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# Letter of Intent for a Demonstration Experiment in Proton-Driven Plasma Wakefield Acceleration

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# 1 Executive summary

We propose an experiment on proton-driven plasma wakefield acceleration (PDPWA) which could lead to a future TeV-scale $e^+/e^-$ collider of much reduced length compared to conventional designs [1]. The advantage of proton- over laser- or electron-driven PWA is the high stored energy available in the driver, both for the bunch as a whole and for the individual drive particles. Existing proton bunches can easily carry many kJ of stored energy while high power lasers are presently approaching the 1-5 J regime. Proton bunches are therefore ideal drivers for high energy lepton accelerators, with the potential of reducing drastically the number of required driver stages.

Ideally one would use short, high energy proton bunches as drivers, adapted to the wavelength of the plasma wakefield (mm). Such short proton bunches are not available and are difficult to produce in the existing CERN accelerators. Instead proton-plasma self modulation is exploited. By using a plasma to modulate a long proton bunch, a strong plasma wave can be generated by a series of 'micro-bunches', so that an experimental program can start today with the existing proton beams. In this letter of intent, we propose a demonstration experiment using the existing CERN SPS beam. This project would be the first beam-driven wakefield acceleration experiment in Europe, and the first proton-driven plasma-wakefield acceleration experiment worldwide. We have set as an initial goal the demonstration of 1 GeV energy gain for electrons in 10 m of plasma. A proposal for reaching 100 GeV within 100 m of plasma will be developed using results from the initial round of experimentation.

The major elements of a PDPWA demonstration experiment consist of a beamline switch for proton bunches from the SPS (prepared as part of HiRadMat), a beam transport (TT61) to the surface, a beam delivery (TT4/TT5), a plasma cell with diagnostics, an electron bunch injection system and diagnostic equipment (for measurements of the bunch modulation, fields in the plasma and particle acceleration). The request to CERN is for allocation of the required tunnel space, and the beam extraction, delivery and focusing system. The collaborating institutes will provide the plasma cell, electron injector and the diagnostic equipment. It is estimated that one year will be needed to work out the detailed technical design and two years to set up the experiment. An initial round of experiments would take a further two years. The running time would consist of approximately 4 periods of two weeks per year, with bunch repetition rates of approximately 1/30 Hz during the running periods.

It is envisaged that the proposed experimental setup can be extended in the future to perform additional advanced accelerator research at CERN. Several topics have already been suggested and are listed at the end of this document. The proposed location of the experiment in TT4/TT5 is compatible with such future usages.

The proto-collaboration is already significant in size, and includes expertise from previous PWA experiments.

## 2 Introduction

Particle accelerators are the fundamental research tools of the high energy physics community for studying the basic laws that govern our Universe. The experiments conducted at the LHC will give us new insights into the physical world around us. Next generation lepton colliders should reach the TeV scale. Circular colliders are not feasible at these energies due to synchrotron radiation losses. Hence future collider designs are based on linear colliders. However, as the beam energy increases, the scale and cost of conventional machines become very large. For a linear accelerator, the size and cost mainly depend on the breakdown limit of the wall of RF cavities from which the beam particles gain energy. At present, metallic cavities (copper or niobium) achieve maximum accelerating gradients around $100$ MV/m. To reach the TeV scale in a linear accelerator, the length of the machine is therefore tens of kilometers.

It is natural to think about how to make future machines more compact, and plasma acceleration is a possible solution. A plasma is a medium consisting of ions and free electrons; therefore, it has an extremely high ($>$GV/m) breakdown limit and it can sustain very large electric fields [2, 3]. In the last few decades, more than 3 orders of magnitude higher acceleration gradient than in RF cavities have been demonstrated with plasmas in the laboratory [4, 5]. The laser-driven generation of 1 GeV beams of $10^8$ electrons, with bunch length below 50 fs, 2.5% energy spread and small transverse emittance has demonstrated the promise and potential of this technology.

Generally speaking, a plasma acts as an energy transformer; it transfers the energy from the driver (laser or beam pulse) to the witness bunch that is accelerated. Current proton synchrotrons are capable of producing high energy proton beams, reaching up to multi TeVs (the LHC), so that a new research frontier would be opened if we could efficiently transfer the energy in a proton bunch to a witness electron bunch.

It has been recently proposed to use a high energy proton bunch to drive a plasma wakefield for electron beam acceleration [1]. Numerical simulations have shown [6] that a $1$ TeV bunch, with $10^{11}$ protons and an rms bunch length of $100$ $\mu$m as driver could indeed excite a large amplitude plasma wave. Surfing the appropriate phase of the wave, an electron bunch reaches energies over $600$ GeV in a single passage through a $450$ m long plasma. Recent studies [7, 8] have shown that similar gradients can be reached with a modulated long proton bunch, opening the path for immediate experimental investigations with the existing proton bunches at CERN. The modulation of the proton density on-axis results from the modulation of the transverse profile along the bunch length. For coherent wakefield excitation, this is equivalent to having a series of ultra-short proton bunches with an effective length set by the plasma wavelength.

In this Letter of Intent (LOI), we propose an experimental study of proton-driven plasma wakefield acceleration (PDPWA) utilizing the existing proton beam from the CERN Super Proton Synchrotron (SPS). By sending the beam into a plasma, a large amplitude plasma wakefield will be excited. No compression of the proton beam will be necessary, as the plasma will naturally modulate the long bunch, which in turn will generate the plasma wave for the witness bunch acceleration. A demonstration of strong electric fields will be performed by measuring the acceleration of externally injected electrons up to $1$ GeV in $10$ m of plasma.

In the next sections, we review the simulations of PDPWA, focusing on the self-modulation effect. The proposed experimental setup is then introduced and the related issues such as the plasma cell, electron injector and diagnostic techniques are discussed. The beam requirements are then given, followed by a possible timeline of the project, along with a task breakdown and cost estimate. We first discuss the choice of the beamline.

# 3 Choice of SPS beam

Two beam lines at CERN, from the PS and SPS, could be used to provide an adequate relativistic proton beam for the experiment. One is located in the East Area of the PS and the other is connected to the West Area of the SPS. As the injectors for the LHC, the PS and SPS could provide proton beams with maximum momenta of $24$ GeV/c and $450$ GeV/c, respectively. For the two selected candidate beam lines, the bunch intensities vary from $10^9$ to $3.0 \cdot 10^{11}$. Particle-in-Cell (PIC) simulations of interactions between a proton bunch and a plasma have been performed with realistic beam parameters of the PS and SPS [8, 9]. The results show that high amplitude wakefields can be achieved not only by a short-bunch proton driver (not existing), but also through the micro-bunches produced by the transverse two-stream instability of a long driver bunch. Simulation also indicates that the SPS beam can drive a much higher amplitude plasma wake than the PS beam. The lower emittance of the SPS beam allows the instability to develop before the beam diverges due to the intrinsic angular spread. In addition, the available tunnel in the current SPS extraction line is around 600 m long, which much better fits the space needs for the experiment optics, plasma source and instrumentation, while leaving room for possible future extensions in this research. Therefore, we propose to use the SPS beam in our first demonstration experiment on PDPWA. The experimental area would be located in TT4/TT5 (see discussion of experimental layout). The basic beam parameters are listed in Table 1.

Table 1: Basic beam parameters of the SPS.

| Parameter | Nominal | Optimized |
|---|---|---|
| Momentum [GeV/c] | 450 | 450 |
| Protons/bunch [$10^{11}$] | 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 transverse normalized emittance [$\mu$m] | 3.5 | 3.5 |
| beam size [$\mu$m] | 200 | 200 |
| beta function at plasma cell [m] | 5 | 5 |

# 4 PDPWA via bunch modulation

The interactions between a long proton bunch and a plasma have been studied both theoretically [7] and in simulations. These studies reveal that a strong self-modulation effect occurs due to the transverse wakefields in the plasma. The wakefield excited by the bunch head modulates the density of the bunch tail and many ultra-short bunch slices are naturally produced, with a spacing of one relativistic plasma wavelength.

For a highly relativistic drive bunch, the electric field seen by the plasma electrons is in the transverse direction, and the passage of the bunch causes the plasma electrons to oscillate around their equilibrium position with frequency $\omega_p$ given by

$$\omega_p^2 = \frac{n_p e^2}{\epsilon_0 m}$$

where $n_p$ is the plasma density, $\epsilon_0$ is the permittivity of free space and $m$ is the electron mass. A useful formula for the plasma wavelength is $\lambda_p = (1\ \mathrm{mm}) \cdot \left(10^{15}\ \mathrm{cm}^{-3}/n_p\right)^{1/2}$. Given their large mass, the plasma ions are effectively immobile at the $1/\omega_p$ time scale. The oscillating electrons initially move toward the beam axis. The oscillations of the plasma electrons produces regions of high and low electron density. The structure repeats, and the pattern moves with the proton bunch velocity. An appropriately timed witness electron bunch can be placed in a region of very strong longitudinal electric field and accelerated. The plasma also provides a radial force that keeps the witness bunch, as well as the tail of the drive bunch, from expanding radially.

In the case of a short bunch (compared to the plasma wavelength) the maximum axial electric field is given approximately by [10]

$$E_{z,\max} \approx 2(\mathrm{GV/m}) \left(\frac{N}{10^{10}}\right) \left(\frac{100\,\mu\mathrm{m}}{\sigma_z}\right)^2 .$$

where $\sigma_z$ is the rms length of the drive bunch and $N$ is the number of particles in the drive bunch. As is clear from this formula, short drive bunches are necessary for the generation of strong wakefields. In the modulated bunch case, the fields from many microbunches with $\sigma_z \approx \lambda_p/2\pi$ and $N \ll N_p$ add coherently ($N_p$ is the number of protons in the drive bunch). Simulations indicate that field strengths resulting from modulating a long bunch are only about a factor three smaller than those which would be achieved by compressing the long bunch to $\sigma_z \approx 100\ \mu$m.

### 4.1 Seeding the modulations

The modulation of the long proton bunch can start from any perturbation, and grows exponentially until full modulation is achieved [7]. Since inhomogeneities of various kinds (noise) are always present, we expect to see the bunch modulation effects for standard SPS bunches. However, to make the results more reproducible, we will investigate the possibility to seed the modulations - i.e., to produce a large perturbation at the sub-plasma wavelength scale in a controlled way. One possibility we are investigating is to generate this perturbation by forming the plasma at a fixed phase of (position along) the proton bunch. In this scheme, the plasma is created by firing an intense short laser pulse into a gas cell, as described below. We can time the laser pulse such that it co-propagates with the proton bunch but offset from the front of the bunch. Viewed from the frame of the proton bunch, the plasma density increases from 0 to its maximum value in a very short distance at a fixed position along the bunch. This generates the large perturbation and seeds the modulation. In the simulations described in this LOI, we have assumed that the plasma starts at the midpoint of the proton bunch.

Other seeding options for the modulations are currently under evaluation:

1. Creating a plasma wave with a short and intense laser pulse ahead of the proton bunch. The distance the laser pulse would have to travel in the plasma and effectively seed the modulation of the proton bunch is presumably much shorter than the full length of the cell, so that a less powerful laser would be needed than in the option described above. The parameters are currently under investigation with numerical simulations.
2. Creating the plasma ahead of the arrival of the proton bunch, and starting a plasma wave with a short electron bunch. Again, the seeding would presumably only be needed for a short segment at the start of the plasma cell. The parameters for this option are also currently under study with simulations. It is foreseen that the same electron injector could be used to both seed the modulation and to provide the witness bunch for acceleration.

While the latter two options are very attractive, simulation results will have to guide the choice of parameters and indicate whether they are feasible.

### 4.2 Simulations based on the SPS beam

To study numerically the evolution of the beam in the plasma, we employ various Particle-in-Cell (PIC) codes: VLPL [11], OSIRIS [12], QUICKPIC [13] as well as a hybrid code, LCODE [14]. The simulations show that when the bunch propagates through the plasma, a strong density modulation occurs, as shown in Fig. 1. In Fig. 1, a standard SPS bunch as injected in the LHC is used as the drive bunch. $\xi$ ($\xi = ct - z$) denotes the position along the bunch with $\xi = 0$ the midpoint of the bunch and $n_b$ the bunch density normalized to the background plasma density $n_p$. The figure gives the on-axis beam density profile after $4.8$ m propagation in the plasma of density $10^{14}$ cm$^{-3}$. It clearly shows that the bunch density is strongly modulated. Some particles in the bunch are focused and the density is periodically enhanced. Other particles are defocused and therefore the density is reduced. The length of each micro bunch is around one half of the plasma wavelength. These bunches excite the plasma wake resonantly and the wakefield can be used to accelerate some of the drive-beam protons as well as externally injected electrons.

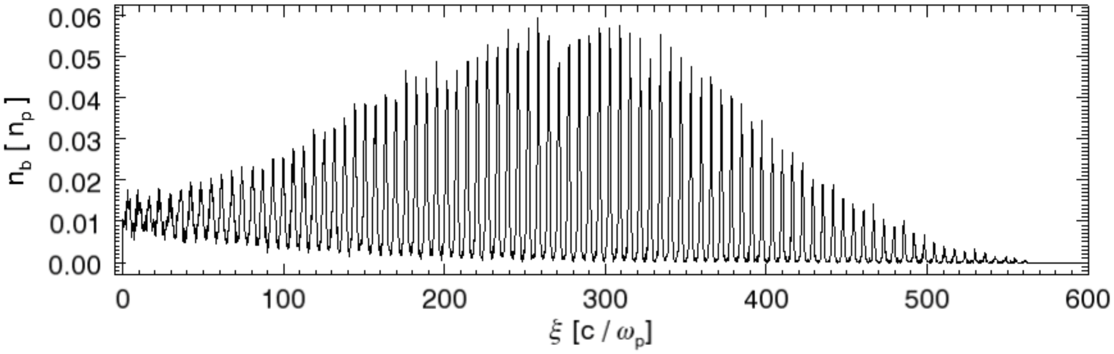


Figure 1: On-axis proton beam density profile after $4.8$ m propagation in a plasma. $\xi$ is the distance along the bunch in units of $c/\omega_p$. The beam density is given in units of the plasma density, here taken as $1 \cdot 10^{14}$ cm$^{-3}$.

The strengths of the electric fields produced in the plasma depend strongly on the plasma density. This is shown in Fig. 2, where the electric field generated in the plasma is shown as a function of propagation distance for two different density plasmas. Accelerating fields as large as $1$ GV/m have been observed in the simulations for parameters in the range of those considered for this experiment. One of the goals of the experimental program is to study the field strengths as a function of plasma density and thereby verify and ultimately improve the simulation results. The results from the different simulation codes have been compared to each other, and agree well.

### 4.3 Particle acceleration

To provide the clearest demonstration of the strong electric fields present in the plasma, we intend to demonstrate $1$ GeV particle acceleration with $10$ m of plasma. To demonstrate directly the energy gain in the plasma, we will inject electrons into the plasma cell simultaneously with the protons and measure their output momentum distribution. Simulation studies show that electrons of energy around $10$ MeV are accelerated to several hundred MeV in a few meters of plasma. Observing such changes in electron energies should be much more straightforward than observing an effect in the stiff proton beam. No bunching of electrons will be necessary - we will just observe an energy gain for electrons injected at the correct phase. We anticipate that with further tuning of parameters, an acceleration up to $1$ GeV will

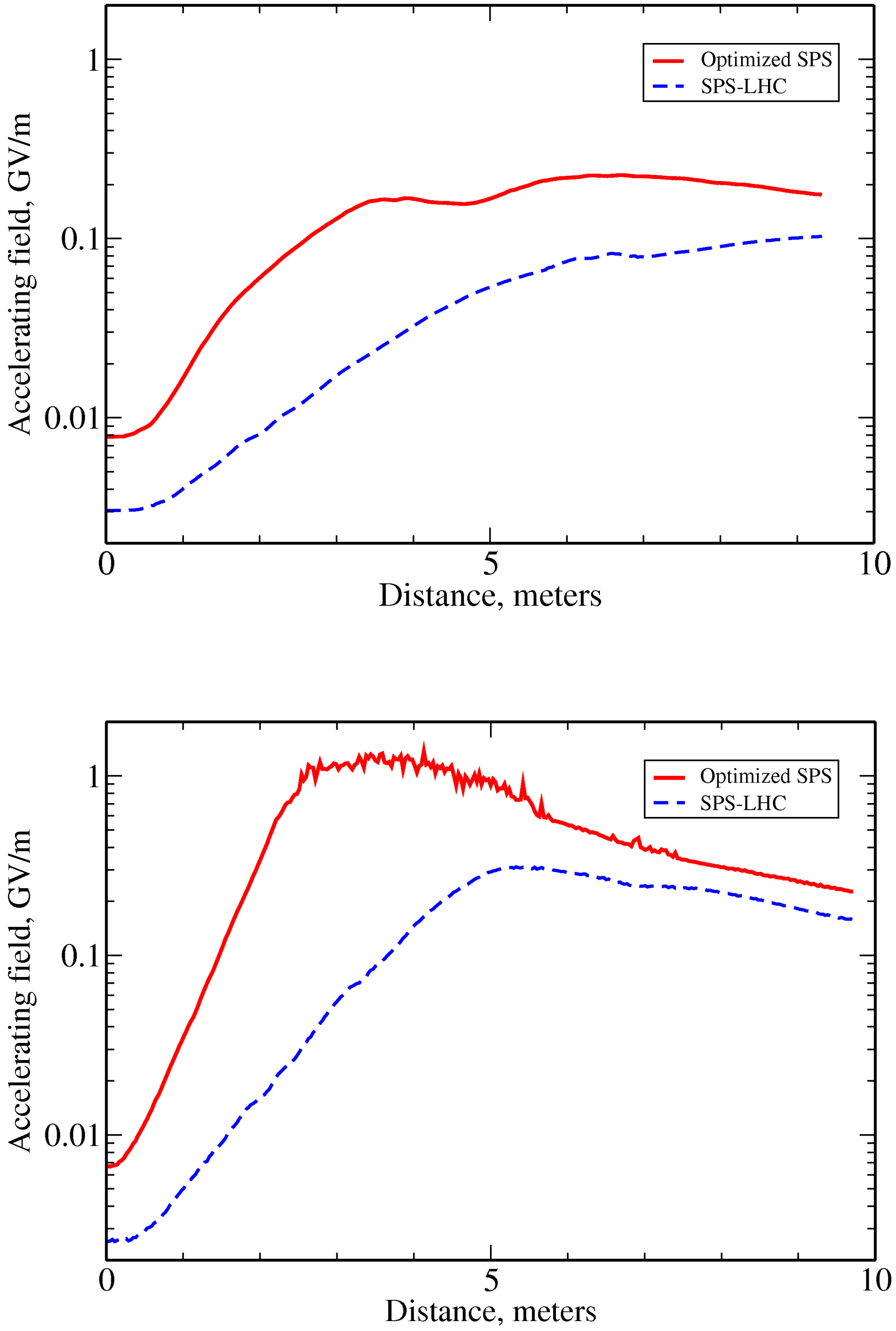


Figure 2: The longitudinal electric field generated in the plasma as a function of propagation distance in the plasma for the nominal (blue-dashed) and optimized (red-solid) SPS beams and for plasma densities of $1 \cdot 10^{14}$ cm$^{-3}$ (top) and $7 \cdot 10^{14}$ cm$^{-3}$ (bottom).

be possible within 10 m of plasma. We will use simulation results to guide the design of the optimal electron injector.

# 5 Experimental Aspects

## 5.1 Beamline

A possible beam line layout assuming the TT61 tunnel (see Section 6) is shown in Fig. 3. We anticipate bringing the proton beam up to the surface and locating the plasma cell and diagnostics in the TT4/TT5 area, as shown in the schematic. The major components of the experimental setup at the surface include an electron beam injection system, a plasma cell, a spectrometer to measure the outgoing electron energies and a beam dump. A possible laser driven electron injector is also indicated as an option for the future.

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. After the plasma cell, a beam line with an energy spectrometer can be used to analyze the electron beam energy variation caused by the plasma. Diagnostic equipment will be employed to characterize the proton and electron beam properties (beam size, current, emittance, energy , modulation, etc.) with and without the plasma present. The beam dump will absorb the spent beams.

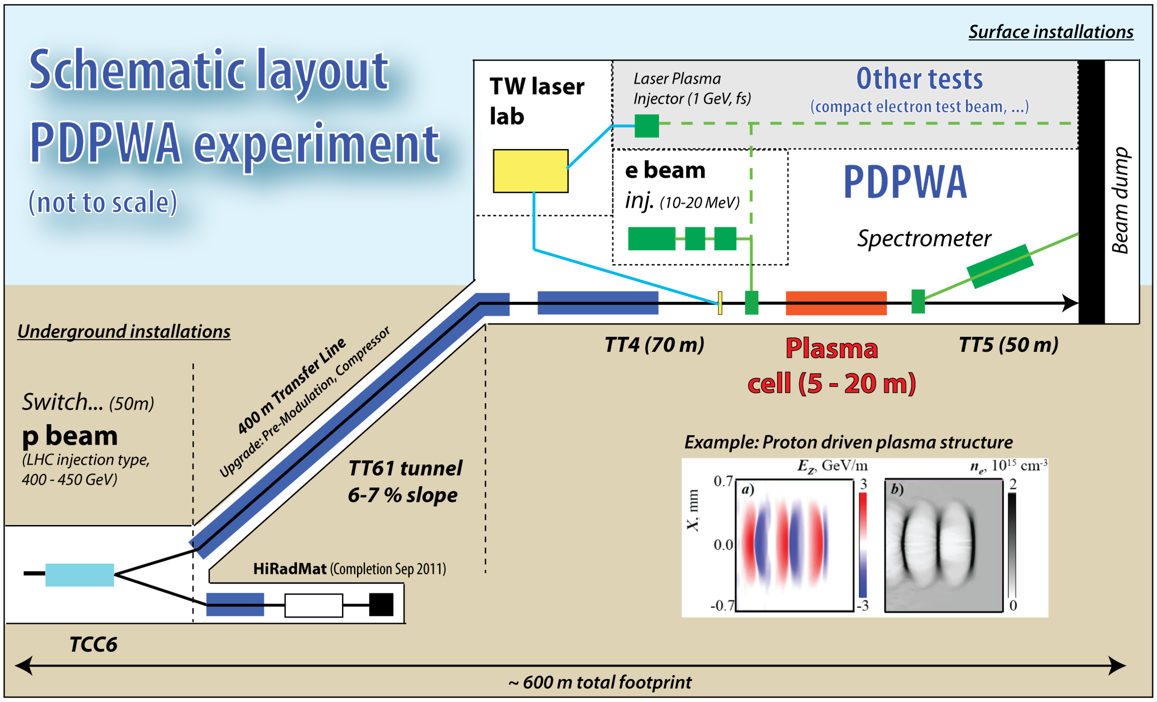


Figure 3: A possible beamline layout for a PDPWA experiment.

The beam line design is currently being worked out based on realistic SPS beam parameters. To design the beam line for a tunnel with this large slope, the vertical dispersion will be taken into account. Initial beam transport schemes have been studied and these have been used to estimate the number of components necessary to deliver the SPS proton bunches to the plasma cell. These are summarized in Section 6. After exiting the plasma, the beam line design will be performed based on the PIC simulation results for the beam emerging from the plasma.

## 5.2 Aspects of radiation, safety and interlocks

Radiation protection aspects that will have to be addressed include:

- Prompt doses to areas adjacent to the surface installations: Their limitation and minimization can be achieved with placing sufficient shielding and an appropriate design of access passages. The assessment will include accident scenarios.
- Air activation and releases into the environment: The results of related studies define the requirements on the ventilation system that will be designed and implemented accordingly. It has to minimize both the releases into the environment as well as doses to personnel entering the accelerator and experimental areas.
- Activation of beam-line components and dumps: Significant experience exists at CERN in design optimizations of components and their handling in order to limit dose to personnel according to the ALARA principle. In particular, residual dose rates have to be sufficiently low in areas where frequent accesses are required.
- Activation of liquids, especially cooling and infiltration water: Depending on the predicted activation levels handling constraints and release pathways will be defined.
- Definition and implementation of a radiation monitoring system in order to control prompt dose rate levels in adjacent accessible areas during operation, to assess residual dose rates during beam-off periods as well as to monitor releases of air and liquids into the environment.
- An estimation of the production of radioactive waste: It will include an optimization in the choice of materials in order to minimize costs for waste disposal.

Furthermore, radiation safety aspects have to be considered and related systems designed (e.g., the access and interlock system) in order to allow a safe operation of the facility.

Detailed studies on all above issues will be performed after a positive review of this LOI.

## 5.3 Plasma sources

A plasma can be produced by ionization processes that raise the degree of ionization much above its thermal equilibrium value. Two commonly used ionization processes are photo-ionization and electric discharge or field ionization. The electric field of the SPS beam is too weak to directly ionize the vapor, and we are thus investigating laser-based plasma sources, discharge sources and Helicon plasma sources. The plasma parameters we plan for in the first phase of the experiment are a cell length of $5-10$ m and a plasma density range of $1-20\cdot 10^{14}$ cm$^{-3}$. The plasma will most likely use Lithium, Cesium or Argon gas.

### 5.3.1 Laser-based plasma source

Metal vapors have been used or considered for laser ionized plasma cells in past beam-driven plasma wakefield experiments. E.g., Lithium has a relatively low ionization potential for the first electron ($5.4$ eV) and it allows ionization over a broad range of laser parameters. The large ionization potential of the second electron ($75.6$ eV) ensures that the plasma density does not evolve significantly along the laser pulse due to secondary ionization. Cesium (Cs), Xenon (Xe) and nitric oxide (NO) also have relatively low ionization potentials for the first electron. The potentials are $3.89$ eV, $12.13$ eV and $9.25$ eV, respectively. Therefore they are possible alternatives to Li.

In order to produce a homogenous plasma, we can use a configuration similar to the plasma sources of the SLAC E-157 and E-162 experiments. These sources were based on a Li heat-pipe oven in which the Li gas was $10$ % pre-ionized using a long focal length laser. Figure 4 shows the essential elements of the plasma source in the SLAC experiment. A neutral Li vapor density in the $10^{15}$ to $10^{16}$ cm$^{-3}$ range can be obtained by heating the Li to around $750°$ C. The hot Li vapor is confined to the heated central part of the oven by a room temperature He buffer gas located on both ends of the heat-pipe. The vapor temperature is such that the Li vapor pressure is equal to the He pressure. The Li density is thus determined by the adjustable He pressure. The length of the Li column is approximately equal to the length of the heated section of the pipe, and can be varied to some extent by changing the heating power delivered to the oven.

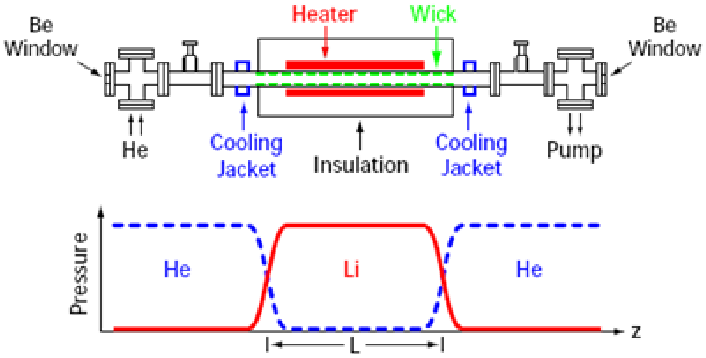


Figure 4: Schematic of the Li vapor plasma source (not to scale).

One option is to ionize the gas via single-photon absorption; e.g., in a 20 ns, $F_0 = 145$ mJ/cm$^2$ ArF UV laser pulse [15]. In this scheme, the laser pulse is much longer than the proton pulse, and therefore the plasma has to be created before the arrival of the proton bunch. The laser parameters are relatively easy to reach and the requirements on optical elements are moderate. An important issue is the relaxation time of the plasma, and the resulting control of the density. Also, in this scheme, there is no seeding of the modulation via the generation of the plasma. The line integrated plasma density $n_pL$ can be measured by UV absorption, and also by CO$_2$-laser and visible-laser interferometry. The plasma density varies linearly with $F_0$ and can reach full ionization of the vapor atoms.

Another option being investigated is to use a ca. 5-TW, 50-fs laser focused down to 2 mm [16]. The plasma is formed by field ionization from the intense laser pulse. In this case, the plasma could be formed simultaneously with the passage of the proton bunch, and therefore seeding of the modulations could be implemented. The requirements on the laser and on the optics are however more demanding in this case. Studies are underway on the possibility to produce a $10$ m long Cs plasma with density of $10^{15}$ cm$^{-3}$ in this approach.

As mentioned above, laser ionized plasma cells of length $1.4$ m have been successfully built and operated in the past. Our requirements are for cell lengths of $5-10$ m. While we do not foresee major technical hurdles in producing plasma cells of this length via laser ionization, this however needs to be demonstrated with prototypes.

### 5.3.2 Helicon plasma cell

With laser powers available today the setup of a plasma cell with $l \gg 5$ m is challenging for single laser operation. In contrast, scalability is an intrinsic feature of the helicon plasma cell concept. In this scheme, low-frequency electromagnetic plasma waves are excited and the wave energy is non-resonantly dissipated in the plasma center. Thus, they represent an extremely efficient plasma source [17]. The prerequisite for the propagation of helicon waves, however, is an ambient magnetic field. The plasma density of helicon discharges is given by a dispersion relation which combines helicon wave parameters with operational parameters of the plasma cell [18, 19]:

$$\frac{k_{\|}k}{\omega} = \frac{e\mu_0 n_p}{B},$$

where $k_{\|}, k$ are the parallel and total wavenumber of the helicon wave, $\omega$ is its frequency, $B$ is the ambient magnetic field and $\mu_0$ is the magnetic permeability, respectively. Three important consequences result from the dispersion relation: *(i)* In principle, there is no plasma density limit for helicon discharges. *(ii)* Within the frequency range of helicon waves the plasma density scales linearly with ambient magnetic field. *(iii)* The operational regime of the plasma density is determined by the wave parameters, which are primarily set by the cell geometry. It is a very appealing feature of helicon plasmas that the helicon waves are excited by antennas, which are located outside the plasma volume, as shown in Fig. 5. In particular this allows for a distribution of the plasma heating along the plasma cell and allows for scaling of cell to arbitrary lengths. However, to date helicon plasma cells have not been operated at the densities we require. Also, the uniformity of the plasma will be a critical issue to ascertain.

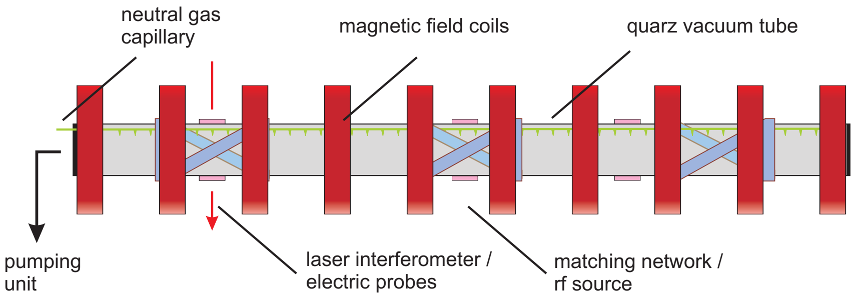


Figure 5: Schematic of one stage of a Helicon plasma source.

We intend to set up and operate a prototype helicon plasma cell, which represents the scalable core module for the required long plasma cell arrangement. Given successful tests, helicon plasma cells would be an attractive option for the long plasma cells needed for future experiments, and we would anticipate testing them in our experimental setup.

### 5.3.3 Pulsed plasma discharges

Long plasmas with the range of plasma densities adequate for the PDPWA experiment can be produced in a plasma source based on a pulsed plasma discharge in argon. A plasma of $\mathrm{Ar}^+$ close to 100 % ionization (temperature around 1 eV) with electron density of $10^{14} - 10^{15}$ cm$^{-3}$ can be produced by a discharge current density around 1000 A/cm$^2$ with a duration of a few microseconds. Accessing higher electron densities will also be investigated by optimizing the source operation as well as the plasma ignition mechanism. A scheme of the plasma source is presented in Fig. 6. The pulsed plasma will be contained inside a sequence of dielectric tubes of about 1 cm diameter. The small interruptions of the tube are used for fast gas injection before each shot and they can also be used for transverse diagnostics. Since a long and uniform plasma is required ($L > 5$ m, uniformity better than $1$ %) and the plasma should exist between vacuum tubes carrying the beams, the mechanism for initiation of the plasma will play an important role. For low density plasmas ($10^{14} - 10^{15}$ cm$^{-3}$ ), a low current glow discharge may be started in order to produce a partially ionized uniform plasma. Alternatively, several low power ($< 2$ kW) microwave surface discharges can be used to start a glow discharge between electrodes E1 and E2 producing a partially ionized plasma of high uniformity with using a low current (typically $< 20$ A). The ionization level can then be increased before the interaction with a higher current discharge (up to $1000$ A/cm$^2$ over a few microseconds). Continuous operation will also be investigated by using additional microwave and radiowave heating to maintain high plasma temperatures.

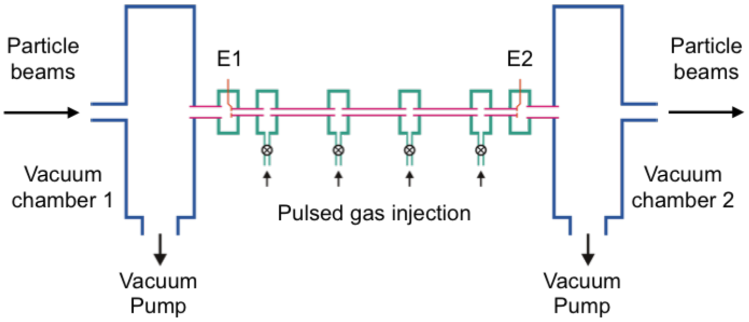


Figure 6: Schematic of one stage of the plasma source based on a pulsed plasma discharge.

Although the production of the desired plasma in a closed tube seems not difficult its inclusion in the experimental setup is challenging mainly due to the interface between the hollow electrodes and the metal vacuum chambers limiting the plasma source. An intensive test program of the source is required to find the adequate operation for different plasma densities and lengths as well as to optimize the design of the most critical components. One of the main advantages of the proposed plasma source is the possibility of staging as many discharges as required to perform acceleration experiments with plasma lengths longer than the present $5 - 10$ m goal.

## 5.4 Diagnostic equipment

The diagnostics include the measurements of the properties of the incoming proton drive bunch and of the proton bunch exiting from the plasma, measurements of an injected electron beam, as well as the parameters of the plasma. Beam parameters, such as beam energy, bunch charge, bunch length, transverse size and emittance etc., need to be known exactly before the plasma. After the interaction with the plasma, the exit beam properties also need to be measured so as to infer the effect of the plasma wakefields on the proton and electron bunches. Possible measurements in the demonstration experiment are sketched in Fig. 7.

### 5.4.1 Measurements of the proton bunch

A few ferrite-core toroidal current transformers will be employed to measure the beam charge along the beam line on a pulse-to-pulse basis. Prior to the plasma channel, a wire scanner can be used to measure the average projected beam profile in the horizontal and vertical direction. While wire scanners use many bunches to measure the beam profile, an Optical Transition Radiation (OTR) foil or screen combined with a CCD camera will give single bunch images of the beam profile.

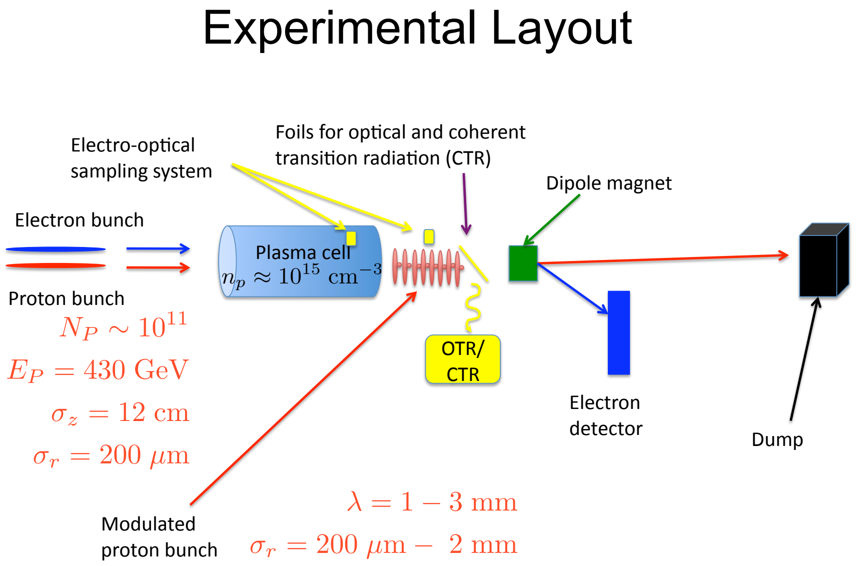


Figure 7: Schematic indicating the measurements related to the modulation considered in the first demonstration experiment. In addition, standard proton and electron beam diagnostic equipment are foreseen before the plasma cell (not shown).

### 5.4.2 Single-shot (Terahertz) diagnostic

In general, we will want information about the temporal development of the proton bunch current profile to study the modulation process as the bunch passes through the plasma. Measurement results will be compared with simulations to gain a detailed understanding of the bunch modulation process and its dependence on the bunch and plasma parameters. We want to utilize different techniques for the longitudinal bunch diagnostics: OTR with streak camera, coherent transition radiation (CTR) detection, and electro-optical (EO) sampling. Each of these techniques is influenced by different secondary effects, but the combined results will give us the needed information of the bunch density profile in each stage of the setup.

In the first round of experiments, we will look for the modulation of the proton bunch in the transverse direction via OTR. We expect to see variations in the density profile modulated at the plasma wavelength as shown in Fig. 1. These modulations will be visible with the use of a streak camera. Streak cameras have been used in previous plasma wakefield experiments and can resolve time structures below 1 ps (300 $\mu$m). This resolution is sufficient to resolve modulation at the mm-scale expected with plasma densities in the $10^{14} - 10^{15}$ cm$^{-3}$ range.

More advanced techniques will be developed to obtain time and frequency domain information from inside and outside the plasma channel via electro-optic sampling. Here, the electric field of the proton bunch induces an optical birefringence (Pockels-effect) in a non-centro-symmetric material (e.g. InP or GaP) placed in the vicinity of the beam path.

Another option we plan to study is the use of coherent transition radiation in the frequency domain. Coherent transition radiation will be generated by placing foils in the path of the bunch, as shown in Fig. 8. Radiation at wavelengths longer than the size of the bunch add coherently and provide a higher

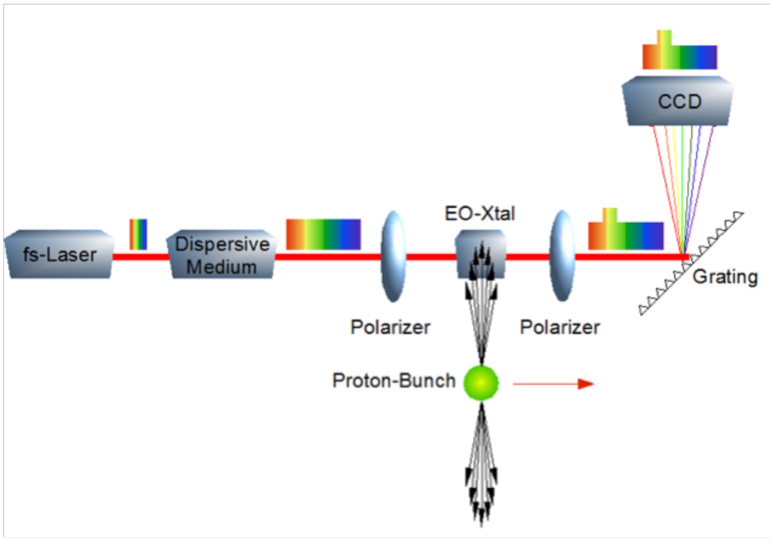


Figure 8: Principle of spectral encoding in a single shot sampling system.

intensity signal, whereas wavelengths short compared to the bunch length are incoherent and give much weaker signals. If the bunch has a micro-bunch substructure, then particular frequencies will produce large coherent radiation signals (at the harmonics of the modulation frequency). From the observed frequency spectrum, one can therefore gain information on the micro-bunch structure. The basic idea for the measurement is depicted in Fig. 9. A grating spectrometer is used to separate the frequency components, and the amplitudes in the different frequency ranges are measured by pyroelectric detectors. These have a bandwidth in the range $< 100$ GHz-10 THz and should be well suited for the measurements we have in mind. Tests of the system could be performed at existing accelerator facilities such as ANKA in Karlsruhe. Initial discussions to this effect have already taken place.

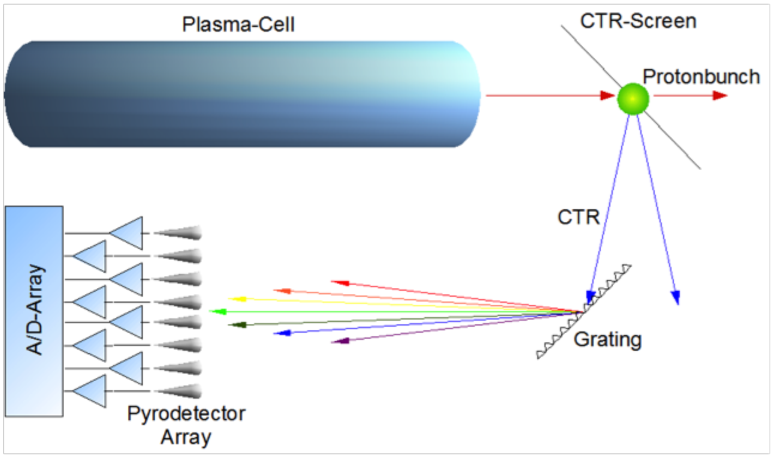


Figure 9: Principle of measurement using coherent transition radiation.

### 5.4.3 Electron spectrometer

The incoming electron beam will have a momentum of the order of 10 MeV/c, while the beam exiting the plasma will have particles spanning the $10 - 2000$ MeV energy range depending on the incoming proton beam parameters (nominal vs. optimized), the plasma length, and the plasma density (see Fig. 10). For the simulations shown in the figure, we have $\sigma_r = 0.2$ mm, $\sigma_z = 5$ mm, $E = 20$ MeV, no energy spread, and a normalized emittance of 2 $\mu$m. The electron beam is centered 24 cm behind the center of the proton bunch, and $10^6$ electrons have been injected. The efficiency for capturing and accelerating electrons depends on the injection scheme, and in simulations has reached 80 %.

We will design a spectrometer system which will allow us to measure this large momentum range. The electrons will be separated from the proton beam by a dipole magnet. The protons will only be minimally affected given their large momenta relative to the electrons. As an example of an electron spectrometer which could be suitable for our purposes, we describe the device developed at Strathclyde, which is a dipole spectrometer with a magnetic field strength up to 1.65 T [20] (see Fig. 11). The spectrometer features a Browne-Buechner design [21] to provide strong focusing in the horizontal and vertical planes thus enabling excellent energy resolution to be maintained over a wide range of energies. Two operating modes are possible: the first ("high resolution mode") uses a high field strength to bend the electrons through approximately 90 degrees with relatively narrow bandwidth (approximately ±20 % of the central energy). The second ("high energy mode") allows for wide bandwidth (300 MeV per Tesla) at the expense of a lower resolution, imaging beams with energies up to 660 MeV. Due to the higher energy of the electrons, additional upstream focussing of the beam by quadrupole magnets is required for optimal transport through the spectrometer. Scintillating Ce:YAG crystals positioned at the focal plane are used to image electrons exiting the spectrometer field and the image is captured on a CCD camera. We will investigate a similar design capable of reaching the 2 GeV possible with the optimized SPS beam.

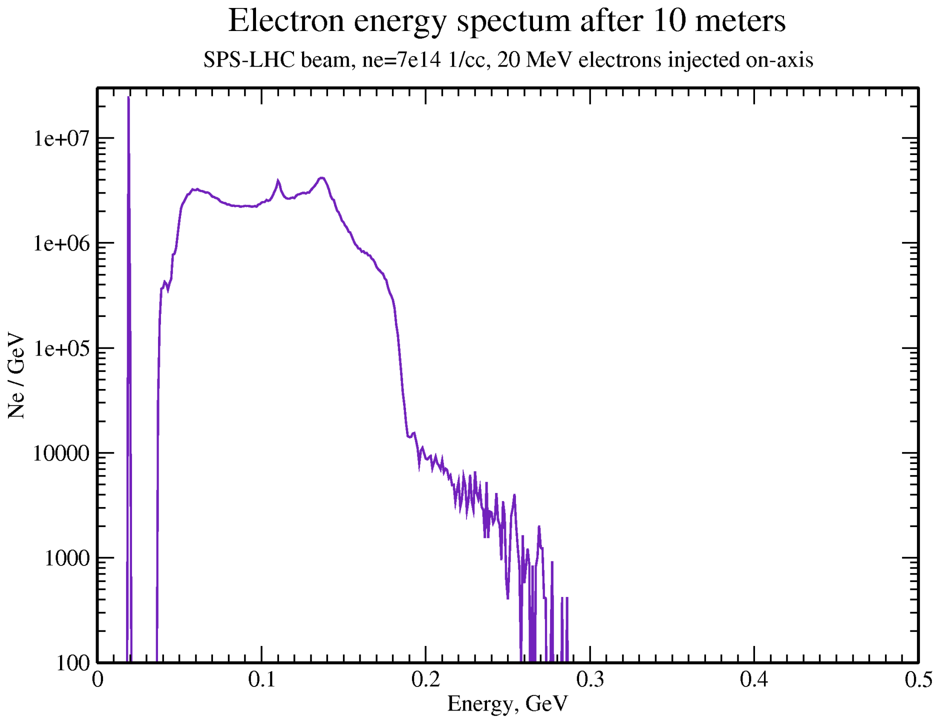
## 6 Accelerator requirements

For the location of the first demonstration experiment on PDPWA, we propose to use the TT61 tunnel in the West Area, starting close to TI2, and the TT4/TT5 areas. The length of tunnel is about 620 meters. The SPS can provide a proton beam with a maximum energy of 450 GeV and an rms bunch length of about 12 cm. The basic beam parameters are listed in Table 1. Figures 12 and 13 show the extraction beam line layout and a photo of the current TT61 tunnel (same direction as TI2 tunnel).

### 6.1 Proton beamline and components

For the demonstration experiment, two sets of proton beam parameters have been requested from the CERN-SPS and are summarised in Table 1. While the quoted standard SPS-LHC beam parameters are already operational, the high intensity SPS beam, with one bunch operation, remains to be demonstrated with the quoted parameters (in particular the combination of high intensity and small transverse emittances).

In order to keep the option open for such an experiment on PDPWA, during the design and construction of the High Radiation to Material Facility (HiRadMat) [22] a very preliminary study evaluated the possibility of sending protons into such an 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 [23]. These magnets would switch and transport 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 is 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.



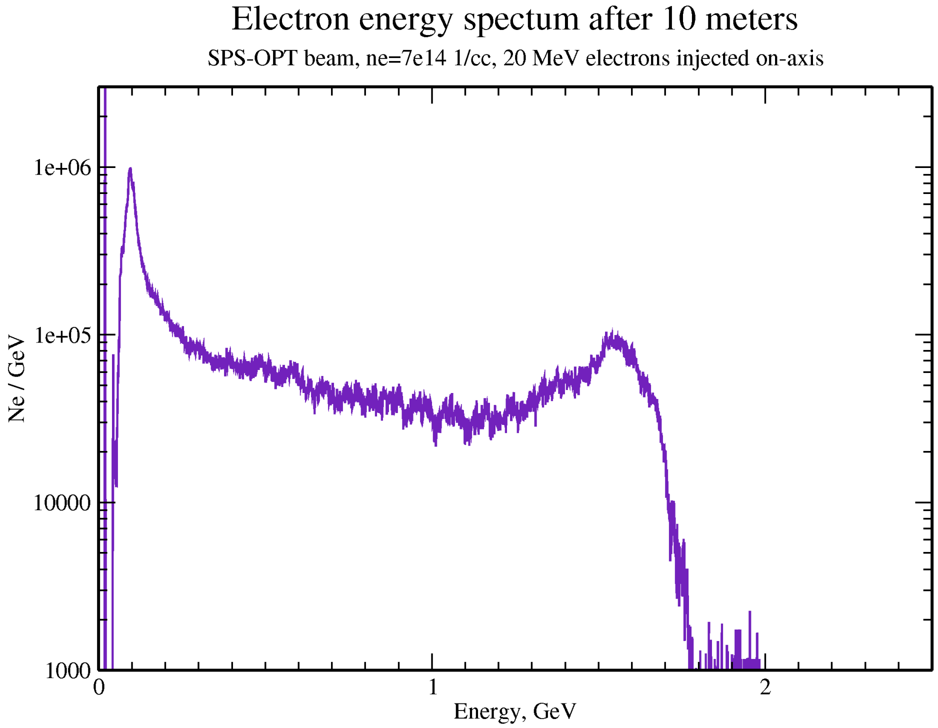


Figure 10: Simulated electron energy spectra from the plasma cell for the nominal SPS parameters (top) and the optimal parameters (bottom) after 10 m propagation in a plasma of density $7 \cdot 10^{14}$ cm$^{-3}$.

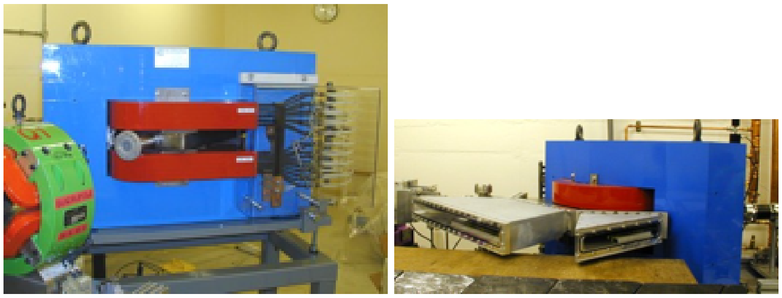


Figure 11: The Strathclyde electron spectrometer looking from the entrance side (left) and the output viewing windows of the electron spectrometer showing the Ce:YAG detector screens (right). The positions of the imaging CCD cameras are not shown.

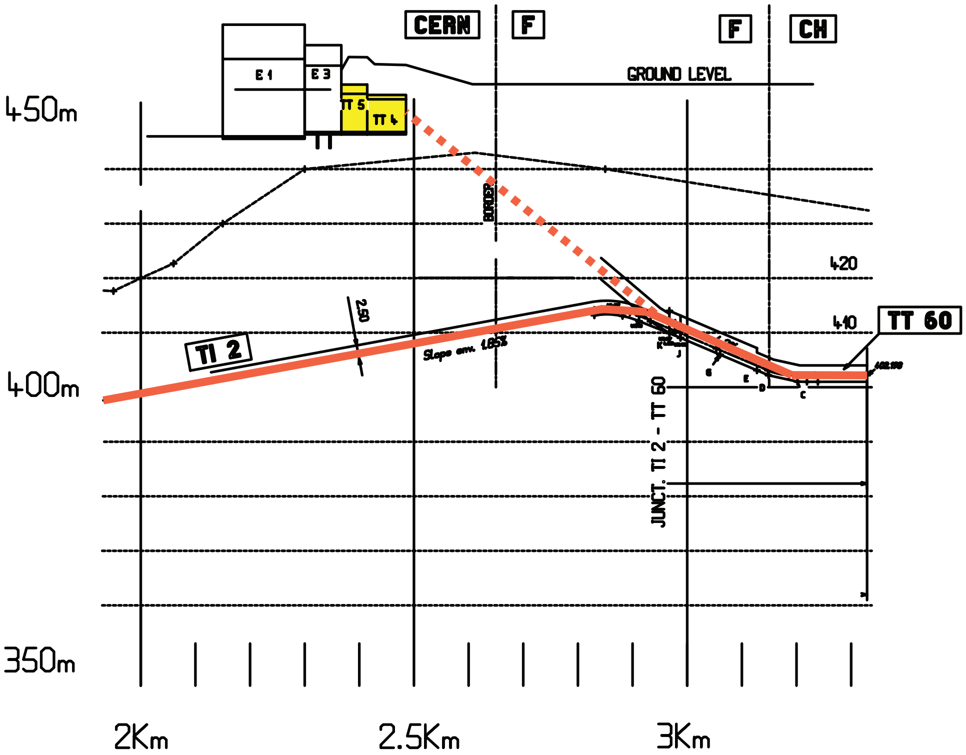


Figure 12: The beamlines needed for the PDPWA experiment: the TT4/5 tunnels on the surface (marked in yellow); the new transfer line (red dashed) and the existing lines (red solid).

Figure 13: The TT61 tunnel at present.

The very preliminary feasibility study showed that a PDPWA beam line is 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:

- To replace the last 2 bending magnets in TT66 (MBB type) by 4 new switch magnets (MBS type) which deflect the beam towards TT61;
- 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;
- The other deflections are done by standard SPS-MBB and MBE magnets;
- 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 PDPWA beam line, the energy of the PDPWA 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. For the moment, we anticipate designing the beamline to allow for the range $400 - 450$ GeV. 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 from old transfer lines.

## 6.2 Electron injector

An electron injector with the right properties (bunch charge, bunch length, emittance, etc.) will be needed for the experimental program. Many suitable injectors have been realized world-wide, so that we are confident that we will have electron bunches with the correct parameters for our project. We give two examples of electron injectors which could be used for our purposes: the LEP injector, and the Strathclyde ALPHA-X photoinjector.

### 6.2.1 LEP injector

One of the options is to re-use components of the LEP injector LIL. The LIL injector system is composed of three elements: the thermionic electron gun, the pre-buncher/buncher and the accelerating structure. Focusing of the beam is provided by additional solenoids. The thermionic gun produces a pulse of 20 ns duration. The total length of the electron gun system is about 1 m, and the gun requires 100 kV pulsed power. The 3 GHz S-band pre-buncher/buncher produces an up to 4.5 MeV (starting from the 100 keV input) electron beam. The buncher is driven by a 2.5 MW RF supply. An additional accelerating structure can be placed after the buncher to increase the energy up to about 15 MeV with a 1 m long structure. The normalized emittance produced by LIL injector, based on its historical performance, is about 70 mm-mrad for 1 A beam current. The most recent emittance measurements at 200 MeV and at very low current (which avoids beam loading effects) have shown normalized rms emittances to be 40 mm-mrad (in both planes). CERN and the JAI are currently planning to equip the Accelerator Science Lab in JAI with the LIL and other injector hardware now at CERN. The plans are under finalization at the moment. It is possible that in the future this hardware, or newly constructed hardware designed using the experience gained at the ASL, can be used for the PDPWA demonstration experiment.

### 6.2.2 ALPHA-X injector

Electron bunches with a charge up to several nC are extracted from a cathode surface that forms part of a resonant accelerating structure. The cavity is based on a Brookhaven National Laboratories design [25]. The irises are “elliptically” shaped rather than “circular” shaped, which reduces the peak electric field on the iris for a given axial accelerating field, which helps to reduce the dark current. As the production of a low emittance beam favours a cylindrically symmetric cavity the RF power is coupled to the gun via a co-axial “doorknob” antenna. The input coupler is a hollow 50 $\Omega$ co-axial line that couples to the 2nd cell of the gun. The waveguide is terminated in a suitably positioned short circuit to provide a correct RF match to the cavity. The photoinjector is capable of producing 100 fs long bunches [26]. The ALPHA-X photo-injector is a 2-1/2 cell, standing wave, $\pi$-mode S-band cavity operating at 2,998.550 MHz, with a maximum energy of 7.5 MeV.

### 6.2.3 Injection position

The possibility of electron injection at different places along the plasma should be envisaged, since recent simulations indicate that this could lead to much higher quality beams. To produce a high quality beam, electrons must be injected after the proton bunch modulation has had a chance to sufficiently develop, and this location depends on beam parameters and seeding options. We will need the freedom to move our electron injection along the plasma, and will design the electron injection system (and plasma cell) in a way to allow for this option.

### 6.3 Running scenario

We anticipate requiring a running time of 4 periods of two weeks per year. During the running time, we would request one bunch from the SPS per cycle, or approximately 1/30 Hz.

## 7 Project phases and goals

### 7.1 Phases of the project

The project is broadly divided into three phases:

- Phase I would be the development of a technical proposal for a demonstration experiment with proton driven wakefields, and would last one year starting from the time of submission of this LoI;
- Phase II would be the preparation of the experiment, and would last approximately two years;
- Phase III would be the actual running of the experiment, and would initially last two years.

We anticipate that positive experimental results will lead to the development of a full experimental/simulation/theoretical program aimed at accelerating an electron bunch to the TeV-energy scale using PDPWA.

#### 7.1.1 Phase I

Assuming positive review of this LOI, a more detailed technical design will be prepared. There are many open questions at this point, such as the design of the plasma cell, whether seeding of the modulations will be possible, how the beam delivery will be realized, etc. Expertise on these fronts has been assembled in a proto-collaboration. The groups will need time to build up to the desired strength and funding will be sought during this period.

We have identified the following items as requiring R&D to demonstrate feasibility:

- A plasma cell of the desired length. Plasma cells based on laser ionization of a metal vapor have been successfully operated at lengths up to $1.4$ m, while we require a plasma cell of $5 - 10$ m. While we are confident that such a cell can be built, a demonstration is still required. Alternative designs (discharge, helicon) are in principle scalable to long lengths, but the required uniformity and plasma density need to be demonstrated.
- The concept for seeding the instability needs to be understood. We are currently investigating three scenarios:
  - generating the seeding by forming the plasma with a short laser pulse co-propagating with the proton bunch (all simulation results reported here assume this type of seeding);
  - sending a short laser pulse into a pre-existing plasma just before the arrival of the proton bunch;
  - sending a short electron bunch into a pre-existing plasma just before the arrival of the proton bunch.

Though these schemes look promising, the simulations and optimization have still to be performed.

- Several of the THz optical diagnostic techniques require R&D to demonstrate their effectiveness; e.g., electro-optical sampling in the plasma cell and photon acceleration techniques. These techniques are not required for the demonstration of the acceleration mechanism, but will be essential in the analysis of the dynamics of the beam-plasma interaction.
- Evaluation of the radiation safety aspects. We are confident that we will find solutions for the radiation protection aspects. However, they will need to be studied in detail.

The delivery of the proton bunch, the electron injection and spectrometer systems and the beam dump are judged to be technically realizable.

### 7.1.2 Phase II

The second phase of the project will be the preparation for the experimental effort. It is expected that CERN will prepare the proton bunch delivery system. The bulk of the work will need to be done after the long shutdown of the LHC, which is currently foreseen for 2013; i.e., we anticipate that the beamline in the TT61 tunnel will most likely be installed in 2014. However, the work which needs to be done to send a beam into the TT61 tunnel should be performed in the 2013 shutdown since it will be difficult to continue work in this area while the LHC is running. In the meantime, the plasma cell will be designed, built and commissioned. The electron injection system has to be designed and constructed. Diagnostic systems will be developed and tested, and detailed simulations will be performed to optimize the experimental setup and to provide a basis for benchmarking.

### 7.1.3 Phase III

Phase III of the project will be the carrying out of the experimental program. This will clearly require a collaborative effort with participation from CERN and all institutes contributing equipment to the experiment. The data acquired will be compared to simulation results, and this feedback would allow the benchmarking and improvement of codes. Analysis of the results will lead to a refinement of parameters for further rounds of experimental tests.

## 7.2 Simulations

The experimental program, together with the ongoing simulation studies, will be the basis for the second deliverable of the project - a proton-driven plasma-wakefield acceleration scheme capable of reaching 100 GeV energy gain for electrons in 100 m of plasma. This should prepare a path to a TeV scale electron accelerator. The further development of simulation codes will proceed during the full period of this experimental program, and the refined codes, benchmarked against the acquired data, will be used to design a large scale experiment. A critical issue will be to determine if PWA with modulated proton beams is a feasible path to this goal, or whether compression of the proton bunch will be necessary. Schemes for producing short proton bunches will be studied in parallel so that a cost/performance comparison can be made. Also, we will continue R&D on different plasma cell concepts such that 100 m of plasma cells can be produced on the necessary time scale.

# 8 Task lists, estimated costs and institutional responsibilities

A broad breakdown of the responsibilities has been discussed amongst the interested institutes, and is given in Table 2. The major categories are described briefly here, and a first, very approximate, cost estimate is given. The manpower costs, travel, etc. are not included in the table. The abbreviations for the institutes are listed in the table caption.

## 8.1 Tasks

### 8.1.1 Plasma Cell

We anticipate starting with a laser driven plasma cell since this technology is the most advanced. The UCLA, Tsinghua, and MPP groups are interested in this task. The cost listed in the table consists of R&D costs as well as the costs for producing a 10 m scale cell. The cost of the laser is not included (see below). In parallel, we will develop other plasma cell technologies which hold promise for scaling to large cell lengths. These are the Helicon cell concept (IPP) and pulsed discharge cells (IST, IC and SC).

### 8.1.2 Beams

The major cost item will be the proton beam delivery to the experiment, which will be a CERN responsibility. Other accelerator labs have been approached concerning in-kind support for this effort, and once a design of the beamline is defined contributions from other laboratories will be determined. The design of the experimental area as well as beam monitoring and diagnostics are also under the responsibility of CERN, but again we will investigate the possibility for other laboratories to contribute to these tasks. The electron injector will be provided by a combination of UK groups, the TH group from China, and the Brookhaven National Laboratory ATF.

### 8.1.3 Radiation Protection and Safety

As described above, the radiation safety aspects have to be considered and related systems designed (e.g., the access and interlock system) in order to allow a safe operation of the facility. This is an important task, and will be the responsibility of CERN.

### 8.1.4 Diagnostics

The optical sampling techniques needed to study the modulation process will be provided by a combination of external groups, under the leadership of the MPP and UCL groups. The electron spectrometer is expected to be a responsibility of CERN, KIT, the UK groups (IC, SC, UCL) and Dsseldorf.

### 8.1.5 Laser system

A powerful laser will likely be required for forming the plasma, for diagnostic purposes and possibly also for the electron injection. Procuring this laser will be a responsibility of the non-CERN participating institutes.

### 8.1.6 Simulations

The experimental program will be accompanied by an extensive simulation effort, which will be carried out by a large number of groups. Simulations will be performed to optimize the design of the experiment, to extract the physically important information from the measurements, and to work out designs for future experiments. While no cost is listed in the table, this task will involve many FTEs and will require the acquisition and use of extensive computing infrastructure.

| Category | Task | Institute(s) | Cost (kEuro) |
|---|---|---|---|
| Plasma Cell | | | |
| | metal vapor Cell | UCLA, TH, MPP | 1000 |
| | Helicon Cell | IPP | 400 |
| | Pulsed discharge Cell | IST, IC, SC | 600 |
| Beams | | | |
| | Proton delivery/dump | CERN + | 16000 |
| | Design of experimental area | CERN, KIT, + | |
| | Beam monitoring/diagnostics | CERN, LAL, + | |
| | Radiation safety | CERN | |
| | Electron Injection | JAI, CI, TH, BNL, SC | 2000 |
| Diagnostics | | | |
| | Electron spectrometer | CERN, IC, SC, KIT, UCL, D | 500 |
| | optical sampling methods | MPP, UCL, RAL, DESY, IC, CI, SC, D | 2000 |
| Laser system | plasma, e injector, diagnostics | MPP, UCLA, TH, UCL, SC | 1200 |
| Simulations | | BINP, D, UCLA, IST, LANL, RAL, UCL, CERN | |

Table 2: Breakdown of tasks and groups expressing interest. The codes are as follows: BINP-Budker Institute for Nuclear Physics, BNL-Brookhaven National Laboratory, CI-Cockroft Institute, D-Uni. Düsseldorf, CERN-CERN, IC-Imperial College, IPP-Max Planck Institute for Plasma Physics, JAI-John Adams Institute, KIT-Karlsruhe Institute of Technology, MPP-Max Planck Institute for Physics, RAL-Rutherford Appleton Laboratory, SC-University of Strathclyde, TH-Tsinghua University, UCL-University College London, UCLA-University of California at Los Angeles

## 8.2 Organizational structure of the proto-collaboration

The institutes listed on the cover page have expressed their interest in participating in this project. At present, Allen Caldwell is acting as spokesperson of the proto-collaboration and there are two scientific coordinators: Ralph Assmann for the beam related tasks and Patric Muggli for the tasks related to experimental aspects.

We foresee a technical organization based on the tasks described in Table 2, where each task will have a task leader, and groups of tasks will have a coordinator. These task group leaders will be selected once the LOI is approved and we move to the technical design phase.

There will additionally be a coordination based on regions, since in many cases coordination of funding requests will be necessary. Institutes with a long history of collaborative work may additionally decide to form their own groupings and nominate their spokespersons.

# 9 Future uses of facility and outlook

The establishment of a beamline and experimental area as discussed in this Letter of Intent will open up possibilities for a wide range of other projects. A few ideas which have been discussed are briefly mentioned here.

## 9.1 Future uses of the facility

### 9.1.1 Laser PWA injection

Laser driven PWA can generate very short bunches of electrons. These short bunches can be used as a diagnostic tool for the plasma wave generated by the modulated proton bunch, while also allowing a test area for laser driven PWA.

### 9.1.2 Density step tests and higher energy gains

As has been shown in simulations [27], it is possible to control the modulation of the proton bunch via a density step. This allows the modulated proton beam to propagate over very large distances in plasmas and thus to accelerate electrons to very high energies (several TeV have been seen in simulations using the LHC proton beam) [28]. We can test these ideas by introducing a second plasma cell, presumably at the start of the TT61 tunnel. If the modulations can be frozen as expected, then this opens up the possibility for much higher energy gains in the plasma. A much longer plasma cell will be necessary for this, e.g., using the helicon or discharge concepts. The first, short, plasma cell would be used to modulate the proton bunch, and the second, long, plasma cell would be used for acceleration to high energies. Initial simulation studies have begun on how to realize this concept in the test beam environment.

### 9.1.3 Plasma cell as energy recovery dump

In the long-term, energy recovery for TeV accelerators will be an important issue in order to limit the power requirements of the accelerator. Ideas for using plasmas as beam dumps with the possibility of energy recovery have been discussed [29] and could possibly be tested in this facility.

### 9.1.4 Plasmas as beam elements

Plasmas can be used not only for acceleration and longitudinal bunching, but also as transverse beam-focusing elements. The facility would allow tests of plasmas for these purposes as well.

## 9.2 Interest in 'low luminosity' high energy colliders

The main focus of the particle physics community for future accelerators has been on high luminosity colliders, since interesting cross sections typically scale as $1/s$, where $s$ is the center-of-mass energy squared. However, there are scenarios where interesting physics would be probed at high energies also at low luminosities. We give two examples here.

### 9.2.1 Search for alternative UV completions of the Standard Model

Our current theories, without the Higgs, are inadequate to explain the high energy behavior of scattering cross sections. For example, the cross section for longitudinal $W$ scattering will grow without bound and violate perturbative unitarity if there is no light, weakly-coupled Higgs. The usual approach is to introduce new interactions which set in at the higher energy scales and which correct this behavior; e.g., supersymmetry. Discovering and studying this new physics will not only require colliders with high energies, but will also require very high luminosities (typical goals are $10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$). Reaching such luminosities in a plasma wakefield accelerator, or any other high energy $\mathrm{e}^{+}\mathrm{e}^{-}$ collider, will be extremely challenging. However, there are alternative approaches to correcting the high energy behavior of scattering cross sections which do not require such weakly-coupled new physics, such as 'classicalization' [30]. In this approach, a new scale becomes manifest at an intermediate energy - the classicalization scale - whereby scattering already becomes effectively classical (black disk scattering) at relatively low energies. An example of this is QCD, with the color-glass-condensate [31] showing the classicalization behavior. If classicalization sets in also in electroweak interactions, then the scattering cross sections will be very large (increasing as a power of the center-of-mass energy) and high luminosities will not be necessary to study this new physics. Towers of new states should be produced and the details of this new physics paradigm could be studied with a PDPWA. Another universal classicalizing force is gravity, and in a class of theories with low (TeV) scale Planck mass that are motivated by the hierarchy problem, the cross-section will also grow at high-energies.

### 9.2.2 Lorentz invariance and quantum gravity

At PeV ($10^{15}$ eV) energies, it is possible that the wavelengths of particles and photons will be short enough to feel the 'texture of the vacuum' [32]. Even the production of a single particle of PeV energy per shot would allow the study of revolutionary physics which could not be probed by higher luminosity but lower energy colliders. The vacuum structure could be probed by very high energy photons, produced by converting PeV electrons into gammas of similar energy. These could then be propagated through vacuum over long distances, and arrival times of the photons could be measured as a function of energy to look for small vacuum structures and fluctuations.

Violations of Lorentz boost symmetry can also be constrained by studying the energy dependence of synchrotron radiation [33]. The Lorentz symmetry violation would be seen by a different (stronger) dependence of the radiated power on the energy of the electron. This effect could set in at a fraction of the PeV scale and thus be observable in a future version of the PDPWA accelerator.

## 9.3 Other experimental programs in PWA

The FACET program will get underway in 2011, and should yield important results on the possibility of accelerating bunches of particles in a plasma. The possibility to study positron-driven PWA at FACET on a time scale comparable to the time scale of this proposed experiment is under discussion [34]. We consider this effort to be complementary to ours. We intend to keep in close contact with the researchers in FACET - in fact, there will be an overlap of the membership in the two efforts. While driving a plasma with positrons has features similar to proton-driven PWA (charge of driver) [35], there are many differences in the setup and final goals (short versus long pulses, energy of the driver, possibility for single stage electron acceleration to high energies, etc.)

### 9.4 Connection to the European Network for Novel Accelerators

The EU co-funded European Coordination for Accelerator R&D (EuCARD) is a common venture of 37 European Accelerator Laboratories, Institutes, Universities and Industrial Partners, coordinated by CERN. As part of the EuCARD project a European Network for Novel Accelerators (EuroNNAc) has been formed. This network will explore possibilities for applying ultra-high gradient acceleration techniques in large electron beam facilities. It will prepare a coherent European strategy, maximizing synergy and maintaining productive competition.

A kick-off workshop for EuroNNAc was held at CERN in May 2011 with representatives from 51 institutes (41 from Europe). The proposed experiment on proton-driven plasma acceleration at CERN was presented at the workshop and was very well received. It was recognized as a unique experiment and that this research direction could be one of the pillars for novel accelerator research in Europe, fully complementary to other ongoing research activities.

## 10 Summary

We are proposing a novel and exciting research program on the acceleration of electrons by the wake driven in a plasma by a proton bunch. The experiment will be the first beam-driven PWA experiment in Europe and the first proton-driven PWA in the world. The proposed research program has already attracted the interest of many research groups from around the world. A core group of experts in the various fields needed to conduct this program including the experimental aspects, simulations and theory have expressed their interest. We have started evaluating the various experimental options and simulating the expected results. The success of the first experiments will lead to a full fledge long term proton-driven PWA program towards accelerating an electron bunch to the TeV energy scale.

# 11 Appendix

This appendix summarizes the expertise brought to the project from the interested institutes (external to CERN), and provides an estimate of the manpower which should be available if the project is approved and funding applications are successful. Internal CERN manpower needs will be estimated at a later stage.

### Budker Institute on Nuclear Physics

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| Expertise | Theory and simulations of beam-driven plasma wakefield acceleration. Experiments on transverse two-stream instability of 300 MeV electron beam in parameter regimes close to those of PDPWA. The knowledge and expertise obtained will be valuable for the PDPWA project. |
| Manpower | One faculty, 1-2 students. Estimate 3 FTE. |

### Institute of Computational Mathematics and Mathematical Geophysics SB RAS

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| Expertise | Simulations of PDPWA. |
| Manpower | 2 staff, 2 FTE. |

### Cockcroft Institute

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| Expertise | Advanced and novel acceleration, beam manipulation and control techniques; experts in linear and circular accelerators design; beam dynamics; energy recovery techniques; microwave superconductivity and SRF cavities; magnetics and novel magnet design; free electron lasers and synchrotron radiation; laser-beam-plasma interaction and femto- and attosecond beams; beam phase space monitoring and control; beam diagnostics and manipulation; machine-detector interface; RF sources and simulations and design; anti-proton accelerators; meta-materials and photonic structures; polarised beams; medical accelerators, etc.. |
| Manpower | Combination of several staff, students and post-docs:, estimated at 1-2 FTE. |

### DESY

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| Expertise | Considerable interest due to complementary programme at DESY. Experience from FLASH in beam line design, beam instrumentation and diagnostics. Specific expertise in fs-synchronisation and monitoring, in particular EO-techniques. |
| Manpower | Staff and students; predominantly for scientific exchange on experimental planning and setup and participation in measurements. Actual engagement depending on synergy with ongoing DESY projects and time. |

### Universität Heidelberg

Expertise Physikalisches Institut: ASIC laboratory with expertise in HF analogue designs; experts for GPU computing; expertise in triggering and fast data processing; some experience in beam-simulations.

Manpower two staff + students, estimated at 2-3 FTE.

### Heinrich Heine Universität Düsseldorf

Expertise Theory of plasmas, 3D simulations, plasma generation, plasma diagnostics and laser and e-beam diagnostics.

Manpower In the area of simulations, one faculty, one postdoc and one PhD student. In the area of plasma generation and diagnostics 1 FTE. Total estimate is 4 FTE.

### Imperial College

Expertise Plasma sources, plasma characterisation, plasma wakefield diagnostics, lasers and laser generated plasmas, beam diagnostics, pulse power, some experience in PIC simulations.

Manpower three staff + RA (applied for) + student (expected on acceptance of LOI), expected 3 FTE.

### IST, Lisbon, Portugal

Expertise IPFN: expertise in laser-plasma interactions, long plasma sources, gas discharges and gaselectronics, plasma diagnostics, triggering and complex experimental installations; expertise in massively parallel computing; expertise in particle-in-cell simulations; experience in beam-plasma theory.

Manpower 2 staff + 2 students, estimated at 2.5 FTE.

### John Adams Institute (JAI)

Expertise Advanced and novel accelerator technology; experts in accelerators design; beam dynamics; laser-plasma interaction and acceleration; nano-metre and femto-second beam diagnostics and manipulation; machine-detector interface, RF simulations and design, etc.

Manpower fractions of several staff + students, estimated at 1-2 FTE.

### Karlsruher Institute of Technology KIT

Expertise Laboratory for Applications of Synchrotron Radiation:
Experts in measurement of coherent synchrotron radiation; Expertise in beam diagnostics; Some expertise in beam simulations

Manpower 1 PhD full time, 2 master students estimated. 2 FTE.

### LOA

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| Expertise | Laser science, laser plasma interaction, plasmas physics and beam dynamics, plasma and beam characterization. Expertise in laser plasma accelerator physics both in theory and in experiment. |
| Manpower | four permanent staff : 1 FTE. |

### Ludwig Maximilian University Munich

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| Expertise | Theory of wakefields in general. The conceptual aspects of wakefield acceleration. Scope for extreme high energies. Compact laser acceleration of short bunched ion beams. |
| Manpower | Two Lehrstuhl chairs are committed to guide the two theoretical groups' activities. Several graduate students. Estimated to be 2-3 FTE. |

### Max Planck Institute for Physics

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| Expertise | Expertise in lasers, plasma cells, diagnostics and all experimental aspects through leadership in previous PWFA experiments (SLAC and BNL). Expertise in THz diagnostic techniques. Expertise is accelerator physics. Technical divisions available for design and construction of mechanical and electronics components. |
| Manpower | Three senior staff will spend a considerable fraction of their time on the PDPWA experiment, in addition to 2-3 postdoctoral researchers and PhD and Masters' students. Estimate 7 FTE. |

### Max Planck Institute for Plasma Physics

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| Expertise | IPP is one of the largest fusion research centres in Europe. At IPP Greifswald the cylindrical helicon plasma experiment VINETA is operated since 2001, which aims at the study of electromagnetic waves and instabilities in high density plasmas generated with radio-frequency heating. |
| Manpower | The number of researchers involved in the VINETA program is typically 10-12 consisting of Diploma and PhD students, PostDocs and group leader. The development of the helicon plasma cell for wakefield acceleration will be headed by a senior staff 2 PostDocs and 1-2 PhD students. The estimated effort on the PDPWA experiment is 5 FTEs. |

### Panjab University, Chandigarh, India

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| Expertise | Simulations. |
| Manpower | one staff + two students (to be engaged on acceptance of LOI), expected 1.5 FTE. |

### Rutherford Appleton Laboratory

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| Expertise | laser-and beam-plasma interactions (theory, simulations and experiment); plasma wakefield and beam diagnostics; laser systems. |
| Manpower | two staff + students, estimated at 2-3 FTE. |

**State Key Laboratory of Nuclear Physics**

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| Expertise | The theory and simulation for $10-100$ GeV short proton bunch generation. |
| Manpower | 2 faculty, 1 postdoc, 1 PhD, estimate 2 FTE equivalent. |

**Tsinghua University, Beijing (THU)**

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| Expertise | RF photoinjector and Linac manufacture and test, ultrafast electron beam diagnostics, sub-ps synchronization of laser and RF, laser plasma accelerators, plasma diagnostics, large scale PIC simulation of laser and beam plasma interaction |
| Manpower | three staff + students, estimated at 1-2 FTE. |

**University of California at Los Angeles**

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| Expertise | All aspects of plasma acceleration using lasers and beams. |
| Manpower | Not possible to state at this time. |

**University College London**

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| Expertise | Beam diagnostics, also building up expertise in plasma diagnostics, mainly through experiments to be performed at the Astra TA2 laser in RAL. |
| Manpower | 2–3 staff, one RA, techical effort and PhD students, estimated at about 4 FTE. |

**University of Oslo**

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| Expertise | beam physics simulations (e- and p), operation of prototype electron machines (CTF3), experience with beam driven plasma wakefield acceleration (FACET) |
| Manpower | Not possible to state at this time. |

**University of Strathclyde** The main contributors will be from the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA) including six universities from the Scottish Universities Physics Alliance (SUPA) (Strathclyde University - as lead, Glasgow University, University of the West of Scotland (UWS), University of Edinburgh, University of Dundee and Heriot-Watt University). The expertise in this consortium is as follows:

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| Expertise | Strathclyde (ALPHA-X): Laser-plasma wakefield accelerators experiment and theory, diagnostics, plasma media, injector technology, applications, X-ray sources, free-electron lasers Glasgow, UWS, Edinburgh, Dundee: detectors, diagnostics, nuclear physics applications Heriot-Watt University: plasma physics |
| Manpower | Strathclyde: ten staff, two technicians + eleven students, estimated at 4 FTE in experiments and theory for the PDPWA project. |

At the present stage, we estimate that we will initially have about 40 FTE's working on the PDPWA program outside of CERN, including simulation efforts. The proto-collaboration contains expertise in all areas required for the project.

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