.1016/j.nima.2016.01.060
0168-9002/

Please cite this article as: M. Turner, et al., Nuclear Instruments & Methods in Physics Research A (2016), http://dx.doi.org/10.1016/j.nima.2016.01.060

growth rate of the instability can be obtained by tracking particles back and measuring where the protons experienced transverse kicks. By looking at the beam image itself it can be seen if hosing instability developed. In addition, technical parameters about the screen, the interaction of the screen with the proton beam and the expected resolution for the angle measurement are presented.

2. The indirect SMI measurement principle

The basic idea of the indirect SMI measurement is to insert two beam-imaging screens (BTVs) downstream of the plasma in order to measure the transverse bunch shape and the beam size at two locations ≈ 8 m apart (see Fig. 1). The following information can be extracted from the measurement.

2.1. Estimation of transverse wakefield strength

Defocused protons experience transverse kicks with an angle θ in the plasma. The order of magnitude of the defocusing angle can be estimated as follows. The defocusing angle θ is defined as

$$\theta = \frac{\Delta p_r}{p_z} \tag{1}$$

where Δp_r is the change of radial momentum and p_z the longitudinal momentum. Under the influence of an electric field E_r protons move according to Newton's equation:

$$\frac{\Delta p_r}{\Delta t} \approx eE_r \Rightarrow \Delta p_r \approx eE_r \Delta t \tag{2}$$

with Δt being the time that the particle takes to travel that transverse distance Δr. In this particular case Δp_r, the change of radial momentum, is due to transverse electric fields E_r, which can reach a fraction of the wave-breaking field E_0, the maximum electric field that can be generated at a given plasma density:

$$E_0 = \frac{m_e c^2}{e(c/\omega_{pe})}. \tag{3}$$

From Eq. (3) one can see that E_0 is the electric field which accelerates an electron to the energy of $m_e c^2$ over a distance of c/ω_{pe}. Assuming that the transverse electric field reaches a significant fraction of the wave-breaking field, let us say $E_r = E_0/2$ and using $\Delta r/\Delta z \sim \Delta p_r/p_z$, Δt can be estimated as

$$\Delta t \sim \sqrt{\frac{p_z}{eE_r}\frac{\Delta r}{c}} \tag{4}$$

with Δr being the plasma channel width of $\sim 2\, c/\omega_{pe}$. Combining Eqs. (4) (with 1) and (2) and $p_z = \gamma m_p c$ with m_p being the proton mass and assuming that the proton bunch moves with the speed of light, the following expression for the defocusing angle θ can be obtained:

$$\theta = \frac{\Delta p_r}{p_z} \sim \sqrt{\frac{m_e}{\gamma m_p}}. \tag{5}$$

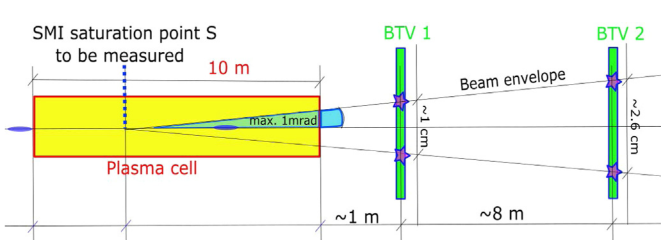

Fig. 1. Schematic drawing of the measurement setup in AWAKE. Two measurement screens (BTV 1,2) are inserted downstream the plasma. The distance between the screens is ≈ 8 m. S is the SMI saturation point.

Using the AWAKE parameters of a proton beam with 400 GeV/c corresponding to $\gamma = 427$, θ is estimated to be ≈ 1 mrad. For example for LHC parameters ($\gamma = 7478$) θ would be around 0.3 mrad. Note that according to this estimate the maximum angle of the defocused protons does not depend on the plasma density, provided that the wakefield amplitude reaches half of E_0 also independently of the plasma density. Plasma simulation results obtained with LCODE [6,7] show that protons experience angular kicks of about 1 mrad in AWAKE. This means that observing diverging angles in the order of 1 mrad, as opposed to ≈ 0.01 mrad without plasma, from the two beam images is a proof that high amplitude plasma wakefields are excited by SMI.

2.2. Understanding the SMI growth rate

The saturation point of the SMI (as illustrated in Fig. 1), which is the point of the maximum wakefield amplitude, can be estimated by connecting the beam edges on the two screens and tracking back to the crossing point inside the plasma cell. This assumes that the protons will get most of the kick close to the point of maximum wakefield amplitude. According to simulations the saturation point is around 3000 λ_p which is around 4 m for a plasma density of 7×10^{14} atoms/cm^3. The worst case resolution of the saturation point can be calculated by using the simulated resolution of the defocused beam edge of 0.6 mm to $\Delta S = 1.2$ m, which was obtained as will be described in Section 3.4. This error can be improved by taking more than one measurement of the defocused beam radius or by combining independent measurements.

2.3. Detecting hosing instability

More information can be extracted from the measurement by looking at the beam edge shape on the screen. A round defocused beam-edge shape is expected if SMI dominates, because the SMI is cylindrically symmetric. If the hosing instability [8,9] develops, the defocused beam-edge shape is expected to be smaller and changing in radius, because wakefields are weaker and non-axis symmetric. The wakefields are weaker because the number of microbunches driving the wakefield resonantly is less than when only SMI developed.

3. Design of the imaging screens

The proposed screen material for this experiment is the scintillator material Chromox ($Al_2O_3 : CrO_2$). It has a light yield of 10^4 photons per MeV of deposited energy [10] that is suitable for detecting the radius of the defocused beam. The chosen screen thickness is 1 mm (explained in more detail in Section 3.2). The material is pink, thick and opaque which means that photons that will be detected are emitted from a surface layer.

3.1. Layout

Simulations of the interactions of the proton bunch with the scintillator screens were performed with FLUKA [11]. FLUKA is a bench-marked Monte-Carlo code that simulates particle interactions with matter. The simulation geometry comprises the laser dump (1 mm of aluminum), used to stop the laser pulse 50 cm upstream the first screen, the two imaging screens (each 1 mm of alumina) and a vacuum pipe (iron) with a diameter of 80 mm. The simulation input beam is shown in Fig. 2 and was obtained from plasma simulations performed with LCODE, using the AWAKE baseline parameters. The front part of the proton bunch is transversely Gaussian, but the second half of the bunch is self-