

Inorganic single crystalline fibers

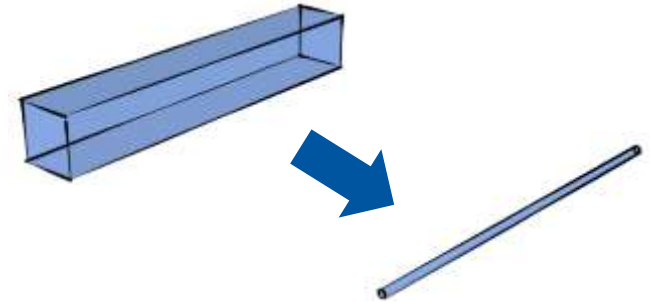
Growth, characterization and applications

Kristof Pauwels

University of Milano-Bicocca (Italy)
CERN (Switzerland)

What is it ?

As in previous talk



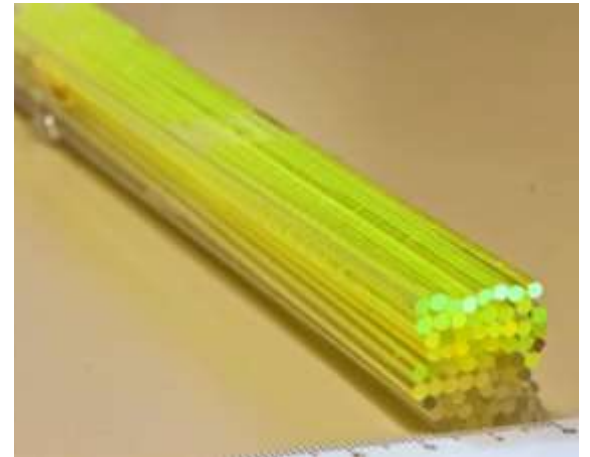
inorganic single crystalline fibers

As opposed to organic fibers
=> not “standard optical fibers”!

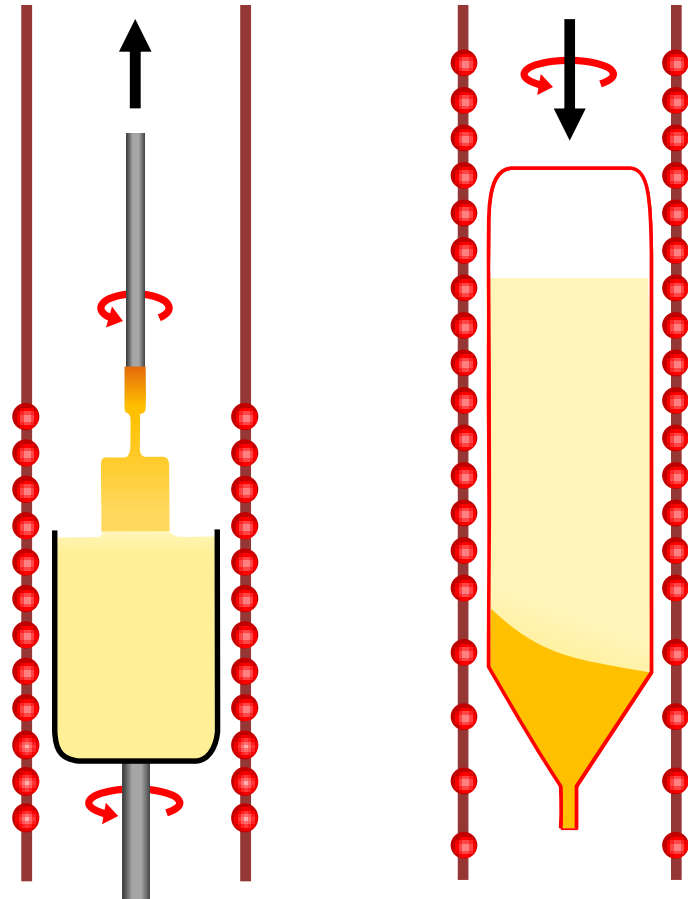


> The specificity comes from their shape!

The basic idea:

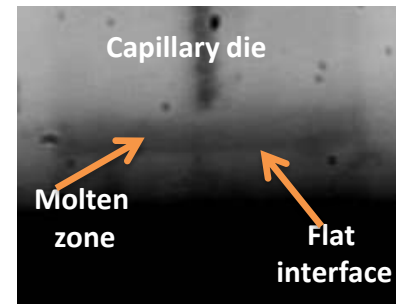
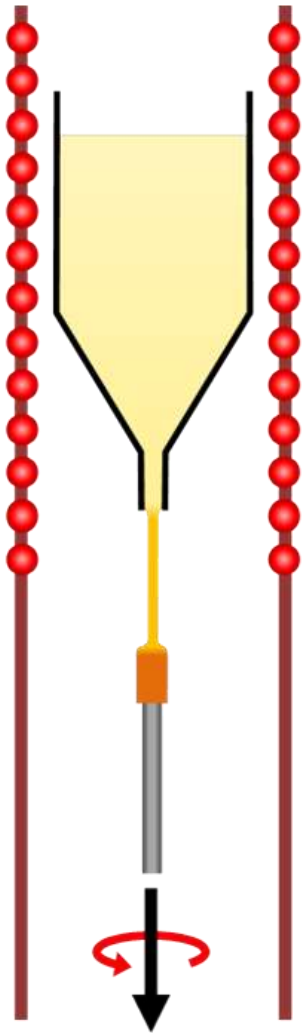


Shaping crystals is not easy



And it supposes to grow large quantities!

The micro-pulling down (μ PD) technique allows growing single crystals of small diameter



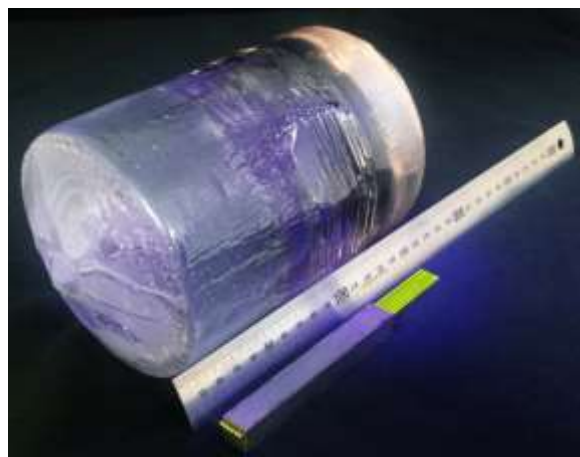
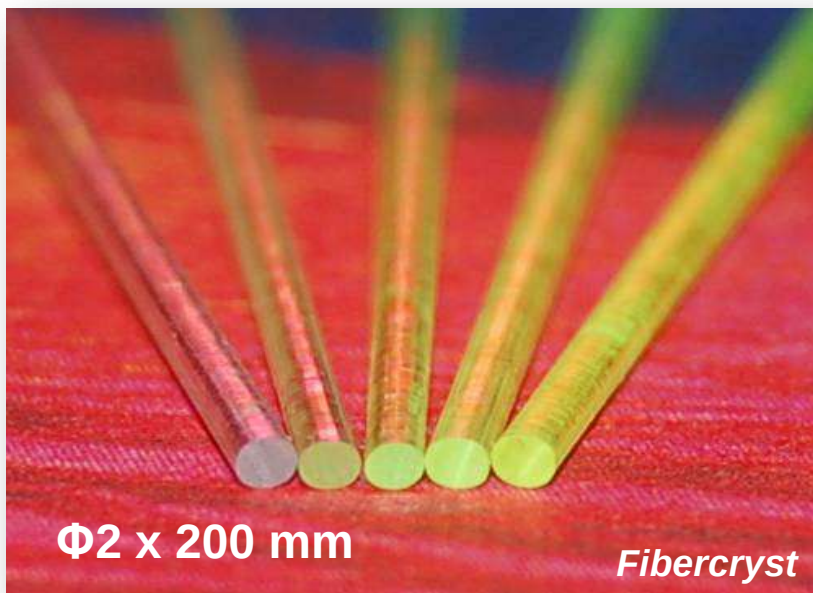
Micro-pulling down (μ PD) combines multiple advantages

- Diameters 300 μ m – 3 mm
- Lengths up to 2 m
- Multiple geometries for capillary die ○ □ ◇
- Fast pulling rates
- Multi-fibers pulling possibilities (in parallel)
- Cost effective wrt traditional growth techniques

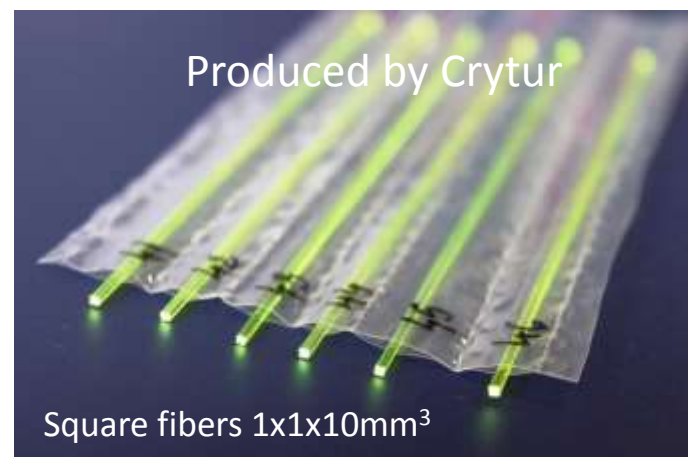
Fast prototyping

Reduces the price

However, cutting and polishing technique recently made a lot of progress, μ PD not the only approach to consider !



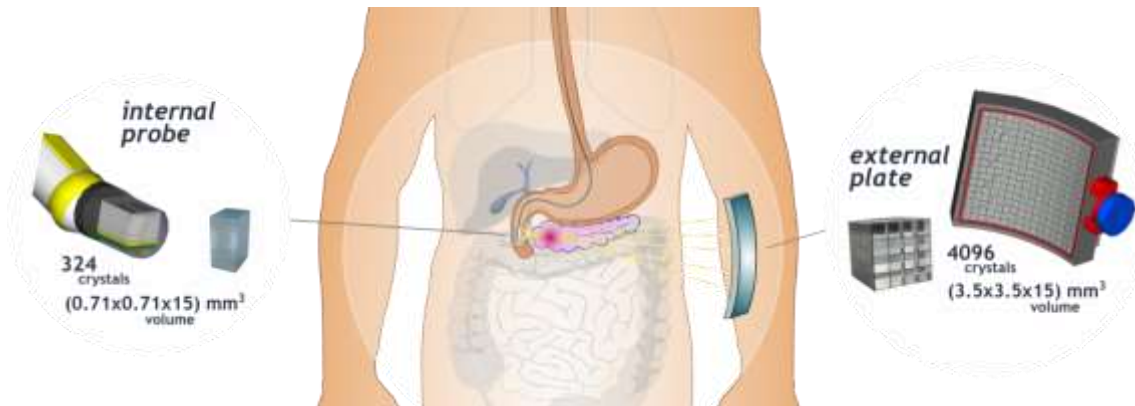
Cutting
&
Polishing



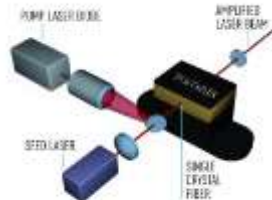
Crystal Fibers are very useful for fine segmentation

Scaling down

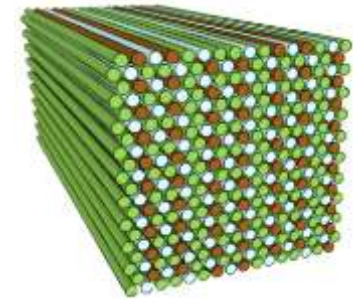
PET scanners / heads



Compact laser rods/modules



Multi-functional (méta-)materials

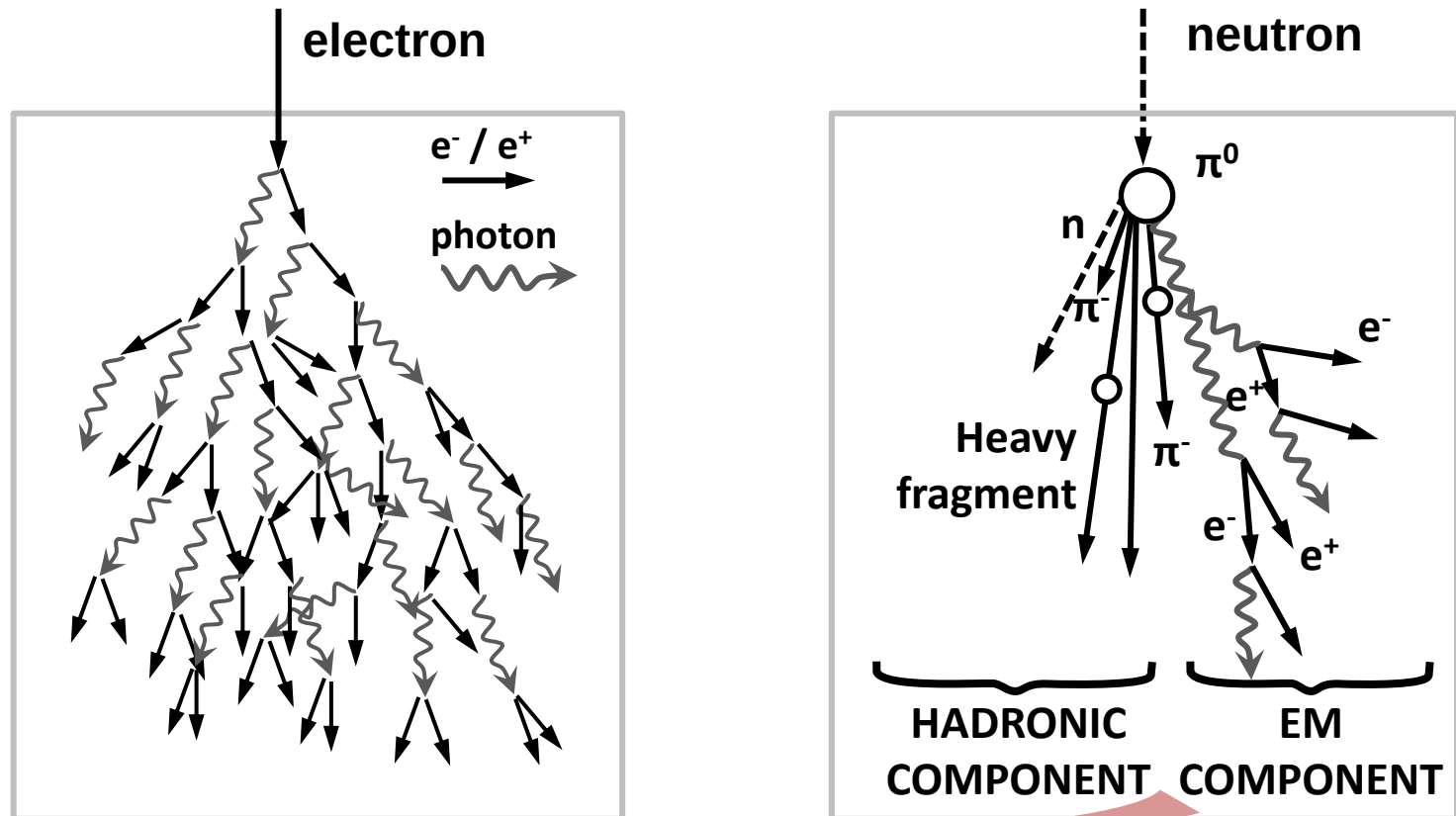


Especially in HEP

Applications In High Energy Physics (HEP)

Influence of the particle type

Standard calorimeters have a conversion factor which depends on the particle type (photons, leptons or hadrons)



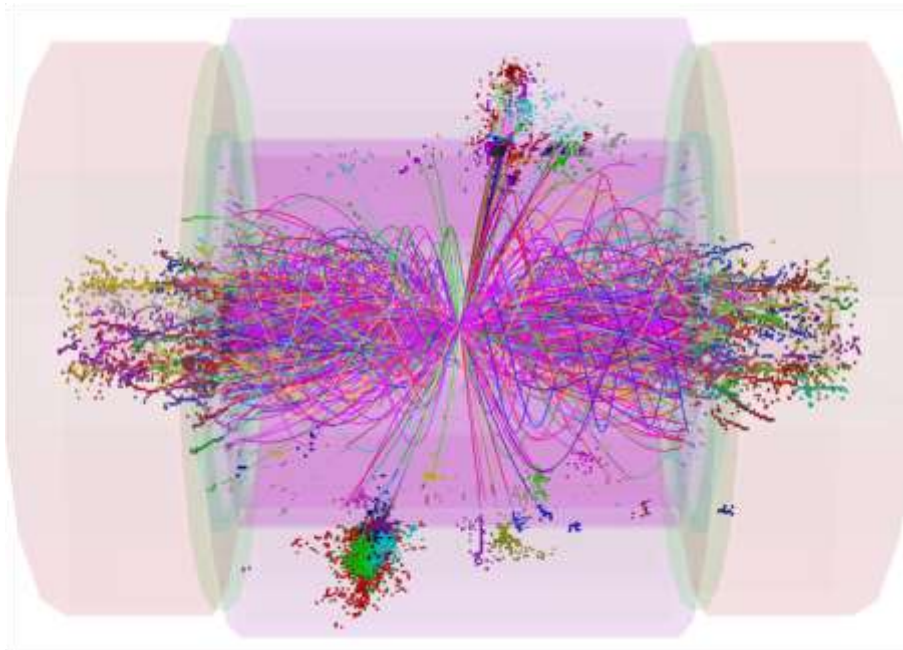
The fluctuations in the electromagnetic fraction (*fem*) of the shower then cause fluctuations in the calorimeter response

How to identify a particle?

Option 1

Track them!

Particle **Flow** approach



Option 2

Check their speed!



Very convenient speed
controler for particles:
Cherenkov light

Dual Readout Approach

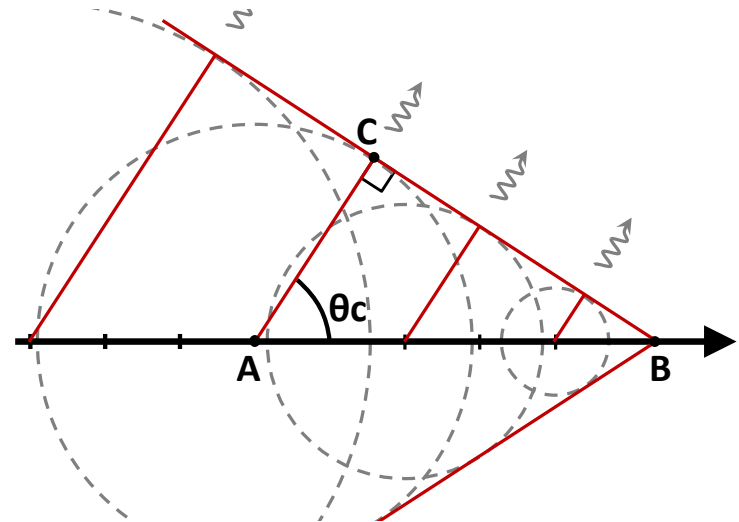
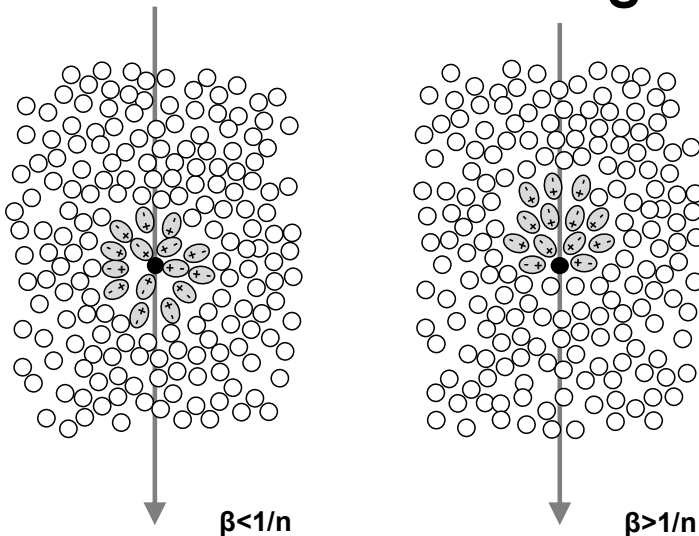
What is Cherenkov light ?



Cherenkov light is emitted when charged particles travel faster than the phase speed of light in the medium



For high energy calorimeters, leptons can be discriminated since they are more likely to emit Cherenkov light (as compared to hadrons)



Dual readout: {Scintillator + Cherenkov radiator} High density!

Homogeneous detector

with an optical or timing separation of signals

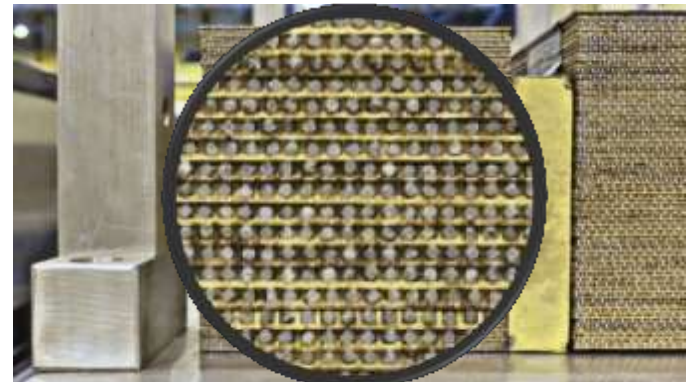


Example: PbWO_4 crystals
CMS ECAL [TDR 97]

Problem: Non strict separation...

Sampling calorimeter

with both scintillators and Cherenkov radiators



DREAM collaboration
[Wigmans et al. NIM-A 617 (2010)]

Problem: sampling fluctuations

Extrinsic scintillators with no doping can be efficient Cherenkov radiators!

Material with:

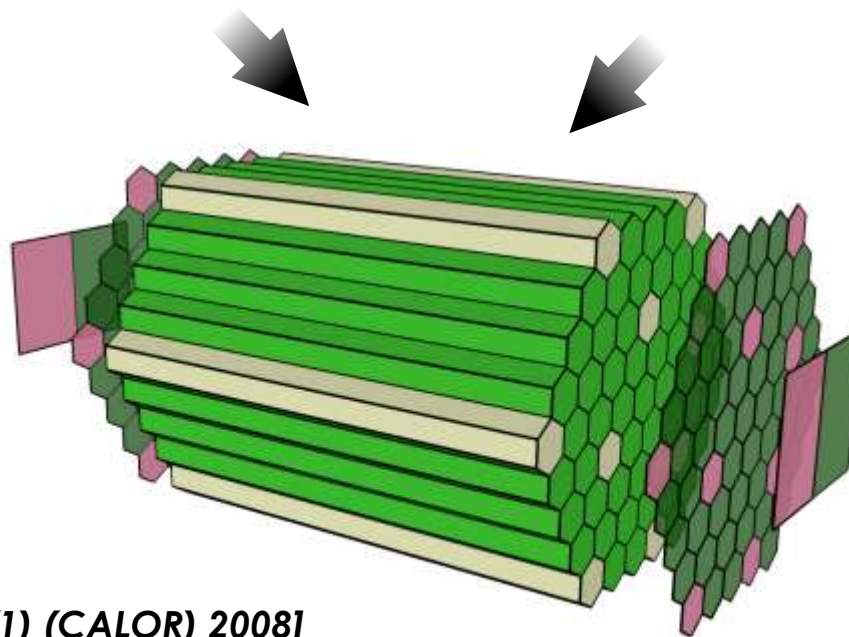
- high refraction index
- good UV transmission

Doping centers with:

- high light yield
- fast decay

Cherenkov radiator

Scintillator



[Lecoq IEEE TNS & JoP 160(1) (CALOR) 2008]

Example of chosen material: $\text{Lu}_3\text{Al}_5\text{O}_{12}$ (LuAG)

$\rho=6.73 \text{ g/cm}^3$, $X_0=1.41 \text{ cm}$, $\lambda_{\text{int}}=23.3 \text{ cm}$

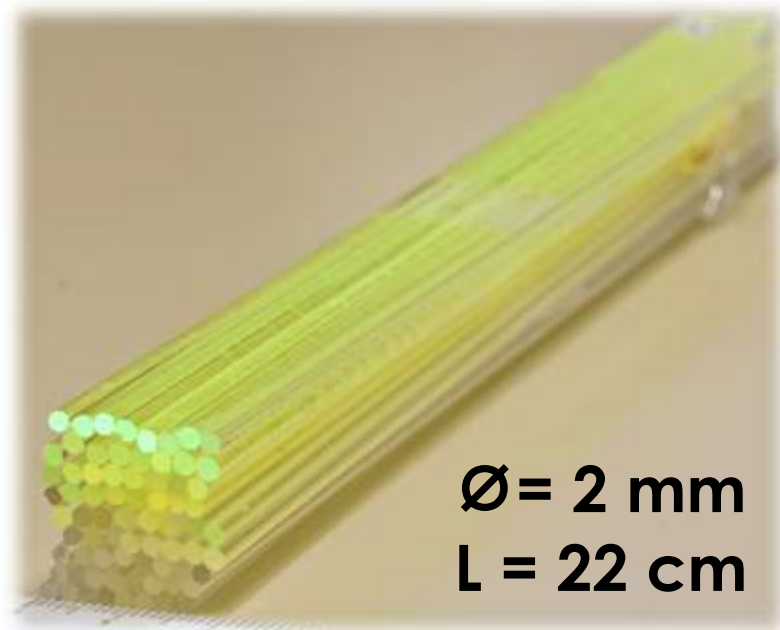
[E. Auffray et al., NSS 2009 p2245](#)
[E. Auffray et al., TNS 2010 57 \(3\) p1454](#)

Cherenkov radiator

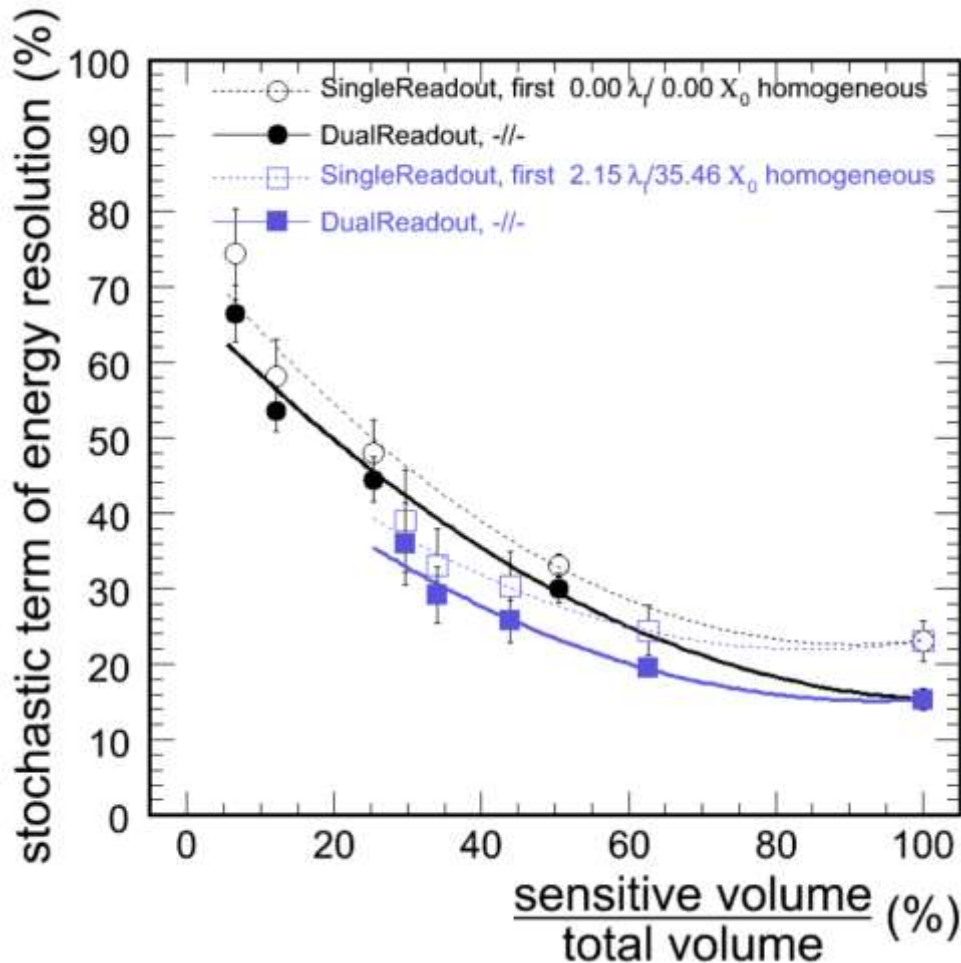
Transmission cutoff	250 nm
Refractive index (250-650 nm)	2.14 – 1.84
Energy threshold	97 keV
Photon yield	1400 ph/cm

Scintillation activated with RE dopant

	Ce^{3+}	Pr^{3+}
Light yield (ph/MeV)	30 000	15 000
Emission	520 nm	350 nm
Decay	70 ns	20 ns



Predictions for detector performances



Better performances

Full homogenous
single readout

$$22 \% / \sqrt{E}$$

Full homogenous
Dual readout

$$15 \% / \sqrt{E}$$

Increase of cost →

G. Mavromanolakis et al., *Journal of Instrumentation*, 6 p10012 (2011)

Fiber Characterization ... how to maintain performances ?!

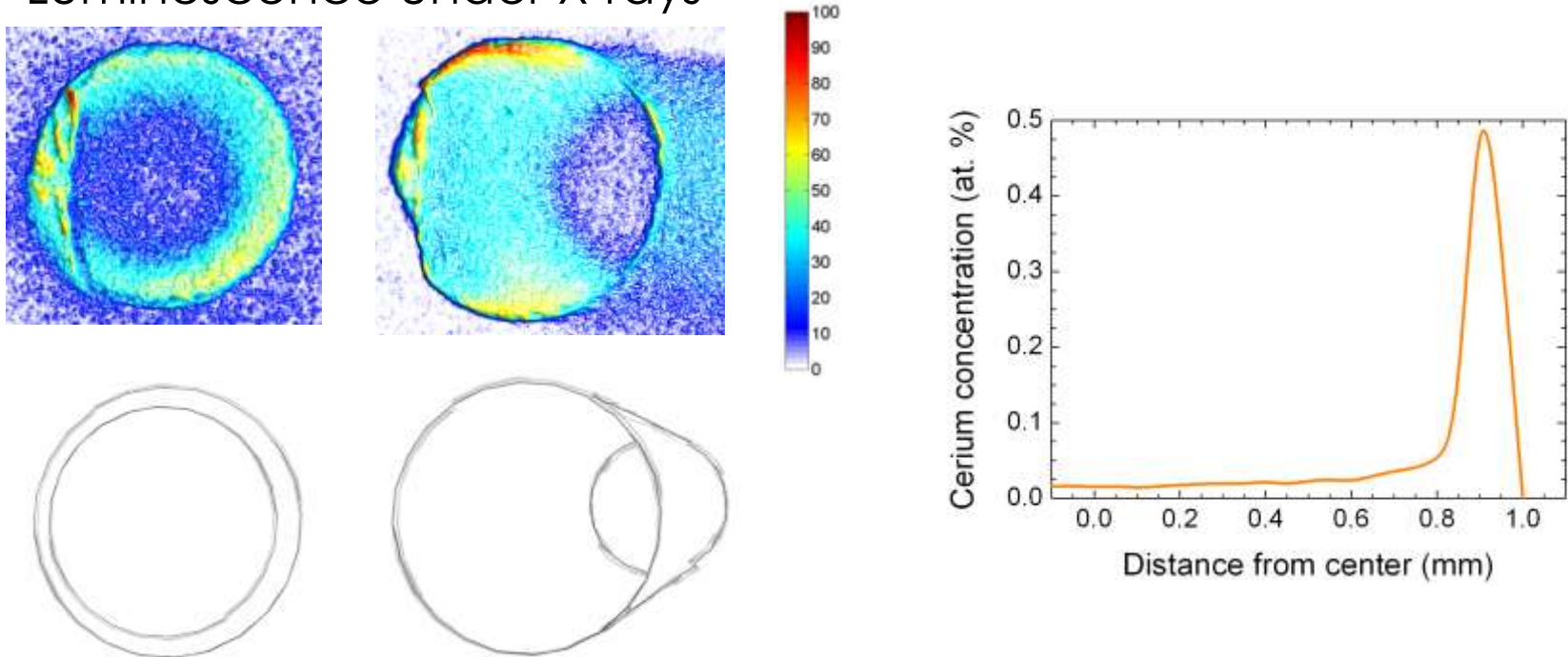
**The fiber geometry is dominated
by surface effects/defects**

Fiber Characterization

- **Radial uniformity**
- Longitudinal uniformity
- Light output
- Radiation hardness

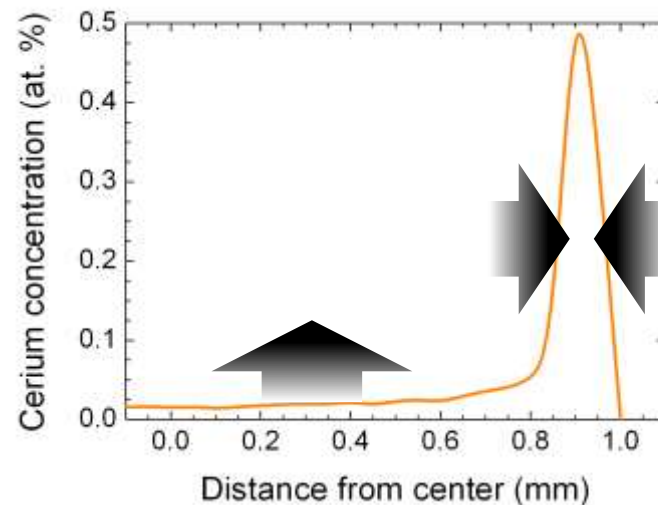
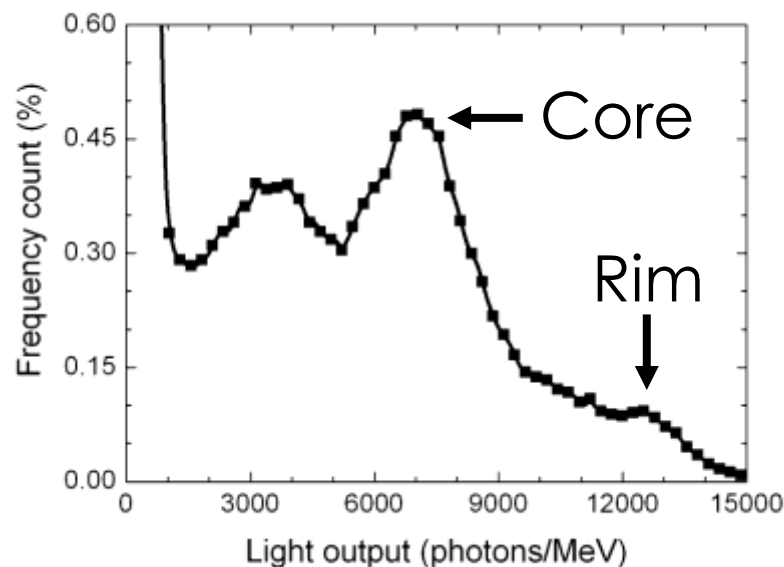
The radial distribution of the dopant has to be checked

Luminescence under X-rays

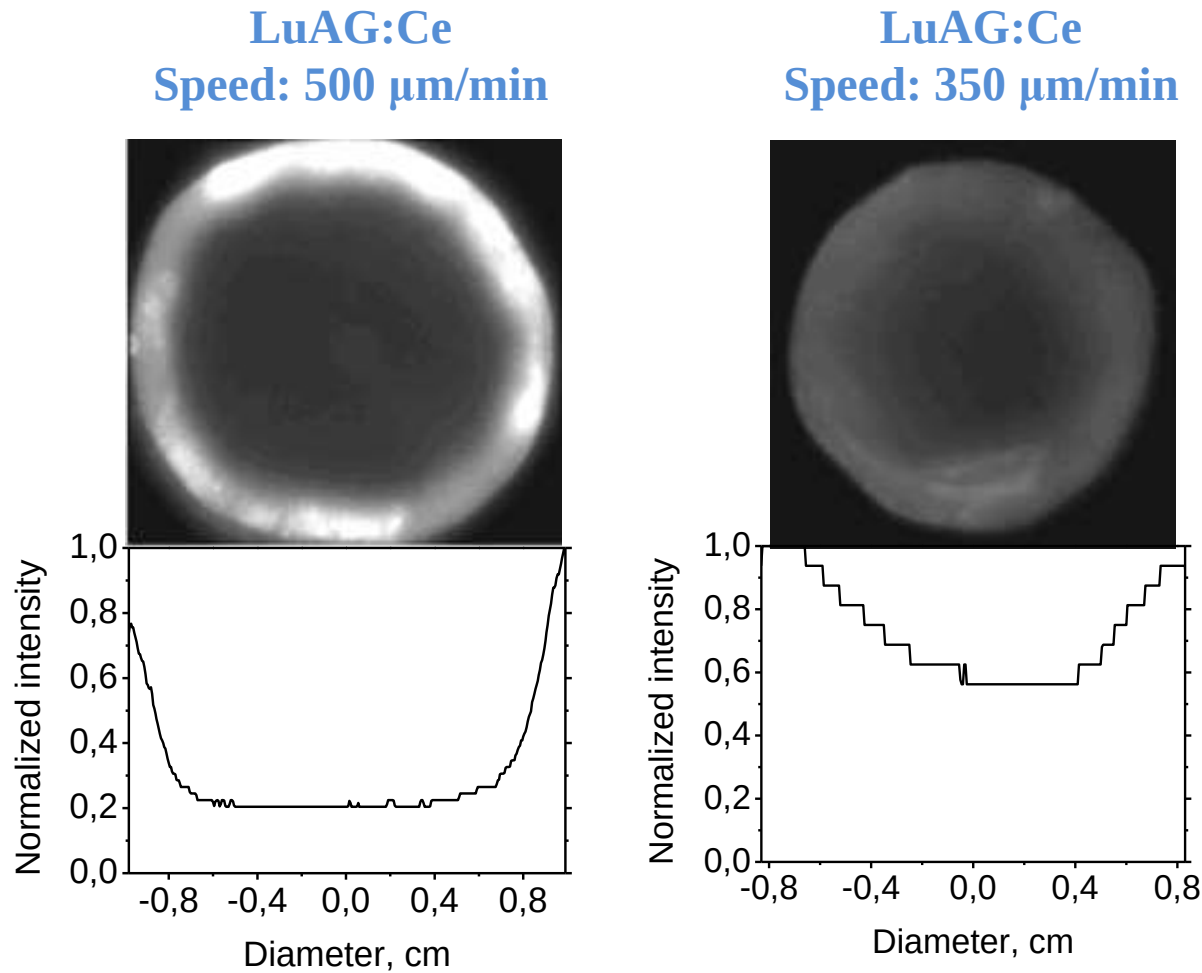


> It is also the case for crystals grown as ingots (Cz,Bg) but the non-uniformities are usually removed (cut out).

This non-flat distribution of dopant yields a non uniform response of the fiber



Ce^{3+} radial segregation can be minimized e.g. with the pulling speed



XU X., et al., *Acta Materialia*, vol. 67, p. 232-238 (2014)

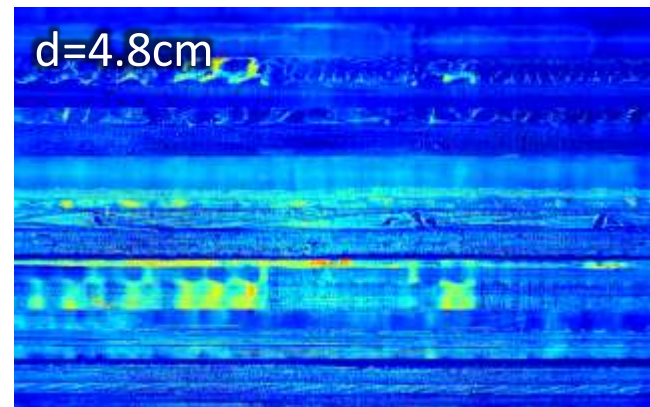
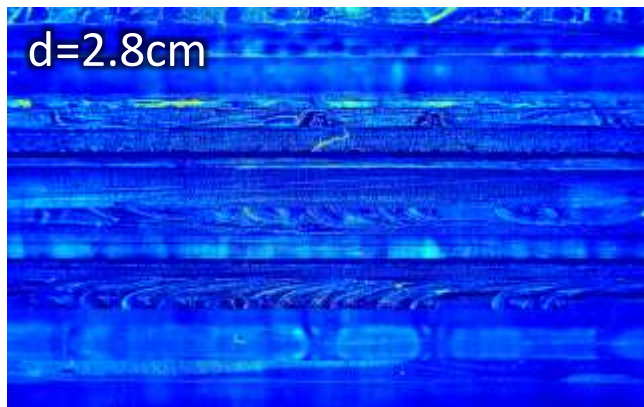
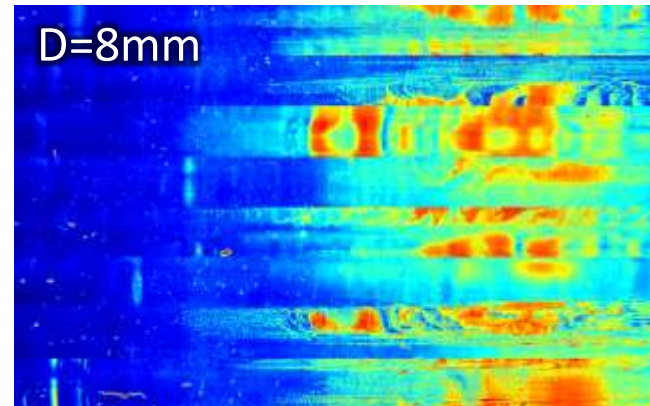
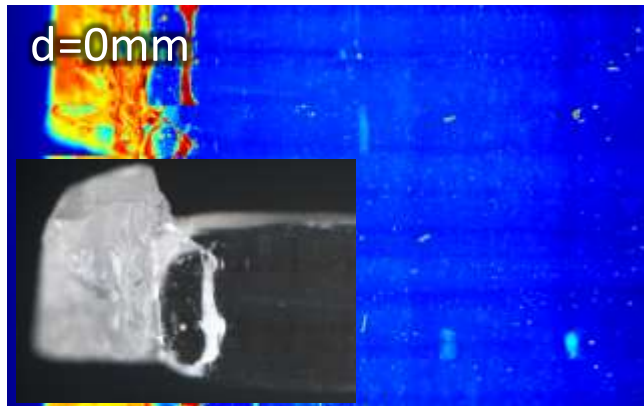
V. Kononets, et al., *Submitted to journal of crystal growth* (29 july 2015)

S. Fara, et al., *SCINT2015 conference*, June 2015

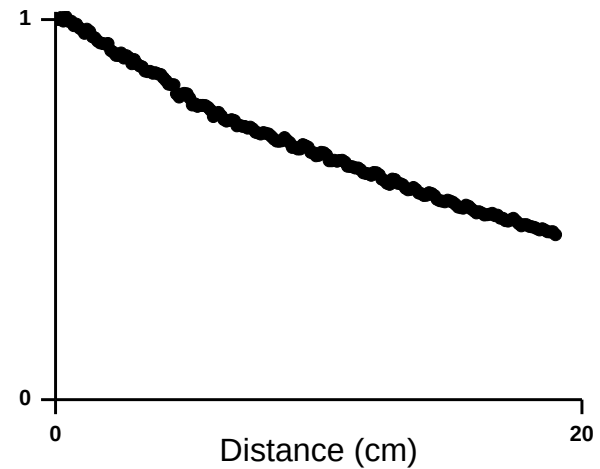
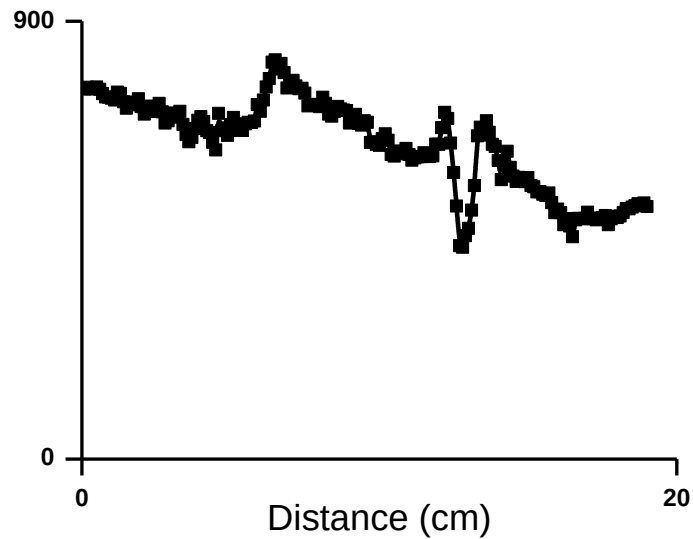
Fiber Characterization

- Radial uniformity
- **Longitudinal uniformity**
- Light output
- Radiation hardness

Any problem during the growth translates into a loss in optical quality

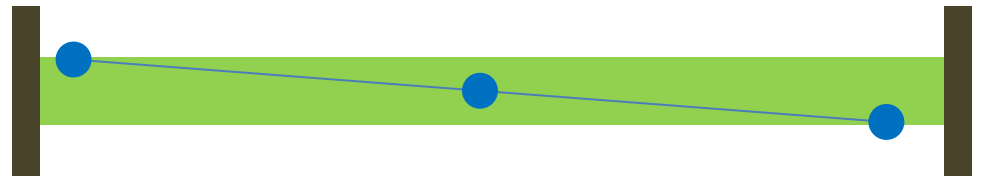


The light propagation has to be controlled

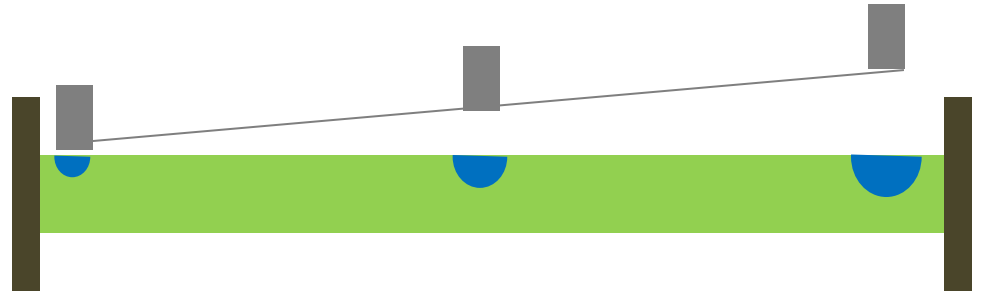


Misalignments & surface defects influence the attenuation curve

With fiber axis misalignments



Vertical misalignments



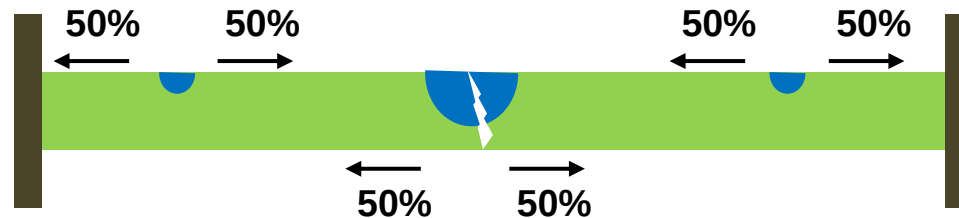
Surface defects



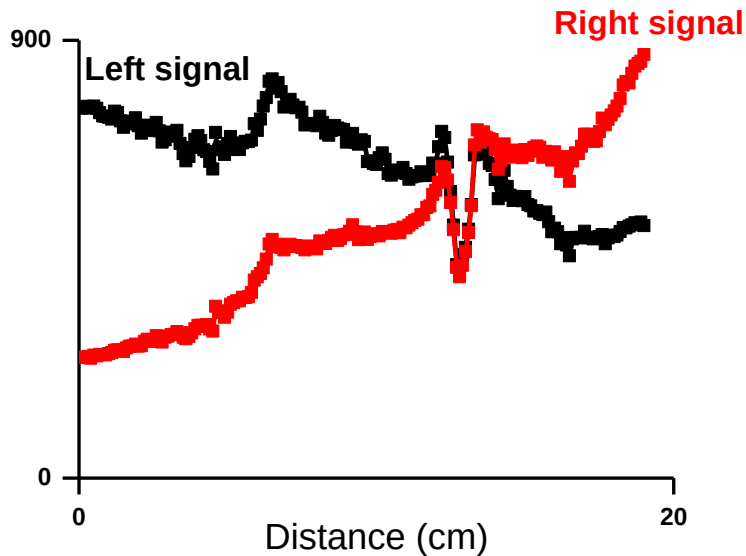
Readout on both sides cancels out the fluctuations

Scintillation light is isotropic
(equally emitted in all directions)

Regardless of the amount of light generated,
the same amount is shared between left and right

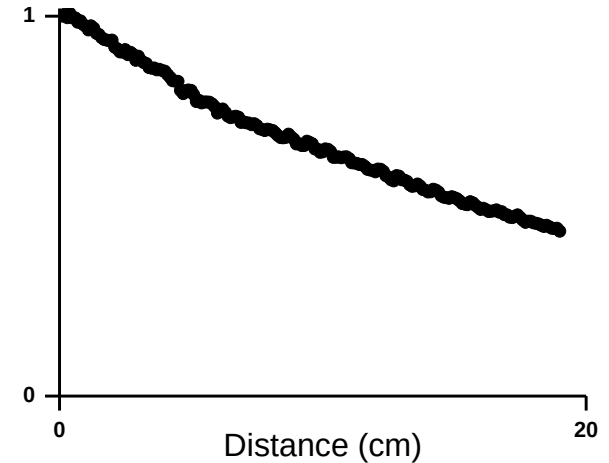


This separates the light propagation from the light generation

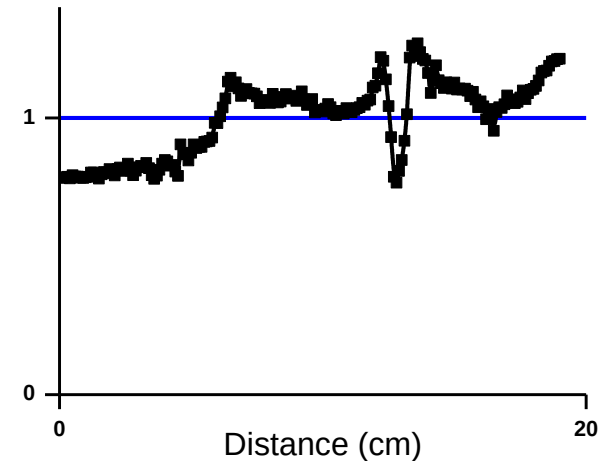


Possible reasons: cracks, gradient in dopant concentration, non smooth extension of the growth chamber...

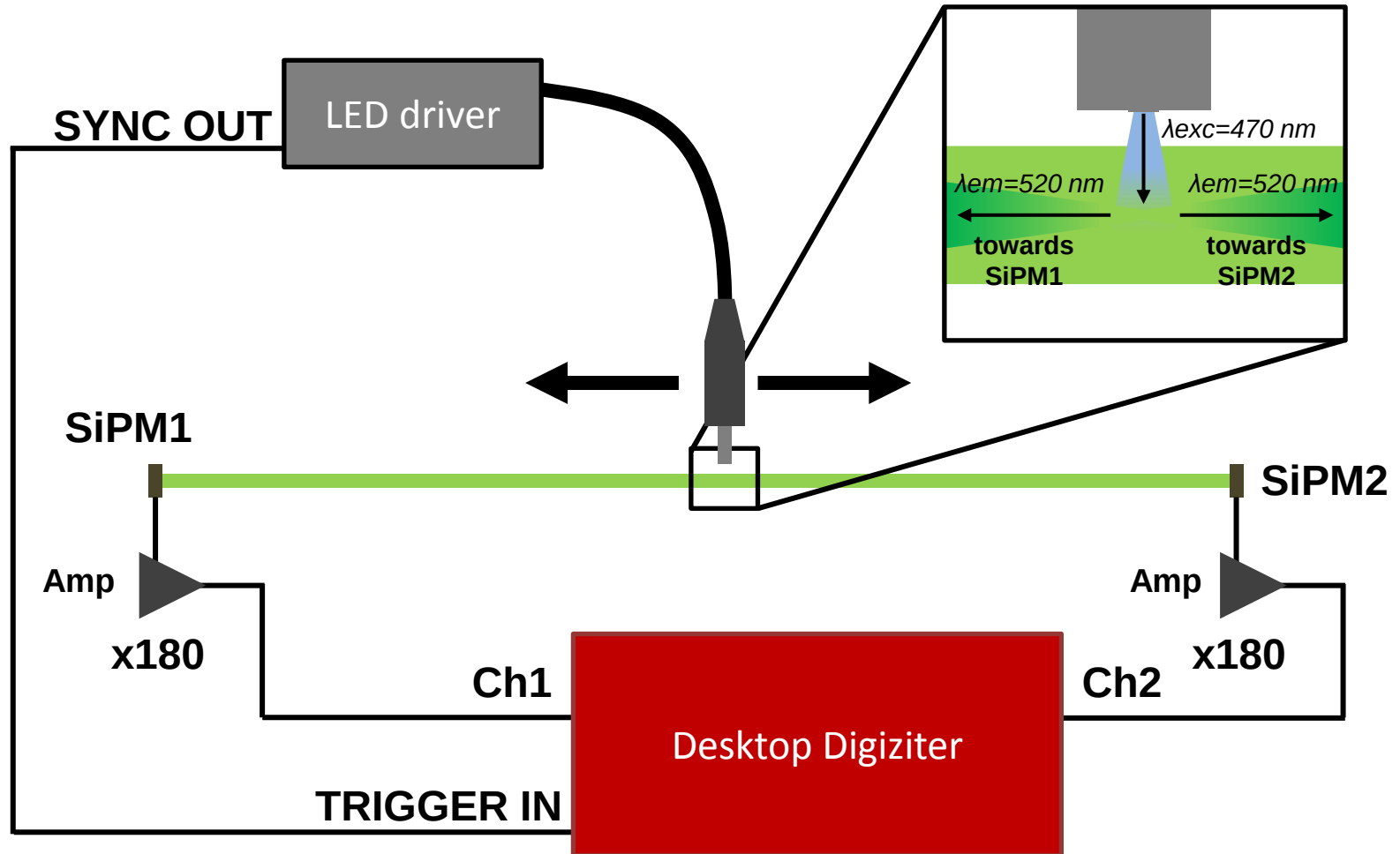
Attenuation (light propagation)



Uniformity (light generation)

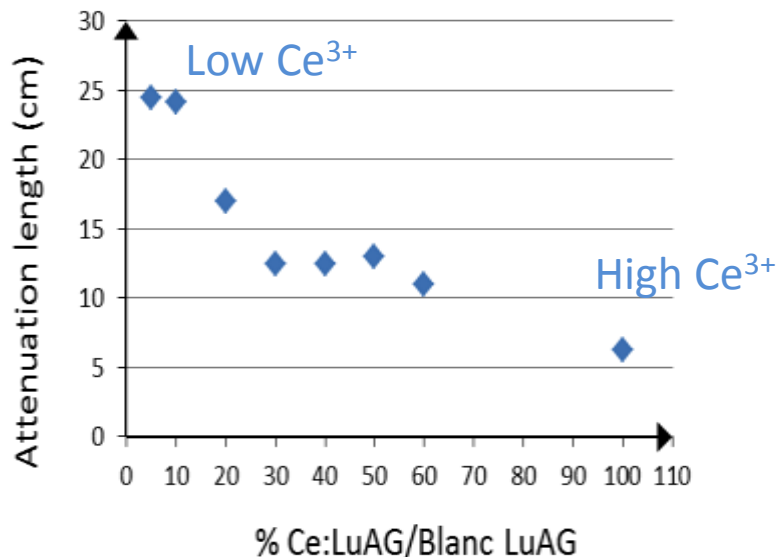


Example of setup for LuAG/YAG crystal fibers

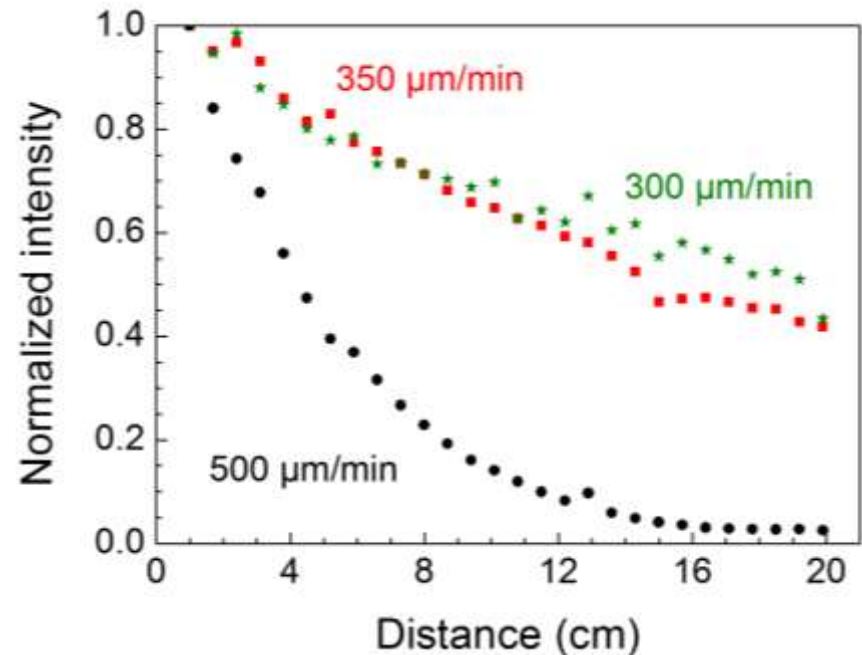


The growth parameters directly affect the optical quality of the fibers

By reducing the Cerium Concentration



By reducing Growth speed

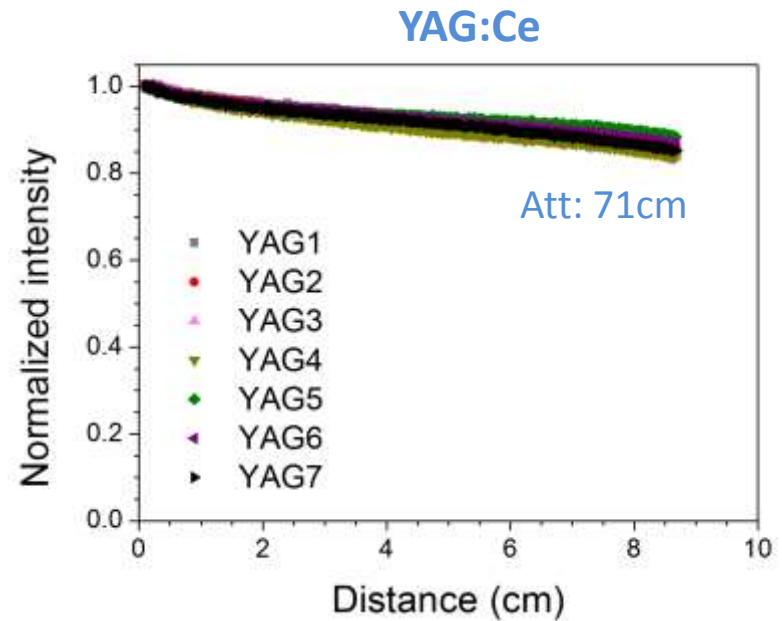
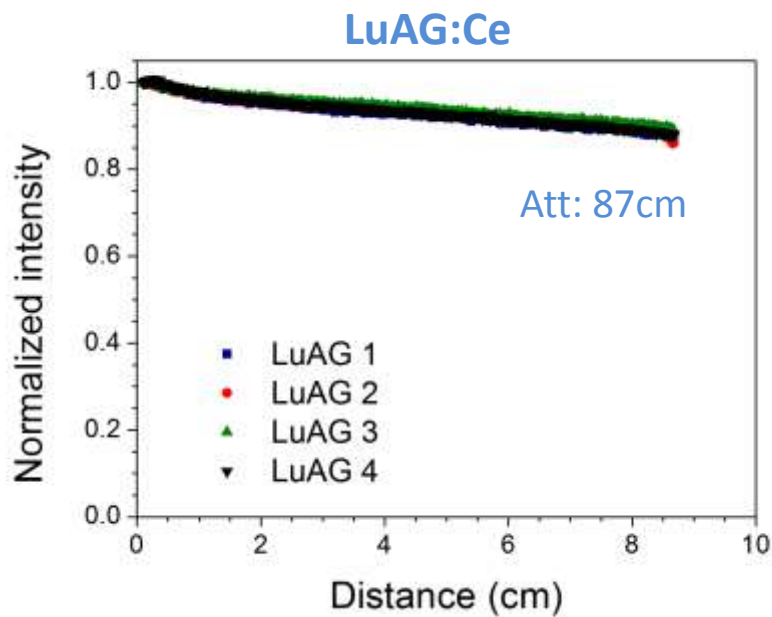


XU X., et al., *Acta Materialia*, vol. 67, p. 232-238 (2014)

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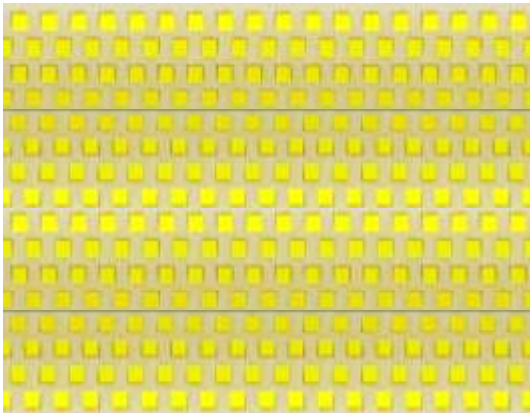
Best results are obtained with fibers cut out from Cz-grown ingots



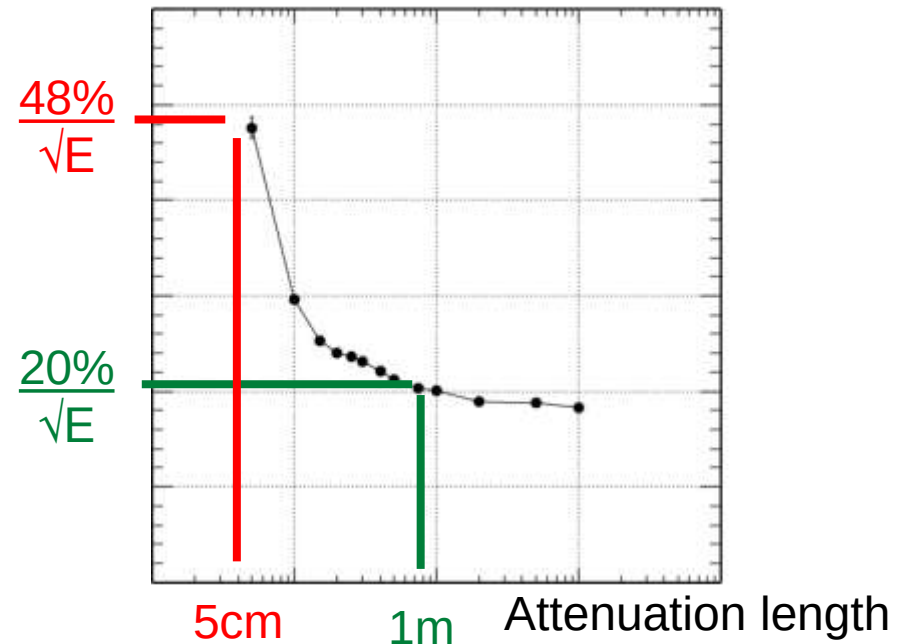
This parameter is important because it drives the detector performance!

Example of calorimeter:

Equipped with 1x1 square fibers (YAG) embedded into an absorber (W-Cu)



Energy resolution
(Stochastic term)

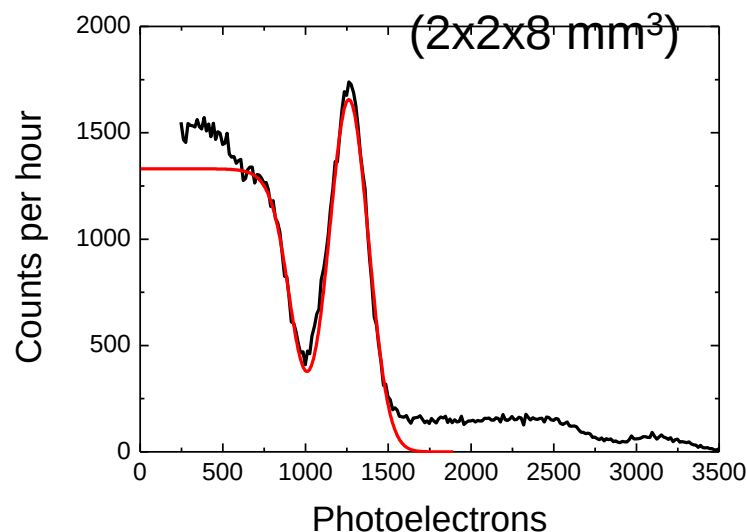


Fiber Characterization

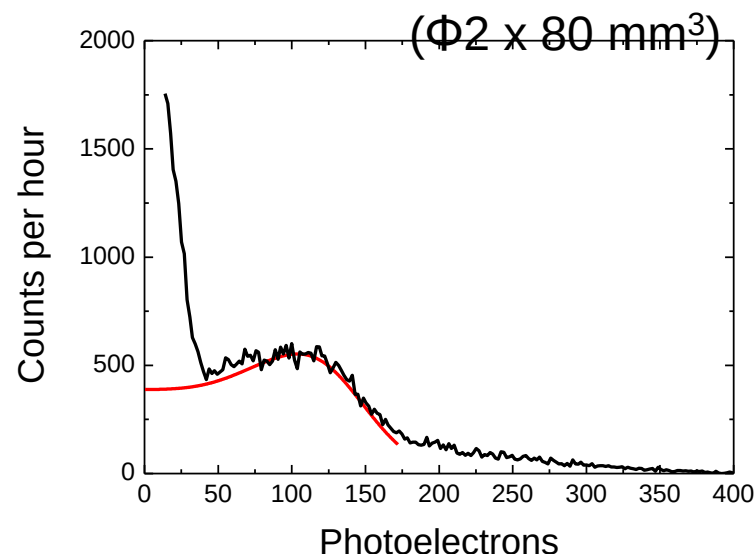
- Radial uniformity
- Longitudinal uniformity
- **Light output**
- Radiation hardness

Not easy to “find the photopeak”!

LuAG:Ce Crystal (Czochralski)

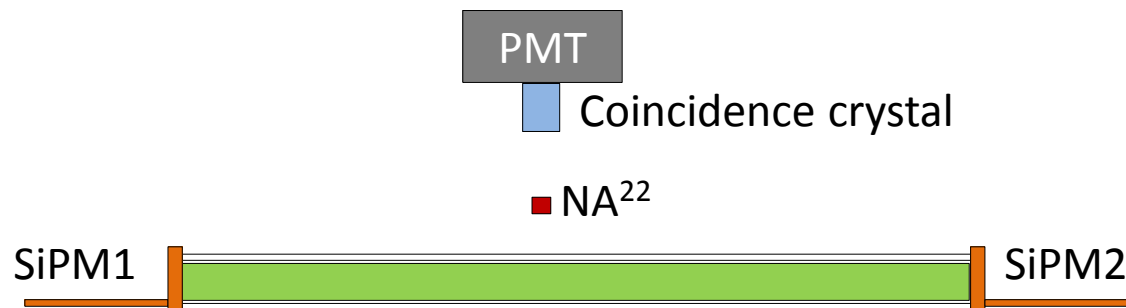
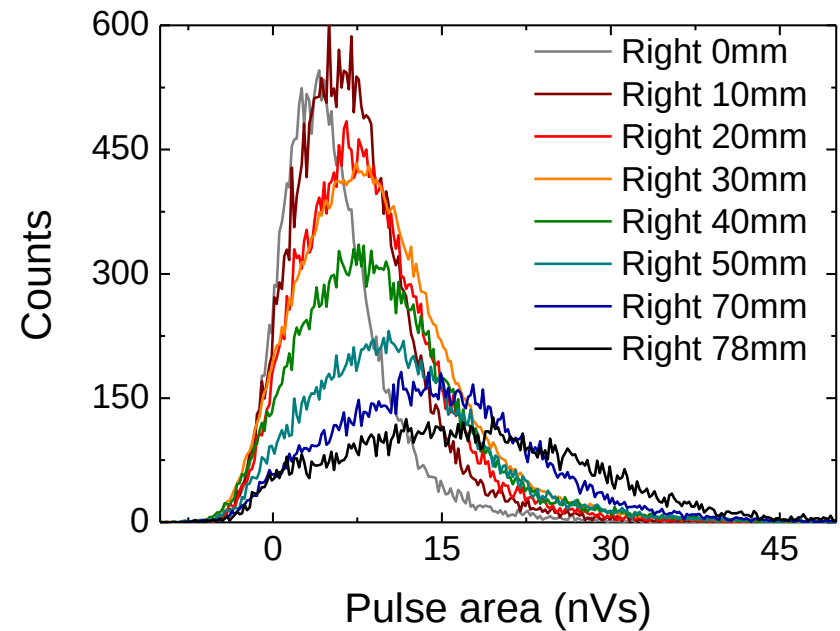
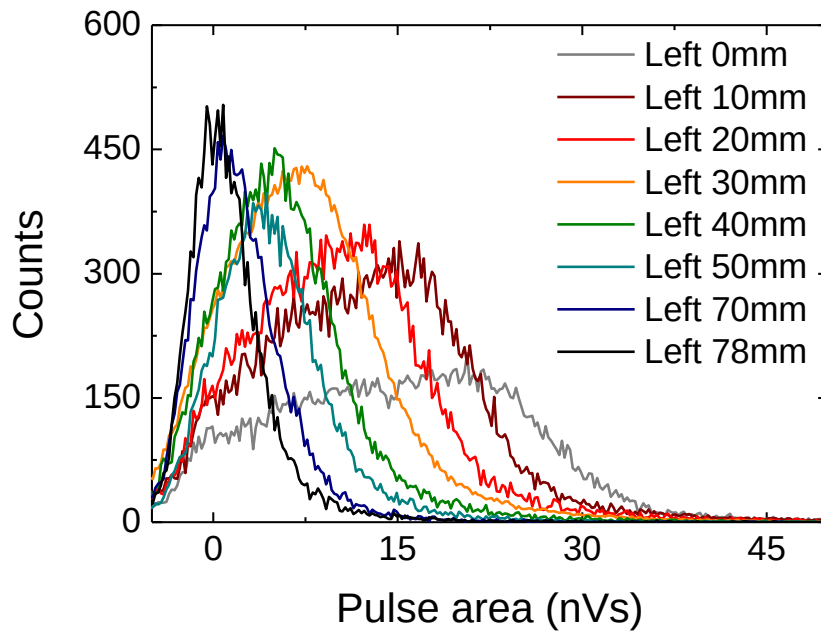


LuAG:Ce Crystal Fiber (μ PD)

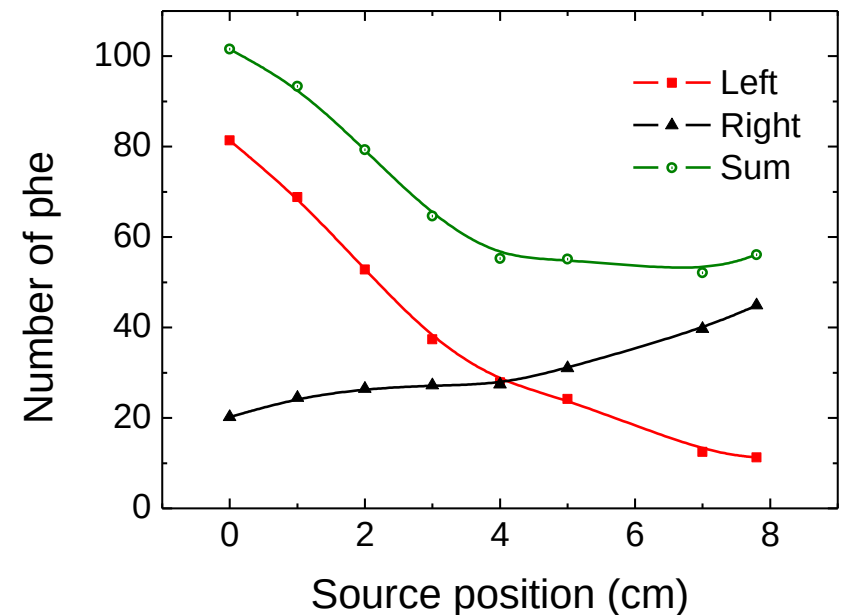
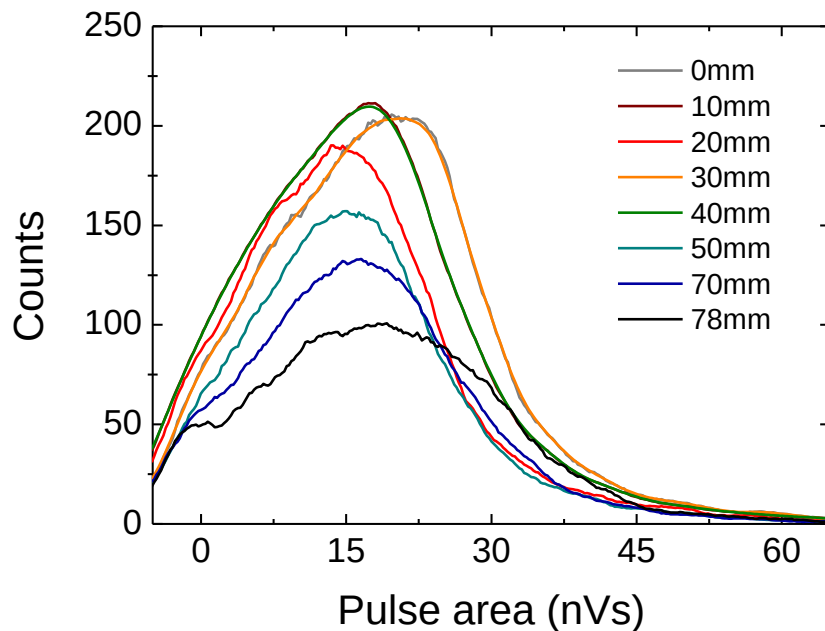


The radial and longitudinal non-uniformities observed previously sum up and make the measurement of the light output very difficult. In addition the small section of the fibers make lateral measurements more difficult (less stopping power).

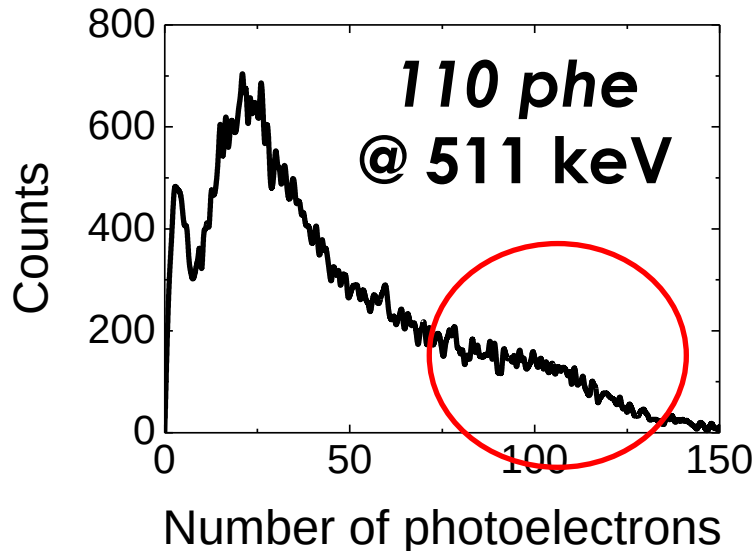
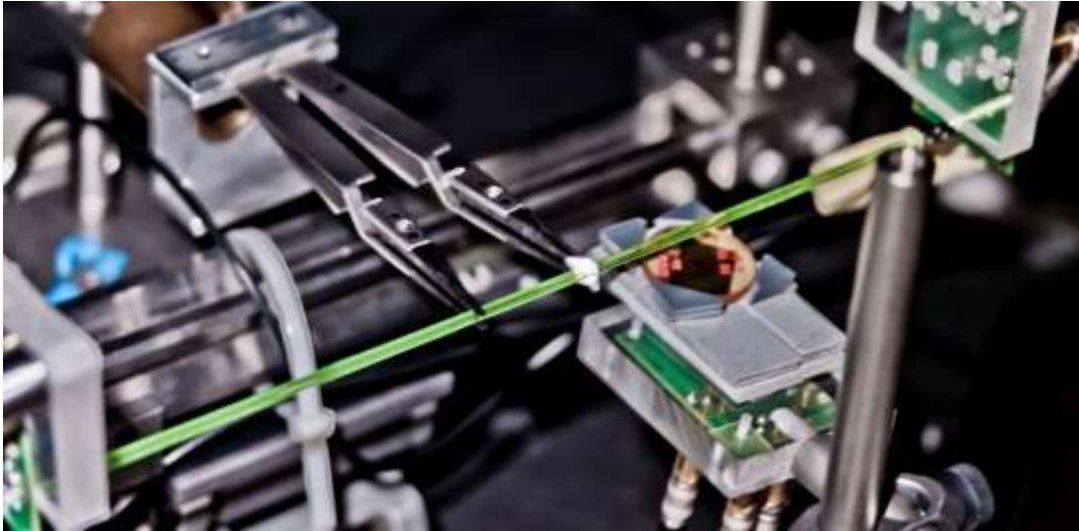
Reading both ends of the fiber and tagging the particules helps (a bit...)



Summing the signals compensates for the light attenuation



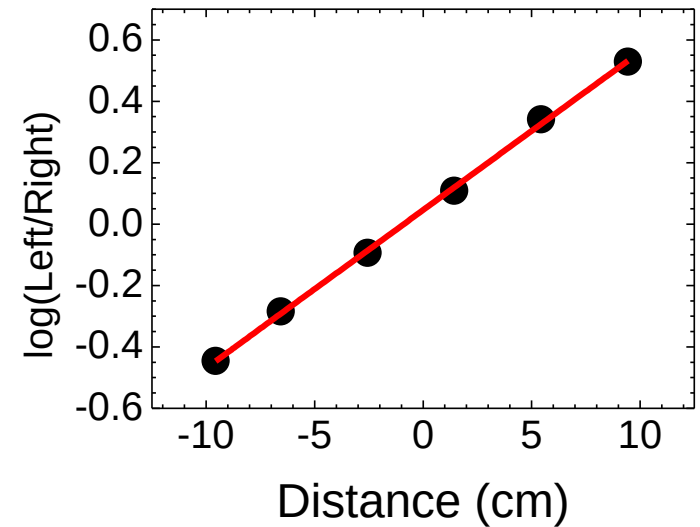
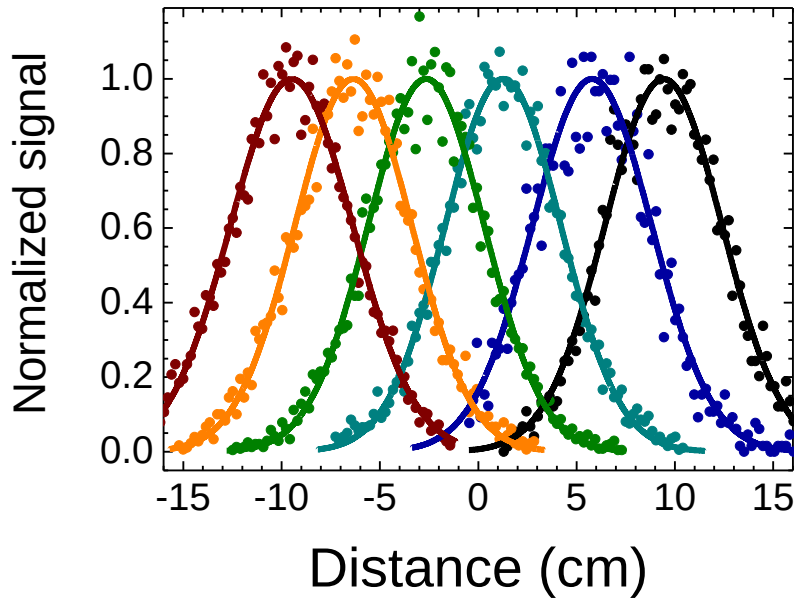
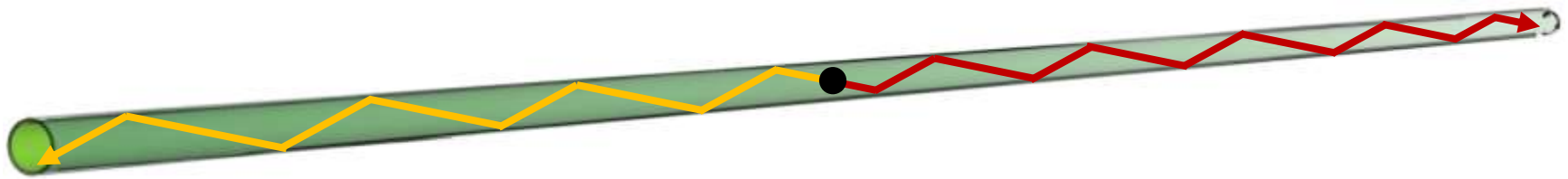
Example of Light output measurement



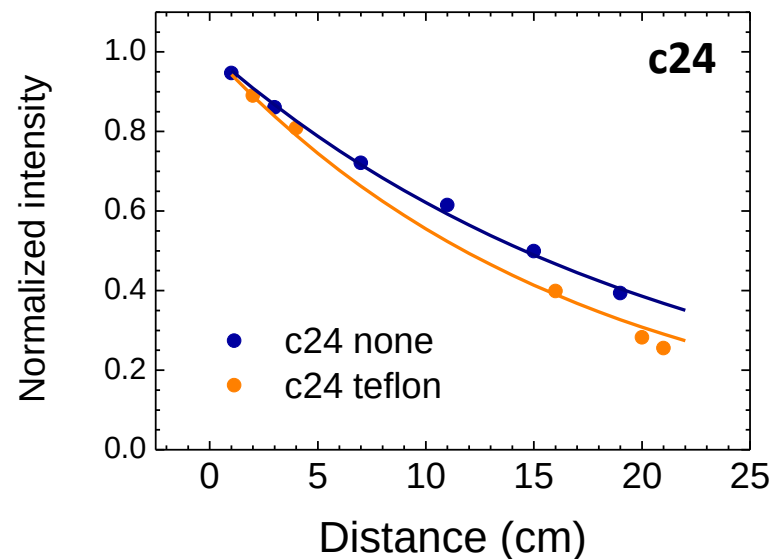
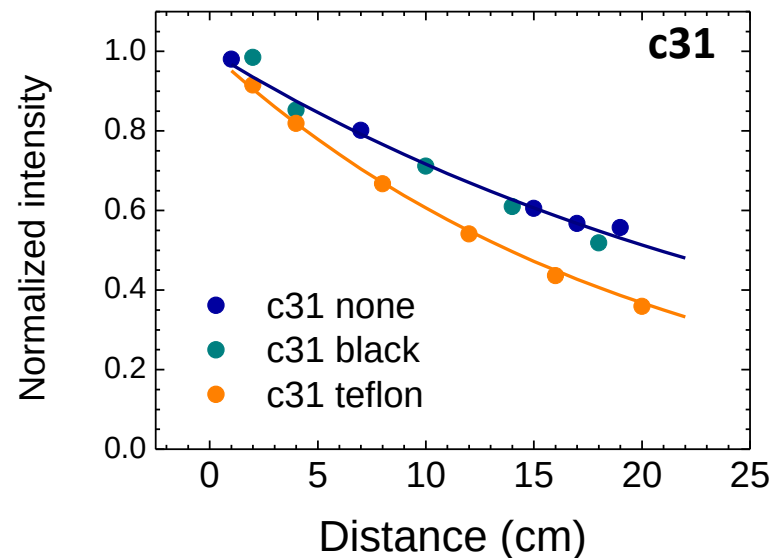
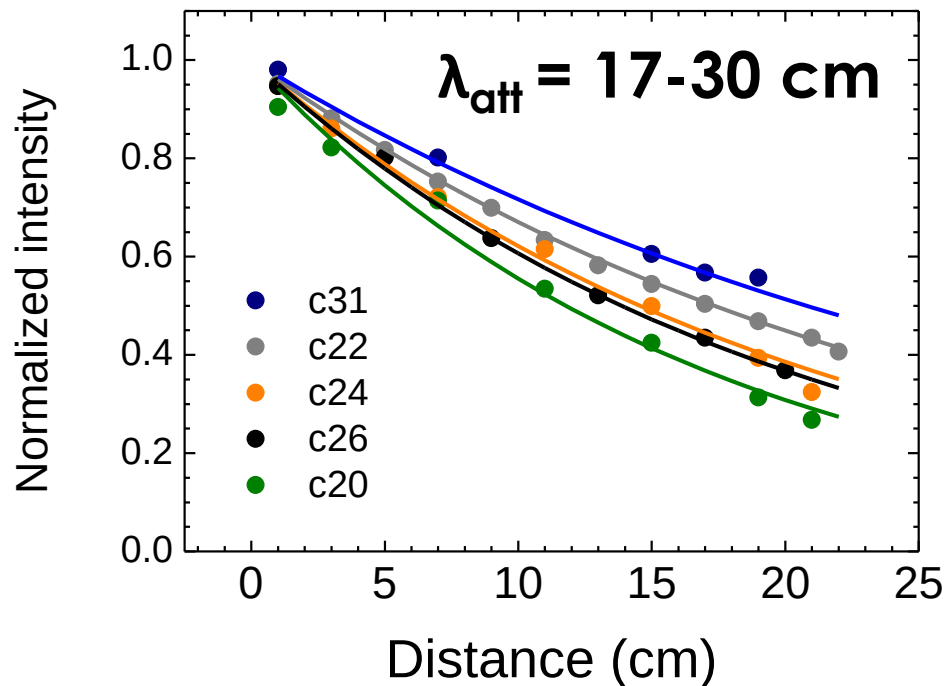
Seems low...

**But for HEP this means
>200'000 phe per GeV deposit!**

Based on Left and Right signals the interaction point can be computed

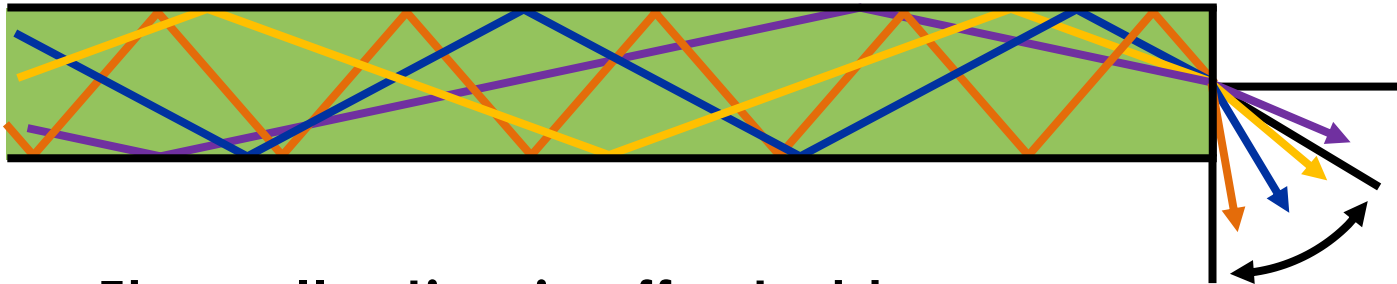


Light attenuation in LuAG fibers



Teflon wrapping does not improve light attenuation

Selection of the collection angle

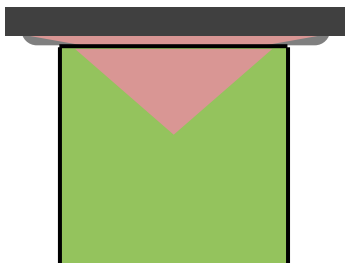


The collection is affected by wrapping/coating conditions

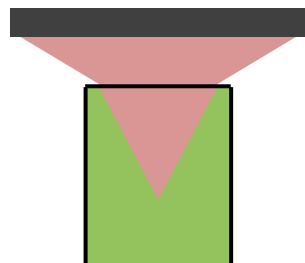
More light here
But... what light ?

It is was investigated here by changing
the out-coupling conditions

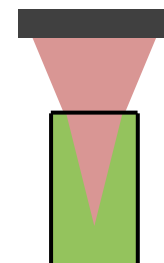
Coupling with
optical grease



Air 1.5mm

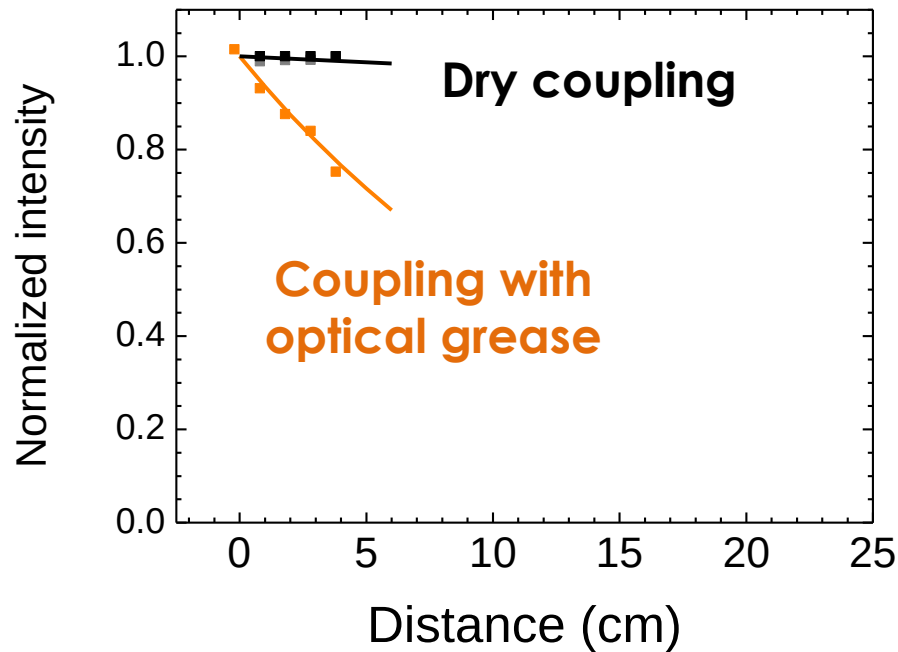


Air 3mm

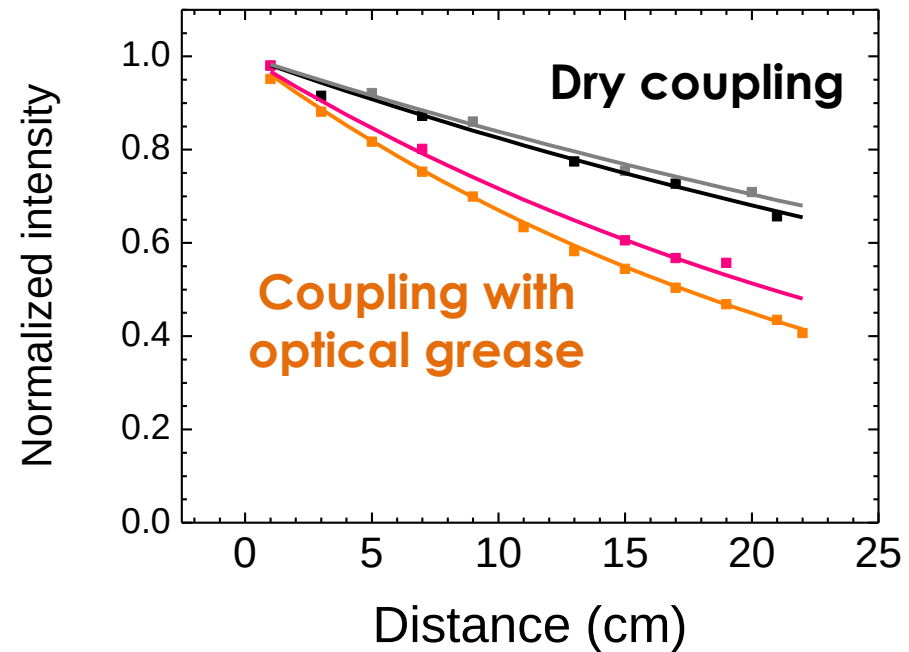


Light attenuation as function of the collection angle

LuAG crystal 2x2 mm



LuAG fibers $\phi=2$ mm

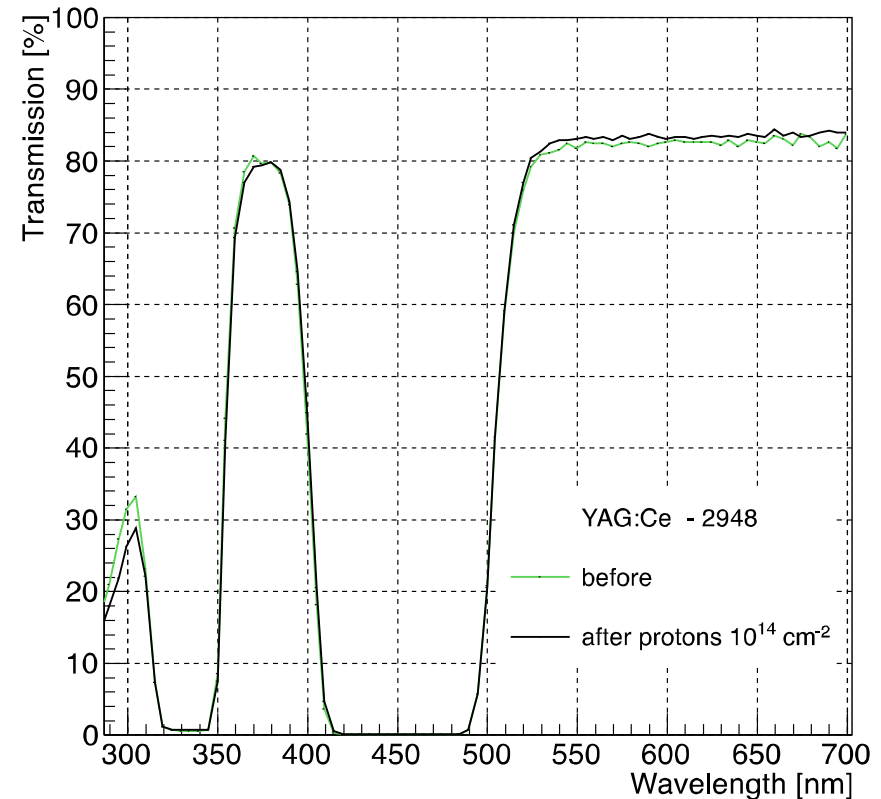
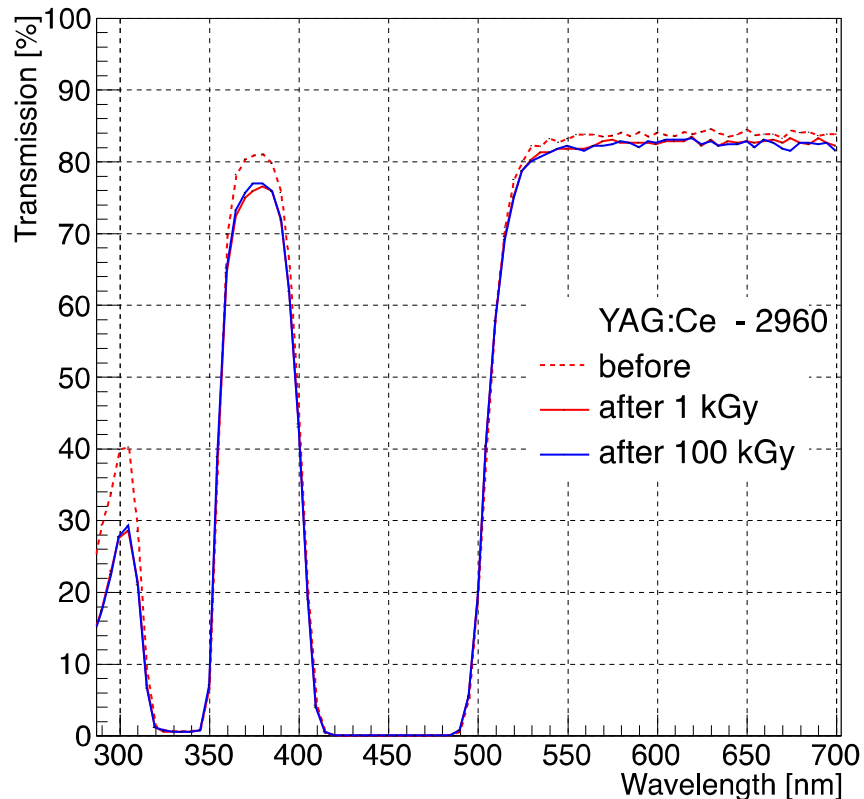


The reduction of the collection angle yields better λ_{att}

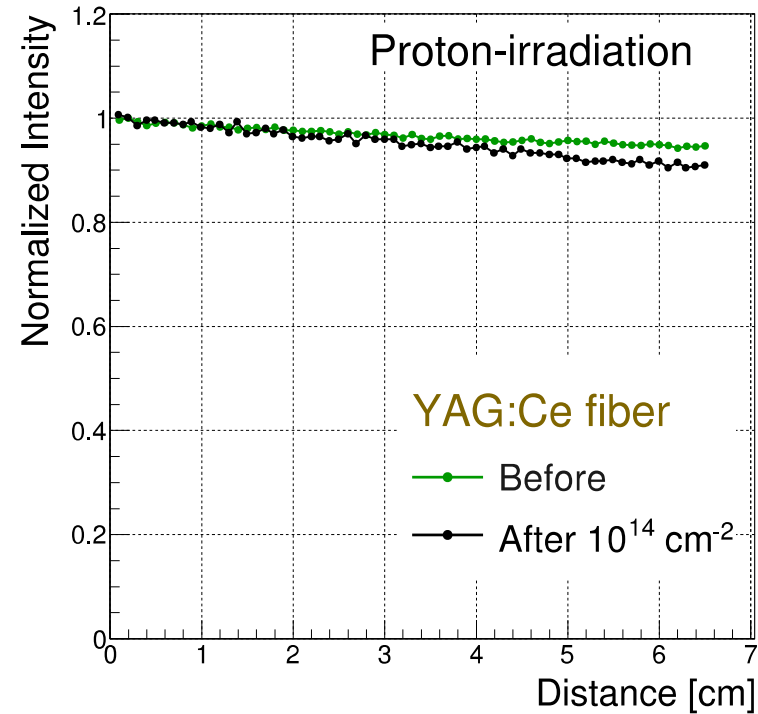
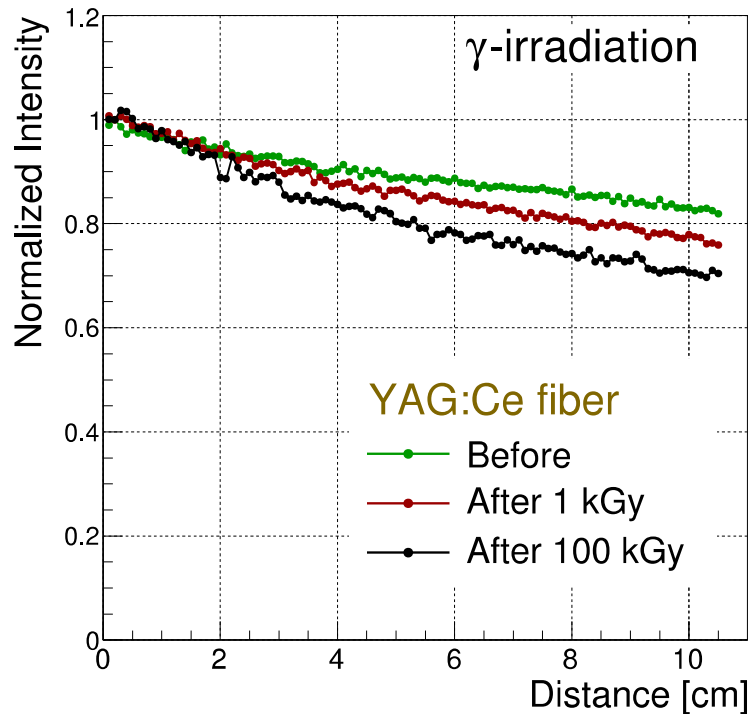
Fiber Characterization

- Radial uniformity
- Longitudinal uniformity
- Light output
- **Radiation hardness**

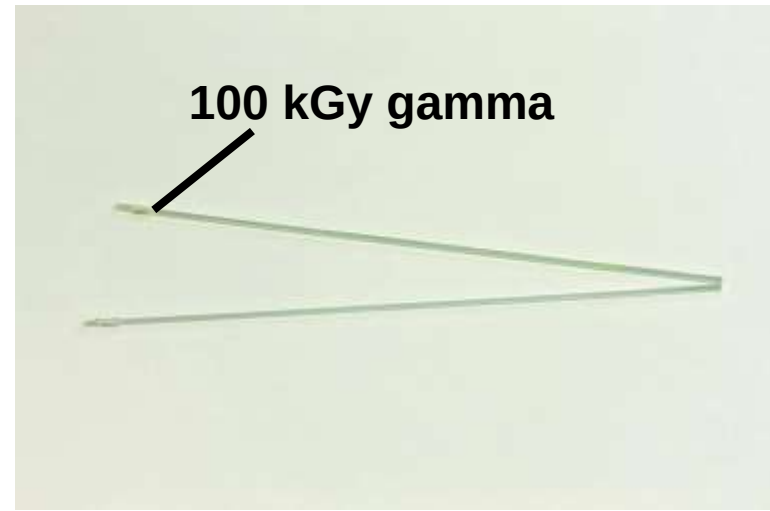
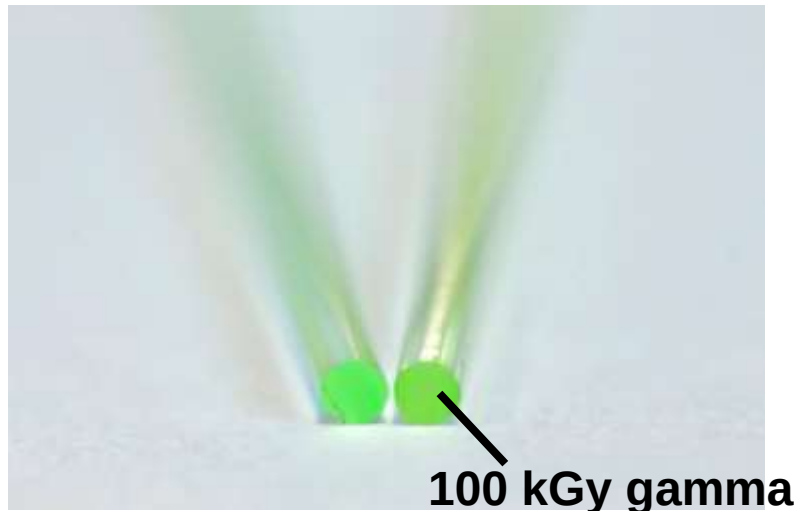
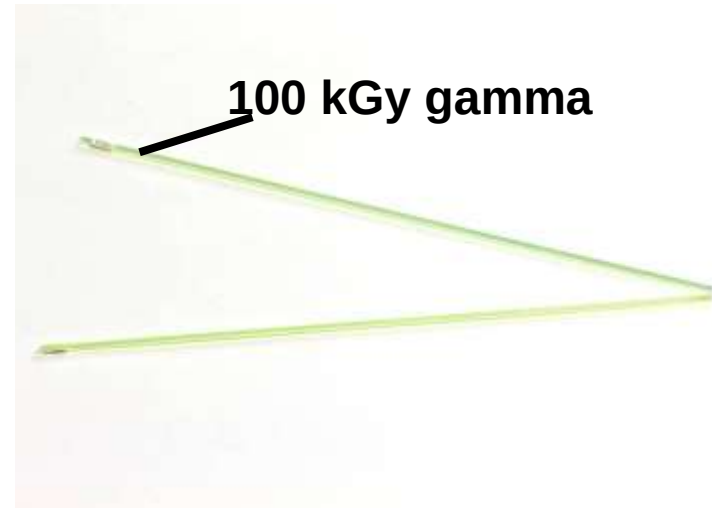
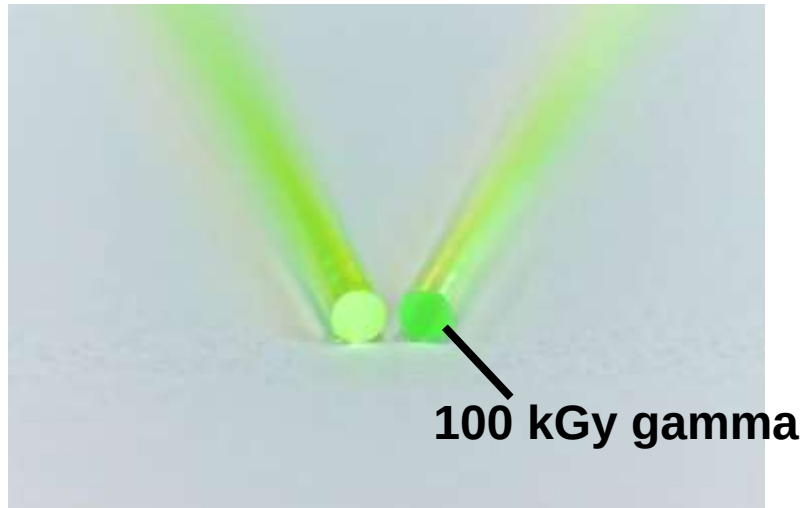
A good radiation hardness for bulk crystal (YAG)



Same behavior in YAG crystals shaped into fibers



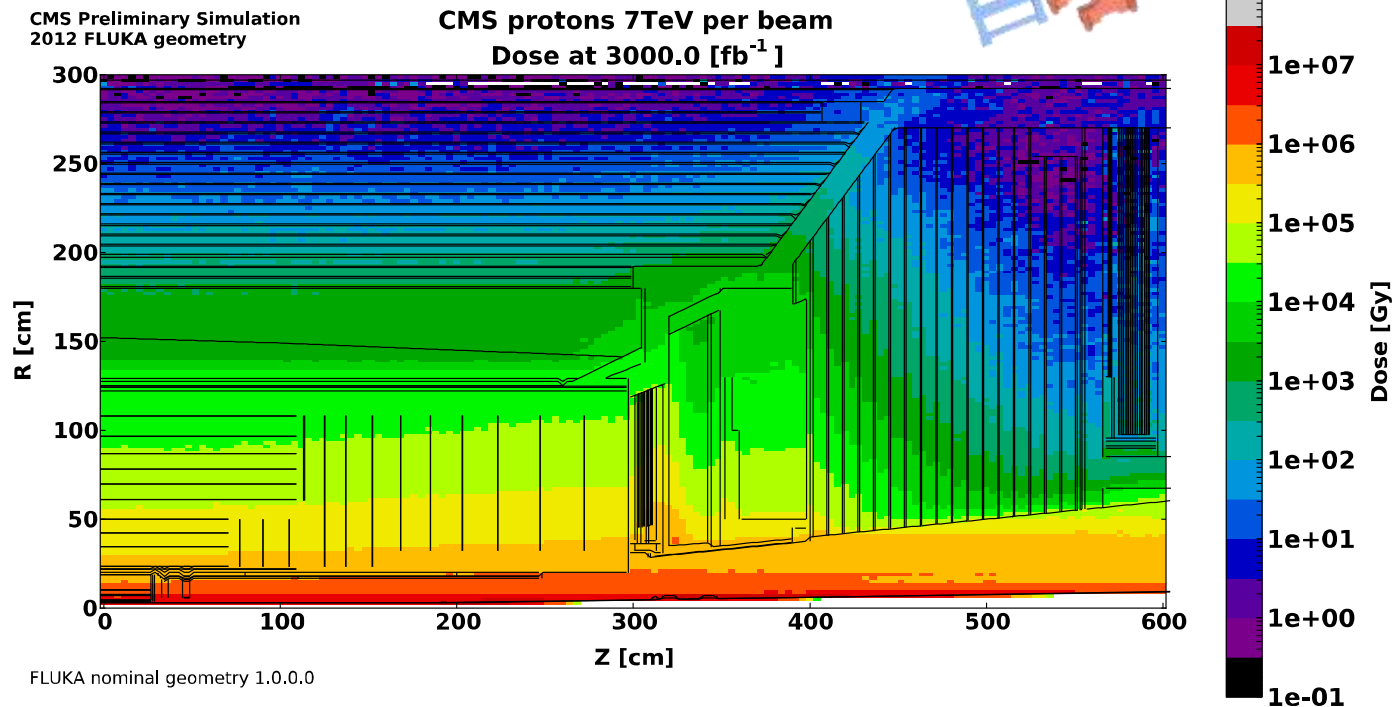
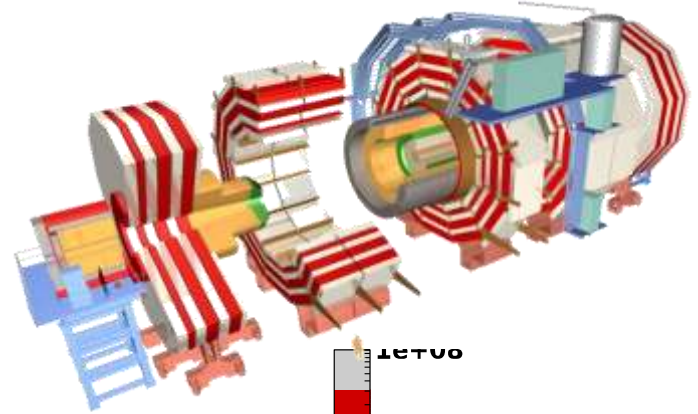
A moderate radiation hardness for fibers grown by μ PD (LuAG here)



Radiation hardness is a requirement for operation at high lumi colliders

Example: HL-LHC @CERN (~2025)

- ⇒ Ionising radiation dose 1MGy
- ⇒ Charged hadron fluences up to $2 \cdot 10^{14}$ p.cm⁻²



**How to assess the performances
of the fibers for HEP detectors ?**

=>Prototyping & Test Beam

First prototypes

Nov. 2009

Blocks of fibers

40 fibers ($L=8$ cm)
Scint+Cherenkov

Results dominated by
a **rather strong light
attenuation** in the fibers



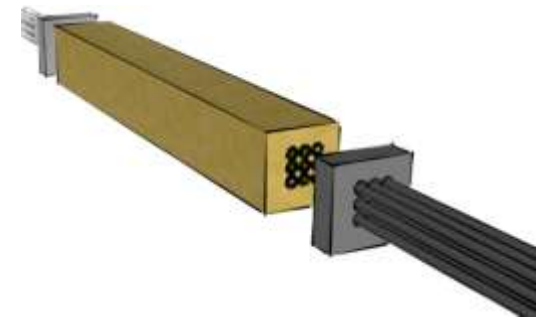
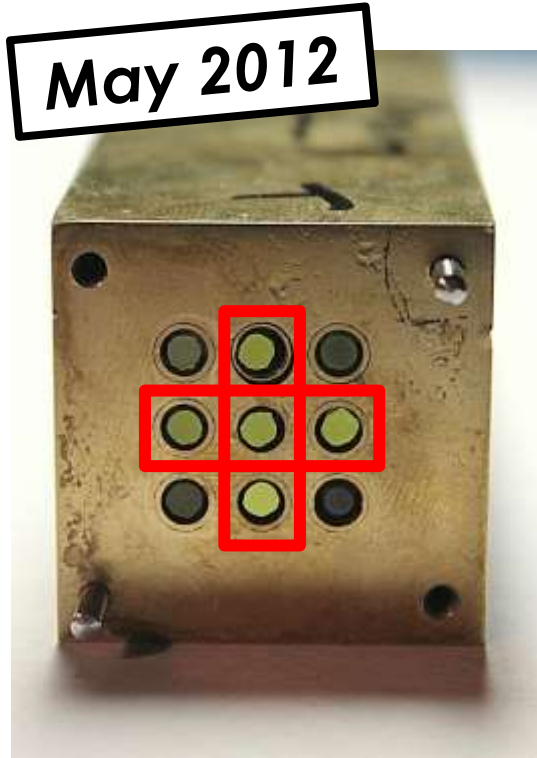
Nov. 2011



Change of approach

- Use of a brass absorber
- Small selection of fibers (4!)
- Length of 22 cm (~PBWO4 crystal in CMS)

Prototype as building block



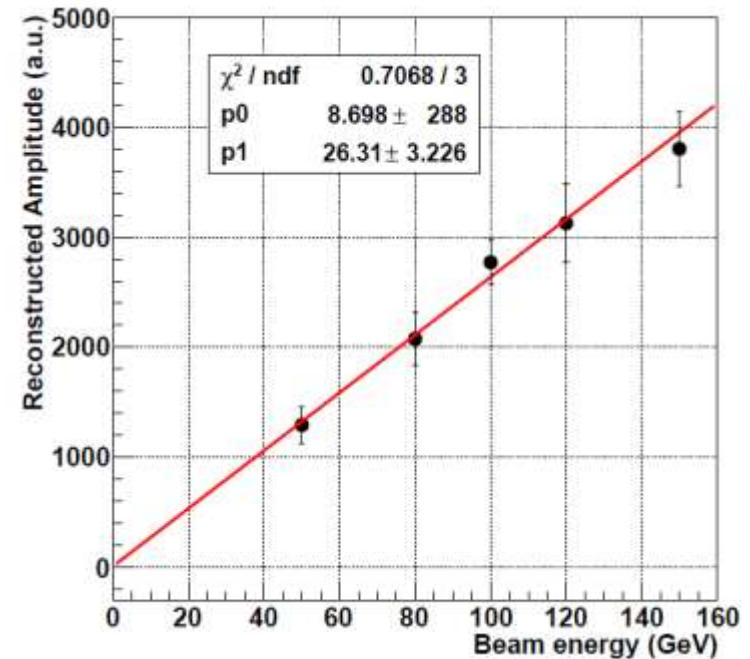
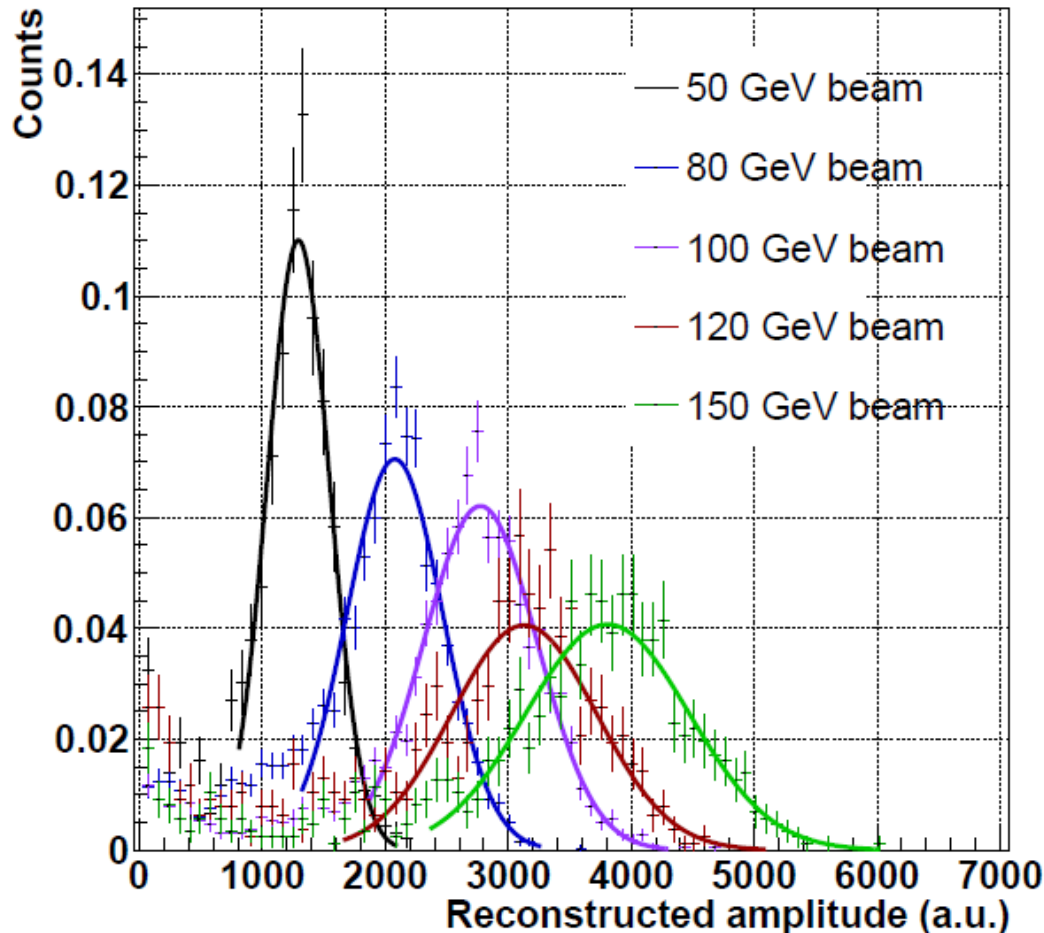
Electron beam
 $E=50\text{-}150\text{ GeV}$



Fibers selected

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

The energy deposit in the 9 fibers scales with energy (even if unit is of small size)

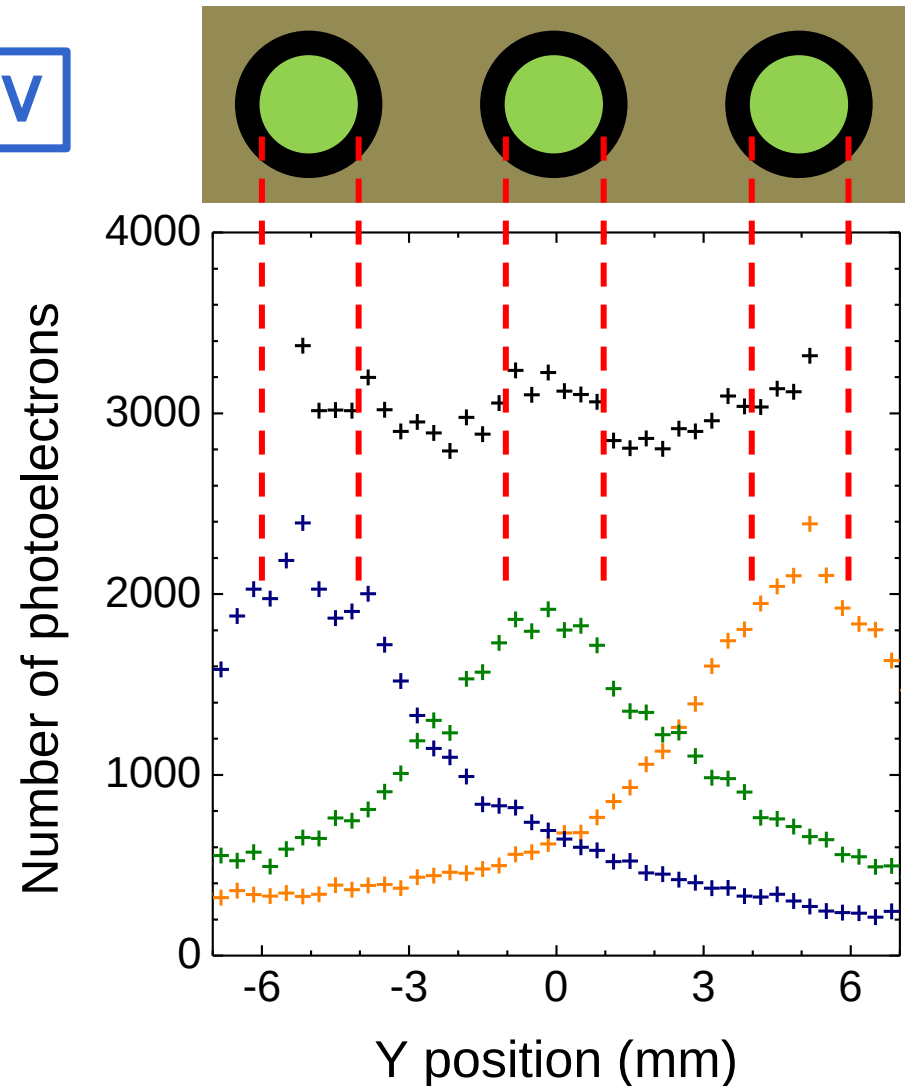
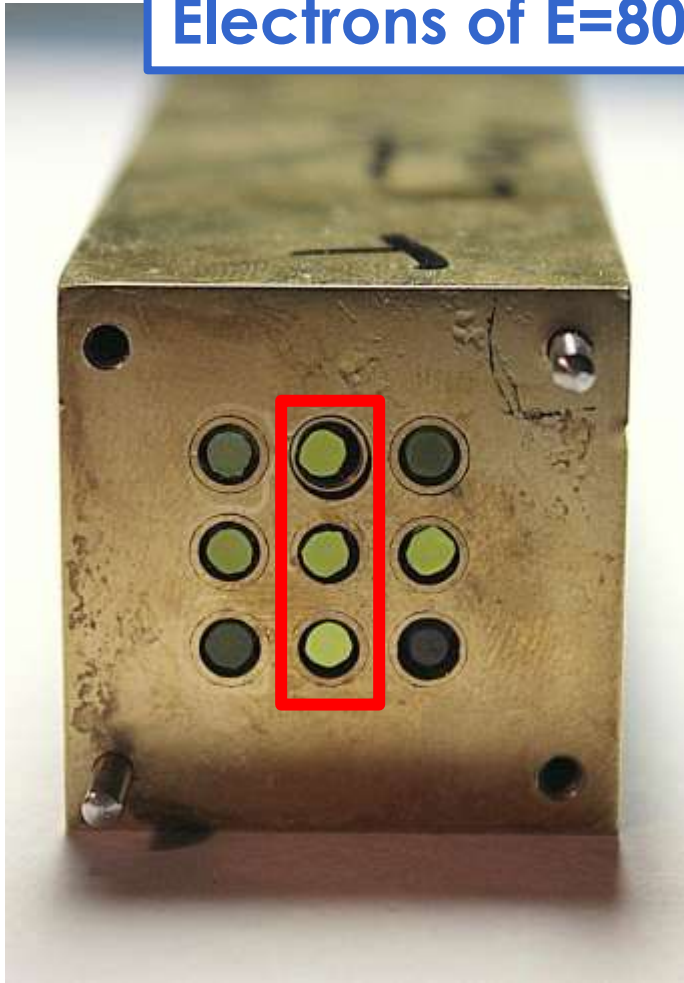


*Obtained after
intercalibration of
the 9 fibers*

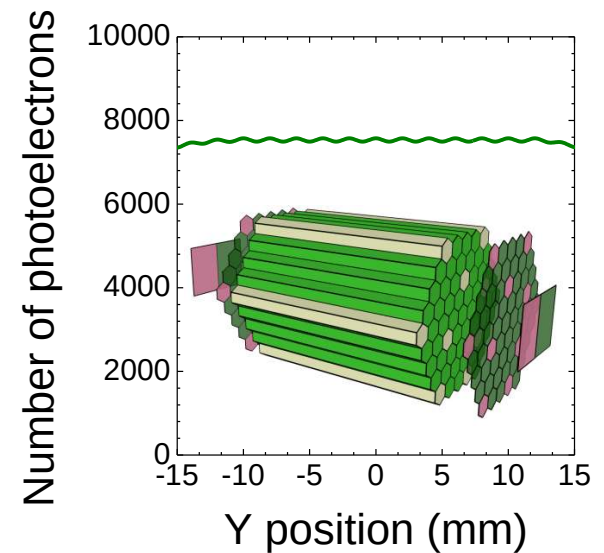
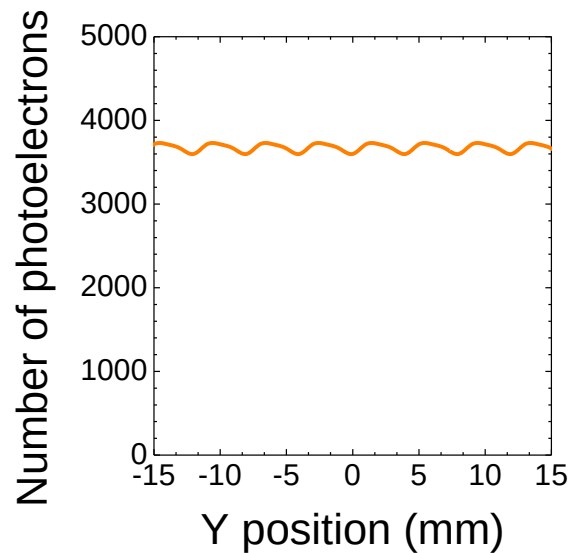
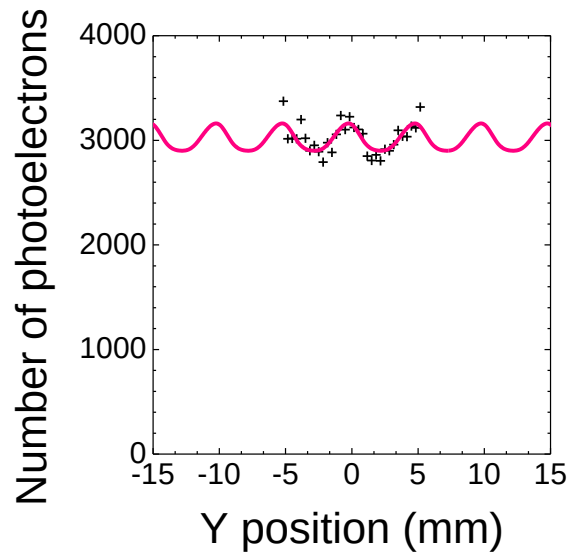
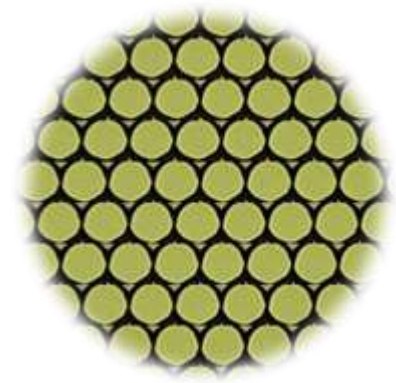
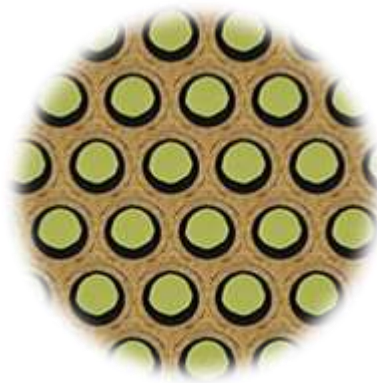
M. Lucchini et al, JINST 8 10017 (2013)

A lateral segmentation can be seen

Electrons of $E=80$ GeV

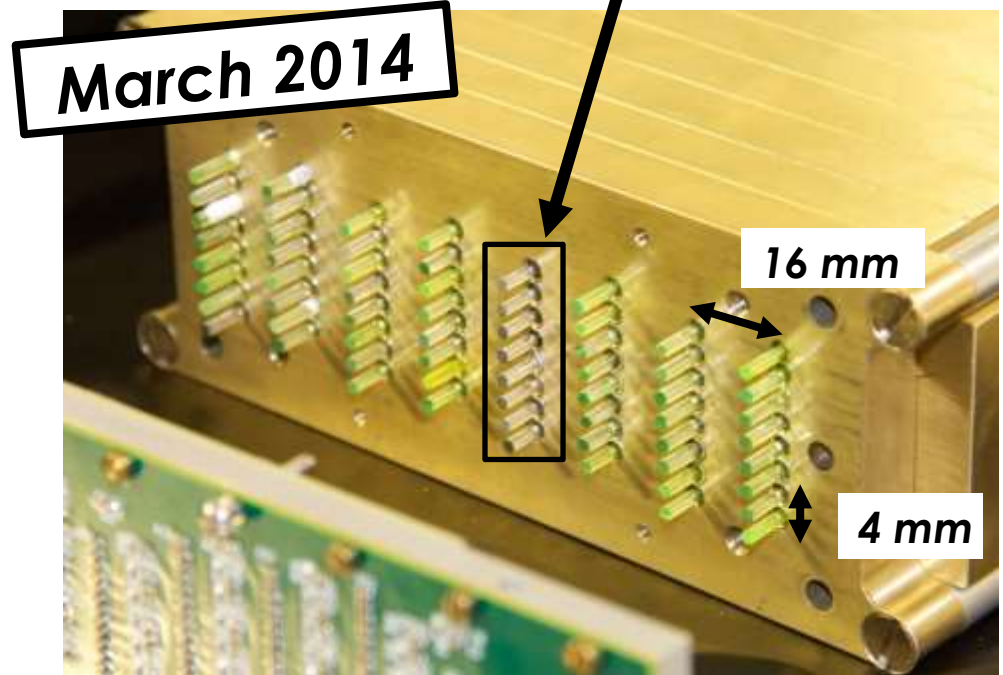
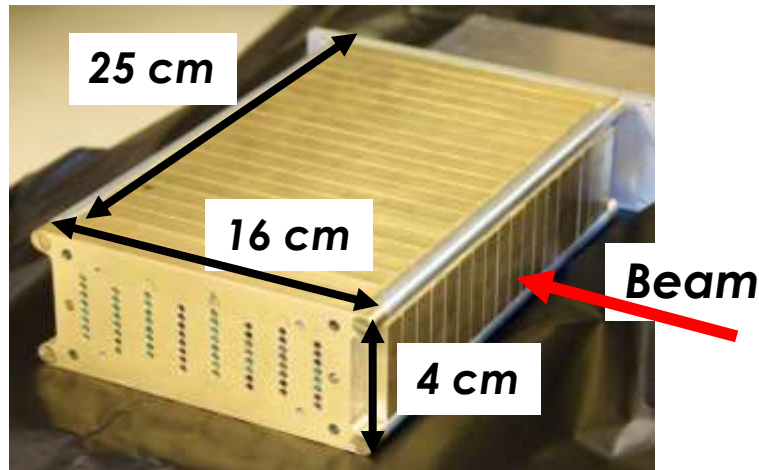


Extrapolation to better sampling fractions!



Scaling up!

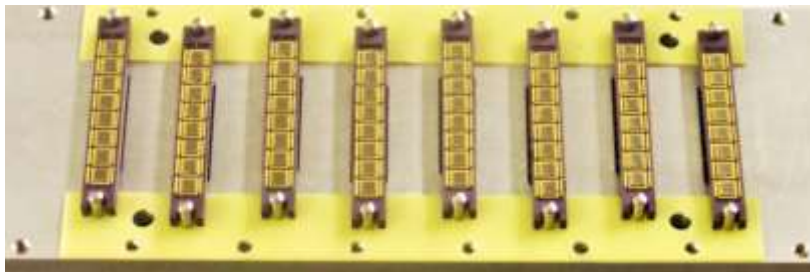
64 LuAG fibers (56 Scint. + 8 Cherenkov)



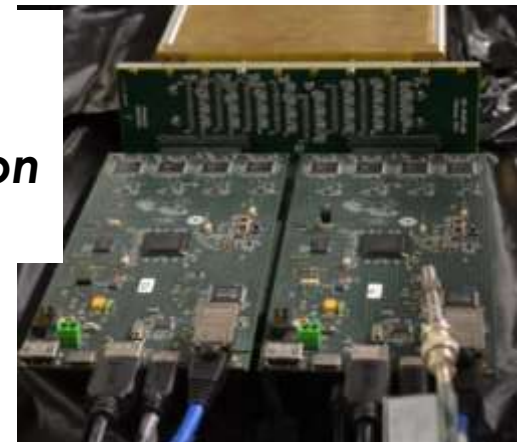
Individual readouts

8 x 8 ch SiPM arrays from KETEK

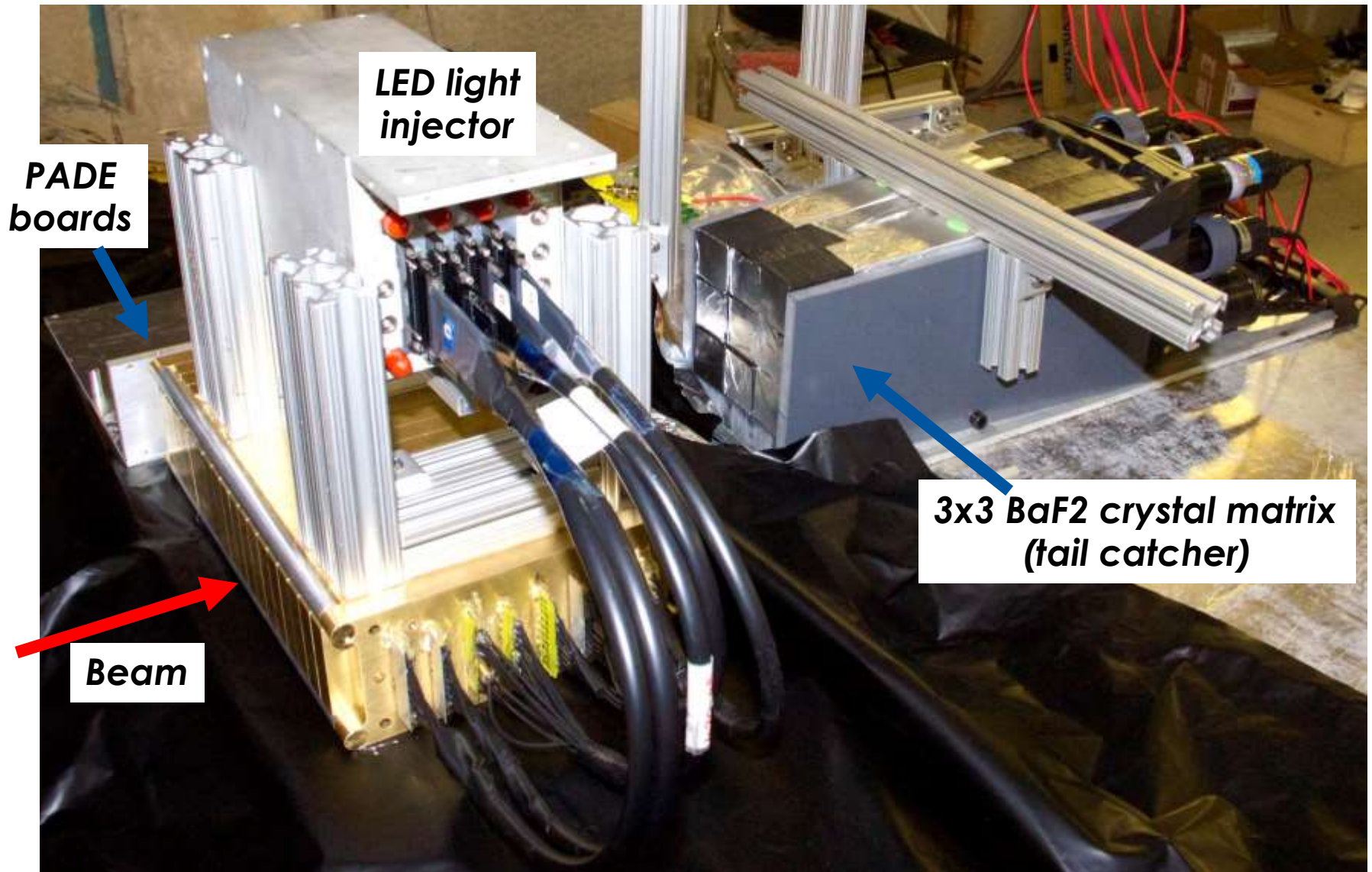
Area = $2.2 \times 2.2 \text{ mm}^2$ Rec. time: 30 ns
(12100 cells of $20 \mu\text{m}$) PDE ~ 20 %



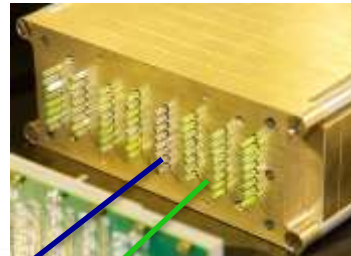
2x 32 ch
PADE boards
for data acquisition
(and SiPM bias)



The full experimental setup



Some results obtained with this prototype

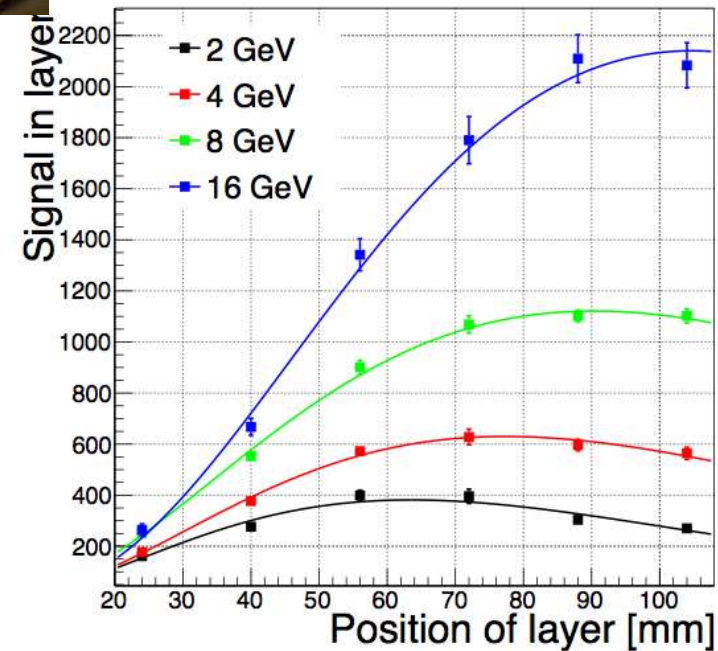
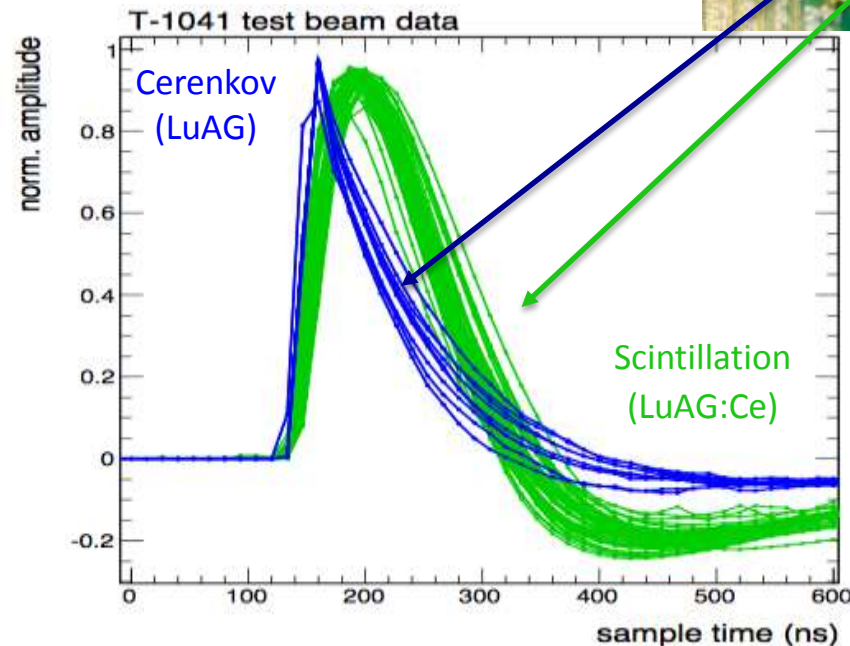


electron beam from 2 to 16 GeV

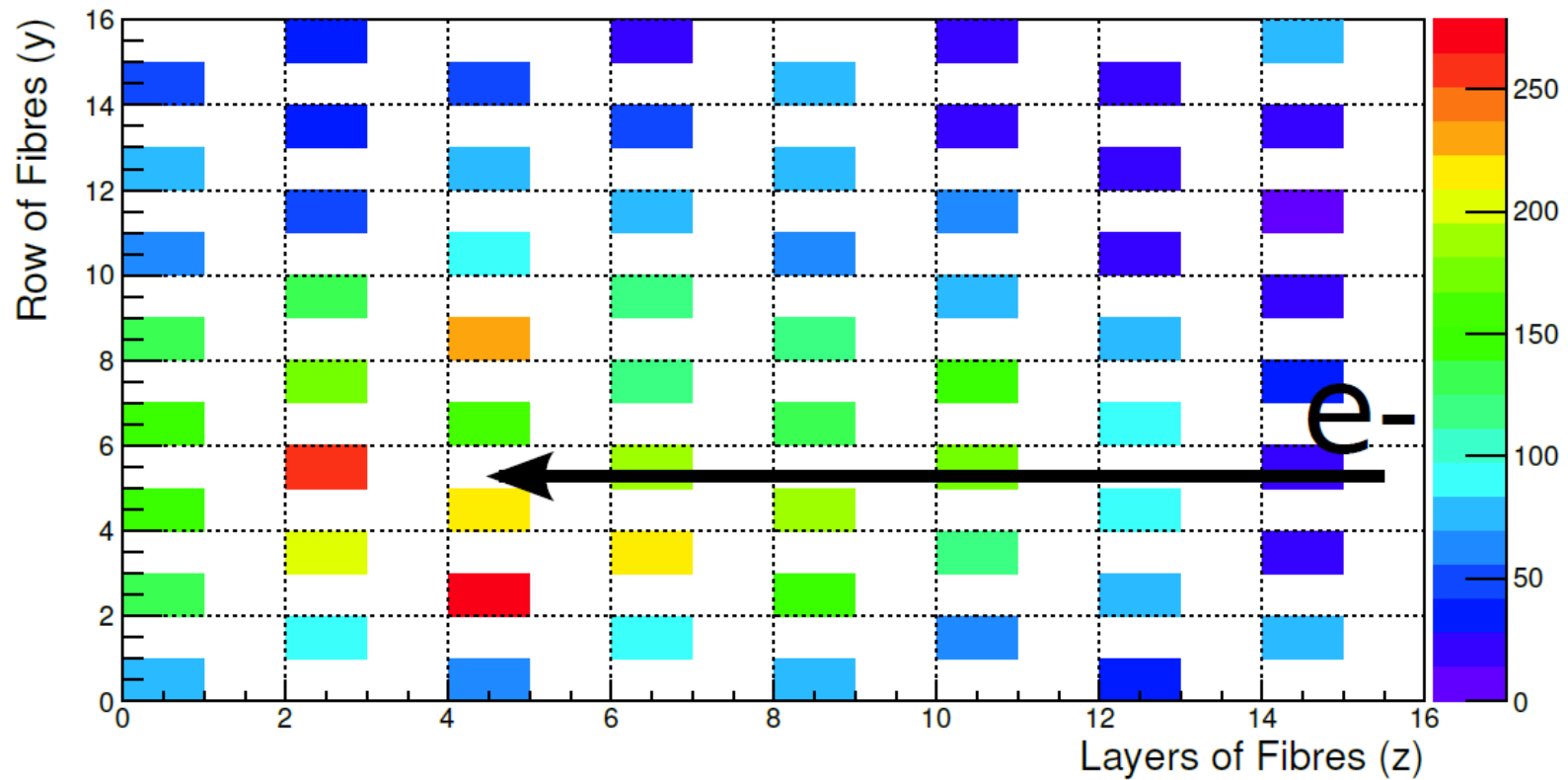


Good separation of
scintillation/Cerenkov pulses

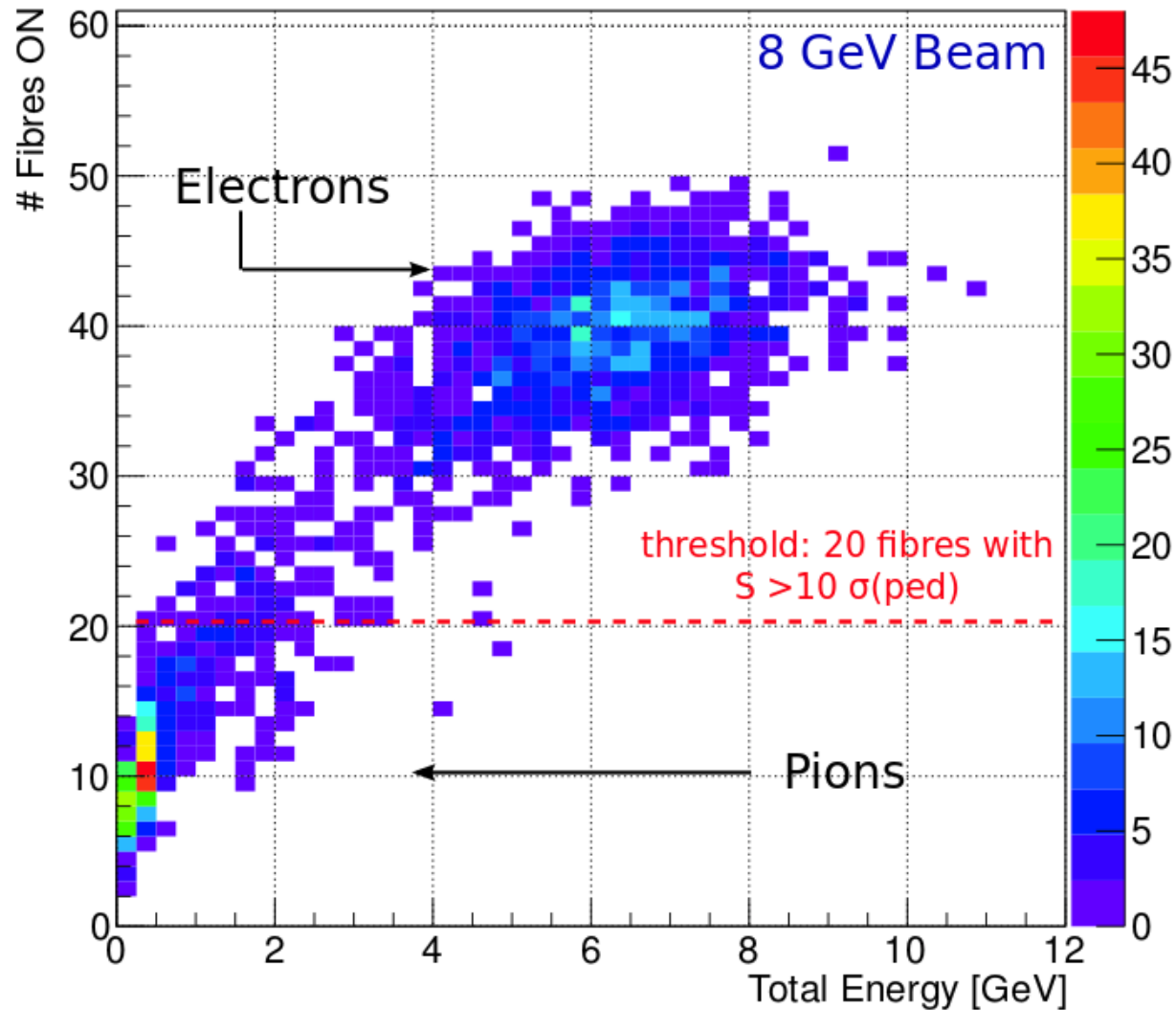
Energy scan



The 64 fibers allowed a mapping of the beam

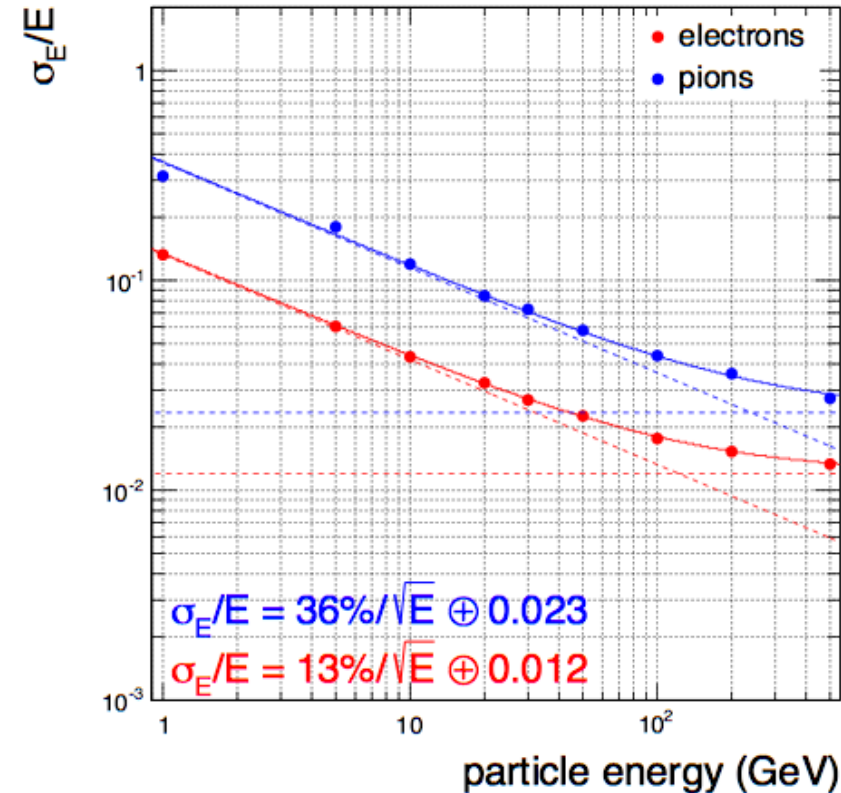


Particles can be identified based on the beam profile

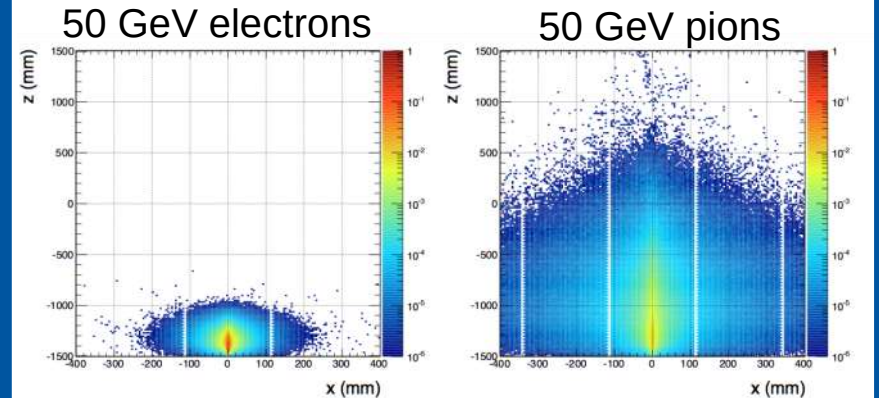


Predicted performances (Geant4)

Expected performance for a 1x1x3 m³ calorimeter:
big enough to have ~full containment for e/ π

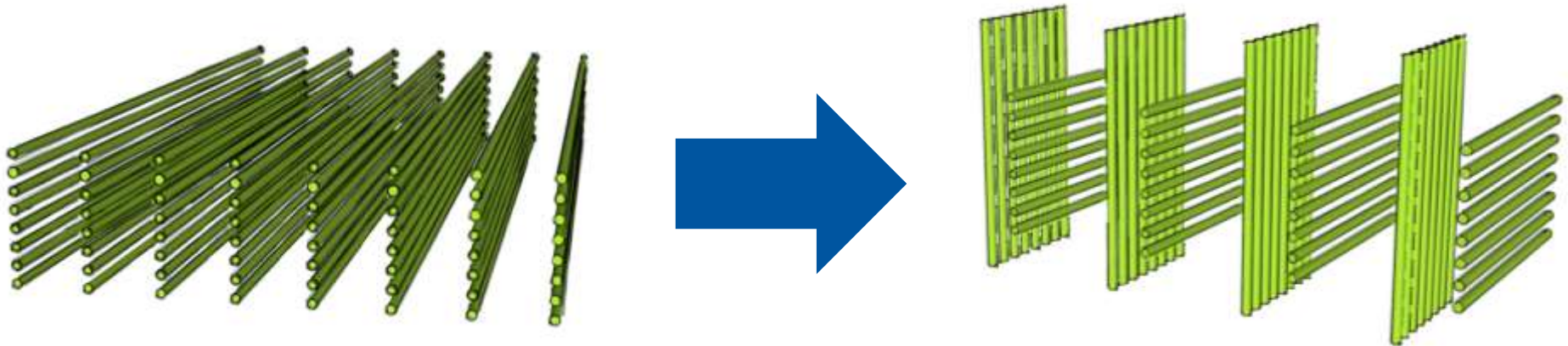


Shower shapes

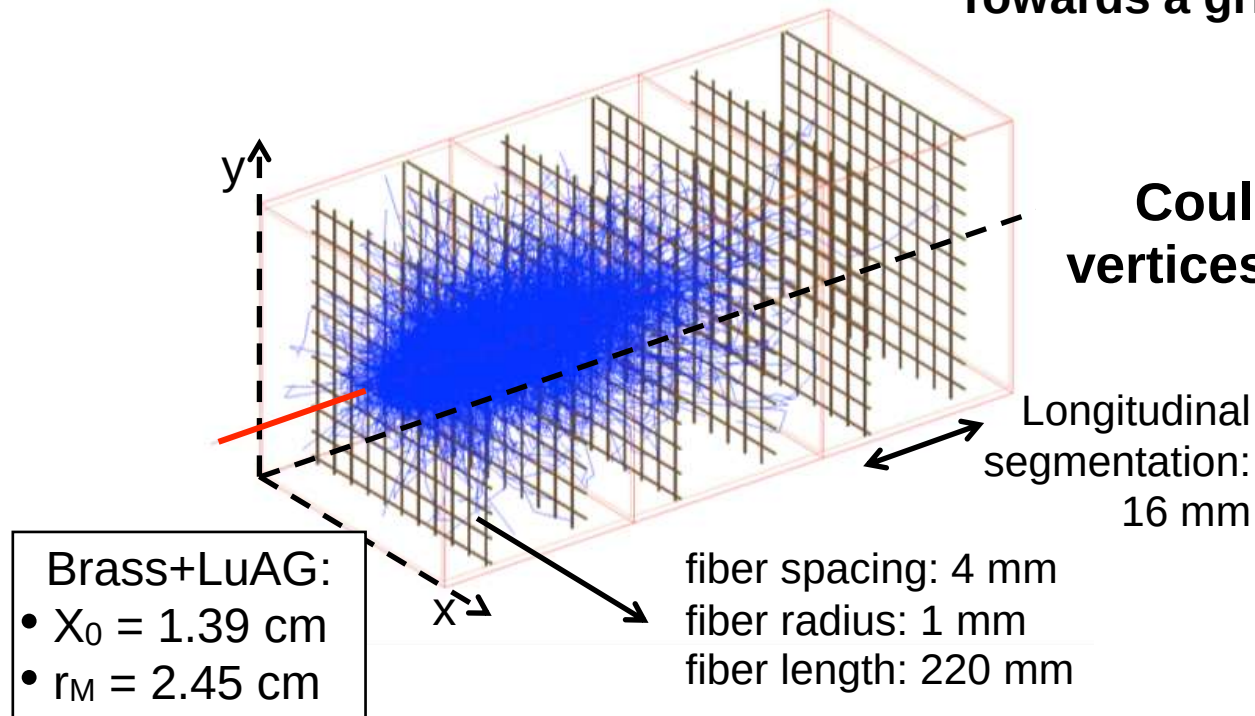


- residual effect of
transverse non uniformity
- electrons “see” the fiber position
 - can be corrected for

Possible evolution of the design



Towards a grid configuration



Could be used for
vertices reconstruction

Longitudinal
segmentation:
16 mm

Brass+LuAG:

- $X_0 = 1.39$ cm
- $r_M = 2.45$ cm

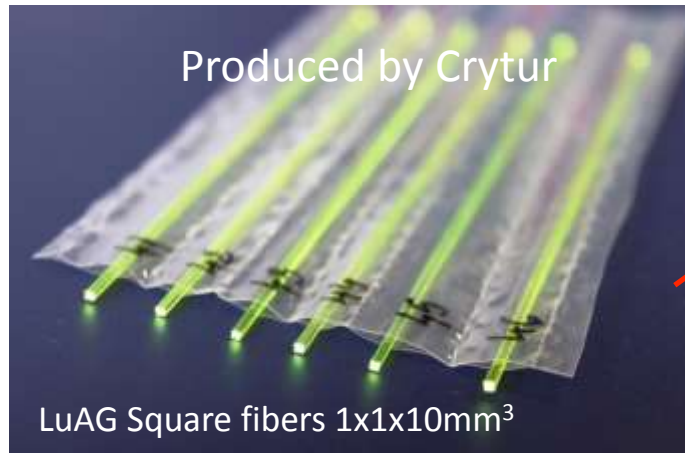
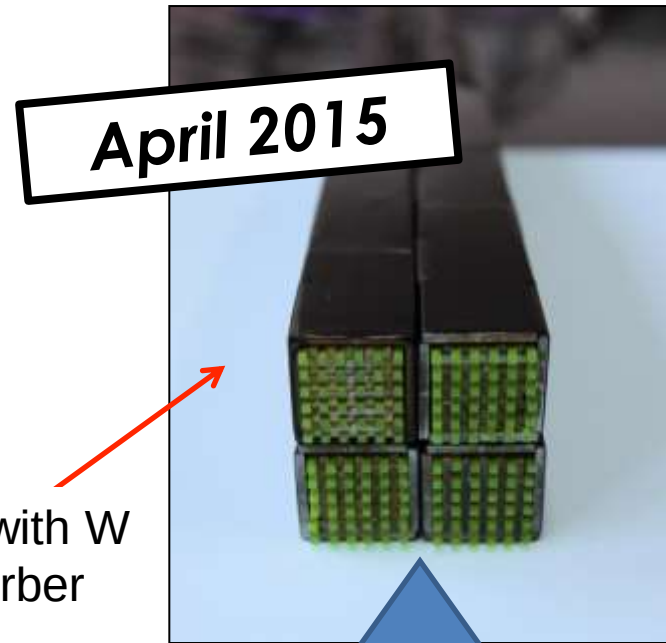
fiber spacing: 4 mm
fiber radius: 1 mm
fiber length: 220 mm

Pushing for better performances with square fibers (cut from Cz crystals)

Choice of geometry : SPACAL
(Spaghetti Calorimeter)
Tagged photon beam
from 56 to 766 MeV



Tested @ MAMI (Mainz, Germany)

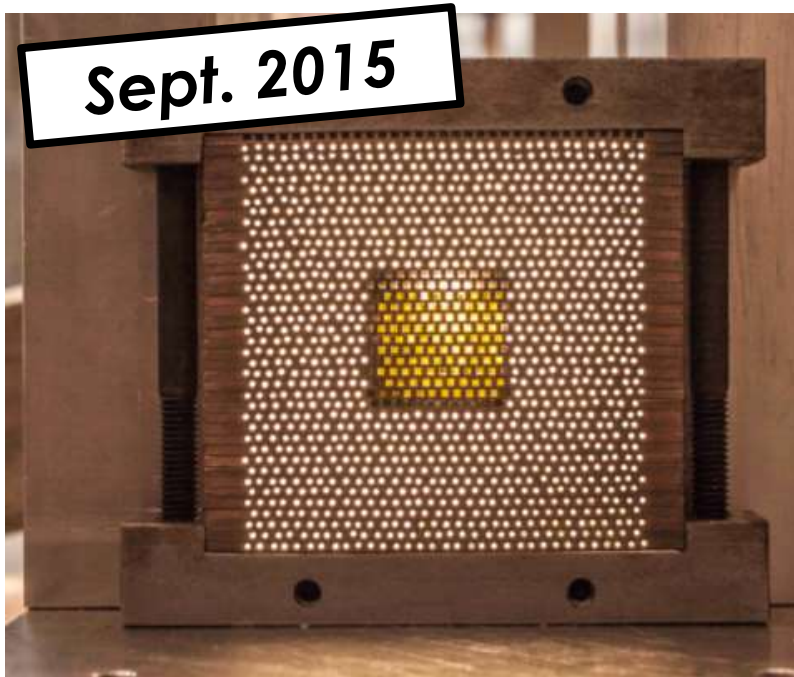


Mixed with W
Absorber

Tagged photon beam
 $E=0.056$ to 0.766 GeV

A larger SPACAL module also measured at CERN

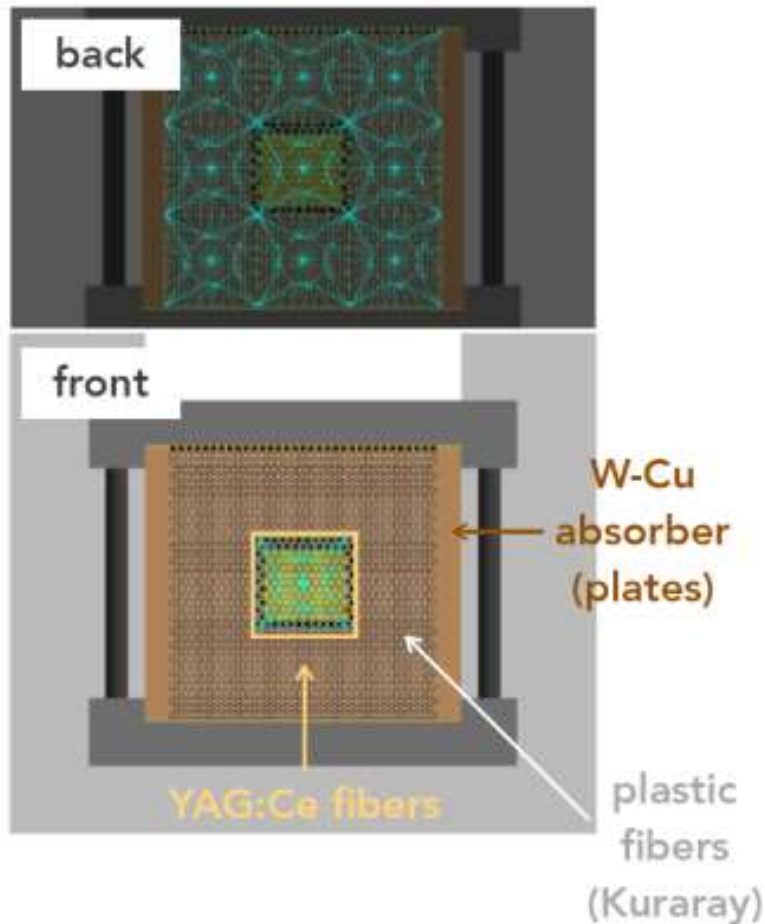
Electron beam (pointing)
 $E=10\text{-}200\text{ GeV}$



YAG square fibers
in a W-Cu Absorber
(stacked grooved plates)

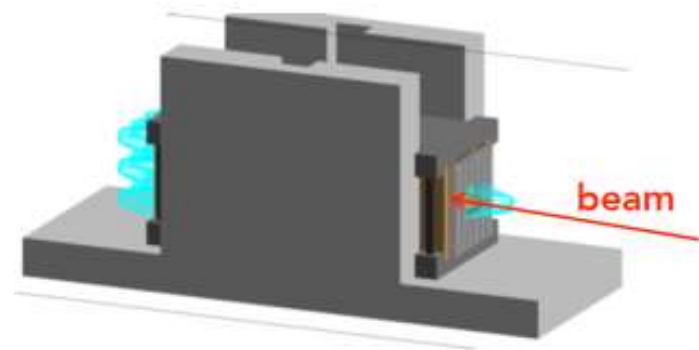


A larger SPACAL module also measured at CERN



Absorber block:

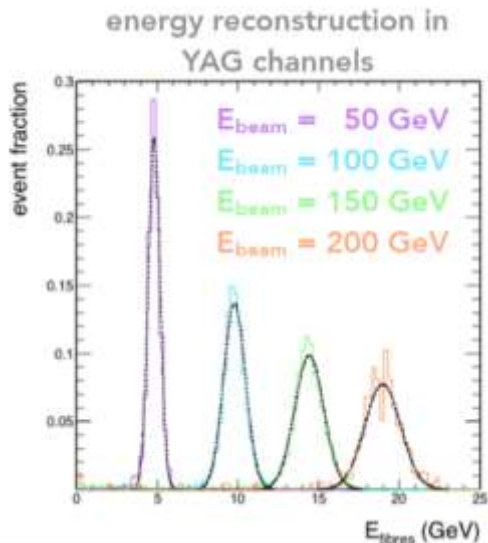
- Total dimensions 60x60x200
- 1235 square $1.1 \times 1.1 \text{ mm}^2$ / 1.8mm apart
- $3 r_M$ in transverse size



Fibers

- 200 YAG fibers (two layers of 10 cm) in central module
- 1000 plastic Kuraray fibers around
- 9 PMMA cones for light collection

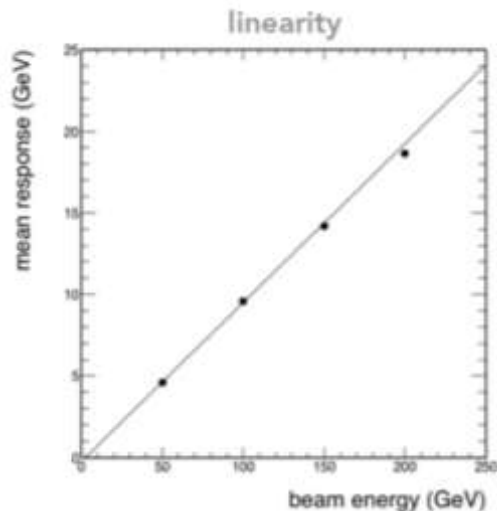
Measured performances and expectations!



The measured energy resolution has a dominating constant term of $\sim 6\%$

Could be further improved to:

$$\frac{\sigma E}{E} \sim \frac{19\%}{\sqrt{E}} + 2.7\%$$

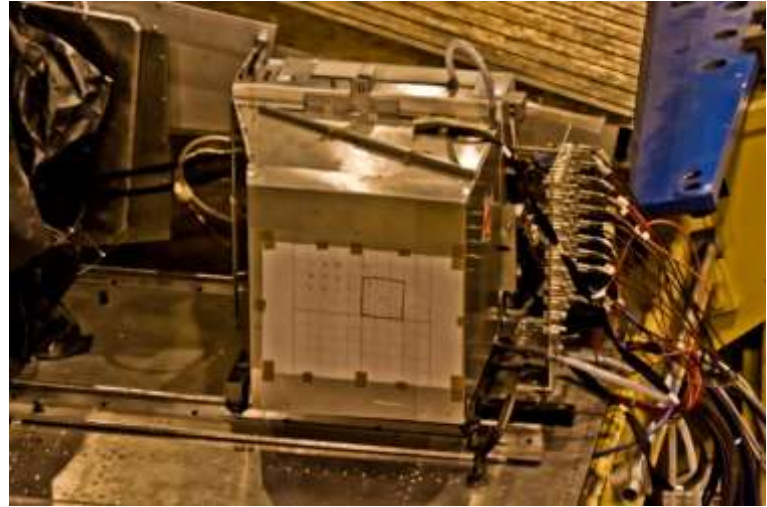


This requires:

- all channels are filled with YAG
- the intercalibration is more accurate
- the beam spot better restricted

BONUS

What does a test beam facility look like ?



Test beam facilities @ FNAL (Illinois, USA)

