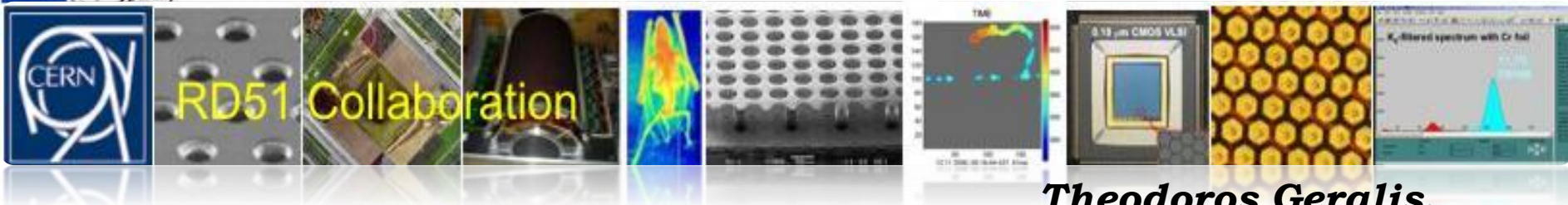




Introduction to the RD51 Collaboration

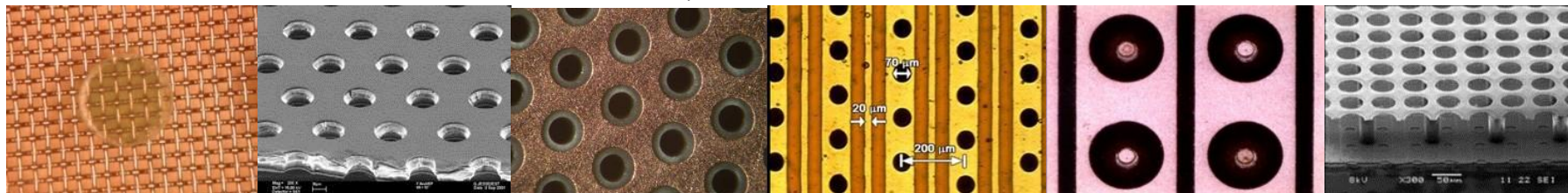


*Theodoros Geralis,
NCSR Demokritos, Greece
On behalf of the
RD51 collaboration*

OUTLINE

- **RD51/MPGD history**
- **Organization/Infrastructures**
- **Technological achievements**
- **Applications**

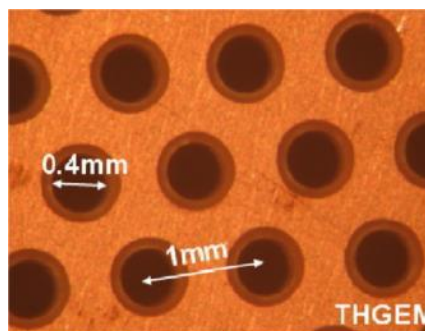
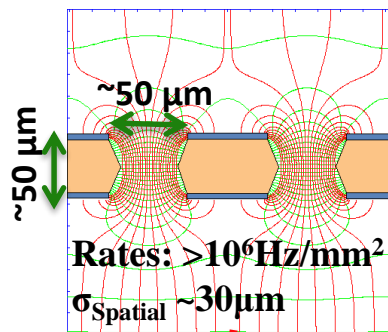
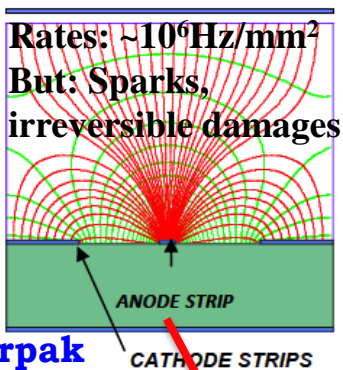
*Workshop on Neutrino Near Detectors based on gas TPCs
CERN, 8-9 Nov. 2016*



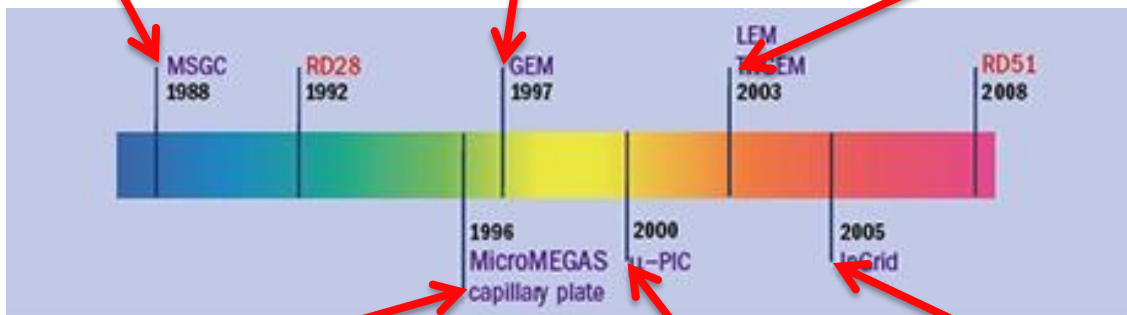
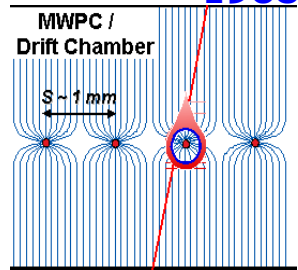
From Multi-Wire Proportional Chambers to Micro Pattern Gaseous Detectors

MSGC: Oed 1988

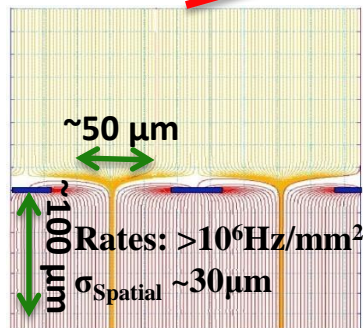
GEM:Sauli 1997



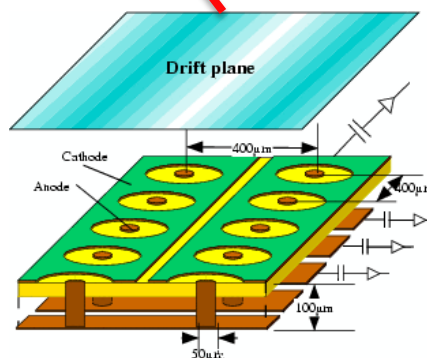
MWPC: Charpak 1968



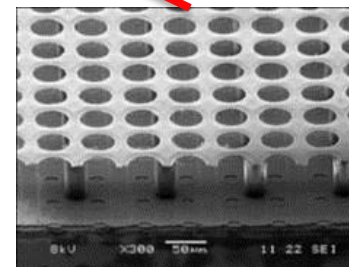
RD51 Collaboration:
 86 Institutions
 500 Scientists



Micromegas: Giomataris 1996



μ -PIC
 Theo Geralis



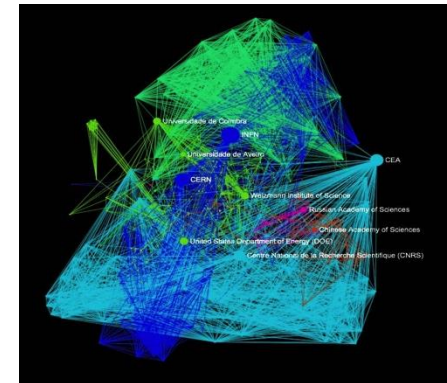
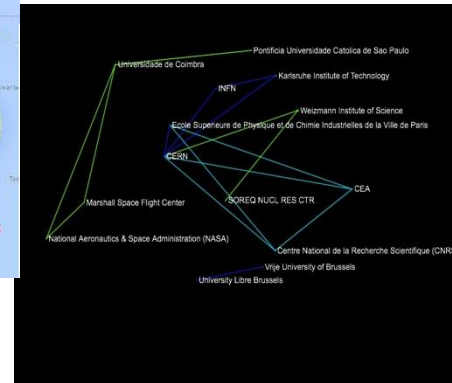
Ingrid

The RD51 Collaboration



Main objectives:

- MPGD technological development
 - Provide the collaboration framework
 - Develop common simulation packages
 - Develop common read out electronics
- Access to “MPGD know-how”
- Foster Industrial production



Gem 2000

Gem 2006

Gem 2014



Micromegas 2000

Micromegas 2006

Micromegas 2014

Map: RD51

Current year:	1998
Organisations:	40/717
Clusters:	5
Publications:	35/1059

Map: RD51

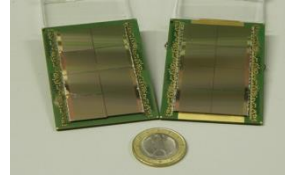
Current year:	2015
Organisations:	717
Clusters:	12
Publications:	1059

→ huge growth in interest in the MPGD technologies

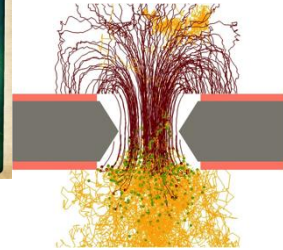
Collaboration Spotting Software:
<http://collspotting.web.cern.ch/>

The RD51 Collaboration: Working Groups

Technological Aspects
New Detector Structures



Detector Physics and Performance
RD51 Common Projects



WG1:

WG2:

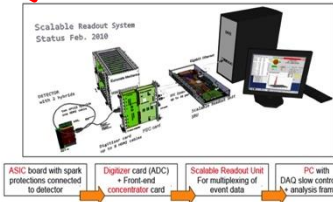
WG5:

RD51

WG4:

Modeling of Physics Processes
Software Tools

MPGD
Electronics



WG7:

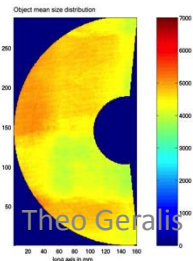
WG6:



Applications, Training
and Dissemination

WG3:

Common Test Facilities



Production and
Industrialization

RD51 related infrastructures:

1) EP DT MPT Workshop (Head: Rui De Oliveira)

The heart of the MPGD Globe: Design, prototyping, production
New infrastructure (building, MPGD production machines, clean room etc)
will be soon ready



CERN Building 107
Basis of Design

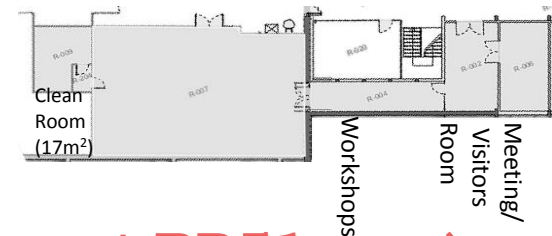
2) GDD Laboratory (RD51)

The Detector R&D laboratory:

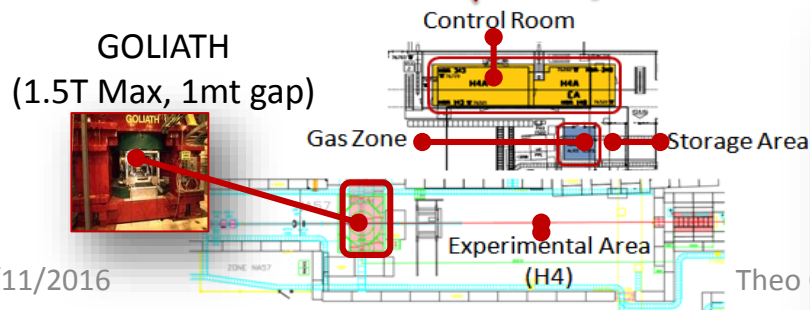
- Permanent users (ALICE, ATLAS, ESS)
- Temporary Users stations
- Cosmic stands, X-ray and radioactive sources
- Clean room, Workshop
- Vacuum and Gas System
- MPGD Electronics support
- 15 visiting groups, synergies with companies



Laboratory (140m²)



3) Test Beam Area (SPS/H4 semi permanent RD51 area)



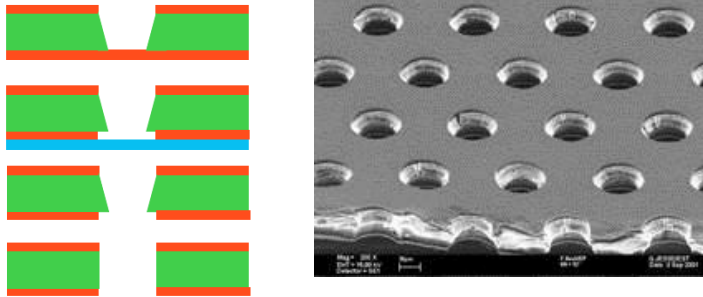
R&D for Experiment
HEP Experiments:
LHC upgrades
CERN & Others
Applications
Electronics

Organize test beam
3 times (2 weeks)/year

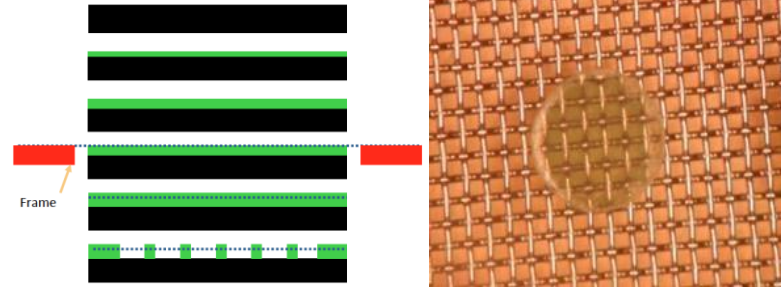
RD51 Technological achievements (I)

- **Large MPGDs production/industrialization of GEM, THGEM, Micromegas:**
 single mask GEM Bulk Micromegas

Single mask process

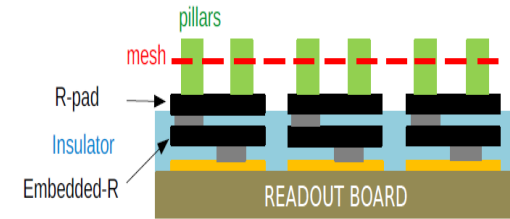
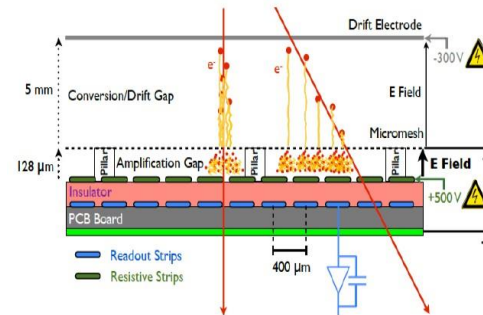
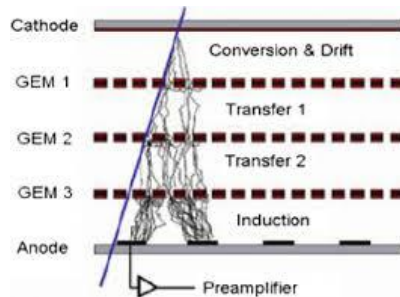


Micromegas bulk production processes



- **High rates and spark mitigation:**
 Staged Gain: multiple layers
 GEM, THGEM, MHSP

Resistive coating, buried resistors
 Micromegas, RETGEM, RPWELL

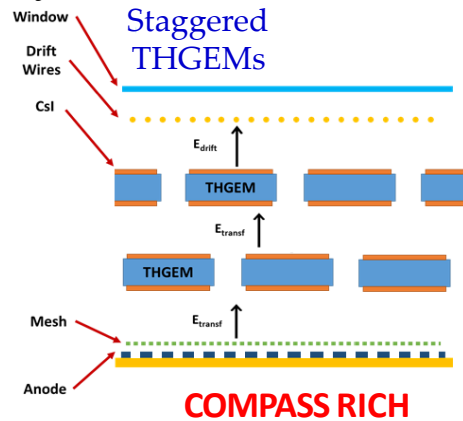


RC-constant controlled with embedded R-pattern

RD51 Technological achievements (II)

- Ion Back Flow (IBF)**, Application in TPCs (field distortion) and photon detection (photocathode protection): Multiple Layers

Hybrid: THGEM+ CsI and MM



COMPASS RICH

$$\text{IBF} \sim 5 \cdot 10^{-2}$$

Multi layer GEM

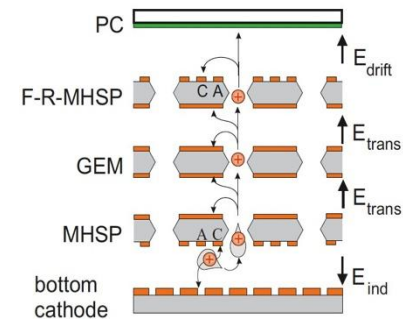
- Best results in terms of **IBF and energy resolution**:
 - 4 GEM stack
 - S-LP-LP-S configuration
 - S: standard GEM foils
 - LP: large hole pitch foils
 - Optimized V settings: V_{GEM} , E_T (transfer fields)



ALICE TPC

$$\text{IBF} \sim (5 - 25) \cdot 10^{-3}$$

stack MHSP/GEM/F-R-MHSP



$$\text{IBF} \sim (1-3) \cdot 10^{-4}$$

- Radiation hardness**

LHC MPGD Upgrades (ATLAS NSW project - Resistive Micromegas and CMS GEM muon chambers) proven to withstand the equivalent of 10 years of operation at the HL-LHC. Irradiation with: neutrons, X-rays, α and β .

RD51 Technological achievements (III)

- **Sealed detectors** (purity) for space and non-laboratory applications
- **Physics simulations and tools**

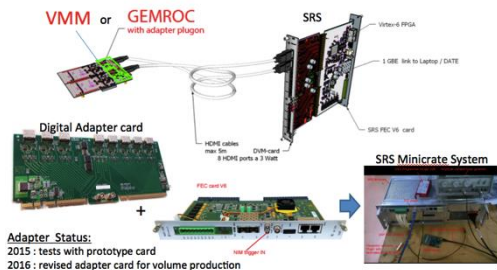
Software tools: Magboltz (transport equations), Degrad (cluster size), Garfield++ (speeding up), optimization of charging up simulation

Modeling of Physics processes: Penning in Ne mixtures, CO2 impact, GEM gas gain dependence on hole diameter, impact of mesh geometry to micromegas

- **Read-out electronics**

Scalable Readout System: Development of the readout system for MPGDs adaptable to various FE ASIC chips (APV25, VMM2, GEMROC)
Development of generic electronic devices for MPGDs:

Adapter for digital frontends



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APIC pickup amplifier/shaper

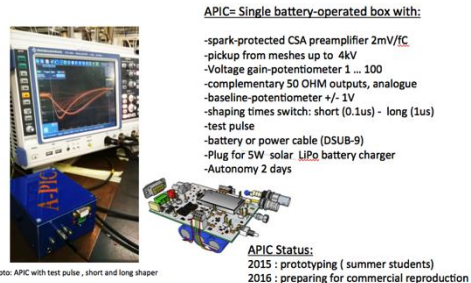
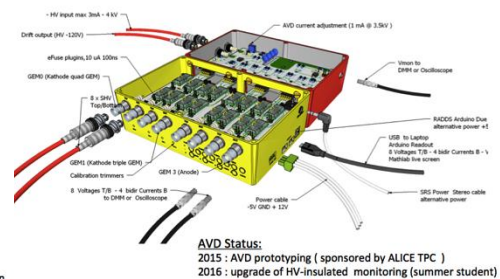


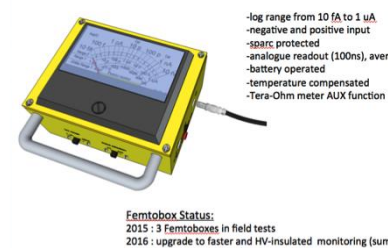
Photo: APIC with test pulse , short and long shaper

AVD Active Voltage Divider



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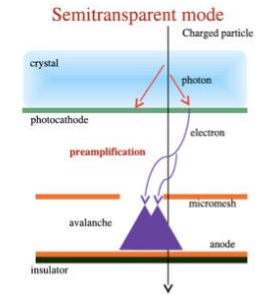
Femtoibox



Generic Detector R&D

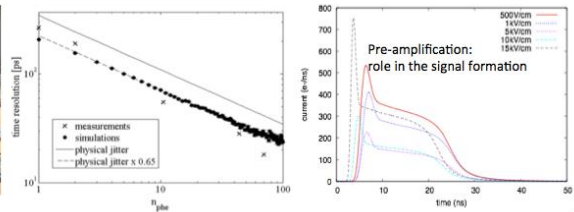
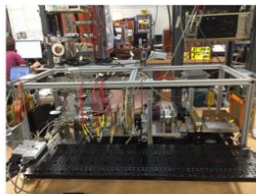
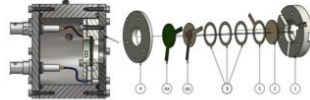
Collaboration with Saclay and Princeton

Fast timing with MM



Aim at < 50ps resolution
 - Cherenkov radiator
 - Photocathode
 - 200um drift
 - MicroMeGas

R&D on:
 - photocathode protection
 - photocathode alternatives
 - secondary emitter materials



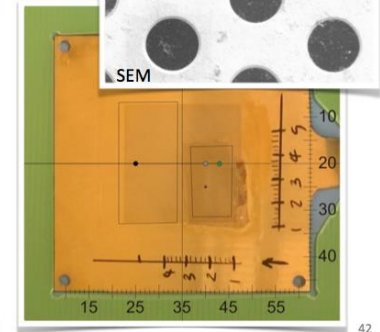
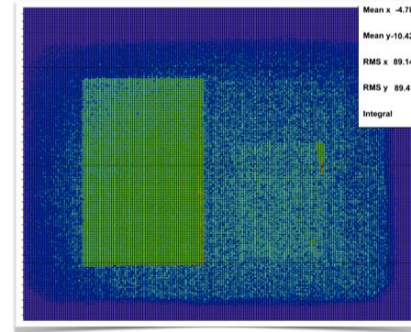
39

Collaboration with UCL

Graphene

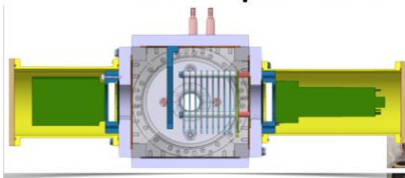
Membrane opaque to ions and transparent to electrons
 - solution of the ion back-flow in gaseous detectors
 - protective layer on photocathodes
 - enhancement of electron emission

~99% (suspended)
 graphene tri-layer coverage

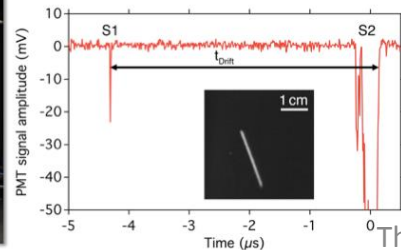
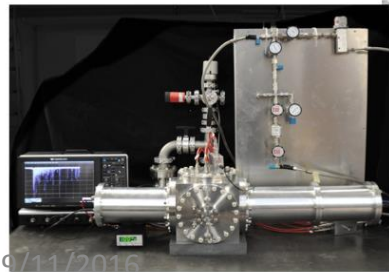
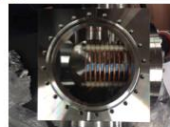
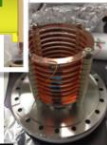


42

GEM optical readout and OTPC



Study:
 - Visible (near UV and near IR) scintillation of gasses
 - Event topology study
 - Imaging



Theo Geralis

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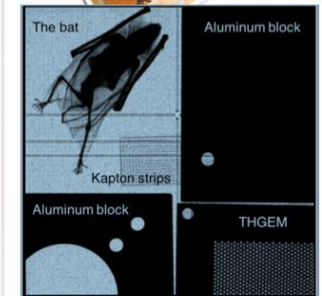
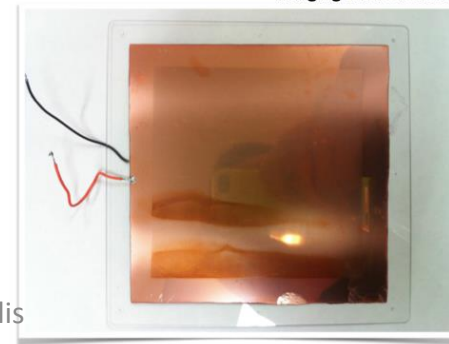
Collaboration with Tokyo University

Glass GEM

Photo Etchable Glass 3 (PEG3):
 Rigid (self sustained structure)
 'Laser assisted etching' opens new possibilities
 Slightly conductive (milder charge-up)
 Clean and low outgassing (sealed operation)



Imaging with electronic readout



41

9

9/11/2016

MPGD Technologies for Present and Future:

- **Hadron / Nuclear Physics Experiments-Heavy Ion Facilities**
- **High Energy Physics**
- **Hadron / Lepton Colliders**
- **Photon / Neutron Detection**
- **Neutrino Physics / Dark Matters Detection**
- **X-Ray Detection and γ -Ray Polarimetry**

MPGD Technologies: LHC experiments Upgrades

Challenges: Ultra high rates, radiation harsh environment, longevity, large area detectors

Present:

TOTEM (GEM), LHCb (GEM)

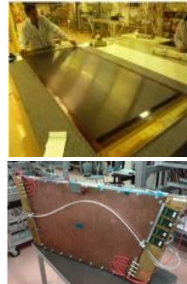
Future:

ATLAS Muon System NSW (μM), Muon tagger $\mu\text{-PIC}$, CMS Muon System (GEM), ALICE (GEM TPC), FCC Collider (GEM, THGEN, Micromegas, $\mu\text{-PIC}$, InGrid)

ATLAS NSW (mm)

The ATLAS Muon Spectrometer and the Small Wheel

- In the Barrel Region the ATLAS Muon Spectrometer is realized by TPC and MDT detectors, while in the End-Cap Regions CSC, MDT and TGC detectors are used
- The Small Wheel (Innermost Endcap Muon Station) in the region with highest background rates in the present ATLAS Muon Spectrometer
- The present system is based on Cathode Strip Chambers (CSCs), Monitored Drift Tubes (MDTs) and TGC for particle tracking
- Located between endcap calorimeter and endcap barrel



CMS (GEM)

The CMS GEM project

- GE11:** $1.55 < |\eta| < 2.18$
 - Active detector for GEM project
 - 36 staggered super-chambers per endcap, each super-chamber spans 10°
 - One super-chamber is made of 2 back-to-back triple-GEM detectors
 - Will guarantee high trigger performance during late Phase I and throughout Phase II
 - Installation: LS3 (2018-19)
- GE21:** $2.15 < |\eta| < 2.45$
 - 18 staggered super-chambers per endcap, each chamber spans 20°
 - Installation: LS3 (2022-24)
- MEB:**
 - Muon trigger at highest η
 - $2.0 < |\eta| < 2.5$
 - 6 layers of Triple-GEM
 - each chamber spans 20°
 - Installation: LS3 (2022-24)



ALICE (GEM)

Content

- The ALICE upgrade strategy
- ALICE TPC overview
- Operation from RUN1 to RUN3
- GEM readout for the TPC
- Ion backflow optimization
- Prototype tests
- Expected performance in RUN3
- Read-out electronics
- Summary and Outlook



Micromegas Technology for the ATLAS NSW Upgrade

Micromegas will be the main precision tracker of the NSW (expected spatial resolution: $100\mu\text{m}$). Two different methods are used in order to extract the correct spatial information:

- Using charge amplification (Central hit)
- Acquiescence rapidly decreasing for larger track angles
- Using time information (TPC regions)
- Performance improving with increasing cluster size

Resolution achieved with central method for peripheral track using chamber with 400 μm strip pitch

Resolution achieved with pTPC method for 90° central track using chamber with 400 μm strip pitch

NSW expected track angles

Resolution studies

Performance of MMs prototype

Extremely wide performance analysis program ongoing since 2008 in order to fully characterize the Micromegas chambers. The analysis program has made use of:

- Several test beam campaigns
- Test with cosmic ray
- X-ray gain for gain and mesh transparency measurements
- Irradiation tests (γ , e^- , neutrons) for aging and radiation hardness studies

MM performance in magnetic field

The MM chambers of the NSW will operate in a magnetic field of a magnitude up to about 0.3 T with different orientations with respect to the chamber planes but a sizable component orthogonal to the MDT electric field. The effect of the magnetic field on the detector operation has been studied with test beam data and simulations.

The drift direction of the sensitive electrons is tilted with respect to the electric field direction by the Lorentz angle θ_L . The tilt of the drift direction gives a sizable shift (Δx) of the reconstructed hit position. As the magnetic configuration, the hit performance of the chamber is not affected, due to the very small cluster size. A compensation algorithm can be applied to have a constant resolution through all configurations.

R&D: 6 generations of triple-GEMs

Generations I to VI of triple-GEMs. Performance improving with increasing cluster size.

- GEM foil production uses single mask technology for production
- Chemically reduces foil production costs and
- Improves yield in the manufacturing process
- Yield increases in the foil of double mask
- Mechanical foil stretching procedure
- Construction time reduced from weeks to two hours per chamber

Performances

Over the years numerous tests, also with beam (CERN SPS), have been performed.

Test with GE11-IV at the CERN Gamma Irradiation Facility (GIF):

- ^{137}Cs source of 506 GBq
- Irradiation rate: $\sim 100 \text{ kRad/h} \rightarrow$ few kRad/cm^2
- $\text{AuCO}_2/\text{CF}_4$ 45/15/80 (0.3L/h), gas gain 2×10^4
- No gain drop after 10 mC/cm^2 (over 12 months)
- Next steps:
 - Moved to GIF \rightarrow to reach $\sim 100 \text{ mC/cm}^2$ (16.7 Tbh ^{137}Cs)

Outgassing studies:

- At room $^\circ\text{T}$ and at 50°C
- Being performed on all materials in contact with gas
- Ongoing test on SW-PC-10x10 cm 2 triple-GEM
- Chromatograph to identify impurities
- Vitex O-ring: OK
- Polyurethane Cellpack: OK
- Polyurethane Nonwoven: OK

Aging studies

IBF optimized configuration (2)

Satisfactory performance could not be achieved with 3 GEM stack

Best results in terms of IBF and energy resolution

- 4 GEM stack
- SC-APS configuration
- Standard GEM foil
- 10 μm large pitch foil foil
- Optimized V settings: $V_{\text{drift}} = E_1$ (transfer fields)

IBF optimized configuration (7)

Electron transport properties for IBF optimized voltage settings

- ϵ_{coll} = collection efficiency
- ϵ_{ext} = extraction efficiency
- ME = gas multiplication factor
- $G = \epsilon_{\text{coll}} \times \epsilon_{\text{ext}} \times \text{ME} \rightarrow$ effective gain
- n_{coll} = number of produced ions pairs
- n_{ext} = number of ions drifting back into the drift volume

Prototype beam tests: PID

4GEM BROC prototype tests dE/dx resolution measurements at CERN PS

Excellent dE/dx resolution: $\sim 10\%$ (BROC only)

Performance equal to adding MWPC BROC's

Prototype beam tests: Stability

Challenge with CERN SPS

- Discharge probability: 10^{-13} to 10^{-14} per particle
- Additional dE/dx measurements with 0 and 1 particles
- Performance similar to standard triple GEMs
- Gain stability measurements by addition of ^{137}Cs beam test
- Expected number of discharges in 4.5 TPC per typical yearly heavy ion run at 50 kHz
- 4 GEMs per TPC \rightarrow 180 discharges per TPC
- Not expected to create any damage to the GEM detectors

MPGD Technologies: Hadron and Nuclear and Heavy Ion Physics experiments

Challenges: Ultra High rates, IBF

Present:

COMPASS (GEM, μ Megas, THGEM RICH), rates: 100kHz/mm²

First experiment to use MPGDs (GEM, Micromegas and recently THGEM)

KEDR (GEM), Rates: 1MHz/mm²

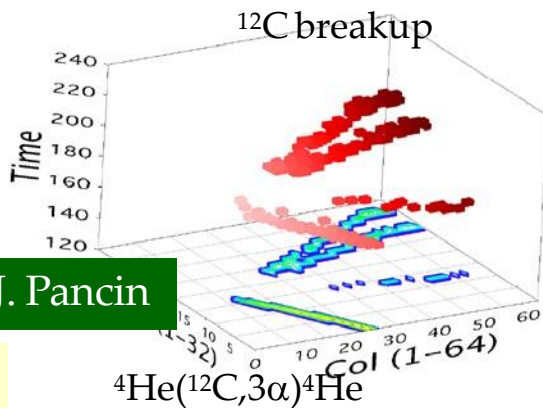
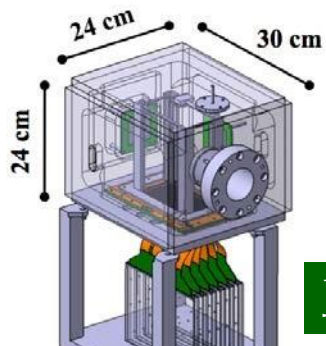
CLAS12: Cylindrical MM

Future: JLAB: SBS, pRad, SoLID (GEM, NP, tracking), JPARC: E42, E45 (Hadron Physics, ACTAR TPC

The ACTAR TPC Project

(gas is used as a secondary target for nuclear reactions):

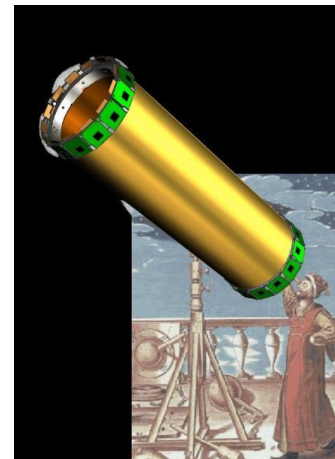
Goal: Nuclear structure with rare-isotope beams



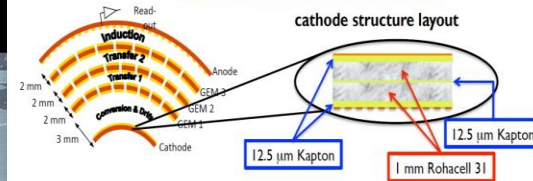
J. Pancin

MM-based readout

Cylindrical GEM for BESIII Experiment @ e+e- collider Beijing



Rohacell technique for mechanical structure



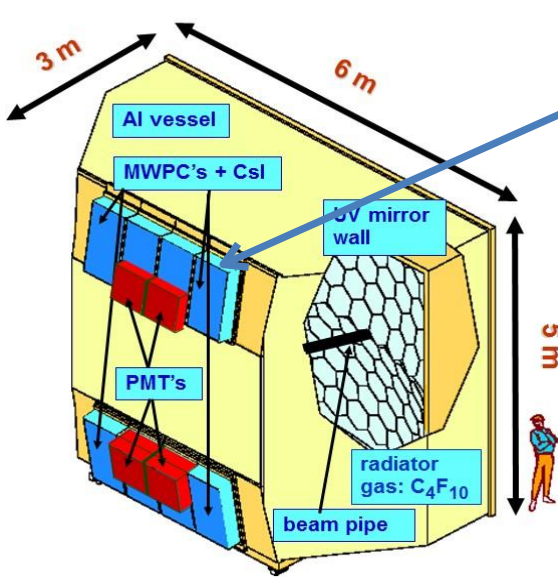
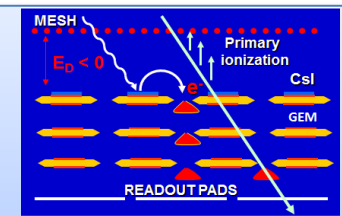
MPGD Technologies: Photon detection

Challenges: IBF photocathode protection

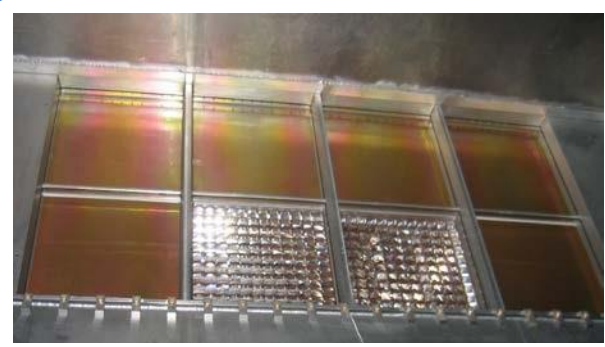
Present:

COMPASS (THGEM RICH)

Future: JLAB: SBS, pRad, SoLID (GEM, NP, tracking), JPARC: E42, E45 (Hadron Physics, ACTAR TPC)



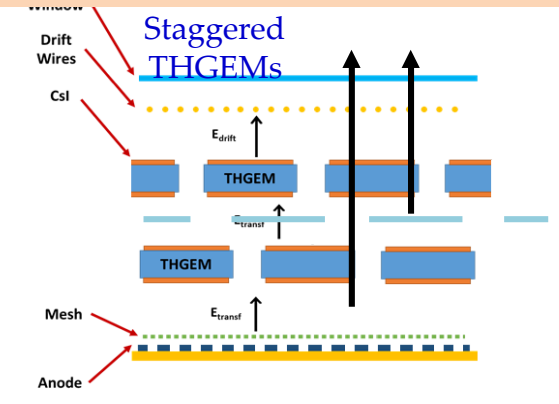
MWPC's + CsI



F. Tessarotto



Hybrid: THGEM+ CsI and MM



mass production ongoing

After a long-term fight for increasing electrical stability at high rates: MWPC **robust operation is not possible at gain $\sim 10^5$** because of photon feedback, space charge & sparks

PMTs not adequate \rightarrow only small demagnification factor allowed; 5 m² of PMTs not affordable.

MPGD Technologies: Neutron detectors (ITER spallation sources, Macromolecular Crystallography Beam diagnostics)

Challenges: Low mass detectors

Present:

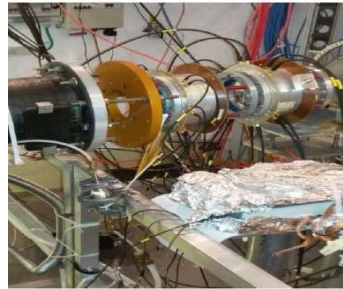
nTOF

Future:

ESS (macromolecular crystallography, neutron scattering)

nTOF at CERN

GEM detector



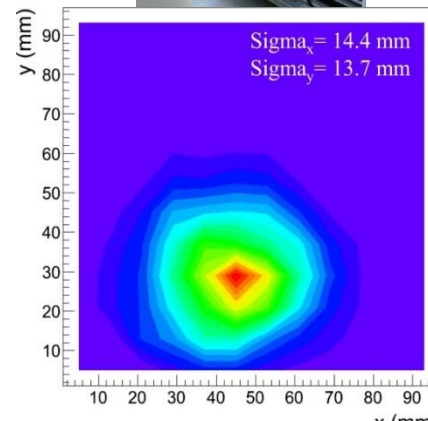
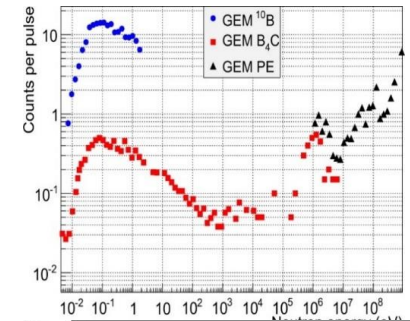
Installation on NTOF



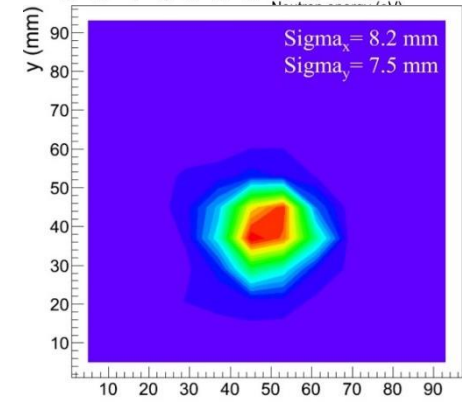
4 pad detector



GEM detector



2D image of thermal neutron



2D image of fast neutron

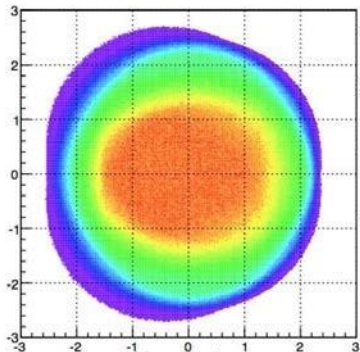
μ Megas detector:

2 D reconstructed image

T. Papaevangelou

μ M Neutron Monitor applied to fission reactor

Beam profile at detector



F. Murtas

MPGD Technologies: Neutrino Physics

Challenges: Large area TPCs

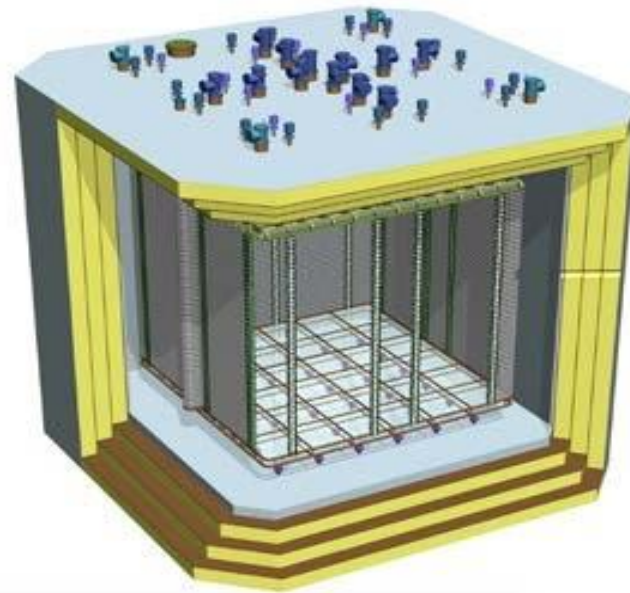
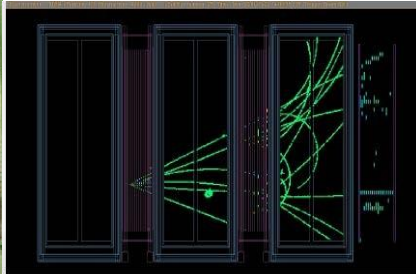
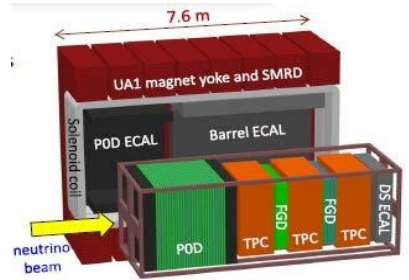
Present:

T2K (Japan), first large scale neutrino experiment with MPGD (9 m² TPC with micromegas)

Future:

LBNO-DEMO (LAr TPC THGEM), DUNE 720 m² (LAr TPC THGEM), Ship (26 m² micromegas, GEM, mRWELL)

T2K experiment



- 72 Micromegas, 120k channels (since 2009)
- Charge, momentum and dE/dx PID)
- Spatial resolution : 0.6 mm
- Momentum res.: 9% at 1 GeV
- dE/dx: 7.8 % (distinguish μ/e , identify ν_e)

MPGD Technologies: Dark Matter detection

Challenges: Ultra low background detectors $< 10^{-7}$ cnts/keV/cm²

Present:

CAST (Micromegas μ bulk and Ingrid), NEWAGE (Kamioka, TPC GEM, μ PIC)

Future:

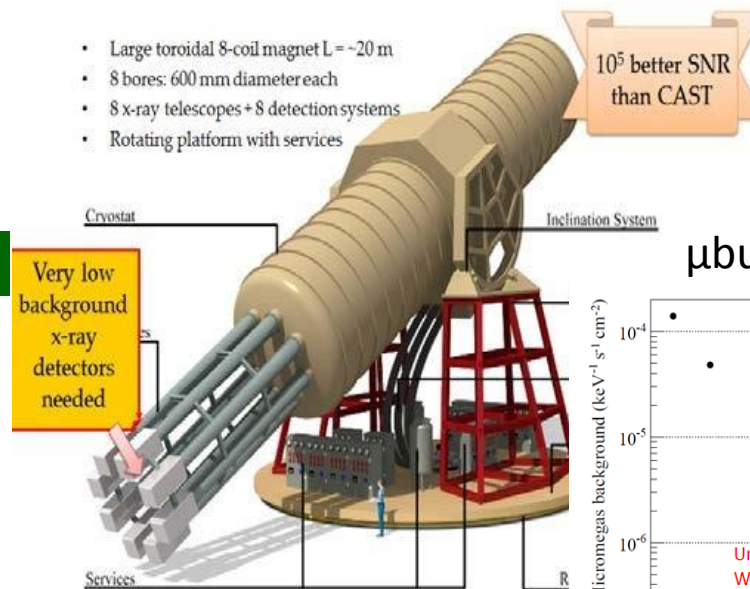
PANDA-X(TPC μ bulk micromegas, DARWIN (THGEM GMPT), IAXO (μ bulk micromegas)

NEWAGE
 μ -PIC based TPC with electronics
 Only DM experiment with 3-D tracks

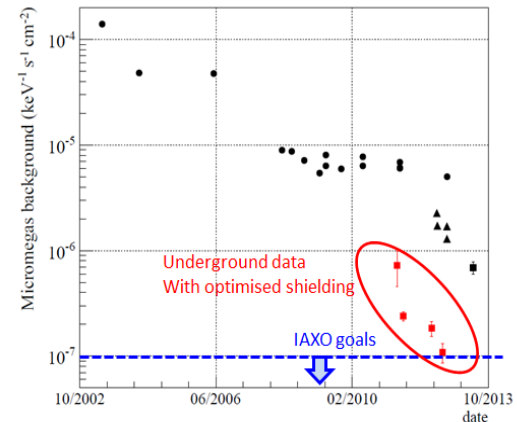
IAXO: Axion searches

- Large toroidal 8-coil magnet L = -20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services

10⁵ better SNR than CAST



μ bulk background



K. Miuchi, A. Ochi

GEM
 -31 × 32 cm²
 -70 μ m/140 μ m
 -LCP 100 μ m
 -made by Scienergy, Japan

μ -PIC
 -31 × 31cm²
 -made by DNP, Japan

MPGD Technologies: X and γ ray detection and polarimetry

Astrophysics and fusion plasma monitor

Challenges: Track photoelectrons and low energy e

Present:

KSTAR Korea (Plasma monitor), SMILE II (γ -ray imaging, GEM and μ PIC) , ETCC camera (GEM and μ PIC) environmental γ ray monitoring

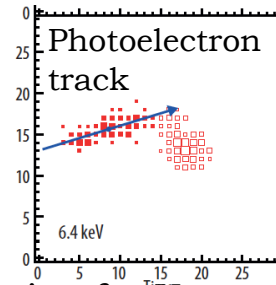
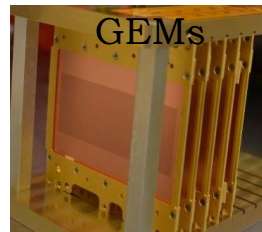
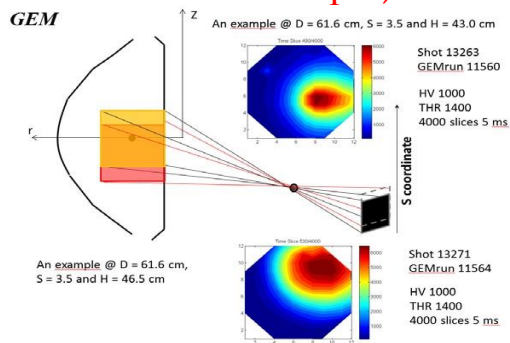
Future:

PRAXyS (TPC GEM x-ray polarimetry), CALISTE (piggy back micromegas, X-ray polarimetry)

PRAXyS X-ray polarimetry



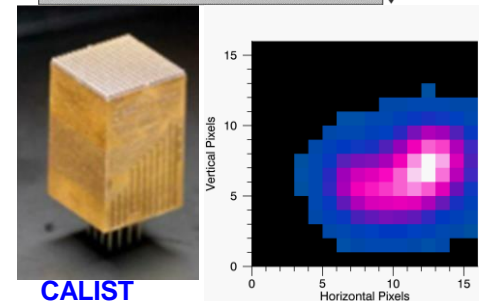
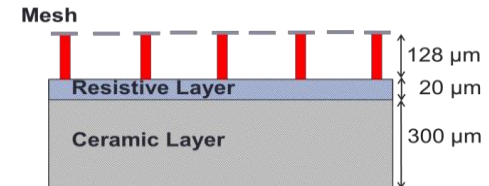
KSTAR Tokamak **GEMPIX (GEM + Timepix) for fusion**



- The first dedicated mission for X-ray polarimetry in astrophysics
- US-Japan joint mission (NASA lead)
- The space craft carries two identical **GEM-TPC**

CALIST-MM: X-ray polarimetry

Piggyback Micromegas



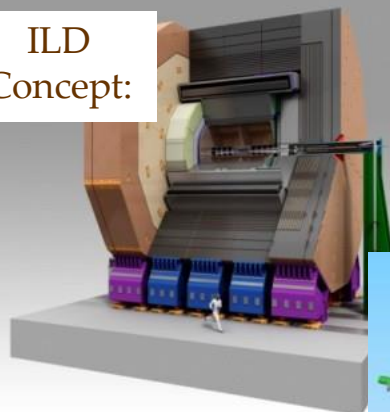
CALIST

- $10 \times 10 \times 20,7$ mm³ (Compact)
- 16x16 pixels : 8 ASICs of 32 channels
- Pixel $\varnothing = 500$ μ m ; Pixel Pitch = 580 μ m
- Consumption = 850 μ W/channel (218 mW in total)
- Low Noise (ENC = 50 e⁻ rms)

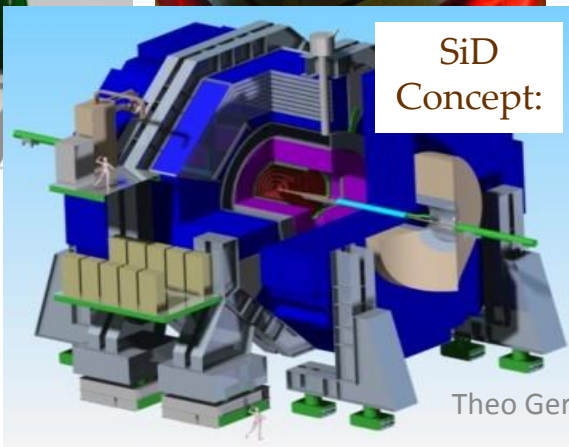
MPGD Technologies for the International Linear Collider

Experiment/ Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements/ Remarks
ILC Time Projection Chamber for ILD: Start: > 2030	High Energy Physics (tracking)	Micromegas GEM (pads) InGrid (pixels)	Total area: ~ 20 m ² Single unit detect: ~ 400 cm ² (pads) ~ 130 cm ² (pixels)	Max. rate: < 1 kHz Spatial res.: < 150 μm Time res.: ~ 15 ns dE/dx: 5 % (Fe55) Rad. Hard.: no	Si + TPC Momentum resolution: dp/p < 9*10 ⁻⁵ /GeV Power-pulsing
ILC Hadronic (DHCAL) Calorimetry for ILD/SiD Start > 2030	High Energy Physics (calorimetry)	GEM, THGEM RPWELL, Micromegas	Total area: ~ 4000 m ² Single unit detect: 0.5 - 1 m ²	Max.rate: 1 kHz/cm ² Spatial res.: ~ 1cm Time res.: ~ 300 ns Rad. Hard.: no	Jet Energy resolution: 3-4% Power-pulsing, self- triggering readout

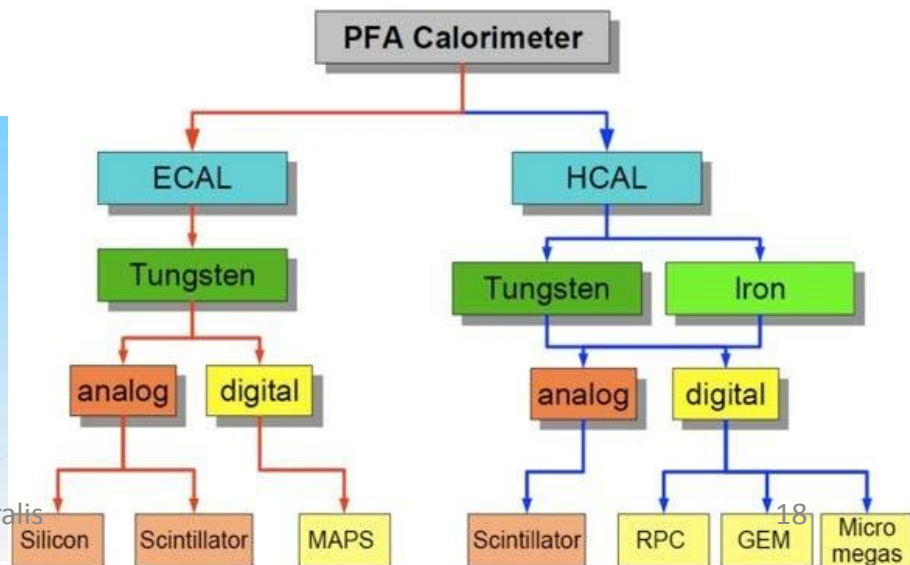
ILD
Concept:



SiD
Concept:



Particle Flow Calorimetry (ILD/SiD):



MPGD Conferences and Special focus events

MPGD Conferences since 2009:

- 1st MPGD2009, Crete, Greece
- 2nd MPGD2011, Kobe, Japan
- 3rd MPGD2013, Zaragoza, Spain
- 4th MPGD2015, Trieste, Italy

**NEXT: 5th MPGD2017, Temple University, USA
May 22 – 26, 2017**



4th MPGD2015, Trieste, Italy
140 participants, 120 abstracts

Special focus MPGD events. Most recent :

- Academia-Industry Matching event:
 - Second special workshop on **neutron detection** with MPGDs, CERN, March 2015
- Rd51 Academia-Industry Matching event:
 - Special workshop on **photon detection** with MPGDs, CERN, June 2015
- Topical workshop on **resistive electrodes**, CERN, Dec. 2015
- Topical workshop on **discharges** in MPGDs, CERN, March 2016
- MPGD **Applications Beyond Fundamental Science** Workshop, Aveiro, Portugal, Sept. 2016
- Schools, visits, events

CONCLUSIONS

RD51 collaboration contribution:

MPGD technologies have received enormous boost over the last decade

MPGDs are used in many scientific domains

MPGDs are used in many applications beyond Particle Physics

Exciting field for creative new ideas, attractive for young scientists !