Fundamental research and applications with the EuPRAXIA facility at LNF

Instrumentation for nuclear physics experiments: **Silicon Carbide** detectors

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On behalf of SiCILIA collaboration

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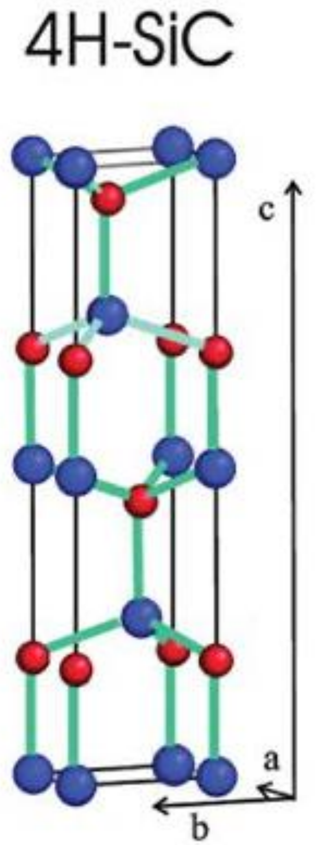
Outline

- ✓ Why Silicon Carbide for radiation detection
- ✓ INFN activity on SiC detectors: SiCILIA
- ✓ Main SiCILIA results
- ✓ Devices performance overview
- ✓ R&D of new set-up
- ✓ Perspectives for new devices

Why Silicon Carbide for radiation detection

Property	Si	Diamond	Diamond	4H SiC
Material	MCz, FZ, epi	Polycrystal	single crystal	epitaxial
E_g [eV]	1.12	5.5	5.5	3.3
$E_{breakdown}$ [V/cm]	$3\cdot10^5$	10^7	10^7	$2.2\cdot10^6$
μ_e [cm^2/Vs]	1450	1800	>1800	800
μ_h [cm^2/Vs]	450	1200	>1200	115
v_{sat} [cm/s]	$0.8\cdot10^7$	$2.2\cdot10^7$	$2.2\cdot10^7$	$2\cdot10^7$
Z	14	6	6	14/6
ε_r	11.9	5.7	5.7	9.7
e-h energy [eV]	3.6	13	13	7.6
Density [g/cm3]	2.33	3.515	3.515	3.22
Displacem. [eV]	13-20	43	43	25
e-h/µm for mips	~80	36	36	55

- **Wide band-gap** (3.3 eV)
  - ⇒ Low Leakage current
  - ⇒ Insensitivity to the electromagnetic radiation in the visible range
- **High Breakdown**
  - ⇒ Electrically robust devices
  - ⇒ Radiations hardness
- **Different e-h mobility**
  - ⇒ Charge Identification - pulse shape analysis
- **Fast devices**
  - ⇒ Timing applications
- **Higher displacement threshold**
  - ⇒ Radiation hardness more than Silicon
- **Signals amplitude**
  - ⇒ Less charge than Si, SiC≈Si/2
  - ⇒ A problem for MIP!
  - ⇒ No problem in all other case



Applications
- UV - Soft-X detection
- Charged Particle detection and identification
- Neutron detection

Rad Hard devices!

INFN R&D on SiC detectors

2017 - INFN call CSN5 - SiCILIA

Silicon **C**arbide Detectors for **I**ntense **L**uminosity **I**nvestigations and **A**pplications

SiCILIA strategy

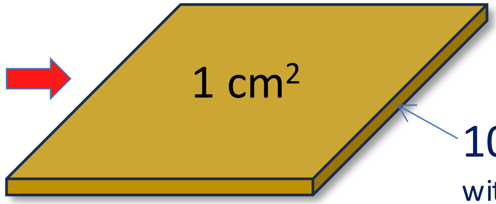
Aims

Epitaxial growth SiC beyond the state of the art (~30 µm → 100 µm)

Processing => from Schottky → **to p-n junctions**

SiC particles detectors

Goal →

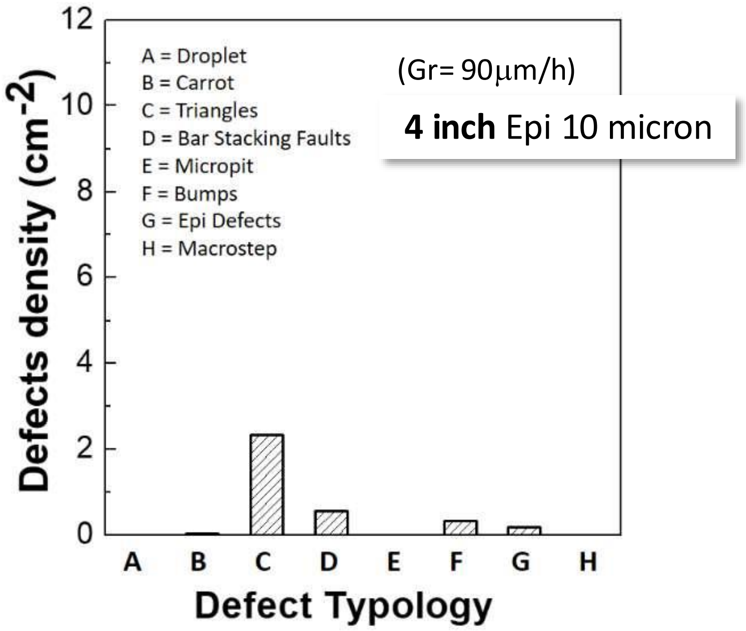


100 µm
without dead layers

SiCILIA collaboration

INFN
CNR-IMM – Catania
CNR-INO – Pisa
PSI – Switzerland
ENEA- Frascati
Fondazione Bruno Kessler (**FBK**) – Trento
ST Microelectronics – Catania
LPE – Catania (**LPE**)

SiCILIA results: Epitaxial growths



Macroscopic defects

- polytype inclusions
- micropipes
- comets, carrots

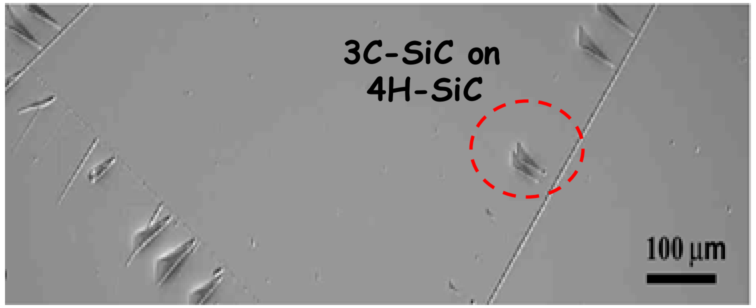
Extended defects

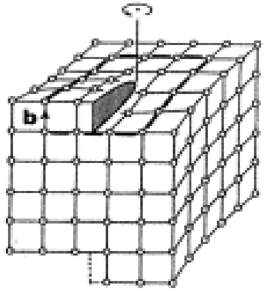
Microscopic defects

- dislocations
- stacking faults
- interstitial, vacancies
- divacancies, antisites

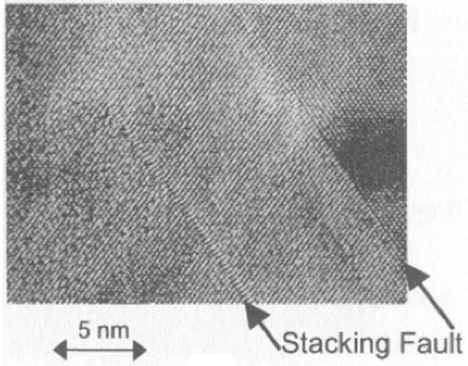
polytype inclusions

Micro-pipe

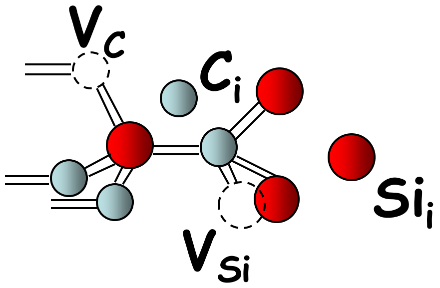




dislocations



Point and Point-like defects



Vacancies and interstitials

Donor & Acceptor Impurities

→ **Deep levels** in the gap

Charge trapping!

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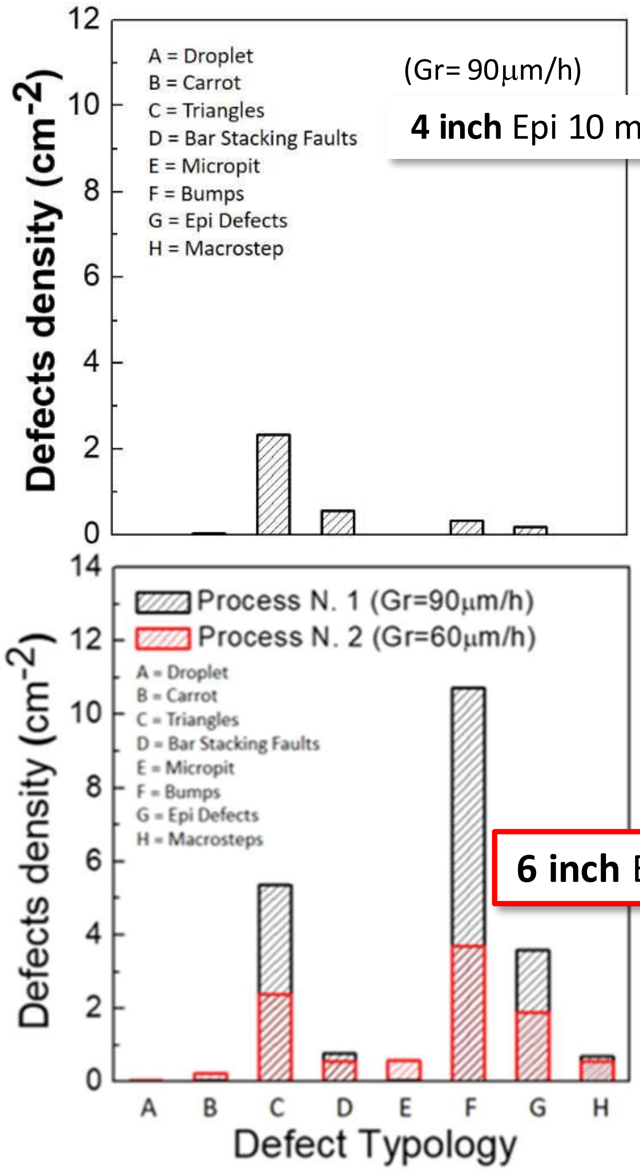
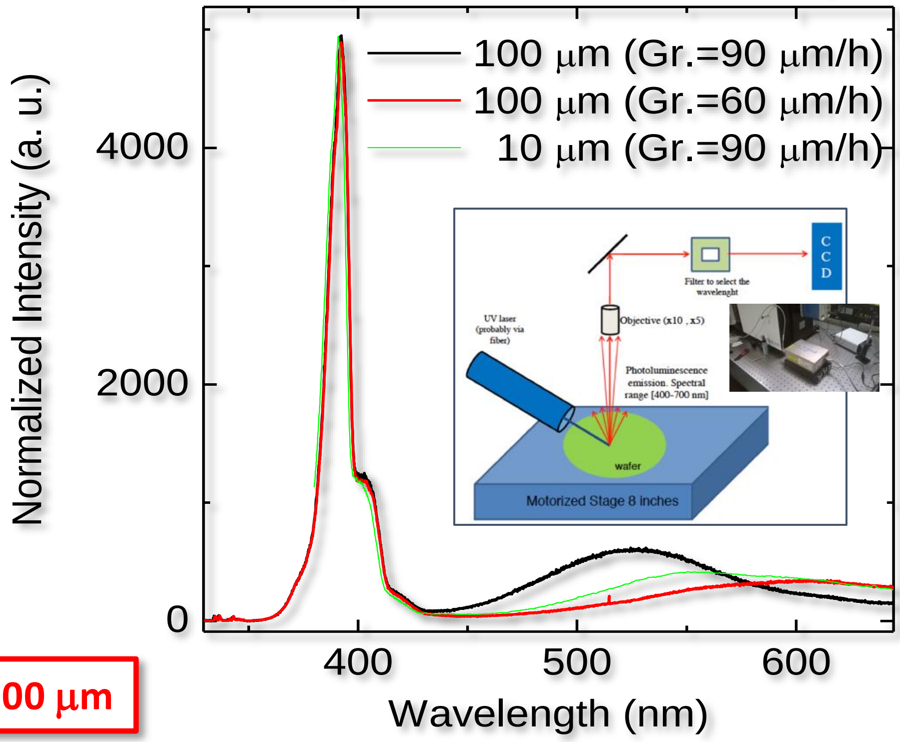
SiCILIA results: Epitaxial growths

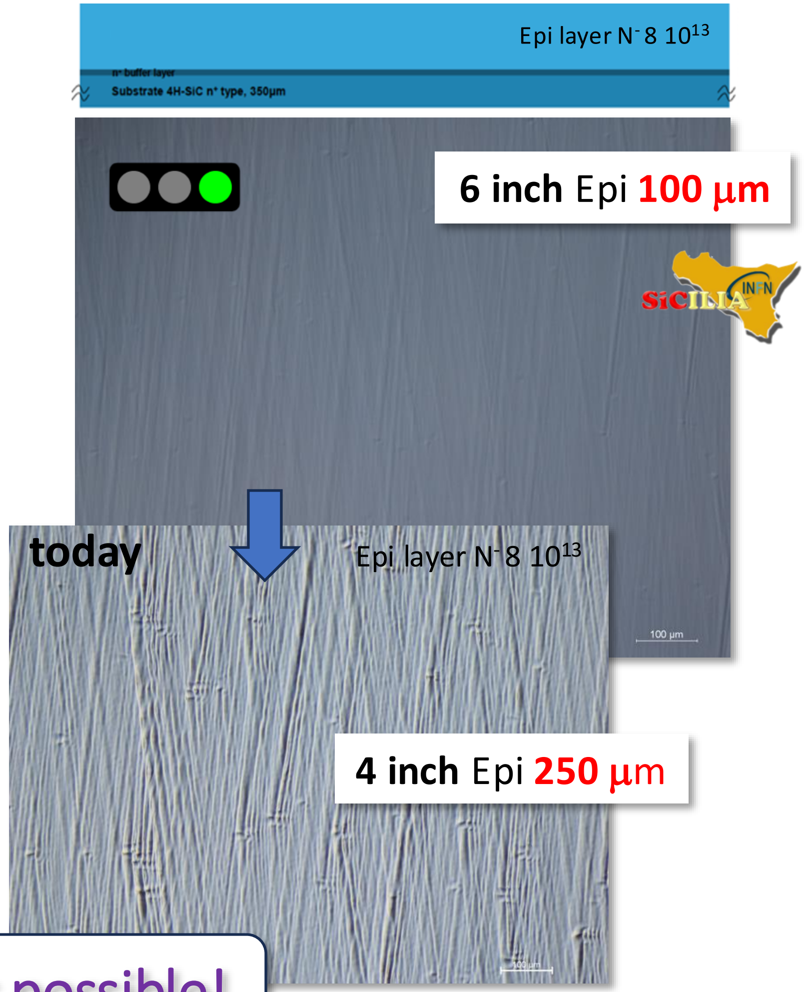


4 inch Epi 10 micron

6 inch Epi **100 μm**

Micro-photoluminescence analysis





6 inch Epi **100 μm**

4 inch Epi **250 μm**

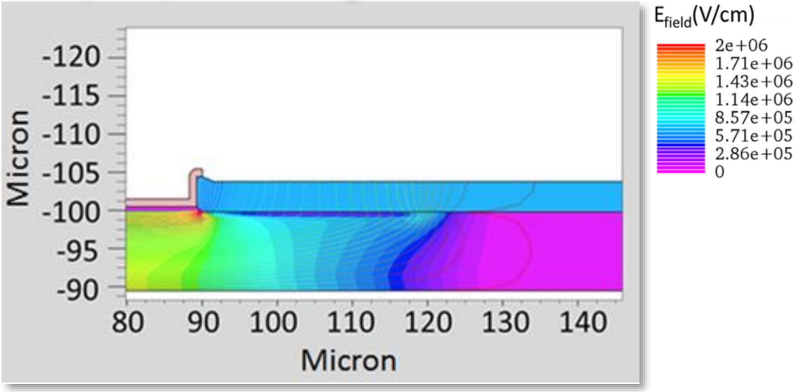
Epi 100 μm => 300 μm is possible!

SiCILIA results: Processing

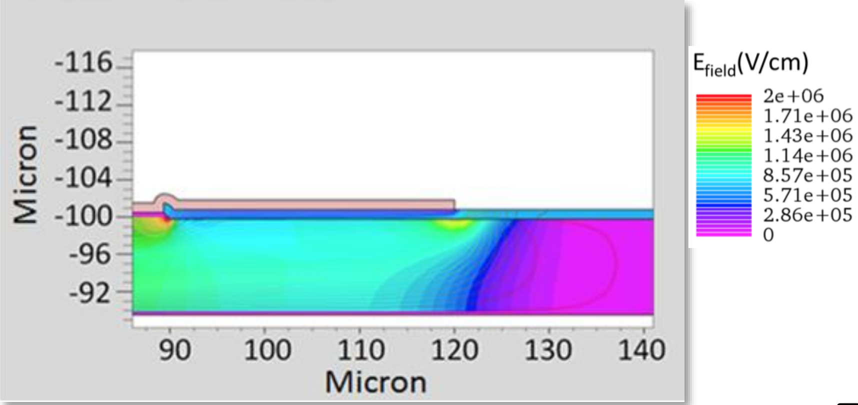
p-n diodes

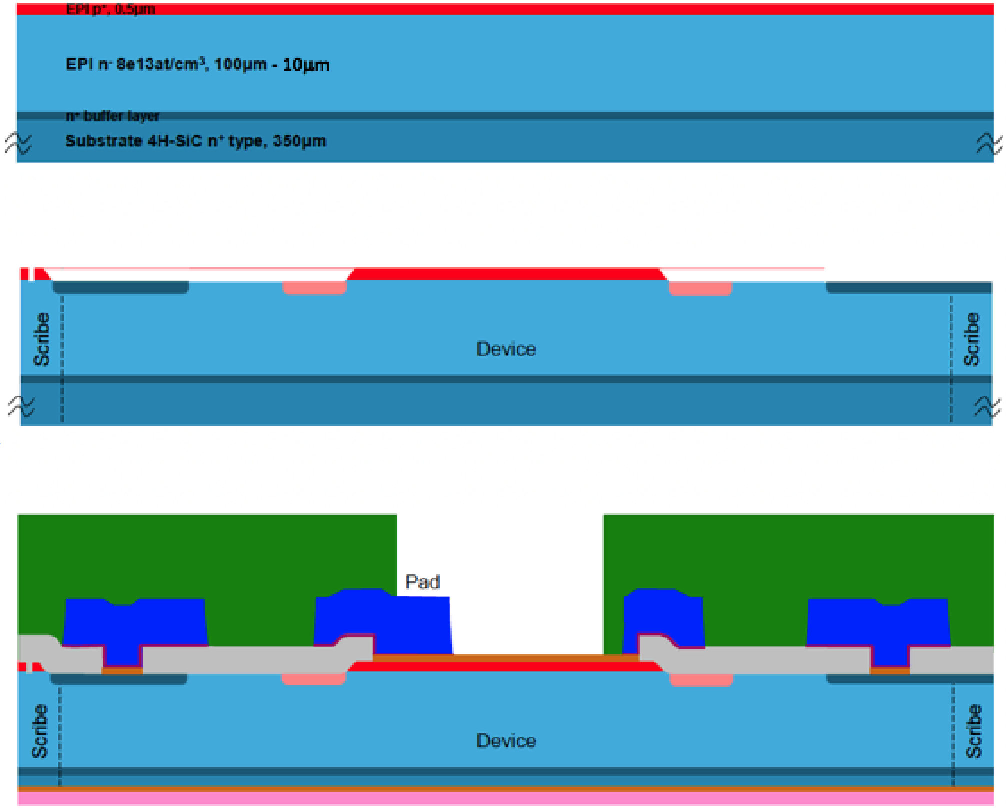
Breakdown
≥ 1.5 kV

JTE p- implanted ring



Metal Field Plate



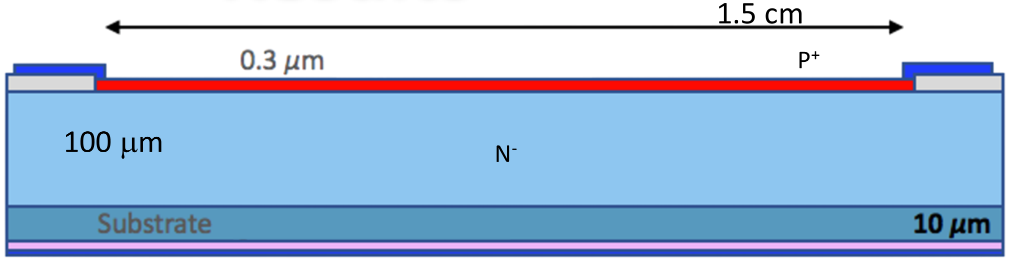


Mechanical Substrate Thinning (~10 µm)

Effecincy 30%

Results

New p-n junction devices

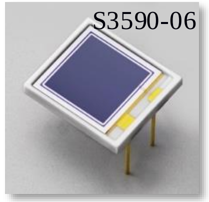


Large area
1.5x1.5 cm²

Performance overview: Energy Resolution

p-n$_{diodes}$

Hamamatzu

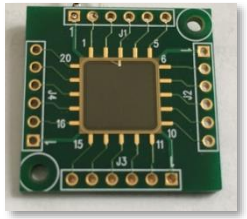


300 um

Si % **SiC**

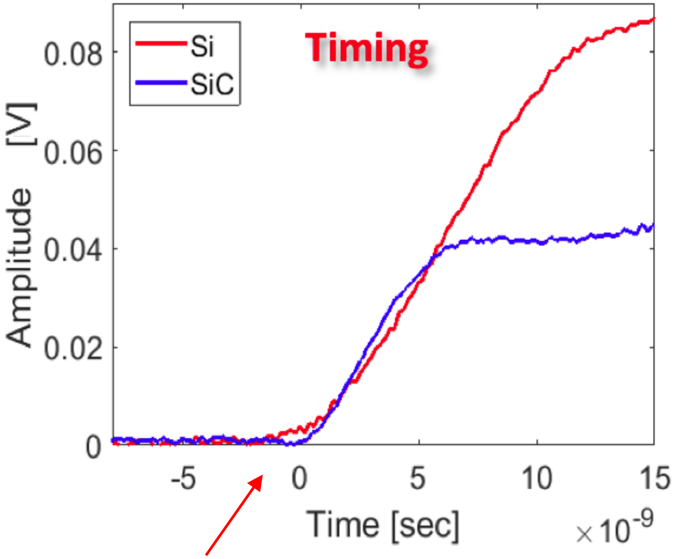
1x1 cm^2

100 um

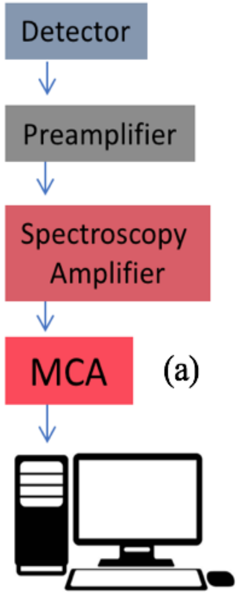


p-n diode

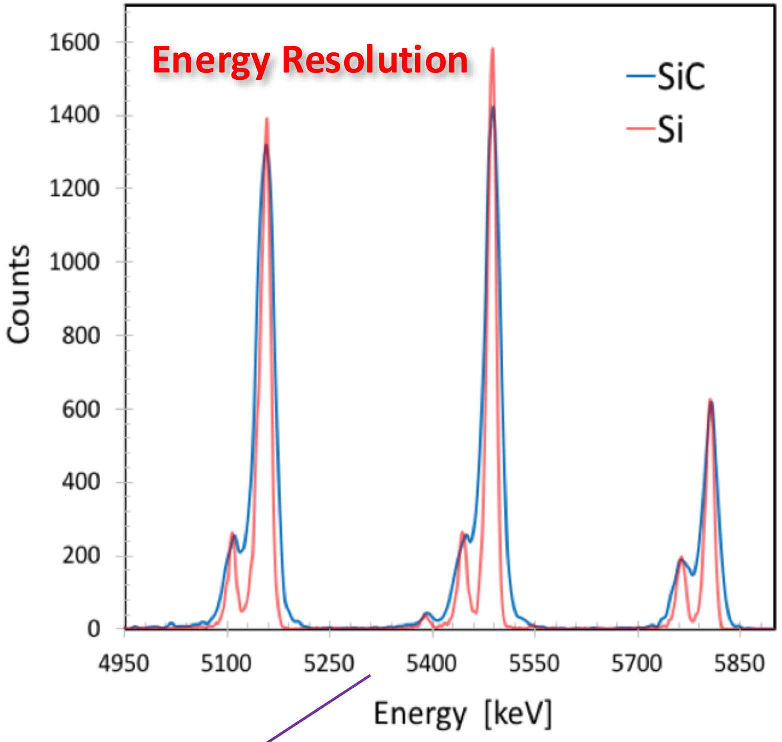
Test with radioactive ^{241}**Am Alpha** source



SiC ~ Preamp limit!



Test with radioactive ^{241}**Am Alpha** source



SiC → $FWHM_{exp}$ = 42.8 keV (0.4%)

Si → $FWHM_{exp}$ = 21.4 keV (0.22%)

$$FWHM^2_{exp} = FWHM^2_{det} + FWHM^2_{Ele}$$

Electronic Noise

Si=7.3 keV

SiC=10.3 keV

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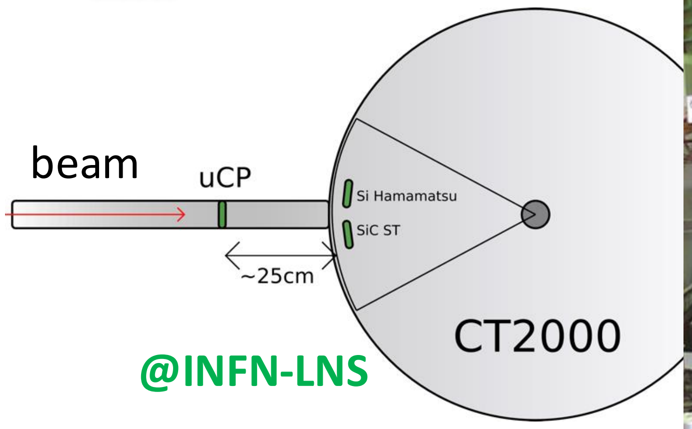
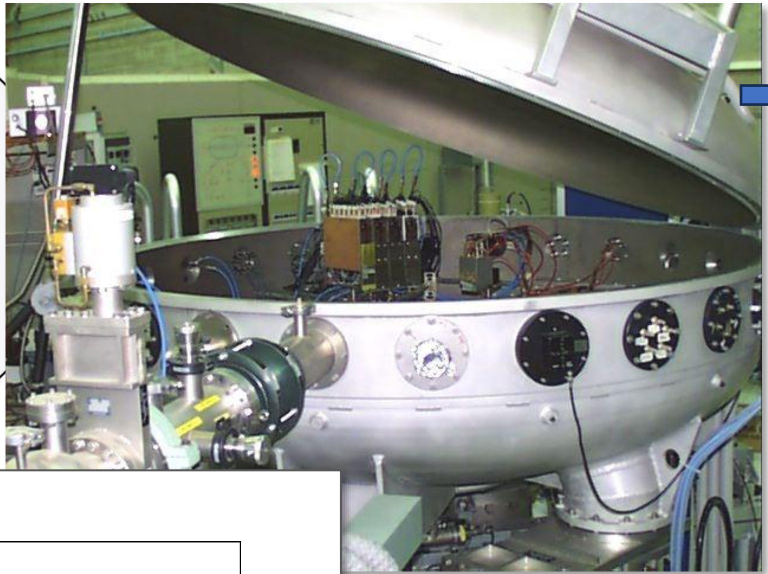
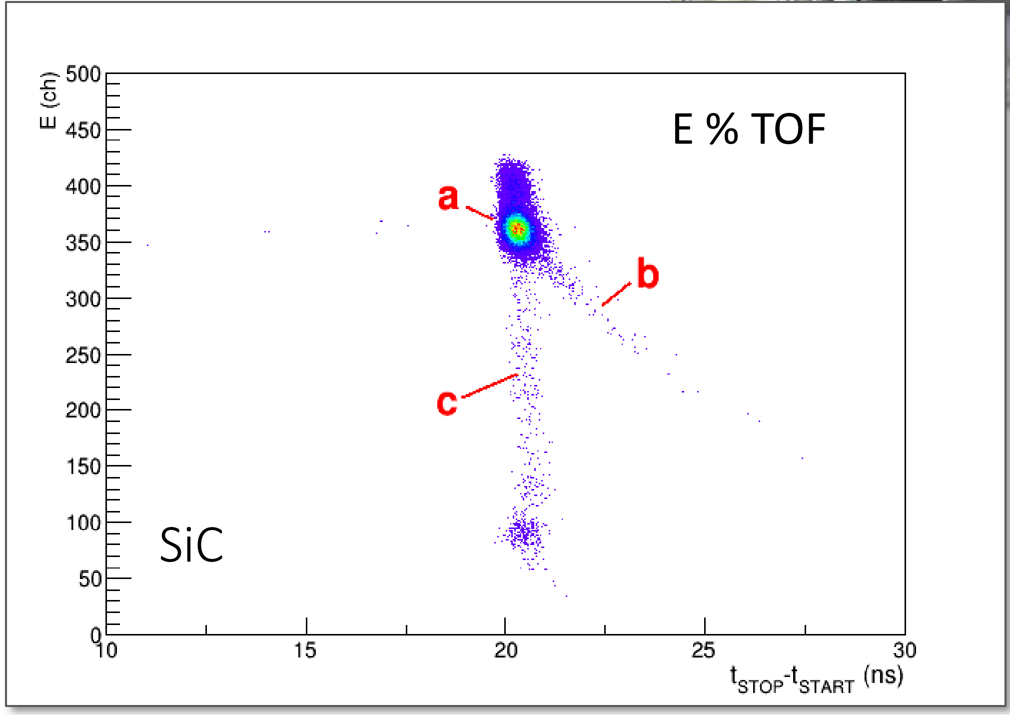
Performance overview: SiC-Timing

p-n diodes





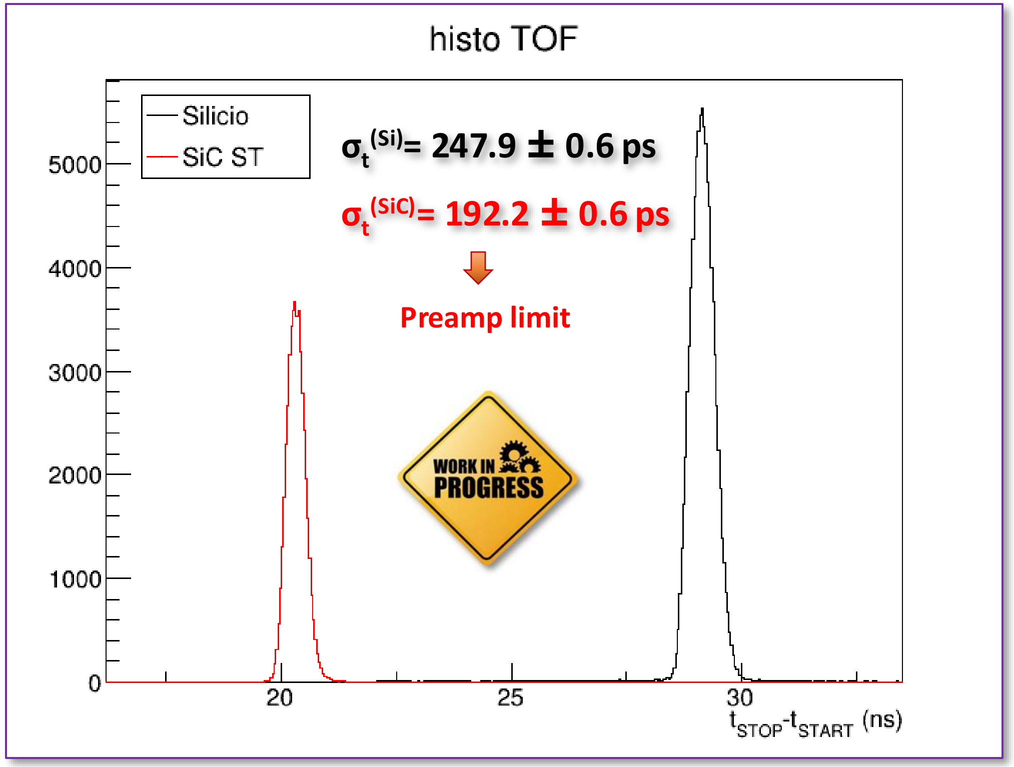
- Beam ^{58}Ni @ 60MeV, 70MeV
- Digitazer CAEN DT5751
- START: **µCP**, STOP: Si Hamamatsu o SiC STM



a: good events

b: **µCP-**wires contribution

c: SiC edge effects SiC



New beam test are in preparation

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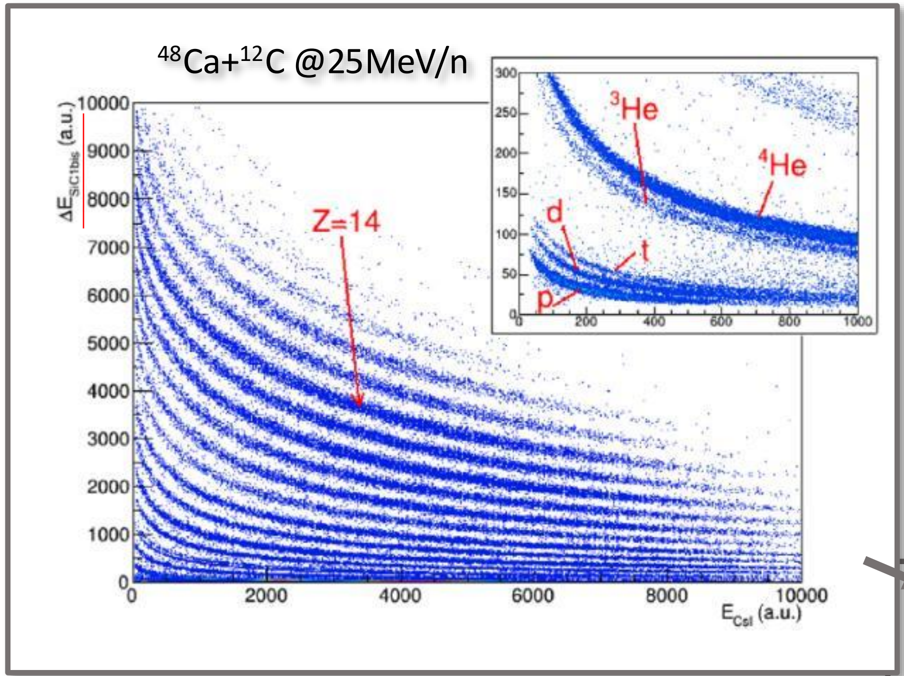
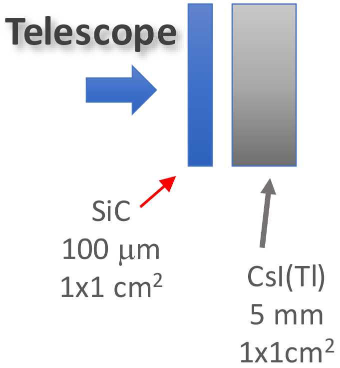
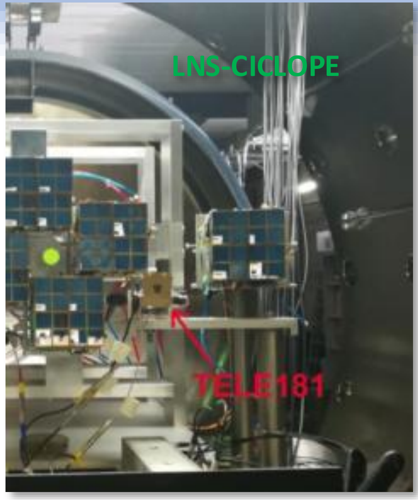
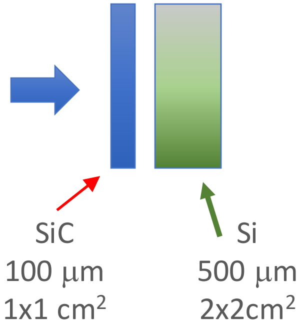
Performance overview : particles identification









Isotopes	FoM	Elements	FoM	Elements	FoM
p-d	1.4	B-C	1.9	Na-Mg	1.6
d-t	1.1	C-N	1.9	Mg-Al	1.5
^{7}Be-^{9}Be	0.7	N-O	1.9	Al-Si	1.5
		O-F	1.8	Si-P	1.6
		F-Ne	1.6	P-S	1.5
		Ne-Na	1.6	S-Cl	1.6

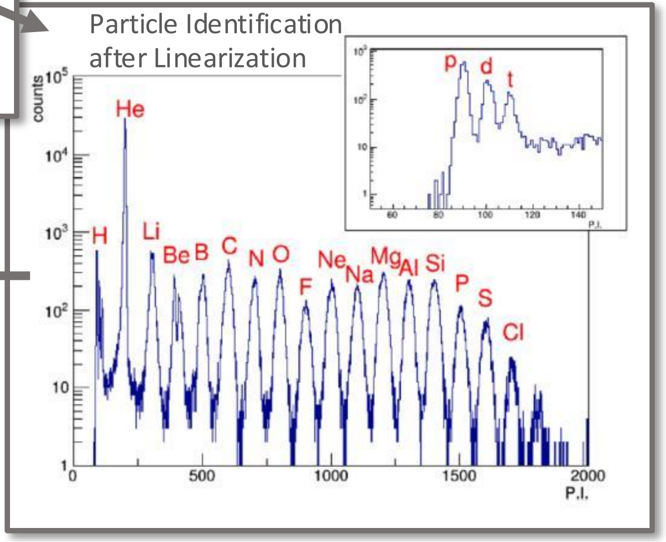
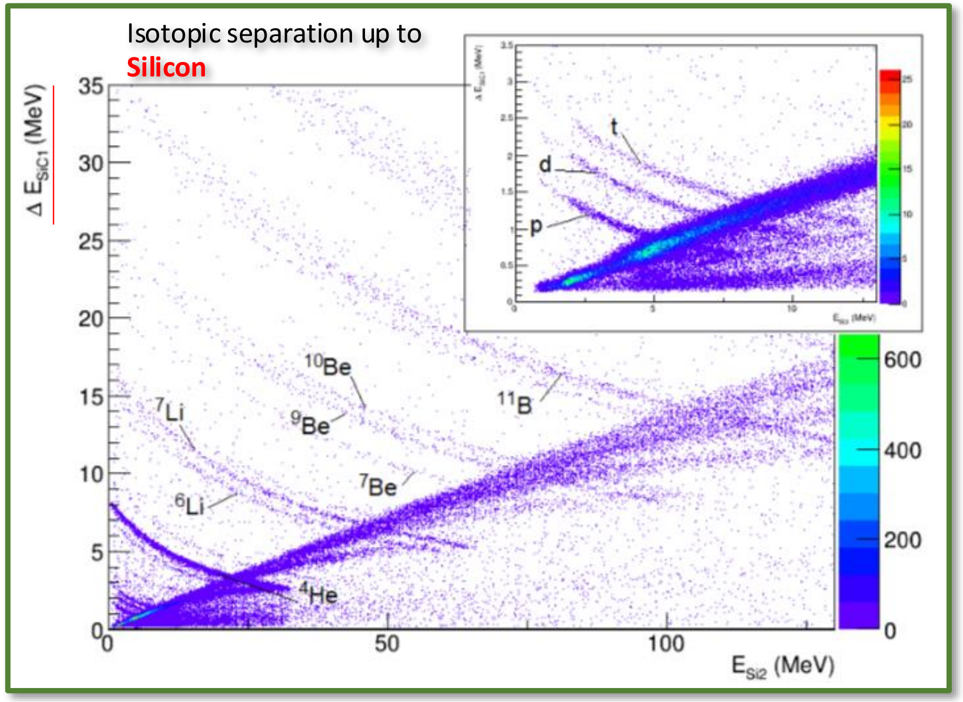


Figure of Merit: $FoM = \frac{|PI_2 - PI_1|}{(FWHM_2 + FWHM_1)}$

good separation if $FoM > 0.7$



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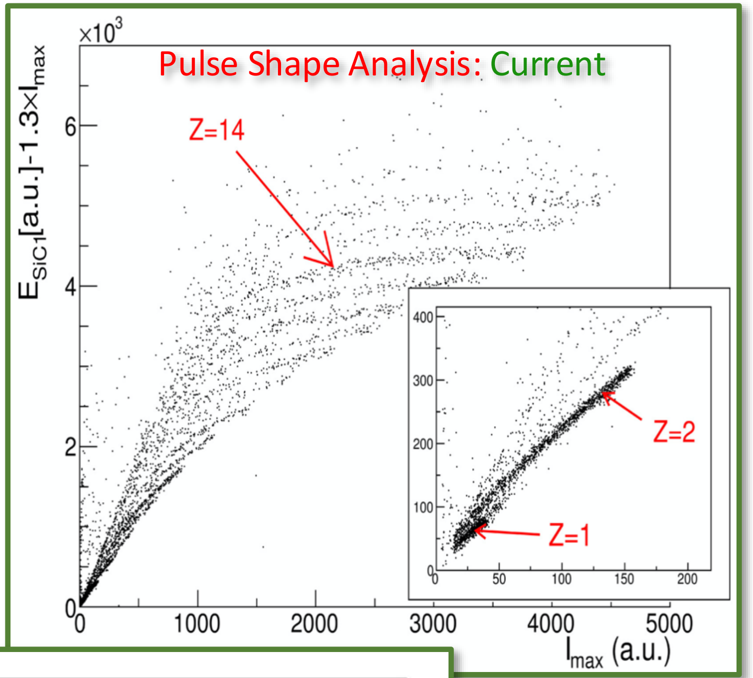
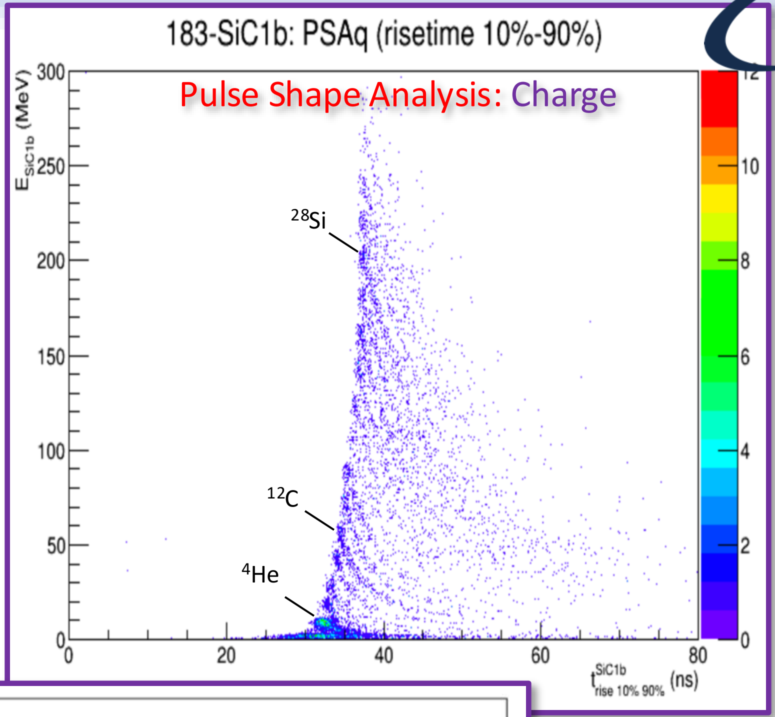
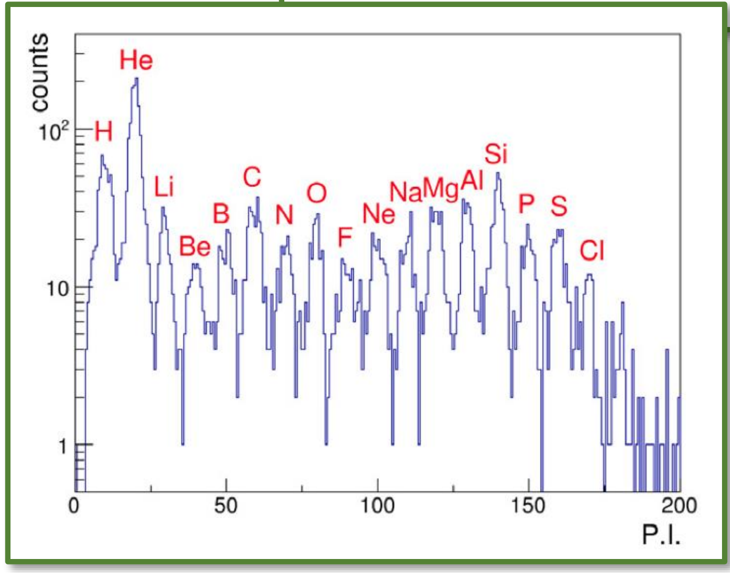
Performance overview : particles identification

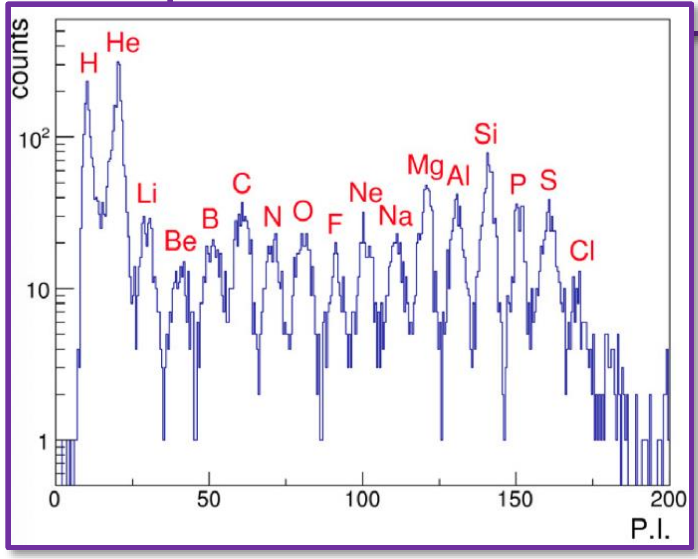


Pulse Shape Analysis





Pair	FoM	Pair	FoM
H-He	5.1	F-Ne	1.0
He-Li	3.1	Ne-Na	1.2
Li-Be	1.7	Na-Mg	1.2
Be-B	1.4	Mg-Al	1.2
B-C	1.3	Al-Si	1.3
C-N	1.3	Si-P	1.4
N-O	1.4	P-S	1.2
O-F	1.1		



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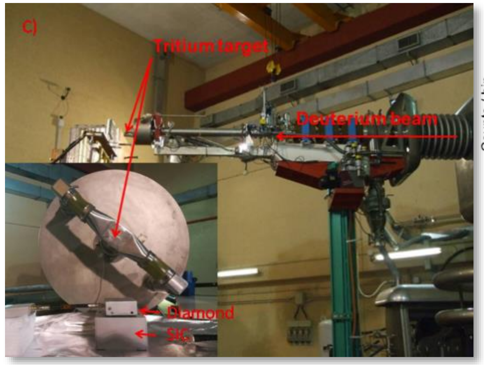
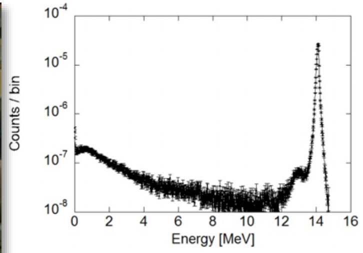
Performance overview : Neutrons detections

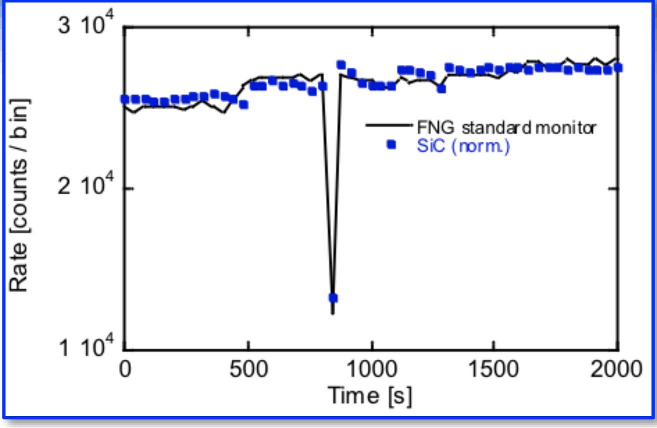
p-n diodes

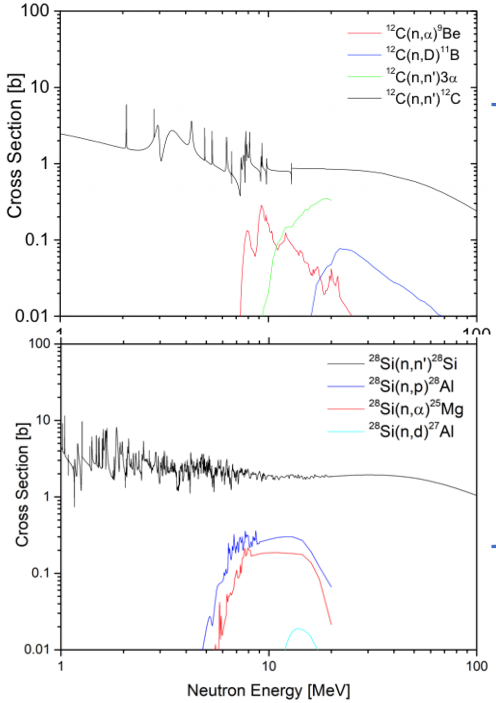




FNG ENEA - Frascati

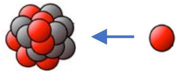
SiC neutron Beam Monitor



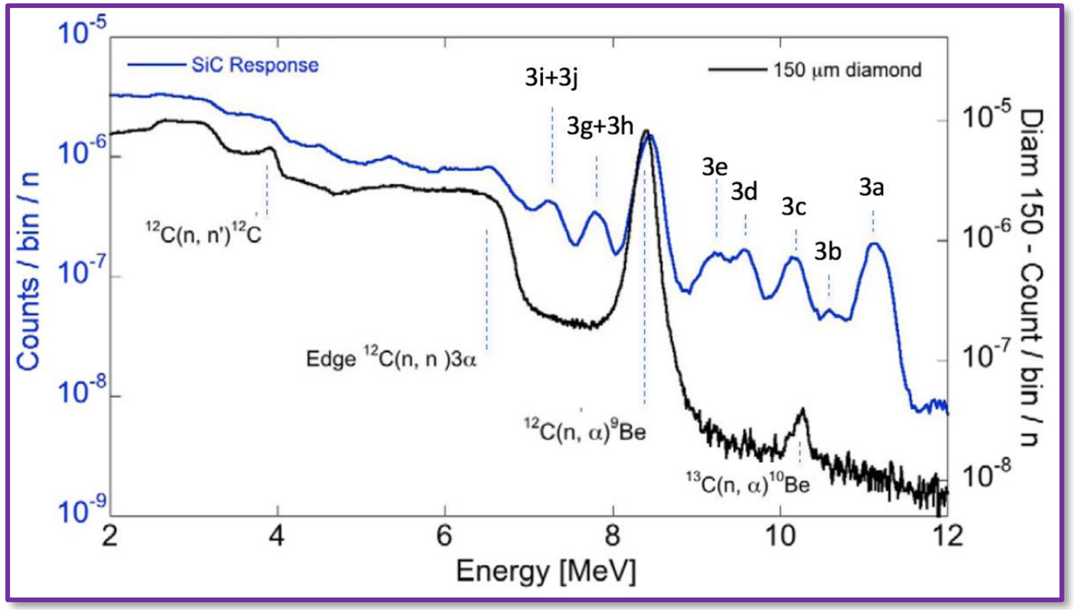


Energy deposition

n + ^{12}C



n + ^{28}Si



Absence of instabilities for 14 MeV neutron up to **$5*10^{11}$ n/cm²**

Efficiency

Detector	Atomic/molecular density [cm^{-3}]	Efficiency measured for E_d> 1.2 MeV [and normalized per atom]	Efficiency measured in the $^{12}C(n, \alpha)^9Be$ peak
SCD 150 μm	$1.76*10^{23}$	$(1.59 \pm 0.25)*10^{-3}$ [$2.97*10^{-24}$]	$(0.91 \pm 0.15)* 10^{-4}$
SiC 100 μm	$4.8*10^{22}$	$(5.69 \pm 0.78)*10^{-4}$ [$4.74*10^{-24}$]	$(2.02 \pm 0.30)*10^{-5}$

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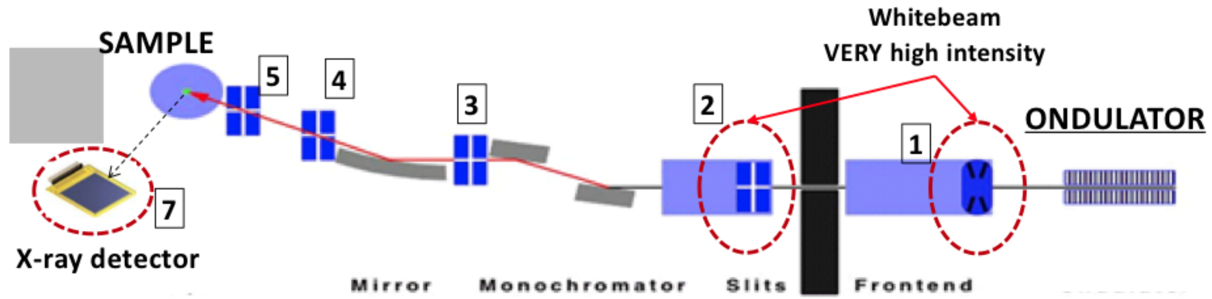
Performance overview : X-Ray detection

p-n diodes



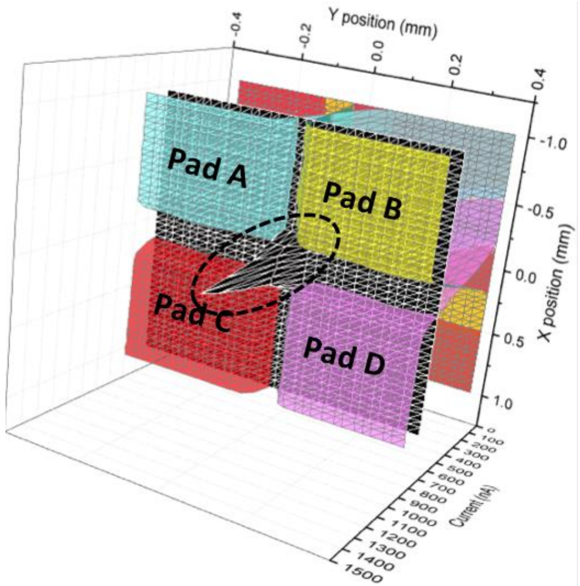
Beam Position Monitor (XBPM)
1,2,3,4,5

- Transparency
- Extreme radiation hardness
- Fast response

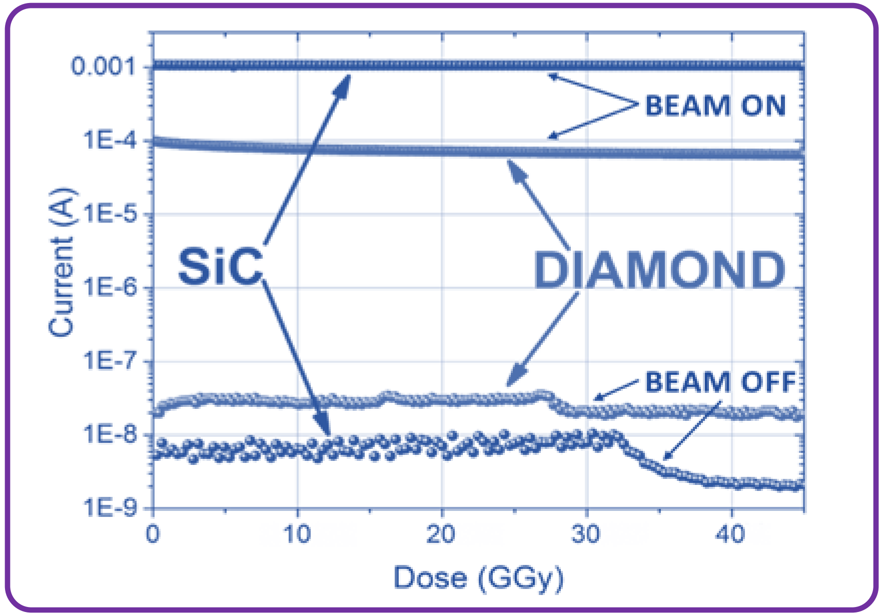
Synchrotrons radiation

X-ray beam 10x10 µm², 5E10 ph/sec @ 12.4keV

SiC 100 µm



Radiation hardness



Radiation Hardness

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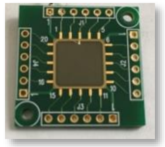
Performance overview : Beam Monitoring

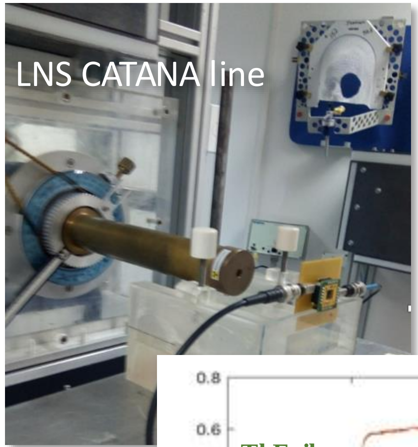
p-n diodes

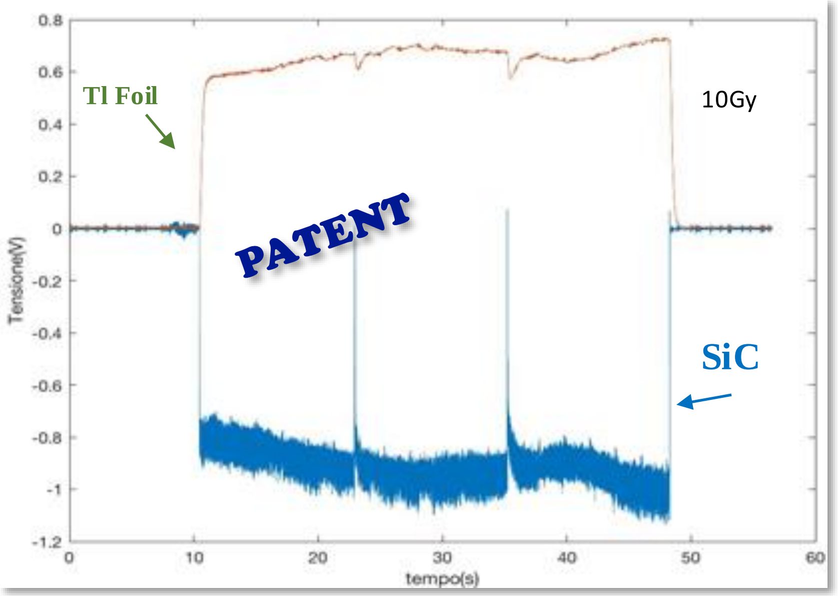
Protons beam

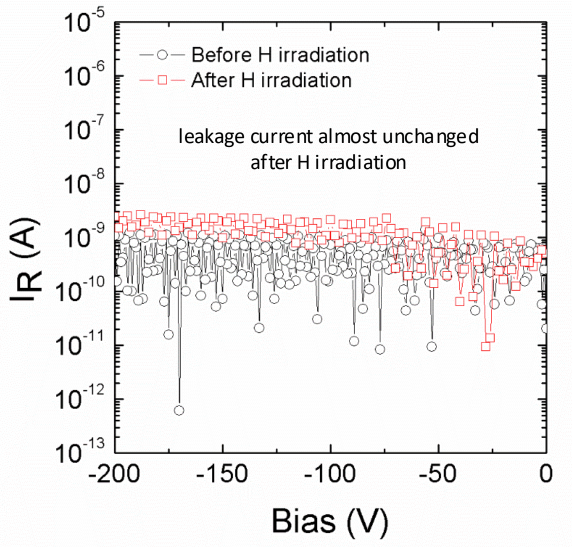
irradiation → 60 MeV H^+ → SiC 10μm 1x1 cm^2

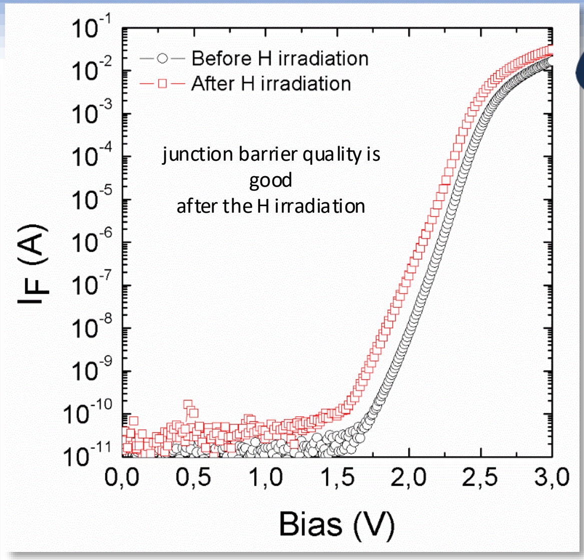


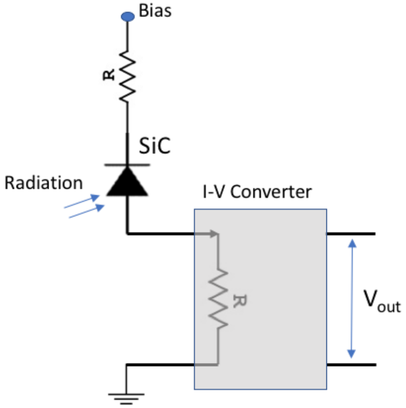
5 x 10^{13} H^+/cm^2 3 kGy





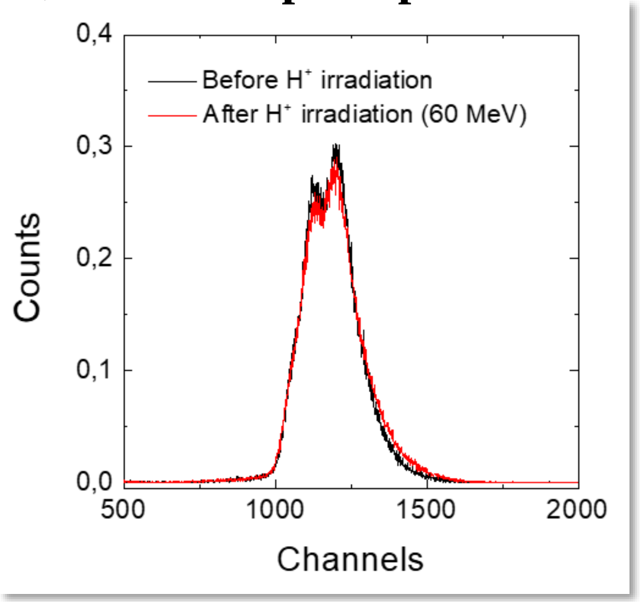






Beam Monitor and dosimetry applications

^{241}Am Alpha Spectrum



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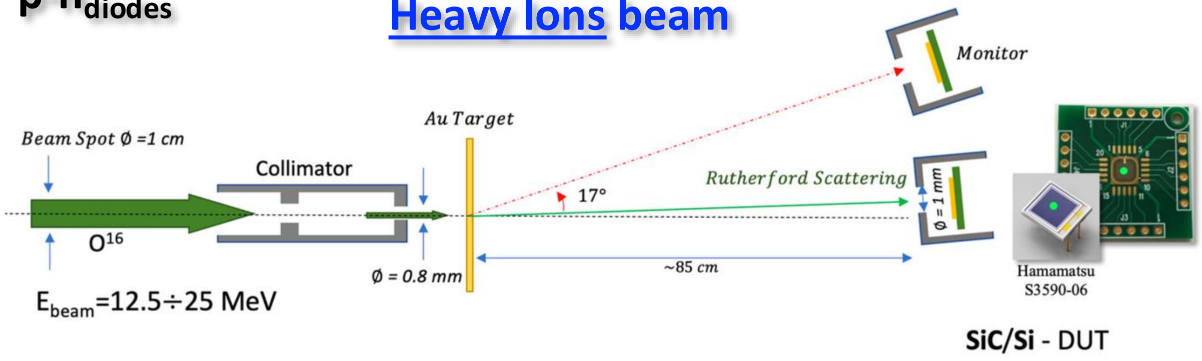
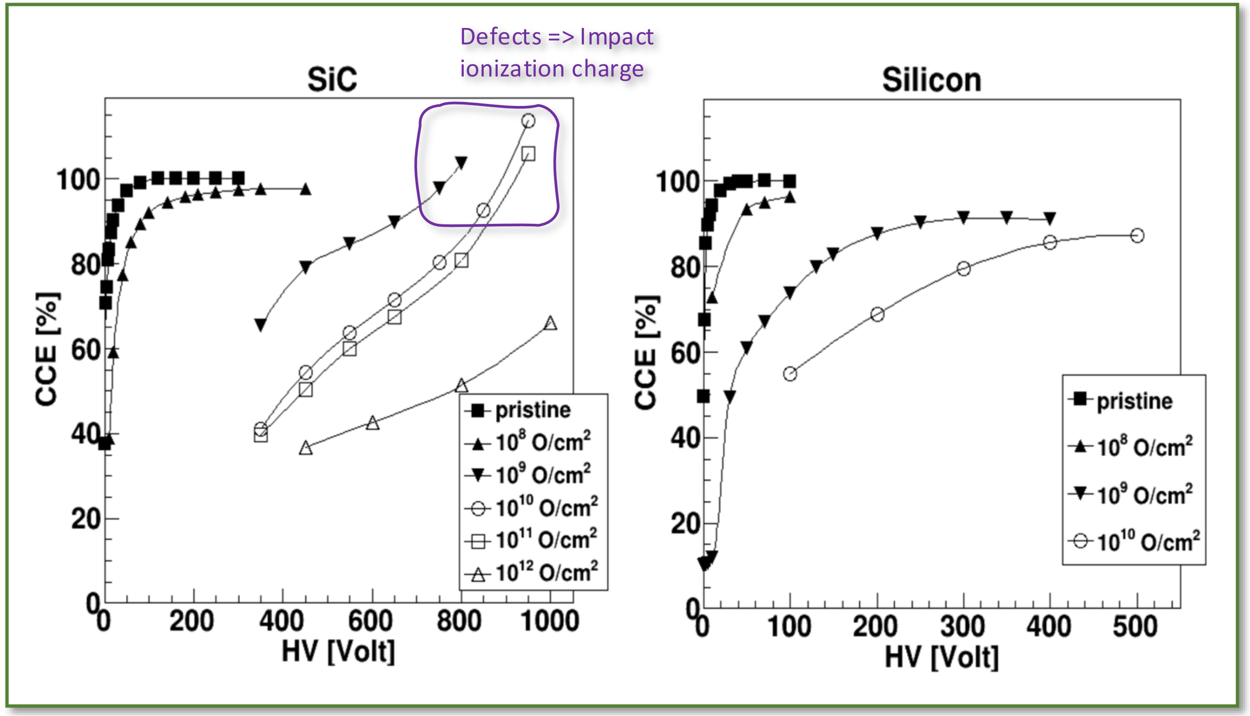
Performance overview: Radiation Hardness

p-n$_{diodes}$

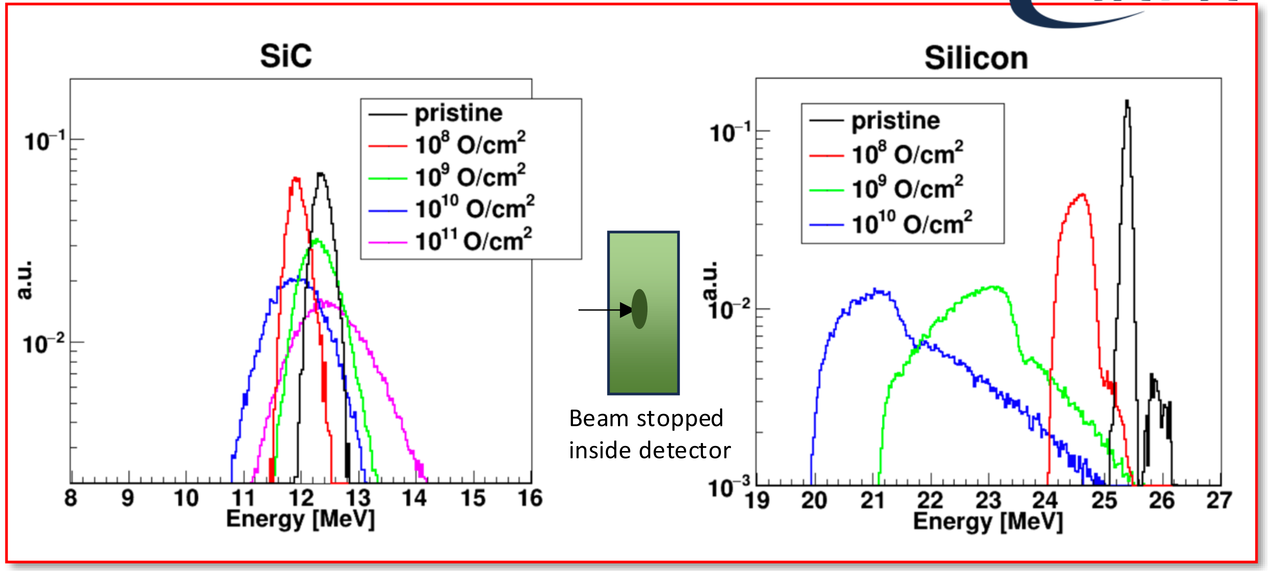
Heavy Ions beam



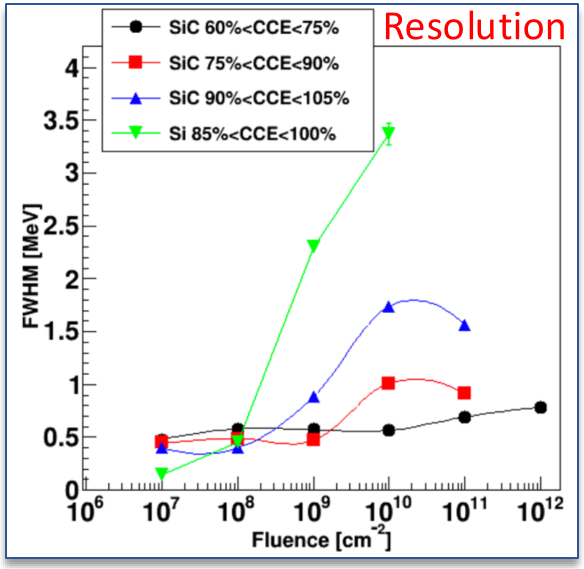
Charge Collection Efficiency

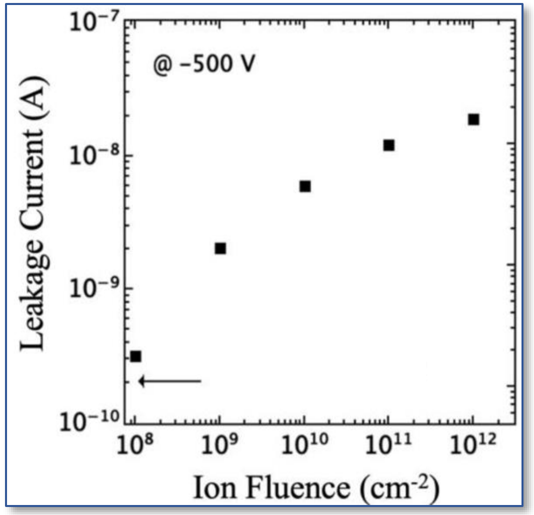


Energy spectra



Resolution





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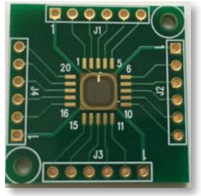
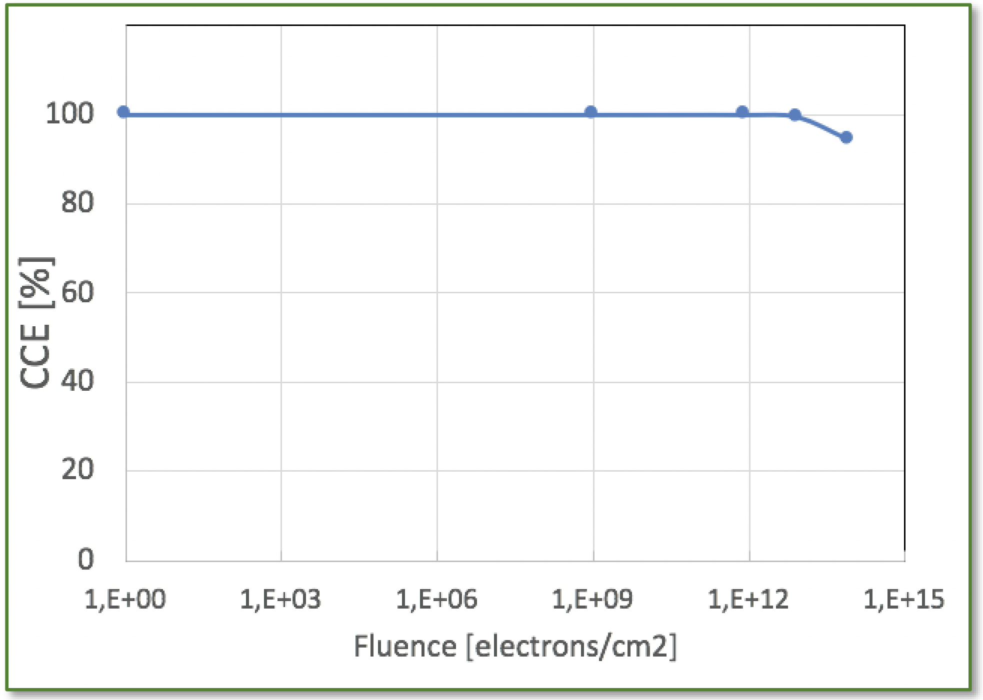
Performance overview : Radiation Hardness

p-n diodes

electrons beam

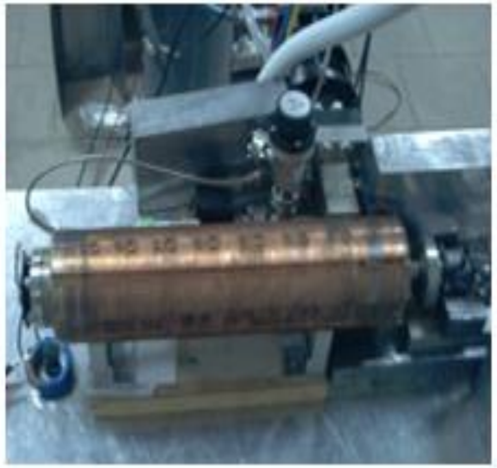




LINAC @ UniMe

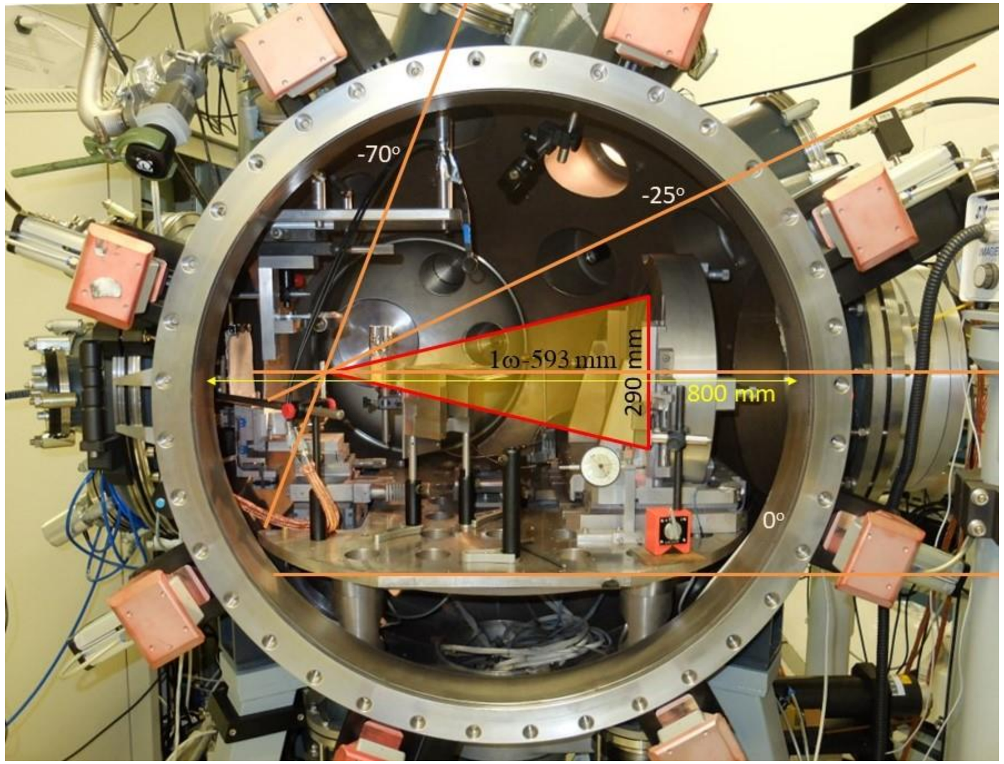
Electrons irradiation

- Energy 5 MeV
- Current 1-200 mA
- Rep. Rate 1-300 Hz
- Pulse duration 3 µsec

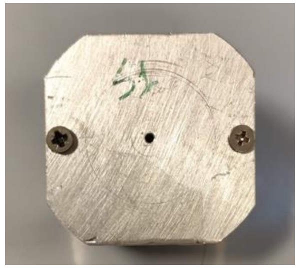


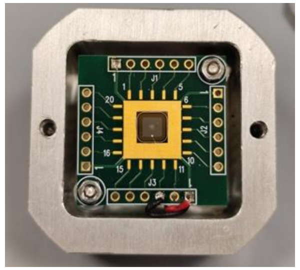
Electrons Beam Monitor

Performance overview : ToF mesurements on Laser facility

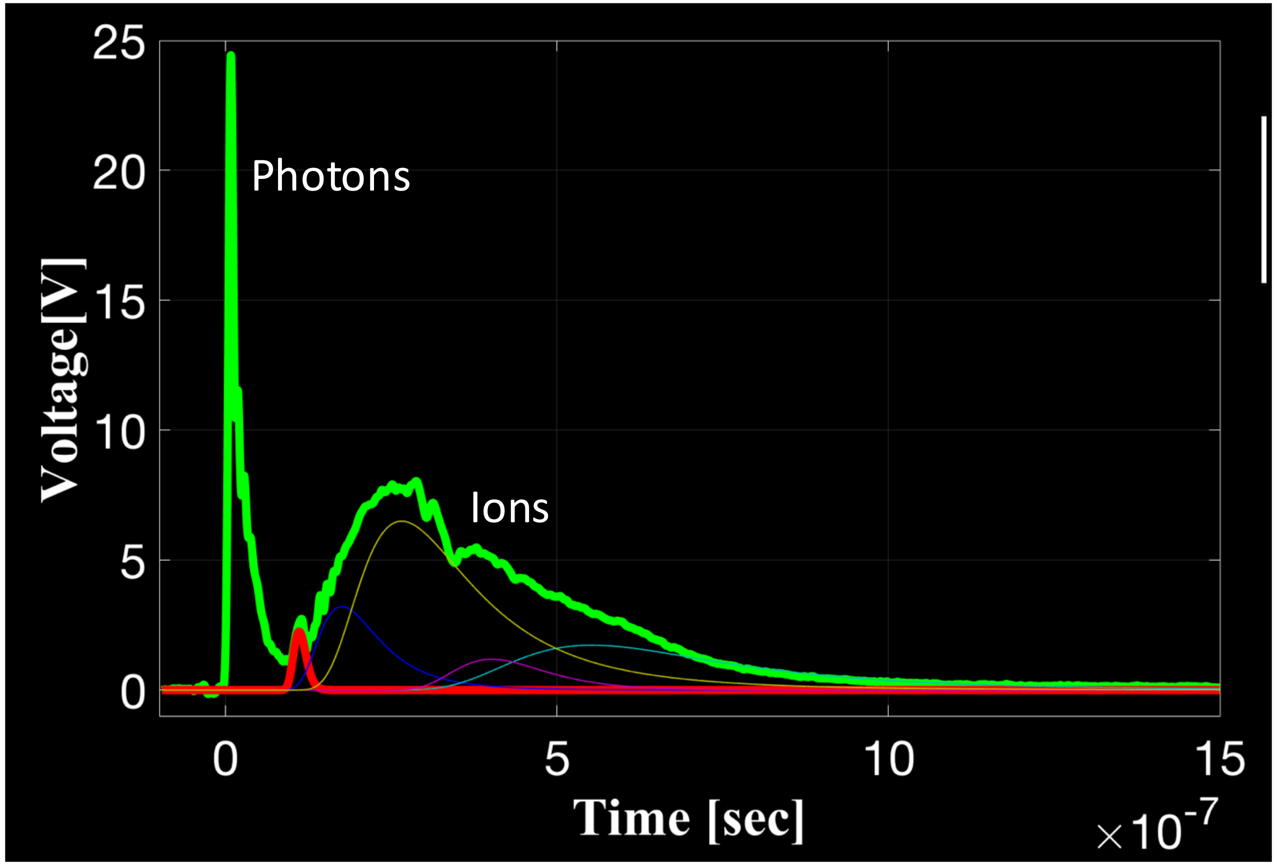


PALS facility (Prague, CZ)





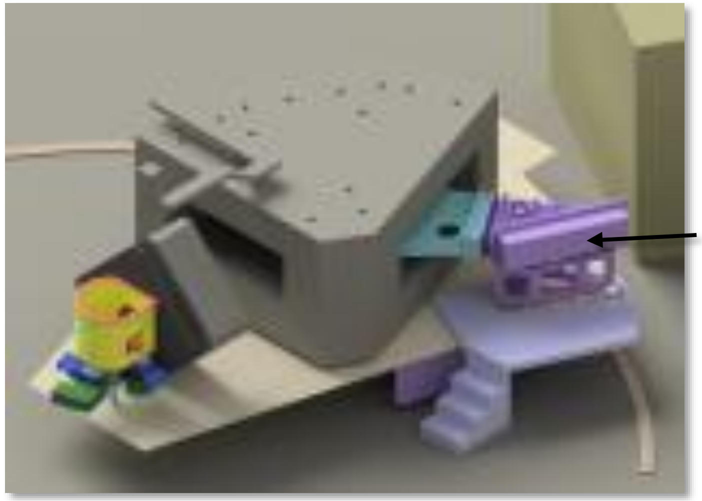
ToF - Spectrum



New set-up: NUMEM @ INFN-LNS

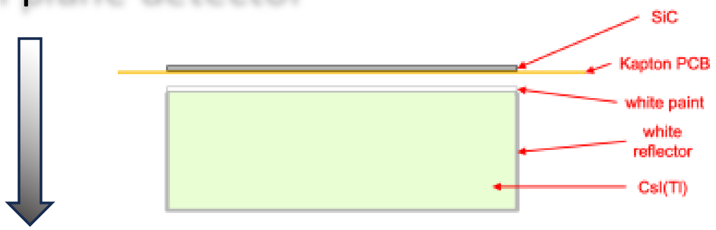
NUclear **M**atrix **E**lements of **N**eutrinoless Double Beta Decays by Heavy Ion **D**ouble **C**harge **E**xchange Reactions

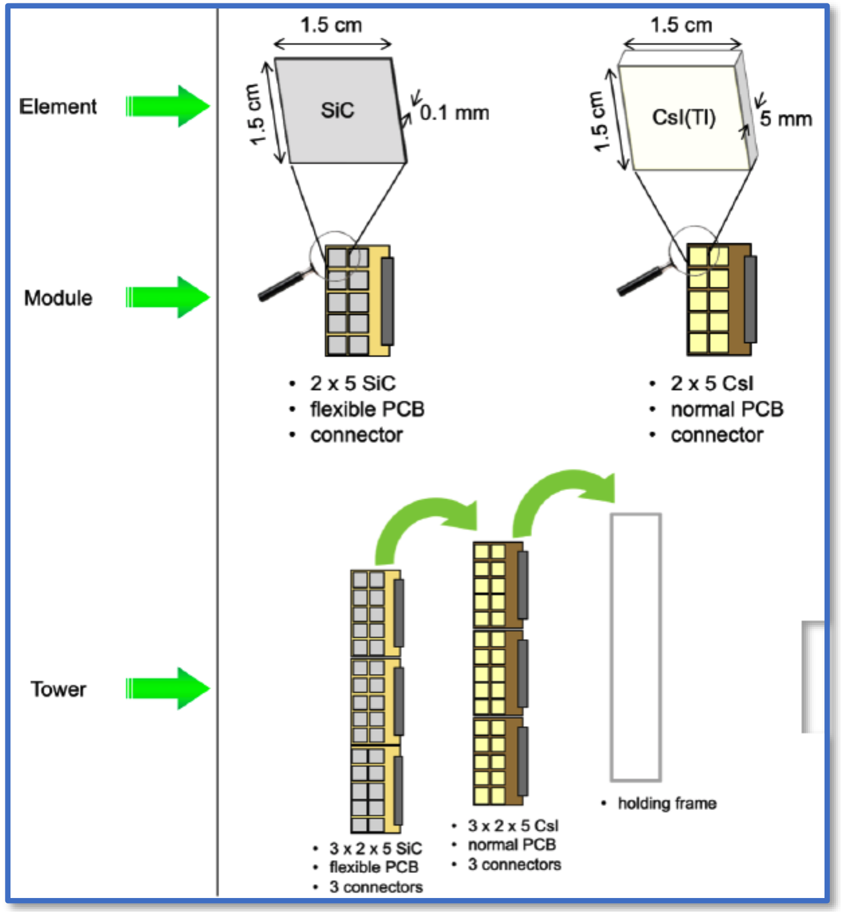
MAGNEX – Magnetic spectrometer



- ❑ Small nuclear cross-sections
- ❑ High intensity ions beams

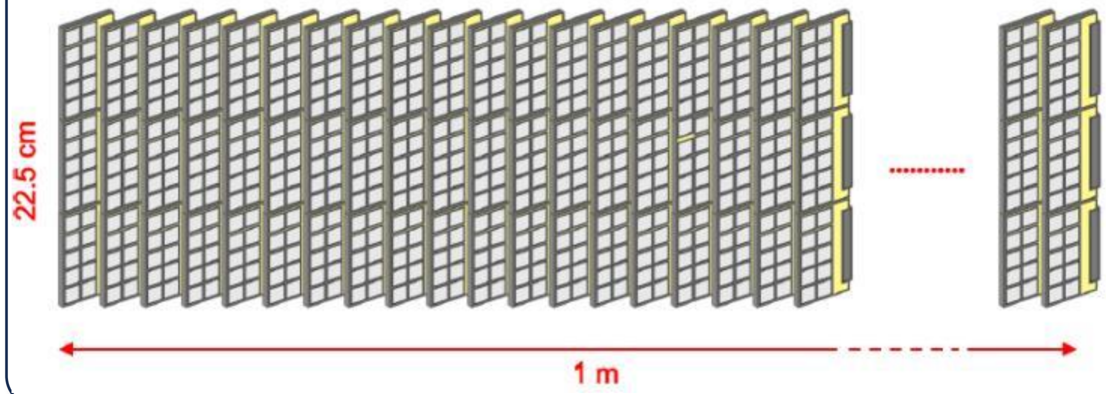
Focal plane detector





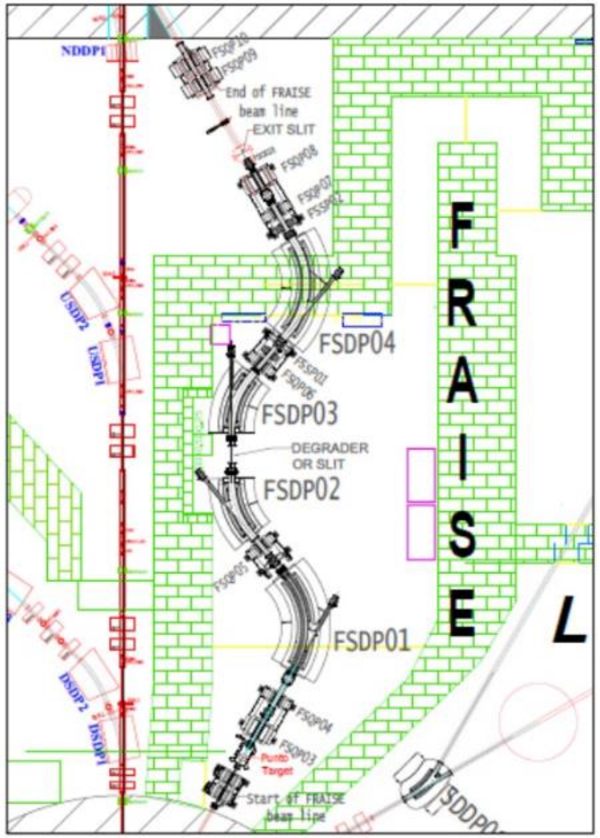
Geometry of the final PID wall

40 columns
1200 telescopes

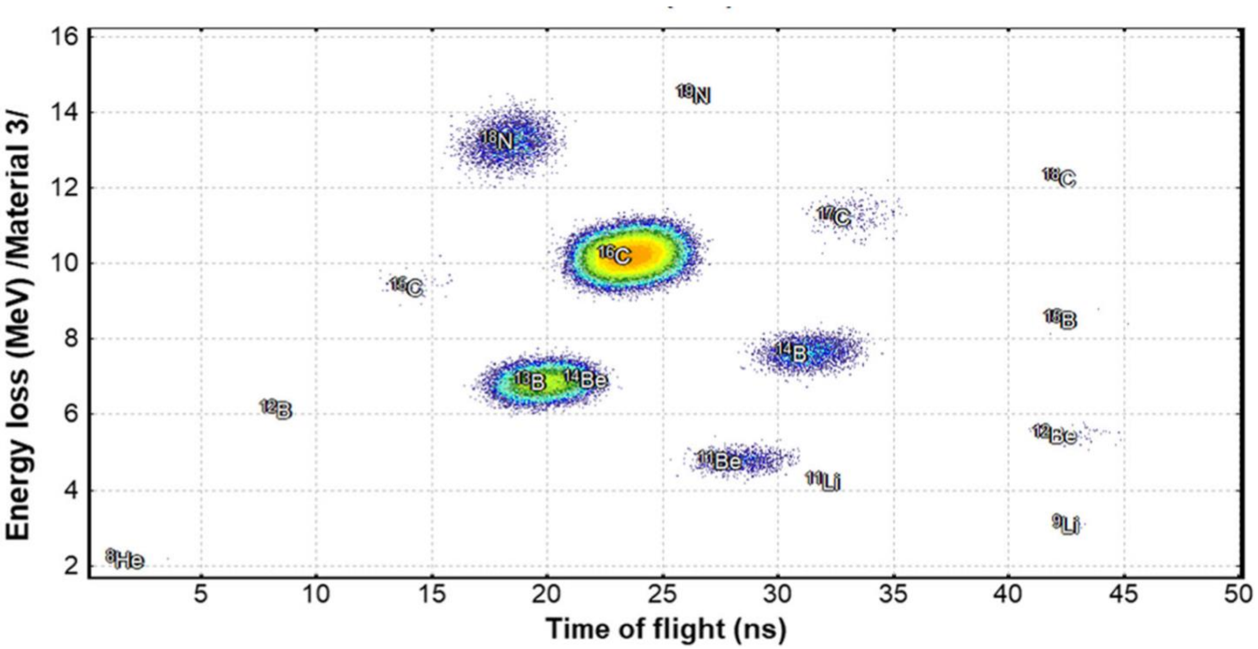


New set-up : FRAISE @ INFN-LNS

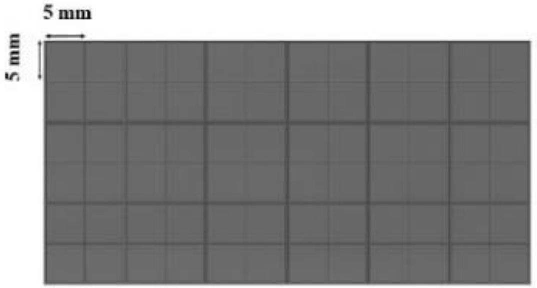
Will provide fragmetation beams with very high intensity (up to 10^7 p/s for ions like ^{16}C)



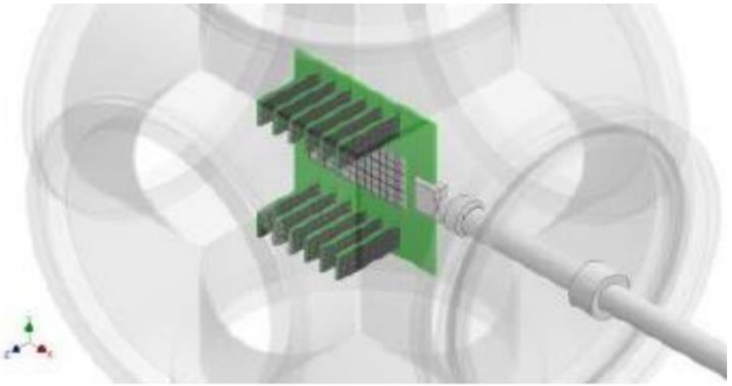
New fragment separator



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

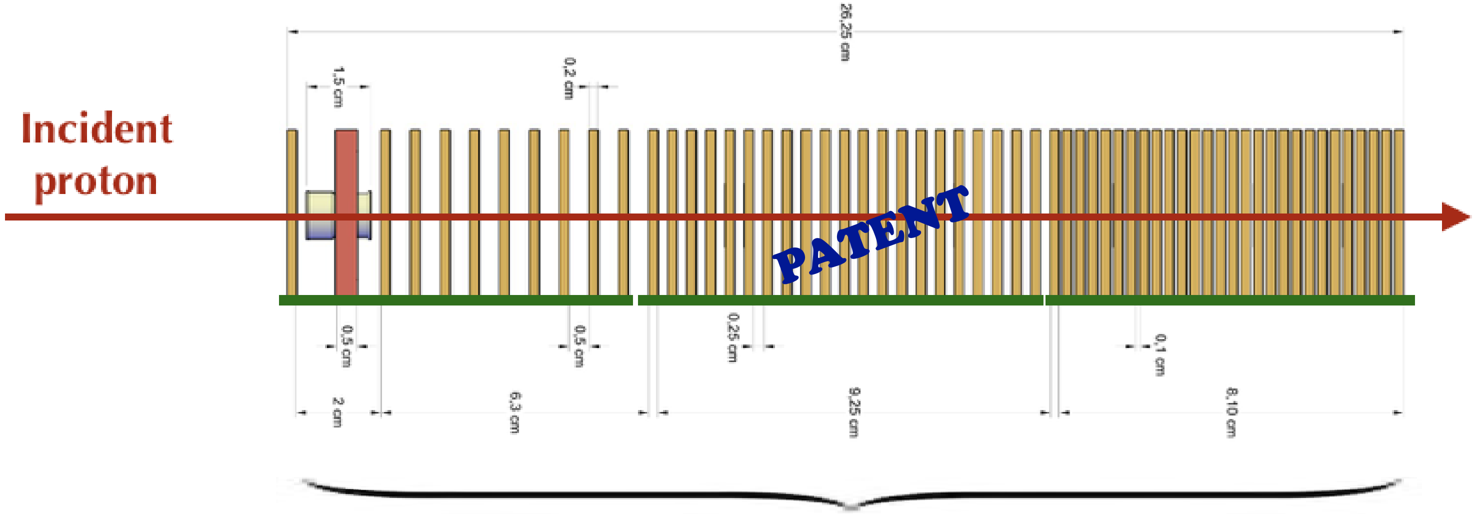


The new tagging device must be fast & radiation tolerant, therefore SiC was chosen as

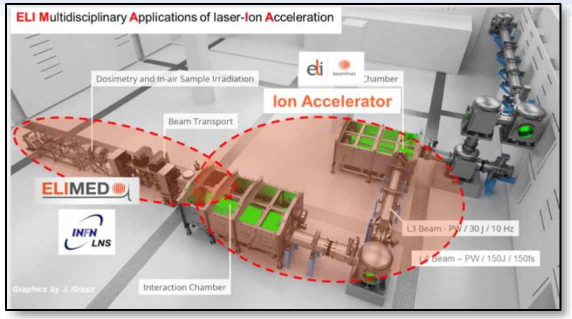


One of the studied configuration foresees the use an array of pads of 5 mmx 5mm able to cover a surface up to 6 cmx 5cm

SiC New set-up: PRAGUE - Particle RAnGe measure Using Silicon CarbidE



60 SiC 1.5x1.5 cm^2

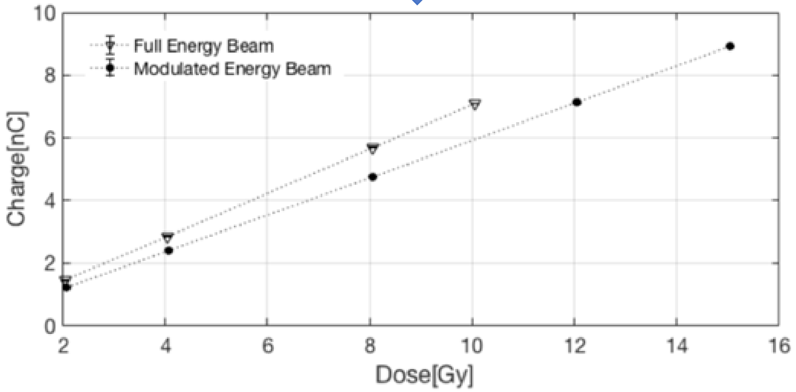


PRAGUE

LUCE

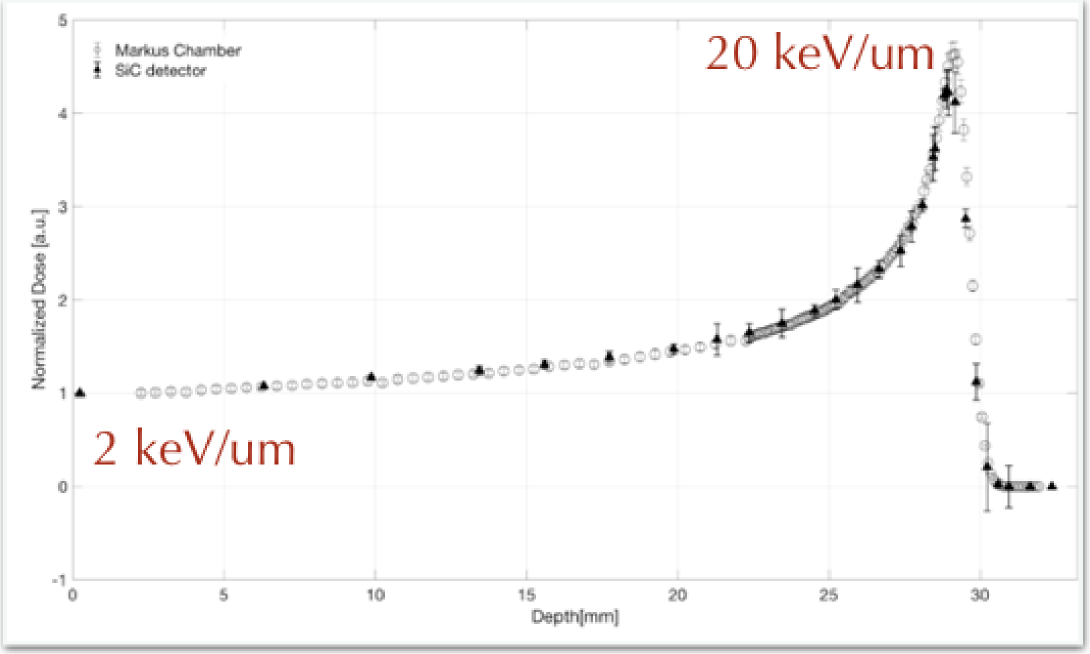
INFN - Laser indUCEd radiation production

Experiental test @CATANA Facility of LNS-INFN



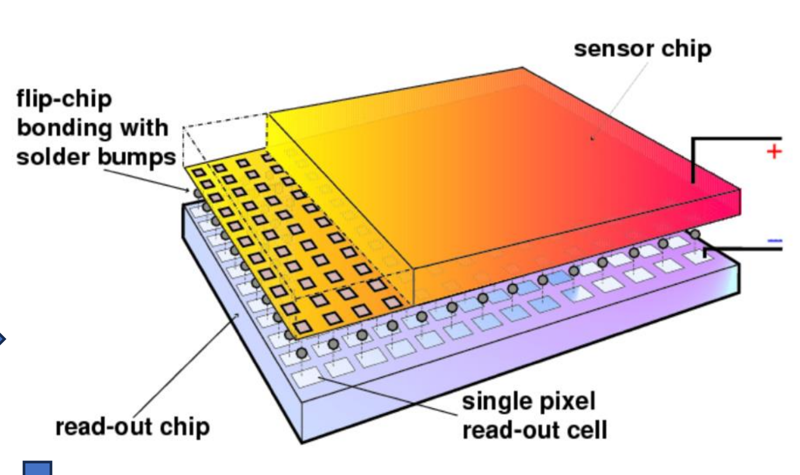
SiCILIA INFN

62 MeV proton beam, Modulated and Pristine beam, Beam Current: 10^6-10^8 p/cm^2



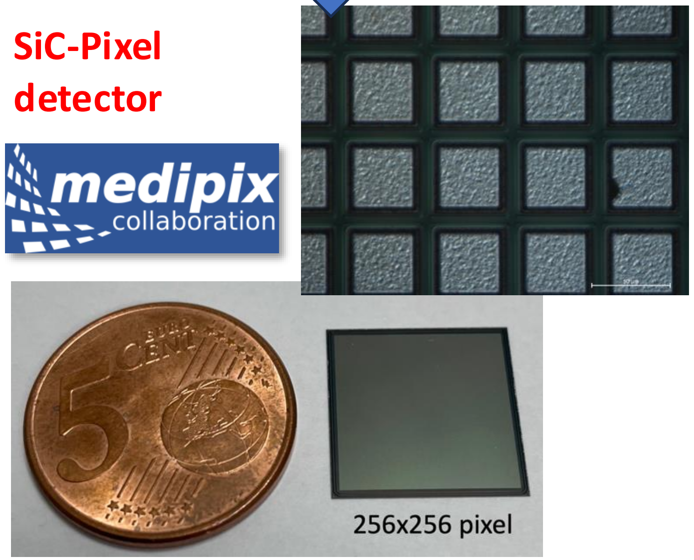
Perspectives for new devices

TIMEPIX



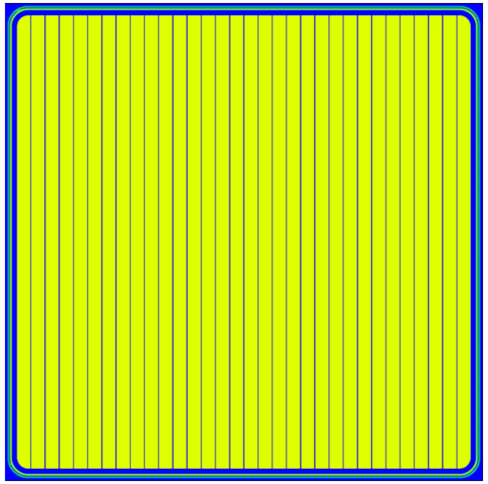
SiC-Pixel detector

medipix collaboration

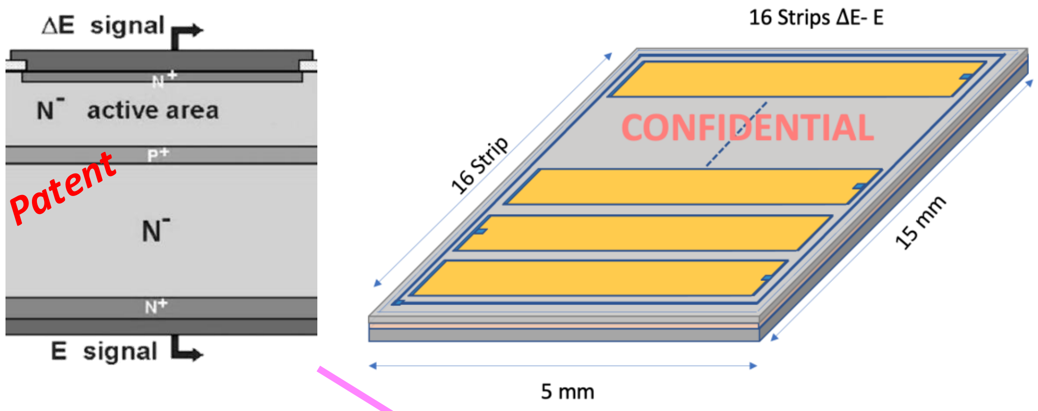


SiC-Strip Detector

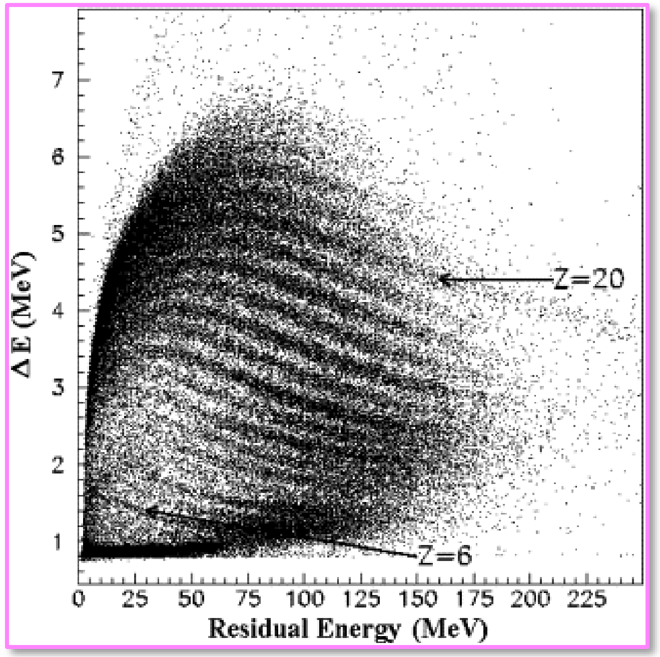
15x15 mm^2
32 strip



Monolithic Structure *SiC Buried anode*

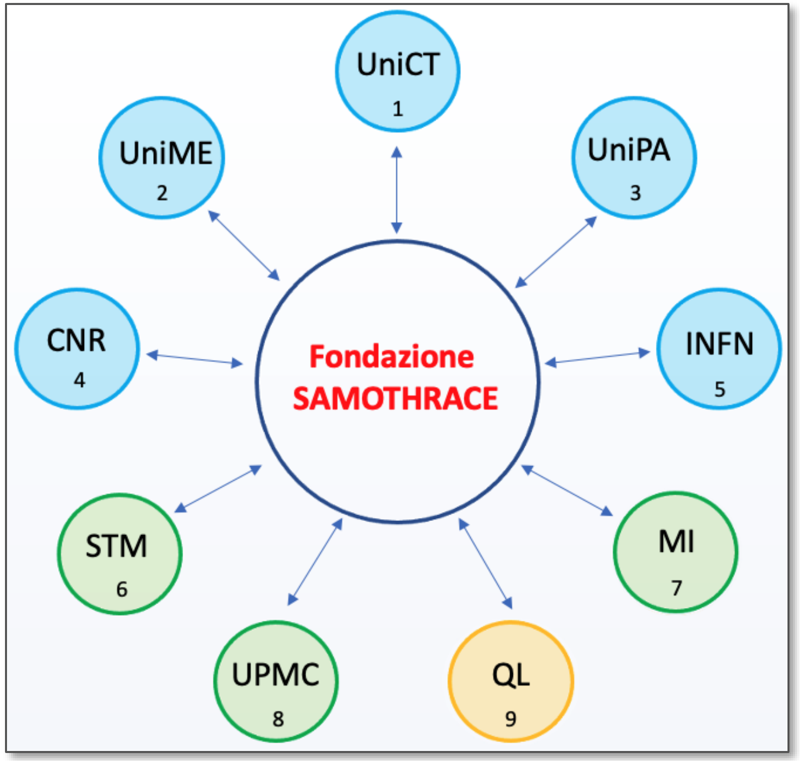


G. Cardella et al NIMA 378 (1996) 262
S. Tudisco et al NIMA 426 (1999) 436
F. Amorini et al NIMA 550 (2005) 248



PNRR - SAMOTHRACE R&D on Medical devices

SiciliAn MicrOnanoTecH Research And Innovation CEnter

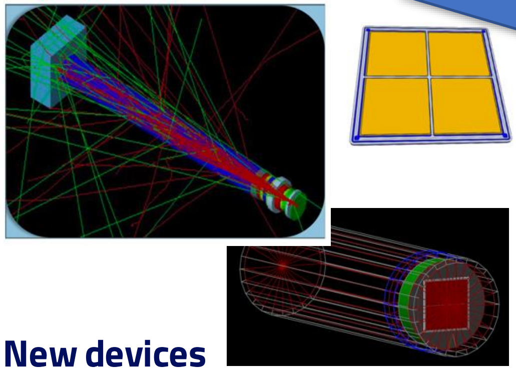


https://samothrace.eu

samothrace
Sicilian Micro and Nano Technology Research and Innovation Center

Wp4-**SiC Detectors** for particle therapy, dosimetry e micro-dosimetry

- **New SiC Radiation hard detectors** for: Particle therapy, dosimetry, beam monitoring, radio-protection
- **Micro-Dosimetry devices**
- **Imaging devices**



New devices
✓Dosimeters
✓Micro-dosimeters
✓beam-monitors
✓Imaging devices

Synergy
IMM-CNR, LPE, STM

Silicon Carbide devices for radiation detection

Thanks for your attention !

Sicilian Micro
and Nano Technology
Research and Innovation Center