The experimental set-up of the RIB in-flight facility EXOTIC

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on behalf of the EXOTIC collaboration

Outline

- EXOTIC facility
- Experimental program
- Experimental set-up
- Experiments with RIBs impinging on a gas target
- Conclusions and perspectives

The EXOTIC project @ LNL

A facility to produce in-flight light radioactive ion beams (RIBs) through two-body inverse kinematics reactions induced by high intensity heavy-ion beams from the XTU Tandem accelerator impinging on light gas targets (p, d, ^{3}He, ^{4}He)

- **Commissioning** of the EXOTIC facility in 2004

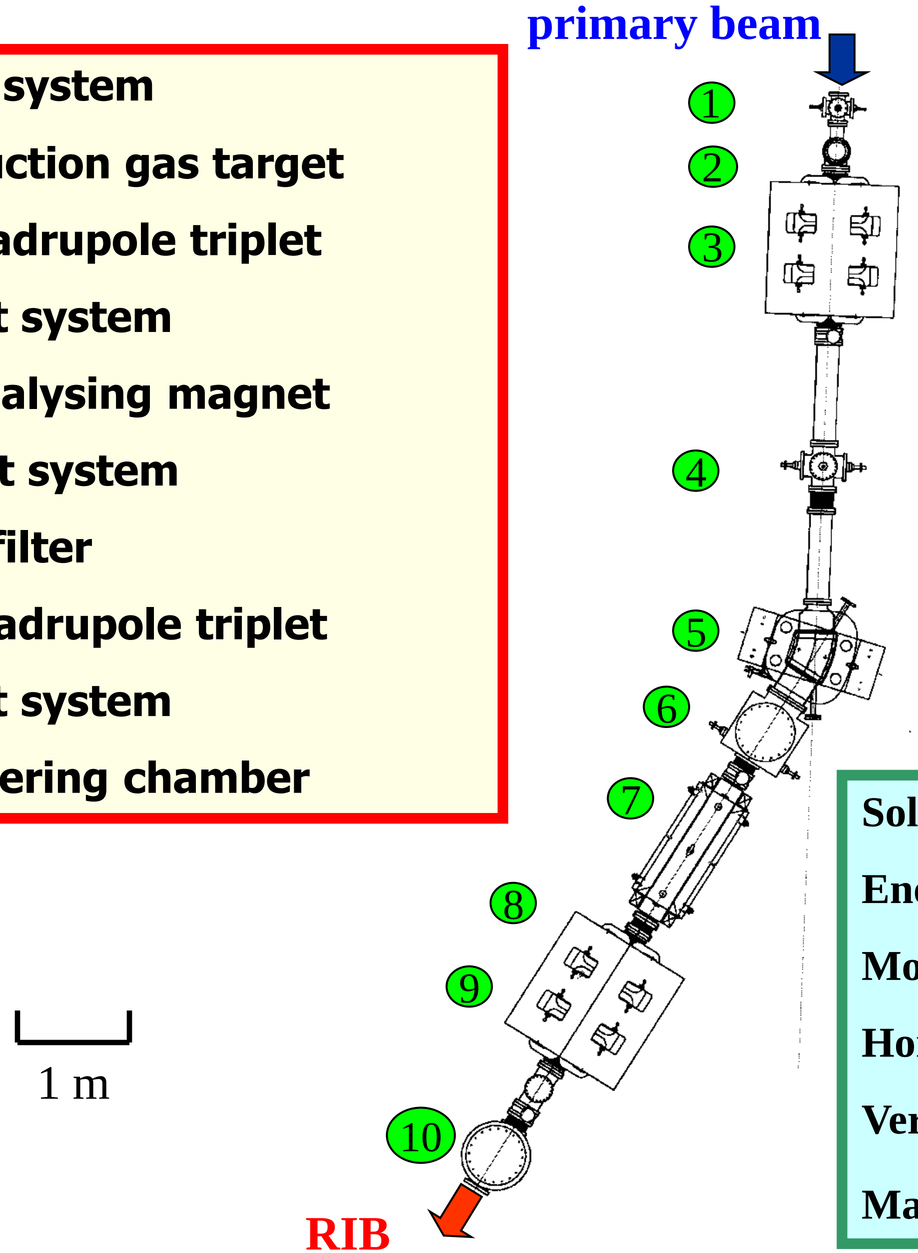
V.Z. Maidikov et al., Nucl. Phys. A 746 (2004) 389c, D. Pierroutsakou et al., EPJ SP 150 (2007) 47, F.. Farinon et al., NIM B 266 (2008) 4097, M. Mazzocco et al., NIM B 266 (2008) 4665, M. Mazzocco et al., NIM B 317 (2013) 223

- First **"beam for experiment"** (^{17}F) in 2006

D. Pierroutsakou et al., EPJ SP150 (2007) 47, C. Signorini et al., EPJA44 (2010) 63

The EXOTIC project @ LNL

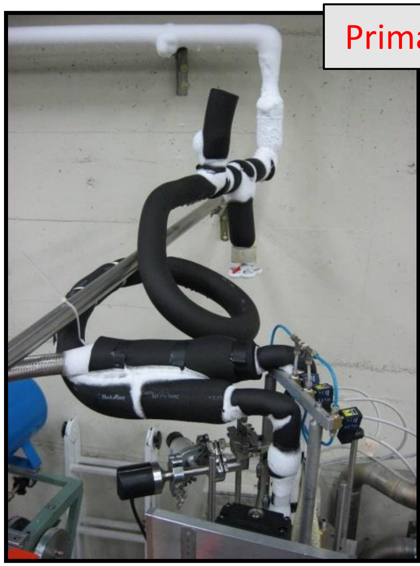
- 1 – 1st slit system
- 2 – production gas target
- 3 – 1st quadrupole triplet
- 4 – 2nd slit system
- 5 – 30° analysing magnet
- 6 – 3rd slit system
- 7 – Wien filter
- 8 – 2nd quadrupole triplet
- 9 - 4th slit system
- 10 – scattering chamber



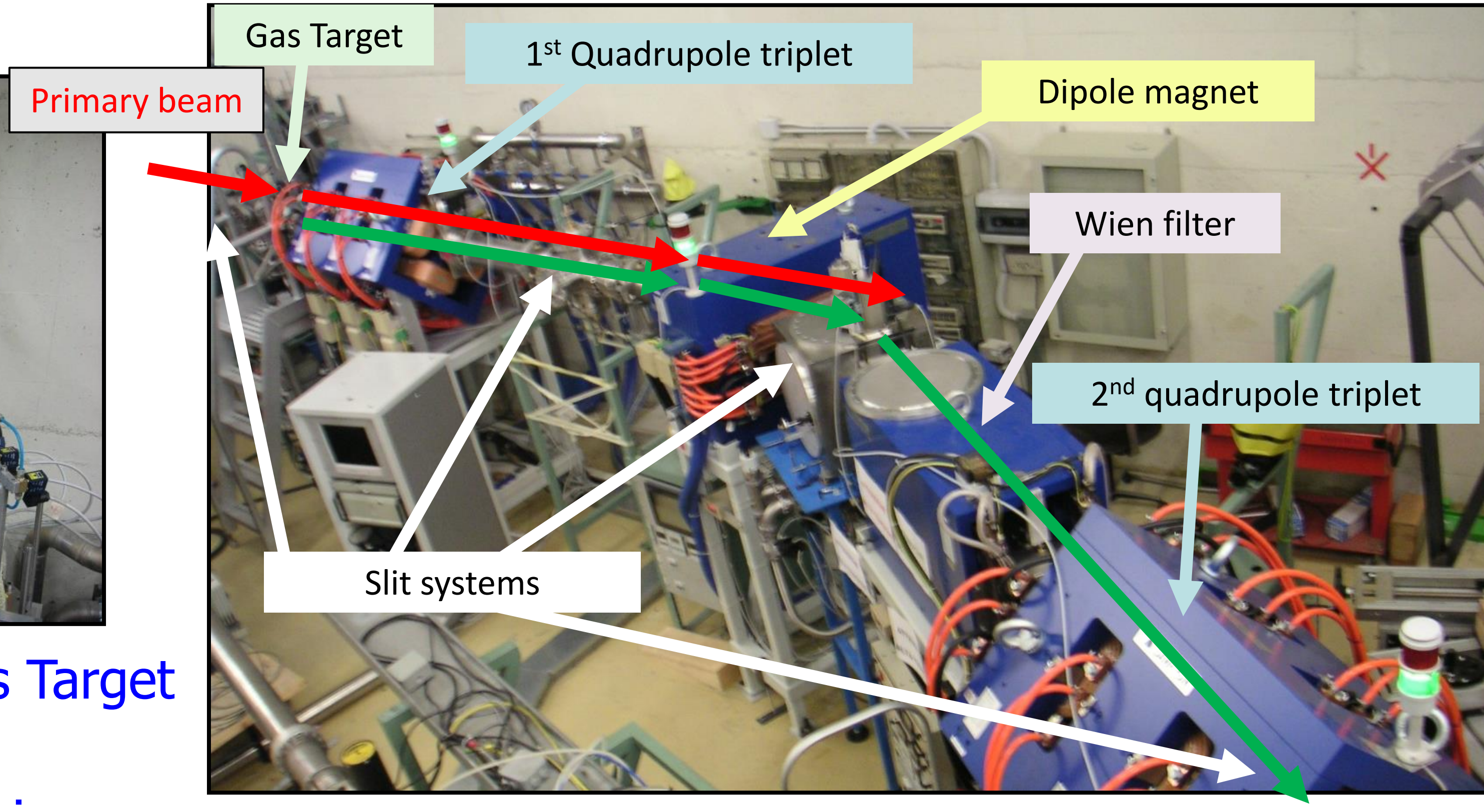
Cryogenic production gas target: 5-cm long double-walled cylindric cell
Entrance (exit) windows: 14 (16) mm
2 havar: 2.2 μm
Pressure: up to 1 bar.

Solide angle $\Delta\omega$	~ 10 msr
Energy acceptance $\Delta E/E$	±10%
Momentum acceptance $\Delta p/p$	± 5%
Horizontal acceptance $\Delta\theta$	± 50 mrad
Vertical acceptance $\Delta\phi$	± 65 mrad
Magnetic rigidity $B\rho$	0.98 Tm

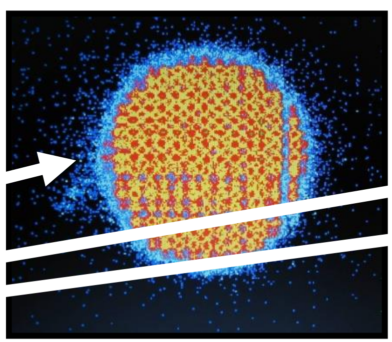
The EXOTIC project @ LNL



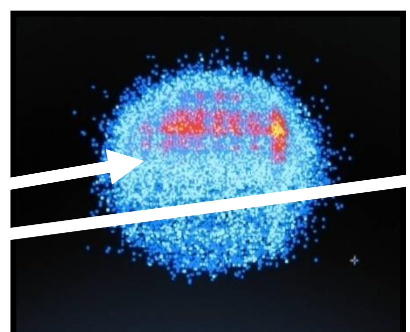
Cryogenic Gas Target



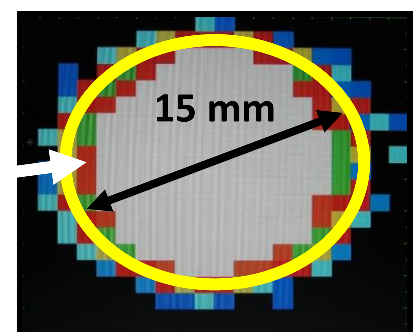
Beam-Tracking



PPAC A
909 mm

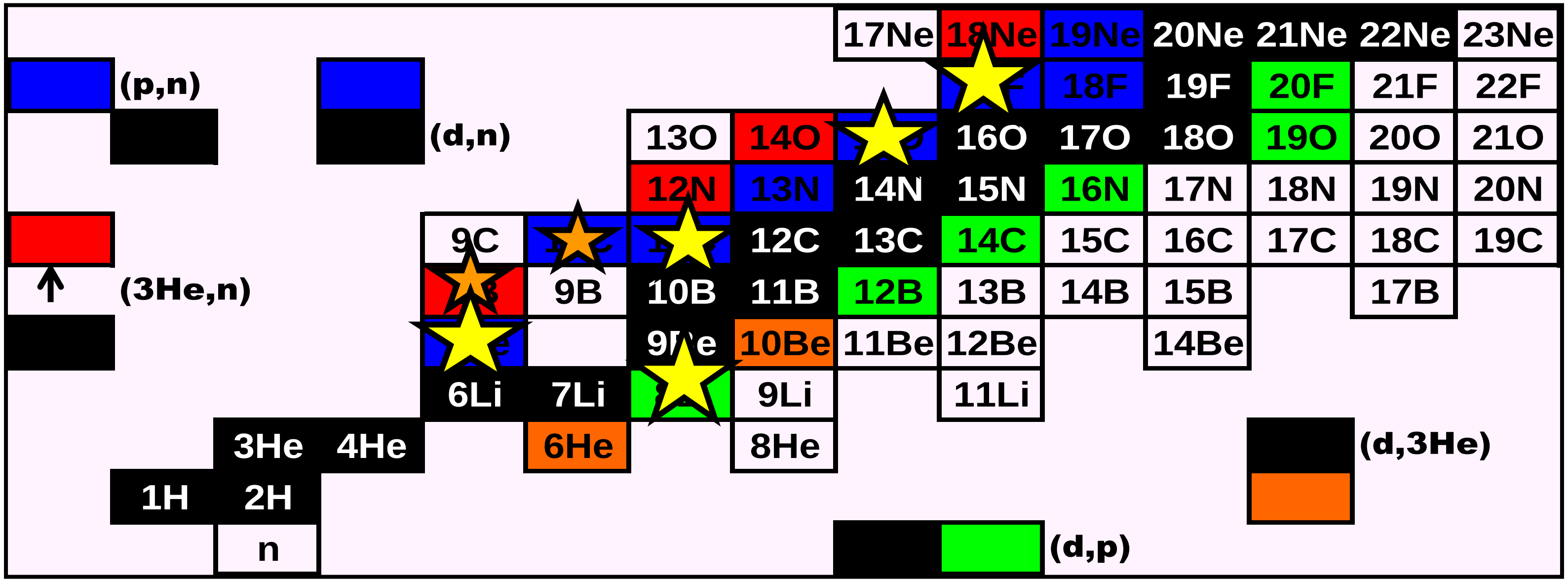


PPACB
365 mm



Reconstruction on the target

Light RIBs @ EXOTIC



^{17}**F** (Sp=600 keV)	***p(^{17}O,^{17}F)n***	Q=–3.54 MeV	E=3–5 MeV/u	P:93-96%	I:10^5 pps
^{8}**B** (S_p=137.5 keV)	***^{3}He(^{6}Li,^{8}B)n***	Q=–1.97 MeV	E=3–5 MeV/u	P:30-43%	I:10^3 pps
^{7}**Be** (S_α=1.586 MeV)	***p(^{7}Li,^{7}Be)n***	Q=–1.64 MeV	E=2.5–6 MeV/u	P:99%	I:10^6 pps
^{15}**O** (S_p=7.297 MeV)	**p(^{15}N,^{15}O)n**	Q=–3.54 MeV	E=1.3 MeV/u	P:98%	I:4*10^4 pps
^{8}**Li** (S_n=2.033 MeV)	**d(^{7}Li,^{8}Li)p**	Q=–0.19 MeV	E=2–2.5 MeV/u	P:99 %	I:10^5 pps
^{10}**C** (S_p=4.007 MeV)	**p(^{10}B,^{10}C)n**	Q=–4.43 MeV	E=4 MeV/u	P:99 %	I:5*10^3 pps
^{11}**C** (S_p=8.689 MeV)	**p(^{11}B,^{11}C)n**	Q=–2.76 MeV	E=4 MeV/u	P:99 %	I:2*10^5 pps

Experimental program @ EXOTIC

From 2006 various experiments have been performed at EXOTIC in the framework of international collaborations

- Study of reaction dynamics in direct kinematics with light RIBs impinging on medium- and heavy-mass targets at near-barrier energies and in inverse kinematics: elastic scattering, breakup, transfer, fusion

- Study of α clustering phenomena in light exotic nuclei employing the Thick Target Inverse Kinematic (TTIK) scattering technique with a RIB impinging on a ^{4}He gas target

- Direct and indirect measurements of astrophysical interest in inverse kinematics with RIBs impinging on solid or gas light targets

  Stellar nucleosynthesis paths involve UNSTABLE species. In astrophysical sites such as novae, x-ray busters and type Ia supernovae (the so called cataclysmic binary systems), the main energy source is thought to be provided by explosive hydrogen and helium burning. Experiments with RIBs provide data for these fast (few seconds to hours) explosive burning scenarios

- The use of the facility EXOTIC as a separator for Heavy-Ion Fusion Evaporation Residues (ER) from stable beams at sub-barrier energies is under investigation: recent tests performed with encouraging results

Experimental requirements for the detection system

- charge- and mass-identification of the reaction fragments

- Large solid angle coverage to compensate the low RIB intensity and to detect breakup fragments emitted at large relative angles

- Good angular resolution (1° FWHM) to detect breakup fragments emitted at small relative angles and to reconstruct the interaction point when using extended reaction gas target

- Δt = 1-1.5 ns (FWHM) is enough to discriminate protons, α and heavy ions for flight paths larger than 10 cm and for event-by event reconstruction of contaminant beams. It is enough furthermore in most cases to separate elastic scattering from other processes when using the TTIK method

- $\Delta E < 400$ keV (FWHM overall energy resolution) for discriminating the elastic from the inelastic scattering of the projectile from the target (^{58}Ni, ^{208}Pb) in direct kinematics.

Often the ΔE is limited by the energetic spread of the RIB and by the energy loss and energy straggling of the ions in the target that should be thick enough to compensate the low RIB intensity.

The experimental set-up @ EXOTIC must meet the following requirements

- event-by-event beam tracking capabilities to account for the typical poor emittance of in-flight produced RIBs in conjuction with a good time resolution for TOF measurements and a fast signal for handling counting rates up to 10^6 Hz → fast and high-transparency tracking detectors

- Z and A identification of the reaction products with the highest achievable energy resolution → ΔE–E_{res} telescopes and/or ToF technique

- a large solid angle coverage and a high segmentation to achieve good angular resolution and for reducing pile up events and low-energy events coming from the radioactive decay of the elastically scattered projectiles → large area Double Side Silicon Strip Detectors (DSSSDs) associated with Ionization Chambers (Ics)

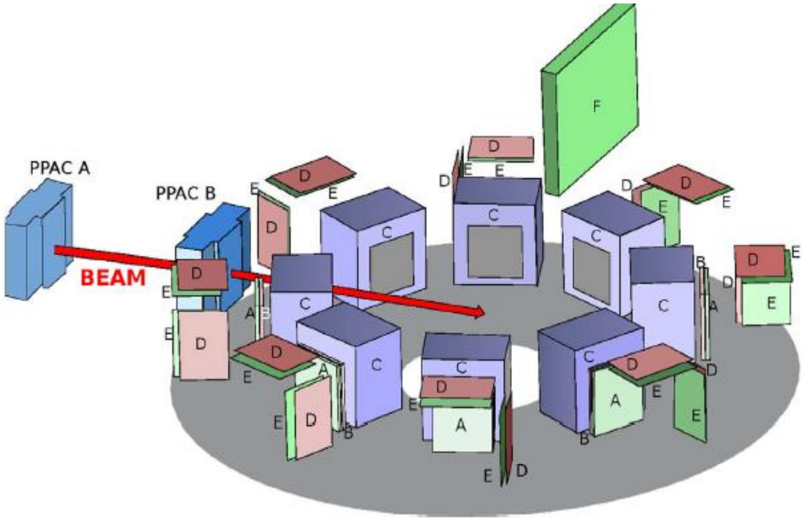
- flexibility in order to be suitable for different experimental needs → modular and expandable array, possibility to change the effective thickness of ΔE, the angular configuration and the distance of the telescopes

The experimental set-up of the EXOTIC facility

Experimental set-up entirely developed by our collaboration

- 2 **position-sensitive Parallel Plate Avalanche Counters** (PPACs) for beam tracking and ToF measurements
  D. Pierroutsakou et al, NIM A 834 (2016) 46

- **EXPADES:** a high-granularity, compact, flexible, portable charged-particle detection array
  E. Strano et al., NIM B 317 (2013) 657
  D. Pierroutsakou et al, NIM A 834 (2016) 46



8 EXPADES Telescopes

ΔE1 – IC

ΔE2 (40/60 μm) + E $_{res}$ (300 μm) - DSSSDs

DSSSDs: 64 x 64 mm^2 active area
32 x 32 strips (2 mm pitch size - 40 μm interstrip separation)
2m x 2m pixel
$\Delta\theta$=1° at d=10.5 cm

→

Z and A identification through ΔE-E
TOF information
Good energy, time and angular resolution
High granularity
Distance from target varies from 10.5 to 22.5 cm
Coverage: 22% of 4π sr at 10.5 cm

The experimental set-up of the EXOTIC facility

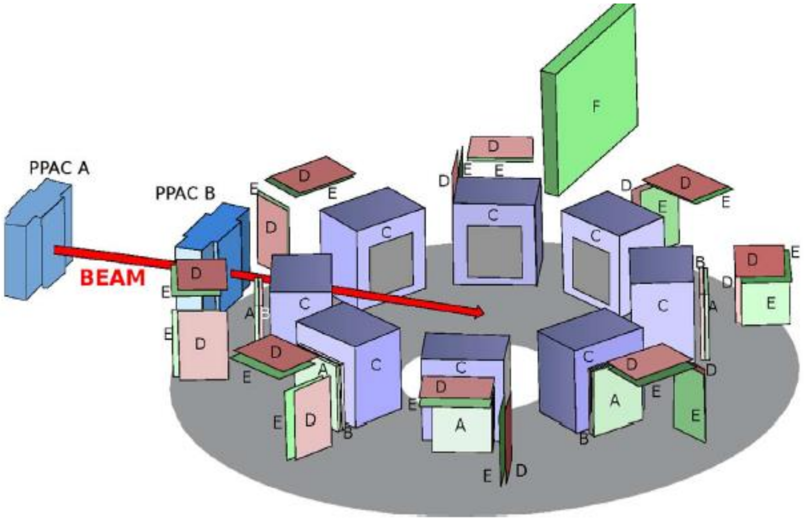
Experimental set-up and electronics
entirely developed by our collaboration

Compact low-noise electronics with large dynamic range and good energy and timing characteristics was developed for the 40/60 μm DSSSD ΔE stage. The 32 strips of each DSSSD side were reduced to 16 by short-circuiting two-by-two adjacent strips to reduce costs.

ASIC-based electronics for the 300 μm DSSSD E_{res} stage to handle 32 energy signals of each side, ensuring a high granularity with a very low cost at the expense, however, of the possibility to perform TOF measurements with the requested time resolution.

Electronic boards placed in the proximity of the array in vacuum:

- to have a compact set-up (detectors + electronics);
- to minimize the internal and external connections and
- to overcome the environmental noise at the EXOTIC beamline.



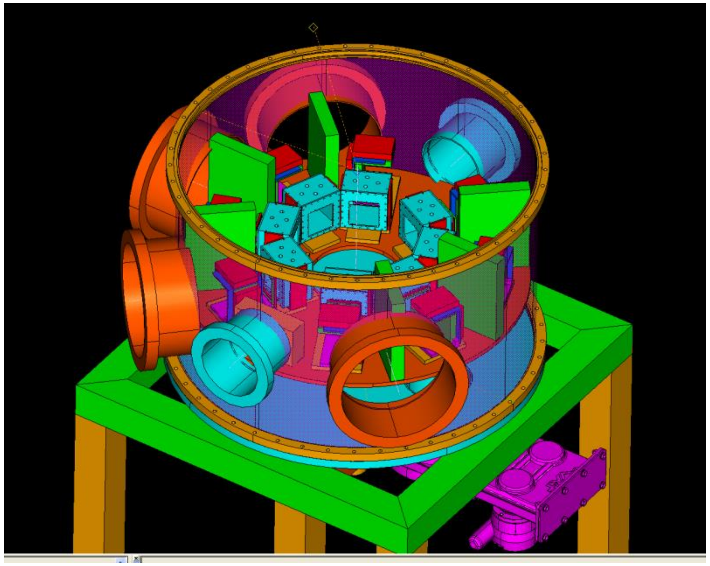
E. Strano et al., NIM B 317 (2013) 657
D. Pierroutsakou et al, NIM A 834 (2016) 46

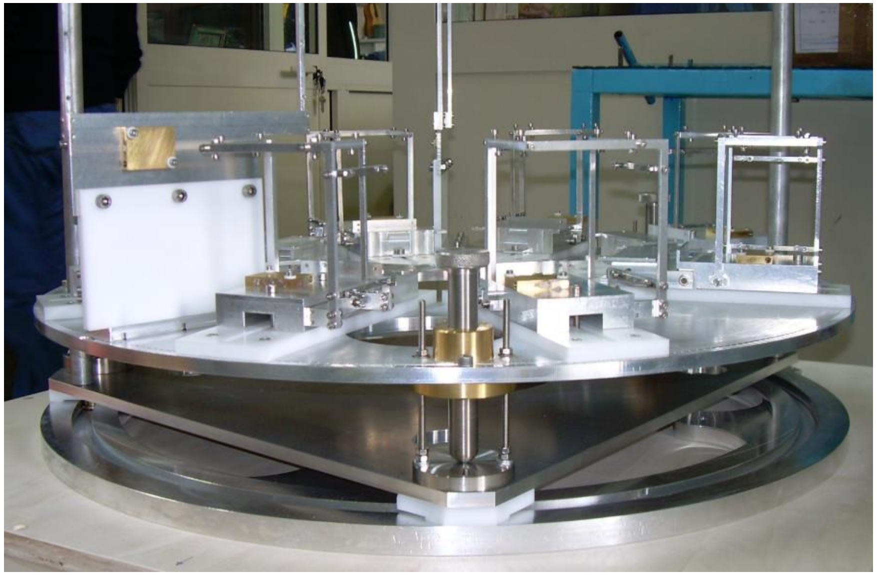
Two newly designed front-end electronic modules: a **sampling ADC** and a **Trigger Supervisor Board (TSB)**

Sampling ADC: A single-slot standard VME card devoted to sample, analyze and digitize the multiplexed analogue signals coming out from the electronic front end of the set-up. The module has 8 differential input channels and is based on a 50 MHz 12-bit ADC integrated circuit

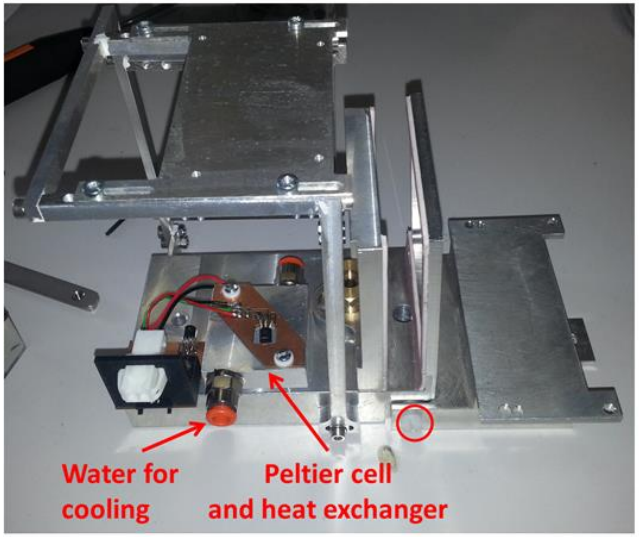
TSB: The TSB is a general purpose VME-standard card accepting up to 64 differential TTL input channels for the proposed trigger signals coming from the different detectors and handles the trigger logic of the whole set up

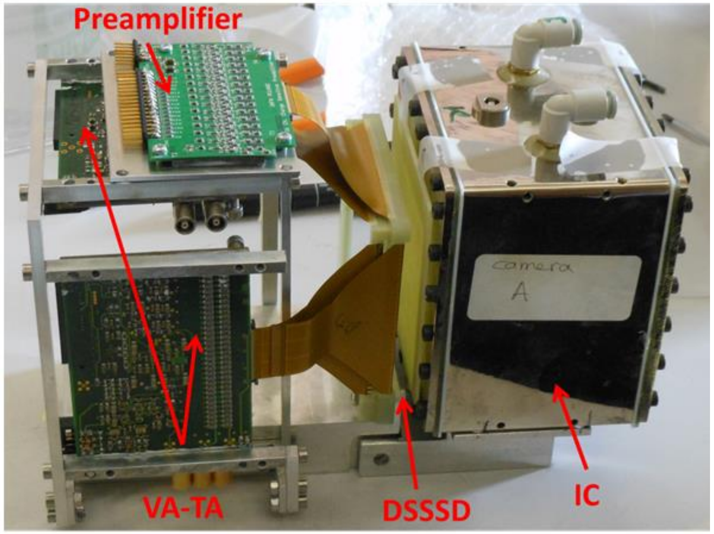
EXPADES telescope mechanical structure





The distances and angle of the telescopes can be changed. The **cooling** of the DSSSDs and the electronic boards is done with Peltier cells and heat exchangers and water at 5 °C as a cooling fluid to improve the energy resolution





RIB tracking detectors @ EXOTIC: PPAC

for EXOTIC RIBs:

$Z < 11$

$E_{lab} = 3 - 5$ MeV/u

$I_{max} \sim 10^6$ pps

The **PPAC** operating with C_4H_{10} gas at P=5-15 torr has:

Good time and position resolution
Radiation hardness
Transparency
Stability
Easy-to-use
Not expensive
Sustains high rates (10^6 pps)

A good position resolution and a high tracking efficiency for **low-ionization events** are achieved with a careful grounding and a fast preamplifier placed very close to the PPAC in vacuum

RIB tracking detectors @ EXOTIC: PPAC

Two wire anode planes and a cathode plane in between

Gas : C_4H_{10}, C_3F_8

P= 5-15 torr

E/P ~ 250 V/cm/torr

Active area: 62 mm x 62 mm

60 x and y anode wires of 20 μm : 1 mm gap

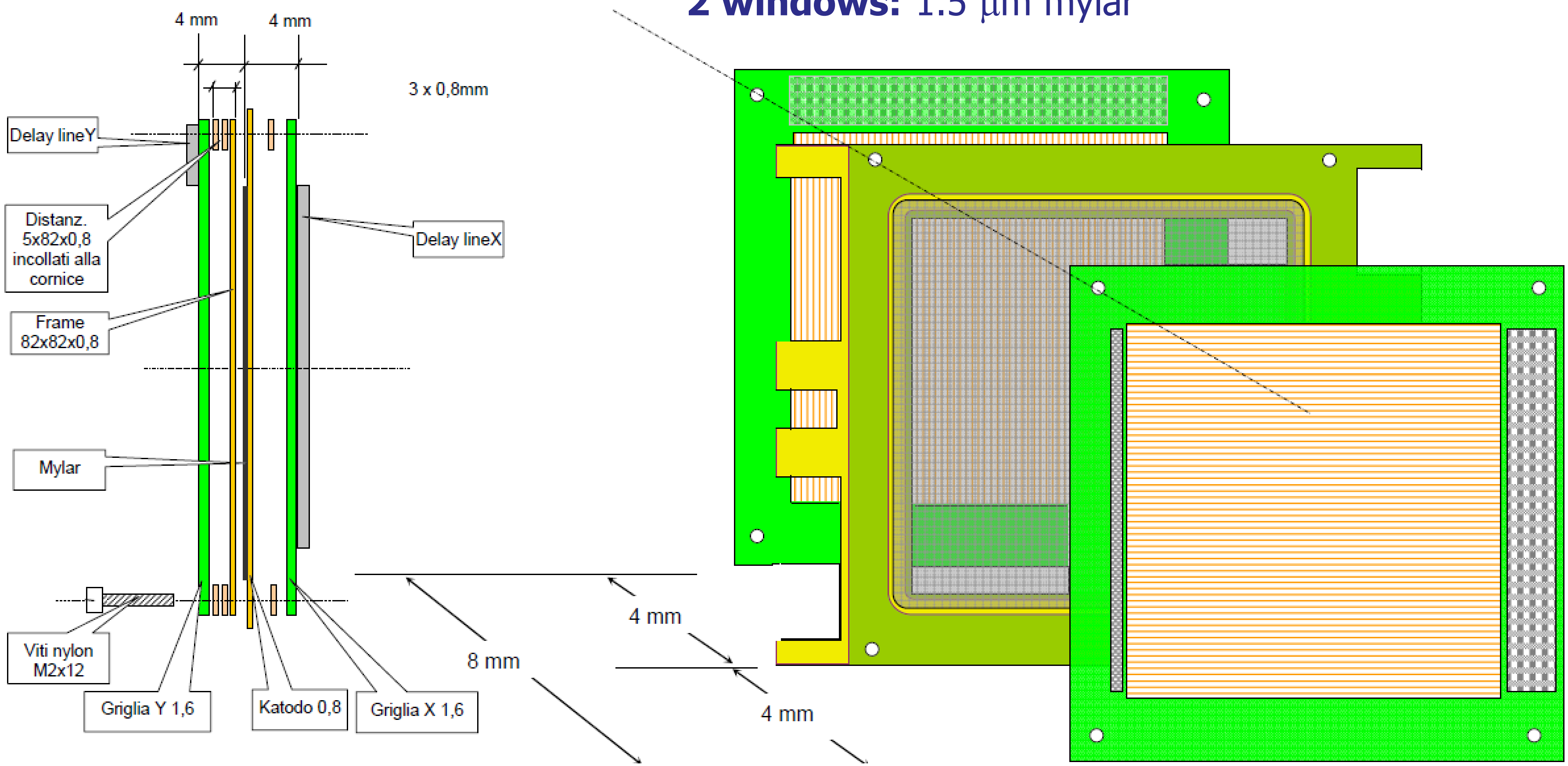
X and y delay line: 60 LC -2.3 ns delay (total 138 ns)

Characteristic impedance: 50 Ω

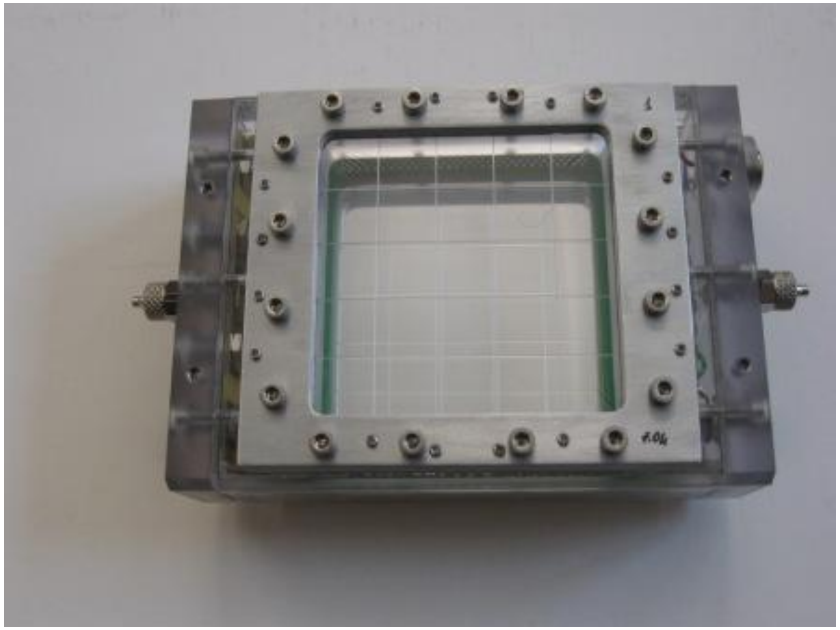
Cathode: 1.5 μm aluminized mylar (both sides)

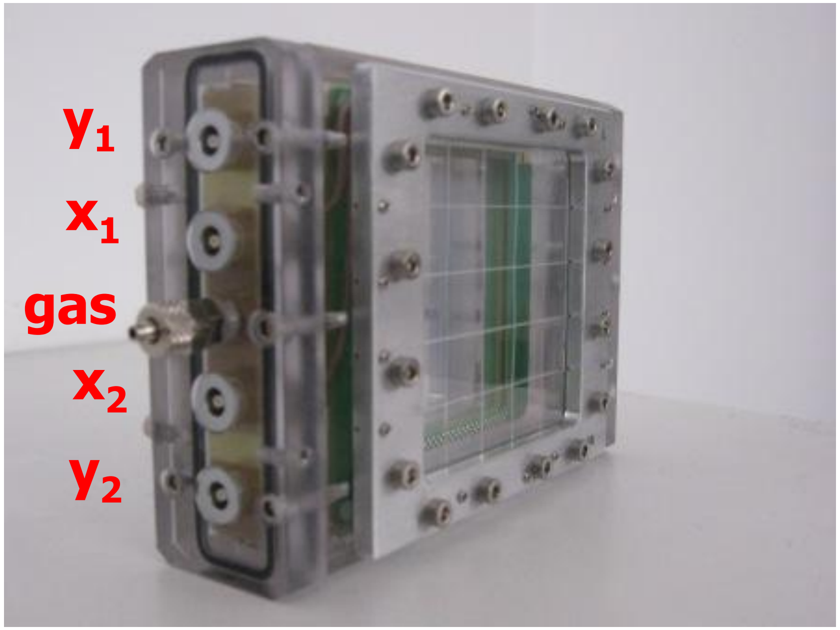
anode – cathode distance: 2.4-4 mm

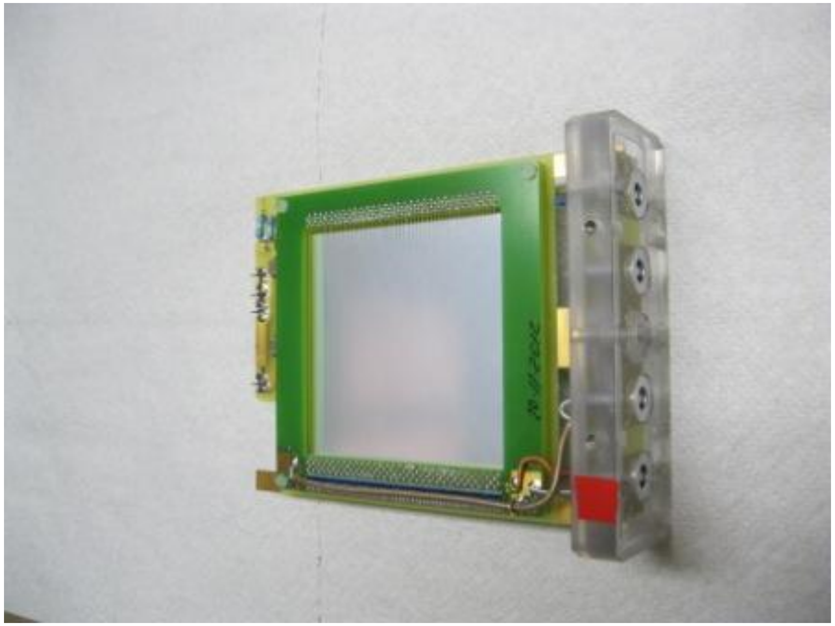
2 windows: 1.5 μm mylar

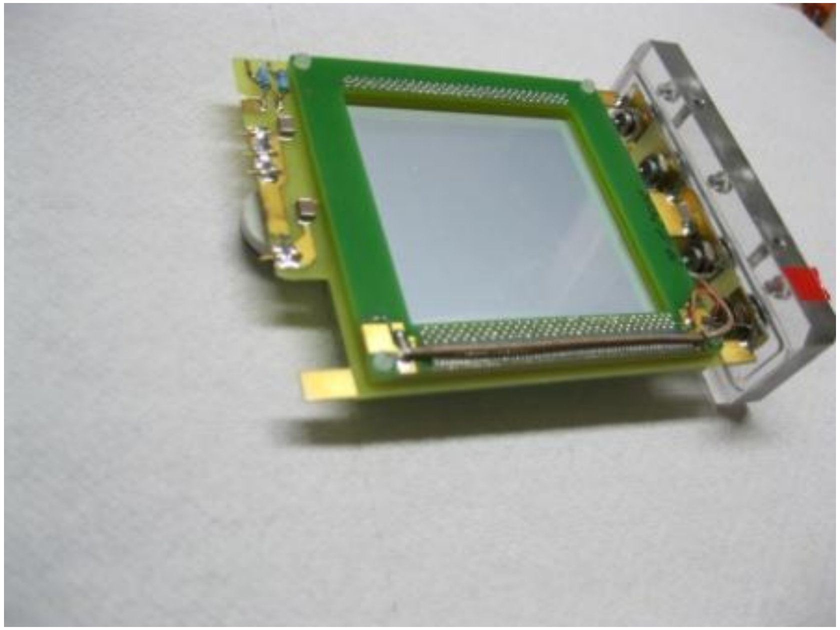


RIB tracking detectors @ EXOTIC: PPAC



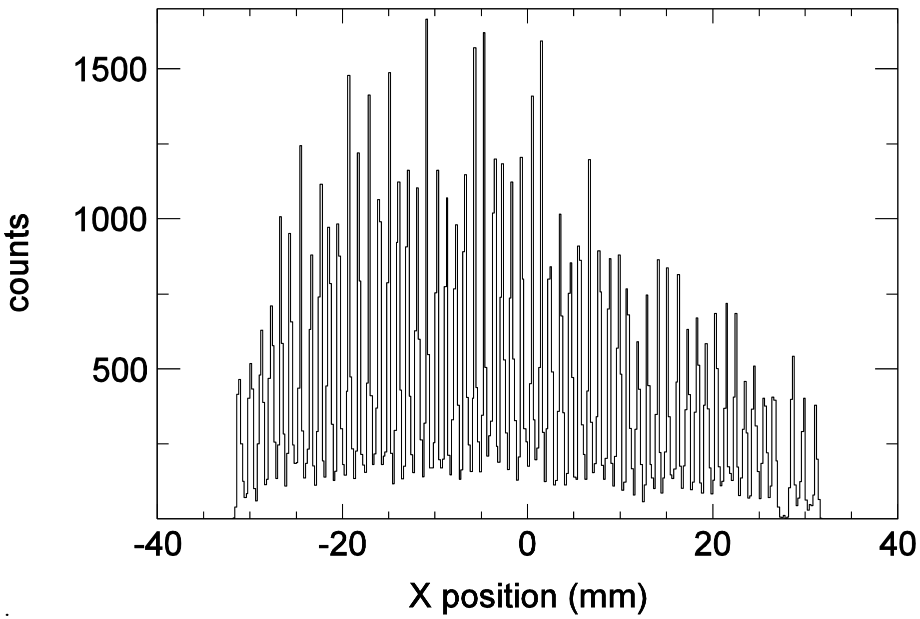




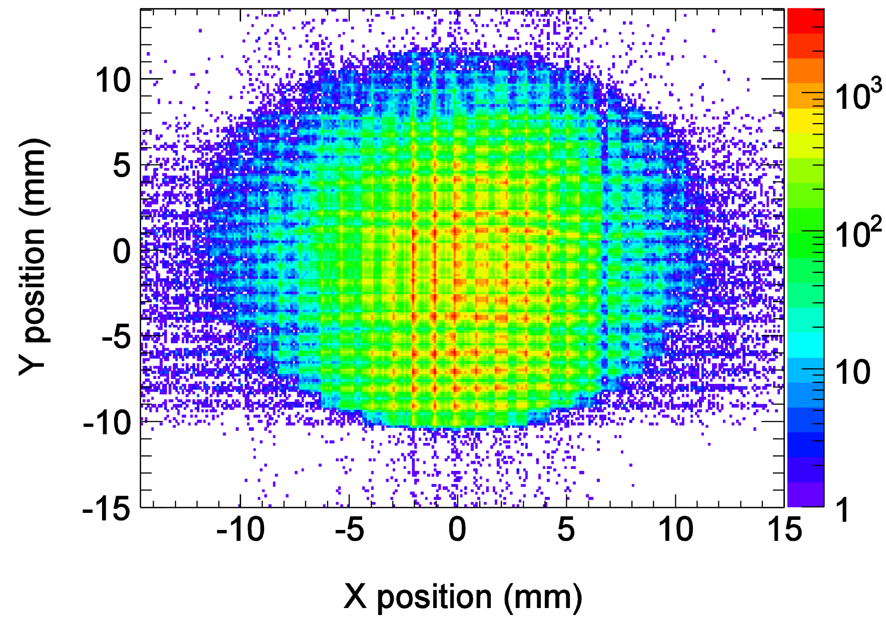


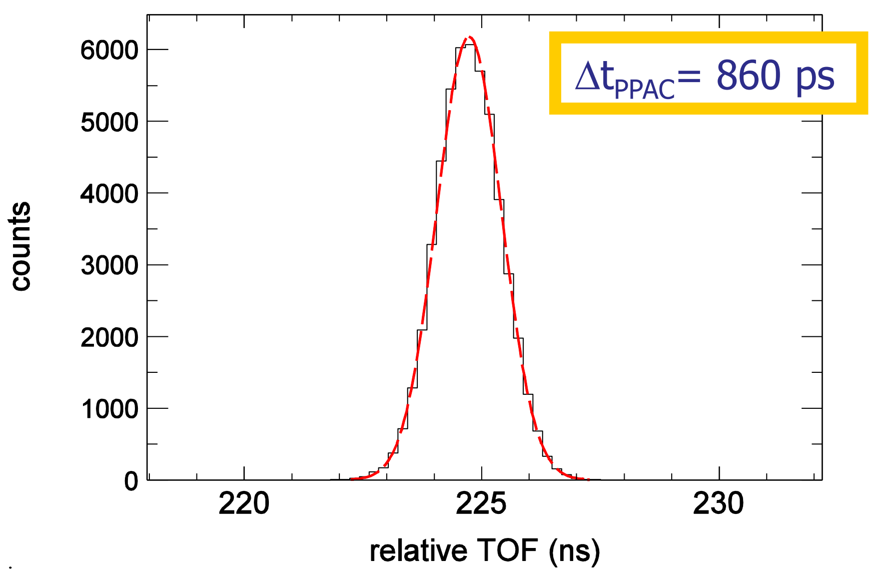
RIB tracking detectors at EXOTIC: PPACs

^{241}Am source (1 mm position resolution)



E_{lab}=31 MeV ^{15}O RIB profile on PPAC B





High tracking efficiency
98% for a ^{15}O RIB (2 x 10^4 pps)
94% for a ^{8}B RIB (10^3 pps)

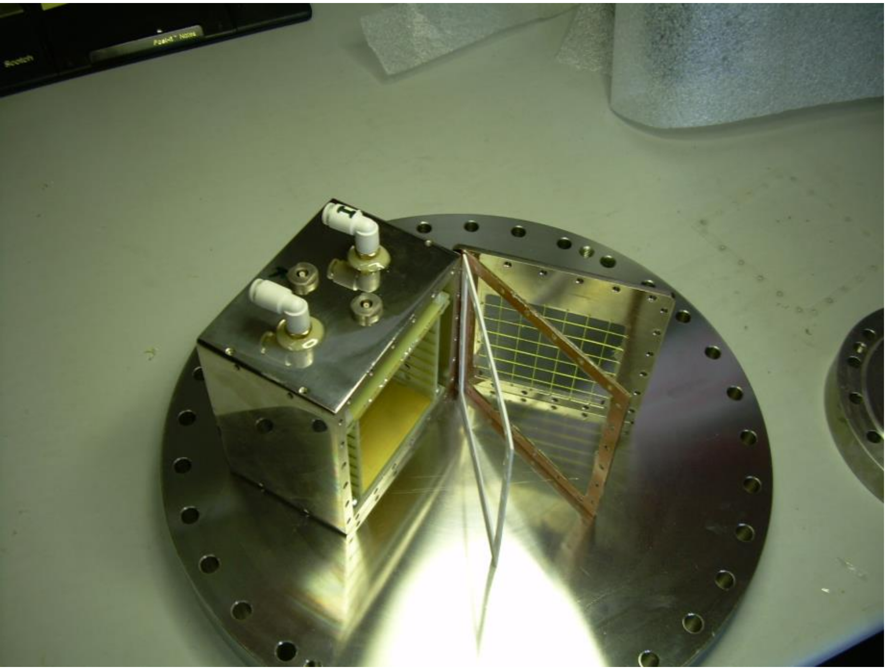
The 1 mm position resolution of PPACs allows a **2.3 mm resolution** (FWHM) for the reconstruction on the reaction target.

D. Pierroutsakou et al, NIM A 834 (2016) 46

Future upgrades of the RIB tracking detectors @ EXOTIC: MCP

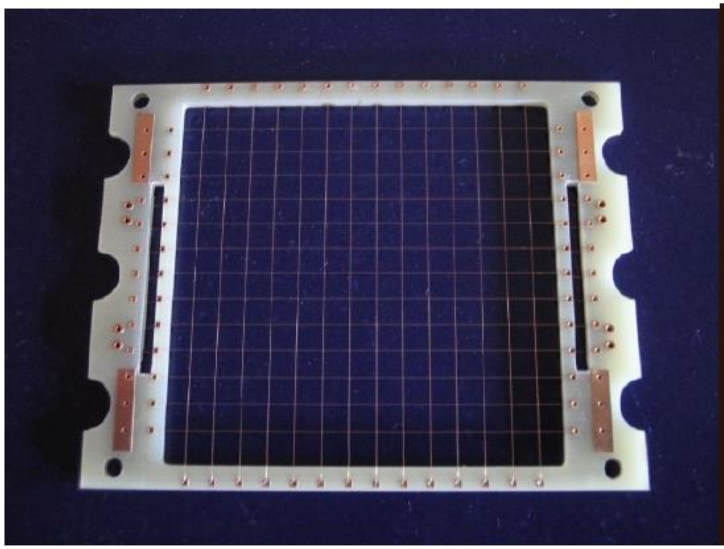
It is planned the use of position sensitive MCP detectors in the cases where the energy loss of the incident ion in the PPAC becomes critical

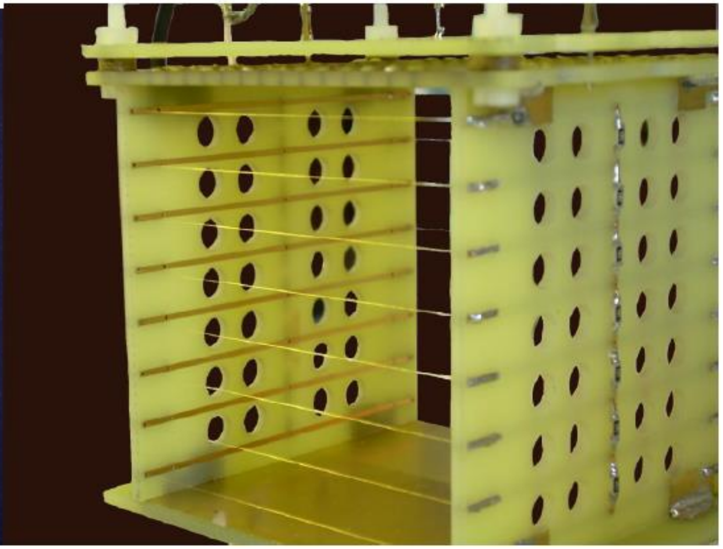
EXPADES ΔE stage transverse field IC



Easy handling, thickness uniformity, possibility to tune the effective thickness, large detection surface, no radiation damage problems, low thresholds

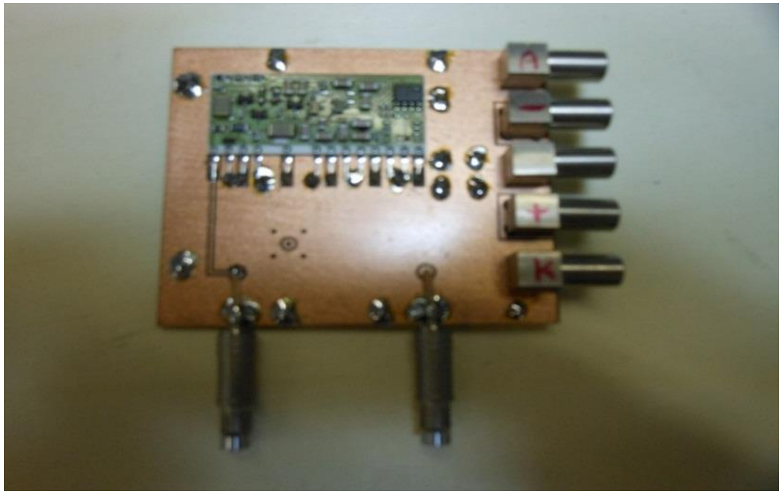
Entrance and exit windows: 1.5 μm-thick mylar
External dimensions: 10 cm x 10cm x 6.8 cm
Active IC depth: 6.15 cm
Anode - Cathode: 6.8 cm
Anode - Frish grid: 0.4 cm
V_C= -300 V
V_A= 50 V
Frish grid held at ground
Gas: CF_4 at 50-100 mbar





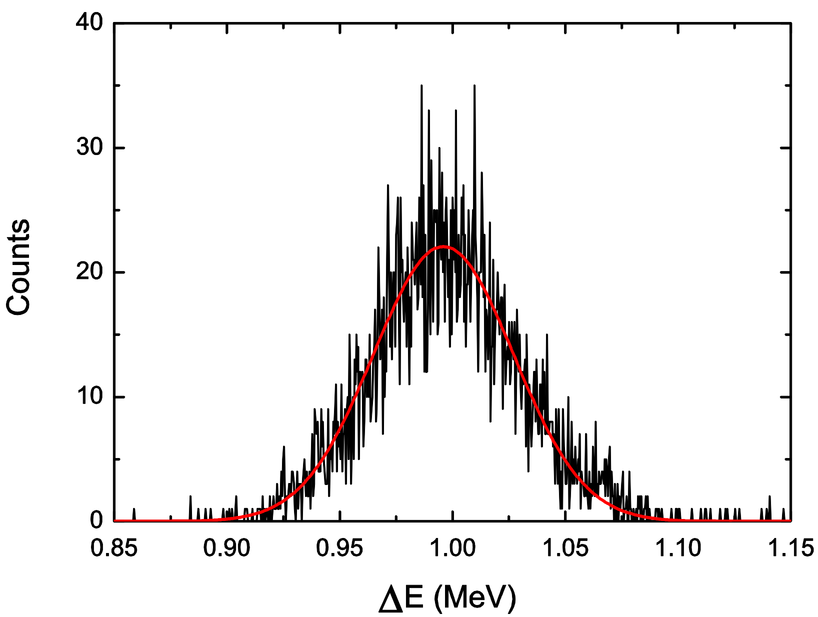
EXPADES ΔE stage transverse field IC

low-noise charge sensitive preamplifier placed close to the detetor



Energy sensitivity	90mV MeV
Output Voltage	8V max. (4V on 50ohm Term.)
Decay Time	600uS
Noise	1.5 KeV (0 pF) 12 eV/pF Slope
HV to Input resistance	100 Mohm
Max HV input	200V
Test capcitance	1pF
Power consumption	250mW

C. Boiano, R.Bassini, A.Pullia, T-NS Oct 02, 2436-2439 Vol. 49



Offline tests: readout traditional electronics

^{241}Am α source at 22 cm illuminated through a Ø=0.3 cm hole

P=61.5 mbar CF_4

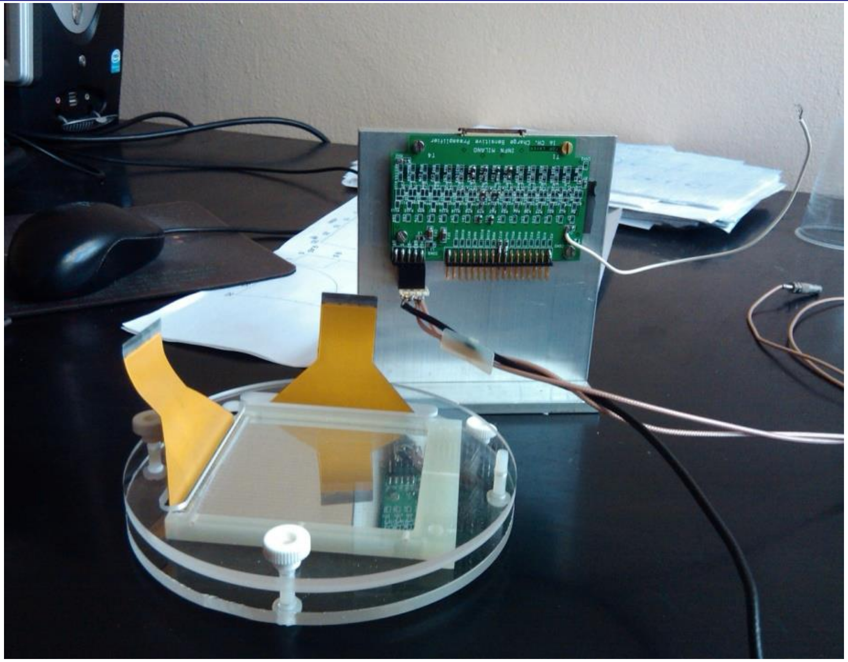
FWHM ΔE= 73 keV ΔE=1 MeV

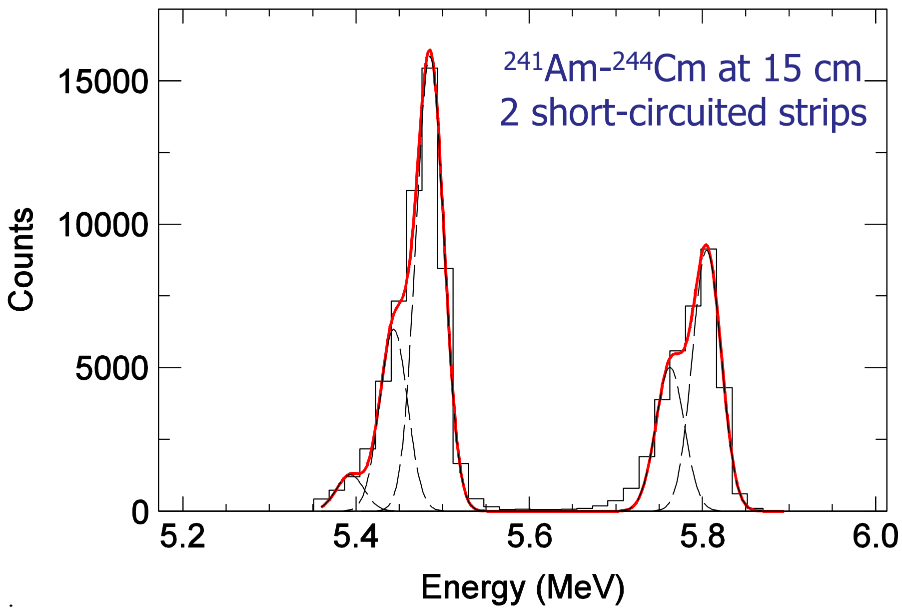
ΔE/E= 7.3% (6.5% intrinsic)

similar to that of an axial field IC for the same **ΔE**

S.K. Bandyopadhyaya et al., NIM A 278 (1989) 467

ΔE stage: DSSD 40/60 μm





Readout: home made highly integrated low-noise electronics

16 channel low-noise pre–amplifier boards

16 channel MEGAMP: (SA+CFD+TAC) modules that allow a sequentially read out of both energy and timing information by means of a fast multiplexer circuit

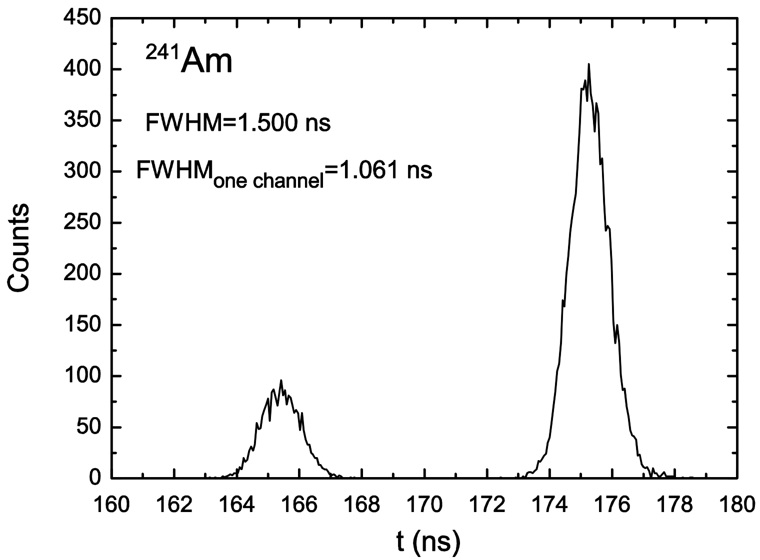
C. Boiano et al, 2012 IEEE NSS 2012

FWHM ΔE=38 (34 intrinsic) keV for E=5.6805 MeV

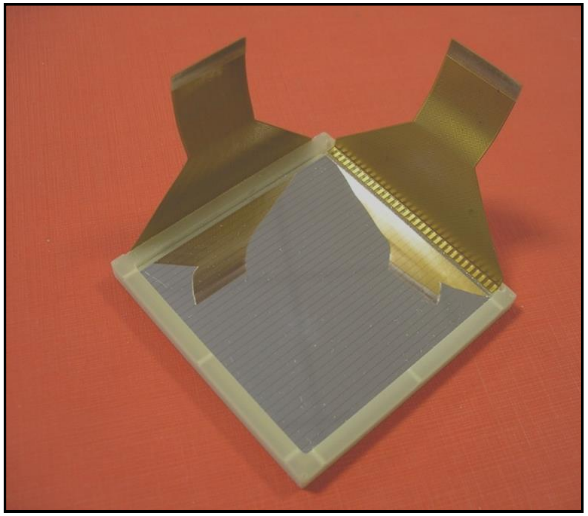
ΔE/E= 0.65%

FWHM Δt (FWHM): 1 ns (71 ps from the CFD module)

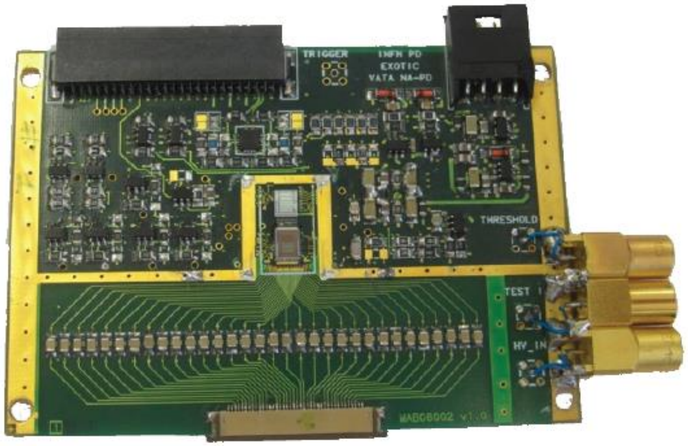
For the overall chain DSSSD+electronics



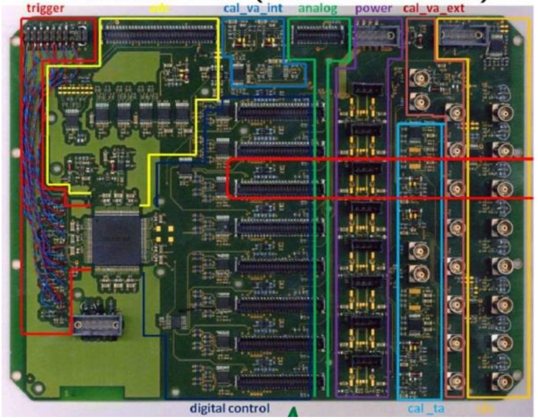
EXPADES E_{res} stage 300 μm DSSSD



ASIC electronic board VATA

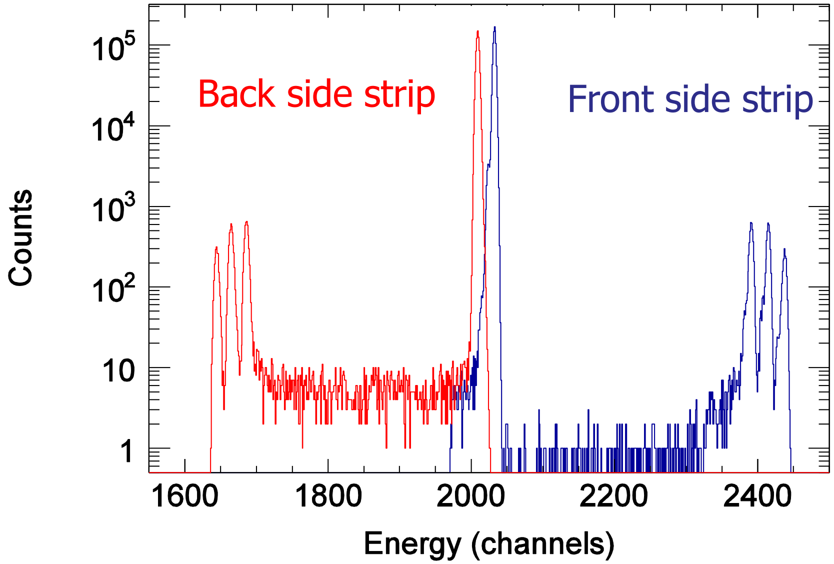


Motherboard (ASIC electronics)



Innovative readout electronics by means of an 32-channel ASIC chip manufactured by IDEAS-GM (Norway) dedicated to the treatment of the linear and the logical part of the electronic signals coming from the detector strips.

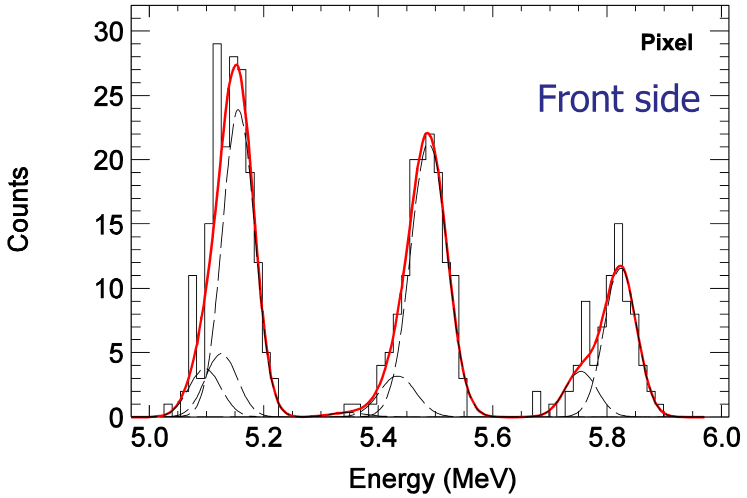
^{239}Pu - ^{241}Am - ^{244}Cm at 4 cm



^{239}Pu - ^{241}Am - ^{244}Cm at 4 cm

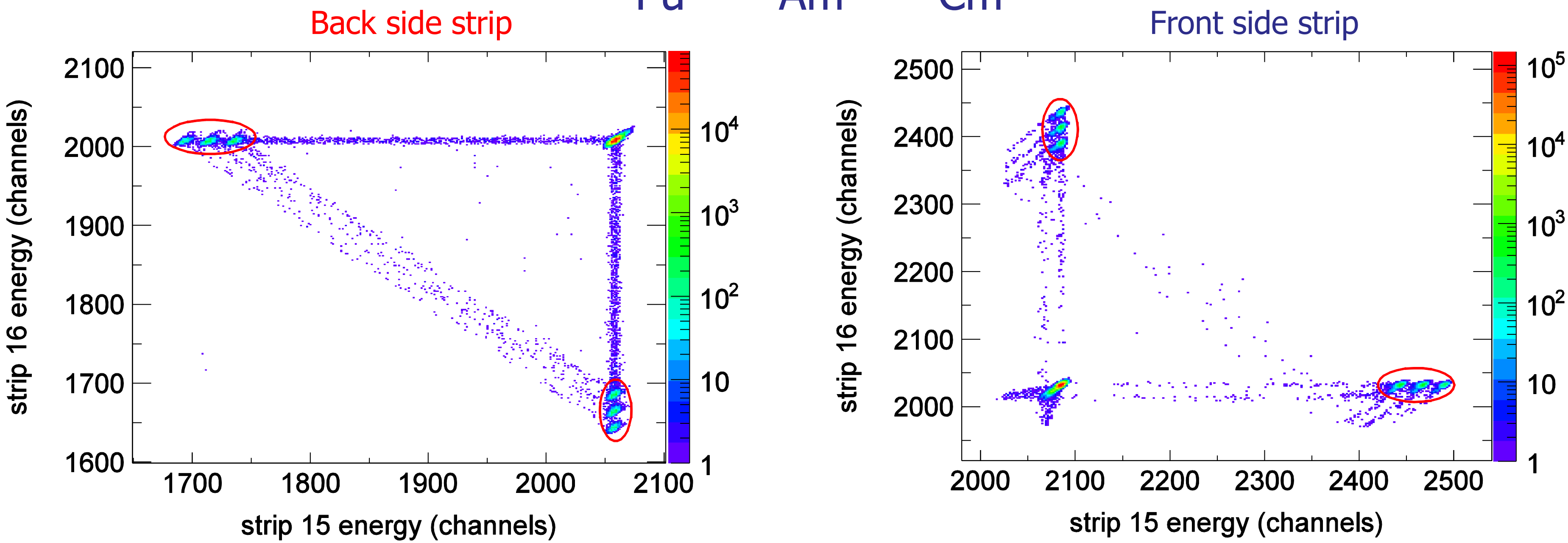
FWHM ΔE=66 (33 intrinsic) keV for E=5.805 MeV

$\Delta E/E$= 1.14%



EXPADES E_{res} stage 300 μm DSSSD: interstrip events

^{239}Pu - ^{241}Am - ^{244}Cm



``full energy events": particles entering the detector through the central region of a strip and producing in this strip a full energy signal and no signal in the adjacent one

interstrip events: particles entering the detector through the region of separation between two adjacent strips. The behaviour of front and back interstrip events is in agreement with that observed in previous works [D. Torresi et al., Nucl. Instr. and Meth. A 713 (2013) 11]

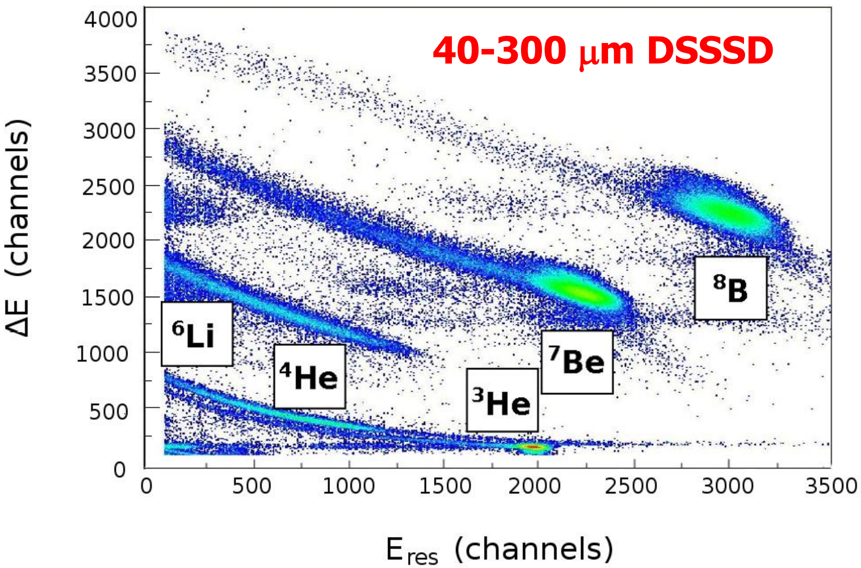
For the **back side**, just charge sharing is observed, i.e. the full energy of the event can be recovered summing the signal of the two adjacent strips.

For the **front side** this operation is not possible due to the generated opposite polarity signals.

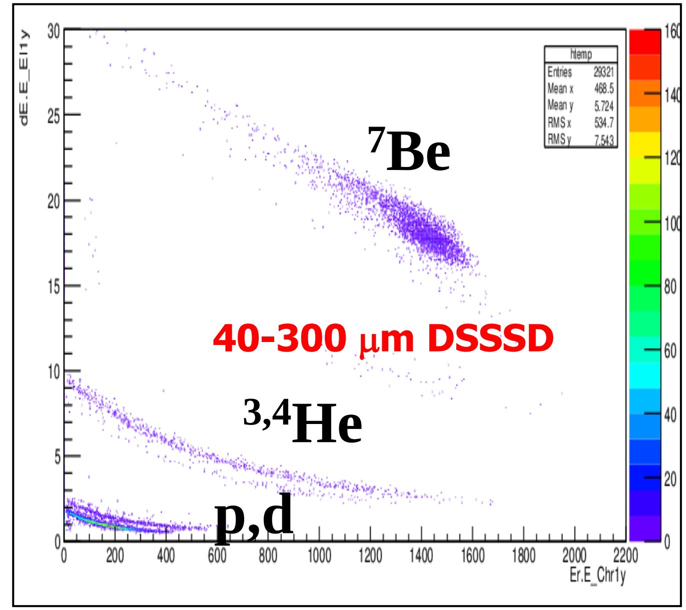
In the data analysis, the imposed condition requires that the full energy of the event be equal for the front and the back sides.

EXPADES: particle identification

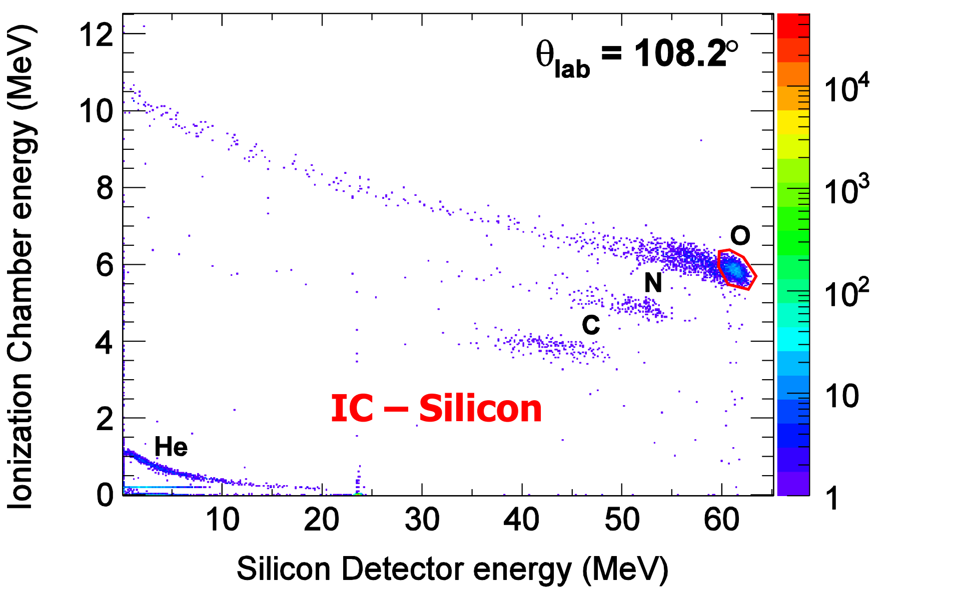
^{8}B + ^{208}Pb at CRIB (RIKEN, Japan)



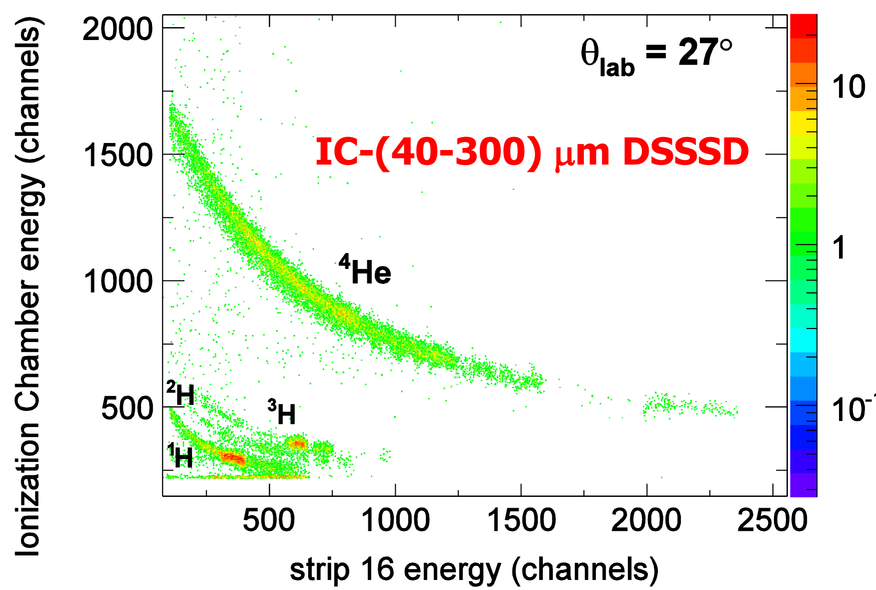
^{7}Be + ^{208}Pb at EXOTIC



^{17}O + ^{208}Pb at LNL

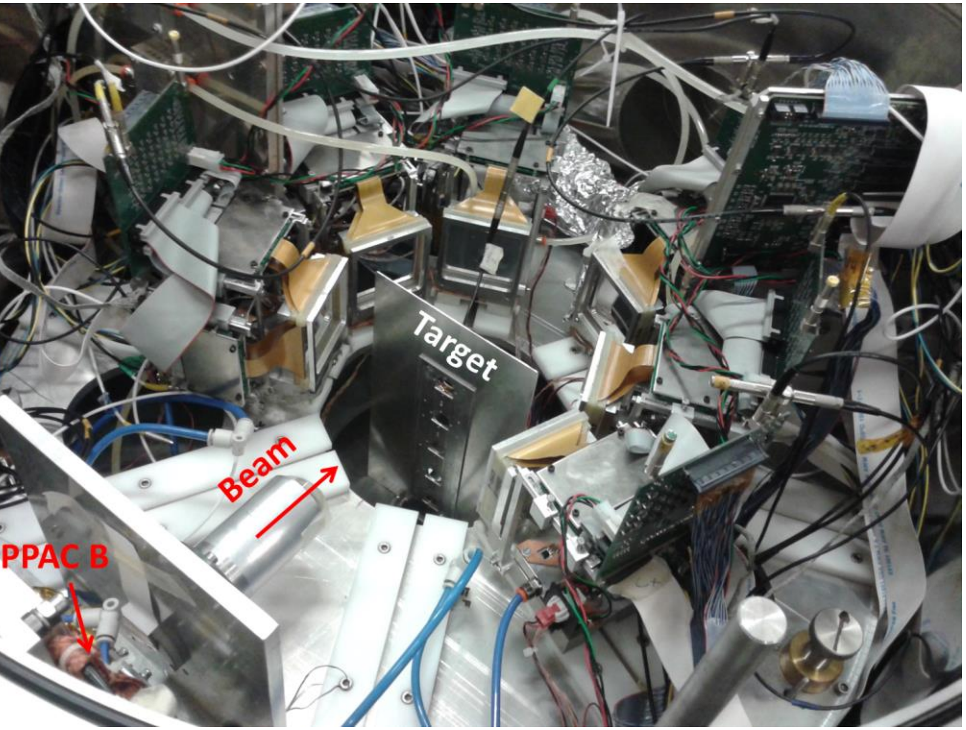


^{7}Li + ^{12}C at EXOTIC

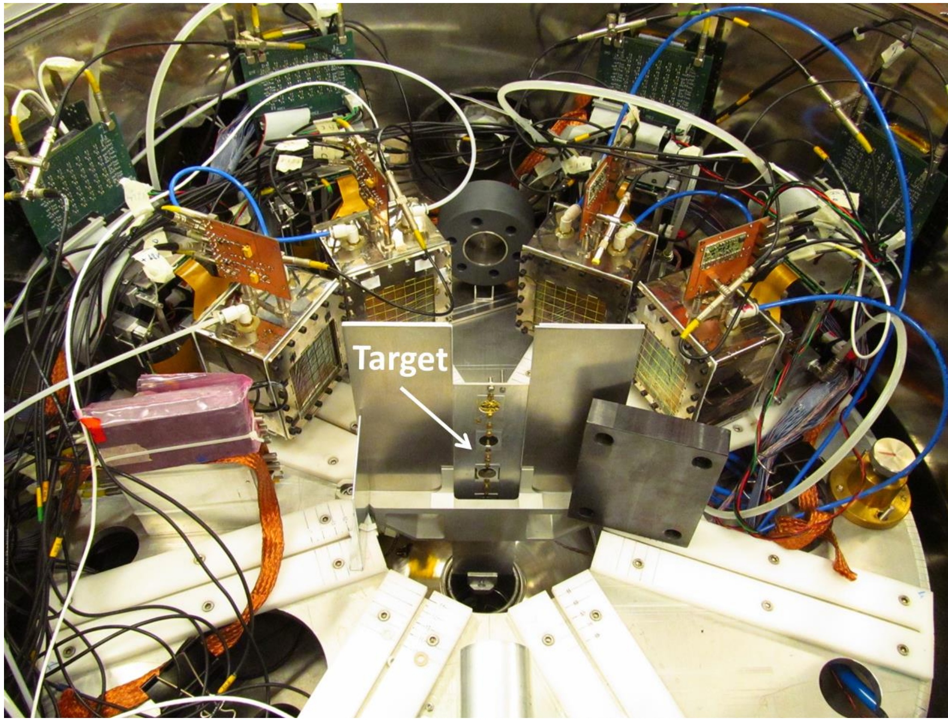


EXPADES configurations

6 two-stage DSSSD telescopes



4 three-stage IC-DSSSD telescopes



To date EXPADES has been used in various configurations for experimentation at **EXOTIC**. The array has also been moved at **CRIB (RIKEN, Japan).**

Future upgrades of the EXPADES

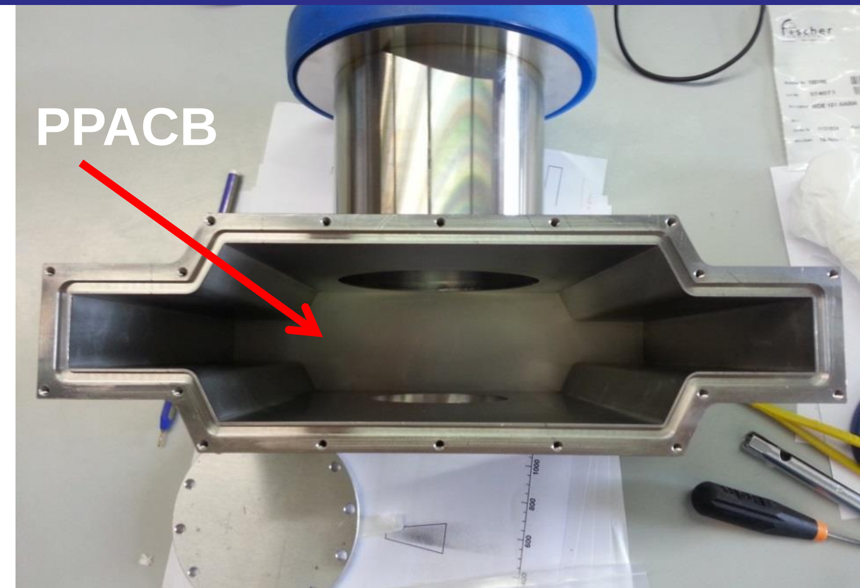
It is planned the use of 1 mm-thick DSSSD for the detection of more energetic particles in addition or in alternative to the 300 μm-thick E_{res} DSSSDs.

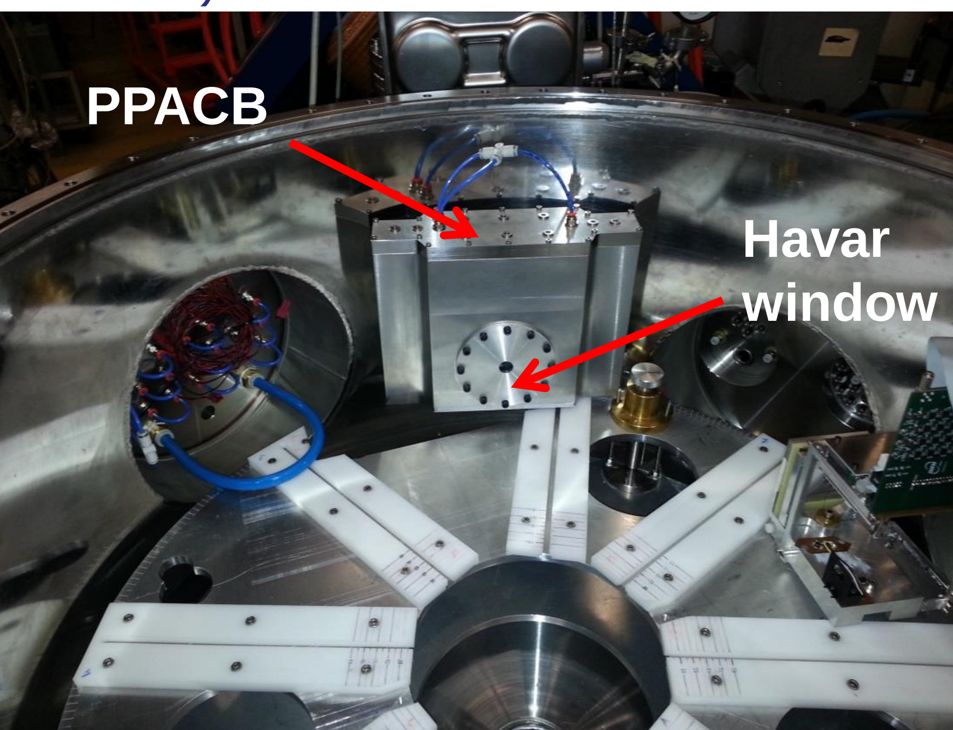
In case we need a better overall energy resolution for the telescope, low-noise electronics can be used also for the E_{res} stage instead of the ASIC-based one

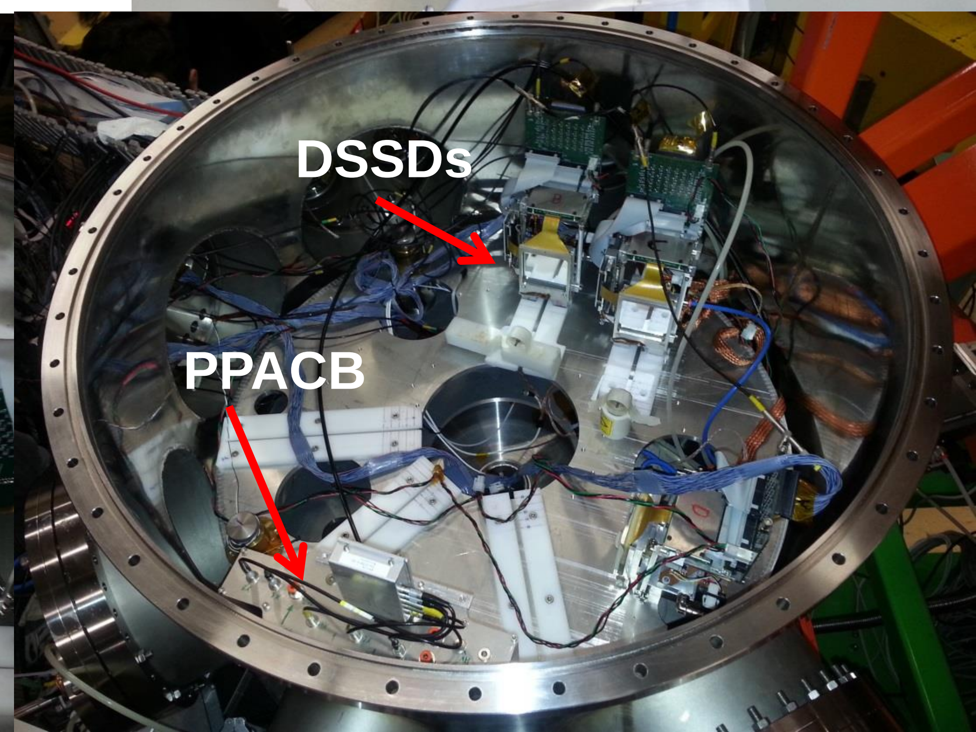
EXOTIC upgrade for experiments with reaction gas targets

Modifications of the EXOTIC beam line were performed in early 2015, to allow the realisation of experiments by employing **RIBs** impinging on reaction **gas targets (thick targets)**.

A new small chamber was built hosting the PPACB that separates, through a havar window, the scattering chamber (filled with ^{4}He gas) from the beam line (at high vacuum).







Search for ^{15}O-α configurations associated to ^{19}Ne excited states @ EXOTIC

Spokespersons: D. Torresi, C. Wheldon

The experimental technique called Thick Target Inverse Kinematics method (TTIK) was employed to study the elastic scattering of the system ^{15}O+^{4}He, never measured before.

- ✓ Measurements of the elastic scattering excitation function
- ✓ R-matrix analysis for the extraction of
  - Energy and width of the resonances
  - Reduced α-width

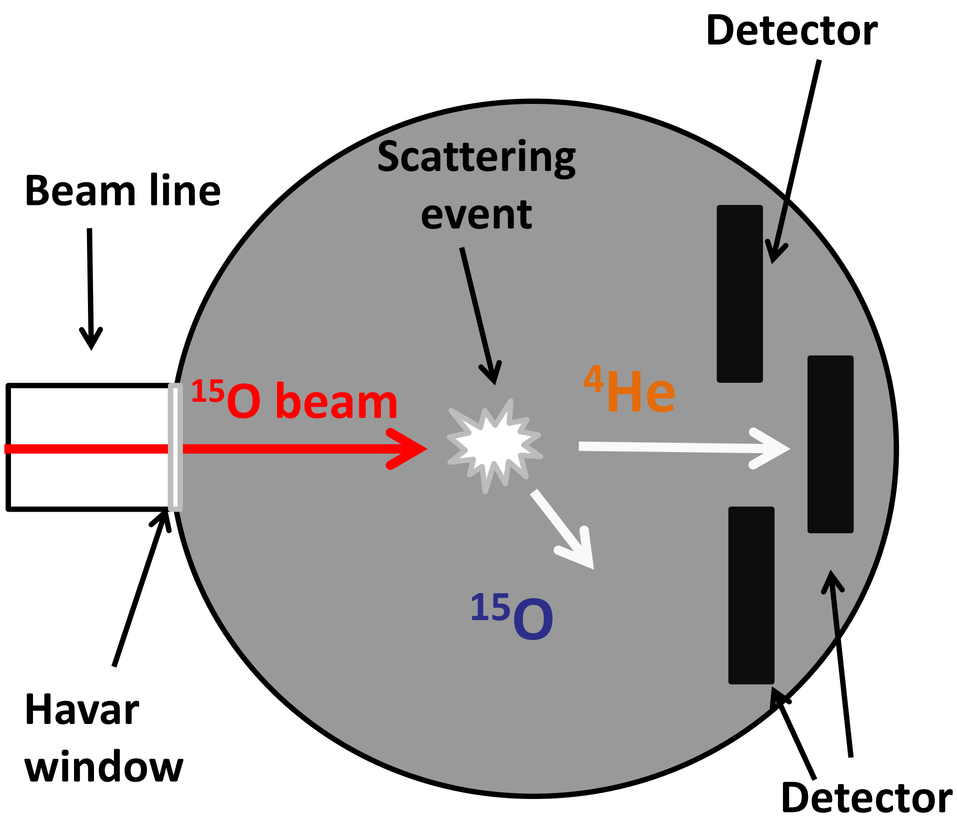
Why ^{19}Ne?

1. A number of Ne isotopes manifest evidences of clustering phenomena. This makes the ^{19}Ne a good candidate to manifest cluster structures.
2. The structure of low-lying levels in ^{19}Ne near the ^{15}O+^{4}He threshold are important: their study can improve our knowledge on the ^{15}O(α,γ) ^{19}Ne reaction rate of astrophysical interest.

The Thick Target Inverse Kinematics (TTIK) Method

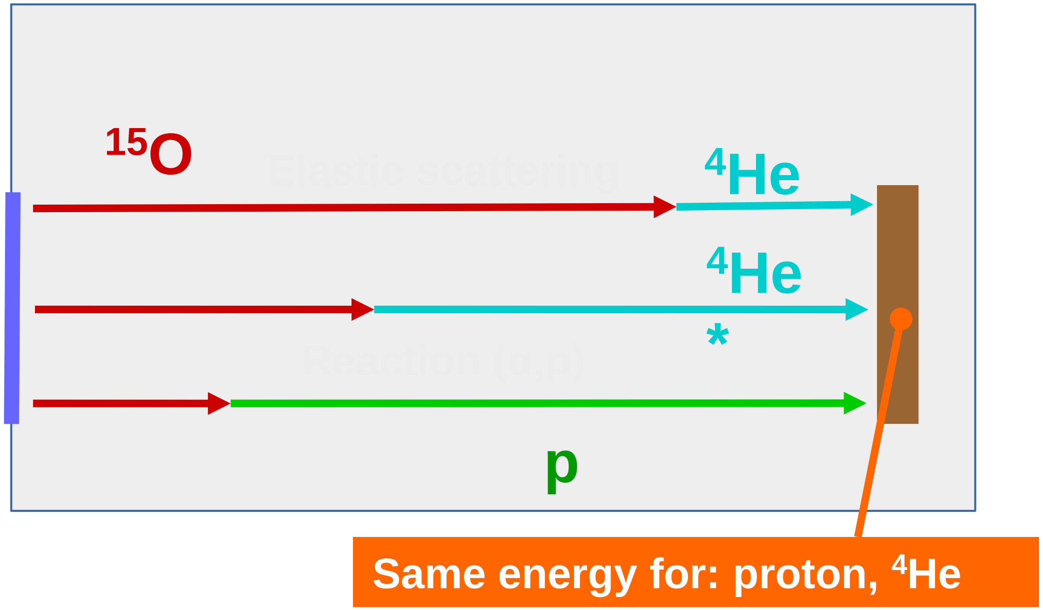
K. P. Artemov et al., Sov. J. Nucl. Phys. 52, 408(1990)
G. Rogachev PhD thesis

Measurements of elastic scattering excitation function in a wide range of energies using a single beam energy. Suitable for low intensity beams.



- ✓ The chamber is filled with gas at such a pressure to stop the beam
- ✓ The beam slows down into the gas
- ✓ Elastic scattering occurs at different positions in the chamber
- ✓ Detectors placed at 0° and around detect the recoiling α particles
- ✓ Energy and position where the reaction occurs can be reconstructed from the energy and position of the detected α particle
- ✓ stopping power of the beam and α particle should be known

The Thick Target Inverse Kinematics (TTIK) Method: ToF



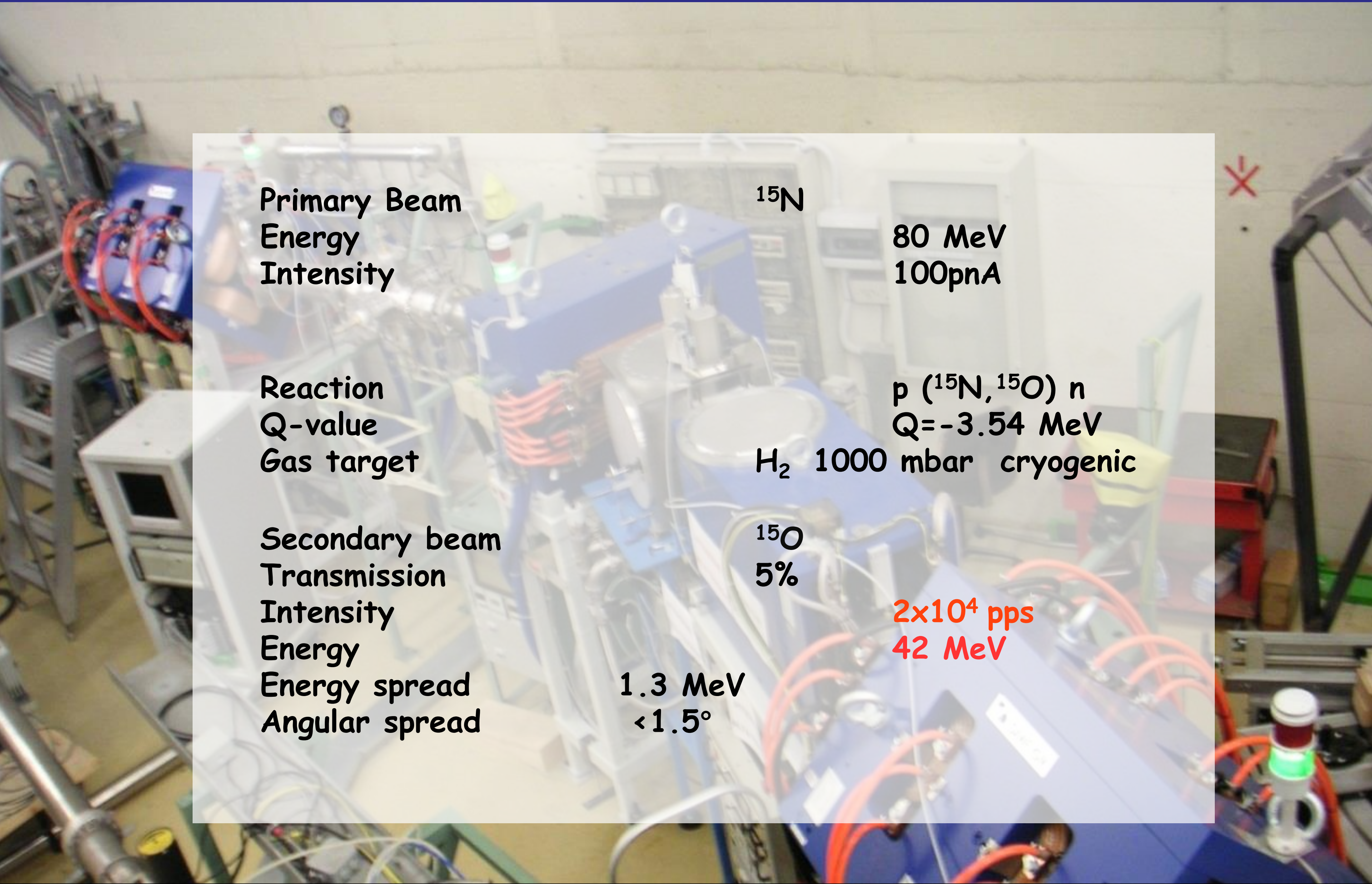
Different processes can
- Occur at different position of the chamber
- Produce particle with the same energy on the detector

But the time of flight will be different

ToF:
Start: entering of the particle in the chamber
Stop: recoil of the reaction impinges on the detector

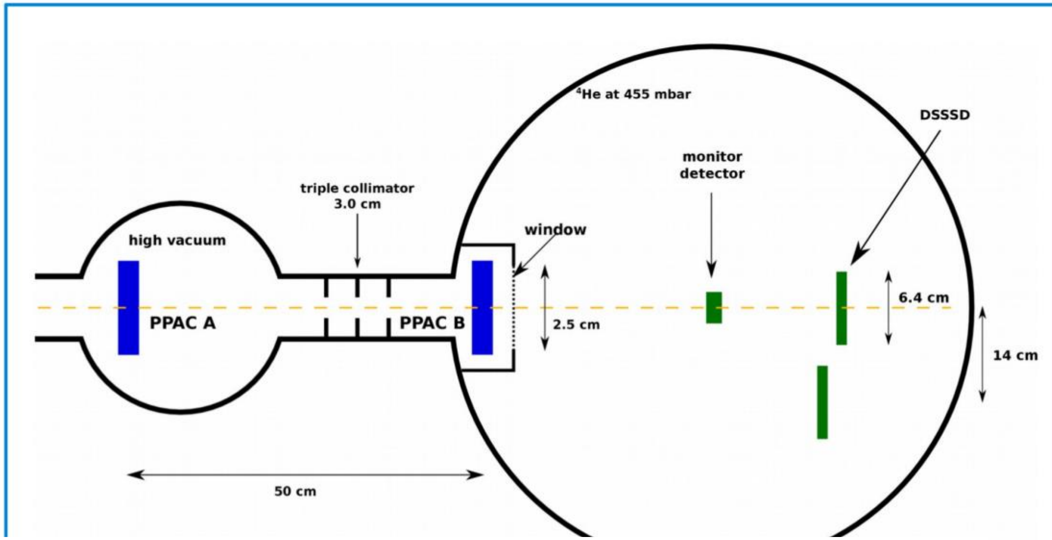
ToF measurements allow to distinguish not only different particles but also different processes!

The ^{15}O Beam @ EXOTIC

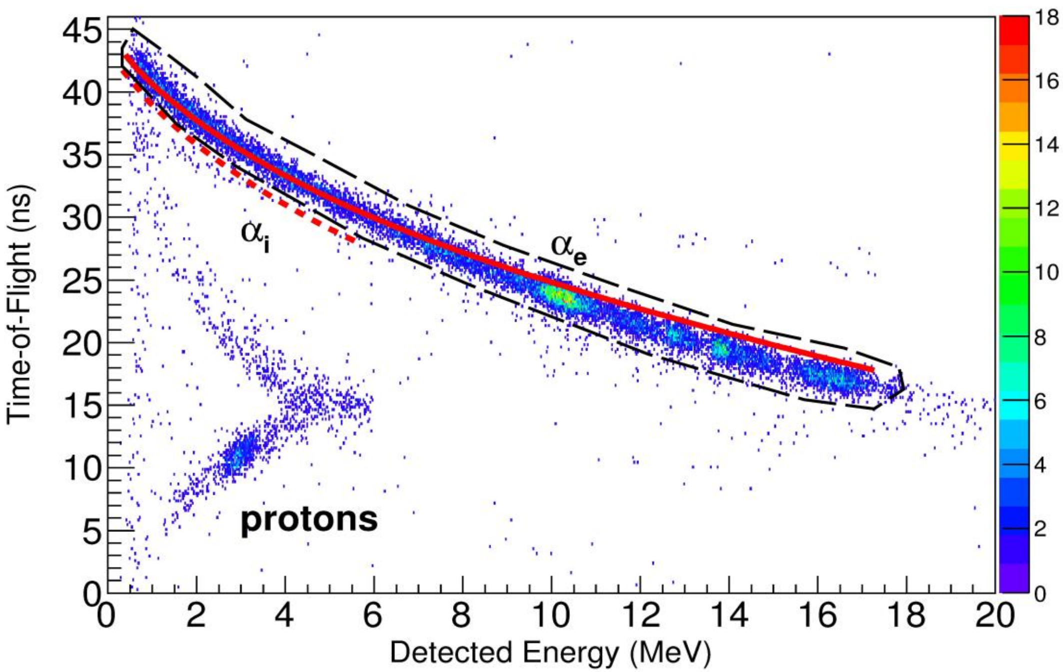


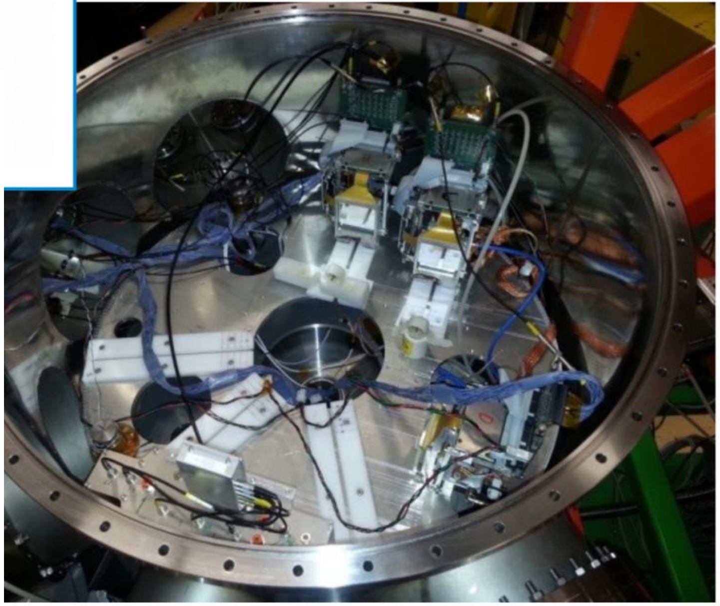
Primary Beam	^{15}N	
Energy		80 MeV
Intensity		100pnA
Reaction		p (^{15}N,^{15}O) n
Q-value		Q=-3.54 MeV
Gas target	H_2 1000 mbar cryogenic	
Secondary beam	^{15}O	
Transmission	5%	
Intensity		2×10^4 pps
Energy		42 MeV
Energy spread	1.3 MeV	
Angular spread	<1.5°	

The Experimental set-up



- **Two PPACs**: ToF, beam counting and diagnostic purposes.
- **Two DSSSDs:** recoiling detection.
- **Temperature** and **pressure** of the gas continuously monitored.



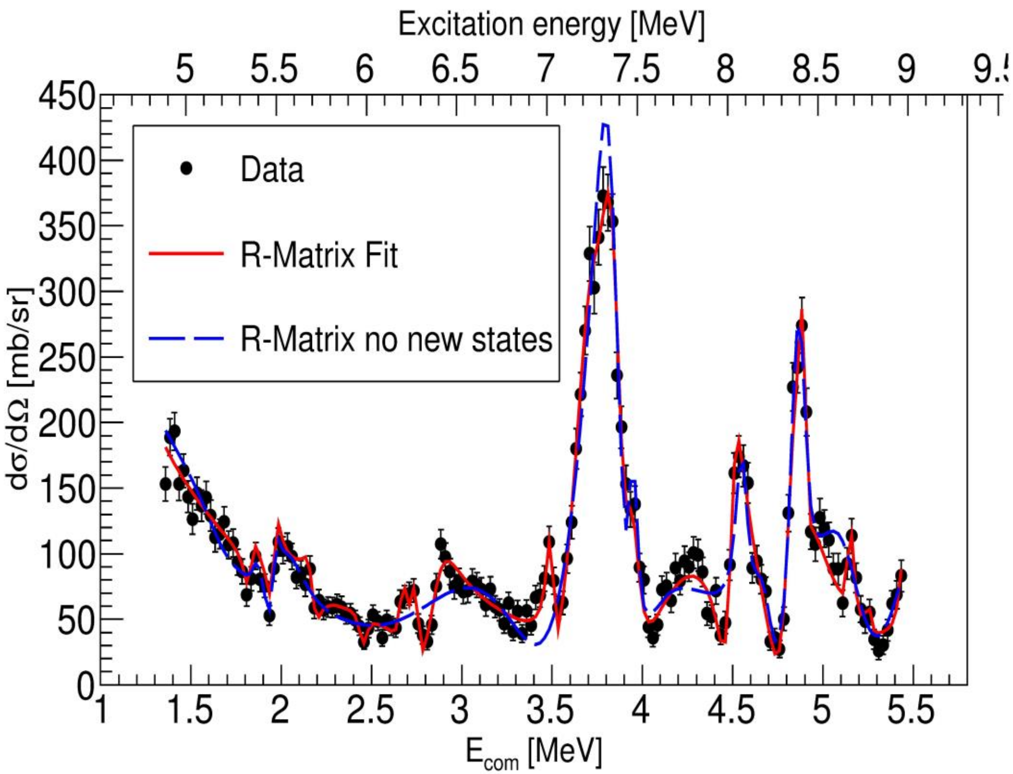


$^{15}O+^{4}He$ Elastic Scattering Excitation Function

The R-matrix fit was performed with **AZURE2**

- Data at 180° in COM frame.
- R_0 = 1.4 fm.
- Convolution with 50 keV for experimental resolution (FWHM).
- χ^2/d.o.f. = 1.2.

E_a= 3.58 MeV
E_p= 6.41 MeV



Significant new results using *R*-Matrix formalism for resonant reactions.
– spins and parities of the states have been established
– large number of partial decay widths
- Clustering below the proton threshold suspected from previous studies confirmed by the present one

D. Torresi, XL Symposium on Nuclear Physics – January 4-7 , 2017 Cocoyoc Mexico

Conclusions and perspectives

The **low-energy light** RIBs of the **EXOTIC** facility are employed to do stimulating physics attracting external users

Besides experiments using RIBs, possibility to use the facility as a **velocity filter** to perform **fusion-evaporation experiments at sub-barrier energies** with stable beams is being investigated

The **experimental set-up** installed at EXOTIC is fully operational and consists of: two **PPACs** for the RIB tracking and for ToF measurements and the compact, high-granularity, flexible, portable charged-particle detection array **EXPADES**.

Althouh EXPADES was built primarily to fully exploit the EXOTIC RIBs, its components can be easily reconfigured to suit many experiments. **Upgrades of the EXPADES** are under way for the detection of more energetic ions. Moreover, it can be employed as an ancillary detection system with neutron and γ-arrays in view of the SPES RIBs.

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