Scintillating Fibers for Calorimetry Applications at HL-LHC

INFN Workshop on Future Detectors for HL-LHC

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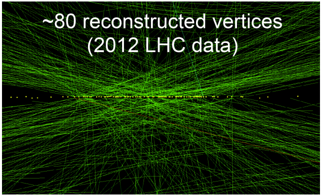
Challenges for calorimetry at HL-LHC

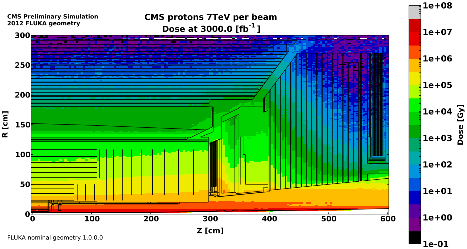
High Luminosity LHC conditions:

- High pileup:
  - $\langle 140 \rangle$ multiple interactions in the same bunch crossing
- High radiation levels:
  - ionizing radiation dose up to $\sim$1 MGy
  - charged hadron fluences up to $\sim 2 \cdot 10^{14}$ cm^{-2}



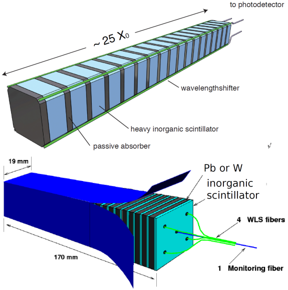
Requirements for calorimeters upgrade:

1. Fast time response
2. Radiation hardness to withstand HL-LHC conditions
3. Affordable costs and mass production

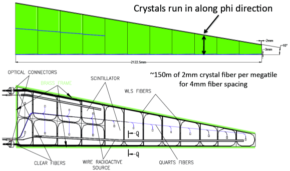


Fibers applications for CMS Endcap Calorimetry

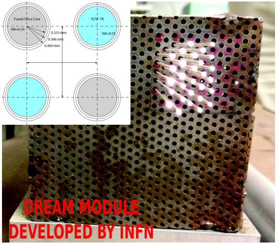
1. ECAL
– Shashlik/Sandwich (LSO/CeF_3) for sampling EE
– WLS fibers + quartz capillary to collect and transport light to the PD.



2. HCAL
– HE megatiles replacement with crystal fibers (LuAG)
– Crystal fibers as rad-hard active material



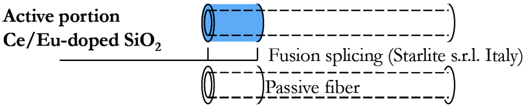
3. ECAL+HCAL
– CFC for dual readout calorimetry (SiO_2-DSB-crystal)
– Quartz clear fiber for cherenkov
– Ce-doped fibers for scintillation



Fibers geometry is estremely flexible and technology can be used for other designs of calorimeters.

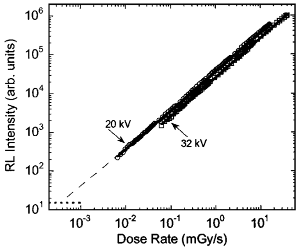
SiO_2:Ce Fibers for Dosimetry Application

- **SiO_2 doping with rare Earth** has been successfully developed for dosimetry applications [1]
- **Sol–gel technique** developed at Dip. Scienza dei Materiali Milano-Bicocca [2] (and with INFN CSN V for dosimetry application)



- Short fibers (∼2 cm) + long clear fibers are used for dosimetry applications

- Fibers were tested after ∼1 kGy of x-rays and showed no signal degradation
- **R&D is needed to transfer this technology to calorimetry**



SiO_2:Ce Fibers for Calorimetry

- Application to calorimetry being investigated within the CMS collaboration in a R&D program supported by INFN CSN I for 2014
- Collaboration with Dip. Scienza dei Materiali (University of Milano-Bicocca) for sample preparation and optimization
- Collaboration with industries: Polymicro and Southampton

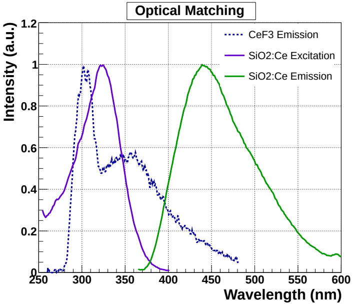
Features:

As scintillator:

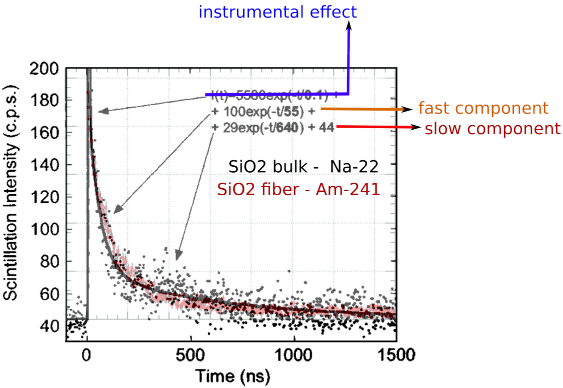
- Good light yield (~2000 ph/MeV)
- First measurements in many labs (Milano-Bicocca, CERN, TTU)

As wavelength shifter:

- Good optical matching with CeF3 emission peak
- First tests performed by ETH-Zurich



SiO_2:Ce – Time response



Pulses measurements

- Pulse shape from fibers has been measured with Am^{241} source
- Good agreement with previous measurements on bulk SiO2 [2]
- Non optimized yet for fast response, but fast component is present
- $\tau_1 = 55$ ns and $\tau_2 = 640$ ns

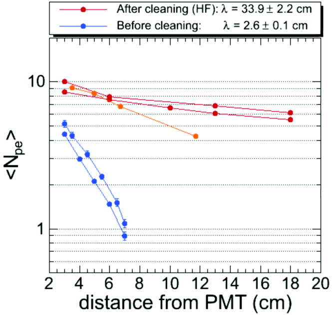
Specific R&D necessary to optimize the scintillation time:

- Quenching slow component by adjusting Ce concentration (a lower light yield might enhance non-radiative decays resulting in a faster response)
- Doping with Praseodymium: faster decay time but emission shifted to UV (based on succesful experience with crystals [3])
- $\sim$ 2 years could be required for this R&D

SiO_2:Ce – Attenuation Length and Radiation Hardness

Attenuation Length

- Core properties are OK, but **application to calorimetry requires longer fibers**
- Surface effects dominate the light transmission inside fibers
- Attenuation length improvement with cleaning is observed
- Cladding is necessary (technique is known although it reduces the light collection efficiency due to smaller numerical aperture)



Radiation Hardness

- Radiation hardness was good for dosimetry applications
- **Specific tests are required for HL-LHC doses**
- Quartz is known to be radiation hard due to high content of OH^- [4] (good results were achieved for the HF calorimeter of CMS)

DSB:Ce Fibers

- New generation of scintillating material based on glass with Cerium nanoparticles
- Being developed by RINP and CERN

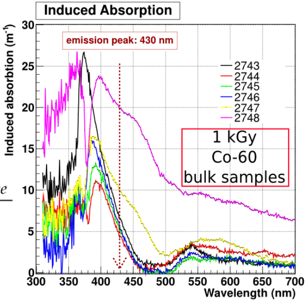
Features:

- Well developed mass production
- Radiation hardness improvement is possible optimizing production parameters

Under study:

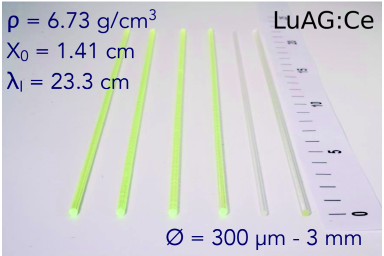
- Selection of best quality raw material
- Optimization of dopant concentration

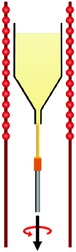
$$\mu_{ind} = \frac{1}{L} \ln \frac{T_{before}}{T_{after}}$$



LuAG:Ce Fibers

- Crystal fibers grown using micro-pulling down technique [5]
- Being developed by CERN, University of Lyon and Fibercryst within the Crystal Clear Collaboration (*with support from the French National Agency for Research ANR*)





Features:

- High density material
  $\rightarrow$ good Cherenkov radiator
- High light yield:
  $\sim$ 15000 ph/MeV
- Same material can be used for a dual readout calorimeter
- Preliminary tests on radiation hardness of bulk samples are promising ($\mu_{ind} \sim 1.5\ \mathrm{m}^{-1}$ for both 1 kGy γ-dose and $3.5 \cdot 10^{13}\ \mathrm{p/cm^2}$)

Under study:

- Improvement of optical properties [6]
- Performance in beam tests [7]
- Improvement of radiation hardness

Scintillating Fibers: options overview

Overview of materials options

Material	Emission peak (nm)	Dominant decay Time (ns)	Light Yield (ph/MeV)	Density (gr/cm^3)
SiO_2:Ce	440	55	2000	2.6
DSB:Ce	430	55	2000	4.0
$Lu_3Al_5O_{12}$:Ce	530	55	15000	6.7
Lu_2SiO_5:Ce	390	30	26000	7.1
$Y_3Al_5O_{12}$:Ce	550	90	24000	4.6
$Lu_3Al_5O_{12}$:Pr	308	20	13000	6.7

Crucial requirements

- Sufficient light yield
- Good attenuation length
- Good radiation hardness
- Emission peak matching photodetectors QE or WLS excitation

Attenuation length of few meters and LY$\sim$ 2000 ph/MeV are sufficient not to affect constant and stochastic terms.

Next steps

Different type of fibers will be tested in lab and with beam tests **before and after** irradiation

Radiation hardness studies:

- γ-irradiation up to 300 kGy ($\sim$ dose of HL-LHC)
  in progress ...
- Exposure to neutrons (up to fluence of $\sim 10^{16}$ n/cm^2)
  already planned at ENEA (Frascati) ...
- Irradiation with 24 GeV protons (up to fluence of $\sim 10^{15}$ p/cm^2)
  will be performed at CERN PS in September-October ...

Test beam studies:

- Evaluate fibers performance with high energy beams
  (light yield, timing, attenuation length, light collection efficiencies, ...)
- Validate calorimeters prototype resolution predicted by simulations
- Beam tests will be performed at FNAL (March-April),
  Frascati (April) and CERN (October)

Summary

- Stringent requirements for calorimeters at HL-LHC
- Need to identify adequate technology and to optimize it
- Fibers have multiple applications in different calorimeter designs

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Ongoing R&D on SiO_2 fibers

- Optimization of SiO_2:Ce fibers for calorimetry:
  1. Investigating options to improve fast time response
  2. Study of fiber cladding to improve attenuation length
  3. Study of radiation hardness
  4. Beam tests

Other fibers R&D

DSB:Ce fibers

LuAG:Ce crystal fibers

References

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Backup slides ...

Calorimeters resolution

Shashlik

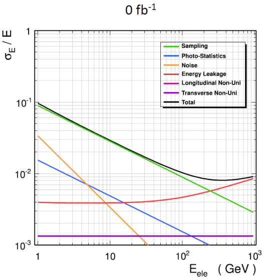
- $X_0 \sim 0.51$ cm , $R_M \sim 1.37$ cm
- EM resolution (plot below):

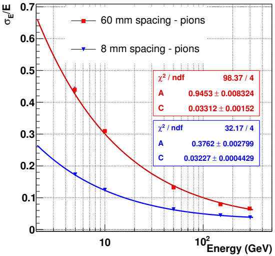
HE with LuAG fibers

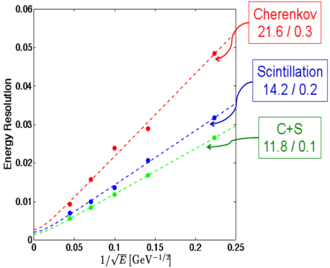
- $X_0 \sim 1.2$ cm , $R_M \sim 2.6$ cm
- (current HE: $\frac{\sigma(E)}{E} \approx \frac{100\%}{\sqrt{E}} + 5.5\%$)
- Pions resolution (plot below):

CFC

- $X_0 \sim 2.0$ cm , $R_M \sim 3.5$ cm
- Pions resolution: $\frac{\sigma(E)}{E} \approx \frac{28.7\%}{sqrtE} + 1.1\%$
- EM resolution (plot below):







CeF3–SiO2 optical coupling: proof of concept

- Measurements made by ETH, Zurich (F. Nessi-Tedaldi)

First test of Ce-doped quartz fibers

Preliminary results

- Measurements using cosmics
- A wavelength-shifted signal is observed
- Various cross-checks have been performed (black paper between crystal and WLS, no crystal, no fibers, two crystals) and confirm the result
- The ratio of direct-to-WLS light still needs the fibers to be optimized