Nuclear Physics Mid Term Plan in Italy

LNF – Session

Frascati, December 1st - 2nd 2022

Nuclear Physics
Mid Term Plan in Italy

WG: Charged Particle Detectors
Subgroup: Active Targets, SiC detectors, Pulse Shape Discrimination

Gabriele Pasquali
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INFN
Istituto Nazionale di Fisica Nucleare

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Gaseous Active Targets

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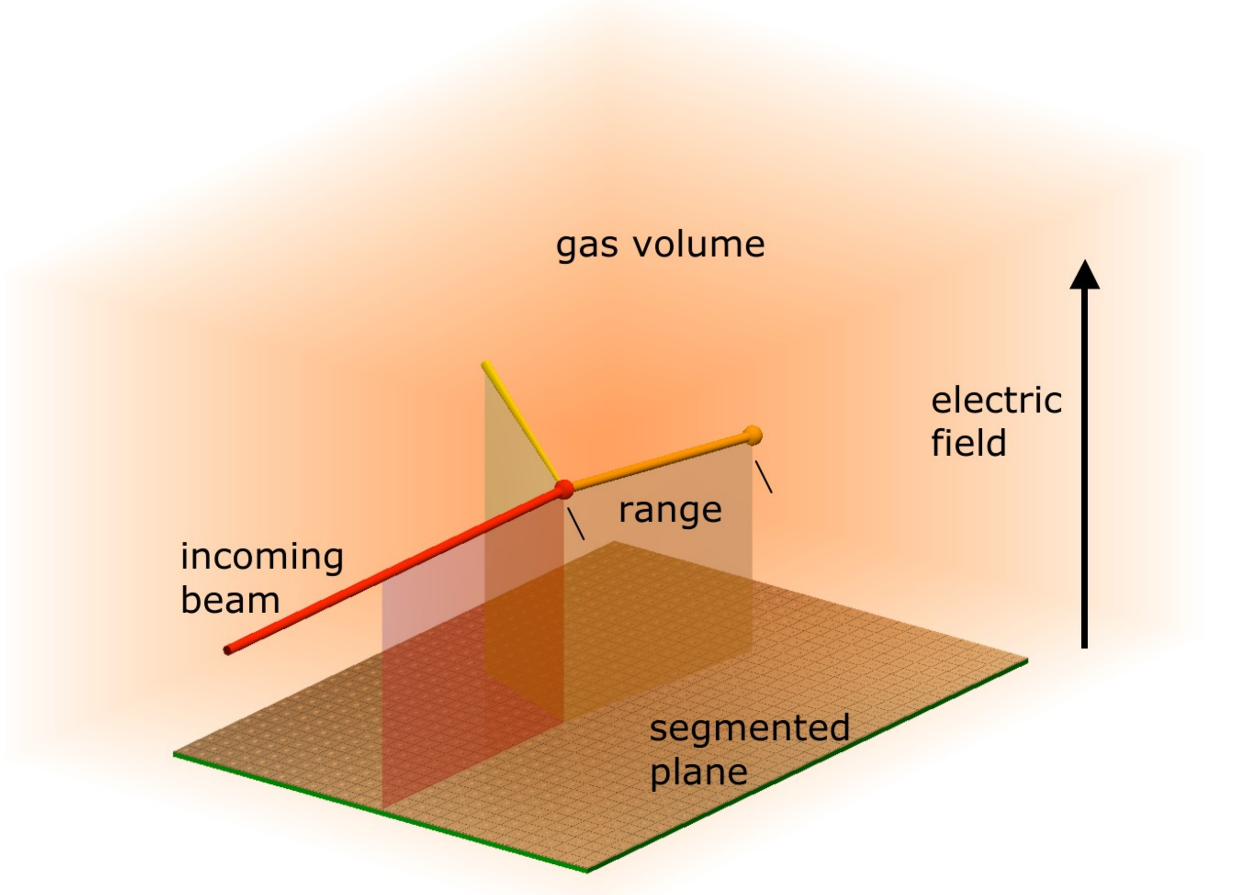
Active target

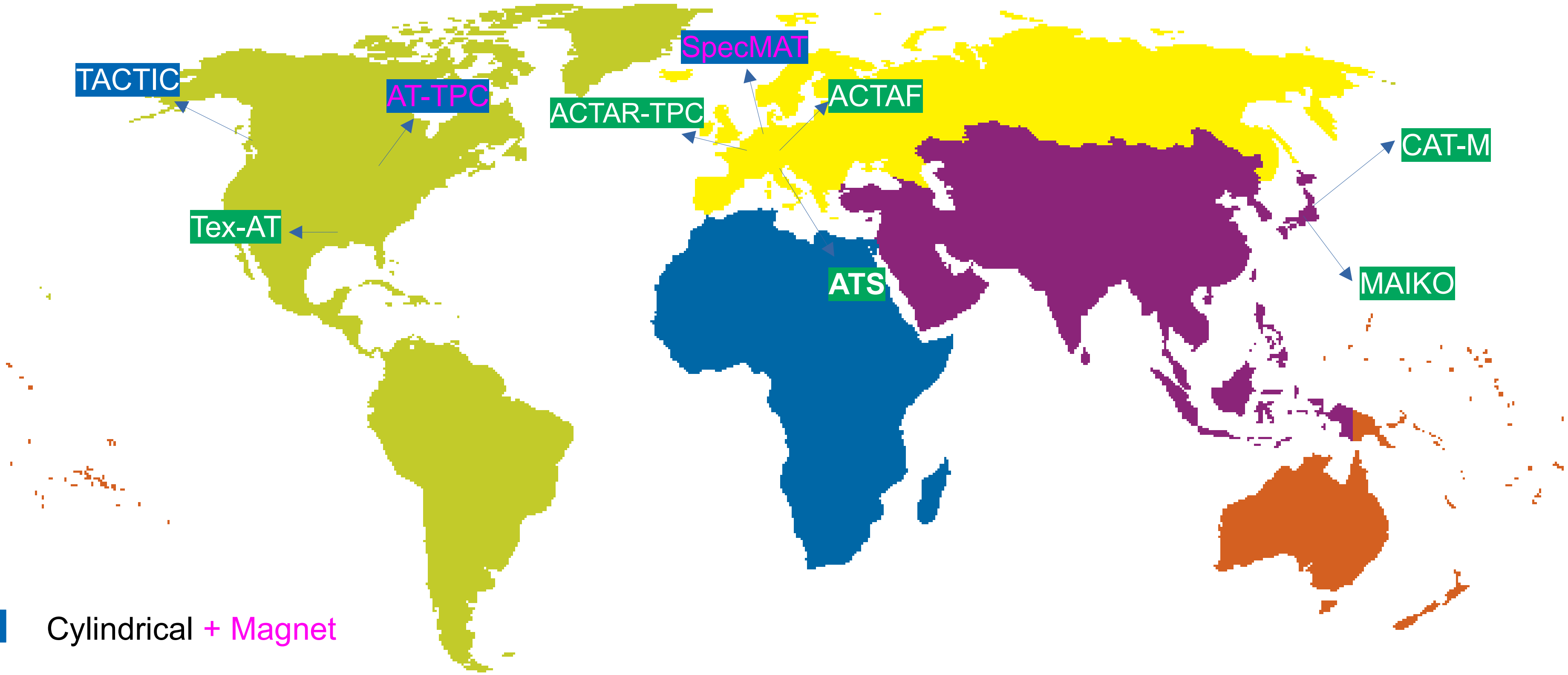
A time projection chamber (TPC) working in an active target mode



- Large angular coverage
  - ✓ Wide range of the light-ejectile scattering angles
  - ✓ Compensate RIB intensity
- Vertex reconstruction
  - ✓ Precise reaction energy information
- Low detection threshold
  - ✓ Light target ejectile detection

Active target

Ideal devices to perform inverse kinematics studies with radioactive ion beams

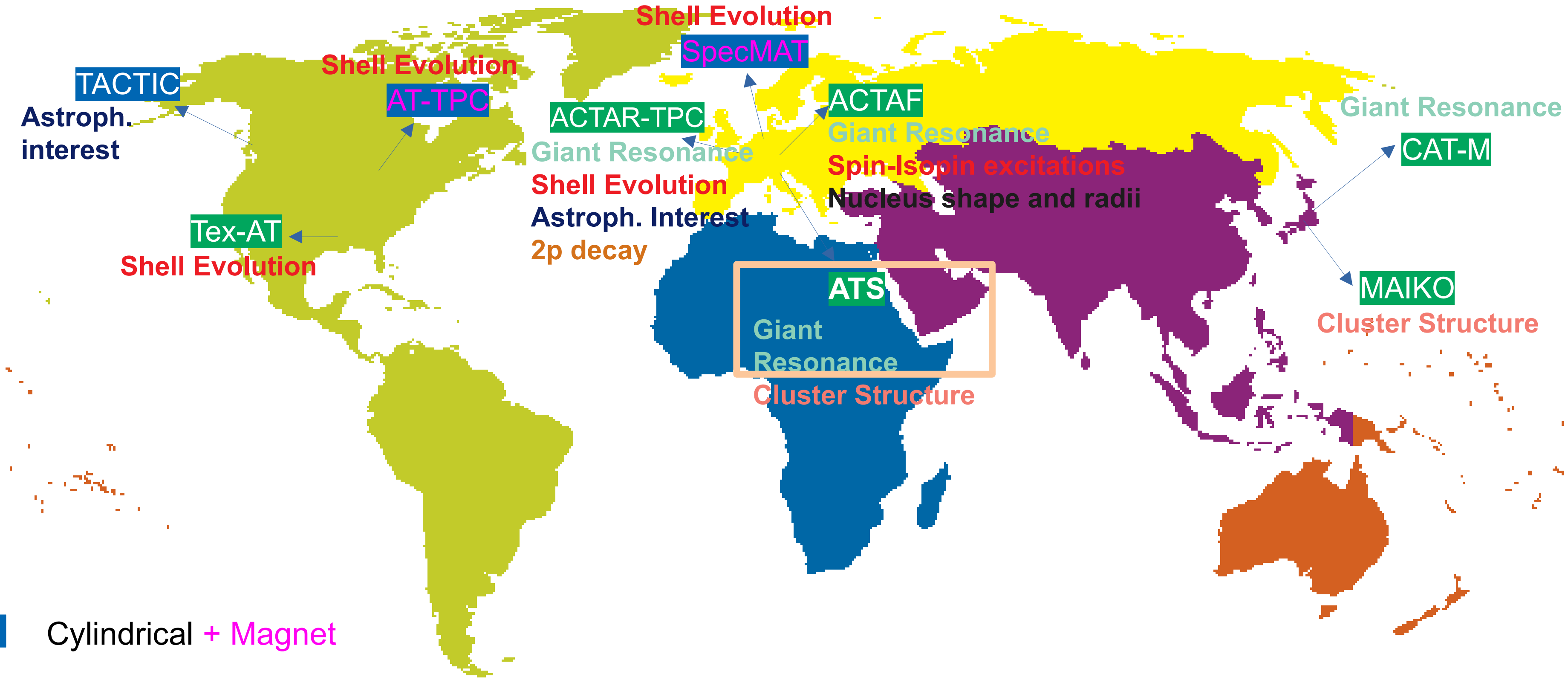


Cylindrical + Magnet

Cubic

Active target

Ideal devices to perform inverse kinematics studies with radioactive ion beams



Cylindrical + Magnet

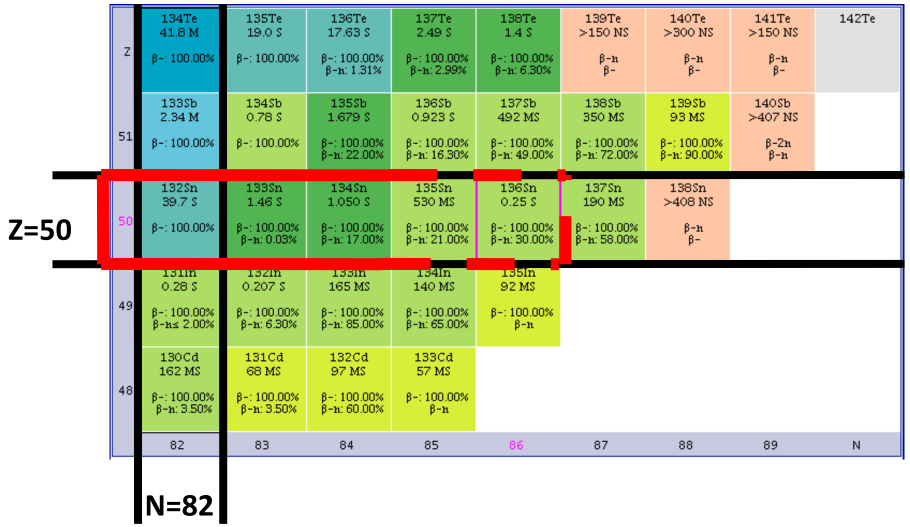
Cubic

- D. Bazin, T. Ahn, Y. Ayyad et al. / Progress in Particle and Nuclear Physics 114 (2020) 103790
- https://edms.cern.ch/ui/file/1816116/2/TDR_R3B_ACTAF_public.pdf
- https://tactic.triumf.ca/
- https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/instrumentation/actar/

At SPES

Hot topic: transfer reactions along Sn isotopic chain to study shell evolution.

Expected beam intensities @ 10 AMeV		
	SPES 1st day (5 µA p beam)	SPES full power (200 µA p beam)
^{132}Sn	7.8 10^5	3.1 10^7
^{133}Sn	7.0 10^4	2.8 10^6
^{134}Sn	1.2 10^4	4.9 10^5
^{135}Sn	1.6 10^2	6.2 10^3
^{136}Sn	-	0.9 10^2



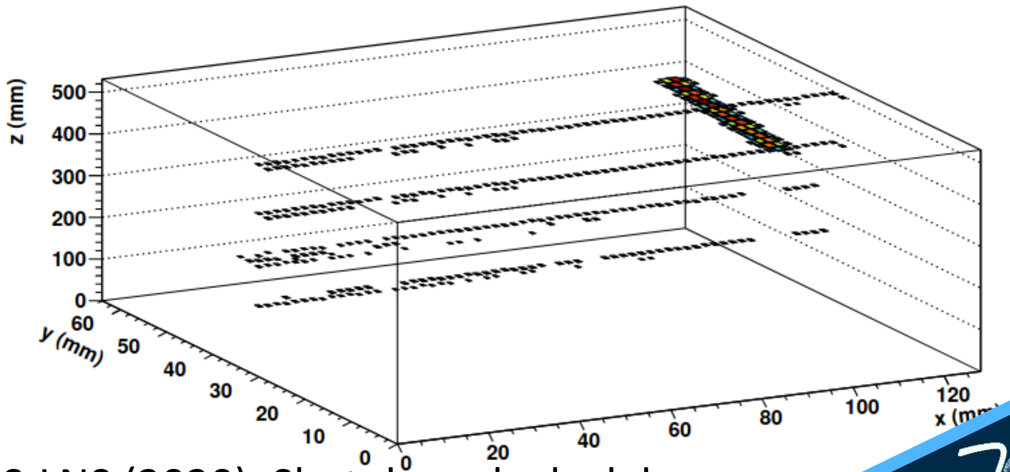
Other cases:

- **resonant reactions to study cluster states;**
- **fission in inverse kinematics;**
- **Complete vs incomplete fusion;**

See also MTP – LNL

At LNS (also w/ FRAISE)

Study of collective excitations using inelastic scattering.



First trial: ^{20}Ne+α at CS-LNS (2020). Shut down by lockdown…

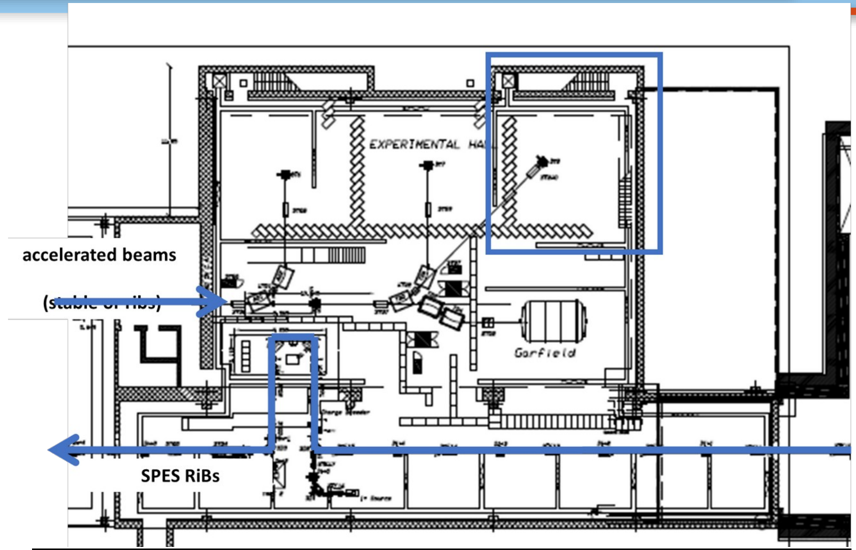
ATS: an Active Target for SPES

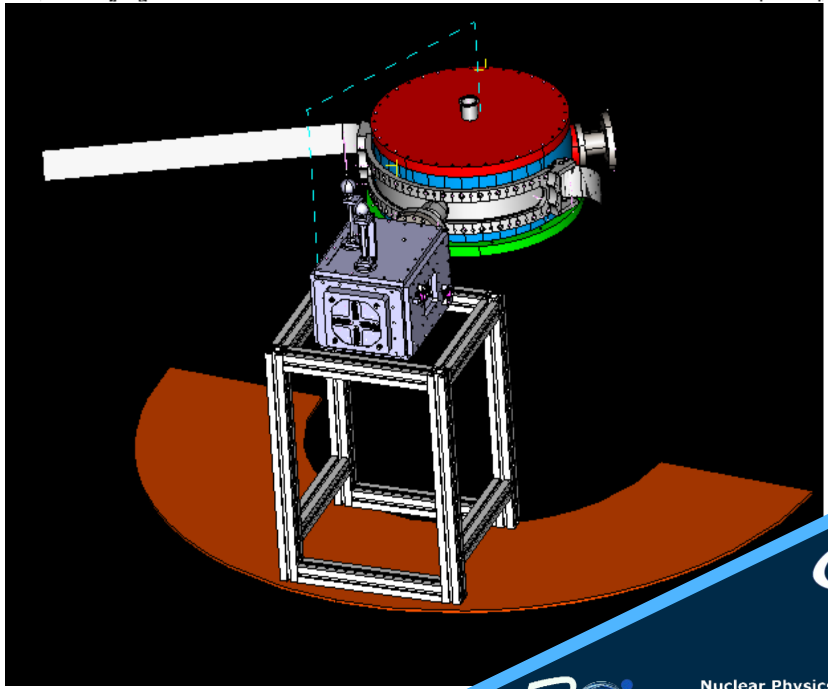
The facility:

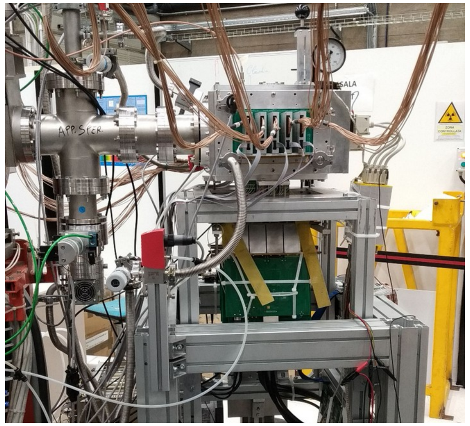
- beam-line installation
- installation of a sliding-seal chamber
- installation of a rotating mechanical support for the AT
- installation of the gas circulation system

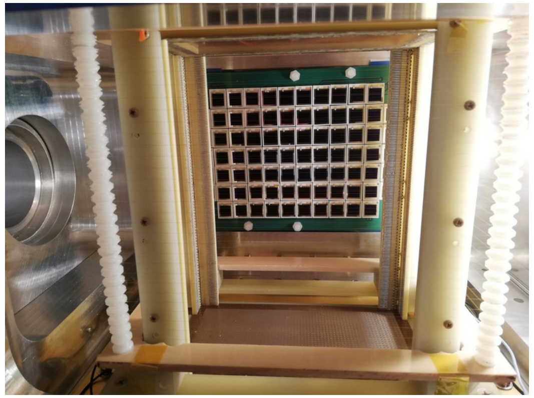
The detector (upgraded version of the ACTAR Demonstrator):

- new pad-plane and field cage
- use of ZAP connectors for FEE
- dedicated ancillaries (OSCAR-like Si walls, neutron detectors, etc)



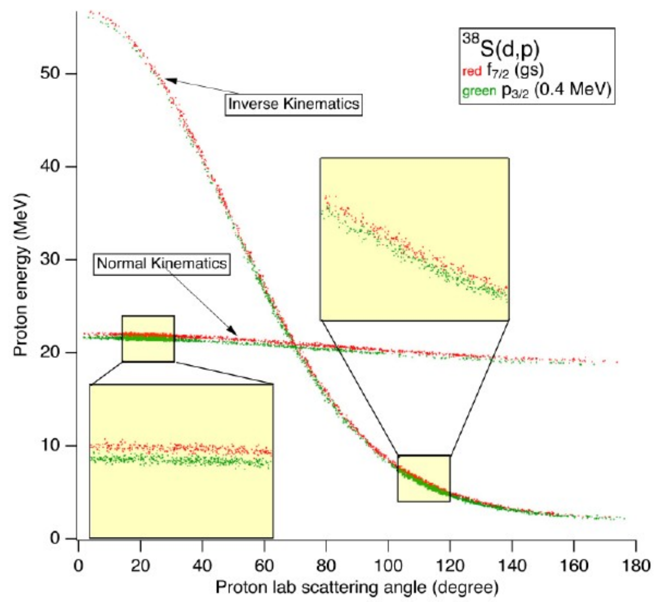


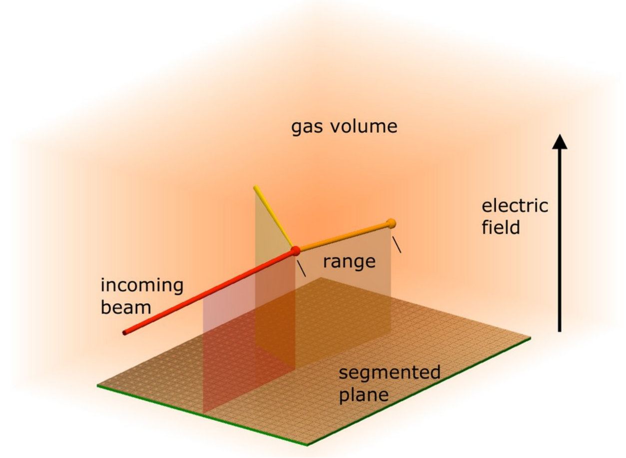




Active target: pros

- Vertex reconstruction
  - ✓ Precise reaction energy information
- Low detection threshold
  - ✓ Light target ejectile detection
- Large angular coverage
  - ✓ Wide range of the light-ejectile scattering angles
  - ✓ Compensate RIB intensity





Active target: pros and cons

- Large angular coverage
  - ✓ Wide range of the light-ejectile scattering angles
  - ✓ Compensate RIB intensity
- Vertex reconstruction
  - ✓ Precise reaction energy information
- Low detection threshold
  - ✓ Light target ejectile detection

Active volume

- Different ionization density between light ejectile and heavy recoil.
  - ✗ Difficulty to match them within the same dynamic range
- Delta ray production
  - ✗ Spurious hit affecting the trigger
- Space charge effect in the drift volume
  - ✗ Deformation of the electric drift field

Detection plane

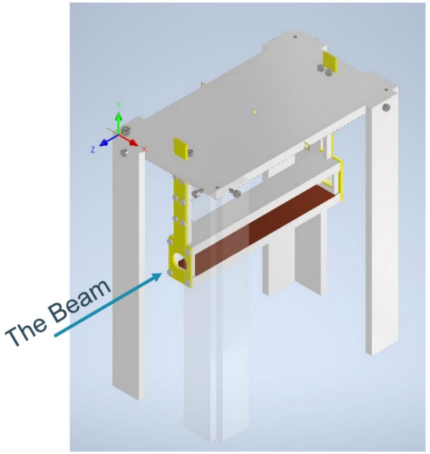
- Working with pure (di-atomic) gases
  - ✗ Discharge regime

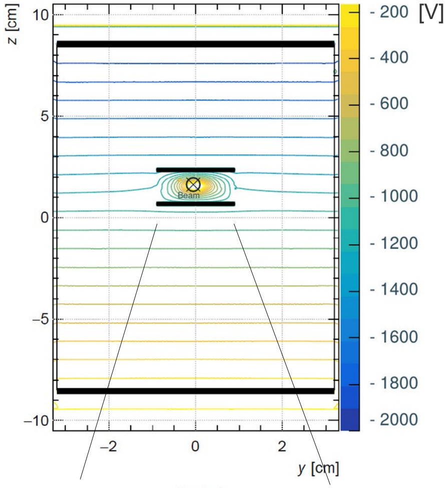
Acquisition

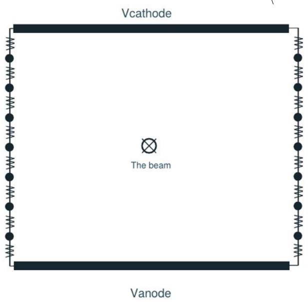
- Better trigger strategies needed to avoid acquisition of too many not useful events

ATS: Towards a new field cage

Space charge effects: electrostatic mask







Principle taken from
Tajes NIM A 768,
tested for
^{136}Xe at 7 MeV/u at 10^5 pps

ATS: Towards a new field cage

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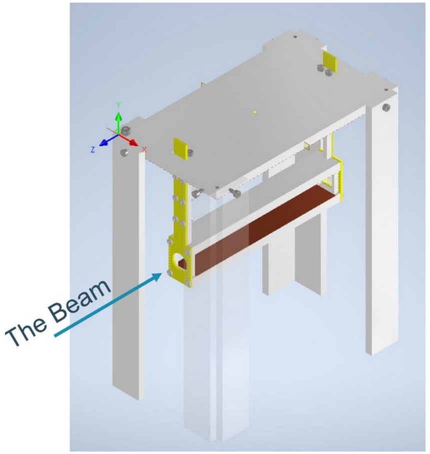
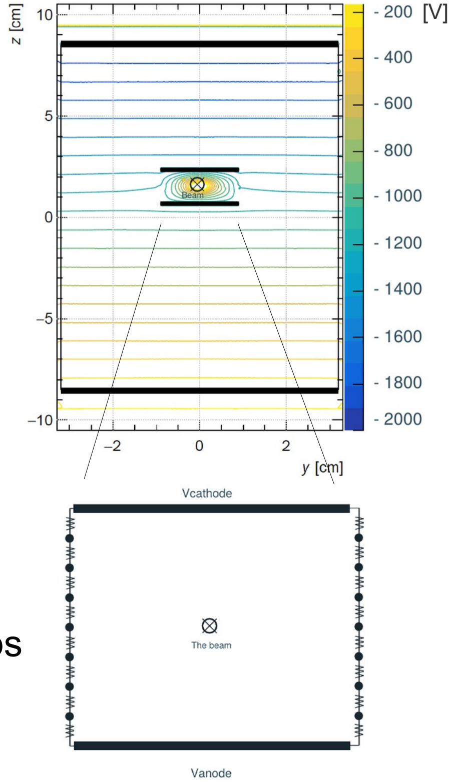




Principle taken from Tajes NIM A 768, tested for ^{136}Xe at 7 MeV/u at 10^5 pps

δ-rays: the CAT-M solution

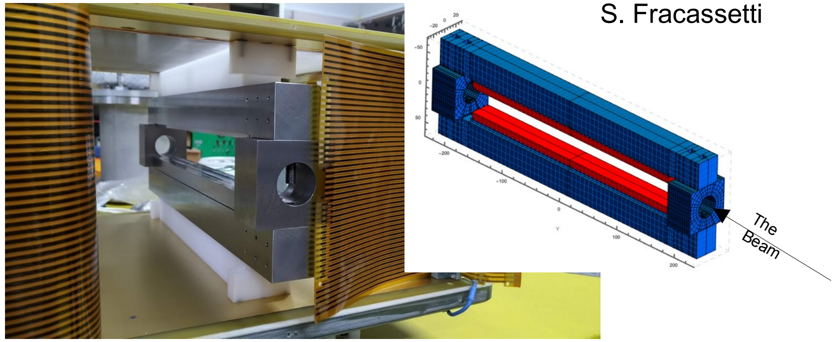
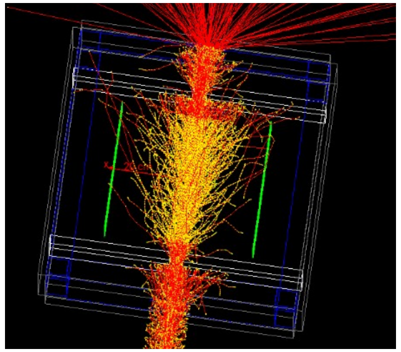
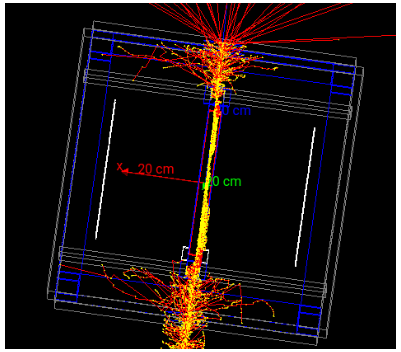


Figure credit:
S. Fracassetti

^{86}Kr at 115 MeV/u



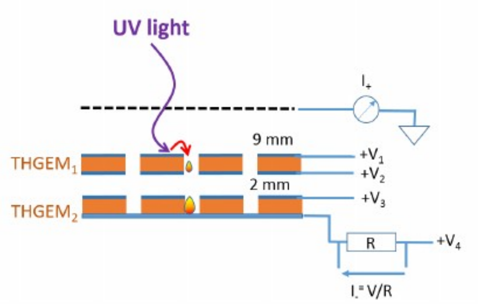


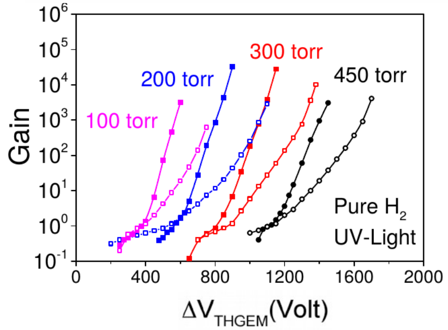
Future Development: a new field cage allowing the introduction of a EM mask

ATS: Perspectives for a new detection plane

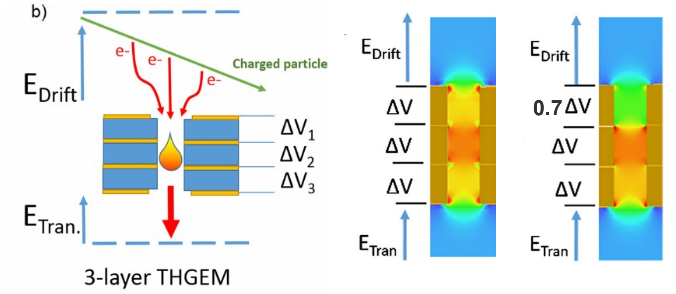
Pre-amplification stages to work in stand alone mode or with MICROMEGAS

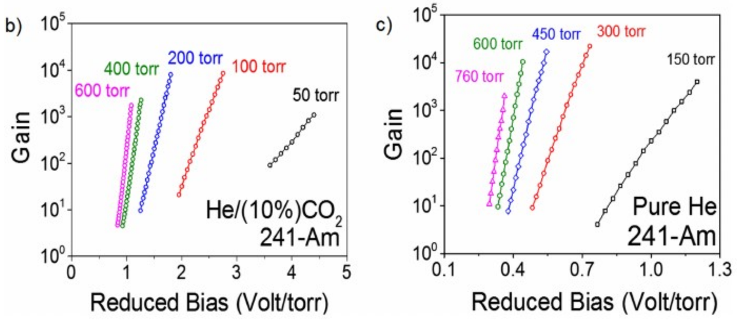
Thick GEM (THGEM)



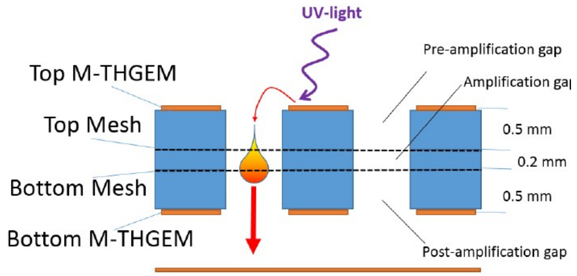


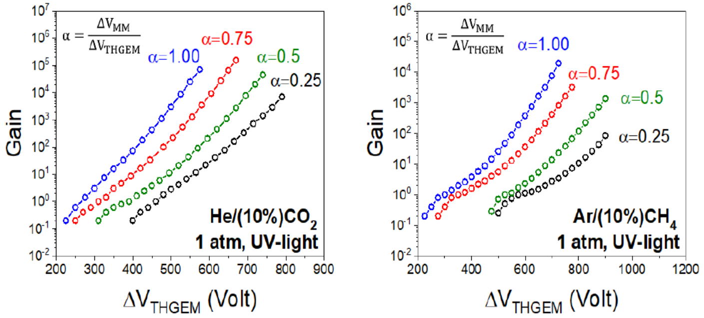
Multi-THGEM (M-THGEM)





Meshed M-THGEM (MM-THGEM)

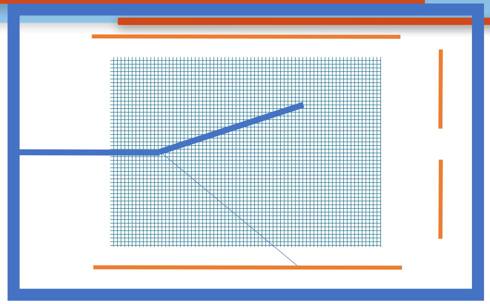




M. Cortesi et al 2015 JINST 10 P09020
M. Cortesi et al., Rev. Sci. Instrum. 88, 013303 (2017);
R. de Olivera and M. Cortesi 2018 JINST 13 P06019

Not yet tested with pure H_2 or D_2

Smart trigger for ATS



Trigger on **side SI** detectors

Current standard – trigger on side silicon detectors*
*Depending on reaction case of interest

Problem

No selection on reaction channel
Events not containing an interaction vertex are still acquired
Es. Multifragmentation and (in)elastic scattering events are both acquired

Pipeline Trigger → Acquisition → Sign. Processing → Clustering → **Classification**

Smart trigger for ATS

Current standard – trigger on side silicon detectors*
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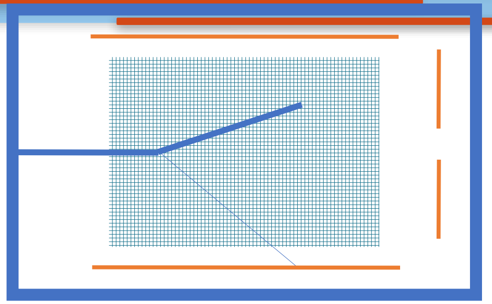

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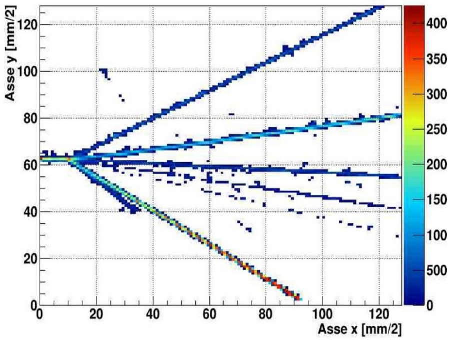

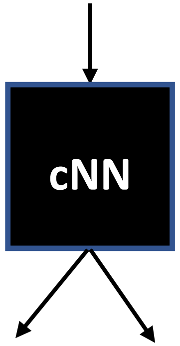

Problem
No selection on reaction channel
Events not containing an interaction vertex are still acquired
Es. Multifragmentation and (in)elastic scattering events are both acquired

Pipeline Trigger → **Classification** → Acquisition → Sign. Processing → Clustering

Idea
Use detector configuration to perform a first-level event classification
2D pad-plane image used as input to retrieve event classification

How
Implementation of classification through **CNN** (convolutional neural network)

Results (cfr. L. Domenichetti, Master Thesis, UniPD 2021/22)
98% accuracy with respect to classification after clustering
2kHz prediction rate (comparable to acquisition rate) leads to a possible **online** selection

Active Targets Summary Table

		comment/description	Critical items for R&D	Expected Time
DET-ATa0	**A**	**new field cage at LNL**	**fully funded by CSN3**	**2023-2024**
		mechanical design and construction		2023
		design, simulation, and implementation of an electrostatic mask		2024
DET-ATa1	**A**	**new pad plane at LNL**	**fully funded by CSN3**	**2023-2024**
		design and construction from CERN PCB workshop	long waiting list	
DET-ATa2	**A**	**installation of a "resident AT" at SPES**	**beam line completion up to experiment location**	**2023-2024**
		design of support mechanics (gas chamber and front-end electronics support)		
DET-ATb0	**B**	**pure-gas mult. and read-out**	**to be realized from scratch following AT-TPC works**	**2023-..**
		implementation of a parallel bench test point		
DET-ATc0	**C**	**2nd level trigger w/ CNN**	**new readout electronics**	**>2**[illegible]

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Silicon Carbide detectors

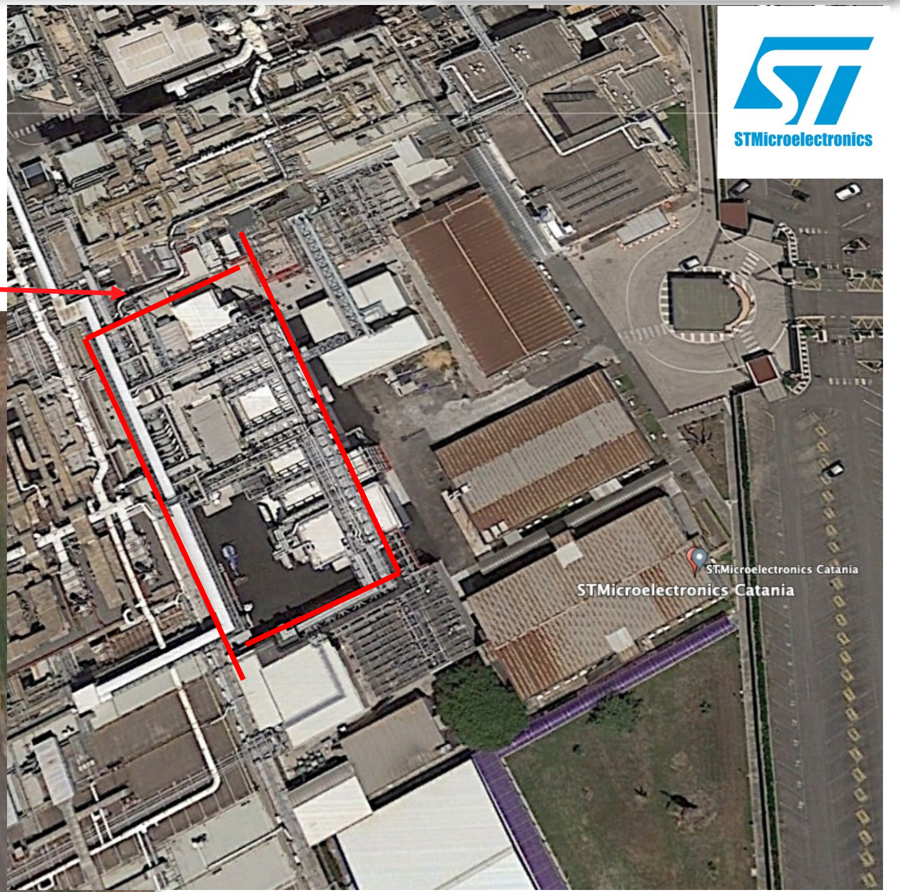
Gabriele Pasquali

Università degli Studi di Firenze and INFN-Firenze

SiC-Technopole Catania

INFN

New SiC Clean-room



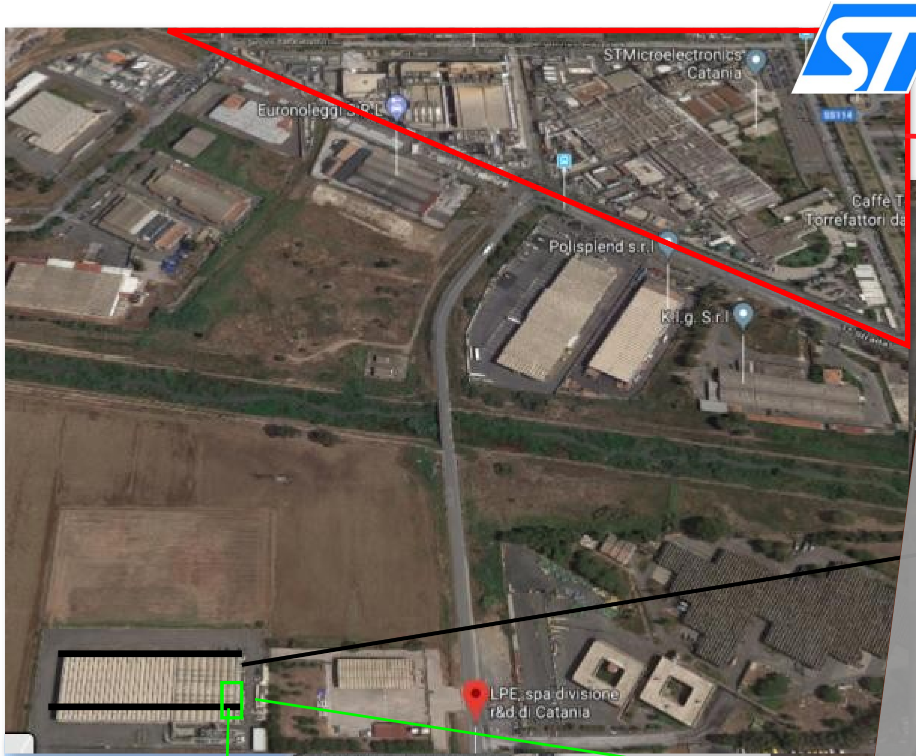
INFN ↔ IMM

SiCILIA INFN

S. Tudisco **INFN-LNS**

SiC-Technopole Catania

INFN

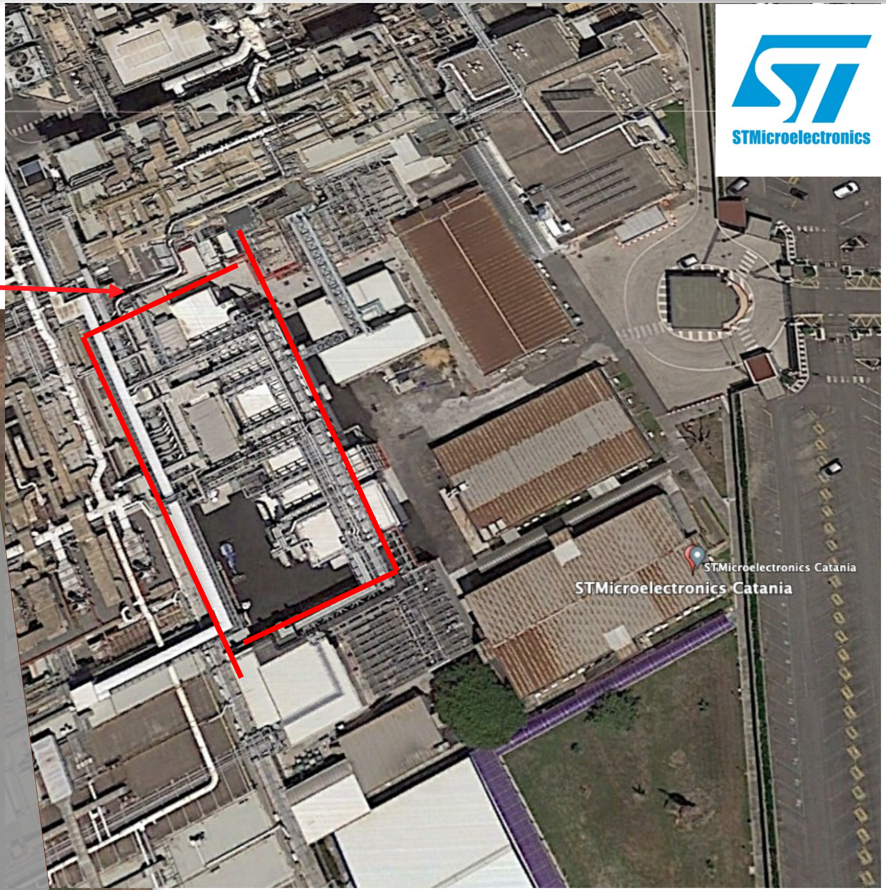


INFN ↔ IMM

New SiC Clean-room

Why SiC?

- Radiation hardness
- Not sensitive to visible light
- Much less sensitive to temperature than Si

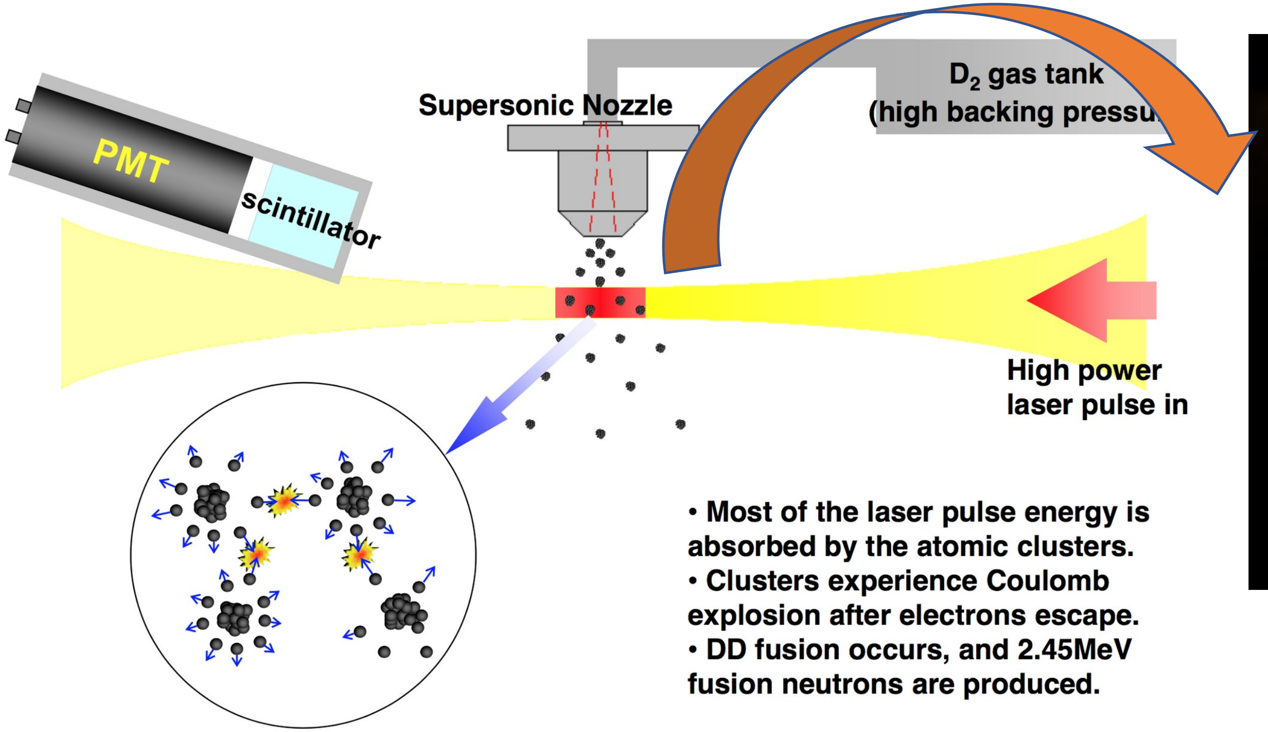


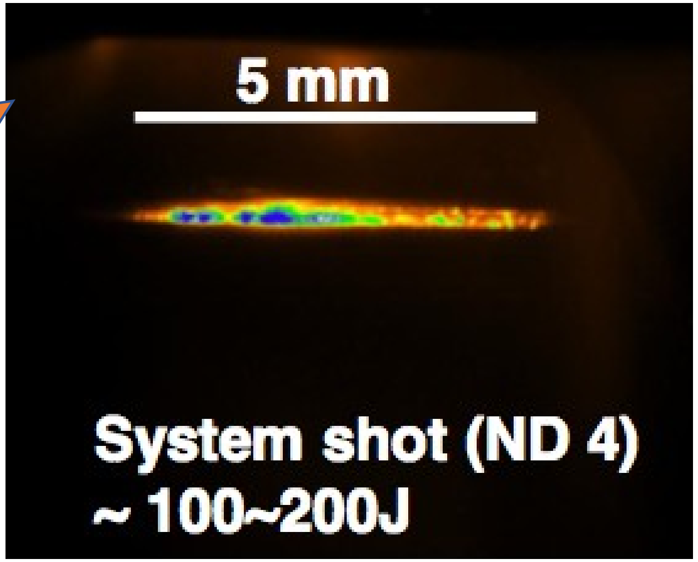
STMicroelectronics

SiCILIA INFN

S. Tudisco ***INFN-LNS***

Nuclear fusion from laser-cluster interaction





@ Texas Petawatt UT

Harsh environment:

- Light
- Huge number of low-energy ions moving around
- EMP
- Heat

Need of radiation hard detectors

Silicon carbide (SiC)
→ high band gap (3.28 eV)
→ fast (saturated electron velocity $v_{SiC} > v_{Si}$)

Ideal for laser driven experiments because
- large thermal stability
- insensitivity to photons in the visible
- radiation hardness,
- thermal shock resistant

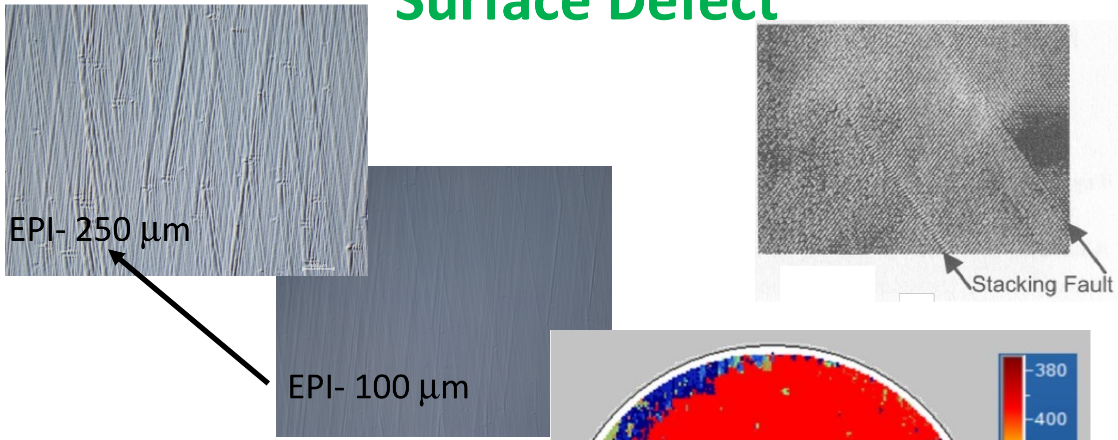
Also:
- **excellent timing for TOF**
- **PSA**

SiC - Detectors R&D

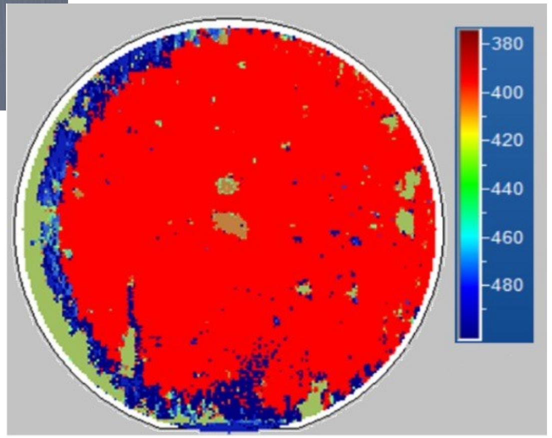
- New geometries large area/Pixel devices (NUMEN, FRAISE, MEDIPIX…)
- Thicknesses

SiC Epi-Layers beyond the state of the art → 250 μm

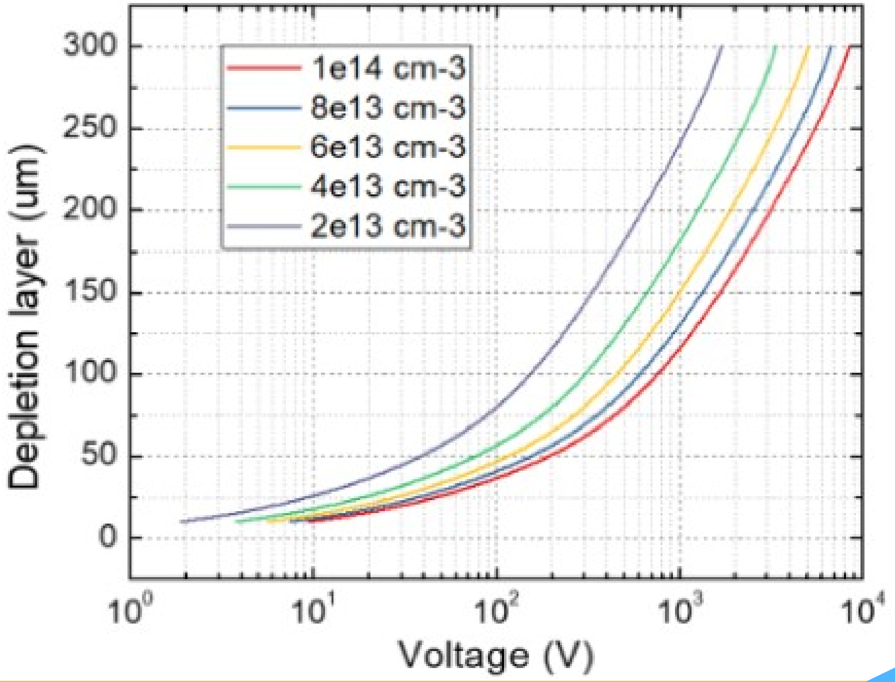
Surface Defect



DEFECTS MAP
Photoluminescence spectroscopy
4-inch 250 μm SiC wafer



Epi Doping-concentration



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SiC-Monolithic ΔE-E telescope

Silicon Carbide

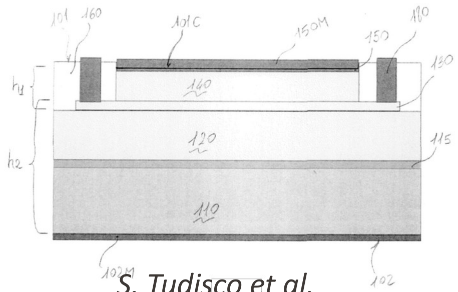
- Wide band-gap semiconductor
- Visible Blind
- High Breakdown
- Low Leakage current
- Fast timing
- Radiations hardness
- Biocompatibility

Monolithic Structure

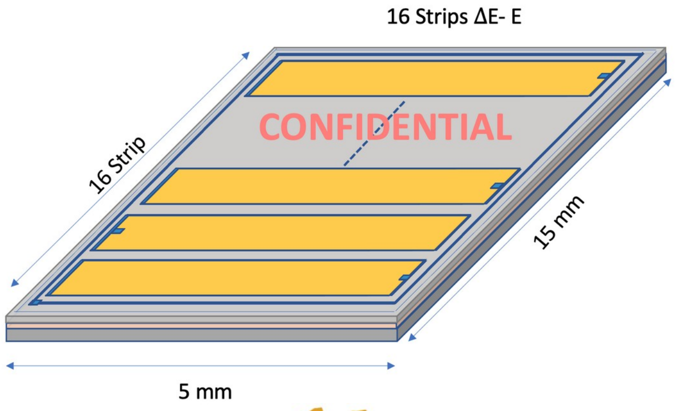
SiC Buried anode

~~Implantation~~ → EPI-layer

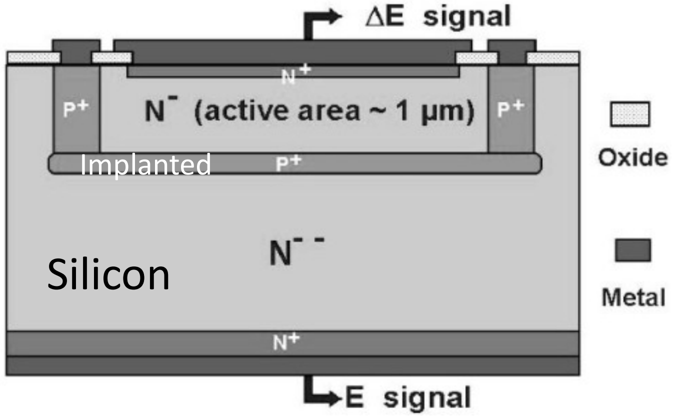
Patent

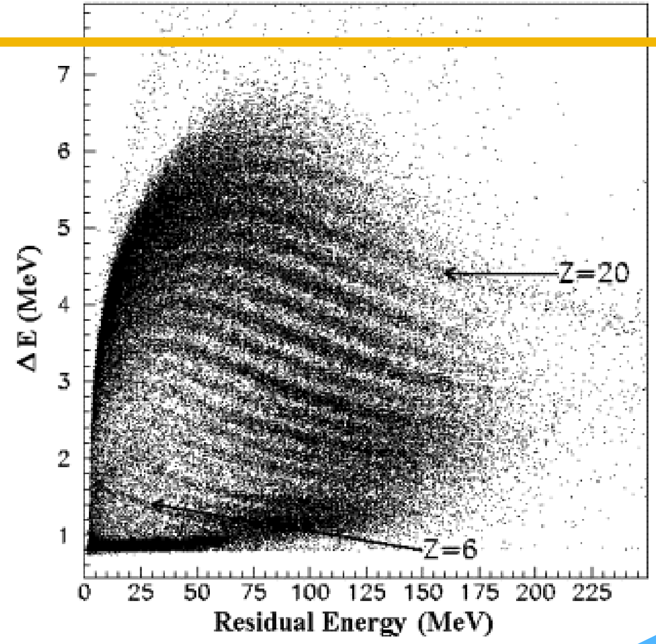


S. Tudisco et al.
EU n° EP3821276A1



History





G. Cardella et al NIMA 378 (1996) 262
S. Tudisco et al NIMA 426 (1999) 436
F. Amorini et al NIMA 550 (2005) 248

S. Tudisco ***INFN-LNS***

SiC ultra-thin *monolithic telescopes* for low-energy and high-intensity *frontier* experiments

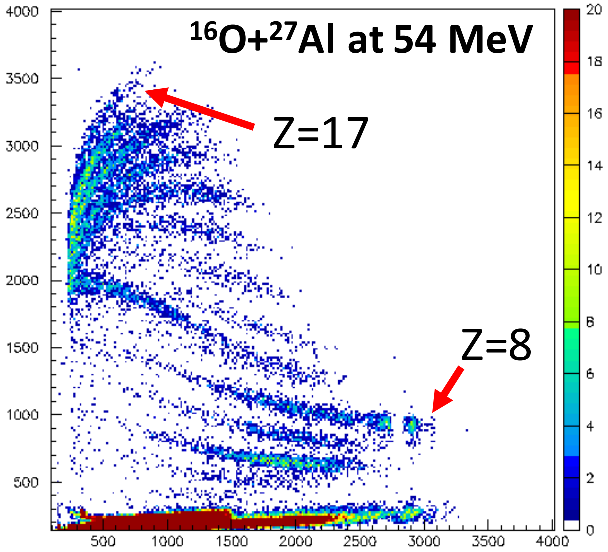
***Low-energy* experiments in nuclear physics**

***Light ions* (nuclear structure and astrophysics)** → Low Q-value CN reactions → need for AZ identification of ejectiles having very low energies ($\approx 1-2\ MeV$) → (p,α) on medium mass nuclei (NeNa cycle), clustering in self-conj. nuclei, spectroscopy, etc.

***Heavy ions* (nuclear structure and dynamics)** → Fusion-evaporation, fusion-fission, deep inelastic collisions → at least Z identification of one or two heavy fragments to tag the reaction dynamics! → boundaries of ℓ_{crit}, structure effects in fusion etc.

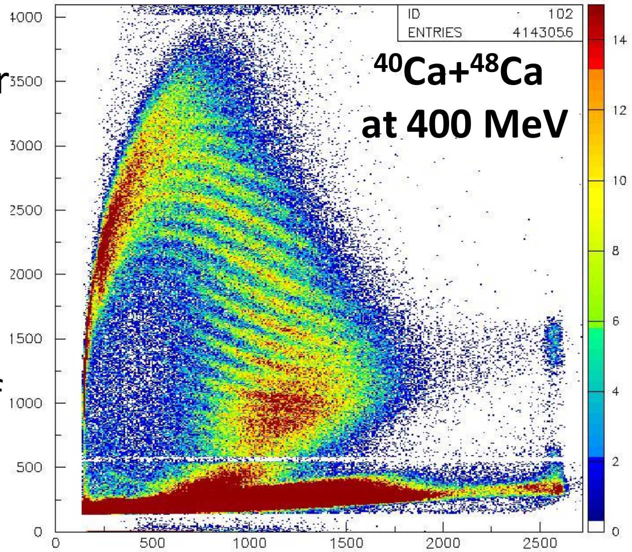
In both cases → «hostile» environments: very *large rates* of elastic particles at forward angles → SiC !

In past times, the **TRASMA** collaboration developed a ***monolithic Silicon detector*** with $\mathbf{1.5\ \mu m\ \Delta E}$ stage and **implanted** anode → excellent performances on the Z identification, ultra-low thresholds (**200-300 A.keV**!)



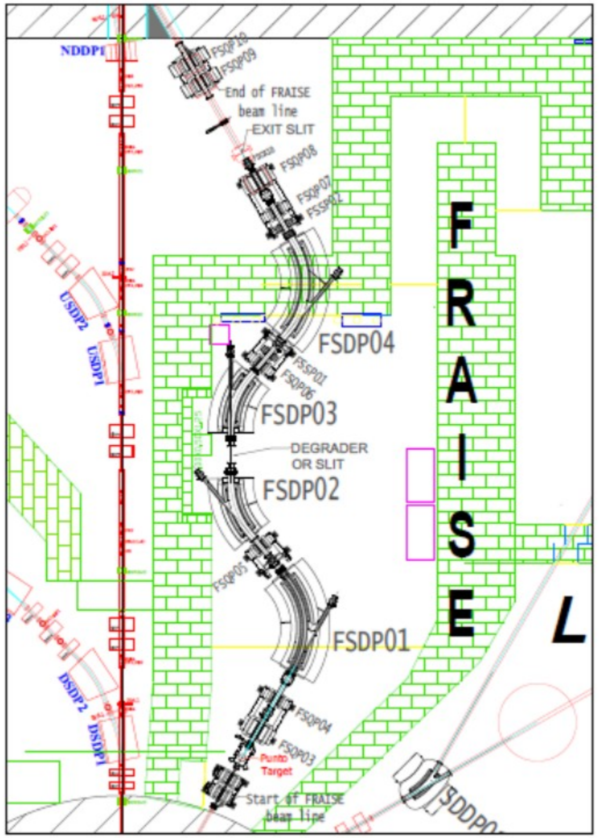
One-by-one *residue identification*, both for light and heavier systems

→ Enormous *versatility* of this type of device, especially if operated with high particle rate (SiC)

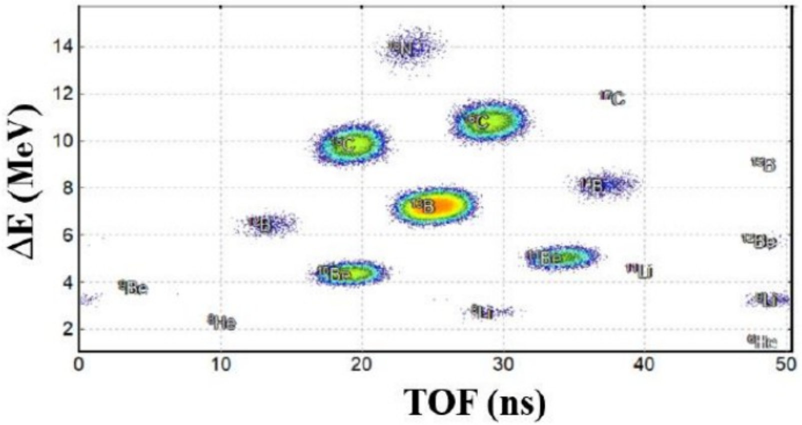


G.Cardella et al. NIM A 378 (1996) 262
M.Papa et al, Phys. Rev. C 72 (2005) 064608
A.Musumarra et al. NIM A 409 (1998) 414
F.Amorini et al, NIM A 550 (2005) 248

Monolithic SiC → anode performed by ***epitaxy*** → much better control of the ***thickness*** of the ***buried anode*** → less *noise* and *induction*

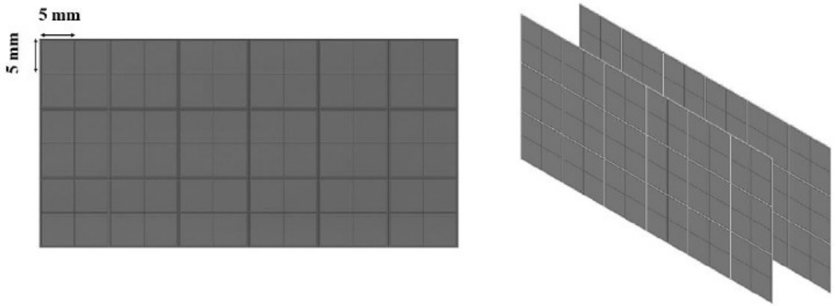


The new fragment separator FraISe will provide fragmentation beams with very high intensity (up to 10^7 p/s for ions like ^{16}C)



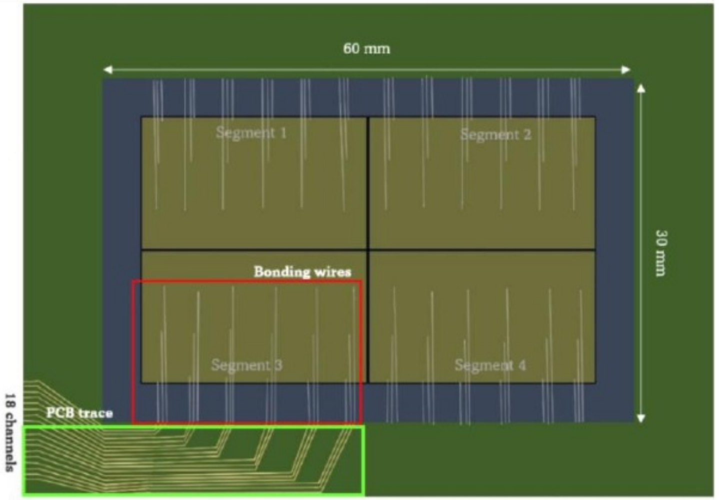
Most of the produced beams will be «cocktail» and need event by event identification through the measurement of time of flight and energy loss

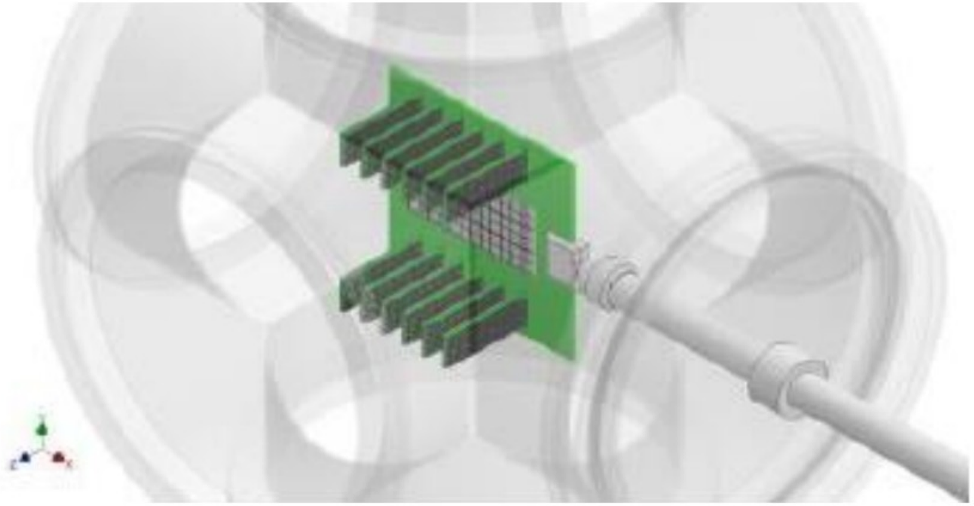
The new tagging device must be fast & radiation tolerant, therefore SiC was choosen as material



One of the studied configuration foresees the use an array of pads of 5mmx5mm able to cover a surface up to 6cmx3cm

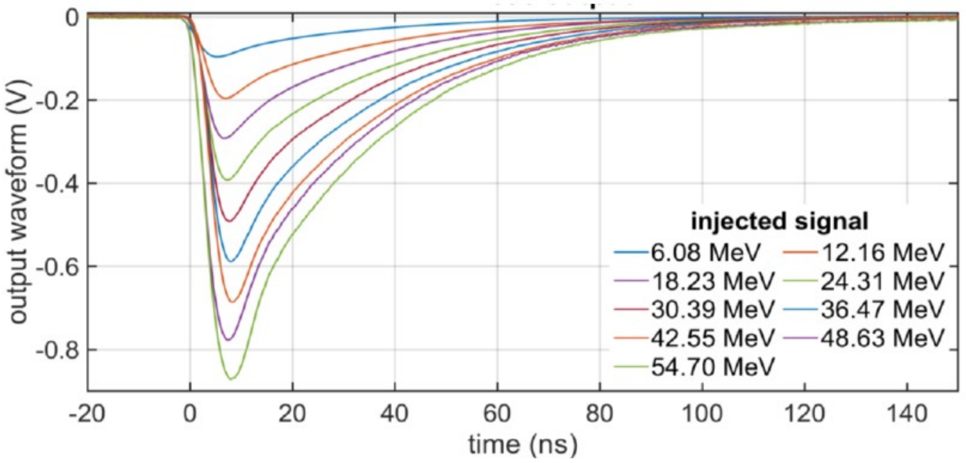
SiC detectors: beam tagging at FRAISE



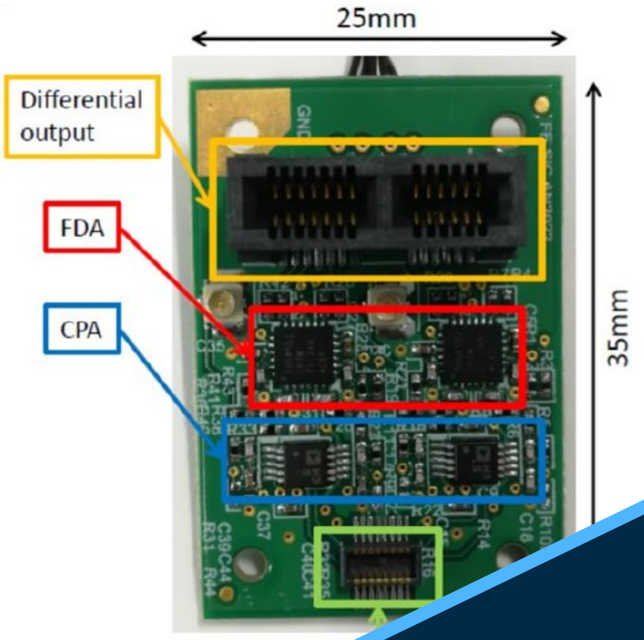


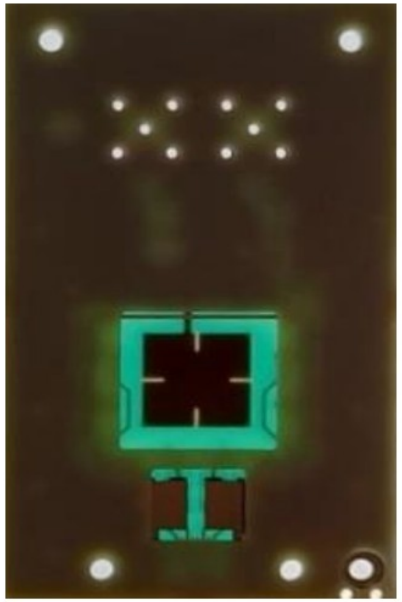
The system including electronics will be mounted in a mother board that can be moved, using a pneumatic system, into the beam line to intercept the fragmentation beam

This is an example of solution for the bonding system needed to connect the array to the electronics



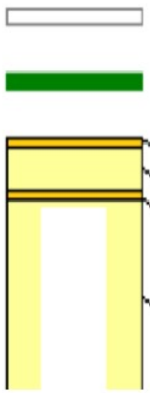
A fast electronic is being developed by Politecnico & INFN-MI able to assure a reasonable energy resolution (<1%) and a very good time resolution <300 ps – Two devices mounted at a distance >15 m will assure in this case a precision in the time of flight measurement enough to measure the beam energy with 0.5% resolution



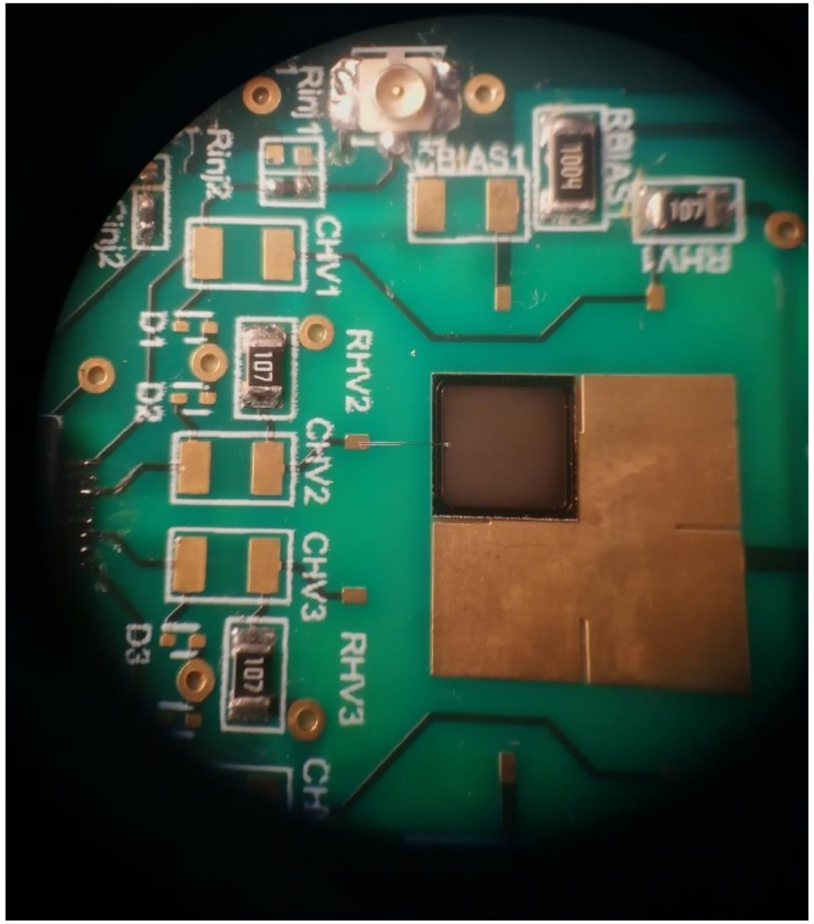


In order to characterize the first prototype we are using a smaller pcb able to host 1cmx1cm detectors – the reduced thickness of the PCB in the detector region will assure a simple test also in transmission – future prototypes will be mounted in total transmission mode by using an ad-hoc hole in the PCB frame

Overview of the structure

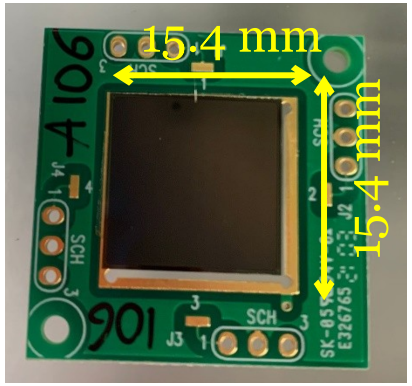


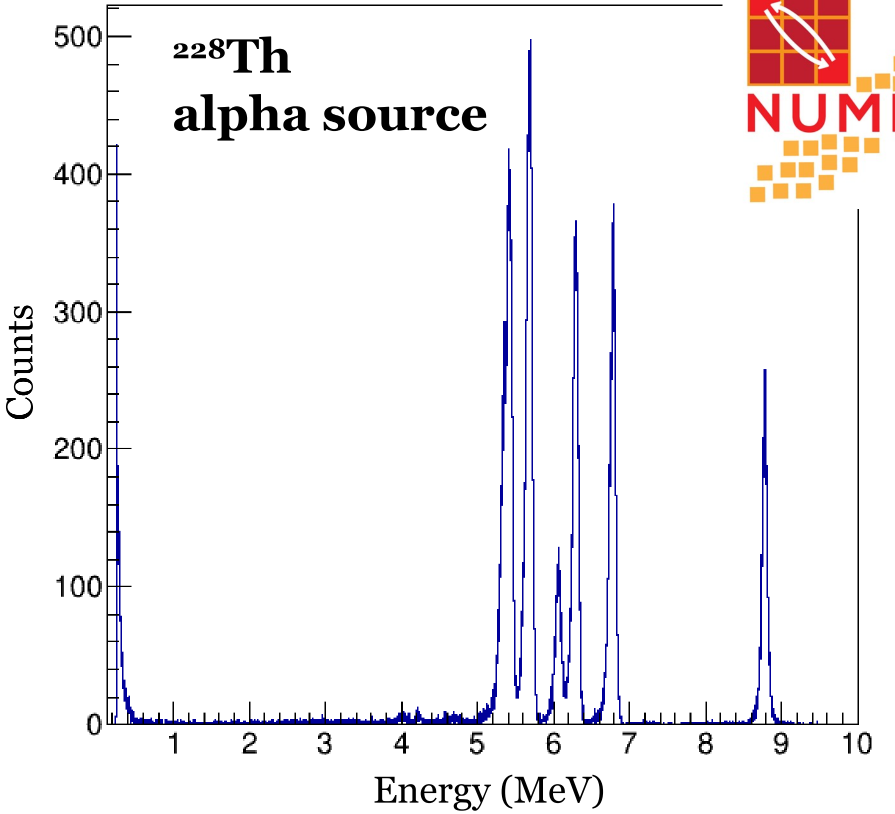
Layer	Min toler. notes (1-2-3-4)	Thickness selected	Your selection
Ink TOP			Your selection : Ink white
Soldermask T	20 µm	20 µm	Your selection : Soldermask green
CU - 1	32 µm	35 µm	35µ / 1 Oz
FR4 - 1	270 µm	300 µm	300 µm
CU - 2	32 µm	35 µm	35µ / 1Oz
FR4 - 2	1107 µm	1230 µm	1230 µm
Total thickness		1620 µm	



This is one of the first detectors bonded and its motherboard

Use of SiC detectors for PID at the focal plane of MAGNEX magnetic spectrometer





First SiC detectors produced

- Accurate characterizations needed

Methods

- C-V and I-V curves
- Radioactive alpha particle sources up to ~ 9 MeV
- Ions beams with sub-millimetric size (microbeam)
- Tests in vacuum and gas environments

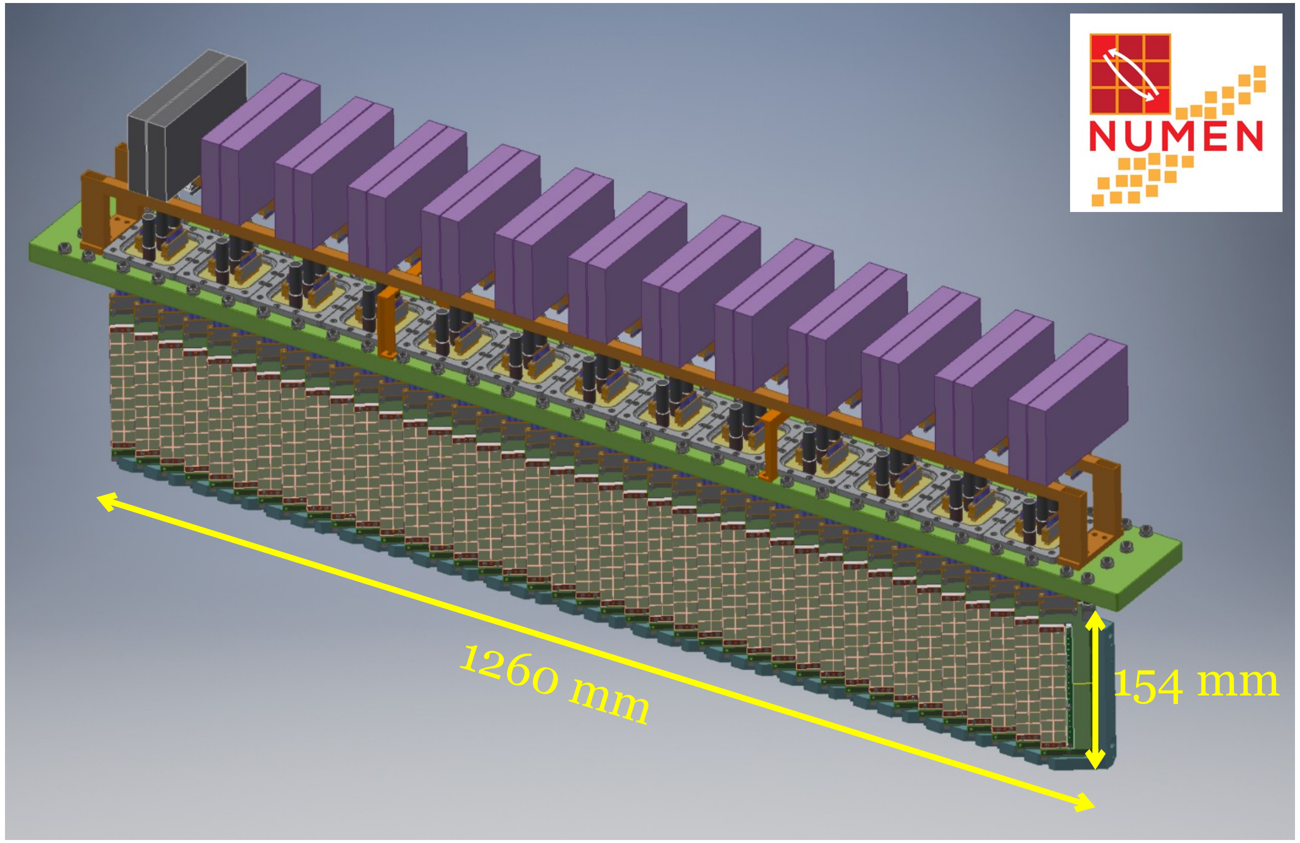
Aims

- 3D characterization of the charge collection efficiency
- Dead layer measurement
- Full depletion voltage and thickness measurement
- Edge profile characterization
- Energy and time resolutions

Use of SiC detectors for PID at the focal plane of MAGNEX magnetic spectrometer

PID wall

- 720 SiC-CsI telescopes to cover the full spectrometer focal plane
- ΔE stage state-of-the-art SiC detectors (100 μm active thickness, 10 μm dead layer, 15.4 x 15.4 mm^2)
- Low pressure (tens mbar) gas environment
- High heavy ion fluency (10^{11} ions/(cm^2/yr))

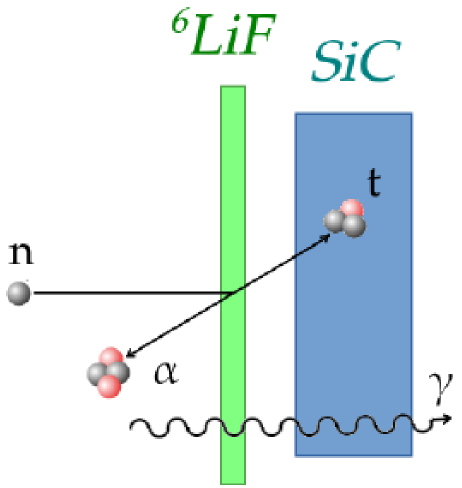


See D. Carbone talk

Requirements

- High geometrical efficiency of the wall
- Thin dead layer
- Low depletion voltage
- Thickness and charge collection uniformity within each detector
- Homogeneity among different detectors (depletion voltage, thickness, resolution)
- High radiation hardness

PSD in SiC for neutrons

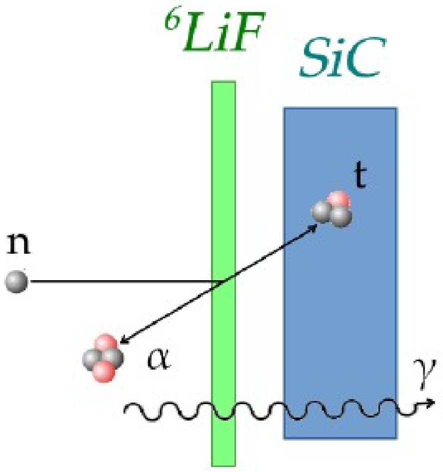


SiC+converter configuration for neutrons:
e.g. ^{6}LiF converter: n+^{6}Li→^{3}H (2.73 MeV) + ^{4}He (2.05 MeV)

γ-background → need to separate low-energy products of neutron conversion from the γ contamination

Particle identification methods can be of use:

PSD in SiC for neutrons



SiC+converter configuration for neutrons:
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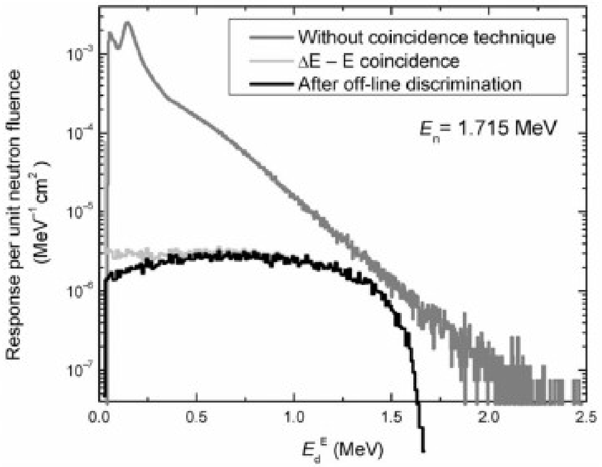
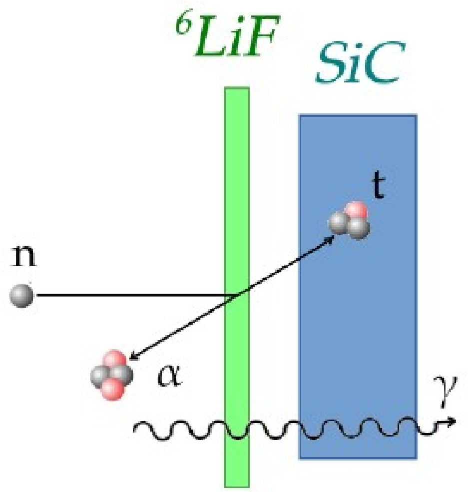
γ-background $\rightarrow$ need to separate low-energy products of neutron conversion from the γ contamination

Particle identification methods can be of use:

- **ΔE-E method**, with SiC-based monolithic telescope:
  e.g., Si monolithic tele+polyethylene
  S. Agosteo et al., Rad. Prot. Dos. 126 (2007) 210



PSD in SiC for neutrons



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- **ΔE-E method**, with SiC-based monolithic telescope:
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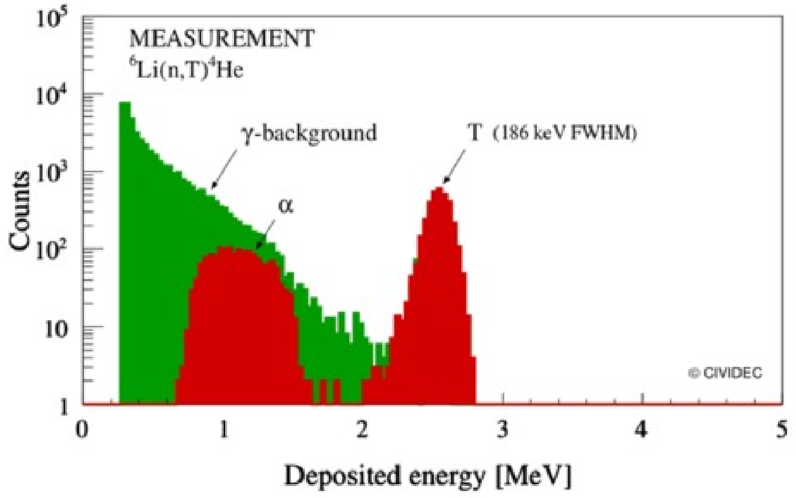
  S. Agosteo et al., Rad. Prot. Dos. 126 (2007) 210
- **PSD** e.g., with diamond det.+^{6}LiF
  (P. Kavrigin et al., Nucl. Instr. Meth. A 795 (2015) 88–91)
  or thick, reverse mounted SiC



SiC detectors: Summary Table

		Comment/ description	**Critical items for R&D**	**Expected time**
DET-SiCa0	A	thick SiC detectors	bias voltage (doping), need characterization	2024
DET-SiCa1	A	array of pixelated SiC detectors	low defect density, mech. mounting, active/dead area ratio	2024
DET-SiCa2	A	fast front-end electronics for sub-ns timing	component availability and procurement, radiation hardness	2024
DET-SiCb0	B	monolithic SiC telescope	buried electrode construction, high capacitance read-out	2025
DET-SiCb1	B	SiC neutron detector	moderation stage study and design	2025
DET-SiCb2	B	systematic study of PSD in SiC	experiment approved by PAC at LNS: need CS beams	2025

Pulse Shape Discrimination

(in semiconductor detectors)

Gabriele Pasquali

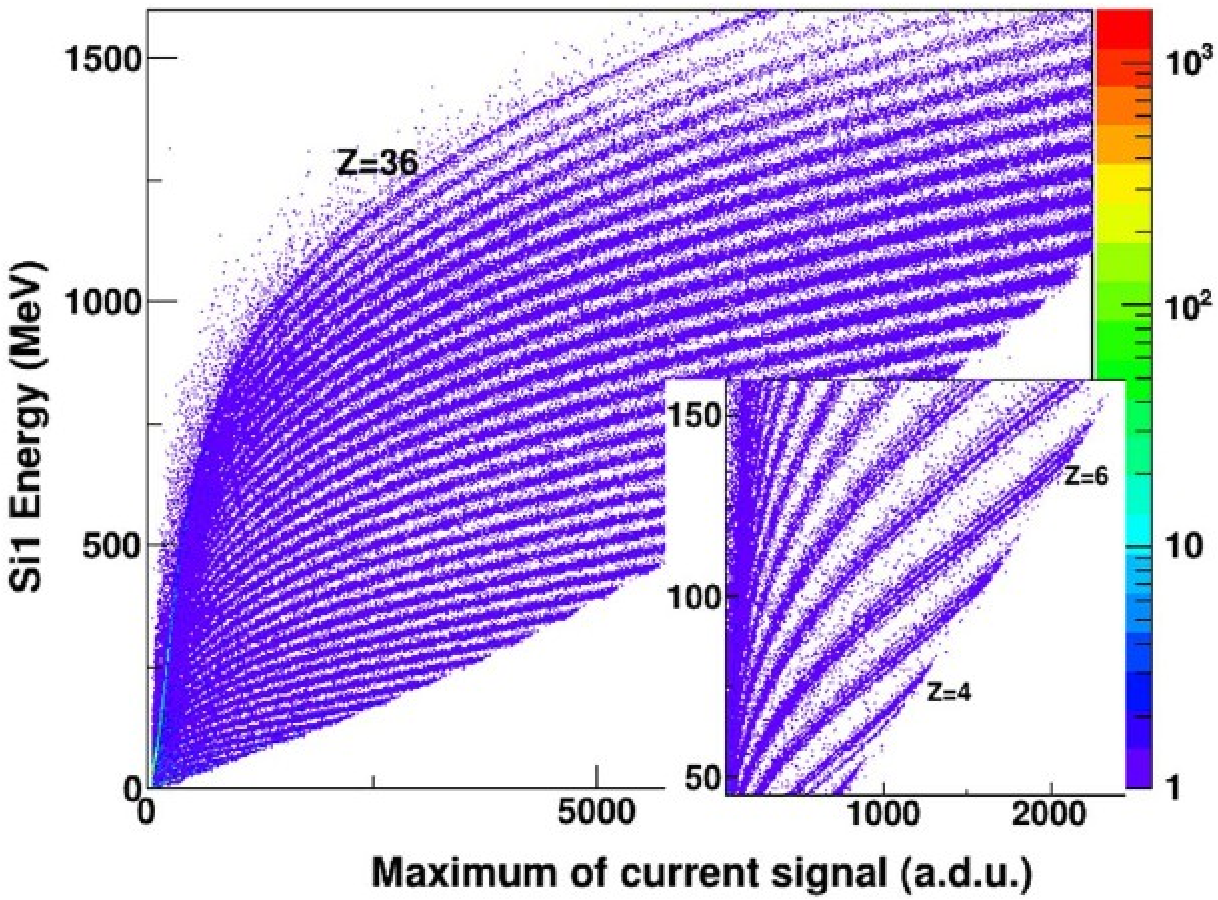
Università degli Studi di Firenze and INFN-Firenze

PSD: a remind of the basics

Pulse Shape Discrimination: particle identification from the shape (behavior in time) of the detector signal

Results of ~20 years of R&D:

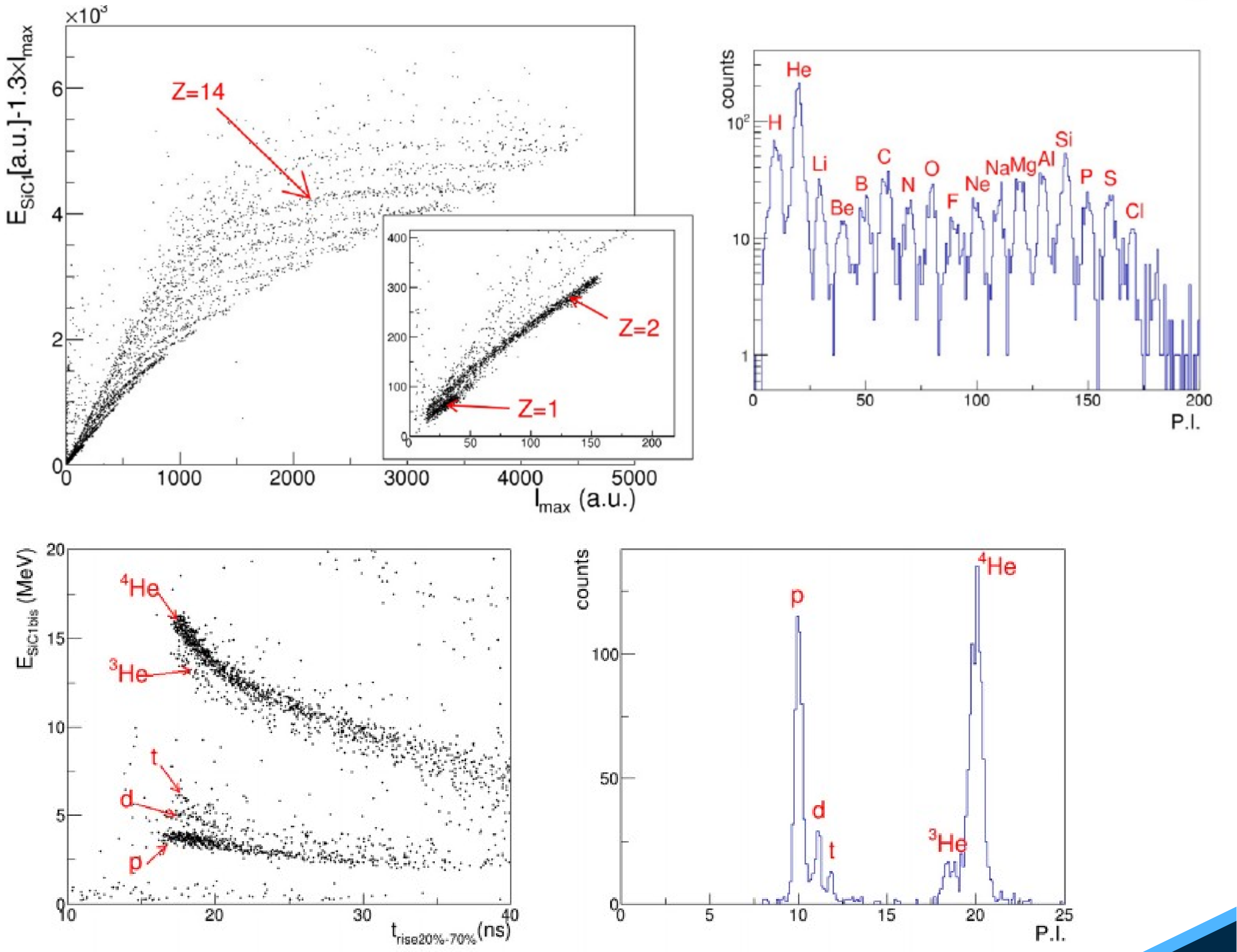
- **make fragments imping on low-field side**
- **bias the detector at ~depletion**
- **crystals cut as to minimize channeling**
- **optimize detector bulk for doping uniformity (nTD-Si, UHPS-Si)**
- **keep bias constant (in time) on junction**
- **optimize read-out chain for fidelity**



From G.Pastore et al., NIM A860 (2017) 42

PSD: performance for SiC detectors

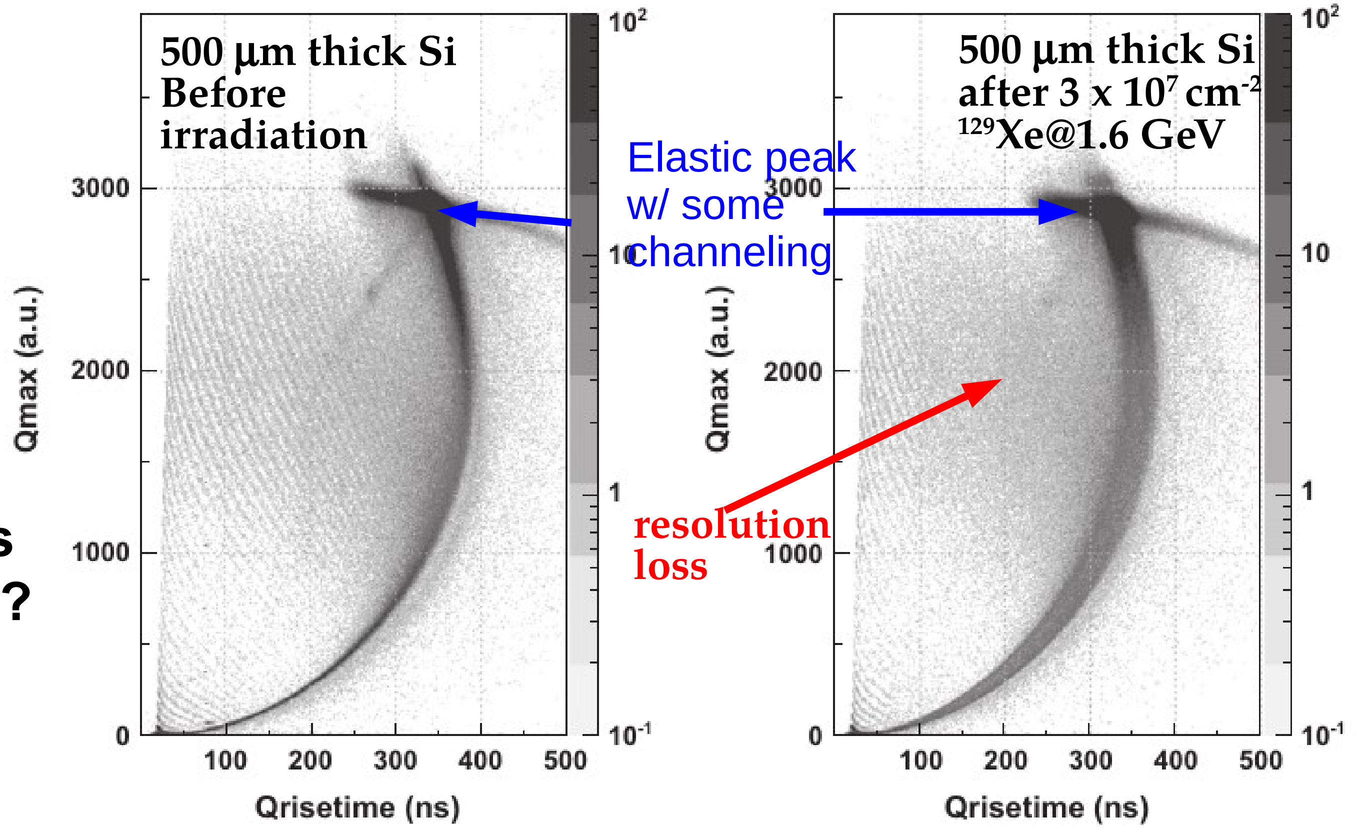
- **preliminary study of PSD in SiC performed by SiCilia (see pictures)**
- **systematic studies like those available for silicon should be performed**
- **e.g. systematic studies of best shape parameters, best bias voltages (an experiment already approved at LNS: "SICPSD")**

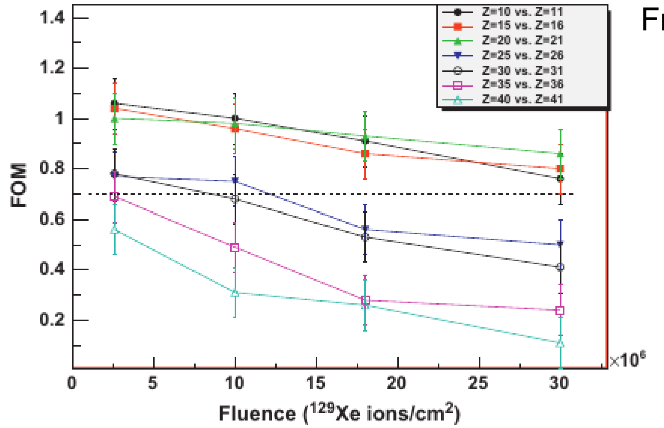


From C.Ciampi et al. NIM A925 (2019) 60

PSD: effect of radiation damage

- **a few results available for Si detectors**
- **systematic study still lacking**
- **study extension to SiC needed**
- **robustness of different shape parameters to RD: is there one better than the others?**
- **most used shape parameters:**
  - **rise-time of charge signal (this slide)**
  - **maximum of current signal (previous slides)**





From S.Barlini et al., NIM A707 (2013) 89

PSD: microscopic understanding?

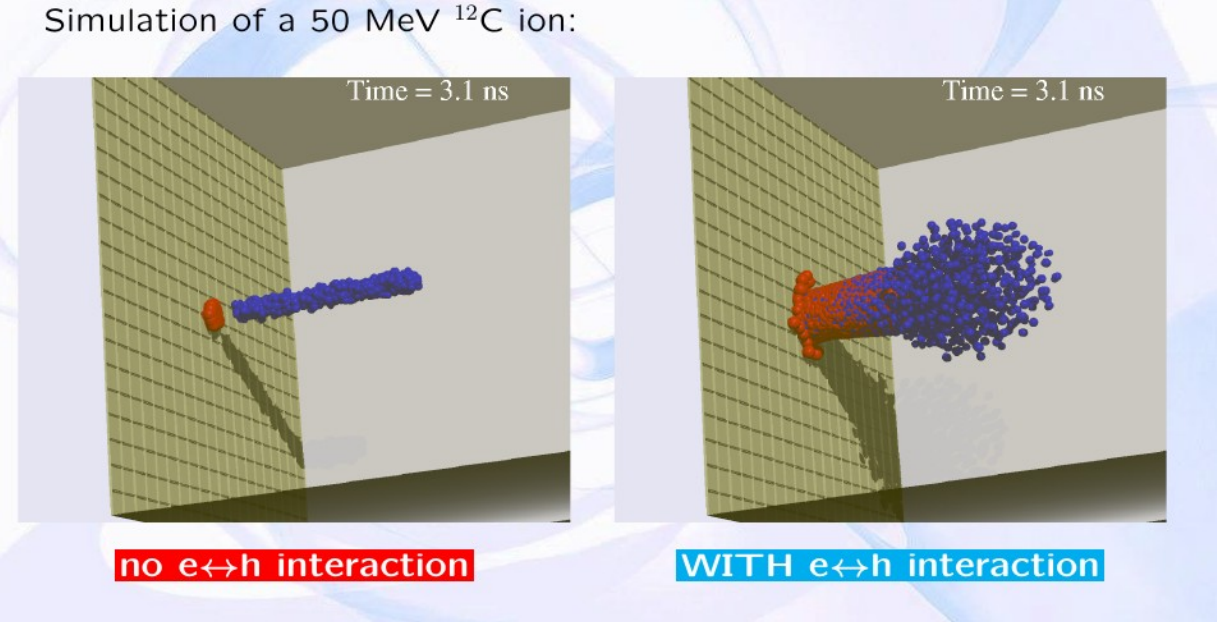
- **microscopic description needed to produce detailed signal shapes including electron-hole interactions (plasma column);**

- **a few attempts in the last decade:**
  - **M. Pârlog et al, NIM A613 (2010) 290**
  - **L.Bardelli, PhD Thesis, UniFI, 2005**
  - **Z.Sosin, NIM A693 (2012) 170; P.Kulig, EPJ Web of Conferences 66, 03049 (2014)**
  - **D.Tomasella, Master Thesis, UniPD, 2021 and LNL Annual Report 2020**

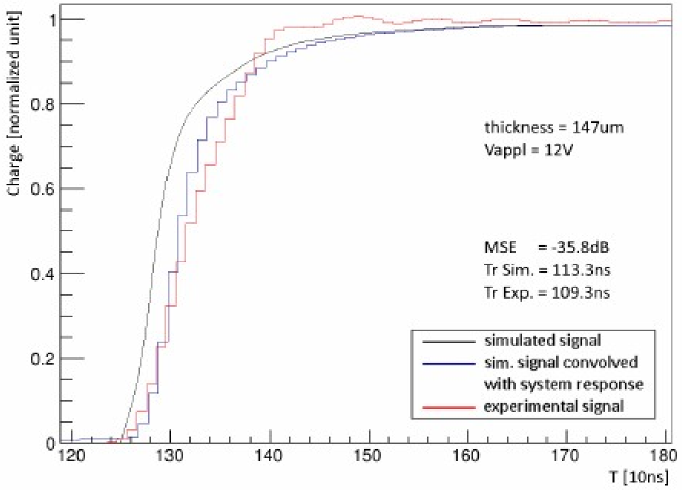
- **naïf approach to semiconductor physics**

- **include the effect of radiation damage?**

- **understand collection process for low ranges (below identification threshold)**



from R.Bougault et al., E.P.J. A (2014) 50



from D.Tomasella, Master Thesis, UniPD 20/21

PSD: combining PSD and timing

- PSD ID works for fragments ranges larger than a minimum value (depending on the fragment)
- add ToF information to lower ID thresholds (e.g. mass from E vs ToF)
- extension to new setups employing digitized signals: needs careful synchronization of all digitizing channels (see picture)
- combining ToF and shape related information (e.g. from unavoidable rise-time walk of the ARC-CFD) even Z can be retrieved (see, e.g., J.Lu et al. NIM A471 (2001) 374)

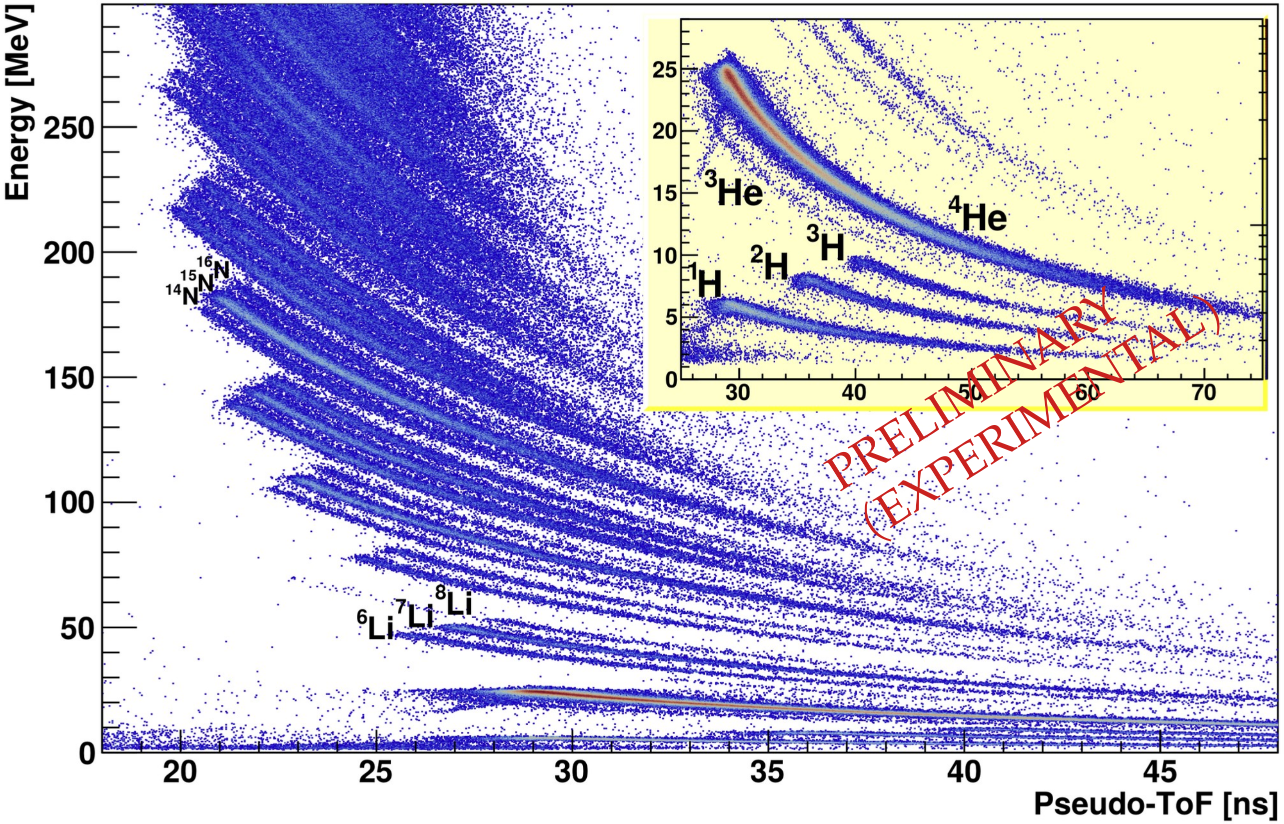


Fig.: E vs ToF correlation (all FAZIA Si1 stages).
Flight base: ~100 cm
Reaction: $^{48}Ca+^{12}C$ 25 MeV/nucleon,
S.Valdrè et al. to be published.

WG participants (Active Targets, SiC detectors, PSD)

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Elena Geraci, Giovanni Luca Guardo, Chiara Guazzoni,
Marco La Cognata, Livio Lamia, Gaetano Lanzalone, Dario Lattuada,
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Stefano Romano, Paolo Russotto, Alessandro Spatafora,
DavideTomasella, Salvo Tudisco, Aurora Tumino, Simone Valdrè

* in blue: slide contributors

BACKUP SLIDES

ΔE-E telescopes based on SiC detectors

From C.Ciampi et al. NIM A925 (2019) 60