# Upgrades in the Fission@VAMOS program

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Workshop NACRE, Strasbourg

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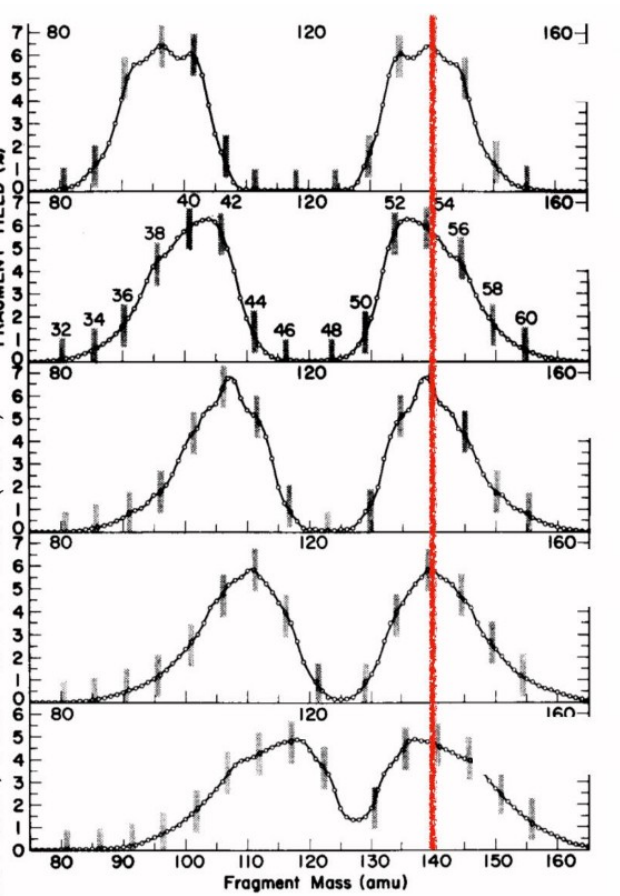
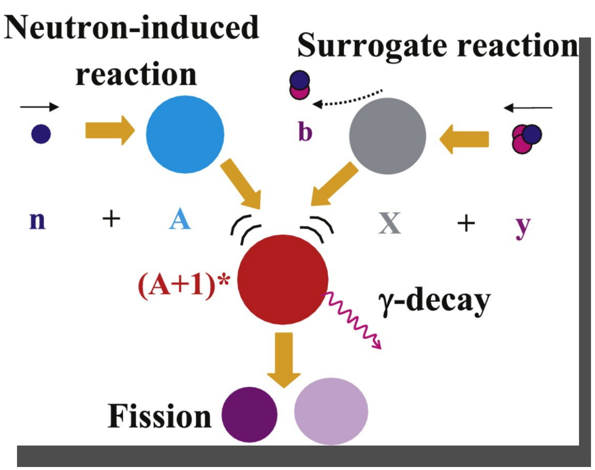
# The Surrogate-Reactions Technique

**Neutron induced fission:**
- Access to fission-fragments masses of stable/long-live actinides
- In the early 70's the stabilization of A~140 was observed

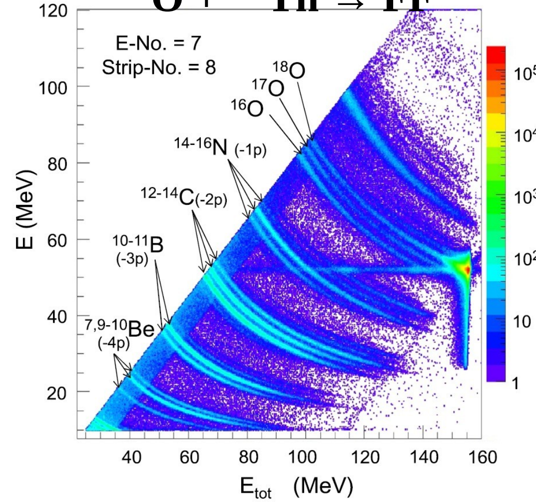
**Surrogate Reactions:**
- Access to fission-fragments masses of short-live radioactive actinides
- Multinucleon Transfer Reactions → Excitation energy

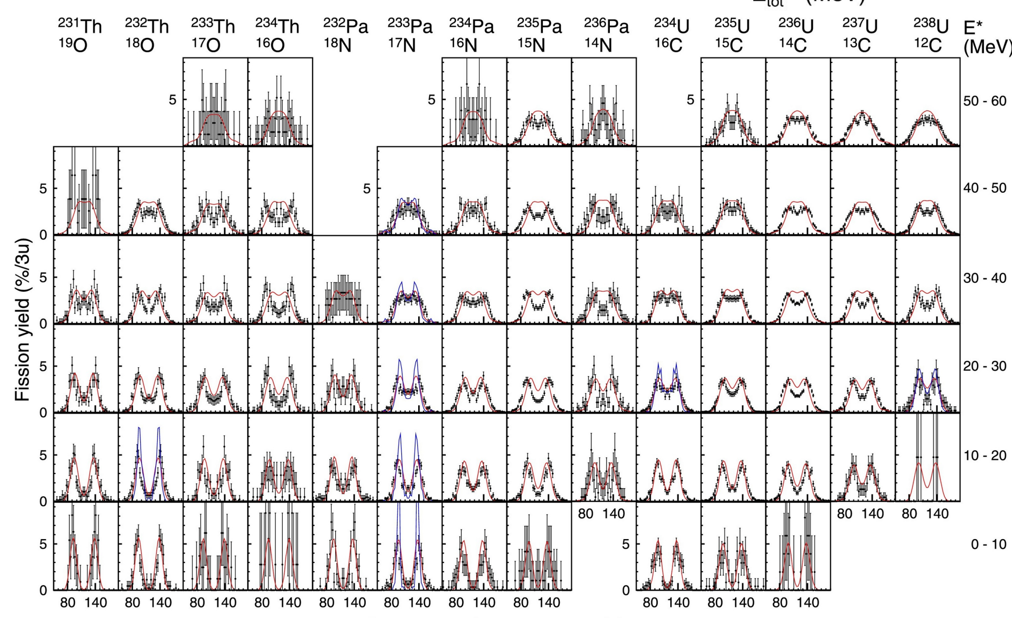



J.P. Unik, IAEA –SM-174/209 (1974)




$^{18}O + ^{232}Th \rightarrow FF$



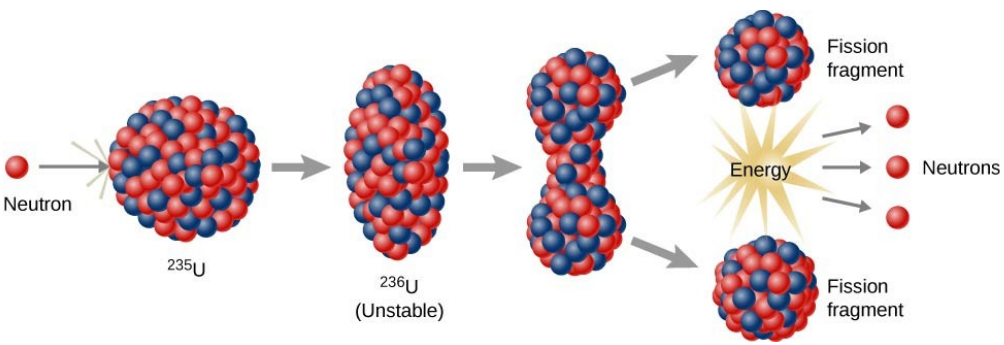

R. Léguillon et al. PLB 761, 125 (2016)

- **LIMITATION:**
  - **Restricted/Indirect access to FF nuclear charge**

# The Inverse-Kinematics Technique

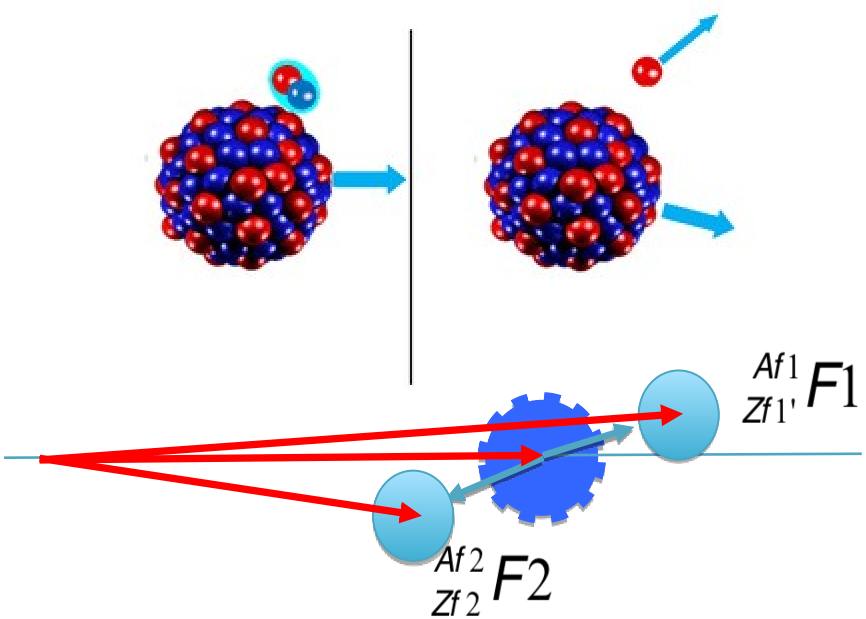
**Direct-Kinematics fission**

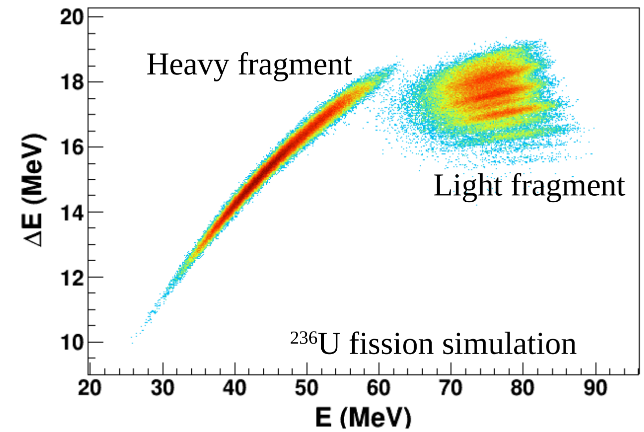
- Light beam + Actinide Target → Fission at rest



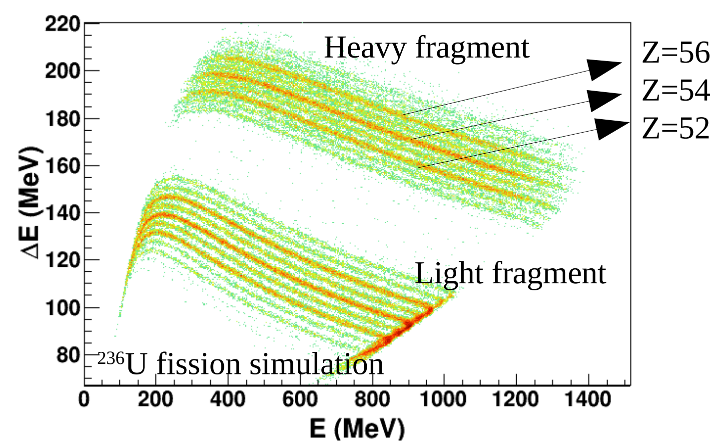

**Inverse-Kinematics fission**

- Actinide beam + Light Target → In-flight Fission
- Lorentz Boost → High Fission Fragments Energy



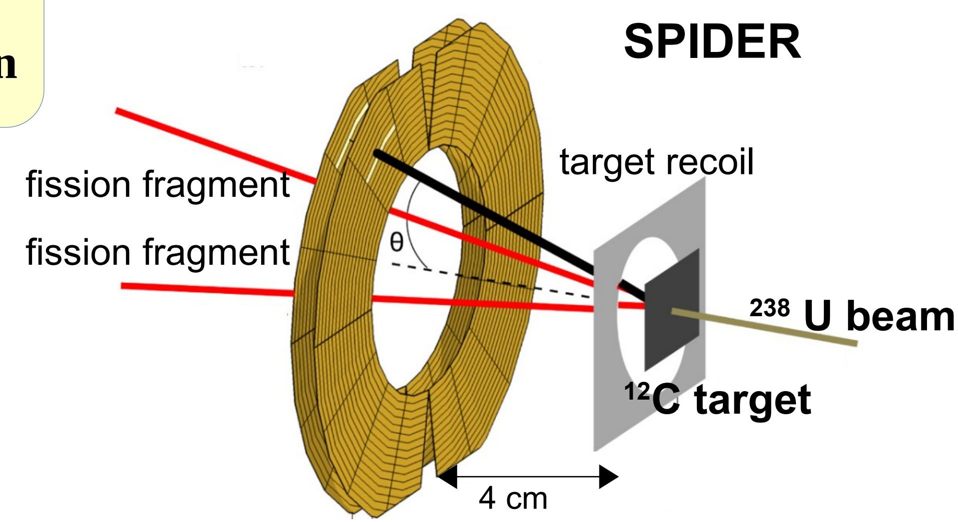

- Very low energy in light fission fragments means poor Z resolution
- Heavy fragment in the Bragg region, no Z identification



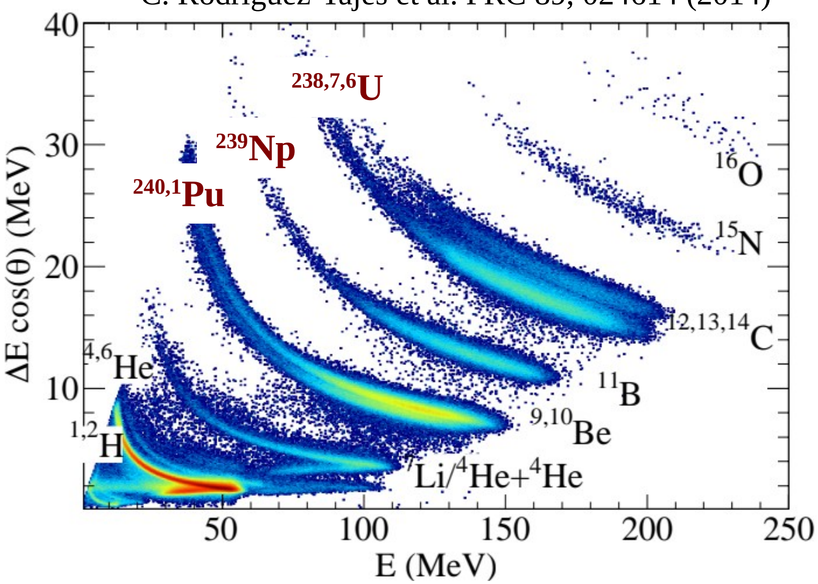

- Both light and heavy fragment out of the Bragg region,
- High resolution in Z identification using dE vs E method

# Fission of Actinides @ VAMOS/GANIL

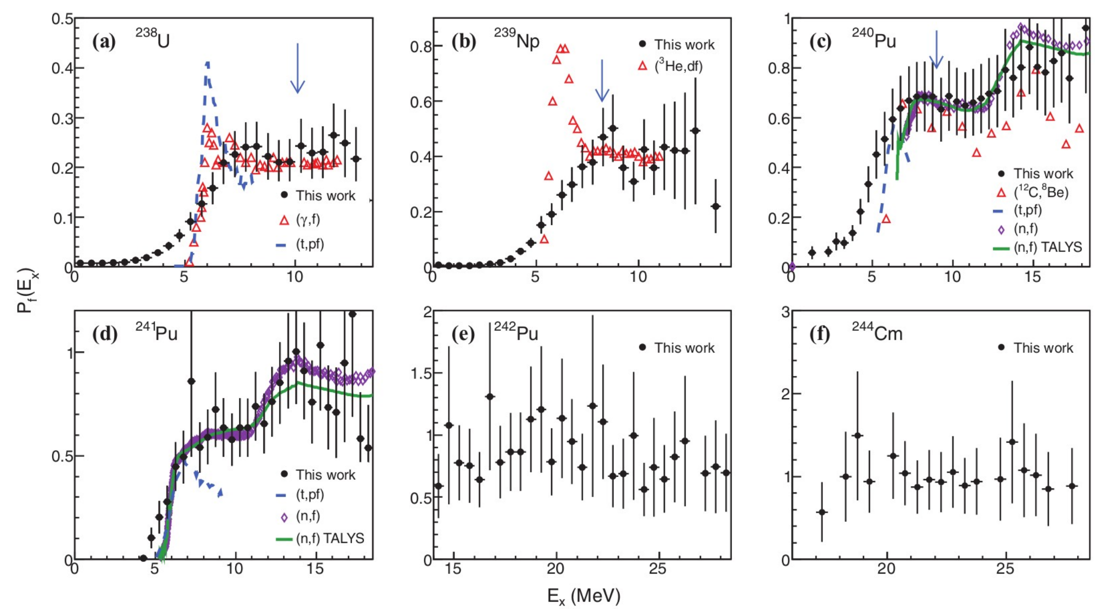
- **$^{238}$U beam at ~6 MeV/u** (Coulomb energies)
- **C/Be targets**
- **Multi-Nucleon Transfer/Fussion induced fission**



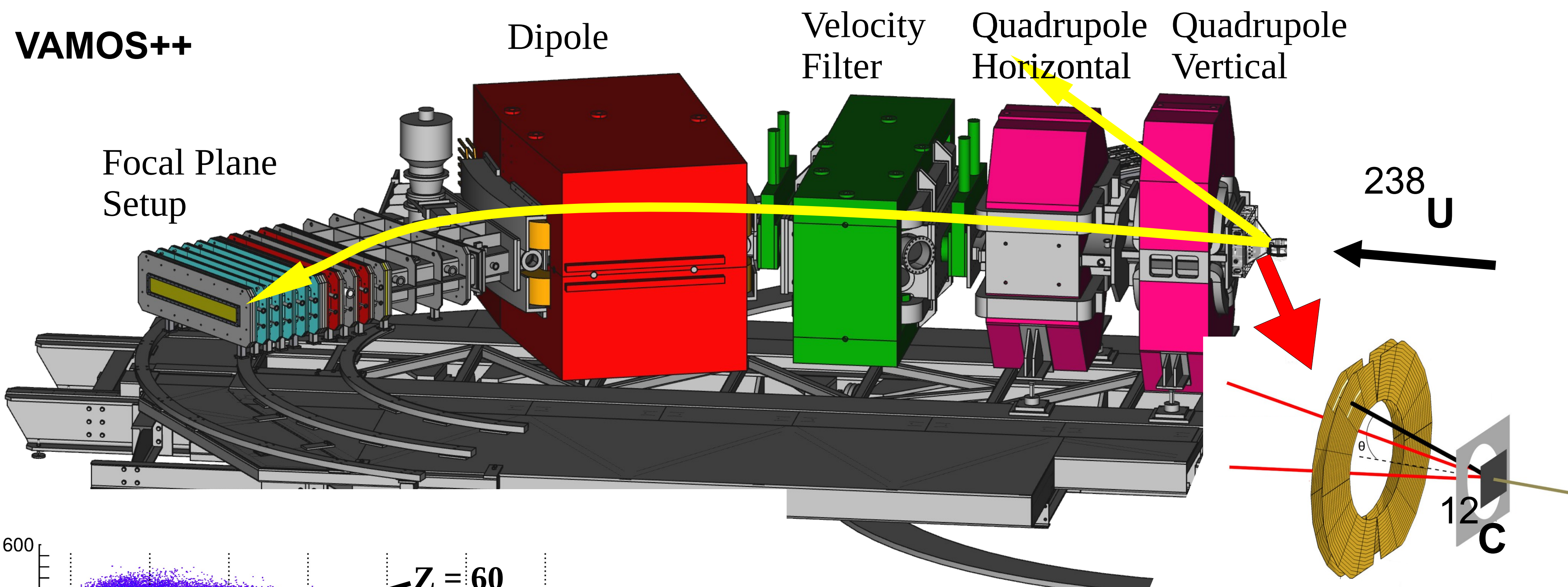

C. Rodriguez-Tajes et al. PRC 89, 024614 (2014)

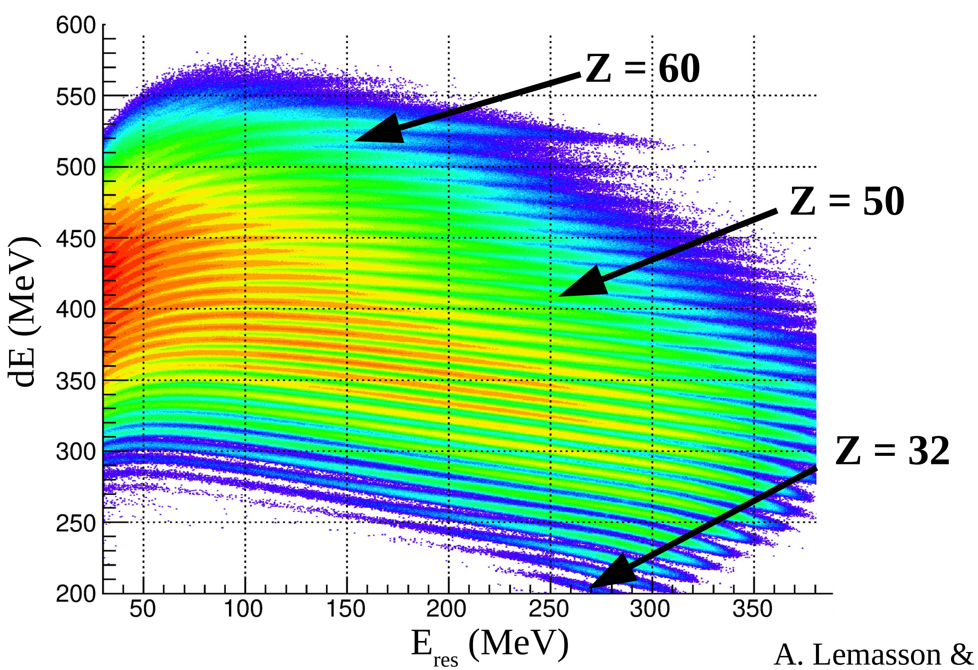


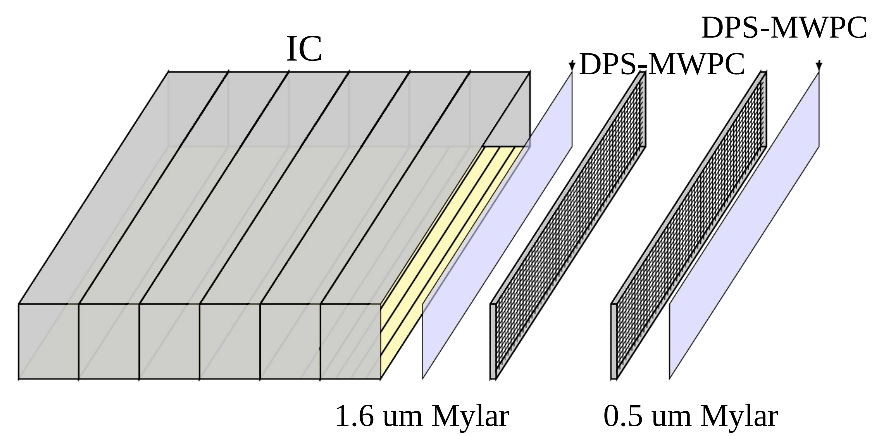

- **Identification of the fissioning system** by detection the target-like recoil
- **Measurement of the Excitation energy** by reconstruction the binary reaction
- **Measurement to fission barriers** by detection fission fragments



# Fission Fragments Identification



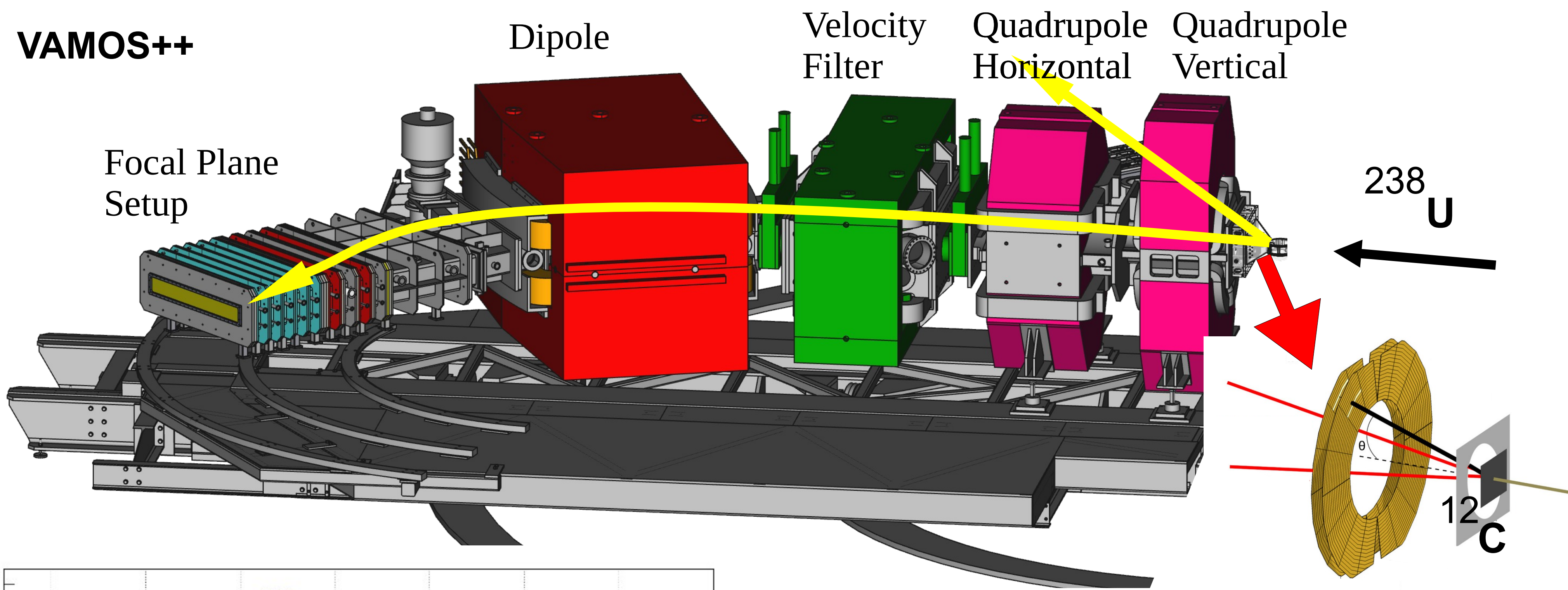



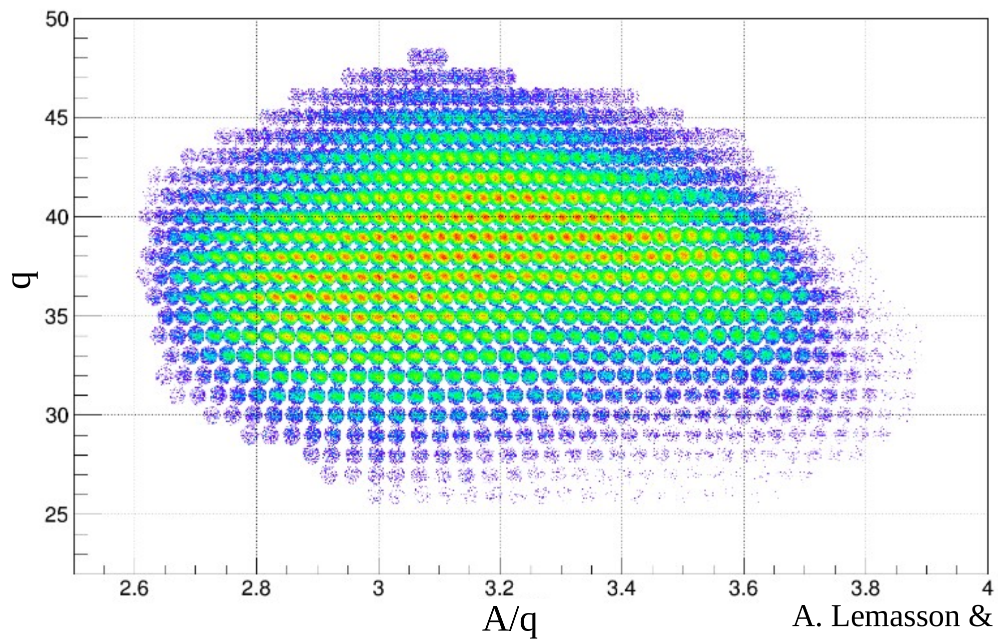



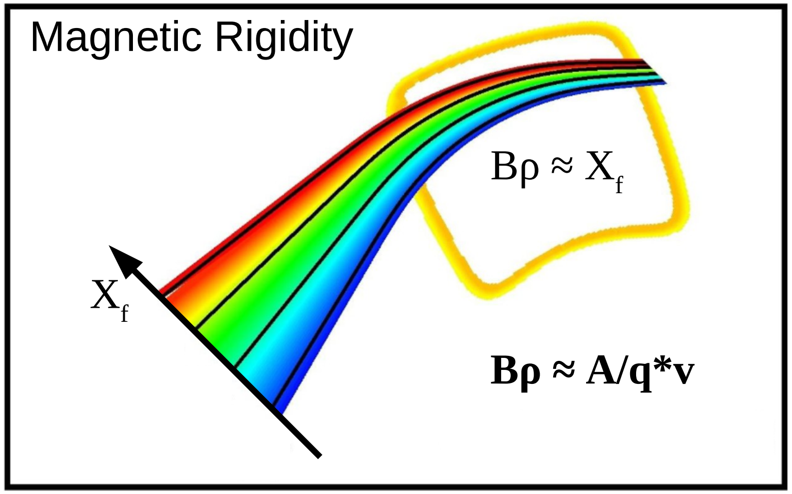

A. Lemasson & M. Rejmund, NIMA 1054, 168407 (2023)

# Fission Fragments Identification

**VAMOS++**

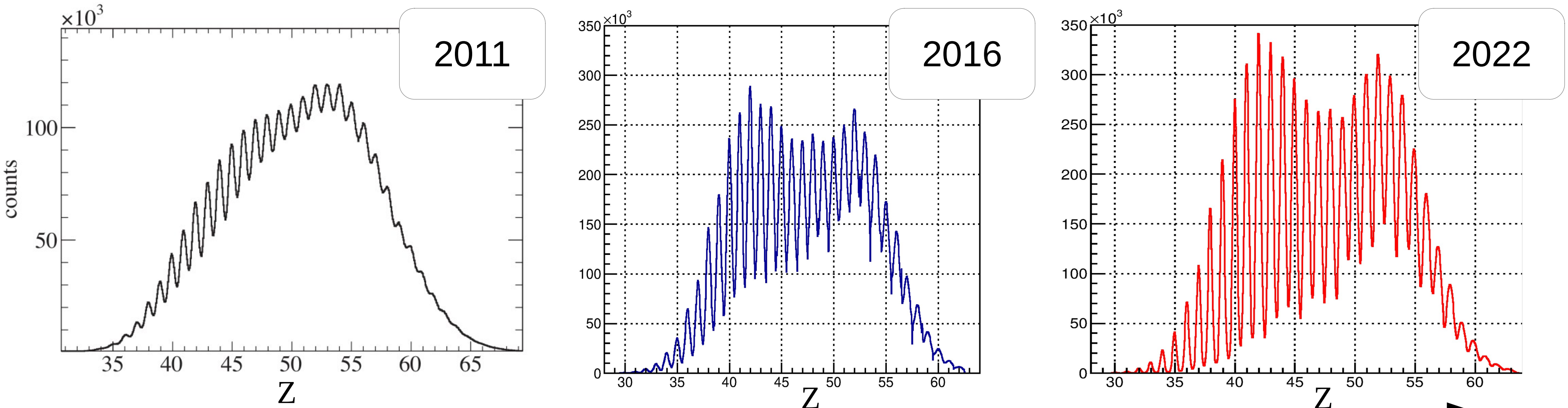



A. Lemasson & M. Rejmund, NIMA 1054, 168407 (2023)

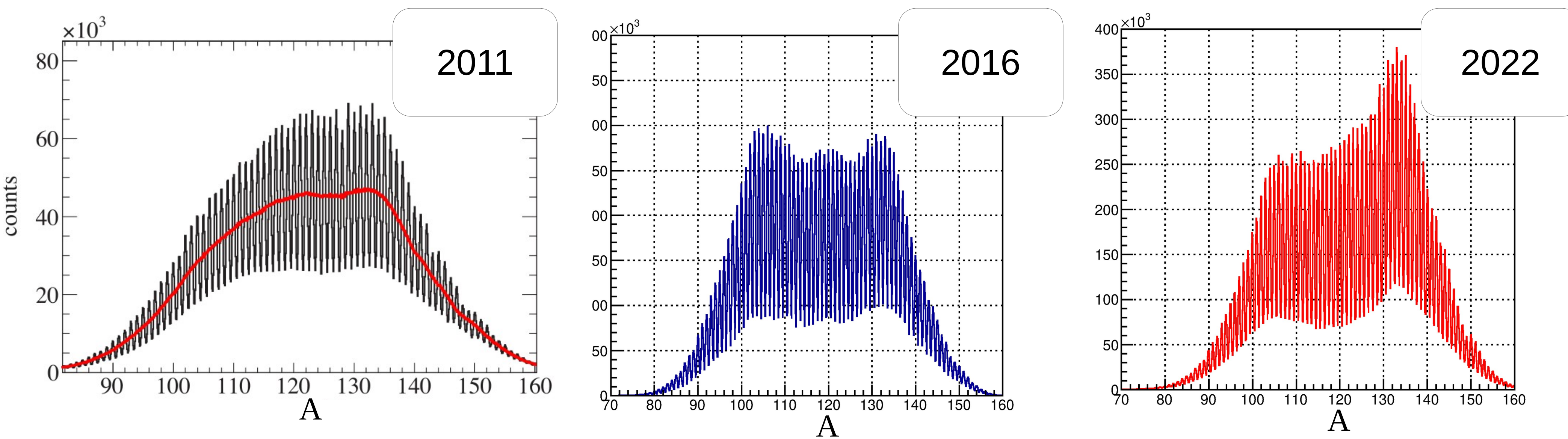
# Evolution of the VAMOS Detection Setup




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

Target PS-MWPC
High Segmentation IC
Digital Electronics

Focal Plane PS-MWPC
Higher Segmentation IC



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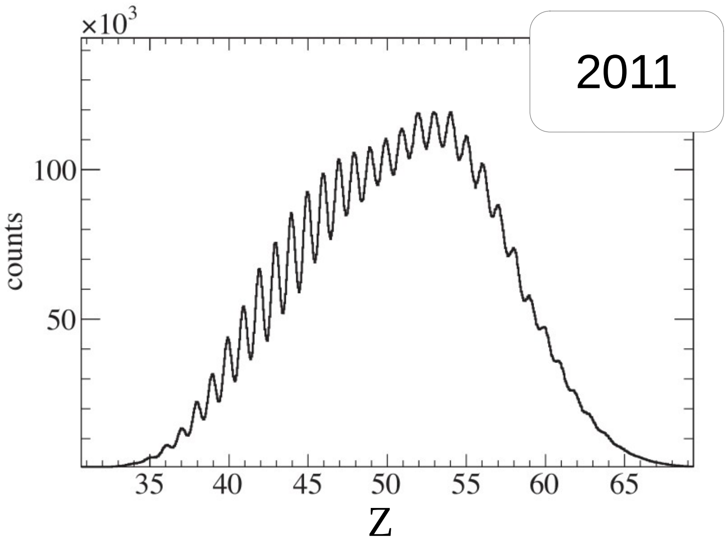
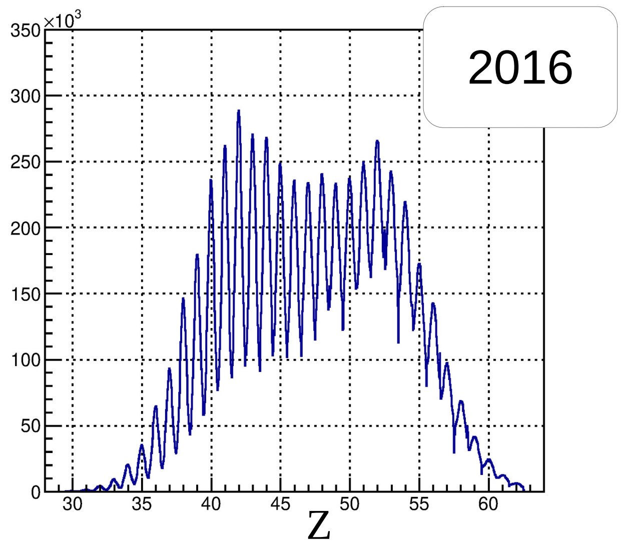
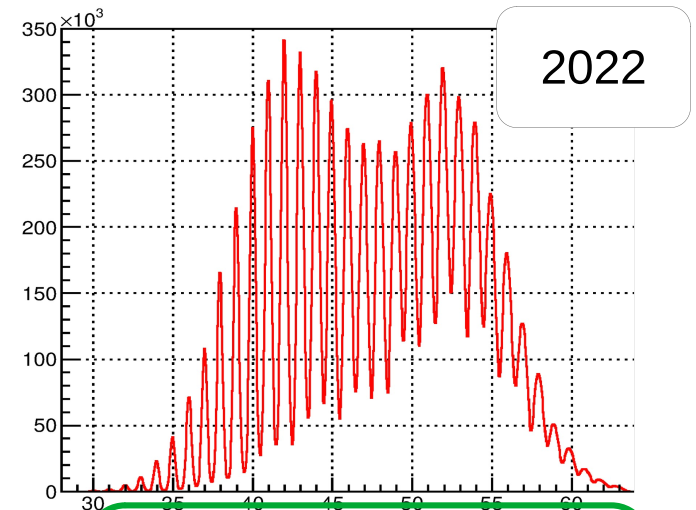


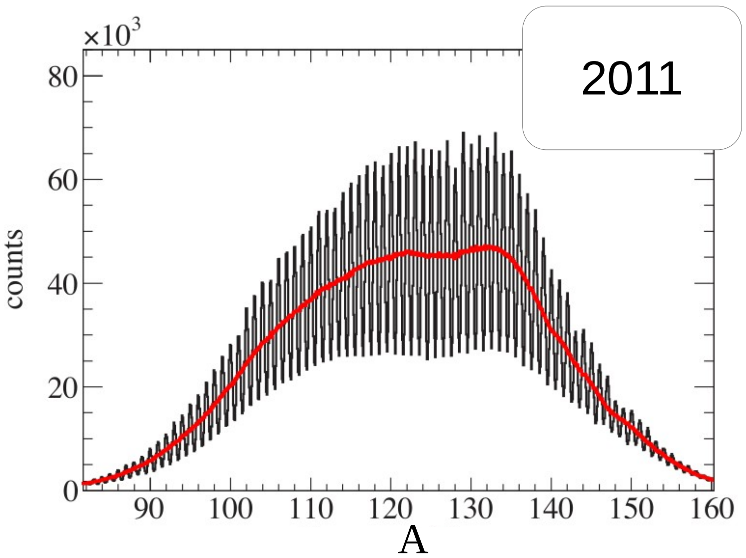



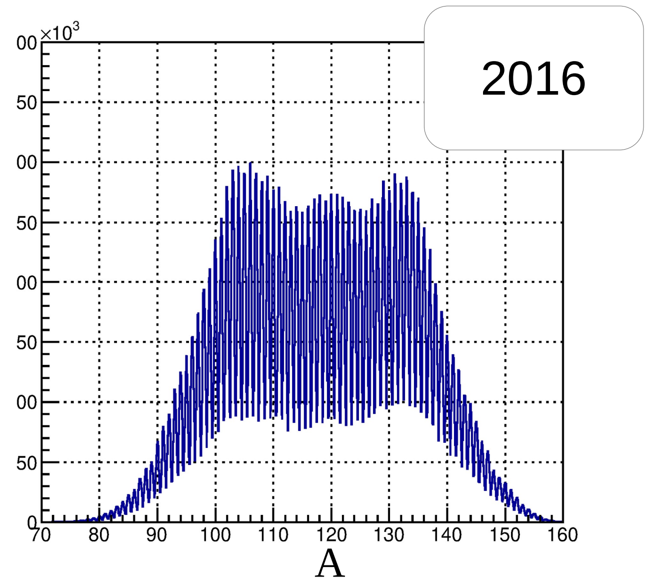



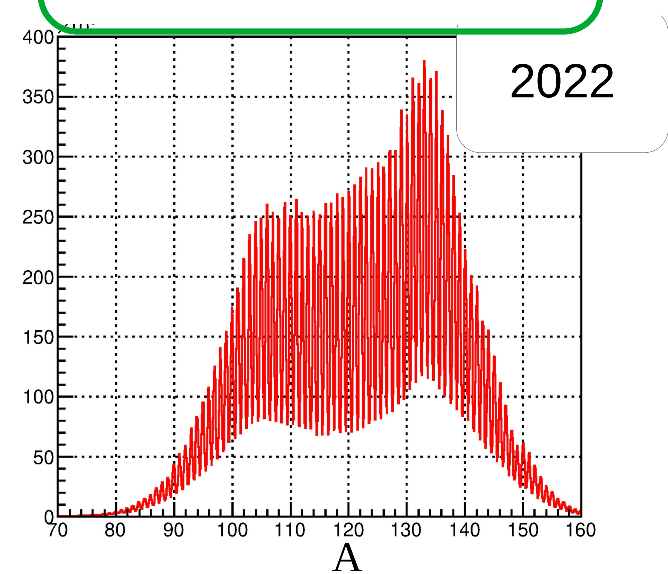

No Target PS-MWPC
DC + IC + Si (focal plane)

Target PS-MWPC
High Segmentation IC
Digital Electronics

**RESOLUTIONS:**
- $\sigma Z/Z \sim 1.3$ % (FWHM)
- $\sigma A/A \sim 3\text{x}10^{-3}$ (FWHM)



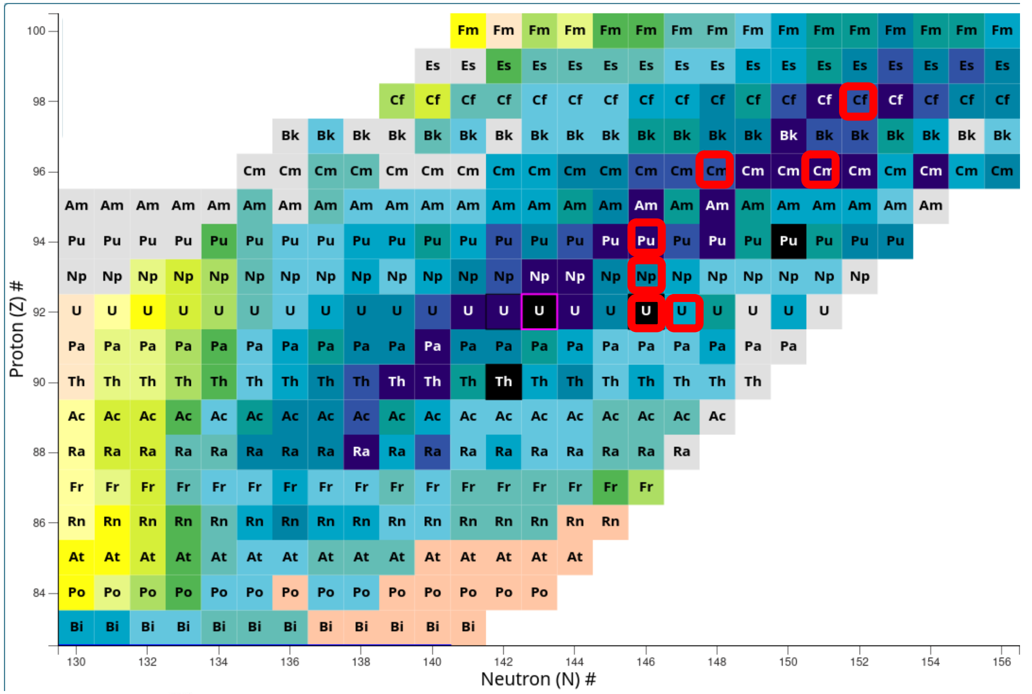



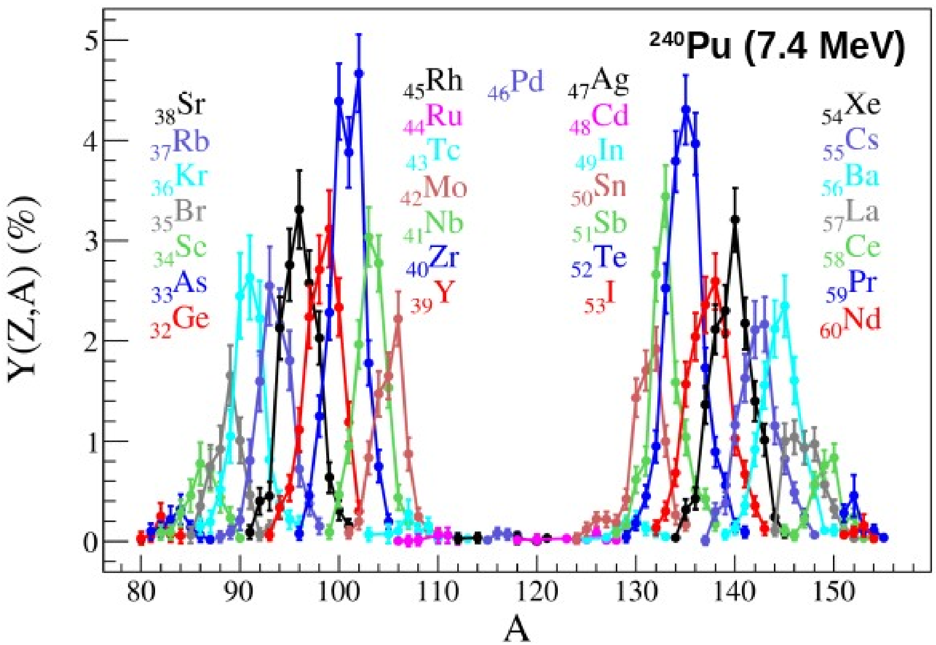
# Isotopic Fission Yields of n-rich Actinides

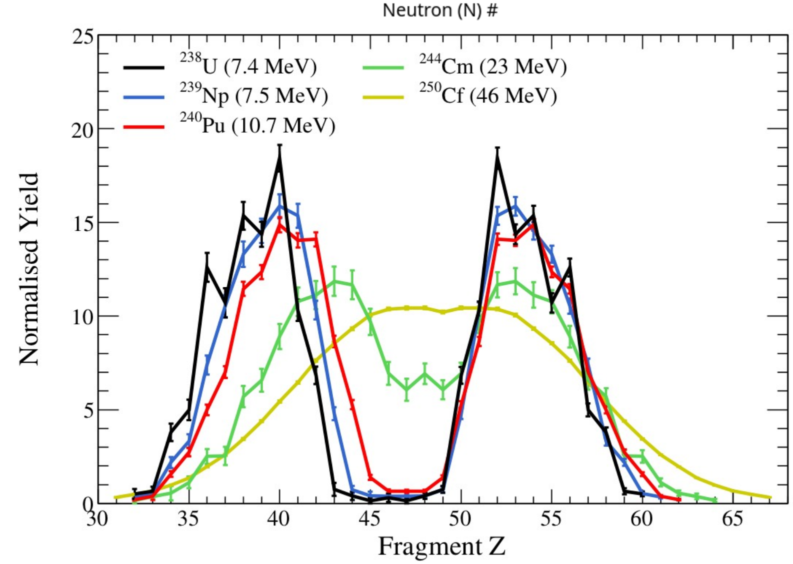
$^{238}U + ^{12}C \rightarrow$
- $^{238}U$ (7.4 MeV) + $^{12}C$
- $^{239}Np$ (7.5 MeV) + $^{11}B$
- $^{240}Pu$ (10.7 MeV) + $^{10}Be$
- $^{244}Cm$ (23 MeV) + $^{6}He$
- $^{250}Cf$ (46 MeV)

$^{238}U + ^{9}Be \rightarrow$
- $^{239}U$ (8.3 MeV) + 2α
- $^{247}Cm$ (43 MeV)

- Access to the **full distribution of fission fragments** of n-rich actinides in both, proton and neutron numbers.





M. Caamaño et al., Phys. Rev. C 88, 024605 (2013).
D. Ramos et al., Phys. Rev. C 97, 054612 (2018).
D. Ramos et al., Phys. Rev. C 99, 024615 (2019).
D. Ramos et al., Phys. Rev. Lett 123, 092503 (2019).


- Asymmetric fission at low $E_x$ with **stabilization of the heavy fragment Z~54.** Observation extended to actinides above U

# NEW Isotopic Fission Yields of n-rich Actinides

$^{238}$U + $^{12}$C →
- $^{238}$U (7.4 MeV) + $^{12}$C
- $^{239}$Np (7.5 MeV) + $^{11}$B
- $^{240}$Pu (10.7 MeV) + $^{10}$Be
- $^{244}$Cm (23 MeV) + $^{6}$He
- $^{250}$Cf (46 MeV)

$^{238}$U + $^{9}$Be →
- $^{239}$U (8.3 MeV) + 2α
- $^{247}$Cm (43 MeV)

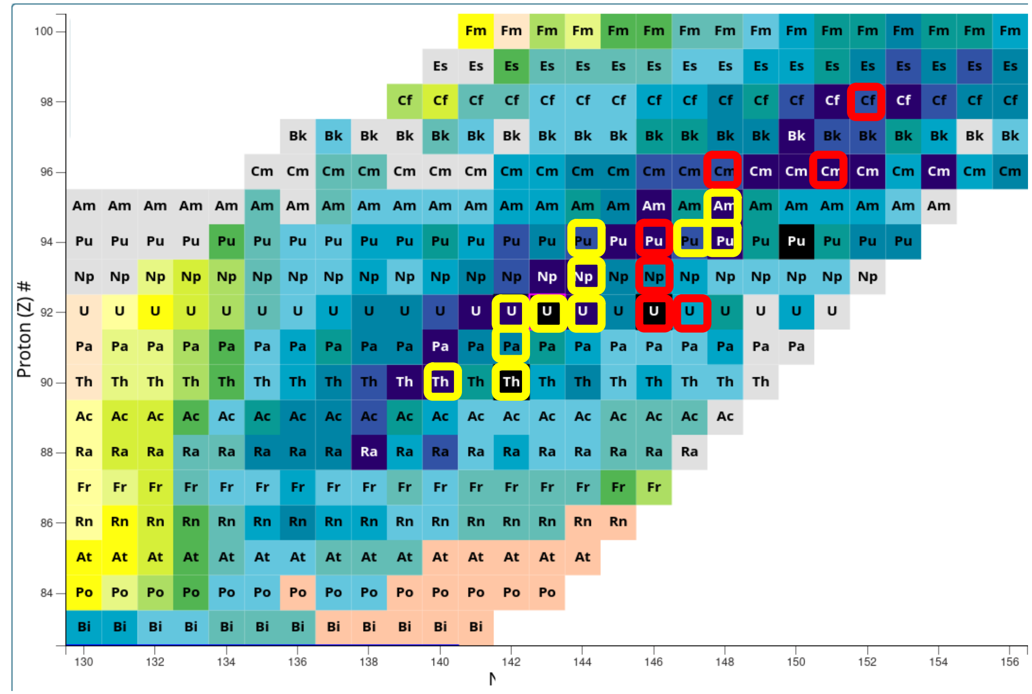
**GANL – CEA/DAM Collaboration :**

$^{238}$U + $^{12}$C →
- $^{236}$U + $^{14}$C
- $^{241}$Pu + $^{9}$Be
- $^{242}$Pu + 2α
- $^{243}$Am + $^{7}$Li

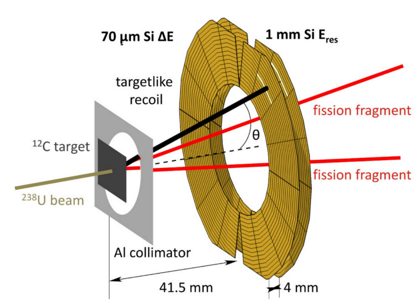
ONGOING

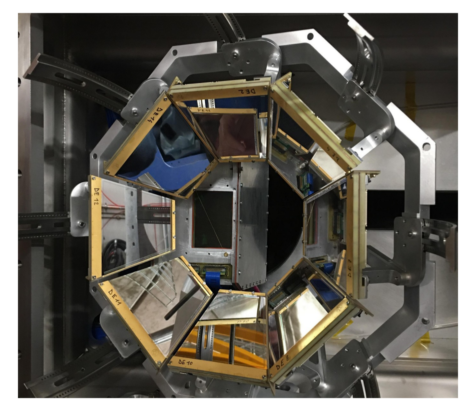
$^{232}$Th + $^{12}$C →
- $^{232}$Th + $^{12}$C
- $^{230}$Th + $^{14}$C
- $^{233}$Pa + $^{11}$B
- $^{234}$U + $^{10}$Be
- $^{235}$U + $^{9}$Be
- $^{237}$Np + $^{7}$Li
- $^{238}$Pu + $^{6}$He

IN PREPARATION




**SPIDER** → **PISTA (2023)**



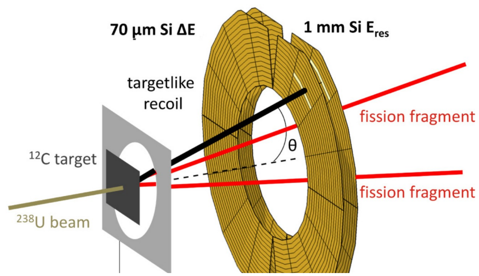



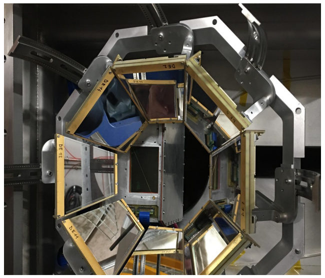
- Higher energy resolution (2.5 MeV → <1 MeV)
- Larger angular coverage
- Full Isotopic Identification of Actinides

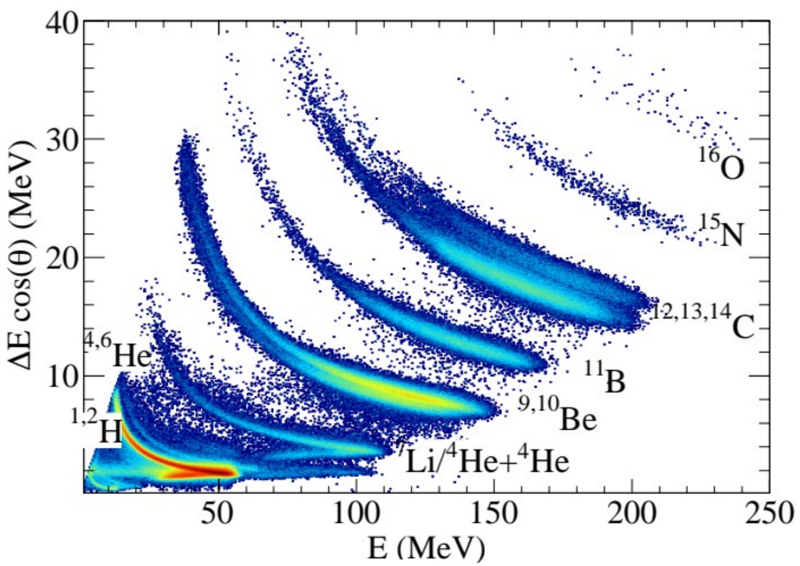
# Improved determination of the Incoming Channel

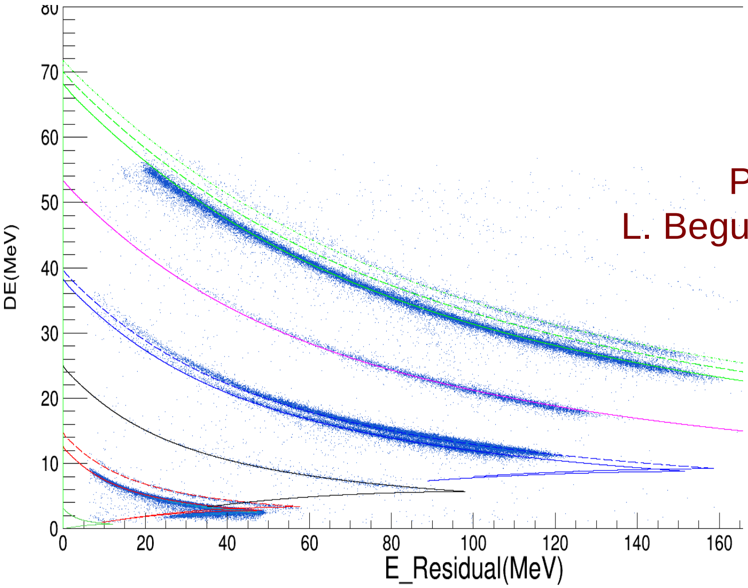
**SPIDER**

**PISTA**



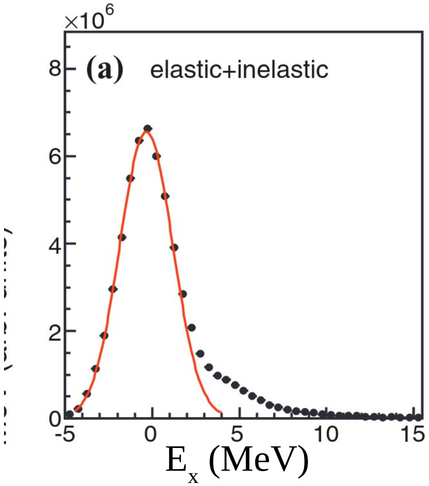





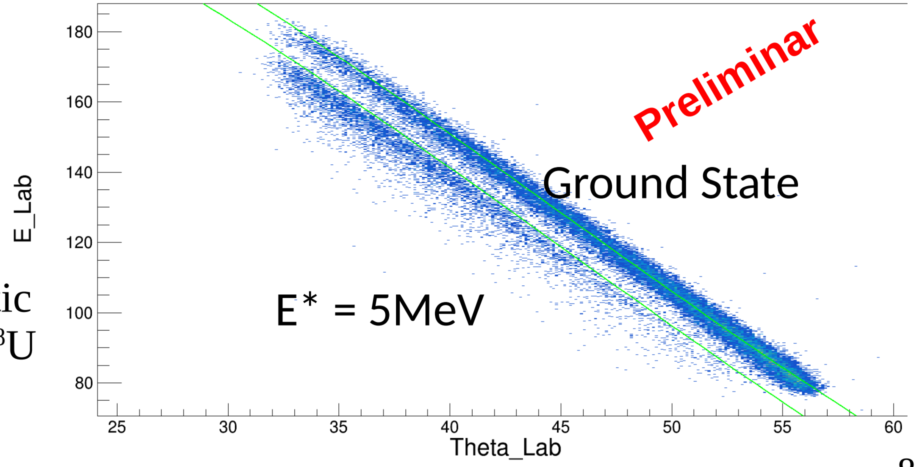

PhD Work of
L. Begué-Guillou (GANIL)

**Preliminar**




- Excitation energy distribution of $^{238}$U from SPIDER

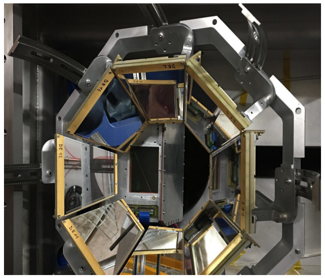
- Elastic + Inelastic kinematics of $^{238}$U from PISTA

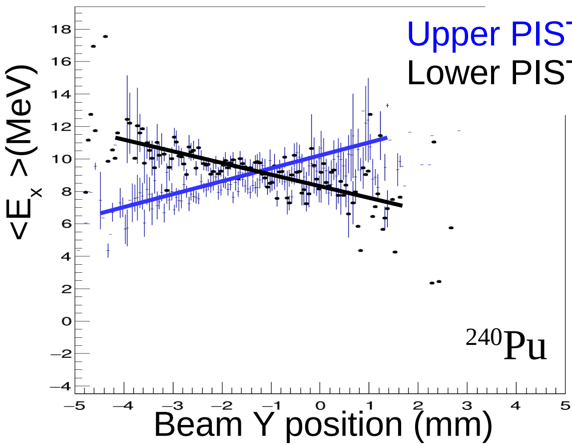


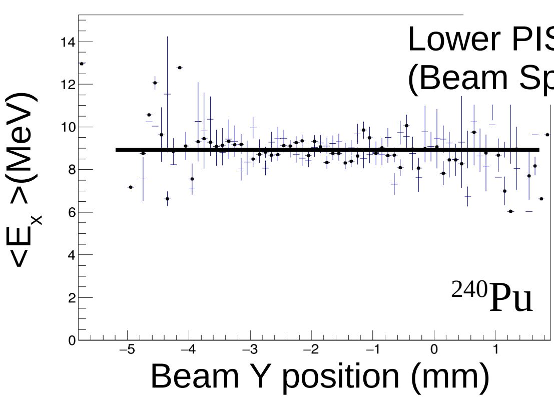
# Improved determination of the Incoming Channel

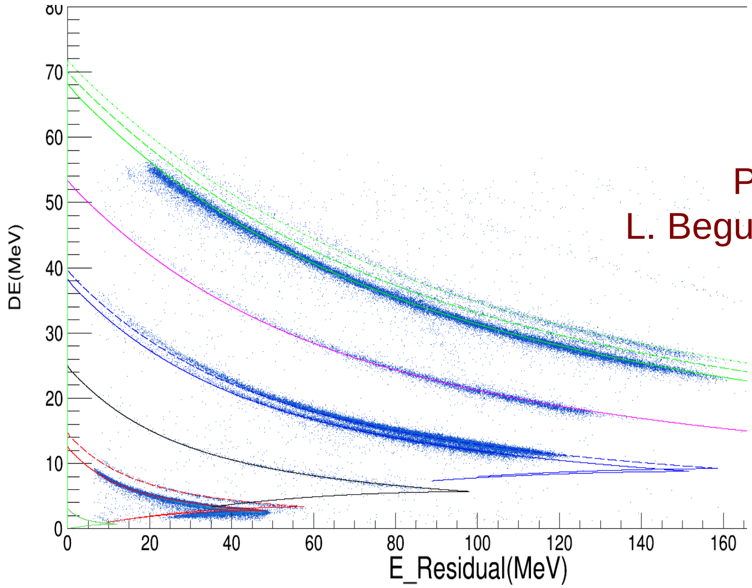
- High segmentation - High position sensitivity
  - 1 mm shift beam spot effect

**PISTA**





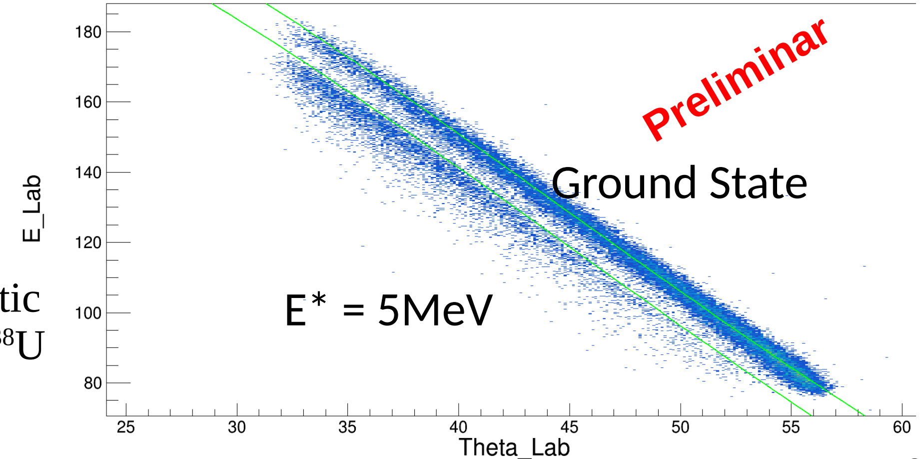




PhD Work of
L. Begué-Guillou (GANIL)

Preliminar

- Elastic + Inelastic kinematics of $^{238}$U from PISTA




Preliminar

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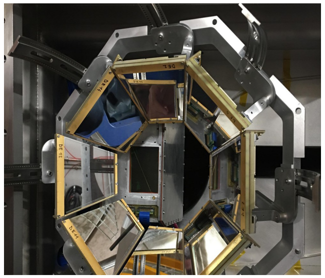
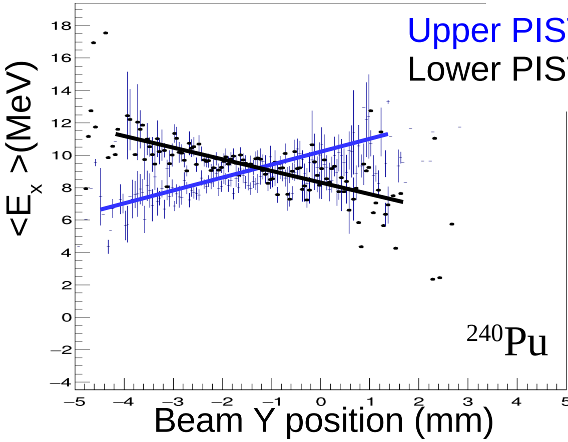
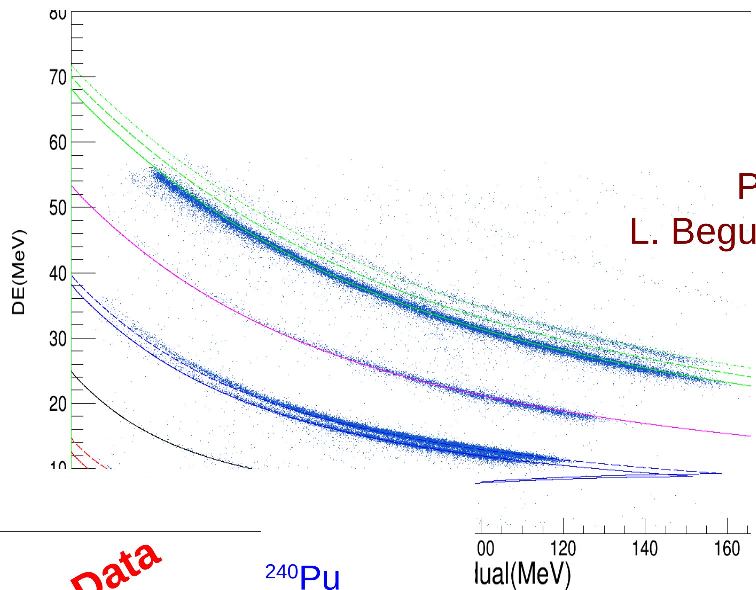
- High segmentation - High position sensitivity
  - 1 mm shift beam spot effect

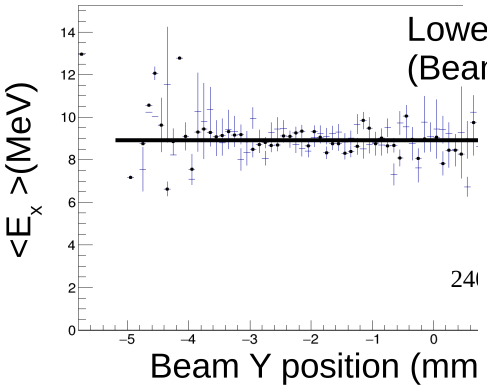
**PISTA**

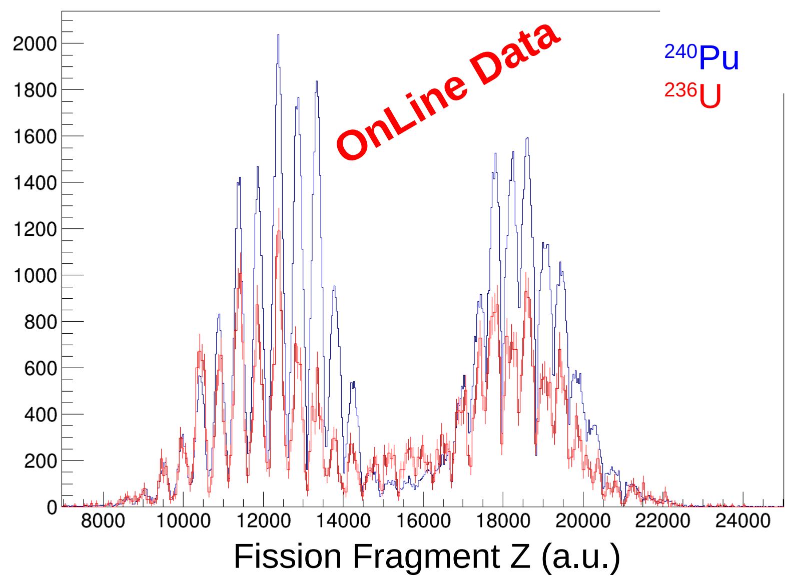


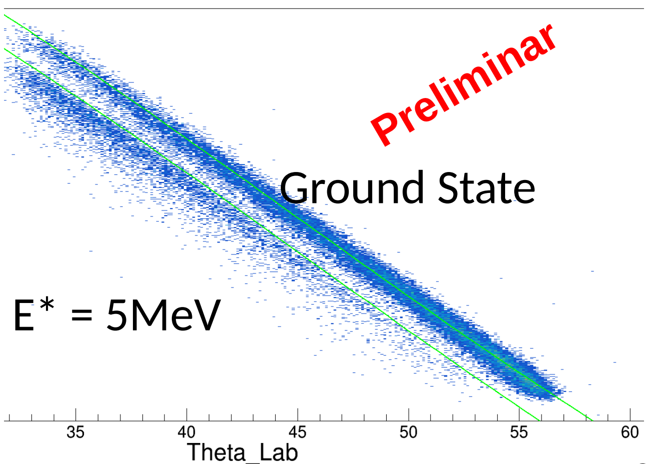



PhD Work of
L. Begué-Guillou (GANIL)



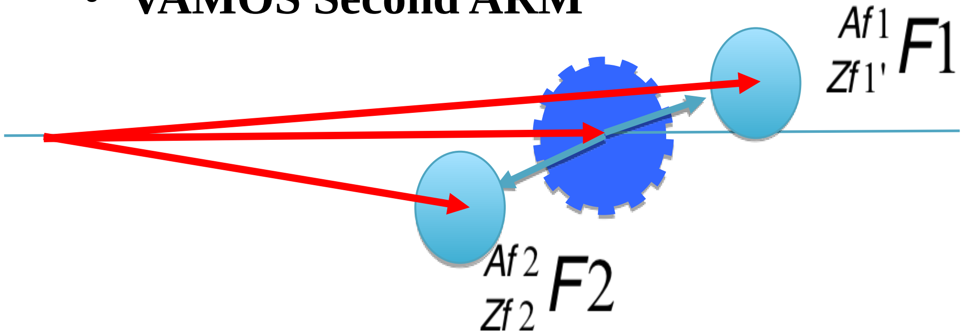



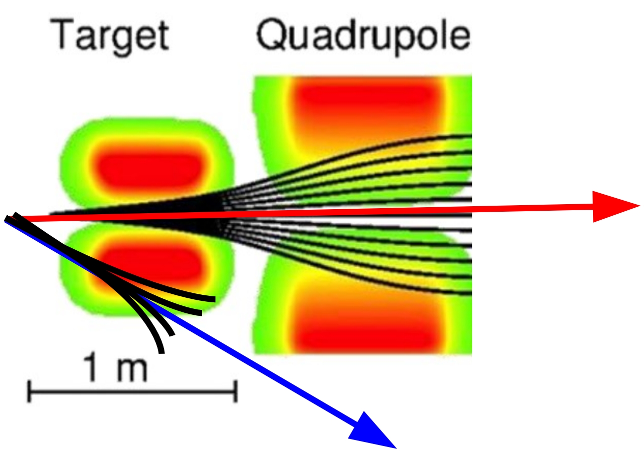
# Both FF detection @ VAMOS

- **VAMOS Second ARM**

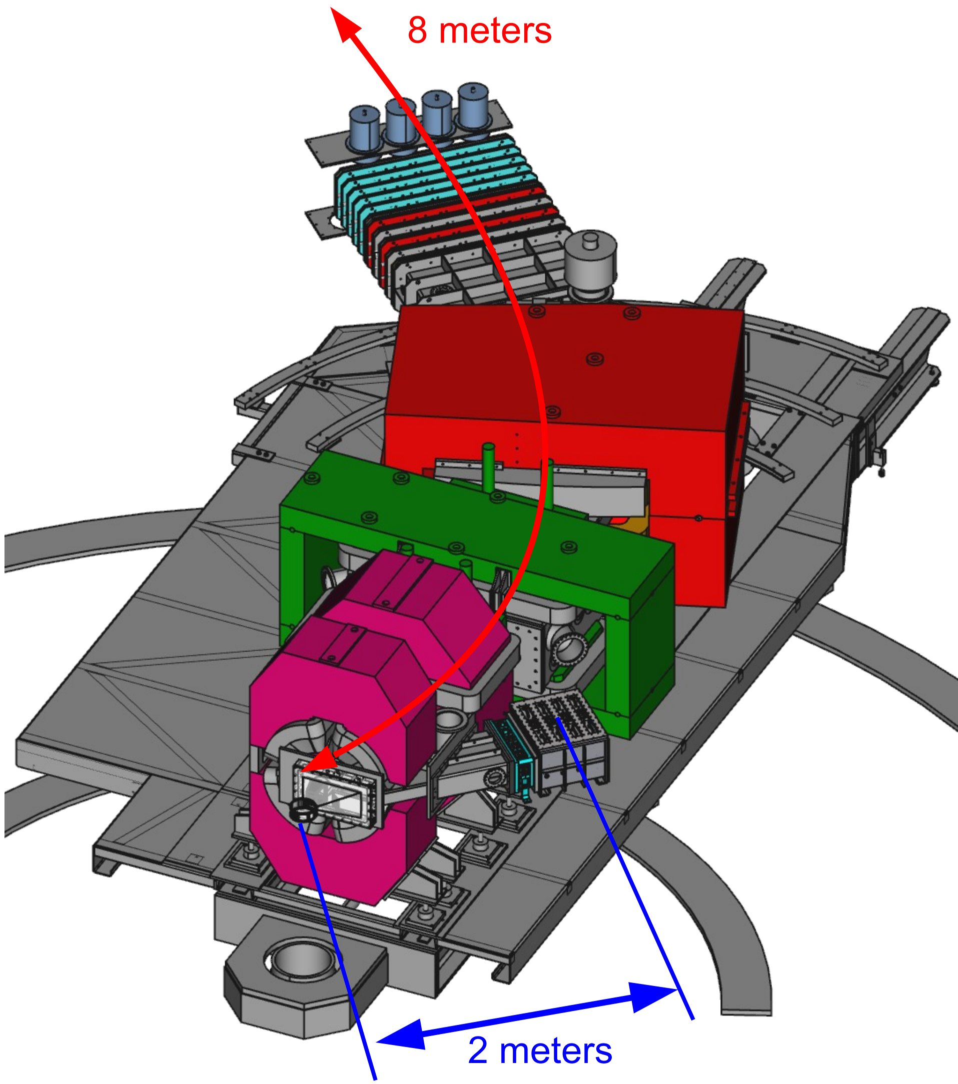



- **2V method :**
  - **Pre n-evaporation Isotopic** Fission Yields
  - Isotopic **TKE**

- **RIN-EMERGENTS PROJECT (2023-2025)**
  - **Reconstruction of the ff trajectories in 2 arm**

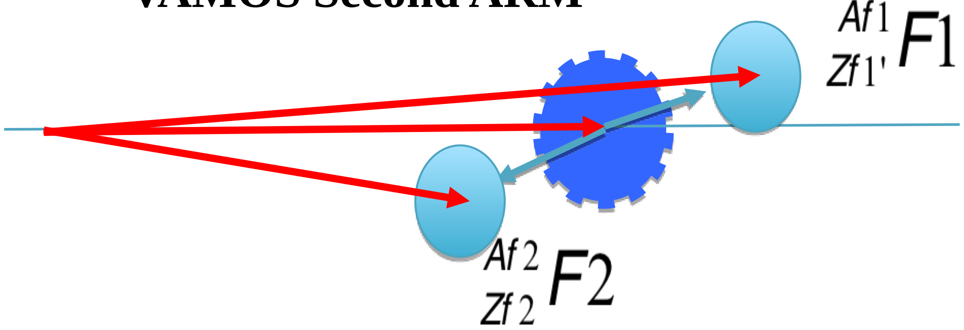



  - **Development of High-resolution Time detectors**



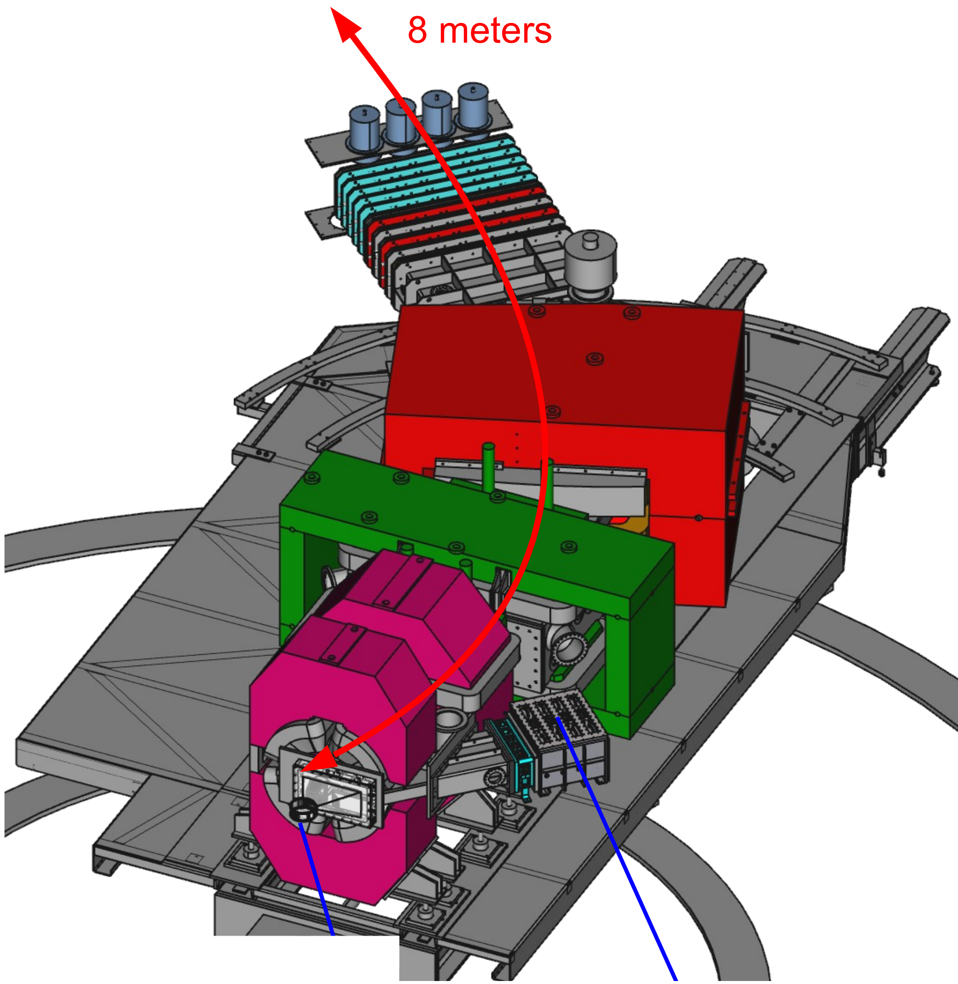
# Both FF detection @ VAMOS

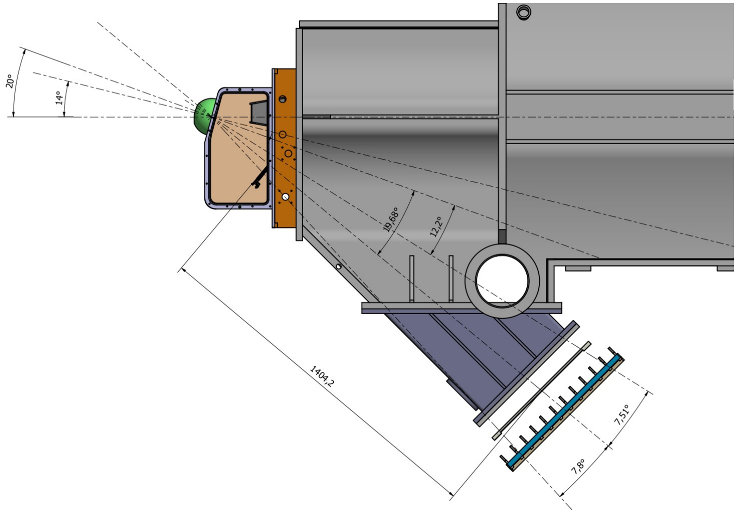
- **VAMOS Second ARM**

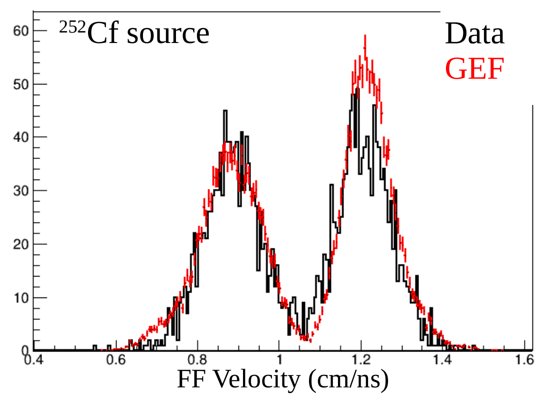


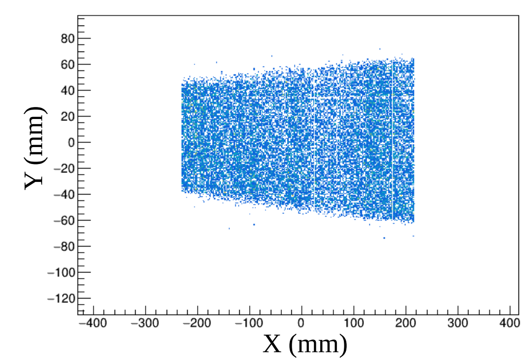

- **2V method :**
  - **Pre n-evaporation Isotopic** Fission Yields
  - Isotopic **TKE**

- **First in-beam measurement in March 2024**
  - **2 Position-sensitive MWPC**
    - **~ 300 ps Time resolution (FWHM)**
    - **< 1 mm position resolution**



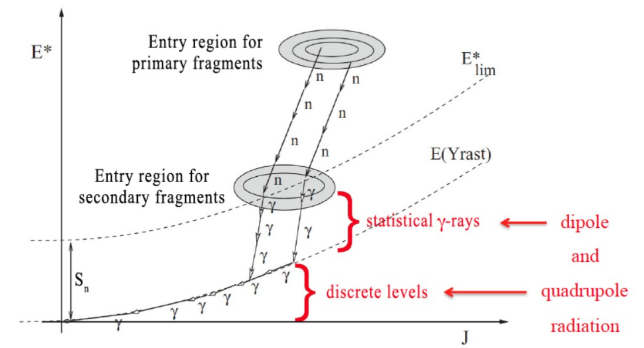



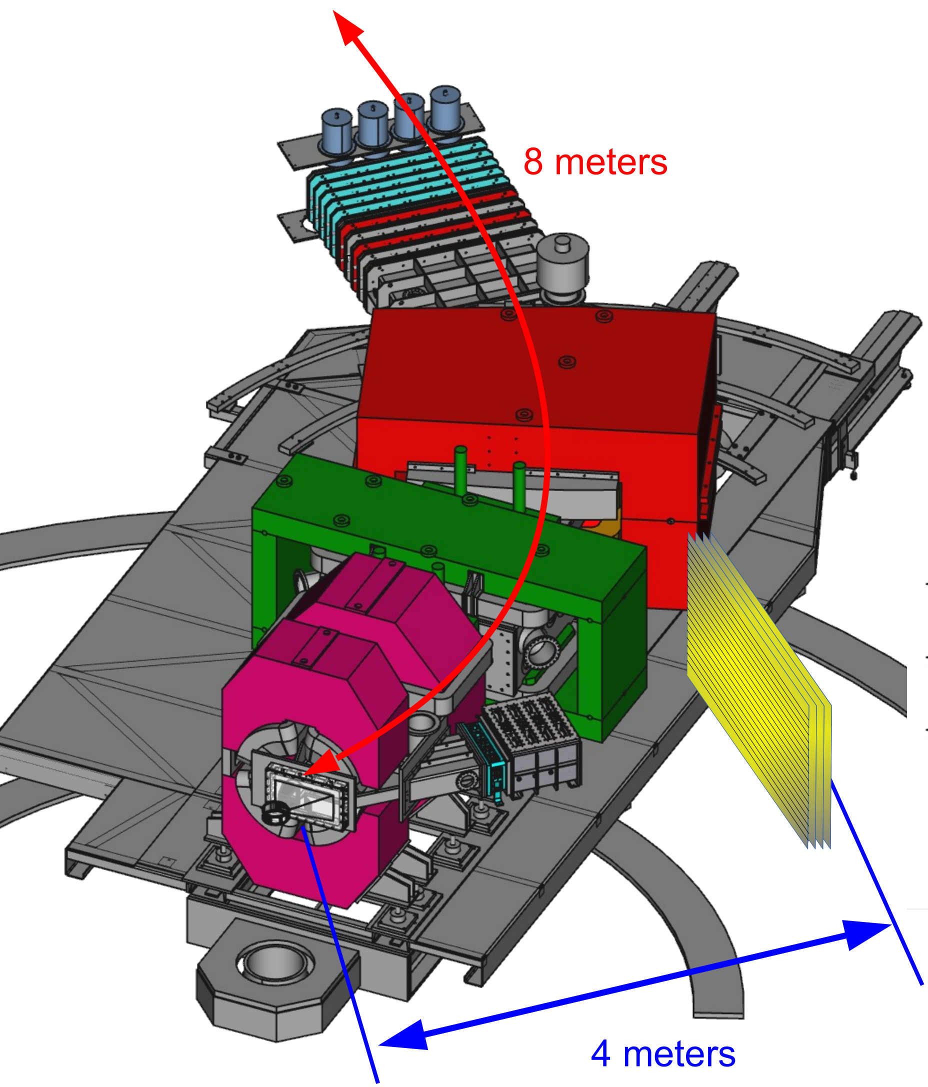



# Neutron Detection @ VAMOS

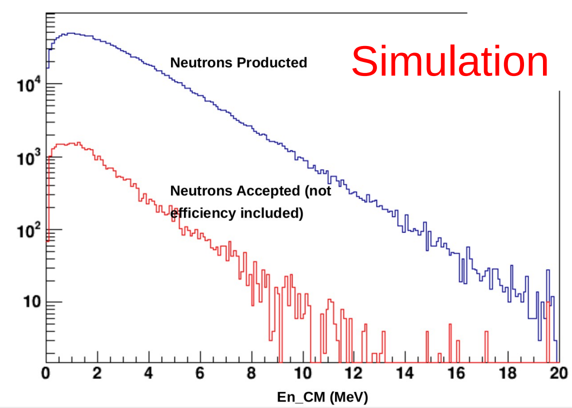
- **Neutron multiplicity**
- **Neutron energy**
  - **Determination of the entry point of fission fragments**



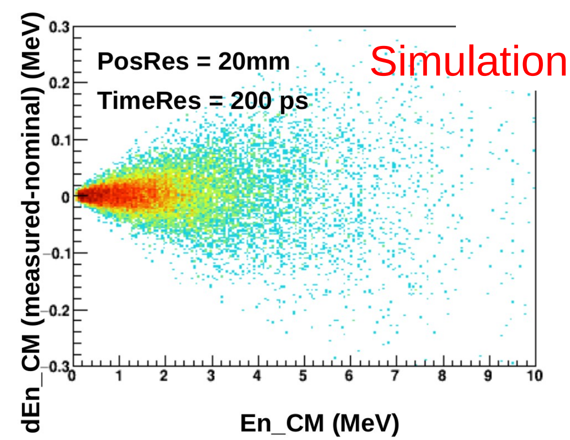

**A. Oberstedt et al. EPJ WoC 193, 03005 (2018)**




- **Inverse-kinematics Kinetic boost**
  - High Time resolution required (~200 ps)
  - High Granularity required (~2 cm)
  - Neutrons geometrically focussed (Area =100x50 cm)



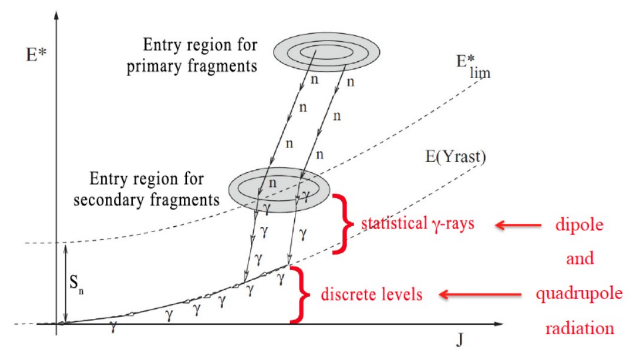

AREA = 100 x 50 cm
Neutrons Accepted /Produced = 2 %




Energy resolution ~ 200 keV

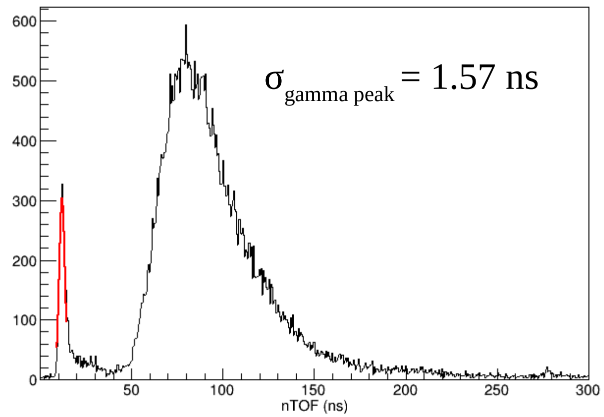
# Neutron Detection @ VAMOS

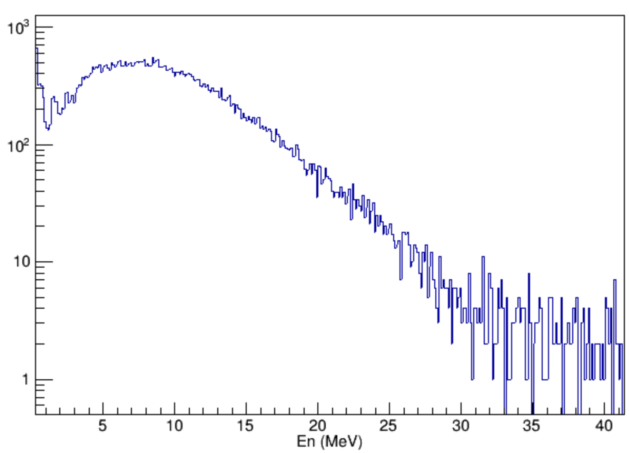
- **Neutron multiplicity**
- **Neutron energy**
  - **Determination of the entry point of fission fragments**

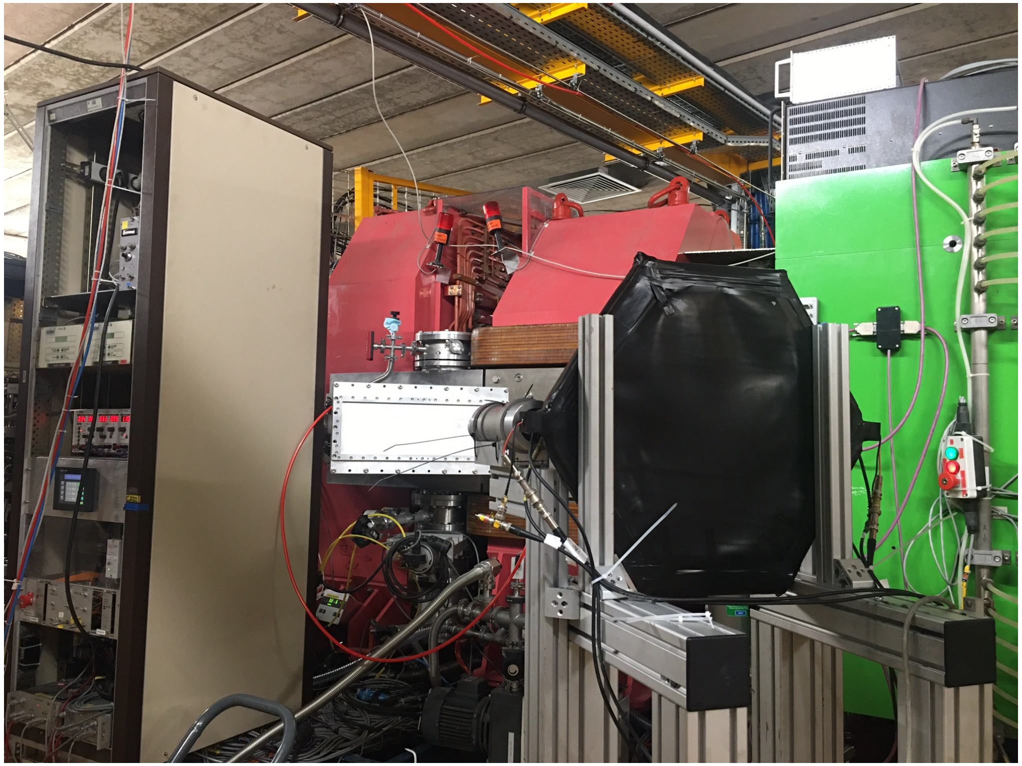



**A. Oberstedt et al. EPJ WoC 193, 03005 (2018)**

- **First Test in 2023 ( $^{238}U + ^{12}C \rightarrow FF$ )**
- Small Size (20x50 cm)
- Not postion sensitivy → No Energy in center of mass
- Not optimum time resolution



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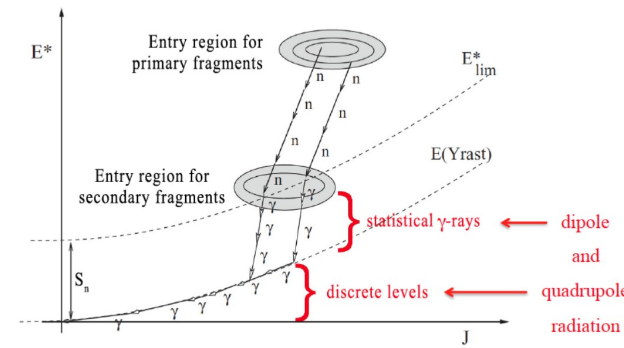


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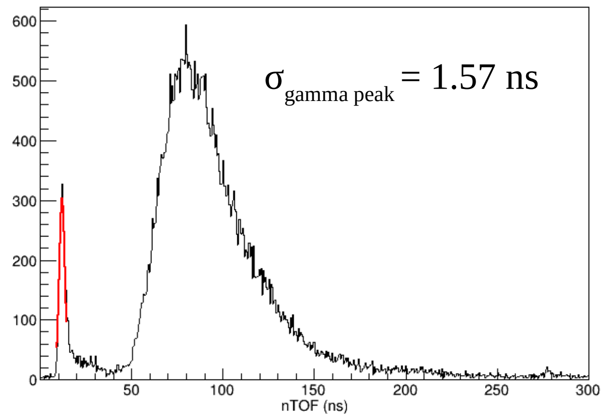
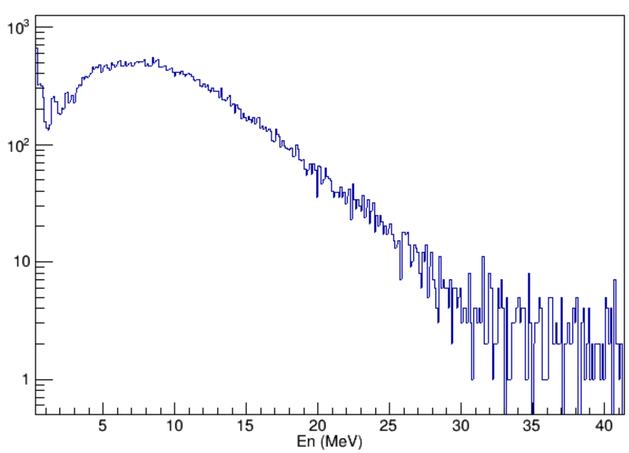
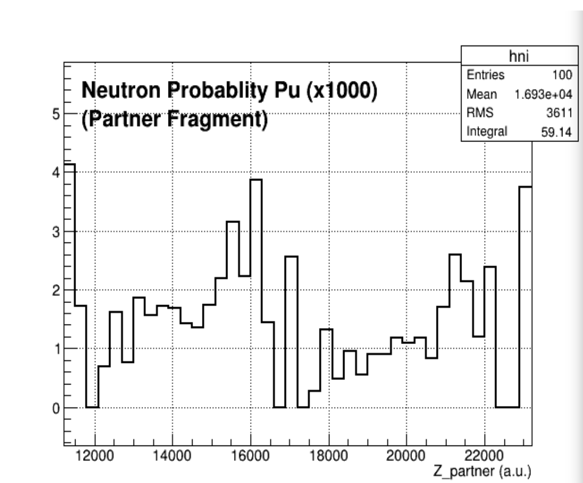
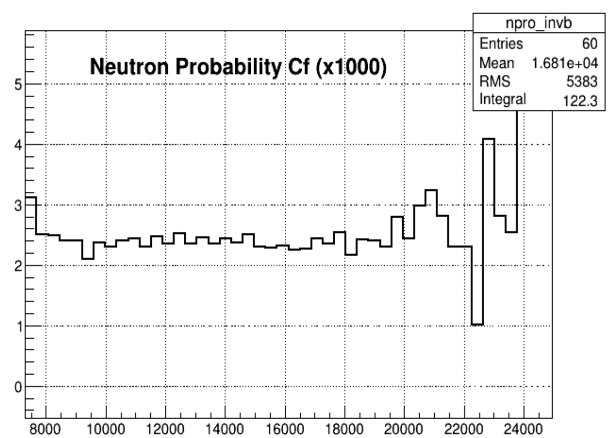



- Fission Fragment detected in VAMOS in coincidence with neutron detected in 2-Arm




- Expected Sawtooth behaviour of the neutron multiplicity at low energy!
- **The Neutron detector is sensitive to fission-fragments neutrons.**

# Summary

- The fission program at VAMOS++/GANIL is an already well stablished program providing experimental data for more than 10 years.

- The combination of inverse kinematics with a magnetic spectrometer allows to study fission with a wide set of observables in a common setup.

- The fission program at VAMOS++/GANIL is unique, very competitive, and rich. The upgrade of the setup is in progress in order to:
  - Improve the determination of the incoming channel.
  - Isotopic fission-fragments identification at the scission point.
  - Study of decay of primary fragments through neutron evaporation.

- For first time, the scission point will be accessible isotopically by measuring the proton and neutron content of the fragments at scission, as well as the reaction energy balance.

- The production of stable Thorium beam would give access to new fissioning systems in a region of interest barely explore.