Experimental challenges in the detection of heavy ions at high rate within the NUMEN project

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for the NUMEN collaboration
INFN - LNS

The NUMEN project

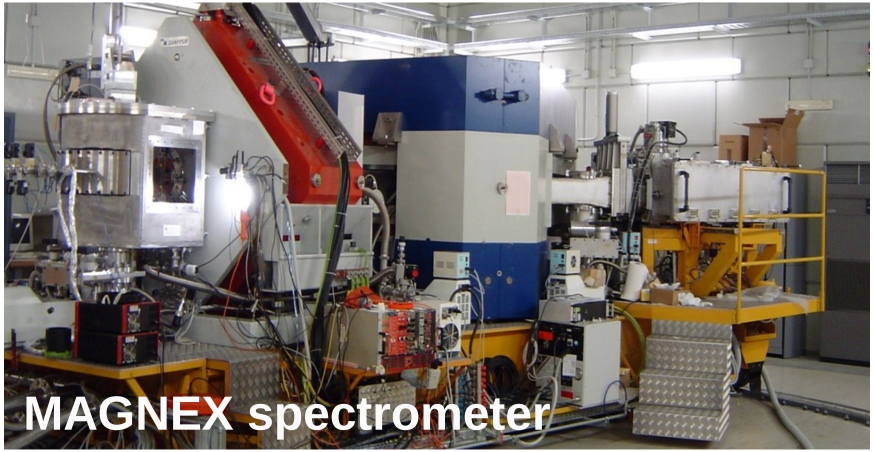
The goal: to get *“data-driven”* information on Nuclear Matrix Element of 0νββ-decay for all the candidate nuclei.

The method: Measurement of nuclear reaction cross sections, in particular **Double Charge Exchange** reaction.

The instruments:

- ✔ High-intensity beam from the K800 superconducting cyclotron
- ✔ Large-acceptance spectrometer MAGNEX

INFN-Laboratori Nazionali del Sud



The very tiny value of the studied cross section requires an **upgrade** of both the accelerator machine and the detection apparatus of the spectrometer.

Cappuzzello et al. EPJ A (2018) 54: 72

The NUMEN project

It is a compact three-sector accelerator that accelerate ion beams from H to U at energies up to 80 AMeV

- New coils
- New criostat
- New beam extraction method based on a stripping foil.

Beam current will be increased from the present 100 W to 5-10 kW)

C. Agodi et al., Universe 7, 72 (2021)

Angular acceptance	**50 msr**
Angular range	**–20° - +85°**
Momentum acceptance	**-14%, +10%**
Energy acceptance	**-28%,+20%**
Maximum magnetic rigidity	**1.8 T m**

Performances

- Energy °E/E ~ 1/1000
- Angle Δθ ~ 0.2°
- Mass Δm/m ~ 1/300
- From H to Zn ions detected

M. Cavallaro et al., EPJ A 48, (2012), 59
D.Torresi et al. NIMA 989, (2021), 164918

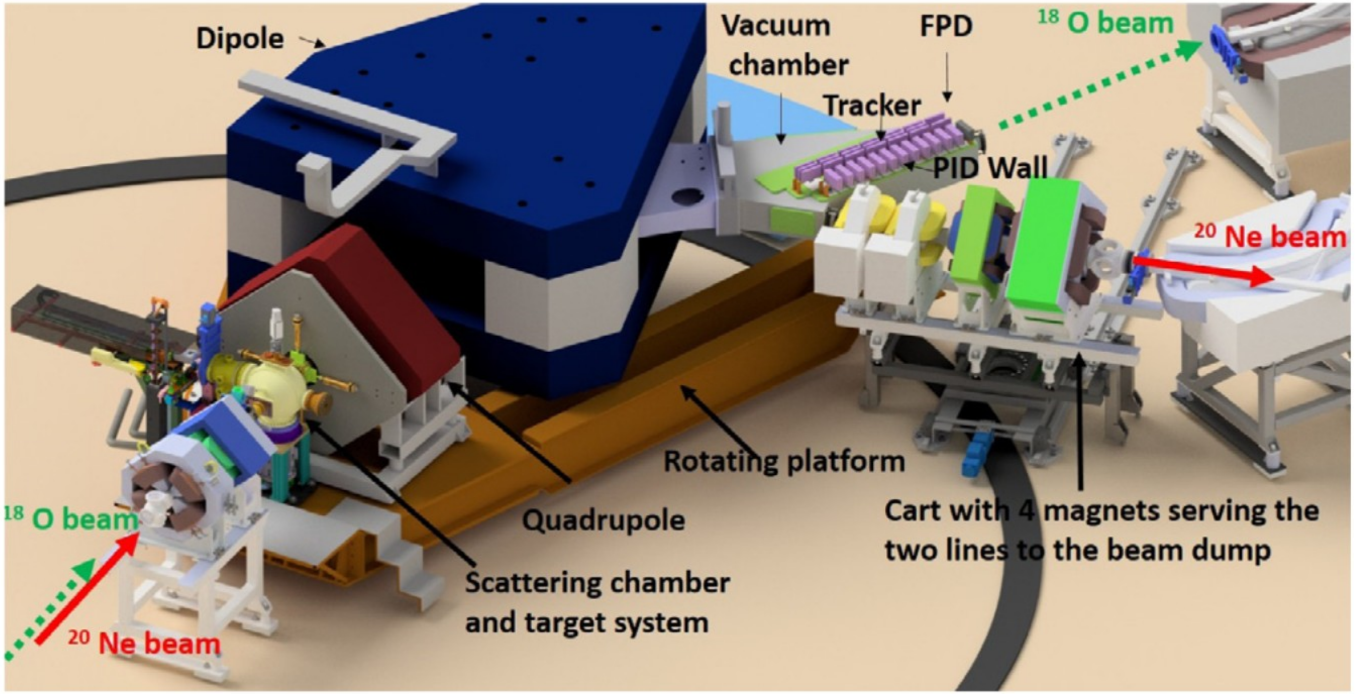
The MAGNEX spectrometer

Major upgrades

1) The focal plane detector
   - The gaseous tracker

     3D tracks of the reaction products on the focal plane to determine enery and momentum of ions
   - The PID wall

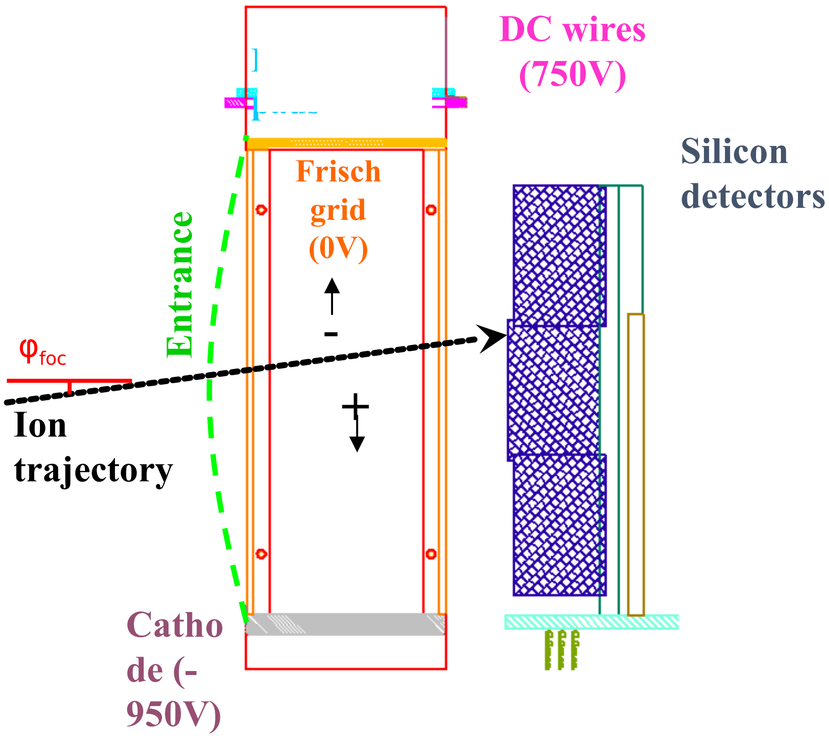
     Identification in Z and A
2) γ-array GNUMEN
   - Used to distinguish reaction to the GS or to the 1st e.s.
3) New target system
4) Higher magnetic rigidity
   - New power supply for the dipole
5) Exit beam lines



The old Focal Plane Detector

It is a **two-stage** detector

- A proportional drift chamber based on wire working at very low pressure (10-30 mbar iC_4H_{10})
- Silicon detector stopping wall



3D track reconstruction with high resolution of the phase space parameters at the focal plane (X_{foc}, Y_{foc}, θ_{foc}, φ_{foc})

Z & A identification of the reaction products in a wide range

X resolution < 0.6 mm
Y resolution < 0.6 mm
θ resolution < 5 mrad
φ resolution < 5 mrad

Main limitations:

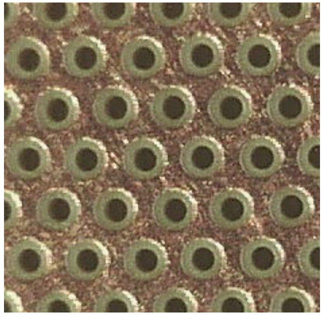
Rate: maximum value of few kHz

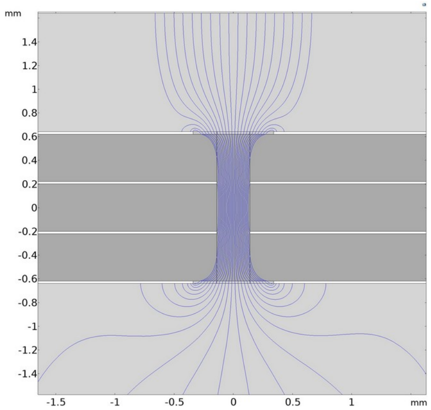
Low **radiation hardness** of the Si stopping wall

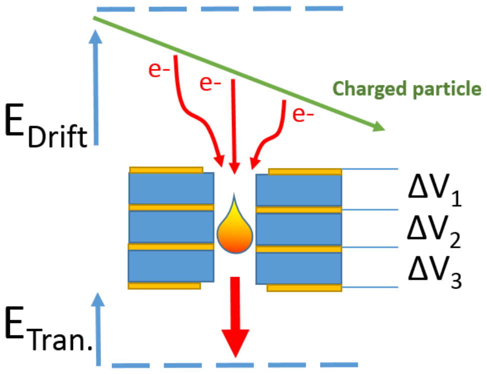
The new Focal Plane Detector

Wires → MPGD (THGEM)

- Very robust
- Submillimetric position resolution
- Can bear high rate
- Good timing properties



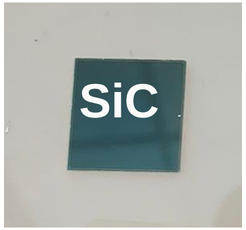




3-layer THGEM

Silicon detectors → SiC + CsI

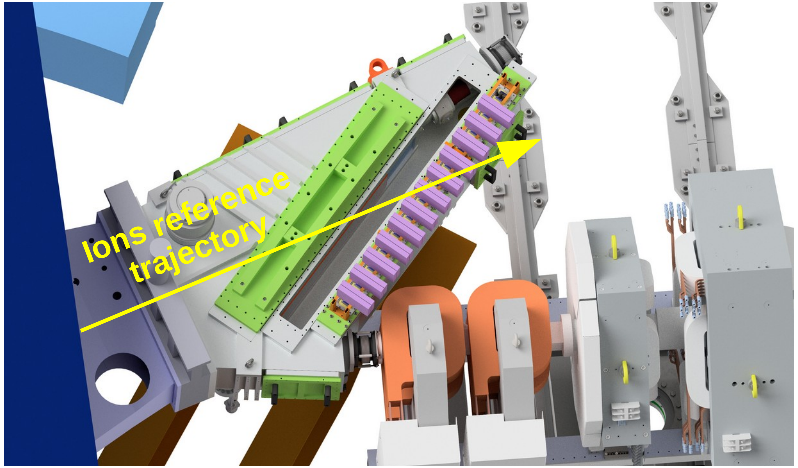
- SiC energy resolution comparable with silicon detector
- Very good timing properties
- High radiation tollerance for both SiC and CsI



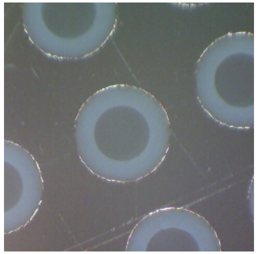
Tudisco et al., Sensor 2018, 18,2289

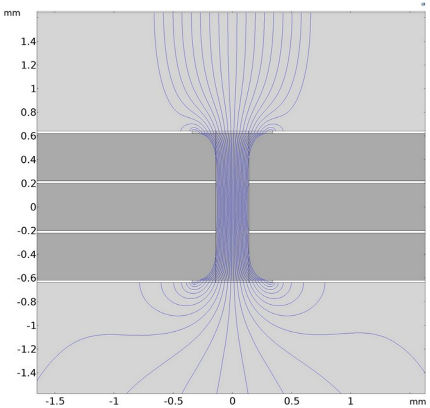
Gaseous tracker

The FPD chamber



The **focal plane gas tracker** is a **proportional drift chamber** 1.2 m wide. The **gas** used in the detector is **isobutane** (other gas are under test) The **multiplication stage** is based on multiple **THGEM**





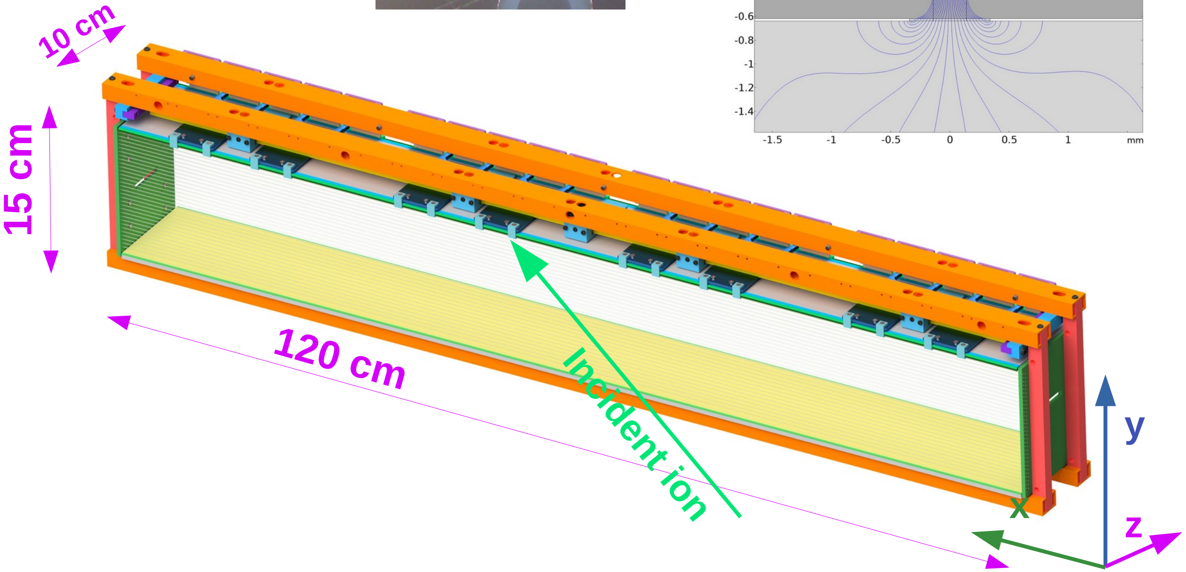
Main demands

Track heavy ions: O-Ne
At energies: 5-60 AMeV

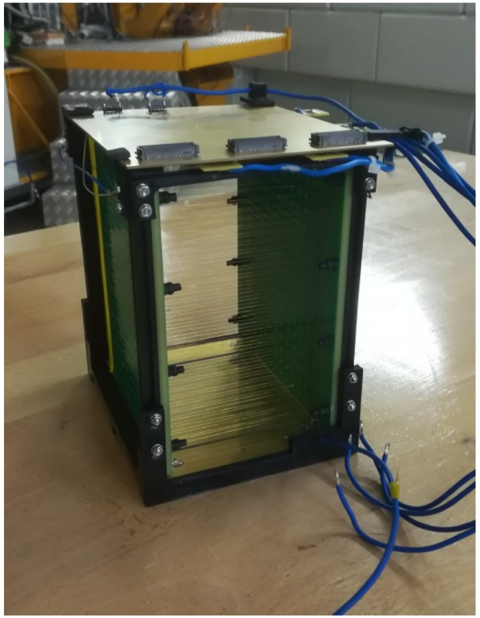
Rate: $3x10^4$ pps/cm

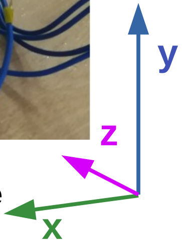
X resolution < 0.6 mm
Y resolution < 0.6 mm
θ resolution < 5 mrad
φ resolution < 5 mrad

Operate in gas at low pressure iC_4H_{10} @ 10 mbar

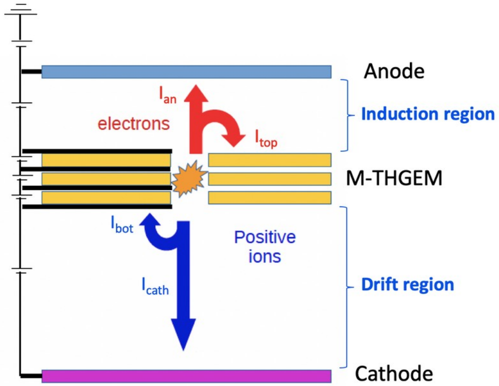


Gaseous tracker
test with picoammeter



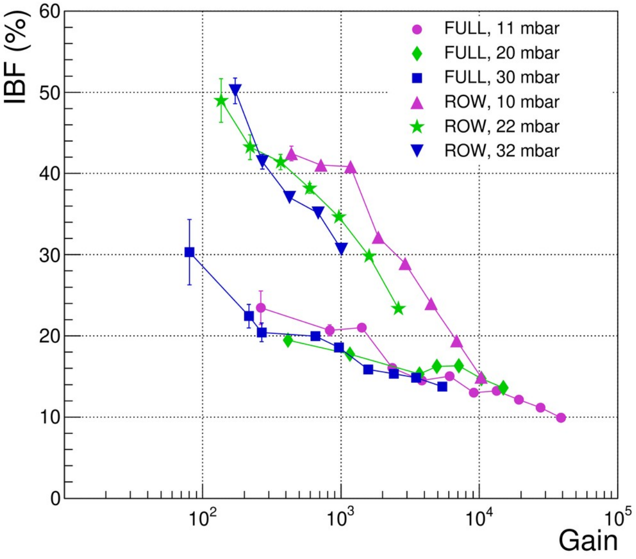


The small size prototype
108x185x108 mm³

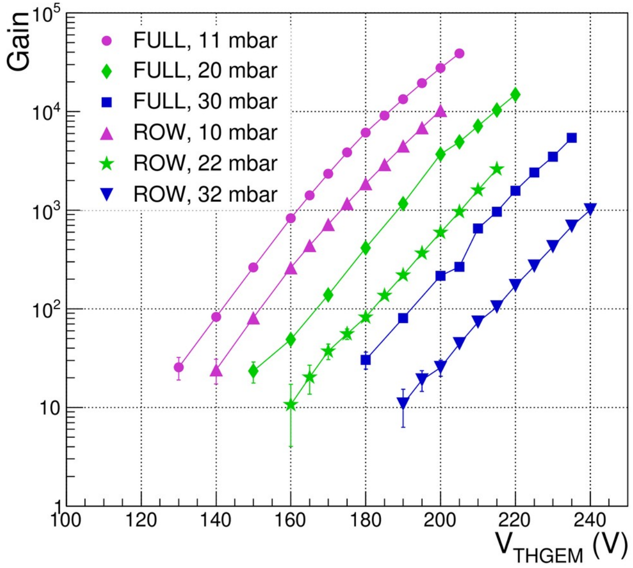


Characterization done with a picoammeter (sensibility < 1 pA)
α-sources 55 kBq - 10 MBq

Ion Back Flow

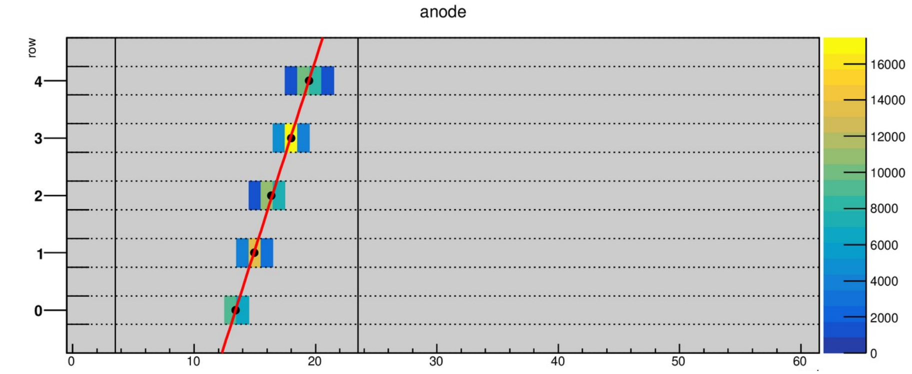


Gain

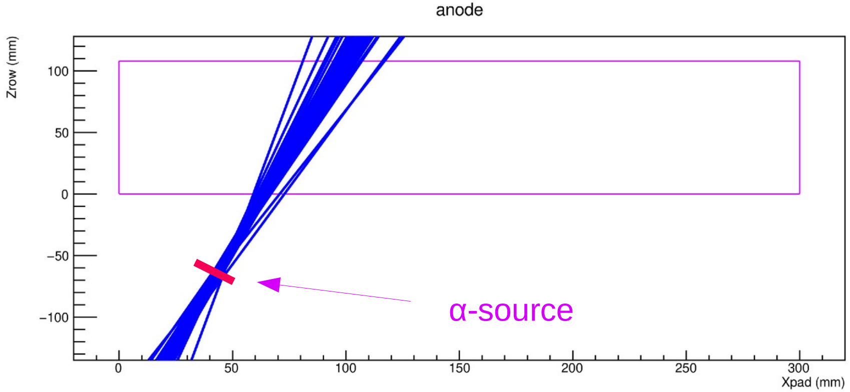


Ciraldo et al. NIMA 1048 (2023), 167893

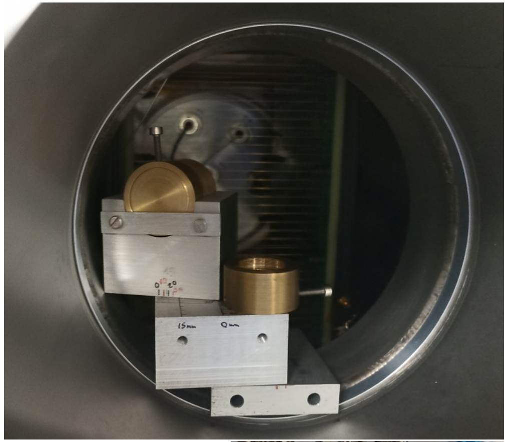
Gaseous tracker
tracking performances

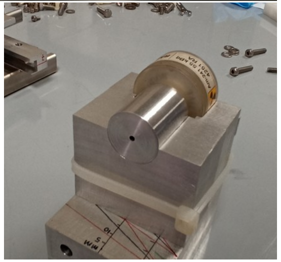


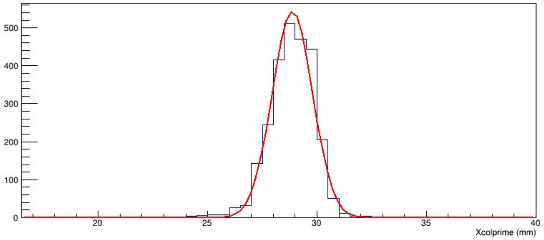
For each cluster the centroid is extracted and a fit of the position of the five centroids gives the track



The trajectory of each alpha is tracked back to the alpha-source position. The histogram of all the starting point of the trajectory must be compared with the collimator size: 1mm.





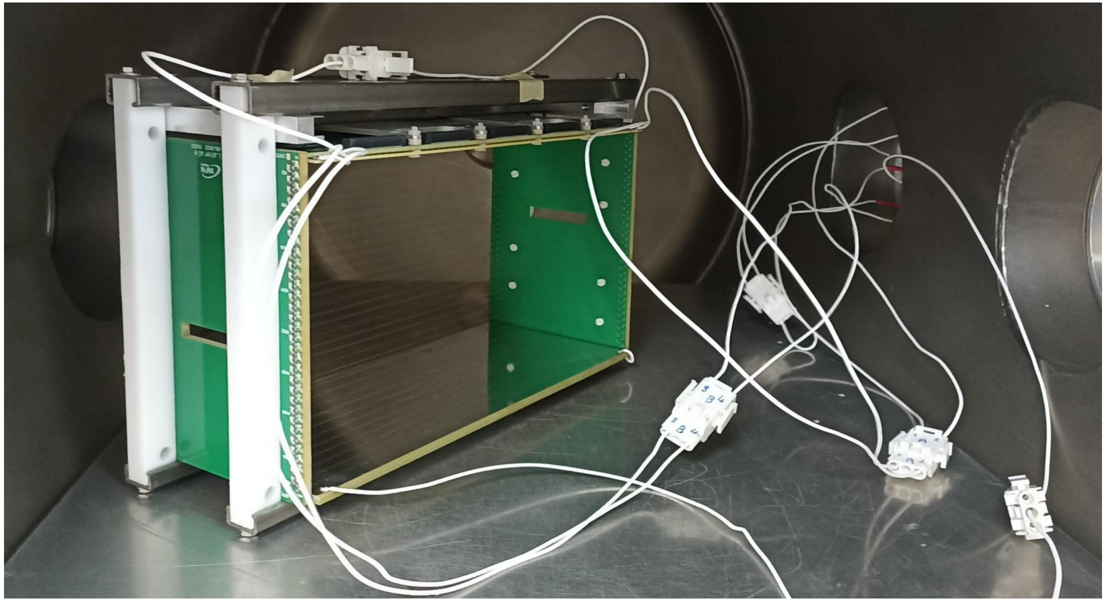


Resolution for the x coordinate of about 0.6 mm was obtained.

Run with smaller collimator (0.3 mm) are planned with a new prototype.

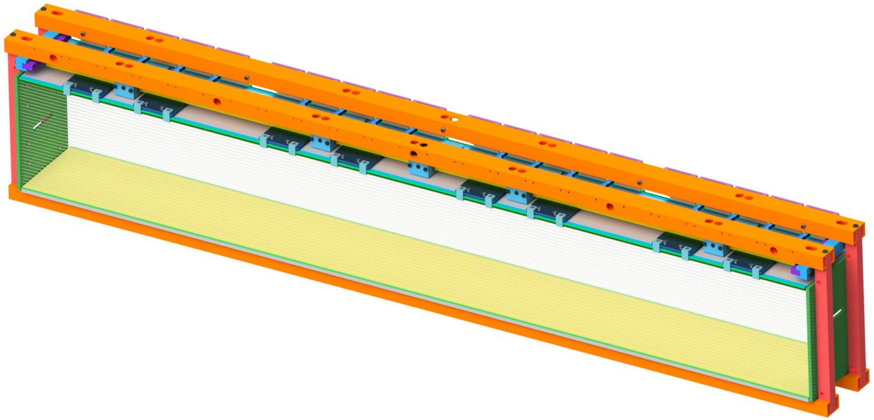
$\Delta x \sim 0.6$ mm
$\Delta\theta \sim 5$ mrad

Gaseous tracker
the new prototype

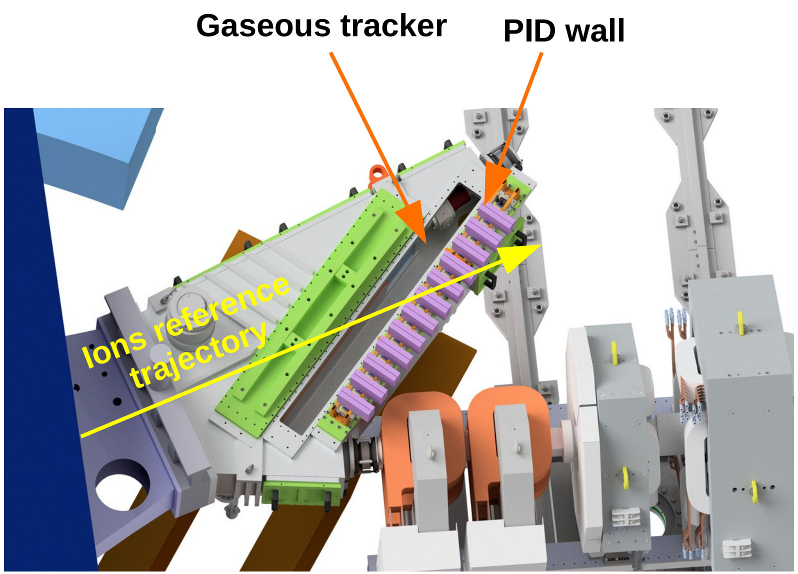


New prototype
- larger dimensions
- same mechanic assembly of the final detector
- optimization of the anodic and THGEM geometry

- Optimization of the **mechanical design** to reduce the discharge probability and maximize the voltage applied to the cathode
- New characterization with a **picoammeter** and different THGEM geometries
- Study of the **tracking performances** with α-source
- **In beam test** with tandem

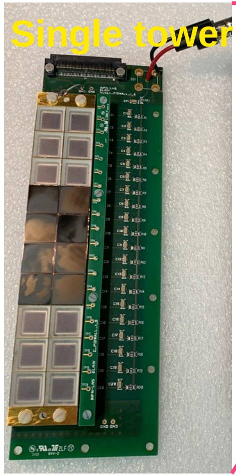


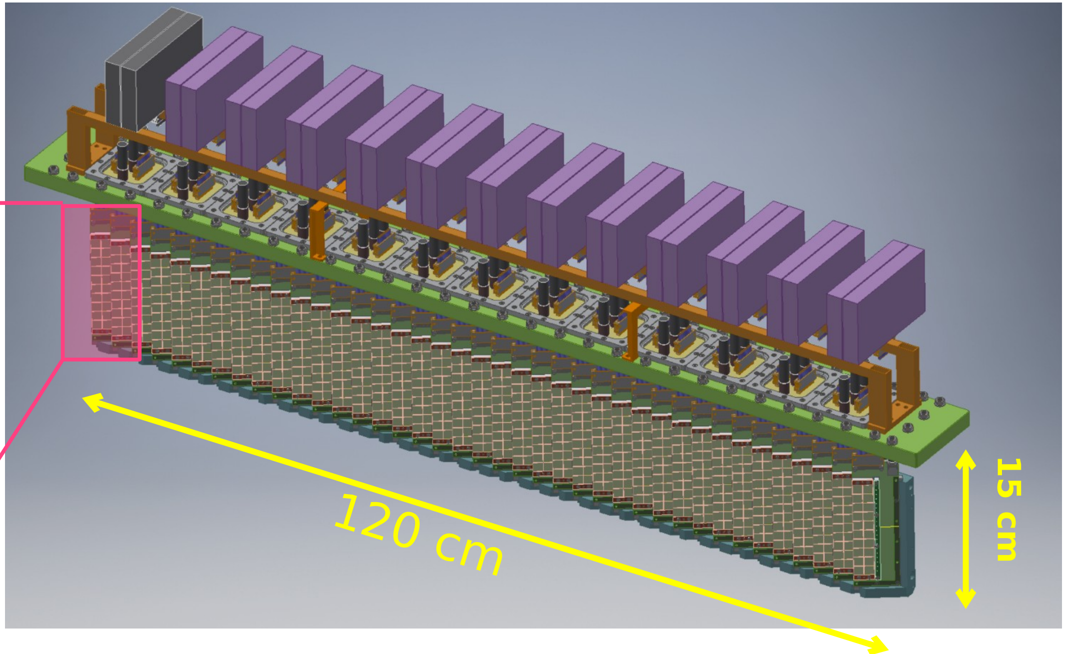
The PID wall



The **PID wall** cover a total area of 120x15 cm^2 is made of 36 towers

Each **tower** is tilted of 35° with respect to the focal plane and is made of 20 telescopes for a total of 720 telescopes





Main demands

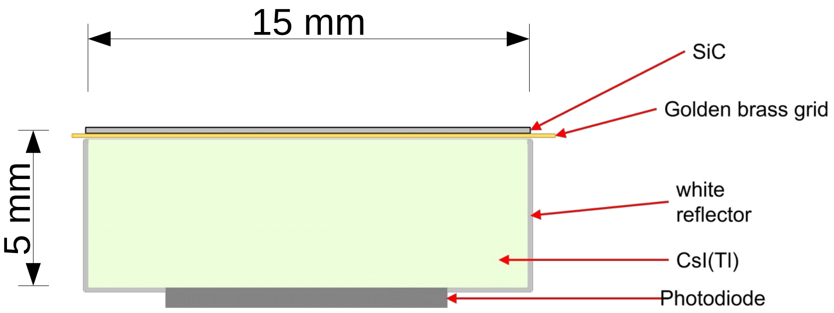
Radiation Hardness
> 10^{11} ions/(cm^2)

Time resolution: 2-3 ns

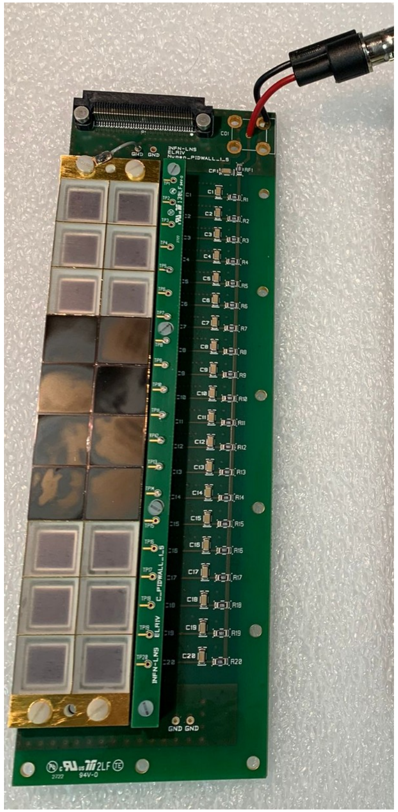
Double-hit probability: <3%

Must operate in gas at low pressure (~10 mbar)

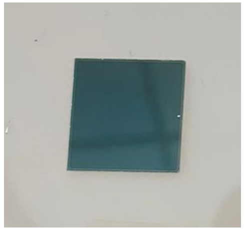
The PID wall
the telescope



Tudisco et al. Sensors 2018, 18, 2289



SiC
Thickness 100 μm
Area 1.54 x 1.54 cm^2
Bias -600/-1000 V



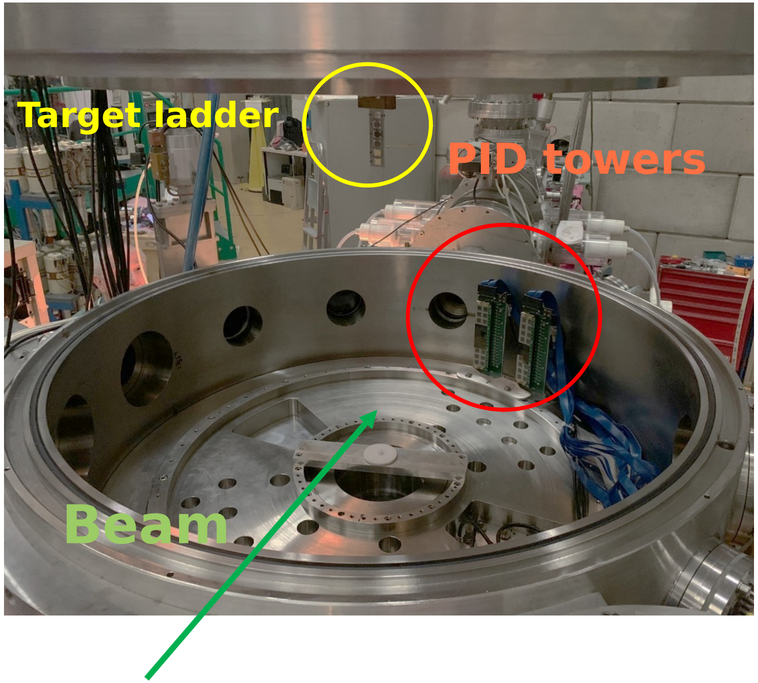
Radiation hardness

SiC 10^{13} ions/cm^2
Si 10^{10} ions/cm^2
CsI $7.5 \cdot 10^{11}$ ions/cm^2

E stage CsI (Tl)
Thickness 5 mm
Area 1.5 x 1.5 cm^2

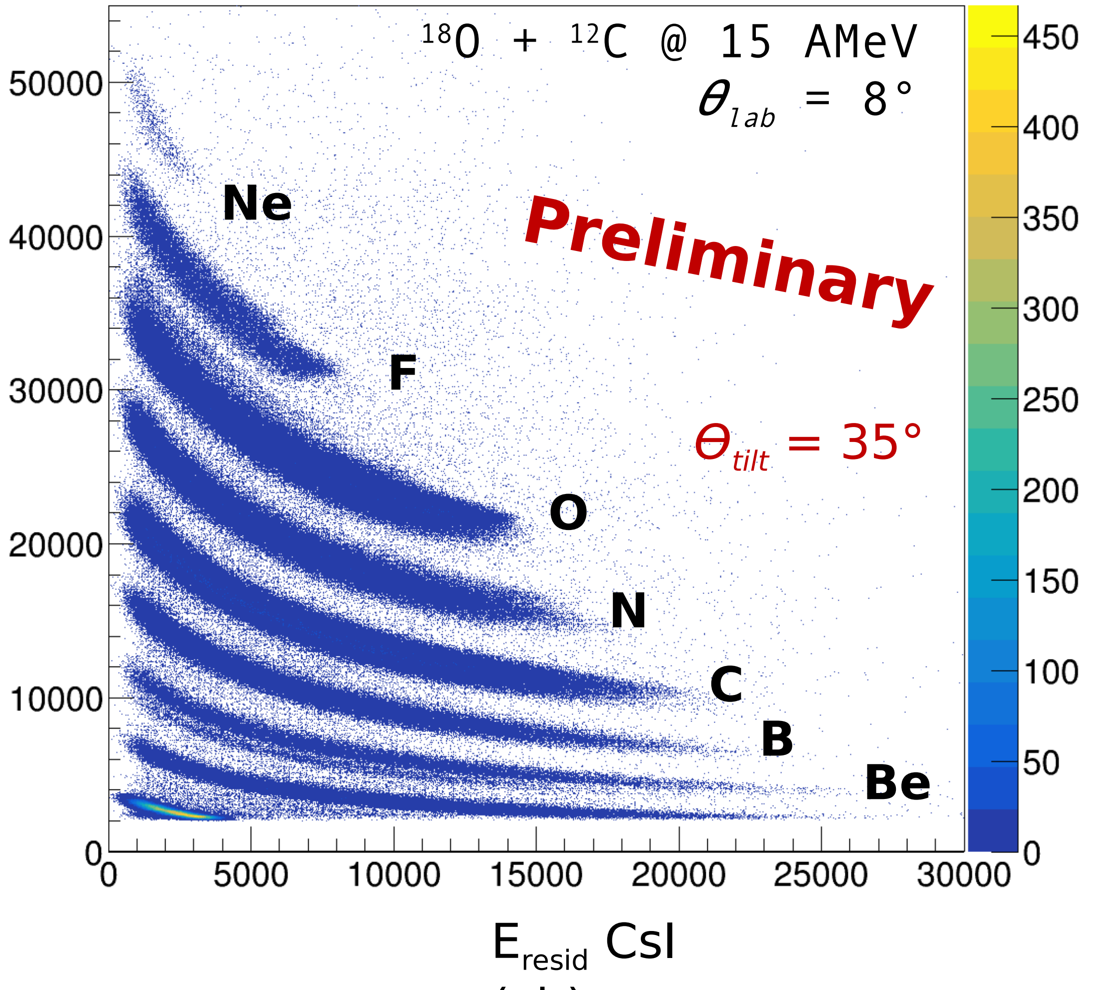
Hamamatsu Photodiode S3590-0887
Area ~ 1 x 1 cm^2
Bias -70 V

The PID wall
the ID performances



Test at INFN-LNL ^{18}O beam @ 15 AMeV
Target of Au and C

Resolution $\Delta Z/Z \approx 1/34$

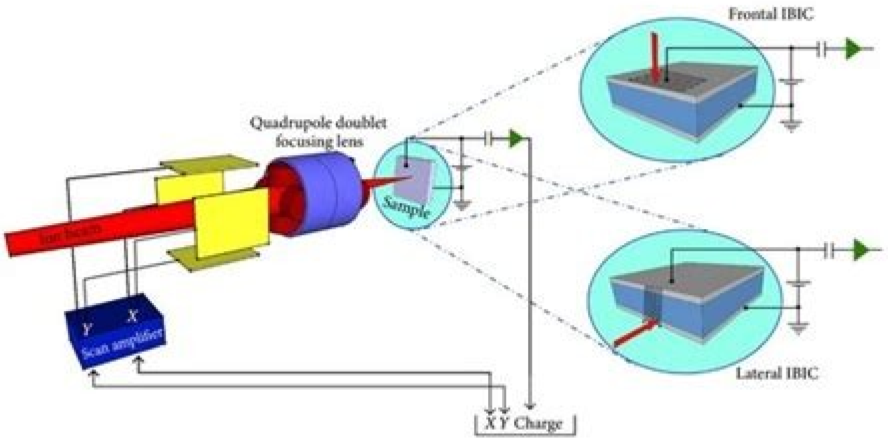


Ruđer Bošković Institute, Zagreb (Croatia)

The PID wall
IBIC characterization

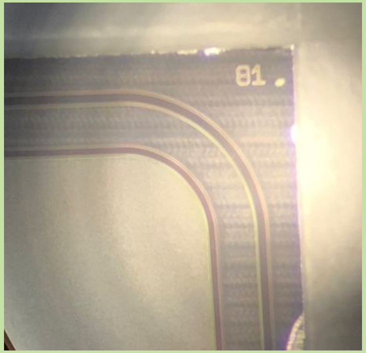
IBIC (Ion Beam Induced Charge) Technique

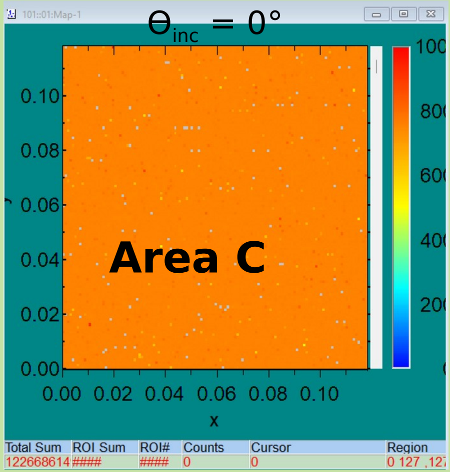
For each proton the **hitting position** is known with a precision of 10 μm and the **charge** is collected by the SiC is measured.
Six region of the detector have been investigated to study its uniformity.

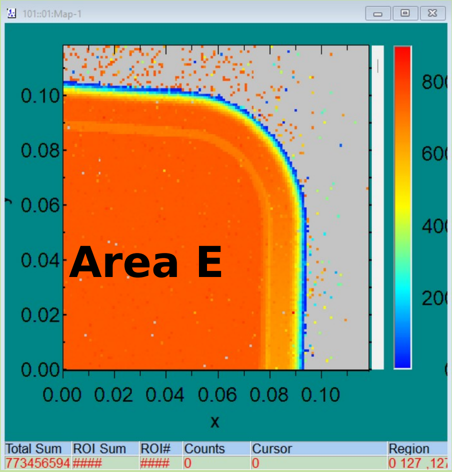


From *E. Vittone, ISRN Materials Science 2013, Article ID 637608*

- **Good uniformity** of the inner area
- **Edge effect** in the collection efficiency







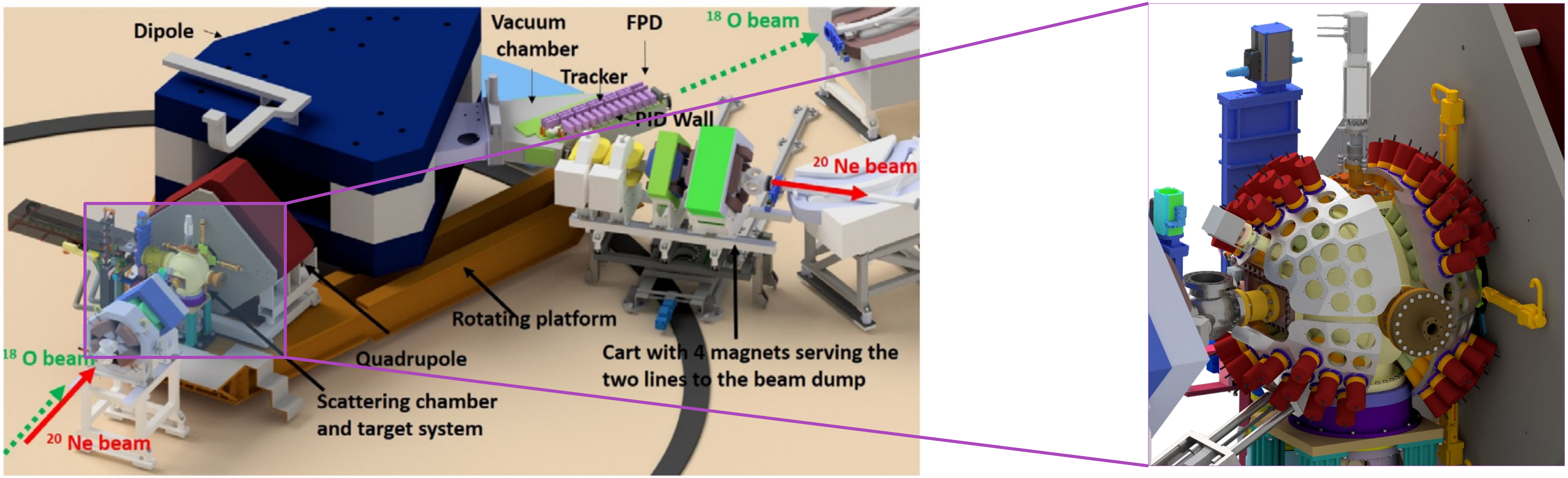
The γ detection array: G-NUMEN

The motivation:

Typical MAGNEX **energy resolution** at high energies is not enough for many systems to distinguish the reaction to ground state from the reaction to the 1st excited state of ejectile or recoil.

Requirements	
Energy resolution	3-25% (depends on the nucleus)
Time resolution	< 5 ns
radiation hardness	10^{10} n/cm^2
high granularity	

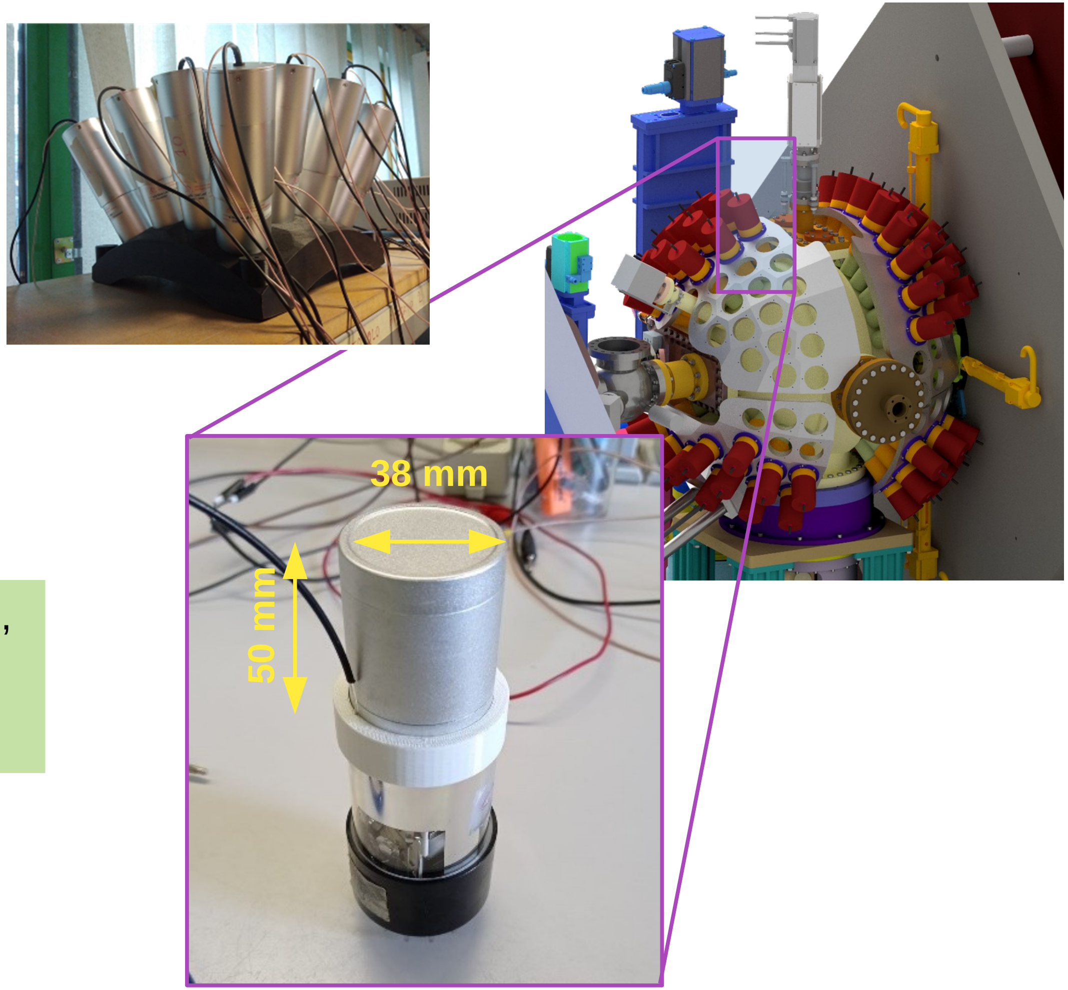
J.R.B. Oliveira et al, EPJA 56, 153(2020)



The γ detection array:G-NUMEN

Array of **110 LaBr3(Ce)** scintillators coupled to standard **PM tubes** arranged in seven rings covering a total solid angle of 20% of 4π

The scattering chamber will have a spherical shape with a diameter of 0.5 m, it will be made of aluminum 6 mm thick.



- Total **photopeak efficiency** of the array near 4%,
- **energy resolution** around 3%, at 1.3 MeV.
- Expected **timing** resolution under 1 ns

Gandolfo, E.M. et al.. Preprints.org 2023, 2023070575.

The Electronics & DAQ

A1429

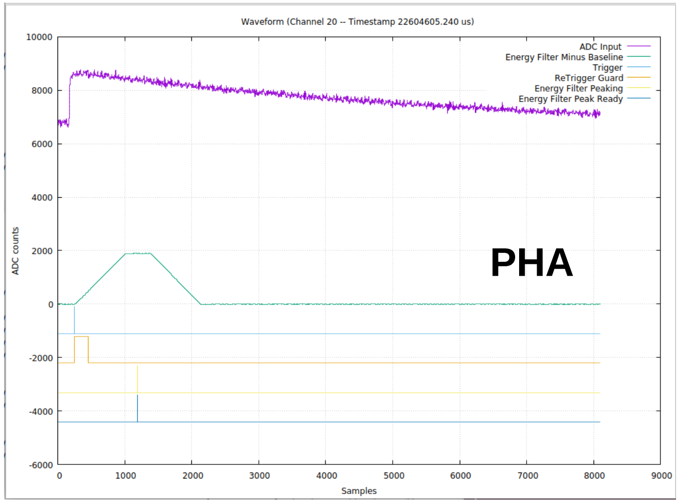
(20+24)

VX2745

(20+24)

Gas tracker & PID wall
64-channel preamp A1429

64-channel digitizer VX2745
16 bit @ 125 MS/s ADC
Analog Gain up to x100
Open FPGA
DPP-Pulse Height Analysis mode



VX2745(B)

(2)

G-NUMEN
64-channel digitizer VX2745
16 bit @ 125 MS/s ADC
Analog Gain up to x100
Open FPGA
DPP-Pulse Shape

A totally new DAQ system: **NUDAQ** based on the CAEN library is under development.

The target system

High intensity beam represent a problem also for the target system.

The power dissipated on the target itself by the heavy ion beam is sufficient to melt most of the target.

A solution based on a substrate with high capability to dissipate heat have been developed.

More information in the next talk of Mauro Giovannini

Conclusion

- The measurement of the tiny cross section of the DCE reaction requires an upgrade of the superconducting cyclotron that allow to increase the **beam intensity form 100 W to 5-10 kW**
- The increase of the beam intensity on MAGNEX target requires in turn a **global upgrade of the detection system** of the spectrometer
  - **Gaseous tracker** based on **THGEM** a novel MPGD that ensure the capability to bear rate as high as $3 \cdot 10^4$ kHz/cm, with submillimetric resolution and that can easily be built in large size. A prototype ¼ the size of the final tracker is under a phase of test and characterizzation
  - The **PID wall** has been designed with a modular structure based on a **telesope SiC+CsI** that is the elemental unit. The detector must have a high radiation hardness and good resolving power for charge identification of ions.
  - The **γ-array** The introduction of a γ-array is required when the energy resolution of the spectrometer is not sufficient to s sufficient to discriminate between the ground state and first excited states of both ejectile and recoil. It will made of 110 **LaBr3** that are able to provide the correct energy resolution the radiation hardness required.

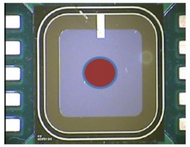
THANK YOU!

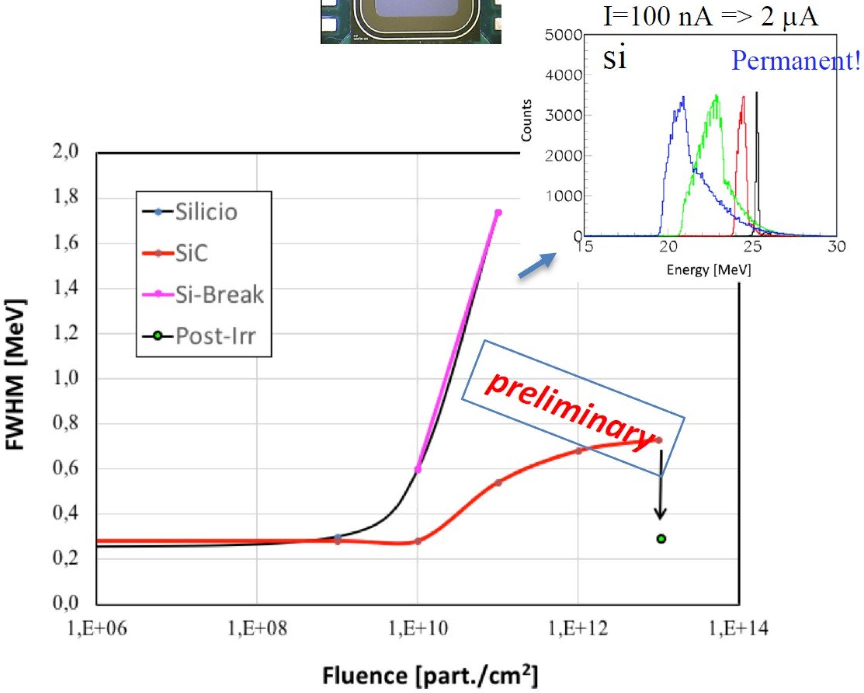
BACK UP

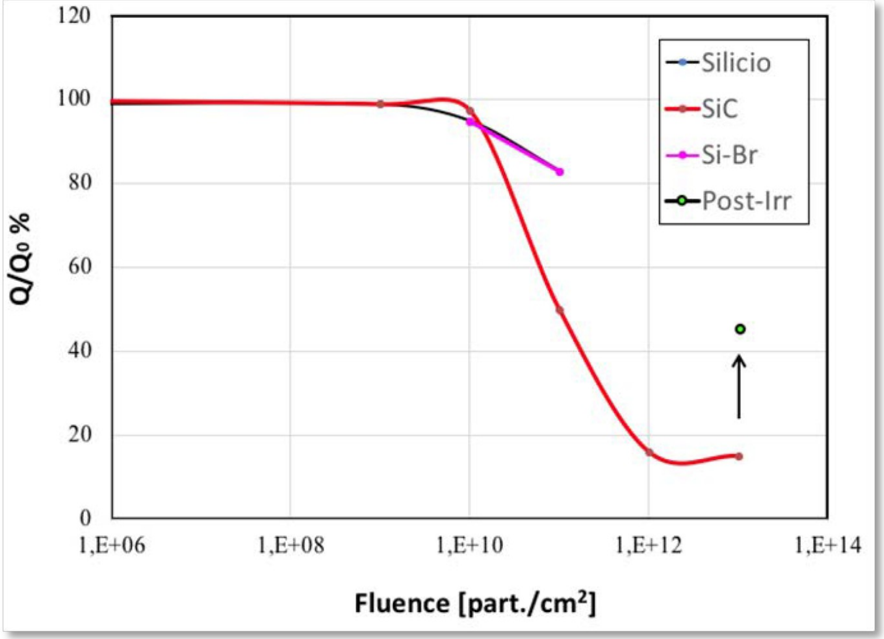
SiC Radiation hardness tests

^{16}O @ 25 MeV

SiC 10μm 5x5 mm²







NUMEN TDR F. Cappuzzello et al., Int. Jour. Mod. Phys. A 36, 2130018 (2021)

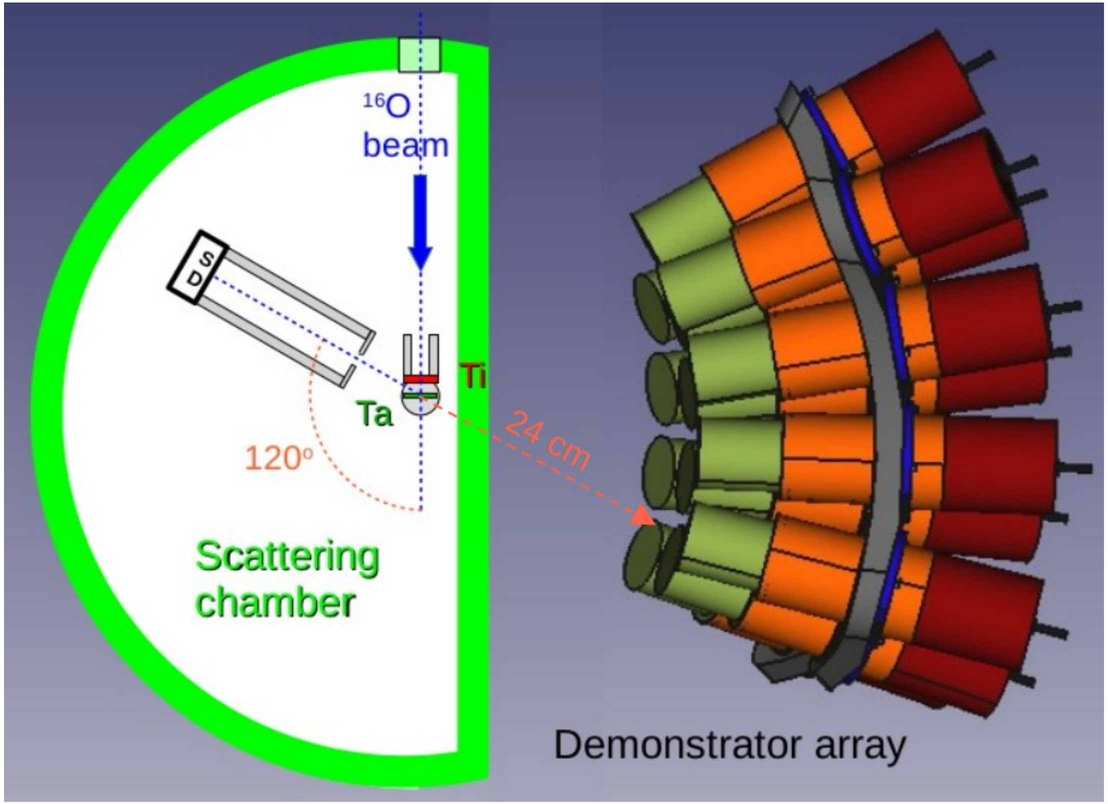
Array of 110 $LaBr_3$(Ce) scintillator crystals coupled to standard **PM tubes** disposed in rings covering a total solid angle of 20% of the unit sphere

38 mm diameter, 50mm length, 245 mm distance from the target

Expected total photopeak efficiency of the array

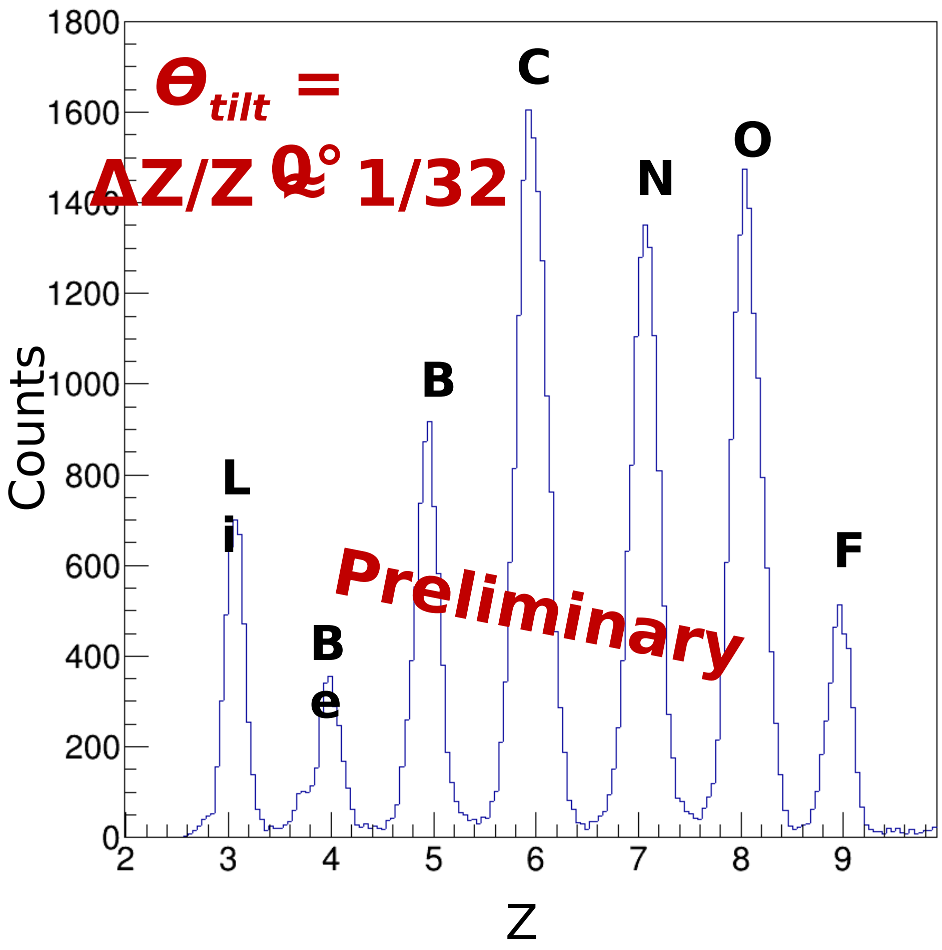
The LNS cyclotron upgrade

G-NUMEN demonstrator



15 LaBr3(Ce) crystal scintillator detectors

Ready to be assembled and tested


θtilt = 0°
ΔZ/Z ≈ 1/32
Counts
0
200
400
600
800
1000
1200
1400
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Z
2
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6
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9
Li
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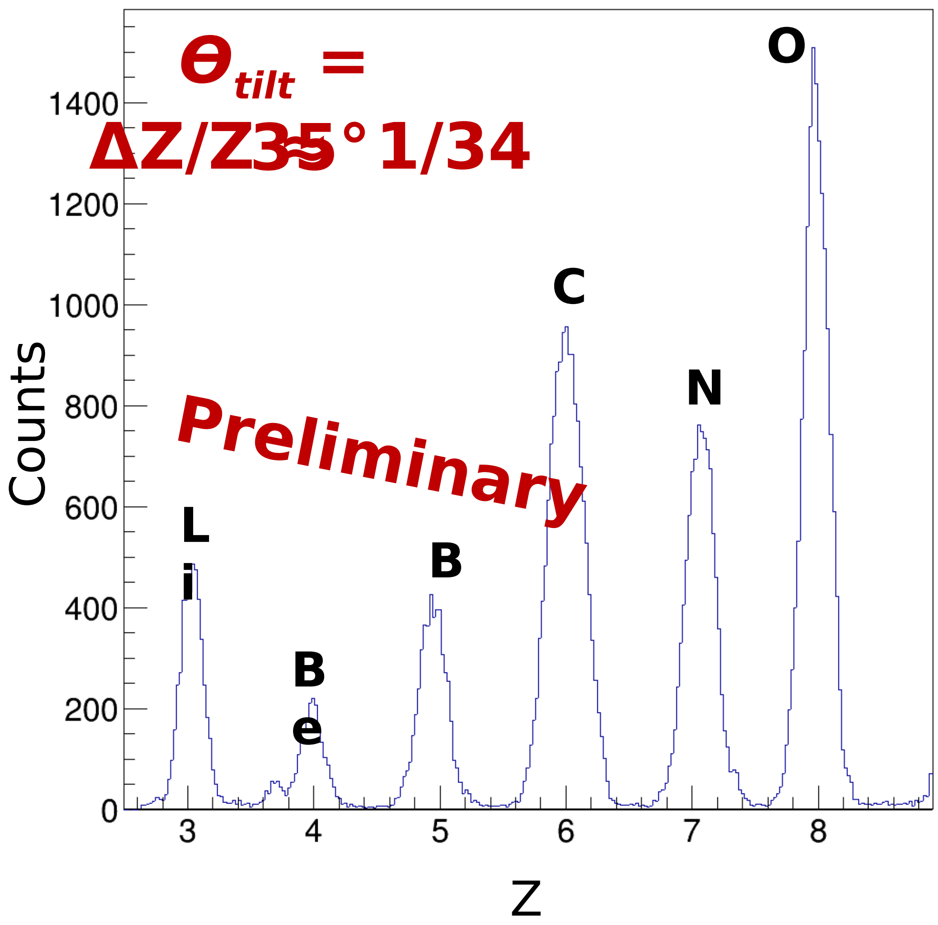
O
F
Preliminary


θtilt = 35°
ΔZ/Z ≈ 1/34
Counts
0
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1400
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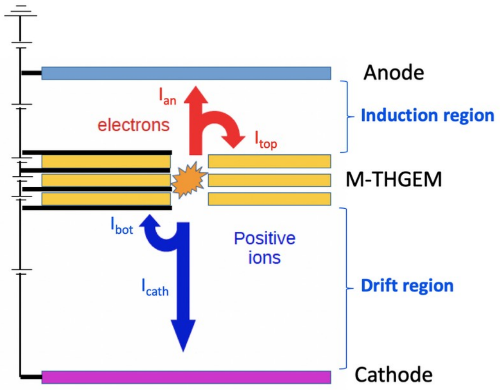
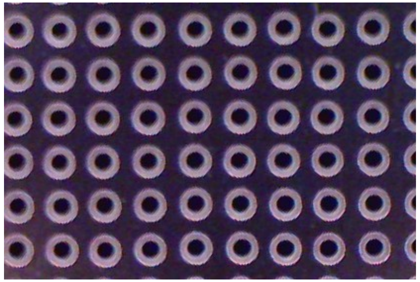
Preliminary

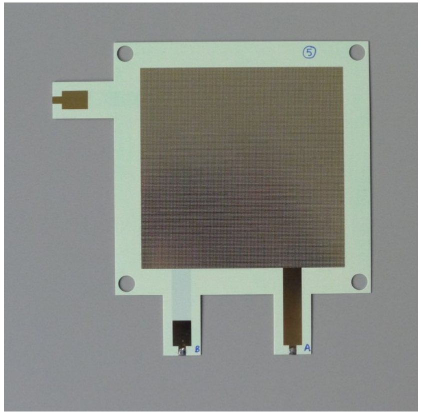
Full THGEM 300um holes pitch 750 mm ceramic and FR4 substrate

Row THGEM 300um holes pitch 750 mm just FR4 substrate

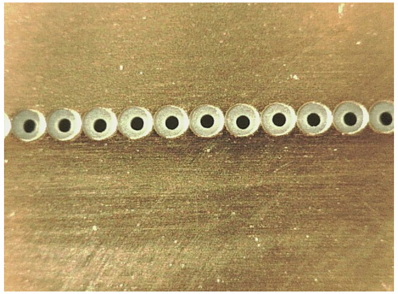


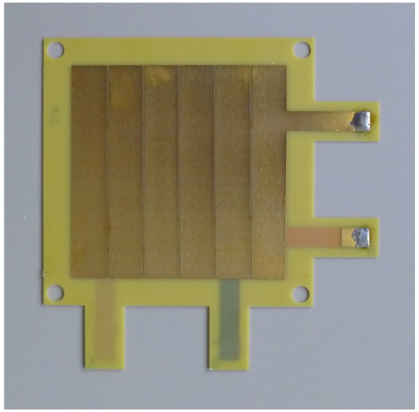
Full THGEM



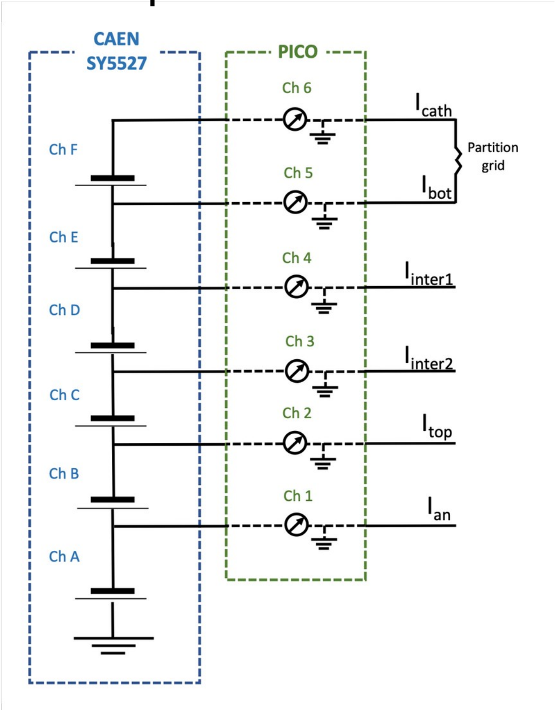


Row THGEM

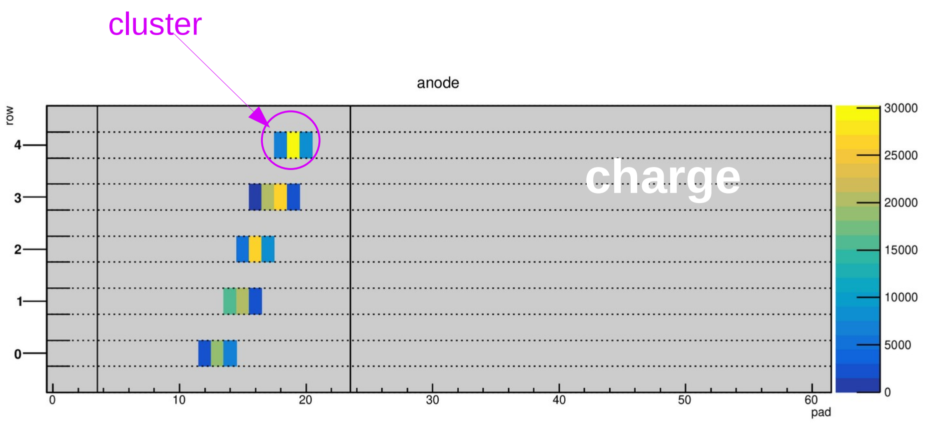


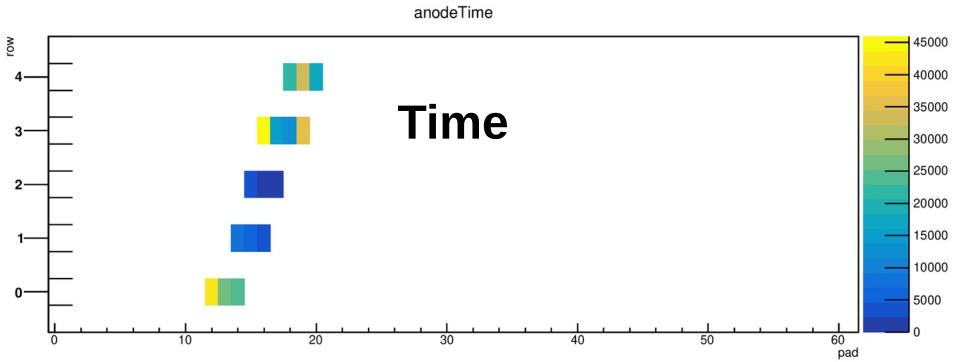


PICO picoammeter

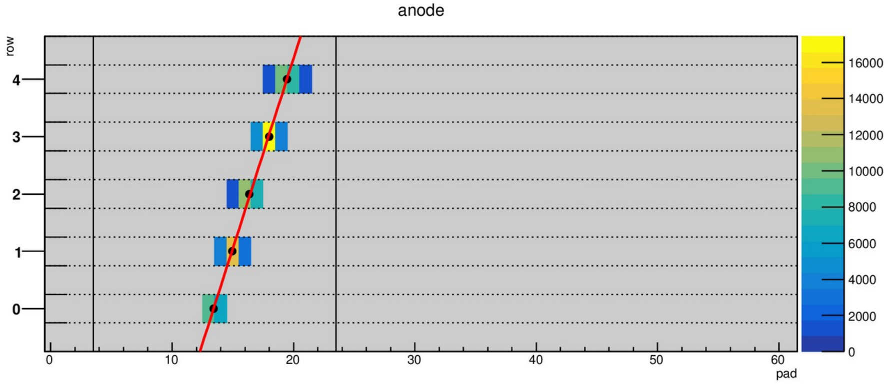


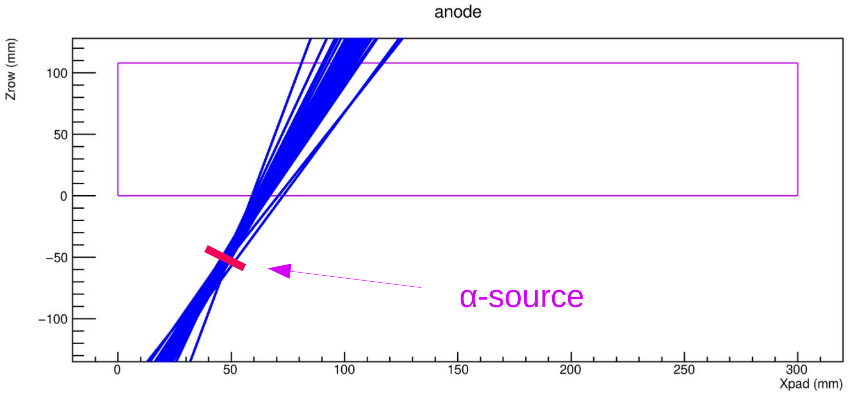
Tracking



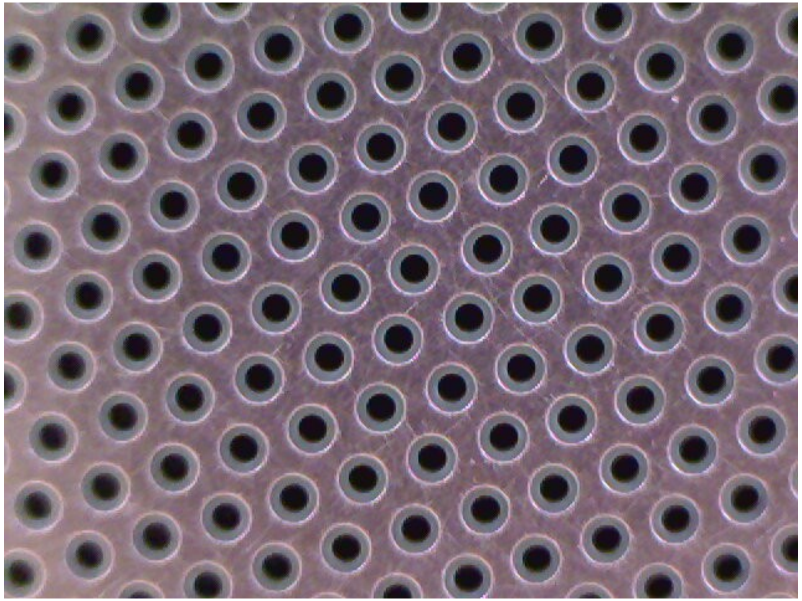


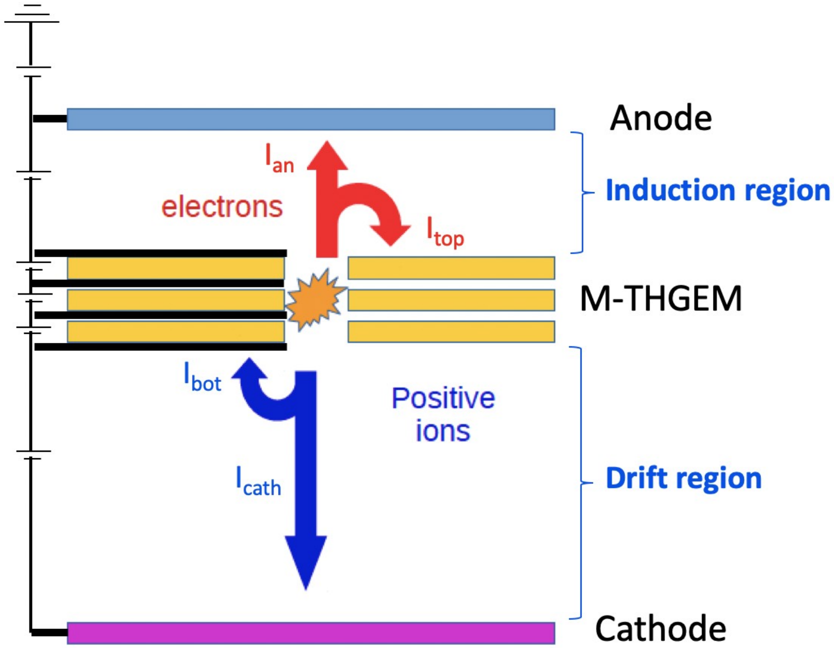
For each cluster the centroid is extracted and a fit of the position of the five centroids gives the track



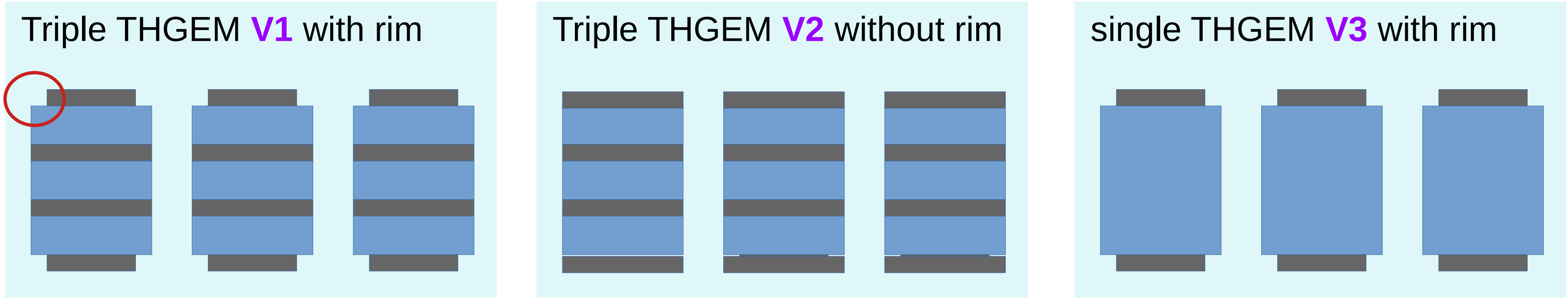


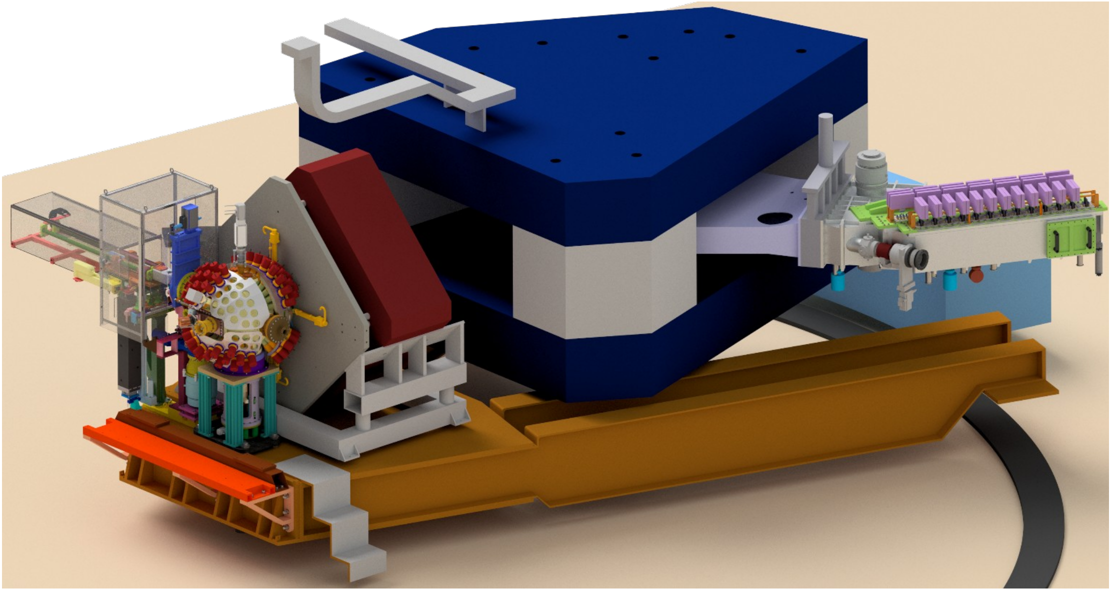
Backup

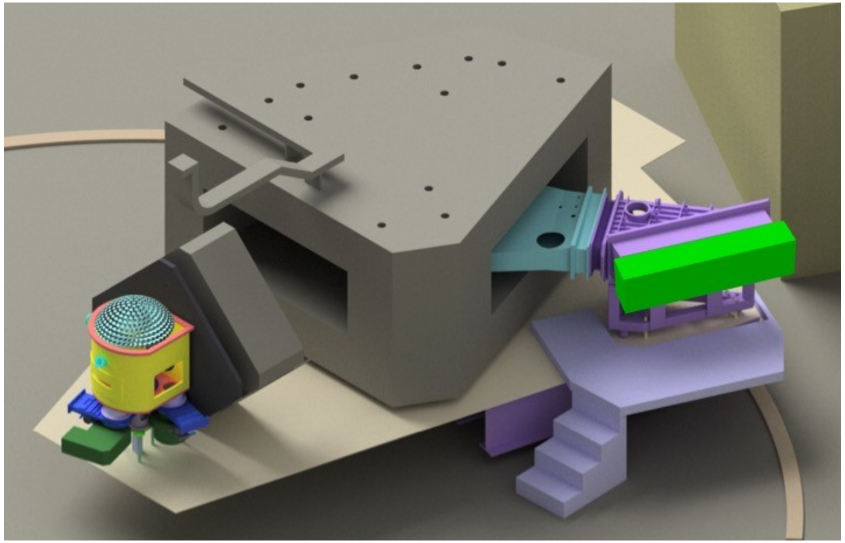



Anode
I_{an}
electrons
I_{top}
Induction region
M-THGEM
I_{bot}
Positive ions
I_{cath}
Drift region
Cathode

The three THGEM designs

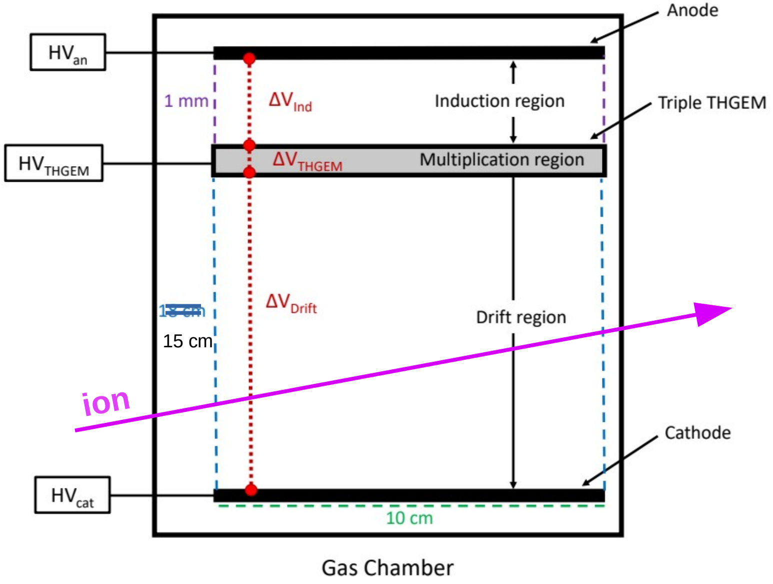


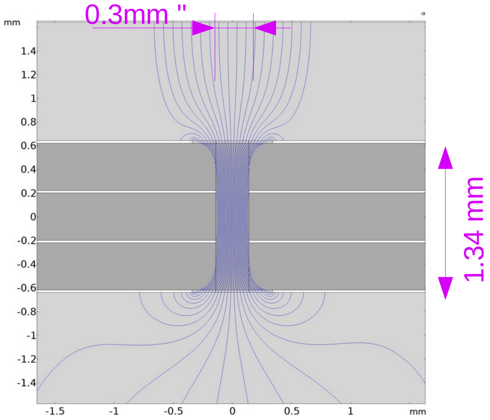




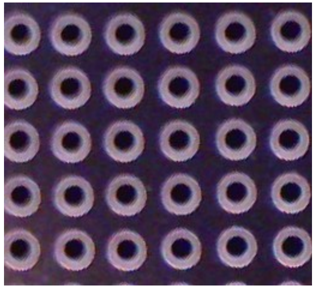
The gas tracker

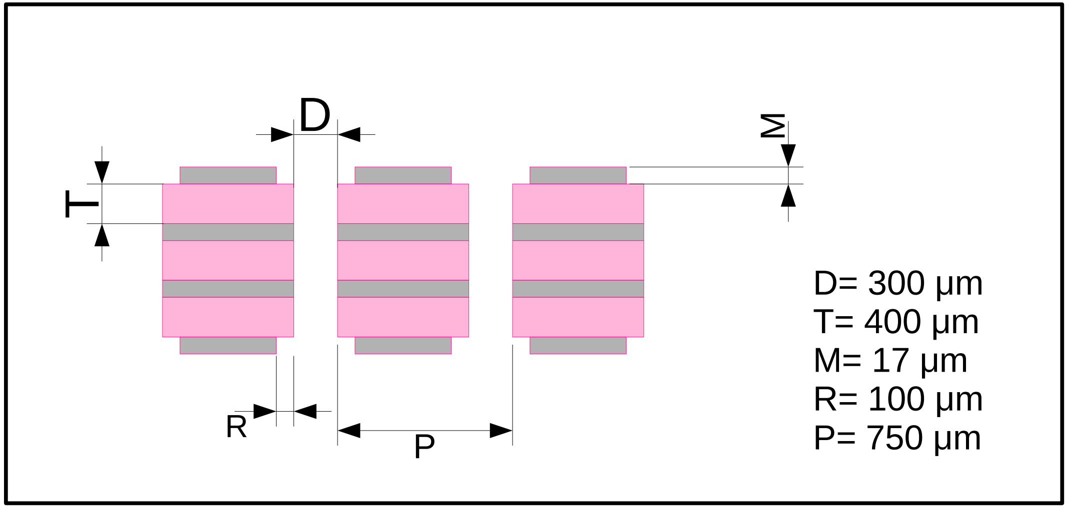
Scheme of the lateral section of the drift chamber





The triple THGEM



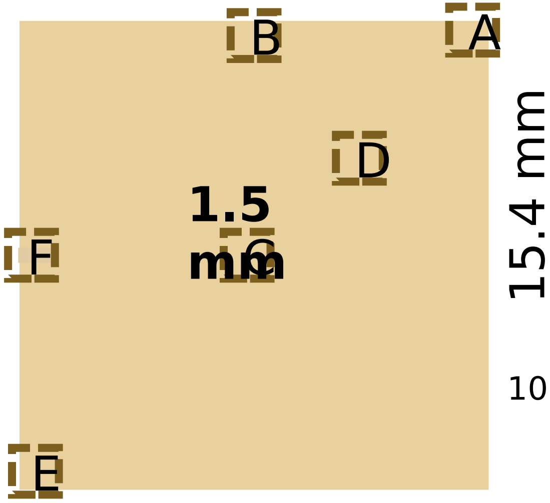


SiC characterizations with microbeams

Ruđer Bošković Institute, Zagreb (Croatia)

Experiment funded by EURO-LABS

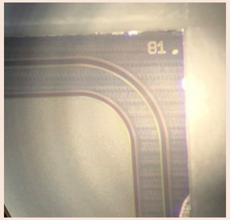
- SiC CCE profile: 3D characterization
- Dead layer thickness measurement

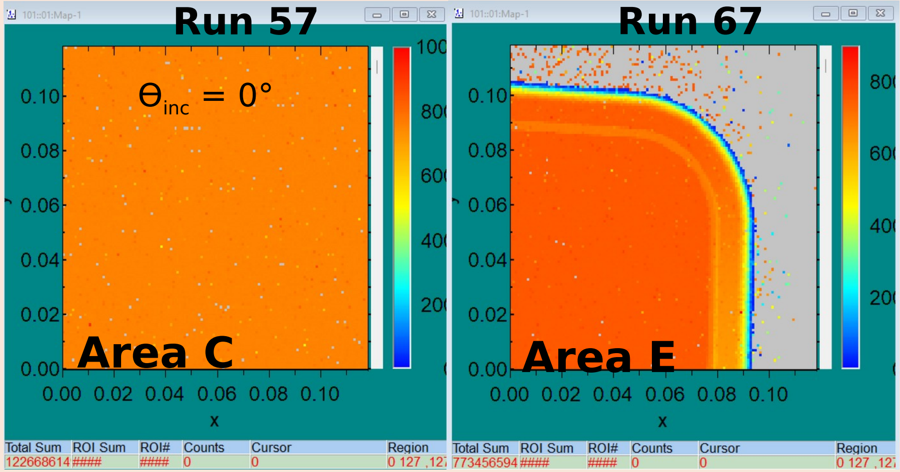


10 µm scanning pitch

Front irradiation

Proton energy 3.4 MeV

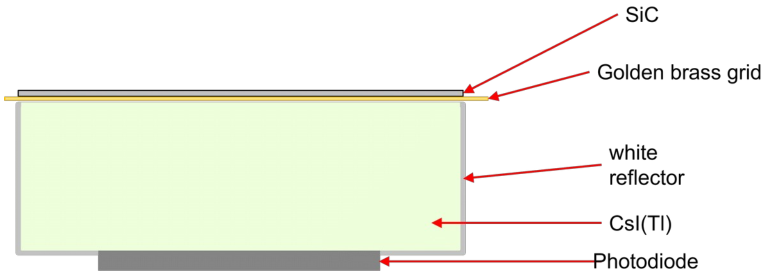




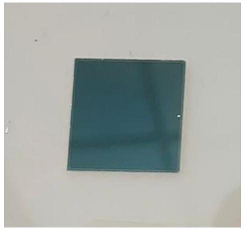
IBIC (Ion Beam Induced Charge) mode

- Good uniformity in the inner areas
- Rapid drop of the CCE at the edge

The PID wall

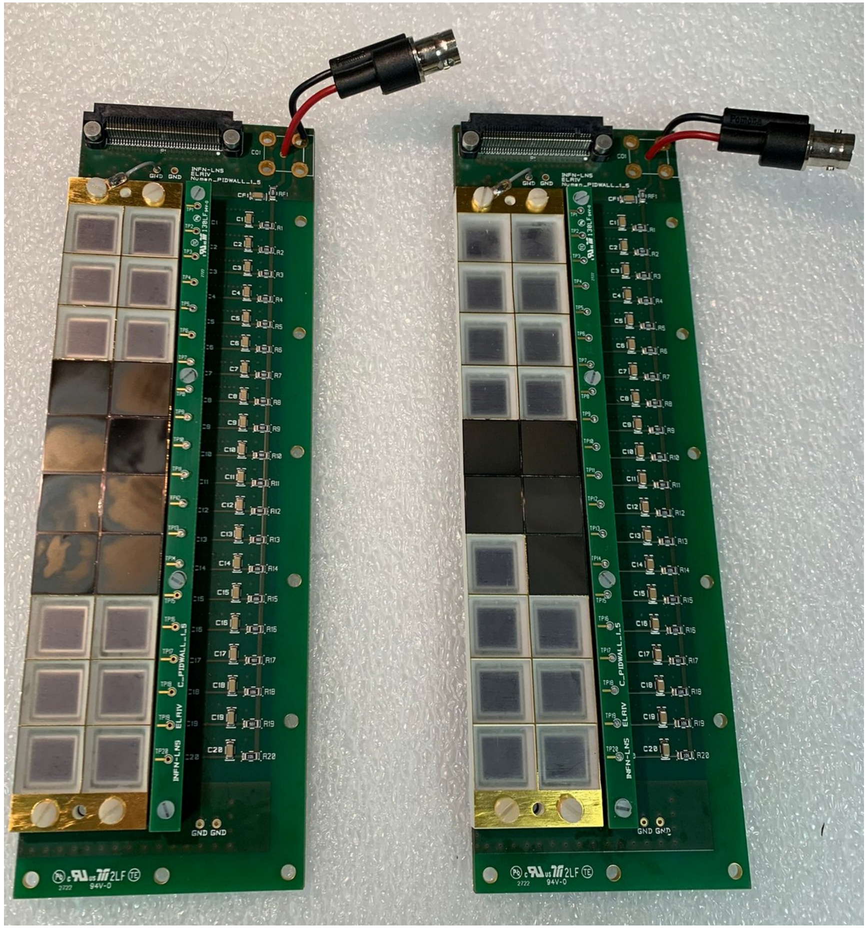


SiC
Thickness 100 µm
Area 1.54 x 1.54 cm^2
Bias -600/-1000 V



E stage CsI (Tl)
Thickness 5 mm
Area 1.5 x 1.5 cm^2

Hamamatsu Photodiode S3590-0887
Area ~ 1 x 1 cm^2
Bias -70 V



The anode