Development and Tests of Full Scale GEMs for CMS Muon High Eta Upgrade

Andrey Marinov
On behalf of CMS GEM collaboration
PH - Detector Seminar
20.9.2013
Outline

• Introduction
• Physics and Trigger Motivation
• Small Prototypes
• First Full-Size Prototype
• Validation in Test Beams
• Final Full-Size NS2 Detector
• DAQ and Electronics
• Production and Quality Control
• Conclusions
The CMS experiment

Total weight 14,000 t
Overall diameter 15 m
Overall length 28.7 m

3.8T Solenoid

ECAL
76k scintillating PbWO₄ crystals

HCAL
Scintillator/brass interleaved ~7k ch

3.8T Solenoid

Particles & Tracker
• Pixels (100x150 µm²)
  ~ 1 m² ~66M ch
• Si Strips (80-180 µm)
  ~200 m² ~9.6M ch

Iron Yoke

Preshower
Si Strips ~16 m²
~137k ch

Foward Cal
Steel + quartz Fibers ~k ch

Muon endcaps
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)

Total weight 14,000 t
Overall diameter 15 m
Overall length 28.7 m

September 20, 2013
The CMS Muon System combines different technologies:
- Drift Tubes & Cathode Strip Chambers for tracking and triggering
- Resistive Plate Chambers for triggering

After LHC LS1, the $|\eta|<1.6$ endcap region will be covered with 4 layers of CSCs and RPCs; the $|\eta|>1.6$ region not instrumented.
New Technology is Needed

Present CMS RPC design not suitable for high rate environment

- New technology needed for $|\eta|>1.6$ region of muon system
  - Sustain $O(5-10)$ kHz/cm$^2$ environment
  - Need for improved spatial resolution $O(1.0-0.1)$ mm
Gas Electron Multiplier (GEM)

- Rate capability: $10^5$ Hz/cm$^2$
- Spatial/Time resolution: ~100 μm / ~4-5 ns
- Efficiency > 98%
- Gas Mixture: Ar-CO$_2$-CF$_4$ (non flammable mixture)

- Combine triggering and tracking functions
- Enhance and optimize the readout ($\eta$-$\varphi$) granularity by improved rate capability

GEM foils developed using PCB manufacturing techniques
- Large areas ~ 1m x 2m with industrial processes (cost eff.)
- Each foil (perforated with holes) is 50μm kapton sheet with copper coated sides (5μm)
- Typical hole dimensions: Diameter = 70μm, Pitch = 140μm,

V=const. 50-80kV/cm
• **Overview**
  – **First** high-luminosity experiment that used Triple-GEM detectors (running at CERN SPS)
  – 22 31cm \(\times\) 31cm Triple-GEMs with 2D strip readout (400 \(\mu\)m pitch);
    central circular region (d = 5 cm) deactivated (beam passage)
  – 11 stations with 2 detectors each (x-y; u-v at 45\(^\circ\) wrt x-y)
  – Low-mass tracker: 0.4 - 0.7 % \(X_0\) per Triple-GEM
  – Operated w/ gas gain \(\sim\) 8,000 in Ar/CO\(_2\) 70:30
  – Readout with APV25 chip w/ 40 MHz sampling
    (same as for the CMS Si-tracker)

• **GEM performance during running**
  – Sustained rates up to 2.5 MHz/cm\(^2\)
    \(\rightarrow\) corresponds to \(\approx\)1000 \(\times\) est. CMS GE1/1 rate @ HL-LHC (few kHz/cm\(^2\))
  – Uniform efficiency of 97.5\% for two OR’ed detectors
  – 70 \(\mu\)m spatial resolution achieved (very close to normal incidences)
  – 12 ns time resolution achieved at high beam intensity using leading edge of pulse
  – Accumulated charge during 2002-2007 running: 200 mC/cm\(^2\)
    \(\rightarrow\) corresponds to \(>\) 12 years est. CMS GE1/1 charge @ HL-LHC
  – No gain drop observed in this running period
GEMs in LHCb M1 muon station (LHCb L0 Muon Trigger):

- Operating since LHC startup; rate up to 500 kHz/cm$^2$ (>> CMS)
- Gas mixture Ar/CO$_2$/CF$_4$ (45:15:40)
- Gas gain $\approx$ 6,000
- Efficiency $\geq$ 98% in 25 ns window using OR of two GEM
- Rad-hard up to integrated charge of $\geq$ 2 C/cm$^2$ (15 LHCb years)

**GEMs @ LHCb**

**σt=2.9 ns**

- Readout: 1 cm $\times$ 2.5 cm pads

**GEM module**

**20 $\times$ 24 cm$^2$ GEM module**

**Two Triple-GEMs (OR'ed)**

**12 Double Triple-GEMs in front of calorimeter; total area 0.6 m$^2$**

A. Marinov CERN PH Seminar
very forward at $5.3 \leq |\eta| \leq 6.5$

About 99.5% of all non-diffractive minimum bias events and 84% of all diffractive events have charged particles within the acceptance of the TOTEM detectors T1 and T2.

- 360° φ coverage
- Readout Granularity:
  - $\delta r = 400\mu m$ [pitch]
  - $\delta\phi = 2.9^\circ$ [pitch]
- 4 quarters with 10 detectors aligned each
- very low material budget: $x = 0.2\% X_0$

E. Oliveri (INFN Pisa), 3rd CMS GEM Upgrade Workshop, April 2012
Install triple-GEM detectors (double stations) in 1.6<|\eta|<2.1-2.4 endcap region:

- Restore redundancy in muon system for robust tracking and triggering
- Improve L1 and HLT muon momentum resolution to reduce or maintain global muon trigger rate
- Ensure ~100% trigger efficiency in high PU environment
Motivation: Exploiting GEM-CSC Bending Angle

- An increased lever arm of the combined CSC+GEM system allows accurate measurement of the bending angle
  - Note that half of CSC-GEM chamber pairs are “close” and the other half is “far” (see the figure above)
- Excellent discrimination power to distinguish soft muons from hard
  - Larger lever arm for “far” chambers provides even better separation

Vadim Khotilovich (Texas A&M University)
Limitations for large size applications ~ 4 Years ago

Double mask technology process.

A-the GEM foil copperclad,

B- Photomask for top and bottom layer. Photoressist exposure,

C-Metal etching,

D-Kapton etching,

E-second masking,

F-metal etching and cleaning

Based on this technique the maximum size of the GEM foils was limited to 30x30 cm
OVER FOUR YEARS OF R&D

• **2009-2010**
  – Small prototypes, bench tests; picked GEMs among MPGDs for further study
  – Established space and time resolution achievable
  – First Large-area GEM foils produced with Single Mask technology
  – First large-area GE1/1 prototype; beam test

• **2011**
  – Second redesigned GE1/1 prototype (smaller gaps b/w GEMs)
  – “GEM Collaboration (GEMs for CMS)” constitutes itself in May CMS week (76 collab. from 15 inst.)
  – Summer beam tests (including first test in CMS test magnet)
  – Established 100µm (300µm) res. with analog (binary) r/o chip
  – NS2 GEM foil assembly technique w/o spacers
  – Preliminary electronics design starts
2012

- Beam tests – Magnetic Field Operation and fine space and time resolution on large size established
- **Working Groups (Physics, Trigger Simulations, Integration Services, Electronics and DAQ, Detector HW) with weekly meetings**
- Third GE1/1 prototype designed (new GEM design “NS2”; and readout), 5 detectors produced! One more to be assembled outside of CERN
- Started GIF long term aging test
- Collaboration Expanded 42 Institutions, 183 collaborators EOI

2013

- GE1/1 - 6 Detectors produced in 2013 (Two outside CERN)
CMS Project Achievements Together RD51 and CERN Surface Treatment Workshop

- Detector efficiencies above 98%
- Spatial resolution of about 290μm with VFAT2 (digital) and <110μm APV (analog) readout chip
- Time resolution of 4ns
- Operation of GEMs in magnetic field
- Validation of single-mask technology
- Production of large area GEM foils
- New self-stretching technique for GEM assembly

![Standard GEM Timing Performance](image)

DOUBLE MASK

50 mm polyimide foil, copperclad
photoresist lamination, masking, exposure and development
metal etching
polyimide etching
metal etching
second masking to define electrodes
metal etching and cleaning

SINGLE MASK

Readout connector
O-ring
Drift electrode
GEM
GEM attaching structure (4 pieces defining gaps)
External screws to adjust O-ring
Free to slide
Embedded nut
GND
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Small Prototypes (2009-2010)

- 10x10 cm² triple-GEMs, 1D or 2D readout, 128 or 256 channels:
  - Standard double-mask triple-GEM - “Timing GEM”
  - Single-mask triple-GEM
  - “Honeycomb” triple-GEM
- 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 GEM reaches similar performance level as double-mask GEM
- Single-mask technique used for large CMS-size prototypes
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• **First Full-Size Prototype**
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Full-size GE1/1 Detectors
Developments in Time

Generation I
The first 1m-class detector ever built but still with spacer ribs and only 8 sectors total. Ref.: **2010 IEEE** (also RD51-Note-2010-005)

Generation II
First large detector with 24 readout sectors (3x8) and 3/1/2/1 gaps but still with spacers and all glued. Ref.: 2011 IEEE. Also RD51-Note-2011-013.

Generation III
The first self-stretched sans-spacer detector, but with the outer frame still glued to the drift. Ref.: **2012 IEEE N14-137**.

Generation IV
The current generation that we have built two of at CERN so far, with four more to come from the different sites. No more gluing whatsoever.

**Upcoming papers from MPGD 2013.**

Generation V
The upcoming detector version that we will install. One long and one short version. Optimized final dimensions for max. acceptance and final eta segmentation.
GE1/1 Prototypes
Proto1 Generation I (2010)

A. Conde Garcia
GEM Foil Stretching and Assembly (I)

Thermal stretching in large oven (CERN)

The assembly time for this detector was 1 week
Photograph of First Full-Size Detector

- HV divider and filter
- HV connector
- 128 channel readout connector
- Generation I
  Fully glued
  Gap configuration 3/2/2/2mm
  1024 readout strips
- Gas inlets
- October 2010
- 1m
- 0.5m
- October 2010
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CMS-RD51 Test Beams

- SPS H4 beam line, 2010
- RD51 GEM tracking telescope
- VFAT2/Turbo frontend electronics
- 20 million events taken with CMS Prototype I

*GEM Tracking telescope*
Excellent performance observed:

- ≥ 98% efficiency
- 230 µm resolution
  (≈ pitch/√12 for binary electronics)
- uniform performance in different sectors

**Track residuals**

<table>
<thead>
<tr>
<th>Counts</th>
<th>600</th>
<th>500</th>
<th>400</th>
<th>300</th>
<th>200</th>
<th>100</th>
<th>0</th>
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</thead>
<tbody>
<tr>
<td>Entries</td>
<td>3682</td>
<td>Mean = -0.02183</td>
<td>RMS = 0.964</td>
<td>$\chi^2$/ndf = 142.8/38</td>
<td>Constant = 568 ± 12.9</td>
<td>Mean = -0.0817 ± 0.0040</td>
<td>Sigma = 0.2298 ± 0.0033</td>
</tr>
</tbody>
</table>

**Efficiency**

- RUN = 37 – 181
- Thr = 40 V$_{u}$
- Lat = 14
- Position = P1

**SINGLE MASK**

RUN = 175
HV = 4.50 kV
I = 738.90 uA
Thr = 40 V$_{u}$
$\eta$ = 99.5%
Position = P1
Gas: Ar/CO$_2$ (70:30)

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2nd GE1/1 Detector (2011)

Magnet test

- Smaller GEM gap sizes: 3/1/2/1 mm
- More sectors: 3 columns, 8 $\eta$ partitions
- Smaller strip pitch: 0.6-1.2mm
- 3072 channels, 1D readout

- Expect max. $B_\perp \sim 0.6T$, $B_\parallel \sim 3T$ and $B^E \sim 8^\circ$ for GE1/1

H2 beam line @ SPS

Prototype inside the M1 magnet (side view along Z)

Simulation (no diffusion) Measurements

![Diagram of magnet test setup]

- CMS_TB_06&07_2011_GE11new@M1
- GE11_II:3/1/2/1[128ch_1D]
- ArC02CF4(45:15:40)
- MuonBeam150GeV-H2@06_11
- THR=40

![Graph of displacement vs. magnet field strength]

- $B^E = 90^\circ$
- $B^E = 30^\circ$
Successful data taking with analog APV chip and Scalable Readout System in addition to TURBO/VFAT2 DAQ system

Measured resolution $\sigma_x < 103 \mu m$ in section with smallest pitch

$\Delta x_{hit}$ measurement:
Tracker GEM vs. CMS full-size GE1/1

Strip cluster size

$\mu^+/\pi^-$ beams

Strip Pitch: 0.573 mm

Strip Pitch: 1.146 mm

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Current state-of-the-art: **Self-stretching assembly without spacers (CERN)**

- **Readout PCB**
- **GEMs**
- **Drift electrode**
- **Detector base pcb**

Tightening the horizontal screws tensions the GEMs.

Only glue joint in assembly.

2012

Allows re-opening of assembled detector for repairs if needed.
- Single-mask & self-stretching techniques
- Gap sizes: 3/1/2/1 mm
- Sectors: 3 columns x (8-10) η partitions
- Strip pitch: 0.6-1.2mm
- 1D readout of up to 3840 channels
- 35 HV sectors
Generation IV GE1/1 Prototype
Full-size NS2
GEM foil in inner frame assembly

GEM foil with inner & outer frame

Inside of readout board with O-ring seal

Base pcb with drift electrode

No spacers in active volume

η-sector with 384 radial readout strips

Add-film 1 min
**GE1/1 Readout & Drift Board**

**Strip side**

**Readout board:** Metalized vias bring the signal to the other side of the board; panasonic connector with 128 entries is soldered on the strips.

**Drift board:** HV spring contacts to connect foils to HV; 4 contacts per GEM (Top/Bottom + redundant connection).

**External side**

**HV divider**

**HV filter**

**Soldering spring contacts**
• The assembly of one single detector is about 2 hours
• All preparatory work has to be done in advance
• Clean room of class 1000 is required.
• Sites at Frascati and FIT quite advanced
• Other sites getting ready

May 2013
Final detectors for installation in CMS will undergo strict Quality Control in the different assembly sites:

- Measure the leakage current of the GEM foils before, during and after the detector assembly
- Validate the readout board by verifying the connections of the strips to the readout connector
- Measuring the detector gain uniformity with Mini-X and SRS/APV system

Response to x-ray checked for each $\eta$ sector

GE1/1 detector uniformity

10$\sim$12%
Long Term Sustained Operation for CMS GEMs at LHC Phase 2

- Rate capability of Triple-GEM detectors for CMS
- Double-GEM
  - Ar/CO2 (90-10%)
  - Gain = 1.2 10^3

Next Steps
- Perform aging tests of CMS GEM detector (final configuration)
- Study the properties of materials used in the detector (in term of radiation hardness, outgassing..)

Integrated charge of 13C/cm^2 is expected
10 years @ LHCb
50MHz/cm^2 integrated
Cleaning the Line Without DUT

No Evidence of Aging after 3 weeks of operation

J. Merlin
GE1/1: more than two months of operation -> 9% of the total charge (80mC/cm²).
Two additional pico-ammeters after one month (irradiated + protected sector).

Readout current: protected sector 15x lower than irradiated one
(scattering + fluorescence)
Normalized Corrected Gain for GE1/1 Prototype 2

Ongoing Tests

ArCO2CF4 (45,15,40%)

Normal behaviour up to 7mC, No aging

GIF : Good improvement of the efficiency !

- -> initially 30-40 %
- -> July: 50%
- -> August : 90%

J. Merlin
Material Outgassing Tests

Outgassing test:
Started

-> most critical materials: polyurethane, O-rings...
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Global Requirements on electronics: provide necessary input from all GEM detectors to Muon Triggering and Tracking

- **GEM detectors:**
  - Design optimized for gas detectors, in particular GEMs

- **Triggering:**
  - Provide “Fast OR” trigger information with granularity of 2 or more channels to send locally to CSC Trigger Mother Board
  - Timing resolution <8ns

- **Tracking:**
  - Provide full granularity tracking data on receipt of a LV1A
  - Be compatible with CMS trigger upgrade possibilities:
    - LV1A latency < 20μs
    - LV1A rate < 1MHz
DAQ and Electronics

On Detector

- GEM_PCB
- FPGA/GBTs
- VFAT3/GdSP
- DC/DC converters
- Power Supplies
  - LV
  - HV

Off Detector

- TCA crates
  - Trigger
- GLIB Ser/Des
- AMC13
- DAQ
- DCS
- TTC

Links to CSCs

Optical links @ 3.2Gbps

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VFAT3 chosen for the 2016 Slice Test and GE1/1 full installation during LS2

- VFAT3 analog discriminator will use CFD or TOT to correct time walk

- VFAT3 STT version (Separate Tracking & Triggering)

- GEM OptoHybrid contains FPGA performing “concentrator” and driving optical link @ 3.2Gbps; FPGA programming via the GBT
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Full-size GE1/1 Detectors
Developments in Time

- **2010**: Production and QC of detectors. First prototype of VFAT3
- **2011**: Slice installation
- **2012**: Slice and trigger commissioning
- **2013**: QC of Production GE1/1 chambers with final electronics
- **2013/14**: Full installation of GE1/1 with final electronics

- **2014/15**: Full-production of chambers and electronics started
- **2015/16**
- **2016/17**
- **2017/18**
- **2018/19**

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Possible Production Sites

CERN Production and final QC

USA
FIT

Italy

India

Belgium
Gent
University

Installation in CMS
Two Super-chambers will be installed in the YE-1 of CMS.

There will be the sectors 01 and 35.

To have this possible all the services must be ready and commissioned during the LS1 period!!!
3 Super-Chamber dummies were produced earlier this year to optimize design and to perform trial insertion into CMS:

- no detector and no electronics inside
- all positions for gas, cooling, and electronics connections at the right place
- weight and dimensions as a real super chamber
Trial Installation in CMS - 2013
Conclusions

• GEM a viable technology for CMS Upgrades established
• Extensive R&D program launched and carried out
• Large size GEM foils made with single mask technology
• 6 Full scale GE1/1 detectors built and assembled with NS2 technology
• Performance commensurate with requirements demonstrated by test beams and lab tests
• Long term sustained operation tests ongoing
• Services for the slice test in 2016 must be finished and commissioned before the end of LS1 period.
• Production sites gearing up for final chamber assembly and test
• QC and validation procedures optimized
• Next steps
  • Launching production of 10 final detectors for slice test and other laboratory tests

For more Information you can refer to our twiki page:
https://twiki.cern.ch/twiki/bin/view/MPGD/CmsGEMCollaboration
Thank You!
Cable Routing on YE-1

- No Dismounting needed
- RE-1/3+ME-1/3
- GE1/1 Routing Path (HV, LV, Fibers)
- RE-1/2+ME-1/2
- GE1/1 area |η| (2.1-1.6)

- Cables will go on top of ME1/2 as first option

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Spare Slides
VFAT3:
- Front-end with programmable shaping time
- Internal calibration
- Binary memory
- Interface directly to GBT @ 320Mbps
- Designed for high rate (10kHz/cm² depending on segmentation)

GdSP:
- Similar to VFAT3, except has an ADC for each channel instead of comparator
- Internal DSP allows subtraction of background artifacts, enabling clean signal discrimination
- Center of gravity is possible to achieve finer pitch resolution
Improving Muon System Coverage

- Reconstruction coverage critical for multi-muon signatures
  - Eg. $H \rightarrow ZZ \rightarrow 4\mu$ channel:
    - Acceptance increases by 50% if muon reconstruction coverage extends from $|\eta_{\text{max}}|=1.5 \rightarrow 3.5$
    - Archana to check......
CMS Muon Trigger Challenges

- Forward region $|\eta|>1.6$ trigger relies entirely on the CSC system
  - General trend is lowering efficiency towards higher eta to compensate for higher background rates
  - Optimal operating point is a function of PU (7 and 8 TeV are different)
- CSC is a superb system but it is not PU-proof:
  - Efficiency losses grow with PU
  - High L1 trigger rates in the very forward region
  - L1 trigger rates “flattening”
- The period between LS2 and LS3 is the most difficult time:
  - Current system at the edge and the foreseen L1 Tracking Trigger is not yet online
Forward Muon Trigger

- Muon momentum from stub positions
  - $\Delta \phi_{XY} = \phi(ME-X) - \phi(ME-Y)$
  - Measurement driven by $\Delta \phi_{12}$: ME-I/I “drives” precision (least scattering)

- Slow turn-on:
  - Efficiency plateau is 20-25% above L1 threshold

- “Flattening”: mismeasured soft muons
  - Soft muons scattering in the absorber can occasionally have stubs aligned like for a high $p_T$ muon (rare, but lots of soft muons); tails in L1 momentum resolution

- Only two handles on $p_T$ mismeasurements:
  - $N_{\text{stubs}}$ (out of 4) and ME-I/I stub presence; both are used to define quality of the CSC TF tracks (used in GMT)
  - Can’t push too far without large efficiency losses

- PU reduces trigger efficiency by few %
CMS Trigger Rate

The luminosity corresponds to $N_{\text{PU}}=100$ and 25 ns bunch crossing rate

$|\eta| < 2.1$

ME1/b is the upper half of the ME1/1 chamber and spans $1.55 < |\eta| < 2.1$

Illustration of the achievable trigger rate reduction in the region covered by GEM station GE-1/1 using bending angle measured using GEM and CSC stations

Vadim Khotilovich (Texas A&M University)
Example of where GE1/1 ($1.6 < |\eta| < 2.1$) can help:

- **Upgraded Muon TrackFinder** alone only allows decreasing the threshold from 42 to 25 GeV (with 9% efficiency loss).

  Using GEM-CSC “bending angle”, allows to lower $p_T$ threshold from 42 to 13 GeV while increasing the efficiency.

- $H \rightarrow \tau \tau \rightarrow \mu \tau_{\text{had}}$ signal: fast falling muon momentum spectrum requires low $p_T$ thresholds; loose half (!) of the acceptance every time $p_T$ threshold by 10 GeV.

  GEM+CSC yield improved background rejection and result in $\sim 20\%$ increase in acceptance.
Exploded GE1/1 View

Cover

Position of HV Divider

DC-DC Converters

GBT’s

Connectors & FE Hybrids

Cooling

GE1/1 Triple-GEM Chamber
## Upper limits on chamber power

<table>
<thead>
<tr>
<th>Element</th>
<th>Number of units</th>
<th>Voltage</th>
<th>Power/unit</th>
<th>Power/chamber</th>
<th>Power/super-chamber</th>
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</thead>
<tbody>
<tr>
<td>GdSP/VFAT</td>
<td>24</td>
<td>1.5V</td>
<td>GdSP: 0.9W</td>
<td>GdSP: 21.6W</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>VFAT: 600mW</td>
<td>VFAT 14.4W</td>
<td></td>
</tr>
<tr>
<td>GBTX</td>
<td>3</td>
<td>1.5</td>
<td>1414mW</td>
<td>4.242W @ 1.5V</td>
<td>13W</td>
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<tr>
<td>GBTIA</td>
<td>3</td>
<td>2.5</td>
<td>250mW</td>
<td>2.25W @ 2.5V</td>
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<tr>
<td>GBDL</td>
<td>3</td>
<td>2.5</td>
<td>400-500mW</td>
<td>4.242W @ 1.5V</td>
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<tr>
<td>FPGA</td>
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<td>25W</td>
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<td>Dc/dc</td>
<td>7</td>
<td>2.5</td>
<td>?V in 1.5V &amp; 2.5V</td>
<td>80% efficiency</td>
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<td>regulators</td>
<td>(2 per column</td>
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<tr>
<td></td>
<td>+ 1 for GBT 2.5V</td>
<td></td>
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<tr>
<td>LDOs (on or</td>
<td></td>
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<tr>
<td>off chip)</td>
<td></td>
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<tr>
<td>Total</td>
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<td>GdSP 63W VFAT 53W</td>
<td>GdSP 126W VFAT 106W</td>
</tr>
</tbody>
</table>

**Super-chamber = double sided single chamber**

VFAT2 power consumption used in table, VFAT3 consumption will be less.

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The installation slot of the GE1/1s has only 100mm clearance.
• The super-chamber has to emit zero heat to the nearby detectors.
• Cooling has to be done with considering all these factors.
GE1/1 Cooling System

- The cooling system has been studied/simulated taking into account electronics power dissipation (based on VFAT).

- The cooling system will ensure a chamber temp. uniformity of (20 ± 1) °C.

VFAT power – 600mW
VFAT chip dimensions ~10×10mm
Connectors – 6mm high
Cable Routing from USC to UXC

All Cu Cables

All fibers
In situ thermal stretching in clean room with infrared heating lamps (Fl.Tech)

- 1”-diameter aluminum rods support the frame – allows for greater versatility and mobility. Several stations can easily be set up on the same optical table.

- Sixteen 125W heat lamps; stretch foils at 35°C
LHC Upgrade Program

High eta region present hostile conditions.

<table>
<thead>
<tr>
<th>Region</th>
<th>Rates (Hz/cm²) LHC (10⁻³⁴ cm⁻²/s)</th>
<th>High Luminosity LHC 2-3 × LHC</th>
<th>Phase II (10⁻³⁵ cm⁻²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel RPC</td>
<td>30</td>
<td>Few 100</td>
<td>≈ kHz (tbc)</td>
</tr>
<tr>
<td>Endcap RPC 1, 2, 3, 4 η &lt; 1.6</td>
<td>30</td>
<td>Few 100</td>
<td>≈ kHz (tbc)</td>
</tr>
<tr>
<td>Expected Charge in 10 years</td>
<td>0.05 C/cm²</td>
<td>0.15 C/cm²</td>
<td>≈ C/cm²</td>
</tr>
<tr>
<td>Endcap RPC 1, 2, 3, 4 η &gt; 1.6</td>
<td>500Hz ≈kHz</td>
<td>Few kHz</td>
<td>few 10s kHz</td>
</tr>
<tr>
<td>Total Expected Charge in 10 years</td>
<td>0.05-1 C/cm²</td>
<td>Few C/cm²</td>
<td>few 10s C/cm²</td>
</tr>
</tbody>
</table>

GE1/1 installation