Silicon detectors in nuclear physics: Challenging resolution and particle identification

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Silicon detectors: key devices for nuclear physics experiment

- **Large amount of charge carriers** formed following the passage of ionising radiations (3.6 eV/pair) => good energy resolution (≤1%)
- **Silicon detectors have been widely used in nuclear physics :**
  - Particle identification with ΔE-E when used in multilayer devices
  - Particle identification with PSA (only one layer)
  - Particle identification from E-ToF (only one layer)
  - Energy measurement
  - Position sensitivity (for example, strip detectors)
  - X-ray spectroscopy
- New materials involving silicon such as SiC, showing more radiation hardness, are under study

*The third national commission (CSN3) of INFN has recently produced a paper (**A.Badalà et al., accepted in La Rivista del Nuovo Cimento**) reviewing all the main particle identification techniques used in INFN-funded experiments.*

This presentation focuses on the silicon-based detectors described in such publication.

The standard particle identification technique: the ΔE-E method

The energy loss of a heavy particle through matter is given by the well-known ***Bethe-Bloch equation*** *(for the stopping power)*

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Where the most important (for us) ingredients are:

Z atomic number of absorber

A atomic mass of absorber

z charge number of incident particle

m atomic mass of incident particle

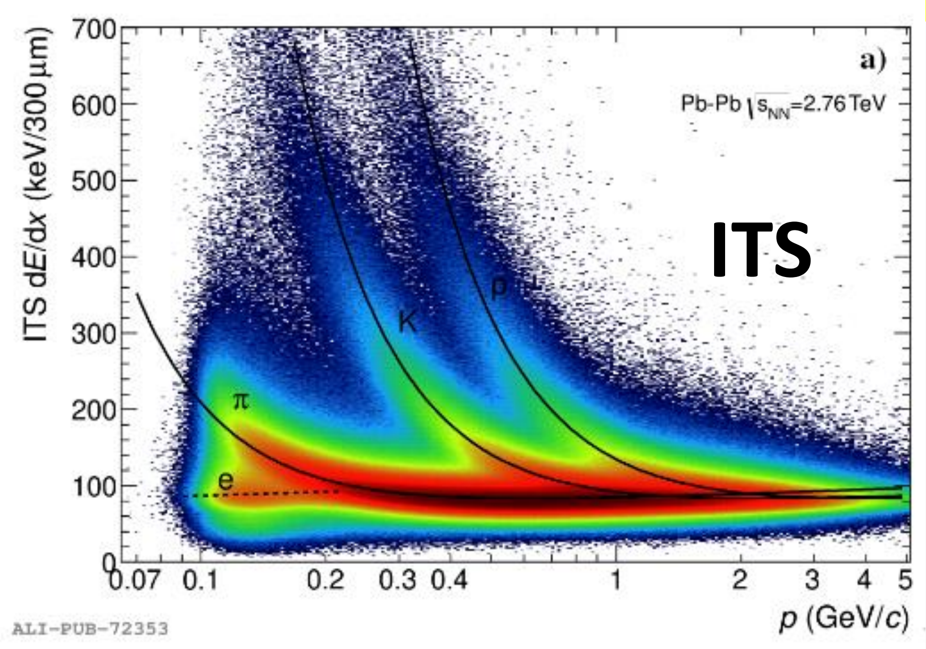
(E → kinetic energy in the non-relativistic limit)

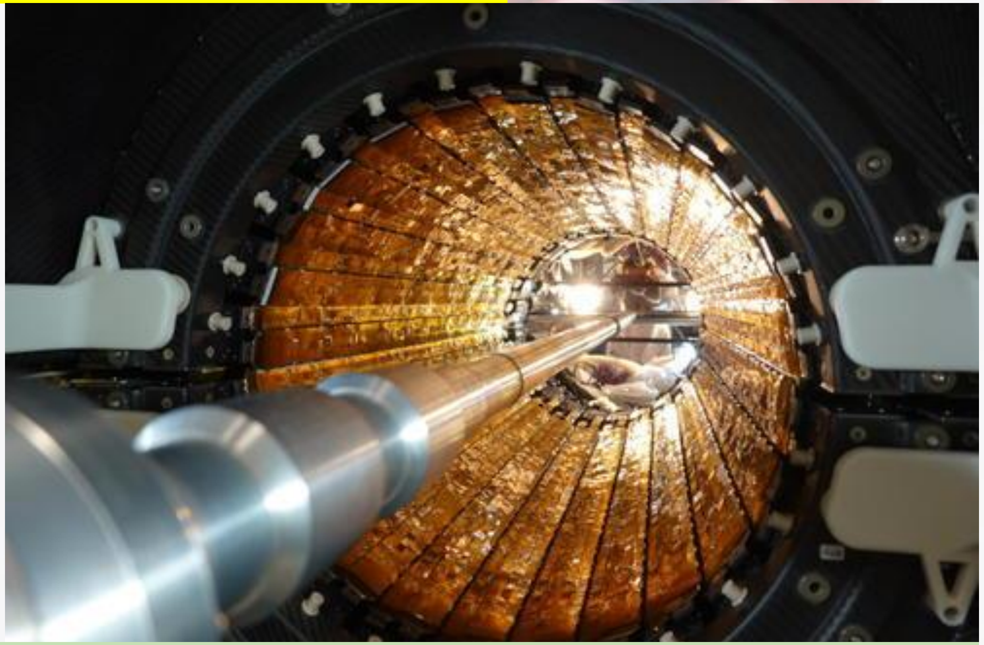
In the non-relativistic limit

$$\left\langle -\frac{dE}{dx} \right\rangle \sim \frac{z^2 m}{E}$$

- Two detection layers are necessary and particles must cross the first layer and be stopped in the second
- The dependence of the energy loss on z and A of the incident particle makes it possible to perform the identification in charge (and, below low-medium Z, also mass) **by plotting the energy loss ΔE in the first layer against the residual energy E measured in the second layer**
- **Silicon detectors** are especially suited for the application of the ΔE-E approach thanks to the energy resolution and the variety of thickness in which they can be produced

ΔE-E method at high energies: ALICE





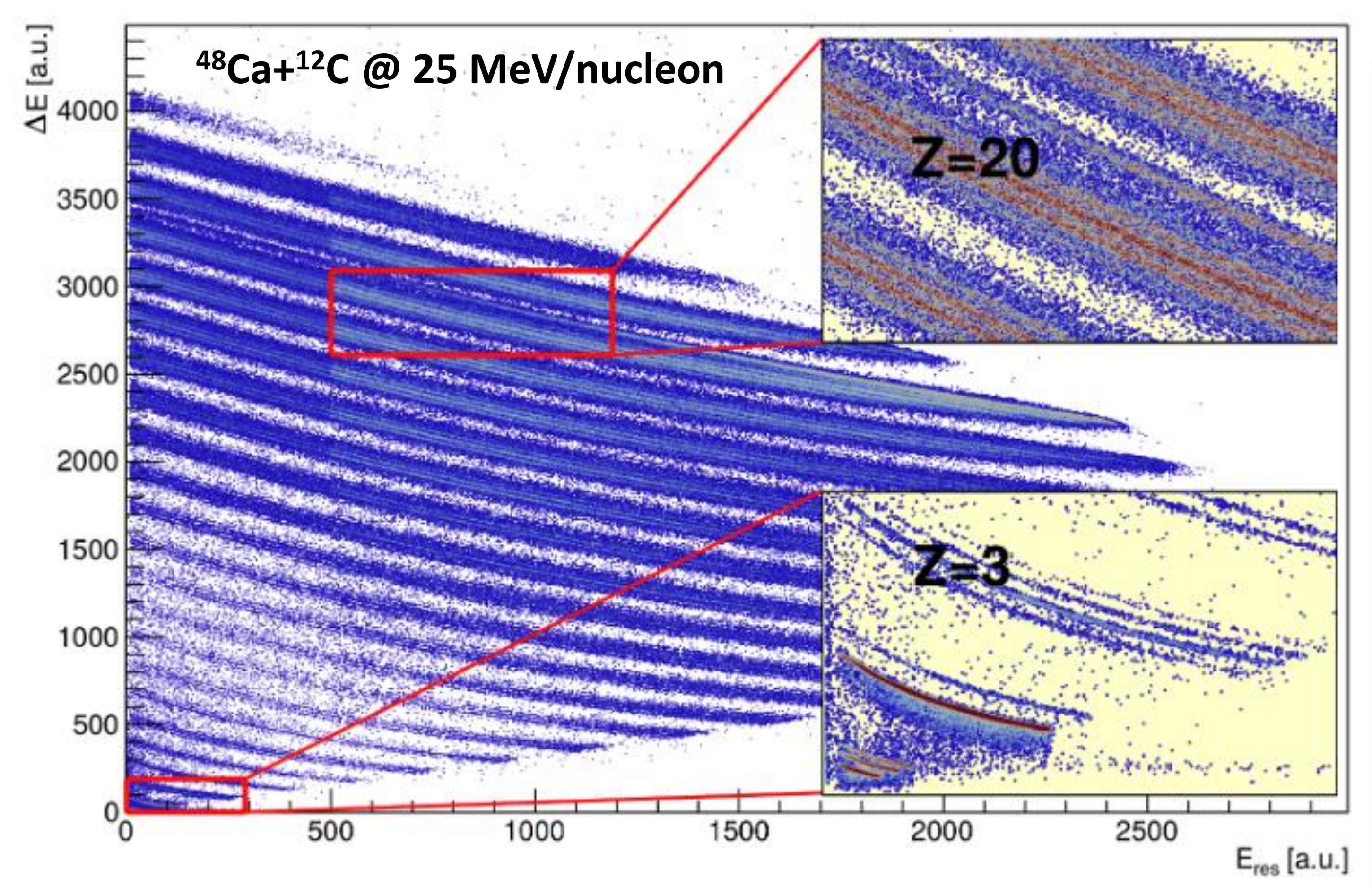
In the ALICE experiment, most of the detected particles by means of energy loss measurement like barions, mesons and nuclei are MIP's. PID is performed by the Inner Tracking System (ITS) and by the Time Projection Chamber (TPC).

In the ITS the two central layers (Silicon Drift Detectors SDD) and the two outermost layers (Double Sided Silicon Strip Detectors SSD) are used to identify particles by means of dE/dx vs. p in the non relativistic region.

The ALICE SDDs were produced from very homogeneous high-resistivity 300µm thick **Neutron Transmutation Doped (nTD)** silicon

nTD silicon*: an undoped Si wafer is irradiated with neutrons in a reactor; thermal neutrons are captured by ^{30}Si (about 3% in pure Si) which becomes ^{31}Si and then β^- decays at ^{31}P, thus obtaining a n-doped Silicon*

ΔE-E method at intermediate energies: NUCLEX



ΔE–E correlation in a typical FAZIA telescope (first vs second silicon layer)
Isotopic resolution up to Z~25 (up to Z=21 in the shown case)

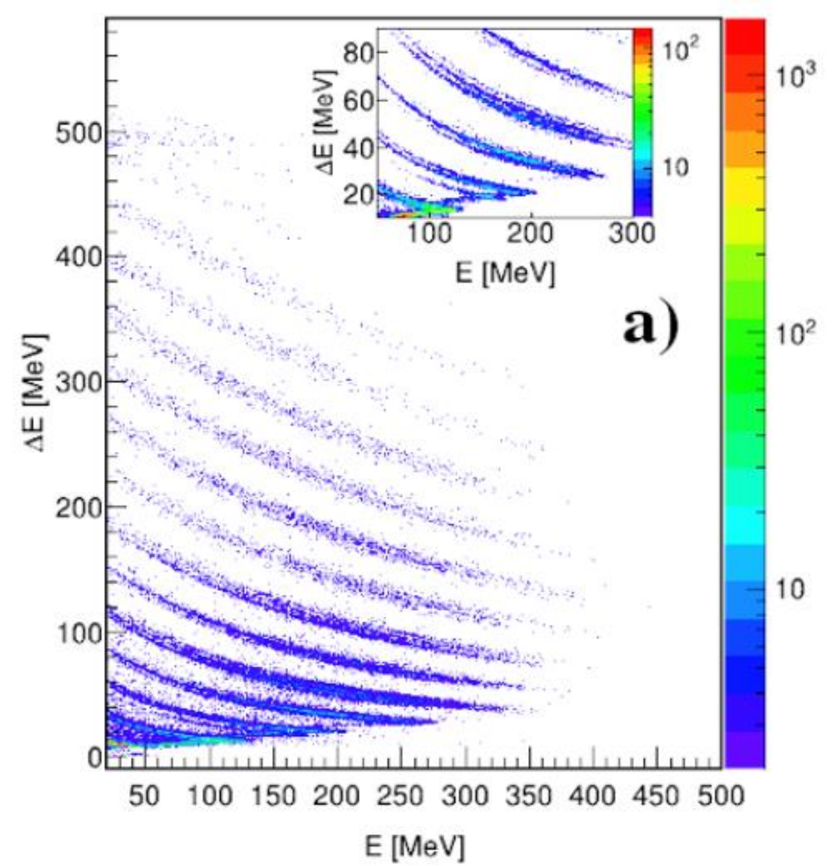
- In heavy ion reactions at intermediate energies many fragments are produced
- Broad angular coverage, high granularity, identification capabilities in a very wide range (Z=1, Z> $Z_{Projectile}$) are necessary

- **The goal of the European FAZIA Collaboration is the design of a new-generation detector array for heavy-ion collisions with greatly enhanced isotopic identification capabilities.**

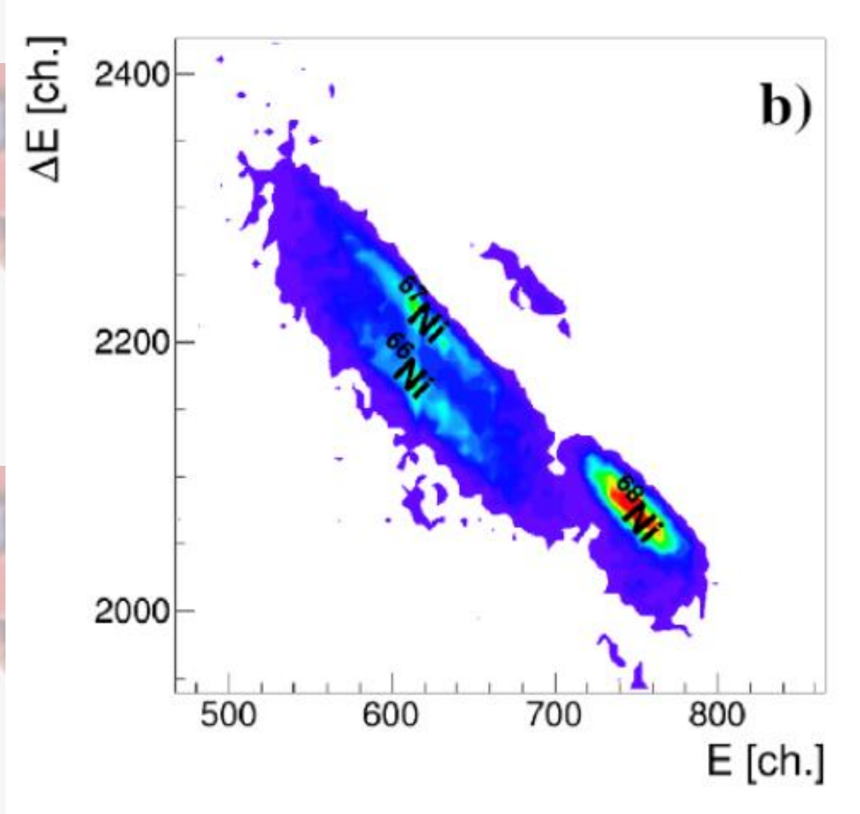
- ***FAZIA*** consists of blocks of 16 telescopes, each of which is made up of two 20x20 mm^2 silicon pads (300 and 500 μm thick) followed by 10 cm CsI(Tl) scintillators, fully equipped with digital electronics, and it is designed for beam energies above 20 MeV/nucleon

ΔE-E method at intermediate energies: CHIRONE

FARCOS is a modular array of telescopes, each of them consisting of two Double-Sided Silicon Strip Detectors (DSSSD), 300μm and 1500μm thick, respectively, followed by a last stage including four CsI(Tl), 6 cm thick, to stop very energetic particles

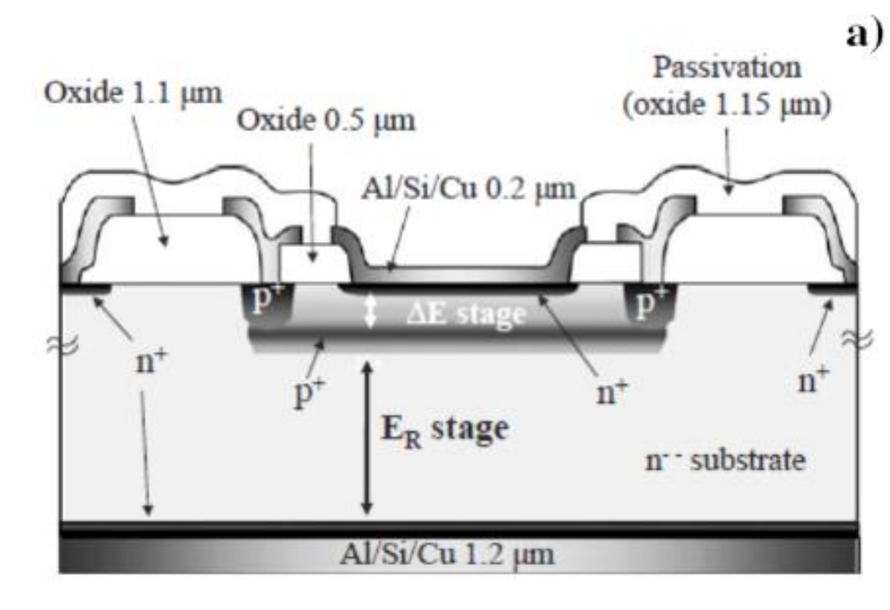


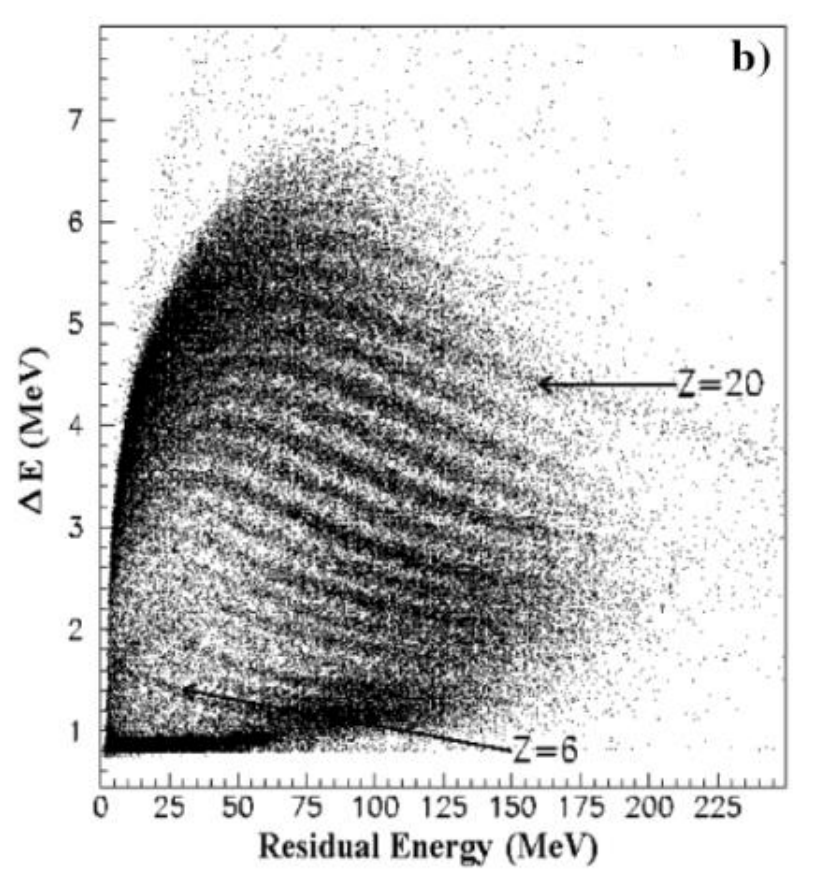
ΔE−E plot obtained using a telescope of the FARCOS array in the reactions ^{124}Xe+^{64}Zn,^{64}Ni at 20 MeV/nucleon.



ΔE−E plot obtained in the reaction ^{68}Ni+^{12}C at 28 MeV/nucleon. The ΔE−E plot was obtained considering a strip of the 300μm stage and the corresponding strip of the 1500 μm detector, for a FARCOS telescope

ΔE-E method in nuclear astrophysics: ASFIN





In nuclear astrophysics, beam energies and the energies of the emitted particles are often very low, so the energy loss in standard Si detectors may stop the impinging particles and no ΔE-E spectra could be deduced

→ Very thin ΔE detectors, of the order of few microns, called monolithic are necessary

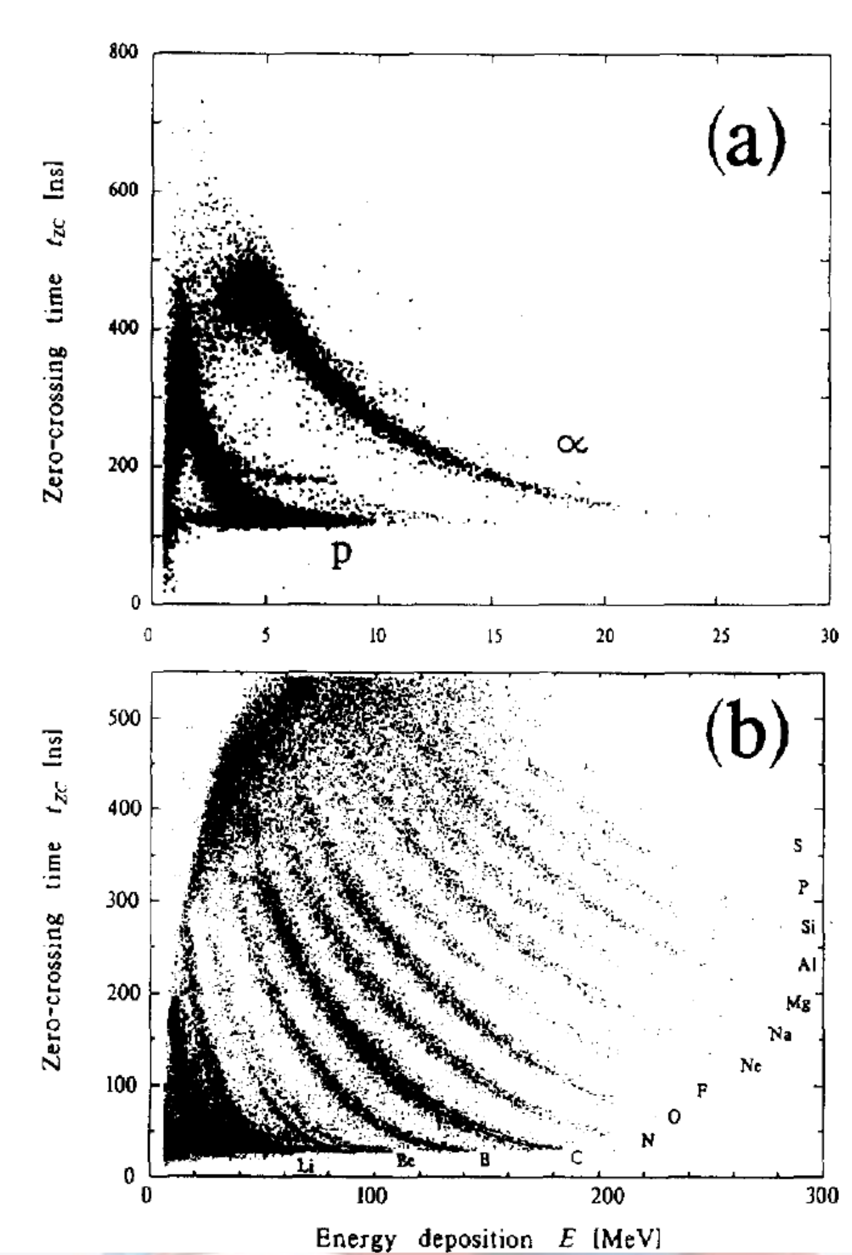
- they are built on a single silicon crystal, by combining photolithographic and ion implantation techniques

A similar problem is found when heavy ions must be detected, since the stopping power is very large, and they can be stopped in the first layer.

→ example: $^{40}Ca+^{48}Ca$ collision at E_{beam} = 400 MeV

PSA in Silicon detectors: a technique to reduce the identification thresholds

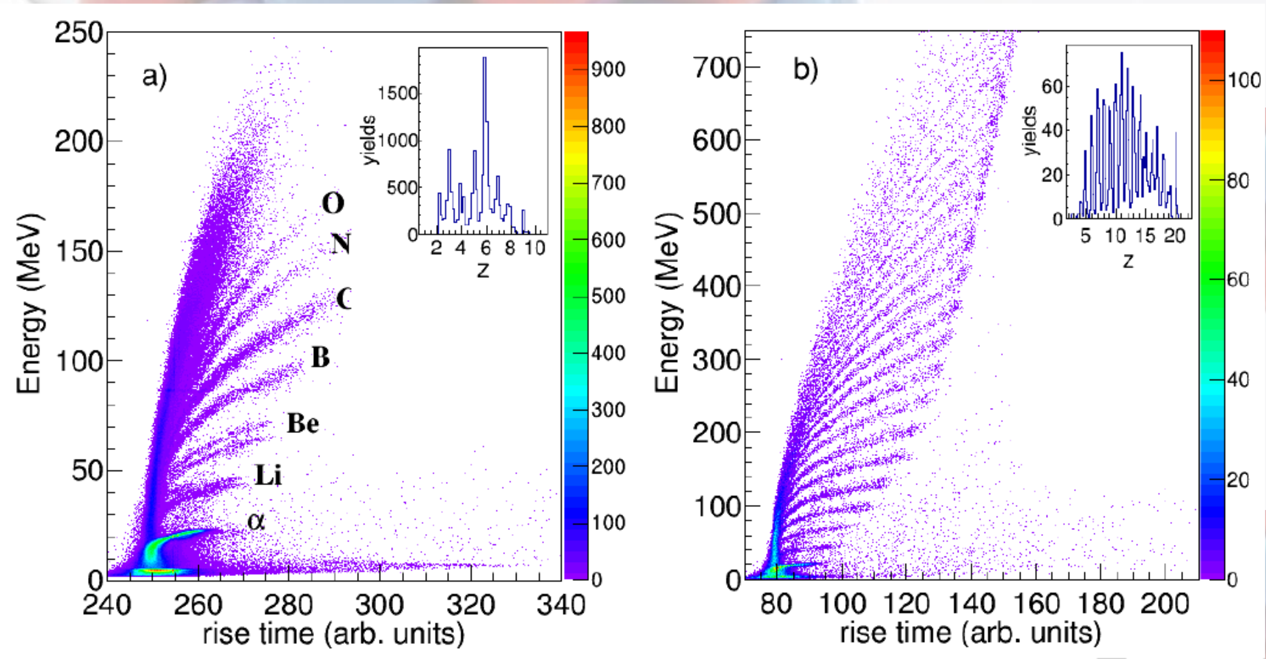
- Identification thanks to the different shape of the signal induced in the detector by particles with different Z and A, being equal the energy
- The identification is obtained by correlating the deposited energy and a parameter related to the shape of the signal (i.e. the signal rise time)
- The main advantage with respect to the ΔE-E tecnique is the threshold reduction: the identification is achieved with only one detection layer **provided that the range of the particle in silicon is beyond a minimum value** (increasing with the charge)



G.Pausch et al., NIMA 365(1995) 176

CHIRONE: PSA in CHIMERA

CHIMERA: a 4π detector consisting of Si (300μm) -CsI(Tl) telescopes designed for medium-high beam energies



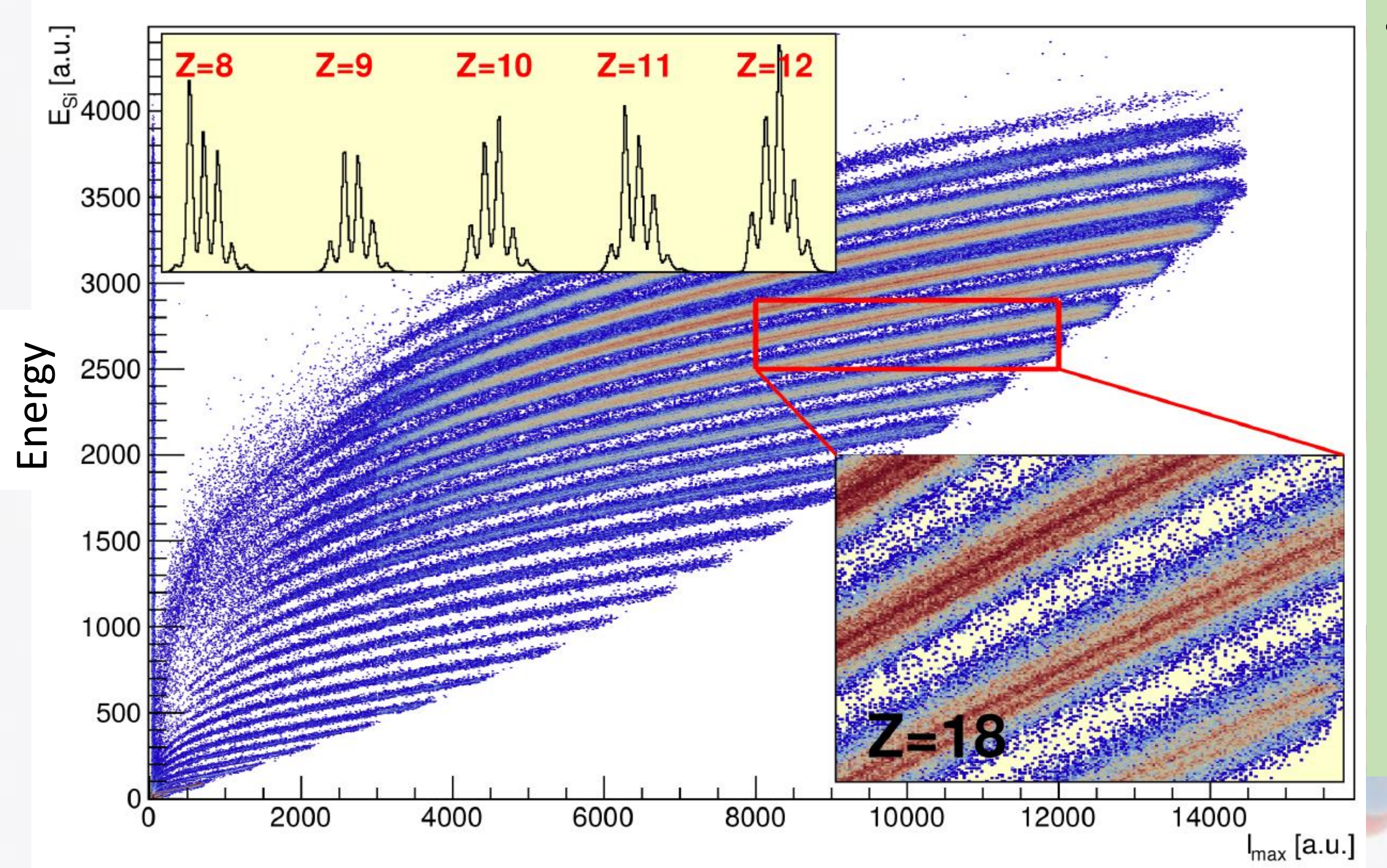
Direct configuration of the Si detector(entrance from the high field side) to preserve the quality of the time of flight

Partly analog partly digital electronics

Charge identification for 3 ≤ Z≤ 18

Identification threshold: 4-9 MeV/nucl (increasing with Z)

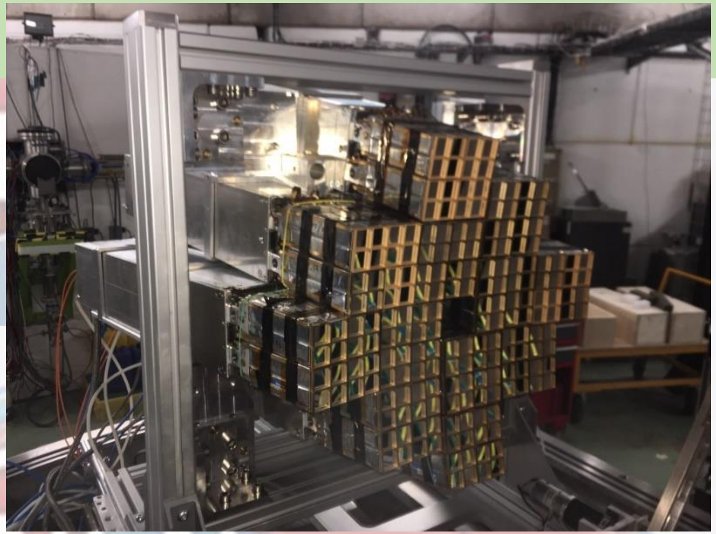
NUCLEX: PSA in FAZIA



Maximum of the current signal

The FAZIA recipe:

- Reverse mounting (i.e. entrance from low electric field side)
- Good doping uniformity (nTD detectors)
- Fully digital electronics coupled to proper identification algorithms
- Channeling reduction (using properly cut wafers , i.e. 7° off the main crystal axis)
- Bias voltage corrected for the drop due to the reverse current
- Thin metalization to reduce the sheet resistance

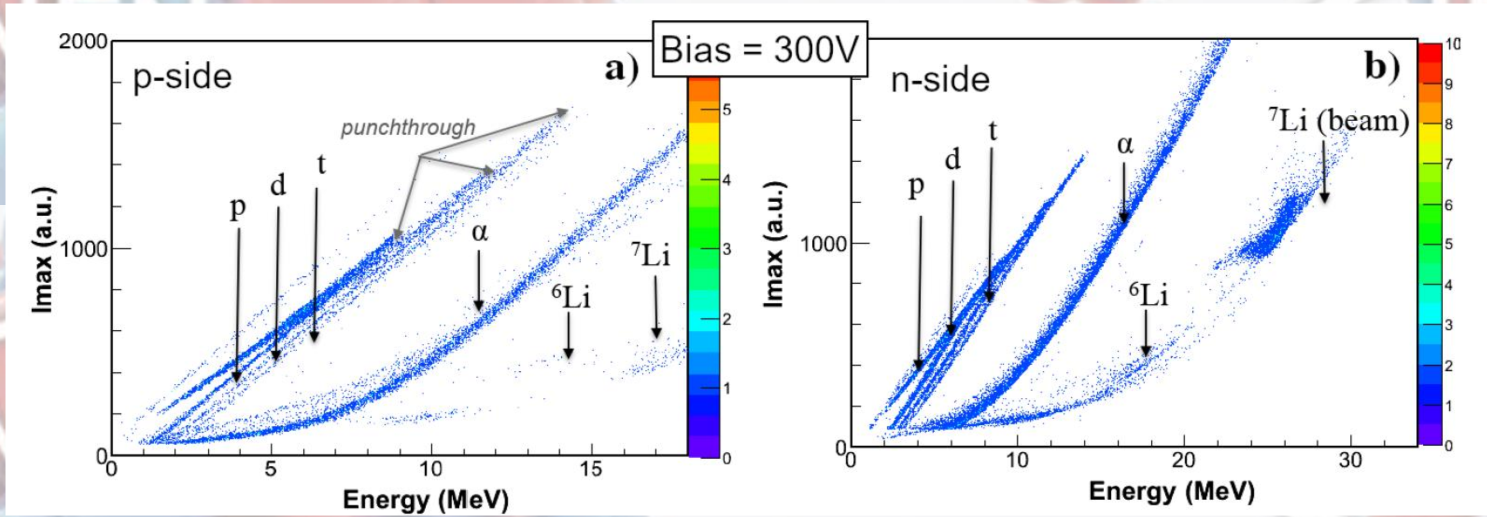


Charge identification tested up to Z=54 (threshold: 2-5 MeV/nucl)
Mass identification up to Z=20 (threshold: 10 MeV/nucl)

GAMMA: PSA in GRIT detector

GRIT is designed to be used as stand alone detector or as an ancillary to γ spectrometers

48 ΔE-E telescopes in a spherical geometry
The first silicon layer is a 500 μm thick nTD strip detector (128 strips on each side)
The second layer is 1.5mm thick (128 strips on each side)



Identification in Z and A of light charged particles

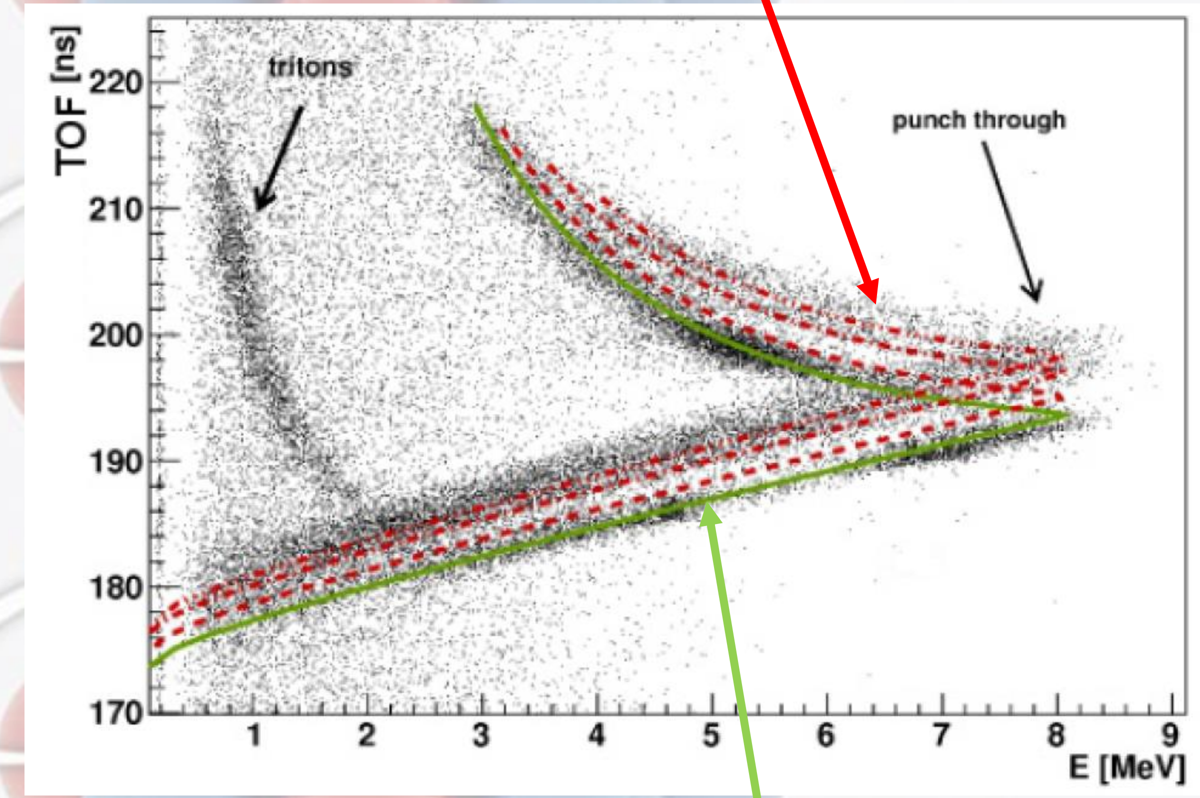
Identification threshold for light particles: 1MeV/nucl

Another identification technique: E-ToF

- Only one detection layer is needed => threshold reduction with respect to ΔE-E
- For particles stopped inside the detector $E = \frac{1}{2}mv^2$ => E-ToF correlation is sensitive to the mass of the particles.
- For particles punching through the detector the ΔE-ToF correlation is sensitive to Z
- For a good measurement of ToF a long base of flight is fundamental
- To extract a correct mass, a recursive procedure is generally applied, since the measured time of flight must be corrected for plasma delay effects and the walk effect for signals of very different amplitude

ASFIN: the E-vs. TOF to discriminate between elastic and inelastic reactions

Inelastic scattering

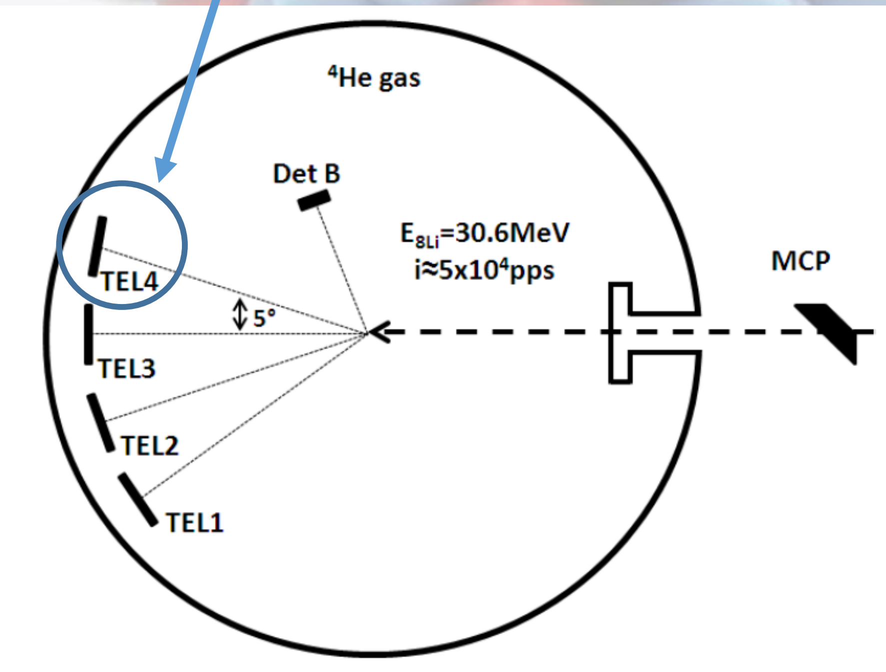


Elastic scattering

ToF:

- Stop signal provided by a microchannel plate
- Start signal: a 500 µm Double Side Strip Silicon Detector (DSSSD)

E: DSSSD



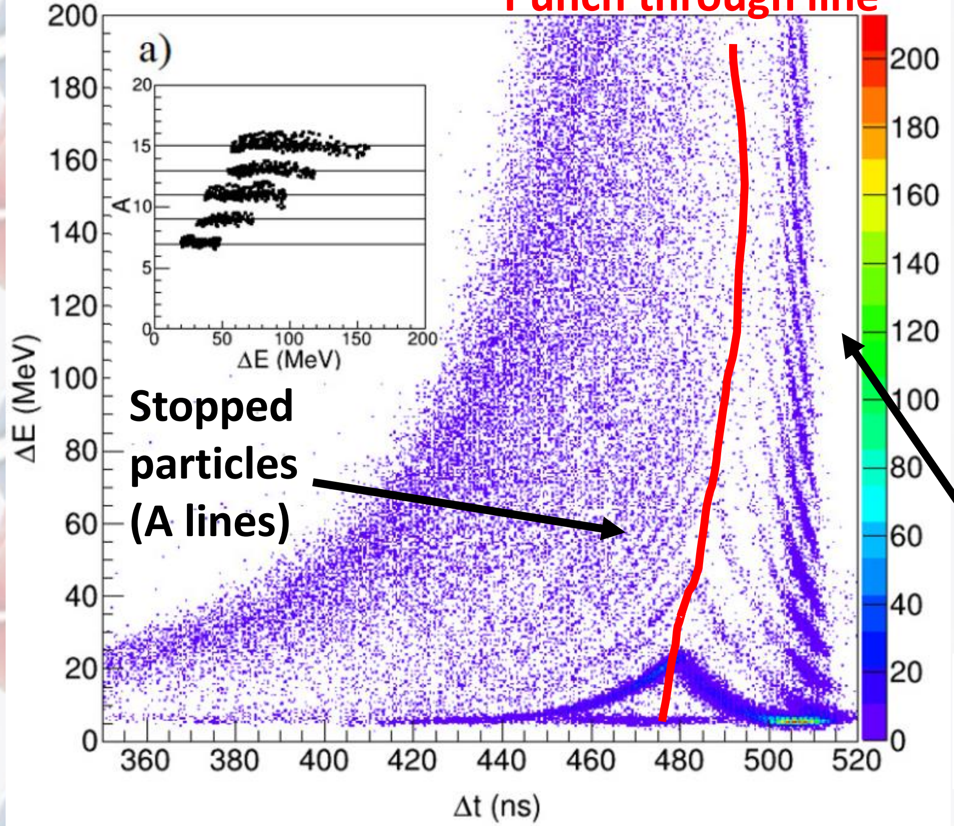
CHIRONE: E-ToF in CHIMERA

Standard CHIMERA Si detector

ToF used for direct measurement of the velocity of ions with Z≥2

From E-ToF mass identification for particles stopped in Si layer (1-3.5 m long base of flight)

Punch through line



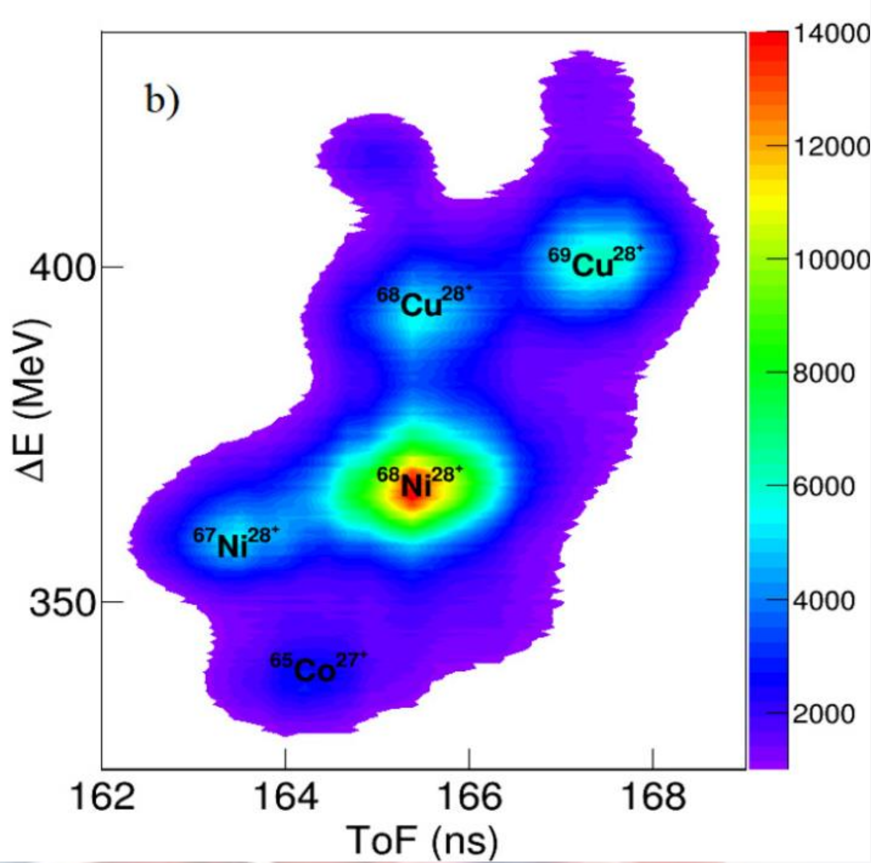
Stopped particles (A lines)

Punching through particles (Z lines)

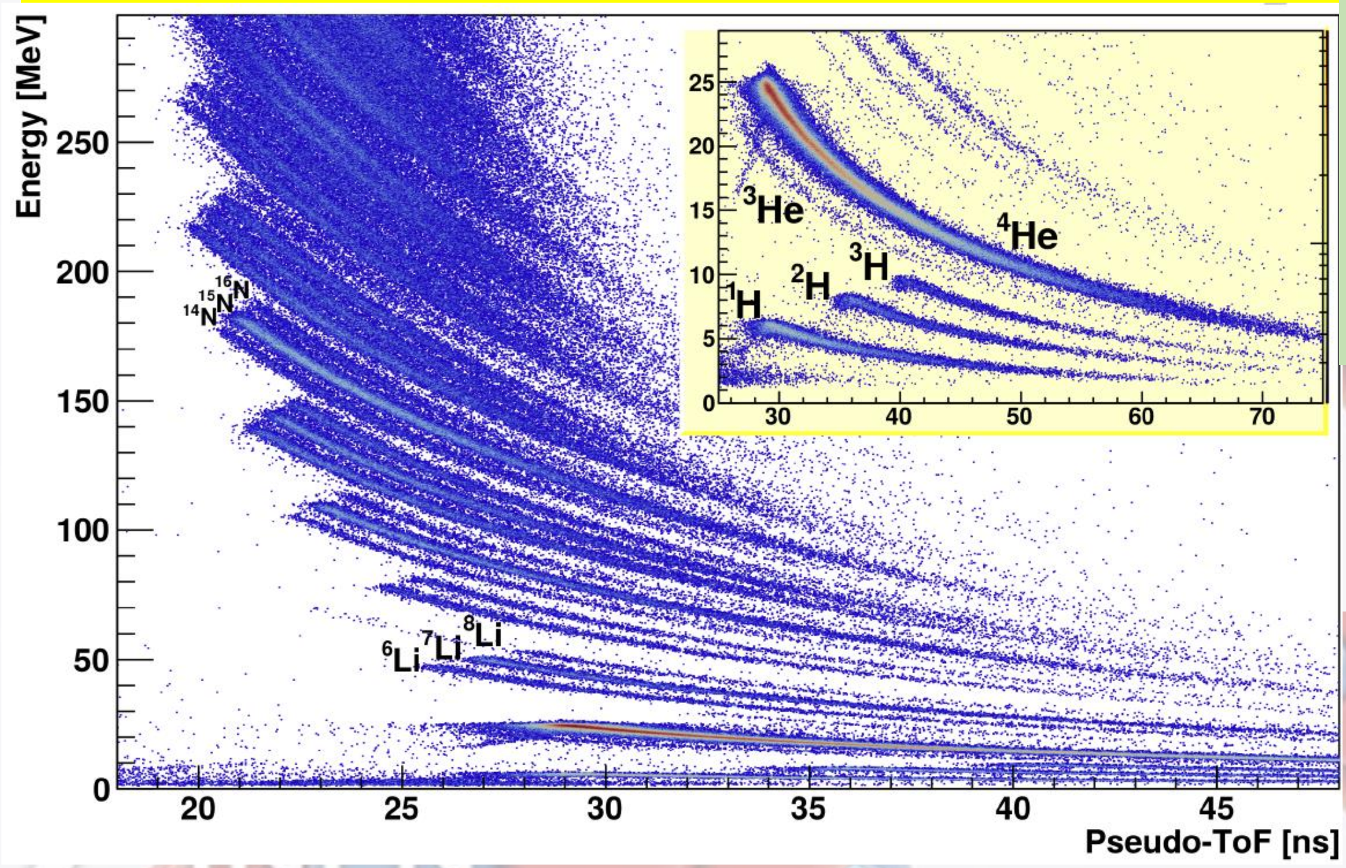
ΔA/A ~ 1/20 with an energy threshold of 5 MeV/nucl

Tagging system for the fragmentation beams FRIBS@LNS

Start: microchannel plate
Stop and ΔE measurement: a DSSSD



NUCLEX: Tof with FAZIA for the identification of particles stopped in the first silicon layer



ToF without a dedicated start detector (working also for no pulsed beams).
A reference ion (identified in A in PSA or ΔE-E) is used to calculate the interaction time
The ToF of all the other particles of the event is referred to this interaction time («pseudo ToF»)

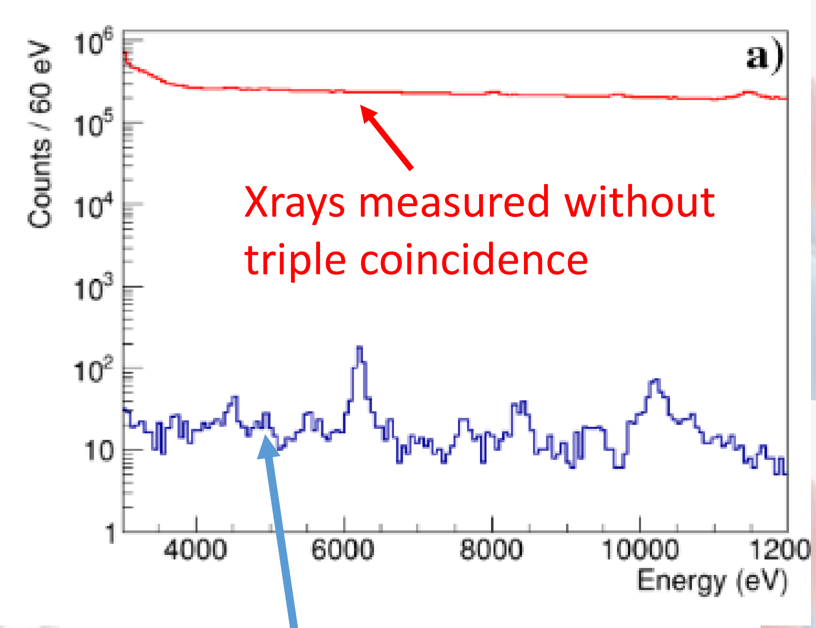
Reverse mounted detector (not the best choice for ToF because signals are slower)
Since the rise time of the signals depends on Z, the observed ridges depends also on Z (and not only A)

Useful when the PSA does not provide the isotopic identification (e.g. Z=1,2 or range in Si too small). It works for Z<10

X-ray spectroscopy using silicon detectors: KAONNIS

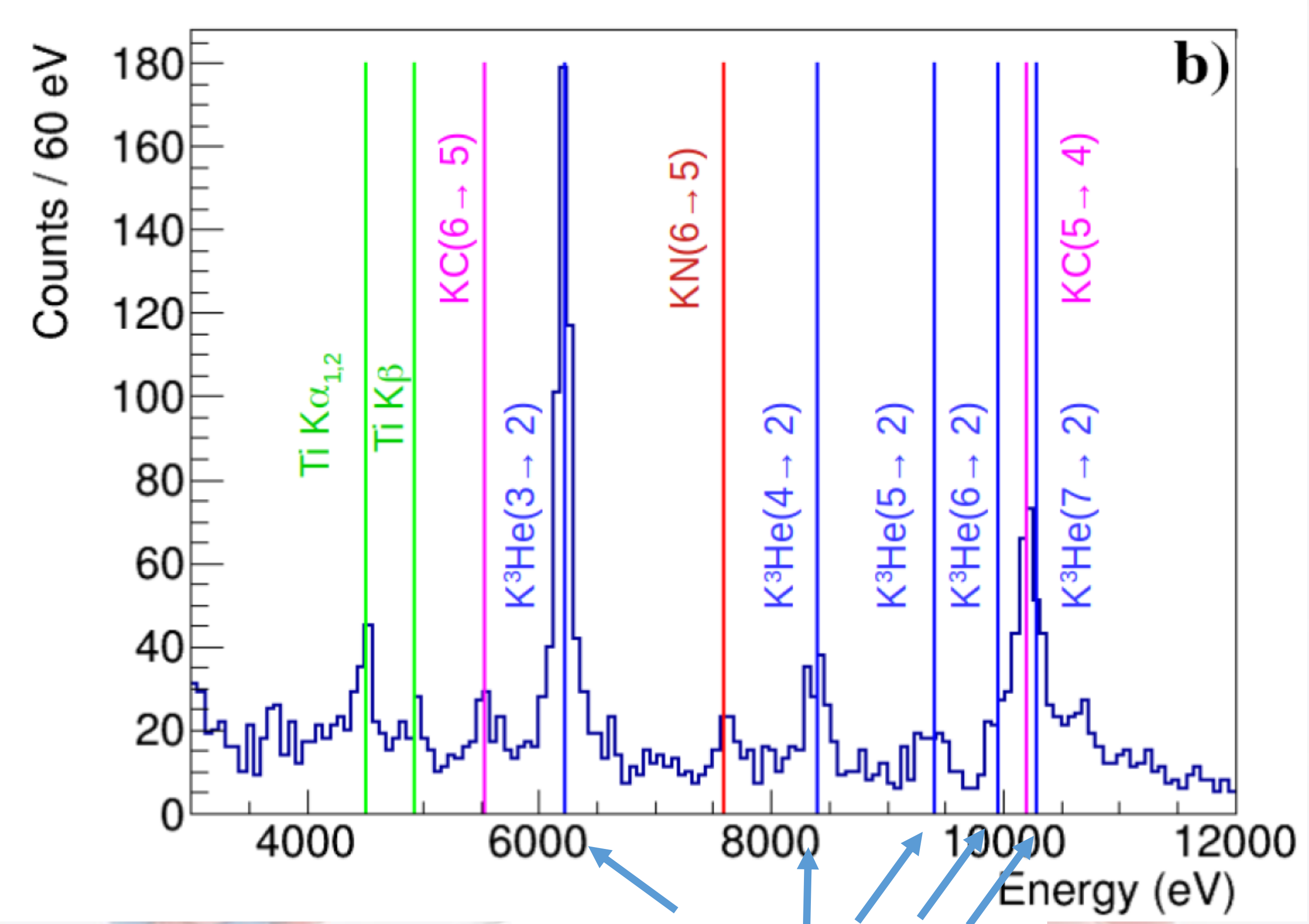
Silicon detectors (in particular SDD) offer the best compromise between energy resolution, efficiency (intrinsic and geometric) and timing capability and were adopted by the KAONNIS experiment to perform kaonic atoms X-ray spectroscopy

SIDDHARTA experiment, K-3He run



Triple coincidence between TOF (to measure K+K-) and SDD (to measure Xrays)=> very good background suppression

Background subtracted K-3He spectrum



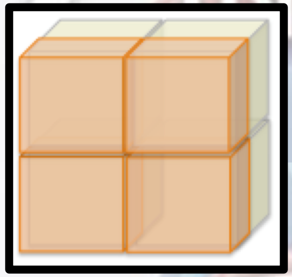
Various K^3He transitions

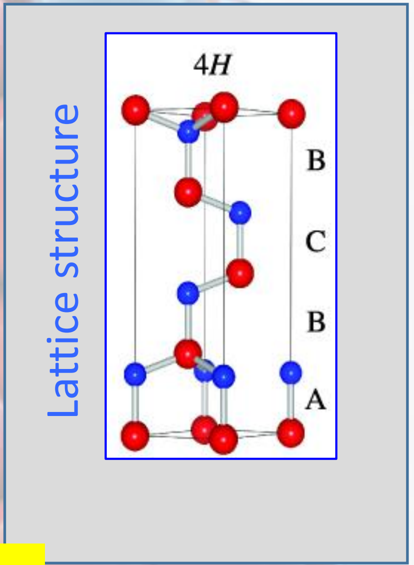
COMING SOON: SILICON CARBIDE (SiC)

General Properties of SiC

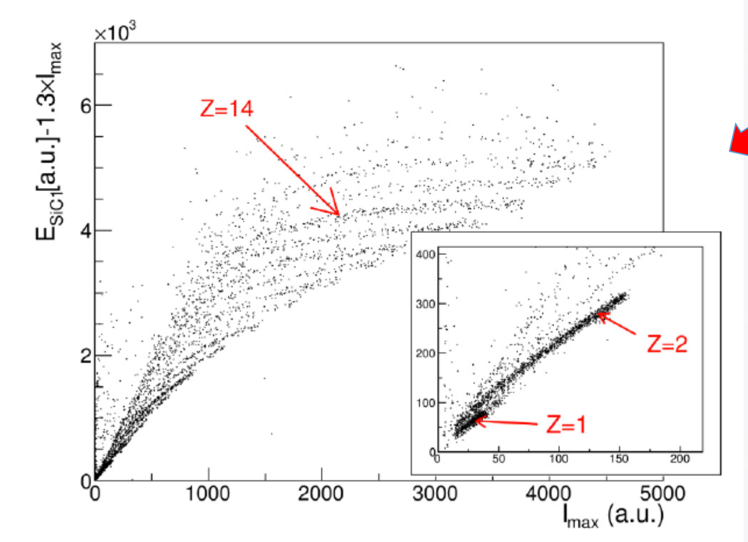
- high thermal conductivity
- low thermal expansion
- high strength (hardness)
- chemical inertness
- Radiation hardness

→ Exceptional thermal shock resistant qualities

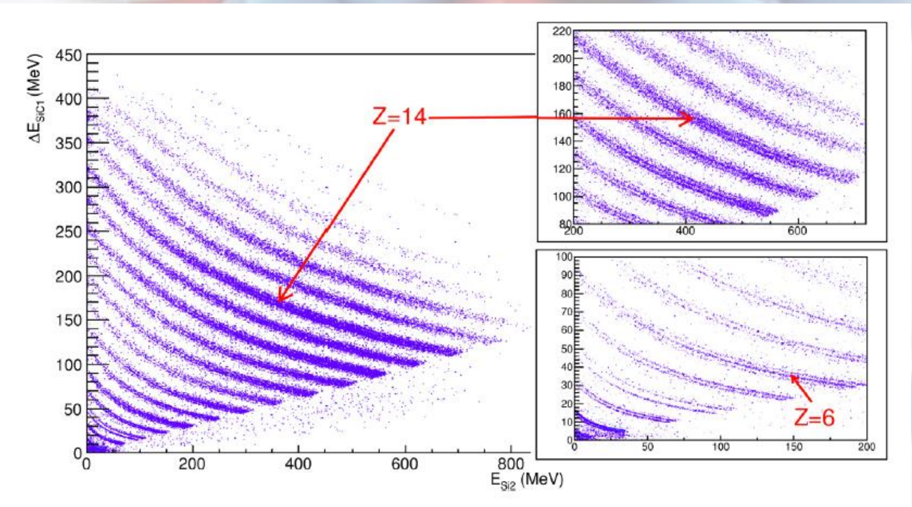




While it shows performances very similar to silicon detectors…



$^{40}Ca/^{48}Ca$ @ 40 MeV/ nucleon on ^{12}C target



Pulse shape identification plot for particles stopped in the SiC (100 μm)

C.Ciampi et al., NIMA 925(2019)60

ΔE-E correlation plot for a SiC (100 μm) followed by a standard Si detector (500 μm)

COMING SOON: SiC

… there are many additional advantages linked to the physical properties of the crystal.

In fact, SiC is a wide-band-gap semiconductor

Visible blind
Lower leakage current

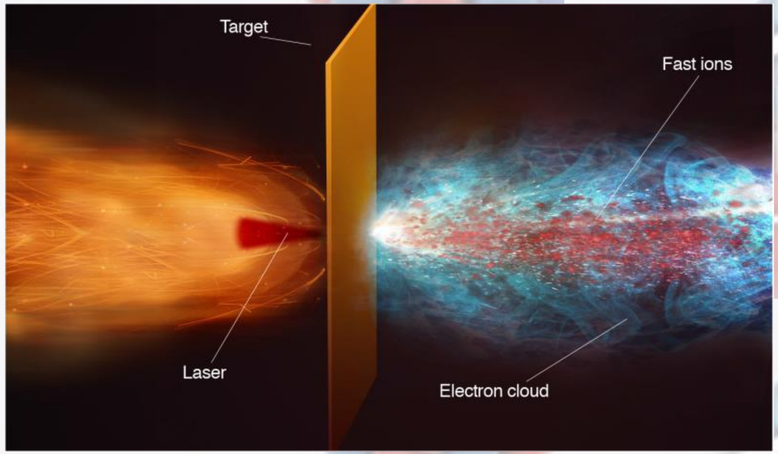
Energy gap => E_{SiC}=3.28 eV > E_{si}=1.12 eV
Breakdown Field => BF_{SiC}=3-4 MV/cm > BF_{Si}=0.3 MV/cm
Saturated electron velocity => $v_{SiC} > v_{Si}$

R&D
- SiC Telescope
- SiC monolithic detectors

S. Tudisco et al. SENSORS Vol. 18 (2018) 2289

Applications on ELECTRONIS and DEVICES

- High power
- High frequency
- High temperature
- Radiation hard detectors



Especially suitable for extreme environments (such as plasma generated by high power lasers) and for beam monitoring (due to radiation hardness)

Summary and conclusions

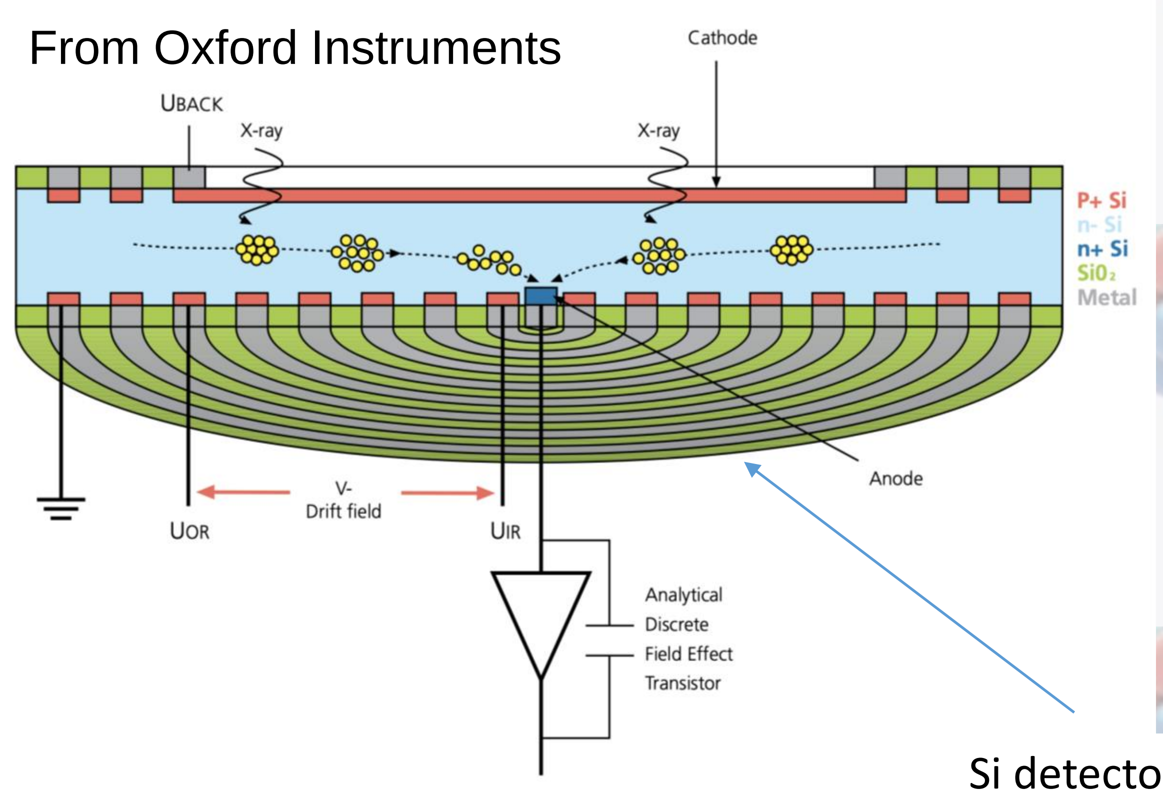
- Silicon detectors allow to perform particle identification by means of different techniques:
  - ΔE-E
  - PSA
  - E-ToF
- Promising materials as SiC will add to an identification capability similar to Si also the radiation hardness
- A review of the identification techniques involving Si used in INFN-CSN3 experiments has been presented, as described in the review paper ***A.Badalà et. al., accepted on La Rivista del Nuovo Cimento***

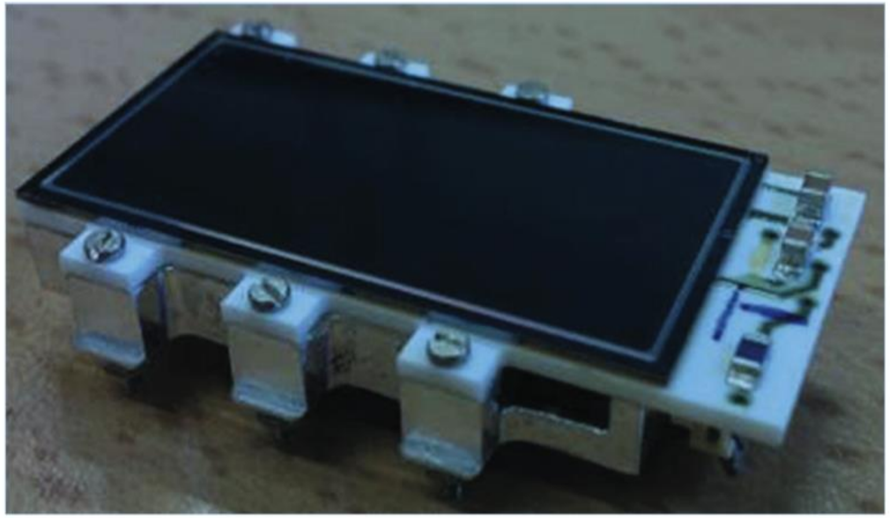
Trends in particle and nuclei identification techniques in nuclear physics experiments

A. Badalà[1] , M. La Cognata[2], R. Nania[3], M. Osipenko[4], S. Piantelli[5], R. Turrisi[6], L. Barion[7], S. Capra[8][9], D. Carbone[2], F. Carnesecchi[3][26], E.A.R. Casula[11][12], C. Chatterjee[13], G.F. Ciani[14][25], R. Depalo[6][15], A. Di Nitto[16][17], A. Fantini[18], A. Goasduff[19], G. L. Guardo[2], A.C. Kraan[20], A. Manna[10],[3], L. Marsicano[4], N.S. Martorana[21][2], L. Morales-Gallegos[16], E. Naselli[2][21], A. Scordo[22], S. Valdré[5], G. Volpe[23][24]

Thank you for your attention!

SILICON DRIFT DETECTORS





The SIDDHARTA-2 SDD array together with the readout electronics.

Si detectors with a tranverse electric field due to to ring electrodes

These detectors show better performance than Si(Li) devises usually used in x-ray spectroscopy

- Lower voltage noise since SDDs have much smaller anodes
- SDDs can therefore tolerate higher leakage current so Peltier cooling is enough
- Thanks to the transversal field causing the electrons to drift towards the anode, significantly higher count rates can be achieved
- FET integrated in the chip → reduction of capacitance between anode and FET → reduction of electronic noise.