Italian National Agency for New Technologies, Energy and Sustainable Economic Development

# Characterization of p-$^{11}$B fusion reactions in laser-matter experiments

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# Collaborators

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# Summary

- The characterization of low-rate fusion reactions, and in particular of $^{11}B(p,\alpha)2\alpha$, is one of the recognized main problems in experiments where they are initiated by intense and high-energy laser interactions with matter.

- In this talk, diagnostic methodologies commonly used for alpha particles generated by the $^{11}B(p,\alpha)2\alpha$ reaction will be discussed and, for each, advantages and limitations will be outlined.

- Examples of advanced solutions, designed to deal with these limitations, will be described.

- The use of several simultaneous diagnostics may in some cases give suitable detection

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# Presentation Outline

- $^{11}B(p,\alpha)2\alpha$ nuclear reaction
- Laser-initiated schemes for $^{11}B(p,\alpha)2\alpha$ nuclear reaction, problem of diagnostics
- Actual spectrum of alpha products
- Diagnostic methodologies
    - Track Detectors
    - Thomson Spectrometry
    - Time-Of-Flight technique
    - Detecting Products of Different Simultaneous Reactions
- Conclusions

# Diagnostics of $^{11}B(p,\alpha)2\alpha$ nuclear reaction

- **Characterization of the interaction**
  - **Laser coupling**
  - **Plasma density profile and time evolution**
  - **Electron and ion energies**
    - **Fusion reactans and products**

- **Characterization of reactant and fusion products is usually performed by measurements far from the interaction.**

  - **We measure p, B, α but we need their energies and their number in plasma/target**
  - **Many of them are stopped within plasma and/or target**
  - **Those actually reaching the detector have somehow lost part of their energy.**
  - **Information on stopped – and then 'lost' - particles may be achieved by those actually detected**

→ **Reconstruction requires reliable information**
  - **on the expected spectrum**
  - **on the ion stopping power <u>in plasma</u>**

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# $^{11}B(p,\alpha)2\alpha$ nuclear reaction

- The reaction induces three-particle decay [1-4]

- <u>Predominant channels</u>.
  - Through the $^{8}Be$ ground state, decaying into $2\alpha$ (Q = 91.8 keV):

    $p+^{11}B \rightarrow \alpha_0 + ^{8}Be$,  Q = 8.59 MeV  (1)

  - Through the $^{8}Be$ excited state:

    $p+^{11}B \rightarrow \alpha_1 + ^{8}Be^*$,  Q = 5.65 MeV and a large width of 1.5 MeV.  (2)

  - The decay of $^{8}Be^*$ :

    $^{8}Be^* \rightarrow 2\alpha_{12}$,  Q = 3.028 MeV  (3)

- In both channels (1) and (2) → formation of a nucleus of $^{12}C^*$ followed by α decays via an unbound $^{8}Be$ in its fundamental (1) or first-excited state (2).

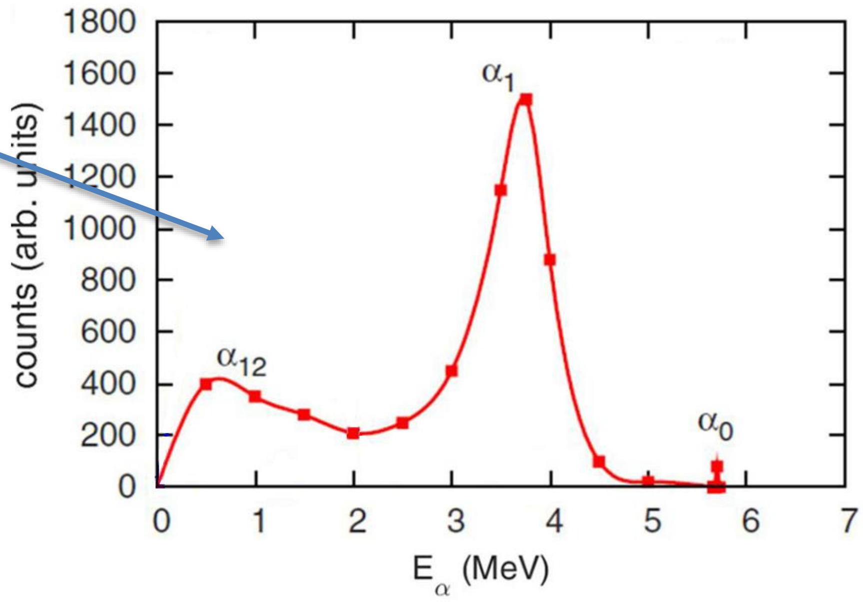
- A further channel, with a very low cross-section, produces a $^{12}C^*$ compound nucleus that decays by γ emission, releasing ~15.9 MeV [2,6].


[1] Nevins WM, Swain R. Nucl Fusion. (2000) 40:865–72. ;
[2] Liu J, et aal . NIMB. (2002) 190:107–11.
[3] Freidberg JP, Kadak AC. Nature Phys. (2009) 5:370–2.
[4] Ajzenberg-Selove F. Nucl Phys A. (1990) 506:1–158.
[5] Becker HW, et al. Z Physik A Atomic Nuclei. (1987) 327:341–55.
[6] Kimura S, et al, Phys Rev E. (2009) 79:038401.

# $^{11}B(p,\alpha)2\alpha$ nuclear reaction

- **Estimated alpha energy spectrum in the reaction $^{11}B(p,\alpha)2\alpha$ at 660 keV incident proton beam energy [1]**

- **In laser-matter experiments, alpha spectrum is highly dependent on the scheme used**

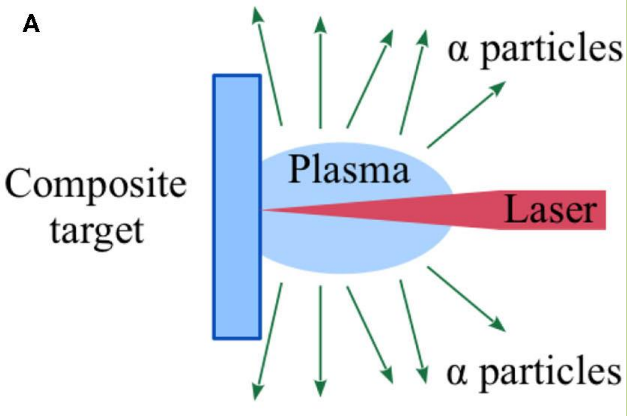



[1] Kimura S, et al, Phys Rev E. (2009) 79:038401.

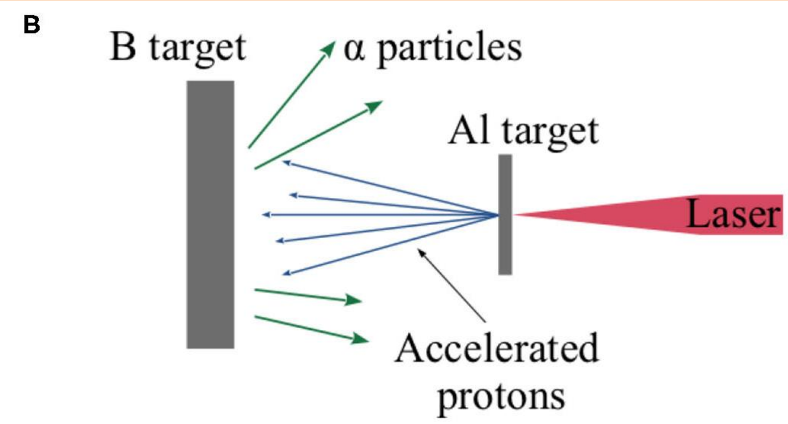
# Laser-initiated $^{11}B(p,\alpha)2\alpha$ nuclear reaction

- **Two main approaches followed to trigger fusion reactions from H and $^{11}$B in laser-matter experiments (Scheme A and B)**

**Scheme A: Laser on target**
-H and B plasma by laser pulses on composite targets: i.e. B-doped plastic, BN or Si enriched with H and B.
-ns and/or ps/fs laser pulses.




**Scheme B: Pitcher-Catcher**
-Laser accelerated protons sent to a borate target or to a borated plasma.
-ps or fs laser pulses

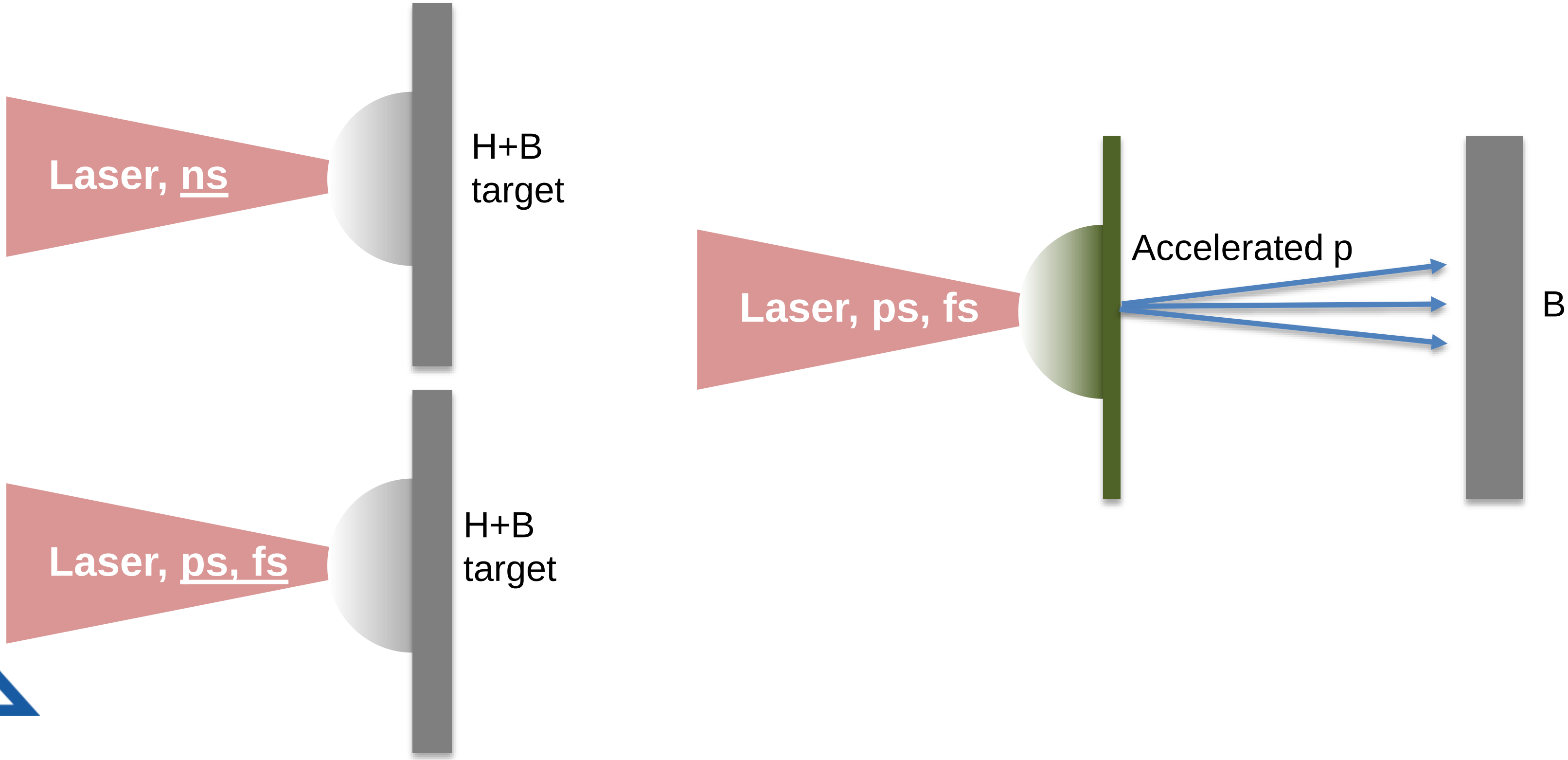




[1] Consoli F. Frontiers in Physics (2020) 8, 561492

# Actual spectrum of produced alphas

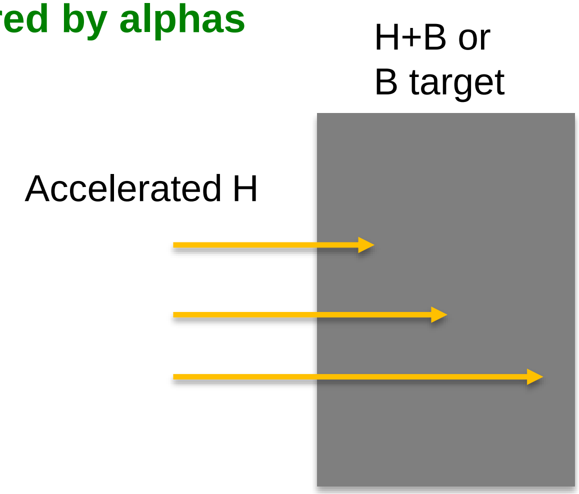
- It is important to point out that the actual spectra of the alpha particles detected in each of the two Schemes may differ also significantly, mainly because
  - before reaching the detector, the produced alphas interact with the solid target and/or the surrounding plasma
  - momentum conservation leads to anisotropic deformation of the alpha spectrum, along proton main incoming direction, more visible in case of high energy protons in either Scheme A or B



# Modified spectrum because of interaction

- For ideally-monochromatic protons interacting with borated targets, the actual alpha spectrum observed outside the interaction region is the superimposition of alphas produced at different thicknesses in the borated target. The main emitting region is where protons will excite the main 660 keV fusion resonance. The situation becomes more complicated with broadband proton spectra.

- Then, this alpha spectrum will be highly dependent on
  - incoming proton spectrum and maximum energy
  - target thickness
  - direction of measurement with respect to proton trajectory, since paths with different lengths will be covered by alphas



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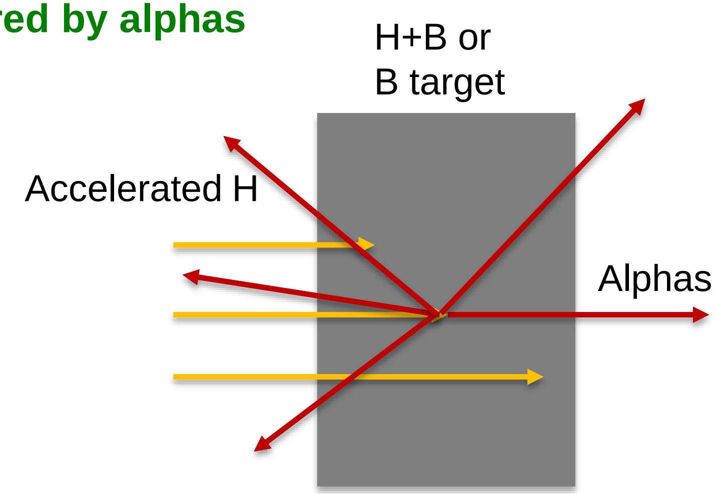


  - Accurate modeling is needed to take this into account, and also accurate p and or B characterization

# Diagnostic methodologies

- **Track Detectors**
- **Thomson Spectrometry**
- **Time-Of-Flight technique**
- **Detecting Products of Different Simultaneous Reactions**

# Diagnostic methodologies: Track Detectors

- **Solid-State Nuclear Track Detectors (SSNTD): fundamental method of detection for alpha products in this type of experiments.**

- **Solid materials where exposition to ionizing radiation generates local damaging to the detector. In the polymer SSNTD, damages are caused by the breaking of the long polymer chains due to incoming radiation.**

- **Typical examples: CR39 plastic polymer, or allyl diglycol carbonate (ADC), and PM-355 plastic.**

- **Along these damaged regions, the material is more susceptible to chemical attack (typically NaOH solution with specific concentration and temperature), and thus has a much faster velocity of etching compared with the undamaged material.**

- **Tracks created in the damaged regions, with sizes increasing with the duration of the bath. For etching of several hours, tracks of micrometer dimension are achieved and can be characterized by confocal microscopes, giving high-resolution images.**

- **Etching time: dependence on the CR-39 conditions, aging, producer, exposed radiations (i.e. flows of energetic electrons or X-gammas)**

**Nikezic, D, Rad. Meas. 28,185, 1997**
**Nikezic, D, Mat. Sci & Eng R 46, 51, 2004**
**Consoli F. Frontiers in Physics (2020) 8, 561492**

# Diagnostic methodologies: Track Detectors

- **Problem: besides alphas, the detector is also reached by all the other radiations produced in the experiment of $p+^{11}B$ and by background (i.e. radon decay,…)**

- **Electrons, X-rays, and γ-rays do not produce a remarkable effect on the detector but change its average solubility. It is to be taken into account for particle identification techniques**

- **→ Problem of discrimination. Because of the low rate of these reactions, the number of alpha products reaching a given detector is usually much lower than the number of H, B, C, etc. ions reaching the same detector.**

- **Classical approaches for particle discrimination**
  - **Use of filters**
  - **Track dimension and evolution along etching**
  - **Track shape**

**Nikezic, D, Rad. Meas. 28,185, 1997**
**Nikezic, D, Mat. Sci & Eng R 46, 51, 2004**
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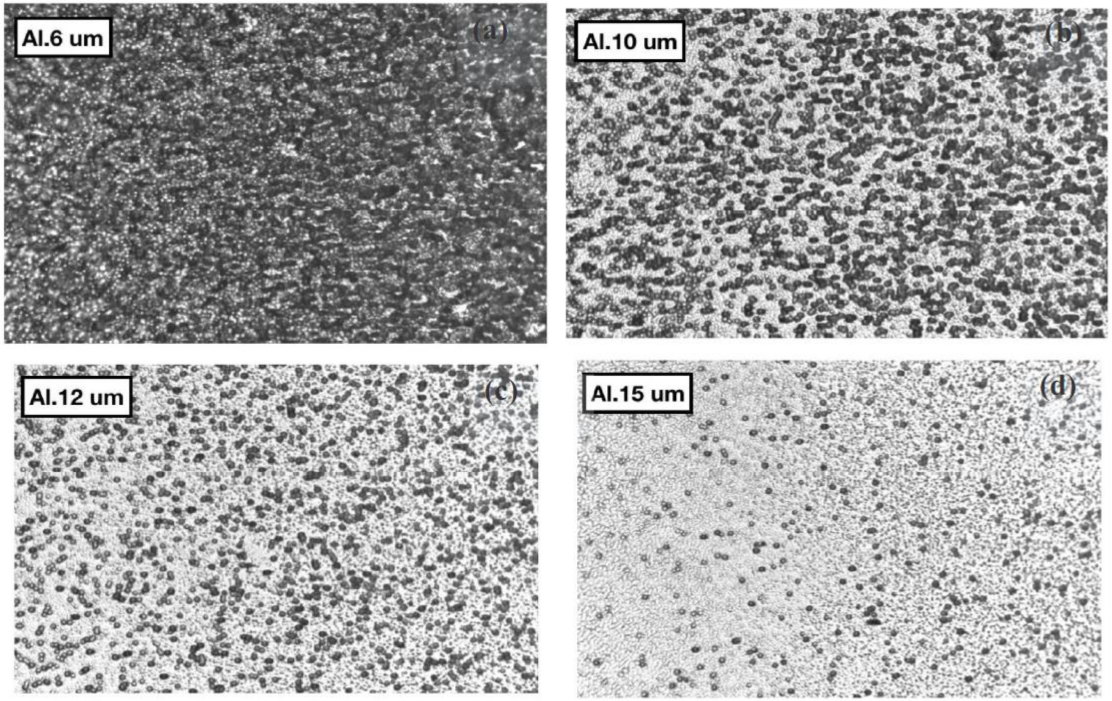
# Diagnostic methodologies: Track Detectors

- **Use of foil filters**
- **It is possible to use plastic or metal foils as filters, capable of stopping low-energy and heavy particles and leave high-energy alphas to pass through them.**

- **This may be quite effective for incoming B, C, or heavier ions but can show many limitations for protons, due to their maximum range.**

**PALS laser (600 J, 0.3 ns, $3\times10^{16}$W/cm$^2$ on BN target)**

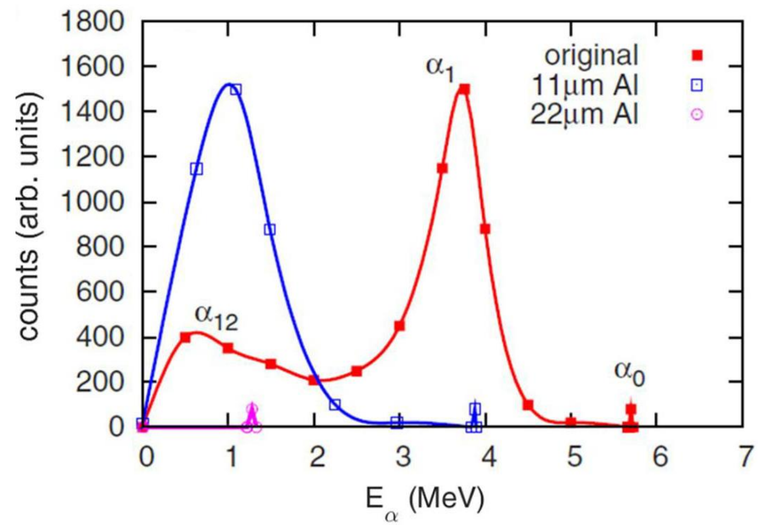



**Giuffrida L. PHYSICAL REVIEW E 101, 013204 (2020)**
**Consoli F. Frontiers in Physics (2020) 8, 561492**

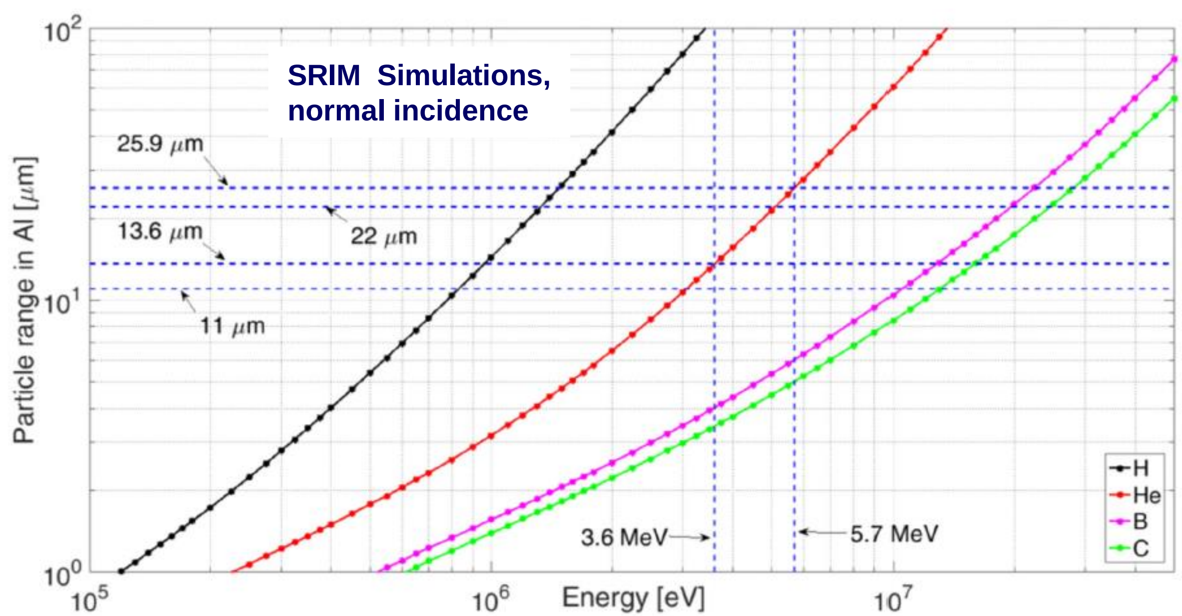
# Diagnostic methodologies: Track Detectors

- <u>**Use of foil filters**</u>
- **From the alpha spectrum, Emax = 5.7 MeV, the main peak is placed at around E2 = 3.6 MeV.**

- **It is reasonable to use Al filters with thickness about 11 μm at most, allowing the 3.6 MeV peak to pass it through and stop up to about 800 keV protons.**




- **This is roughly the <u>operative limit</u> for the use of this technique, advantageous in some experiments with ns-regime lasers.**




**Consoli F. Frontiers in Physics (2020) 8, 561492**
**Kimura S, et al, Phys Rev E. (2009) 79:038401.**

# Diagnostic methodologies: Track Detectors

- <u>**Use of foil filters**</u>
- **When using filters, it is necessary that the spectrum of protons is accurately known. This will enable to understand <u>if</u> unique alpha selection by the filtering method can be obtained.**

- **The use of filters decreases the energy of alphas reaching the detector and may cut most of the alpha spectrum.**

- **With ps or fs regime pulses this approach is rarely usable, because protons of several MeVs are commonly generated**

- <u>**→ No discrimination from detector background**</u>

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# Diagnostic methodologies: Track Detectors

- <u>Track dimension and evolution along etching</u>
- **Information on particle energy can be inferred by track dimension and etching rate, compared with that of the detector bulk. Information on the particle type may also be achieved**

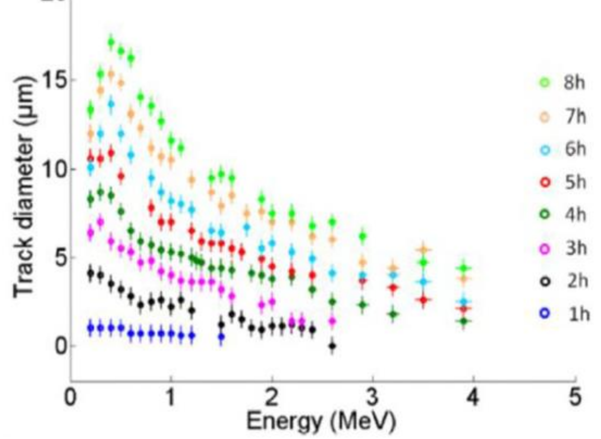
- **Requirement: <u>a prior exposition of the same detector to reference particle beams</u>, and the study of the produced tracks with respect to different conditions of the etching solution, temperature, and immersion time.**

- **<u>But this can be not enough</u>, since electrons, X, gammas during laser-matter interaction may change the solubility of the bulk**

- **For NaOH solution (6N,70 ºC) and an incoming proton beam, track diameters are monotonically decreasing versus the energy of the incoming protons for etching times up to 2 h, but the decreasing remains within the diameter tolerance**

- **Larger times should be thus needed but the relation is no more univocal in the whole energy range even if still usable for the higher energies**

NaOH solution (6N,70◦C) - protons




Consoli F. Frontiers in Physics (2020) 8, 561492
Baccou C. Rev Sci Instr (2015) 86:083307

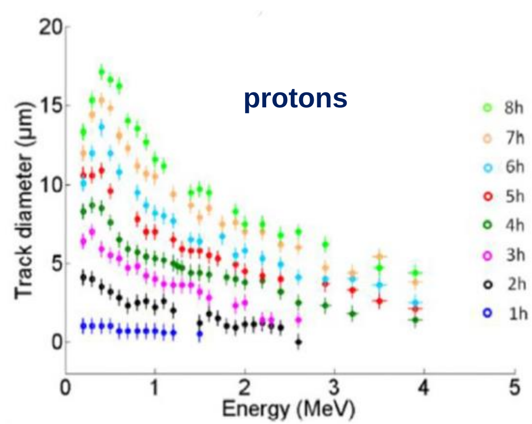
# Diagnostic methodologies: Track Detectors

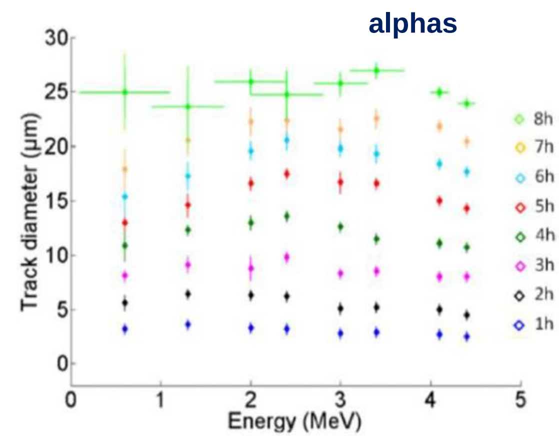
- **No discrimination of alphas and protons at 1-2 h etching times**

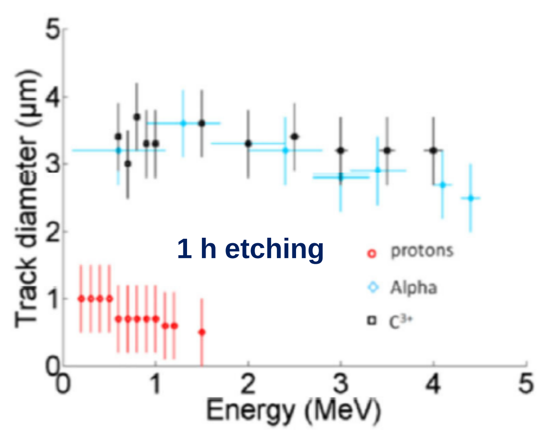
- **Better at larger times, but always with small gaps between maximum for protons and minimum for alphas → discrimination not always reliable**

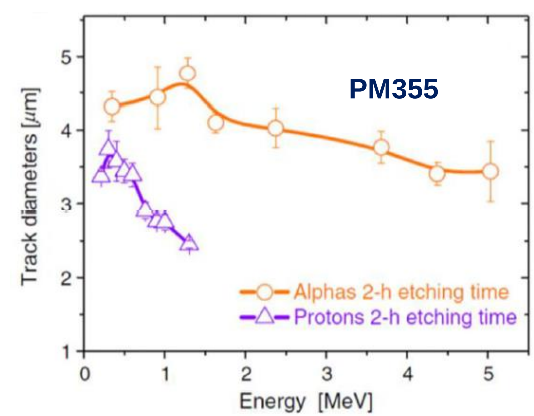
- **It is important to avoid the presence of heavier ions (C,B,…)**

- **The application of foil filters in using this technique may lead to some improvement on the discrimination of α tracks from proton tracks.**



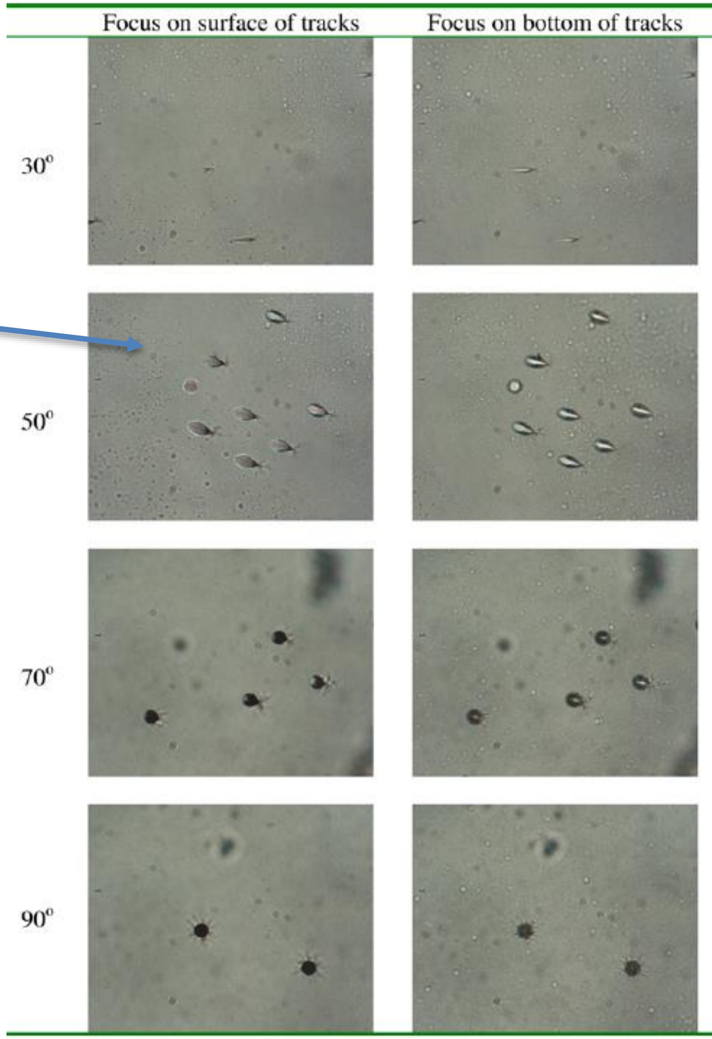




Consoli F. Frontiers in Physics (2020) 8, 561492
Baccou C. Rev Sci Instr (2015) 86:083307
Picciotto A. Phys Rev X. (2014) 4:031030.

# Diagnostic methodologies: Track Detectors

- <u>Track shape</u>
- Track shape depends on directions of incoming ions with respect to the detector surface
- Ellipses: major axis along the direction of particle propagation for particles not normal to the surface
- Ellipticity and orientation to discriminate tracks actually due to the nuclear reactions of interest from those associated with the detector background → ***<u>Directional Track Selection</u>*** method
- Environmental radioactivity, in fact, causes the presence of some tracks on the SSNDTs.
- This background constantly increases after the production of the detector.
- ***<u>Directional Track Selection</u>*** increases the detector sensitivity effectively.

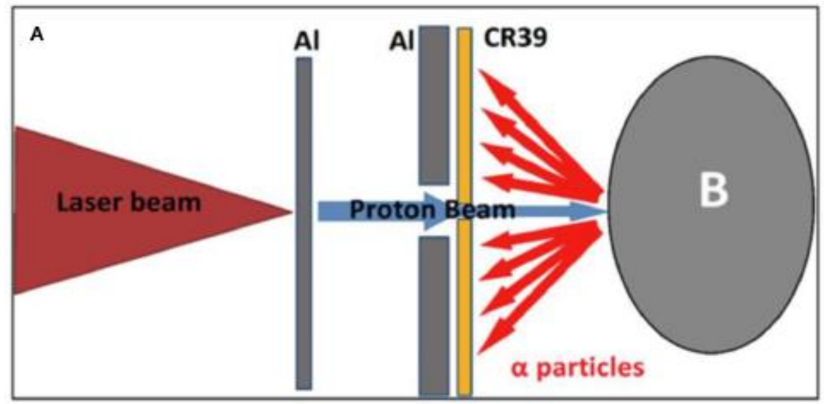




Ng F.M.F. et al, NIMB 263 (2007) 279
Ingenito F., EPJ Web Conf. (2018)167:05006
Jeong T. W., Scientific Reports (2017) 7: 2152

# Diagnostic methodologies: Track Detectors

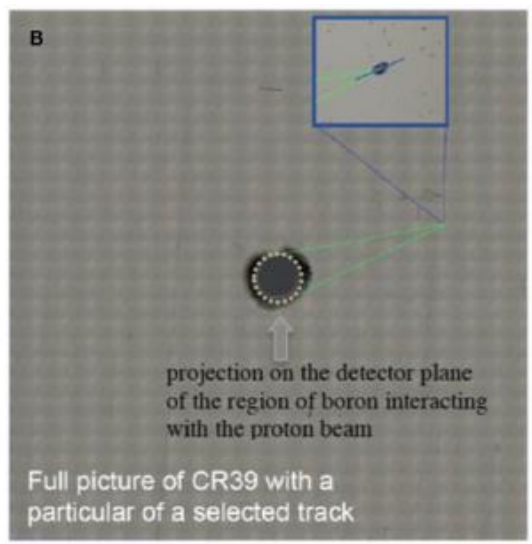
- **The drawback of this technique is the necessity that fusion products have some preferential direction with respect to the detector place, which complicates the preparation.**
- **Experiment on pitcher-catcher scheme on Eclipse laser (110 mJ, 2 × $10^{18}$ W $cm^{-2}$, 35 fs)**
- **Ellipticity and orientation of the tracks were used to define an acceptance angle**

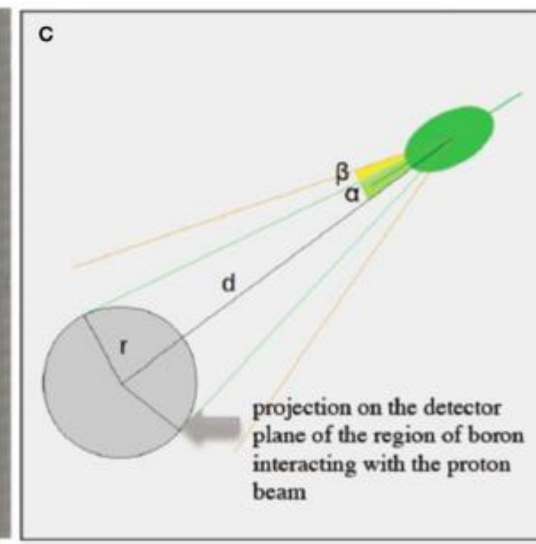



$$\gamma = \arcsin( r / d ) + \beta,$$

**with β due to the uncertainties on tolerances in assessing both the source dimension and the center position**

- **This technique was capable of reducing the background noise level <u>of about one order of magnitude</u>.**
- **Very useful to increase the actual detector sensitivity, especially when the number of estimated alphas is comparable with background**




**Ingenito F., EPJ Web Conf. (2018) 167:05006**
**Giulietti D, NIMB (2017) 402:373**

# Diagnostic methodologies

- Track Detectors
- **Thomson Spectrometry**
- Time-Of-Flight technique
- Detecting Products of Different Simultaneous Reactions

# Diagnostic methodologies: Thomson Spectrometers

- **Thomson spectrometers are well-known effective devices used for discriminating ions with different charge-mass ratios in high-power laser experiments**
- **An electrostatic and a magnetostatic field, both orthogonal to the incoming charged beam direction, determine a vertical (the electric field) and a horizontal (the magnetic field) deflection of the particles, leading to parabolic traces, each univocally associated with different charge-over-mass ratios.**
- **From the trace profile and the use of calibrated detectors, as imaging plates, scintillators, MCPs,… it is possible to retrieve the absolute particle spectrum**

**Simplified model for parabolas for disuniform fields**

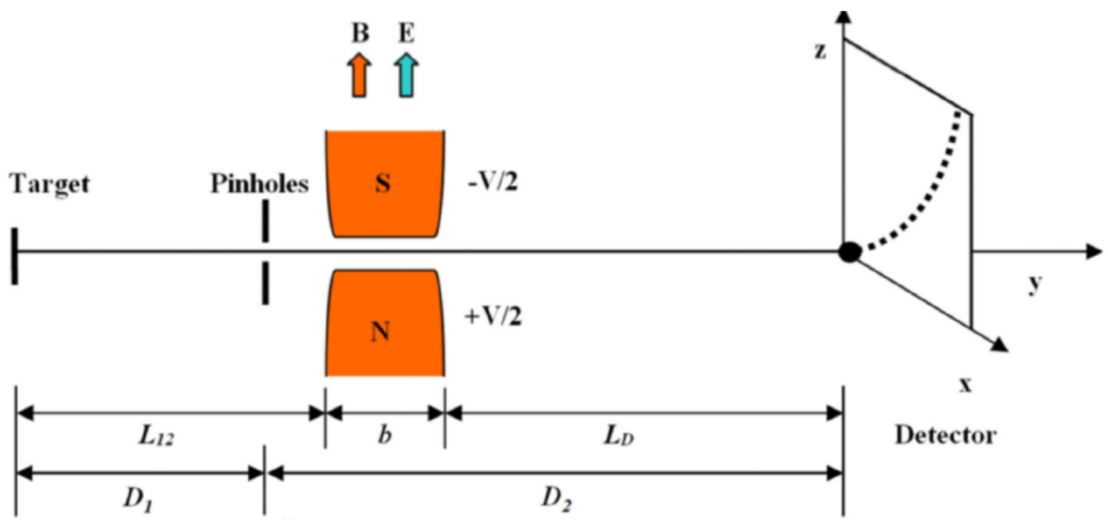
$$x = \frac{q_i}{\sqrt{2m_i E_i}} A_B \,,$$

$$z = \frac{q_i}{2E_i} A_E \,,$$

$$z = \frac{m_i A_E}{q_i A_B^2} x^2 \,,$$

$$A_B = \int_0^{L_{A1}+L_{A2}+L_B+L_C} \int_0^{y} B_\perp(\zeta)\, d\zeta\, dy \,,$$

$$A_E = \int_0^{L_{A1}+L_{A2}+L_B+L_C} \int_0^{y} E_\perp(\zeta)\, d\zeta\, dy \,.$$




**Thomson JJ. Proc R Soc Lond A. (1913) 89:1; Consoli F. JINST (2016) 11:C05010.**

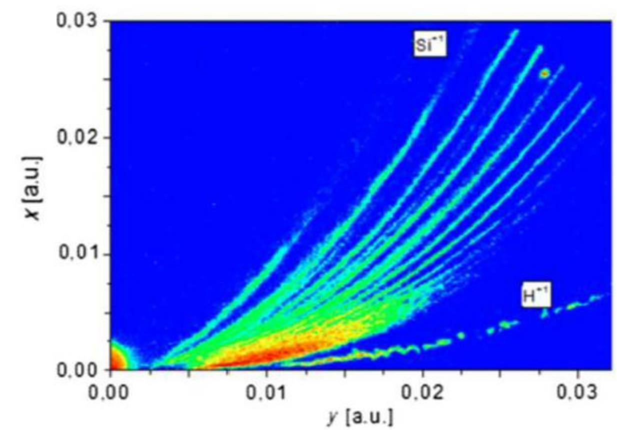
# Diagnostic methodologies: Thomson Spectrometers

- **The use of pinholes for spatially limiting the transversal plane is a key factor for the determination of the spectrometer sensitivity (dependent on solid angle Ω) and resolution**
- **Large pinholes enhance sensitivity but reduce spectral resolution and determine larger parabola widths $S_t$.**

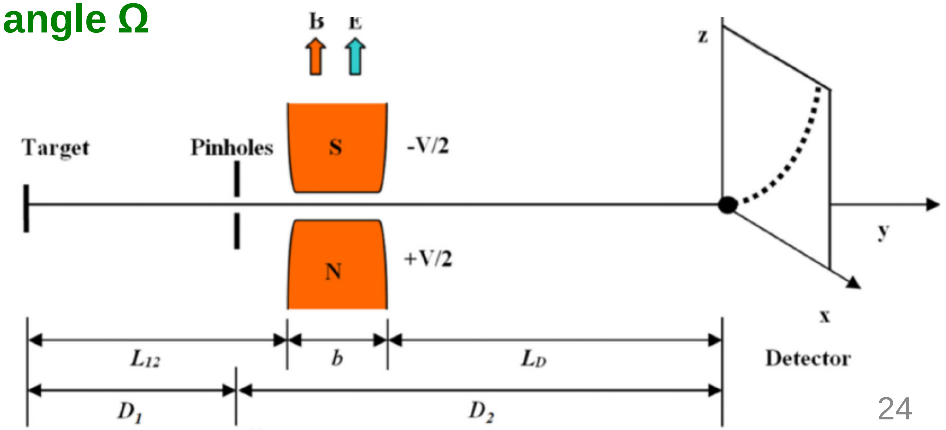
$$S_t \sim 2\,(D_1 + D_2)\,\sqrt{\Omega/\pi}$$

$\varphi_p$ **pinhole diameter**

$$\Omega = \frac{\pi}{4}\left(\frac{\varphi_p}{D_1}\right)^2$$




- **$S_t$ limited by available electric and magnetic fields**
- **High sensitivity, of primary importance for the detection of fusion products in these low-rate reactions, means large solid angle Ω**
- **For a given $S_t$ it means small D1, D2, and large pinholes.**
- **Minimum detectable yield limited by the solid angle Ω**

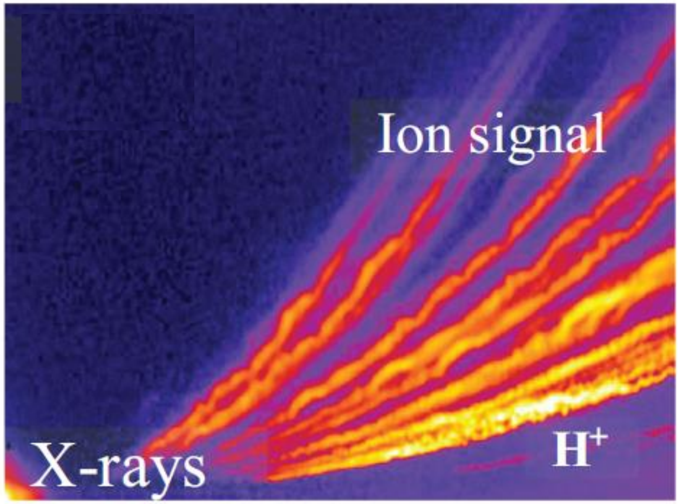



**Consoli F. Frontiers in Physics (2020) 8, 561492**
**Piccotto A. Phys Rev X. (2014) 4:031030.**

# Diagnostic methodologies: Thomson Spectrometers

- **On the other hand, the enhancement of the solid angle implies larger background noise that can be coupled with the spectrometer, usually scaling with the square of the distance to target. This comes from the following contribution:**

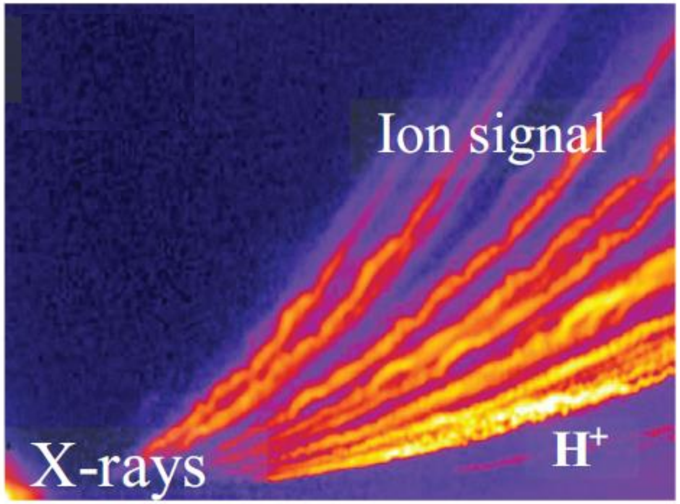
  - **Ionizing electromagnetic radiation.**
  - **Electron bremsstrahlung inside the spectrometer**
  - **Laser-generated Electromagnetic Pulses (EMPs). These radiofrequency-microwave fields of high intensity usually determines sinusoidally-modulated parabolas, worsening trace superimposition and thus overall sensitivity**




**Consoli F. Frontiers in Physics (2020) 8, 561492**
**Giuffrida L. PRE 101, 013204 (2020)**
**Consoli F. HPLSE (2020) 8, e22**

# Diagnostic methodologies: Thomson Spectrometers

- **Thomson spectrometers suitable to detect products of low-rate fusion reactions should have the following features:**
  - **high electric and magnetic fields, for a suitable trace separation at high energies;**
  - **small dimensions**
  - **large pinholes, for improved solid angle of detection;**
  - **positioning as close as possible to the interaction point;**
  - **careful shielding for ionizing electromagnetic radiation and electrons;**
  - **careful EMP shielding and particle trajectory characterization.**

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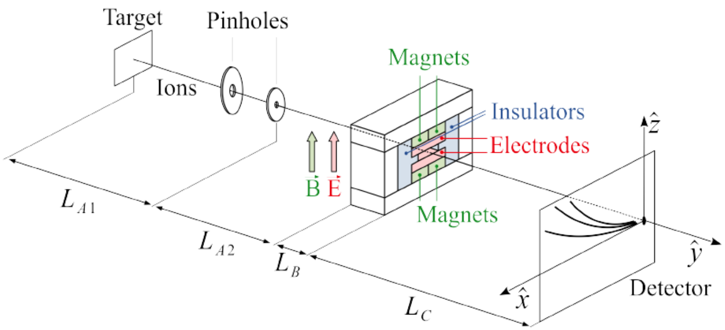
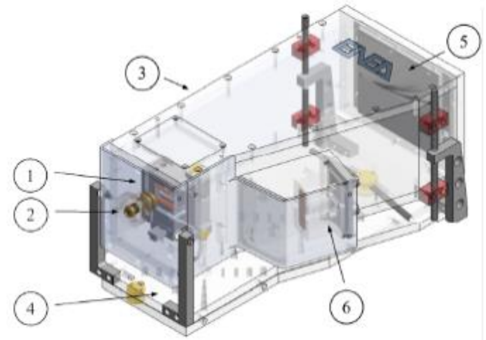
**Giuffrida L. PRE 101, 013204 (2020)**
**Consoli F. HPLSE (2020) 8, e22**

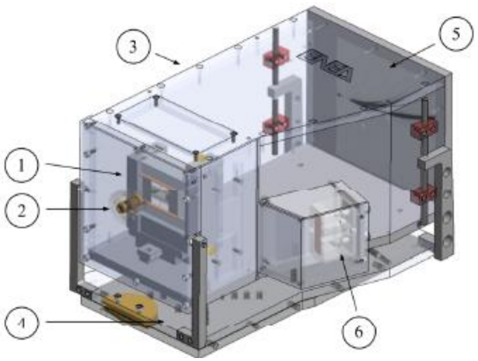
# Diagnostic methodologies: Thomson Spectrometers

- **Advanced Thomson prototypes tailored for low-rate fusion reactions**



**Protons: 5 keV- 200 keV**

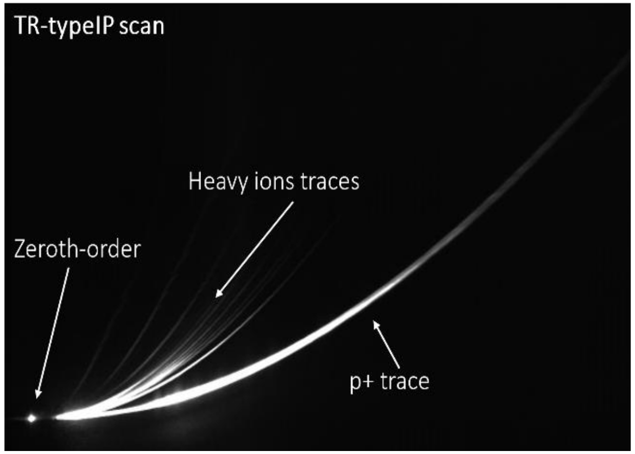


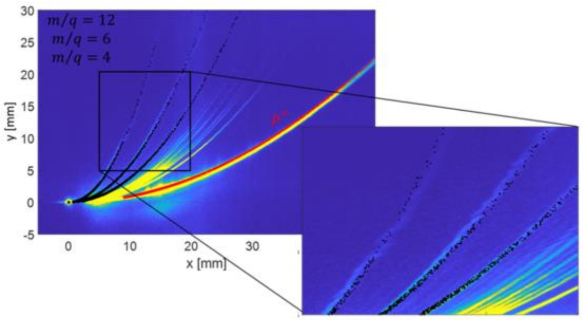
**Protons: 100 keV- 10 MeV**

**Experiment Phelix (GSI)**

~750 fs, ~180 J. ~7 × $10^{20}$ W/cm$^2$ on titanium (10 μm thick) foil target (with a contrast >$10^{11}$). The TS was placed at a distance d = 53 cm

- **High sensitivity was obtained, with <u>no modulations</u> of traces even if at close distance from target and in conditions of measured high EMPs**
- **Further successful tests performed at PALS at 600 J energy and some tens cm distance from target**





**Di Giorgio G, JINST (2020), 15 C10013**
**Scisciò M. JINST, 17_C01055 (2022)**
**Scisciò M. submitted to LAPB, today talk**

# Diagnostic methodologies: Thomson Spectrometers

- **On the same parabolic trace, different ion species may be present, with the exception of that for q/m = ‘1’: protons**

- **For a specific point <u>on same q/m trace</u>, energies of the possible ion $E_i$ will be linked to those of alphas by the relation**

$$E_i = (q_i / q_\alpha) E_{\alpha},$$

**so with value proportional to the charge ratios.**

- **It means that if we want to stop those energetic ions and have a ‘clean’ alpha trace, the use of suitable filters may be thought. This can be not always possible**

- **A solution may be to use SSNTD as detectors in Thomson Spectrometers. The techniques described for particle discrimination can give some help.**

- **This is possible only if the trace is not saturated, i.e., if there are not too many particles, so that the different tracks are clearly separated. In many situations this can be not true.**

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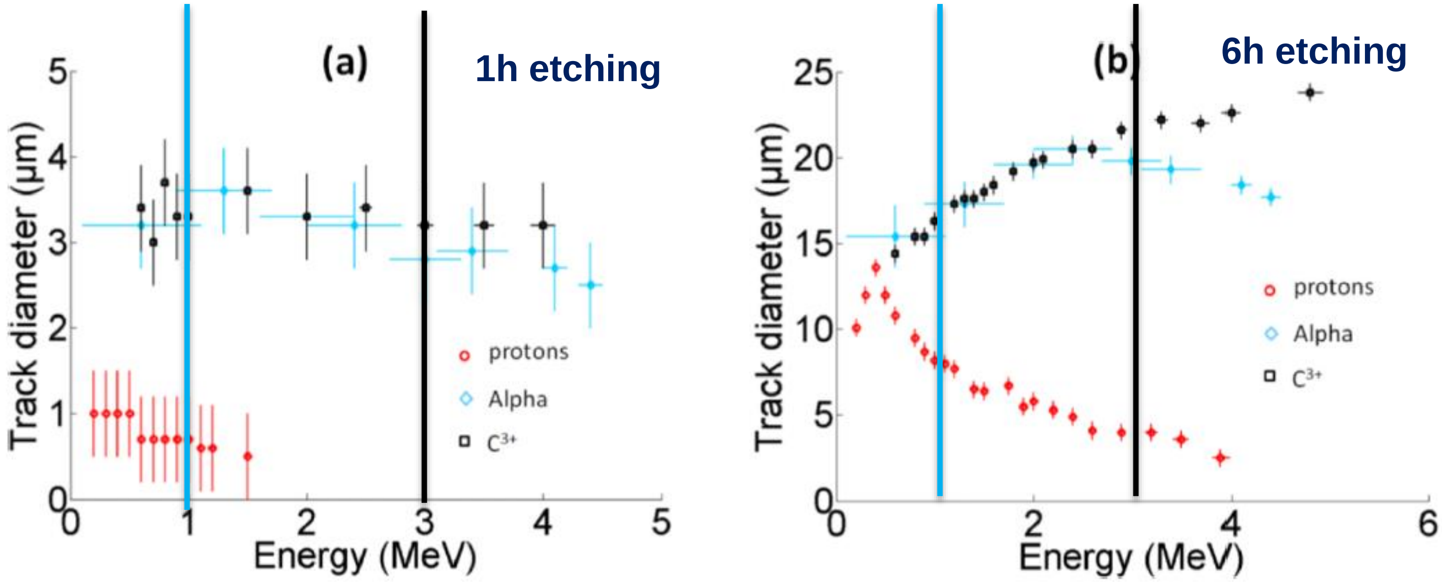
**Consoli F. Frontiers in Physics (2020) 8, 561492**

# Diagnostic methodologies: Thomson Spectrometers

- In the A/Z = 2 parabola, $C^{6+}$ ions with energy $E_{C6+} = 3E_{He2+}$ will share the same point with related alphas. They also have the <u>same energy per nucleon, and the same velocity</u>

- In CR39, in some conditions it is possible to have some discrimination, but <u>only at large etching times and for high energies. But track diameters increase remarkably</u>



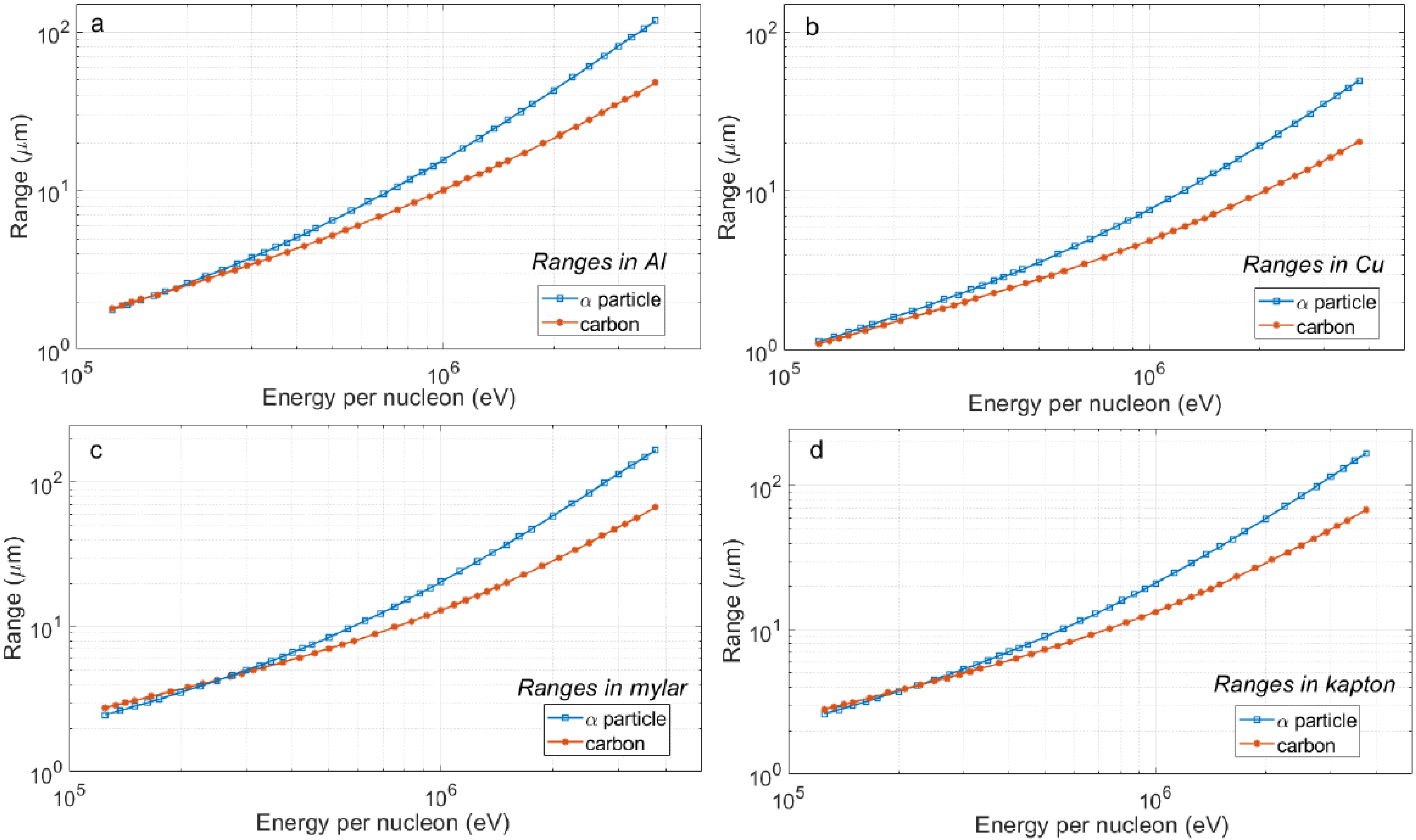

- Ok for accumulation, but to some extent because trace saturation has to be avoided, and there are normally far more C than alphas. <u>No real-time features</u>

C. Baccou, RSI 86, 083307 (2015)

# Diagnostic methodologies: Thomson Spectrometers

- **Alternative: to exploit the filtering method.**
- **Discrimination possible at large energies**

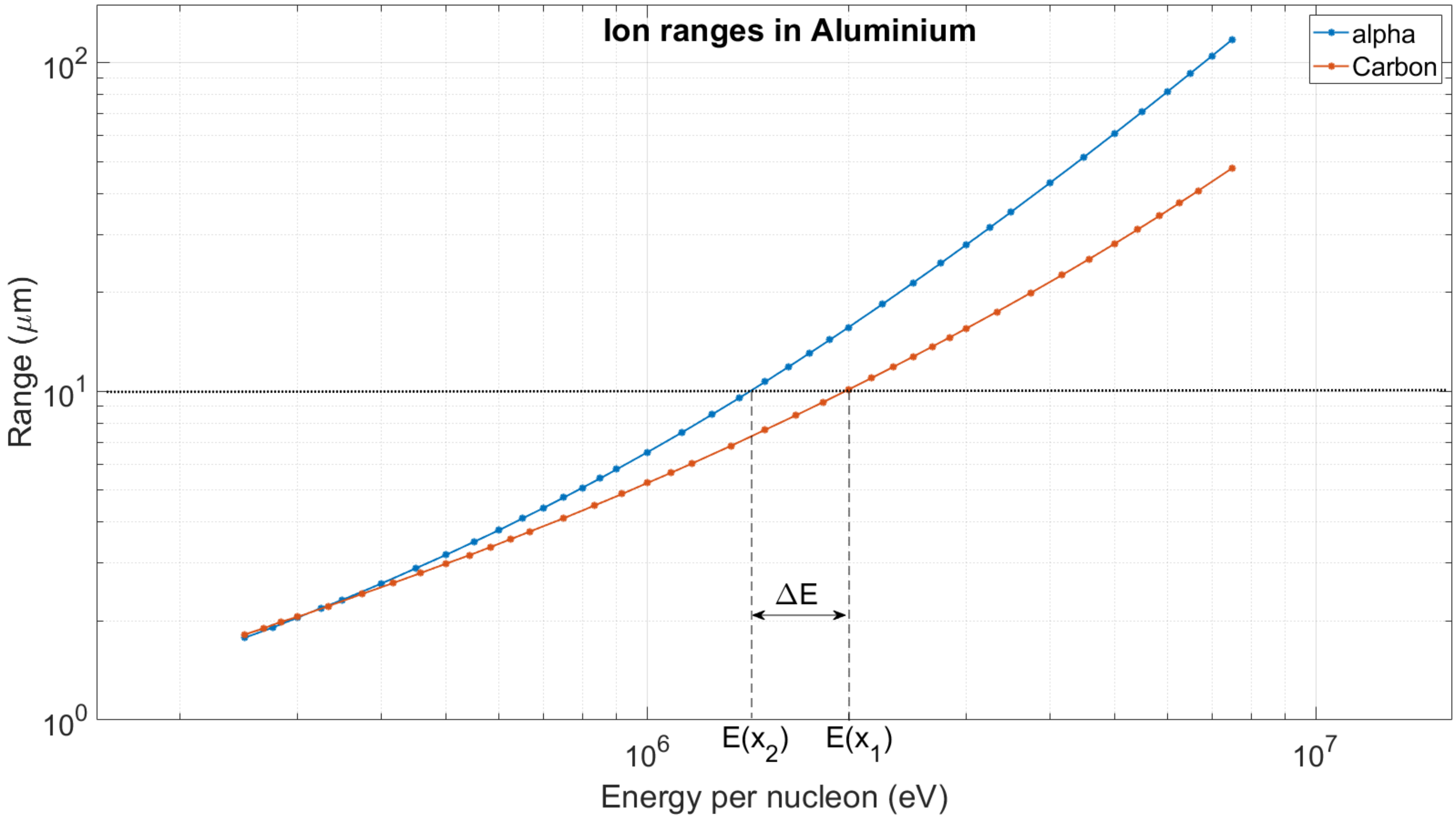
**M. Salvadori, subm to Las. Part. Beams**



# Diagnostic methodologies: Thomson Spectrometers

- **A filter with given thickness ok for some energy ranges**

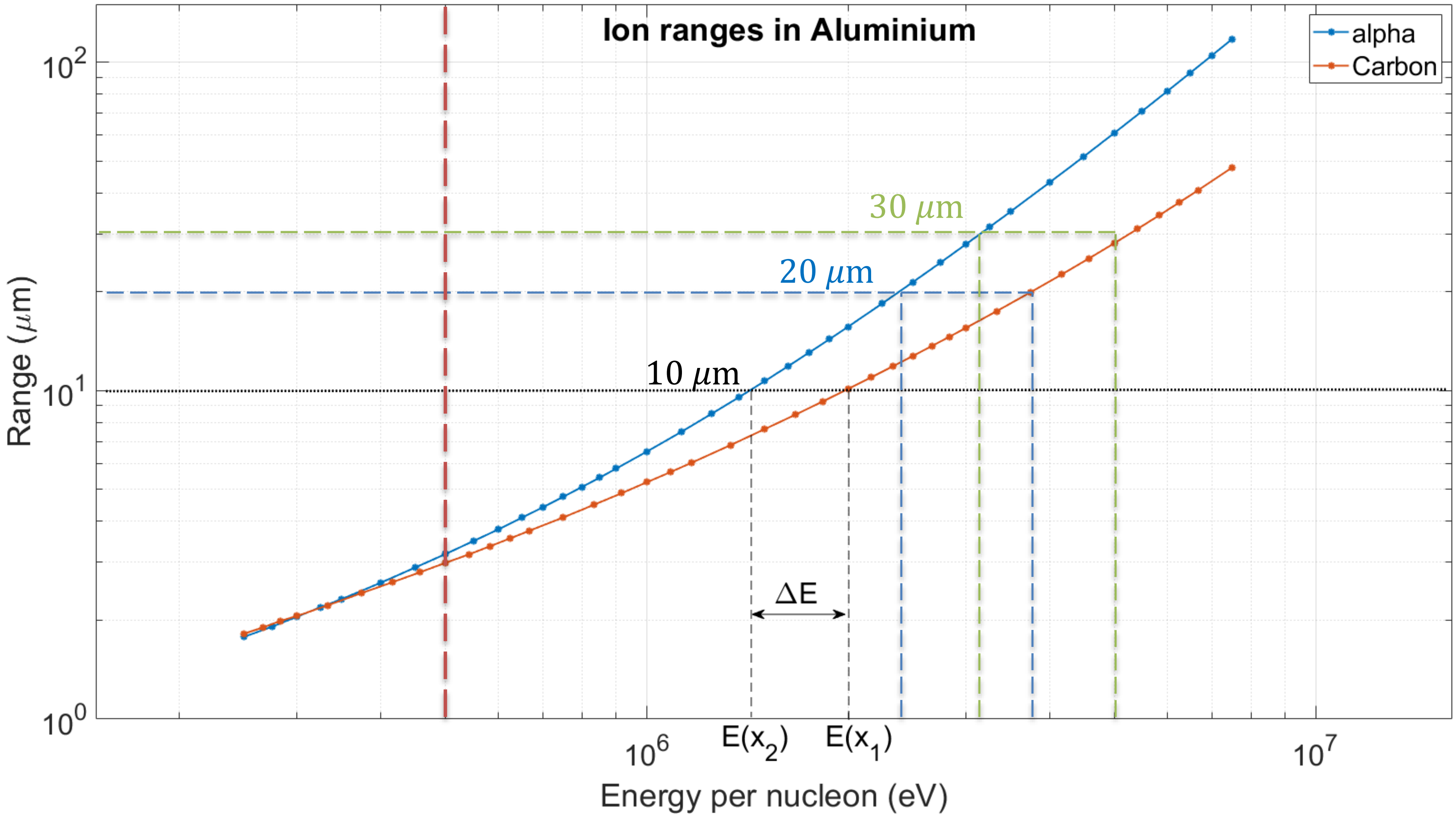
**M. Salvadori, subm to Las. Part. Beams**



# Diagnostic methodologies: Thomson Spectrometers

- **A filter with given thickness ok for some energy ranges**

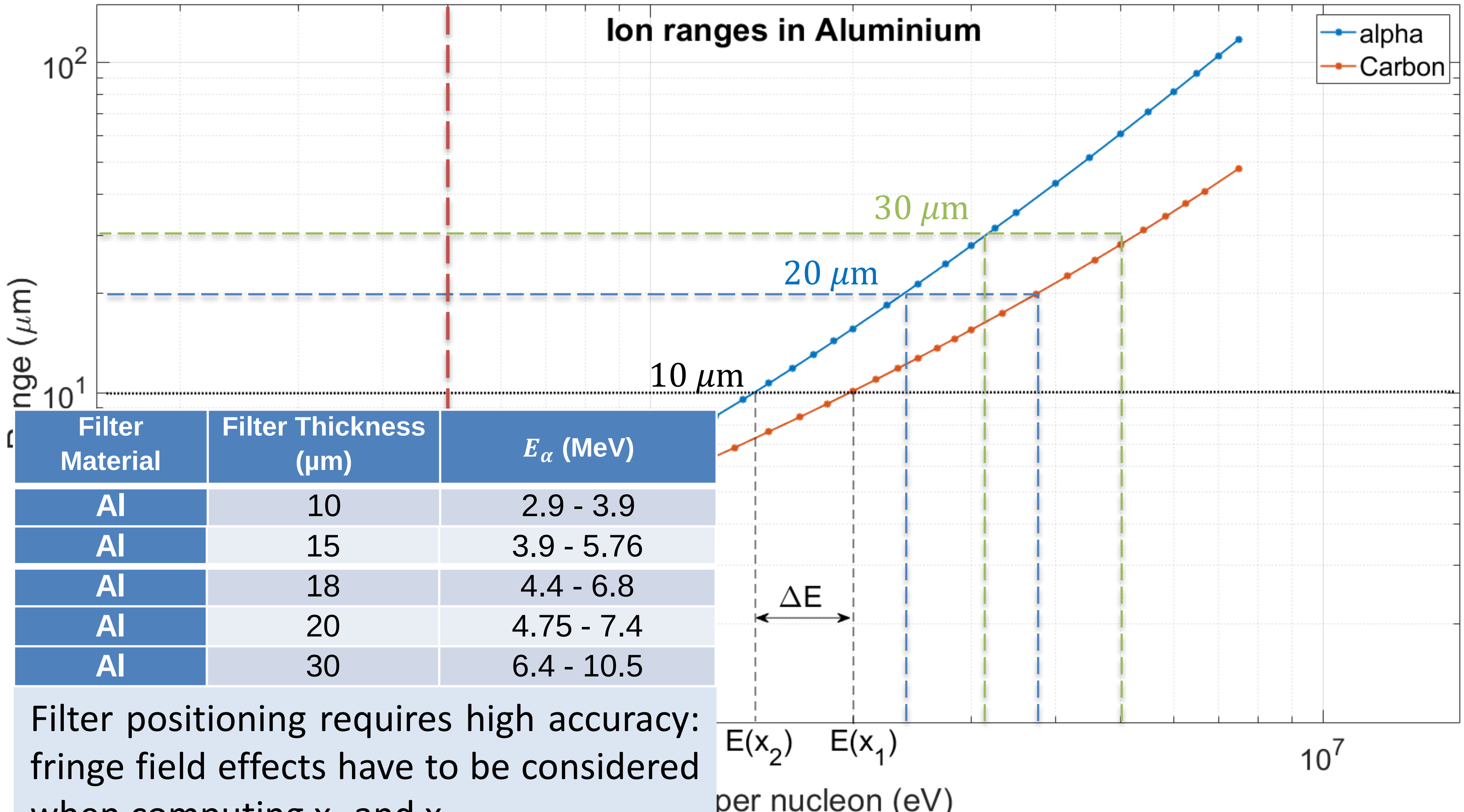
**M. Salvadori, subm to Las. Part. Beams**



# Diagnostic methodologies: Thomson Spectrometers

- **A filter with given thickness ok for some energy ranges**

**M. Salvadori, subm to Las. Part. Beams**



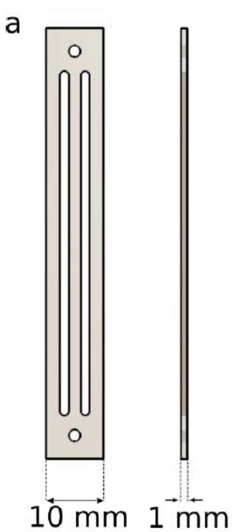

| Filter Material | Filter Thickness (μm) | $E_\alpha$ (MeV) |
|---|---|---|
| Al | 10 | 2.9 - 3.9 |
| Al | 15 | 3.9 - 5.76 |
| Al | 18 | 4.4 - 6.8 |
| Al | 20 | 4.75 - 7.4 |
| Al | 30 | 6.4 - 10.5 |

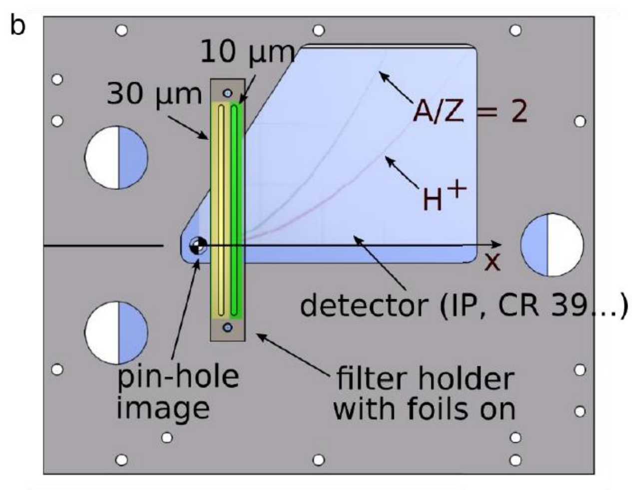
Filter positioning requires high accuracy: fringe field effects have to be considered when computing $x_1$ and $x_2$.

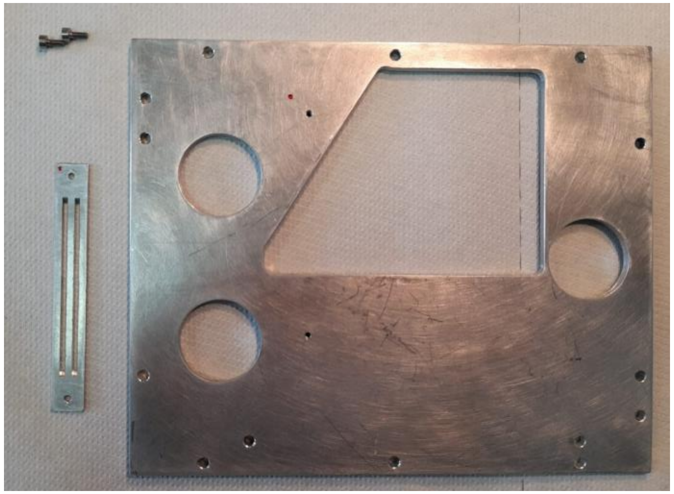
# Diagnostic methodologies: Thomson Spectrometers

- **Differential filtering**
- **Necessity to have filters with accurate thickness**
- **Prototype ready and first test performed**

**M. Salvadori, subm to Las. Part. Beams**



| Filter Material | Filter Thickness (μm) | $E_\alpha$ (MeV) |
|---|---|---|
| Al | 10 | 2.9 - 3.9 |
| Al | 30 | 6.4 - 10.5 |

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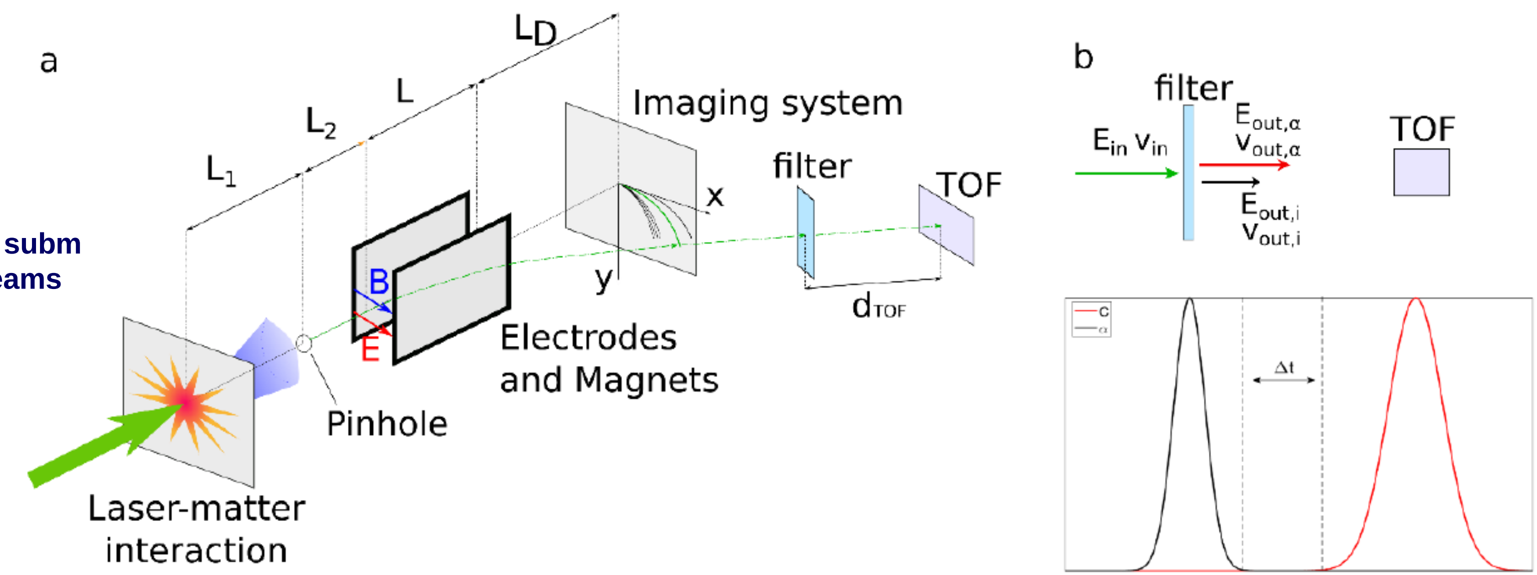
# Diagnostic methodologies: Thomson Spectrometers

- **Active detectors can be then used behind the filter. Real-time features**
- **Problem: filtering decreases the energy of alpha particles. Necessity of photomultiplier/MCP or other signal enhancers.**
- **Alternative methodology: use filtering to create different velocity attenuation between alphas and C arriving on specific points of the detectors. Time-of-flight schemes can be then applied!**

$$\Delta t = t_c - t_\alpha = d_{TOF}\sqrt{\frac{m_p+m_n}{E_{in_\alpha}}}\left(\frac{\sqrt{k_\alpha(E_{in,\alpha})}-\sqrt{k_C(E_{in,C})}}{\sqrt{k_\alpha(E_{in,\alpha})k_C(E_{in,C})}}\right)$$

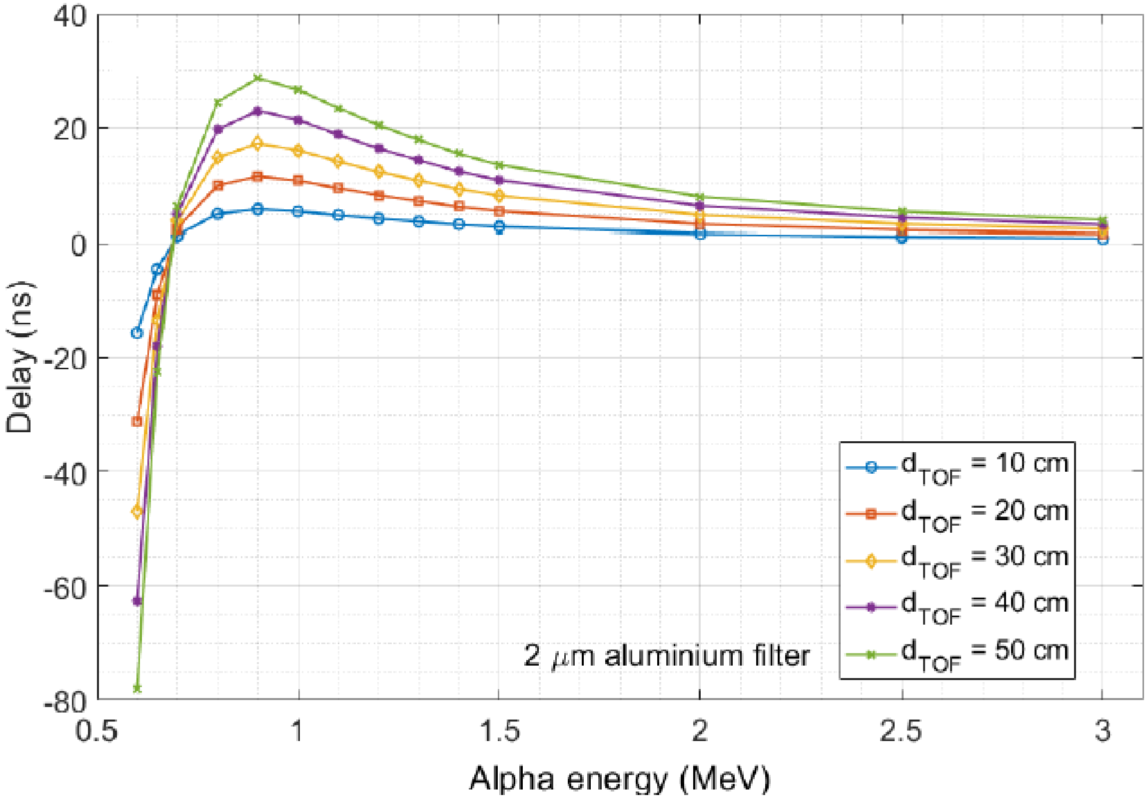
**M. Salvadori, subm to Las. Part. Beams**



# Diagnostic methodologies: Thomson Spectrometers

- **Delay spread according to the distance to the detector and to the filter used for velocity modulation**
- **For some energies alpha arrive first, for some other C instead**
- **Important issue of particle beam optics**

**M. Salvadori, subm to Las. Part. Beams**

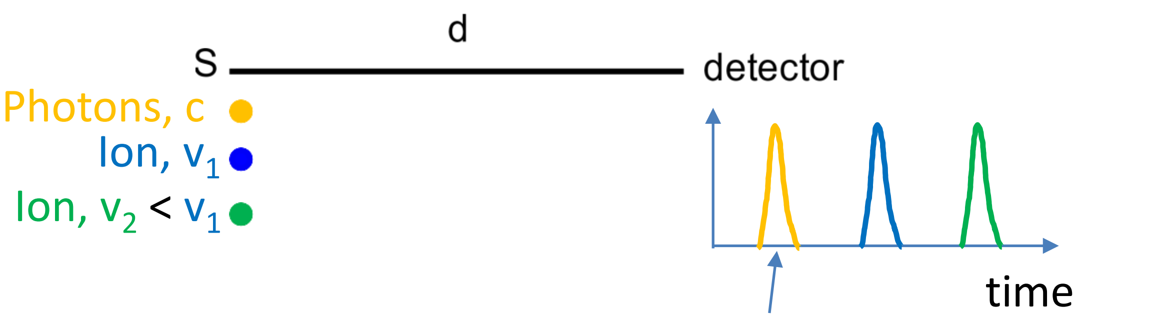


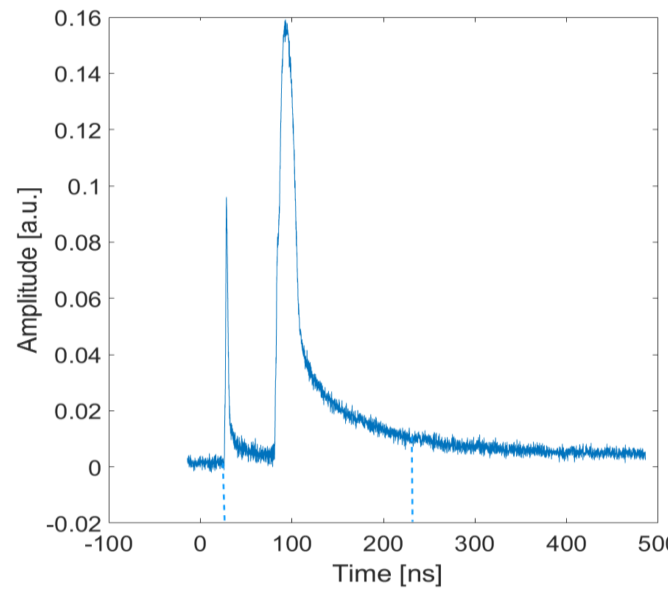
# Diagnostic methodologies

- Track Detectors
- Thomson Spectrometry
- **Time-Of-Flight technique**
- Detecting Products of Different Simultaneous Reactions

# Diagnostic methodologies: Time-Of-Flight Detection

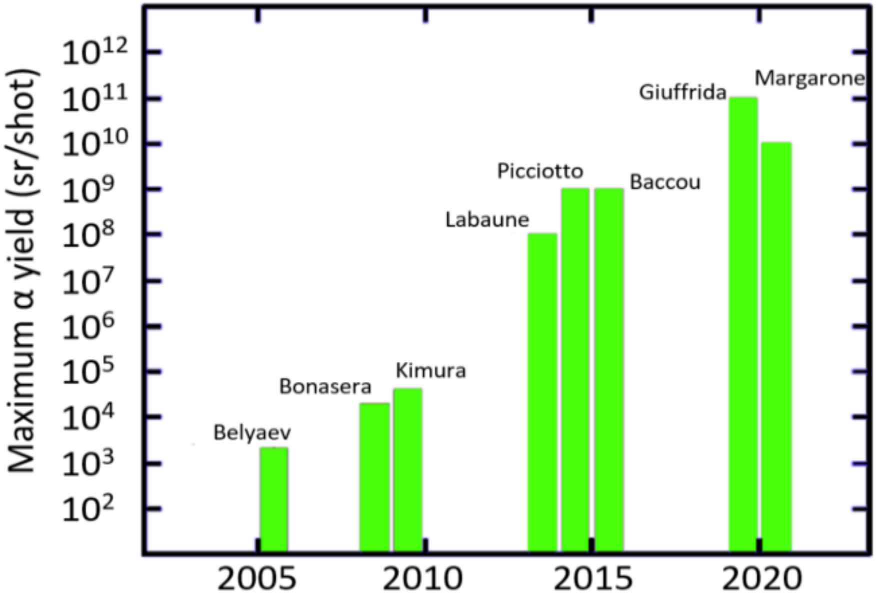
- **TOF techniques: measurements of <u>particle velocities</u>, as the time needed for traveling through a known distance. They <u>DO NOT</u> supply information on the particle type.**
- **Real-time features → ideal candidate for high repetition rate experiments**
- **'Photopeak': absolute reference for time measurements**
- **Intrinsic high dynamic range → necessity to characterize it properly**
- **High accuracy**
    - **energy resolution → large distances to target and/or fast detectors**
    - **exploitation of high dynamic range → background suppression & high dynamic range electronic read-out**



# Diagnostic methodologies: Time-Of-Flight Detection

- **In last experimental results in terms of p+$^{11}$B → $10^{10}$ – $10^{11}$ α / sr per shot were measured.**
- **For a classical detector used in TOF schemes of 5 mm x 5 mm area, placed at 1 m distance from target → $10^5$ – $10^6$ alphas are expected to hit the detector, which are low numbers**
- **Two solutions for increasing sensitivity**
  - **Use fast detection systems. In this way it is possible to decrease the distance to target, and then increase the solid angle. Anyway, there are intrinsic limitations on this sense**
  - **Use large-area detectors. Problems for**
    - **manufacturing**
    - **signal readout**
    - **EMP shielding**
    - **Intrinsic reduced detector sensitivity**

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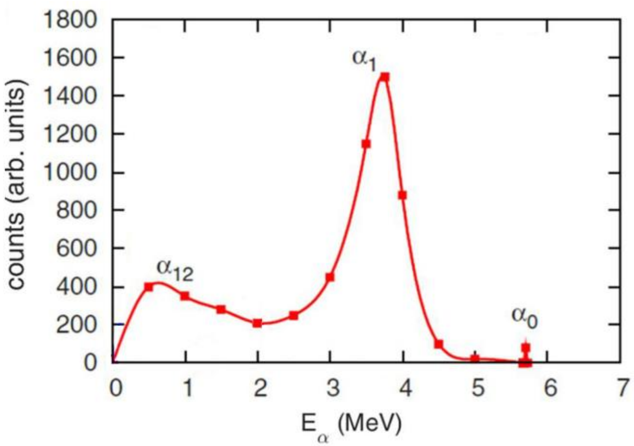
# Diagnostic methodologies: Time-Of-Flight Detection

- **Main issue: no discrimination on particles but only on their velocities.**
- **Possible simultaneous arrival of alphas and other ions (mainly protons) to the detector.**
- **'ideal' spectrum: alpha max energy = 5.7 MeV and max peak at 3.7 MeV. Alphas with these energies will be simultaneous to protons with 1.425 MeV and 0.95 MeV energies, respectively**
- **Filters (Al foils, …) can be beneficial to stop ions such as B and C, but will be not useful for protons, that have larger ranges than alphas**
- **Alphas usually much less than protons → modulations on proton signal due to alpha contribution expected to be rather small and thus barely visible and not recognizable.**
- **One possible way: to use a Thomson spectrometer on the same line of the TOF link, to have suitable description of the incoming protons**




**Consoli F. Frontiers in Physics (2020) 8, 561492**

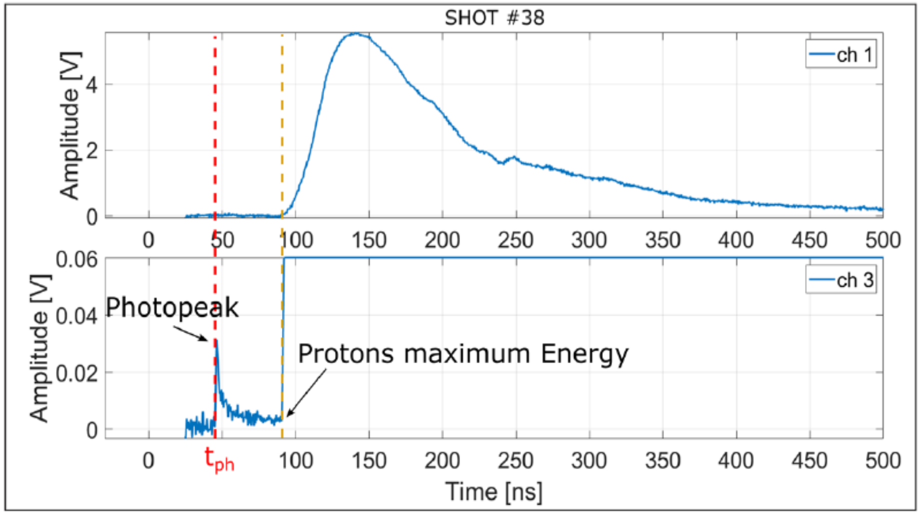
# Ion spectra. Univocal discrimination?

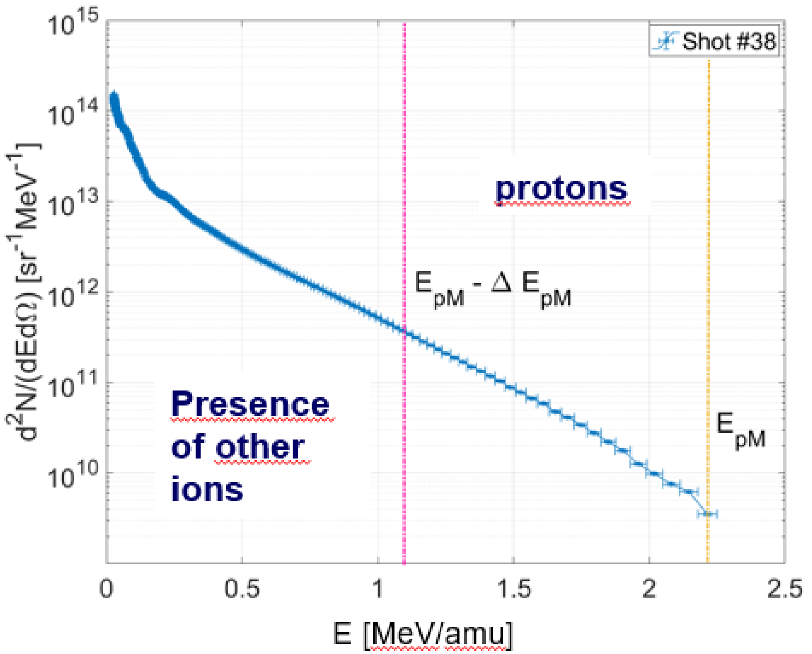
- **Absolute calibration of sensors by radioactive decay (i.e. $^{241}$Am $\alpha$-particles) or particle beams → absolute spectrum computation**
- **High accuracy on quantitative spectrum, also when foil filters are used**
- **For a test ion accelerated in the target by a potential drop:**

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

$$\Delta E_p \geq \frac{E_{pM}}{2},$$

**$E_{pM}$ maximum detected proton energy**
**$Z_i$ atomic number**
**$A_i$ mass number**

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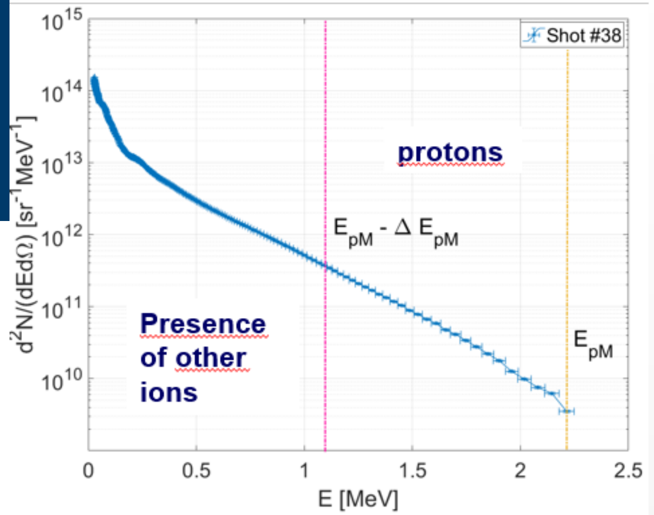
**M. Salvadori, et al. Scientific Reports 11, 3071 (2021**
**See C. Verona Talk today**

# Configuration of detector stack




**How to deal with this?**

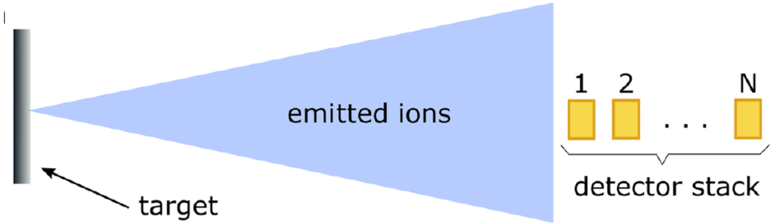
**→ Use of foil filters**

**This helps, <u>but cuts all ions</u>**

**Solution: use a stack configuration of active detectors**

- **Methodology for <u>Direct Drive schemes of ICF</u>**

**and for <u>all the contexts of laser-accelerated ions</u>**



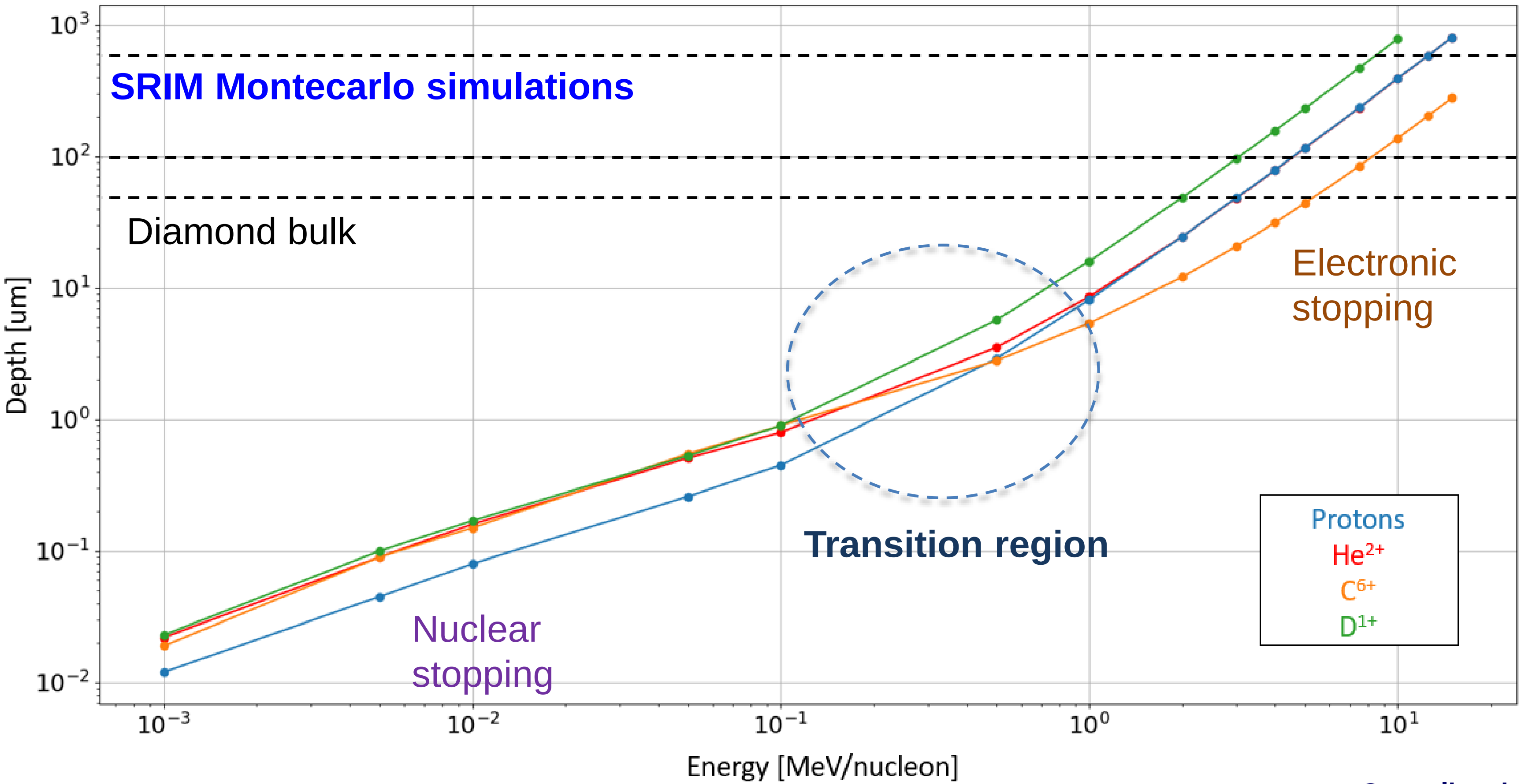

**Main issues:**

- **To reduce general background → high care of design and testing iteratively**
- **To have extremely high rejection of cross-talk between detectors → use small faraday cages**
- **To have accurately calibrated detectors & read-out system (active&passive) → simultaneous calibration on site**
- **To insure accurate alignment of each detector in the stack → optical alignment**
- **To take into account ion losses due to lateral straggling after each interaction → montecarlo simulations and experimental tests**

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

# Ranges in diamond

- **Idea for discriminating particles: use their different stopping power and range Solution? Not for each energy, not for each ion specie**




**Consoli, to be submitted**

- **At high energies, no discrimination is possible between p and alphas**
- **At low energies, discrimination difficult for D, alpha, C, …**
- **It is possible to exploit the discused <u>velocity modulation</u>, at some extent**

# Detector choice

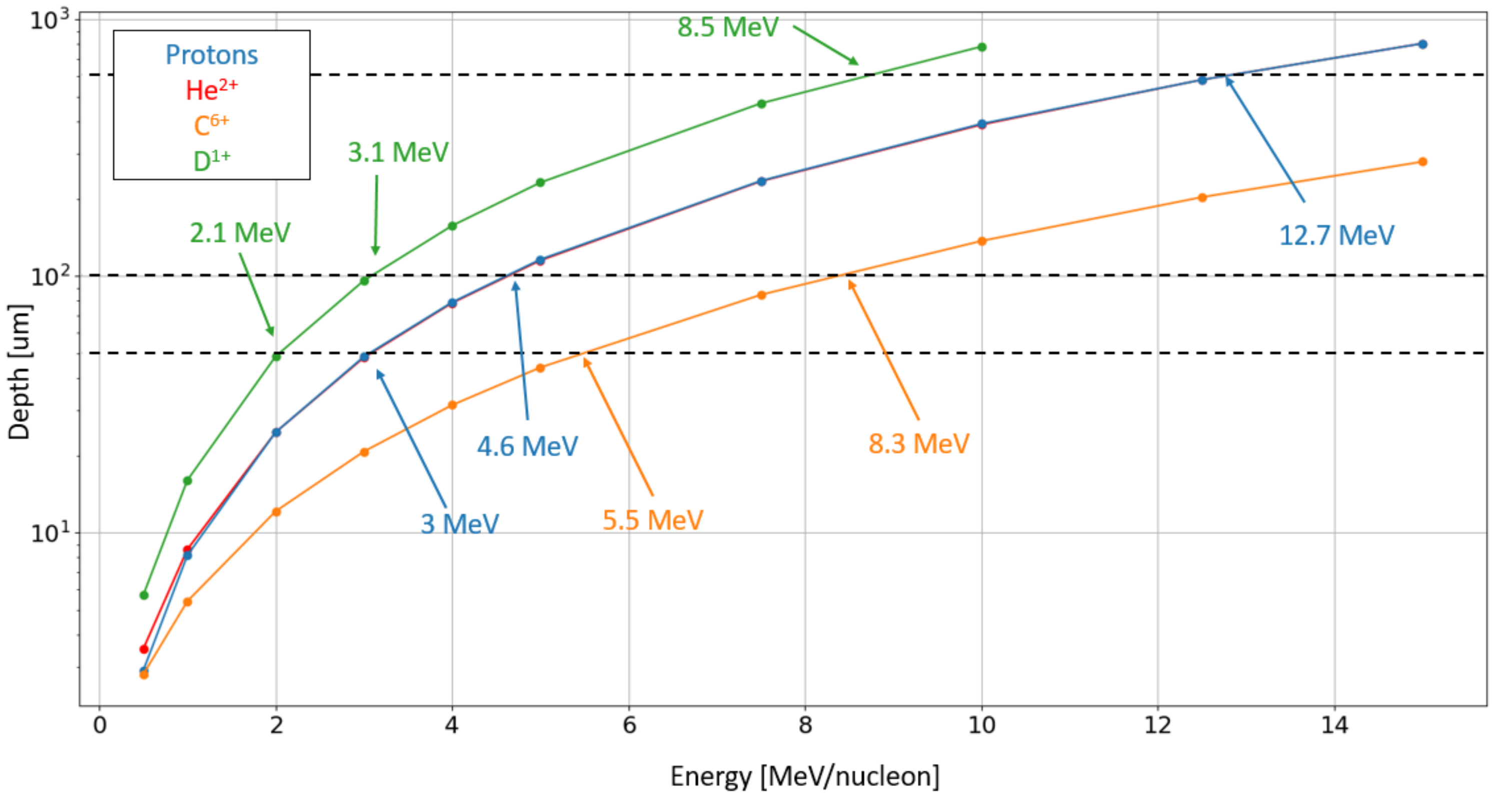
- It is possible to exploit
  - the different ranges of ions in materials, and thus cut a specific component
  - the different attenuation of the signals from consecutive detectors.
- Thin detectors are needed at least for the first detector in the stack.
- The configuration can be applied to different solutions, by choosing different detectors (material, configuration, thickness,…).
- Proof-of-principle prototype, to assess technological issues. Diamonds chosen.
- Layers: 1) 50 micron; 2) 50 micron; 3) 500 micron; Response: the first layers about a few hundreds picosecond, and the last a few nanosecond time resolution.
- The choice for the first two layers depend on capability to make metallization and bonding, for these free-standing diamonds. The idea is to decrease it in the future, by also exploiting thin film technology

Consoli, to be submitted

# Detector choice

- **Set of three detectors.**
- **Monocristalline diamond**
  - **higher gap with respect to SiC**
  - **high hardness to damages due to radiation**
  - **High efficiency with respect to policristalline.**
  - **4.5 mm x 4.5 mm active area**

**Consoli, to be submitted**

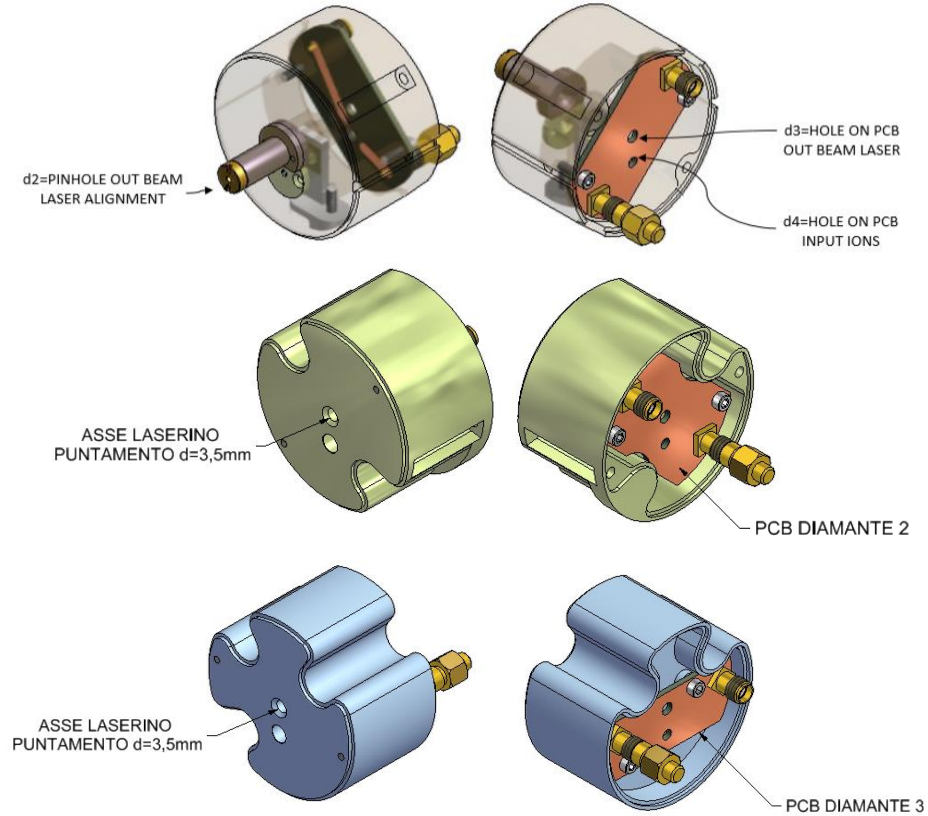


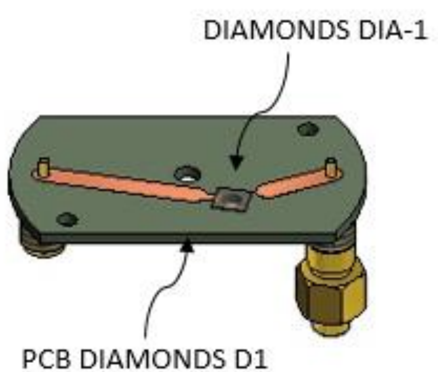
# Configuration of detector stack

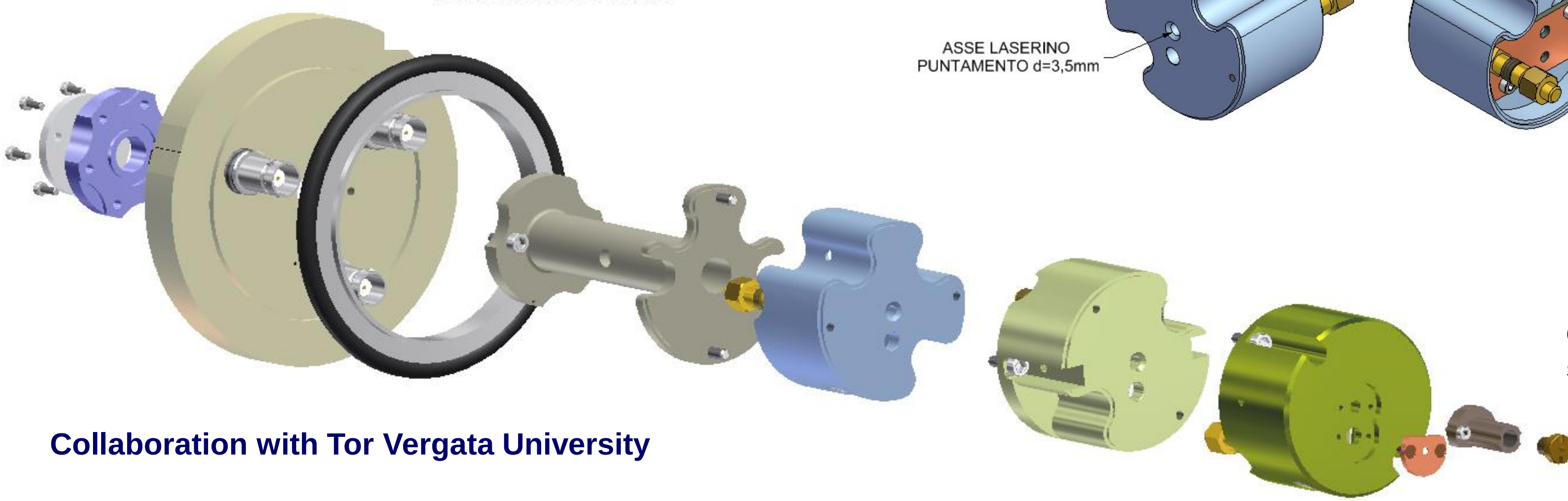
- Set of three detectors: modular structure
- Each is inside a faraday cage

→ no cross talk between them

- Off axis structure



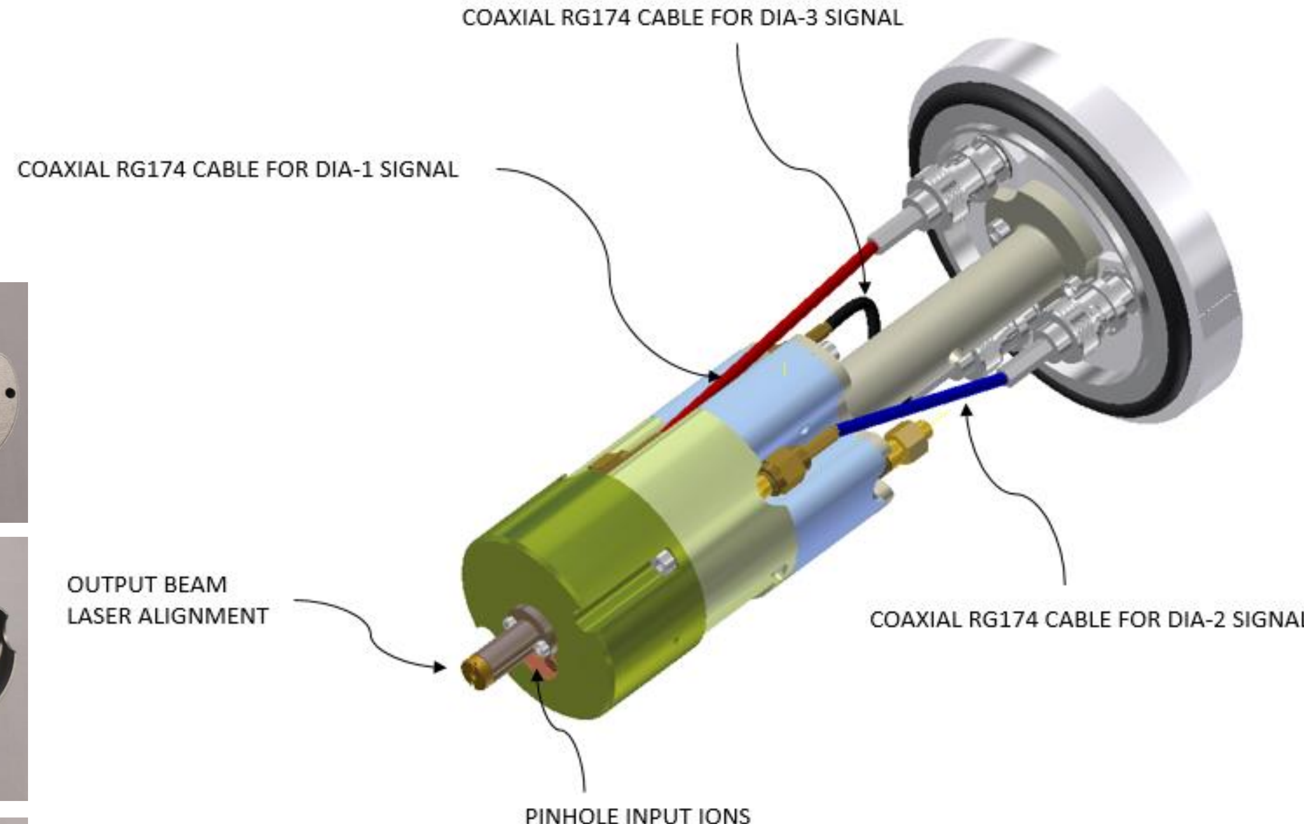
Consoli, to be submitted

Collaboration with Tor Vergata University

# Configuration of detector stack

- **Set of three detectors**

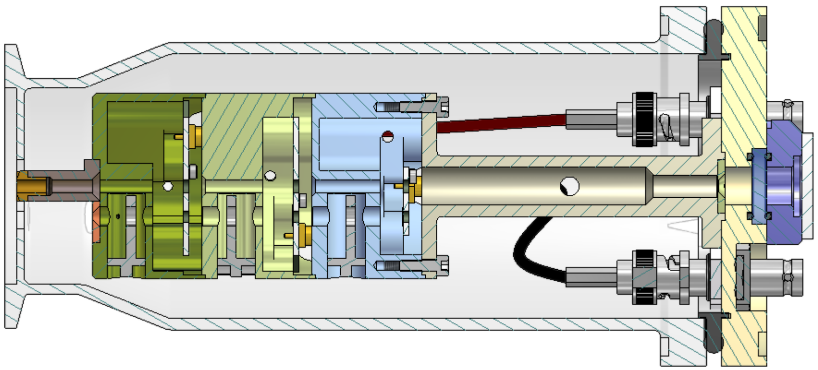
**1** **2** **3**

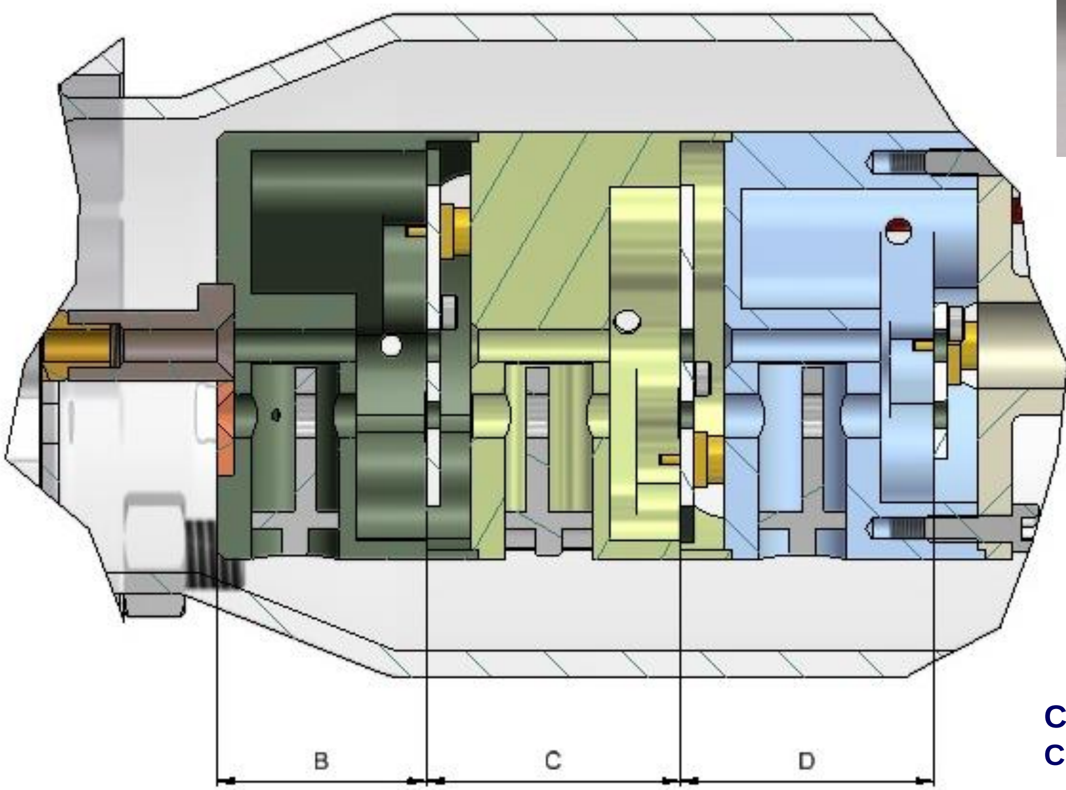


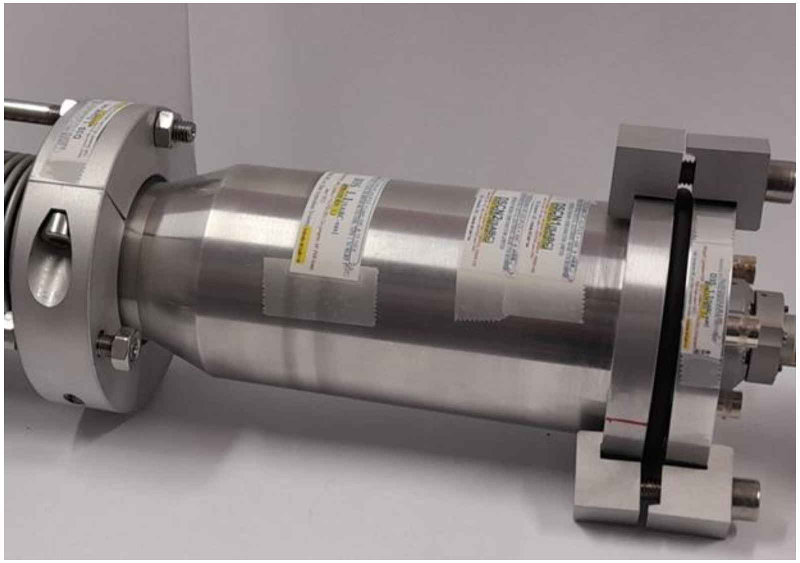

**Consoli, to be submitted**

**Collaboration with Tor Vergata University**

# Configuration of detector stack





**Foil filters can be mounted before of each detector**

| B [mm] | C [mm] | D [mm] |
|---|---|---|
| 24 | 29 | 29 |

**Collaboration with Tor Vergata University**
**Consoli, to be submitted**

# Diagnostic methodologies

- Track Detectors
- Thomson Spectrometry
- Time-Of-Flight technique
- **Detecting Products of Different Simultaneous Reactions**

# Diagnostic methodologies: Detecting Products of Different Simultaneous Reactions

- One of the important and appealing features of reactions such as $^{11}B(p,\alpha)2\alpha$ is that they release only alpha products. This, on the other hand, gives the discussed issues on product diagnostics

- In some cases, it is indeed possible to obtain information on $^{11}B(p,\alpha)2\alpha$ fusion reactions from the study of other reactions occurring in the same experiment and generating products different from alphas, that can be detected more easily.

- In principle, it might be even possible to get a link between the number of products from these side reactions and the number of $^{11}B(p,\alpha)2\alpha$ reactions which were simultaneously obtained, and so a possible estimation of the yield.

- Practically speaking, the methods consists in adding some dopants to the fuel, and in detecting radiations from the residues of the target and its stalk after the interaction

- An easy way to do it is to use natural B instead of $^{11}B$. In fact, $^{11}B$ is present in about 80% of natural B, the remaining being $^{10}B$.

- In this way, there is some probability that the reaction $^{10}B(p,\alpha)^{7}Be$ may take place simultaneously to the expected $^{11}B(p,\alpha)2\alpha$ one, even if with a smaller cross-section

# Diagnostic methodologies: Detecting Products of Different Simultaneous Reactions

- The released radioactive $^{7}Be$ has a half-life of 53.22 days. By electron capture, the nucleus of $^{7}Be$ decays to the $3/2^{-}$ ground state of $^{7}Li$ directly, with a branching ratio of 89.5% and to its first excited state with a 10.5% ratio, which decays subsequently to its ground state by emitting 478 keV gamma rays [1].

- So, the great advantage of this reaction is that the associated gamma signature from $^{7}Be$, collected from the residues of the target and its stalk after the interaction, can be detected more easily than alphas, by classical high sensitivity gamma detectors.

- From these measurements, it can be possible to obtain information firstly on the correct operation of the designed scheme, and then on the lower threshold on the number of expected alphas.

- As an example of this technique, ~478 keV γ-rays were detected by means of a high purity germanium semiconductor detector on samples collected after a certain number of laser shots at the ABC laser facility, with laser directly on natural boron-doped plastic targets at $\sim 3 \times 10^{15}$ $Wcm^{-2}$ laser intensity, 3 ns pulses [2].

- Another useful reaction is $^{10}B(p,\gamma)^{11}C$, releasing the radioactive $^{11}C$, with a half-life of 20.364 min. The decay is normally due to positron emission, $^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e + 0.96$ MeV. Also in this case the gamma emission can be an important observable.

[1] Firestone RB. 1999 Table of Isotopes. Wiley (1999).
[2] Bonasera A, Caruso A et al, Fission and Prop. Neutron-Rich Nuclei. World Scientific (2013). p. 503–7.

# Diagnostic methodologies: Detecting Products of Different Simultaneous Reactions

- Another possible option is, for instance, to dope pB targets with deuterium at a known concentration. In the plasma, D-D fusions will be achieved, and the corresponding neutron yield will be measured more effectively than alphas.

- Being the associated cross-section higher than for $^{11}B(p,\alpha)2\alpha$, this will give an upper constraint on the number of expected fusion reactions occurring in the simultaneous $^{11}B(p,\alpha)2\alpha$ processes.

[1] Firestone RB. 1999 Table of Isotopes. Wiley (1999).
[2] Bonasera A, Caruso A et al, Fission and Prop. Neutron-Rich Nuclei. World Scientific (2013). p. 503–7.

# Conclusions

- Several methods can be used for the possible detection of $^{11}B(p,\alpha)2\alpha$ fusion-reaction products were discussed, outlining their actual application to this purpose and the limitations with respect to the different scenarios.

- The difficulties of this task and the actual uncertainties on the use of one method or the other have been highlighted.

- The unique detection of the alpha particle products given by the reaction is not accomplished normally using a single detection technique, but the simultaneous use of different techniques is required.

- The actual number and type of diagnostics and their configuration may differ, also of a large extent, for each of the different possible experiments included in both schemes of laser interacting with target or pitcher-catcher.

- The considerations here developed apply not only to the $^{11}B(p,\alpha)2\alpha$ reaction but, in general, to all the low-rate nuclear reactions producing ions that need to be detected in the context of laser-matter interactions, such as $p+^{6}Li$ and $p+^{7}Li$, to name a few examples.

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# Acknowledgments

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Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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