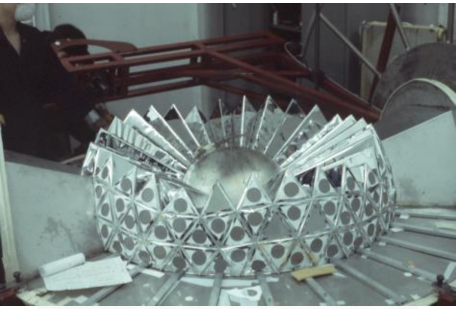
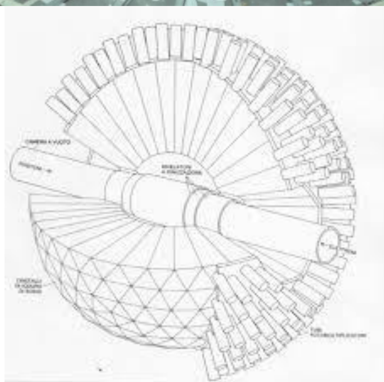
Crystal Clear Collaboration and HEP applications

E. Auffray, CCC Spokesperson
CERN, EP-CMX

Scintillating crystals used in HEP before 1990

NaI

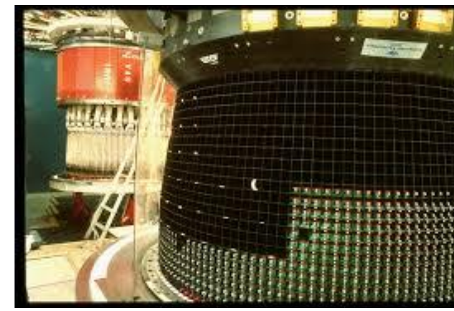




Crystal ball, 1979

	Before 1990		
	NaI(Tl)	CsI(Tl)	BGO $Bi_4Ge_3O_{12}$
Xo [cm]	2.59	1.86	1.12
r [g/cm^3]	3.67	4.53	7.13
t [ns]	230	1050	340
l [nm]	415	550	480
Ref index n@l $_{max}$	1.85	1.80	2.15
LY [%NaI]	100	85	10

BGO



L3 electromagnetic calorimeter, 1989

Not appropriate for LHC working conditions

History

- In 1990 CERN launched the Detector Research and Development Committee (DRDC) to finance the R&D on future detectors for future LHC accelerator
- In April 1991 DRDC approved the R&D proposal initiated by P. Lecoq for the study of new fast and radiation hard scintillators for calorimetry at the LHC

=> **Birth of Crystal Clear Collaboration**

CERN / DRDC / 91-15
DRDC / P27
06 march 1991

R&D PROPOSAL FOR THE STUDY OF NEW FAST AND RADIATION HARD SCINTILLATORS FOR CALORIMETRY AT LHC

CERN , Geneva , Switzerland
A. Hervé , P. Lecoq (spokesman), J. M. Le Goff

Consorzio Milano Ricerche , Milano , Italy
F. Allegretti , S. Pizzini

INFN , Roma
B. Borgia , F. Ferroni , E. Longo , M. Mattioli , F. De Notaristefani

Laboratoire de Physico-chimie des Matériaux Luminescents Université Claude Bernard , Lyon , France
B. Moine , C. Pedrini

LAPP , Annecy , France
M. Lebeau , M. Schneegans , M. Vivargent

Leningrad Nuclear Physics Institute , Leningrad , USSR
V. Samsonov , V. Schegelski , V. Yanovski

Lund University
L. Jønsson

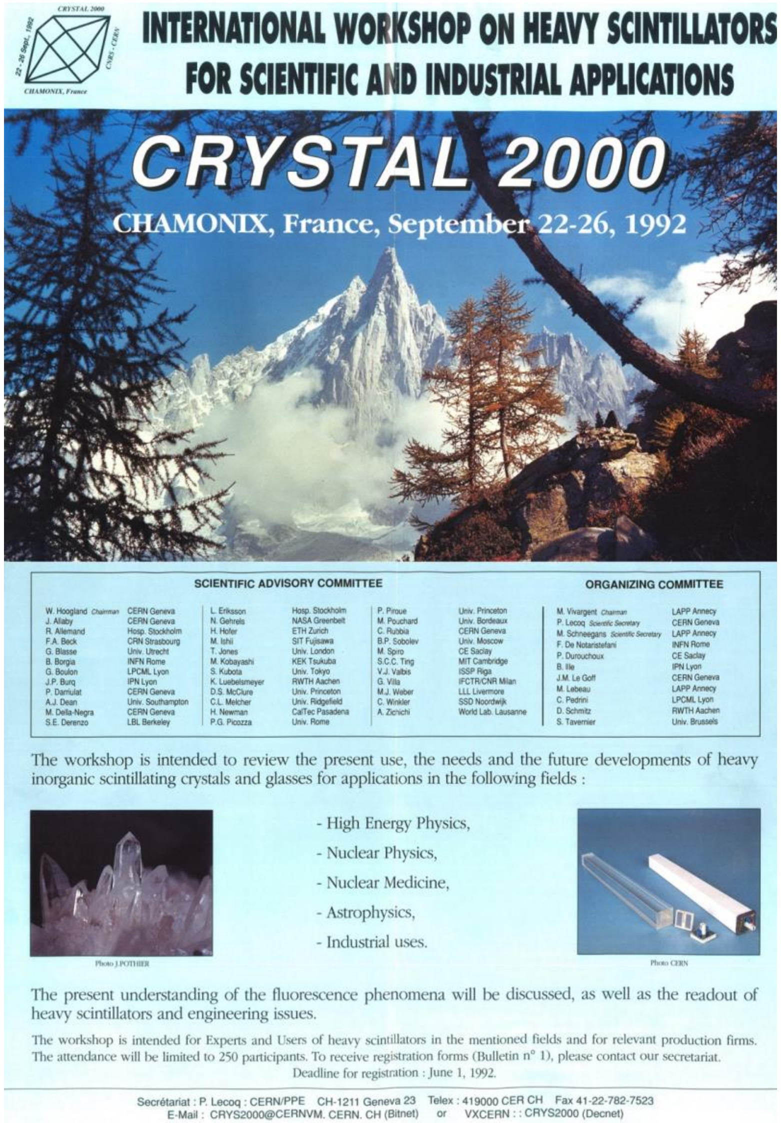
Physics Institute , RTWH Aachen , Germany
K. Lubelsmeyer , D. Schmitz , W. Wallraff

Tata Institute of Fundamental Research , Bombay
T. Aziz , S. Banerjee , S.N. Ganguli , S.K. Gupta , A. Gurtu , P.K. Malhotra , K. Mazumdar , R. Raghavan , K. Shankar , K. Sudhakar , S.C. Tonwar

Abstract

In the recent past, several scintillating crystals have been developed and mass produced for large high resolution electromagnetic calorimeters, such as NaI, CsI, and BGO. In the new generation of ee and pp colliders, the very high design luminosities bring new constraints on the crystals : they must have a fast response, higher resistance to radiation, and be as dense as possible for calorimeter compactness. From our systematic studies of scintillation properties and radiation damage mechanisms in scintillators, several fluoride crystals or glasses should have the wanted properties. The purpose of this R&D program is to study these materials and the conditions of their mass production in order to find the best suited scintillator for calorimetry at future colliders.

Crystal 2000



First conference on inorganic scintillators (SCINT conf)

Birth of the scintillator community

The Crystal Clear Collaboration

Initial Objective:

Develop scintillating materials suitable for use at the future LHC collider

From 1991 to 1994: R&D on several types of scintillator

CeF$_3$: a new fast scintillator

Properties of the High-Density Scintillator Cerium Fluoride

IEEE Transactions on 137

D.F. Anderson
Particle Detector Group
Fermi National Accelerator Laboratory
Batavia IL 60510

A new radiation-hard scintillator, CeF$_3$, has been found. It has a density of 6.16 g/cm^3 and a radiation length of 1.7 cm. Two scintillation decay constants have been detected with time constants of ≈2 ns and 31 ns peaking at 310 nm and 340 nm, respectively. The amount of scintillation light from our present samples is about 50% that of BGO.

Introduction

In both the fields of high energy physics and positron emission tomography (PET) there is always an interest in a new fast, high-density scintillator. The material CeF$_3$ is such a scintillator, which we discovered while examining various crystal samples at Optovac, Inc., North Brookfield, MA. CeF$_3$ has also been discovered independently by W.W. Moses and S.E. Derenzo (see these proceedings) from the same source of crystals.

At present, the two major scintillators used for PET are BGO and BaF$_2$. Because of its high density and high atomic number, BGO is the workhorse of high-resolution, non-time-of-flight PET. It has the best total absorption efficiency of any of the crystals used. It does have one drawback: its relatively long scintillation decay constant of 300 ns somewhat limits its application at high rates.

For time-of-flight PET, BaF$_2$ is the crystal of choice. About 20% of its light is in the "fast component" with a decay constant of only about 0.8 ns [1]. This makes it the fastest inorganic scintillator known. For high rate applications the "slow component," with a decay constant of 620 ns, can be removed electronically. The major drawback of BaF$_2$ is that the fast component has its peak emission at 225 nm; thus, quartz photomultipliers (PMT) must be used. This greatly increased the cost of a PET camera. In high-energy physics, this scintillation in the uv is sometimes used to advantage by the use of photosensitive wire chambers (see ref 2 for a review of the subject).

As can be seen in Table I, CeF$_3$ falls somewhere between BGO and BaF$_2$ in many aspects such as density, absorption length at 511 keV, and index of refraction with values of 6.16 g/cm^3, 1.9 cm, and 1.68, respectively. Like BaF$_2$, it also has two emission components, and although CeF$_3$ is not as fast as the fast component of BaF$_2$, its slow component is a factor of 20 faster than the slow component of BaF$_2$ and a factor of 10 faster than BGO. We hope to demonstrate in this work that in the field of nuclear medicine, the role of CeF$_3$ is for relatively inexpensive, high-rate (and possibly time-of-flight) PET cameras using glass PMTs. There may also be a role for CeF$_3$ as a high resolution calorimeter in high-energy physics.

Transmission, Emission, and Light Yield

Pure CeF$_3$

The information that is presented here must be taken as somewhat preliminary, since we have only two samples of pure CeF$_3$. The sample of highest optical quality is 5x10x11 mm^3 (hereafter crystal no. 1) cut from a 10 mm diameter rod, and the other is a 1-cm cube (hereafter crystal no. 2), which is slightly cloudy.

In order to measure the emission spectrum of CeF$_3$, we excited the samples with a uv light source passed through a narrow transmission filter with peak transmission at 254 nm. Figure 1 shows the transmission and emission of crystal no. 1. The emission line is a broad continuum extending from about 290 nm to about 500 nm with peak emission at around 340 nm. When the front surface of the crystal was illuminated with the uv light source there was a little emission on the short-wavelength side that is removed by

Physical and timing properties of some scintillators

	CeF$_3$	BaF$_2$[1]	BGO[1]	CsF[1]
Density	6.16[3]	4.87	7.13	4.64
Absorption length (1/e in cm, at 511 keV)	1.9	2.3	1.1	2.3
Radiation length (cm)	1.7	2.1	1.1	2.0
Decay constant -short	≈2	0.8	300	2.5
(n sec) -long	31	620		
Peak emission -short	310	225	480	390
(nm) -long	340	310		
Index of refraction at peak emission	1.68[4]	1.57	2.15	1.48
Timing resolution (ps FWHM) (crystal 2 cm ϕ x 4 cm)	522*	300	2500	450
Light yield [NaI(Tl)=100]	3	5 / 16	7	6
Hygroscopic	No	No	No	Very

* crystal 1-cm cube used

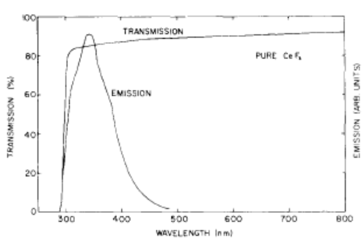


Fig. 1 Transmission and emission as a function of wavelength for pure CeF$_3$.

the cutoff of the material.

The uv cutoff of CeF$_3$ is about the same as that of the window of a glass PMT. In comparing the light output of CeF$_3$ with quartz and glass PMT's, the number of photons detected with the quartz PMT was only 15% larger. If there were a reason to try to get this small additional amount of light, uv glass could be used, which adds little to the cost of the PMT.

It is always difficult to estimate the absolute light output of a scintillator. In the case of CeF$_3$ the best we could do is compare the light yield with that of a BGO crystal of the same geometry. Crystal no. 2 was therefore compared with a similar 1-cm cube BGO crystal. Both crystals were wrapped in Teflon tape and coupled to a quartz PMT with silicon oil. The pulse height of the CeF$_3$ crystal was almost exactly 50% that of the BGO. The resolution of the BGO crystals for 662-keV gamma rays was 11.3% FWHM, demonstrating that the BGO is of high quality.

Temperature Dependance of Pure CeF$_3$

As will be discussed later in the section on scintillation decay constants, CeF$_3$ has two decay constants and two emission spectra.

0018-9499/89/0200-0137$01.00 © 1989 IEEE

IEEE TNS 36 (1989) 137-140

CERIUM FLUORIDE, A NEW FAST, HEAVY SCINTILLATOR

IEEE Transactions on 173

W.W. Moses and S.E. Derenzo,
Donner Laboratory and Lawrence Berkeley Laboratory,
University of California, Berkeley, CA 94720

Abstract

We describe the scintillation properties of Cerium Fluoride (CeF$_3$), a newly discovered, heavy (6.16 g/cm^3), inorganic scintillator. Its fluorescence decay lifetime, measured with the delayed coincidence method, is described by a single exponential with a 27 ± 1 ns time constant. The emission spectrum peaks at a wavelength of 340 nm, and drops to less than 10% of its peak value at 315 nm and 460 nm. When a 1 cm optical quality cube of CeF$_3$ is excited with 511 keV photons, a photopeak with a 20% full width at half maximum is observed at approximately half the light output of a Bismuth Germanate (BGO) crystal with similar geometry. We also present measurements of the decay time and light output of CeF$_3$ doped with three rare-earth elements (Dy, Er, and Pr). The short fluorescence lifetime, high density, and reasonable light output of this new scintillator suggest that it would be useful for applications where high counting rates, good stopping power, and nanosecond timing are important, such as medical imaging and nuclear science.

1 Introduction

This paper describes the scintillation properties of Cerium Fluoride (CeF$_3$), a newly discovered inorganic scintillator. It begins with measurements of the fluorescent decay time, light output, emission spectrum, and coincidence timing resolution for undoped CeF$_3$, then explores the effect that several rare-earth dopants have on these scintillation properties. The paper concludes with a description of a technique that uses synchrotron radiation x-rays to rapidly measure the scintillation decay time and light output of powdered compounds. All measurements described in this paper were made with crystals provided by Optovac, Inc. of N. Brookfield, MA.

The physical characteristics of CeF$_3$ are well suited for use as a radiation detector. It has a density of 6.16 g/cm^3 [1], is not hygroscopic [1], and has an index of refraction of 1.62 [2]. The crystal structure is hexagonal [1], and it

*This work was supported in part by the U.S. Department of Energy, under contracts No. DE-AC03-76SF00098 and DE-AC03-82ER-13000, and in part by Public Health Service Grant Nos. P01 25840 and R01 CA38086.

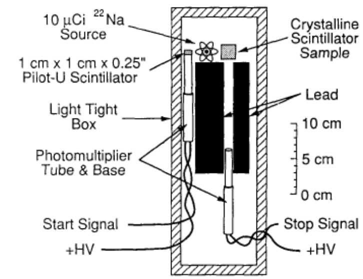


Figure 1: Delayed-Coincidence Apparatus

is colorless, transmitting wavelengths between 5000 nm and 300 nm [2].

2 Undoped Cerium Fluoride

2.1 Fluorescent Decay Time

The fluorescent decay lifetime was measured using the delayed-coincidence method of Bollinger and Thomas [3], as modified by Moszyński and Bengtson [4]. A diagram of this set-up is shown in Figure 1. A piece of Pilot-U plastic scintillator coupled to a Hamamatsu R-2055 photomultiplier tube provides a start signal, and another quartz-windowed Hamamatsu R-2055 photomultiplier tube placed 13 cm away from the CeF$_3$ sample provides the stop signal. A 10 µCi ^{22}Na source provided the 511 keV photon pairs that excited both the plastic scintillator and the scintillator sample. Timing signals from both photomultiplier tubes are generated using Ortec 437A constant fraction discriminators, and the time difference between the start and stop signals was digitized with an Ortec 457 time to amplitude converter and a Tracor-Northern TN-1705 multi-channel analyzer.

The results of this measurement are shown in Figure 2.

0018-9499/89/0200-0173$01.00 © 1989 IEEE

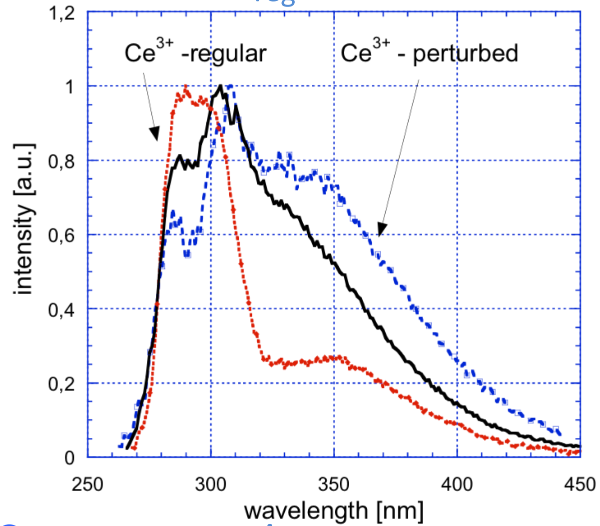
IEEE TNS 36 (1989) 173-176

1991-1995: R&D on CeF_3

- Understanding of Ce^{3+} scintillation mechanisms

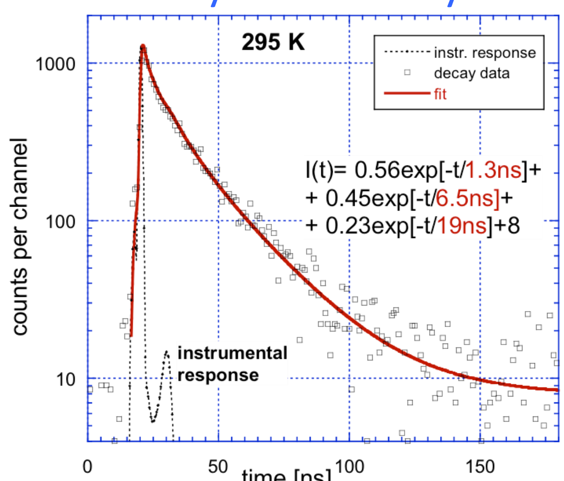
=>The existence of regular (Ce_{reg}) and perturbed (Ce_{pert})

Photoluminescence
(exc = 250 nm)



⇒ Quenching per Ce concentration

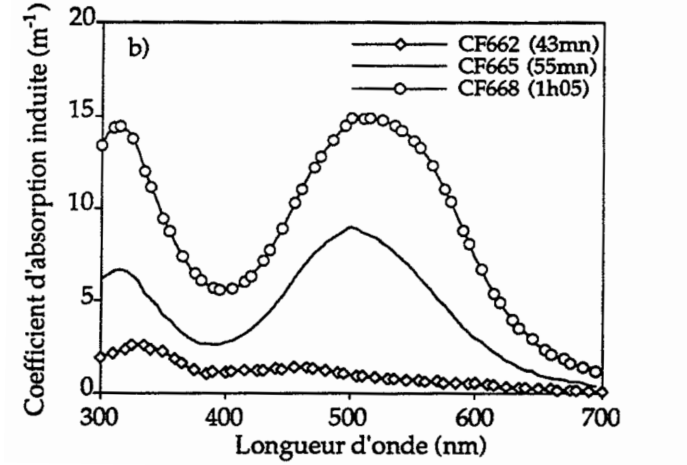
=> very short decay time



Scintillation decay of CeF_3
(exc. 22Na, 511 keV)

- Understanding of radiation damage

Radiation Hardness

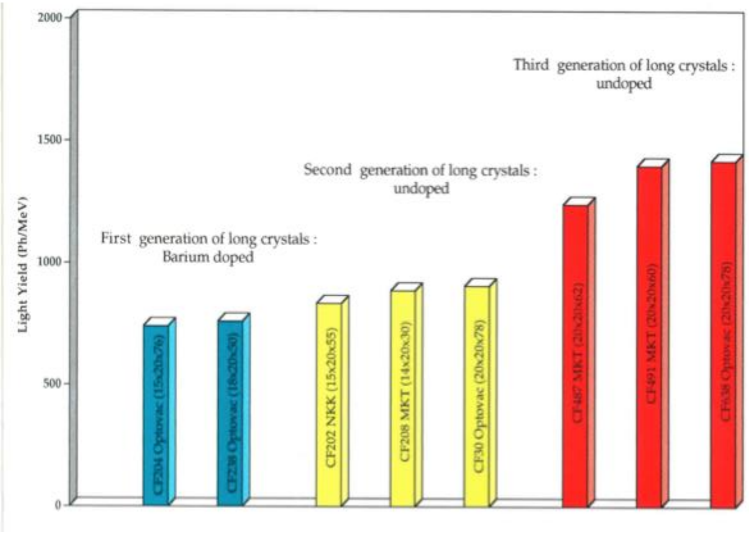


Many CCC papers
E. Auffray, PhD thesis 1995
E. Auffray et al (CC collaboration, Nucl. Instr. Meth. Phys. Research ***A380****, 524-536 (1996)*
M. Nikl (review paper), phys.stat.sol. (a) ***178****, 595-620 (2000).*
M. Nikl, C. Pedrini, Sol.St.Comm. ***90****, 155-159 (1994))*

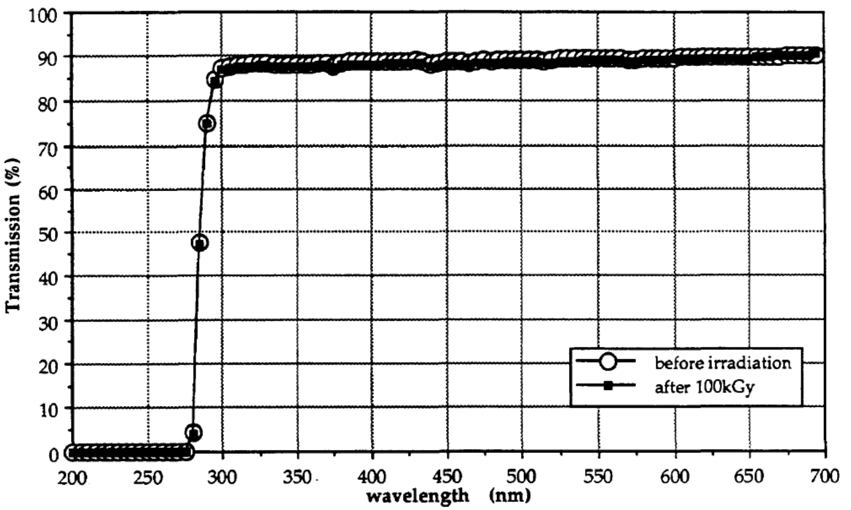
Achievements on CeF_3

In 1989: 1 crystal of 1 cm^3 => in 1993 large crystals (length > 20cm) produced by several companies

Improvement of LY of a factor 2



Excellent radiation hardness



E. Auffray, PhD thesis 1995

CeF_3 Test beam in 1994

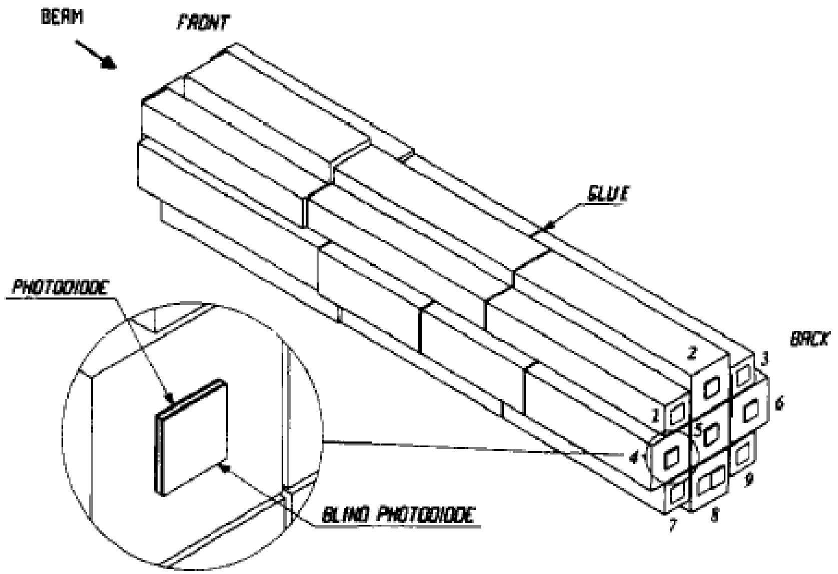
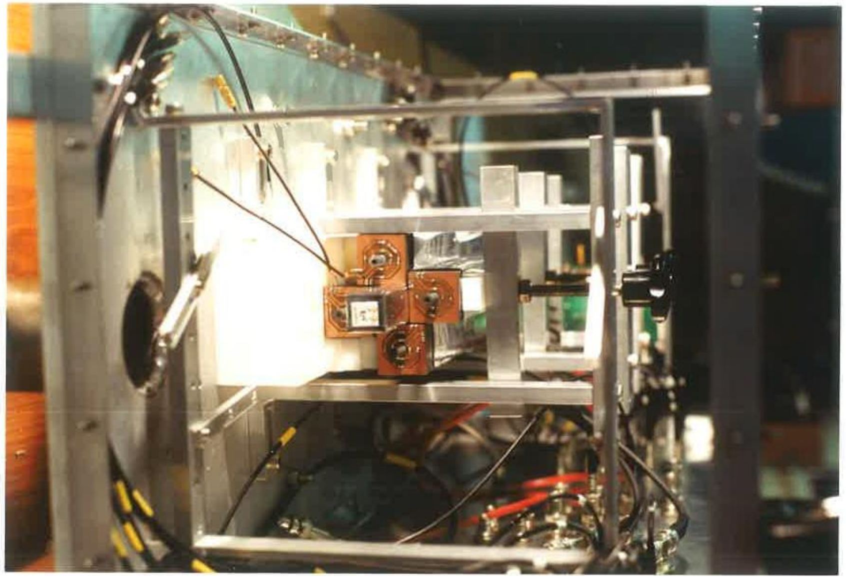
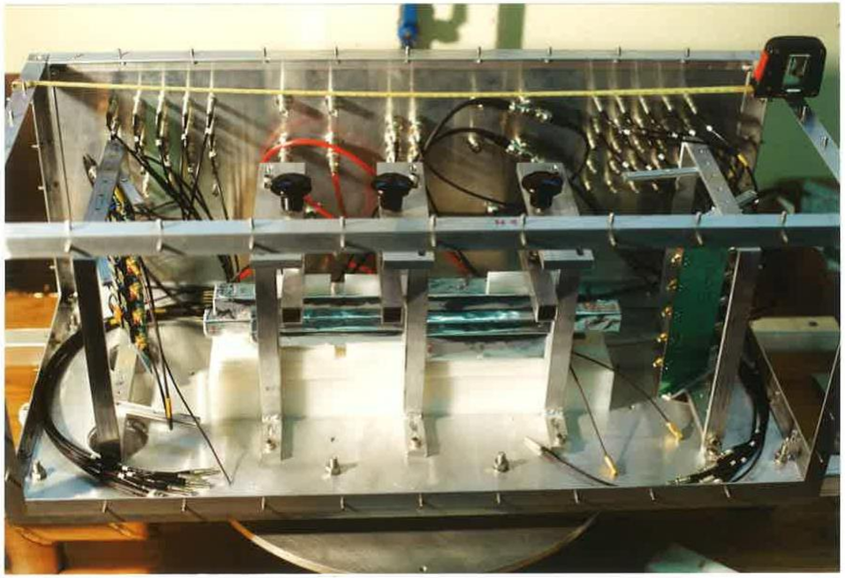


Fig. 1. The CeF_3 9-tower matrix geometry. The positioning of a "blind" SiPD with respect to a SiPD seeing the crystal light is shown.

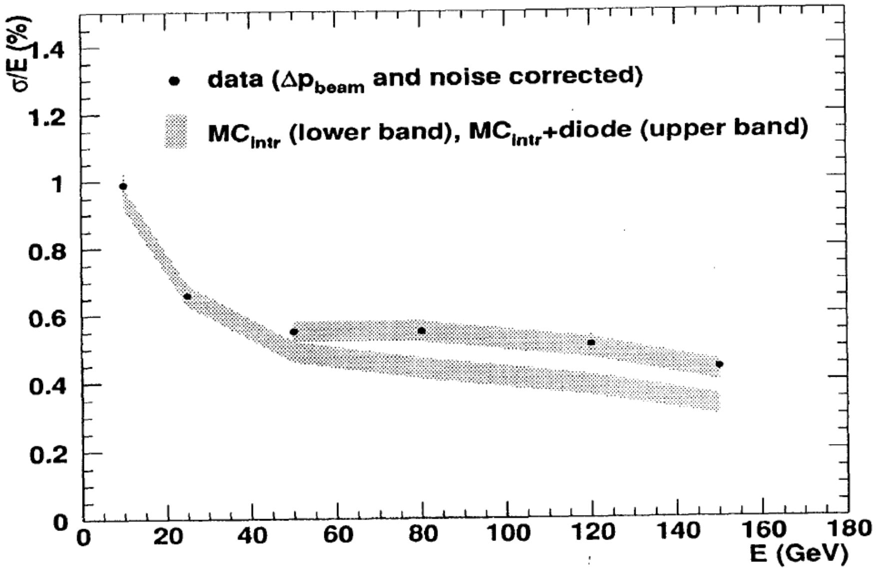




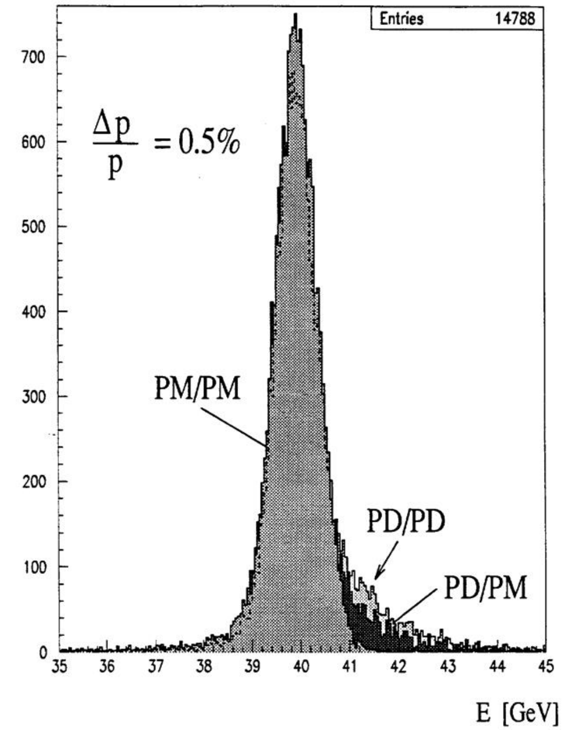
H. Hillemanns, PHD Thesis, 1995
E. Auffray et al., NIMA 378 (1996) 171-178

CeF_3 Test beam

Energy resolution of the CeF_3 matrix



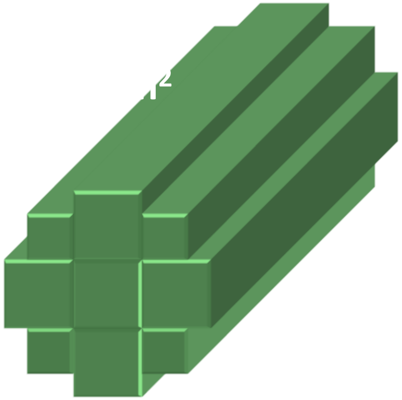
Energy resolution of the central crystal of the CeF_3 matrix with photodiode and PMT

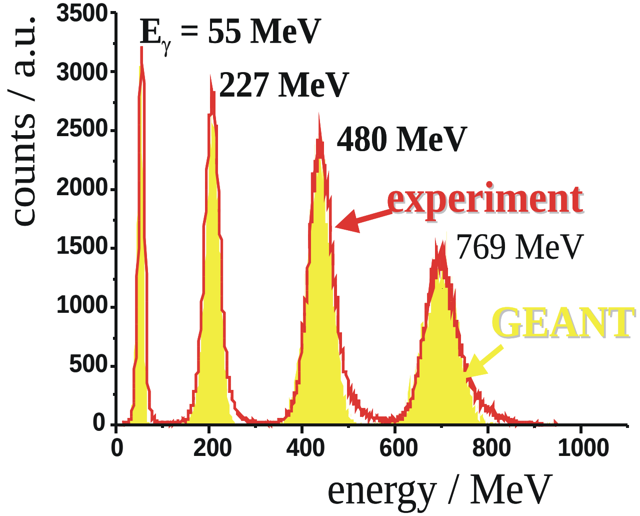


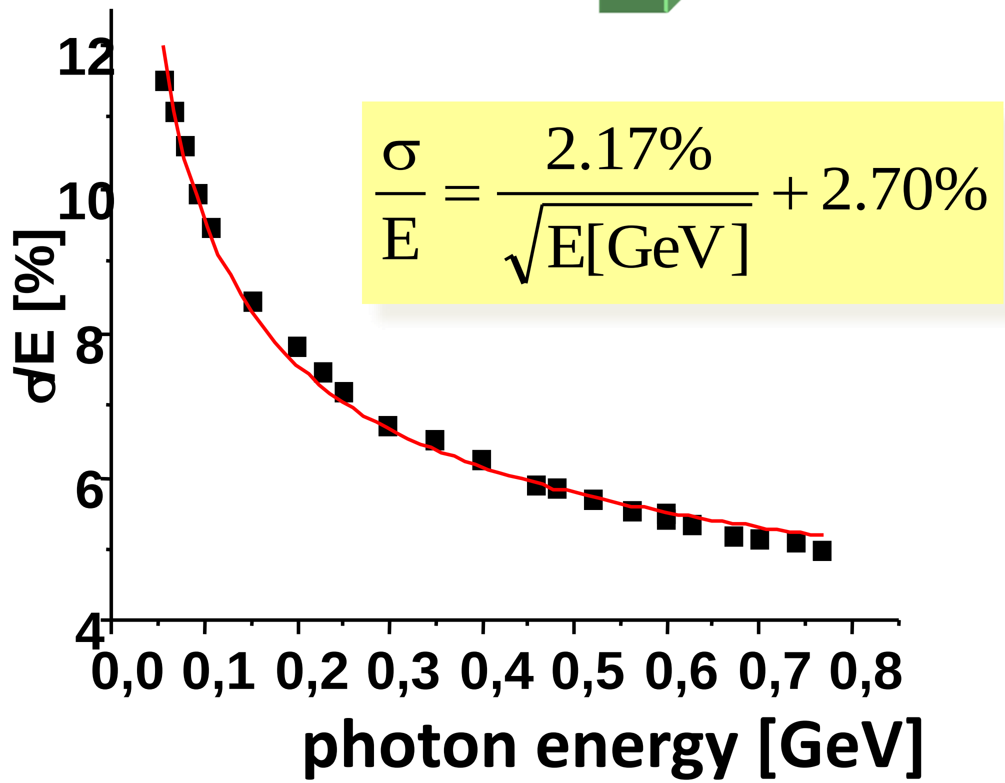
H. Hillemanns, PHD Thesis, 1995
E. Auffray et al., NIMA 378 (1996) 171-178

CeF_3 matrix at low energy
(R. Novotny group)

CC Matrix tested by Giessen group





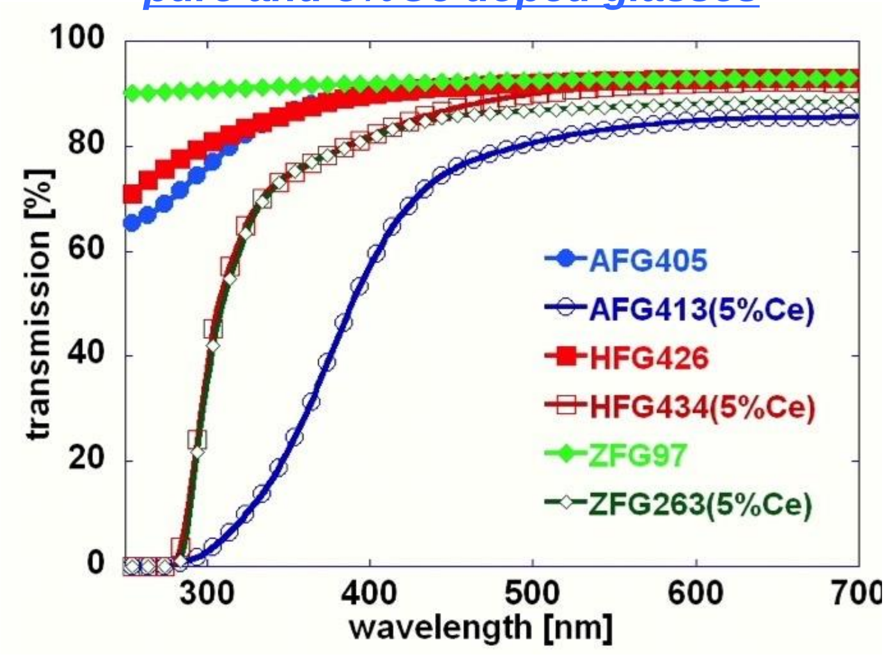


Courtesy R. Novotny

R&D on heavy scintillating glasses

Study of several types of heavy glasses

pure and 5%Ce doped glasses



Extensive work with Le verre fluoré, Rennes, France

AFG became coloured at Ce doping (AFG413, d=1mm)

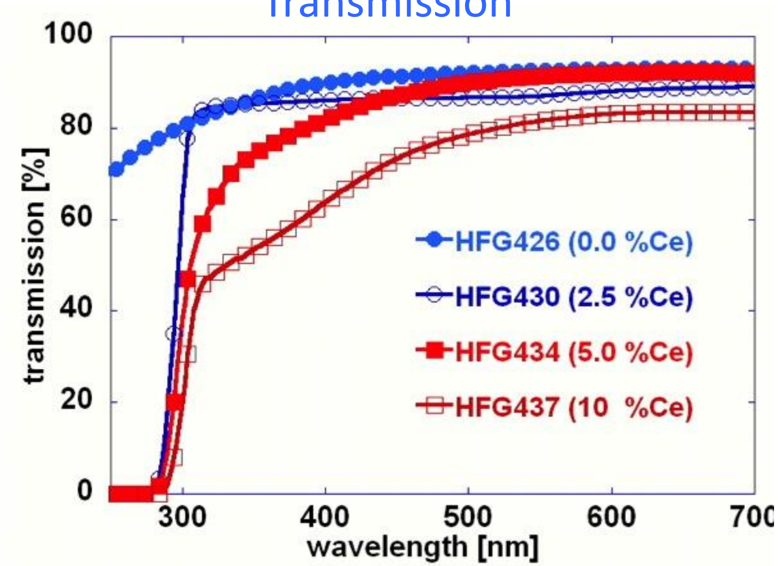
ZFG did not scintillate

HFG selected to study possible improvements

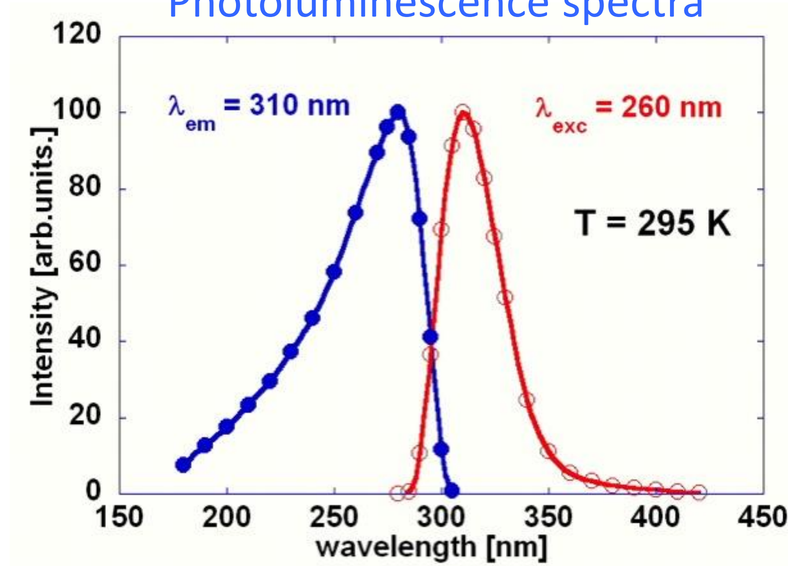
E.Auffray, I.Dafinei, P.Lecoq, M.Schneegans, MRS94, vol348, San Francisco, (1994) 217-224
E. Auffray, et al, NIM A 380 (1996) 524-536

Main results on HFG glasses

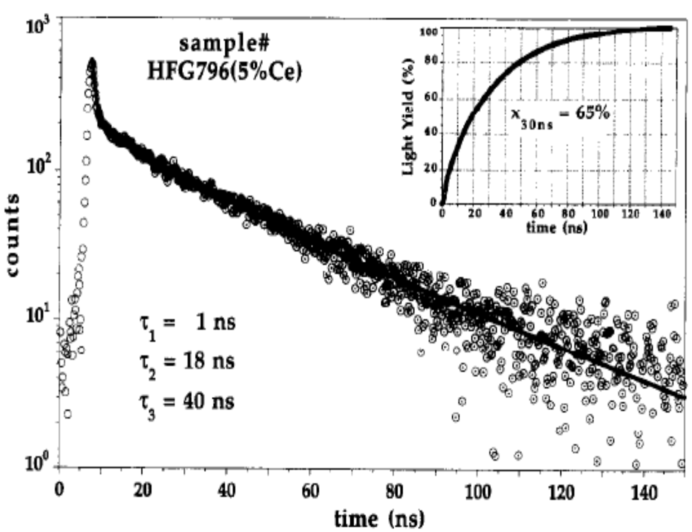
Transmission



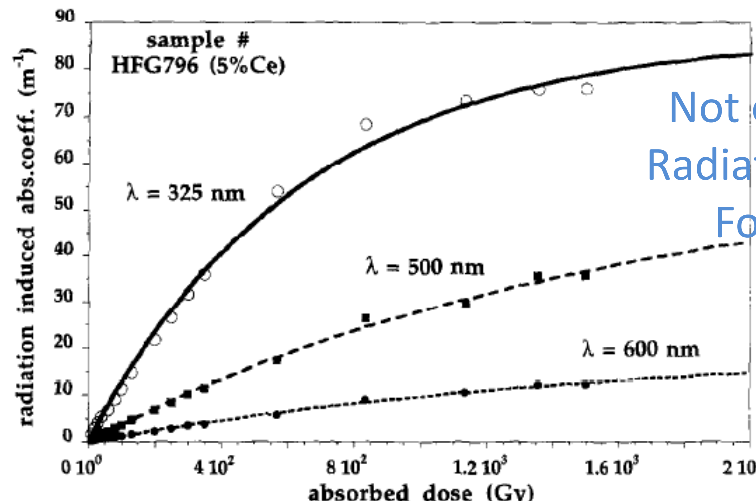
Photoluminescence spectra



Decay time



Radiation hardness

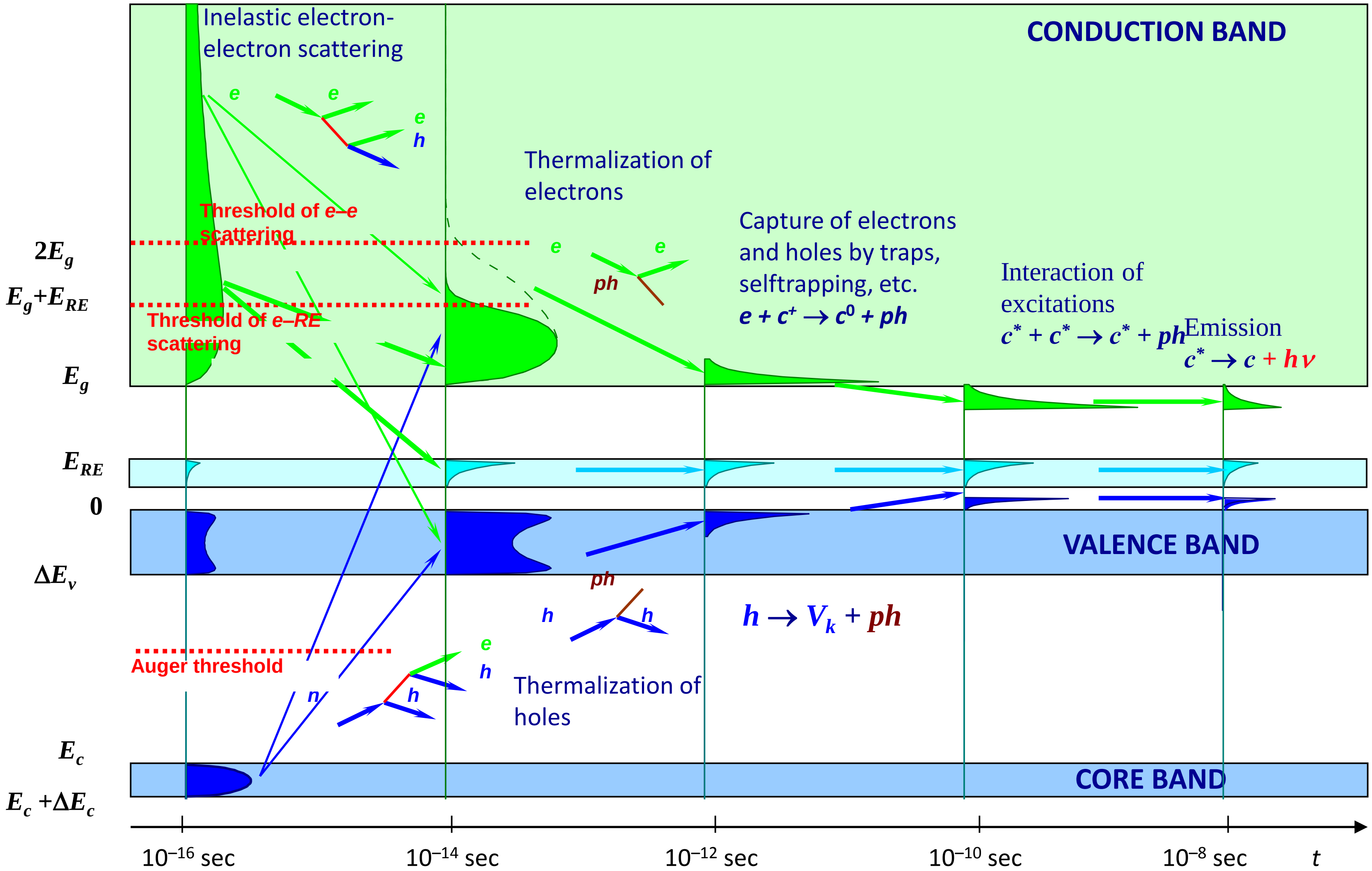


Not enough Radiation hard For LHC

E. Auffray, *et al, NIM A* **380** (1996) 524-536

Understanding of the scintillation process chain

Case of Ce^{3+} doping



A. Vasiliev, Proceedings of The SCINT99 conference, Moscow, Faculty of Physics, Moscow State University, 2000, p. 43-52

4 first papers on PWO for High Energy Physics applications

STUDY OF CHARACTERISTICS OF REAL-SIZE $PbWO_4$ CRYSTAL CELLS FOR PRECISE EM-CALORIMETERS TO BE USED AT LHC ENERGIES

V.A. Kachanov IHEP Protvino, CIS

Y.D. Prokoshkin V.G. Vasilchenko L.L. Nagornaya

M.V. Korzhik

FAST SCINTILLATORS BASED ON LARGE "HEAVY" TUNGSTATE SINGLE CRYSTALS.

L.Nagornaya, V.Ryzhikov, ISC, Kharkov, Ukraine

$PbWO_4$ SCINTILLATOR AT ROOM TEMPERATURE

Masaaki KOBAYASHI[a], Mitsuru ISHII[b], Yoshiyuki USUKI[c] and Hiroshi YAHAGI[d]

a) KEK, National Laboratory for High Energy Physics, Tsukuba 305, Japan,
b) SIT, Shonan Institute of Technology, Fujisawa 251, Japan,
c) Furukawa Co., Kamiyoshima, Yoshima, Iwaki 970-11, Japan,
d) Fujitok Co., Kamijyujyo 1-9-16, Kitaku, Tokyo 114, Japan.

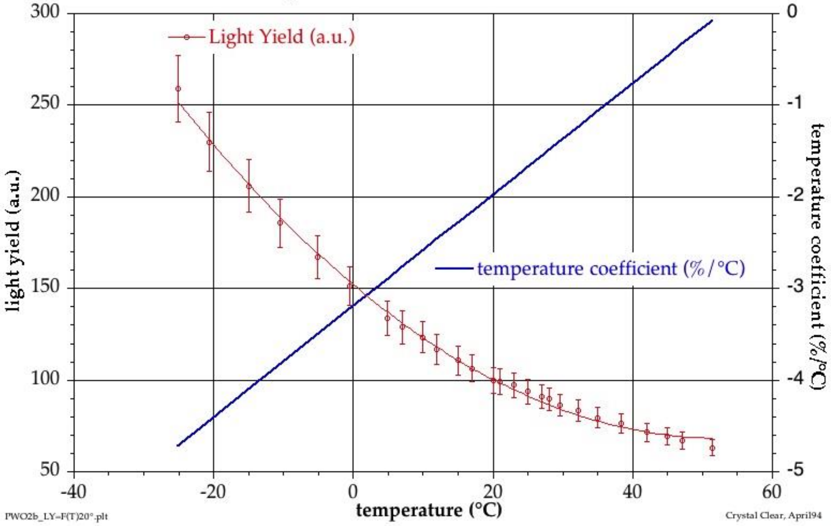
$PbWO_4$: A HEAVY, FAST AND RADIATION RESISTANT SCINTILLATOR FOR EM CALORIMETRY

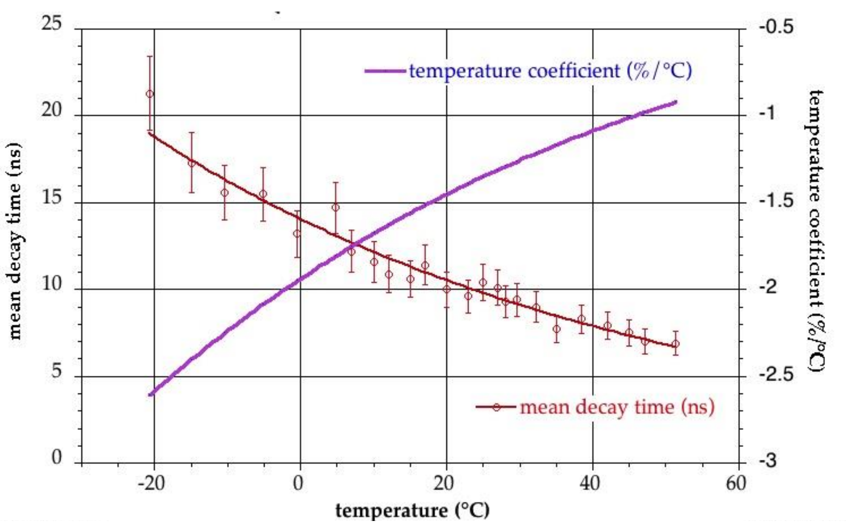
L.V.Miassoedov, V.I.Selivanov, I.V.Sinitsin, V.D.Torokhov
Kurchatov National Center, Moscow 123182, Russia
L.L.Nagornaya, Y.Ia.Vostresov, I.A.Tupitsina
Monocrystal Institute, Kharkov, Ukraine

The promoters of PWO

Some results on PWO

Temperature dependance of scintillating properties



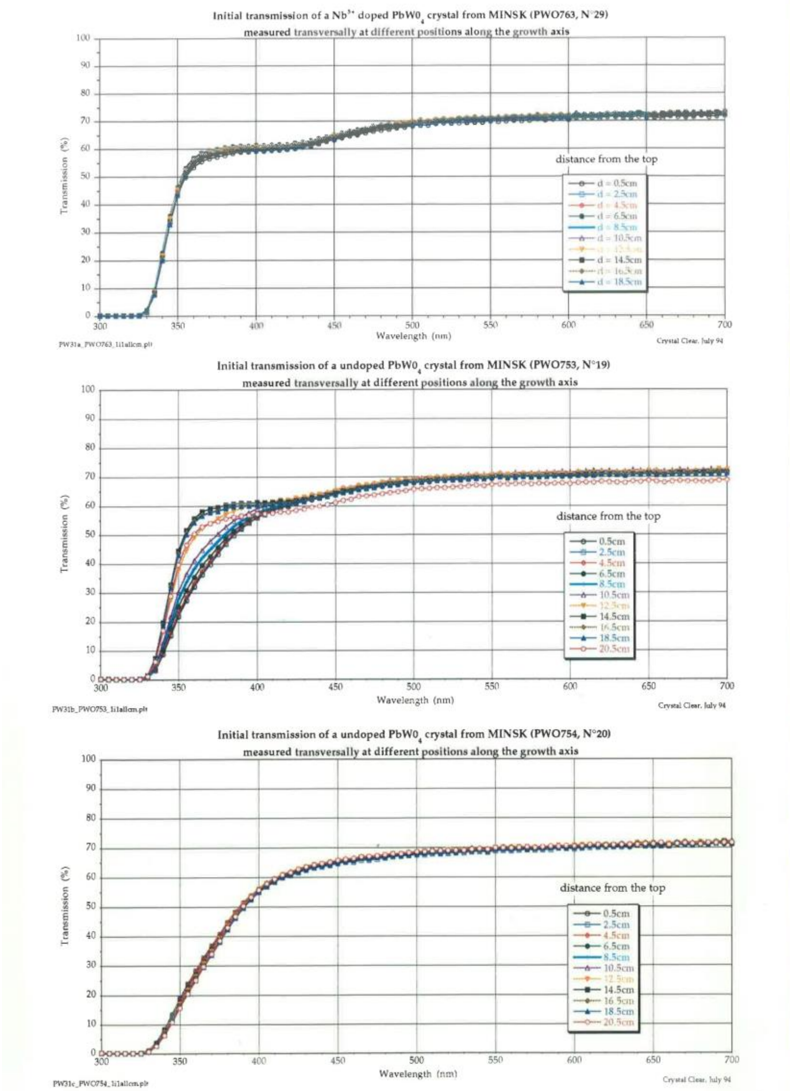


I. Dafinei, E. Auffray, P. Lecoq, M. Schneegans, MRS94, vol348, San Francisco, (1994) 99

P. Lecoq et al., NIM A, 365, Issues 2–3, (1995) 291

Three types of crystals

=> influence on radiation damage



E. Auffray et al. Scint95 conference

Crystal choice in 1994

From 1991 to 1994:

- Birth of the “scintillator community”
- Many progress in the understanding of the properties of 3 materials:
- CeF_3 had very good scintillation and radiation hardness properties **but no capability for large production**
- Heavy Glasses had good scintillation properties, **low cost but were not enough radiation hard for LHC**

⇒ **In 1994: Choice of PWO by CMS for the electromagnetic calorimeter**

⇒ **Choice of PWO for PHOs detector in ALICE**

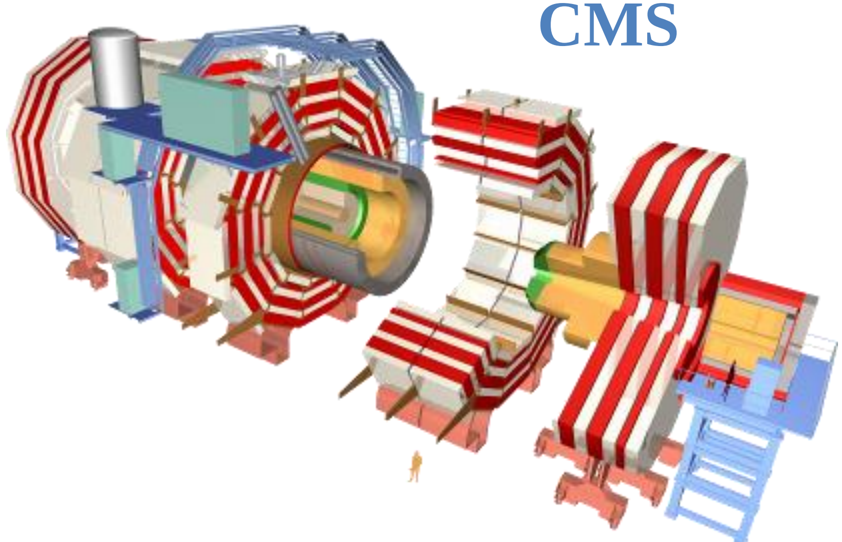
	Developed for LHC Crystal Clear/CMS		
	CeF_3	PWO $PbWO_4$	HFG Glass
Xo [cm]	1.66	0.89	1.6
r [g/cm^3]	6.16	8.2	6
t [ns]	30	15	25
l [nm]	310 340	420	320
Ref index n@l $_{max}$	1.68	2.3	1.5
LY [%NaI]	5	0.5	0.5

PWO crystals @CERN in LHC

2 LHC experiments use Lead tungstate crystals

ALICE :17920 crystals

CMS



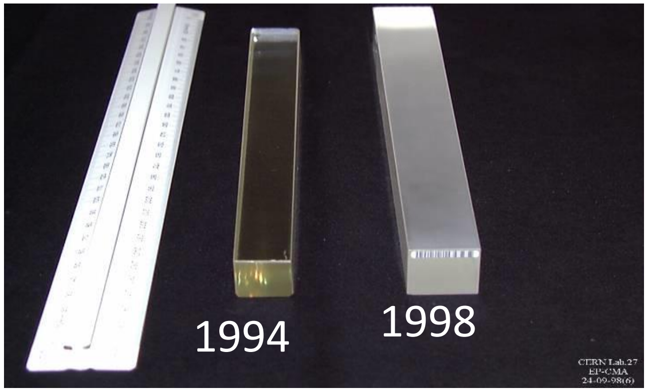
75848 Crystals = 100 tons

15 years of CMS ECAL construction

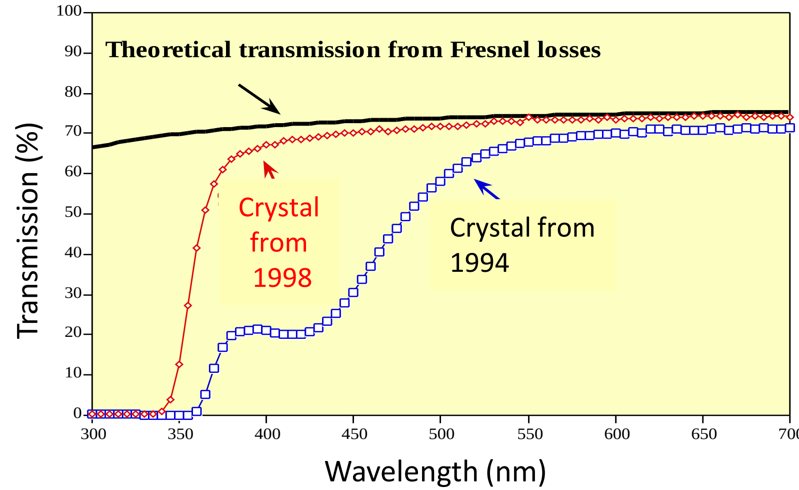
- 1994 : Choice of PWO for CMS electromagnetic calorimeter
- 1994-1998 : extensive R&D on PWO with strong participation of crystal clear
- 1998-2000 : Preproduction of 6000 crystals in BTCP
  - Increase production rate
  - Make crystal quality consistent over a large amount of crystals
- 2001 : Start of the Production in BTCP, Russia
- 2005 : Start of the Production in SIC, China
- 2007 : Barrel installation in CMS
- 2008 : Endcaps installation in CMS
- 2009 : First data taken in LHC
- 2012: Higgs discovery

From R&D to Production 1994 to 1998

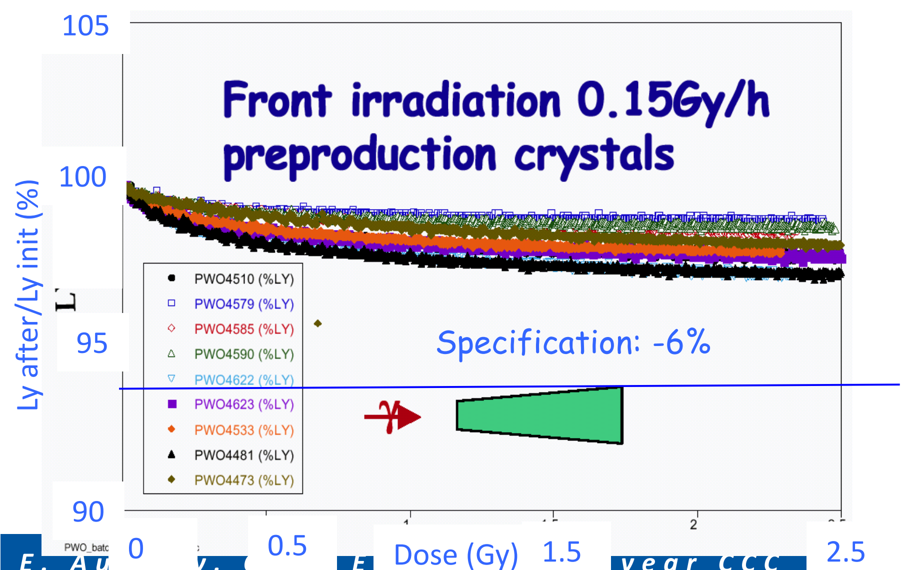
Optical properties improvement



Transmission improvement



Radiation hardness improvement



Delivery of the first 100 PWO Crystals Sept 98

Main results on PWO radiation hardness improvement

Radiation damage mainly due to host structure defects :

Primary defects :

- Lead vacancy $V_k(Pb)$
- Oxygen vacancy V(O)

Secondary defects created for charge compensation

- for $V_k(Pb)$: O^{--} + h, Pb^{2+} + h
- for V(O) : F and F^+ centres

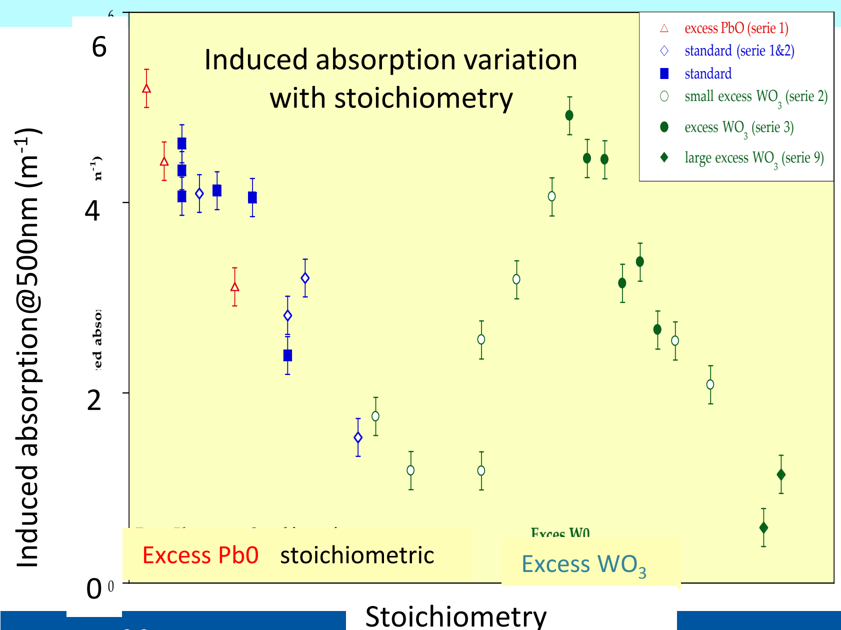
Optimisation of growth conditions, stoichiometry

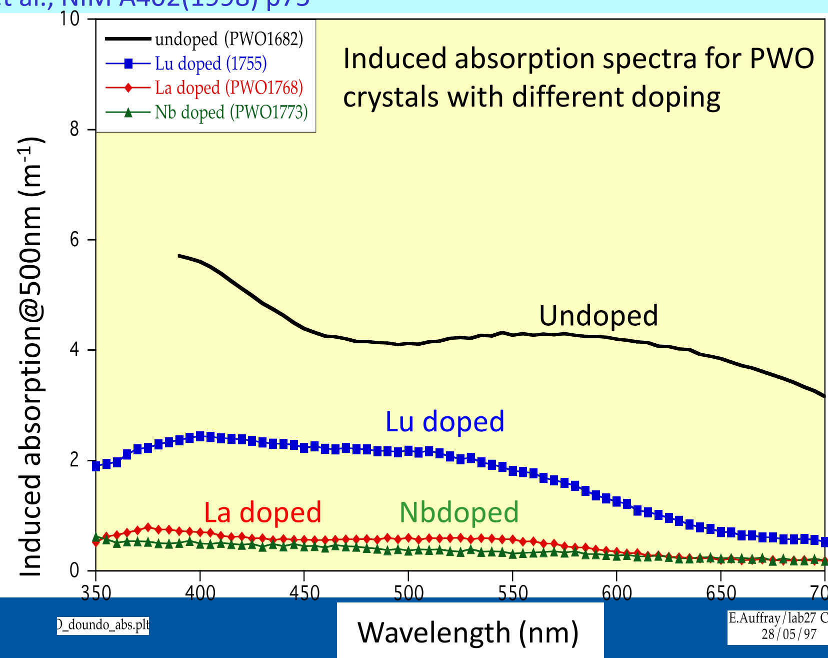
A.Annenkov et al., Rad. Measurements Vol29, p27
E. Auffray et al, proceedings of SCINT2007

Compensation by

- doping :Y, La, Lu, Nb, Sb
- optimum codoping Y-Nb

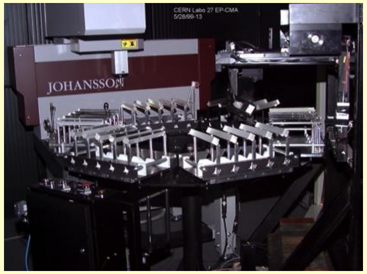
S. Baccaro et al, phys. stat. sol. (a) 160, R5 (1997) /A.Annenkov et al., NIM A426 (1999) 486
M. Kobayashi et al., NIM A404 (1998) 149. / X. Qu et al., NIM 486 (2002) 102
P. Lecoq et al., NIM A402(1998) p75





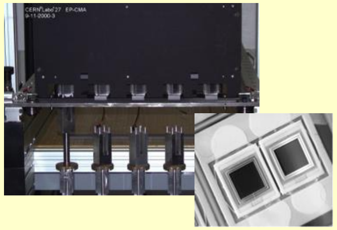
CMS ECAL assembly: 1998-2007

61200 crystals



Caracterisation des cristaux/

61200 sub-units



Collage des photodétecteurs sur les cristaux

6120 sub-modules

Montage des sous-modules

144 modules

Montage des modules

36 Super- modules

Montage des Supermodules

36 Super- modules

Installation d'écran thermique

36 Super- modules

Installation du système de monitoring

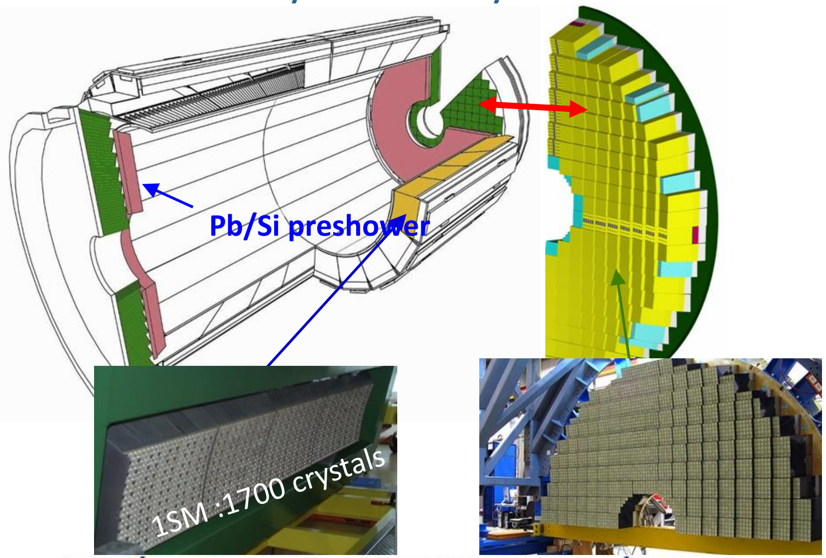
36 Super- modules

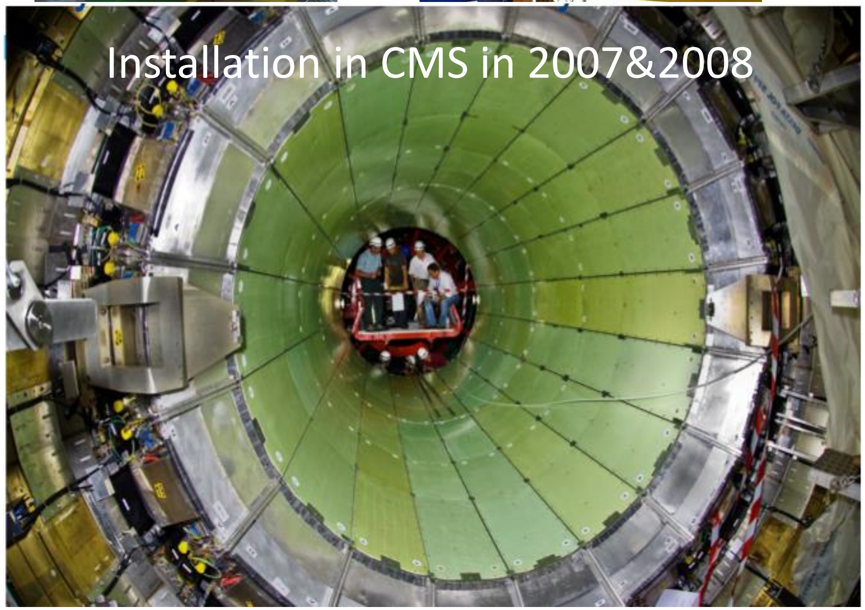
Installation du système de refroidissement

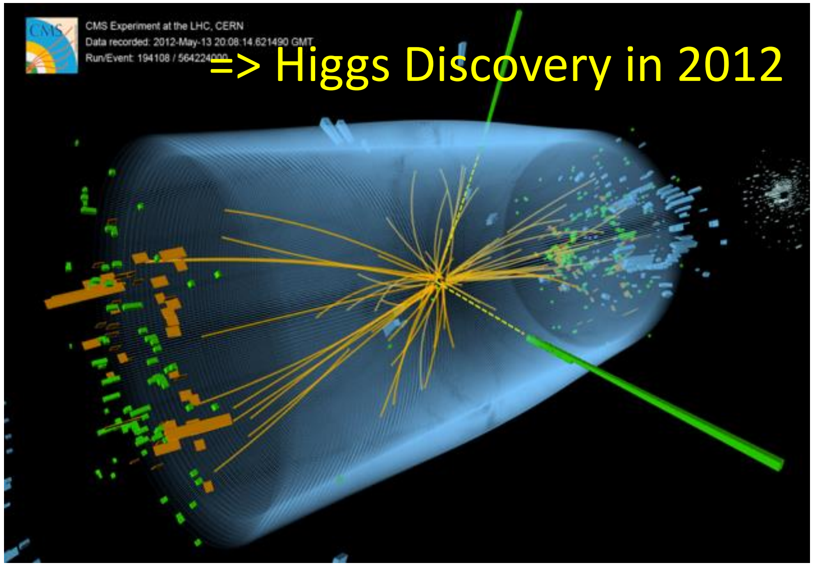
36 Super- modules

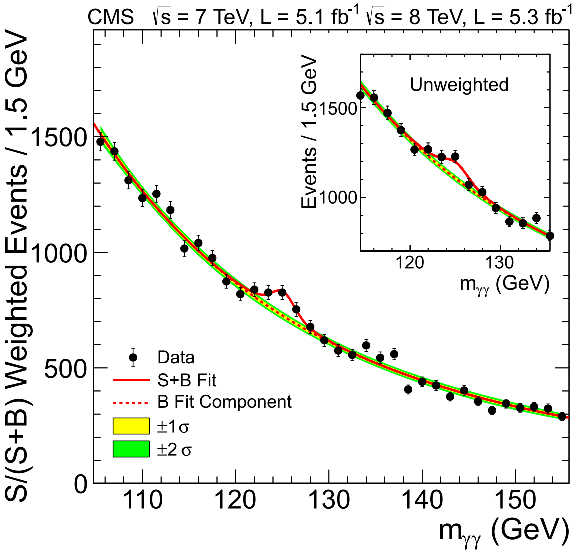
CMS ECAL: Higgs bosons discovery

75848 PWO Crystals : 10 years of construction









Other experiments with PWO

After the choice of PWO by CMS many others experiments proposed to use PWO

Alice: 17920 crystals 18cm length, produced in Apatity

***BTeV**: 10000 crystals, 22cm length*

CEBAF: (measure of electron beam polarization) 25 crystals

PRIMEX (precise measurement of the neutral pion lifetime): HYCAL: 1200 crystals, 18cm length

Neutral particle spectrometer (NPS) in JFLab (hall12): 1116 Xtals, 18cm length

Panda: Target Spectrometer @ PANDA:

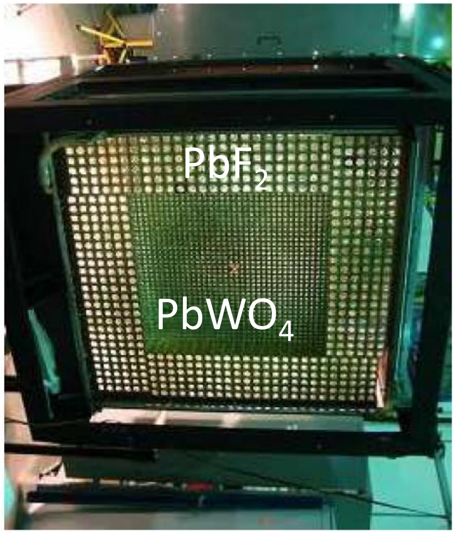
CLAS2 at Jlab: (study the light meson spectrum) :forward tagger detector: 332 crystals, 20cm length

Inner Crystal Calorimeter for EIC @JLab & BNL

Some examples

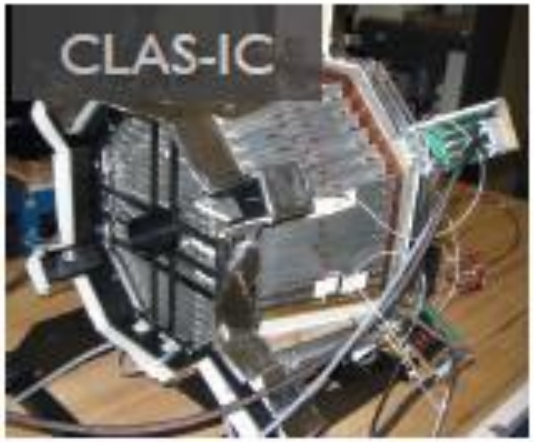
Module of PHOS in Alice experiment

HYCAL, Primex, JFlab



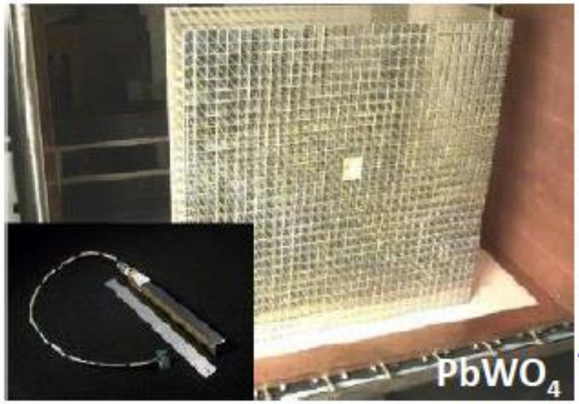
http://arxiv.org/abs/physics/0609201v1

Forward tagger, Class2, JFlab



Courtesy M. Battaglieri

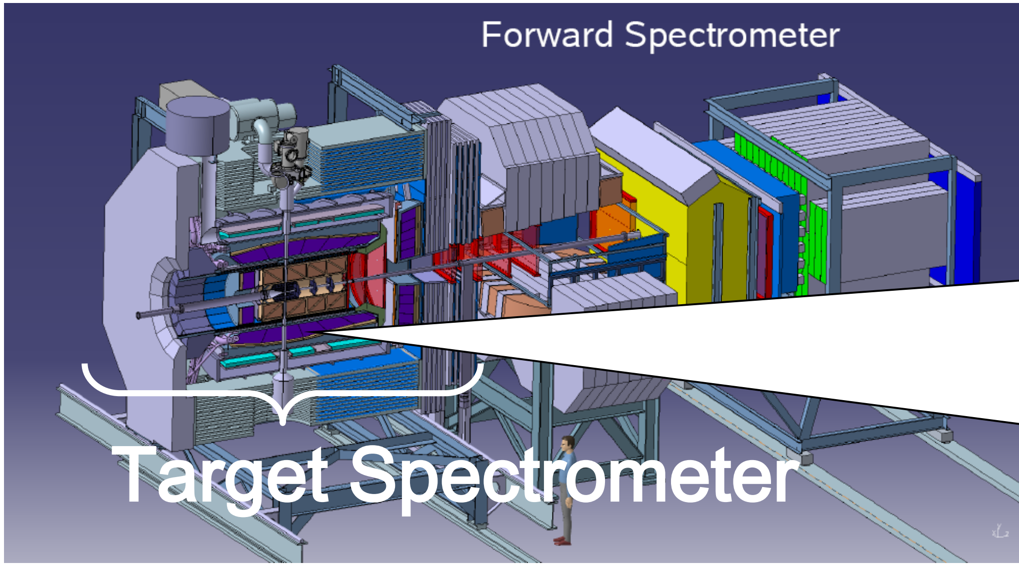
NPS, JFlab

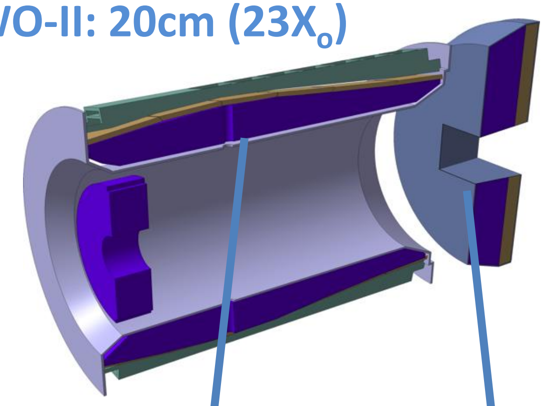


Calor2014, JP, conference seies 587 (2015)012048

the PANDA detector at FAIR

4π detector for spectroscopy & reaction dynamics with antiprotons





- **photon detection with high resolution**

over a large dynamic range: 10MeV < E_γ < 15GeV

- **high count-rate capability ($2 \cdot 10^7$ Annihilations/s)**
- **nearly 4π coverage**
- **sufficient radiation hardness**
- **timing information for trigger-less DAQ concept**

Need 15164 PWO crystals

8000 produced in BTCP

⇒ Need new producer

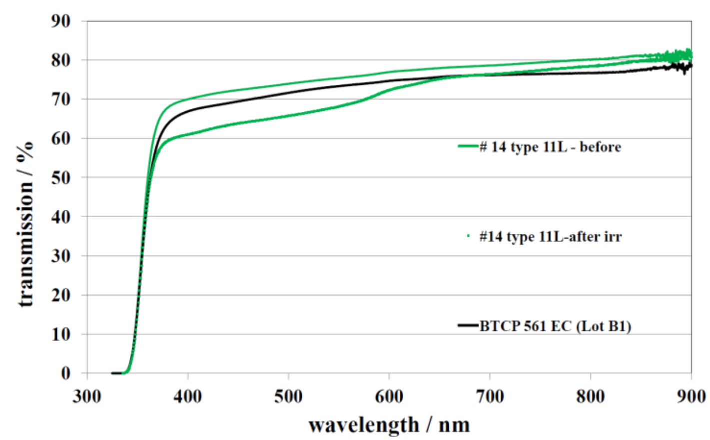
⇒ **Crytur company coming back**

R. Novotny, IEEE 2016

PWO production in Crytur in 2016

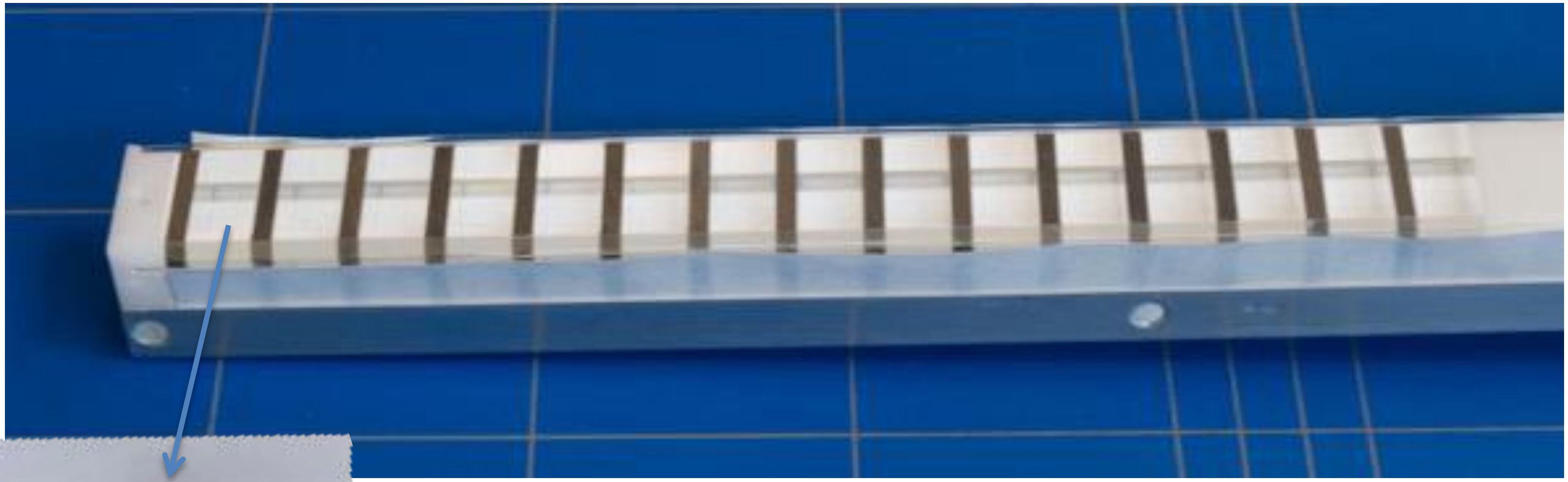
- **production based on Czochralski technology**
- **use of existing pre-mixture of raw material (*NeoChem*, Moscow) (BTCP)**
- **Preproduction starts in 2016**

R. Novotny, IEEE 2016



New interest for CeF_3

For CMS upgrade endcap calorimeter:
Sandwich calorimeter CeF3/W proposed by ETHZ Group: F.Nessi et al.



CeF_3 plate
$24*24*10mm^3$

F. Ness.-T. et al., CALOR 2014, JoP Conf. Ser. 587 (2015) 012039
F. Ness.-T. et al., **IPRD 2016, 14th Topical Seminar on Innovative Particle and Radiation Detectors, Siena, Italy**

CCC Impact on HEP

- Creation of the scintillator community
- Cerium understanding
- Radiation hardness study:
  - Understanding of radiation damage mechanisms,
  - Acquire knowledge of different investigation technics

More recently

- Engineering of scintillator: mixed materials, codoping
- New crystal growth development: micro pulling down technic
- Timing properties

Since 2010: investigations of radiation hardness under gamma and hadrons radiations for HL-LHC

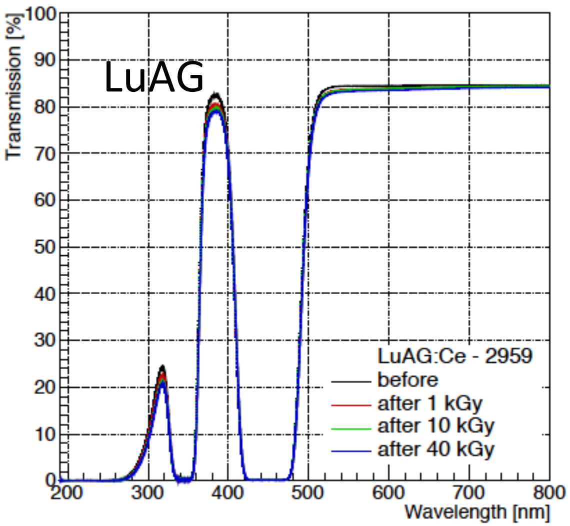
List of the scintillation materials studied at different irradiations

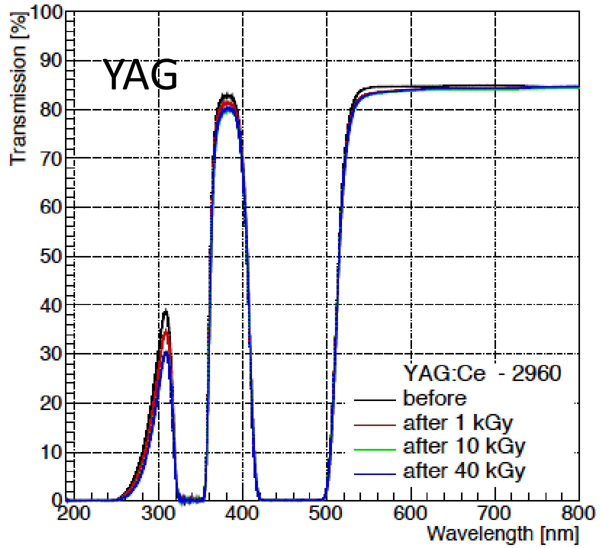
ϒ-quanta 60Co(1.22MeV), absorbed doses 10-2000Gy	24 GeV & 150 MeV protons	reactor neutrons
PWO, PWO-II	**PWO, PWO-II**	**PWO, PWO-I**
LSO:Ce(LYSO:Ce)	LSO:Ce(LYSO:Ce)	
LuAG:Ce	LuAG:Ce	**Plastics:**
BSO	BSO	**EJ260**
PbF_2	PbF_2	**EJ200**
BaF_2	BaF_2	
GSO:Ce	GSO:Ce	
YSO:Ce	YSO:Ce	
YAG:Ce(Pr)	YAG:Ce(Pr)	
YAP:Ce (Pr)	YAP:Ce (Pr)	
DSB:Ce(glass and glass-ceramics)	DSB:Ce(glass and glass ceramics)	
Y_2O_3 (micro-ceramics)	Y_2O_3 (micro-ceramics)	
LiF	LiF	
Plastics	Plastics	

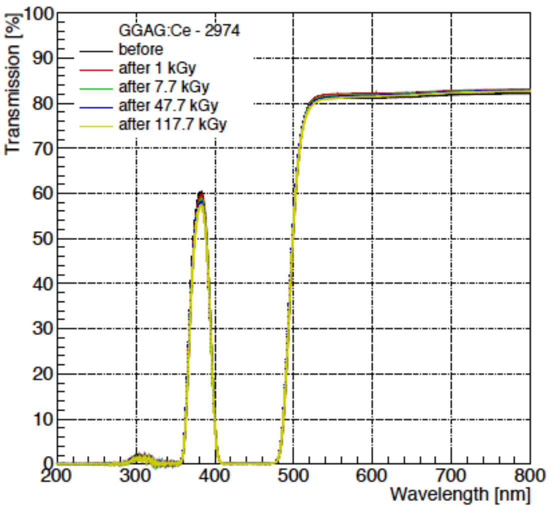
Results have been published in 12 articles and reported regularly at IEEE NSS-MIC, SCINT and INTELUM Conferences

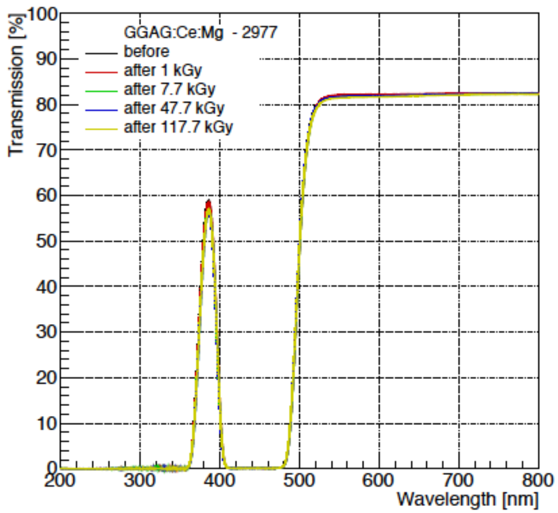
Radiation tolerant crystals: Garnet crystals

gammas

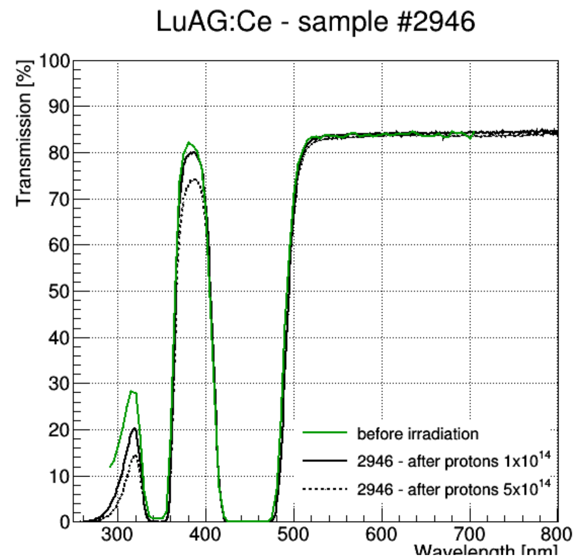


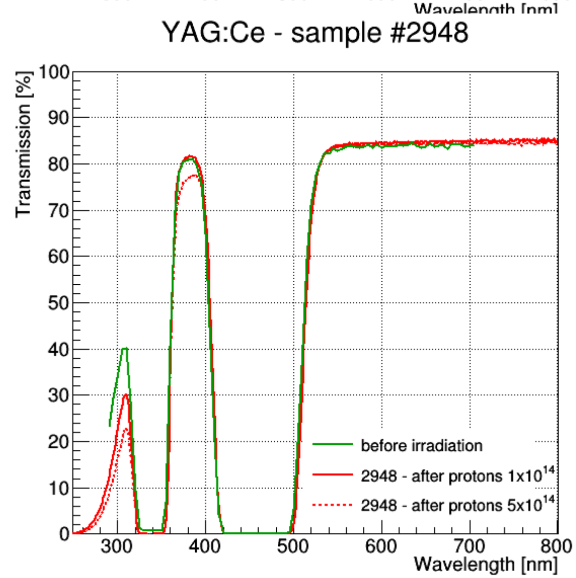




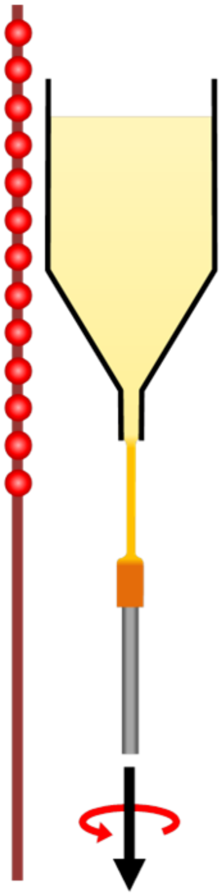


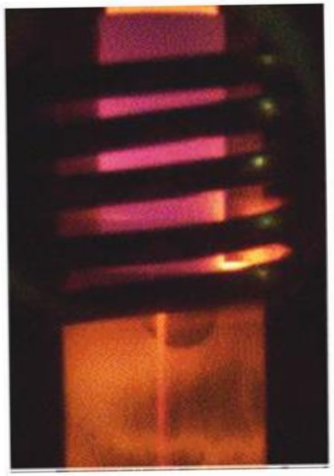
Protons

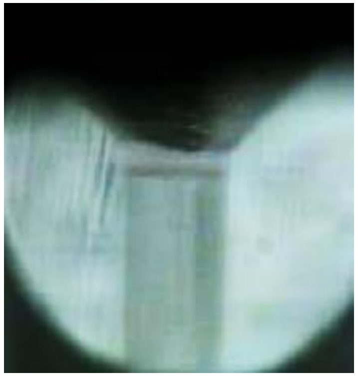




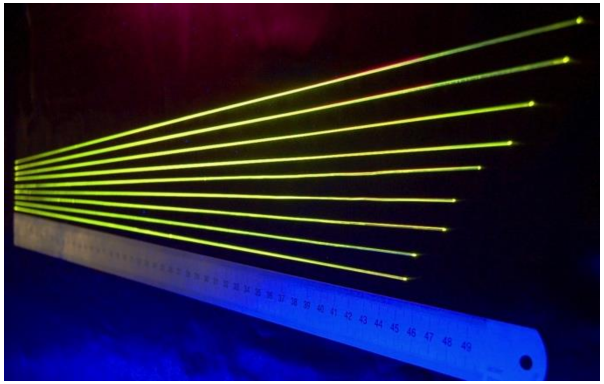
Micro-Pulling down technology for crystal fiber growth







Courtesy Fibercryst



Fibers produced @ILM

Intelum

Micro-pulling down (μPD) : multiple advantages

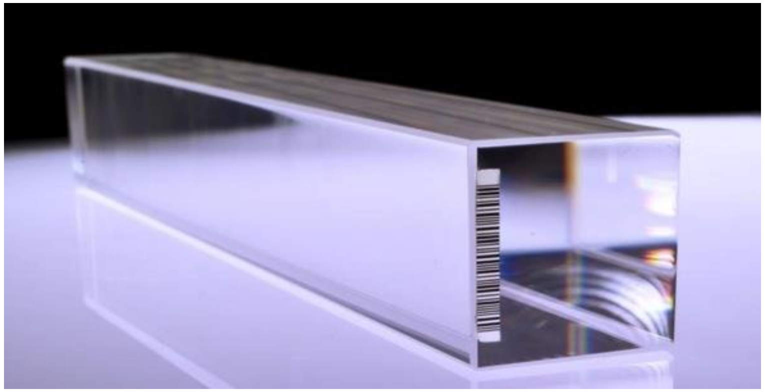
- Wide range of diameters 300 μm – 3 mm
- Lengths up to 2 m
- Multiple geometries for capillary die ○ □ ⬡
- Fast pulling rates
- Multi-fibers pulling possibilities (in parallel)

=> Investigation of mass production capability

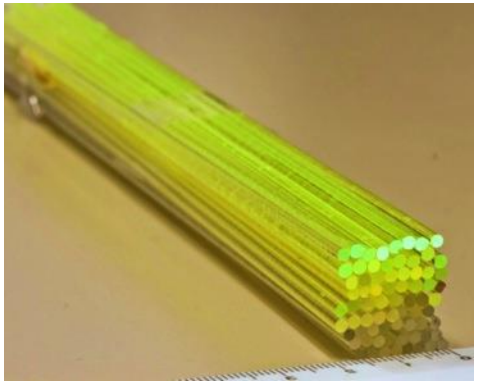
Scintillating crystal fibers: Flexibility for the calorimeter design

Homogeneous calorimeter

From bulk crystal

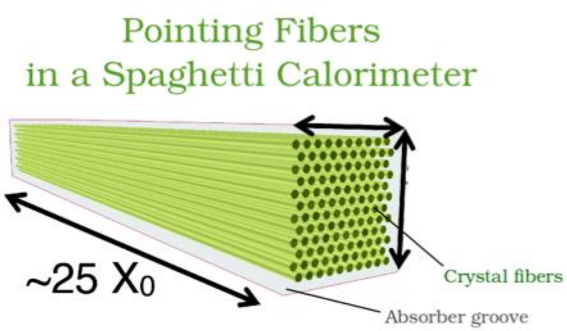


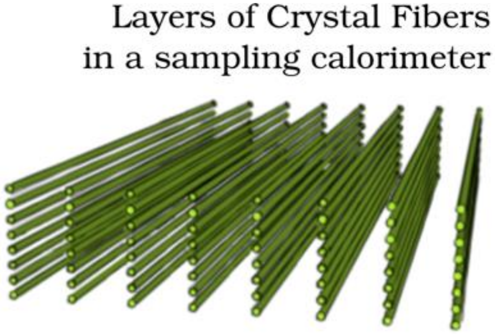
To bloc of fibers



=> Need large volume of fibers with high density

Sampling calorimeter





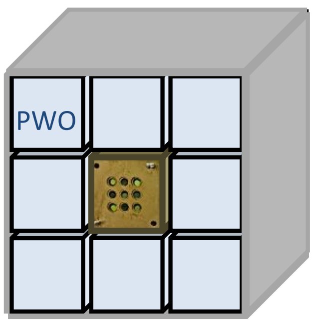
=> Need less fibers, possibility to use materials with lower density

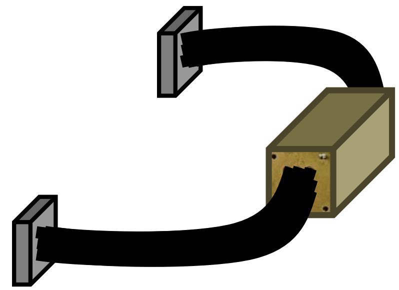
First calorimeter prototypes

In the frame of the CMS HCAL/ECAL upgrade:

We performed several test beams with crystal fibers

in CERN H2 beam November 2012: 9 fibers



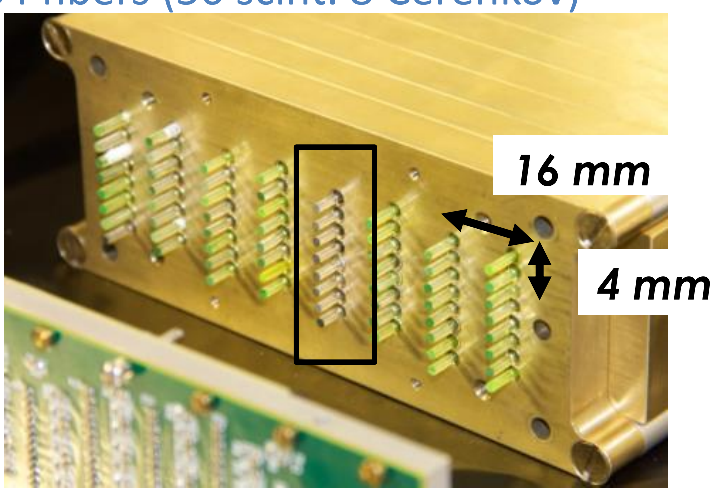


SiPM readout
On 2 sides of each chanel

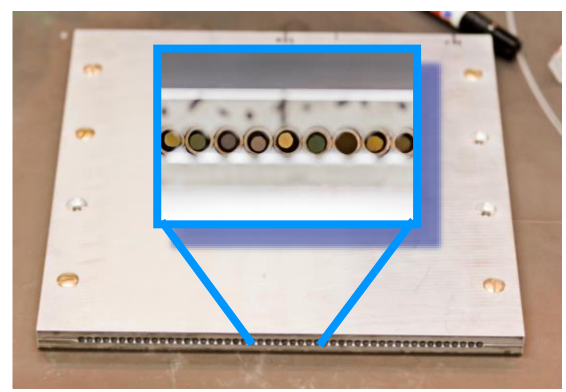
M. Lucchini et al, JINST 8 10017 (2013)

5 LuAG fibers with highest concentration of Cerium
3 with lower Ce concentration
1 undoped for Cherenkov signature

- in Fermilab March2014:
- 64 fibers (56 scint. 8 Cerenkov)



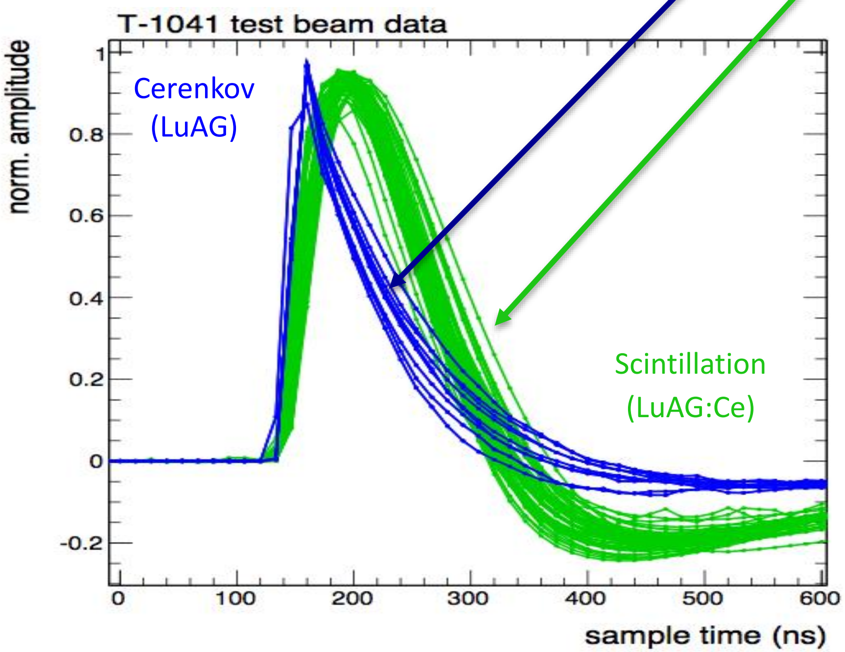
- At CERN August 2014:



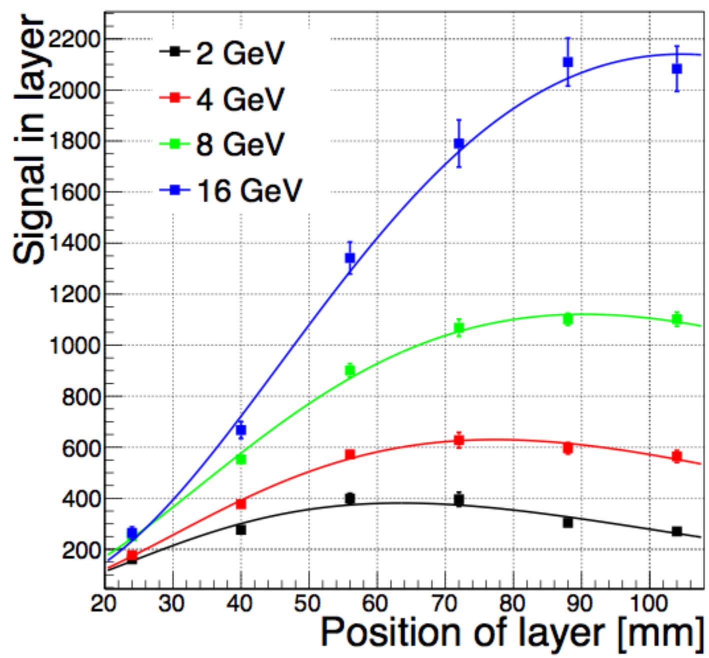
Few results from Fermilab test beam

electron beam from 2 to 16GeV

Good separation of scintillation/Cerenkov pulses



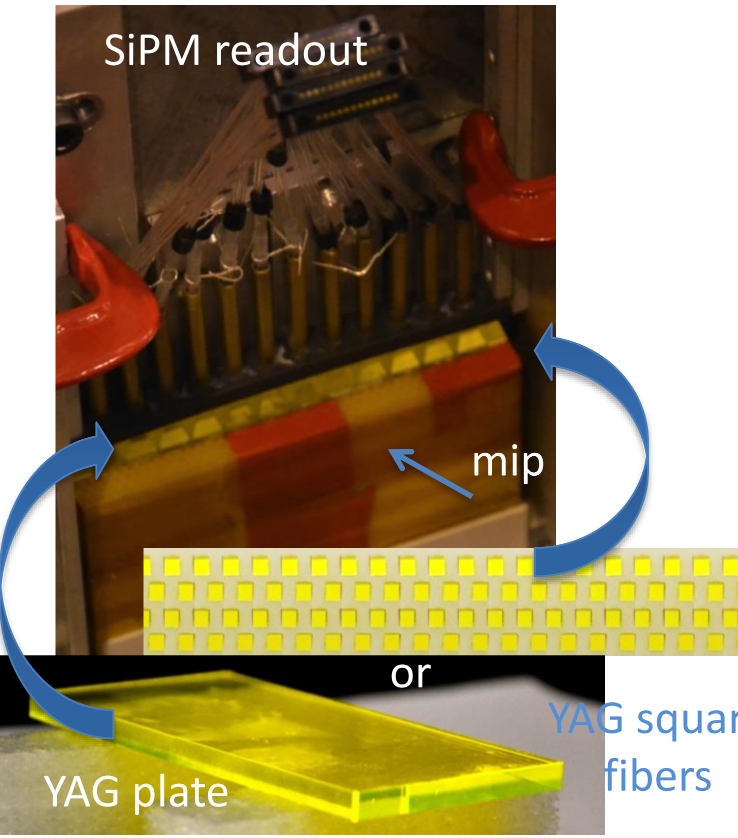
Energy scan



A. Benaglia,et al., submitted to JINST

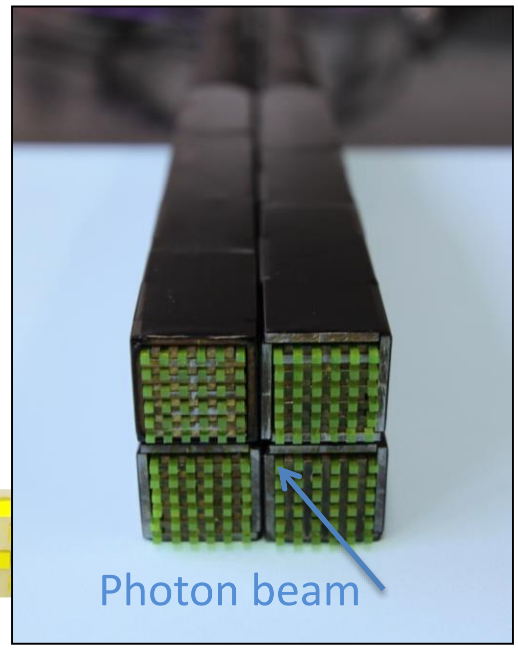
First calorimeter prototypes with square fibers in 2015

Tile concept
Test in CERN H2 150GeV muons



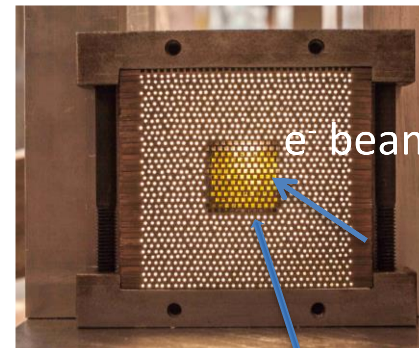
YAG square fibers

SPACAL concept @ MAMI (Mainz)
Tagged photon beam
from 56 to 766 MeV



LuAG square fibers
in W Absorber

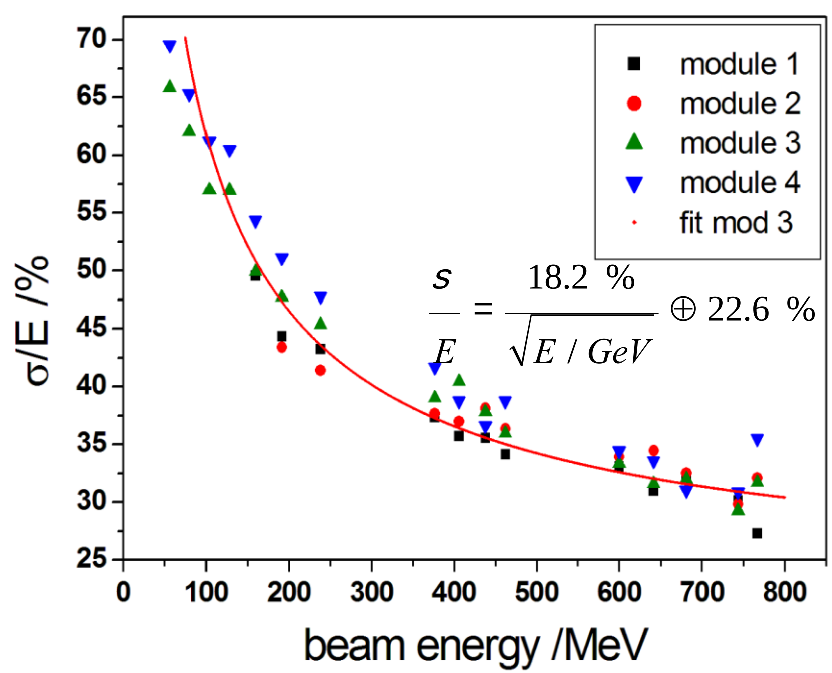
SPACAL concept
Test in CERN H4 with e- beam
10GeV to 200GeV

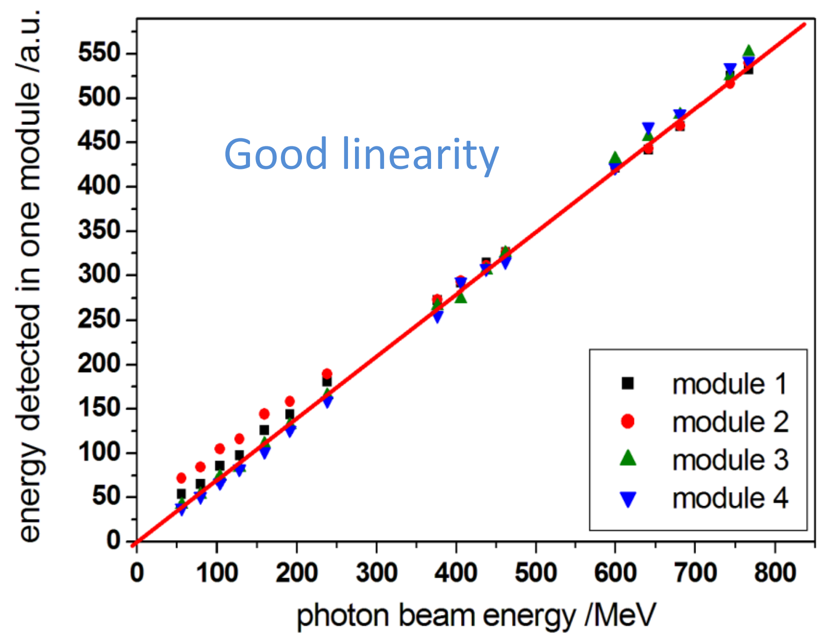


YAG square fibers
in a 0,75W/0.25Cu Absorber

Few results tests @MAMI

photon beam from 56 to 766 MeV
Readout PMT

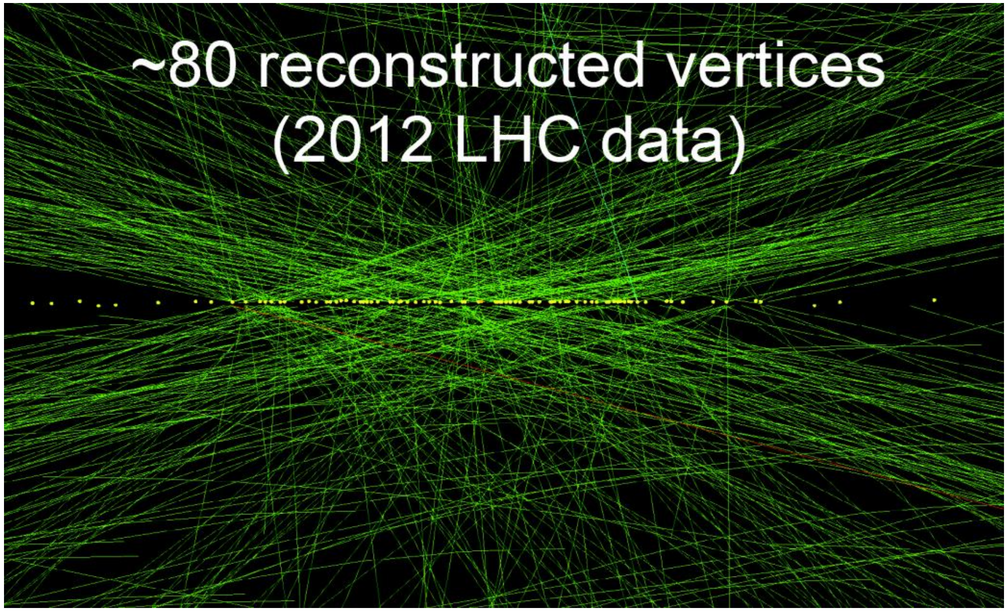




Future: fast timing detection

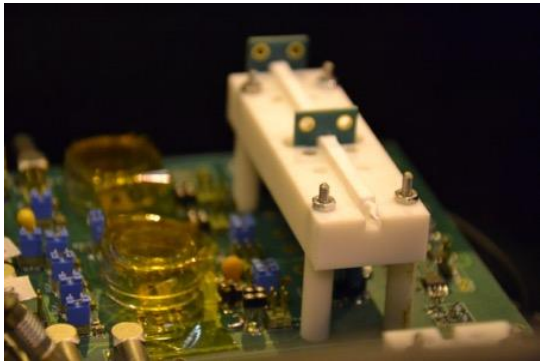
In HEP: Search for rare events implies high luminosity accelerators

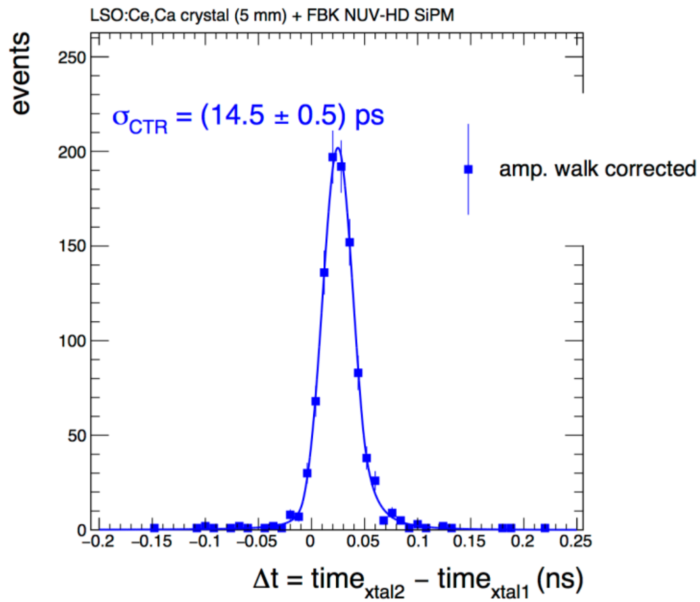
- → Rate problems;
- → Pileup of >140 collision events per bunch crossing at High Luminosity-LHC;
- → Pileup mitigation for better vertex reconstruction via TOF requires TOF resolution < 50ps.



Time resolution with MIP

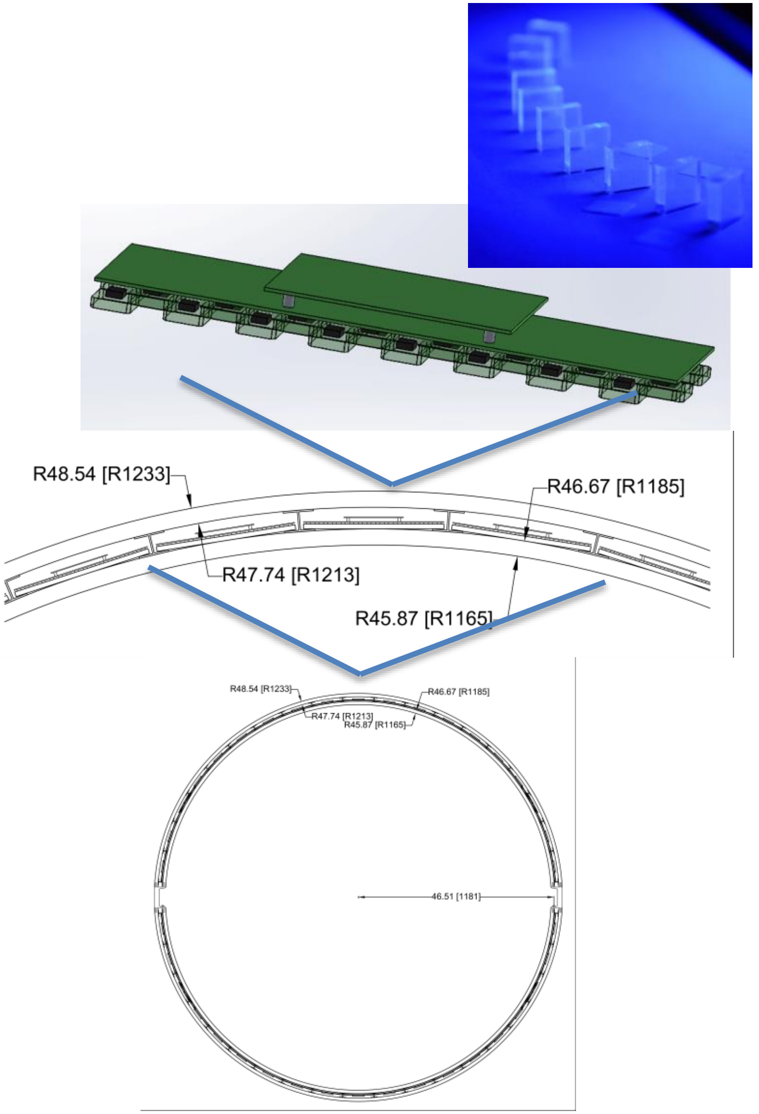
LSO:Ce:Ca crystal 2x2x5mm³– SiPM (FBK NUV-HD) with MIP (muon 150GeV) in H2



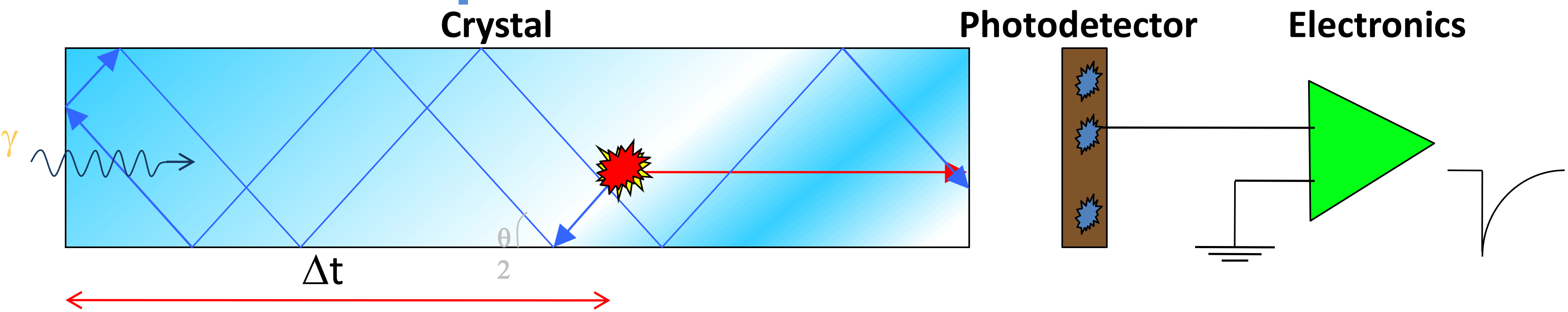


A. Benaglia et al, NIM. A, vol. 830, pp. 30-35, May 2016

Possible timing layer in CMS



Need to understand the photodetection Chain



$t_{kth\ pe} = \Delta t + t_{k'\ ph} + t_{transit} + t_{SPTR} + t_{TDC}$

Conversion depth | Scintillation process | Transit time jitter | Single photon time spread | TDC conversion time

Scintillator R & D
- Particule Interaction
- Light generation
- Light transport
- Light transfer
- Light collection

Photodetector R & D
- Reduce SPTR and DCR
- Increase fill factor (PDE)
- Digital SiPM
- MCP for PET & HEP

Electronics R & D
- TDC < 10ps bins
- Monolithic architecture
- High bandwidth
- Low noise
- Massive parallel data
- High number of channels

⇒ **Challenge: Understanding key factors of timing resolution**

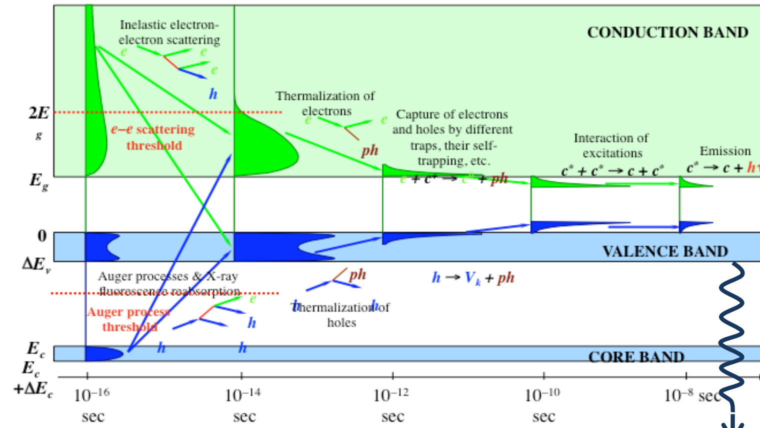
⇒ **Proposing routes toward 10ps**

ENDO TOFPET US Endoscopic TOFPET & Ultrasound — THE PICOSEC MC-NET PROJECT — FAST Fast Advanced Scintillator Timing — TICAL

Understanding of the Scintillator limits for time resolution

1) The scintillation mechanism

- Light yield;
- Rise time;
- Decay time.

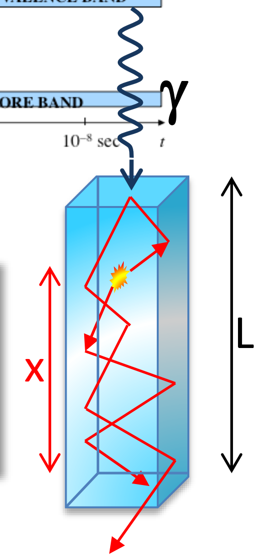


A. Vasil'ev, SCINT2001 proceedings, NIMA 486 (2002) 367

2) The light transport in the crystal

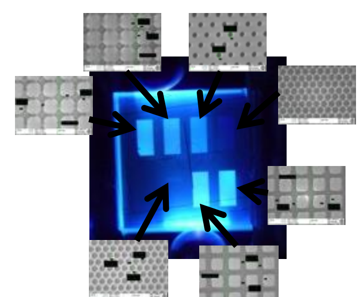
- Time spread related to different light propagation modes

Δt_{max}= 71 ps for x = L
Δt_{max}= 384 ps for x = 0
(L = 20mm



3) The light extraction efficiency

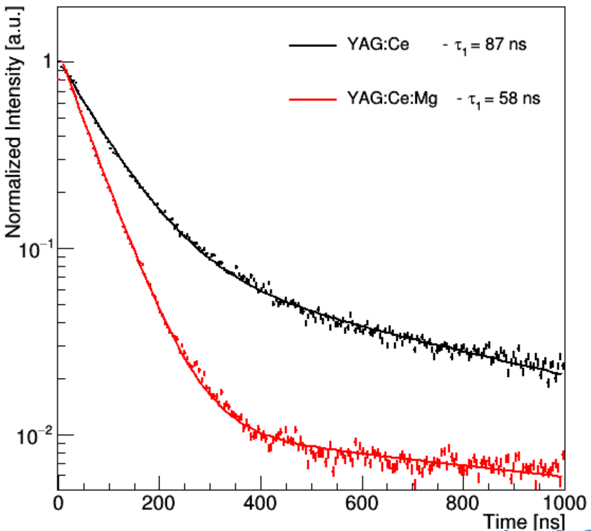
- Light Yield → Light Output;
- Impact on photostatistics;
- Weights the distribution of light propagation modes.



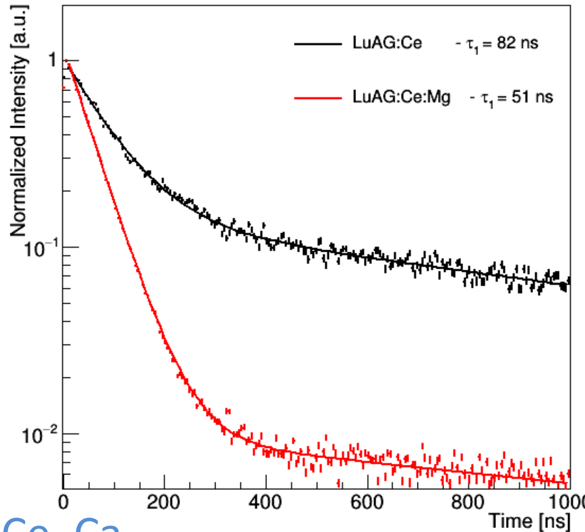
Photonic X^tals
P. Lecoq, A. Knapitsch, Int. J. of Mod. Physics A Vol. 2(2014) 1430070

Study of Codoping Ce,X^{2+} in Garnet crystal

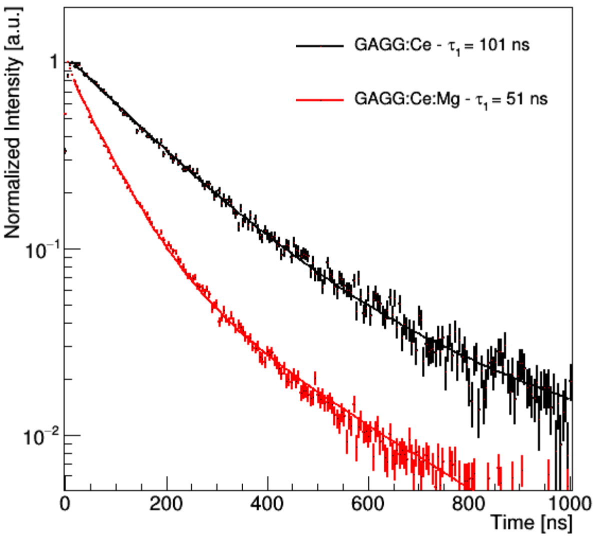
YAG



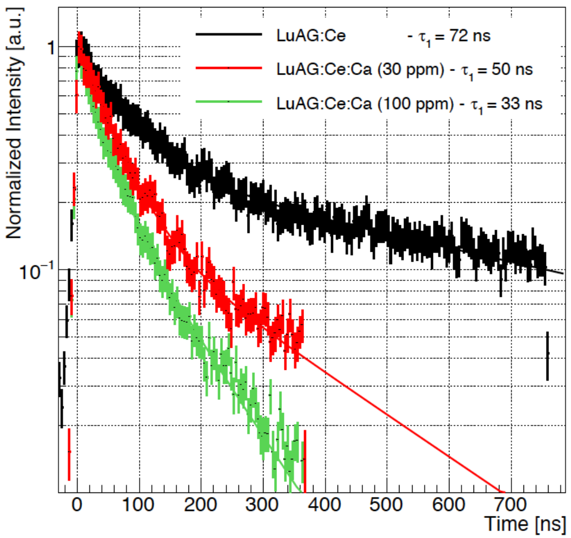
LuAG



GAGG



LuAG: Ce, Ca



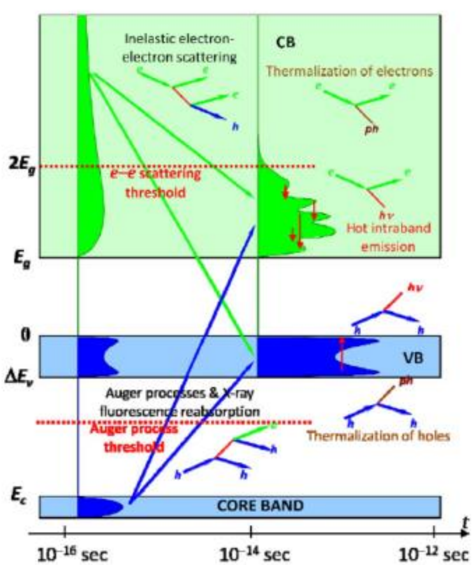
Shorter decay time with codoping

=> Role of Ce^{4+}

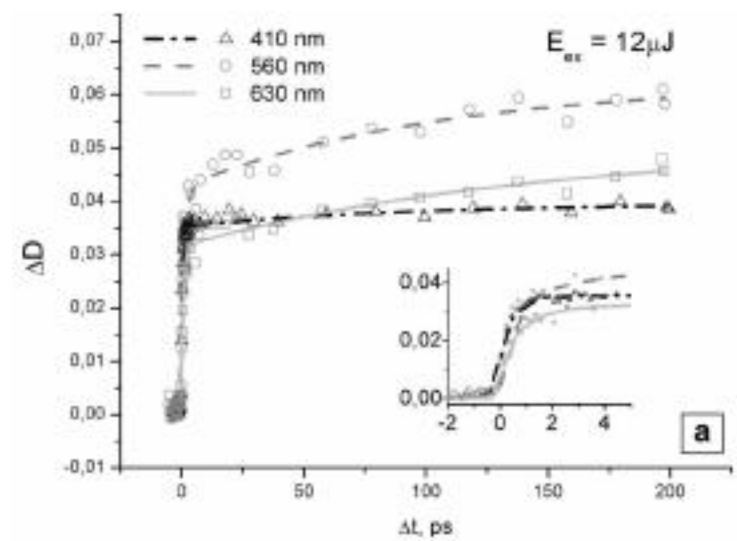
Kamada et al, O-14-3 at SCINT2015
M. Lucchini et al, NIM A Volume 816, pp 176–183,
A. Petrosyan et al. , Journal of Crystal Growth (2015), pp. 46-51

Study of fast phenomena is scintillators

- Cerenkov
- **Hot intraband luminescence**
- Quantum confinement driven luminescence



A. Vasiliev



The transient absorption kinetics of a CeF_3 single crystal obtained at different wavelength of the probe pulse:

E. Auffray et al., JINST 9 (2014) P07017

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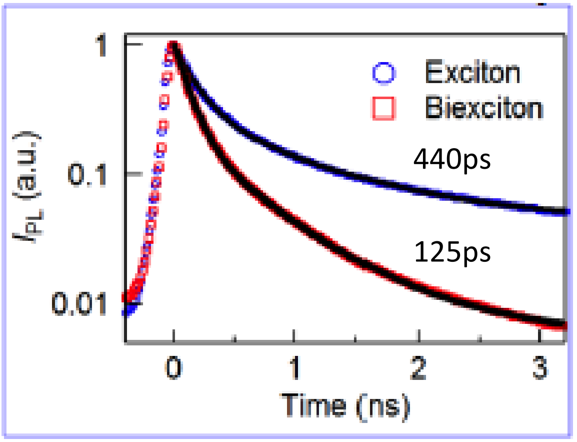
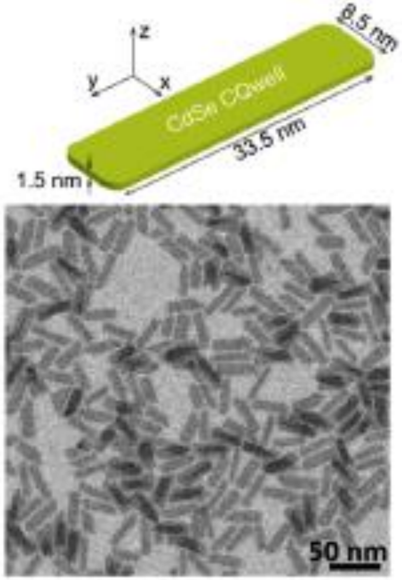
colloidal quantum wells

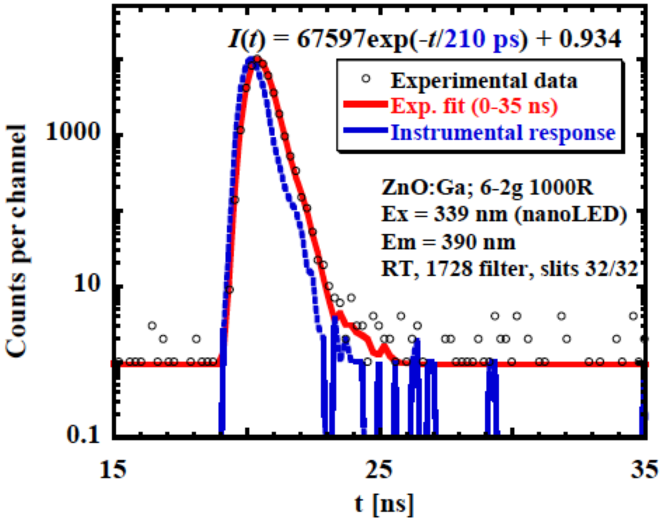
CdSe CQwell





ZnO based quantum dot

Photoluminescence ZnO:Ga



J. Grim et al. Nature nanotech. **9**, 891–895 (2014),
R. M. Turtos et al. Submitted to JINST

L. Prochazkova et al. Opt Material
R. M. Turtos et al. Submitted to Physica Status Solidi (RRL)

Conclusion

Since 25 years Crystal Clear has been very active in the development of scintillators for HEP in particular:

- In the understanding of scintillation mechanisms and radiation hardness
- The development of new materials

The recent developments initiated in Crystal Clear:

- New production technology
- Engineering of the materials
- Fast timing

Open new promising perspectives for the future detectors