Advanced Instrumentation for Laser-Driven Acceleration Experiments

Channeling in Plasma Physics by Laser and Applications (PPLA)
Ischia Sep 26, 2018

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Overview

- Introduction
- Generalities about beam diagnostic devices
- Overview of on-line measurement techniques and instruments
- Experience reported at the L3IA facility

Introduction

An accelerator can never be better than the instruments measuring its performance!

Different uses of beam diagnostics

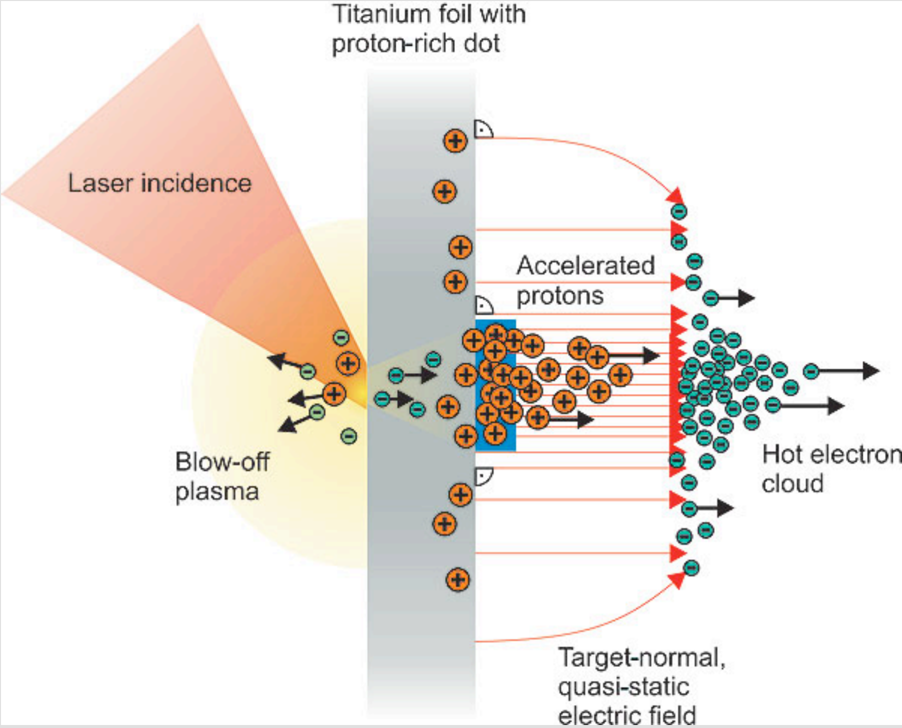
- **Check of accelerator performances**

  1. Beam intensity
  2. Beam energy
  3. Beam position
  4. Beam profile

- **Advanced measurements**

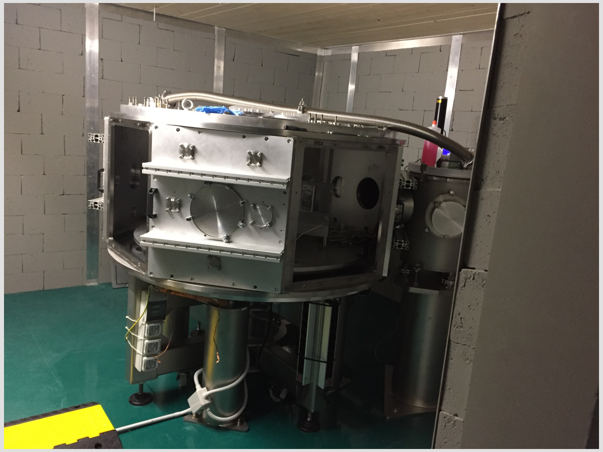
  1. Beam particle identification
  2. Beam emittance

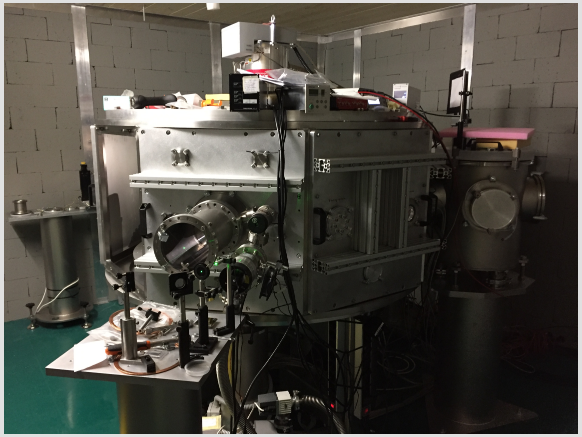
Expected values for the main beam parameters



Protons per shot:	10^{10} -10^{13}
Max proton energy:	80 MeV
Bunch temporal profile:	ps
Source size:	µm
Emittance:	5 10^{-3} π mm mrad
Beam angular divergence:	10-20°
Energy spread:	large (20%)
Ripetibility:	poor

L3IA: Line for laser light ion acceleration (INFN and CNR)





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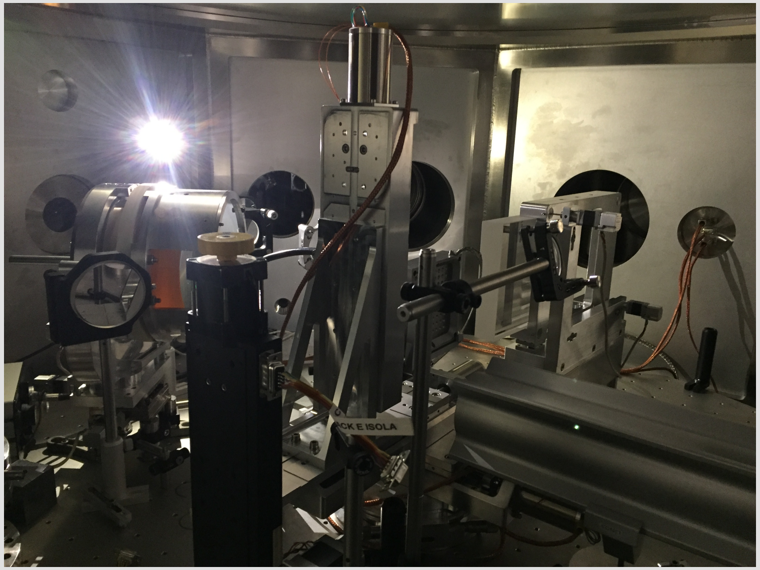
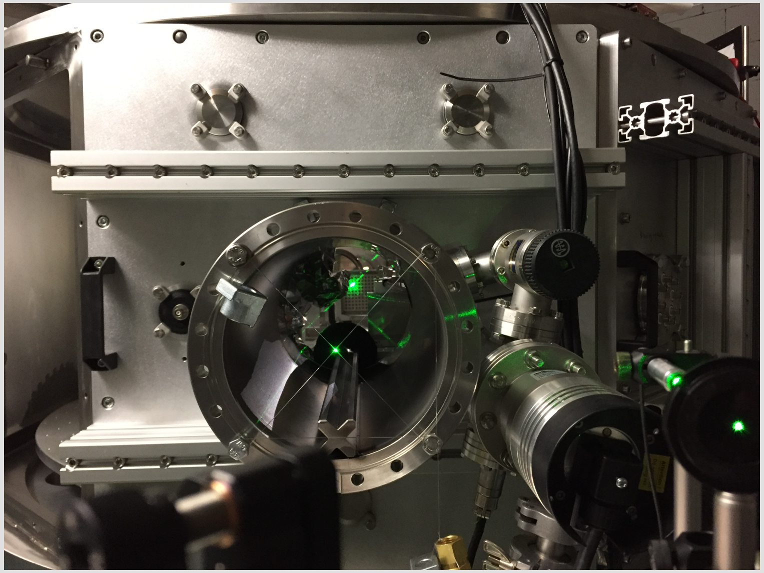
L3IA facility



Target holder



Thomson Spectrometer

Diagnostic devices and quantity measured

Measured quantity	Physical Effect	Instrument	Effect on the beam	Analysis
Charge, fluence	Charge collection	Faraday Cup	Destructive	OnLine
Charge, fluence	E.m. induction	Current transformer	Non destructive	OnLine
Transverse size/shape/ position	Excitation with light emission	Scintillator materials	Destructive	OnLine
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Transverse size/shape/ position	Direct Ionization	Pixel Detectors	Destructive	OnLine
Fluence (low) Particle Ident.	Radiation damage	Track detectors (CR39)	Destructive	OffLine
Energy/Particle Ident.	B and E deflection	Thomson Parabola	Destructive	OnLine
Energy/fluence	Dynamics/Ionization	Time of flight	Destructive	OnLine
Flux Spectral Distribution	Nuclear Reactions	Nuclear activation	Destructive	OffLine

Electromagnetic Pulse

Interaction of high-energy and high-power laser pulses with a target is accompanied with the generation of a significant number of energetic electrons producing many secondary effects. The intense x-ray emission, ion acceleration and many other effects have been intensively studied and have been used in many applications. However there is a domain related to the laser electron acceleration, which has not yet been fully investigated. This is **the generation of an intense electromagnetic pulse (EMP) during and after the laser pulse spanning a very broad frequency range from megahertz to terahertz.** This transient EMP has been measured in several laser facilities with different regimes of laser intensity and pulse duration. The EMP generation is commonly attributed to radiation by laser-driven currents within the plasma and, at higher intensities, to high-energy electrons leaving the target and hitting either the chamber internal surface and/or the other elements

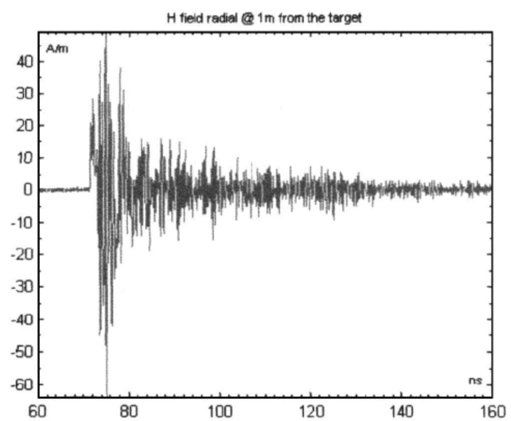

FIG. 1. H field radiated in the target chamber.

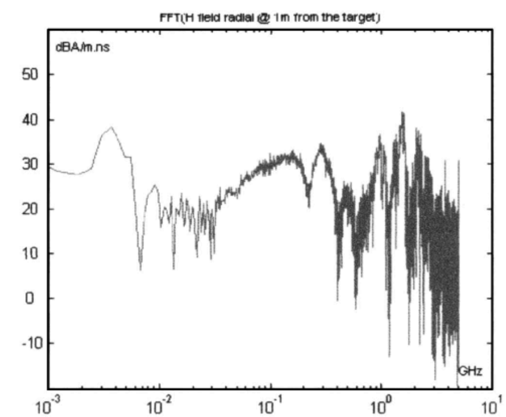

FIG. 2. H field radiated in the target chamber (spectral density).

J.Raimbourga
Electromagnetic compatibility management for fast diagnostic design
REV. SCIE.INSRUM., 75, N.10, OCT 2004

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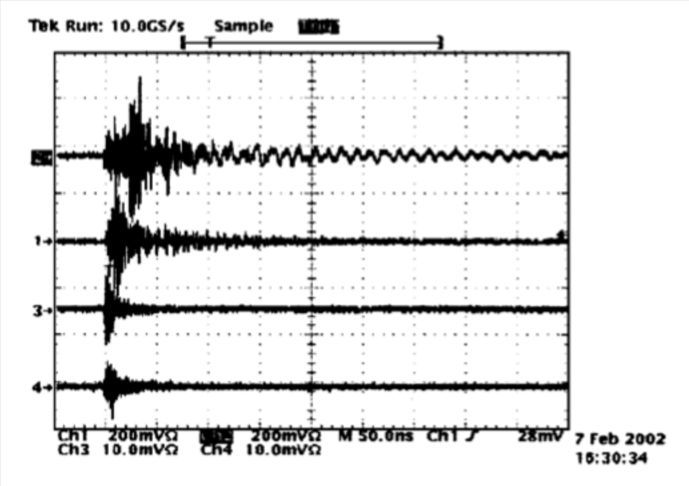
Electromagnetic Pulse

The EMP represent a **serious limitation for the plasma diagnostics** and in general for the operation of the electronic devices. The mechanism of generation of the electric and magnetic fields in the broad frequency domain are not well known, yet. It is accepted that the fields are generated during the interaction of the laser pulse with the target and increase with the ejected charge but the exact mechanism is not defined. It could be related either to the electric current carried out by escaping electrons or with the charge accumulated on the target. The experimental data indicated that the signal strength and the temporal profile depend on the target material and geometry on the shape and the place of the metallic elements of the chamber, as well as on the laser pulse intensity and duration.



Electromagnetic Pulse

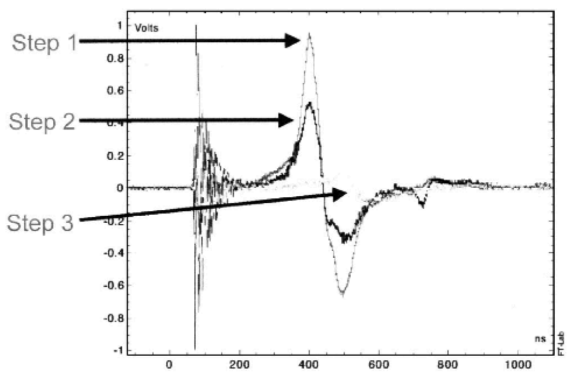
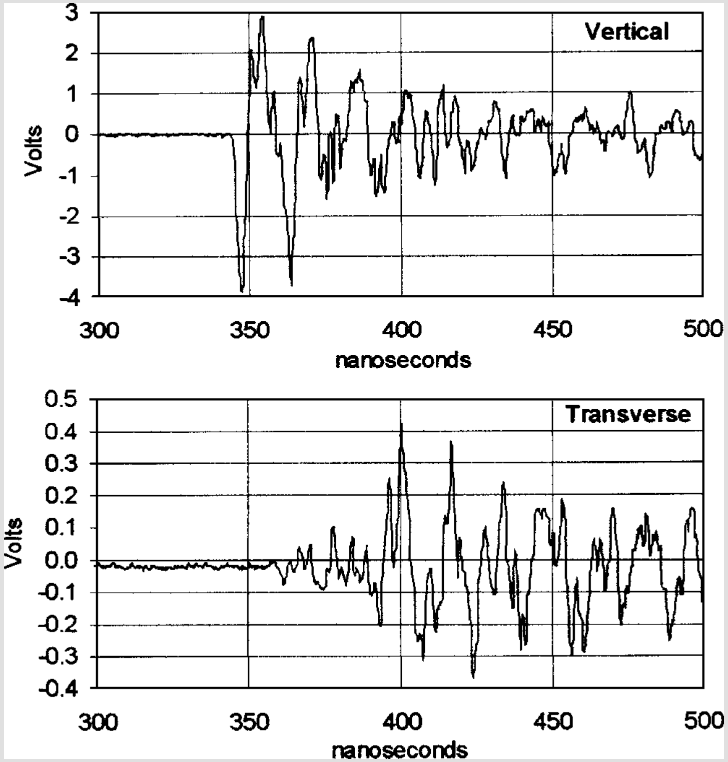


FIG. 5. Single point vs multiple point grounding effect.

V. SINGLE POINT/MULTIPLE POINT GROUNDING

The OMEGA laser facility is single point grounded. For EMI measurements, we first needed to insulate the BNC feedthrough connector located in the target chamber wall. Our first measurements showed the EMI field plus a strange large pulse a few hundred nanoseconds later (step 1). The second pulse could have been ion impact from the target to the probe.

We removed the insulation on each BNC connector. This reduces the level of the pulse (step 2). Next, we put a glass screen to filter ions in front of the H field probe. We changed low EMC immunity BNC connectors for SMA connectors and we chose a higher EMC immunity cable with two braids (step 3). Figure 5 shows the results of these three steps and clearly indicates that it was an EMI problem.



Electromagnetic Pulse

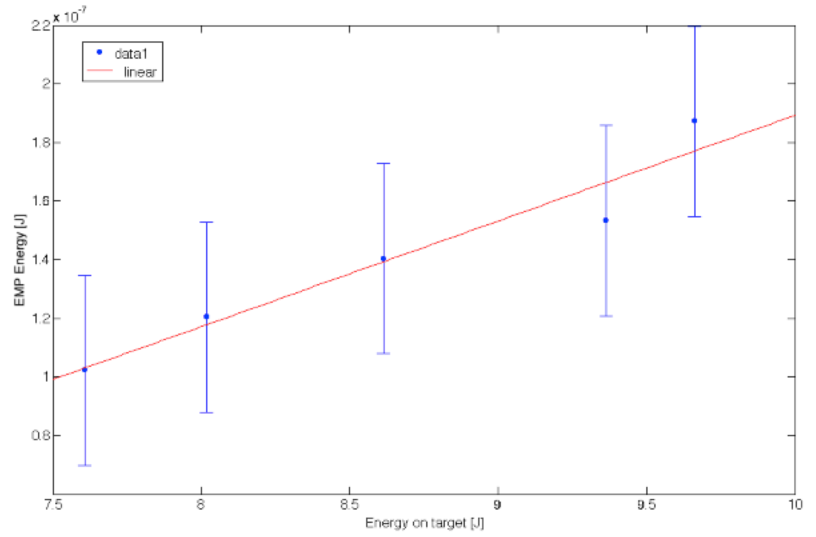


Figure 5.26: EMP energy emission at TARANIS facility as function of Energy relased on target (The error bars represent the standard deviations)

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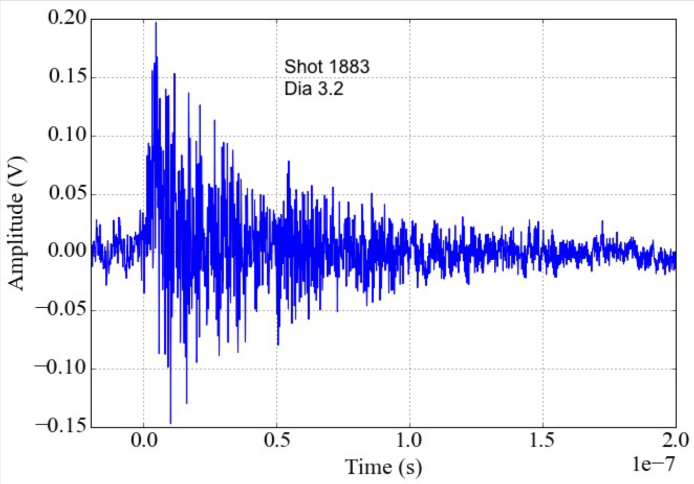
Electromagnetic Pulse



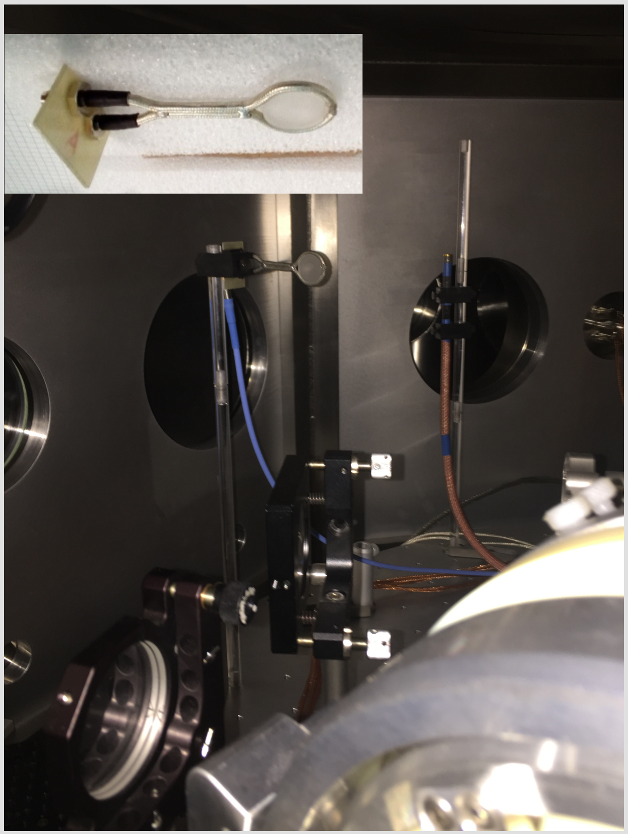
R. De Angelis et al
High performance diagnostics for Time-Of-Flight and X ray measurements in laser produced plasmas, based on fast diamond detectors
2016_J._Inst._11_C1204

E_{laser} = 12 J, <u>3ns</u> and <u>10^{13}</u> W/cm2 intensity
on a 7 mm Al target

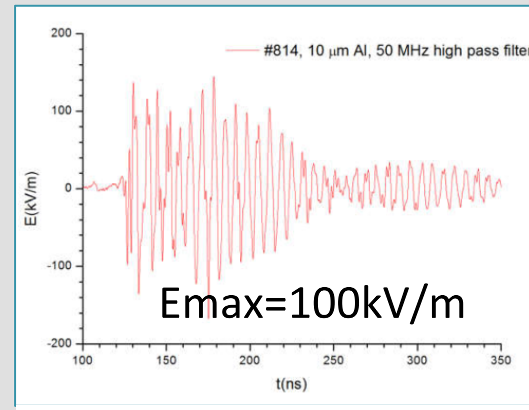
Plasma Physics by Laser and Applications (PPLA 2015)
ENEA Research Centre, Frascati, Italy
5-7 October, 2015

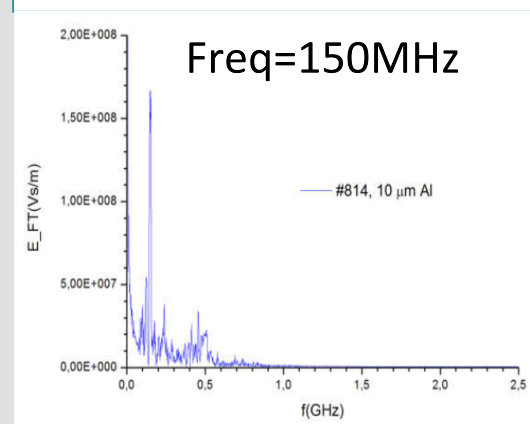
Electromagnetic Pulse in L3IA

Collaboration with Institute of Plasma Physics and Laser Microfusion of Warsaw



EMP detectors
B-dot
D-dot





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Shielding and grounding

Starting point

- Background em pick up noise along signal cables (length up to 30 m): +/- 50 mVp, 5 MHz

- Em noise induced after the laser shot on the target, lasting **hundreds of ns** **+/-1 Vp, 250-350 MHz** with reflections due to impedance mismatch

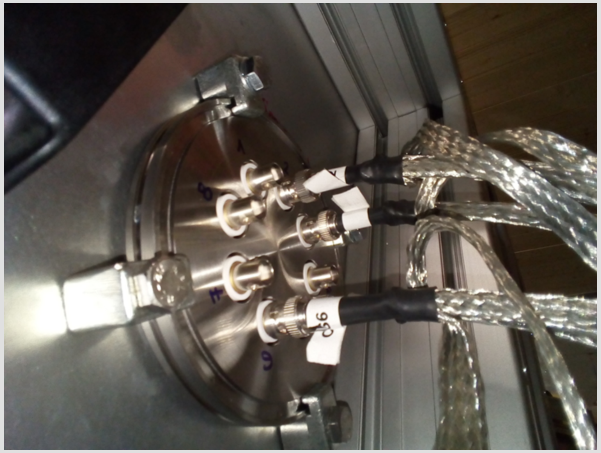
Shielding and grounding

In june 2016 we made some significant improvements:

All the internal cables were substituted using a new shielded Coaxial Cable named SPUMA_240-FR-01

Electrical Data

Impedance	50 Ω +/- 2
Operating Frequency	6 GHz
Capacitance	78.9 pF/m
Velocity of signal propagation	82.6 %
Signal delay	4.05 ns/m
Min. screening effectiveness	≥ 90 dB (up to 6 GHz)
Max. operating voltage	≤ 0.9 kV_{rms} (at sea level)
Test voltage	1.5 kV_{rms} (50 Hz/1 min)



A new electrical line devoted to grounding and shielding of signal paths was installed with a direct connection to the bulding main transformer reference.
The target holder was referenced to this ground along with the whole chamber

Results:

Shooting the laser on a glass target we had a reduced noise of +/- 15 mVp on a diamond detector
Shooting the laser on an aluminium target we had an overall noise **of +/- 200 mVp** on a diamond detector

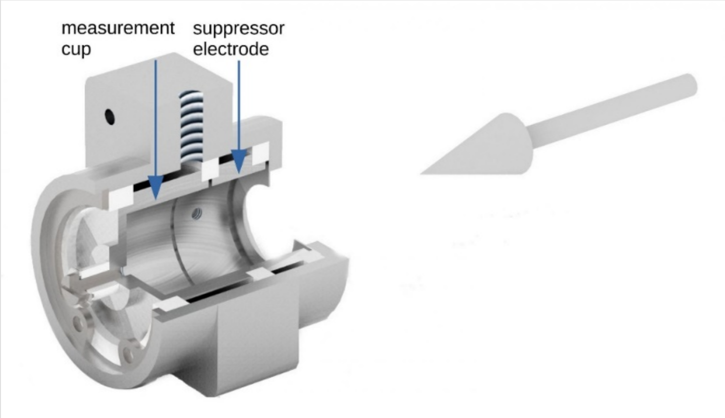
Diagnostic devices and quantity measured

Measured quantity	Physical Effect	Instrument	Effect on the beam	Analysis
Charge, fluence	Charge collection	Faraday Cup	Destructive	OnLine
Charge, fluence	E.m. induction	Current transformer	Non destructive	OnLine
Transverse size/shape/ position	Excitation with light emission	Scintillator materials	Destructive	OnLine
Transverse size/shape/ position/dose	Radiation damage	Radiochromic films	Destructive	OffLine
Transverse size/shape/ position	Direct Ionization	Pixel Detectors	Destructive	OnLine
Fluence (low) Particle Ident.	Radiation damage	CR39	Destructive	OffLine
Energy/Particle Ident.	B and E deflection	Thomson Parabola	Destructive	OnLine
Energy/fluence	Dynamics/Ionization	Time of flight	Destructive	OnLine
Flux Spectral Distribution	Nuclear Reactions	Nuclear activation	Destructive	OffLine

Faraday Cup

Only low energy particles can be measured

- Very low intensities (down to 1 pA) can be measured
- Creation of secondary electrons of low energy (below 20 eV)
- Repelling electrode with some 100 V polarisation voltage pushes secondary electrons back onto the electrode

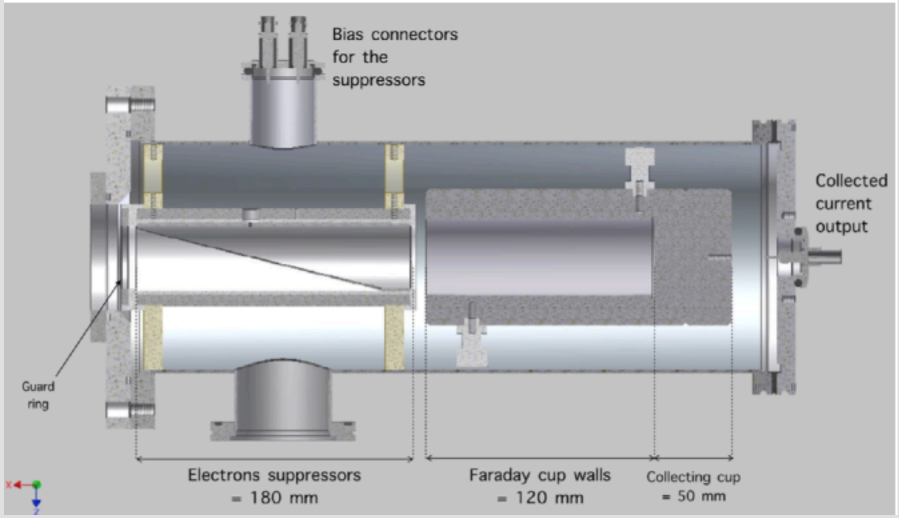


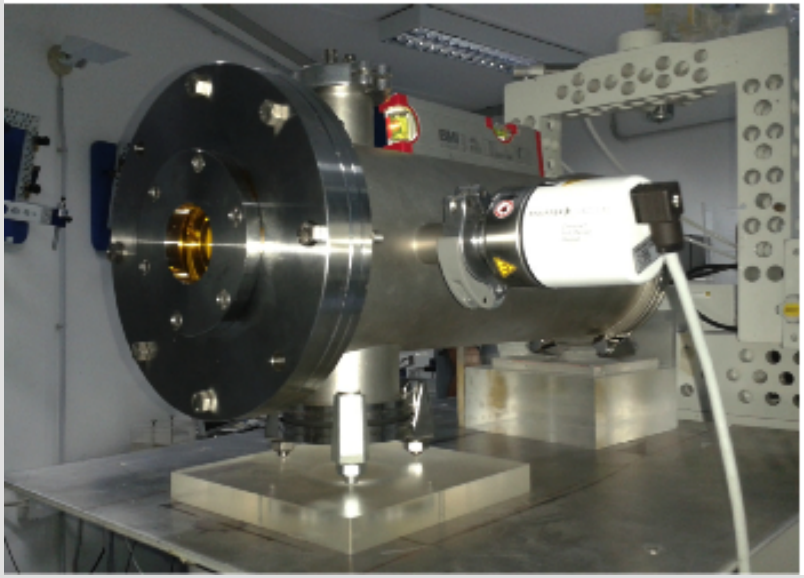
The Faraday Cup as absolute dosimeter system

$$D_W = \Phi \frac{S_W}{\rho_W} \Pi_{ki}$$

Only for <u>monoenergetic</u> beam or <u>known</u> spectrum

$$D_W = \frac{S(E)_W}{A} \frac{Q}{e} 1,602 * 10^{-10} (Gy)$$





Courtesy of G.P. Cirrone –ELIMED Project

Applied Voltage [V]	FC Charge [C]	FC Dose [Gy]	Reference dose [Gy]	Absolute Discrepancy [%]
-1500	3,97E-09	12,86 ±2.57	13,68	6.01
-1000	3,99E-09	12,92± 2.58	12,92	5.62

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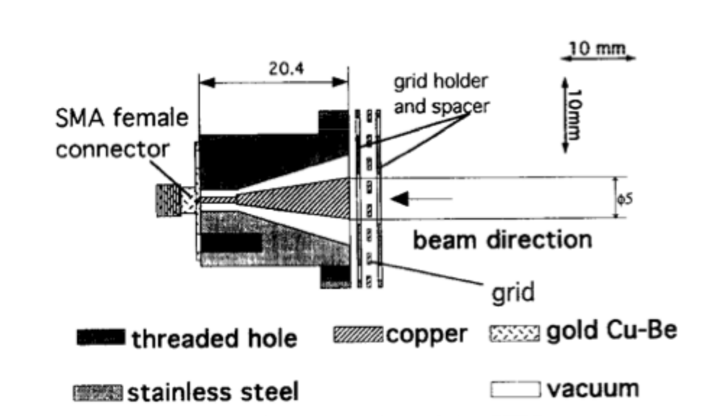
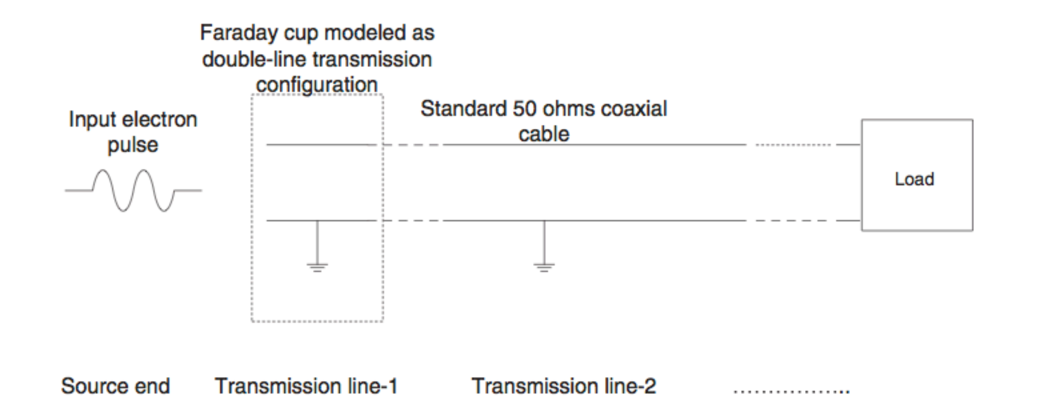
Fast Faraday Cup

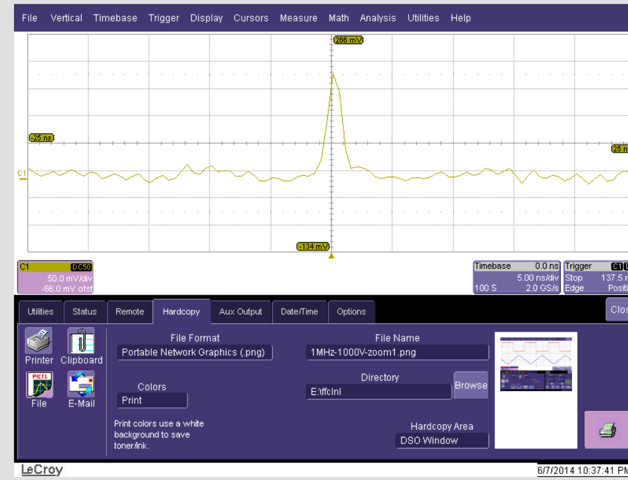
The FC is designed to measure an electron beam pulse signal with duration of the order of 50 ns and **rise time shorter than 10 ns**. For such a short pulse, the maximum signal frequency can be up to **0.1–1 GHz**, thus the characteristic impedance and the **impedance matching** between the FC and test network are important design considerations. A schematic of the design is shown in Fig. 1 and the corresponding transmission line model is illustrated in Fig. 2.

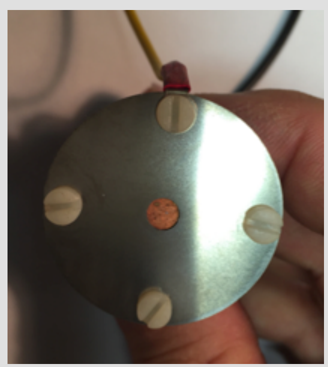


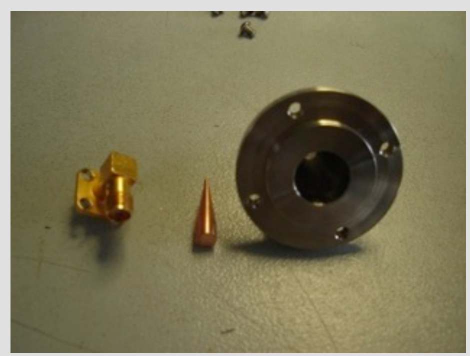


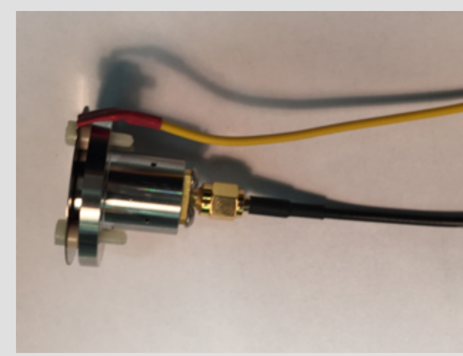
Fast Faraday Cup

A **fast faraday cup**, with **a 2 GHz** bandwidth, has been developed and tested. Pulsed beams with FWHM of the order of 500-700 ps have been measured**.** It may be a very nice and simple tool to be used in TOF experiments. We will test the **sensitivity** in the specific environment.









Diagnostic devices and quantity measured

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Charge, fluence	Charge collection	Faraday Cup	Destructive	OnLine
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Transverse size/shape/ position	Direct Ionization	Pixel Detectors	Destructive	OnLine
Fluence (low) Particle Ident.	Radiation damage	CR39	Destructive	OffLine
Energy/Particle Ident.	B and E deflection	Thomson Parabola	Destructive	OnLine
Energy/fluence	Ionization	Time of flight	Destructive	OnLine
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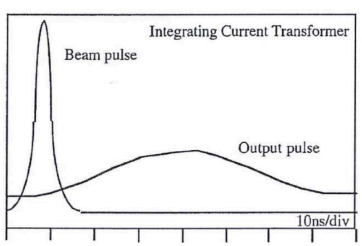
Integrating Current Transformer

measure the **charge** in a very **short particle bunches** of **unipolar** charge (ions or electrons)

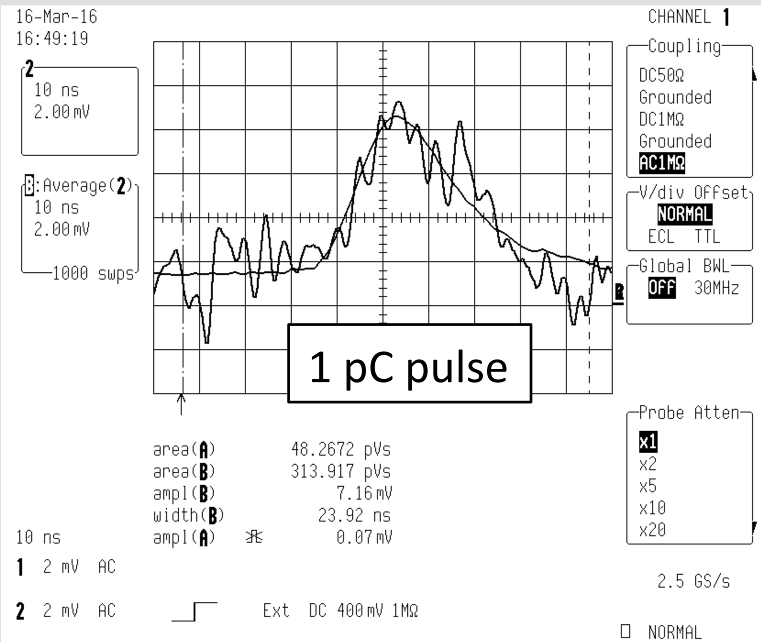
high accuracy (very precise calibration is possible)
no significant HF losses
Linearity
Noiseless (<1 nA rms for active ICT)
Very small beam position dependency
No TOF device

The ICT delivers a pulse with ca. 20 ns rise time irrespective of the beam pulse rise time. The ICT output pulse charge is in exact proportion to the beam pulse charge.

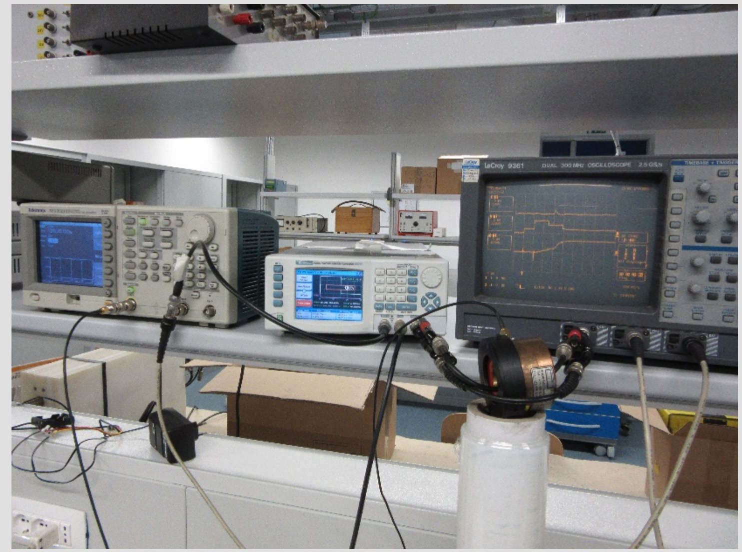


ICT measured performances

Test bench measurements of the detector performances



1pC corresponds to an emission of 3 10^8 protons in a 10° semi-aperture cone.



EMP sensitive

Better suited for electron acceleration experiments

Bergoz Turbo ICT

New alloys: core **losses** <1% up to 350 MHz.
Integration time reduced by a factor 25
Signal-to-noise ratio improved by 25
Multiple cores further increase the signal.
Integrated FE pHEMTamplifier and
Signal modulation assure EMI immunity.

Turbo-ICT-VAC is installed in a laser-plasma vacuum enclosure
Vacuum compatible to 1E-7 mbar

Noise in single bunch measurement 10 fC

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Scintillators

Pros: spatially resolve the transverse profile
reusable
Light can be transported outside the interaction chamber (EMP)
Cons: Need absolute calibration on proton energy and flux.
Quenching

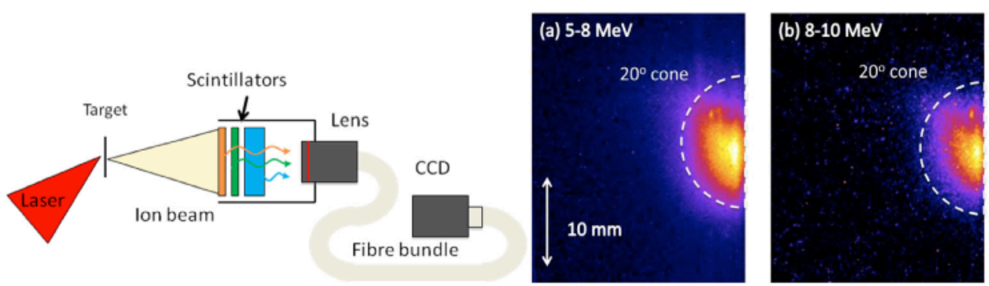
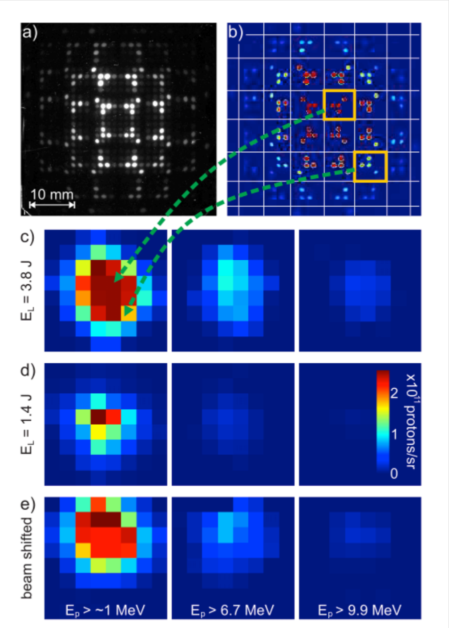
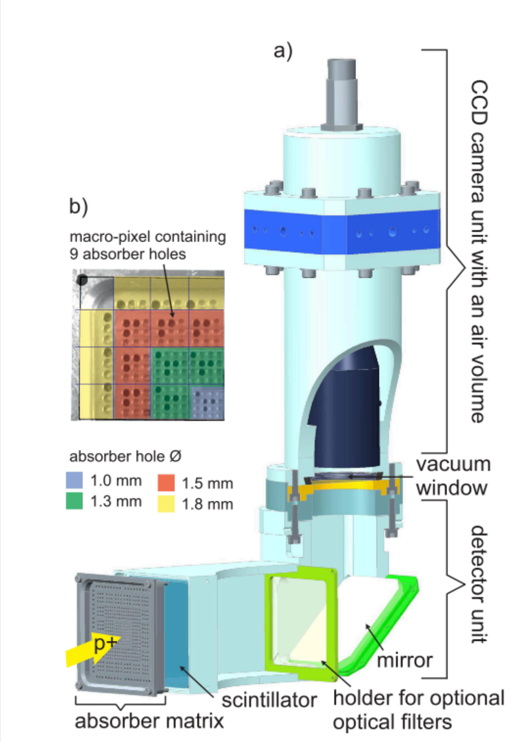


Figure 6. (Left) Schematic for a three colour proton beam spatial profiler. Higher energy protons are stopped in the shorter wavelength scintillators located further downstream in the stack. The combined optical signal is collected and relayed to a CCD camera via a fibre optic bundle. (Right) Proton (half) beam profile for two energy windows for a 100 nm Al target irradiated at $\sim 5 \times 10^{20}$ W/cm^2 with high contrast ($>10^9$).

Scintillators

A compact scintillator-based online area detector





The online detector system resolves the spatial profile of a laser-driven proton beam (4 mm spatial resolution in the central part of the detector) and it can distinguish up to 9 threshold energies.

An online, energy-resolving beam profile detector for laser-driven proton beams (2016)
J. Metzkes, K. Zeil, S. D. Kraft, L. Karsch, M. Sobiella, M. Rehwald, L. Obst, H.-P. Schlenvoigt, and U. Schramm

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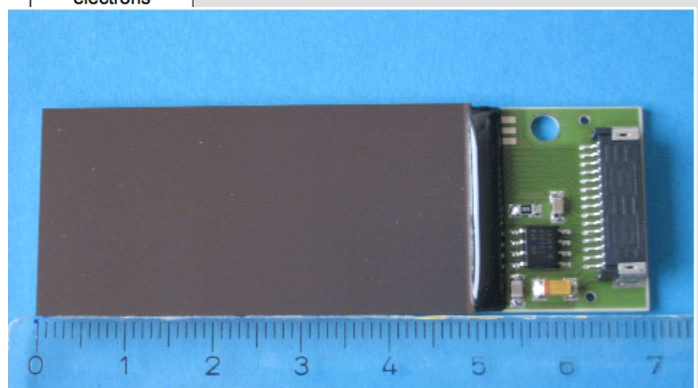
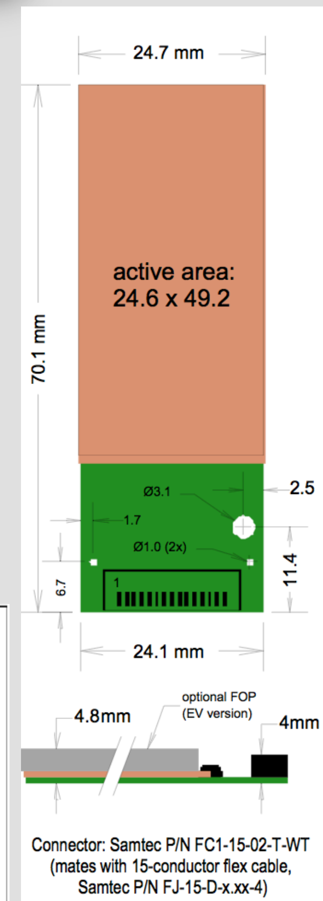
Pixel detectors

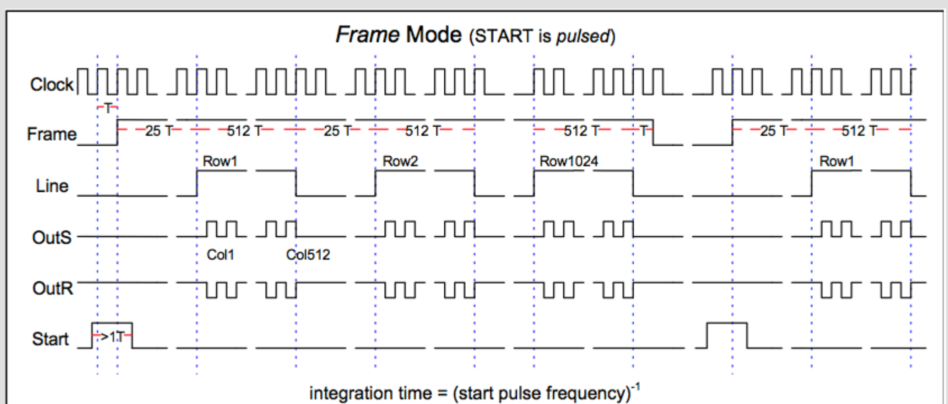
Specifications	*Minimum*	*Typical*	*Maximum*	*Units*
Avg. dark current (at 23°C)*	-	4,000	10,000	electrons/sec
Read noise (rms, at 1 fps)	-	150	-	electrons
Saturation	-	2,800,000	-	electrons
Dynamic range	-	85	-	
Frame rate	0.01	-	4.5	
Data rate (CLOCK)	0.01	-	2.5	
Conversion gain	-	0.5	-	
Response linearity (average)	-	± 1	± 2	
Quantum efficiency (500-700nm)	-	> 30	-	
Supply voltage (VDD)	4.5	5.0	5.1	
Supply current (IDD)	-	20	-	
Reference voltage (VD)	2.5	3.8	4.3	
Analog output + (VD = 3.8 V)	-	2 (dark)	2.7 (sat)	
Analog output – (VD = 3.8 V)	1.3 (sat)	2 (dark)	-	
Digital "low" voltage in	-0.1	0	0.5	
Digital "high" voltage in	4.5	5	5.1	
Operating temperature	0	-	50	°C
Storage temperature	-25	-	85	°C





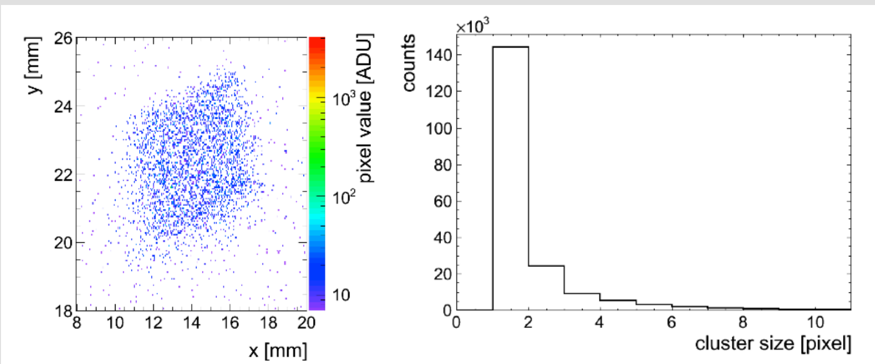
RadEye detector
CMOS imager

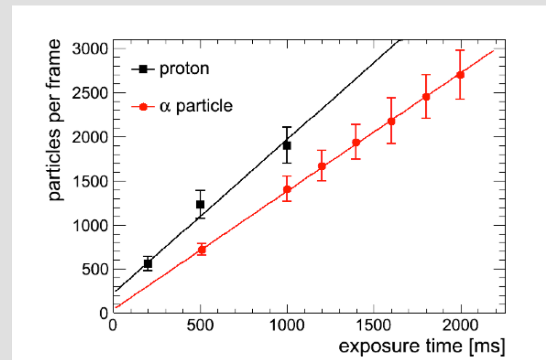
Fluence dynamic range
$4.4 \bullet 10^7$ protons/cm2

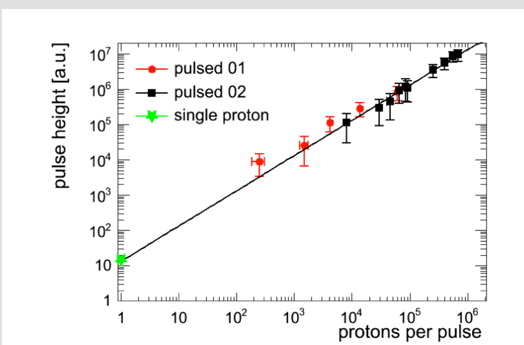


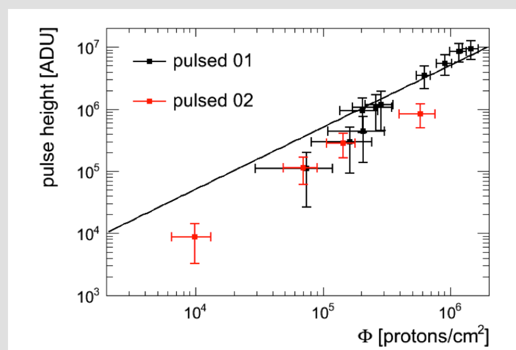
Pixel detectors

Continuous and pulsed irradiation with 15 and 20 MeV protons









Characterisation of the response to fluence and fluence rate.
Sensibility
Dynamic range

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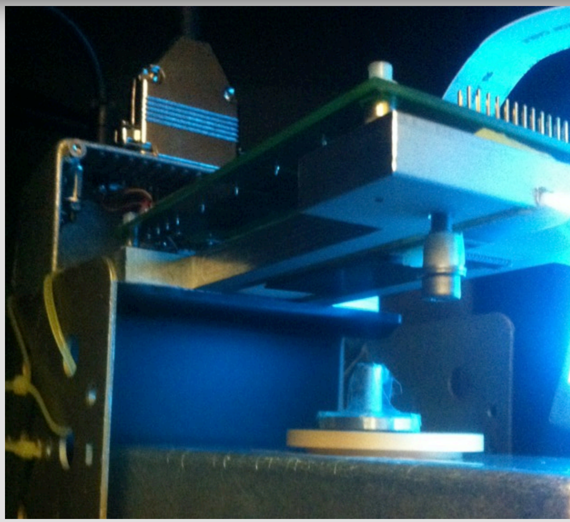
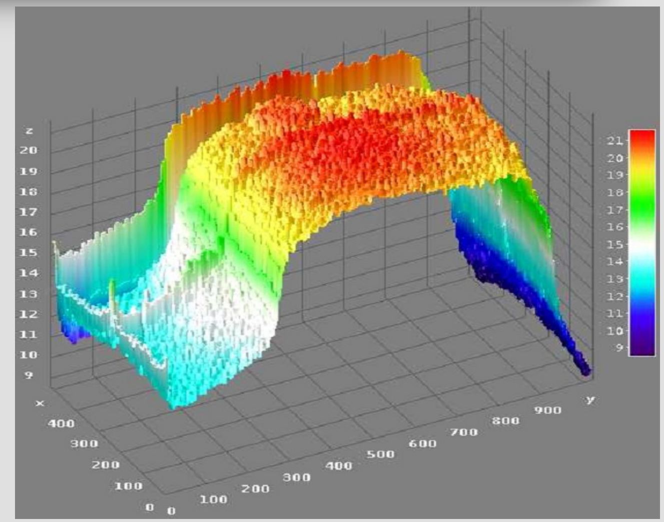
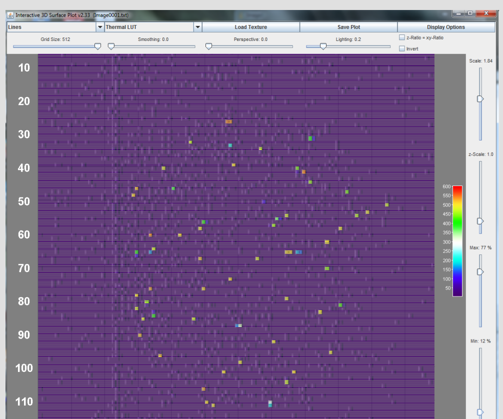
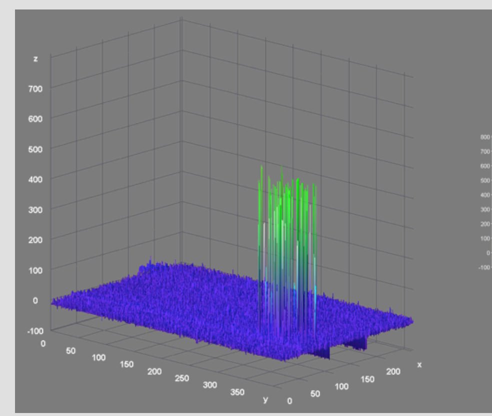
Pixel detectors









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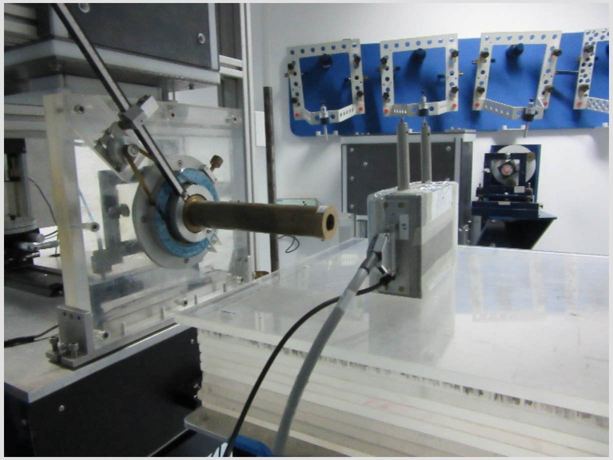
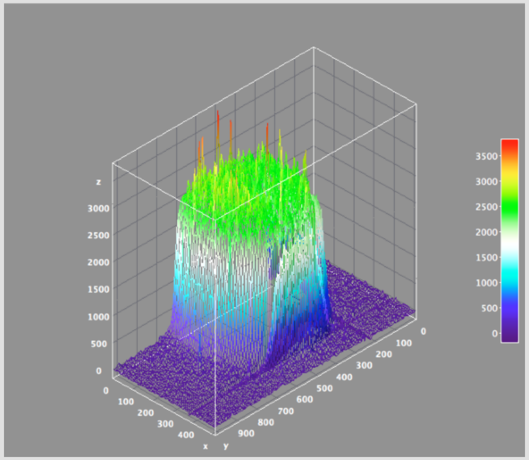
Pixel detectors

In February 2015 a preliminary test has been carried out at the SC at LNS using proton beams from 62 MeV down to 15 MeV (degraded).

Low intensity beams (down to 10^6 protons after a 20 mm diameter collimator) have been successfully detected.



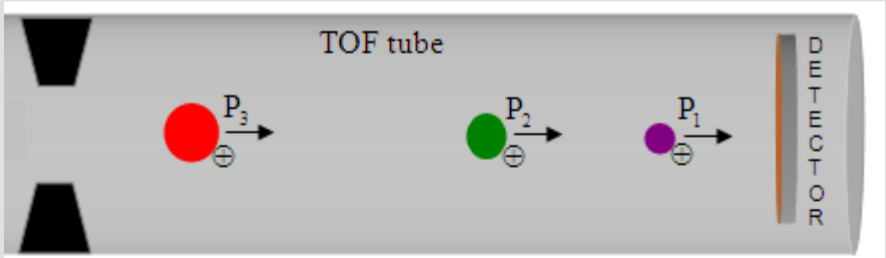


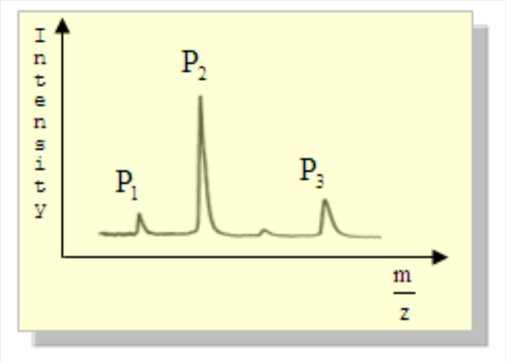
Diagnostic devices and quantity measured

Measured quantity	Physical Effect	Instrument	Effect on the beam	Analysis
Charge, fluence	Charge collection	Faraday Cup	Destructive	OnLine
Charge, fluence	E.m. induction	Current transformer	Non destructive	OnLine
Transverse size/shape/ position	Excitation with light emission	Scintillator materials	Destructive	OnLine
Transverse size/shape/ position/dose	Radiation damage	Radiochromic films	Destructive	OffLine
Transverse size/shape/ position	Direct Ionization	Pixel Detectors	Destructive	OnLine
Fluence (low) Particle Ident.	Radiation damage	CR39	Destructive	OffLine
Energy/Particle Ident.	B and E deflection	Thomson Parabola	Destructive	OnLine
Energy/fluence	Ionization	Time of flight	Destructive	OnLine
Flux Spectral Distribution	Nuclear Reactions	Nuclear activation	Destructive	OffLine

Time of Flight Technique

Detectors in time of flight configuration are widely used in laser-plasma experiments. Thank to this technique it is possible to obtain information on particles emitted from the knowledge of their speed. The most direct way to determine the particle speed is, of course, by measuring the time that it takes to travel a certain distance.





Time of Flight Detectors

Independent of which semiconductor material is employed, specific material properties are required for the realization of high performance spectrometers that provide both high-energy resolution and high counting efficiency at and above room temperature and in intense radiation environments. Some of them are as follows :

Radiation hardness	(up to 10^{12} ppp)
Time resolution	(ns)
Low capacitance	(tens of pF, better energy resolution)
Thickness	(10s and 100s micron)
Low sensitivity to X and γ rays	
Large bandgap energy	(low noise)
High purity	(full charge collection, low leakage current)

Time of flight detectors

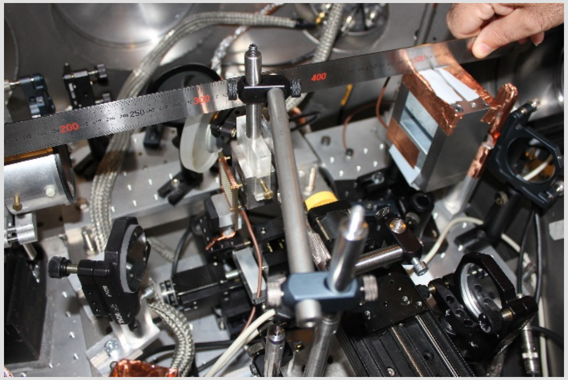
Table 1. Comparison of properties of selected important materials mostly used for radiation ionizing detector realization with semiconductor 4H–SiC. Data compiled from [14, 23–25] and references therein.

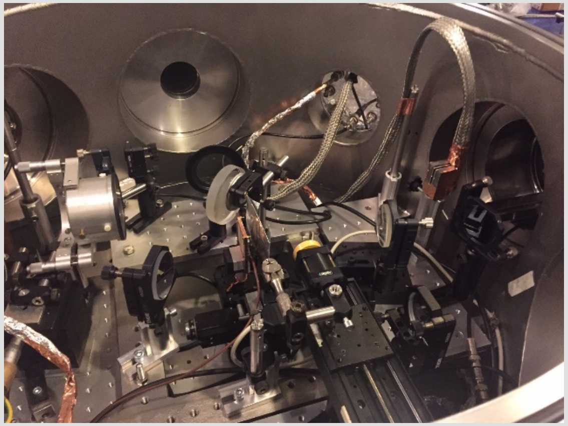
Property	D	Si	Ge	GaAs	CdTe	4H–SiC
Bandgap (eV)	5.5	1.12	0.67	1.42	1.49	3.27
Relative dielectric constant	5.7	11.9	16	13.1	10	9.7
Breakdown field (MV cm^{-1})	10	0.3	0.1	0.4	0.5	3.0
Density (g cm^{-3})	3.5	2.3	5.33	5.3	5.9	3.2
Atomic number Z	6	14	32	31–33	48–52	14–6
e–h creation energy (eV)	13	3.6	2.95	4.3	4.42	7.78
Saturated electron velocity (10^7 cm s^{-1}) at 300 K	2.2	1.0	0.6	1.2	1.0	2
Electron mobility (cm^2 V^{-1} s^{-1}) at 300 K	1800	1300	3900	8500	1100	800
Hole mobility (cm^2 V^{-1} s^{-1}) at 300 K	1200	460	1900	400	100	115
Threshold displacement energy (eV)	40–50	13–20	16–20	8–20	6–8	22–35
Minimum ionizing energy loss (MeV cm^{-1})	4.7	2.7	6	5.6		4.4

Time of flight detectors

Diamond based TOF measurements

(300 mm length of flight)
end of june 2016





0.7 Tesla permanent magnet inserted to remove unwanted electrons

500 micron thickness diamond
collimator bore diameter 2 mm

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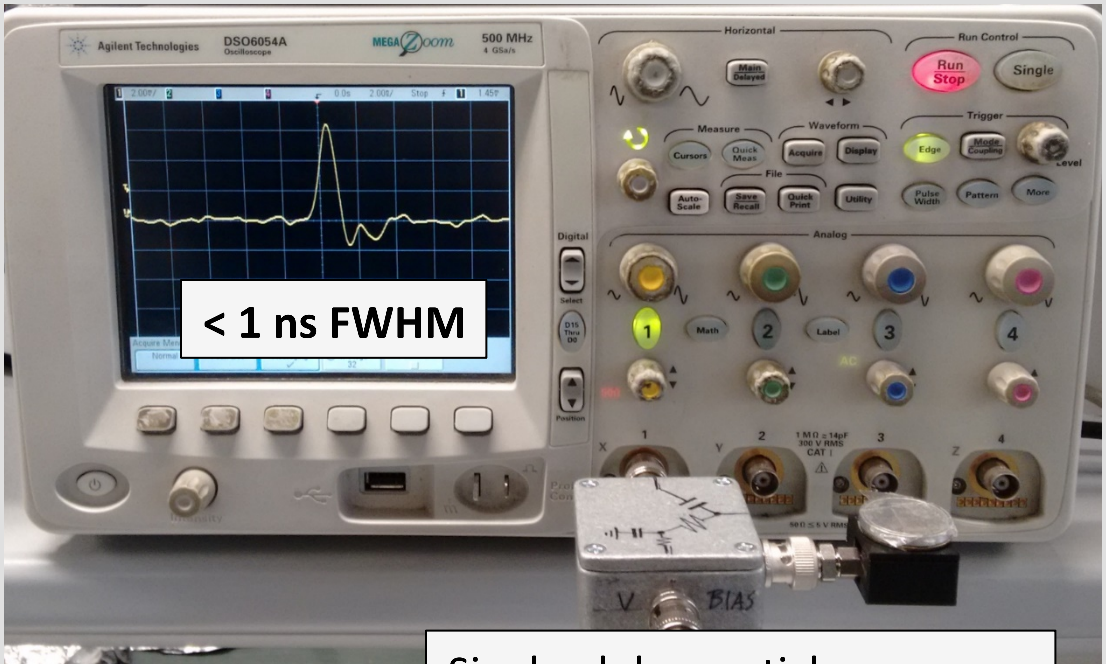
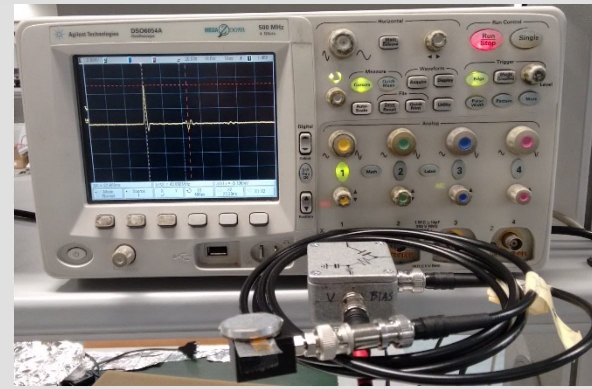
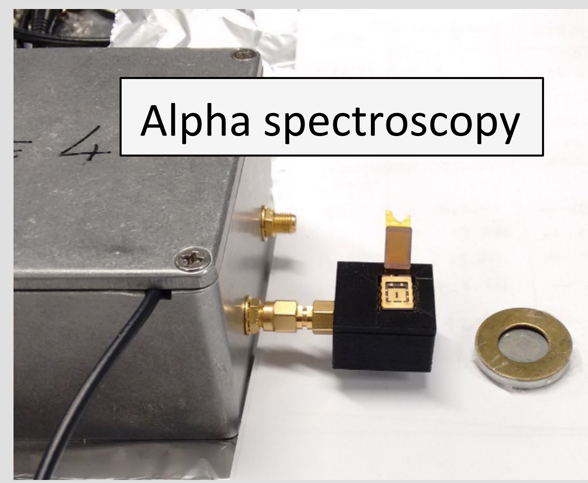
Time of Flight

Proton Energy	TOF (ns/m)
2	51,16
4	36,23
6	29,63
8	25,70
10	23,02
12	21,05
15	18,87
20	16,41
25	14,73

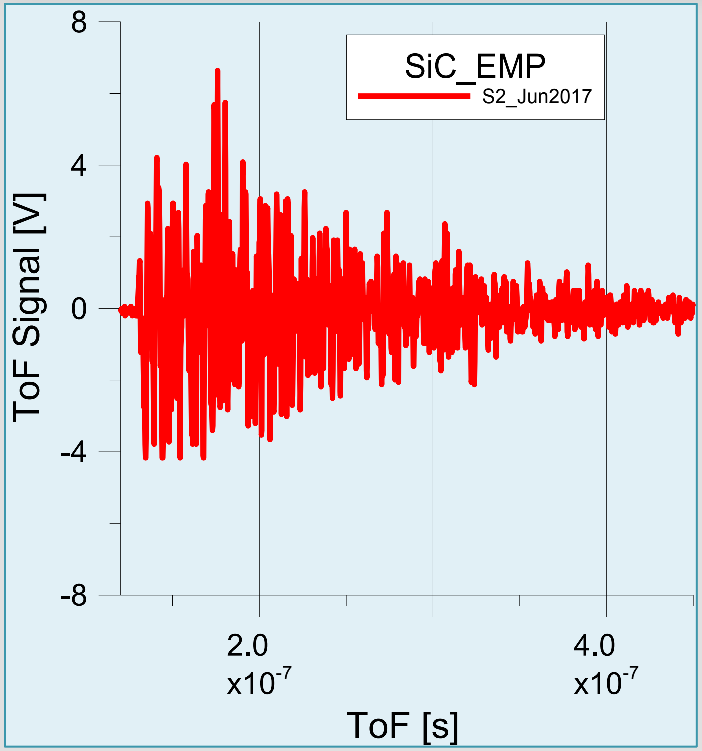
Time of Flight Detectors





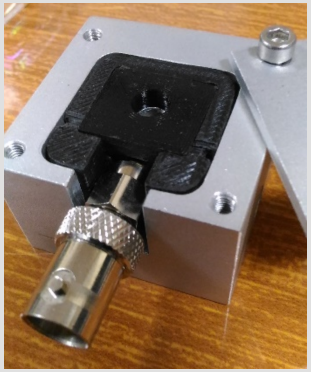


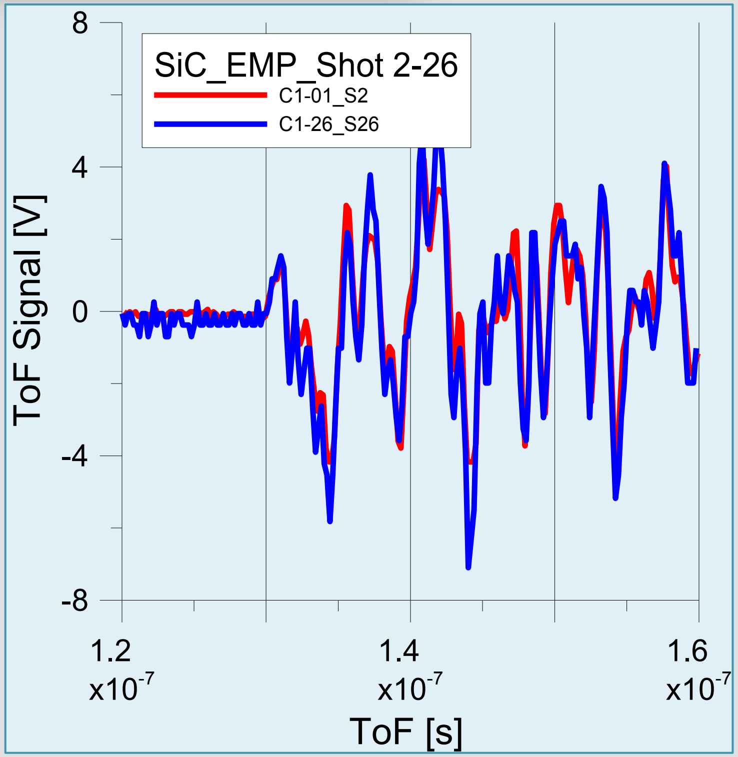
Time of Flight Detectors



pick-up of EMP

TOF detector '17 original design





Zoom of pick-up Repeatability

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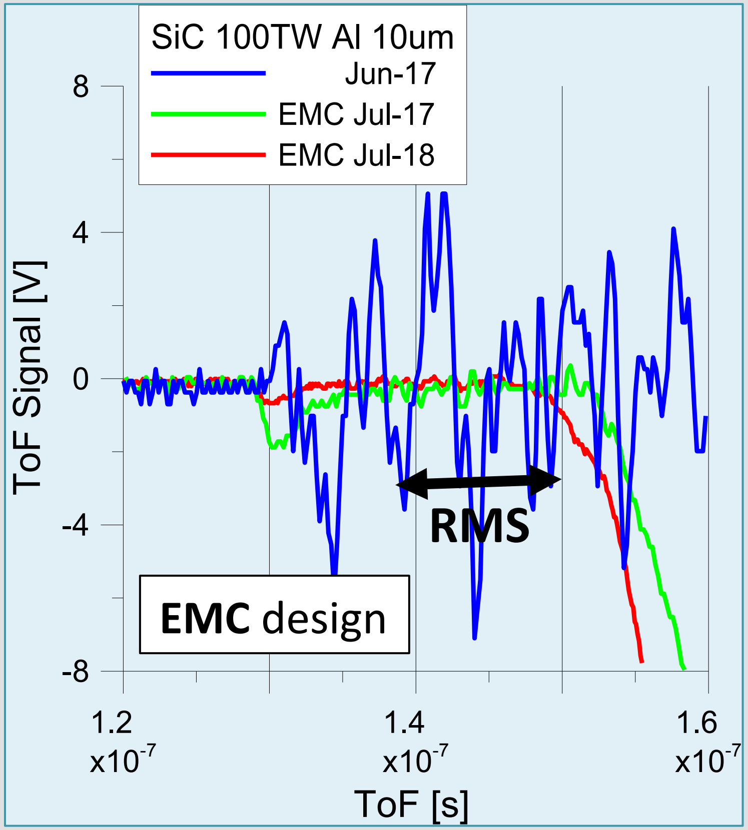
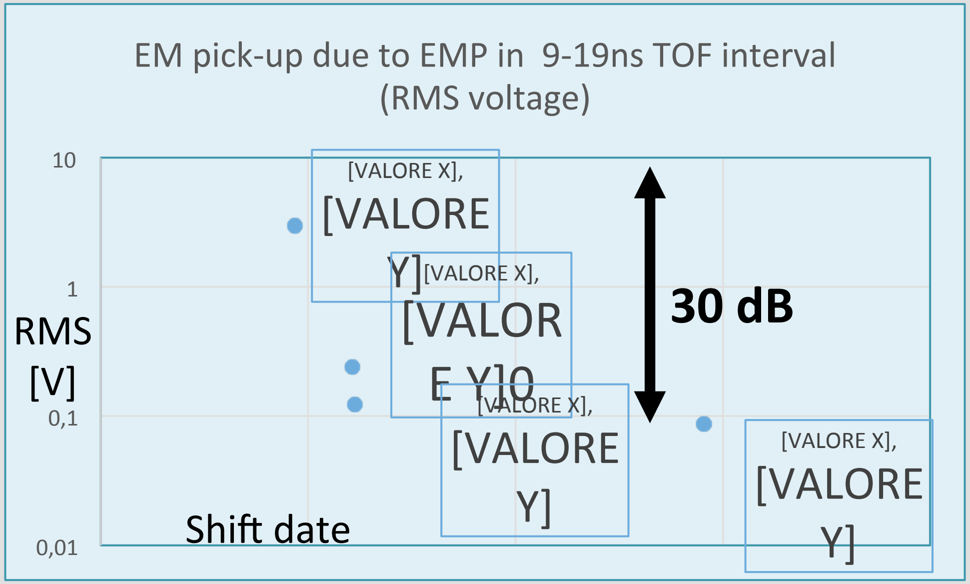
Time of Flight Detectors

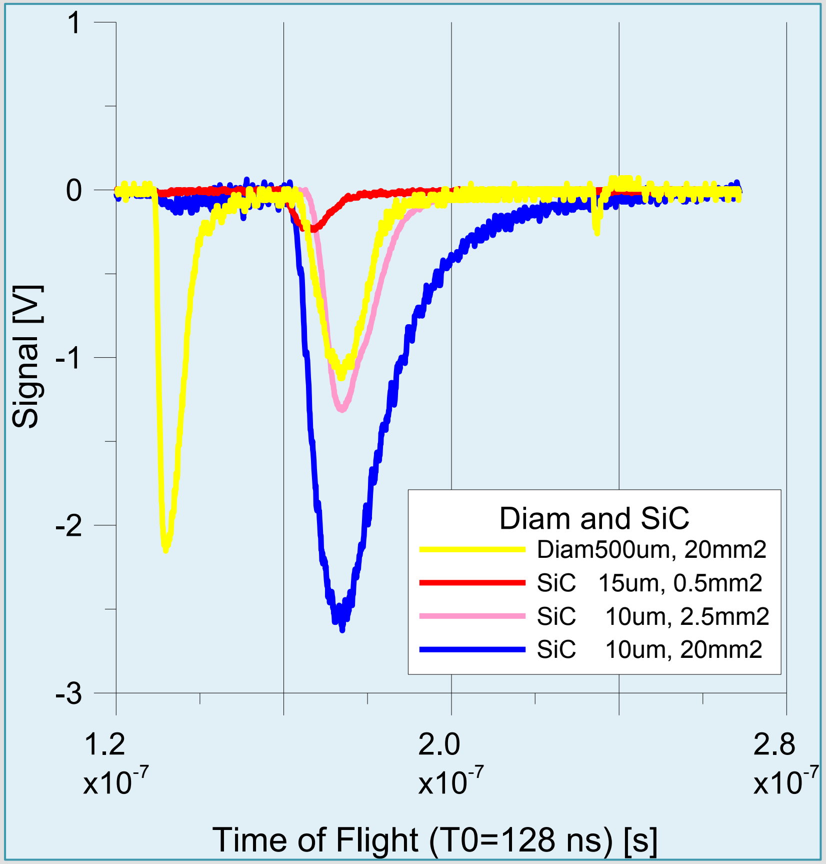




Noise rejection improvement of 30 dB

Time of Flight

Detector current



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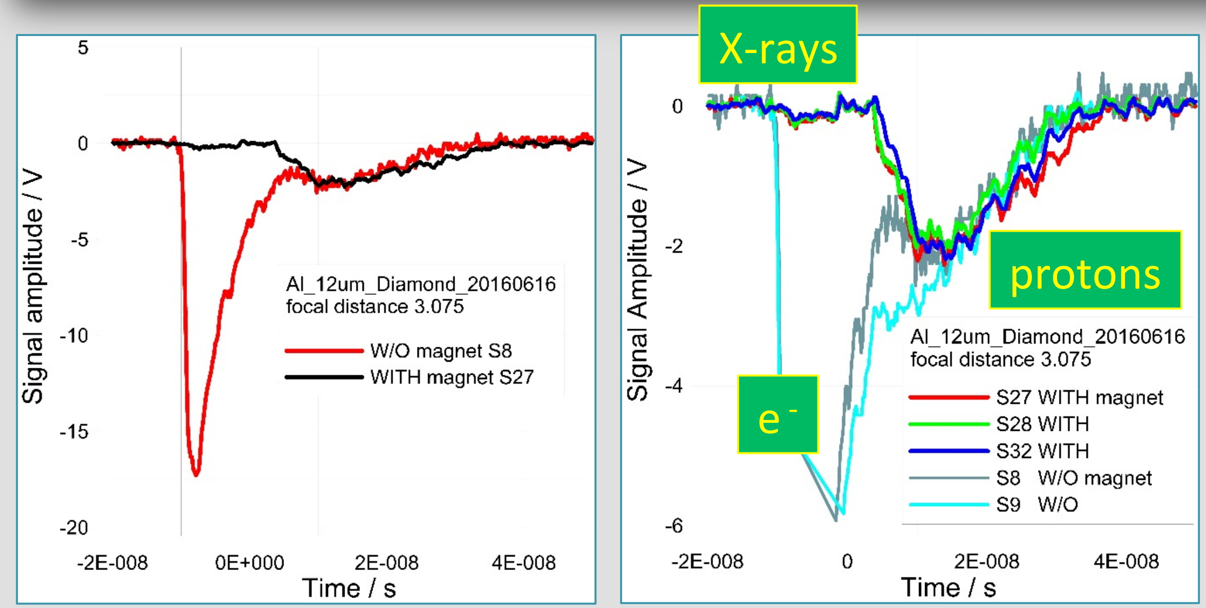
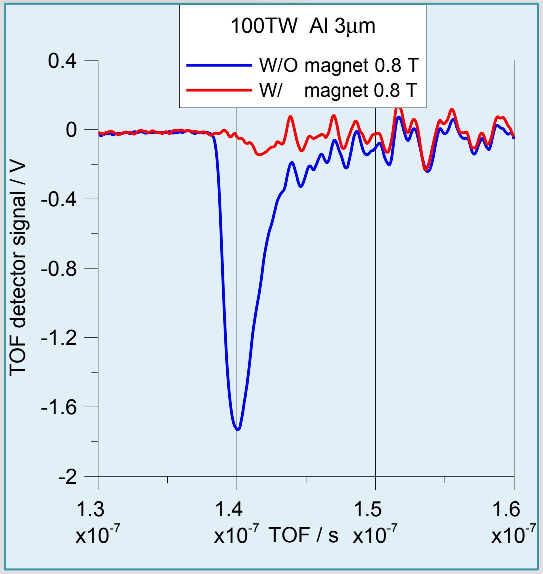
Time of flight



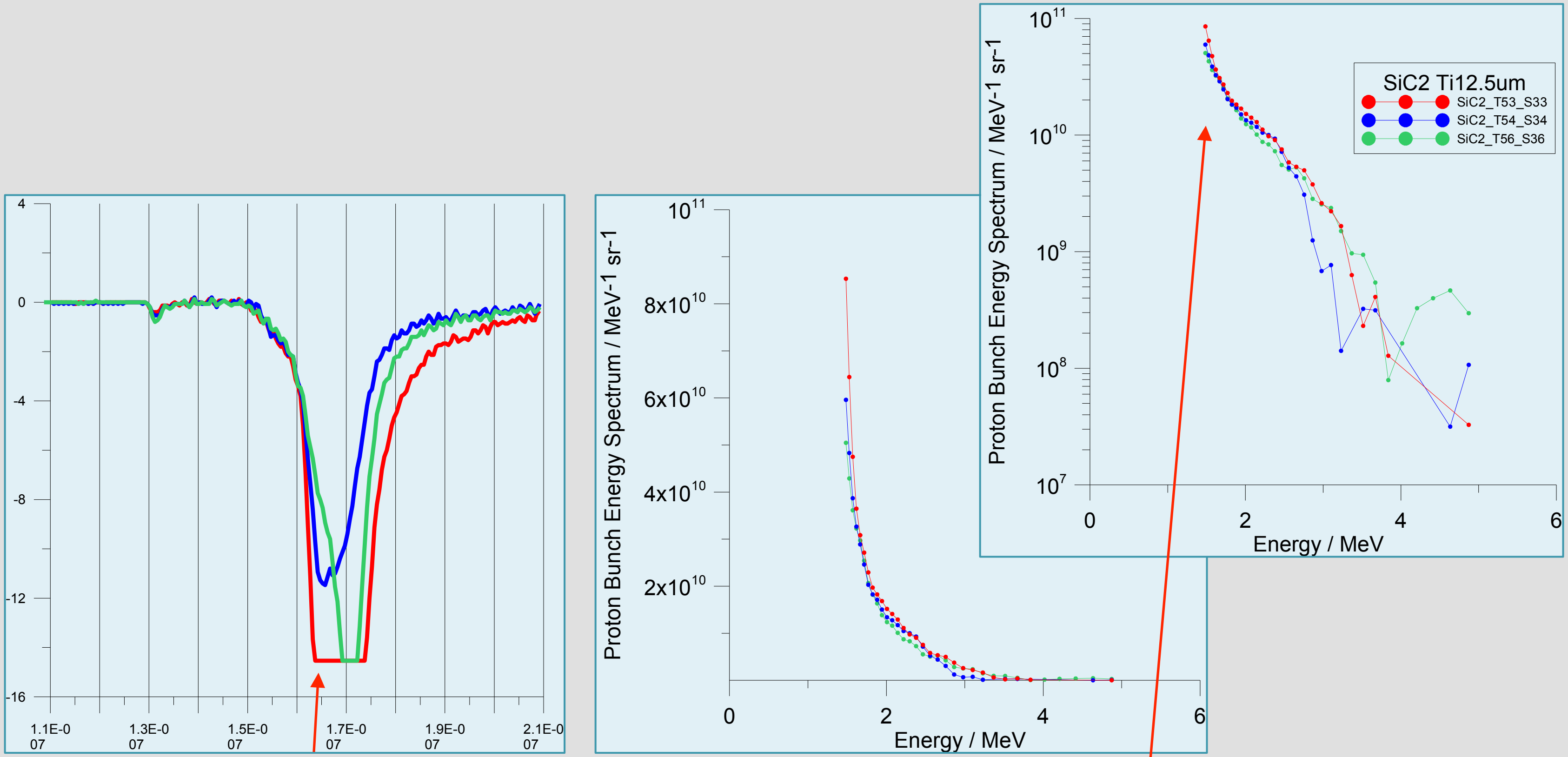
2016, SCDiamond, 60ns FS



2018, SiC, 30ns FS

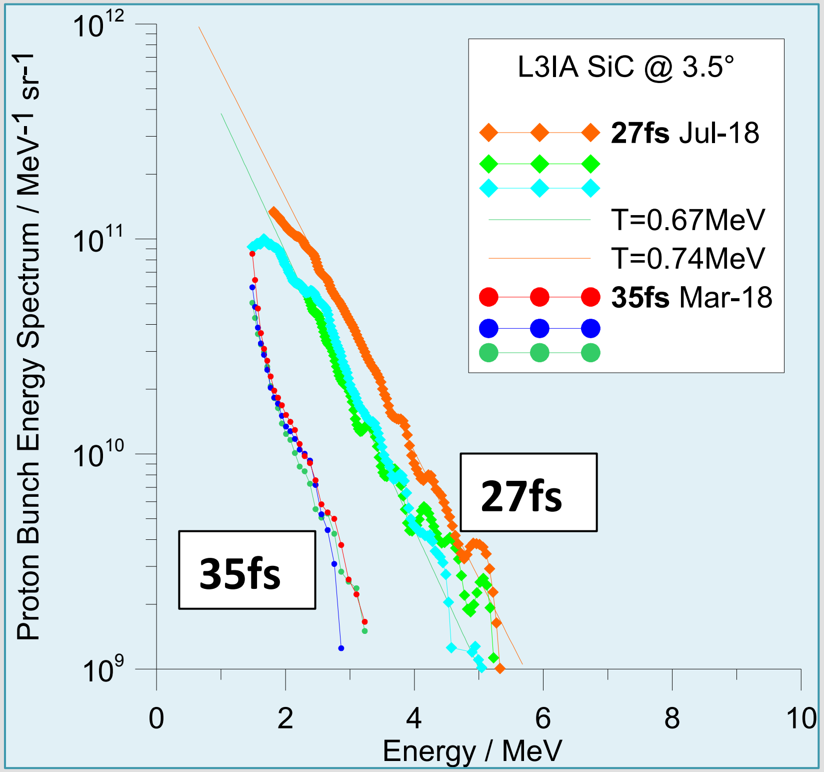
The prompt peak seems dominated (!) by electrons with a small contributions from X rays (and perhaps secondary electrons)

Time of flight



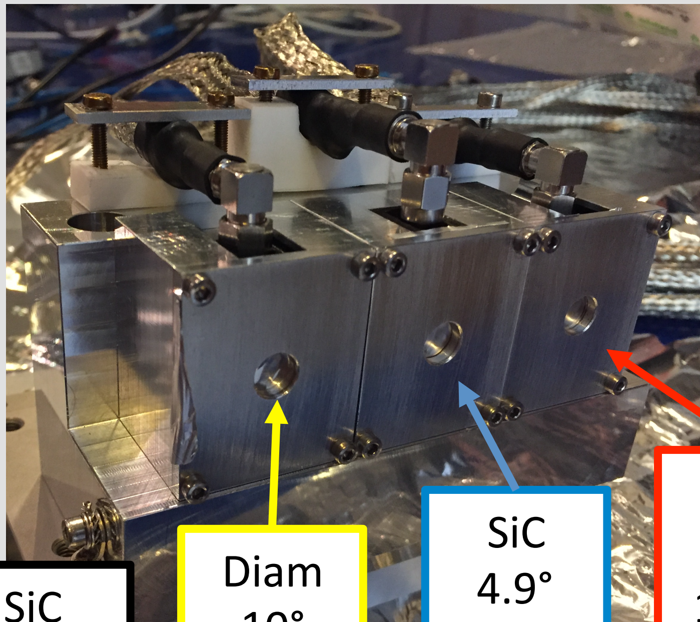
Saturation at 37.2ns   Minimum energy 1.37MeV

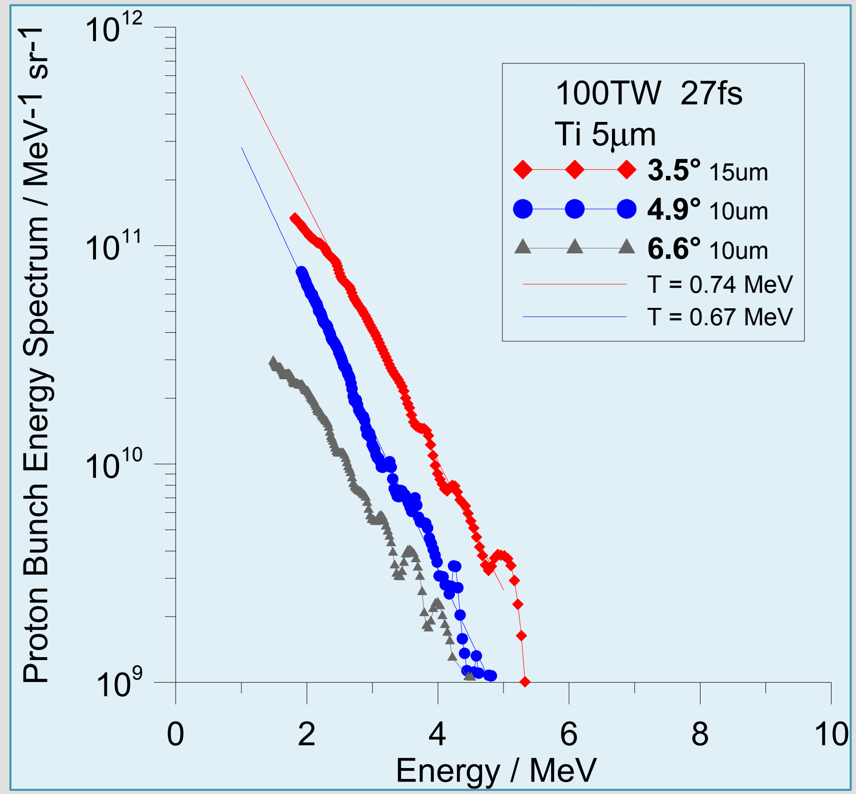
Time of flight



Laser Pulse shortening

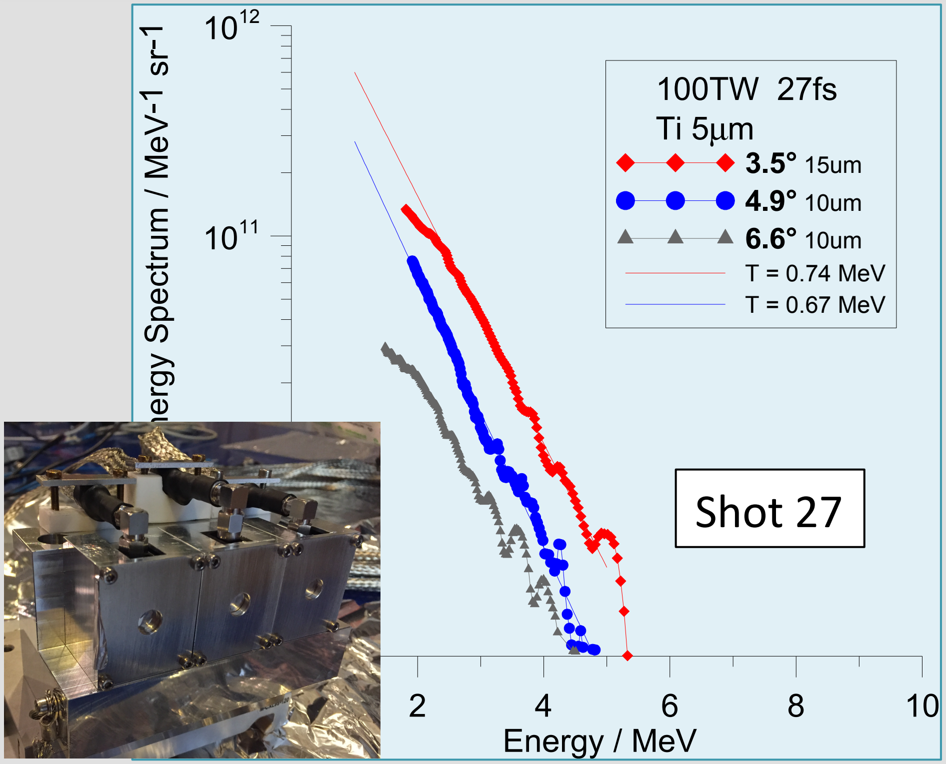
Time of flight

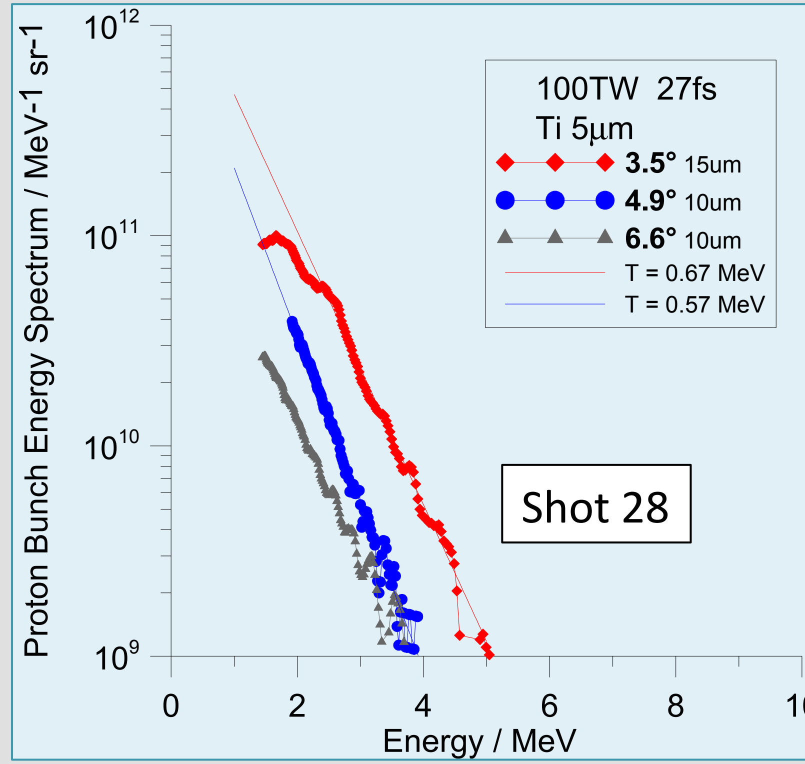




Angular dependance of the proton energy spectrum

Time of flight





Angular dependance of the proton energy spectrum

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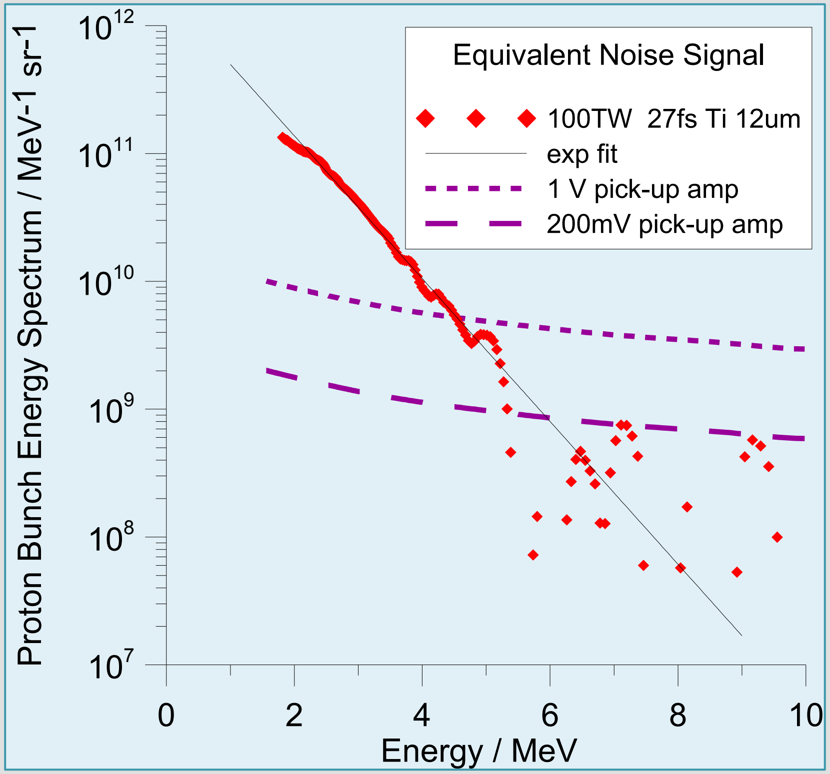
Time of Flight

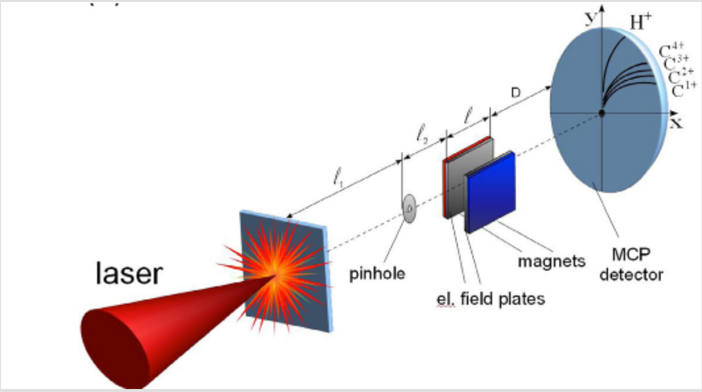


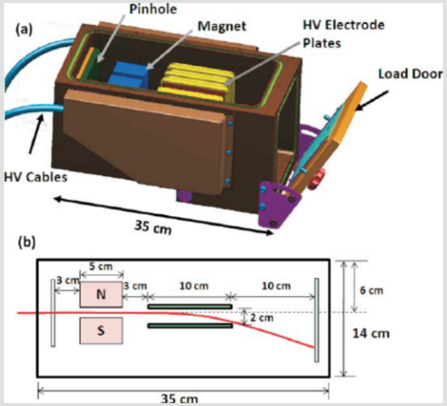
Thomson spectrometer

One of the most interesting detectors in the characterization of charged particles produced by laser-target interaction is the Thomson spectrometer.

Information on **energy**, **momentum** and **charge to mass ratio** of particle beams can be provided by a Thomson Parabola spectrometer, widely used to study ion sources such as ion accelerators, laser produced plasma, etc. In such a device charged particle are deflected by parallel electric and magnetic fields.

The electric deflection depends on the energy of particles while the magnetic ones depends on their momentum; moreover particle with different charge to mass ratio are deflected on different trajectories.
Its principle of operation is based on the Lorentz force and, in particular, the use of electric and magnetic fields that deflect the particles.





Thomson spectrometer

The Lorentz force can describe the motion particle:

$$F = q(E + v \wedge B)$$

Assuming that both fields are uniform over a length L and zero outside. Since the fields are parallel, the deflections are orthogonal each other and the deflections are proportional to deflection angle by means of the drift length between the electromagnetic device and the detector plane D.

Thus assuming that the magnetic field deflects on x axis and the electric field deflects on y axis, from the above equations one gets:

$y = qElD/ 2Tkin$ $\qquad$ $x = qBlD/(2mT)^{0.5}$

where q, m e T are respectively the charge particles, the mass and the kinectic energy ions.

Solving the second equation for v and replacing it in the first one we get the parabolic equation:

$$x^2 = (q\, B^2 lD/mE)y$$

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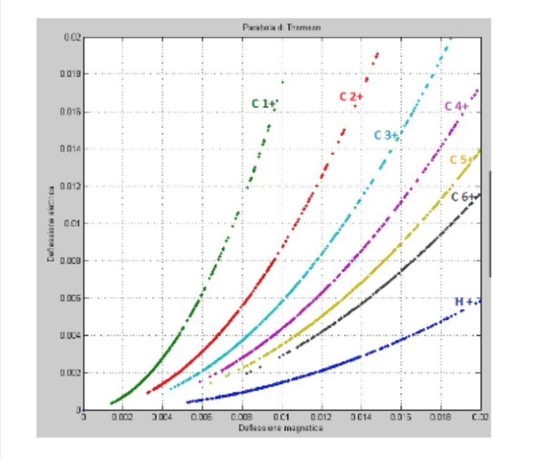
Thomson spectrometer

$$x^2 = (q\,B^2 lD/mE)y$$

which means that particles with the same charge-to-mass ratio and different energies are deflected on a parabolic trace on the detector plane.

The previous equation shows that a TP provides a separation of all ion species and charge state according to their q/m. Every single parabola on the detector belongs to a different ion charge-to-mass state ratio.

Thus knowing the charge-to- mass ratio and the charge state it is possible to get the ion mass and to identify the ion species



Simulation of a particle beam laser product of the interaction with a target of CH2

Thomson parabola

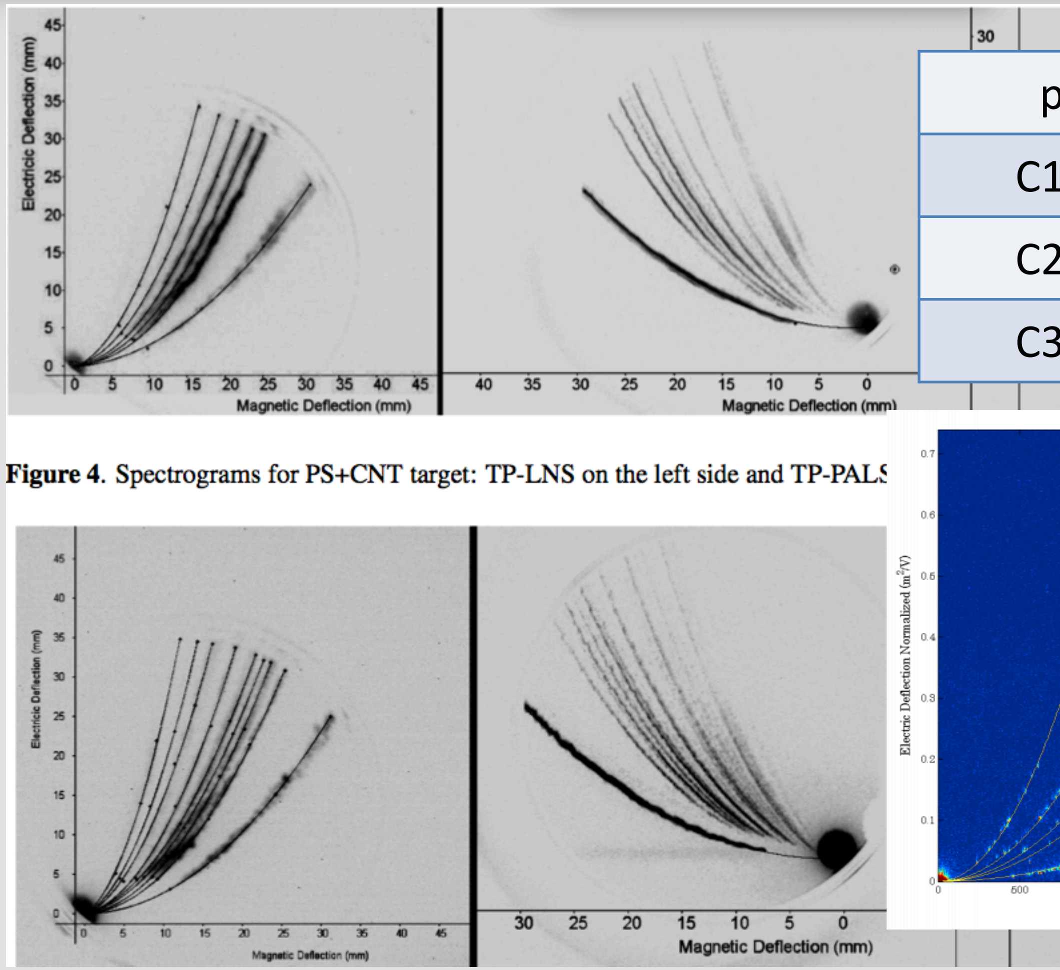
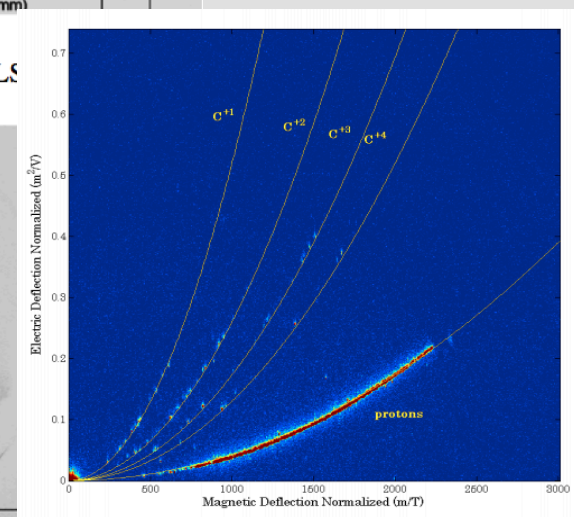


Figure 4. Spectrograms for PS+CNT target: TP-LNS on the left side and TP-PALS

p	1,55 MeV
C1+	1.05 MeV
C2+	1.09 MeV
C3+	1.17 MeV



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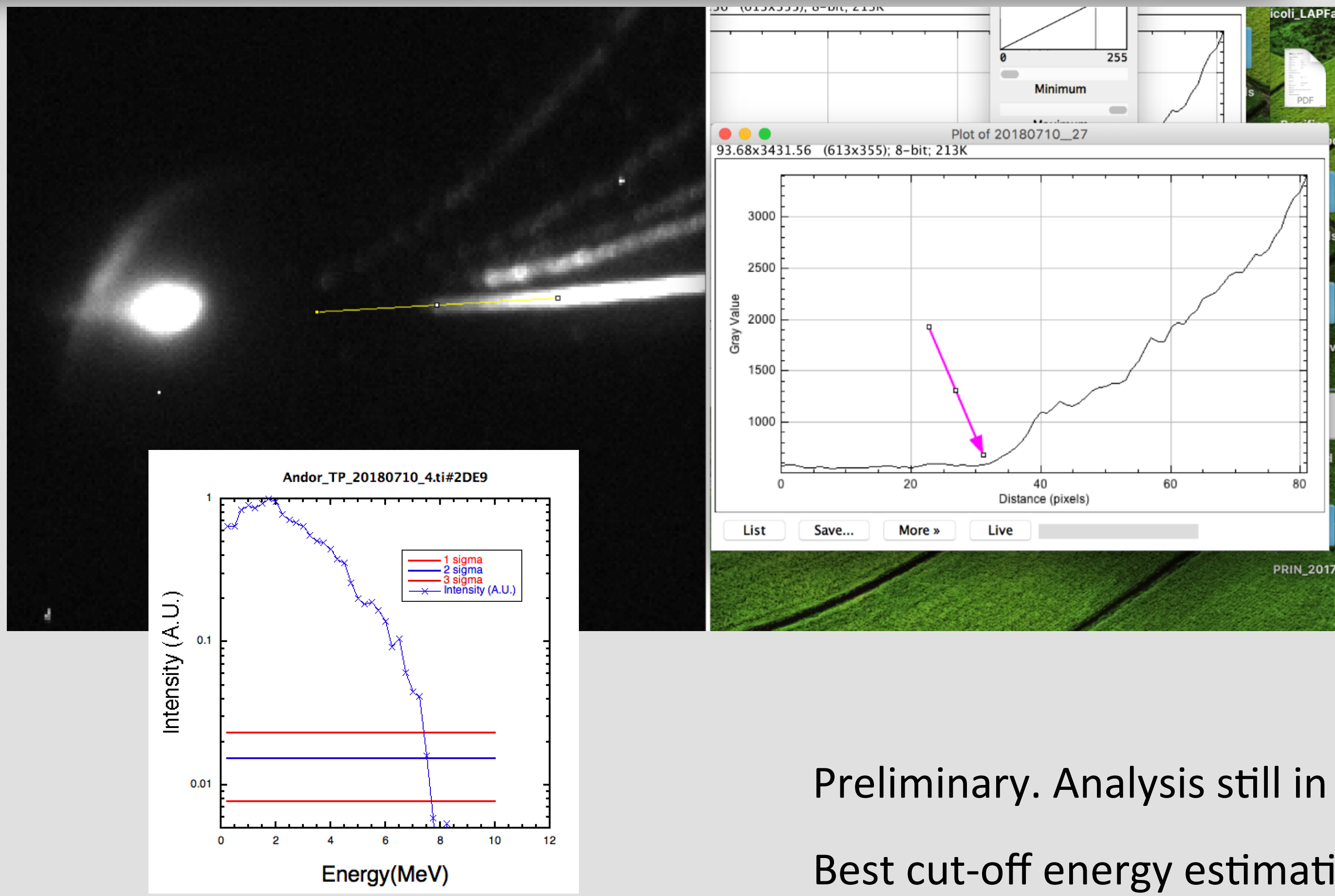
Thomson parabola in L3IA



Preliminary. Analysis still in progress.

Best cut-off energy estimation

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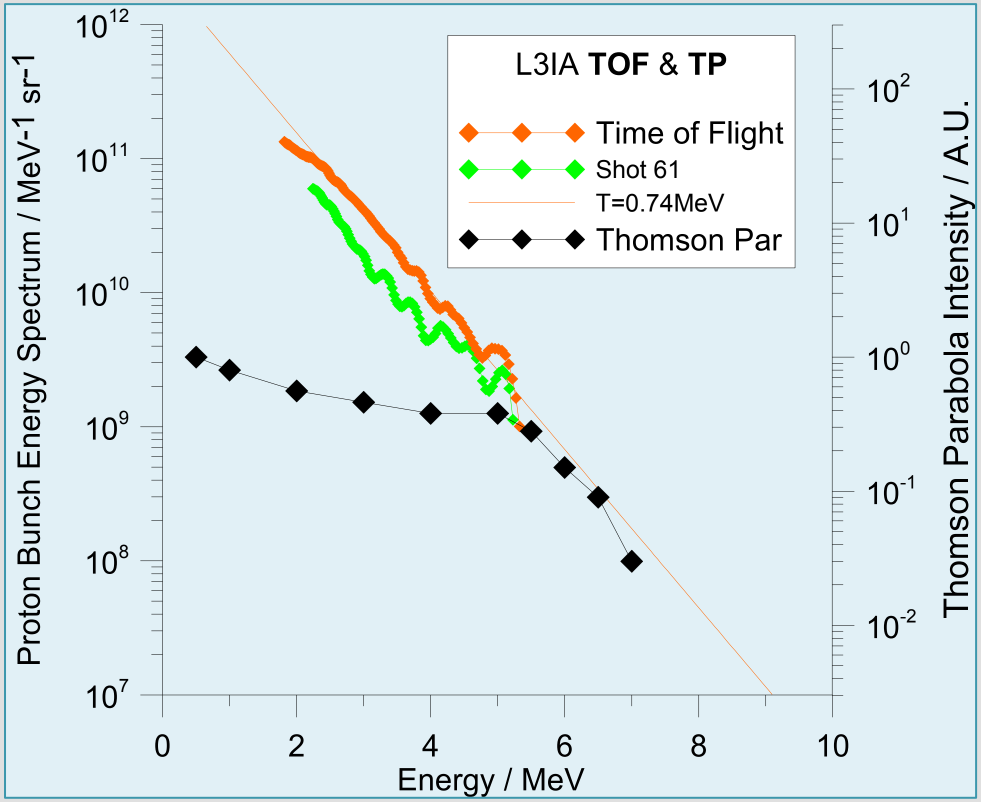
Thomson parabola 'and' TOF



L3IA TP extends the dynamic range more than 1 decade

For E<5MeV PT response is linear and the particle spectrum joints.

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Conclusion

In this talk I described the status and the results of a long time work about detectors and related signal transport and analysis chains.

The experience we gained in such an activity is valuable and we may state that it represents a safe and solid solution for any experiment nvolved in laser beam acceleration.

Nevertheless since the physics is still in a rapid evolution we are evolving our activities too.

Stay tuned (and we wait for you in our labs) !