FIDIAS:
Development of a Micromegas TPC for low energy heavy ions detection

F.J. Iguaz

On behalf of

IRFU/CEA-Saclay: S. Panebianco, D. Doré, F. Druillole, I. Giomataris & T. Papaevangelou

NCSR Demokritos: M Axiotis, G. Fanourakis, T. Geralis, S. Harrissopulos & A. Lahoyannis.

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The FIDIAS project: development of a Micromegas TPC for the detection of low-energy heavy ions

F.J. Iguaz[a,b,*], S. Panebianco[a], M. Axiotis[c], F. Druillole[a], G. Fanourakis[c], T. Geralis[c], I. Giomataris[a], S. Harissopulos[c], A. Lagoyannis[c], T. Papaevangelou[a]

[a] *CEA, Centre de Saclay, Institut de Recherche sur les lois Fondamentales de l'Univers, 91191 Gif-sur-Yvette, France*
[b] *Laboratorio de Fisica Nuclear y Astroparticulas, Universidad de Zaragoza, 50009 Zaragoza, Spain*
[c] *Institute of Nuclear Physics, NCRS Demokritos, 15310 Aghia Paraskevi, Athens, Greece*

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* Motivation
* Fidias project
* Description of prototypes
* General performance
* Detection of low energy heavy ions
* Conclusions and prospects

Why a TPC?

Full reconstruction and identification of low energy heavy ions

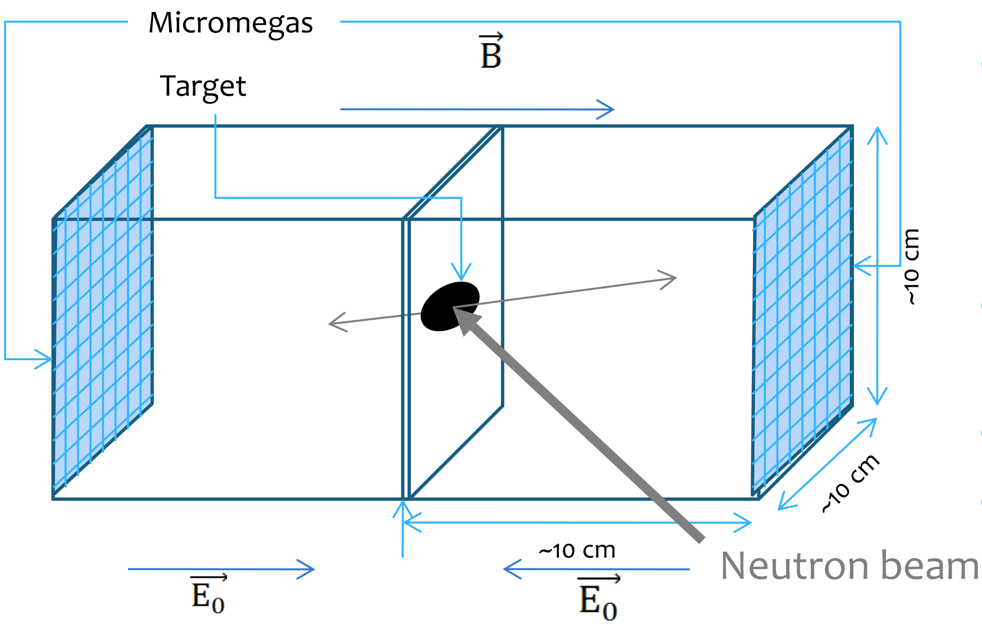
* TPCs are widely used in high energy physics (MIPs detection)
  * Good tracking capabilities (3D reconstruction)
  * Precise momentum measurement (PID)
  * High multiplicity events
  * Good energy resolution (isotopic ID for light ions from ΔE or range)
  * Can cover large surfaces (high detection efficiency)
  * Low material budget (radiation hardness)

* Rarely used in low energy physics (heavy ions)
  * Active target technique (inverse kinematic reactions)
    * Thick target without loss of energy resolution
  * High detection efficiency and 4π coverage (low cross section reactions)
  * Very compact setup (easy coupling with other detectors)

Physics cases

* **Nuclear fission characterization**
  * Measurement of fission fragments mass, charge, TKE & neutron multiplicity.
  * Neutron induced fission (thermal, resonance and fast regions).
  * Gamma induced fission.
* **α-capture reactions relevants to stellar nucleosynthesis**
  * Study of p-process puzzle.
  * Few data available on reaction cross-sections.
  * Well established program (ex. ^{78}Kr (α, γ) ^{82}Sr at GANIL-Lise III).
  * Measurement of (α, p), (α, γ) & (α, n) and their "inverse reactions".
* **Measurement of the stopping force (STF) of heavy & super-heavy elements**
  * Relevant topic for nuclear physics and radiochemistry.
  * Development of physical pre-separation between target & collection chamber.
  * Interest in validating & improving STF calculation methods.

FIDIAS:
The FIssion Detector at the Interface with AStrophysics



- 4π angular coverage (highest efficiency)
- Portability and radiation hardness
- Choice of Micromegas detector: high space resolution, high rate, low space charge, not sensitive to gammas, low material budget
- Make benefit of digital FEE development at Irfu (AFTER & A-GET chips)
- Use of He gas: best choice for physics.
- Evolution of the project:
  - Test of prototypes
  - Benchmark of simulation codes

FIDIAS prototypes

Vessel:

* 10x10x10 cm3 vessel.
* Field shaper cage.
* Gas, feedthroughs & window.

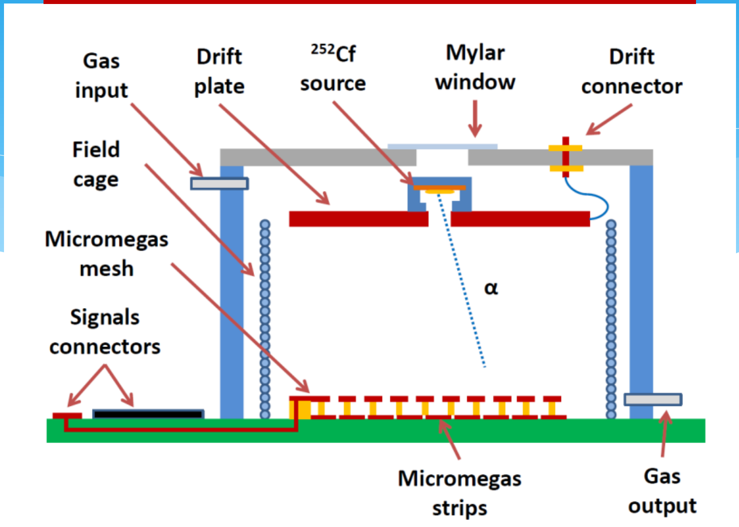
1D prototype:

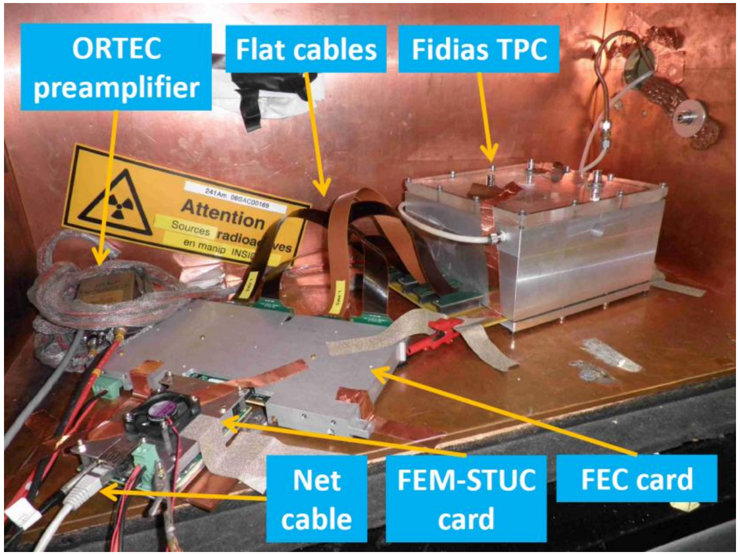
* MAMMA design.
* Active area: 2.4x10 cm^2.
* AFTER-chip based electronics.
* Tested in a ^4H beam line.

2D prototype:

* Modified MIMAC design.
* Active area: 10x10 cm^2.
* XY structure: 144x144 strips.
* AFTER-chip based electronics.
* ^{55}**Fe**: general performance.
* ^{252}**Cf**: response to alphas & fission fragments.
* Tested in Ar, Ne & He-iso mixtures.

Schema of the prototype





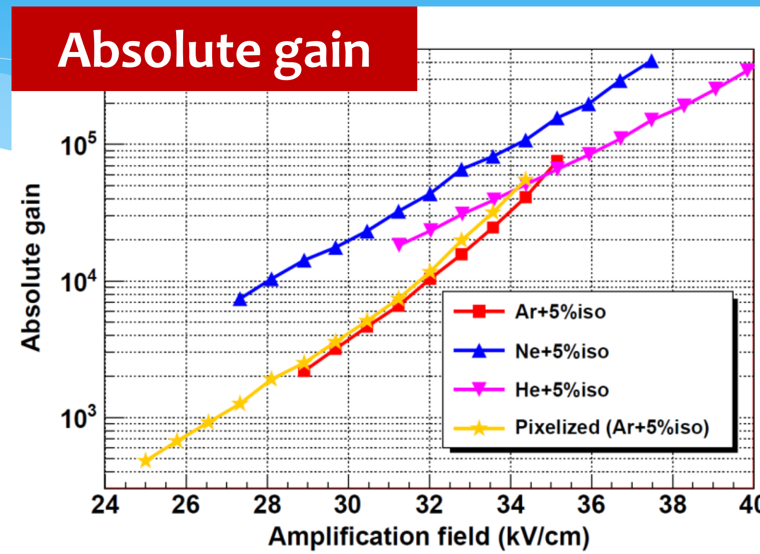
General performance: Gain & energy resolution

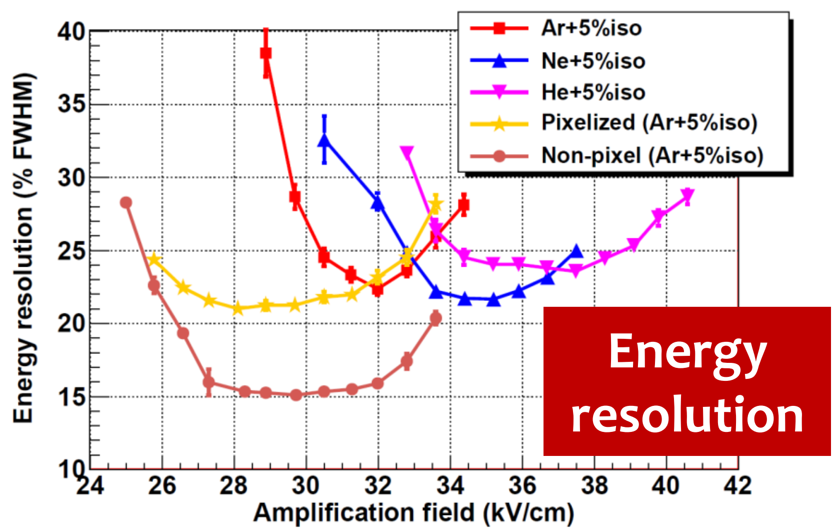
Gain:

* Maximum values: **7 x 10^4** in Ar+5%iso, **2x10^5** in Ne+ & He+5%iso.
* Ar+5%iso: Agreement with 128μm bulk.

Energy resolution at 5.9 keV:

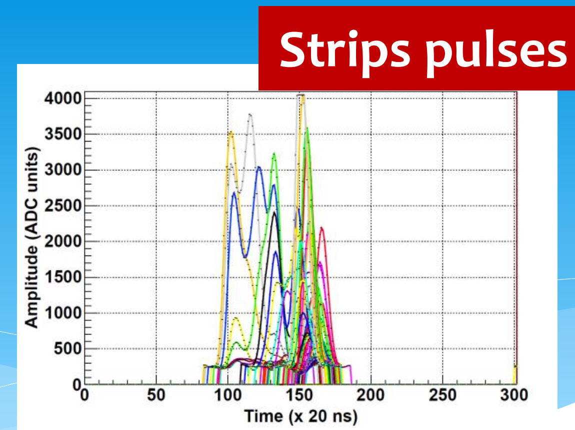
* **21.7% FWHM** for Ne+5%iso & **23.6%FWHM** for Ar+ & He+5%iso.
* Argon values are similar to bulk detectors.
* Limited by uniformities of the mesh & PCB.
* A longer gap (**256 μm**) will reduce the influence of local non-uniformities.

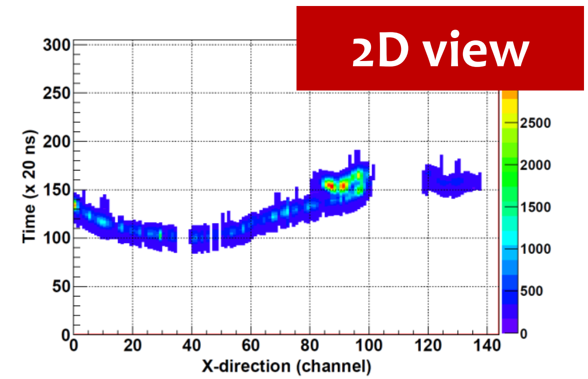


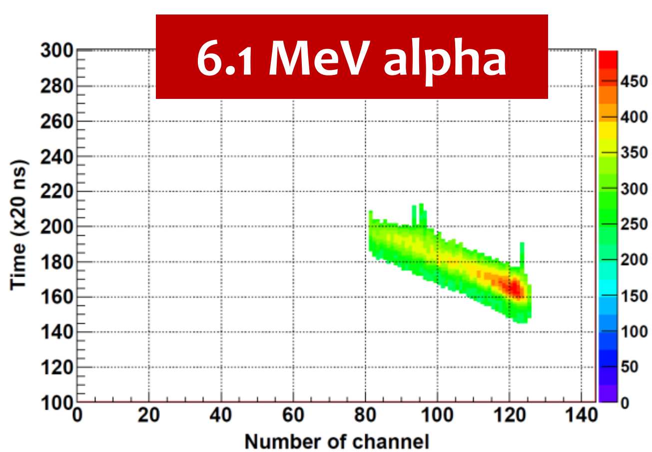


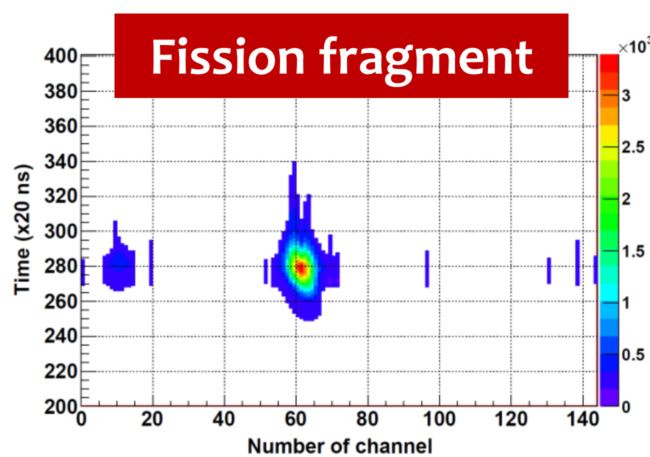
Event reconstruction by the AFTER-chip based electronics

* Strip pulses sampled by AFTER-chip based electronics.
* Two event's 2D-views are reconstructed by the pulse sampling and the readout decoding.
* Cross-talk signals induced in neighboring channels are removed in the off-line analysis.
* Alphas & fission fragments observed.
* Their track length has been calculated by summing the partial distances between consecutive hits.



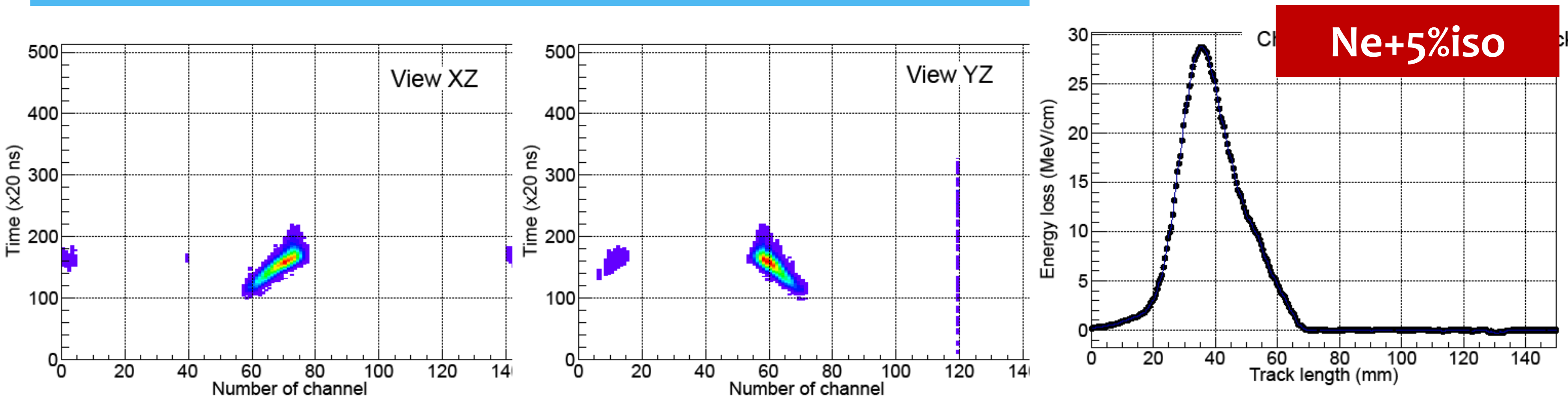


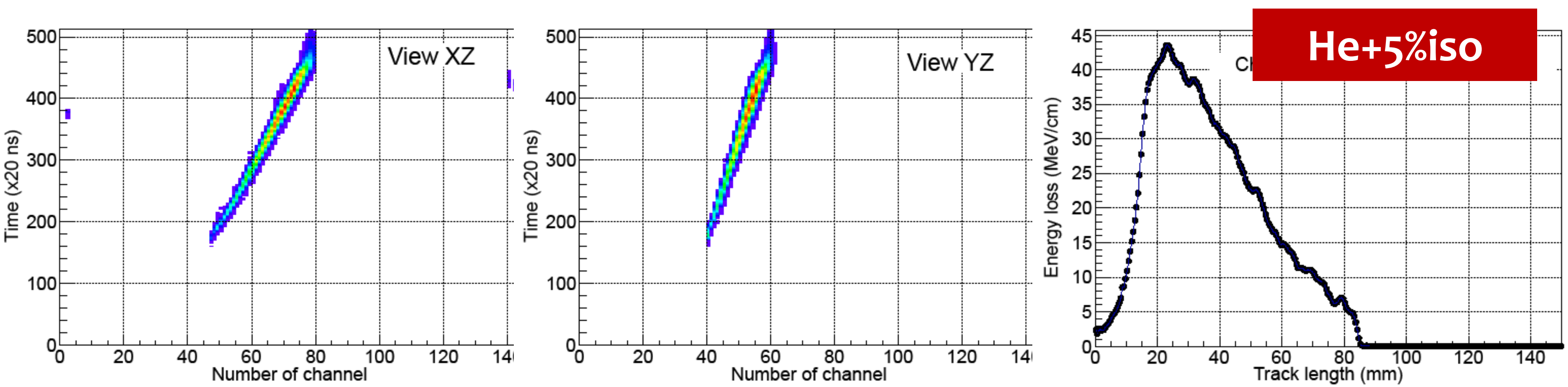




Ar+5%iso

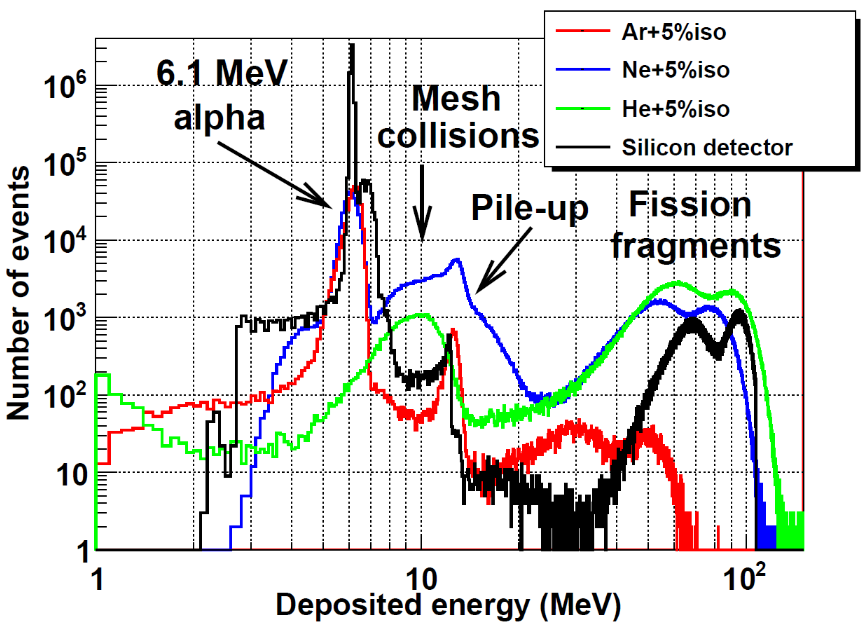
Some images of fission fragments





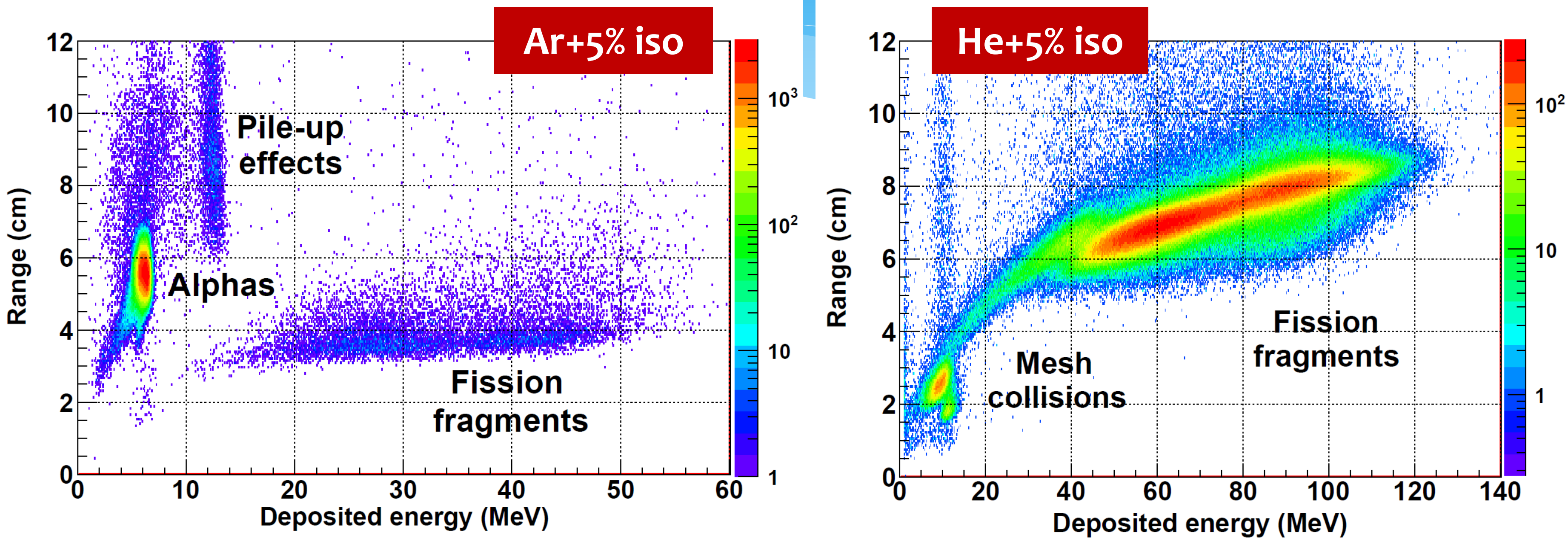
Energy spectrum of ^{252}Cf

* Clear alpha peak at **6.1 MeV**, absent in helium (low energy loss & long range). 2nd peak due to pile-up effects.
* Energy resolution of alphas is modest (**10% FWHM**). Two combined effects: two thin layers (gold 25.9 nm & mylar 0.9 µm) & dead gap (5 mm).



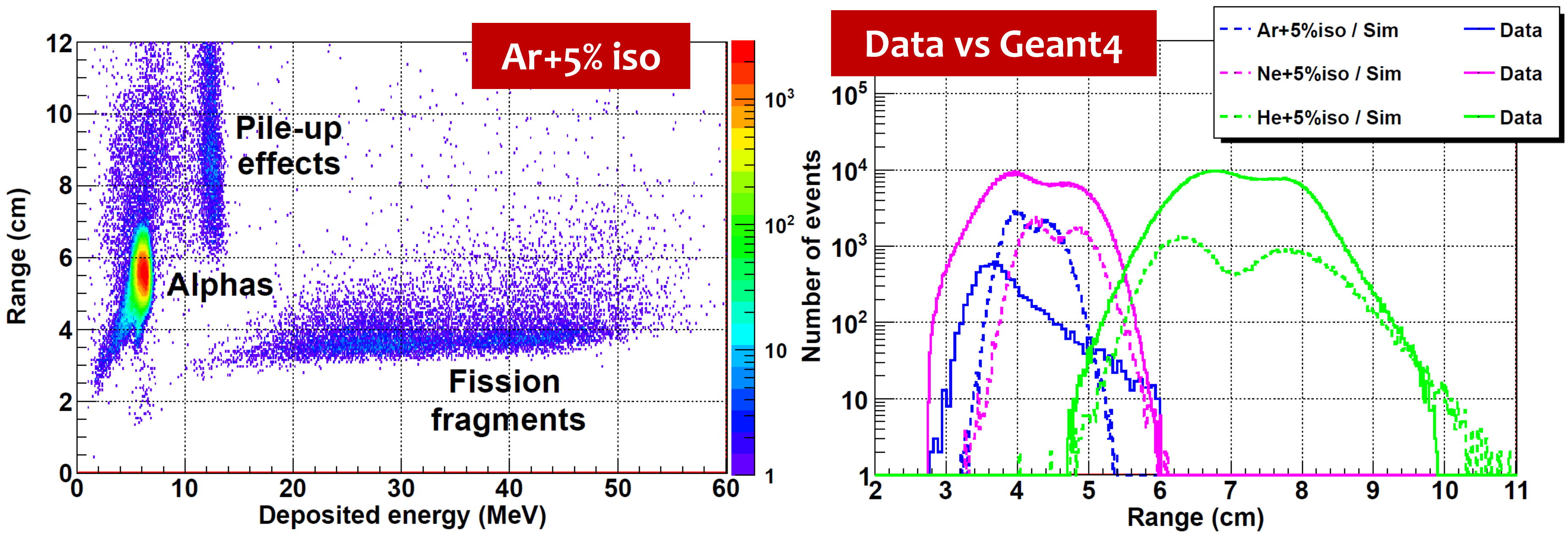
* Deposited energy is low for argon (up to **60 MeV**) & neon (**100 MeV**) due to the effect of dead gap in the first millimeters while ion path is short.
* Unexpected population of events at **~ 10 MeV** for neon & helium. Track lengths: **5 & 2 cm**. Collisions of fission fragments against the mesh.

Particle identificaton: Range vs deposited energy



- Clear separation of alphas & fission fragments distributions.
- Alphas in Ar+5%iso show a length ~6 cm, compatible with GEANT4 (6.7 cm).
- The experimental range distribution of fission fragments is fairly compatible with GEANT4 simulations.

Particle identificaton: Range vs deposited energy



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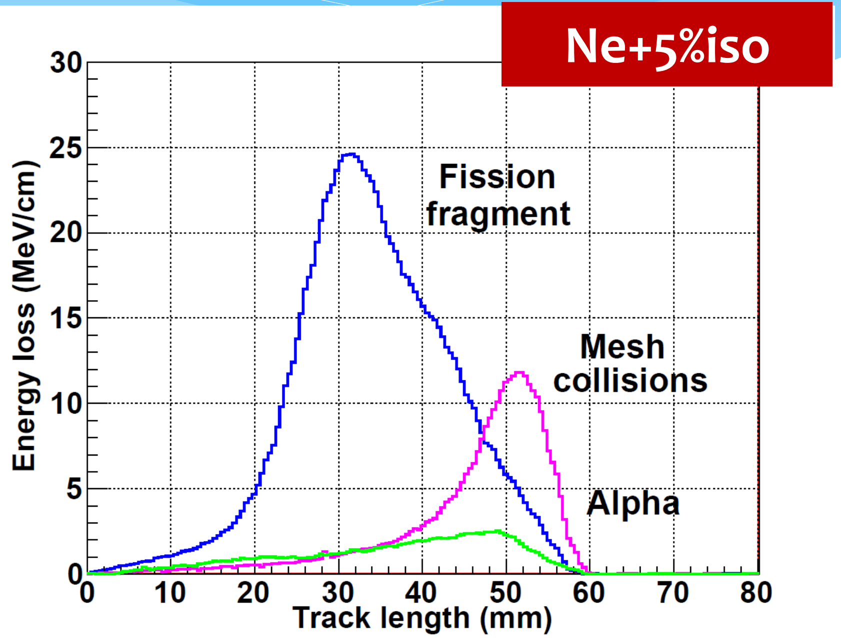
Particle identification: the mean energy loss

* Excellent parameter to discriminate alphas from fission fragments.
* Alphas deposit most of their energy at their path's end (creating a Bragg peak).
* Fission fragments deposit most of their energy at the beginning of their track.
* Mesh collision show a similar distribution to alphas but energy loss is higher.



Conclusions & prospects

* The goal of the FIDIAS project is the development of a Micromegas-based TPC for the detection of low energy heavy ions. Presently in R&D phase.
* The FIDIAS-2D prototype is able to detect low energy heavy ions in a very large dynamic range, from alphas to fission fragments.
* Its tracking capabilities are well suited for energy-range studies.
* Maximum gain values: **7×10^4** (Ar+5%iso), **$2\text{x}10^5$** (Ne+ & He+5%iso).
* Energy resolution: **21.7% FWHM** (Ne+5%iso), **23.6%FWHM** (Ar+ & He+5%iso). Improvement expected by enlarging the amplification gap & better gas purity.
* FIDIAS-2D is being tested with the new FEE called **A-GET**, with self-triggering capabilities. For its application in high intensity ion beams.
* A new 2D prototype (double-phase, dedicated fission source) is foreseen, to be tested inside a vertical solenoid (3.5 Teslas) for a better study of fission fragments.

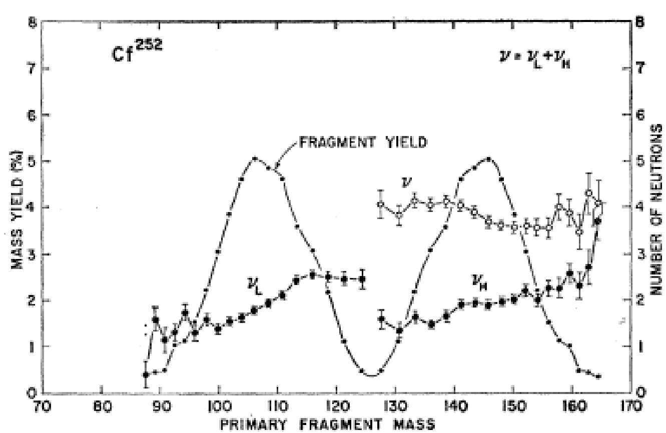
Back-up

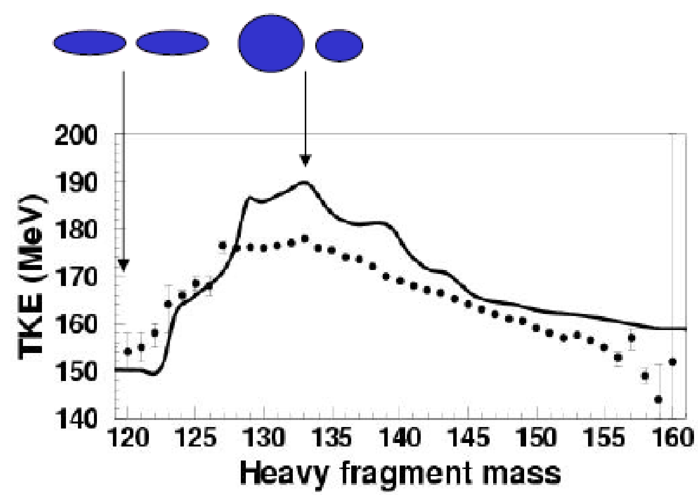
Physics cases: fission

Full reconstruction and identification of low energy heavy ions

Three identified physics cases :

- **Nuclear fission characterization (main interest at Irfu)**
  - Measurement of FF mass, charge, TKE and neutron multiplicity
    - Improve phenomenological and microscopic models
      - shell effects, even-odd, deformations, scission conf.
    - Nuclear data important for applications (fast reactors, RIB prod.)





Physics cases: fission

Full reconstruction and identification of low energy heavy ions

Three identified physics cases :

- **Nuclear fission characterization**
  - Measurement of FF mass, charge, TKE
    - Improve phenomenological and microscopic models
      - shell effects, even-odd, deformations, scission conf.
    - Nuclear data important for applications (fast reactors, RIB prod.)
  - Neutron induced fission
    - Thermal region (ILL unpolariz. or polariz., Orphée,…)
    - Resonance region (n-TOF, IRMM-Geel,…)
    - Fast region (NFS@SPIRAL2,...)
  - Gamma induced fission (ELSA, S-DALINAC,…)

The interest of a TPC

- High efficiency and versatile setup (coupling with n det.)
- Compact setup: can provide coherent data at different facilities

Physics cases: α-capture

Full reconstruction and identification of low energy heavy ions

Three identified physics cases:

- **α-capture reactions relevant to stellar nucleosynthesis**
  - Study the p-process puzzle
  - Few data available on reaction cross sections
  - Well established program (ex. ^{78}Kr (α,γ) ^{82}Sr @ GANIL-Lise III)
  - Measurement of (α,p), (α,γ), (α,n) and their "inverse"
    - Energy range between 1 and 3.5 AMeV (1.5 - 3.5 10^9 K)
    - Mass region: *A=80÷140* and *A=170÷200*
    - Possible installations: GANIL-SPIRAL2, ISOLDE, S-DALINAC
      - Stable beams: ^{74}Se, ^{78}Kr, ^{84}Sr, ^{92,94}Mo, ^{96,98}Ru, ^{106,108}Cd, ^{112,114,115}Sn
      - Radioactive beams: ^{74,76}Kr, ^{108,110}Sn, ^{120,122}Xe

The interest of a TPC

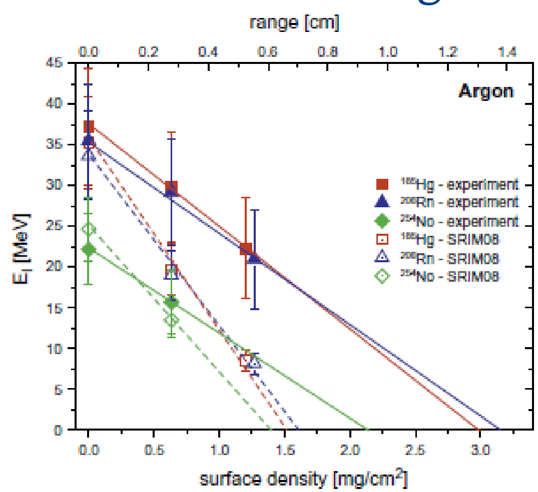
- Active target to study α induced reaction in inverse kinematics
- Thick target with high efficiency detection

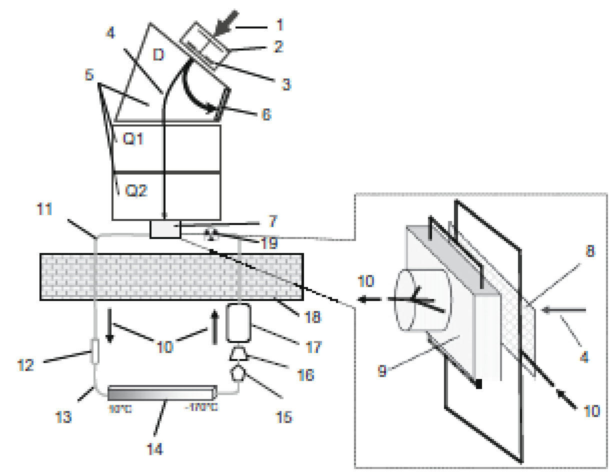
Physics cases: STF of super-heavy

Full reconstruction and identification of low energy heavy ions

Three identified physics cases:

* **Measurement of stopping force (STF) of heavy and super-heavy elements**
  * Relevant topic for nuclear physics and radiochemistry (***collaboration with PSI radiochemistry lab***)
  * Innovative development of physical pre-separation between target and collection chamber (Dubna gas filled recoil separator)
  * Common interest in validating and improving STF calculation methods

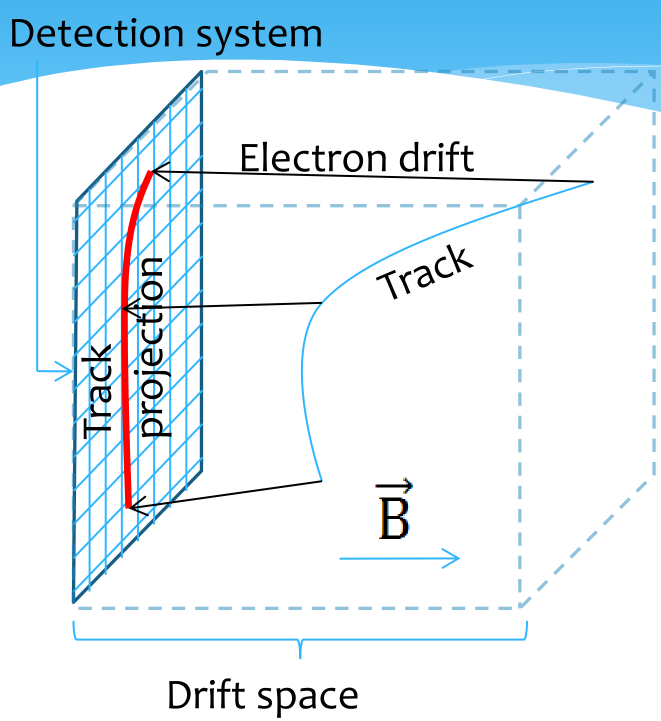




The interest of a TPC

- Good energy resolution and tracking capabilities
- Can be used for STF in gas (active target) or in solid layers

The TPC option



$$x(t) = \frac{v_{0x}}{\omega_B}\sin(\omega_B t) - \frac{v_{0y}}{\omega_B}(\cos(\omega_B t) - 1)$$

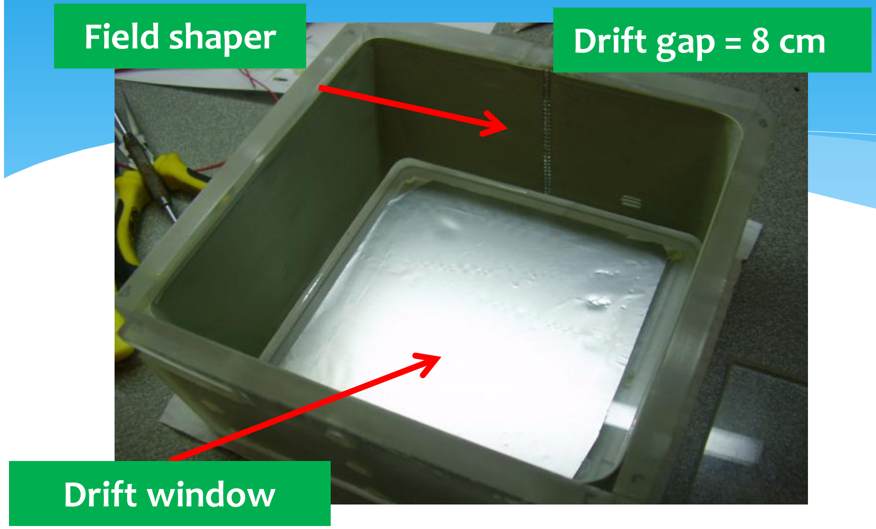
$$y(t) = \frac{v_{0x}}{\omega_B}\cos(\omega_B t) + \frac{v_{0y}}{\omega_B}(\sin(\omega_B t) - 1)$$

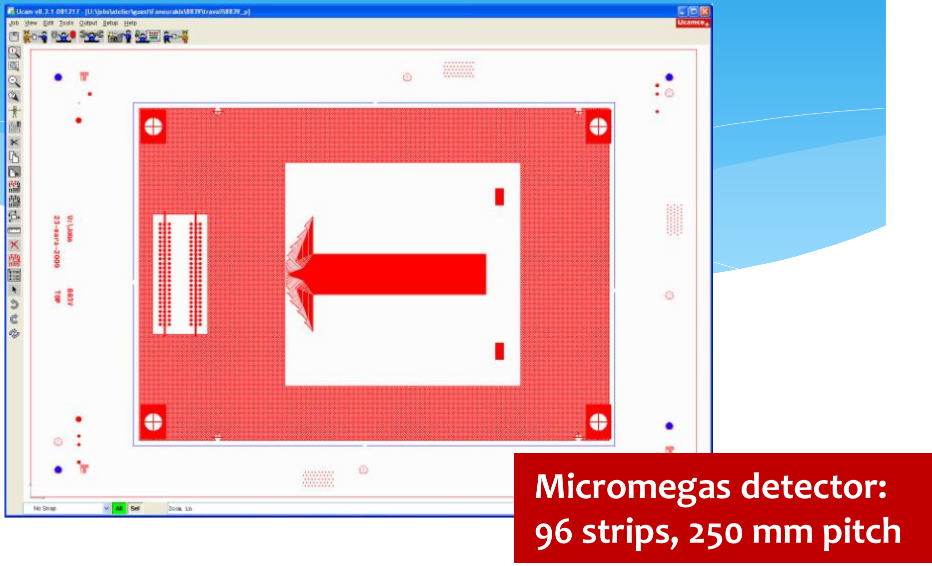
$$z(t) = \frac{\omega_E}{2}t^2 + v_{0z}t$$

$$\omega_{E,B} = \frac{(E,B)_z Q}{A}$$

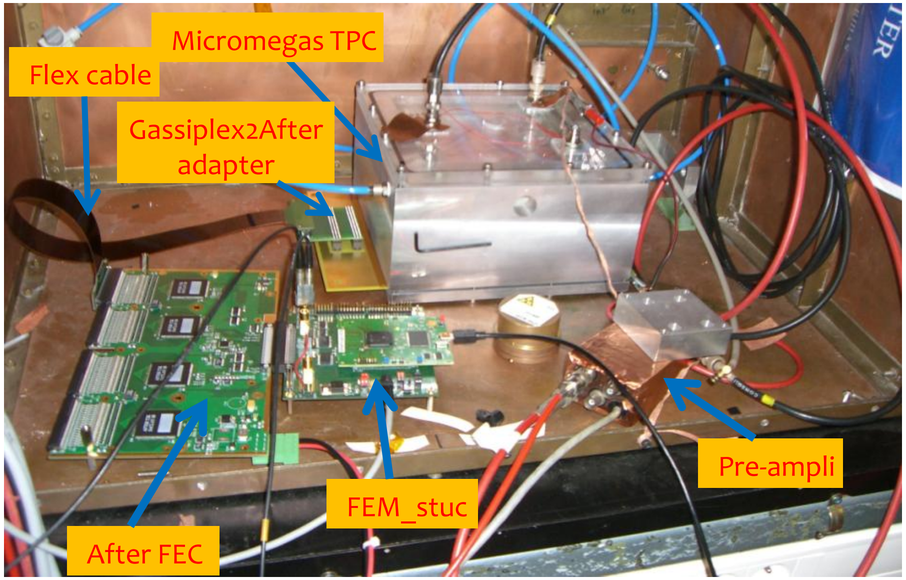
- Ion's complete kinematics (3D reconstruction)
- Use of He gas
  - Largest path for FF
  - Study of α-induced reactions in inverse kinematics
- Fission case (double-side TPC):
  - The unknowns:
    - A_1, A_2
    - q_1, q_2
    - 2 * (v_x, v_y, v_z)
  - Solve the equations of motion:
    - 3 + 3 eq. of motion
    - 3 momentum conserv. eq.
  - Complete with:
    - $q=Z^{-1/3}v/v_0$
    - *Z* from *ΔE-E* or *range*

Test of prototypes: first tests in Saclay



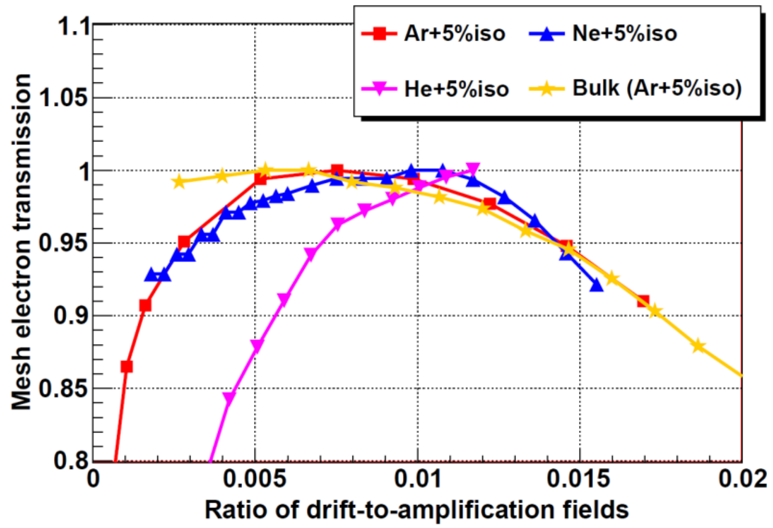


- Micromegas TPC proto (***Demokritos***)
  - 1D det. (96 strips, 250µm pitch)
  - Gas: Ar (90%) C_4H_{10} (10%)
  - Gain ≈ 100
- After electronics (dev. for T2K TPC)
  - Gain : 120÷600fC
  - Shaping time : 100ns÷2µs
  - Sampling frequency : 50MHz
- Test with cosmic rays, Fe, Cd sources
  - Response of the system
- Test with unsealed Cf source
  - First fission data



General performance: the mesh electron transmission

- The ratio of drift-to-amplification fields must be adjusted so as the mesh shows the maximum electron transmission.
- For a fixed mesh voltage, the drift voltage was varied.
- In Ar+5%iso there is a plateau where the mesh is transparent.



- For ratios > 0.01, the mesh stops being transparent. This region matches with similar bulk detectors.
- For ratios low than 0.005, there is a degradation due to gas quality (not fully controlled in this setup). It is more important for light gases as they are more sensitive to water & oxygen impurities.

The AFTER readout

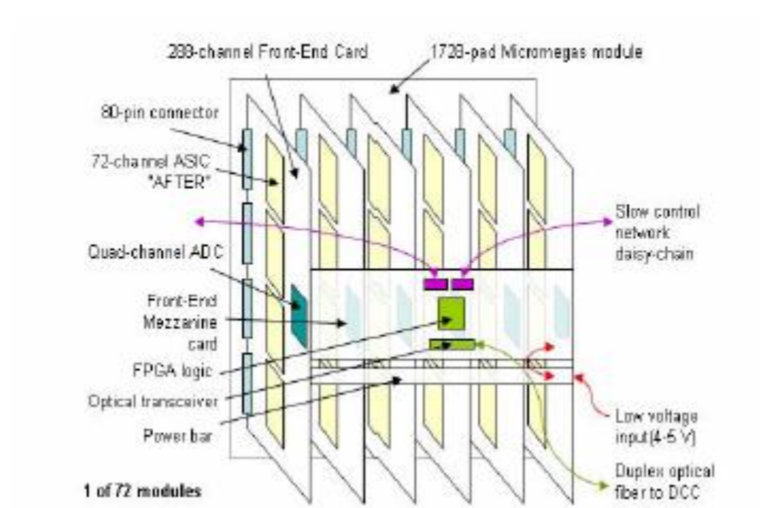
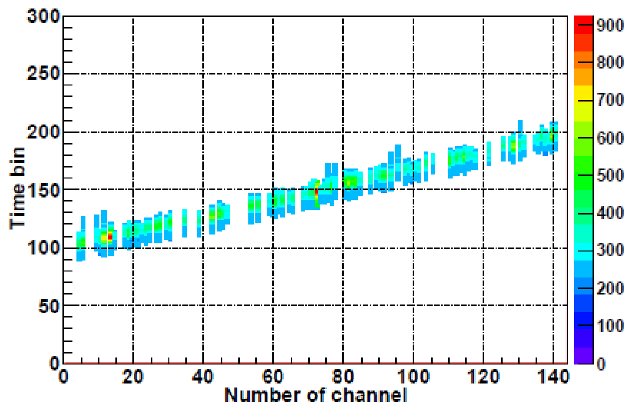


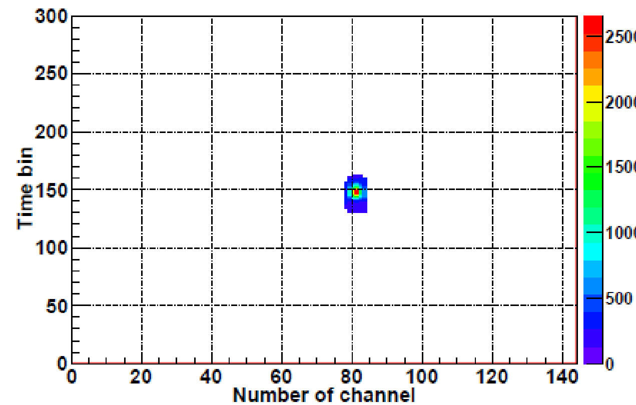
TABLE 1: MAIN REQUIREMENTS AND SPECIFICATIONS

Parameter	Value
Number of channels	72
Samples per channel	511
Dynamic Range	2 V / 10 MIPs on 12 bits
MIP charge	12 fC to 60 fC
MIP/Noise ratio	100
Gain	Adjustable (4 values)
"Detector" capacitor range	20 pF -30 pF
Peaking Time	100 ns to 2 µs (16 values)
INL	1% 0-3 MIPs; 5% 3-10MIPs
Sampling frequency	1 MHz to 50 MHz
Readout frequency	20 MHz to 25 MHz
Polarity of detector signal	Negative(T2K) or Positive
Test	1 among 72 channels or all

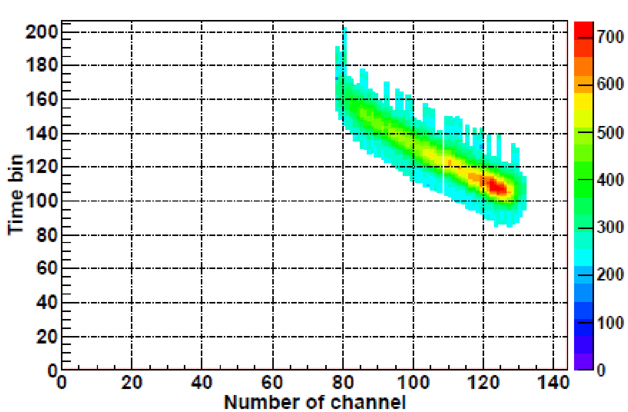
Particle identification



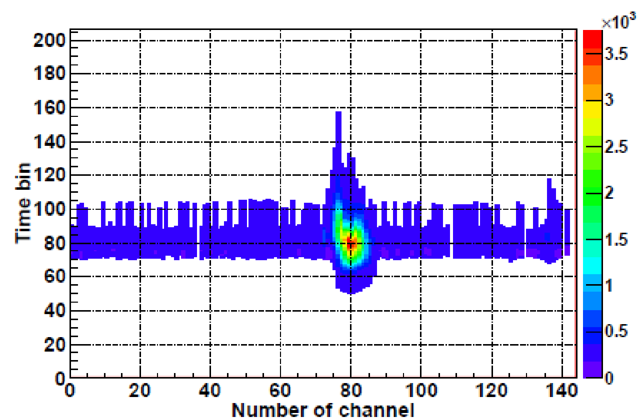
Muon crossing the chamber



6 keV x-ray



^{252}Cf alpha



^{252}Cf fission fragment

General performance: Operation point for ^{252}Cf source

- Event energy calculated by summing the pulse integral of all fired strips (Q_{strips}) & then using the equation:

$$E_{event} = Q_{strips} \times F_{T2K} \times W_{gas}/G$$

- Gain curves fitted to the **Rose-Korff** model.
- The resulting curves were used to fix the mesh voltage for each desired gain **(~ 10)**.
- The desired gain was crosschecked by 6.1 MeV alphas, using both by mesh & strips signals, for Ar+ & Ne+5%iso.
- Energy threshold, imposed by the trigger chain, adjusted to get the largest dynamic range (detection of alphas & fission fragments).

Rose-Korff model

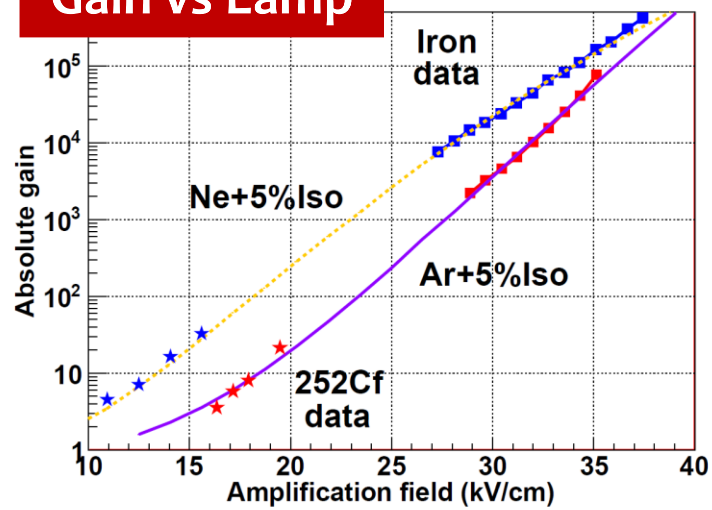
$$ln(G) = \frac{d}{\lambda} \exp\left(\frac{-I_e}{\lambda\, E_{amp}}\right)$$

Gap

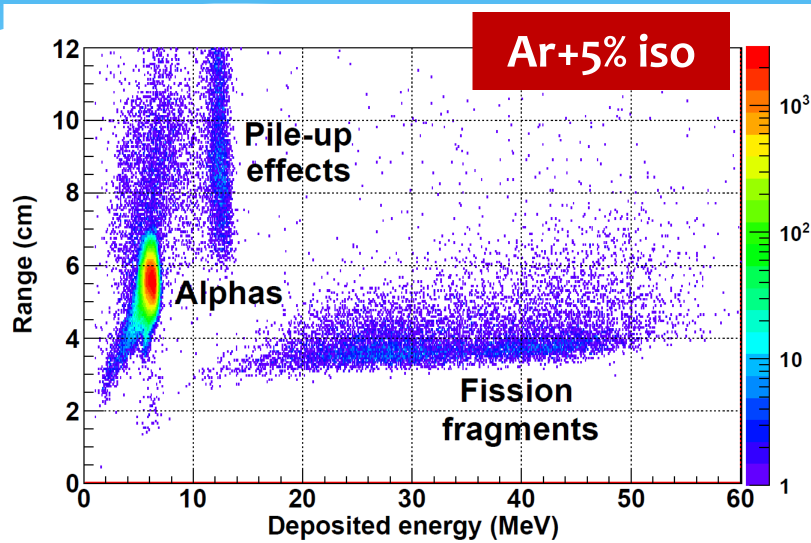
Electron mean free path

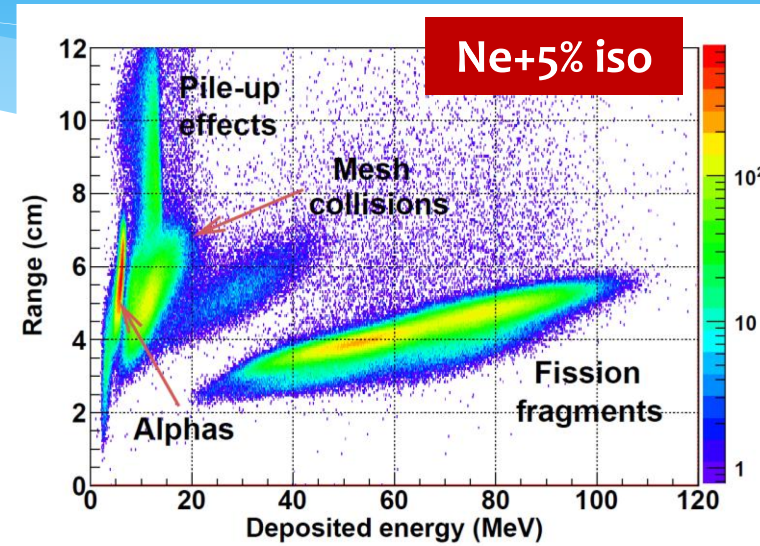
Ionization Energy threshold

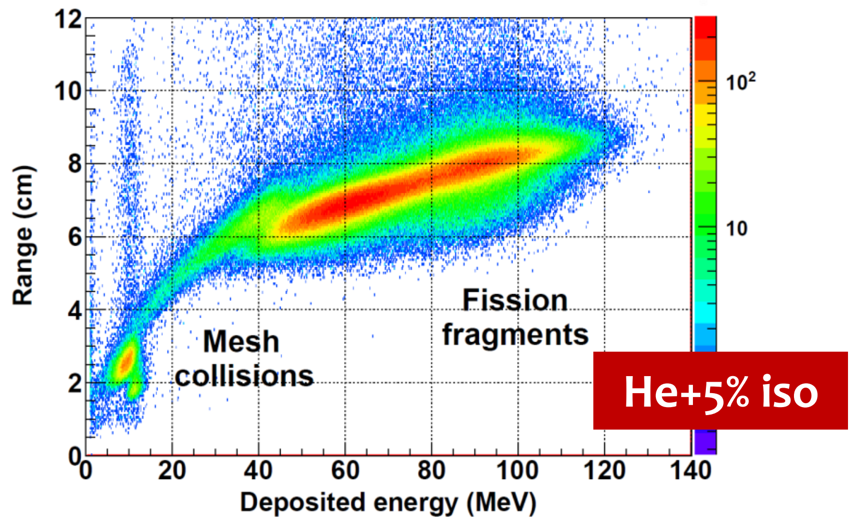
Gain vs Eamp



Particle identificaton: Range vs deposited energy

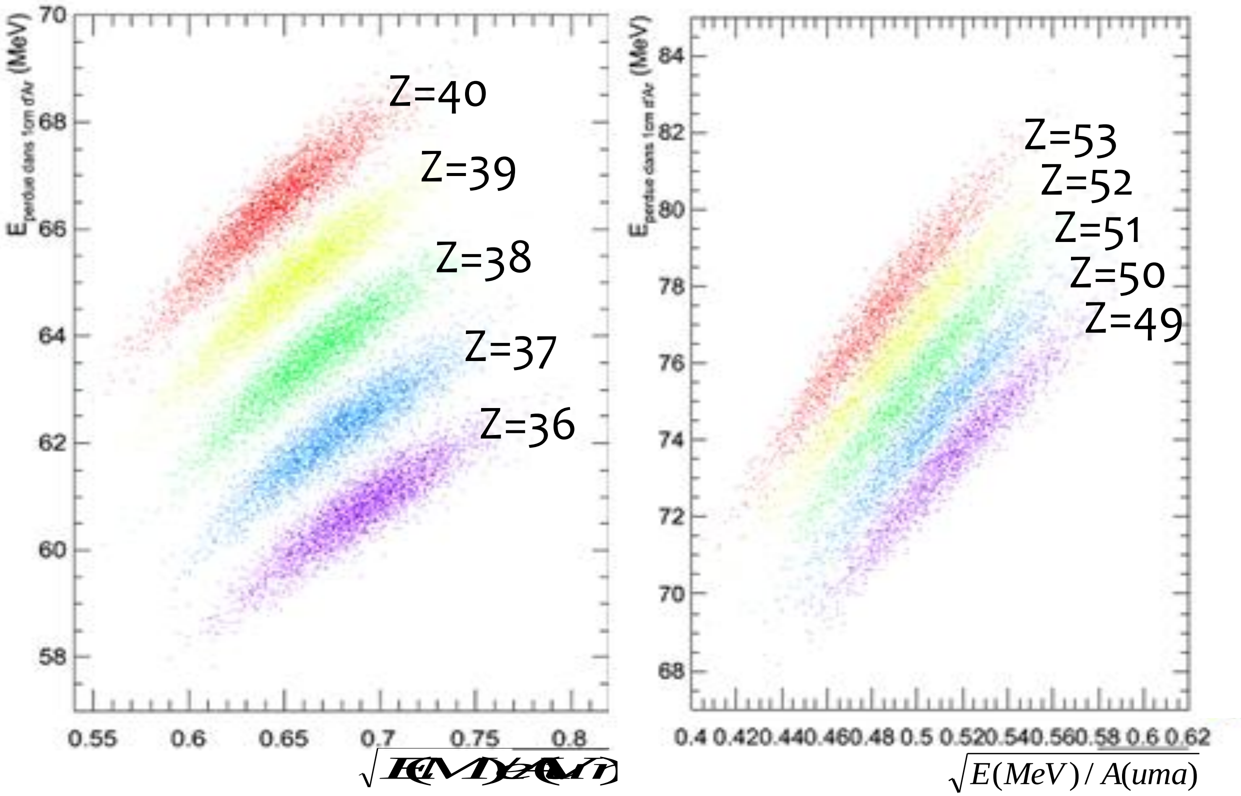






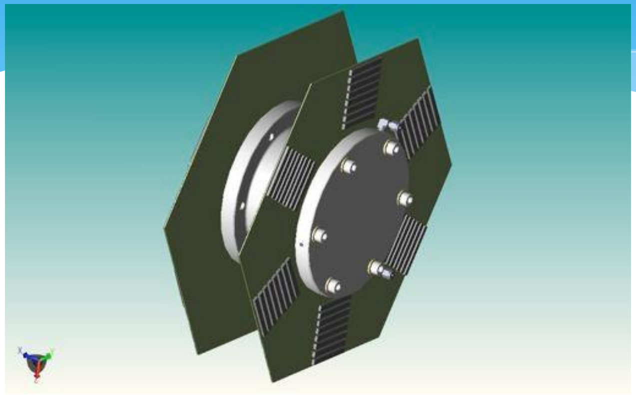
Benchmark of simulation codes

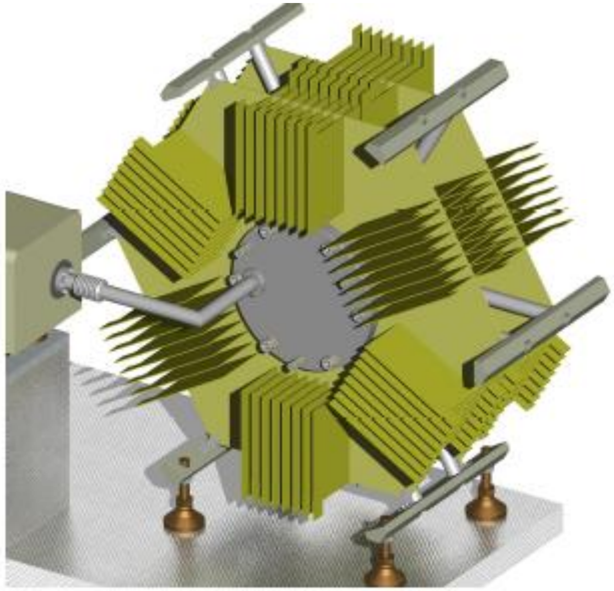
Isotopic separation



- Geant4 able to reproduce isotopic separation based on energy losses
- Separation limit around Z=45 (quite an ideal case!)

The NIFFTE project





Parameter	Value
Drift gases	1H 3He (neutron measurement) P10 (as in fission chambers)
Gas pressure	5 bar, nominal (0–10 bar range)
Typical fragment track length	18 mm
Magnetic field	None
Beam diameter	20 mm
Readout structure	0.9 mm X 0.9 mm square pads
Typical samples per track	20
Target diameter	20 mm
Fiducial area guard radius	9 mm, (50% of track length)
Drift length, including fiducial guard radius	27 mm = 18 mm + 9 mm
Pad plane diameter	74 mm = 20 mm + 2 x 27 mm
Number of pads per side	5300 = (74 mm/0.9 mm)2 π/4
Gas amplification	MICROMEGAS or GEM
Drift field	5 kV/cm
Maximum field	27 kV @ 10 bar
Drift velocity	11.5 mm/µs
Drift time	2.35 µs
Sampling rate	13 Mhz

Lawrence Livermore National Laboratory