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Abstract

There has been a proposal by Caldwell et al to use proton beams as drivers for high energy linear colliders. An experimental test with CERN's proton beams is being studied. Such a test requires a transfer line for transporting the beam to the experiment, a focusing section for beam delivery into the plasma, the plasma cell and a downstream diagnostics and dump section. The work done at CERN towards the conceptual layout and design of such a test area is presented. A possible development of such a test area into a CERN test facility for high-gradient acceleration experiments is discussed.

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INTRODUCTION

It is well established that plasmas can be used to transform transverse fields into longitudinal fields [1]. Transverse fields in the plasma can be excited by short pulses of laser light (high transverse electrical fields, ponderomotive force) or by pulses of charged particles (space charge force). The principle of such a "plasma converter" is best understood by considering a short pulse of charged particles that is sent into a neutral plasma channel, a fully ionized gas with equal distribution of ions and free electrons. The plasma response to a short electron beam is described:

1) The electron driver pulse enters the plasma and expels the free electrons that are transversely accelerated (transverse driving force). The plasma ions move a negligible amount due to their higher mass.

2) Along the path of the electron driver pulse a positively charged ion channel is formed. Electrons have been pushed out transversely by space charge.

3) Once the electron driver pulse has passed, the plasma electrons rush back in, attracted by the ion channel (transverse restoring force).

4) Due to their speed they over-shoot the center of the ion channel, rush back out and are attracted back by the ion channel. A space charge driven oscillation has formed.

5) Alternating regions of negative net charge and positive net charge form behind the driver beam pulse. Strong longitudinal fields are induced ("plasma wakefields").

The detailed dynamics of this process depends on the plasma density (determines plasma wavelength and accelerating gradient) and the transverse and longitudinal density of the driving beam pulse. Electron beam-driven experiments were pioneered at SLAC and accelerating gradients of up to 53 GV/m were reached over a length of 85 cm [2]. Alternatives for powerful drivers are short laser pulses (a 100 TW laser can have a transverse electrical field of 22 TV/m). Laser-driven accelerators have generated GeV-class electron beams with gradients of up to 100 GeV/m over 3.3 cm and an rms energy spread of 2.5% (see for example [3]).

Proton beams as drivers for plasma wakefields have only recently been investigated theoretically [4]. It was shown that proton beams could act as ideal drivers in plasma accelerators for High Energy Physics. A single or few accelerating stages would be sufficient for a TeV scale linear collider. This is due to the high stored energy in proton driver pulses (10-100 kJ versus about 100 J in an electron beam driver and a few J in a laser driver). A single proton beam pulse can accelerate an electron to significantly higher beam energies than other drivers. Therefore a proposal has been submitted to the SPS Committee (SPSC) at CERN for a beam test of proton-driven plasma wakefield acceleration [5]. As the CERN proton beams are much longer than the plasma wavelength, the proposed experiment relies on proton-plasma self modulation that generates a series of micro-bunches. The goal of this experiment is to demonstrate the novel concept of proton-driven plasma acceleration for the first time. The initially expected energy gain is 1 GeV in a 10 m long plasma.

Table 1: Parameters of the proton drive beam. The two right columns refer to nominal and optimized parameters.

Parameter	**Unit**	**Nom**	**Opt**
Momentum	[GeV/c]	450	450
Bunch population	[10^{11}]	1.15	3.0
Rms longitudinal emittance	[eVs]	0.05	0.05
Rms energy spread	[MeV]	135	135
Rms bunch length	[cm]	12	12
Rms transv norm emittance	[μm]	3.5	3.5
Beam size	[μm]	200	200
Beta function at plasma cell	[m]	5	5

PROPOSED DRIVE BEAM

Various proton beams from the CERN accelerator complex have been reviewed for use in a plasma acceleration experiment. Finally, the 450 GeV beam from the SPS was identified as the best choice. The beam parameters for the proton drive beam are summarized in Table 1.

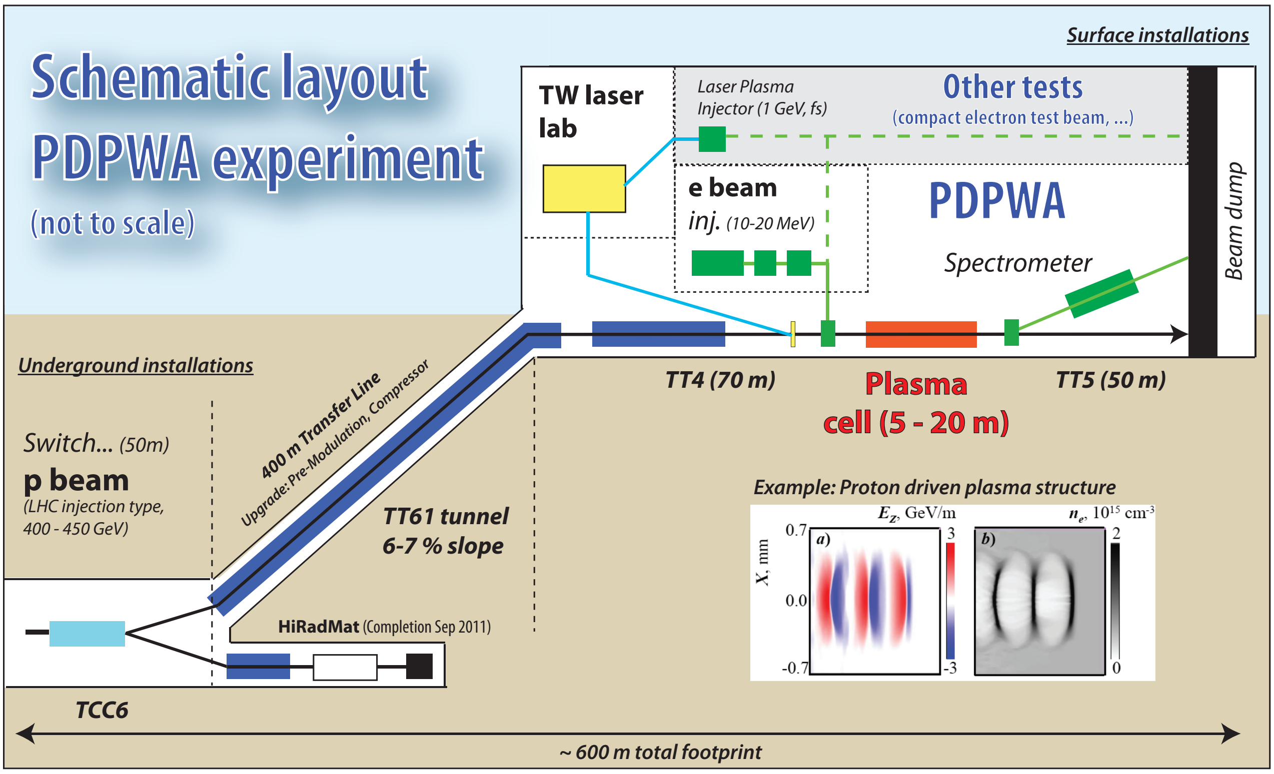

Figure 1: Layout of the experimental installation for a proton-driven plasma acceleration experiment at CERN. The total footprint is about 600 m.

POSSIBLE LOCATION AT CERN

Several CERN locations have been investigated. An optimal location was identified in the so-called TT4/TT5 area on the CERN surface (the now decommissioned West area for neutrino physics at CERN). The location is served by the old TT61 transfer tunnel that can be used to transport the beam extracted from the SPS to the surface. Being at the surface and far away from the underground high intensity lines allows access to the experiment without interference to CERN accelerator operations. The proposed plasma wakefield acceleration experiment is a research activity and frequent access to laser, plasma, diagnostics and beam systems will be important.

The conceptual layout of the proposed setup is shown in Fig. 1. The layout shows the underground switch of the beam from the SPS, the TT61 transfer tunnel and the TT4/TT5 area for the experiment. The surface installation includes the proton beam delivery, the proton beam dump, a Tera-Watt laser laboratory, an electron beam injector for the beam to be accelerated, the plasma cell, a spectrometer and diagnostics. It takes some time for the full self-modulation of the long proton bunch in the plasma to build up. Simulations show that the length of plasma cell should be at least 5 m with a final goal of 10 m [5]. The tunnels and buildings proposed for usage exist and are presently either empty or used for storage.

Radiation protection aspects that will have to be addressed include prompt doses to areas adjacent to the surface installations, air activation and releases into the environment, activation of beam-line components and dumps, activation of liquids, especially cooling and infiltration water, definition and implementation of a radiation monitoring system to control prompt dose rate levels and an estimation of the production of radioactive waste. Extensive experience exists at CERN about these topics and required solutions. Detailed studies on all above issues will be performed after approval of the letter of intent.

DRIVE BEAM DELIVERY

In order to keep the option open for such an experiment on proton-driven PWA, during the design and construction of the High Radiation to Material Facility (HiRadMat) [6] a very preliminary study evaluated the possibility to send protons onto such experiment. As a consequence, a long drift has been left along the beam line (at the location of the former T1 target) to allow for the installation of additional magnets [7]. These magnets would switch and focus the TT66 beam towards the entrance of the TT61 tunnel, which leads to the West Experimental hall. This hall is envisaged as a possible location for the PDPWA experiment, as is the TT61 tunnel itself. It has to be noted that the TT61 tunnel has a large slope of 8.5 % and that some equipment of the previous H3 beam line are still installed and would have to be removed for the new beam line. Also the former H3 beam line was designed for a 250 GeV beam so the suitability of the TT61 tunnel geometry for a 450 GeV beam needs to be checked in detail.

The very preliminary feasibility study showed that a PWA beam line seems to be compatible with the TT66 beam line from the geometrical point of view. For this study, only bending magnets were added into the TT61 magnet sequence file, for survey purpose only, to check if the TT61 tunnel could be reached within a reasonable amount of recuperated magnets in TCC6 (switch yard of TT66). No quadrupoles, correctors or instrumentation elements were added in the beam line design. The main ideas that were pursued for this first feasibility study were the following:

1) To replace the last 2 bending magnets in TT66 (MBB type) by 4 new switch magnets (MBS type) which deflect the beam towards TT66;

2) To deflect the beam towards TT61, these 4 MBS will be switched off and 4 other new MBS further downstream will deflect the beam additionally to the left side. So, in total 8 newly built MBS magnets are needed;

3) The other deflections are done by standard SPS-MBB and MBE magnets;

4) If the switch starts further along the beam line e.g. at the start of the long TT66 drift space, more magnets would be needed.

It should be noted that, in order to allow for failsafe interlocking of the switching process between the different beam lines for LHC, HiRadMat and a PWA beam line, the energy of the PWA beam line should be at least a few percent different to both that of LHC and HiRadMat, to facilitate interlocks based on dipole magnet currents. For example, a beam energy of 430 or 445 GeV (to be confirmed) could be envisaged. With the agreed set of beam parameters and overall requirements, the next step is the detailed optics design, taking into account the constraints of the existing tunnel geometry and the location and optical requirements of the proposed demonstration experiment. It is expected that the majority of the beamline can be equipped with recuperated magnets.

ACCELERATED BEAM

The 450 GeV proton beam will be diagnosed for transverse effects from the plasma wakefield. The experiment relies on self-modulation of the long proton bunch [5]. Though there will be some protons that are accelerated by 1 GeV, it turns out experimentally not feasible to distinguish the strong transverse effects on many protons from the longitudinal acceleration effects for a few protons. The parameters for an adequate spectrometer and imaging optics would be prohibitive [8].

Therefore it was decided that it is a much more efficient solution to inject a low energy electron beam that serves as witness of the accelerating plasma wakefields. For the initial operation, an incoming electron beam energy of around 10 MeV and a long bunch length (longer than the plasma wavelength) are envisaged. In this case, a fraction of the injected electrons will be accelerated to energies of several hundreds MeV (later up to 1 GeV). Proton and electron beams are separated after the plasma and the accelerated electrons can be easily diagnosed with a compact spectrometer [8].

NOVEL ACCELERATOR TEST FACILITY

The proposed setup would provide space for constructing a plasma-based electron beam accelerator (“laser plasma wakefield accelerator”) [3] on CERN site. Such an advanced CERN accelerator could be part of the worldwide efforts to develop a GeV-class electron injector and accelerator with femto-second bunch length, sub % energy spread, high transverse density and good availability (7 days per week, 24 h per day operation). Such a short bunch (fs regime) could also be injected into the proton-driven plasma accelerator. It would fit into the bucket of the plasma wakefield and would be coherently accelerated. This advanced phase would require mastering various challenges, including fs timing issues. Other possible tests in a novel accelerator test facility at CERN could include plasma cells as energy recovery dumps, ultra-strong focusing plasma lenses and plasma collimation.

CONCLUSION

Proton beams are potentially very powerful drivers for compact, high energy e^+e^- colliders for particle physics. Accelerator studies on first tests of proton-driven plasma acceleration with CERN beams have led to a layout of a possible experimental setup. The proposed layout uses existing tunnels and buildings at CERN that are presently not used or used for storage. A proto-collaboration of 25 institutes interested in proton-driven plasma acceleration has submitted a letter of intent to CERN that is presently being reviewed by the committee in charge for SPS experiments (SPSC). The proposed setup provides space for creation of a CERN test facility for novel, ultra high-gradient particle acceleration. In such a facility many other exciting research topics towards novel high energy physics e^+e^- colliders could be addressed.

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