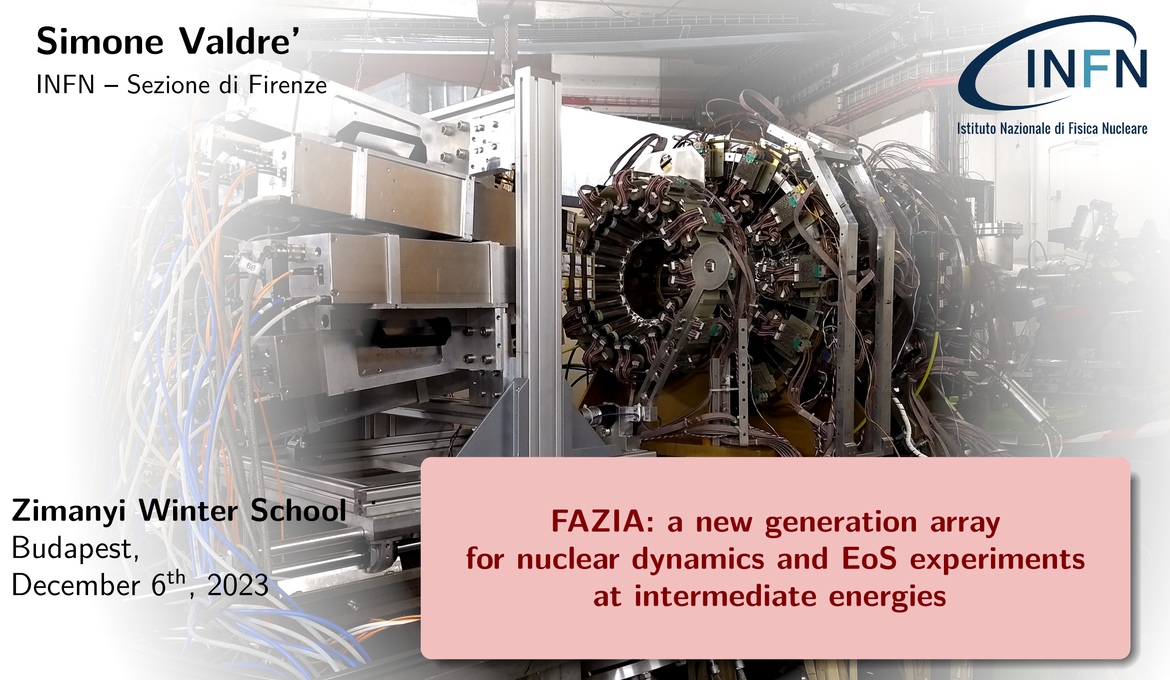


Simone Valdre'

INFN – Sezione di Firenze

INFN
Istituto Nazionale di Fisica Nucleare

FAZIA: a new generation array for nuclear dynamics and EoS experiments at intermediate energies

Zimanyi Winter School
Budapest,
December 6th, 2023

Intermediate energies

Two opposite worlds "colliding"

Low energies ($<$ 20 AMeV)

Mean field driven reactions

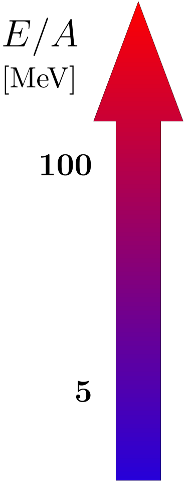
- Compound nucleus
  - Evaporation residue
  - Fission fragments
- Deep inelastic collisions
- Direct reactions

High energies ($>$ 100 AMeV)

Nucleon - nucleon interactions

- Fireball
  - Vaporization
  - Radial / elliptic flow
- Participant / spectator
- π / K production

Heavy-ion collisions

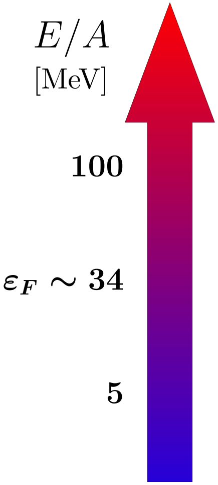


Finite nuclear matter

Ideal homogeneous system made of protons and neutrons

- Ultrarelativistic regime
  - Vaporization
  - Gaseous state
- Coulomb barrier region
  - Compound Nucleus formation
  - Binary reactions and DIC
  - Liquid state

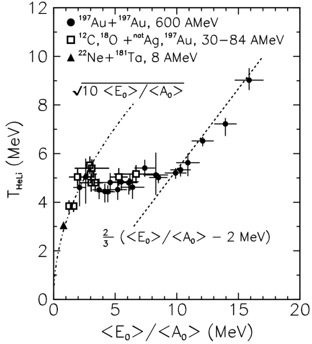
Heavy-ion collisions



Finite nuclear matter

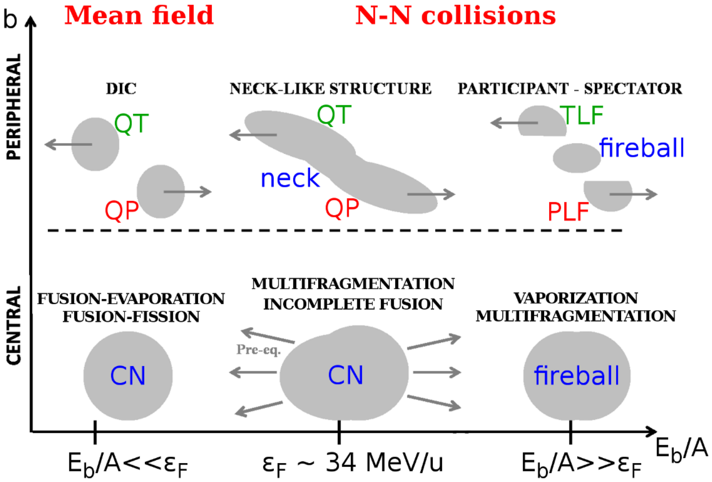
Ideal homogeneous system made of protons and neutrons

- Ultrarelativistic regime
  - Vaporization
  - GASEOUS STATE
- Fermi energy region
  - Multifragmentation
  - PHASE TRANSITION
- Coulomb barrier region
  - Compound Nucleus formation
  - Binary reactions and DIC
  - LIQUID STATE



J. Pochodzalla *et al.*, arXiv:nucl-ex/9607004

Reaction mechanisms



Equation of state

Asymmetric nuclear matter Equation of State (EoS)

- Symmetry energy term depending on proton and neutron densities:

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{\mathrm{sym}}}{A}(\rho) I^2$$

Isospin parameter

$$I = \frac{(\rho_n - \rho_p)}{\rho} = \frac{N - Z}{A}$$

E_{sym} behaviour is known only near ρ_0

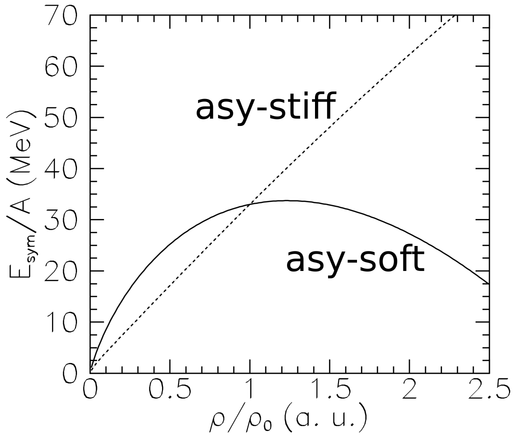
Equation of state

Asymmetric nuclear m

- Symmetry energy

nsities:

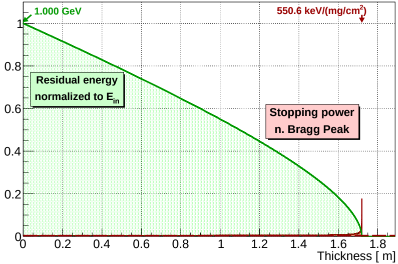
Isospin parameter



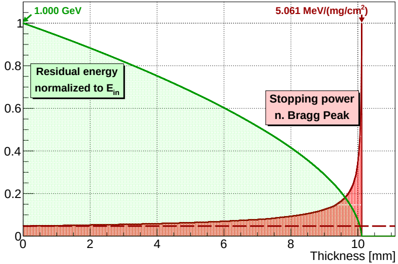
E_{sym} behaviour is known only near ρ_0

Very different energy loss profiles!

p



^{12}C



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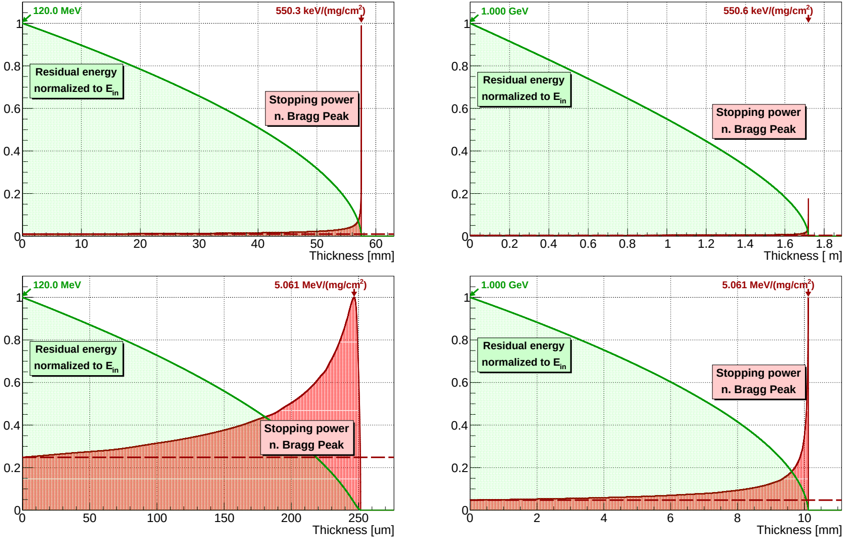
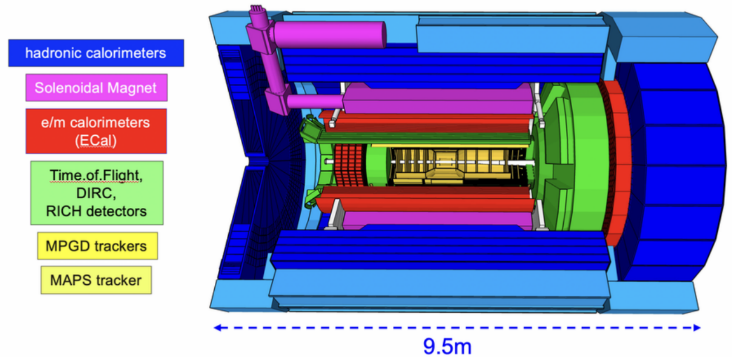


High energy detectors

Tracker + calorimeter concept



Trackers

Capable to measure very small charge release

Calorimeters

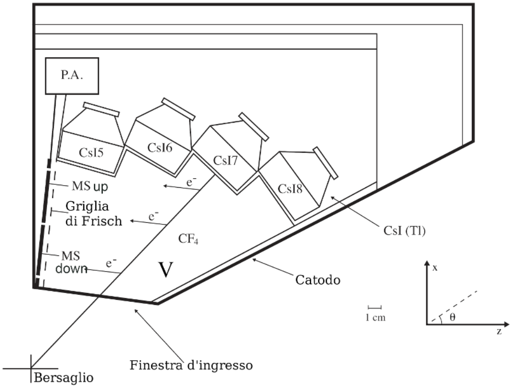
Large dimensions in order to stop particles and ions

---

picture from A. Jaroslav talk (**ePIC detector @ EIC**)

Low energy detectors

Telescope concept



GARFIELD detector @ LNL

First layer

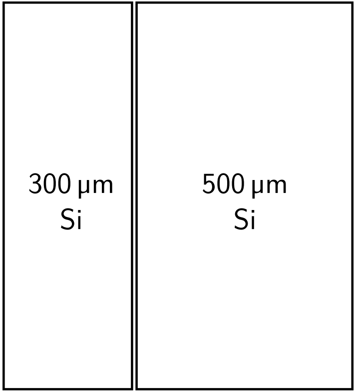
Gas detector or thin silicon to avoid stopping low energy ions

Further layers

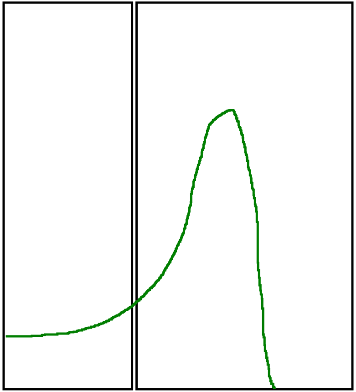
Thick silicon sensors or scintillators in order to stop particles and ions

All sensors are both trackers and calorimeters!

Telescope concept



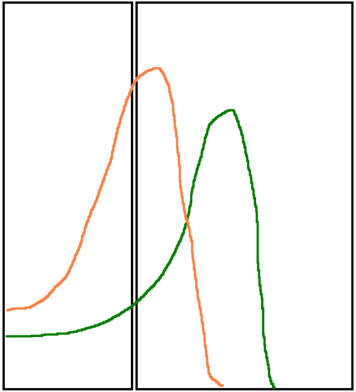
Telescope concept



^{12}C @ 180 MeV

77 MeV + 103 MeV

Telescope concept



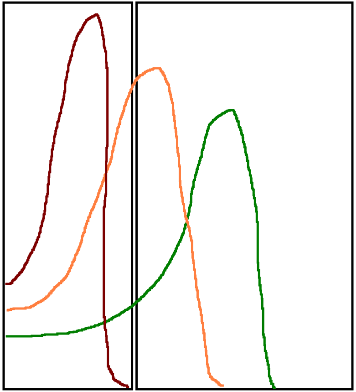
^{12}C @ 180 MeV

77 MeV + 103 MeV

^{14}N @ 180 MeV

152 MeV + 28 MeV

Telescope concept



^{12}C @ 180 MeV

77 MeV + 103 MeV

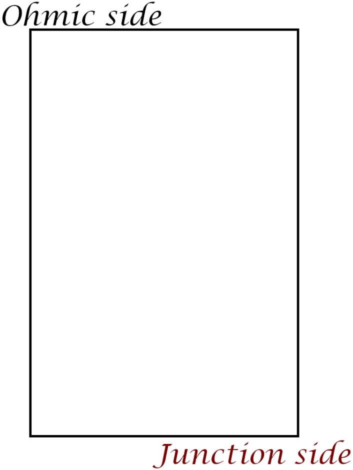
^{14}N @ 180 MeV

152 MeV + 28 MeV

^{16}O @ 180 MeV

180 MeV + 0 MeV

Pulse Shape Analysis

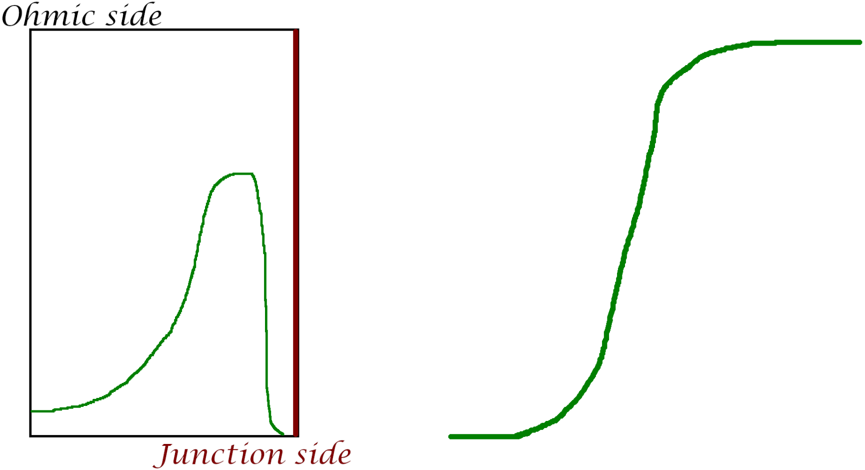


Ohmic side

Junction side

Pulse Shape Analysis

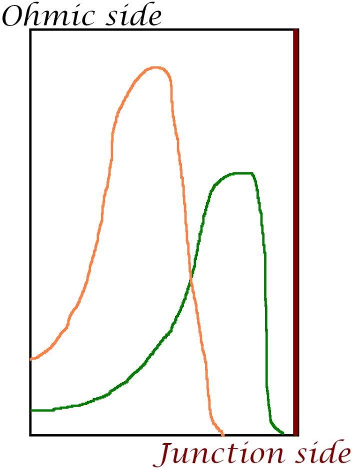
^{12}C
120 MeV

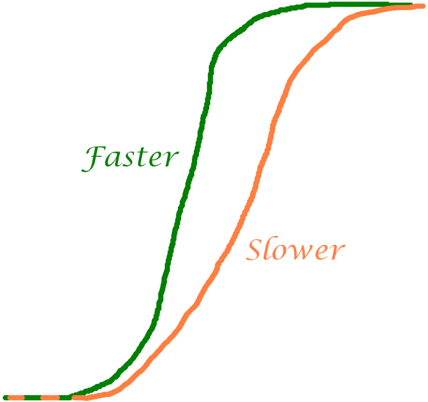


Pulse Shape Analysis

^{16}O
120 MeV

^{12}C
120 MeV





The FAZIA telescope

The telescope stages

1. 300 µm reverse-mounted Si detector;
2. 500 µm reverse-mounted Si detector;
3. 10 cm CsI(TI) cristal read by a photodiode.

To achieve the best possible energy resolution and A *and* Z *identification Si detectors come from a nTD ingot cut at random angle to avoid channeling effects.*

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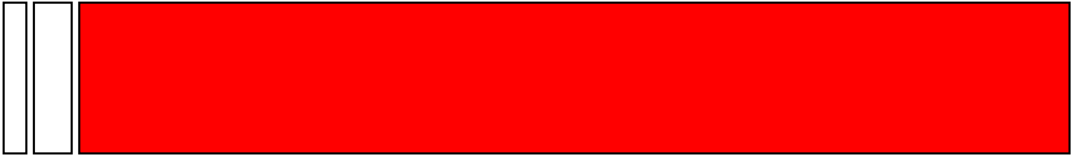
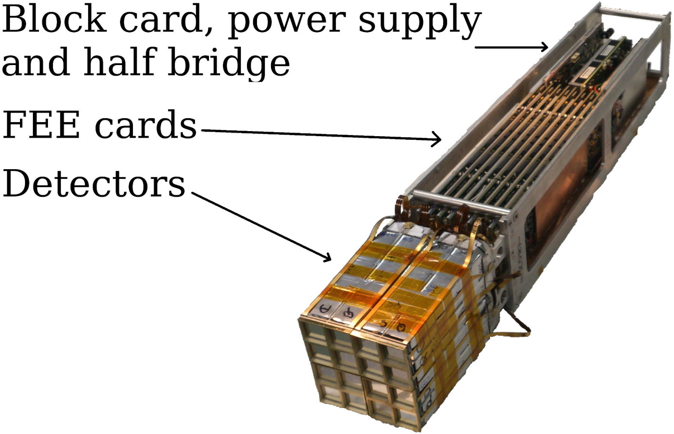


The FAZIA block



Block card, power supply and half bridge

FEE cards

Detectors

16 telescopes, *together with* ***front-end electronics***, *form a* ***block*** *operating in* ***vacuum***.

FAZIA front-end electronics

- Analogue chain: charge preamplifiers and anti-aliasing filters
- Signals are immediately digitized with **14-bit** ADCs:
  - on-line processed on FPGAs
  - energy resolution is better than $1\,\%$ from $5\,\mathrm{MeV}$ to $4\,\mathrm{GeV}$

S. Valdré *et al*, Nucl. Instr. and Meth. A 930 (27), 2019

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$\Downarrow$

- Compactness and modularity
- Very good isotopic discrimination capabilities
- Thresholds ($\lesssim$10 MeV/u) suited for Fermi energies

S. Valdré *et al*, Nucl. Instr. and Meth. A 930 (27), 2019

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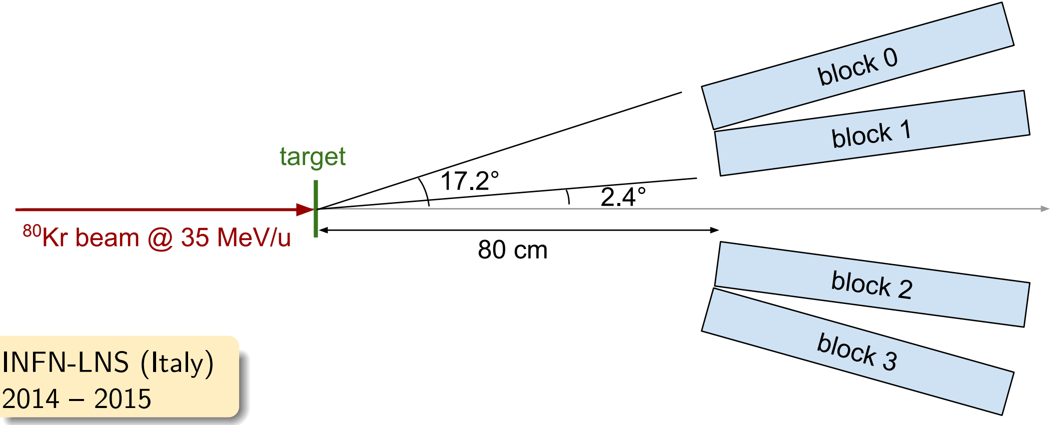
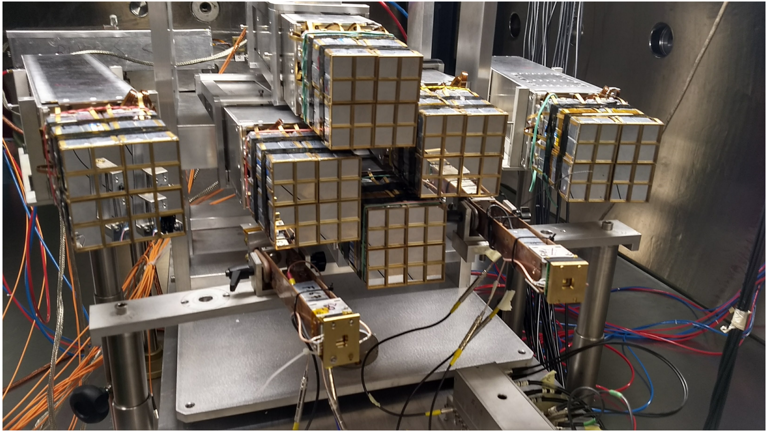
FAZIA modularity



INFN-LNS (Italy)
2014 – 2015

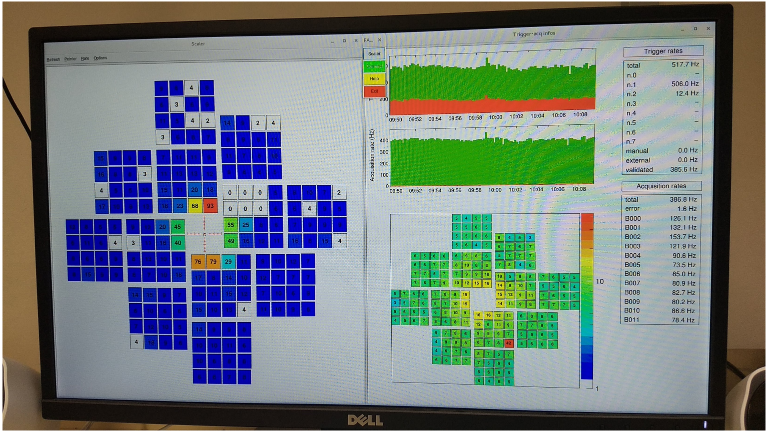
FAZIA modularity



INFN-LNS (Italy)
2016 – 2018

FAZIA modularity

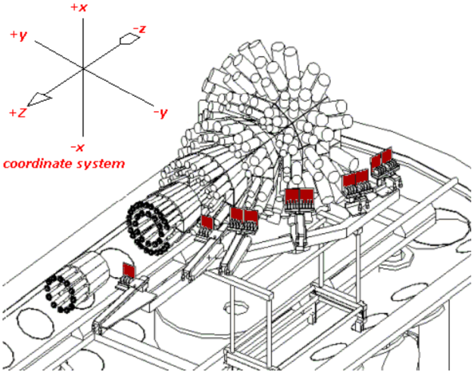
GANIL (France)
2018 – today



Trigger rates	
total	517.7 Hz
n.0	–
n.1	506.0 Hz
n.2	12.4 Hz
n.3	–
n.4	–
n.5	–
n.6	–
n.7	–
manual	0.0 Hz
external	0.0 Hz
validated	385.6 Hz

Acquisition rates	
total	386.8 Hz
error	1.6 Hz
B000	126.1 Hz
B001	132.1 Hz
B002	153.7 Hz
B003	121.9 Hz
B004	90.6 Hz
B005	73.5 Hz
B006	85.0 Hz
B007	80.9 Hz
B008	82.7 Hz
B009	80.2 Hz
B010	86.6 Hz
B011	78.4 Hz

INDRA setup

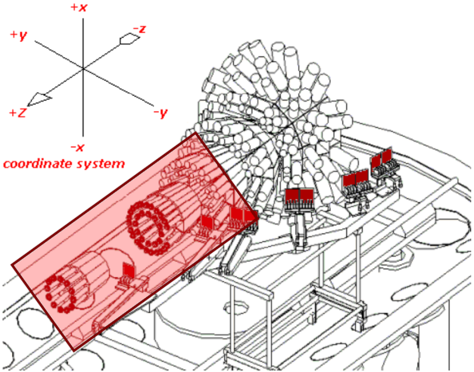


Original configuration (1992-2016)

- 90% of the solid angle covered
- 17 telescope rings (8-24 sectors per ring)
  - ring 1: IC + plastic scintillators
  - rings 2-9: IC-Si-CsI telescopes
  - rings 10-17: IC-CsI telescopes

J. Pouthas *et al*, Nucl. Instr. and Meth. A 357 (418), 1995

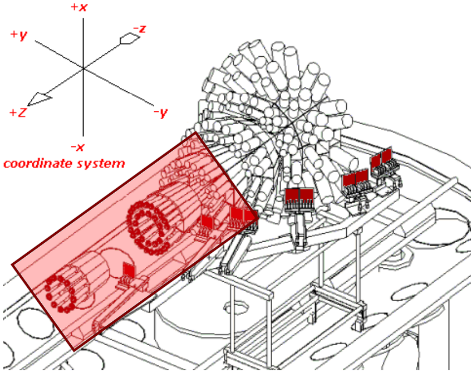
INDRA setup



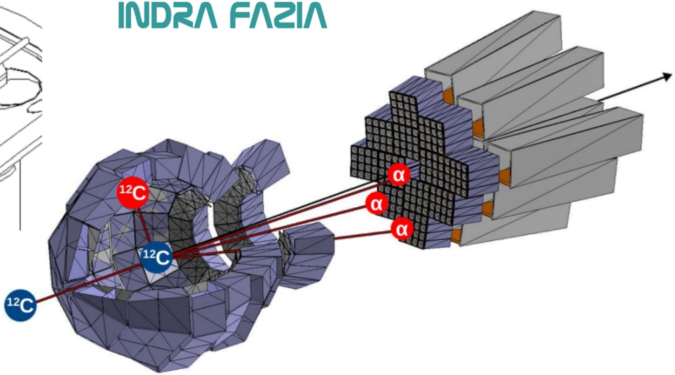
Present configuration (2017-today)

- FAZIA at forward angles!
- 12 telescope rings (8-24 sectors per ring)
  - rings 1-5: removed!
  - rings 6-9: IC-Si-CsI telescopes
  - rings 10-17: IC-CsI telescopes

INDRA setup



INDRA FAZIA



Identification methods

$\Delta E - E$ correlation

- exploits the Bethe-Bloch energy loss relation
- identification threshold due to first layer thickness

Pulse Shape Analysis[a]

- charge collection depending on the impinging nuclei
- identification threshold corresponding to $\sim 50\,\mu\mathrm{m}$ penetration

---

[a] N. Le Neindre *et al*, Nucl. Instr. and Meth. A 701 (145), 2013

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Pulse Shape Analysis[a]

- charge collection depending on the impinging nuclei
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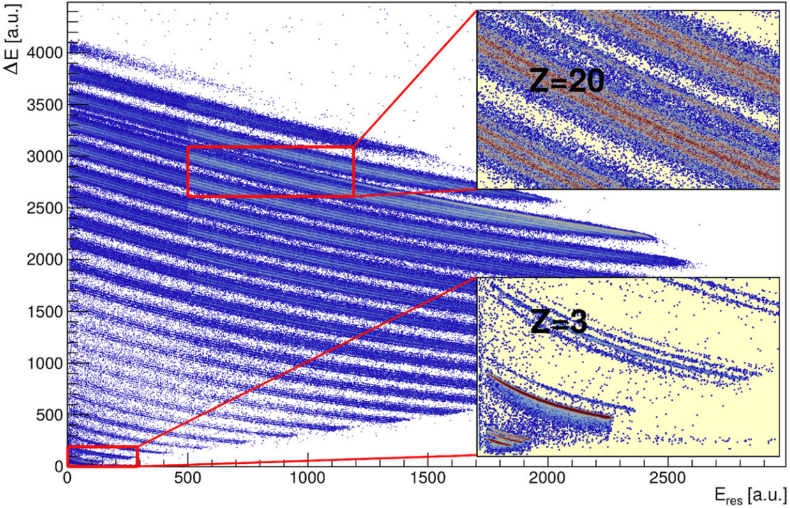
$E - ToF$ correlation

- under implementation
- lowest identification threshold

---

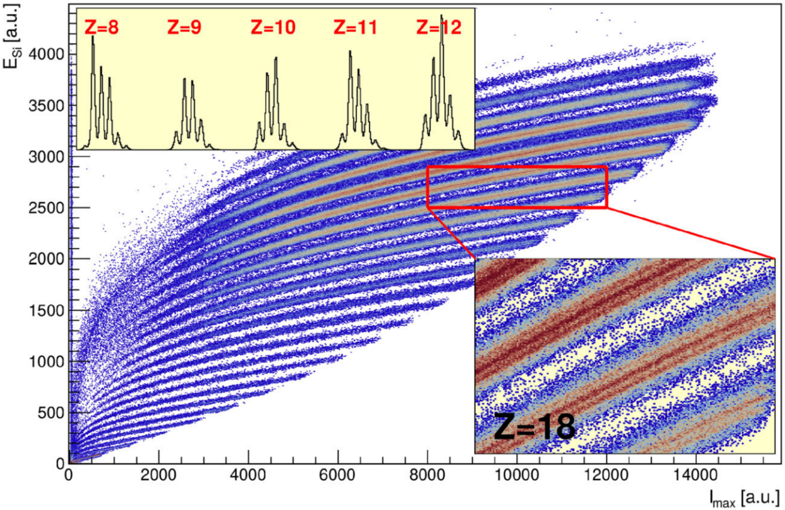
[a] N. Le Neindre *et al*, Nucl. Instr. and Meth. A 701 (145), 2013

$\Delta E - E$ correlation



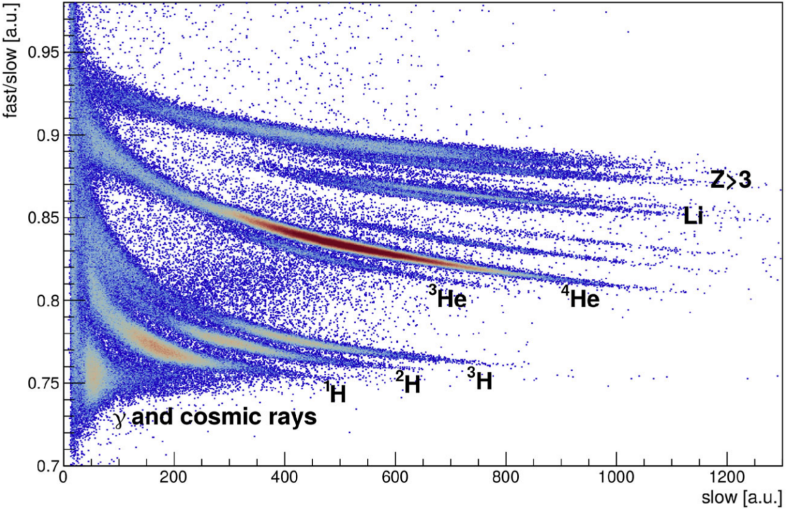
A. Badalà *et al*, Riv. Nuovo Cim. 45 (189), 2022

Pulse shape in Silicon sensors



A. Badalà *et al*, Riv. Nuovo Cim. 45 (189), 2022

Pulse shape in CsI(TI) scintillators



A. Badalà *et al*, Riv. Nuovo Cim. 45 (189), 2022

Time of flight with FAZIA

Not the first heavy-ion experiment to implement ToF[a]

---

[a] F. Amorini *et al*, IEEE T. Nucl. Sci. 55 (717), 2008

Time of flight with FAZIA

Not the first heavy-ion experiment to implement ToF[a]

Our challenges:

- **large area** ($2 \times 2\,\mathrm{cm}^2$), **reverse-mounted** Si detectors;
- signal slowed down by anti-aliasing filter;
- time mark extraction from 250 MS/s sampled signals;
- not using beam radiofrequency;
- 1 m flight base

---

[a] F. Amorini *et al*, IEEE T. Nucl. Sci. 55 (717), 2008

FAZIA time mark

For time mark extraction, after some tests we decided to adopt a **digital ARC-CFD**[a] with $t_{\mathrm{D}} = 20\,\mathrm{ns}$ and $f = 20\,\%$

---

[a] Even if the CFD is compensated, there is still a residual dependence on pulse shape, thus we discriminate both **mass** and **charge** of detected particles

FAZIA time mark

For time mark extraction, after some tests we decided to adopt a **digital ARC-CFD**[a] with $t_{\mathrm{D}} = 20\,\mathrm{ns}$ and $f = 20\,\%$

FAZIA time mark is digitally extracted from the acquired signal:

- we used the first layer **low range** signal ($\sim 300\,\mathrm{MeV}$ range, 14-bit @ $250\,\mathrm{MS/s}$);
- all signals are referred to the same validation time, which must be subtracted to obtain the true time mark:

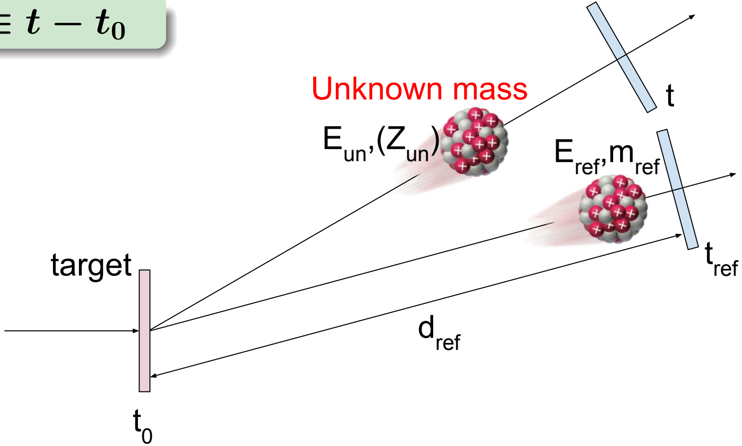
$$t^{(\mathrm{ev},\mathrm{det})} = t_{\mathrm{CFD}}^{(\mathrm{ev},\mathrm{det})} - t_{\mathrm{val}}^{(\mathrm{ev})}$$

---

[a] Even if the CFD is compensated, there is still a residual dependence on pulse shape, thus we discriminate both **mass** and **charge** of detected particles

Time of flight identification (only $M > 1$ events)

$$\boxed{ToF \equiv t - t_0}$$

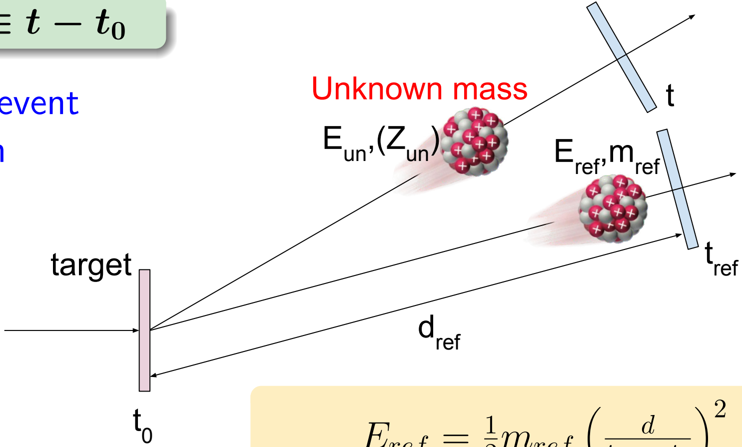


Proposed solution **without a start detector**

Time of flight identification (only $M > 1$ events)

$$\boldsymbol{ToF \equiv t - t_0}$$

event by event correction



$$E_{ref} = \frac{1}{2} m_{ref} \left(\frac{d}{t_{ref} - t_0} \right)^2$$

Time of flight identification (only $M > 1$ events)

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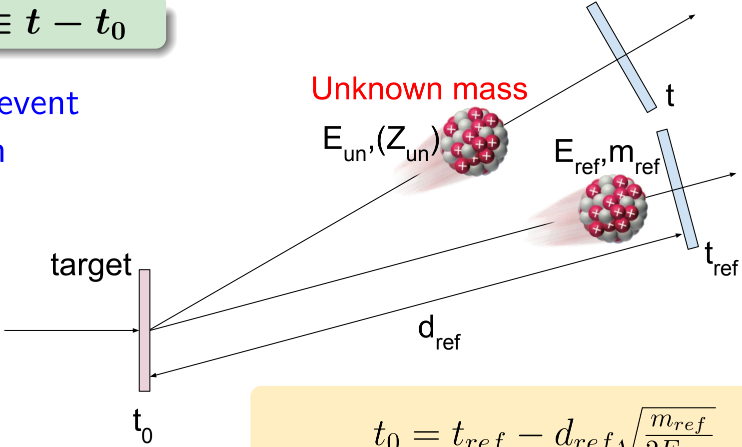

$$t_0 = t_{ref} - d_{ref}\sqrt{\frac{m_{ref}}{2E_{ref}}}$$

Time of flight identification (only $M > 1$ events)

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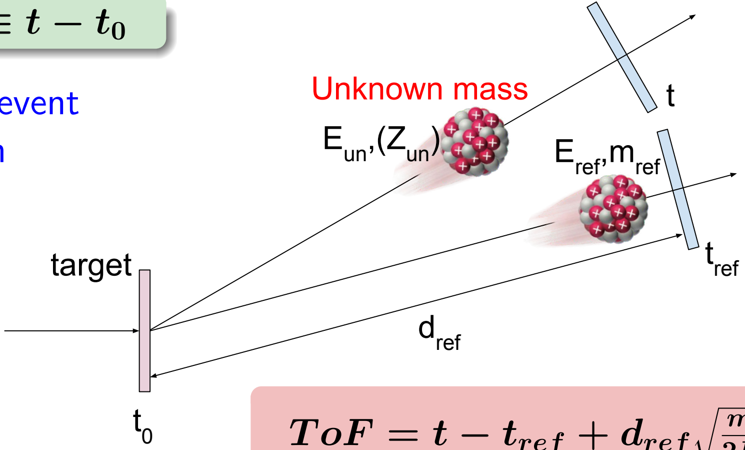
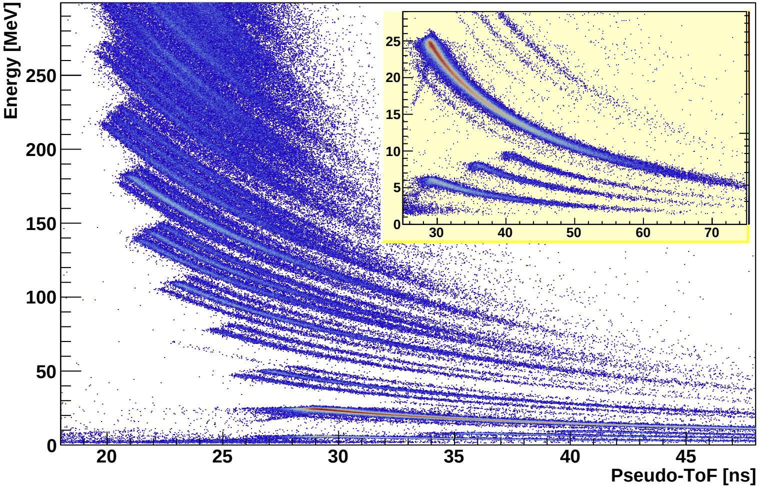
event by event correction

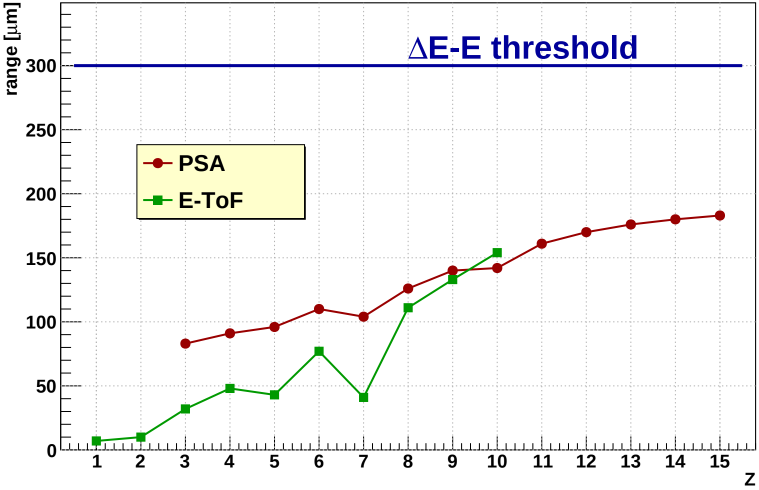


$$\boldsymbol{ToF = t - t_{ref} + d_{ref}\sqrt{\frac{m_{ref}}{2E_{ref}}}}$$

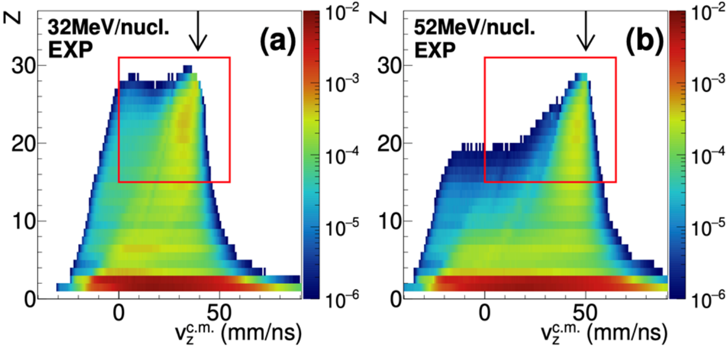
Final $E - ToF$ correlation



Improvement of isotope discrimination



Quasi-projectile physics



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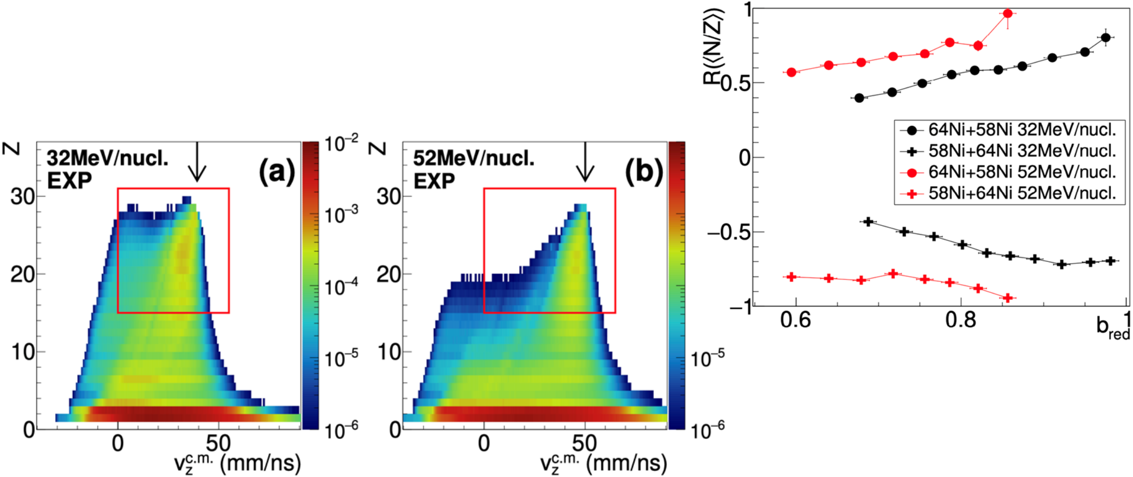
pictures from G. Verde talk

Quasi-projectile physics



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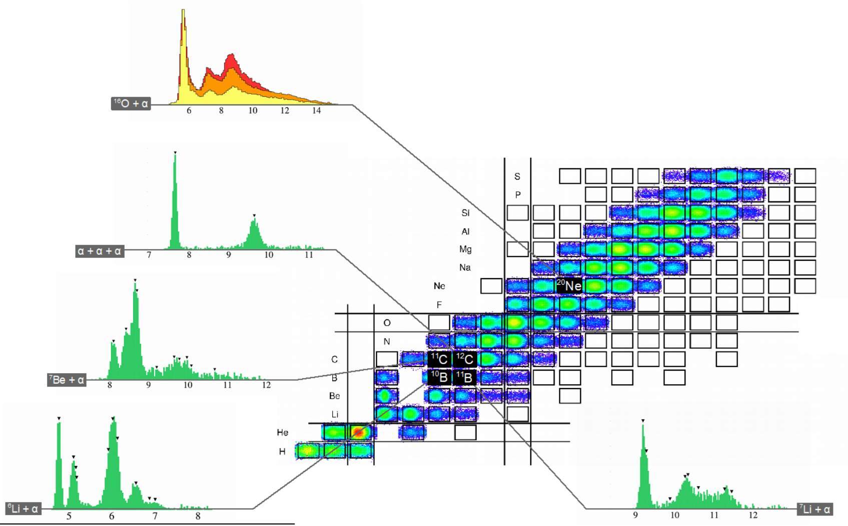
pictures from G. Verde talk

Charged particle spectroscopy



pictures from G. Verde talk

Conclusions

Present status

- FAZIA is a general purpose, modular and flexible apparatus
- almost full solid angular coverage achieved with INDRA+FAZIA coupling
- setup designed for **Fermi energies** (15–50 AMeV)

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BUT

Future perspectives

- lower energies ⇒ **ToF** and **thin Si** layers
- higher energies ⇒ **thick Si** layers or new detectors at all

Conclusions

Future challenges

Collaboration is planning to measure at higher energies (FRIB @ MSU) to explore the supra-saturation regime of the nuclear matter. We are considering many alternatives:

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FAZIA technology will be fundamental for the future developments

Conclusions

Future challenges

Collaboration is planning to measure at higher energies (FRIB @ MSU) to explore the supra-saturation regime of the nuclear matter. We are considering many alternatives:

- Thicker sensors with the same FAZIA electronics
- New block design with the same FAZIA acquisition protocols
- Full re-design of the apparatus based on the FAZIA expertise

FAZIA technology will be fundamental for the future developments

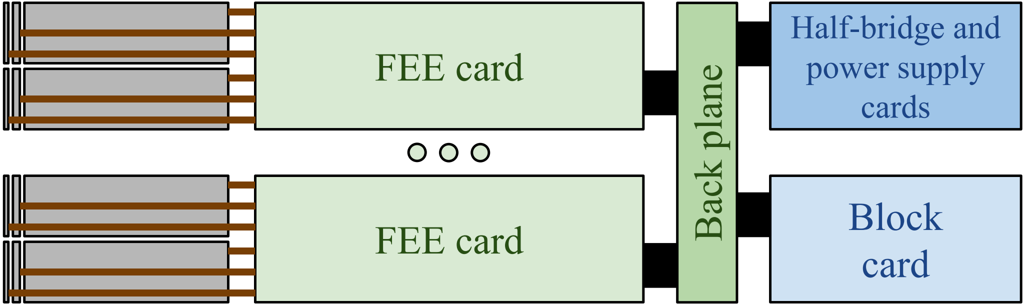
Thanks for your attention

Backup slides

The FAZIA block

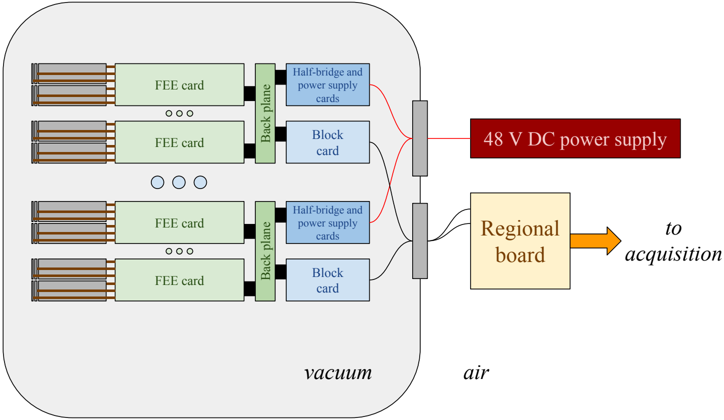
2 telescopes are connected to a FEE card.

The FAZIA block



8 FEE cards are connected to a block card via a back plane.

The FAZIA block



up to 36 block cards are connected to a regional board via a full duplex 3 Gb/s *optical link*

Energy range for Z,A discrimination in FAZIA

Ion	E_Z **[AMeV]**	E_A **[AMeV]**
H	0.5 – 195	0.5 – 195
He	0.5 – 195	0.5 – 195
Li	1.5 – 250	1.5 – 250
C	3.5 – . . .	4 – 25
Ne	6 – . . .	9 – 40
S	8 – . . .	13 – 55
Cr	10 – . . .	20 – 35
Xe	25 – . . .	no