The ATLAS/Demokritos group
Research activities – R&Ds

Theodoros Geralis
NCSR Demokritos
20/4/2019

OUTLINE

1) **The ATLAS New Small Wheel project**
2) **Current activities and prospects**

3) **R&D Projects**
    i. **Real x-y microbulk micromegas**
    ii. **Resistive Micromegas for high rates**
    iii. **Micromegas and Graphene**

HEP 2019 - Conference on Recent Developments in High Energy Physics and Cosmology
17-20 April 2019, NCSR "DEMOKRITOS", Athens, Greece

The ATLAS Group – 2018/2019

- **October 2017**: NCSR Demokritos **full member** of **ATLAS**

Researchers
Georgios Fanourakis
Theodoros Geralis
Georgios Stavropoulos

Doctoral Students
Maria-Myrto Prapa

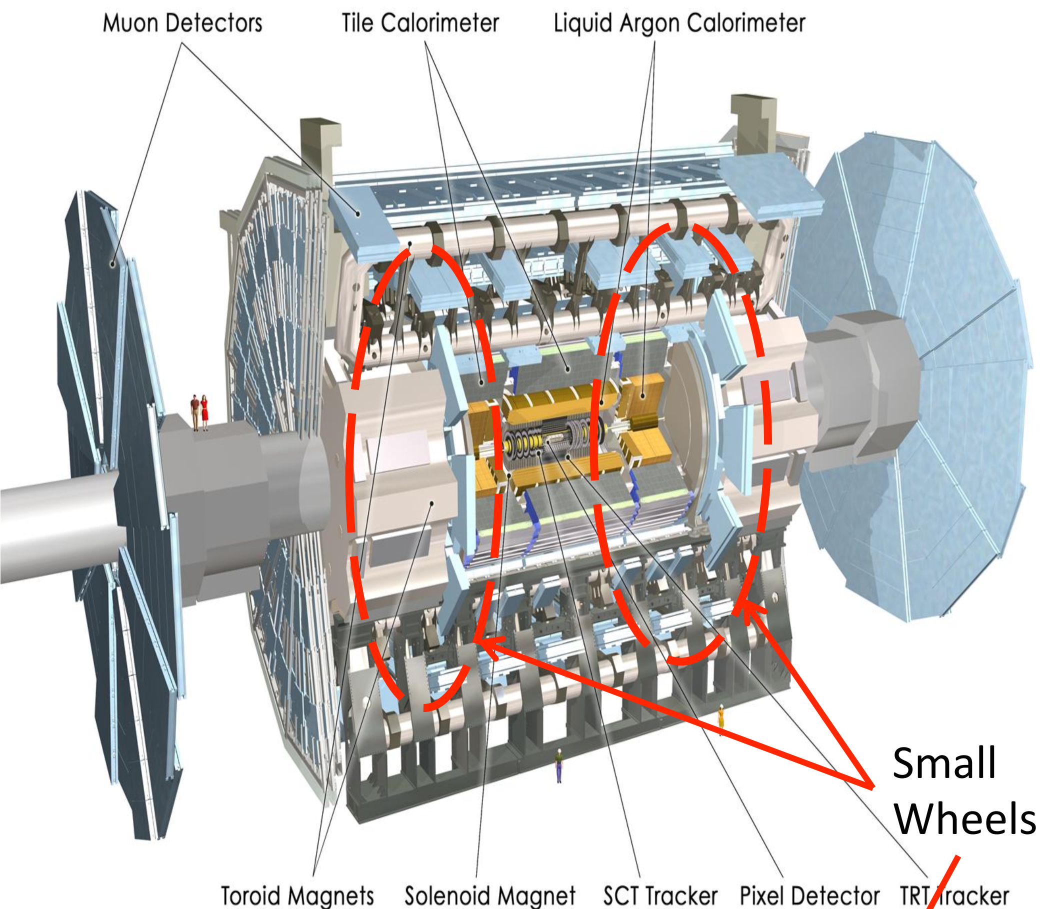
Master Thesis
Kostas Damanakis
Olga Zormpa

Diploma
Vasilis Blanas

Technician (Electronics)
Yiannis Kiskiras

Practical work (2018)
Stamatis Tzanos (NTUA)
Vasilis Blanas (NTUA)
Stathis Logothetis (NTUA)
Eva Eleftheriou (Univ. Patras)
Despina Stasinou (Univ. Patras)
Athanasia Papaioannou (Univ. Patras)

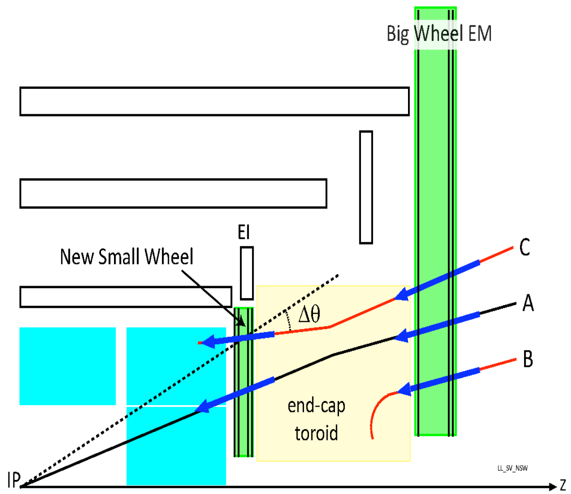
The ATLAS Experiment - Upgrade



- ATLAS - General purpose detector
- Small wheels are part of the muon spectrometer and are located between the end-cap calorimeter and end-cap toroid
- 10 m in diameter
- Consist of:
  - Cathode Strip Chambers (CSC)
  - Thin Gap Chambers (TGC)
  - Monitor Drift Tube (MDT)

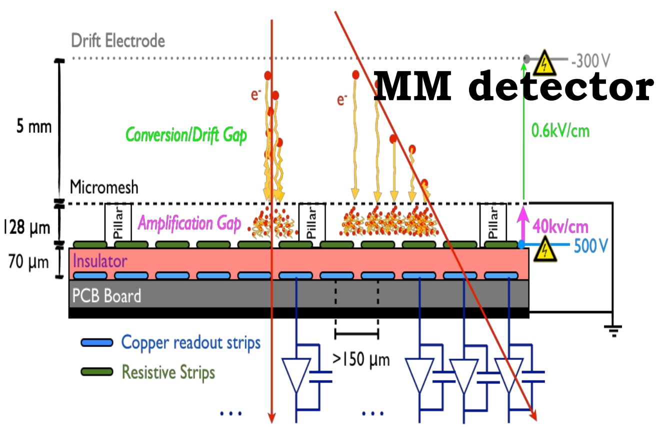
NEW SMALL WHEELS

Operation principle MMs and sTGC (NSW Technologies)

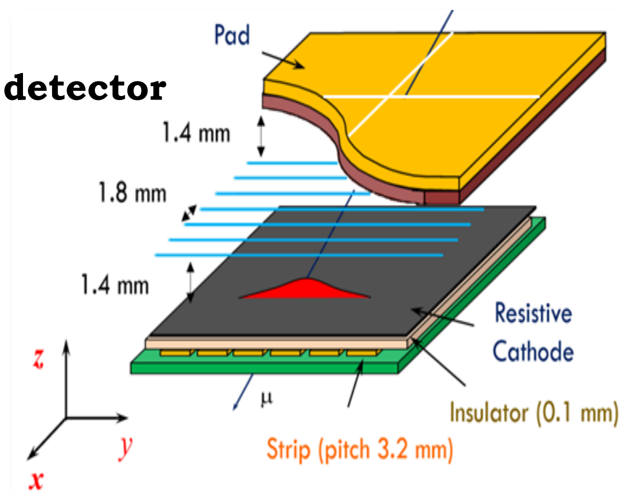


New Small Wheels (NSW)

- Work at high rates 20kHz/cm^2
- Will provide online high angle resolution (σ_θ~1 mrad) IP pointing segments
- Spatial resolution at 100 μm
- Significant reduction of fake triggers



sTGC detector



Micromegas – 2,097,152 channels

MM strips for tracking, first hit for trigger

-Strip pitch: 450 μm, Readout
Strips: 300 μm

-Data rates: Up to 8 Gbps/plane

sTGC – 331,744 channels

- sTGC wires/strips for tracking, strips/pads for trigger

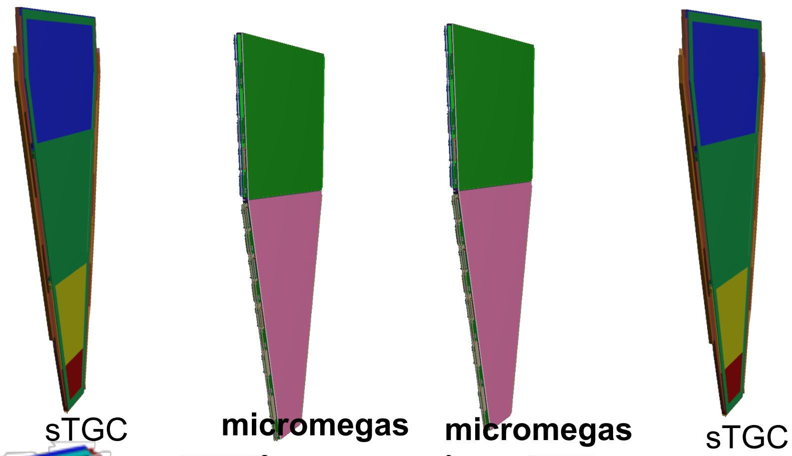
-Wires: 50 μm, pitch 1.8 mm

-Strips: pitch 3.2 mm

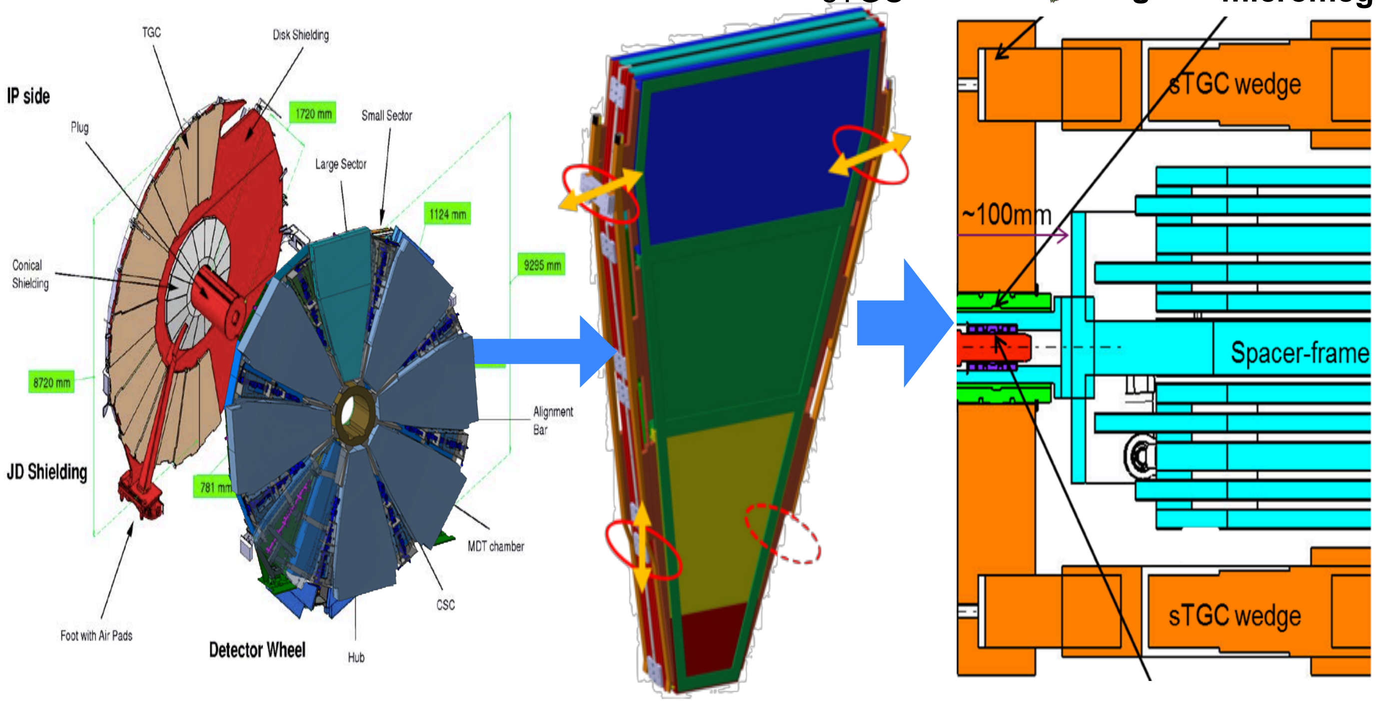
-Data rates: up to 1.77 Gbps/plane

New Small Wheel (NSW) Layout

8 MM + 8 sTGC layers per NSW sector



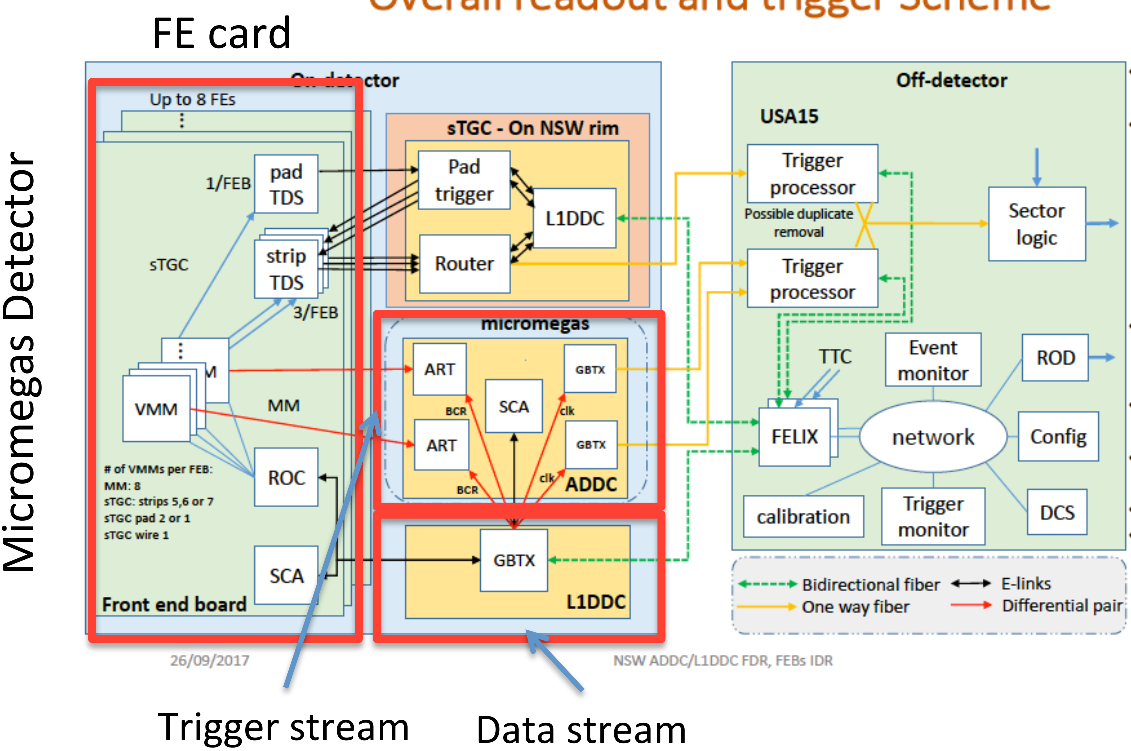
- Two technologies: Both Micromegas & sTGC detectors will provide tracking and trigger data
- 16 Sectors per Wheel (8 large, 8 small)
- 2 Multilayers (Modules) per Sector for Micromegas & 3 Multilayers (Modules) per Sector for sTGC
- 8 Micromegas Layers & 8 sTGC Layers per Multilayer

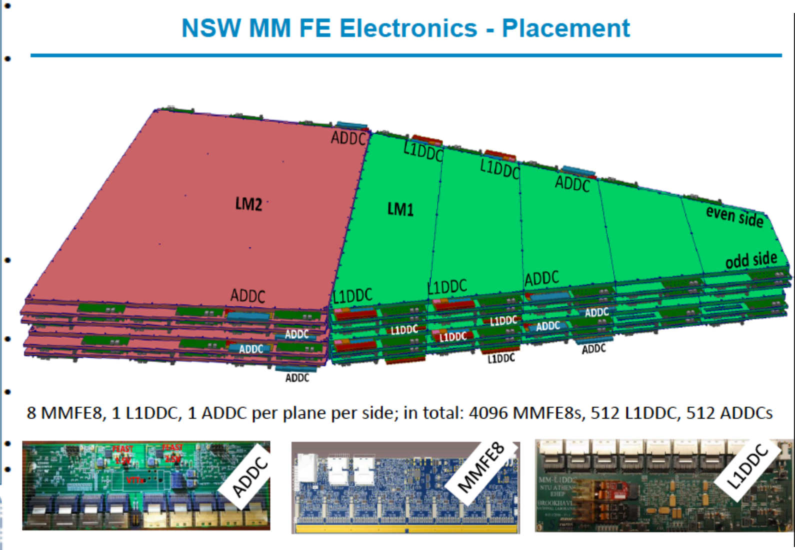


sTGC (mainly for triggering) & Micromegas (mainly for tracking) detectors, both providing tracking and triggering information, combined into a fully redundant NSW system!

NCSR Demokritos group responsibilities

Overall readout and trigger Scheme





QA/QC of NSW Electronic Boards

- **L1DDC:** Micromegas Data Concentrator Cards test-setup
- **ADDC:** Micromegas Trigger Concentrator Cards test-setup

Current major Project

- **Repeaters:** Responsibility for full construction/tests of Repeater cards

VMM ASIC irradiation studies (2013 – 2018)

Collaboration
INPP: A. Kourkoumeli (PhD), G. Fanourakis, T. Geralis
NTUA: T. Alexopoulos, M. Kokkoris, G. Tsipolitis
Aegean Univ.: K. Papageorgiou, I. Gialas

VMM will be used at the s-LHC➔ Should test radiation tolerance and SEU ASIC specifications: 130 nm Technology, 64 channels, BNL design

VMM will be used by ATLAS muon Micromegas group and also as the SRS FE chip

Irradiation took place at the Tandem Accelerator

Credits: T.Alexopoul

Nuclear Reaction	Energy Range (MeV)	Range (MeV)
$^{7}Li(p,n)^{7}Be$	1.9 to 8.4	0.1 to 6.7*
$^{2}H(d,n)^{3}He$	0.8 to 8.4	3.9 to 11.5**
$^{3}H(d,n)^{4}He$	0.8 to 8.4	16.4 to 25.7***

[0.1,0.5] MeV & quasimonoenergetic up to ~2.5 MeV

** Quasimonoenergetic neutrons up to ~7.5 MeV

*** Monoenergetic neutrons [16.4,22] MeV

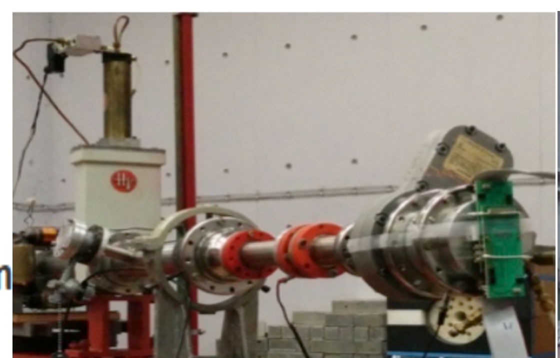
Tritium target (10 ci):

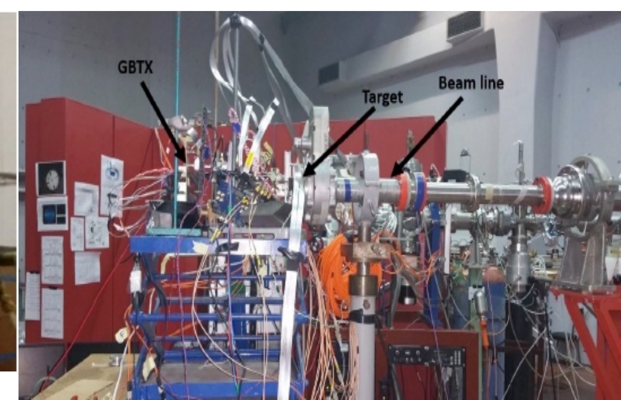
~10^6 neutrons/cm^2s of 18-22 MeV

Testing:

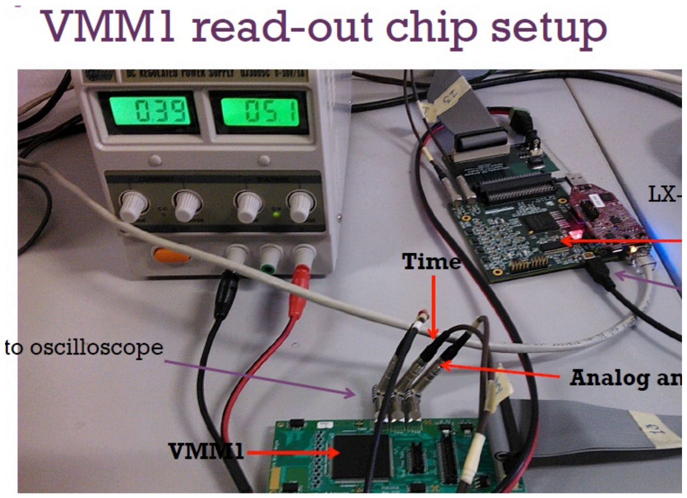
2 days @ E_d = 5.5 MeV, VMMs @ 26,36 mm

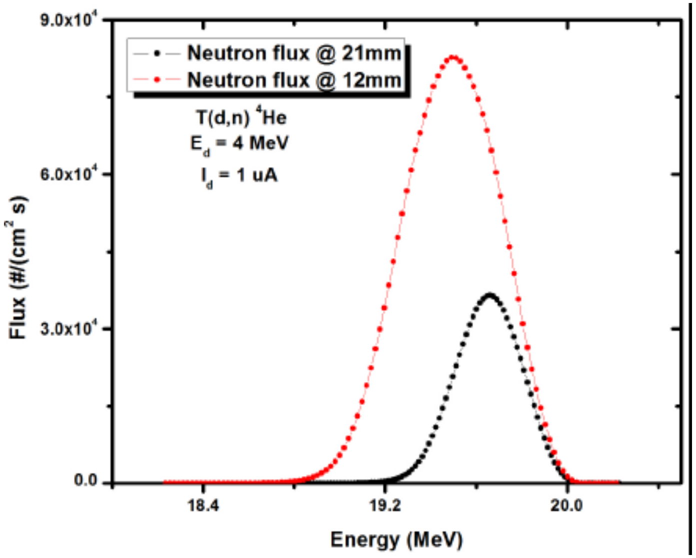
3 days @ E_d = 4 MeV, VMMs @ 12,21 mm



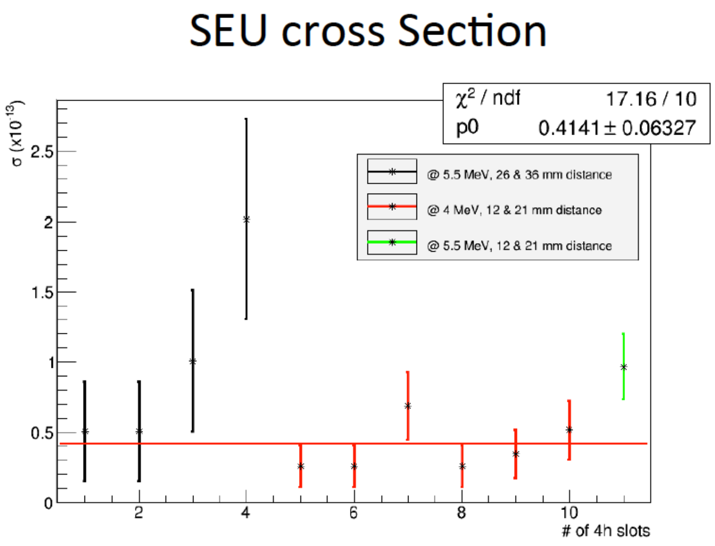


1) Redesign Control FPGA firmware for the testing





2) Irradiate with high energy neutrons (~ 20 MeV)



Use Tritiated solid target $^3H(d,n)^4He$

Instantaneous flux(max): 1.8 x 10^7 n/cm^2/s

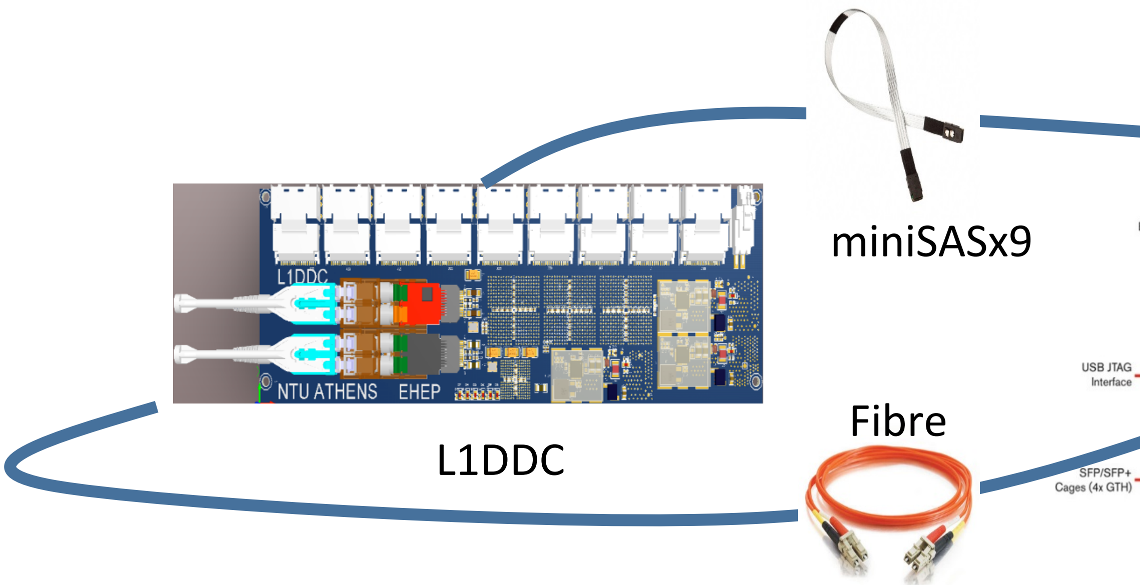
Total flux: 3.1 x 10^{11} n/cm^2

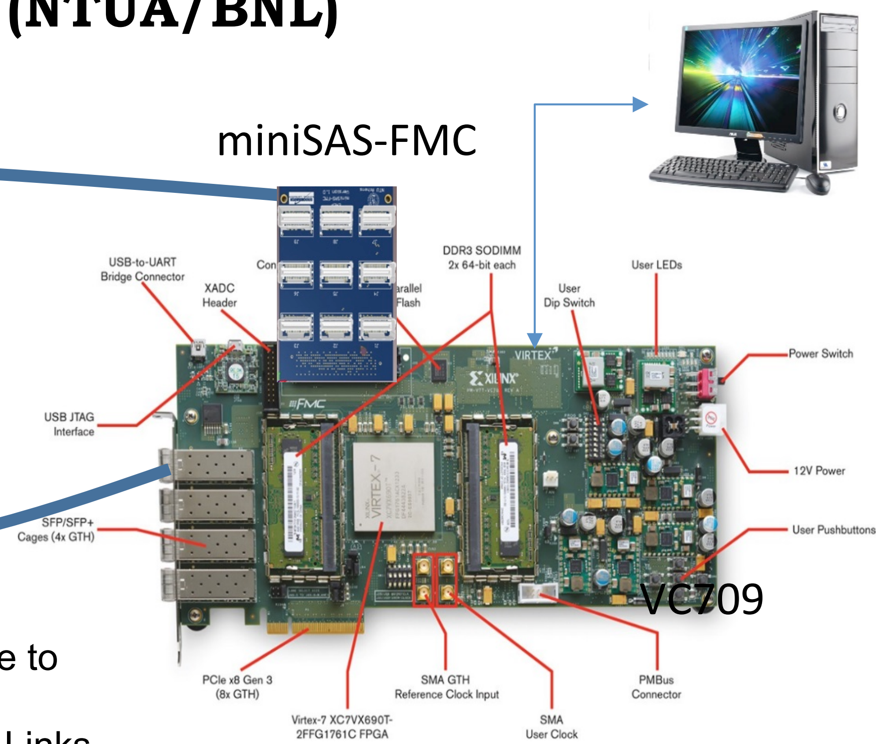
SEU Cross section = (4.1 +-0.7) x 10^{-14} cm^2/bit

Conclusion: SEU occurrences non tolerable , provision for auto-correction.

Work published in JINST

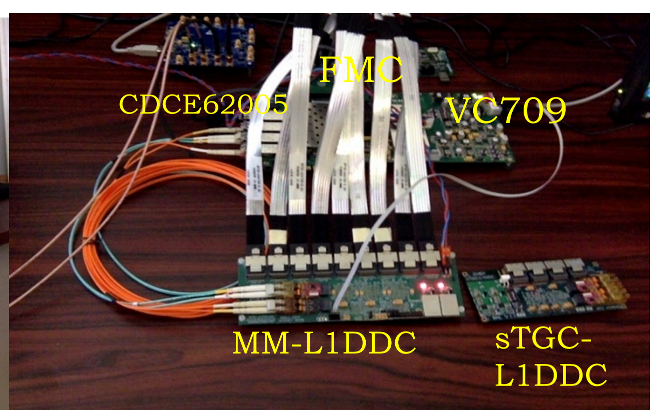
Testing the L1DDC boards (NTUA/BNL)

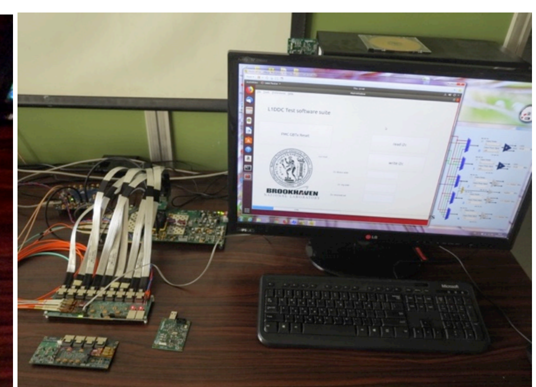




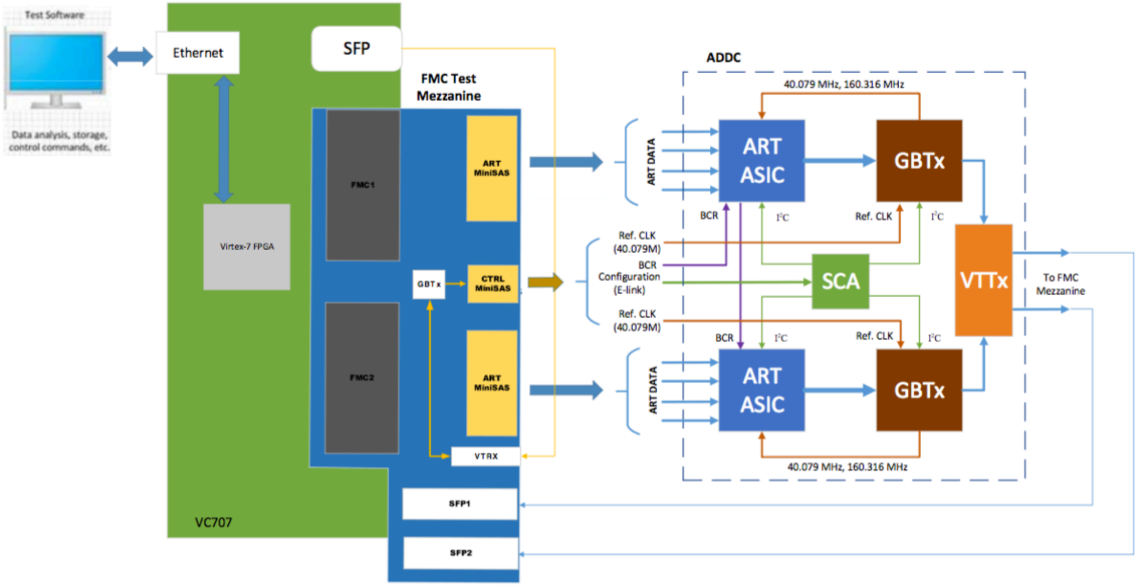
- Use an evaluation VC709 board and GBT-FPGA firmware to validate the L1DDC boards
- Evaluation board runs GBT-FPGA firmware along with E-Links
  - Data are generated in VC709 with respect to that clock and send to L1DDC via E-links and then through fiber back to the evaluation board

Test setup at Demokritos



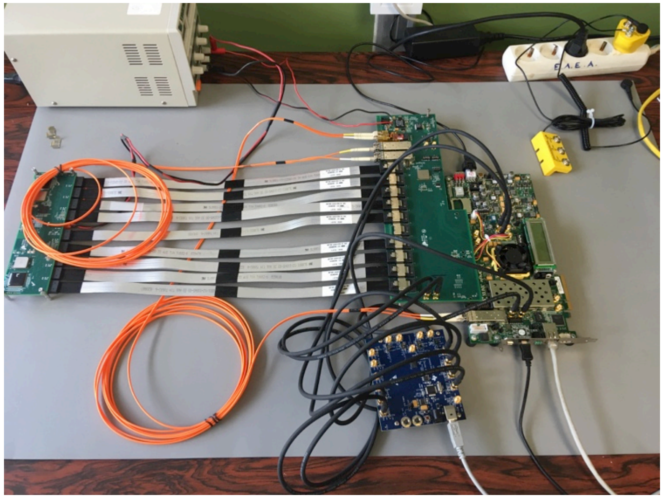


ADDC (NTUA/BNL) Test Setup



Xilinx VC707 platform
FMC mezzanine
CDCE62005 clock source board.
ADDC board.
VTRx module with 1 meter LC fiber.
VTTx module with 1 meter LC fiber.
0.5m miniSAS cable x 9.

Demokritos ADDC test setup



- The test data are sent through the 8 minisas channels and the results will be received through the two SFP connectors;
- The minisas connector located at the center of the mezzanine board will be used to simulate the configuration signals from L1DDC and provide the reference clock.

Serial and LVDS Repeaters
Demokritos responsibility

Collaboration

T. Geralis[a], Y. Benhammou[f], A. Coimbra[d], P. Gkountoumis[b,c], Y. Kiskiras[a], A. Koulouris[b], U. Landgraf[g], L. Levinson[d], J. Narevicius[d], M. M. Prapa[a], A. Roich[d], G. Stavropoulos[a], S. Siyuan[e], X. Wang[e]

[a]NCSR Demokritos, Athens, Greece
[b]National Technical University of Athens, Greece
[c]Brookhaven National Laboratory, USA
[d]Weizmann Institute of Science, Israel
[e]University of Michigan, USA
[f]Tel Aviv University, Israel
[g]University of Freiburg, Germany

Current Major Project:
Serial and LVDS Repeaters for the sTGCs

Problem addressed

1) High rate signals are attenuated at long transfers

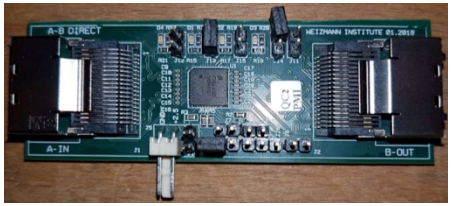
2) We need repeater cards to boost the signals to the receiving end.
   Critical for Trigger paths

3) Initial design by Weizmann Institute

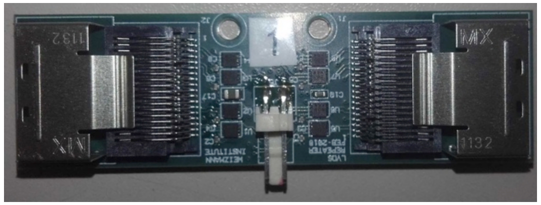
4) We are responsible for: final design, Manufacturing and assembly,
   Test setup development, QA/QC of ~1500 Repeater cards

5) Commissioning, allocation and cables layout and ordering

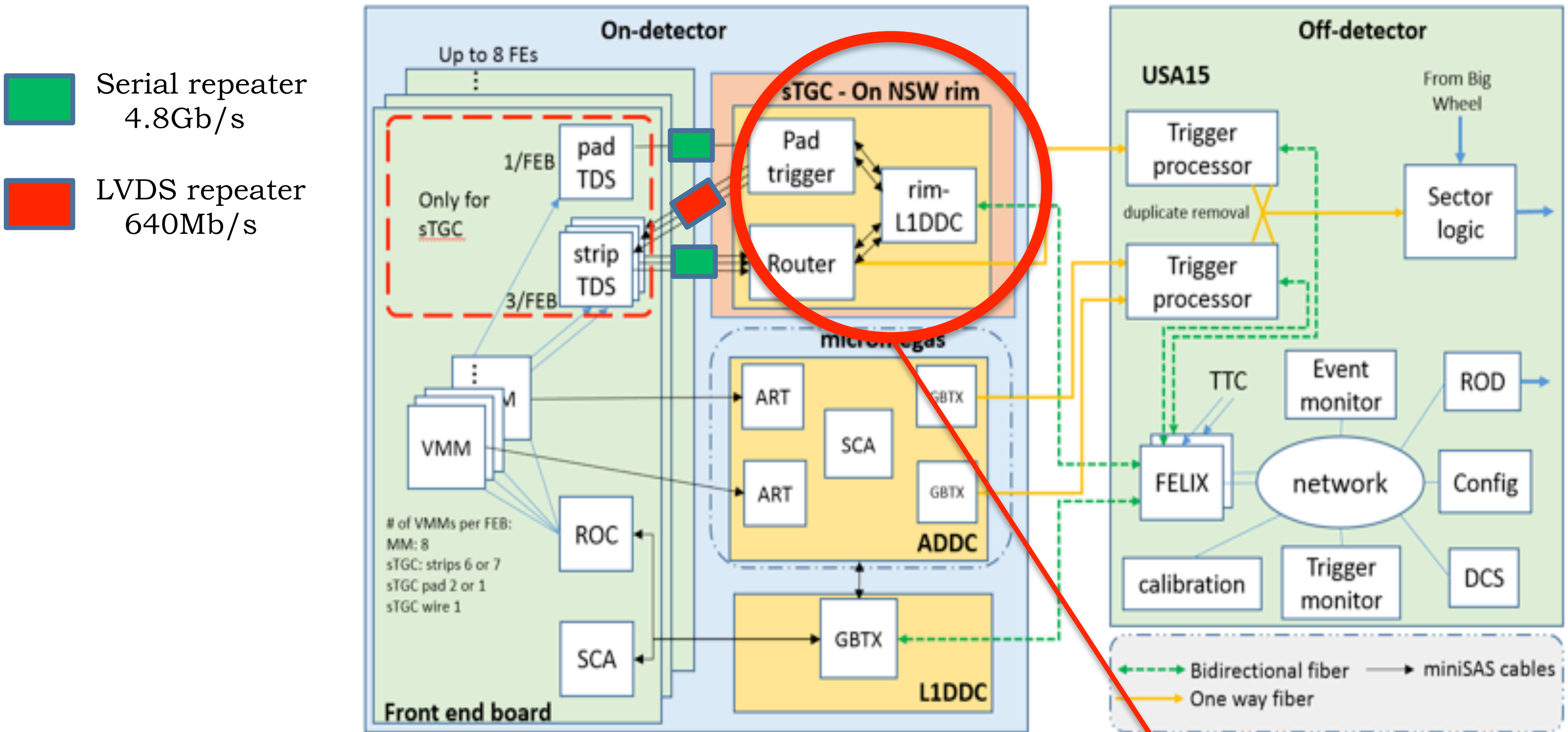
Serial repeater_V0



LVDS repeater_V0



NSW Electronics and Trigger

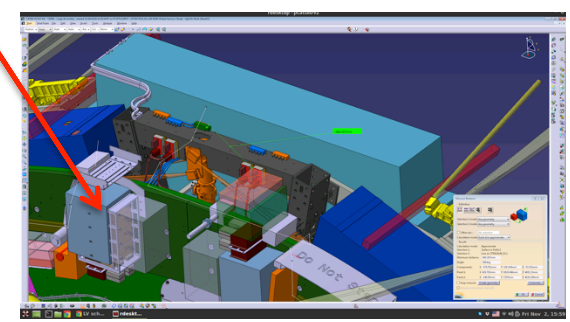


Distance between FEBs – Rim crate: Up to 6.25m

3M SL8800 Twinax cables (Tin or Silver plating)

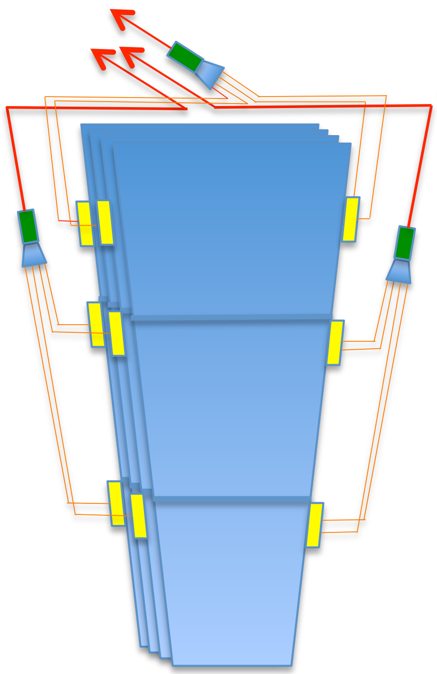
➔ attenuation

Frequency (GHz)	0.50	1.0	2.0	5.0	10.0	15.0	20.0
Tin Plating (dB/m)	-0.90	-1.4	-2.2	-4.0	-7.5	-10.9	-14.6
Silver Plating (dB/m)	-0.85	-1.2	-1.7	-3.2	-4.9	-6.8	-8.8
difference	-0.05	0.2	-0.5	-0.8	-2.6	-4.1	-5.8

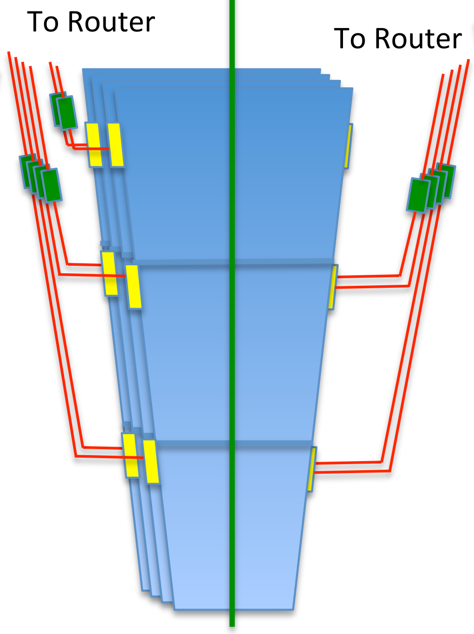


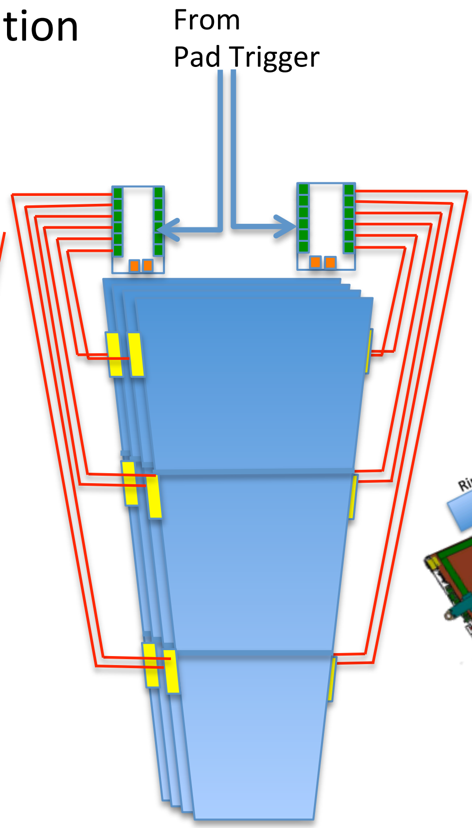
Serial & LVDS Repeaters: Location and population

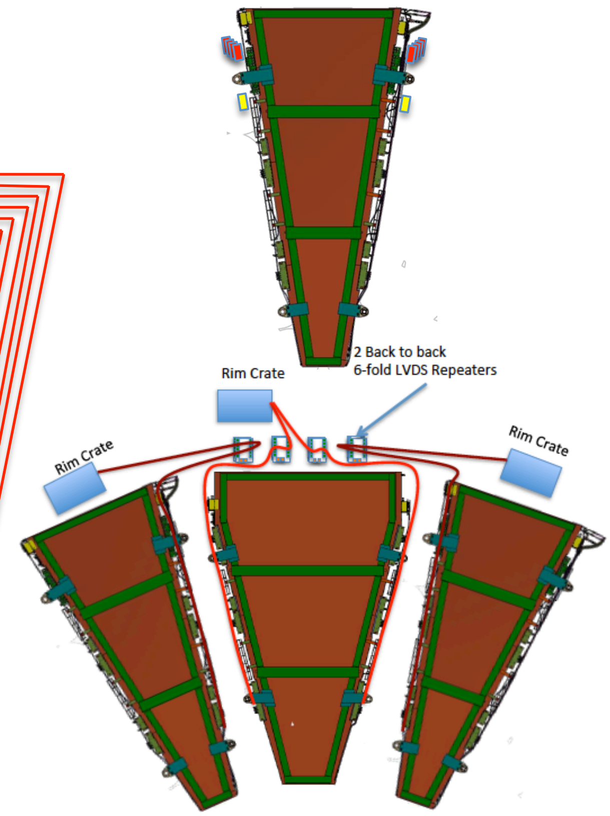
Large sector



Large sector | **Small sector**





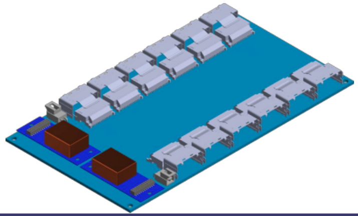


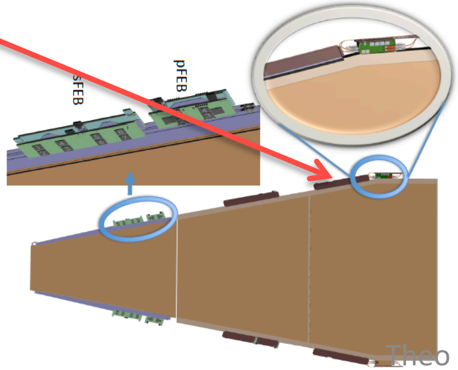
Total Serial Repeaters: 800 + spares

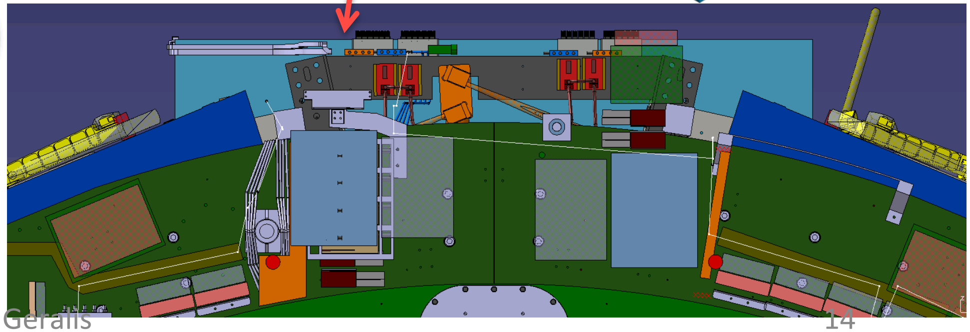
Total LVDS Repeaters: 768 + spares

Design 6-fold LVDS Repeater

Cooling is available on the Large Sectors spokes

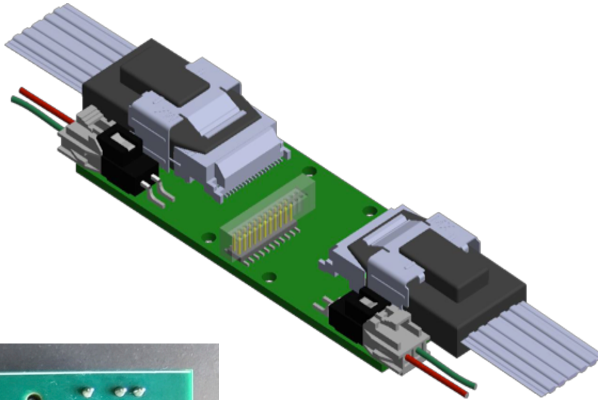


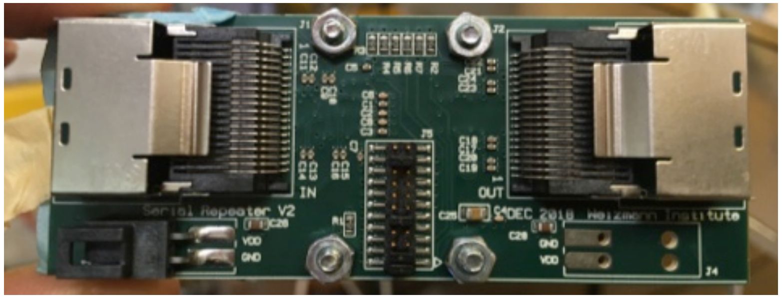




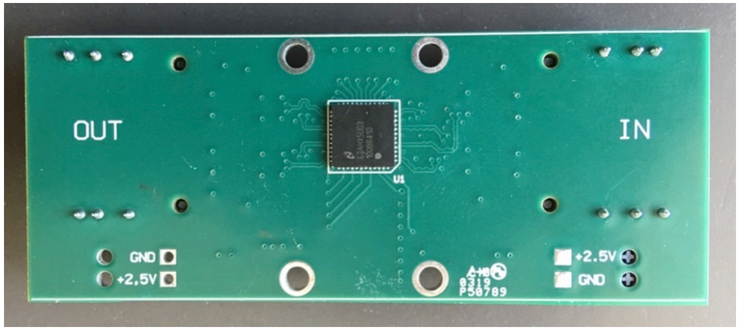
Serial Repeaters – SRL1R

- pFEB → Pad Trigger & sFEB → Router
- 4.8 Gbps connection



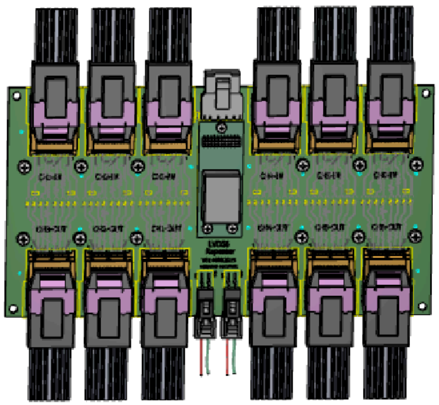


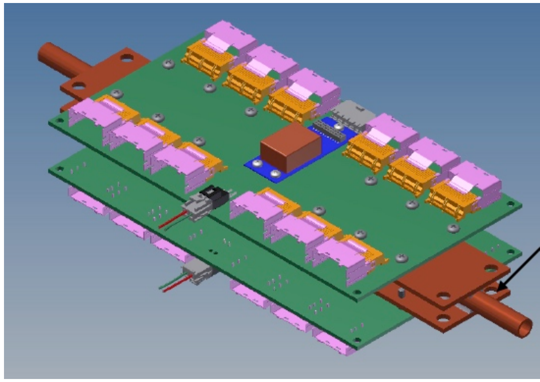
SRL1R_V1



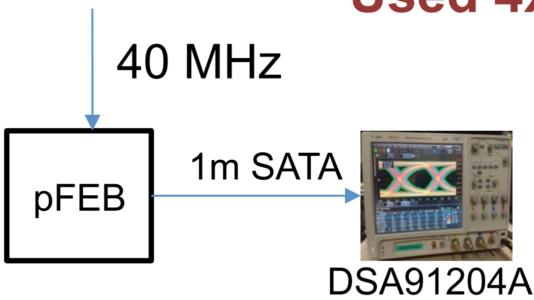
LVD6R Repeater

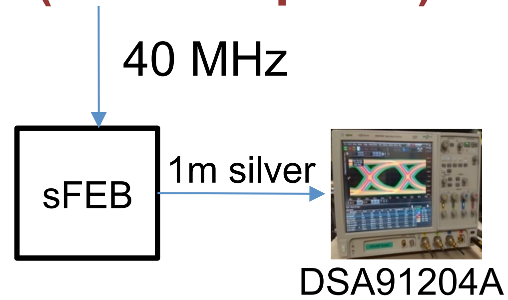
- Final design
- Preproduction, Lab tests, Detector tests
- Cooling tests
- Final Productio
- Develop Test Bench for QA/QC
- (Demokritos boards)

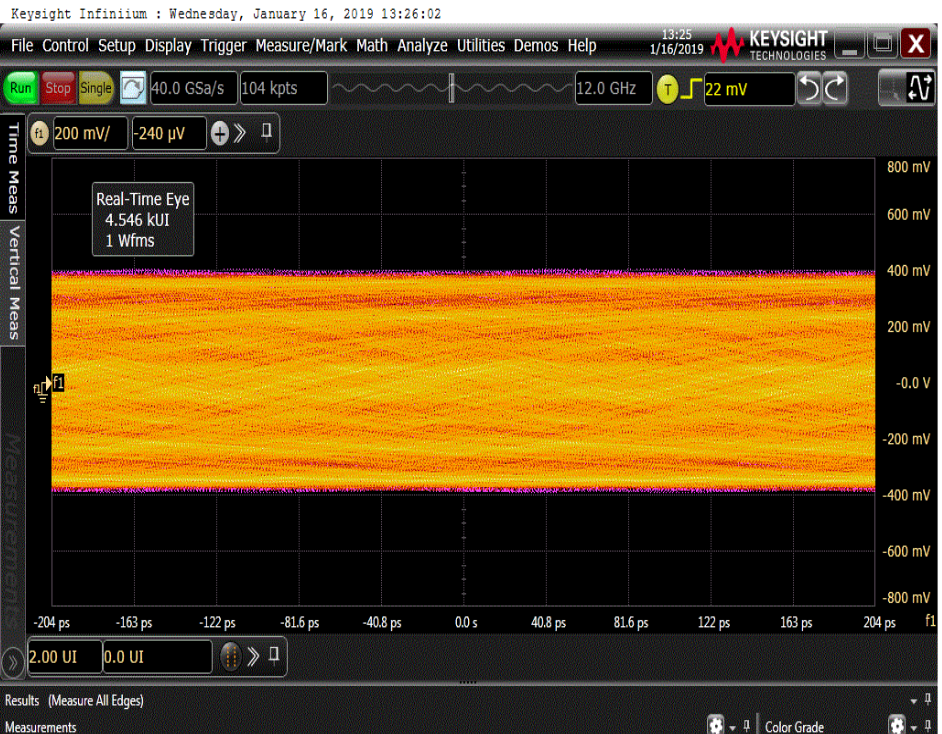




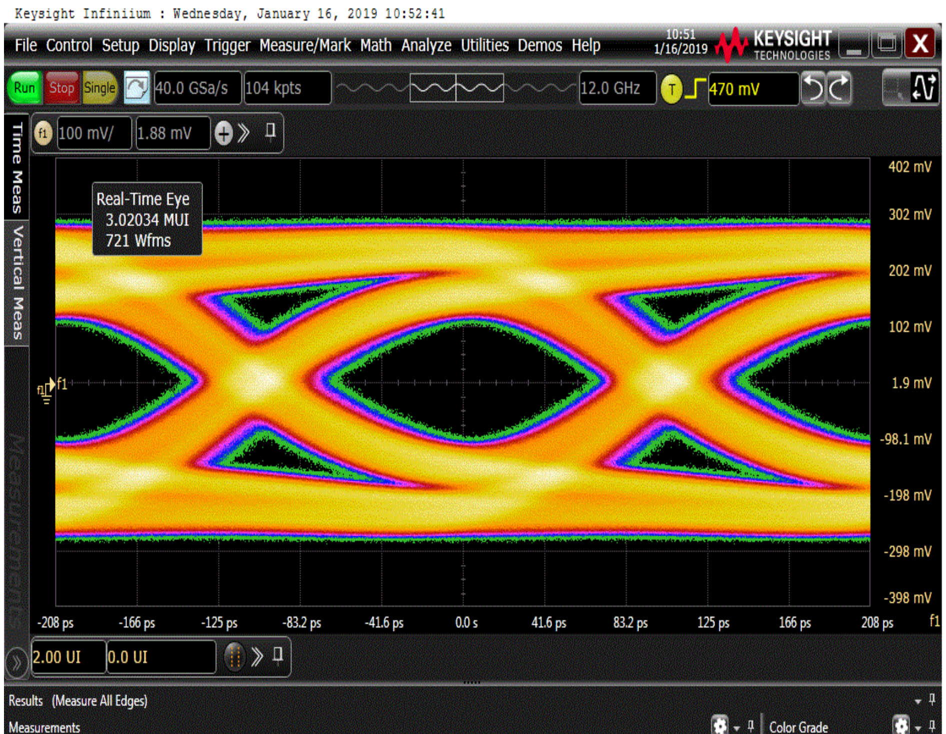
pFEB → Pad Trigger:1m SATA vs 1m silver twinax
Used 4xSATA to miniSAS (non compliant)





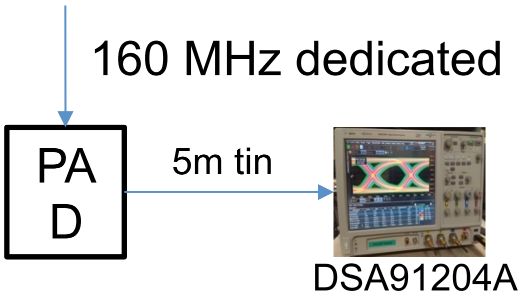


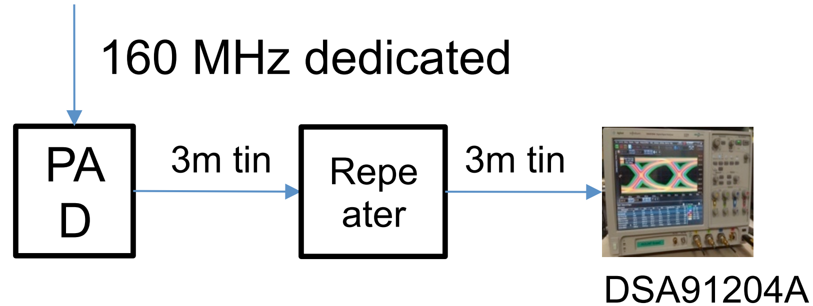
Measurement	Current	Mean	Min	Max	Range (Max-Min)	Std Dev	Count
DutCyc dist(f1)	0%	0%	0%	0%	0%	0%	1
Q-factor(f1)	1.63	1.63	1.63	1.63	0.0	0.0	1
Crossing %(f1)	51.4%	51.4%	51.4%	51.4%	0.0%	0.0%	1
Eye jit RMS(f1)	32.79 ps	32.79 ps	32.79 ps	32.79 ps	0.0 s	0.0 s	1
Eye zero level(f1)	-186 mV	-186 mV	-186 mV	-186 mV	0.0 V	0.0 V	1
Eye one level(f1)	179 mV	179 mV	179 mV	179 mV	0.0 V	0.0 V	1
Eye width(f1)	0.0 s	0.0 s	0.0 s	0.0 s	0.0 s	0.0 s	1
Eye height(f1)	0.0 V	0.0 V	0.0 V	0.0 V	0.0 V	0.0 V	1



Measurement	Current	Mean	Min	Max	Range (Max-Min)	Std Dev	Count
DutCyc dist(f1)	0%	0.0%	0%	0%	0%	0.0%	43
Q-factor(f1)	4.40	4.401	4.40	4.43	30 m	5 m	43
Crossing %(f1)	50.1%	50.2%	49.7%	50.3%	0.60%	0.129%	43
Eye jit RMS(f1)	12.05 ps	12.105 ps	12.00 ps	13.54 ps	1.54 ps	241 fs	43
Eye zero level(f1)	-187.6 mV	-187.71 mV	-187.9 mV	-186.4 mV	1.6 mV	240 µV	43
Eye one level(f1)	196.9 mV	196.95 mV	196.0 mV	197.1 mV	1.2 mV	180 µV	43
Eye width(f1)	127.68 ps	129.769 ps	126.05 ps	147.49 ps	21.44 ps	4.347 ps	43
Eye height(f1)	150.0 mV	152.22 mV	150.0 mV	182.0 mV	32.0 mV	6.14 mV	43

Direct 5m VS 3m+3m and repeater (Pad to sFEB)





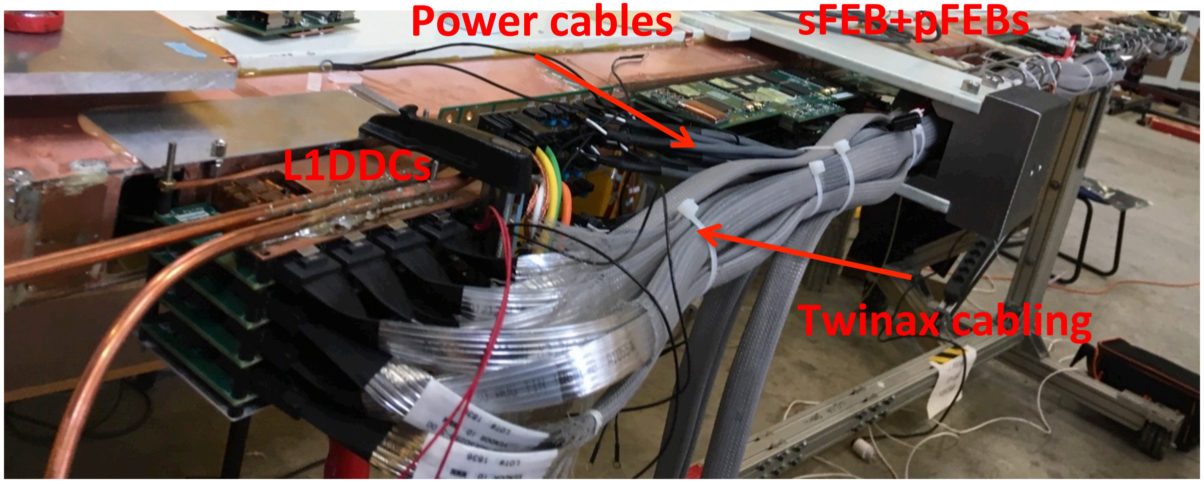
Stable link with data from PAD to sFEB and checker

Stable link with data from PAD to sFEB and checker (0 errors)

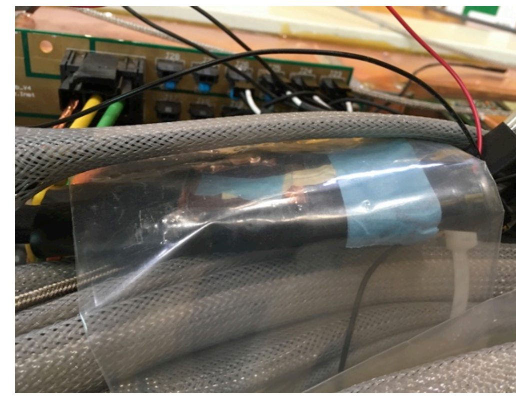
On Detector tests: sTGC wedge

Operate full electronics (pFEB, Pad Trigger, sFEB, Router) chain
With final cabling and:

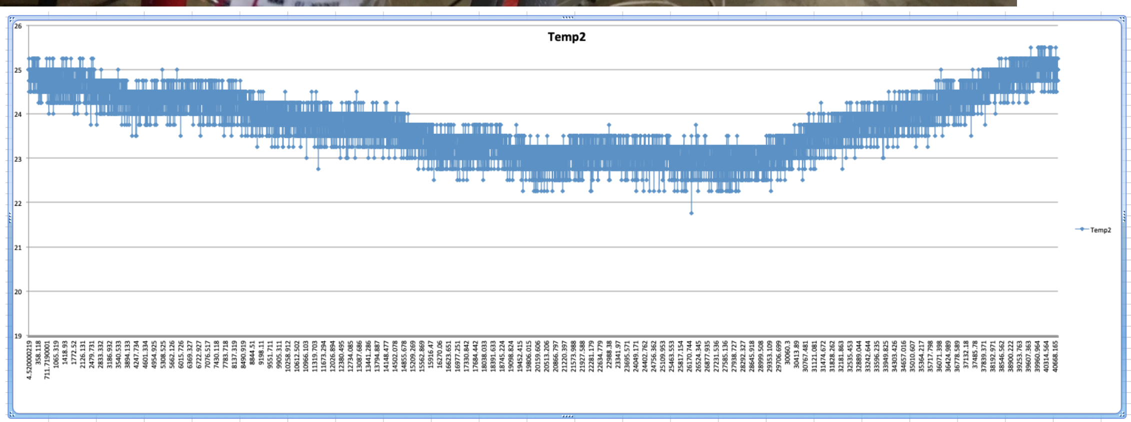
1) Test functionality ➔ No errors (0 for 10^{14} transmitted bits)
2) Monitor the temperature during operation



SRL1R in the twinax bundle
Covered with plastic bag



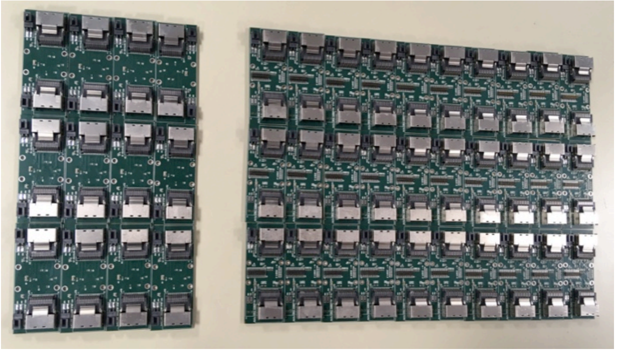
Temperature: 22 – 25.5ºC



11 hours monitoring (12 – 11am)

Preproduction of SRL1R and LVD1R Repeaters

30 Serial + 12 LVDS1 Repeaters



Tested all Repeaters at the VS setup, sFEB → Router

pFEB→ Pad.

Short tests (IBERT) few x 10^{11}

SRL1R: 29 OK

1 Problem with one link (2^{nd})

LVD1R: 12 OK

Temperature on open air during operation:

SRL1R → 34 ^{o}C

LVD1R → 45 ^{o}C

Serial and LVDS Repeaters

Responsibility for building the Serial and LVDS Repeaters for the sTGC

- Design by Weizmann in Collaboration with Demokritos
- **Serial Repeaters − SRL1R**
  - Preproduction completed (assembly by Prisma)
  - 30 SRL1R (29/30 OK) − Tests performed in VS and on wedge
- **PRR 2 weeks** ago: Order Components/pcb to **build 900 SRL1R boards**
- **LVDS Repeaters − LVD6R**
  - Preproduction of LVD1R
  - 12 LVD1R build and tested in VS and on wedge
  - 3 LVD6R assembled this week − will be delivered next week
  - Need studies on: functionality, cooling, mechanical support
  - FINAL production: 140 LVD6R boards
- **Test bench for QA/QC**

NCSR Demokritos group responsibilities

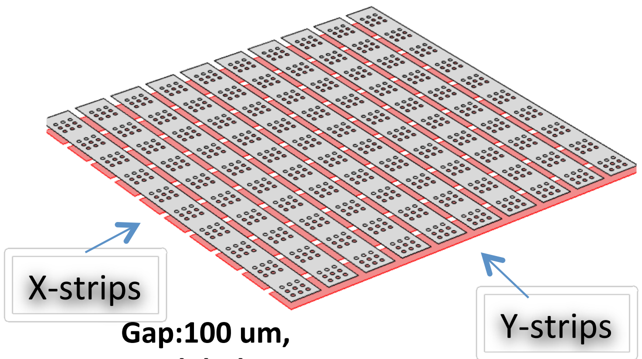
ELEA Activities

- **Continued R&D on:**
  1) Resistive Micromegas
  2) Real x-y Micromegas (segmented mesh)
  3) Double phase Micromegas using Graphene

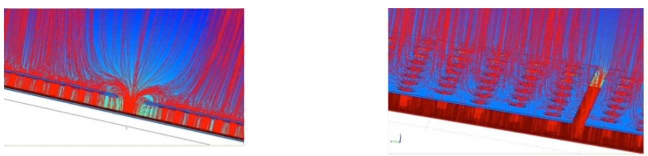
- **Develop infrastructure for Micromegas studies and electronics (Gas Mixer, Cosmic Stand, Electronics stations)**

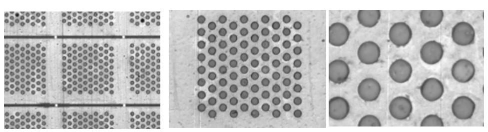
Real x-y Segmented Mesh Microbulk Micromegas

1) Real x-y structure
2) Mass minimization
3) Production Simplification

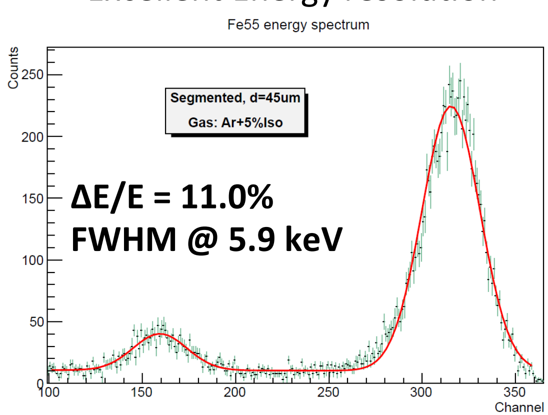


Gap:100 um,
Mesh holes: 50 um

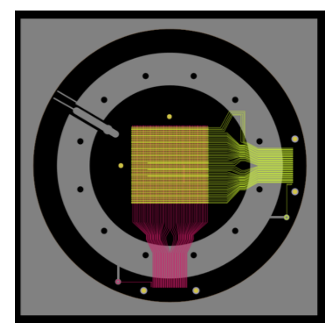




Excellent Energy resolution



1) Rare searches (axion, dark matter)
Segmented microbulk background
→ ~ 10^{-7} cnts/keV/cm^2/s
2) Neutron Beam profiler (nTOF)
Very low material Budget:
5 μm + 5 μm of Cu + 50 μm polyimide



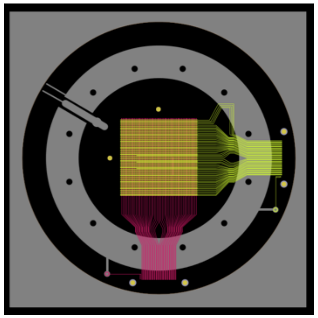
Current activity:
Building large area (10 cm x 10 cm)
Real x-y microbulk with strip pitch 700 µm

Applications

1) Rare searches (axion, dark matter)

Microbulk background: ~ 10^{-6} cnts/keV/cm^2/s

The segmented microbulk background → ~ 10^{-7} cnts/keV/cm^2/s



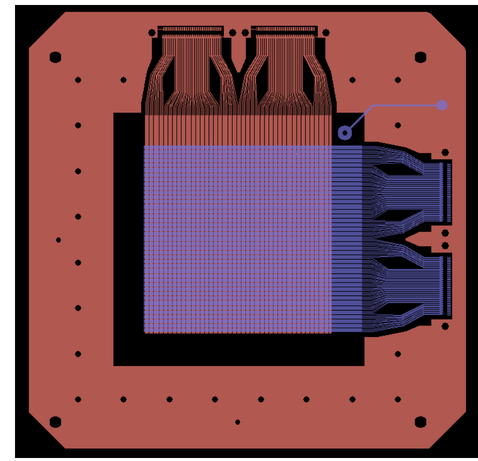
2) Neutron Beam profiler (nTOF)

Very adequate due to very low material Budget: 5 μm + 5 μm of Cu only

The thinest ever neutron detector worldwide

3) Produce large area detector (10 x 10 cm2)

(recently constructed – under study)



Presentation in TIPP2014 Conference, 2 – 6 June 2014, Amsterdam :
T. Geralis et al., “A real x-y Microbulk Micromegas with segmented mesh”
Published in PoS (TIPP2014)055.

2018:NEW development

Nuclear Inst. and Methods in Physics Research, A 903 (2018) 46–55

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

2018: NIM publication

Development of a novel segmented mesh MicroMegas detector for neutron beam profiling

M. Diakaki [a,b,*,1], E. Berthoumieux [a], T. Papaevangelou [a], F. Gunsing [a], G. Tsiledakis [a], E. Dupont [a], S. Anvar [a], L. Audouin [c], F. Aznar [f,g], F. Belloni [a,d], E. Ferrer-Ribas [a], T. Dafni [f], D. Desforge [a], T. Geralis [e], Y. Giomataris [a], J. Heyse [d], F.J. Iguaz [f,a], D. Jourde [a], M. Kebbiri [a], C. Paradela [d], P. Sizun [a], P. Schillebeeckx [d], L. Tassan-Got [c], E. Virique [a]

SCREAM: Sampling Calorimetry with Resistive Anode MPGDs
Resistive Bulk Micromegas for High Rate applications

Collaboration

INPP
G. Fanourakis
T. Geralis

LAPP Annecy
M. Chefdeville
I. Karyotakis
2 Engineers

IRFU Saclay
M. Titov

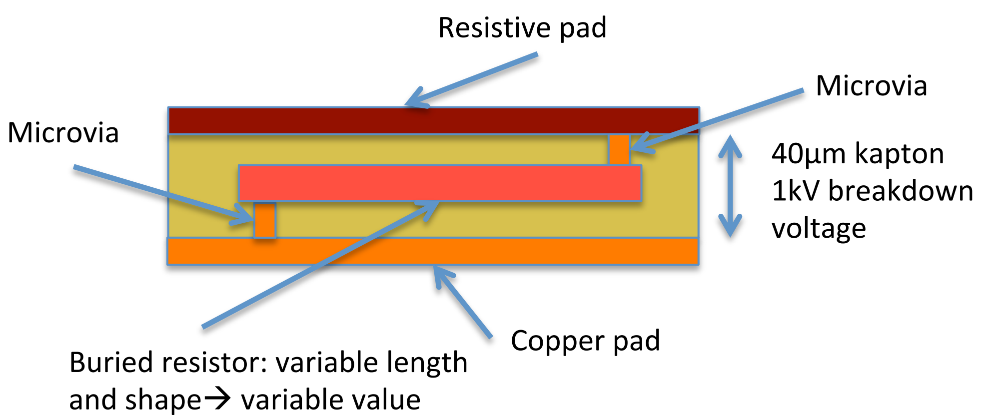
Future Resistive Micromegas applications within ATLAS

1) At HL-LHC (ATLAS upgrade)
   Muon High-Eta Tagger (rates up to 10 MHz/cm2)

3) At the Future Circular Collider (FCC)

Completing the RD51 Common Fund project now:

Publication in preparation (to be submitted to NIM early 2019)

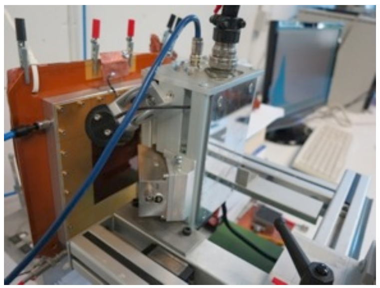
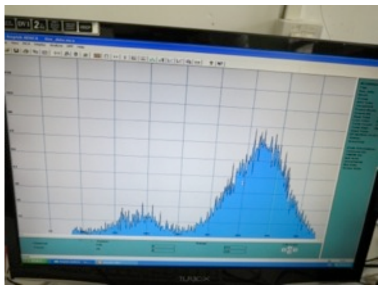


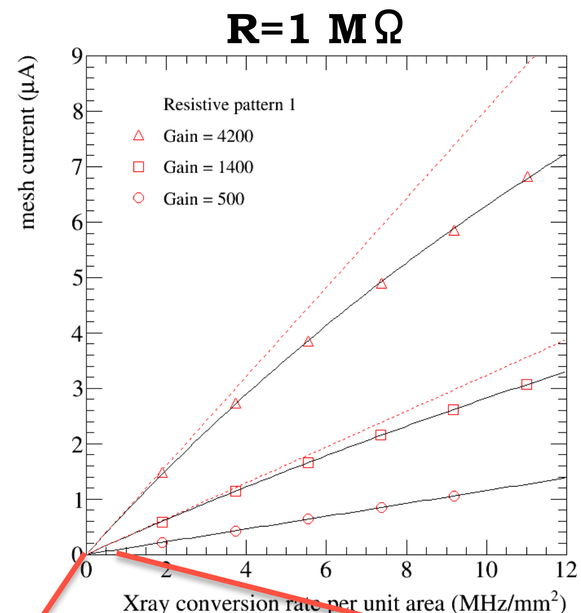
Linearity tests: Resistive Micromegas High rate tests with X-rays

X-ray Gun tests at the RD51 lab: Cu 8 keV at very high rates

Measure the Mesh current as a function of the X-ray tube current

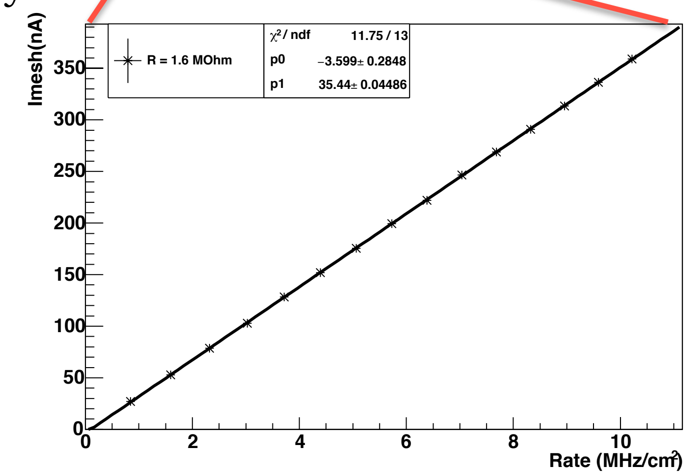
Intermediate R: excellent linearity up to rates 1 MHz/mm^2
25% lower gain for rates 10 MHz/mm^2



X-ray Gun tests at Demokritos: Rh 3 keV at very high rates

Energy Resolution not very good → should improve homogeneity
Test linearity and measure the discharge rate and the Mesh Voltage drop spectrum (rates up to 11 MHz/cm^2)

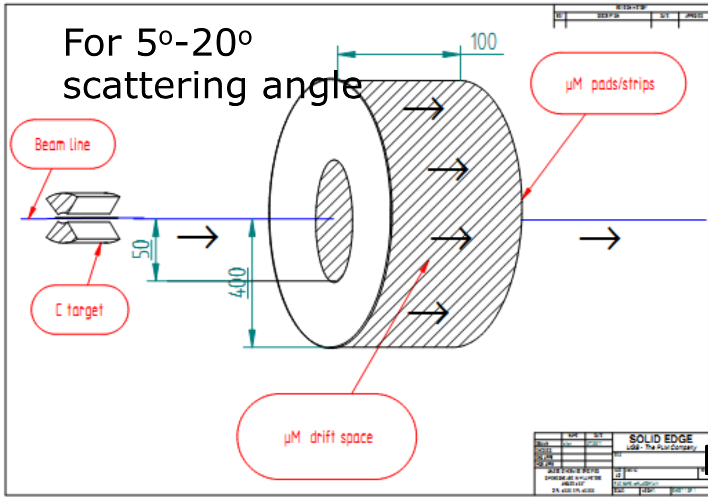


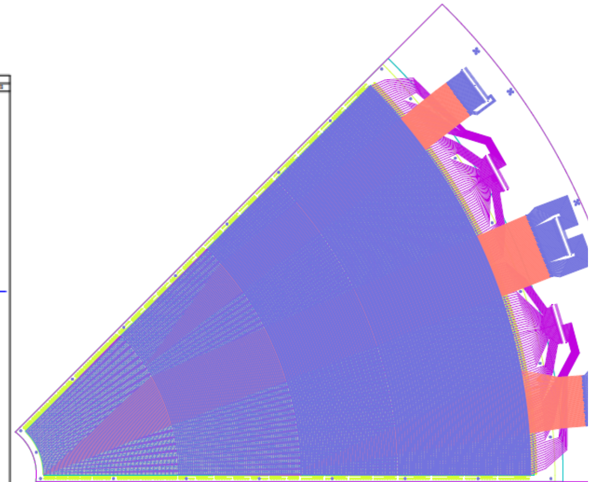
Linearity test at
Rates: 0 – 0.1 MHz/mm^2

Or 0 - 10 MHz/cm^2

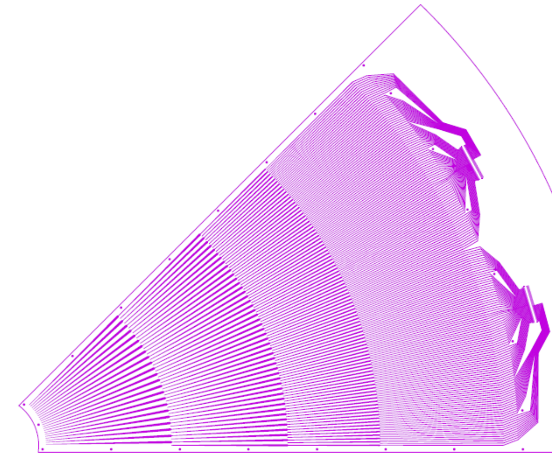
Excellent linearity

R- ϕ Micromegas

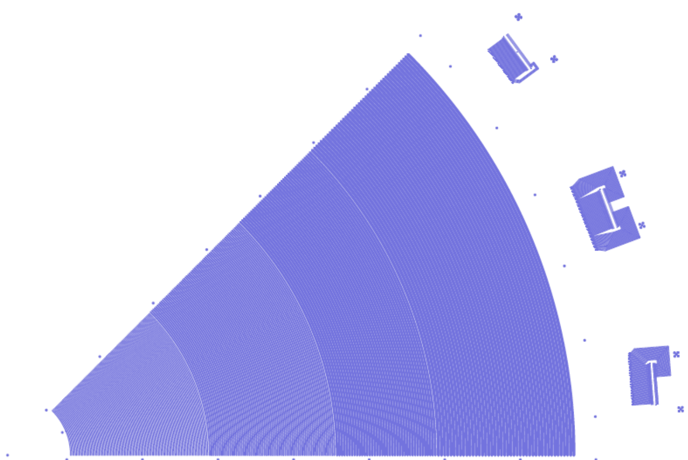




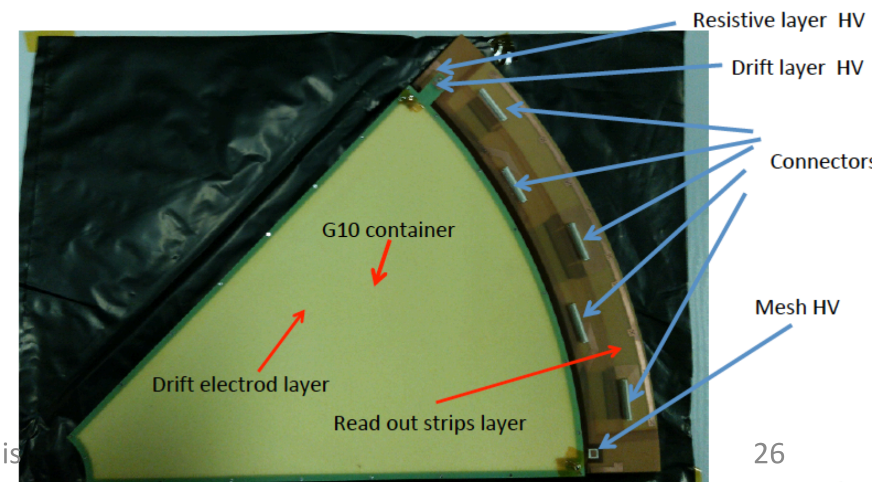
Readout routing to Panasonic connectors



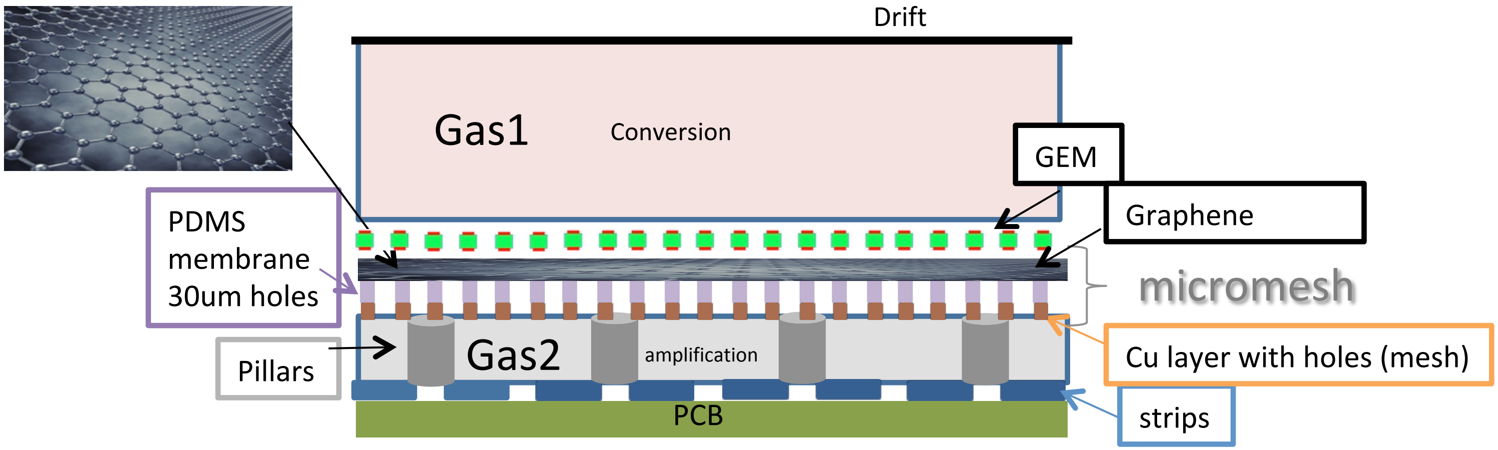
R and phi strips



Two r-phi prototype octants have been ordered and constructed in the electronics lab of CERN. One with a 10 MOhm/sq and one with a 100MOhm/sq resistivity of the resistive layer, to test the behavior in various beam density situations (fast or less fast operation).



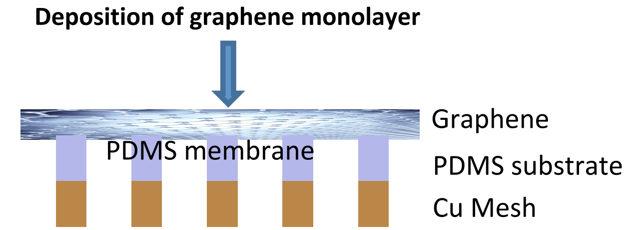
R&D on Double gas Phase Micromegas



Our ambition:

1) Two-gas phase detector separated by a Graphene layer
2) Exploit differences in gas properties to improve performance
3) Should have high electron transparency (test to be performed)
4) It may be used to eliminate ion backflow

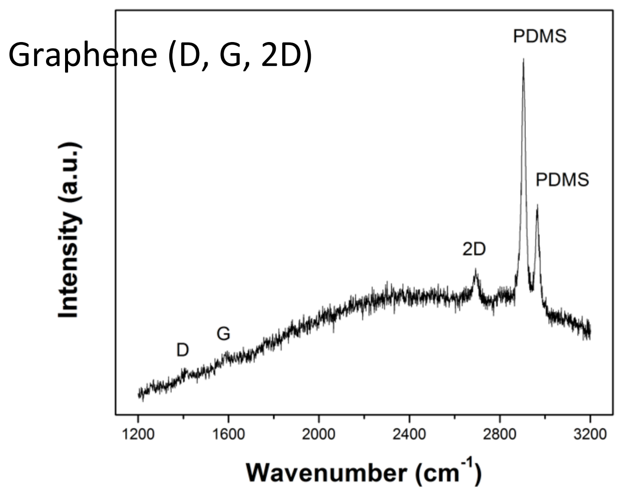
Transport Graphene on PDMS



i) Produce Graphene on Cu foil
ii) Cover it with PMMA
iii) Dissolve Cu
iv) Place PMMA+Graphene on PDMS
v) Dissolve PMMA

- Raman spectroscopy was used to confirm the graphene transfer uniformly on the PDMS membrane

We have placed a graphene surface of 1 x 1 cm^2 on to of the PDMS substrate



Future plans

1) Optimize technique for the Graphene – PDMS – mesh membrane
2) Add GEM foil and test electron transparency
3) Measure gas diffusion through Graphene
4) Possibly lay double or triple layers

Gas Detectors

Proposal of the Wording Group WG2 to R&D on experimental technologies in the CERN EP Department

25.9.2018
Eraldo Oliveri & Christoph Rembser

Ongoing activities worldwide & at C

	Activity/summary	Speaker/
1	GD Research for AD2020 and beyond	F. Sauly
2	Possible further developments of micropattern detectors	V Peskov
3	InGrid& GridPix	H Van Der
4	R&D on double gas phase MMs using graphene	T. Geralis et al
5	Progress in MPGD -based photon detectors	S. Dalla Torre et
6	Robust gas-avalanche multiplier concepts with resistive elements	A. Breskin et al
7	The μ-RWELL	G. Bencivenni
8	Large-area MM detectors - Mesh-support studies industrial production	J. Wotschack et
9	Embedded Resistors	M. Chefdeville
10	Thin GEMs	Stefano
11	Fast Timing MPGD	P. Verwilligen et
12	R&D at USTC/China	Y. Zhou
13	High Resolution TPC based on GEM optical readout	D. Pinci et al
14	New design of a thick gas electron amplifier	A. Reshetin et
15	A new generation of (M)RPC	I. Laktineh et al
16	Muon Detector Development at the MPI for Physics	H. Kroha et al
17	Neutron Gaseous Detector R&D Activities at ESS ERIC	D. Pfeiffer et al
18	Detector electronics - RD51 and beyond	H. Mueller et al
19	RD51	L. Ropelewski

Worldv
collabora
Glim
contribu
meeting
indico.

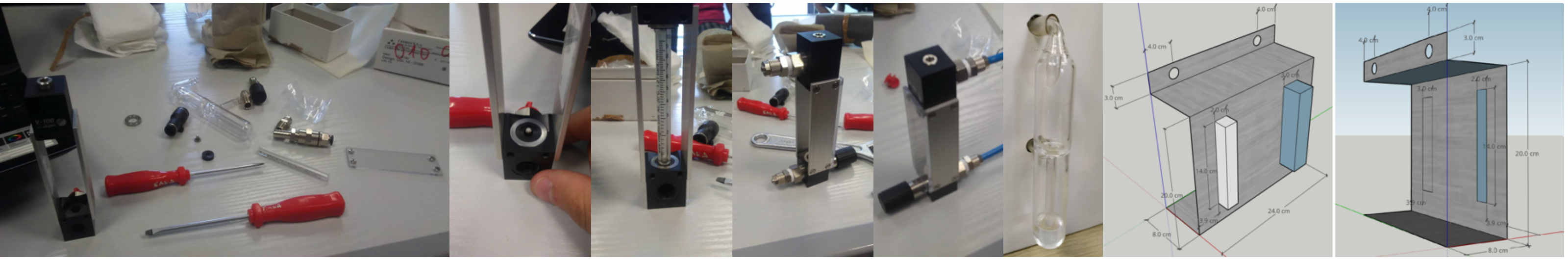
Many t

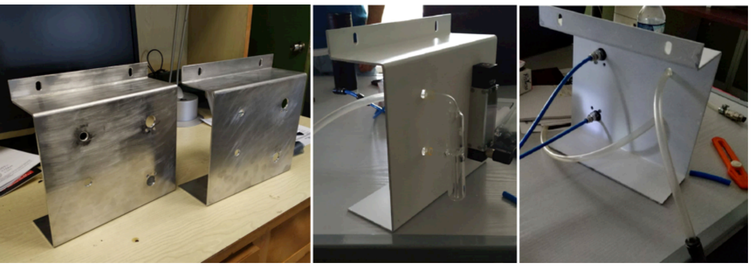
At CERN and EP, strong contributions to

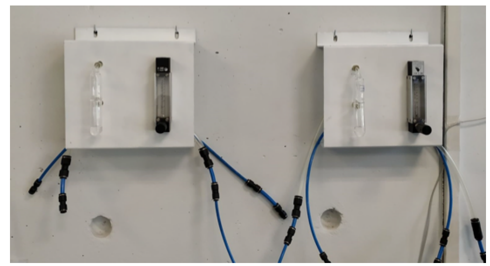
- Experiments: participation of groups and support groups in CMS GEMs, ATI
- RD51: development of advanced gas-avalanche Micro-Pattern Gas Detector R&D support for the LHC experiments and upgrades, generic R&D; develo and simulation tools, development and maintenance of software of SRS elec MPGD technology, maintenance and extension of the RD51 laboratory and in education & training for MPGDs, organisation of a series of specialised w
- Reduction of Greenhouse gases (GHG, C2H2F4, CF4 and SF6) for GD's: re less invasive gases (also CERN-wide: CEPS - CERN Environmental Protecti

Work by the Practical students: Stamatis Tzanos, Vasilis Blanas

Build 2 Gas Flow Controllers

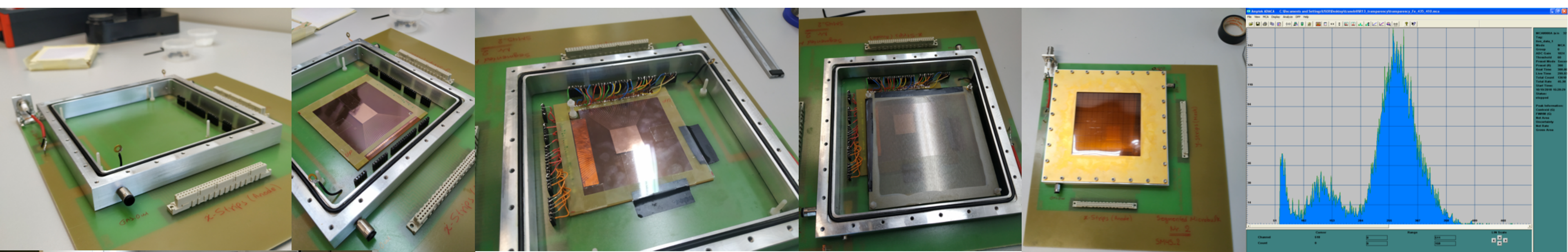






Excellent work
Done from A-Z

Work on the "Real x-y Segmented Microbulk": First real x-y with 700 μm strip pitch



Working in the
Clean Room

Preparing the Cloud Chamber
For Researcher's Night

CONCLUSIONS

Our group has undertaken important responsibilities within the ATLAS NSW Upgrade project:

- QA/QC of 400 L1DDC cards (Test bench ready)
- QA/QC of 300 ADDC cards (Test bench ready)

- Full responsibility of the Serial (SRL1R) and LVDS (LVD6R) Repeaters
  - Finalize design (done)
  - Preproduction SRL1R and LVD6R
  - Laboratory testing (done)
  - Detector Testing (only SRL1R)
  - Final Production: launched for SRL1R
  - Waiting validation for the LVD6R

R&Ds on:

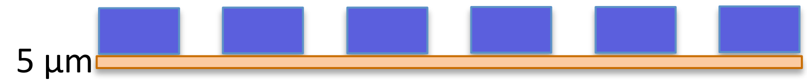
- Real x-y microbulk (completed)
- Resistive μM for High rates (completed)
- Double phase Micromegas with Graphene (under development)

BACKUP

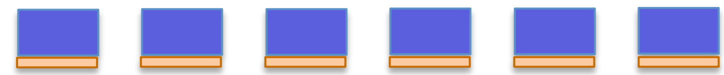
Steps to be performed:

1) Create substrate with holes (PDMS)
   Holes diameter: 50 μm, S = 2 x 2 cm^2

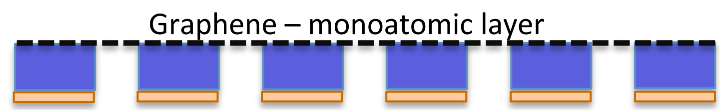
2) Bond it on a Cu foil



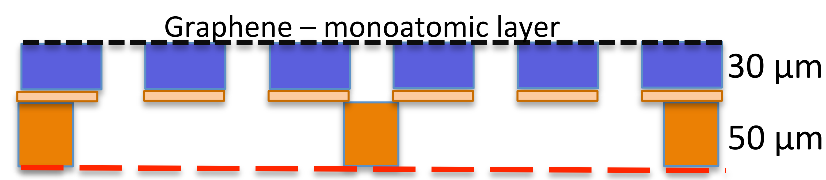
3) Etch copper holes to create mesh



4) Place Graphene on top of PDMS



5) Place the structure on top of the Anode
   that has the pillars attached to it



➢Lithography process to generate the appropriate master for the PDMS membrane (30um Width, 50um diameter holes)

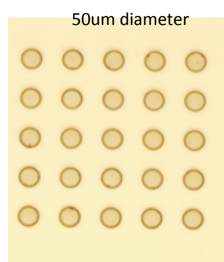
A) Use mask

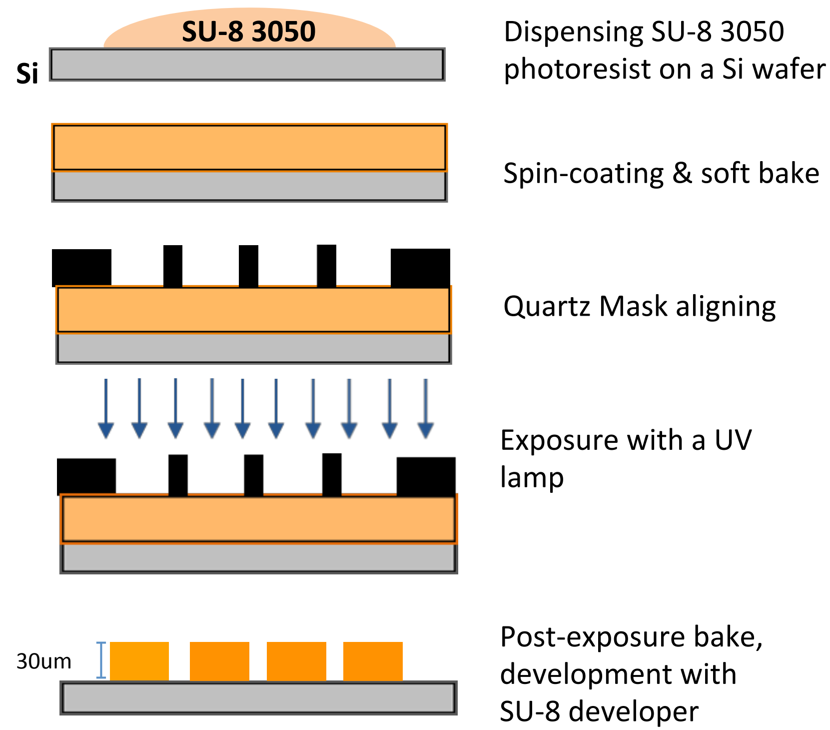
Design and build quartz mask with holes of 50 μm. Mask dimension: 2 cm x 2 cm

Several hole option on the same mask

Basic lithography steps

- Spin-coating :
- Soft bake
- Exposure
- Post bake
- Development
- Post bake



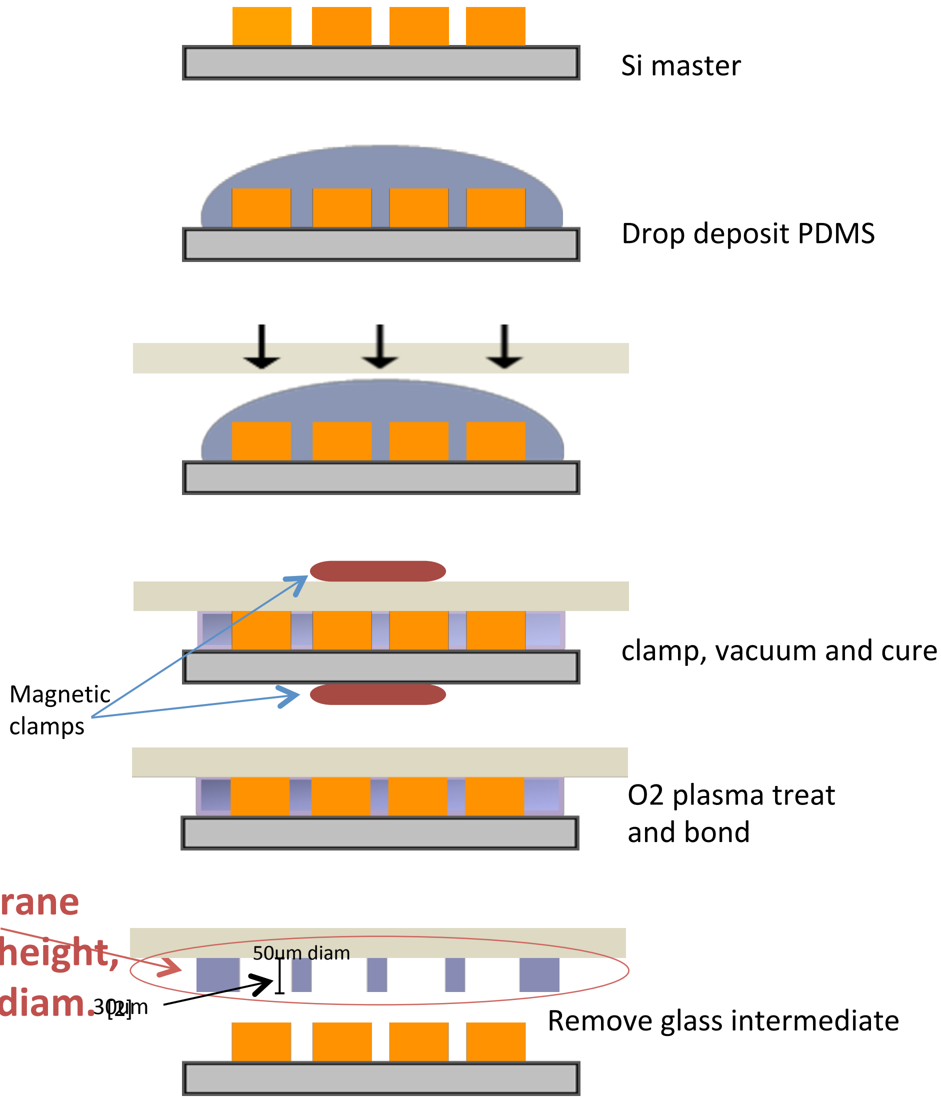


B) Use UV-curable (OrmoComb)polymer to produce substrate

1) PDMS membrane formation

Polydimethylsiloxane or **PDMS**

PDMS membrane 30 um transfer to modified glass substrate

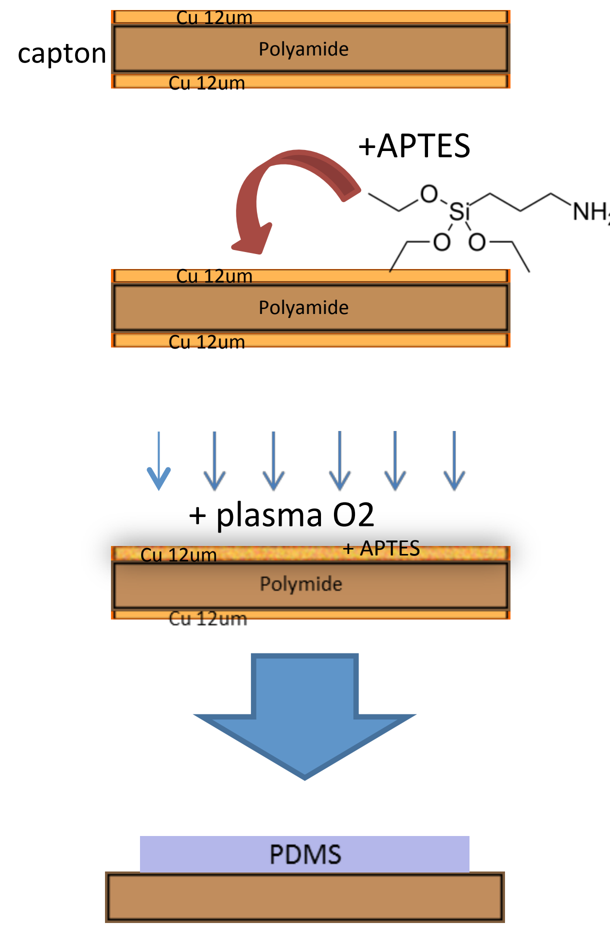


PDMS membrane 30um height, 50um diam.

Successful release from Si master

ACHIEVEMENTS SO FAR

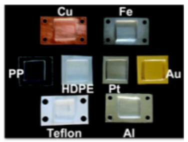
2) Bonding Cu to PDMS



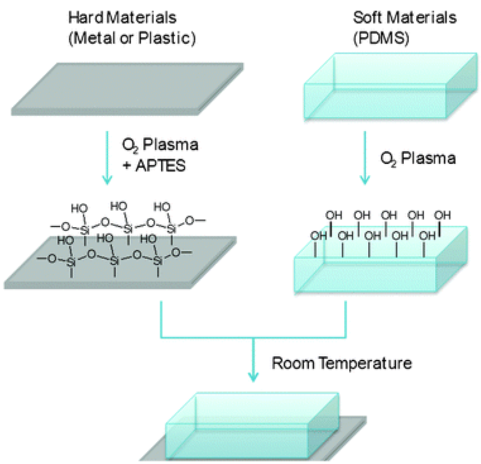
(c) Bonded substrates

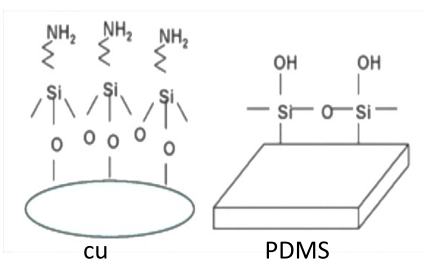
Successful
bonding Cu-PDMS !!!

➤ Bonding technique for Cu to PDMS



[3], [4]





(a) (b)

(a) : Cu coated with APTES

(b) : PDMS treated with plasma O2

(c) Bonded substrates

- **(3Aminopropyl)triethoxysilane** or **APTES :**
- APTES is an aminosilane frequently used in the process of silanization
- use with PDMS → APTES can be used to covalently bond thermoplastics to PDMS

Oxidation of PDMS → Oxidation of PDMS using plasma, changes the surface chemistry of PDMS and produces silanol terminations (SiOH) on its surface. This helps make PDMS hydrophilic for thirty minutes. This process also makes the surface resistant to the adsorption of hydrophobic and negatively-charged molecules