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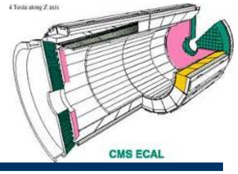
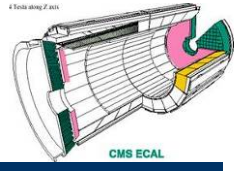
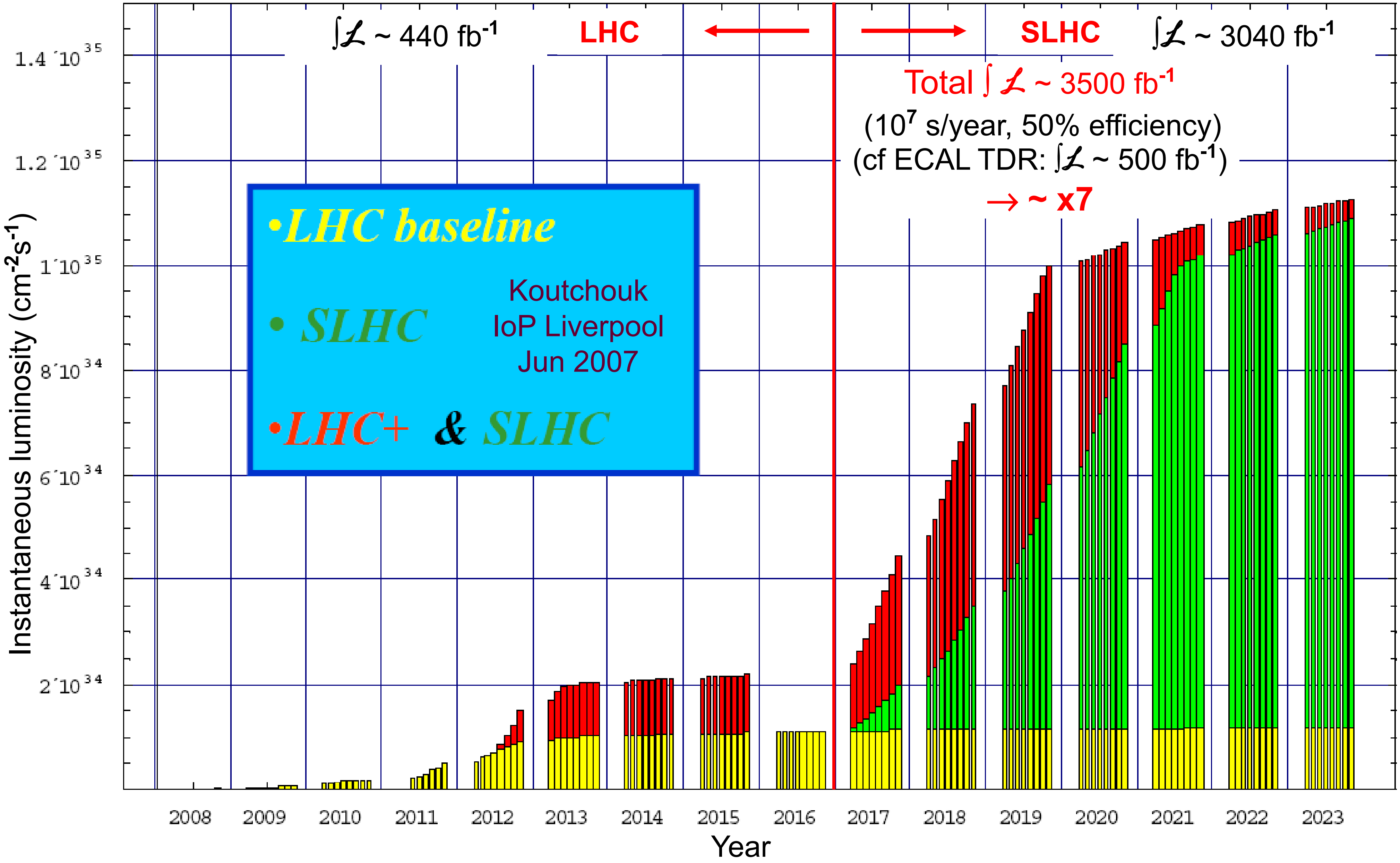
Vacuum photodetectors: present and future



- **What do we expect at SLHC?**
- **VPT properties**
- **Anticipated losses in VPT performance at LHC**
  - **- Photocathode fatigue**
  - **- Faceplate darkening**
- **Possible future approaches**
- **A word of caution**
- **Summary**

What do we expect at SLHC?





$\int\mathcal{L} \sim 440$ fb^{-1} **LHC** ← → **SLHC** $\int\mathcal{L} \sim 3040$ fb^{-1}

Total $\int\mathcal{L} \sim 3500$ fb^{-1}

(10^7 s/year, 50% efficiency)

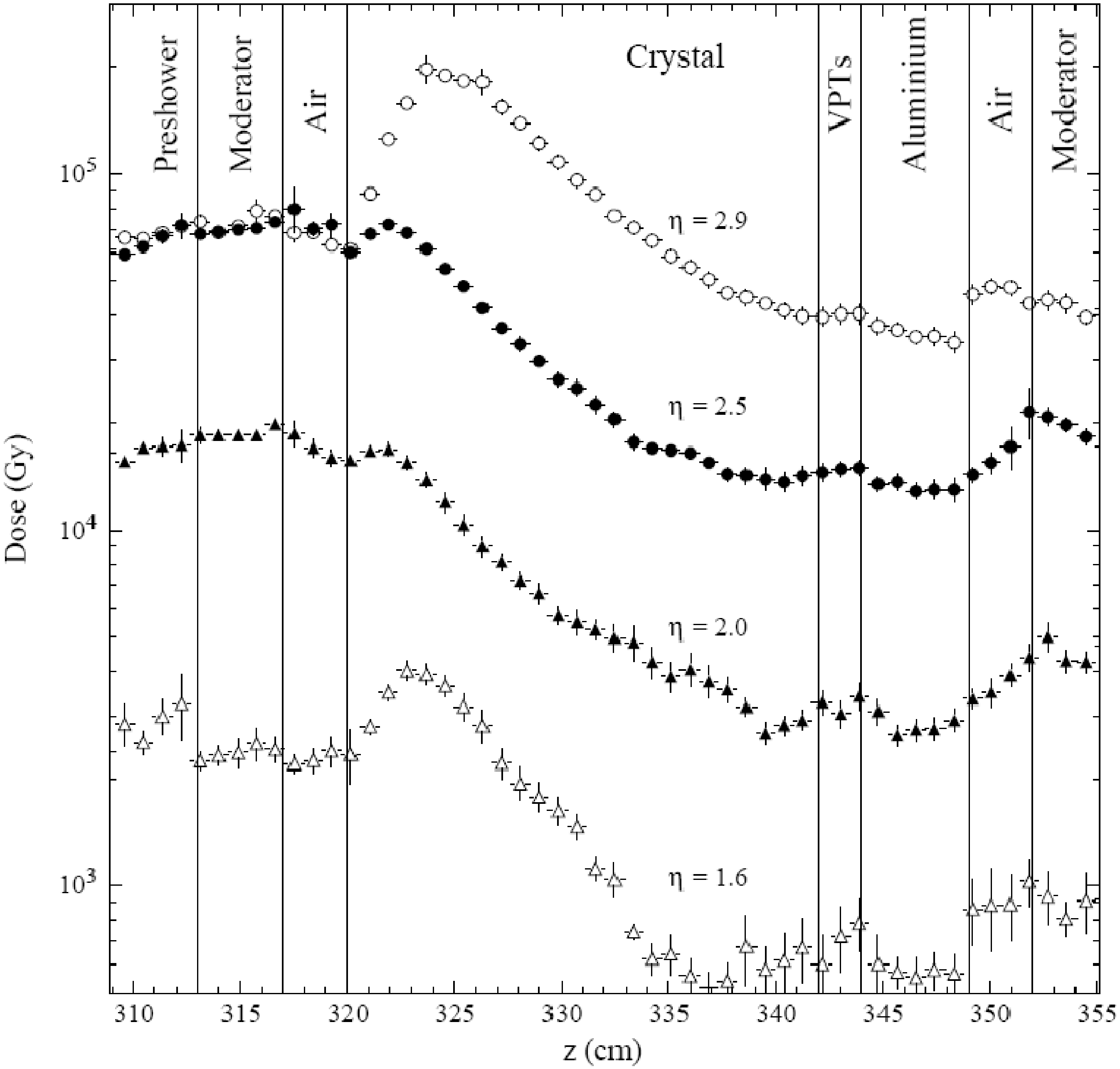
(cf ECAL TDR: $\int\mathcal{L} \sim 500$ fb^{-1})

→ **~ x7**

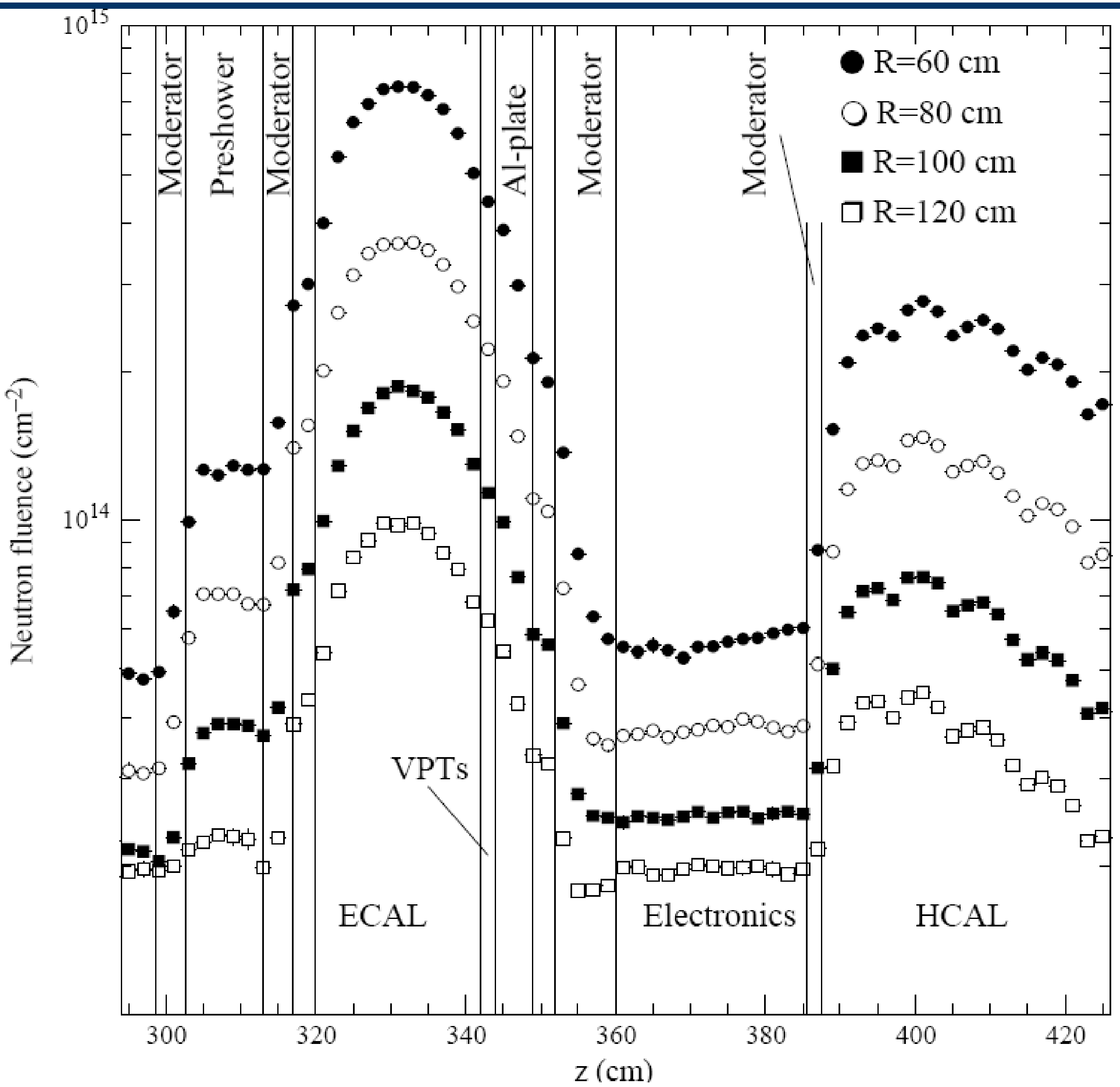
- *LHC baseline*
- *SLHC*
- *LHC+ & SLHC*

Koutchouk
IoP Liverpool
Jun 2007

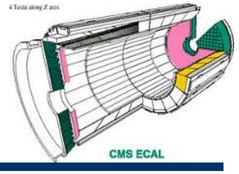
Dose versus η in EE (LHC)

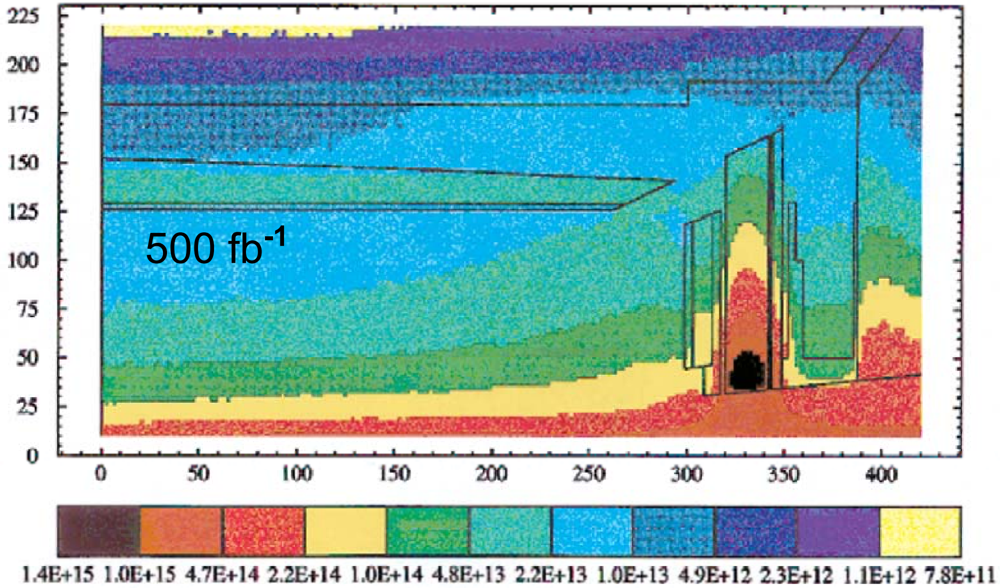


Neutron fluence (>100keV) in EE

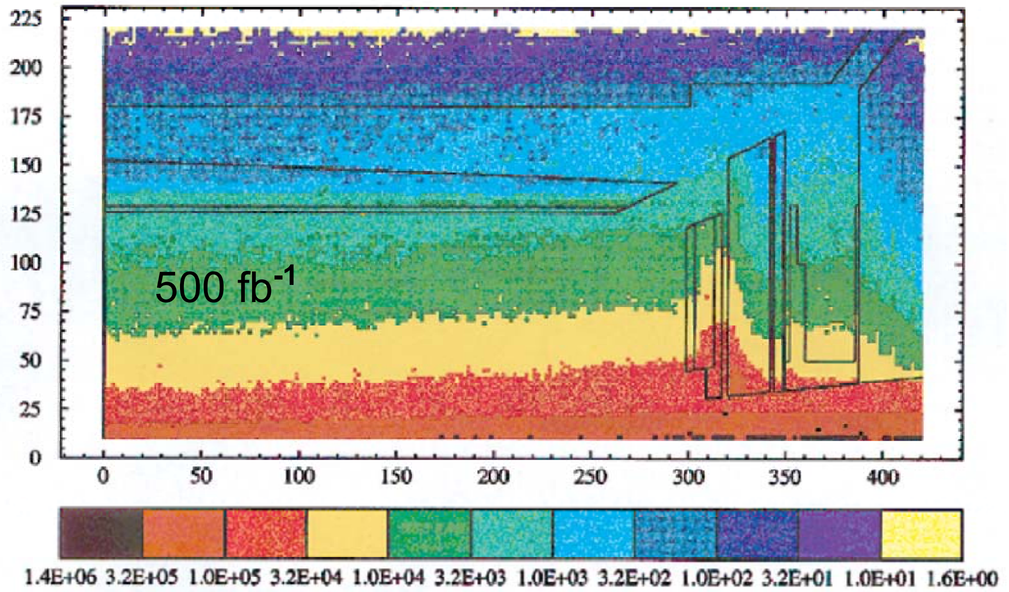


Fluence and Dose for 500 fb^{-1}

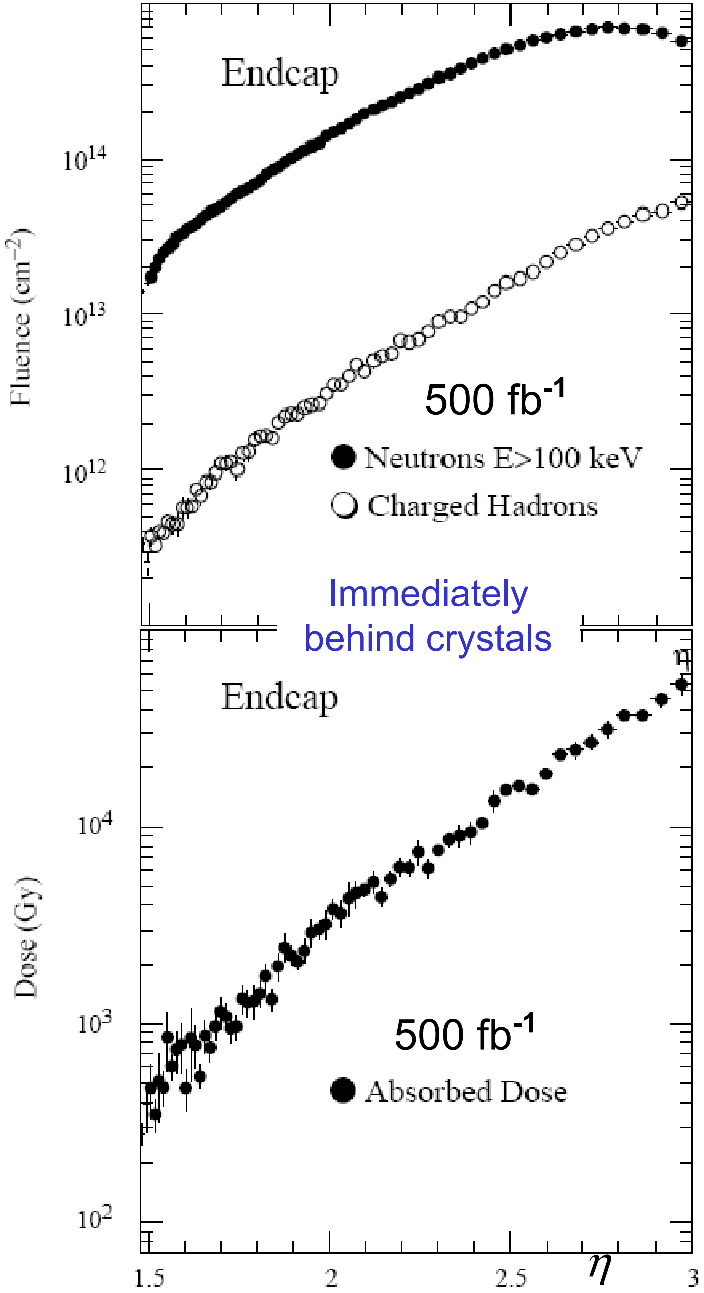




Neutron + charged hadron fluence (cm^{-2}) for E>100 keV

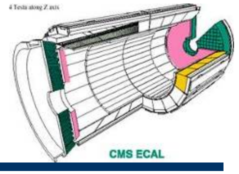


Absorbed dose (Gy)



Immediately behind crystals

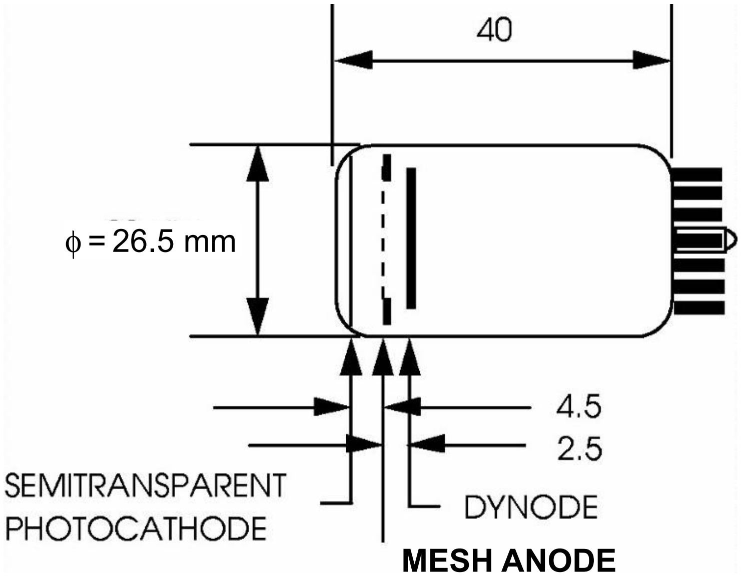
CMS Vacuum phototriodes



Vacuum Phototriode (VPT):

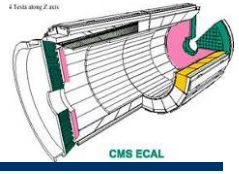
Single stage photomultiplier tube with fine mesh grid anode

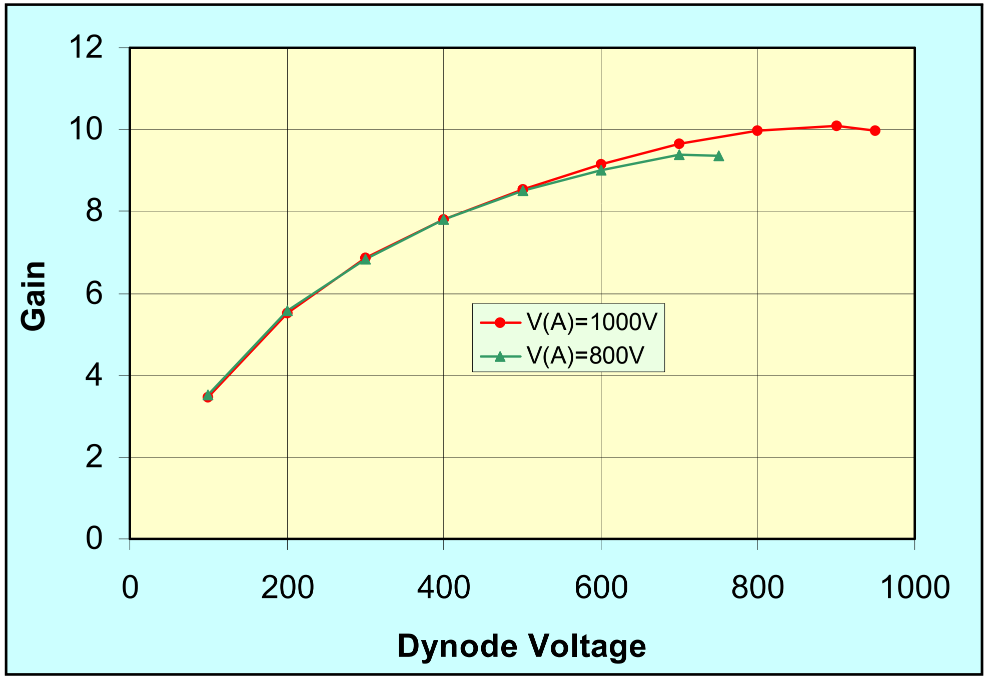
Type PMT188
National Research
Institute Electron,
St Petersburg



- Favourable B-field orientation in EE (VPT Axis: $8.5^o < |\theta| < 25.5^o$ wrt to $\vec{B}$)
- Active area of ~ 280 mm^2/crystal
- ‘ Bialkali’ (CsK_2Sb) photocathode + dynode coating
- Gain 8 -10 at B = 4 T
- Q.E. ~ 20% at 420 nm

Gain in a strong magnetic field



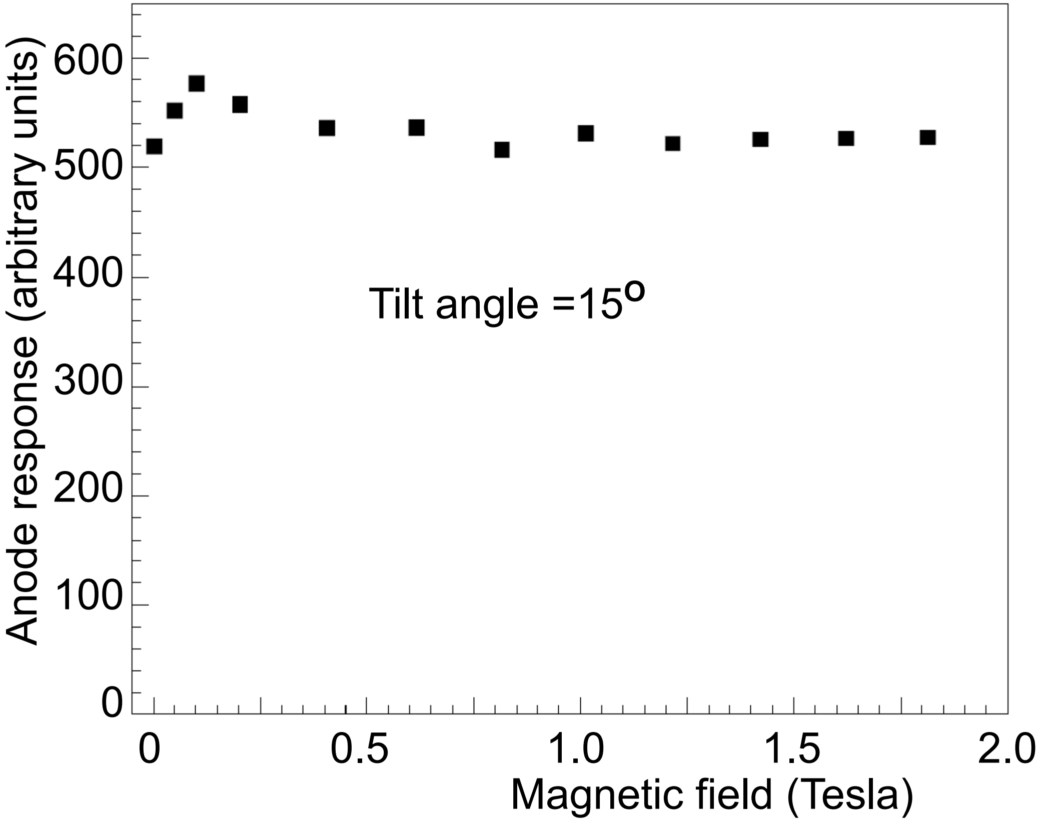


B-field immunity requires a very fine anode mesh

→ Anode pitch =10 μm

Primary electrons should pass through the anode and strike the dynode, but secondary electrons should be captured by the anode

→ Anode transparency = 50%



Gain ~ 10 achieved with:

- High bias voltages: V(A)/V(D) ~ 1000/800
- CsK_2Sb coating on dynode

→ secondary emission coefficient ~20

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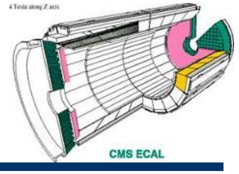
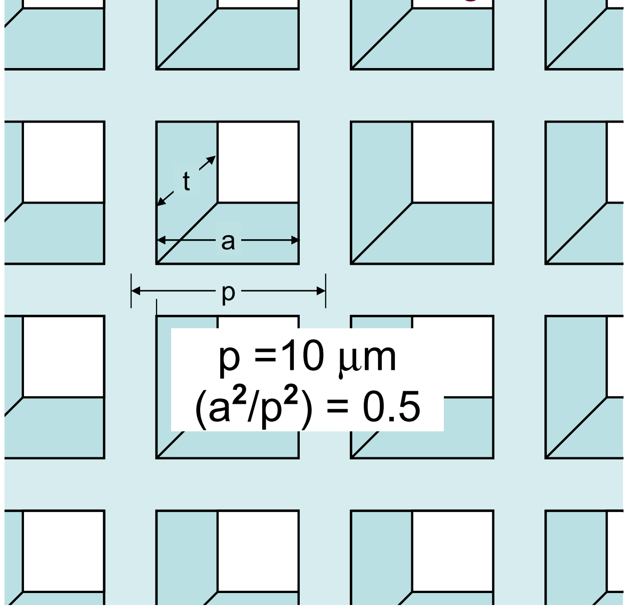
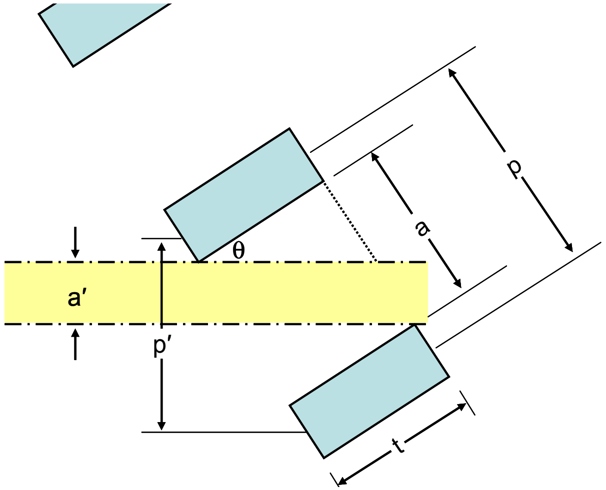
Response vs tilt angle



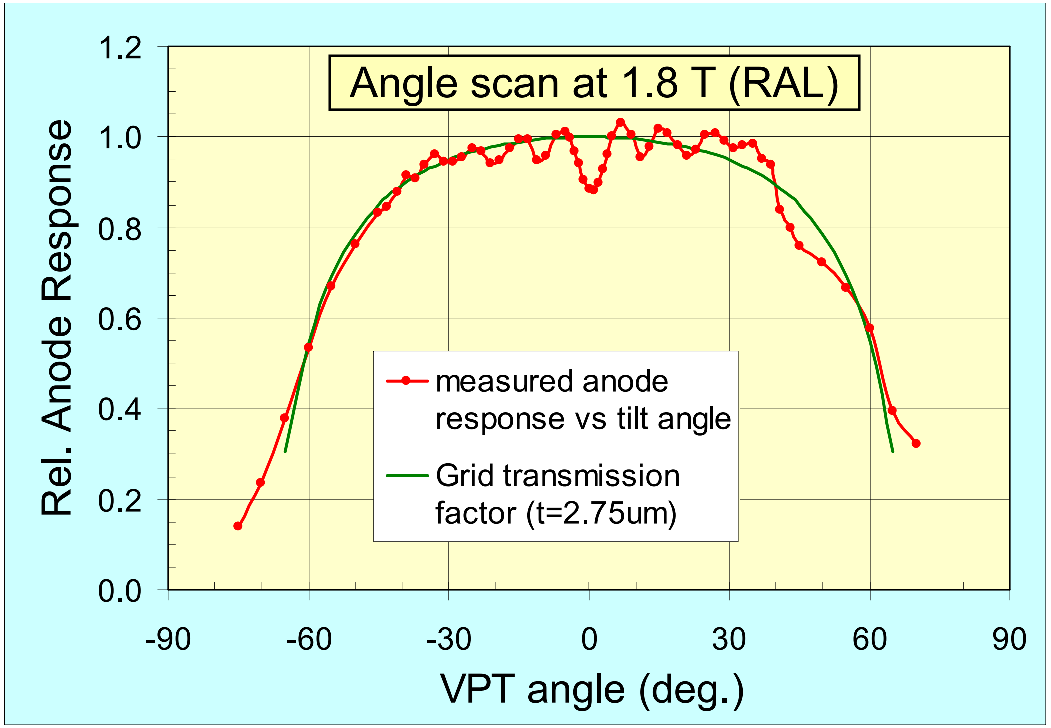
Schematic of anode grid

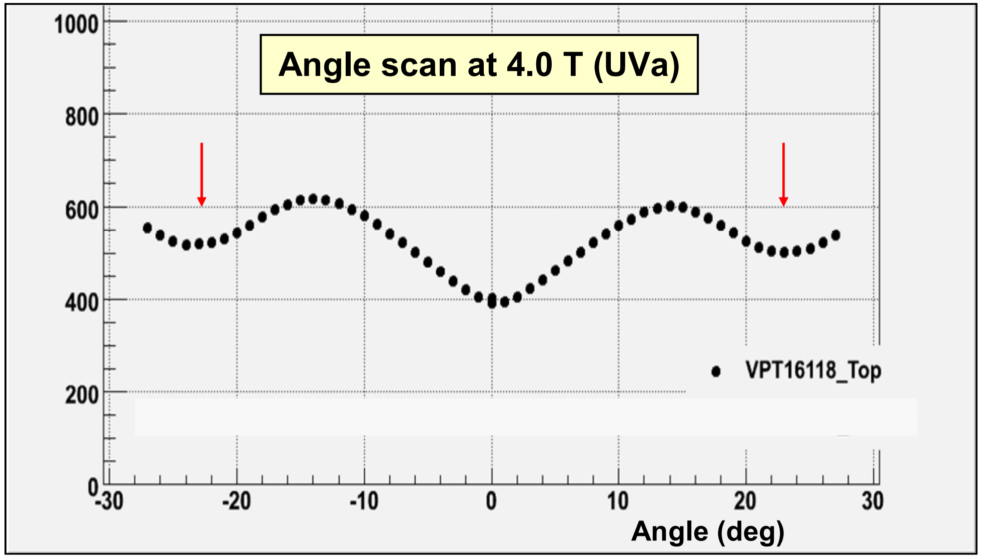


p =10 µm
$(a^2/p^2) = 0.5$

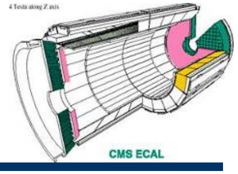


Effect of tilt on anode transparency





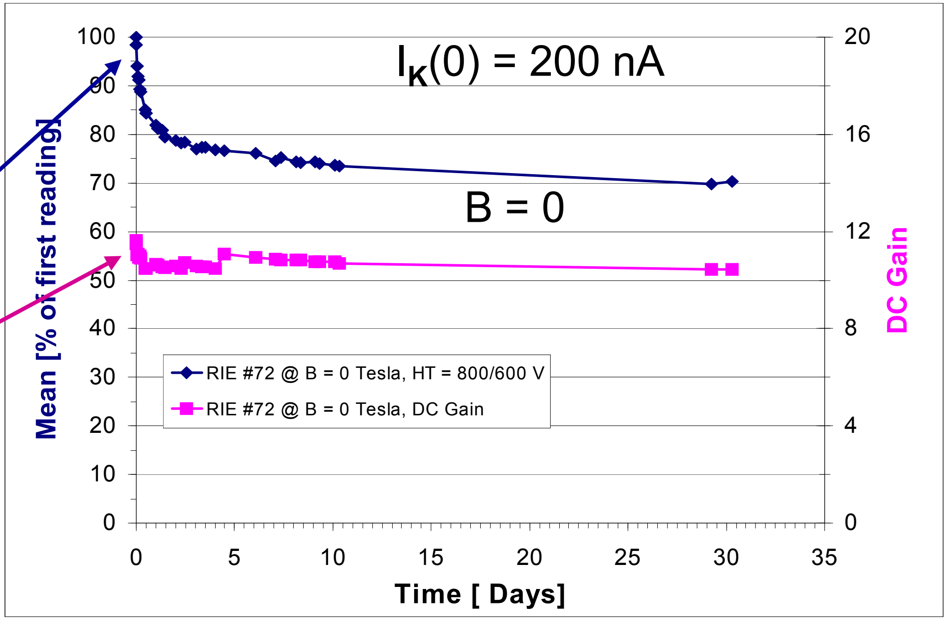
Phototube ageing



~ 10 years ago, ageing tests were made at RAL and at Brunel on 1 inch VPTs from several manufacturers, at B=0 and B=1.8T. Most tubes showed similar behaviour. These plots are for RIE tubes.

The fall in anode response is dominated by degradation of the photocathode

The gain remains ~ constant



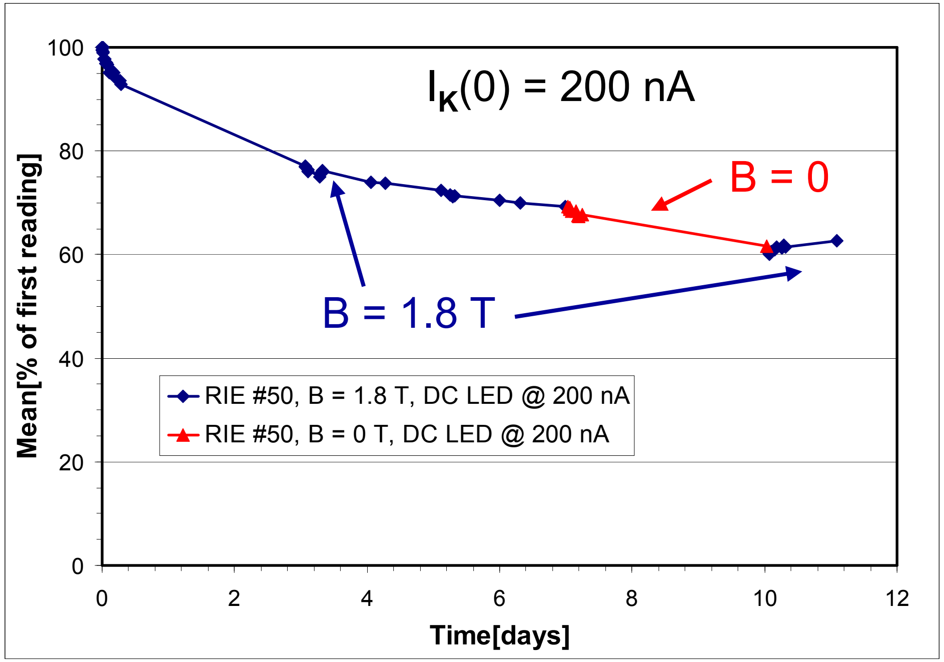
VPT Photo-currents at LHC

η	Photocurrent (nA) $\mathcal{L}=10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
2.9	8.0
2.5	2.5
2.0	0.6
1.6	0.1

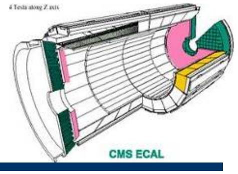
30 days at $I_K(0)$ = 200 nA

→ ~ 650 fb^{-1} at $\eta = 2.9$

→ ~ 2000 fb^{-1} at $\eta = 2.5$



Causes of photocathode degradation



Photocathode lifetime is often expressed as the ‘charge lifetime’, in Coulombs/cm^2

- Positive ion bombardment
- Cs desorption
- Oxidation due to faulty metal in glass seals ⟵ Not a problem with well-constructed tubes
- Electrolysis of the glass of the window ⟵ Bias with cathode at 0V (a/c couple anode)
- Other

Measurements on an RIE tube show a behaviour that is well described by the sum of two exponential terms – indicating two distinct effects.

These are sometimes termed ‘conditioning’ and ‘ageing’.

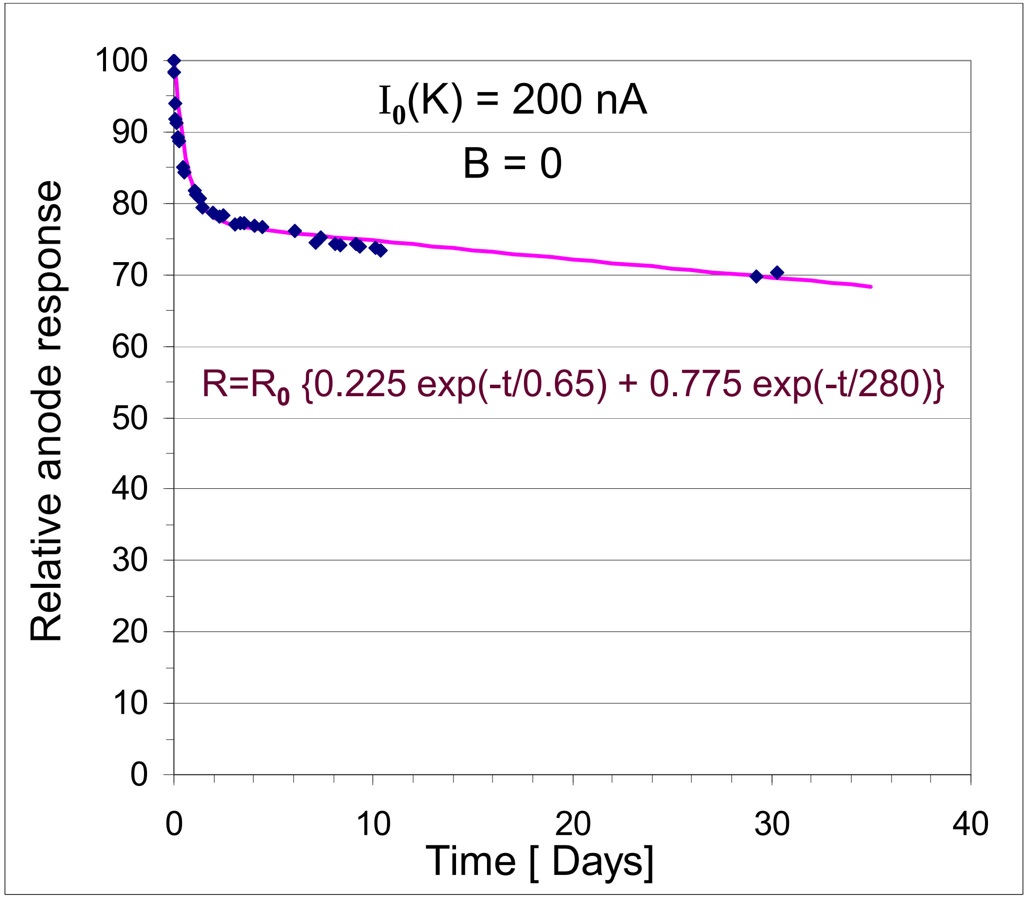
Assuming linear scaling to a typical EE/LHC photocurrent of 2 nA:

C_1 ~0.25 and τ_1 ~ 65 days

C_2 ~0.75 and τ_2 ~ 3x10^4 days

τ_1 is consistent with a simple estimate of the time to sweep up the residual gas in the tube (positive ion bombardment)

It is tempting to attribute τ_2 to Cs desorption



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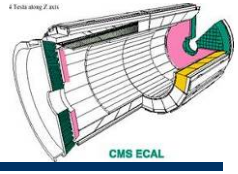
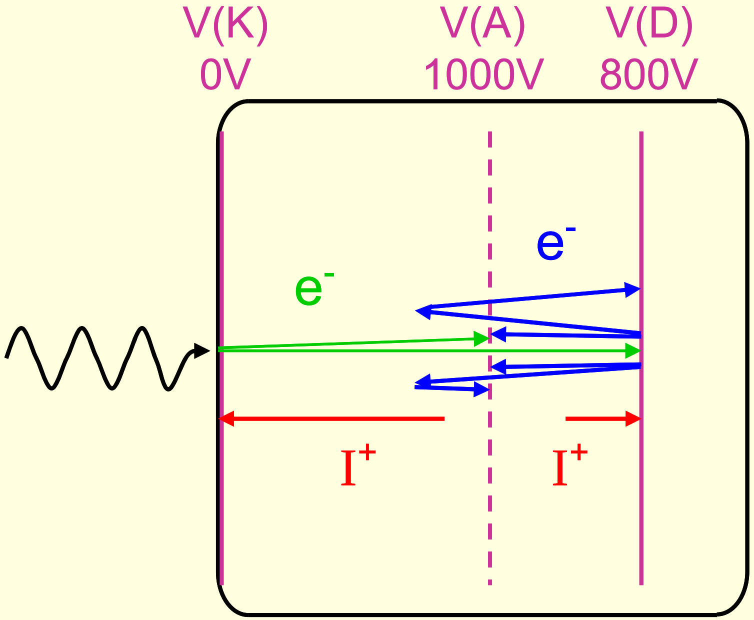
Positive ion bombardment





Not to scale!!!

The secondary emission coefficient of the dynode ~20.

→ Positive ion production is dominated by secondary electrons -
both in the anode-dynode gap
and the anode-cathode gap

Ions strike the cathode with $<E(I^+)> = 900$ eV

Ions strike the dynode with $<E(I^+)> = 100$ eV

Photocathode damage caused by positive ion bombardment increases with ion energy.

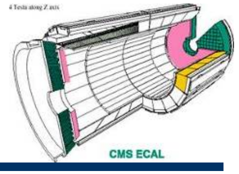
→ Pre-condition by operating the tubes at low bias for ~100d at I_k = 2nA ??
(tests are planned but note importance of gain)

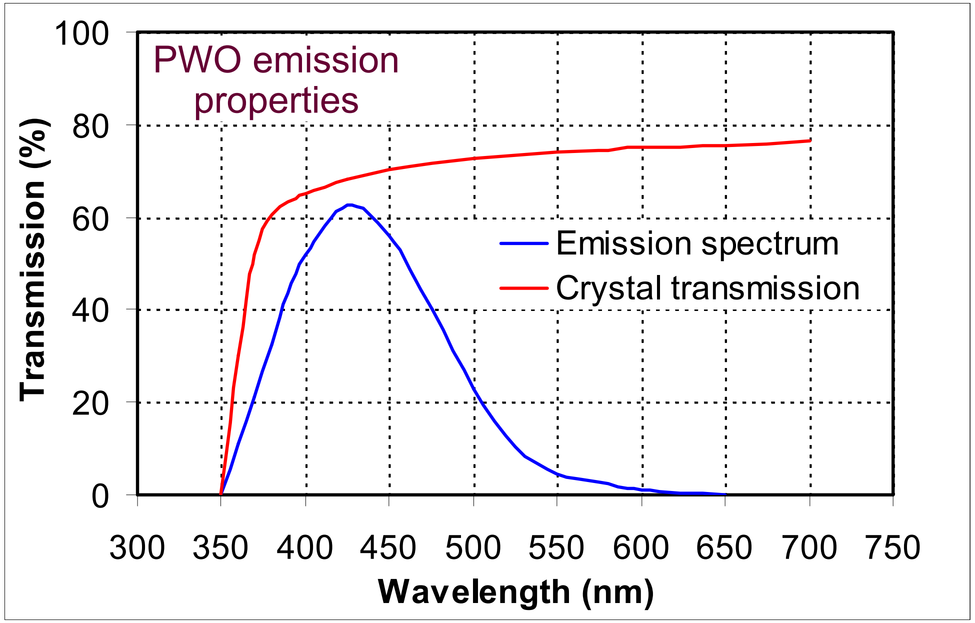
(Note: in principle one could precondition the tubes as diodes with V(K) = V(A) =0 and V(D) = -200V, using the dynode as the photocathode. In this configuration all the ions would be swept on to the dynode, which appears to be less sensitive to damage.

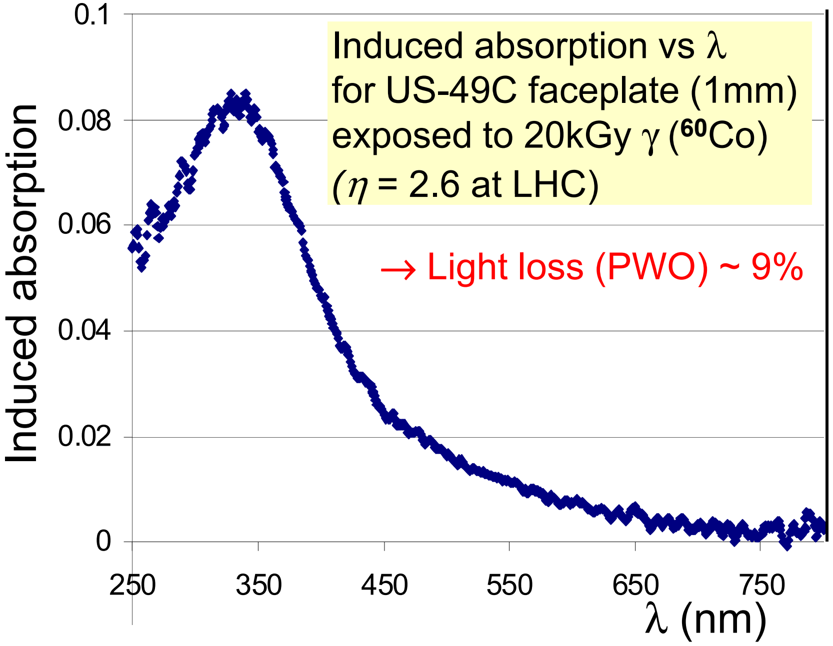
However, without internal gain, this would take a prohibitively long time at practical levels of illumination.)

Note also that positive ion damage self-anneals to some extent when a tube is ‘rested’ for several months – so a pre-conditioning strategy would need repeating.

Radiation-darkening of faceplates (n & γ)

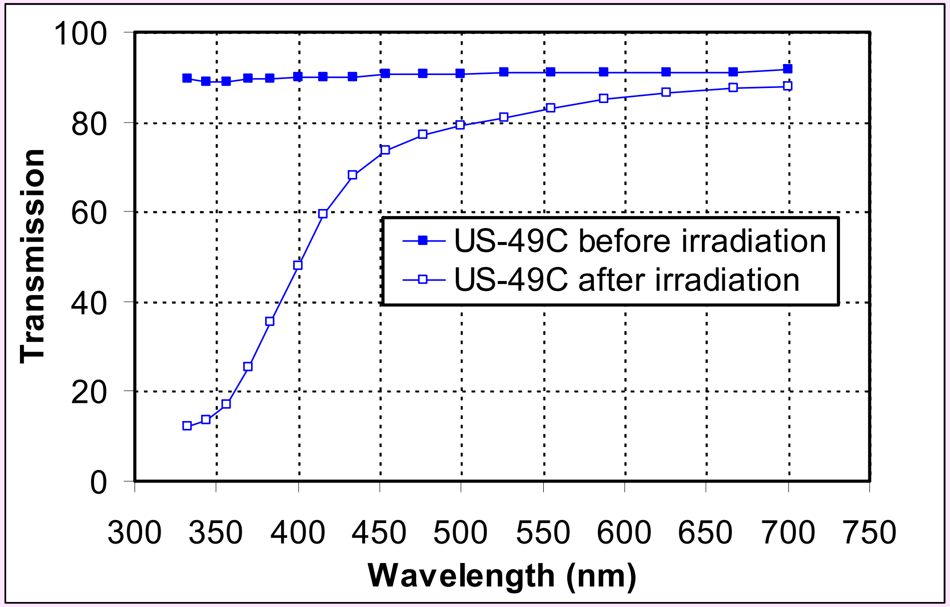






Induced absorption vs λ for US-49C faceplate (1mm) exposed to 20kGy γ (^{60}Co) (η = 2.6 at LHC)

→ Light loss (PWO) ~ 9%



Neutron fluence is 7x10^{14} n/cm^{2} (Reactor)
Accompanying γ-dose ~100 kGy
Relative loss, weighted by emission, = 23.5%

For comparison, expected exposures at LHC (500 pb^{-1}) at η = 3 are:
7x10^{14} n/cm^{2} and 50 kGy

(Super radiation hard vacuum phototriodes for the CMS endcap ECAL, NIM A535, 2004, 511-516 Yu.I.Gusev, et al.)

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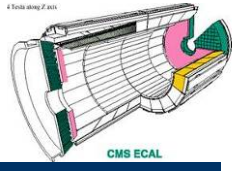
‘Ruggedizing’ vacuum photodetectors (1)



Window transparency:

Fused silica (‘quartz’) is extremely radiation hard, but requires ‘graded seals’
→ increased cost, increased length, increased vulnerability to He ingress.

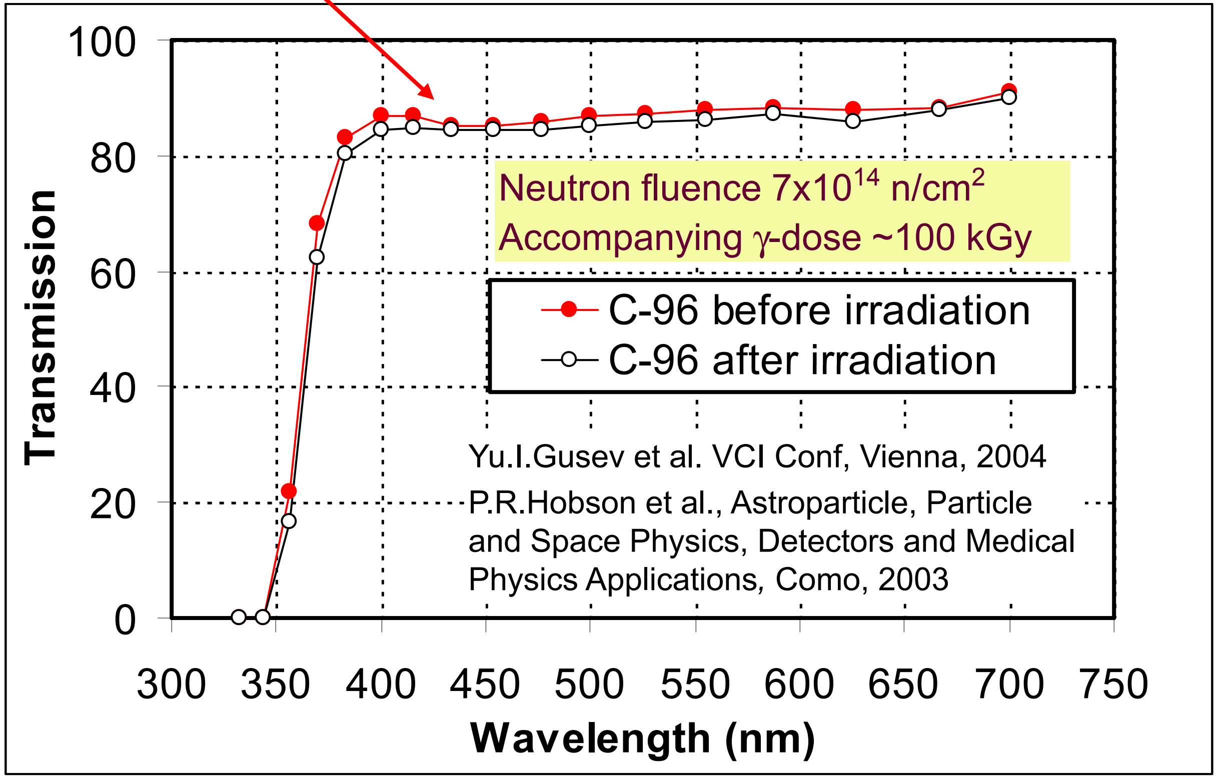
However, UV-transmitting and Ce-doped glasses with improved radiation resistance are now available

US-49A faceplate exposed to 10^{16} n/cm^2 together with a γ dose of 1600±250 kGy

[Yu.I. Gusev et al., NIM A 581, 438, (2007)]

Unfolding neutron damage using extrapolated ^{60}Co data (and ignoring γs from induced activity in the glass):

→ $\Delta T/T_0$ (neutron) < 15% for EE $\eta < 3.0$ at SLHC



Yu.I.Gusev et al. VCI Conf, Vienna, 2004
P.R.Hobson et al., Astroparticle, Particle and Space Physics, Detectors and Medical Physics Applications, Como, 2003

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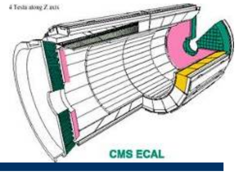
‘Ruggedizing’ vacuum photodetectors (2)



Positive ion damage (‘conditioning’):

- Improve the vacuum: for example, incorporate a getter
  – tests on a single device during R&D for CMS showed a marked improvement.
- Operate at low bias voltage
  - incompatible with large internal gain → use vacuum photodiodes?

Caesium desorption:

Popular high efficiency photocathodes for visible light almost all incorporate Cs.

However, alternatives are available:
E.g. ‘High temperature bi-alkali’ (Na_2KSb) (used in oil-well logging)
- Q.E. ~16% at 400 nm.

EE replacement/upgrade??

$PbWO_4$ → LYSO ?

λ_{emiss} ~ (380-460) nm, LY(LYSO) ~ 200 x LY(PWO)

What photo-detector?

Silicon devices:

Neutron damage → high leakage currents → amplifier noise?

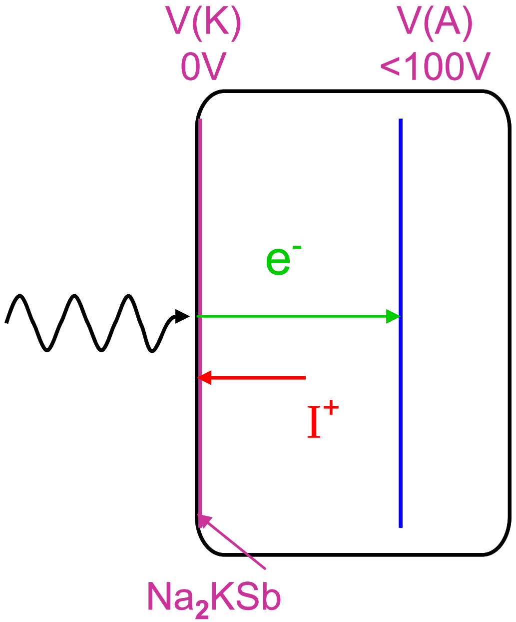
'Nuclear counter effect' (for a simple photodiode, direct sensitivity to shower leakage particles >> sensitivity to scintillation light → high energy tail on energy measurement)

APD?

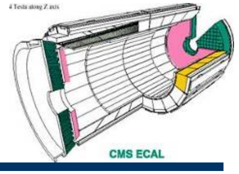
Vacuum devices:

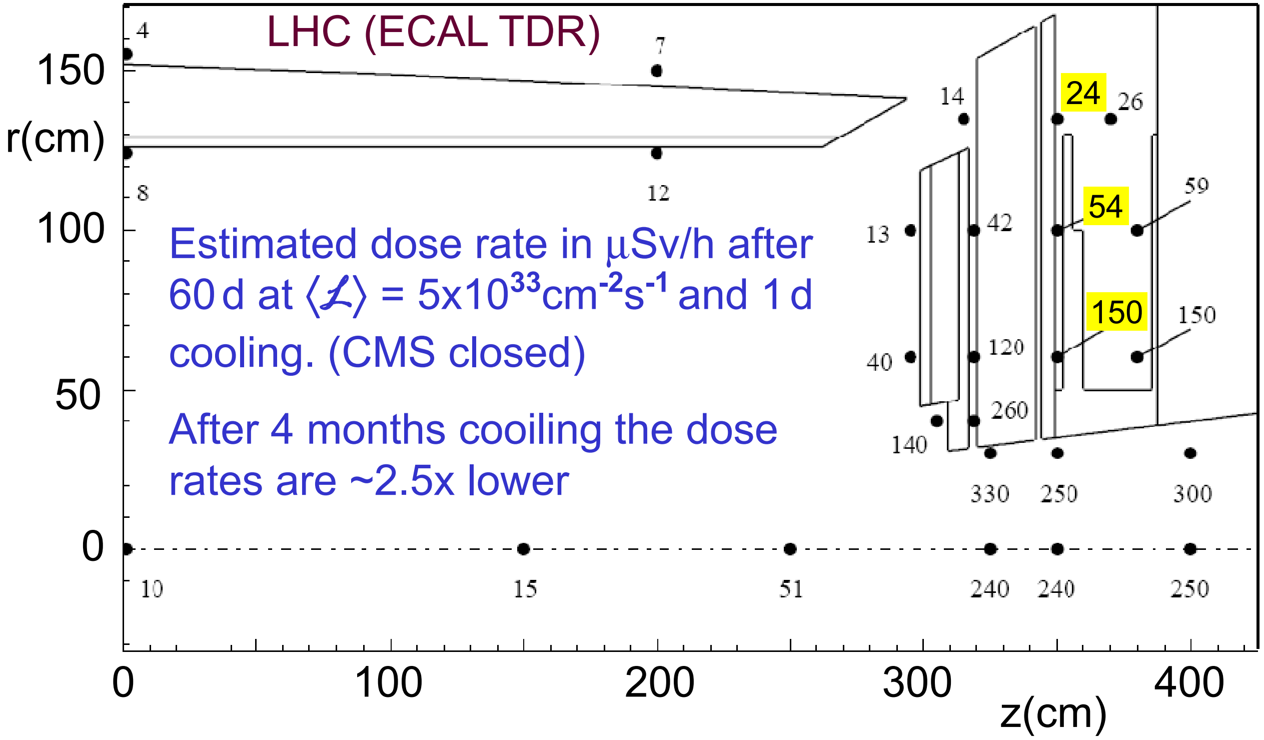
- Good match to biakali photocathode
- Internal gain not necessary

→ Vacuum photodiode?



EE Activation





Estimated dose rate in µSv/h after 60 d at ⟨$\mathcal{L}$⟩ = 5x10^{33}cm^{-2}s^{-1} and 1 d cooling. (CMS closed)

After 4 months cooiling the dose rates are ~2.5x lower

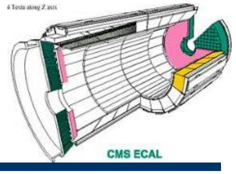
Occupational dose limit: 20 mSv/yr

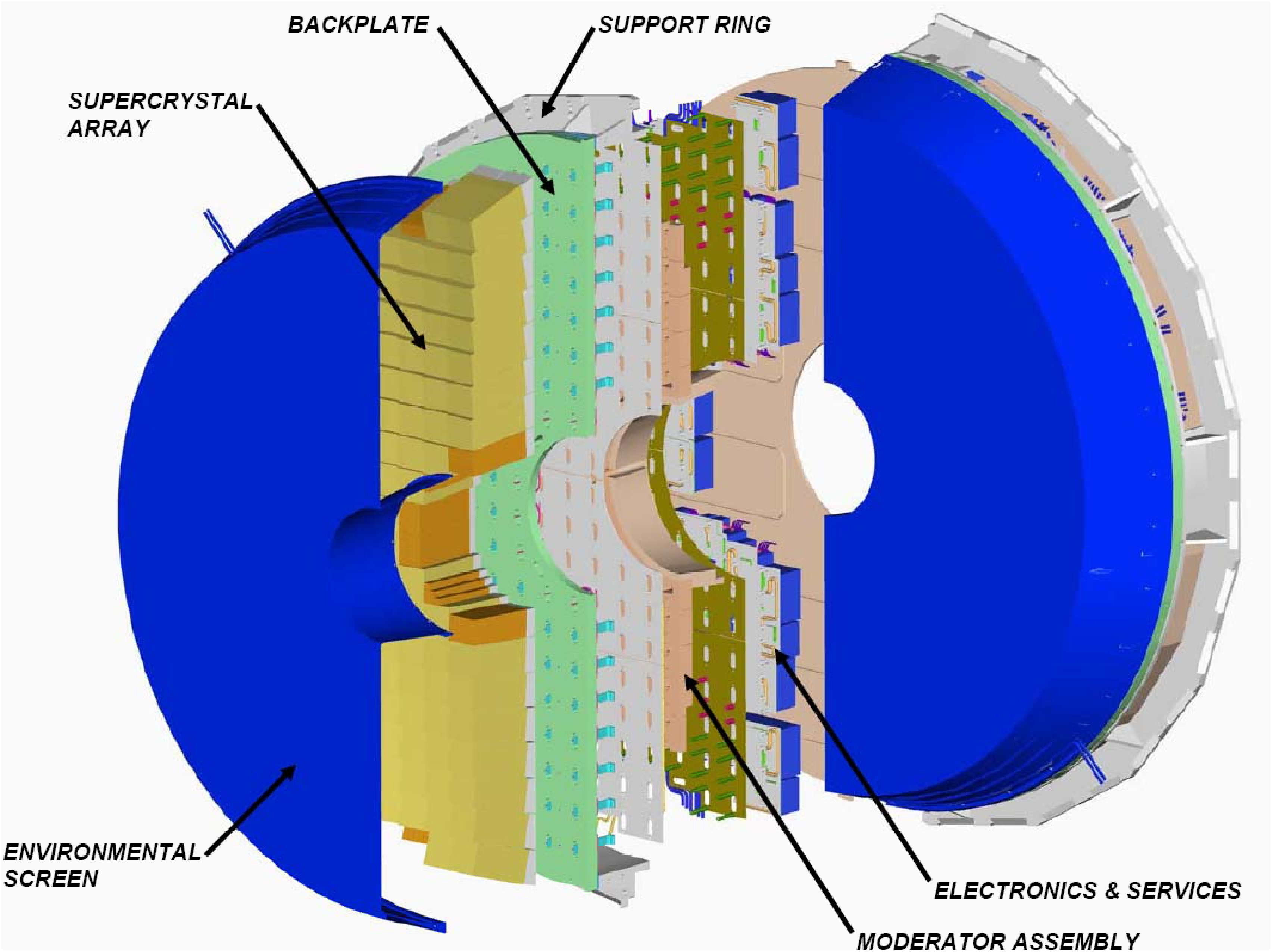
(Note: this is the **legal** limit, the normal CERN limit is 6 mSv/yr – except for the (very few) ‘Class A’ workers)

Assume induced activity levels at SLHC ~10xLHC

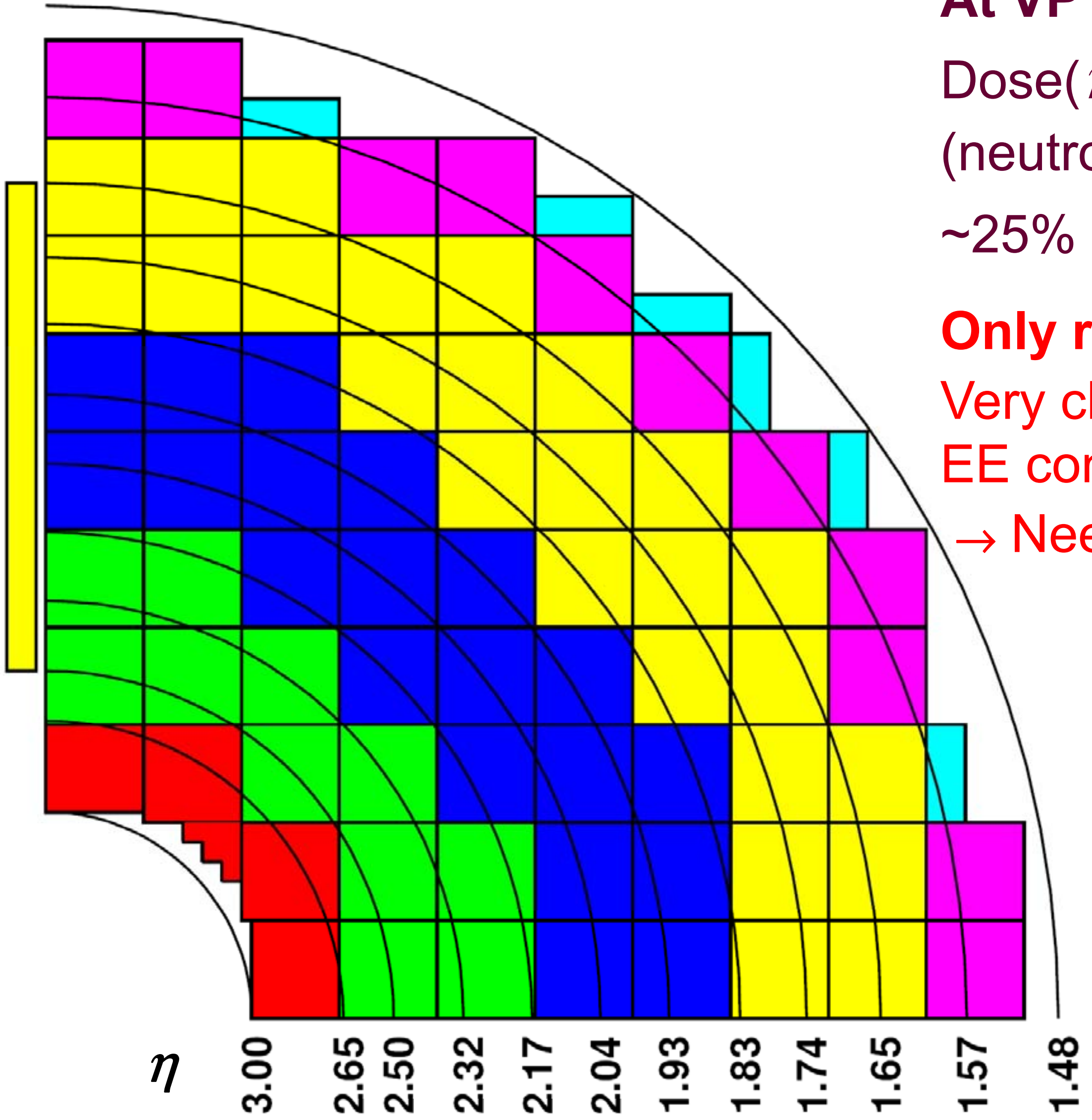
→ Time to Annual limit at η = 3 is ~12 h

Layout of EE elements





Partial endcap upgrade for SLHC?



At VPTs:

Dose(η =2.2)/Dose(η =3.0) ~1/10
(neutron fluence ~1/3)

~25% (18/71) Supercrystals are at η >2.2

Only replace detectors at small radius ?

Very challenging because of complexity of EE construction and high radiation levels

→ Needs detailed study

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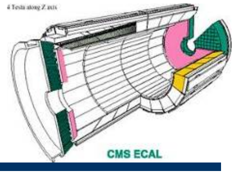
Summary



- EE photodetectors at small radius will be significantly degraded after 500 fb^{-1}

  (Anode response → ~ 50% at η = 3.0)
- Development of ‘ruggedized’ vacuum photo-detectors appears feasible (Interest from Brunel, RAL, UVa……)
- A partial replacement of EE would be challenging