A Multi-GeV Electron Spectrometer for laser-plasma acceleration experiments

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1 Laser-plasma acceleration technique

In order to study particle physics high energy colliders are used. Particles are accelerated by radio frequency cavities (RF) where the energy gain per meter is limited to $\sim 100$ MeV/m, because of the break-down that occurs on the walls of the structure. To overcome this limit a new acceleration technique was first explored in 1979 by Tajima and Dawson [1]. They proposed a mechanism to exploit the high-power electromagnetic radiation from lasers to extract electrons from plasma and accelerate them to high energies in a short distance: laser plasma acceleration will allow building ultra compact accelerators.

A plasma is a globally neutral ionized gas. When perturbed it exhibits a collective behavior characterized by the plasma frequency:

$$\omega_p = \left( \frac{4\pi n_e e^2}{m_e} \right)^{\frac{1}{2}} \sim \sqrt{n_e}$$  \hspace{1cm} (1)

which depends only upon the electron density $n_e$. In laser-plasma electron accelerators [2] the non-linear ponderomotive force $F_{NL}$ of an ultrashort and ultraintense laser, proportional to the gradient of the laser intensity,

$$F_{NL} = -\left(\frac{\omega_p}{\omega_L}\right)^2 \nabla \langle E^2 \rangle \frac{1}{8\pi}$$  \hspace{1cm} (2)
pushes the plasma electrons out of the laser beam path, separating them from ions. As a consequence, the variation of the electron density creates a traveling longitudinal electric field in the wake of the laser beam.

\[ E_{\text{max}} = \frac{cm_e \omega_p}{e}. \]  

(3)

If we consider that experimentally we can achieve \( n_e \sim 10^{18} \text{cm}^{-3} \), or in terms of frequency \( \omega_p \sim 10^{13} \text{Hz} \), we find energy gains per meter \( \sim 100 \text{ GeV/m} \) [3].

In order to accelerate electrons a resonant condition between the length of the laser pulse and the length of the plasma wave has to be satisfied

\[ c\tau_L \sim \lambda_p/2. \]  

(4)

As a consequence, for \( \lambda_p \sim 10-30 \mu \text{m} \) ultrashort laser pulses (\( \tau_L \ll 100 \text{ fs} \)) are required, characteristic that only the last generation of lasers has achieved and that makes laser-plasma acceleration a hot research topic today.

PlasmonX (\textit{PLASma acceleration and MONochromatic X-ray generation}) is a new very innovative experiment at the Frascati National Laboratories of INFN, focused both on plasma acceleration and monochromatic X-ray production [4]. For the first time an ultra-short (\( \tau \sim 30 \text{ fs} \)) and ultra-intense (\( I_0 \sim 10^{19} \text{W/cm}^2 \)) laser, FLAME (\textit{Frascati Laser for Acceleration and Multidisciplinary Experiments}), is built in close interaction with a Free Electron Laser (FEL), generating ultra-short electron bunches. This opens the possibility to explore two different acceleration schemes:

- self-injection, in which the electrons are extract from the plasma itself;
- external-injection, in which already pre-accelerated electrons from the FEL are injected into the electron plasma waves excited by the laser.

The final aim of the PlasmonX project is to reach a stable and reproducible acceleration regime, generating high-quality quasi mono-energetic electron beams.

My PhD thesis is the design, commissioning simulation and data analysis of an electron spectrometer for the PlasmonX experiment, optimized for the particular electron beams produced in laser plasma experiments.

## 2 The electron spectrometer: choices and realization

To design the spectrometer, it is important to know the characteristics of the electron bunches. To this aim a 3D PIC simulation was performed with
plausible laser and gas parameters: pulse duration = 30 fs, pulse energy = 5 J, peak power = 166 TW, spot size radius = 9 µm, pulse intensity = $6.54 \times 10^{19}$ W/cm$^2$ and electron density $n_e = 3 \times 10^{18}$ W/cm$^3$ [5].

At the end of the simulation (see Fig. 1) a bunch with an energy peak at 0.9 GeV and a momentum spread of 3.3% is obtained: the charge is 0.6 nC, the bunch length 1.8 µm, the beam divergence 2.8 mrad; the simulated spectrum is also characterized by the presence of a low energy tail with ∼3 nC of charge and a higher angular divergence [6].

![Energy spectrum and angular divergence as expected from 3D PIC simulation.](image)

The spectrometer must be capable of measuring the spectrum of tens of millions of particles arriving simultaneously spread over three orders of magnitude in energy with a divergence of few mrad, originating from a point-like spot located more then a meter before the region with magnetic field [7].

To match these characteristics, unprecedented both in high energy field, because of the huge number of particle simultaneously to detect and for the laser-plasma field, that operates in the MeV region, a magnetic spectrometer composed by an electromagnet that deflects the charged particle, a vacuum chamber with the position monitor detectors inside it and the read out system has been designed.

Taking into account the magnetic field dispersion, the angular divergence, the misalignment and crosstalk effects between different channels we can simulate the detector response for different initial electron energies. In order to reconstruct the energy distribution we perform a Bayesian unfolding [8].

The dipole we are using for the first step of the PlasmonX project can generate a magnetic field up to 0.5 T. The pole gap of 6 cm allows to insert the vacuum chamber for the detectors inside it. The scintillating fibers chosen as position monitoring detectors are placed on the focal plane (i.e. where two different trajectories of the same energy converge regardless their initial
angular divergence) for the low momentum particles (E < 200 MeV), while the high momentum detector (E > 200 MeV) is simply placed in the forward direction (see Fig. 2), orthogonally to the laser beam propagation direction, in order to maximize the spread for different energies.

![Figure 2: Left: top view of the spectrometer set-up: in dark is the density plot of the magnetic field, detectors are indicated through lines and trajectories for two different energies are evaluated. Right: expected resolutions: in red the only detector resolution is taken into account, in blue the angular divergence is also considered.](image)

In order to study if this simple idea will work with the electron beam produced in laser-plasma interaction a prototype of 64 scintillating fibers read by a single PMT has been realized. Two sets of test performed at the Beam Test Facility of LNF [9] using electron beams with characteristics close to that expected to be produced in the PlasmonX experiment gave as result the calibration of the detector response both in position and in charge: a device normally used to detect a single particle was tuned and forced to work with few $10^9$ particle beams.

Once we have characterized the response of the first prototype the complete detector was realized. It is an array of about 800 Kuraray scintillating fibers with 1.00±0.05 mm as diameter with the emission wave length in the blue region at 437 nm. The fibers allow the propagation of the photons generated by inside the fiber core to the entrance of the 64 channels Hamamatsu multi-anode photomultiplier H7545 (R7600-00). In order to reduce the number of electronic channels we group 3 fibers for a single PMT channel in the low momentum region, while to keep the best possible resolution we need to read all the 128 fibers in the high momentum region. We have a total number of 320 electronics channels (5 PMTs) read simultaneously by Maroc2 chips [10] which allow to multiplex up to 4092 channels. Tests for the validation and the operation of the device are ongoing: the PMTs pixel-fibers alignment
and the reduction of the crosstalk between near pixels were followed out.

Once the PlasmonX experiment will start and data will be available, the developed software tools will be used to reconstruct the energy spectra starting from the signals recorded on each fiber of the detector (the signal is proportional to the number of impacting electrons). The analysis is based on the Bayes theorem: if we observe a charge deposition on the $i$-th fiber, the probability $P(j|i)$ that it has been due to the momentum $j$-th is proportional to the a-priori probability $P(j)$ of the momentum $j$ times the probability $P(i|j)$ of the momentum $j$ to produce the charge deposition $i$. In formula

$$P(j|i) = \frac{P(i|j) \times P(j)}{\sum_j P(i|j) \times P(j)}$$

(5)

where the estimated probability distribution $P(j|i)$ gives the best estimate of the charge deposited in the $j$-th fiber

$$Q_j = \sum_i P(j|i) \times Q_i$$

(6)

The a-priori momentum distribution $P(j)$ is initially assumed flat. Further improvement in the estimate can be achieved by reapplying the equations after replacing the a-priori probabilities with the calculated $P(j|i)$. Using this approach the expected resolutions are less then 5% for $E < 200$ MeV, while grow up to 10% for energies in the GeV region (see Fig. 2).

At the present moment the laser system is under commissioning and is expected to operate with the full energy before the end of the 2010 year. Then the interaction with the plasma will be optimized in order to lead to electrons acceleration. The operation of the electron spectrometer has to be tested in the real experimental conditions. In particular: problems related to electromagnetic and acoustic noise have to be considered, the read-out system has to be triggered on time with respect to the laser trigger and other unknown difficulties have to be expected with the real laser shots.

The PhD work will be completed with a full Geant4 simulation of the detector response and a deeper understanding of the laser-plasma physics. In particular aspects as how the plasma wave brake and which parameters can be tuned to realize a stable mono-energetic acceleration regime seem to be still unknown.
References