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Development of a Multi-GeV spectrometer for laser–plasma experiment at FLAME

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A R T I C L E   I N F O

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A B S T R A C T

The advance in laser–plasma acceleration techniques pushes the regime of the resulting accelerated particles to higher energies and intensities. In particular, the upcoming experiments with the 250 TW laser at the FLAME facility of the INFN Laboratori Nazionali di Frascati, will enter the GeV regime with more than 100 pC of electrons. At the current status of understanding of the acceleration mechanism, relatively large angular and energy spreads are expected. There is therefore the need for developing a device capable to measure the energy of electrons over three orders of magnitude (few MeV to few GeV), with still unknown angular divergences. Within the PlasmonX experiment at FLAME, a spectrometer is being constructed to perform these measurements. It is made of an electro-magnet and a screen made of scintillating fibers for the measurement of the trajectories of the particles. The large range of operation, the huge number of particles and the need to focus the divergence, present challenges in the design and construction of such a device. We present the design considerations for this spectrometer that lead to the use of scintillating fibers, multichannel photo-multipliers and a multiplexing electronics, a combination which is innovative in the field. We also present the experimental results obtained with a high intensity electron beam performed on a prototype at the LNF beam test facility.

1. Introduction

Laser wake-field acceleration experiments pose challenging requirements on the measurement of the resulting electron energy, due to the wide range of the region of interest, from few MeV to 1 GeV and above, and due to the broad angular distribution and pointing uncertainties. Also the number of electrons ejected from the plasma can have large variations, up to a few nC total beam charge. As an additional requirement, the instrument has to operate in vacuum (in order not to spoil the electron distribution due to multiple scattering) and in the presence of strong electromagnetic fields, due to the high-power laser operation.

In particular, we describe the development and commissioning of a magnetic spectrometer for the momentum analysis of the electrons produced by laser–plasma acceleration (LPA) experiments at FLAME.

FLAME is a 250 TW, 30 fs pulse duration laser realized for the PlasmonX project [1] at LNF. The first step of this project, aimed to the laser wake-field acceleration of externally injected electron

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bunches, is a Test Experiment of Self-Injection SITE [2]. In this experiment the laser FLAME is focused on a 4 mm gas-jet with the goal of producing sub-GeV electron bunches from laser–plasma interactions.

2. Spectrometer design

From 3D particle-in-cell simulation, we expect the whole energy spectrum to cover three orders of magnitude in energy, from few MeV to few GeV, only the high energy electrons are expected to be collimated in few mrad, contrary to the low energy tail showing an angular spread of several tens of mrad. The expected electron charge of the high energy part of the distribution is of the order of 10^9 particles, with a momentum spread of few percent, while in low-energy part we expect a 3–4 times larger charge, spread over several hundreds of MeV.

To match this characteristics, we have designed a wide-acceptance magnetic spectrometer composed of a dipole electro-magnet that deflects the charged particles, and position detectors inside a vacuum chamber [3], aiming to reach a 1% resolution in the widest possible momentum range.

In order to be ready for the first test experiments already by Fall 2010, we have adopted a two-step strategy:

1. in a first phase, we are re-using a spare sector magnet from an existing beam-line in Frascati. It is a 22.5° bending for the SPARC 150 MeV electron beam, so that the maximum magnetic field is only 0.45 T over a magnetic length of 20 cm, and with a pole gap of 60 mm;
2. at the same time, we have started the detailed design of a new dedicated dipole magnet, with a much stronger magnetic field (<1.8 T since we intend to use normal-conducting coils) and an optimized length and geometry.

We consider the classic design principle of a magnetic momentum analyzer: charged particles with different momentum values are dispersed in a uniform magnetic field generated by a dipole magnet: the bending radius r of the trajectory inside the magnetic field is of course connected to the momentum p by the Lorentz force, so that p can be determined by measuring the impact point on a position sensitive detector. The main parameters determining the momentum resolution σ_p are the resolution of the detector in the dispersive plane, σ_y, and the magnetic field strength, B, and length, L:

$$\sigma_p \propto \frac{\sigma_y}{BL^2} p^2$$

but, since in general the particles are entering the magnetic field with a broad angular distribution, such a resolution can be obtained only if same energy particles with different angles are focussed in a single spot.

The focussing condition in a dipole uniform field, neglecting fringe field effects, for a prismatic (sector) magnet of angle ϕ and bending radius r (for a given momentum p) is given by Barber's rule:

$$\phi + \theta_1 + \theta_2 = \pi,$$

where, for sake of generality, we also consider a straight path of length l_1 before entering the magnet, and a straight path after the magnet (and before reaching the sensitive detector) of length l_2, thus defining $\theta_{1,2} = \mathrm{arctg}(l_{1,2}/r)$ (see Fig. 1).

In our case, the straight path before the magnetic field (l_1) is practically fixed by the need of placing our spectrometer outside the vacuum interaction chamber hosting the gas-jet: $l_1 > 50$ cm.

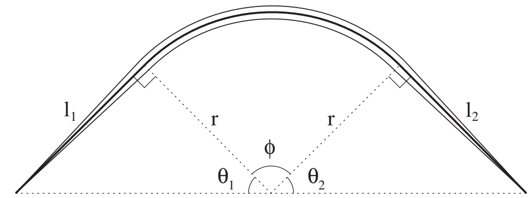

Fig. 1. Schematic illustration of Barber's rule and definition of variables (see text).

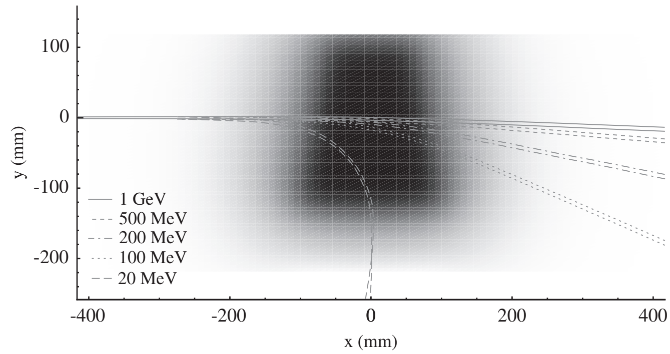

Fig. 2. Trajectories inside the 0.45 T phase-1 dipole for electrons of different energy and angular divergence of 2 mrad. The measured field-map of the magnet has been used for the calculation.

A focal plane can be found for lower bending radii, if the trajectories of same-energy particles entering the magnet with a given angular spread, converge in a single spot. However, for our phase-1, 0.45 T dipole magnet, this would imply that these foci can be found only for particles of few tens of MeV, while all high energy electrons would be imaged on larger spots, with a resolution dominated by the angular spread, almost independently from the accuracy of the detector (Fig. 2).

In order to focalize as much as possible the electrons with the same energy but different initial unknown angular divergence, we have to choose how to use the dispersion power of the dipole magnet, and the geometry of the detector in the bending plane.

For electrons entering a dipole magnet close to the magnetic center it is possible to use the "hard-edge" approximation, replacing the bending power with an effective value along the path s: $B_{max}R_{eff} = \int B(s)\, ds$. If electrons enter the dipole close to the edge where the field has a strong variation, i.e. far from the dipole center ($y=0$ in Fig. 3), the deflection will be strongly dependent from the distance of the trajectory from the magnetic center. In this "fringe" area, particles going towards the center of the magnet will undergo a higher bending power, with respect to particles with the same energy with a more external trajectory: this turns out in a focussing effect, even though the total deflection will be smaller since the field integral will not be the maximum one.

This is the optimal configuration with the magnet which is available. By firing 13 cm off the center of the magnet we exploit the dipole focussing effect and thus improve significantly the resolution for low energy particles.

As far as high energy particles are concerned, the firing point is at the very beginning of the fringe and therefore the magnetic length is reduced by only 20.

Making use of this "fringe-focussing" effect, with the phase-1 magnet ($B_{max} = 0.45$ T) we can find a focus for energies up to 200 MeV, as shown in Fig. 3. The position sensitive detectors are thus placed on the focal plane for the low-momentum particles; electrons of more than 200 MeV are instead detected by another sensitive plane simply placed in the forward direction, orthogonally to the laser beam propagation direction, as far as possible

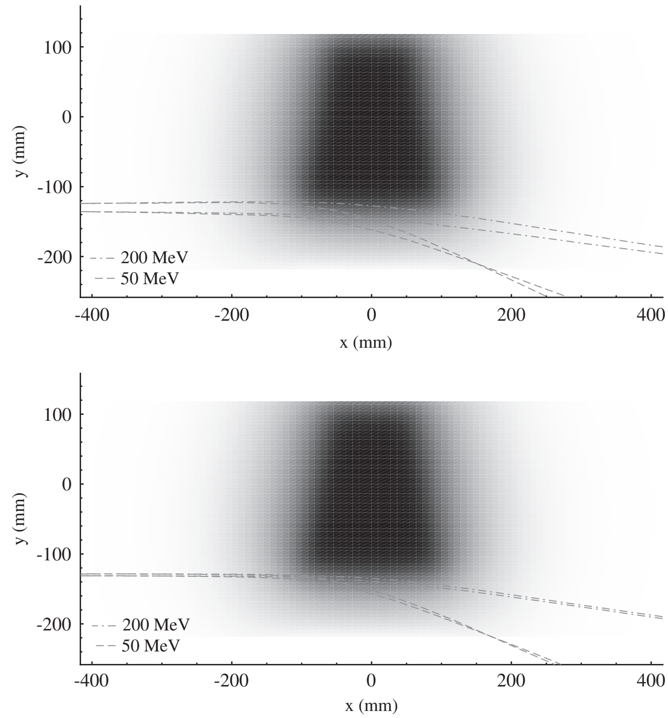

Fig. 3. Trajectories inside the 0.45 T phase-1 dipole for electrons of 50 and 200 MeV, and angular divergence of 10 mrad (top) and 2 mrad (bottom). The measured field-map of the magnet has been used for the calculation.

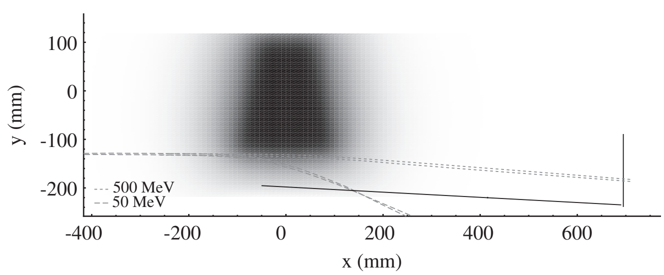

Fig. 4. Configuration of sensitive detectors of the spectrometer: particles up to $\simeq 200$ MeV are focussed on the side detector (low-momentum), while higher energy particles are detected by the front sensitive plane (high-momentum), placed at the maximum possible distance to optimize the momentum separation.

from the magnet in order to maximize the spread for different energies. The high-momentum detector extends also in the direction opposite to the bending, in order to be able to image the electron beam spot with the magnetic field off.

The detector scheme is shown in Fig. 4: the fibers constituting the sensitive part are enclosed in an aluminum vacuum chamber through a long aperture in the top part of the chamber, sealed with epoxy glue. The height of the vacuum chamber, and thus of the sensitive part of the screens, is driven by the size of the gap between the magnet's poles of 60 mm, while the total length of the low-momentum detector, and thus of the vacuum chamber itself, is dictated by the available space between the gas-jet interaction chamber and the wall of the experimental hall. The technical drawing of the spectrometer (using the 0.45 T phase-1 magnet) is shown in Fig. 5. This configuration of the detector with two separated sensitive segments has been designed keeping in mind different practical constraints: a very narrow experimental hall, with very limited space downstream of the interaction vacuum chamber where the laser–plasma interaction takes place, and the need of driving the ejected electrons on the beam dump

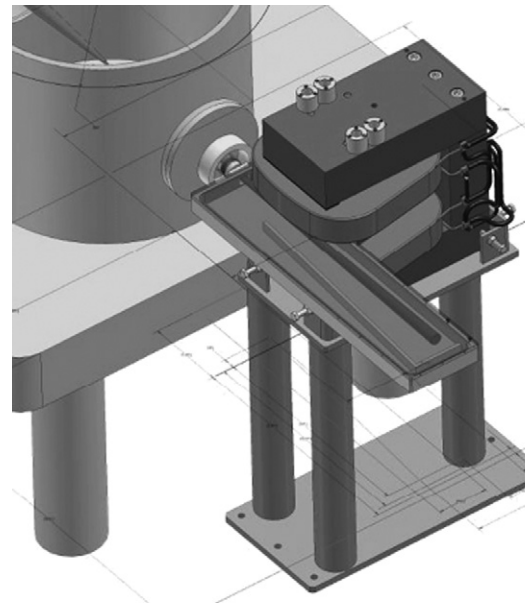

Fig. 5. Technical drawing of the spectrometer: the vacuum chamber, inserted between the magnet's poles, encloses the two sensitive screens.

placed in front of the interaction chamber, immediately downstream of our spectrometer.

Having fixed the geometry of the sensitive area, the position resolution can be chosen for optimizing the momentum separation. In the low-momentum part, thanks to the simultaneous effect of focussing and of the large deflection, a detector resolution of a few millimeters is sufficient to keep the resolution below the 1% level over the whole momentum range (20−200 MeV). In the front, high-momentum part, while on one side a good position resolution is desirable to have a good momentum separation, due to the smaller deflection, on the other side the dominant contribution to the momentum resolution is given by the angular dispersion, so that a resolution much better than 1 mm would not give a significant improvement, considering a beam divergence of a few mrad. Should the divergence be greater than that, we are equipped with lead collimators inside the interaction chamber to block all particles above few mrads (with adjustable aperture).

Having fixed an optimal granularity of 1 mm, we have then chosen scintillating fibers as a sensitive medium, considering that fibers:

- are very flexible and easy to be arranged in the desired shape, also covering large sensitive areas;
- can be easily used in a moderate vacuum;
- are essentially blind to photons;
- can be coupled to the photo-detector at some distance, outside the vacuum, without significant loss of light, and without any carefully aligned optical system;
- are sensitive also to very low beam charges, due to the high light-yield;
- can be easily calibrated, moreover the light-yield is largely independent from the electron energy.

There are of course also some disadvantages, such as:

- having one readout channel per each fiber we end up with a few hundred channels for the readout electronics;
- the spatial resolution is limited by the fiber size and fixed by the readout granularity;

- saturation effects at high beam charges should be considered due to high light-yield.

We have used SCSF-81 single-cladding scintillating fibers from Kuraray, Japan, with 1.00 ± 0.05 mm as diameter. The core material is polystyrene (PS) with refractive index $n_{co} = 1.59$, while the cladding material is polymethylmethacrylate with refractive index $n_{cl} = 1.49$; the trapping efficiency is 3.1%. The nominal attenuation length is about 3.5 m. The emission peak is in the blue region at 437 nm.

In LPA experiments, CCD are widely used as photo-detectors also for the readout of the scintillation light from fibers. In our case, we have chosen to use segmented-anode photomultipliers, mainly considering the possibility of adjusting the sensitivity of the screen to a very wide range of beam intensities. Photomultiplier tubes (PMT) can indeed reach gain values as high as 10^6, and thus be sensitive to single photo-electrons, but they can as well as be efficiently operated at much lower gains, down to the 10^2 range. This can be done as easily as changing the supply power to the voltage divider, and the voltage–gain curve can be easily calibrated. The fibers are grouped into bundles and coupled to our photo-detector: 8×8 multi-anode Hamamatsu photomultiplier H7546B. The anode size is 2×2 mm^2 with a total effective area of 18.1×18.1 mm^2. The typical cross-talk between pixels, about 2% is adequate for our purposes. The coupling between the fibers and the PMT is realized with a precision machine-drilled metal mask into which the fibers' extremities are glued, using an optical cement (Bicron BC-400 from Saint-Gobain).

Since a few mm resolution is more than enough in the low-momentum region, in order to reduce the number of readout channels we group three fibers for a single PMT channel, and we read only three out of each four fibers, while we keep a one to one correspondence for the high-momentum part. We end up with 192 channels in the low-momentum region, covering a sensitive length of 768 mm, and 128 in the high-momentum region, covering 128 mm. We then use three 64-channels PMT's in the low-momentum detector and two in the high-momentum one.

The readout of the 320 channels is performed simultaneously by a system based on MAROC2 chips (Multi Anode ReadOut Chip, developed in LAL, Orsay [4]), custom designed [5] for the readout of PET/SPECT detectors with multi-anode PMT's, and which allow to read up to 4096 channels. The MAROC2 chip amplifies and shapes the analog input signals, sample and holds them, and then feeds them to a 10-bit Wilkinson ADC multiplexing the 64 channels. The gain of the amplifier and shaping stage can be adjusted from $g = 4$ to 0.25 with 6 bits resolution. This also gives a handle to adjust the dynamic range of our instrument to the beam charge.

In order to further extend the dynamic range, and to reduce the possibility of having saturation of the detector's response to very high-charge beams, we have also foreseen the possibility of interposing a neutral-density optical filter (NDF) between the scintillating fibers mask, and the surface of the PMT, in order to attenuate the light by a known factor A_{NDF}. The total charge measured by our acquisition system can thus be written as

$$Q_{measured} \propto N \times n_{ph.el.} \times A_{NDF} \times G_{PMT} \times g$$

where N is the number of electrons impacting the fibers, $n_{ph.el.}$ the number of photo-electrons generated for each particle (including the fibers efficiency and attenuation, the optical coupling to the photomultiplier and its quantum efficiency), G_{PMT} the gain of the PMT, and g the gain of the electronics.

3. Prototype tests and absolute calibration

In order to test the entire readout chain and to perform an absolute calibration of the fiber detector, we have built a prototype made-up by 64 scintillating fibers and readout by a single H7546B PMT. We have performed two different sets of test, using the electron beam provided by the Frascati Beam Test Facility (BTF), in order to calibrate the detector response with respect both to the beam position and charge.

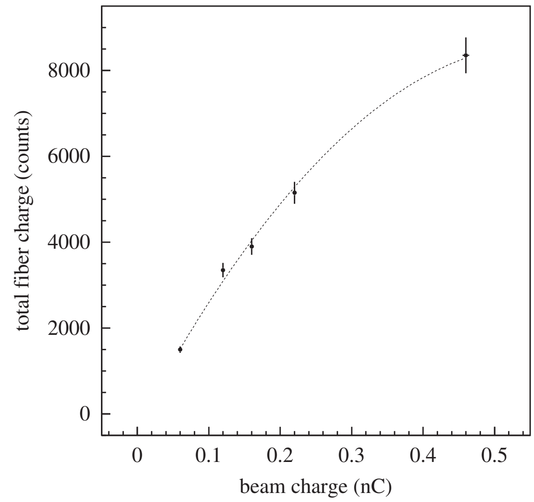

Fig. 6. Calibration of the fiber detector signal as a function of the beam charge measured by the ICT, with 500 MeV electrons from the BTF line.

In the first set of tests we used an electron beam with characteristics close to the expected one in the self-injection experiments. For a fixed electron energy of about 250 MeV, we observe the beam position before and after the propagation inside the magnetic field. The initial beam has a Gaussian shape with a spot size of the order of few mm. We have extensively checked our expectations of the focussing in the fringe field, measuring the beam spot size variations as a function of the position and angle of the beam entrance point in the magnet.

In the second set of tests at the BTF we used electron beams of 500 MeV and charges from the pC up to the nC range. The beam charge is measured by an Integrating Current Transformer (ICT) toroid (Bergoz, 10:1 transformer ratio, 30 ns risetime), and the beam-spot independently measured by means of a high-fluorescence flag readout by a videocamera. The scintillating fiber of the prototype is placed perpendicularly to the electron beam, and readout by our standard MAROC electronics. The profile of the beam was clearly visible and compatible with the measured beam-spot. In this configuration we have studied the linearity of the gain curve of the PMT, of the MAROC electronics and we have calibrated the response of the detector with high beam charges. For this purpose, we have used a neutral density filter with attenuation factor $A_{NDF} = 0.4\%$. In this configuration we were able to perform a calibration up to 0.5 nC, and we observed a good linearity up to ≈ 0.2 nC, as shown in Fig. 6.

4. Phase-1 spectrometer installation and commissioning

During Summer 2010, the two-screens fiber detector, inside its vacuum chamber, the multi-anode PMT's and MAROC-based electronics readout, and the phase-1 magnet has been installed in the FLAME underground experimental area for self-injection experiments. The size of the vacuum chamber and of the active area of the detector has been actually chosen in order to fit the limited space available downstream the vacuum interaction chamber. In order to reduce the impact of electromagnetic noise

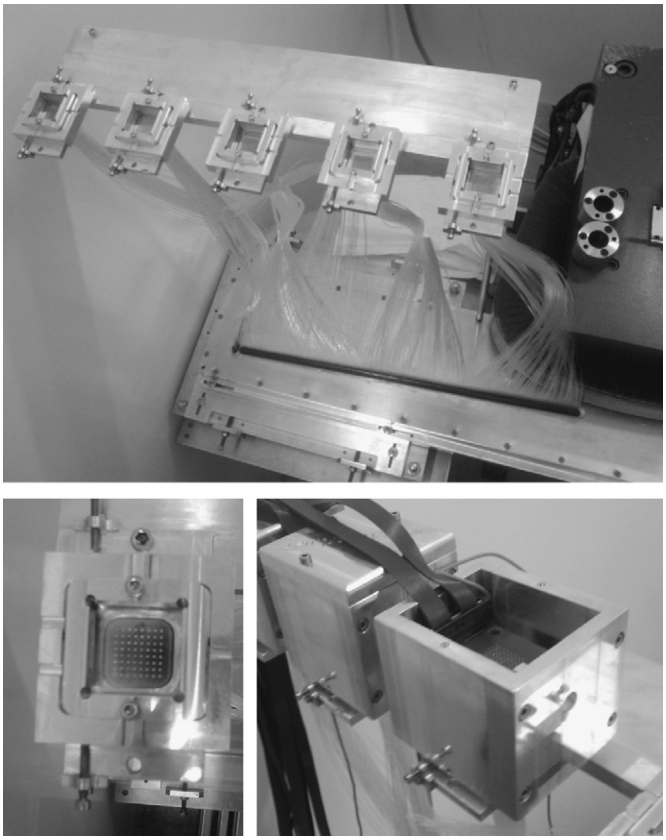

Fig. 7. Photos of phase-1 spectrometer installation: (top) top view of the vacuum chamber, the shape of the high and low momentum screens can be clearly seen by looking at the fiber bundles exiting the vacuum flange; (bottom left) top view of the fibers mask, with the PMT adjustable holder, the two-dimensional movement can be achieved by means of precision screws; (bottom right) the PMT mounted in the holder, cabled to the HV supply and to the flat-cable of the MAROC electronics, and closed inside an aluminum box for light-tightness and electromagnetic shielding.

during laser–plasma interactions, the fibers are bundled and fed to the PMT's, which are placed on an aluminum holding frame, at about 70 cm height from the beam-line.

The fibers are glued onto aluminum drilled masks (two with single fiber holes, for the high momentum screen, and three with three-fibers holes for the low momentum screen, due to the coarser pitch). Those mask are mounted on a two-dimensional adjustable frames, easy moveable by precision screws, in order to optimize the alignment between fibers and the pixel of the segmented PMT.

The picture in Fig. 7 shows the vacuum chamber, the fibers exiting from it, and then the five fiber bundles going to coupling masks where the PMT's are installed and cabled to the electronics. The 10 mm thick aluminum box guarantees light-tightness and shielding of the PMT.

Before starting the commissioning with electrons ejected from LPA, we have performed a careful alignment of the PMT's with respect to the fiber-masks, using a blue-emitting LED, directly coupled to the unshielded fibers. By minimizing the cross-talk between adjacent pixels, we were able to perform a satisfactory alignment. These tests also allowed us to check the mapping of the fibers in our readout and reconstruction software.

In order to extend the dynamic range of the measurable electron charges, we have prepared five neutral-density filters, with 1% transmittance (Kodak Wratten 2.0 gelatin filters, cut in $30\times30\,\mathrm{mm}^2$ square pieces fitting the PMT holder), to be placed between the fiber mask and the PMT entry face, indeed we have measured an overall attenuation factor of about 100, shining the blue LED light on a group of fibers.

During the Fall 2010, timing and noise tests are going on at FLAME, and the spectrometer is ready to start the commissioning with LPA ejected electrons.

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