Status of the BAND-GEM detector

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From 2011 to present-day

- bGEM
- BAND-GEM Prototype
- BAND-GEM Demonstrator
- Improved BAND-GEM Demonstrator
- BAND-GEMPIX
- BAND-GEM detector option for LOKI
- Full Module

bGEM

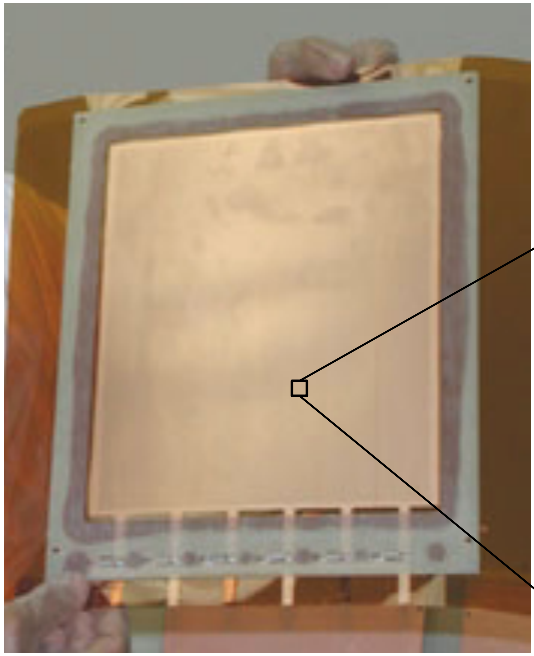
SHOULD WE DETECT THERMAL NEUTRONS WITH GEMS?

- GEM detectors born for tracking and triggering applications (detection of charged particles)....

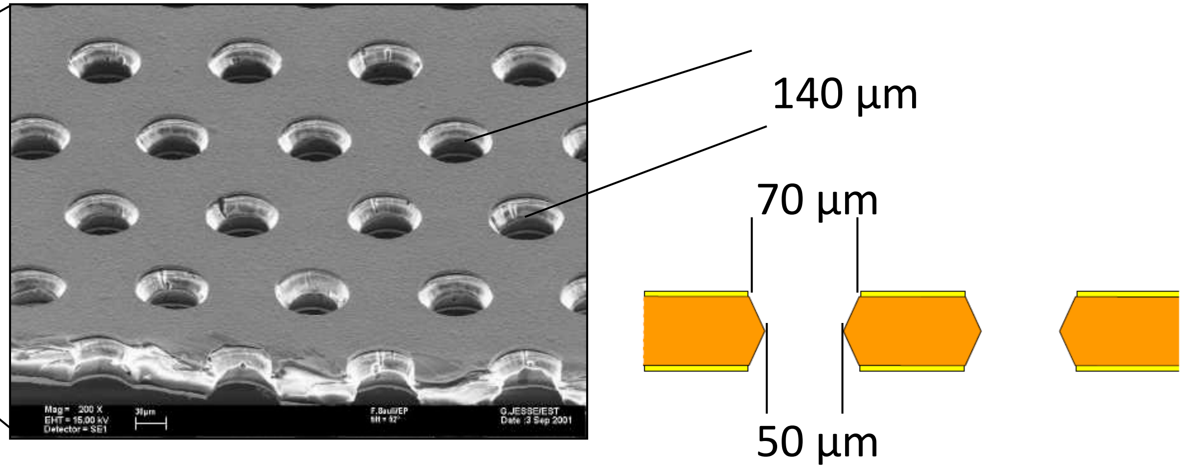
- ...but if coupled to a solid converter they can detect
  - Thermal Neutrons → ^{10}Boron converter
    - Neutrons are detected using the productus (alpha,Li) from nuclear reaction ^{10}B(n,alpha)7Li

- GEMs offer the following advantages
  - High rate capability (up to MHz/mm^2) suitable for high flux neutron beams like at ESS
  - Submillimetric space resolution (suited to experiment requirements)
  - Time resolution from 5 ns (gas mixture dependent)
  - Possibility to be realized in large areas and in different shapes
  - Radiation hardness
  - Low sensitivity to gamma rays (with appropriate gain)

WHAT IS A GEM?

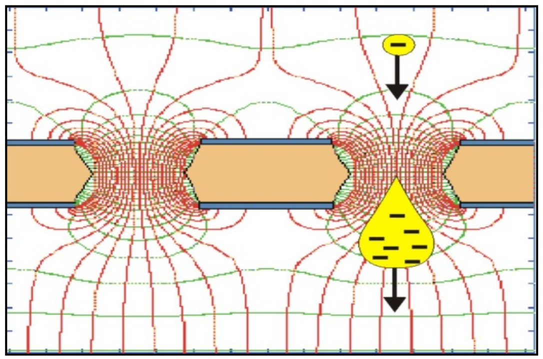


A Gas Electron Multiplier (F.Sauli, NIM A386 531) is made by 50 µm thick kapton foil, copper clad (5 µm thick) on each side and perforated by an high surface-density of bi-conical channels;



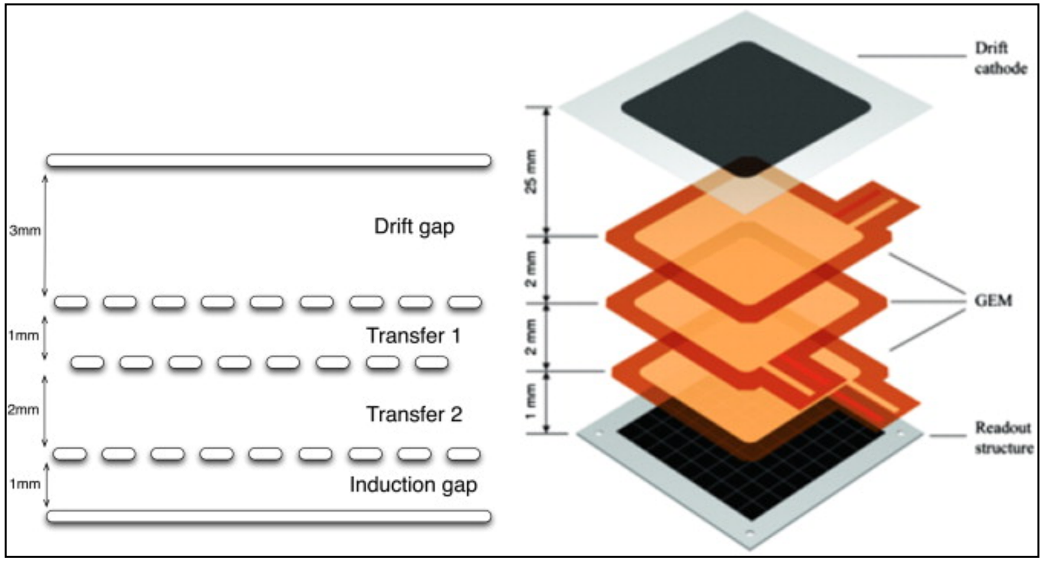
Applying a potential difference (tipycally between 300 and 500 volts) between the two copper cladding, an high intesity electric field is produced inside the holes (80-100 kV/cm).

GEM is used as a proportional amplifier of the ionization charge released in a gas detector.

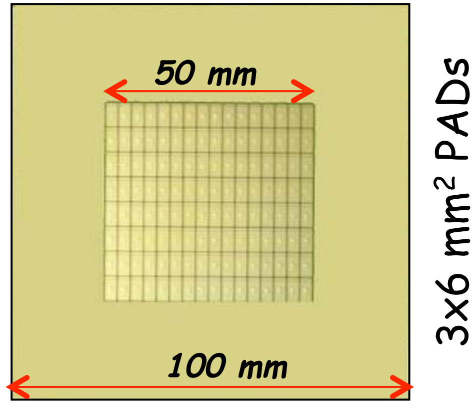


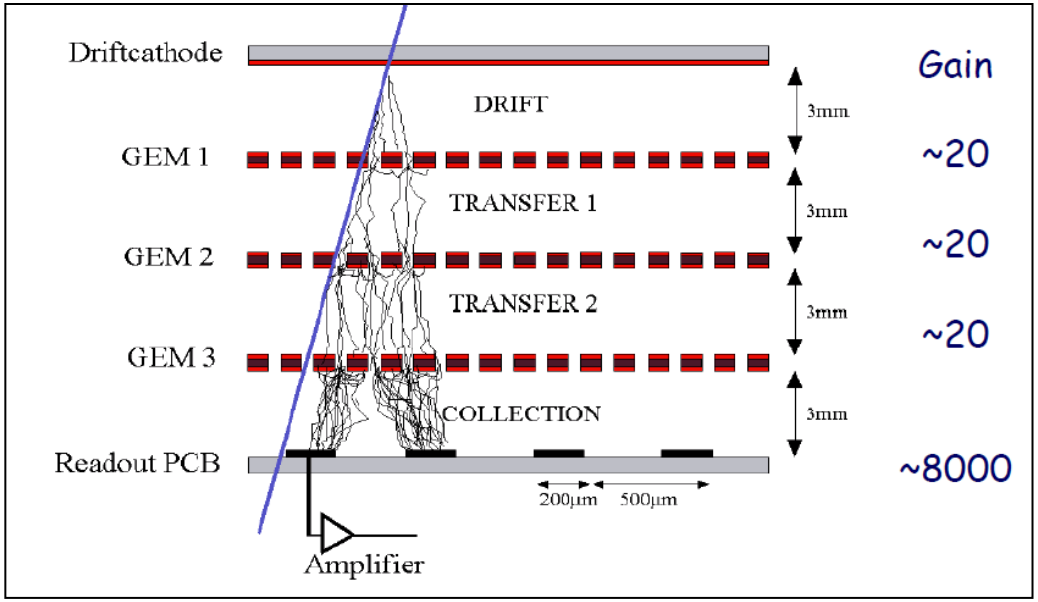
Triple-GEM detectors

Layout of a typical Triple GEM detector constructed with standard 10 x 10 cm².

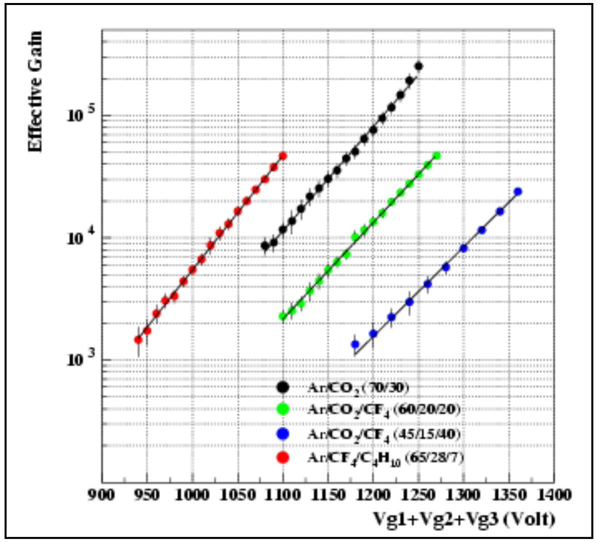


The anode has 128 pads. Each PAD can have a different geometry depending on detector applications.

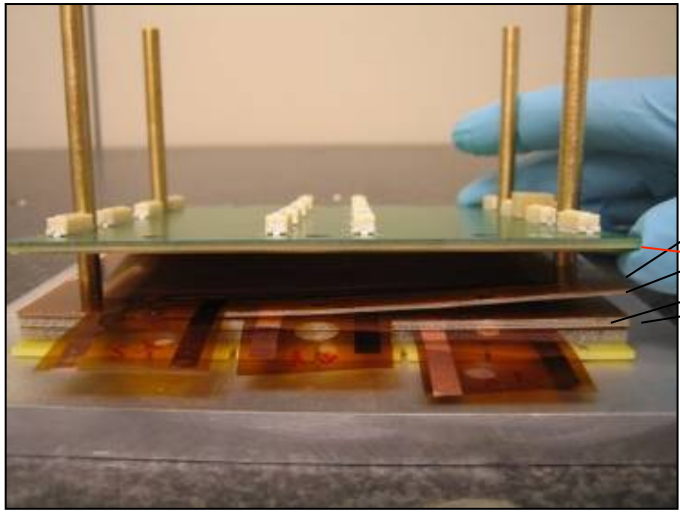


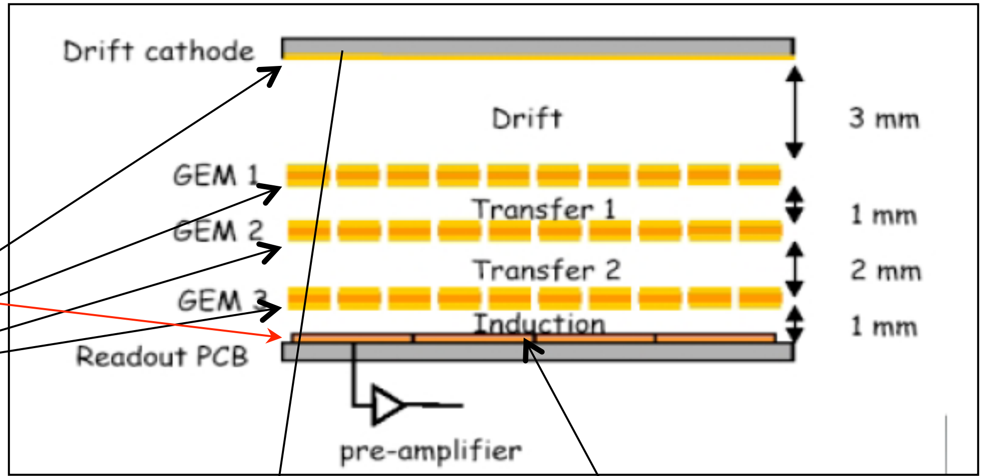


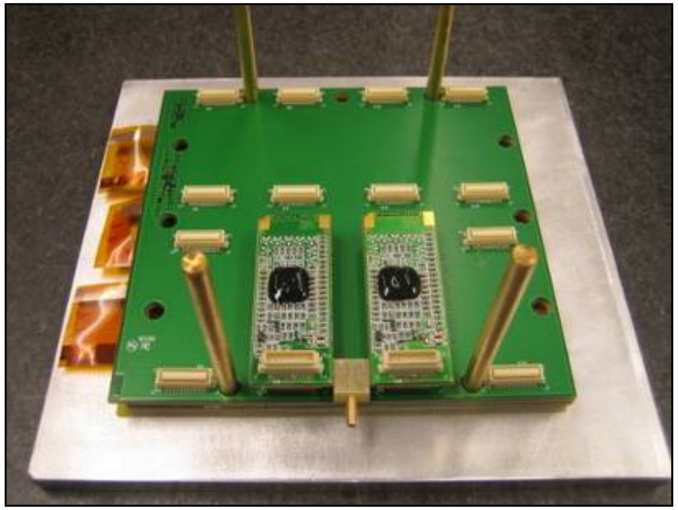
Gas Gain Curves



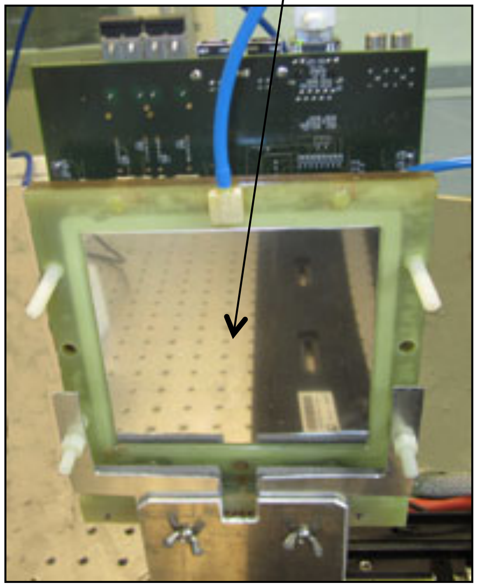
A STANDARD Triple-GEM detector



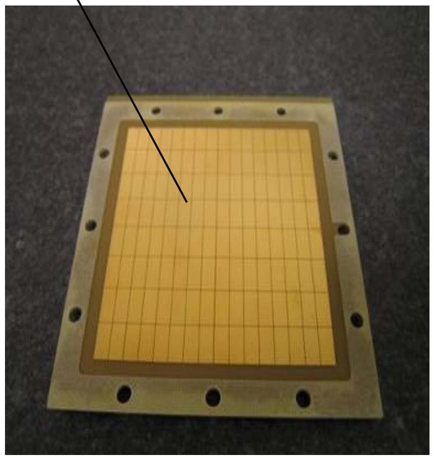




All the anode PCB have been designed with the same connector layout for a total of 128 channels.



Detector window: typically made of Aluminate Mylar or Fiberglass

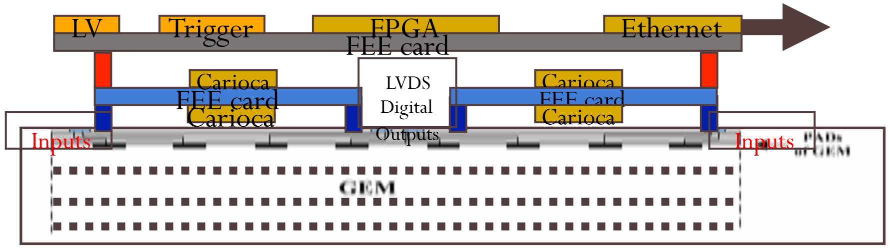


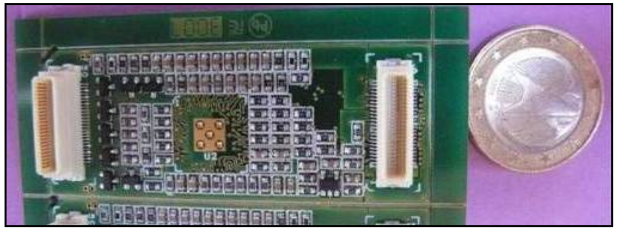
PCB anode divided in 128 PADs

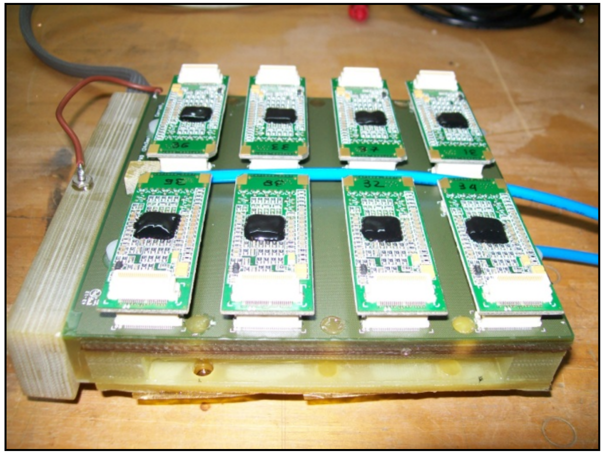
PADs dimension and geometrical configuration can be chosen according to the application of the detector.

FEE: CARIOCA GEM chip cards

CARIOCA chip cards







The card is based on Carioca GEM Chip and has been designed and realized in Frascati (LNF, Gianni Corradi); Total dimension : 3x6 cm^2
16 channels for each card: channel density of 1 ch/cm^2
Sensitivity of 2-3 fC,LVDS output (25 ns), Radhard.

New GEMINI chip: can manage 16 channels, in comparison to the 8 channels of the old one.

It will be able to measure also the charge released in the drift gap (not used here)

FEE: FPGA Mother Board

We have an Intelligent Mother Board with an FPGA (Field Programmable Gate Array) on board able to count the 128 channel hits and/or measure the time respect to a trigger (1 ns) ; the data are readable through an Ethernet connection (LNF A.Balla, P.Ciambrone, M.Gatta).

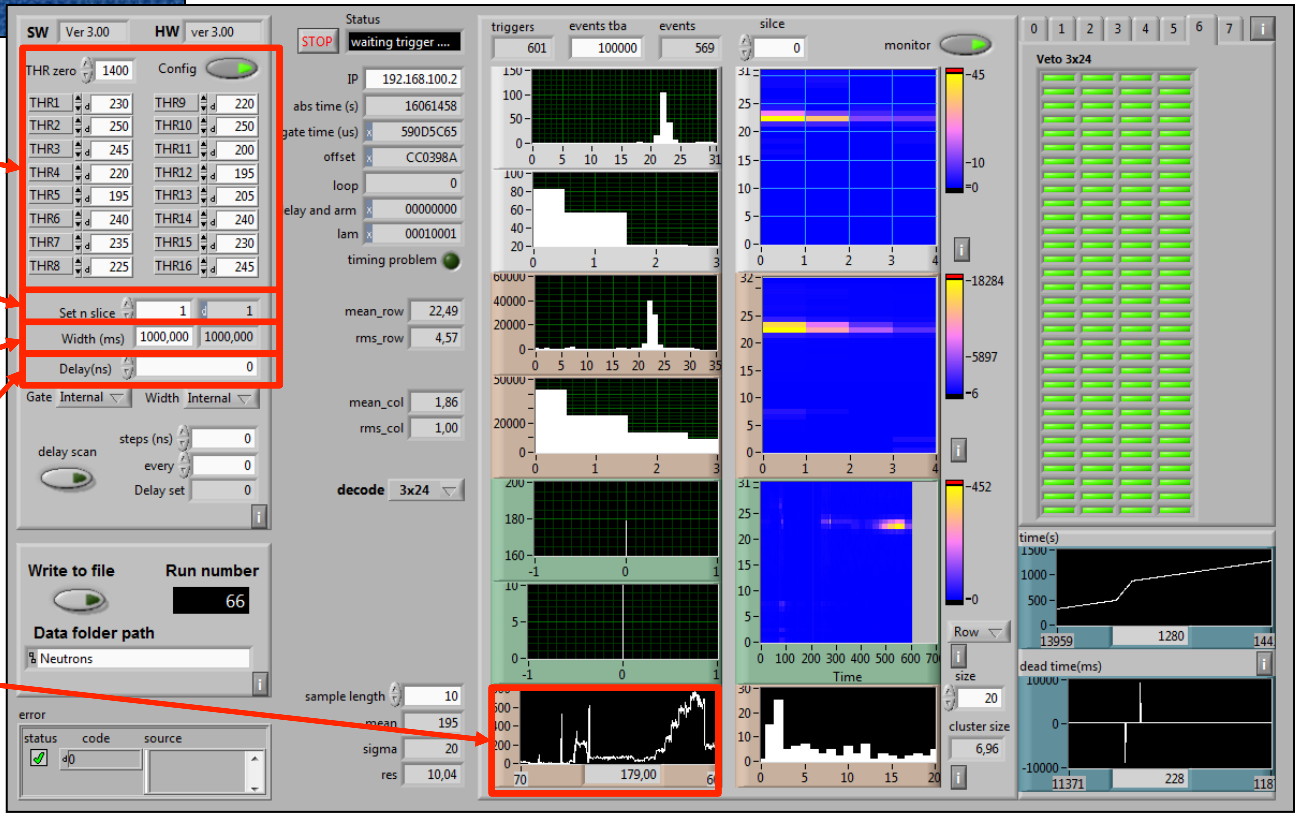
Threshlds settings

Slices acquisition

Integration time (untill 20-30 µs)

Delay to trigger

Total Counts vs time

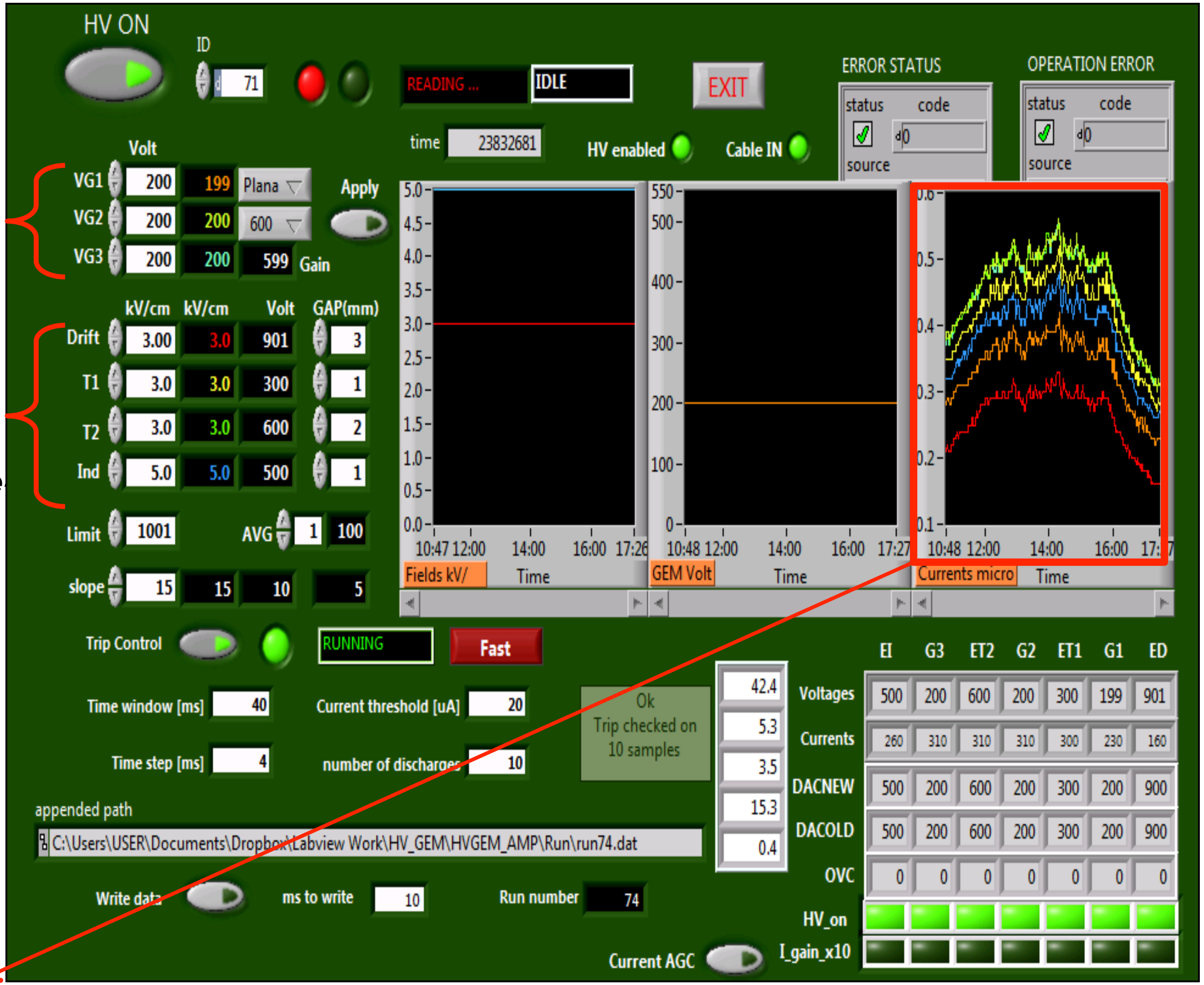


High Voltages: NIM standard HVGEM module

Labview Control Pannel for the High Voltage

GEM Voltage (gain)

Fields

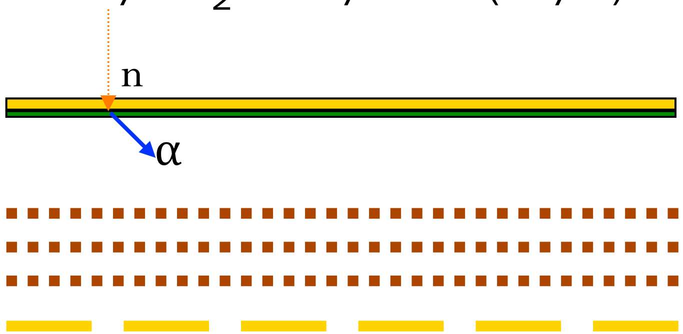


High Voltage Module for triple GEM detector

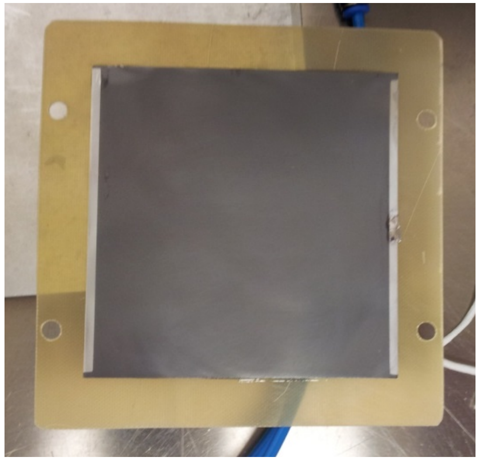
Real-time electrodes current measurements: each channel has a nano-Ammeter which measures the current with a sensitivity of 10 nA.

GEM detector for thermal neutrons (bGEM)

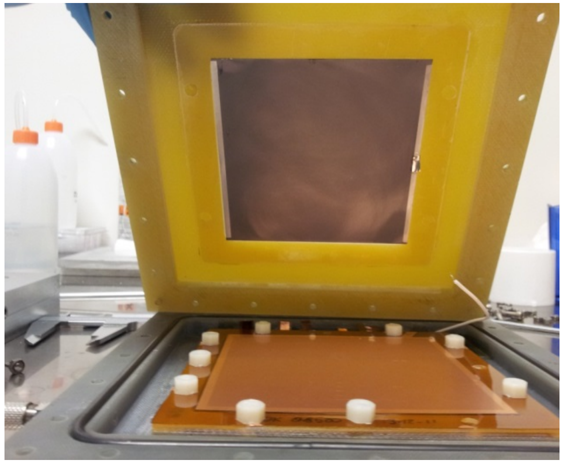
- Triple GEM detector equipped with an aluminum cathode coated with 1μm of B_4C
- Exploits the $^{10}B(n,\alpha)^7Li$ reaction in order to detect thermal neutrons
- $\Delta V_{GEM} = \Sigma V_{GEM} = 870$ V
- Gain ≈ 100
- Ar/CO_2 70%/30% (5 l/h)



Detector Schematics



B_4C coated aluminium cathode mounted on its support



B_4C coated aluminium cathode assembled inside the bGEM chamber layout

Natural B: Low efficiency detector: 1%

Enriched ^{10}B: 5% efficiency

G3-2 irradiation station at the ORPHEE reactor (LLB-Saclay)

Neutron beam

Thermal (E_{peak} = 3.5 meV) neutron flux:

7.88×10^8 n/s cm^2

Full beam about 2cm x 3 cm (6 pads....)

* BGEM: triple GEM with B_4C-deposited cathode
  Ar/CO_2 70/30 (5 l/h)
  V = 870 V (gas gain = 100)

**Borated cathode from HZ Geesthacht*

LINEARITY (comparison with fission chamber)

1.8 mm calibrated plastic slabs credited with a beam reduction of a factor 2 each

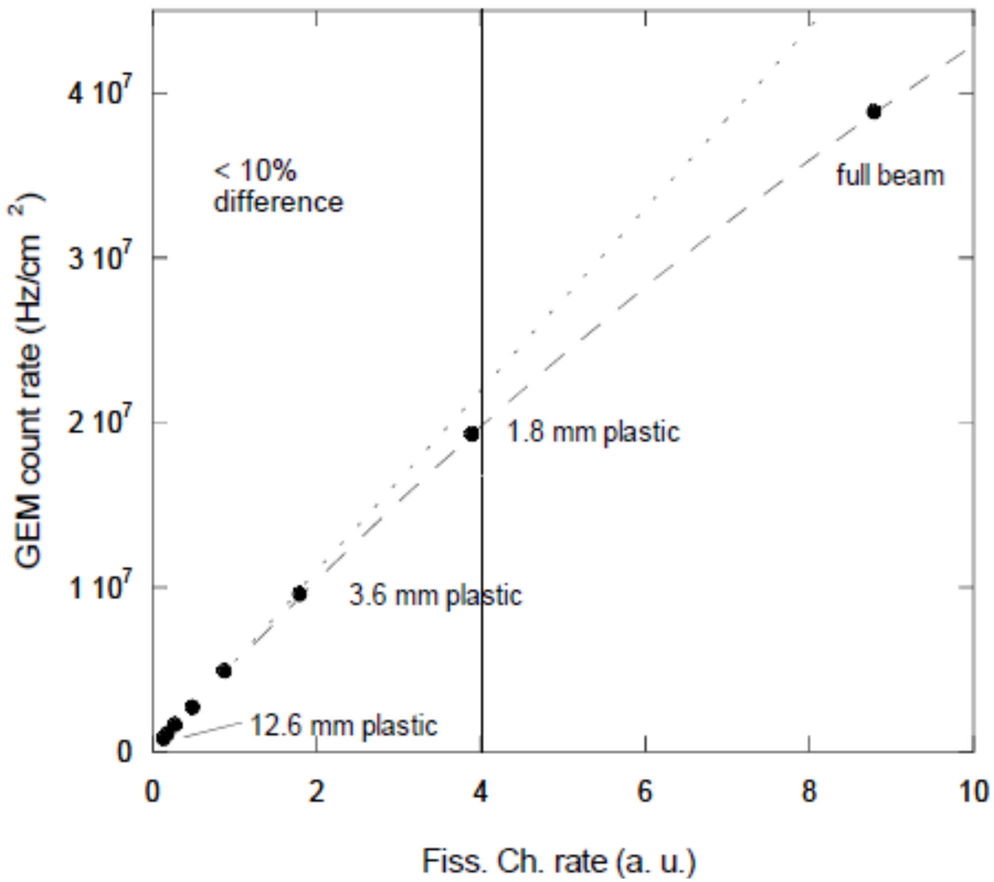
$y = a\,x \,/\, (1 + b\,x)$

x = FC rate; y = GEM rate

a = 3,5191e+06 [Hz/(pad a.u.)]
b = 0,028143 [a.u.-1]

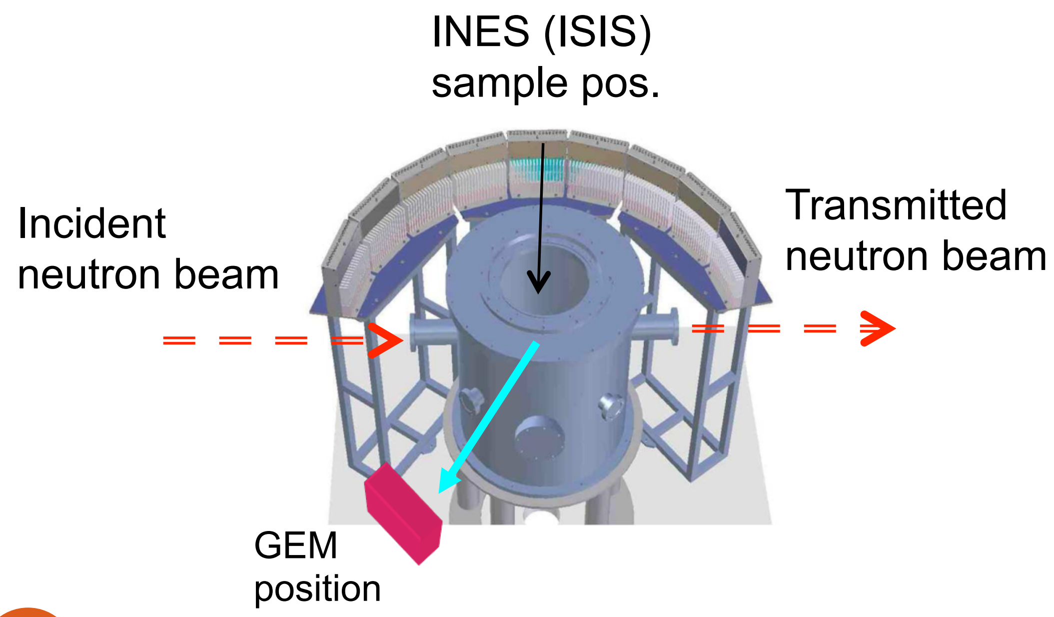
dead time of the detector+electronics system = b/a = **5.7 ns**

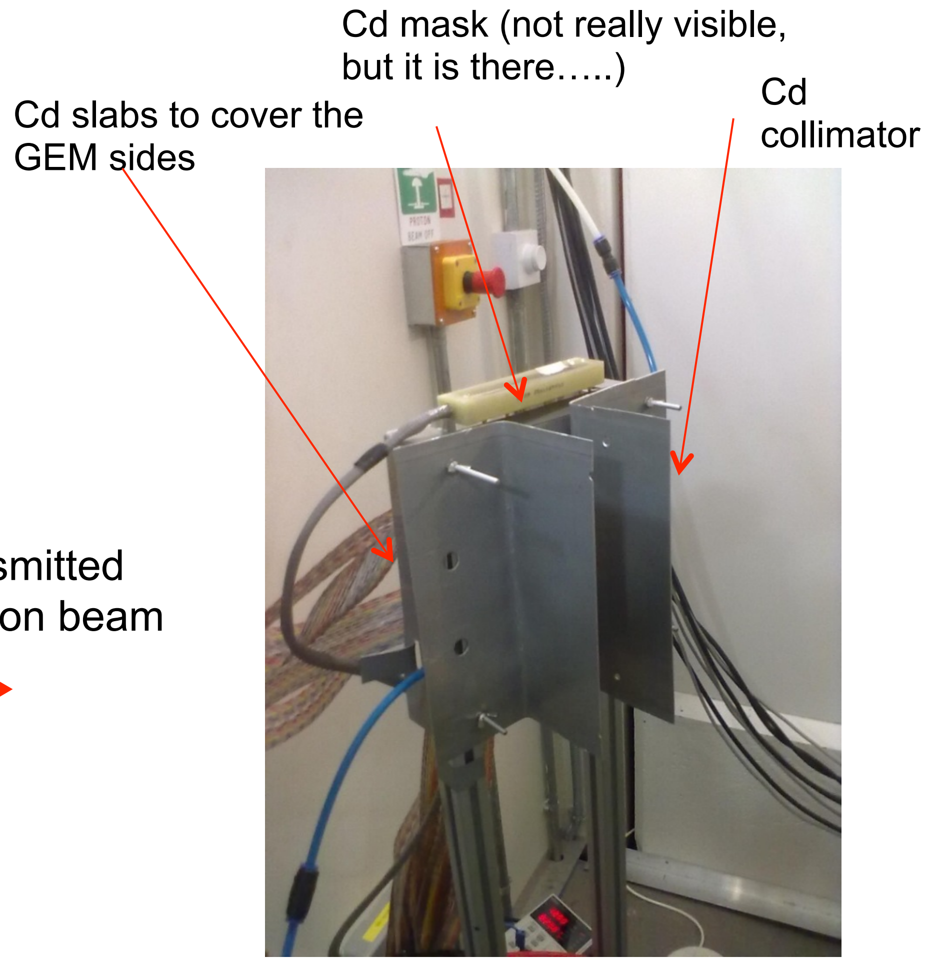
This value is compatible with GEM time resolution which is around 5 ns for this gas mixture



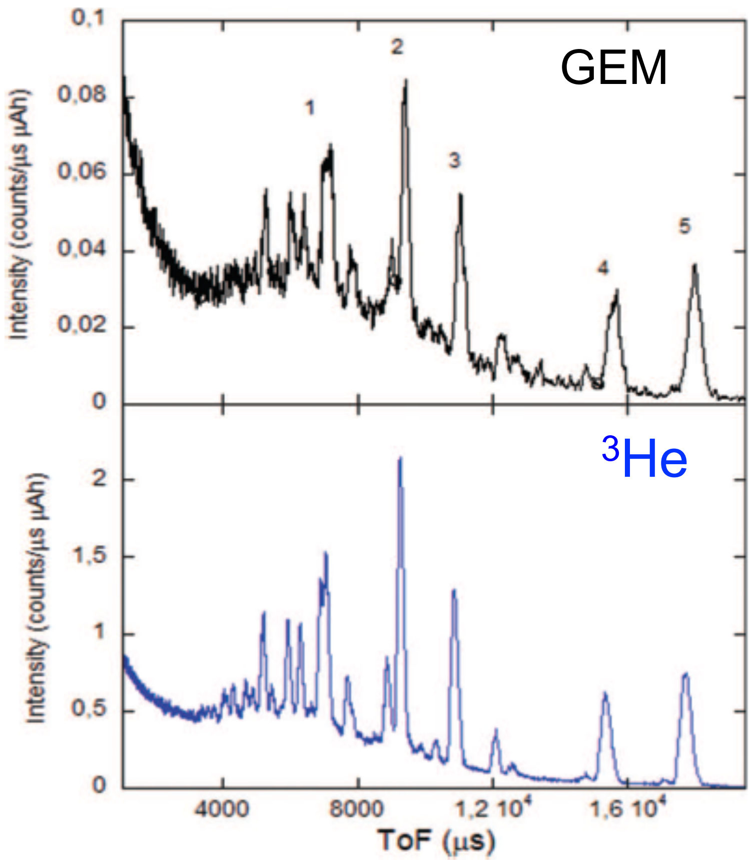
Test of bGEM detector for neutron diffraction measurements

- bGEM with enriched borated cathode
- Cd mask and **rough** collimator
- The bronze sample is different
- The same bGEM position (90°) was no longer available → FOCUSSING

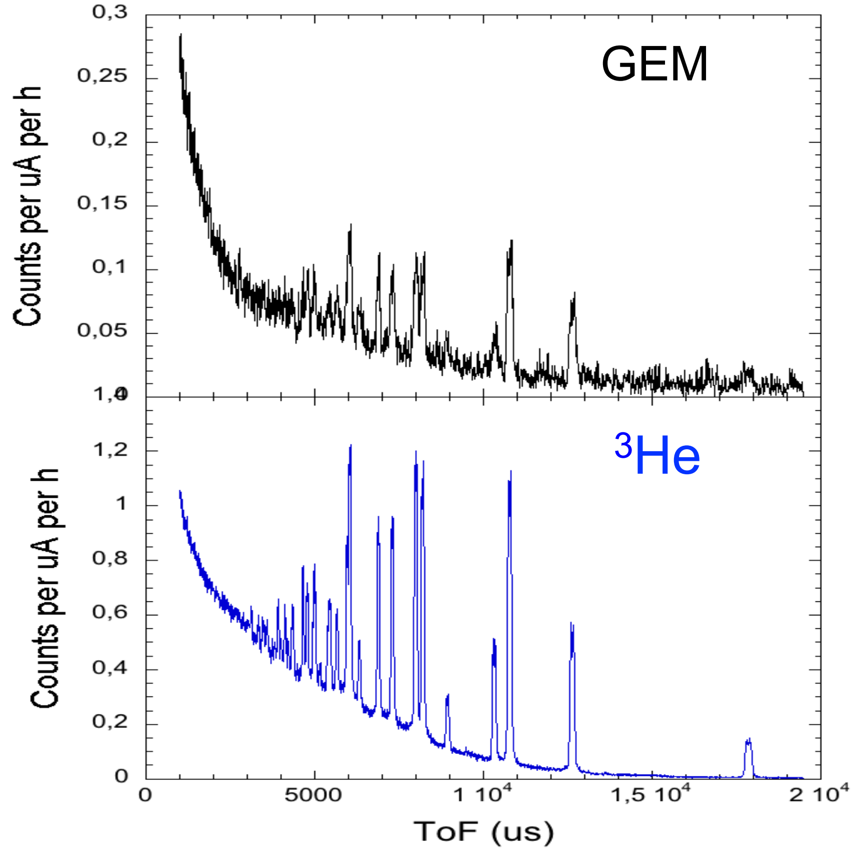




Comparison GEM vs ^{3}He tubes



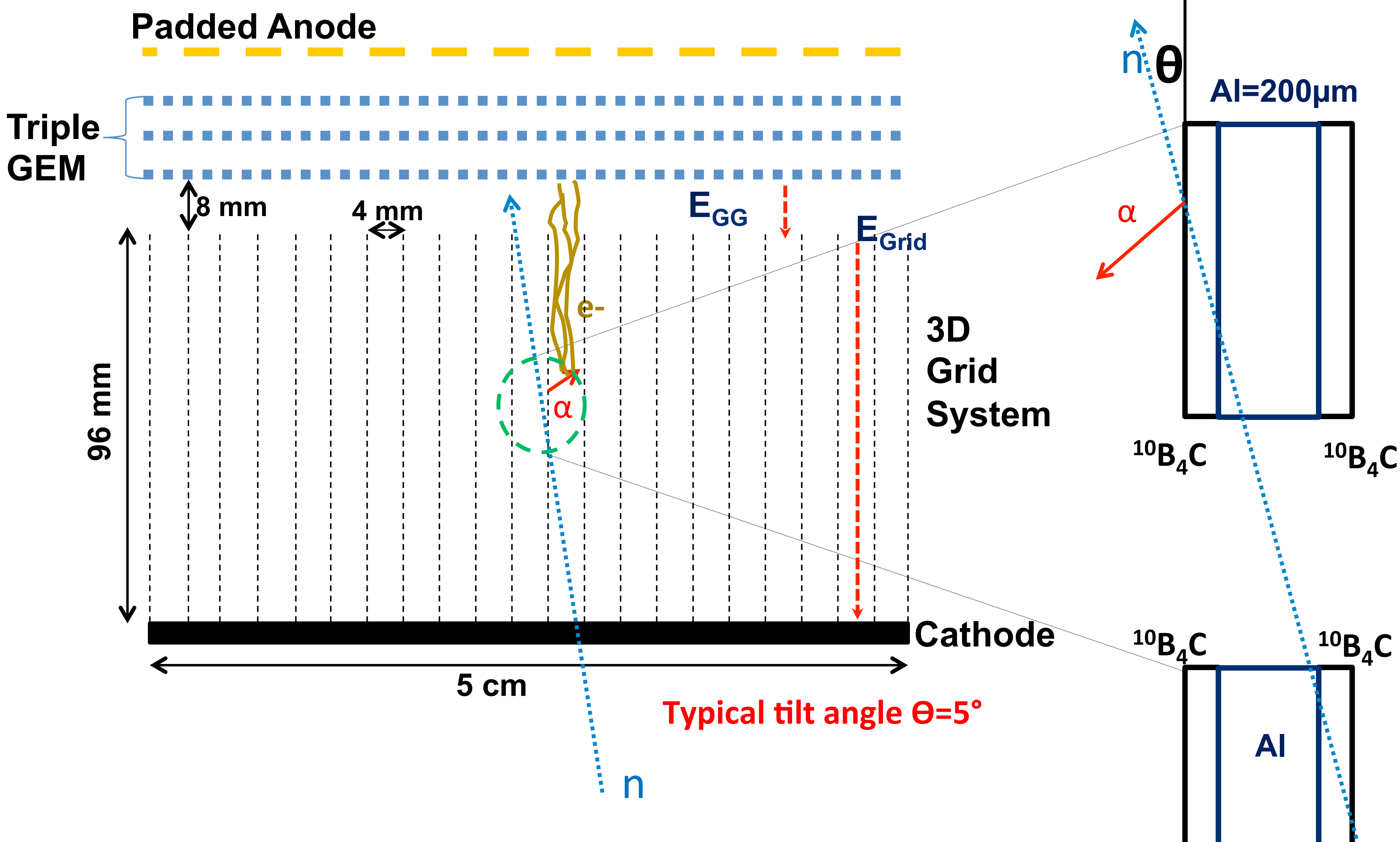
1st test (natural B)
He^3 rate x25 GEM rate



2nd test (enriched ^{10}B)
He^3 rate x8 GEM rate

BAND-GEM PROTOTYPE

BAND-GEM detection principle

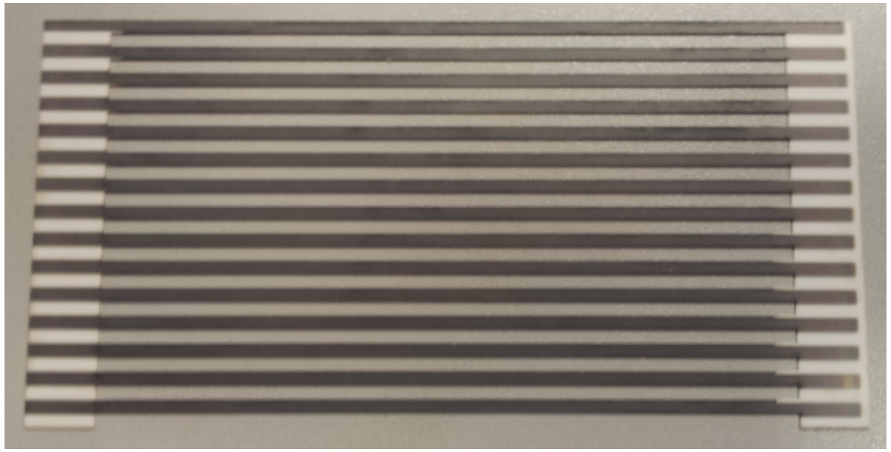


Alluminium grids coated on both sides with $^{10}B_4C$

Using low θ values (few degs) the path of the neutron inside the B_4C is increased → Higher efficiency when detector is inclined

$^{10}B_4C$ Coating on the lamellas

Deposition done by Dr. Carina Hoglund

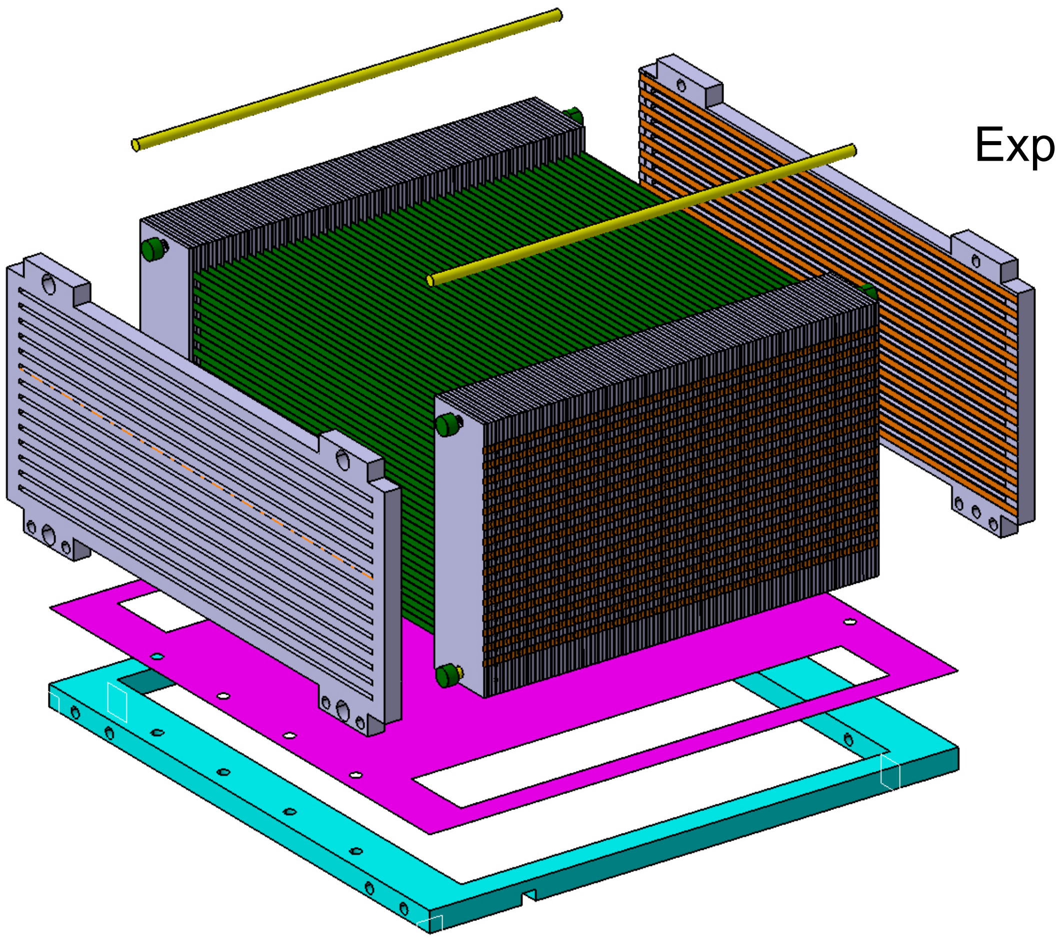


1 μm $^{10}B_4C$ coating on both sides

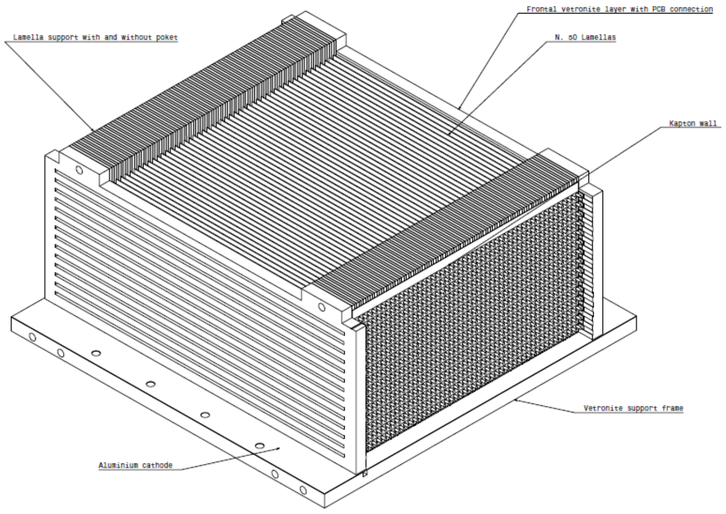
Determined by neutron absoprtion measurements (at ISIS-ROTAX)

Assembly of the 3D Lamellas Cathode

Exploded View

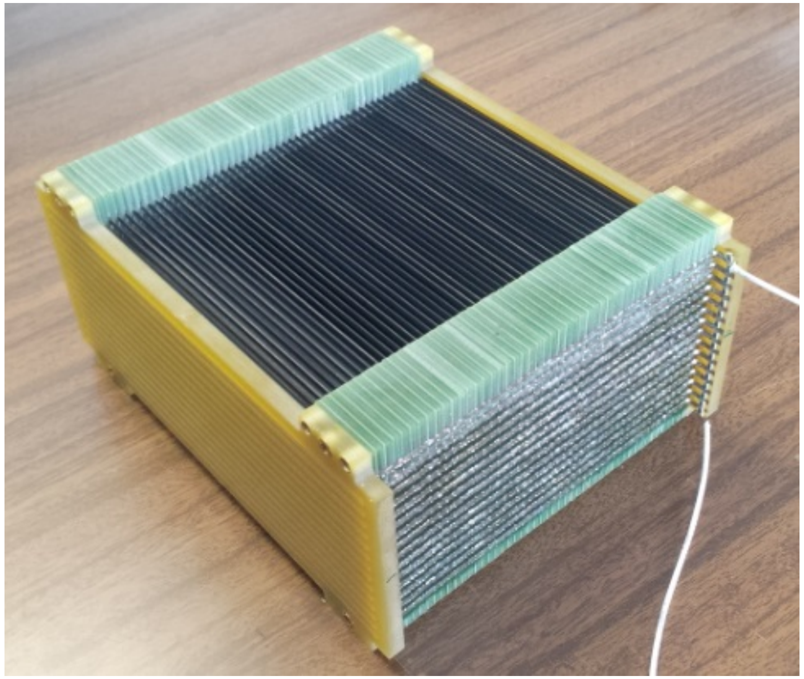


Assembled

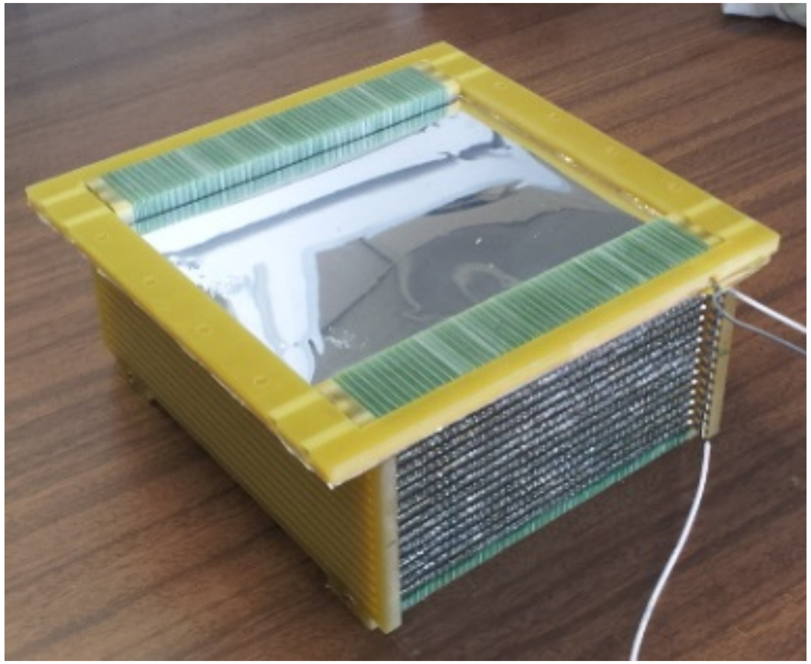


Neutrons come from the bottom.
GEMs + anode (not shown) are at the top

Detector Assembly

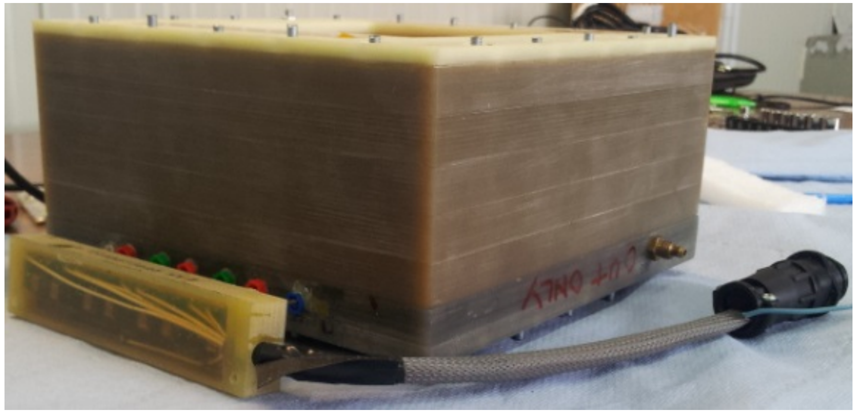


The full Lamella System



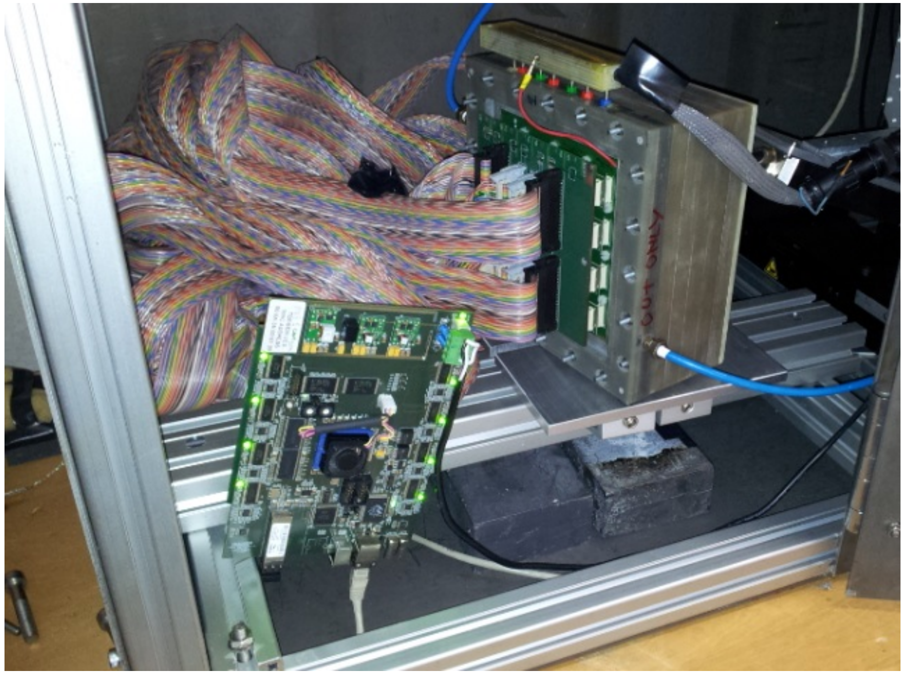
An aluminium cathode (few microns thick) has been mounted on top

Detector test with X-Rays

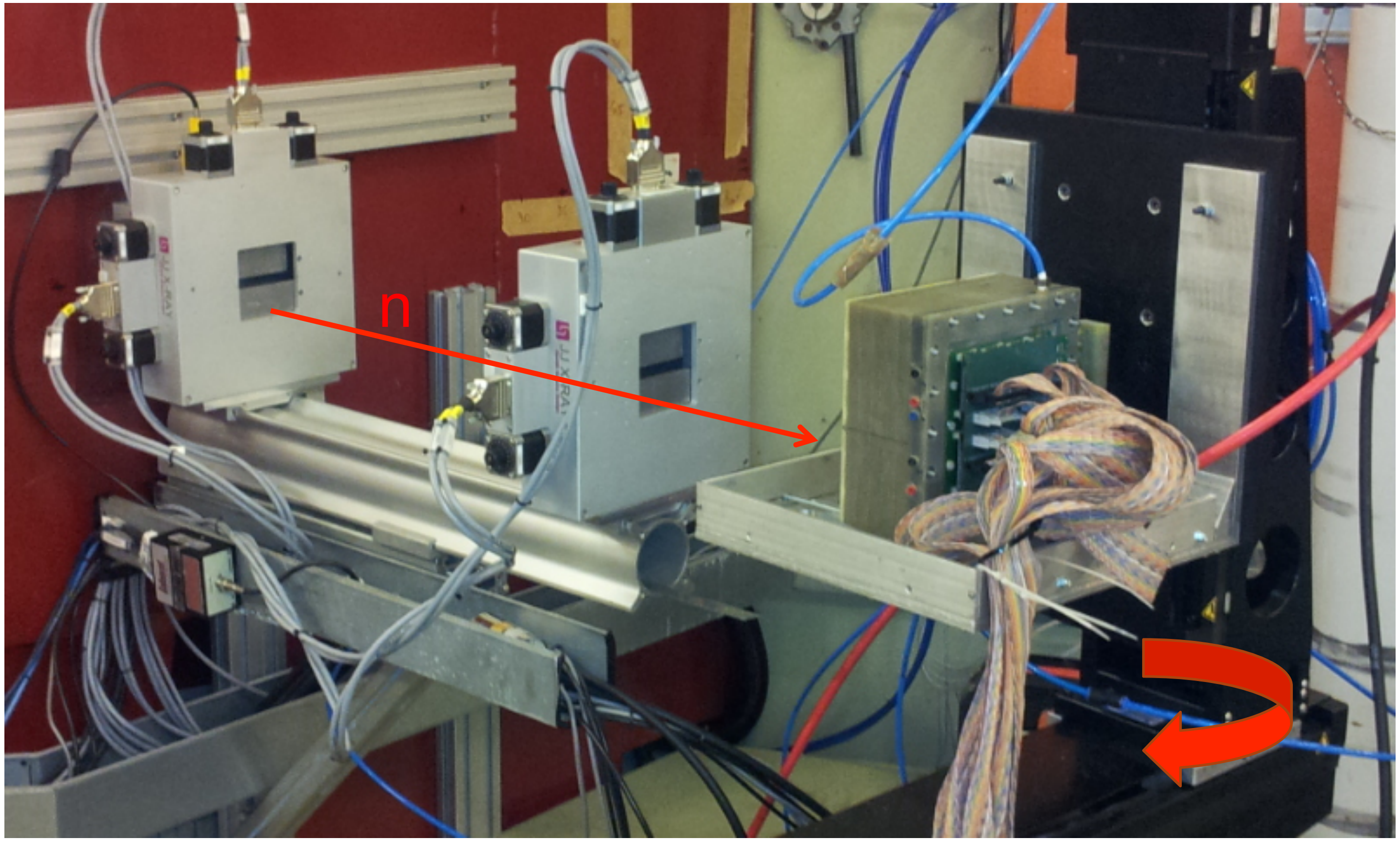


Detector completed

Test with X-Rays (in IFP-lab)



Detector test at IFE (JEEP II Reactor, RD2D beamline)



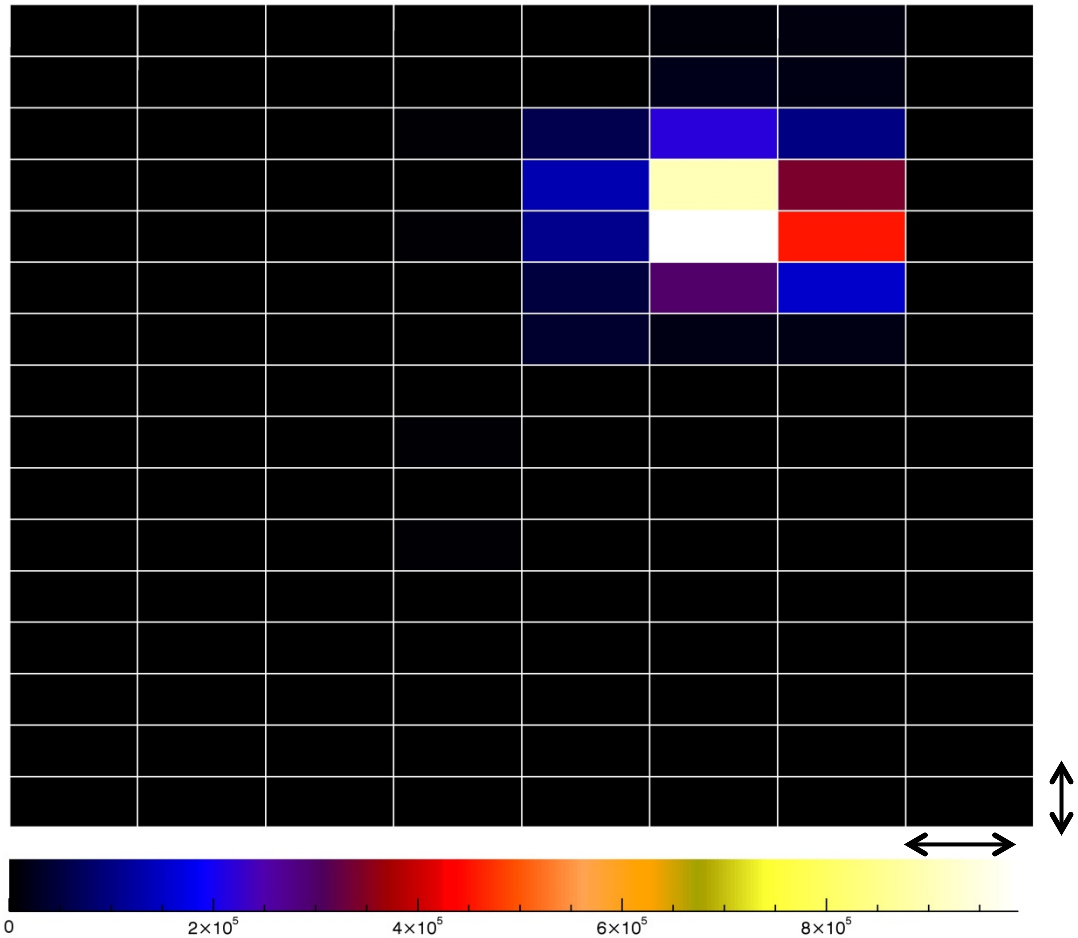
Monochromatic neutron beam: possibility to select two wavelenghts:

λ = 1.54 Å, E = 34.5 meV

λ = 2 Å, E = 20.45 meV

Possibility to set different beam sizes

Beam Profile



6 mm

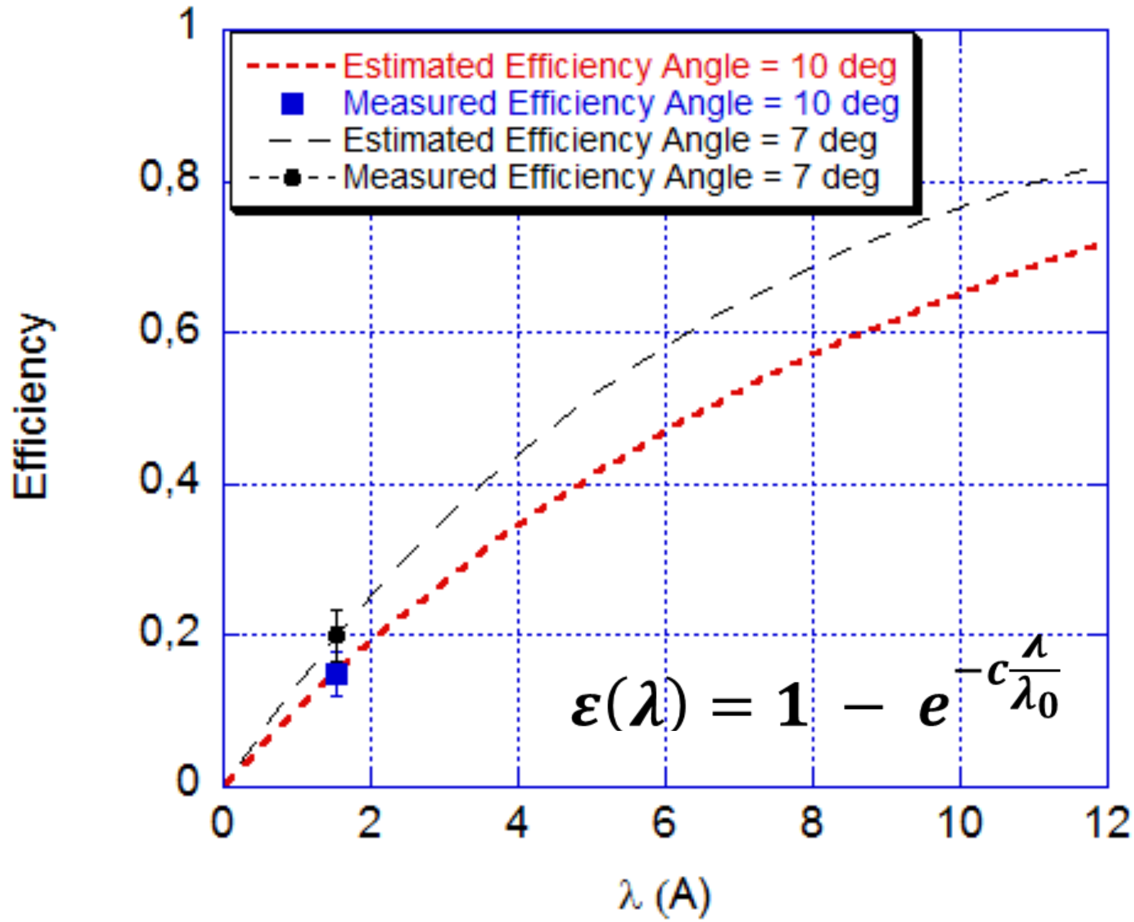
12 mm

E_d = 230 V/cm
E_{t1}=E_{t2}= 3 kV/cm;
E_i = 5 kV/cm

Mixture Ar/CO2 70%/30%
Angle = 10 degrees

VGEM = 980 V

Efficiency



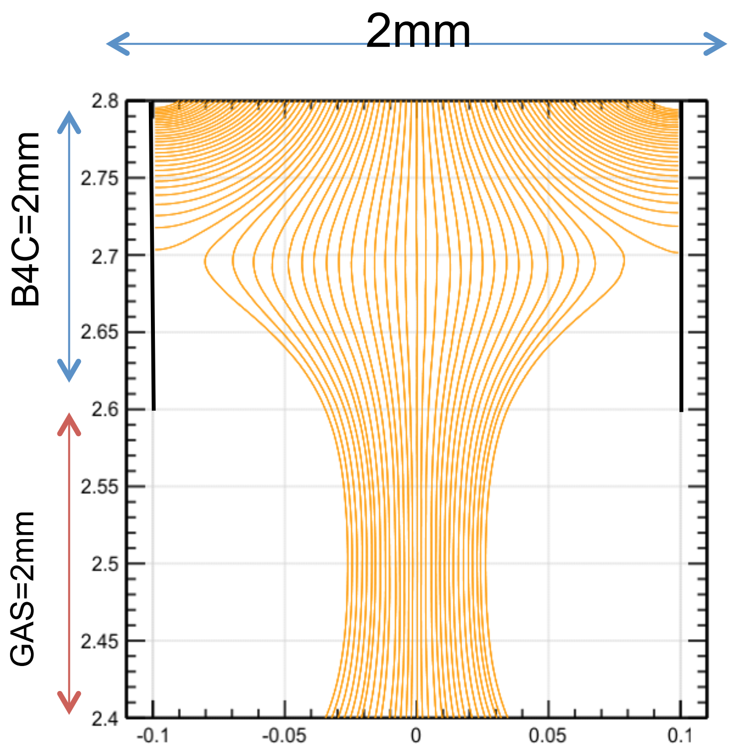
c comes from $\sigma(\lambda) = \sigma_0 * \lambda / \lambda_0$

where if $\lambda=\lambda_0=1.54$ A $\varepsilon=\varepsilon_0=0.15$ for 10 degrees and $\varepsilon=\varepsilon_0=0.20$ for 7 degrees

BAND-GEM DEMONSTRATOR

BANDGEM Demonstrator Electrons extraction Simulation

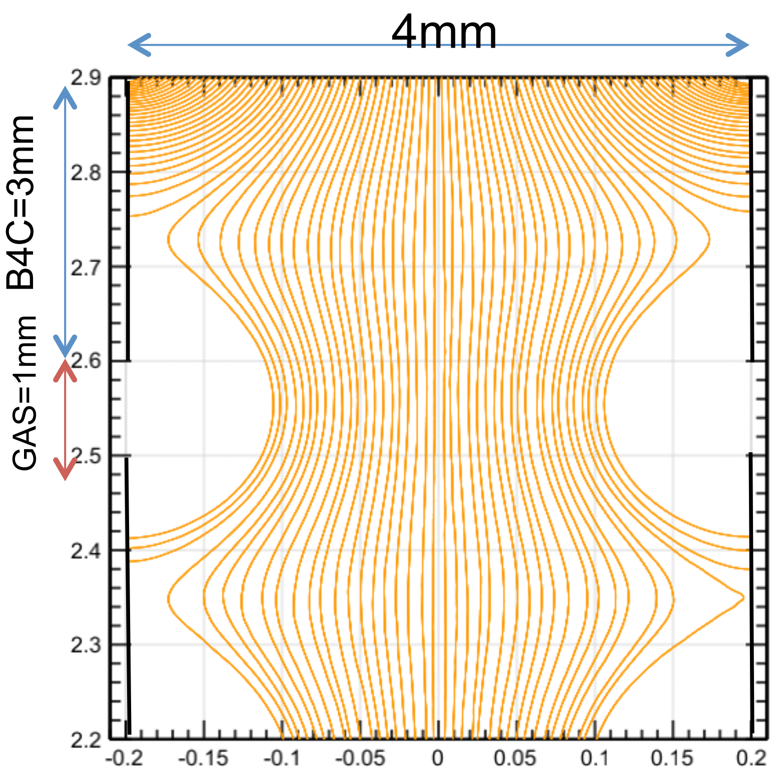
Prototype Geometry



Volumetric Simulation (1000 e-) Diffusion ON
Good Electron 1000, Out Electron 263
Percentage 26.3

Volumetric Simulation (1000 e-) Diffusion OFF
Good Electron 1000, Out Electron 486
Percentage 48.6

Demonstrator Geometry



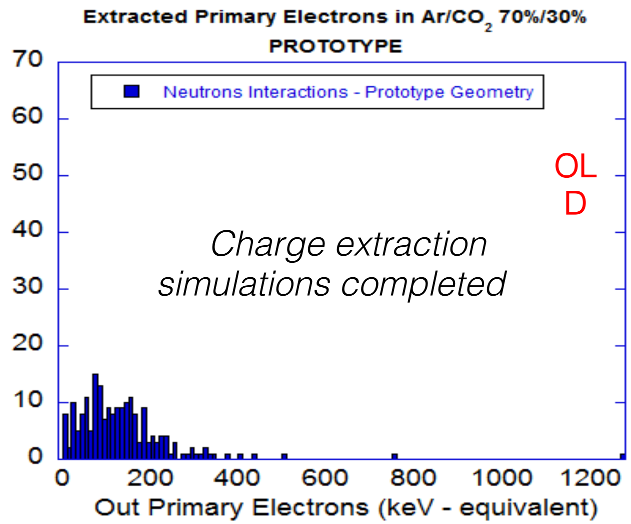
Volumetric Simulation (1000 e-) Diffusion ON
Good Electron 1000, Out Electron 544
Percentage 54.4

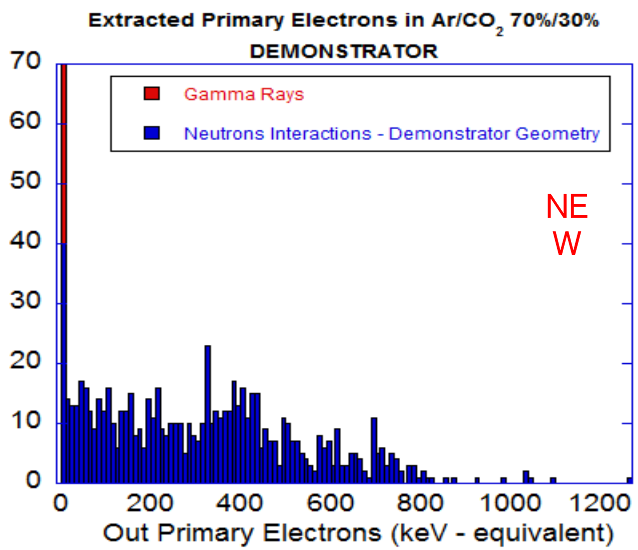
Volumetric Simulation (1000 e-) Diffusion OFF
Good Electron 1000, Out Electron 670
Percentage 67

Performance: Prototype and Demonstrator

EUROPEAN SPALLATION SOURCE

Consiglio Nazionale Ricerche

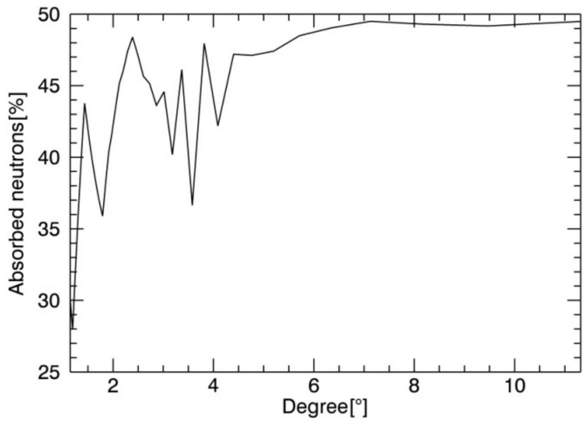




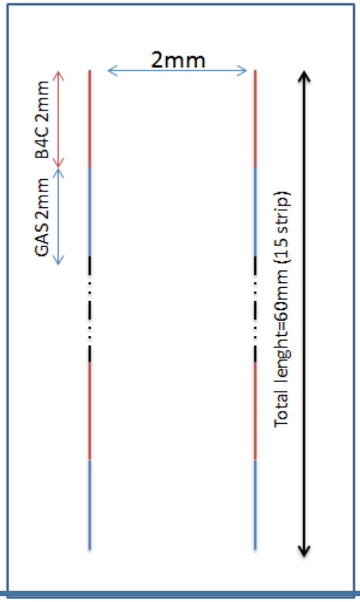
BAND-GEM demonstrator simulation

Numerical Simulation of Neutron conversion efficiency

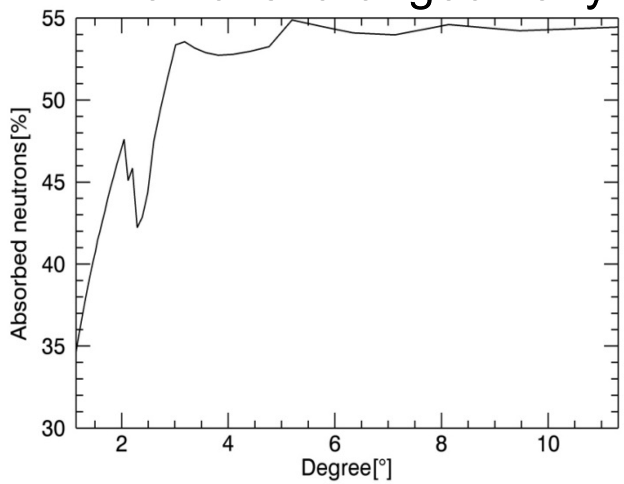
Prototype geometry



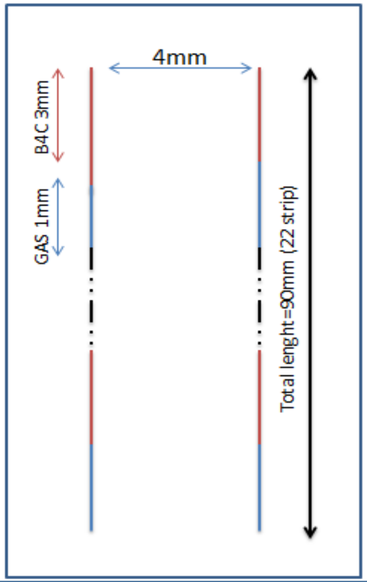
Actual geometry



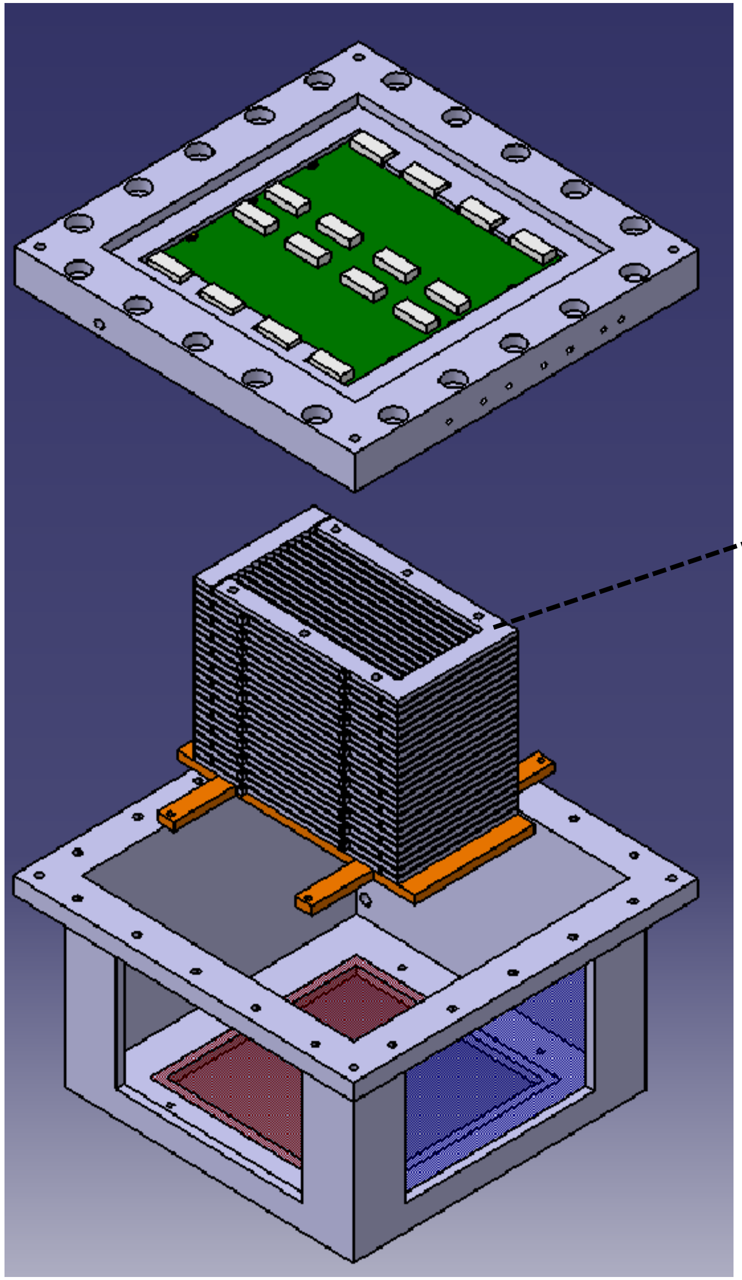
Demonstrator geometry

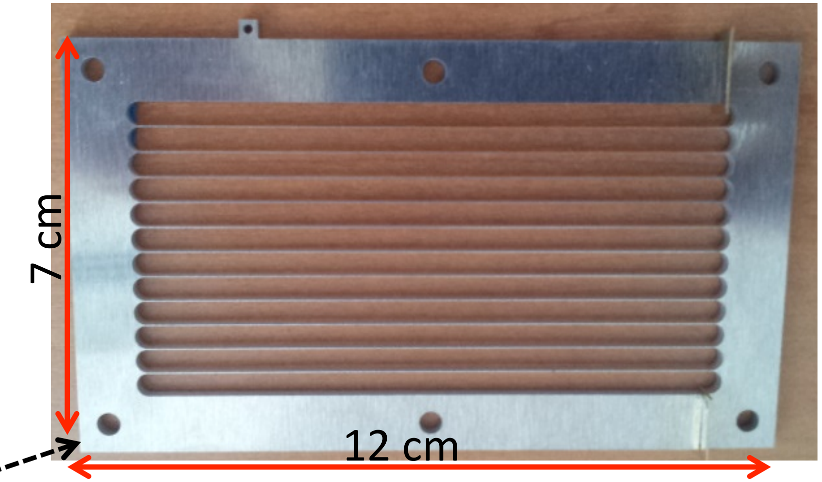


New geometry

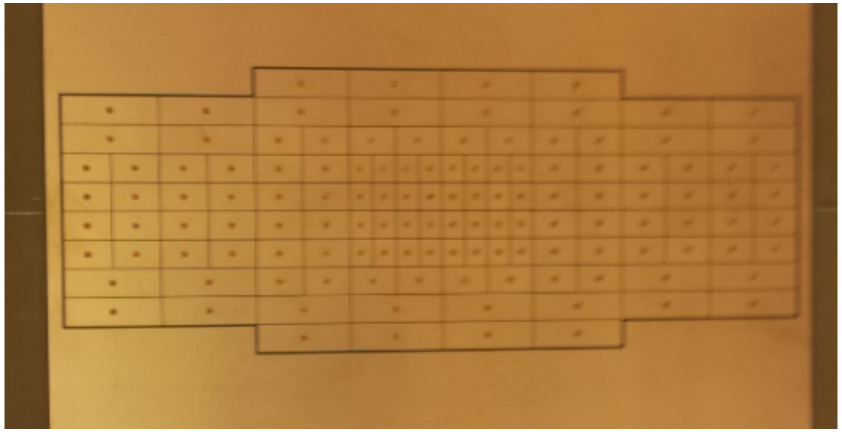


5x10 cm^2 active area detector



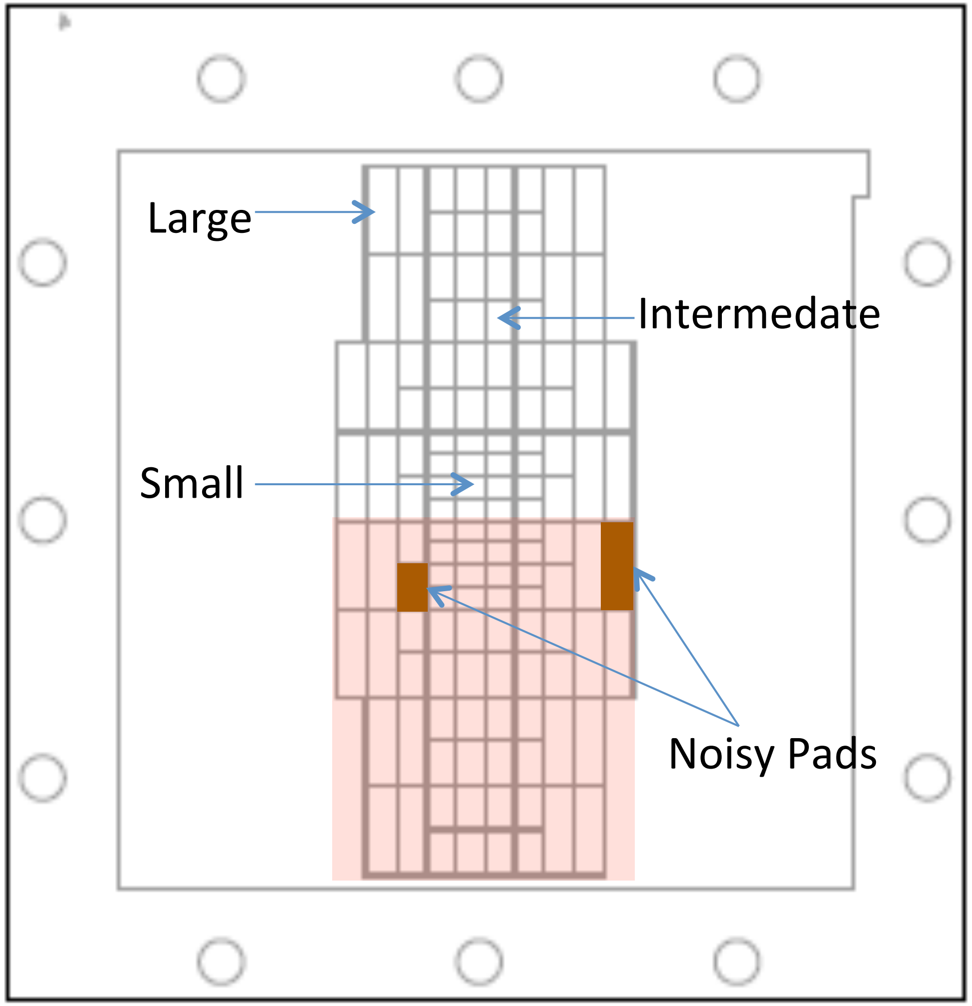


Strip thickness = 200 µm
Al + tensioning screws
Contact



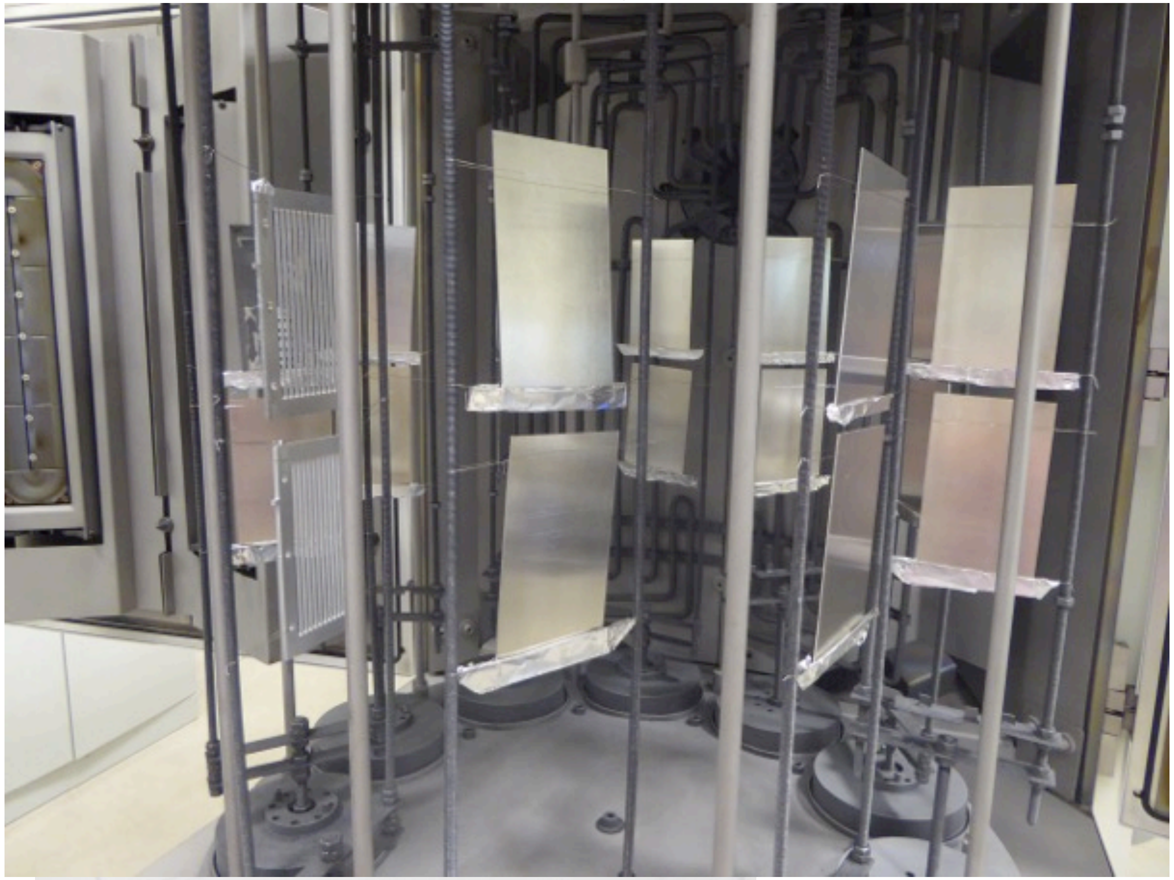
128 read-out pads of different sizes

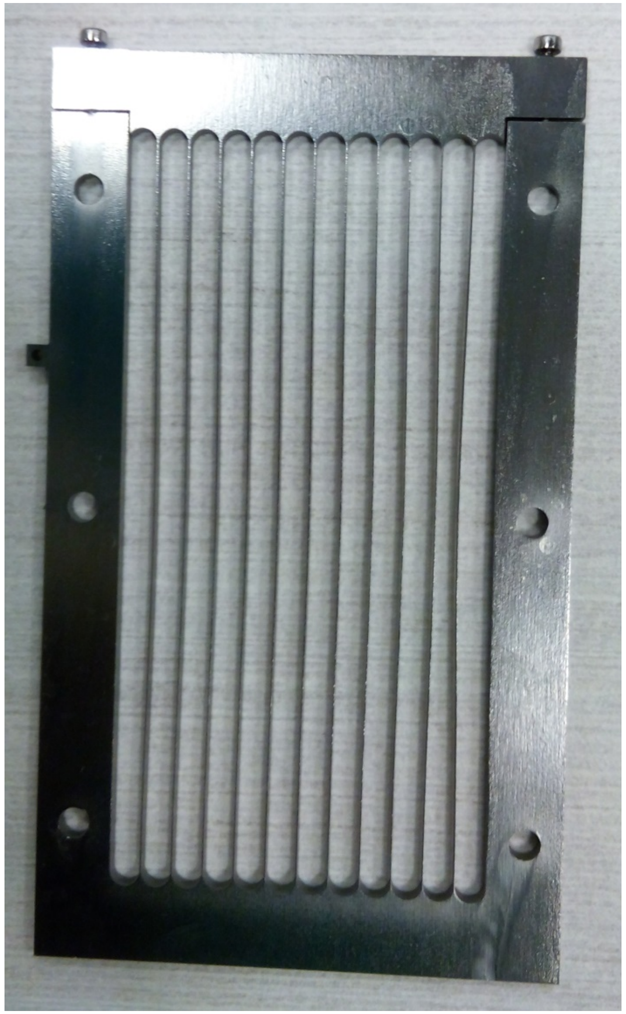
Detector Anodic Pads – 5x10 cm^2 active area

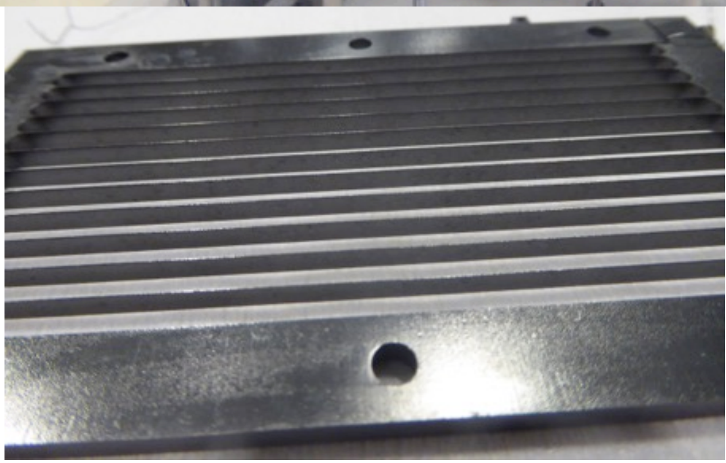


- Three different types of pads *representative of final geometry*
  - Small 4x3 mm^2
  - Intermediate 4x6 mm^2
  - Large 4x12 mm^2
- 64 BANDGEM pads (half detector) connected to DAE
- For each pad (from 65 to 128) DAE-TOF spectra are produced:
  - Single hits
  - Multiple hits (channel number > 128): more than one pad hit in same time-bin
- 2 noisy pads

Nominal 1 µm of $^{10}B_4C$ DEPOSITION @ ESS Workshop (Linkoeping)

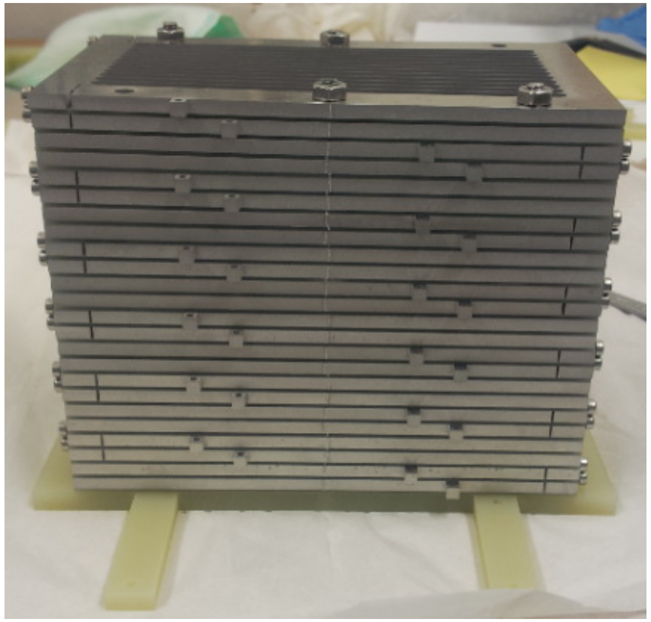


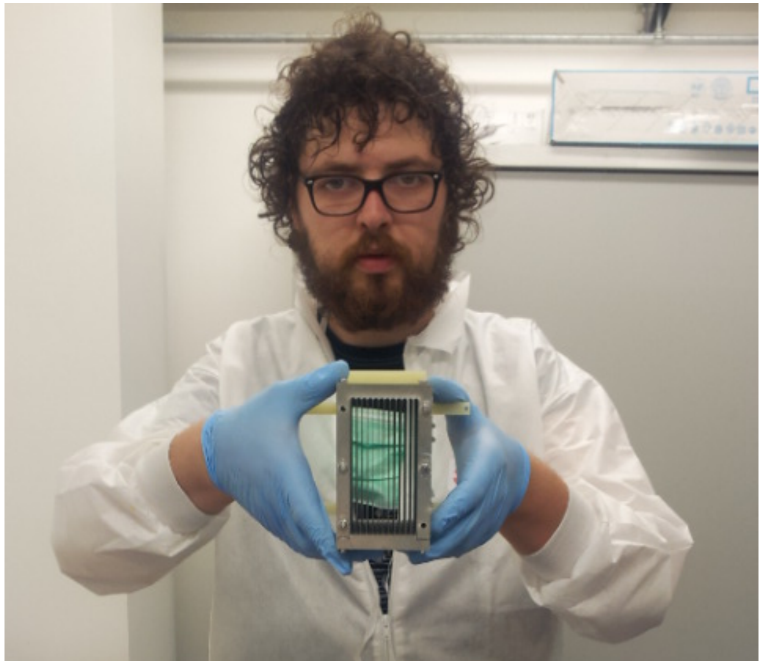


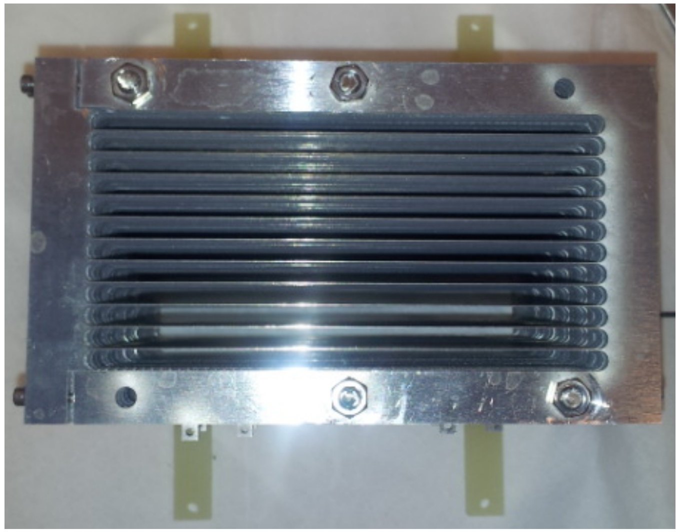


B4C thickness 550 nm
measured @ Linkoeping University using SEM

New BAND-GEM detector assembly (1)







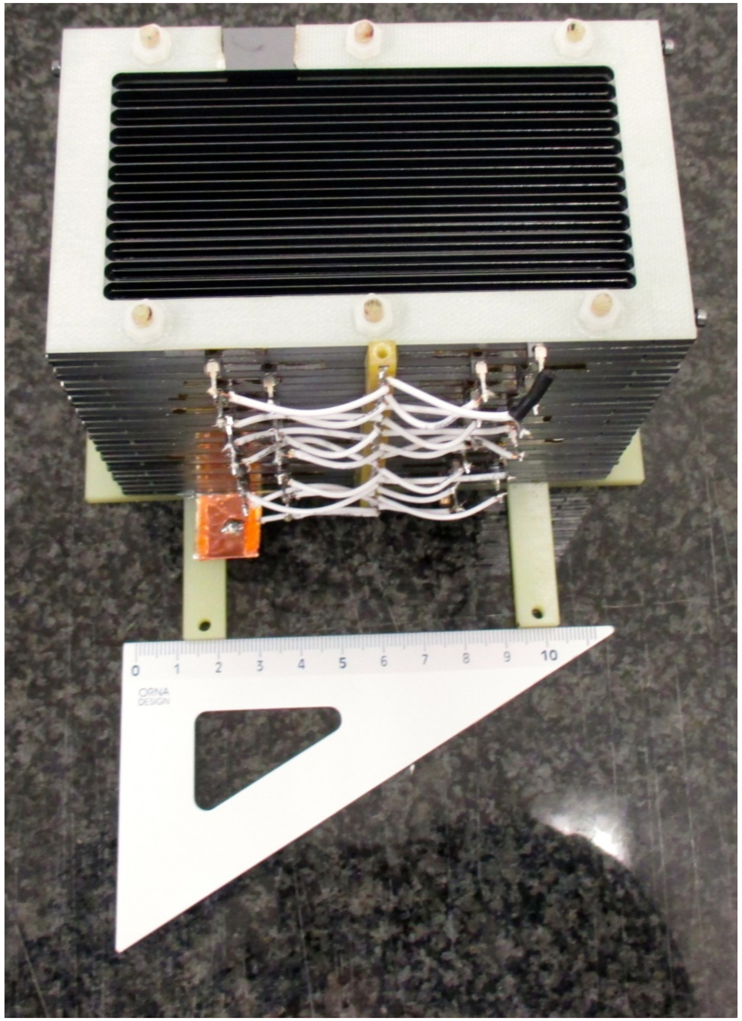
Stack of 24 grids with spacers

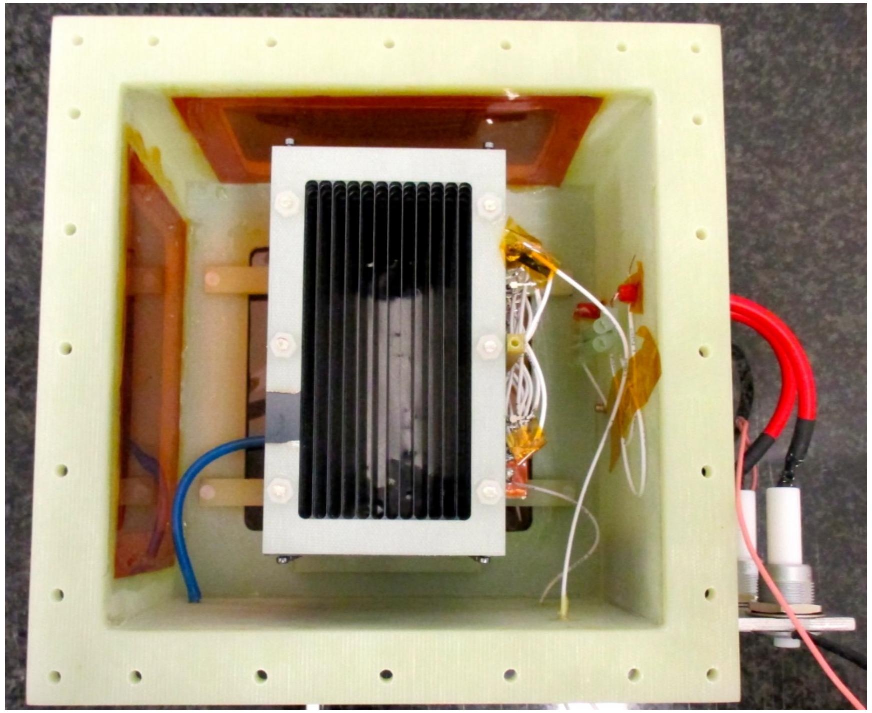
Electropolished

Boronization completed 08/2016

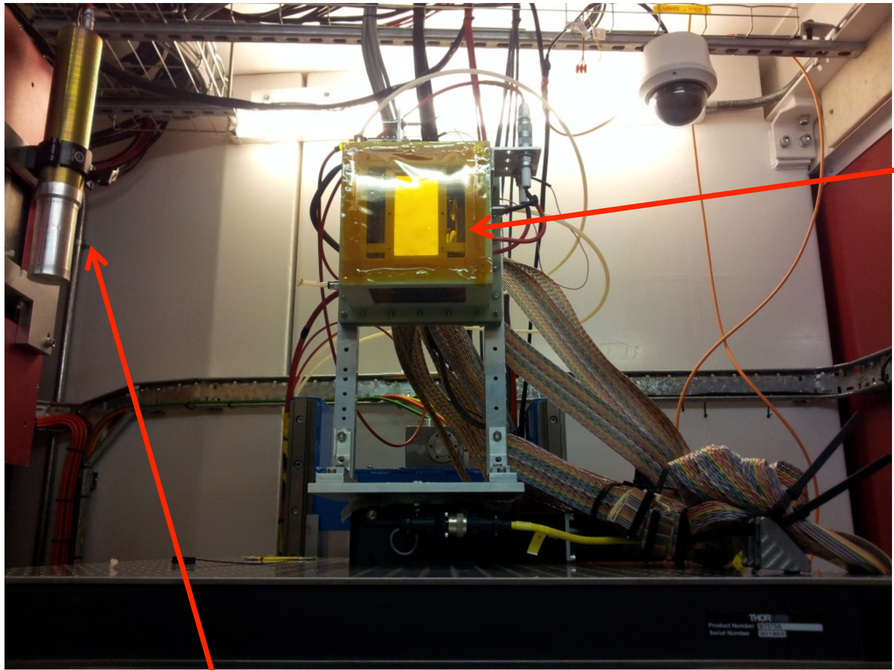
BANDGEM demonstrator

Detector box equipped with three diagnostic windows 75 mm x 100 mm
Borated Grids – 0.55 µm $^{10}B_4C$

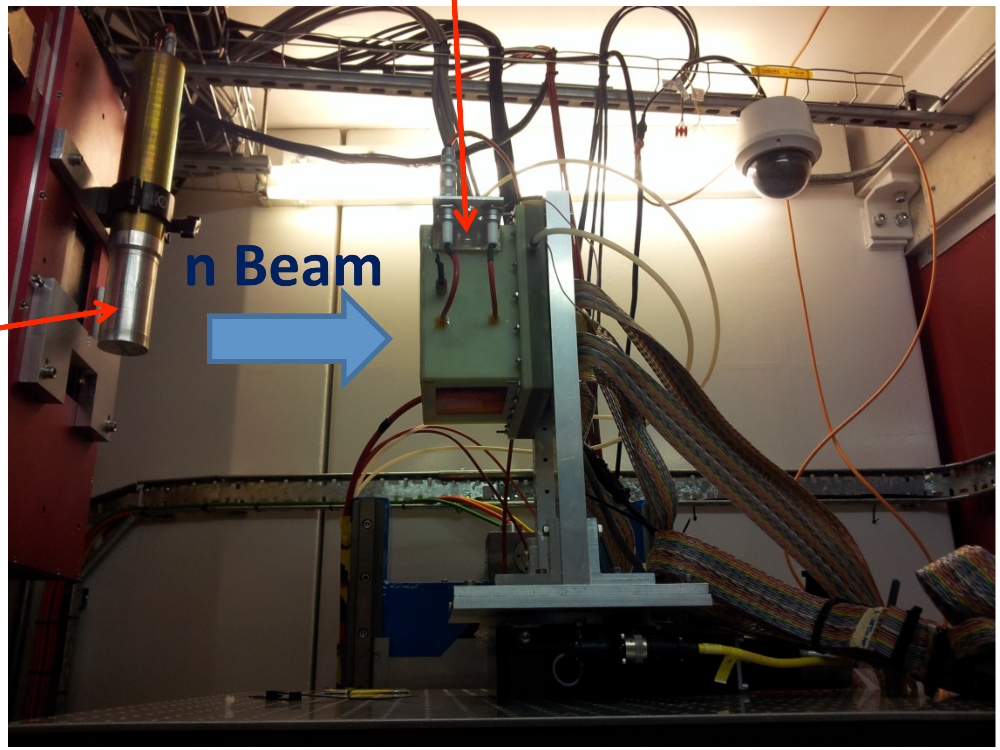




Tests @ EMMA (ISIS)

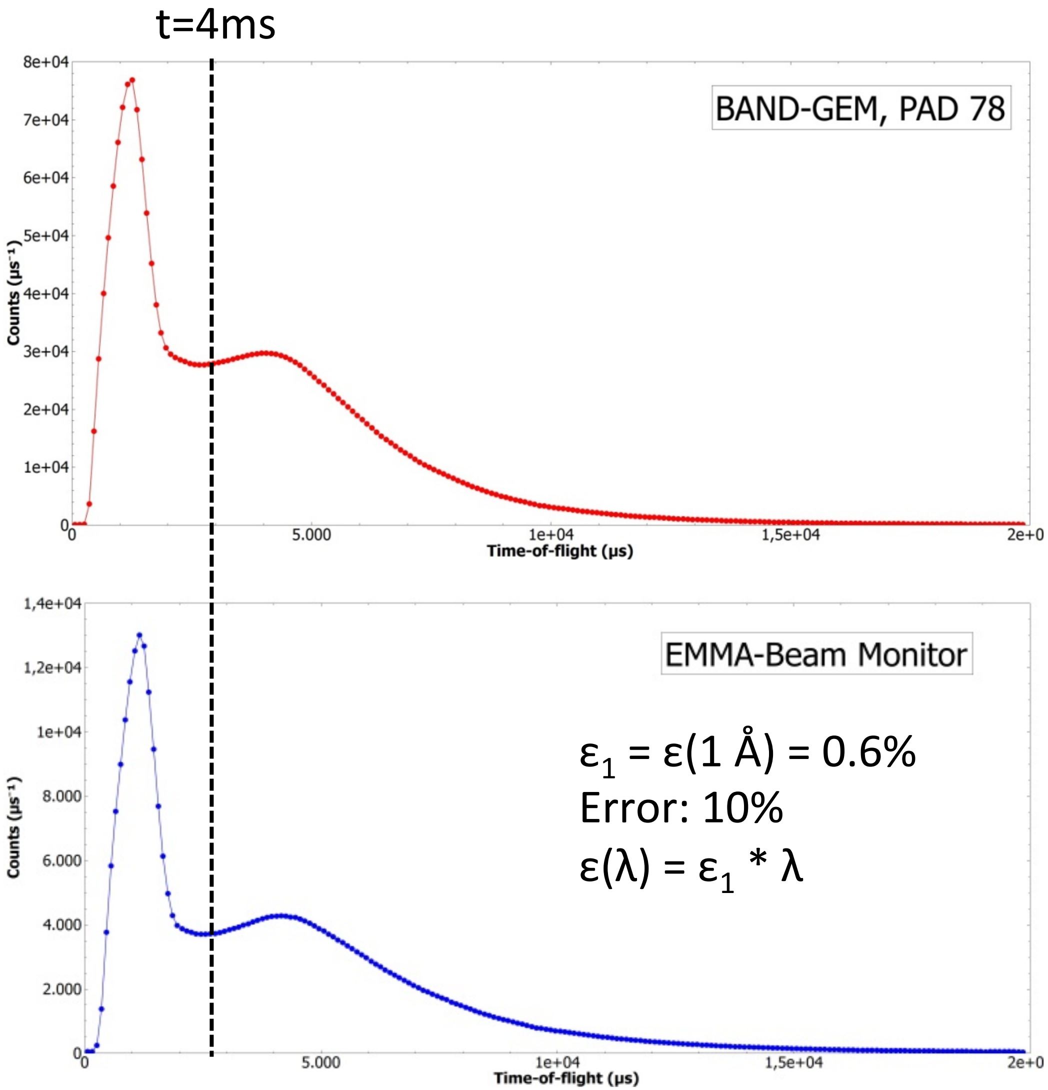


BAND-GEM
on turntable



BEAM MONITOR
GS-20 Lithium Glass Scintillator
ε(1 Å) = 0.6%

Time of Flight Spectra – EMMA 1 Å < λ < 4 Å



$\varepsilon_1 = \varepsilon(1\ \text{Å}) = 0.6\%$

Error: 10%

$\varepsilon(\lambda) = \varepsilon_1 * \lambda$

$$C_{BANDGEM,PAD\ i}(t = \lambda) = \int_{t=t_1\ ms}^{t=t_2\ ms} BandGEM\ _i(t)dt$$

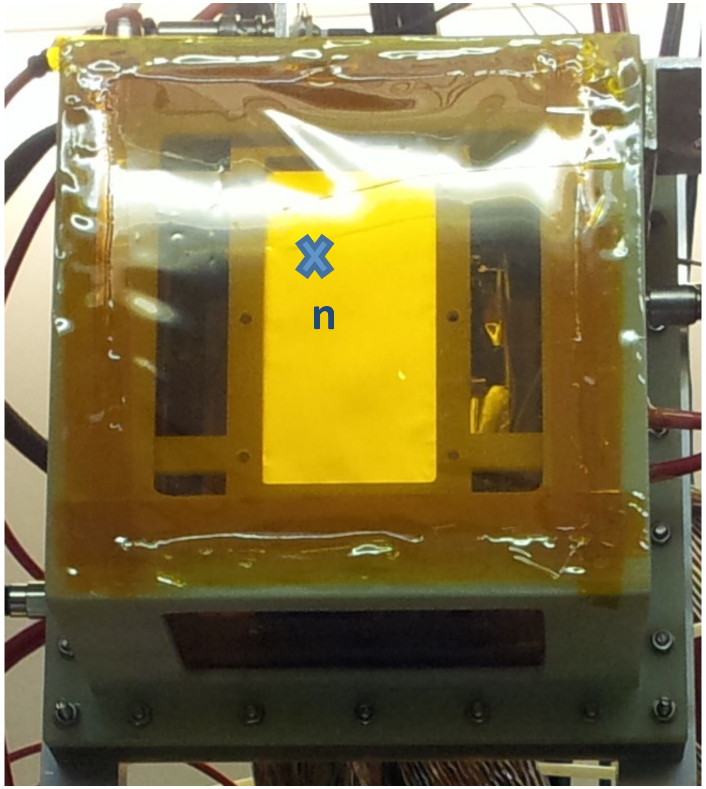
$$C_{Mon}(t = \lambda) = \int_{t=t_1\ ms}^{t=t_2\ ms} Monitor(t)dt$$

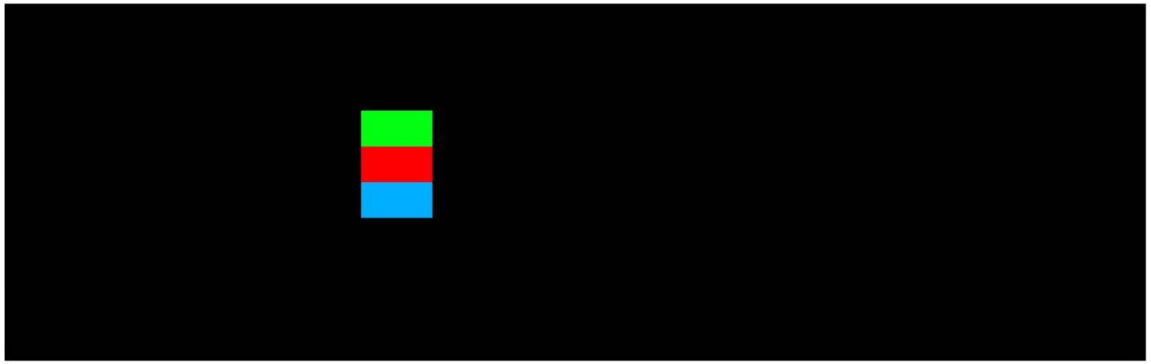
λ(Å)	TOF (μs)
1	4000
2	8060
3	12560
4	17060

$$\varepsilon_{GEM}(\lambda) = \frac{C_{GEM}(t=\lambda)}{C_{Mon}(t=\lambda)} * \varepsilon_1$$

Monitor Efficiency previously calibrated using ^{3}He tube

Beam footprint





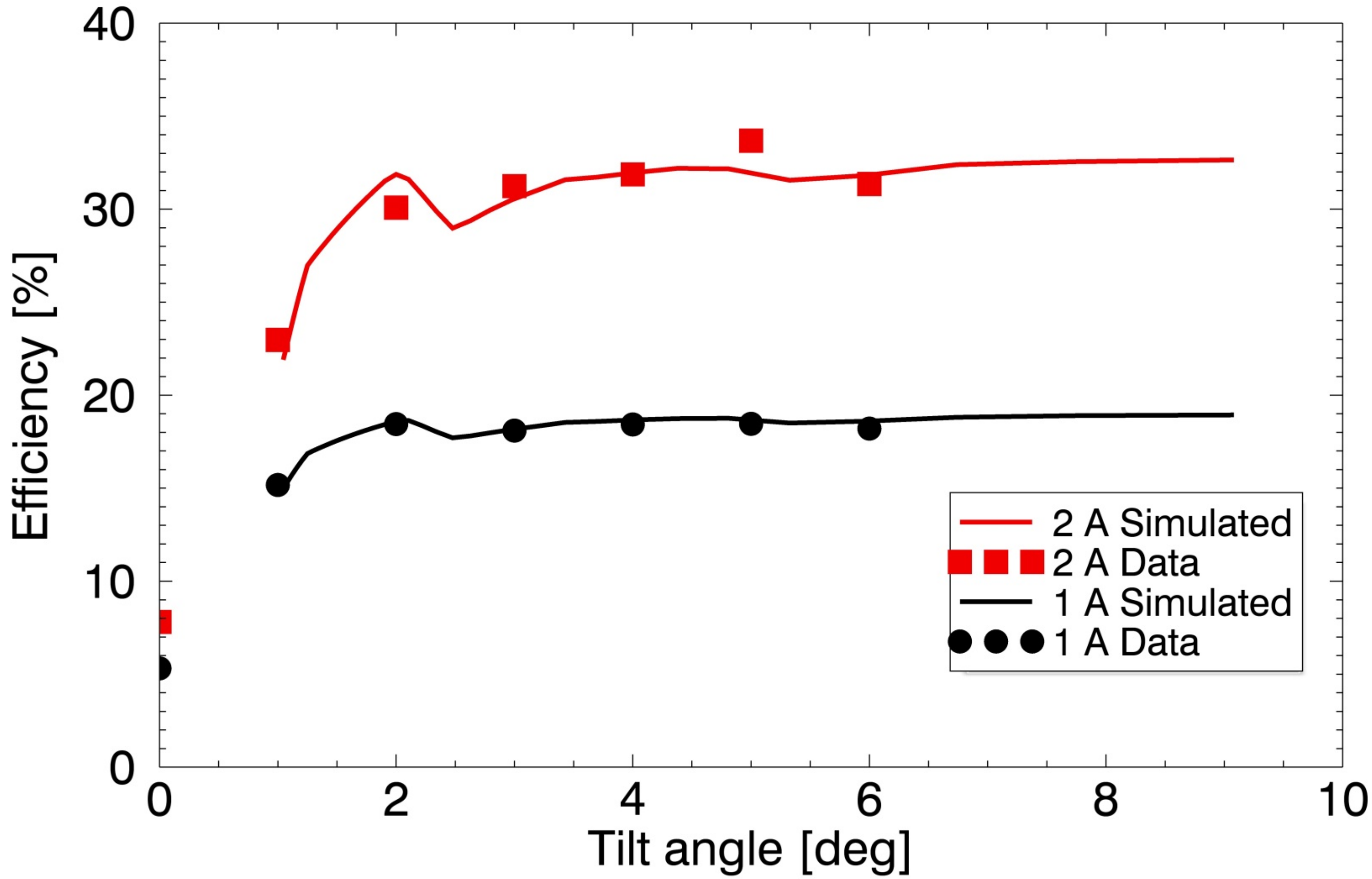
$$I_{GEM} = \sum_{ON-pads} \int_{t=4\,ms}^{t=20\,ms} BandGEM(t)dt$$

ON-pads are defined as pads whose intensity is > 1% of the pad with the max intensity

Beam dimension 4 mm (t) x 4 mm (y)

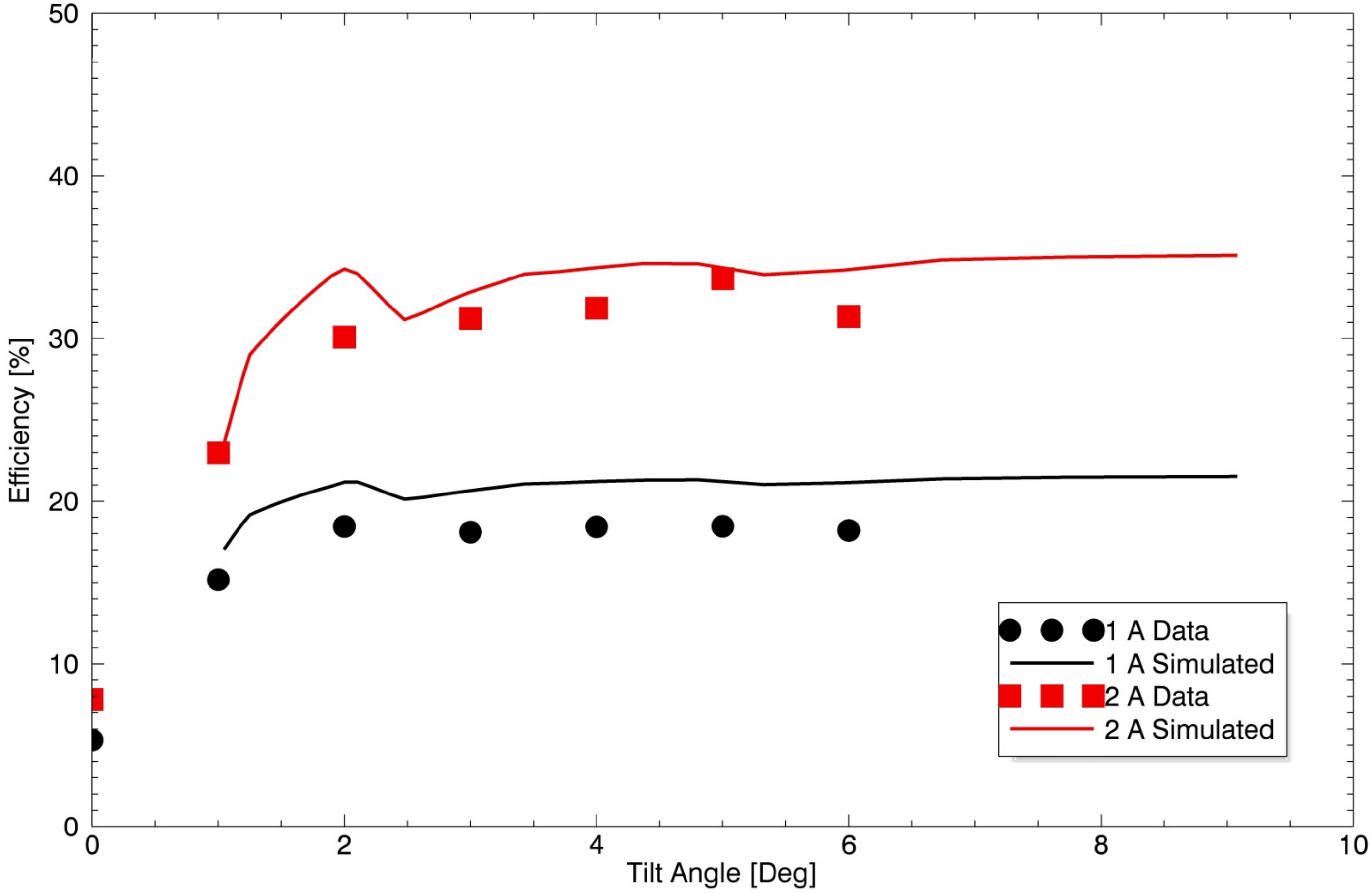
Colour = I_{GEM}/Pad Area

Efficiency (at 1 and 2 A) vs tilt angle



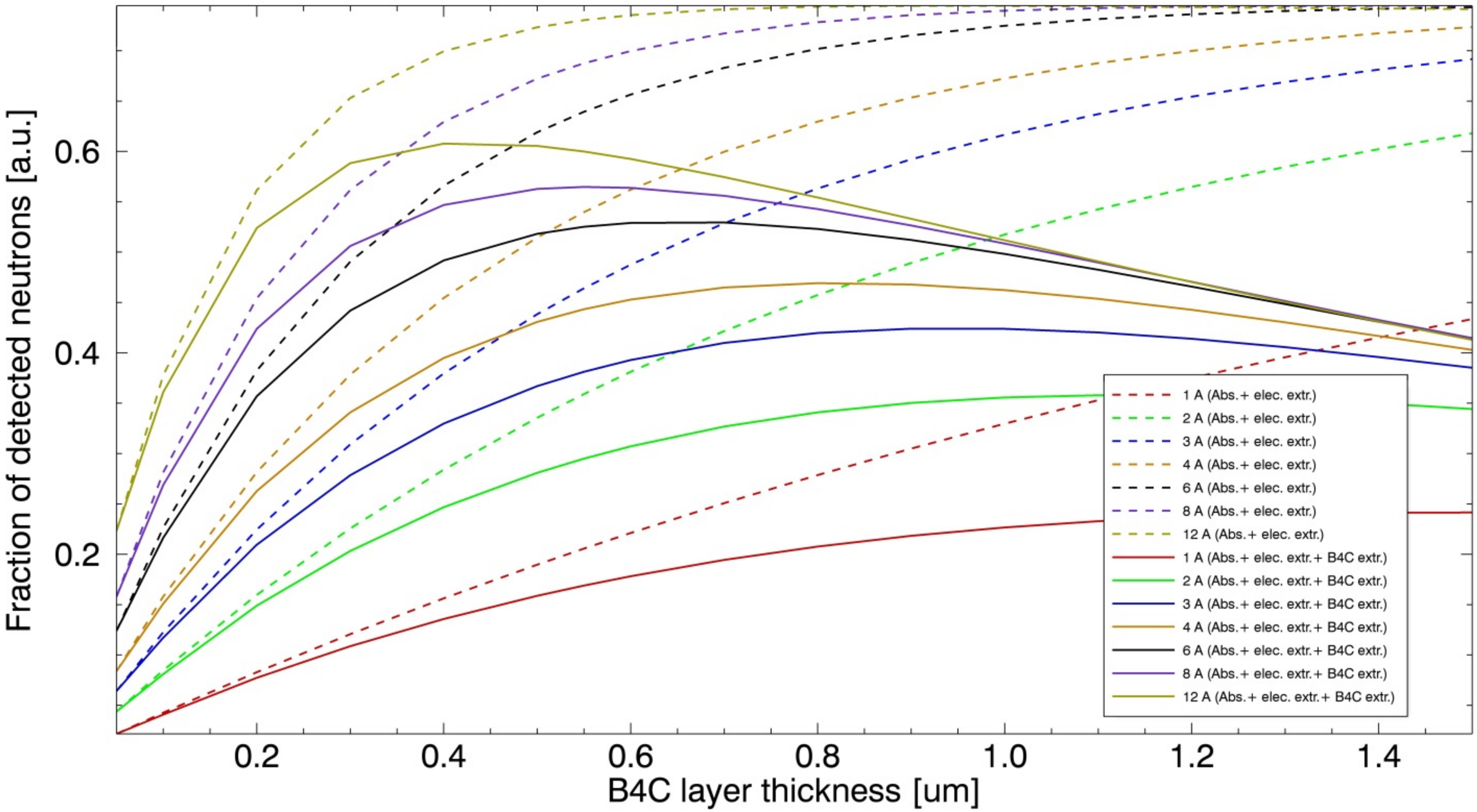
Good agreement with simulated values ^{10}B4C thickness 550 nm

Efficiency vs tilt angle

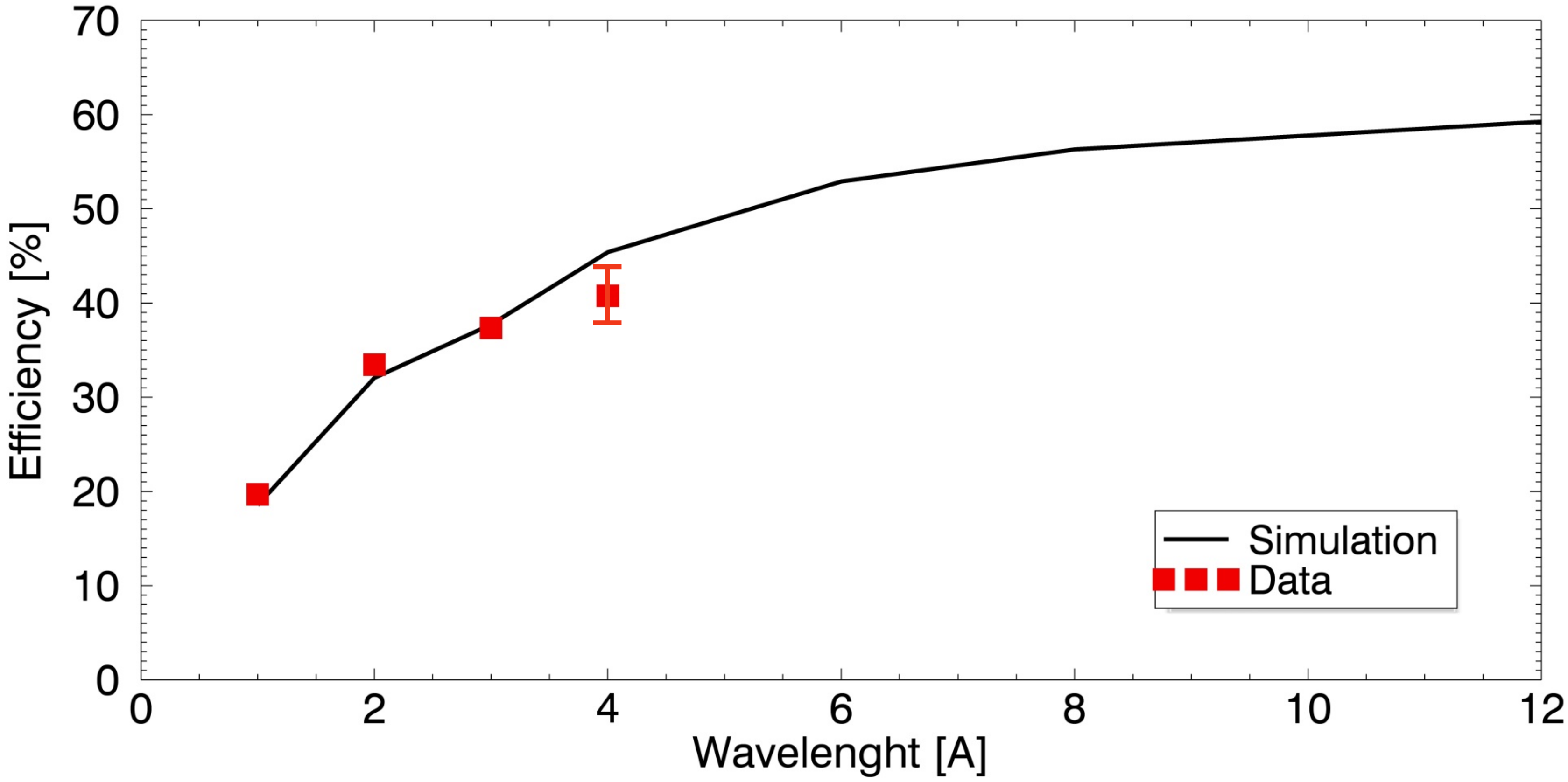


Simulation with 900 nm ^{10}B4C thickness

Simulation of detector efficiency as a function of $^{10}B_4C$ thickness

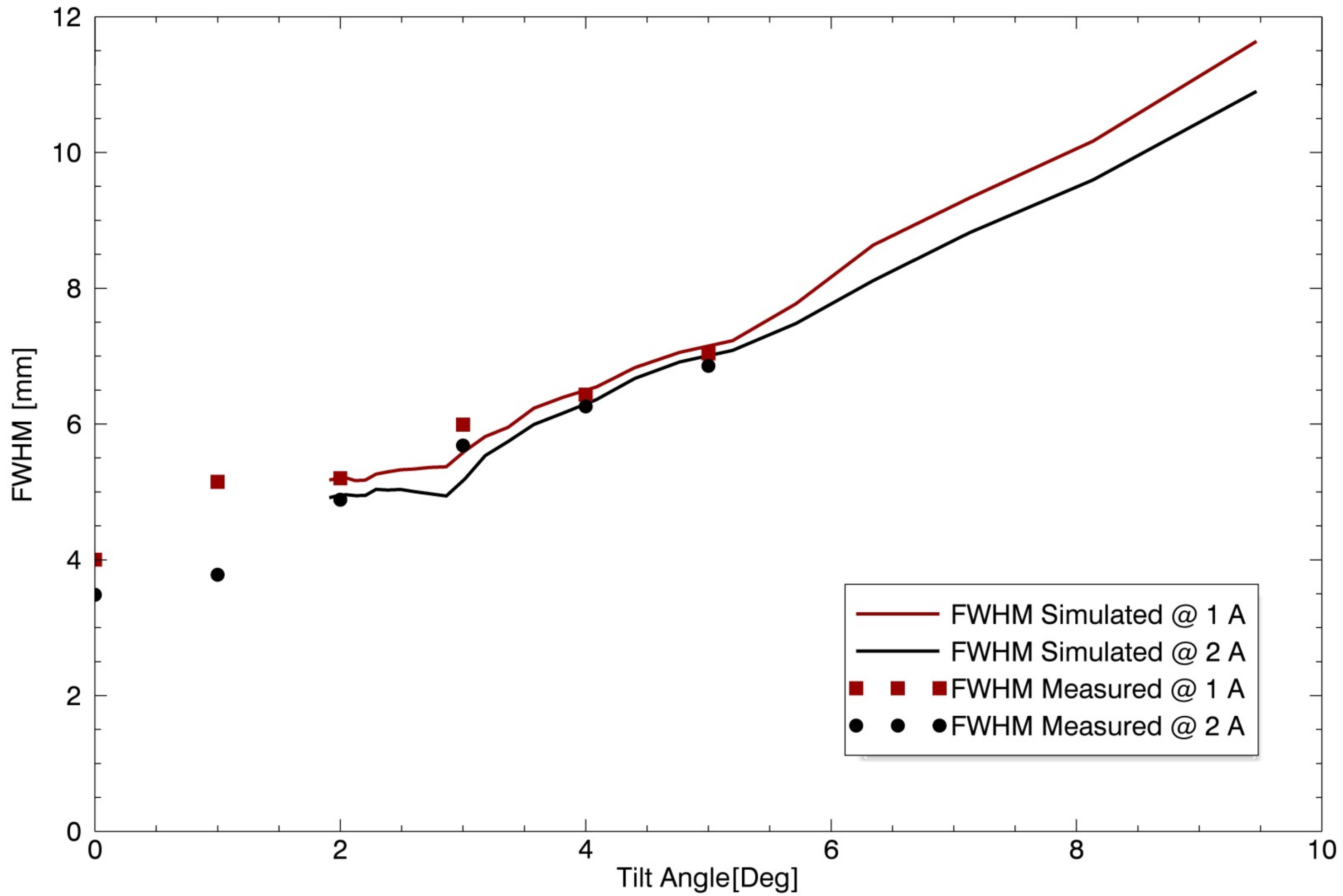


Efficiency vs λ



- Alpha and Li ion escape efficiency from a 550 nm thick $^{10}B_4C$ layer = 75%
- Assumes the measured extraction efficiency in the simulation model

Space resolution (FWHM) vs tilt angle

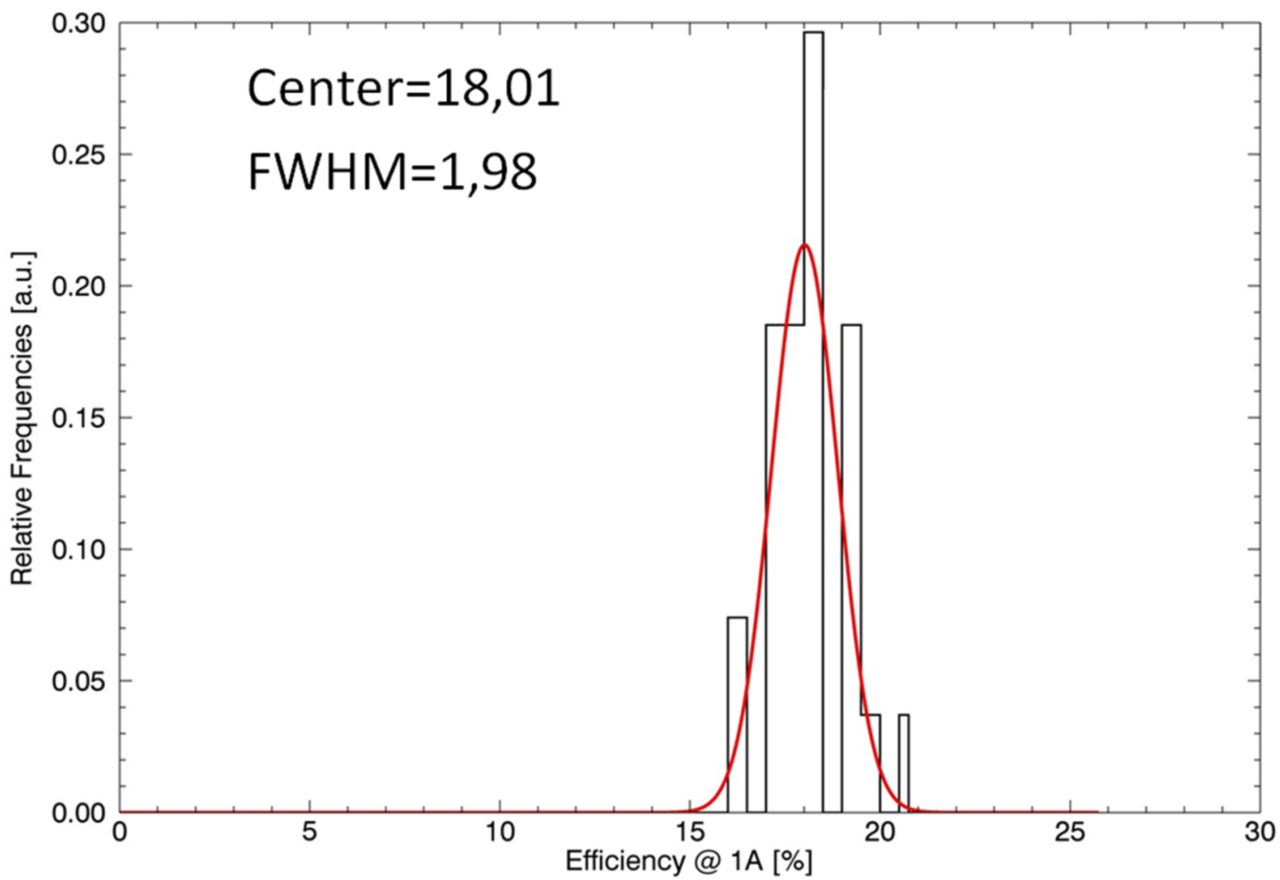


Good agreement with simulated values

Experimental corrected for offset by about 5 degrees

Effective resolution ~ independent of λ

Efficiency uniformity @ λ=1 Å, Θ=5°

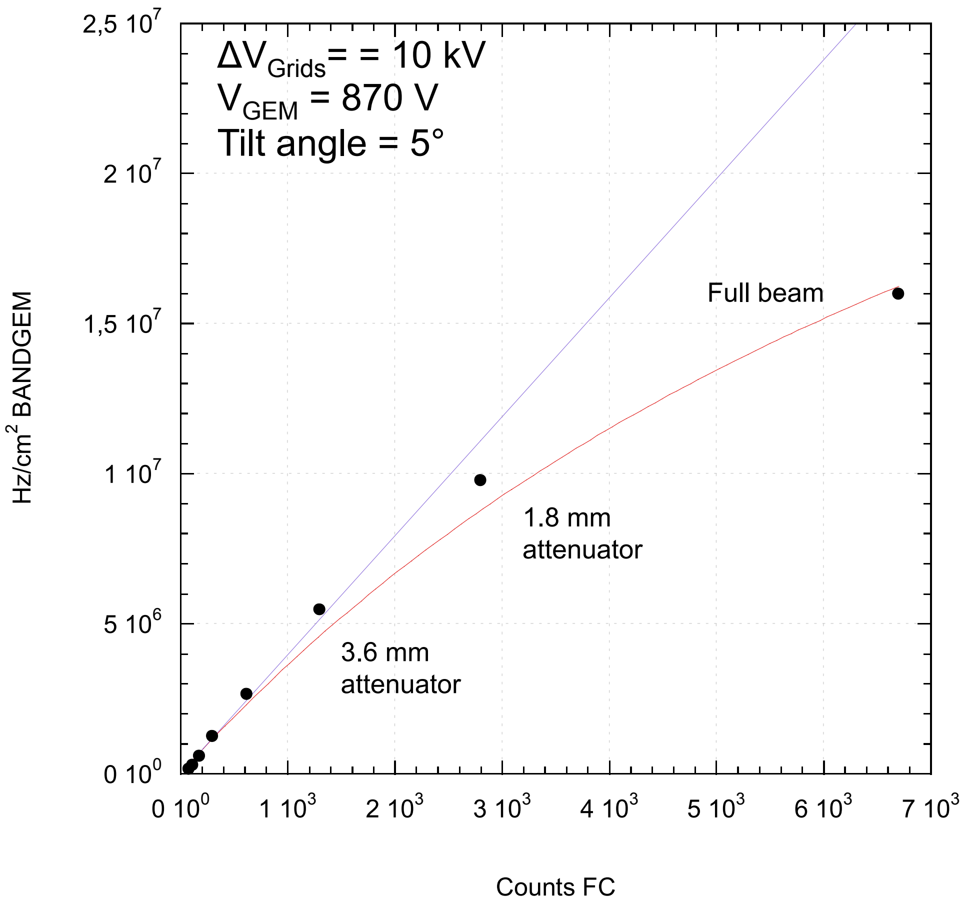


Efficiency values all over the active area are well represented by a gaussian function with a mean of 18% and a FWHM of 2%.

High rate test at the ORPHEE Reactor @ LLB-CEA

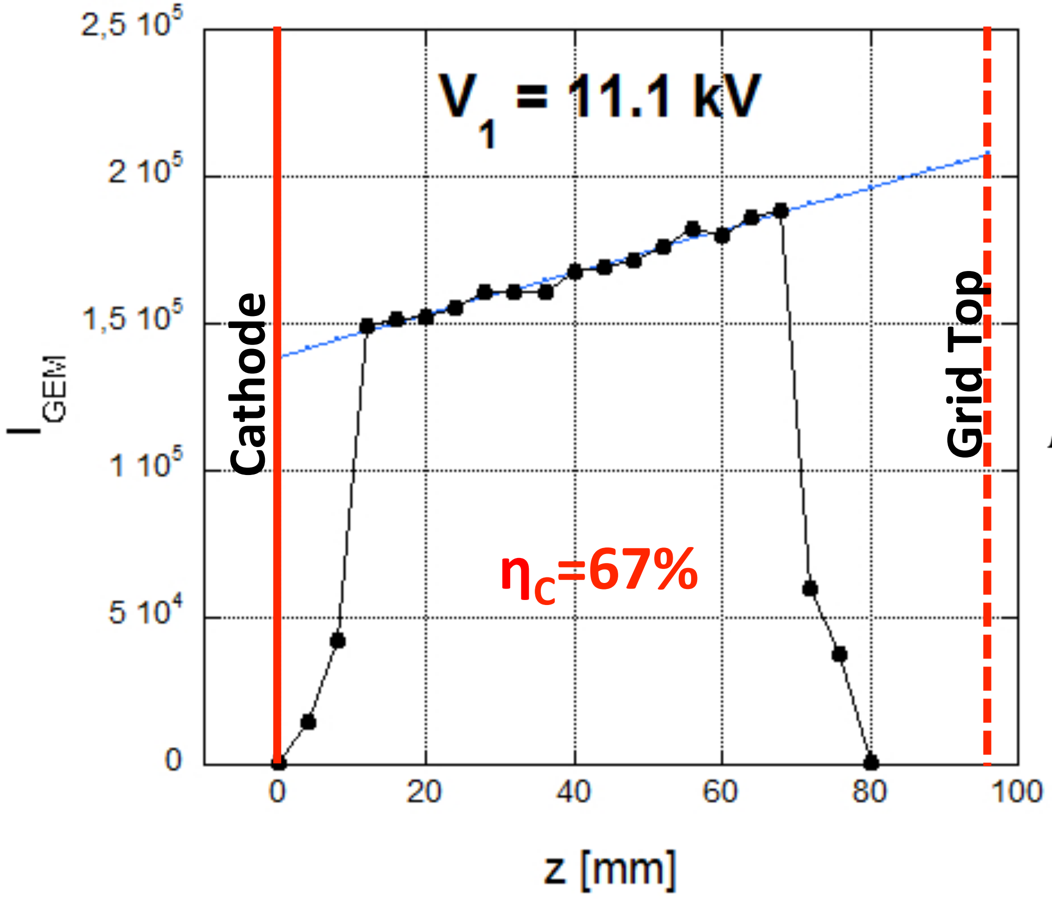
Neutron Flux = 7.88×10^8 n/cm^{2}s

Linearity scan of BAND-GEM demonstrator relative to Fission Chamber, performed at reactor power 10.1 MW.
The BAND-GEM is linear (relative to the reference FC detector) up to about 5 MHz/cm^2.



Black dots: BANDGEM count rates per cm^2; red line: fit of the data with saturation law; purple line: linear component of the saturation law.

Relative (bottom/top) Charge Extraction Efficiency



Beam entering from the side Θ=90°

Considering all ON-pads for IC_{GEM} calculation

$$I_{GEM} = \sum_{ON-Pads} \int_{t=4\,ms}^{t=20\,ms} BandGEM(t)dt$$

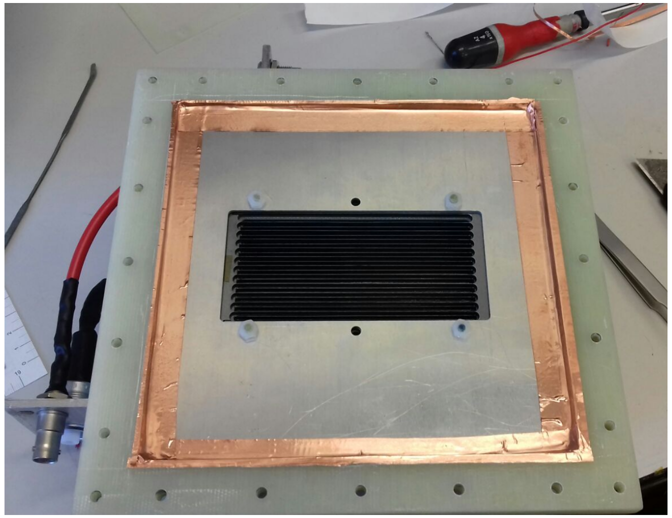
Relative Extraction Efficiency @ Cathode

$$\eta_C = \frac{I_{GEM}(z = 0\ mm)}{I_{GEM}\ (z = 96\ mm)}$$

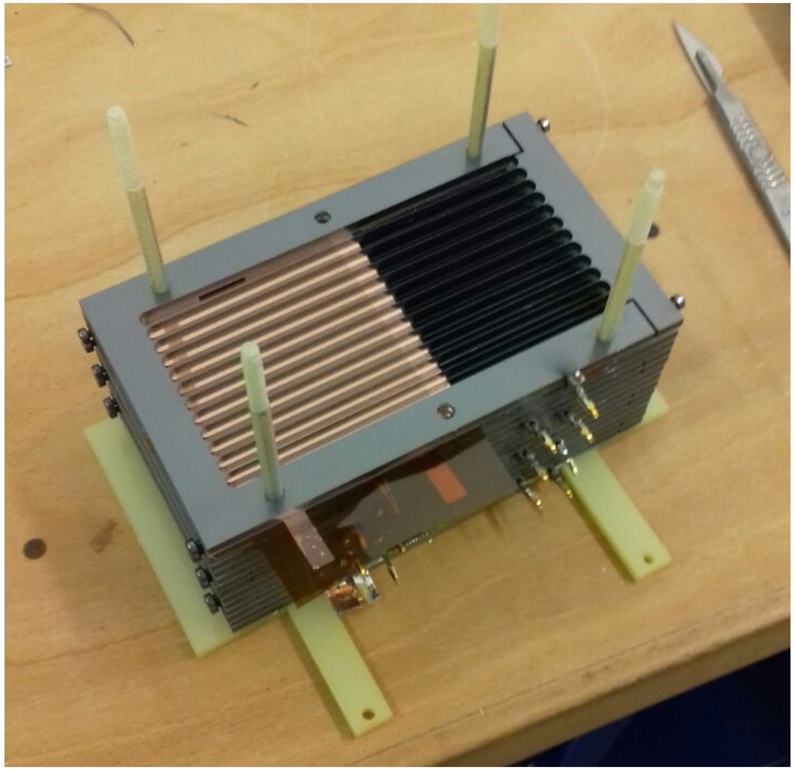
Width of lateral diagnostic window = 75 mm

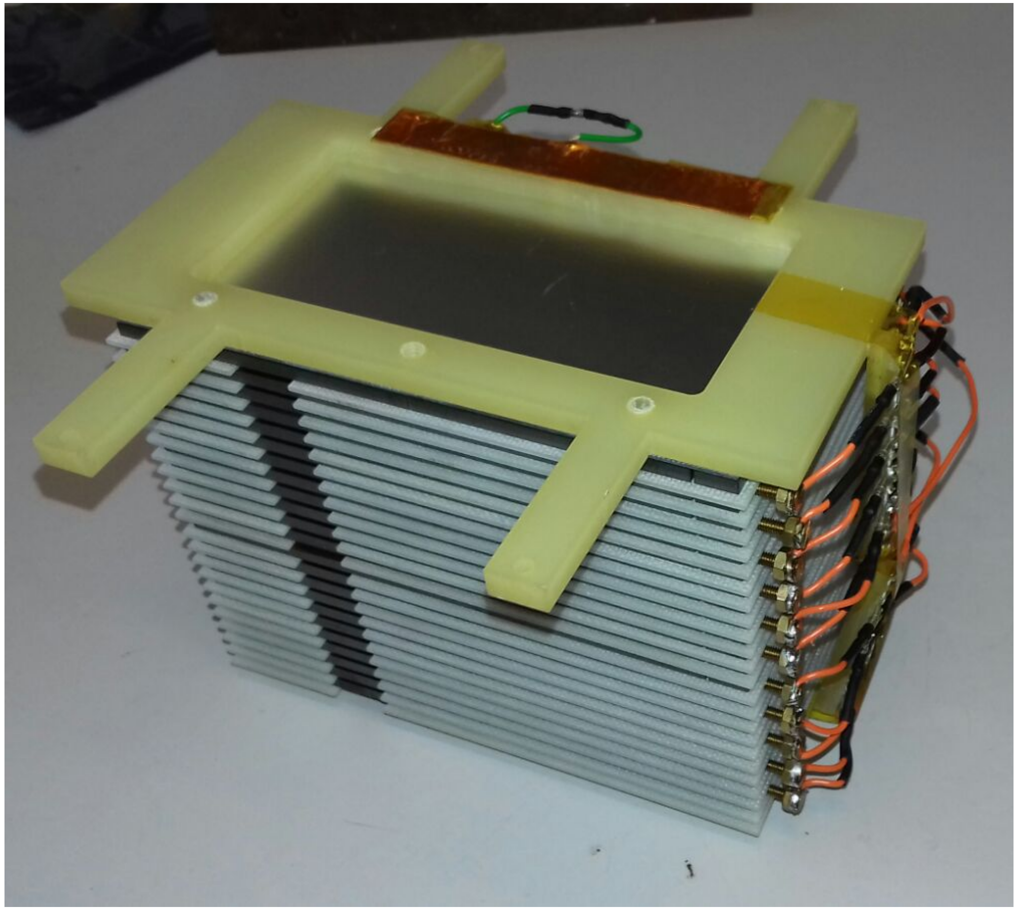
IMPROVED BAND-GEM DEMONSTRATOR

Improved BANDGEM demonstrator



Detector box equipped with three diagnostic windows 75 mm x 100 mm
Borated Grids – 0.91 μm of $^{10}B_4C$
GEM in the middle of the stack
Cd sheet on one side for 3D stack

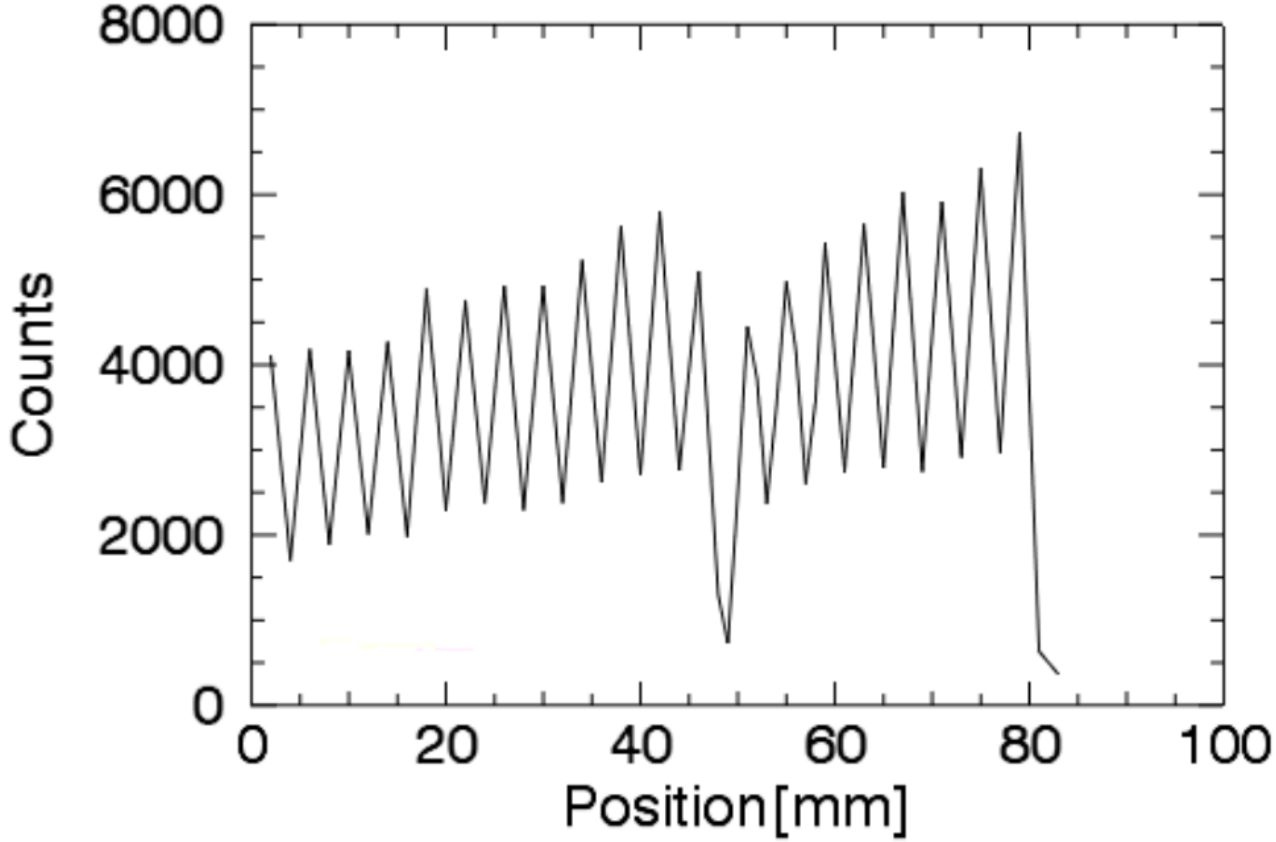




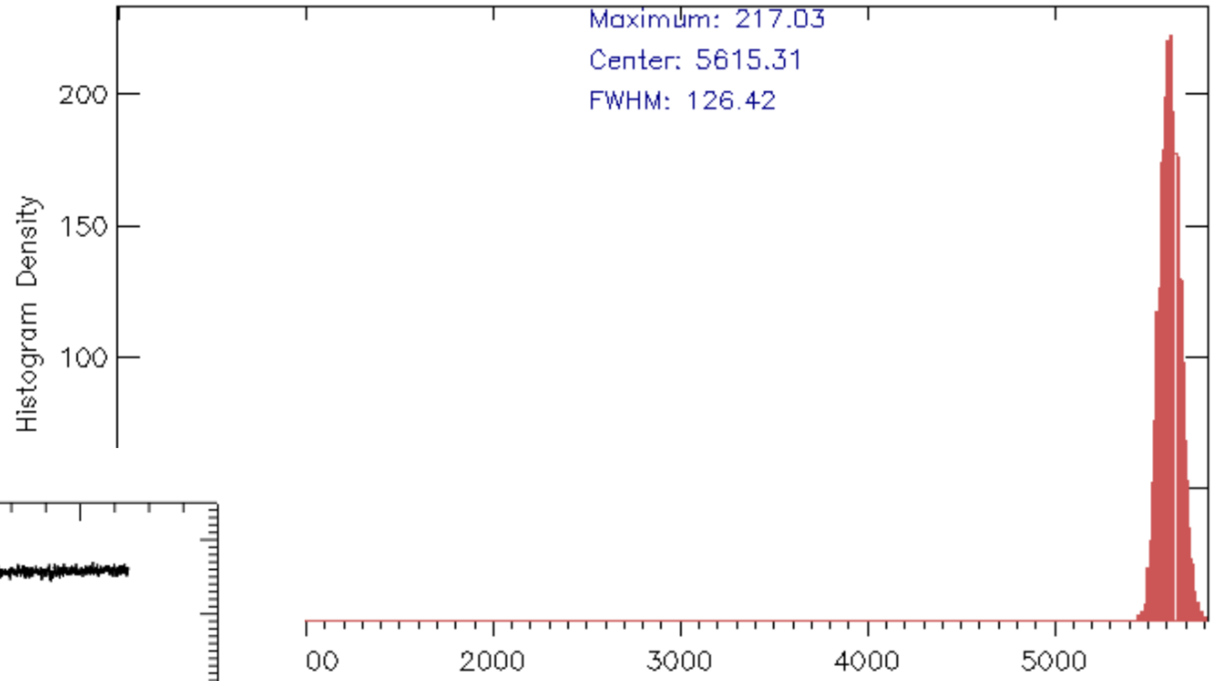
TREFF-FRMII Test (18-22 Sept 2017)

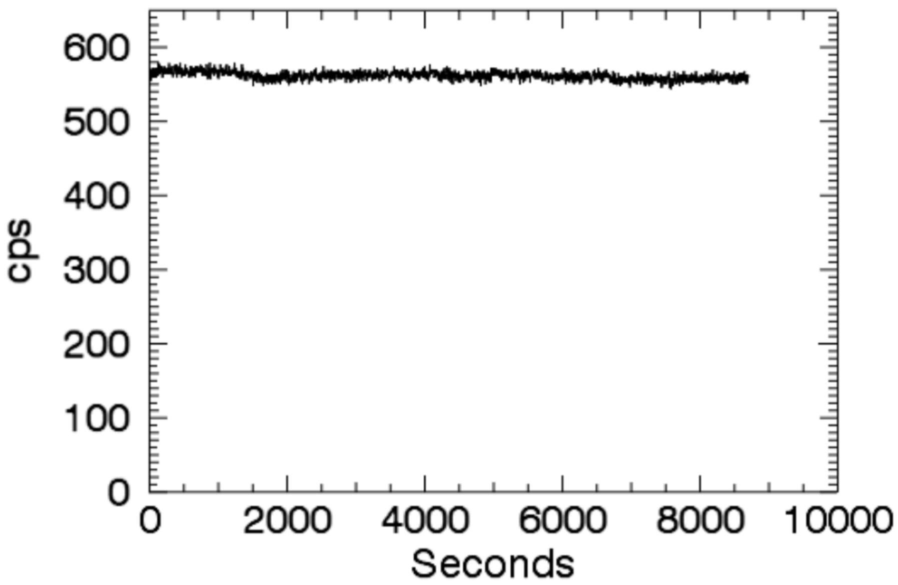
- $\varepsilon > 45\%$ at $\lambda = 4.73$ A

TREFF-FRMII Test: Scan 90 degrees



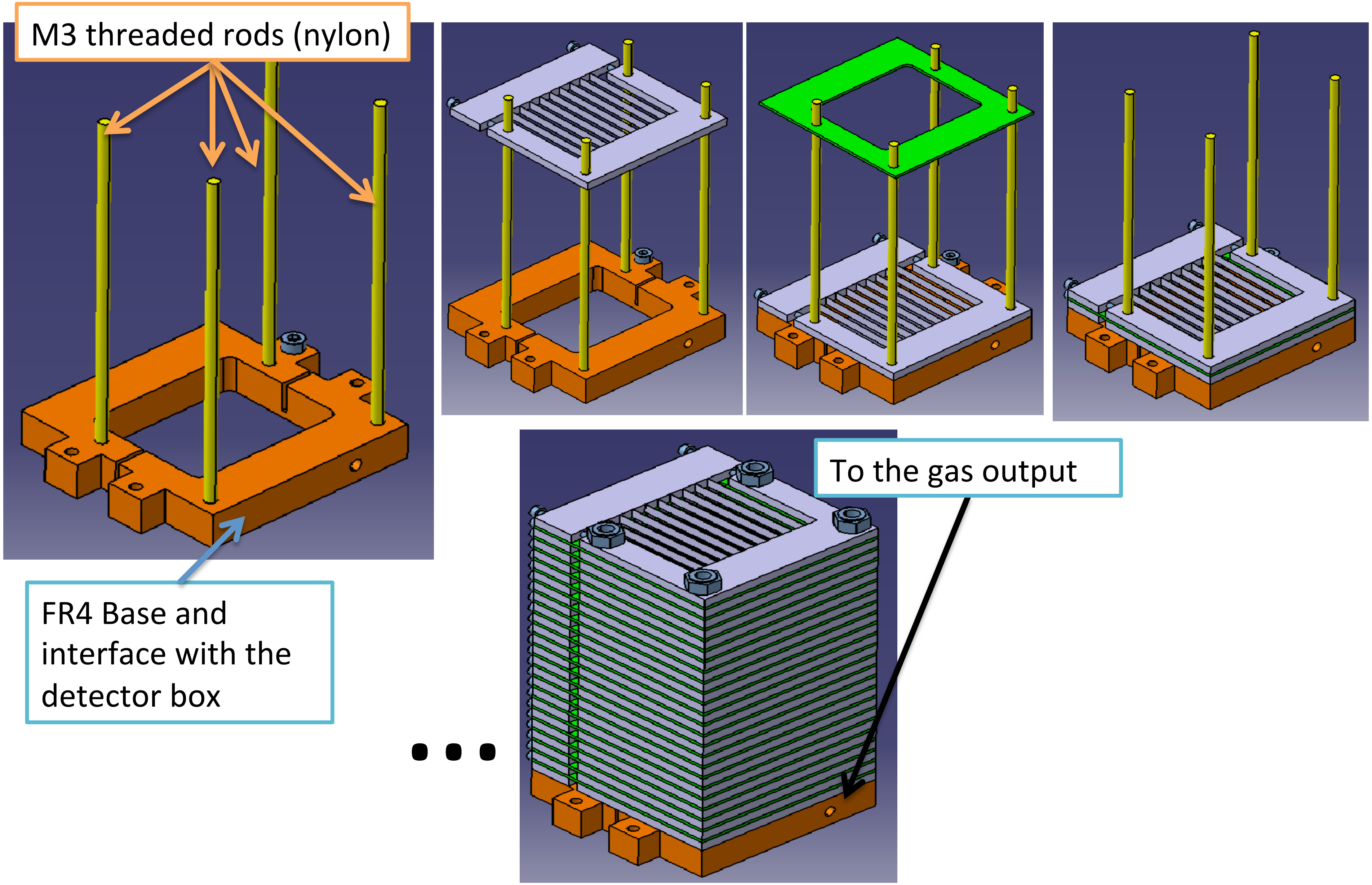
TREFF-FRMII Test: Stability measurment



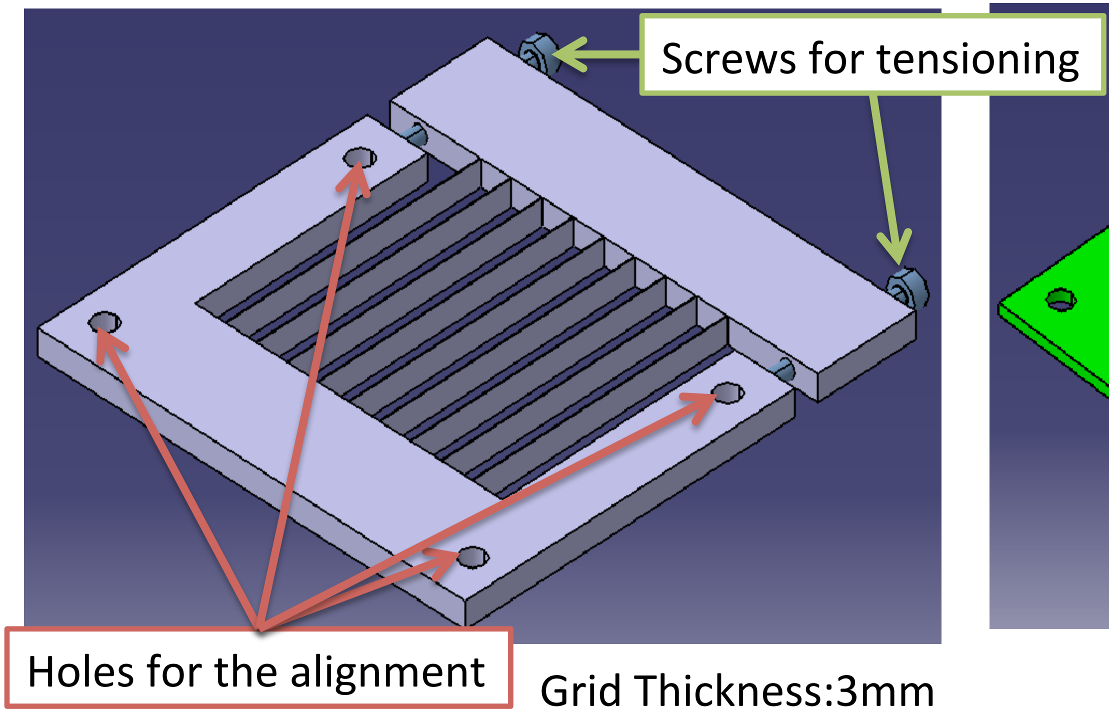


BAND-GEMPIX

First BAND-GEMPix detector

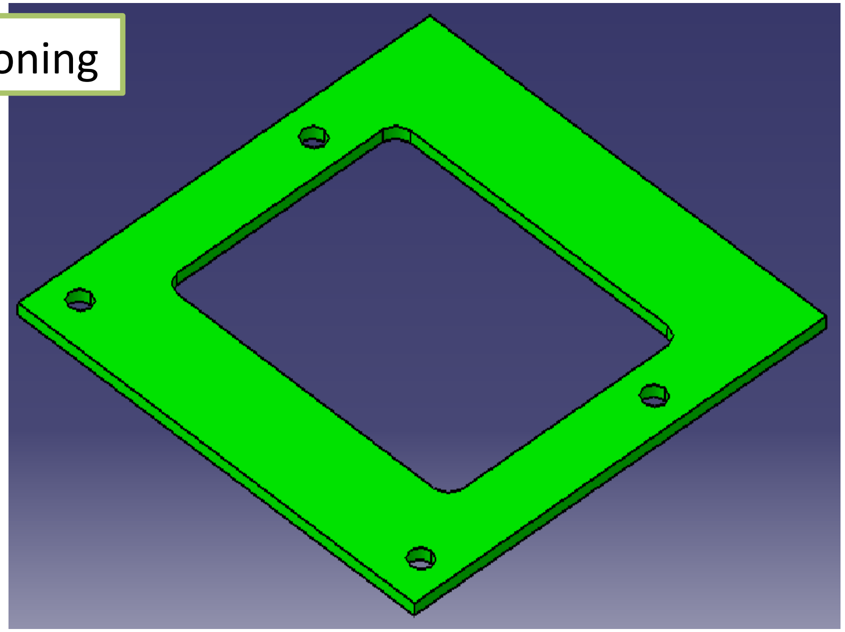


BAND-GEMPix converter Components



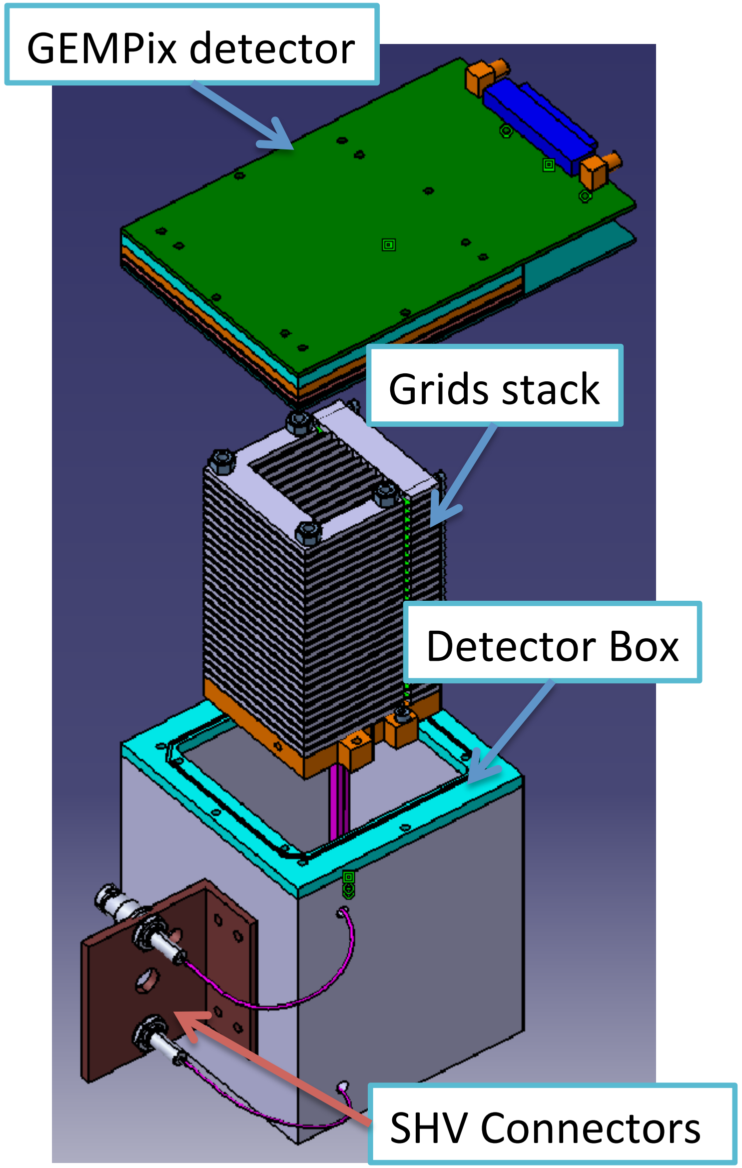
Active Area: 40x35 mm^2

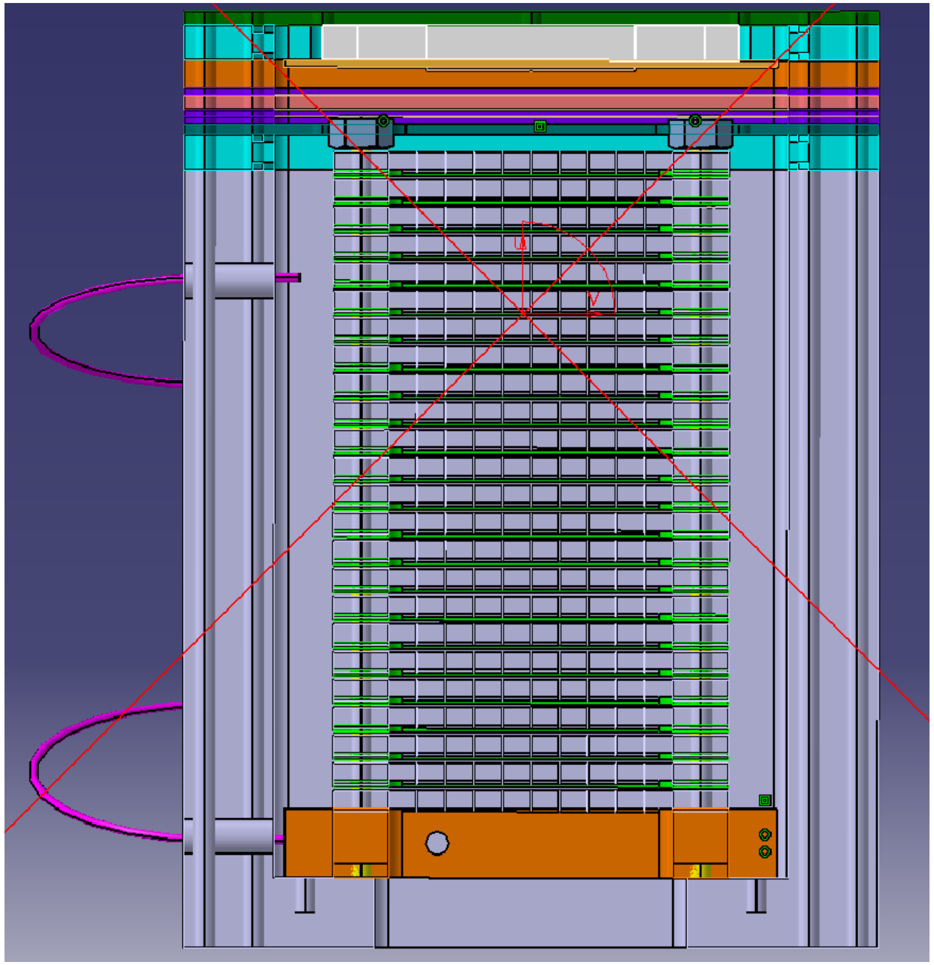
Grid Thickness:3mm
Strip thickness:0.1 mm



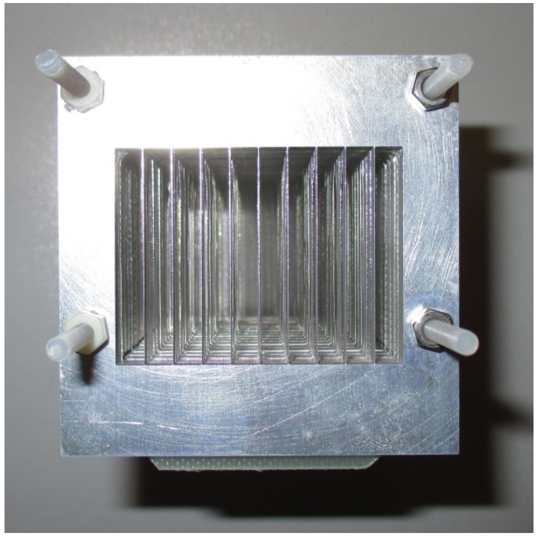
FR4 Spacer
Thicness:1 mm

BAND-GEMPix: detector assembly

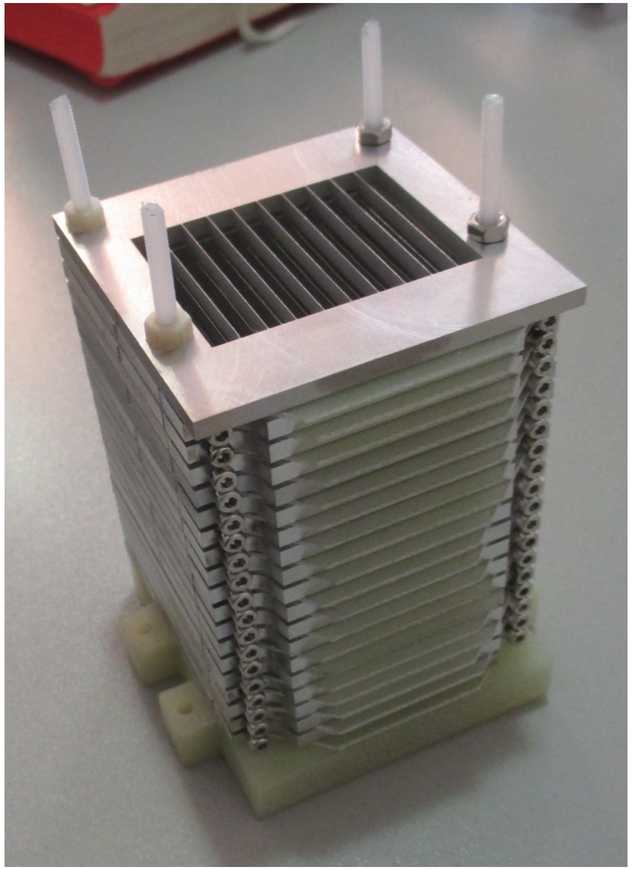




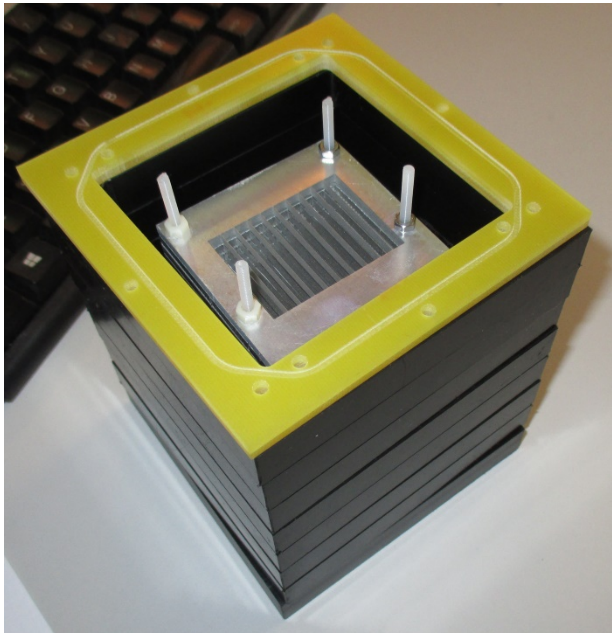
First BAND-GEMPIX assembly test



Top view



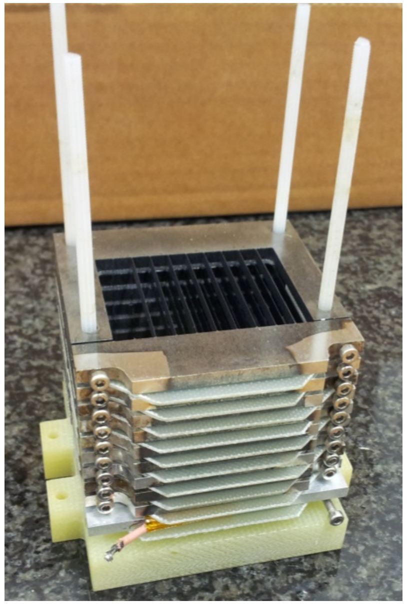
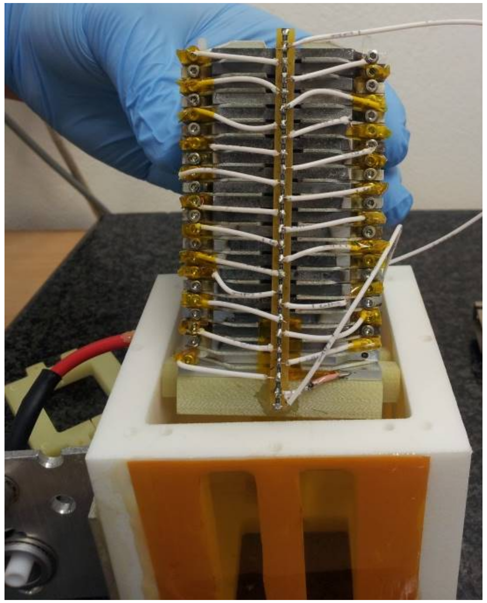
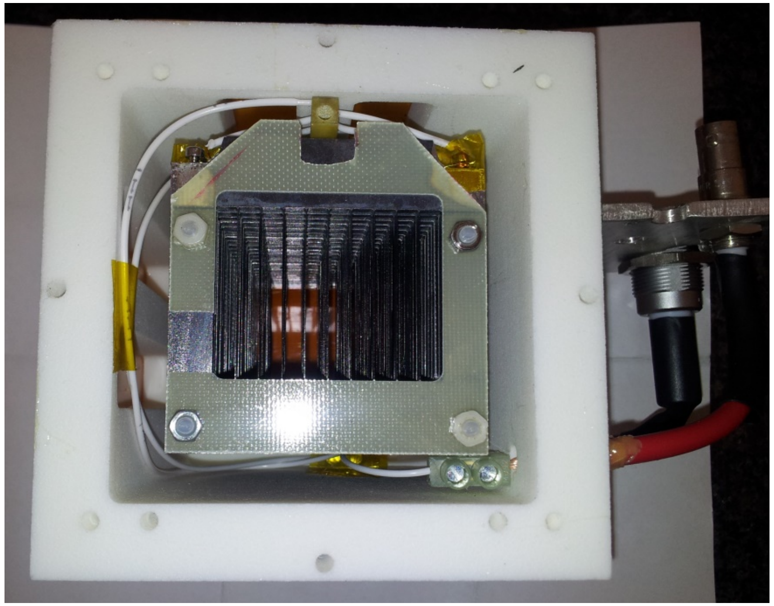
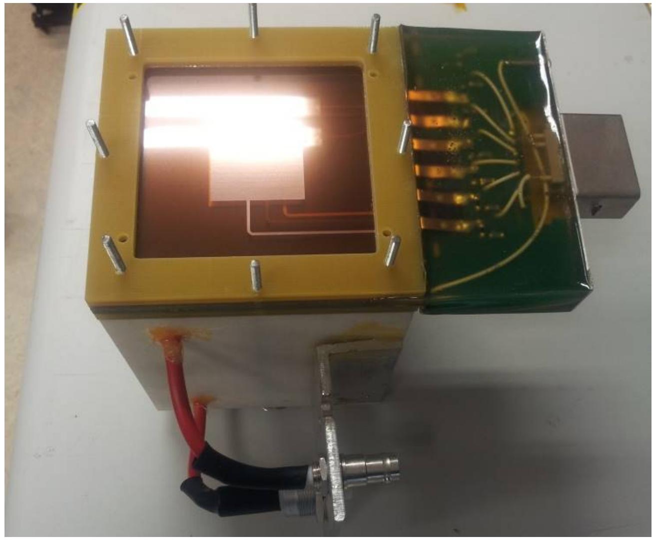
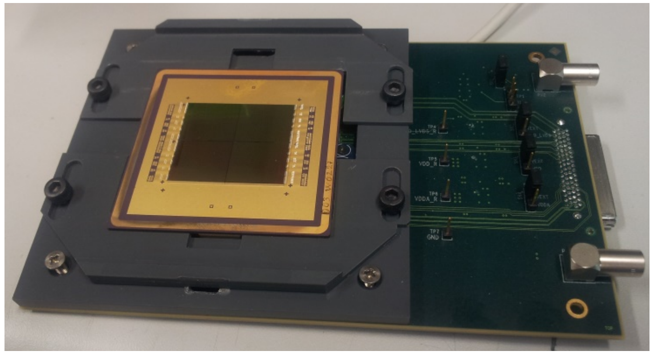
3D view



3D converter placed in
the gas box

BAND-GEMPIX Assembly

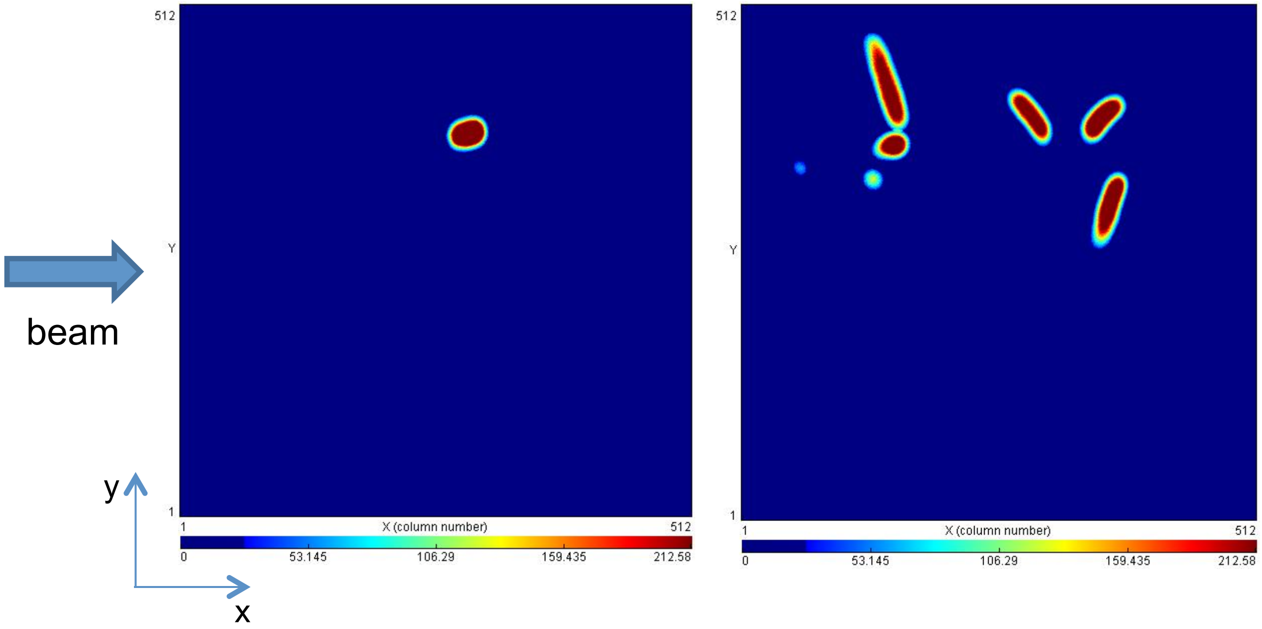
- Small area (4x4 cm^2) BANDGEM read-out by a Quad-Timepix2 chip. Very useful to study BANDGEM space resolution

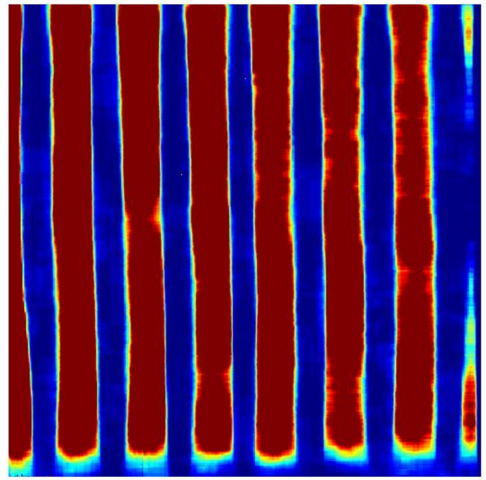
Quad-Timepix2
Timepix 2: 256x256 pixels
with dimension 55 x 55 μm^2

BAND-GEMPIX Results

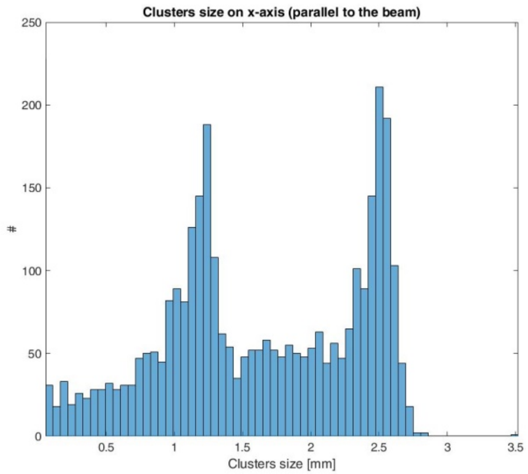
- TREFF-FRMII Test (18-22 Sept 2017). Monochormatic beam 1x1 mm^2 along the x axis



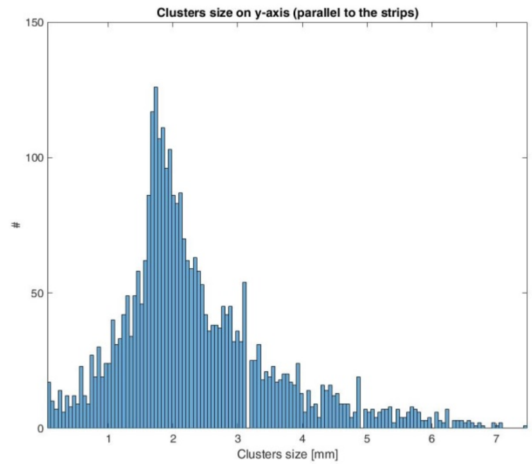
Long (10s) acq frame



Li and α cluster dimension along x (orthogonal to the strips)

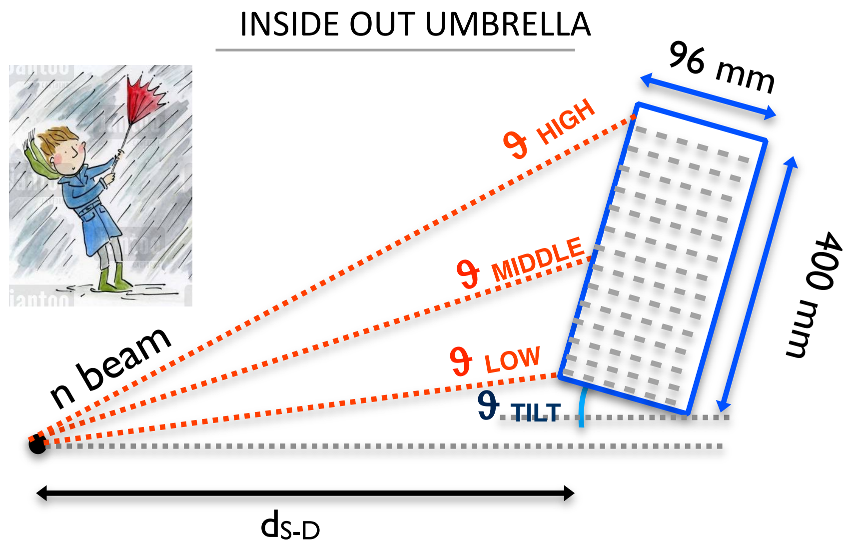


Li and α cluster dimension along y (parallel to the strips)
About 2 mm



BAND-GEM for LOKI

LOKI BAND-GEM Reference parameters

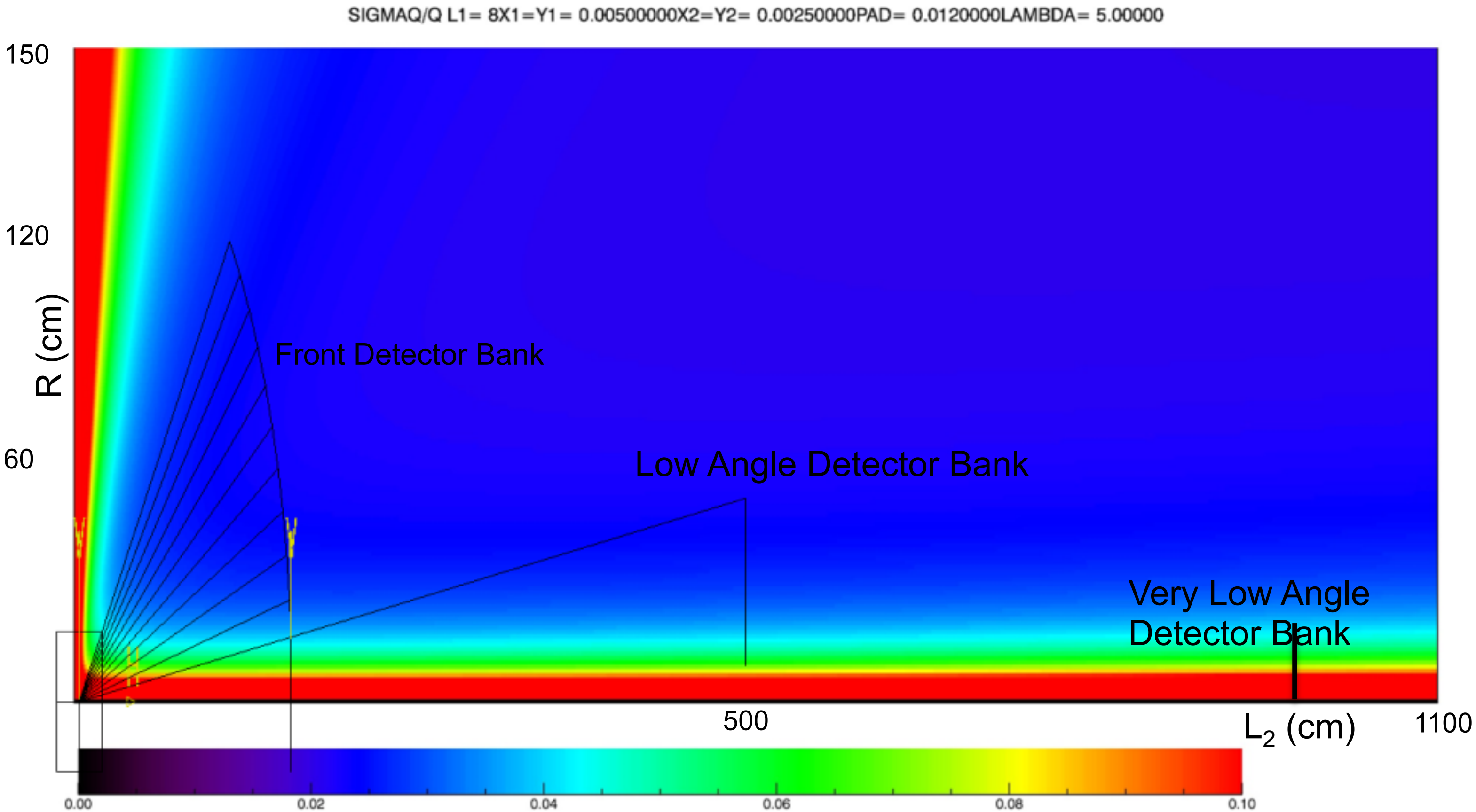


$d_{S-D} = 5$ m

ϑ_{TILT}	ϑ_{LOW}	ϑ_{MIDDLE}	ϑ_{HIGH}
2.4°	2.83°	4.86°	7.41°

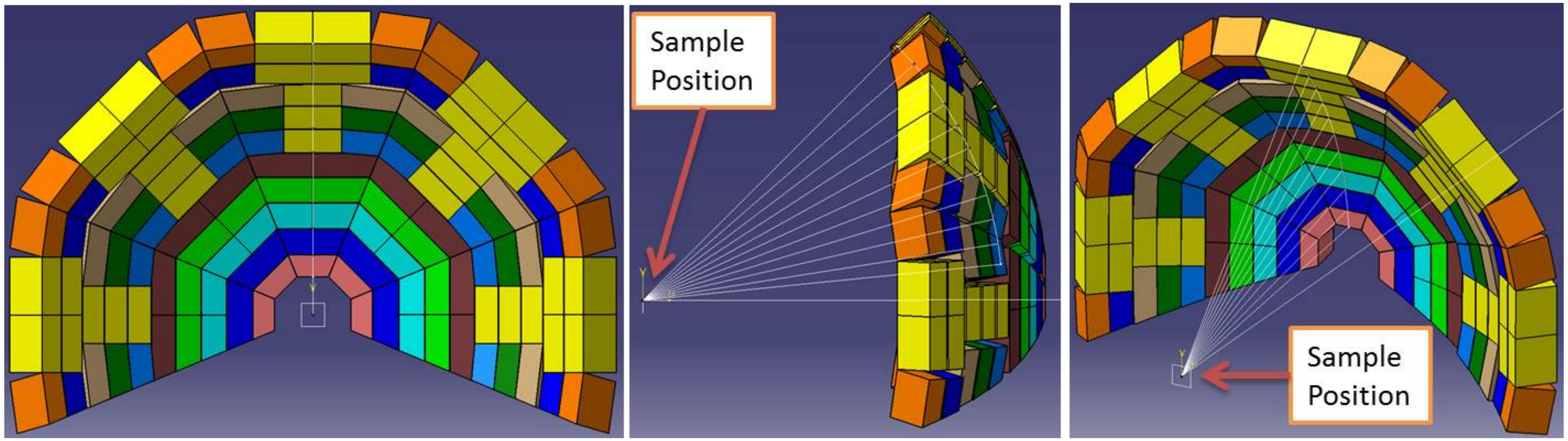
LOKI σ_Q/Q resolution using BANDGEM

$$(\sigma_Q)^2 = \frac{k^2}{12}\left[\frac{x_1^2+y_1^2}{2L_1^2} + \frac{x_2^2+y_2^2}{2L'^2} + \frac{x_3^2+y_3^2}{L_2^2} + \frac{R^2}{L_2^2}\left(\frac{\Delta\lambda}{\lambda}\right)^2\right]$$

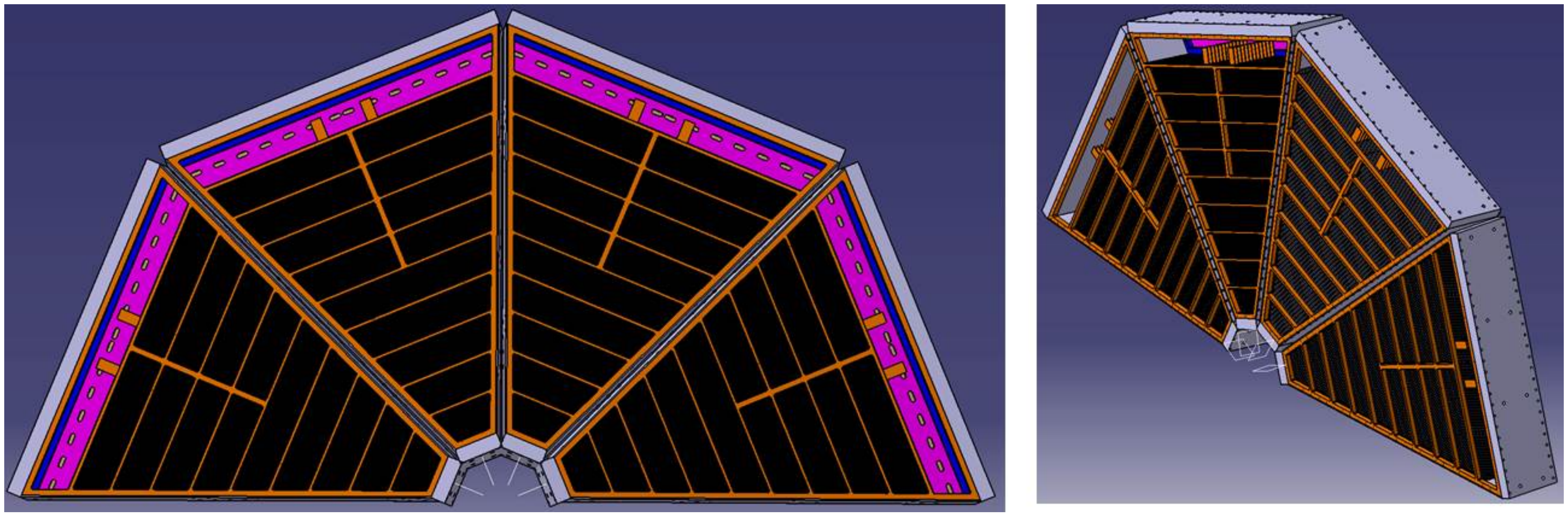


Colour plot of σ_Q/Q values on the (L_2,R) plane. L_2 is between 0 and 11 m and R between 0 m and 1.5 m. Parameters used $x_1=y_1=$ 5 mm, $x_2=y_2=$ 2.5 mm, λ = 5 A, pixel size 12 mm x 12 mm. Detector position is approximate

Front Detector



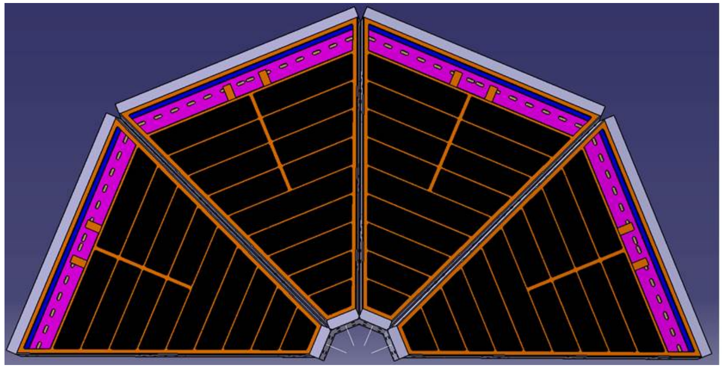
Low Angle Detector

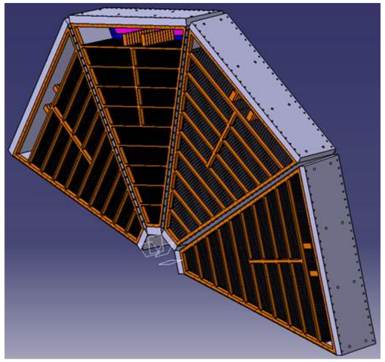


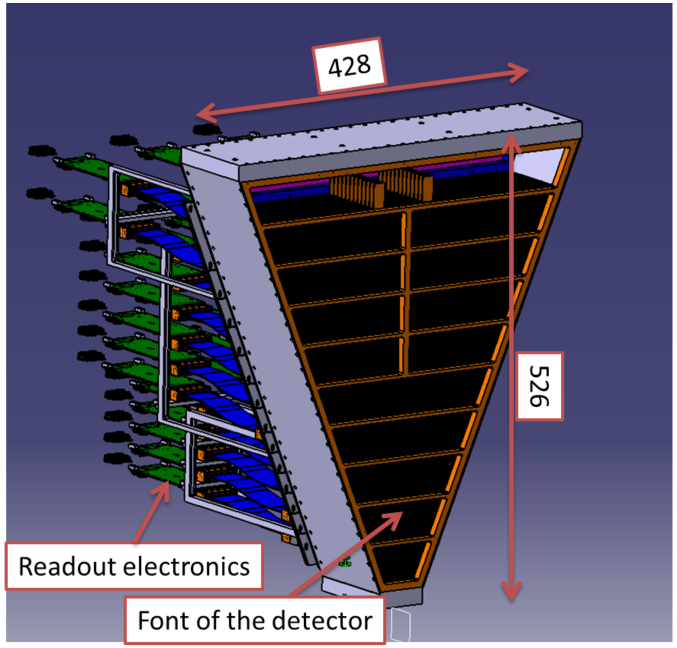
Low Angle Detector

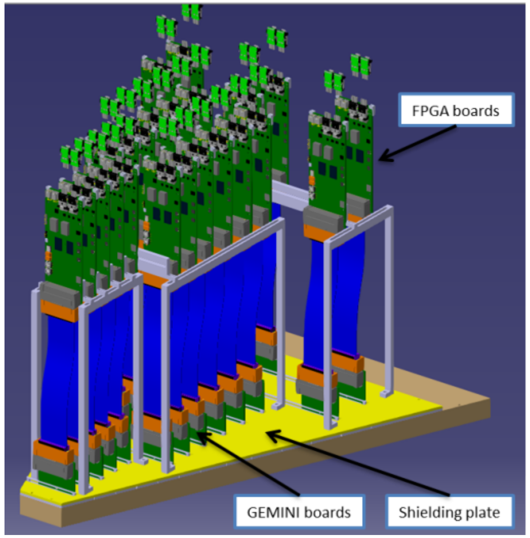
To cover the required area:

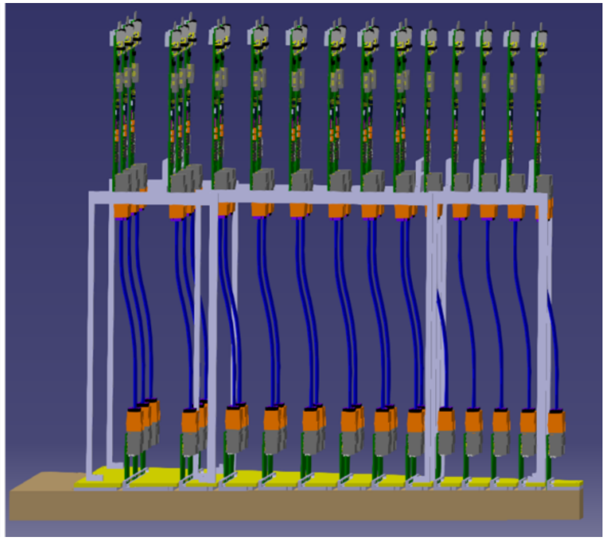
- N.4 45 Degrees detectors







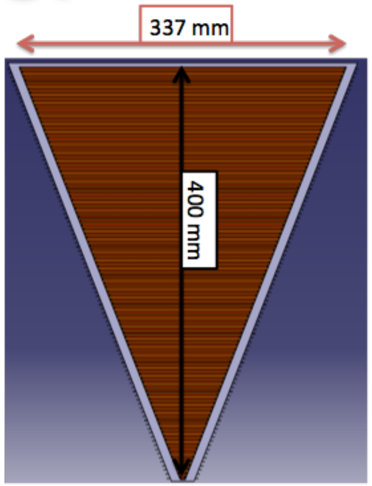


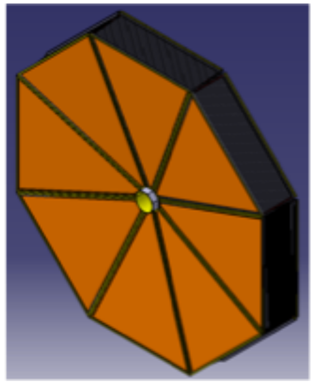


BANDGEM detector module and related front end electronics

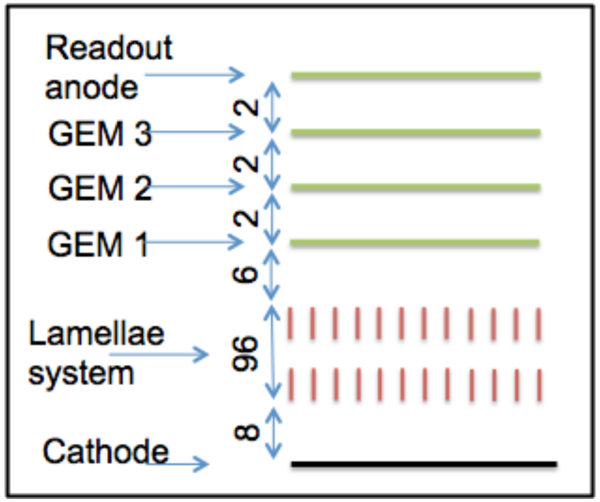
Design parameters
for LOKI low angle detector

Lamella Distance	4 mm
B_4C/empty ratio on lamellas	3
Full Lamella System lenght	96 mm
Lamella Thickeness	200 µm
Lamella Material	Aluminium
Optimal tilt angle	2.4 degrees @ 10 m
Pulse Height Threshold	100 keV
Cathode geometry	Trapezoidal
Count Rate Capability	> 5 MHz/cm^2
Gamma Ray Sensitivity	10^{-7}
Expected Efficiency @ 2.2 Å	37%
Expected Efficiency @ 6 Å	55%
Front-end ASIC	GEMINI – 16 channels/chip



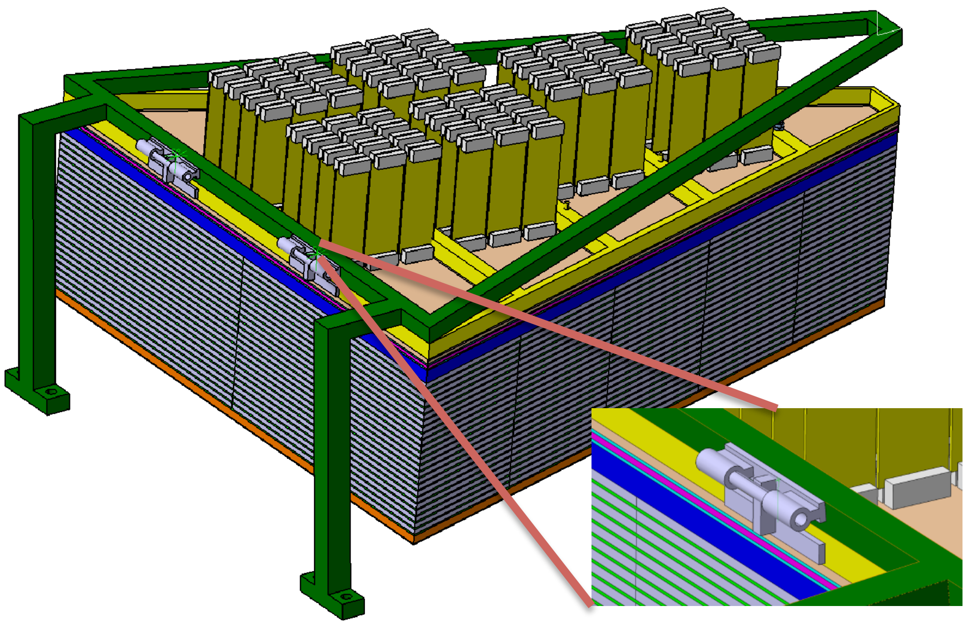


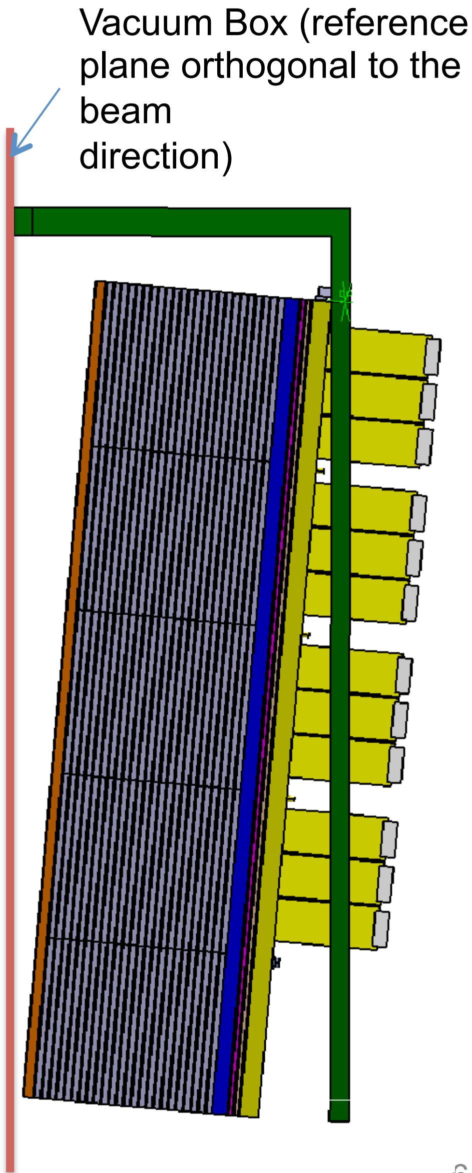
Total active area: 647 cm^2



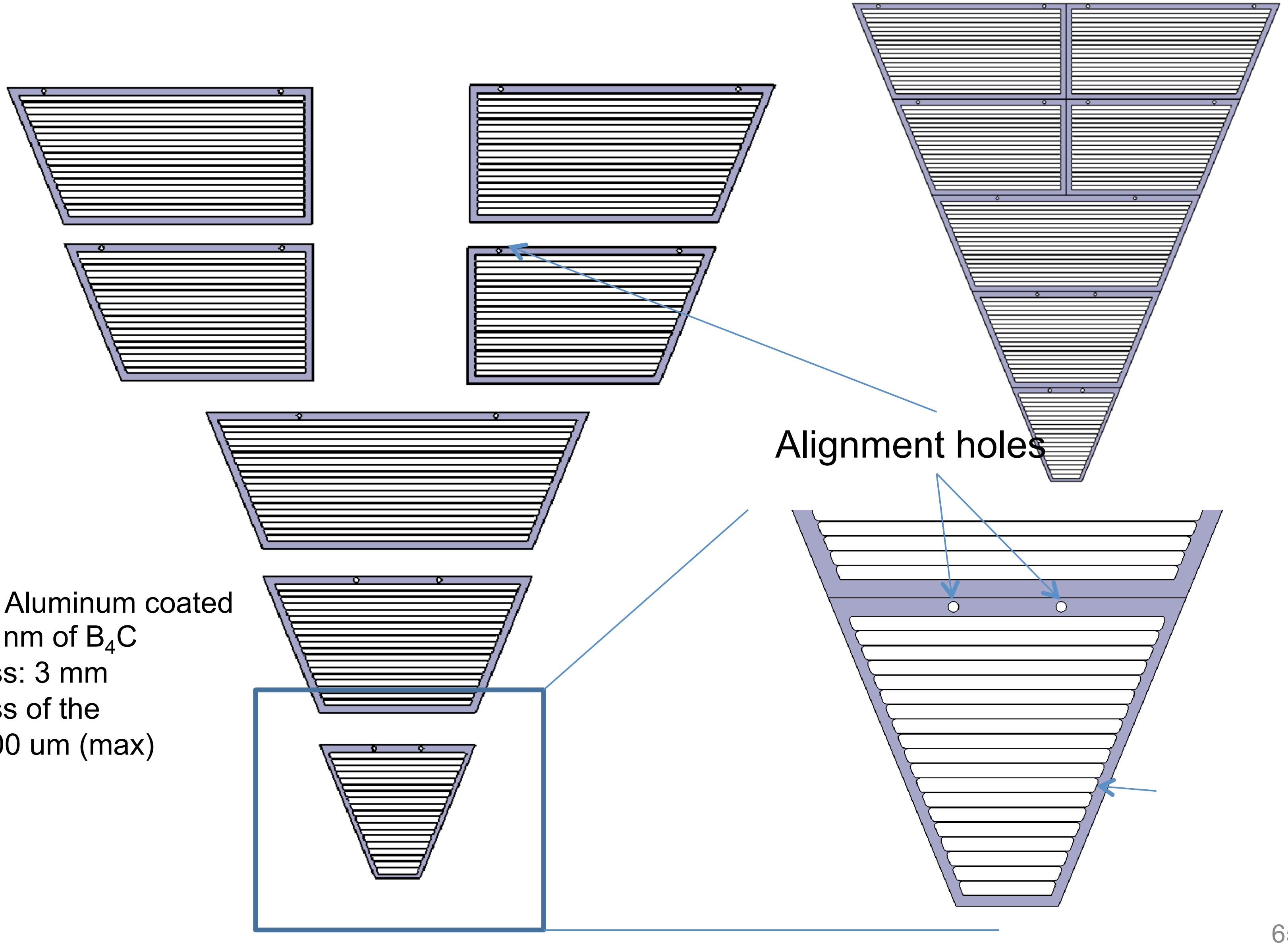
Full Module

Low Angle Detector: full module



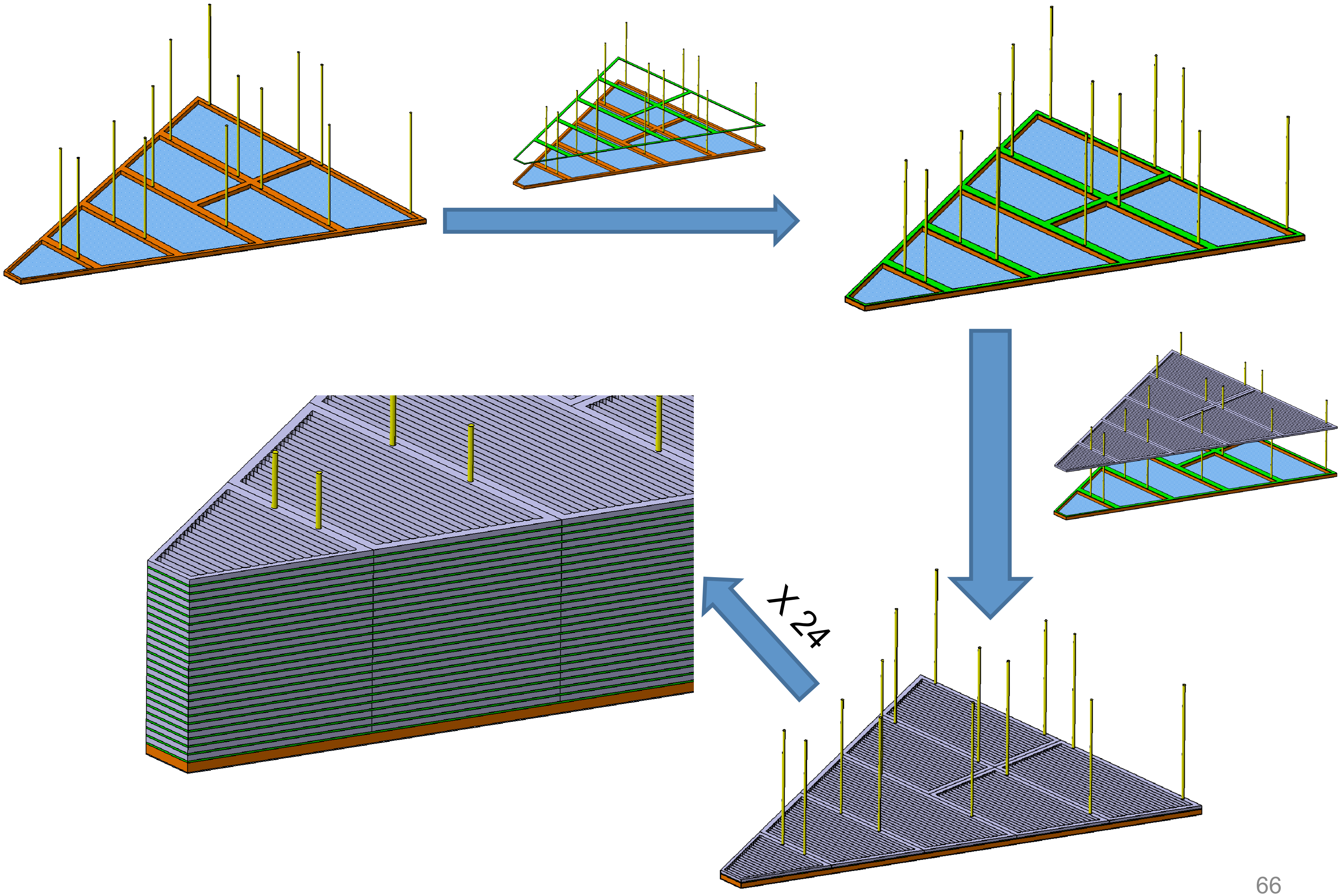


45 degrees Detector: Converter Grids

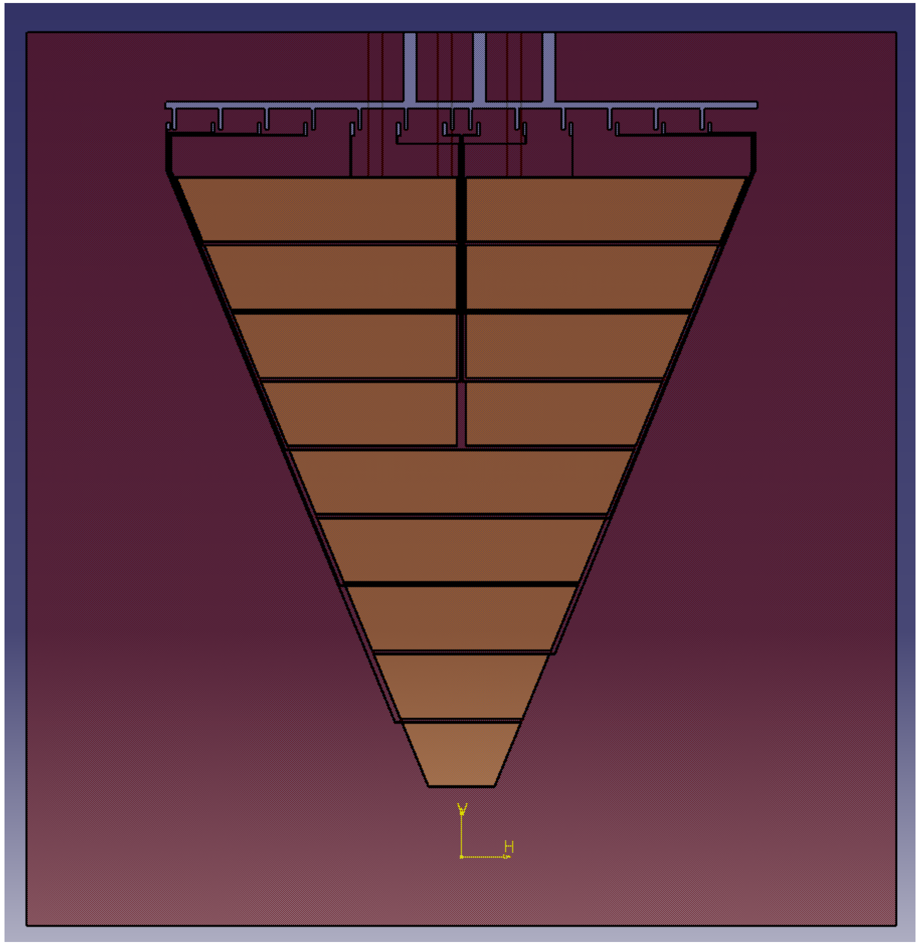


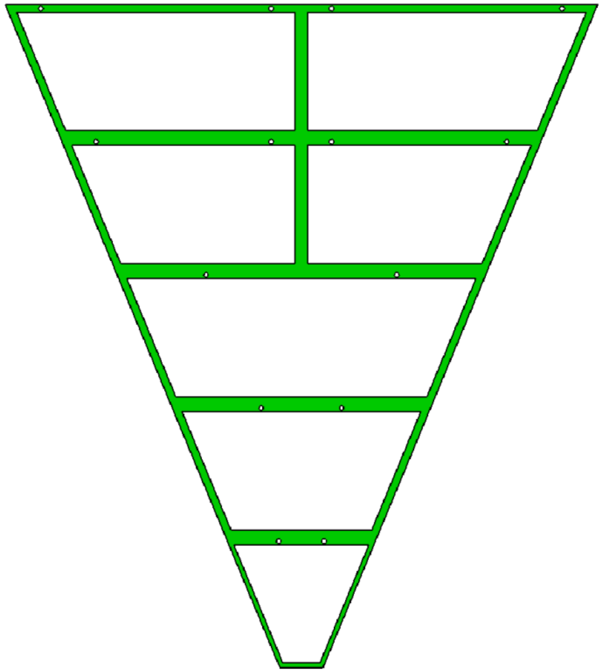
Material: Aluminum coated with 850 nm of B_4C
Thickness: 3 mm
Thickness of the strips: 200 um (max)

Full Module Detector: Cathode assembly



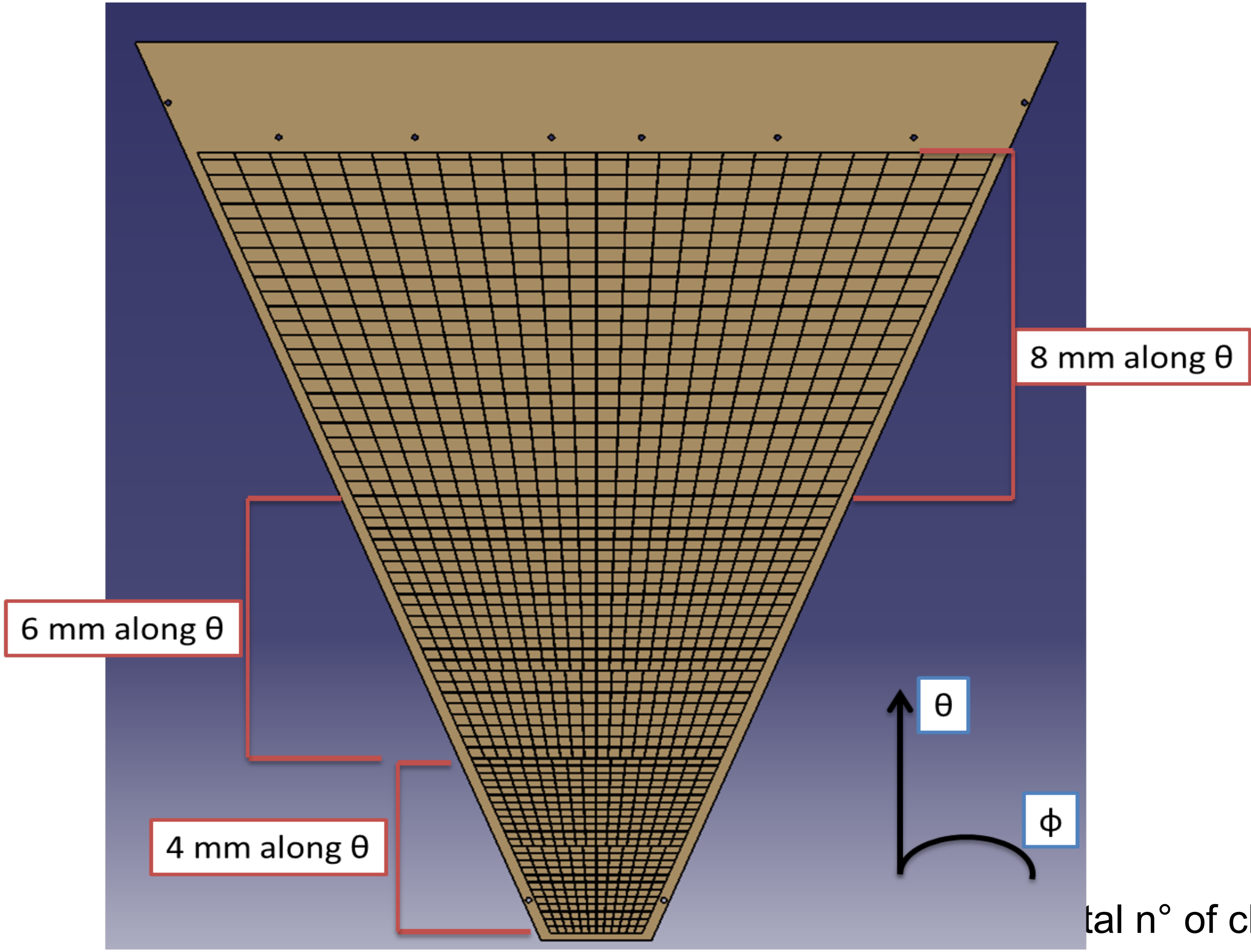
Full Module Detector: GEM foil and frame





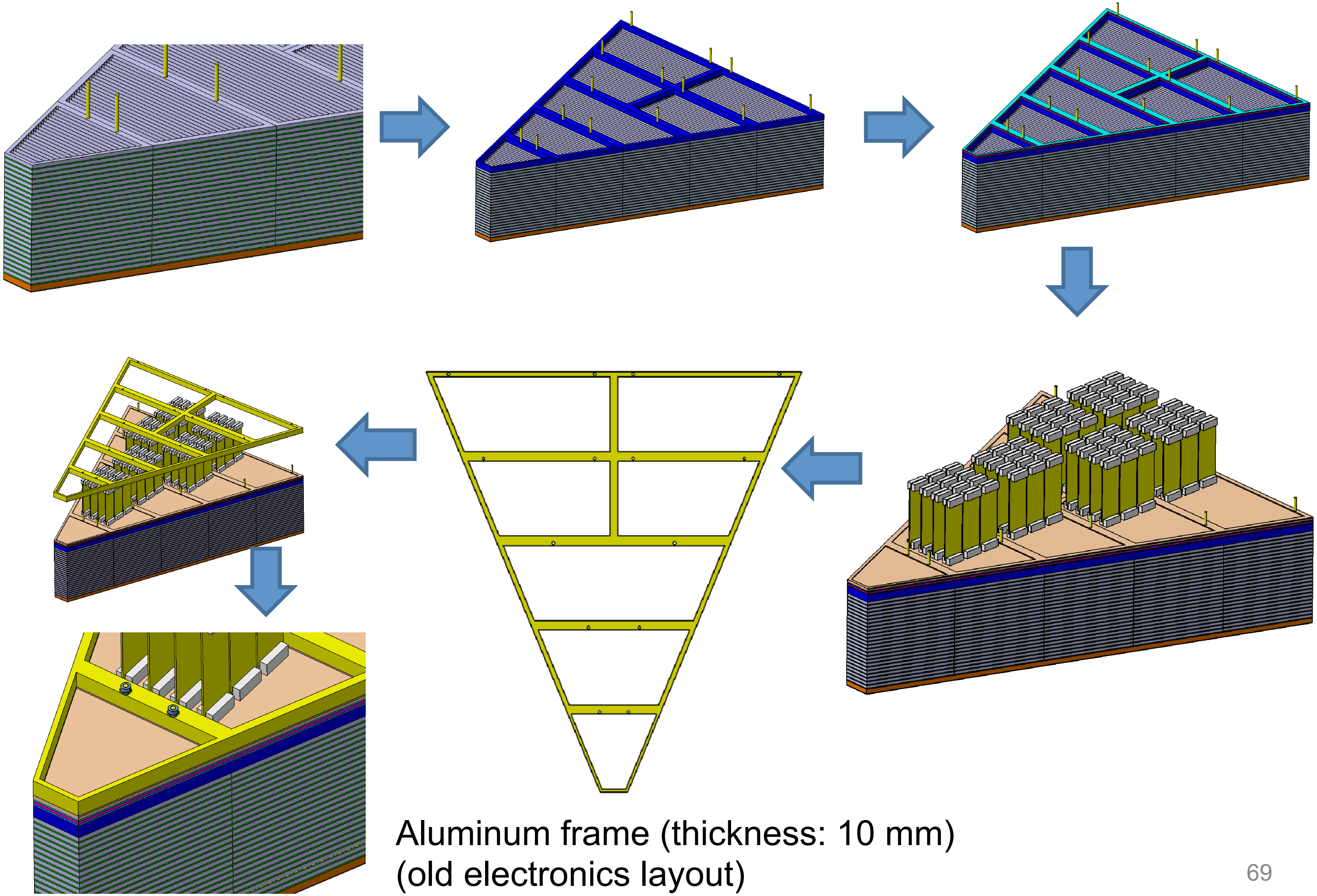
Sectorized GEM (design in progress).
GEM foil stretched and glued to its frame as usual.

Full Module Detector: ReadOut Anode



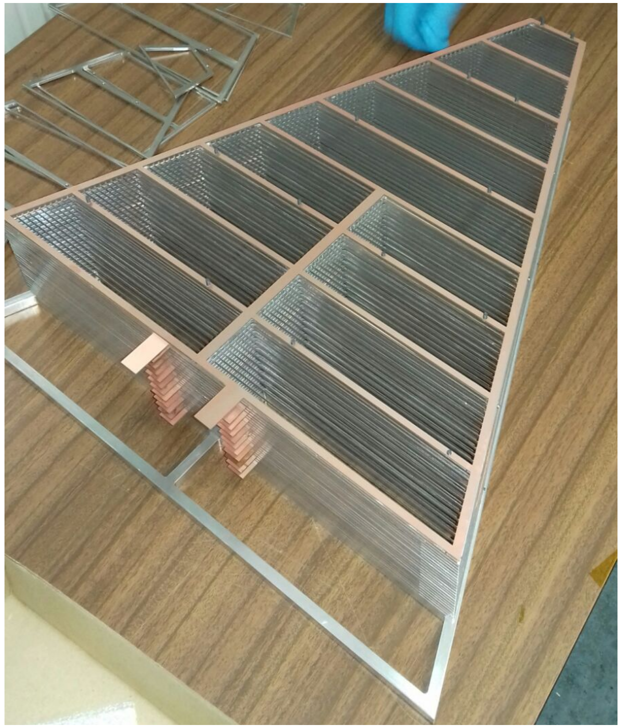
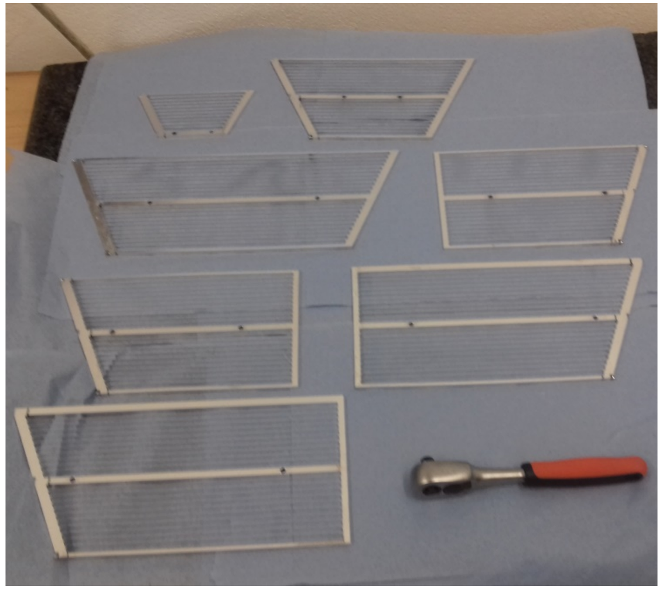
tal n° of channel: 950

45 degrees Detector: Detector Assembly

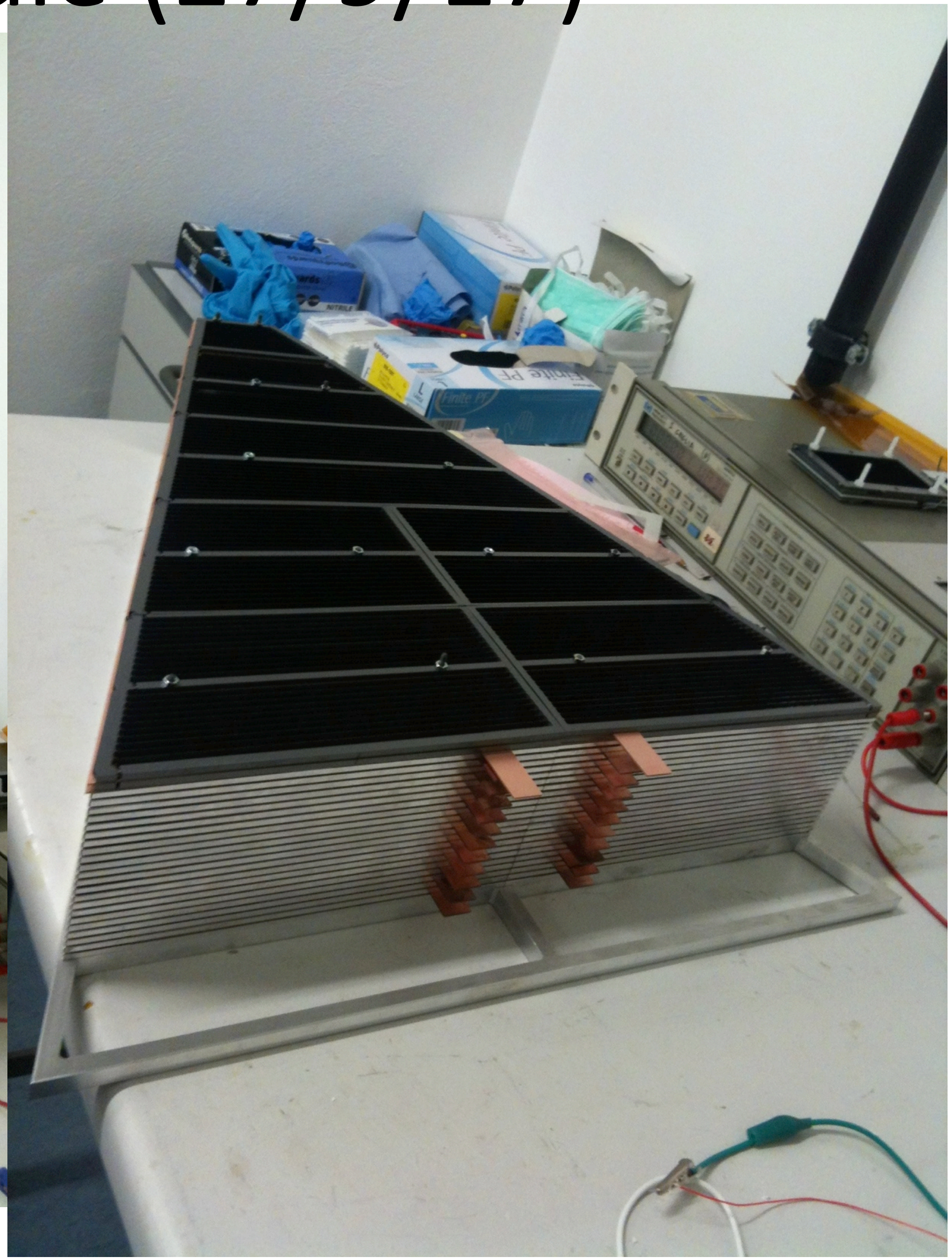


Aluminum frame (thickness: 10 mm)
(old electronics layout)

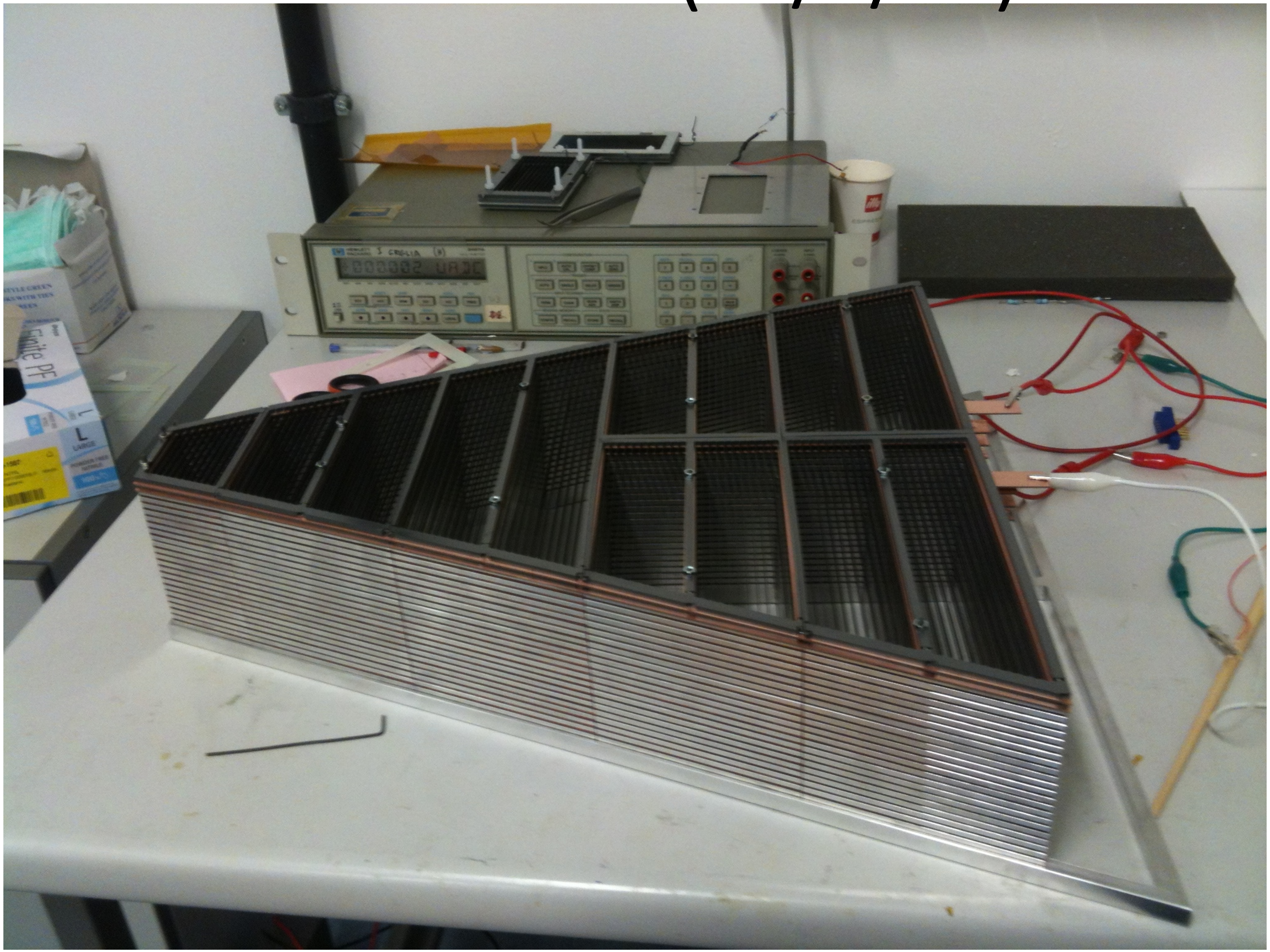
Full Module MockUp and First Grids

Full Module (27/9/17)

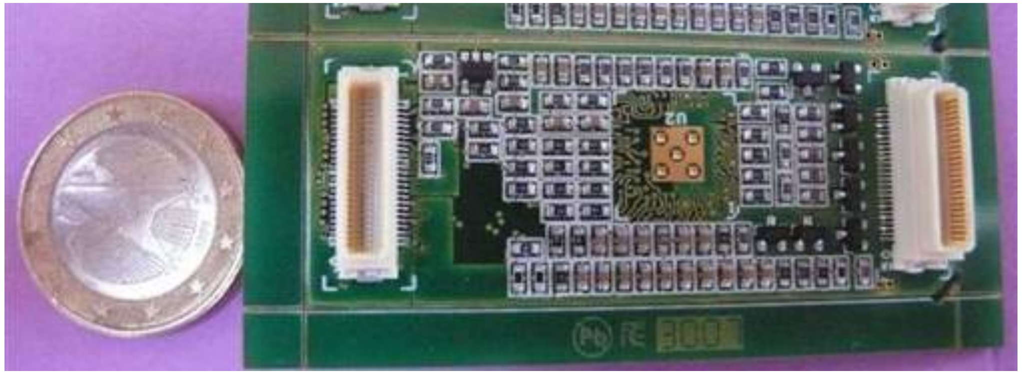


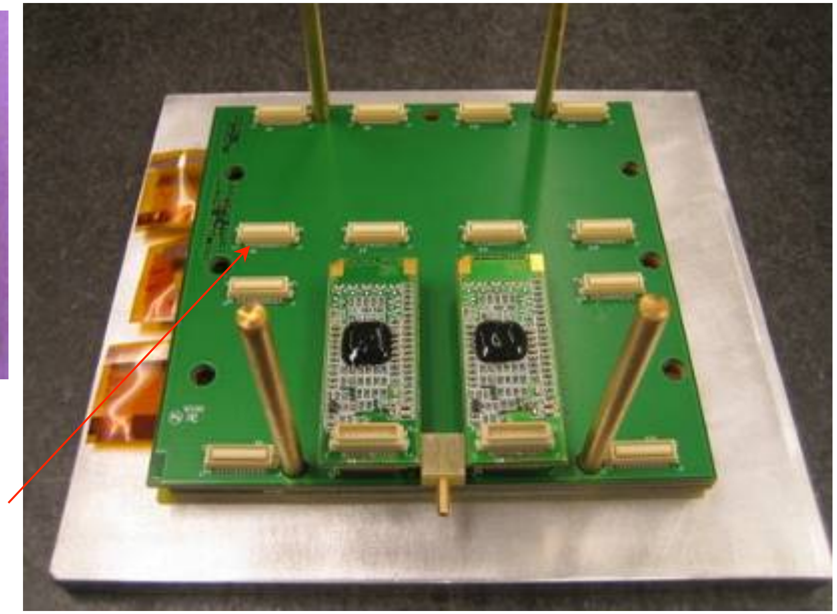
Full Module (27/9/17)



Front End Electronics

The demonstrator electronics is based on Carioca Chips.





Digital Chip with 8 channels
Equips the LHCb GEM detectors
Fast chip – used for triggering
Adapted from MWPC

New chip tested: the GEMINI chip.
Mixed analog and digital
16 channels/chip.
Designed for BANDGEM

Conclusions

- Improved construction design using waterjet-cut grids
- Main parameters:
  - Efficiency @ 4 A > 45%
  - Resolution (FWHM) about 7 mm
  - Rate capability about 10 MHz/cm^2
- Competivite for SANS (Small angle neutron scattering applications)
- Full module for LOKI is being realized and will be tested next year


Thanks from... the BANDGEM band