Review on the R&D Activities within the RD51 Collaboration

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on Behalf of the RD5 Collaboration
Outline

- Introduction to the RD51 Collaboration
- Reviews of RD51 Working Groups & Activities
- Highlight & Achievements
- Future R&D & Flagship Technologies
- Conclusion
Brief History of Micro Pattern Gas Detectors (MPGDs) & the RD51 Collaboration

Start ~ 2010 with R&D white paper


MSGC GEM µPIC THGEM

Supported by a collaboration of people & Institutes with the GERN GDD lab at its core

MPGD Technologies in HEP, NP experiments and beyond:

- GEMs ⇒ COMPASS Trackers, CMS Muon Upgrade, ALICE TPC, KLOE2 CGEM, SBS GEMs (JLab), STAR FGT (BNL). ESS n-Detection …
- Micromegas ⇒ COMPASS Trackers, ATLAS Muon Upgrade, CLAS12 MVT (JLab), T2K TPC, Muon Radiography …
- THGEMs ⇒ COMPASS RICH upgrade, LBNO-DEMO, AT-TPC (NSCL)
Diversity of MPGDs

Gas Electron Multipliers (GEMs)
F. Sauli, Nucl. Instr. and Meth. A386(1997)531

Micro Mesh Gaseous Structure
Y. Giomataris, NIMA 419 (1998) 239

Micro Wire Chamber
B. Adeva et al., NIMA 435 (1999) 402

Micro Gap Wire Chamber
NIMA 398 (1997) 195

Micro Groove
R. Bellazzini, NIMA 424 (1999) 444

Micro WELL
R. Bellazzini, NIMA 423 (1999) 125

Micro Dot

Micro Mesh Gaseous Structure

... and so many others

Angelini F., NIMA 335:69 (1993)

Micro Gap Chambers

μ-PIC
Ochi et al NIMA 471 (2001) 264

MicroWELL

Gas Electron Multipliers (GEMs)

R. Bellazzini, NIMA 424 (1999) 444

Micro Dot

RD51 objectives and achievements

Advance the technological development and application of Micro Pattern Gas Detectors (MPGDs) and contribute to the dissemination of these technologies.

**Development**
- Exploit existing technologies
  - Large size single-mask GEMs
  - Resistive Micromegas
- Develop novel technologies
  - μPIC, μR-WELL, GRIDPIX

**Dissemination**
- High-Energy Physics
  - ALICE, ATLAS, CMS, Compass, KLOE, BESIII, SBS, EIC Detectors
- Fundamental research beyond HEP
  - LBNL-DEMO, active-target TPCs
- Beyond fundamental research
  - Muon radiography, n-detection, X-ray radiographies

**Tools and facilities**
- Common infrastructures
  - (GDD lab, common test beam)
- Electronics
  - (Scalable Readout System SRS, instrumentation)
- Simulation
  - (Garfield, Magboltz, Degrad, neBEM)
RD51 Working Groups

**WG1:** Technologies & New structures ⇒ R&D support for experiments and LHC upgrades

**WG2:** Characterization & Detector physics

**WG3:** Training and dissemination

**WG4:** Software & Simulation Tools

**WG5:** Readout Electronics (RD51 SRS)

**WG6:** MPGD Production & Industrialization

**WG7:** RD51 Lab and Test-Beam Infrastructure
RD51 Working Groups & Its Environment

Expertise & people
- CERN GDD team
- RD51 groups

Tools & facilities
- GDD Lab
- MPT Workshop
- Thin Film Lab
- Test Beams
- Simulation Tools
- Electronics

Activities
- Detector physics
- Meetings & conferences
- Generic R&D
- Industrialization
RD51 Achievements and Highlights

- Consolidation of the Collaboration and **MPGD community integration** (90 Institutes, ~500 members); Conferences, Meetings, Workshops, AIMEs, Schools, Lectures, Trainings

- Major progress in the MPGD technologies development in particular **large area GEM (single mask), MicroMegas (resistive), THGEM**; some picked up by experiments (including LHC upgrades);
  - ALICE, TPC read-out, ~ 500 m² of GEM foils
  - ATLAS, small wheels, 1200 m² to be instrumented
  - CMS, GE1/1 forward detectors, 250 m² of GEM foils
  - COMPASS RICH, 4.5 m² to be instrumented, single photon detection

- **Secured future** of the MPGD technologies development through the EP-DT-MPT workshop upgrade and FP7 AIDA & AIDA2020 contribution;

- Contacts with industry for large volume production, **MPGD industrialization and first industrial runs**;

- Major improvement of the MPGD **simulation software framework for small structures** allowing first applications;

- **Development of common, scalable readout electronics (SRS)** (many developers and > 50 user groups); **Production** (PRISMA company and availability through CERN store); **Industrialization** (re-design of SRS in ATCA in EISYS); SRS Technology CERN spin-off, APV and VMM interfacing.

- **Infrastructure** for common RD51 test beam and lab facilities (>20 user groups)
Development of large area detectors driven by RD51 & LHC Experiments Upgrades

Large GEM ⇨ single masks; Large & spark-resistant Micromegas ⇨ Resistive; single photon Detector THGEM + Micromegas ⇨ Hybrid MPGDs;
WG1: Technologies & New Structures

Calorimetry with MPGD
Resistive Micromegas for Sampling Calorimetry

- Resistive Micromegas
  - Highly segmented calorimeters (small pads, many layers)
  - New version using carbon sputtering is being tested
  - Resistive GEM
    - The resistive electrodes are made by very thin (50 - 300nm) material
    - It will improve the signal gain
    - We have just made it, and it is being tested now.

Resistive Material
Other MPGD development using carbon sputtering

- Resistive μ-PIC
- Resistive GEM

New Materials (Glass GEM)
Introduction - Glass GEM

The Latest Results of Crystalized Glass GEM, Y. Mitsuia, RD51 miniweek (GDD/RD51 lab)

Fast Timing
MicroMegas based:
(Initial tests March/April 2015)
Ne-Ethane(10%)-200 micron drift+50 micron Micro Bulk

36 picosecond rms on first try!!

Neutrons Detection
New Large Area Thin Detectors
The μ-RWELL performance (I)

The detectors have been tested with Ar+CO₂=7/3 and Ar+0.3%Ne+0.7%H₂O, and characterized by measuring the anode pulse, rate capability, and discharge in current mode.
The detectors have been fabricated with a cathode flux of 5.9*10⁶ Χ rays generated by a FW22172/2Phi tube.
The cell has been measured with a spatially resolved measurement of the anode pulse amplitude and the signal shape.

In the Lab
300 keV source neutron moderated with H₂ Over 100 km/h
< 1 keV
> 1 keV

When thin Cu slits are placed the TPC resolution is improved with the sharp edge.
WG2: Common characterization & Detector Physics

Effect of extreme operating conditions on the GEM detector components

Ion density effects in multiGEM

Discharge studies ALICE/CMS

Gating GEM
Ion back-flow at equal fields

**Ion back-flow reaches maximum at approx. same voltage** as for electron transparency

**Higher voltages** than for electrons to fully close gate

Very preliminary data with large error bars (not shown)!

IBF normalized to \( \Delta V_{\text{GEM}} = 20 \text{ V} \)
WG3: Training & dissemination

CULTURAL NET-WORK, DISSEMINATION & TRAINING

- Previous conferences:
  - MPGD2009, Crete, Greece
  - MPGD2011, Kobe, Japan
  - MPGD2013, Zaragoza, Spain
  - MPGD2015, Trieste, Italy
  - MPGD2017, Philadelphia, USA

- Next conferences:
  - MPGD2021, Weizmann, Israel
  - MPGD2023, USTC, China

CULTURAL NET-WORK: special events

- Academia-industry matching events
  - Workshop on specific aspects
  - Precise Timing Workshop
    - CERN, 21-22 February 2017
**WG4: Modelling of Physics Processes and Software Tools**

Gas detector simulation: new areas

- Discharges and Resistive layers.
- Ion diffusion.
- Refinement of ionisation esp. at low energy.
- Integration of boundary element methods.

**Mesh transparency**

- Electron tracking requires improvement.

**High-precision data from AGH**

- Current reference is taken at the ionisation level.
- Main source of error: ~5%.

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**Charging-up of a GEM**

- Gain changes as a result of the charge deposits.
- Electron tracking to be refined.

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**single-electron spectra**

- Blue: Pulse signal + Gaussian noise (fit red: Monte Carlo (Myrrha), not fits useful)
- Ar 95% + CH4 5%, E=28.12 kV/cm
- Ne 95% + CH4 5%, E=28.25 kV/cm
- He 95% + CH4 5%, E=28.25 kV/cm

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**Ion distribution at the hole entrance: reduction of the amplification field**

- $10kHz/mm^2$
- $100kHz/mm^2$
- $1000kHz/mm^2$
WG5: Electronics - Scalable Readout System (SRS)

A multi-purpose Scalable Readout System with different front-end chips is developed and maintained in the RD51 collaboration.

This simplifies detector R&D and can be scaled from small prototypes to operational experiments.

• Dedicated community built around detector electronics
• Fully supported by RD51 collaboration

H. Müller, Development of multi-channel readout system optimized for gaseous detectors

https://indico.desy.de/indico/event/7435/material/1/4.pdf
WG5: Wide deployment of the SRS

SRS+SiPM (NEXT TPC)

SRS-FEC+TOTEM DAQ

SRS+Timepix (LC-TPC) – Bonn/Desy

SRS & APV25 (PRad JLab)

- PRad e-p scattering experiment in Summer 2016 @ JLab (HallB)
  - PRad GEMs with APV25-SRS (9k strip read out)
  - Large scale SRS to run in an experiment \(\Rightarrow 9k\) e\(-\) Ch,
  - @ a trigger rate \(= 4\) kHz
- Untold success story of SRS

SRS crate / SRU combo

SRS for R&D on Detectors

SRS for experiments (ATCA)

LHC experiments: from detector to counting room

- Detector
- Detector-Frame
- Cables
- Counting room
- Offline

- High resolution up to 100 kHz
- Low power supply
- Low noise
- Low magnetic field
- SPS-ATCA

- SPS-ATCA
- Standard electronics
- Customized electronics
- Calorimeter
- LNGS
- OR

- LSND
- LNGS
- Calorimeter
WG5: Lab Equipment developed by The RD51 community

- **GAVD board and E-fuse board**
  - 36...54 e-fused sectors per G-AVD Unit*
  - (* SRS compliant)
  - 18 HV wires to GEM sectors/board
  - 2..3 stacked E-fuse boards
  - PCB design pending

- **APIC Analogue Pickup box**
  - (* SRS compliant)
  - APIC N10, C5A, preamplifier, dual-polarity, 100 ns shaper
  - Variable gain max. 900 mV / 100 mV
  - Calibration 30 kHz 50 Hz

- **QUAD MPGD signal amplifier**
  - 2 GHz, 25dB

- **a scalable HV power supply system with SoC control and real-time, high resolution I, V monitoring**

- **Femtometer V 1.3**
  - (* SRS compliant)

- **Floating Multichannel Pico Ammeter**

- **MoCoS: Monitoring and control system**

- **a Radio-Controlled High-Voltage Insulated Picoammeter**

- **[CERN]**

- **[CERN]**

- **[CERN]**

- **[CERN]**

- **[Zagreb Univ.]**

- **[INFN-Trieste]**

- **[INFN-Trieste]**
WG6: Production - MPT Workshop

- State-of-the-art facility pioneering MPGD technologies through advanced manufacturing techniques
- Contributing to generic R&D and large volume production for upgrades of LHC experiments

New building with advanced capabilities

Rui De Oliveira et al., Micro-Pattern Technologies
https://ep-dep-dt.web.cern.ch/micro-pattern-technologies
WG6: Industrialization

Technology Industrialization → transfer “know-how” from CERN workshop to industrial partners

GEM Technology (contacts):
- Mecharonix (Korea, Seoul)
- Tech-ETCH (USA, Boston)
- Scienery (Japan, Tokyo)
- TECHTRA (Poland, Wroclaw)

GEM Licenses signed by:
- Mecharonix, 21/05/2013
- TECH-Etch, 06/03/2013
- China IAE, 10/01/2012
- ScEnergy, 06/04/2009
- Techtra, 09/02/2009
- CDT, 25/08/2008
- PGE, 09/07/2007

MicroMegas Technology (contacts):
- ELTOS S.p.A. (Italy)
- TRIANGLE LABS (USA, Nevada)
- SOMACIS (Italy, Castelfidardo)
- ELVIA (France, CHOLET)

THGEM Technology (contacts):
- ELTOS S.p.A. (Italy)
- PRINT ELECTRONICS

GEM Industrialization Status (today):

TECH-ETCH
- Single Mask process fully understood. Many 10cm x 10cm produced and characterized.
- 40cm x 40cm GEM successfully produced
- CMS GE1/1 size of 1m x 0.5m started

TECHTRA
- Production Line Operational
- Stable process for 10cm x 10cm
- Single Mask process completely understood – 10cm x 10cm produced
- 40cm x 80cm Single Mask Produced

MECARO
- 10cm x 10cm double mask produced and tested
- 30cm x 30cm double mask under evaluation at CERN
- CMS GE1/1 size of 1m x 0.5m

MICROMEGAS industrialization status (today):

ELVIA
- Bulk MM detectors are routinely produced with size up to 50x50cm²
- production for ATLAS NSW started

ELTOS
- Several small-size Bulk MM detectors produced
- production for ATLAS NSW started

THGEM industrialization status (today):

ELTOS
- THGEM for COMPASS RICH upgrade
- (final polishing in house)
- LEMs for LBNL-DEMO

Regularly producing for CERN store

Capability to produce CMS GE1/1 foils

The long-lasting TT effort

MPGD TT today
Hosting groups from RD51 and providing access to facilities

- MPGD Detectors
- Gas system and services
- Readout electronics (std and custom RD51 SRS&APV)
- Radioactive Sources & X-ray tubes
- Cosmic stand
- Interface with CERN services (RP, gas, metrology, irradiation facilities, …)

Acting as interface to Thin Film Lab & MPT workshop at CERN
WG7: Common Facilities - Test beam Facilities

- Test beam periods at EHN1-H4 North Area
- shared between RD51 groups
- Typically 3 periods of 2 weeks / per year

Examples of the test beam user teams

- CMS (GEM)
- WIS/A/C (WELL, THGEM)
- ATLAS NSW (mm)
- BESS III & SHIP (GEM)
- LAPP/DEM/IRFU(µm)
- ALICE TPC (GEM & µm)

~ 30 groups in total with several running in parallel
**RD51 Breakthrough: Single Mask GEMs & NS2 Assembly**

### Single Mask Techniques for large GEM foils production
- Allow for the production of large GEM foils (> 50 cm x 50 cm)
- Require single photo lithography mask on one side of the GEM foil during the different etching processes
- Big step forward for current and future GEM project like CMS Muon detector upgrade, SBS and SoLID @ JLab, Muon Chamber for PANDA @ FAIR

### NS2 Triple GEM assembly technique
- Mechanical stretching with small frames with the use of a set of screws, fittings for the stretching
- Control of the stretching and the flatness of the GEMs
- **No glue involved:** Chamber can be re-opened
- **No need for spacers in active area**
- **BUT:** Lots of screws and rigid supports to hold tension

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**Figure 1.** Schematic comparison of procedures for fabrication of a double-mask GEM (left) and a single-mask GEM (right).

**Limitation from mask alignment**
- max active area ~ 40×40 cm²

**No alignment required**
- Very large GEM foil
RD51 Breakthrough: Resistive Micromegas

Unacceptable rate of discharge with standard Micromegas
- Not destructive for the detector ⇔ Robust and sturdy device
- However: long dead time and discharge critical for the FE chips (need to be very well protected)

Spark signals on the oscilloscope (on 50 Ω, attenuated 1:100) and under neutron irradiation
J. Wotschack et al, Large-size Micromegas for ATLAS (MAMMA), RD51 mini week, 17/01/2011

R&D effort by the RD51 Coll & the ATLAS Muon Upgrade
- playing with the induction of the signal in the readout to protect against the damaging effects of spark
- A sketch (not in scale) of the resistive-strip protection principle with a view along and orthogonal to the strip direction
- Induced signal on the strips (no direct collection charges)
RD51 Breakthrough: Single Photon Detection with MPGD

Hybrids MPGDs for COMPASS RICH1 PD Upgrade:

MWPCs replaced by THGEMs + CsI + Micromegas

Typical PARAMETERS:

- Diam. = 0.4 mm, Pitch = 0.8 mm
- Thick. = 0.4 mm, Rim = 10 μm
- Fast signal (ns), Gain @ HV = 2kV: $10^5$ atmospheric pressure

R. Chechik, A. Breskin, C. Shalem

GEM-like multipliers for large area UV-RICH detectors

PCB Etching and drilling

Simple and robust & cost effective

F. Tessaroto, MPGD2015, Trieste, Italy, 10/12/2015
The µ-RWELL_PCB is realized by coupling:

1. a “suitable WELL patterned kapton foil” as “amplification stage”
2. a “resistive stage” for the discharge suppression & current evacuation:
   i. “Low particle rate” (LR) << 100 kHz/cm²: single resistive layer → surface resistivity ~100 MΩ.cm (CMS-phase2 upgrade - SHIP)
   ii. “High particle rate” (HR) >> 100 kHz/cm²: more sophisticated resistive scheme must be implemented (MPDG_NEXT- LNF & LHCb-muon upgrade)
3. a standard readout PCB

G. Benvenuti et al., 2015_JINST_10_P02008

- Like Micromegas ⇔ One amplification stage, no need to stretched etc …
- Like GEM ⇔ Simple structure (Just like GEM foil); ideal for a full cylindrical detector

Robust and simple detector
RD51 Highlights & Achievement: Cylindrical MPGDs

**GEM KLOE-2 @ Frascati.**

**Micromegas CLAS12 (Hall B, JLab)**

**GEM: BoNuS rTPC in Hall B @ JLab**

D. Domenici

INSTR2014, Novosibirsk

M. Vandenbroucke,

MPGD2015 Trieste, Italy

E. Christy

Tagged SF, JLAB 2014
RD51 Highlights & Achievement: Even Spherical MPGDs


Even Spherical GEM
RD51 Flagship Technologies: Fast & Precise Timing

Cherenkov radiator + Photocathode + Micromegas

Prototype in Test beam

Photocathode Robustness

Scaling up
From single pad to multi-pad module

Cherenkov radiator + Photocathode + Micromegas

Florian Brunbauer, INSTR20, Novosibirsk Feb 26, 2020

https://indico.inp.nsk.su/event/20/session/3/contribution/17/material/slides/0.pdf
RD51 Flagship Technologies: New Hybrids Detectors

Coupling fast camera readout with GEM amplification

- Many applications in:
  - HEP (optical readout TPC)
  - Radiography
  - Medical Imaging …

Combined electronic and optical readout

Depth dose curve

Patient treatment plan

Visible picture of a painting and its X-ray fluorescence image. Different colours refer to different materials (energy resolved)

Radiography of a bat and closeup of the GEM holes

Freeze-frame of an X-ray movie of a flying drone

Radiography of a crushed cup with pans and its 3D tomographic reconstruction

Schematics not drawn to scale
RD51 Flagship Technologies: New Hybrids Detectors

**InGrid & TimePix:** the ultimate gaseous TPC

(H. Van Der Graaf)

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**CAST**

256 x 256 pixels, 55 x 55 \( \mu \text{m} \) pitch, about 1.4 x 1.4 cm\(^2\) sensitive area

Figure 1: SEM image of an InGrid structure on top of a Timepix ASIC (a), taken from [13]. In the SEM image parts of the mesh have been removed to show the good alignment between pixels and mesh holes. A bare Timepix ASIC on a carrier board (b).

F. Hartjes, [link](https://agenda.linearcollider.org/event/7795/contributions/40334/attachments/32507/49403/QUAD_development.pdf)

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Gempix Sample Tracks

- Low Energy Electrons
- Proton
- Energetic Electrons
- Alpha (4 MeV)

Color denotes the (relative) charge deposited in the pixel.

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A large TPC prototype for a linear collider detector P. Schade, J. Kaminski, NIMA, 628, 1, 1 February 2011, Pages 128-132

[link](https://indico.cern.ch/event/391665/contributions/1827282/attachments/1230061/1802690/GridPix.pdf)
RD51 Flagship Technologies: New Materials & Technologies

Innovative photocathodes by ND powder

Highly efficient and stable ultraviolet photocathode based on nanodiamond particles

DLC photocathodes

μRWELL with DLC

Graphene layers


Resistive DLC GEM

https://indico.cern.ch/event/709670/contributions/3020863/attachments/1672927/2684424/NEW_structures.pdf

https://indico.cern.ch/event/709670/contributions/3020862/attachments/1672921/2684467/
Advanced materials can boost detector performance and applicability. Solid converters and photocathodes enable new detector concepts and resistive materials with well-controlled parameters can be used to develop robust and performant MPGDs.
Conclusion

- Micro Pattern Gas Detector: versatile technology. Offers different options for different requirements

- MPGD field is expanding with the emergence of “Resistive” and new materials

- New processing techniques will open the field for new micro structures

- RD51 Collaboration is the glue for the MPGDs communities and a critical support for the development of MPGDs and emergence of new technologies