The CMS Beam Condition Monitoring Leakage system at the LHC

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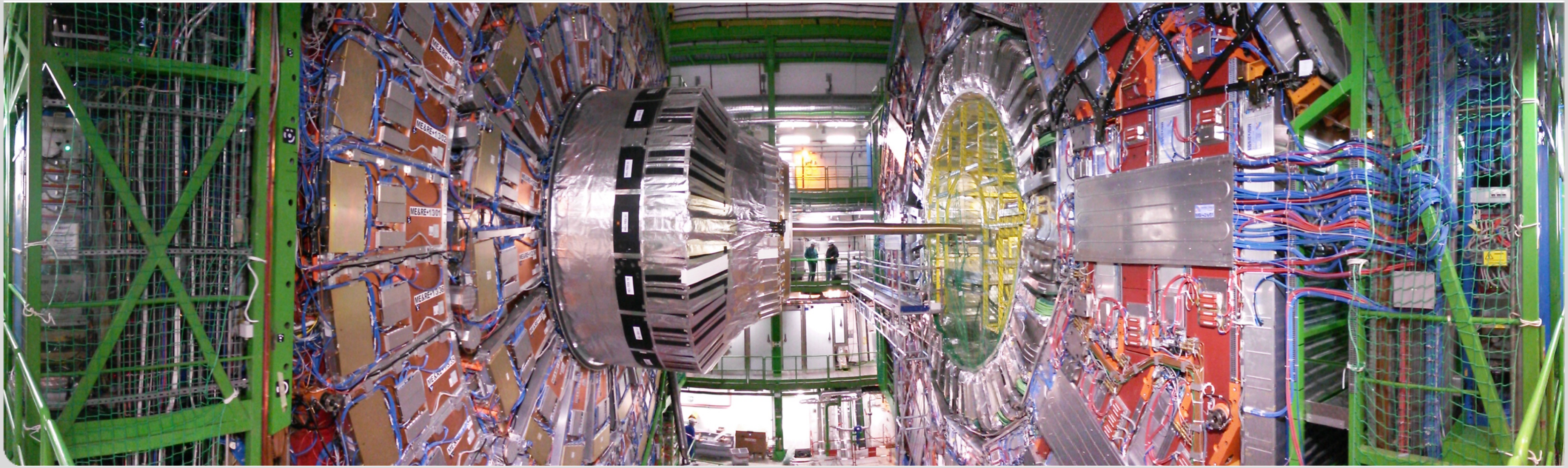
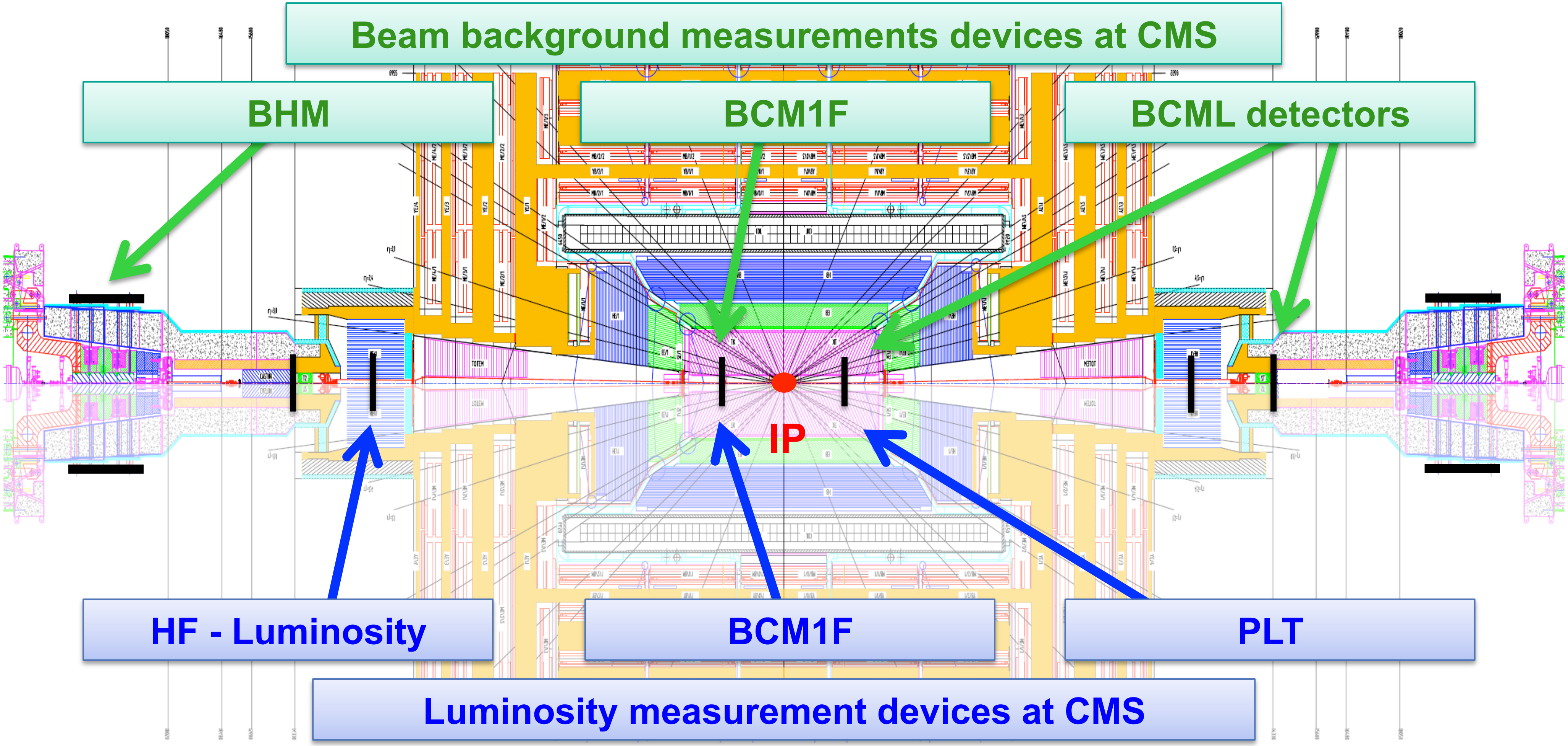


Outline

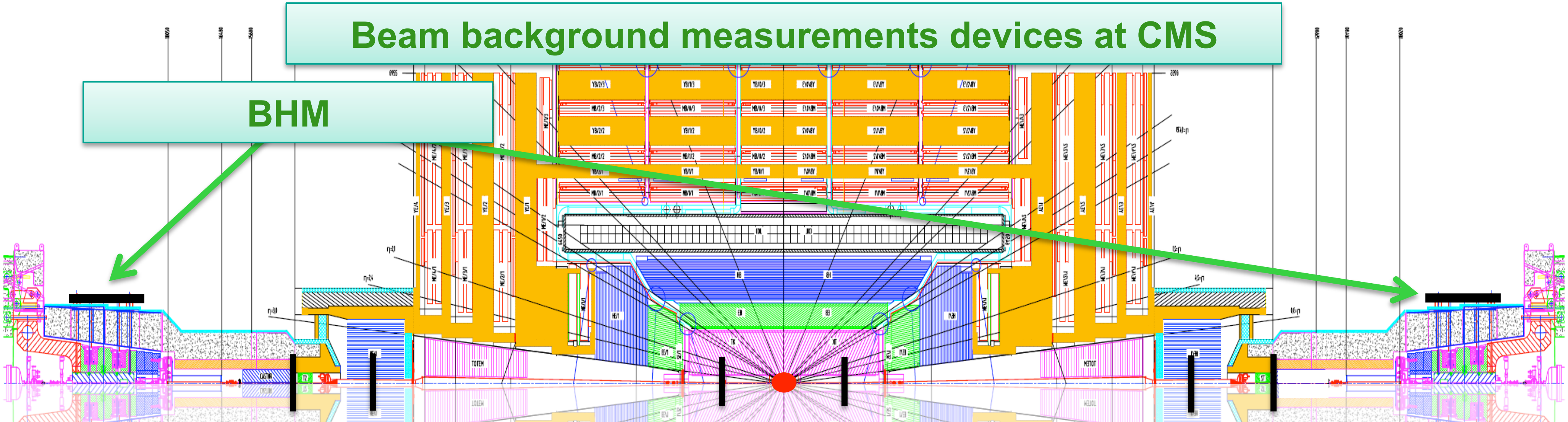
- The CMS BCML system
- The BCML detector during operation in 2015/16
  - Typical beam loss event at LHC
  - Radiation induced detector degradation
- BCML detector upgrade:
  - New BCML sensor materials
  - Upgrade of the BCML2 detector unit

BRIL project –
Overview of Luminosity and Background measurements

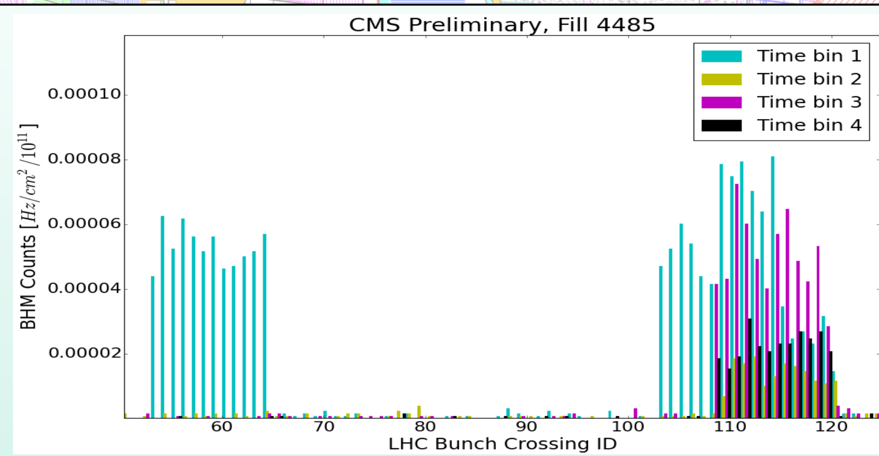


BRIL Project – Background measurements

Beam Halo Monitor (BHM)

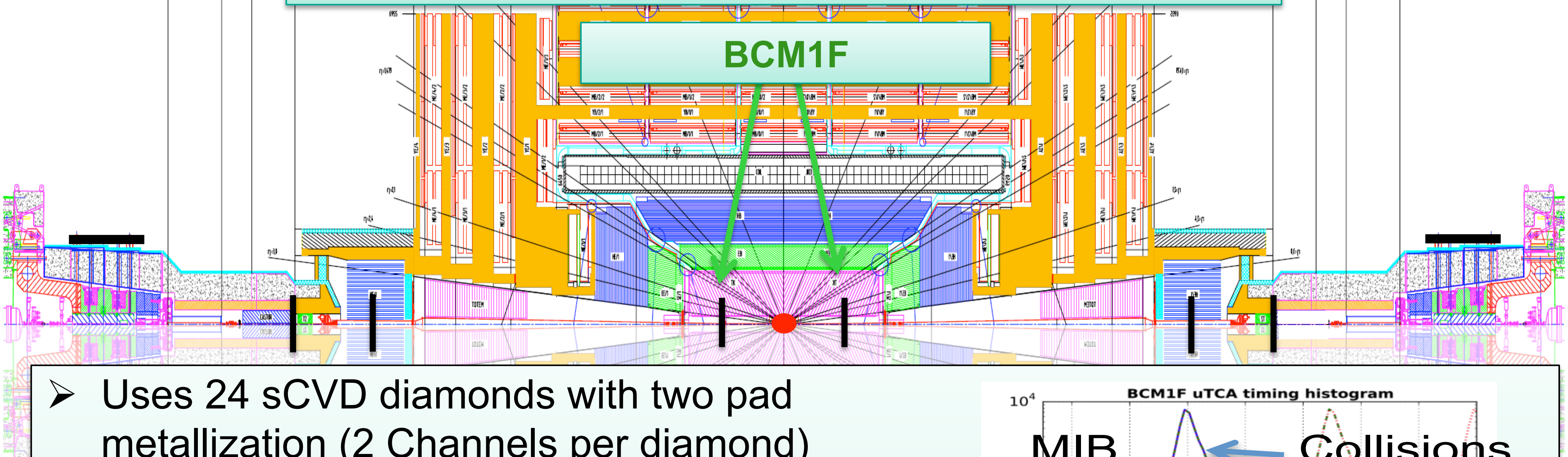


- Measurement of muon halo created in beam loss events
- Directional Cherenkov light created in quartz bar measured by PMT
- 20 BHM detectors per side.
- Fast timing allows separation between MIB and collision products

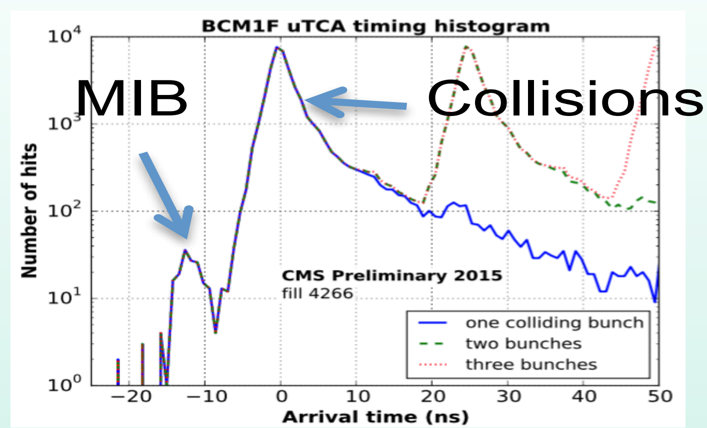


BRIL Project – Background measurements
Fast Beam Condition Monitor (BCM1F)

Beam background measurements devices at CMS



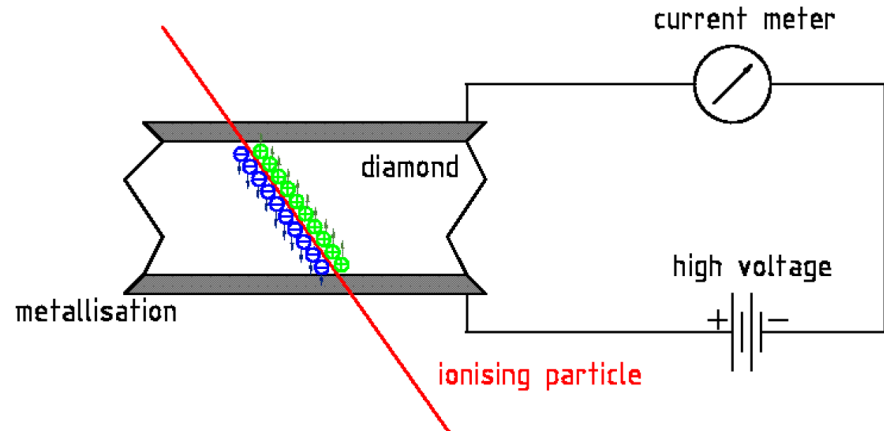
- Uses 24 sCVD diamonds with two pad metallization (2 Channels per diamond)
- Dedicated fast ASIC pre-amplifier to particle hits ~10 ns.
- Fast read out (1 bin = 6.25ns) allows separation between MIB and luminosity
- New µTCA readout with 1.25GS/s



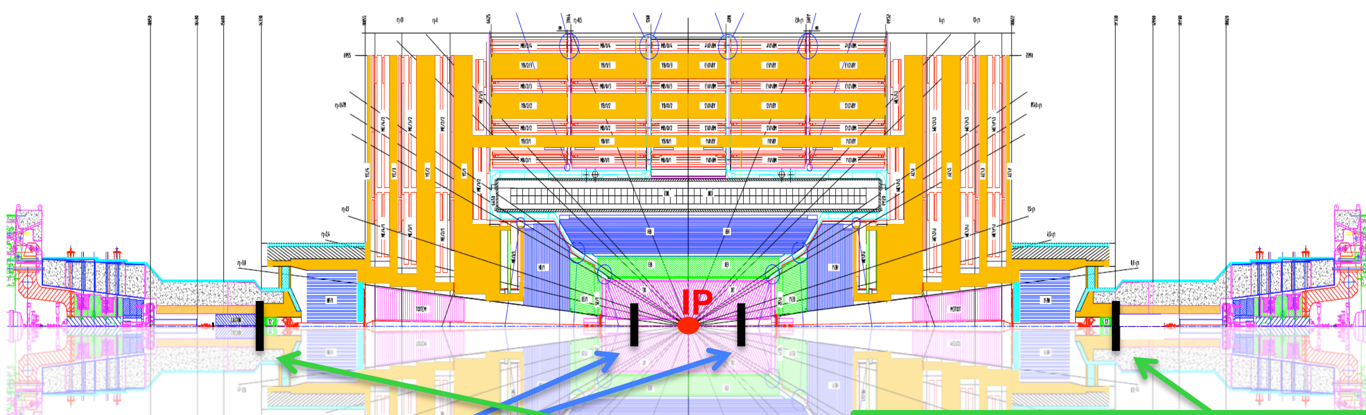
The CMS BCML system
Overview

Working principle of diamond detectors

- High voltage applied to metallized surfaces of the pCVD diamond
- Ionization creates e/h-pairs
- Measurement of charge carrier drift



Positions of diamond detectors at CMS

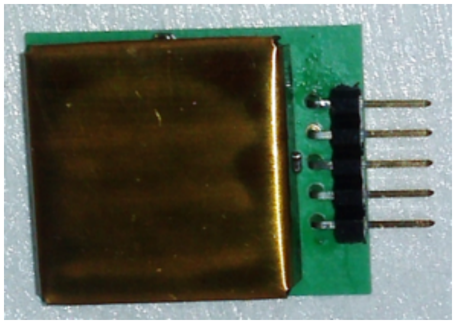


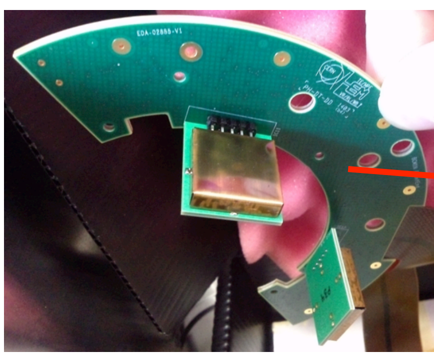
BCML1
- Z = +/-1.8 m, r = 4.5 cm
- 4 diamonds per location

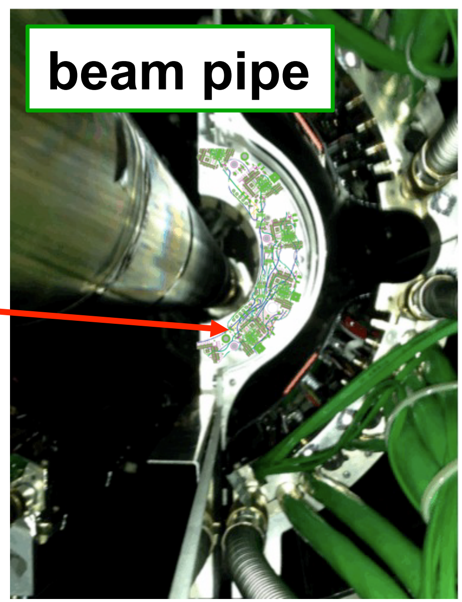
BCML2
- Z = +/-14.4m, r = 5 & 28 cm
- 12 diamonds per location

The CMS BCML system
Overview

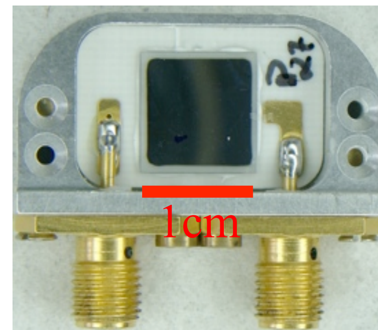
BCML1
- ➢ **Mounted on BCM carriage**

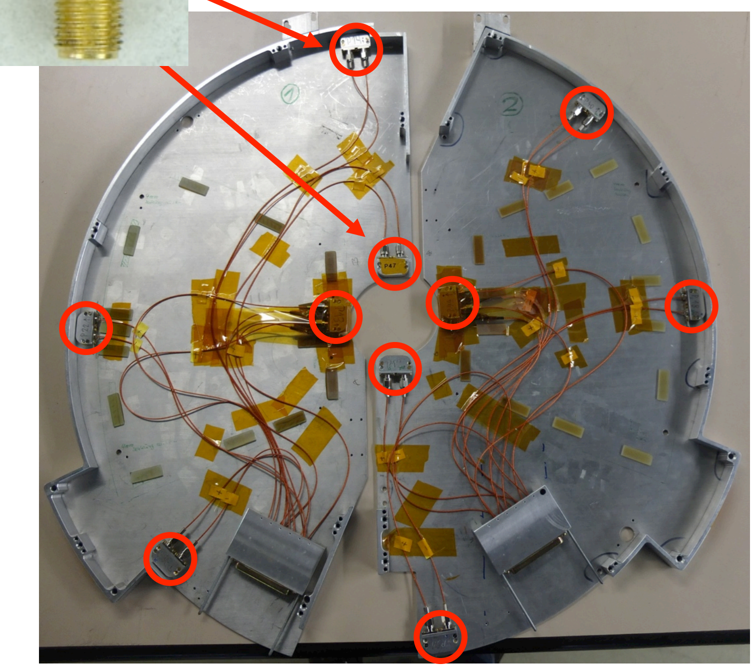






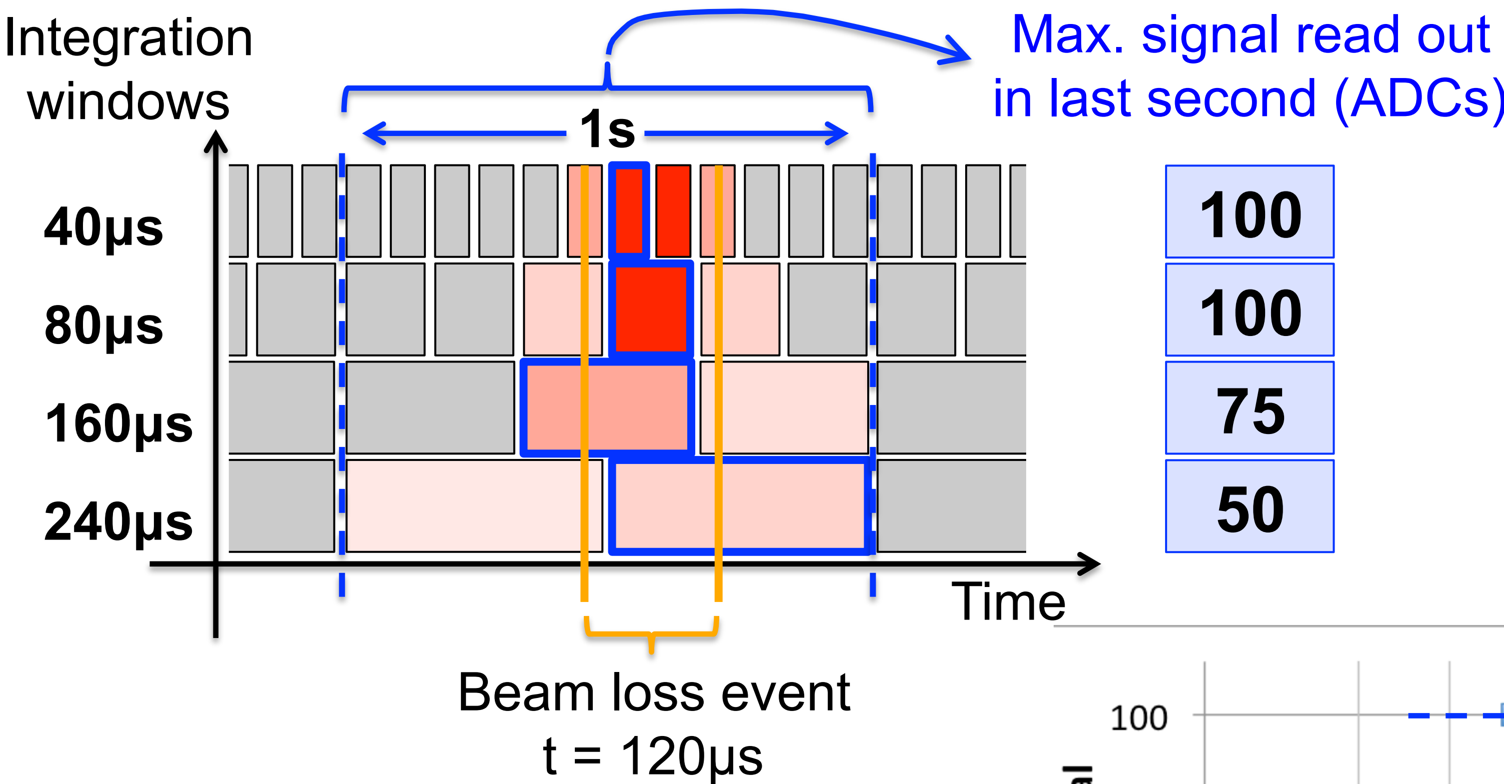
BCML2
- ➢ **Mounted on wheel structure around the beam pipe**

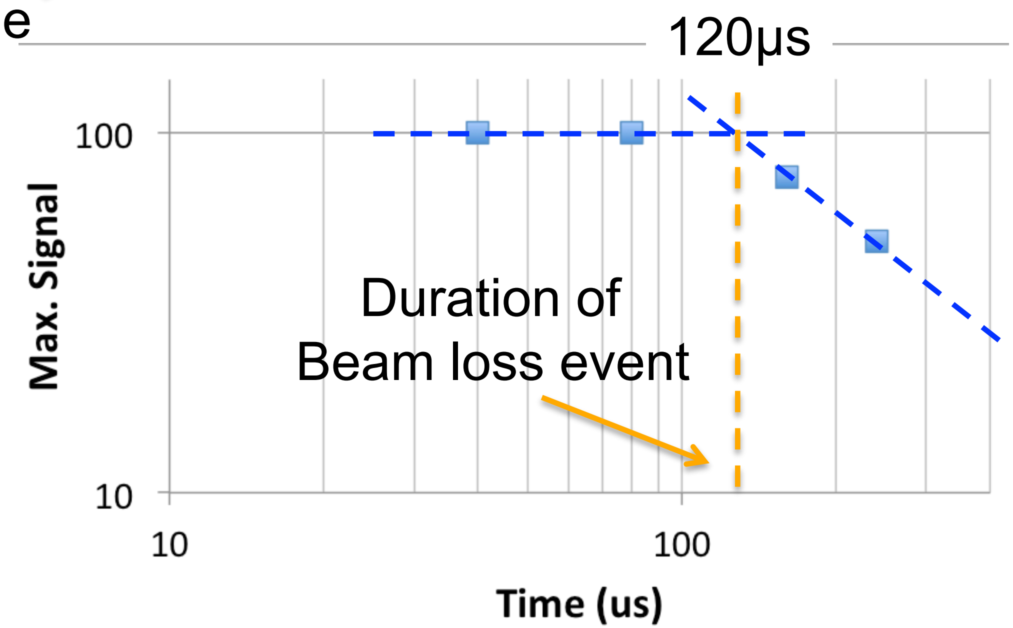




Signal read out

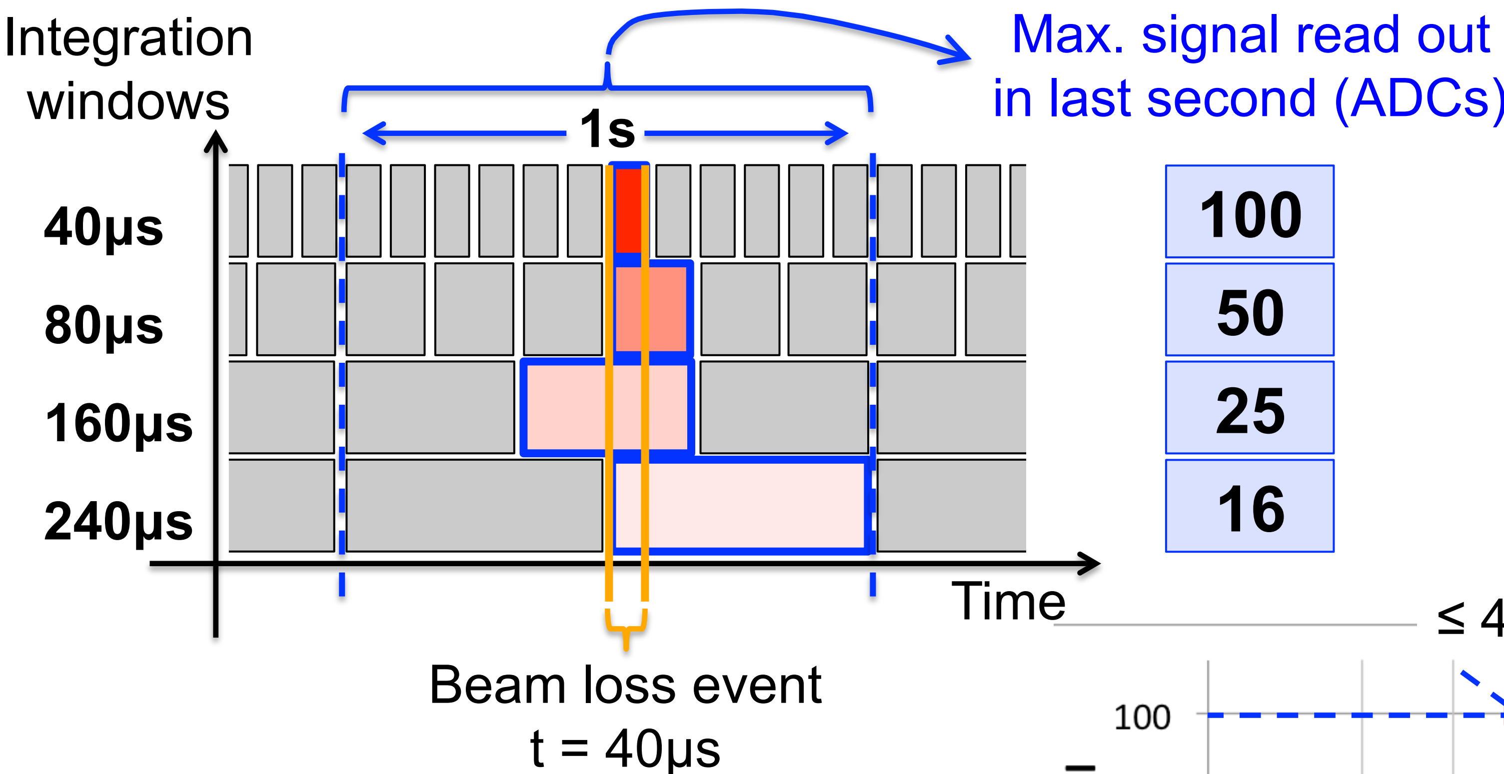
Identically to BLM read out system of LHC

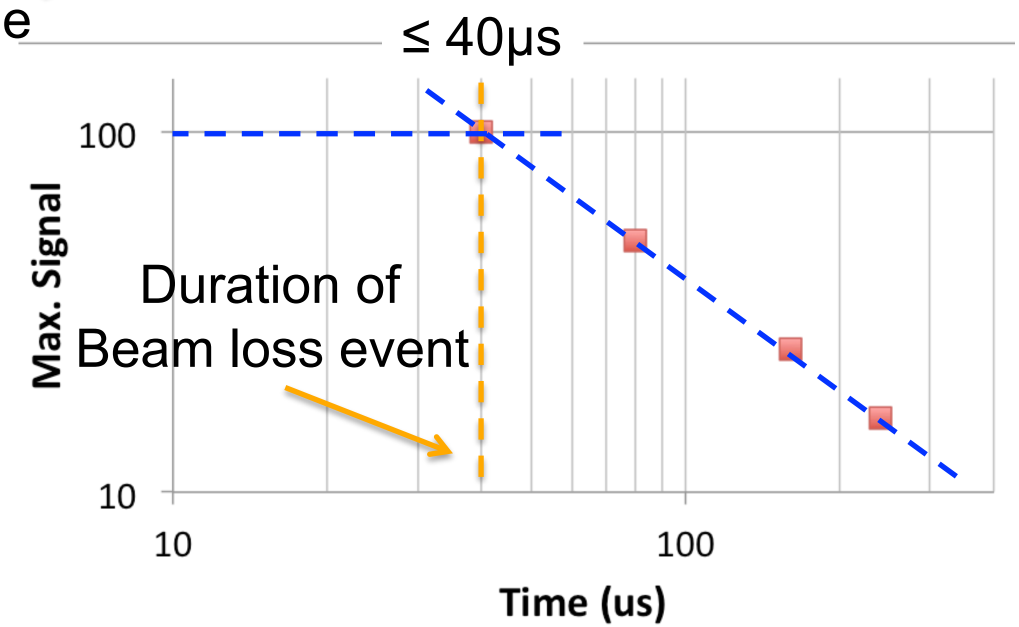




- Double logarithmic plot
- Intersection point indicated the beam loss duration

Signal read out
Identically to BLM read out system of LHC





- Double logarithmic plot
- Intersection point indicated the beam loss duration

BCML: Electrical read out - Properties

Electrical read out - Hardware:

- Identical to the BLM system of LHC.
- Abort functionality is ‘hard coded’ into system, no software used in process of sending the beam abort signal.

Electrical read out - Measurement:

- In total 12 integration windows = called ‘Running Sums (RS)’
- RS1 (40 µs) till RS12 (83 s)
- Read out frequency is 1 Hz

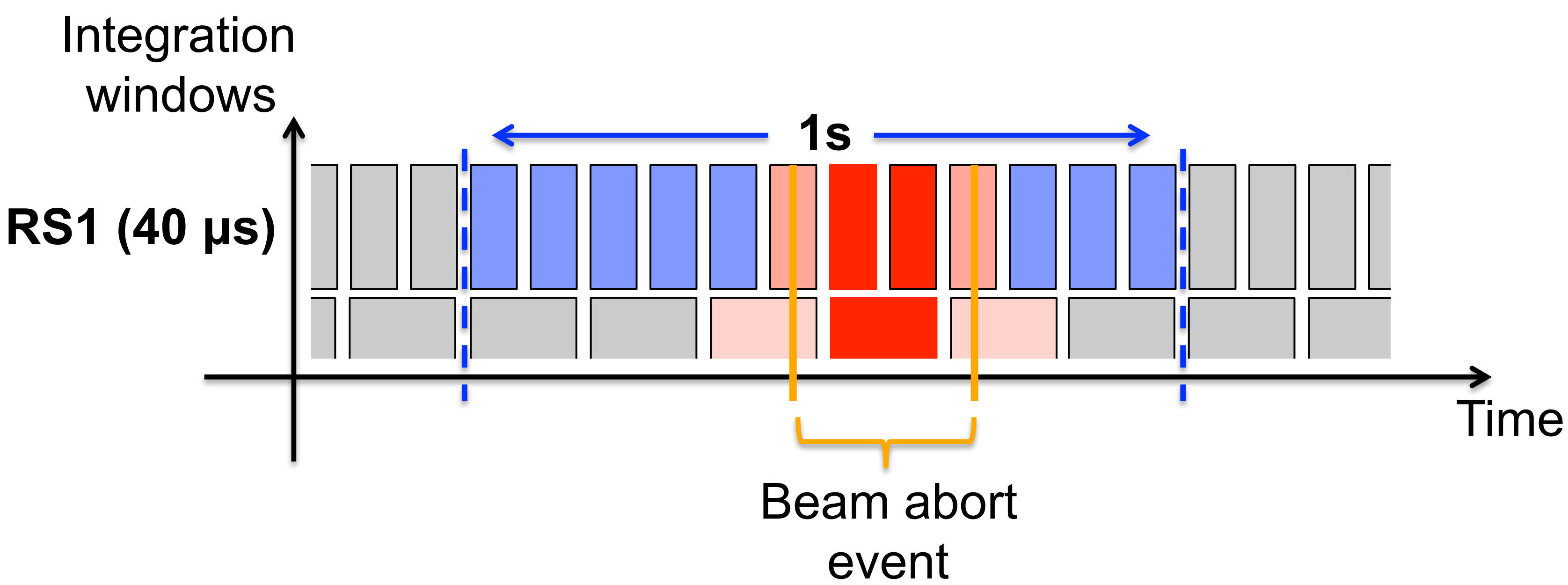
Abort definition:

- Abort threshold are defined for RS1 and for RS12
  - RS1: Protection against very short beam loss events (≤ 40 µs)
  - RS12: Protection against a long term increase in beam background (> 60 s)

BCML: Electrical read out – Beam abort

When a beam abort is initiated a so called ‘post mortem’ read out is triggered.

- The entire RS1 (40 μs) information of the last measurement period (1 s) is read out. In total 25000 measurements.
- Exact timing structure of beam loss event can be investigated.



BCML detector during operation in 2015/16:

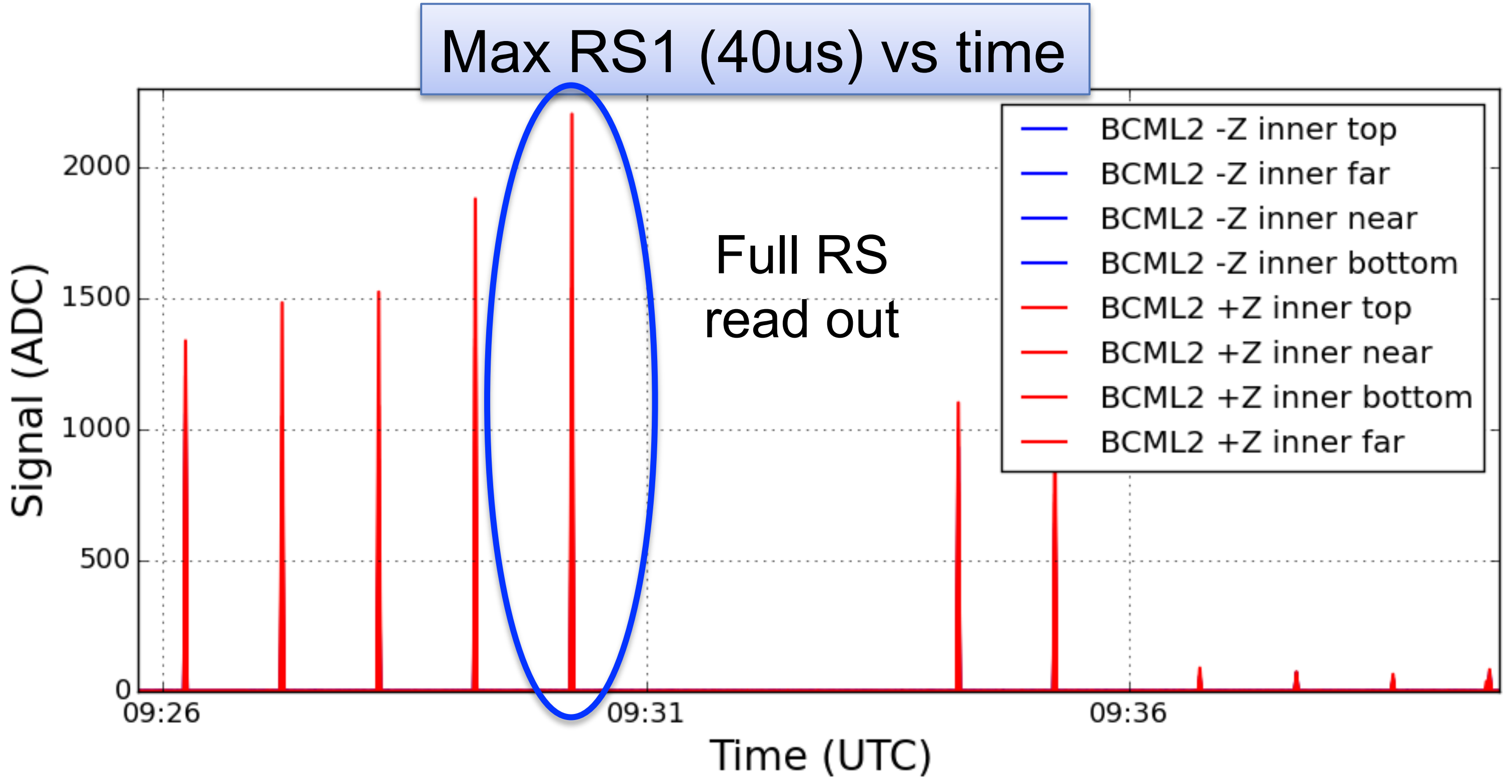
1. Beam losses events:
   - First detector check out with splash events
   - Typical beam loss events (UFOs) measured with BCML
   - Beam los event triggering the LHC beam abort

2. Detector degradation caused by irradiation damage

BCML detector check-out in 2015/16:

Artificially created splash events by closing collimators

- An entire proton bunch was splashed against almost entirely closed collimators.
- Short (≤ 100ns) and intense beam loss event created that could be measured with all BCML sensors



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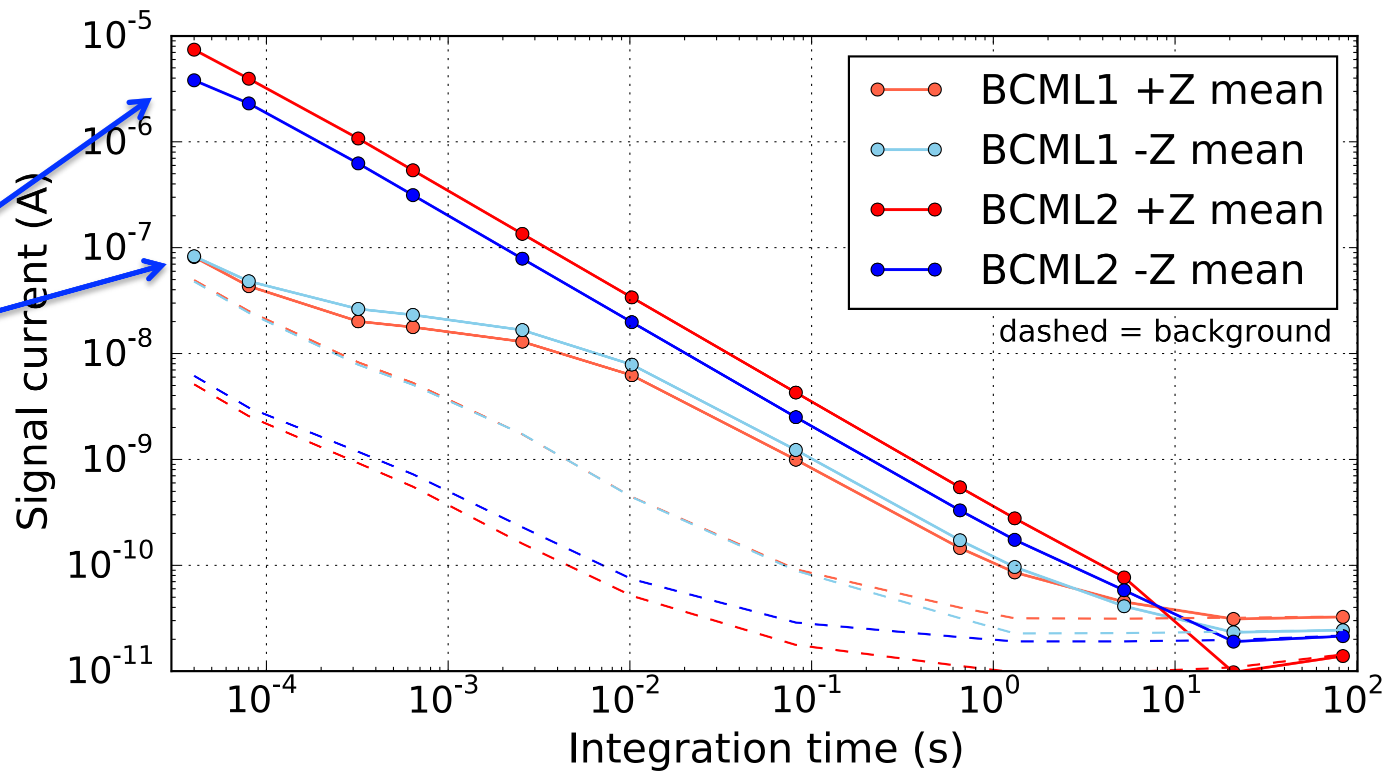
Difference between BCML1/2 caused by a wrong filter

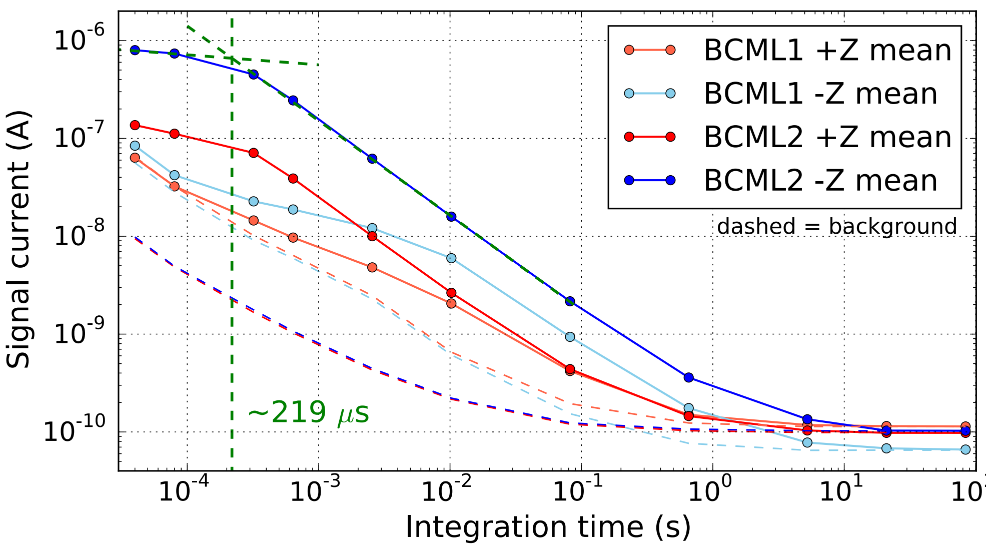


BCML detector operation in 2015/16:
Typical beam loss events – UFOs

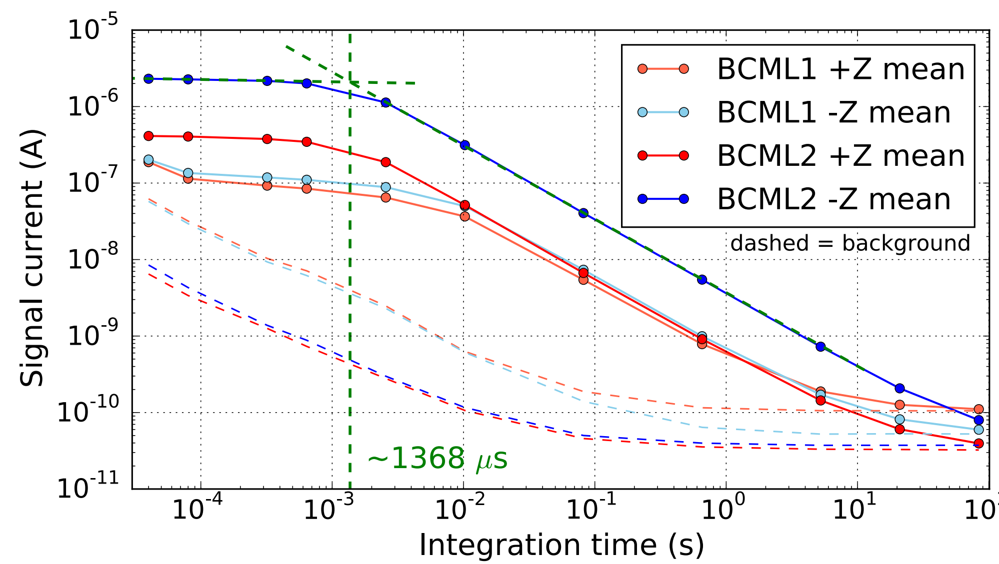
Phenomena of ‘Unidentified Falling Objects’ (UFO) are macroparticles from the beam pipe inside falling onto the proton beams and hence causing beam losses.

Properties:

- Localized beam loss event.
- Typical duration of ~650 µs.
- Gaussian shape of detector signal as function of time



a) Short UFO event



b) Long UFO event

BCML detector performance in 2015/16:
Trigger of Beam Abort on 16th of August 2016

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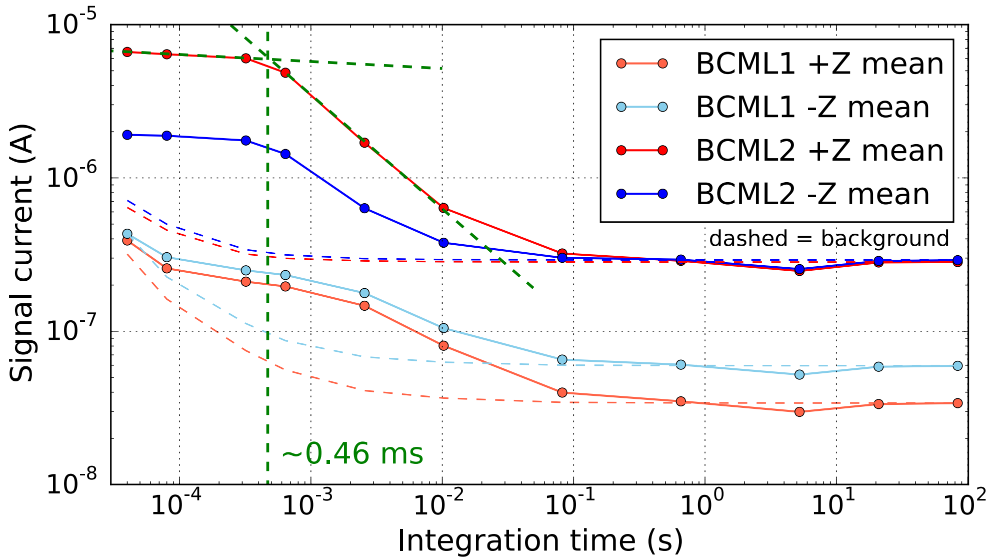
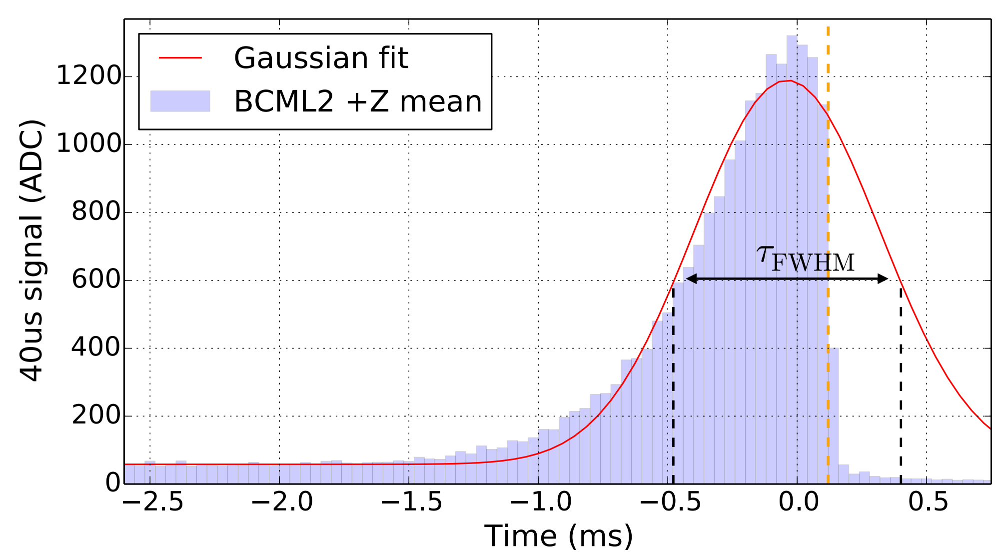
- Highly intense beam loss event event measured by the BCML2 detector.
- 104 % of the beam abort threshold reached.
  - ➢ Neighboring LHC BLM monitor measured 93% of the beam abort.
- Beam loss duration based on running sum spectrum: t~460 µs
- Read out of post mortem (pm) data:
  - ➢ Gaussian shape of beam loss event -> UFO beam loss
  - ➢ UFO time duration based on pm data: t~880 µs



a) Running sum spectrum



b) Read out of pm data

Beam Abort - Global LHC BLM measurements

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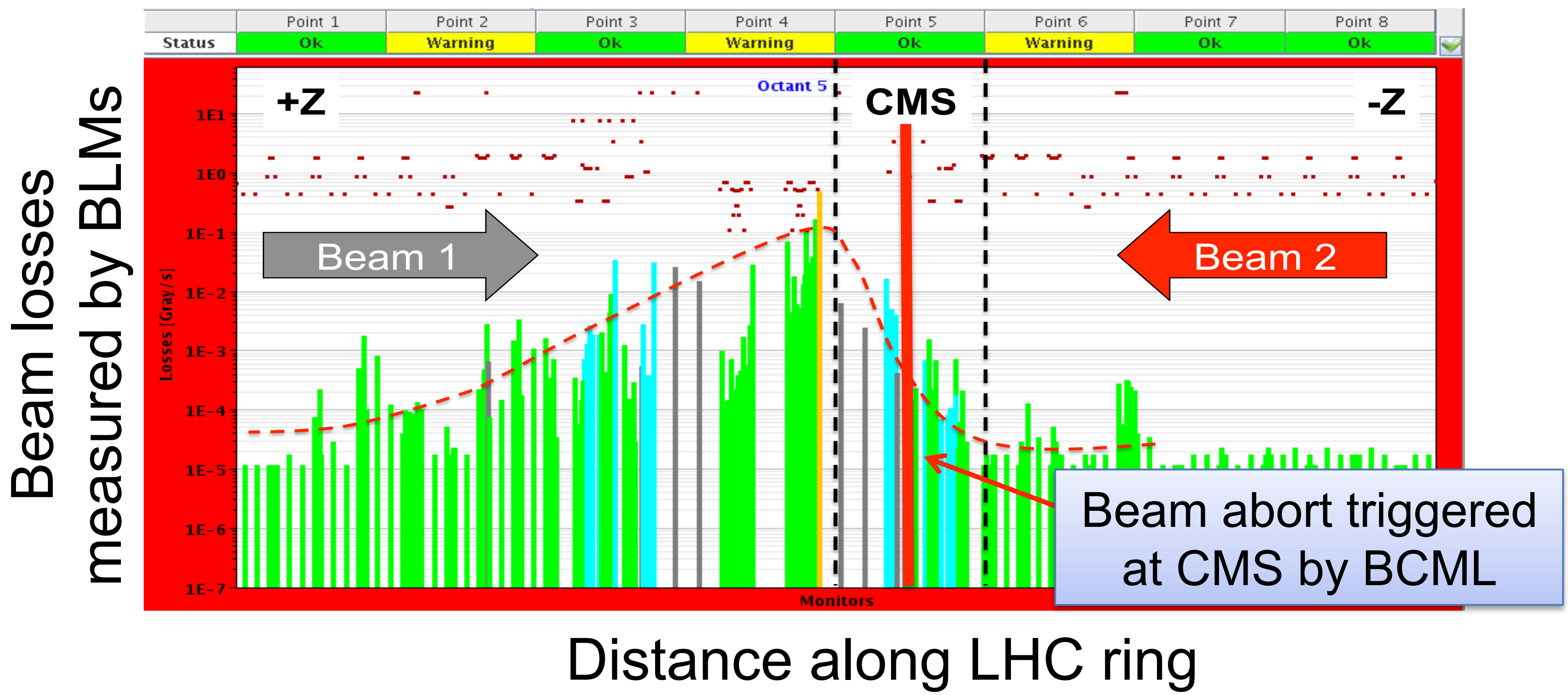
- UFO beam loss measured almost everywhere around the LHC.
- UFO event caused by Beam2 on the –Z side close to CMS (Point 5).
- Increased signal for BCML2 +Z:
  - ➢ Particle scattering through CMS volume causes creation of lots of secondary particle. -> Increased signal on CMS +Z



Radiation induced detector degradation

- Knowing the detector efficiency is essential in order to set the correct beam abort thresholds:
  - ➢ A reduced detector efficiency requires a reduced abort threshold in order to keep the same safety margin.
  - ➢ Detector efficiencies are continuously calculated by comparing current detector signal with the expected signal for an undamaged sensor for nominal luminosity.

- Detector degradation depends strongly from detector location.
  - ➢ BCML2 detector on the –Z side was located close to the CASTOR detector, a source for a high neutron flux.

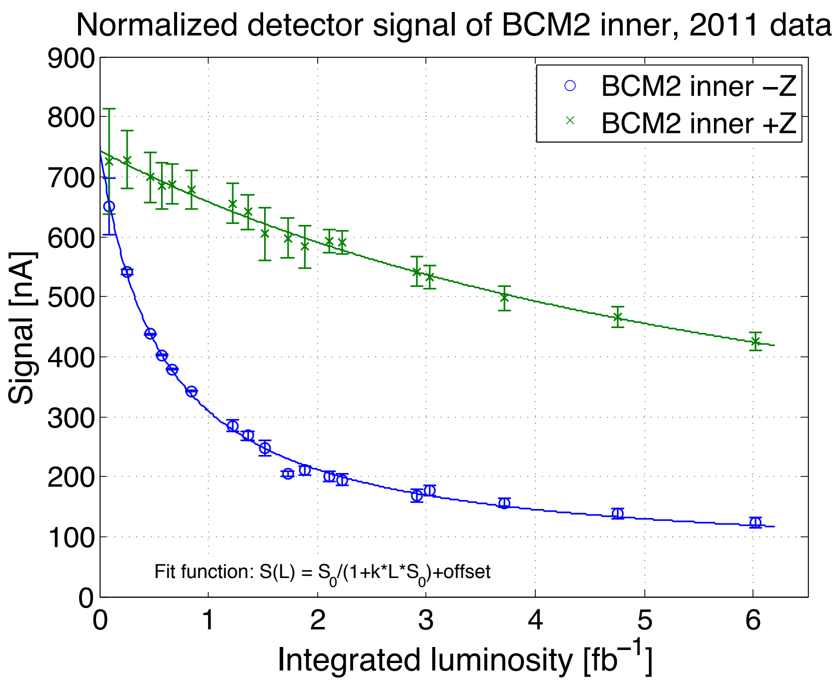


Figure taken from Ph.D. thesis of M.Guthoff

Unexpected strong reduction in signal efficiency due to *diamond polarization*

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- Decrease of detector efficiency was higher than expected compared to laboratory measurements (RD42 [1]).
- This discrepancy can be explained by the particle **rate dependent polarization** of diamond detectors
- Still sensitive enough at current luminosity

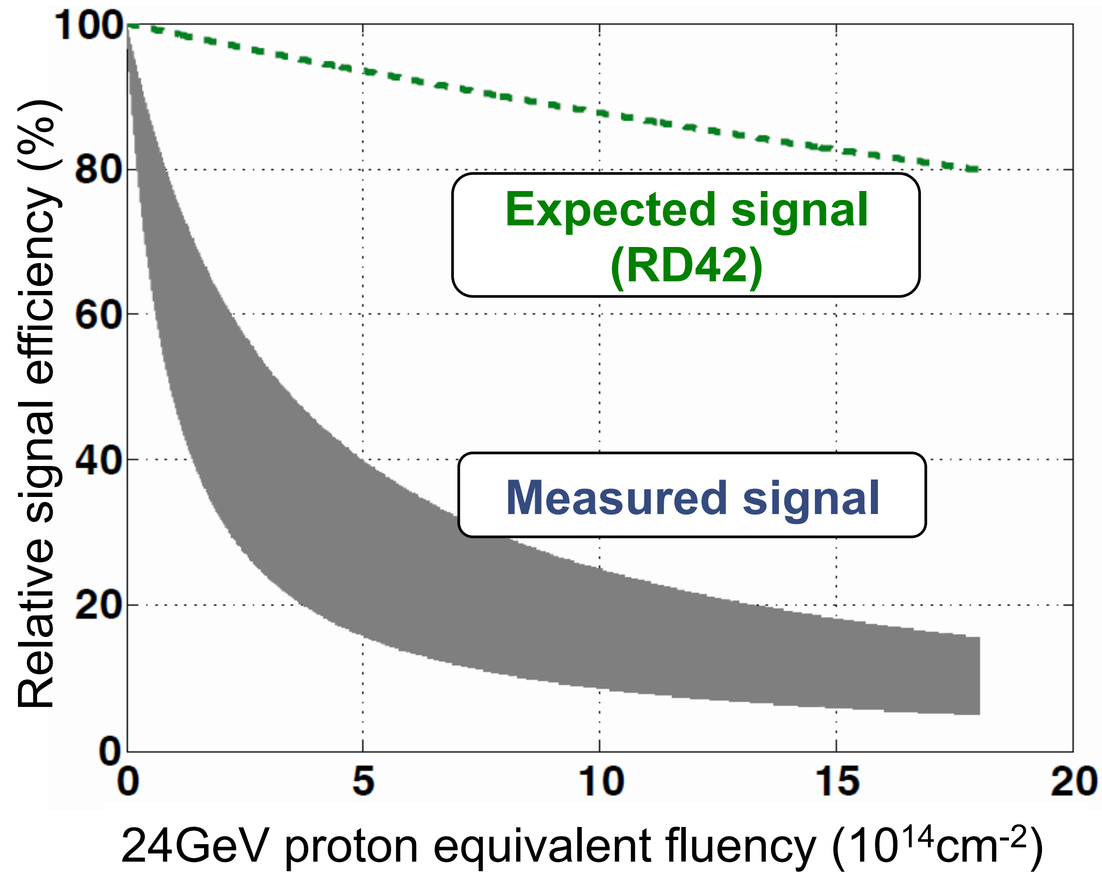

Figure taken from Ph.D. thesis of M.Guthoff

Polarization of an irradiated diamond in a high particle rate environment

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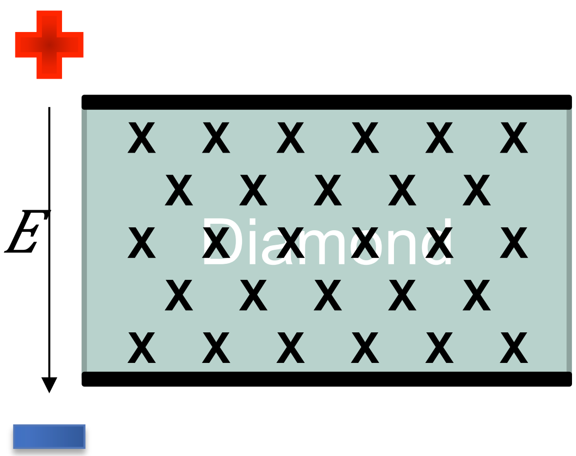
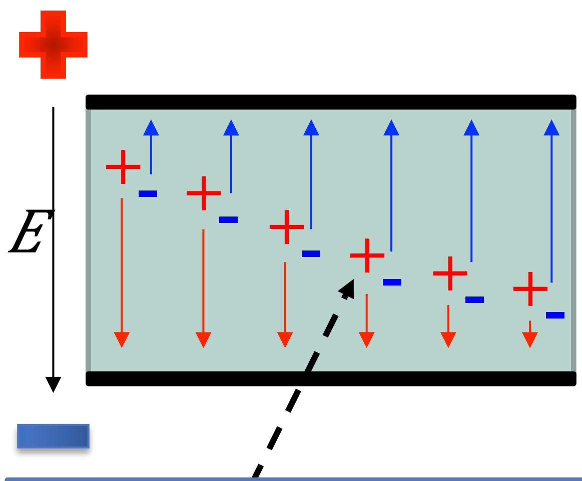
1. Homogeneous trap distribution

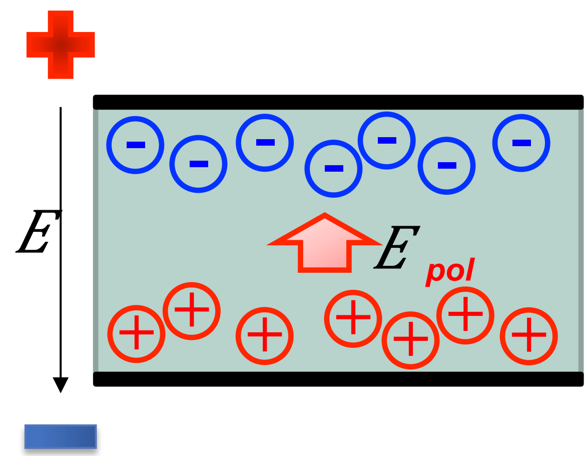


2. Asymmetrical charge carrier density



Homogeneous creation of charge carriers by MIPs

3. Asymmetrical trap filling causes locally reduced E-field



4. Locally reduced electrical field increase recombination and hence results in a reduced charge collection efficiency [2-5].

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Unexpected strong reduction in signal efficiency due to *diamond polarization*

- Decrease of detector efficiency was higher than expected compared to laboratory measurements (RD42 [1]).
- This discrepancy can be explained by the particle **rate dependent polarization** of diamond detectors
- Still sensitive enough at current luminosity
- **Have to find a solution for the upgrade of the BCML sensors!**

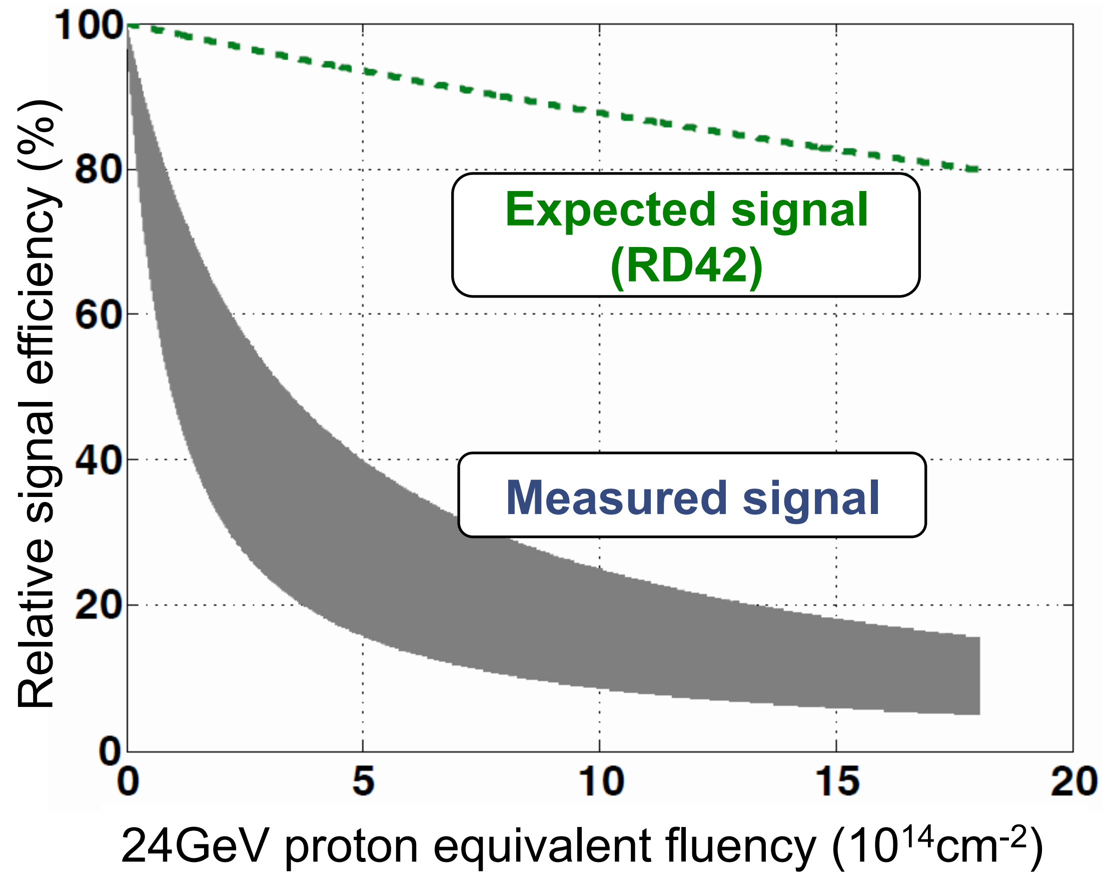


Figure taken from Ph.D. thesis of M.Guthoff

BCML detector upgrades:

1. New detector materials:
   - Poly CVD diamonds (conventional)
   - Diamond on Iridium (DOI)
   - Sapphire

2. Upgrade of the BCML2 detector unit

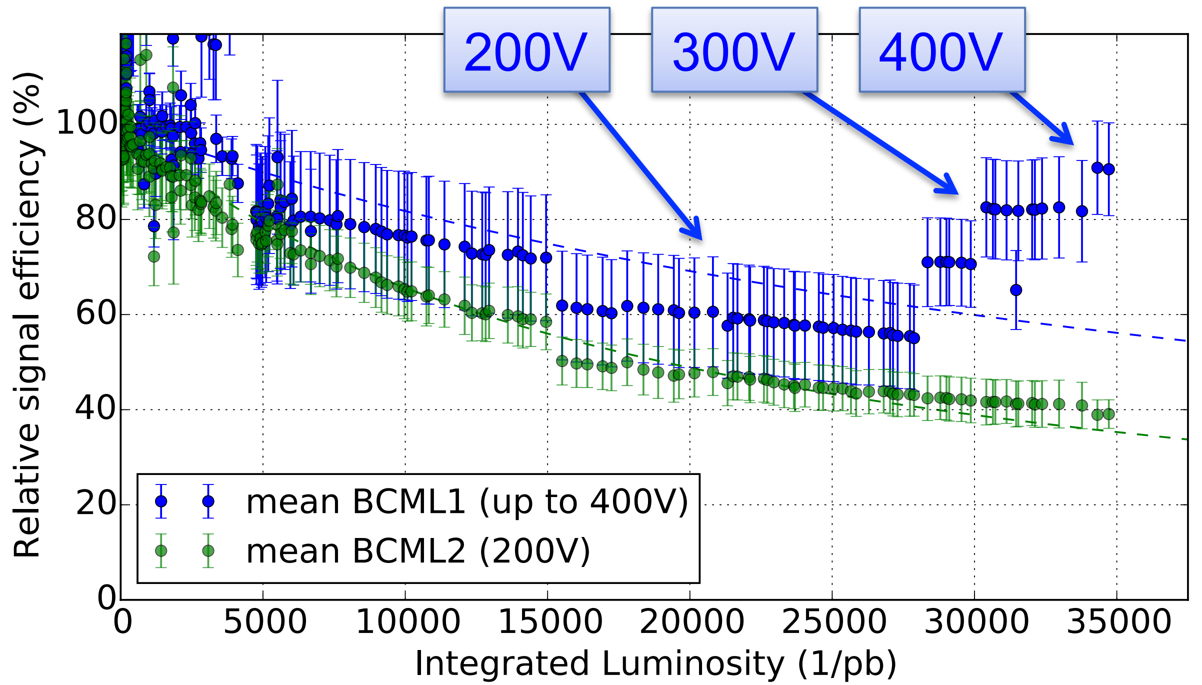
Sensors – pCVD diamonds

Radiation damage:

- pCVD diamonds operated since 2015, suffered radiation damage of currently ~35 fb^{-1}.
- signal reduction of **60%** compared to the initial signal for an undamaged detector.
- Will be replaced with **new** pCVD diamonds.

Operation:

- Bias voltage limited to 200V, creation of erratic currents.
- Erratic currents for pCVD sensor located inside the CMS magnet are suppressed.
  - ➢ Stable signal at 500V
  - ➢ Signal reduction at **500V** around ~ **-10%**



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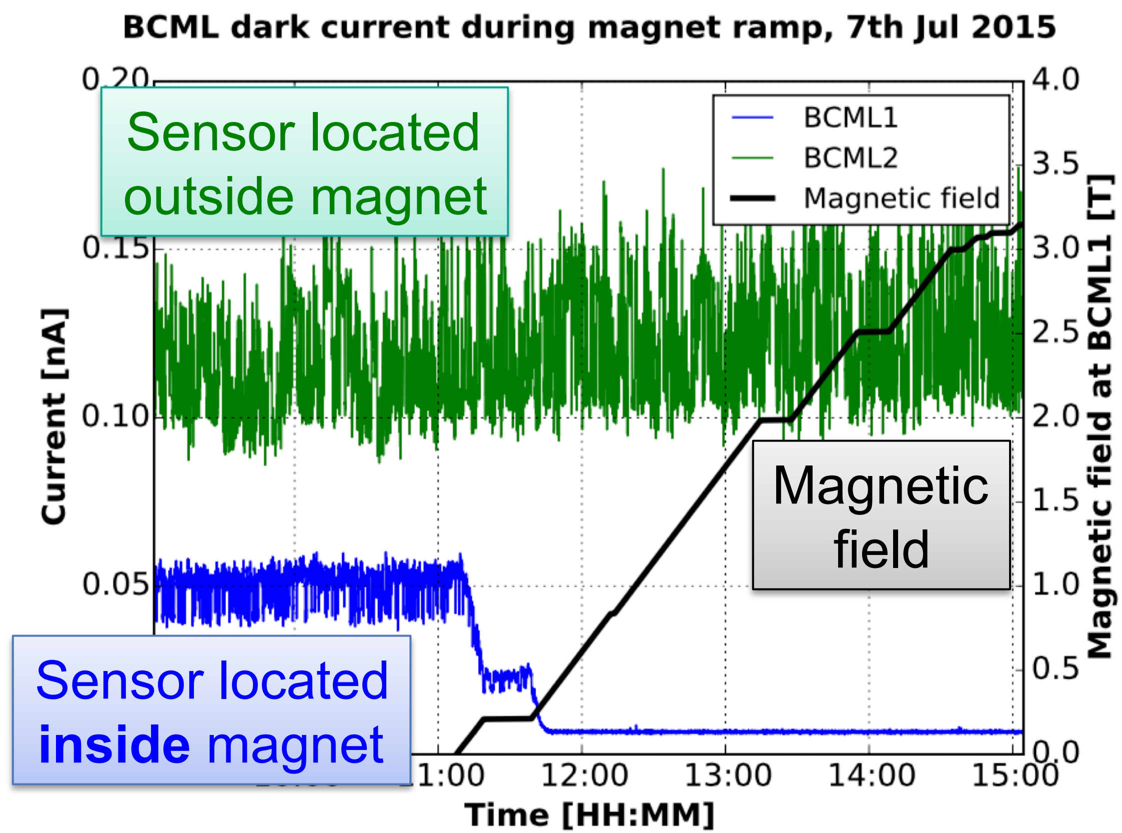

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Sensors – pCVD diamonds: Stability and efficiency

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Comparison of the two BCML detector locations located inside and outside of the CMS magnet:

Sensor located **inside** magnet	Sensor located outside magnet
➢ HV stable up to 500V	➢ HV stable up to 200V
➢ Lower η region, less radiation damage	➢ High η region, high radiation damage
➢ Signal reduction of -10%	➢ Signal reduction of -60%
➢ Sensors can be operated till end of 2017 (another $35fb^{-1}$ expected)	➢ Sensors have to be replaced

BCML detector upgrades:
Sensors – Diamond on Iridium (DOI)

DOI properties:

- Heteroepitaxial growth of CVD diamonds uses iridium as substrate
  - ➢ Can be grown on wafer size!
- Almost sCVD diamond quality.
- Stable signal current at high bias voltages (tested up to 1.8kV)

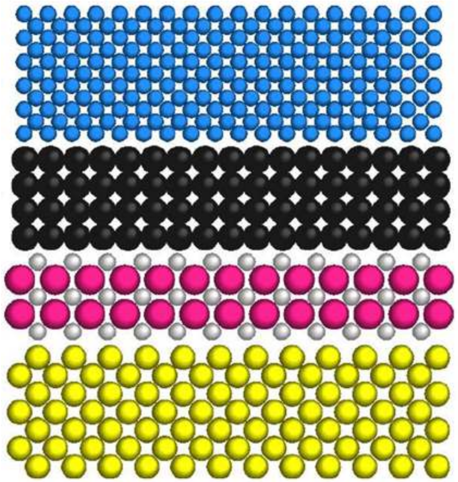
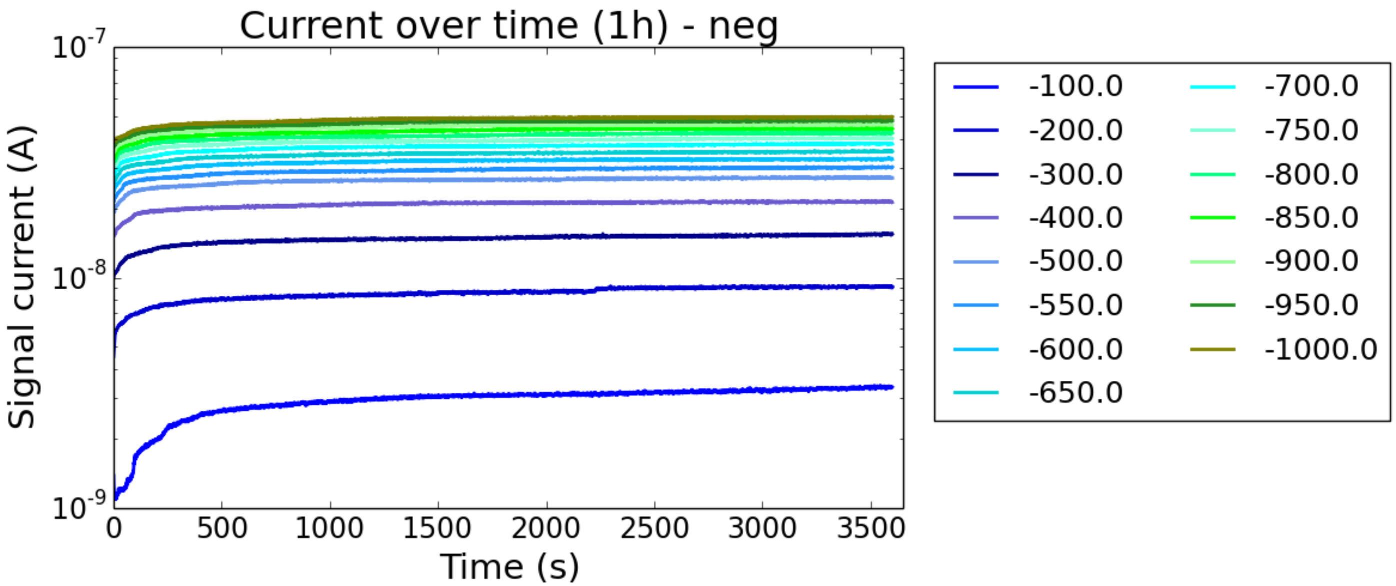


Figure taken from [6].

2016/17:

- 5 DOI diamonds will be installed.
- Gaining experience in terms of radiation damage.
- Max. operation voltage will be limited to 500V.



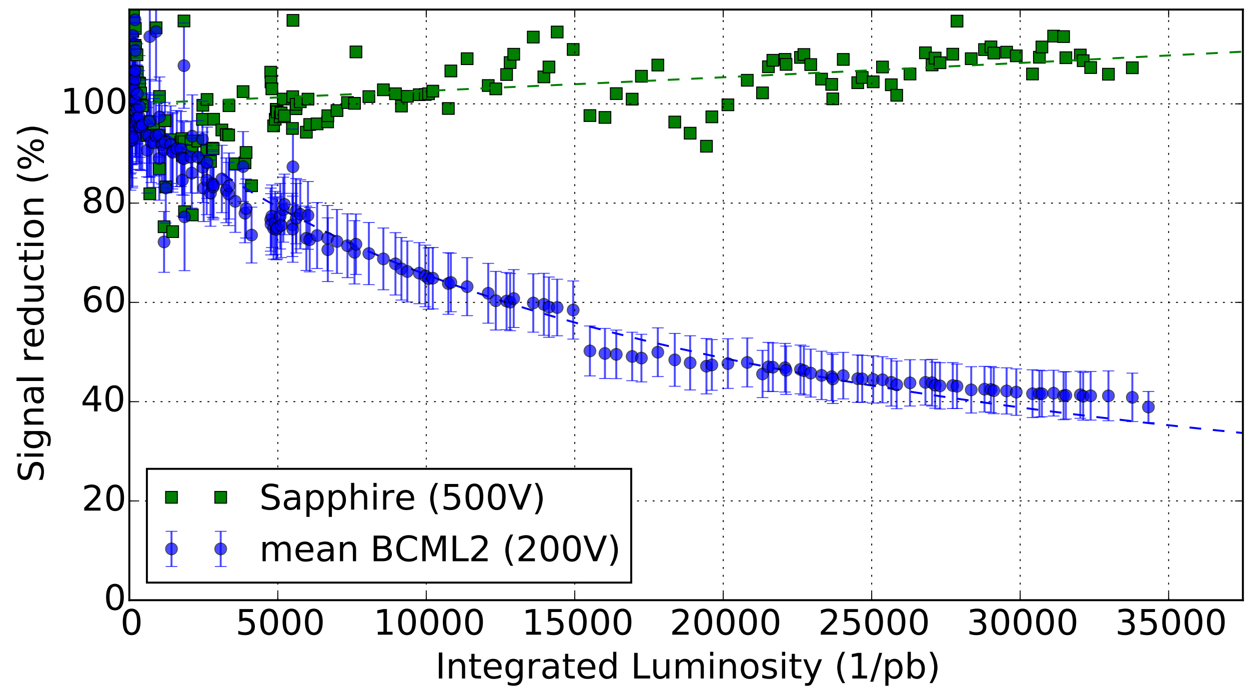
BCML detector upgrades:
Sensors – Sapphires

Properties:

- Sapphire is chemically aluminium oxide Al_2O_3
- Is industrially produced and grown on wafer size.
  - ➢ Typical application are shatter resistant windows, display windows for smartphones
  - ➢ Low cost
- Large band gap of 9.9 eV
- Very low CCE of ~ 5%

First experience:

- Signal around 35x smaller compared to pCVD of comparable size
- Signal remains constant with respect to present integrated luminosity of 35 fb^{-1}



Upgrade of the BCML2 detector unit - Motivation

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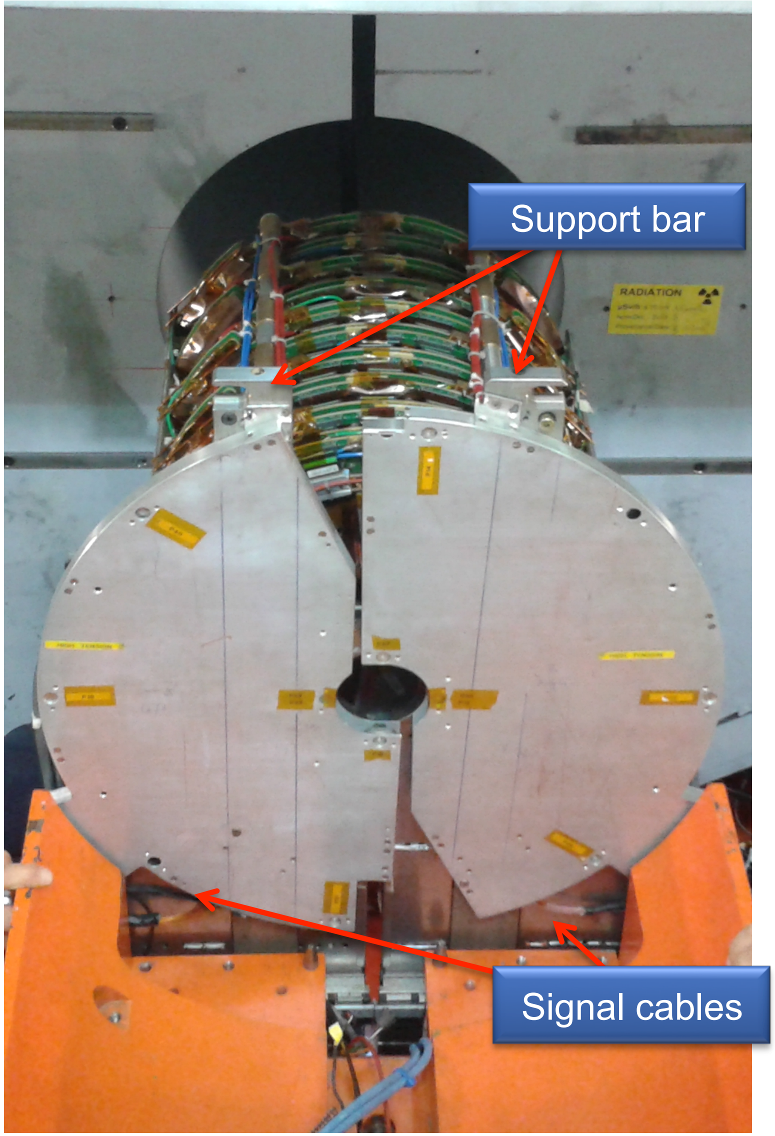
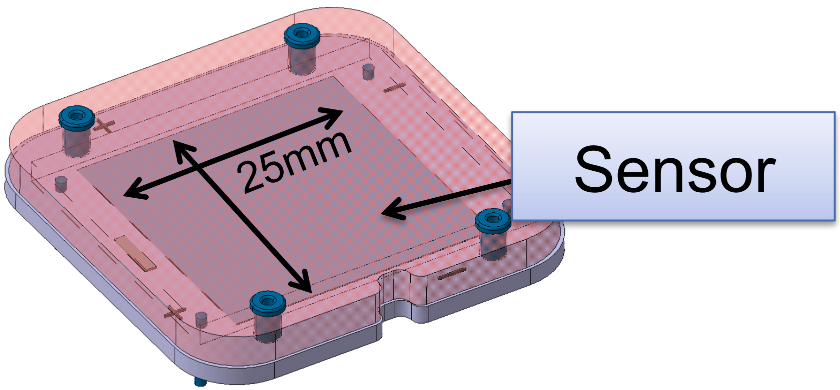
1. Replacing or switching of diamonds sensors or of entire wheel should be possible with *minimum effort* and as *fast* as possible.
2. Regarding Phase 1: Mechanics have to be adjusted to increased beam pipe diameter
3. New design should allow the installation of sensors of different sizes:
   - ➢ Possible usage of 25x25 mm^2 sapphire sensors



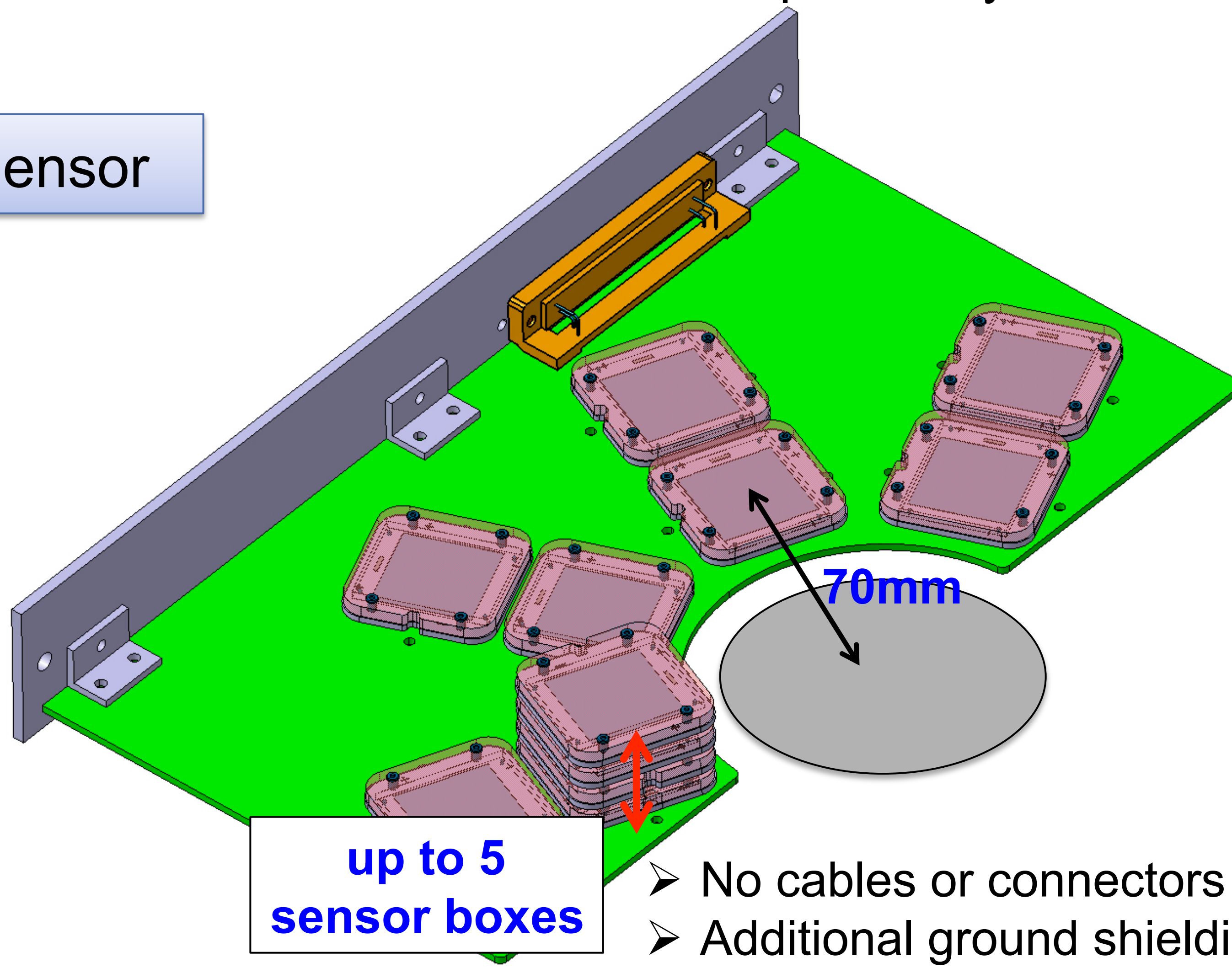
Upgrade of the BCML2 detector unit

Sensor mounted in boxes



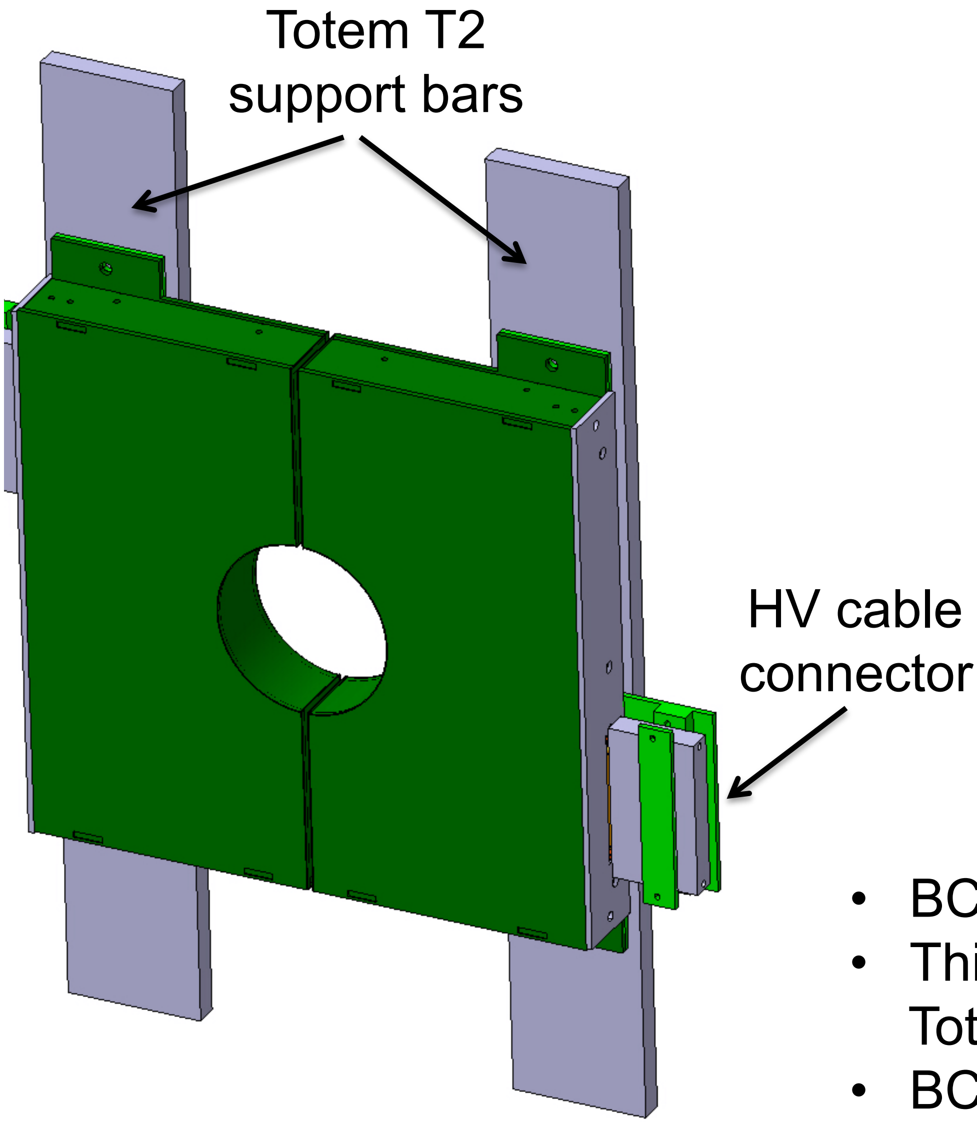
- Plug & Play connection via 4 pins
- Can be stacked
- Provide a Faraday cage
- Ground plate exchangeable:
  - ➢ different detector geometries possible (10x10 or 25x25 mm^2)

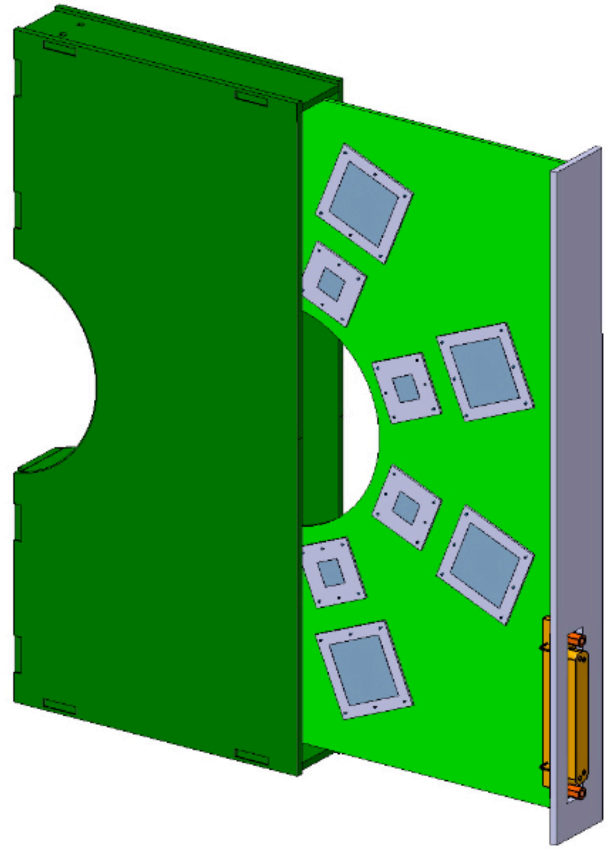
BCML2 wheel will be replaced by a PCB



- ➢ No cables or connectors
- ➢ Additional ground shielding reduces noise pick up

Upgrade of the BCML2 detector unit





- BCML2 PCB will be protected by a box.
- This box will be permanently mounted on the Totem T2 support bars.
- BCML2 PCB can easily be removed from protection box -> Quick access!

Conclusions

Operation during LHC Run2:

- BCML measured several beam loss event, mainly UFO events.
  - Beam abort once triggered to prevent further damage to the CMS detector.
- Radiation induced signal degradation:
  - At the most exposed detector location a signal reduction of ~60% observed.
  - Signal degradation severely enhanced by diamond polarization.
  - Increased bias voltage of 500V reduces signal reduction to ~10%.
- New BCML sensors:
  - pCVD, DOI and sapphire sensors.
  - Sapphire in particular seems very radiation hard.
- Upgrade of the entire BCML support hardware:
  - Different sensors sizes mountable.
  - Stacking of sensors possible .

References:

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3. M. Guthoff et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 730, 168 - 173 (2013).
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6. M. Mayr et al., *Efficiency and mechanism of dislocation density reduction during heteroepitaxial growth of diamond for detector applications*, ADAMAS workshop - talk (2013).

Backup: TCT pulse modification with increased radiation damage

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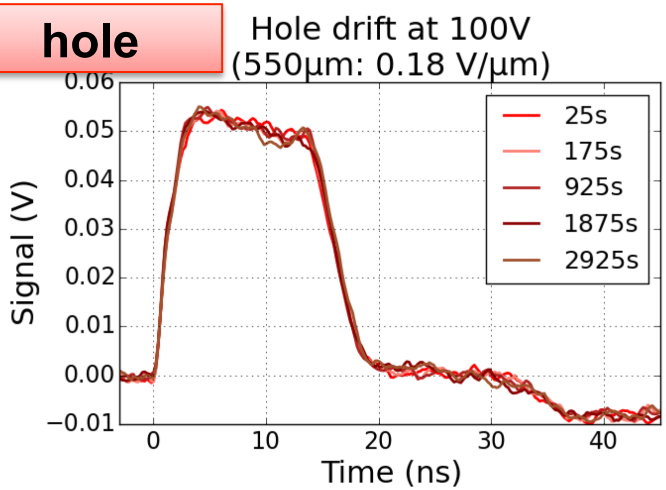
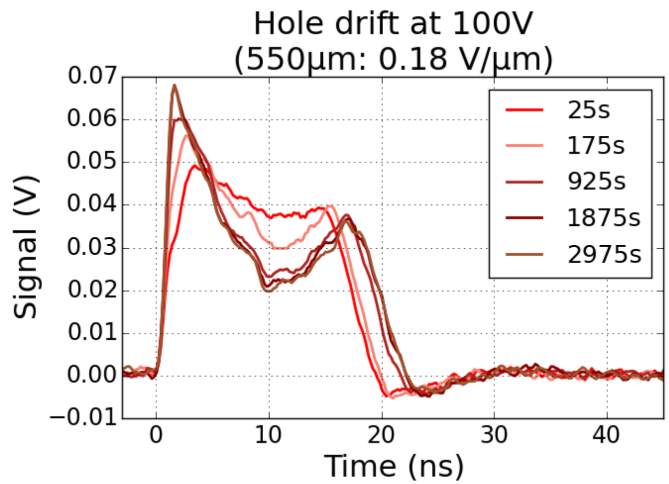
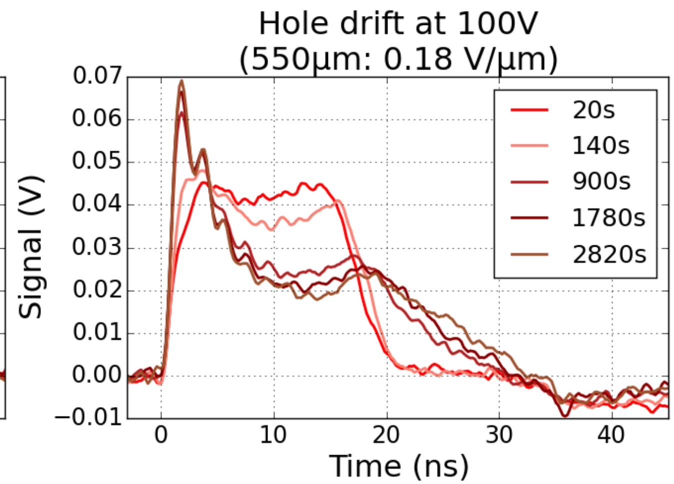
HV = 100V

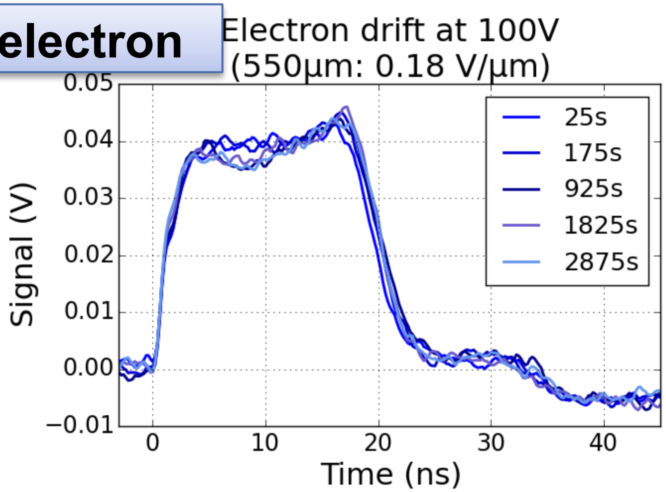
hole

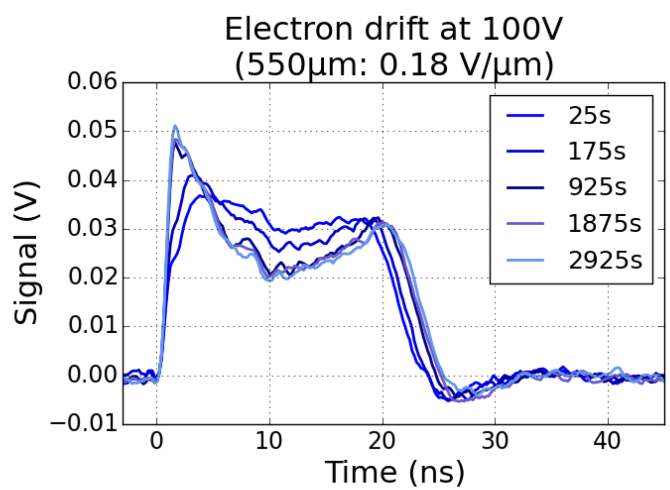


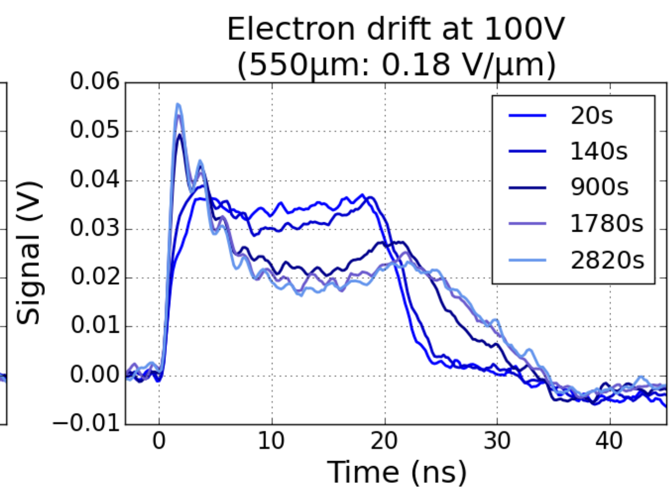




electron



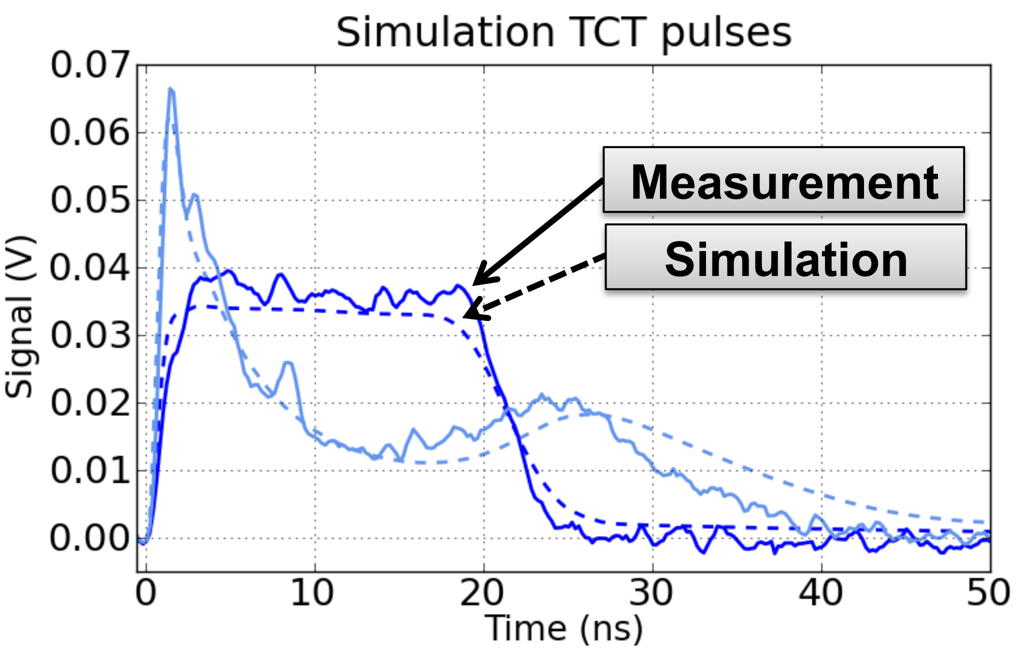


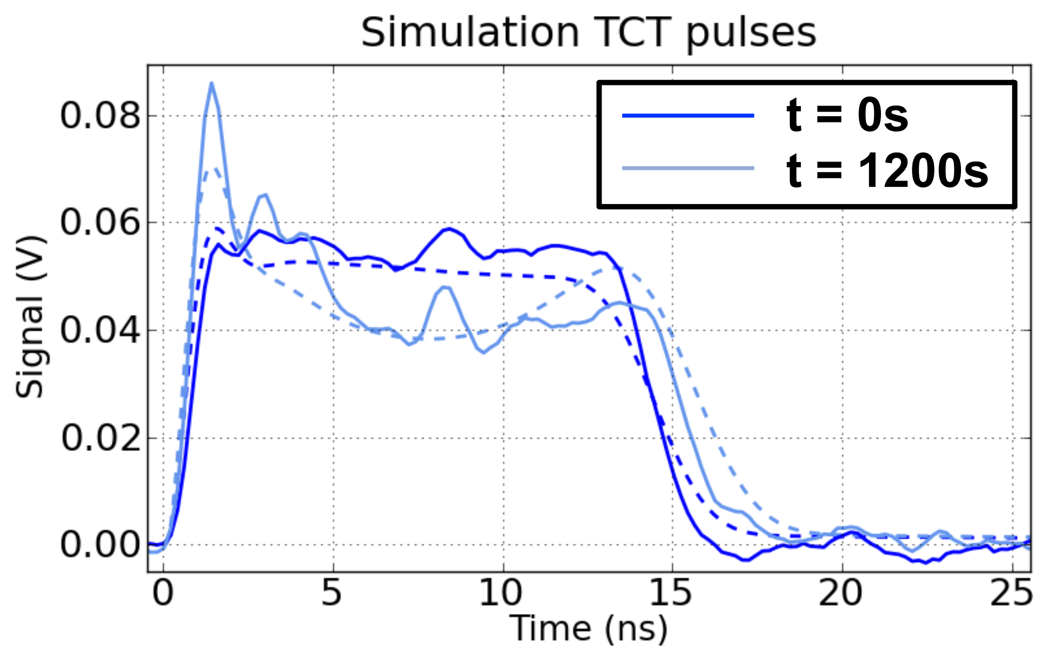


unirradiated | **f = 6.3 x 10^{12} 24GeV p_{eq}** | **f = 1.3 x 10^{13} 24GeV p_{eq}**

CERN BRIL

Backup: TCT pulse measurement vs simulation for an irradiated diamond



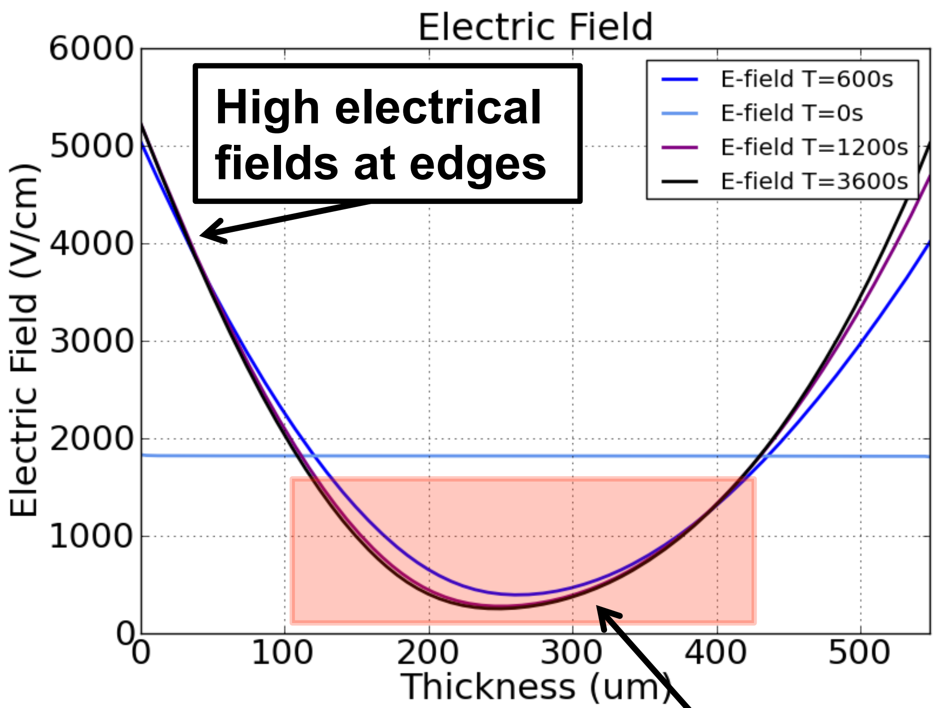


HV = 100V

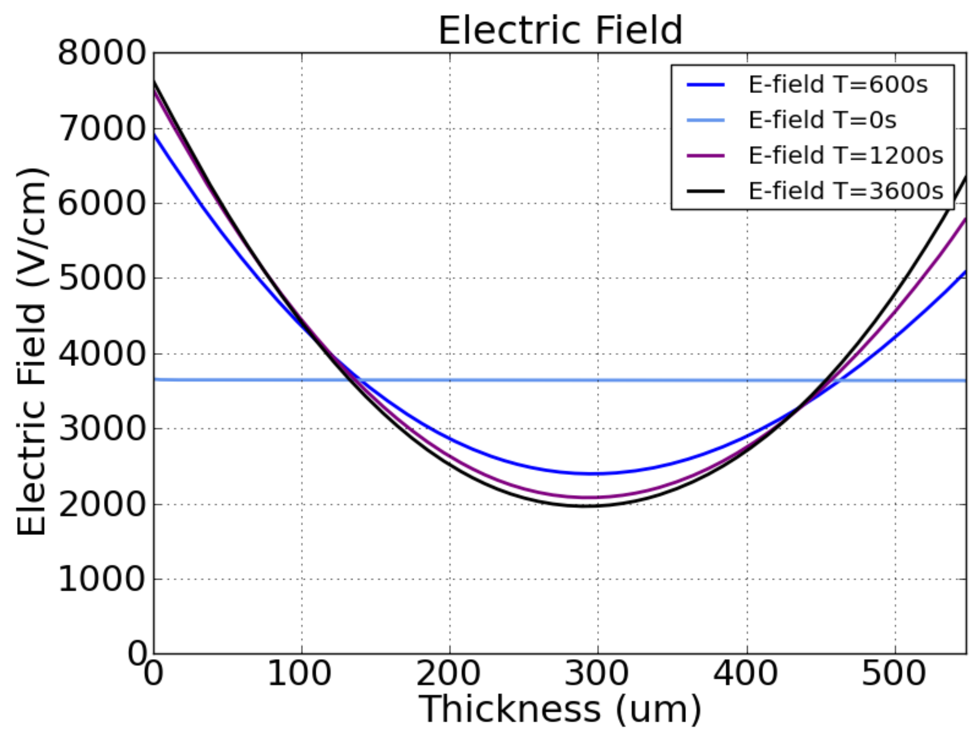
HV = 200V

Backup: Corresponding simulated electrical field

HV = 100V



HV = 200V



Low electrical field supports recombination of charge carriers -> reduced CCE!