A multi-GeV spectrometer for laser-plasma acceleration experiments

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New acceleration technique

Plasma-based accelerators are of great interest because of their capability of sustaining extremely large acceleration gradients.

The accelerating gradients in conventional RF Cavity are currently limited to 100MV/m

Accelerating gradients of the order of 100GV/m have been inferred in plasma based acceleration experiments.
Laser Electron Accelerator

T. Tajima and J. M. Dawson

Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density $10^{18}$ W/cm$^2$ shine on plasmas of densities $10^{18}$ cm$^{-3}$ can yield gigaelectronvolts of electron energy per centimeter of acceleration distance.
The wave breaking

Figure 1 Wakefield acceleration. a, In a plasma excited by a laser pulse, the wake potential rises until it steepens and breaks. Electrons from the plasma are caught in the ‘whitewater’ and surf the wave. b, The load of the electrons deforms the wake, stopping further trapping of electrons from the plasma. c, As the electrons surf to the bottom of the wake potential, they each arrive bearing a similar amount of energy.

\[ n \approx 10^{18} \text{ cm}^{-3} \]

\[ \omega_p \approx 10^{13} \text{ Hz} \]

\[ E = \frac{cm\omega_p}{e} \approx 100 \text{ GeV/m} \]
Near infra-red 800nm
Pulse duration = 30 fs
Pulse energy = 5 J
Peak pulse power = 166 TW
Spot size radius = 9 μm
Maximum Intensity $5.2 \times 10^{19}$ W/cm$^2$

Plasma density $n_e = 3 \times 10^{18}$ cm$^{-3}$

$\lambda_p \approx 10\,\mu m$  $c\tau_L \approx \frac{\lambda_p}{2}$  $\tau_L \approx \text{fs}$
Main beam (>250 TW) Vacuum transport line to SPARC linac

Radiation protection walls

Compressor vacuum chamber

spectrometer

Main target chamber

Off-axis parabola
Generic layout

“beam”
plasma
Dipole magnet

Momentum spectrum
Position measurement
Unfolding

P(GeV)  Y(m)  P(GeV)
Atypical bunch properties

Angular divergence of the beam as a function of the momentum

3D PIC simulation: outgoing energy spectrum

3 nC low energy tail
Peak with total charge 0.7 nC @ high energy
The PlasmonX group in Rome is developing a device capable to measure the momentum of e\(^-\) over three orders of magnitude (from few MeV to a few GeV) under not negligible angular divergences.

- Resolution: <1\% over a broad momentum range
- Number of e\(^-\) to detect simultaneously: \(10^{10}\)

These requirements are unprecedented both for the high-energy and laser-plasma field.
Design of the spectrometer:

• where and how to impact the magnetic field and where to locate the position detectors

• which solution to use for the detectors and readout electronics

• tests and calibration

• data analysis and results
The Magnet

Voltage = 23 V
Current = 103 A
Water flow = 1.7 l/min
Pressure drop = 3 bar
T rise = 18°C
Weight = 600 Kg
Height on support = 120 cm

Deflection angle = 30°
Bending radius = 50 cm
Entrance angle = 5°
Exit angle = 5°
Pole gap = 6 cm
Induction = 0.5 Tesla
Intrinsic angular divergence

The momentum resolution is dominated by the angular dispersion which overlays in a given position trajectories from significantly different momenta.
Detector Position

- low momentum detector on the locus of focii
- high momentum detector as far as possible

Focusing property: all trajectories of a given momentum converge **regardless** of the angle at the origin.
An interesting observation

With:
B=1.8T
L=75cm
We have focii up to 1 GeV

Critical point:
exit from a lateral face
(90° with respect to the entrance one)
Test Beam @ Frascati BTF

Electron beam, 500 MeV

Detector are in AIR, will be in vacuum
Focusing property

Experimental data from BTF Beam Test Facility
Comparison between **prediction** and **measurement** for beam deflection vs. beam distance from magnetic center.

![Graph showing comparison between prediction and measurement for beam deflection vs. beam distance from magnetic center.](image)

Experimental data from BTF Beam Test Facility.
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Optimize Detector: fibers

Scintillating fibers Kuraray SCSF-81-SJ

- diameter: $1.0 \pm 0.05$ mm
- thickness of cladding: $50 \pm 5$ $\mu$m
- emission wavelength (peak maximum): 437 nm
- material (core): polystyrene
- refractive index (core): 1.59
- material (cladding): 'fluorinated PMMA'
- refractive index (cladding): 1.42
Multi-channel photo-tubes

Main problem: alignment of fibers

High momentum detector: 1 fibers/pixel

Low momentum detector: 3 fibers/pixel

Hamamatsu H7546 (R7600-00)
64 channels multi-anode PMT
Fibers and photo-tubes

1 fiber/PMT channel → 128 mm in 2 PMTs

3 fiber every 4 in 1 PMT channel → 76.8 cm in 3 PMTs
Read out: Multiplexing

Front end card in collaboration with INFN-BA, GE and ISS-RM1
(A.G. Argentieri et al, NIMA (2009))

The technology based on MAROC2 chips allows to multiplex up to 4096 channels (LAL-Orsay)
The detector, a prototype

- Scintillating fibers Kuraray, emission wavelength 437nm
- Multi-channel PMT Hamamatsu H7546
- Maroc readout board
Design of the spectrometer:

• where and how to impact the magnetic field and where to locate the position detectors
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• data analysis and results
BTF setup with **toroid** for charge calibration
Saturation effects

\[ Q_{\text{Measured}} = N_{\text{particle}} \times N_{\text{phe/particle}} \times G_{\text{PMT}} \times G_{\text{el}} \]

We can tune this three parameters in order to avoid saturation effects
Counts vs Charge

- 0.4% optical filter
- HV=400 V
- MAROC gain=8

Total fiber charge

Beam charge(nC)
Design of the spectrometer:

• where and how to impact the magnetic field and where to locate the position detectors

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• data analysis and results
Data analysis: Bayesian unfolding

\[ P(C_i \mid E_j) = \frac{P(E_j \mid C_i)P(C_i)}{\sum_{l=1}^{n_c} P(E_j \mid C_l)P(C_l)} \]

If we observe a Q deposition on a given \( j \) channel, the probability that it has been due to the momentum \( i \) is proportional to the prob of the mom \( i \) times the prob of the mom \( i \) to release Q in channel \( j \).
Calibration – low

Numerical integration of the eq of motion

Momentum $p_i$ \rightarrow Position $y_i$

Low detector

$d < 1 \text{ mm}$
Results – low

Charge distribution on the fibers

Energy spectrum

Smeared distribution
Calibration – high

Numerical integration of the eq of motion

Momentum $p_i$ → Position $y_i$

$\theta_{\text{min}}$, $\theta_{\text{max}}$

High detector
Results – high
Simulated ADC distribution on the 320 channels

BLUE true energy distribution
RED reconstructed with the Bayesian unfolding

Simulated xtalk 2%

E = 250 MeV

ADC channel

E (GeV)
Expected resolutions

Low momentum detector $\sigma \ll 1\%$

High momentum detector $\sigma \sim 10\%$

Detector resolution
Angular divergence
Total resolution
• A spectrometer for Laser-Plasma acceleration experiments has requirements challenging for high energy physics:
  – Wide range of energies in spectrum
  – Very high charge in a single bunch
  – Large angular dispersion

• Critical aspects and chosen solutions have been discussed, quantified with an existing (preliminary) device. Points to stress:
  – Importance to find ‘focussing’ points
  – Scintillating fibers + PMT + Maroc2 chips
  – Bayesian unfolding
Still to do

- Full Geant4 simulation in order to control the detector response
- Commissioning of the detector
- Systematic data acquisition: the final aim of the PlasmonX project is to reach a stable and reproducible acceleration regime
- Deeper understanding of the laser-plasma interaction physics.

Publications:


Speaker@Conferences:

1. IPRD10 12th Topical Seminar on Innovative Particle and Radiation Detectors, Siena, 7-10June
2. IFAE2010 Incontri di Fisica delle Alte Energie, "Sapienza" Università di Roma - Dip. di Fisica, Roma, 7-9 Aprile 2010
3. SIF, XCV Congresso Nazionale, Bari, 28 Settembre - 3 Ottobre 2009
**Lanex vs Scintillating fibers**

**Pros**
- Easy to deploy
- Extremely small position resolution
- Two dimensional
- Works in vacuum

**Cons**
- Difficult to read for large areas
- Frequent alignment needed
- Sensitive to radiation
- Linearity in charge for high energy particles?

**Pros**
- Insensitive to radiation
- Easy to integrate in a DAQ
- Flexible in shape
- Works in vacuum
- Calibration required only once

**Cons**
- Lot of electronic channels (expensive)
- Low space resolution
\[ Q_{\text{Measured}} = Q_{\text{Signal}} \times G_{\text{electronics}} \]

\[ Q_{\text{Signal}} = N_{\text{particle}} \times N_{\text{phe/particle}} \times G_{\text{PMT}} \]

We can reduce \( Q_{\text{Measured}} \) by a factor 30.
We can reduce $Q_{\text{Measured}}$ by 4 order of magnitude.

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If the number of incident electrons is very high (\(10^6-10^7\)) an optical filter with a known attenuation factor can be used to reduce the number of photo-electrons at the entrance of the phototube.
If the number of incident electrons is very high ($10^6$-$10^7$) an optical filter with a known attenuation factor can be used to reduce the number of photo-electrons at the entrance of the phototube.
Traditional optical detectors

LANEX screen read by CCD cameras

But

- large size of the magnet make it difficult to tune the optical device for such a detector
- synchrotron radiation photons are also detected --> bias
Single fiber charge (QDC counts)

BTF Beam intensity (Toroid)

Maroc ADC

Maroc saturation occurs @ 2300!!

N. of fiber

HV = 500 V
Detector response vs Charge
XTalk effect from experimental data

Signal - Pedestal

| subPed |
| Entries | 64 |
| Integral | 1552 |

Signal

Xtalk between nearest PMT pixels
Unique configuration: LINAC(\textsc{sparc}) + Laser(\textsc{flame})

**NOVITA’: INIEZIONE ESTERNA**

FEL triggerato da un laser, sincronizzazione al fs

20 fs
800nm
300TW
10Hz

... multi-stage!
Test Beam ai LNF

Rivelatore a fibre
UPSTREAM

Rivelatore a fibre
DOWNSTREAM

E=198 MeV, B0=0.44T
Setup sperimentale - Rivelatore

- In vacuum per limitare multiple scattering
- Risoluzione detector necessaria ~mm
- No finestre ottiche → no CCD

Fase iniziale con fibre scintillanti lette da multichannel - multiplexed PM (~320 canali per 5PM)
Configurazioni Sperimentali

Plasma creato dal pre-pulse del laser

**LOA**

Gas-jet 4mm
En >350 MeV

Il pre-pulse ionizza il gas e l’impulso crea il wakefield accelerante

Capillari & scarica elettrica

**LOASIS**

Uso del capillare come guida d’onda per il laser

e- a 1GeV in 33 mm

e- accelerati per 85 cm con ∆E>42GeV
Oscillazioni di Plasma (1)

Hp:
ioni fissi; B=0; modello 1D

\[ m\left(\frac{\partial v_e}{\partial t} + (v_e \cdot \nabla)v_e\right) = -eE \]
1) Eq moto e-

\[ \frac{\partial n_e}{\partial t} + \nabla \cdot (n_e v_e) = 0 \]
2) Eq continuità

\[ \nabla \cdot E = 4\pi e(n_i - n_e) \]
3) Eq Maxwell

0 → Equilibrio; 1 → Perturbazione

\[ n_e = n_0 + n_i \quad v_e = v_0 + v_i \quad E = E_0 + E_1 \]

Quantità nulle nell’approssimazione

\[ \nabla n_0 = v_0 = E_0 = 0 \]
\[ \frac{\partial n_0}{\partial t} = \frac{\partial v_0}{\partial t} = \frac{\partial E_0}{\partial t} = 0 \]
\[ n_{0i} = n_{0e} \quad n_{1i} = 0 \]
Oscillazioni di Plasma (2)

Linearizzando le eq iniziali si ha:

\[ m \frac{\partial v_i}{\partial t} + (v_i \cdot \nabla)v_i = -eE_i \]
\[ \frac{\partial n_i}{\partial t} + n_0 \nabla \cdot v_i + v_i \nabla \cdot n_0 = 0 \]
\[ \nabla \cdot E_i = 4\pi n_i \]

Assumendo andamento sinusoidale per le quantità oscillanti si deriva:

\[ v_i = v_i e^{i(kx - wt)} \]
\[ n_i = n_i e^{i(kx - wt)} \]
\[ E_i = E_i e^{i(kx - wt)} \]

\[ -imwv_i = -eE_i \]
\[ -iwn_i = -n_0 ikv_i \]
\[ ikE_i = -4\pi n_i \]

Frequenza di oscillazione del plasma

\[ w^2 = \frac{4\pi n_0 e^2}{m} \]
Che tipo di laser → **Chirped Pulse Amplification**

1. **Low energy** → 10 nJ

   *Initial short pulse*

   **Short-pulse oscillator**

   - The pulse is now long and low power, safe for amplification

2. **Stretcher**

   *A pair of gratings disperses the spectrum and stretches the pulse by a factor of a thousand*

3. **Amplifier stages:**

   - nJ → mJ → J

   **Power amplifiers**

4. **Compressor** → fs

   *A second pair of gratings reverses the dispersion of the first pair, and recompresses the pulse.*

**Oss:** Allungando la durata temporale l’intensità W/cm² non daneggia le componenti ottiche!
Risultati sperimentali → **Il primo esperimento Italiano** (Pisa)

Elettroni del plasma accelerati con laser
Shot to shot fluctuation: +−5% in energy; +−30% in charge
Elettroni esterni accelerati con laser

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

1- Wakefield creato dal fascio e- !!
2- parte del fascio perde energia
3- frazione di e- vengono accelerati per 85 cm con $\Delta E > 42\text{GeV}$

Campo accelerante > 52 GeV/m !!
Stato dell’arte delle ricerche

E' tra i temi più investigati, a livello mondiale, nelle maggiori facilities esistenti

Le ricerche hanno portato alla produzione di:

**PROTONI**: energia massima 60 MeV (spettro termico)

**ALTRI IONI**: C - 90 MeV  
F – 100 MeV  
Pb – 430 MeV (+altri...)

N° particelle: $\sim 10^9-10^{13}$  
Emittanza long.: $< 10^{-4}$ eV.s  
Emittanza trasv.: $< 10^{-8}$ m rad  
Durata temporale pacchetto: $\sim$ ps

...in una scala spaziale $\sim \mu$m
Accelerazione di ioni indotta da impulsi laser intensi

Se un impulso laser ultraintenso ultrabreve colpisce la superficie di un film solido sottile si osserva la produzione di popolazioni di ioni energetici Target Normal Sheath Acceleration (TNSA)

Parametri fisici caratteristici del sistema

**Laser** — energia: 0,1-1000 J, 
durata impulso: 10-1000 fs, intensità $10^{18}$-$10^{21}$ W/cm²

**Bersaglio solido** — tipo: conduttori e isolanti, 
spessore: 0,1-100 μm

**Ioni accelerati** — protoni in condizioni ordinarie, 
altri ioni in condizioni specifiche

Le ricerche (tema “hot” a livello mondiale) hanno portato alla produzione di:

**PROTONI:** energia massima 60 MeV (spettro termico)

**ALTRI IONI:** C - 90 MeV; F - 100 MeV; Pb - 430 MeV (+altri…)

$N_p$ particelle: $\sim 10^3$-$10^{13}$; Emittanza long.: $< 10^{-4}$ eV.s; Emittanza trasv.: $< 10^{-8}$ m rad; Durata temporale: $\sim$ ps

...in una scala spaziale $\sim$ μm
Concetto di base

\[ \sigma_{p,e} = \left( \frac{n_e e^2}{m_e e_0} \right)^{1/2} \approx 900 (n_e [cm^{-3}])^{1/2} \]

Wave wake / Plasma wave

\[ F_{NL} = - \left( \frac{\omega_p}{\omega_L} \right)^2 \vec{\nabla} \left\langle \frac{E^2}{8\pi} \right\rangle \]

Forza prop all’Intensità del laser

Forza prop alla densità e⁻