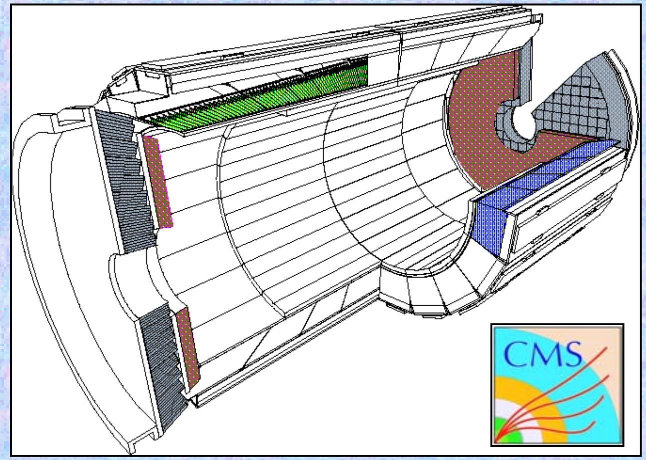
Recent Developments in Crystal Calorimeters featuring the CMS $PbWO_4$ Electromagnetic Calorimeter



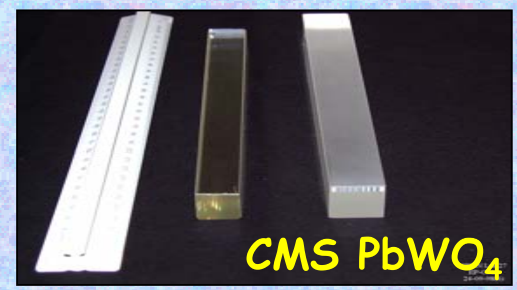
Suzanne GASCON-SHOTKIN

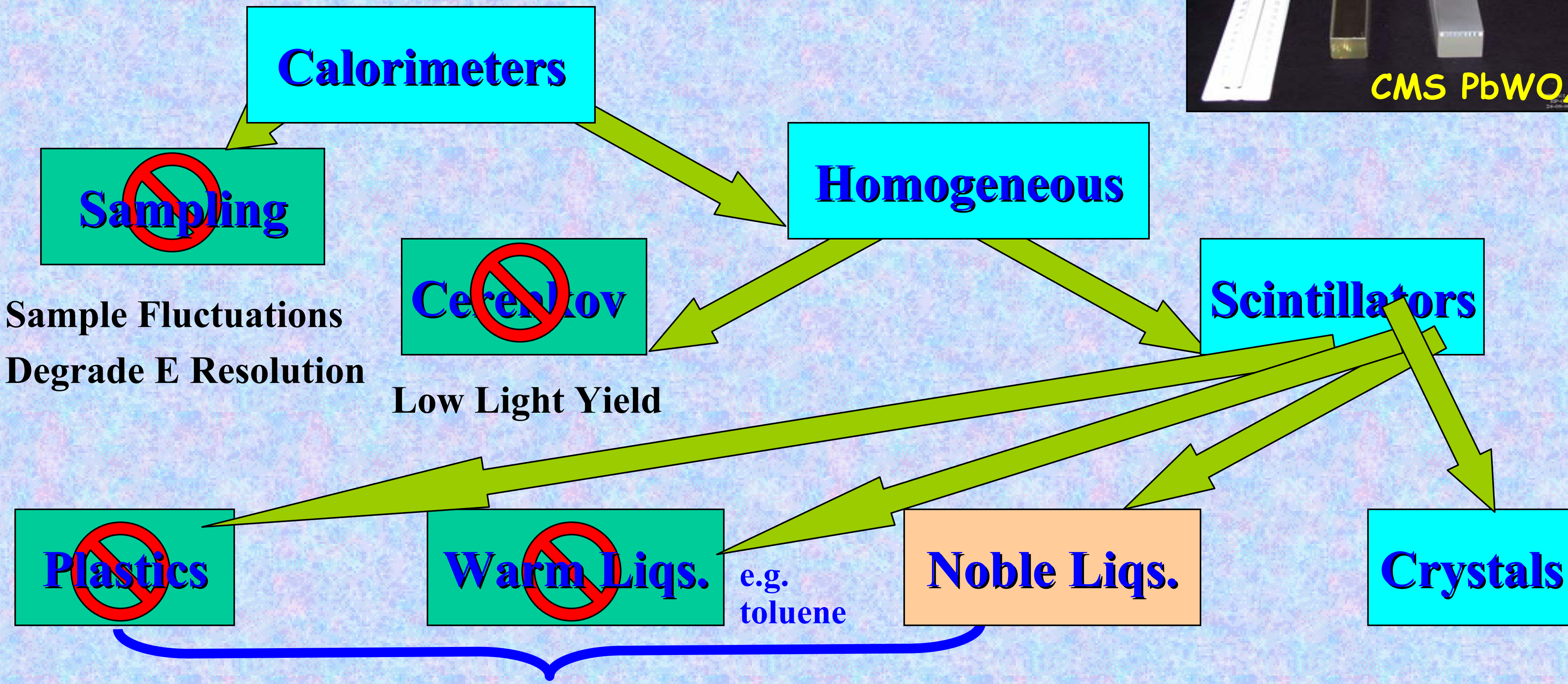
Institut de Physique Nucleaire de Lyon/Universite Claude Bernard Lyon I

For the CMS ECAL Collaboration

Crystal Calorimeters have been historically used in HEP:

- For precision E measurements of e, γ, π^0 ..
- To help in position measurement

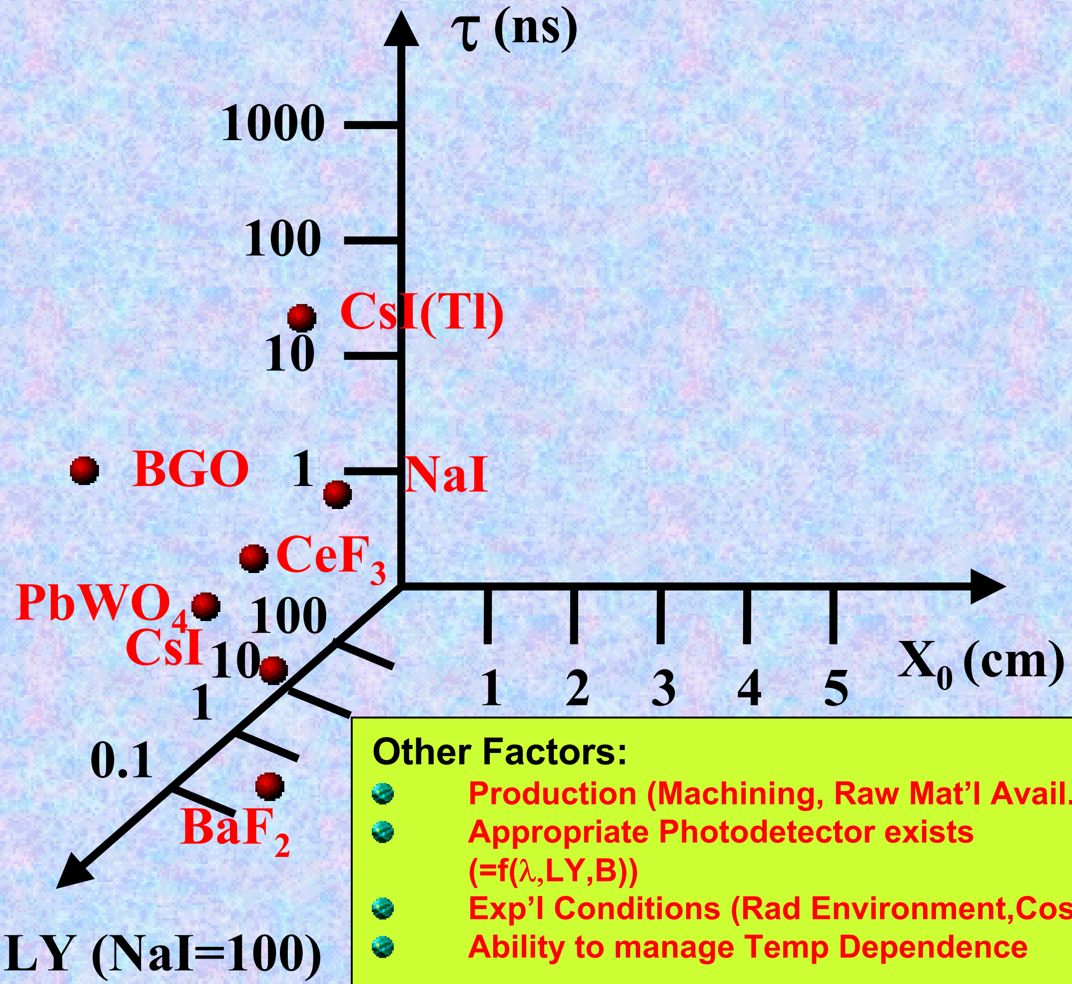




X_0 too long to be practical (factor of 2-20 wrt crystals) exc. LiXe (avail, purity)

Design issues in Crystal Calorimetry:

- A calorimeter design ‘phase space’:

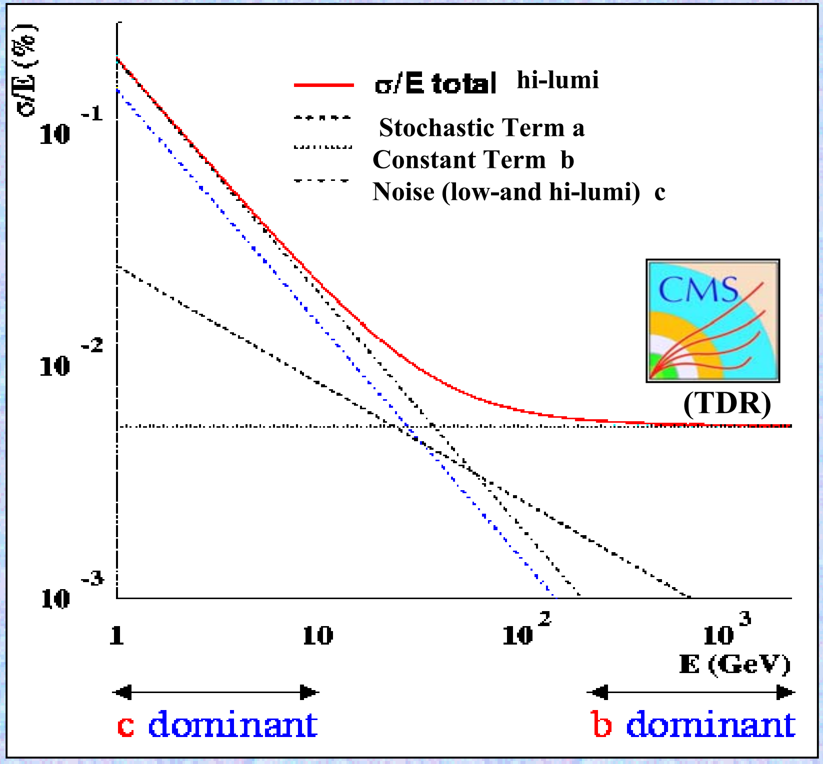


Other Factors:

- Production (Machining, Raw Mat’l Avail.)
- Appropriate Photodetector exists (=f(λ,LY,B))
- Exp’l Conditions (Rad Environment,Cost)
- Ability to manage Temp Dependence

- Focus on energy resolution:

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



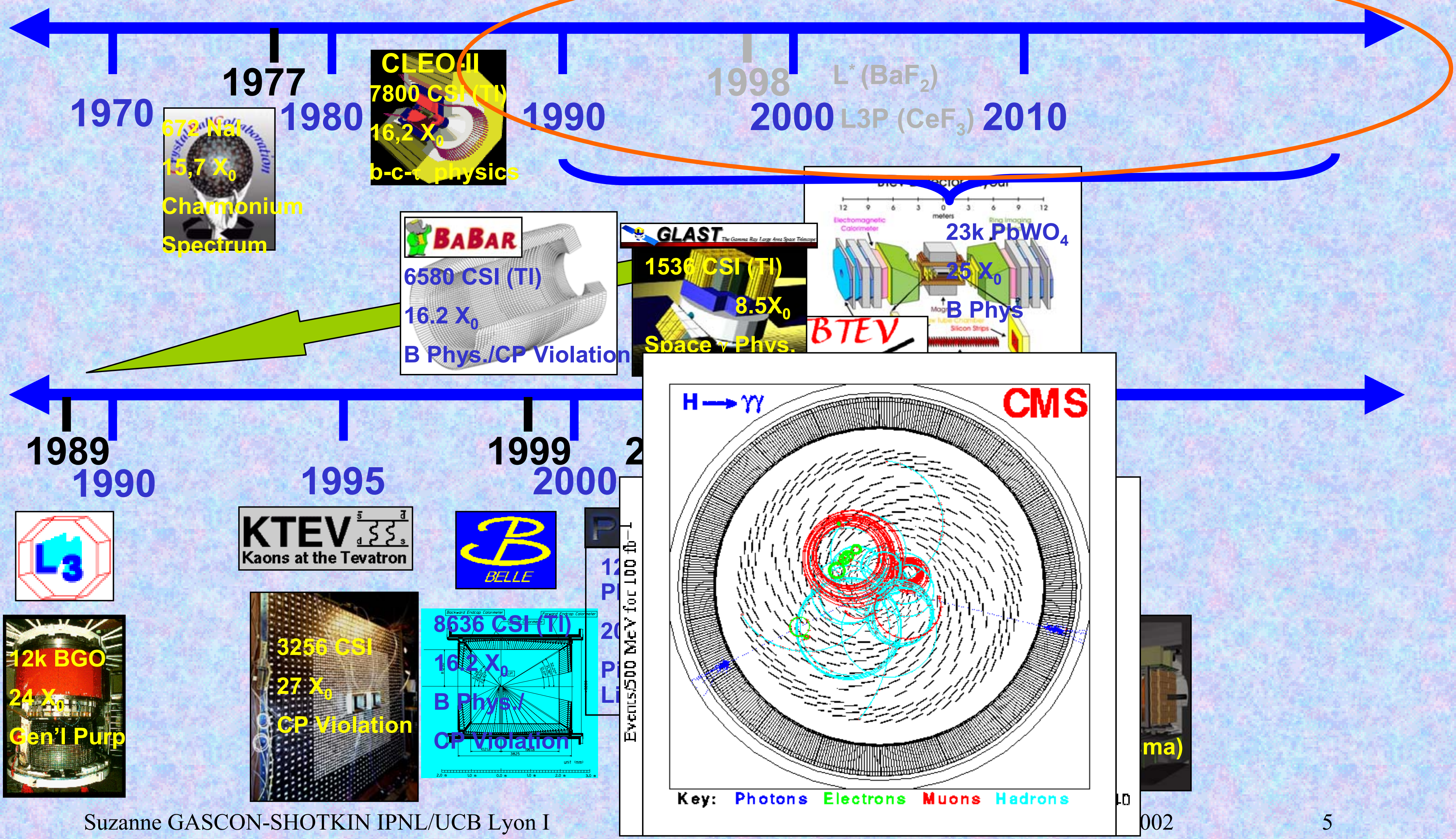
The 'Why' and 'How' of Crystal Calorimeters III

Adapted from R.-Y. ZHU, presentation at UCSC Linear Collider Retreat, June 2002

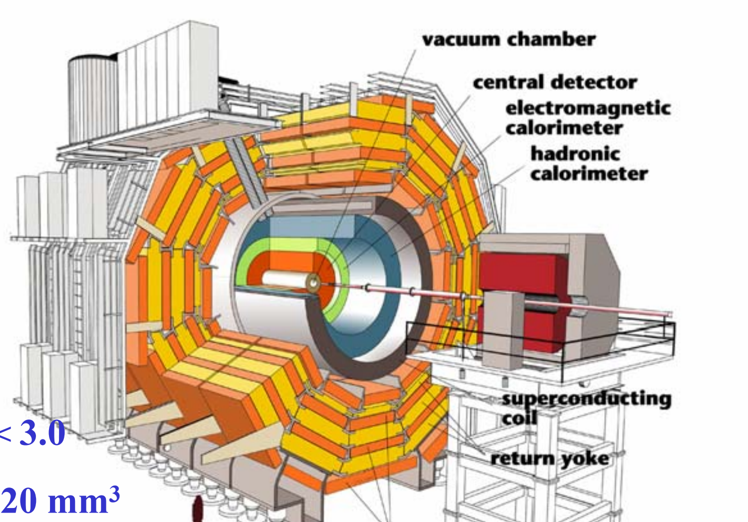
Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	CeF_3	BGO	$PbWO_4$	LSO(Ce)	GSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.89	6.16	7.13	8.3	7.40	6.71
Radiation Length (cm)	2.59	1.85	1.85	2.06	1.68	1.12	0.9	1.14	1.37
Molière Radius (cm)	4.8	3.5	3.5	3.4	2.63	2.3	2.0	2.3	2.37
Interaction Length (cm)	41.4	37.0	37.0	29.9	26.2	21.8	18	21	22
Refractive Index [a]	1.85	1.79	1.95	1.50	1.62	2.15	2.2	1.82	1.85
Hygroscopicity	Yes	Slight	Slight	No	Slight	No	No	No	No
Luminescence [b] (nm) (at peak)	410	560	420 310	300 220	300 340	480	560 420	420	440
Decay Time [b] (ns)	230	1300	35 6	630 0.9	25 8	300	50 10	40	60
Light Yield [b,c] (%) (Room temp)	100	45	5.6 2.3	21 2.7	8	9	0.1 0.6	75	30
d(LY)/dT [b] (%/ °C)	~0	0.3	-0.6	-2 ~0	<0.1	-1.6	-1.9	?	?
Experiment	Crystal Ball	CLEO-II BaBar, BELLE	kTeV	L^*, GEM	L3P	L3	CMS, ALICE..	?	?

a. at peak of emission; b. up/low row: slow/fast component; c. measured by PMT of bi-alkali cathode.

A Crystal Calorimeter Timeline



The CMS $PbWO_4$ Electromagnetic Calorimeter



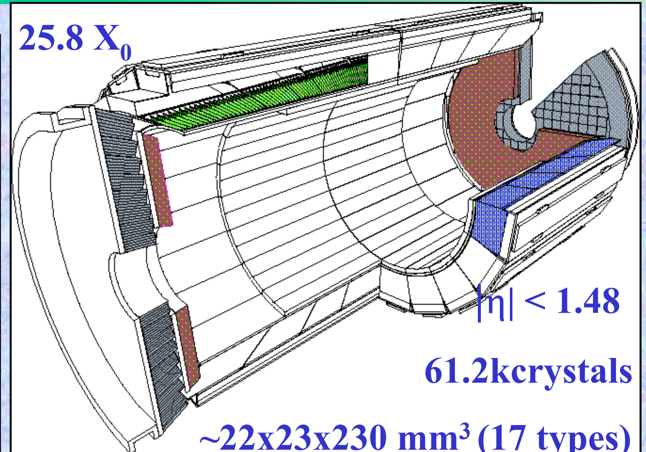
Endcap

25 X_0

$1.48 < |\eta| < 3.0$

$30 \times 30 \times 220\ mm^3$

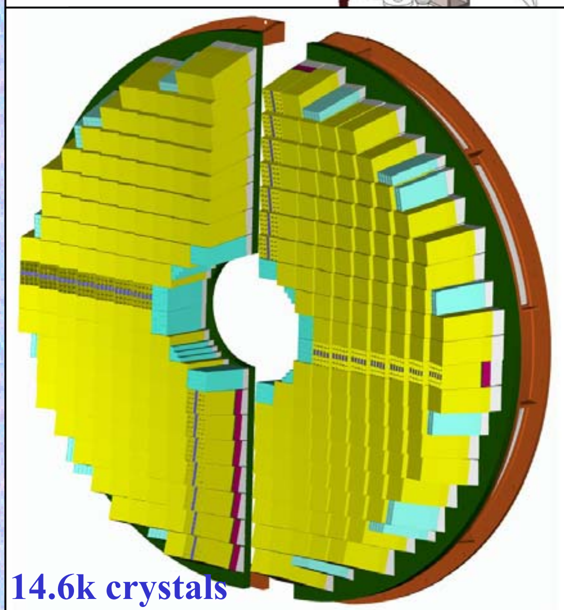
25.8 X_0



$|\eta| < 1.48$

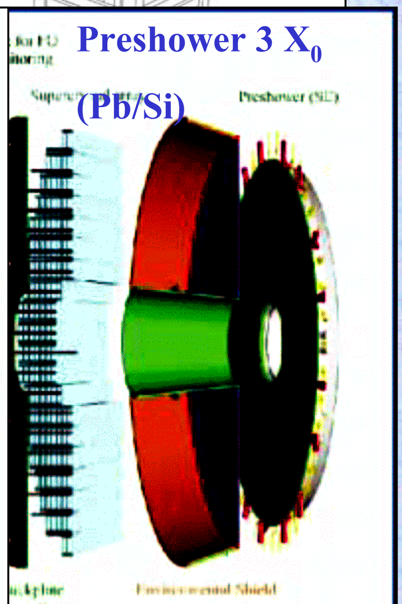
61.2kcrystals

$\sim 22 \times 23 \times 230\ mm^3$ (17 types)



14.6k crystals

Preshower 3 X_0 (Pb/Si)



Choice of $PbWO_4$:

- LHC Rate (25 ns)
- Radiation Env't
- Longitudinal Containment (X_0)

Photodetectors:

- $|B|=4T$,
- $PbWO_4$ Low room-temp LY

APD(barrel),VPT (EC)

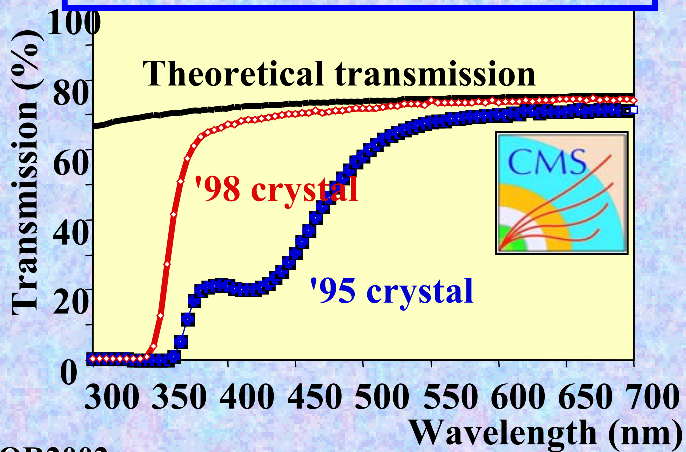
Barrel
$$\frac{\sigma}{E} = \frac{2.7\%}{\sqrt{E(\mathrm{GeV})}} \oplus 0.55\% \oplus \frac{0.155\ (0.210)}{E(\mathrm{GeV})}$$

Endcap
$$\frac{\sigma}{E} = \frac{5.7\%}{\sqrt{E(\mathrm{GeV})}} \oplus 0.55\% \oplus \frac{0.770\ (0.915)}{E(\mathrm{GeV})}$$

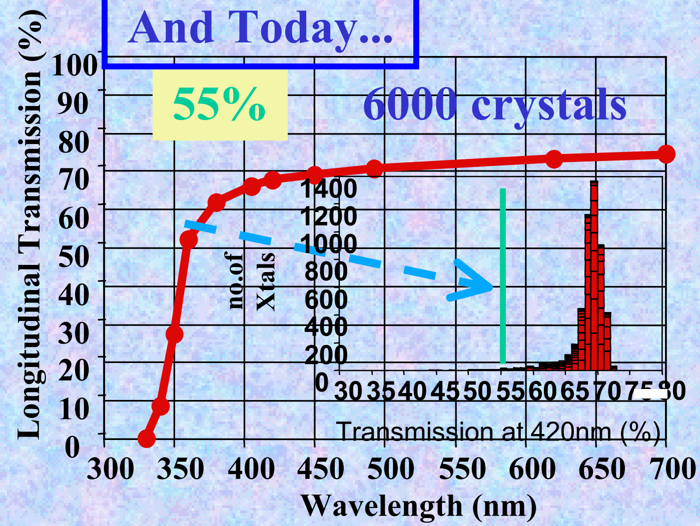
Target Performance		Barrel	Endcap/Presh
a	Shower Flucs. /Tr. Lk.	1.5% $GeV^{1/2}$	1,5% $GeV^{1/2}$
	Sampling Flucs.	nil	5% $GeV^{1/2}$ (Presh)
	Photodet.	2.3% $GeV^{1/2}$	2.3% $GeV^{1/2}$
b	Calibration	0.4%	0.4%
	LY Non-Uniform.	0.3%	0.3%
	Rear Shower Leak.	<0.2%	<0.2%
c	Electronic Noise	150 MeV	750 MeV
	Rad-induced I_{dark}	30(110) MeV	
	Pileup	30 (95) MeV	175 (525) MeV

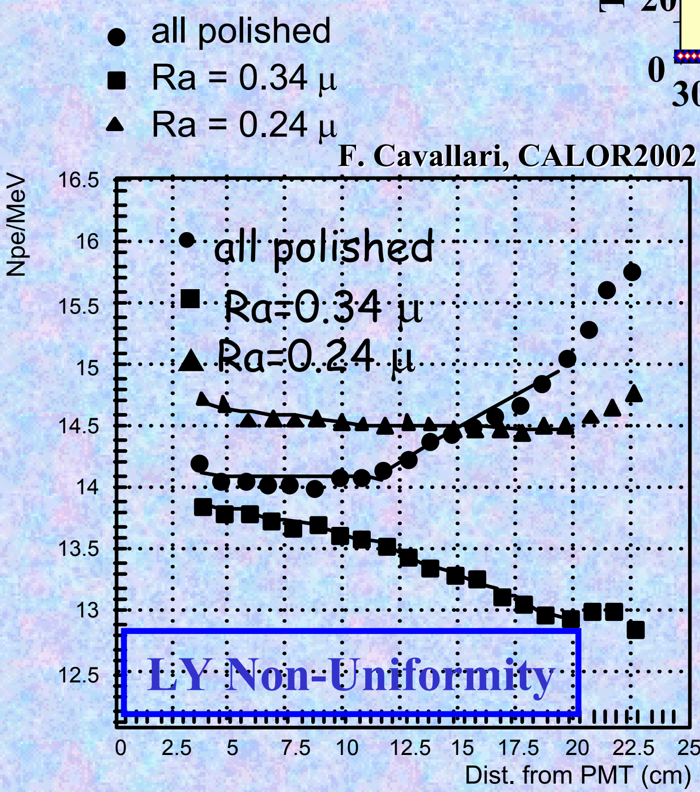
Crystals: Physical and Optical Aspects I

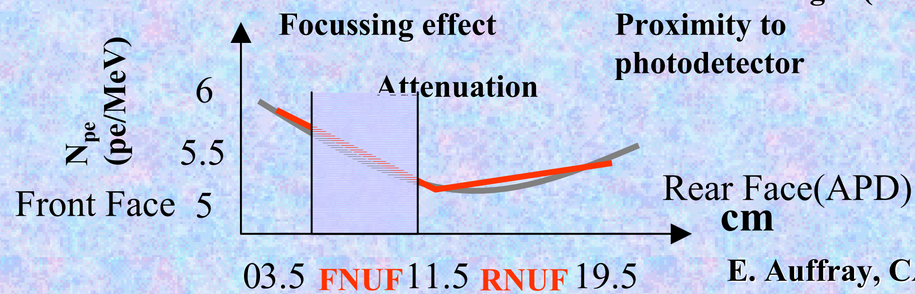
Transmission Yesterday....



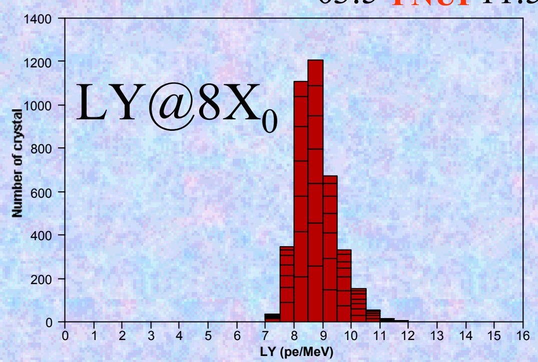
And Today...

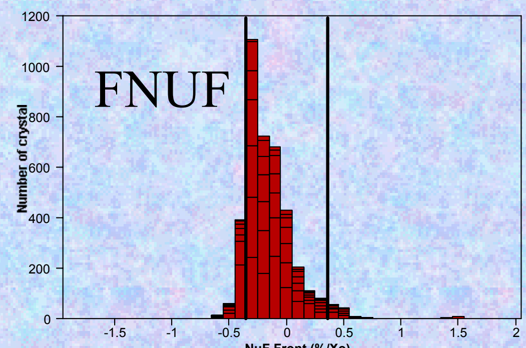






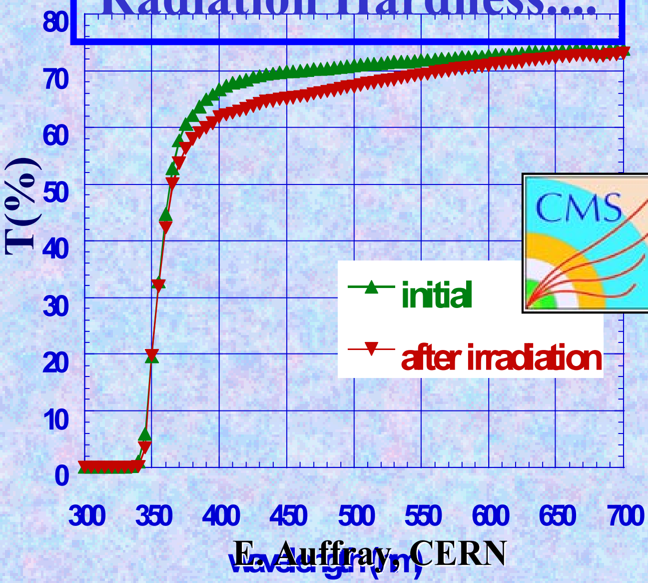
E. Auffray, CALOR2002

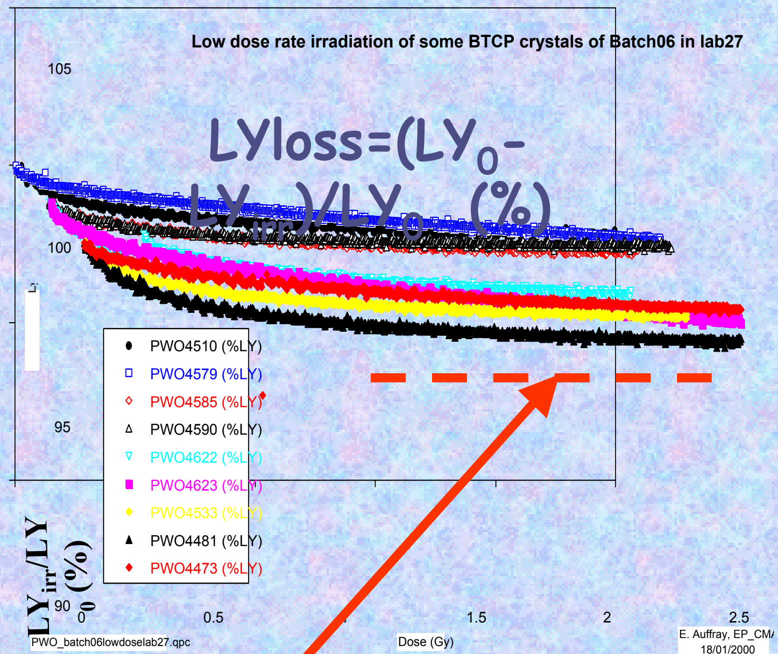




Crystals: Physical and Optical Aspects II

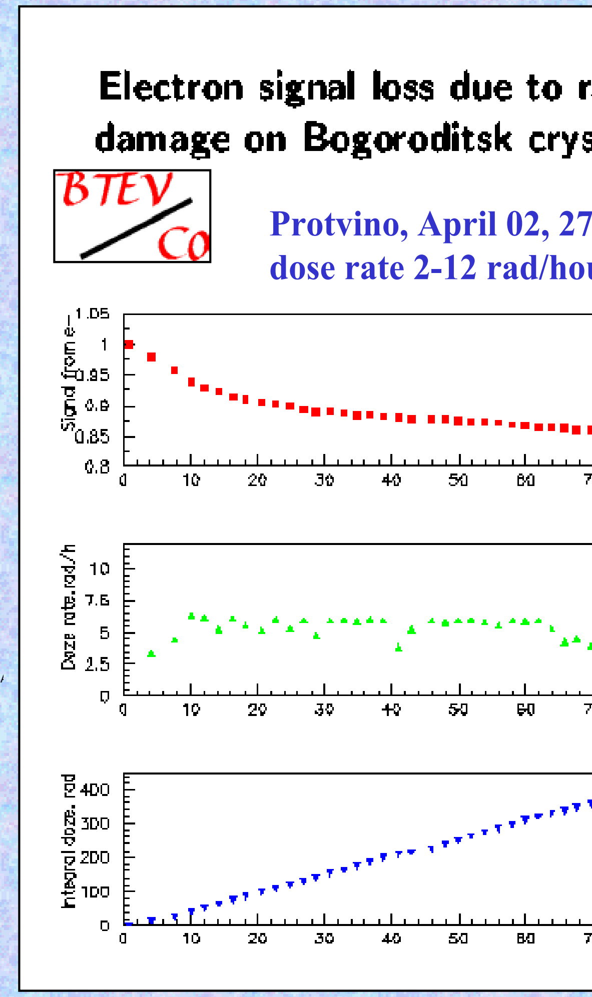
Front irrad., 1.5Gy, 0.15Gy/h





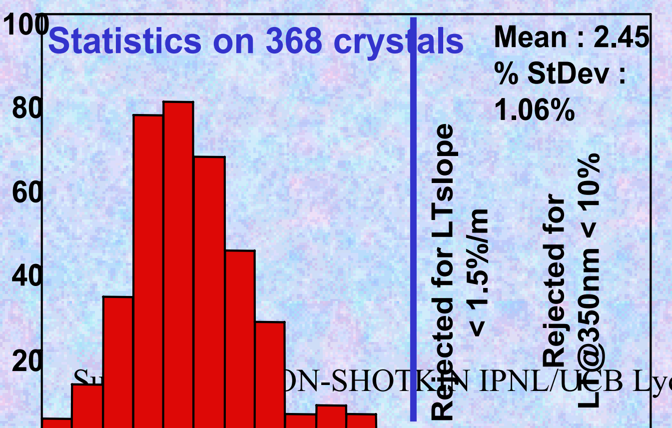
$LYloss=(LY_0-LY_{irr})/LY_0$ (%)

2) Saturation level



Y. Matulenko, V. Mochalov, A. V

BTeV Collaboration Meeting, Ju



Rad-Hardness improvements:

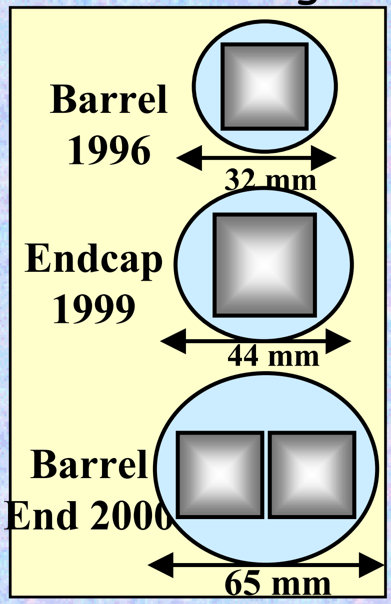
- Stoichoimetric fine-tuning
- Optimizing growth conditions
- Doping (Y,Nb)

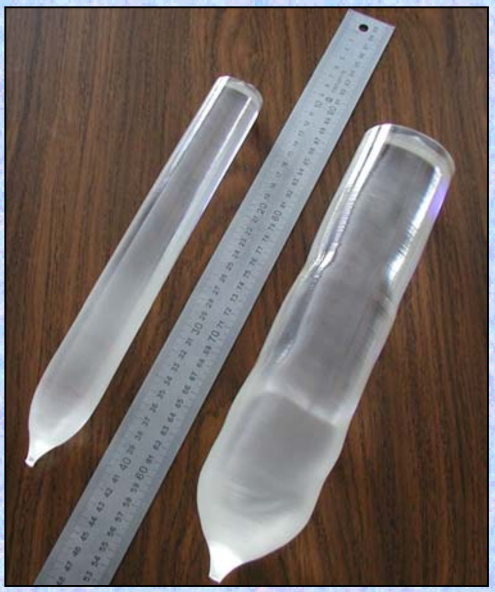
(Last 2 also improved transmission)

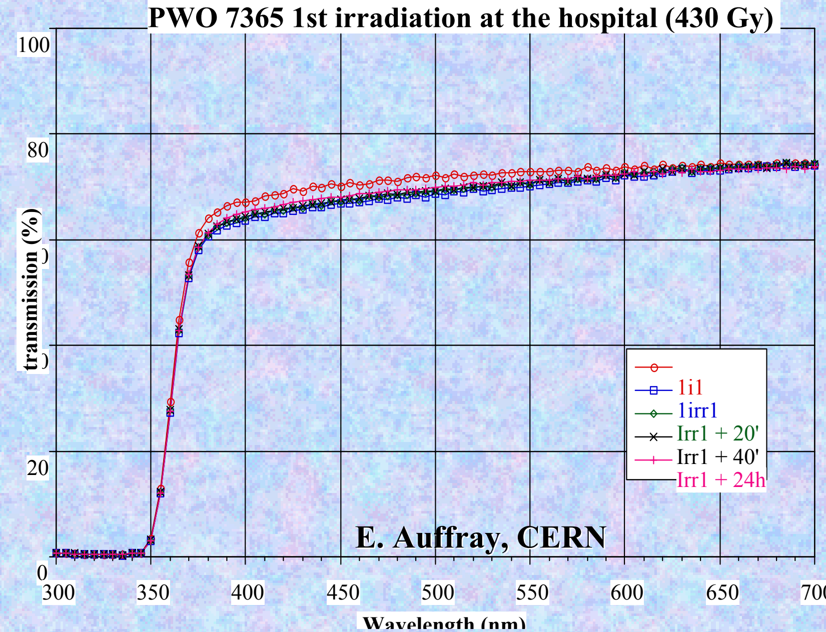
Also, CMS/BTeV crosscheck on 2 CMS endcap

Crystals: Technological Aspects

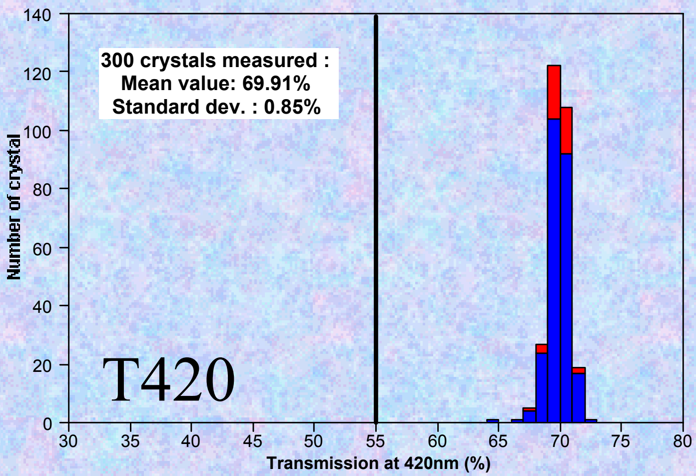
Increased Ingot Size: 2 Barrel crys/ingot…





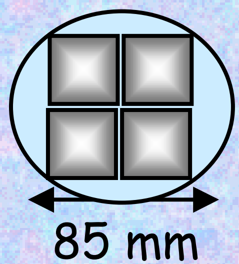


…with no change in optical properties.

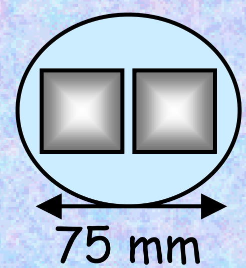


In the future,

4 Barrel crystals

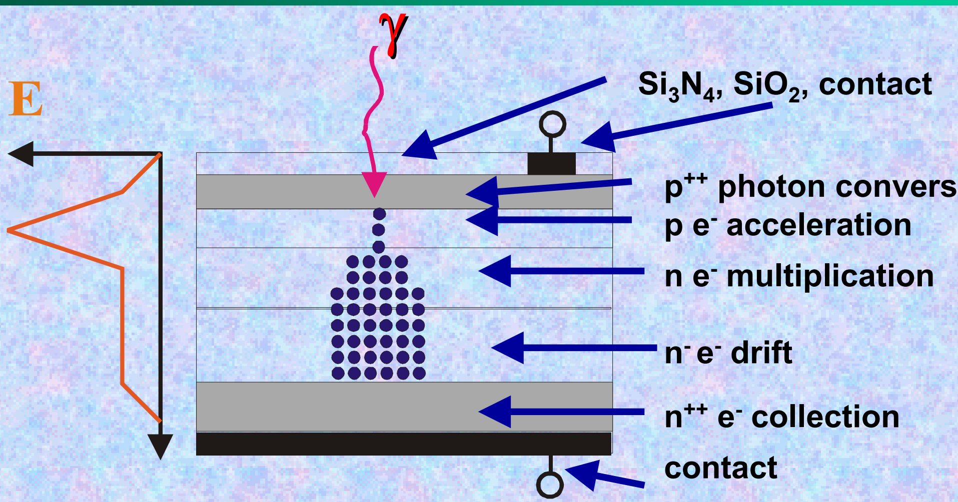


… or 2 Endcap crystals



may be possible.

Photodetection: Si Avalanche Photodiodes (APD)



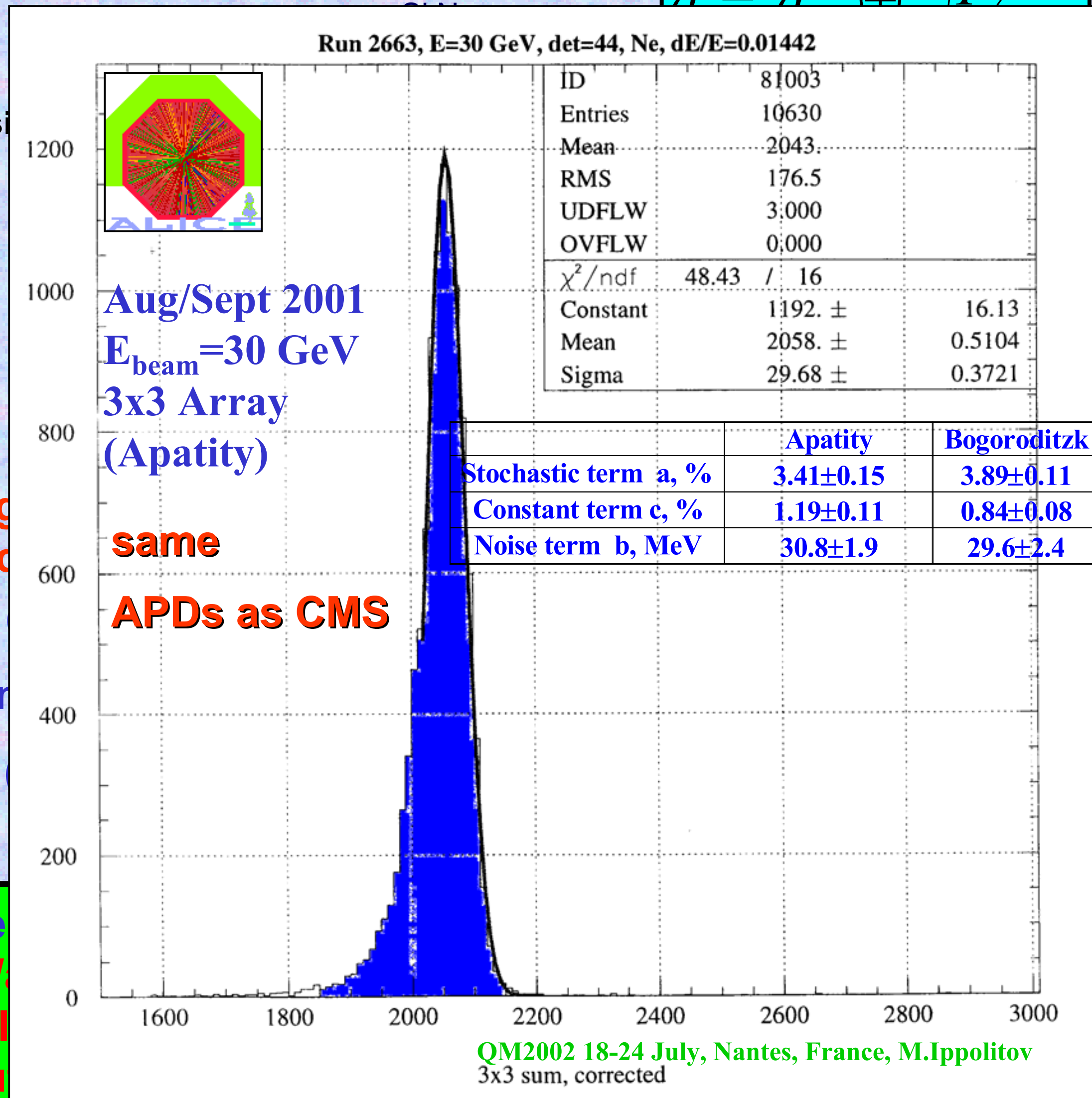
Hamamatsu Photonics, 10-year R&D

The CMS APD: A Gain-amplification-providing magnetic-field-insensitive, fast, radiation-hard

- Operating Gain of 50 (can go up to >1000)
- Active Area/crystal=2 X 25mm^2 (BIG)=50mm
- QE~75% at λ=420nm, C=80pF, F=2@M=50
- Charged-particle-insensitive (d_{eff}~6μm)

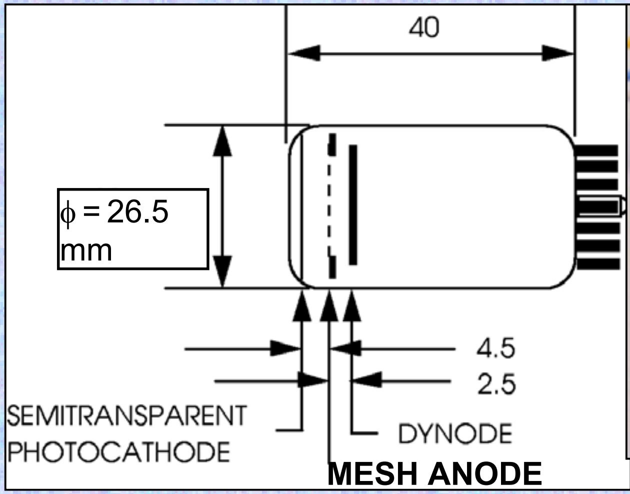
Inaccessibility→Need for 1/1000 reliability ove
100% Co^{60} 500 krad pre-irradiation, annealing/
aging, then **selection** based on: V_B-V_R, ΔV_B, I_d, I
Also: Sample neutron-irradiation (2 X 10^{13} neu

K. Deiters, PSI



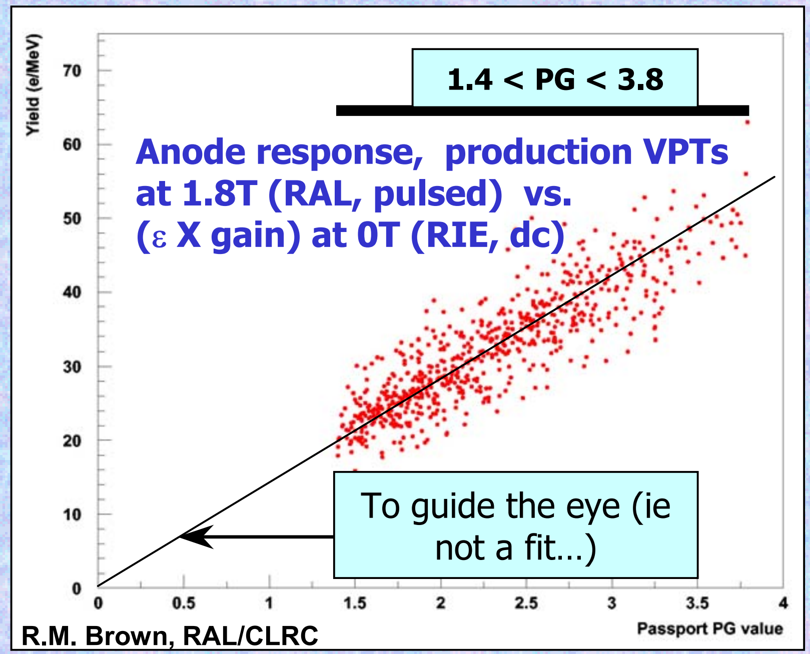
	Apatity	Bogoroditzk
Stochastic term a, %	3.41±0.15	3.89±0.11
Constant term c, %	1.19±0.11	0.84±0.08
Noise term b, MeV	30.8±1.9	29.6±2.4

Photodetection: Vacuum Phototriodes (VPT)

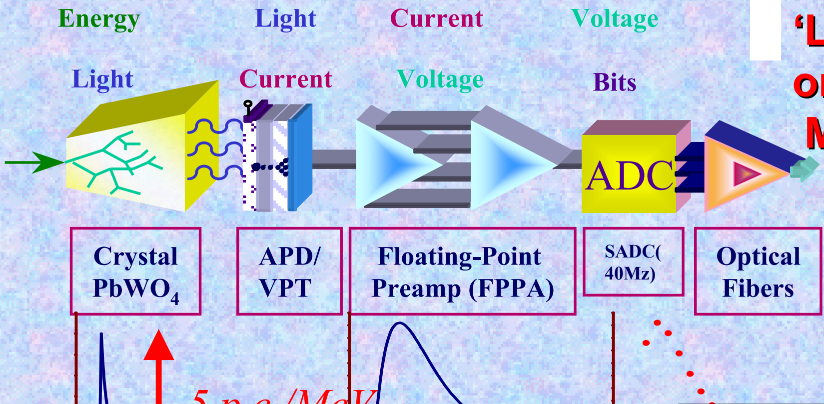


Vacuum Phototriode (VPT): Single stage photomultiplier tube with fine metal grid anode

- B-field orientation favourable for VPTs (Axes: 8.5° < |θ| < 25.5° wrt to field)
- More radiation hard than Si diodes (with UV glass window)
- Gain 8 -10 at B = 4 T, Excess noise factor F~ 3
- Active area of ~ 280 mm^2/crystal
- Q.E. ~ 20% at 420 nm
- <10 % decrease in response after 10 years of operation

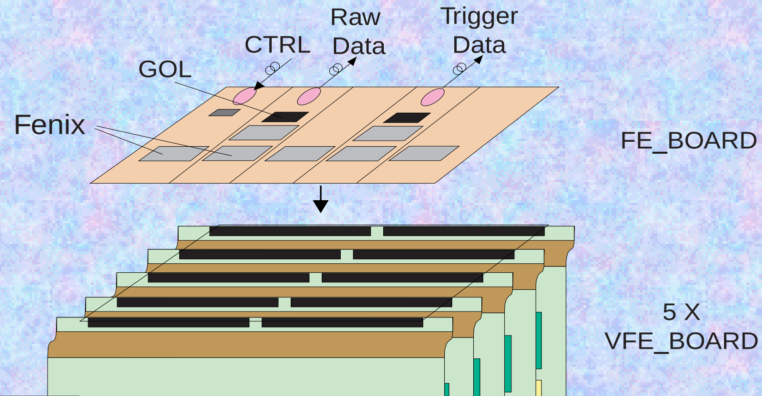


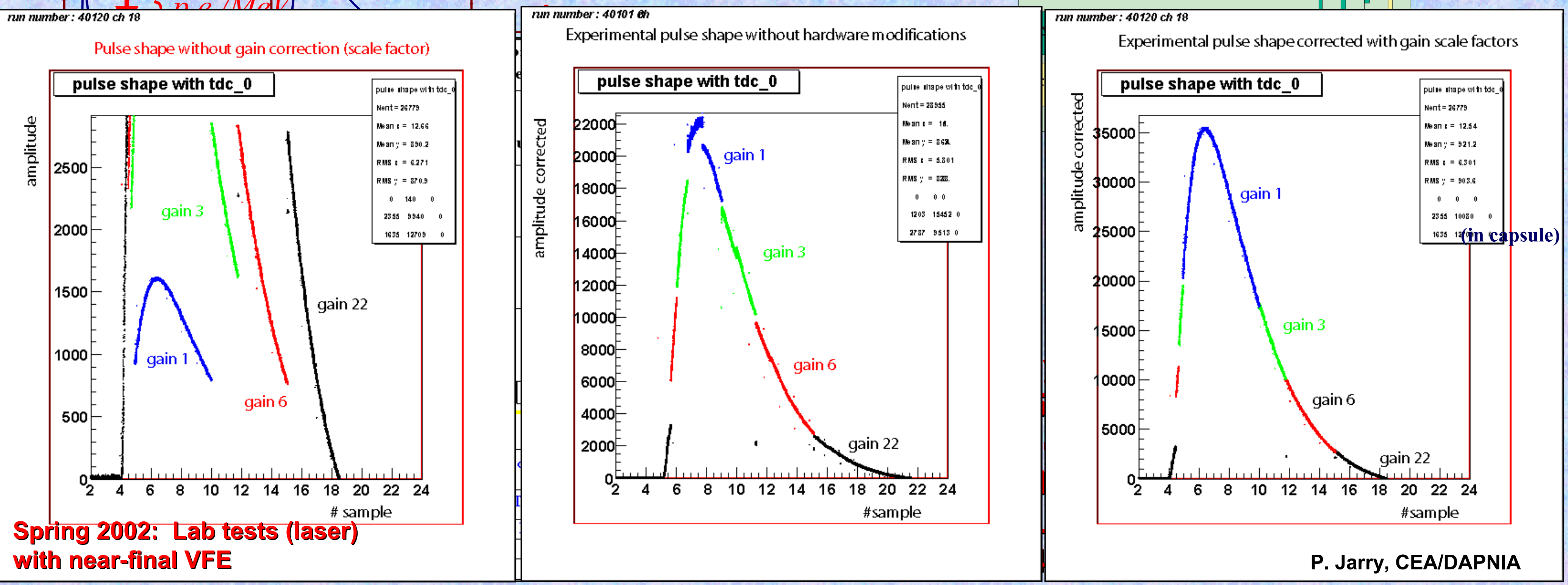
Treatment of Photoelectric Signals



'Light-to-light' on-detector readout: Must be rad-hard!

Acquisition (DAQ)



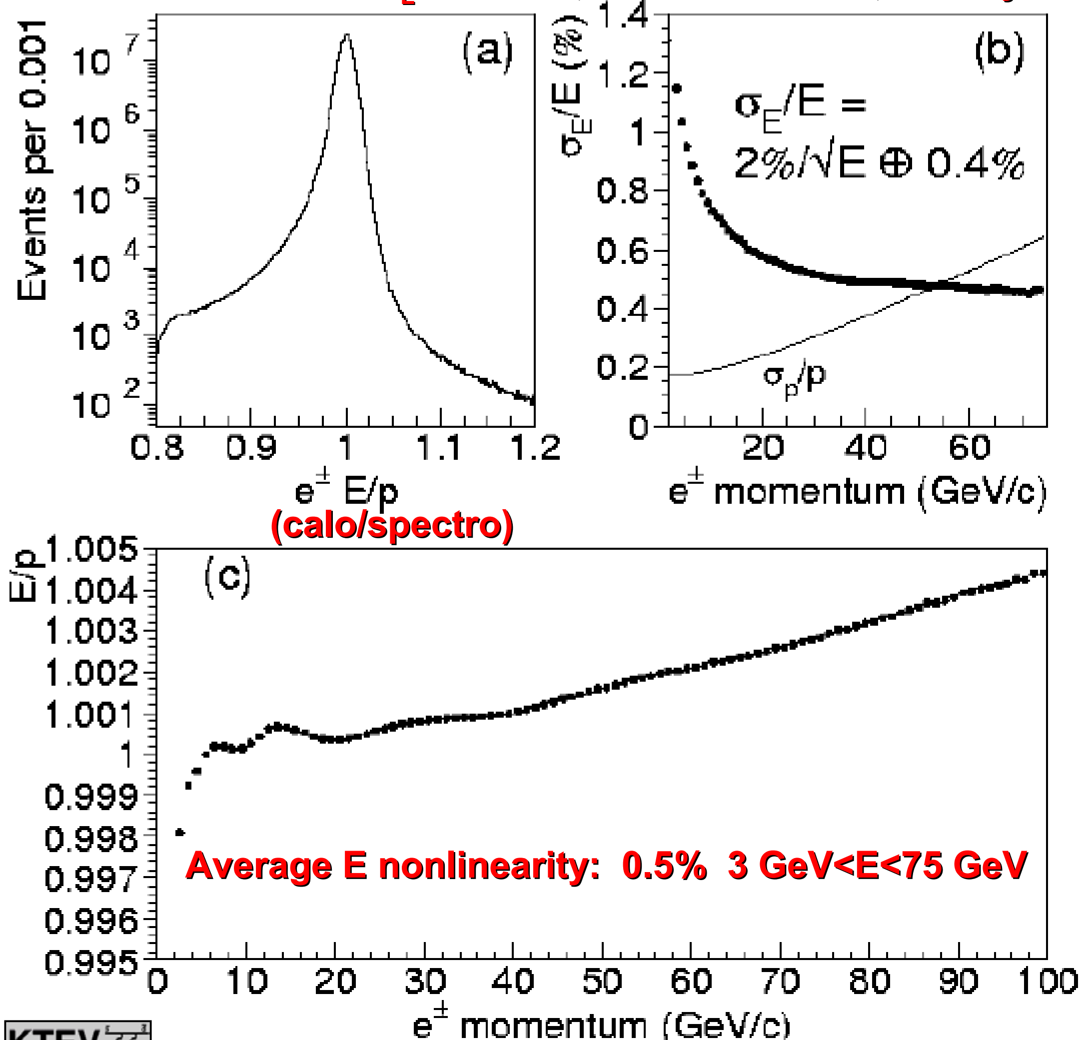


Spring 2002: Lab tests (laser) with near-final VFE

P. Jarry, CEA/DAPNIA

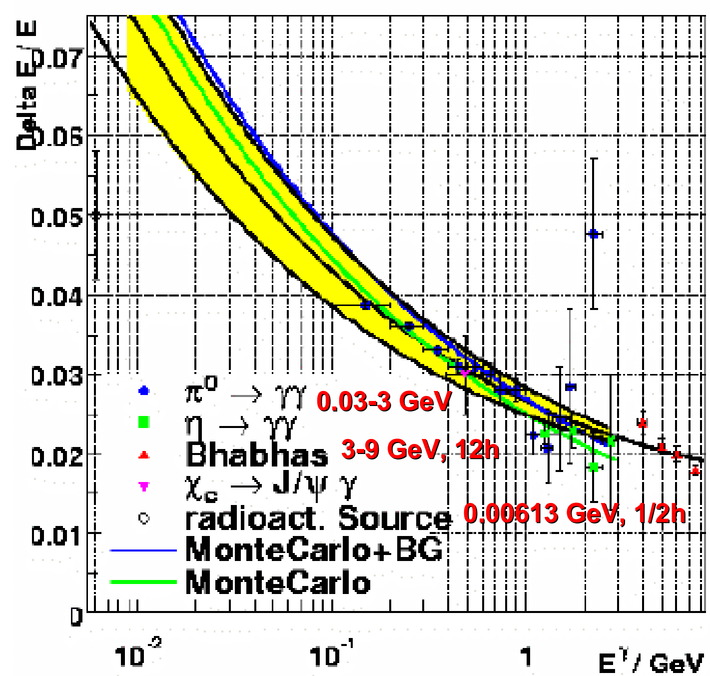
Detector Calibration

Abs. E scale from $K_L \rightarrow \pi^{+/-} e^{-/+} \nu$, ~0.03%/channel, 1-2 days



Energy resolution

M. Kocian, SLAC, CALOR2002



$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt{E}} \oplus \sigma_2$$

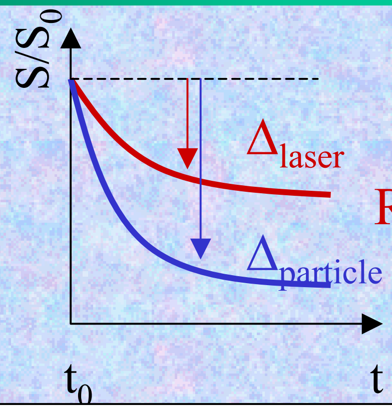
$$\sigma_1 = (2.30 \pm 0.03 \pm 0.3)\%$$

$$\sigma_2 = (1.35 \pm 0.08 \pm 0.2)\%$$

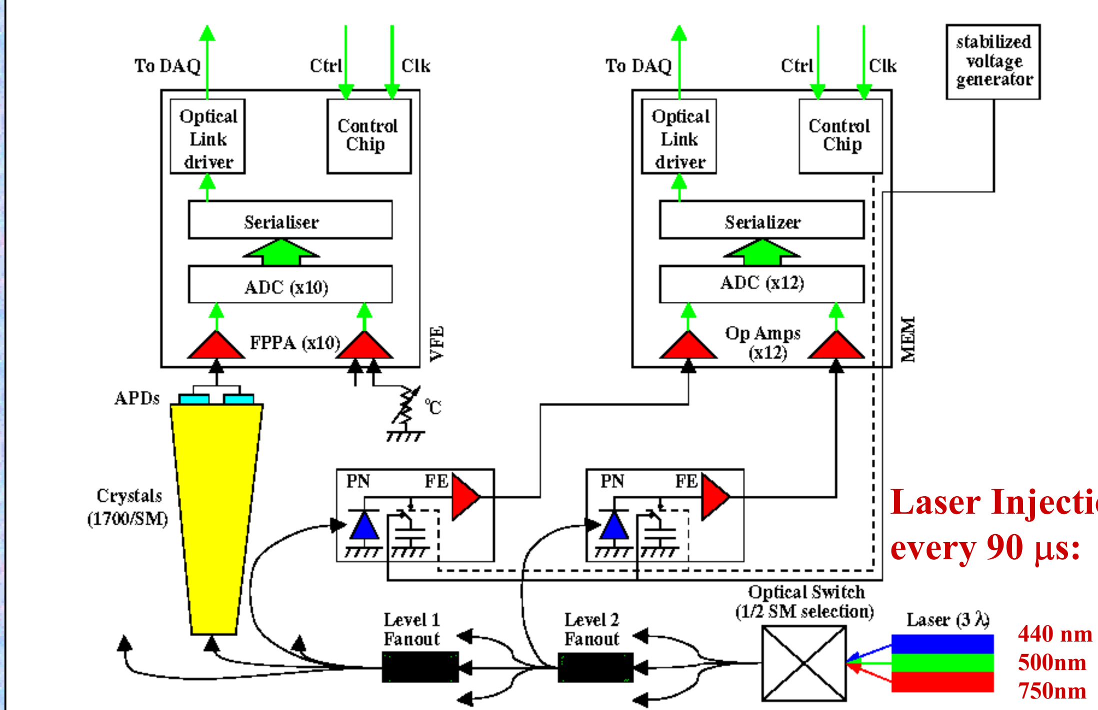
BABAR

Scintillation Light Loss Monitoring

Dynamic (between physics calibrations) correction of calibration constants by following light loss due to radiation:

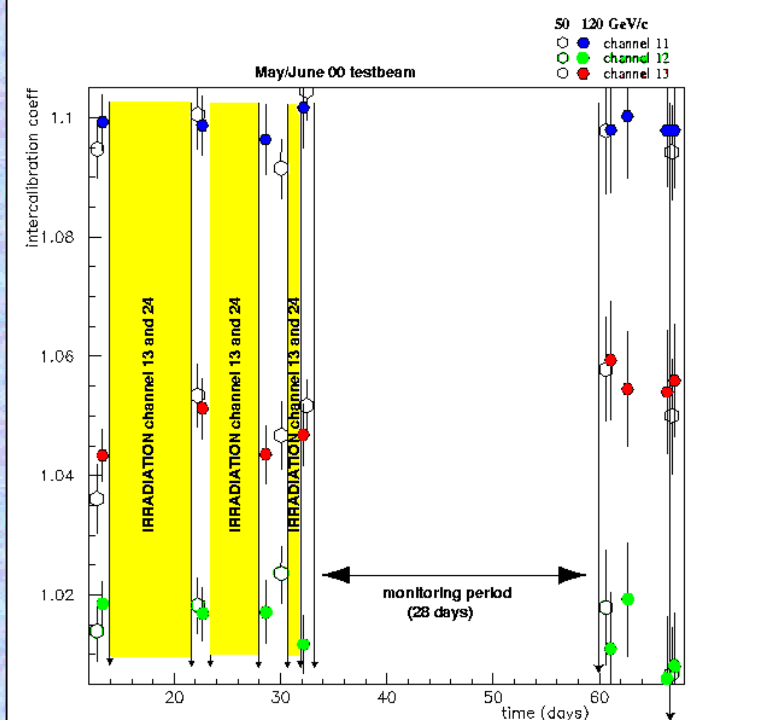


$$R = \Delta_{particle} / \Delta_{laser}$$



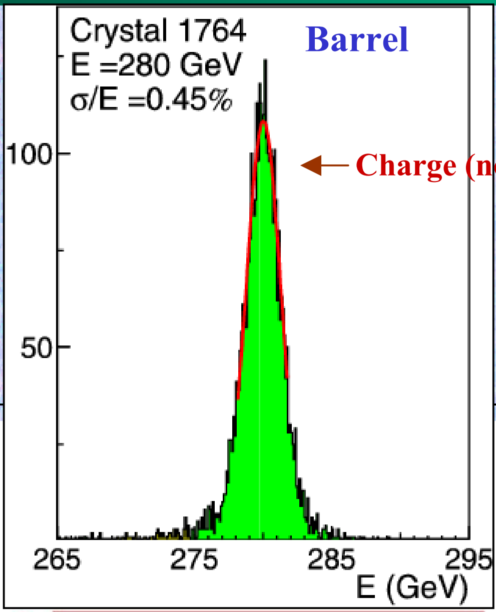
Laser Injection every 90 μs:

CMS Saclay group, CMS IN 2002/012

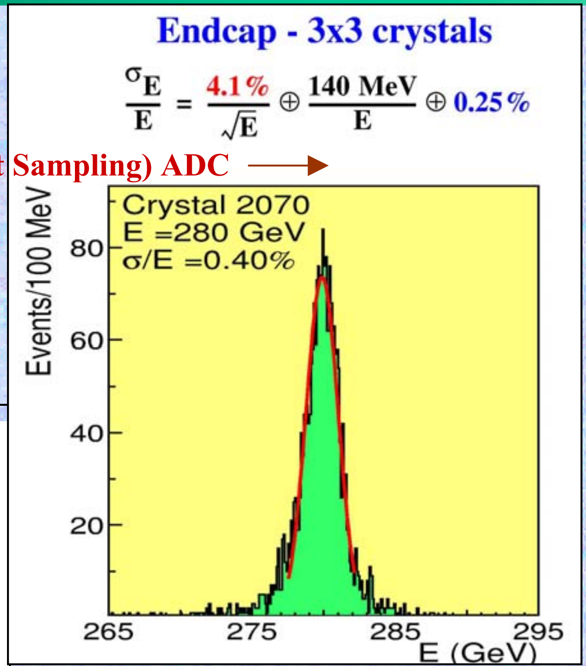


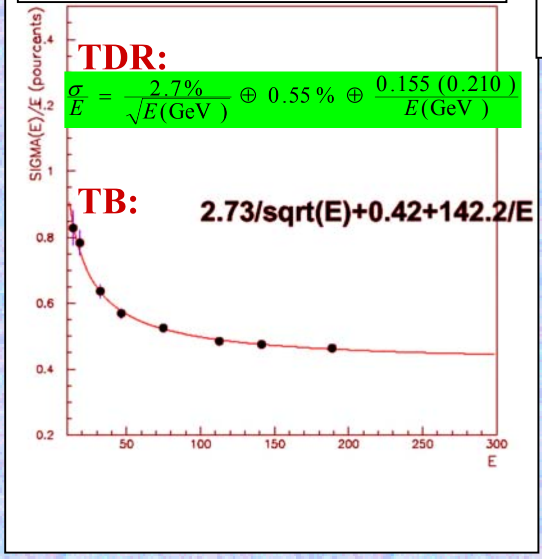
M. Dejardin,CEA/DAPNIA

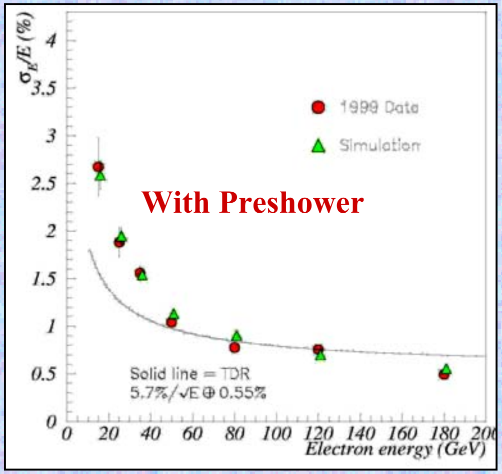
Results from Test Beam



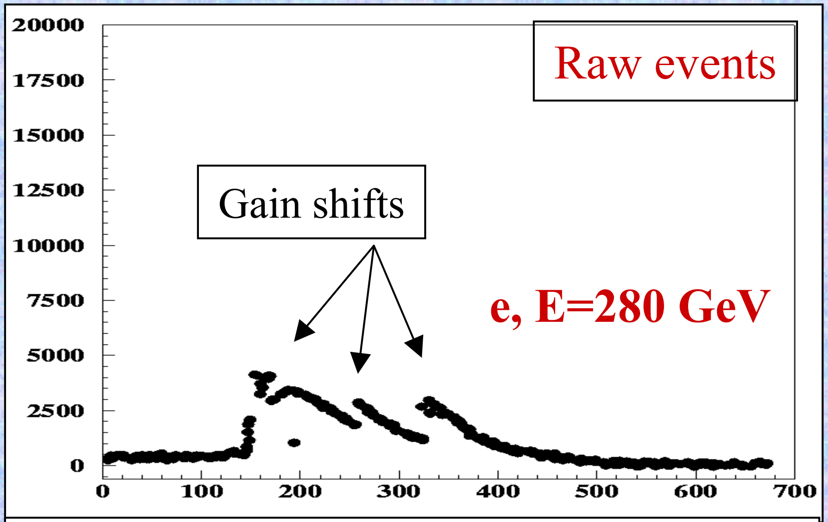
Charge (not Sampling) ADC

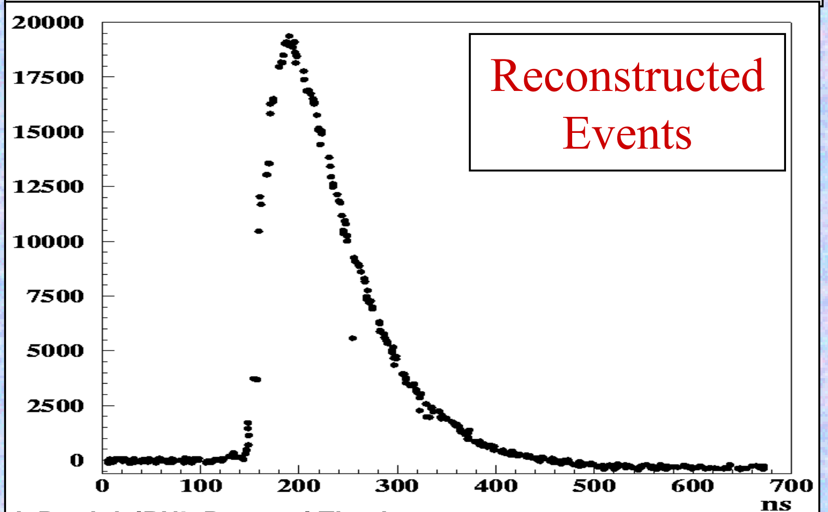






Summer 2000: 3 submodules (30 xtals) Proof-of-principle of 'Light-to-light' readout, ASIC FPPA:

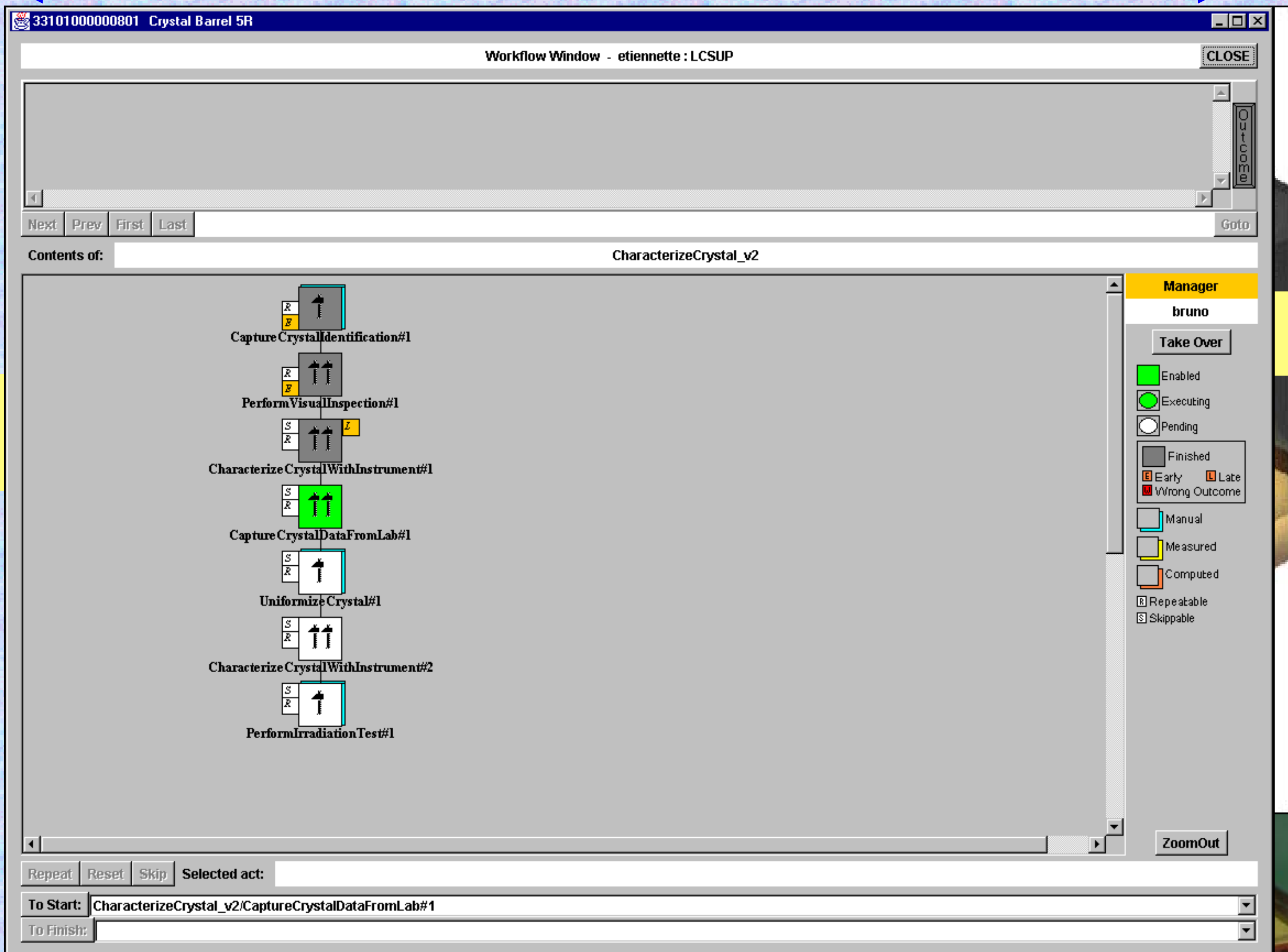




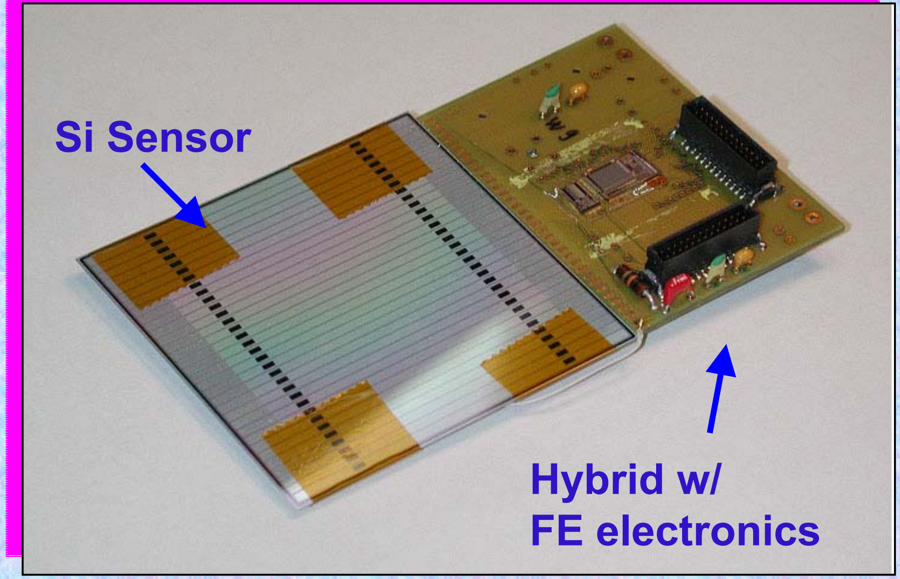
J. Donini, IPNL Doctoral Thesis

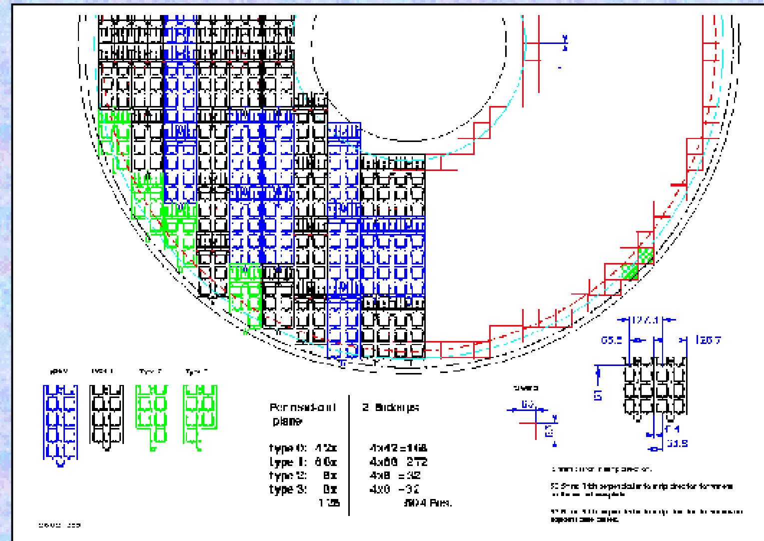
Assembly/QC Status: Barrel

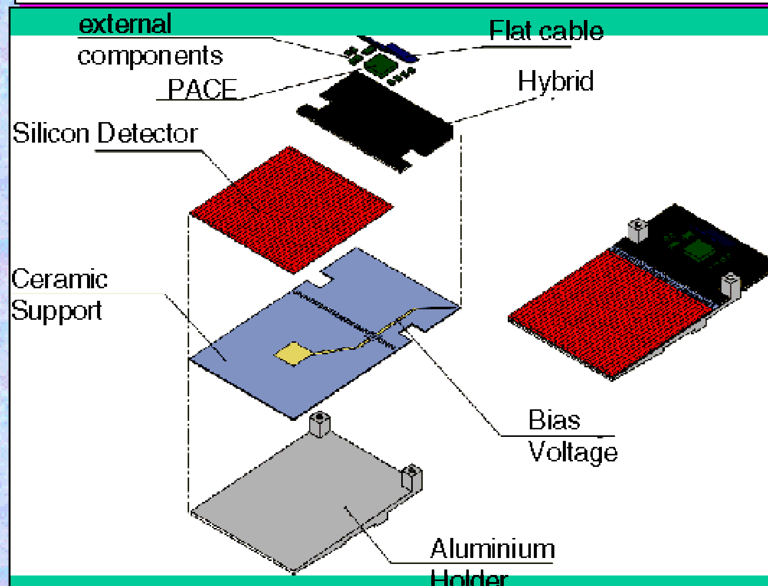
Assembly centers at CERN, ROMA — **CERN Assembly Center**



Assembly/QC Status: Preshower





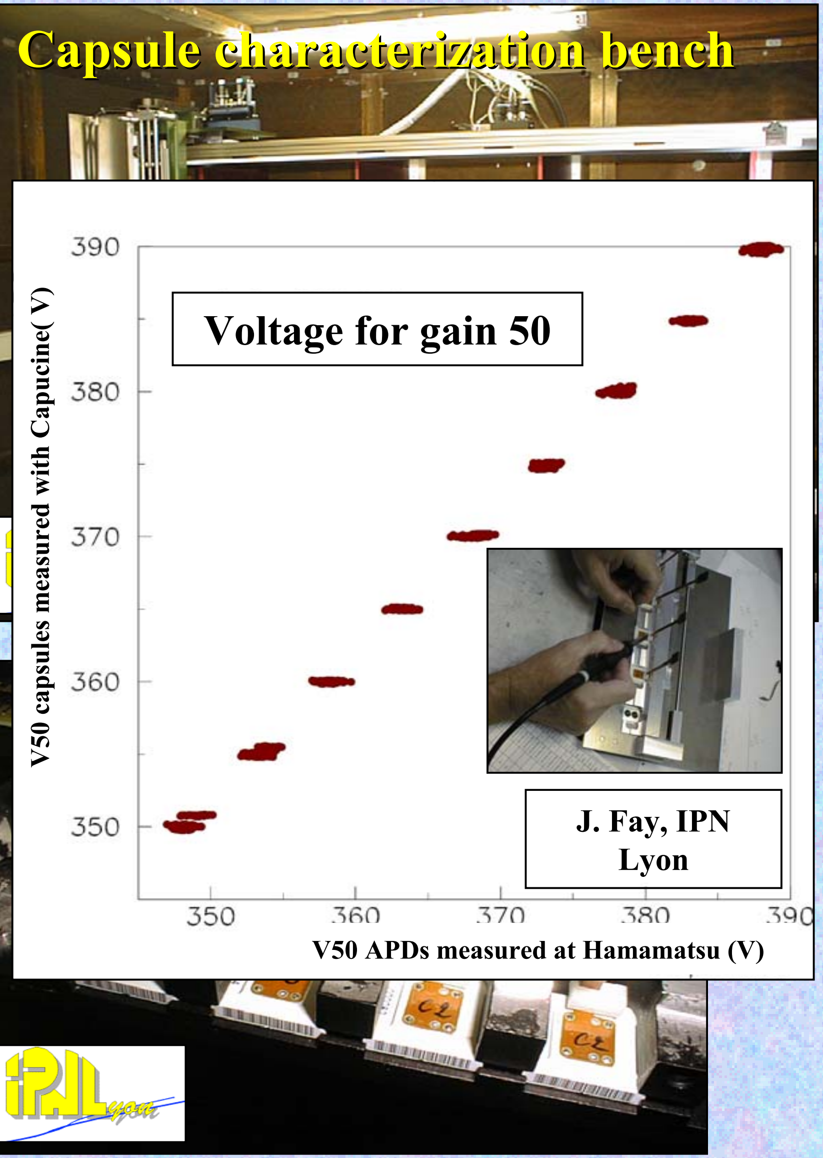


Purpose: Help in π^0 rejection in endcap

Status of Production:

- **600 Si Sensors rec'd (3 production ctrs)**
- **100 preproduction**
- **VFE Electronics: PACE-2 (DMILL, 65% yield, demonstrated functionality), final version PACE-3 in 0.25μ**

Assembly/QC Status: Photodetectors

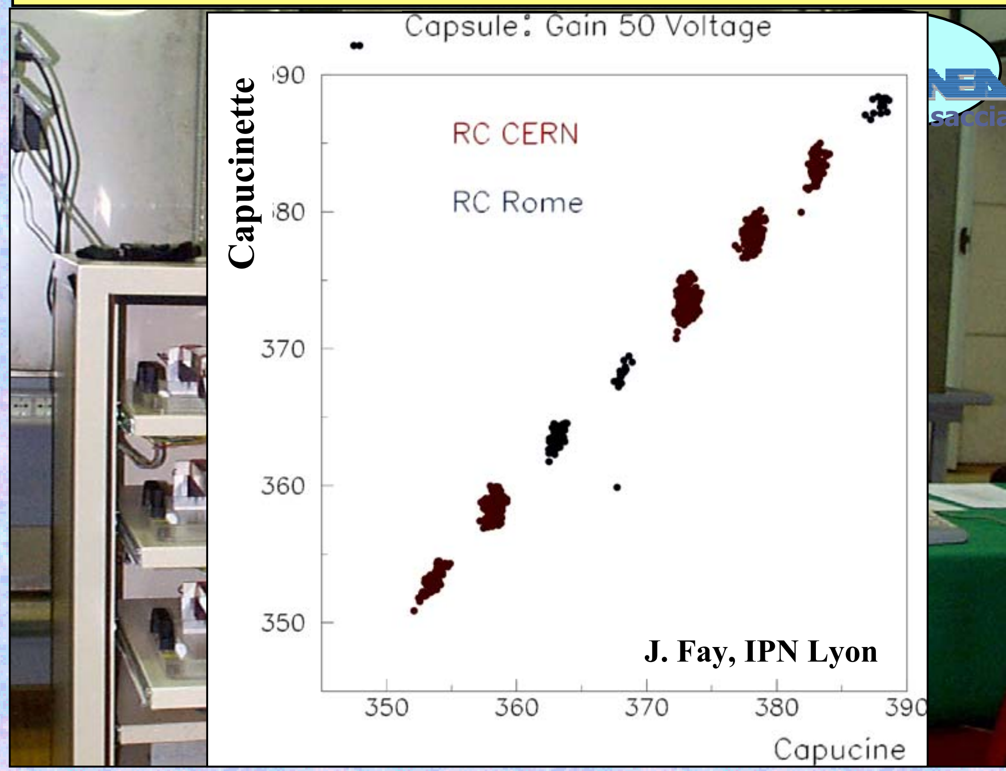


~35,000 APD received, ~6500 capsules made (~10%)

Photodetecton verification at each ass'y stage:

- **Capsule: Gain, I_{dark}, $V_{B,}$ Noise under bias**
- **Subunit: Idem except noise**
- **Submodule & Module: Photovoltaic tests**

SubUnits functionality test (Capucinette)



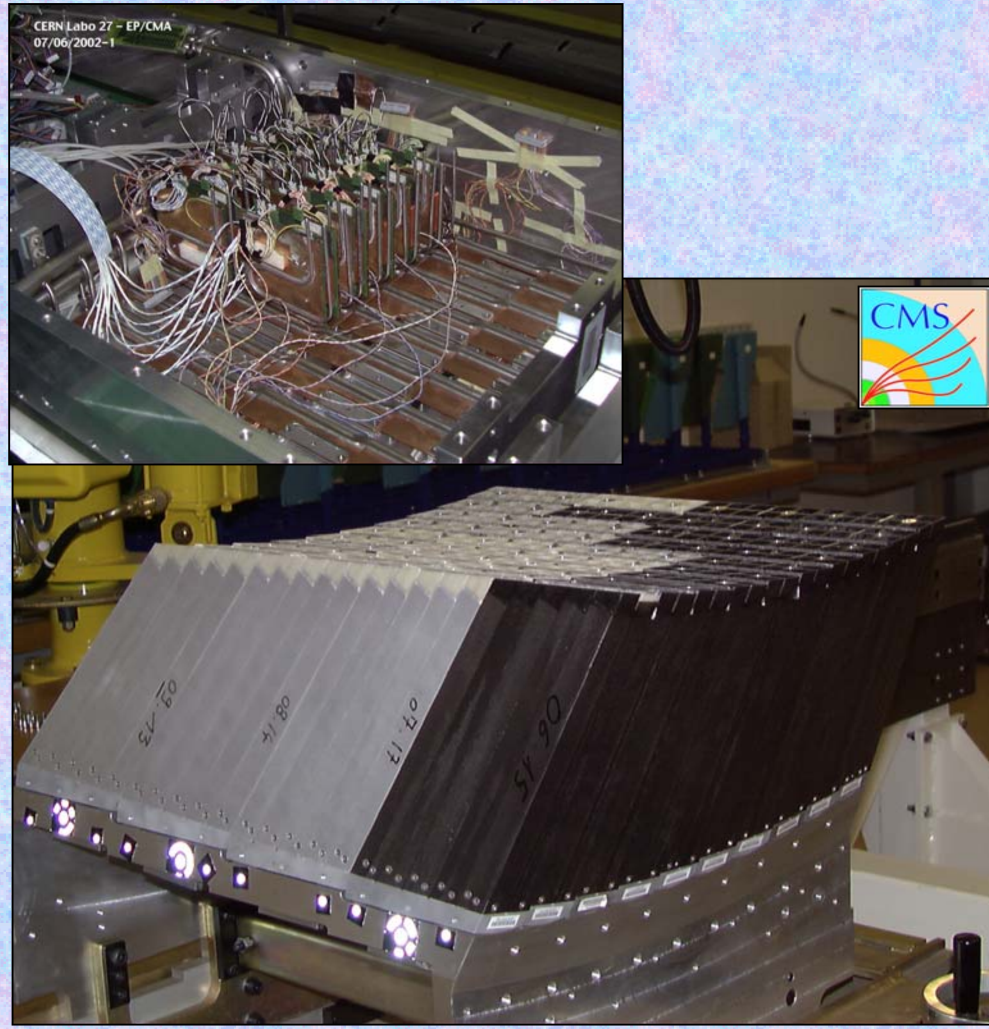
Conclusions

- As we speak, a complete CMS ECAL **module** with 100 channels equipped with near-final VFE electronics is going into beam: First large-scale system test.

- In summer 2003 the first complete CMS ECAL **supermodule** (1/36 th), equipped with final light-to-light electronics, will be beam-tested.

- The CMS ECAL is by more than a factor of 5 the largest crystal calorimeter ever built, with 10% of some components already fabricated.

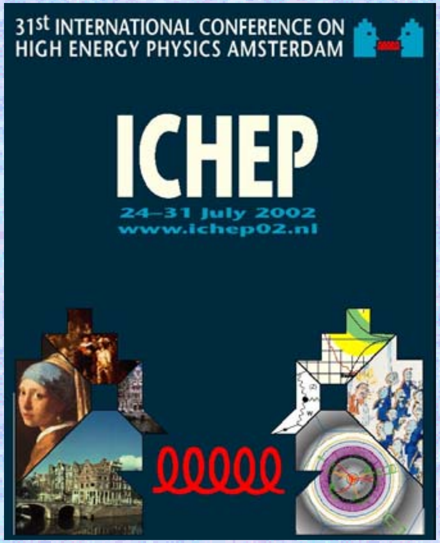
- The range of applications for crystal calorimeters has never been as wide, crystals remain the medium of choice for precision energy measurements.



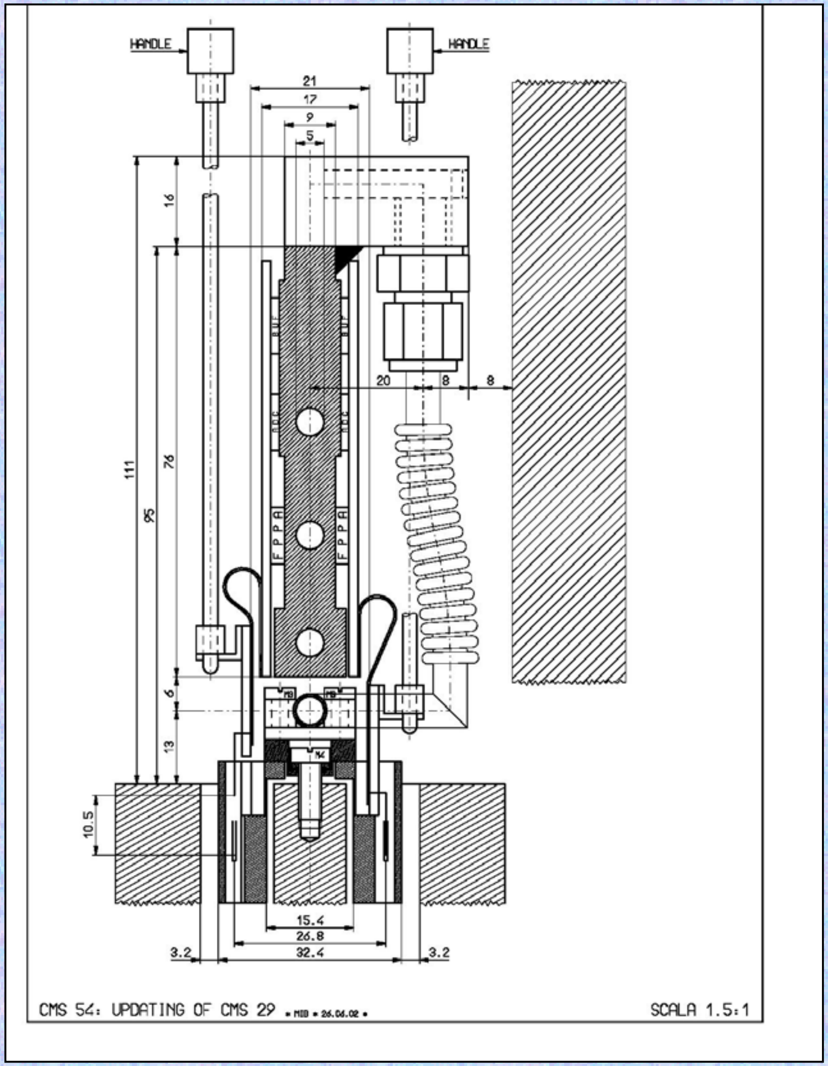
Acknowledgements

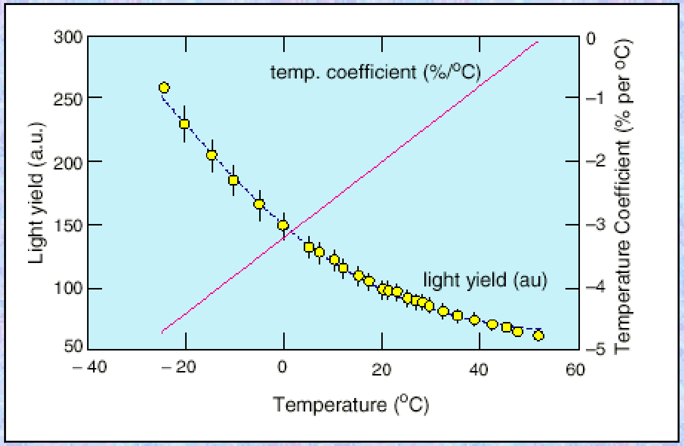
Many thanks to:

- The members of the CMS ECAL Collaboration
- The KTeV (esp. E. Blucher), BaBar (esp. Y. Karyotakis, M. Kocian), ALICE (esp. M. Ippolitov, V. Manko) and BTeV (esp. S. Stone, A. Vasiliev) collaborations
- And last but not least, the organizers and session convenors of ICHEP2002!!



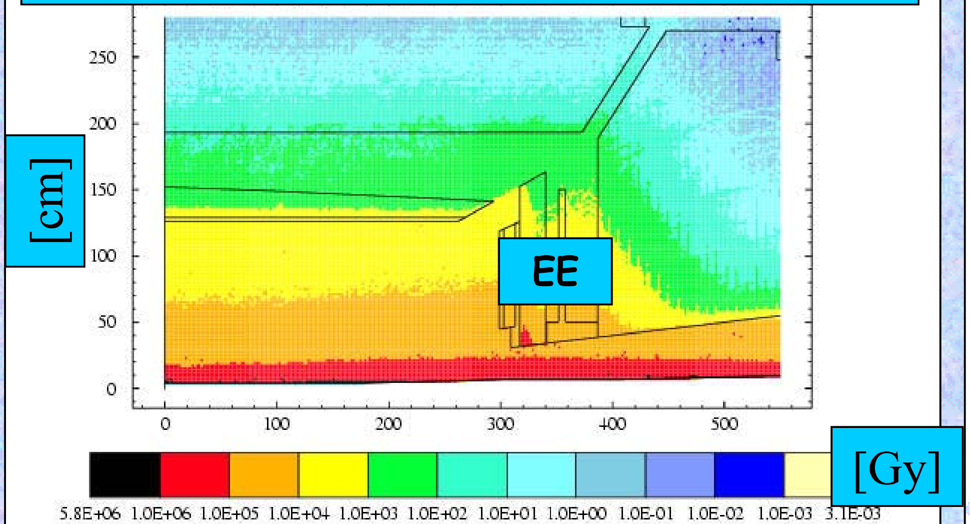
Cooling

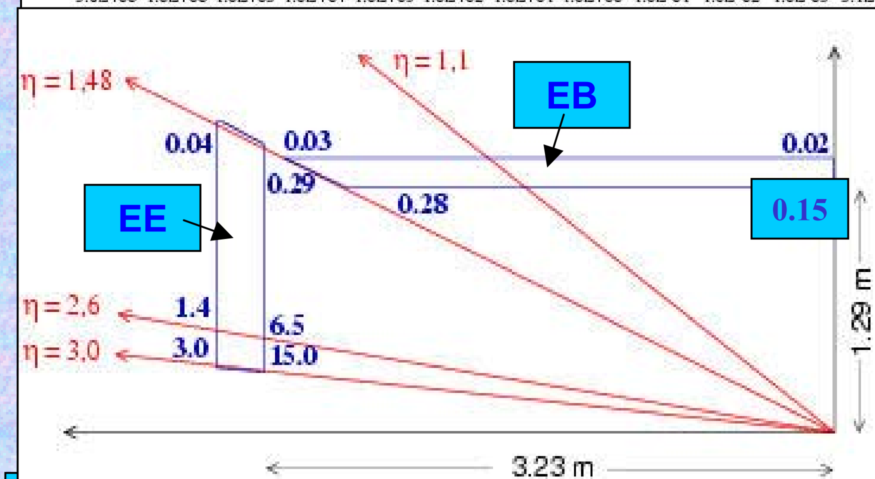

HANDLE
HANDLE
21
17
9
5
16
111
76
95
20
8
8
6
13
10.5
15.4
26.8
32.4
3.2
3.2
CMS 54: UPDATING OF CMS 29
SCALA 1.5:1


temp. coefficient (%/^oC)
light yield (au)
Light yield (a.u.)
Temperature Coefficient (% per ^oC)
Temperature (^oC)
300
250
200
150
100
50
0
−1
−2
−3
−4
−5
− 40
− 20
0
20
40
60

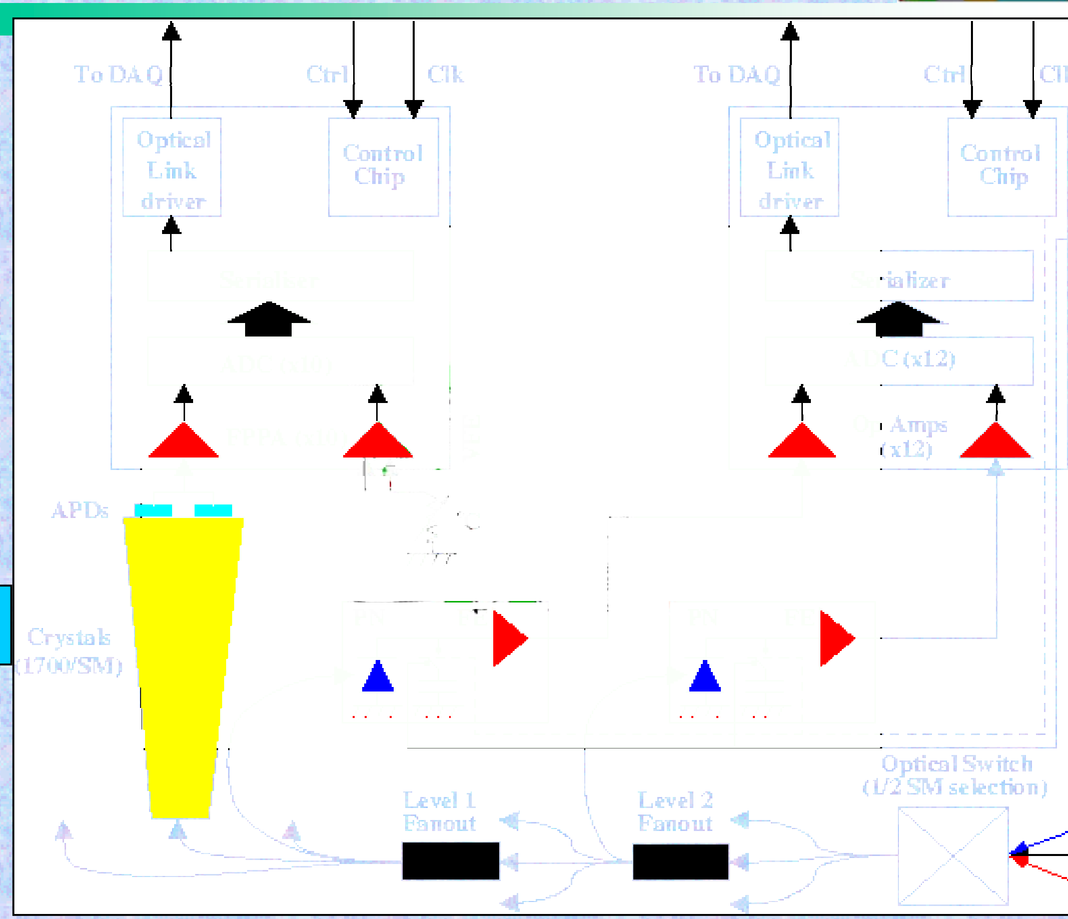
Graphiques utiles

Total dose after 10 years of running ($5x10^5$ pb^{-1})

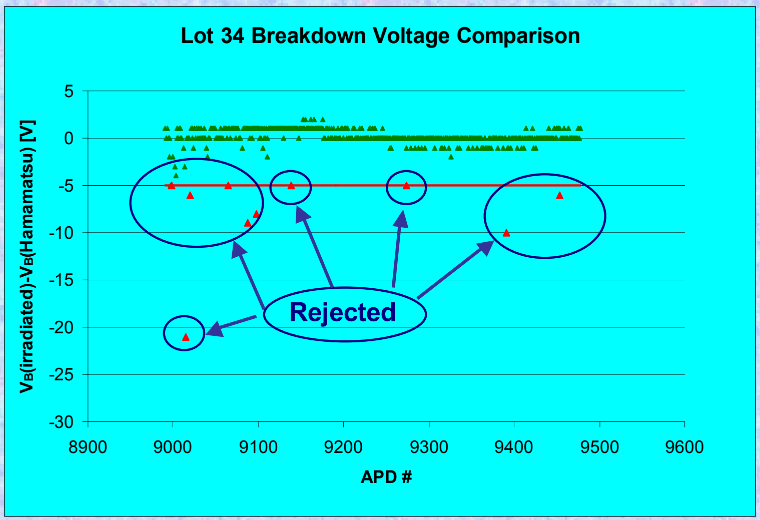


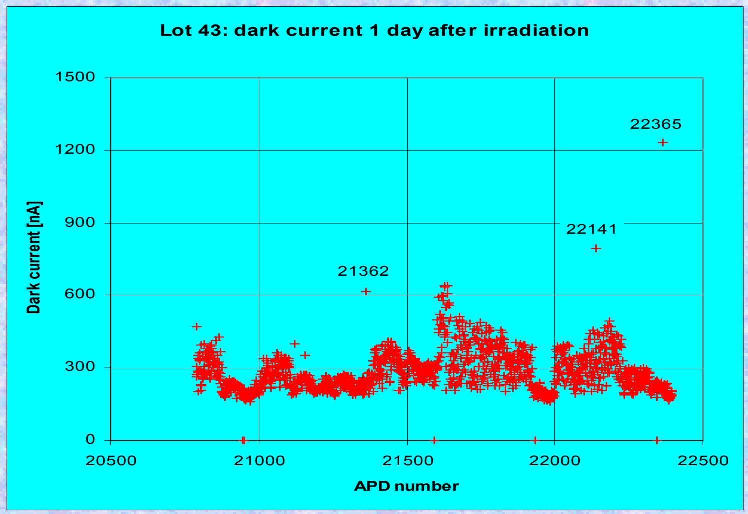


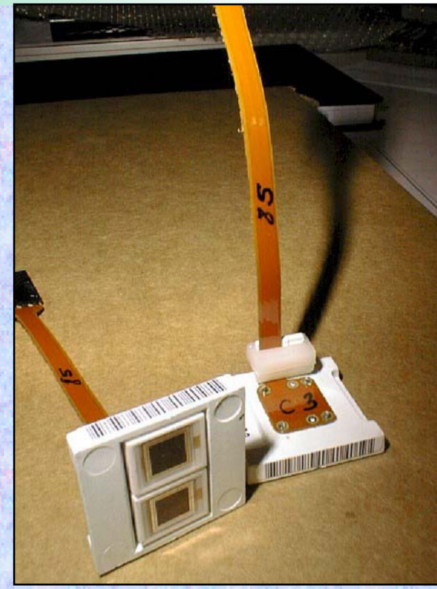
Dose rates [Gy/h] in ECAL at luminosity $L=10^{34} cm^{-2}s^{-1}$

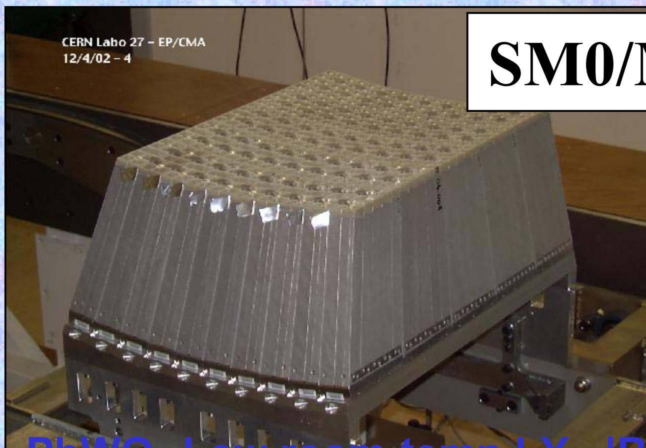


Graphiques utiles









SM0/M1

$$\sigma^2_{\text{series}} = \frac{4kT.RC^2}{2\tau}\frac{0.7}{g}$$

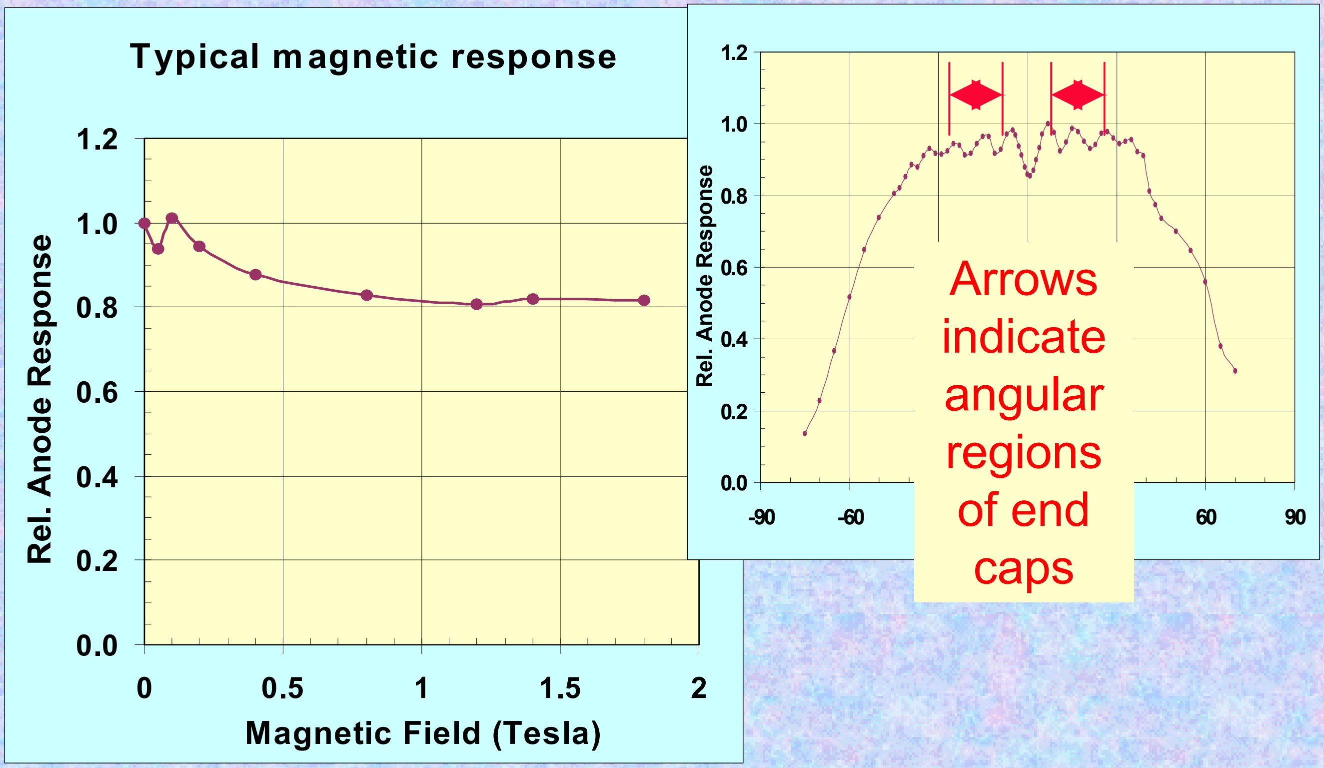
$$\sigma^2_{\text{parallèle}} = (I_{ds} + I_{dv} M^2 F).q\tau$$

$$\sigma^2_{\text{série}} = \frac{4kT.RC^2}{2\tau}\frac{0.7}{g}$$

$PbWO_4$ Low room-temp LY, |B|=4T, 25ns LHC rate,

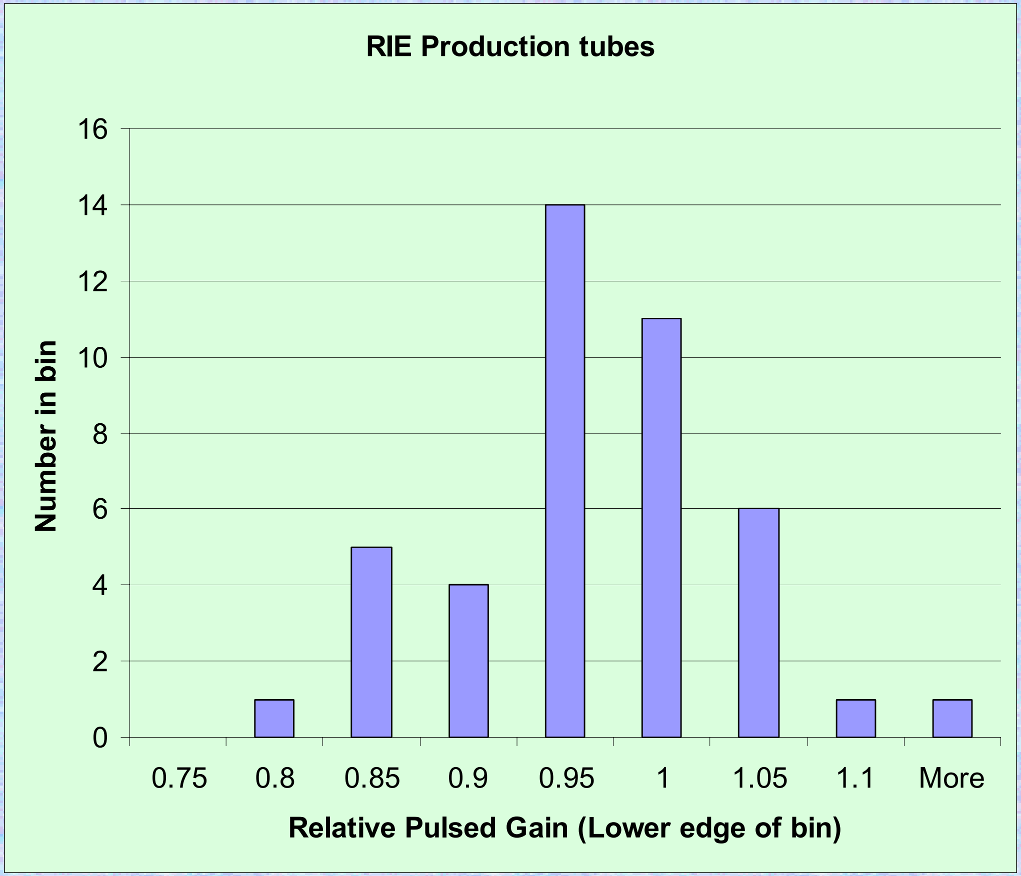
Integ dose=2.4kGy→

Graphiques utiles



Anode response of production VPTs at 1.8T (averaged over 8° – 25°), in units of e⁻/MeV (using data from beam tests with PWO), plotted versus the product of photocathode efficiency and gain, as measured by RIE at B=0T

Graphiques utiles

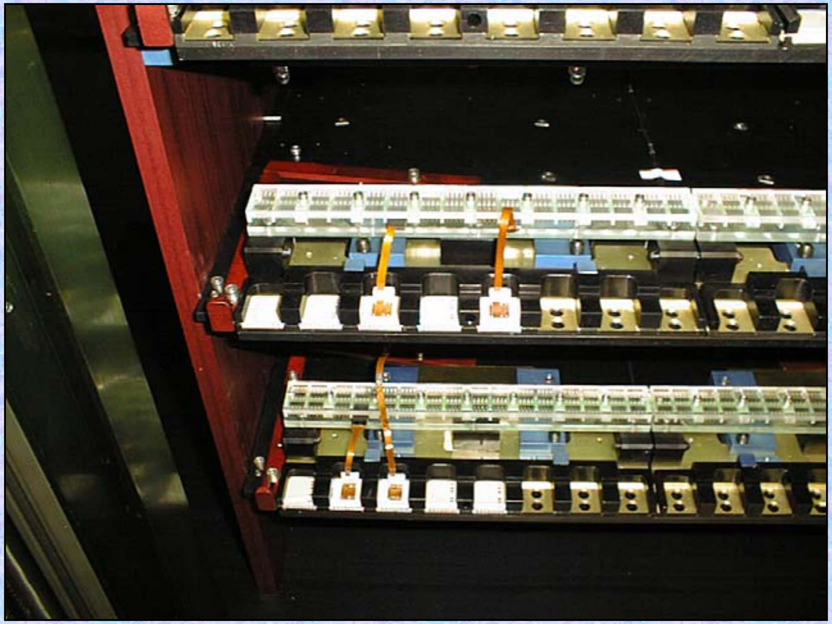


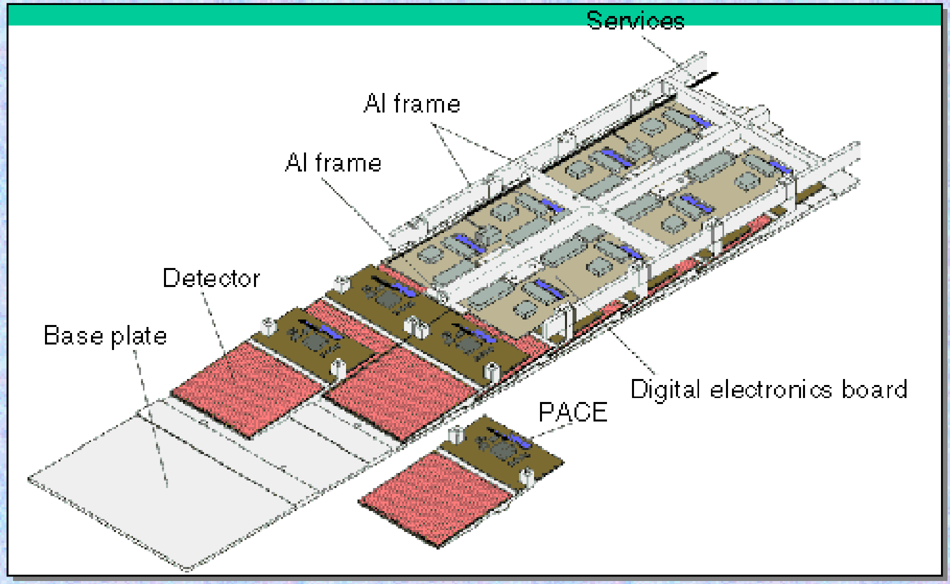
Ratio:

Gain(4T)/Gain(0T)

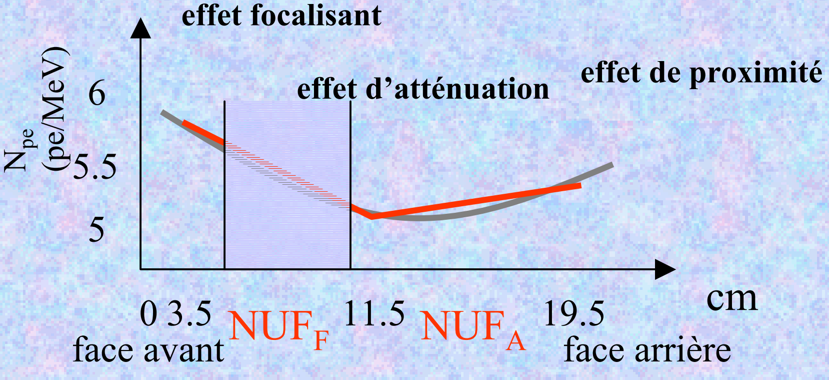
For a sample of production VPTs (Measured at Brunel University)

Graphiques utiles





Graphiques utiles



J. Donini, IPNL

Batch 8 to 14 <Ra> depolished face +0.39µ