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The Upgrade of the RIB Facility EXOTIC at INFN-LNL

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RIB In-Flight Production with EXOTIC

In-flight production of **light weakly-bound RIBs**, employing **two-body inverse kinematics reactions** with heavy-ion beams delivered from the LNL-XTU tandem accelerator impinging on **gas targets** (**p**,**d**,**^{3}He**).

The **commissioning** of the facility EXOTIC was performed in 2004.
F. Farinon et al., NIM B 266, 4097 (2008)

A **substantial upgrade process** was subsequently held in 2012.
M. Mazzocco et al., NIM B 317, 223 (2013)

8 Radioactive Ion Beams have been delivered so far:

1.	**^{17}F (S_p = 600 keV)**	**p(^{17}O,^{17}F)n**	Q_{value} = – 3.54 MeV;
2.	**^{8}B (S_p = 137.5 keV)**	**^{3}He(^{6}Li,^{8}B)n**	Q_{value} = – 1.97 MeV;
3.	**^{7}Be (S_α = 1.586 MeV)**	**p(^{7}Li,^{7}Be)n**	Q_{value} = – 1.64 MeV;
4.	**^{15}O (S_p = 7.297 MeV)**	**p(^{15}N,^{15}O)n**	Q_{value} = – 3.54 MeV;
5.	**^{8}Li (S_n = 2.033 MeV)**	**d(^{7}Li,^{8}Li)p**	Q_{value} = – 0.19 MeV;
6.	**^{10}C (S_p = 4.007 MeV)**	**p(^{10}B,^{10}C)n**	Q_{value} = – 4.43 MeV;
7.	**^{11}C (S_p = 8.689 MeV)**	**p(^{11}B,^{11}C)n**	Q_{value} = – 2.76 MeV;
8.	**^{18}Ne (S_p = 3.923 MeV)**	**^{3}He(^{16}O,^{18}Ne)n**	Q_{value} = – 3.19 MeV;

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Facility EXOTIC at LNL

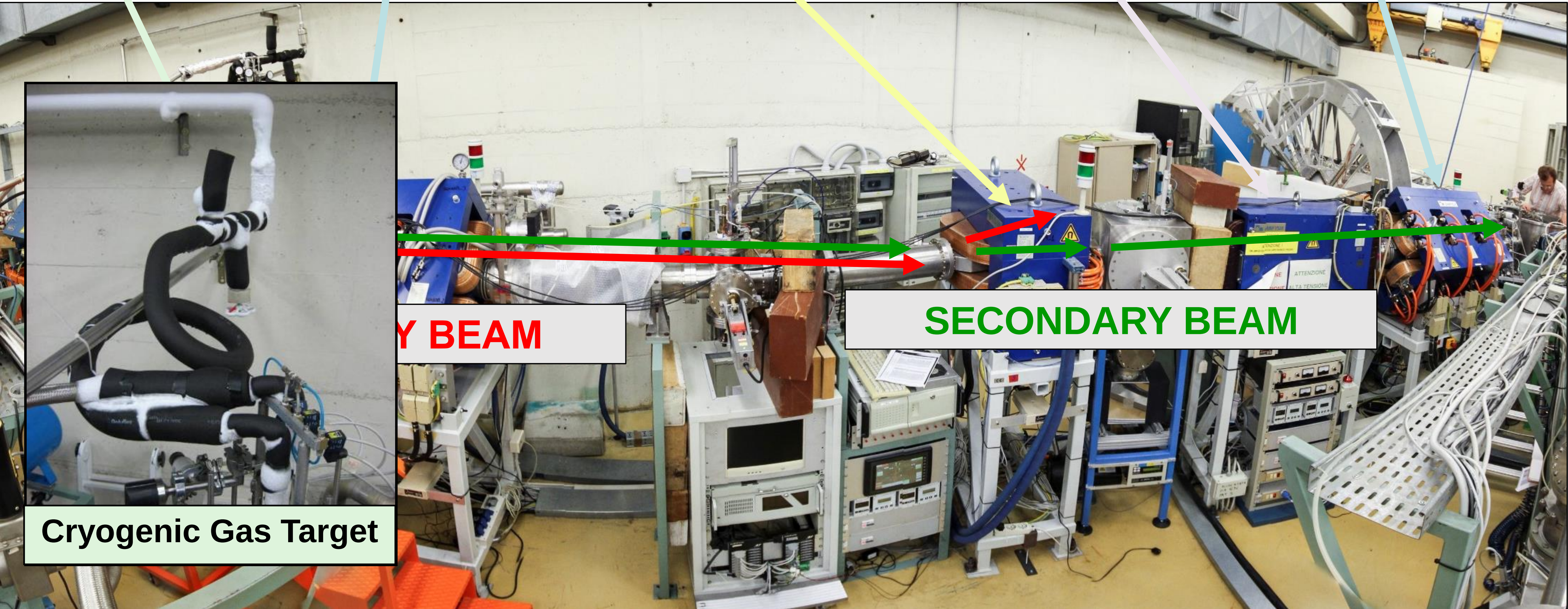
Gas Target

1st Quadrupole Triplet

30°-Dipole Magnet

Wien Filter

2nd Quadrupole Triplet



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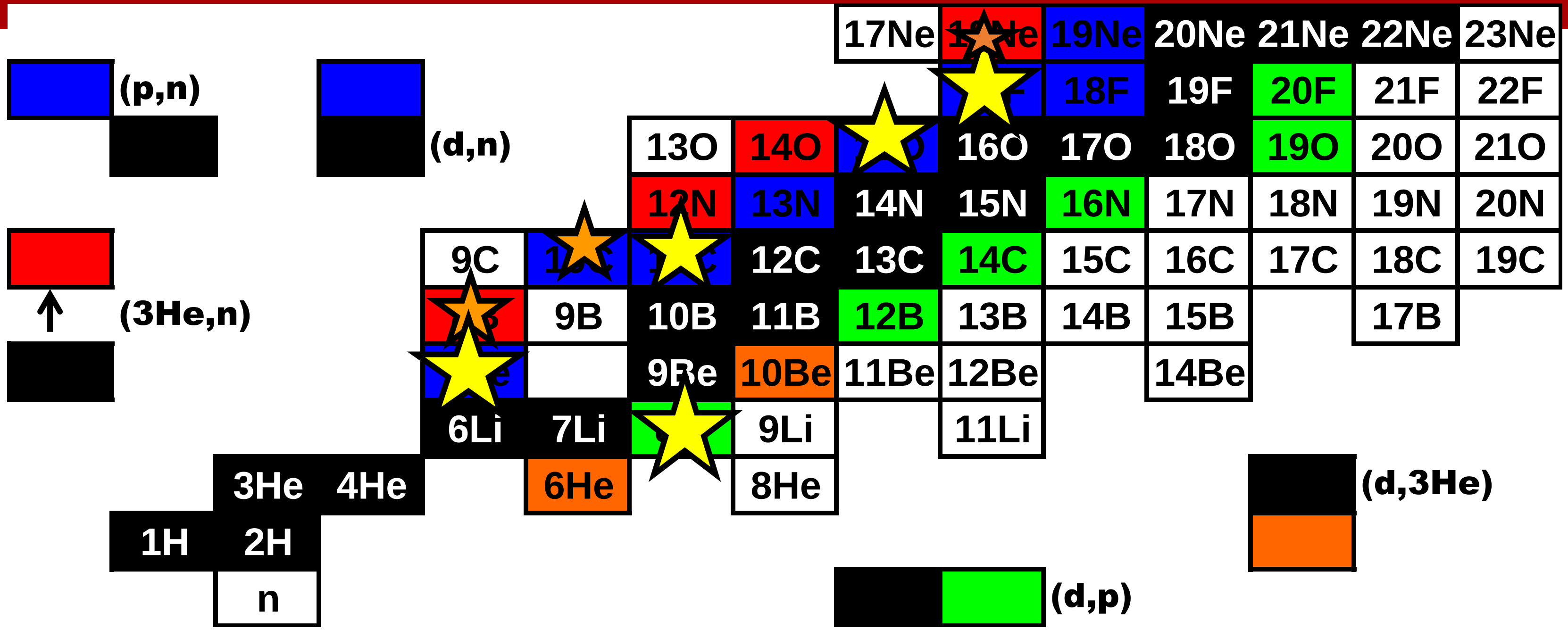
Light RIBs at EXOTIC



^{17}F	E = 3–5 MeV/u	Purity: **93-96 %**	Intensity: **10^5 pps**
^{8}B	E = 3–5 MeV/u	Purity: **30-43 %**	Intensity: **~ 10^3 pps**
^{7}Be	E = 2.5–6 MeV/u	Purity: **99 %**	Intensity: **10^6 pps**
^{15}O	E = 1.3 MeV/u	Purity: **97-98 %**	Intensity: **$4*10^4$ pps**
^{8}Li	E = 2–2.5 MeV/u	Purity: **99 %**	Intensity: **10^5 pps**
^{10}C	E = 4 MeV/u	Purity: **99 %**	Intensity: **$5*10^3$ pps**
^{11}C	E = 4 MeV/u	Purity: **99 %**	Intensity: **$2*10^5$ pps**
^{18}Ne	E = 1.3 MeV/u	Purity: **95 %**	Intensity: **$6*10^3$ pps (under dev.)**

Main Investigated Topics with EXOTIC

Reaction Dynamics at Coulomb Barrier Energies

$^{17}F + ^{208}Pb$ C. Signorini *et al.*, Eur. Phys. J. A 44, 63 (2010)

$^{17}F + ^{58}Ni$ M. Mazzocco *et al.*, Phys. Rev. C 82, 054604 (2010)

$^{17}F + ^{1}H$ N. Patronis *et al.*, Phys. Rev. C 85, 024609 (2012)

$^{8}B + ^{28}Si$ A. Pakou *et al.*, Phys. Rev. C 87, 014619 (2013)

$^{7}Be + ^{58}Ni$ M. Mazzocco *et al.*, Phys. Rev. C 92, 024615 (2015)

$^{7}Be + ^{208}Pb$ M. Mazzocco *et al.*, Phys. Rev. C 100, 024602 (2019)

$^{7}Be + ^{28}Si$ O. Sgouros *et al.*, Phys. Rev. C 94, 044623 (2016), Phys. Rev. C 95, 054609 (2017)

$^{8}Li + ^{90}Zr$ A. Pakou *at al.*, Eur. Phys. J. A 51, 55 (2015), Eur. Phys. J. A 51, 90 (2015)

$^{8}B + ^{28}Si$ C. Parascandolo, D. Pierroutsakou *et al.*, (in preparation)

Resonant Scattering – α clustering

$^{15}O + ^{4}He$ D. Torresi *et al.*, Phys. Rev. C 96, 044317 (2017)

$^{11}C + ^{4}He$ D. Torresi, C. Wheldon, C. Parascandolo *et al.*, (in preparation)

Reactions of Astrophysical Interest via Trojan Horse Method

$^{7}Be + ^{2}H$ L. Lamia *et al.*, Ap. J. 879, 23 (2019)

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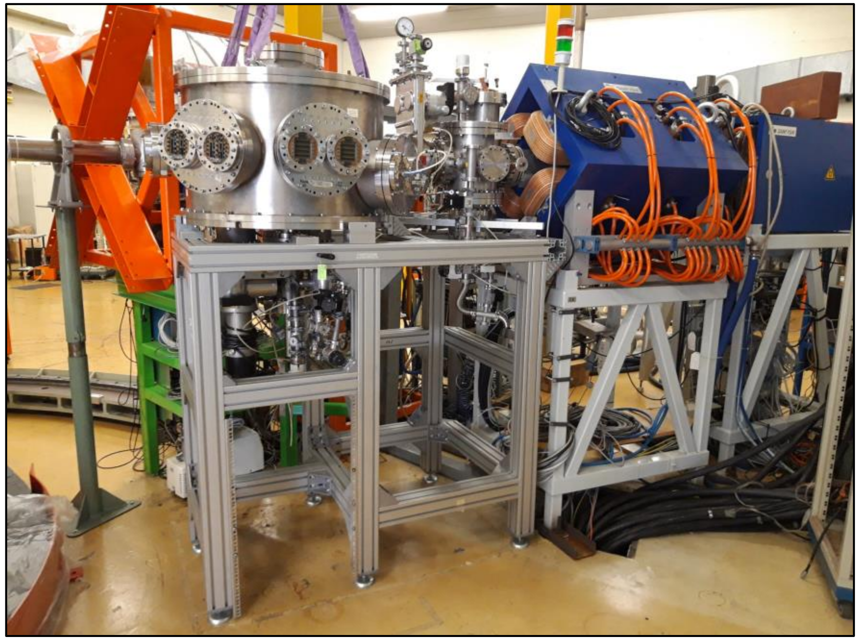
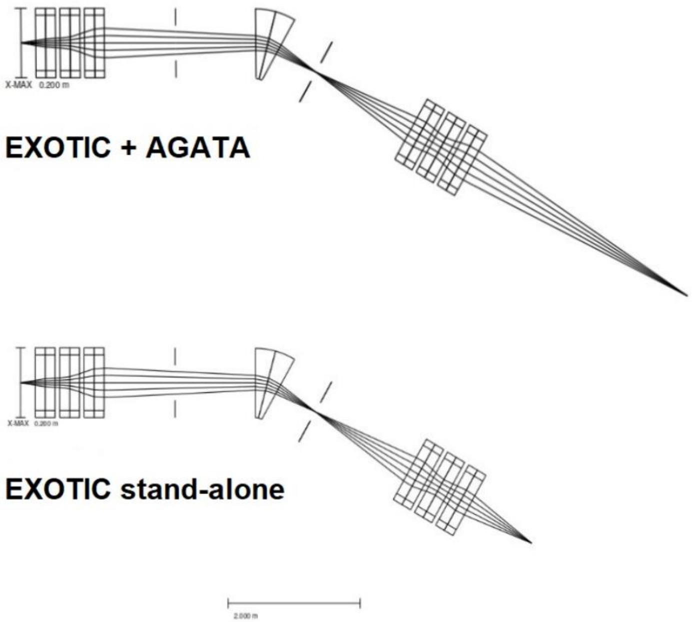
EXOTIC and





With the installation of AGATA, the **two reaction chambers** located in the proximity of the final focal plane of EXOTIC had to be **removed**.

Nevertheless, the **AGATA focal plane**, in the PRISMA-AGATA configuration, is located **2.68 m downstream** the original final focal plane and ion-optical calculations proved the possibility of **coupling EXOTIC** and **AGATA**.

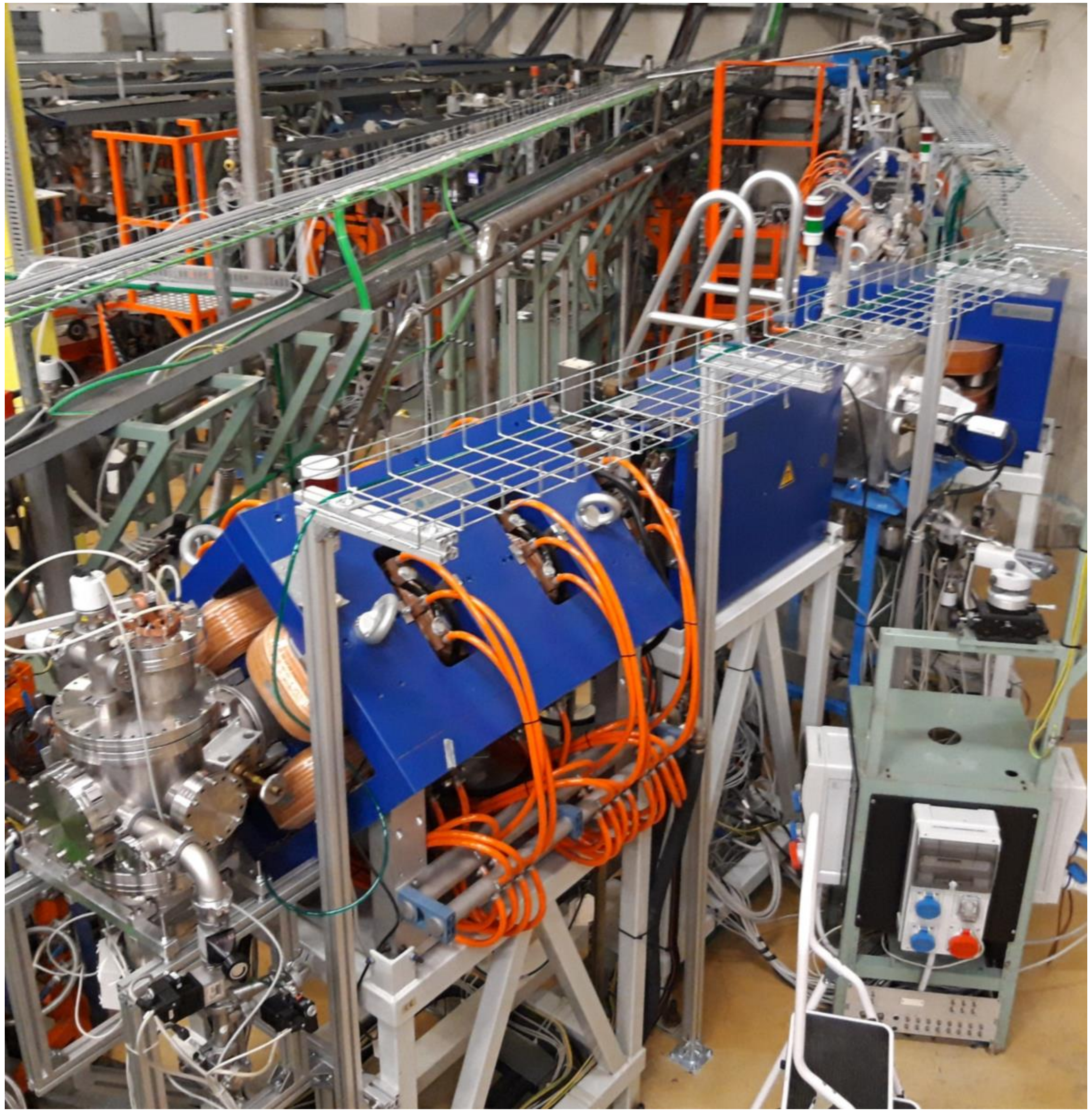
RIB Intensities for EXOTIC + AGATA

According to the ion-optical simulations, a **~50-% reduction** in secondary beam intensity (with respect to the EXOTIC stand-alone configuration) is estimated for a **target diameter of 15 mm**.

RIB	EXOTIC Conf. (pps)	AGATA Conf. (pps)	E_{max} (MeV)
$^{8}Li^{3+}$	10^5	5×10^4	21.7
$^{7}Be^{4+}$	10^6	5×10^5	44.2
$^{8}B^{5+}$	10^3	4×10^2	45.5
$^{10}C^{6+}$	5×10^3	2×10^3	51.8
$^{11}C^{6+}$	2×10^5	10^5	54.2
$^{15}O^{8+}$	4×10^4	2×10^4	70.6
$^{17}F^{9+}$	10^5	4×10^4	79.6
$^{18}Ne^{10+}$	6×10^3	2×10^3	78.1

Upgrade of EXOTIC

- Power lines
- Signal cables
- Beam diagnostics
- Vacuum control
- Gas target control
- LN_2 pile-line insulation
- Water collector and pipelines for cooling the magnets
- Magnets and Wien Filter remote control
- Slit remote control
- Teslameters
- Compressed air
- Tracking detectors



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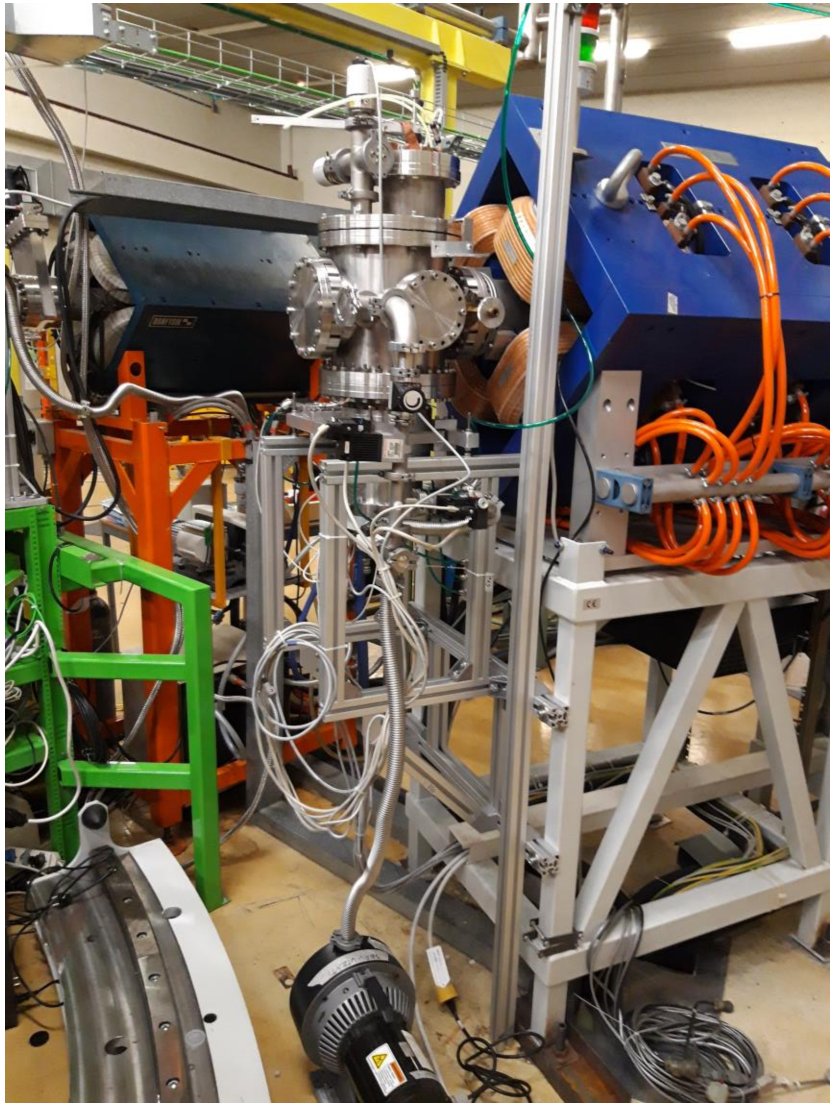
First Commissioning Run (Oct. 28-29)



- First experimental run with EXOTIC after nearly 4 years of inactivity.
- **Beam**: 7Li^{3+}, 48 MeV, 1-35 pnA
- **Target**: $^{1}H_2$, 1 bar, -184° C
- **RIB**: $^{7}Be^{4+}$, ~42 MeV

- Reoptimization of the **primary beam focussing procedure**.
- Quickly reproduced the **secondary beam production conditions** of November 2013.
- **Tuning** of the ion optical elements of the beamline.
- Test of the **AGATA performance** and **neutron flux** on the detectors.

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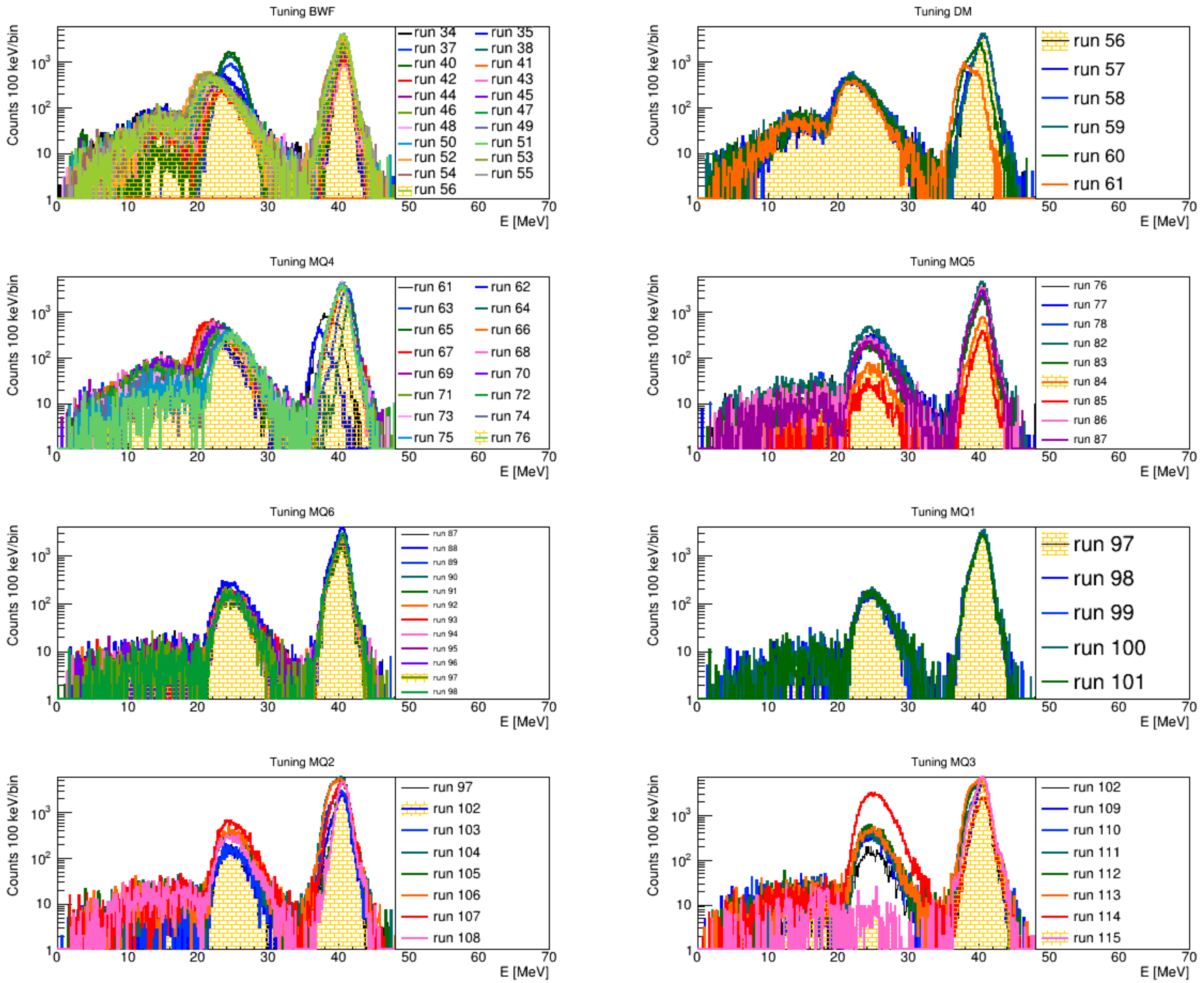
EXOTIC Ion-Optical Tuning



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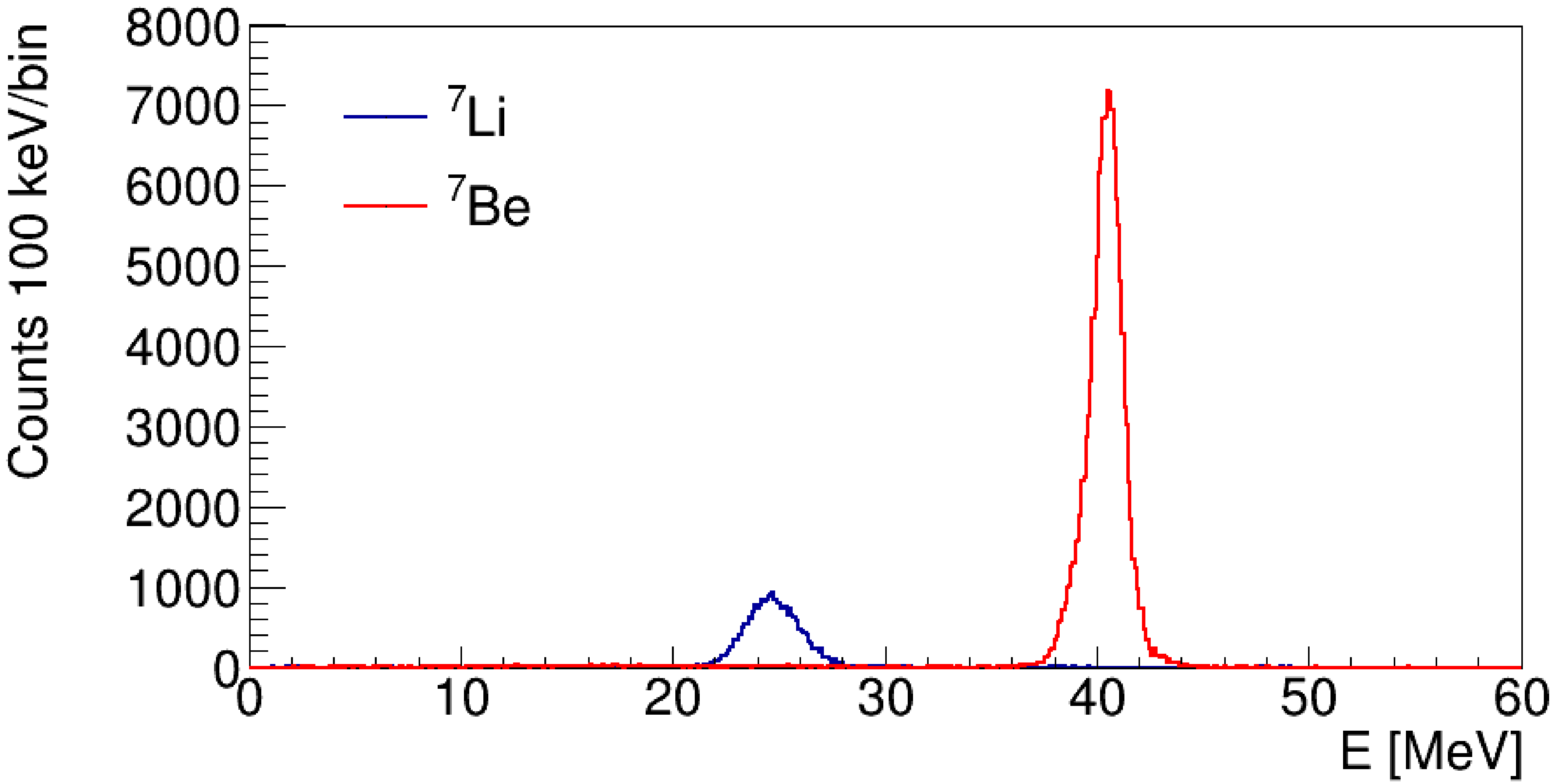
$^{7}Be^{4+}$ Initial and Final Spectrum



Building the MCP

- MCPs from RoentDek (Hamamatsu) delivered at the **end of July 2023**.
- **Circular shape** with a diameter of **104 mm** (active area).
- Lay-out of the mechanical support and electronics based on the MCP of **PRISMA** (rectangular shape of 100 mm x 80 mm).

MCP: Detector

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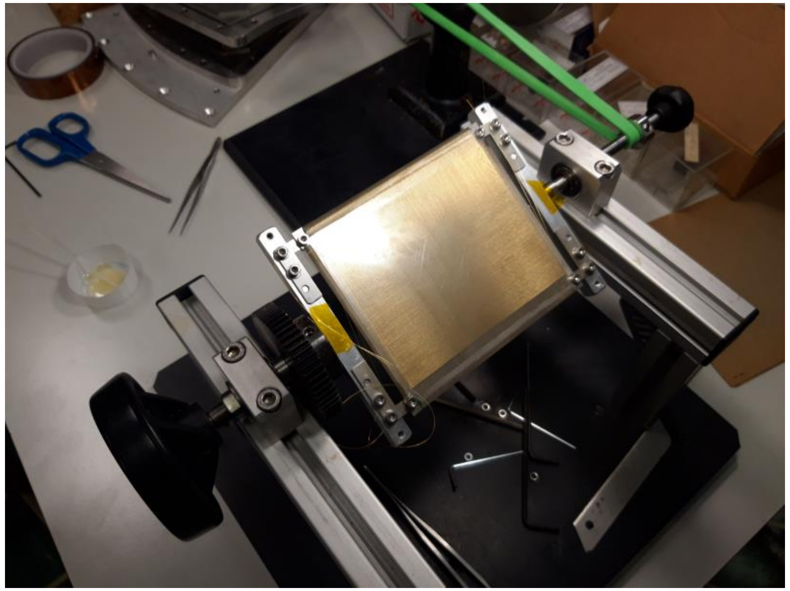
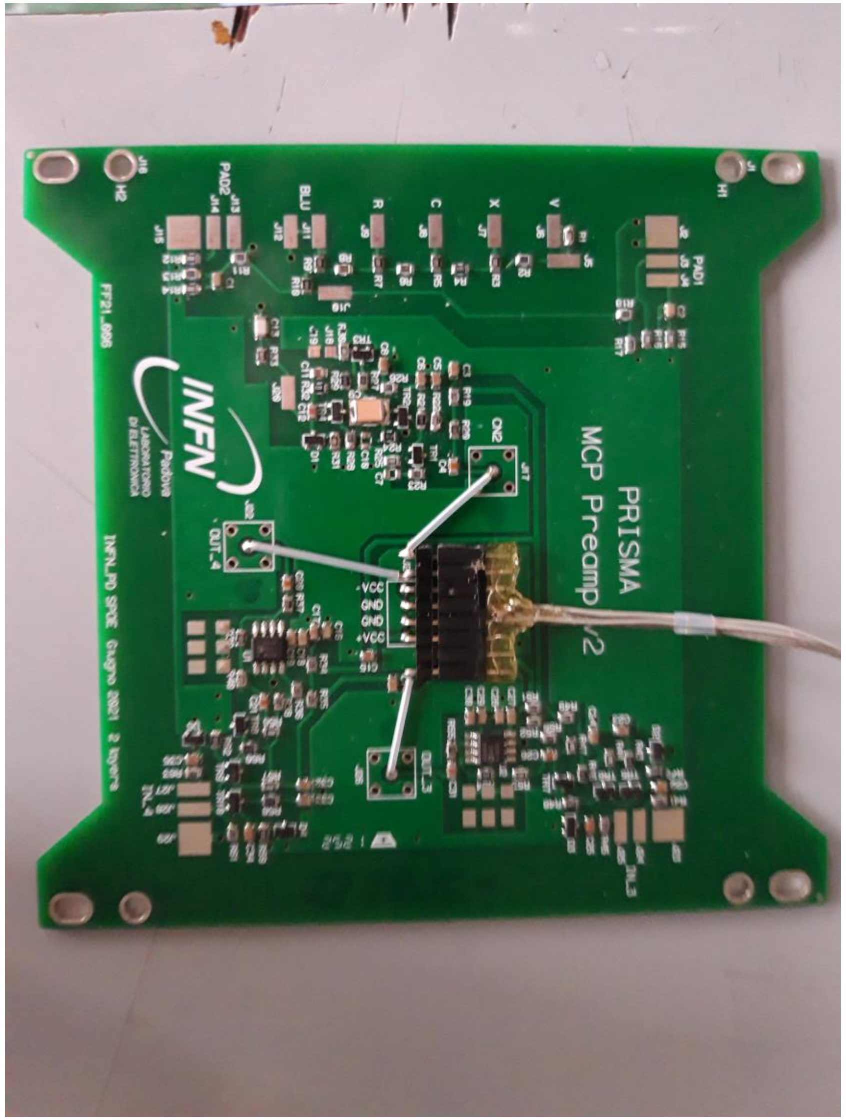
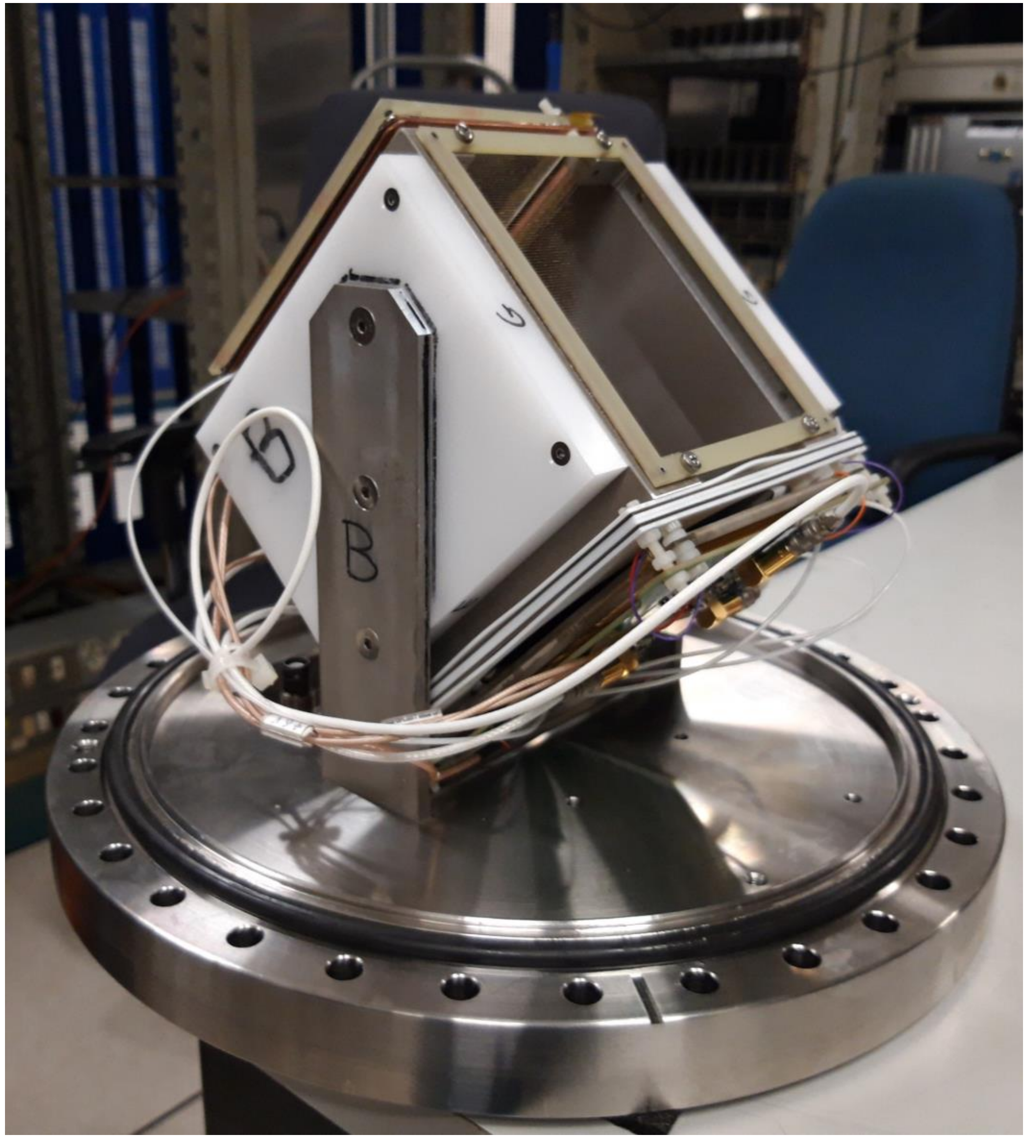
MCP: Delay-Lines

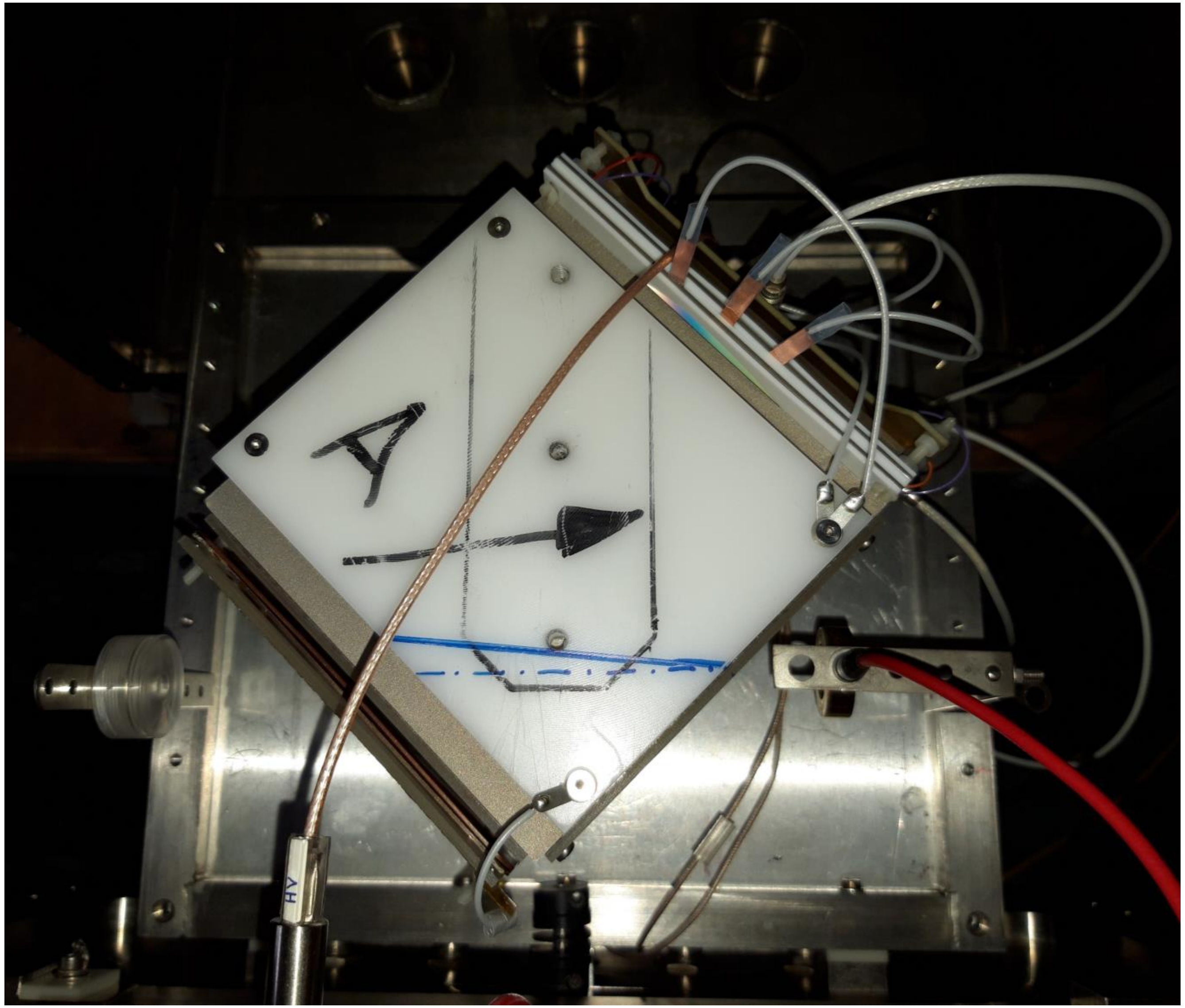


MCP: Readout Electronics



MCP Ready for Tests





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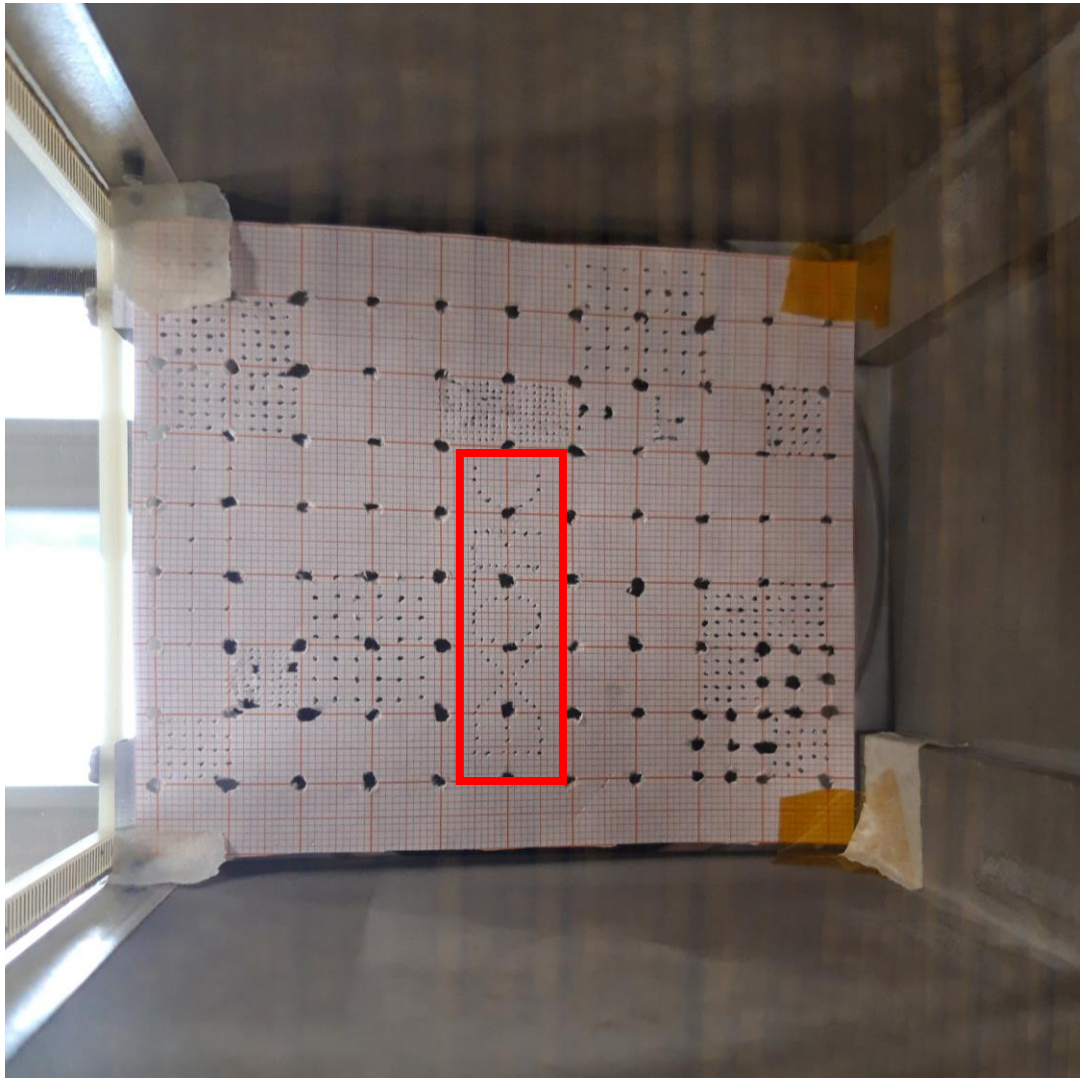
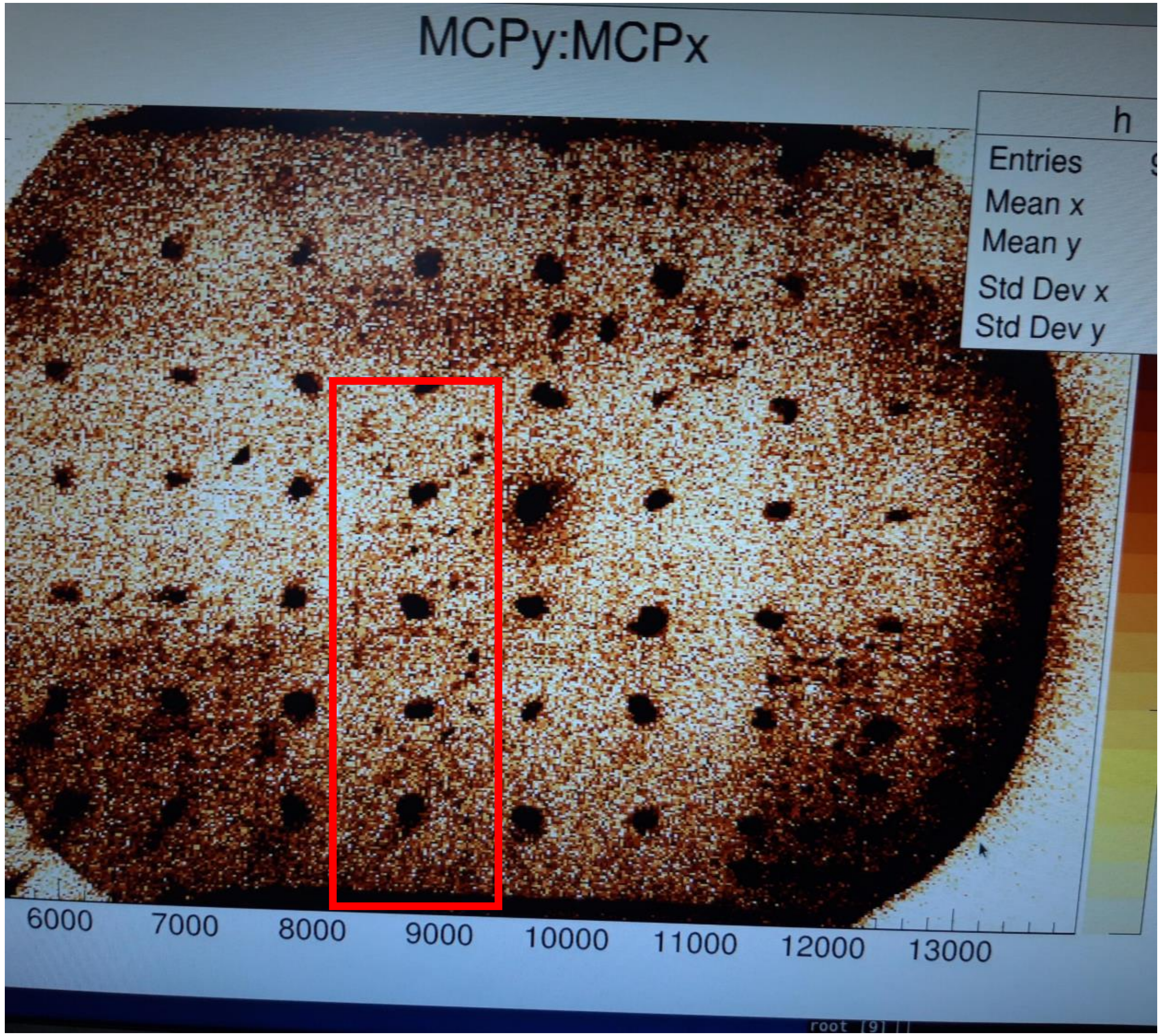
First Test with α-particles





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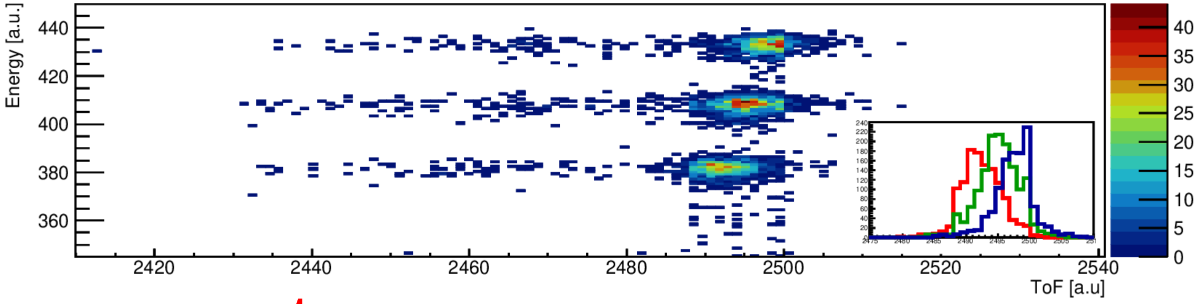
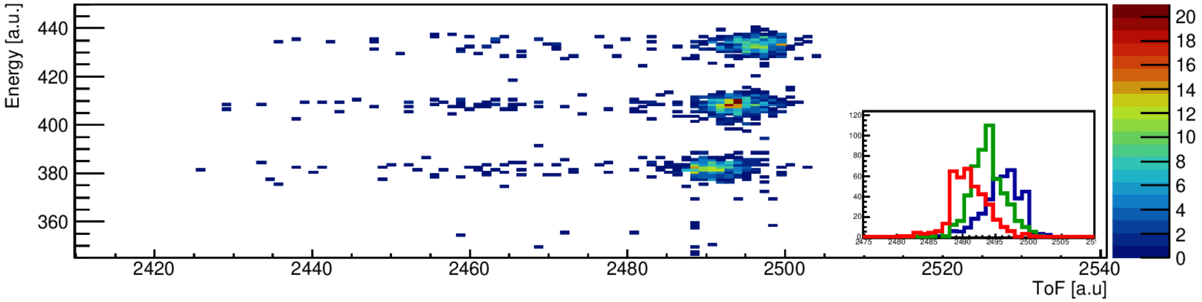
Time and Position Resolution

w/o magnets

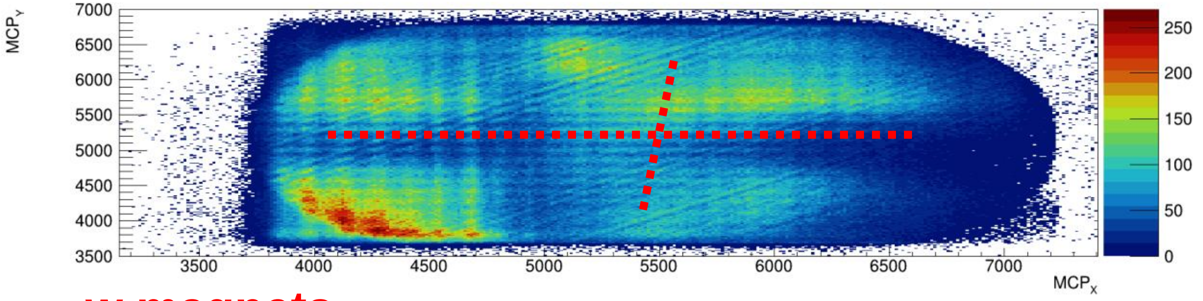


w magnets

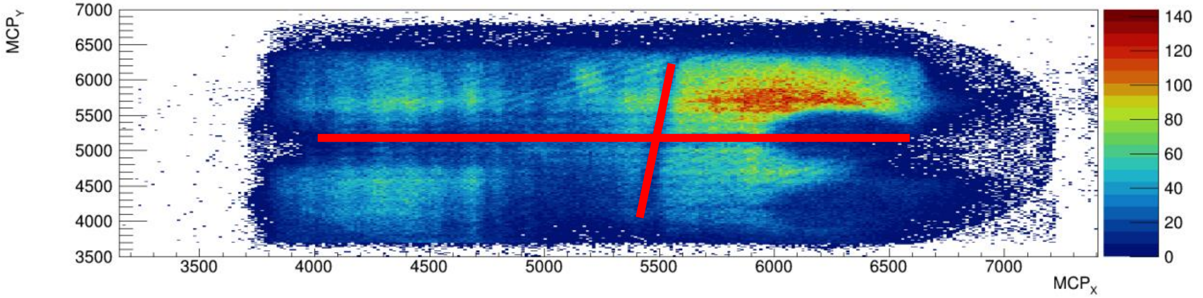


TOF resolution **better than 600 ps**

w/o magnets



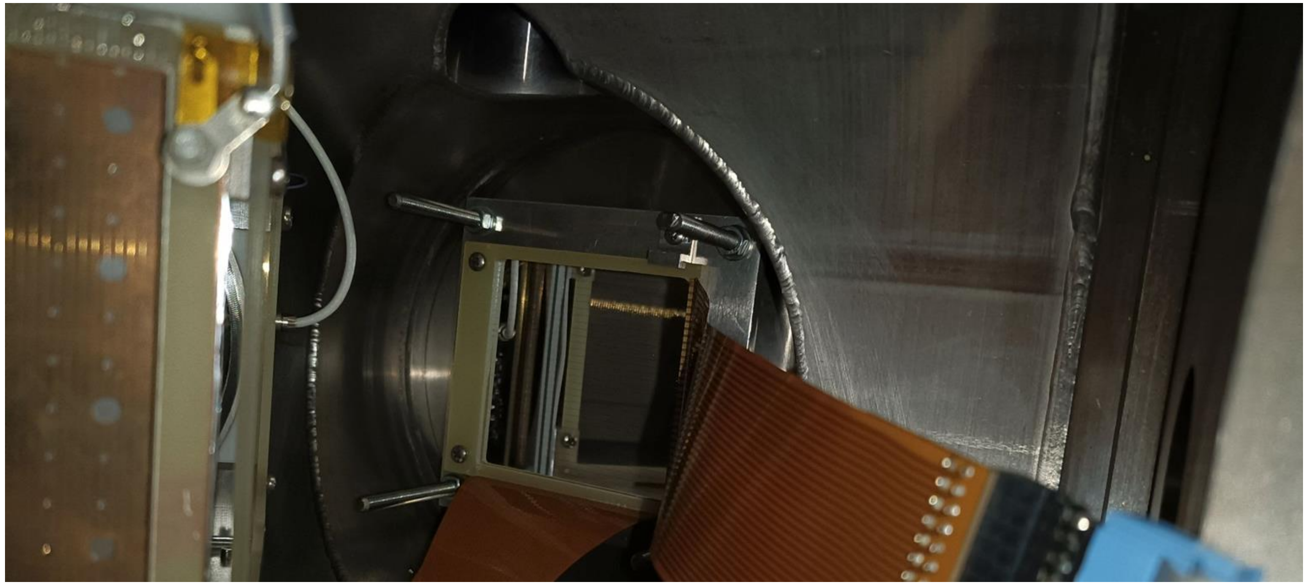
w magnets

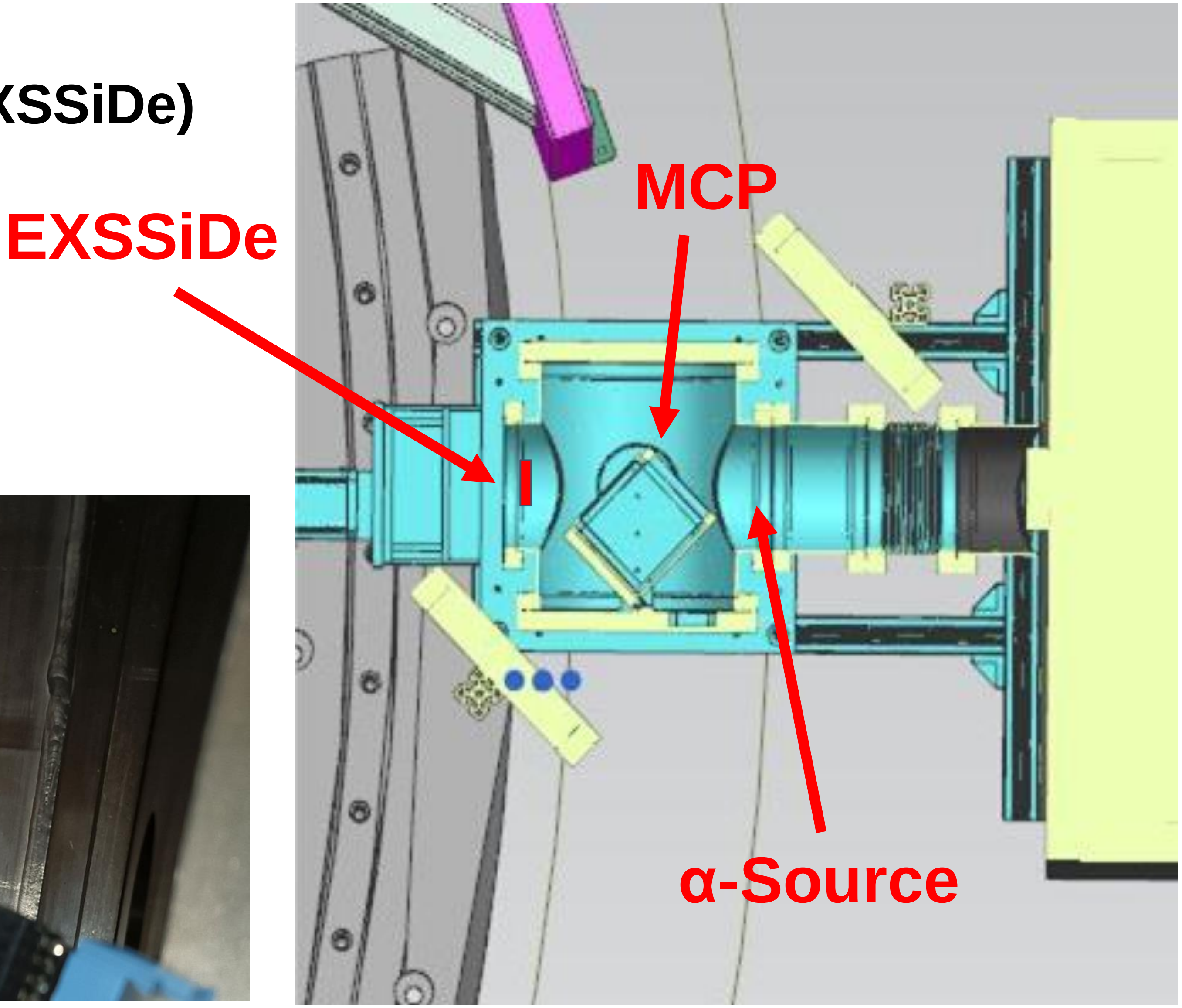


Position resolution: ~ **2 mm**

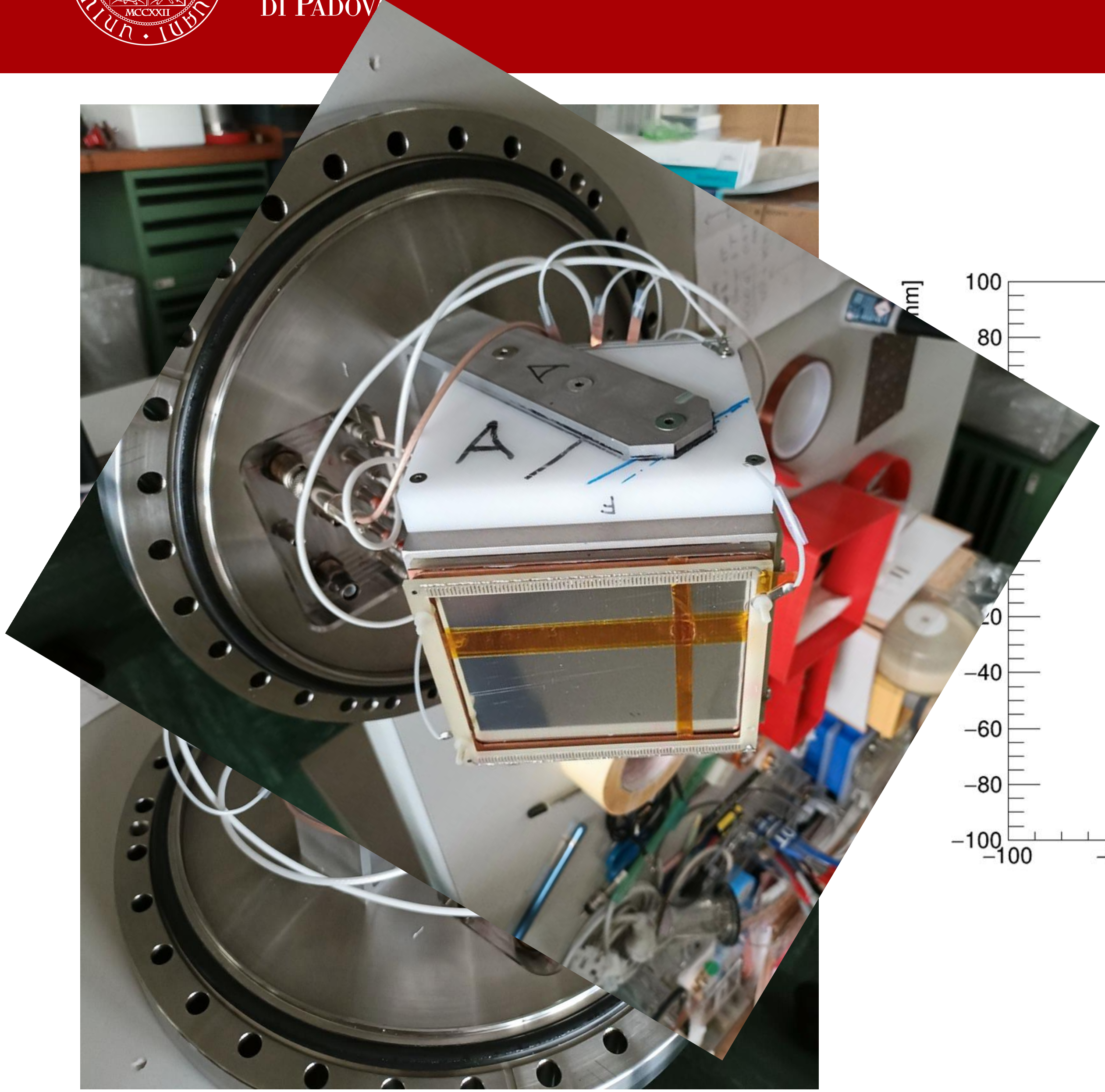
Test of the Tracking System

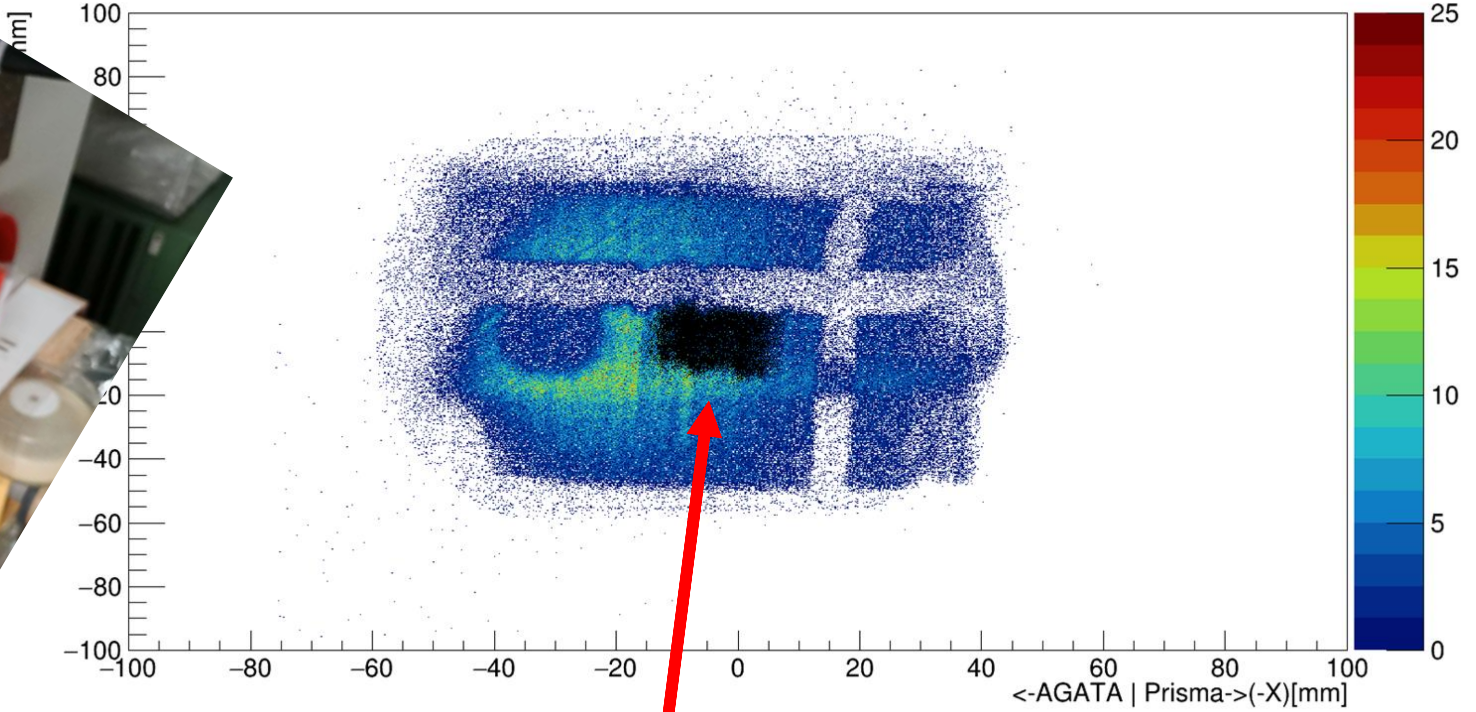
EXotic Silicon Strip Detector (EXSSiDe)
Area: 64 mm x 64 mm
Thickness: 1 mm
Strip: 32 vertical x 32 horizontal
Position Resolution: 2 mm x 2 mm





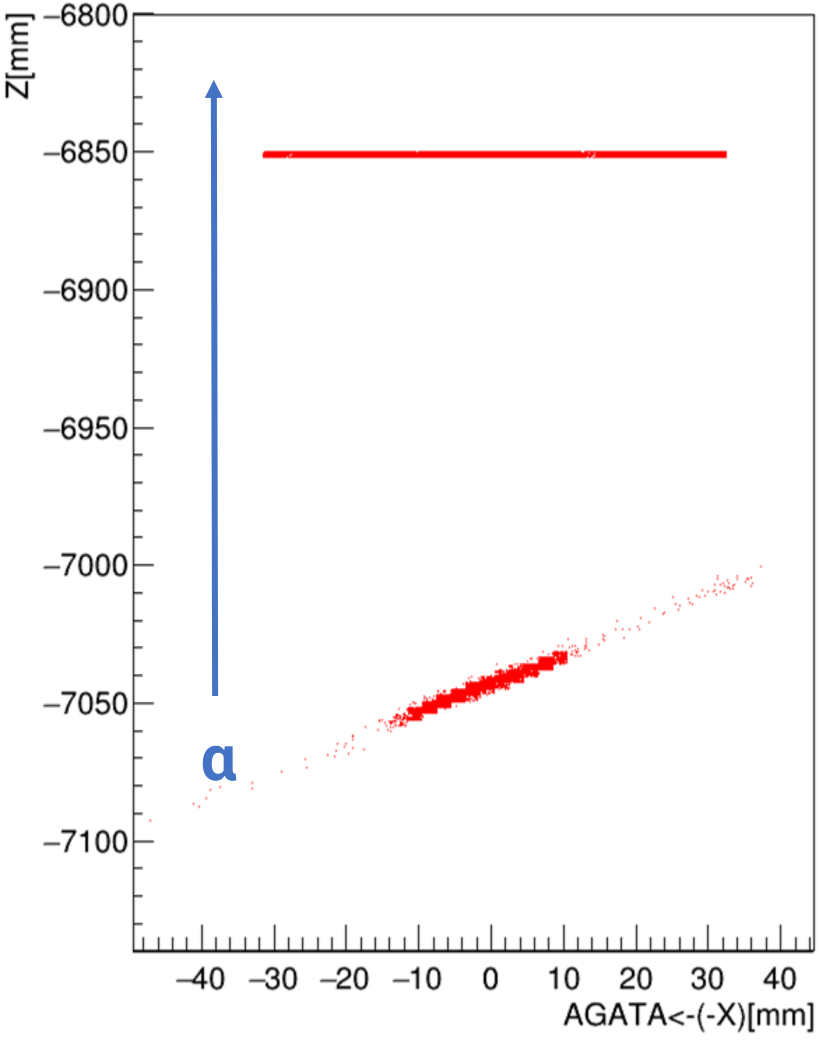
Test of the Tracking System

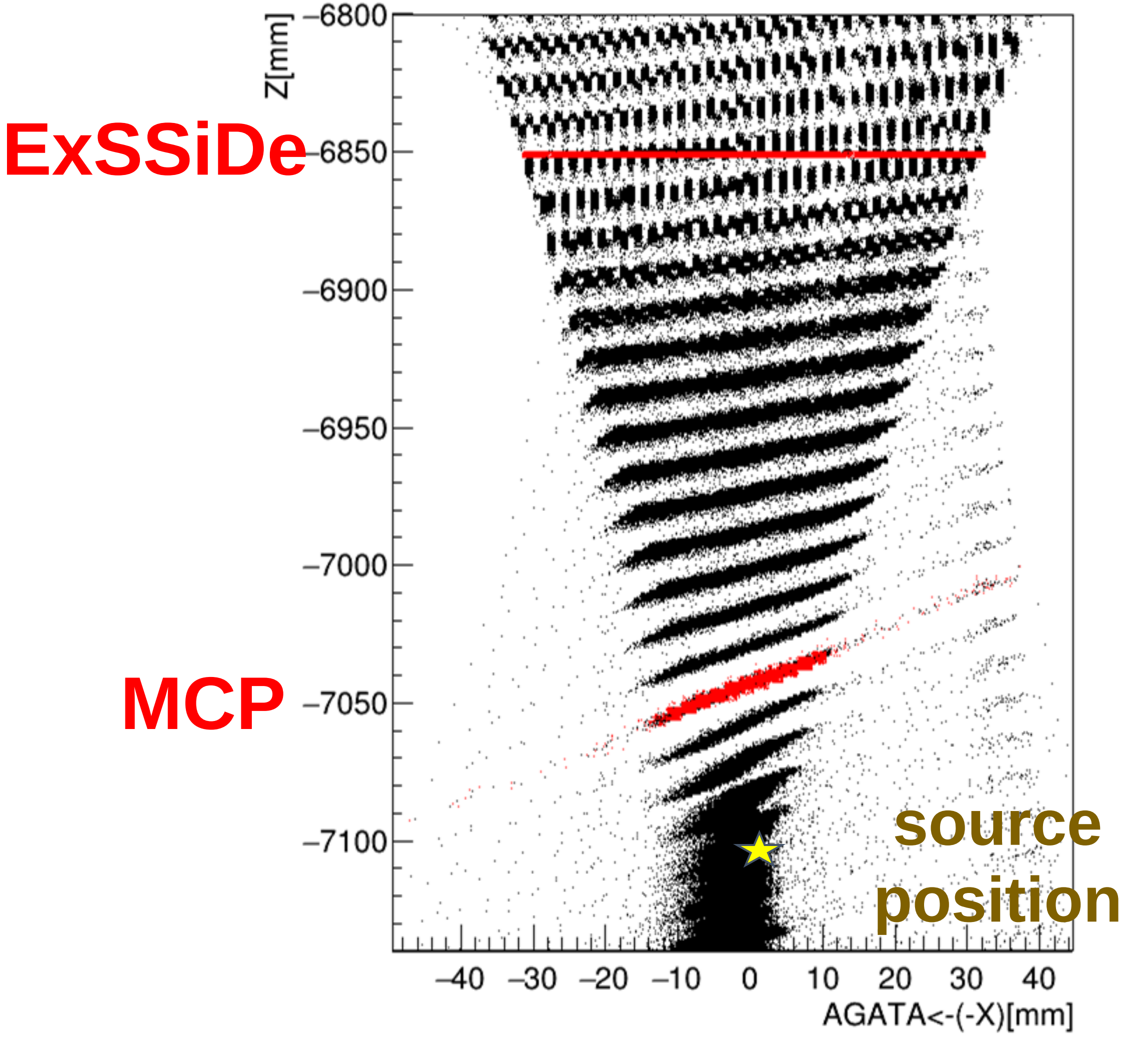




Gate on EXSSiDe

Test of the Tracking Algorithm





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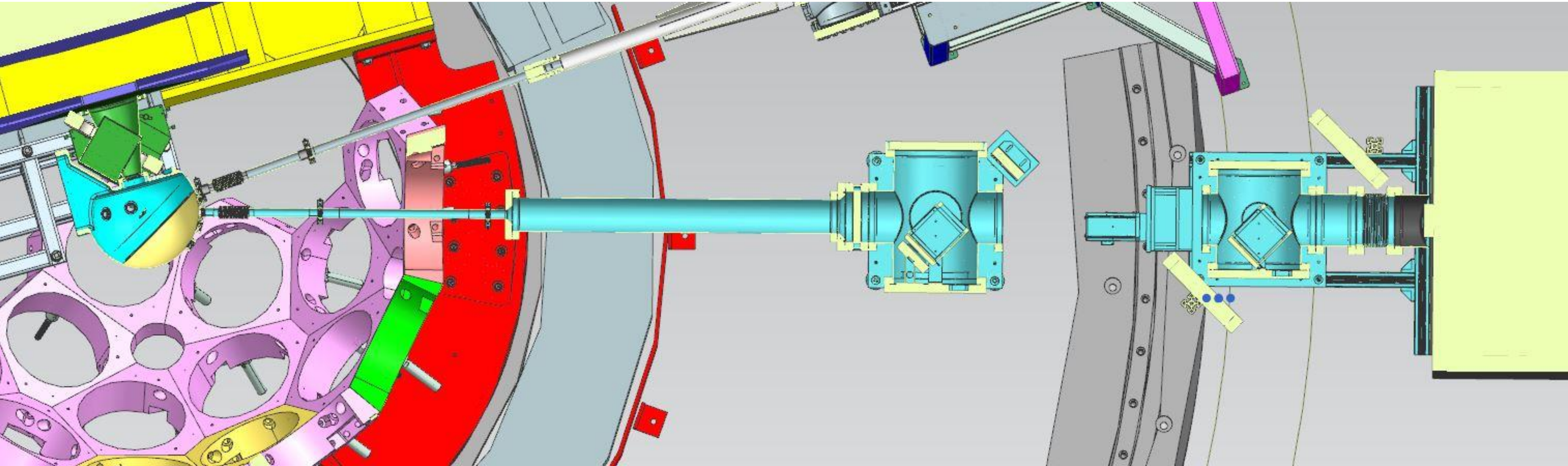
Next Commissioning Runs

Third Run: July 5th-6th 2024: in-beam test of the two MCPs and of the event-by-event tracking algorithm for the beam particles.

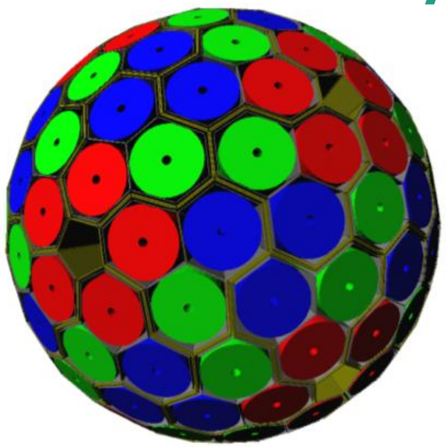
Forth Run: Autumn 2024: first test up to the AGATA reaction chamber.

In case of successful commissioning, we should be able to accept proposals for EXOTIC+AGATA experiments in the **LNL-PAC meeting** of **December 2024**.

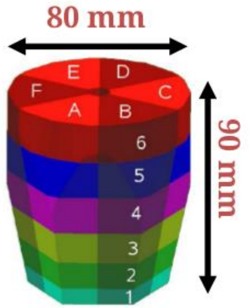


AGATA

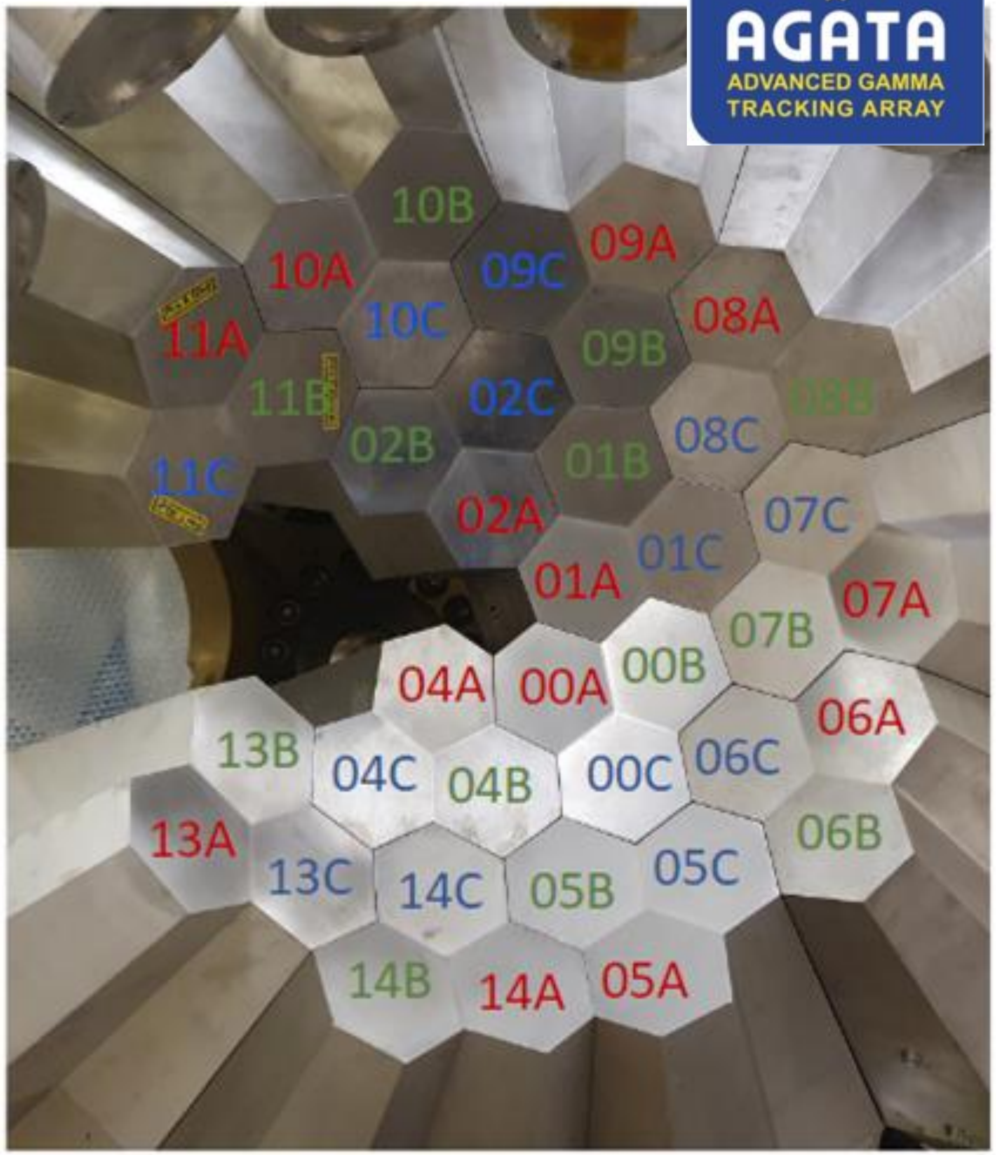
Advanced GAmma Tracking Array



180 hexagonal crystals	3 shapes	
60 triple-clusters	all equal	
Inner radius (Ge)	23.5 cm	
Amount of germanium	362 kg	
Solid angle coverage	82 %	
36-fold segmentation	6480 segments	
Singles rate	~50 kHz	
Efficiency:	43% (M_γ=1)	28% (M_γ=30)
Peak/Total:	58% (M_γ=1)	49% (M_γ=30)



6x6 segmented cathode

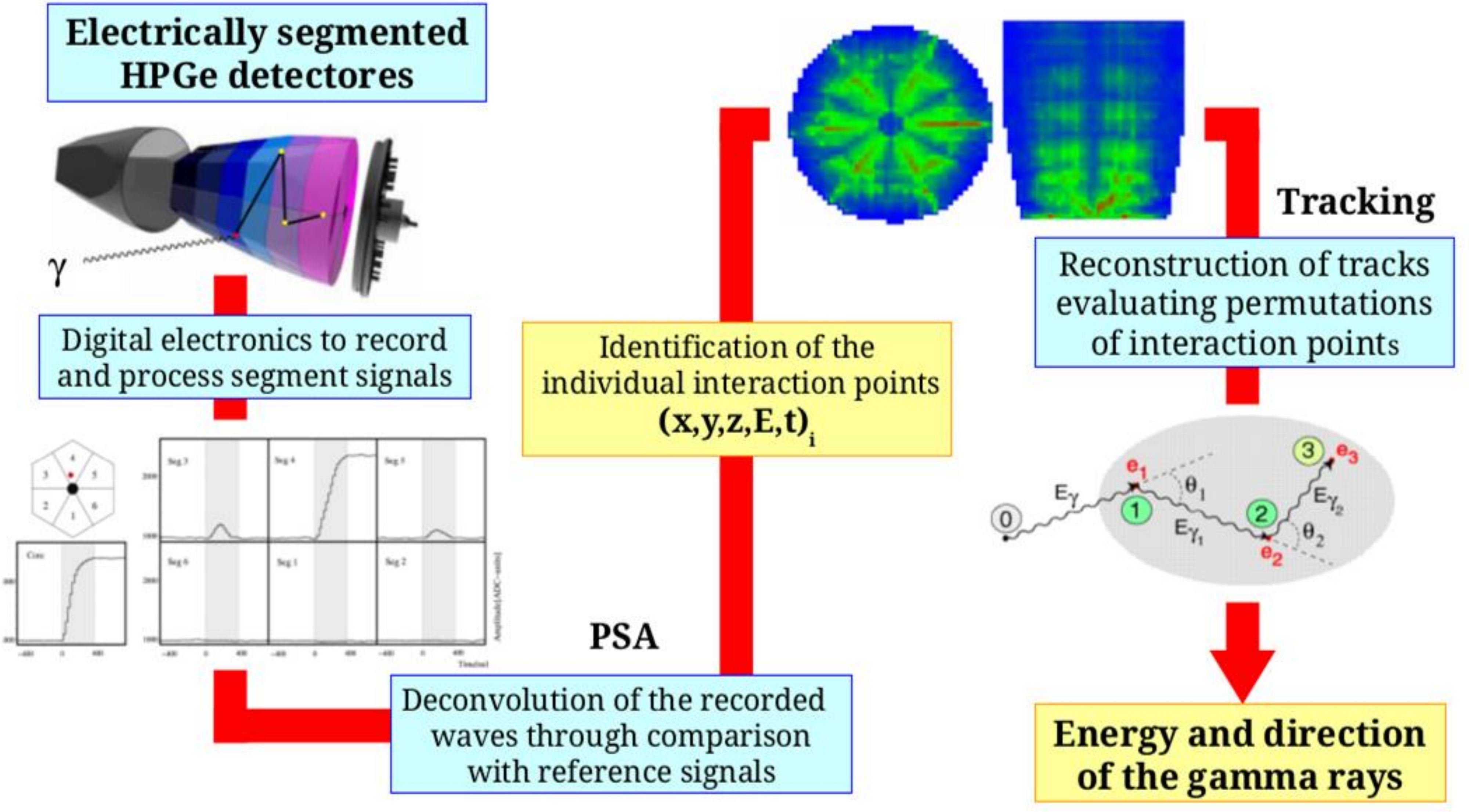


- Digital electronics and sophisticated Pulse Shape Analysis algorithms
- Operation of Ge detectors in position sensitive mode → gamma-ray tracking
- Coupling to complementary detectors for enhanced selectivity

AGATA at LNL:

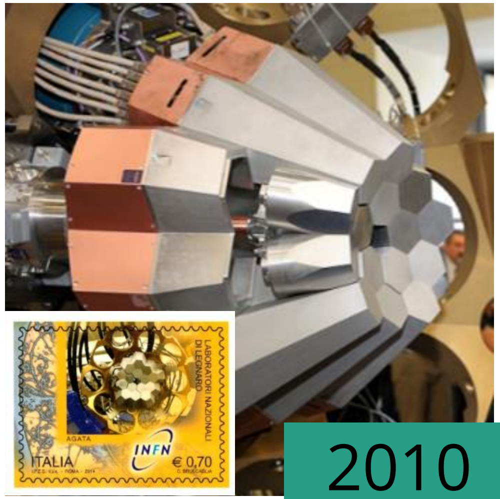
- 36 Crystals operative (12 ATCs)
- Maximum counting rate per detector: 50 kHz
- MWD-risetime 6μs - 2.5 μs
- Position: 23.5cm - 18cm

AGATA: Concept of γ-ray Tracking



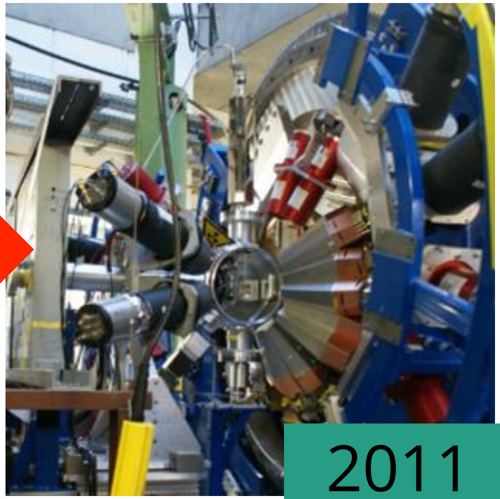
AGATA Time-Line

LNL



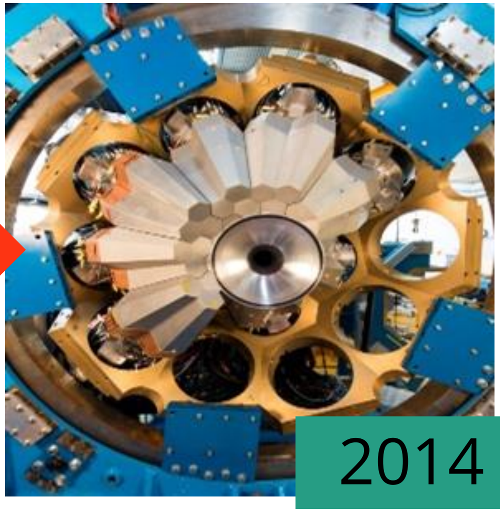
2010

GSI



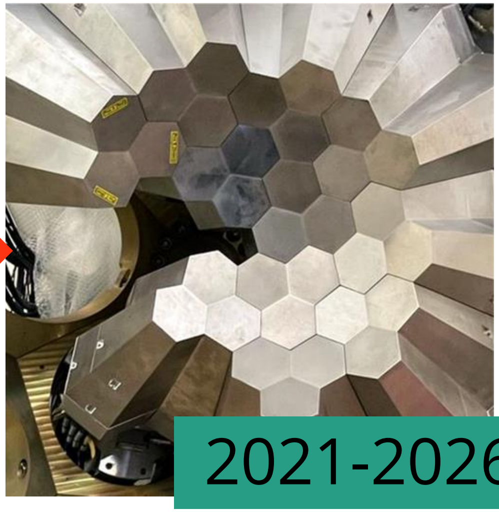
2011

GANIL



2014

LNL



2021-2026

Demonstrator

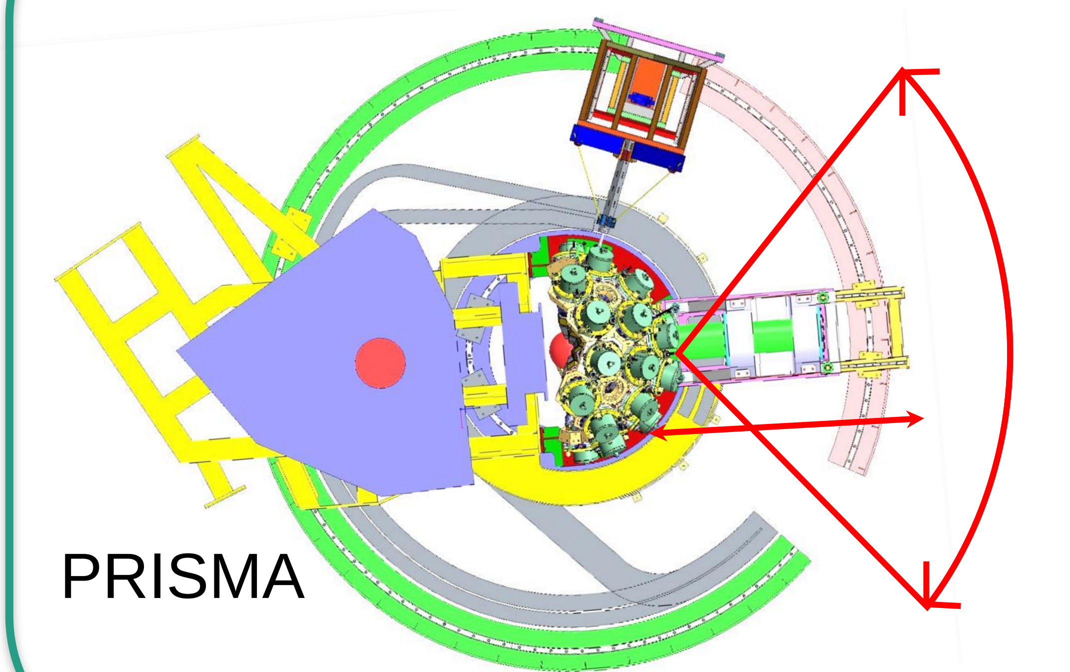
Phase 1

Phase 2: up to 2π

M. Zielinska: physics coordinator
J. J. Valiente Dobon: local coordinator

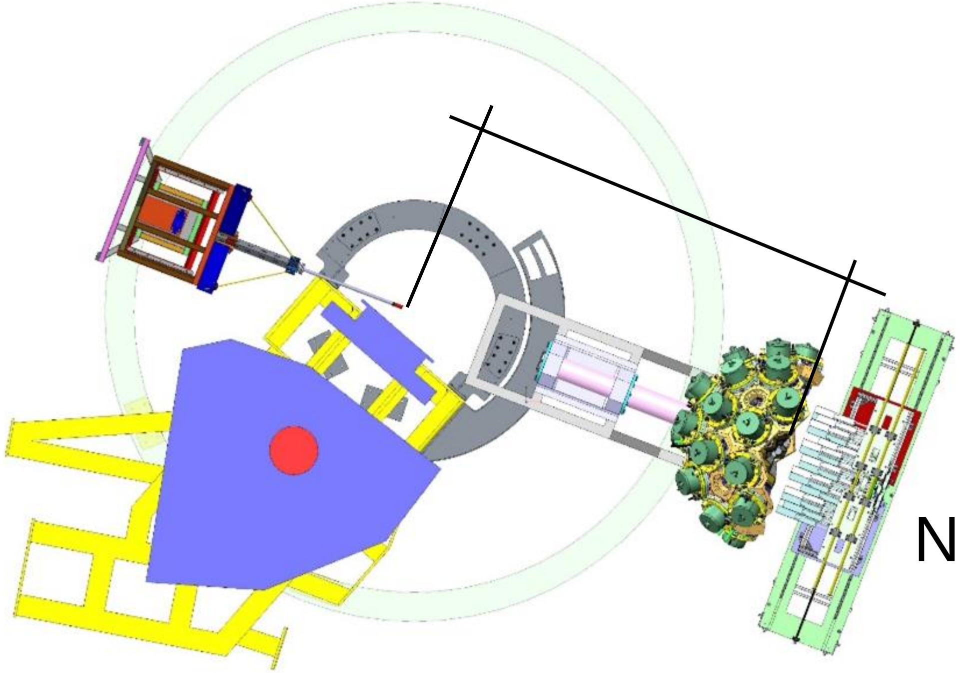
AGATA: Possible Configurations

AGATA coupled with PRISMA



Current configuration

AGATA zero degrees



J. J. Valiente-Dobòn et al., Nucl. Instr. Meth. A **1049** (2023) 168040

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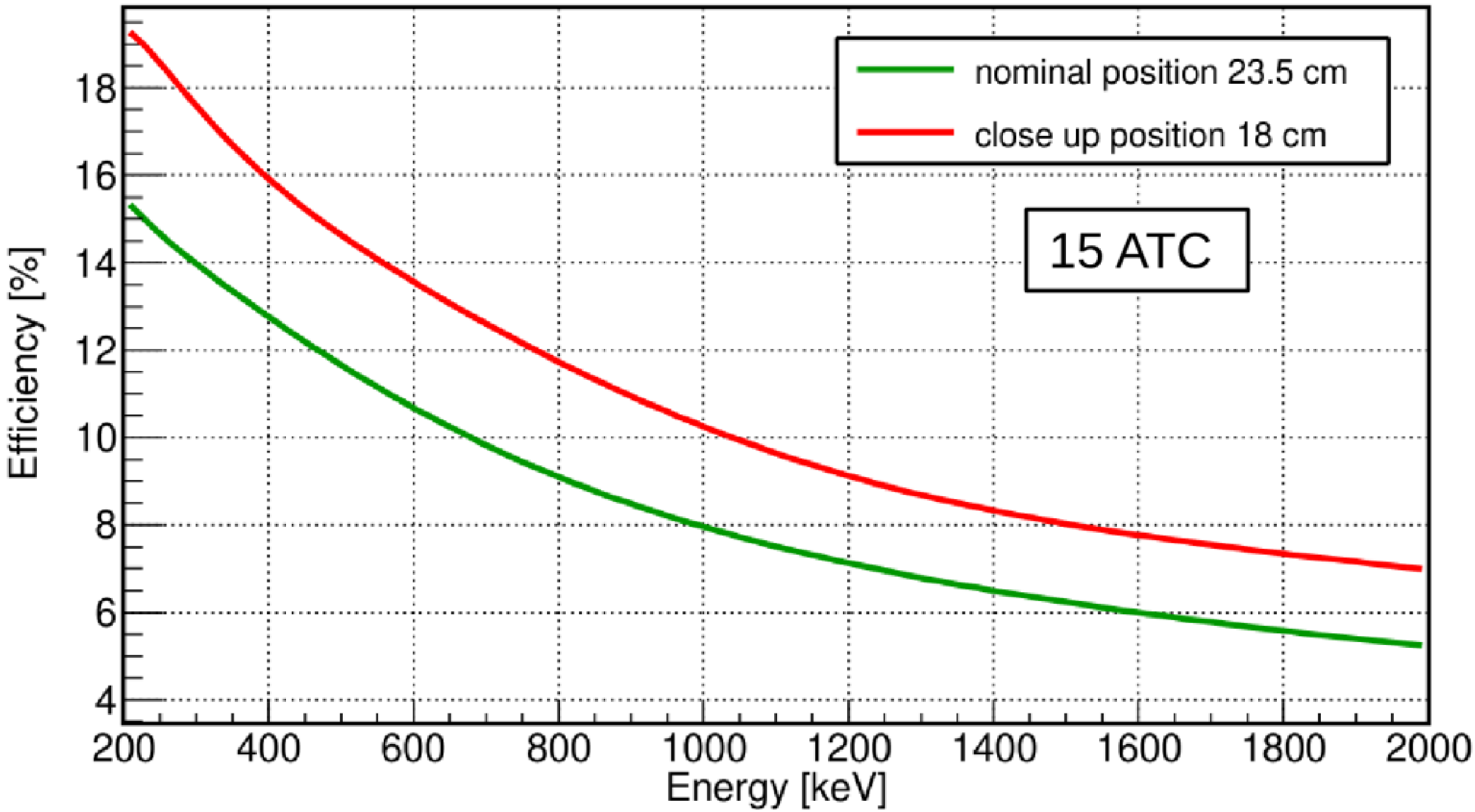
AGATA: Efficiency



Angular ranges of the crystals:

- θ_{lab} = 88°-165.9° for the **nominal position**,
- θ_{lab} =75°-143.2° for the **close-up position**.

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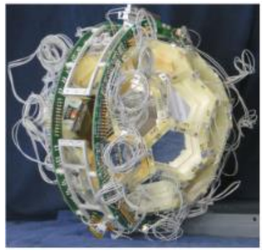
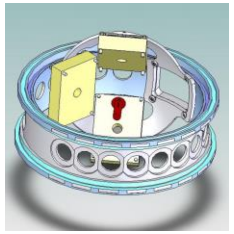
Ancillary Detectors and Targets

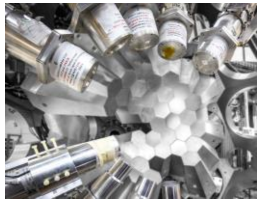
PRISMA
heavy ions

EUCLIDES
light charged particles





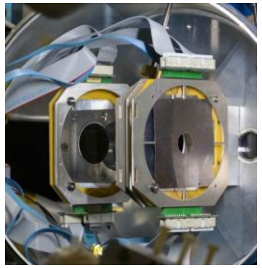
DANTE
heavy ions

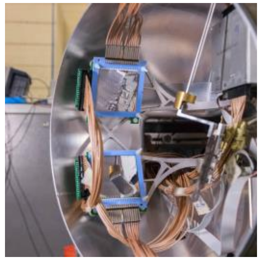


LaBr
γ-rays, fast timing

SPIDER
light and heavy ions

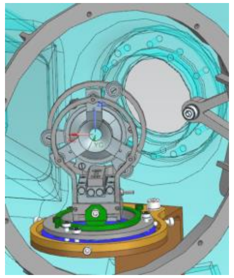
OSCAR
light charged particles



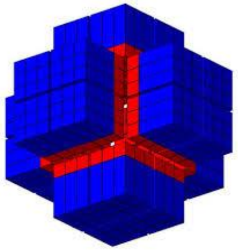


SAURON
light charged particles

PLUNGER
Lifetime measurements

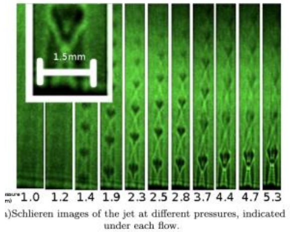


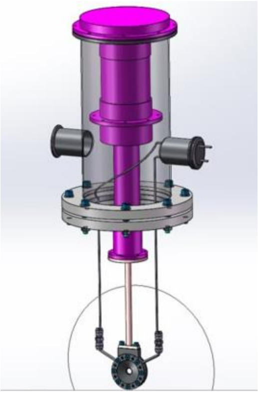
PARIS
γ-rays

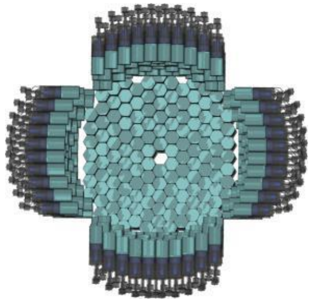


CTADIR
cryogenic target

SUGAR
gas-jet target

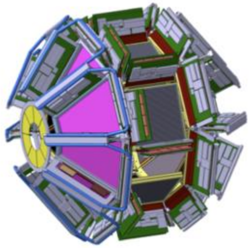




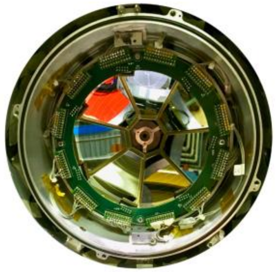


NEDA
neutrons

GRIT
light charged particles

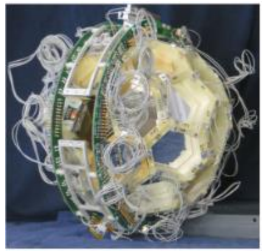


Charged Particle Arrays

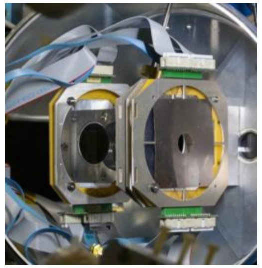


SPIDER: Single layer 300-um tick segmented Si detector. Polar angle coverage θ = 124°-161°. Solid angle coverage: 17% of 4π. The configuration consists of 7 detectors arranged in a cone-like configuration at 10 cm from the target. Further details: M. Rocchini, et al., NIM A 971 (2020) 164030.

GAL-TRACE highly-segmented Si telescopes (up to 5 units): Telescope unit: ΔE (100 μm)-E(1.5mm) . PSA available for light charged particles up to Oxygen. Polar angle coverage: 22°. Angular resolution: 1.5°. Solid angle coverage 6%, coupling with SPIDER possible. Time resolution: few ns. Further details: A. Goasduff et al., in press.



EUCLIDES ΔE-E Si telescopes (with beam absorbers): absolute proton efficiency ~ 60%; absolute alpha efficiency 25%. Average energy resolution: ~120 keV average. Lower detection threshold under experimental conditions: few MeVs. EUCLIDES plunger configuration (with beam absorbers) absolute proton efficiency ~ 25%, absolute alpha efficiency ~ = 15%. Further details: D.Testov et al., EPJA 55, (2019) 47.



SAURON annular DSSDs: 3 thickness available: 300, 500 and 1500 μm. Geometrical position ±5 cm from target, Polar angle coverage θ = 25°-45° (forward) and/or θ = 135°-155° (backward). The position can be slightly adjusted. Further details: https://www.micronsemiconductor.co.uk/product/s1

Summary

1. The **facility EXOTIC** has been **upgraded** (after nearly 4 years of inactivity) and restarted to be operative for the production of light weakly-bound Radioactive Ion Beams.
2. A new **event-by-event tracking system** based on **MicroChannel Plate** detectors has been developed and is currently under commissioning.
3. Two **final commissioning runs** for the coupling beetween **EXOTIC and AGATA** are planned for **July** and **early Autumn 2024**.
4. We should be able to accept **proposals** for expriments exploiting the unique features of **EXOTIC+AGATA** in the **LNL PAC meeting of December 2024**.

Collaboration

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Thank you very much for your attention!

Backup

$^{7}Be + ^{208}Pb$

$^{7}Be + ^{208}Pb$: **quasi-elastic scattering** and **projectile fragments ($^{3,4}He$)** production measured at LNL.

^{7}Be + γ (0.429 MeV) coincidences will permit to single out the inelastic scattering contribution to the quasi-elastic process.

$^{3,4}He$ + γ coindicendes will help to establish the production mechansims from information on the target-like nuclei produced.

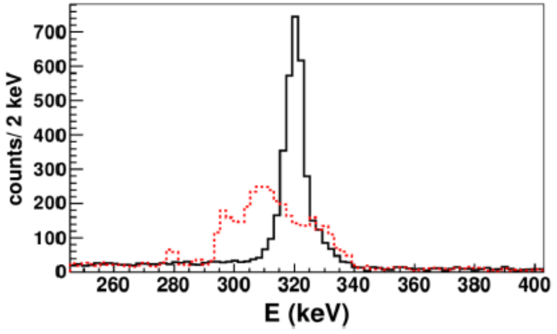


FIG. 2. γ-ray spectrum measured in TIGRESS in coincidence with the forwardmost telescope (14°–43°). Dashed red line: Doppler-shifted spectrum. Black line: Doppler-corrected spectrum for ^{11}Be recoil.

$^{11}Be+^{197}Au$ @ TRIUMF

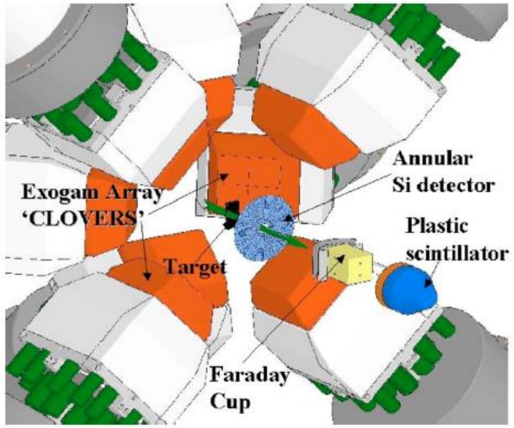


FIG. 1. (Color online) Schematic of the experimental setup at SPIRAL. The Faraday cup (plastic detector) was used for monitoring the beam particles with the $^{6}He(^{8}He)$ beam.

$^{6}He+^{65}Cu$ @ GANIL

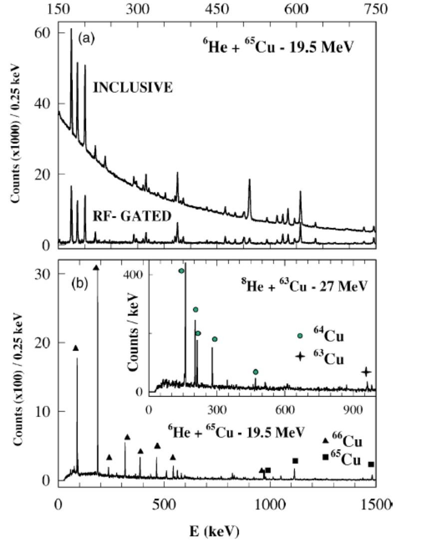
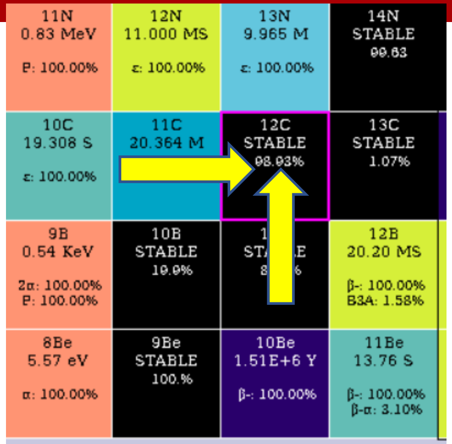


FIG. 2. γ-ray spectra for $^{6,8}He+^{63,65}Cu$. (a) Inclusive spectrum for $^{6}He+^{65}Cu$ at 19.5 MeV and the spectrum gated with the pulsed beam showing the suppression of the background. All dominant peaks are identified. (b) Spectra in coincidence with charged particles detected in the annular Si detector for $^{6,8}He$. The lines corresponding to targetlike products (arising from neutron transfer followed by evaporation) are labeled.

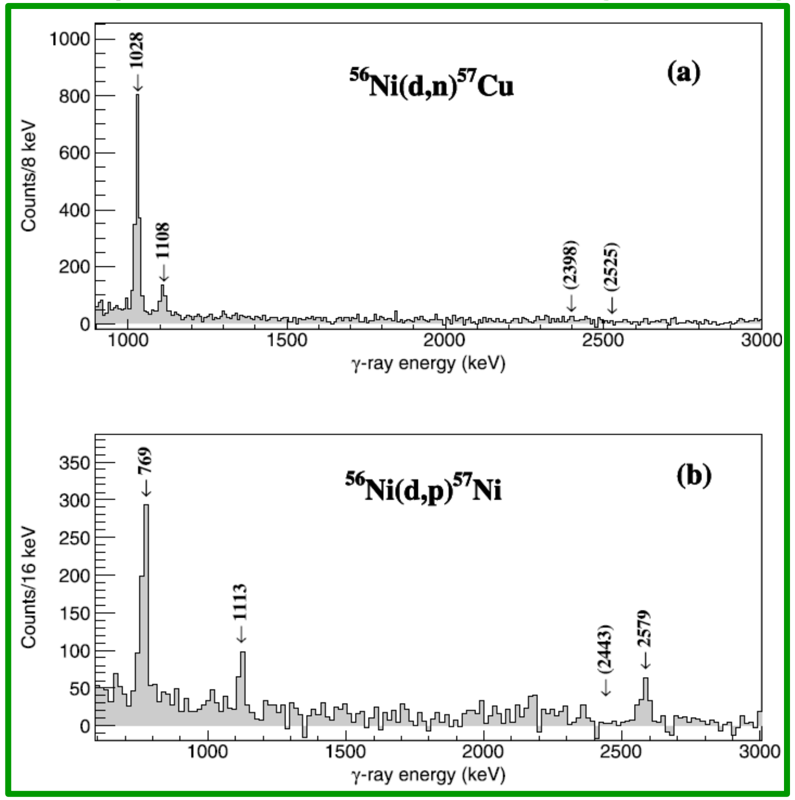
^{11}C-^{11}B Isospin Asymmetry (A. Gottardo)



^{11}C(d,p)^{12}C ⟷ **^{11}B(d,n)^{12}C**

Same final wave function (excited states ^{12}C)
Same reaction in Isospin Symmetry
Same initial wave function in Isospin Symmetry

Example: **^{57}Ni-^{57}Cu Mirror Symmetry**



Isospin Symmetry is obviously **violated** by **Coulomb interaction**, are there **nuclear** sources?
Ab-initio calculations possible for A=11!

Looking at 2$^+$ population, other states possible via particle spectroscopy

$$10^5\ pps\ beam, \sigma = 1\ mbarn$$

$$\Rightarrow 2500\ \frac{reactions}{day}$$

$$\Rightarrow 100\ high - energy\ \frac{\gamma\ rays}{day}$$

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