TIME-OF-FLIGHT (TOF) ION DIAGNOSTIC METHODS FOR HIGH-INTENSITY LASER PLASMA EXPERIMENTS

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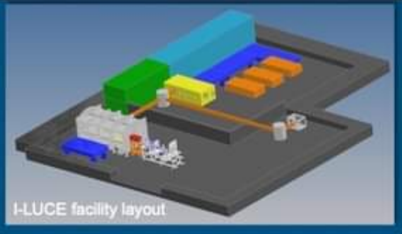
Didactic seminars introducing high-power lasers and their use in radiation production, nuclear physics and applications.



1st INFN Workshop on "High Power Lasers and their Applications" - HPLA2024

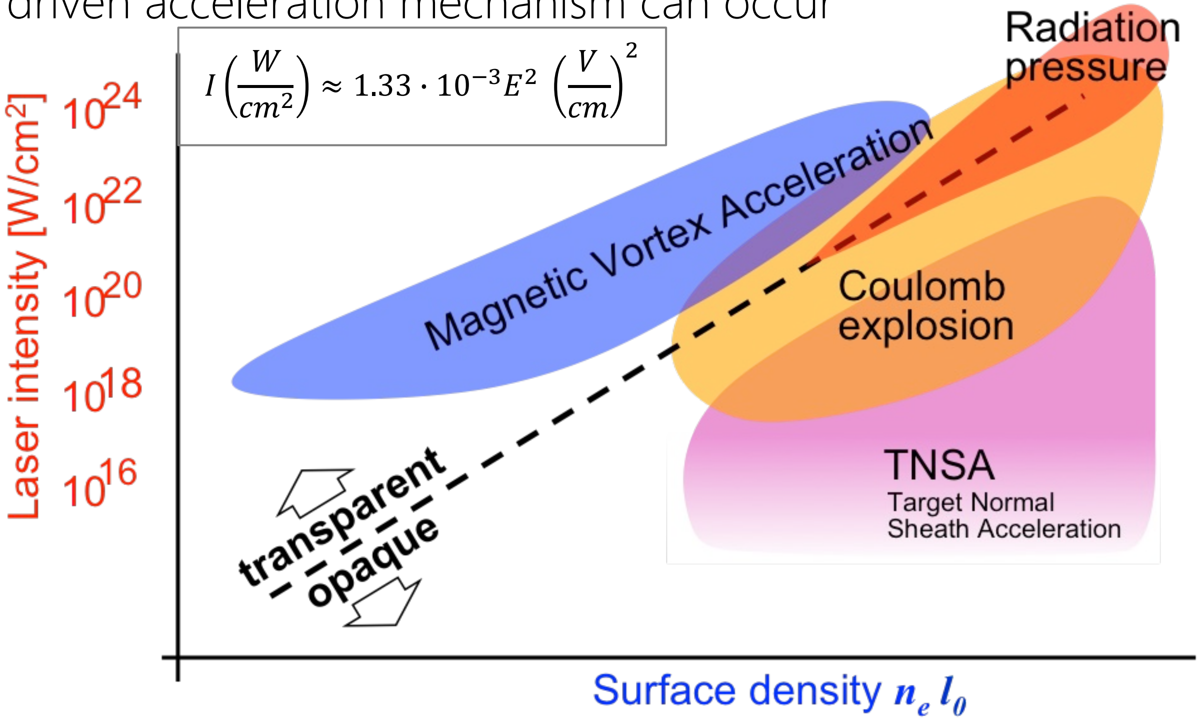
LASER-MATTER INTERACTION: ION ACCELERATION

Energy: from few mJ up to hundreds of J

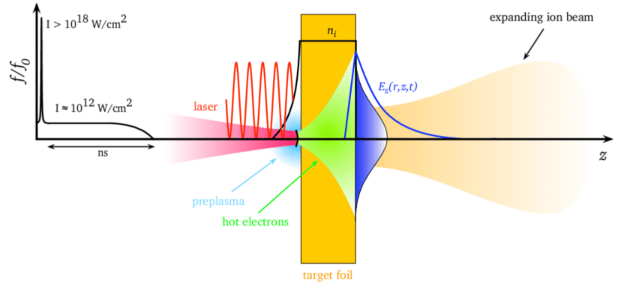
Pulse duration: from tens of fs ("short pulse ") up to ns ("long pulse")

Focal spot size: from few up to tens of μm

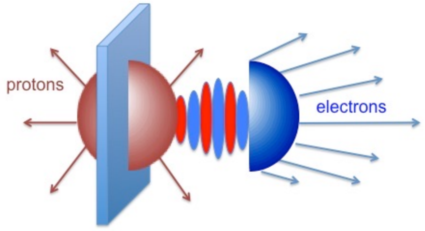
For Laser intensities higher than 10^{18} W/cm^2 several laser-driven acceleration mechanism can occur



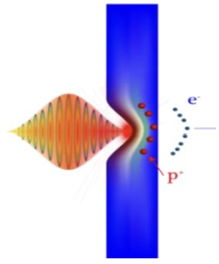
TNSA
Laser: Low Intensity
Target: Thick solid density foils
Ion Energy: ~100 MeV



Coulomb explosion
Laser: High Intensity/ large focal spot
Target: Thin solid density foils
Ion Energy: hundreds of MeV



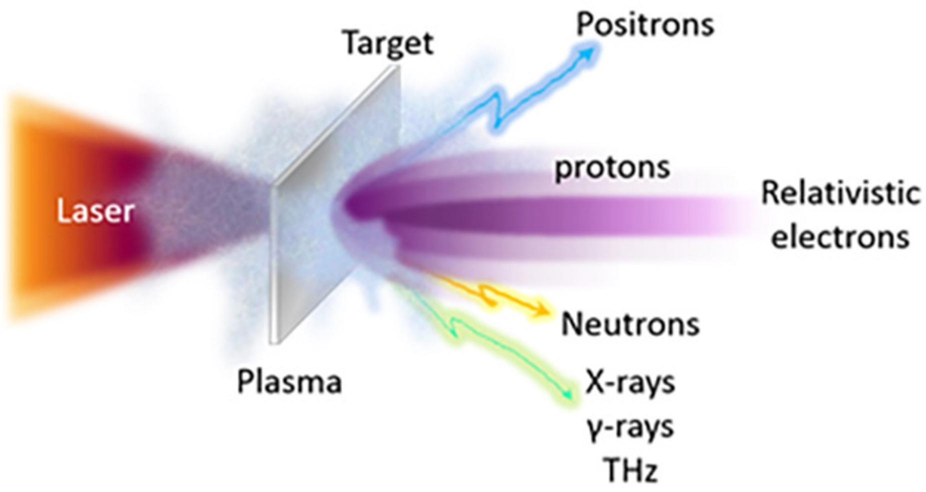
Radiation pressure acceleration (RPA)
Laser: Very High Intensity
Target: Thin solid density foils
Ion Energy: hundreds of MeV



Energy spectrum of ion changes according to the interaction condition:

- ✓ Laser energy and intensity
- ✓ Target type
- ✓ Focal spot

ION DIAGNOSTICS



Laser-generated plasma emission:

- Protons
- Multi ion species
- X-rays and electrons
- Neutrons
- Electromagnetic pulse (EMP)

- Challenges for detection further arise from the harsh plasma environment.
- Experimental setups generally incorporate a combination of complementary devices featuring various detection principles, online and offline analysis and acceptance angles.

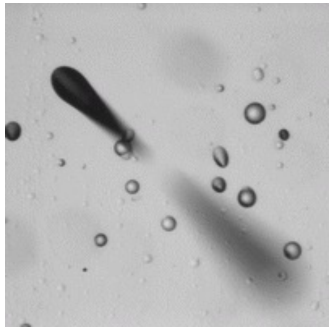
The ideal diagnostic system should have:
- High sensitivity
- High energy resolution

and should allow to retrieve:
- Spectrum of accelerated ions
- Angular distribution of accelerated ions
- Particle discrimination

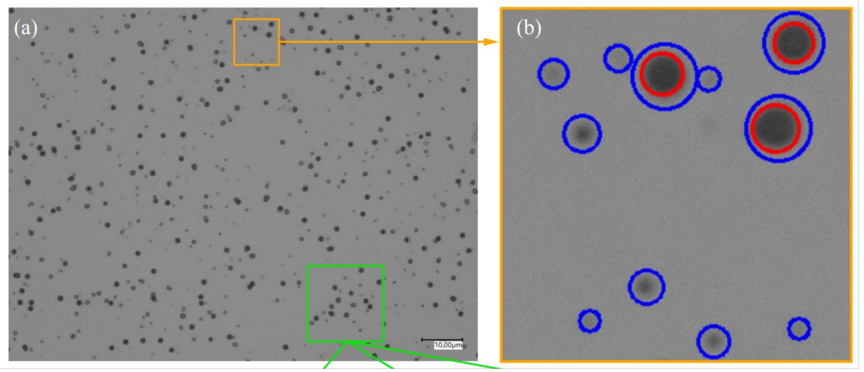
but it also has to provide:
- Electro Magnetic Pulses (EMPs) robustness
- Real-time detection (in particular for high repetition rate lase)

ION DIAGNOSTIC: TRACK DETECTOR

- Solid state nuclear track detectors (SSNTDs) such as CR39 polymer and PM-355 plastic, are used to detect particles by observing their track inside the detector material.



- A particle striking the SSNTD deposits its energy by creating a proportional damage trail, referred to as a latent track, as it penetrates the detector. The geometry of this track (size and shape) depends on the incidence angle, energy and charge-to-mass ratio of the incident particle.
- The latent track is too small (few nanometers) to be observed optically but can be enlarged through chemical wet etching (NaoH). Etching dissolves the polymer to the point where the track opening is large enough (few micrometers) to be observed and imaged by an high resolution optical microscope.

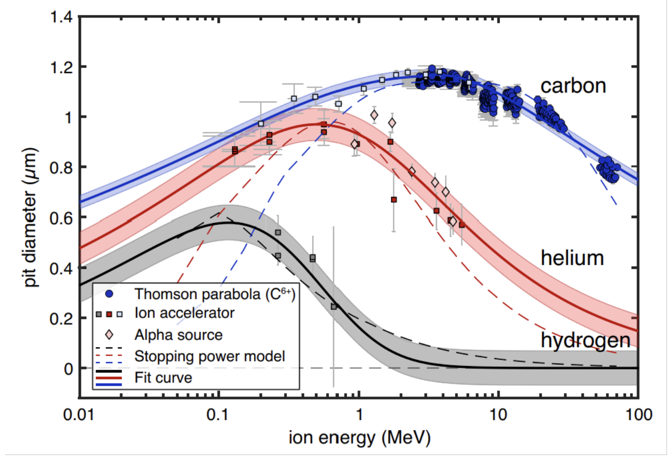


- The etching process depends on several parameters such as etching time, temperature, concentration and inherent purity of NaOH solution, which can differ from one experiment to the other and material from the same manufacturer, resulting in different characteristics of the tracks.
- The reproducibility of the detector parameters affects largely the detector response.

M. S. Schollmeier et al. Sci Rep 13, 18155 (2023)

ION DIAGNOSTIC: TRACK DETECTOR

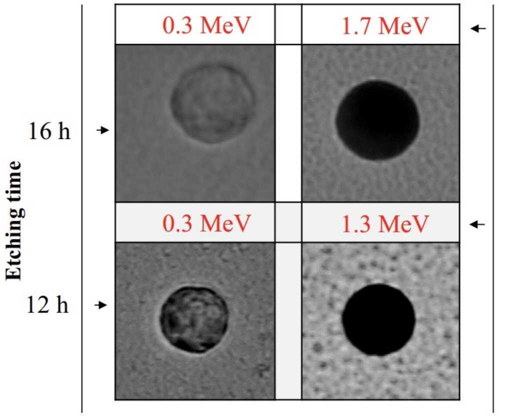
- SSNTD requires careful pit analysis, e.g., via numerical image processing of microscope data. Different particles of different energies might produce a pit of the same size.
- Calibration of SSNTD: exposure of the detector to known ion beams and the examination of the resulting tracks under different conditions of etching solution, temperature and time.
- Typical approach for particles discrimination consists of use of filters capable of stopping heavy ions, track shape/dimension/colour discrimination.

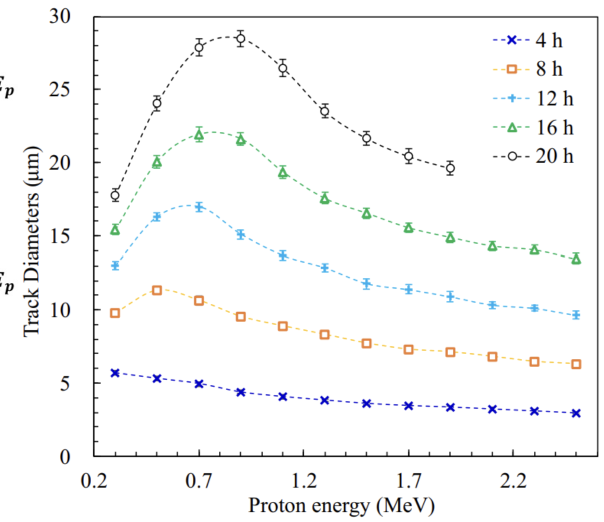


Solid State Nuclear Track Detector (SSNTD)

- Passive detector
- Time consuming (post processing&calibration)
- Strong background

- Angular distribution
- Ion discrimination
- Energy Spectrum reconstruction

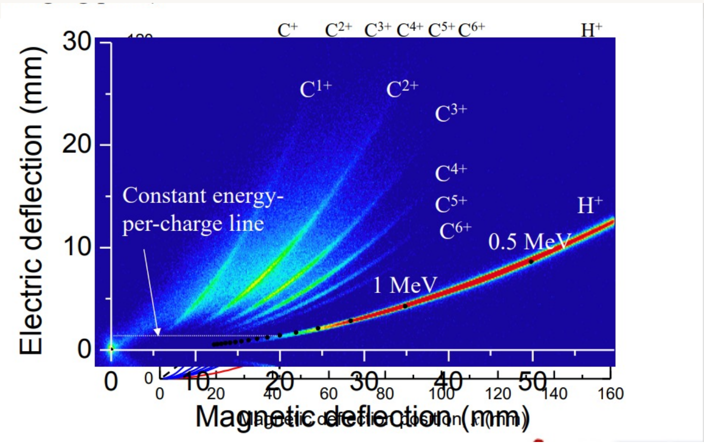




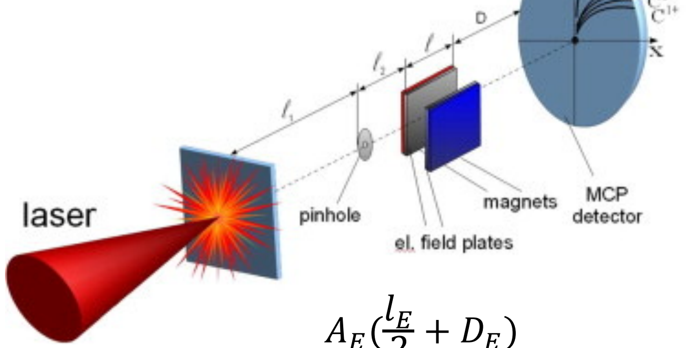
He, YF. Et al. NUCL SCI TECH 31, 42 (2020).
M. S. Schollmeier et al. Sci Rep 13, 18155 (2023)

ION DIAGNOSTIC: THOMSON SPECTROMETER

- Thomson Parabola (TP) spectrometers are well-known effective detectors used for discriminating ions with different $\frac{A}{Z}$ ratio in high power laser experiments.
- An electrostatic and a magnetostatic field, both orthogonal to the incoming particle beam direction, determine a deflection of the particles leading to parabolic traces, each univocally corresponds to one $\frac{A}{Z}$ ratio.
- TP parameters (deflecting fields) affect data acquisition. Indeed, high electric and magnetic fields are necessary for a suitable trace separation at high energies.
- Size and shape of the pinhole must be carefully selected to find the best compromise between resolution and sensitivity as well as the X-ray noise.
- Most used detectors are CCD screen with a micro channel plate (MCP) or image plate detectors as well as scintillators. Using calibrated detectors, it is possible to retrieve the absolute particle energetic spectrum.



$$y(x) = \frac{Am_p}{Zq_e}\frac{A_E}{A_B^2}x^2$$



$$v = \frac{A_E(\frac{l_E}{2} + D_E)}{A_B(\frac{l_B}{2} + D_B)}$$

P. R. Bolton et al., Physica Medica 30 (2014) 255e270

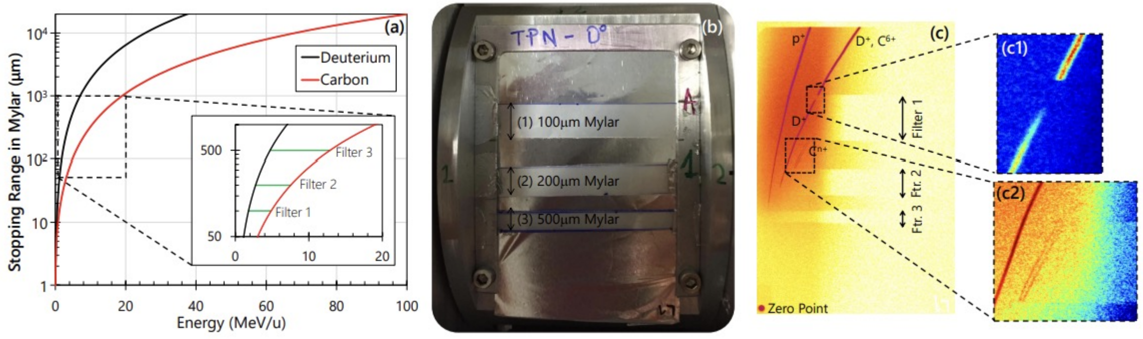
ION DIAGNOSTIC: THOMSON SPECTROMETER

- An image is acquired with the TP and the recorded traces are overlapped with the corresponding parabolas. To every point of the parabola is assigned a velocity value which is converted into a kinetic energy value. The intensity value on the imaging plane is calibrated to a particle number so that reading out the intensity along the parabola with energy assigned to every point yields the energy spectrum for particular particle species.
- The parabolic traces of ion species with the same Z/A will overlap at the detector plane, preventing their spectra to be characterised. Ex: to detect the lightest of the overlapping ion species, foil filters in front of the detector, which would preferentially stop heavier ions and allow only lighter species to be detected.

Thomson spectrometers (TS)

- Ion trace overlaps with fully stripped ions (the same Z/A)
- Sensitive to EMP and X-ray radiation noise
- High voltage operation

- Active detector
- Ion discrimination according to mass-to-charge ratio
- Spectrum reconstruction

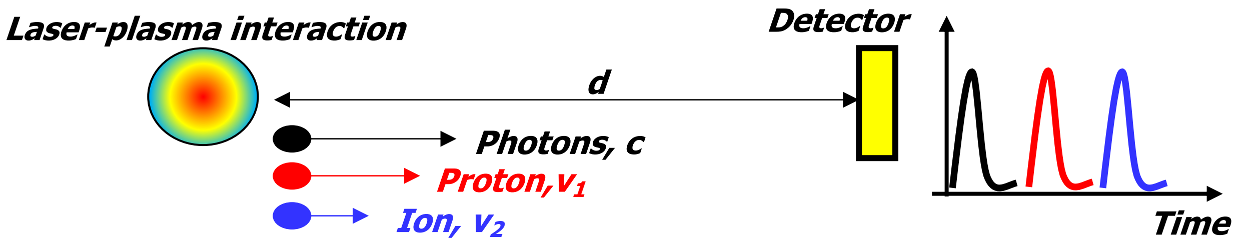


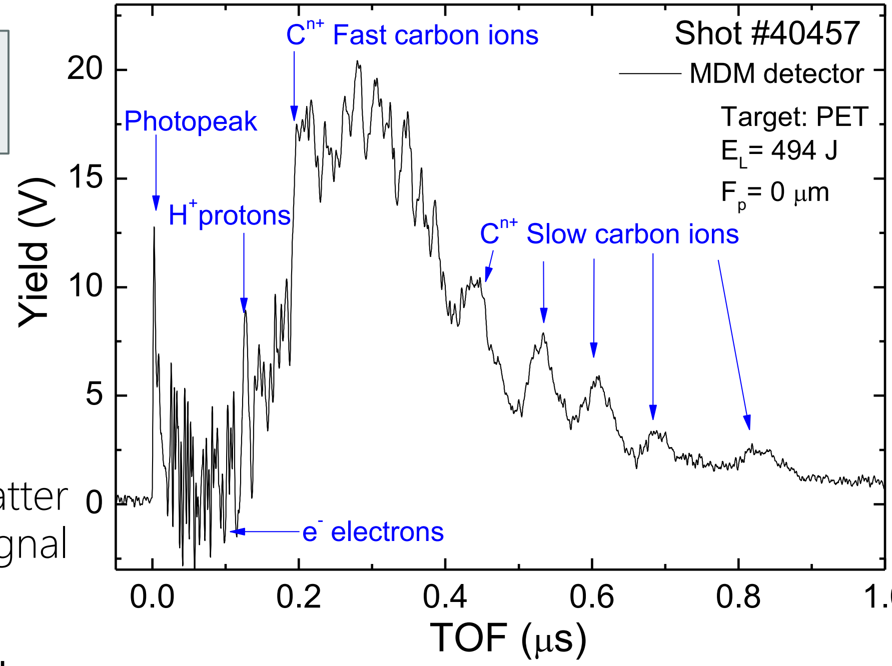
A. Alejo et al, Journal of Instrumentation, 11, C10005 (2016)

ION DIAGNOSTIC: TIME OF FLIGHT (TOF) TECHNIQUE

- Time-Of-Flight (TOF) method is very effective to detect in "real time" contemporary 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

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

For a ion accellerated in the target by a potential drop:

$$\Delta E_p = E_{p,max}\left(1 - \frac{Z_i}{A_i}\right)$$

For ions: $\frac{Z_i}{A_i} \leq \frac{1}{2} \rightarrow \Delta E_p \geq \frac{E_{p,max}}{2}$

There is a temporal window where only protons can be detected (in terms of energy: $(E_{p,max}\, , E_{p,max}/2)$)

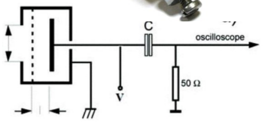
ION DIAGNOSTIC: TIME OF FLIGHT (TOF) DETETORS

The detectors generally used in the time-of-flight scheme can be grouped in three categories:

Electrostatic detectors

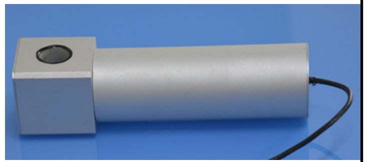
Ion collector or Faraday cups

- Small, robustness and reliability compact metallic device designed to catch charged particles in vacuum.



- Charged particle impinging on a metallic surface cause it to gain a small net charge, generating a electric current that can be measured by a fast oscilloscope.
- The resulting current can be used to determinate the number of ions or electrons hitting the cup.
- The detectors show low efficiency in detecting low-energy particles and secondary electron emissions can compromise the response of the detector.

Scintillators + Vacuum phototubes

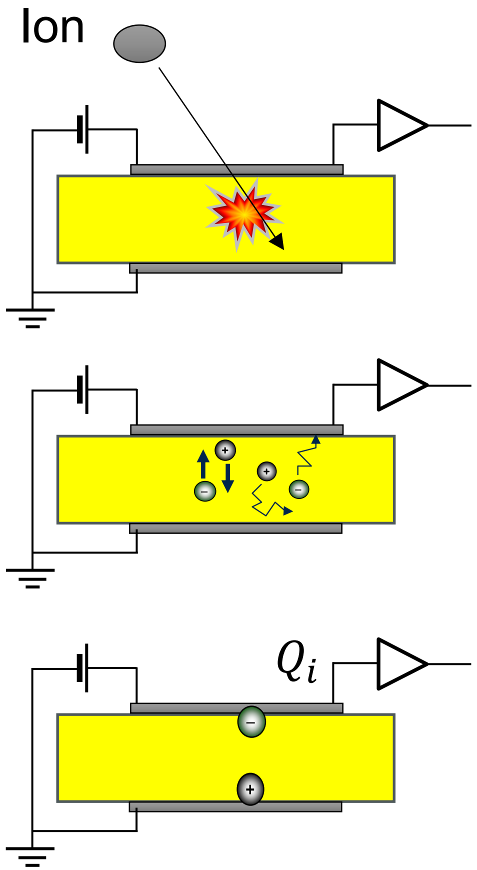


- Scintillator converts the incoming charged and neutral particles in fluorescence light that is then detected by a photo multiplier tube (electric signal).
- Inorganic scintillators have a high light output and a slow response while organic scintillators (crystals, liquids, and plastics) have a low light output but are fast.
- High efficiency: suitable for low particle fluxes characterized by mid-low energies.
- High energy electrons and x- rays are a potential source of the background signal in the scintillators.

Semiconductor detectors

- Semiconductor based detectors are devices that use a semiconductor (i.e. Si, GaAs, SiC and diamond) to measure the impinging radiation. Main composition parts of such detectors are active region, constituted by low-doped or intrinsic semiconductor, and junctions located at two sides of the semiconductor.
- Charged particles deposit their energy generating *e-h* pairs that can be collected by applying an external electric field.
- Detection features depend on the semiconductor properties and detector layout.

TIME OF FLIGHT (TOF) SEMICONDUCTOR DETECTOR



Ions lose their energy **dE/dx**

If $E_{loss} \geq$ 13.1 eV or 7.8 eV

Production of **free electron-hole pairs**

Charge transport:
1. **Drift - in electric field**
2. **Diffusion**

Induced charge **Q** at sensing electrode

$$N_i = Q_{i,c} \frac{\epsilon_g}{E_i q_e \eta} = \int_0^{t_i} i(t)dt \frac{\epsilon_g}{E_i q_e \eta}$$

From the amplitude of the acquired signal, it is possible to retrieve the number of particles generating it.

Signal generation proportional to the energy deposited by the impinging particles and the number of particles generating it

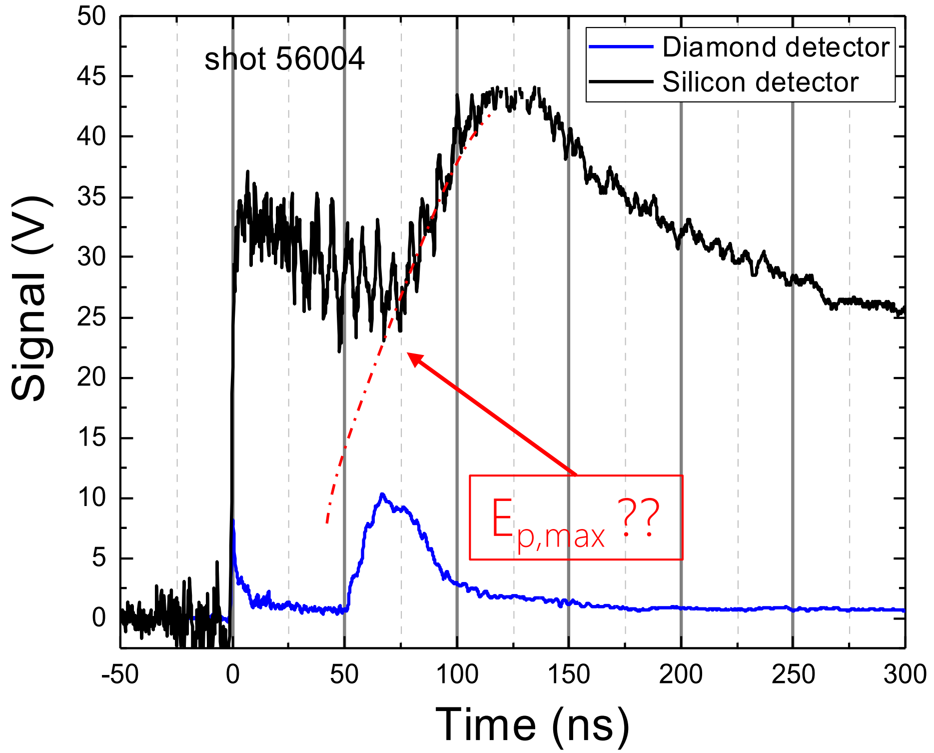
Charge pulse depends on the value of electric field, mobility and lifetime of charge carriers (defects).

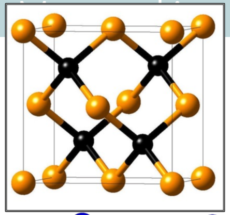
$$Q_{i,c} = N_i \frac{E_i q_e}{\epsilon_g} \eta(E_i)$$

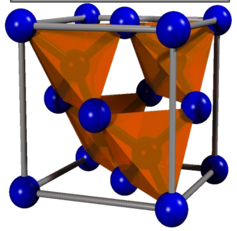
$\eta(E_i)$
Charge **C**ollection **E**fficiency

TIME OF FLIGHT (TOF) DETECTOR MATERIALS

	Si	GaAs	4H-SiC	Diamond
	Diamond	Zinc blende	Hexagonal	Cubic
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
temperature (°C)	300	450	>1000	>1000



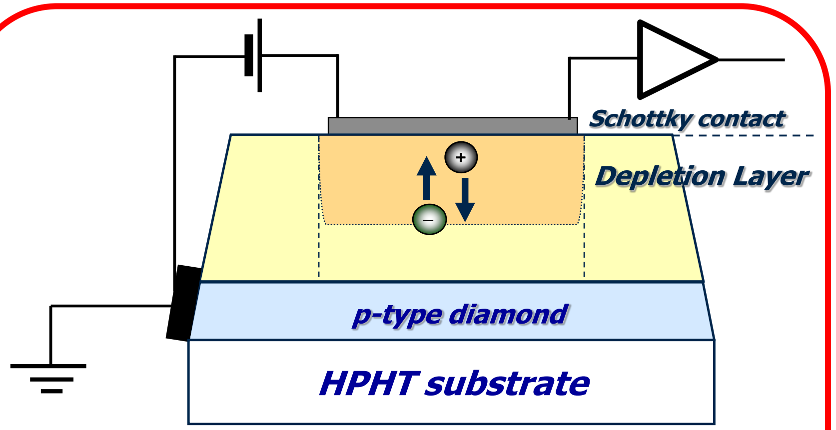




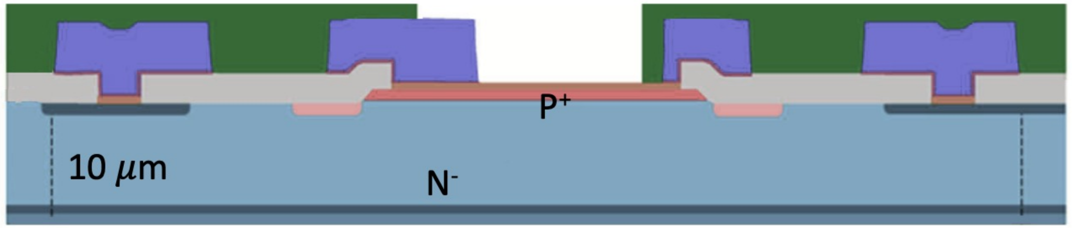
- ✓ VISIBLE BLINDESS (wilde band gap) ➡ Short and narrow photopeak (absolute reference of time measuraments)
- ✓ LOW DARK CURRENT (wilde band gap) ➡ Good signal to noise ratio
- ✓ FAST RESPONSE TIME (high carrier mobility and low dielectric constact) ➡ High energy resolution
- ✓ HIGH RADIATION HARDNEESS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

TIME OF FLIGHT (TOF) SEMICONDUCTOR DETECTOR

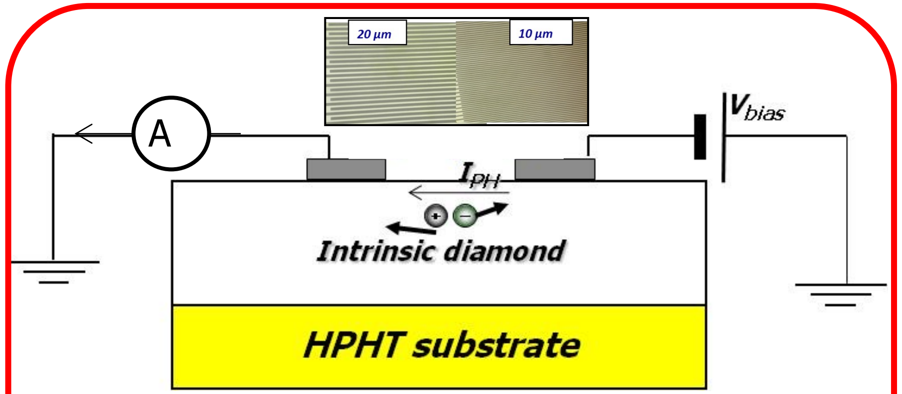
❑ The different electrodes and geometry layout allow to cover a wide range of requirements



✓ *Diamond Schottky diode*

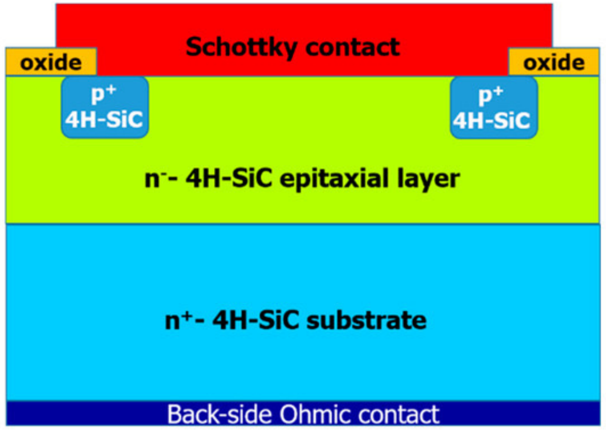


✓ *SIC p-n junction*



✓ *Diamond with interdigited contacts*

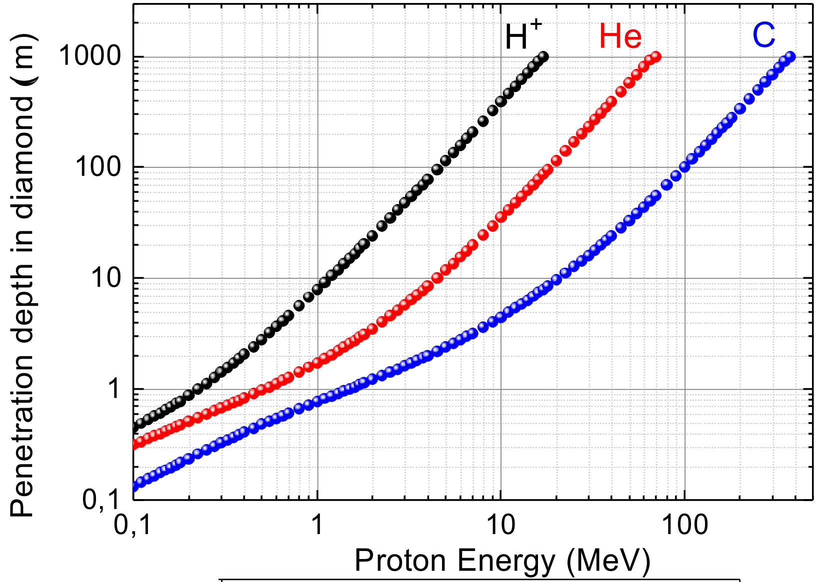
✓ *Metal-Diamond-Metal*

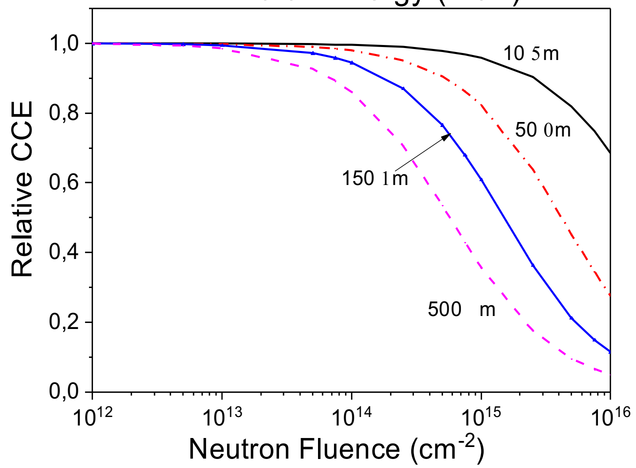


✓ *SIC Schottky diode*

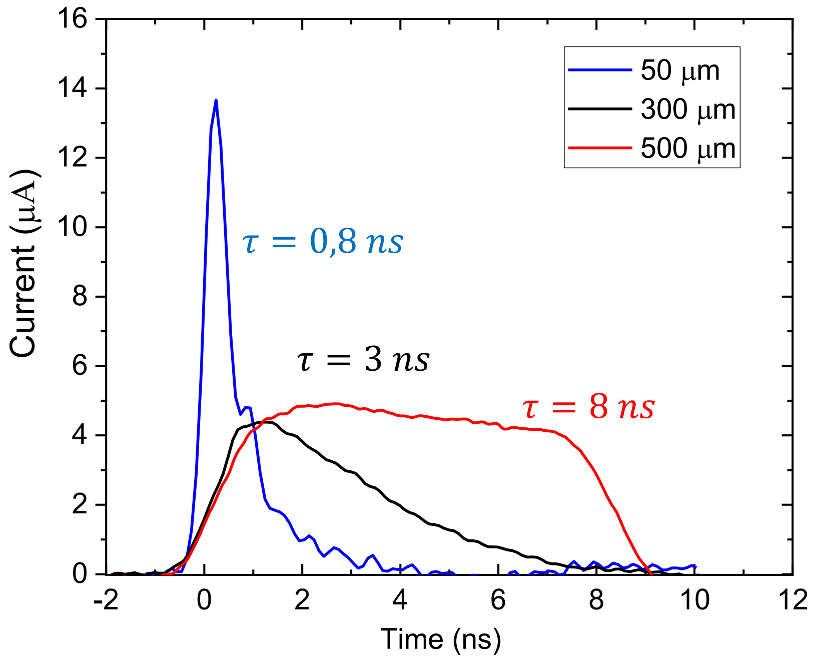
TIME OF FLIGHT (TOF) SEMICONDUCTOR DETECTOR

thickness vs. collection time





Calculated relative CCE Vs 14 MeV neutron fluence



$$\tau_{drift} = \frac{d}{\mu_0 E} \cdot \left(1 + \frac{\mu_0 E}{v_{sat}}\right)$$

d (distance between electrodes)
μ_0 (electron mobility)
$\boldsymbol{E}$ (electric field)
v_{sat} (saturation velocity)

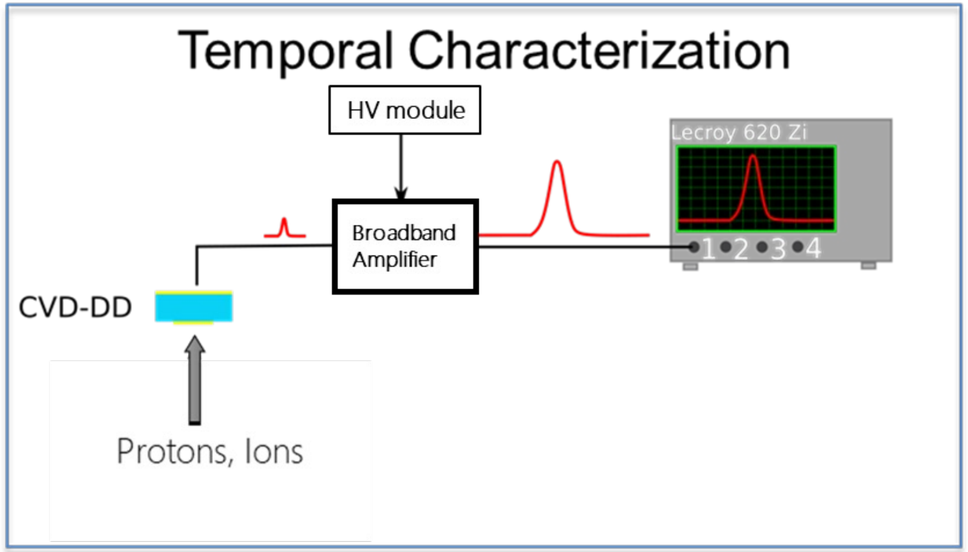
τ_{drift} depends upon the diamond film thickness and electric field

The **collection time** of the measured pulse can be defined as the time required to the excess carriers to move (drift) toward the electrodes

- Thick detector: High sensitivity, low collection time (low energy resolution), low radiation hardness.
- Thin detector: Low sensitivity, high collection time (high energy resolution), high radiation hardness

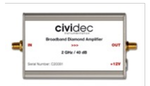
M. Angelone & C. Verona, J. Nucl. Eng. 2021, 2(4), 422

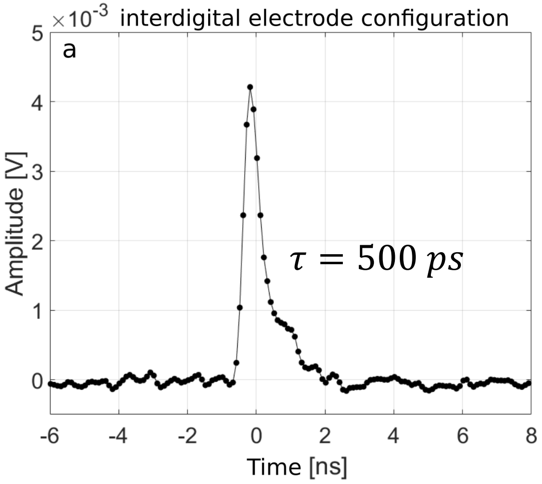
TIME OF FLIGHT (TOF) DETECTOR CHARACTERIZATION

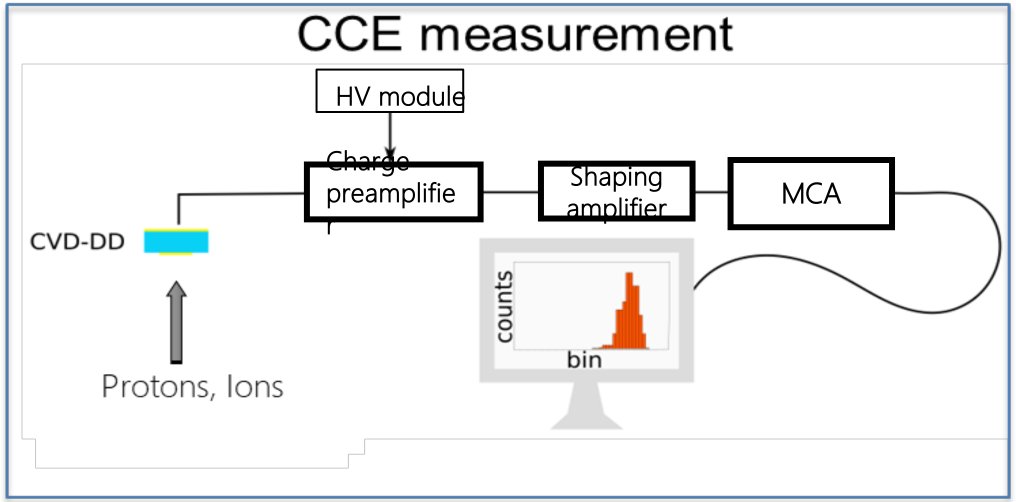


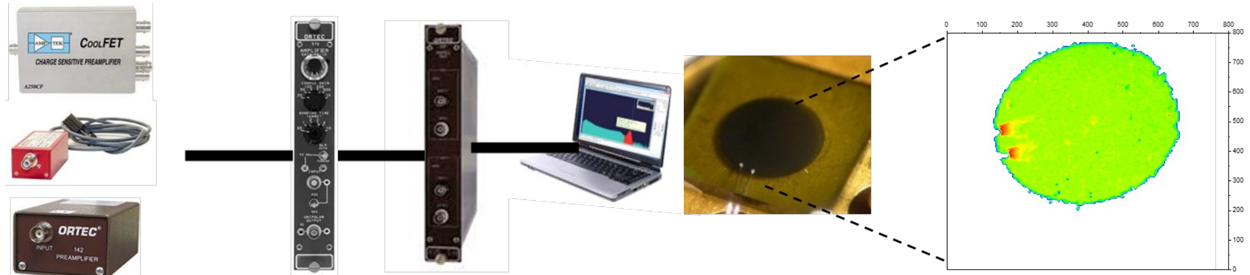

DBA IV (GAIN: 50 dB, Bandwidth: 2 GHz)


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

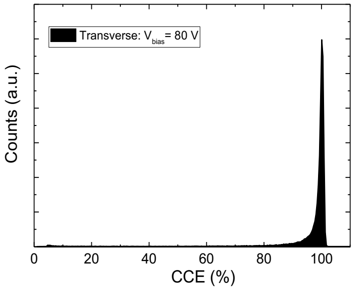

CIVIDEC (GAIN: 40 dB, Bandwidth: 2 GHz)

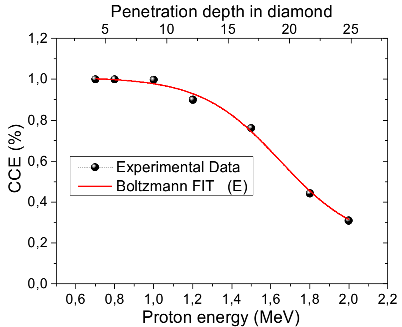






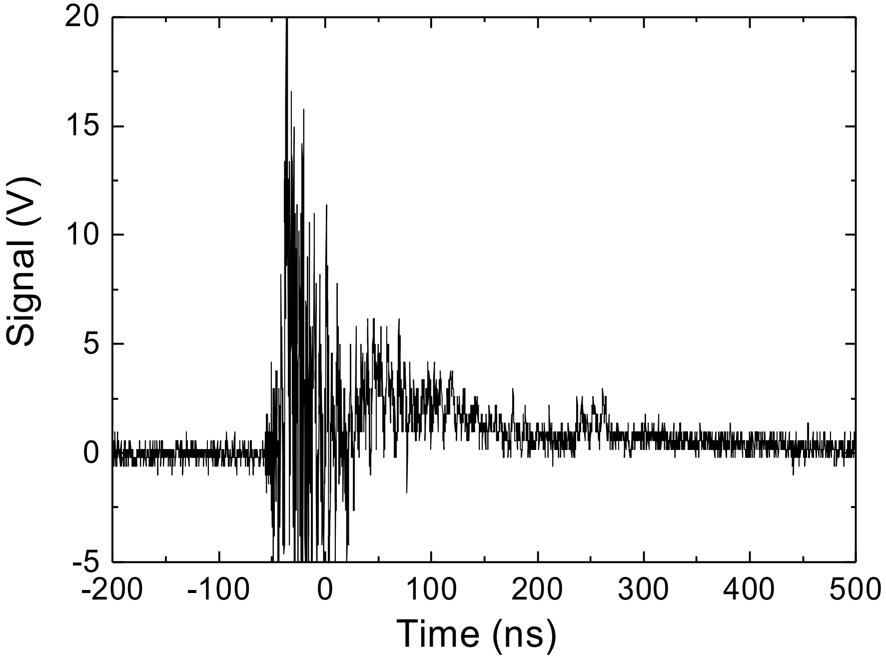
ORTEC 570 ORTEC 927

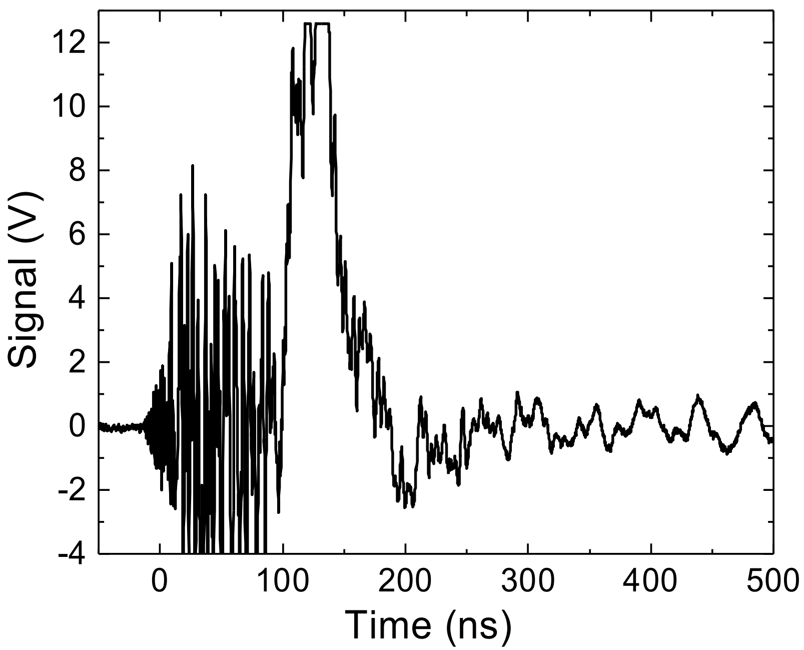


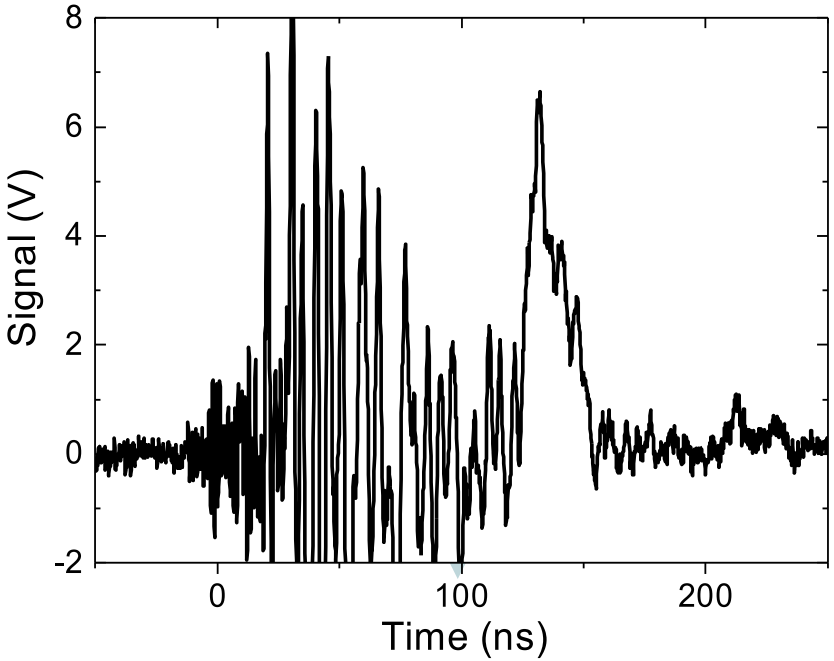


CHALLENGES IN TOF: EMP AND DYNAMIC RANGE

Typical signals from **Time Of Flight detector** in Laser-Matter interaction experiments





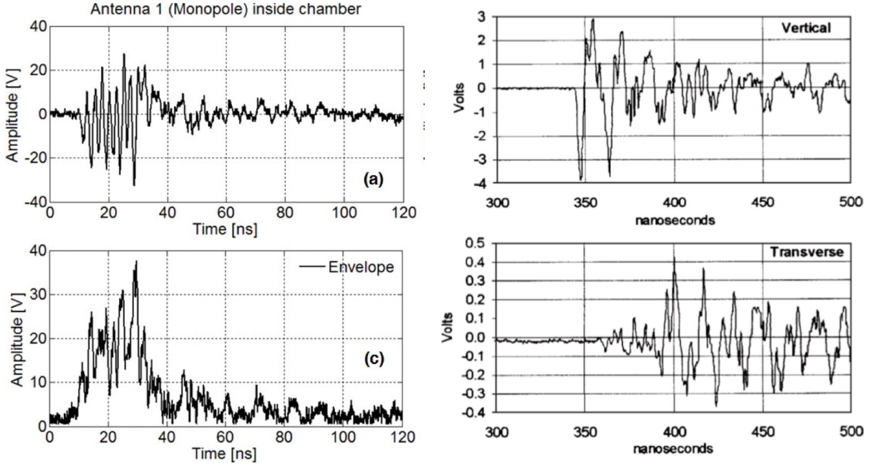


- Low precision in defining t_0 → Poor Energy estimation!
- Bad signal to noise ratio → Poor Energy spectrum reconstruction!

CHALLENGES IN TOF: EMP AND DYNAMIC RANGE

- **EMP pollution** poses a barrier to utilizing TOF detectors in high-energy Laser facilities.

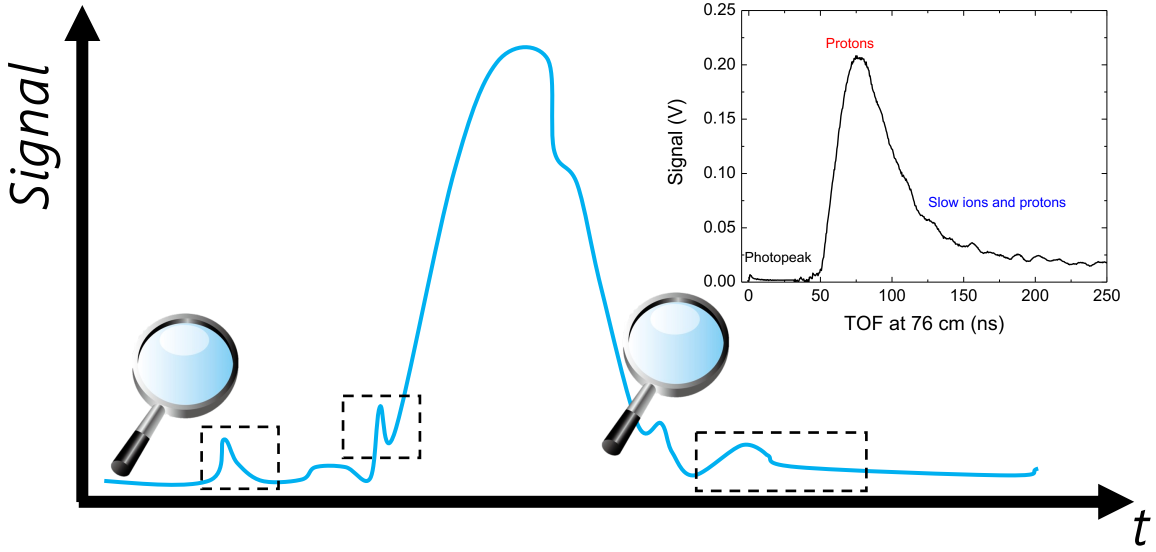
It is necessary to optimize the acquisition system to work in these environments



Examples of time-domain signals measured with Antennas inside the vacuum chamber of the ABC and Vulcan facilities
(*F. Consoli* et al, High Power Laser Science and Engineering, (2020), Vol. 8, e22)

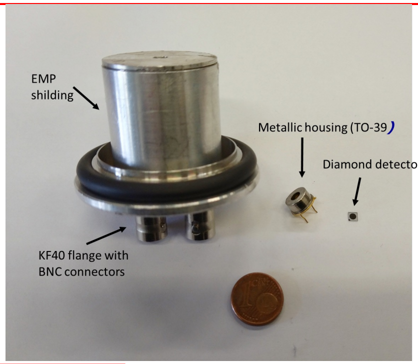
- TOF signals have an intrinsic **high dynamic range**.

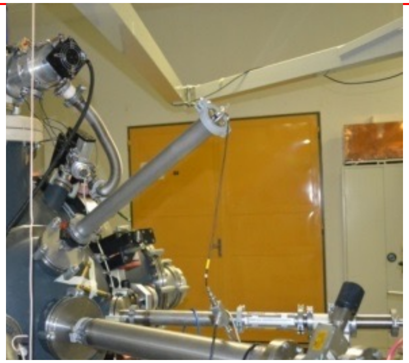
It is necessary to develop a technique able to appreciate the full dynamic range



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.



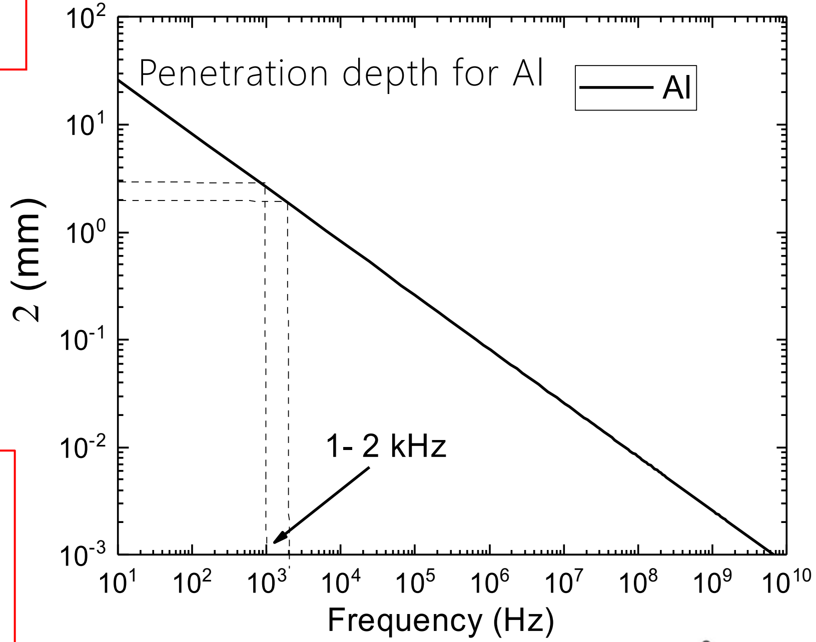


In order to minimize the EMP coupling with the acquisition system and increase the signal/noise ratio, **RG223 low noise, double-shielded coaxial cables** are used.

EMP attenuation (Skin effect) $J_s(z) \propto J_0 e^{-\frac{z}{\delta}}$

$$\delta = \sqrt{\frac{1}{\pi f \sigma \mu}}$$

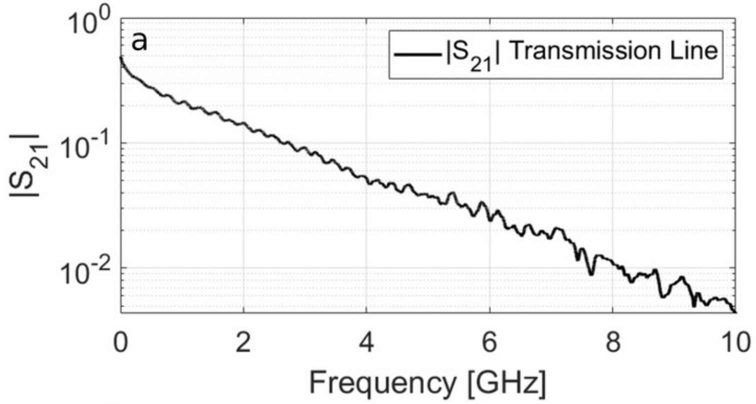
σ conductivity
μ permeability



The 2-3 mm Al thickness can attenuate EMP with frequencies down to 1-2 KHz

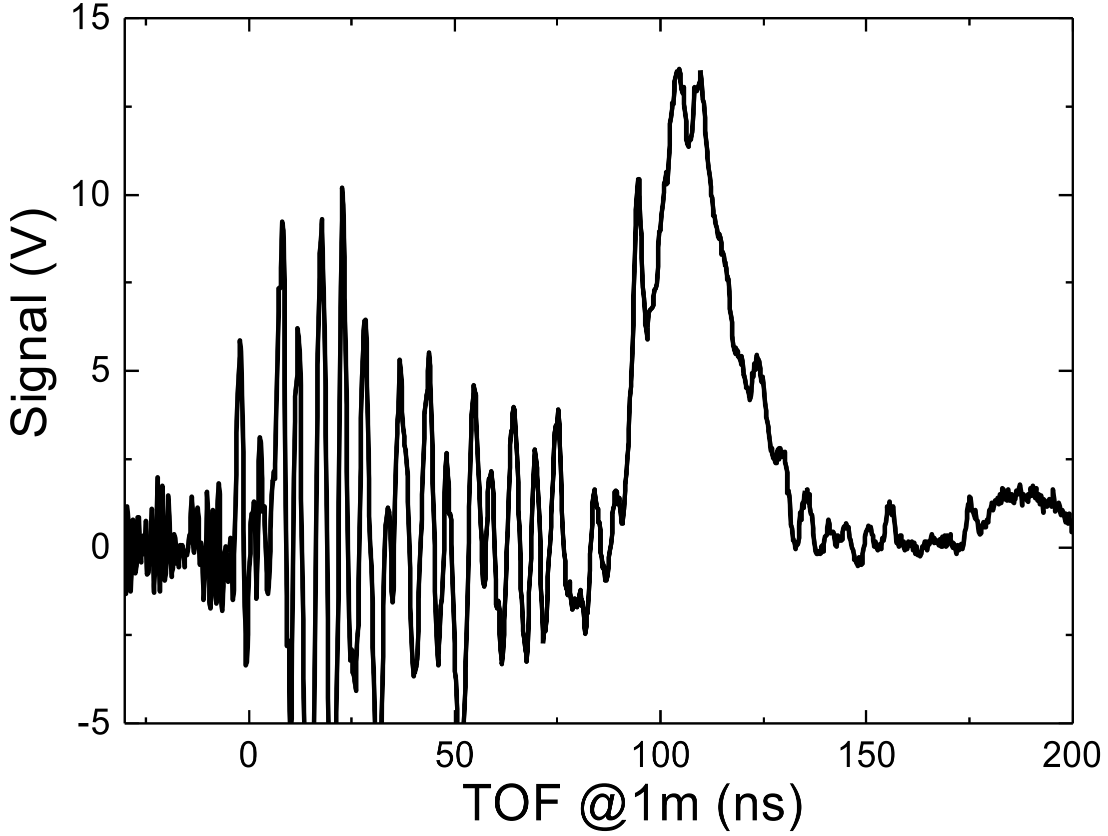
❑ Long double shielded coaxial cables

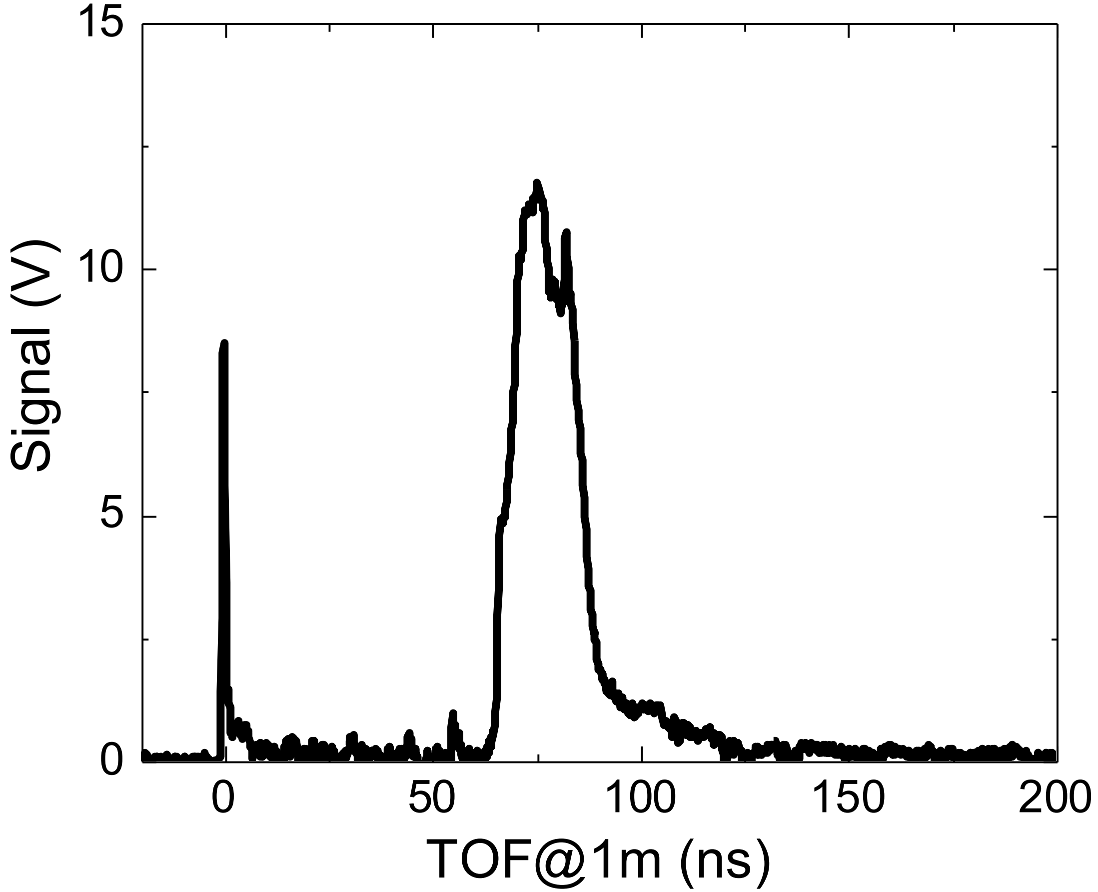
1. Provide high frequency attenuation (low-pass filter)
2. Introduce a temporal delay (tens of ns) between the TOF signal and the EMP contribution
3. Allow to place the scope far from the experimental chamber.
4. De-embbeding signal procedure is necessary



ACQUISITION SYSTEM OPTIMIZATION: EMP MITIGATION

Typical signals from TOF detector in Laser-Matter interaction experiments after EMP optimization

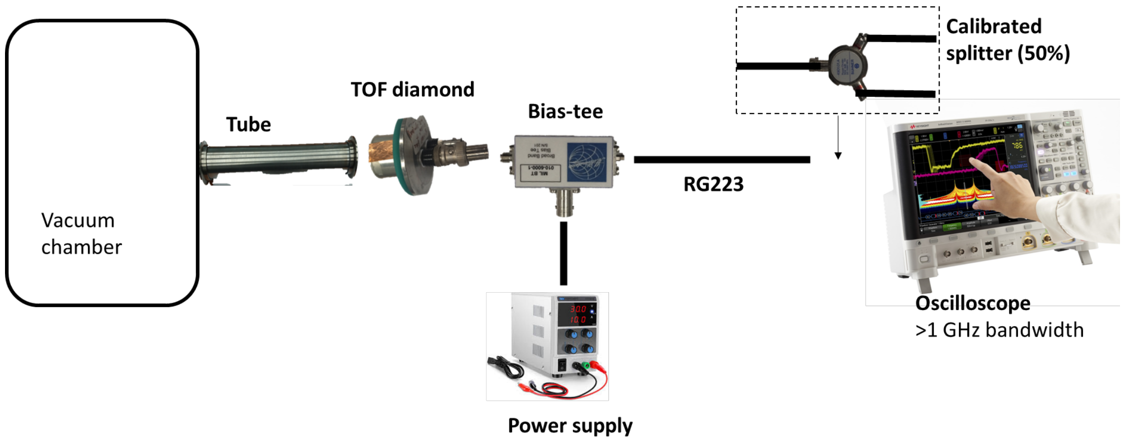


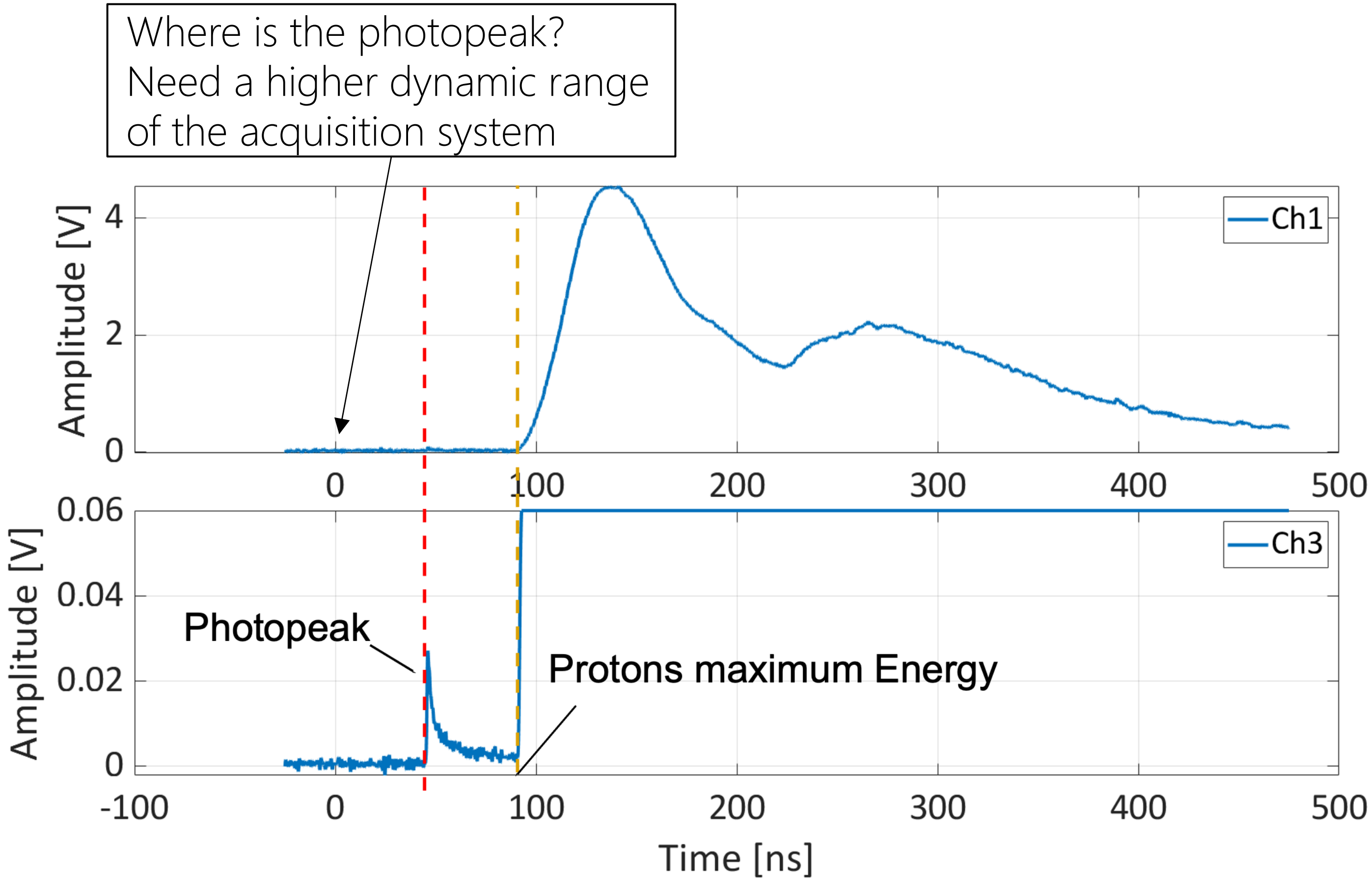


DYNAMIC RANGE ENHANCEMENT

- 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





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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 signa

ANALYTICAL SPECTRUM COMPUTATION

I° method*: For each temporal step, defined by the temporal response of the detector, we can calculate the charge and energy

$$\overline{Q_i} = \int_{t_1}^{t_2} \frac{S_D(\overline{V_i}(t))}{R}\,dt \;\; ; \; \Delta t = t_2 - t_1 = \tau_{drift}$$

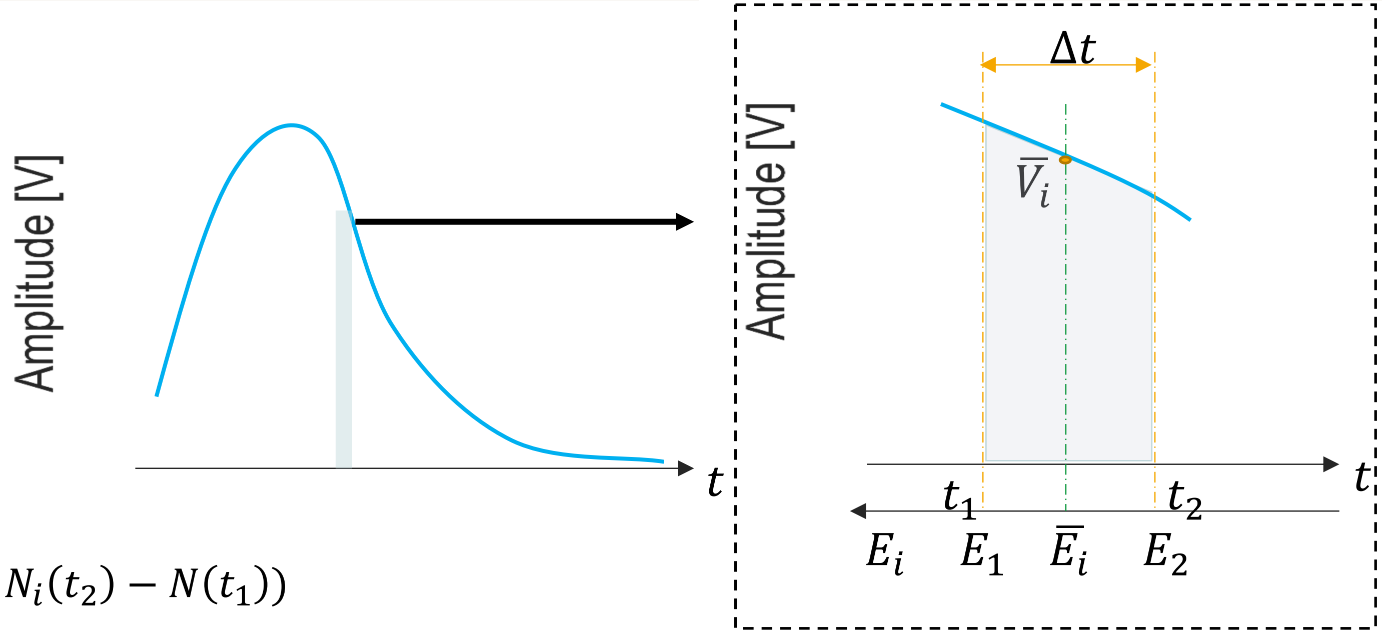
$$\bar{E}_i = m_p\left(\left(1-\left(\frac{v_i}{c}\right)^2\right)^{-1/2} - 1\right)c^2 \;\; ; \; v_i = \frac{d}{t_i - t_0}$$

$$(Energy\ error\ \Delta E_i = m_p \frac{\delta\gamma_i}{\delta t}\Delta t c^2)$$

Number of ions at fixed energy

$$\overline{N_i} = \frac{\overline{Q_i}\epsilon_g}{\eta(E_i)\bar{E}_i q_e}$$

$$(error\ \delta\overline{N_i} = N_i(t_2) - N(t_1))$$



II° method**: By deriving the *dN*, a relation for the signal and the energy distribution can be obtained

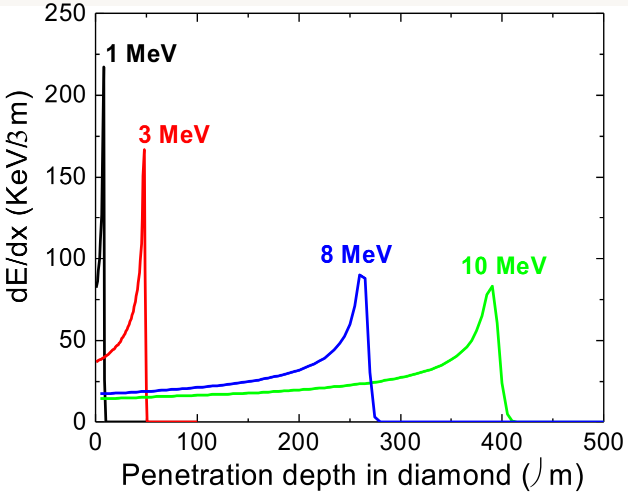
$$dN = \frac{\epsilon_g dQ}{q_e E} = \frac{\epsilon_g V(t)dt}{q_e E R} \;\; ; \; E = m_p(\gamma - 1)c^2$$

$$\left|\frac{dN}{dE}\right| \cong \frac{\epsilon_g V(t) t}{2 q_e E^2 R}$$

A good agreement between the energy spectra extracted from two methods is observed.

*M. Salvadori et al. Scientific Reports 11, 3071 (2021)
**G. Milluzzo et al. Rev. Sci. Instrum. 90, 083303 (2019)

TIME OF FLIGHT (TOF) FOR HIGH ENERGY PROTONS

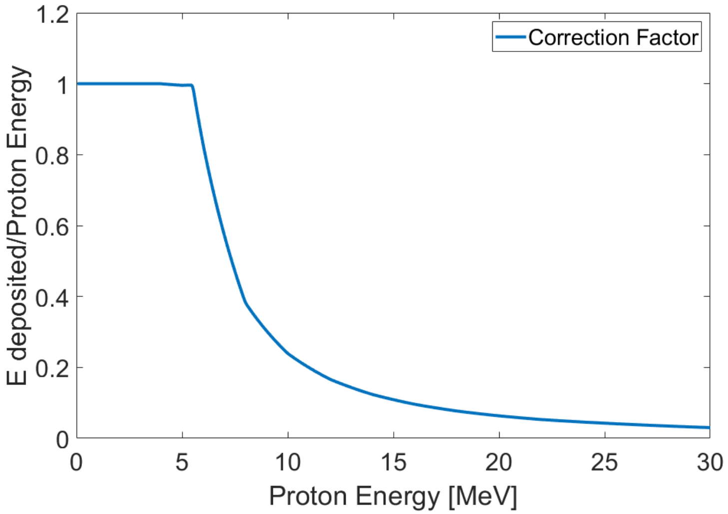


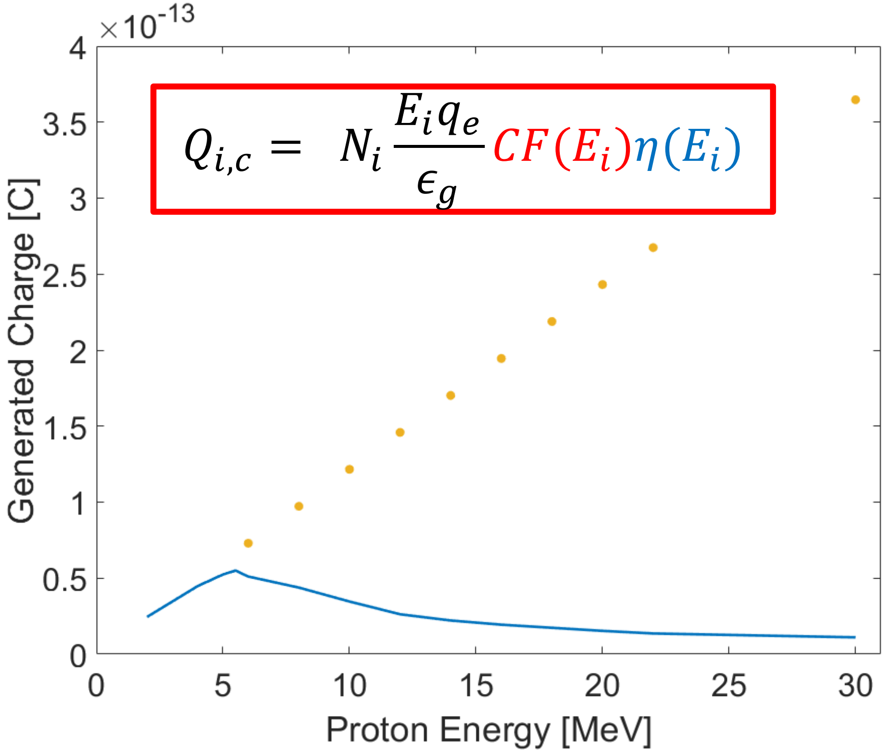
- ➢ Laser-accelerated protons having a range less or equal than the detector's active thickness release completely their energy.
- ➢ High energy particles (tens of MeV) cross the detector volume, releasing only a portion of their actual energy within it, and the generated charge decreases accordingly.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

➢ A correction factor ($CF(E_i)$) for energy released (or produced charge) in the detector must be calculated using SRIM or Geant4 Monte Carlo simulation.

$\boldsymbol{CF} = \mathbf{1}$ the particle is stopped inside the detector: it releases the whole amount of its energy

$\boldsymbol{CF} < \mathbf{1}$ only a portion of the particle energy is released in the diamond bulk





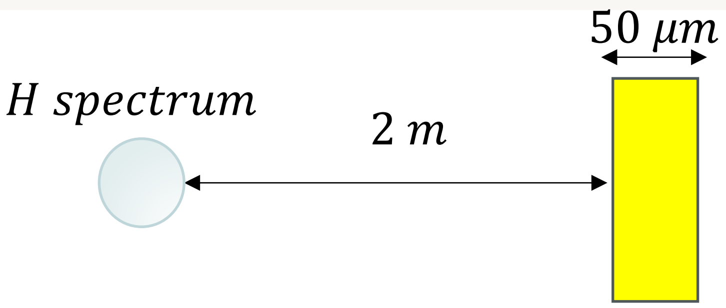
$$Q_{i,c} = N_i \frac{E_i q_e}{\epsilon_g} CF(E_i)\eta(E_i)$$

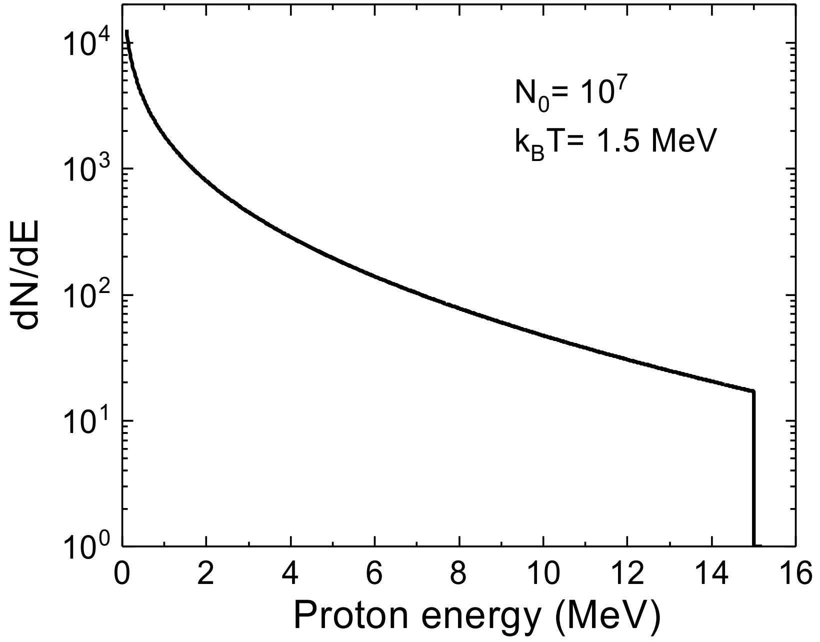
TIME OF FLIGHT (TOF) FOR HIGH ENERGY PROTONS

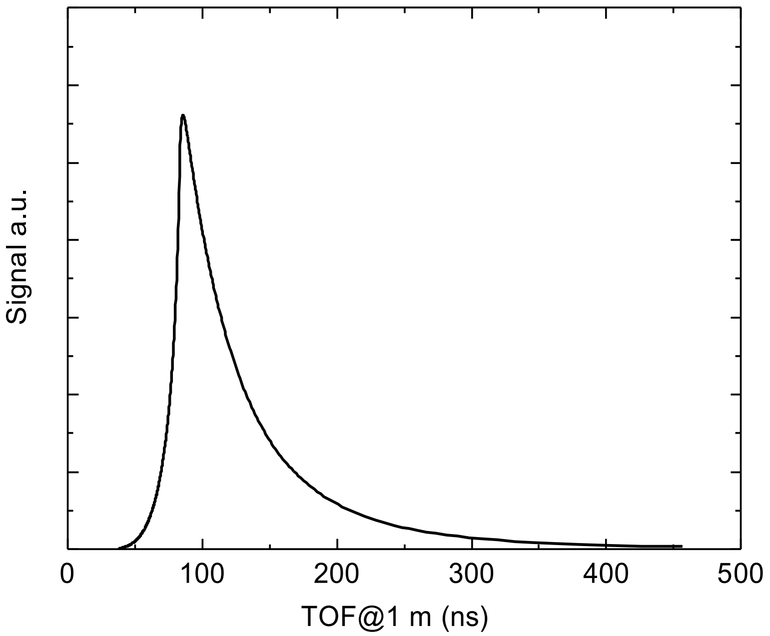
Protons accelerated by laser-plasma typically present a broad and Maxwellian-like spectrum

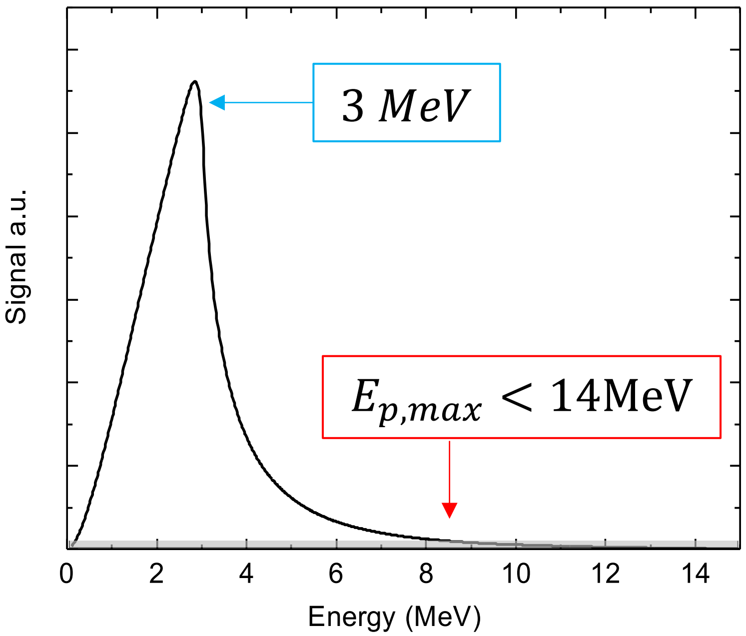
$$\frac{dN}{dE} = \frac{N_0}{\sqrt{2Ek_BT}} \exp\left(-\sqrt{\frac{2E}{k_BT}}\right)$$

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





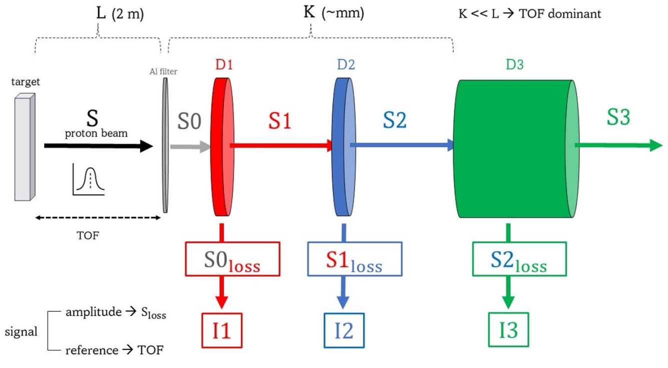




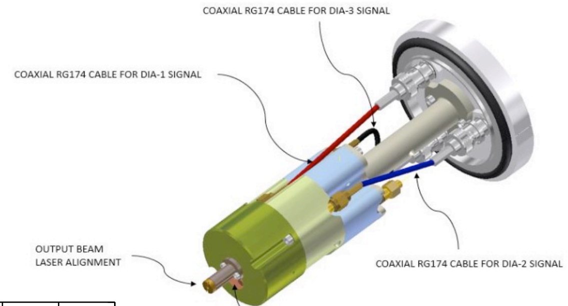
How to overcome this problem?

TELESCOPE CONFIGURATION

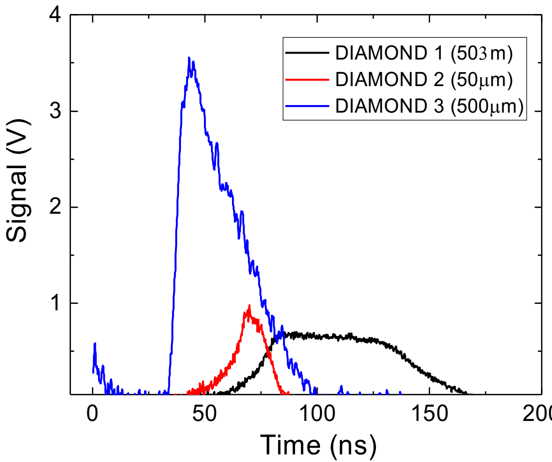
- Development of a **telescope detector**: A stack of multiple detectors arranged consecutively along the direction of ions impinging from laser-matter interaction.
- The main advantage of telescope detector lies in the ability to detect high-energy particles with good sensitivity, without compromising energy resolution.

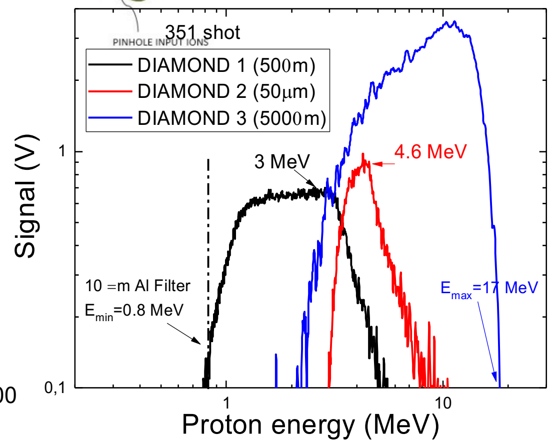


- The use of thin detectors (i.e., 50 μm) could provide high energy resolution and a high radiation hardness for the entire diamond detector.



- The use of a thick detector (i.e. 300 -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.

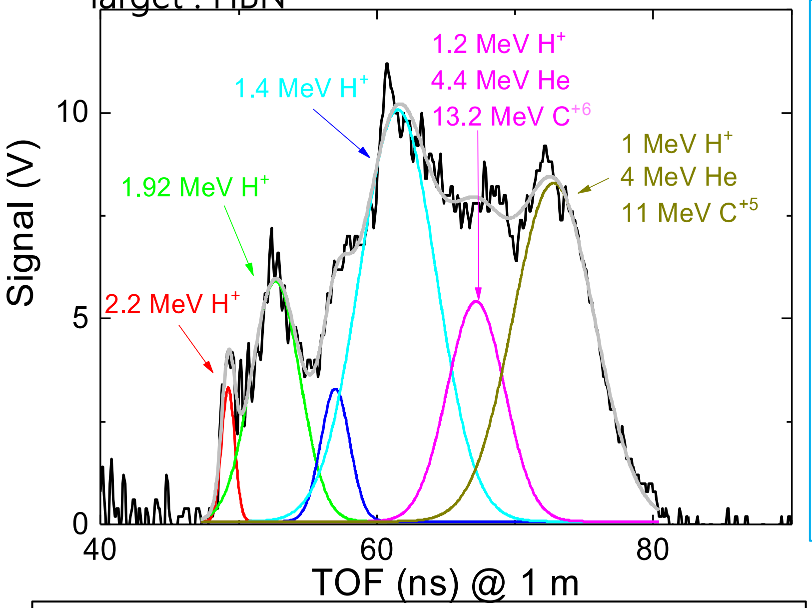




TOF-ION DISCRIMINATION

- ✓ The simultaneous presence of large number of particles makes hard to discriminate them.
- ✓ TOF metodologies 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 (Ex. 1 MeV protons or 4 MeV alpha particles or 12 MeV C^{6+}?)

Target : HBN



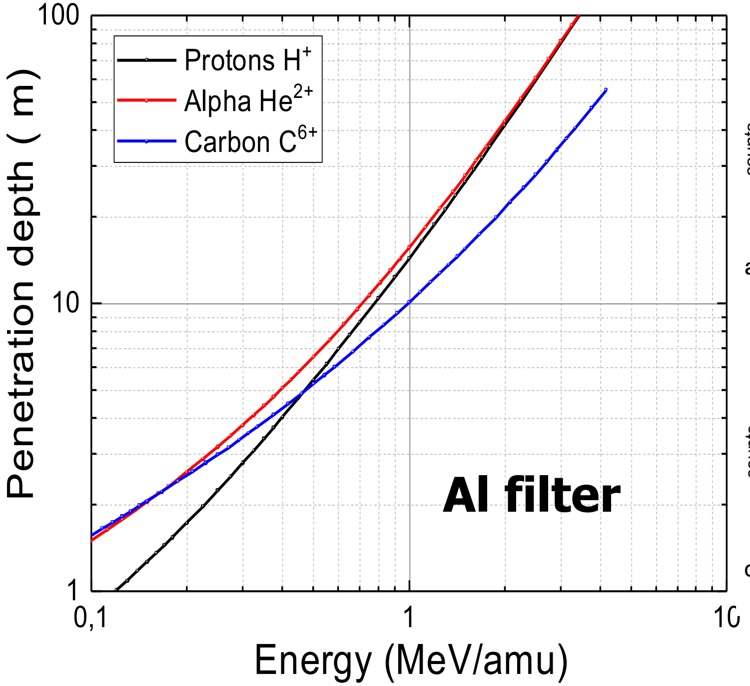
10 μm Al filter	-14.5 μm in Al @ 1 MeV H -15.8 μm in Al @ 4 MeV He - 9.3 μm in Al @ 11 MeV C -11.2 μm in Al @ 13.2 MeV C	

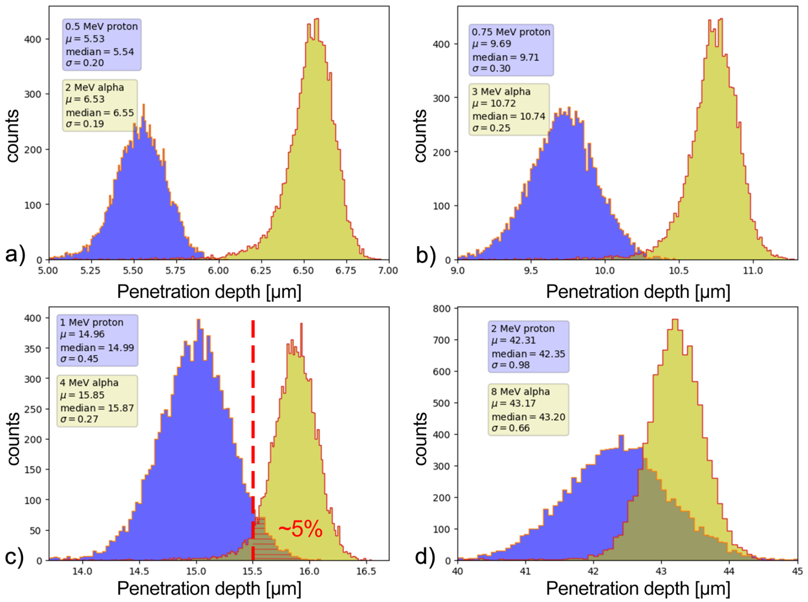
- ➢ Protons, occurring at 49 ns TOF indicate that they have the maximum kinetic energy at 2.2 MeV.
- ➢ The proton energy range is $(E_{p,max}/2,\ E_{p,max})$ where no contribution coming from the superimposition of other ions.
- ➢ The ion acceleration produced by the charge plasma separation in the TNSA regime is of about 2.2 MeV per charge state (Boltzmann-like distribution).
- ➢ Ion energy distributions are shifted toward the higher energy in proportion to their charge state (ex. 13.2 MeV C^{6+} , 11 MeV C^{5+})
- ➢ In $p^{11}B$ fusion experiment, alpha particles (He) centered at about 4 MeV can be also produced.

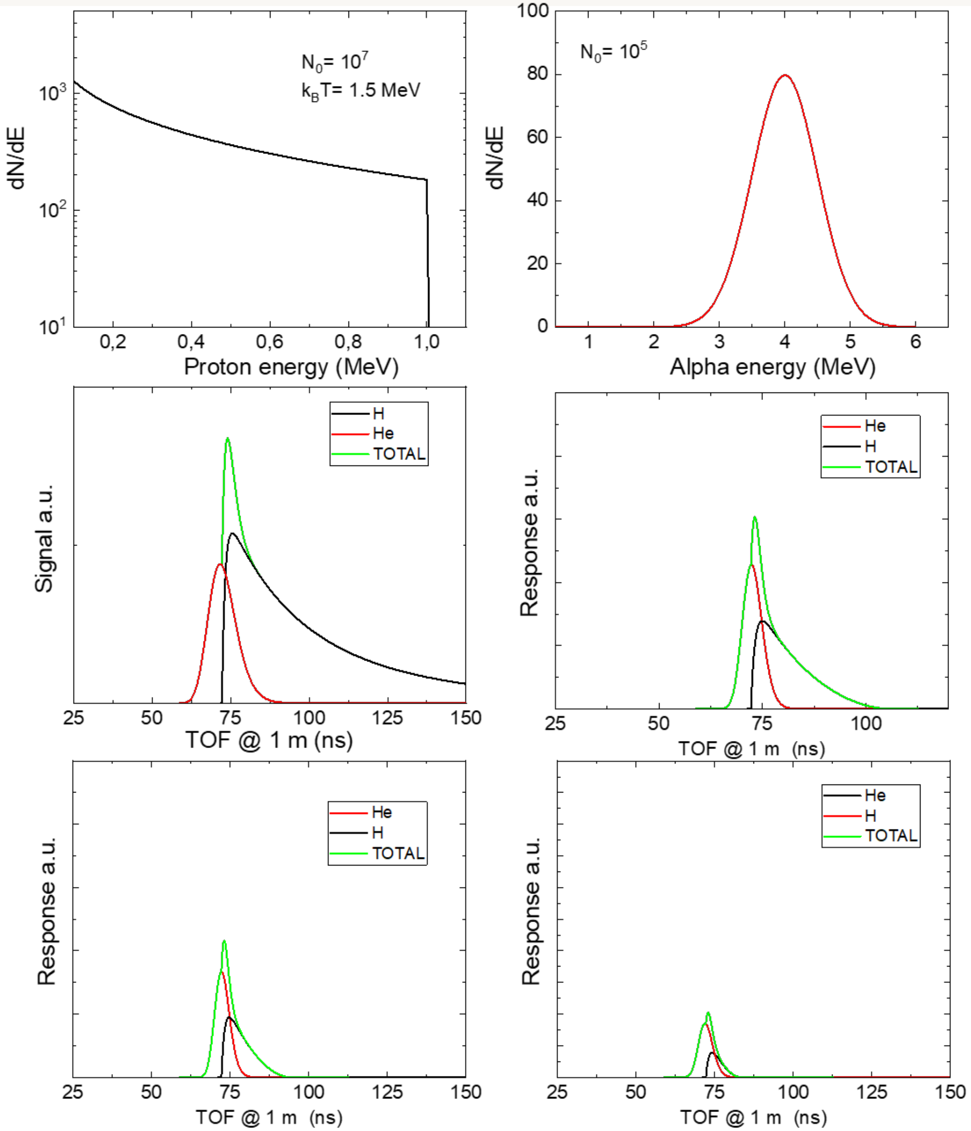
How to overcome this problem?

- ➢ 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.

TOF-ION DISCRIMINATION







- Particle discrimination is not possible for each energy and ion specie.
- At low energies: discrimination difficult for alpha and carbon ions but ok for protons. At high energies (>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.

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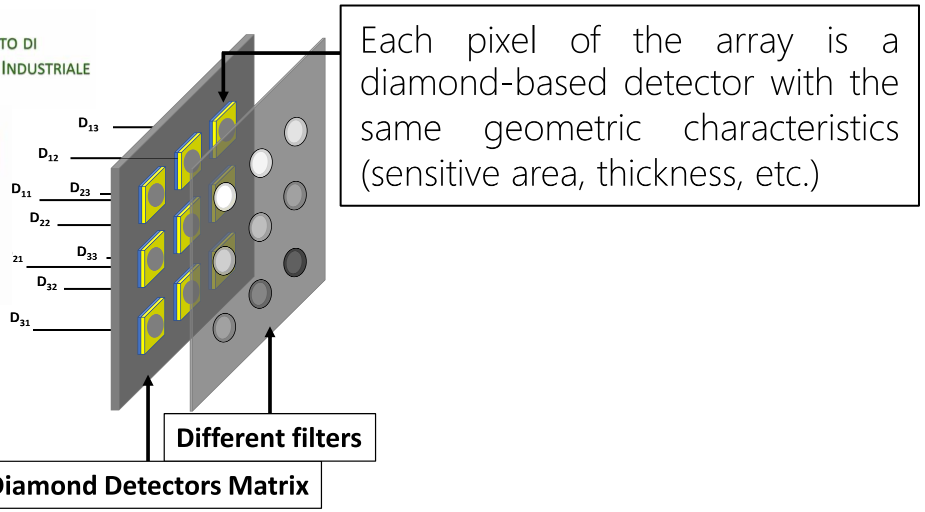
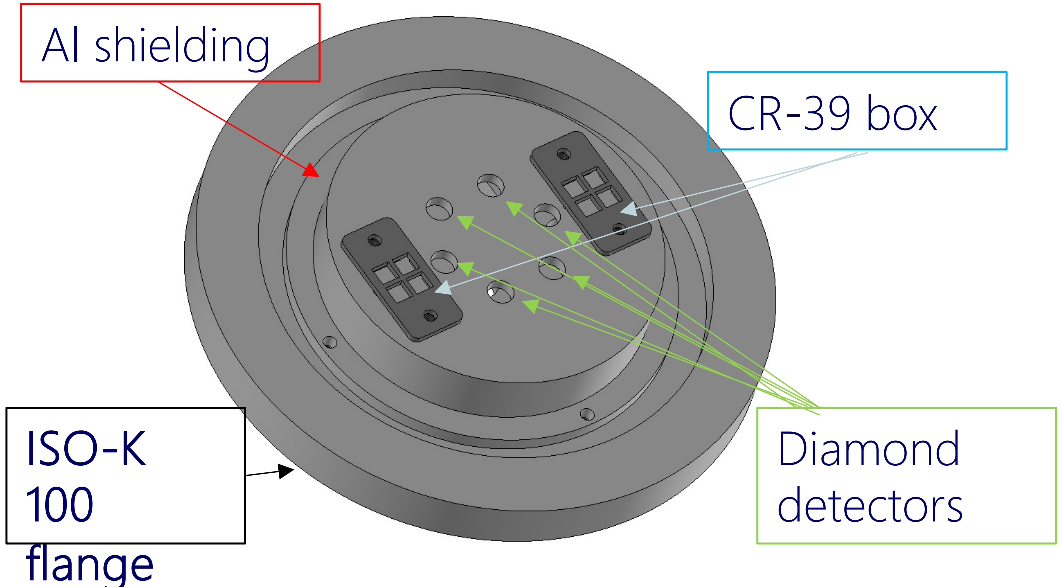
ARRAY CONFIGURATION





- ➢ 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.

METHODOLOGY

1. We start with an assumption of laser-driven ion emission spectra distribution (Boltzmann Distribution for H, C and other ions, Gaussian distribution for He). Spectra distributions depend on few parameters.
2. We employ SRIM data tables to precisely track the energy loss of ions (H, He, C, O, Si, etc.) as they traverse through the filters.
3. Subsequently, we generate a calculated ion distribution impacting the detector for any given ion at any given energy.
4. As a first approximation, the altered ion distribution after passing through the filters modifies the amplitude of the signals (*y*-scale), while the Time of Flight (TOF) (*x*-scale) is correlated with the energies of ion emission spectra.
5. We then calculate the combined signals (V(t)) generated in the detector and compare them to the measured signals.
6. Using convergence methods, ion spectra parameters that best ft the measurements can be selected.

CONCLUSIONS

- ✓ The main ion diagnostics utilized in high-power laser-generated plasma experiments (SSNTD, TP and TOF) are discussed.
- ✓ The optimization of the acquisition system, focusing on electromagnetic pulse (EMP) mitigation and dynamic range, for the Time of Flight (TOF) detector is presented.
- ✓ A telescope configuration for the TOF diagnostic is developed specifically for the detection of high-energy protons.
- ✓ An array of TOF detectors featuring different filter foils is proposed for ion discrimination.

GRAZIE PER L'ATTERNZIONE

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