Upgrade of the CMS Electromagnetic Calorimeter for High-Luminosity LHC Operation

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CMS Collaboration

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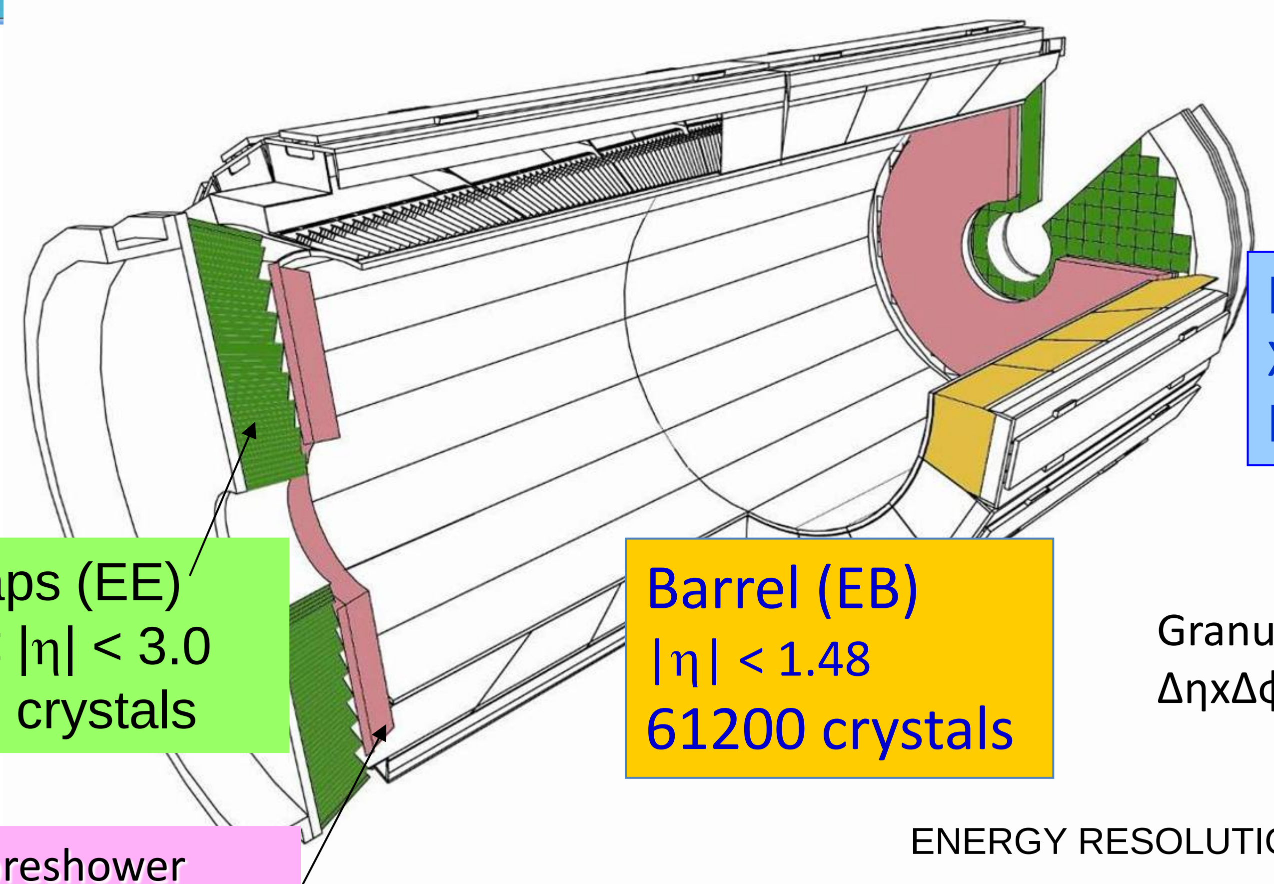
Outline

- The CMS electromagnetic calorimeter (ECAL)
- The role of the ECAL in CMS physics
- The HL-LHC program
- The challenges of the detector at the HL-LHC
- The upgrade of the ECAL

The CMS electromagnetic calorimeter



$PbWO_4$ crystals
X_0 = 0.89 cm
LY~100 γ/MeV

Endcaps (EE)
1.48 < |η| < 3.0
14648 crystals

Barrel (EB)
|η| < 1.48
61200 crystals

Granularity Barrel
ΔηxΔϕ=0.0174x0.0174

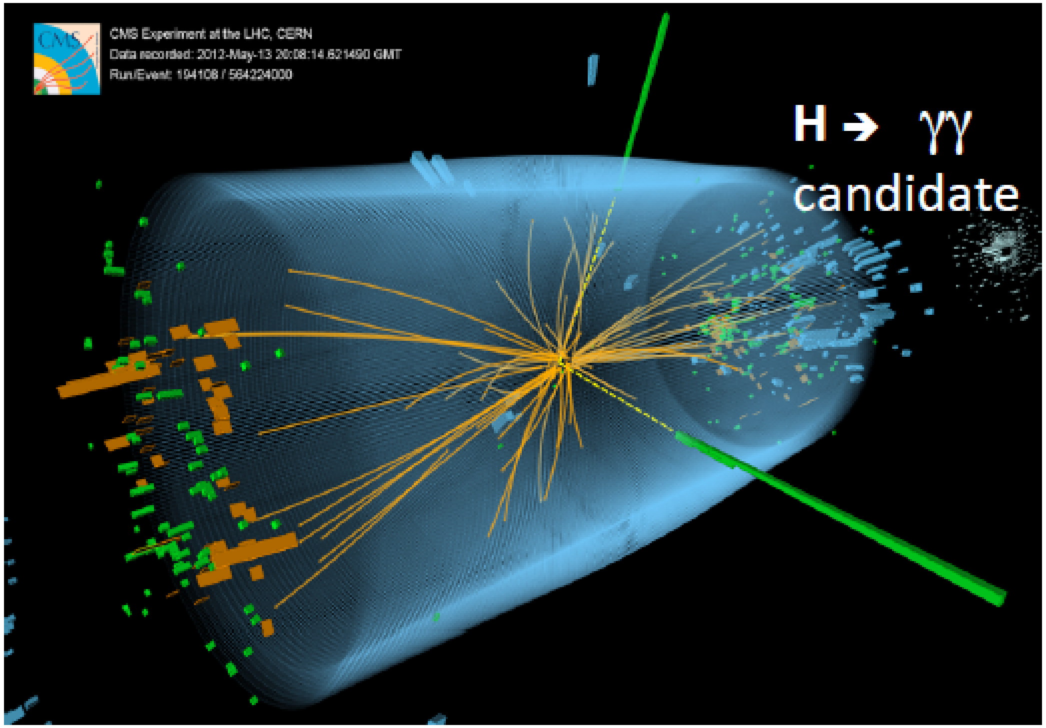
Pb/Si preshower
1.65 < | η | < 2.6

ENERGY RESOLUTION (BARREL)

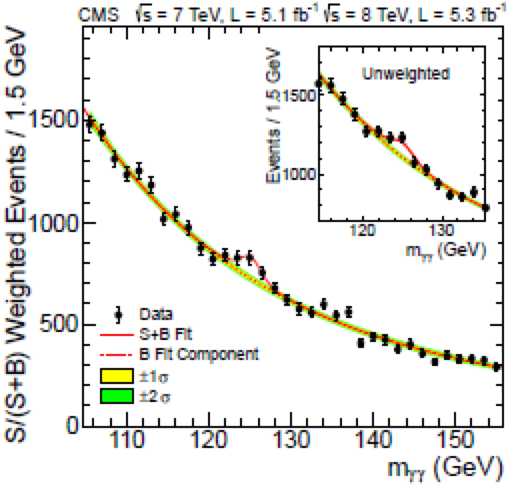
$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E(GeV)}} \oplus \frac{12\%}{E(GeV)} \oplus 0.3\%$$

The energy resolution for photons from H→γγ in EB is 1.1% to 2.6% and in EE 2.2% to 5% .
Timing resolution is 190 ps and 280 ps in EB and EE.

The ECAL role in CMS



CMS Collaboration,
Phys. Lett. B716 (2012) 30-61



- Excellent energy resolution led to the discovery of the H boson in the γγ decay mode
- Electrons and photons are used in many other searches (H→WW, ZZ*, Z') and SM physics analyses (W, Z, top ,...)
- Precision timing used in search for long lived SUSY particles

LHC and HL-LHC

$L=1 \cdot 10^{34}\ cm^{-2}s^{-1}$
3 years
$50 fb^{-1}$ per year

$L=2 \cdot 10^{34}\ cm^{-2}s^{-1}$
3 years
$\geq 50 fb^{-1}$ per year

by the end
of Phase1
$300\text{-}500\ fb^{-1}$

HL-LHC:
$L=5 \cdot 10^{34}\ cm^{-2}s^{-1}$
$250\ fb^{-1}$ per year
by 2033 → $3000\ fb^{-1}$
~140 events per bunch-crossing
spread in *z* over ~ 5 cm

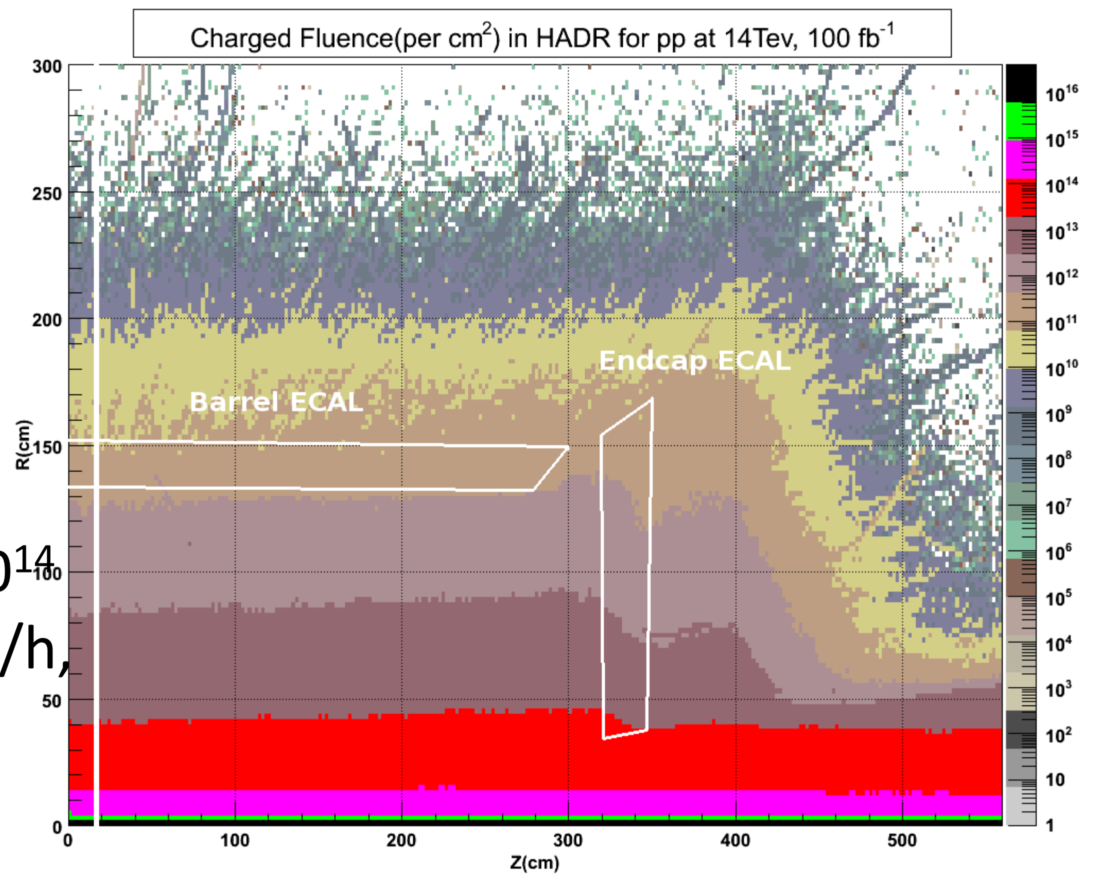
A new machine, for high luminosity, to measure the H couplings, H rare decays, HH, Vector boson scattering, other searches and difficult SUSY benchmarks, measure properties of other particles eventually discovered in Phase1.

Detector challenges

- Number of events per bunch crossing (pile-up) ~ 140

- Radiation levels will be 6 times higher than for the nominal LHC design.
- Strong η dependence in the endcaps

(at η=2.6 hadron fluence $2\cdot10^{14}$ /cm², gamma radiation: 30 Gy/h, total:300kGy)

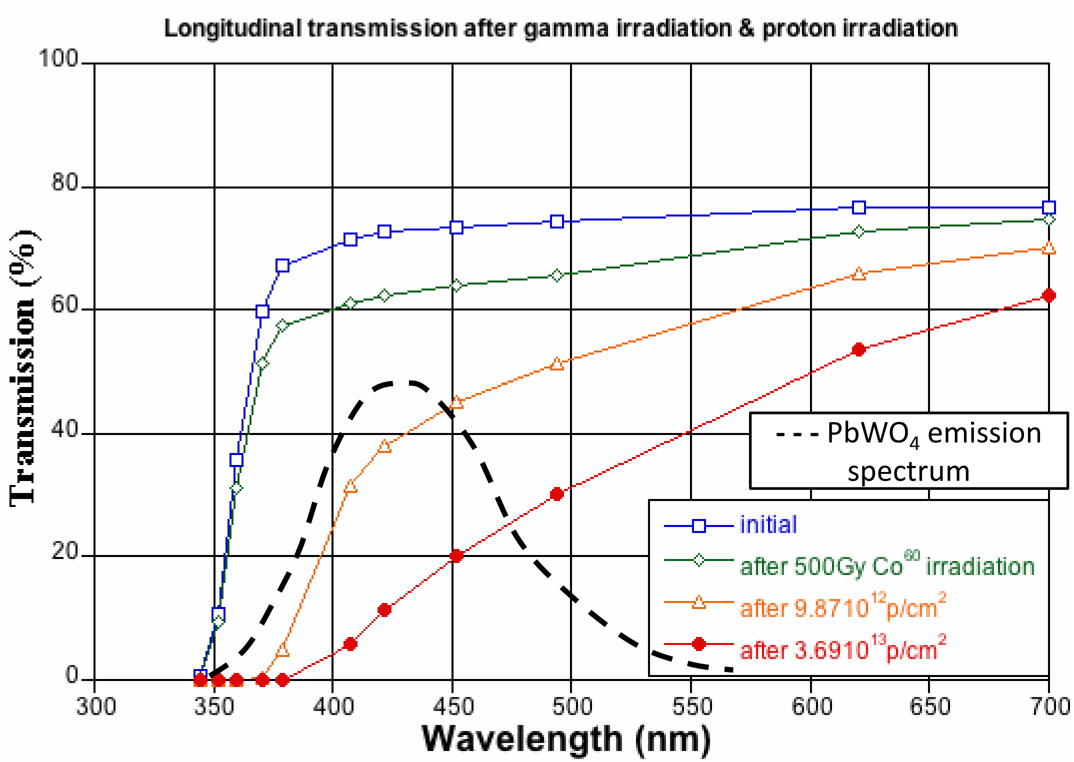


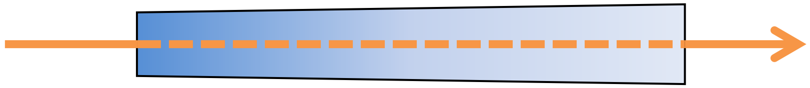
MARS calculations,
P.C. Bhat et al., CERN-CMS-NOTE-2013-001

Radiation damage to crystals

Gamma irradiation damage is spontaneously recovered at room temperature.

Hadron damage creates clusters of defects which cause light transmission loss. The damage is permanent and cumulative at room temperature.





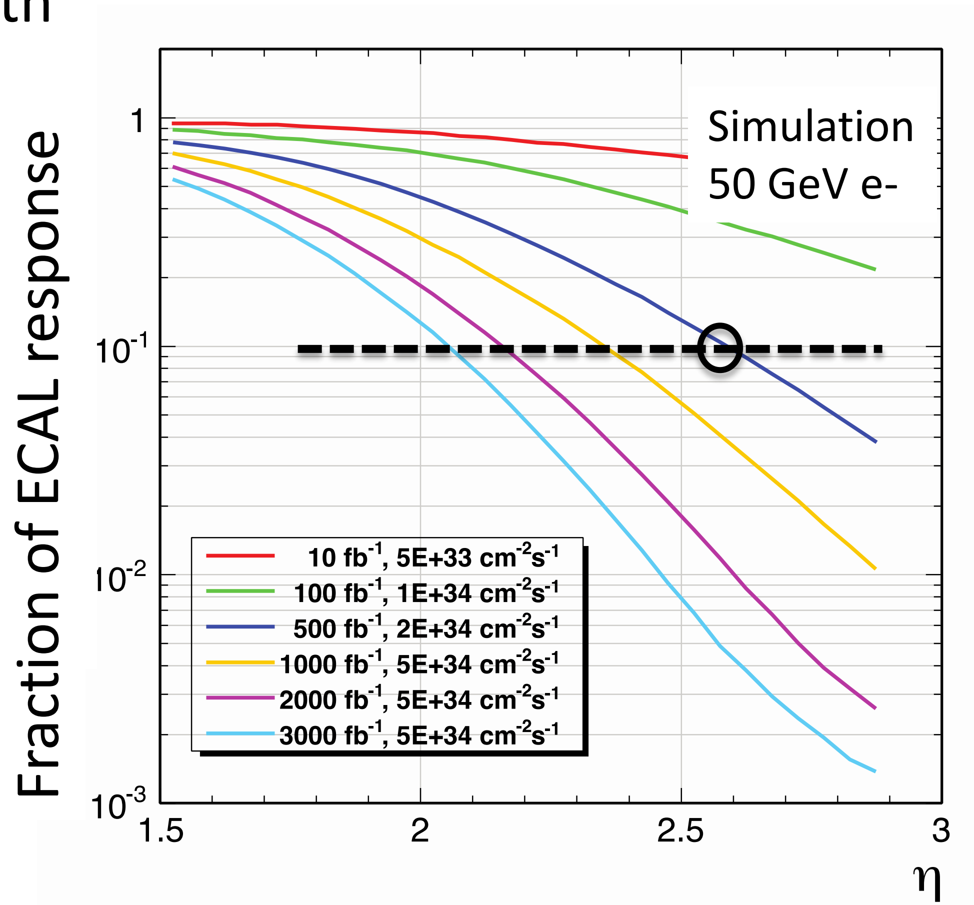
ECAL Endcaps response evolution

→extensive test-beam studies with proton-irradiated crystals

Reduction of light output causes:

- Worsening of stochastic term
- Amplification of the noise
- light collection non-uniformity (impact on the constant term)

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$



Progressive deterioration of energy resolution and trigger efficiency, with strong η dependence

Performance for e/y is acceptable up to 500 fb-1

ECAL endcaps should be replaced after 500fb^{-1} (during LS3)

Possible design options for the endcap calorimeters:

- ECAL plan is to replace the Endcap calorimeters in LS3
- Hadron calorimeter endcaps (HE) may need to replace the active material in LS3.

Two possible scenarios:

1

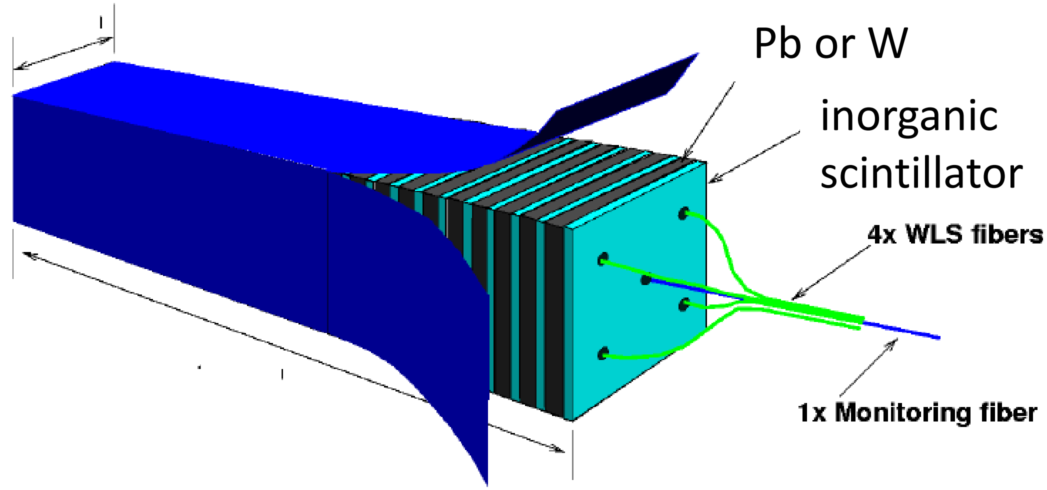
HE absorber is left, only active material is replaced:
New EE will be a standalone calorimeter

2

HE is fully replaced
This opens the possibility of a more coherent redesign of the endcaps calorimeters.

Scenario 1: standalone EE

- **Sandwich calorimeter** in a sampling configuration with inorganic scintillator (LYSO or CeF_3 ,which are rad-hard) and Pb or W as absorber.
- Possibilities for light readout via wavelength shifting fibers (WLS) in a shashlik configuration or with photon sensors on the sides.
- Light path is short → rad- hard
- *<u>Challenges: </u>rad-hard fibers, photo-detectors, mechanical mounting (tolerances)*



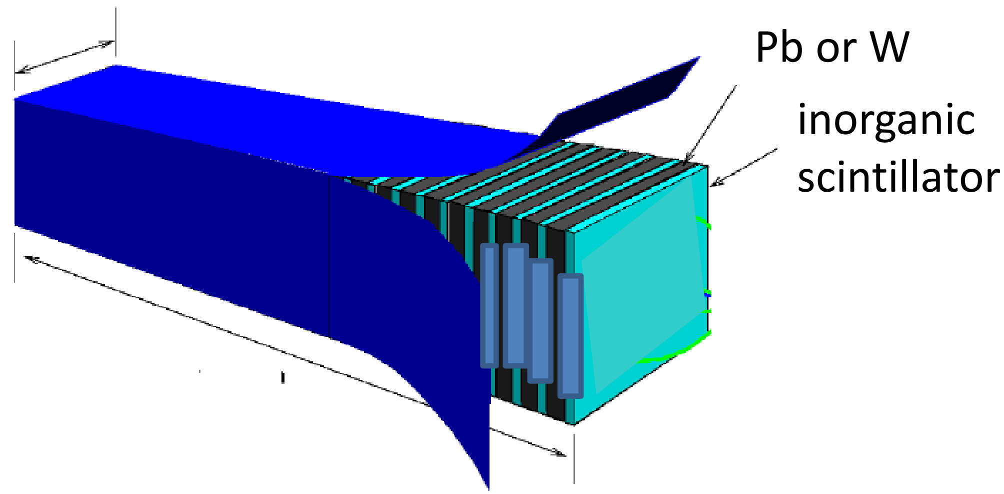
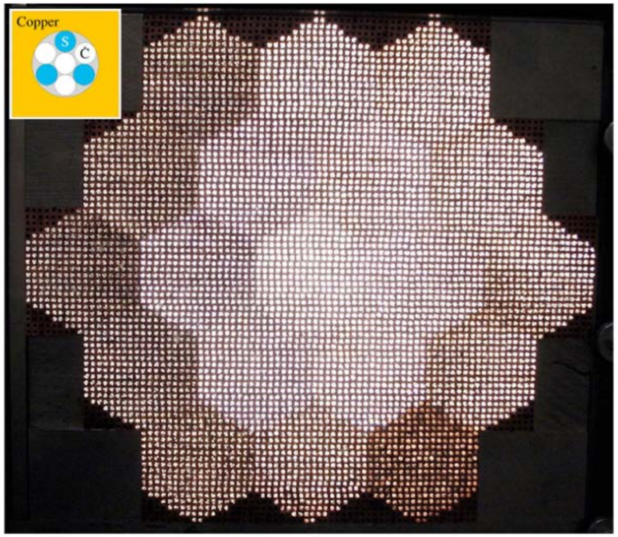


photo-detectors on the plates

Scenario 2: Dual Readout Calorimeter

- **Dual Readout**: simultaneous measurement of the Cerenkov and scintillation signal in the calorimeter in order to correct for intrinsic fluctuations in the hadronic and e.m. component (γ,π^0,η) of the hadronic showers (RD52 Collaboration)
- Other ideas: inorganic crystal fibers, e.g. LuAG
- *<u>Challenges:</u> rad-hard fibers, photo-detectors*

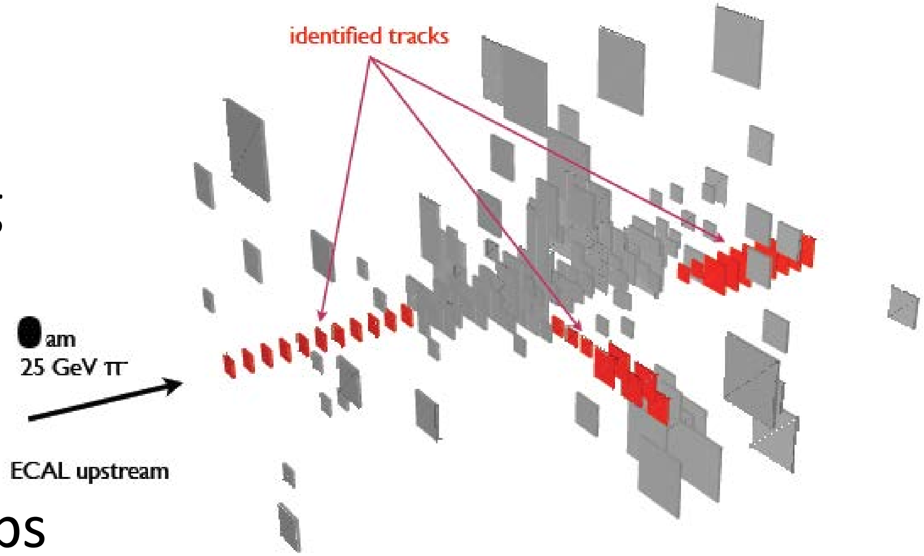
The original DREAM calorimeter



See presentations in this session by R. Wigmans and CALOR 2010-12 E. Auffray et al.

Scenario 2: Imaging calorimeter

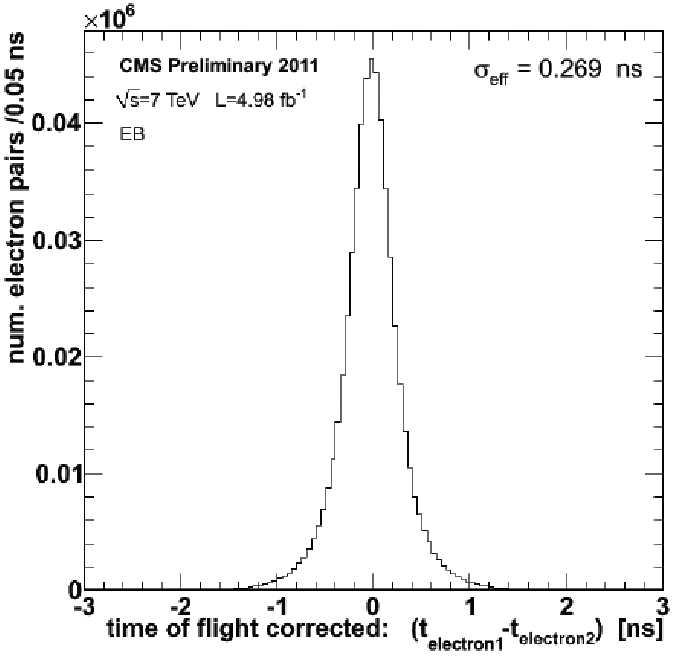
- **Imaging calorimeters**: measure charged particle momentum with the inner tracker, and neutrals in the calorimeter.
- Key point: resolving/separating showers through a finely granulated and longitudinally segmented calorimeter.
- High rates in CMS in the endcaps region drive the detector choice.
- *<u>Challenges:</u> number of channels, compact and inexpensive electronics, trigger, cooling, performance in high pile-up, linearity*

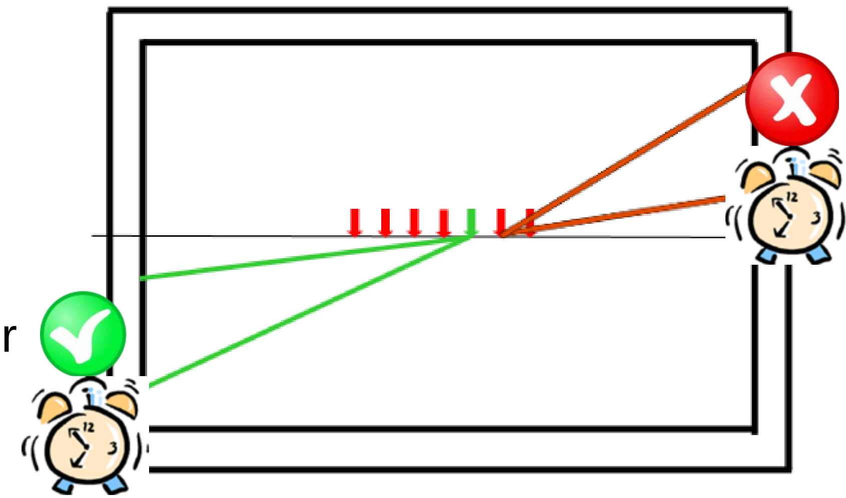


See presentation by M. Chefdeville in this session (CALICE Collaboration)

Pile-up Mitigation

- Pile-up is most critical in the forward region, so upgrades should aim at optimizing the forward detector for high pile-up conditions.
- Two areas of study :
  - **Increased granularity and segmentation** may help to separate out pile-up activity from primary event physics objects
  - **High precision (pico second) timing** may help in pile-up mitigation. The subdetector providing the precision timing may best be associated to precise and finely segmented detector $\Rightarrow$ ECAL.
    - Object reconstruction
    - Object-to-vertex attribution
    - H→γγ vertex
  - Studies on precision timing are ongoing for pile-up mitigation through time-of-flight. Desired resolution is 20-30 ps.





Conclusions

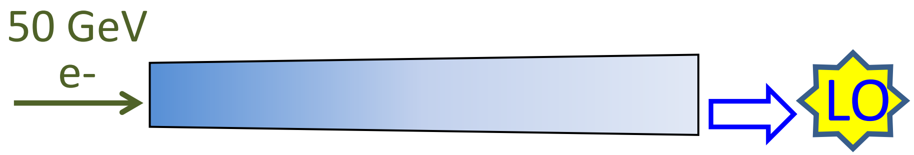
- The HL-LHC poses severe requirements to detectors in terms of performance and rad-hardness.
- ECAL endcaps should be replaced at the end of the LHC phase1 (after 500 fb^{-1}).
- New calorimeter options are being studied. Key points are rad-hardness, granularity and segmentation.
- Timing resolution may add important information for pile-up mitigation.

Backup

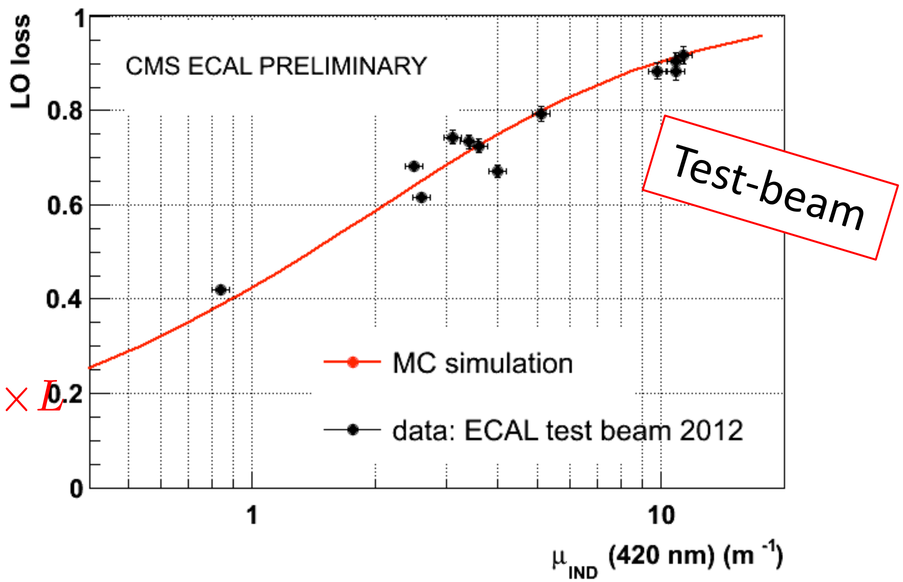
Radiation levels in the detector

			EB		EE (eta=2.6)	
	L (cm^{-2} s^{-1})	Lint (fb^{-1})	gamma dose rate (Gy/h)	Protons /cm^2	gamma dose rate (Gy/h)	Protons /cm^2
design	$1x10^{34}$	500	0.3	$4x10^{11}$	6.5	$3x10^{13}$
2012	$7x10^{33}$	30	0.2	$2.4x10^{10}$	4.5	$2x10^{12}$
HL-LHC	**$5x10^{34}$**	**3000**	**1.5**	**$2.4x10^{12}$**	**30**	**$2x10^{14}$**

Energy resolution of hadron-irradiated crystals



Test-beam setup with hadron-irradiated crystals



Induced absorption μ_{IND} :

$$\frac{LT(\lambda)}{LT_0(\lambda)} = e^{-\mu_{IND}(\lambda)\times L}$$

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

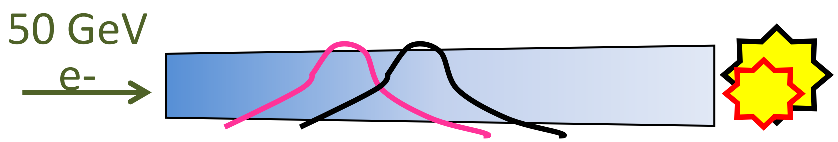
Transparency deterioration→

Light output loss (affects the stochastic term and noise term)

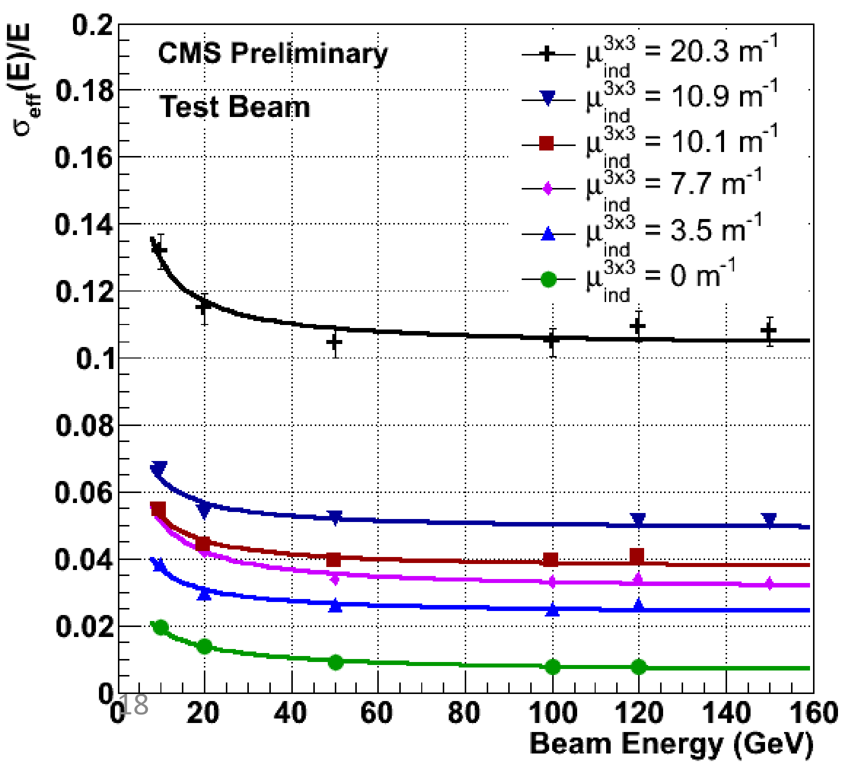
Light collection non-uniformity impacts the constant term

Hadron damage consequences

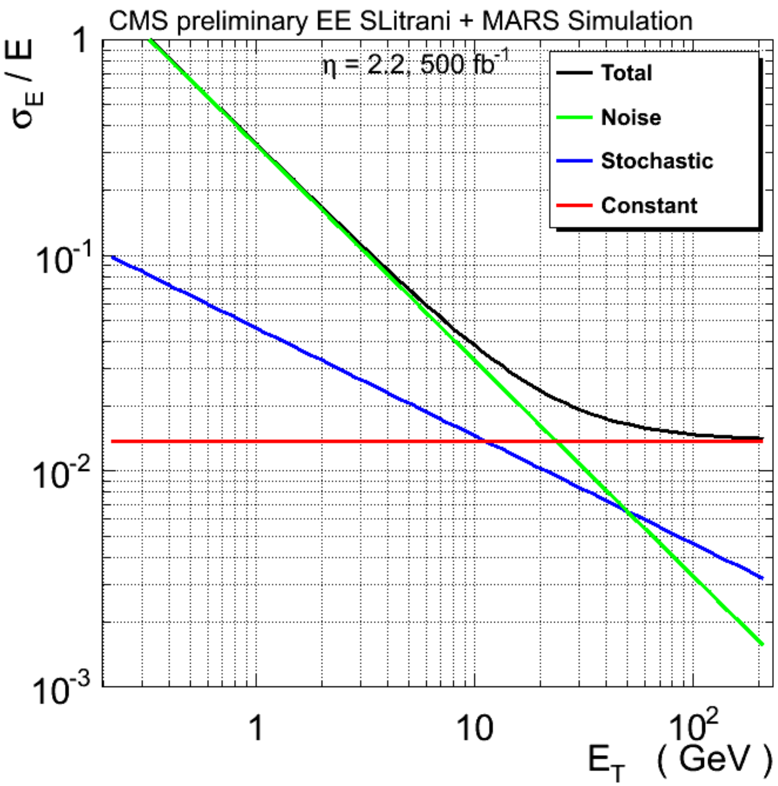
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

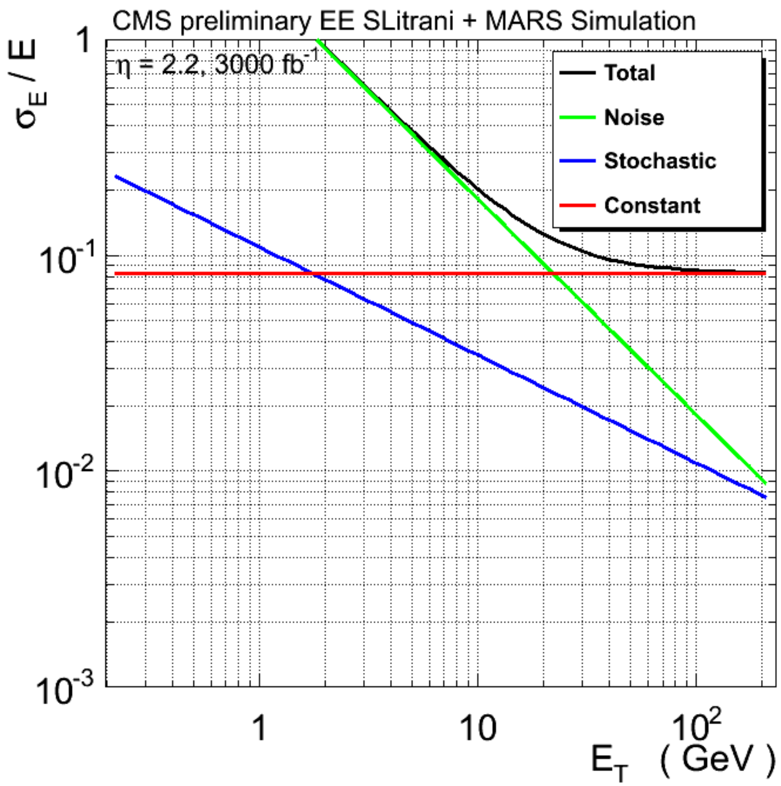


Non-uniformity of light collection deteriorates the constant term



ECAL Endcaps energy resolution evolution



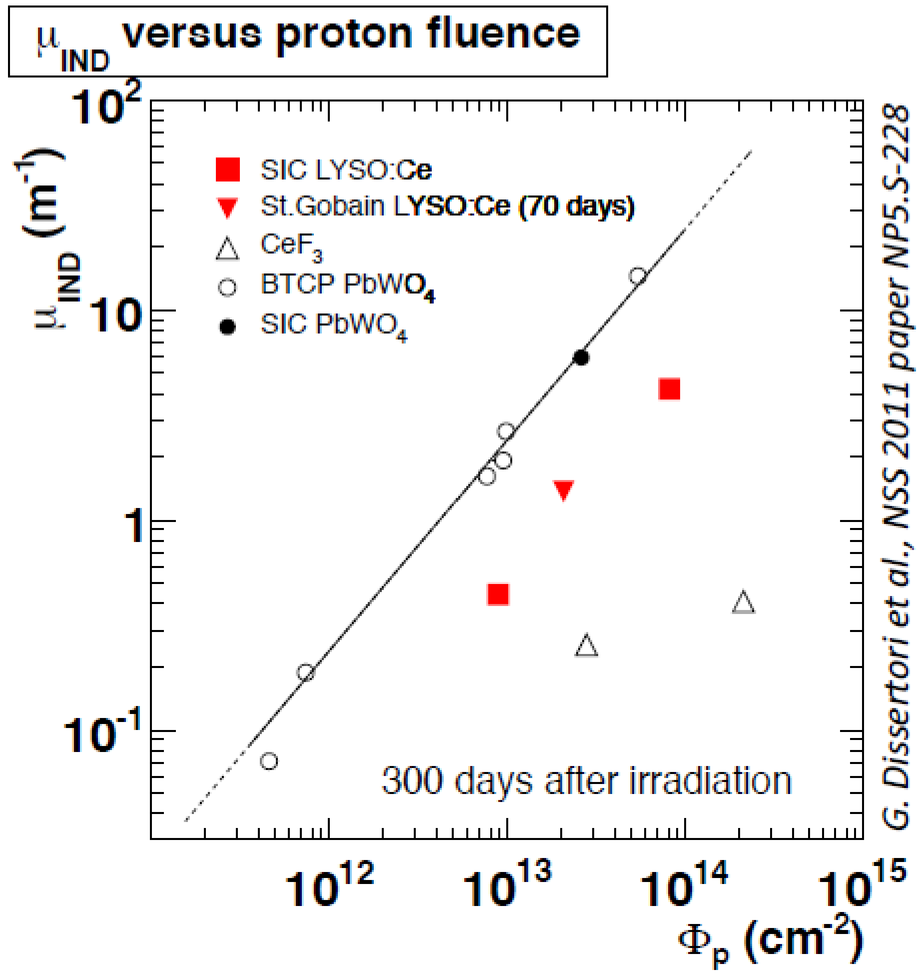


- Progressive deterioration of the energy resolution and trigger efficiency, with strong η dependence
- Performance for e/y is acceptable up to 500 fb-1
- **ECAL endcaps will have to be replaced after 500fb^{-1} (during LS3)**

R&D on new scintillators

- R&D on new crystal materials and new growing techniques are ongoing.

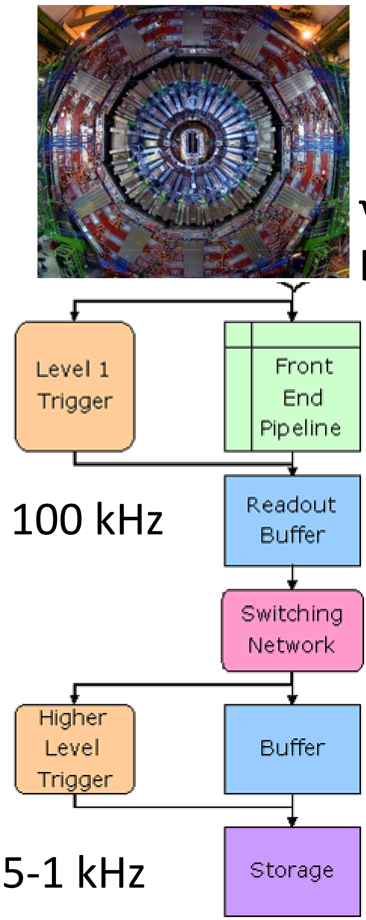
- Key points are:
  - radiation hardness, especially for hadron damage
  - Light emission spectrum matching to WLS fibers or rad-hard photo-detectors



ECAL electronics

- CMS L1 trigger will require an upgrade for the HL-LHC.
- One of the critical points to be added to the system is some **track and momentum** information already at the L1 trigger level.
- **L1 track information will also be beneficial for the e/γ triggers** (e / «π^0 in jets» separation, track-cluster matching, better isolation, primary vertex match for multiple triggers: e+jets)

ECAL front-end electronics cannot meet with the HL-LHC L1 trigger requirement and will need to be replaced.



HL-LHC
$\sqrt{s}$=14 TeV at
L=5·10^{34} cm^{-2} s^{-1}

L1 accept 100 kHz

L1 up to 1 MHz

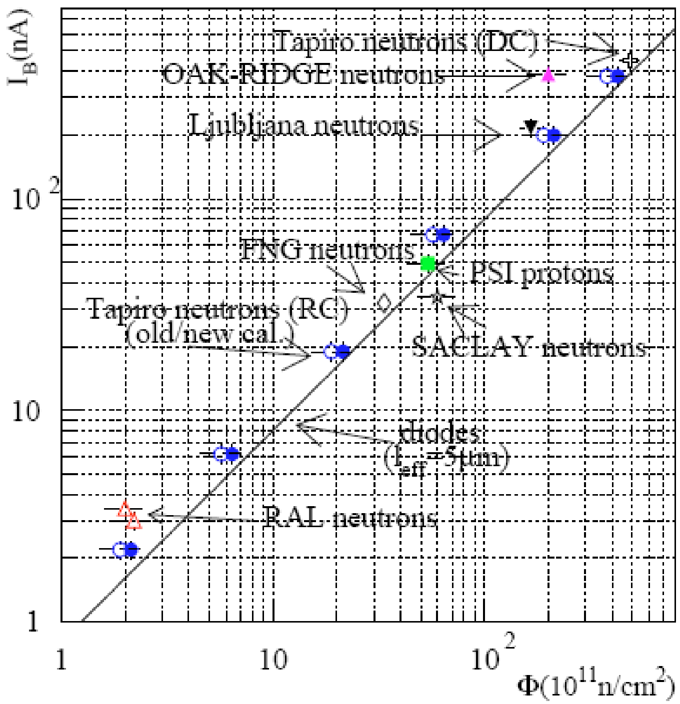
0.5-1 kHz

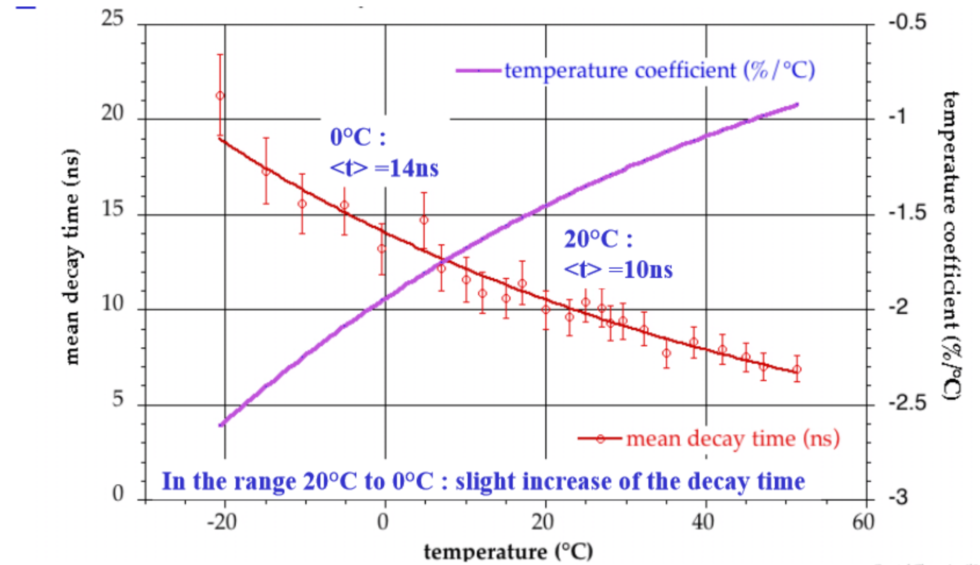
10 kHz

ECAL Barrel

Photo-detectors: APD

PWO





I. Dafinei, E. Auffray, P. Lecoq, M. Schneegans, MRS94, vol348, San Francisco, (1994) 99
P. Lecoq et al., NIM A, 365, Issues 2–3, (1995) 291

Crystal Clear, April9
E. Auffray, PH CM

APD dark current grows linearly with neutron fluence. As a consequence there is an increase in noise in EB.
The dark current can be mitigated cooling the EB.
A reduction of 2-2.5 in current cooling EB to 8 C.

At lower temperature PWO decay time is slower, and e.m. damage spontaneous annealing is less effective.
An optimization of the temperature may be needed.