Simone Valdré
INFN – Sezione di Firenze

INFN
Istituto Nazionale di Fisica Nucleare

Azimuth

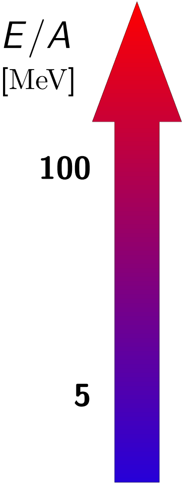
a new generation telescope array for EoS experiments

LNS – Catania,
February 25th 2025

DeSyT-2025

International workshop on detection systems
and techniques for fundamental and applied physics

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

E/A
[MeV]

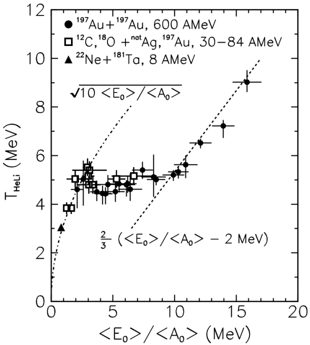
100

$\varepsilon_F \sim$ **34**

5

> ***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

Equation of state

Asymmetric nuclear matter Equation of State (EoS)

- Symmetry energy term depending on proton and neutron densities:

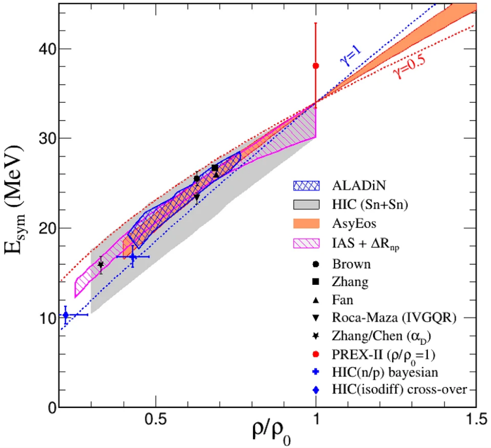
$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{\mathrm{sym}}}{A}(\rho) I^2$$

Isospin *parameter*

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

E_{sym} behaviour is well known near ρ_0 only

Equation of state



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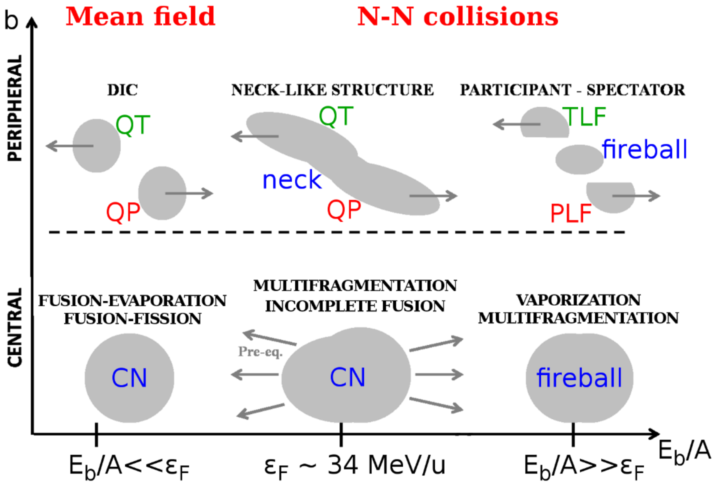
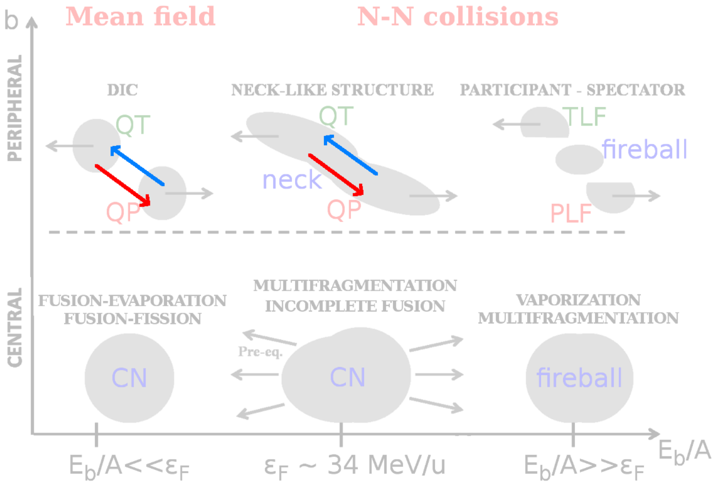
P. Russotto *et al.*, La Rivista del Nuovo Cimento **46**, 1 (2023)

Reaction mechanisms and EoS related observables



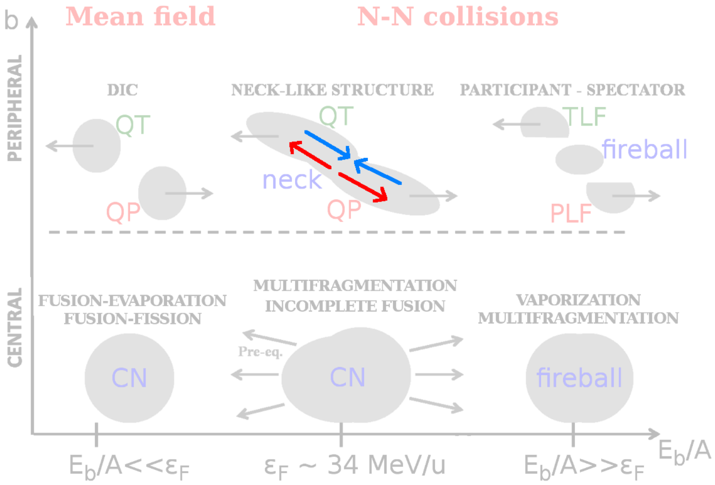
Reaction mechanisms and EoS related observables



Isospin diffusion

Isospin equilibration between QP and QT ($\rho \approx \rho_0$)

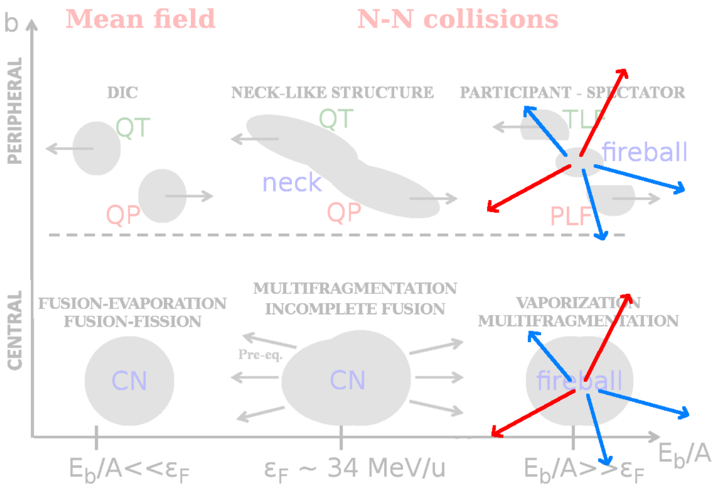
Reaction mechanisms and EoS related observables



Isospin drift

Neutron migration to low density regions (neck) $(\rho \lesssim \rho_0)$

Reaction mechanisms and EoS related observables



$$\rho \gtrsim \rho_0$$

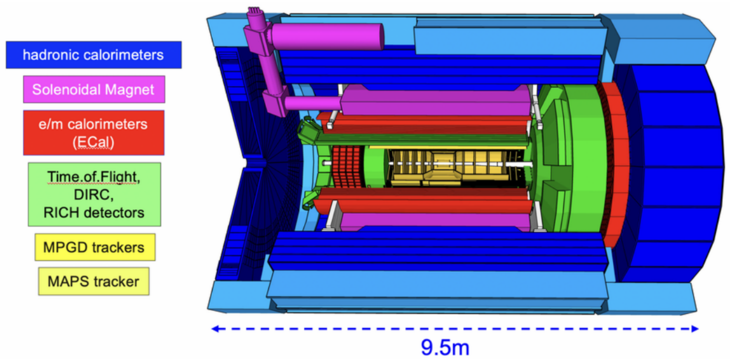
Neutron - proton (double) yield ratios

Elliptic flows

Fourier expansion terms of azimuthal angular distributions

High energy detectors

Tracker + calorimeter concept



Trackers

Capable to measure very small charge release

Calorimeters

Large dimensions in order to stop particles and ions

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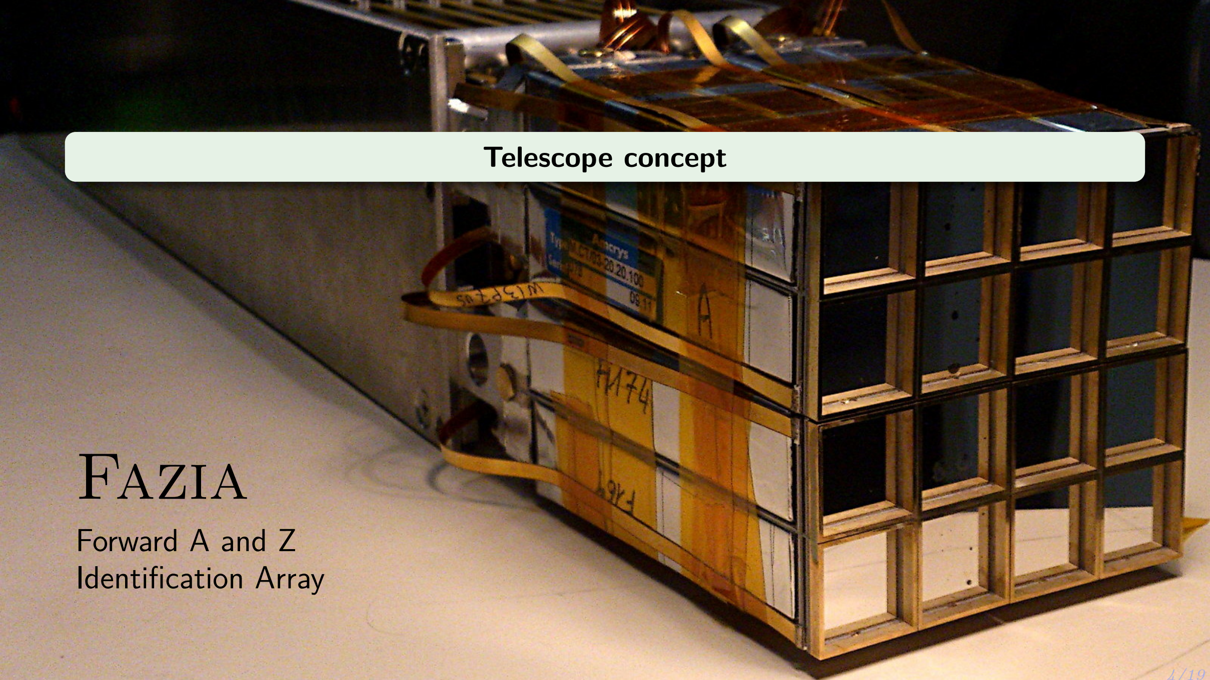
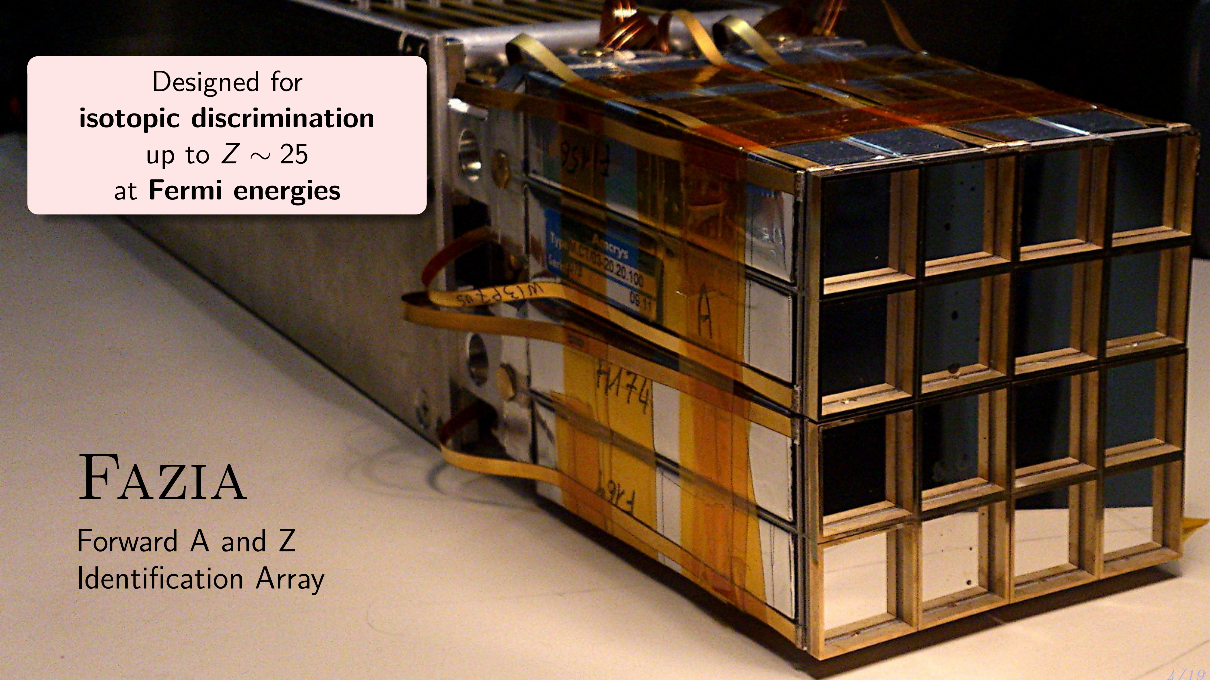
picture from A. Jaroslav talk at Zimanyi School 2023 (**ePIC detector @ EIC**)

Telescope concept



Fazia

Forward A and Z
Identification Array



Designed for
isotopic discrimination
up to $Z \sim 25$
at **Fermi energies**

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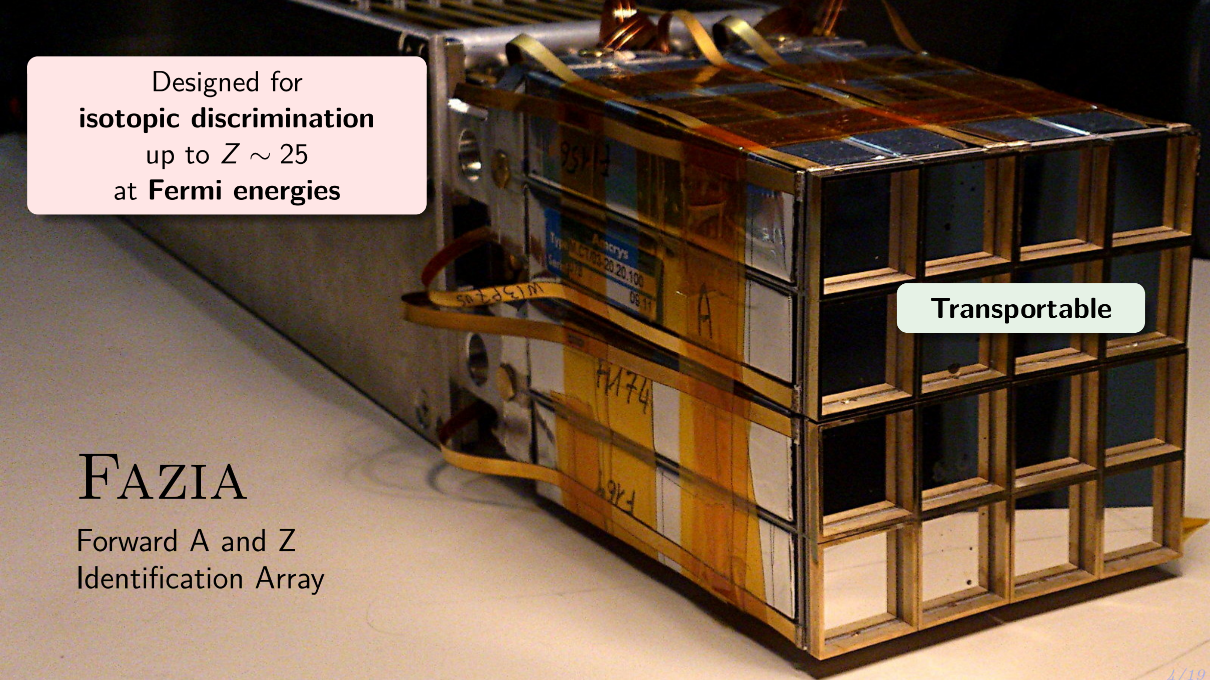

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Transportable

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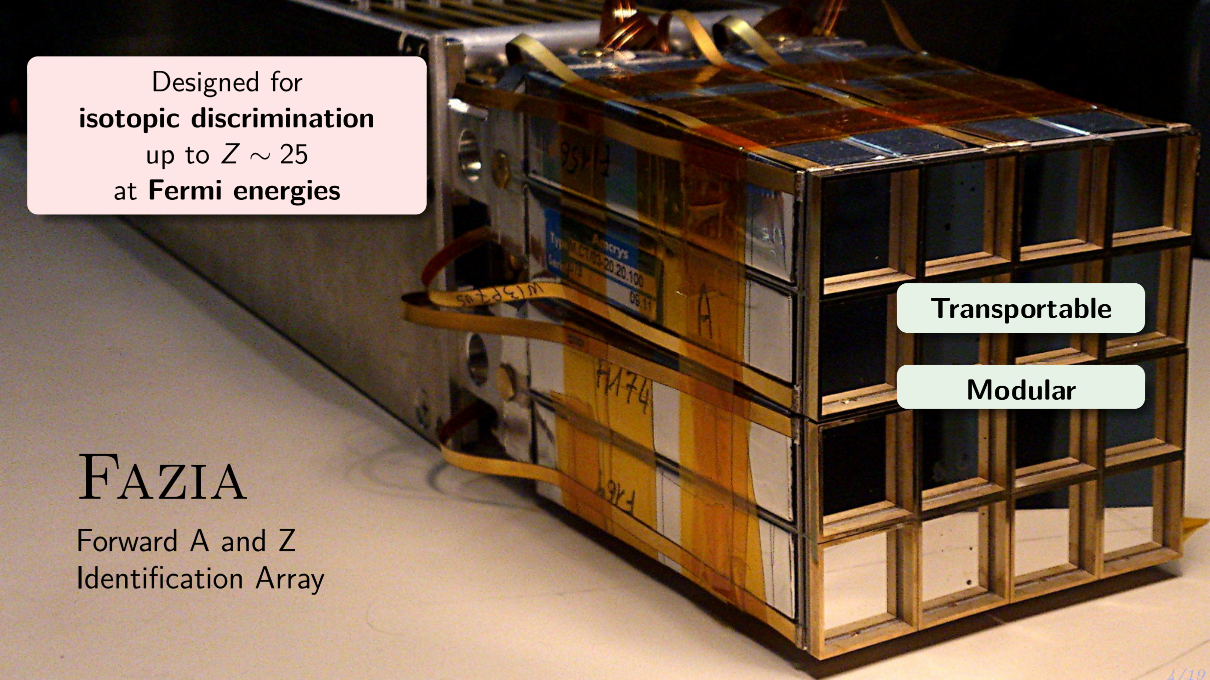

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Transportable

Modular

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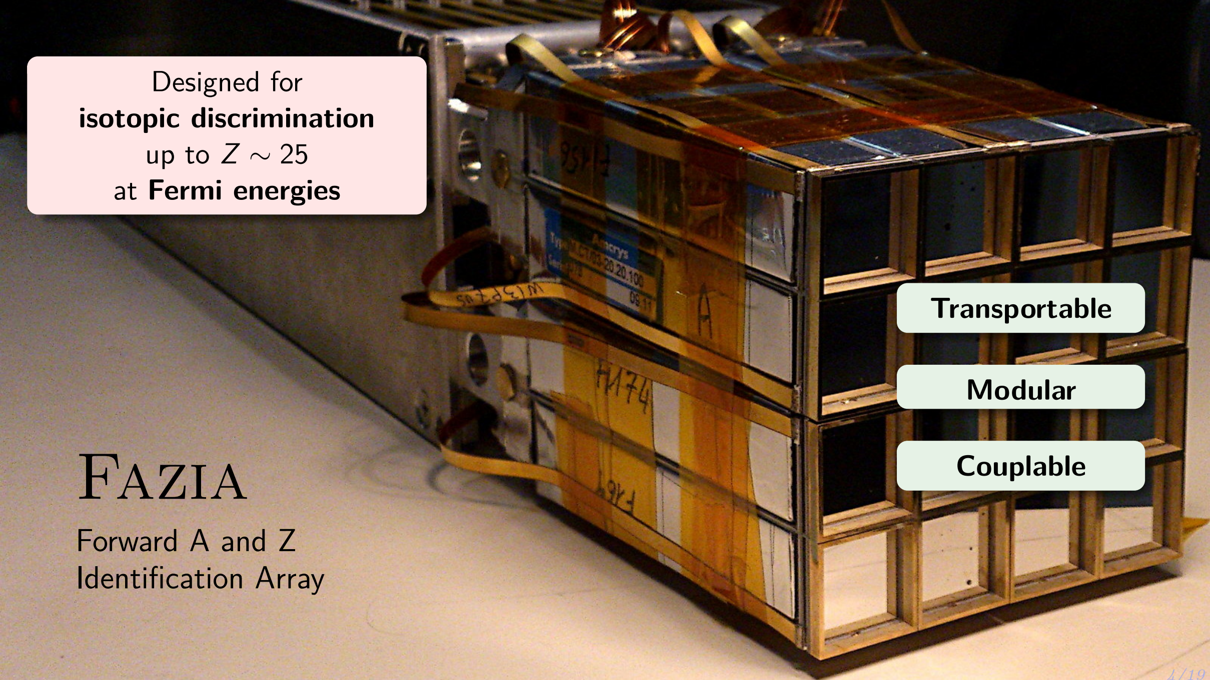
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Forward A and Z
Identification Array

The FAZIA telescope

The telescope stages

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

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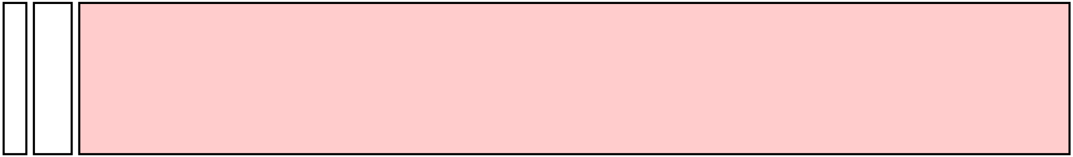

The FAZIA telescope

The telescope stages

1. 300 µm reverse-mounted Si detector;
2. 500 µm reverse-mounted Si detector;
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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.

R. Bougault *et al.*, Eur. Phys. J. A **50**, 47 (2014)

FAZIA future

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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Future at GANIL

There are still many physics cases to be explored

2 experiments scheduled in 2025!

1 experiment approved for 2026!

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FAZIA technology will be fundamental for the future developments

Future of HIC

IN2P3 and INFN are going into the same direction

IRL-NPA	NUSDAF

Future of HIC

IN2P3 and INFN are going into the same direction

IRL-NPA

NUSDAF

$\Downarrow$

Near future of HIC is at FRIB

NUSDAF LoI

Submitted to FRIB-PAC3

Letter of Intent

INFN-NUSDAF (INFN - Nuclear Structure, Dynamics and Astrophysics at FRIB)

Giuseppe Verde[1], C. Agodi[2], M. Battaglieri[9], M. Bondì[1], M. Cavallaro[2], M. Colonna[2], D. Gambacurta[2], A. Gottardo[3], L. Lamia[4,2], S. Leoni[5,6], L. Marcucci[7] S. Pirrone[1], G. Pizzone[2,4], P. Russotto[2], S. Valdrè[8], J.J. Valiente[3], M. Viviani[7]

on behalf of the ASFIN, CHIRONE, EPIC, GAMMA, JLAB12, NUCL-EX, NUMEN, MONSTRE and NUCSYS groups of INFN (see Appendix 3 for detailed list of institutes)

Kyle Brown[10], Giordano Cerizza[10], Zbigniew Chajecki[11], Alexandra Gade[10], Dean Lee[10], Artemis Spyrou[10], Remco Zeger[10]

Local points of contact who agreed to collaborate and support these programs

[1]INFN Catania, [2]INFN Laboratorio Nazionali del Sud, [3]INFN Laboratori Nazionali di Legnaro, [4]University of Catania, [5]University of Milan, [6]INFN Milan, [7]INFN Pisa, [8]INFN Florence, [9]INFN Genova
[10]FRIB, Michigan State University, [11]Western Michigan University

NUSDAF LoI

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Letter of Intent

INFN-NUSDAF (INFN - Nuclear Structure, Dynamics and Astrophysics at FRIB)

Six scientific initiatives

- *SYMEOS* EoS and E_{sym} with HIC
- *GASPEC* γ spectroscopy and Collective excitations
- *RIBDCE* RIB-induced Double Charge Exchange
- *NUSYC* NUcleoSYnthesis and Clustering
- *THEOF* THEOretical physics @ FRIB
- *SYSTERSE* SYnergic Stategy for future ElectRonics and Streaming rEadout solutions

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Developing a new detector. . .

- SYMEOS phase 2 will need **new kind of detectors**, optimized for FRIB energies
- Supra-saturation experiments will produce a broad variety of ejectiles:
  - Very energetic light particles from the fireball
  - Moderately excited fragments from spectator fragments
  - Very slow particles and fragment from spectators in peripheral collisions

Proposed solution in the LoI

- setups constituted by coupling INFN detector systems to equipment already operating at FRIB
- FAZIA upgrade without re-designing a new apparatus from scratch!
- complex setup which may introduce a bias

Developing a new detector. . .

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AZIMUTH solution

- A single apparatus with capabilities typical of correlators, $\Delta E - E$ telescopes, and particle trackers
- **Modular** and **portable** setup, capable to measure fragments emitted in collisions at E/A from 15 to 500 MeV/u
- Less bias (also thanks to **streaming readout** acquisition)

Developing a new detector. . .

European Research Council
Established by the European Commission

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- **Modular** and **portable** setup, capable to measure fragments emitted in collisions at E/A from 15 to 500 MeV/u
- Less bias (also thanks to **streaming readout** acquisition)
- **Project submitted to ERC-CoG 2025!**

AZIMUTH solution

A and Z Identification

the detector shall discriminate **in charge and mass** ions in a broad range of energies to guarantee the best isotopic discrimination ever achieved for a telescope-based detector

Modular

several telescope configurations shall be available, all of them with the **same connection standard** to front-end electronics and with the **same data acquisition protocol**

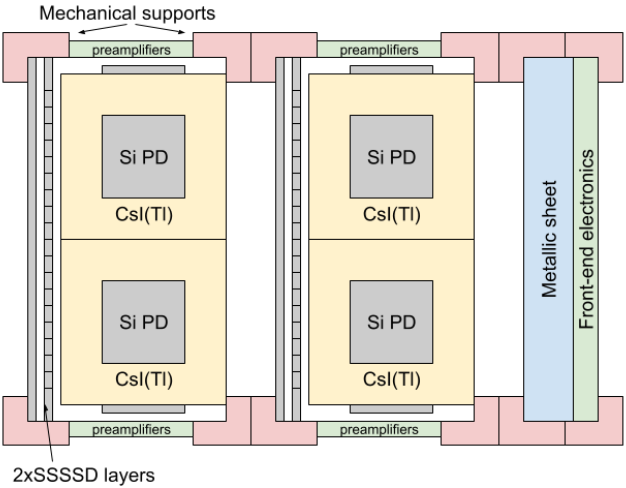
Universal

the apparatus shall be **multipurpose**, apt to measure multiple observables at the time, **couplable with other detectors**, and it shall also be used with a large variety of beams

Tracking Hodoscope

the telescopes shall implement **particle tracking** features through the layers in order to maximize the efficiency of light and energetic particle identification

The AZIMUTH block



The AZIMUTH detector module

- 100×100 mm SSSSD detector (100–500 μm thickness, 20 strips)
- 100×100 mm SSSSD detector (500–1000 μm thickness, 20 strips)
- 4x 50×50 mm CsI(Tl) crystals read by PD (500 mm thickness)

Alternative sensors and material investigation

- **pixel** detector first layer(s)
- **heavier** scintillating crystals ($CdWO_4$, $GdTaO_4$)
- NArCoS-like **neutron sensitive** plastic scintillators (EJ-276(G))[a]
- crystal reading **via SiPM**

[a] E. V. Pagano *et al.*, Front Phys **10**, (2023)

The AZIMUTH front-end module (FEM)

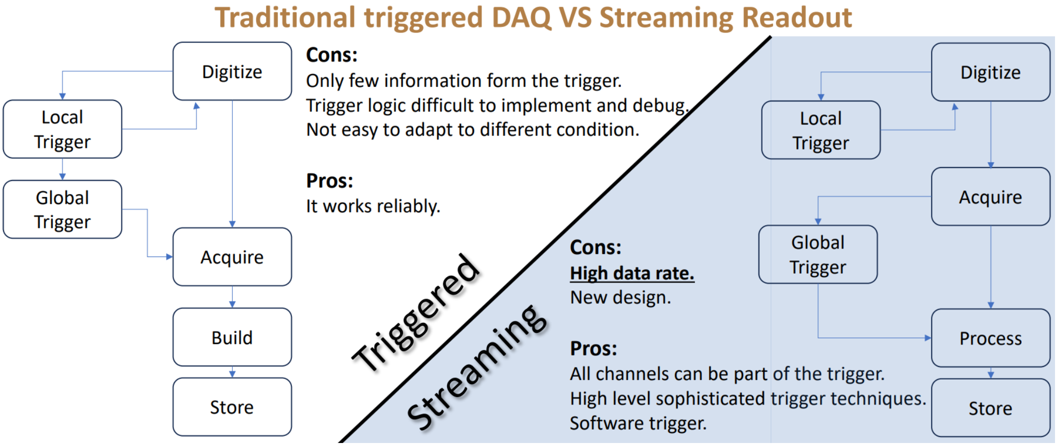
One single FEM per block

- a modern FPGA can handle all 132 ADC outputs
  - up to 3 detector modules made of 2x 20 Si-strip channels + 4 CsI channels
- ASICs will be considered, but **discrete analog chains** are preferred
- Less operations to be performed with respect to FAZIA
  - **Streaming readout** logic (asynchronous data flow to DAQ)
  - No online data processing
  - Nowadays paradigm: disk space is cheap, electronics is expensive!

Relaxing event-centered acquisition paradigm

- A simple clock distribution board outside scattering chamber
- Data from blocks directly to DAQ servers via Ethernet
- Offline (but real-time) data merging and reconstruction

Streaming readout



picture from F. Rossi's talk at SRO-XII workshop (2024)

Streaming readout

Streaming Readout Workshop SRO-XII

02–04 dic 2024
University of Tokyo
Asia/Tokyo fuso orario

> Increased interest to SRO!
> CERN, EIC, **JLAB**, **FRIB**, and SPADI alliance (Japan) involved

MSU-JLab Streaming Data Acquisition System Meeting

12 febbraio 2025
JLAB
US/Eastern fuso orario

AZIMUTH challenges

Main obstacles are related to fast particles energy loss profile

Energy straggling

energy loss of ions inside materials happens through a series of scatterings. The more interactions we have, the large variance in energy loss (straggling) we get[a]

[a] S. Kumar and P. K. Diwan, J Radiat Res Appl Sci **8**, 538 (2015)

Incomplete energy deposition (IED)

as ions react inside large volume crystals, or they scatter, punching-through the crystal surfaces, identification isn't feasible anymore[b]

[b] C. Frosin *et al.*, Nucl. Instrum. Meth. A **951**, 163018 (2020)

Tracking features

Energy loss + position tracking

- "multiple ΔE" measurement to track particle energy loss among layers
- position tracking thanks to SSSSD (or pixel detectors)

A lot of information per event to be analyzed by a neural network:

- training with simulation of reactions and elastic scattering inside sensors
- **reconstruction of trajectories**
- **reconstruction of original particle E, Z, A**

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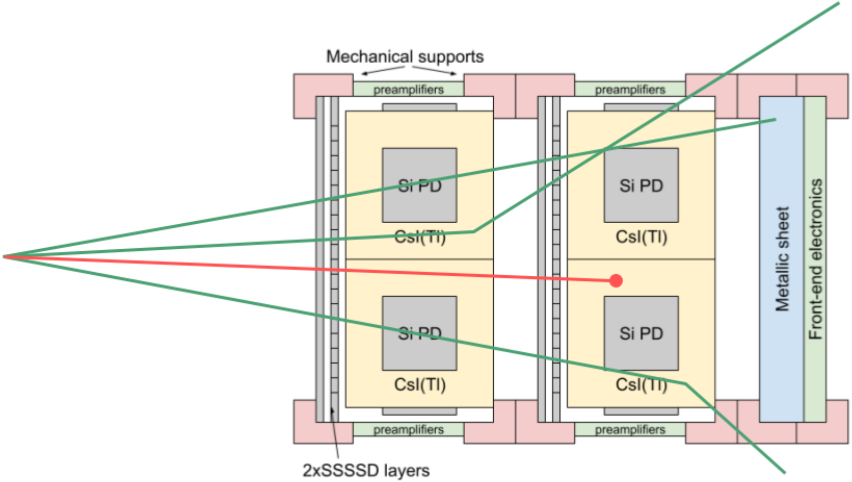
FAZIA

- 1x position (telescope)
- up to 3x partial energy release (Si-Si-CsI)

AZIMUTH

- up to 3x positions (3 stacked modules)
- up to 9x partial energy release (Si-Si-CsI-Si-Si-CsI-Si-Si-CsI)

Tracking features



Summary and conclusions

AZIMUTH

- **Telescope** approach + **tracking** features
- Position sensitive - good for **correlations**
- Designed for **elliptic flow** measurements and **invariant mass spectroscopy**
- Good for FRIB, but also for FAIR (full setup) or low energy Spiral2, SPES, and **LNS-FRAISE** beams (1- or 2-module blocks)

Next steps

- Waiting for ERC-CoG project evaluation
- Improve the design after first FRIB experiments
- Strengthen sinergies among HIC collaborations
  - Great opportunities from **NUSDAF** LoI, **E881_23** and **AsyEOS-II** experiments!

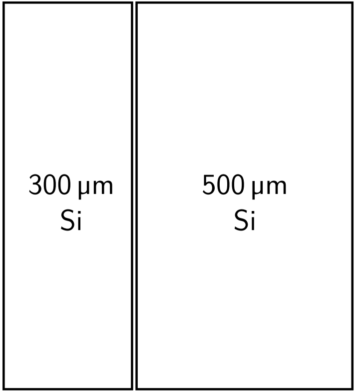
Azimuth

INFN
Istituto Nazionale di Fisica Nucleare

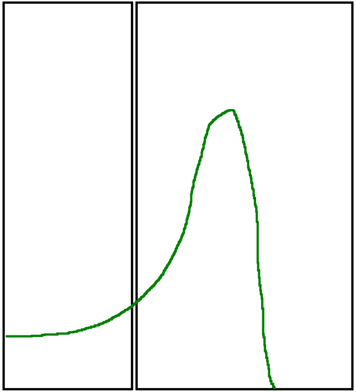
Thanks for your attention

Backup slides

Telescope concept



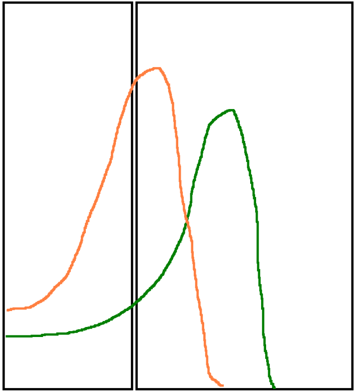
Telescope concept



^{12}C @ 180 MeV

77 MeV + 103 MeV

Telescope concept



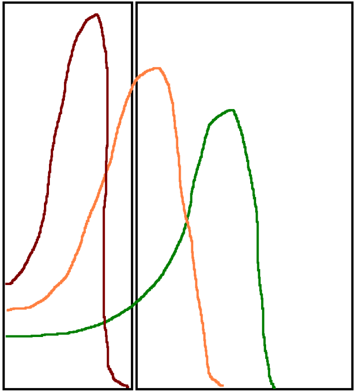
^{12}C @ 180 MeV

77 MeV + 103 MeV

^{14}N @ 180 MeV

152 MeV + 28 MeV

Telescope concept



^{12}C @ 180 MeV

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^{14}N @ 180 MeV

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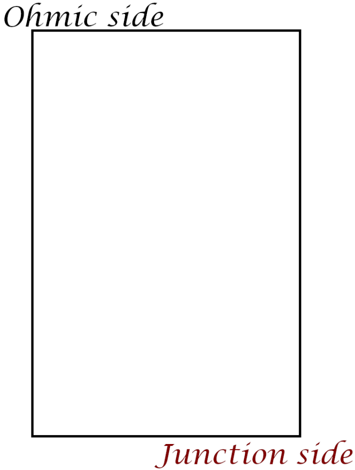
^{16}O @ 180 MeV

180 MeV + 0 MeV

Pulse Shape Analysis



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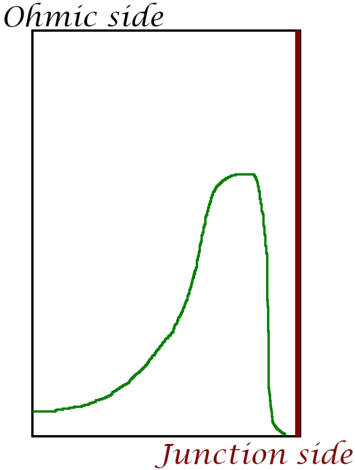

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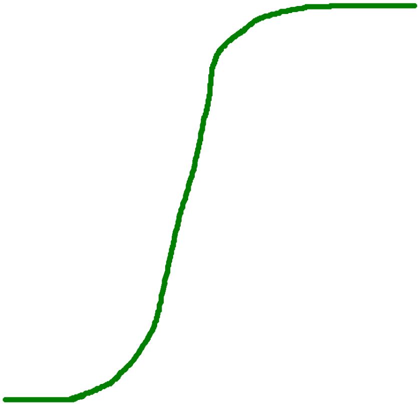
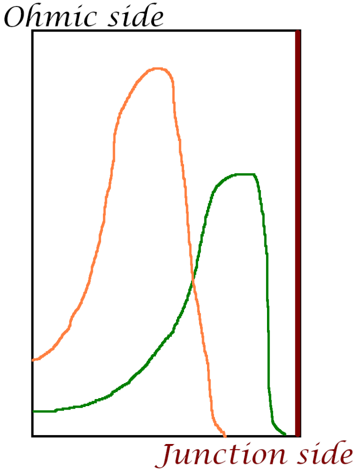
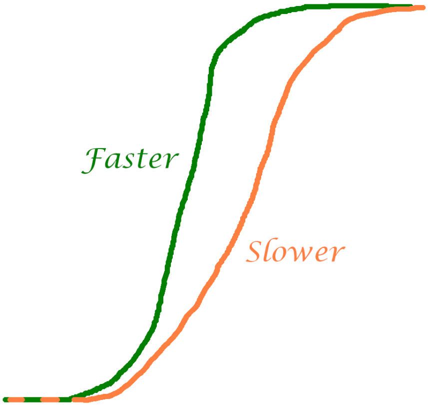


Pulse Shape Analysis

^{16}O
120 MeV

^{12}C
120 MeV





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 $\sim 50\,\mu\text{m}$ penetration

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

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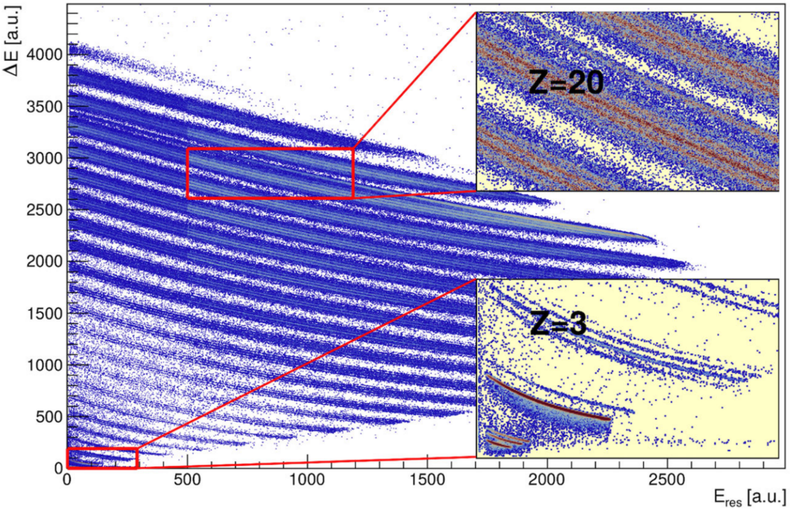
$E - ToF$ correlation

- under implementation
- lowest identification threshold

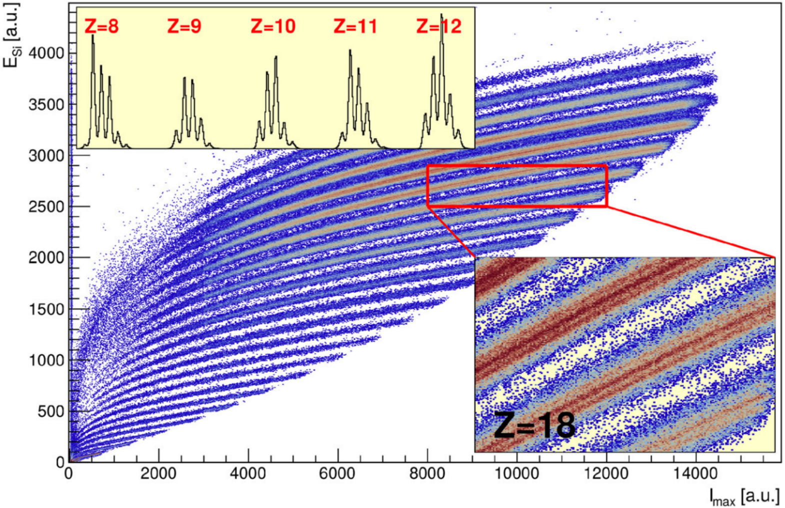
[a] N. Le Neindre *et al*, Nucl. Instr. and Meth. A 701 (145), 2013

$\Delta E - E$ correlation



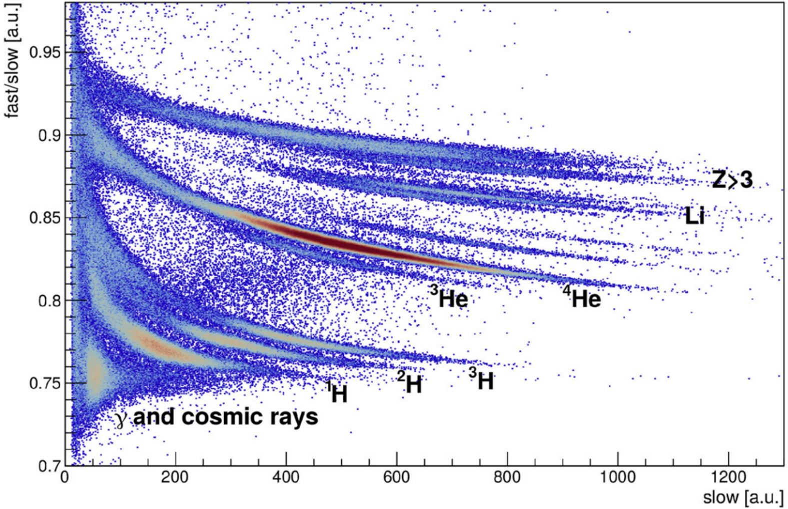
A. Badalà *et al*, Riv. Nuovo Cim. 45 (189), 2022

Pulse shape in Silicon sensors



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

Pulse shape in CsI(Tl) scintillators



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

FAZIA future

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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- New block design with the same FAZIA acquisition protocols

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FAZIA technology will be fundamental for the future developments

SYMEOS – phase 1

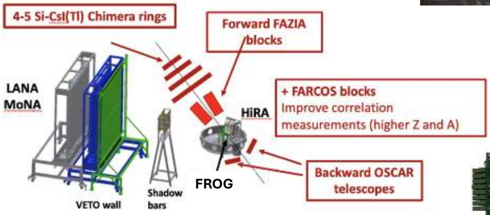
Short-term plans (coupling of existing detectors: FRIB + INFN)

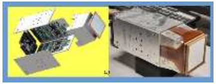
CHIMERA rings @ GSI

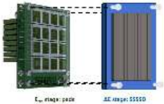
≈350 Si-CsI(Tl) telescopes
+ FROG
→ reaction plane, b, …

FAZIA @ GANIL

12 blocks * 16 units each
→ 192 Si-Si-CsI(Tl) telescopes
→ Isotopic identification and low thresholds up to Z=25
→ Isospin diffusion/transparency, isotopic distributions from participants and spectators







LANA and MoNA
Neutron detectors (flows, femtoscopy, invariant mass spectroscopy)

HiRA + FARCOS + OSCAR DSSSD: Femtoscopy and Invariant Mass Spectroscopy

Straggling compensation