Crystal Fibers for 4D Imaging Calorimeters

K. Pauwels\textsuperscript{a}, N. Aubry\textsuperscript{b}, A. Benaglia\textsuperscript{a}, C. Dujardin\textsuperscript{c}, S. Faraj\textsuperscript{b}, A. Heering\textsuperscript{d}, V. Kononets\textsuperscript{c}, K. Lebbou\textsuperscript{c}, P. Lecoq\textsuperscript{a}, M. Lucchini\textsuperscript{a,e}, T. Medvedeva\textsuperscript{f}, C. Tully\textsuperscript{f}, X. Xu\textsuperscript{c}, and E. Auffray\textsuperscript{a}

\textsuperscript{a} CERN – PH-CMX , Switzerland  
\textsuperscript{b} Fibercryst, Lyon, France  
\textsuperscript{c} ILM, University of Lyon, France  
\textsuperscript{d} University of Notre Dame, IN, USA  
\textsuperscript{e} University of Milano-Bicocca, Italy  
\textsuperscript{f} Princeton University, NJ, USA

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Crystal fibers grown by Micro-Pulling Down

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)

\[ \text{C. Dujardin et al. J. of App. Physics 108 p013510 (2010)} \]

Interest for calorimeters

Crystal fibers allow flexible designs

Virtually possible to combine:
- homogeneity
- high granularity
- dual readout abilities
Up to now, the R&D focus was set on LuAG

Chosen because of the experience acquired on YAG (lasers)

\[ \rho = 6.73 \text{ g/cm}^3, \quad X_0 = 1.41 \text{ cm}, \quad \lambda_{\text{Int}} = 23.3 \text{ cm} \]

### 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\textsuperscript{3+}**
  - Light yield (ph/MeV): 30 000
  - Emission: 520 nm
  - Decay: 70 ns

- **Pr\textsuperscript{3+}**
  - Light yield (ph/MeV): 15 000
  - Emission: 350 nm
  - Decay: 20 ns

E. Auffray et al., NSS 2009 p2245
E. Auffray et al., TNS 2010 57 (3) p1454
Current status of the fiber quality

Optimization of the crystal fiber growth from Dec 2010 to Dec 2013, with support from the French National Agency for Research (ANR INFHINI).

R&D performed within the Crystal Clear Collaboration

Crystal growth know-how successfully transferred to industry

Reproducibility

Light attenuation

Light output

\[ L_{att} = 0.6-2 \text{ m} \]

\[ 100-500 \text{ ph/MeV} \]


Pauwels et al. JINST 8 P09019 (Sept 2013)
Crystal fibers for homogeneous calorimetry

Doped fibers (scintillators)

Undoped fibers (Cerenkov radiators)

P. Lecoq, CALOR 2008

Full Homogenous Calorimeters show excellent energy resolution!

\[
\frac{\sigma_E}{E} = \begin{cases} 
22\% & \text{Single readout} \\
15\% & \text{Dual readout}
\end{cases}
\]

For pions!

G. Mavromanolakis et al. CALOR 2010 + JINST 6 p10012 (2011)
The first prototypes

Blocks of fibers

40 fibers (L=8 cm) Scint+Cherenkov

Results dominated by a rather strong light attenuation in the fibers

Optical quality demonstrated

Very promissing results with electron beam

Longitudinal fibers

May 2012

Short selection of 9 fibers (L=22 cm)

Nov. 2009
Energy deposits for different beam energies

Test beam at CERN / H2 beamline of the SPS North Area

Obtained after intercalibration of the 9 fibers

M. Lucchini et al, JINST 8 10017 (2013)
64 LuAG fibers (56 Scint. + 8 Cherenkov)

Individual readouts

8 x 8 ch SiPM arrays from KETEK

Area = 2.2 x 2.2 mm²
(12100 cells of 20 μm)

Rec. time: 30 ns
PDE ~ 20 %

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

Thanks to Paul Rubinov (FNAL)
The full experimental setup

PADE boards

LED light injector

Beam

3x3 BaF2 crystal matrix (tail catcher)
This last prototype tested in beam @ FNAL

FTBF

Fermilab Test Beam Facility

Mtest Control Room

Thanks to Burak Bilki for organizing the T-1041 runs!!

1 - 32 GeV electron/pion beam

Experimental Area @ MT6.2B

March 2014

24 25 26 27 28 1 2
3 4 5 6 7 8 9
10 11 12 13 14 15 16
17 18 19 20 21 22 23
24 25 26 27 28 29 30
31 1 2 3 4 5 6
All 64 channels working!

Signals from both undoped and doped fibers

Data from FNAL T-1041 beam tests will be thoroughly analyzed:

- detailed performance and characterization of all fibers
- on-beam channel inter-calibration
- position and angle reconstruction
- shower shape analysis
- Q/S studies for e/π separation

+ Comparison of data with Geant4 simulation predictions
How to reduce the number of channels?

⇒ Collect the light from several crystal fibers with quartz capillaries filled with a core of wavelength shifter (WLS)

Collection Efficiency

η ~ 0.2-1 %
Possible evolution of the design

Towards a grid configuration

Brass+LuAG:
- $X_0 = 1.39$ cm
- $r_M = 2.45$ cm

Longitudinal segmentation: 16 mm
fiber spacing: 4 mm
fiber radius: 1 mm
fiber length: 220 mm

Could be used for vertices reconstruction
Predicted performances (Geant4)

Expected performance for a $1 \times 1 \times 3$ m$^3$ calorimeter:
big enough to have ~full containment for $e/\pi$

\[ \sigma_E/E = 36\% \sqrt{E} \oplus 0.023 \]
\[ \sigma_E/E = 13\% \sqrt{E} \oplus 0.012 \]

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

Shower shapes

50 GeV electrons

50 GeV pions
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Crystal have very good timing properties ... to be exploited!

Our lab at CERN deeply involved
... Transferring our know-how learned from the Medical imaging!

Time resolution: $\sigma=32$ ps achieved with 511 keV

LSO 2x2x5 mm$^3$

S Gundacker et al 2013 JINST 8 P07014

PICOSEC (Pico-second Silicon photomultiplier Electronics- & Crystal research)

ENDO TOFPET US (Endoscopic TOFPET& Ultrasound)

Next talk, by M. Zvolsky (O5.5)
Thanks for your attention!