GEM based detector for upgrade of the CMS forward muon system

RD51 Mini Week

April.2013

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on behalf of the

GEMs for CMS Collaboration

Outline

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  - Motivations
- Prototypes construction
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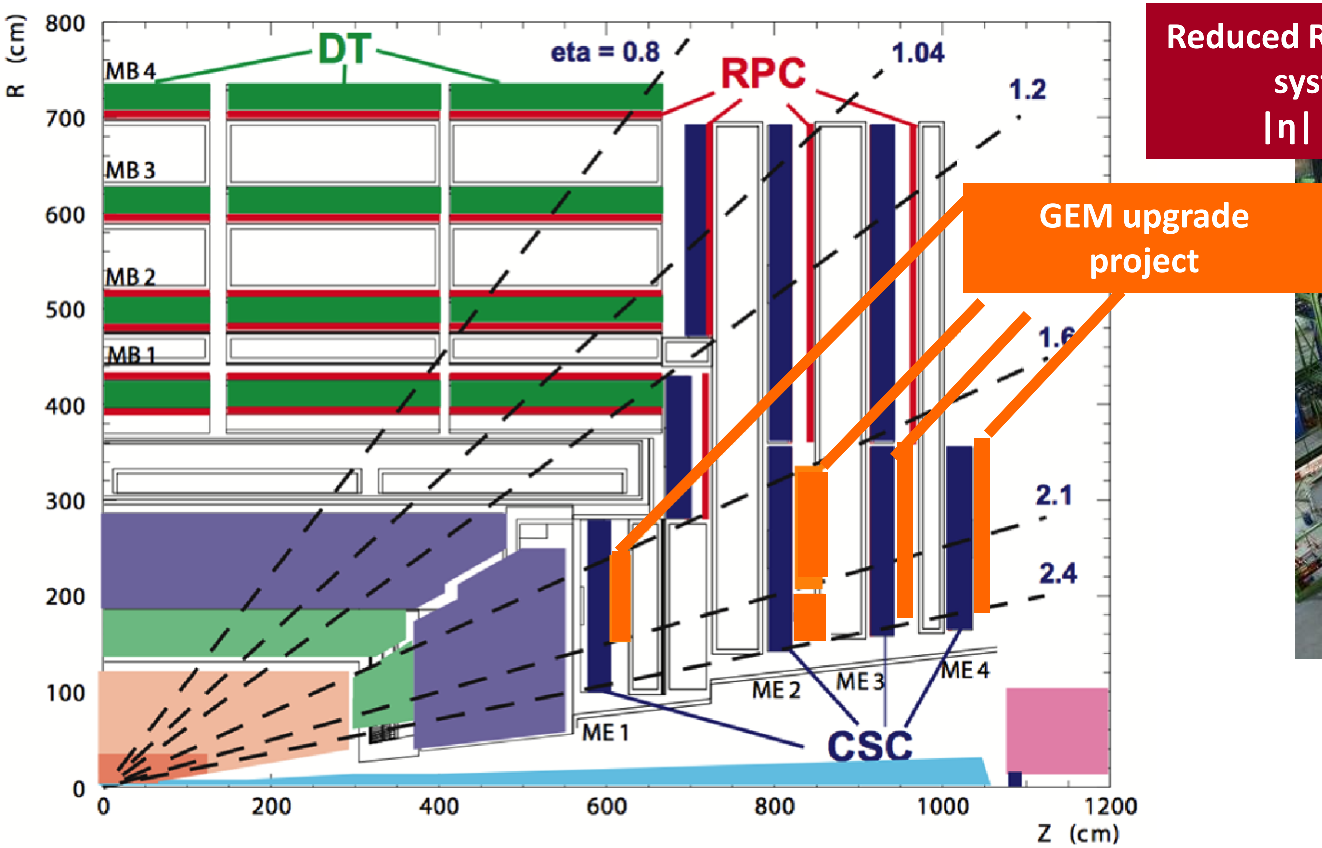
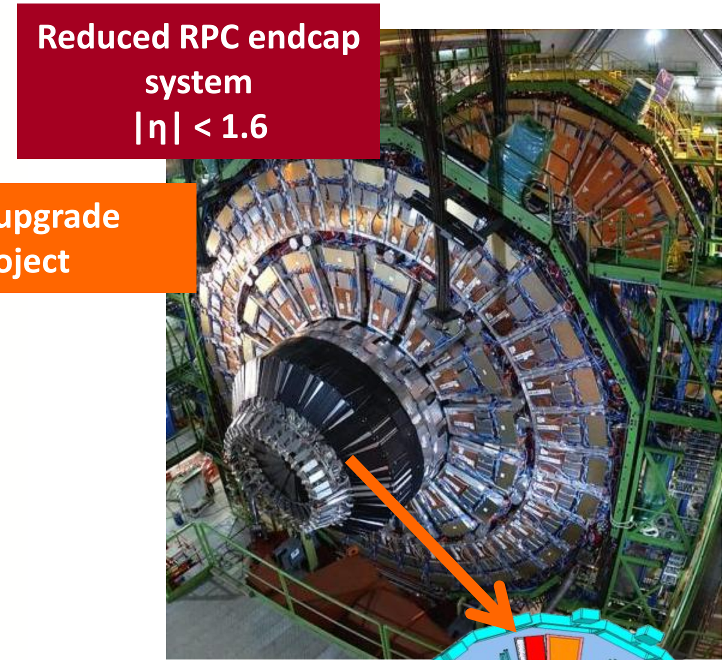
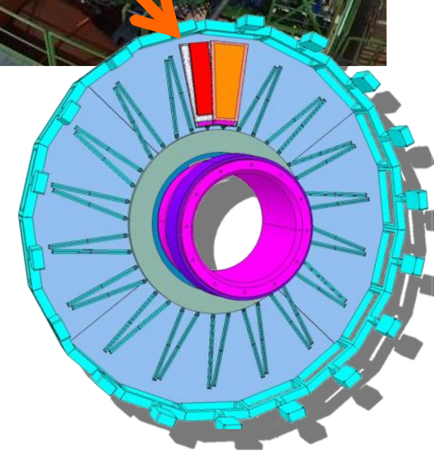
  - Self-Stretching GEMs (new technique)
- The CMS large-size detector
  - System layout,
  - Chamber preparation
  - Detector configurations
  - Gain calibrations
- Test-beam results
  - Timing studies
  - Single-mask results
  - Large-size performance
  - Ageing tests
- Services, integration and installation for the LS2 and the slice test in 2016
- The new CMS GEM lab in bldg.186
- Large-scale GEM production
  - CERN
  - Korea
  - Quality Control
- Electronics system *[μTCA system]*

Introduction: the present CMS Endcap system







The CMS Forward Muon RPC system is equipped with detectors up to | η | < 1.6, while the high-η region is presently vacant.

➢ **Instrument it with a detector technology that can sustain that environment and is suitable for operation at the LHC and its future upgrades.**

Motivations

CMS was designed to have a highly Redundant Muon system but we are missing redundancy in the high-η region.

In particular the high-η region needs robust and redundant tracking capability.

Detectors with high resolution would bring additional benefits in Muon HLT, reconstruction and identification.

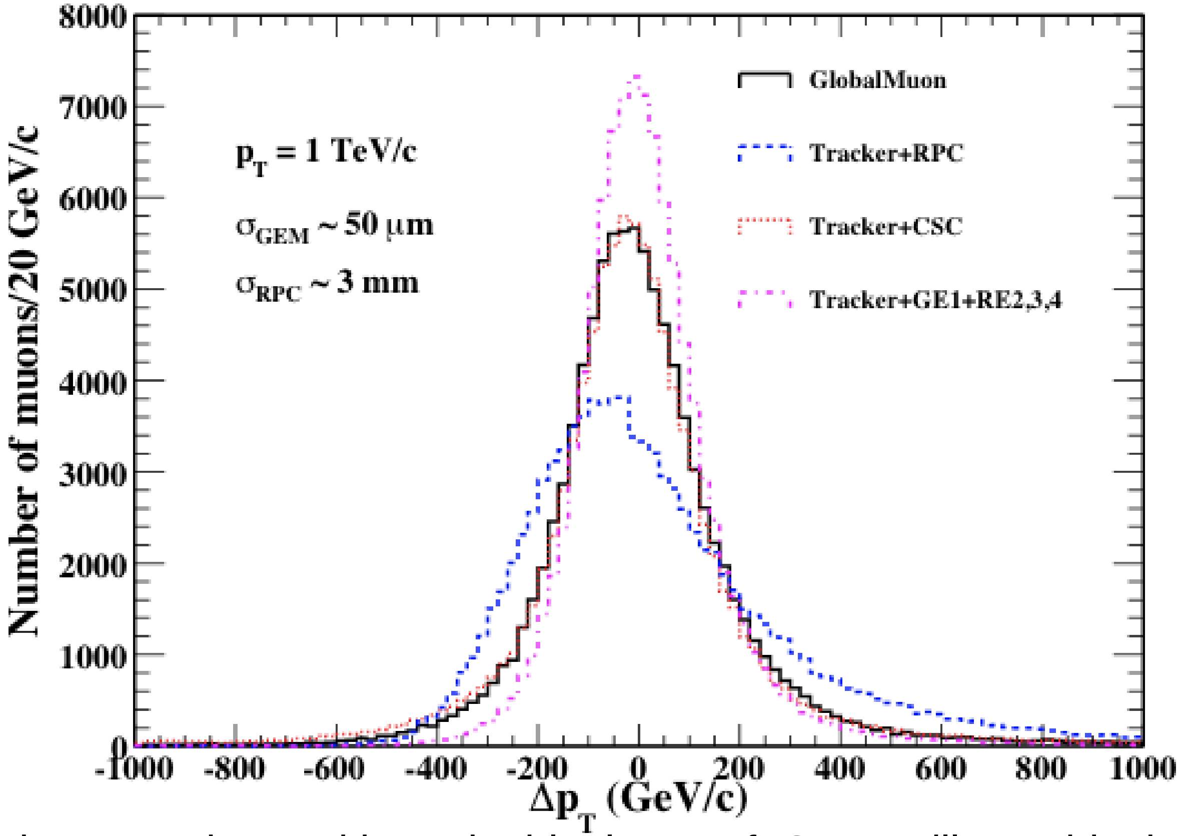
Improve contribution to Muon Trigger Efficiency.

CMS REGION	Rates [Hz/cm²]			Charge [C/cm²]		
	LHC (10^{34} cm²/s)	High Luminosity LHC (3 10^{34} cm²/s)	Super LHC (10^{35}cm²/s)	LHC (10^{34} cm²/s)	High Luminosity LHC (3 10^{34} cm²/s)	Super LHC (10^{35}cm²/s)
Barrel RPC	30	Few 100	~1000 (tbc)	0.05	0.15	~ 1
Endcap RPC $\eta < 1.6$	30	Few 100	~1000 (tbc)	0.05	0.15	~ 1
Endcap RPC $\eta > 1.6$	**500 - 1000**	**Few 1000**	**Few 10k**	(0.05-1)	**few C/cm²**	**Several C/cm²**

CMS high-eta region requirements are demanding in terms of rates and integrated charge

Motivations

Muon transverse momentum resolution for different muon system configurations



Instrumenting the inner stations with a double layer of GEM will provide independent pattern recognition and seeding of the track momentum fit.

GEMs, being also a tracking devices, will allow the muon pattern recognition also in partial, and even total absence, of the CSC allowing a direct measurement of the tracking performances using two independent muon systems.

Prototypes construction

Producing large prototypes for CMS

Key points

New single-mask technology

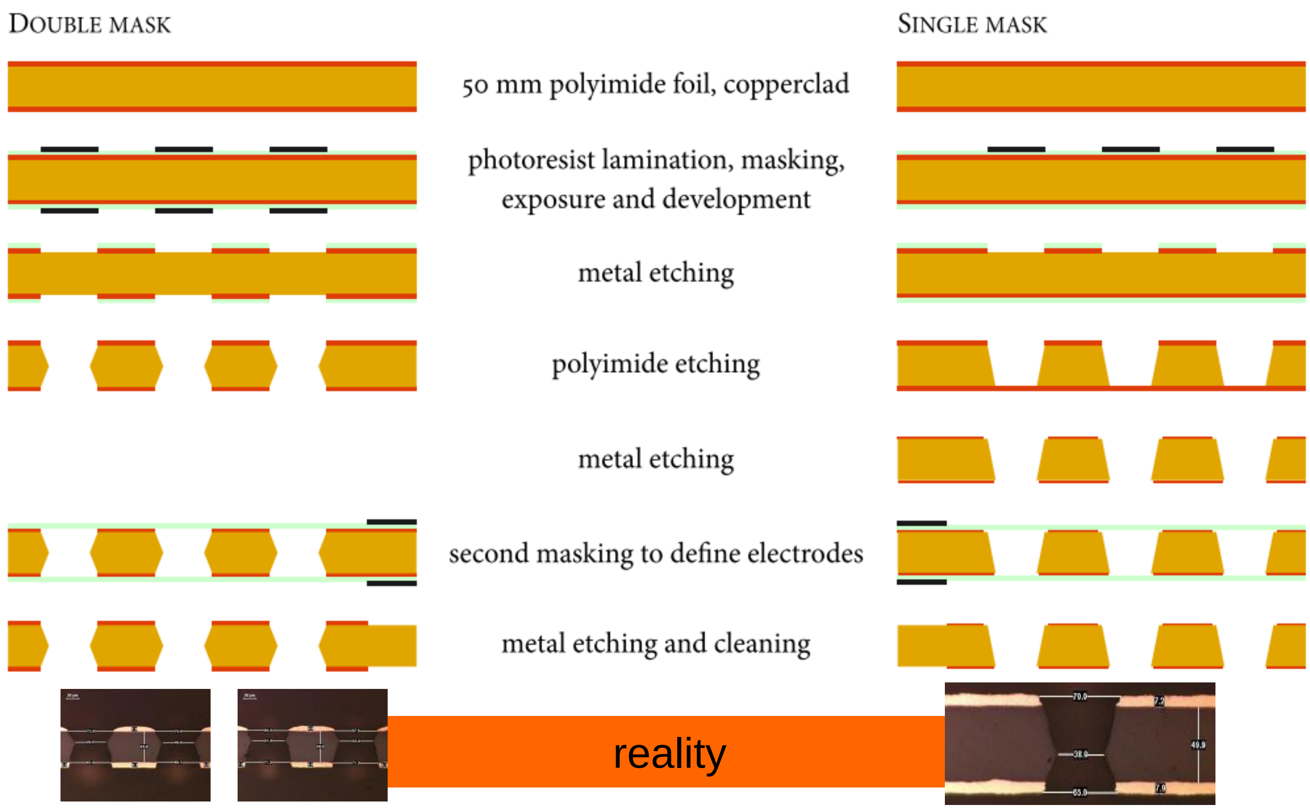
Single-mask technology provides alignment of the GEM foils, while double-mask technology cannot be used for large size foils due to misalignments.

- **Small prototypes demonstrated that single-mask GEMs achieves excellent performance.**
- **Large prototypes confirmed that single-mask technology is mature.**

New Stretching technique

The usual thermal stretching is not suitable for the mass production and large-size detectors.

The new single-mask technology



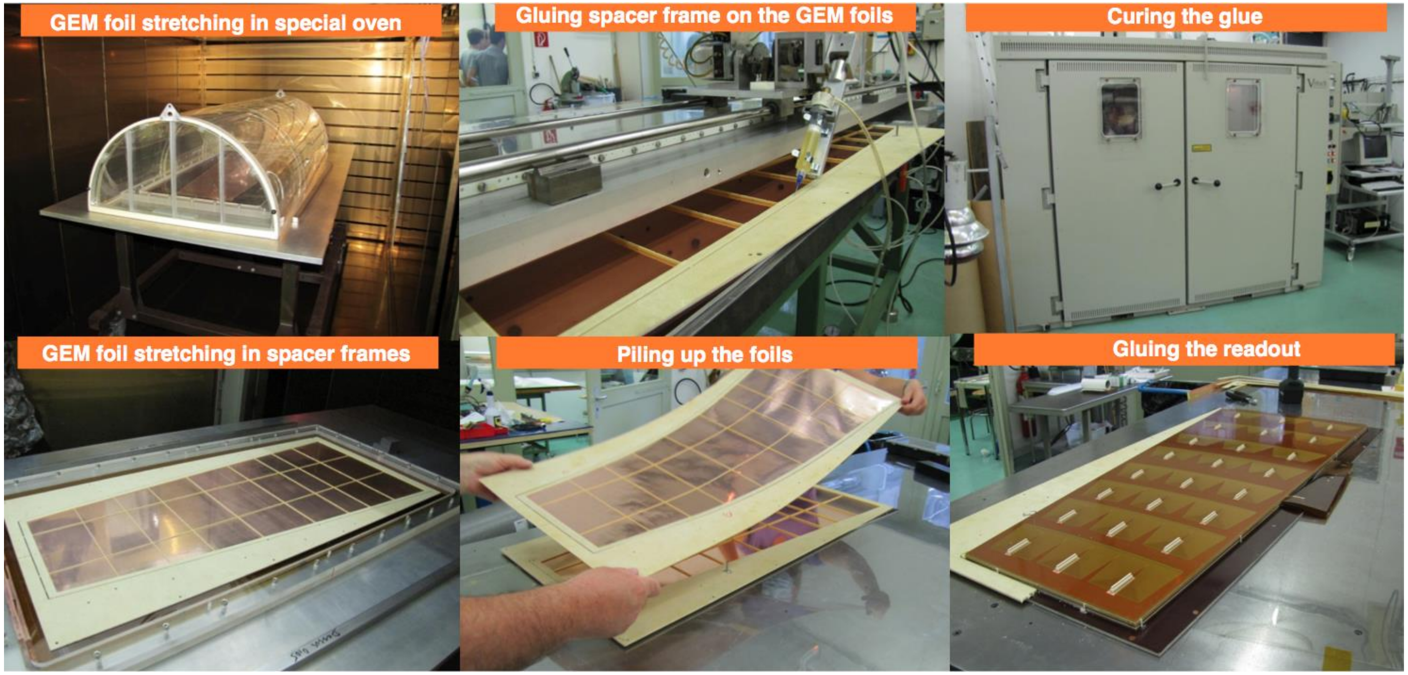
We acknowledge the RD51 Collaboration for the development of the Single-mask technology

Single-mask GEM achieves same performance level as double-mask GEM

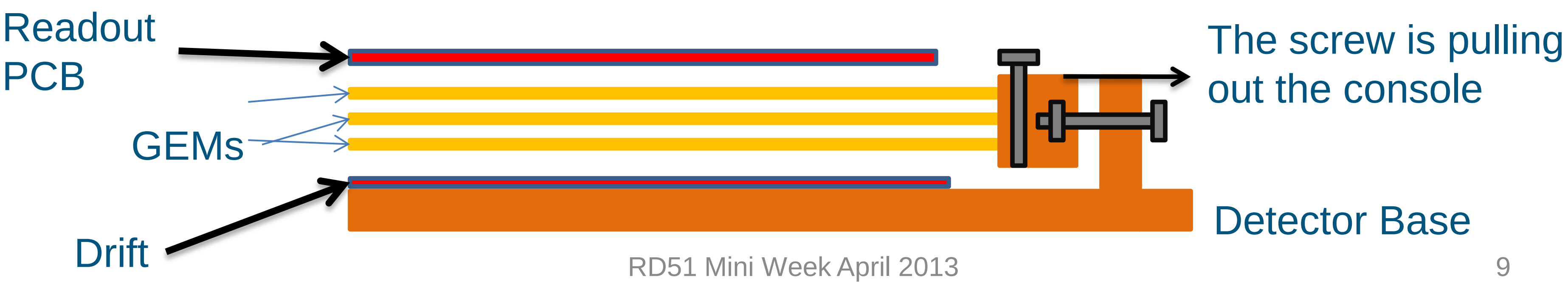
Single-mask technology used for large CMS-size prototypes

Stretching techniques

Old thermal stretching



New self-stretching technique



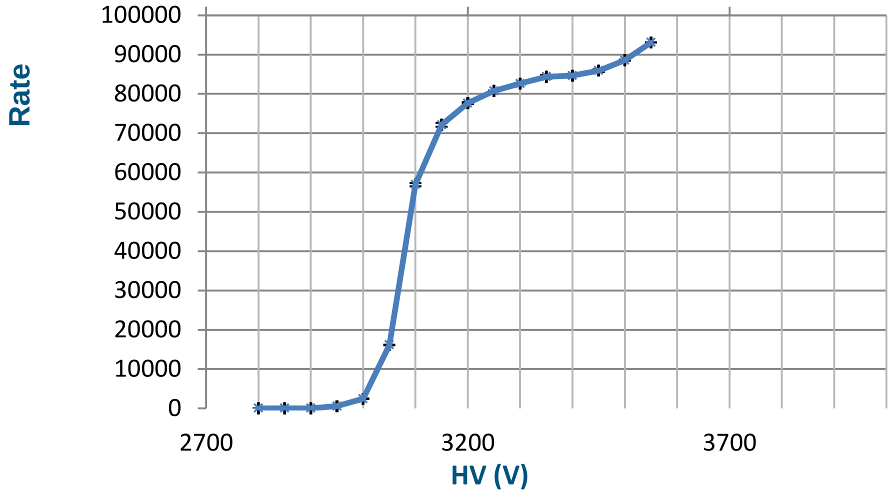
The new self-stretching Technique

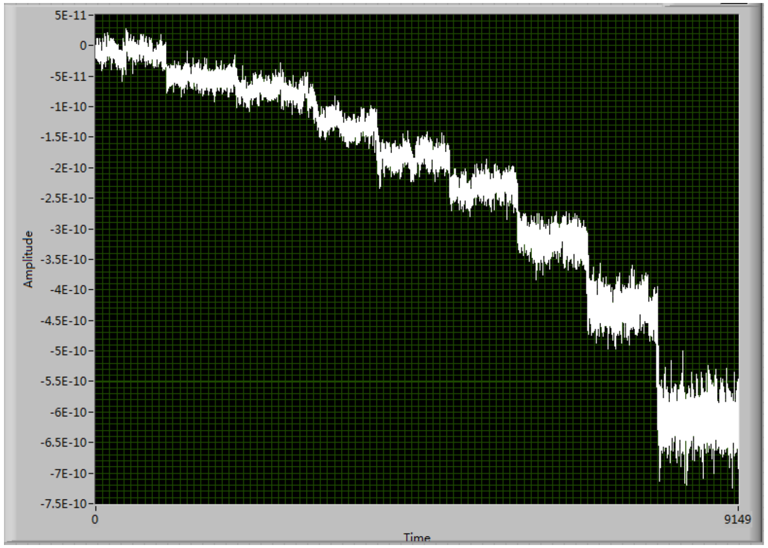
The new self-stretching technique has been applied to the full-size CMS detector.10

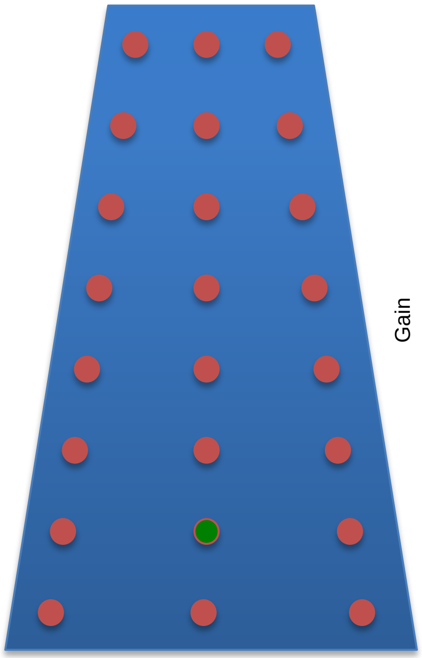
The CMS Full-size NS2 detector prototype for CMS

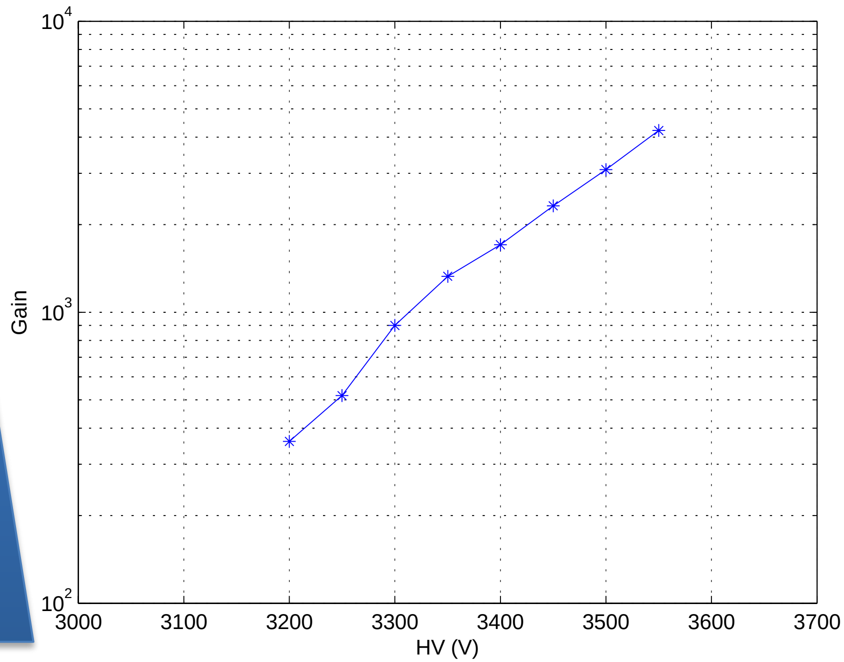
- **GEMs active areas: 990 mm x (220-445) mm**
- **Single-mask technology**
- **1D read-out with (3x10x128) 3184 channels**
- **HV sector: 35**
- **Gas mixtures:**
  - **Ar:CO_2 (70:30; 90:10)**
  - **Ar:CO_2:CF_4 (45:15:40; 60:20:20)**
- **Gas flow: ~5 l/h**

CMS full-size gain measurement

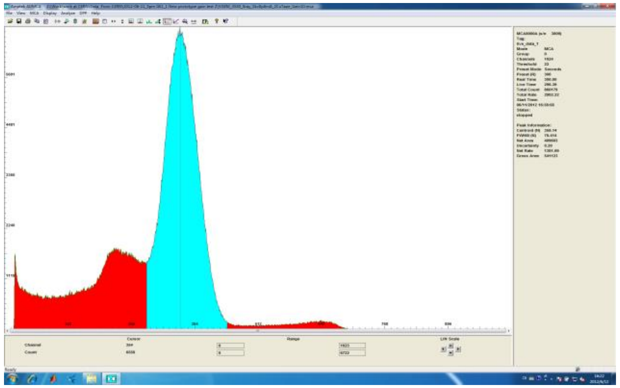




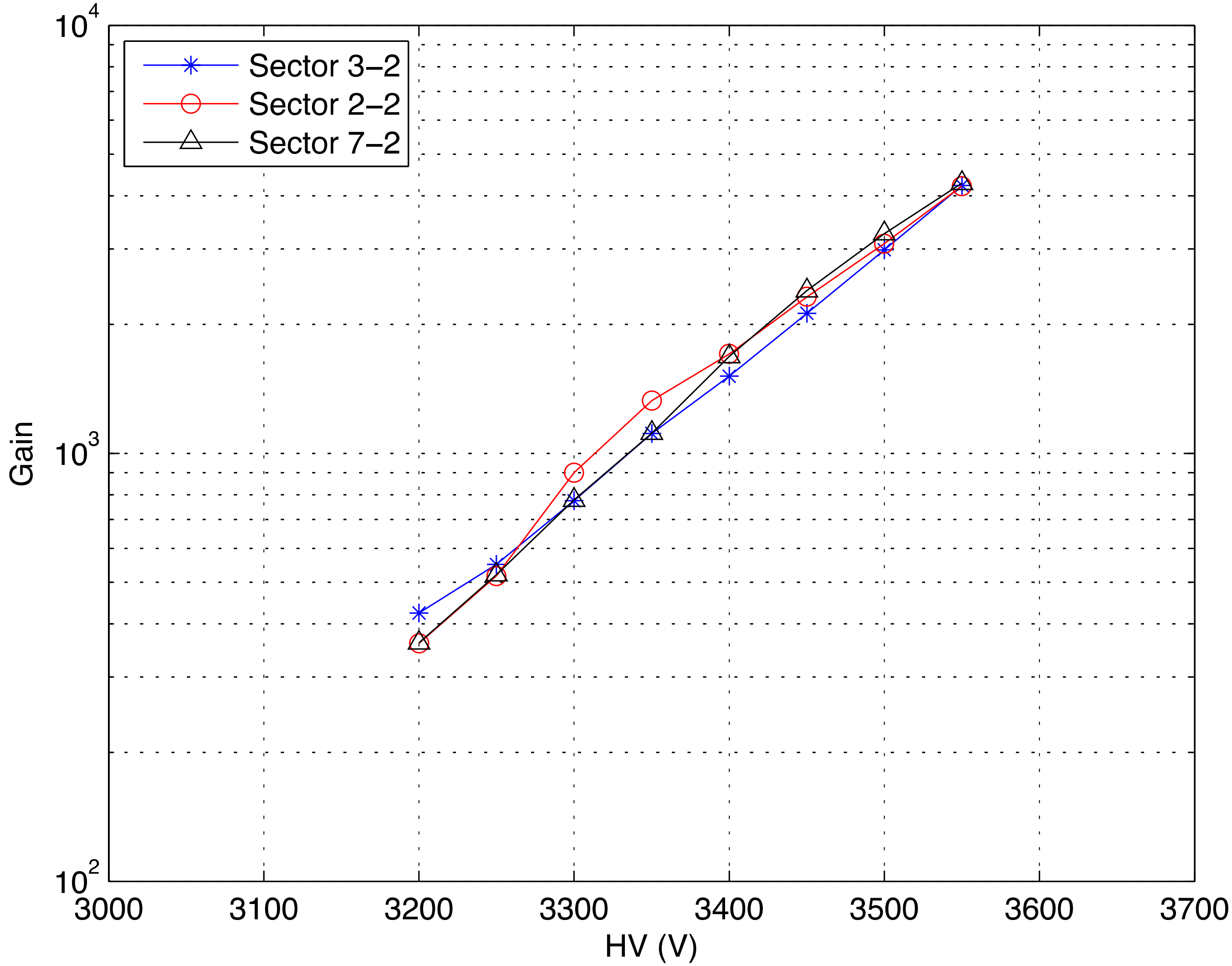




Energy Resolution: 19.61%



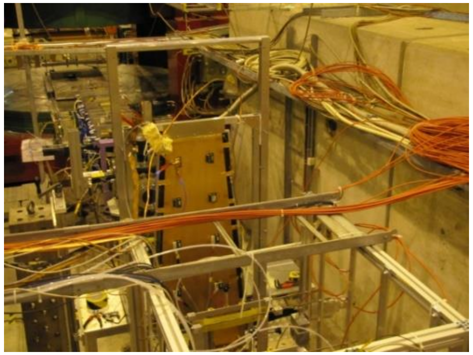
CMS full-size gain uniformity



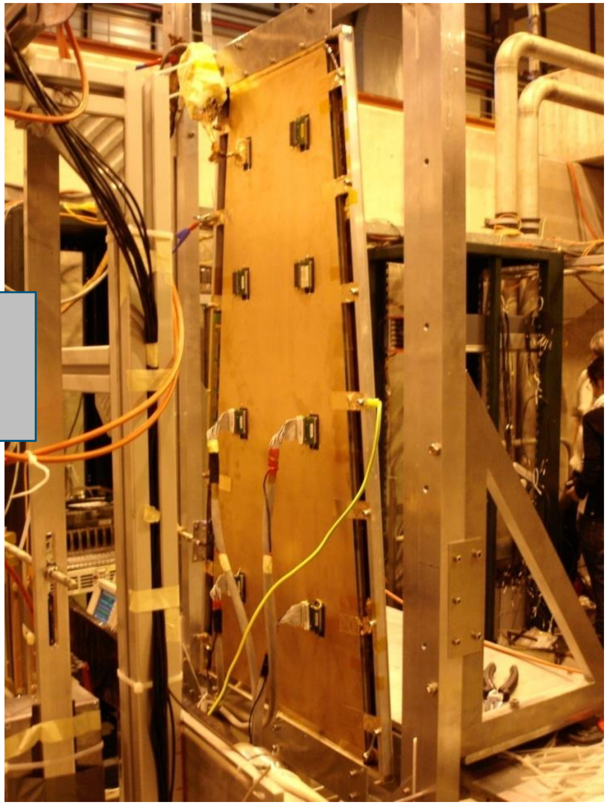
Test beam main results

CMS-RD51 Test Beams (SPS H4 2010)

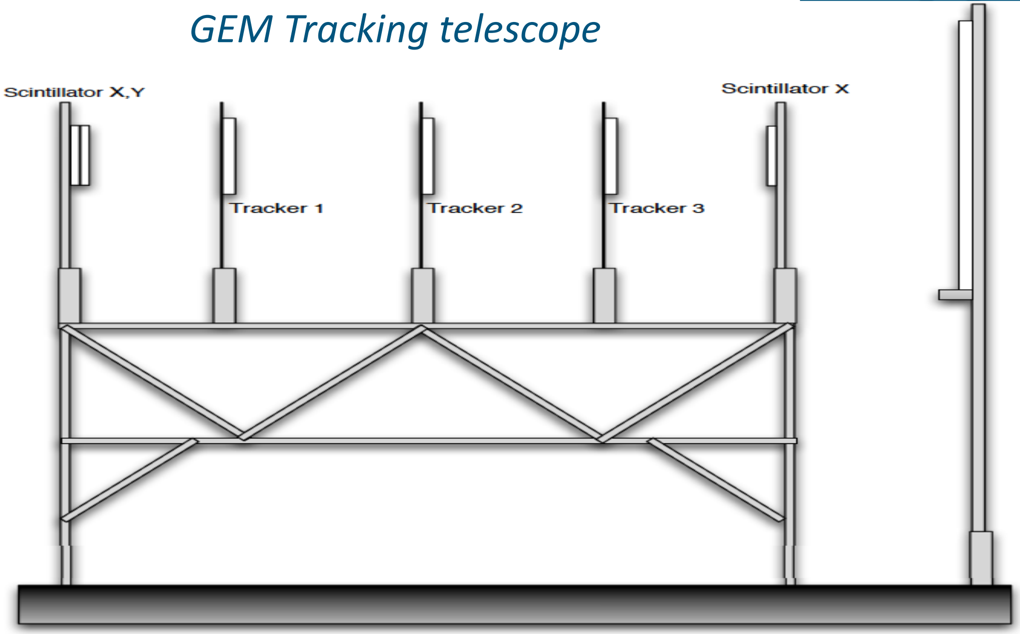
Test Beam @ RD51 SPS-H4 Setup



CMS full-size detector

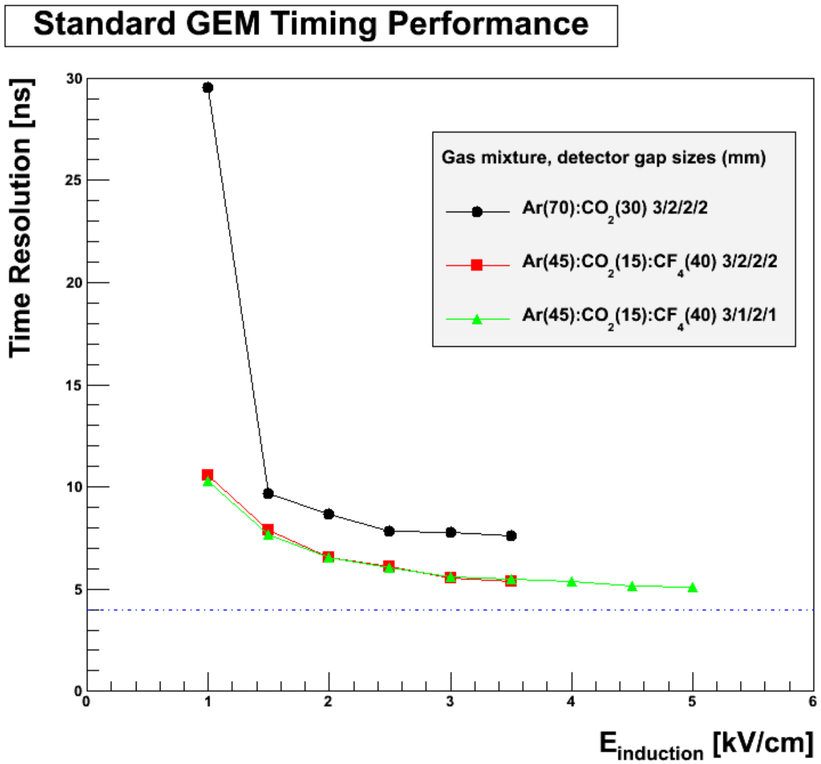


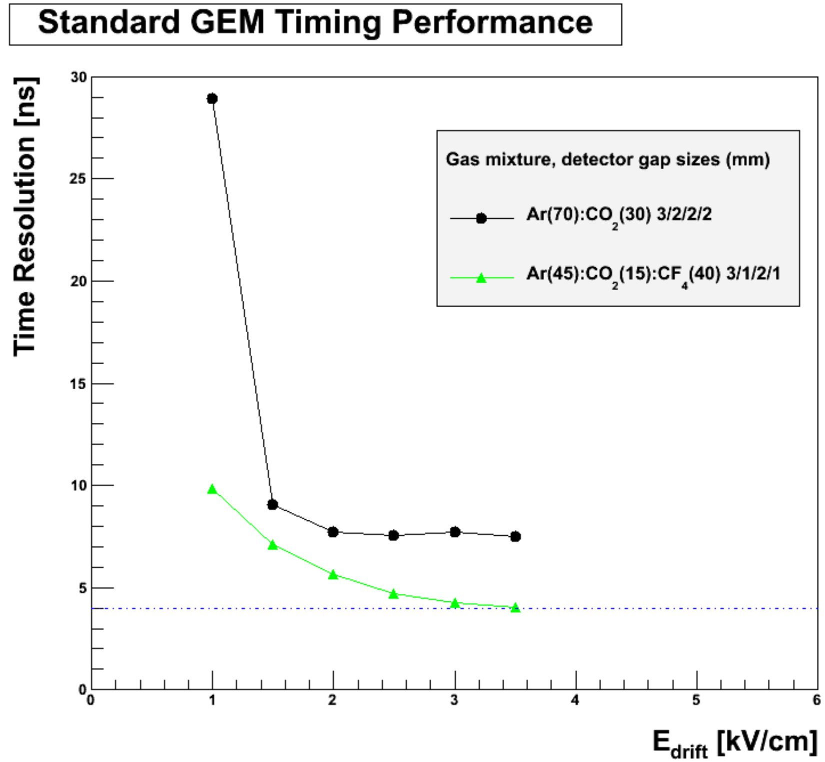
GEM Tracking telescope



Oct. 2010 :
20 million events taken with CMS Proto I

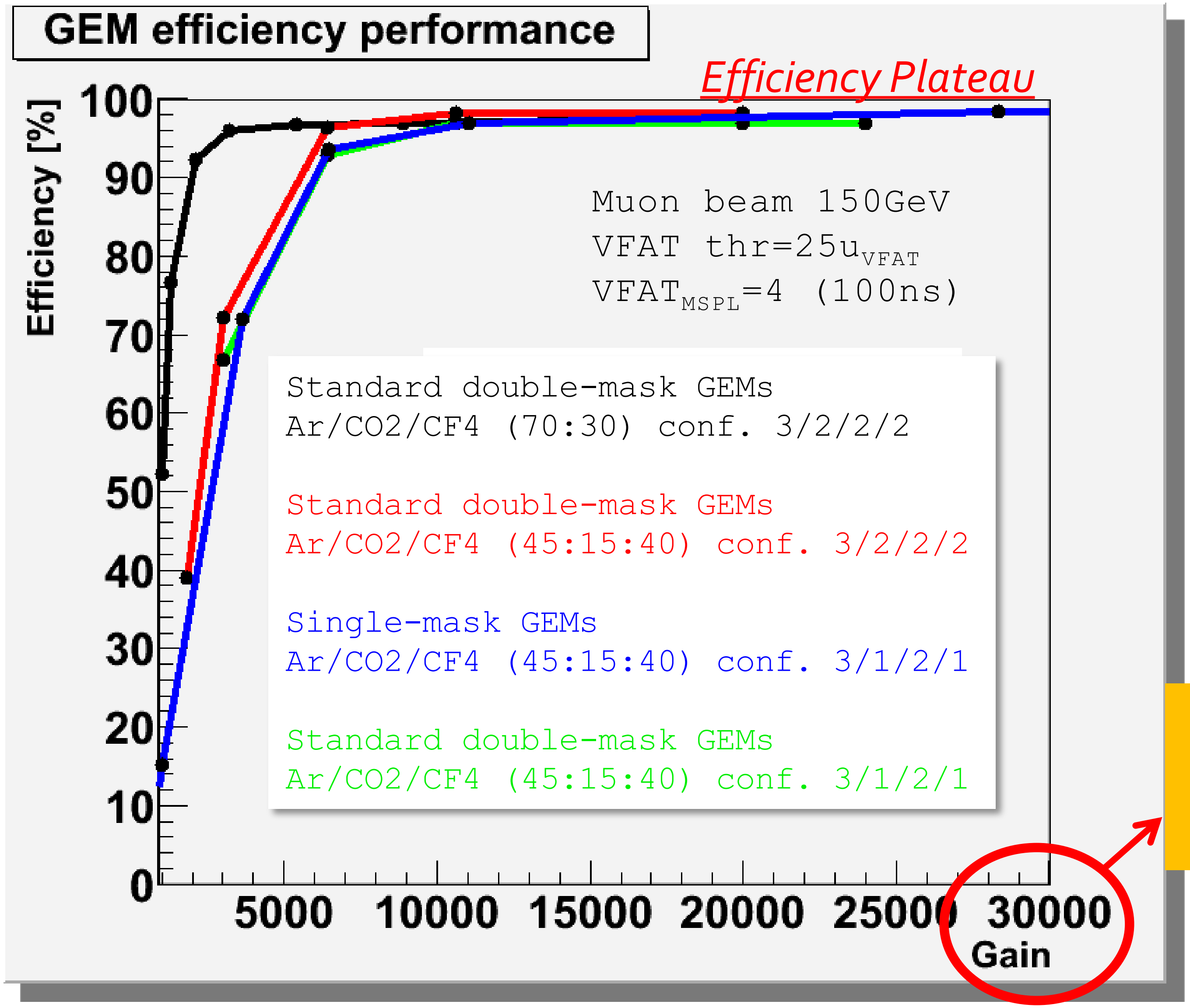
Timing Studies (2010)





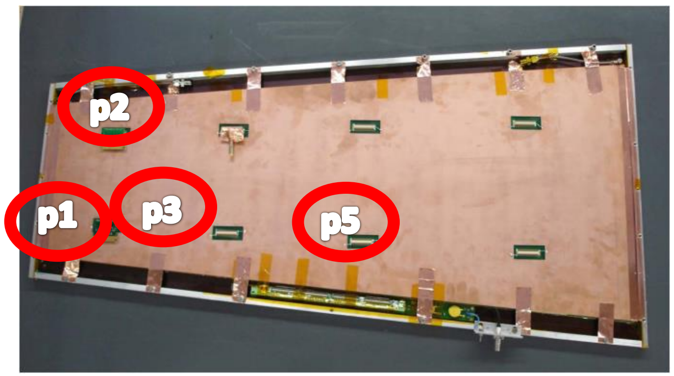
Custom made HV divider for Standard triple-GEM
Clear effect of gas mixture, and induction and drift field
Timing resolution of 4 ns reached

Single mask performance (2010)



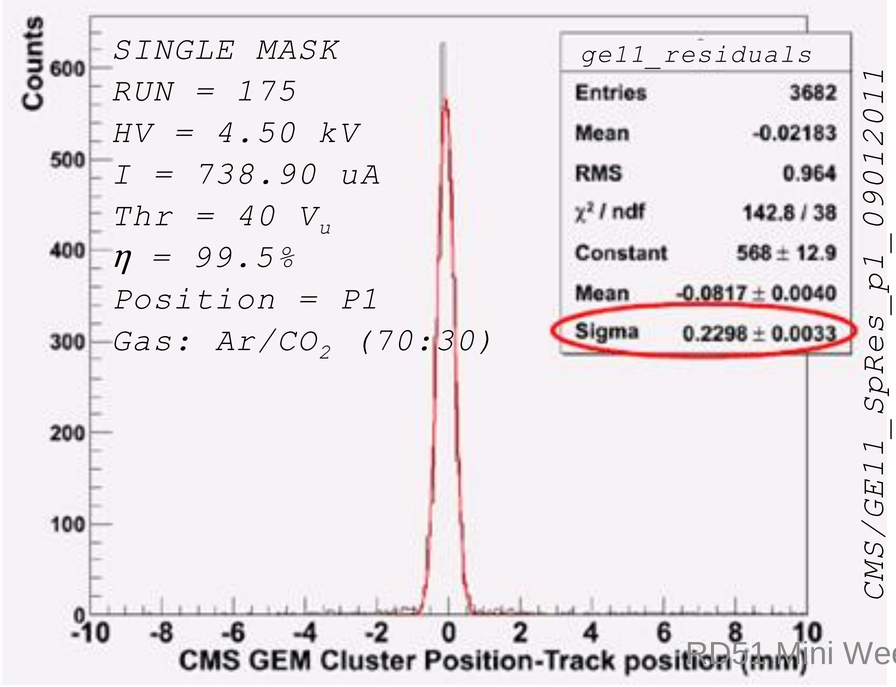
High achievable gain!

CMS full-size prototype (SPS@H4 2010)

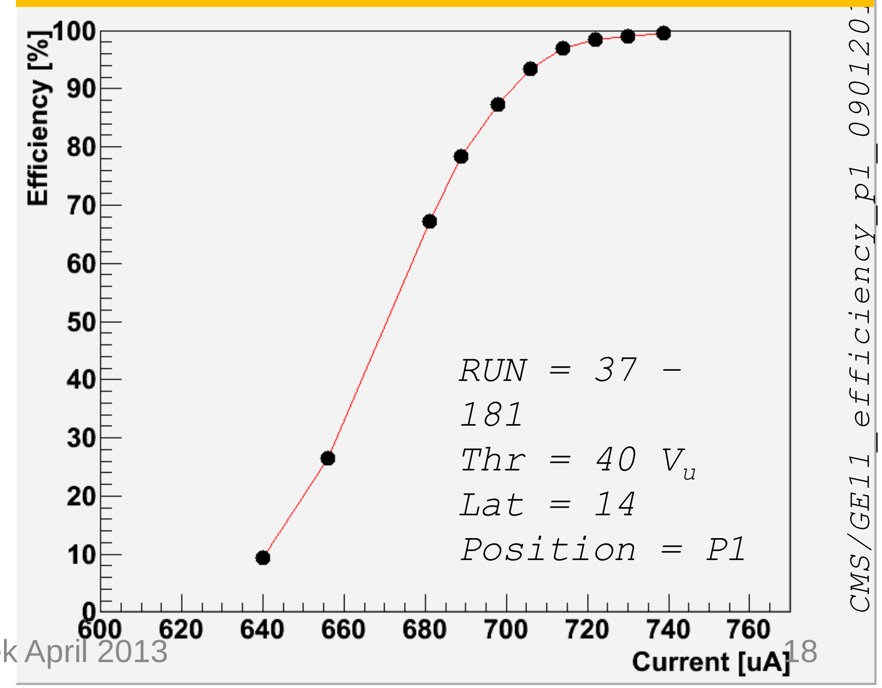


Data-taking focused on different points along the detector to check uniformity
Preliminary results from the first version of large-size CMS detector showed a very good performance.

CMS full-size residuals

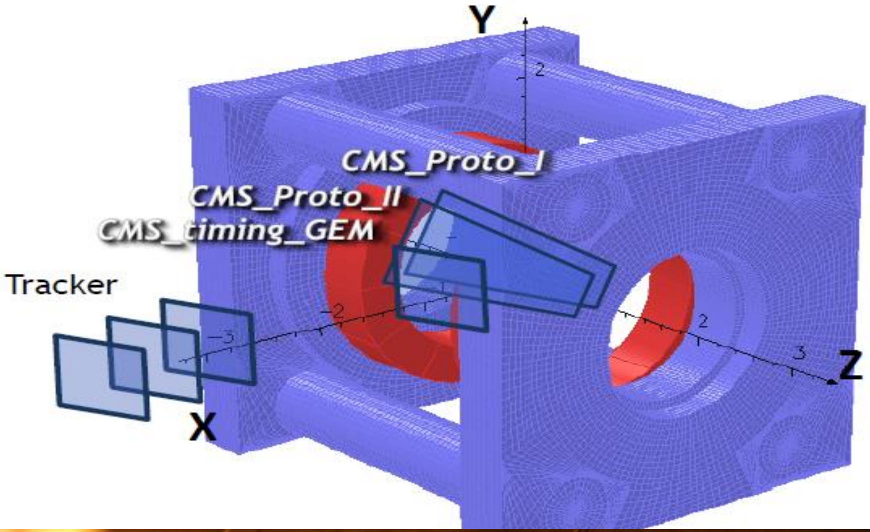


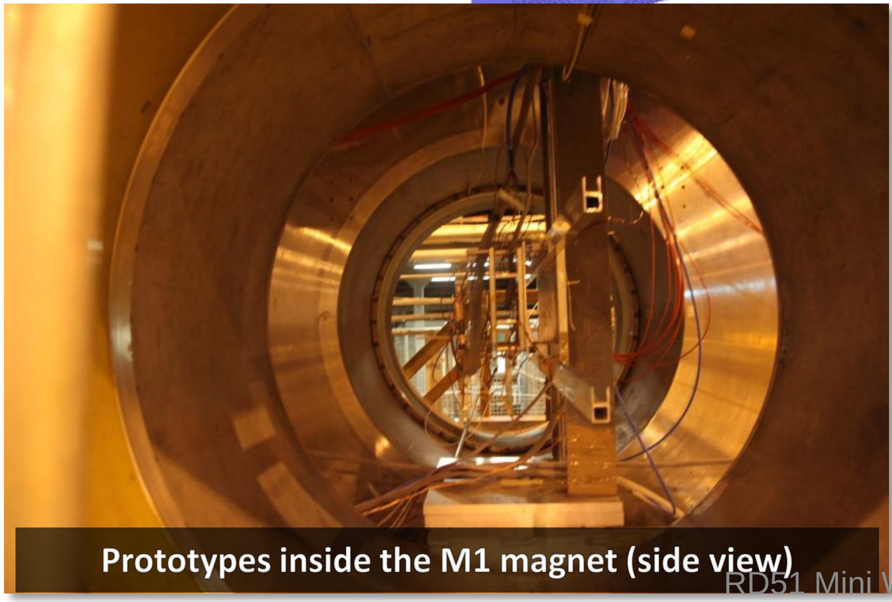
CMS full-size efficiency



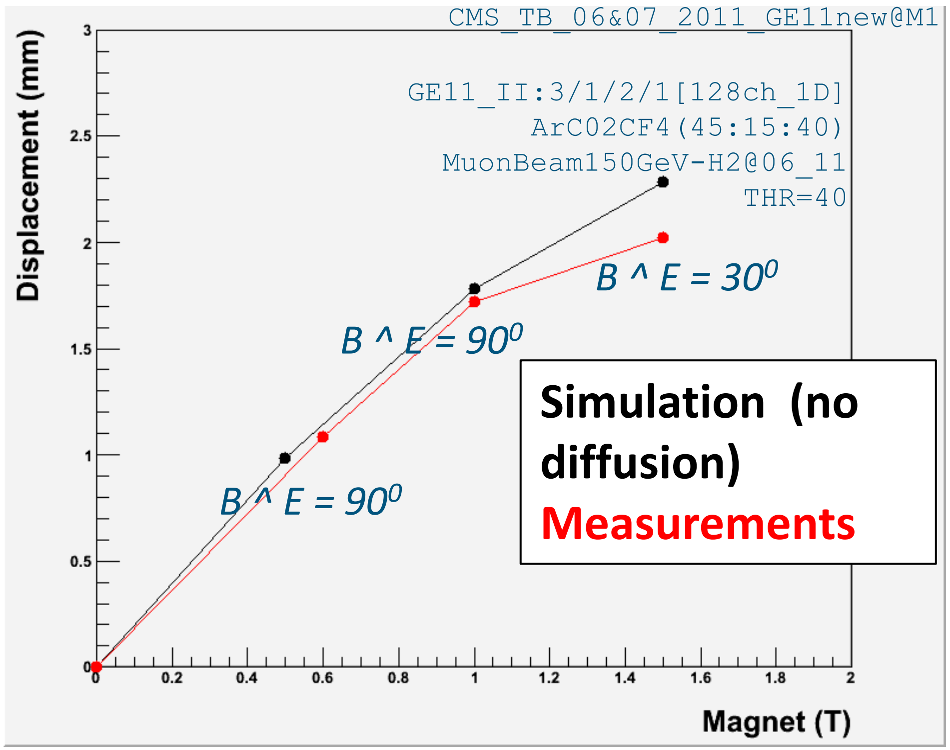
CMS full-size prototype (SPS@H2 2011)

At CMS we expect $B_{\perp}$~0.6 T (while $B_{//}$ ~3 T)



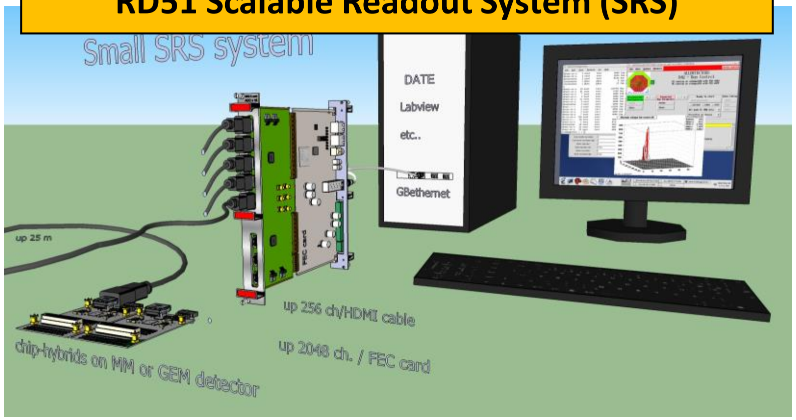


Prototypes inside the M1 magnet (side view)



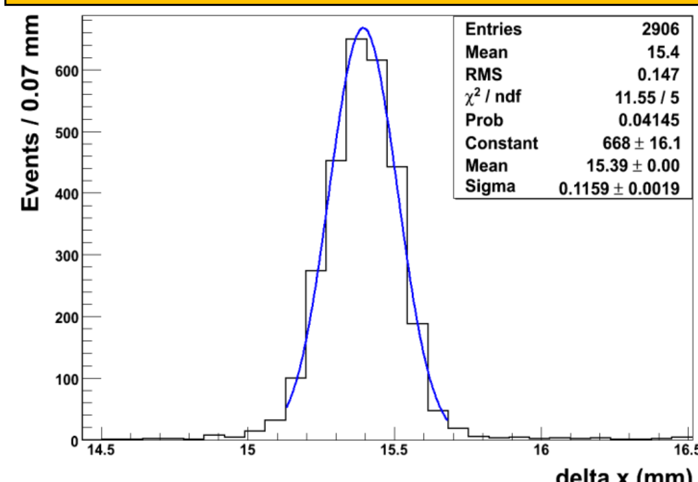
CMS full-size prototype (SPS@H4 2011)

RD51 Scalable Readout System (SRS)

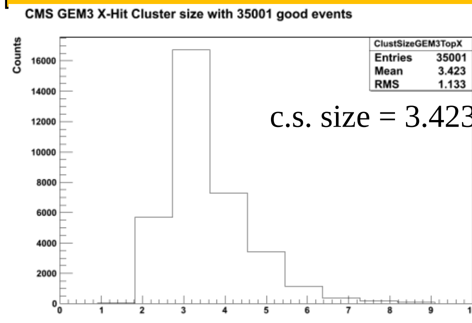


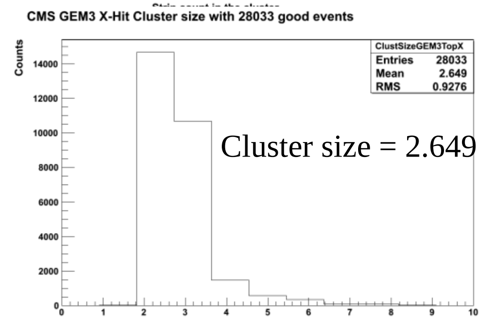
Successful data taking with APV chip and Scalable Readout System (SRS) developed by RD51 Collaboration, instead of TURBO/VFAT system used before.

Δx distr. Tracker GEM & CMS full-size

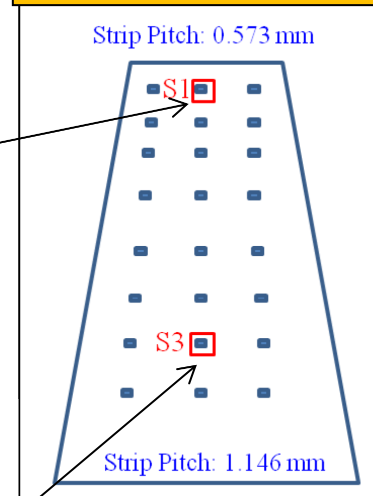


Cluster size Proto II





μ⁻/π⁻ beams



Latest beam test results please refer to the talk of Sinem Salva

CMS full-size prototype:

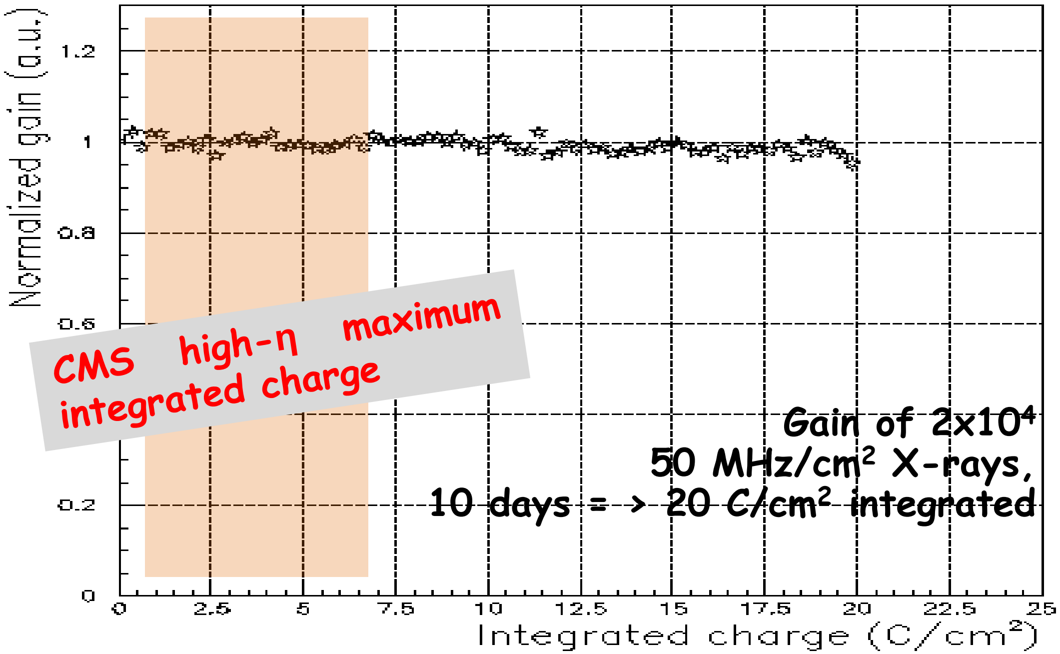
σ_x < 110μm

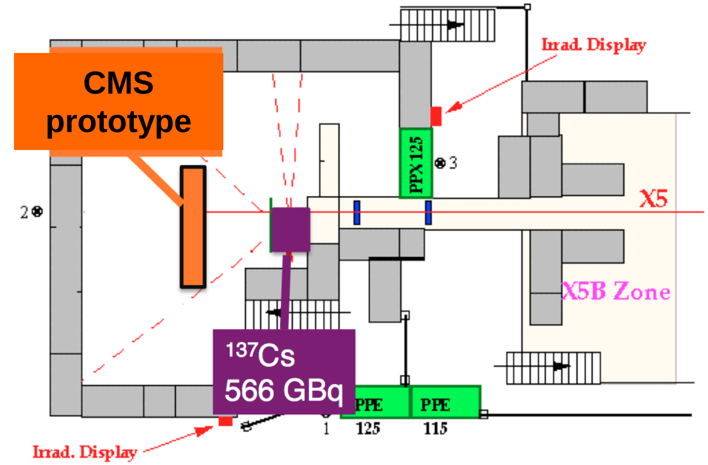
in section with smallest pitch

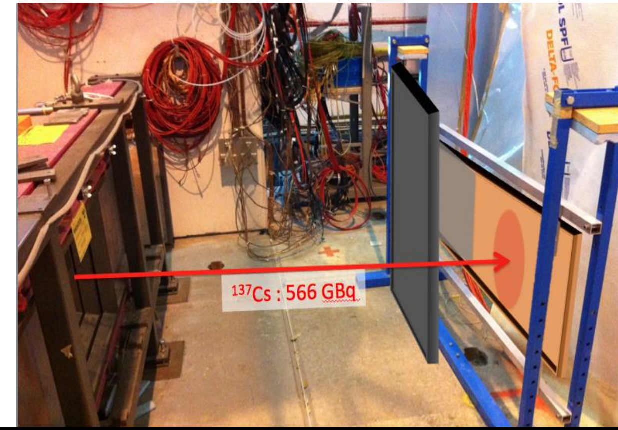
Ageing test preparation

Motivations

- Ensure a long term operation in CMS
- Understand the effects of the radiation on the materials
- Understand ageing origin (if any) and propose solutions







GEM settings:

Drift: 3kV/cm, Others: 3,5 kV/cm Induction: 5 kV/cm

Gain: $8 \times 10^3 - 10^4$

Gas Mix: $Ar/CO_2/CF_4$ (45:15:40)

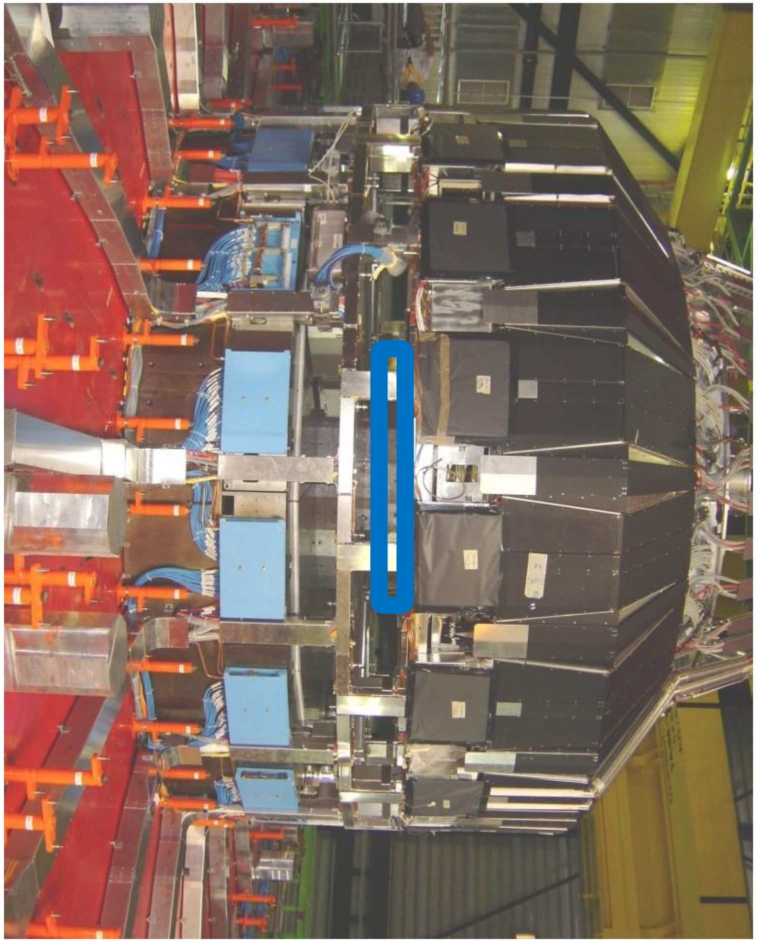
The CMS full-size prototype has been installed in the CERN Gamma Irradiation Facility

The detector performance will be monitored along with environmental/gas variables

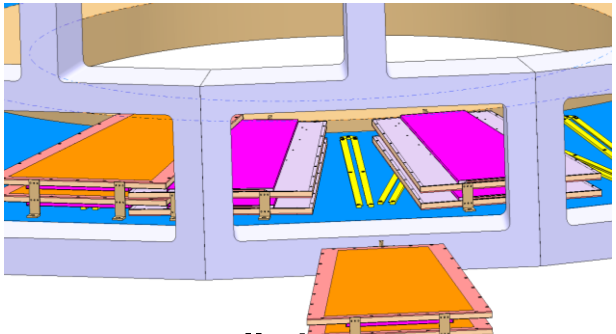
Services, integration, installation for the LS1 GE1/1 Demonstrator

Dummy SCs for LS 1

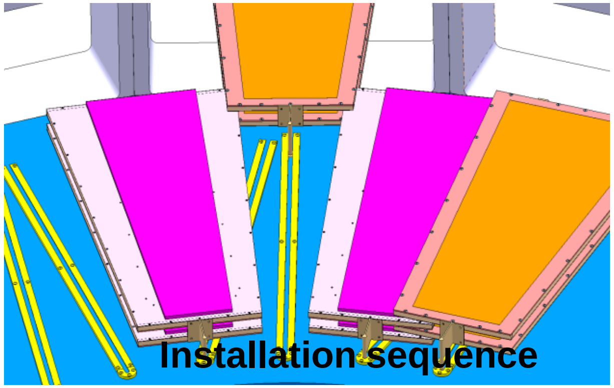
- RWTH Aachen provided 3 Dummies.
- No Detector and no Electronics.
- All positions for Gas-, Cooling- and Electronic-connectors are at the right place.
- Weight and dimensions as a real super chamber.
- 3 Super Chambers needed for the trial installation tests.
- Installation ~ April - 2013 (Shadow ME1/1).



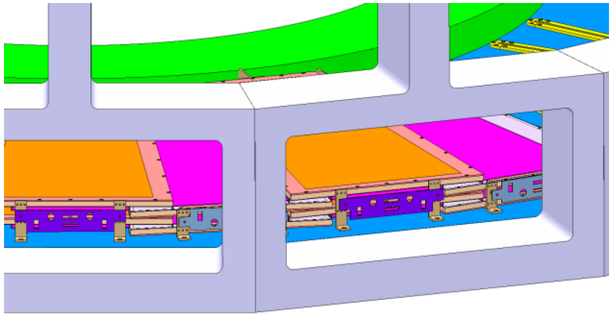
Integration studies



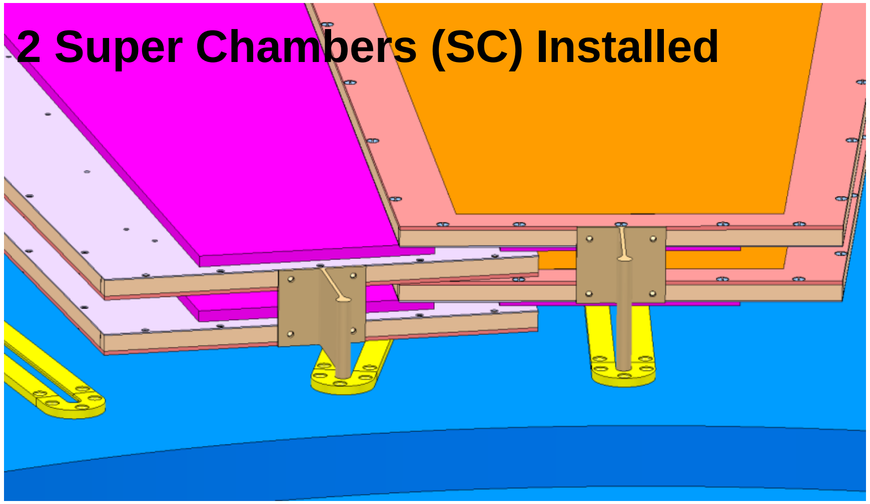
Installation sequence



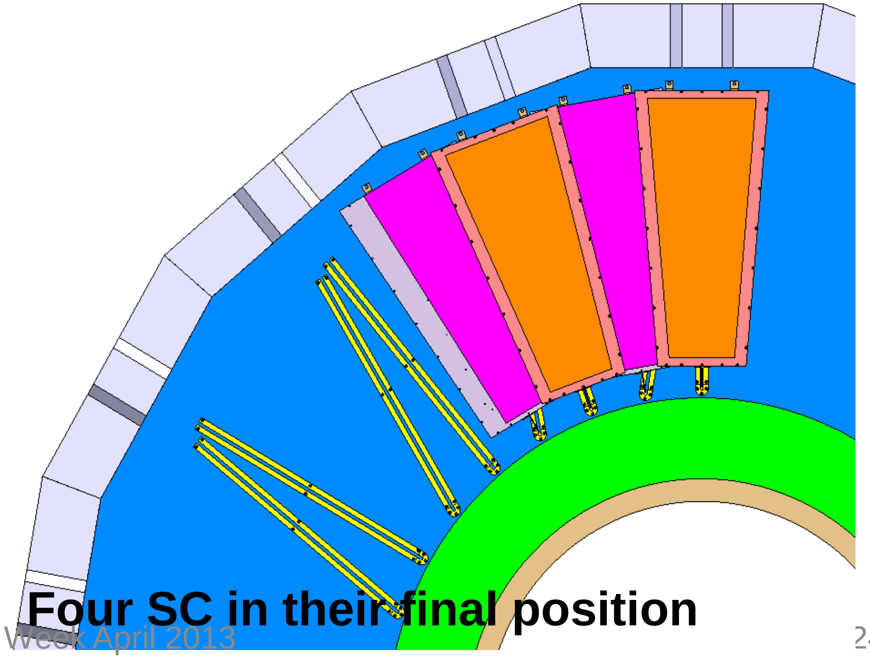
Installation sequence



Installation sequence



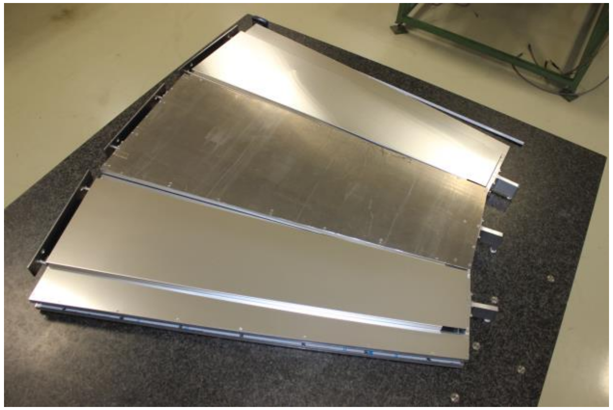
2 Super Chambers (SC) Installed



Four SC in their final position

Super-Chambers (SC) Mockups Installation in CMS

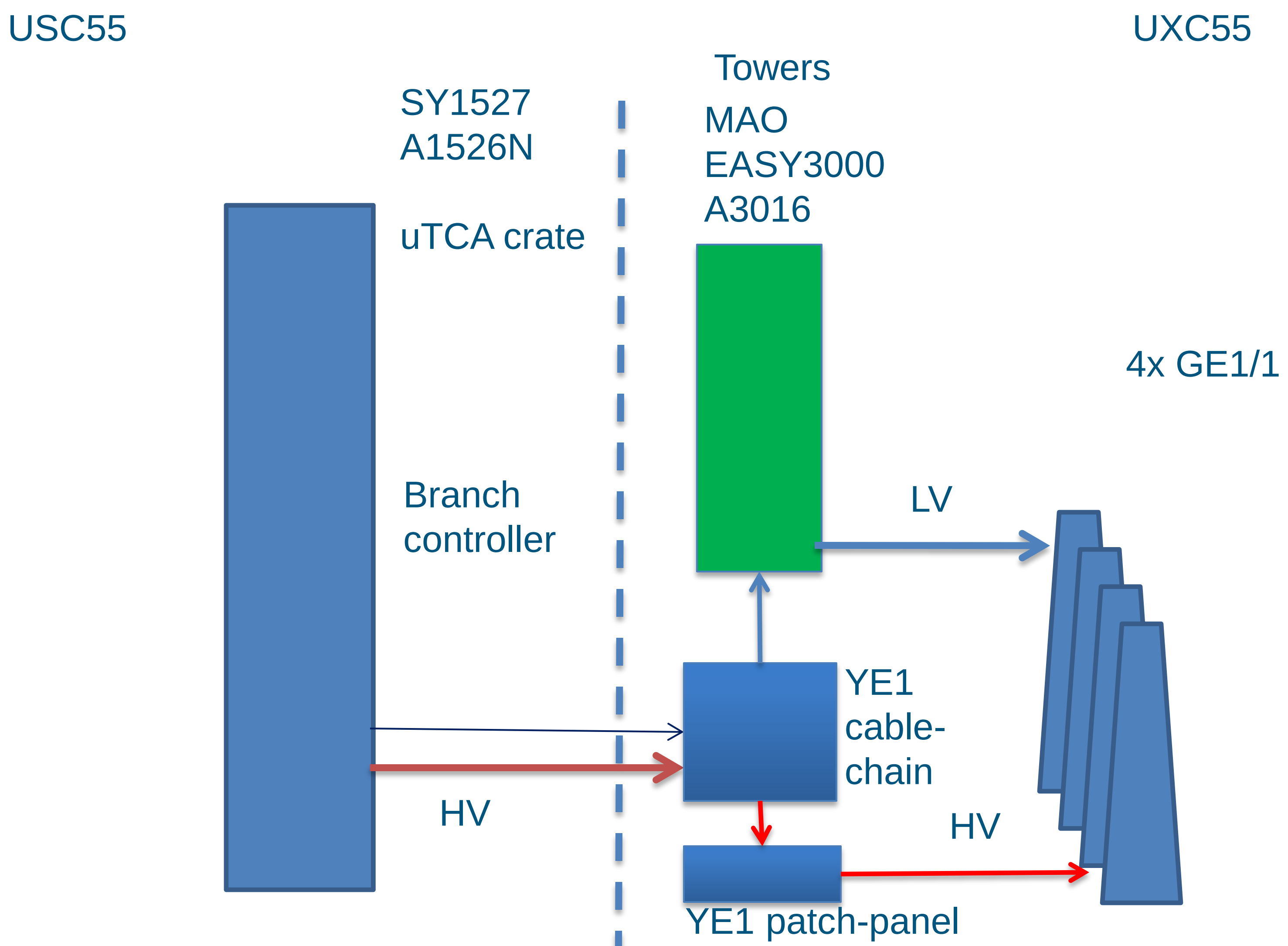
Single SC



The 3 mockups as they should be mounted in CMS.

The reality meets the theory

LS1 GE1/1 – Powering Schema

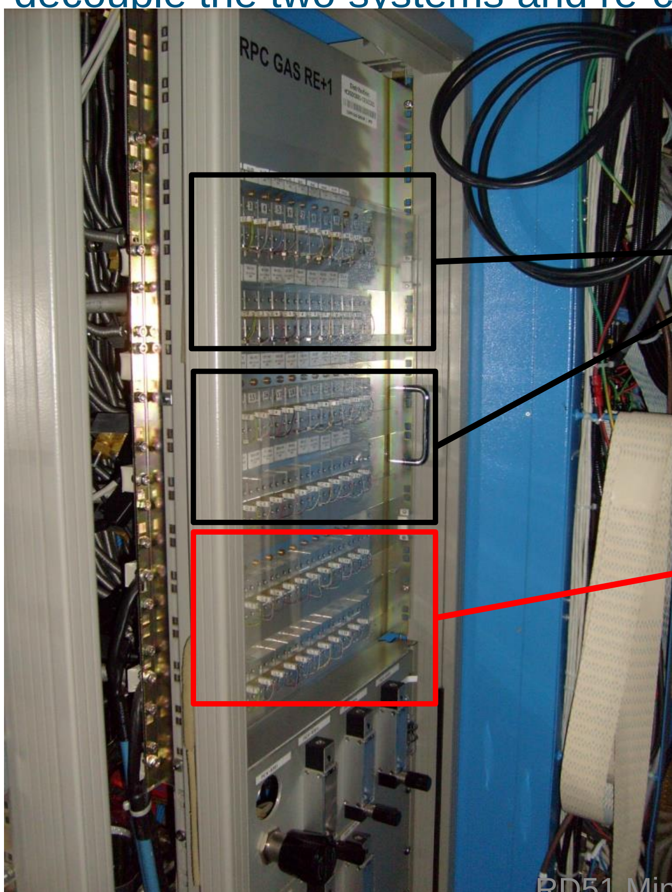


Gas infrastructures already existing

Chamber distribution (UXC)

One manifold (12 supply and return channels) is available in each distribution racks.

At the moment the controls are integrated in the RPC gas system. We need to decouple the two systems and re-calibrate the flow-meters.



RPC RE 1/2, RE1/3

GEM GE 1/1

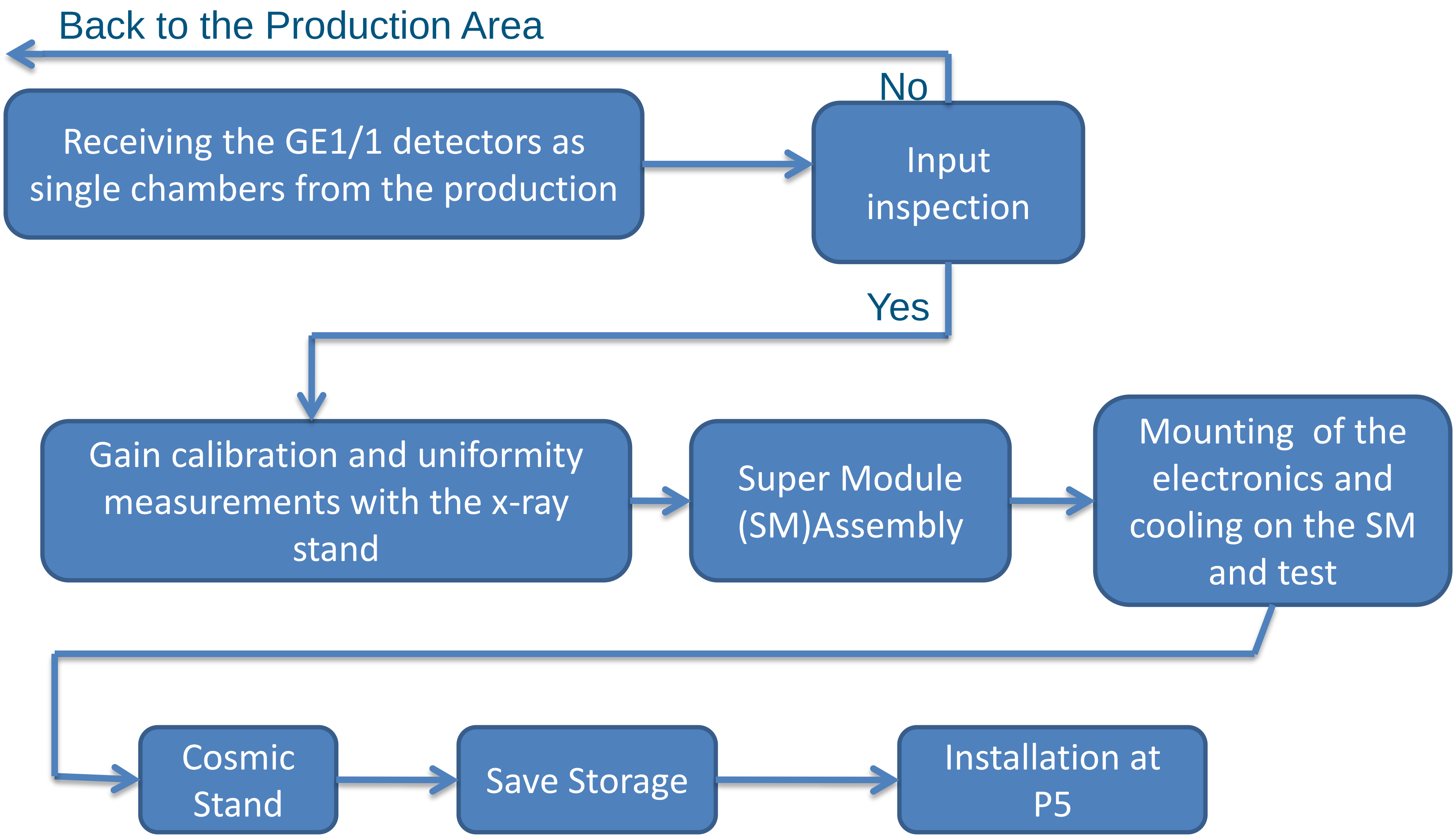
R. Guida

The New CMS GEM Lab. In Bldg.186 @ CERN

Part of the Working area

- The gas installation is in progress. Should be delivered very soon
- Lab infrastructure is available.
- We can start moving soon from RD51 lab to b.186.

The Work Flow Plan for GE1/1

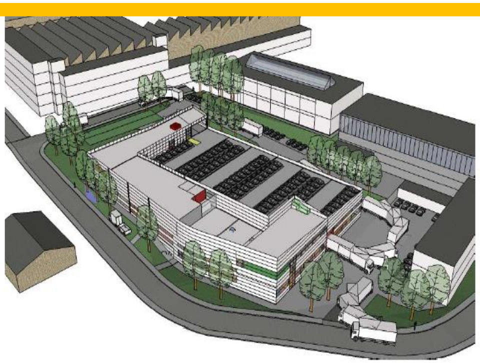


GEM production

GEM Production at/outside CERN

The Goal is to setup a production line being able to face most of the future requests for large GEM productions (from 1 piece to few hundreds, size up to 2m x 0.6m)

New Machine procurement and installation(2011) and new building(2013)



CERN Building 107
Basis of Design

@CERN

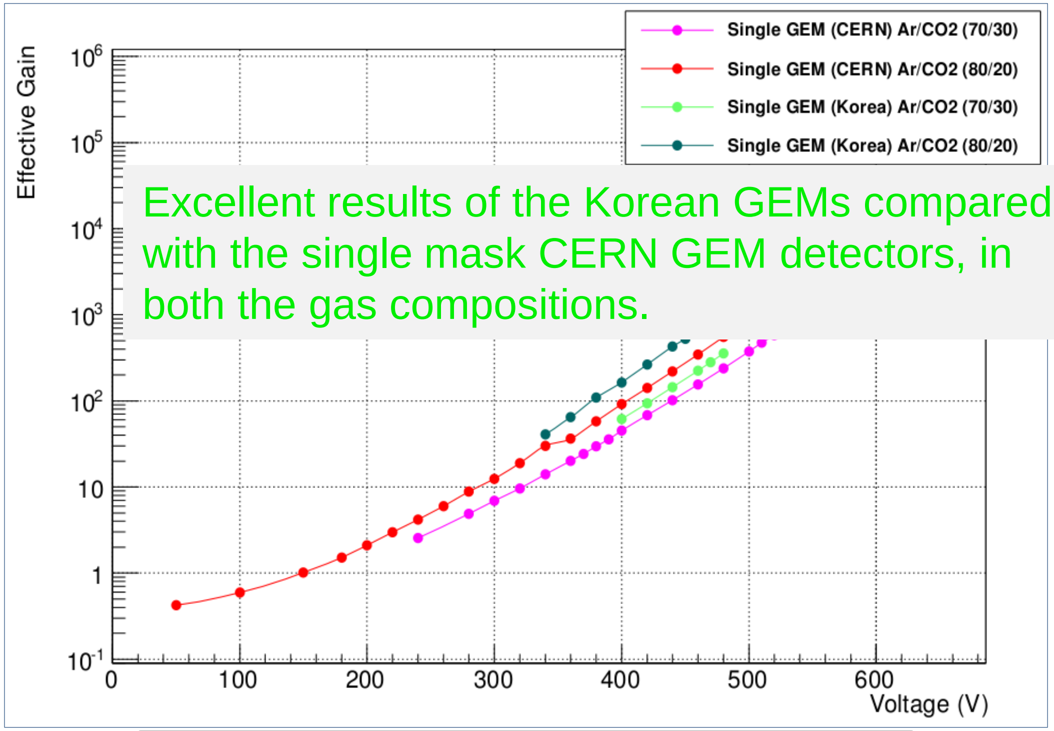
@Korea

New Flex (South Korea near Seoul) has produced 8x8cm^2 and 10x10cm^2 GEM; successfully tested at RD51 lab

- **Initial contact in 2008; new visit in June 2011**
- **Full technology transfer done; large size foils to try gradually...**

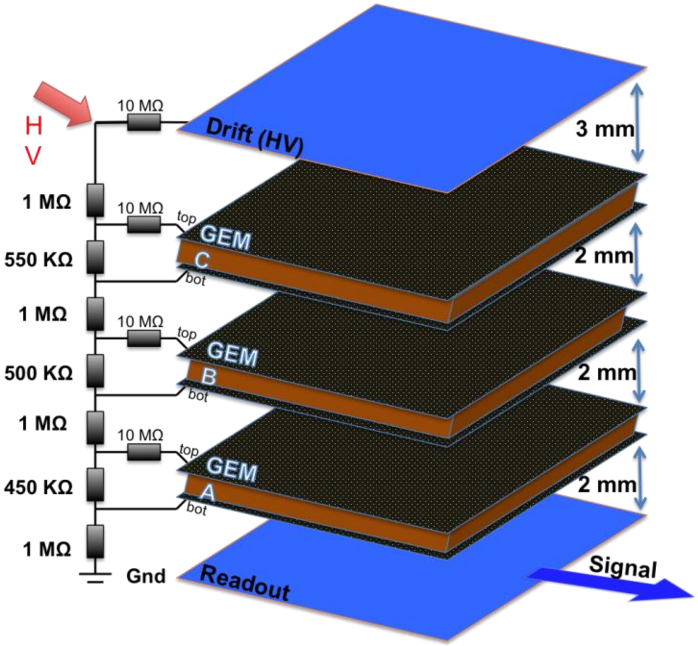
Characterization of Korean GEM

Gain Calibration [Ar/CO_2 (70:30)]

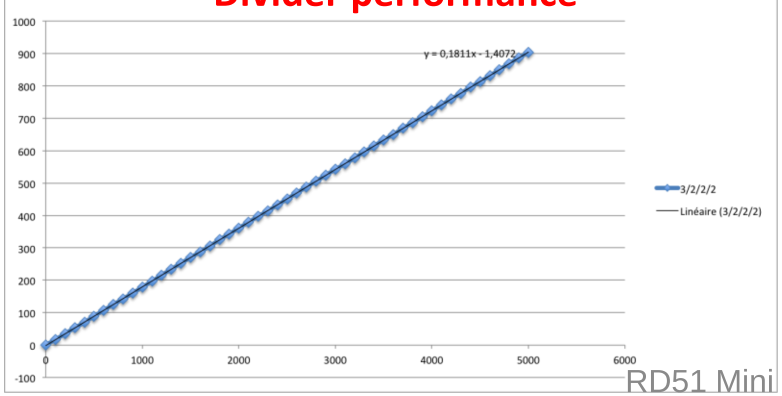


Excellent results of the Korean GEMs compared with the single mask CERN GEM detectors, in both the gas compositions.

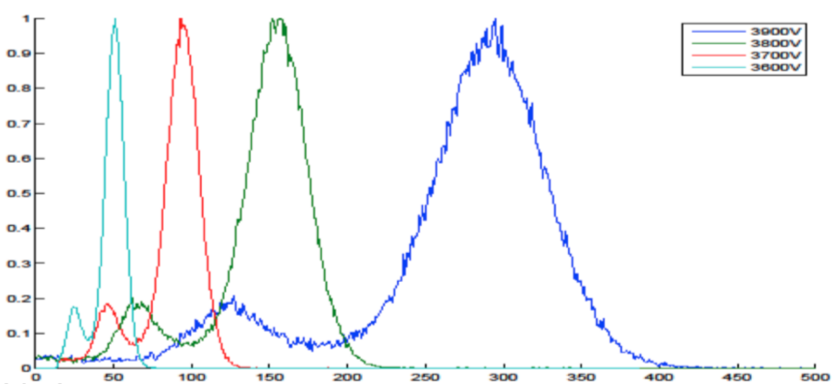
Triple GEM configuration stack



Divider performance



Iron 55 : Spectrum and Count Rate



Quality Control (QC)

GEM FOIL PRODUCTION

DRIFT ELECTRODE PRODUCTION

READOUT ELECTRODE PRODUCTION

MECHANICS PRODUCTION

Electronics Production & QC

ASSEMBLY SITE

CERN?
US?
India?
INFN?

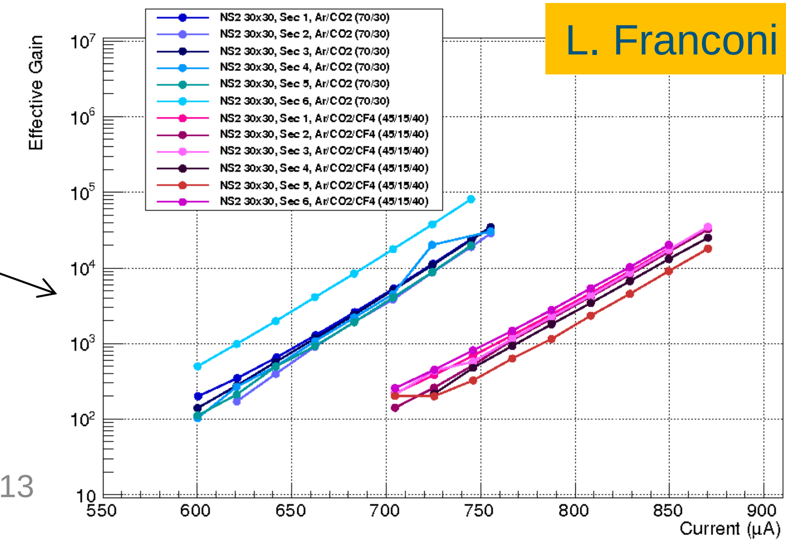
Transport to CERN

Quality Control procedures:

1. *QC-Drift Electrode*
2. *QC-GEM foils*
3. *QC frames (mechanical tolerances)*
4. *QC readout PCB*
5. *QC Gain uniformity test*
6. *QC leak test*

Installation

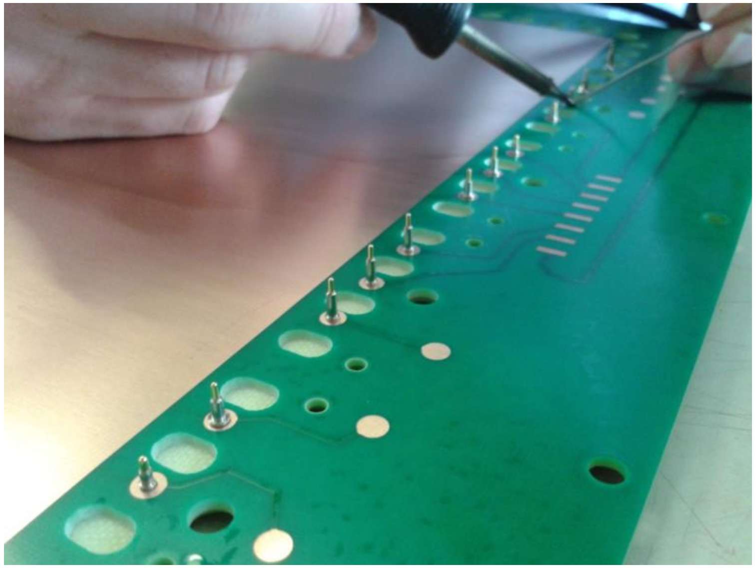
Commissioning

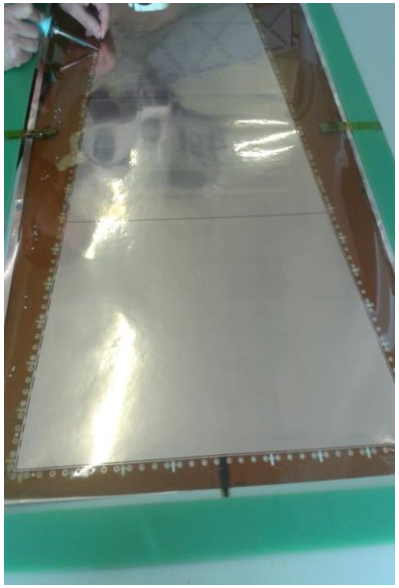


L. Franconi

Production the of GE1/1 Detectors for the Slice Test in 2016

- 6 Triple-GEM NS2 full-size Detectors are under production.
  - Full services will be integrated with the final electronics and cooling.

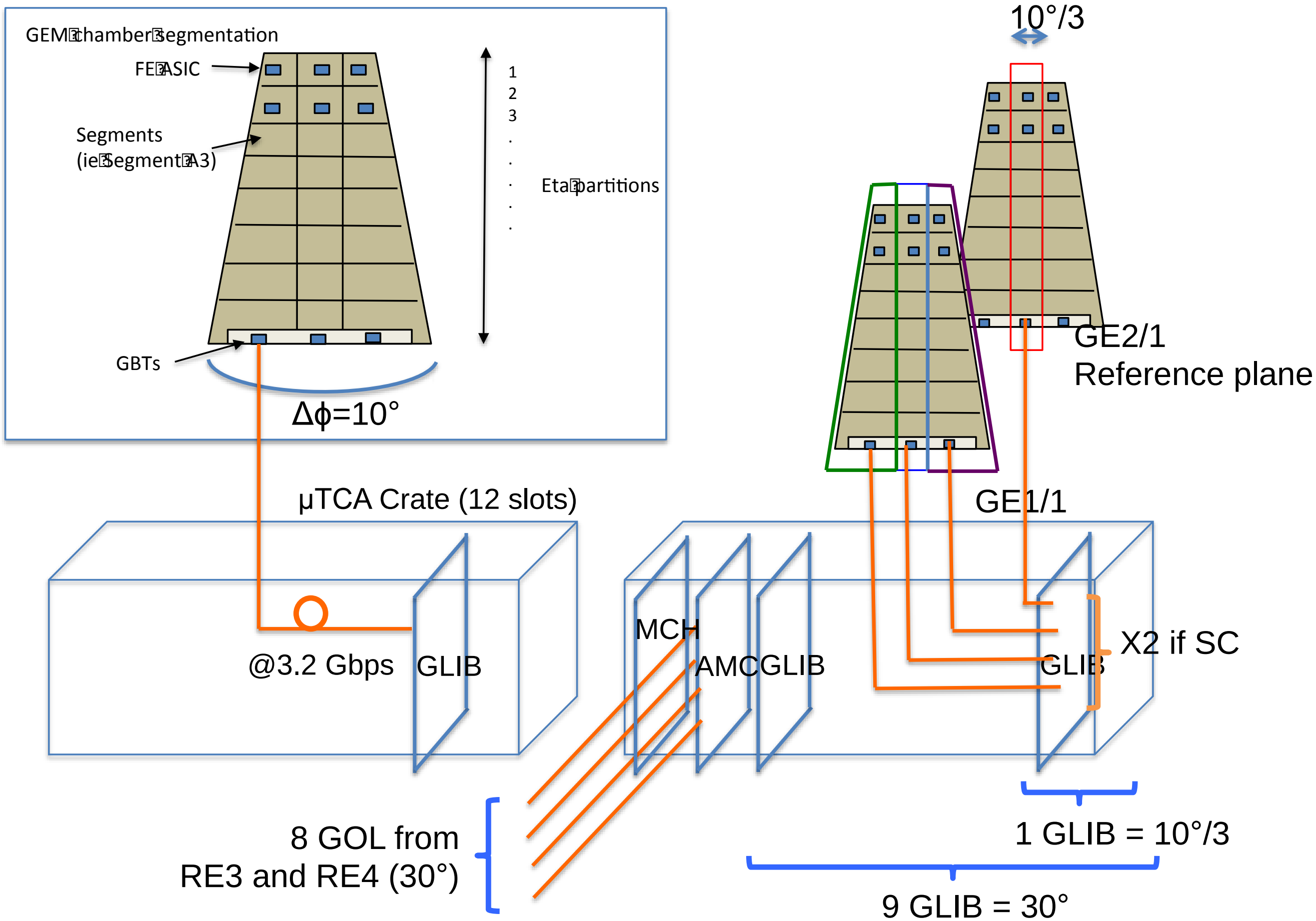




The electronics system

The μTCA development

Design a system that is:
Flexible in terms of detector segmentation.
Uses generic design work as much as possible.



A possible off detector partition:
1 GLIB = one phi segment ie. 10°/3
1μTCA crate = 30° degrees in phi
12 μTCA crates = 360° (24 μTCA crates for both endcaps)

Possible FE chips...

VFAT3:

Front-end with programmable shaping time.

Internal calibration.
Binary memory

Interface directly to GBT @ 320Mbps.

Designed for high rate $10 kHz/cm^2$
(depending on segmentation)

GdSP:

Similar to VFAT3 except has an ADC / channel instead of a comparator.

Internal DSP allows subtraction of background artifacts enabling a clean signal discrimination.

Centre of gravity a possibility to achieve a finer pitch resolution

Status of the GE1/1 Project

- The project review was presented in front of CMS on 18.02.2013.
  - Comments and remarks are taken in to account. Green light to perform a slice test in the end of 2016 was given.
- Next project review will take place in June 2013 during the CMS upgrade week.
- TDR of the GE1/1 project has to be produced by the end of the year.

Conclusions

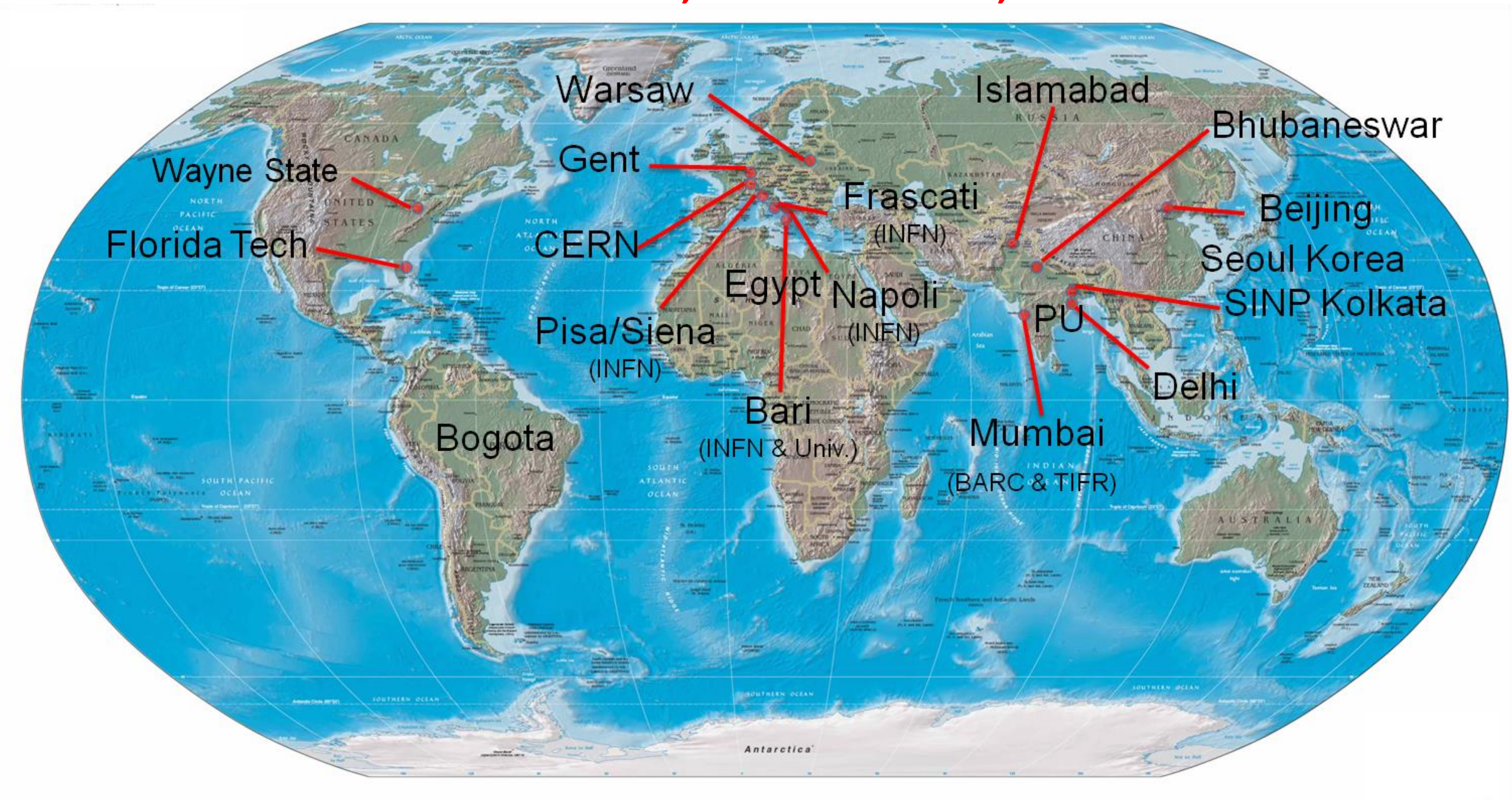
Scope: instrument the vacant high-η region with detectors suitable for high rate, capable of tracking and triggering

- Detector development:
  - New industrial technologies and new cost-effective assembly techniques developed for large-size GEM foils *(large size foils production with no spacers in active area, reduced assembly time, no gluing and no soldering required, possible to re-detector)*
  - High rate, rad. hard triple-GEM technology developed and demonstrated for large area detectors
- Improvements in muon tracking and triggering promising
  - Substantial increase in the acceptance
  - Redundancy and robustness in high-η
  - Lot of interest from trigger and physics groups
- Electronics development: underway
- Integration and services in CMS: studied in sufficient detail
- Preparation of the GE1/1 Slice test at the end of 2016 is ongoing.
- Large participation: currently 39 institutes with 182 collaborators

We gratefully acknowledge the RD51 Collaboration for its strong support of our detector construction, testing and data-taking and for the many fruitful discussions

Thanks to ...

The GEMs for CMS Collaboration:
182 collaborators, 39 institutions, … countries



Backup Slides

Short Project History (2009-2010)

GE1/1
The very first idea.

Meetings
Starting weekly meeting with strong support from DT, RD51 collaboration.

Several feasibilities studies
Integration studies, gas flow, mechanics, electronics, detector performance…

TestBeam 2
At the RD51 setup we performed further studies with small single mask prototype.

TestBeam 3
The GE1/1 is being successfully tested!

Interests
Few groups expressed interest.

Lab tests
Setup preparations in the lab.

TestBeam 1
At the RD51 setup we tested timing performance of small prototype.

GE1/1 proto I ready!
The construction of the first GE1/1 is finished.

World record !

GE1/1 Proto I has been designed, built and successfully tested in only 1 year !

Short Project History (2011)

Constitutional meeting of institutional team leaders to constitute GEMs for CMS

GE1/1 proto II
Design is ready, Material ready, …building it…

TestBeam 5
The GE11_new is tested again in the beam; the campaign is focusing on electronics upgrade

2011

to be continued …

GE1/1 proto II
Started working on the second prototype.

TestBeam 4
The GE11_new has been tested in a strong magnetic field

New 30x30cm^2 prototype self-stretched ready

TestBeam 6
The GE11_new is tested with a new adjustable HV divider

The detector GE11_II with enhanced performance has been designed, built and successfully tested in a very strong magnetic field, a small 30x30 detector with a different stretching technique is nearly ready for testing

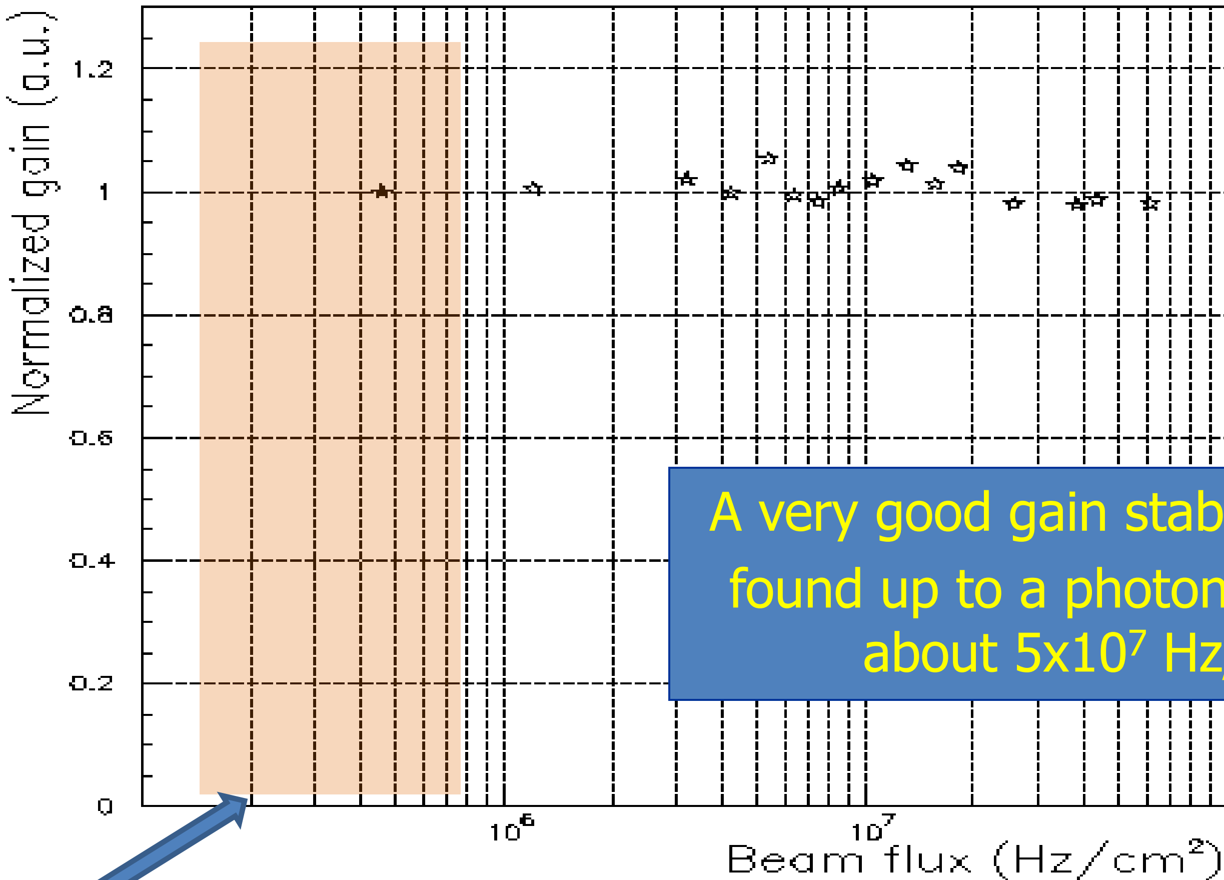
Estimated Particle Rates

RPC Region	Rates Hz/cm^2 LHC (10^{34} cm^2/s)	High Luminosity LHC	SLHC ?? (10^{35}cm^2/s)?
RB	30	Few 100	kHz
RE 1, 2, 3,4 $\eta < 1.6$	30	Few 100	**kHz**
Expected Charge in 10 years	0.05 C/cm^2	0.15 C/cm^2	~ C/cm^2
RE 1,2,3,4 $\eta > 1.6$	**500Hz ~ kHz**	**Few kHz**	**Few 10s kHz**
Total Expected Charge in 10 years	(0.05-1) C/cm^2	few C/cm^2	Few 10s C/cm^2

GEM Rate Capability

Measured with an X-ray (5.9 keV) tube; Ar/CO_2/CF_4 (60/20/20)

Gain of about 2×10^4



A very good gain stability was found up to a photon flux of about 5×10^7 Hz/cm^2

LHCb

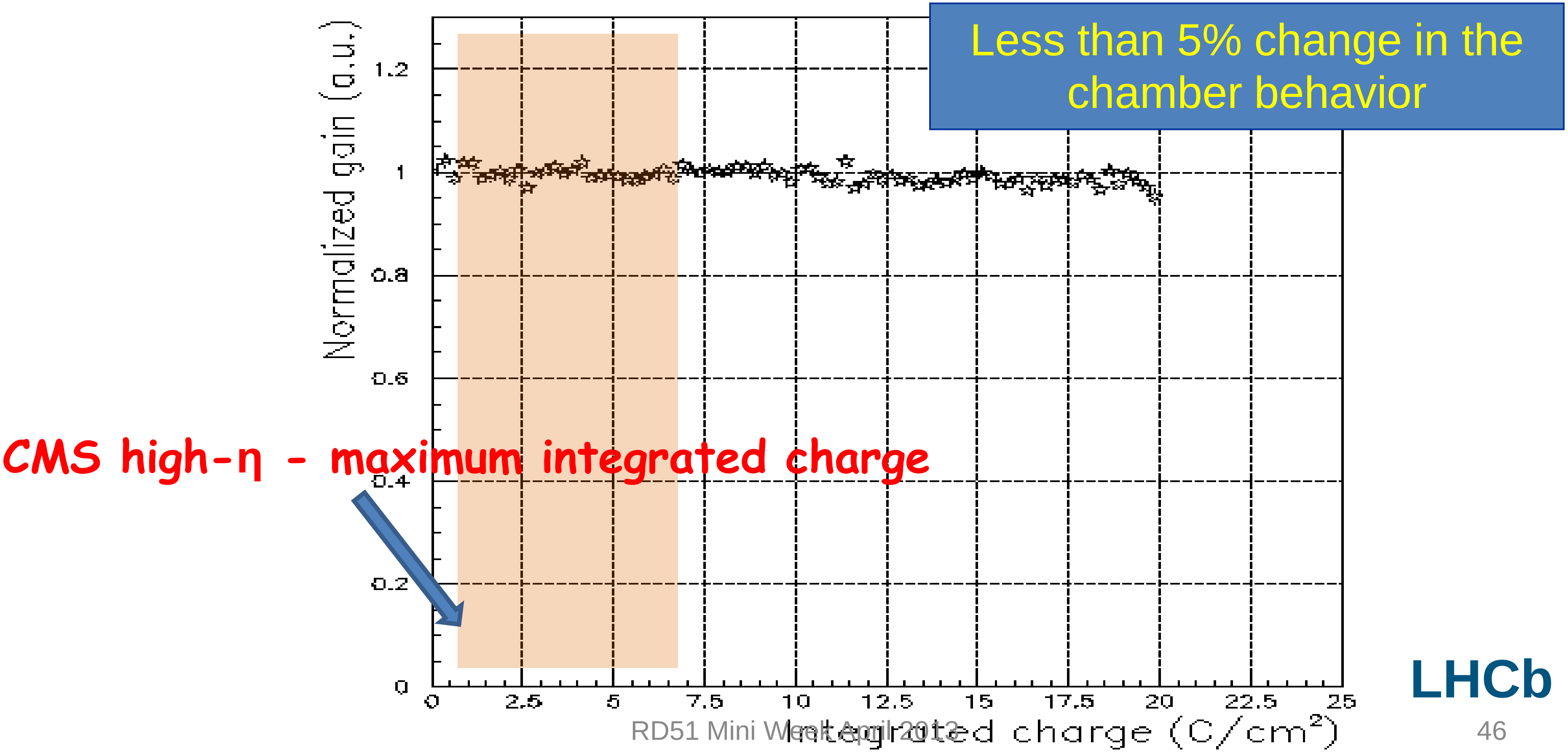
CMS high-η - maximum rate

Triple GEM Ageing test

Gain of 2×10^4

Total integrated charge of 13 C/cm^2 is expected in 10 years of operation in LHCb

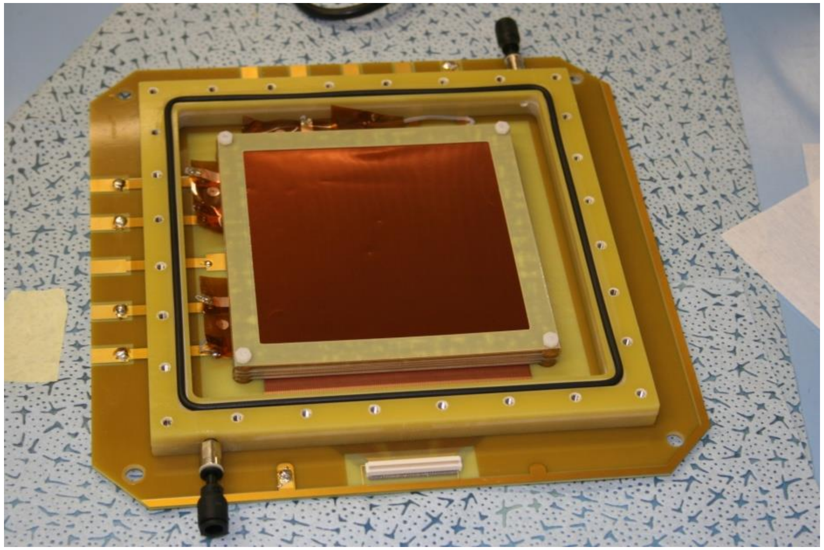
50 MHz/cm^2 X-rays, in 10 days a total charge of 20 C/cm^2 was integrated

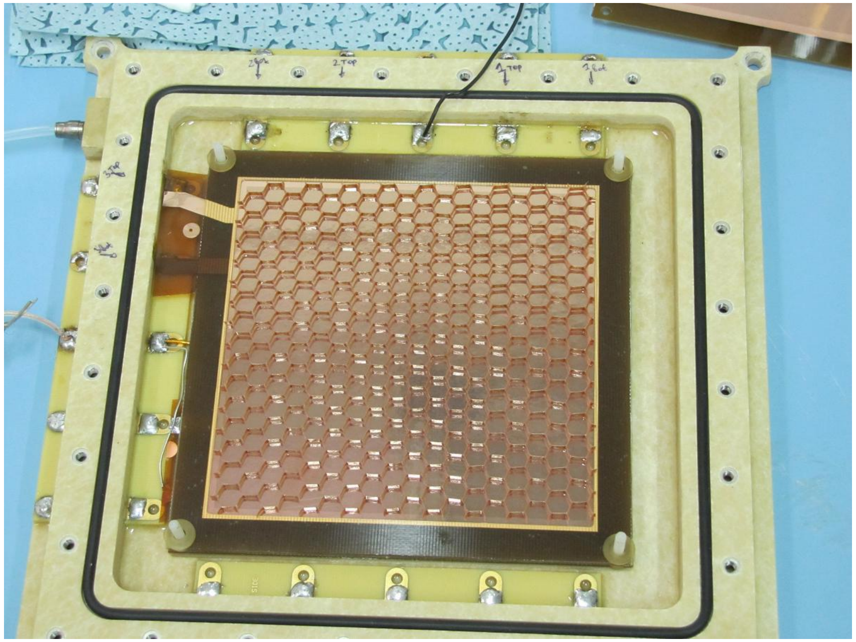


LHCb

Small Prototypes (2009-2010)

- **10x10 cm^2 triple-GEMs, 1D or 2D readout, 128 or 256 channels :**
  - **Standard double-mask triple-GEM - "Timing GEM"**
  - **Single-mask triple-GEM**
  - **"Honeycomb" triple-GEM**

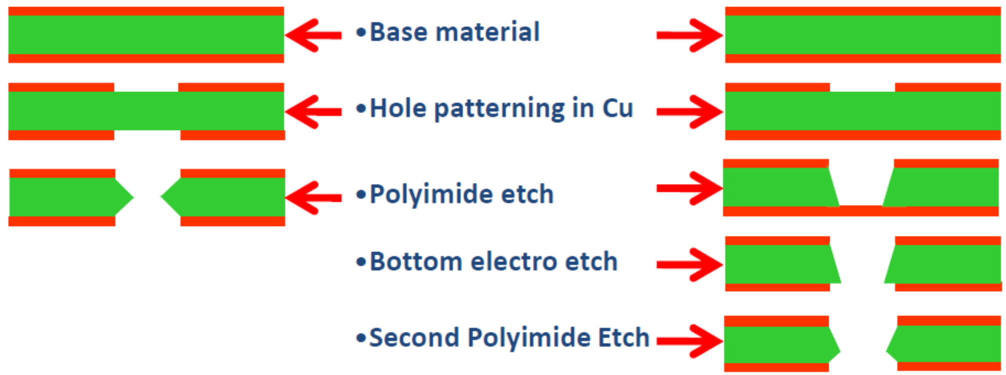




Characterization of GEM Detectors for Application in the CMS Muon Detection System
2010 IEEE Nucl. Sci. Symp. Conf. Rec. 1416-1422; RD51 Note 2010-005; arXiv:1012.3675v1 [physics.ins-det]

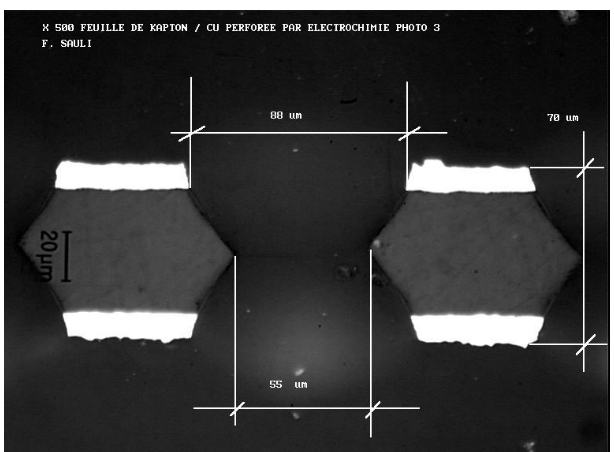
Double-Mask vs. Single-Mask GEMs

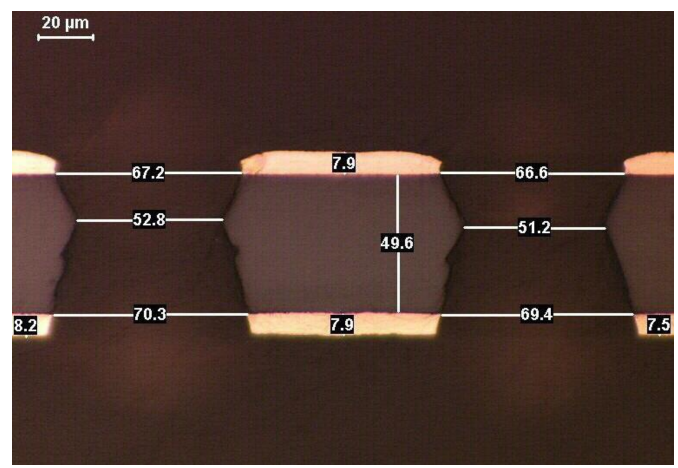
Base material = Polyimide 50µm + 5µm copper cladding on both sides



Achieved 40x40cm^2

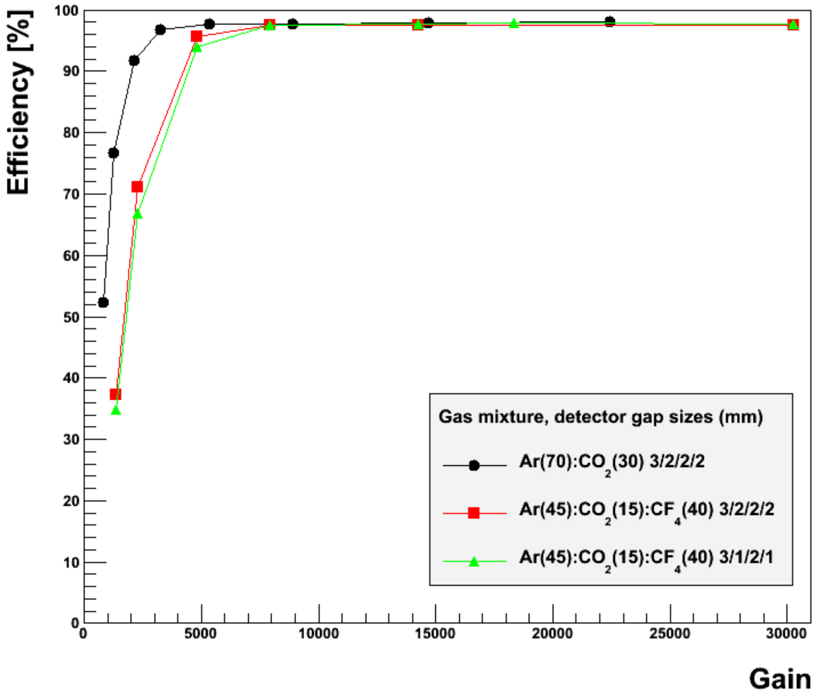
Achieved 200x60cm^2



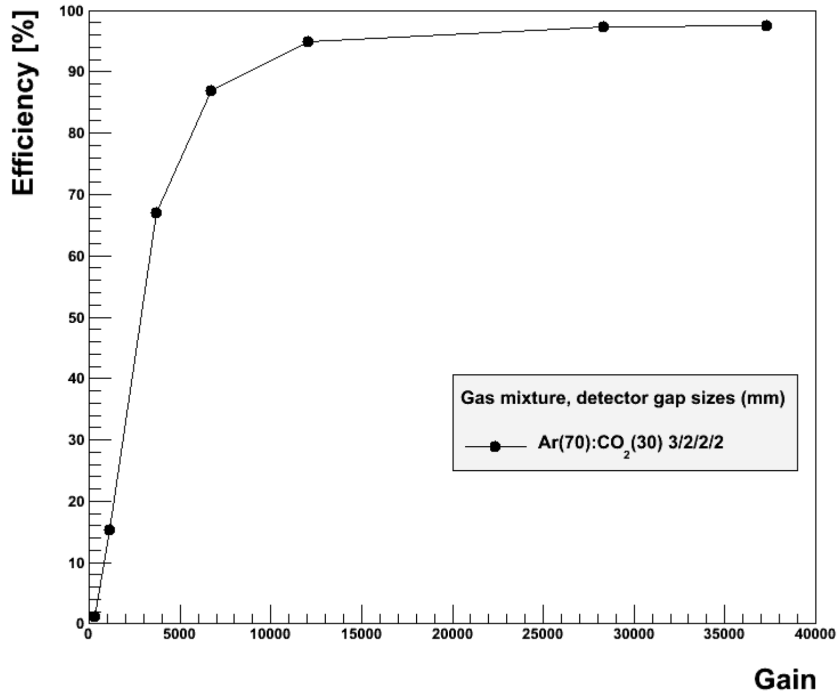


Single vs. Double-Mask GEM

Standard GEM Efficiency



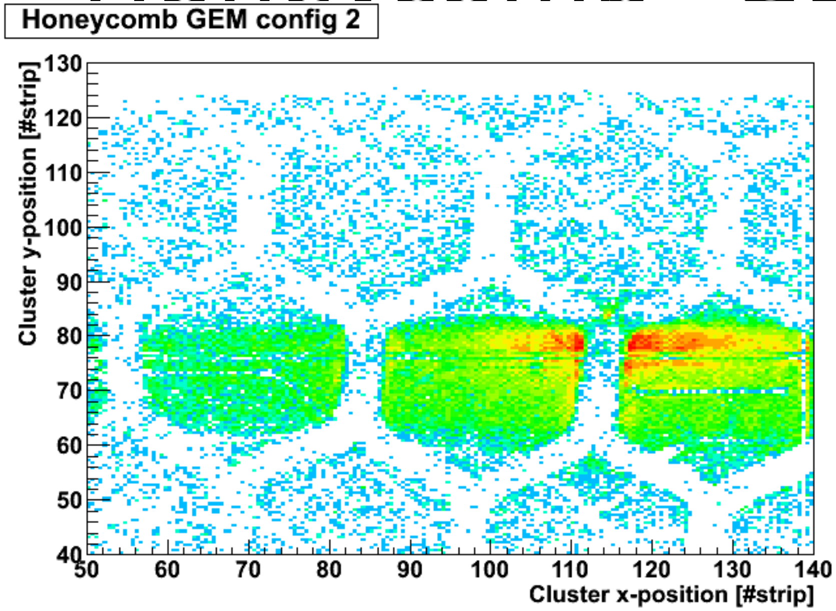
Single Mask GEM performance

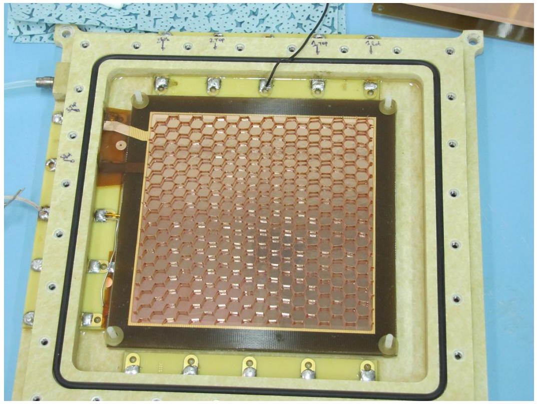


Single-mask GEM reaches similar performance level as double-mask GEM

- **Single-mask technique used for large CMS-size prototypes**

"Honeycomb" GEM Imaging

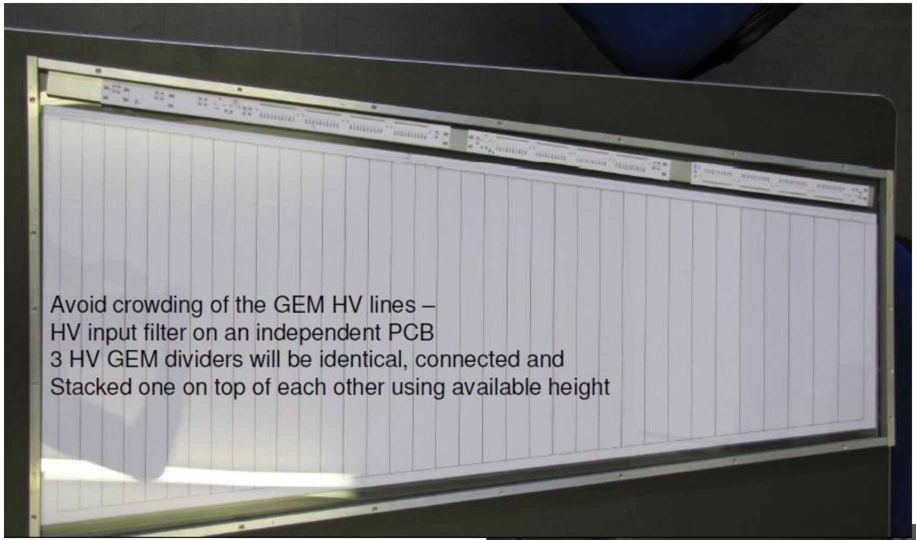


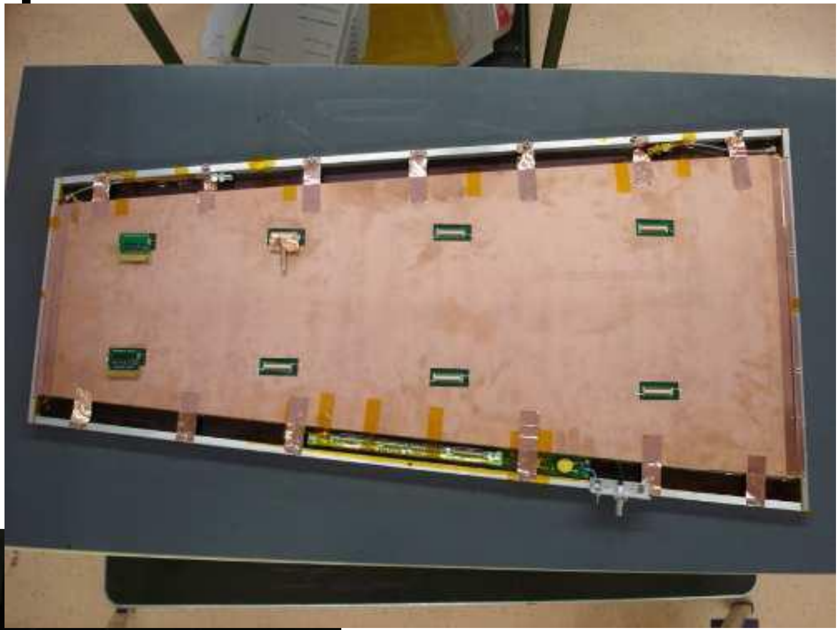


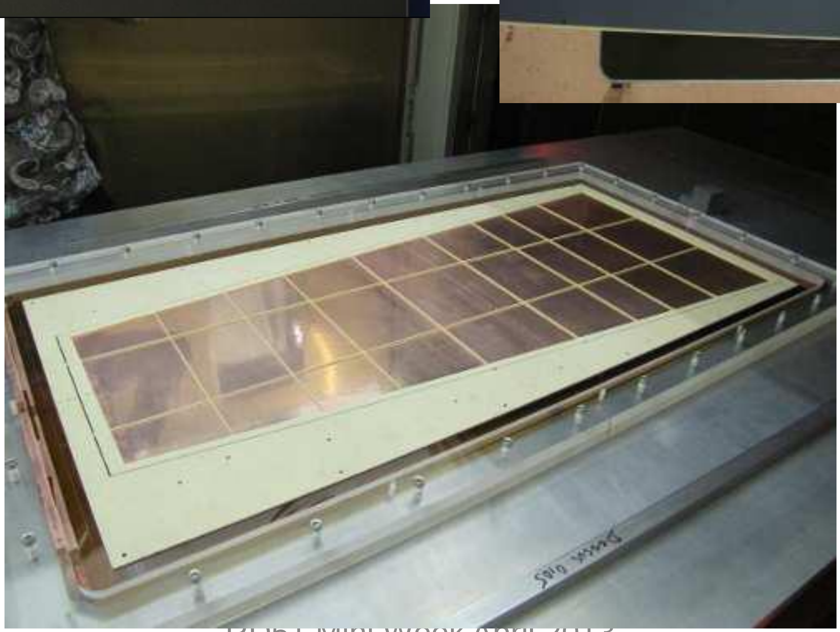
- Insert honeycomb spacers between GEM foils to avoid foil stretching
- Efficiency ~70%; geometrical factor due to spacers roughly estimated at ~65%

Similar performance level observed as for standard GEMs, but local efficiency losses due to spacers (similar effect as seen in CMS RPC)

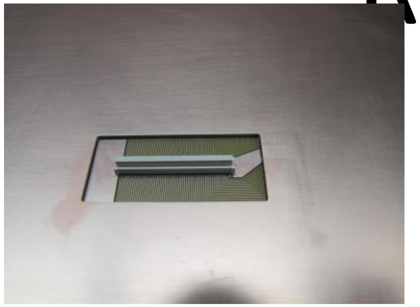
CMS Proto I Mock-up & CMS Proto I

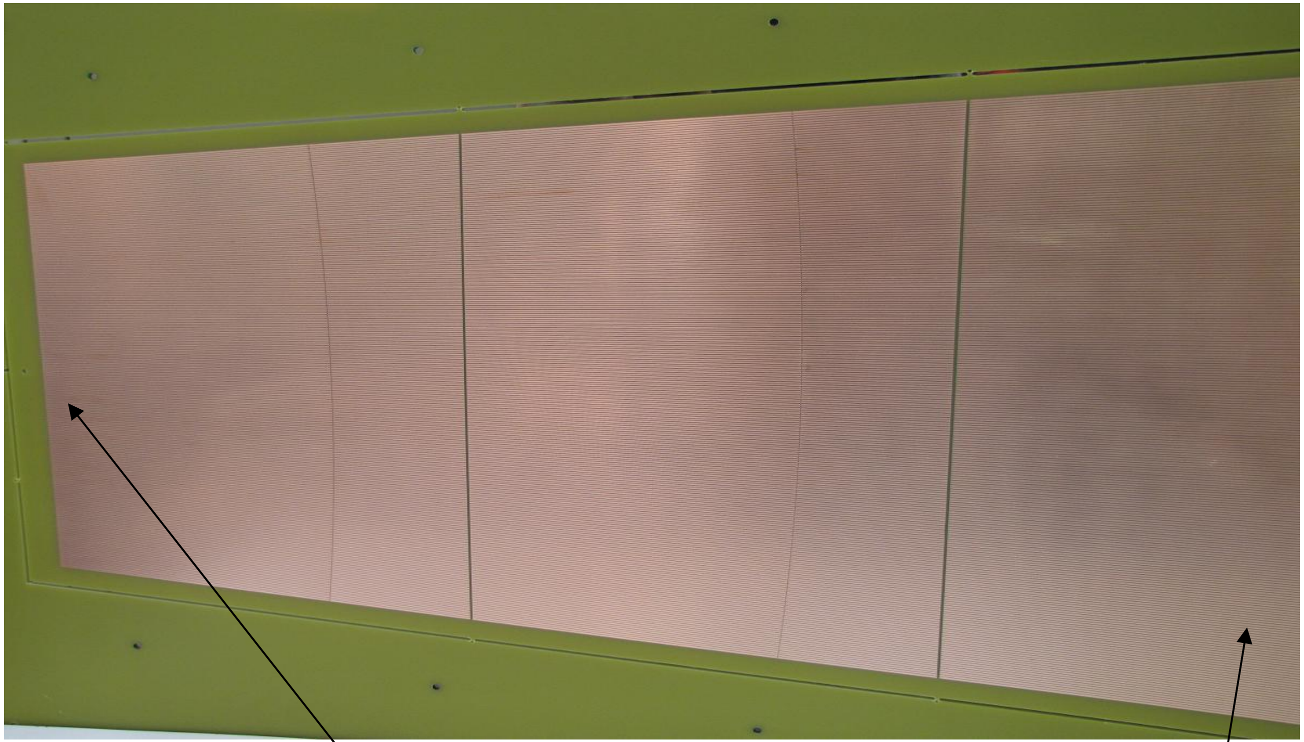






Readout PCB Proto I





0.8mm pitch

1.6mm pitch

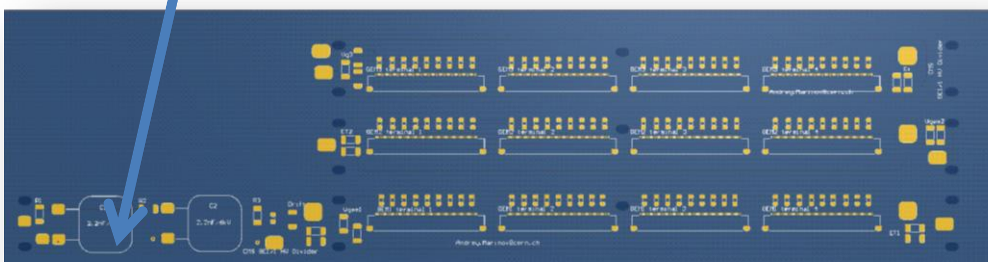
128 channels per VFAT connector

256 strips for each eta partition

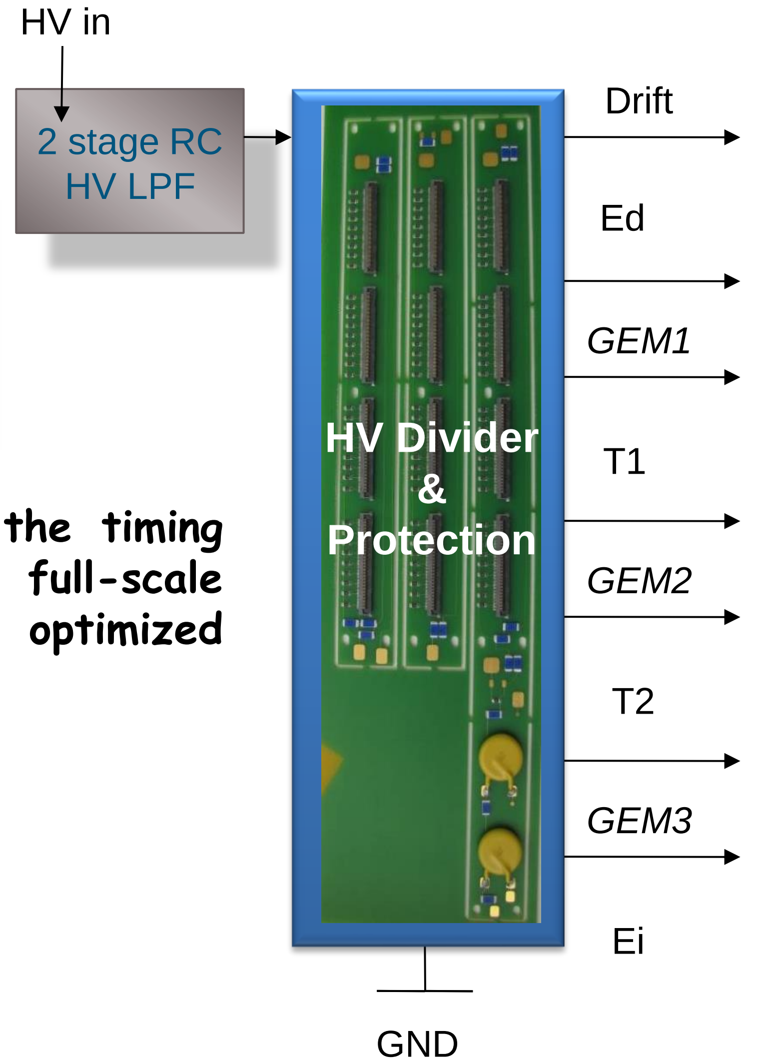
PCB thickness = 3mm

Optimized HV Divider

The HV divider is made by HV SMD Resistors and has built-in RC Filter which cuts the intermediate frequency from the CAEN 1527 power supply (GEM detectors are sensible to HV power supply fluctuation).



Use of ZIF sockets to connect to GEM terminals



Resistors value have been chosen according to the timing GEM performance in order to reproduce on the full-scale prototype the excellent behavior of the optimized timingGEM.

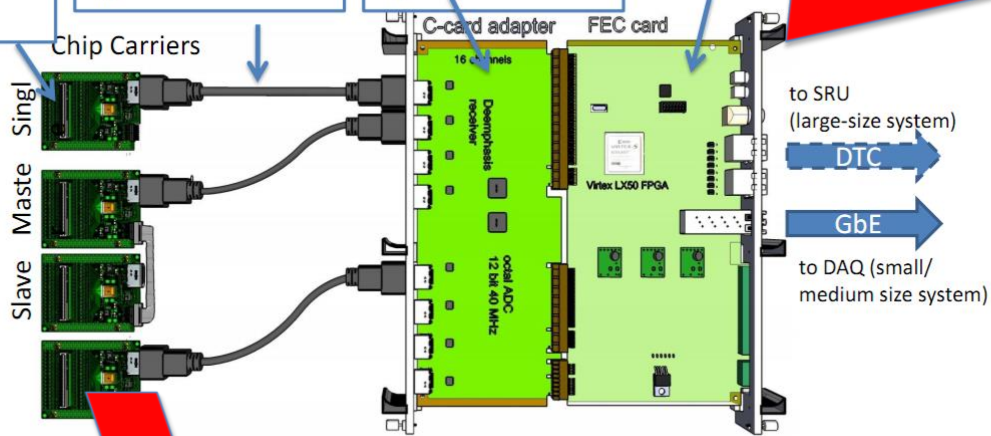
SRS System (APV)

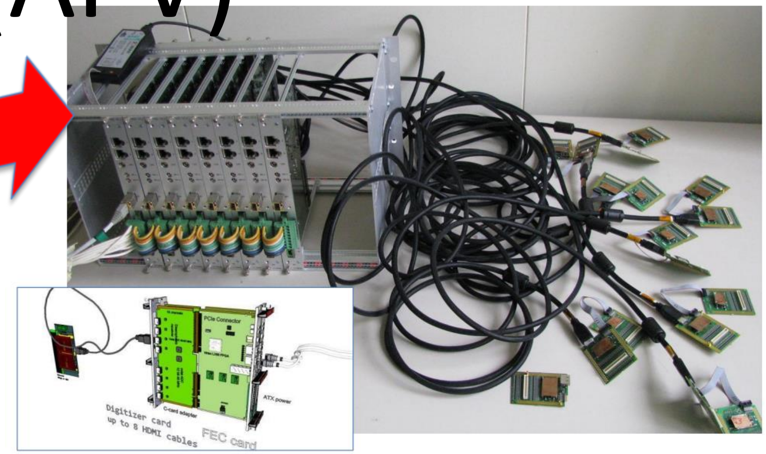
On-detector front-end hybrids
• APV25
• VFAT
• BEETLE
• …

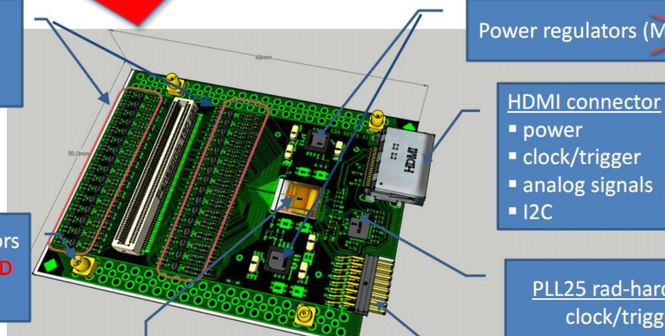
Chip-links
• HDMI
  - analog (APV/Beetle)
  - digital (VFAT/Beetle)
• optical (GBT. …)
•…

Front-end adapter (FE-specific)
• ADC card
• digital FE card (VFAT)
• GBT receiver
• …

Front-end FPGA card (SRS standard) modular firmware:
•SRS control
•application specifi…







Discharge protection (NUP4114)

Power regulators (MAX8556)

HDMI connector
▪ power
▪ clock/trigger
▪ analog signals
▪ I2C

Coax Connectors
▪ <2mohm GND
▪ mechanical

PLL25 rad-hard chip clock/trigger

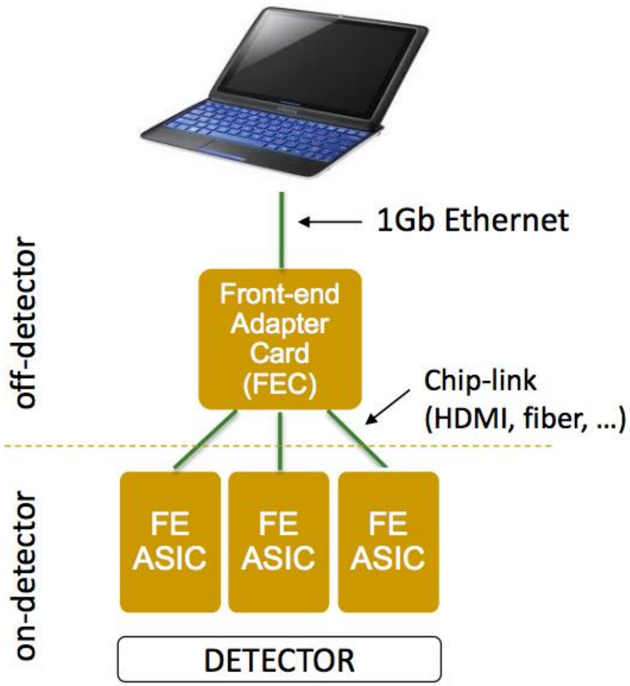
APV25 chip
▪ 128 channels
▪ 192-deep analog sampling memory

Extension connector for a second APV25 Hybrid

The system was successfully adopted with the APV chip during the September 2011 test beam

The RD51-SRS system SPARE

General purpose multi-channel readout solution for a wide range of detector types, detector complexities, and different experimental environments.



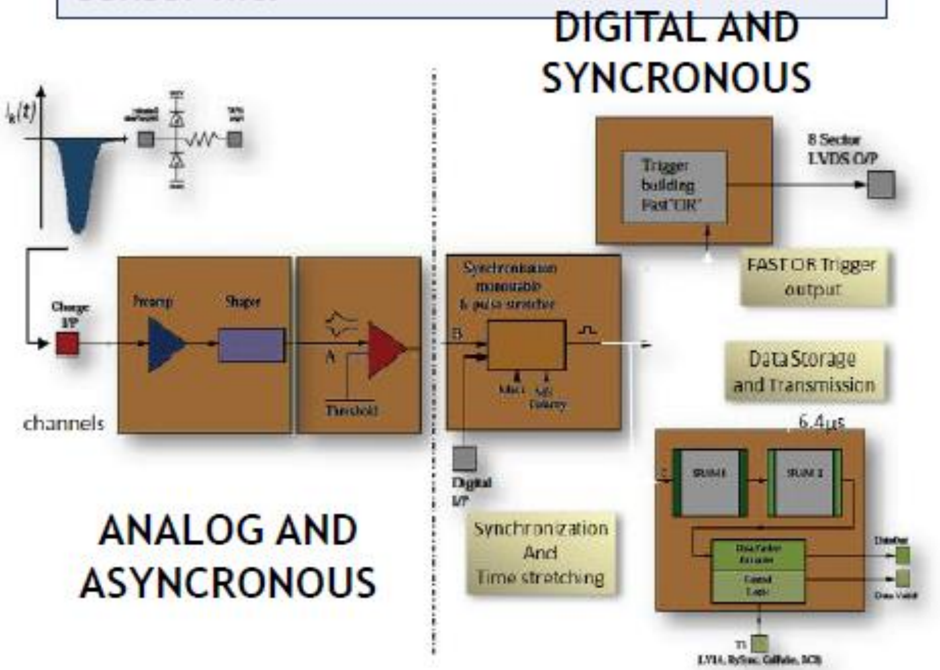
Product of the RD51 Collaboration for the Development of MPGD Technologies

- Scalable - size and applications
- Only point-to-point links. No busses
- Star topology
- Allows the use of different front-ends
- Can integrate different sub-detectors DAQ in the same system
- Cost effective
- Use of cost-effective components from high-volume markets (eg. HDMI cables, PCIe connectors, Cat5/6 UTP cables, …)

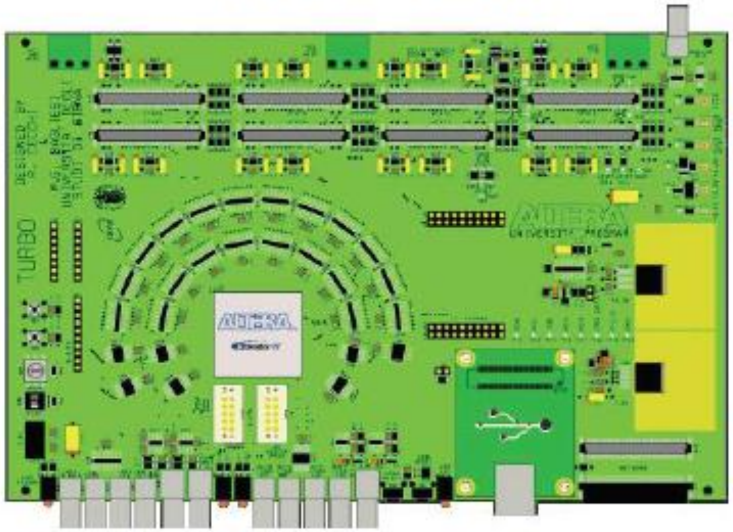
Production of SRS base components externalized.
Purchase via CERN store.
Full VFAT2 SRS system (HW & SW) may be ready for Aug-Sep. 2012.
Possible upgrade path with xTCA, optical, GBT, …
A lot of interest from RD51 for VFAT2/VFAT3/GdSP.

TURBO (VFAT) SPARE

The VFAT(TOTEM) is a digital on/off chip for tracking and triggering with an adjustable threshold for each of the 128 channels; it uses 0.25μm CMOS technology and its trigger function provides programmable "fast OR" information based on the region of the sensor hit.



Turbo board layout



For prototype testing we used electronics developped by INFN (Siena and Pisa), based on the TOTEM VFAT chip.

Prototypes construction (2009-2012)

REARRANGE! prototypes

- "CMS Timing GEM": Standard double-mask; 10x10cm^2; 1D readout; (3/2/2/2); 256 channels
- "Single-Mask GEM": Single-mask; 10x10cm^2; 2D readout; (3/2/2/2); 512 channels
- "Honeycomb GEM": Standard double-mask; 10x10cm^2; 1D readout; (3/2/2/2); 256 channels

Characterization of GEM Detectors for Application in the CMS Muon Detection System
2010 IEEE Nucl. Sci. Symp. Conf. Rec. 1416-1422; RD51 Note 2010-005

- CMS Proto III : Single-mask; 10x10cm^2; NS2; (3/1/2/1); 256 channels
- CMS Proto IV : Single-mask; 30x30cm^2; NS2; (3/1/2/1); 256 channels
- Korean I : Double-mask; 7x7cm^2; (3/2/2/2); 256 channels

Full-size prototypes

- CMS Proto I: Single-mask; CMS FULL-SIZE; 1D readout; (3/2/2/2); 1024 channels

Construction of the first full-size GEM-based Prototype for the CMS High-η Muon System
2010 IEEE Nucl. Sci. Symp. Conf. Rec. 1909-1913; RD51 Note 2010-008

- CMS Proto II: Single-mask; CMS FULL-SIZE; 1D readout; (3/1/2/1); 3072 channels
- CMS Proto V, VI: Single-mask; CMS FULL-SIZE; 1D readout; NS2; (3/1/2/1) ~3072 channels