Fission at GANIL using the PISTA@VAMOS setup

Perspective on Nuclear Data for the Next Decade P(ND)^2-3

10th January 2026

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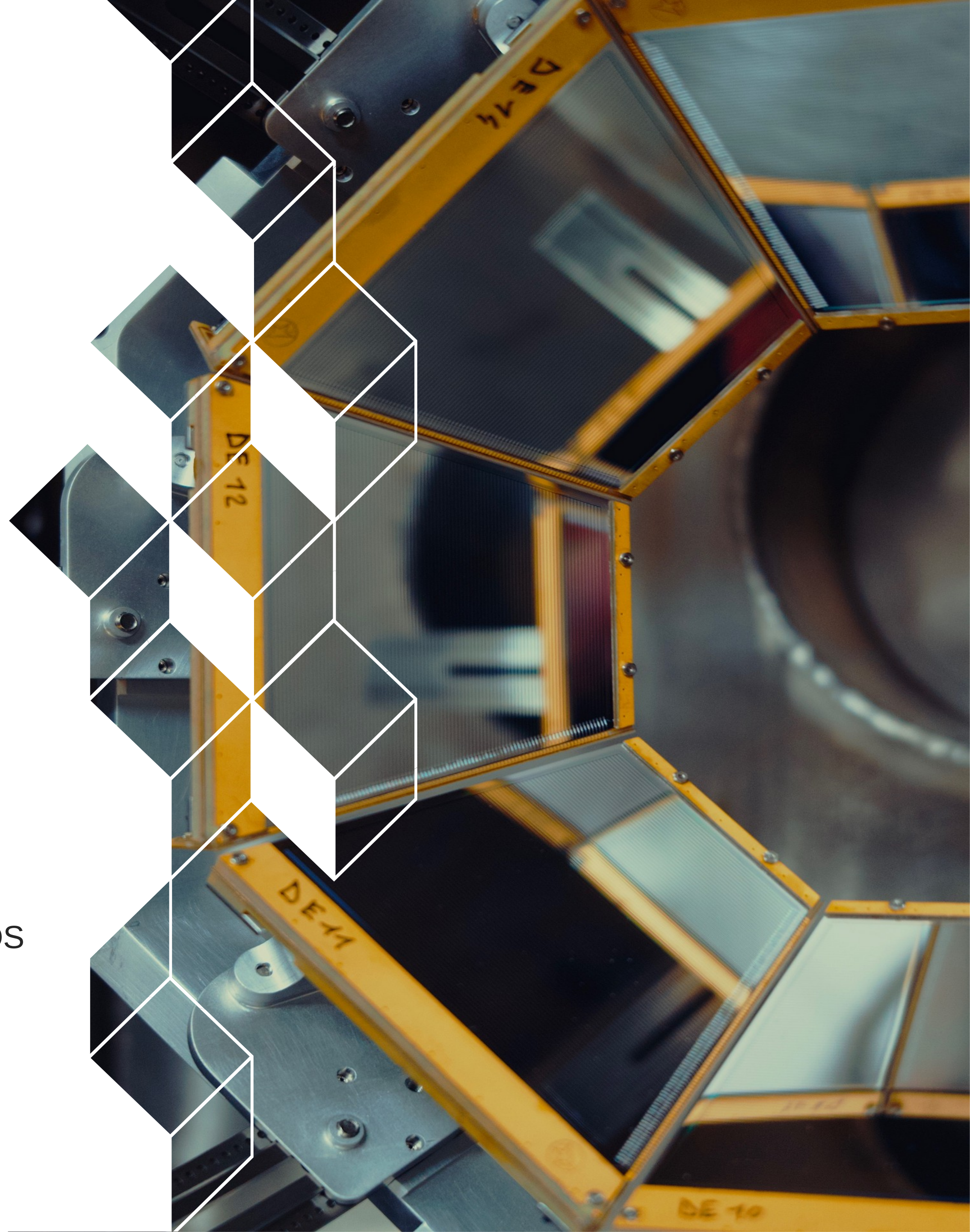


Experiments for basic science and nuclear data

Nuclear physics experiments have often a dual purpose

- **Advancing fundamental knowledge of the nucleus**

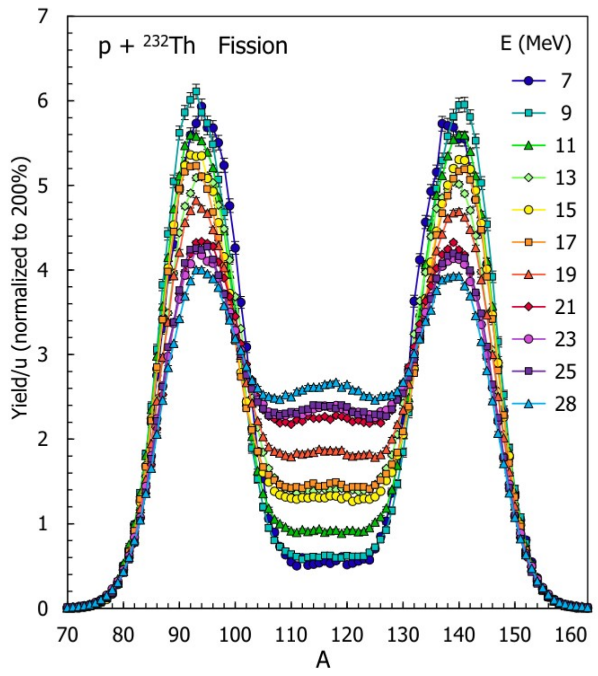
- **Provide key data for applications**

- Reliable predictions require precise experimental constraints.
- Modern facilities and new detectors allow new or more precise measurements and can explore new regions.

- Nuclear physics experiments focused on high-quality nuclear data seek to **reduce uncertainties in fission modeling** for scientific and technological applications:
  - ➔ Reactor design (Gen IV)
  - ➔ Nuclear safeguard
  - ➔ Waste transmutation

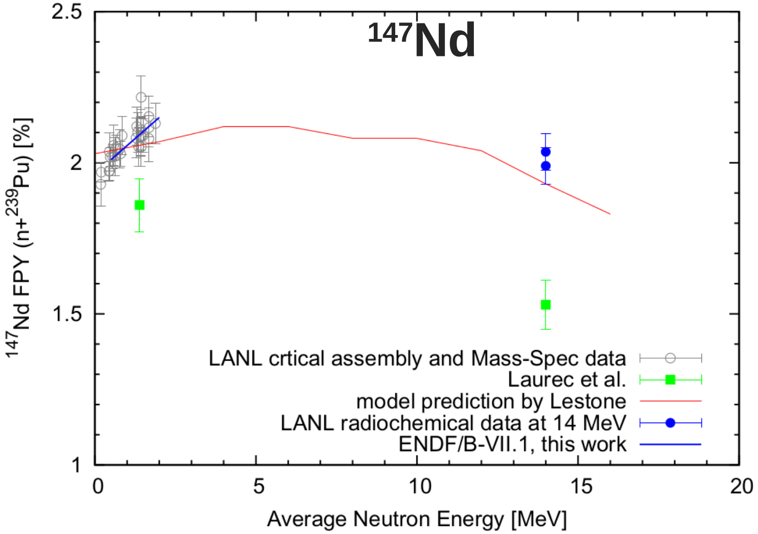
Goals of the PISTA@VAMOS experiments

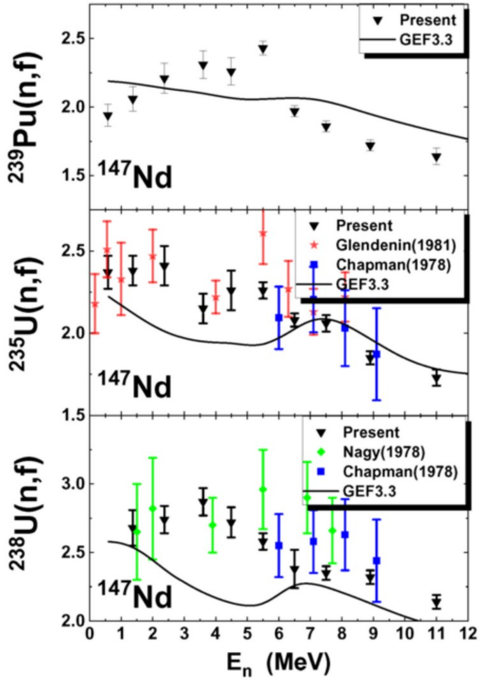
- **Goals**
  - Isotopic measurement of fission fragment yield (after neutron evaporation) as a function of the excitation energy of the fissioning systems.
  - Access different fissioning systems
  - Probe the role of shell effect in the fission process.
- **Fundamental questions**
  - Description of the shell effect damping with E*.
- **Application**
  - Gen-IV nuclear reactors using fast neutrons.
  - Open question on the evolution of some fission yields for ^{239}Pu(n,f).



A.C. Berriman *et al.* Phys.Rev.C **105**, 064614 (2022)

Yield evolution with E_n





- Open questions : evolution with E_n.
- Measurement with fast neutrons
  - ✓ Activation -> separation **α**/fission difficult + normalization.
  - ✓ gamma spectroscopy => Precise measurement with the need to control all the efficiency precisely.
- Recent high quality data at TUNL (A. Tonchev and R. Malone)

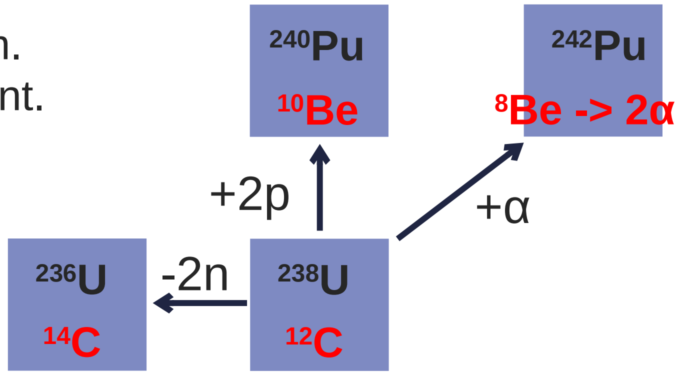
Chadwick *et al.* Nuclear Data Sheets **111** (2010) 2923-2964 A. Tonchev *et al.* Nuclear Data Sheets **202** (2025) 12-29

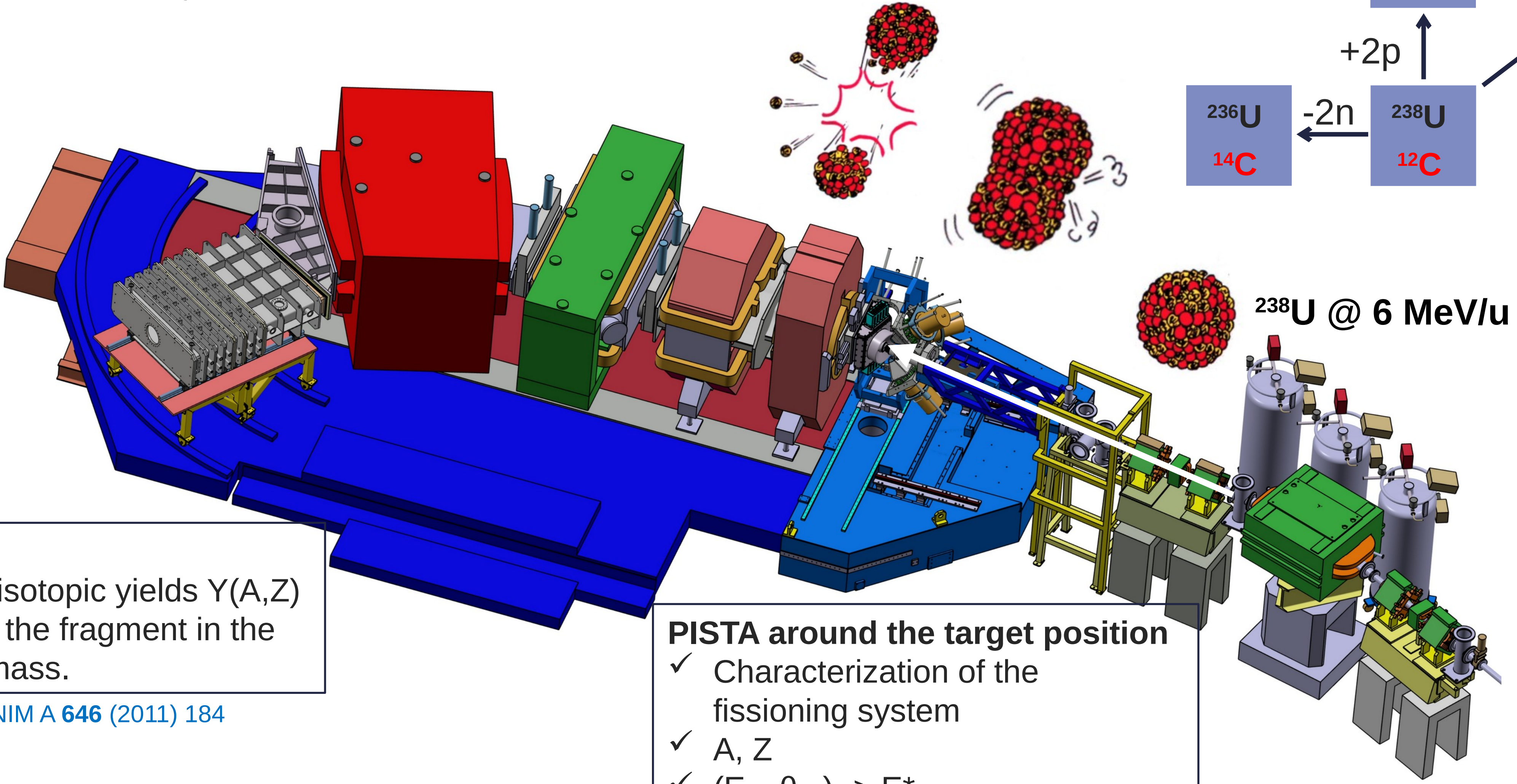
- **New experiment program in collobaration with GANIL to develop a new silicon array: PISTA**
  - ✓ Inverse kinematics and transfer reaction.
  - ✓ Developement of a new silicon array highly segmented, PISTA, to characterize the fissioning system in A, Z and E*.
  - ✓ Following up an existing program => But need a much better precision for nuclear data => PISTA and associated electronics.

What do we do at GANIL with VAMOS

- Inverse kinematics with ^{238}U beam accelerated around Coulomb barrier.
  - ✓ Access heavier systems than ^{238}U.

- Transfer induced fission
  - ✓ Selection of the fissioning system.
  - ✓ Measurement of E* event by event.



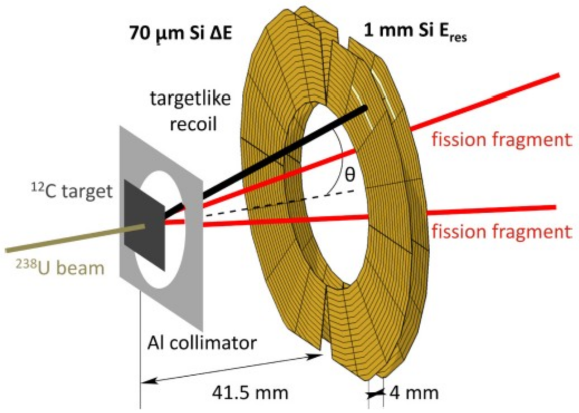


VAMOS
- ✓ Complete isotopic yields Y(A,Z)
- ✓ Velocity of the fragment in the center of mass.

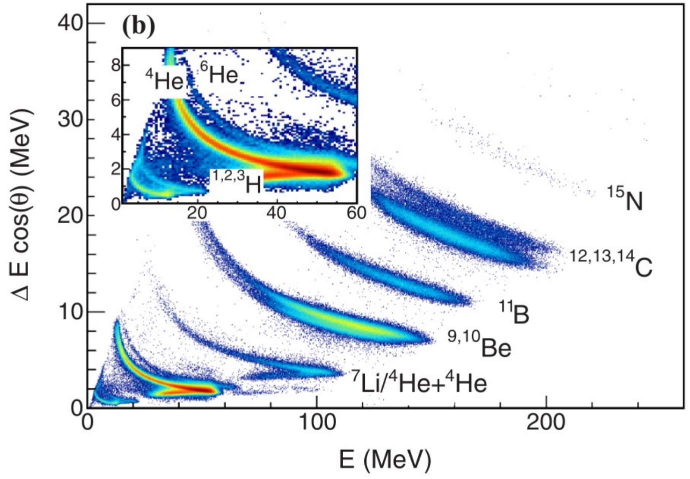
M. Rejmund *et al.* NIM A **646** (2011) 184

PISTA around the target position
- ✓ Characterization of the fissioning system
- ✓ A, Z
- ✓ (E_{lab},θ_{lab}) -> E*

A rich activity with SPIDER and VAMOS

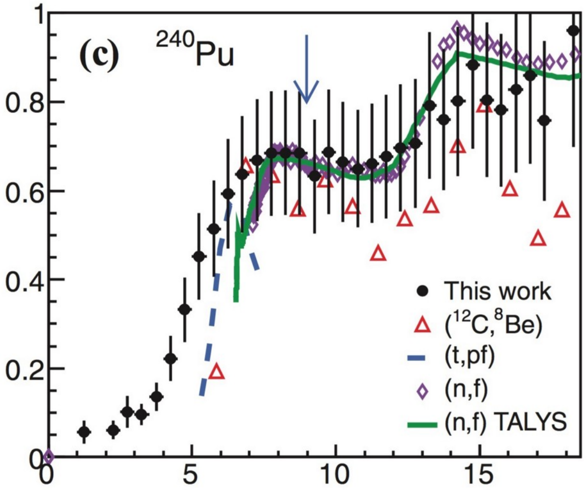


- ΔE = 70 um thickness
- E = 1 mm thickness
- 1,5 mm strips
- 22.5 deg sectors
- Angular coverage : 30 – 47 deg
- Excitation energy resoltuion : FWHM = 2.9 MeV.



The coupling of SPIDER and VAMOS provided a lot a data already, with a limited resolution in excitation energy.

- M. Caamano et al. PRC 88, 024605 (2013)
- C. Rodriguez-Tajes et al. PRC 89, 024614 (2014)
- Ramos et al. PRC 97, 054612 (2018)
- Ramos et al. PRL 123, 092503 (2019)
- Ramos et al. PRC 99, 024615 (2019)

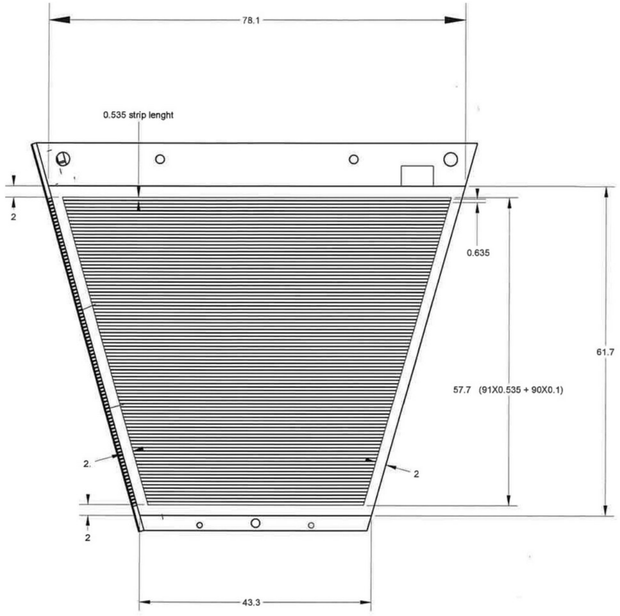


Meeting current nuclear data requirements demands a more precise characterization of the fissioning system in mass (A), charge (Z), and excitation energy (E*), together with improved excitation-energy resolution and significantly higher statistics.

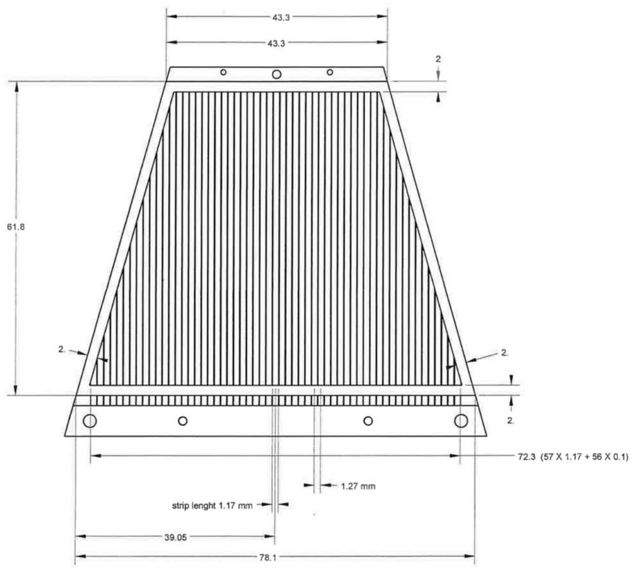
Major upgrade : PISTA, a CEA-DAM/GANIL collaboration

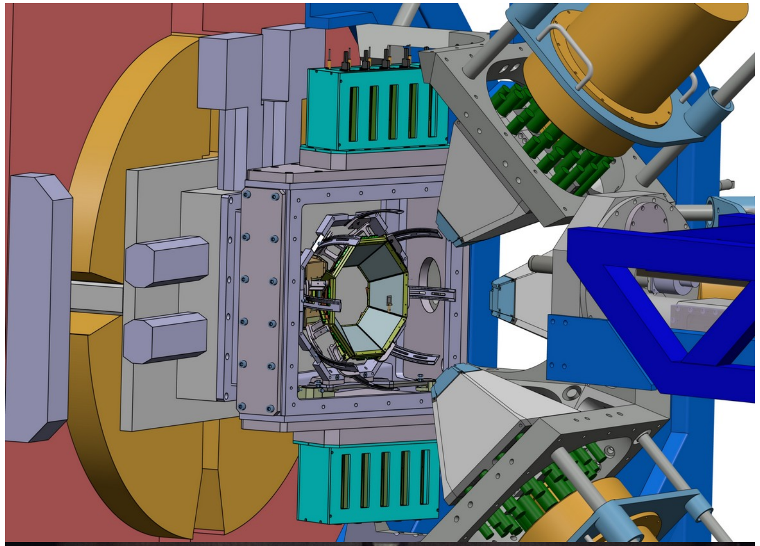
8 telescopes in petal shape

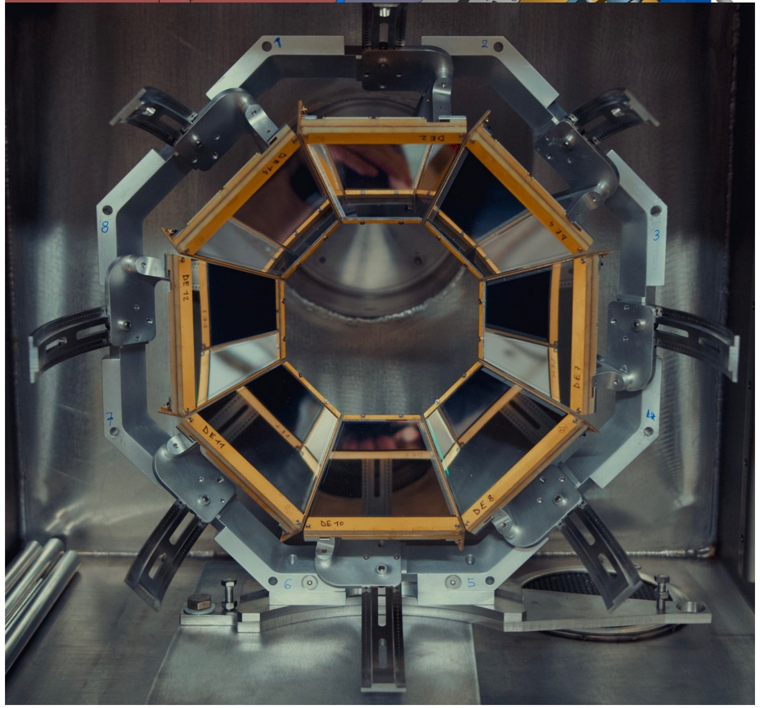
- **ΔE first stage**
  - 100 um thick
  - 91 horizontal strips
  - Dynamic range : 0-60 MeV



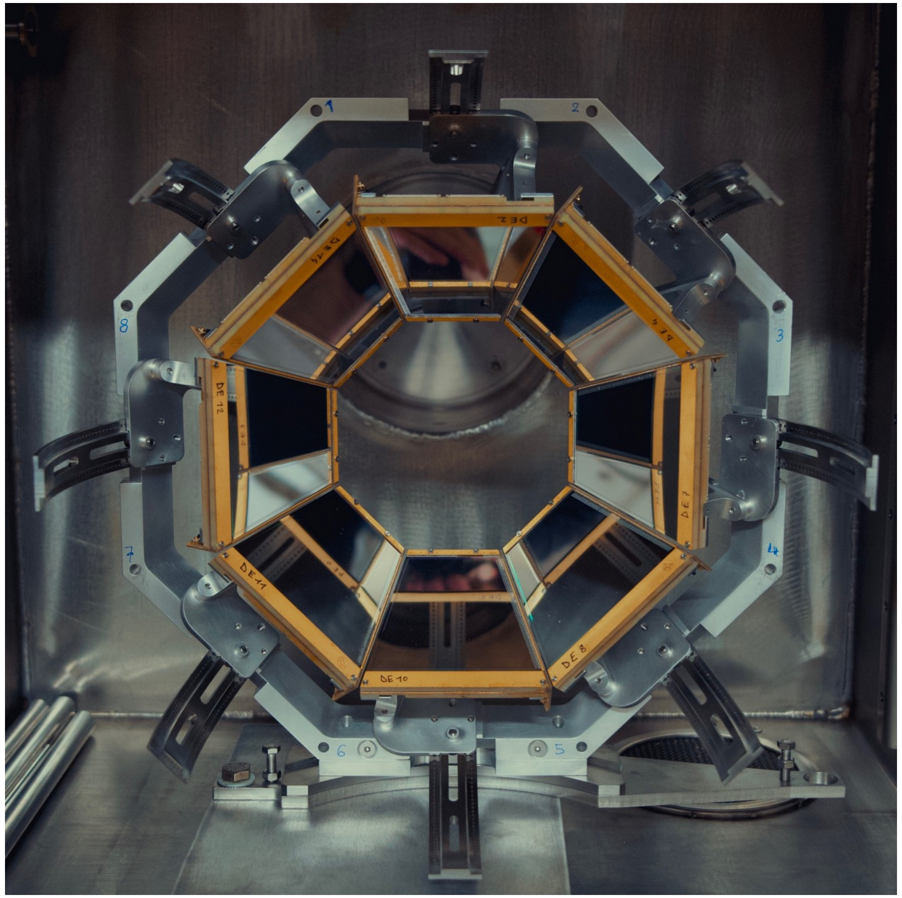
- **E second stqge**
  - 1 mm thick
  - 57 vertcial strips
  - Dynamic range : 0-200 MeV







Major upgrade : PISTA, a CEA-DAM/GANIL collaboration



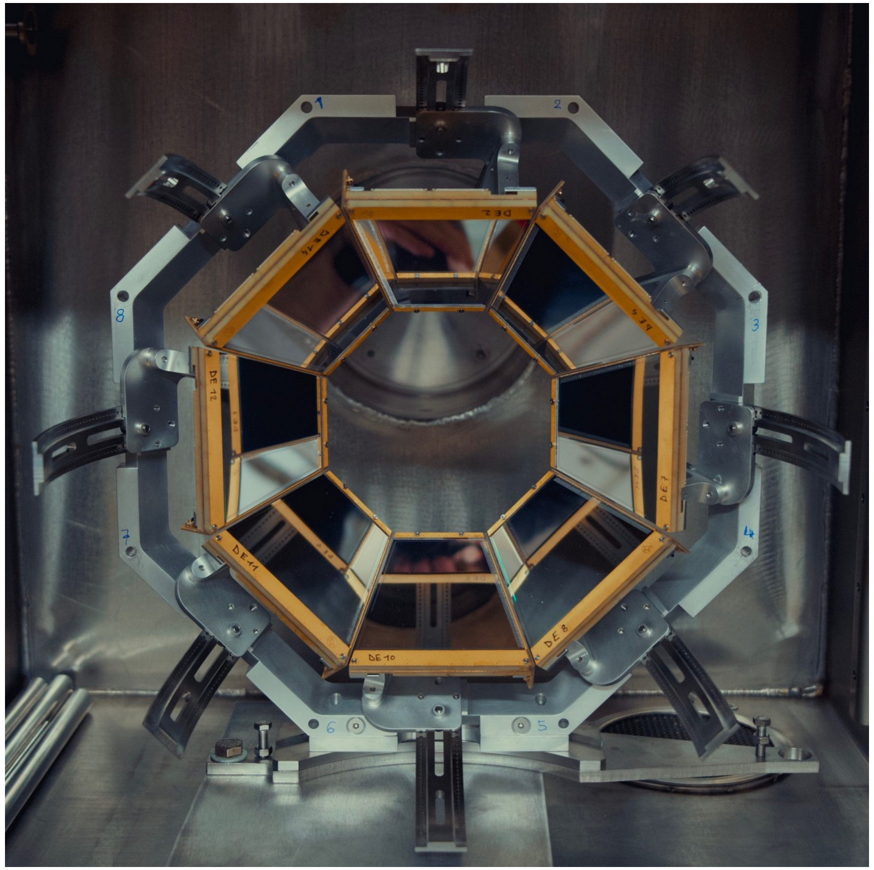
- ✓ Angular coverage: 30-60 deg
- ✓ Better target like identification
- ✓ High granularity => better excitation energy resolution (FMHW = 700 keV)
- ✓ Dedicated electronics capable to sustain higher count rate – For higher statistics.
- ✓ **Better characterization of the fissioning system (A,Z,E*).**
- ✓ PISTA and its electronic founded by CEA.

Two experimental campaigns in 2023 and 2024:

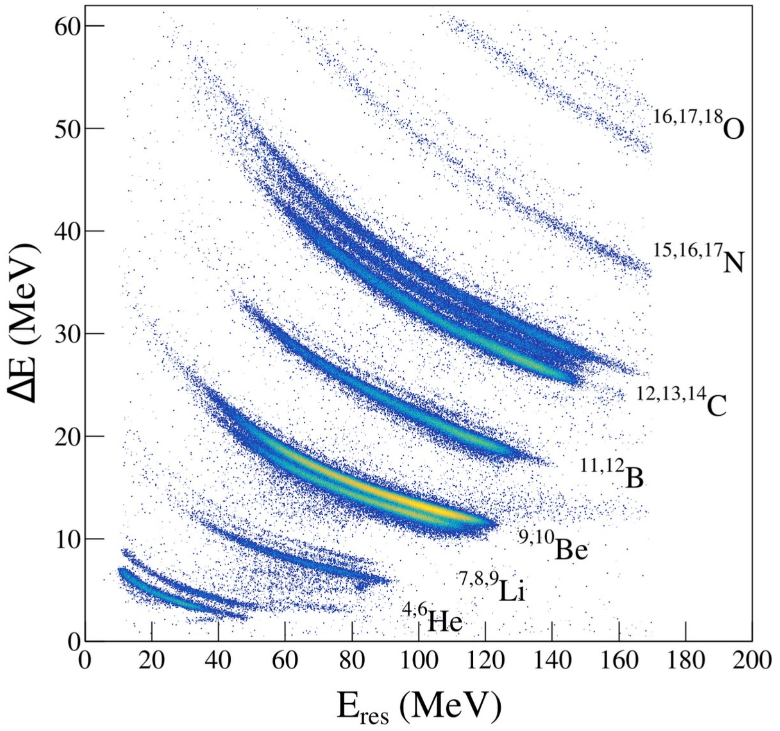
- ^{238}U beam experiment
  - ➔ Thesis Lucas Bégué-Guillou (focus on PISTA analysis)
  - ➔ Thesis Théodore Efremov (focus on yield analysis)
- ^{232}Th beam experiment
  - ➔ Thesis Alex Cobo

PISTA : Particle Identification (PID)

PISTA analysis done by Lucas Bégué-Guillou

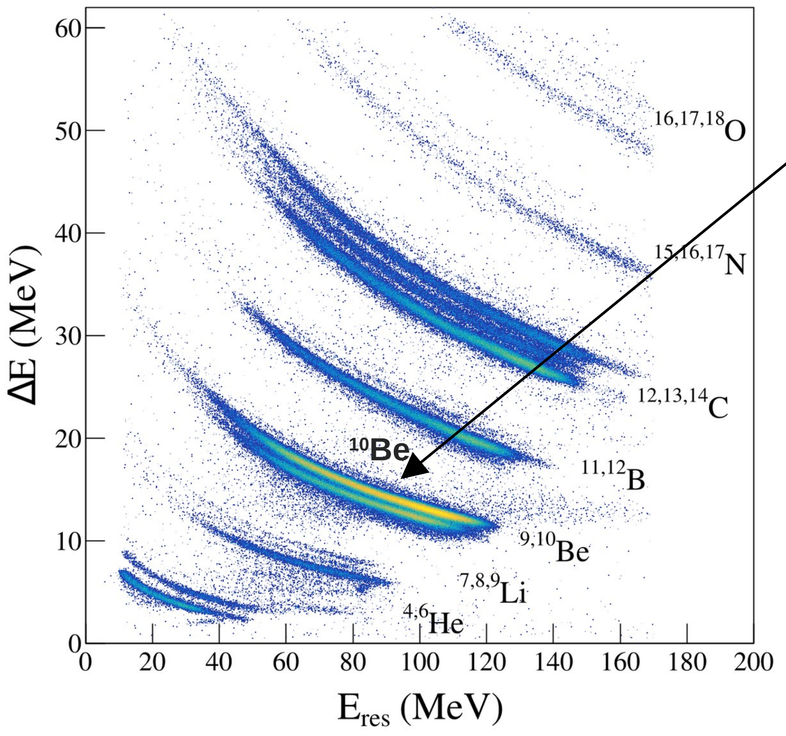


PISTA 2023 experiment



PISTA : first experiment in 2023 (Focus on Pu)

Selection of the fissioning system : ^{240}Pu



PISTA analysis done by Lucas Bégué-Guillou

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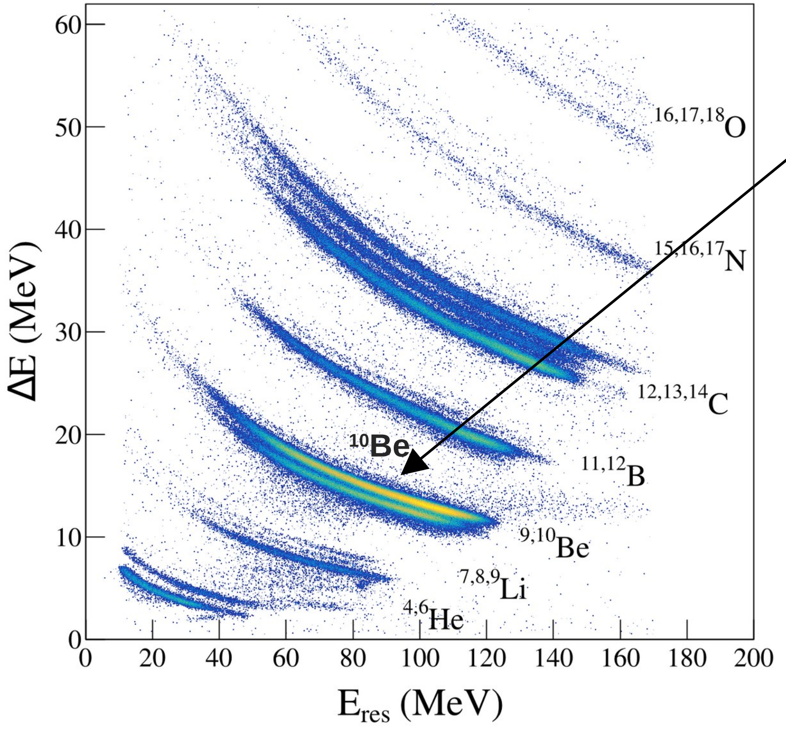
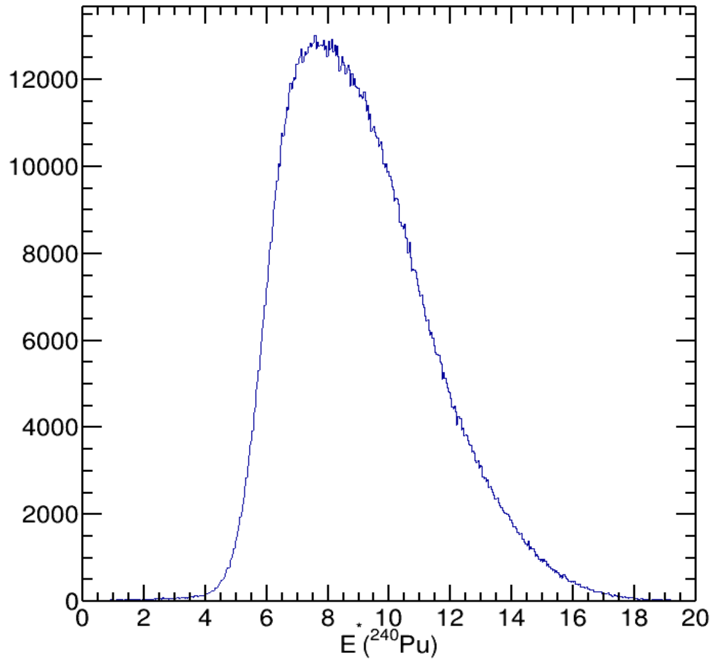


Selection of the fissioning system : ^{240}Pu

Excitation energy distribution of ^{240}Pu

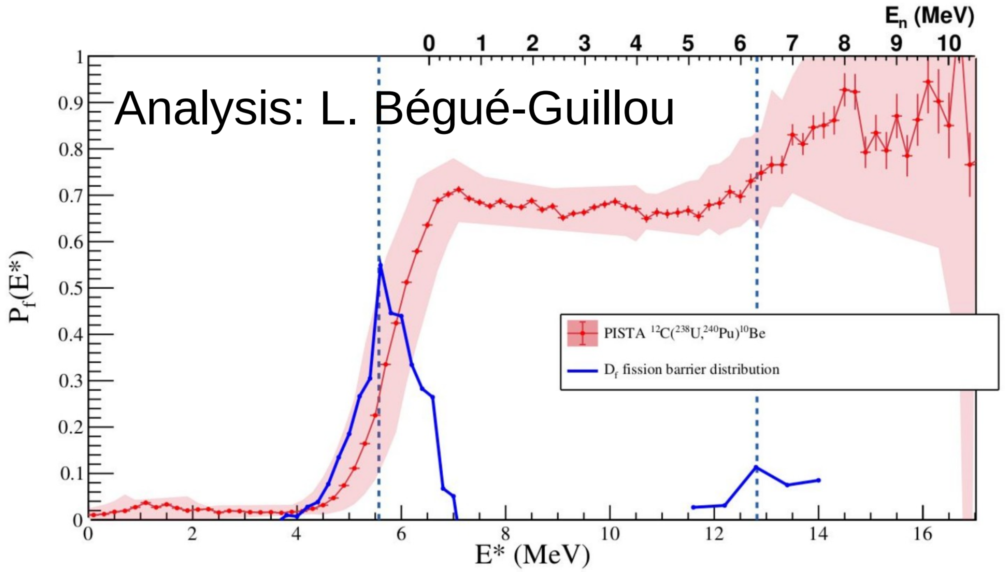


PISTA analysis done by Lucas Bégué-Guillou

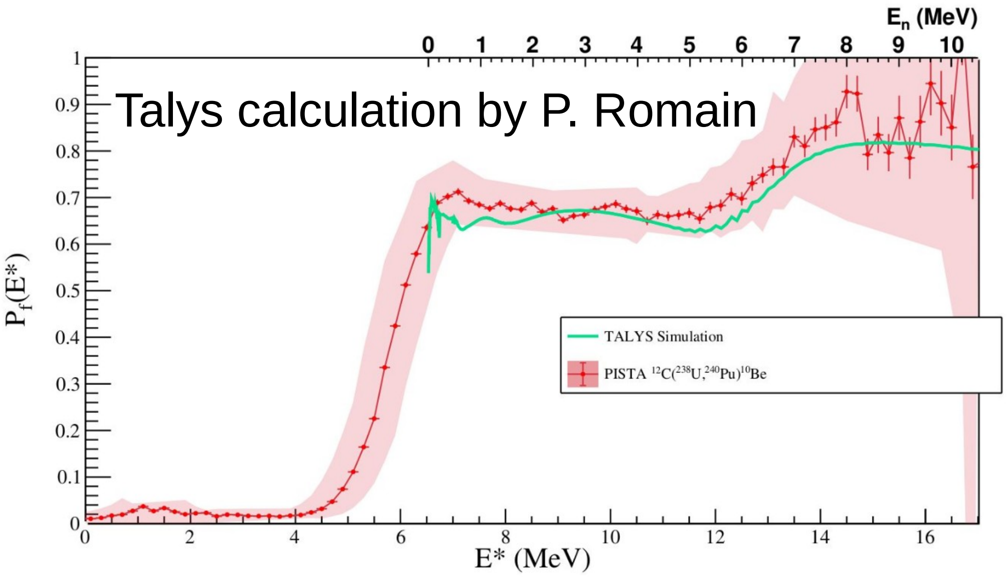
Fission probability

Experimental fission probability

- The derivative of the distribution gives the fission barrier experimentally:
  - B_1 = 5.80 +/- 0.50 MeV
  - B_2 = 13.10 +/- 1.20 MeV
- Good agreement with TALYS calculation (n-induced by P. Romain)

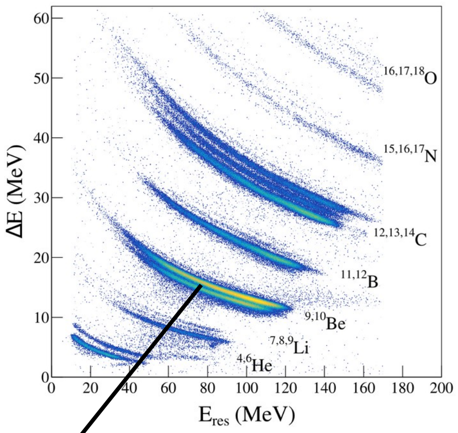


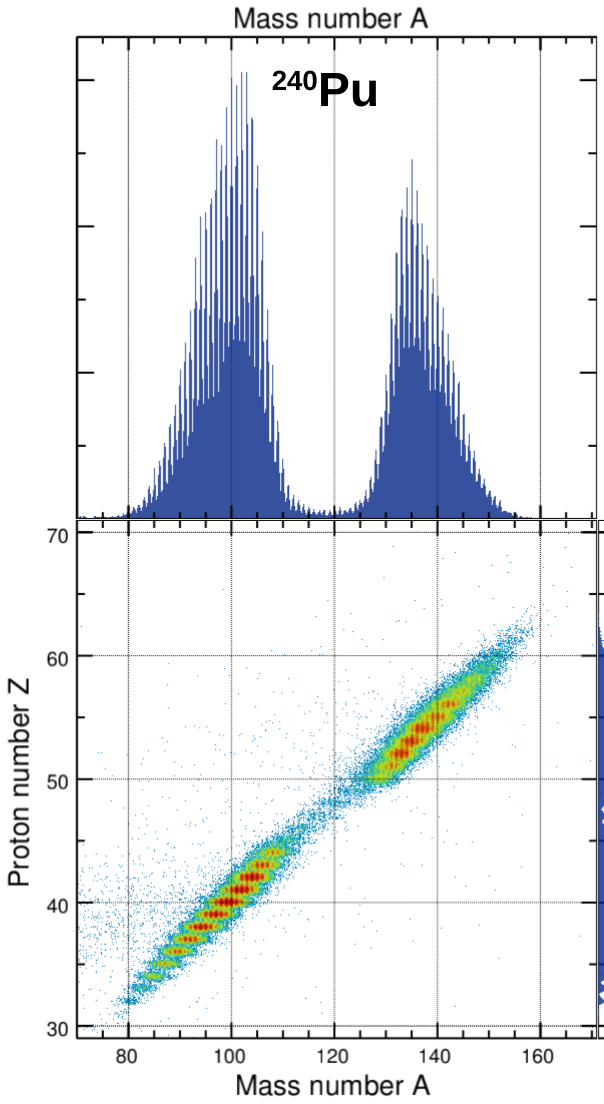
Beyond identifying the fissioning system and measuring its excitation energy on an event-by-event basis, the fission fragments are identified using the VAMOS++ spectrometer in coincidence.

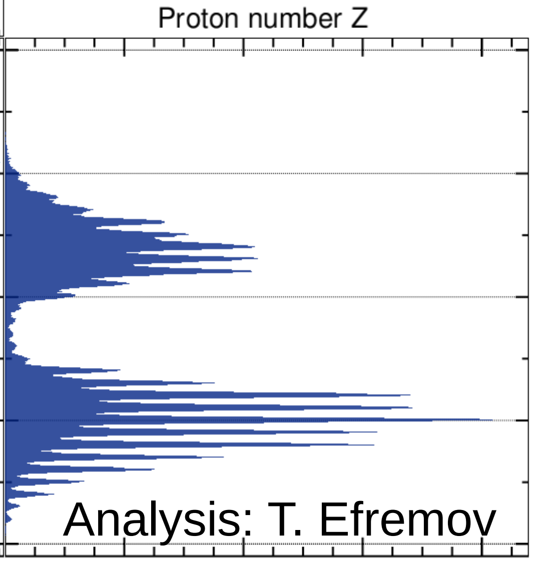


Fragment identification with Vamos++

- **^{240}Pu distribution**
  - Selection of ^{10}Be in PISTA
  - Complete isotopic identification of the fission fragment in coincidence.



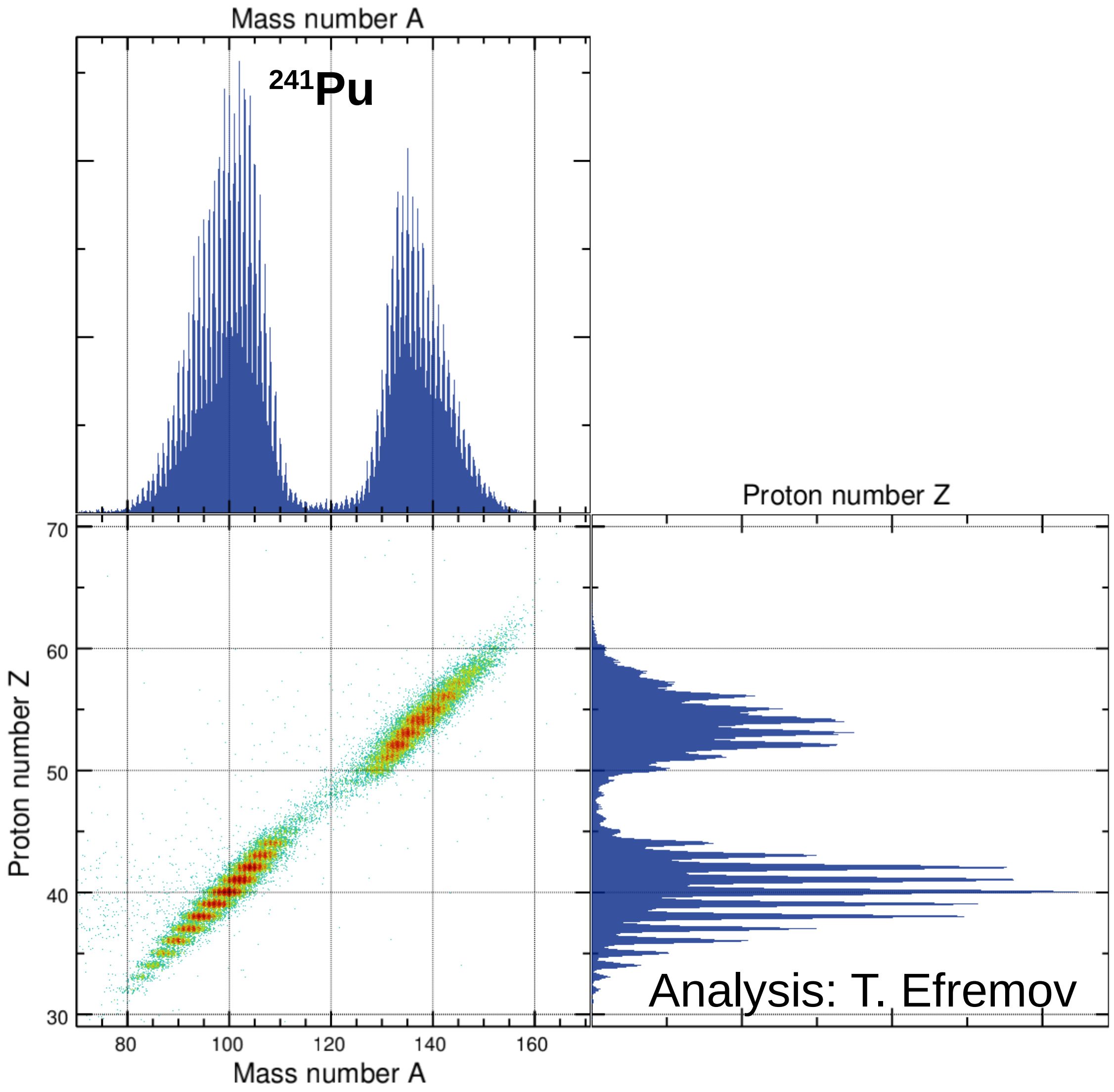




Fragment identification with Vamos++

- **^{240}Pu distribution**
  - Selection of ^{10}Be in PISTA
  - Complete isotopic identification of the fission fragment.

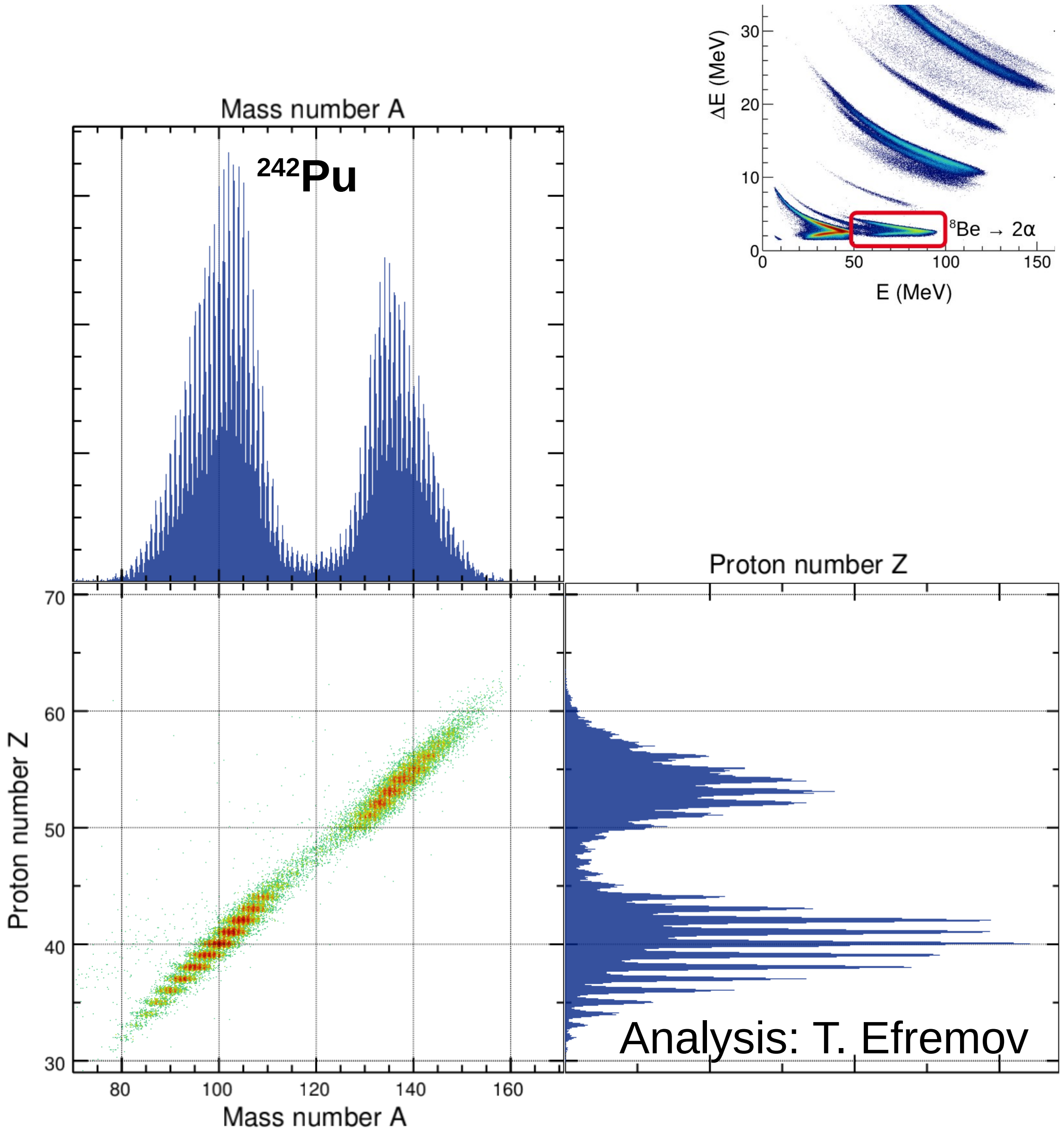
- **Other fissionning system**
  - ^{241}Pu → selection of ^{9}Be in PISTA



Fragment identification with Vamos++

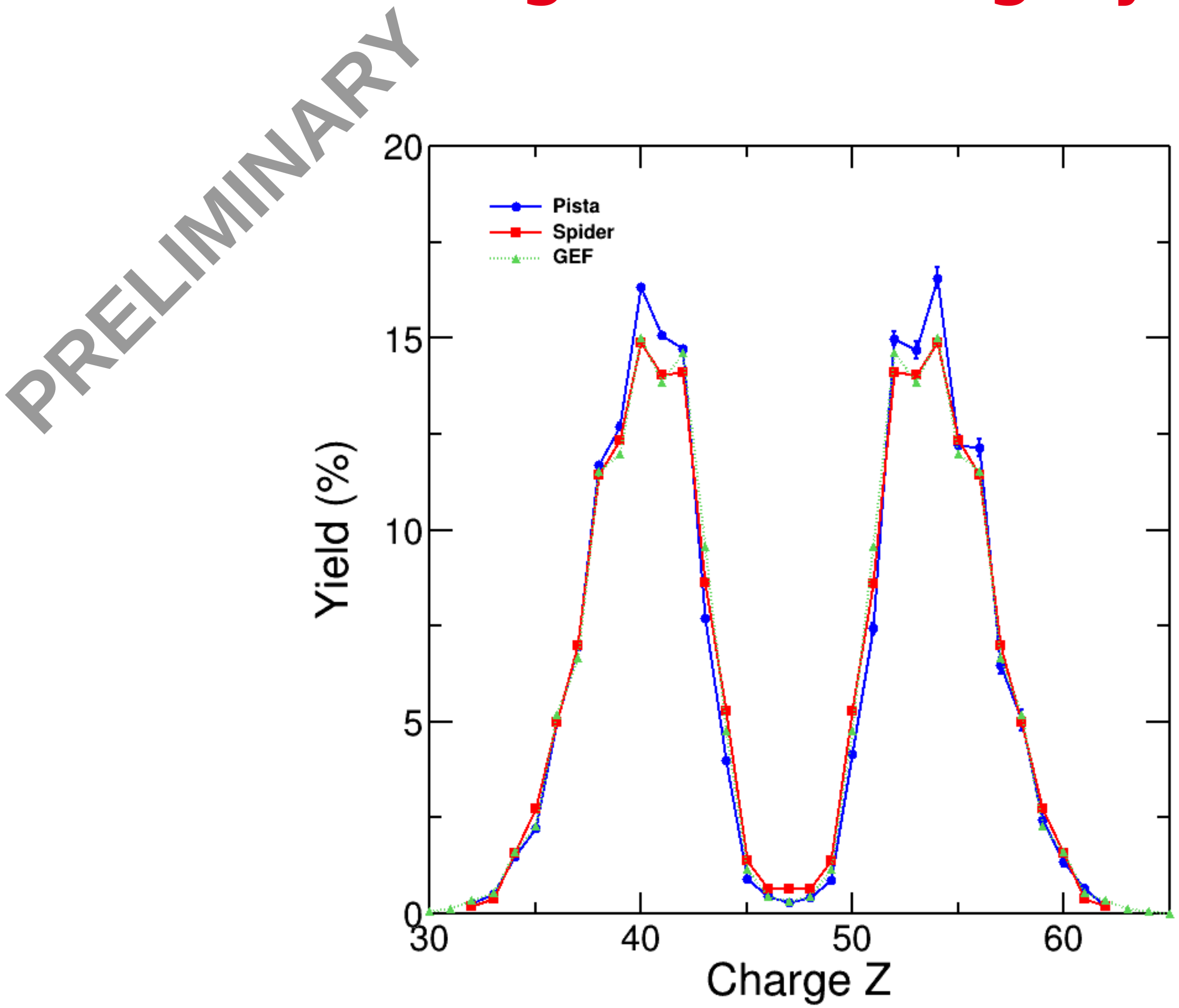
- **^{240}Pu distribution**
  - Selection of ^{10}Be in PISTA
  - Complete isotopic identification of the fission fragment.

- **Other fissionning system**
  - ^{241}Pu → selection of ^{9}Be in PISTA
  - ^{242}Pu → selection of ^{8}Be → 2α in PISTA (multiplicty 2 analysis in PISTA)



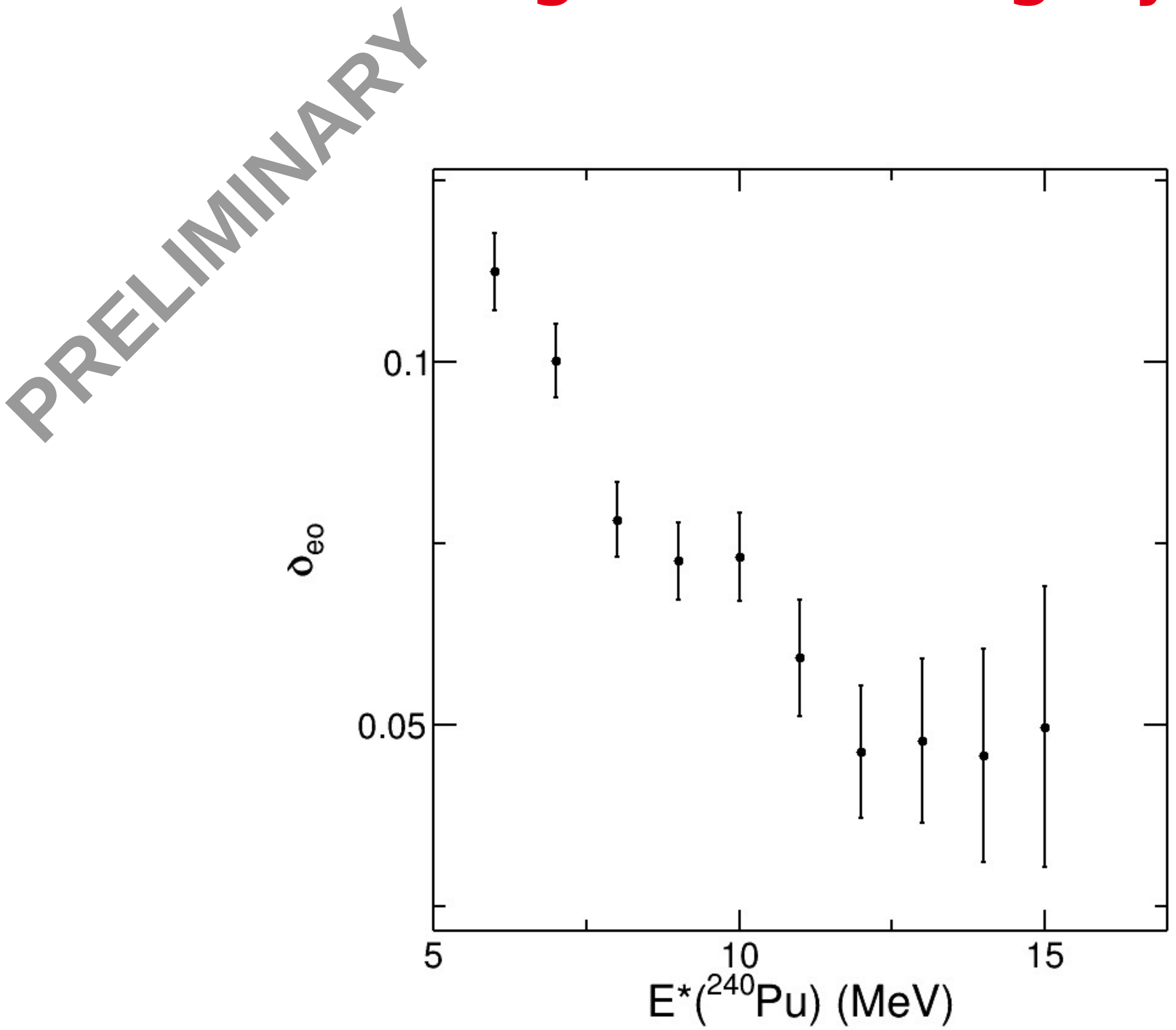
→ **From fission fragment identification to fission yield**

Fission fragment charge yields



- Only few experiments are able to measure the full distribution of the charge yield.
  - One of the key feature of VAMOS.
- We measure it as a function of excitation energy:
  - Proble shell effect damping
  - Probe reduction of the pairing by measuring the evolution of the odd-even effect δ_{oe}.

Fission fragment charge yields



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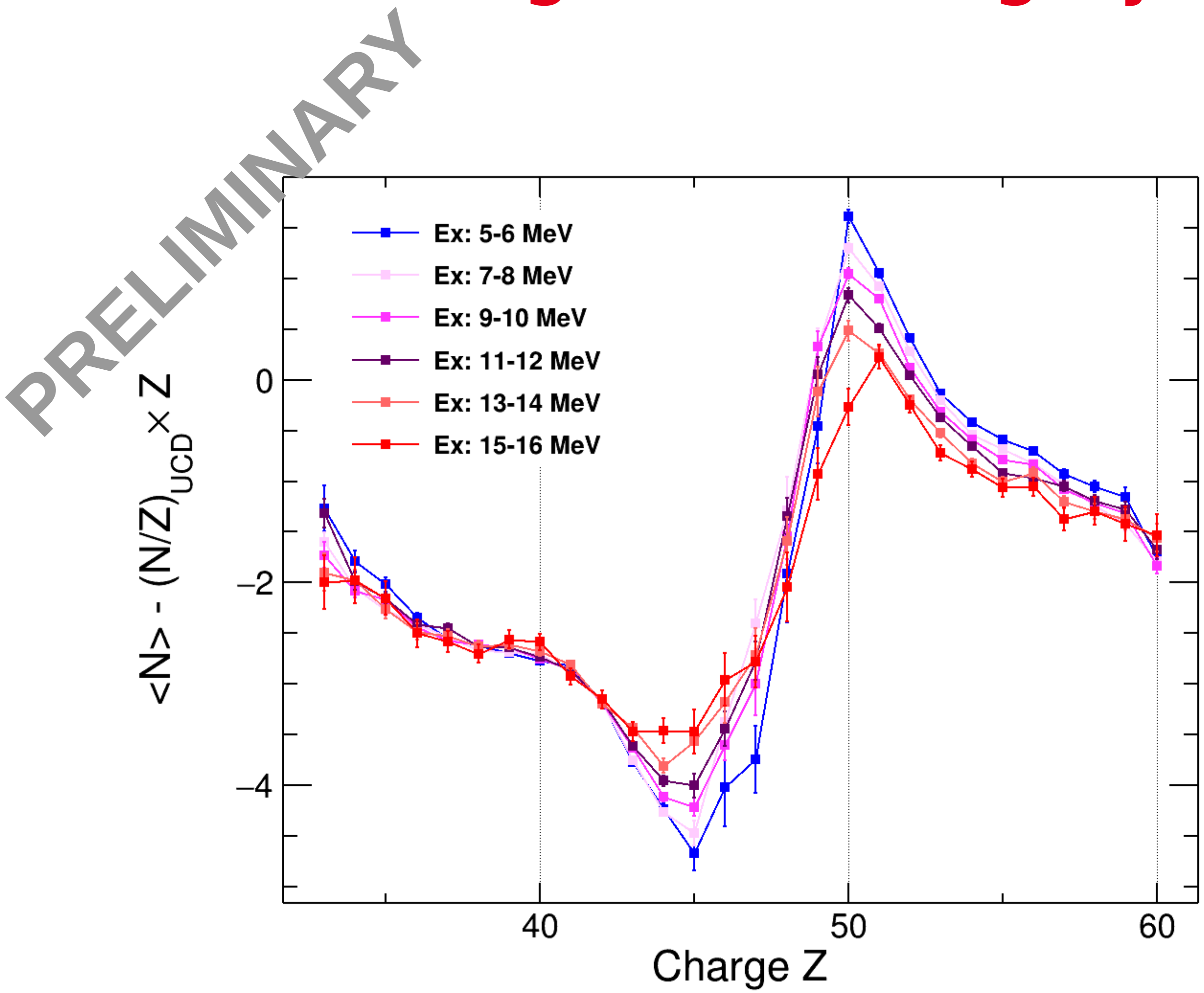
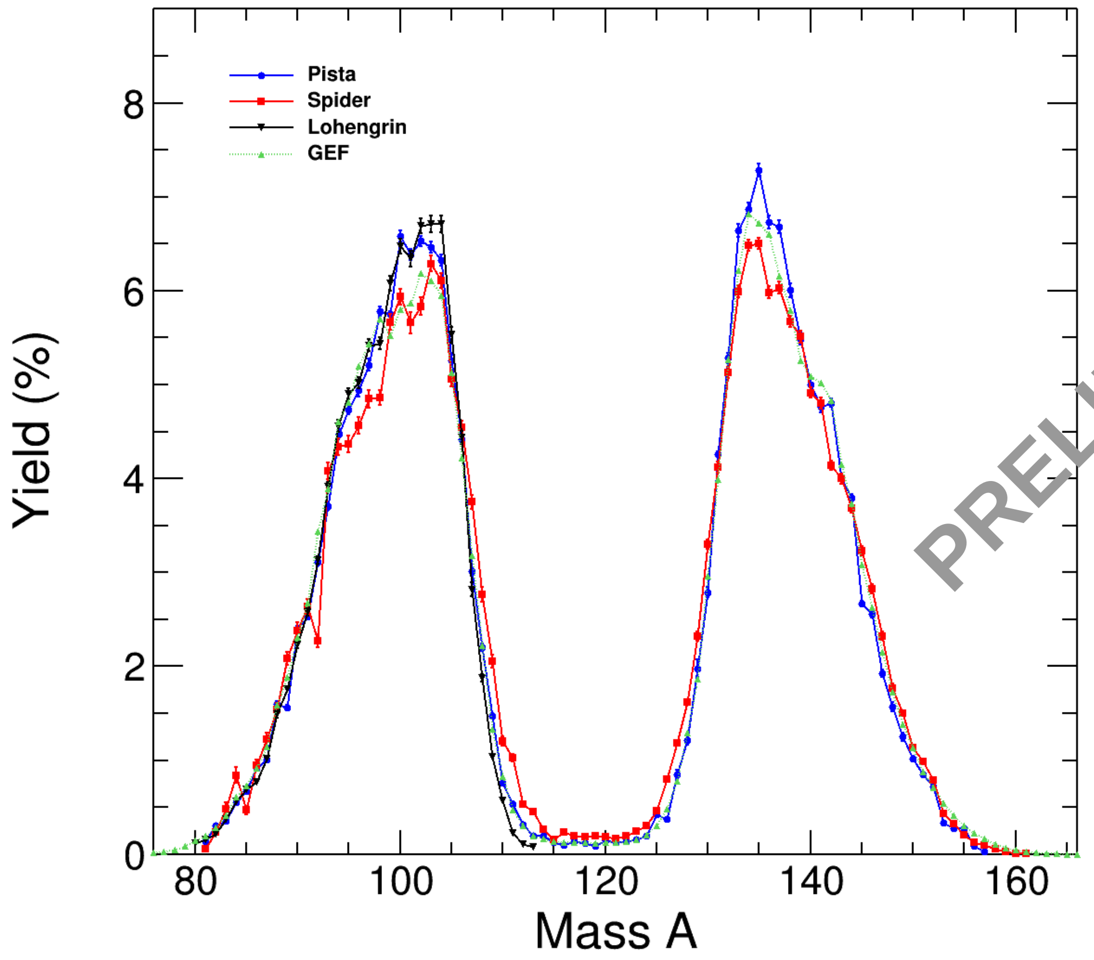
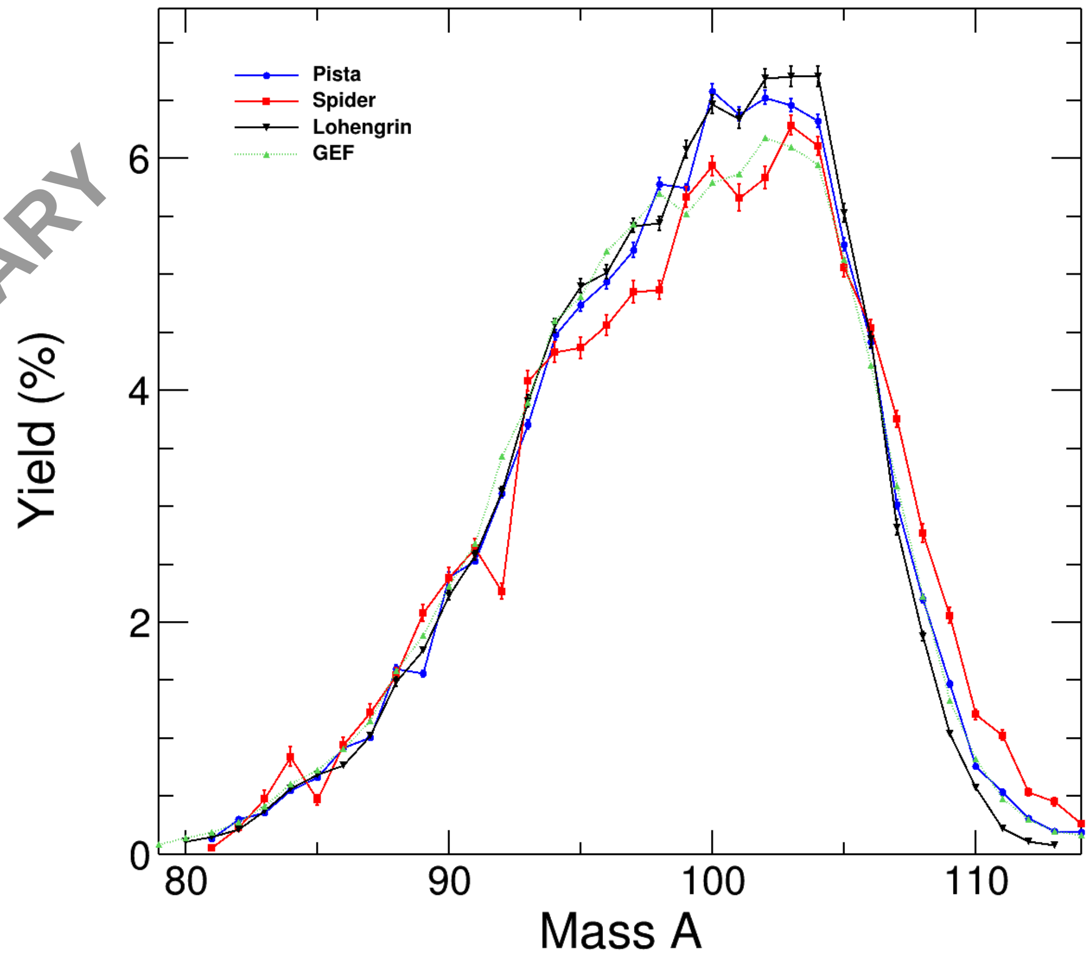
Fission fragment charge yields



- Only few experiments are able to measure the full distribution of the charge yield.
  - One of the key feature of VAMOS.
- We measure it as a function of excitation energy:
  - Proble shell effect damping
  - Probe reduction of the pairing by measuring the evolution of the odd-even effect δ_{oe}.
  - Measuring the evolution of neutron excess in fission fragment (energy sorting).

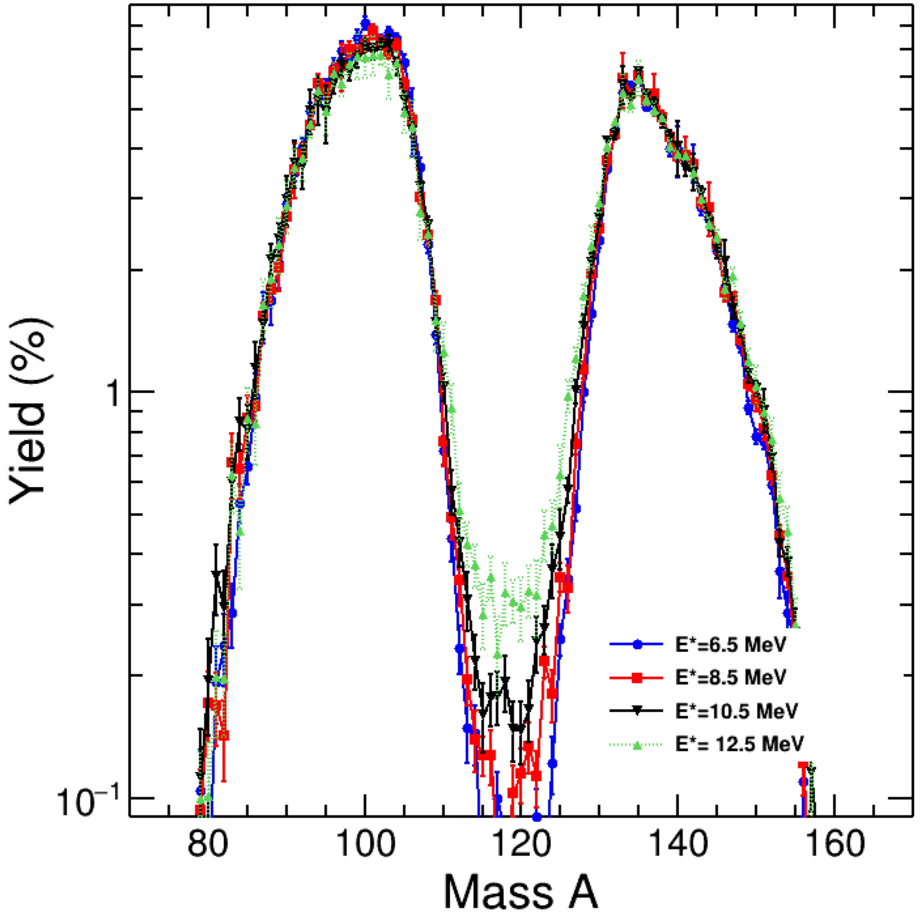
Fission fragment mass yields





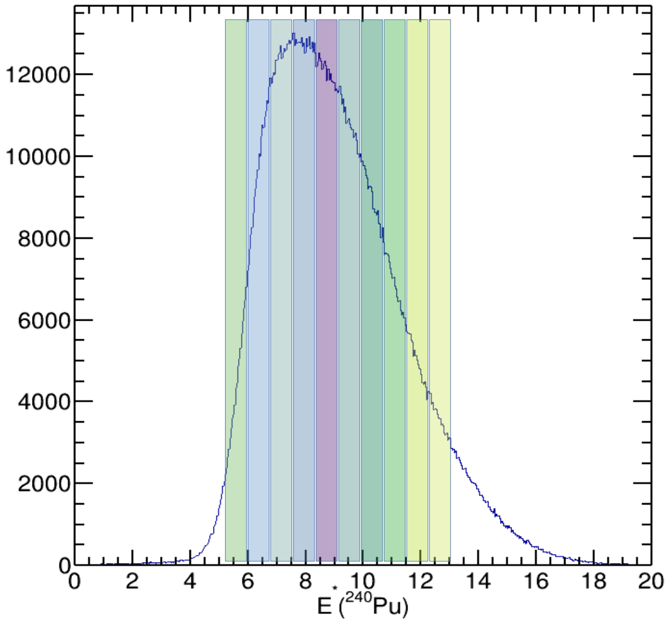
Evolution with E*

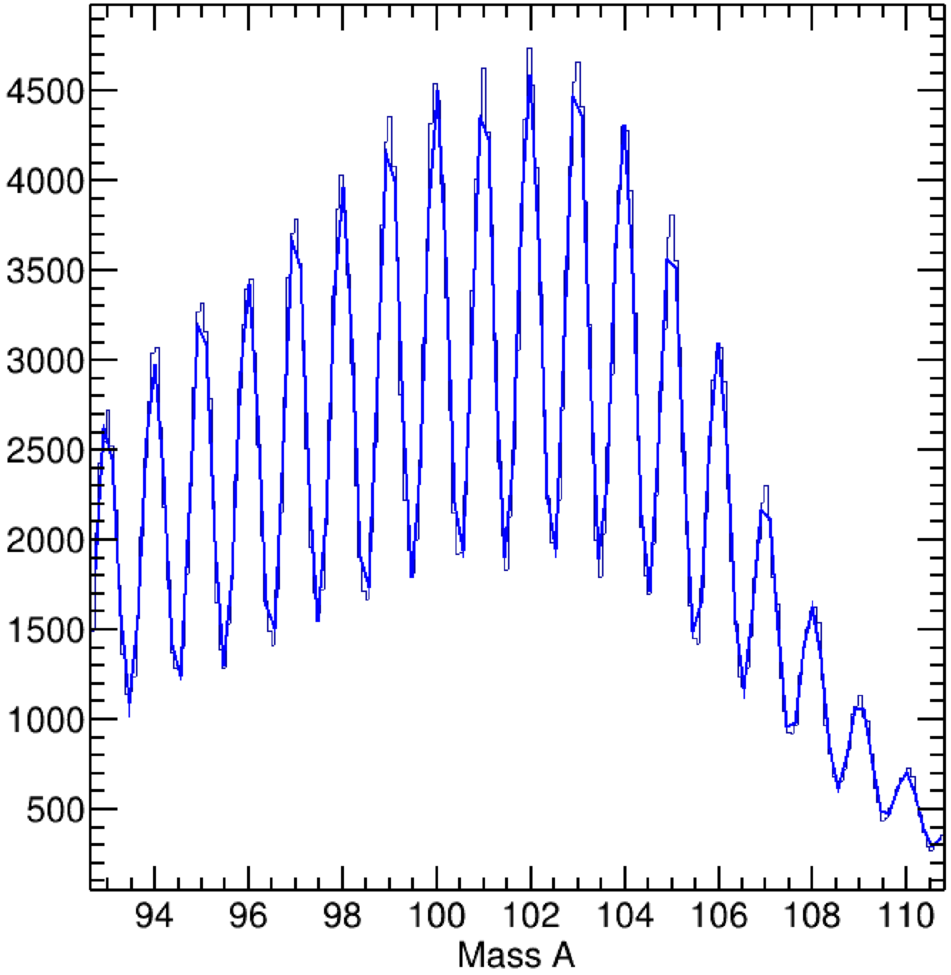
- ^{240}**Pu mass distribution for different excitation energy**
  - ✓ The symmetric component is rising, as expected.



Fission fragment yield

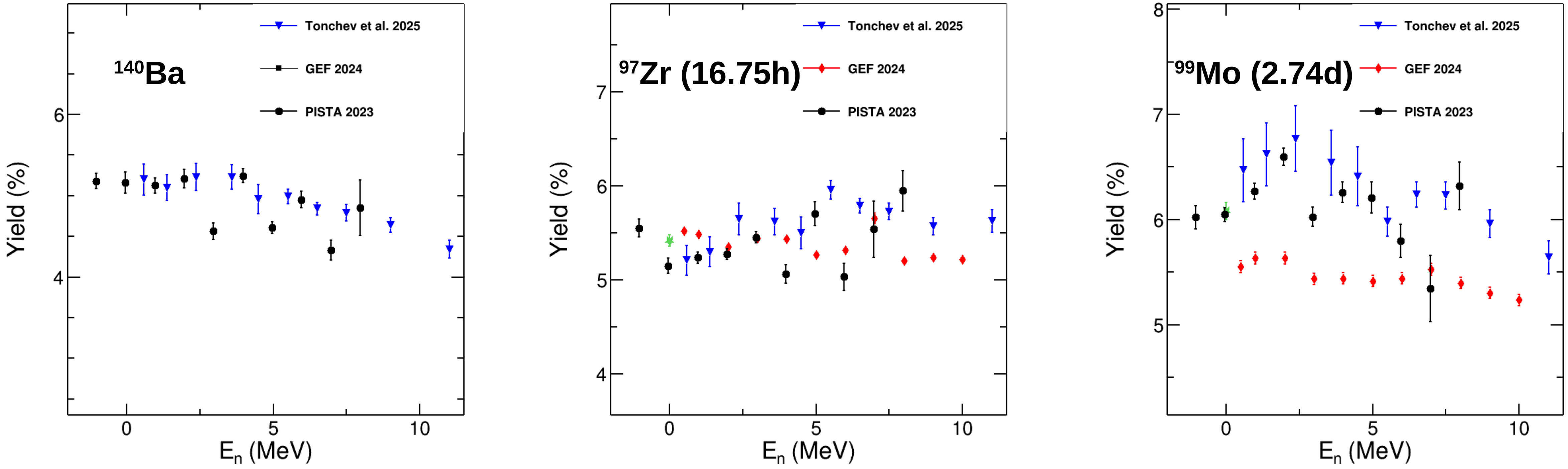
- **Mass distribution with the current acceptance correction**
  - For a bin of 1 MeV in E*, we can look at the evolution of a given mass using a multi-gaussian fit.
  - For example, mass 99 can be compared with cumulative-yield measurements of ^{99}Mo.





Some yield evolution

VERY PRELIMINARY



Conclusion

- The first data analysis combining, for the first time, PISTA and VAMOS are very promising
  - The use of inverse kinematics gives access to full fission-fragment identification.
  - PISTA gives a better characterization of the fissioning system (A_{CN},Z_{CN},E*).
  - VAMOS is a key instrument for heavy ion identification (large acceptance and high resolution in both charge and mass)
  - For ^{240}Pu isotopic yield measurement for 6 < E* < 16 corresponding to **0 < E_n < 10 MeV.**

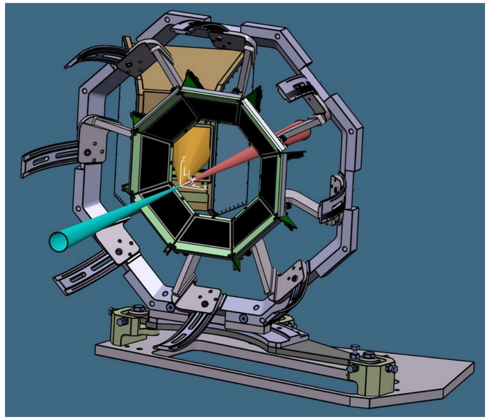
- Ultimately, we will be able to compare these results with the recent cumulative-yield measurements from TUNL.
  - We can compare all masses in a systematic and consistent manner.
  - Examine the effect of the entrance channel on the fission-fragment yield.
  - Study of the shell-effect damping and reduction of odd-even effect especially below second chance fission.

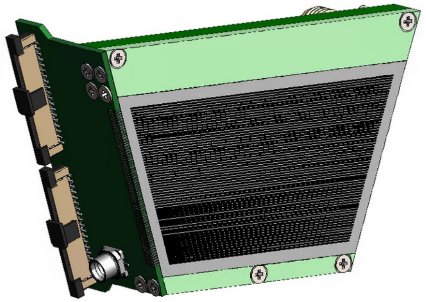
- Different fissioning systems
  - Three Pu isotopes will be studied: ^{240,241,242}Pu
  - The ^{11}B giving ^{239}Np can also be studied

- Collaboration to include these new data for fission yield evaluation.

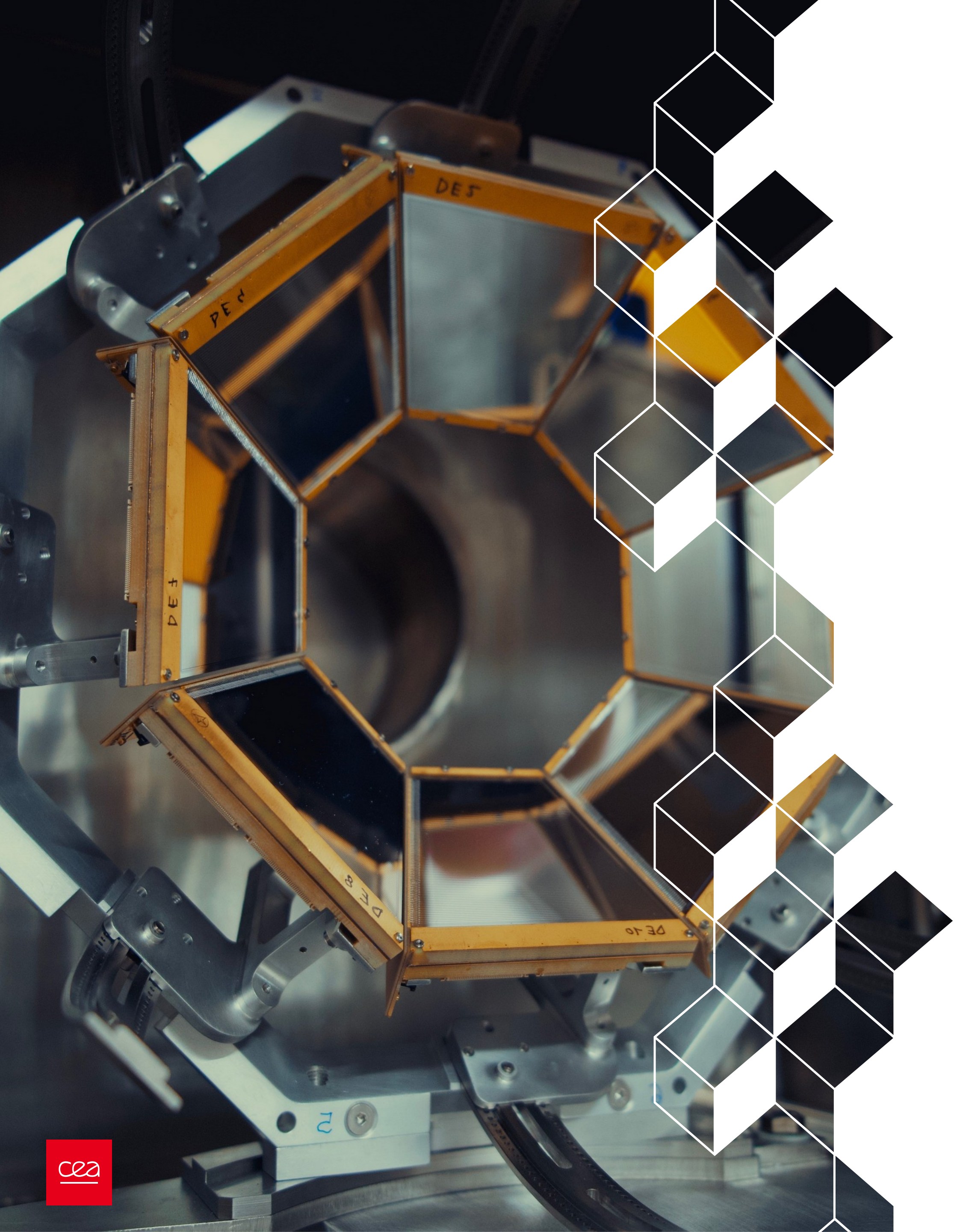
Perspectives

- **PISTA-2 (short term)**
  - Focus on ^{236}U fissioning system (^{235}U+n).
  - $^{232}Th(^{12}C,^{8}Be\rightarrow 2\alpha)^{236}U$
  - Designed for lighter particle detection.
  - High granularity → Very efficient to detector the 2**α** particles.
  - New design
    - ΔE 300 um, 64 horizontal strips
    - E 1.5 mm, 64 vertical strips
  - Approved experiment by the GANIL PAC.
    - Scheduled from 26rd of April to 7th of May





- **A ^{235}U beam at GANIL (longer term)**
  - No strong limitation from regulation.
  - No technical issue.
  - Focus on ^{236}U fissioning system (^{235}U+n).
  - One neutron-transfer reaction: (d,p) or ($^{9}Be,^{8}Be\rightarrow 2\alpha$)
    - PISTA-2 and/or GRIT?
  - Less transferred angular momentum.
  - Direct comparison of the entrance channel.



Thank you

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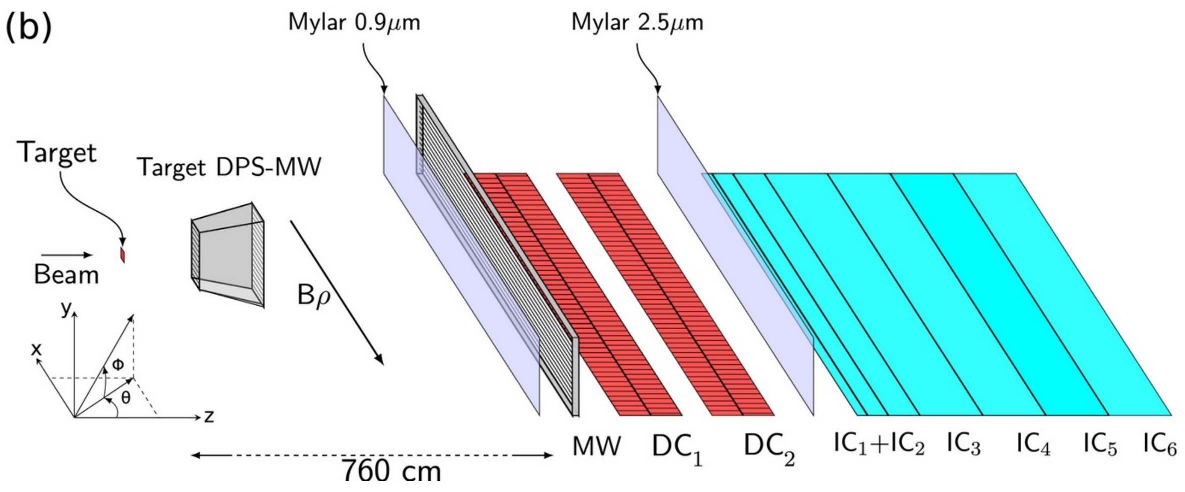
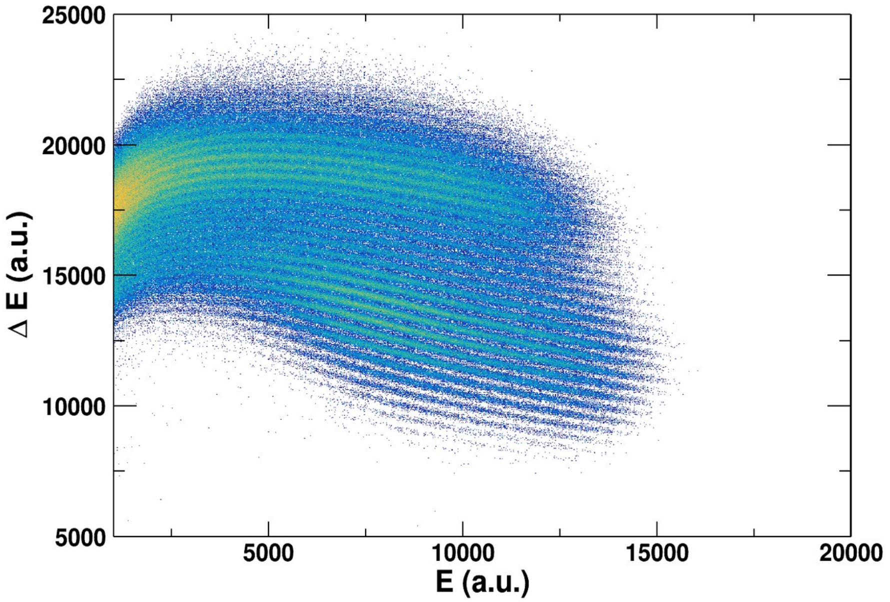
Fragment identification with Vamos++

- **Observables**
  - Magnetic rigidity Bρ
  - Trajectory
  - Energy loss and total energy ΔE-E
- **Detectors**
  - Ionisation chamber (IC) → ΔE-E → Z
  - Position in MWPC → (ToF, L) → Bρ → A/Q

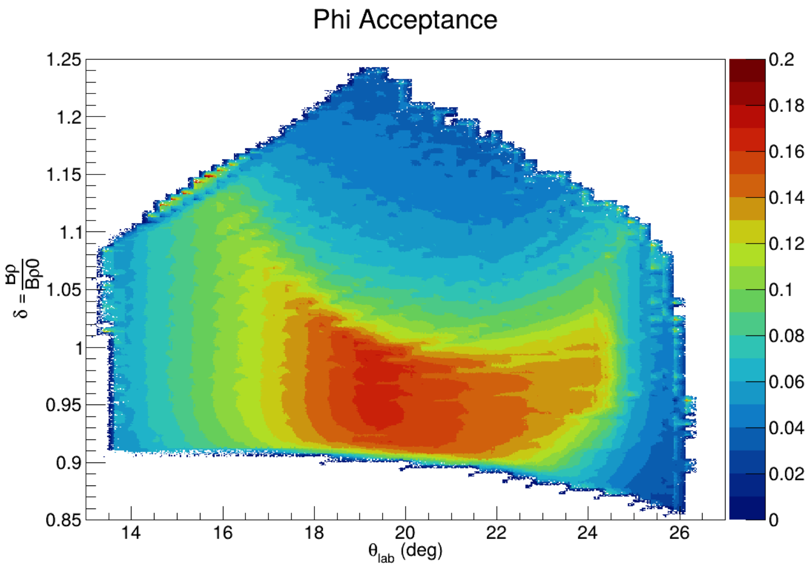


=> With Vamos++, one of the fission fragment is identified in mass A, charge Z and charge state Q.



From fission fragment identification to fission yield

- **Fission fragment identification (A,Z) is complete**
  - $\Delta A/A = 0.55\%$
  - $\Delta Z/Z = 1.3\%$
  - To extract the final normalized yields, one needs to correct from the VAMOS acceptance
    - In ϕ_{lab} => Acc = $\Delta\phi/2\pi$ for a small slice in θ_{lab} and δ
    - In $\theta_{c.m.}$: the difficulty is to make sure, that the full charge state distribution has been measured => analysis in progress.
    - Work in progress...



Some open questions in nuclear fission

- **What drives asymmetric fission?**

→ *Nuclear data need*
  - ✓ High-precision fission fragment mass and charge distributions.
  - ✓ Isotopic yields across a wide range of actinides
  - ✓ Data as a function of excitation energy/incident neutron energy

- **How does the nucleus evolve from saddle to scission?**

→ *Nuclear data need*
  - ✓ Correlated measurements of fragment masses, total kinetic energy (TKE), and excitation energy.
  - ✓ Scission-point observables

- **What determines fragment mass, charge, and kinetic energy distributions?**

→ *Nuclear data need*
  - ✓ Complete fission yield data (independent and cumulative)
  - ✓ Precise TKE distribution
  - ✓ Covariance data for model validation

- **How is excitation energy shared between fragments?**

→ *Nuclear data need*
  - ✓ Fragment-resolved prompt neutron multiplicities
  - ✓ Neutron spectra as a function of fragment mass

- **How does pairing influence fission dynamics?**

→ *Nuclear data need*
  - ✓ Odd-even staggering in fragment yields
  - ✓ High-resolution charge distributions