Techniques for particle detection with active targets

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Outline

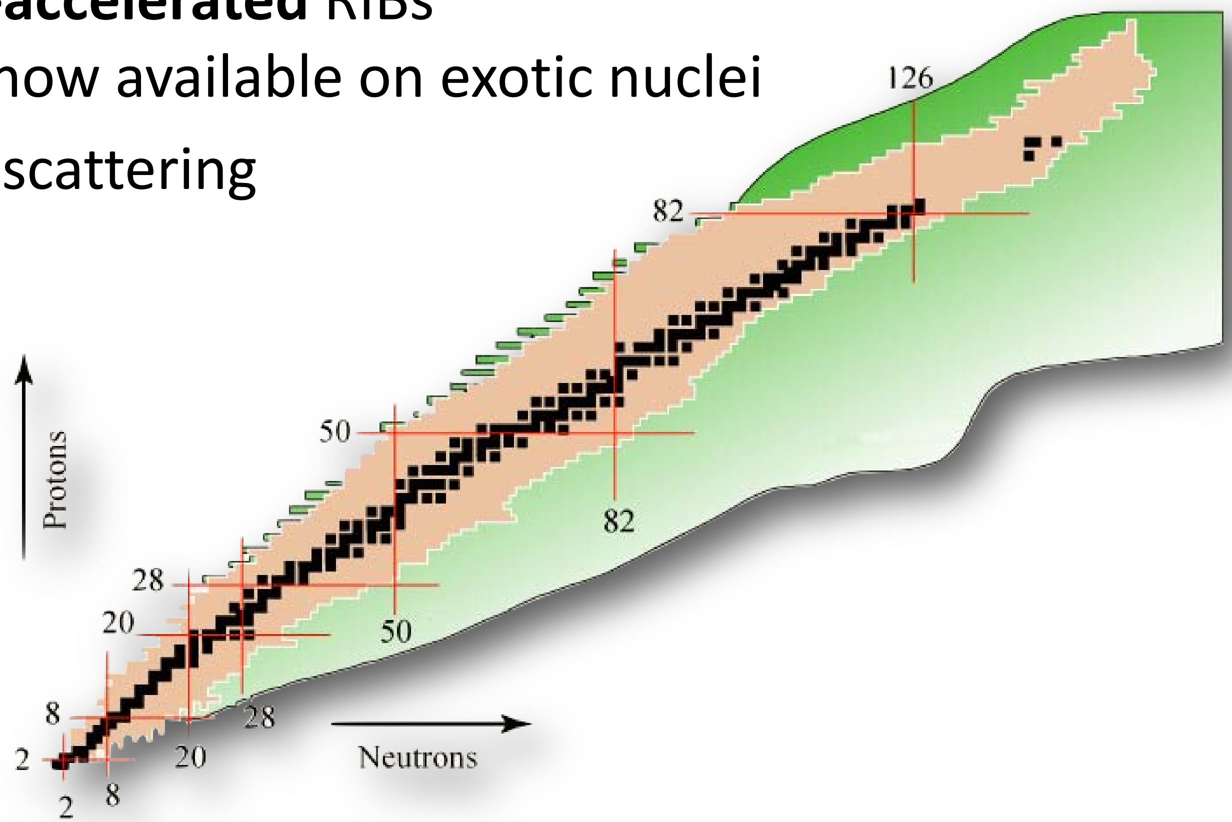
- **Exploring exotic nuclei**
  - Requirements
  - Techniques
- **The active target**
  - Principle
  - Present devices
  - Configurations: physics cases, dynamic ranges
- **Particle detection and identification**
  - Algorithms for track reconstruction
  - Energy: charge and ranges
  - Particle identification
  - Calibrations

Measurements with exotic nuclei

Fragmented and **post-accelerated** RIBs

⇒ **reaction methods** now available on exotic nuclei

- Elastic and inelastic scattering
- Resonant reactions
- Direct reactions



Close to driplines:

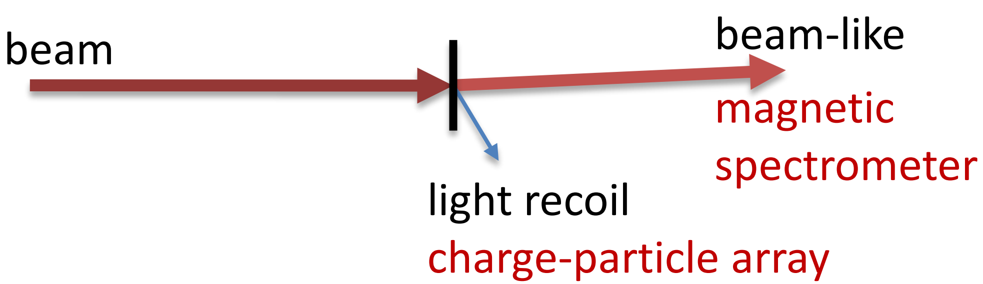
- Exotic decays
  with ion emission

Charged-particle detection methods are central

Requirements on detection methods

- Low-intensity beams $\Rightarrow$ **efficiency** is key
- Identification of channel $\Rightarrow$ particle ID
- Resolution

Reactions: **inverse kinematics**
Heavy beam on a light target

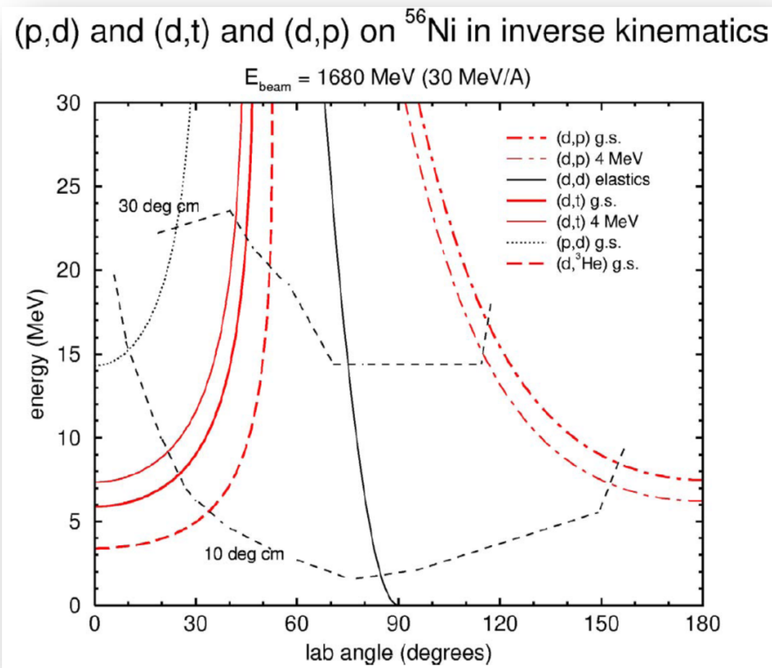


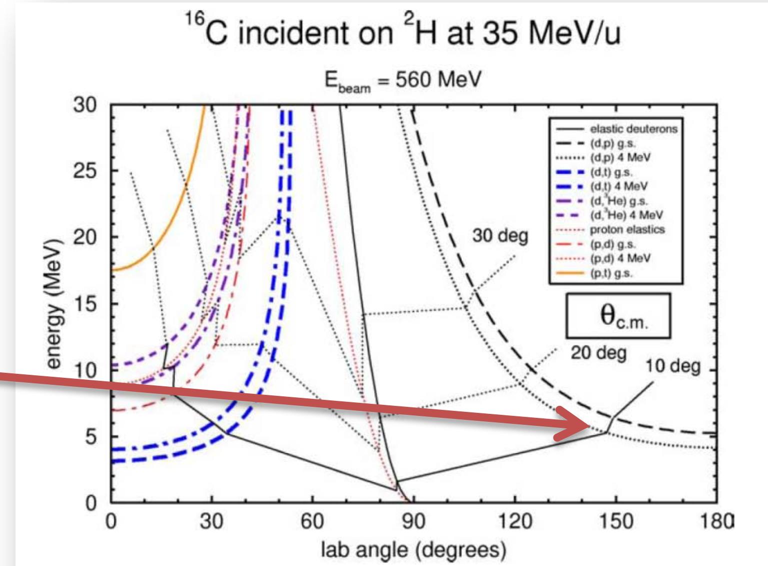
- Reconstruct kinematics from *E* and ϑ of emitted particles (two quantities are sufficient to identify the channnel)

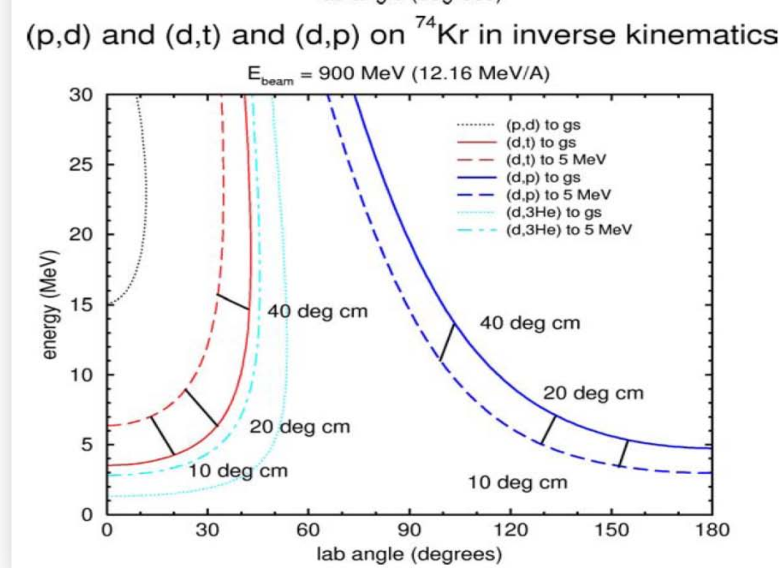
Reactions: kinematics

Example: transfer reactions

- "Universal" kinematic curves
  ⇒ placement of detector depends on channel to be detected (Q-value)
- **Kinematic compression**
  ⇒ resolution, low thresholds







Configurations

Resolution in *E**

- Light beam:
  better detect beam-like particle (limit on angular resolution)
- Heavier beam:
  better detect light recoil (limit on *E* resolution from straggling in the target)
- In general:
  much worse than direct kinematics

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Table 2
Major contributions in keV to the resolution of the excitation energy spectra of single neutron stripping and pickup reactions in inverse kinematics, where the heavy ion is detected in a spectrometer. The detection angle corresponds to 10°_{cm}. The last column is an approximate estimate as a sum in quadrature of the net effect of five non-Gaussian contributions. Other symbols are explained in the text

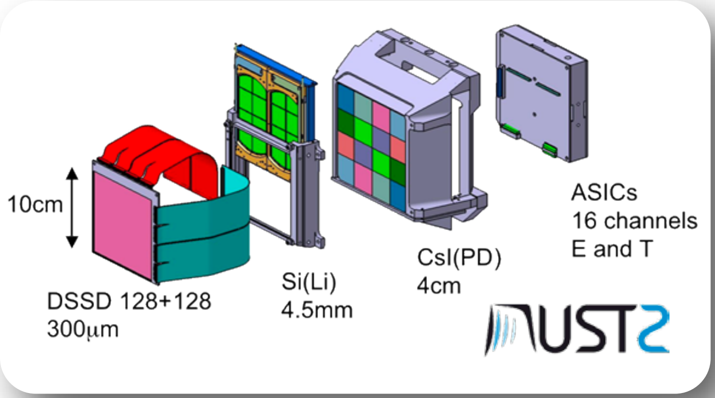
Reaction	E_i/A (MeV)	θ_{lab}	Origin of contribution					Σ_{quad}
			$\Delta\theta$	Δp	E_{stragg}	$\Theta_{1/2}$	dE/dx	
$p(^{12}Be, ^{11}Be)d$	30	1.07°	172	147	101	74	23	259
$p(^{12}Be, ^{11}Be)d$	15	1.06°	84	71	99	74	37	169
$p(^{77}Kr, ^{76}Kr)d$	30	0.16°	1404	811	808	723	56	1952
$p(^{77}Kr, ^{76}Kr)d$	10	0.10°	334	143	502	570	268	883
$d(^{76}Kr, ^{77}Kr)p$	10	0.21°	1140	614	2177	1859	1321	3408

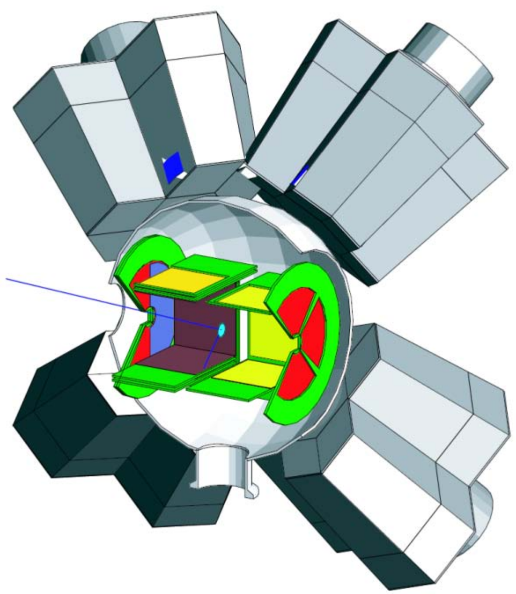
Table 3
Major contributions in keV to the resolution of the excitation energy spectra of single neutron pickup and stripping reactions in inverse kinematics, where the light particle is detected in a silicon detector. Symbols as described in text and Table 2

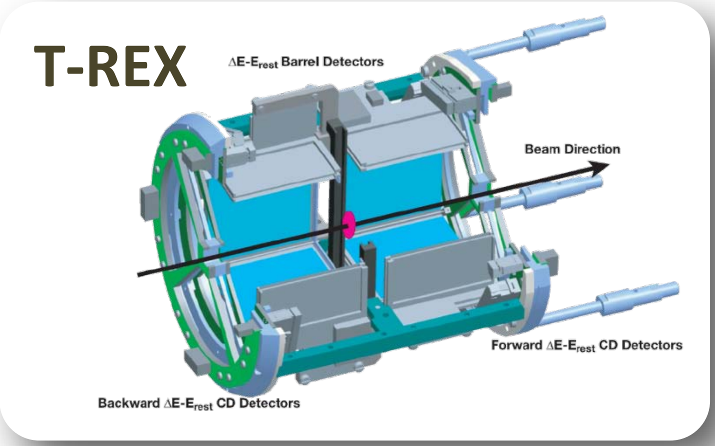
Reaction	E_i/A (MeV)	θ_{lab}	Origin of contribution					Σ_{quad}
			$\Delta\theta$	ΔE_f	ΔE_i	$\Theta_{1/2}$	dE/dx	
$p(^{12}Be, d)^{11}Be$	30	19.0°	136	74	114	96	649	685
$p(^{12}Be, d)^{11}Be$	15	17.8°	66	72	55	89	984	995
$p(^{77}Kr, d)^{76}Kr$	30	15.0°	124	55	64	63	186	249
$p(^{77}Kr, d)^{76}Kr$	10	6.0°	26	24	23	19	775	777
$d(^{76}Kr, p)^{77}Kr$	10	155.3°	52	93	37	60	1309	1316

Instruments

- Charged particle arrays:
  solid-state telescopes (Si, Si+CsI...)
  resolution vs. cost
- How to improve resolution
  γ-ray: very good resolution
  but low efficiency, no g.s.-to-g.s.

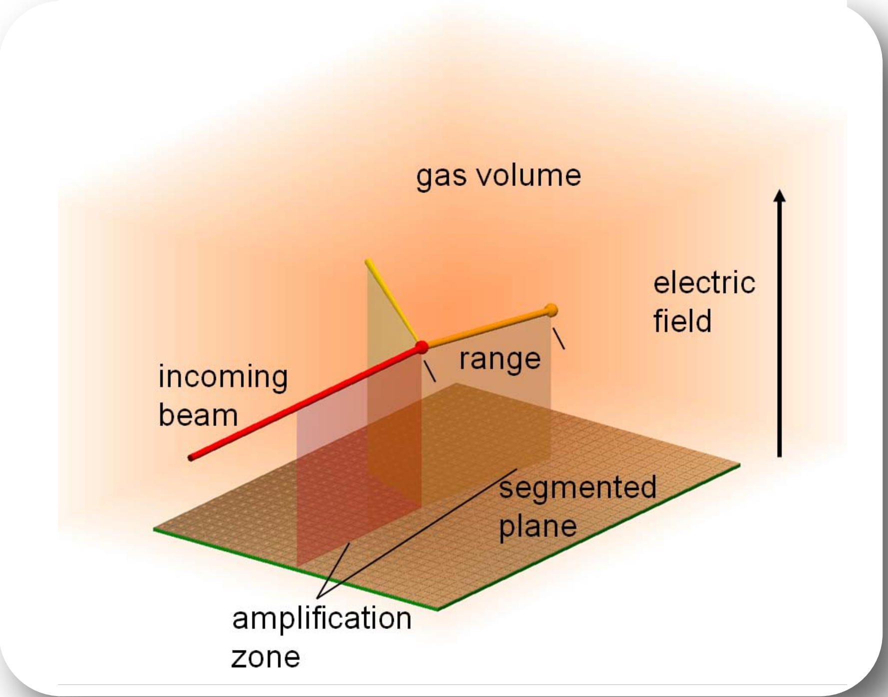


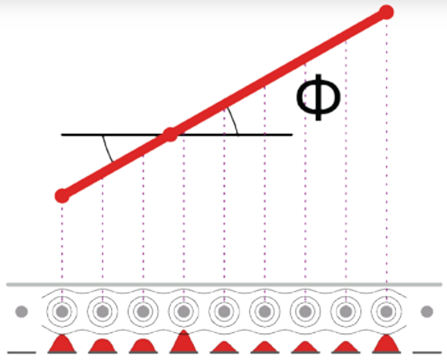




The active target

- Principle:
  Time-Projection Chamber (TPC)
  + the detection gas is the target
- Electrons produced by ionization drift to an amplification zone
- Signals collected on a segmented "pad" plane
  ⇒ 2D-image of the track
- 3rd dimension from the drift time of the electrons
- Large target thickness and still good resolution
- Low detection threshold

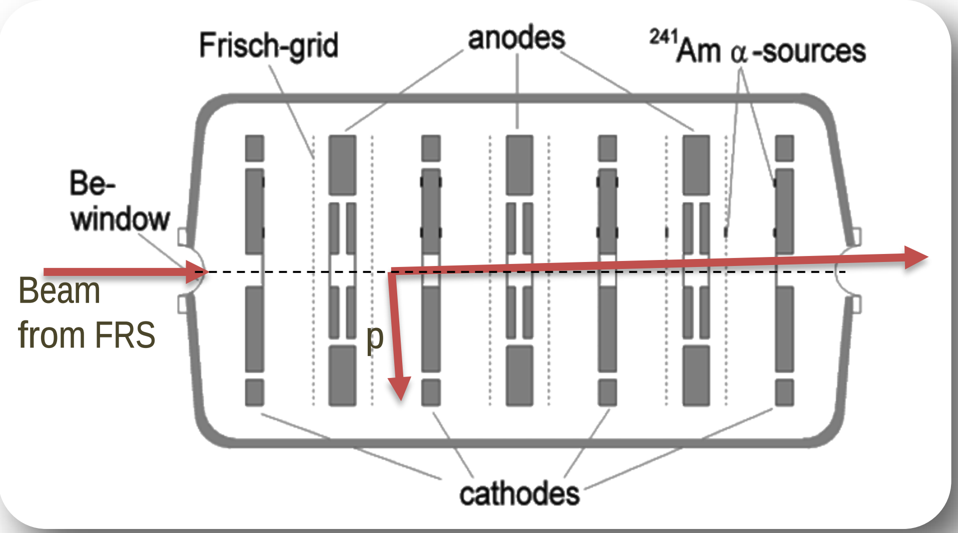




Present and future devices

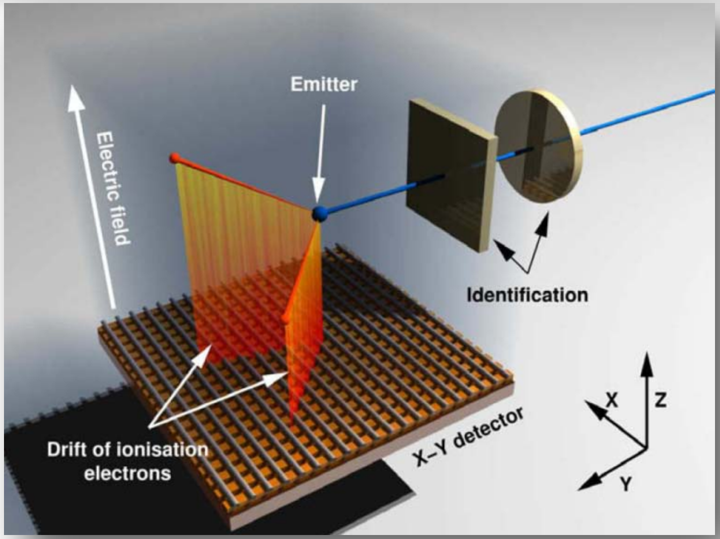
IKAR NPA 712 (2002) 247

- Hydrogen gas, 10 bar
- Multiple ionization chambers
- High energy beam
- Elastic scattering of halo nuclei



CENBG TPC NIMB 266 (2008) 4606

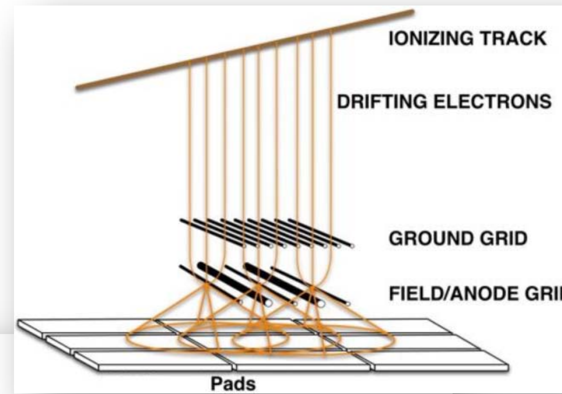
- Mixture 90% Ar + 10% CH_4, ≈1 bar
- Amplification: GEM
- Pad plane: micro-groove detector (orthogonal strips)
- 2p-emission decay studies

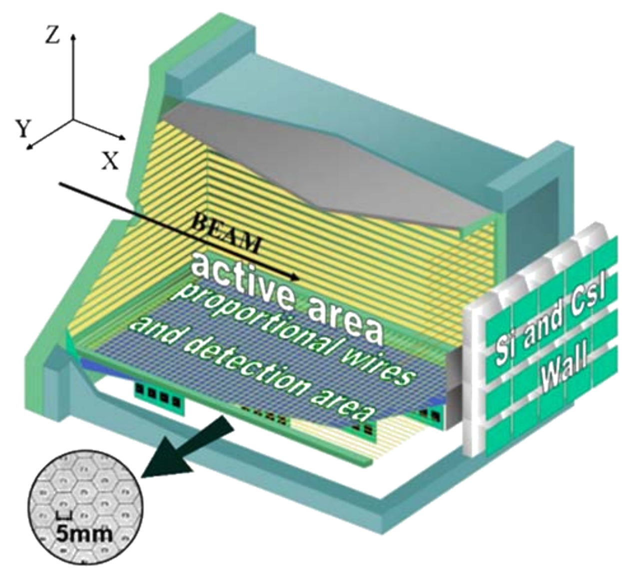


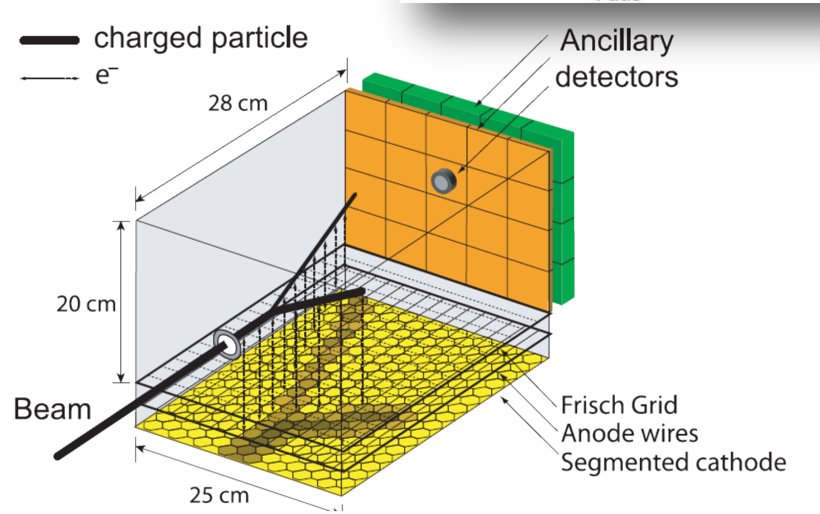
Present and future devices

Maya NIMA 573 (2007) 145

- Various gases: C_4H_{10}, D_2, $^4He+2\%CF_4$, from 30 mbar to 1 bar
- Amplification: wires and induction
- Pad plane: hexagons
- Additional detectors for particles escaping the gas volume



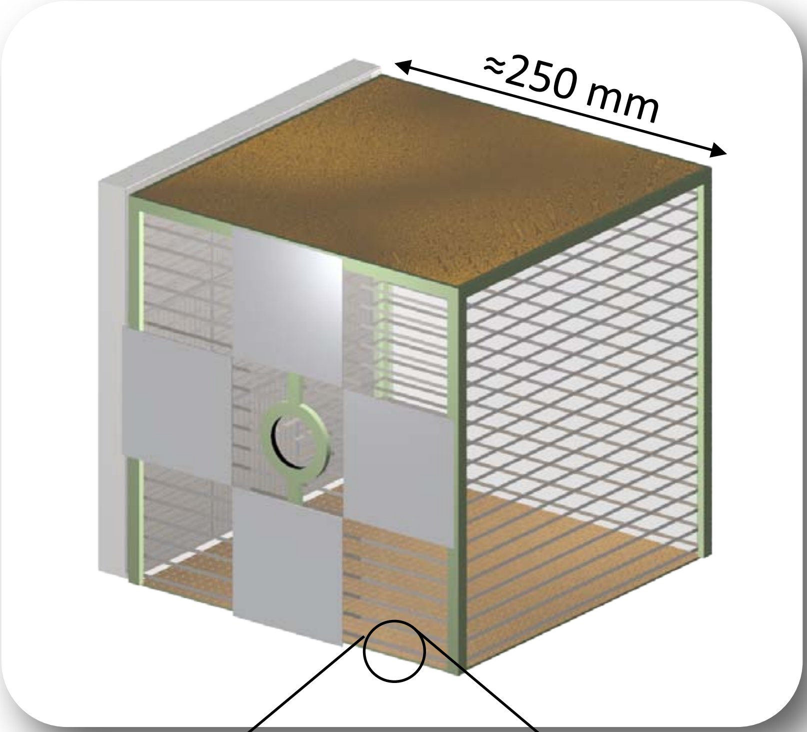


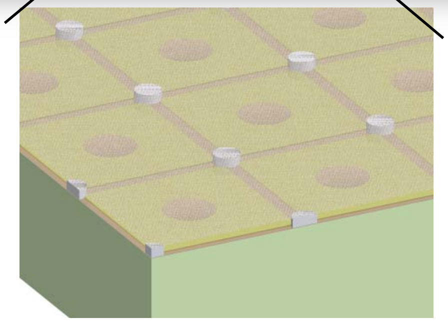


Present and future devices

ACTAR AIP Conf. Proc. 1165 (2009) 339

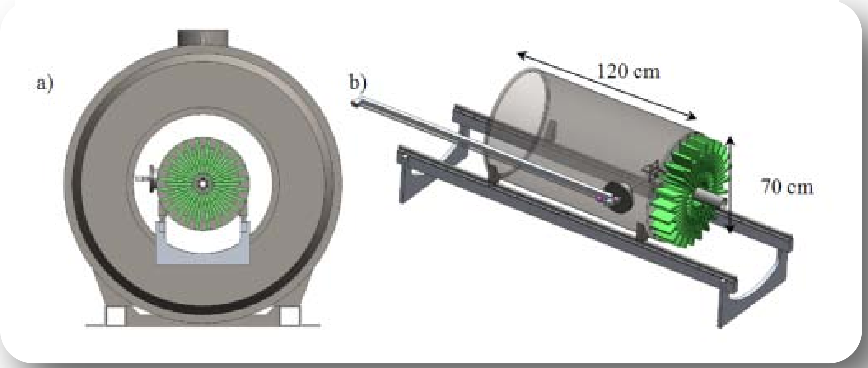
- Cubic geometry (mainly)
- Amplification: Micromegas
- *E* and *T* from pads (≈16000 channels)
- Larger dynamic range (Electronics, pad independence)
- Multiple tracks





AT-TPC, TACTIC

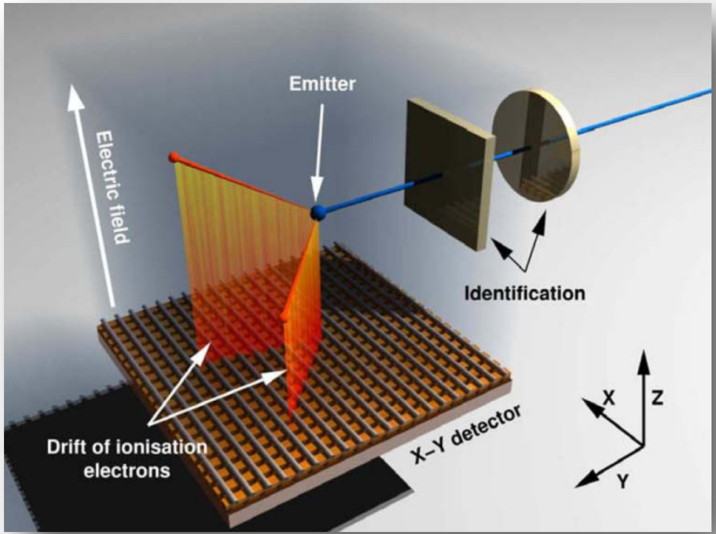
- Cylindrical geometry
- Magnetic field to confine particles



Configurations (physics cases)

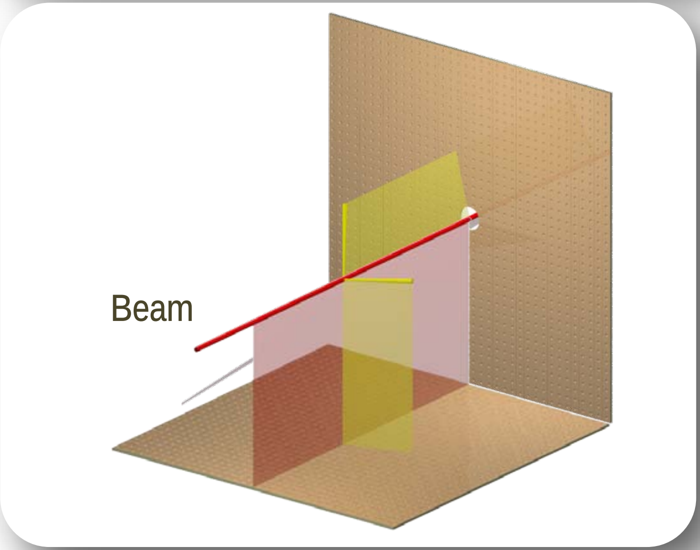
2p-emission decay

- Pressure adjusted to optimize stopping of protons ($E \approx$ few MeV)
- Beam degraded before the detector and stopped in the gas volume
- Measure E, angle between protons, Δt implantation-decay



Elastic and inelastic scattering

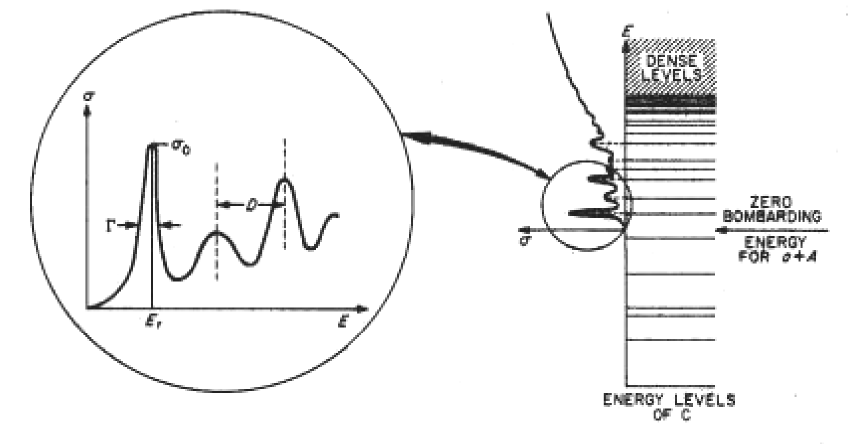
- High pressure for target thickness and stopping of light recoil particles
- Beam leaves the detection volume
- Measure E and angle of light recoils
- If projectile heavy
  dynamic range has to be large

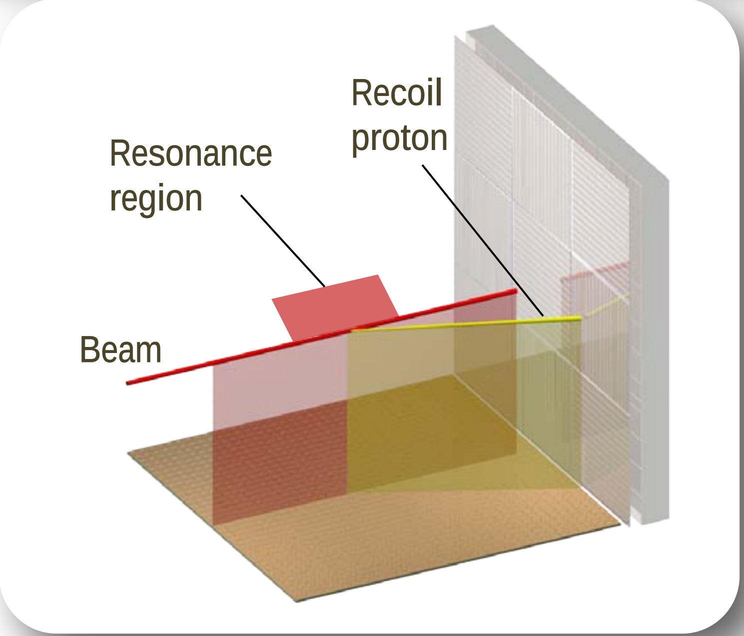


Configurations (physics cases)

Resonant reactions

- Exploration of resonances above particle threshold
- Energy of the beam to reach the resonance of interest
- Pressure adjusted to stop the beam at the end of the gas volume
- Detection of light recoils scattered forward
- Measure: interaction point identification recoil *E*, angle recoil particle
- If projectile heavy dynamic range has to be large

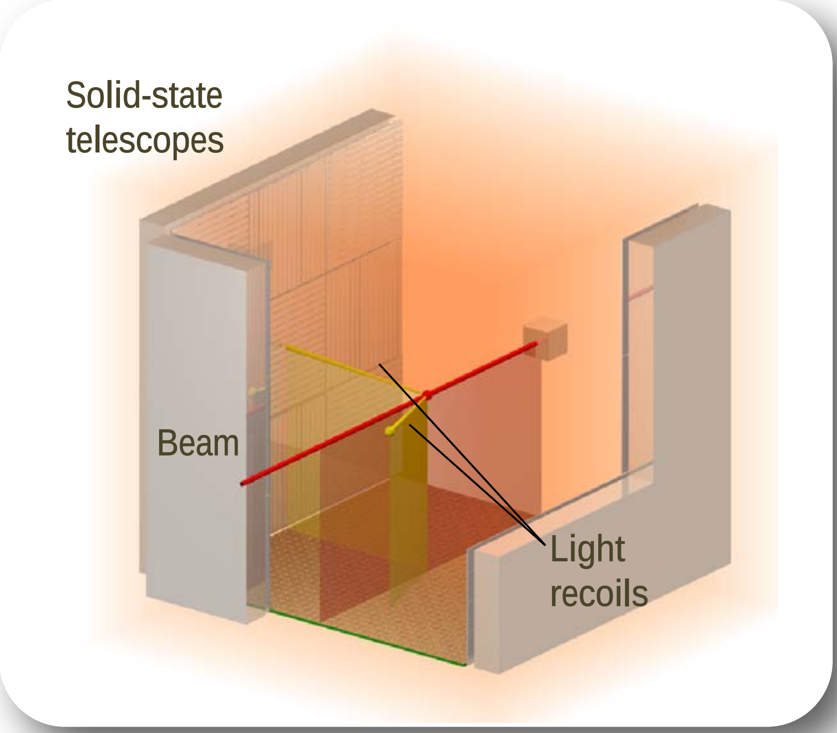




Configurations (physics cases)

Transfer reactions

- (p,d), (d,p), (^{4}He,t), (^{3}He,d), (p,t)…
- Beam leaves the detection volume
- Light recoil at all angles and energies!
- Pressure adjusted for the products of interest
- Identification light recoil
- Measure *E*, angle of light recoil
  - (d,p): low energy protons at backward angles
  - Population of unstable systems: multiple tracks

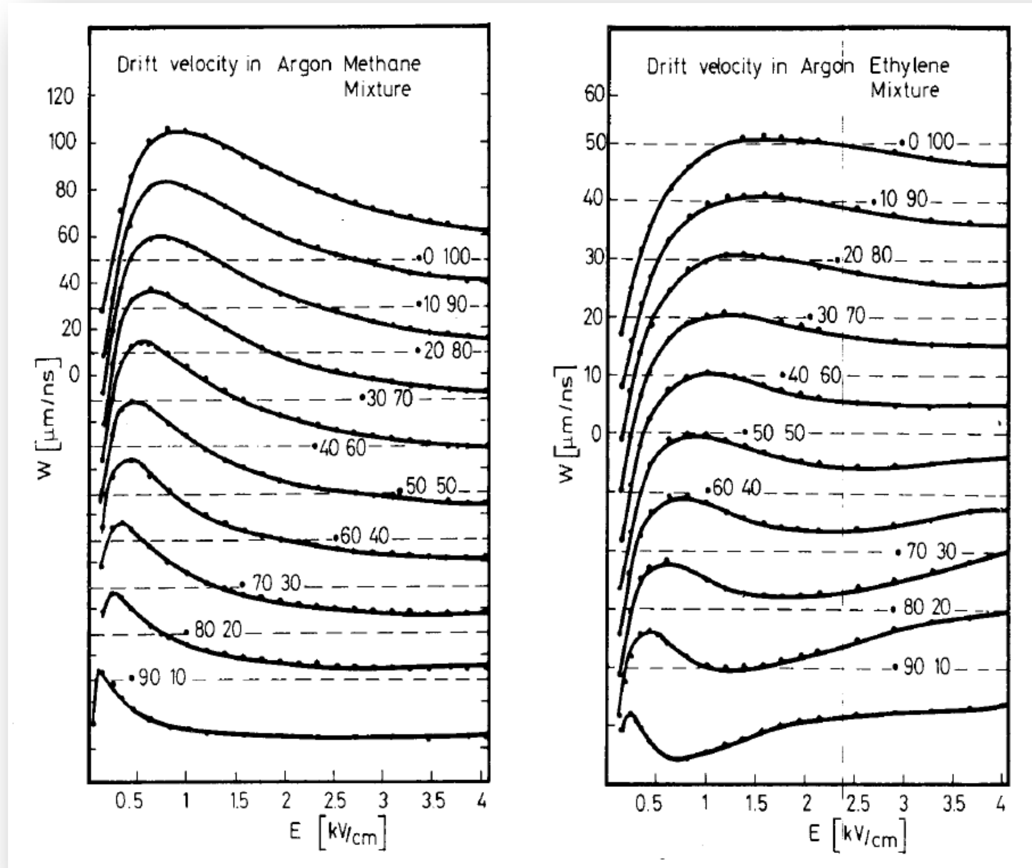


Detector parameters

- Gas and pressure *mostly* dictated by physics
- Electric field: optimize for
  - **Amplification**
  - **Drift velocity** of electrons
- Drift velocity: spatial resolution is

$\delta x = v_{\mathrm{drift}}\, \delta t$

$v_{\mathrm{drift}} \approx$ 5 to 100 µm/ns
$\Rightarrow \delta t \approx$ 200 to 10 ns



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Dynamic range

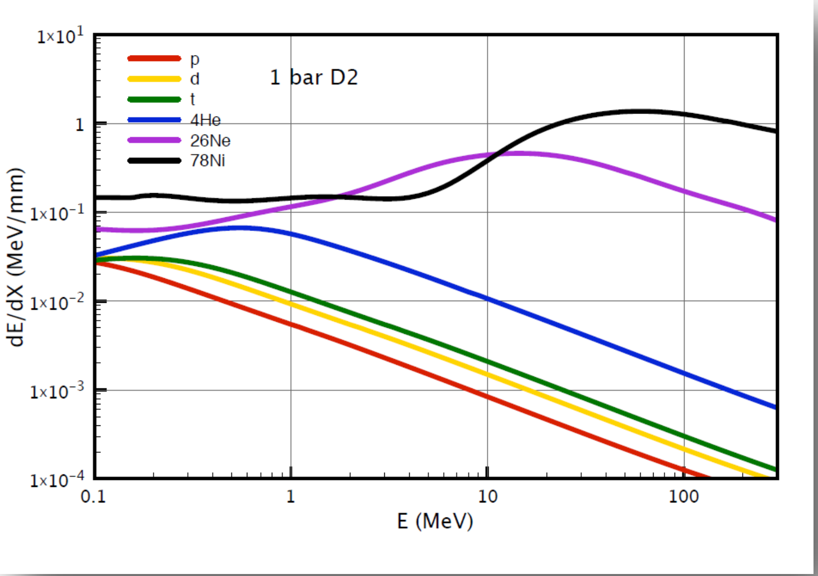
- External detectors are expensive
  ⇒ contain particles in gas volume
- Higher pressure
  ⇒ stronger signal from light ions

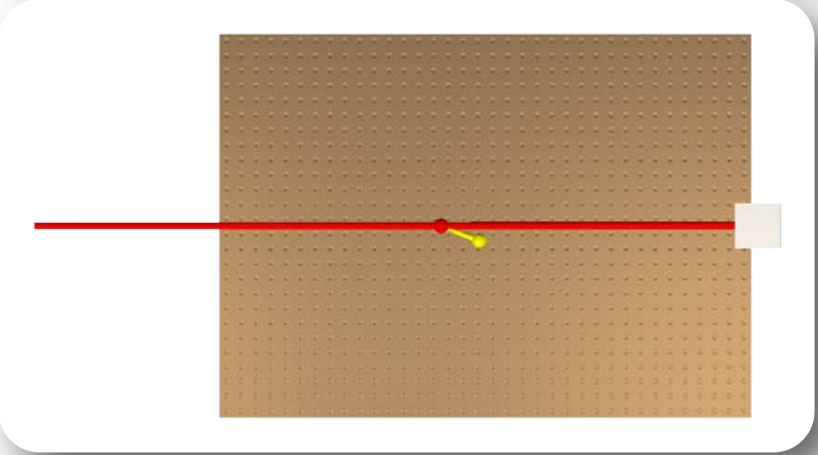
but

- Limit imposed
  by E_{loss} of beam particle
- 3 orders of magnitude difference!

Possibilities

- Electronics (better preamps)
- Software (different gains on pads)
- Hardware: mask the beam

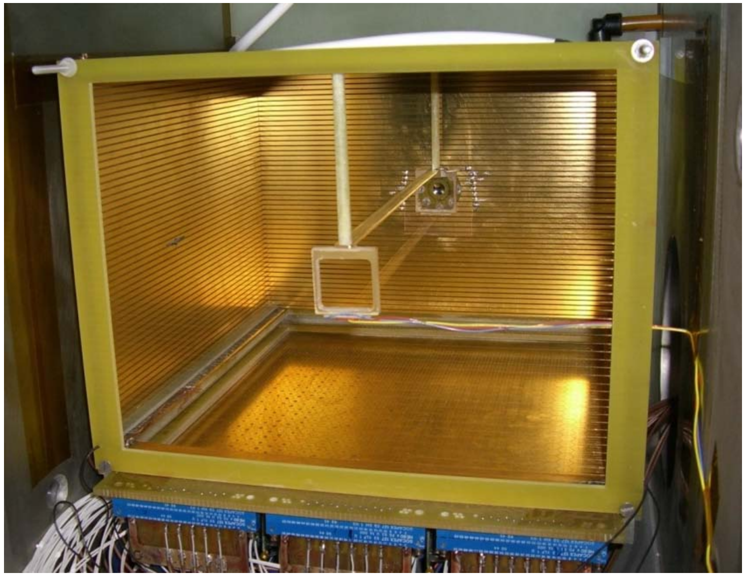




Dynamic range

Possibilities

- Electronics (better preamps)
- Software (different gains on pads)
- Hardware: mask the beam



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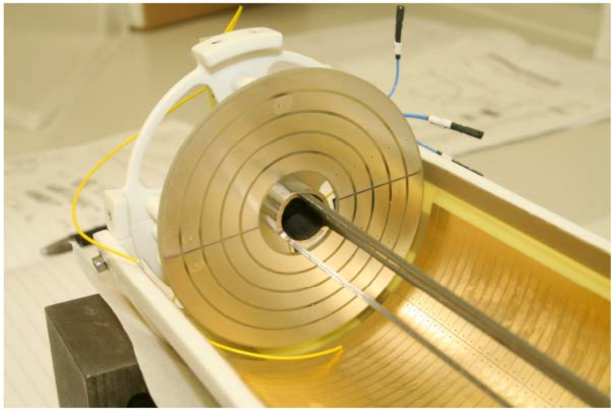
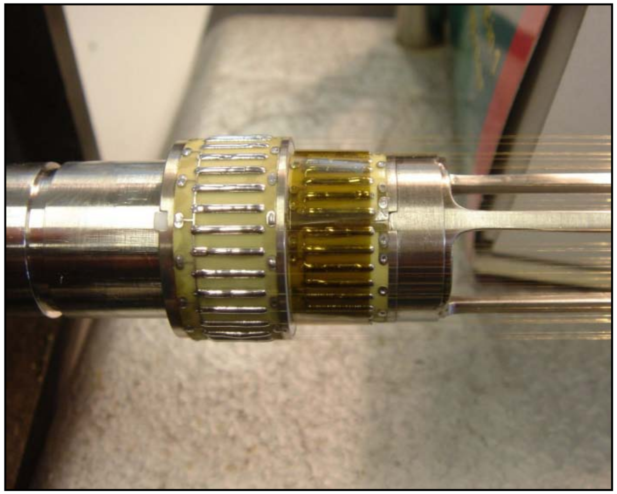




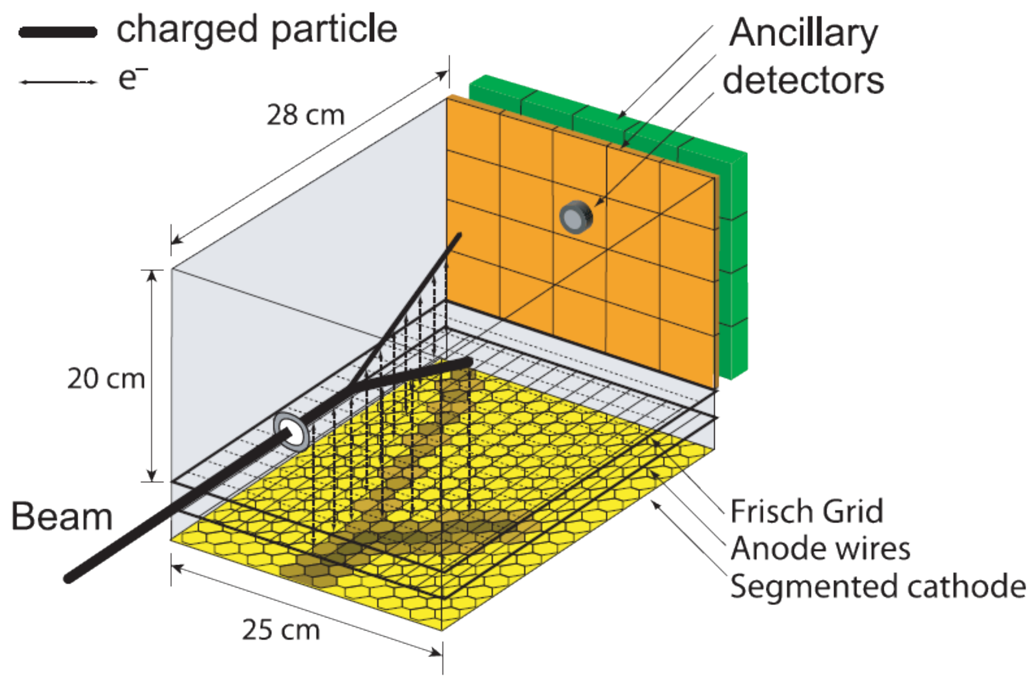
Measured quantities

Energy

- Collected charge
- Path length (range)

Angle

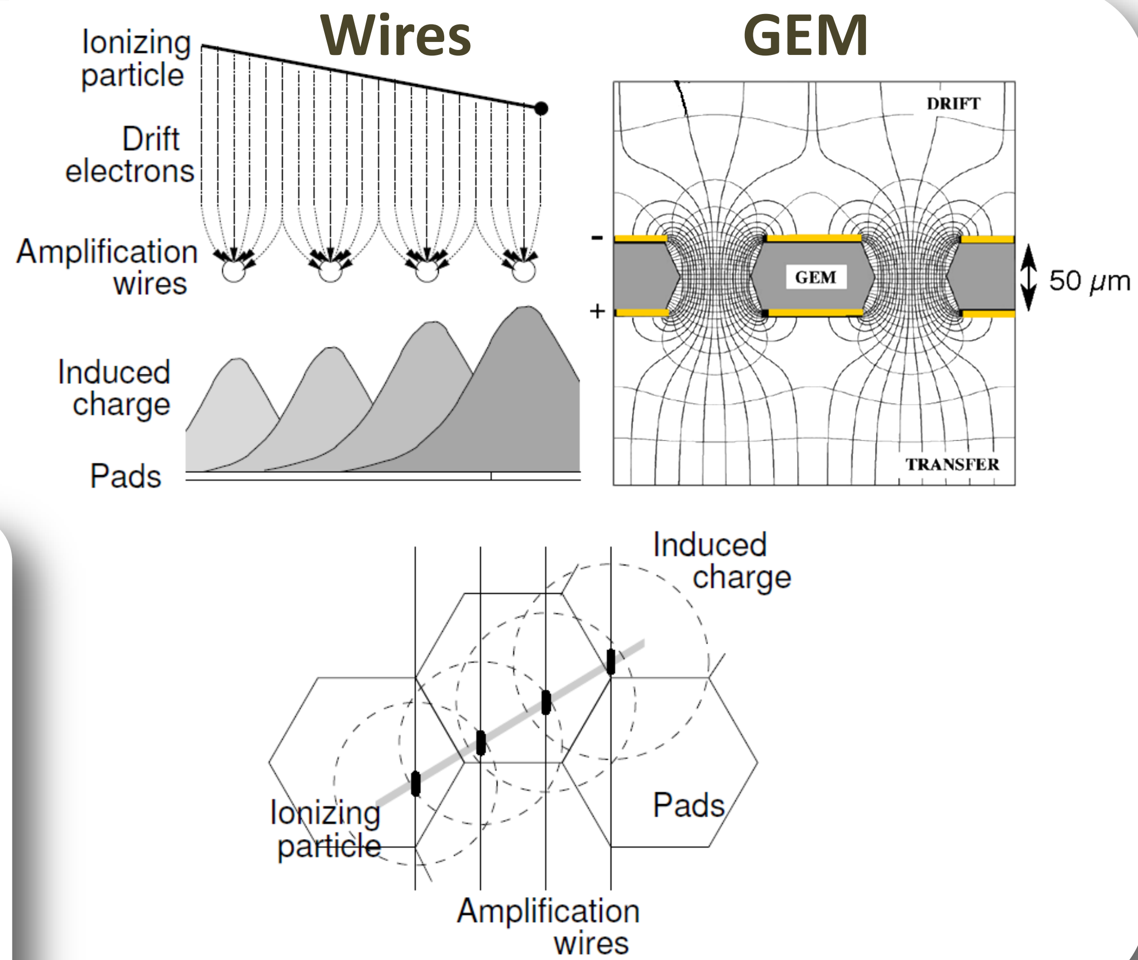
- External detectors
- Track reconstruction



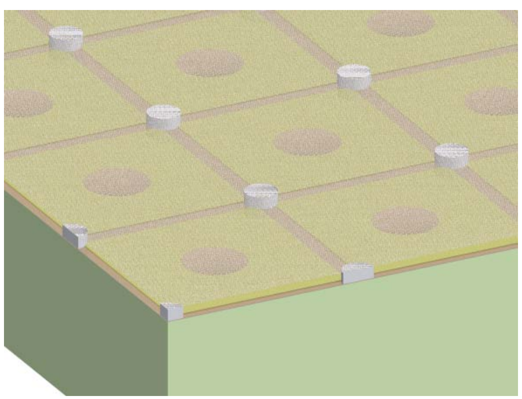
Track reconstruction

T. Roger, PhD Thesis

- Charge distribution depends upon amplification technology and pad shape



Micromegas

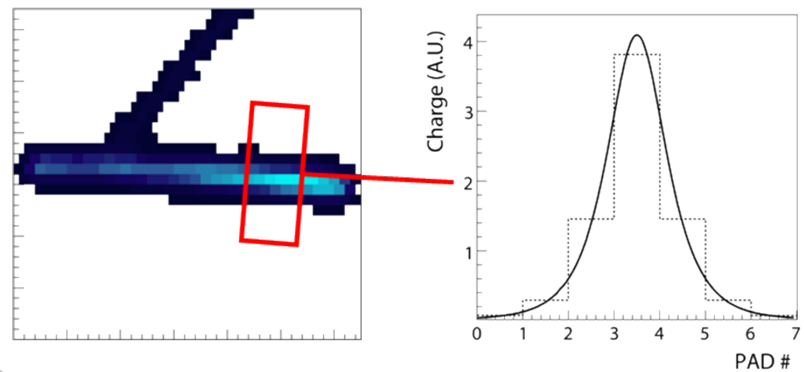


Track reconstruction

T. Roger, PhD Thesis

- Simulation of the charge collection to test reconstruction algorithms

$$\sigma(x,y) = \frac{-Q}{2\pi}\sum_{n=0}^{\infty}\frac{(-1)^n(2n+1)L}{[(2n+1)^2L^2+x^2+y^2]^{3/2}}$$

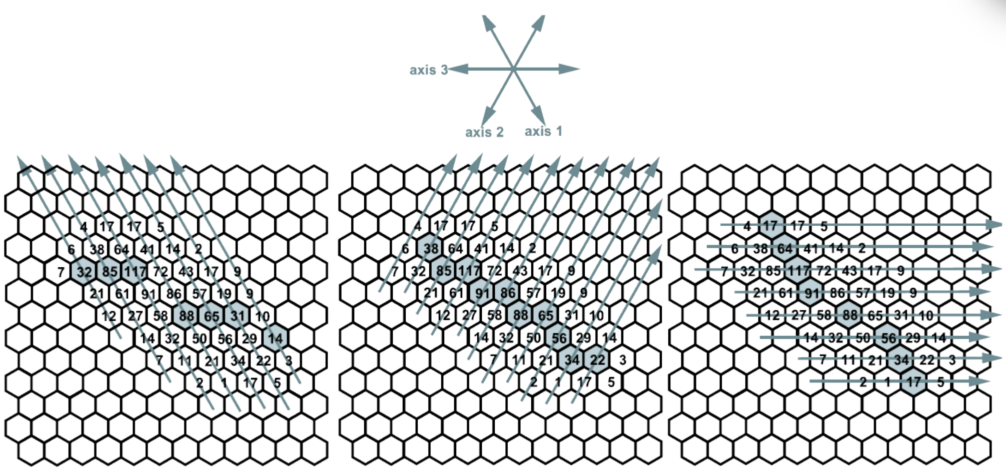


Hyperbolic Secant Squared

1. search for maxima along axes
2. find centroids
3. fit straght line through centroids

$$\Delta_R = \frac{w}{2}\frac{ln(\frac{1+a_1}{1-a_1})}{ln(a_2+\sqrt{a_2^2-1})}$$

$$a_1 = \frac{\sqrt{\frac{Q_0}{Q_+}}-\sqrt{\frac{Q_0}{Q_-}}}{2\,sinh\,a_2} \quad \text{and} \quad a_2 = \frac{1}{2}\left(\sqrt{\frac{Q_0}{Q_+}}+\sqrt{\frac{Q_0}{Q_-}}\right)$$



axis 1
7 maxima found

axis 2
10 maxima found

axis 3
8 maxima found

Accuracy: 0 to 1 degrees depending on orientation

Track reconstruction

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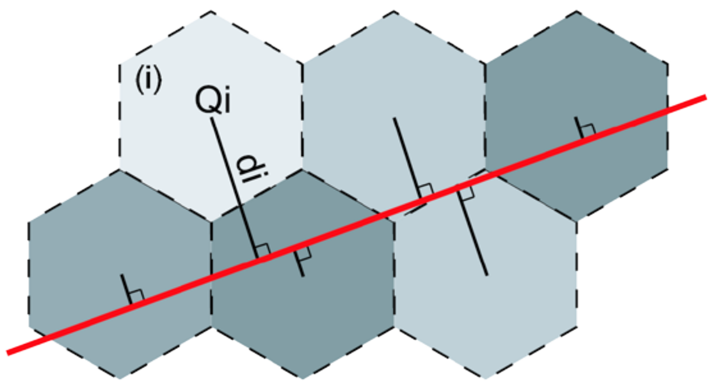
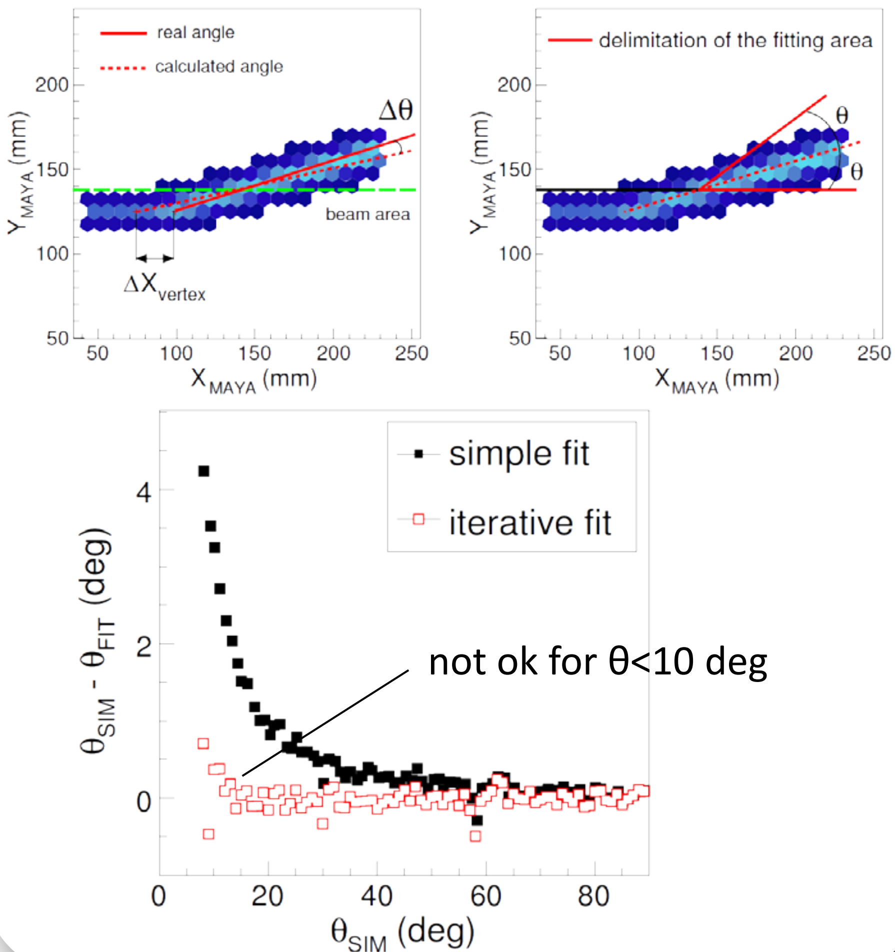
Global Fitting method

For small charges, not spread
(light particles, high energies)

$$\chi^2 = \sum_{n=0}^{Npts} Q_n \frac{(ax_n + b - y_n)^2}{a^2+1}$$





Energy from collected charge

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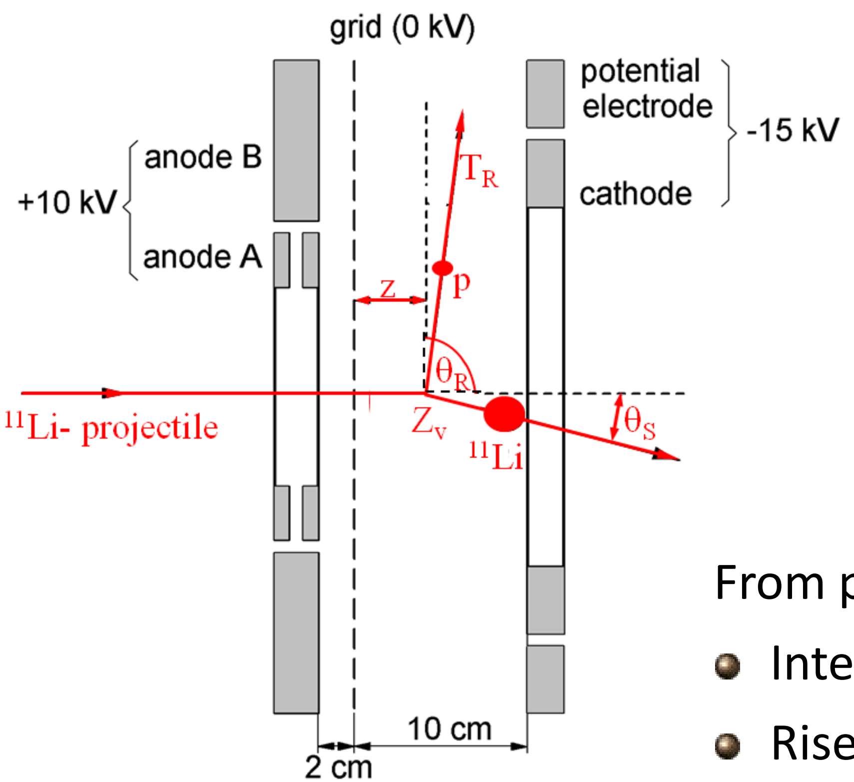

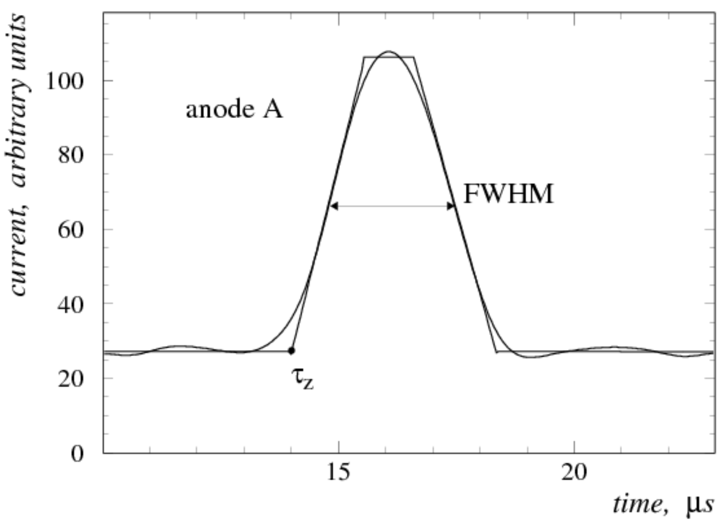

From pulse analysis:

- Integral $\Rightarrow$ recoil energy T_R ($\Delta E_{FWHM} \leq 90$ KeV)
- Risetime $\Rightarrow$ recoil angle θ_R ($\Delta\theta_{FWHM} \leq 0.6°$)
- Time difference anode-cathode
  $\Rightarrow$ vertex point Z_V ($\Delta z_{FWHM} \leq 110$ μm)

Energy from range: end point

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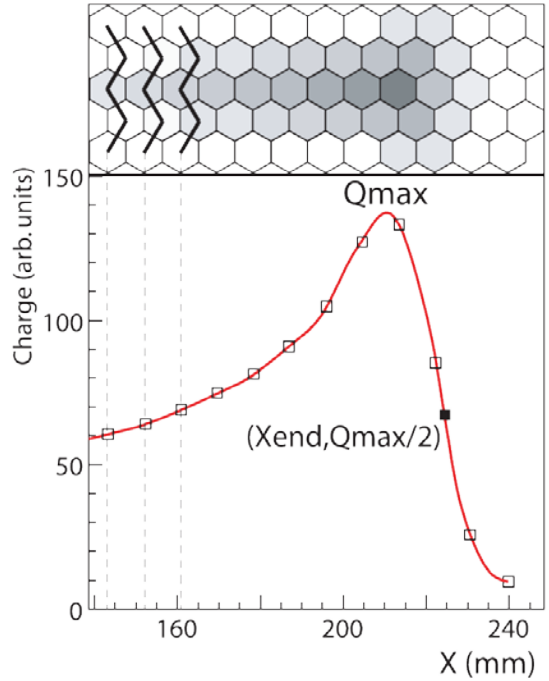
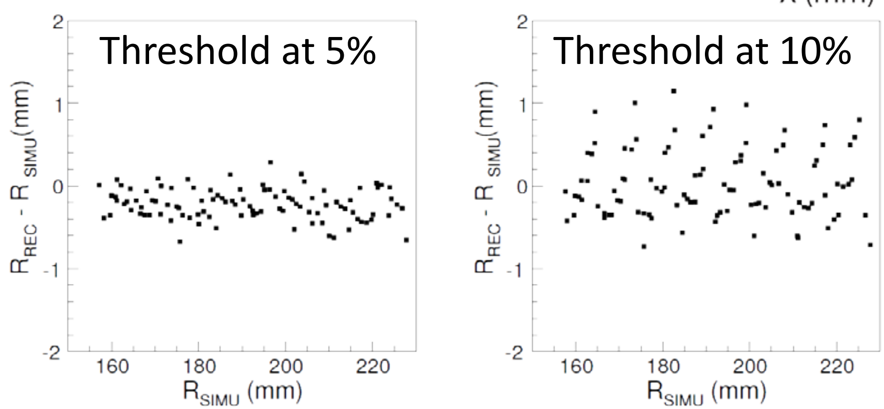
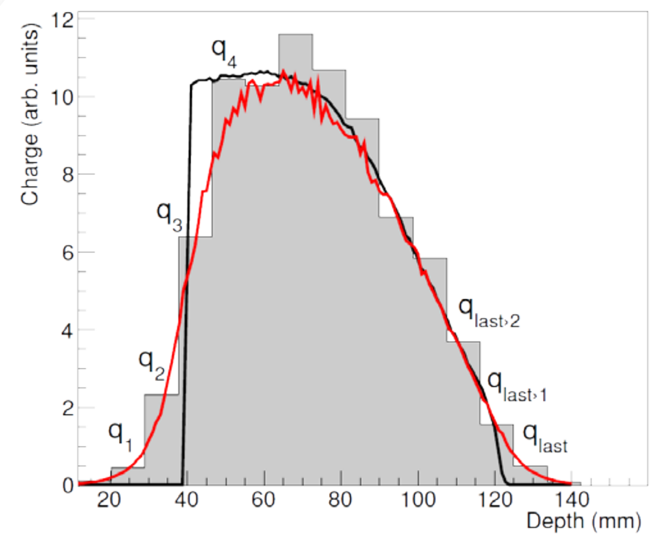
Charge profile

- Bragg peak: threshold effects





- Charge fit accuracy ≈1.5 mm



$$x_{end} = (x_{last} + x_{last-1})/2 + \Delta(\text{slope})$$

Energy from range: reaction vertex

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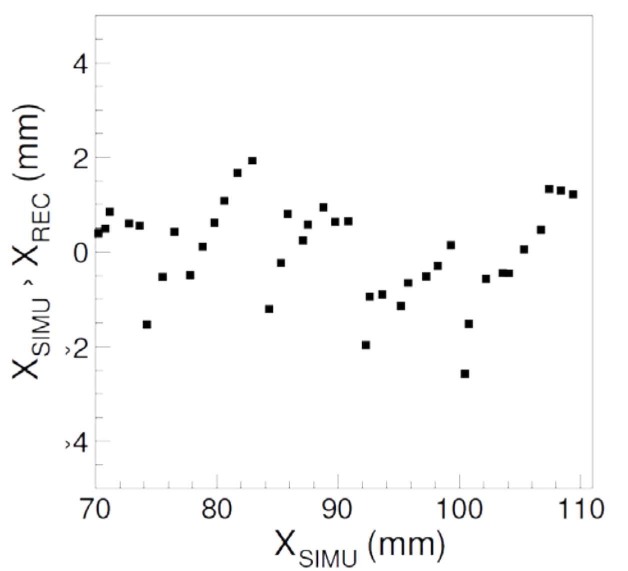
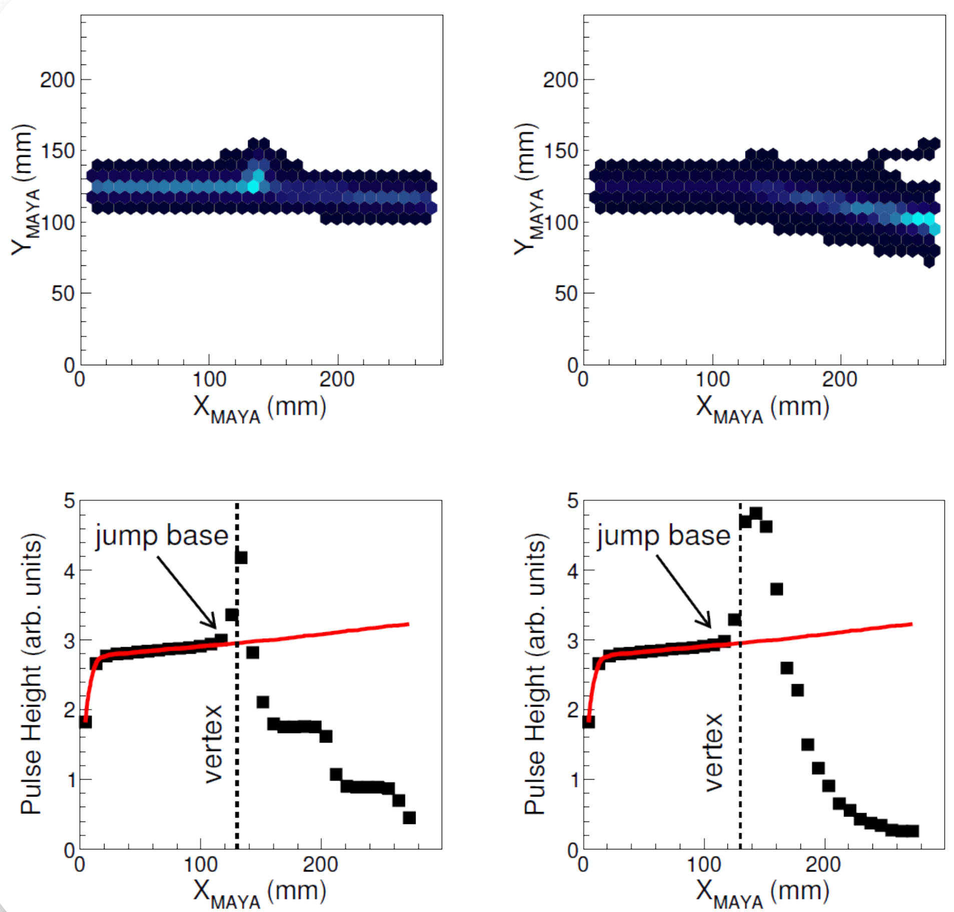
- Large uncertainties for short tracks and small angles
- Use charge profile instead

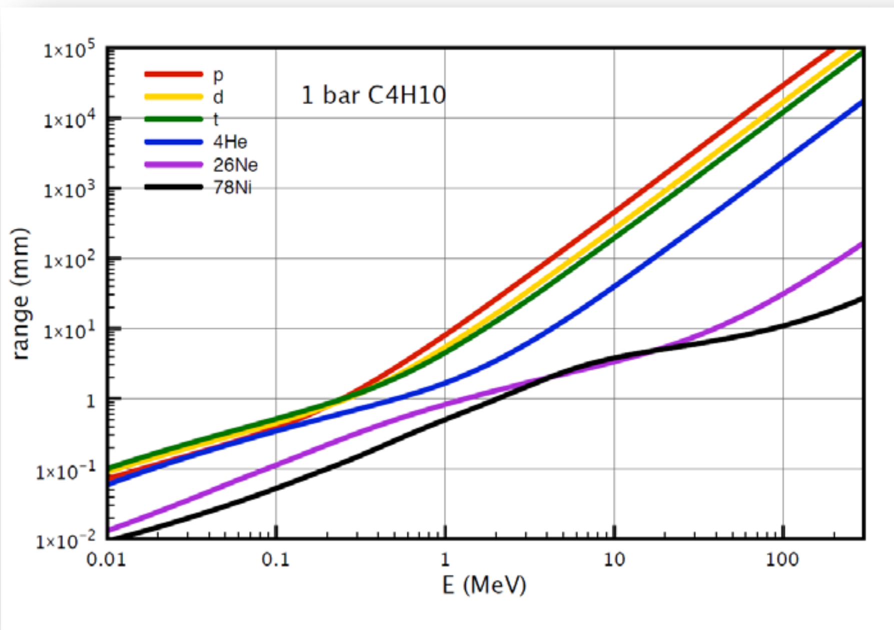




Particle identification

Energy vs. range

- Curves and tables (ex. SRIM)
- Need accurate range
  and a good calibration of pads
  to extract the d*E*/d*x* information



Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Straggling	Lateral Straggling
10.00 keV	4.260E-01	8.152E-03	200.63 um	61.18 um	63.50 um
11.00 keV	4.801E-01	7.584E-03	208.34 um	61.64 um	64.34 um
12.00 keV	5.308E-01	7.097E-03	215.34 um	62.01 um	65.04 um
13.00 keV	5.768E-01	6.675E-03	221.79 um	62.31 um	65.62 um
14.00 keV	6.173E-01	6.304E-03	227.83 um	62.55 um	66.11 um
15.00 keV	6.518E-01	5.976E-03	233.55 um	62.77 um	66.55 um
16.00 keV	6.803E-01	5.684E-03	239.03 um	62.95 um	66.93 um
17.00 keV	7.034E-01	5.421E-03	244.33 um	63.11 um	67.28 um
18.00 keV	7.221E-01	5.184E-03	249.50 um	63.26 um	67.59 um
20.00 keV	7.500E-01	4.771E-03	259.56 um	63.52 um	68.15 um

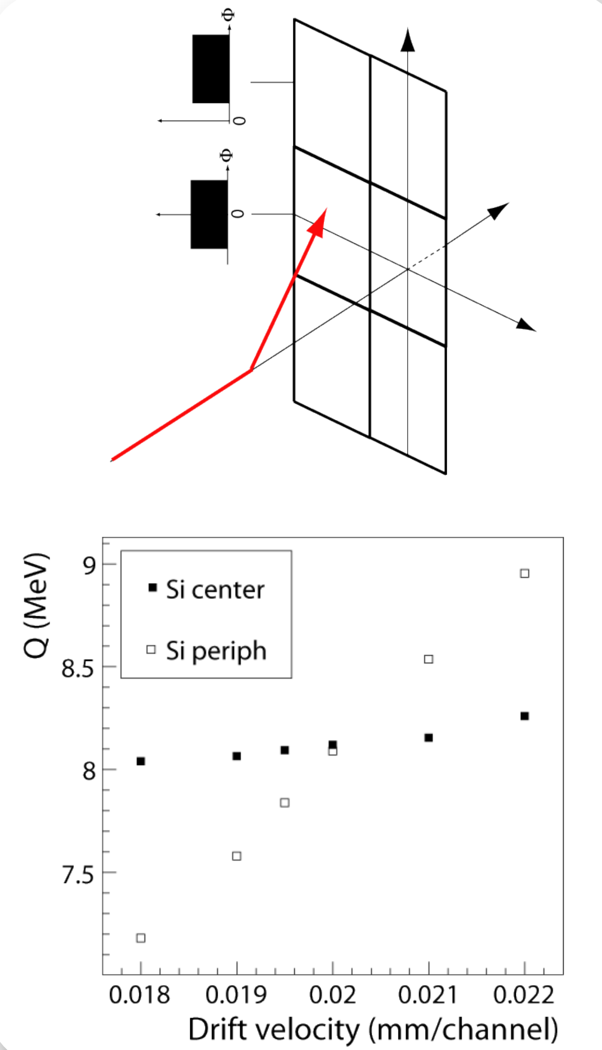
Calibrations

Energy

- Induction: charge in wires with pulser
  Alignment of pad gains
- Calibrated (alpha) source

Time

- Calibrate electronics, or
- "Physics" calibration
  using a known reaction



Summary

- Active targets are very promising instruments for research with exotic beams
  - Large target thickness with no loss in resolution
  - Low thresholds
  - Versatile, different configurations possible
- Many parameters to consider
  gas, pressure, electric field, drift velocity, dynamic range
- Measurements
  - Track reconstruction: check algorithms against simulation
  - Energy: from collected charge or from range
    (→ track reconstruction, energy loss tables)
  - Particle ID from E_{loss}: limited by spatial resolution and dE/dx on pads