- **AWAKE Electron Source Design by: Mohsen Dayyani**

The next energy frontier accelerator should collide electrons and positrons in TeV energy scale to probe the fundamental structure of the world beyond the standard model. Such a future electron-positron collider, need to search for new physics with high precision as a complementary part for large hadron collider LHC [1]. Since the maximum gradient of today's accelerators restricted to $100\ MeV/m$ due to the RF breakdown [2], then access to TeV scale with today's technology requires a very large linear collider with tens of kilometers length. Probably, the two proposed state of the art large linear colliders i.e. CLIC [3] and ILC [4], with total length of $48\ km$ ($3\ TeV$) and $30\ km$ (0.5 TeV), would able to fulfill the requirements. However, manufacturing of such large colliders is too difficult task especially from the cost and maintenance point of view. Last cost estimations for construction of CLIC and ILC show \$7 B and \$7.78 B. Therefore, a new high-gradient acceleration technology is mandatory to ensure TeV scale in reasonable cost and space. Today it is completely revealing that a promising approach which can realize such a goal is usage of plasma wake fields for acceleration of the particles [5]. In this technology (see Fig.1) a witness bunch is accelerated by plasma waves that are already created by an injecting intense beam of laser [6] or electrons [7] as driver.

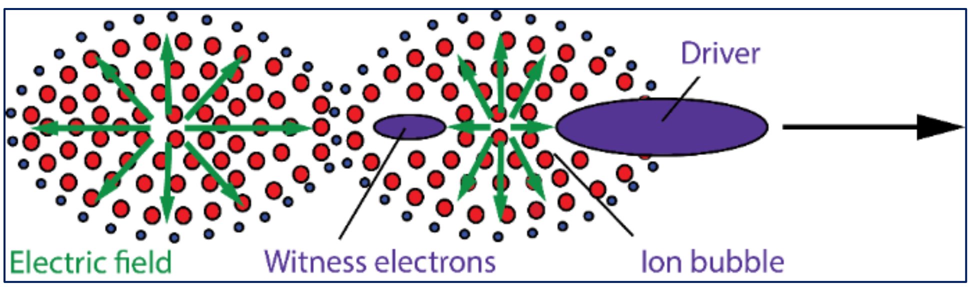

Fig.1: A schematic description of plasma wake-field acceleration concept.

However, since the energy and propagation length of such drivers within plasma are restricted to $100\ J$ and $1\ m$ [8], respectively, then the maximum energy gain becomes limited on the order of a few tens of MeV. For sure, this problem can be overcome using proton bunches that are much more energetic and heavier drivers in comparison with the laser and electrons. This benefits from the unique ability of CERN [9] for production proton bunches with more than 10^{11} particle and a few kJ of energy, currently. For instance, nowadays the CERN super proton synchrotron accelerator (SPS), is producing a bunched beam of $400\ GeV$ protons with 3×10^{11} particle and $19\ kJ$ of energy, routinely [10]. This ability has launched an experimental program at CERN to investigate the power of proton-driven plasma wake field acceleration in the AWAKE project [11]. The main objectives of the AWAKE are to demonstrate high-gradient acceleration with a proton bunch and development of mandatory technologies for the long-term perspectives of proton-driven plasma wake field acceleration. Fig.2 shows the different parts of the CERN accelerator complex including the SPS ring and specially the AWAKE experimental area. As it can be seen in the figure, the WAKE will be fed by SPS high energy proton beam through a direct proton line.

Downstream of this proton line, the proton beam will excite high gradient plasma waves in an appropriate plasma cell.

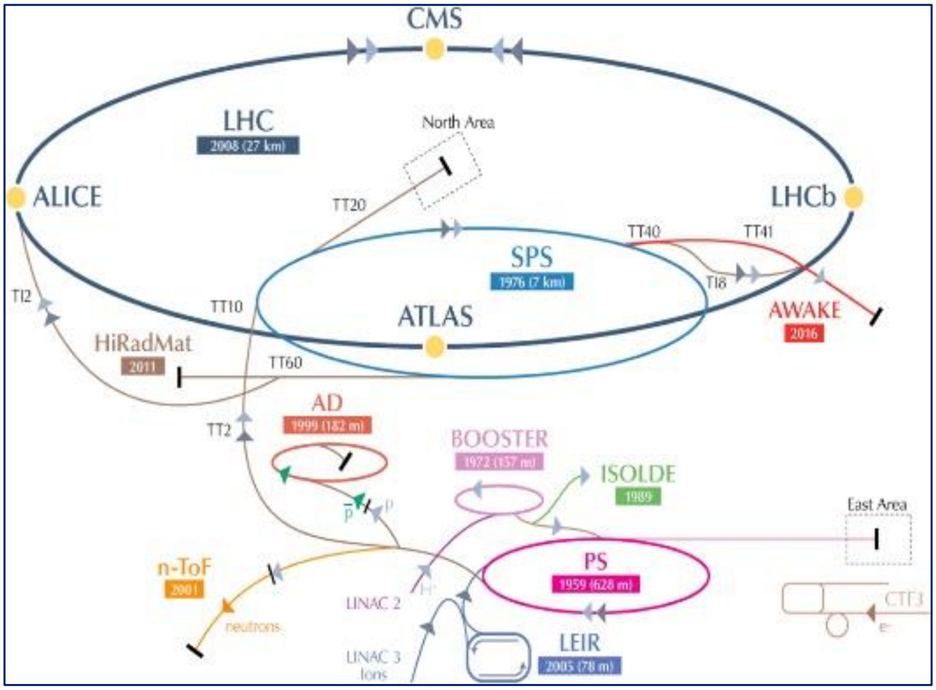

Fig.2: Different parts of the CERN accelerator complex.

Since the maximum electric field (indicated by E_p) which can be excited in a plasma with an electron density of n_e is given by [12]

$$E_p \approx \sqrt{\frac{n_e[cm^{-3}]}{10^{14}}}\ GV/m \tag{1}$$

Then at least $n_e \approx 10^{14} cm^{-3}$ is required to provide an acceleration on the order of 1 $^{GeV}/_{m}$. On the other hand, the corresponding plasma wavelength (indicated by λ_p) for a given n_e is [13]

$$\lambda_p \approx \sqrt{\frac{10^{15}}{n_e[cm^{-3}]}}\ mm \tag{2}$$

Care must be taken that in order to excite the plasma wake fields efficiently, the length of the driver must be close the plasma wavelength. For the AWAKE experiment assuming $n_e = 10^{15}\ cm^{-3}$, the plasma wakes would have $\lambda_p \approx 1\ mm$ while the proton bunches generated from the SPS have $12\ cm$ bunch lengths [10]. Therefore, in AWAKE each incoming SPS proton bunch has to be splitted into several micro-bunches. To this end, a mechanism has been proposed that can automatically splits these proton bunches into a several micro-bunches using what is called self-modulation instability (SMI) [14]. SMI arise from this fact that while a long proton bunch is propagating in a plasma medium, it would generate to some extent low amplitude transverse wake-fields along itself. Later the excited wakes can modulate periodically its transverse dimensions with the period of λ_p. This self-modulation splits the first long proton bunch into several ultrashort bunches of plasma wavelength λ_p. In the next step, the produced micro-bunches will excite in turn some large amplitude plasma waves that are very convenient for plasma acceleration. Fig.3 shows the conceptual design of the proposed layout for AWAKE experiment with the total length of $45\ m$. From the left hand side (see Fig.3), a short (100 fs) Ti-Sapphire laser pulse ($\lambda = 800\ nm$) with $40\ mJ$ in parallel with the SPS $400\ GeV$ proton beam are injected into the first plasma cell [15]. The laser ionizes the metal vapor in the plasma section and seeds the self-modulation instability which in turn splits the initially $12\ cm$ long proton bunches to 100 identical micro bunches as new drivers. Later, these drivers will be transferred to the second plasma section with the total length of $10\ m$ and excite some large amplitude plasma wake-fields with the gradient on the order of $3\ GeV/m$. In the next step, a low energy bunched electron beam is injected to this plasma cell and many of its electron bunches locate between the drivers to harness the excited high gradient fields. The captured electrons in this stage should arrive to multi GeV kinetic energies at the end of the plasma cell.

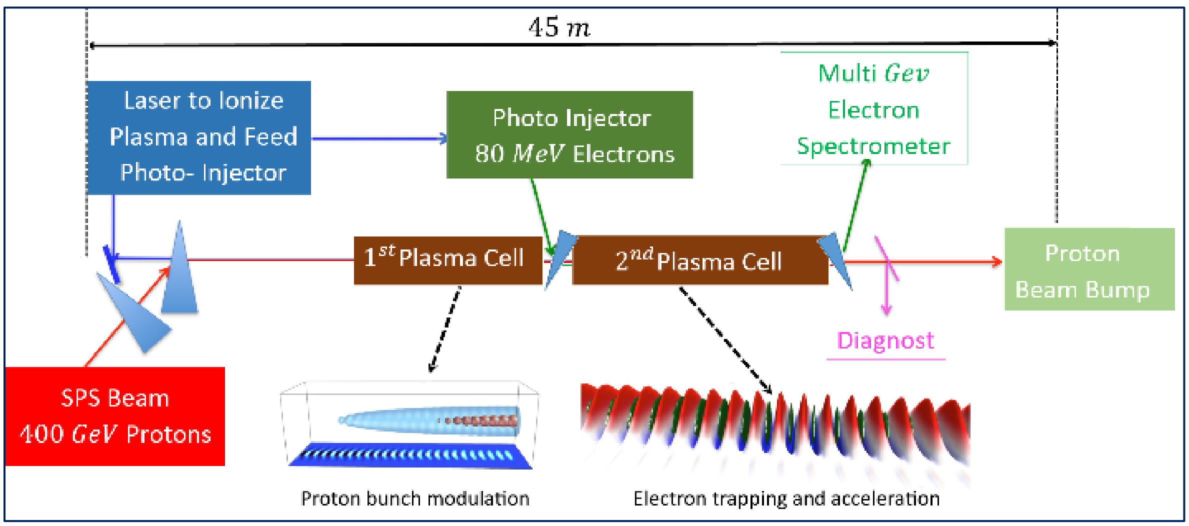

Fig.3: Conceptual design of the AWAKE experiment layout, showing the major sections and describing the main expected effects.

The characteristics of the required electron source for the beam injection to the second plasma cell have a great impact on the performance of the experiment. This component not only will significantly affect the final parameters of the accelerated electrons, but also provides an efficient capture and acceleration of the injected electrons within plasma. Table. 1 shows the latest nominal parameters of the electron beam that need to be satisfied to insure the goal of the experiment [16].Even though access to the required beam parameters is very difficult, but there is also another serious problem due to space restriction in the current setup of AWAKE. The setup has to make use of the existing tunnels and caverns which allow only about $5\ m$ available space to locate the electron source, subsequent accelerating structures and the associated beam line diagnostics [17].

Table.1: The nominal values considered for the beam parameters of the AWAKE electron source in run II. .

Parameter	Size
Beam Energy	$\approx 80\ MeV$
Energy Spread	$\leq 1\ \%$
Bunch Charge	$100\ pC$
RMS Bunch Length	$\leq 100\ fs$
RMS Beam Size	$\approx 0.2\ mm$
Normalized Emittance	$\leq 5\ \mu m$

Due to the great experiences of our accelerator physicists on electron sources design, the design of this critical part of the experiment has been awarded to the IPM accelerator group [18] and to date many differnt proposals on this subject prepared and presented for the AWKE comitee [19], [20] [21]. Currently the scientific group composed of two IPM's scintists (but of course can be extended in future) Dr. Morteza Aslani Nejad and Dr. Mohsen Dayyany Kelisani along with Dr. Steffen Doebert and Dr. Edda Gschwendtner from CERN. Fig.4 shows the general layout of our proposed photo-injector for the AWKE experiment (not to scale).

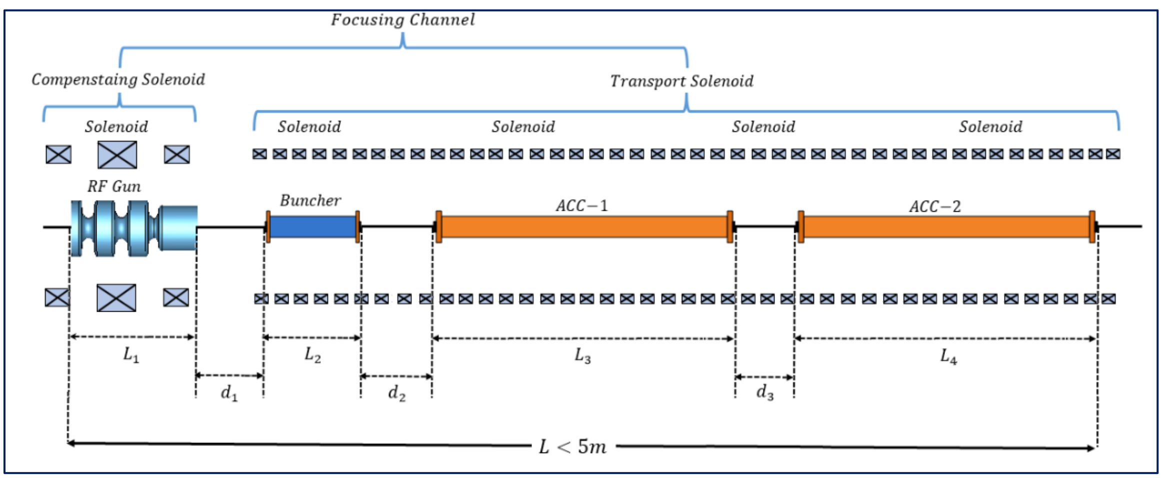

Fig.4: AWAKE photo injector layout.

The photo-injector is started from a high gradient RF cavity (RF gun) where using a high quality laser beam with $1\ ps$ pulse lengths illuminating a cathode, an extremely high quality electron bunch is generated. On the cathode, the emitted electrons have very low energies ($\approx eV$) where the effects of nonlinear space-charge forces are dominated and able to largely degrade the bunch quality. However, fast acceleration of the electrons using high gradient RF fields right after their liberation from the cathode, significantly decreases the action of these nonlinear forces and to a great extent keep the bunch quality [22]. Therefore, what we can gain after the RF gun would be a beam of high quality relativistic electron bunches with few MeV energies but relatively large in length about few ps. Care must be taken that, by the use of a laser with shorter pulses one can directly obtain smaller bunches. However, on the other hand, this increases the nonlinear space-charge forces that their destroying effects on the beam can be extremely large in this critical region. Therefore, to provide very short bunches with very high current and quality, we have to apply a convenient bunch compression scheme after the RF gun. In this scheme, we carry out the velocity bunching process using a buncher cavity located right after the RF gun [23]. The velocity bunching makes the bunches much shorter and in the meantime preserves the beam quality at least to some extent. In fact, since after the RF gun the particles are relativistic, then here we have considerable freedom against the nonlinear space-charge forces to compress the bunches without quality degradation. After this stage, for transportation of the beam without quality degradation, we have to suppress the space-charge forces by means of acceleration up to hundreds of MeV where the beam is called an emittance dominated beam [24]. For this objective, we make use of some appropriate accelerating structures in acceleration phases, subsequently. Up to here, we described the general layout of our proposed electron source for the AWAKE experiment but in the next sections, we explain our beam dynamics studies, theoretical bases and our design approach that we developed to obtain the required beam parameters for this electron source. The required beam parameters of this electron source are still under studying by the plasma physics team and according to the updated values for the parameters we must design a different photo-injector. Then, we planed in our next studies to design a new photo-injector that would be very flexible with respect to this parameters.

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