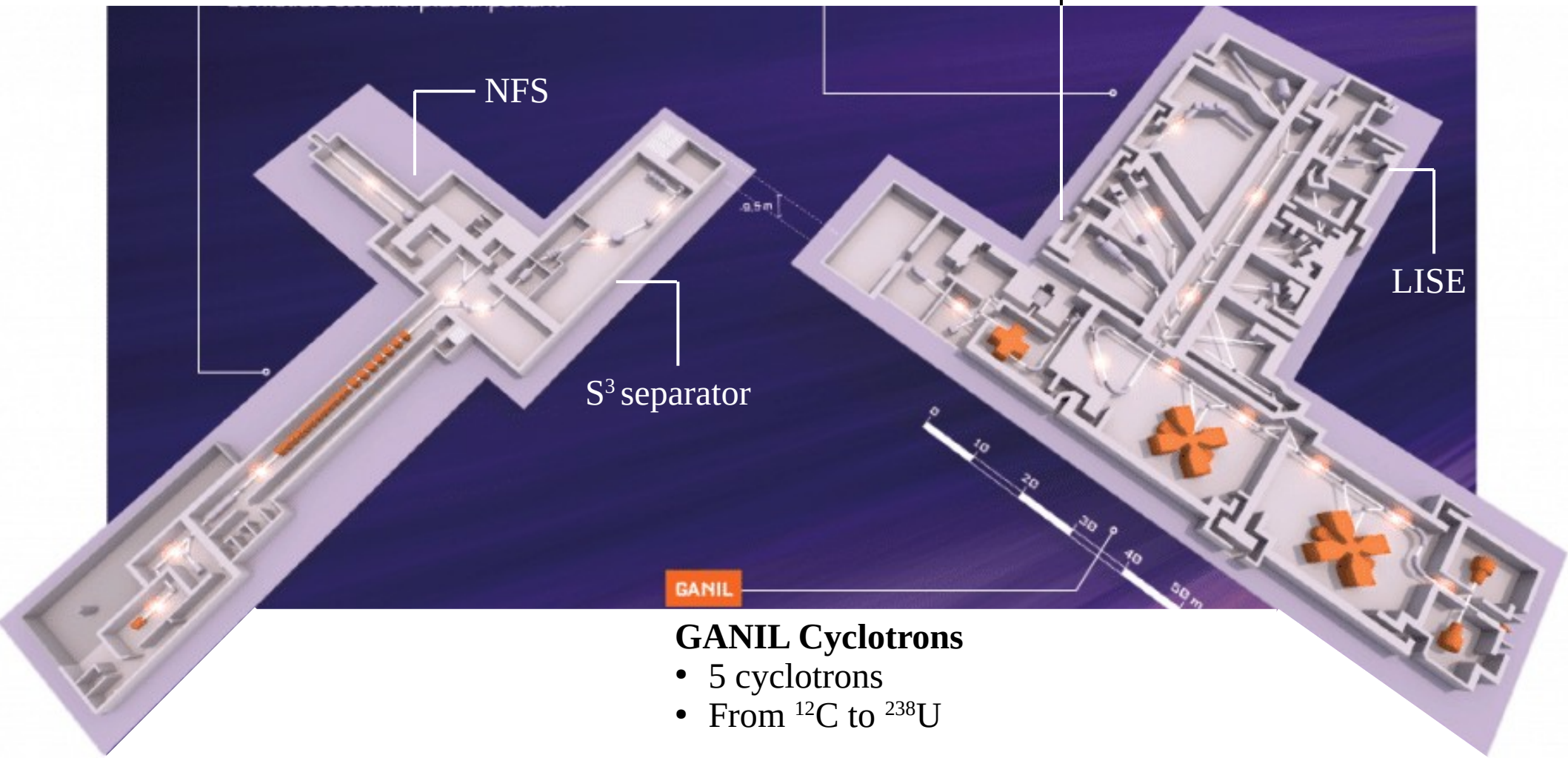
VAMOS :
Performances and Physics Opportunities

Diego Ramos
on behalf of the VAMOS collaboration

GANIL/SPIRAL2

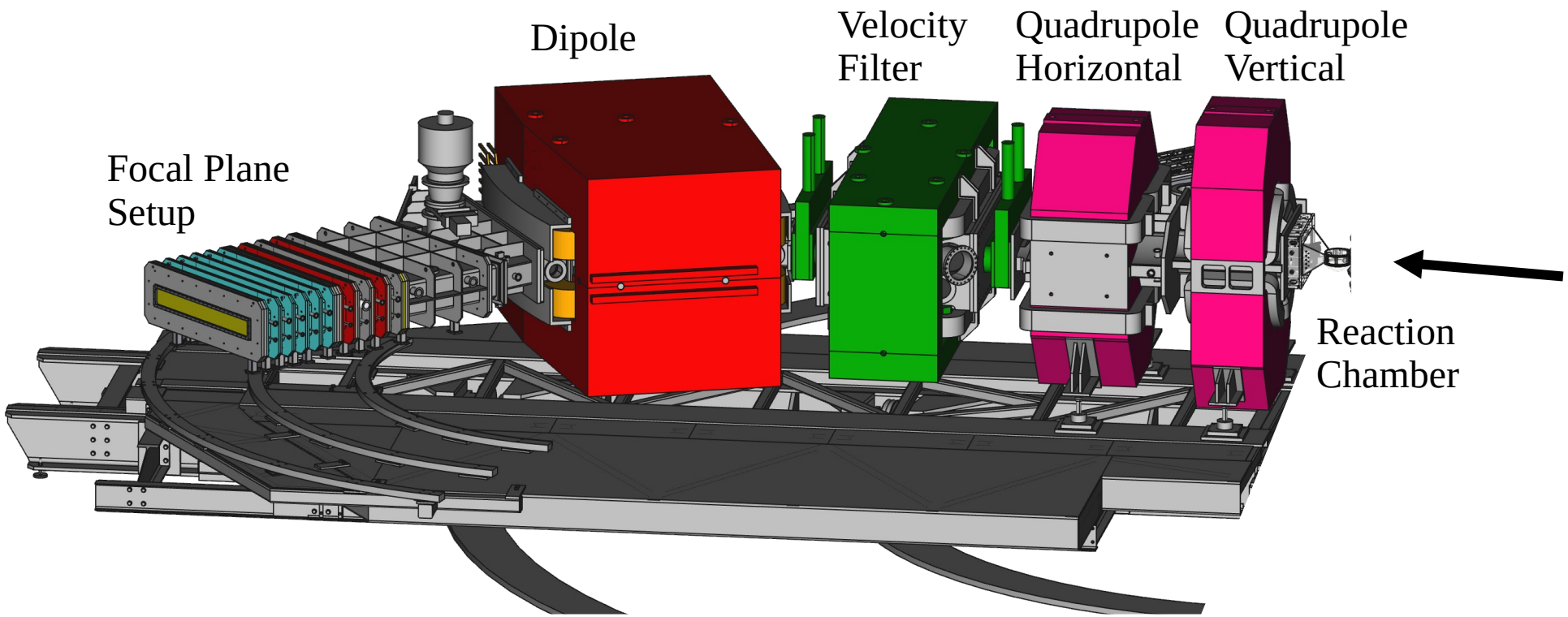
SPIRAL 2 *(talk Herve Savajols)*
- Supraconductive LINAC
- From H to Ni / NewGain (A/q=7)

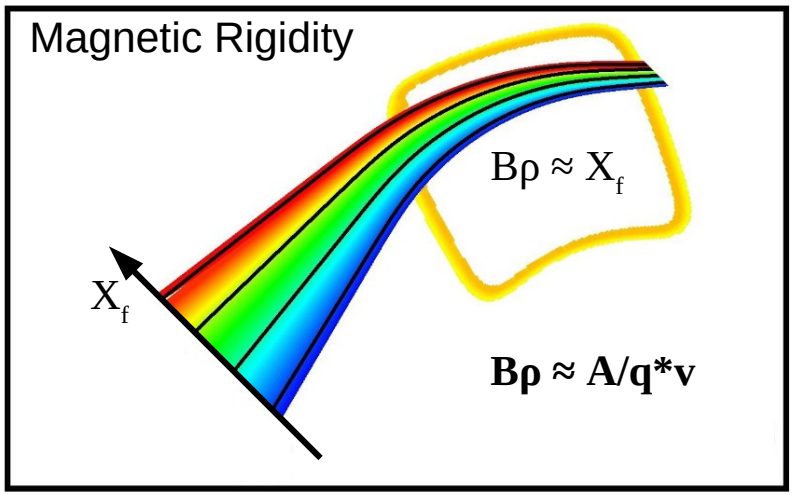
G1 Experimental Area
- **VAMOS**

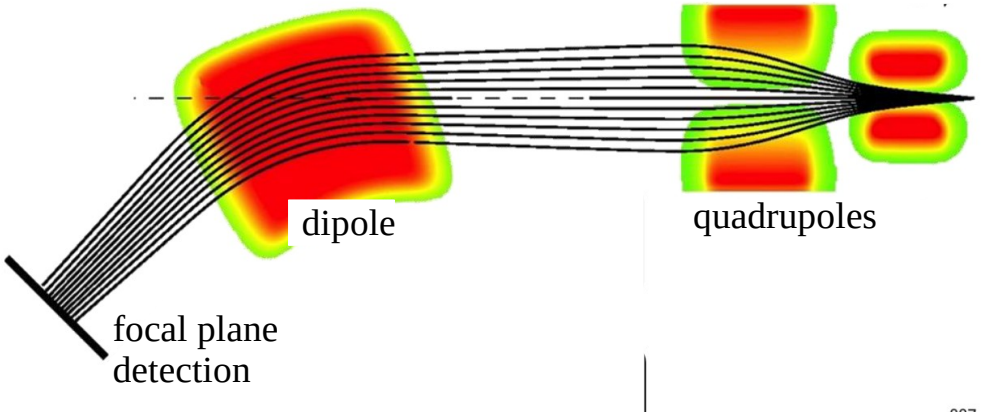


GANIL Cyclotrons
- 5 cyclotrons
- From ^{12}C to ^{238}U

The VAMOS Spectrometer



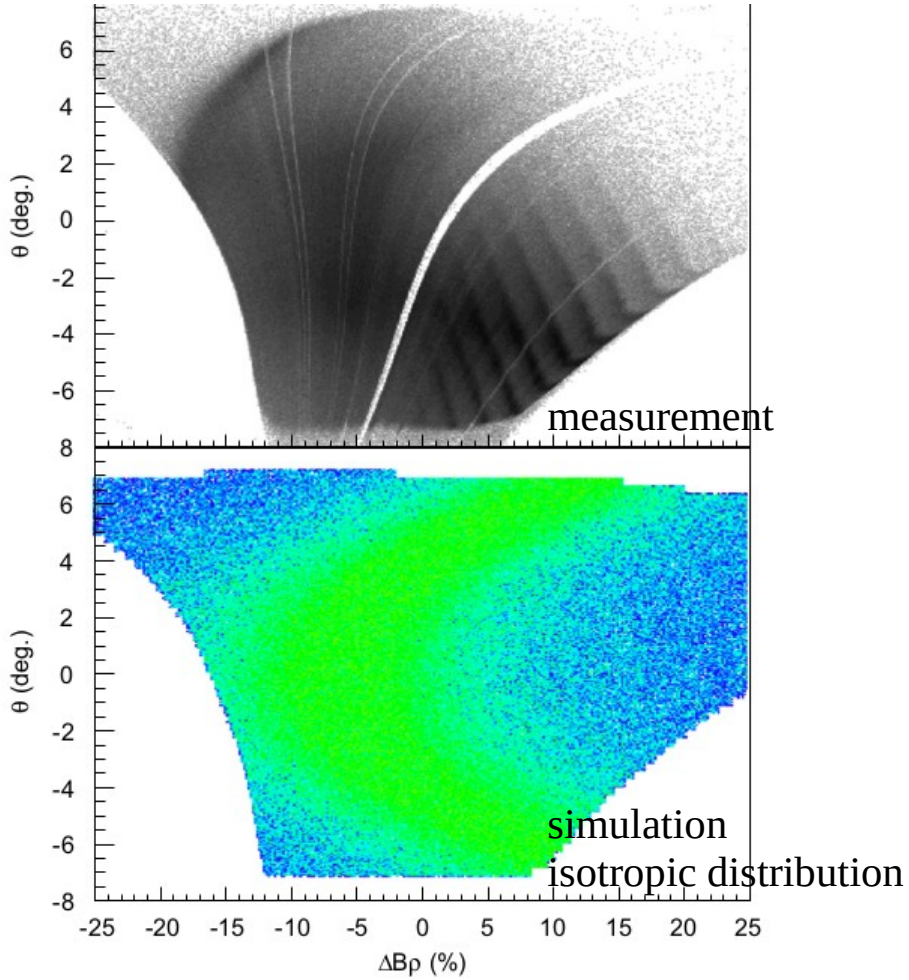




The VAMOS Spectrometer

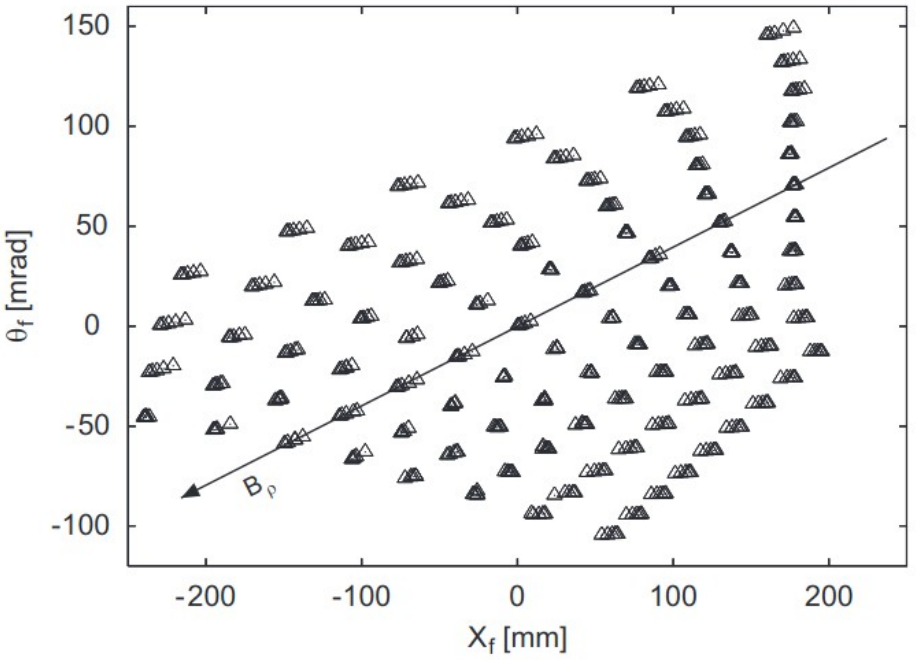
Large Acceptance

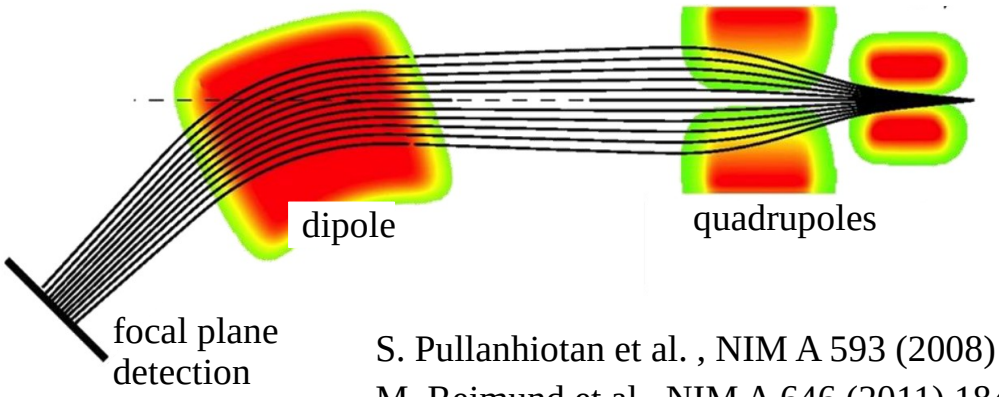
- Horizontal: 7 deg.
- Vertical: 11 deg
- Bρ: 10% (Max Bρ= 1.6 Tm)



Higher order Bρ dependence

- $B\rho = f(X_f, \theta_f, Y_f, \varphi_f)$

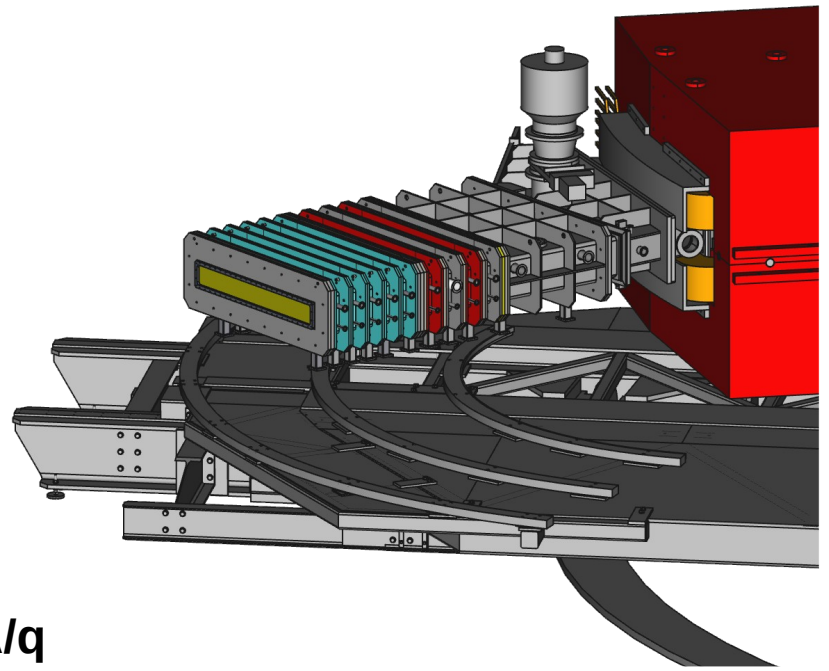




S. Pullanhiotan et al. , NIM A 593 (2008) 343
M. Rejmund et al., NIM A 646 (2011) 184

The VAMOS Detection Setup

Goal: **Isotopic Identificion of Heavy Ions (A, Z)**



1) Position Sensitive detectors

→ (X_f, θ_f)

→ Bρ

Ion optics reconstruction

→ Path

2) Fast Response detectors

→ **Time Of Flight** → **V**

V + Bρ → **A/q**

Bρ ≈ A/q*V

A/q + **A^E** → **(A , q)**

3) Energy Sensitive Segmented detectors

→ **Energy (E)** → **A^E**

→ **Energy Loss (dE)** → **Z**

4) Coulomb-Barrier energies => Challenging detection without stopping

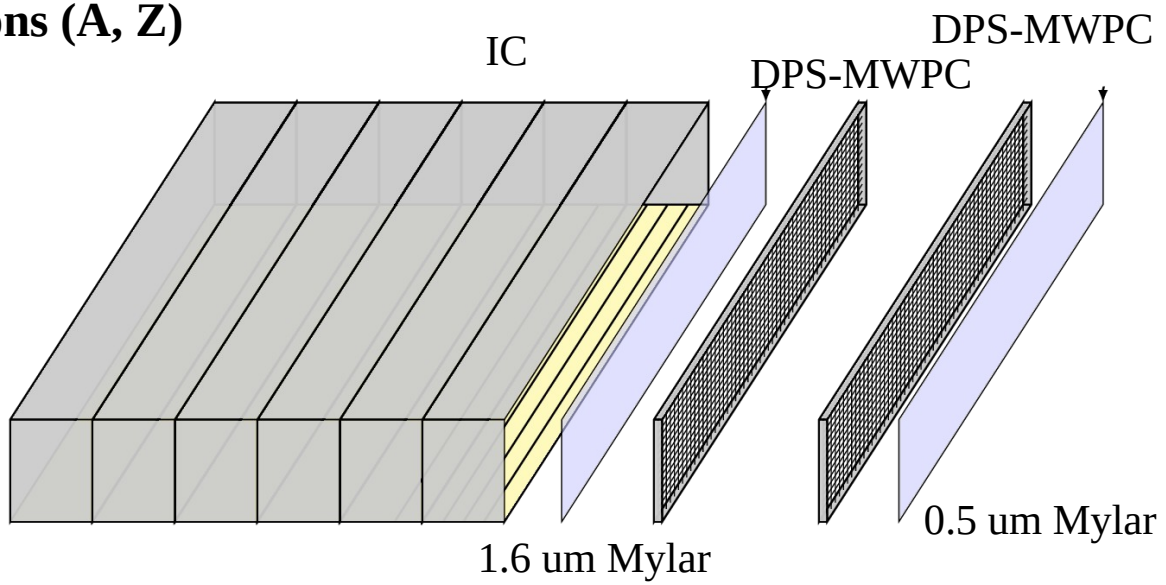
→ **Gaseous Detectors**

The VAMOS Detection Setup

Goal: **Isotopic Identificion of Heavy Ions (A, Z)**

1) Position Sensitive detectors

→ **(X_f ,θ_f)**



2) Fast Response detectors

→ **Time Of Flight**

Dual Position-Sensitive MultiWire Parallel Counter

- Active Area: 1000x150 mm²
- 1150 wires with individual readout
- 6 mbar iC_4H_{10} gas
- < 250 um position resolution
- < 300 ps time resolution

3) Energy Sensitive Segmented detectors

→ **Energy (E)**

→ **Energy Loss (dE)**

4) Coulomb-Barrier energies => Challenging detection without stopping

→ **Gaseous Detectors**

The VAMOS Detection Setup

Goal: **Isotopic Identificion of Heavy Ions (A, Z)**

1) Position Sensitive detectors

→ **(X_f ,θ_f)**

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→ **Time Of Flight**

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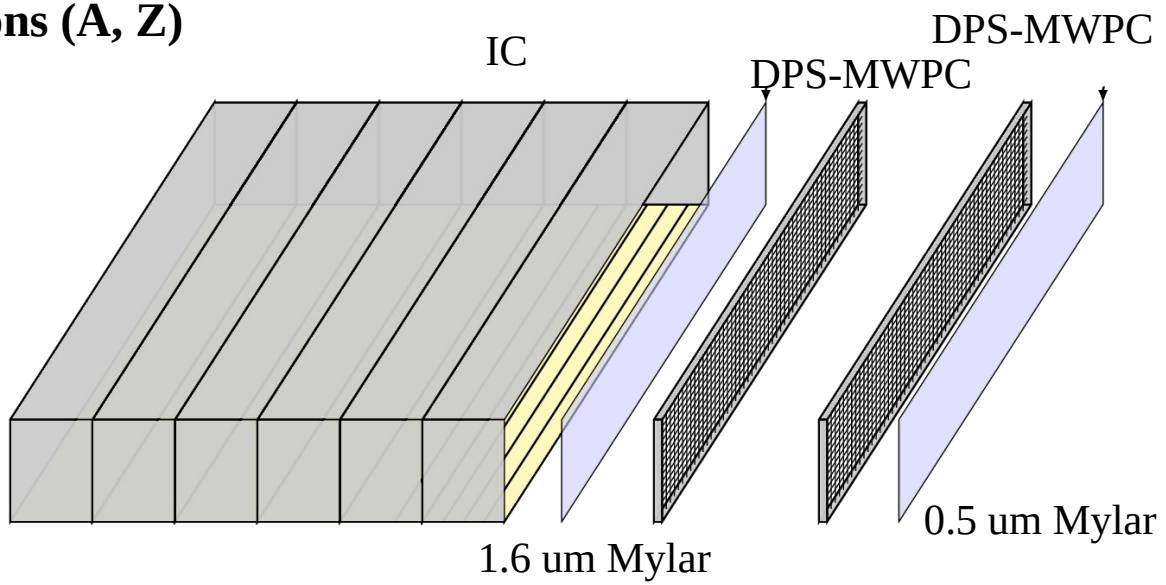
→ **Energy (E)**

→ **Energy Loss (dE)**

4) Coulomb-Barrier energies

→ **Gaseous Detectors**



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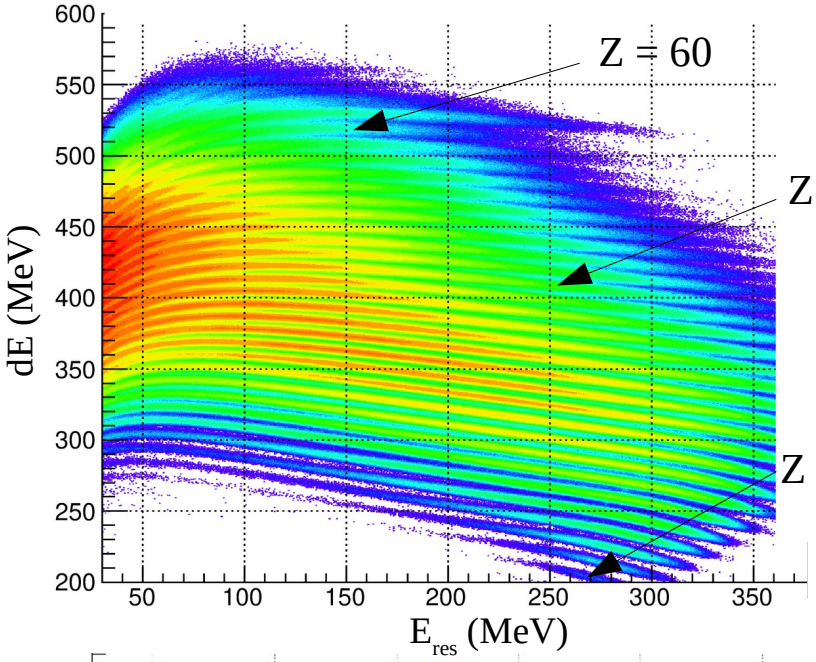
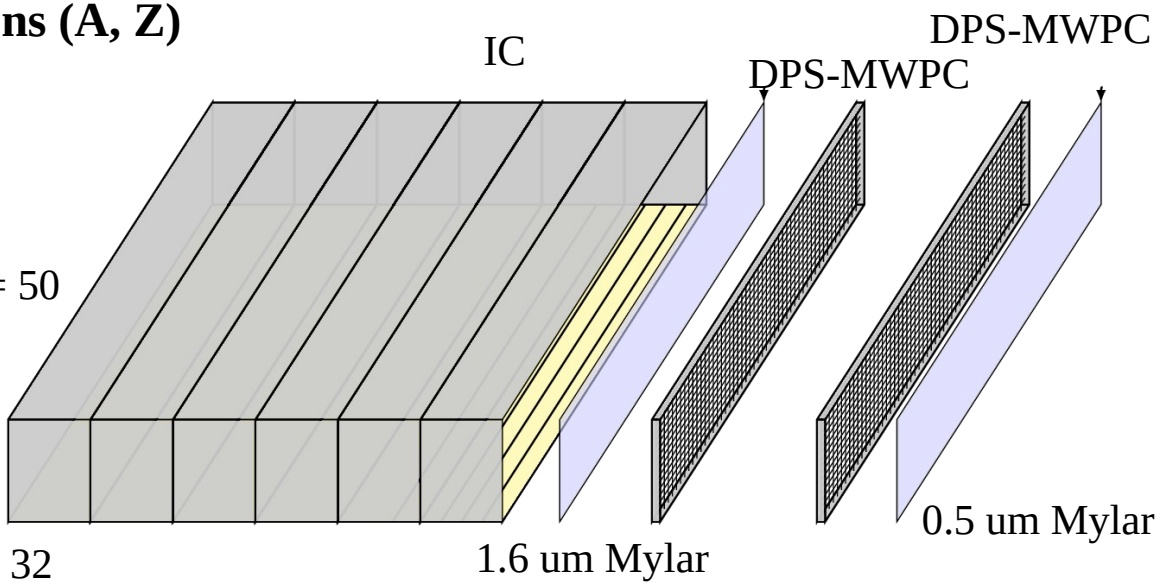
Segmented Ionization Chamber

- 30 – 60 - 120 mm pads
- 50 -150 mbar CF_4 gas
- < 2% energy resolution

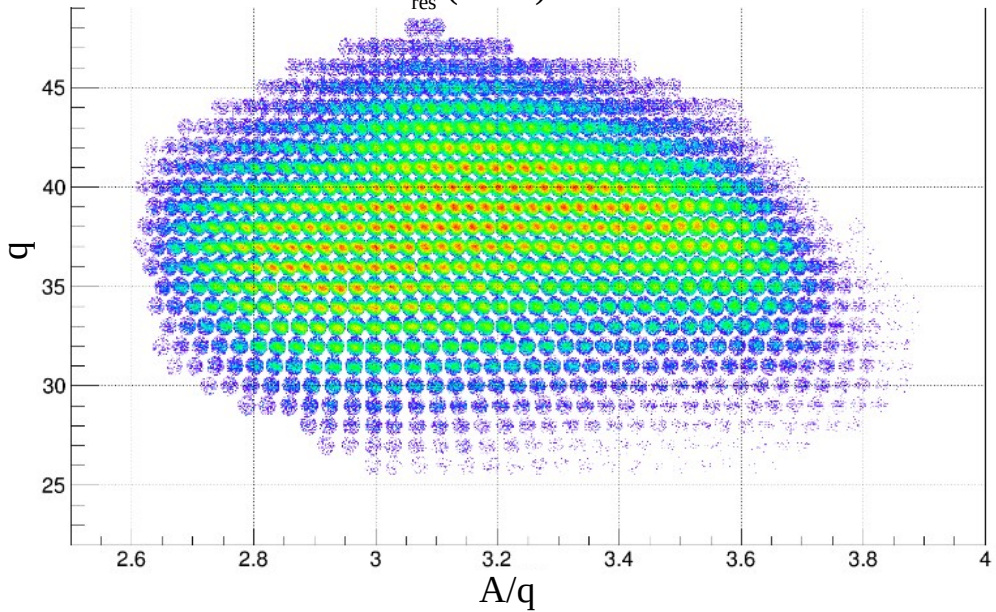
The VAMOS Detection Setup

Goal: **Isotopic Identificion of Heavy Ions (A, Z)**





Dual Position-Sensitive MultiWire Parallel Counter



- Active Area: 1000x150 mm²
- 1150 wires with individual readout
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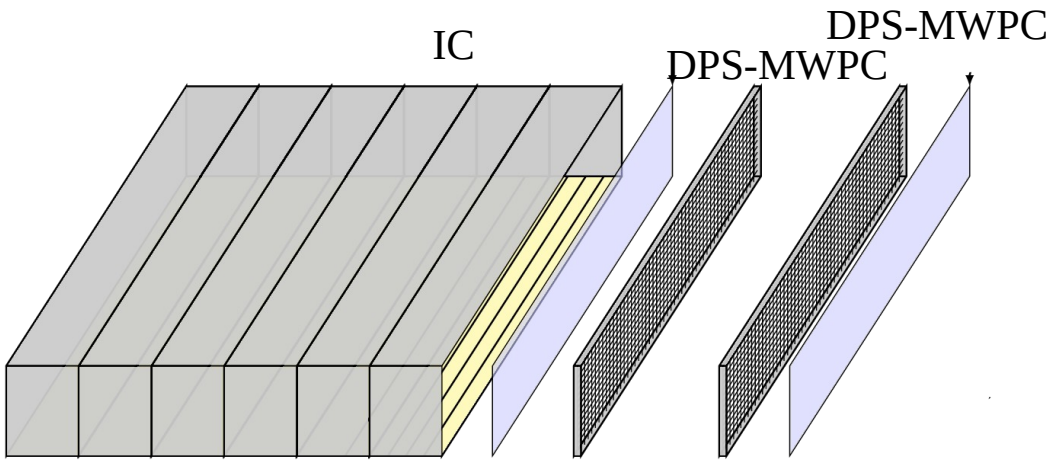
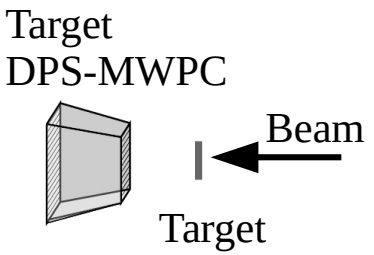
The VAMOS Detection Setup





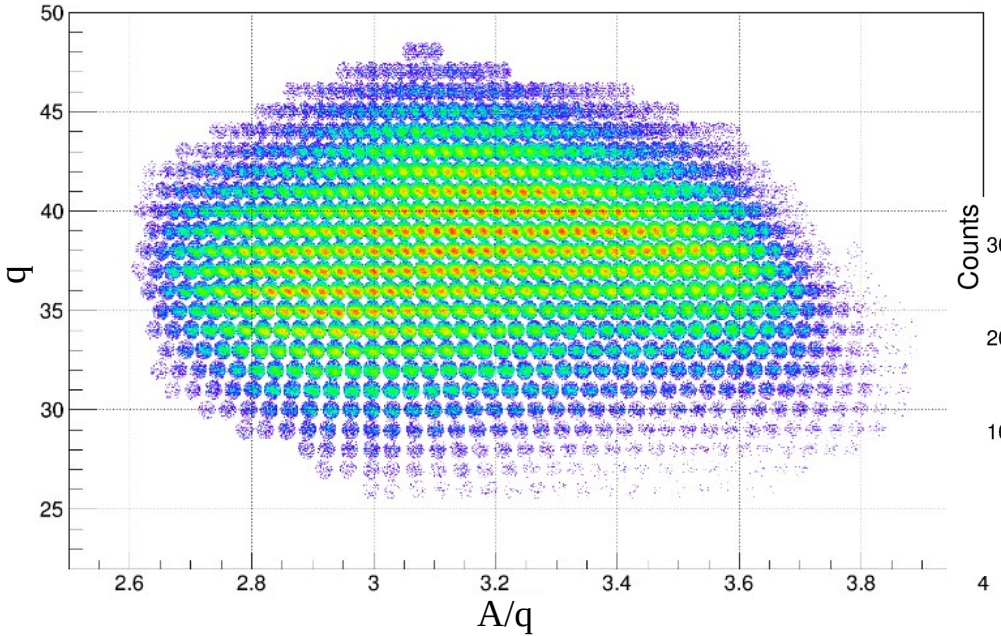
DPS-MWPC @ Target

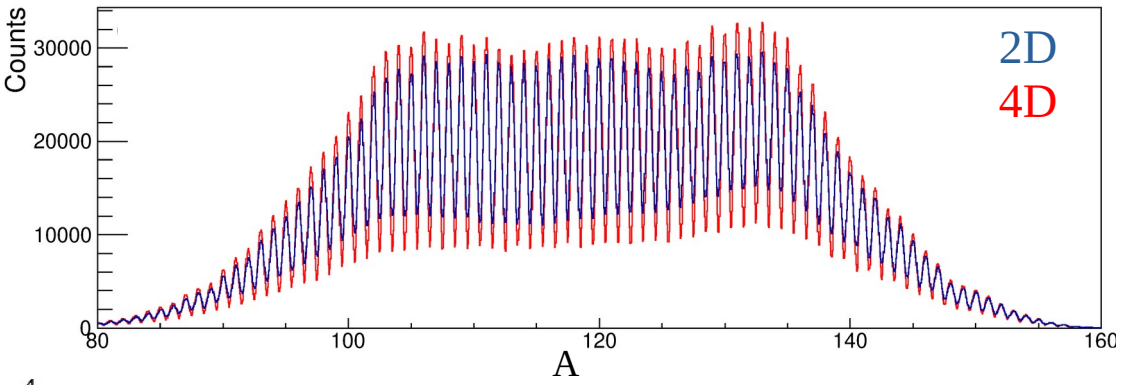
- Velocity vector determination
- Angular constrains for the Bρ reconstruction

M. Vandebrouck et al.,NIM A 812, 112 (2016)

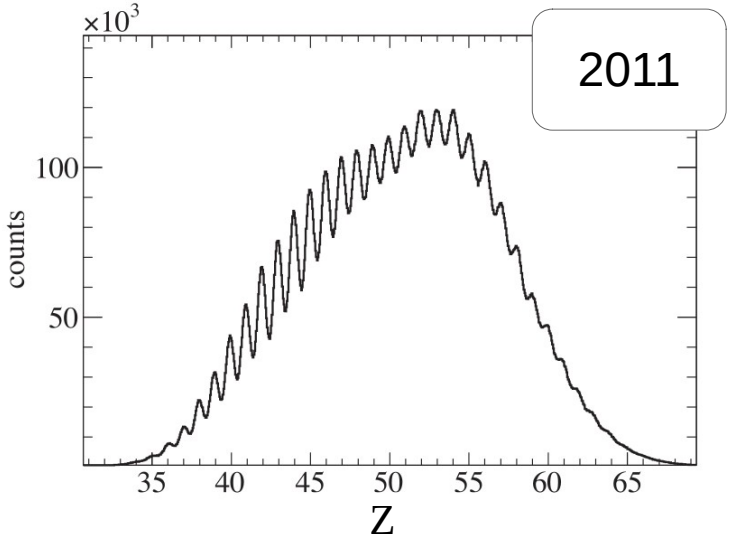
RESOLUTIONS:

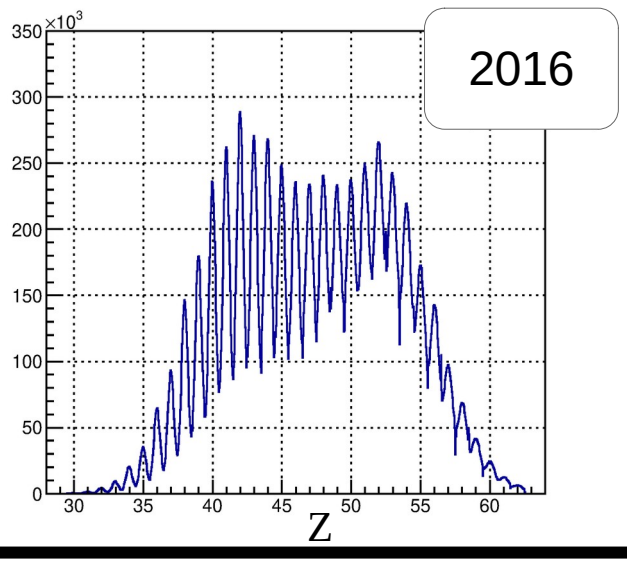
- σA/A ~ $3x10^{-3}$ (FWHM)
- σZ/Z ~ 1.3 % (FWHM)

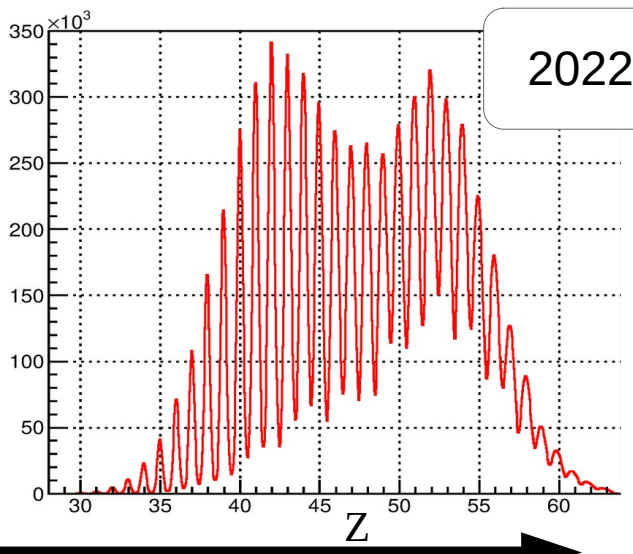




Evolution of the VAMOS Detection Setup



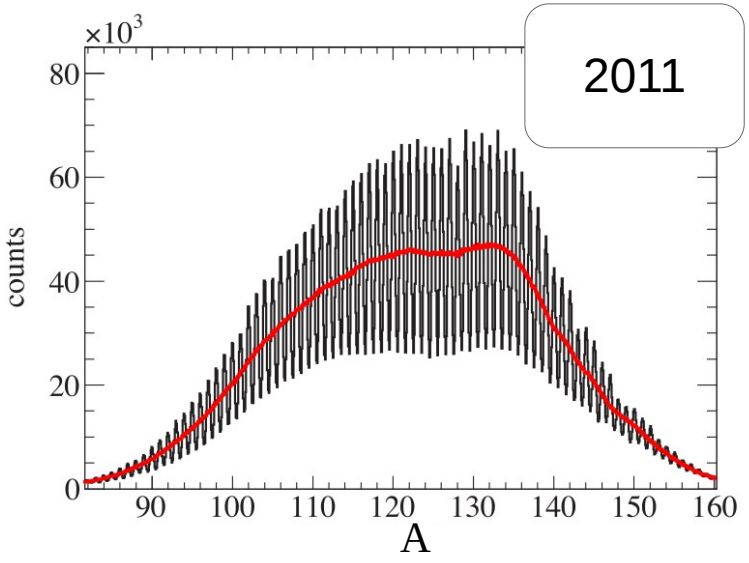


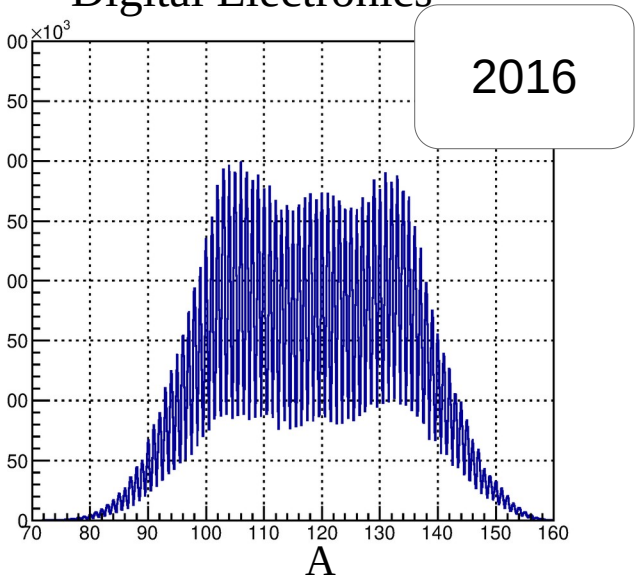


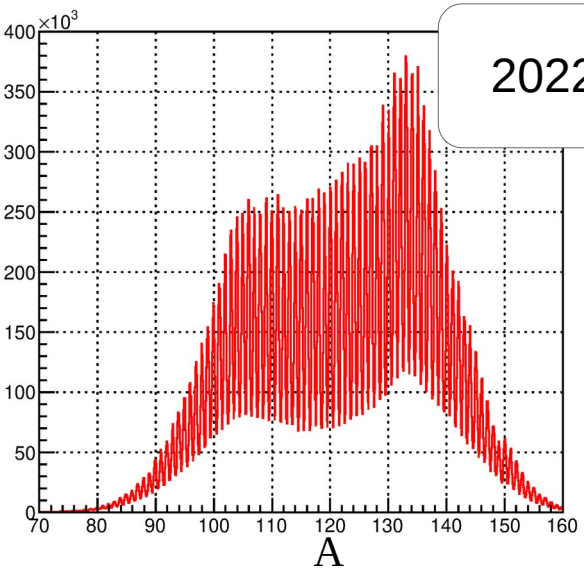
No Target PS-MWPC
DC + IC + Si (focal plane)

Target PS-MWPC
High Segmentation IC
Digital Electronics

Focal Plane PS-MWPC
Higher Segmentation IC



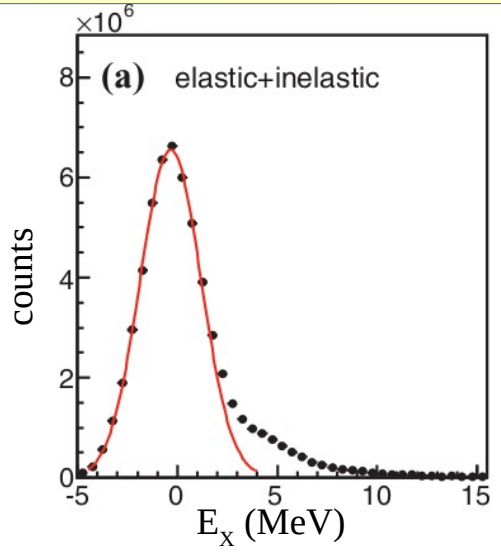


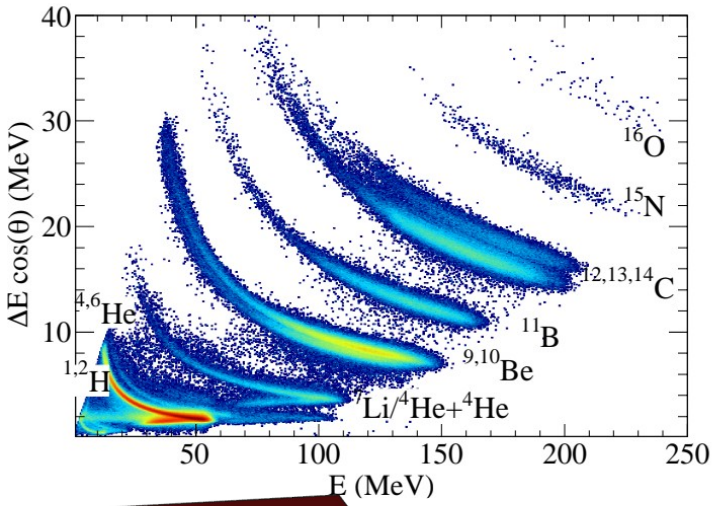


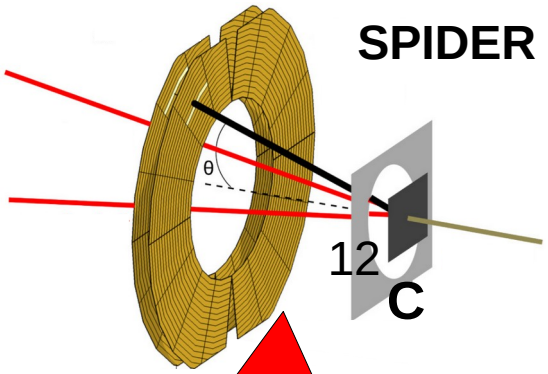
Fission at VAMOS: n-rich actinides region

- **^{238}U beam at ~6 MeV/u** (Coulomb energies)
- **C/Be targets**
- **Inverse-Kinematics Transfer/Fussion induced Fission**

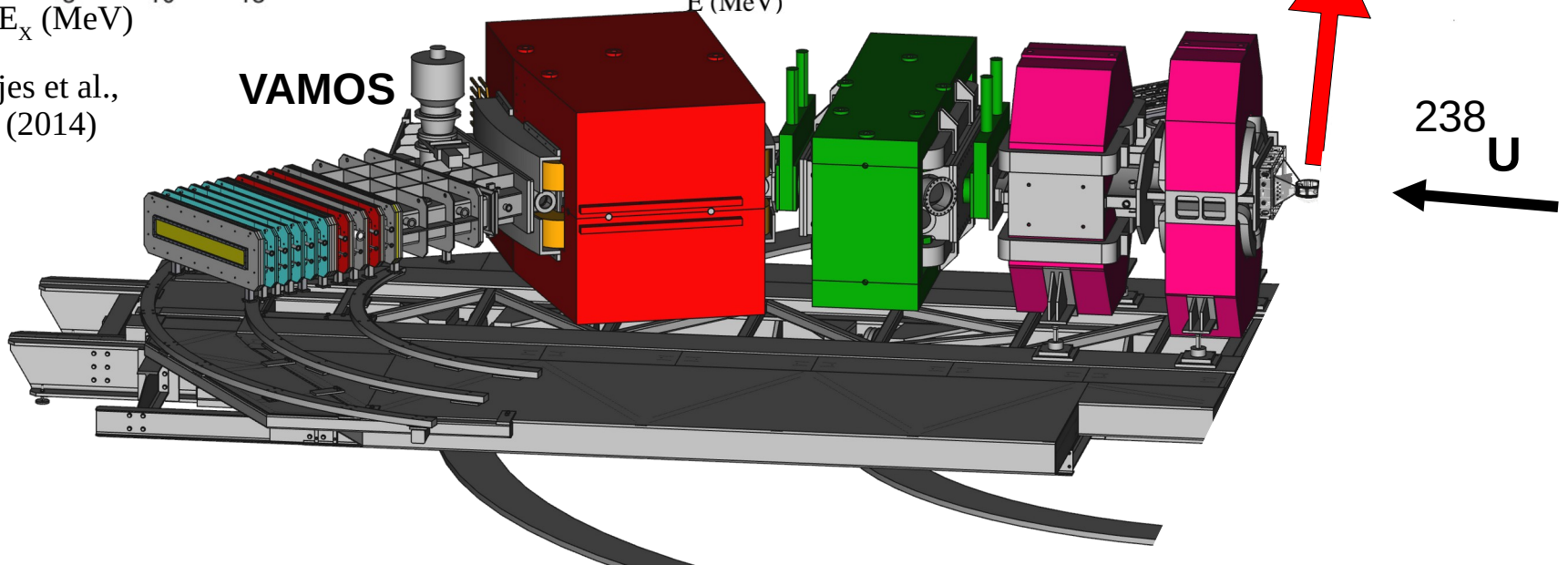
- **SPIDER** :
  Selection of the **incoming channel (A,Z,E_x)**
  - Access to **actinides above Uranium**
  - Control of the fissioning system **excitation energy**



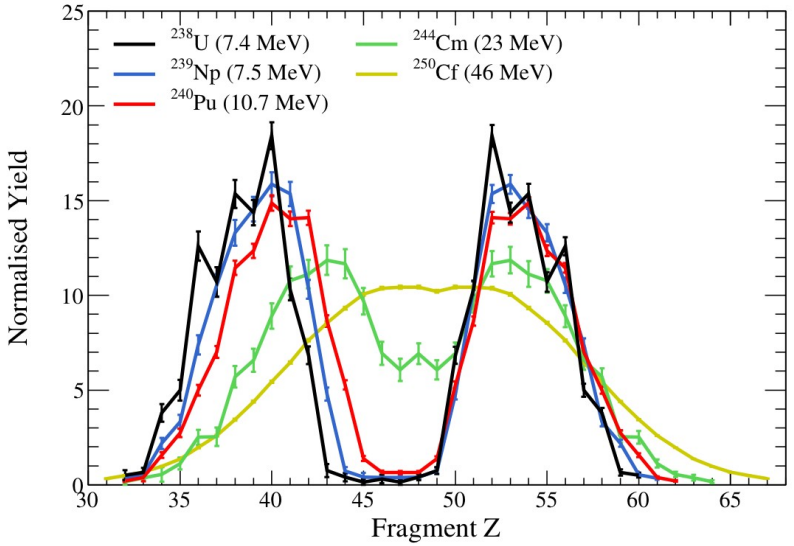




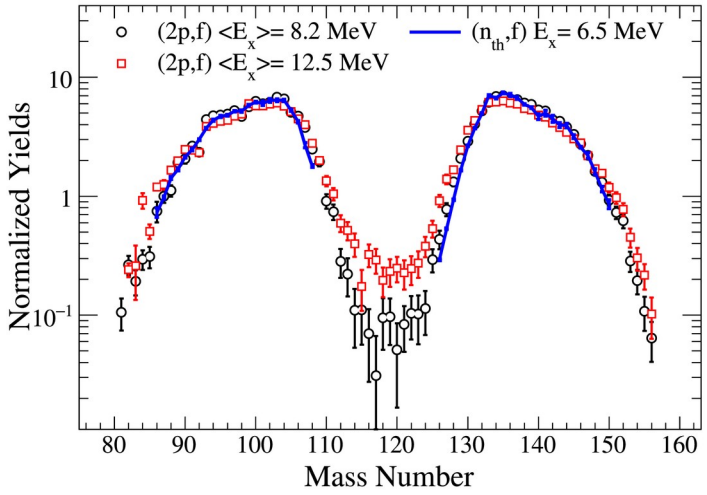
C. Rodríguez-Tajes et al.,
PRC 89, 024614 (2014)



Fission at VAMOS: n-rich actinides region

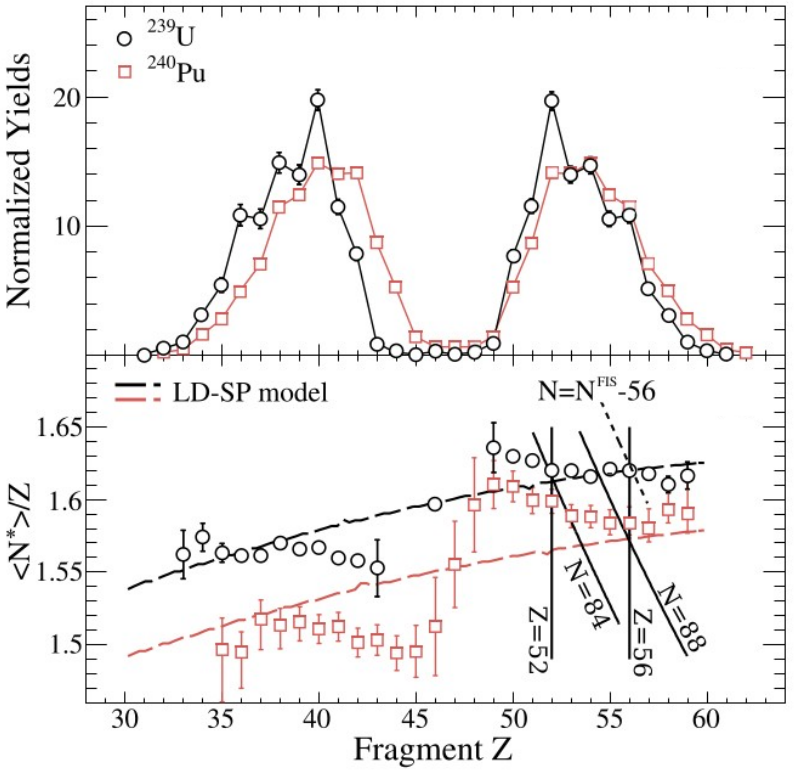


- **COMPLETE Isotopic distribution of fragments from exotic systems at different E_x**



^{240}Pu

- **First direct measurement of ^{239}U isotopic fission yields.**



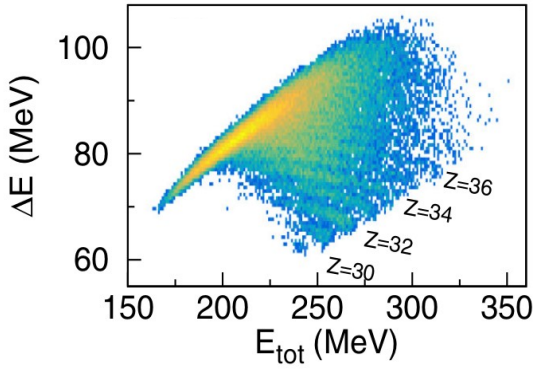
- **Neutron excess**: The role of **proton- and neutron- octupole deformed shells** [G. Scamps Nature 564, 382 (2018)] are reflected

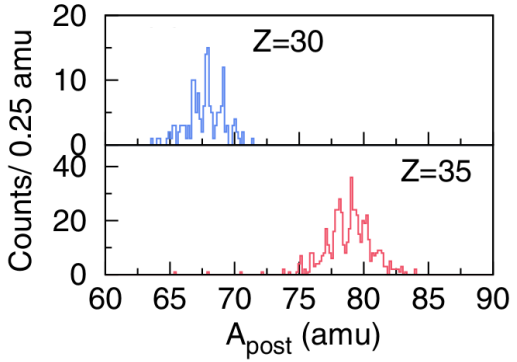
M. Caamano et al. Phys. Rev. C. 92, 024605 (2015)
D. Ramos et al. Phys. Rev. C. 97, 054612 (2018)

D. Ramos et al. Phys. Rev. Lett. 123, 092503 (2019)
D. Ramos et al. Phys. Rev. C. 101, 034609 (2020)

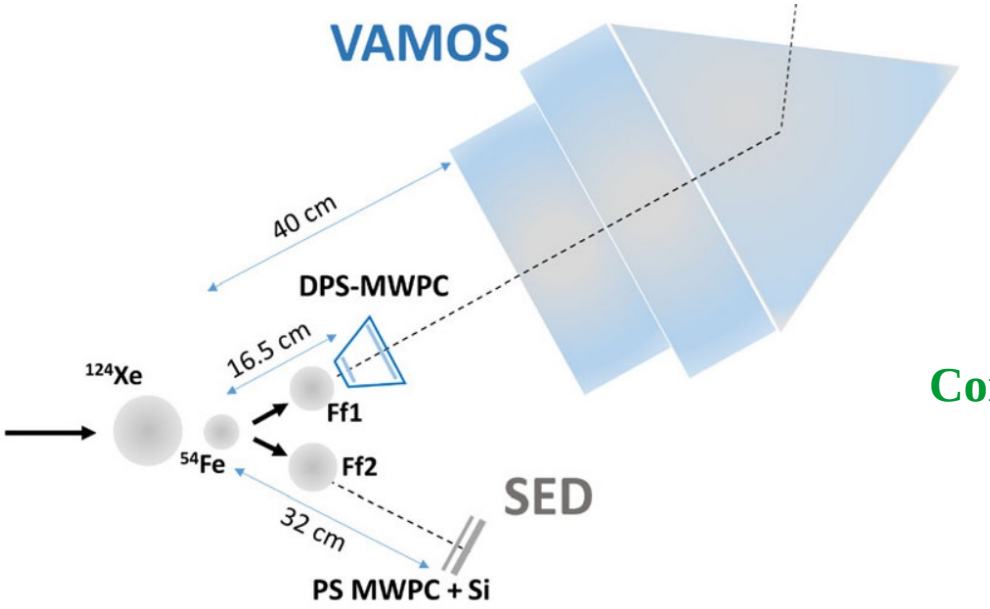
Fission at VAMOS: ^{180}Hg region

- ^{124}Xe (4.3 MeV/u) + ^{54}Fe → ^{178}Hg (E_x=34 MeV)
- 2 arms at 64° (folding angle)
- Complete-Kinematics Measurement



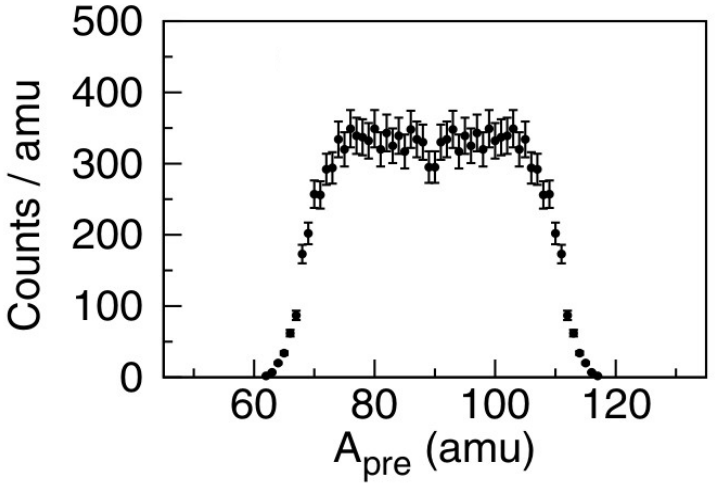


First isotopic FF measurement in pre-actinides



- **2-ARM** :
  - **Complementary fission-fragment velocity vector** measurement
  - **Momentum conservation**: **Pre-neutron** evaporation fission-fragment **masses**

$$\frac{M_1}{M_2} = \frac{\gamma_2 v_2}{\gamma_1 v_1}$$



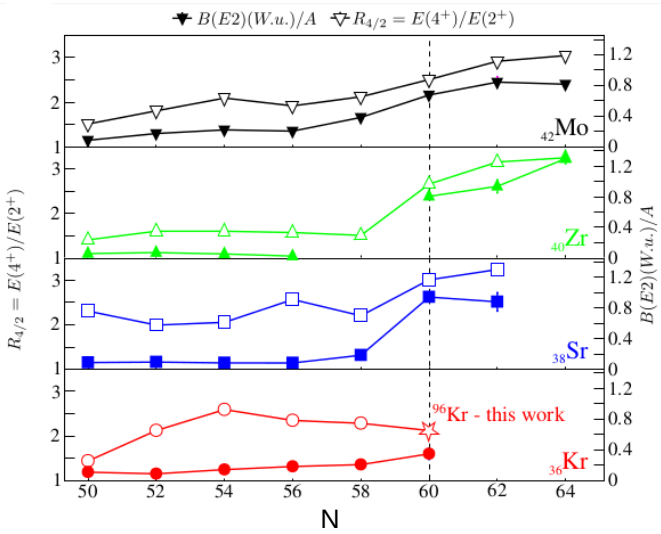
Confirmed presence of asymetric fission in ^{178}Hg

C. Schmitt et al. PRL 126, 132502 (2021)

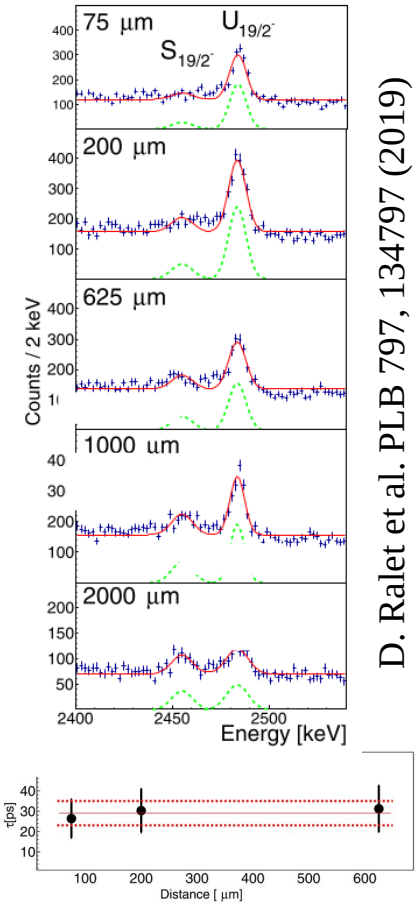
Nuclear-Structure Collectivity Studies

VAMOS + AGATA (High resolution γ-tracking Ge-detector)

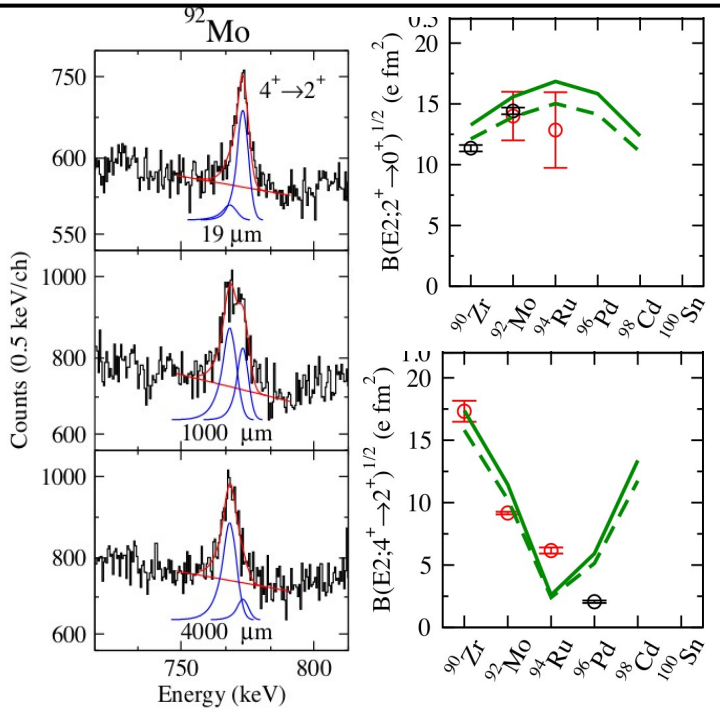
J. Dudouet et al. PRL 118, 162501 (2017)



D. Ralet et al. PLB 797, 134797 (2019)



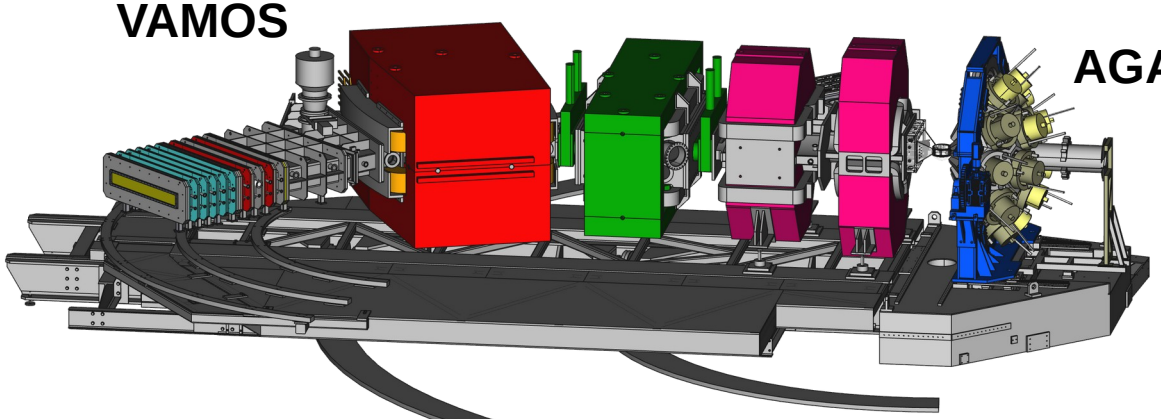
R. M. Pérez-Vidal et al. PRL 129, 112501 (2022)



- Fusion/Transfer-fission reactions ^{238}U + ^{9}Be
  - B(E2) of **^{96}Kr**
  - **Not defined collectivity**

- Multinucleon transfer ^{208}Pb + ^{100}Mo
  - Lifetime of $19/2^-$ in **^{207}Pb**
  - Low B(E3,19/2 → 13/2)
  - **Presence of octupole phonons**

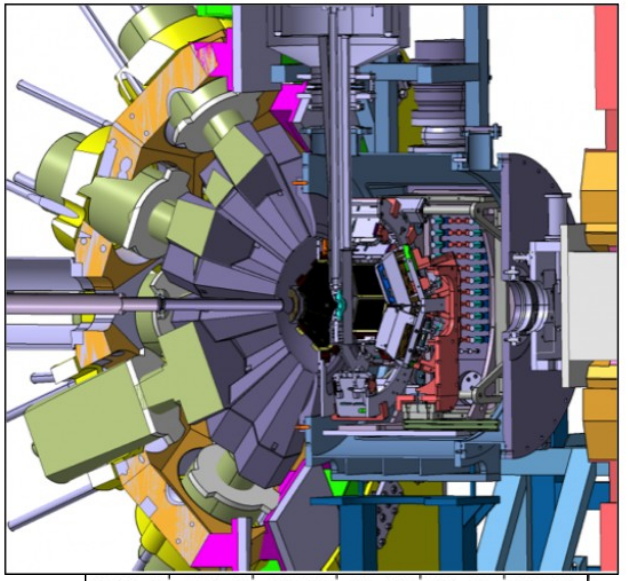
- Multinucleon transfer ^{92}Mo + ^{92}Mo
  - Lifetime and B(E2) of **^{90}Zr, ^{92}Mo, ^{94}Ru**
  - **Seniority conservation in N=50 g9/2**



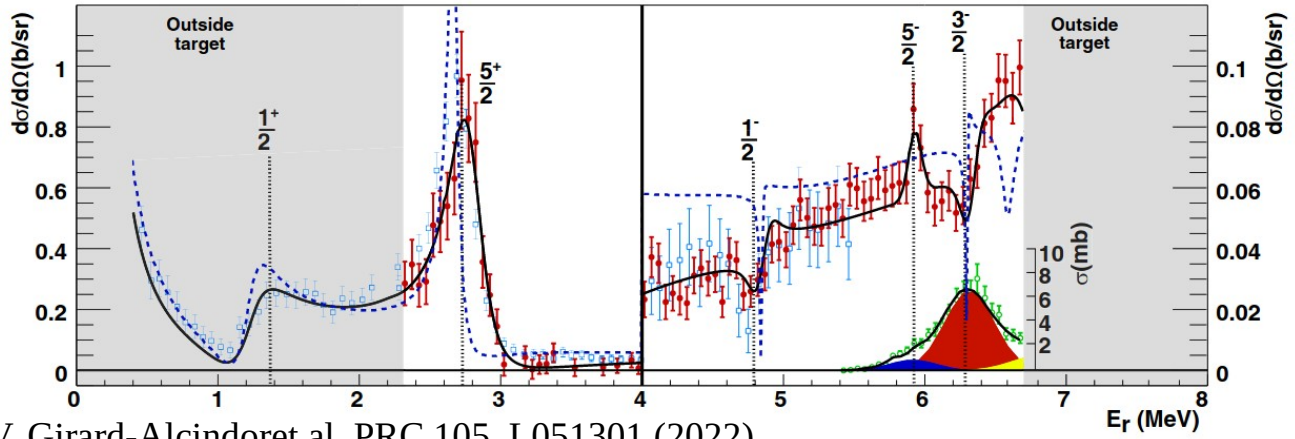
Direct Reactions with Radioactive Beams

VAMOS + AGATA + MUGAST (Highly-segmented silicon array)

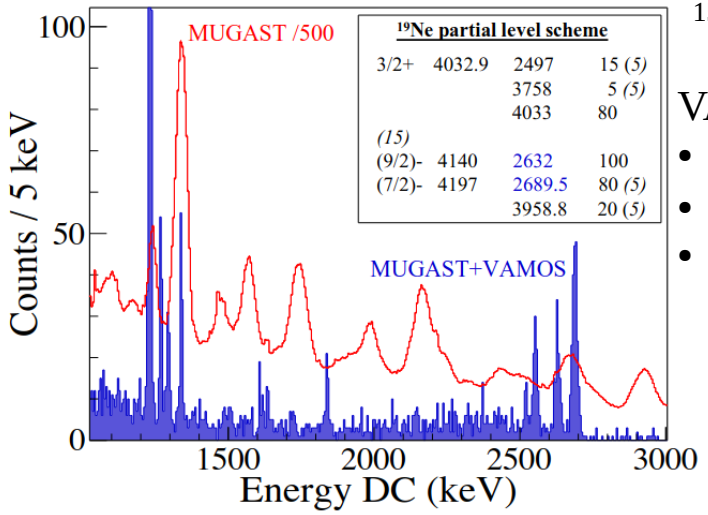
- Nucleon-transfer/scattering reactions in inverse kinematics
- Spiral1 radioactive beams



$^{14}O + {}^{1}H \rightarrow {}^{15}F \rightarrow {}^{14}O + p \,/\, {}^{13}N + 2p$



V. Girard-Alcindoret al. PRC 105, L051301 (2022)



^{19}Ne partial level scheme

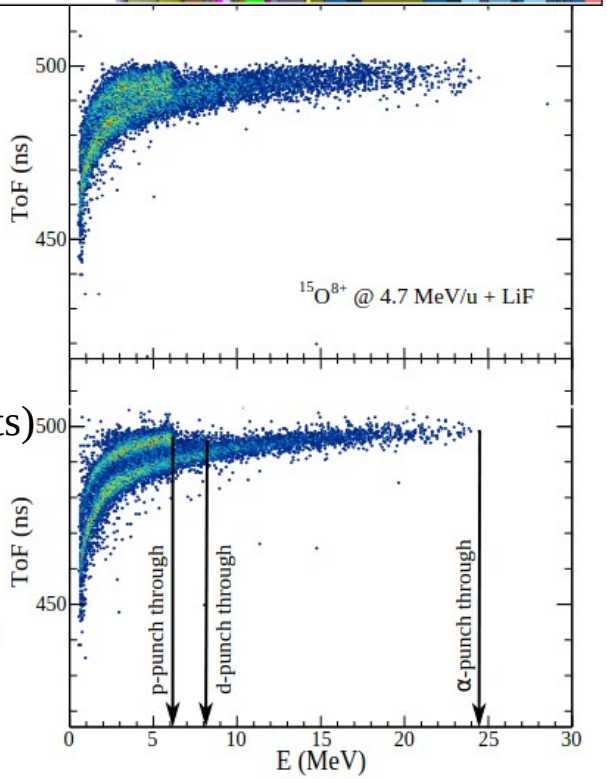
3/2+	4032.9	2497	15 (5)
		3758	5 (5)
		4033	80
(15)			
(9/2)-	4140	2632	100
(7/2)-	4197	2689.5	80 (5)
		3958.8	20 (5)

$^{15}O + {}^{7}Li \rightarrow {}^{19}Ne + t$

VAMOS:

- Background removal (CH_2/CD_2 targets)
- Residuals selection
- Improvement of light charge particles identification (ToF)

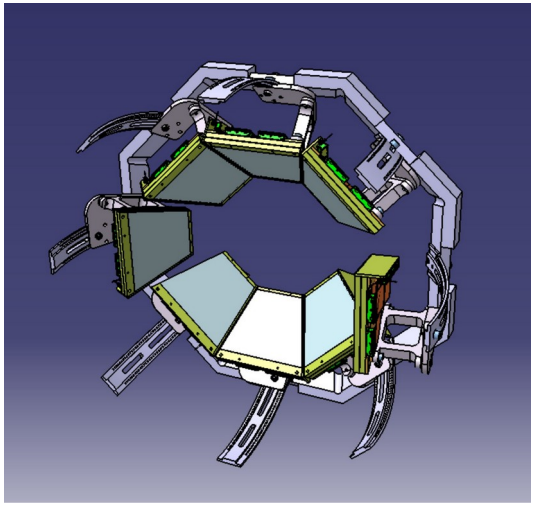
$$\beta = \left(\left(\frac{3.107}{B\rho[Tm]} \frac{\lfloor A \rfloor}{\lfloor q \rfloor} \right)^2 + 1 \right)^{-1/2}$$

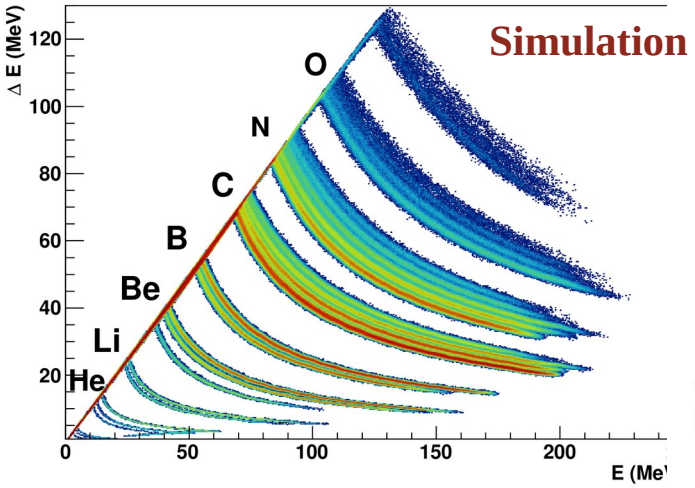


M. Assie et al., NIM A 1014 (2021) 165743

Perspectives : a rich Fission program at VAMOS

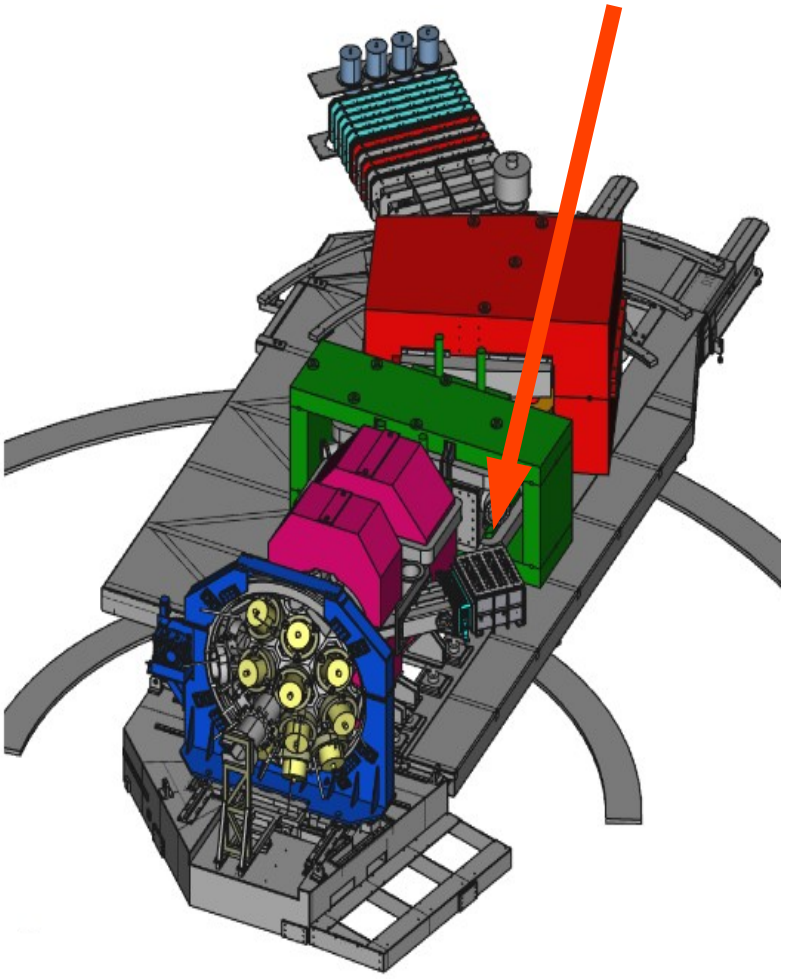
- **Improving the Incoming Channel: From SPIDER to PISTA**





- High particle-identification capabilities
- Higher energy resolution (2.5 MeV → **0.7 MeV**)
- Larger angular coverage

- **High ToF resolution Second Arm**



- Isotopic fission fragments identificaton at the Scission Point
- Isotopic neutron evaporation measurements

Comming soon:

- *Precise* ***^{235}U*** *and* ***^{240}Pu*** *FF as function of* E_X
  ^{238}U @ 6 MeV/u + ^{12}C → ^{235}U / ^{240}Pu
- *Fission around the* ***Th region***
  ^{232}Th @ 6 MeV/u + ^{12}C → $^{230\text{-}232}$Th / ^{233}Pa / ^{234}U
- ***Neutron-deficient*** *pre-actinides fission*
  ^{124}Xe @ 4 MeV/u) + ^{68}Zn → ^{192}Po (28MeV)

Conclusions

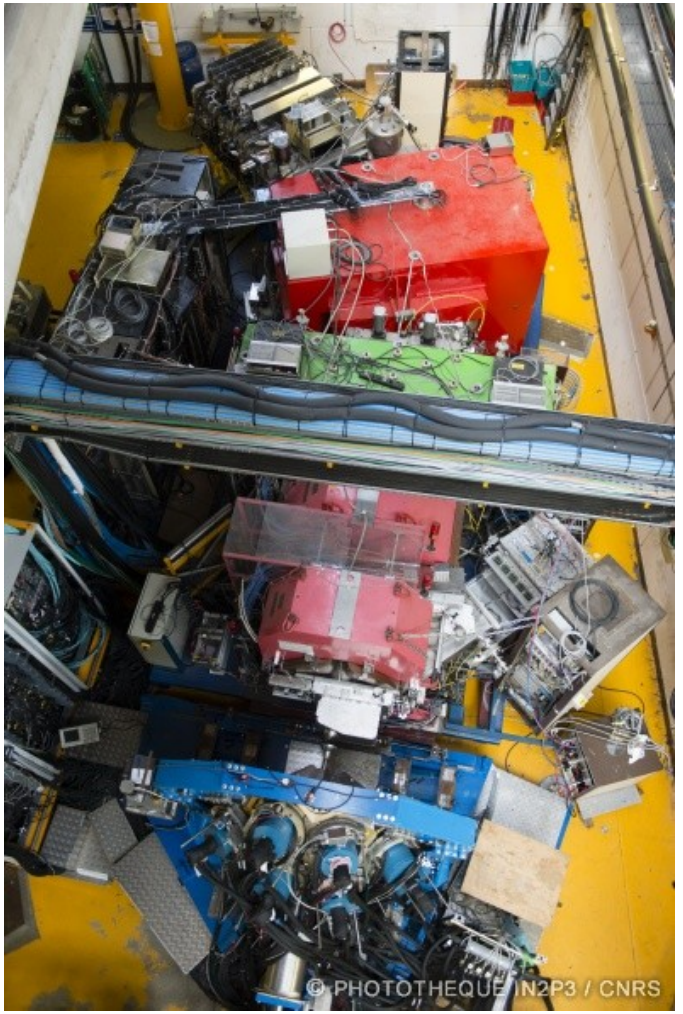
VAMOS is a powerful instrument for heavy ions identification

- Large phase-space acceptance
- High identification resolution

Optimun for Coulomb energies

Very **different physical cases** can be addressed

It is under **continuous improvements**



Posters:

- **PS-8-27 → Second Arm at VAMOS++ Spectrometer**
- **PS-8-29 → Particle Identification in VAMOS++ through machine learning**