# Radiation damage in diamond sensors at the CMS experiment of the LHC

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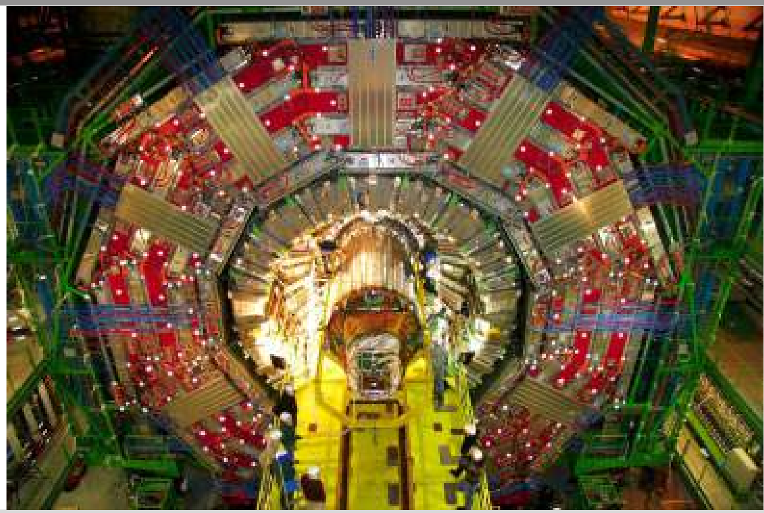
IEKP-KIT / CERN

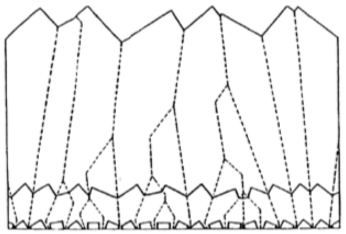


# Overview

- Diamond detectors for Beam Condition Monitor (BCM) at the CMS detector of the LHC.
- Radiation environment at diamond detector locations in CMS.
- Diamond signal under irradiation.
- Measured detector efficiency as function of dose.
  - Single-crystalline vs. poly-crystalline diamonds.
  - Charge collection distance (CCD) measurements of irradiated diamonds.
  - Measurements of irradiated diamonds using the transient current technique (TCT).

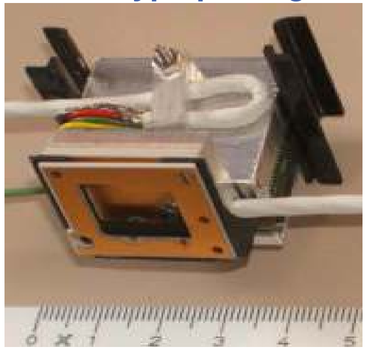
# Diamond detectors used in CMS BCM

- **Poly-crystalline CVD diamonds (pCVD) are used as particle detector. $1x1x0.4\ cm^3$.**
- **Measurement of induced current due to crossing charged particles.**
- **Additionally a single-crystalline diamond (sCVD) is installed to compare performance of both diamond types.**
- **Main purpose is the protection of the Silicon Tracker from damaging beam loss events.**
  - **In case of too high beam losses an automatic emergency beam dump is performed.**

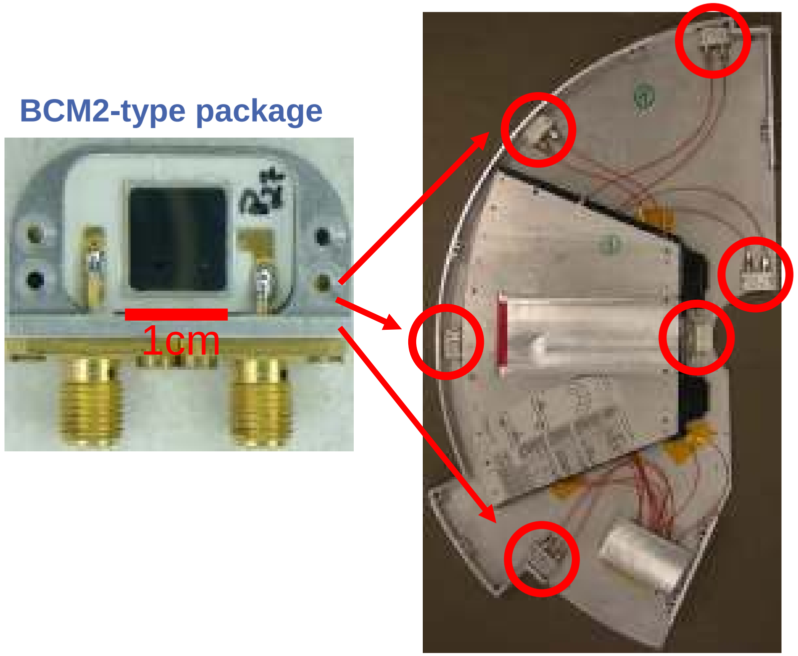


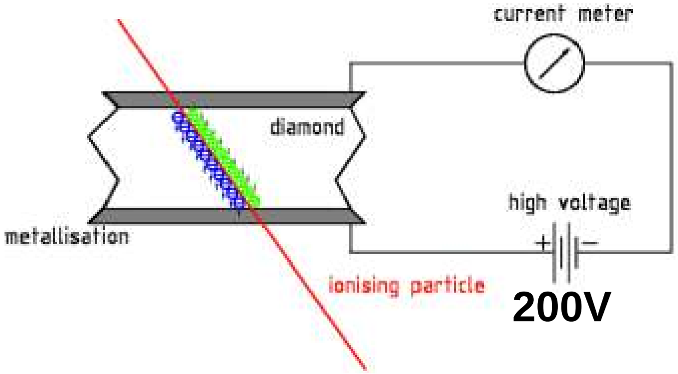
**Cross section trough poly-crystalline diamond**

**BCM1-type package**

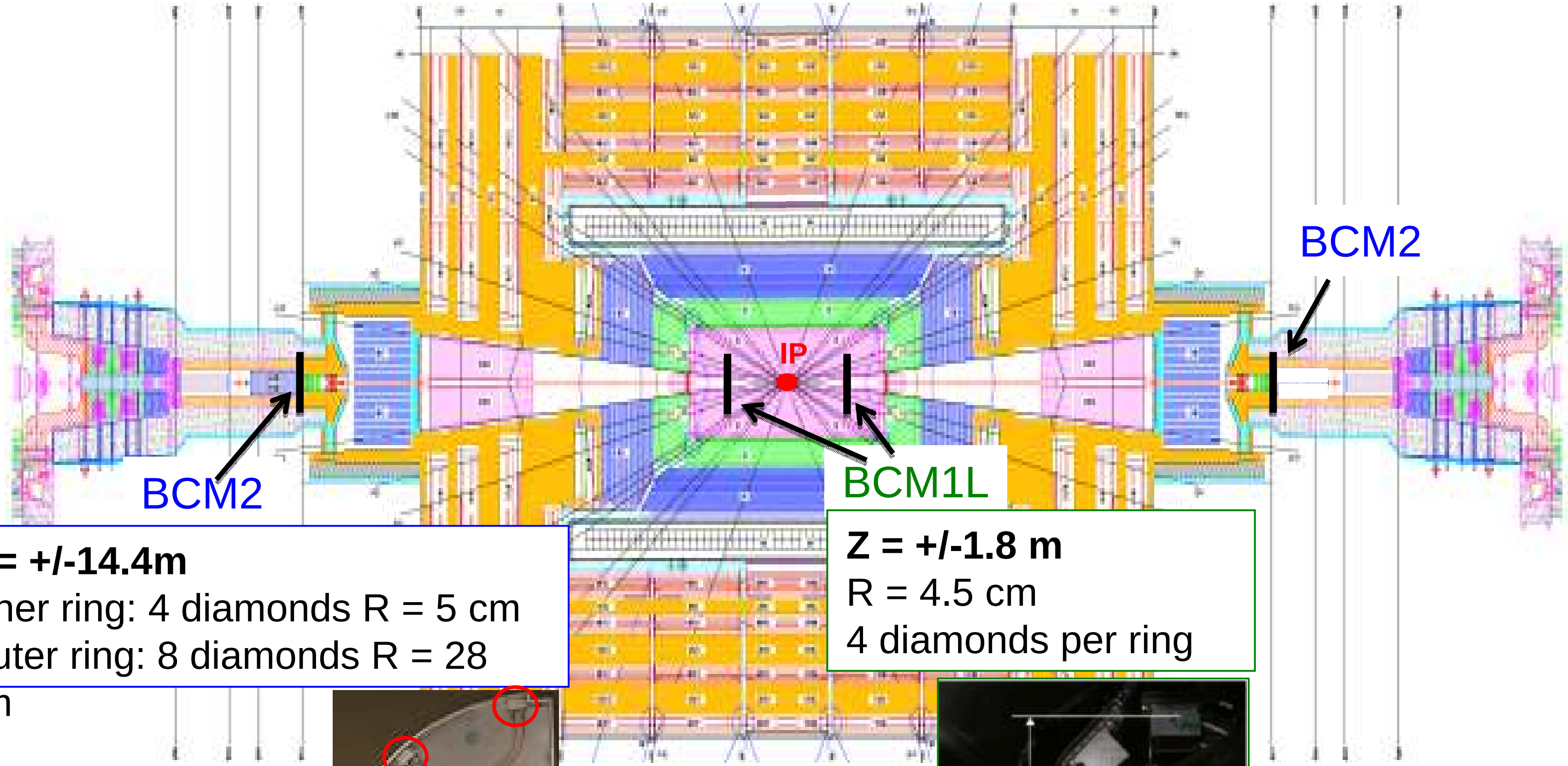


**BCM2-type package**



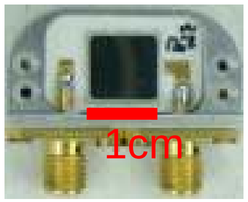



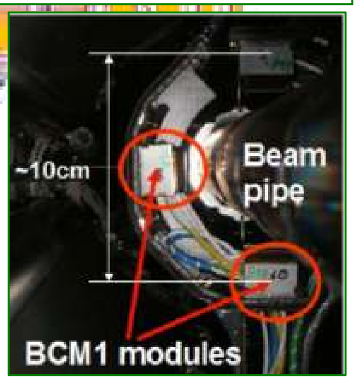
# Installation in CMS




**Z = +/-14.4m**
Inner ring: 4 diamonds R = 5 cm
Outer ring: 8 diamonds R = 28 cm

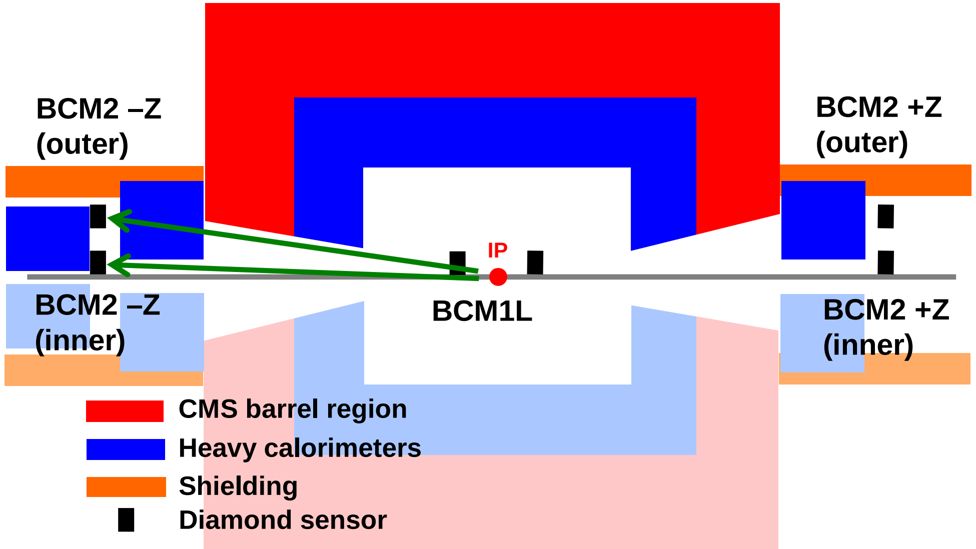
**Z = +/-1.8 m**
R = 4.5 cm
4 diamonds per ring



# Radiation environment of detector groups

- Radiation environment simulated with FLUKA monte-carlo.
- Radiation damage mostly inflicted by low energy neutrons (generated at heavy calorimeters).
- BCM1L far away from calorimeters.
- BCM2 on –Z end directly in front of CASTOR, a heavy quartz tungsten calorimeter.
- Data is averaged over groups with same radiation environment.




| | neutrons | charged particles |
|---|---|---|
| BCM1L | low | medium |
| BCM2 -Z inner | high | high |
| BCM2 -Z outer | high | low |
| BCM2 +Z inner | medium | high |
| BCM2 +Z outer | medium | low |

# Signal evolution as function of fluence

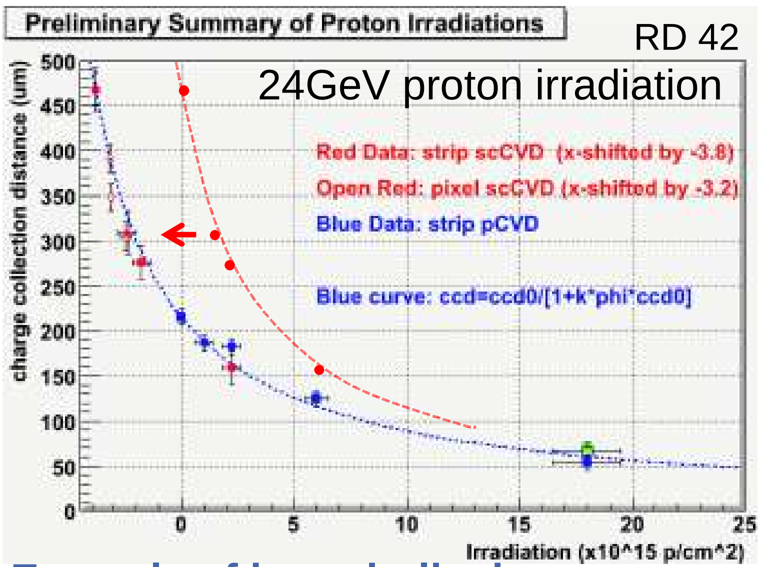
**Assume:**

**i.Nr. of defects N increases with luminosity L:** $N(L) = N_0 + k \cdot L$ **(1)**

**ii.Signal decrease proportional to N, i.e.** $S \propto 1/N$ **(2)**

$N_0$: number of initial defects
k: damage parameter
L: luminosity
S: signal

**(2) in (1):** $1/S = 1/S_0 + k \cdot L$ **or** $\boxed{S(L) = \frac{S_0}{1 + k \cdot L \cdot S_0}}$




**Example of hyperbolic damage curve.**

$\boxed{CCD(\Phi) = \frac{CCD_0}{1 + k \cdot \Phi \cdot CCD_0}}$

CCD: charge collection distance
$\Phi$: fluence

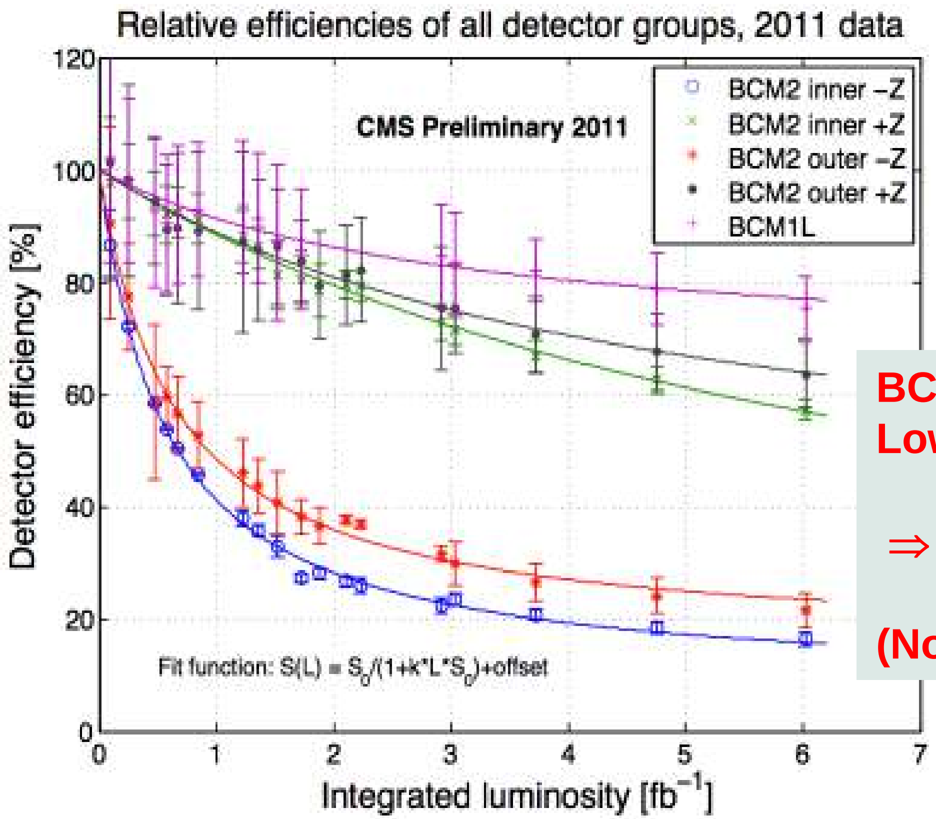
**Hyperbolic decrease implies:**

**Fresh crystals, like scCVD $\Rightarrow$ on steep part, fast decrease of signal as fct. of $\Phi$**

**Damaged crystals $\Rightarrow$ slow decrease of signal**

# Signal evolution for different BCM positions

- **Signal normalized to instantaneous luminosity is used to calculate detector efficiencies relative to the initial values.**
- **Signal decrease in BCM2 -Z about factor 10 higher than on BCM2 +Z.**




**FLUKA simulated hadron flux**

| Hadron fluence [/cm²/fb⁻¹] | |
|---|---|
| **BCM2 +Z** | **3.5 * $10^{12}$** |
| **BCM2 –Z** | **7.3 * $10^{13}$** |

**BCM2-Z: 20 times more fluence because of Low energy neutros from CASTOR calorimeter**

**⇒ factor 4 less signal after 6 $fb^{-1}$**

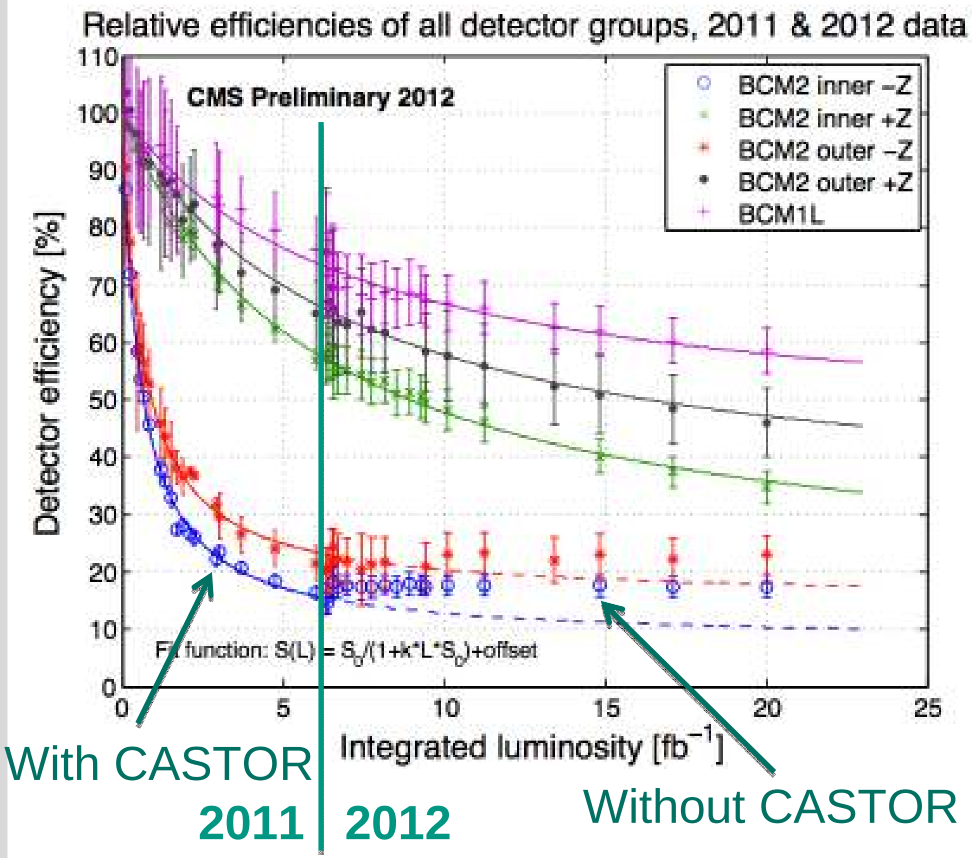
**(Note: LHC takes now about 1 $fb^{-1}$ per week!)**

**Fit used:**

$$S(L) = \frac{S_0}{1 + k \cdot L \cdot S_0} + \text{offset}$$

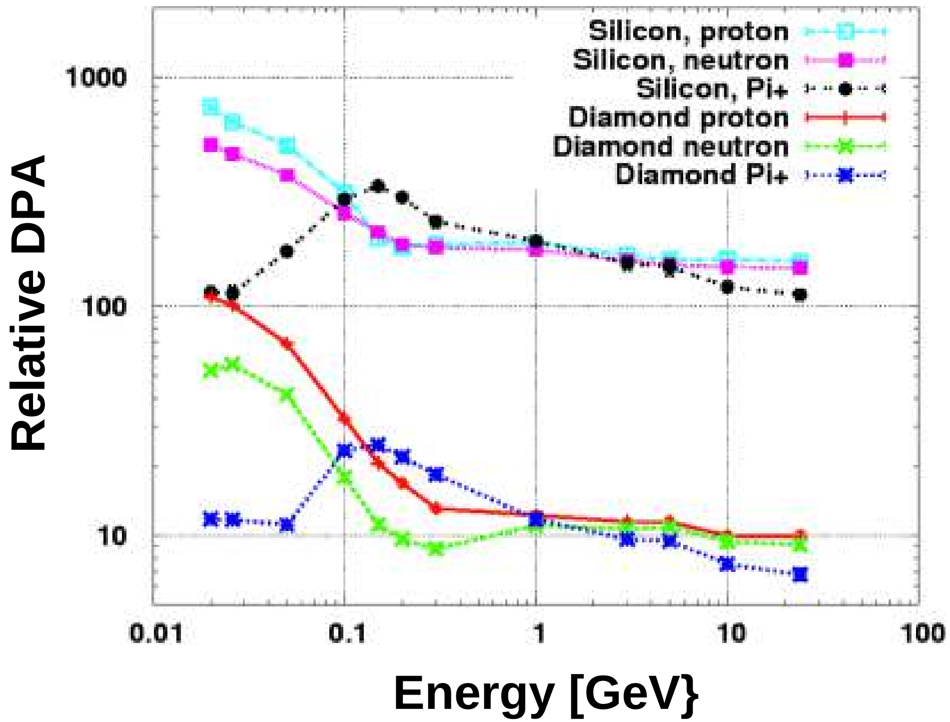
**offset: ~10%**

## Signal evolution in 2012




- For the detectors of BCM1L and BCM2 +Z the decrease continues in 2012 like in 2011.
- CASTOR removed after 2011
  - The BCM2 –Z detectors are not in intense neutron field any more.
  - The strong decay does not continue.
  - No change in efficiency measureable in 2012, as expected from the fact that they are in the flat part of the hyperbolic function.

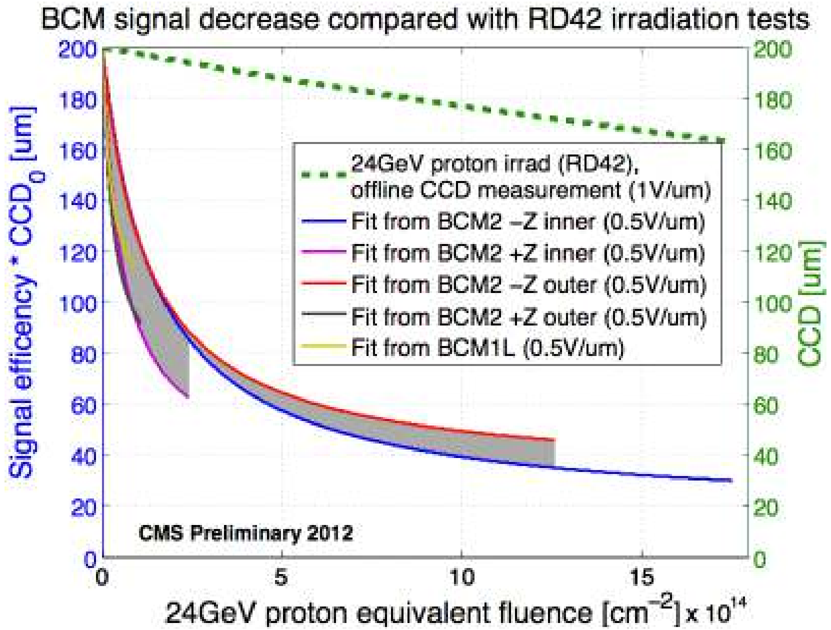
# Energy dependence of radiation damage




Simulated DPA values for protons, neutrons and pions in diamond and in silicon (Thesis: Steffen Müller KIT)

- **Aim is comparison of mixed irradiations with n and p at different energies with mono-energetic test beam.**
- **Use displacement per atom (DPA) calculation of the FLUKA simulation package to scale different energies and particles.**

## Signal as function of 24 GeV proton equivalent



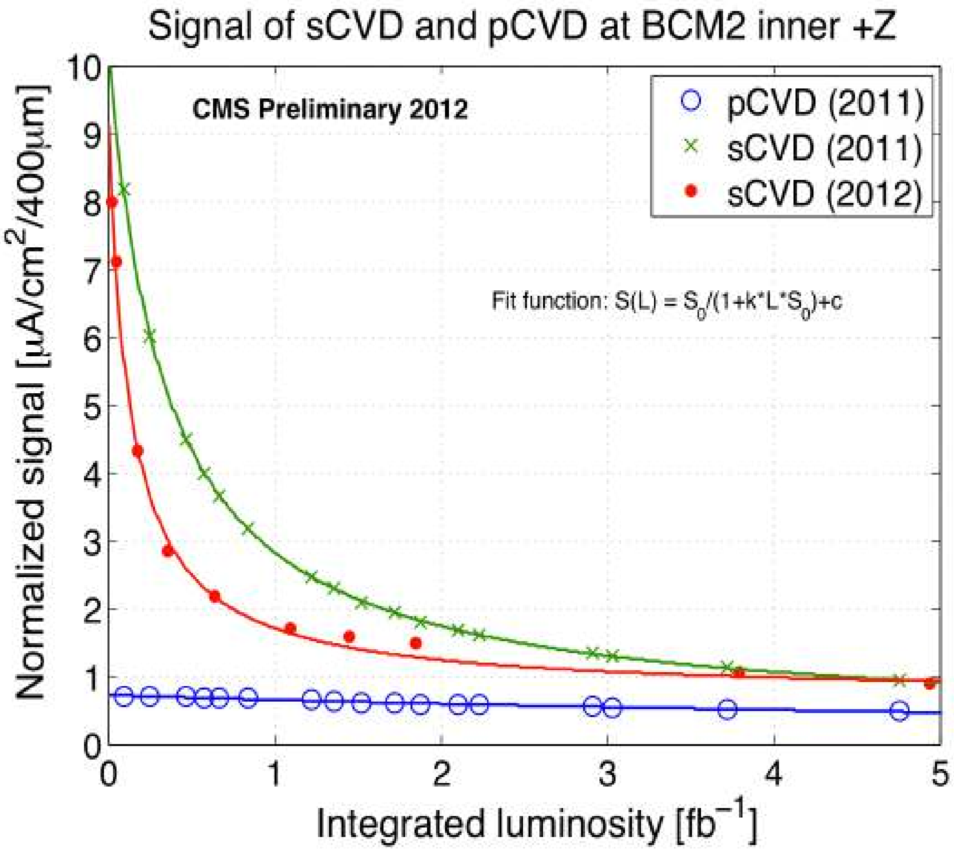

- **Simulate DPA values of the CMS radiation field at diamond locations and scale to *equivalent fluence of 24 GeV protons*.**
- **Data of different BRM positions on top of each other within about factor 2-3.**
- **Direct comparison with RD42 test beam data shows huge discrepancy.**

Using a hyperbolic fit (without offset) a **k** value can be calculated:

| | RD42 | BCM1L | BCM2I -Z | BCM2I +Z | BCM2O -Z | BCM2O +Z |
|---|---|---|---|---|---|---|
| k-fit [$\mu m^{-1} cm^{-2}$] | $6.5 \times 10^{-19}$ | $5.0 \times 10^{-17}$ | $2.3 \times 10^{-17}$ | $5.7 \times 10^{-17}$ | $1.7 \times 10^{-17}$ | $6.8 \times 10^{-17}$ |

**Discrepancy to test beam between factor 25 and 100.**

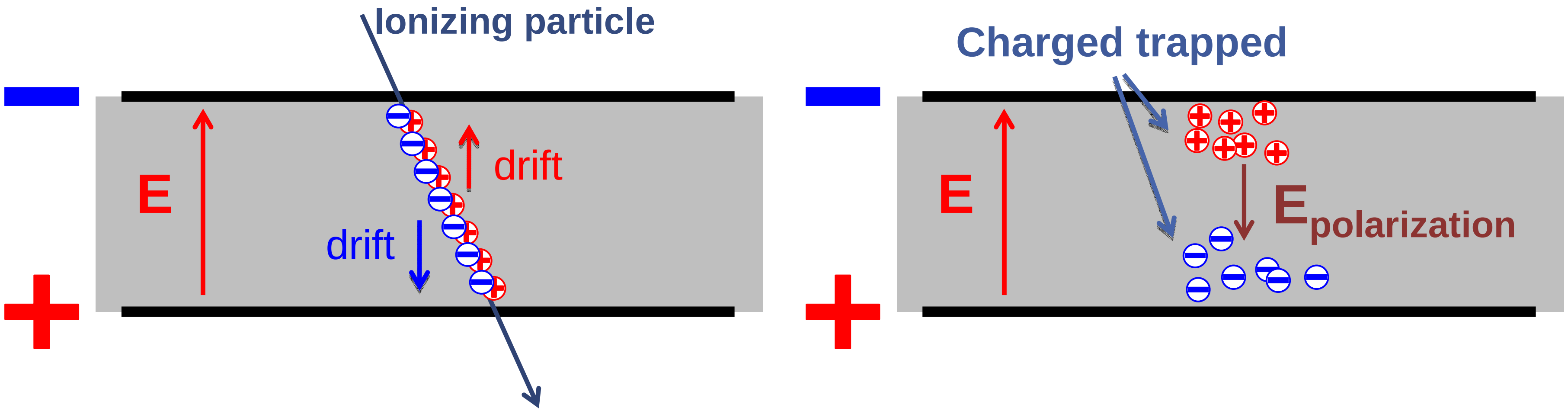
# Single-crystal vs. poly-crystal




**About 3.5 * $10^{12}$ hadrons/$cm^2$/$fb^{-1}$**

- **During 2011 a prototype single-crystal diamond (sCVD) was placed at the location of BCM2 +Z**
- **For 2012 this diamond was replaced by a fresh sCVD.**
- **pCVD metallized in Rutgers with W/Ti.**
- **sCVD metallized at GSI with Cr/Au.**
- **Initial signal of sCVD about factor 10 higher than pCVD.**
- **Both sCVD show a much faster decrease in signal efficiency compared to the pCVD.**
- **Signal decrease faster than expected from test beams**

# The polarization effect




- Trapped charge forms polarization field.
- Total field reduced -> signal output is lower.
- Effect more pronounced at low HV, at higher HV polarization field is less dominant.
- Flipping the HV will temporarily recover the electric field. An alternating HV will prevent the buildup of polarization.

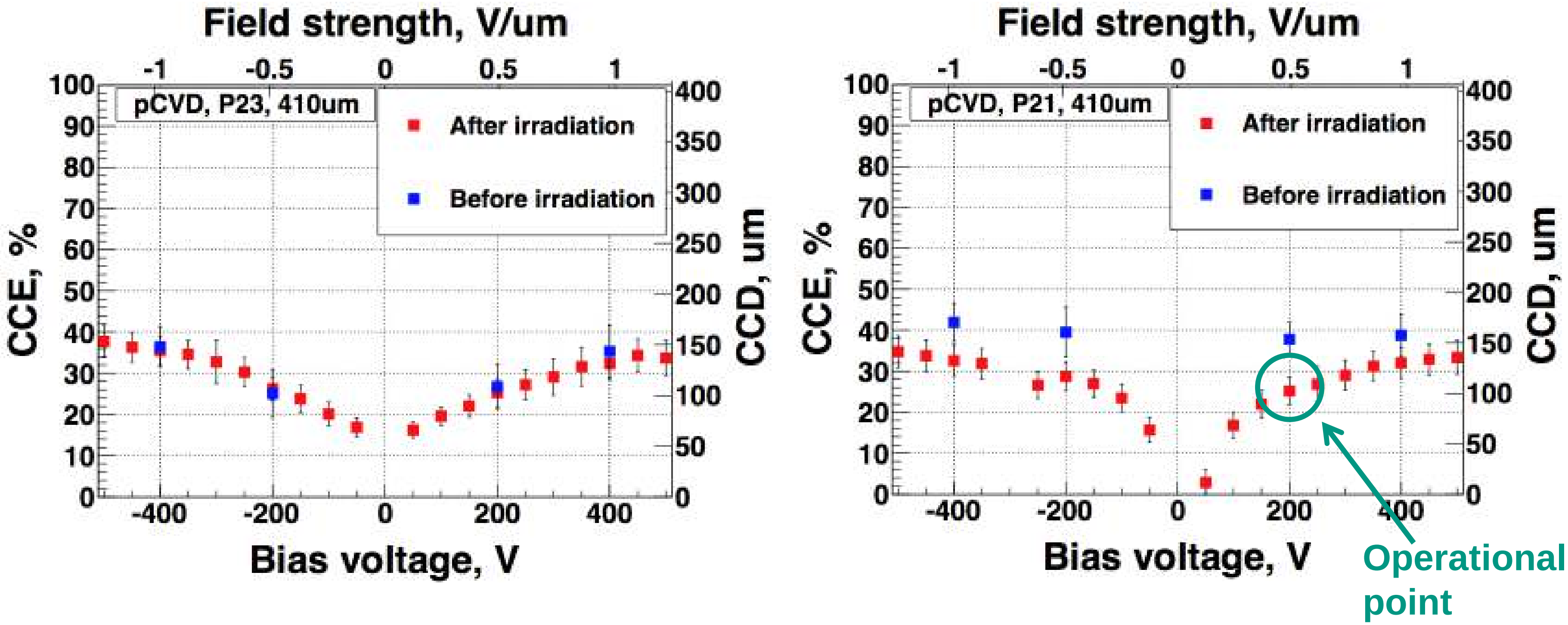
# CCD measurements of removed diamonds

**pCVD (low damage)**

After ~$10^{13}$ $cm^{-2}$ hadrons, signal at 70%

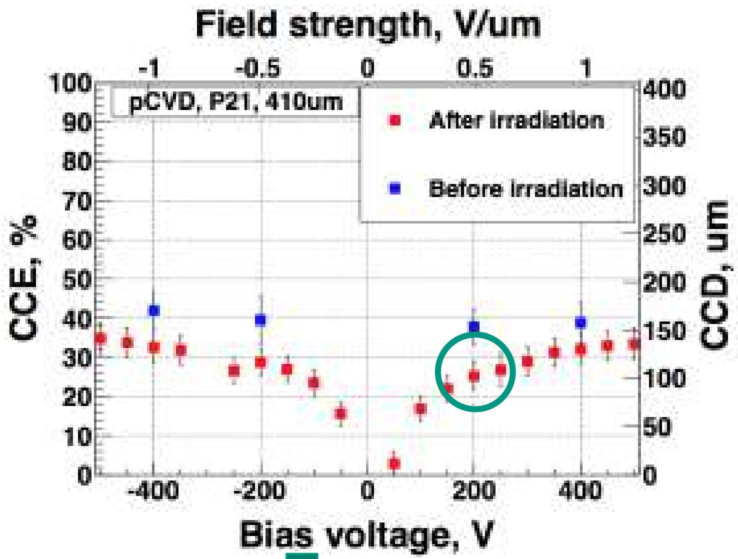
**pCVD (high damage)**

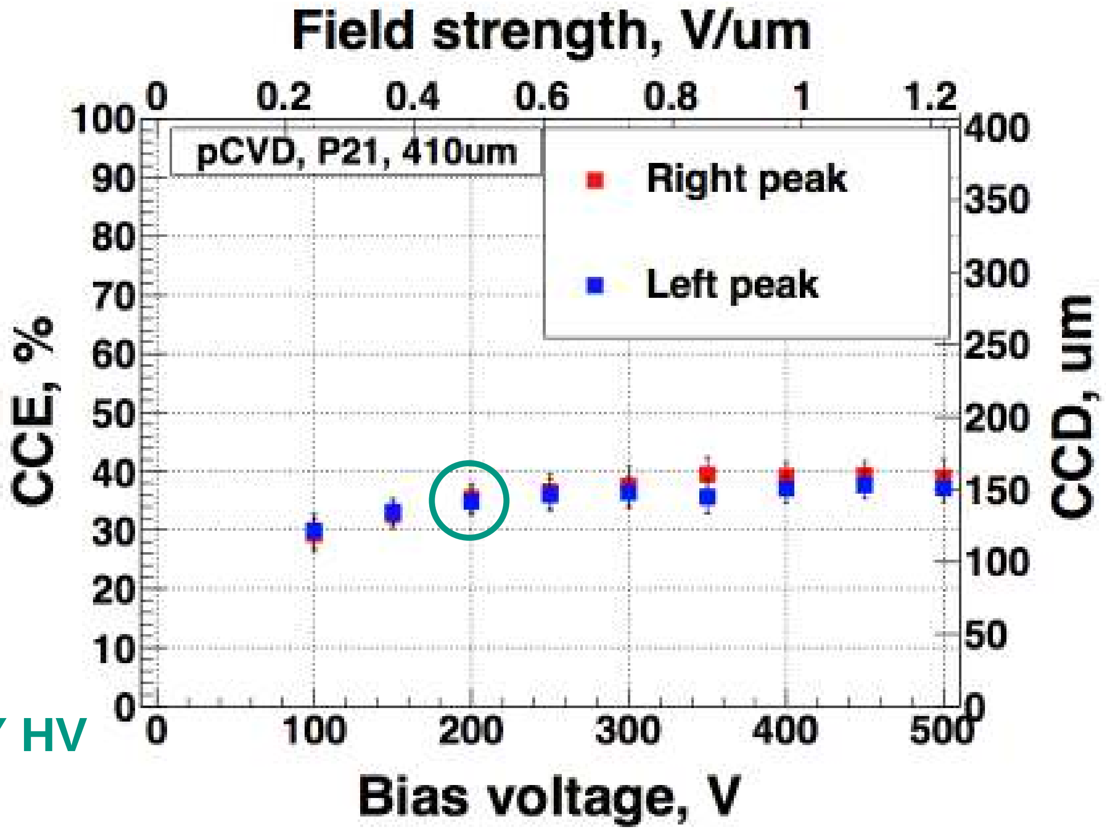
After ~2 x $10^{14}$ $cm^{-2}$ hadrons, signal at 20%




- **No significant change in CCD, does not explain signal decrease.**
- **“Highly” damaged pCVD shows CCD reduction at “low” HV.**

# CCD measurements with alternating polarity HV



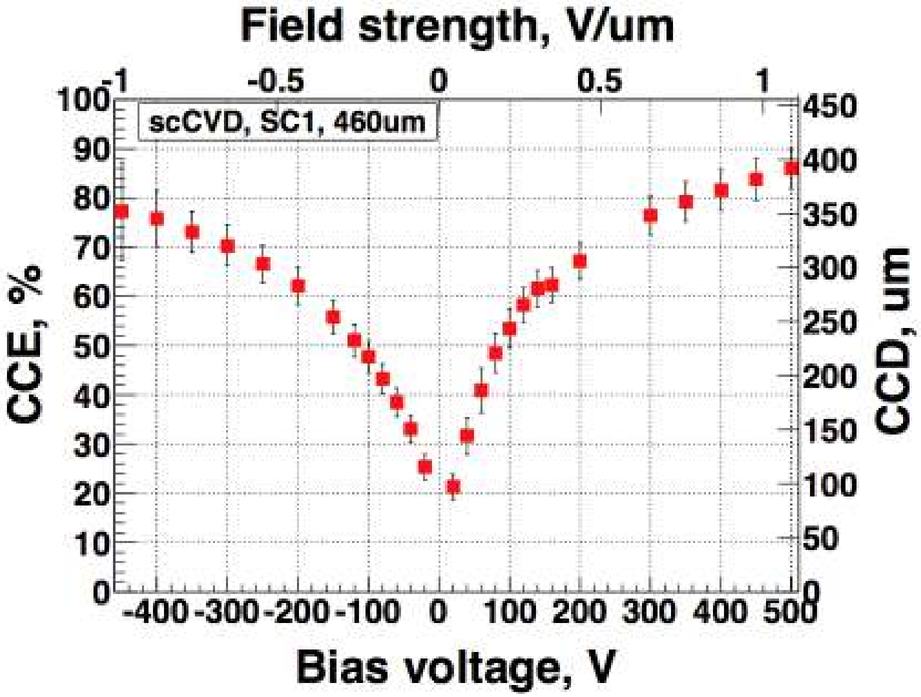




**USE ALTERNATING POLARITY HV**

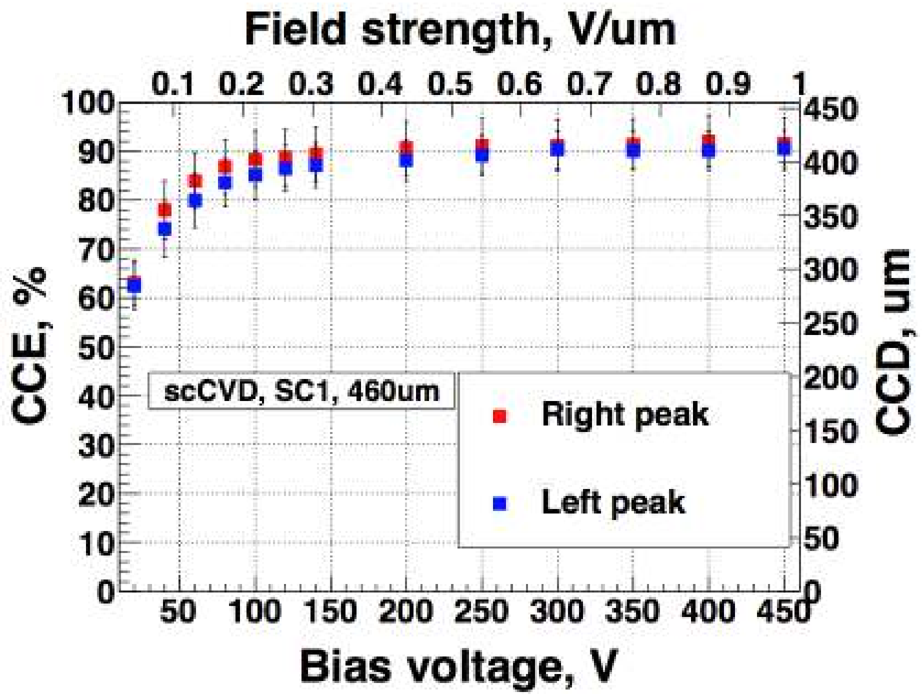
- **Polarization can't build up.**
- **Signal is recovered -> reduction due to polarization.**

# CCD measurement of sCVD diamond

**CONSTANT HV**



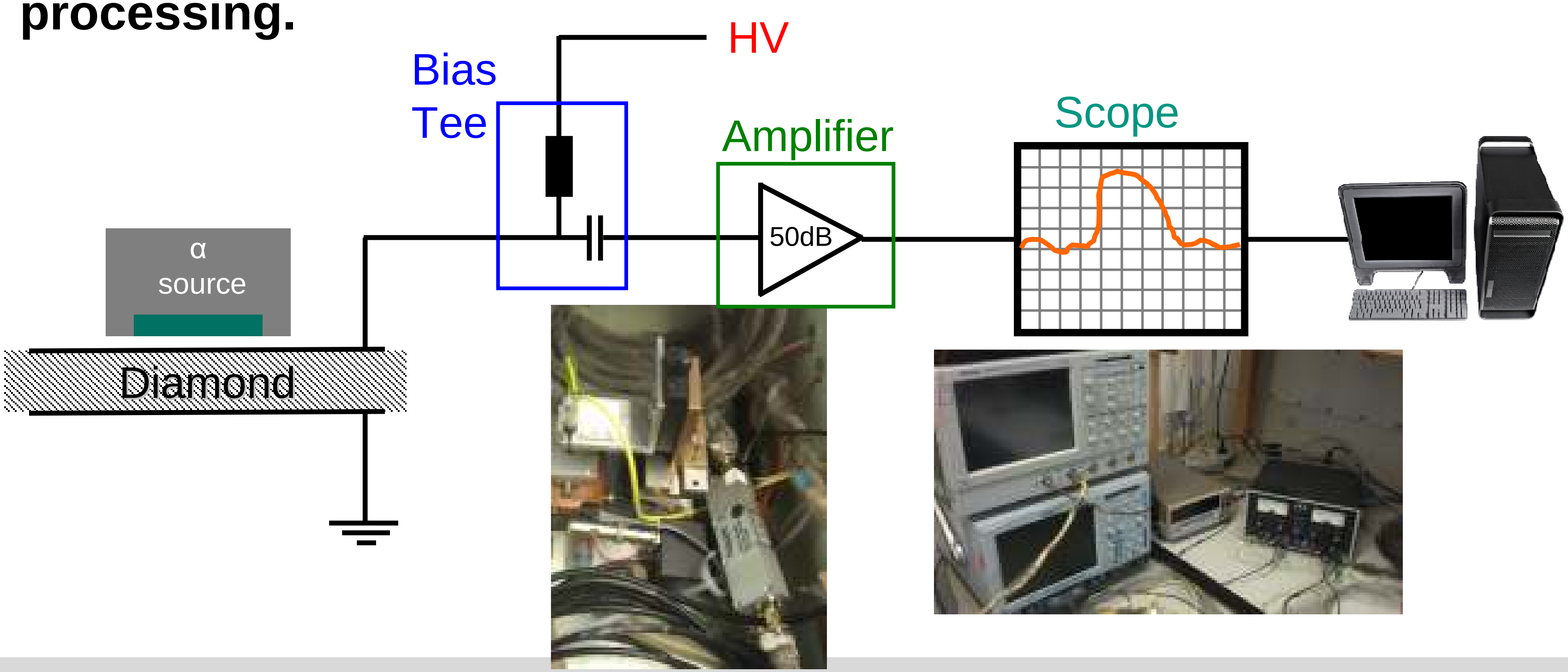

**ALTERNATING HV**



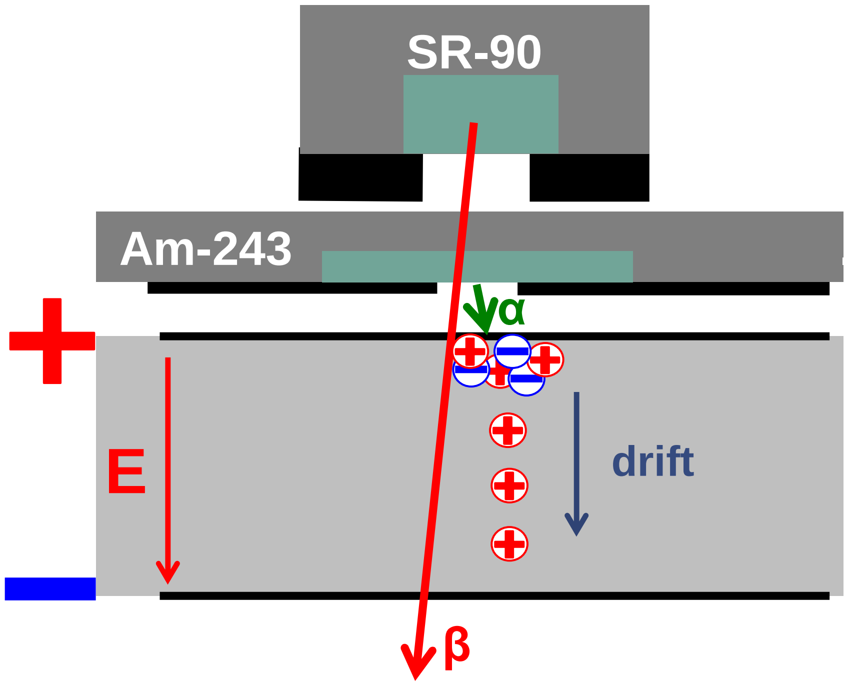

- **After ~2.3 x $10^{13}$ $cm^{-2}$ hadrons, signal was down to 10%**
- **CCD reduced, but recovered with alternating polarity HV**

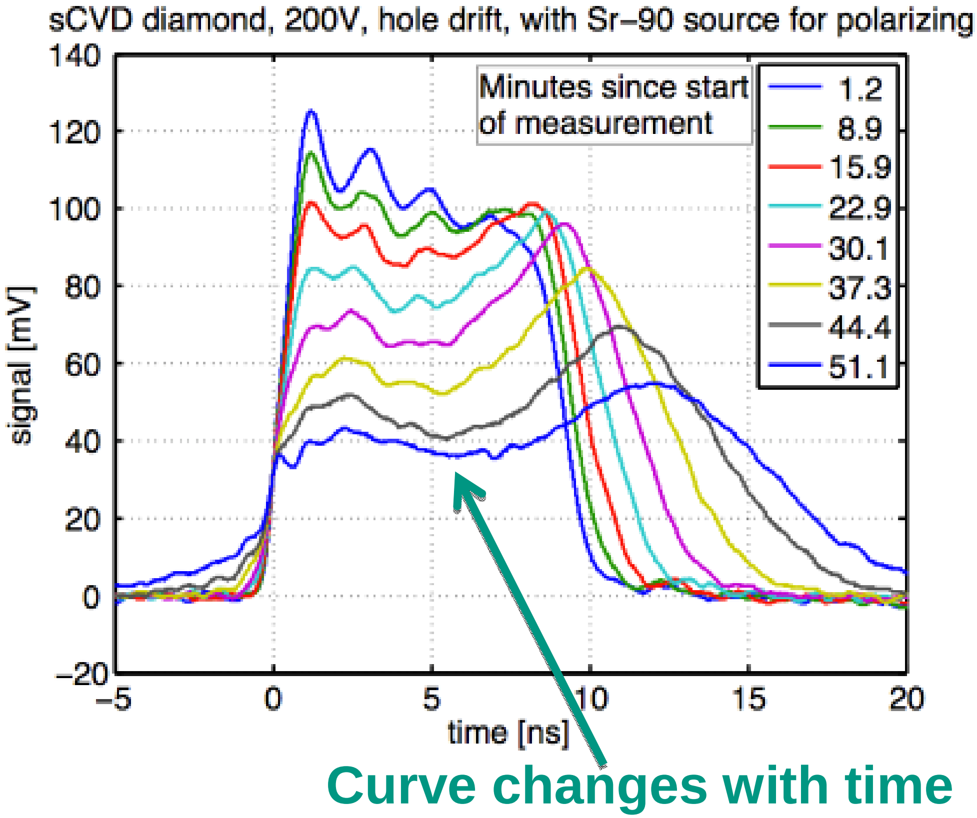
# TCT measurements

- **With the transient current technique (TCT) pulse shapes are measured in order to determine the internal electric field.**
- **A radioactive α-source generate a signal which is amplified and send to a scope. Priming done with Sr-90 source.**
- **Single traces recorded with PC. Data averaging in post processing.**



# TCT scan of sCVD

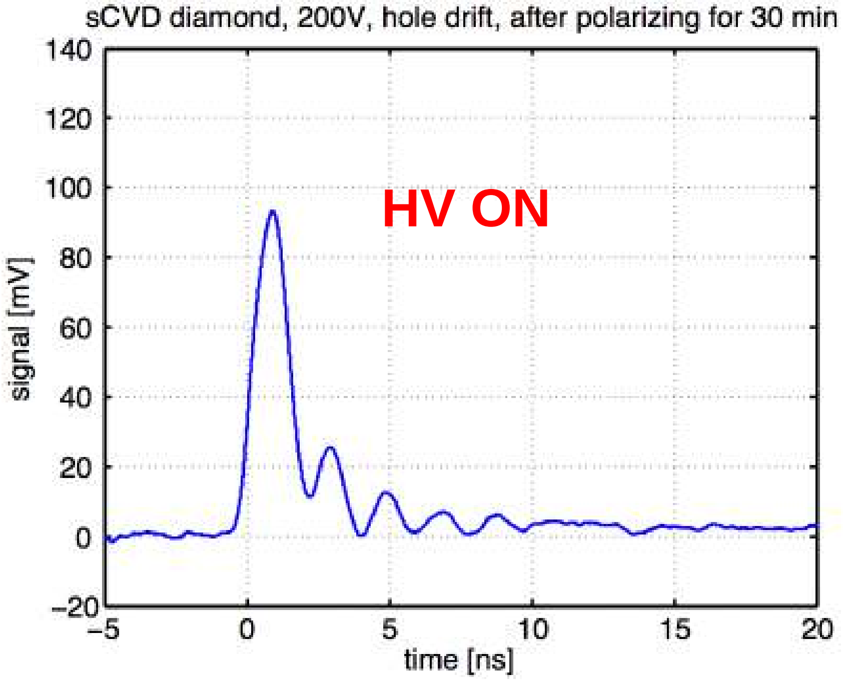



- First pumping of the diamond without HV.
- Sr-90 source used for filling traps. Trigger threshold above β-signal
- Weak Am-243 source used to probe the electric field.
- Decrease in signal height and longer drift time. -> reduced electric field.

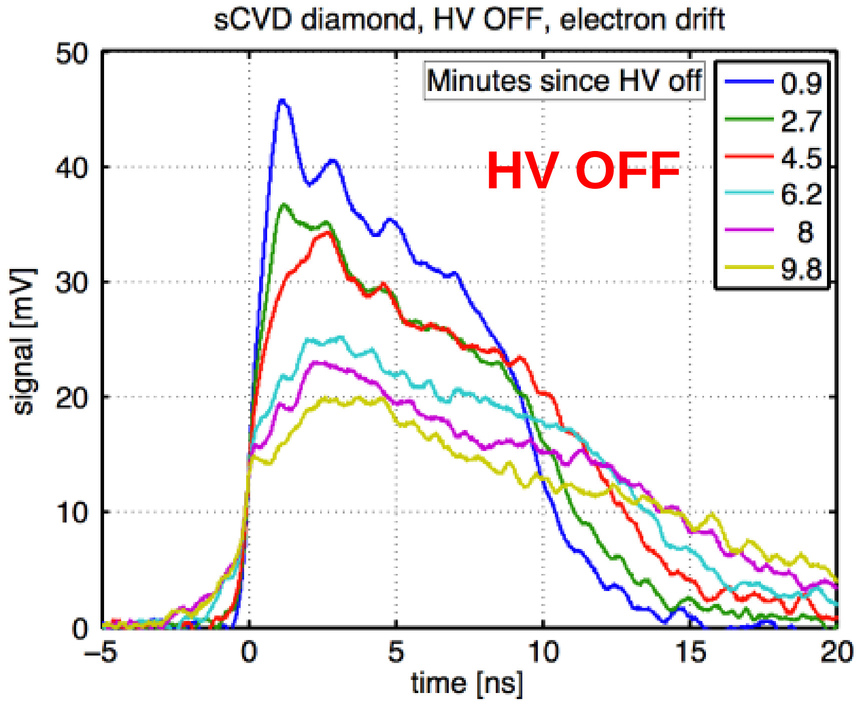
# TCT scan of sCVD

## Polarizing with only Sr-90



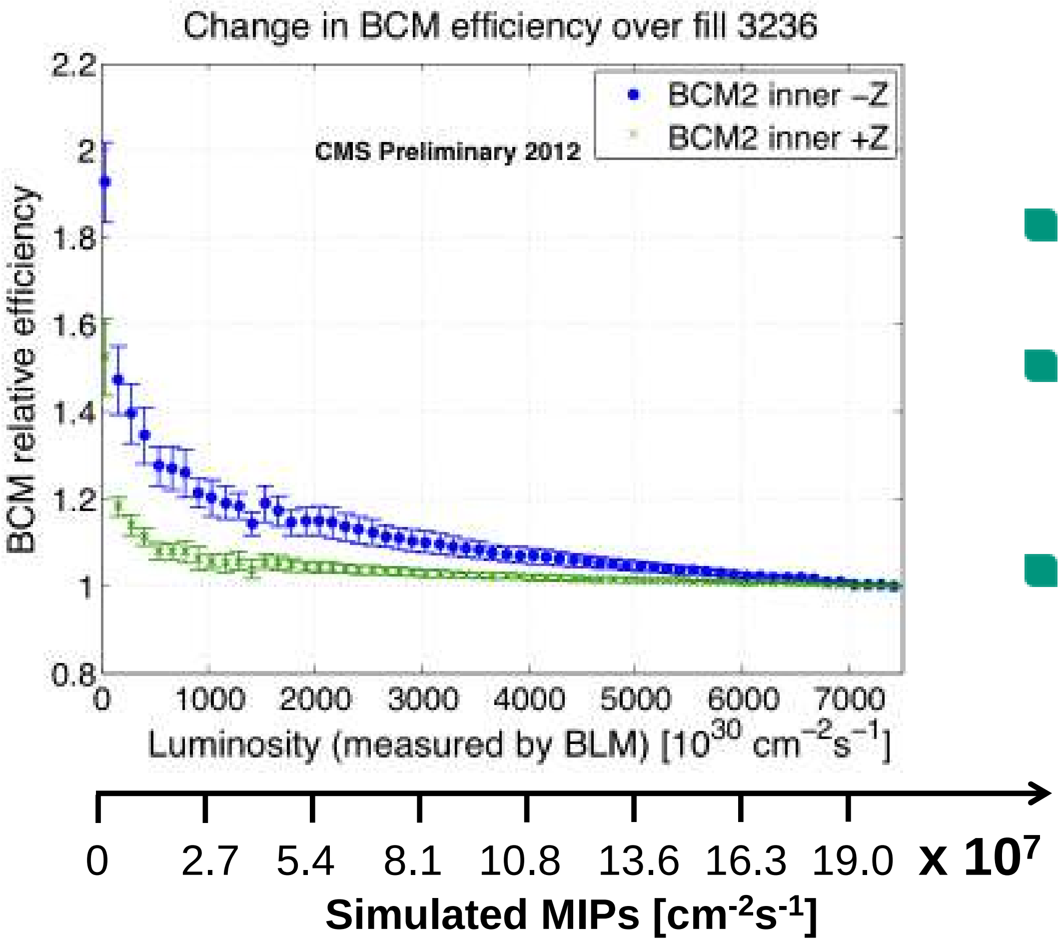

- Applying MIP source for additional 30 minutes (without α-source) and measurement only with α-source (MIP-source removed).
- Only spike left of the signal.

## Switch HV off afterwards




- Only polarization field left.
- Clear signal (with opposite polarity)
- Polarization field over whole diamond bulk, disappearing with time

# Rate dependency of efficiency




- **Signal efficiency lower at high rates.**
- **Possible explanation: Polarization less strong at low rates.**
- **Effect under investigation.**

# Conclusions

- Decrease in detector efficiency stronger than expected. Decrease of measured signal greater than decrease in measured CCD.
  - Most likely: strong polarization in high rate environment
- sCVD sensors initially much more efficient, but loose their relative signal much faster than pCVD.
- Polarization effects showing up at quite low fluences O(~$10^{14}$ $cm^{-2}$) for pCVD and O(~$10^{12}$ $cm^{-2}$) for sCVD in these measurements.
  - Not yet determined if surface or bulk effect. Reprocessing could solve surface problems.
  - If surface effect, will it come back with irradiation?
  - Investigation of various surface treatments of interest.
- Alternating polarity HV prevents polarization. Is this a real option with bipolar readout electronics?

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und Forschung

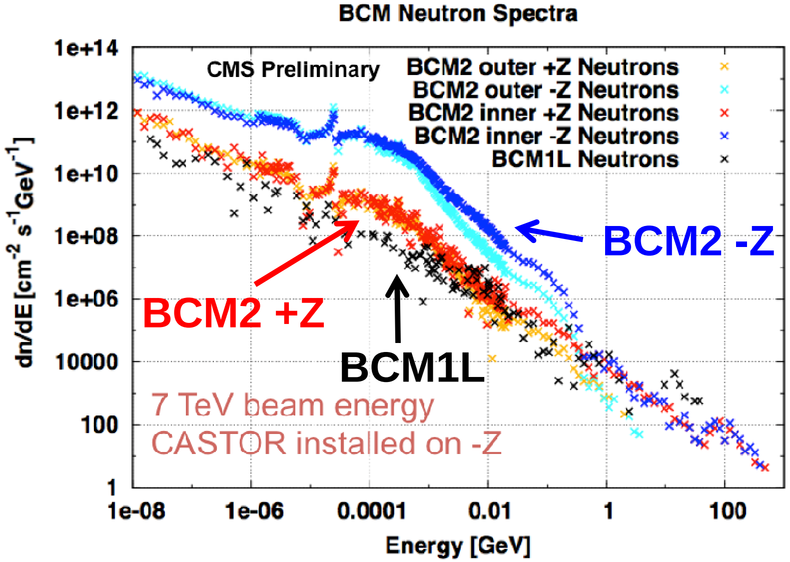
# THANK YOU

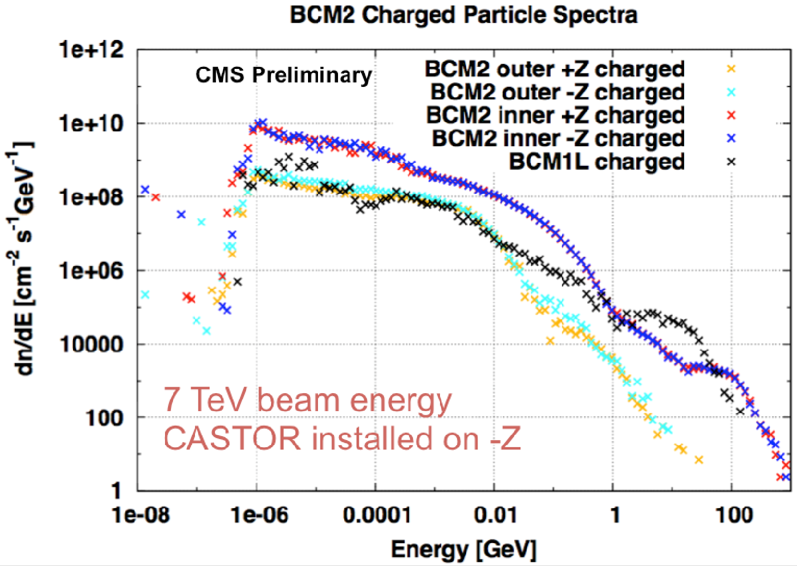
References:

1. S. Müller: “The Beam Condition Monitor 2 and the Radiation Environment of the CMS Detector at the LHC”, CERN-THESIS-2011-085
2. M. Guthoff: “Design and Experiences with the Beam Condition Monitor as Protection System in the CMS Experiment of the LHC”, proceedings of European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators, DIPAC’11, Hamburg, Germany, (2011)
3. A. Dabrowski et al.: “The Performance of the Beam Conditions and Radiation Monitoring System of CMS”, proceedings submitted at IEEE Nuclear Science Symposium, Oct. 2011, Valencia Spain; CMS note: CMS CR-2011/275
4. W. de Boer et al.: "Radiation Hardness of Diamond and Silicon sensors compared.” Phys. stat. Sol. 204(2007)3004

# BACKUP

# Simulates particle spectra

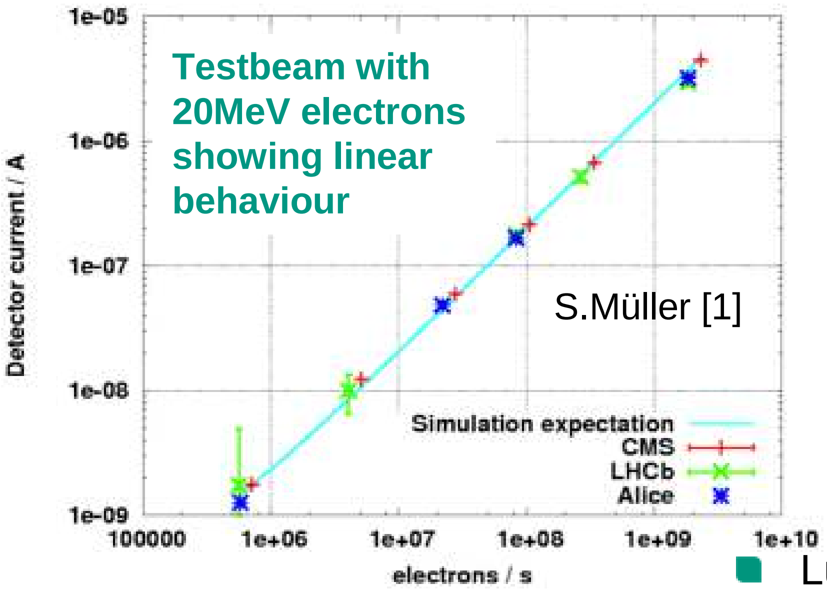


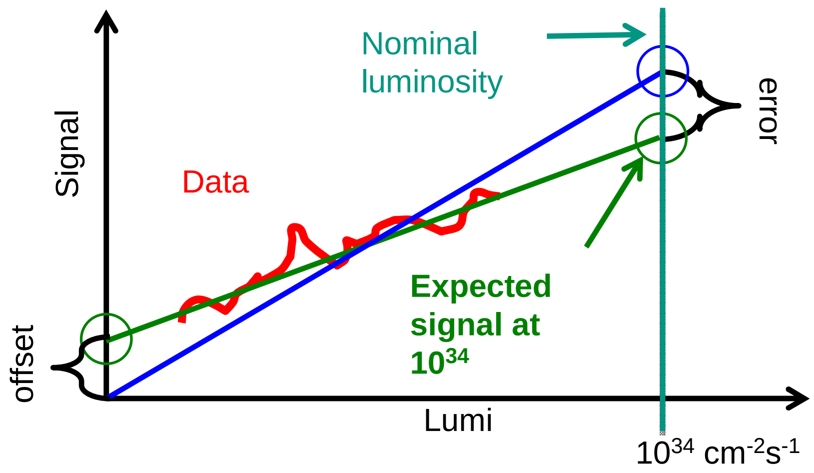



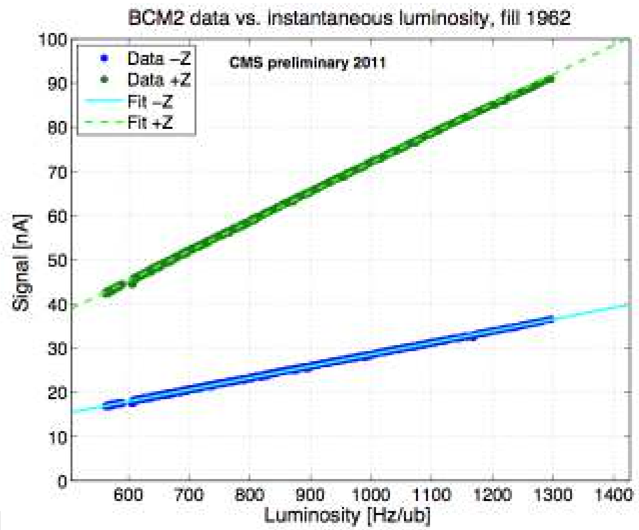

- Neutrons below 100MeV much increased on BCM2 –Z compared to BCM2 +Z
- Neutron content in BCM1L lower than at BCM2

- Charged particle flux the same for BCM2 on +Z and on –Z.
  - Castor does not produce charged particles

# Linearity of the system and normalization



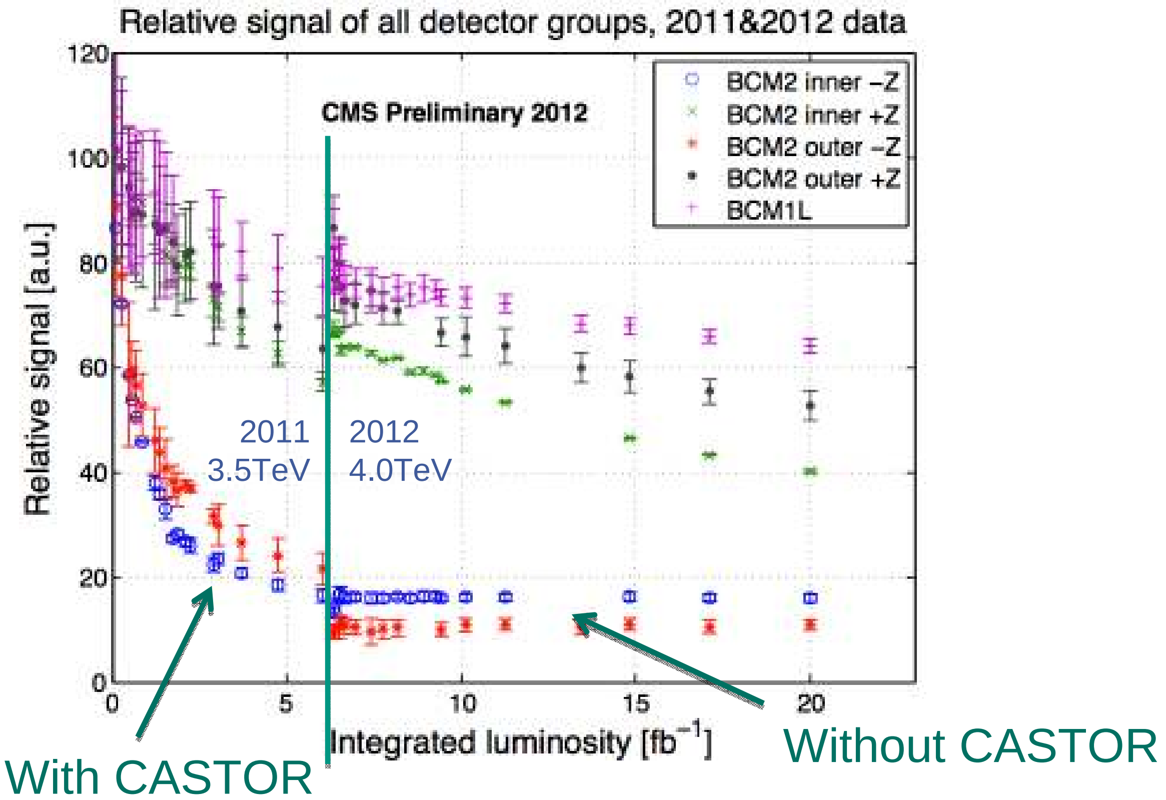




- Luminosities were very different over the last two years.
- It is needed to normalize the signal to the luminosity.
- The system is tested to be linear.
- For every analyzed fill a linear fit is applied to the correlation between signal and luminosity.
- An extrapolation of this fit is used to obtain an expected signal at nominal luminosity. These normalized numbers can be compared.
- A zero offset constrained fit is used for an estimation of the systematic error on this method.

# Changes in 2012 run

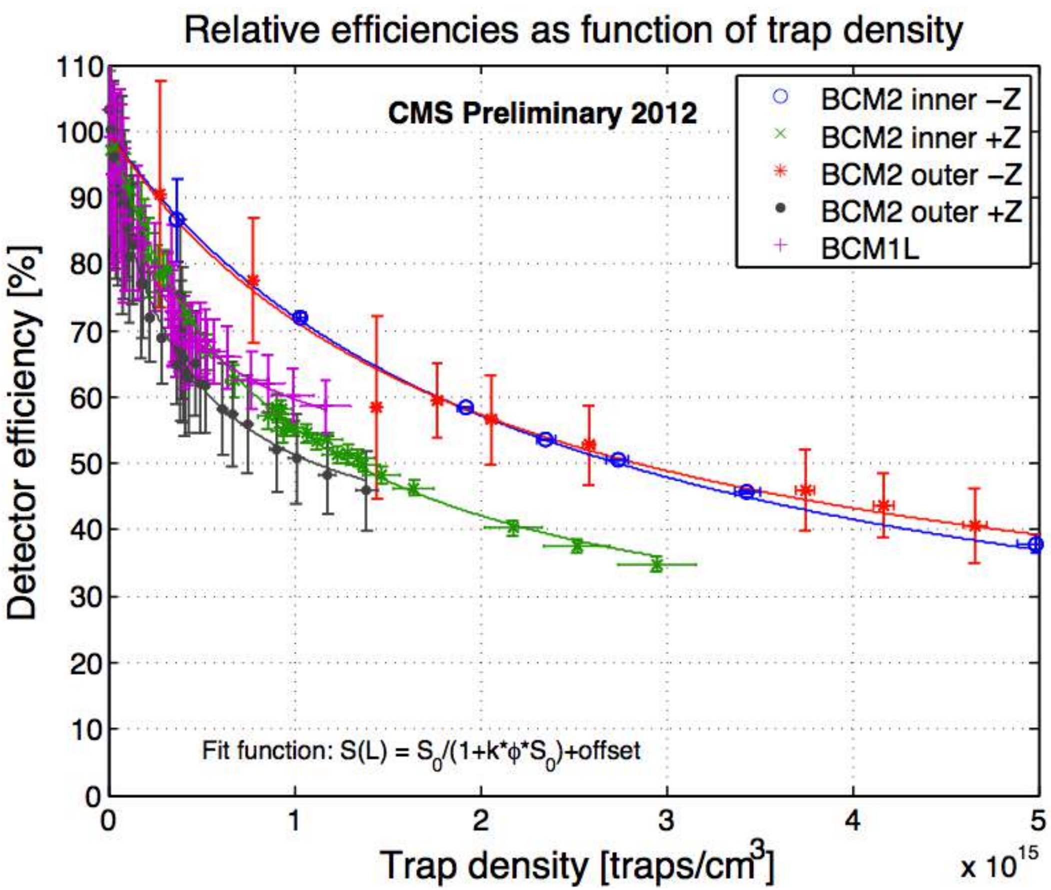
- All detectors stayed the same.
- LHC went to a higher beam energy. **3.5** TeV -> **4** TeV
  - The measured signal relative to instantaneous luminosity increases slightly.
  - The received radiation damage increases slightly.
- The CASTOR detector was removed.
  - Due to the strong decrease in neutron flux at the BCM2 –Z location the signal decreases as well.
  - BCM2 on the –Z end and BCM2 on the +Z end are now in a comparable radiation environment.
  - Still the BCM2 detectors are much more pre-damaged. Hence the signal is still very different.
- The expected signal can be calculated from results of FLUKA monte-carlo simulations. This can be used to correct the the data and make a comparison of 2011 and 2012 data possible.

# 2011 and 2012 data uncorrected



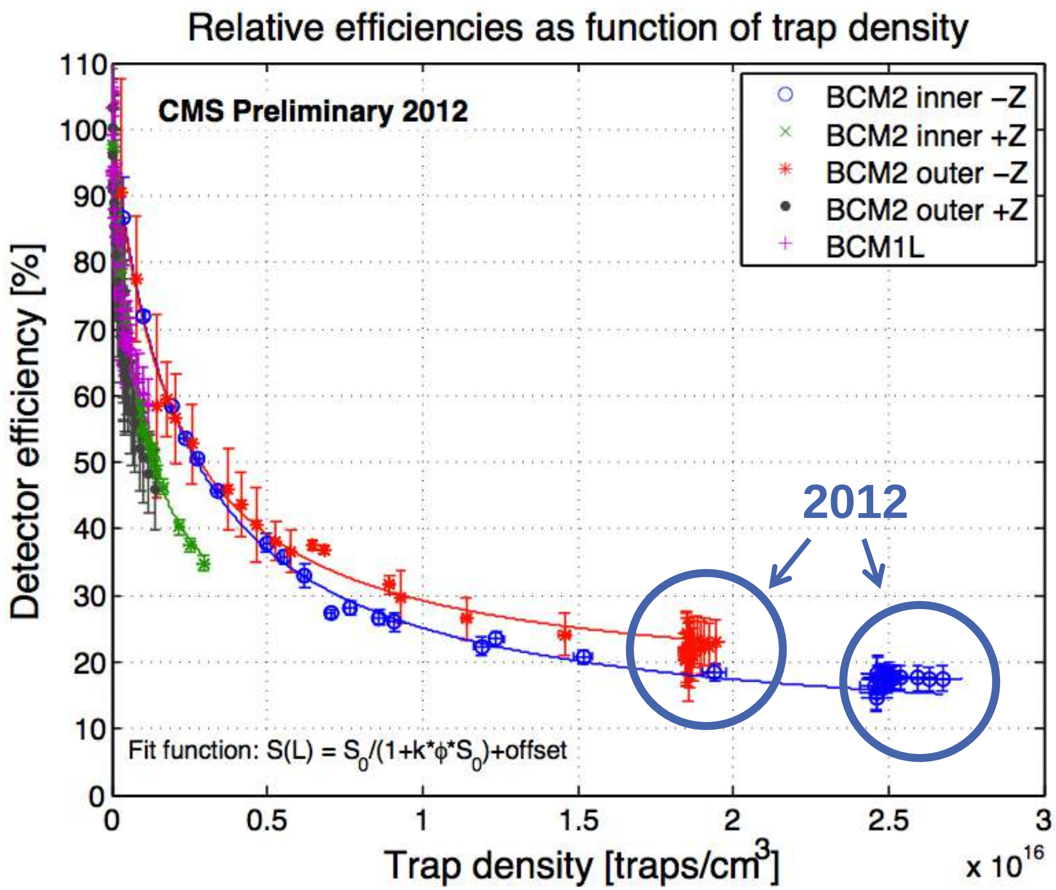

- 2012 data not corrected for different signal due to changed radiation environment.

# Signal as function of trap density



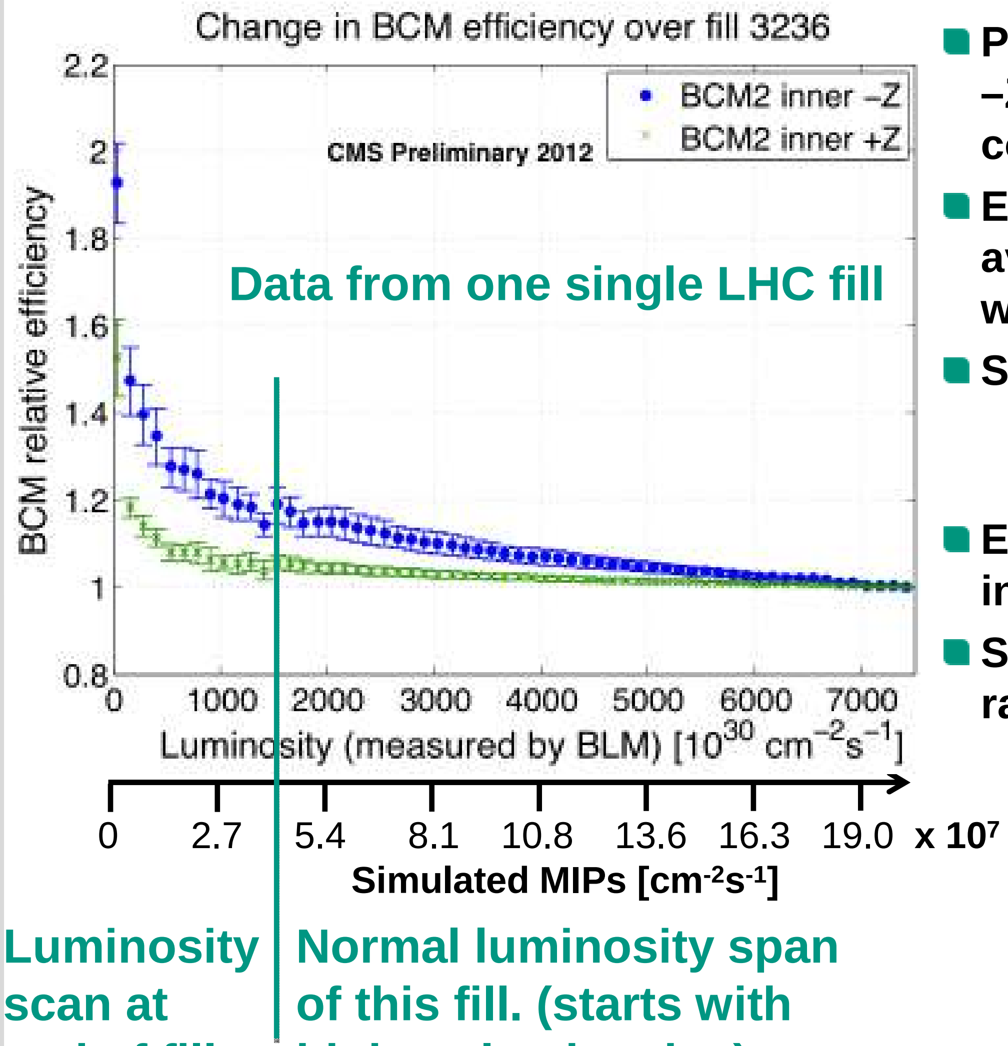

- The number of traps introduced by radiation at a given integrated luminosity can directly be simulated using FLUKA simulations.
  - In FLUKA the displacements per atom (DPA) scoring is used.
- All detectors should now be on the same curve.
- BCM1L and the BCM2 +Z detectors agree within the given errors.
- The simulated trap density for the BCM2 –Z detectors seem to be roughly factor 2 too high.

# Signal as function of trap density full scale




- BCM2 –Z damage in 2012 small compared to 2011.

# Rate dependency of efficiency

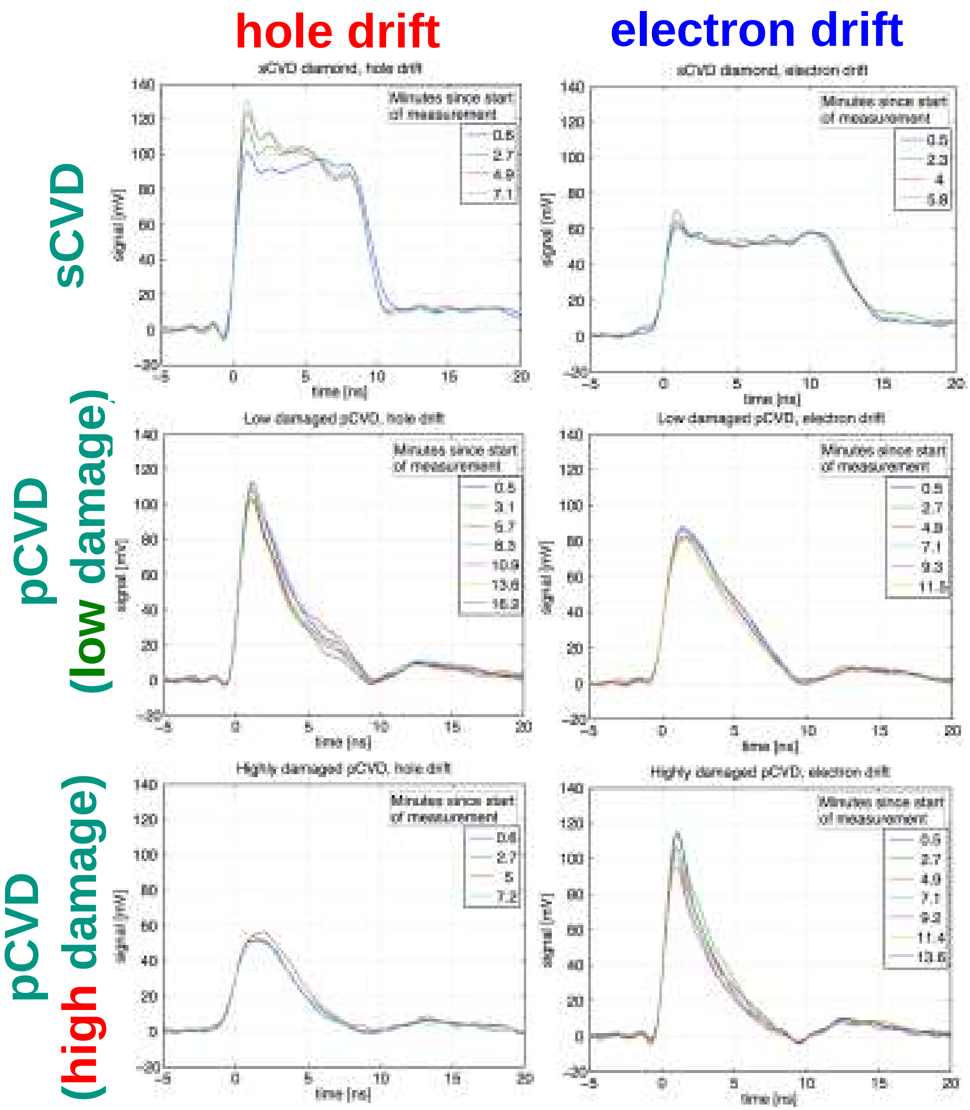



Luminosity scan at end of fill

Normal luminosity span of this fill. (starts with highest luminosity.)

- Plotted: Averaged signals of BCM2 +Z and –Z, divided by collision rate, as function of collision rate.
- Error bars are standard deviation of the average, showing variation of this effect within one group is small.
- Simulated particle fluence after 25.0fb$^{-1}$:
  - BCM2 –Z: 2.3 x $10^{15}$ 24GeVprot.eq./cm$^2$
  - BCM2 +Z: 3.0 x $10^{14}$ 24GeVprot.eq./cm$^2$
- Expect signal being linear with lumi (ratio in this plot should be constant.)
- Significant increase in efficiency at lower rates
  - Could possibly be explained with polarization being not as strong at lower rates.
  - Effect seems to be stronger in detector with higher damage (BCM2 -Z).
  - Possible other reasons for non linearity: Signal from beam background, long term activation giving increased signal.

# TCT measurements using alternating polarity HV




- **Alternating HV (1Hz square-wave) is used to measure polarization free signals.**
- **No drift in time visible.**

- **Average curves of pCVD diamonds are not square due to low CCD.**
  - **Charge gets trapped along the way**

- **The highly damaged pCVD shows a nice electron drift but the hole drift is reduced.**