TIME-OF-FLIGHT (TOF) DIAMOND DETECTORS FOR HIGH-INTENSITY LASER PLASMA EXPERIMENTS

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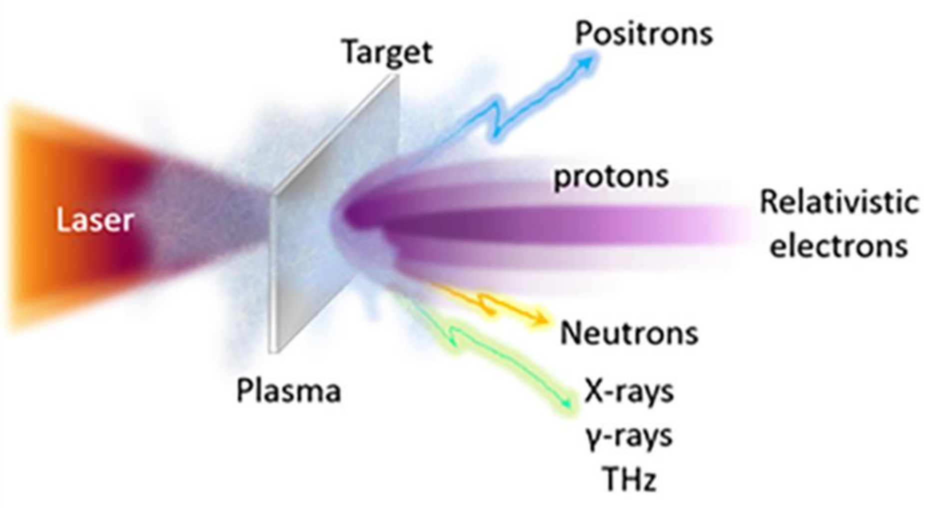
ION DIAGNOSTICS IN LASER-PLASMA EXPERIMENTS



Laser-generated plasma emission:

- Photons
- Electrons
- Protons
- Multi ion species
- Neutrons
- Electromagnetic pulse (EMP)

- The challenge of particle detection in laser-matter experiments arises from the large number of particles of different types and varying energies, all produced within a very short time interval.
- Additional challenges arise from the harsh environment.
- Experimental setups generally incorporate a combination of complementary devices featuring various detection principles.

The ideal diagnostic system should have:

- High sensitivity
- High energy resolution

and should allow to retrieve:

- Spectrum of accelerated ions
- Angular distribution of accelerated ions
- Particle discrimination

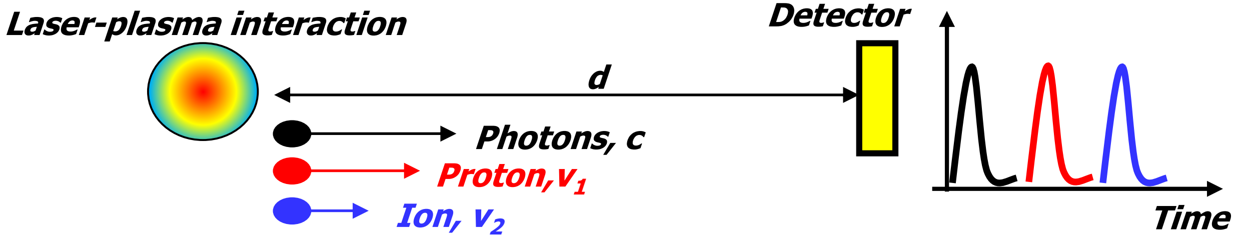
but it also has to provide:

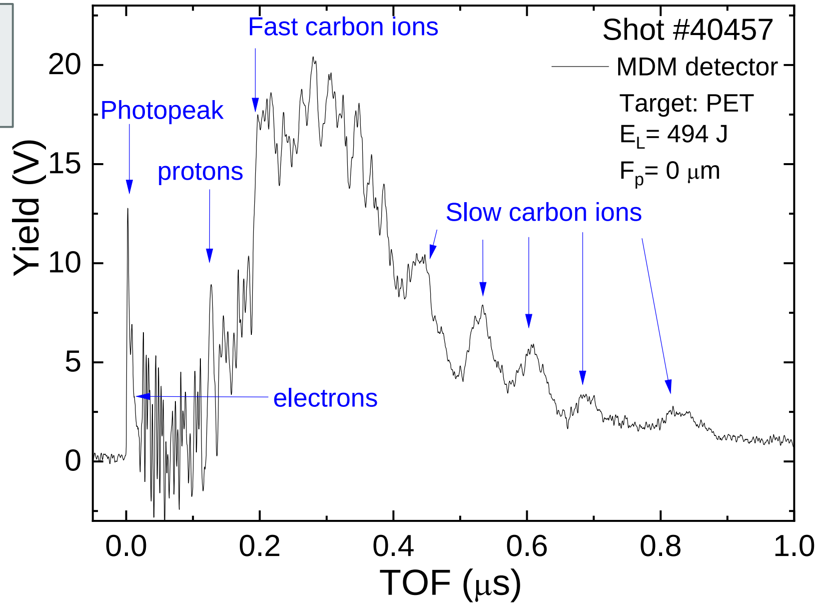
- Electro Magnetic Pulses (EMPs) robustness
- Real-time detection (in particular for high repetition rate lase)

TIME OF FLIGHT (TOF) TECHNIQUE

- Time-Of-Flight (TOF) method is very effective to detect in "real time" electrons, protons and ions accelerated in laser-plasma interactions.

TOF technique relies on the measurement of the time needed by a particle to travel for a known distance *d*





The temporal position T_0 of the photopeak provides a reliable signature of the laser-matter interaction instant. Particle energies are computed evaluating the delay between the signal detection time and t_0.

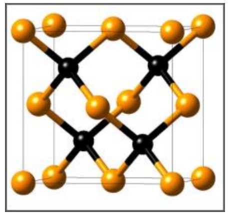
$$t_0 = T_0 - \frac{d}{c} \rightarrow \Delta T = t_i - t_0 \rightarrow v_i = \frac{d}{\Delta T}$$

If the ion mass, *m*, is known, its energy *E* can be retrieved

$$E = m(\gamma - 1)c^2$$

TIME OF FLIGHT (TOF) DETECTOR MATERIALS

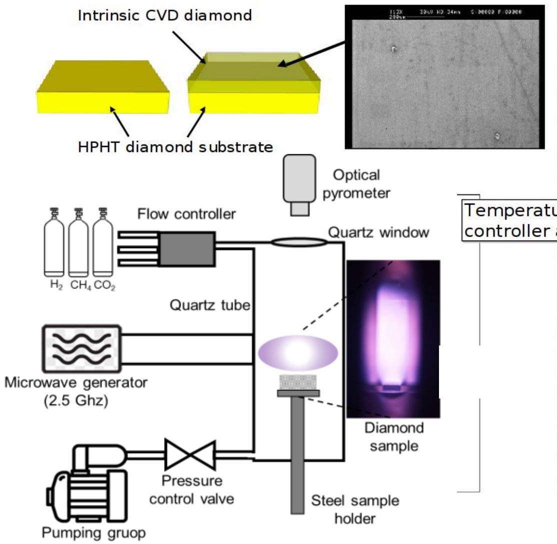
	Si	GaAs	4H-SiC	Diamond
Energy gap (eV)	1.12	1.43	3.26	5.47
Dielectric constant	11.9	12.3	9.7	5.7
Electron mobility (cm²/V·s)	1300-1500	8500	800-1000	1800-2200
Hole mobility (cm²/V·s)	800-1000	400	100-120	1200-1600
Thermal conductivity (W/m·K)	145	0.5	370	2290
Hardness (kg/mm²)	1000	750	3500	10000
Breakdown field (MV/cm)	0.3	0.5	3	>10
Density (g/cm³)	2.3	5.32	3.1	3.5
Atomic Number Z	14	32	10	6
e-h pair energy (eV)	3.6	4.2	7.8	13
Threshold displacement energy (eV)	13-20	32	25-45	40-50
Max working temperature (°C)	300	450	>1000	>1000

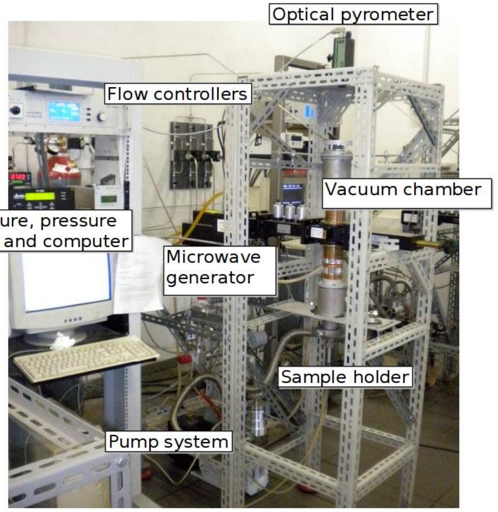


TOF diamond detectors are an ideal ion diagnostic:

- ✓ VISIBLE BLINDESS (wilde band gap) → Short and narrow photopeak (absolute reference of time measuraments)
- ✓ LOW DARK CURRENT (wilde band gap) → Good signal to noise ratio
- ✓ FAST RESPONSE TIME (high carrier mobility and low dielectric constact) → High energy resolution
- ✓ HIGH RADIATION HARDNEESS (high threshold displacement energy)

DIAMOND LAB AT TOR VERGATA UNIVERSITY





- Diamond film is deposited by Microwave Plasma Enhanced Chemical Vapour Deposition (MW-CVD).
- Three MW-CVD reactors (doping, production, research)
- Facilities for the end-to-end fabrication of diamond devices and microdevices

Research

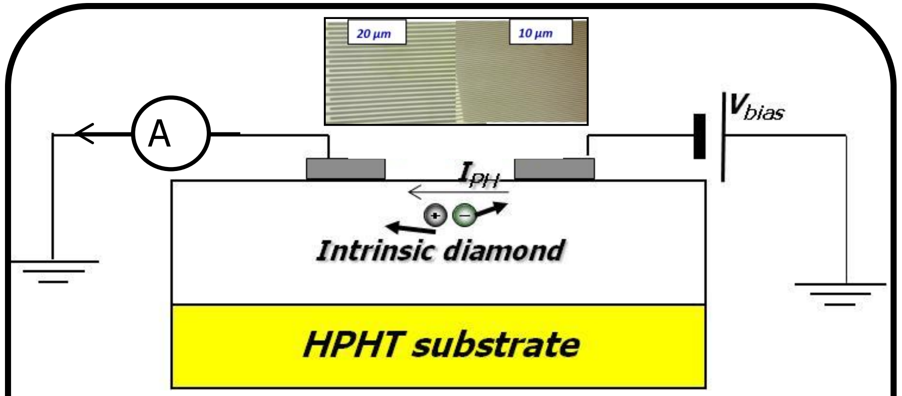
- Fusion diagnostics:
  - Soft X-ray detectors
  - Extreme UV
  - Neutron detectors
- Dosimetry and Microdosimetry
- TOF diagnostic for laser-matter interaction experiments
- High-power/high-frequency field effect transistors

Production of commercial devices

- Radiation therapy dosimetry (microDiamond, flashDiamond, PTW Freiburg, Germany)
- Diamond detectors for pulse-duration measurements of femto-second lasers (APE GmbH, Berlin, Germany)

SINGLE CRYSTAL DIAMOND DETECTORS

- The different electrodes and geometry layout allow to cover a wide range of requirements

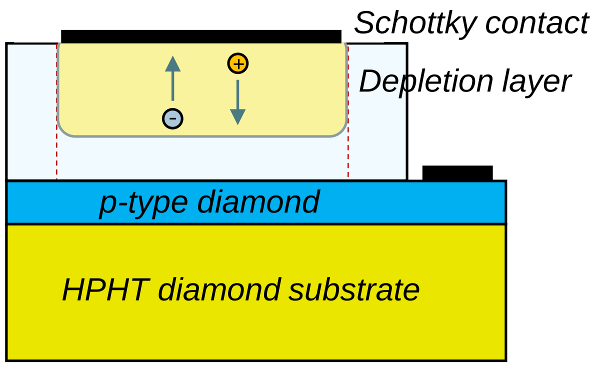


✓ *Diamond with interdigited contacts*

- *Detection at the surface*
- *Very fast response*
- *Optimal performance for EUV or very low penetrating particles*
- *No spectroscopic capability*

✓ *Metal-Diamond-Metal*

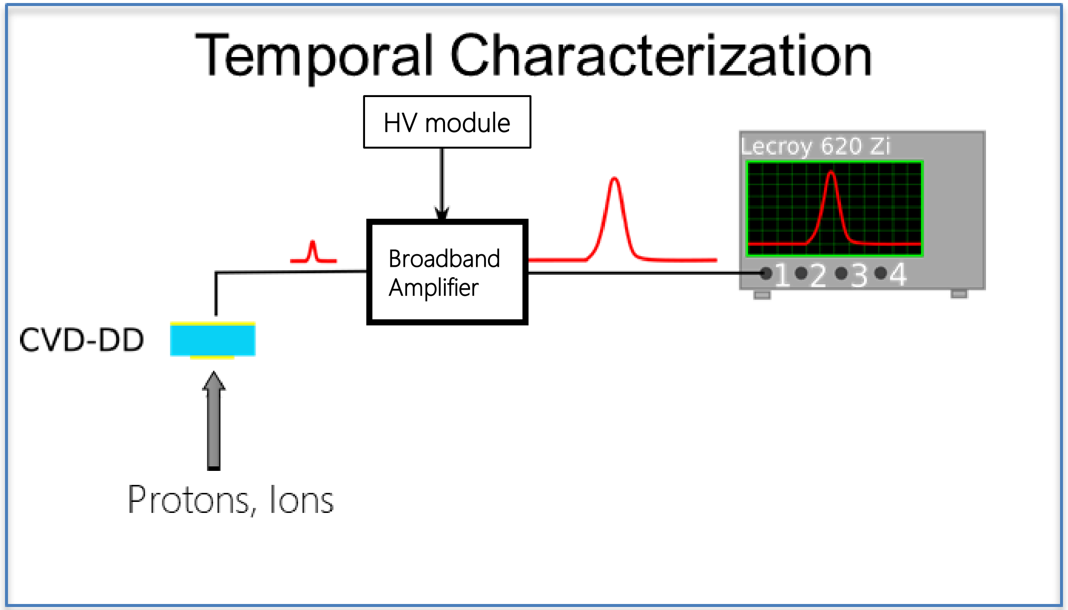
- *Thickness range 50 μm – 500 μm*
- *Response time and radiation hardness decrease as the thickness is increased*

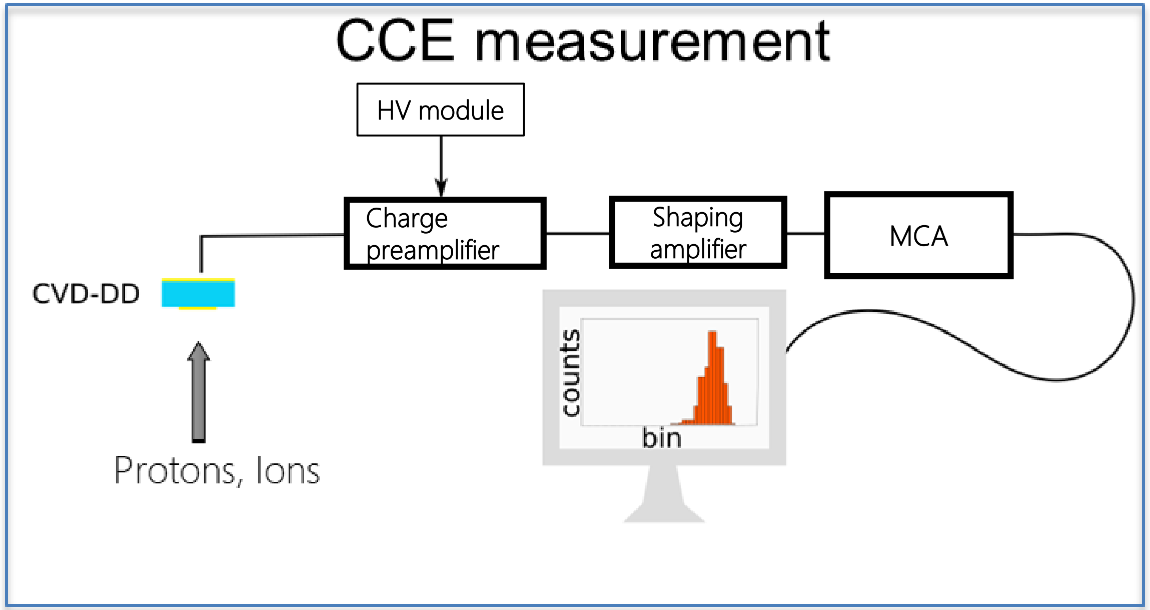


✓ *Diamond Schottky diode*

- *Sensitive volume thickness range 1 μm – 50 μm*
- *No need of applied voltage for thin detectors*
- *Very fast response and very high radiation tolerance (thin detectors)*

TOF DIAMOND DETECTOR CHARACTERIZATION






DBA IV (GAIN: 50 dB, Bandwidth: 2 GHz)

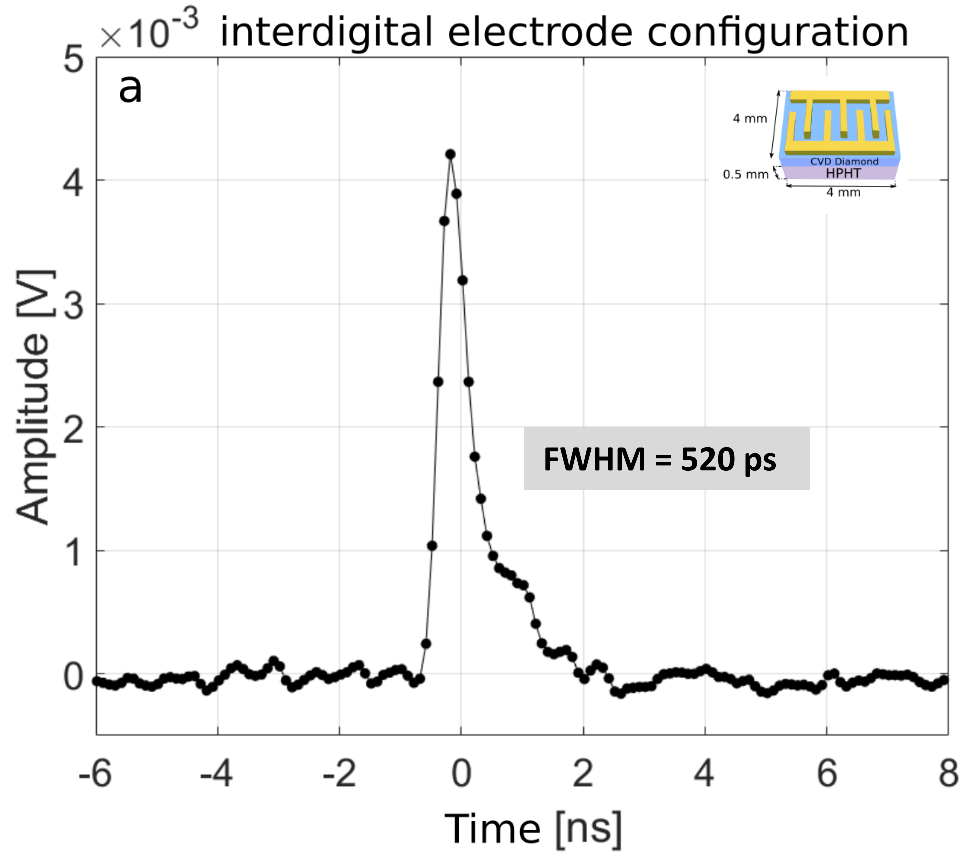

A1423B (GAIN: 18-54 dB, Bandwidth: 1.5 GHz)

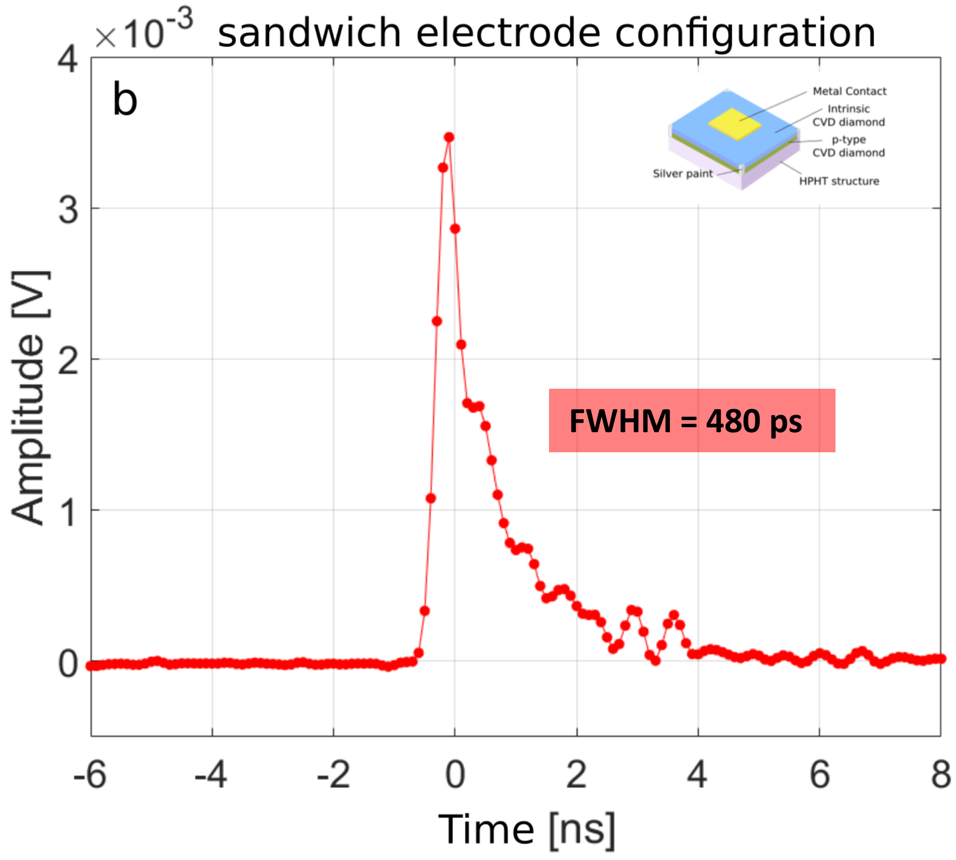
CIVIDEC (GAIN: 40 dB, Bandwidth: 2 GHz)

ORTEC 570 ORTEC 927

TOF DIAMOND DETECTOR CHARACTERIZATION

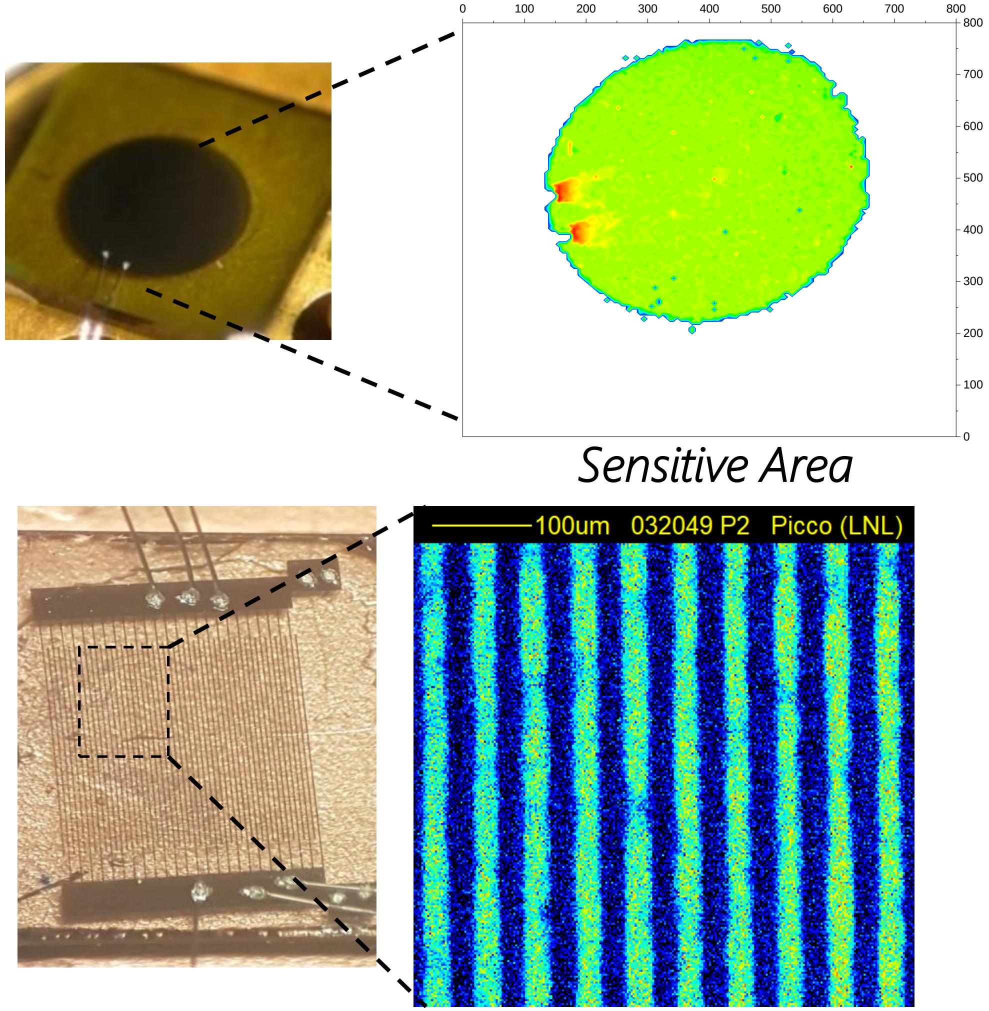
Temporal resolution



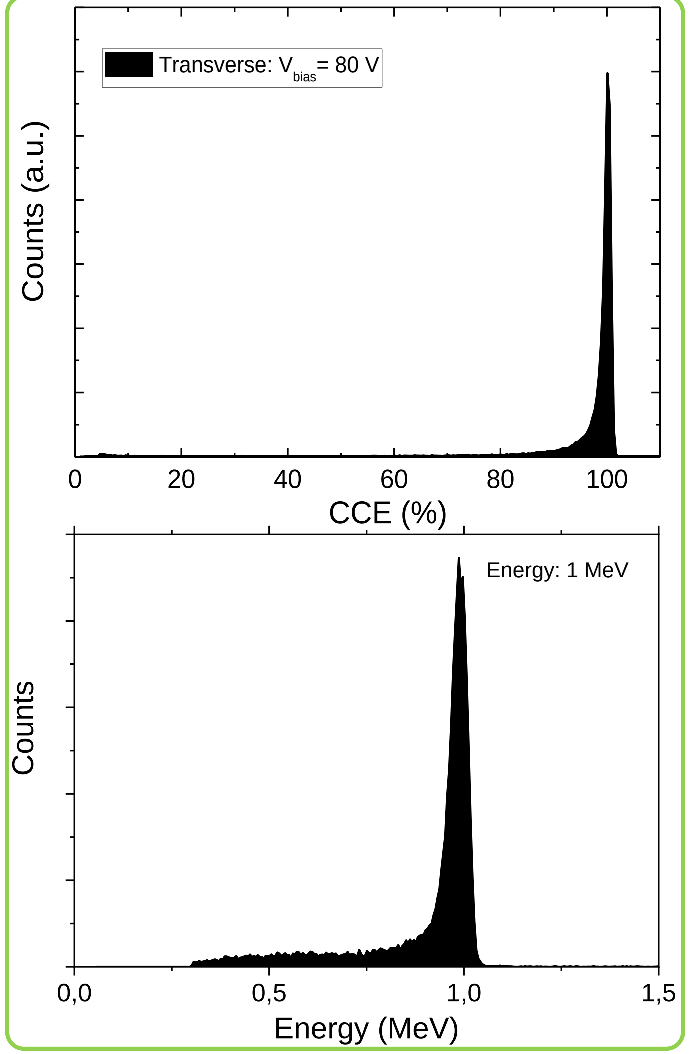


TOF DIAMOND DETECTOR CHARACTERIZATION

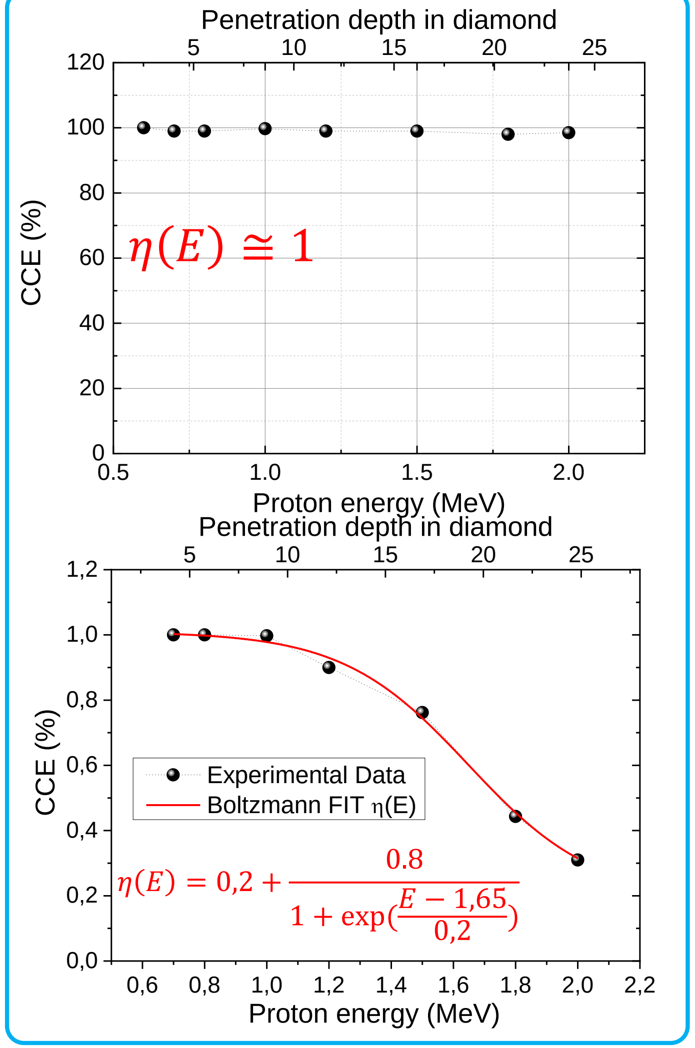
IBIC map@1 MeV H^+



Energy spectrum @1 MeV H^+

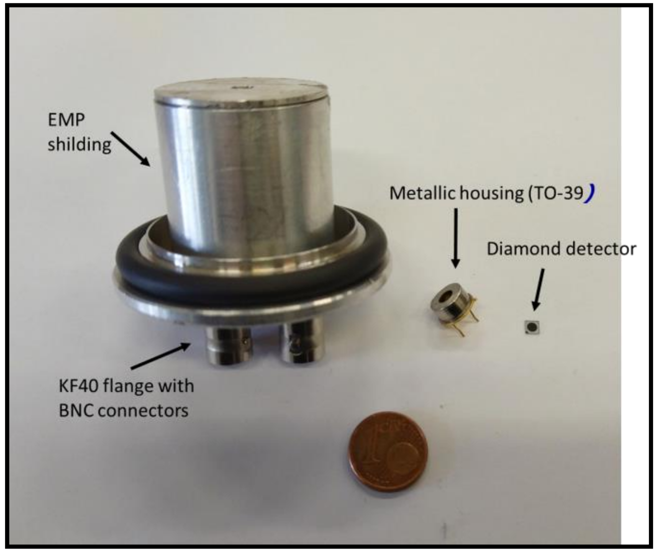


CCE as a function of proton energy



ACQUISITION SYSTEM OPTIMIZATION: EMP MITIGATION

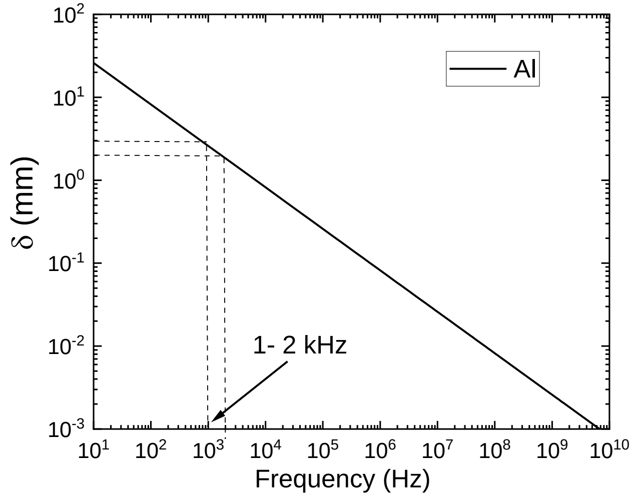
EMP reduction: TOF detectors are placed in a **proper Al shielding holder** having a pin-hole to collimate the radiation only on the detector sensitive area.

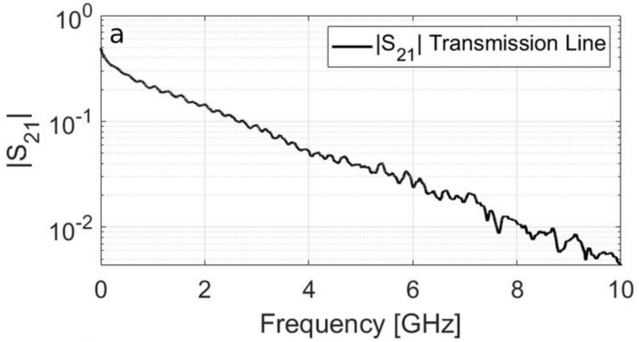


In order to minimize the EMP coupling with the acquisition system and increase the signal/noise ratio, **RG223 low noise, double-shielded coaxial cables** are used.

Skin effect: $J_s(z) \propto J_0 e^{-\frac{z}{\delta}}$ $\delta = \sqrt{\frac{1}{\pi f \sigma \mu}}$

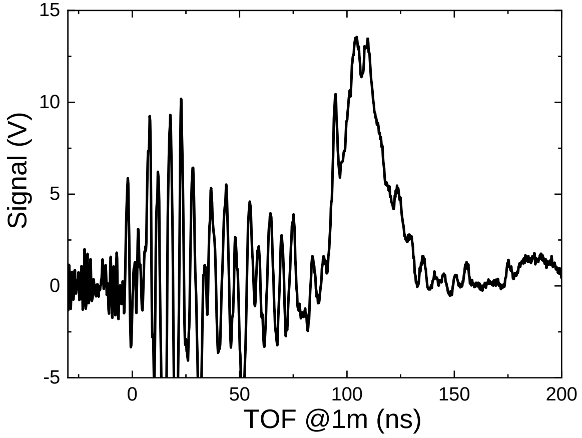
σ conductivity, μ permeability



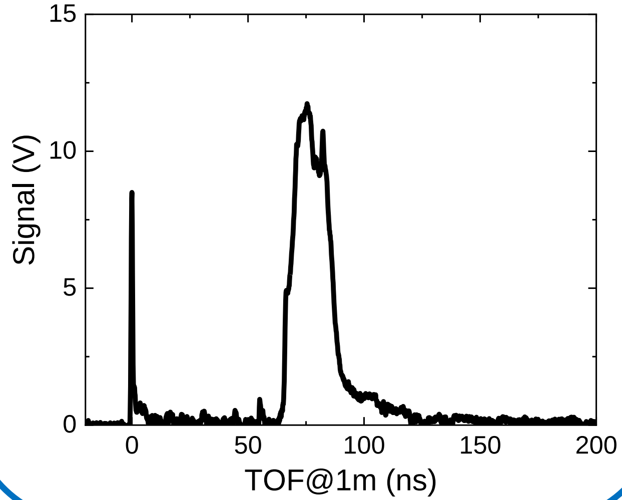


Double shielded coaxial cables and 3 mm Al thickness provide high frequency attenuation.

Before EMP optimization



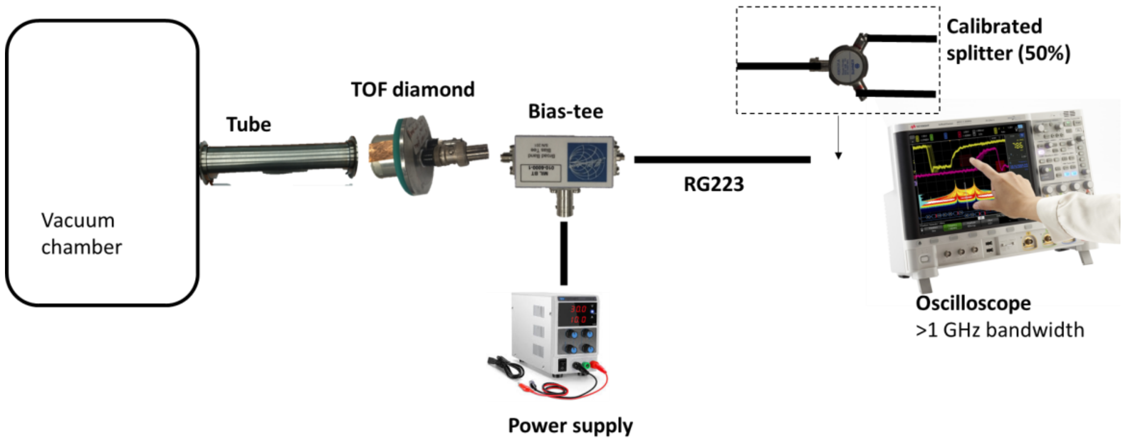
after EMP optimization

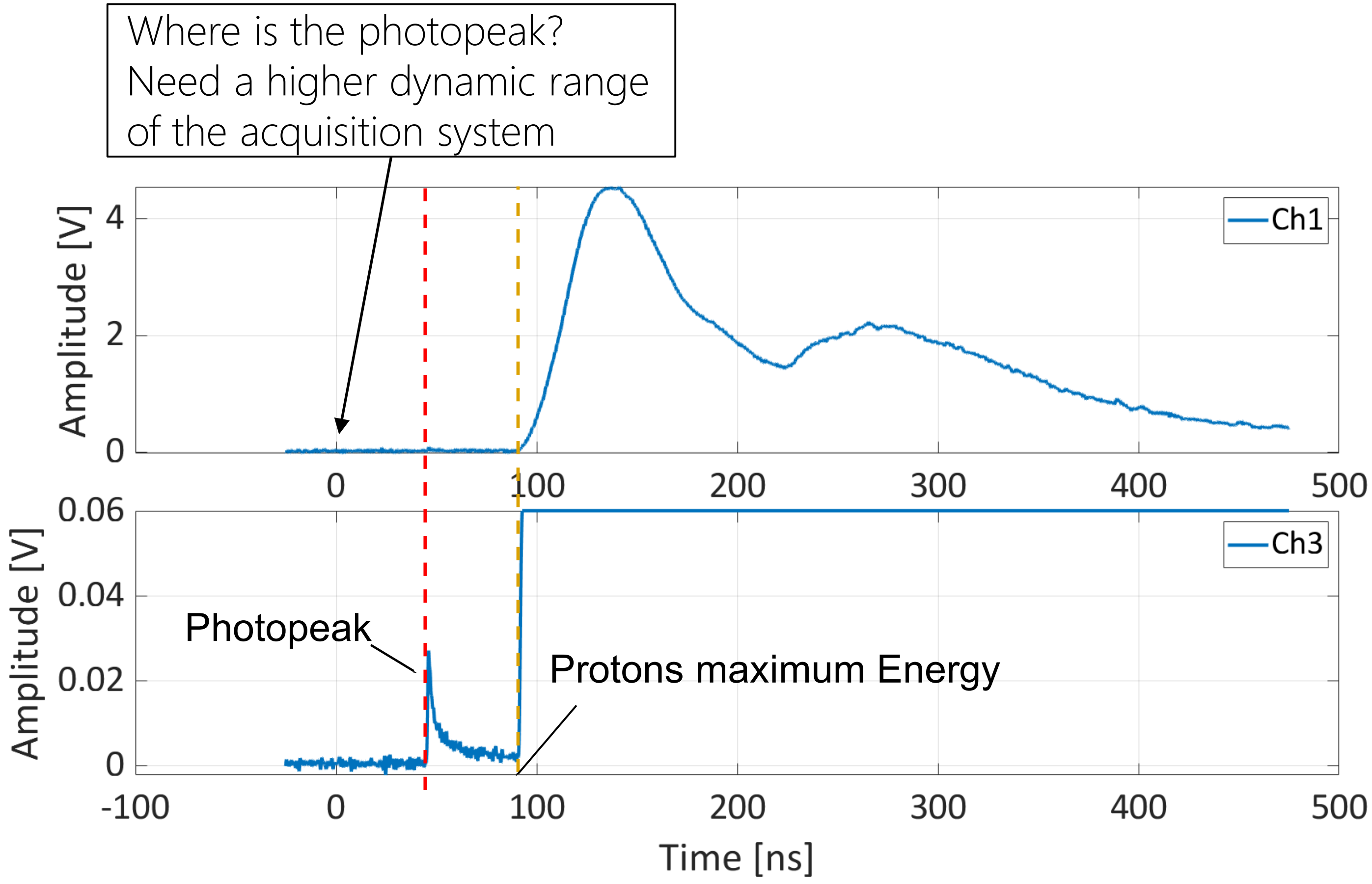


READ-OUT ELECTRONICS

- TOF detectors are connected to fast oscilloscope terminated in 50 Ω though commercial Bias-T.
- **Dynamic range enhancement:** the signal collected from the TOF detector is divided in two parts by a calibrated splitter, both having the same shape but half of the original amplitude. They are acquired by two different channels.

Read-out electronics





THE INGREDIENTS FOR THE SPECTRUM RECONSTRUCTION

PARTICLE SPECTRUM

01 SIGNAL ACQUISITION

1. Acquisition and diagnostic system optimization for EMP robustness
2. Enhanced dynamic range

02 ENERGY ESTIMATION

1. Measure the Time-Of-Flight of particles
2. Compute their velocity
3. Retrieve their energy

03 SPECTRUM COMPUTATION

1. Characterization of the Detector used for TOF measurements
2. The energy distribution for a given ion species can be reconstructed from the TOF signal

ANALYTICAL SPECTRUM COMPUTATION

Charge released in the detector by N impinging particles, being E the energy released by each particle, ϵ_{eh} the mean energy for an electron-hole pair creation and e the electron charge

$$Q = \frac{eNE}{\epsilon_{eh}}$$

Assuming that the particle stops in the detector (t is the time of flight)

$$E = E_{kin} = m(\gamma - 1)c^2 \cong \frac{1}{2}mv^2 = \frac{1}{2}m\frac{d^2}{t^2}$$

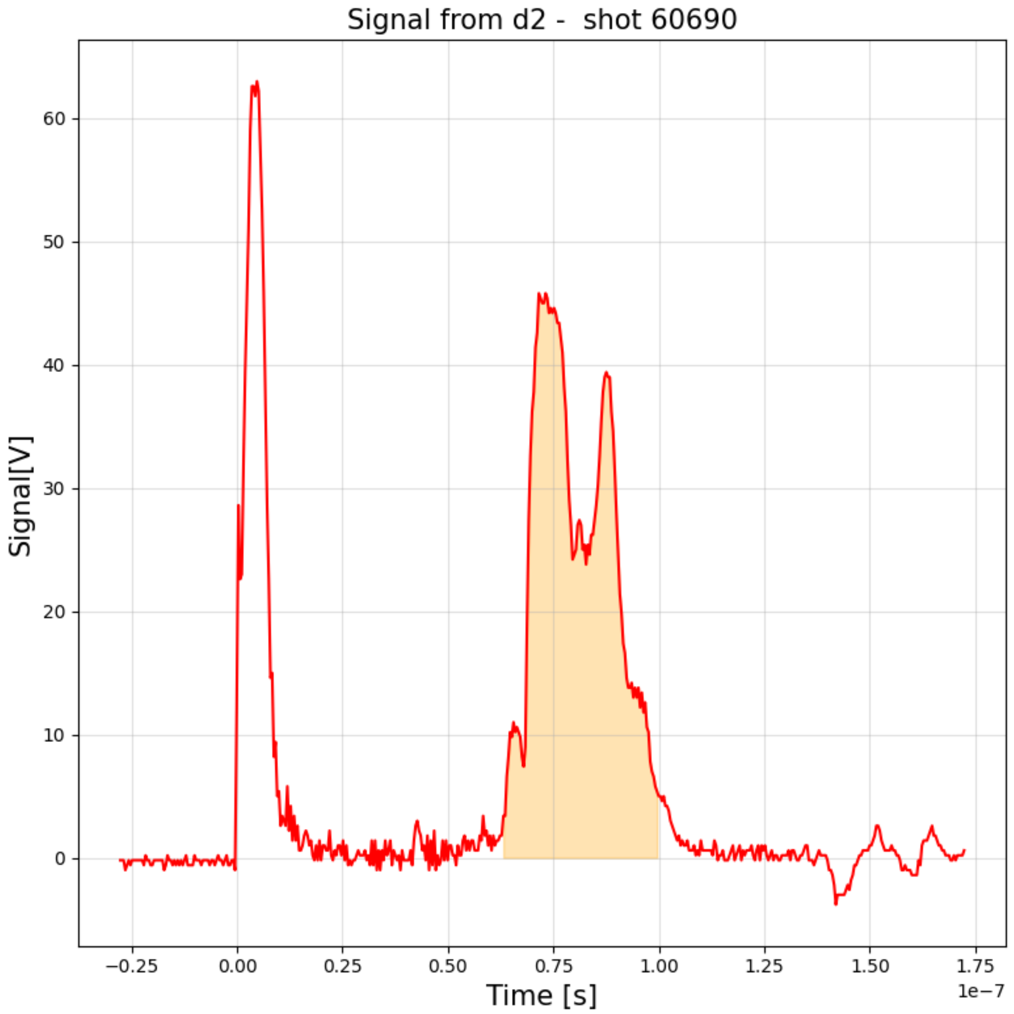
The energy spectrum for a bunch of identical particles generating in the detector a signal $i(t)$ can be finally obtained by:

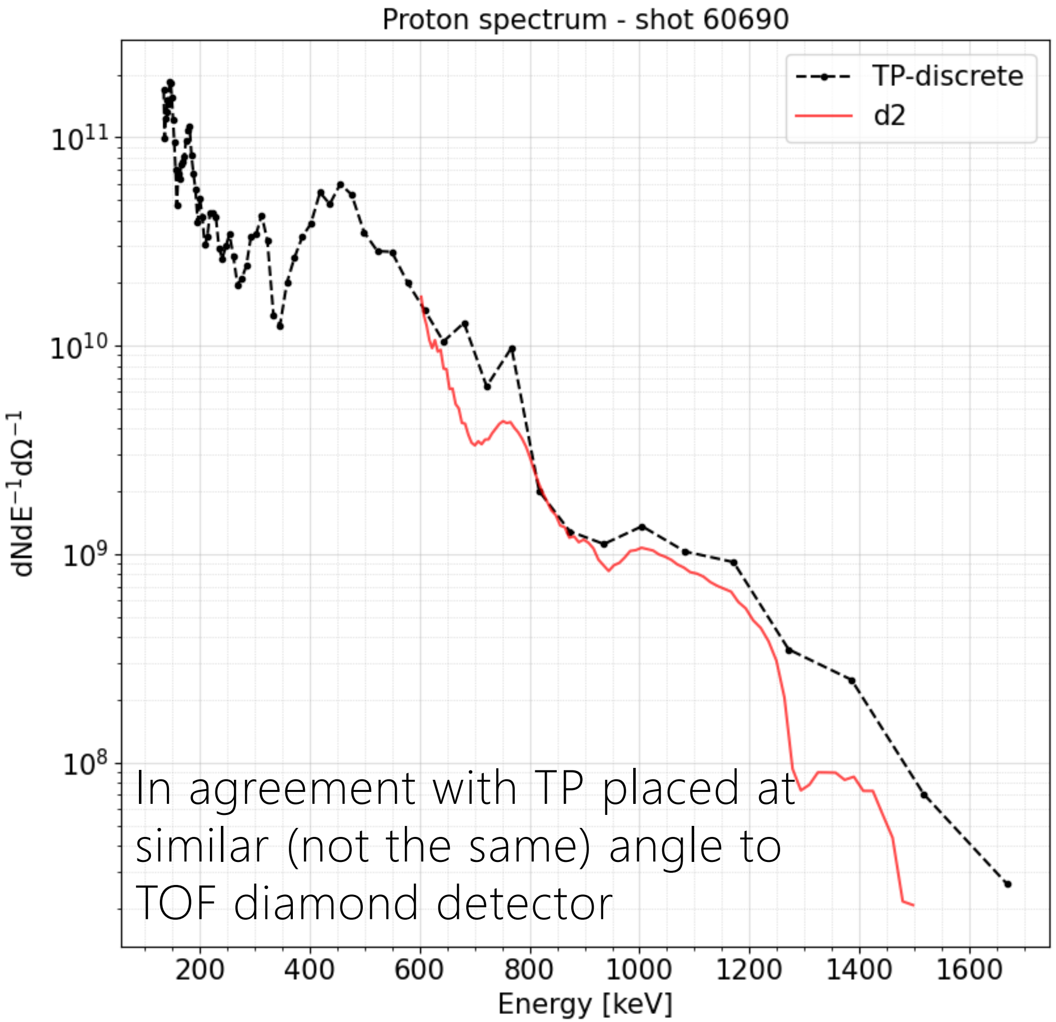
$$\frac{dN}{dE} = -\frac{\epsilon_{eh}i(t)t}{2eE^2}$$

The energy resolution is given by:

$$\frac{\Delta E}{E} = -2\frac{\Delta t}{t}$$

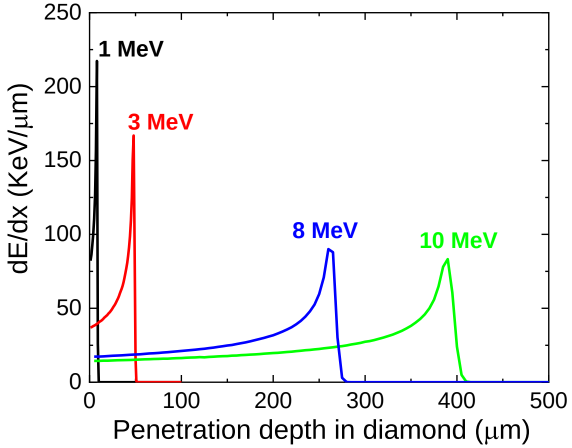
ANALYTICAL SPECTRUM COMPUTATION





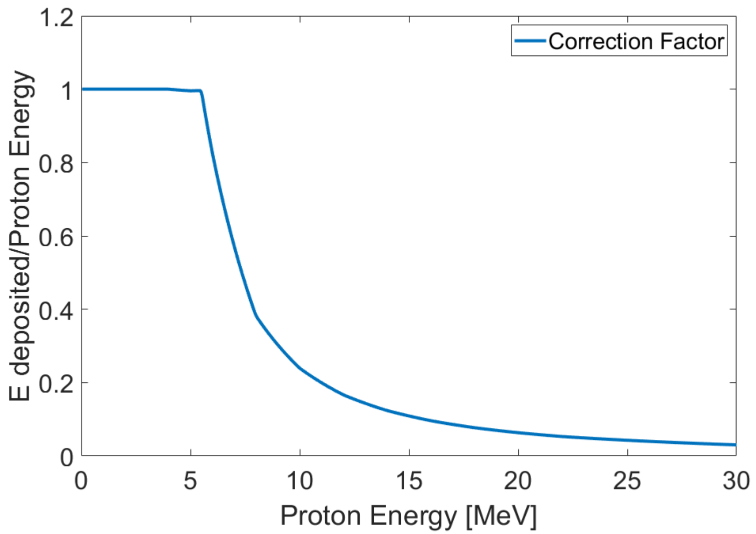
In agreement with TP placed at similar (not the same) angle to TOF diamond detector

TOF DIAMOND DETECTOR FOR HIGH ENERGY PROTONS



- Laser-accelerated protons having a range less or equal than the detector's active thickness release completely their energy.
- High energy particles (tens of MeV) cross the detector volume, releasing only a portion of their actual energy within it, and the generated charge decreases accordingly.
- The energy estimated through the TOF technique differs from the actual energy released in the detector by the particle.

- A correction function $\boldsymbol{\eta}(\boldsymbol{E})$ taking into account the energy fraction released in sensitive region of the detector can be calculated by Monte Carlo simulation.



⇒ The equation for obtaining the energy spectrum modifies as follows ⇒

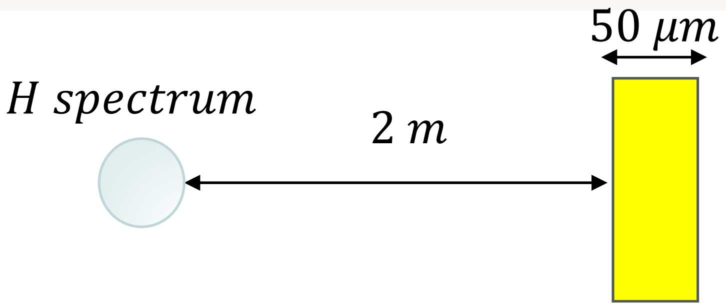
$$\frac{dN}{dE} = -\frac{\epsilon_{eh} i(t) t}{2e\eta(E)E^2}$$

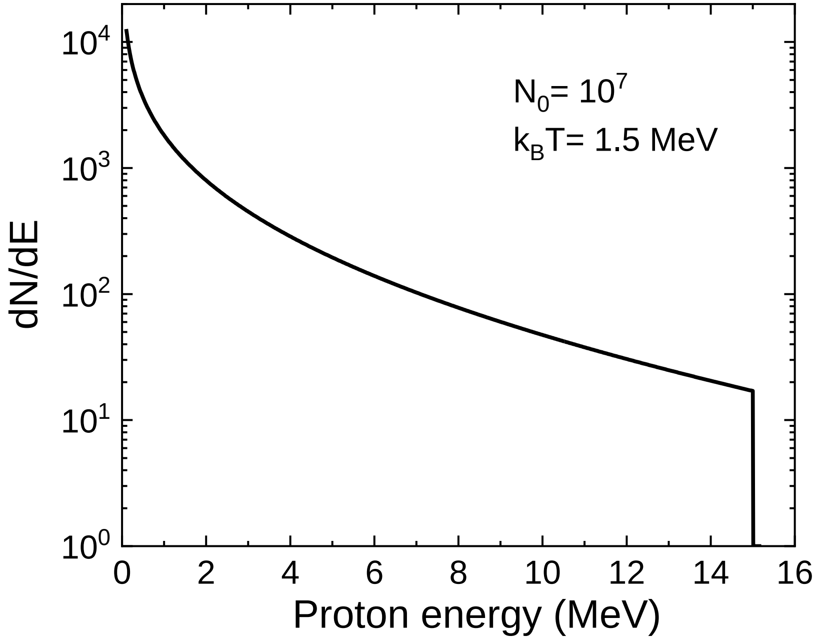
TOF DIAMOND DETECTOR FOR HIGH ENERGY PROTONS

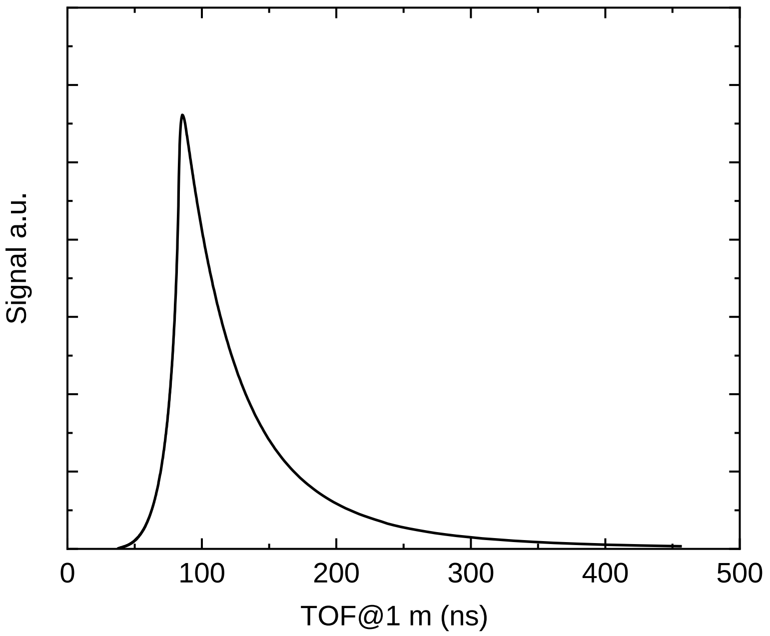
Protons accelerated by laser-plasma typically present a broad and Maxwellian-like spectrum

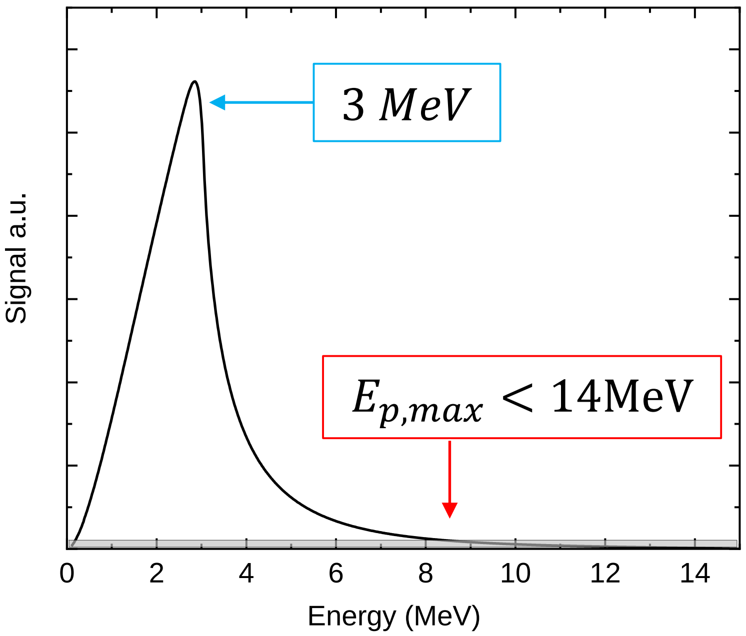
$$\frac{dN}{dE} = \frac{N_0}{\sqrt{2Ek_BT}} \exp\left(-\sqrt{\frac{2E}{k_BT}}\right)$$

N_0: Total particle yeald
k_B: Boltzmann constant
T: Plasma temperature



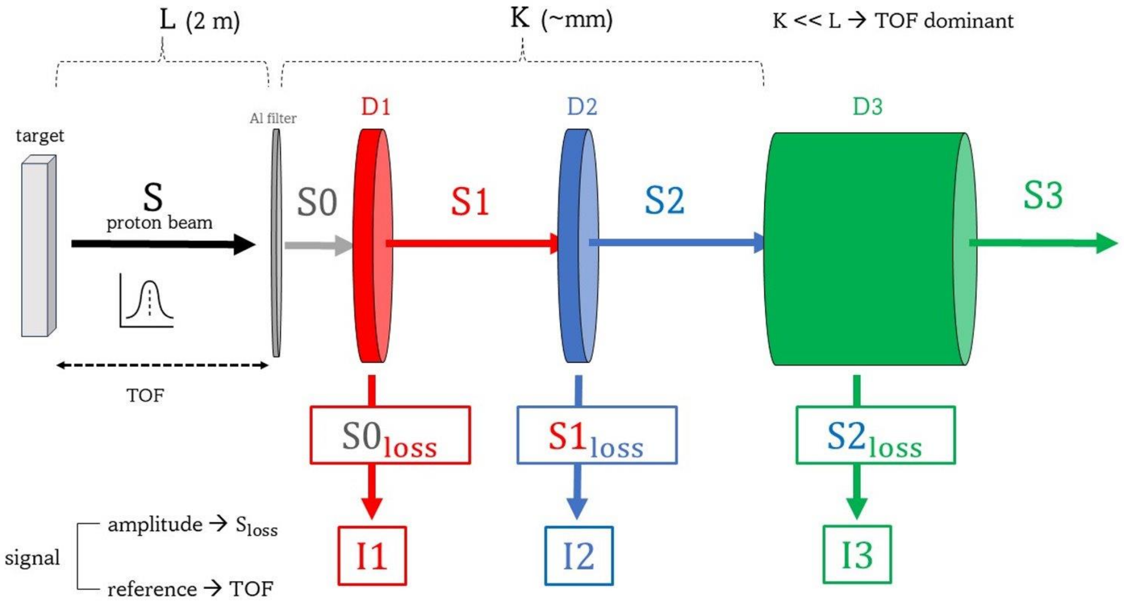






DIAMOND TELESCOPE CONFIGURATION

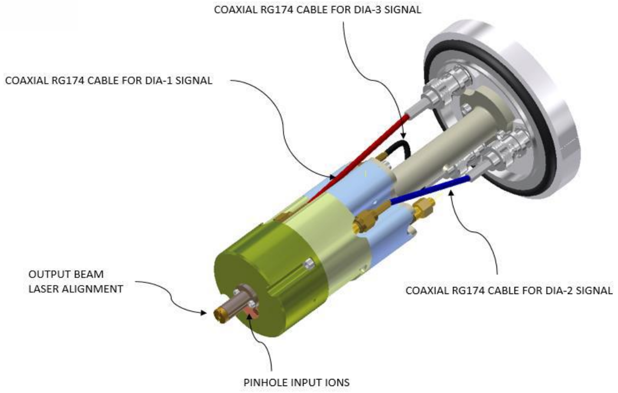
- Development of a **telescope detector**: A stack of multiple detectors arranged consecutively along the direction of ions impinging from laser-matter interaction.
- The main advantage of telescope detector lies in the ability to detect high-energy particles with good sensitivity, without compromising energy resolution.
- The use of thin detectors (i.e., 50 µm) could provide high energy resolution and a high radiation hardness for the entire diamond detector.
- The use of a thick detector (i.e. 500 µm) as a stop placed at the end of the telescope is also required.
- The total thickness of the detector is given by the sum of all the detector thicknesses in the stack.

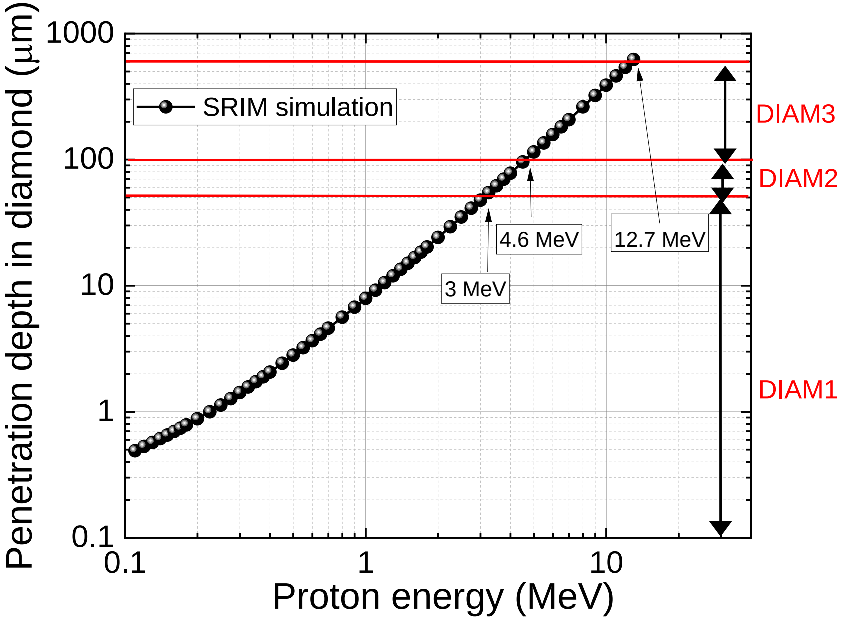


DIAMOND TELESCOPE PROTOTYPE

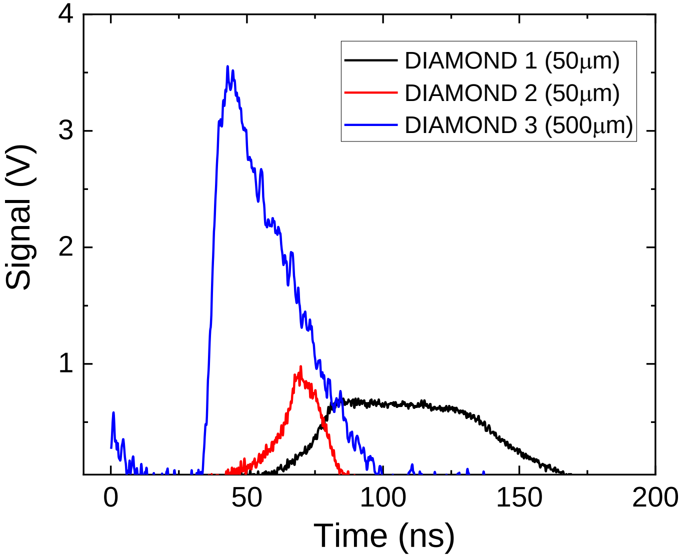
Dipartimento di Ingegneria Industriale

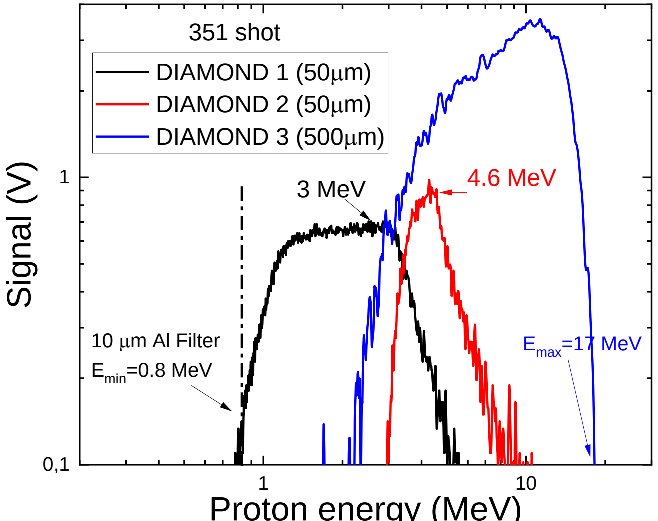
*Telescope diamond **prototype** consists of three diamonds placed in cascade: 1) 50 micron; 2) 50 micron; 3) 500 µm*





Experimental campaign at CLPU-VEGA III





TOF PARTICLE DISCRIMINATION

- ✓ The simultaneous presence of large number of particles makes hard to discriminate them.
- ✓ TOF techniques provide information on particle velocities and the overall energy released but do not supply information on the particle type.
- ✓ Particles reaching the detector at a given time instant have the same velocity, and thus the same energy per nucleon (Eg. 1 MeV protons or 4 MeV alpha particles or 12 MeV ^{12}C)

For a ion of atomic number A_i, mass $m_i \cong A_i m_p$ and charge state z_i, accelerated in the target by a potential drop φ, the time of flight ti is given by:

$$t_i = d\sqrt{\frac{A_i m_p}{2 z_i e \varphi}} = t_p\sqrt{\frac{A_i}{z_i}}$$

Defined $t_{p,min}$ the TOF of the first protons arriving to the detector (corresponding to the maximum proton energy $E_{p,max}$) we have for a given ion:

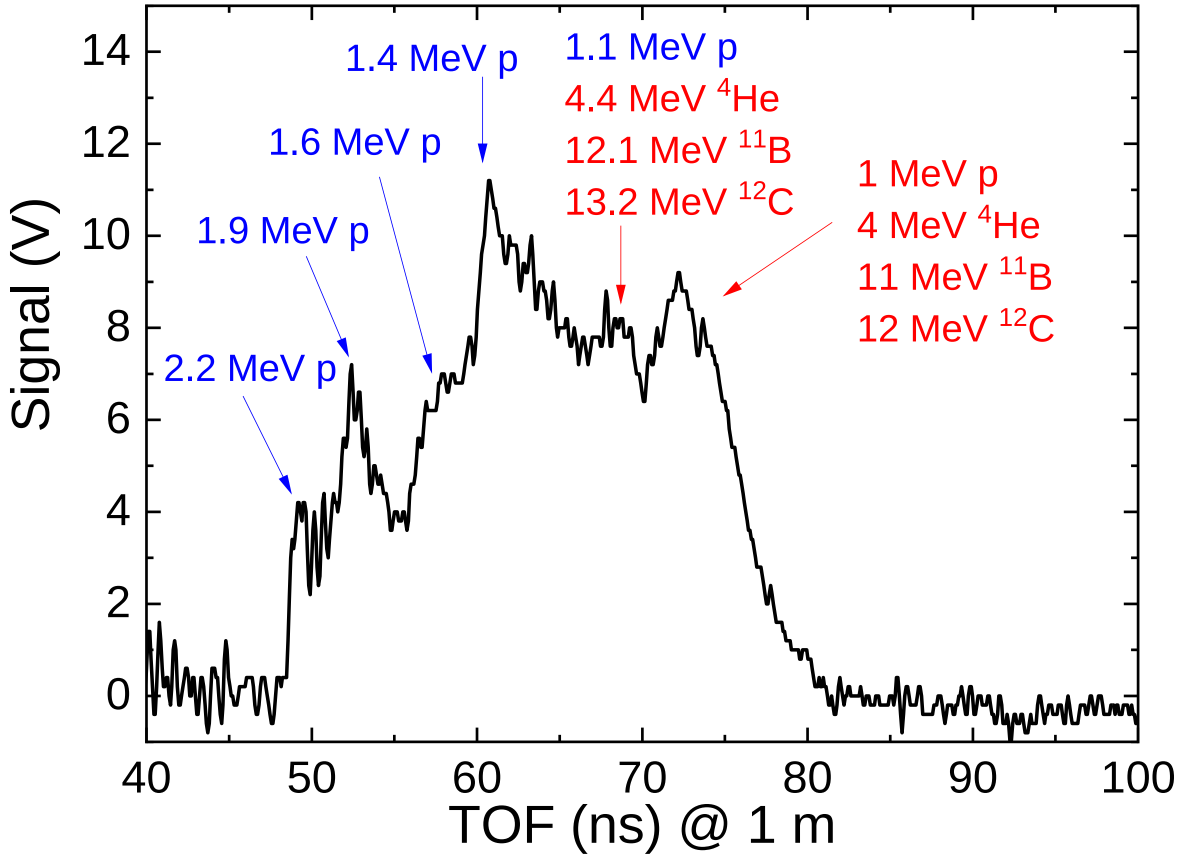
$$t_{i,min} \cong t_{p,min}\sqrt{\frac{A_i}{z_i}} \leq t_{p,min}\sqrt{2}$$

There is a temporal window where only protons can be detected: ($t_{p,min}$, $t_{p,min}\sqrt{2}$)

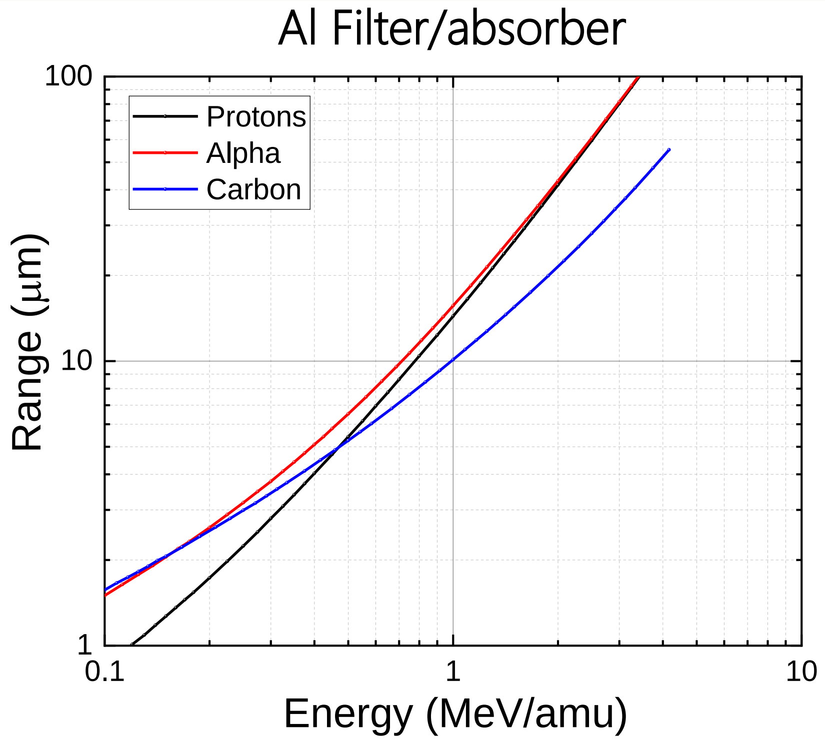
The time $t_{p,min}\sqrt{2}$ corresponds to the TOF of protons having half of their maximum energy.

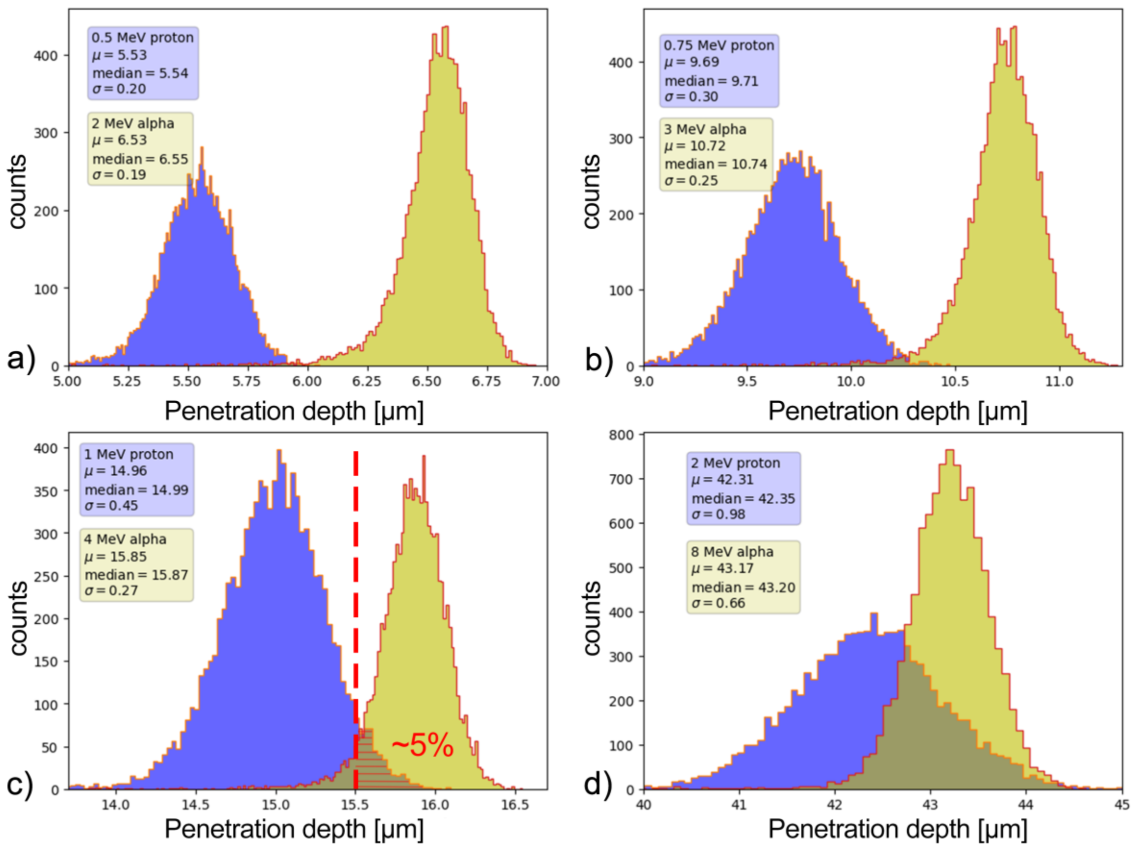
In terms of proton energy, there is a window where only protons can be detected: ($E_{p,max}$, $E_{p,max}/2$)

TOF PARTICLE DISCRIMINATION



TOF PARTICLE DISCRIMINATION



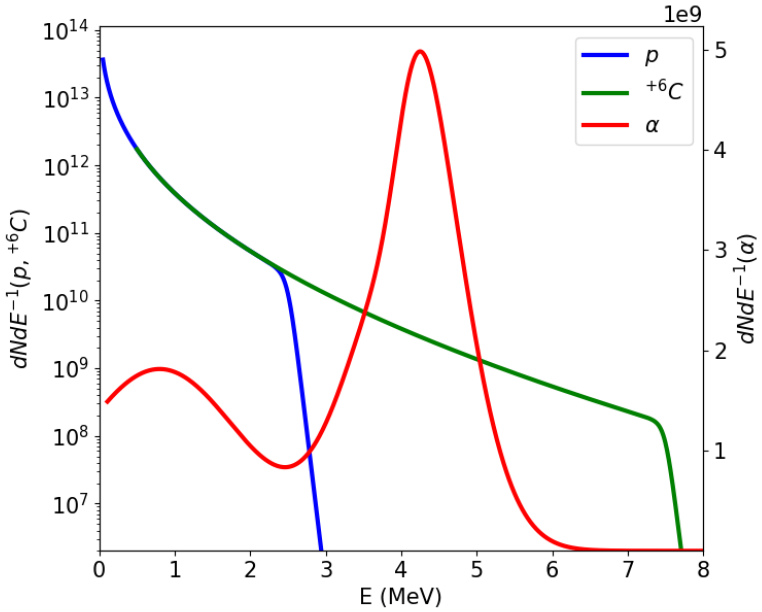


- Particle discrimination is not possible for each energy and ion specie.
- <u>At low energies</u>: discrimination difficult for alpha and carbon ions but ok for protons. <u>At high energies</u> (>1.5 MeV/amu): no discrimination is possible between protons and alphas but ok for the carbon ions.
- The choice for the thickness and material for each filter can vary depending on the species to be discriminated.

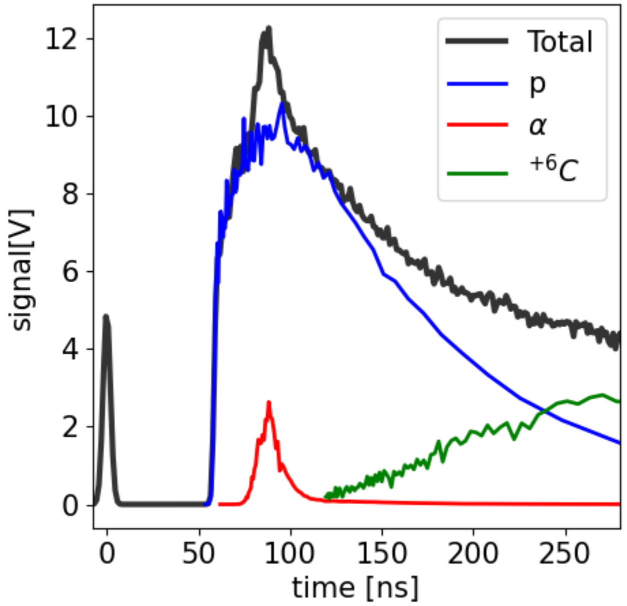
C. Verona et al JINST 18 C07008 (2023)

MULTI FILTER DIAMOND ARRAY TOF DETECTOR

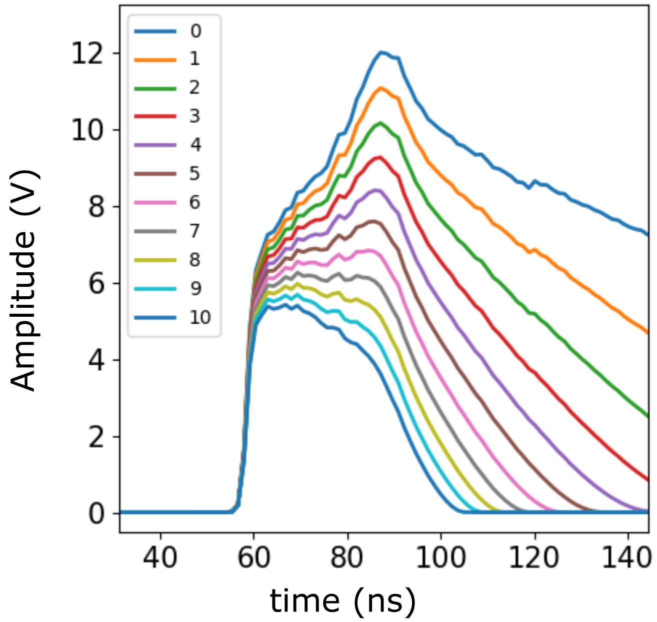
- The use of an array of detectors, nominally identical, featuring different calibrated foil filters of different thicknesses to exploit the different stopping powers of ions of different species and energies.
- A Python code written, integrated with the Monte Carlo SRIM tool help the data analysis.



No filter



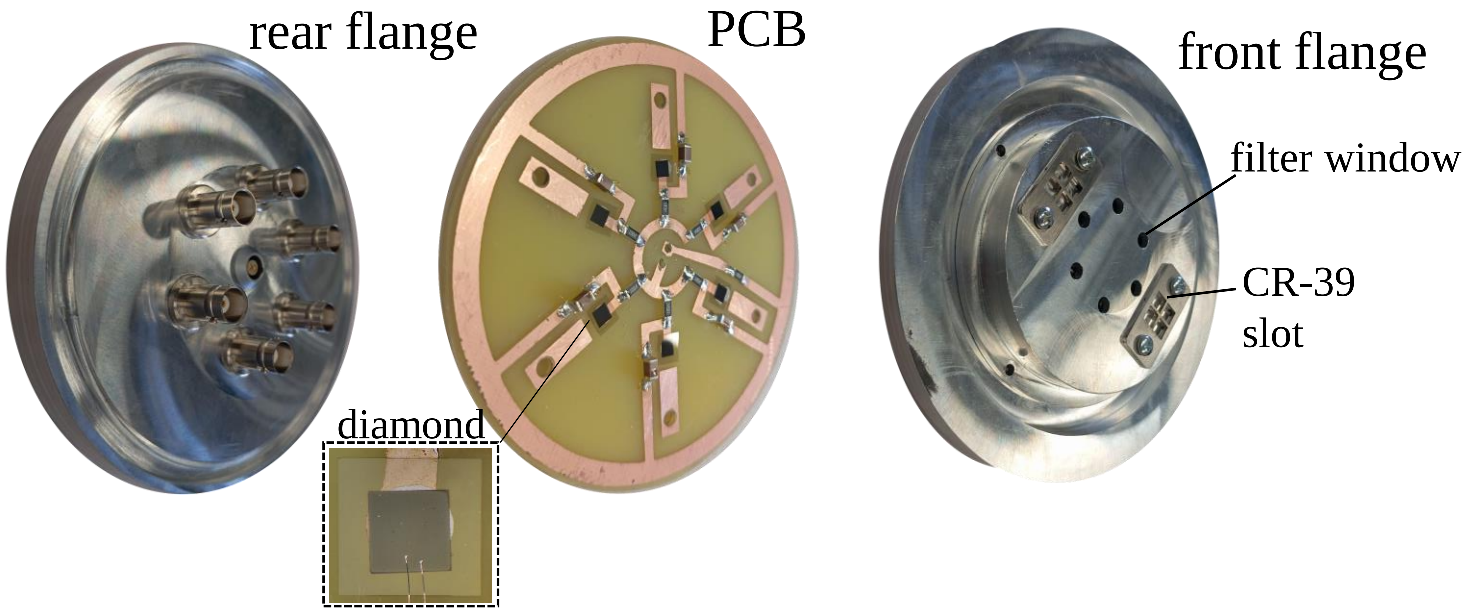
simulated **signal**



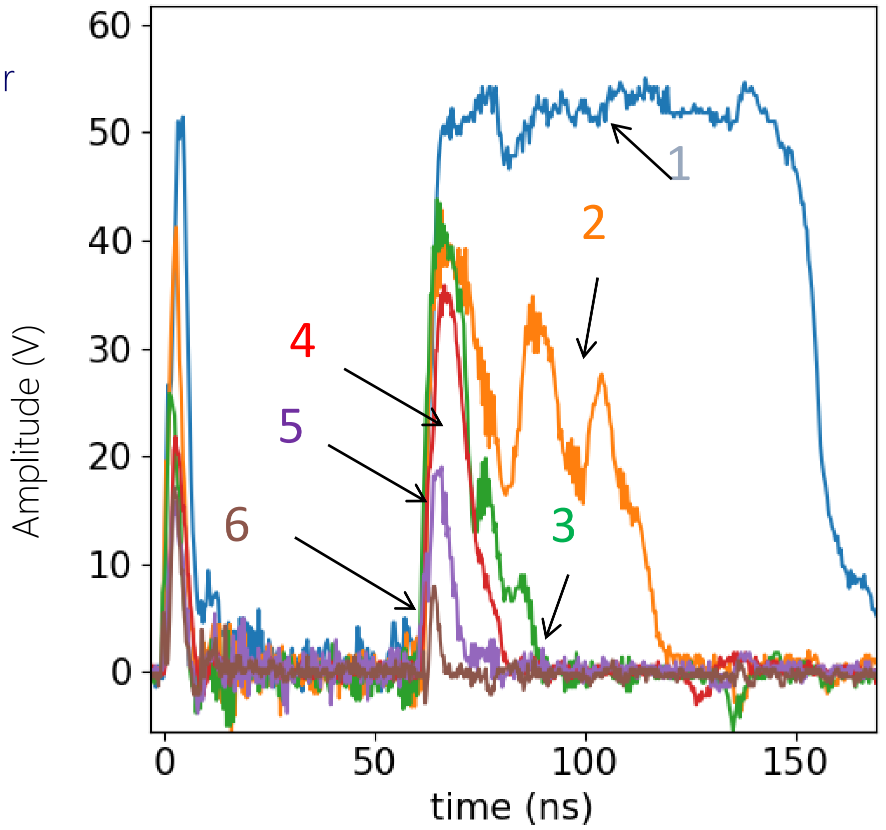
simulated **signal**

MULTI FILTER DIAMOND ARRAY TOF DETECTOR

- Development of TOF diamond detectors arranged in an array configuration with Al filters.
- Thanks to the different stopping powers of particles of different mass and energy within the filters it becomes possible to obtain more information about the respective particle energy spectrum.
- CR39 plates with the same filters are placed next to diamonds for comparison the results.



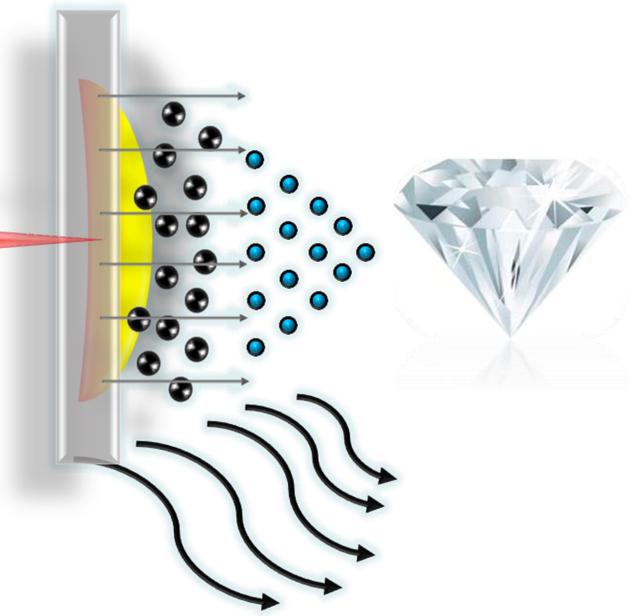
- Experimental campaign at PALS.
- Preliminary results, data analysis in progress.



CONCLUSIONS

- ✓ TOF diamond diagnostics were developed and employed in high-power laser-generated plasma experiments.
- ✓ A telescope configuration for the TOF detector was developed specifically for the detection of high-energy protons.
- ✓ An array of TOF detectors featuring different filter foils is proposed for ion discrimination.

THANK YOU!



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