Fission studies at R3B using the SOFIA setup

DE LA RECHERCHE À L'INDUSTRIE

NUSTAR week 2019

Gif -sur-Yvette, France

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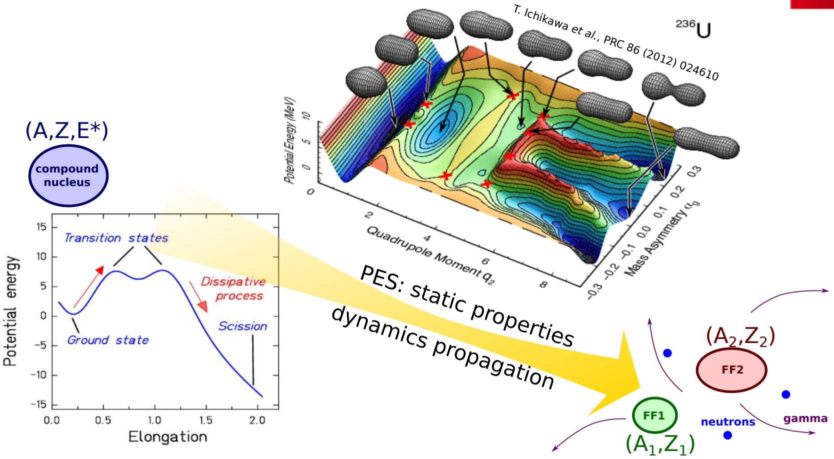
A. Chatillon (CEA, DAM, DIF) for the R^3B/SOFIA collaboration

Why studying fission at R3B ?

I - Large physics case: applications, r-process, understanding the reaction for models



SOFIA@R3B: correlation of several fission observables for a complete description

BARRIER

PROBABILITY

YIELDS: Y(Ai,Zi)

PROMPT EMISSION

EVOLUTION WITH E*

Why studying fission at R3B ?

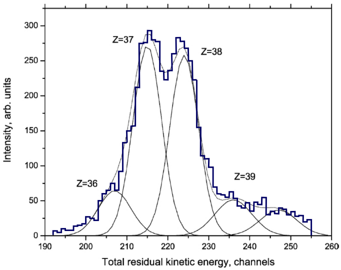
II - To avoid the limitation due to direct kinematics

DIRECT KINEMATICS: FF WITH LOW RECOIL ENERGY IN THE LAB. FRAME

Beam = neutrons, light charged particles, γ & Target = actinides

- **Isotopic yields are incomplete**
- nuclear charge from energy loss measurement:
  $\Rightarrow$ **limitation to Z$\leq$42**
- mass from total energy measurement:
  $\Rightarrow$ **resolution around 4 mass unit FWHM**
- **targets limited** to long-lives nuclei
- very low efficiency due to the 4-π emission
  $\Rightarrow$ **low statistics**

D. Rochman et al. / Nuclear Physics A 710 (2002) 3–28



Why studying fission at R3B ?

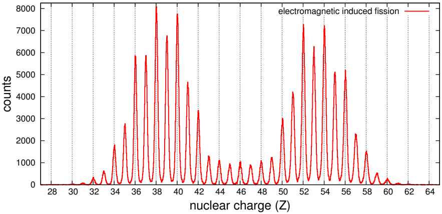
II - To avoid the limitation due to direct kinematics...

... thanks to the powerful tool of the inverse kinematics at relativisitic energy

INVERSE KINEMATICS AT 700 A.MeV: (Z,A) IDENTIFICATION FROM ΔE-Bρ-ToF

Radioactive beam & Surrogate reactions

analysis by L. Grente

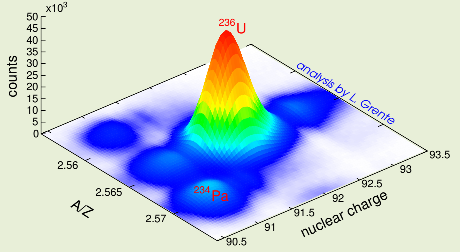


- FRS + R3B : (Z,A) identification of the compound nucleus and both fission fragments after neutron emission
- **ΔZ = 0.35 charge unit FWHM**
- **ΔA = 0.5 to 0.8 mass unit FWHM**
- **total prompt neutron multiplicity** from $A_{\rm CN} = A_{\rm FF1} - A_{\rm FF2}$
- Use of radioactive beams: broad range of fissioning nuclei
- Use of surrogate reactions to produce the compound nucleus:
  $\Rightarrow$ coulex induced fission: accurate measurement of Y(A,Z) and ν_{tot} at $\langle E^*_{\rm CN}\rangle \sim$14 MeV
  $\Rightarrow$ (p,2pf): first experiment in 2020 to measure E* in coincidence: Complementary experiment!
- very high geometrical efficiency: around 90 % (from ^{236}U(γ,f) data in 2014)

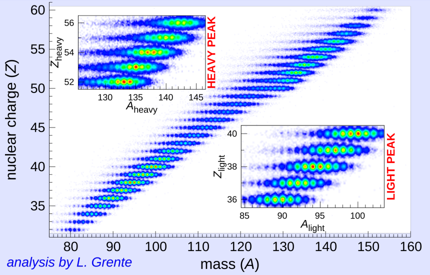
Two experiments in 2012 and 2014 at R3B with ALADIN

- 2012: Coulex-induced fission in the uranium and thorium regions (J. Taieb *et al.*)
- 2012: Spallation-fission of ^{208}Pb (J. Benlliure *et al.*)
- 2014: Coulex-induced fission of ^{236}U (J. Taieb *et al.*)

ΔE-Bρ-ToF applied at FRS

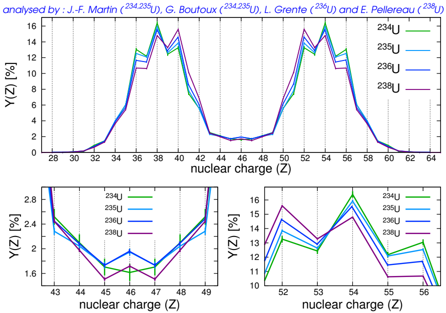


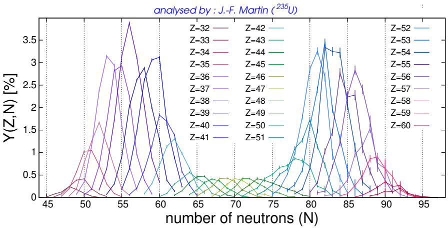
ΔE-Bρ-ToF applied at Cave C



Accurate yields along the uranium chain

- Error bars are shown in figures
  - $\Rightarrow$ Elemental yields: $\sigma_{\text{asym}} \lesssim 1\%$ and $\sigma_{\text{sym}} \lesssim 2\%$
  - $\Rightarrow$ Isotopic yields: $\sigma_{\text{light}} \lesssim 2\%$, $\sigma_{\text{sym}} \lesssim 3\%$ and $\sigma_{\text{heavy}} \lesssim 5\%$



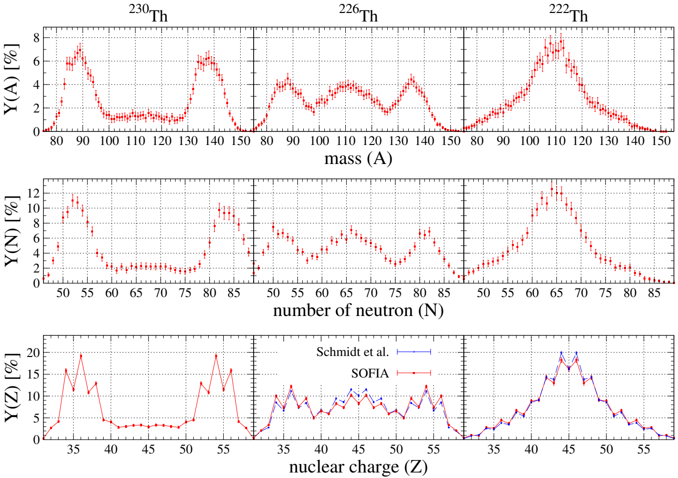


J.-F. Martin, J. Taieb *et al.*, Eur. Phys. J. A **51** (2015) 541

E. Pellereau, J. Taieb *et al.*, Phys. Rev C **95** (2017) 054603

From asymmetric to symmetric fission along the thorium chain (I)

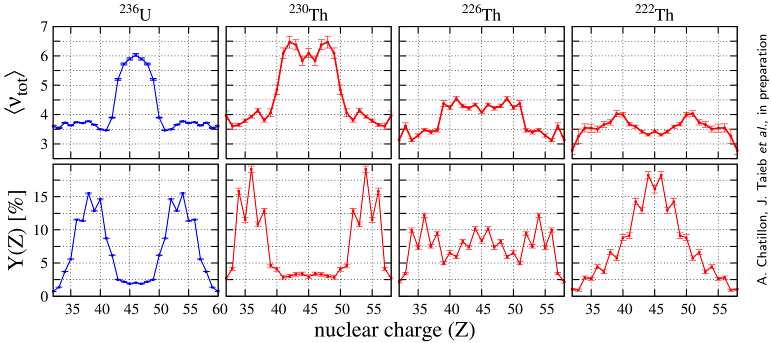
- First observed from Y(Z) measurement in the 90's (K.-H. Schmidt et al., NPA **665** (2000) 221)
- SOFIA: measurement of Y(Z), Y(N), Y(A) and prompt-neutron multiplicity



A. Chatillon, J. Taieb *et al.*, Phys. Rev C **99** (2019) 054628

From asymmetric to symmetric fission along the thorium chain (II)

- **Probe the scission configuration** thanks to $\langle\nu_{\mathrm{tot}}\rangle(Z)$
  $\Rightarrow$ $\langle\nu_{\mathrm{tot}}\rangle(Z)$ increases with the Q_2-deformation of the fission-fragments
- **Prompt neutron multiplicity drops at symmetry**



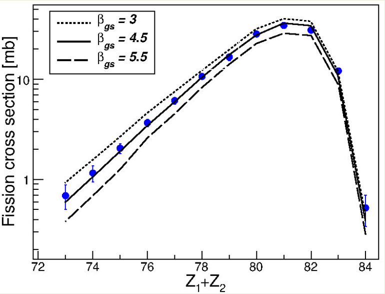
new compact scission configuration at symmetry for the light thorium
totaly different from the known elongated symmetric scission mode in uranium region

$^{208}Pb(p,f)$ at 500 A.MeV

- Application: characterize the spallation neutron sources and secondary beam facilities
- Understanding of the dynamics in fission through the dissipation parameters
- Isotopic identification of both FF: Z_1+Z_2 are obtained unambigously in coincidence with
  - ⇒ fission cross section
  - ⇒ neutron excess in the fission fragments

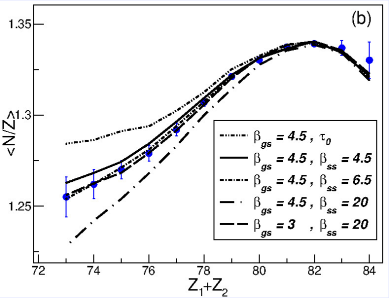
Ground to saddle dynamics

- cross section
- J. L. Rodriguez-Sanchez *et al.*, Phys. Rev C **91** (2015) 064616



Saddle to scission dynamics

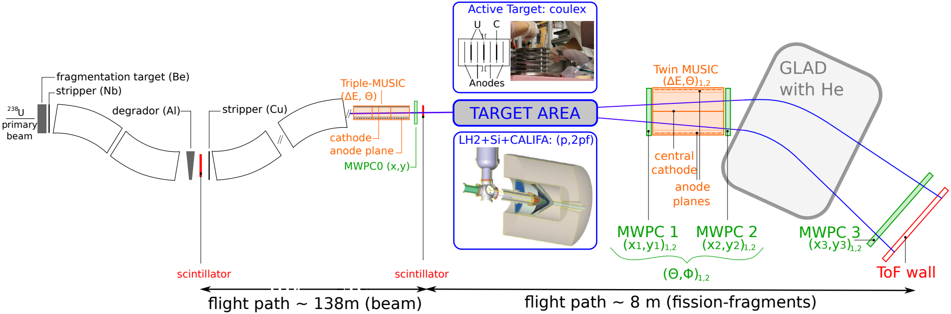
- neutron excess
- J. L. Rodriguez-Sanchez *et al.*, Phys. Rev C **94** (2016) 061601 (R)



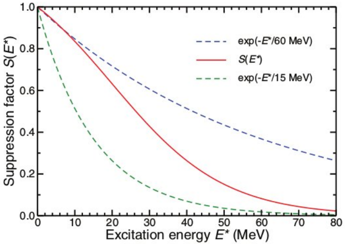
Accepted proposal for Fission@R3B (s455)

1. **Temperature dependance of shell effects in the PES and energy sharing between FF:**
⇒ *(p,2p) induced fission of ^{238}U primary beam*
2. **Fission barrier around N=126 in Po isotopes:**
⇒ *(p,2p) induced fission of radioactive beams*
3. **Symmetric to asymmetric fission in neutron deficient A=180-210 nuclides:**
⇒ *coulex induced fission of radioactive beams*

Setup based on a common basis



(p,2p) induced fission of primary ^{238}U beam. J. Benlliure *et al.*



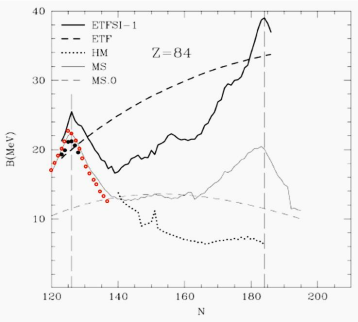
Damping of the shell effects with E^* & Energy sharing between FF

- **AIM**: Evolution of the fission observables as a function of E^* : from B_f to 80 MeV
- Yields and prompt-neutron multiplicity depends on E^* and $(A_{\mathrm{CN}}, Z_{\mathrm{CN}})$
- **BUT**: Difficult to study such effect in direct kinematics
- **SOLUTION**: Couple R3B/SOFIA with LH2 target, the Si tracker and CALIFA
  ⇒ ^{238}U(p,2pf): tracking of the protons to measure E^*
  ⇒ R3B/SOFIA: isotopic identification of both FF and total prompt-neutron multiplicity
- NeuLAND can be used to measure the prompt-neutron multiplicity per fragment
- **Describe the evolution of the shell effects as a function of the excitation energy**
- **How the additional excitation energy is shared between the FF ?**

(p,2p) induced fission of polonium around N=126. D. Müchner *et al.*

Fission barrier: strong test of the models

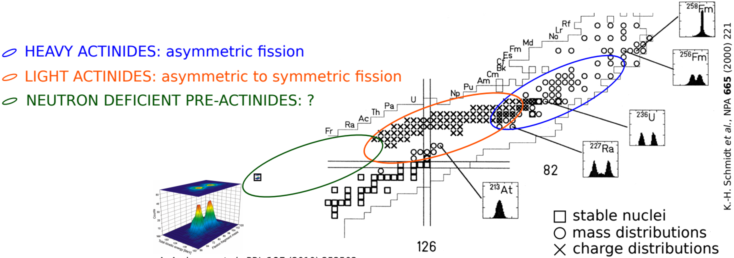
- Fission barriers are known:
  ⇒ for few nuclides only
  ⇒ mostly close to the stability valley
- And for the exotic nuclei?
  ⇒ key data for the r-process cycling simulation
  ⇒ but no experimental data
  ⇒ rely on models
  ⇒ but strong divergence of the predictions
- **New measurements are mandatory to qualify the models**



Mamdouh et al., Nucl. Phys. A 679, 337 (2001)

Coulex-induced fission of neutron deficient pre-actinides. J. Taieb *et al.*

Yields and $\langle \nu_{\mathrm{tot}} \rangle$ from symmetric fission (Ac) down to asymmetric fission (Hg)



A. Andreyev *et al.*, PRL **105** (2010) 252502

- 70's: role of the FF shell effects in asymmetric fission in heavy actinides
- 90's: first experiment using inverse kinematics at relativistic energy:
  ⇒ transition from asymmetric to symmetric fission along the thorium
  ⇒ expected symmetric fission for lighter nuclei
- 2010: unexpected asymmetric fission in Hg
- **2020: characterization of the symmetric to asymmetric fission with SOFIA@R3B**
  ⇒ **deformation at scission** of the symmetric and symmetric fission modes
  ⇒ underlying **p- and n- shell** effects of these fission modes
  ⇒ **pairing** effect in these systems having a high fission barrier

^{242}Pu beam

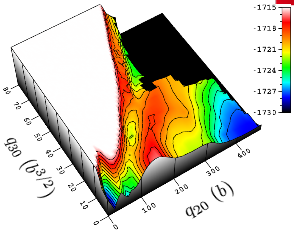
- Accurate yields and prompt-neutron multiplicity of Pu and Am nuclides
  - ⇒ data beyond A=238
  - ⇒ important nuclides for the nuclear technology
  - ⇒ especially for the fast-neutron Gen-IV reactor
- **Pu source: interest for part of the NUSTAR community**
  - ⇒ **beams around ^{132}Sn produced by fission with one order of magnitude higher than with U**
  - ⇒ a factor 10 in the statistics...
  - ⇒ you should tell in case you could be interested by such a source
- ^{242}Pu available at the Oakridge National Laboratory

- FAIR + R3B is a unique facility for the fission studies
- Relativistic secondary beams:
  - ⇒ high intensity 1 A.GeV 238U beam
  - ⇒ production of a broad range of of actinides and pre-actinides
  - ⇒ possibility to study the fission of nuclei unreachable in direct kinematics
- R3B/SOFIA coupled to standard R3B
  - ⇒ identification of both fission fragments in coincidence with $\langle \nu_{\rm tot} \rangle$
  - ⇒ fission observable as a function of E^*
- Fission@R3B can:
  - ⇒ probe the scission configuration
  - ⇒ study the p- and n- shell effects
  - ⇒ extract the fission barrier
  - ⇒ probe the fission dynamics

Thank you !

Fission in the heavy actinides (U) region proposed by Brosa

- 3 fission modes in the **actinides** region:
  - **2 asymmetric modes: ST1 and ST2**
  - **1 symmetric mode: SL**
- each fission mode:
  - proper path in the equipotentiel energy surface
  - different structure effects
  - different scission configurations



standard 1 (ST1)

- quasi-spherical heavy FF

⇒ **A_H ∼132, Z_H ∼50, N_H ∼ 82**

- deformed light FF

standard 2 (ST2)

- deformed heavy FF

⇒ **A_H ∼140, Z_H ∼54**

- p shell in Q_{30}-deformed fragments

superlong (SL)

- less shell influence (LDM)
- **increases with E^***
- very long path

Fission in the heavy actinides (U) region proposed by Brosa

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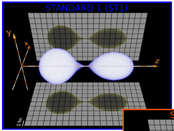
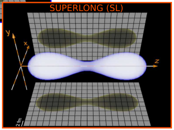




standard 1 (ST1)

- quasi-spherical heavy FF

$\Rightarrow$ **$A_H \sim$132, $Z_H \sim$50, $N_H \sim$ 82**

- deformed light FF
- short path: **compact**

HIGH TKE, LOW ν

standard 2 (ST2)

- deformed heavy FF

$\Rightarrow$ **$A_H \sim$140, $Z_H \sim$54**

- p shell in Q_{30}-deformed fragments

INTERMEDIATE TKE

superlong (SL)

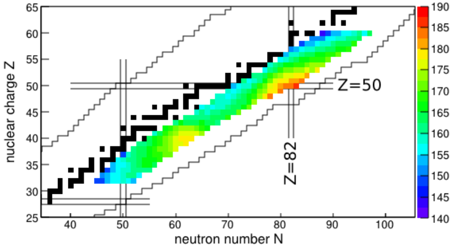
- less shell influence (LDM)
- **increases with E^***
- very long path
- **large elongation**

LOW TKE, HIGH ν

Yields + TKE or ν_{tot}: PROBE OF THE SCISSION CONFIGURATION

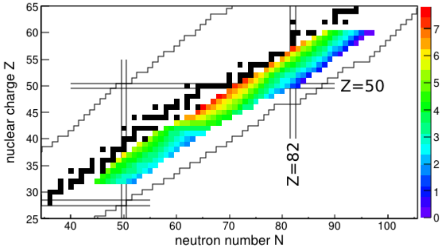
Neutron multiplicity and TKE: ^{235}U case

Analysis by J.-F. MARTIN (PhD)



$\langle \mathrm{TKE} \rangle$ vs (N_{FF}, Z_{FF})

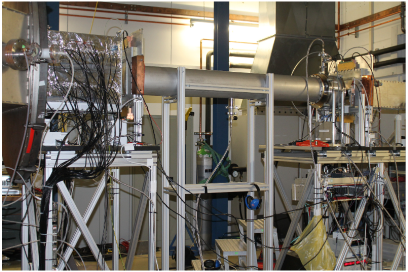
- **high TKE for ST1 mode**
  $\Rightarrow$ compact configuration
- **low TKE for SL mode**
  $\Rightarrow$ large deformation

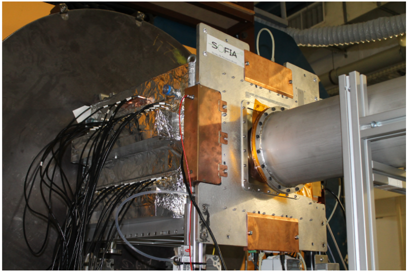


$\langle \nu_{tot} \rangle$ vs (N_{FF}, Z_{FF})

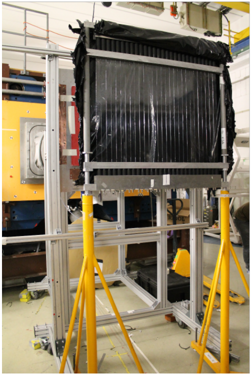
- **high $\langle \nu_{tot} \rangle$ when TKE is low**
  $\Rightarrow$ deformation energy is converted into excitation energy in the fission fragments

Setup upstream ALADIN





Setup downstream ALADIN



List of the detectors (2014), resolution are given FWHM

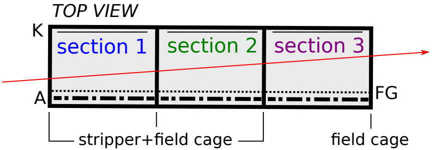
- **3×MWPCs**

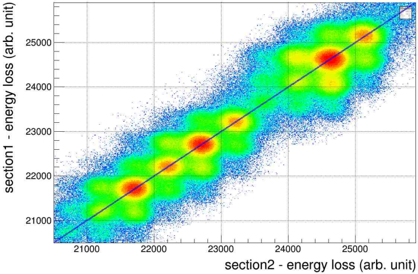
	MWPC0 beam	MWPC1 FFs	MWPC2 FFs
dimension	200×200mm^2	200×200mm^2 900×600mm^2	
x resolution	200μm	200μm	300μm
y resolution	1 mm	1 mm	1 mm

- **Twin-MUSIC**: energy loss and angle of both fission fragments
  ⇒ dimensions: (2×) 110×220×400 cm^3
  ⇒ resolutions: $\Delta Z\sim0.2$, Δx$\sim$60μm, $\Delta\theta\sim0.3$mrad
- **Triple-MUSIC**: energy loss and angle of the secondary beam
  ⇒ dimensions: (3×) 85×85×150 cm^3
  ⇒ resolutions: $\Delta Z\sim0.2$, Δx$\sim$40μm
- **Scintillators at S2**
  ⇒ dimensions: 200×32×1 mm^3
  ⇒ resolution: Δx$\sim$3mm
- **Time-of-flight wall**
  ⇒ dimensions: (28×) 660×32×5 mm^3
  ⇒ resolution: Δy$\sim$3mm, ΔToF$\sim$35 ps
- **Scintillators at Cave C**
  ⇒ dimensions: 50×32×1.5 mm^3
  ⇒ resolution: Δx$\sim$1mm
- **Active target**
  ⇒ dimensions: 10 cm diameter, 2 cm gap

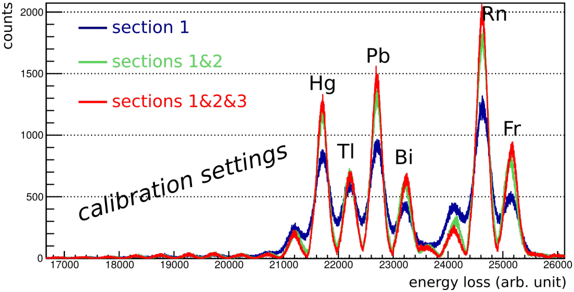
Secondary beam identification: new Triple-MUSIC and MWPC

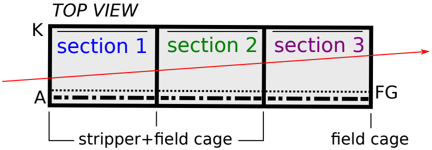
- minimization of the material in the beam path
  - gazeous detector if possible
  - if not, as thin as possible detectors (degrador at S2, plastic at S2 and cave C)
- why a Triple-MUSIC ?
  - three independant energy losses measurement in one detector
  - avoid mis-identification of secondary beam, due to the charge states
- coupled with an absolute position measurement (MWPC)

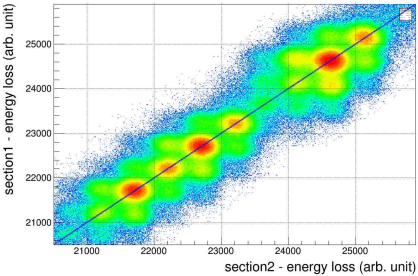




Secondary beam identification: new Triple-MUSIC and MWPC

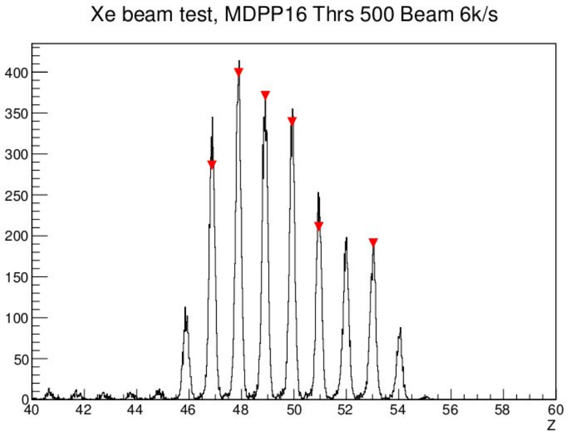






Results from 2016: Sn setting, 450 A MeV

- peak / valley = 200



Results from 2016: Sn setting, 450 A MeV

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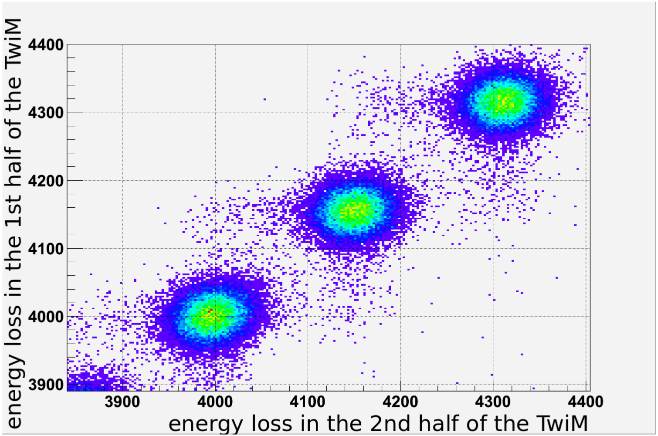
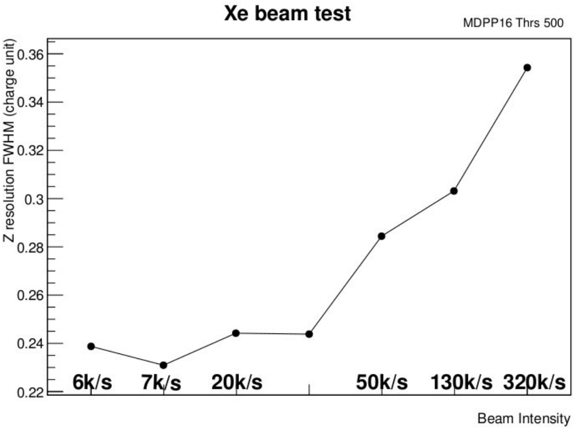
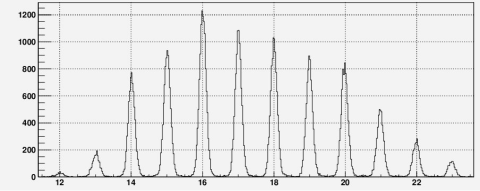


Results from 2016: Sn setting, 450 A MeV

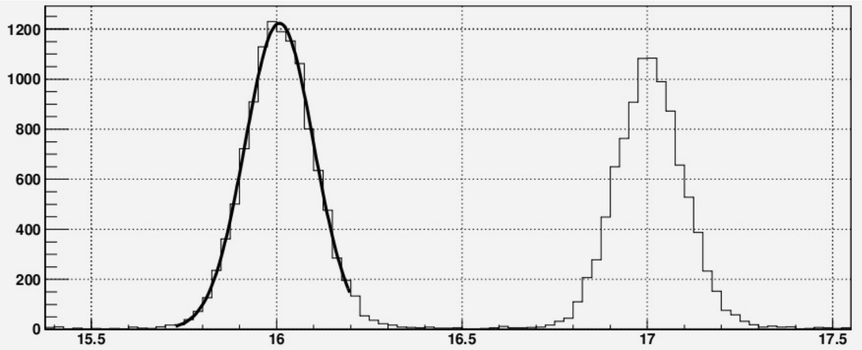
- peak / valley = 200
- some charge state tail in between peaks
- $\Delta Z \sim 0.23$ charge unit (FWHM) for low rate



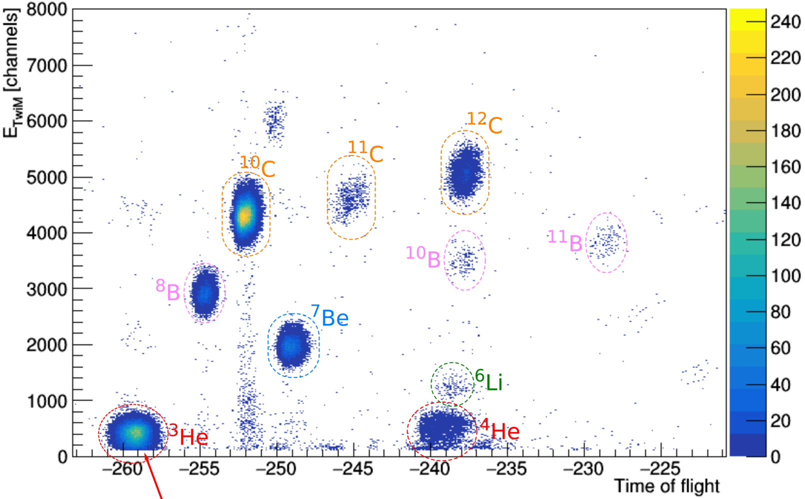
Results from 2016: Si setting



- peak / valley = 1000
- ΔZ = 0.19 charge unit (FWHM)



Results from 2016: C beam



95% detection efficiency