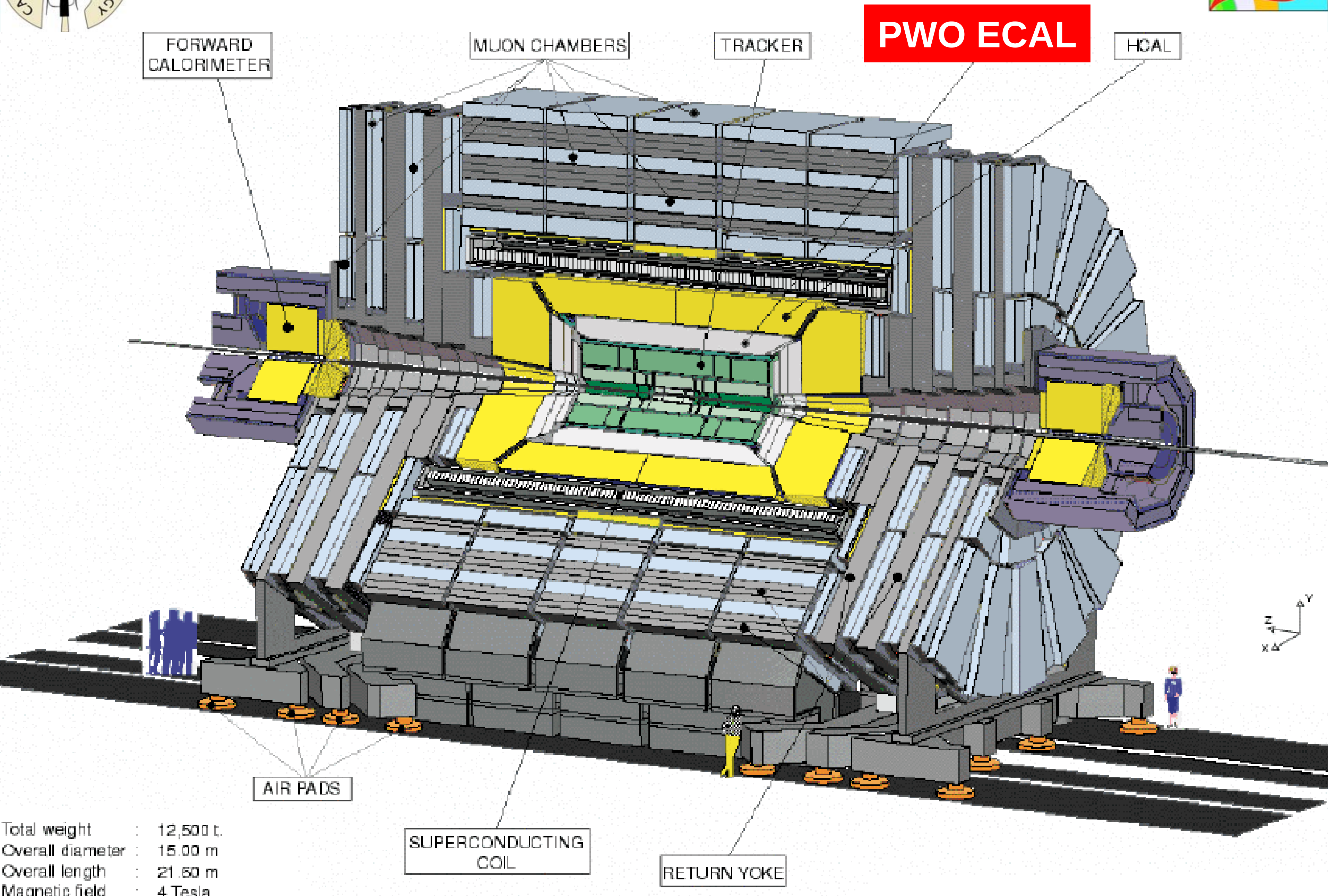
CMS PWO Crystal ECAL



Outline

- Generalities and motivations
- Physics benchmark
- ECAL construction
- Status of PWO crystal quality
- Key point for energy resolution:

Light Monitoring

LHC Experimental Conditions

Machine Luminosity: 10^{34} cm^{-2} s^{-2}

σ_{inel} = 100 mb $\rightarrow$ 10^{9} events/s

σ_{higgs} = 1 pb $\rightarrow$ 10^{-2} events/s

20 events/crossing $\rightarrow$ 1000 tracks

1 crossing/25ns

Neutrons: 10^{17} n/cm^{2}

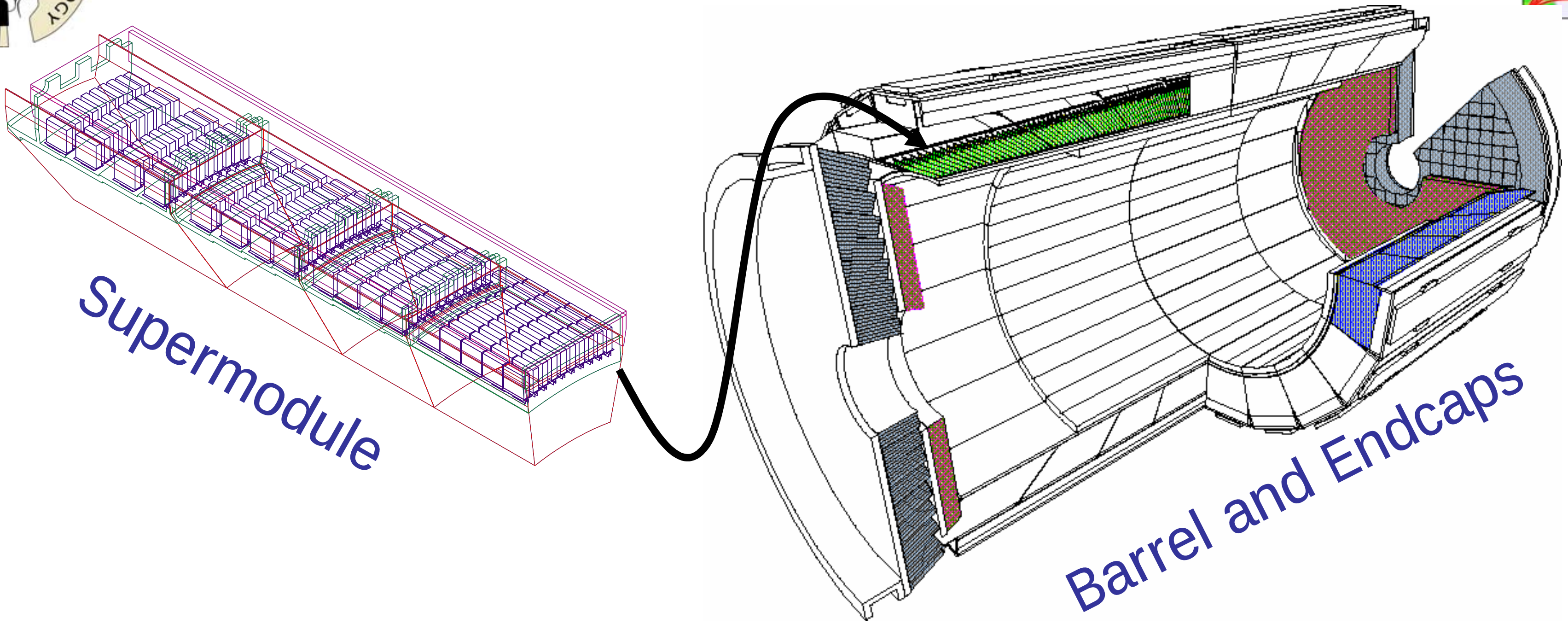
Gammas: 10^{7} Gy

in 10 years

Extreme conditions for detectors

- Granularity ($10^{5} \div 10^{7}$ channels)
- Speed of response
- DAQ + trigger ($10^{9} \rightarrow 10^{2}$ ev/s)
- High radiation resistance

The Calorimeter



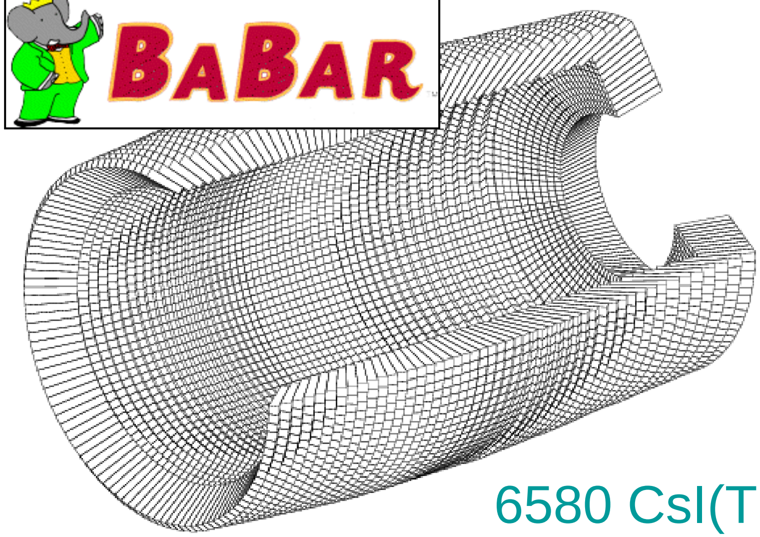
- 36 SMs (1.7k ch) in barrel, 4 Dees (3.5k ch) in endcaps.
- 62k crystal in barrel, 14k crystal in two endcaps. (11 m^3)
- 2 APD's/crystal @barrel, 1 VPT/crystal @endcaps
- 1 monitoring fiber/crystal for *in situ* monitoring.
- Electronics: 0.25 μm ASIC.

Why Crystals?

- Excellent physics potential because of good energy resolution
- High detection efficiency for low energy e/γ
- Structural compactness:
  - simple building blocks allowing easy mechanical assembly
  - hermetic coverage
  - fine transverse granularity
- Tower structure facilitates reconstruction
  - straightforward cluster algorithms for energy and position
  - electron/photon identification

BaBar CsI(Tl) Resolution

Crystal Calorimetry at Low Energies

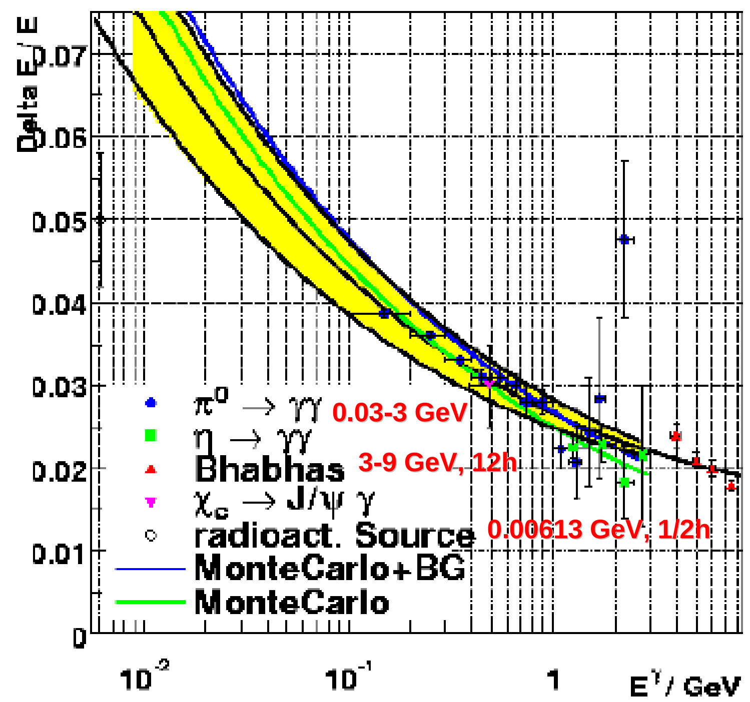


6580 CsI(Tl)

Good light yield of CsI(Tl) provides excellent energy resolution at B factory energies

Energy resolution

M. Kocian, SLAC, CALOR2002



$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt[4]{E}} \oplus \sigma_2$$

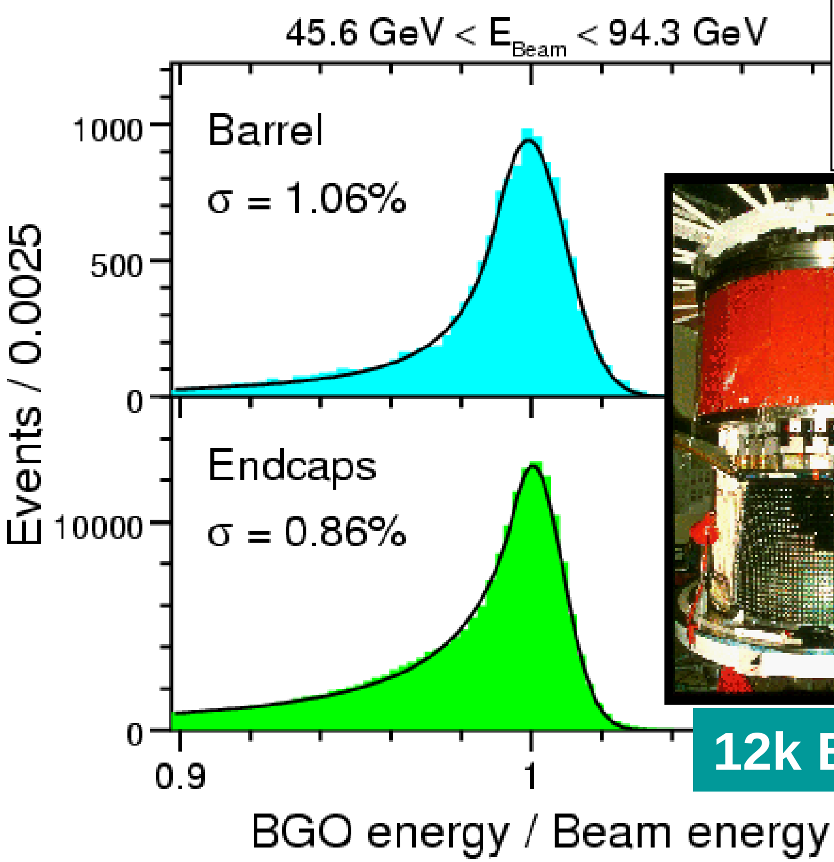
$$\sigma_1 = (2.30 \pm 0.03 \pm 0.3)\%$$

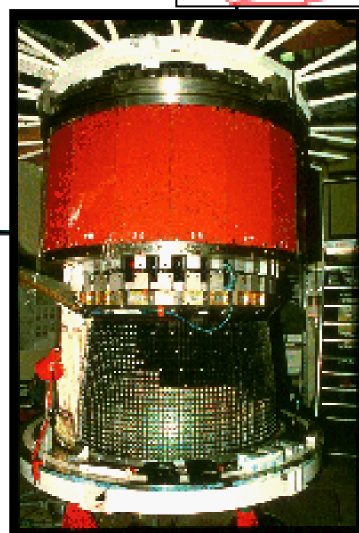
$$\sigma_2 = (1.35 \pm 0.08 \pm 0.2)\%$$

L3 BGO Resolution

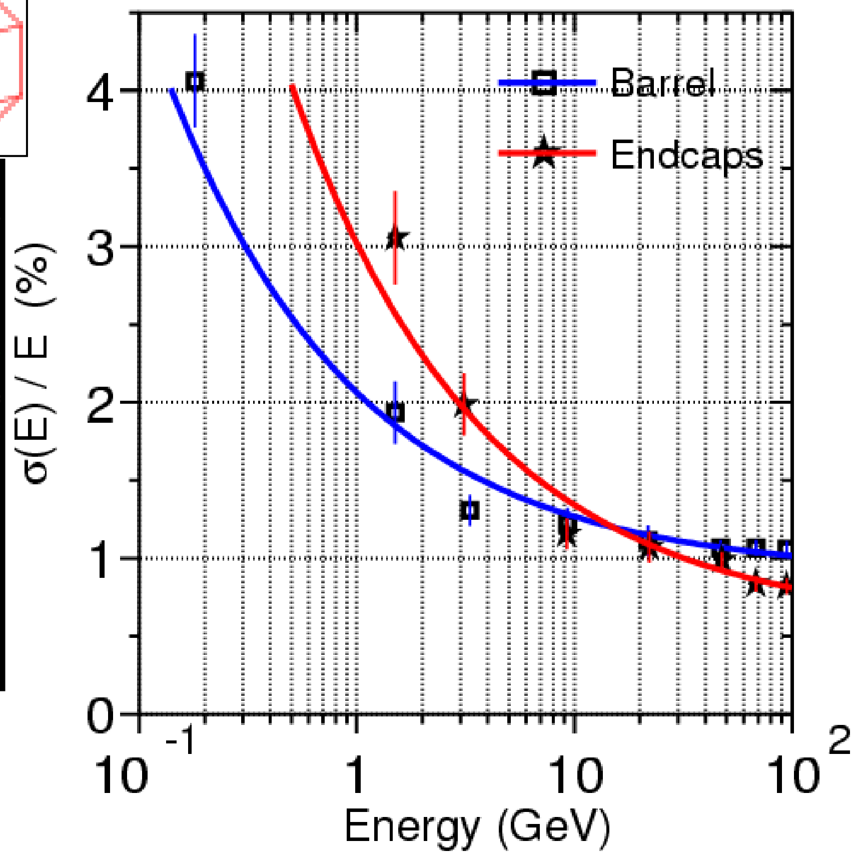
Crystal Calorimetry at High Energies

Contribution	"Radiative"+Intrinsic	Temperature	Calibration	Overall
Barrel	0.8%	0.5%	0.5%	1.07%
Endcaps	0.6%	0.5%	0.4%	0.88%

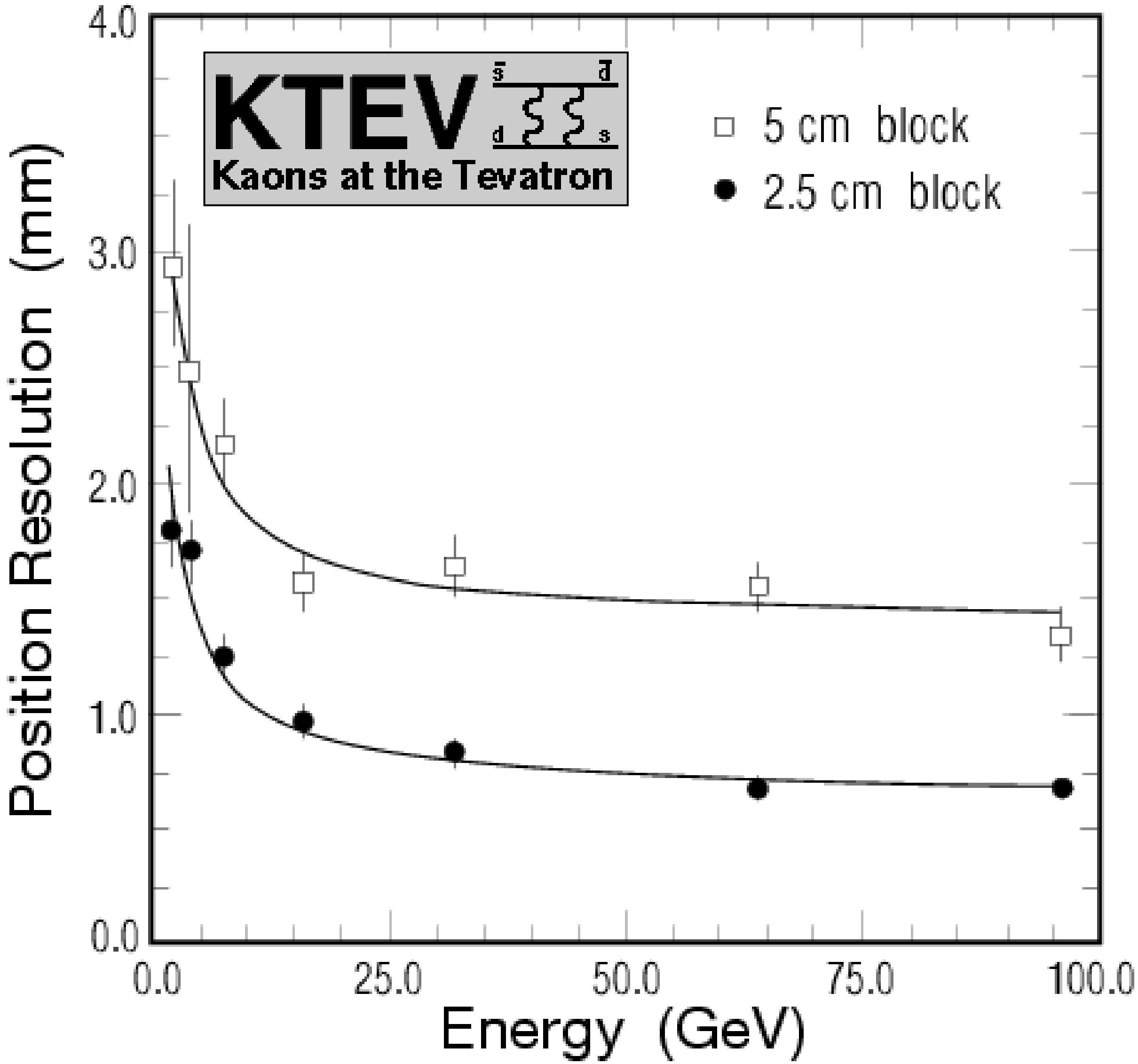


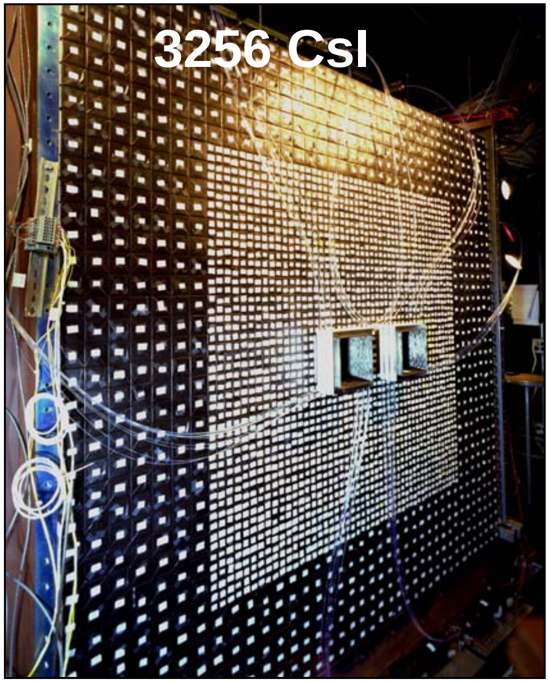


12k BGO



KTeV CsI Position Resolution





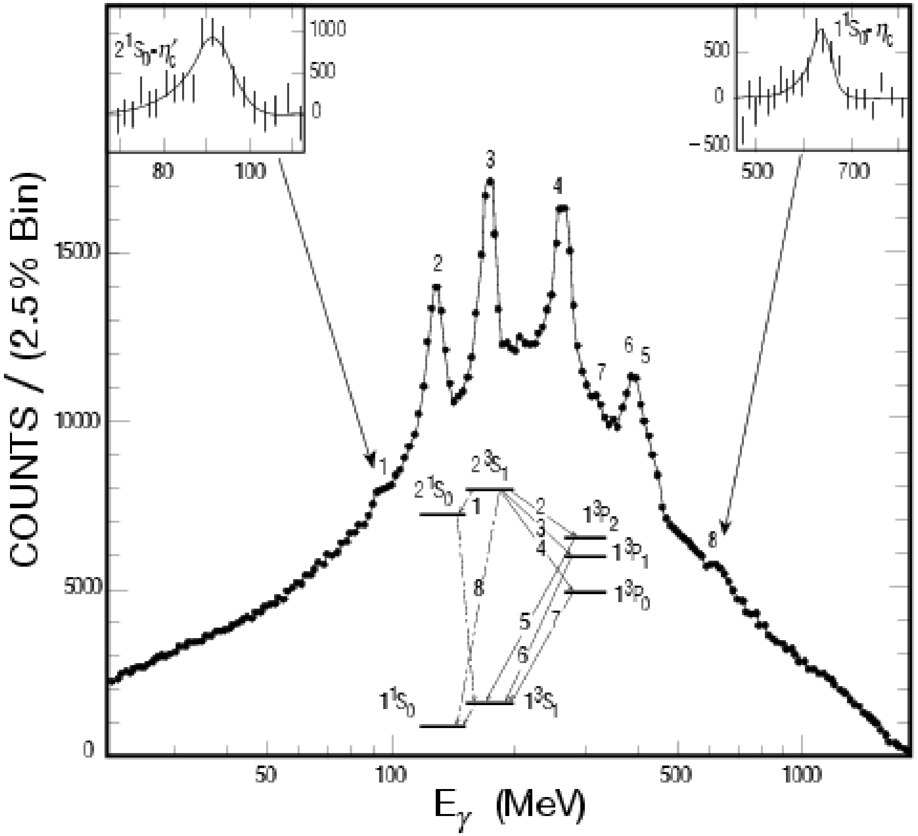
Sub mm position resolution is achievable.

L3 BGO & CMS PWO: 0.3 mm at high energies.

Physics with Crystal ECAL

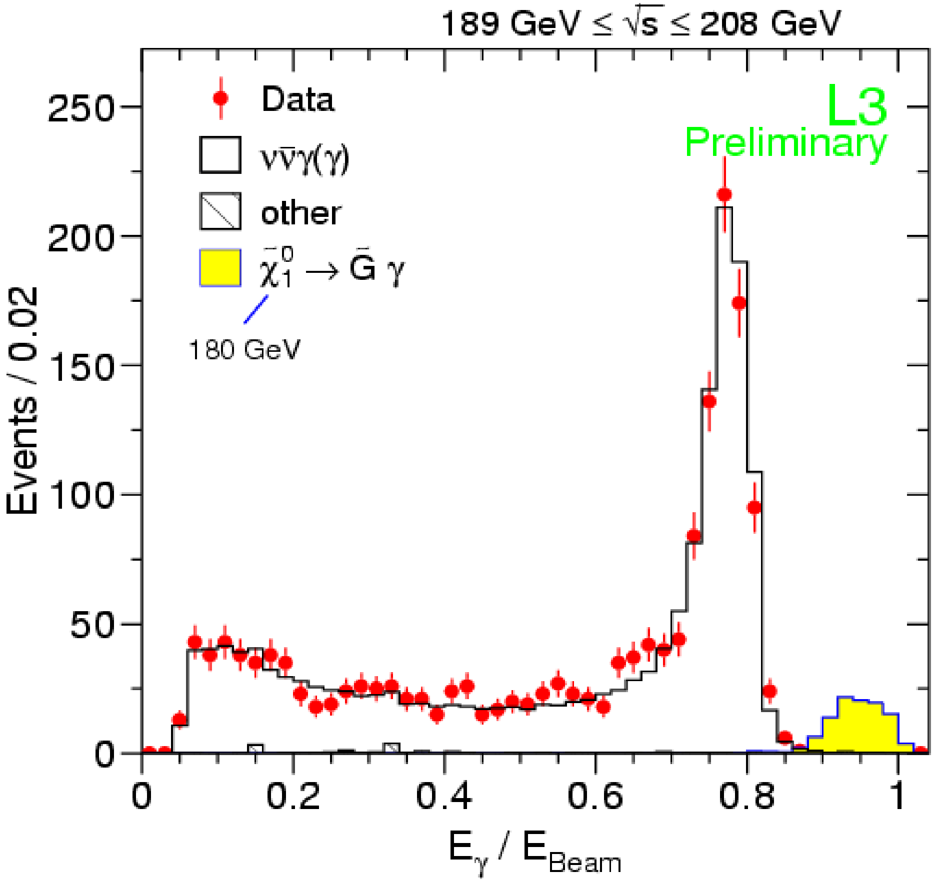
Charmonium System Observed Through Inclusive Photons

Crystal Ball



SUSY Breaking with Gravitino

$$e^+e^- \rightarrow \tilde{G}\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma$$



Physics with Crystal ECAL (Cont.)

The CDF event: **2 e + 2 γ + E_T^{miss}**

SM expectation (WW$\gamma\gamma$) ~ 10^{-6} (PR D59 1999)

Possible SUSY explanation

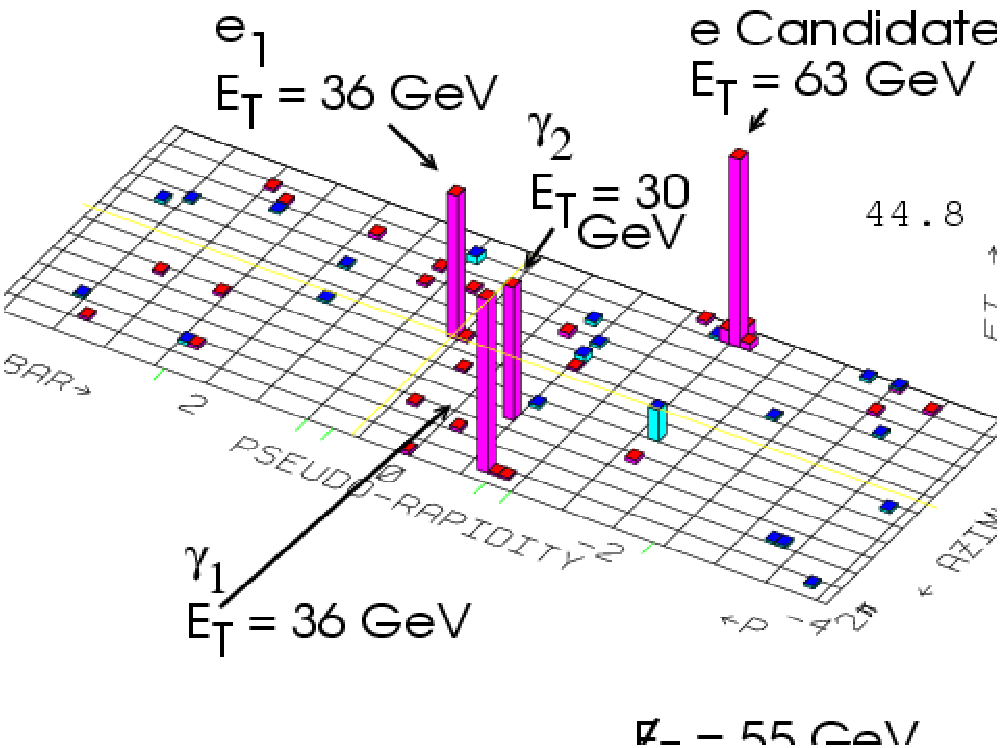
$$q\bar{q} \to \tilde{e}^+\tilde{e}^- \to ee\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ee\gamma\gamma\tilde{G}\tilde{G}$$

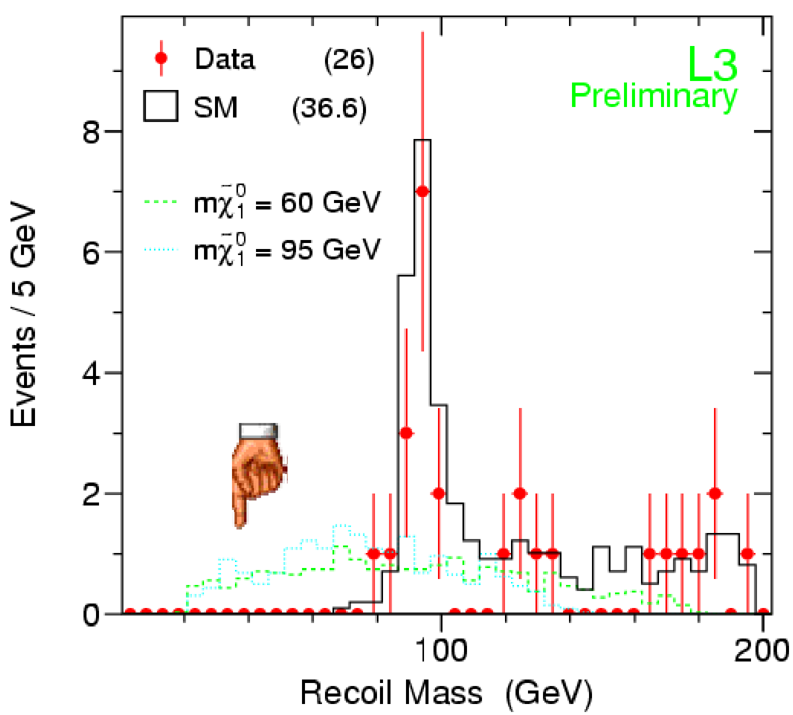
L3 should be able to observe

$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma\tilde{G}\tilde{G}$$

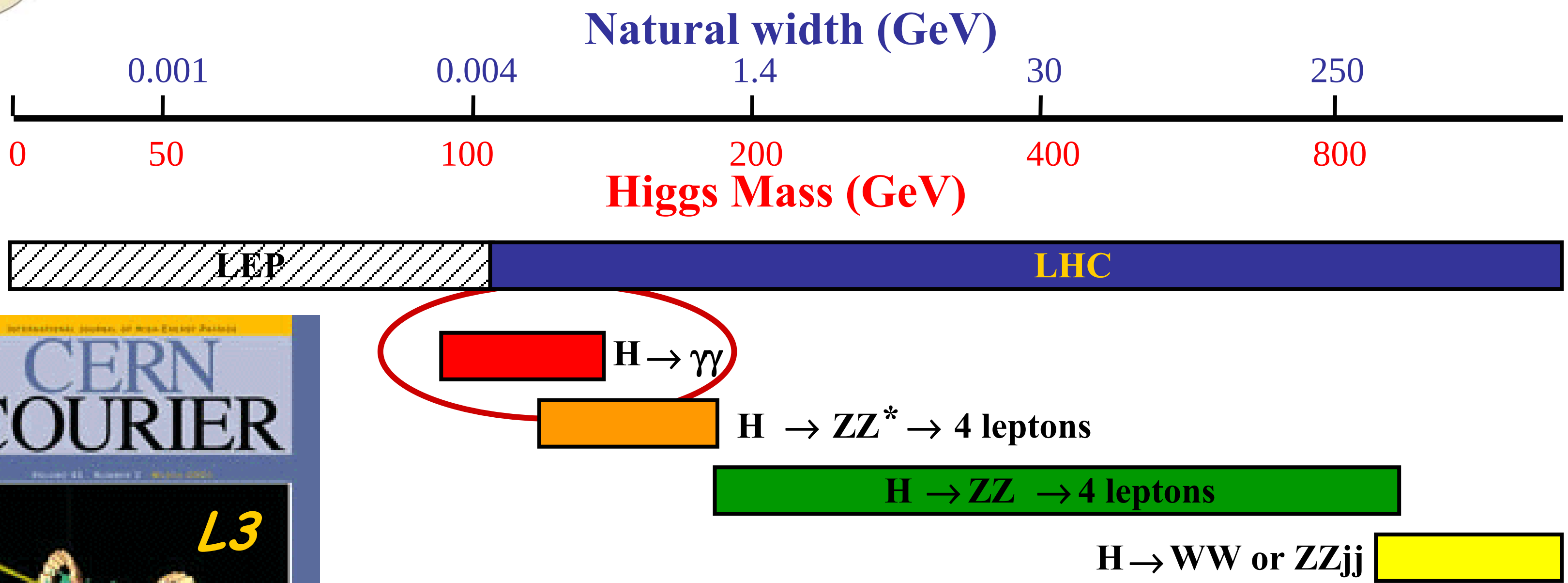
Another possible channel

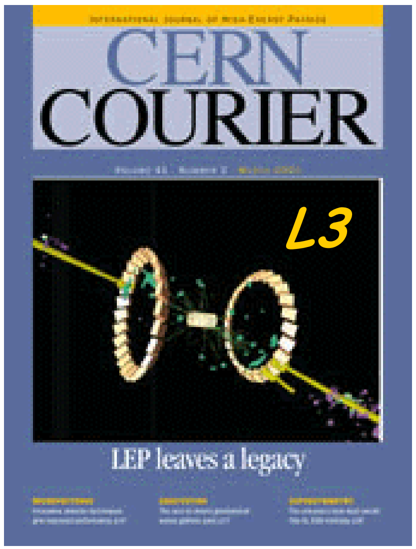
$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to \gamma\gamma\tilde{\chi}_1^0\tilde{\chi}_1^0$$



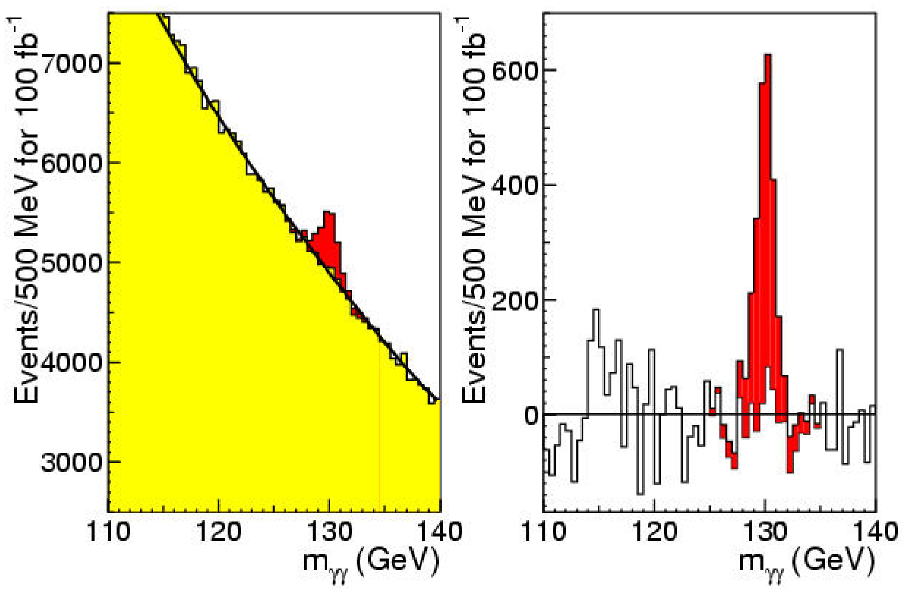


LHC Physics Benchmark: Higgs Hunt





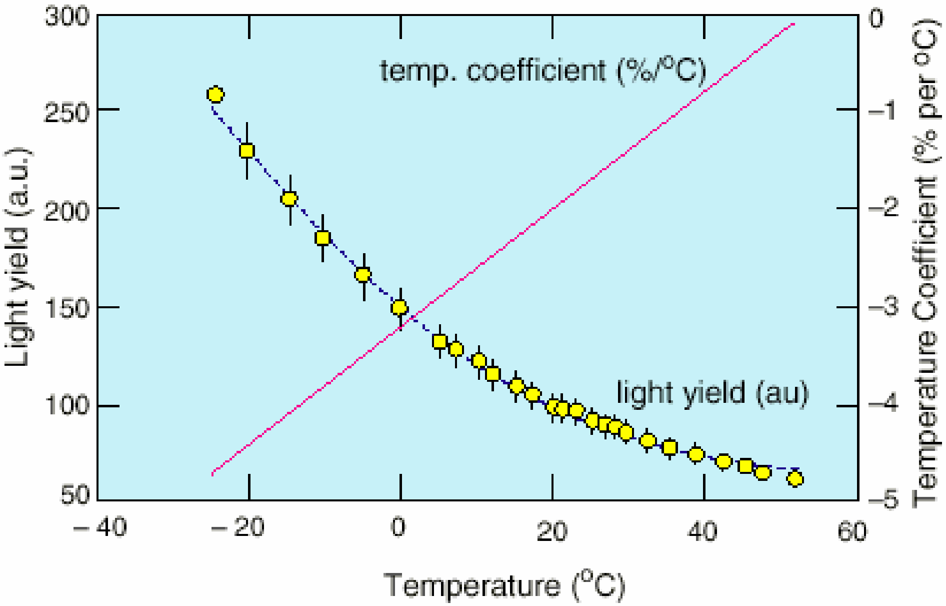
LEP observed an excess of events around 115 GeV



H → γγ signal in CMS ECAL @ design resolution

Why Lead Tungstate (PWO)?

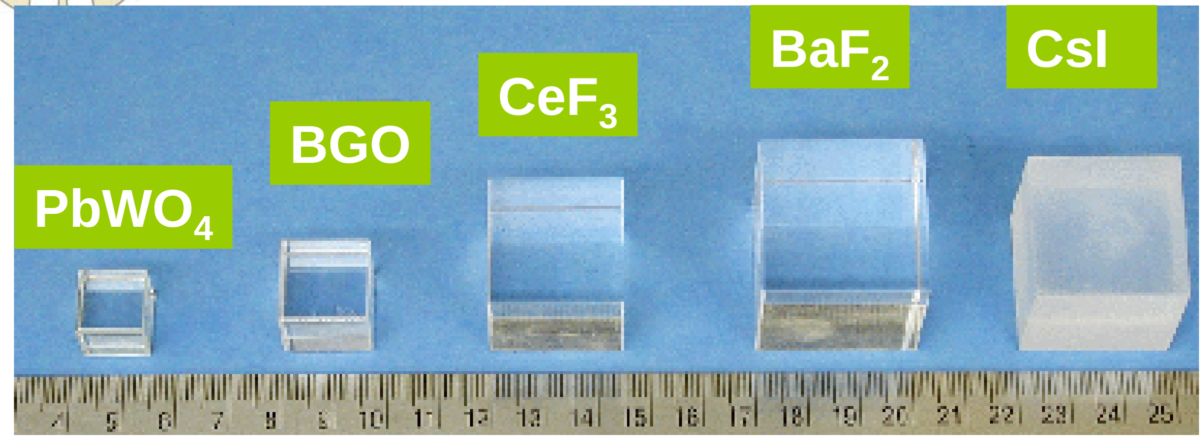
Parameter		Value
Radiation length	cm	0.89
Moliere radius	cm	2.2
Hardness	Moh	4
Refractive index		2.3
Peak emission	nm	440
% of light in 25 ns		80%
Light yield (23 cm)	γ/MeV	100



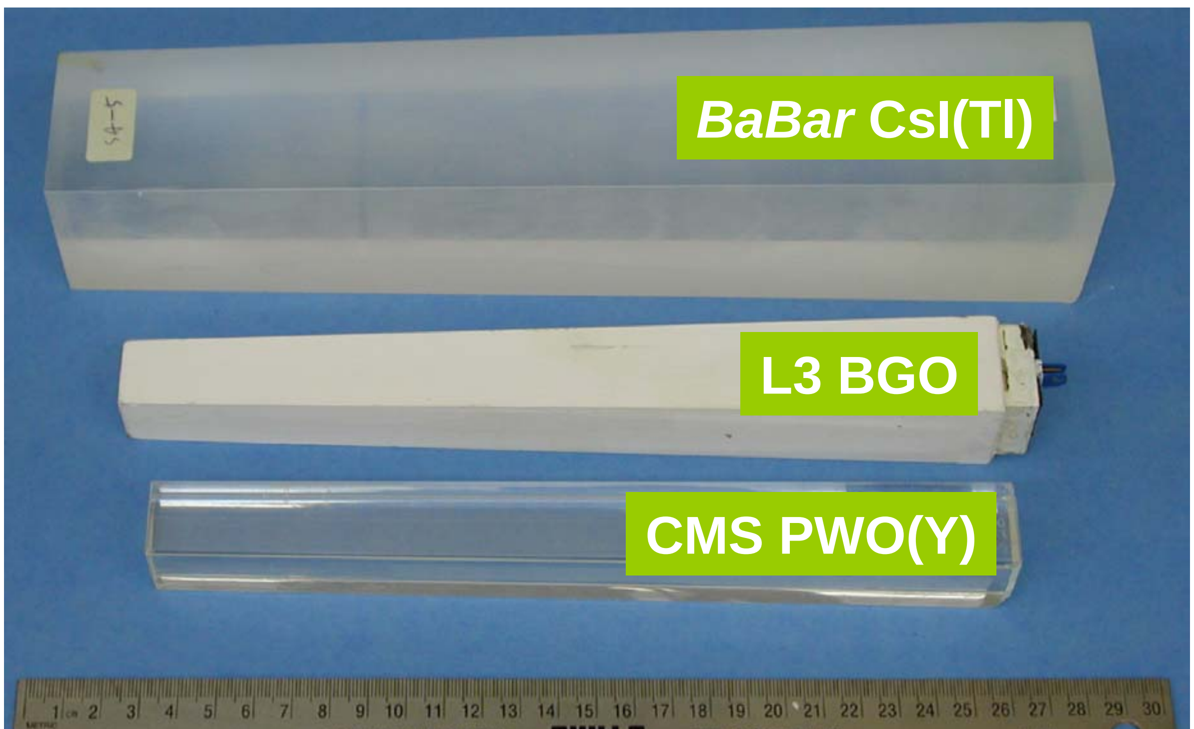
- Fast scintillation
- Small X_o and R_m
- Can be made radiation hard
- Relatively easy to grow
- Massive production capability

- Low light yield
- High refractive index
- LY dependance on T

PWO Crystal is Compact



1.5 X_0 Cubic



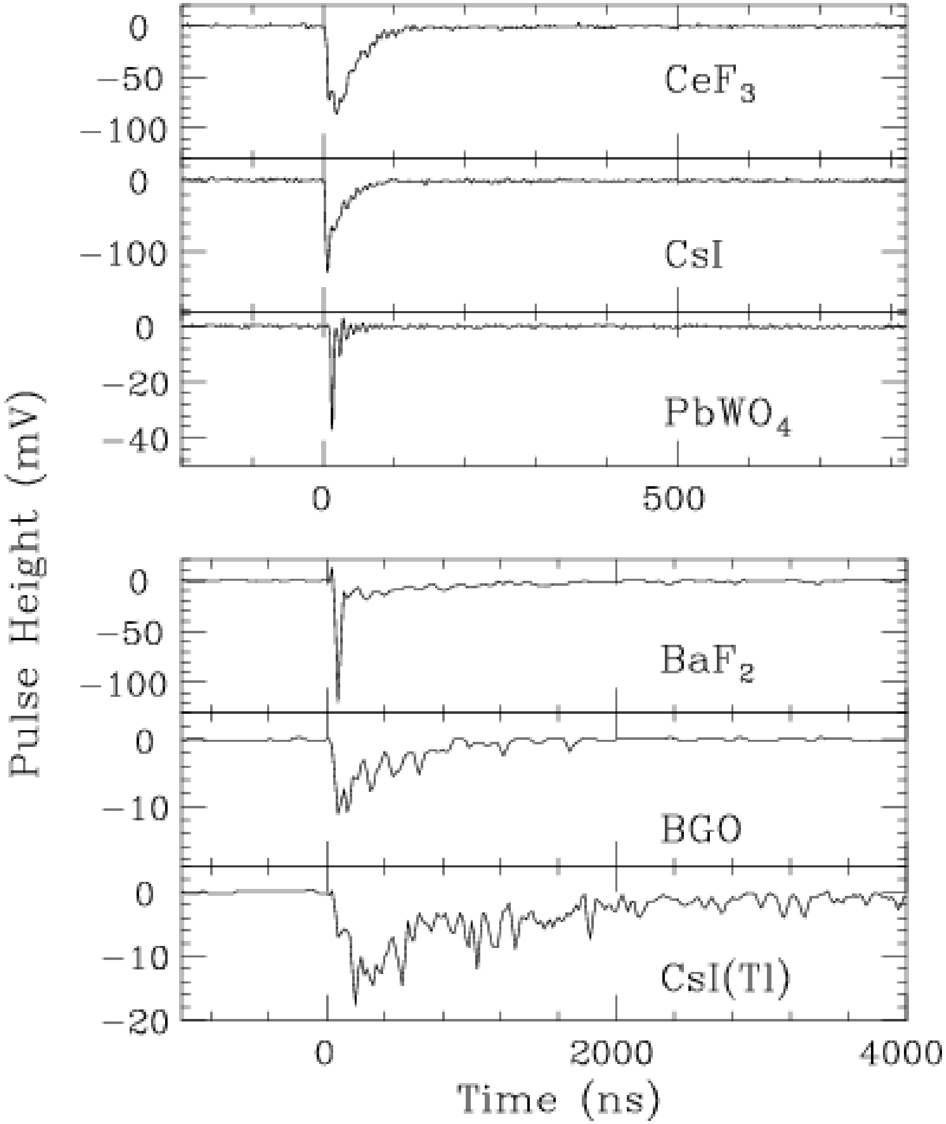
Full Size Samples

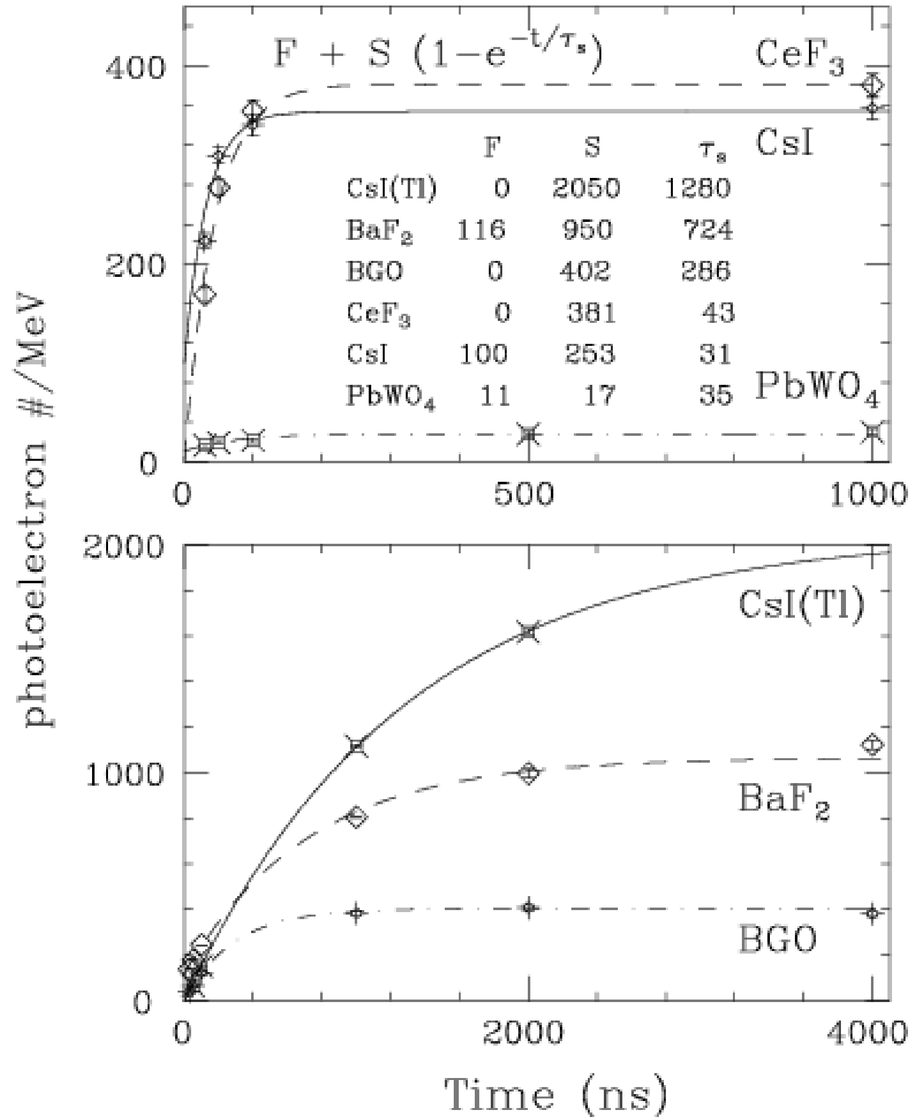
BaBar CsI(Tl): 16 X_0

L3 BGO: 22 X_0

CMS PWO(Y): 25 X_0

PWO Scintillation is Fast





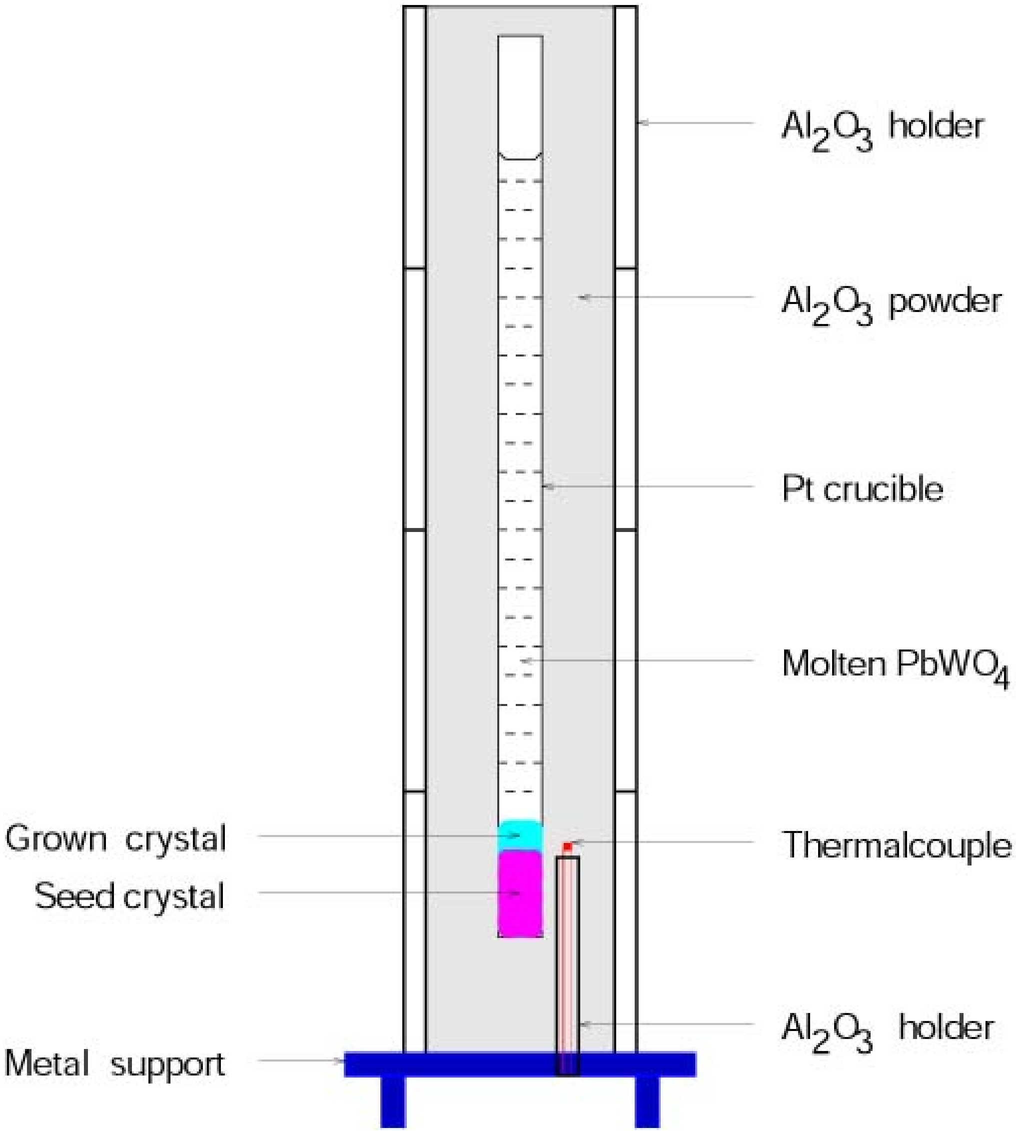
Comparison: Crystals for HEP

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	$PbWO_4$	LSO(Ce)	GSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	8.3	7.40	6.71
Melting Point (°C)	651	621	621	1280	1050	1123	2050	1950
Radiation Length (cm)	2.59	1.85	1.85	2.06	1.12	0.9	1.14	1.37
Molière Radius (cm)	4.8	3.5	3.5	3.4	2.3	2.0	2.3	2.37
Interaction Length (cm)	41.4	37.0	37.0	29.9	21.8	18	21	22
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	2.2	1.82	1.85
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	560	420 310	300 220	480	560 420	420	440
Decay Time [b] (ns)	230	1300	35 6	630 0.9	300	50 10	40	60
Light Yield [b,c] (%)	100	45	5.6 2.3	21 2.7	9	0.1 0.6	75	30
d(LY)/dT [b] (%/ °C)	~0	0.3	-0.6	-2 ~0	-1.6	-1.9	?	?
Experiment	Crystal Ball	CLEO BaBar BELLE	KTeV	TAPS (L*) (GEM)	L3 BELLE	CMS ALICE PANDA BTeV…	-	-

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

PWO Crystals Growth

BTCP: Czochralski SIC: Modified Bridgman

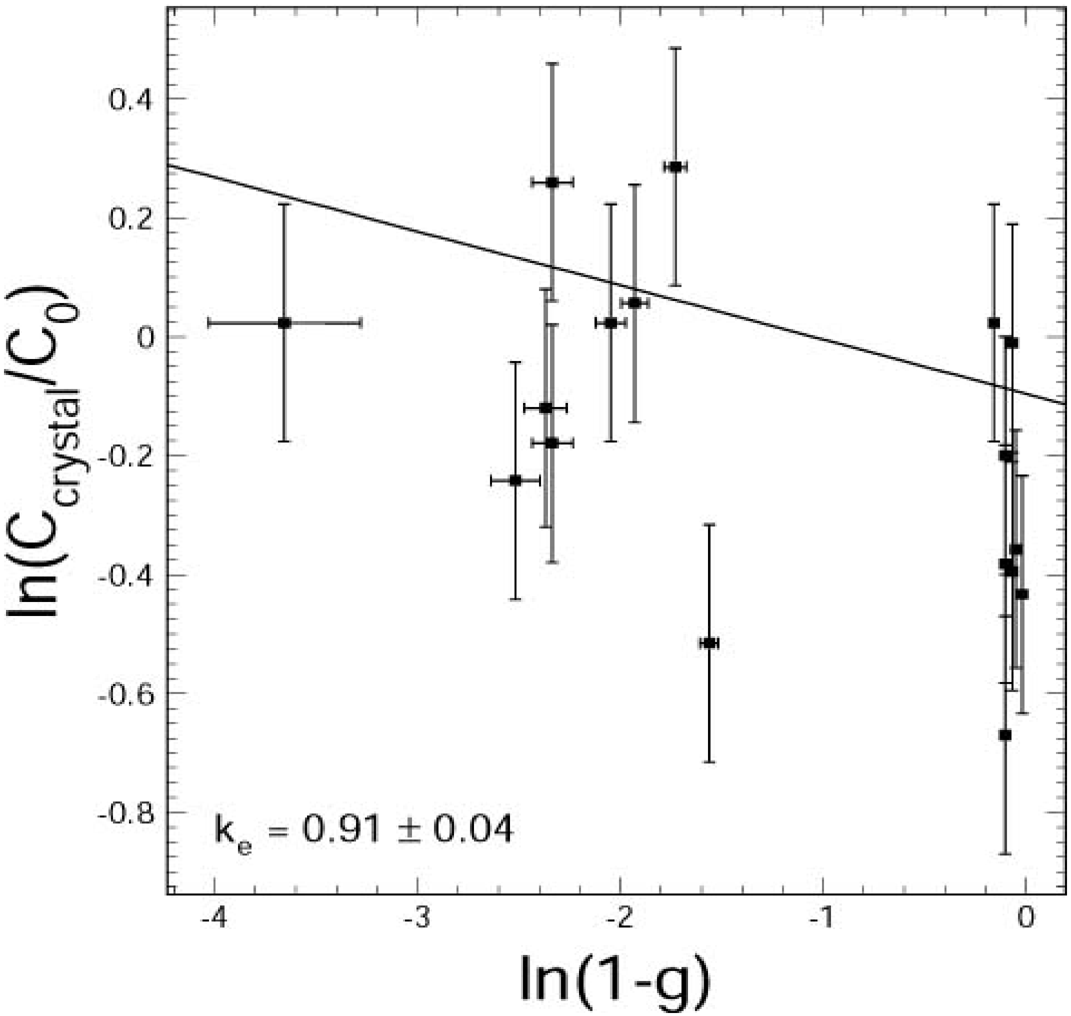


Yttrium Distribution in Crystal

- The Glow Discharge Mass Spectroscopy (GDMS) was used to determine yttrium concentration in PWO crystals.

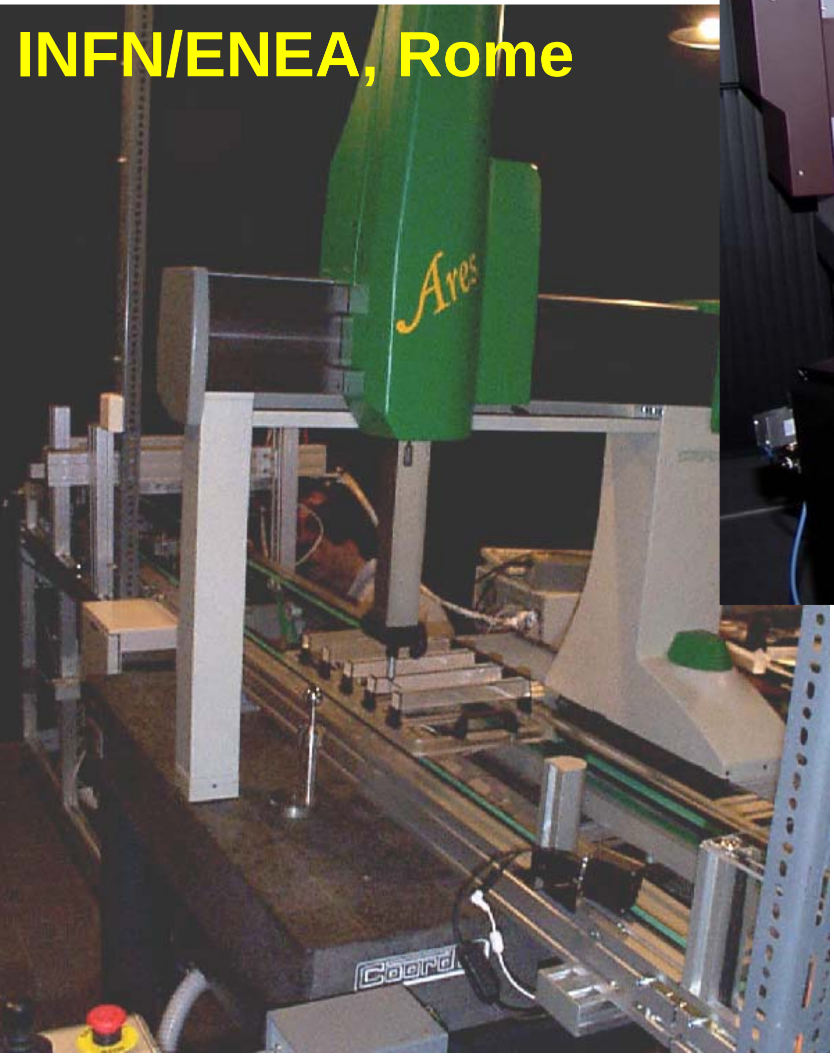
- A fit to the GDMS data extracts the yttrium segregation coefficient in PWO

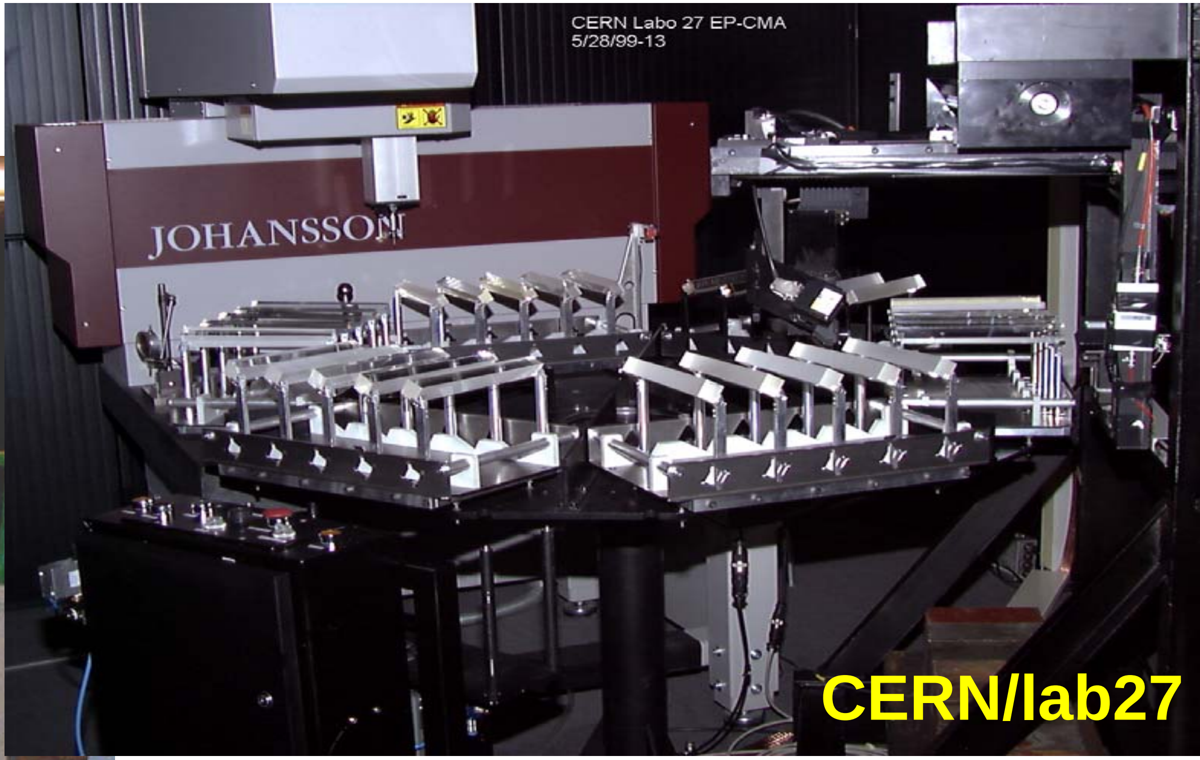
$$K_e = 0.91 \pm 0.04$$



PWO Crystal Quality Control

25 K crystals delivered





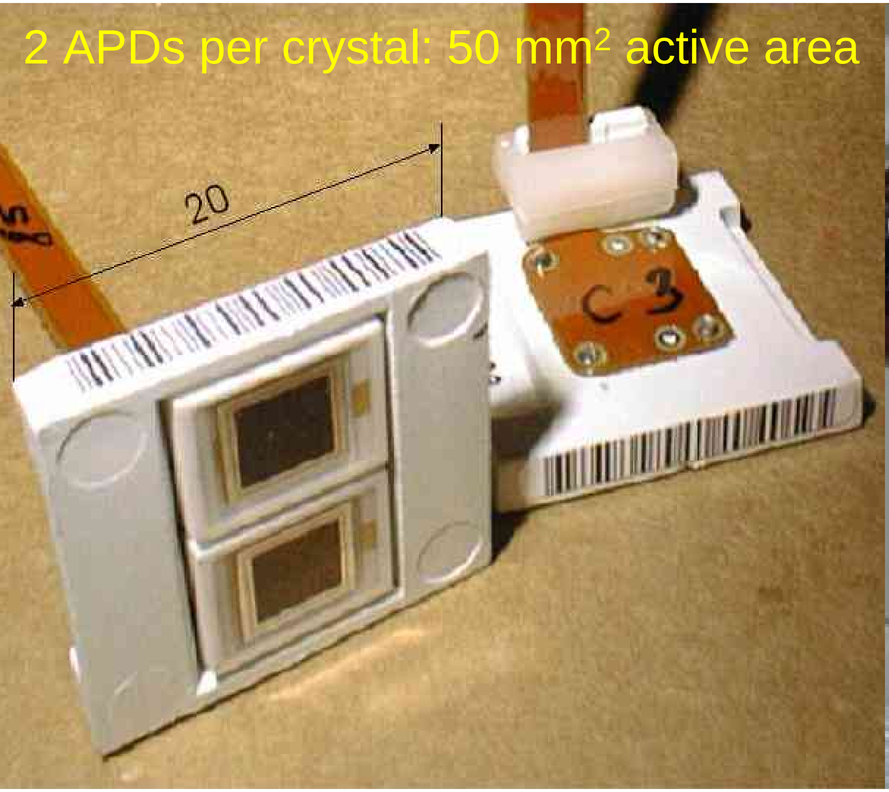
Automatic control of:

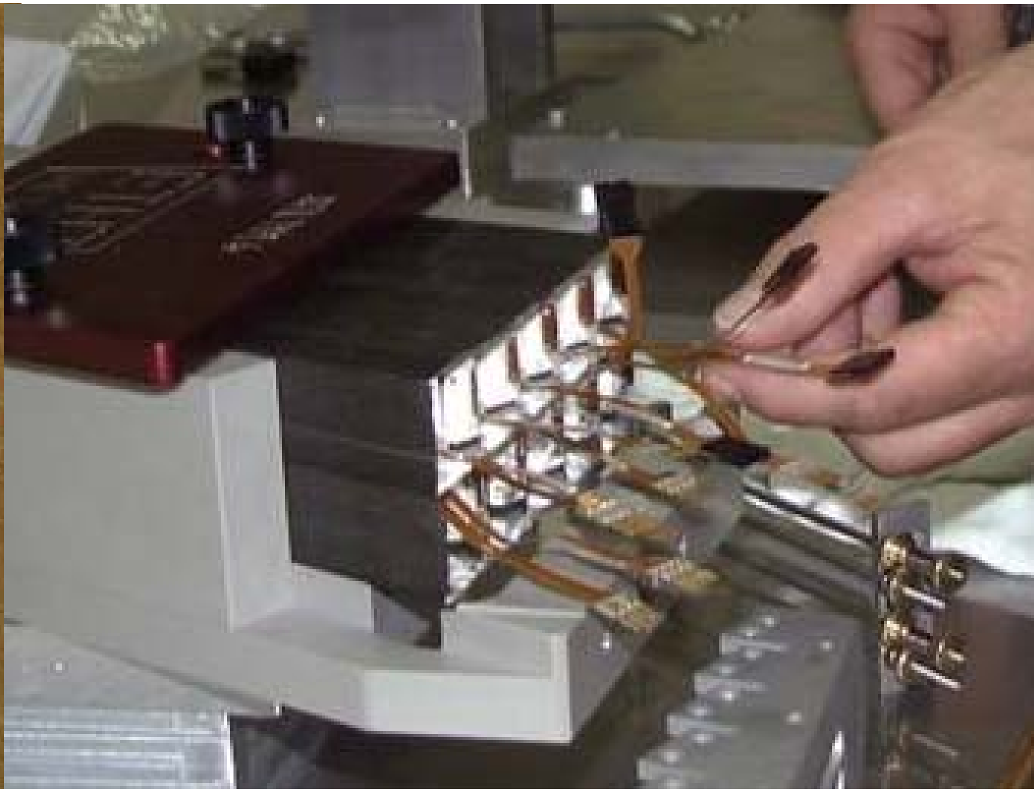
- Dimensions
- Transmission
- Light yield and uniformity

Avalanche Photo Diode (APD)

Delivery, test and screening are completed

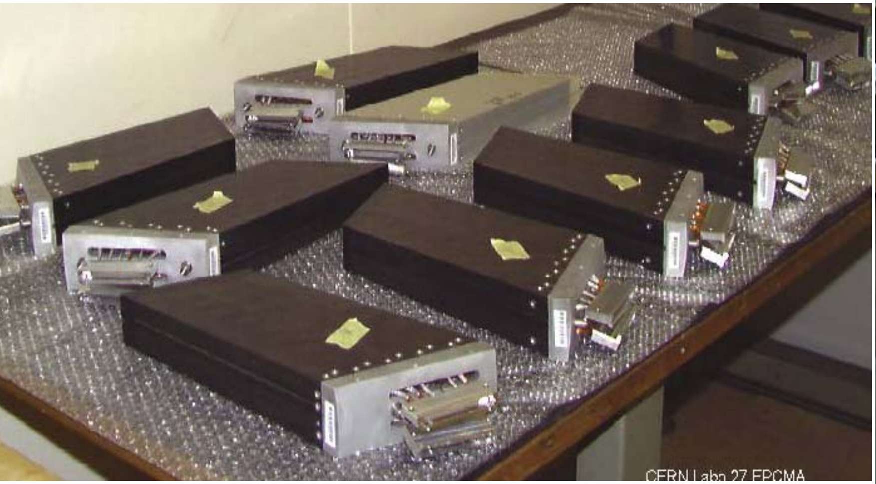
QC: ^{60}Co to 5 kGy in 2 h; 80^{o}C aging one month





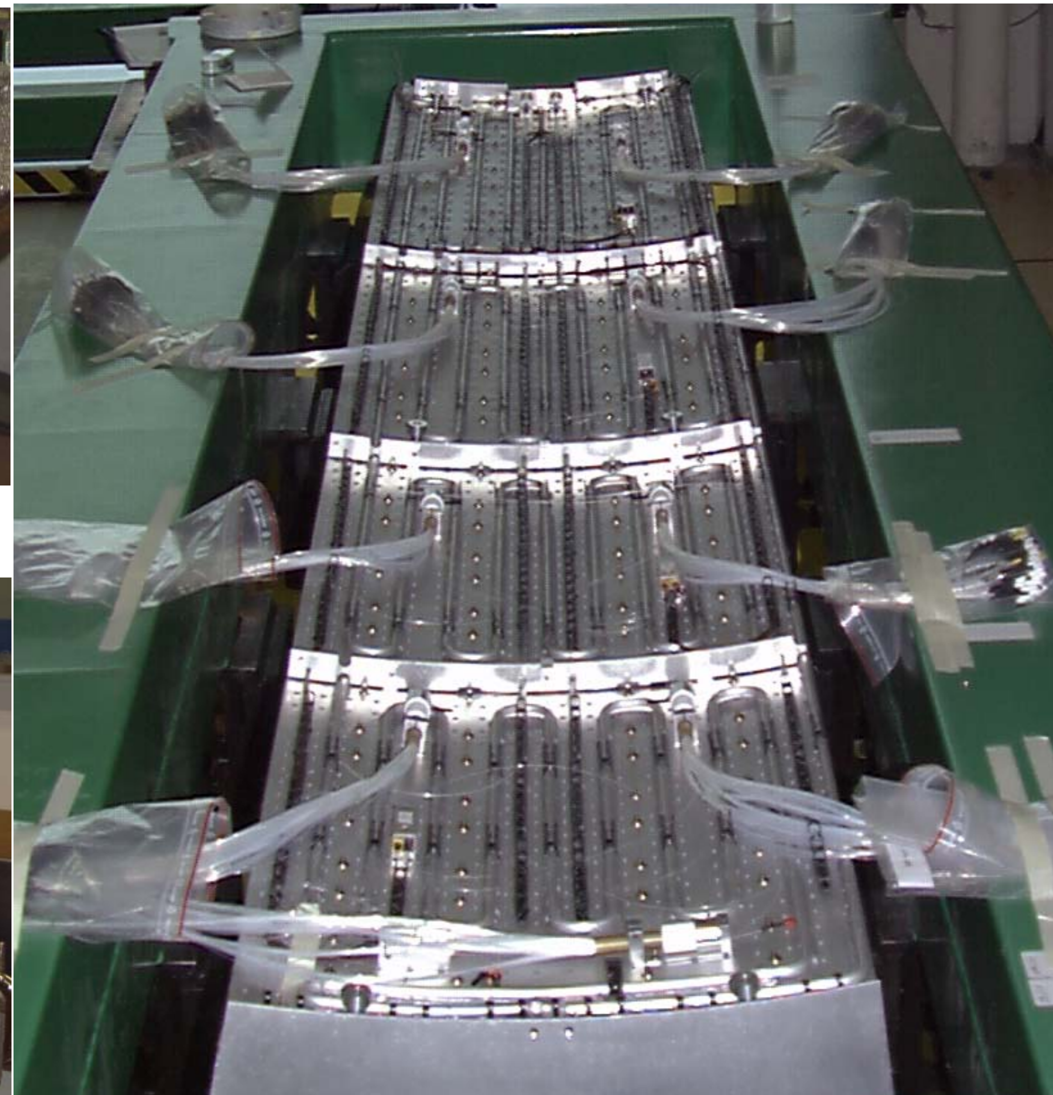
ECAL Module Assembly

Submodule: 10 crystals



Module: 4(5)00 crystals

Supermodule:1,700 crystals



SM Construction

Modules assembled in Rome and CERN centers

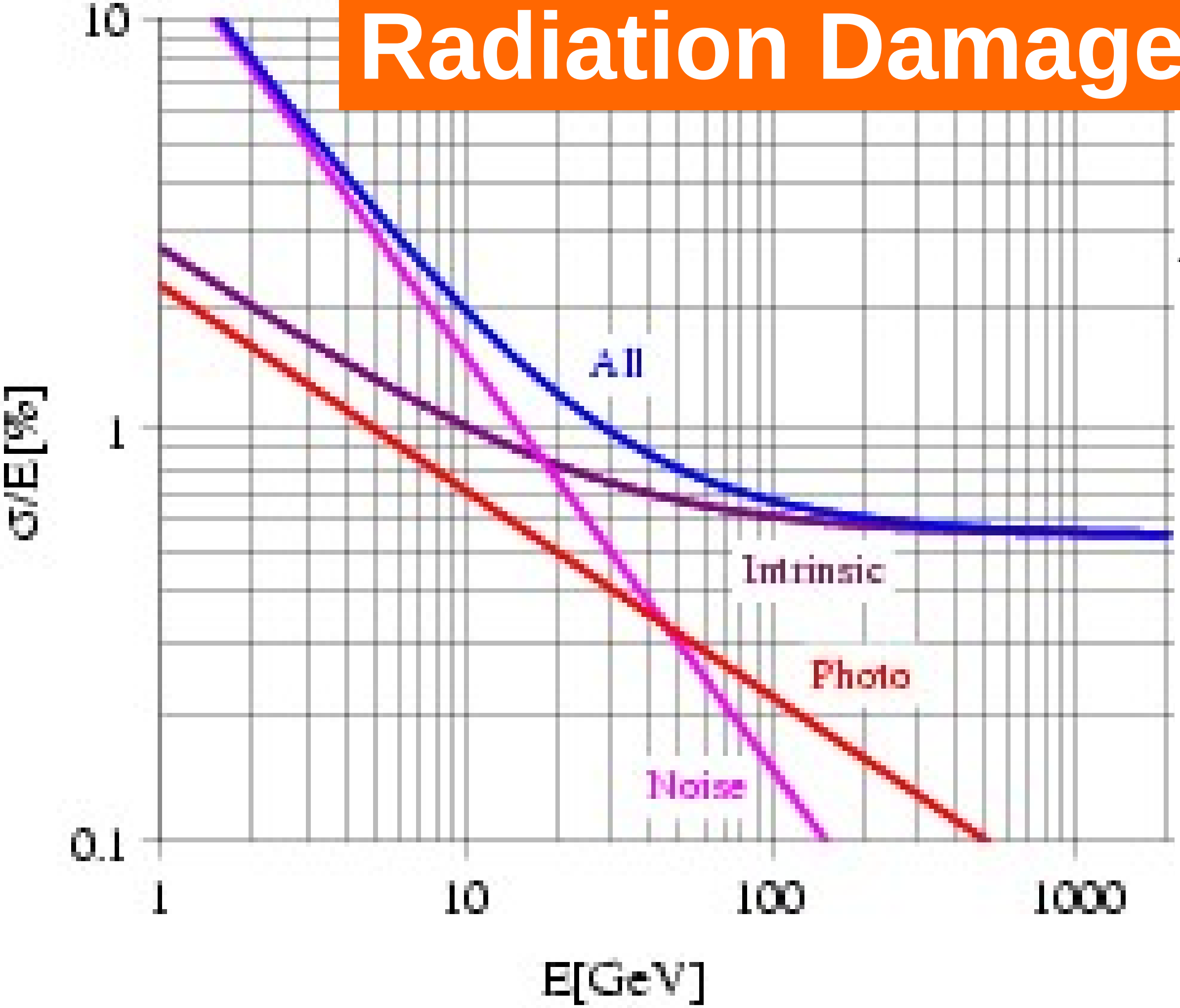
About 40 modules (10 SM) are completed

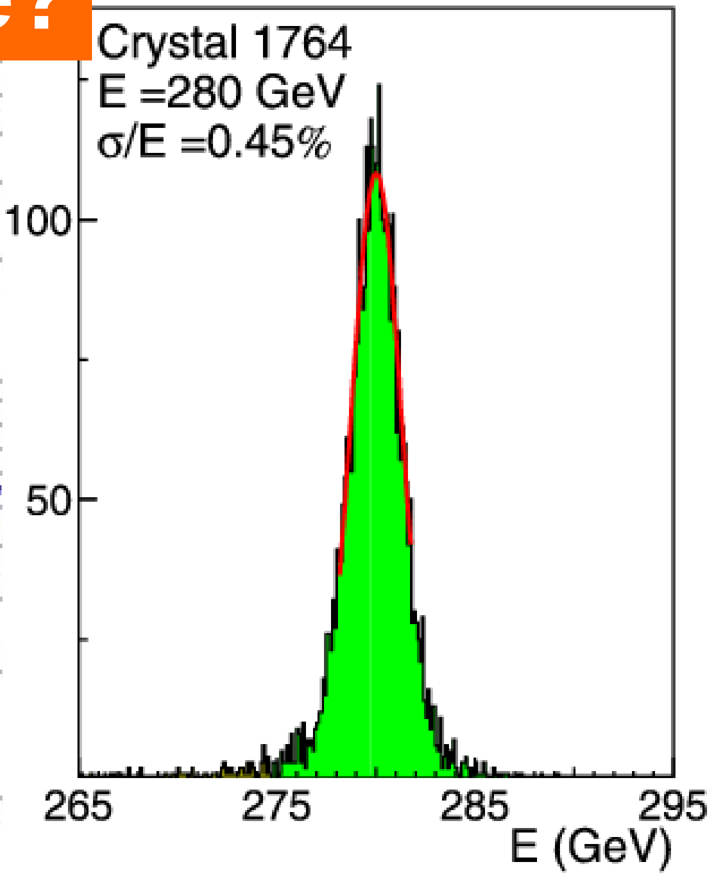
CMS PWO ECAL Resolution

Designed Resolution

Beam Test

Radiation Damage?

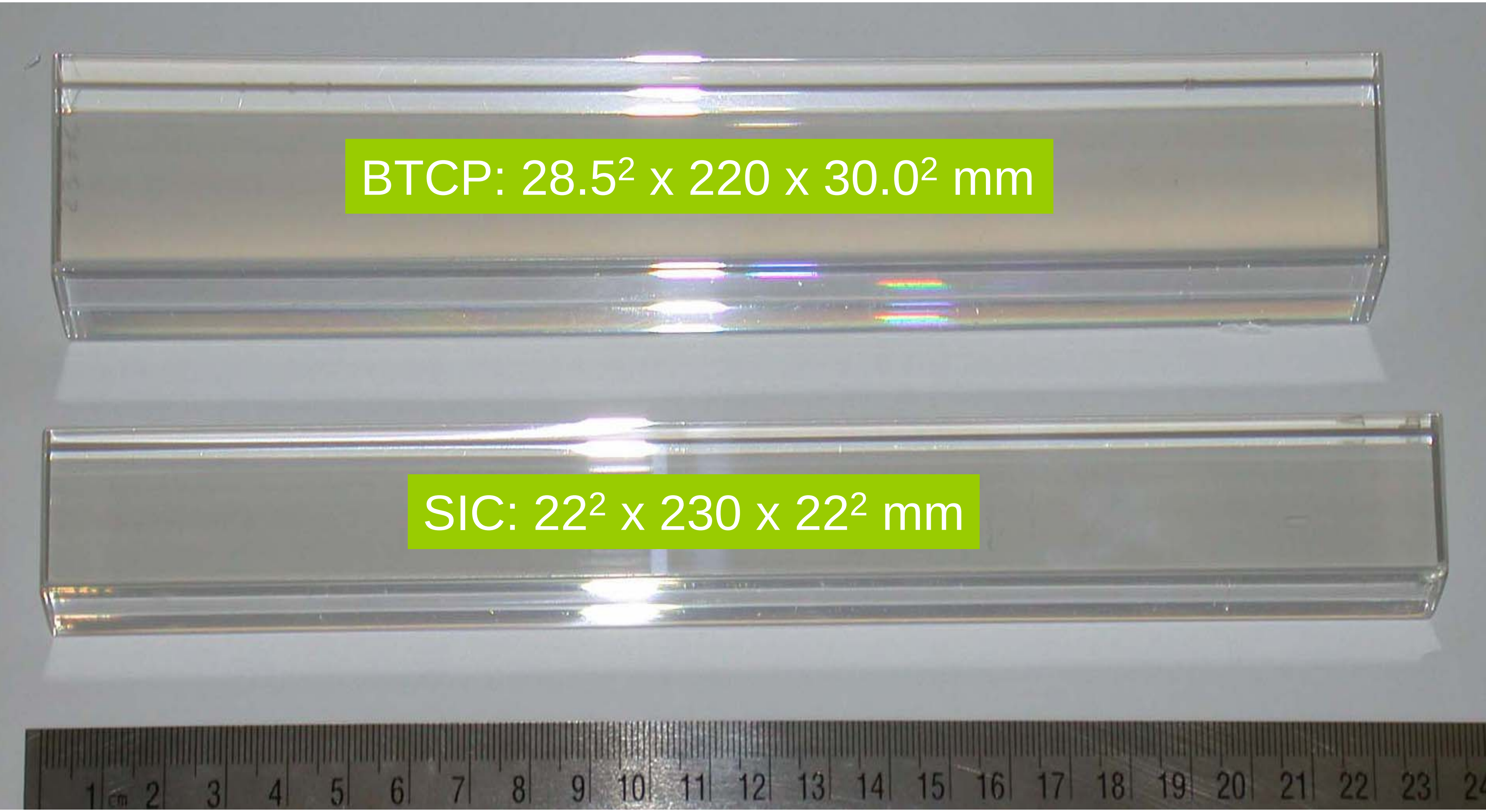




Randomly Selected PWO Samples

BTCP: 20 from 1st batch (100) for CMS endcaps

SIC: 20 from production batch for PrimEx

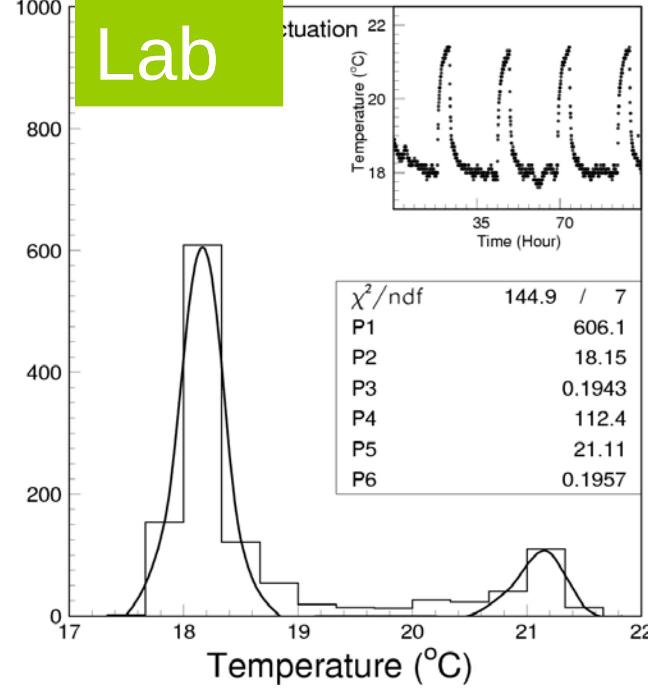


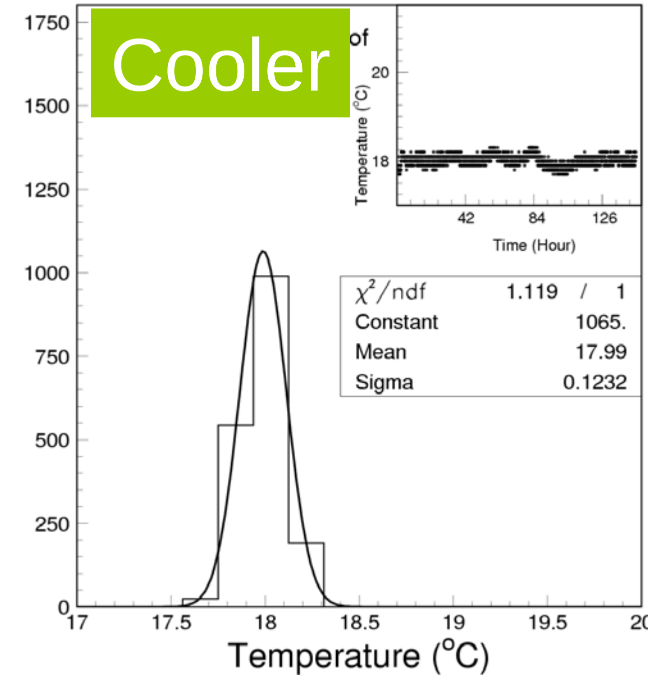
Experiment

- All crystals went through (1) thermal annealing at 200°C, (2) irradiations by γ–ray at 15, 400 and 9k rad/h until equilibrium and (3) recovery.
- Properties measured: Transmittance, emission and excitation spectrum, light output, decay kinetics and light response uniformity, as well as their degradation, radiation induced color center and emission weighted radiation induced absorption coefficients.
- Light output degradation was only measured at 15 rad/h because of limited light output: less than 8 p.e./MeV for BTCP samples.

Thermal Annealing

- Rigorous temperature control both in amplitude and slope:
  - From RT to 200^{o}C: 200 minutes;
  - Maintain at 200^{o}C: 240 minutes;
  - From 200^{o}C to 25^{o}C: 400 minutes.
- Crystals are kept in dark at RT (18^{o}C) after annealing. The minimum time between annealing and the 1st measurement is 48 hours.

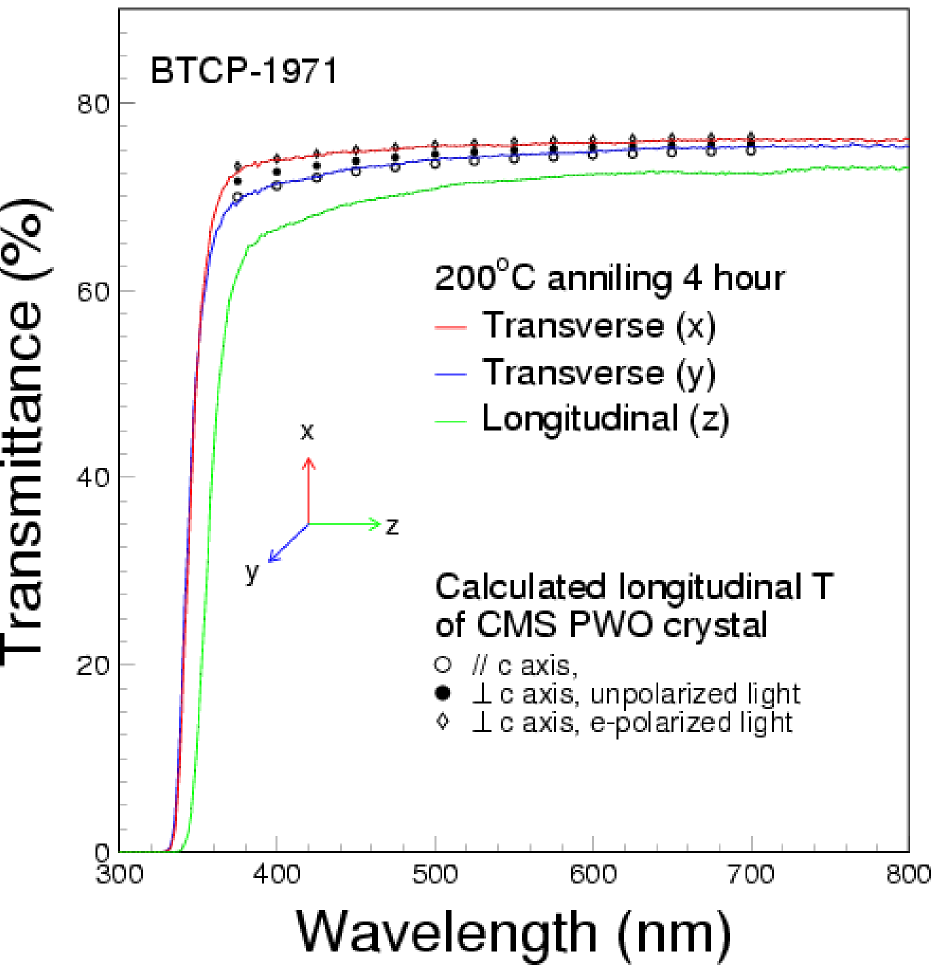




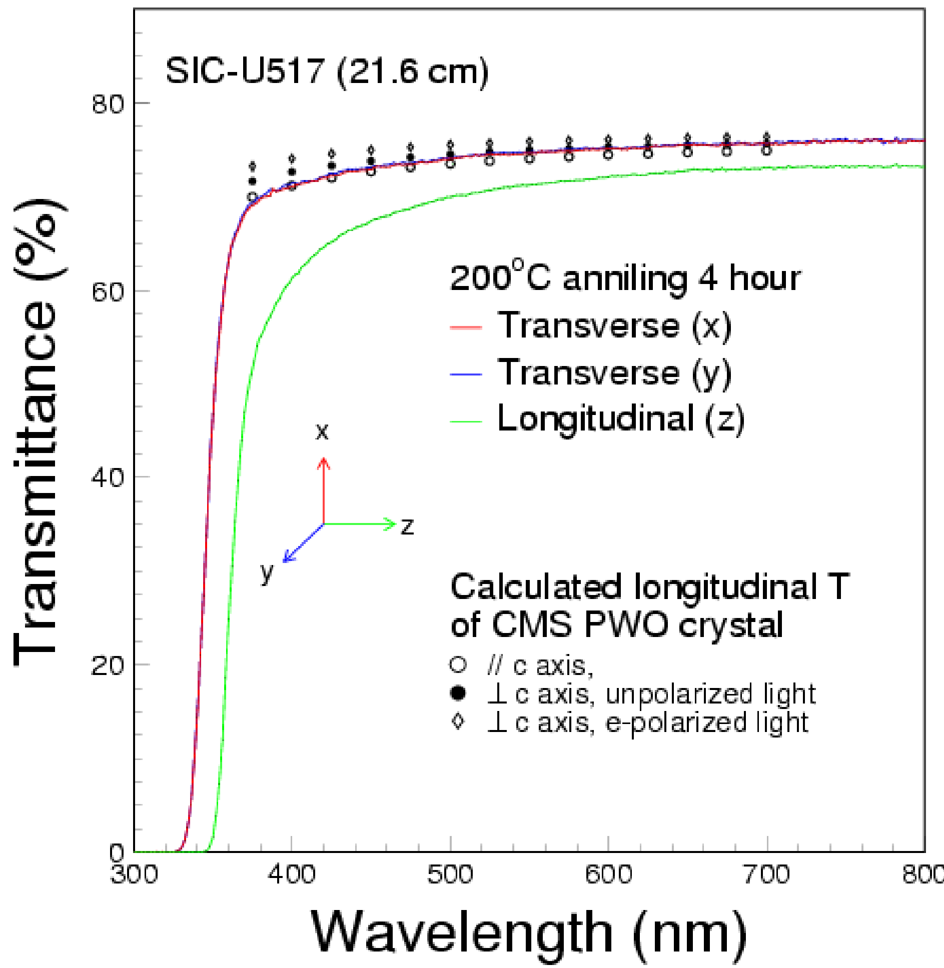
Transmittance and Birefringence

a axis: better L.T., but non-isotropic transverse T.
Both approaching theoretical limit

BTCP: grown along the ***a axis***

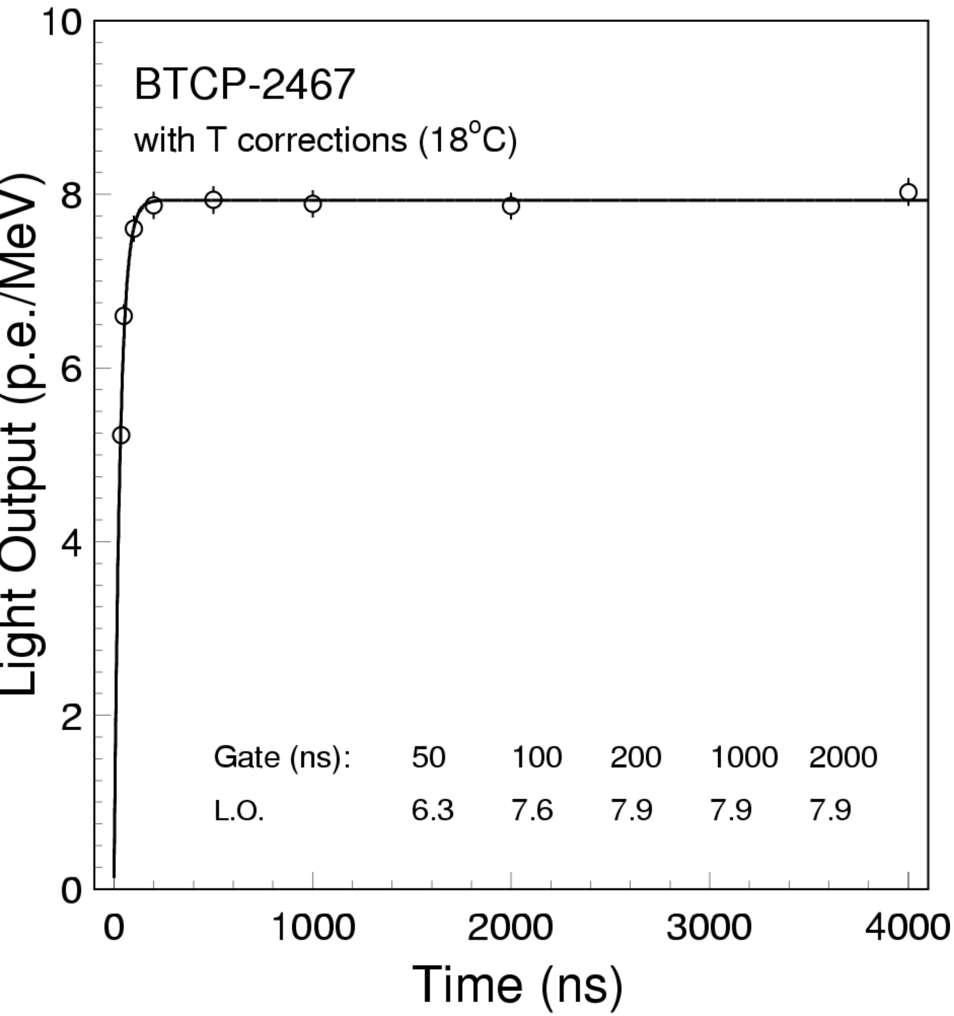


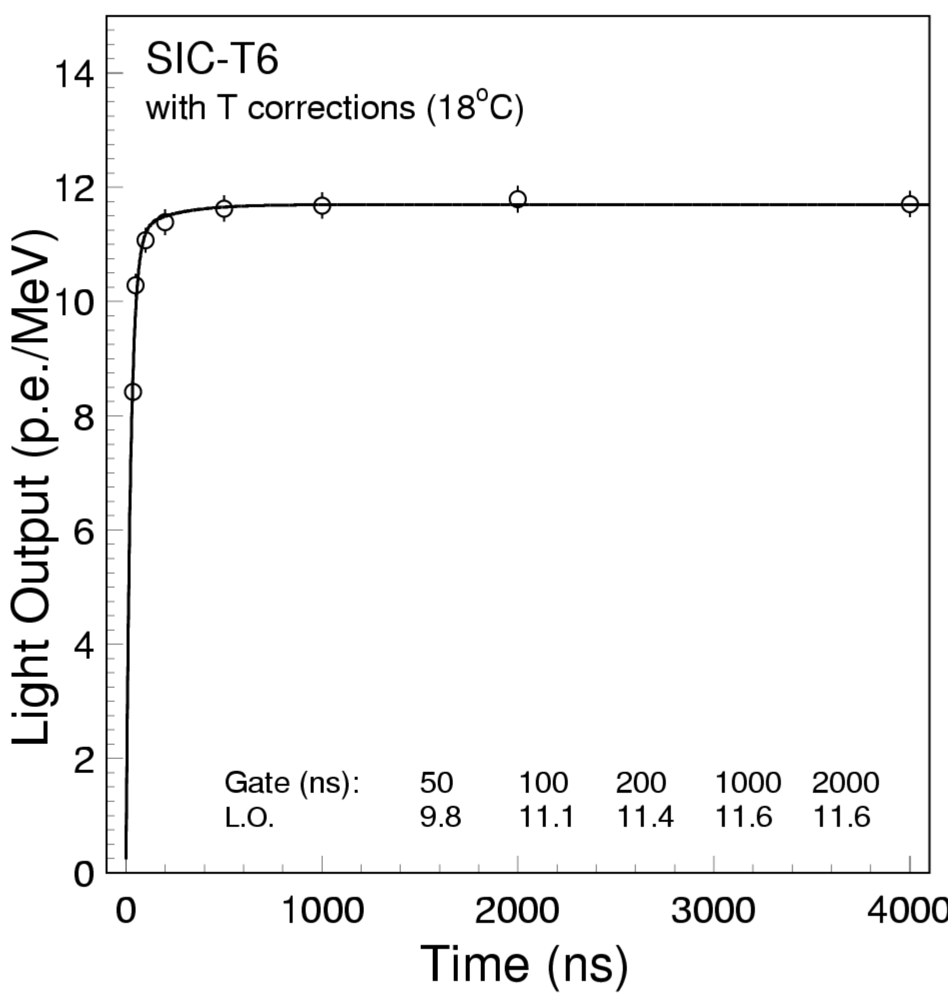
SIC: grown along the ***c axis***



Light Output and Decay Kinetics

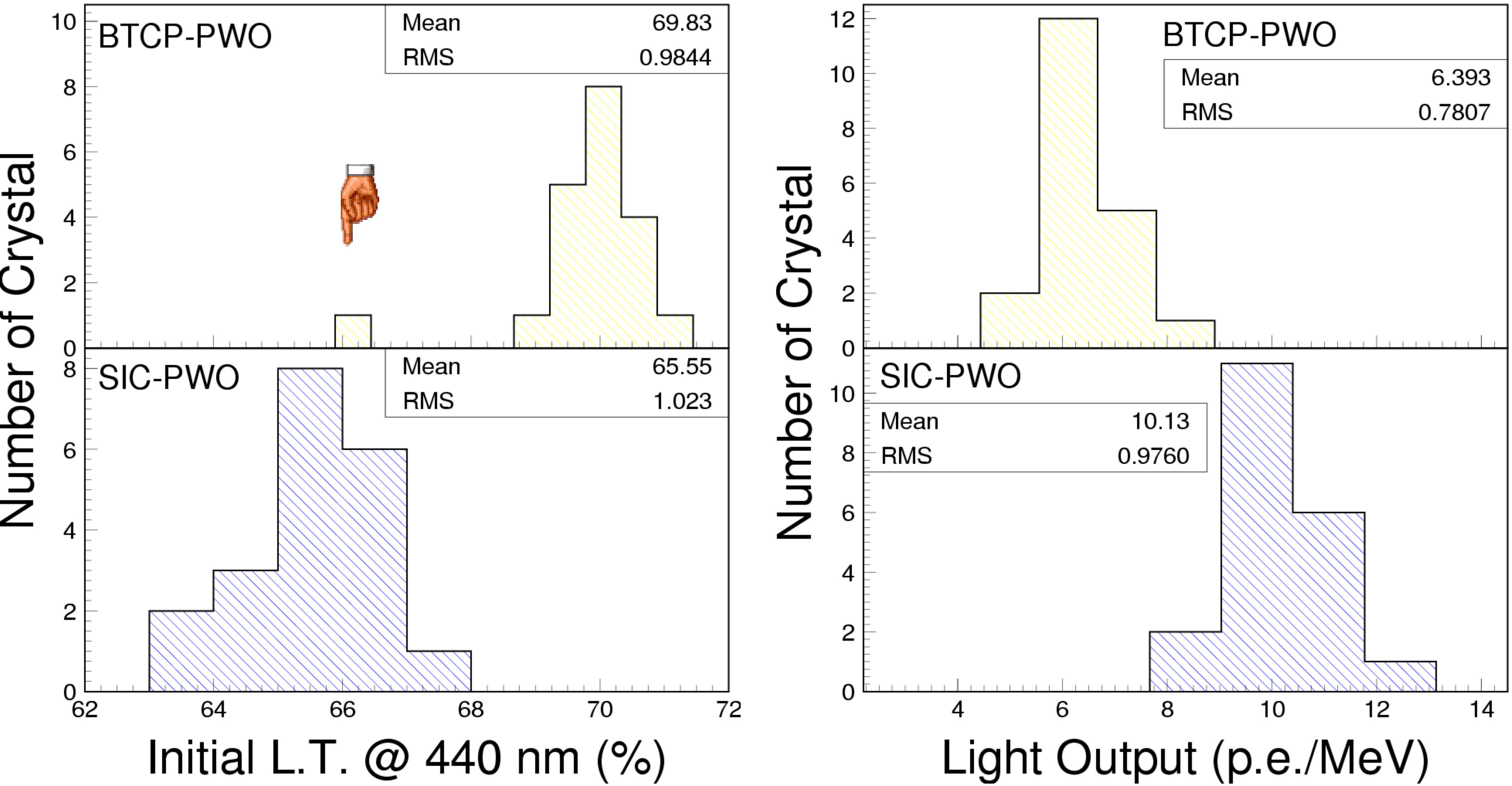
Both are fast, SIC samples have more light





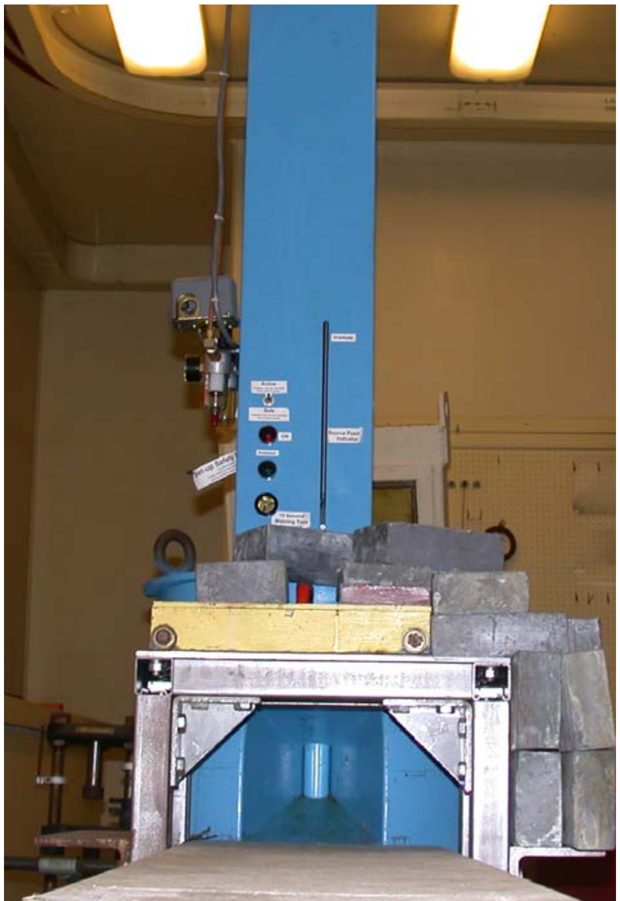
Comparison of L.T. and Light Yield

Vendor	ILT@440 nm (%)	ILO (p.e./MeV)	50 ns/1 us	100 ns/1 us
BTCP	69.8 (1.4%)	6.4 (12%)	81.8 (4.0%)	95.8 (1.6%)
SIC	65.6 (1.5%)	10.1 (9.6%)	83.9 (4.1%)	95.9 (1.9%)



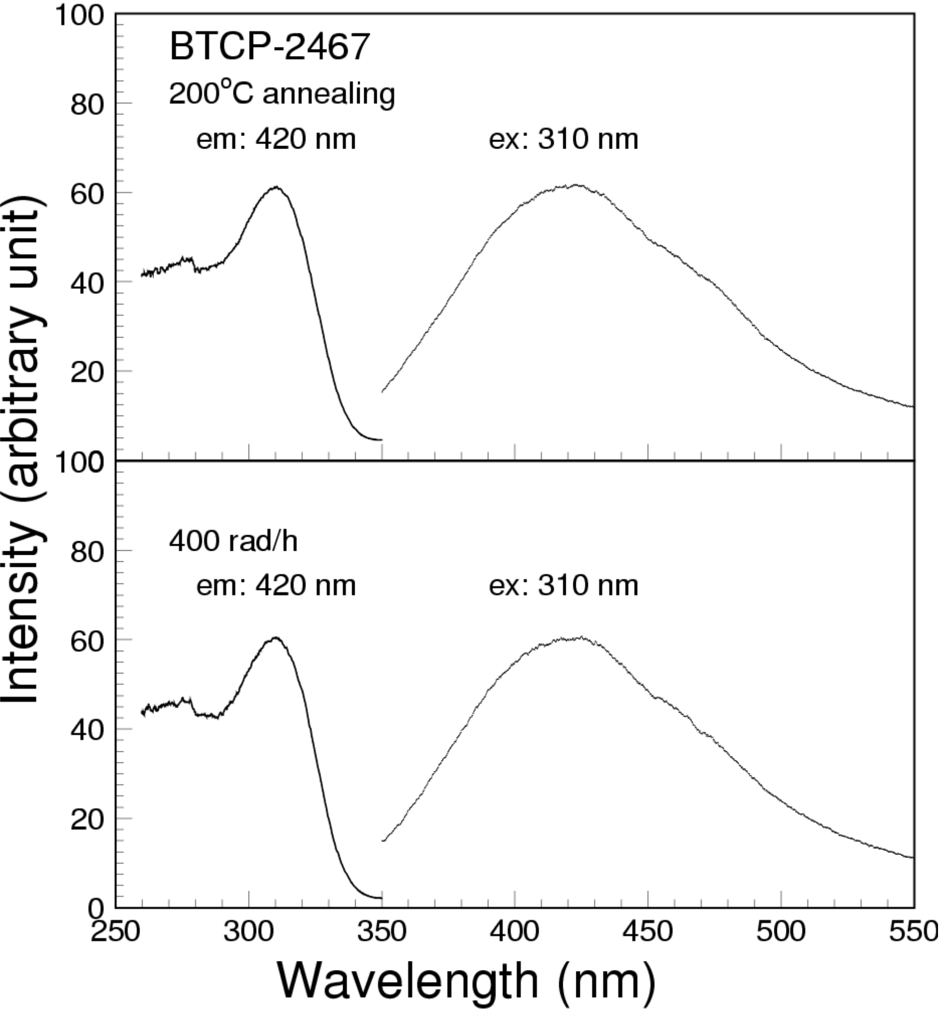
Caltech γ–ray Irradiation Facilities

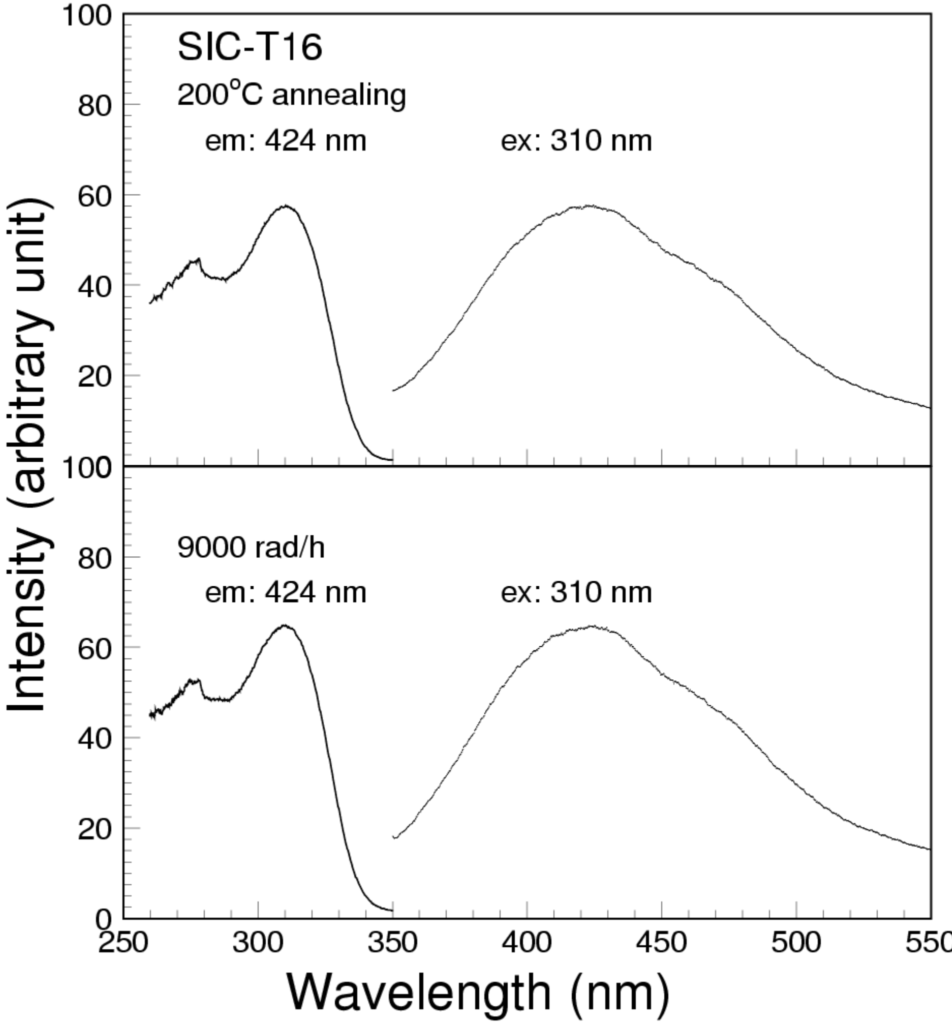
Open 50 curie Co-60: 15, 100 and 400 rad/h	Closed 2,000 curie Cs-137: 9k rad/h at center, up to 36k rad/h



Photoluminescence

No variation in either excitation or emission spectrum
No damage in scintillation mechanism

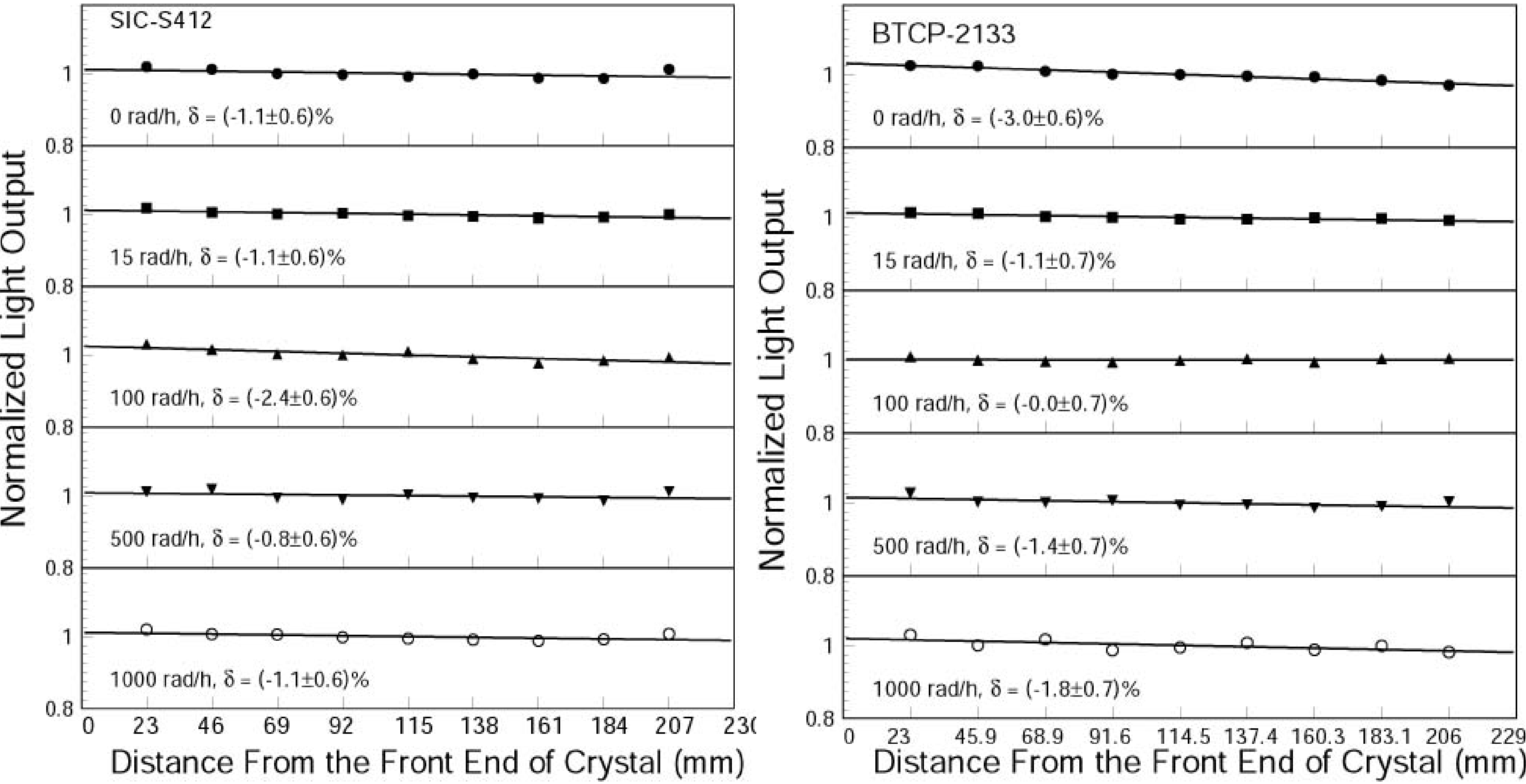




No Variation in Light Response Uniformity

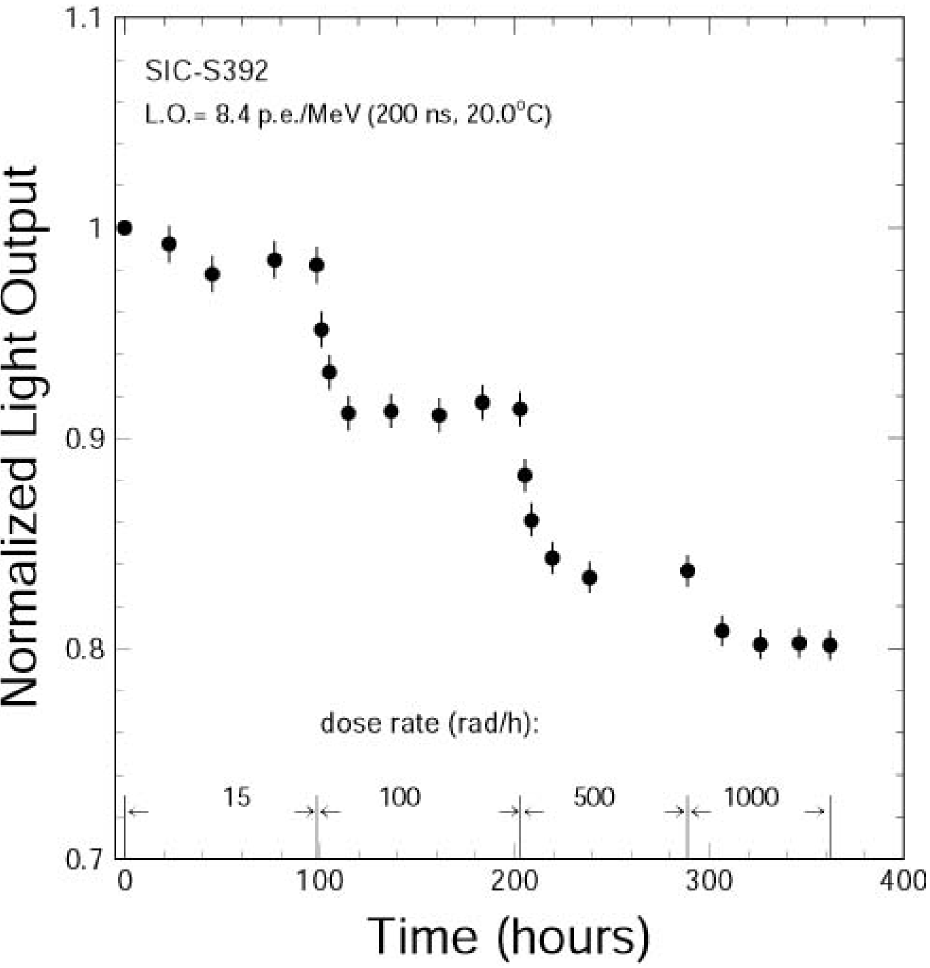
The response (y) along the axis was fit to a linear function

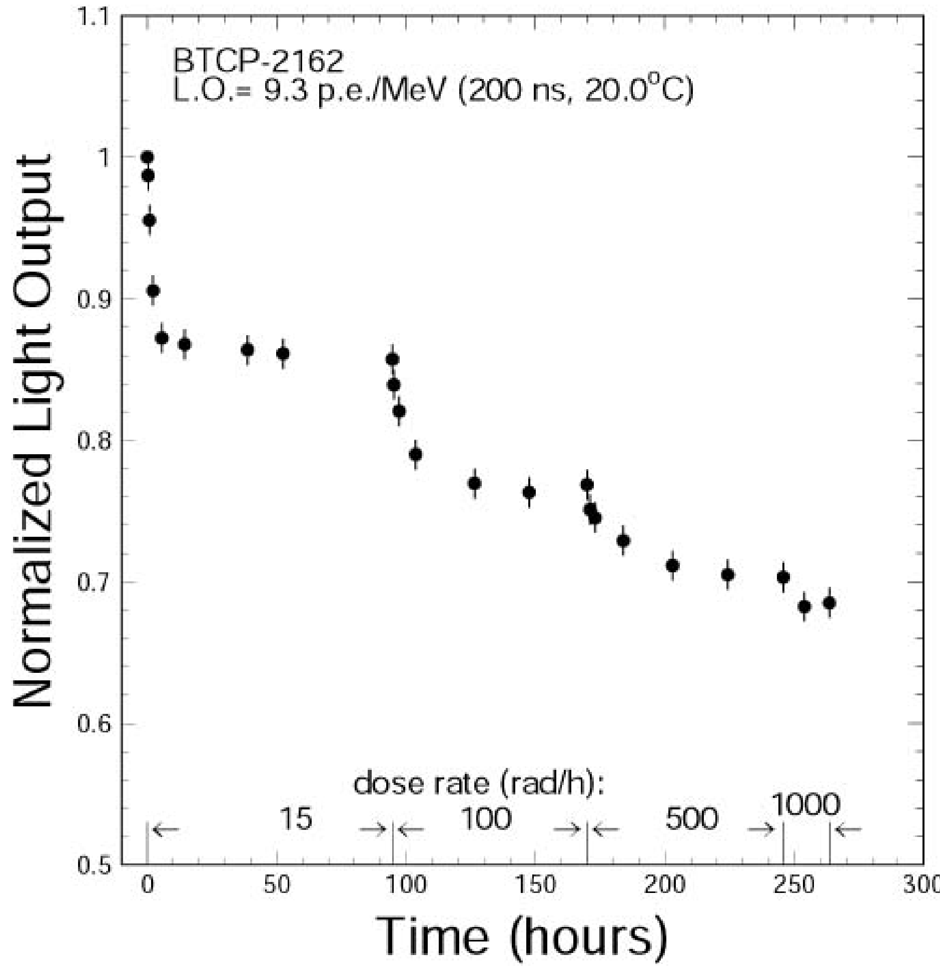
$$\frac{y}{y_{mid}} = 1 + \delta(x / x_{mid} - 1)$$



Light Output Degradation

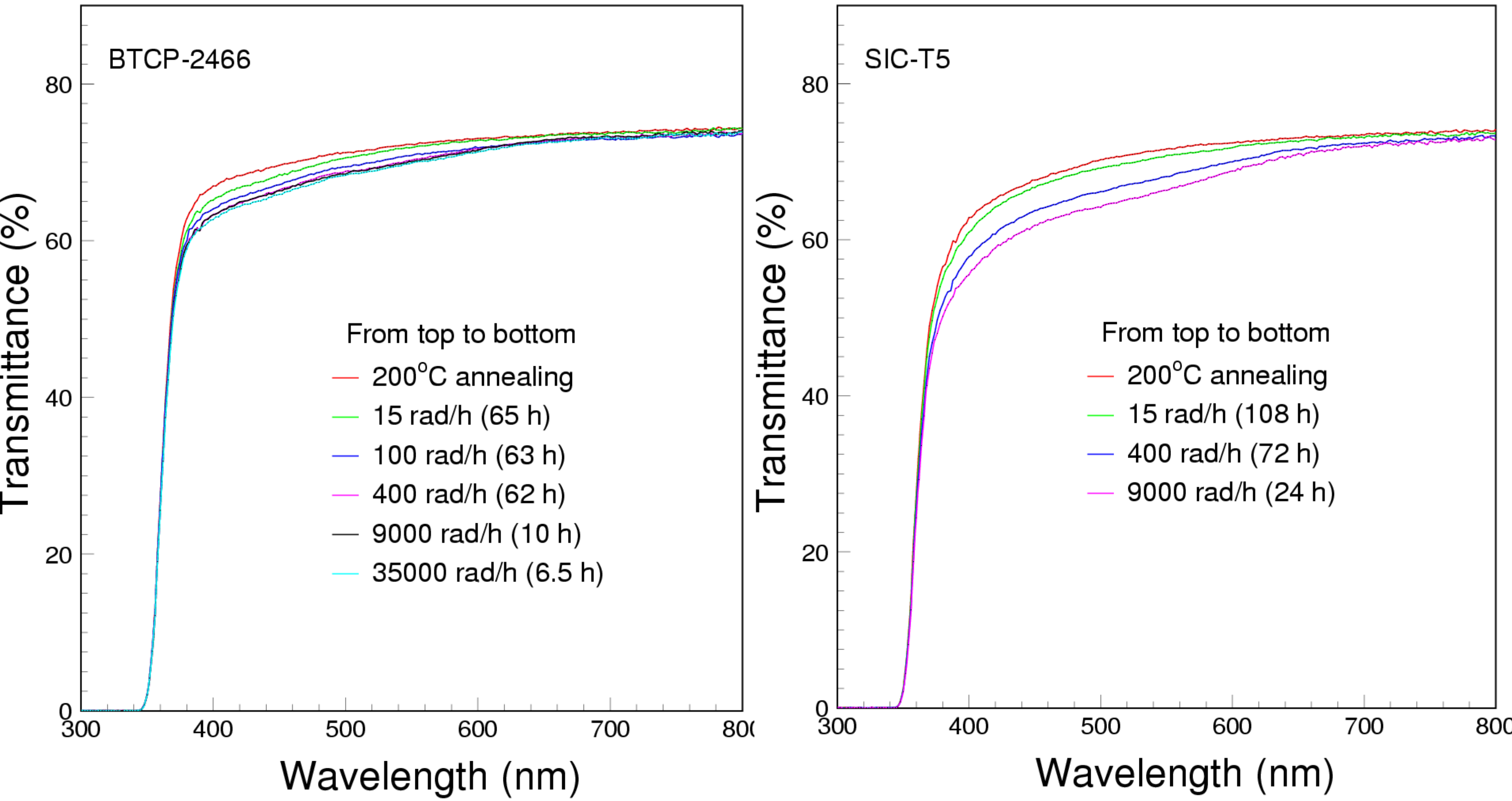
5-15% and 15-30% light output loss under 15 and 500 rad/h
Damage is dose rate dependent





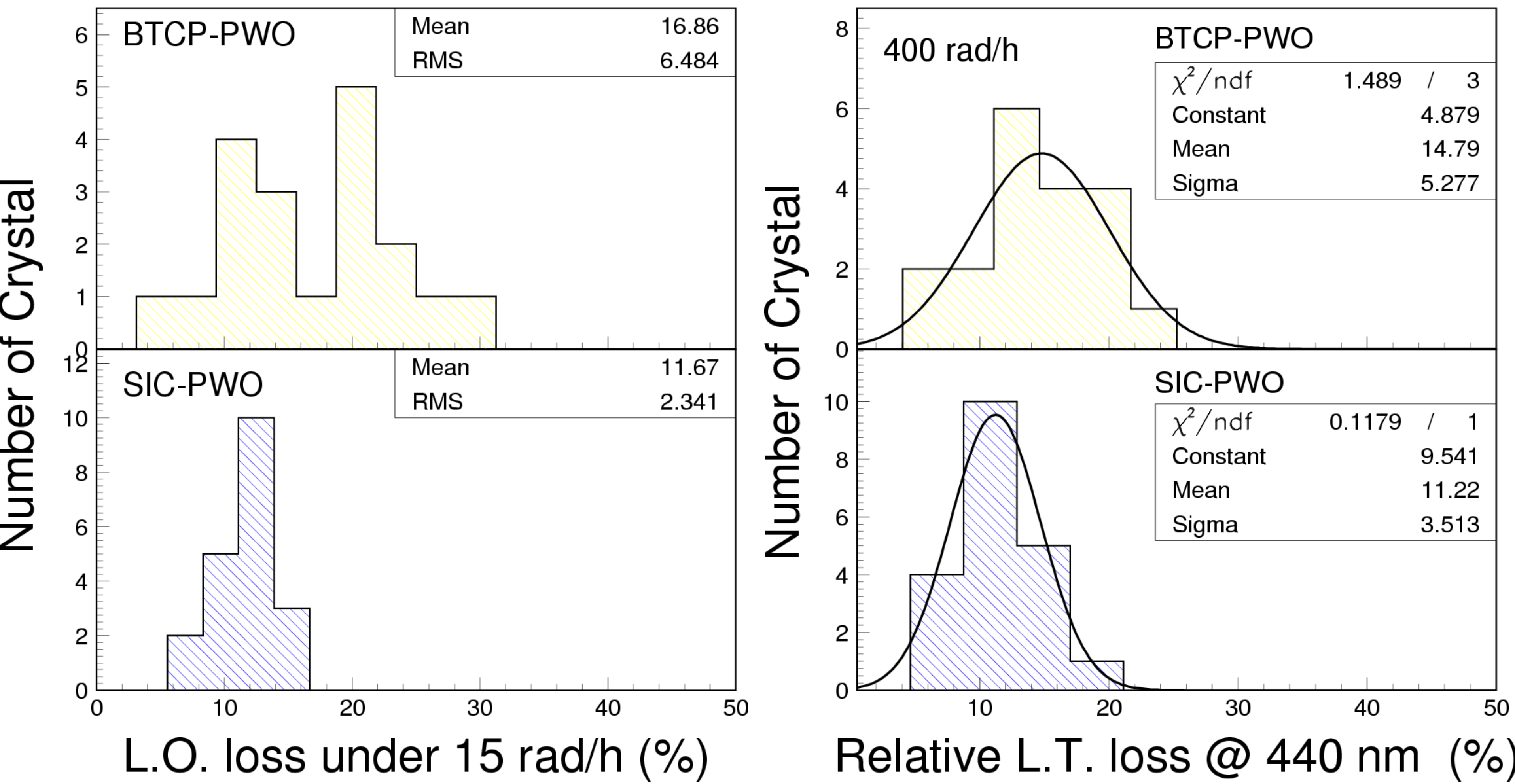
Damage in Longitudinal Transmittance

Radiation induced absorption caused by CC formation



Comparison of Radiation Damage

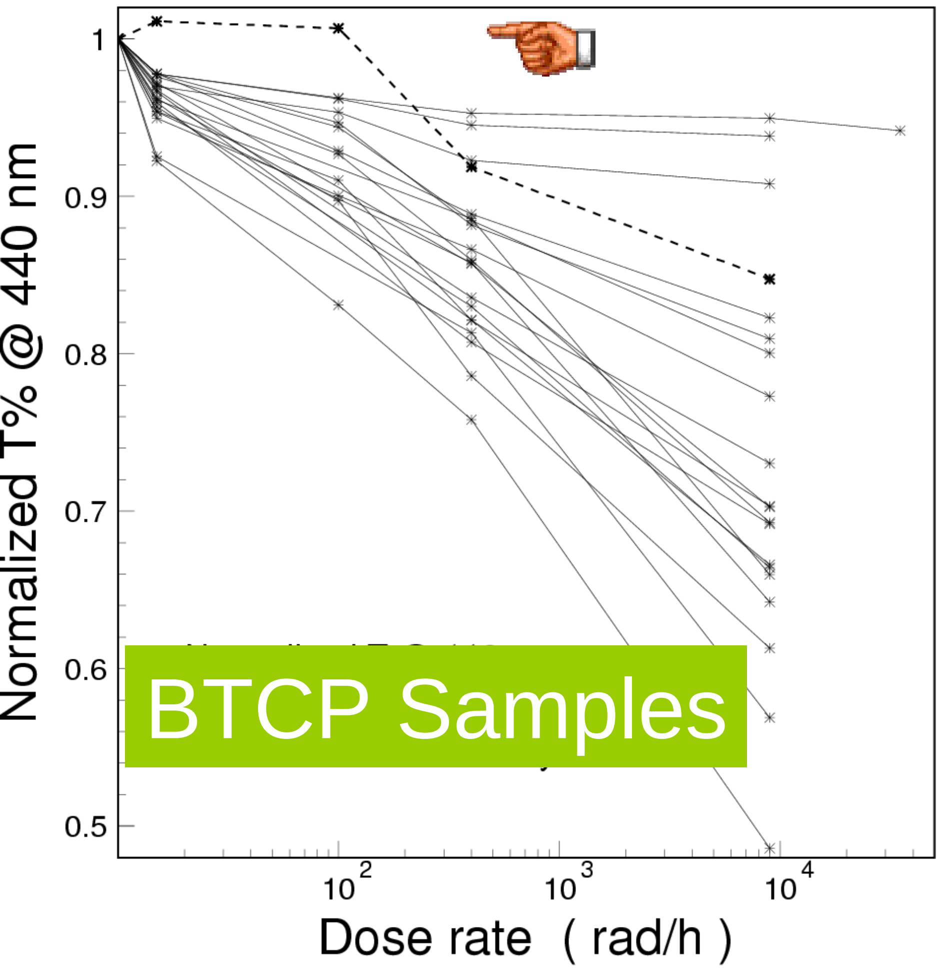
SIC samples seem more radiation hard

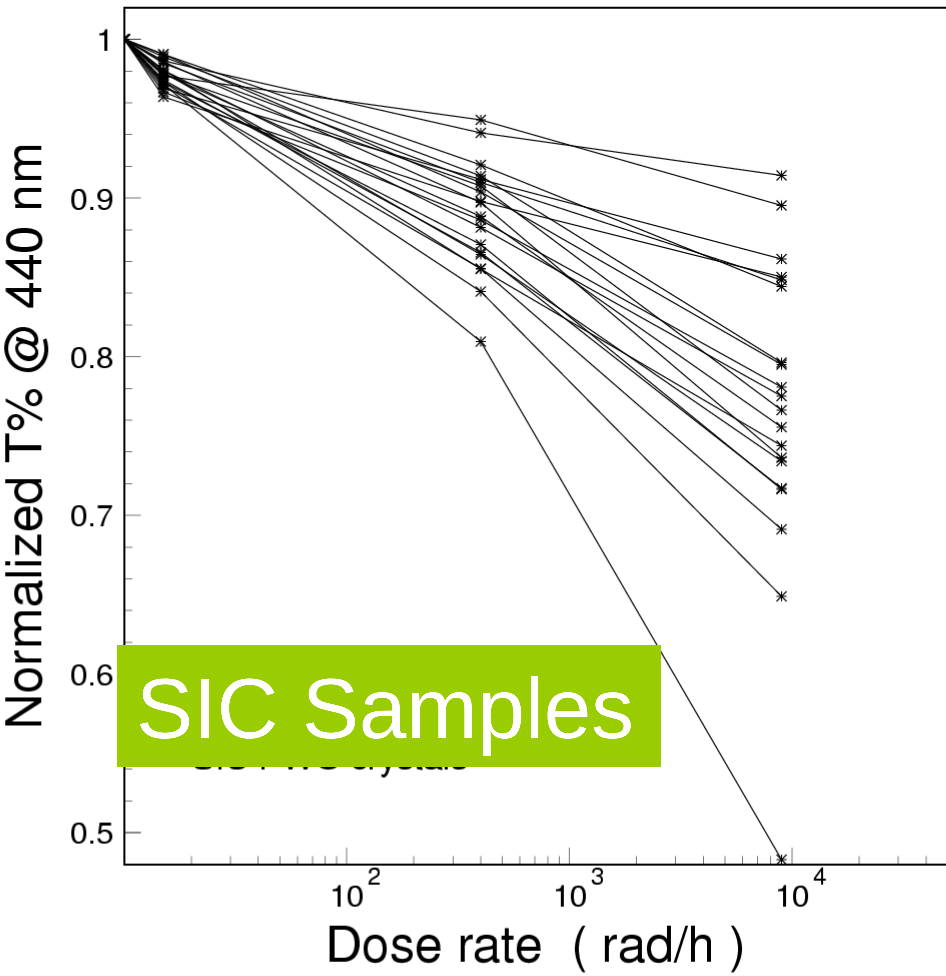


Comparison of Transmittance Loss

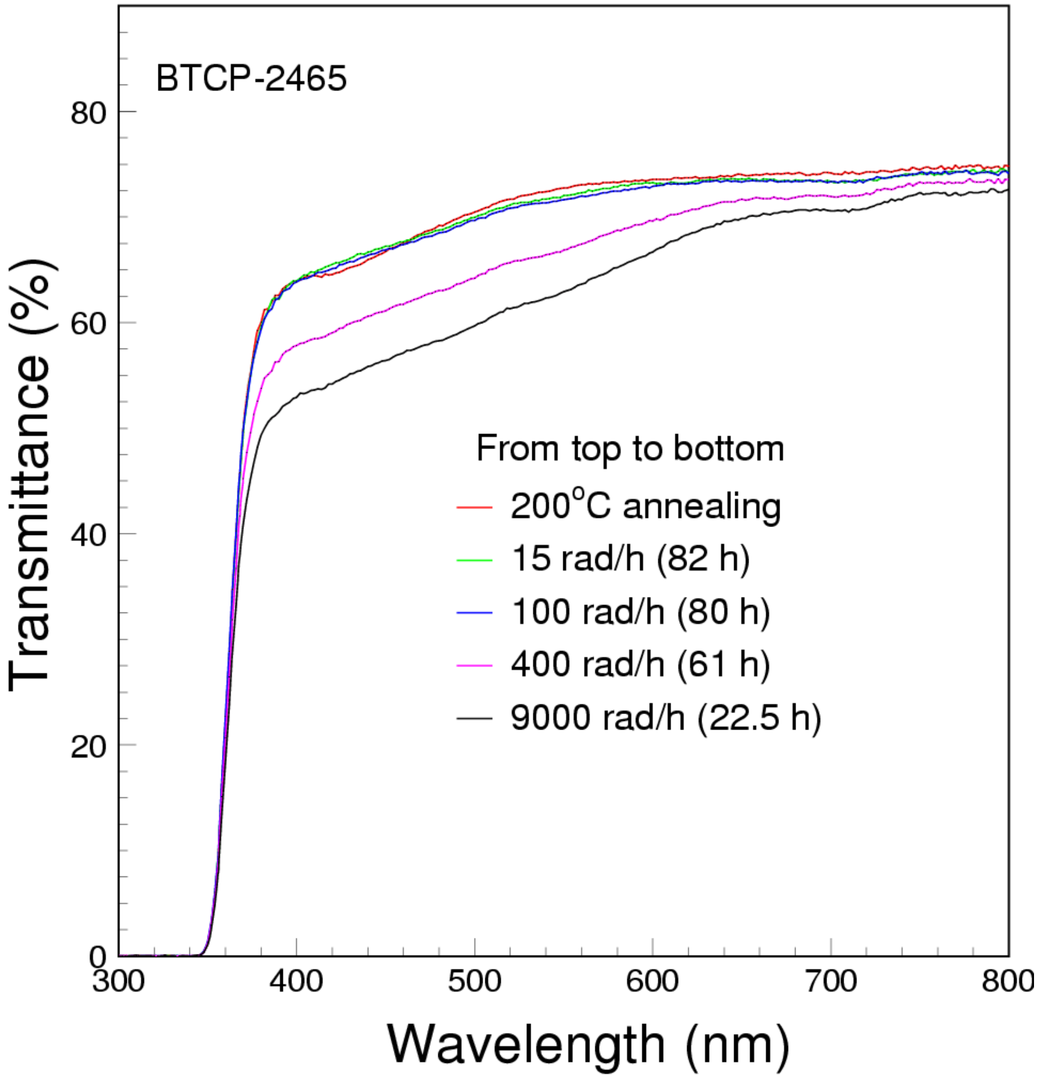
SIC samples less diverse: Bridgman technology

One BTCP sample shows LT increase under irradiation





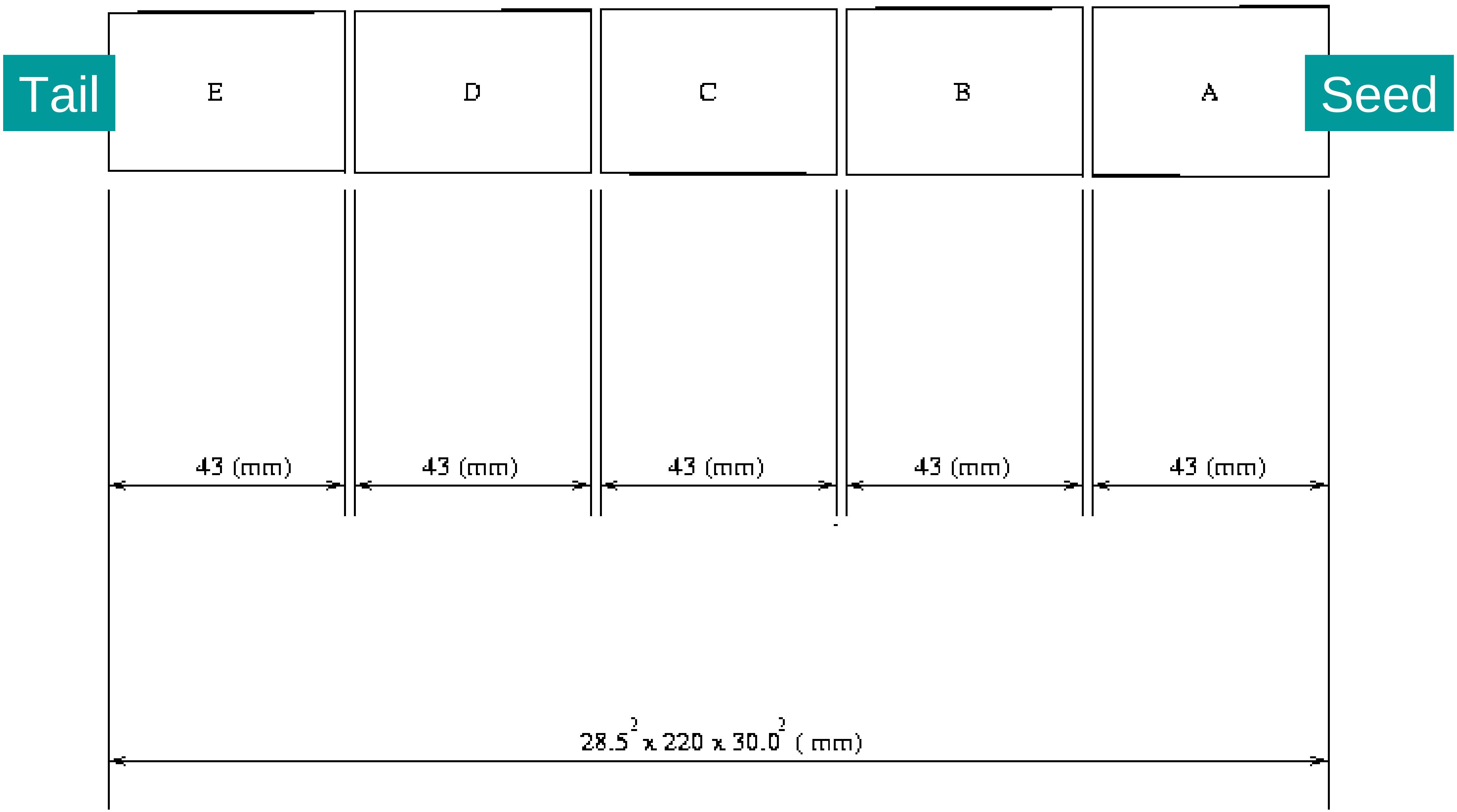
Type III Sample: Transmittance Loss



Type III sample: preexisting intrinsic color center at 420 nm after 200 degree annealing, causing difficulty for monitoring with 440 nm light

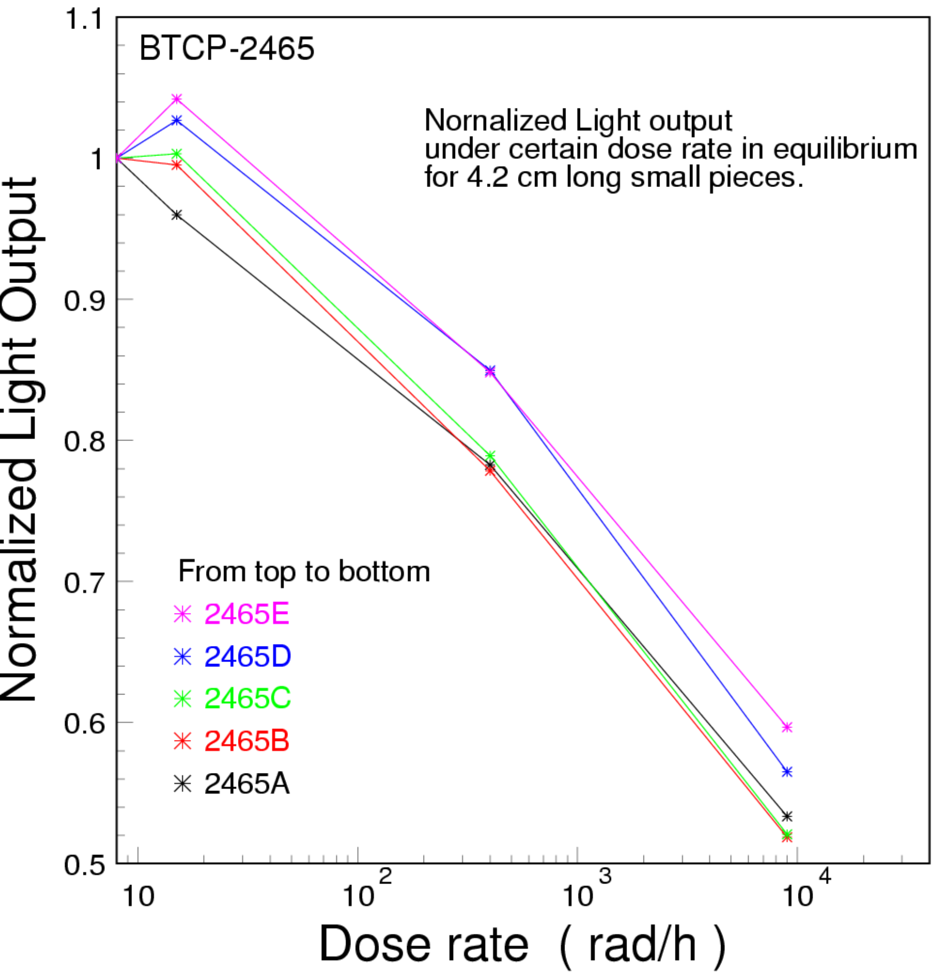
Investigation on BTCP Samples (I)

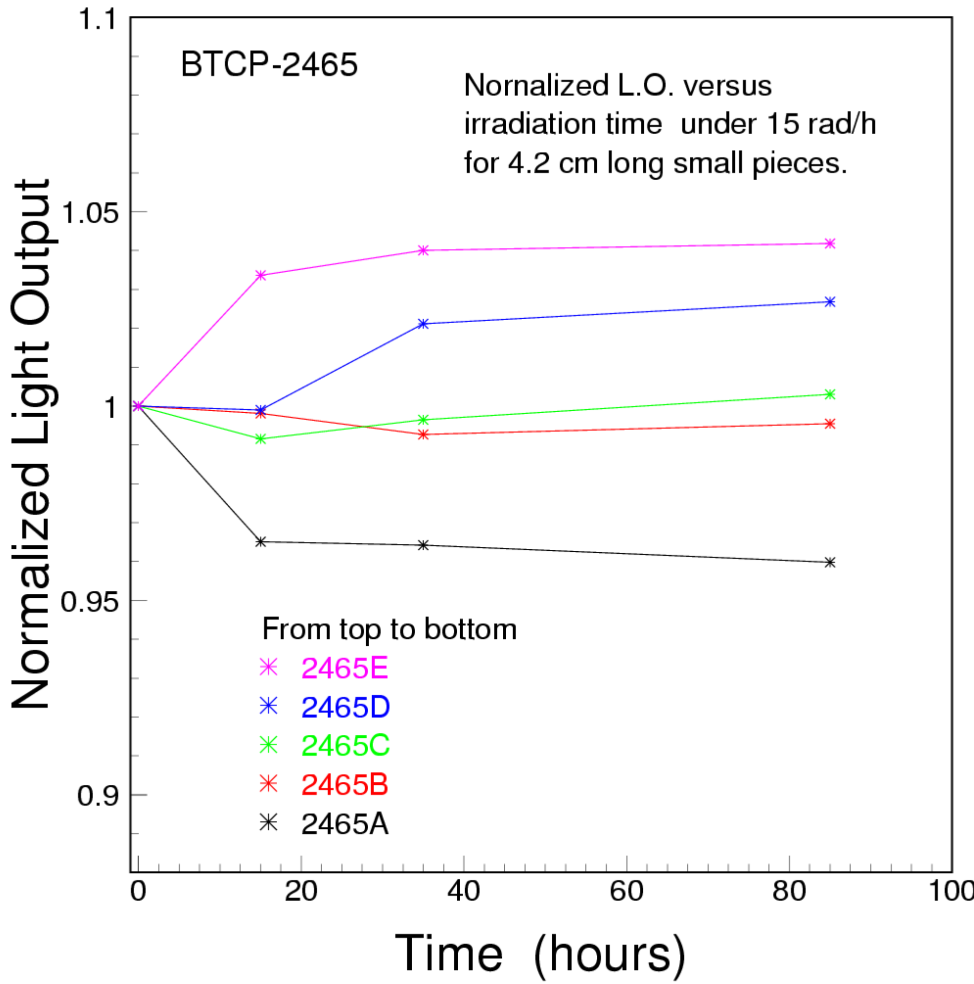
Three samples cut to 5 pieces: 4.3 cm each:
Type I: 2467, Type II: 2436, Type III: 2465



Investigation on BTCP Samples (II)

Anomaly is shown also at the Tail end (E and D)





Investigation on SIC Samples (I)

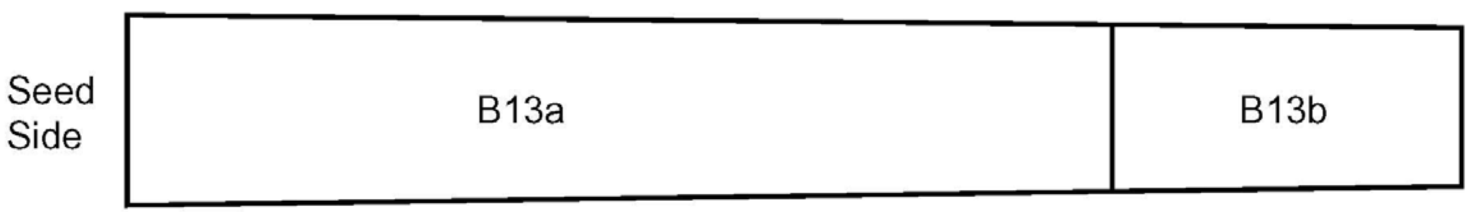
Two anomalous samples were cut to pieces

Crystal ID: NO.4-1-20 Dopant: Y/150 at ppm

The length of seed is 20.0 mm, thickness of 1, 2, 3, 4 is 5.0 mm.

Dimension of AB, CD, EF, GH and IJ is: 25.0 x 25.0 x 44.3 mm^3.

Crystal ID: B13 Dopant: Y/150 at ppm

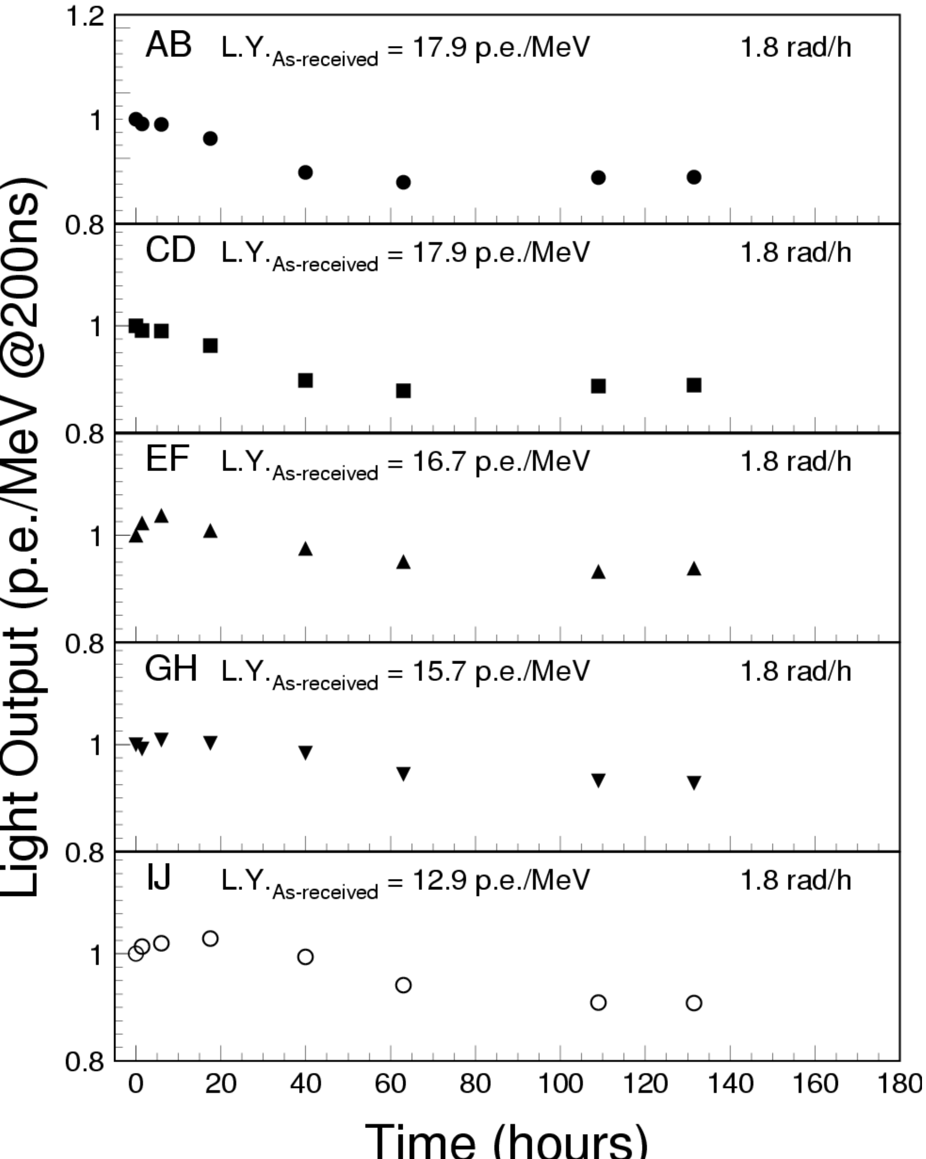


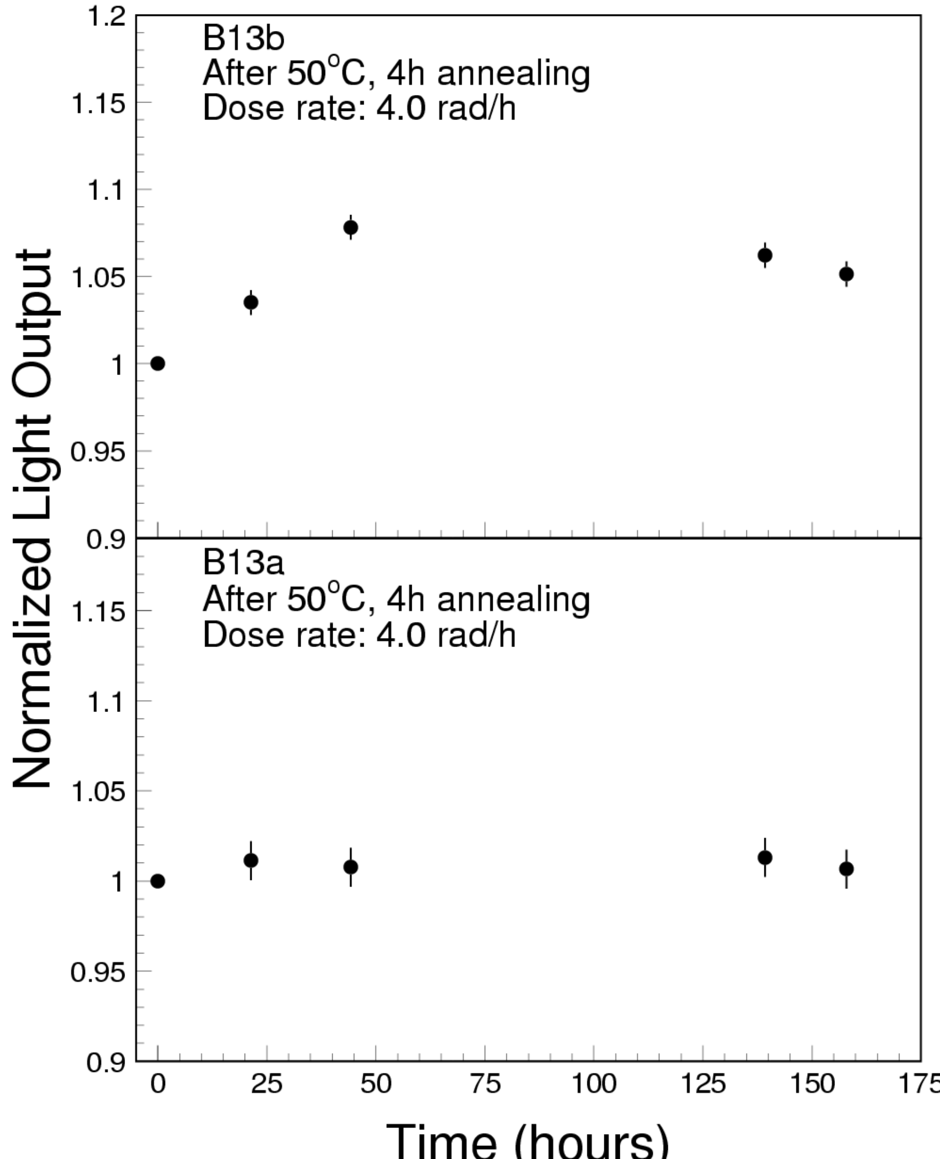
Dimension of B13a: 22.0 x 22.0 x 177.0 x 25.0 x 25.0 mm^3.

Dimension of B13b: 22.0 x 22.0 x 50.0 x 23.0 x 23.0 mm^3.

Investigation on SIC Samples (II)

Anomaly was found at the tail end: impurity related?





Trace Analysis on SIC Samples

GDMS on SIC PWO(Y) Samples (ppmw)

by Shiva Technology West (November, 1999)

		4-1-20-2/3		4-1-20-AB/EF/IJ	
Element	Seed/Tail 1	Seed/Tai 2	Seed/Tail 3	Seed/Middle/Tail 4	Tail 5
Na	0.2/0.8	0.2/2.3	0.4/0.8	0.2/0.8/1.9	0.8
Si	0.5/0.2	0.7/1.3	0.5/1.2	0.5/0.4/0.1	0.05
K	0.3/1.8	0.4/2.9	0.7/1.2	0.5/0.9/2.0	1.3
Ca	0.9/<0.05	0.6/0.08	0.12/0.15	0.8/0.6/0.2	0.15
Cu	0.04/0.2	0.04/0.4	0.3/0.35	0.08/0.1/0.54	0.23
As	0.15/0.35	0.1/0.6	0.5/0.5	0.14/0.16/0.6	0.54
Y	40/45	40/50	30/35	40/40/60	50
Nb	<0.05	<0.05	<0.05	<0.05	<0.05
Mo	0.3/0.55	0.3/0.9	0.6/0.8	0.2/0.5/0.8	1.0
Sb	<0.05	<0.05	<0.05	<0.05	<0.05
Ba	0.1/0.1	0.1/0.1	<0.05/0.06	0.3/0.15/0.07	0.1
La	<0.01	<0.01	<0.01	<0.01	<0.01
Eu	<0.05	<0.05	<0.05	<0.05	<0.05
TC†	3.8/2.1	4.9/4.6	4.4/3.4	5.3/4.0/2.5	4.3

†: Total contamination, excluding Y.

Impurity segregation:

Na, K, Cu, As, Mo: <1;

Ca, Ba: >1;

Y: slightly less, but close to 1.

SIC samples are doped with Y only.

Trace Analysis on BTCP Samples

GDMS on BTCP PWO(Y/Nb/La) Samples (ppmw)

by Shiva Technology (November, 2003)

Element	2467 Seed/Tail	2436 Seed/Tail	2465 Seed/Middle/Tail
Na	0.95/0.98	2.5/5.2	3.8/3.4/5.2
Si	<0.05	<0.05	<0.05
K	0.36/0.58	0.45/0.90	0.71/0.56/1.6
Ca	2.4/1.8	1.3/0.9	1.7/1.3/1.2
Cu	<0.05	<0.05	<0.05
As	<0.05	<0.05	<0.05
Y	71/74	94/120	98/83/100
Nb	0.06/0.11	0.07/<0.05	<0.05/0.27/0.26
Mo	0.2/0.23	0.33/0.38	0.37/0.37/0.41
Sb	<0.05	<0.05	<0.05
Ba	1.7/1.5	1.5/1.2	5.3/1.7/2.5
La	250/140	200/130	280/160/150
Eu	0.6/0.5	0.8/1.4	1.1/0.53/0.3
TC†	6.4/5.7	7.0/10	13/7.9/11

†: Total contamination, excluding Y, Nb and La.

Impurity segregation:

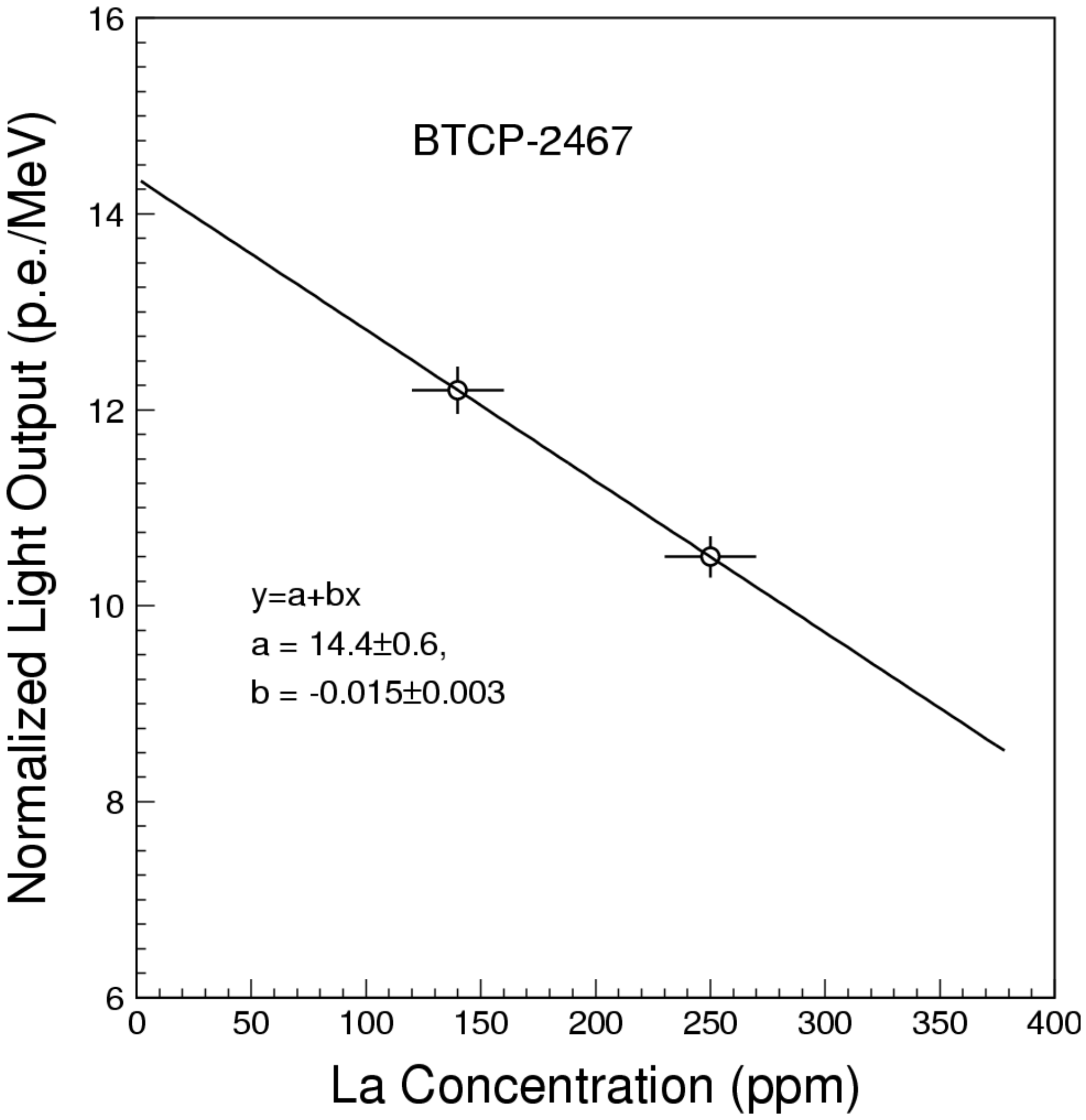
Na, K, Nb, Mo: <1;

Ca, Ba, La: >1;

Y: slightly less, but close to 1.

BTCP PWO is triple doped with Y/Nb/La!!!

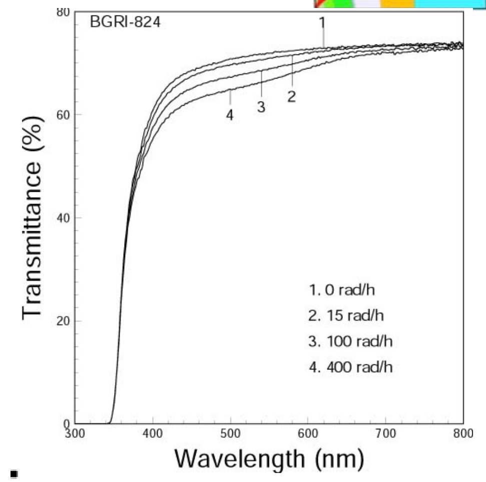
Light Output & La Concentration



- The anti-correlation between the light output of PWO and its La concentration, may explain the low light yield of BTCP PWO.
- Further study is under way to clarify this issue.

Radiation Induced Color Center Density

Nucl. Instr. And Meth. A332 (1993) 442



RIAC or radiation induced color center density can be calculated precisely by using longitudinal transmittance (0.2%)

$$RIAC \ or \ D_{Color-Center} = 1/LAL;$$

$$LAL = \frac{\ell}{\ln\{[T(1-T_s)^2]/[\sqrt{4T_s^4 + T^2(1-T_s^2)^2} - 2T_s^2]\}}$$

where T is transmittance measured along crystal length ℓ and T_s is the theoritical transmittance without internal absorption:

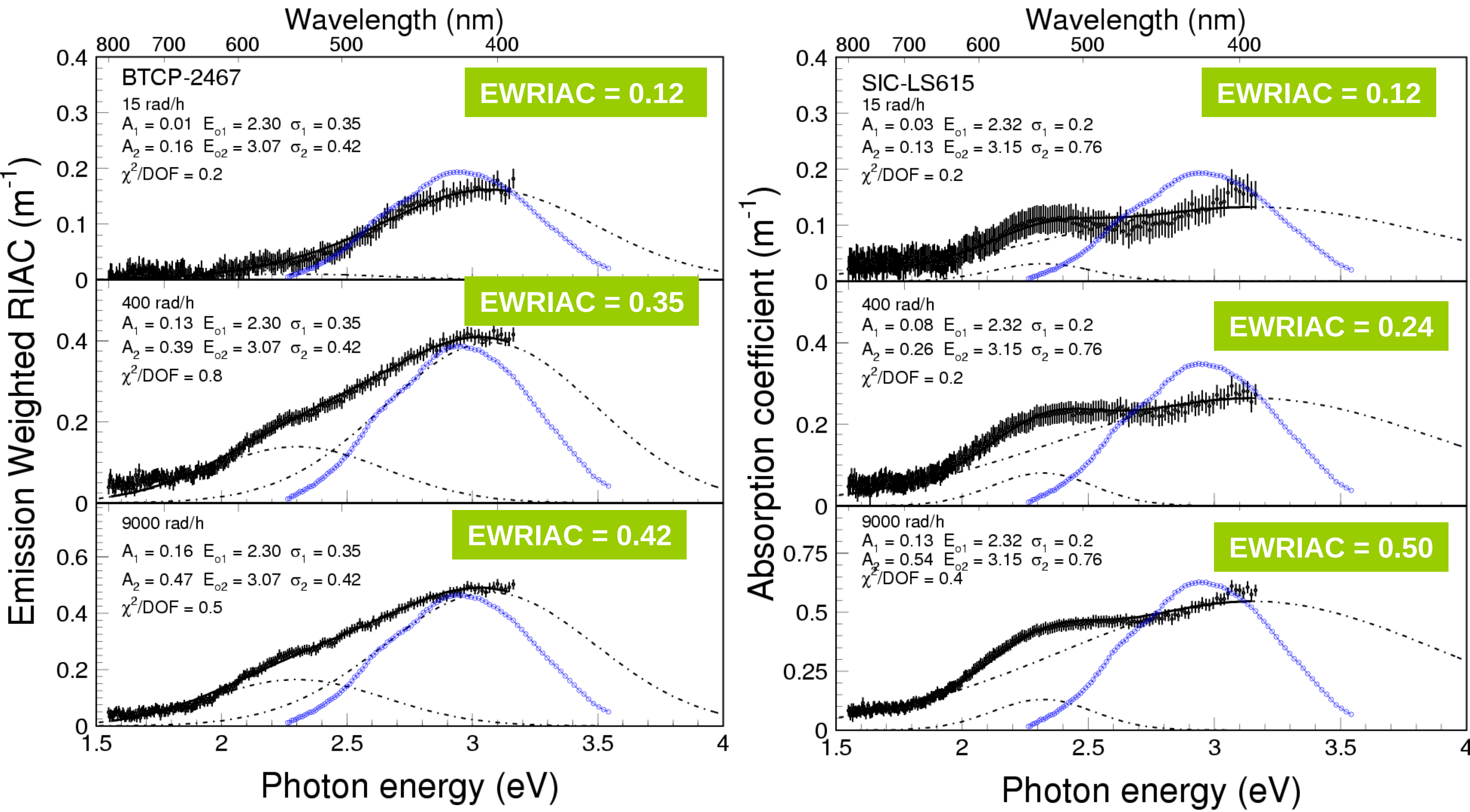
$T_s = (1-R)^2 + R^2(1-R)^2 + ... = (1-R)/(1+R)$, with

$R = \frac{(n_{crystal} - n_{air})^2}{(n_{crystal} + n_{air})^2}$.

Emission Weighted RIAC

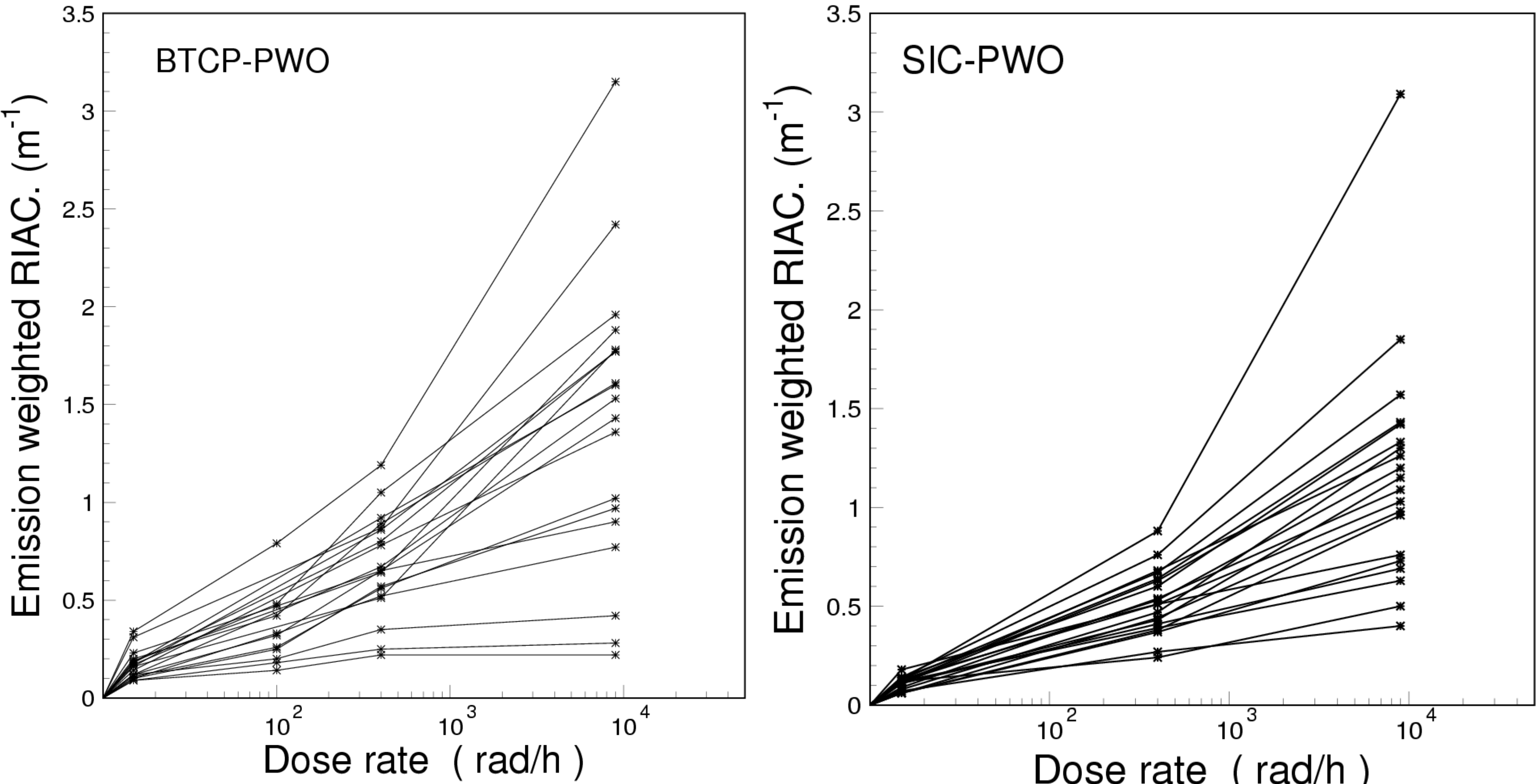
$$EWRIAC = \frac{\int Riac(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda}$$

a good measure of rad. damage



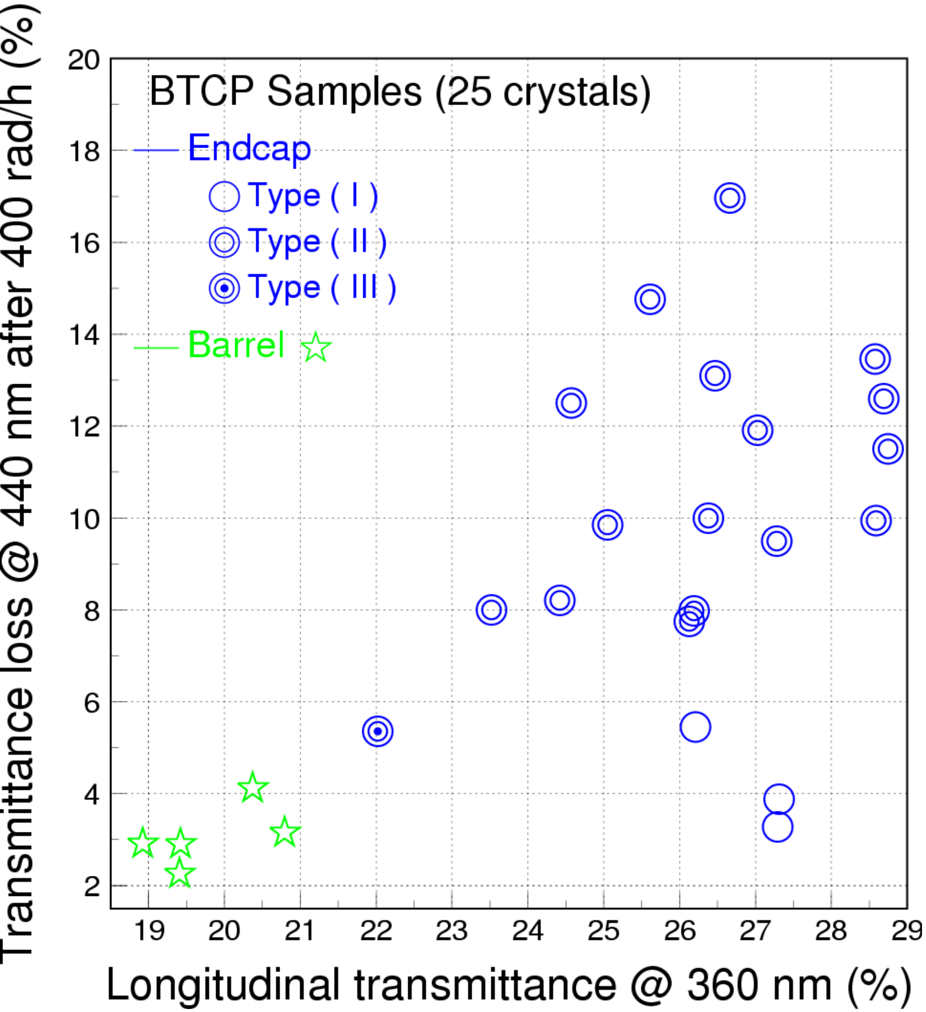
EWRIAC (1/m) and Normalized r.m.s

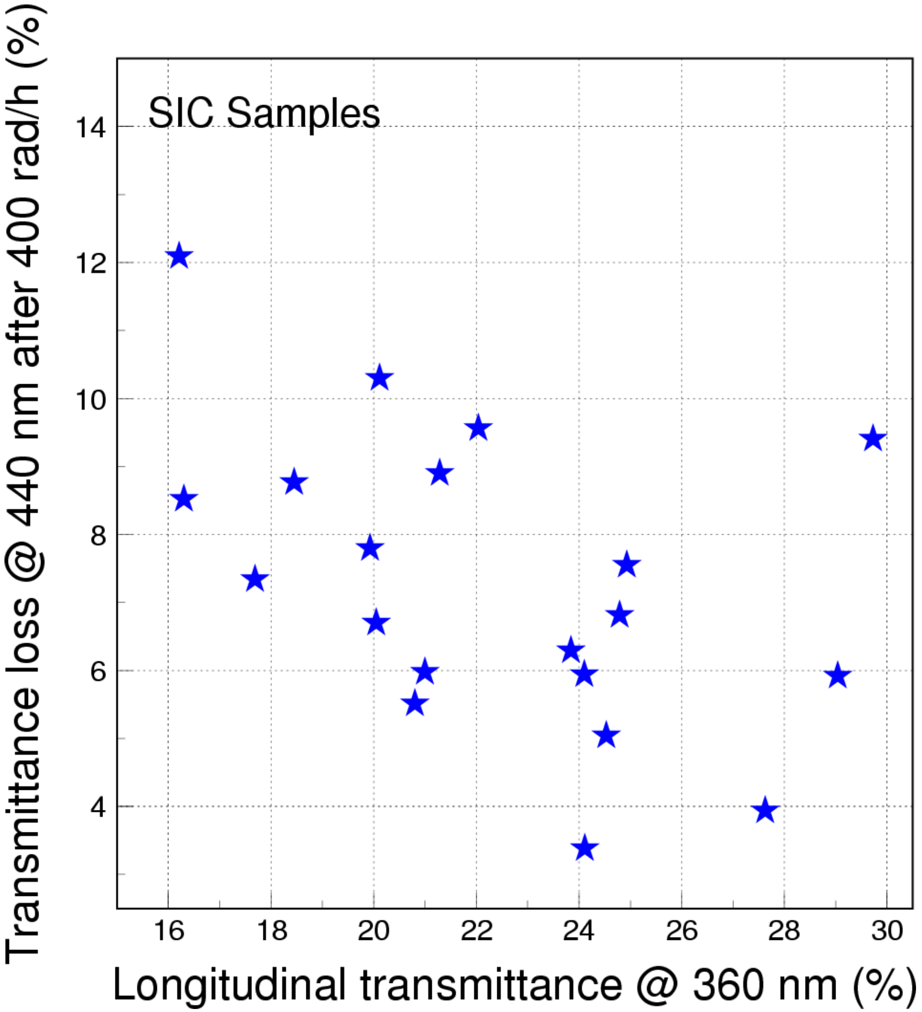
Vendor	15 rad/h	400 rad/h	9.000 rad/h
BTCP	0.16 (45%)	0.69 (37%)	1.43 (50%)
SIC	0.10 (33%)	0.51 (32%)	1.16 (48%)



L. T. Loss versus Initial L.T. @ 360 nm

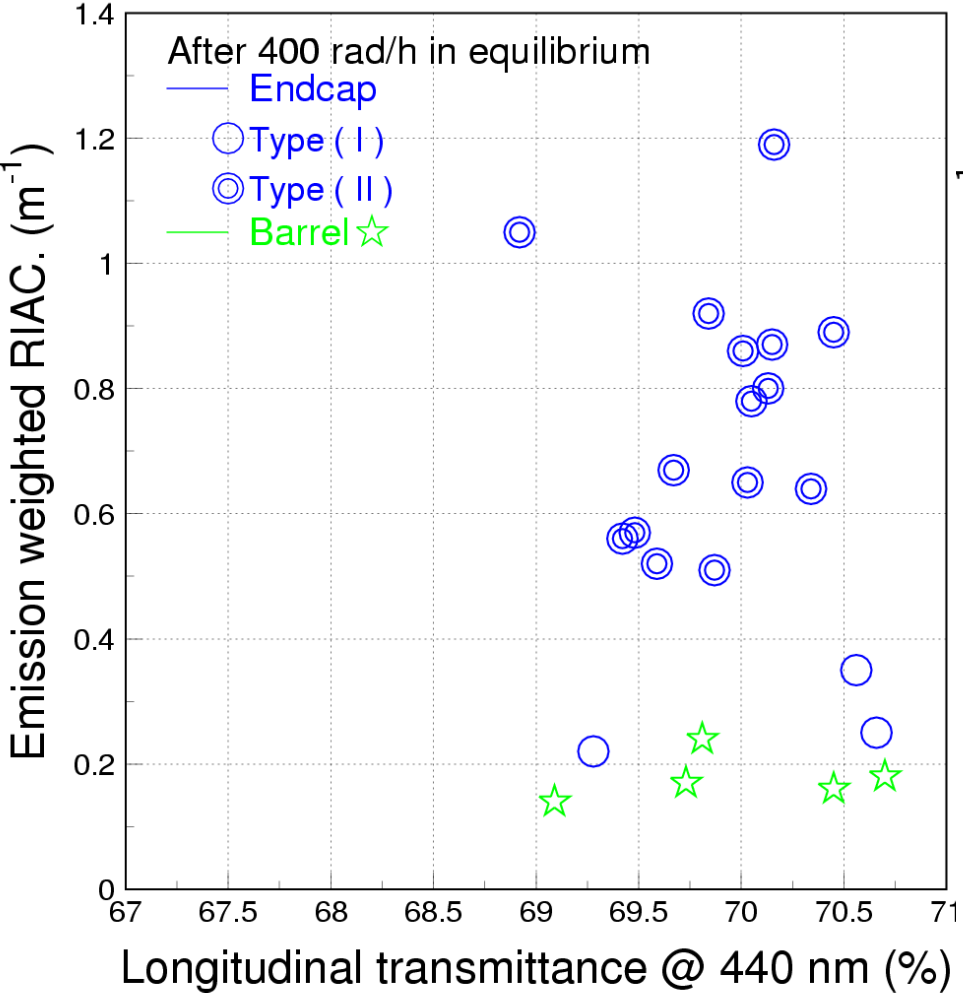
No correlation

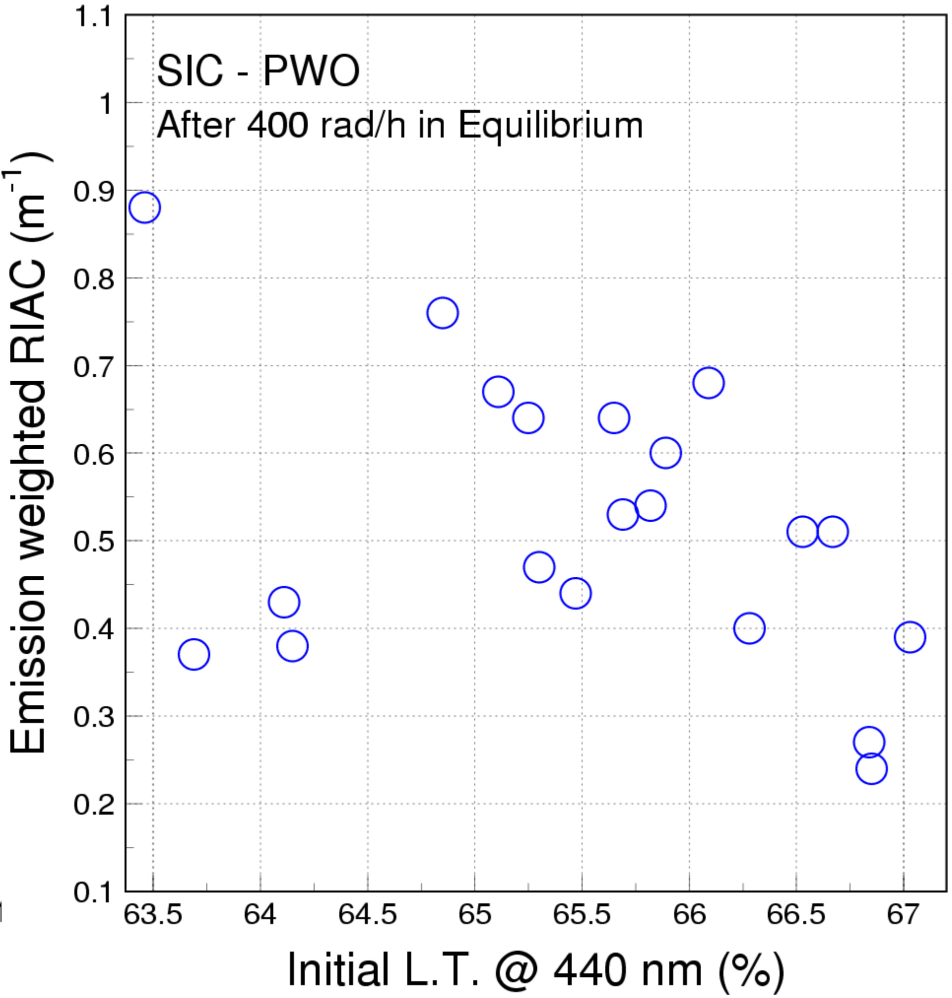




EWRIAC versus Initial L.T. @ 440 nm

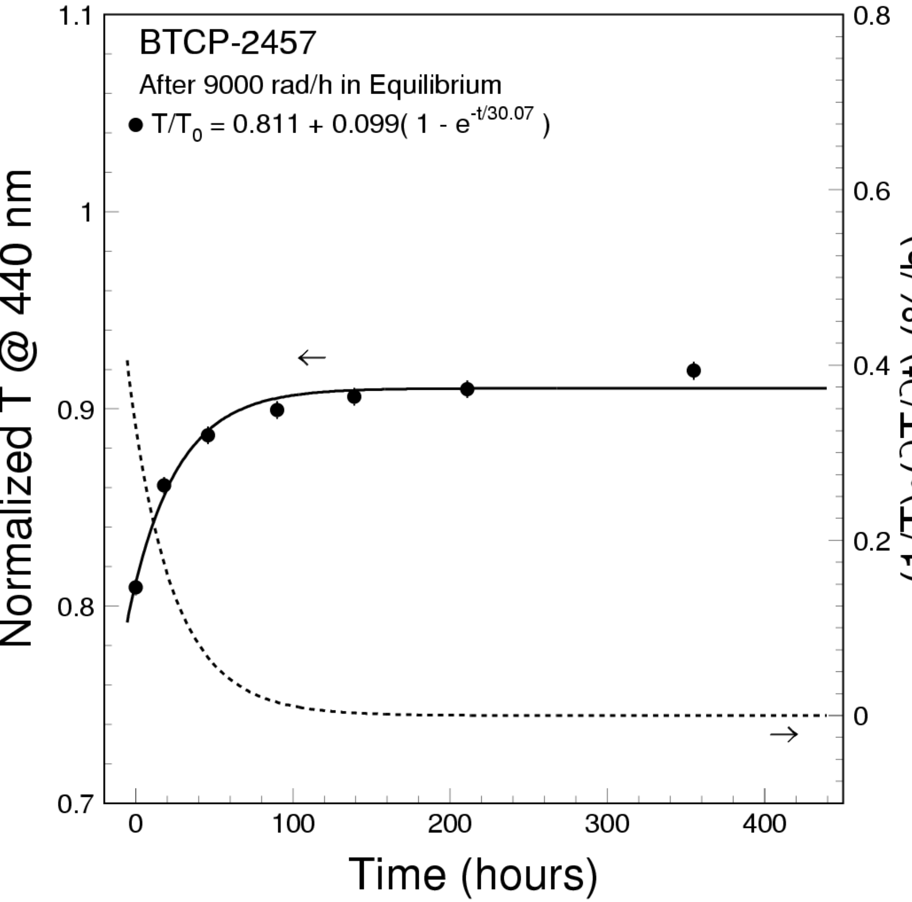
No correlation

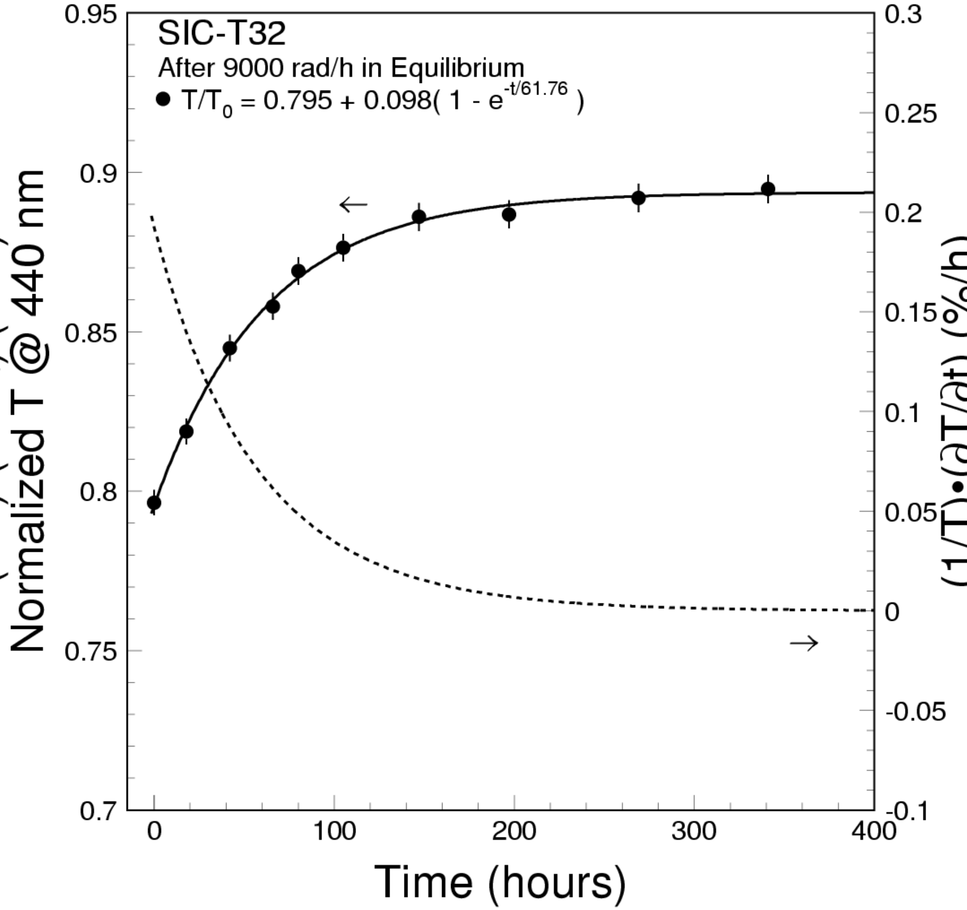




Recovery Speed and Time Constant

Recovery at 18ºC in 160 days: two time constants
Short recovery: BTCP: 36.0 h (27%), SIC: 43.6 h (33%)



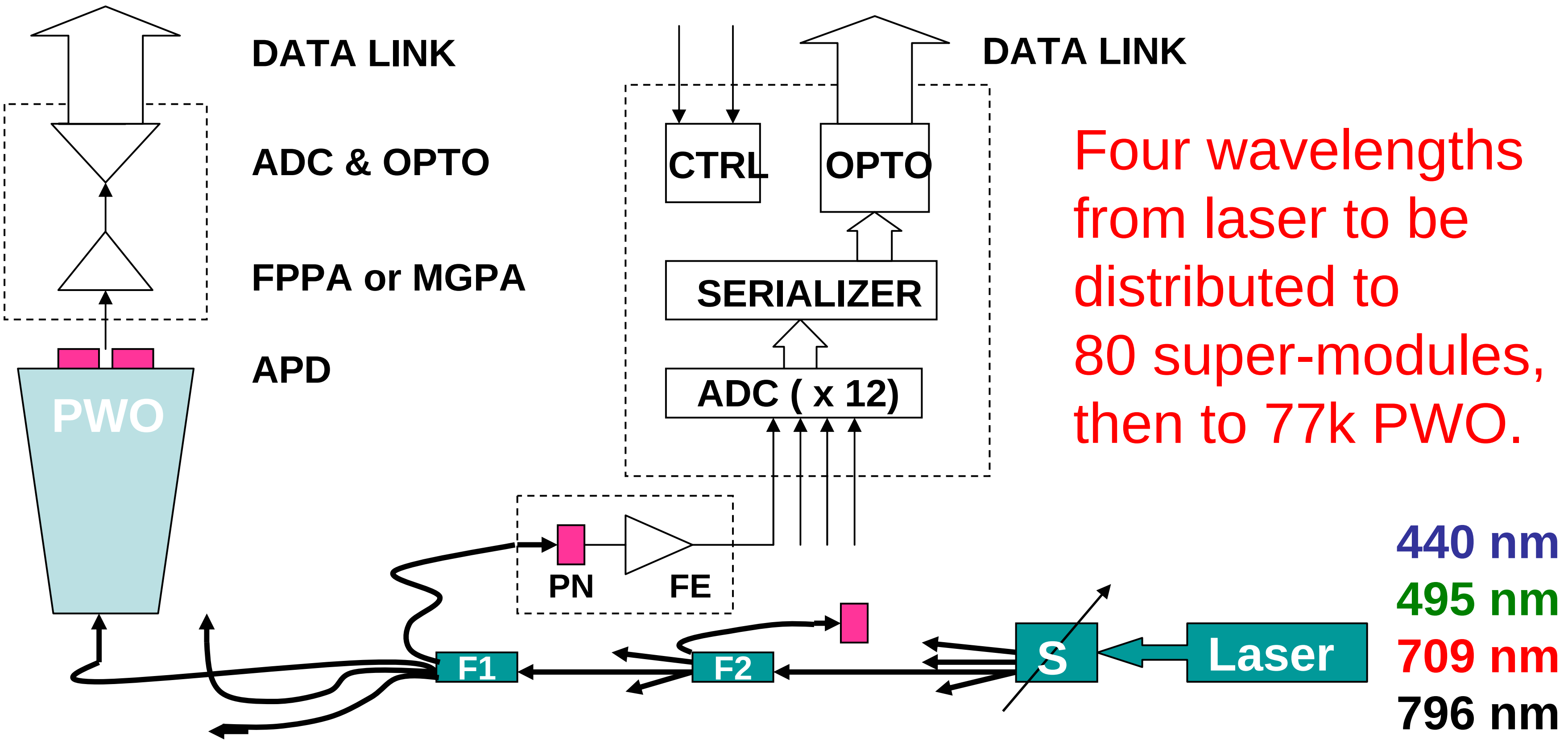


Light Monitoring System

Initial calibration on test beam (as much crystals as possible)

Physics calibration *In situ:* e^+e^- pair (resonance) and e (E/p)

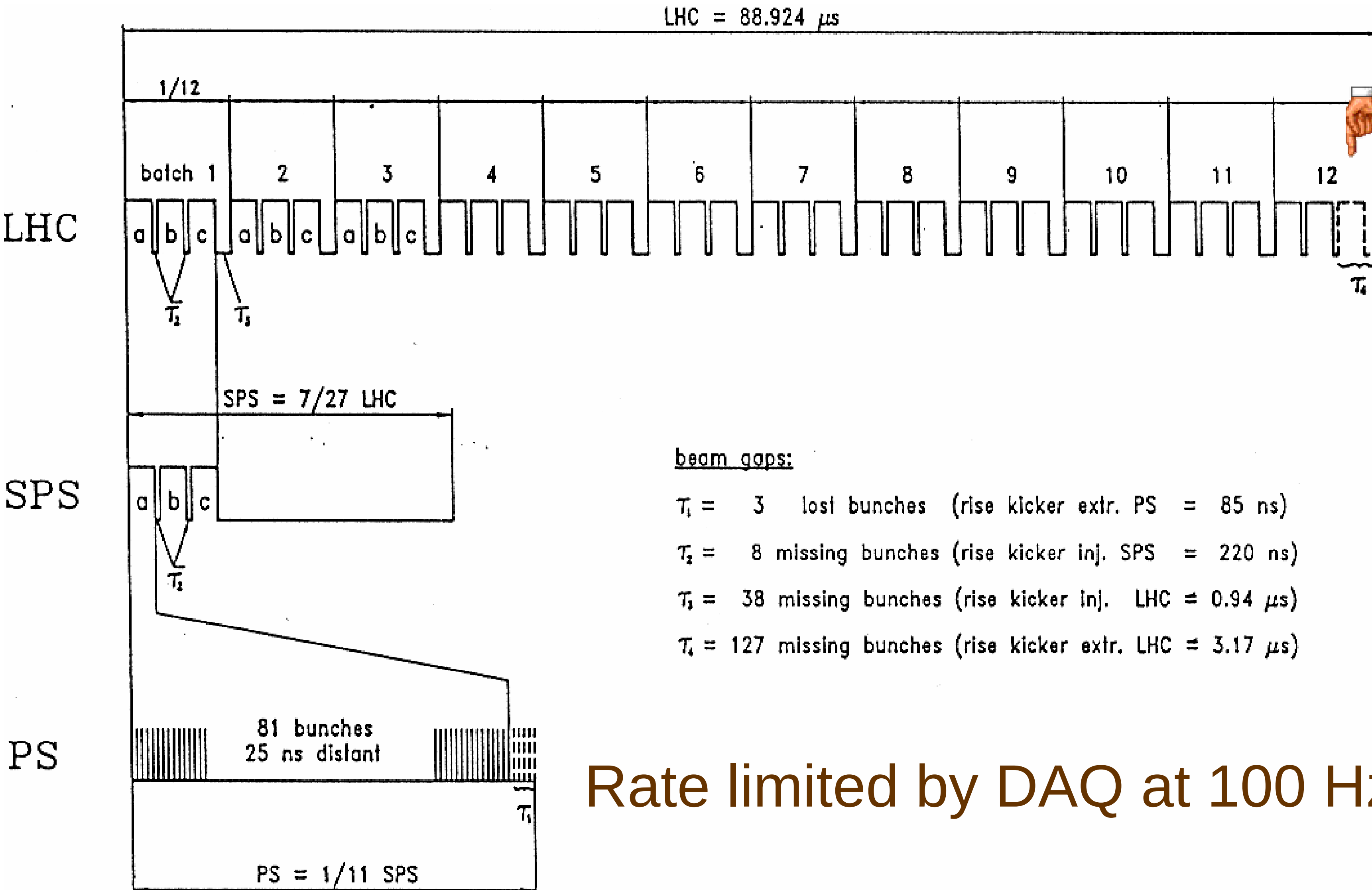
Monitoring crystal evolution by light injection system



Four wavelengths from laser to be distributed to 80 super-modules, then to 77k PWO.

LHC Beam Structure

Continuous monitoring during data taking

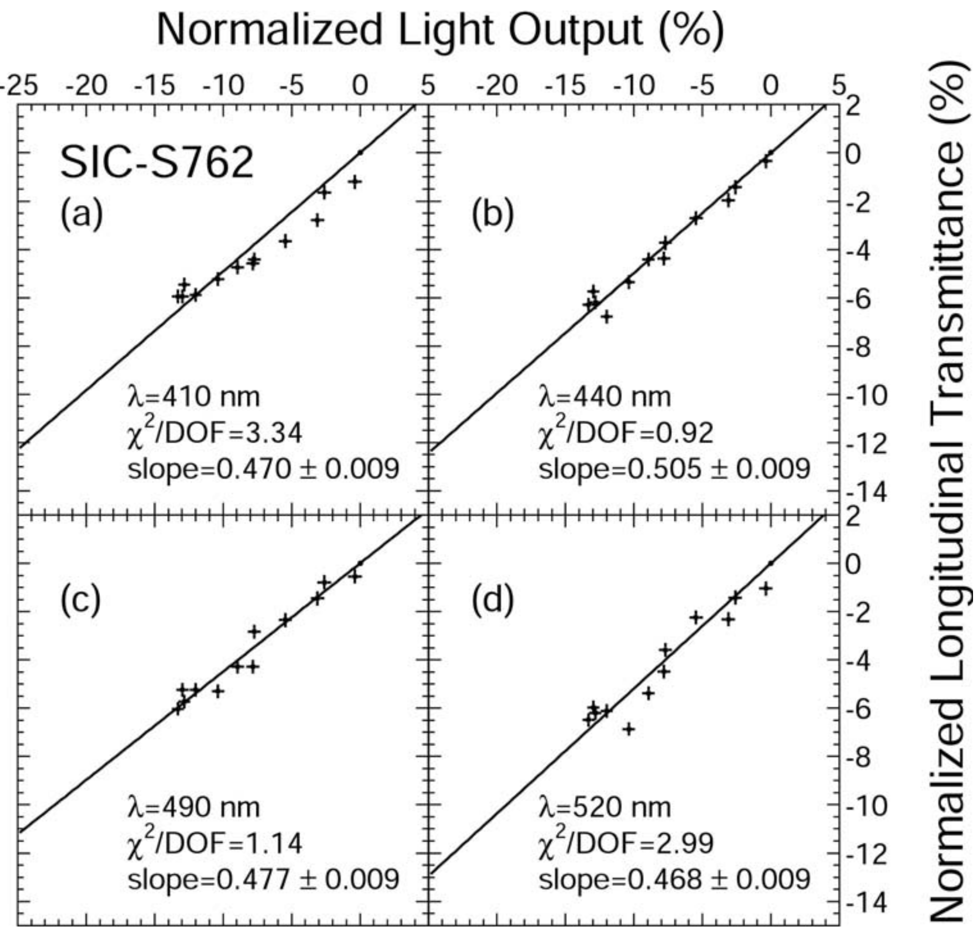


Rate limited by DAQ at 100 Hz

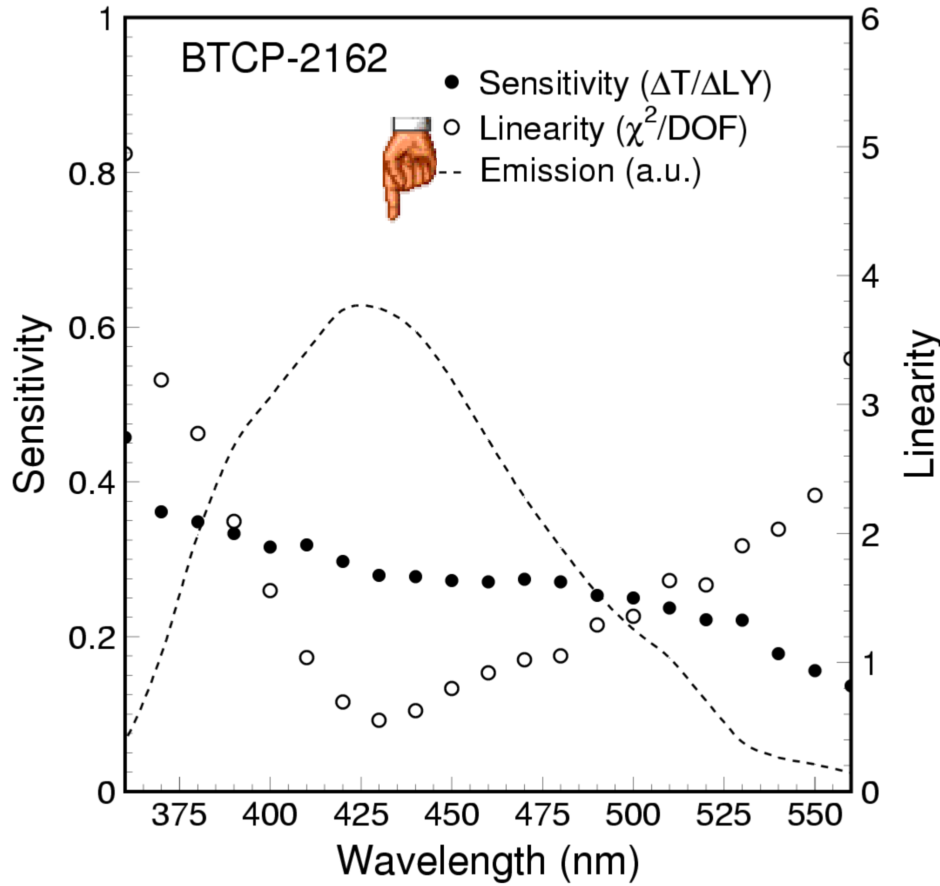
Monitoring Wavelength Determination

IEEE Tran. Nucl. Sci. **V 48 (2001) 372**

Δ(T) versus Δ(LY)



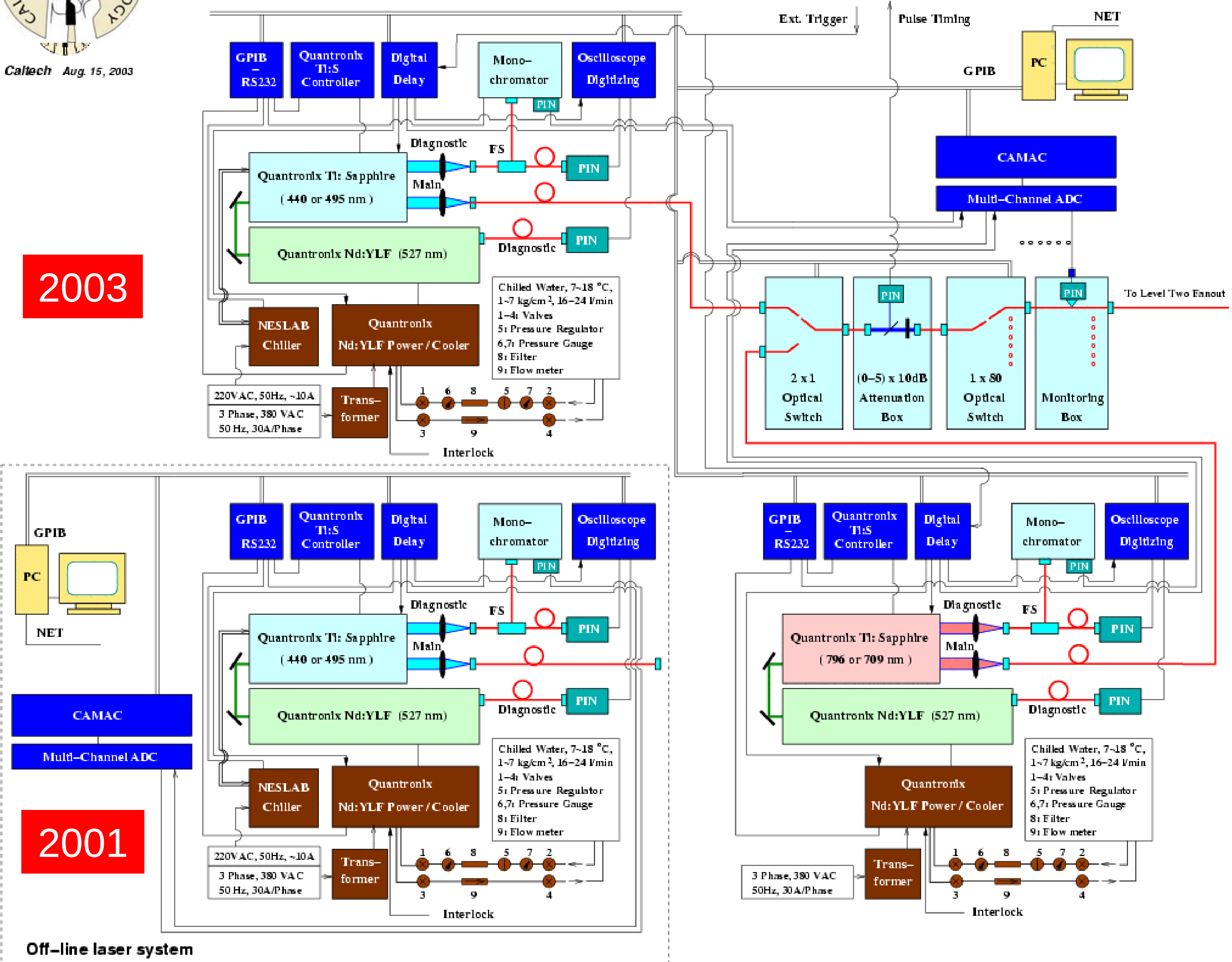
Sensitivity and Linearity



→ 440 nm is chosen for the best linearity

Caltech Aug. 15, 2003

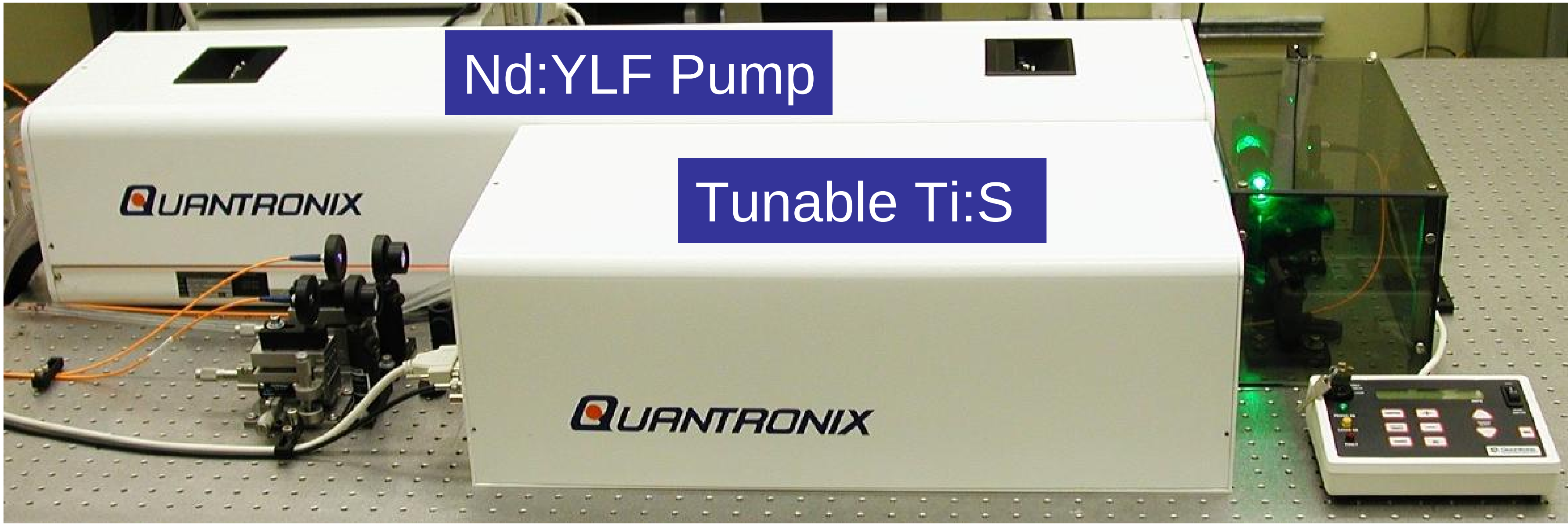
Lasers at CERN for PWO Monitoring

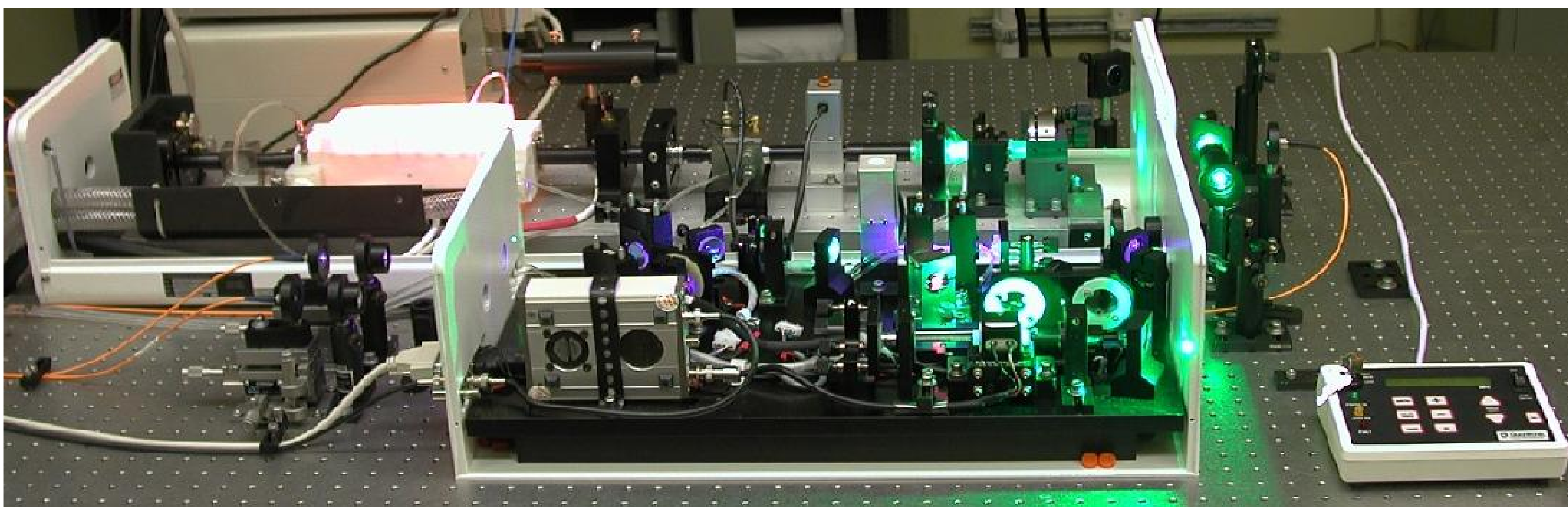


The 1st laser system was Installed in 2001, and used in 2002 beam test.

The 2nd and 3rd laser systems installed at CERN in August, 2003.

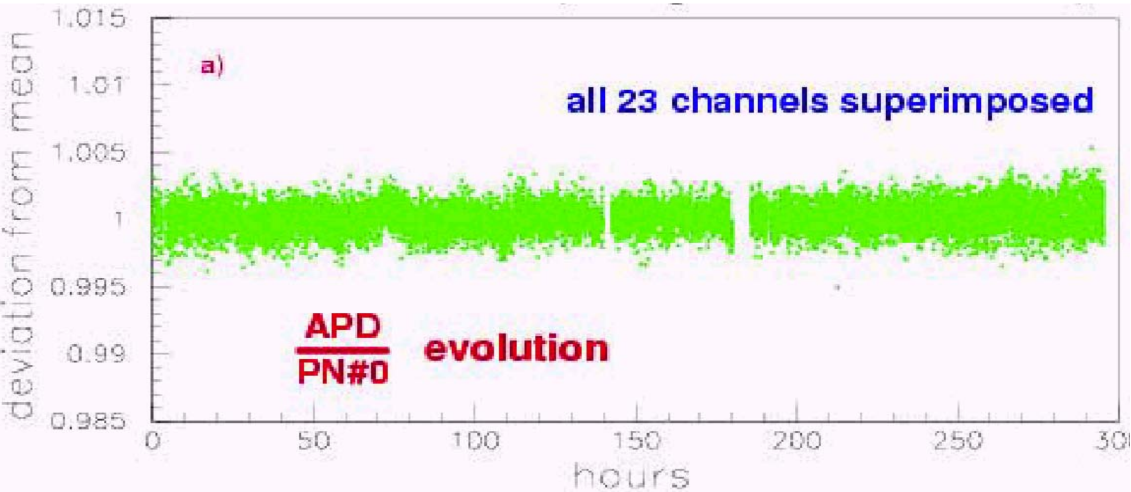
Ti:Sapphire Laser with Two Wavelengths

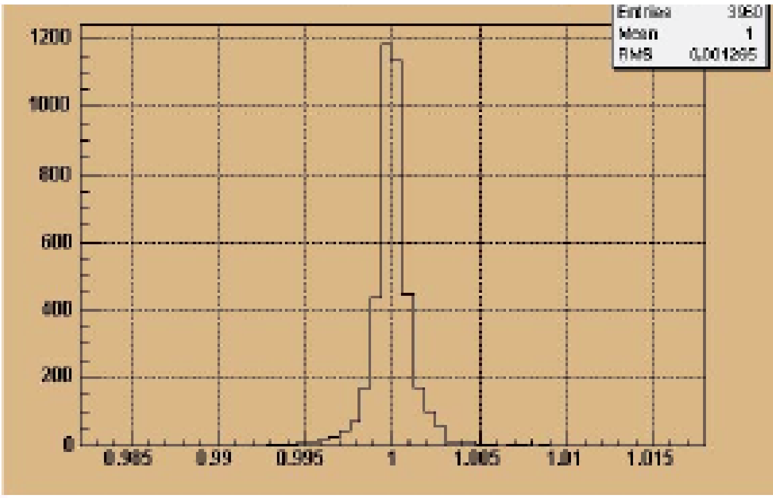


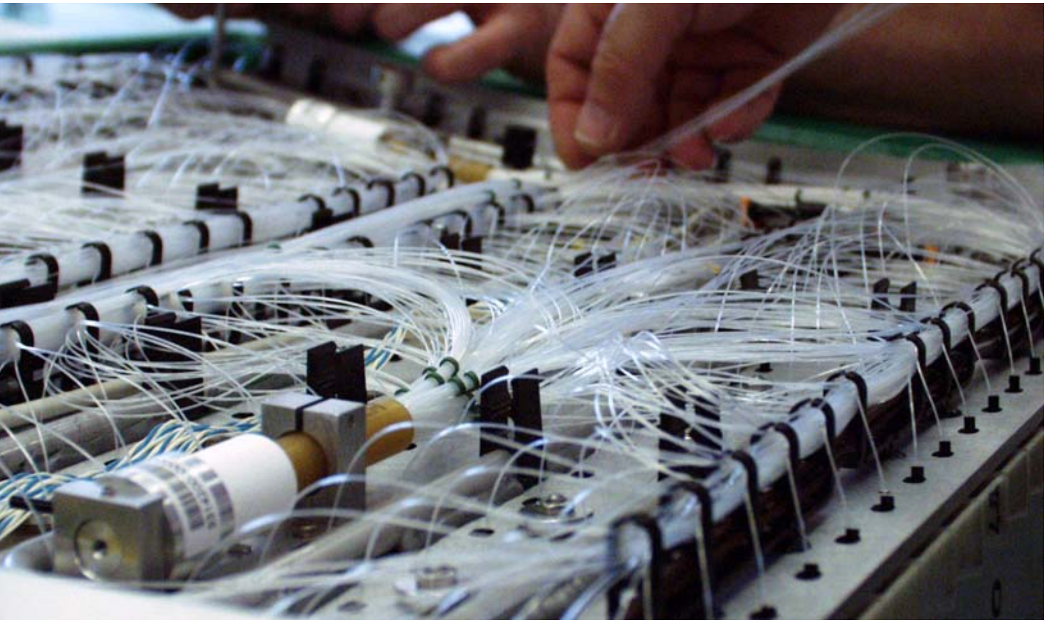


Low Level Light Distribution

Long Term Stability: 0.1%





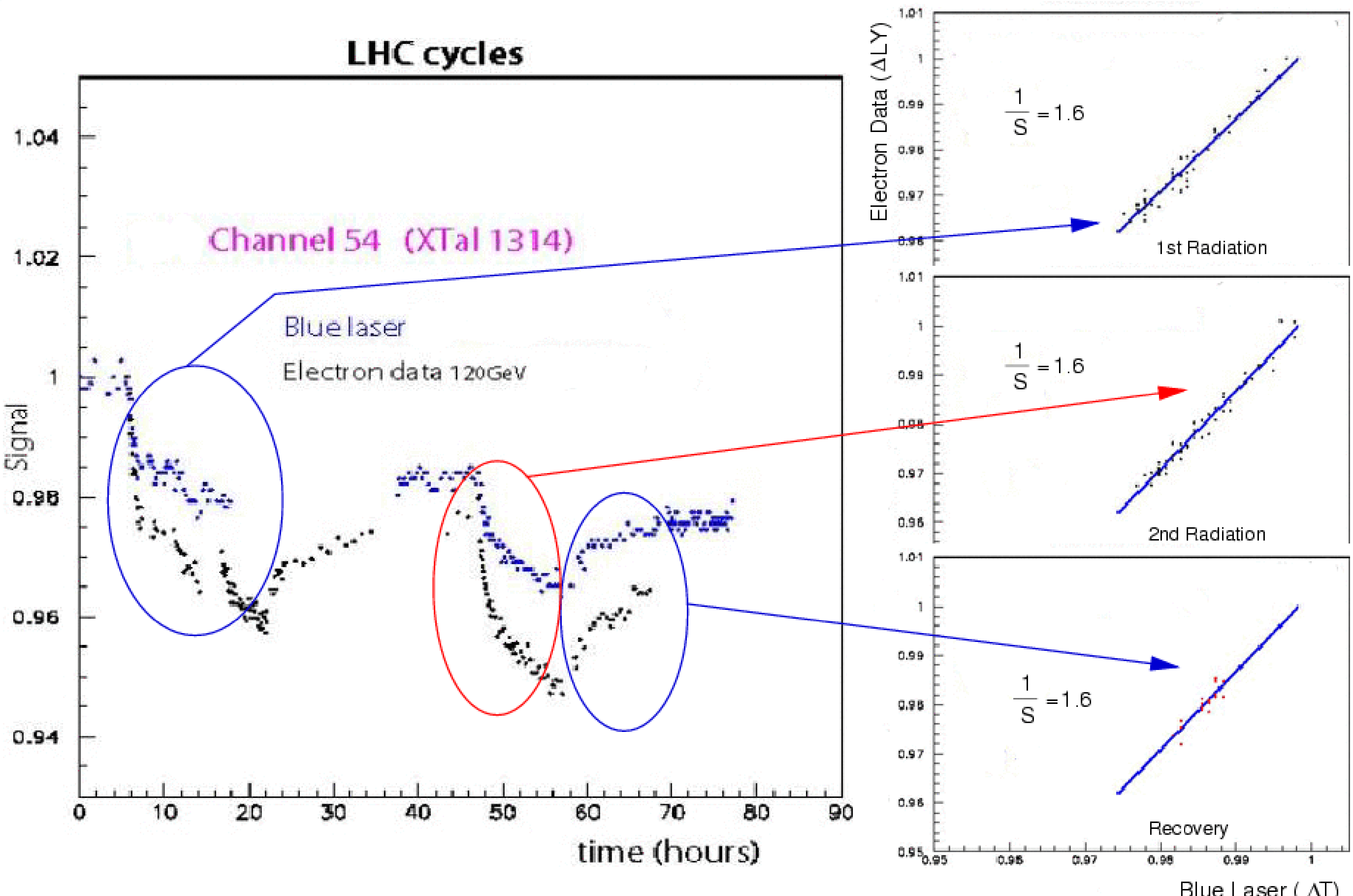


Monitoring

Low Level Fiber

Distribution

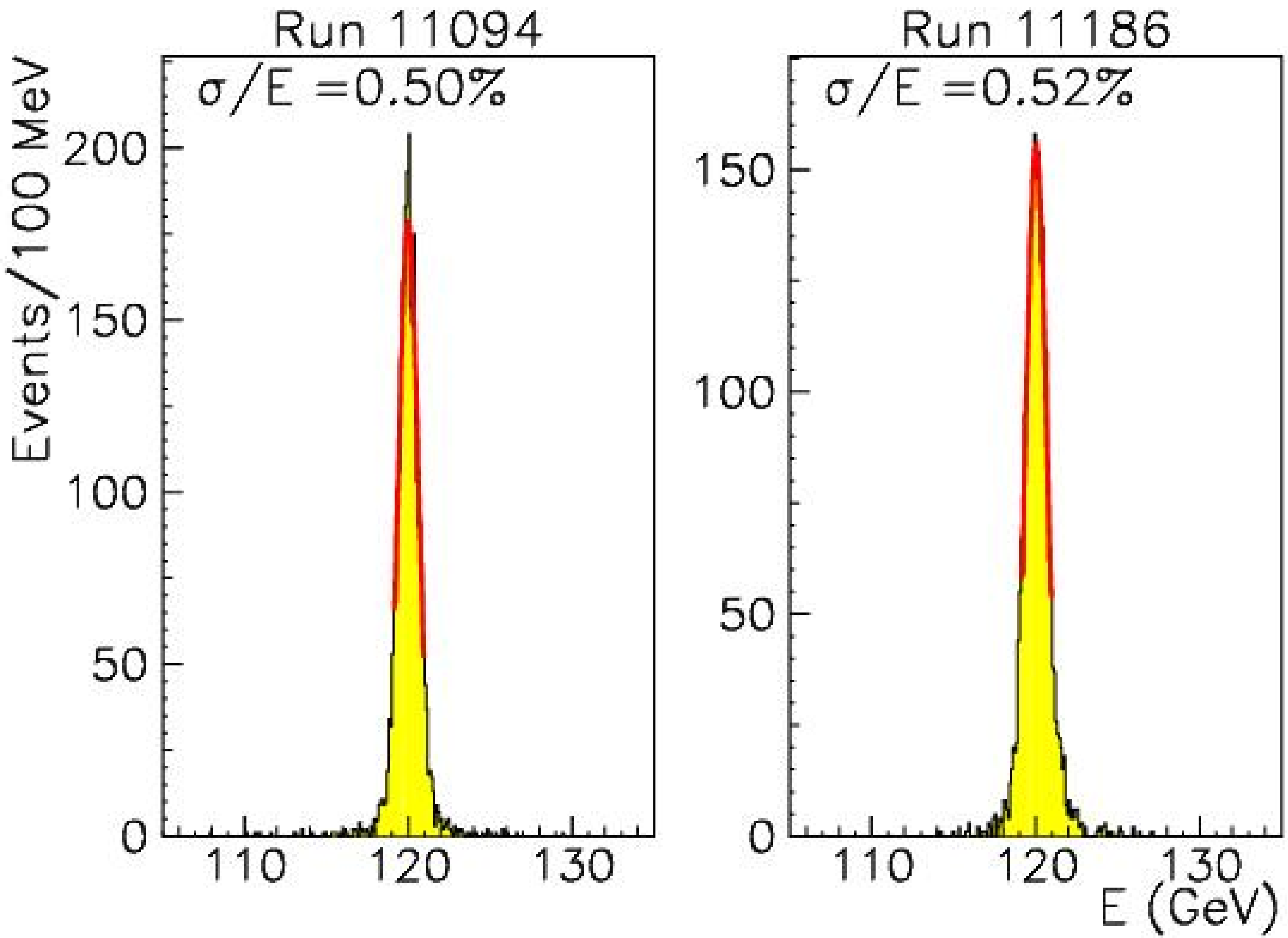
Experiences in 2002 Beam Test



PWO Resolution With Light Monitoring

Nucl. Instr. Meth. **A 412** (1998) 223

Before/after beam irradiation: 10% variation in light output



Summary (I)

- In the last seven years, CMS has taken a challanging project to build a precision crystal calorimeter at LHC.
- High quality PWO crystals and APDs are in mass production and detector construction is well under way.
- Radiation damage in PWO crystals is well understood. Variations of PWO crystal light output are monitored by a light monitoring system *in situ*.
- Important development has been achieved for precision crystal calorimetry in radiation environment. Looking forward to precision e/γ physics at LHC.

Summary (II)

- PWO samples from both BTCP and SIC have very good transmittance and fast light output. SIC samples produce 58% more light, which may be explained by 130-280 ppmw La doping in BTCP samples.
- Preexisting CC, causing light output increase under irradiation, is caused by contamination of mono-valent impurities.
- No correlations between radiation hardness and initial longitudinal transmittance was observed.
- Requiring degraded LAL>1 m, current mass-produced PWO crystals are radiation hard enough for environment of up to a few hundreds rad/h --- a great achievement for HEP and MS.