Time-of-flight diamond detectors for particle detection in laser driven p-B11 fusion experiments

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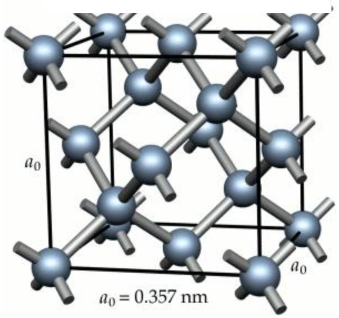
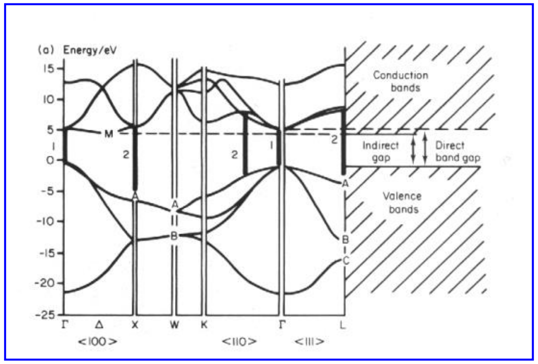
Outline

- Motivations: Why diamond for monitoring the plasma ?
- Fabrication and characterization of our diamond-based detectors.
- P-B11 fusion experimental results at PALS
- Diamond detectors for ion species descrimination
- Conclusions

Diamond properties





HARDNESS	9000 Kg/mm^2
YOUNG'S MODULES	1012 N/m^2
FRICTION	0.05
THERMAL CONDUCTIVITY	20 W/cm K
ELECTRICAL RESISTIVITY	10^{16} Ωcm
ELECTRICAL BREAKDOWN	10^7 V/cm
ELECTRON, HOLE MOBILITY	>2000 cm2/V s
OPTICAL ABSORPTION	transparent from IR to IV (5.4 eV)
MELTING POINT	3350 °C
RADIATION HARDNESS	very high
CHEMICAL REACTIVITY	extremely low

Energy Gap 5.5 eV → *225nm Cutoff Wavelength*; *Few thermal charge Carrier*; *High breakdown electric field*

Physical Properties → *Strong chemical bond*; *High thermal conductivity*

Electric Properties → *Low dielectric constant*; *High electric charge mobility*

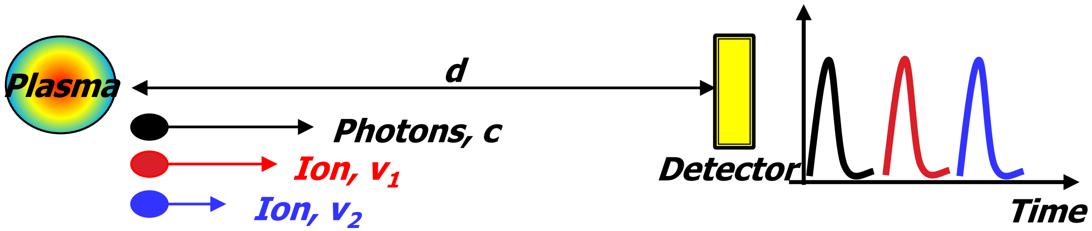
→ *Solar Blindness*; *High X-UV sensitivity*; *Low-dark current*; *High temperature operation*

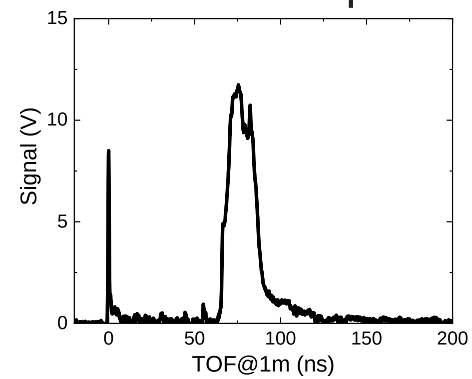
→ *Radiation Hardness*; *Mechanical Robust*

→ *High power dissipation*; *Fast response time*; *Low Capacitance*

TOF Diamond based detector

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





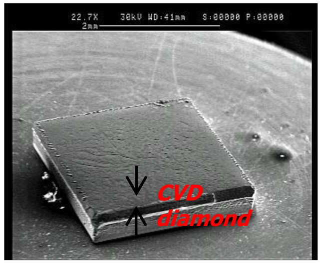
- TOF diamond detectors are an ideal ion diagnostic:
  - ✓ Very short and narrow photopeak (visible blindness properties)
  - ✓ High energy resolution (fast response time)
  - ✓ Good signal to noise ratio (low dark current and EMP noise suppression)
  - ✓ High radiation hardness
  - ✓ High dinamic range (optimization of electronic read-out)
  - ✓ Capability to supply both ion energy spectrum* and angular distribution**

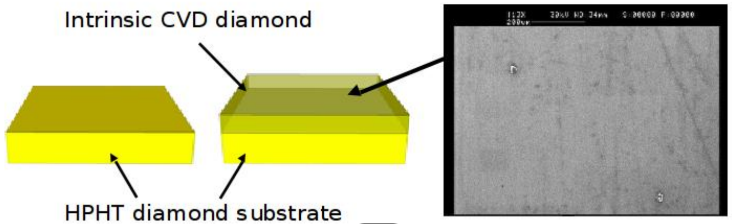
*M. Salvadori et al. Scientific Reports 11, 3071 (2021)

**G. Milluzzo et al. submitted to Laser and Particle Beams

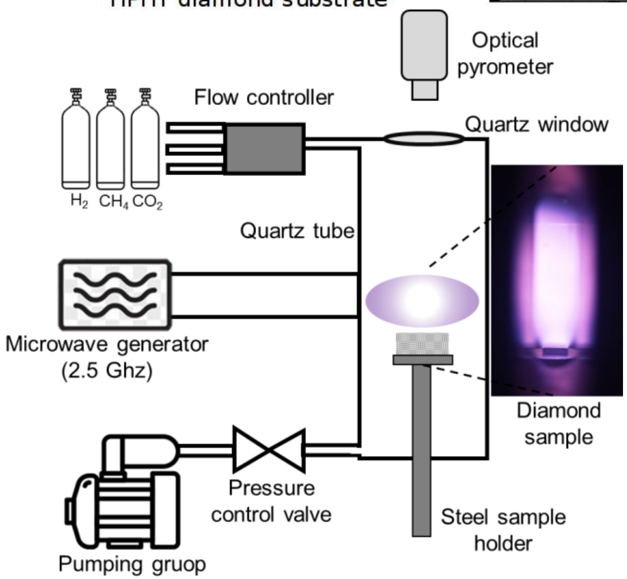
Single Crystal Diamond film synthesis

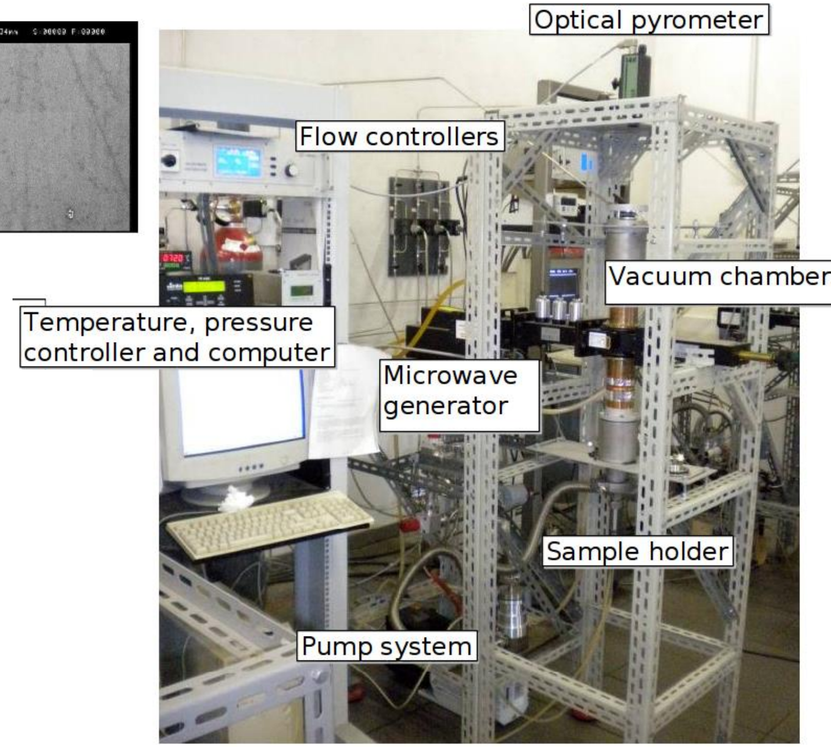
The apparatus of CVD diamond deposition





- ***Diamond film is deposited by Microwave Plasma Enhanced Chemical Vapour Deposition (MWPECVD) on a commercial low-cost diamond substrate.***





Substrates

(100) HPHT type Ib 4×4 mm²

Doping

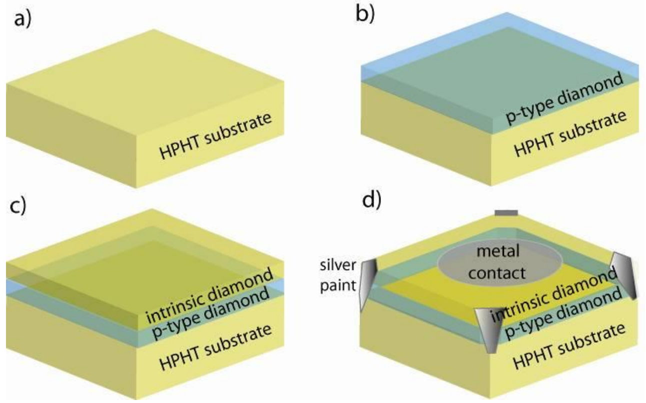
✓ ***B_2H_6 10-30 sccm***

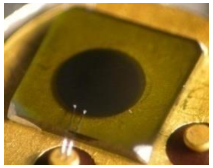
Typical growth parameters

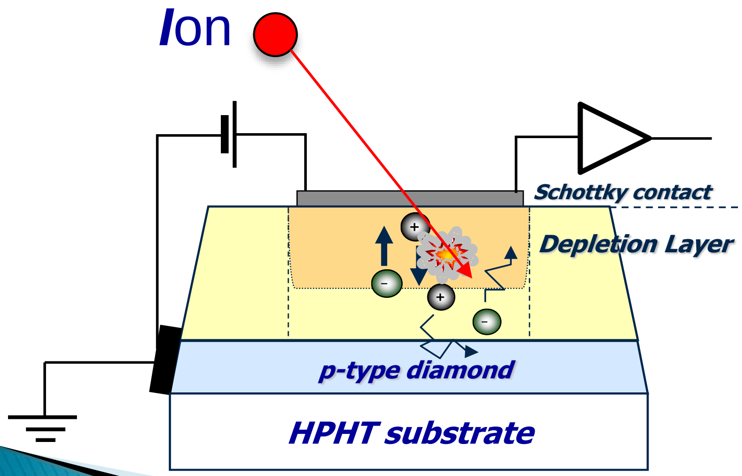
➢ ***Plasma composition***	***99% H_2- 1% CH_4***
➢ ***Temperature***	***650 ÷ 800 °C***
➢ ***Microwave power***	***500 ÷ 1300 W***
➢ ***Pressure***	***100 ÷ 150 mbar***
➢ ***Gas flow rate***	***100 sccm***

Diamond based detector: transverse and planar configuration

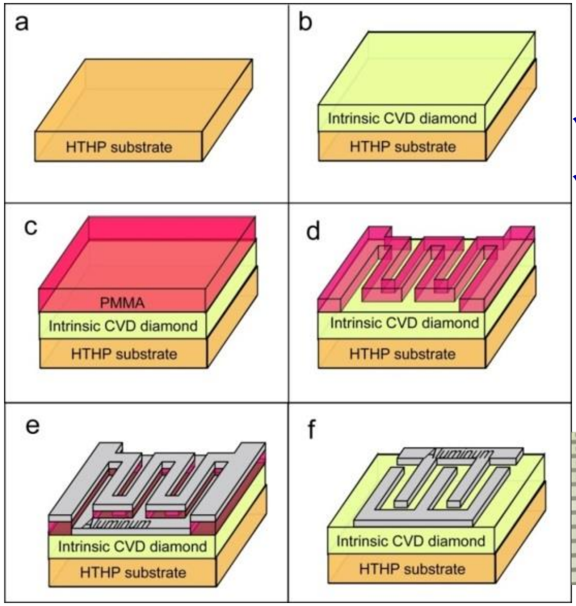
Fabrication process of diamond detector operating in transverse configuration



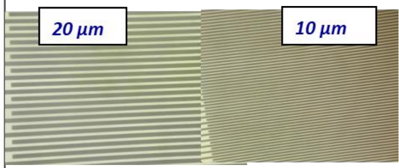


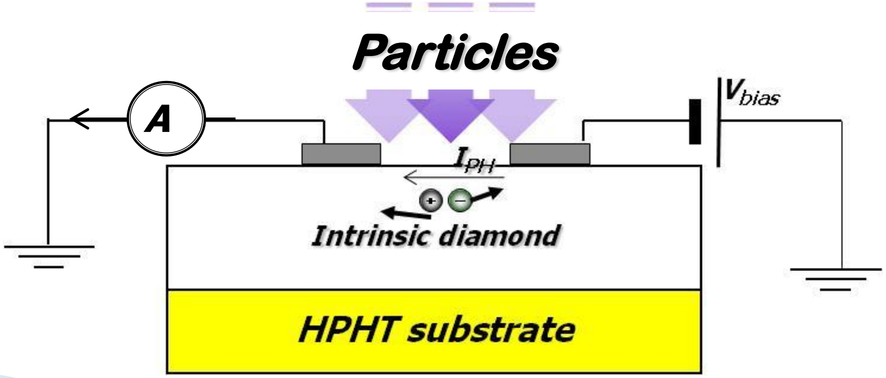


Fabrication process of diamond detector operating in planar configuration



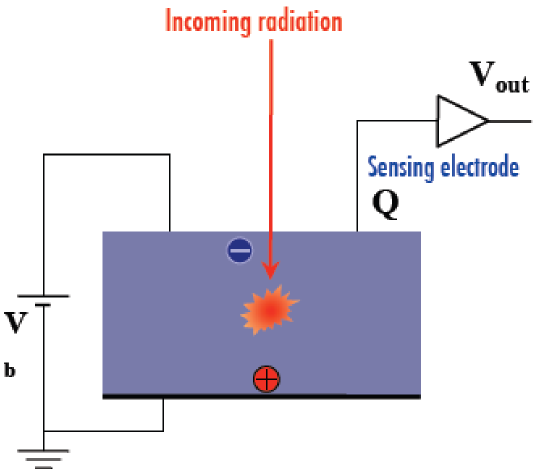
- ✓ *Small dimensions*
- ✓ *Low voltage operation*



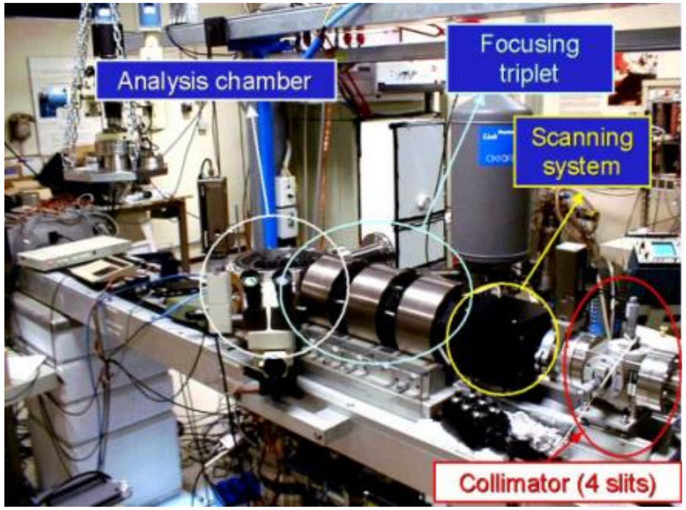


Ion Beam Induced Charge characterization

IBIC characterization were carried out at the micro-beam facility of the Italian National Laboratories of Legnaro by raster-scanning a 1 MeV proton micro-beam over the active area of the diamond detectors.

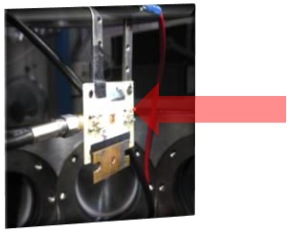


- MeV ion energy deposition
- Electron/hole pair generation
- Motion of carriers according to device electrostatics
- Induced charge at the sensing electrode
- Output signal Vout



The observable is the charge collection efficiency (CCE) at the sensing electrode:

$$\mathrm{CCE} = \frac{\text{induced charge}}{\text{generated charge}}$$



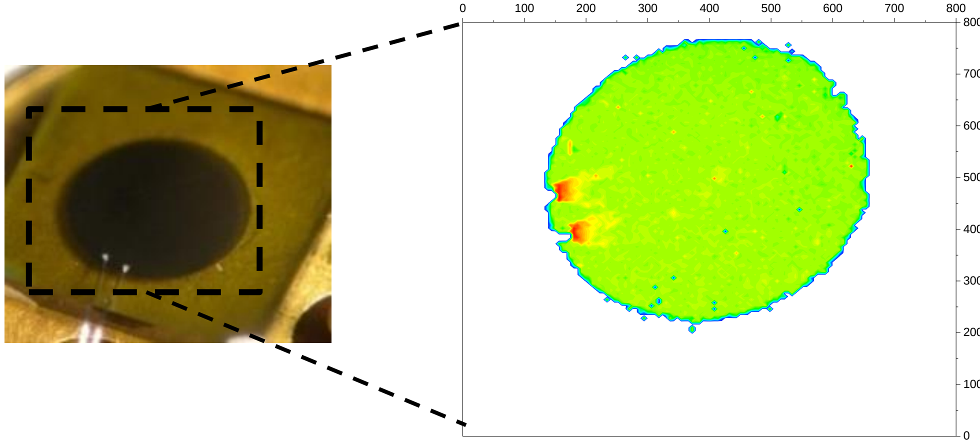
Ions: H^+

Energy: 0.5-2 MeV

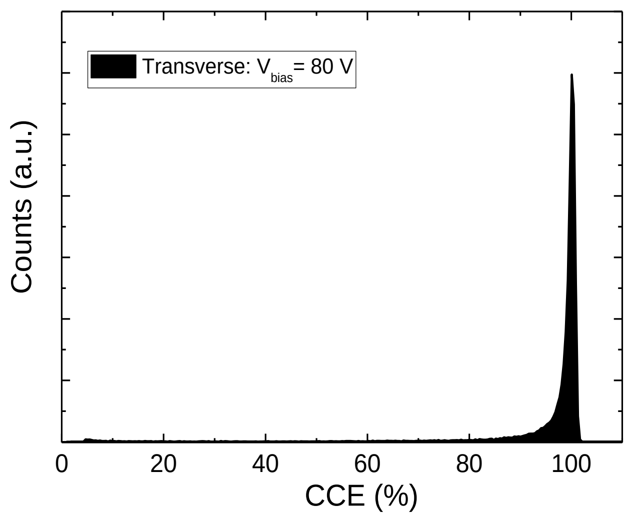
Current: ~ 100 ions/s

Beam spot size: ~ 5 μm

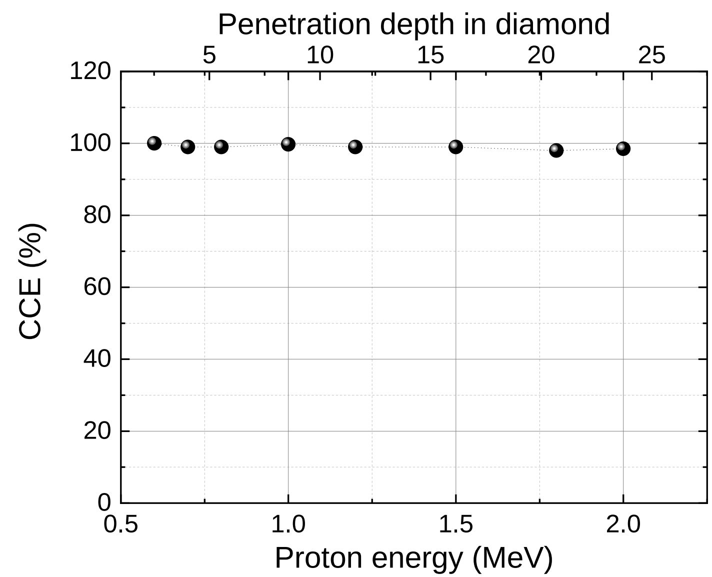
Diamond detector characterization: CCE



CCE map@1 MeV H^+

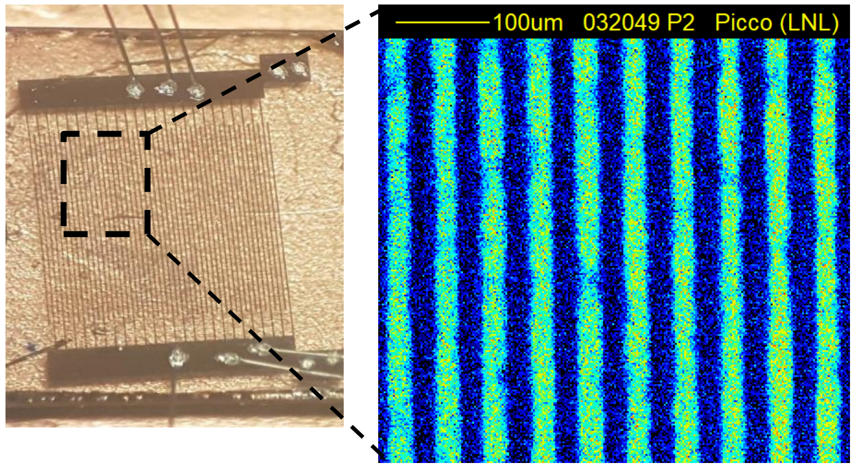


Energy spectrum @1 MeV H^+

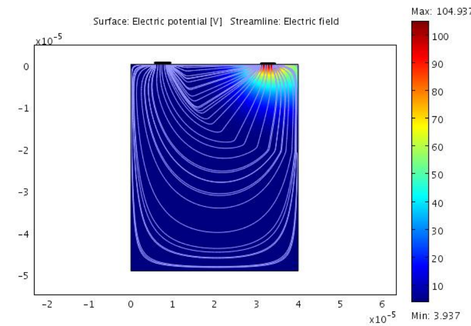


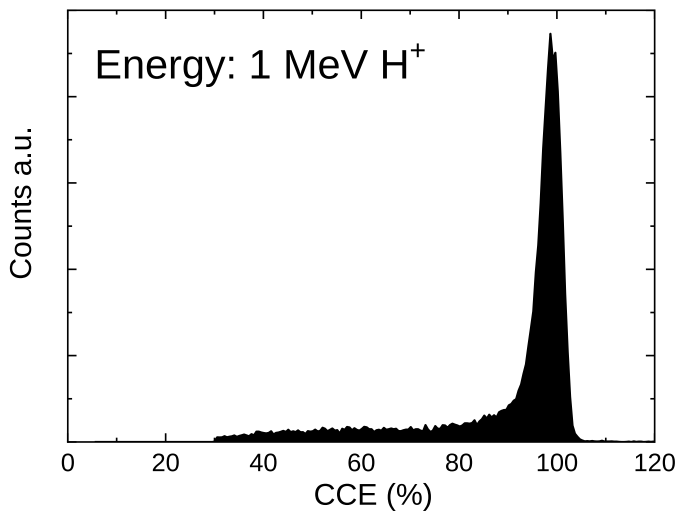
CCE as a function of proton energy

Diamond detector characterization: CCE

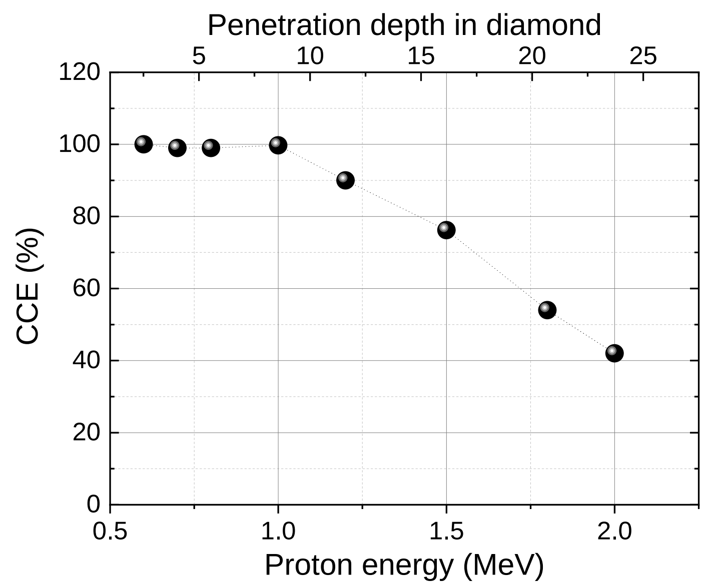


CCE map@1 MeV H^+





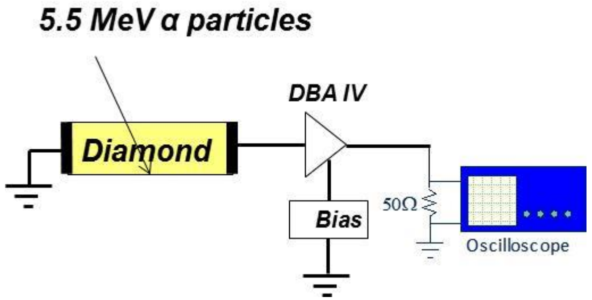
Energy spectrum @1 MeV H^+



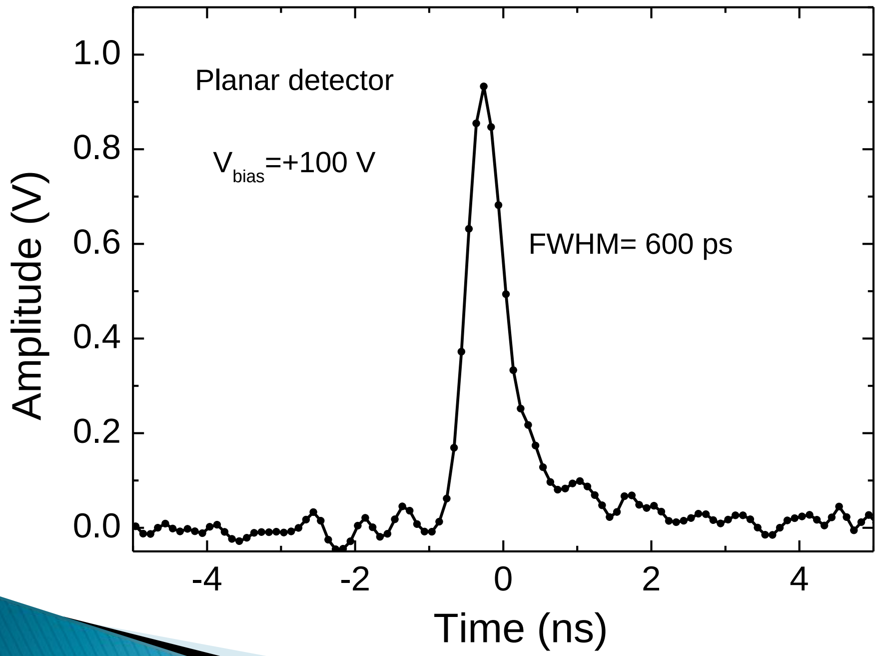
CCE as a function of proton energy

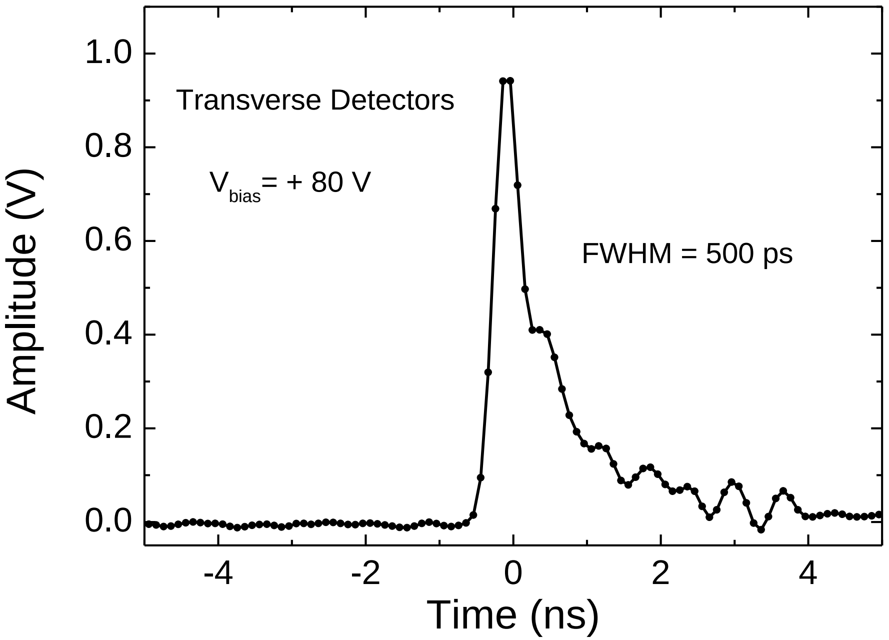
Diamond detector characterization: time response

The detector was placed in vacuum at approximately 2 cm in front of the ^{241}Am source. For such measurement, a low noise Diamond Broadband Amplifier (DBA-IV) was used as fast front-end electronics coupled to a digital fast scope (2.3 GHz bandwidth and 50GHz sampling rate).



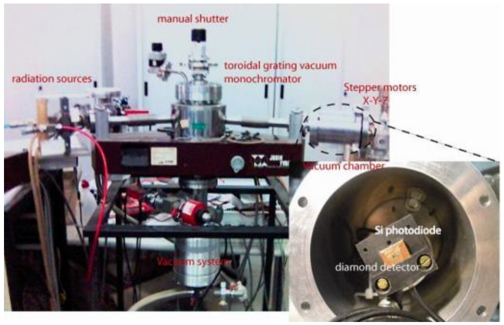
Diamond thickness ~30 μm





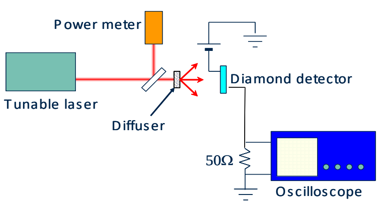
Diamond detector characterization: Extreme-UV / visible ratio

Continuous irradiation



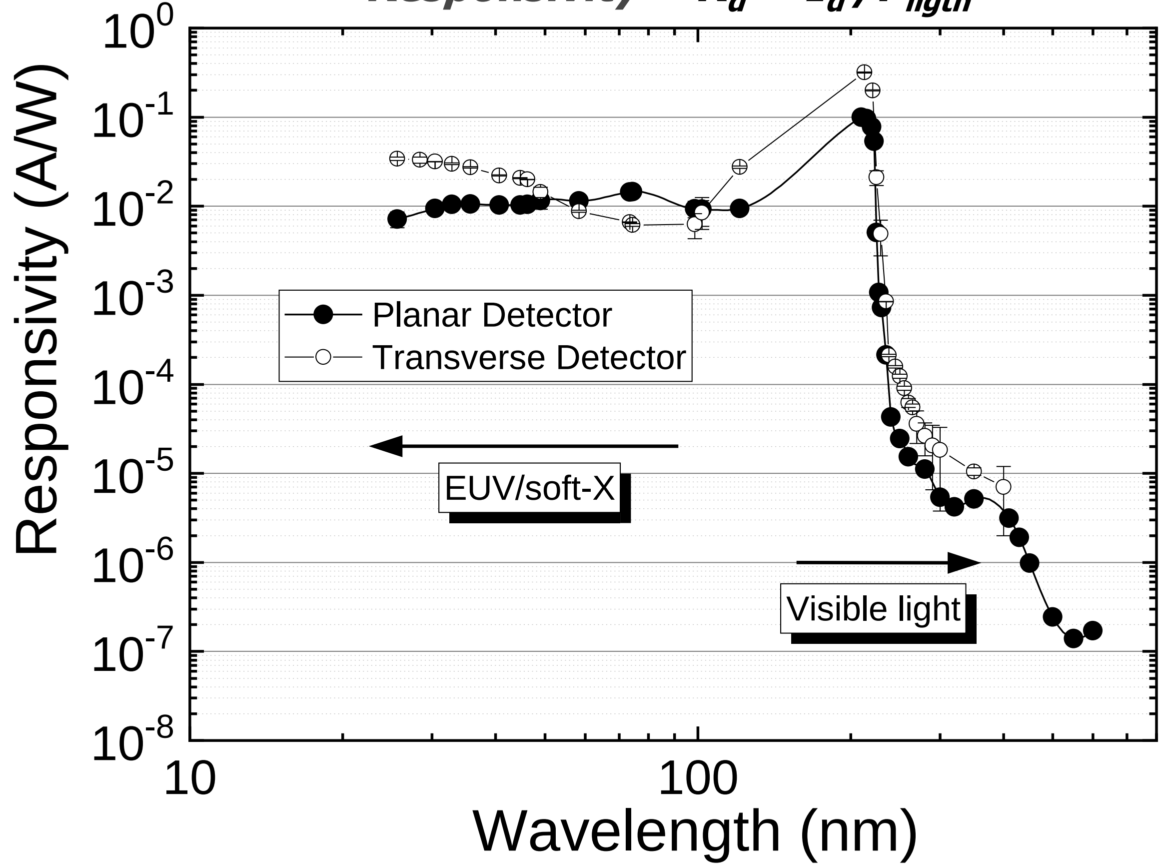
- *EUV toroidal grating vacuum monochromator*
- *20 - 130 nm spectral range*
- *DC He/Ne gas discharge radiation sources*

Fast pulses



- *Tunable laser source (210 – 2400 nm)*
- *5 ns pulses*

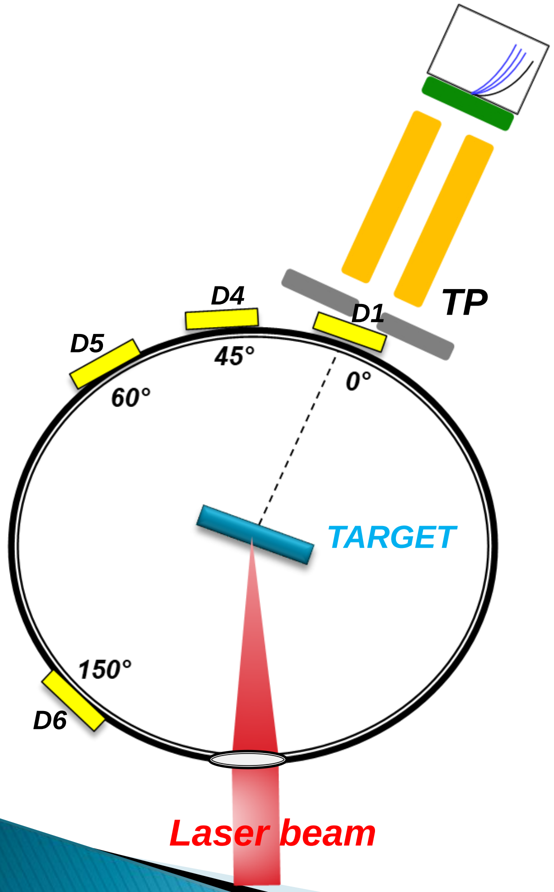
Responsivity $R_d = I_d / P_{ligth}$



- **The spectral response shows a visible/UV rejection ratio of about 4/5 orders of magnitude moving across the band gap of diamond.**

Experimental set-up at PALS

The experimental run was carried out at the PALS (Prague Asterix Laser System) facility in Prague: λ=1315 nm E= 600 J, δt= 300 ps (FWHM)

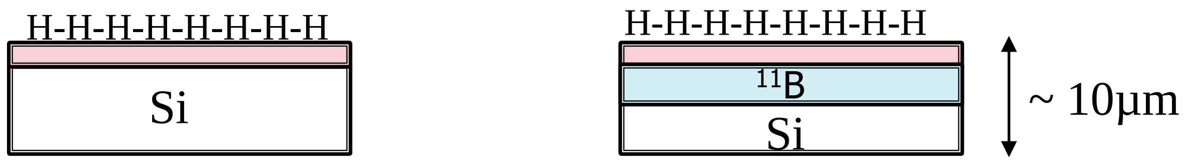


The laser beam passing through a focusing lens reaches the target (30° incidence angle). Particle emission is mainly along the normal to the target surface.
Several diamond detectors were placed at different angles. Diamond detector was installed very close to the Thomson Parabola spectrometer (TP) entrance slit A at 0°.

Diamond detector	Angle	Distance	Al filter	Proton energy cut-off	Alpha energy cut-off
D1	0°	1.49 m	6 μm	600 keV	2.2 MeV
D4	45°	1.46 m	6 μm	600 keV	2.2 MeV
D5	60°	1.51 m	6 μm	600 keV	2.2 MeV
D7	150°	0.85 m	6 μm	600 keV	2.2 MeV

- ***Forward and backward emission of the plasma (Thin Target)***

***by the Micro-Nano Facility of the Fondazione Bruno Kessler**



SiH (reference target)

SiHB

Proton (p) – boron (^{11}B) nuclear reaction:

$$11B + p \rightarrow 3\alpha + 8.7\ MeV$$

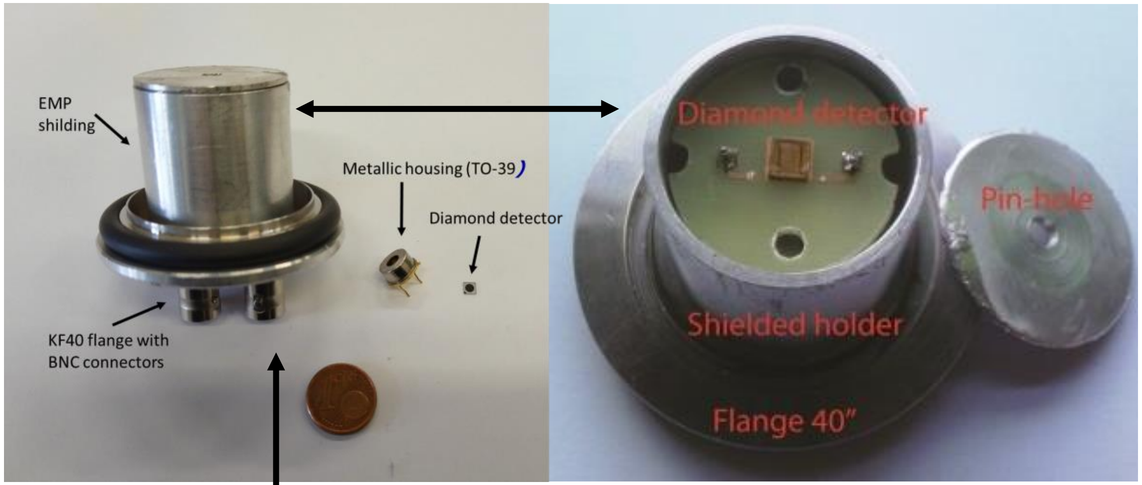
Maximum resonance at 600 keV in the system center of mass. This reaction generates alpha particles with an energy distribution centered at aroun 4.3 MeV (α_1). A secondary channel generating alpha particles in the range 6-10 MeV (α_2) can also be present.

Experimental set-up at PALS

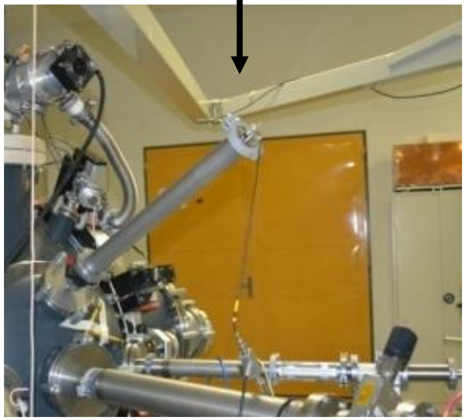
- Diamond detectors are placed in a shielded holder having a pin-hole to collimate the radiation only on the detector sensitive area in order to reduce the electromagnetic pulses (EMPs) due to the laser-plasma interaction

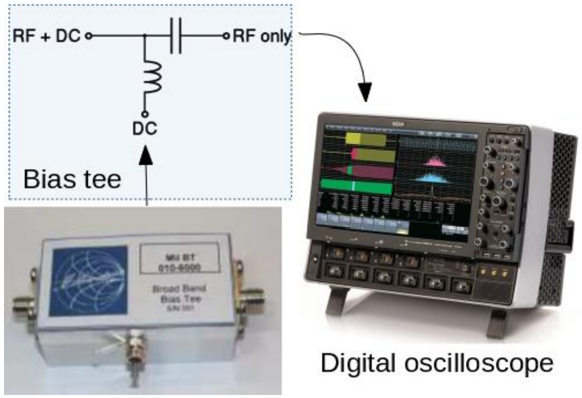
- Diamond detectors are connected to fast oscilloscope (1 Ghz) terminated in 50 Ω though commercial Bias-T and low-noise cables.

- The diamond detectors are generally placed at a distance of the order of 1 m from the target surface in different directions by using vacuum tubes.



Diamond detectors

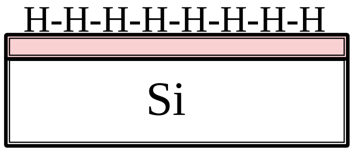




Read-out electronics

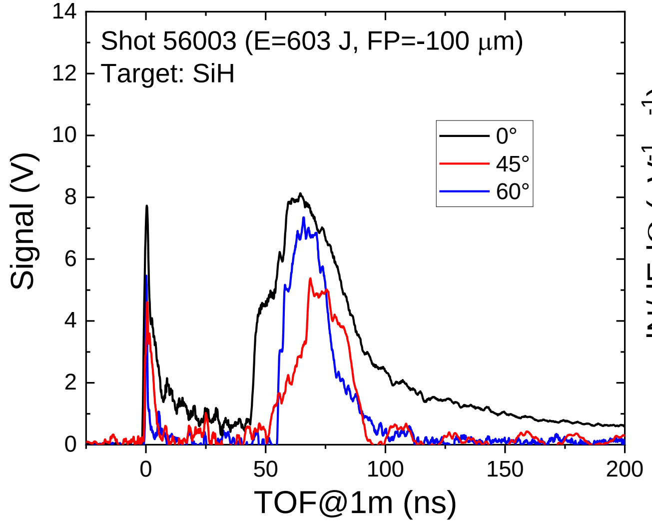
Results at PALS

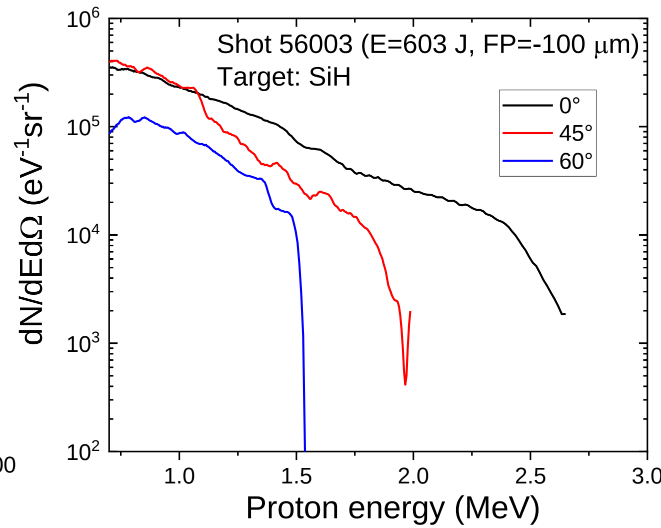
• ***Forward emission of protons (Thin Targets)***

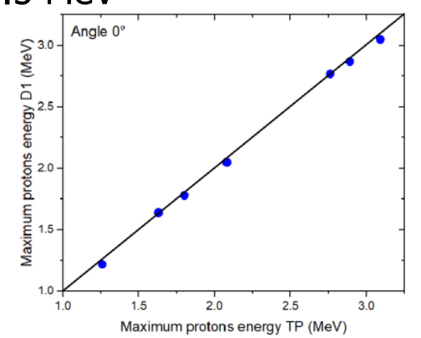


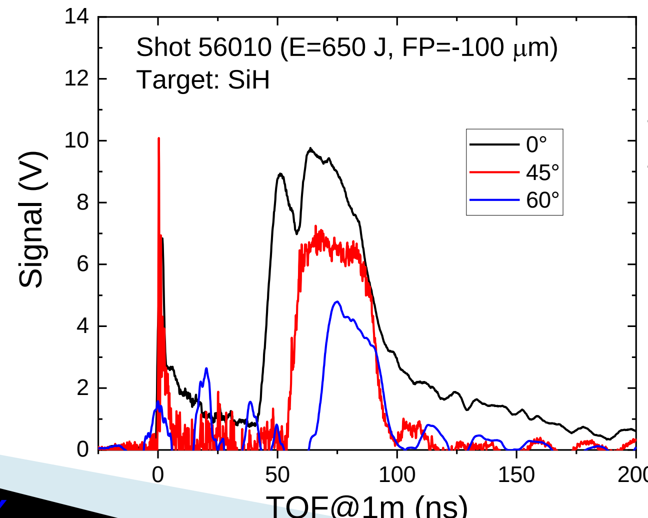
SiH (reference target)

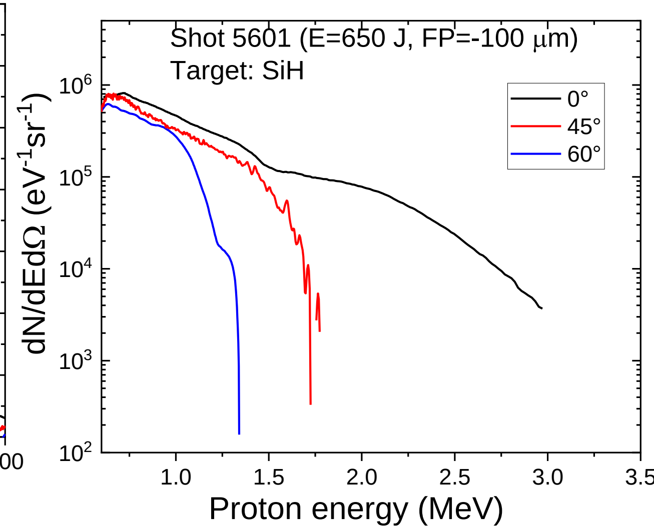
- ✓ Proton energy distributions at different angles is measured by diamond detectors.
- ✓ Maximum proton energy is measured up to 3 MeV.
- ✓ Maximum proton energy decreases as the emission angle with respect to the target normal increases
- ✓ At 60°, the proton energy is below 1.5 MeV





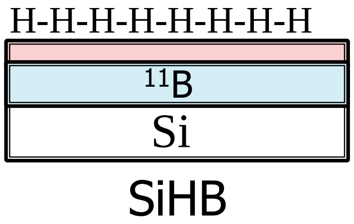




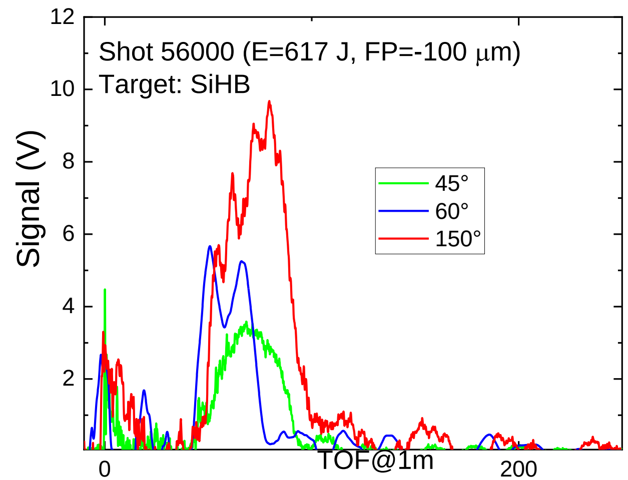


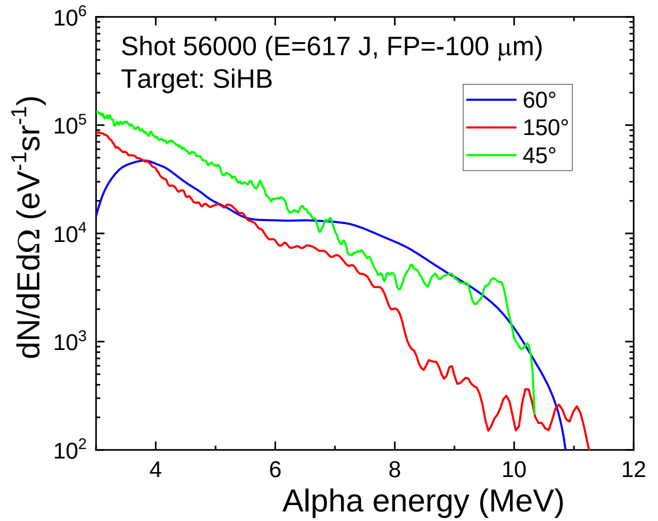
Results at PALS

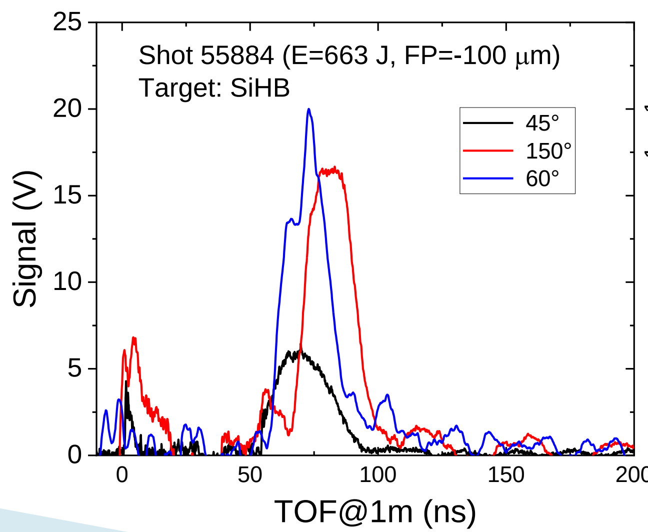
•Forward and beckward emission of alpha particles (Thin Targets)

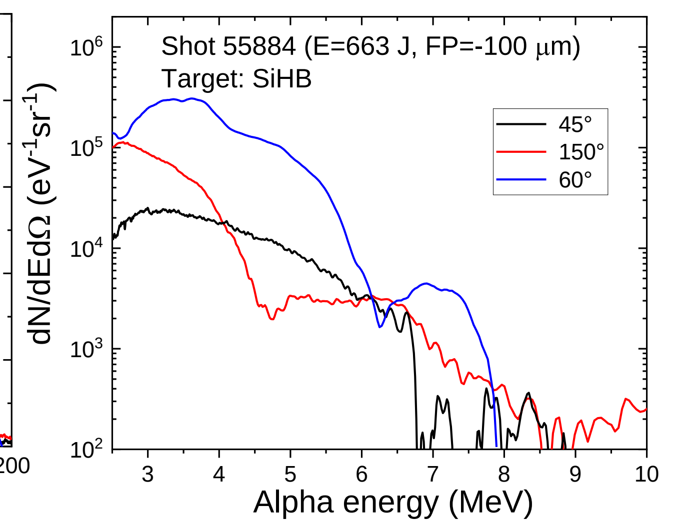


- ✓ The maximum alpha energy is in the range 8 MeV (2 MeV H) and 10 MeV (2 MeV H) at larger angles
- ✓ Such maximum energies detected with SiHB targets are higher than the ones observed in the reference shot
- ✓ It is reasonable to assume that such increase in the maximum energy detected at larger angles can be ascribed to the contribution of alpha particles



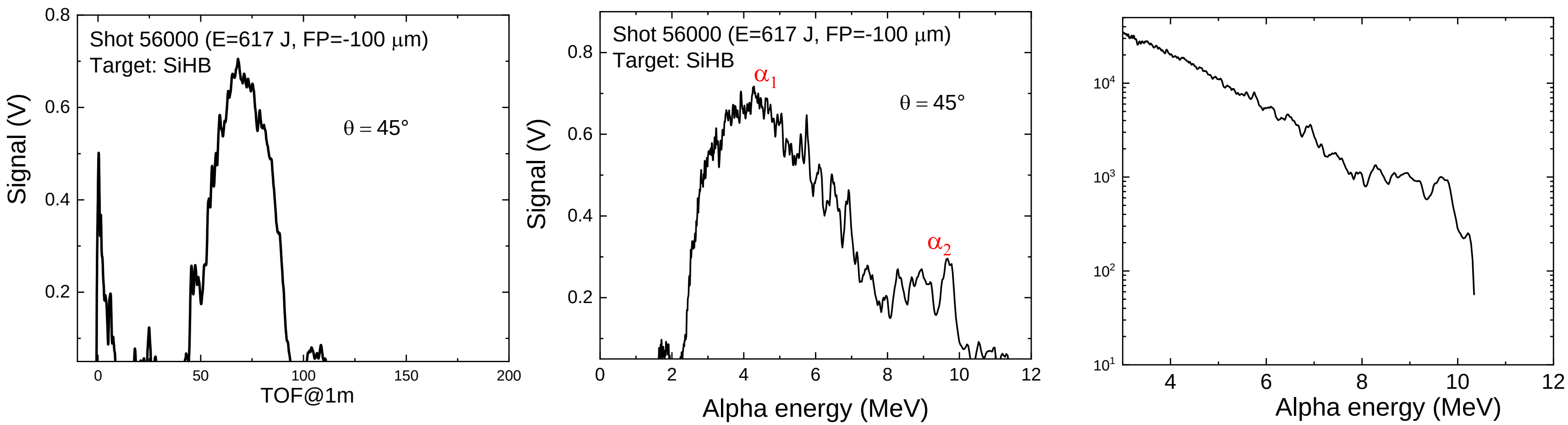






Discrimination of alpha particles

! Discrimination of alpha particles produced by the p-11B reactions !



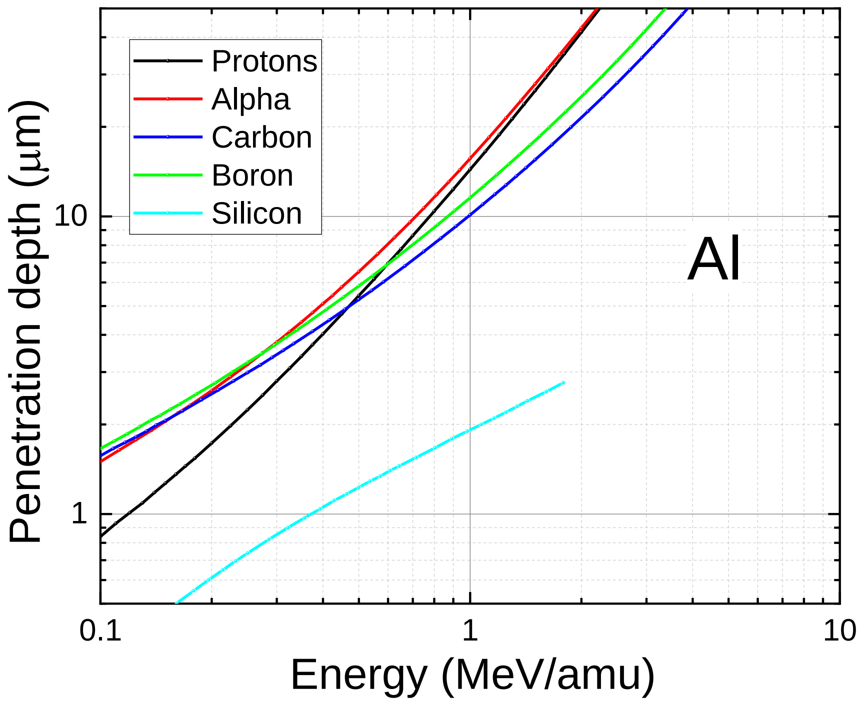
- ✓ TOF techniques provide information on the overall energy of ions <u>BUT DO NOT</u> supply information on the particle type.
- ✓ Particles reaching the detector at a given time instant have the same velocity, and thus the same energy per nucleon (Ex. 1 MeV protons or 4 MeV alpha particles?)

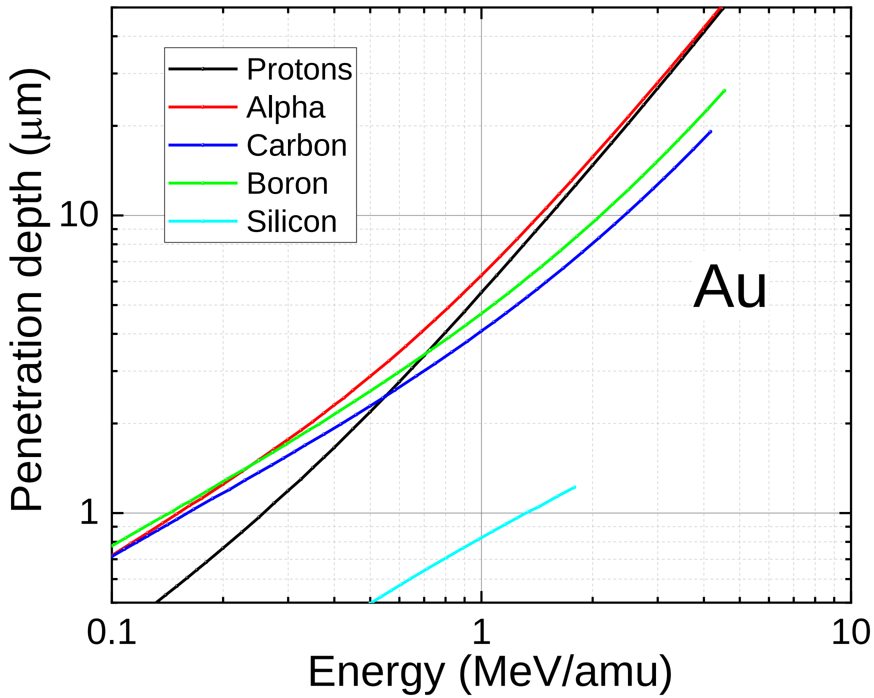
How to overcome this problem?

> Array of diamond detectors, nominally identical, featuring different calibrated foil filters of different thicknesses. These are used by exploiting the different stopping powers and range of ions of different species and energies, in order to have online hints on the type of incoming ions

Particles Identification

Idea for discriminating particles

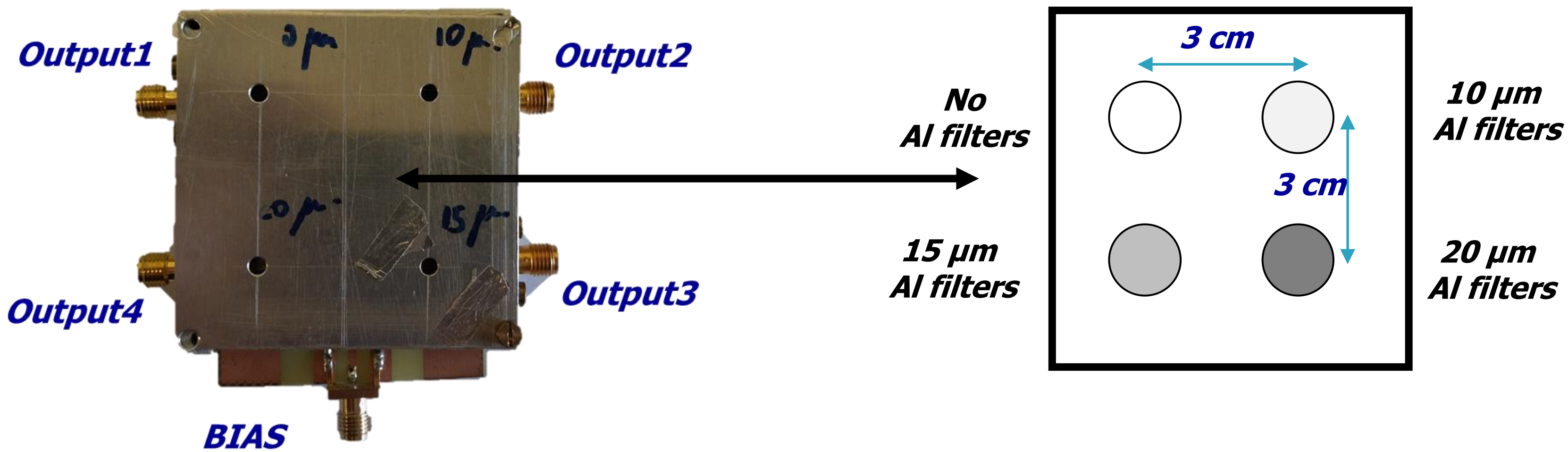




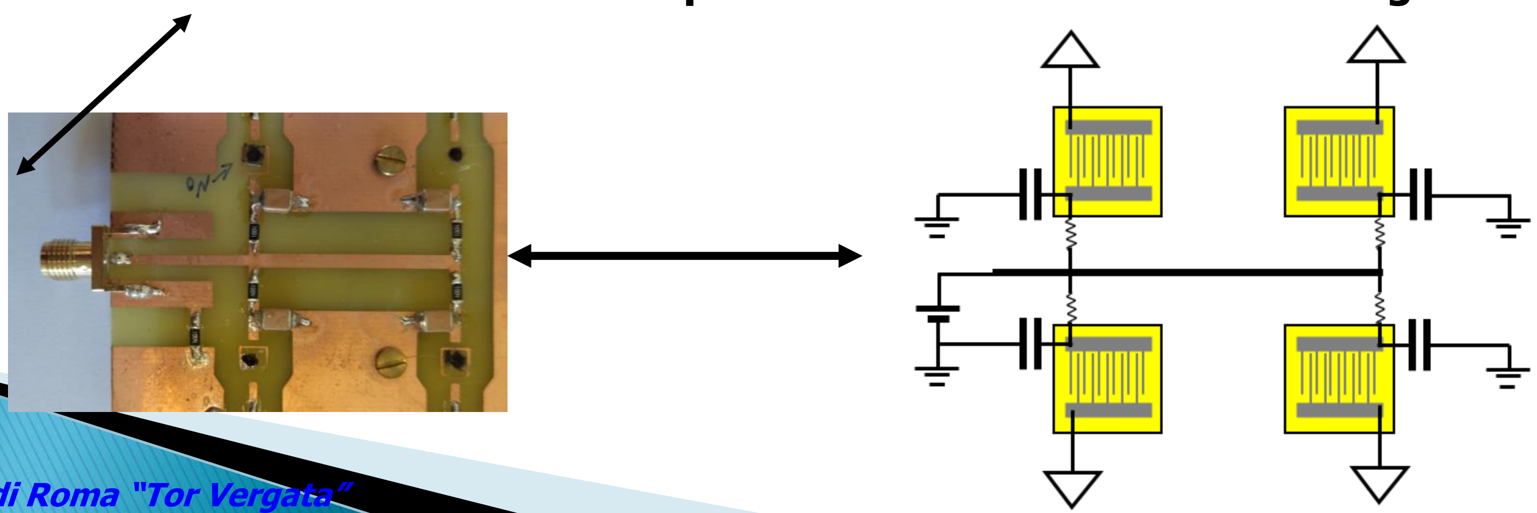
- Discrimination is not possible for each energy and ion specie!
  - At low energies: discrimination difficult for alpha, boron, carbon ions but ok for protons and silicon ions.
    - At high energies (>1 MeV/amu), no discrimination is possible between protons and alphas but ok for the other ions
      - A study on the optimal materials and thicknesses for the different filters to be simultaneously used is necessary.

First prototype of TOF detector matrix

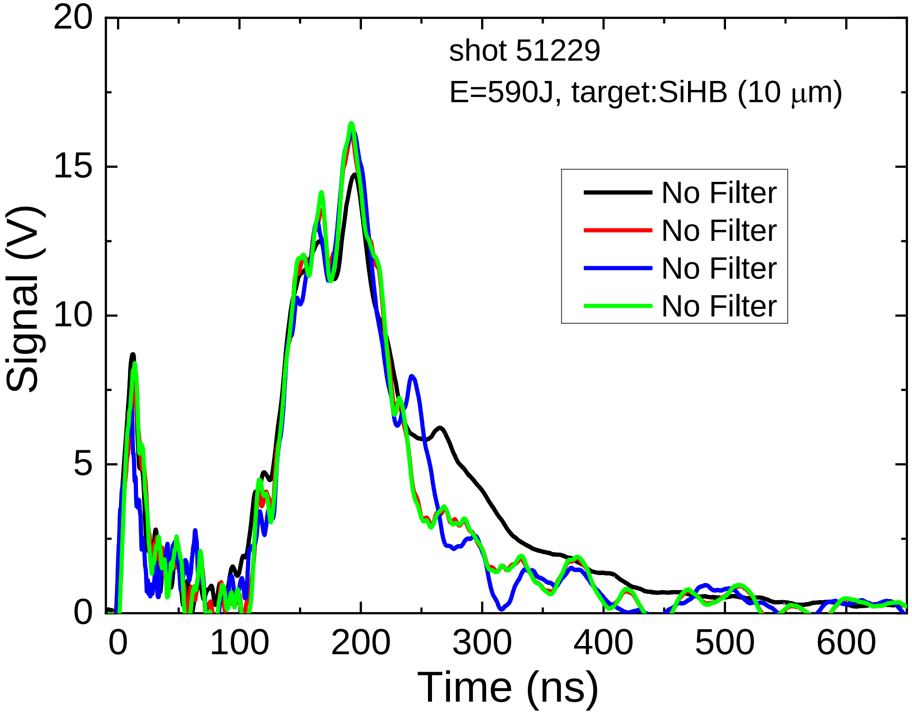
Four diamond detectors featuring different Al filters of different thicknesses.

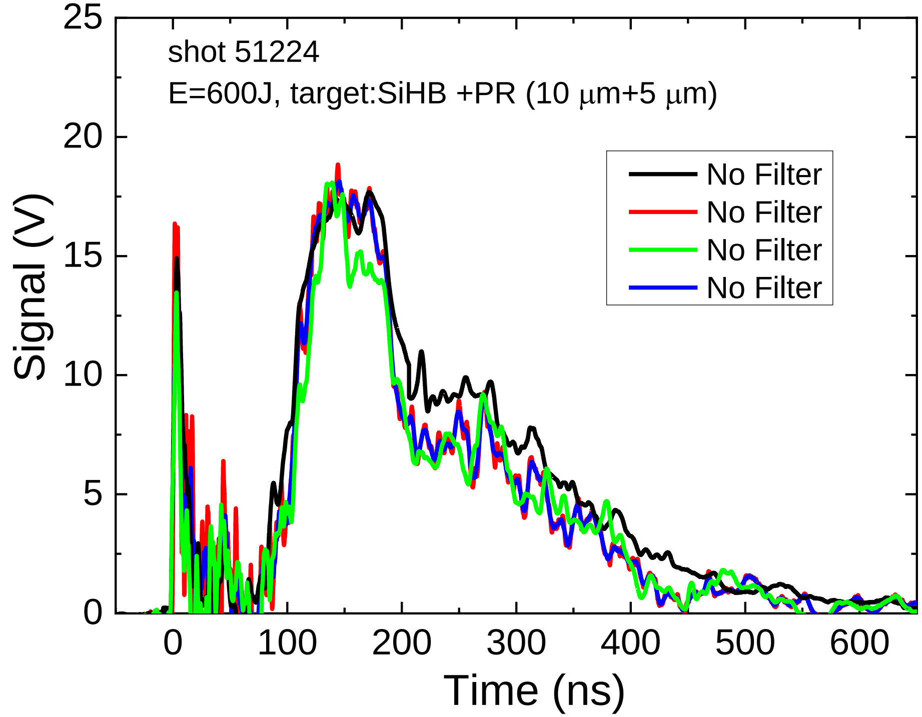


Bias-tees were realized in the PCB placed inside the metallic housing.



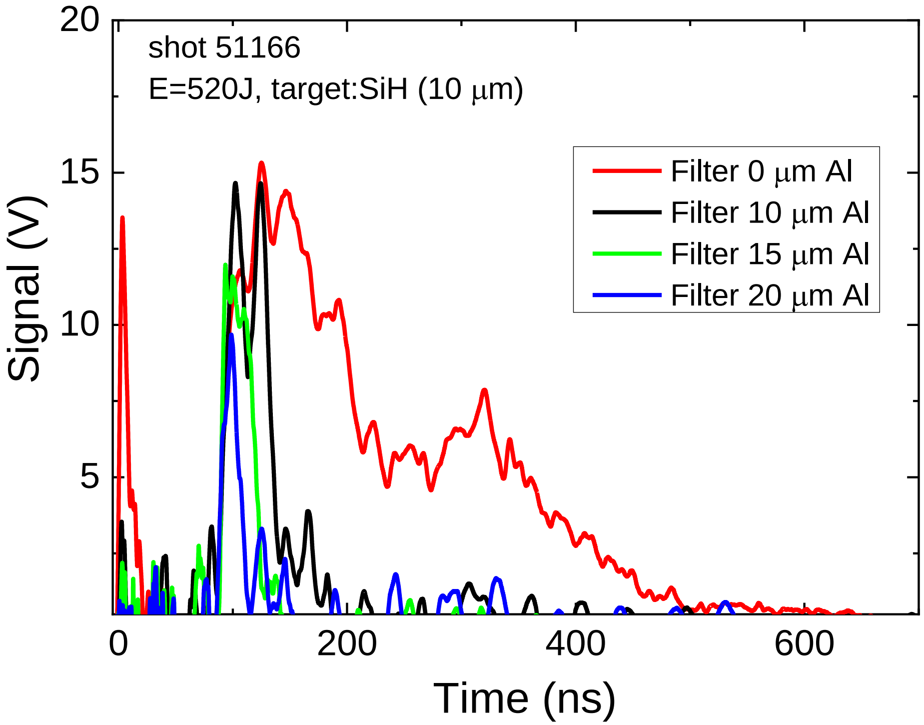
Preliminarily results at PALS

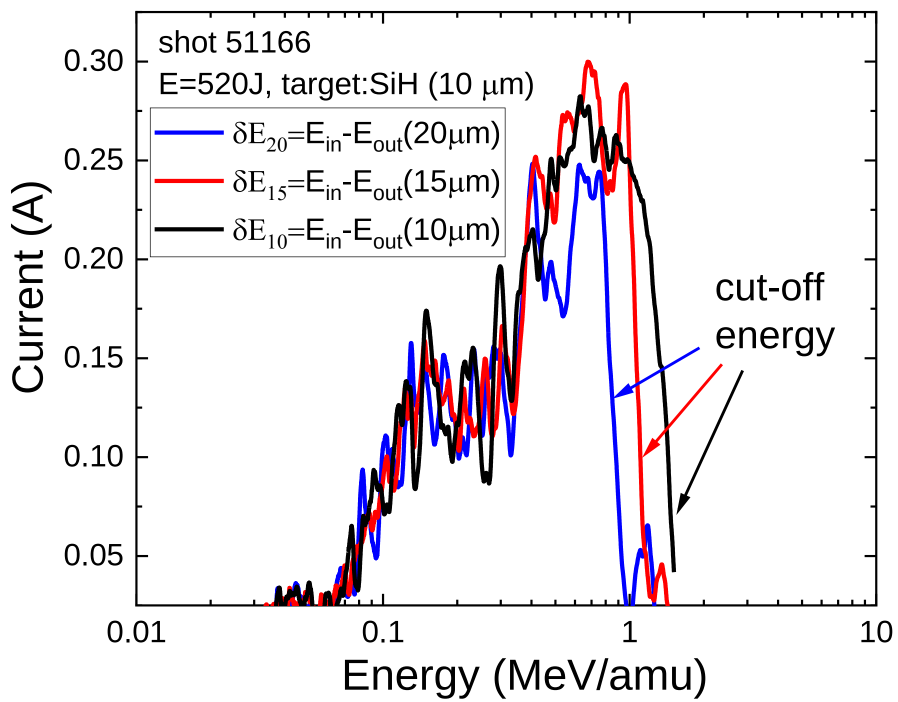




- ✓ The 4 diamond detectors, nominally identical, give very similar TOF signals
- ✓ No cross talk between detectors
- ✓ Signal to noise ratio can be improved (EMP shielded).

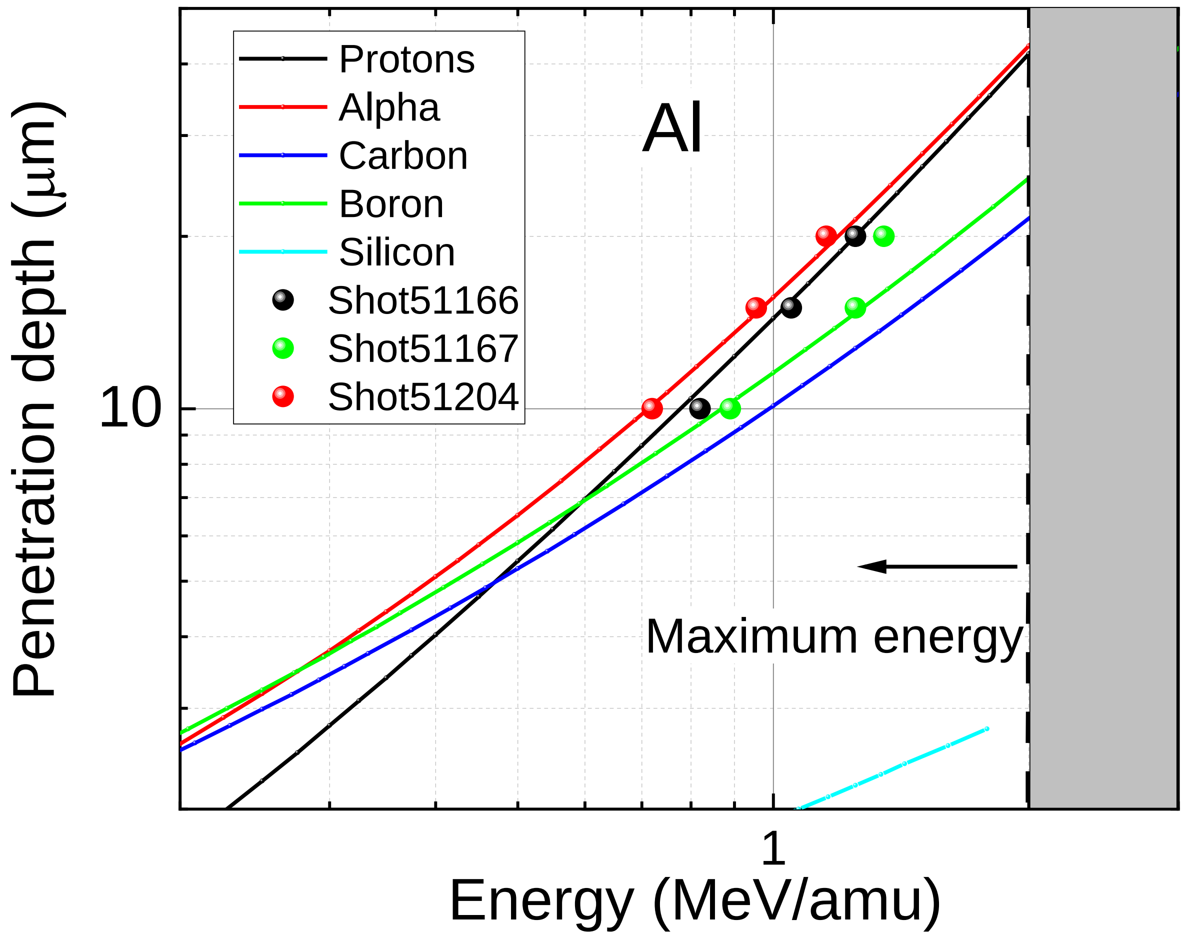
Preliminarily results at PALS





- ✓ The rise time of the signals is the same (corresponding to about 2 MeV/amu maximum energy)
- ✓ Various attenuations and fall-downs of the signals are obtained using different filters
- ✓ The energy loss of ions in the Al filter can be calculated subtracting the signals coming from detectors without and with filter.

Preliminarily results at PALS



Telescope diamond detector

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

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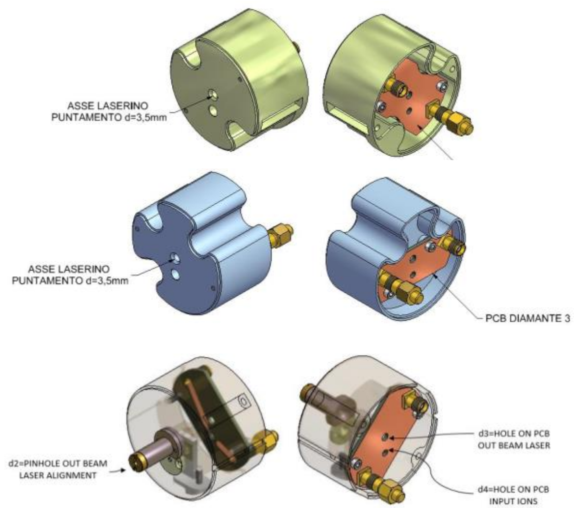
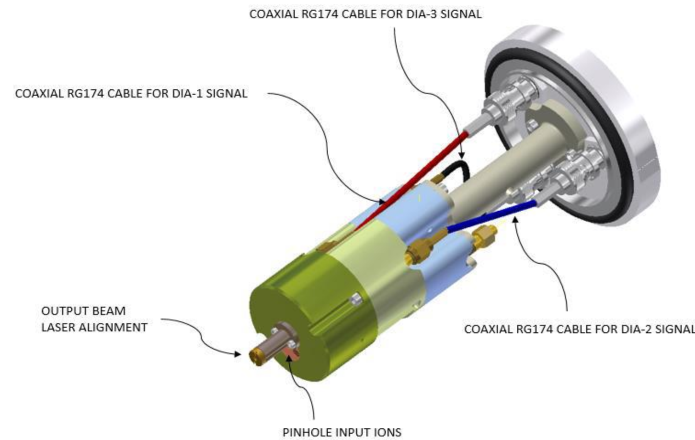
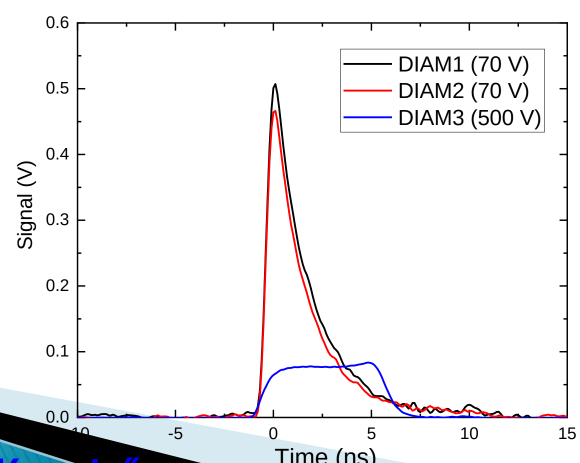
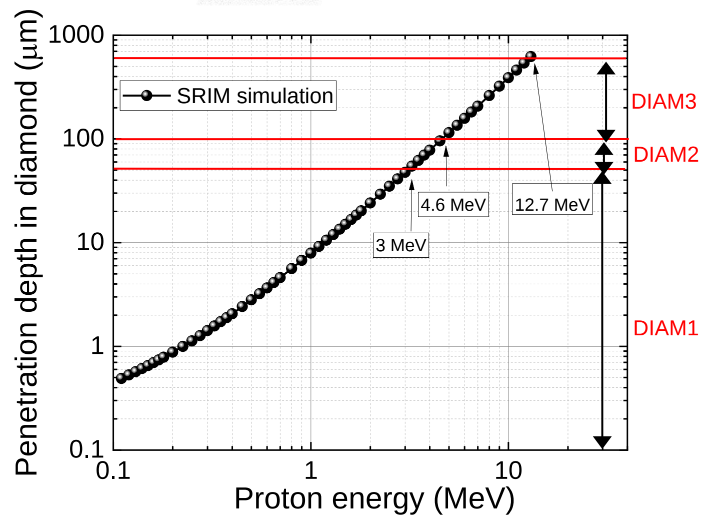




Time resolution:

- DIAM1 : ~ 1.5 ns
- DIAM2 : ~ 1.5 ns
- DIAM3 : ~ 6.5 ns





Conclusions

✓Single-crystal CVD diamond detectors with different configuration, i.e. planar and transverse, have been fabricated at “Tor Vergata” University.

✓CVD diamond detectors were characterized under protons and alpha particles irradiation in terms of CCE and time response.

✓Diamond detectors were employed in Time Of Flight (TOF) configuration to monitor the emission plasma obtained at the Prague Asterix Laser System (PALS) by interaction between sub-ns laser beam and thin hydrogenated silicon targets, doped by boron. Spectral and angular characterizations of the protons and α particles emitted from p-B11 nuclear reaction were performed.

✓A novel identification method to distinguish alpha particles from protons is developed and presented. A first experimental test was carried out at PALS using 4 diamond detectors featuring Al filters of different thicknesses.

✓Work in progress to optimize diamond-based array prototype (i.e. increase the number of pixels and the optimal choice of filters) as well as to develop new analysis to distinguish ion types. This will be done in FUSION project

Thank you!