

Scintillators and optical fibers

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Scintillators

Principle

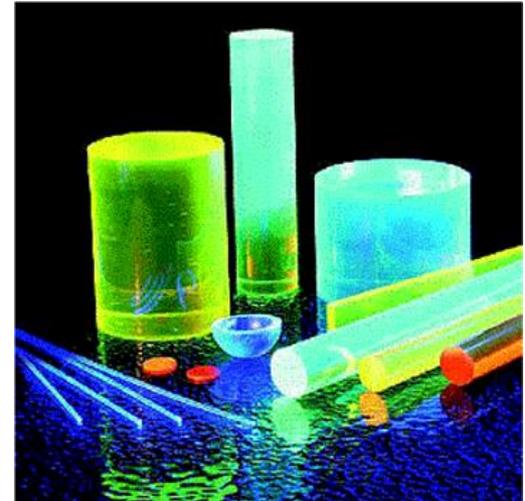
Energy loss converted into visible light
Uses a photosensor for detection

Main features

Sensitivity to energy
Fast time response

Requirements

High efficiency for conversion of excitation energy to fluorescent radiation
Transparency to its own fluorescent radiation to allow light transmission
Emission of light in a spectral region compatible with the envisaged photosensor
Short decay time to allow fast response



Fluorescence and phosphorescence

Scintillation

Emission of photons following the excitation of atoms and molecules by radiation (gamma photons or particle radiation)!

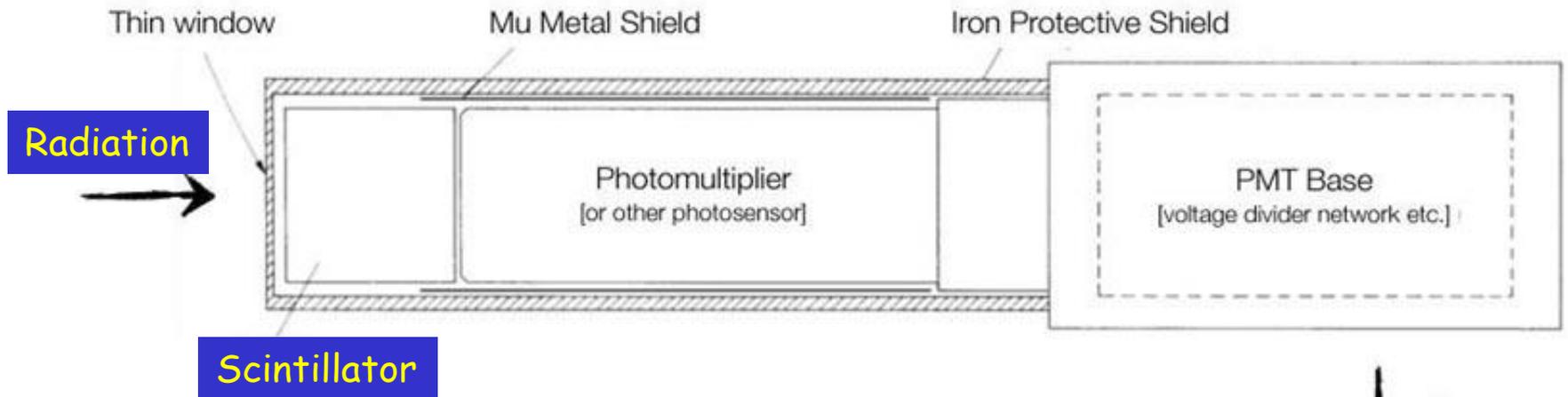
Fluorescence

emission of light by a substance that has absorbed light or another electromagnetic radiation of a different wave length. In most cases the emitted light has a longer wavelength. The emission follows shortly after (typically a few nanoseconds)

Phosphorescence

Similar to Fluorescence, but the re-emission is not immediate. The transition between the energy levels and the photon emission has a large delay when compared with fluorescence (typically ms)

A counter setup using scintillator

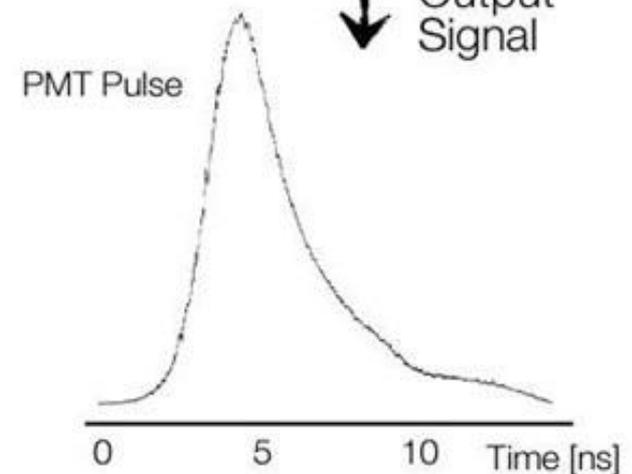


Scintillator Types:

Photosensors

Photomultipliers
 Micro-Channel Plates
 Hybrid Photo Diodes
 Visible Light Photon Counter
 Silicon Photomultipliers

Organic Scintillators
 Inorganic Crystals
 Gases



Inorganic crystals

Materials

Sodium iodide NaI

Cesium iodide CsI

Barium Fluoride BaF₂

Lead tungstate PbWO₄ , etc

Mechanism

Energy deposition by ionization

Energy transfer to impurities

Radiation of scintillation photons

Light yield depends strongly on temperature

Time constants

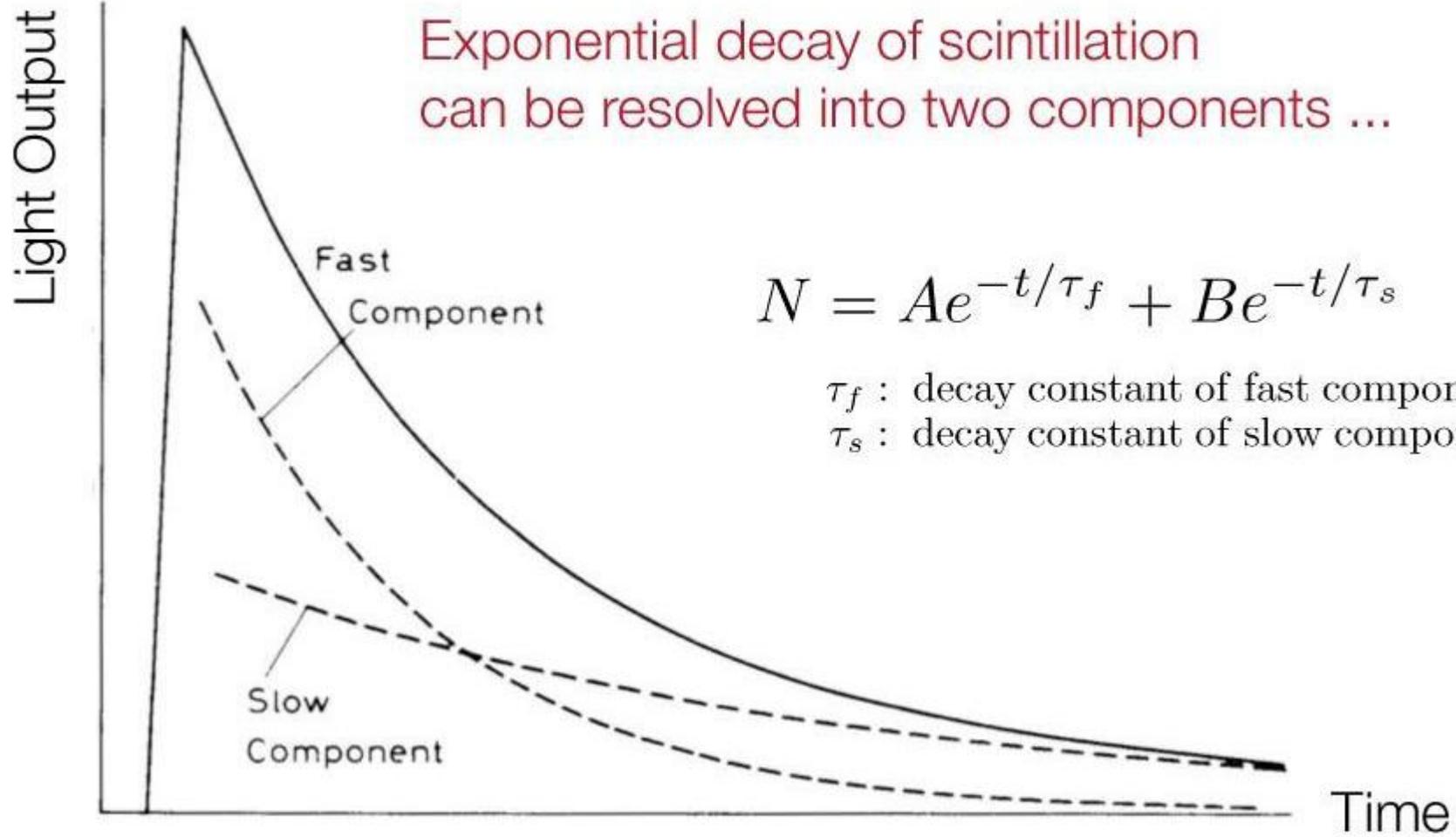
Fast: recombination from activation centers (from ns to μ s)

Slow: recombination due to trapping (from ms to s)



Decay time with 2 components

Exponential decay of scintillation
can be resolved into two components ...



$$N = Ae^{-t/\tau_f} + Be^{-t/\tau_s}$$

τ_f : decay constant of fast component
 τ_s : decay constant of slow component

Inorganic scintillators - properties

Scintillator material	Density [g/cm ³]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [μs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8 \cdot 10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4 \cdot 10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1 \cdot 10^4$
Bi ₄ Ge ₃ O ₁₂	7.1	2.15	480	0.30	$2.8 \cdot 10^3$
CsF	4.1	1.48	390	0.003	$2 \cdot 10^3$
LSO	7.4	1.82	420	0.04	$1.4 \cdot 10^4$
PbWO ₄	8.3	1.82	420	0.006	$2 \cdot 10^2$
LHe	0.1	1.02	390	0.01/1.6	$2 \cdot 10^2$
LAr	1.4	1.29*	150	0.005/0.86	$4 \cdot 10^4$
LXe	3.1	1.60*	150	0.003/0.02	$4 \cdot 10^4$

* at 170 nm

Organic scintillators

Aromatic hydrocarbon compounds

Scintillation based on the electrons of the $C=C$ bonds

Very fast

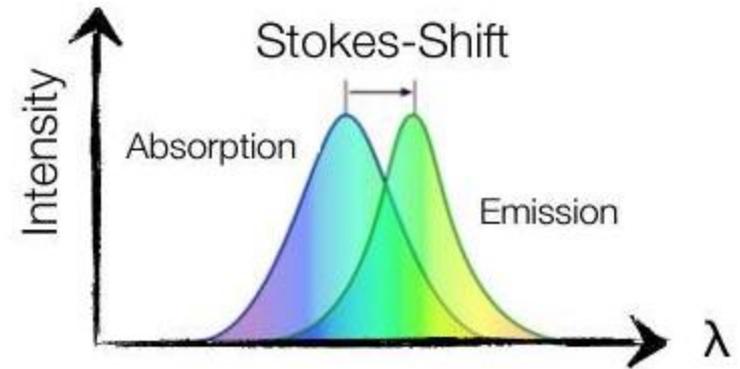
Light yield does not depend strongly on temperature as in crystals

Cheap

Stokes shift

Transparency requires:

Shift of absorption
and emission spectra ...

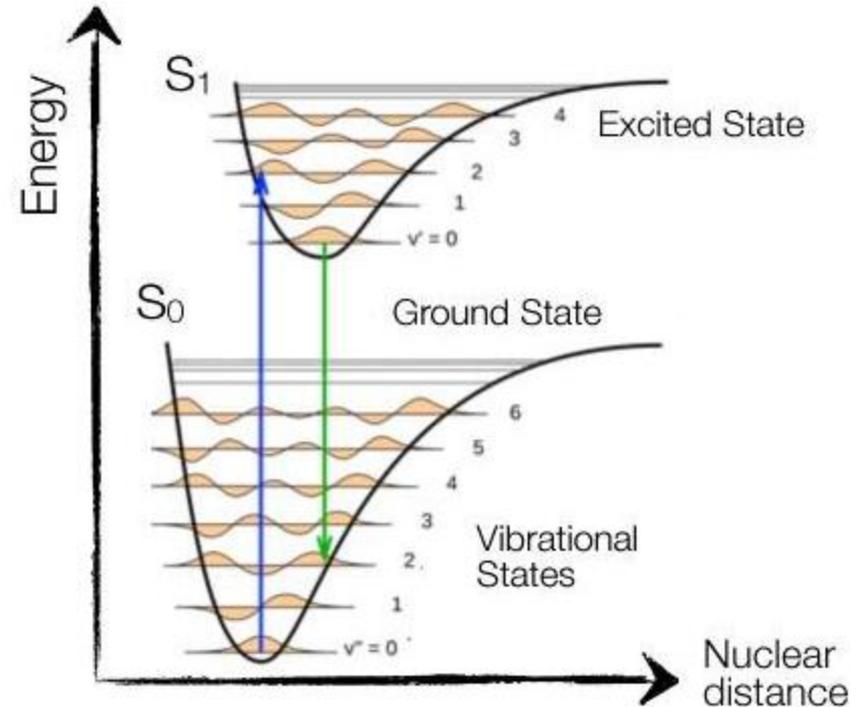


Shift due to

Franck-Condon Principle

Excitation into higher vibrational states
De-excitation from lowest vibrational state

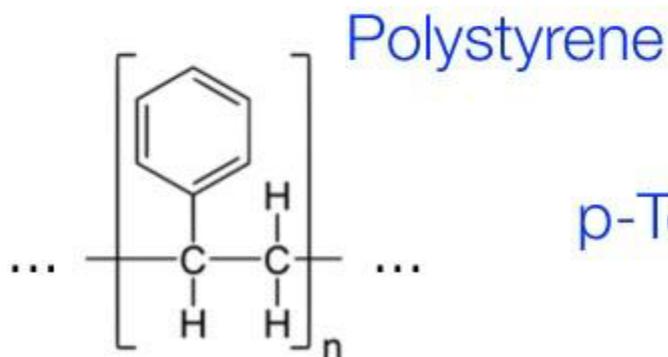
Excitation time scale : 10^{-14} s
Vibrational time scale : 10^{-12} s
 S_1 lifetime : 10^{-8} s



Liquid and plastic scintillators

Some widely used solvents and solutes

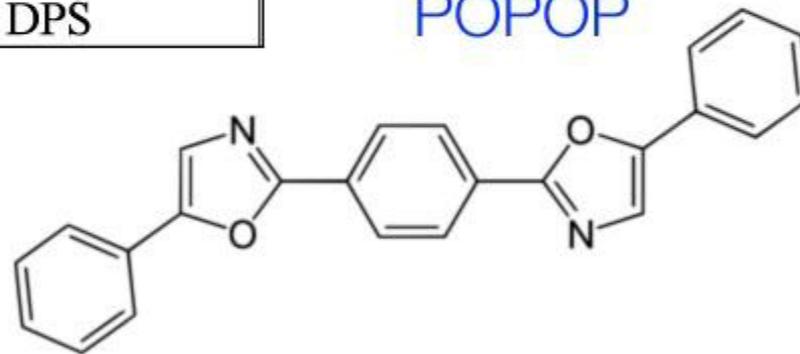
	solvent	secondary fluor	tertiary fluor
Liquid scintillators	Benzene Toluene Xylene	p-terphenyl DPO PBD	POPOP BBO BPO
Plastic scintillators	Polyvinylbenzene Polyvinyltoluene Polystyrene	p-terphenyl DPO PBD	POPOP TBP BBO DPS



p-Terphenyl



POPOP



Organic scintillators properties

Scintillator material	Density [g/cm ³]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

Scintillators - inorganic vs organic

Inorganic Scintillators

Advantages

high light yield [typical; $\epsilon_{sc} \approx 0.13$]
 high density [e.g. $PBWO_4$: 8.3 g/cm^3]
 good energy resolution

Disadvantages

complicated crystal growth
 large temperature dependence

Expensive

Organic Scintillators

Advantages

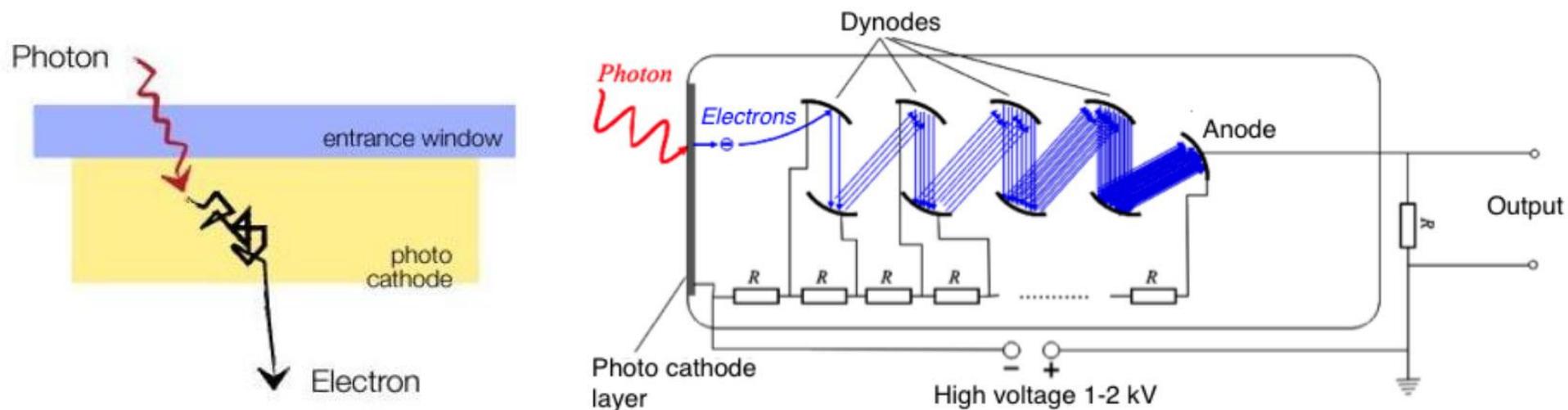
very fast
 easily shaped
 small temperature dependence
 pulse shape discrimination possible

Disadvantages

lower light yield [typical; $\epsilon_{sc} \approx 0.03$]
 radiation damage

Cheap

Photodetector - PMT example



By photoelectric effect, photons hitting the photo cathode release electrons. An applied HV accelerates the electrons towards the 1st dynode where they produce secondary emission. This process is repeated at each dynode. Due to the high gain, a large number of electrons arrives at the anode.

Quantum efficiency 10 - 30%, wave length dependent.

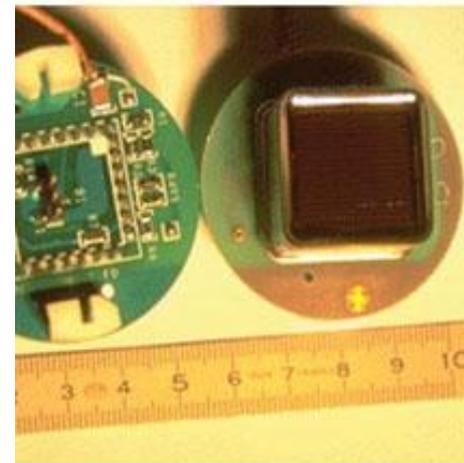
PMT signal is sensitive to magnetic field

Photodetector - PMT example

PMTs exist in many different sizes and shapes.
Quantum efficiency 10 - 30%, wave length dependent.

There exist also PMTs with multiple anodes, with the photocathode divided in the same number of independent PMT pixels:

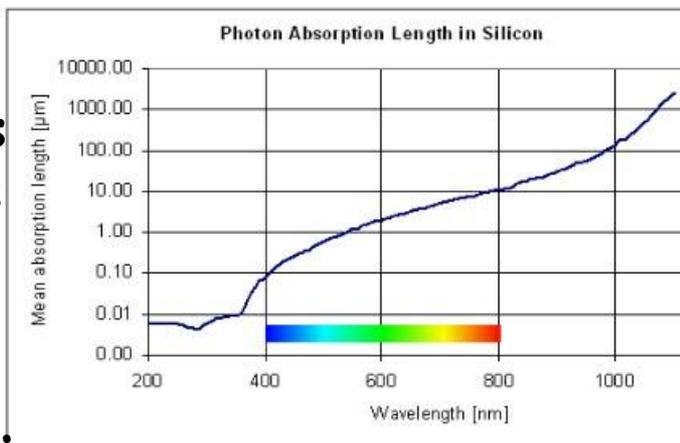
MAPMTs



PMT signal is sensitive to magnetic field

Photodetector - Si PMT example

Silicon absorbs photons easily...



Si PMT:
pixelized photodiodes working in Geiger mode

Single pixel works as a binary device

Typical parameters:

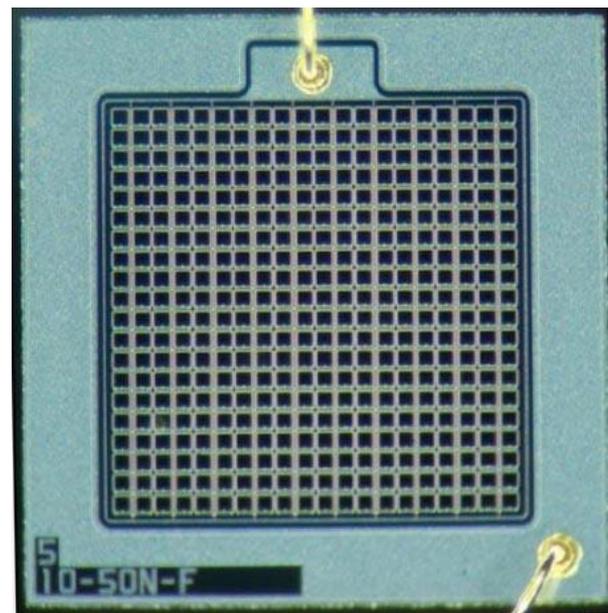
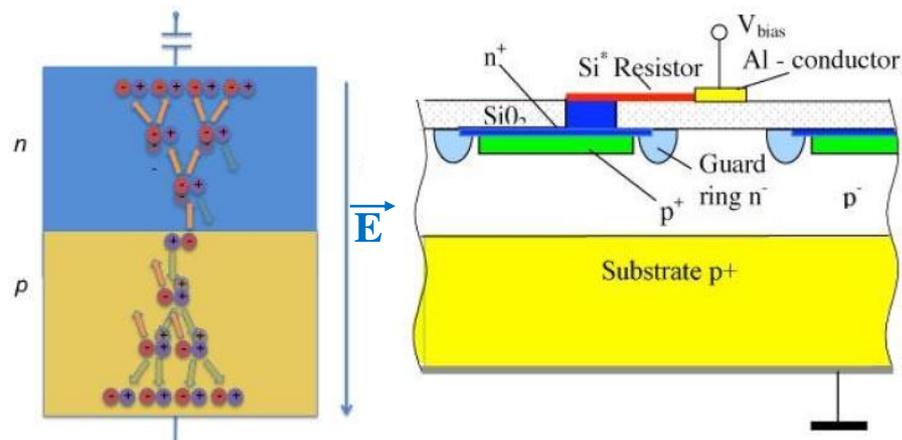
Granularity: 1000 pixels/mm²

Gain: 10⁶

Voltage: <100

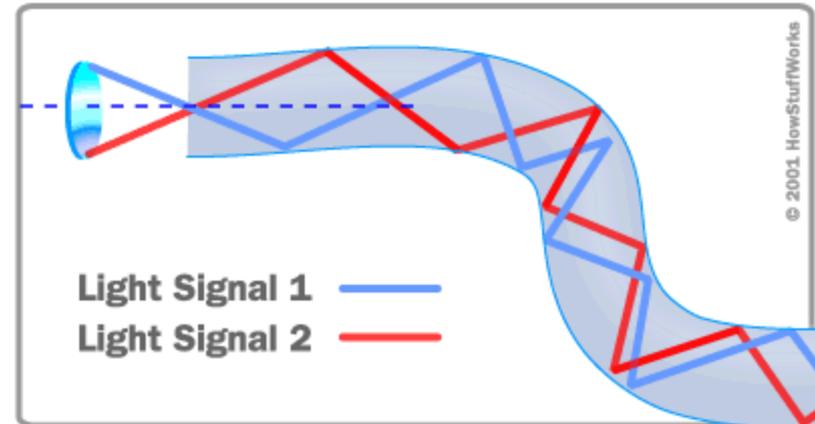
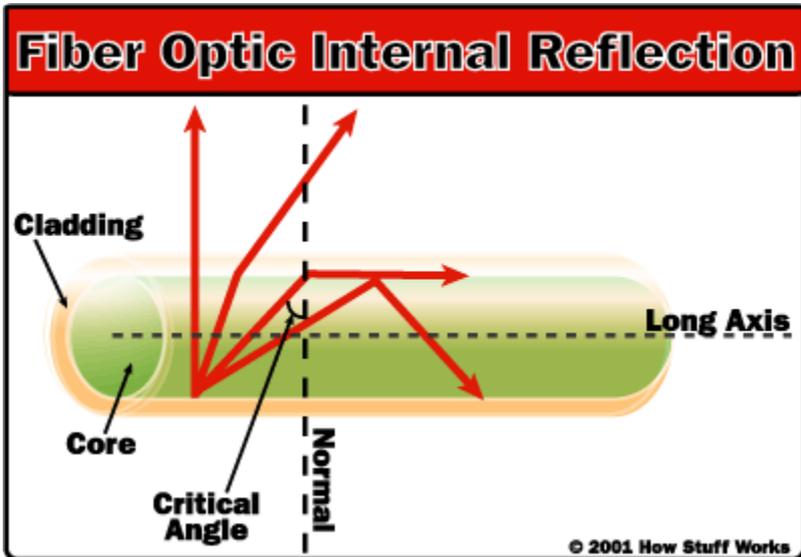
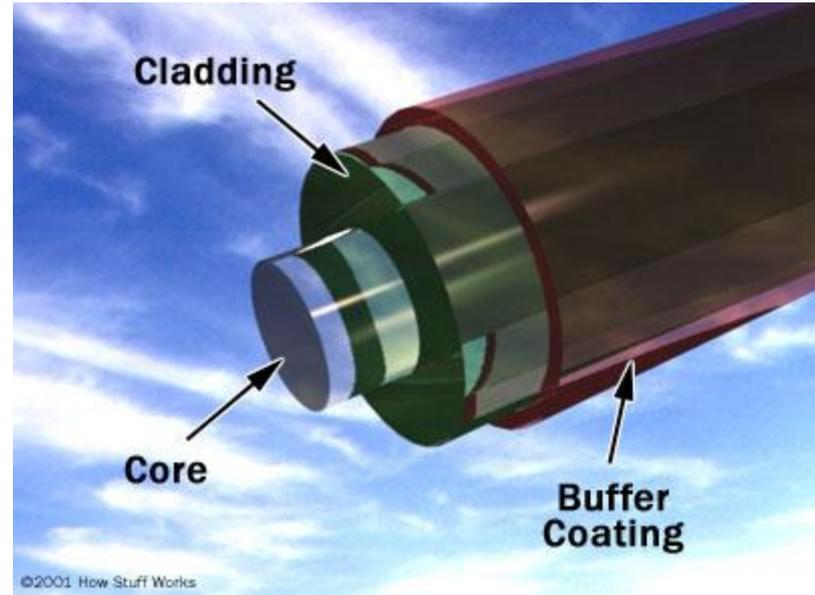
Efficiency: 30%

Energy obtained summing the number of photons seen by the pixels (sensitive from 1 to about 1000 for a 1mm² device)



Si PMT insensitive to magnetic field

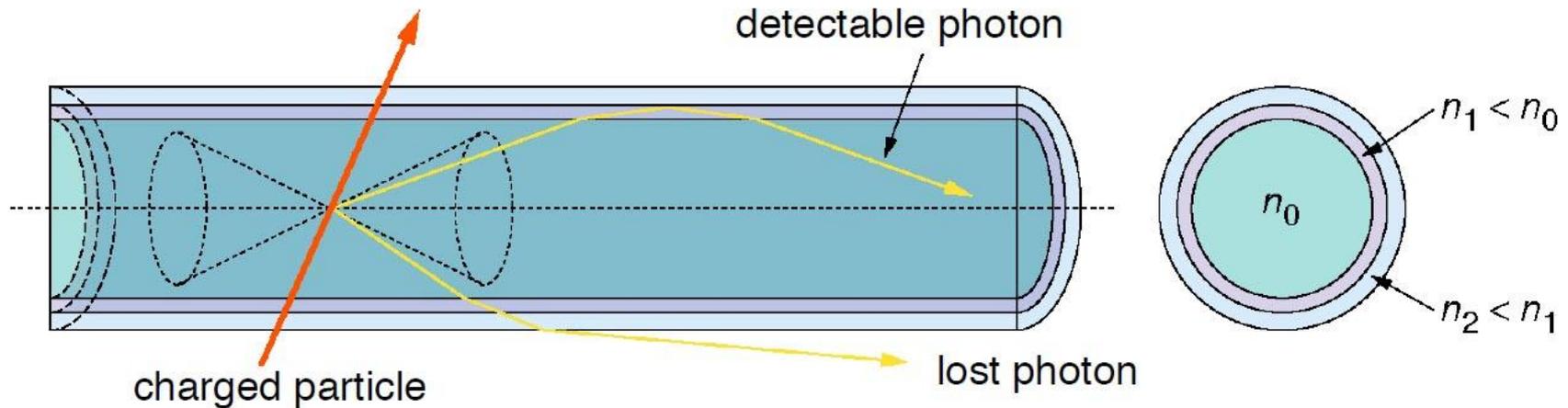
Optical fibers



Optical fibers can be used as detector or as a way to transmit light to a photodetector

Scintillating fibers

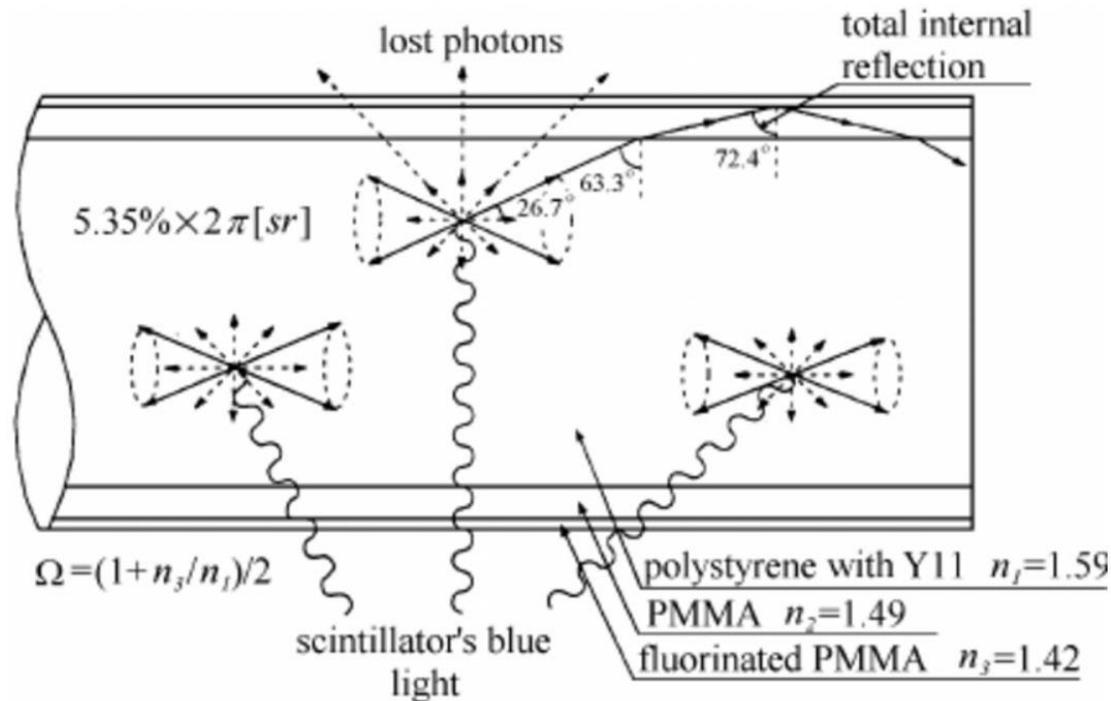
Optical scintillating fibers act as scintillator detector.
A particle crossing it produces scintillation



Fiber with a central core (refraction index n_0) and 2 cladding layers (ref index n_1 and n_2 with $n_2 < n_1 < n_0$)

Wave length shiting (WLS) fibers

WLS fibers are used to collect and transport light. Photons crossing it are absorbed and re-emitted in a different wavelength

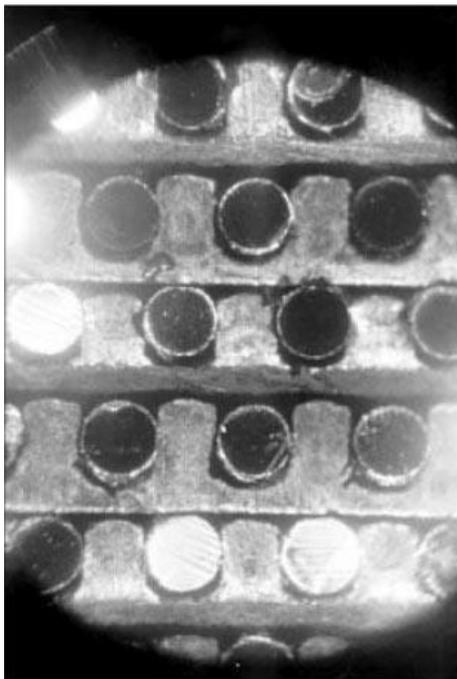


Fiber with a central core Y11 (refraction index $n_1=1.59$) and 2 cladding layers (PMMA with ref index $n_2=1.49$ and fluorinated PMMA with ref index $n_3=1.42$)

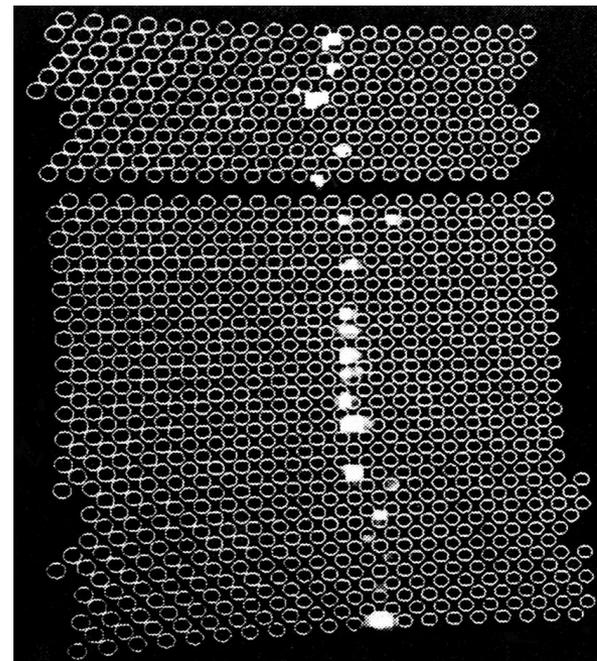
Scintillating fibers

Scintillating fibers can be produced in different lengths, diameters and shapes (square or circular section)

They can be used in trackers or calorimeters

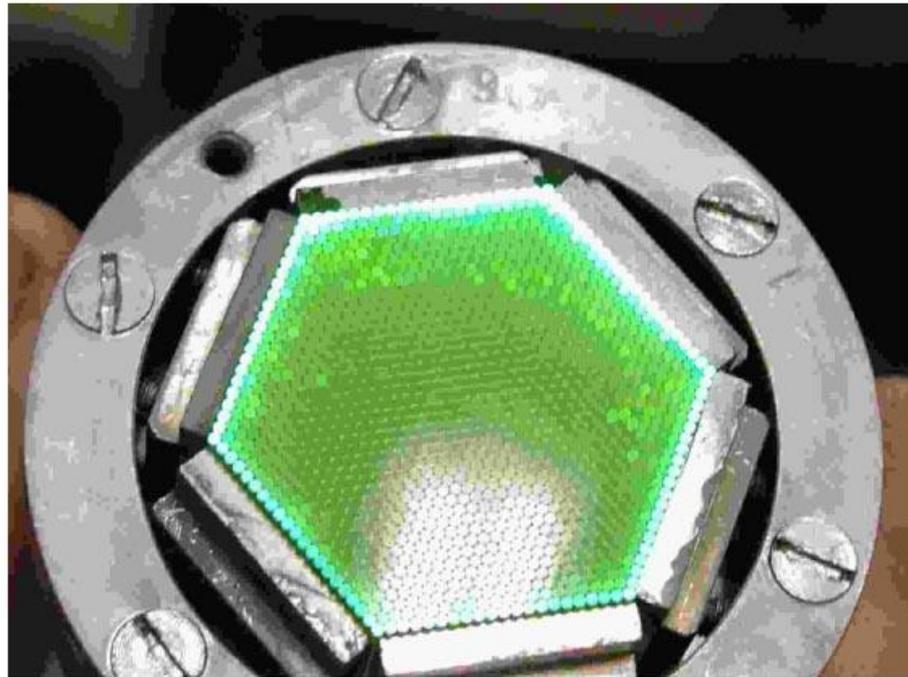
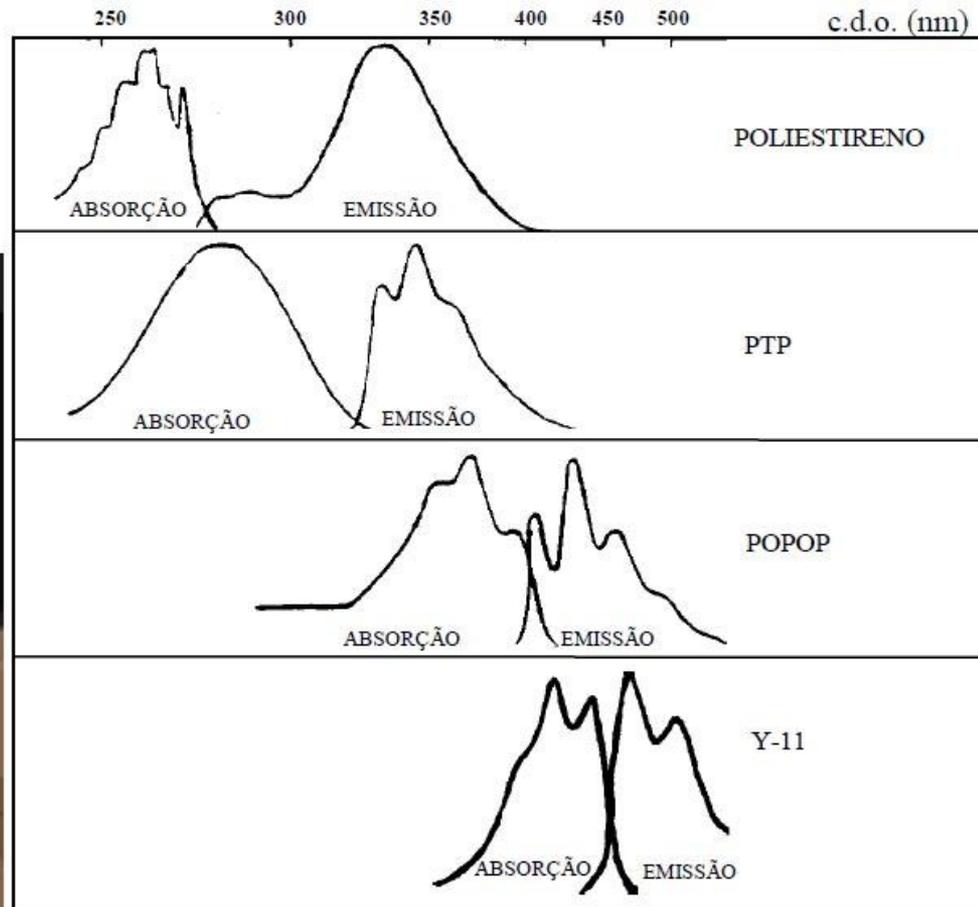


Detail of a spaghetti calorimeter with scintillating fibers



Track of a particle detected with a stack of scintillating fibers

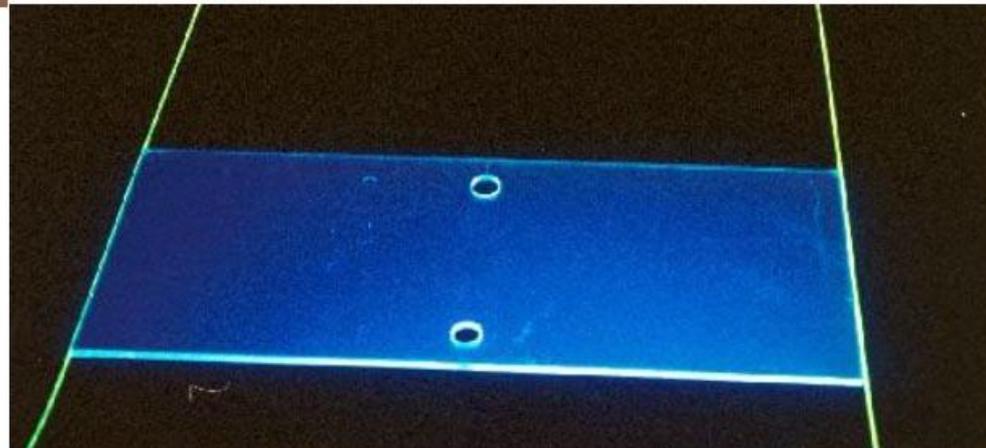
Wavelength shifter (WLS) optical fibers



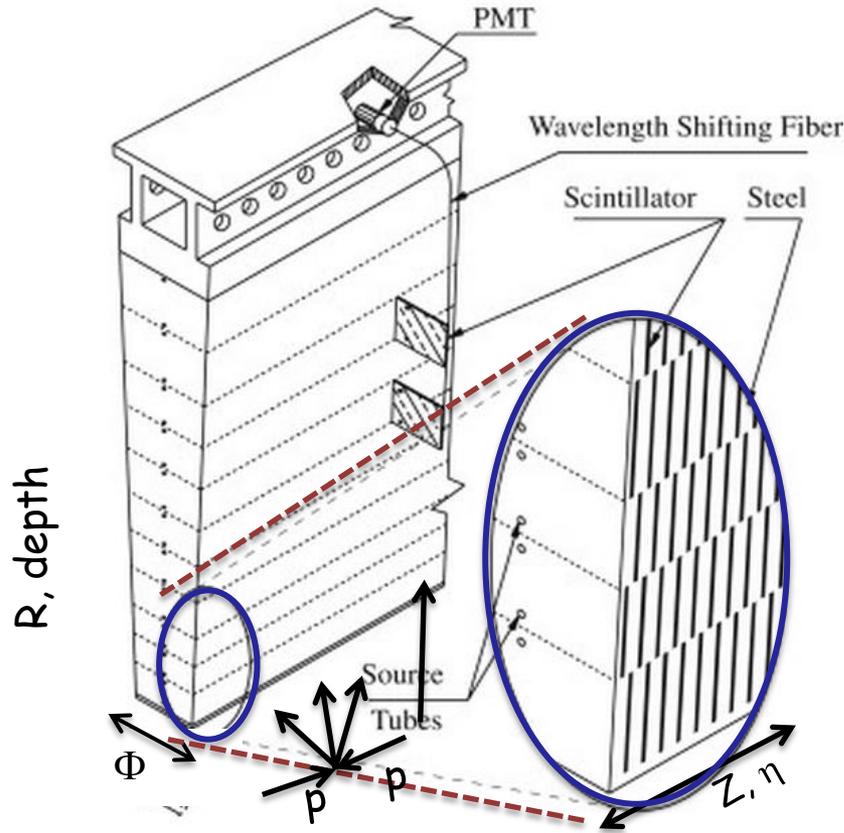
Tilecal example, Kuraray Y11 fibers

Used to transmit light from the scintillators to the PMTs

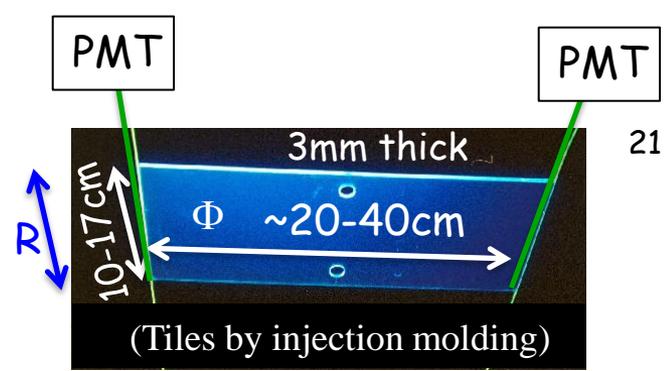
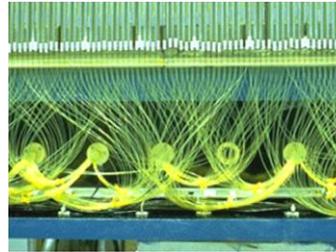
Allow the design of the calorimeter cells (grouping fibers)



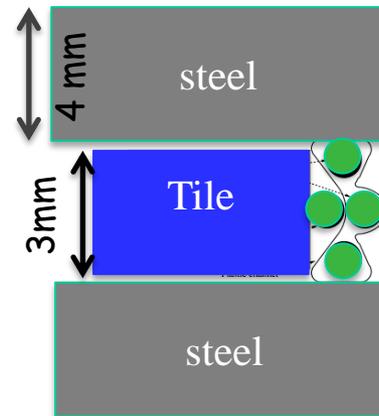
Tilecal layout



Fibre bundles
(at outer radius)



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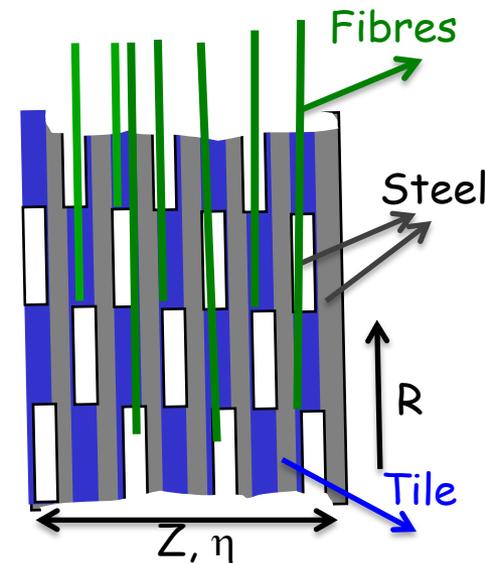


Fibres start at different R and go radially out \Rightarrow

- No cracks in ϕ
- depth segmentation
- PMTs at outer Radius

ATLAS Tile cells $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (0.2×0.1 in outer layer) and 3 layers driven by LHC requirements and electronics readout costs
But much better optics granularity ($\sim 620\text{k}$ fibres 400k tiles):

- $\Delta\eta$: 3mm tiles every 9-18mm in Z
- ΔR : 11 tiles and 8 fibres in R
- $\Delta\Phi$: 20 cm tiles



Tilecal main optics

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Scintillating tiles

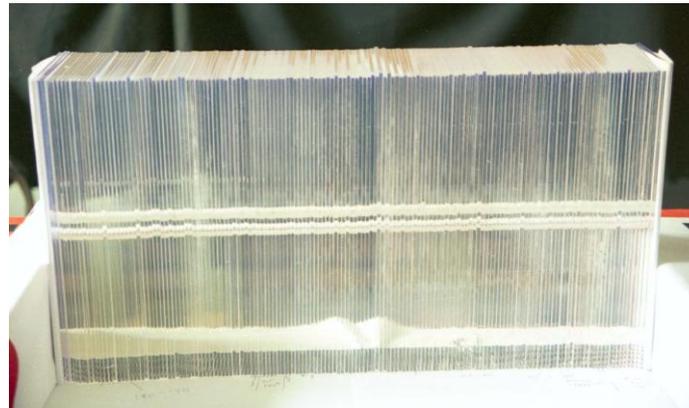
WLS optical fibers: responsibility Portuguese team led by Amélia Maio

Tilecal scintillating tiles

Number of scintillating tiles needed: ~400000,
distributed by 11 sizes

Technique chosen: mould injection (cheap and fast)

Critical parameters: mould walls quality,
polystyrene, dopants, pressure, temperature



A set of scintillators

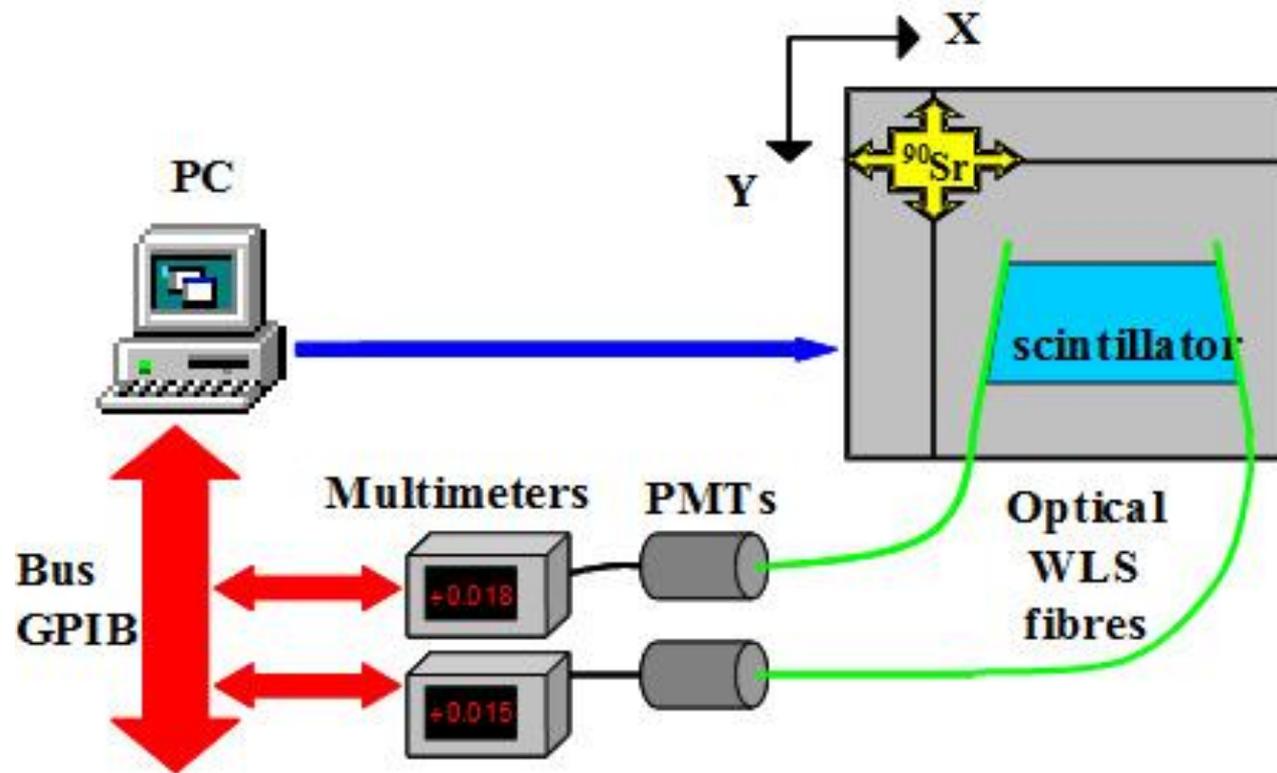


Setup to test scintillators

WaveLength Shifting (WLS) fibers
1 mm diameter, lengths 1 - 2.5 m

Setup to test scintillators light output

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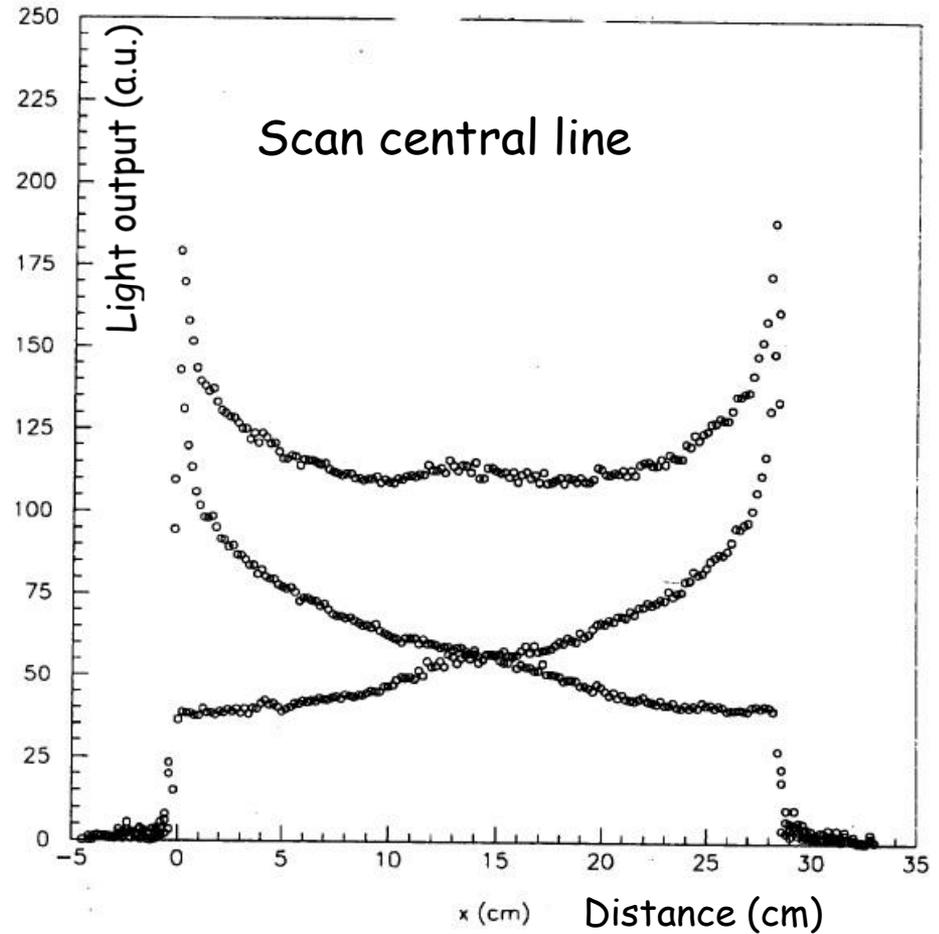
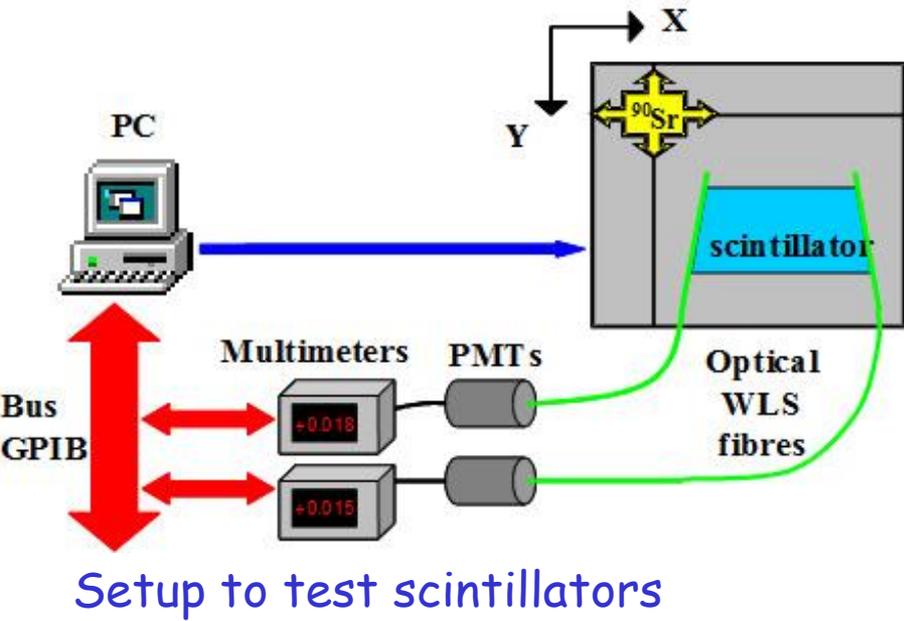


X-Y table to position radioactive source under the scintillator.
Electrons from the source excite the scintillator producing light.
WLS fibers collect the light and transport it to PMTs.

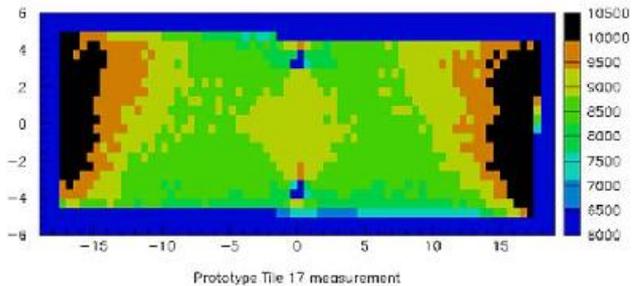
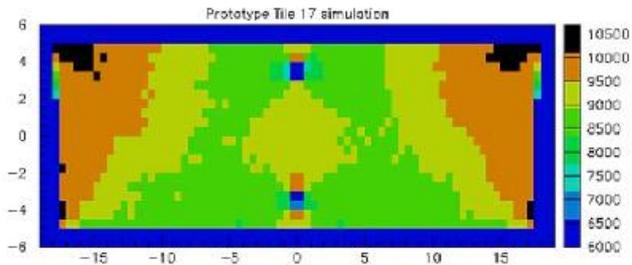
Allows comparative light output measurement and uniformity scans.

Extensively used in the R&D program of Tilecal

Tilecal layout, scintillating tiles



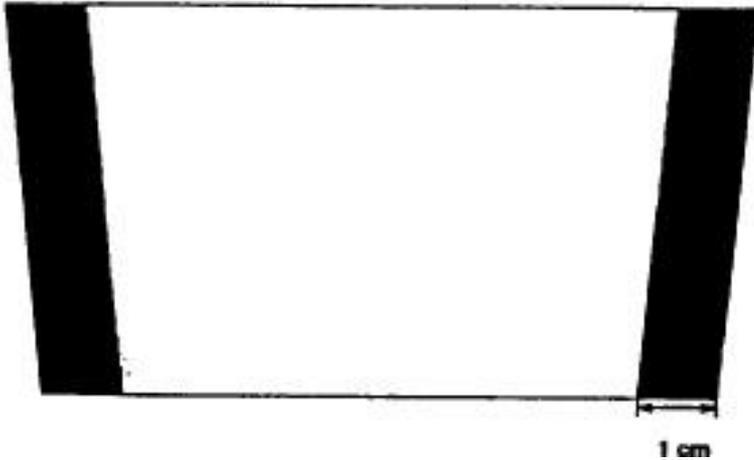
Non-uniformity excessive near edges



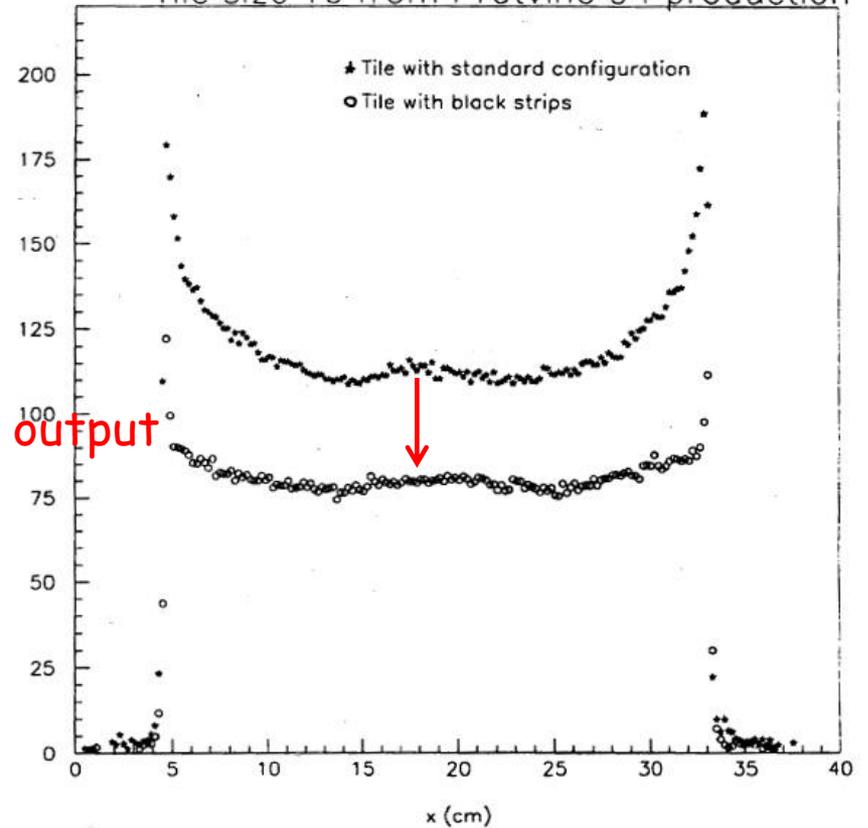
2D light collection scans

Tilecal layout, scintillating tiles

First trial with black strips to improve uniformity



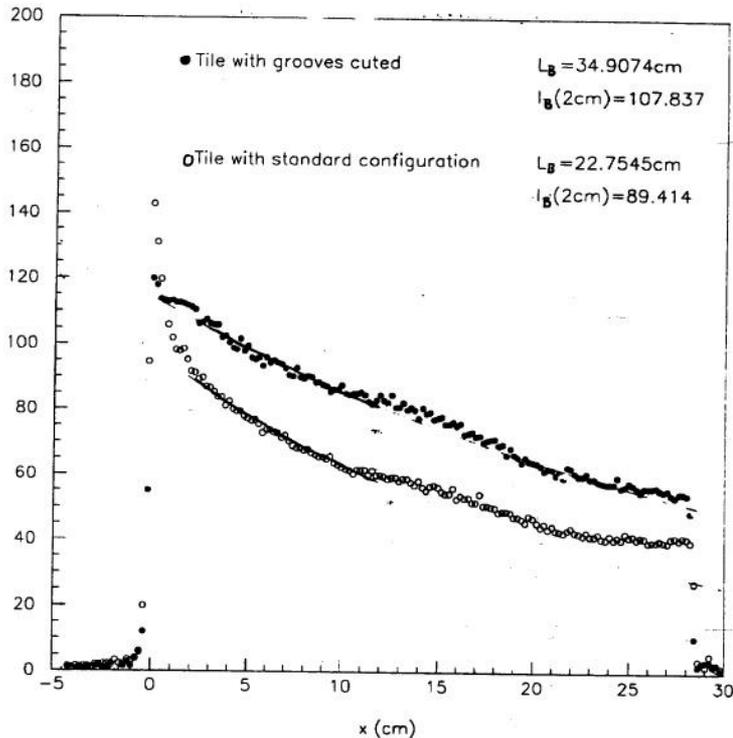
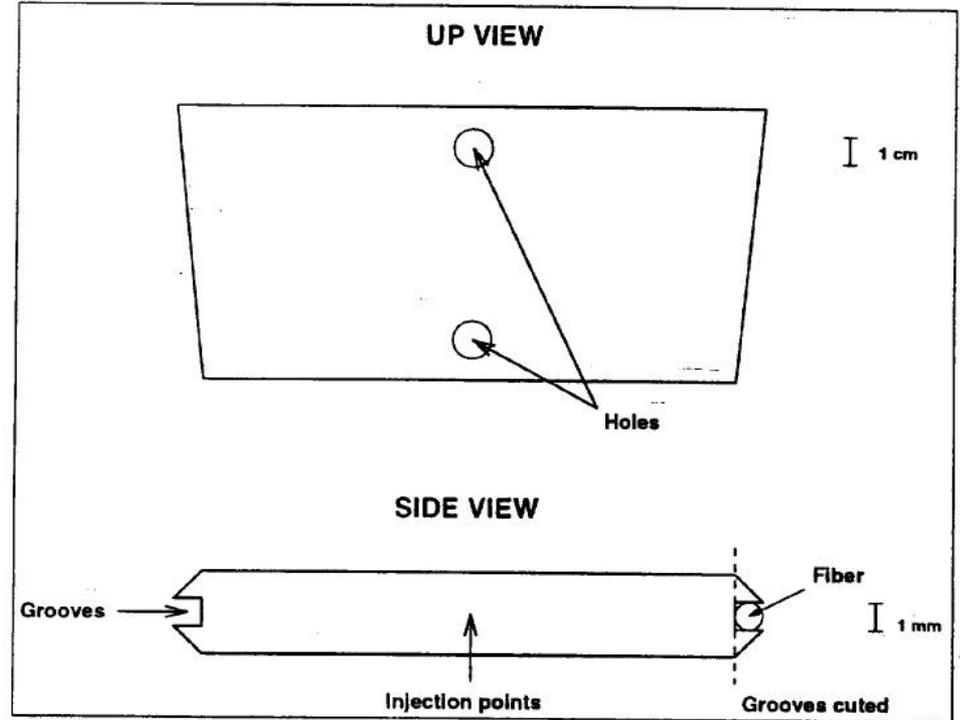
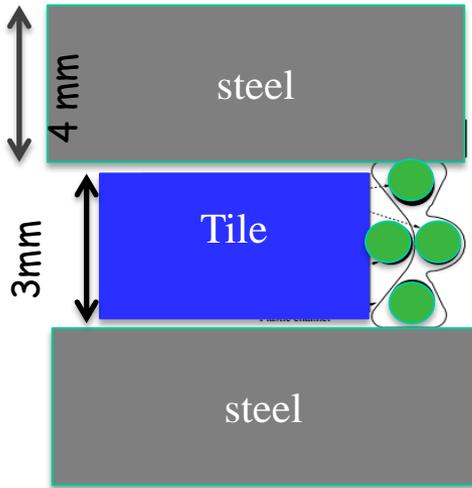
Tile size 10 from Protvino 94 production



But also cut light output

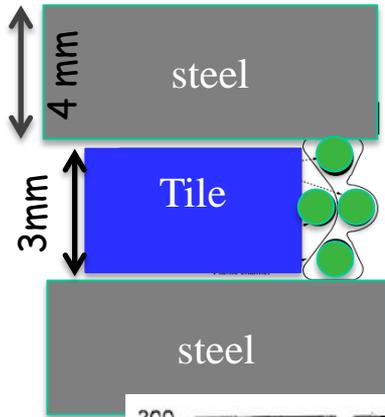
Tilecal layout, scintillating tiles

Geometry of the first tiles, with grooves for the fibers

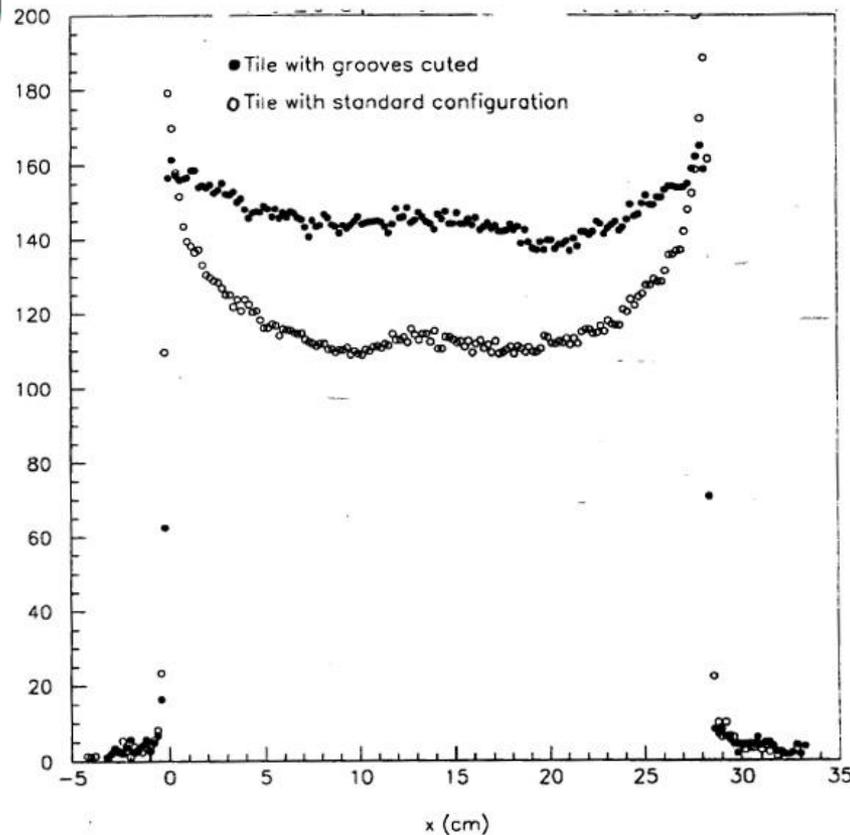
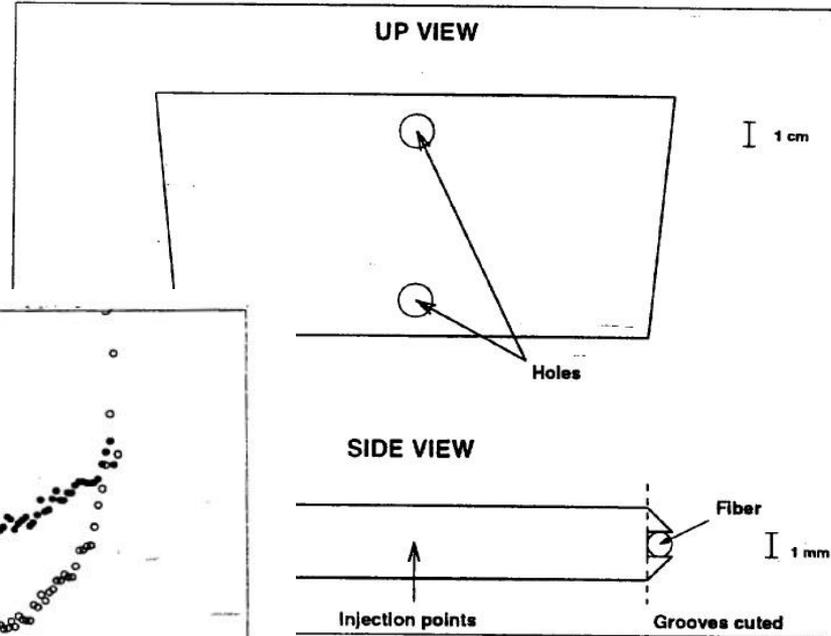


Grooves were cut and the uniformity improved

Tilecal layout, scintillating tiles



Geometry of the first tiles, with grooves for the fibers



In the end both techniques used to improve uniformity:

- No grooves
- Black strips in longer tiles (masks)

The fibrometer

Inside a black box:

Long table with grooves to hold up to 32 fibers

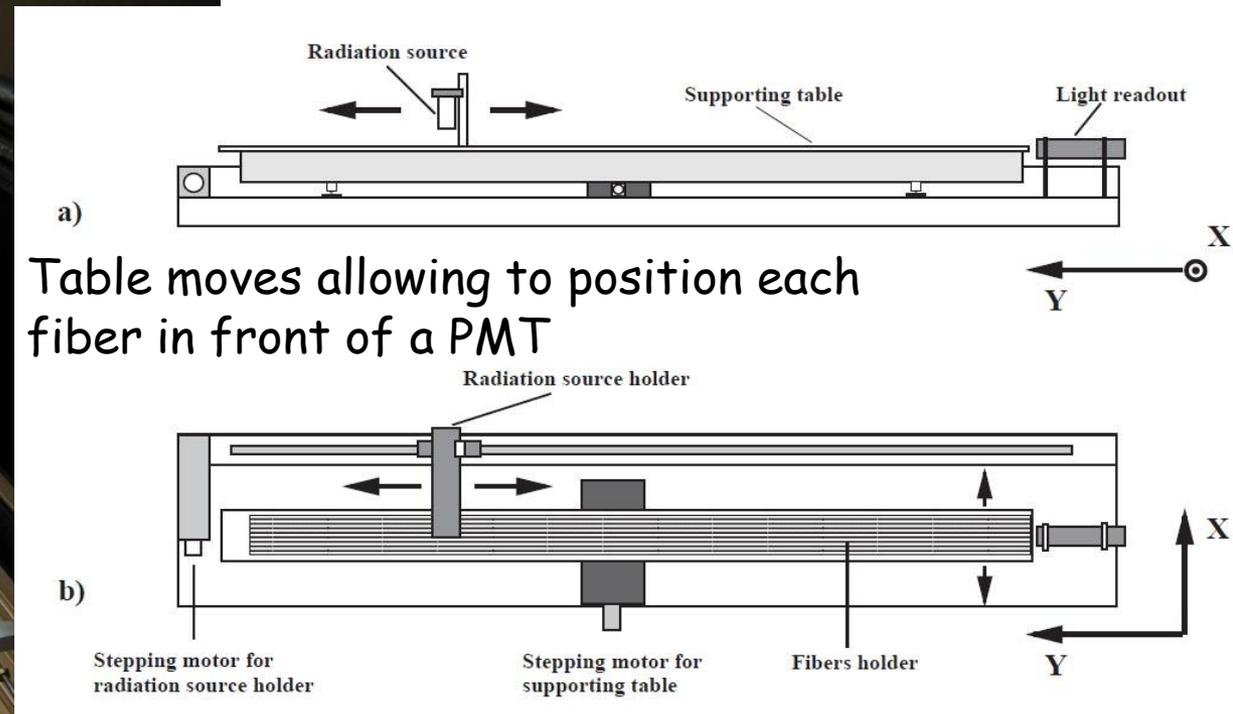
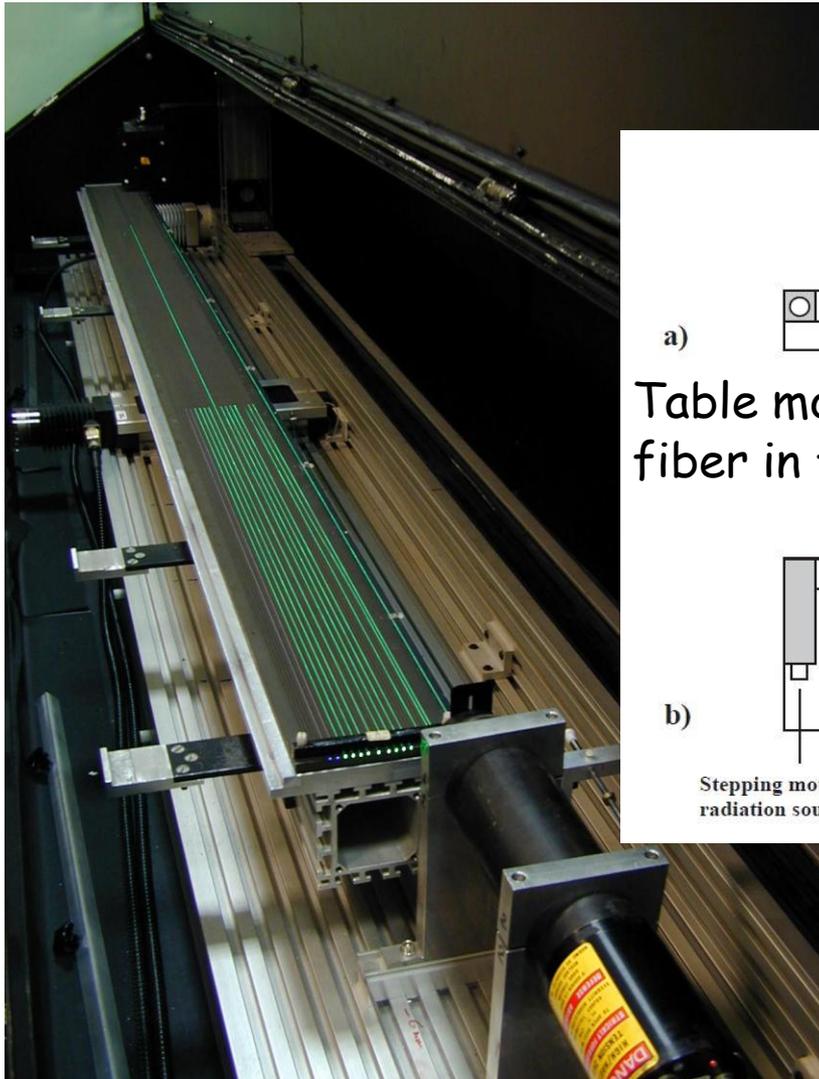
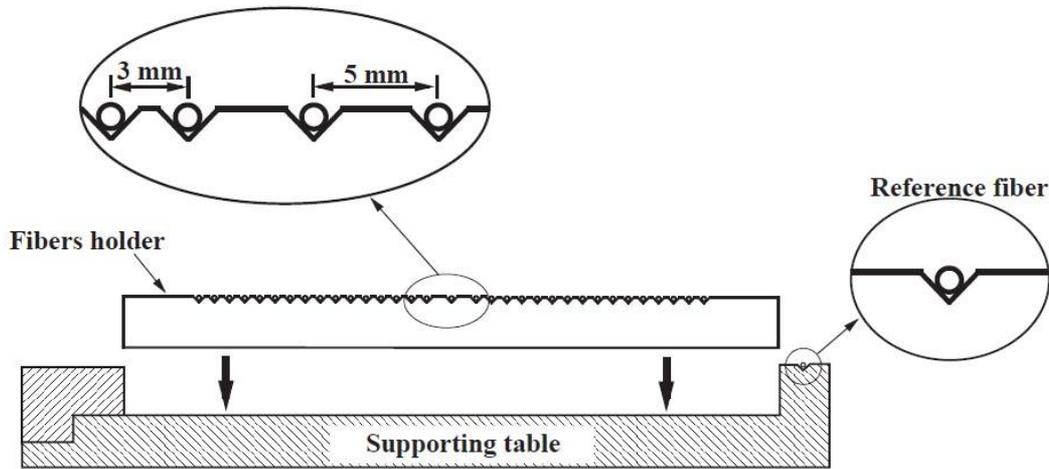


Table moves allowing to position each fiber in front of a PMT

Light source (LED or radioactive source alone or coupled to a scintillator) moves along the fibers

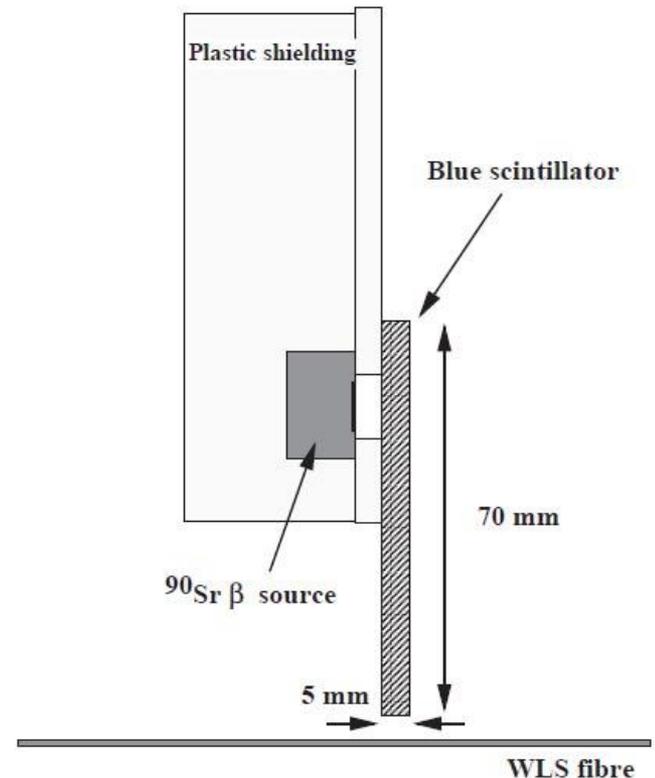
Well adapted for quality control of large number of fibers

The fibrometer



Reference fibers are used to normalize light output. One reference fiber is coupled to the table. A second one is associated with the fibers holder.

For WLS fibers studies usually the light is produced in a scintillator excited by a radioactive source



WLS optical fibers

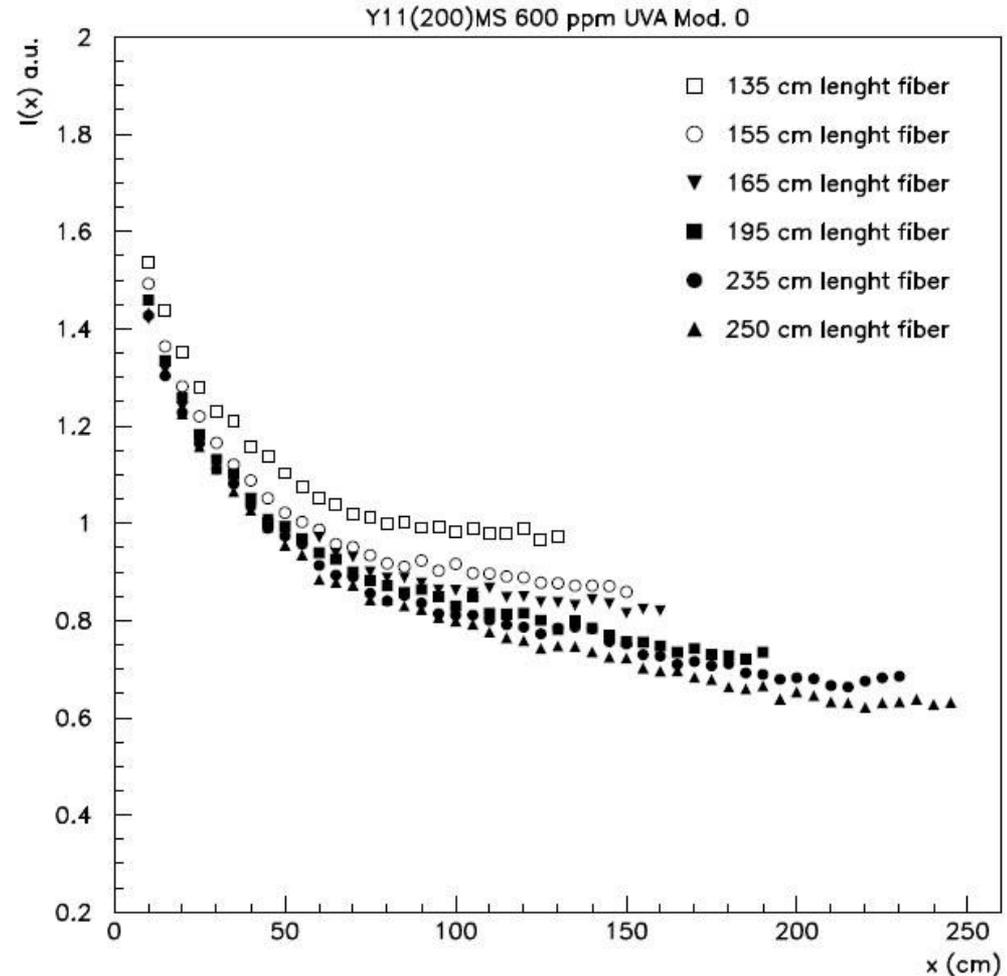
Light output versus distance for fibers with several lengths

In most of the ranges the light output decreases exponentially with distance to PMT

$$I = I_0 \exp(-x/L_{att})$$

L_{att} is the **attenuation length** of the fiber

Light output vs distance



WLS optical fibers - mirror effect

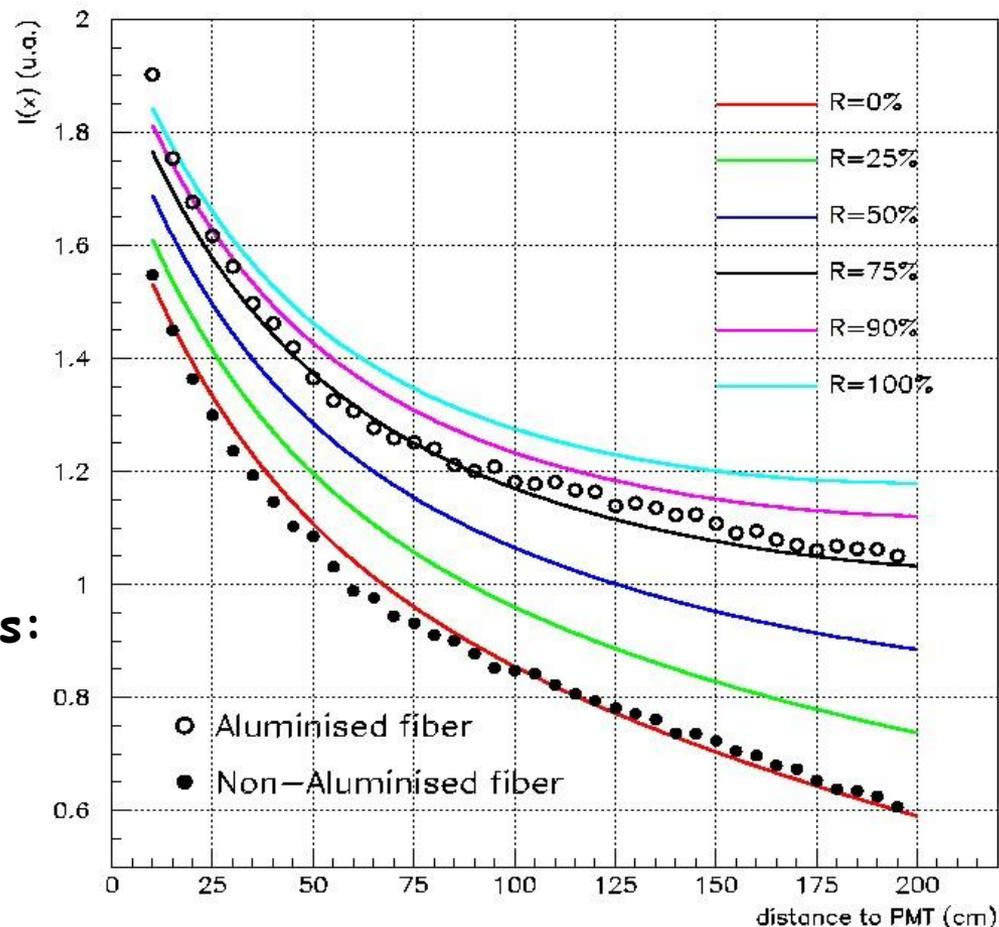
Light moving away from the PMT is going to be lost.

Use mirror to send it to the PMT.

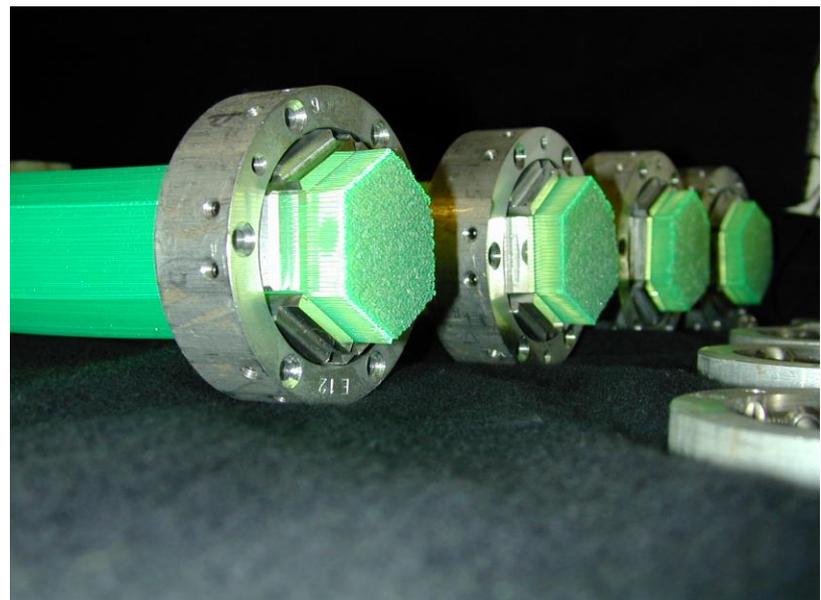
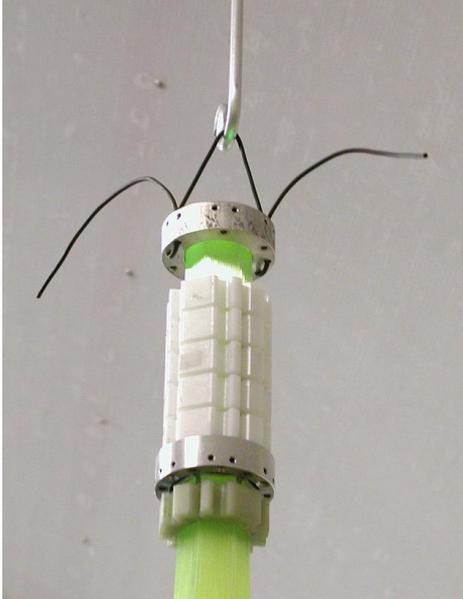
Aluminium mirror at the end allows:

- to improve light collection
- to improve uniformity of light collection in the fiber-scintillator contact area

Light output vs distance



WLS optical fibers (~620000) (preparation for mirroring)



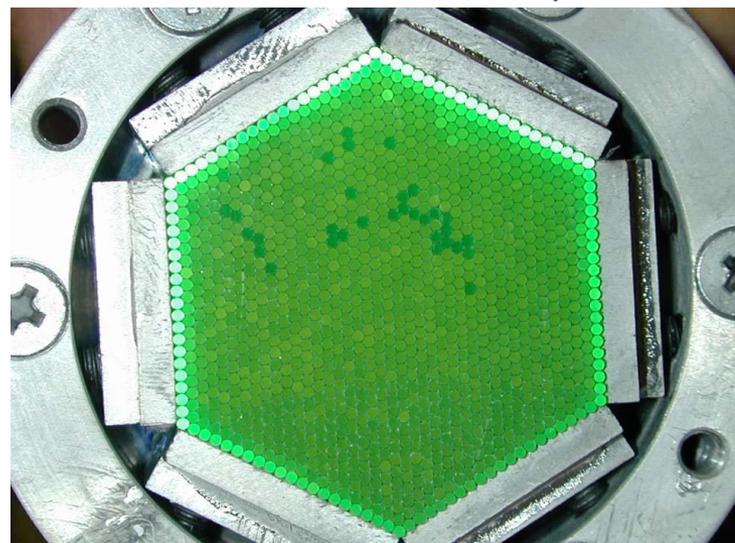
Rods with 1261 fibers each



Milling machine to cut/polish

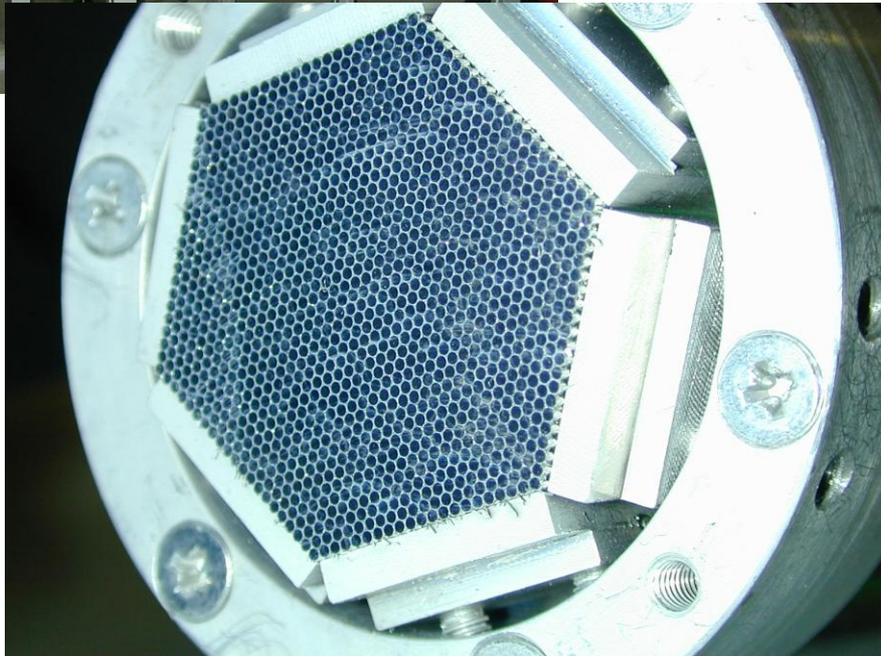


Polished face



Mirroring the WLS optical fibers

Magnetron sputtering technique



Quality control of the WLS optical fibers

Parameters controlled:

With samples from all aluminization rods:

Average light output and attenuation length (compared with reference values)

Light output and attenuation length dispersion (rms)

And in limited control samples:

Radiation hardness

Mechanical stress

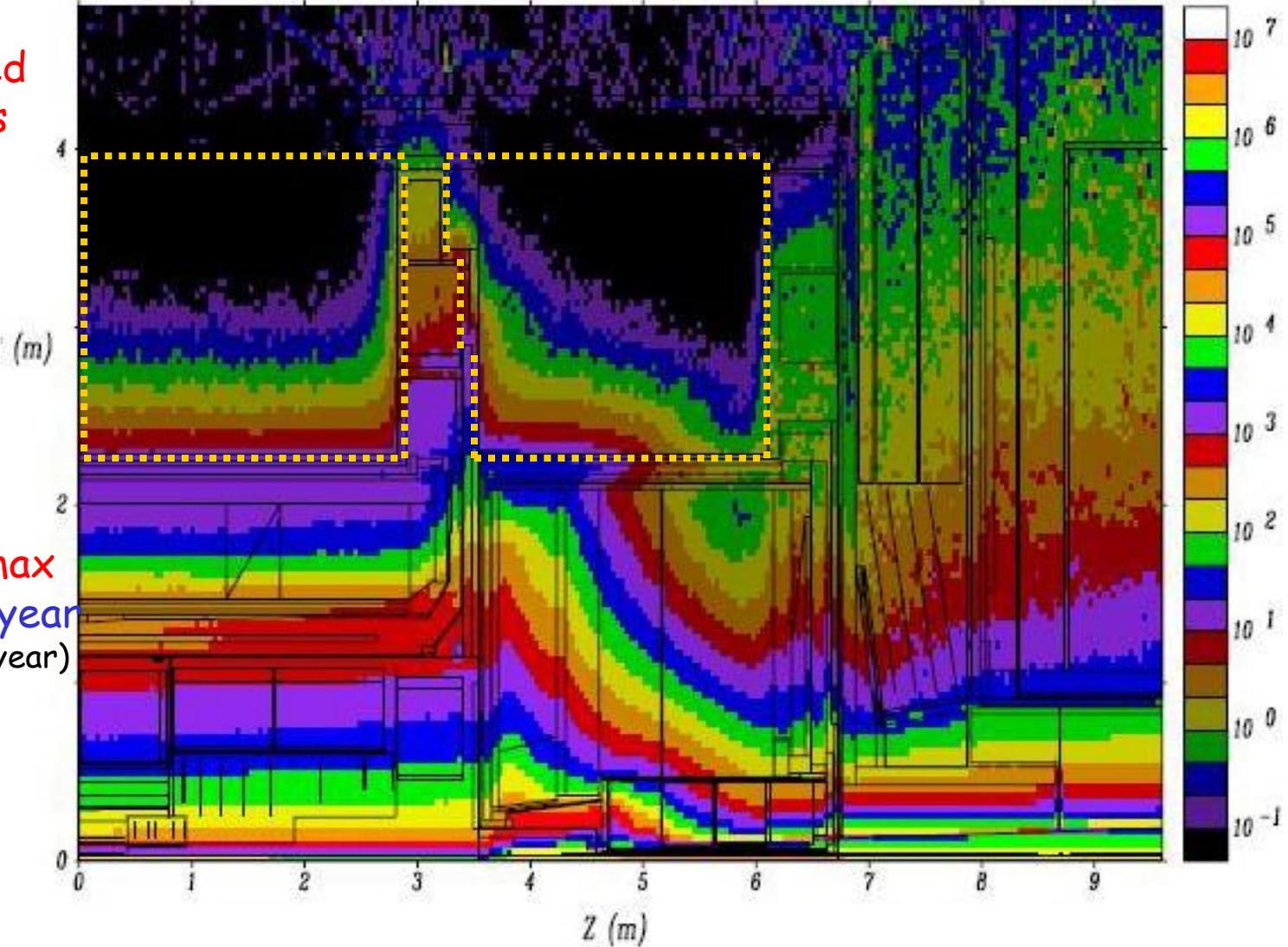
Fiber diameter tolerance (essential for robotized insertion of the fibers)

Radiation - dose deposited per year in ATLAS

Jan03 Base (24620) - Ionization Dose, Gy/Yr (TID)

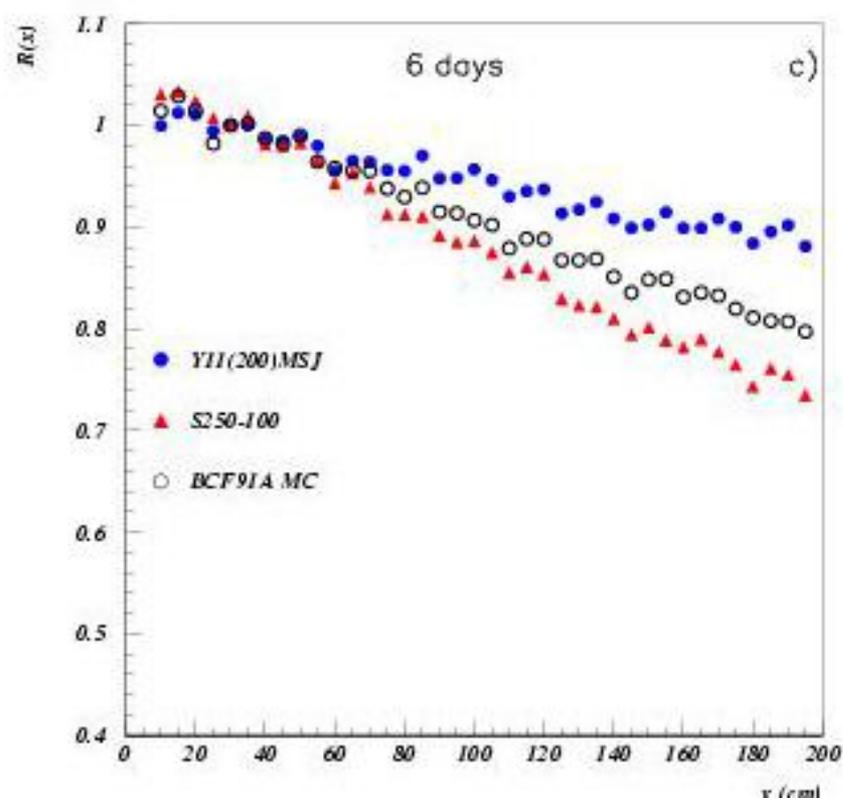
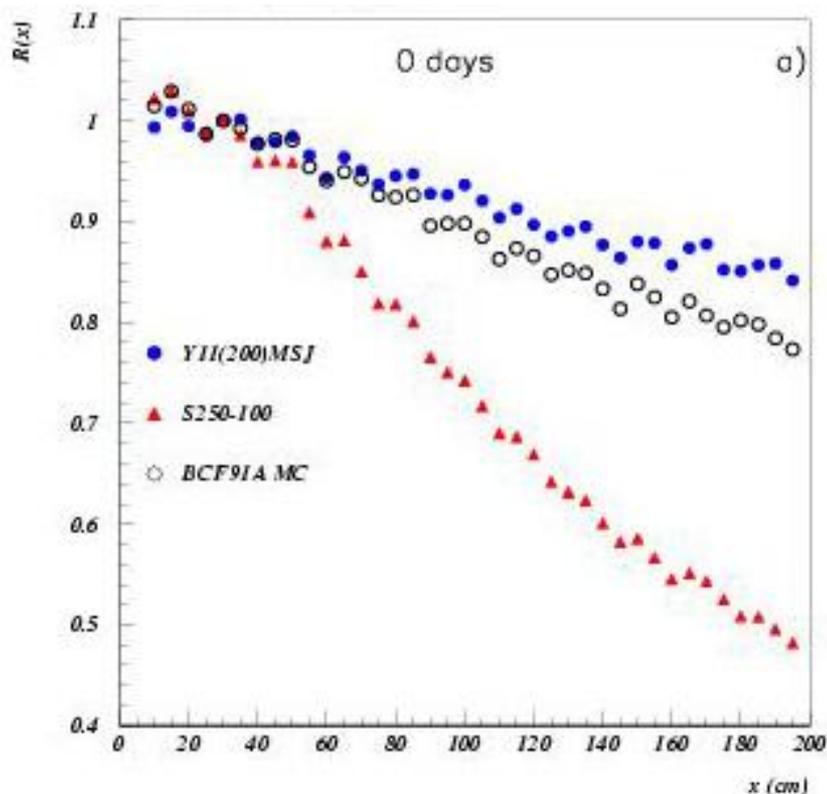
Dose is the energy deposited per mass unit

Tilecal max
~50 Gy/year
(0.5 krad/year)



Radiation damage of WLS optical fibers

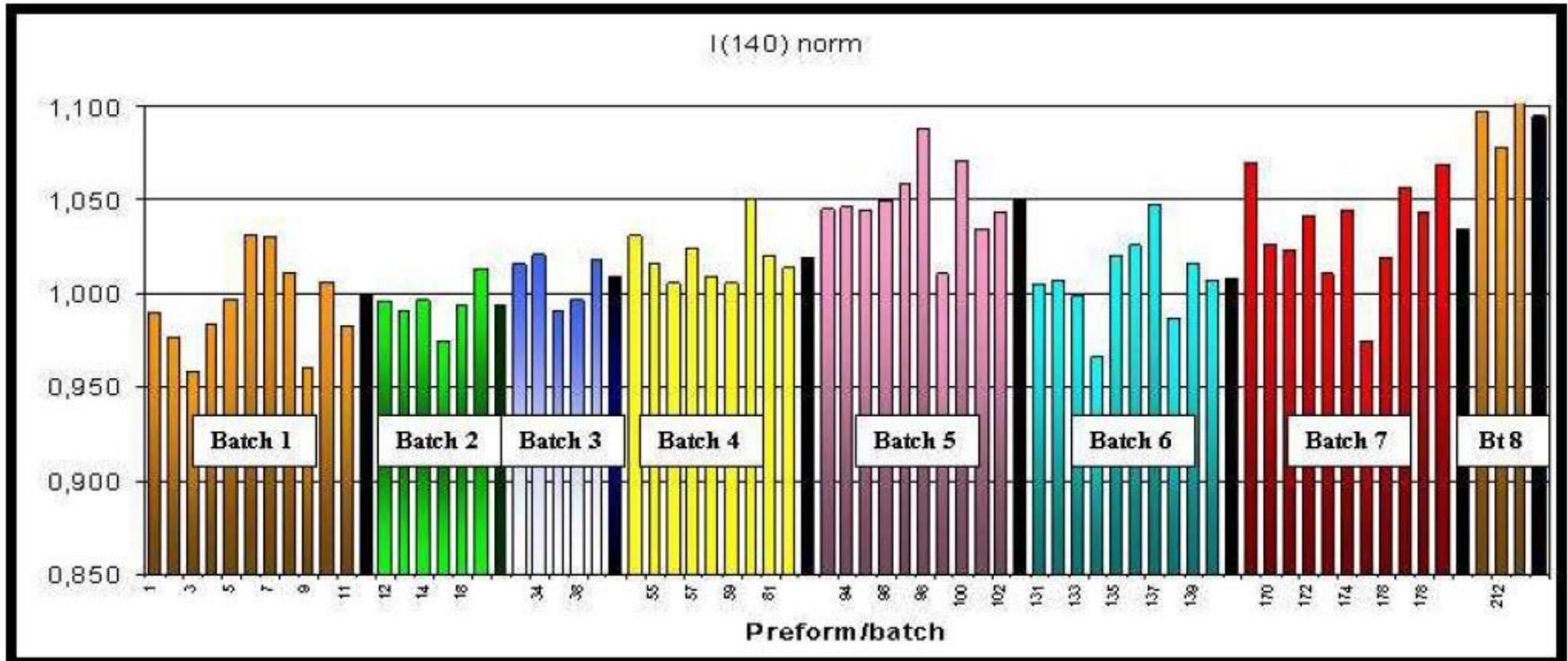
Normalized light output after irradiation as a function of the distance to the photodetector



Used dose: 155 krad, source ^{60}Co

Max dose in Tilecal in 10 LHC years: 50 krad

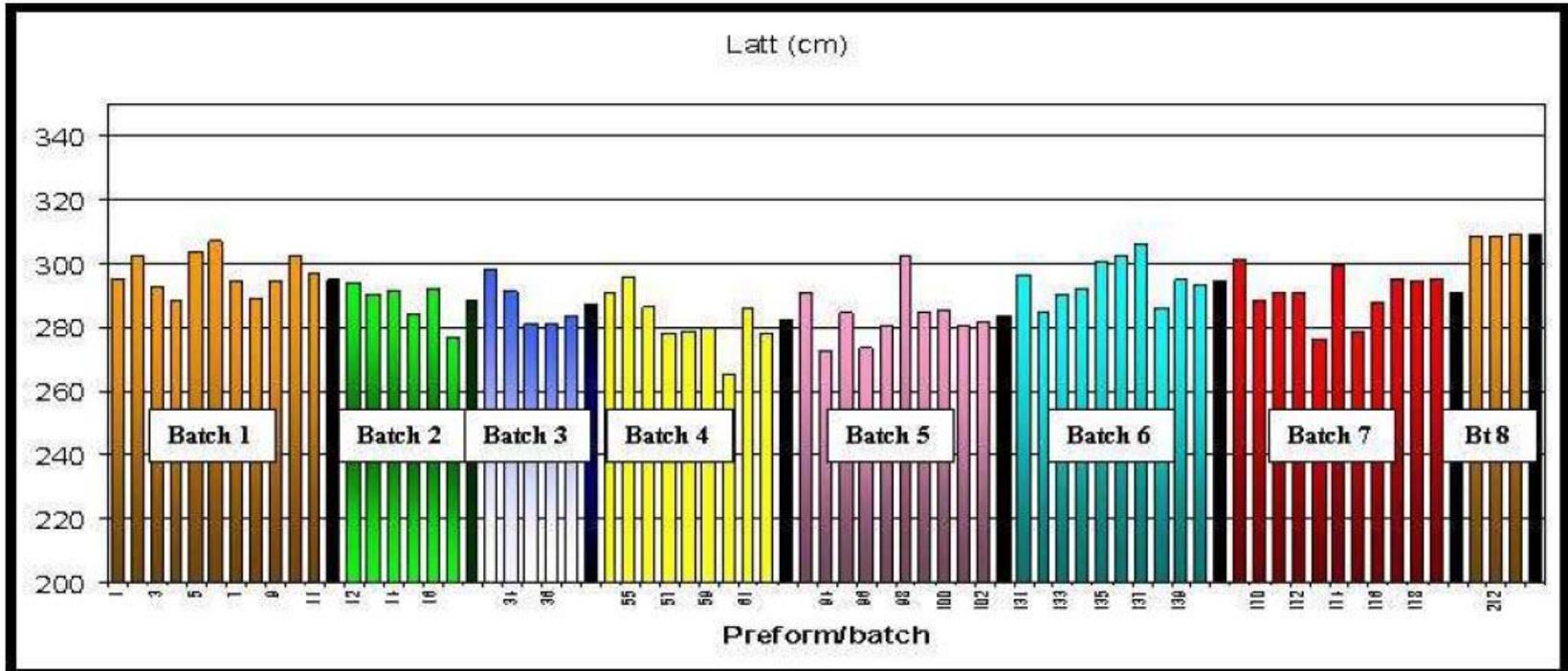
Quality control of the WLS optical fibers



Light output at a distance of 140cm normalized to reference value for the several preforms of the 8 batches produced by Kuraray for Tilecal.

Results are averages of 32 fibers of each preform, for 2m long fibers.

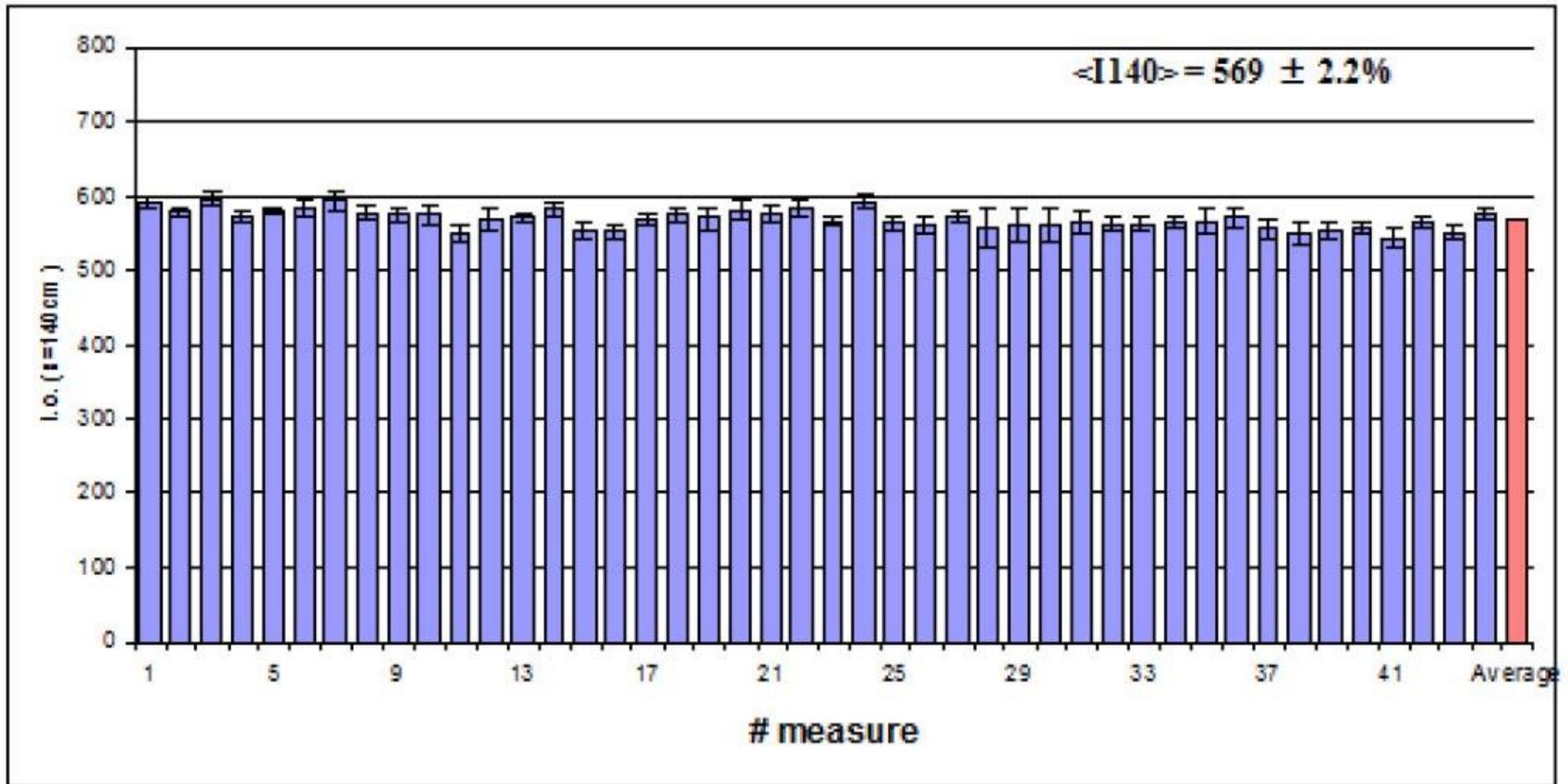
Quality control of the WLS optical fibers



Attenuation length for the several preforms of the 8 batches produced by Kuraray for Tilecal.

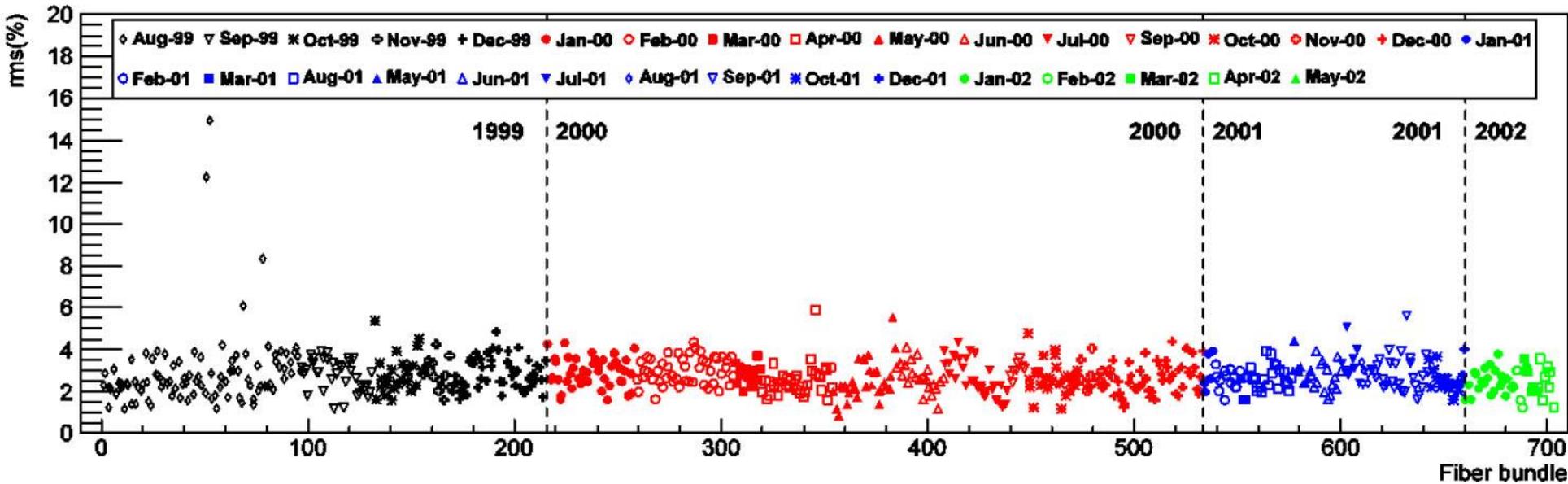
Attenuation length obtained for measurements between 70 and 190cm (single exponential fit), for 2m long fibers

Quality control of the WLS optical fibers



Average light output at 140cm of 16 reference fibers measured during the period of acceptance quality control of the Tilecal fibers (1999-2002)

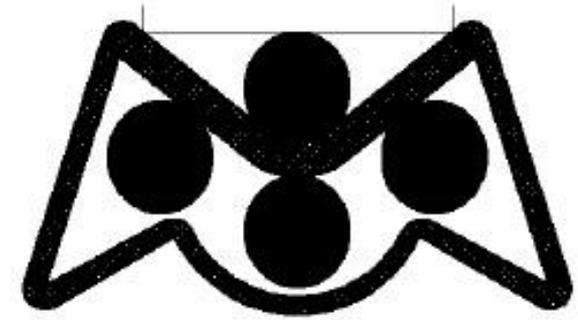
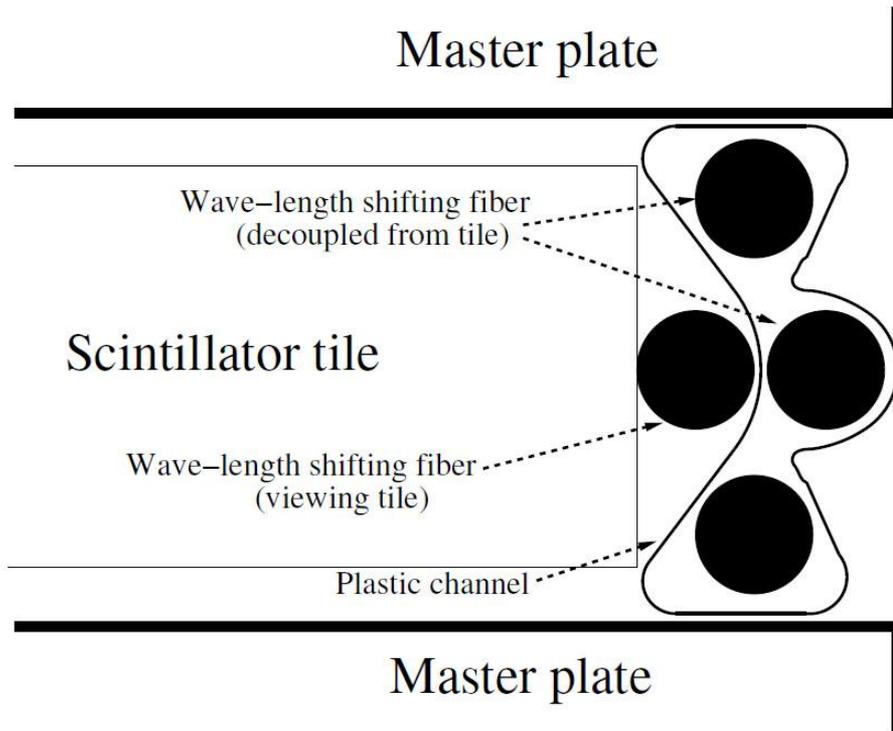
Quality control of the WLS optical fibers



Dispersion of light output in each bundle (3 bundles above 7% redone)

Average reflection coefficient ~70%

How to insert the 620k WLS optical fibers?



Invented long plastic profiles:

Length: 1.5 m

Width: 4 mm

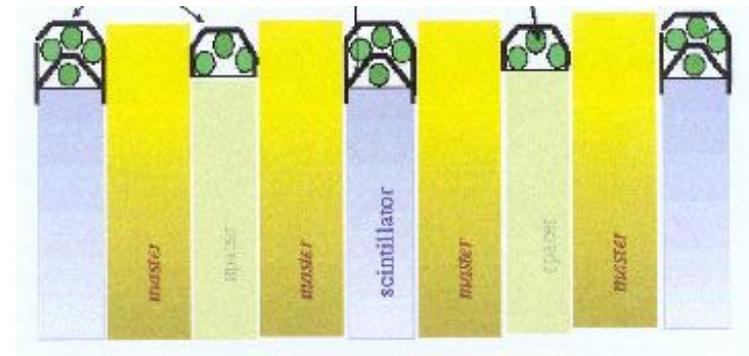
Height: 2 mm

Thickness: 0.1 mm

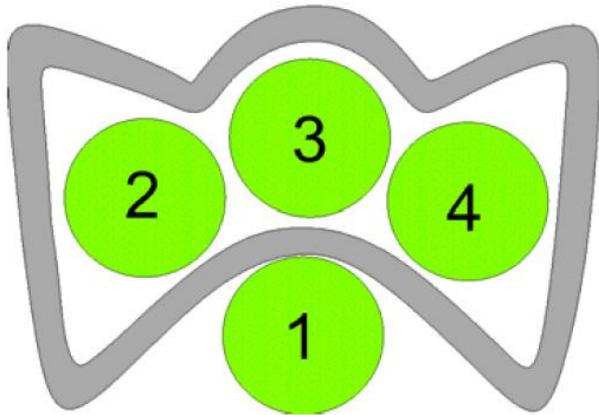
Need to be opaque (black plastic)

Need to be excellent reflector: painted white with ink used in road signs

Need to hold in place mechanically



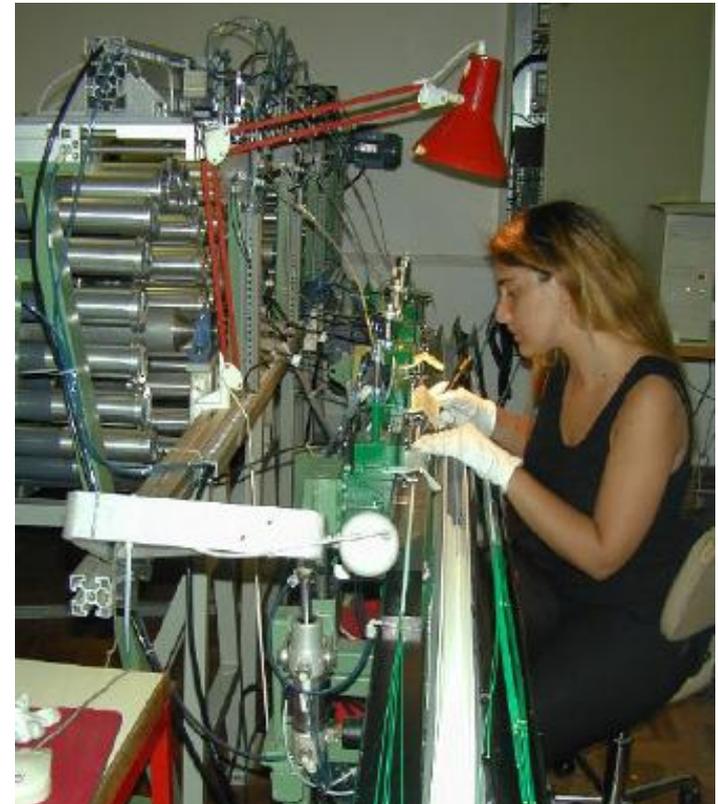
How to insert the 620k fibers in the 160k profiles?



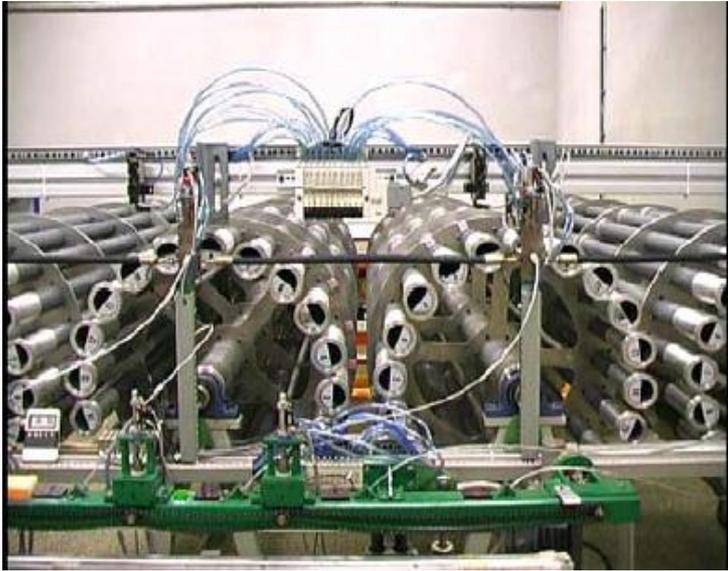
Manually it would take years, need several people, and probability of errors was high: Many combinations of 28 fiber lengths and 4 types of profiles

Solution: a robot

3 or 4 fibers in each profile



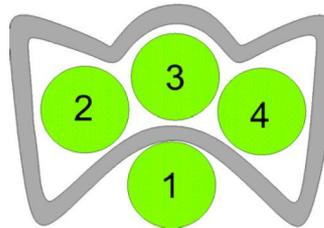
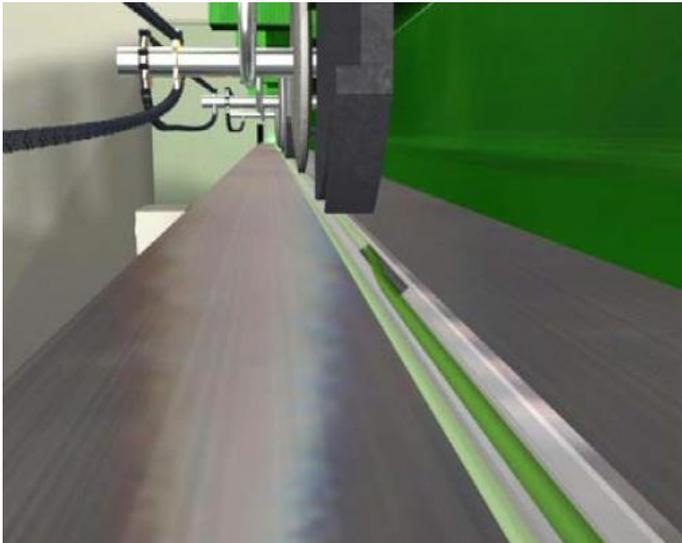
Inserting the fibers in the profiles



picking a fiber from the drums



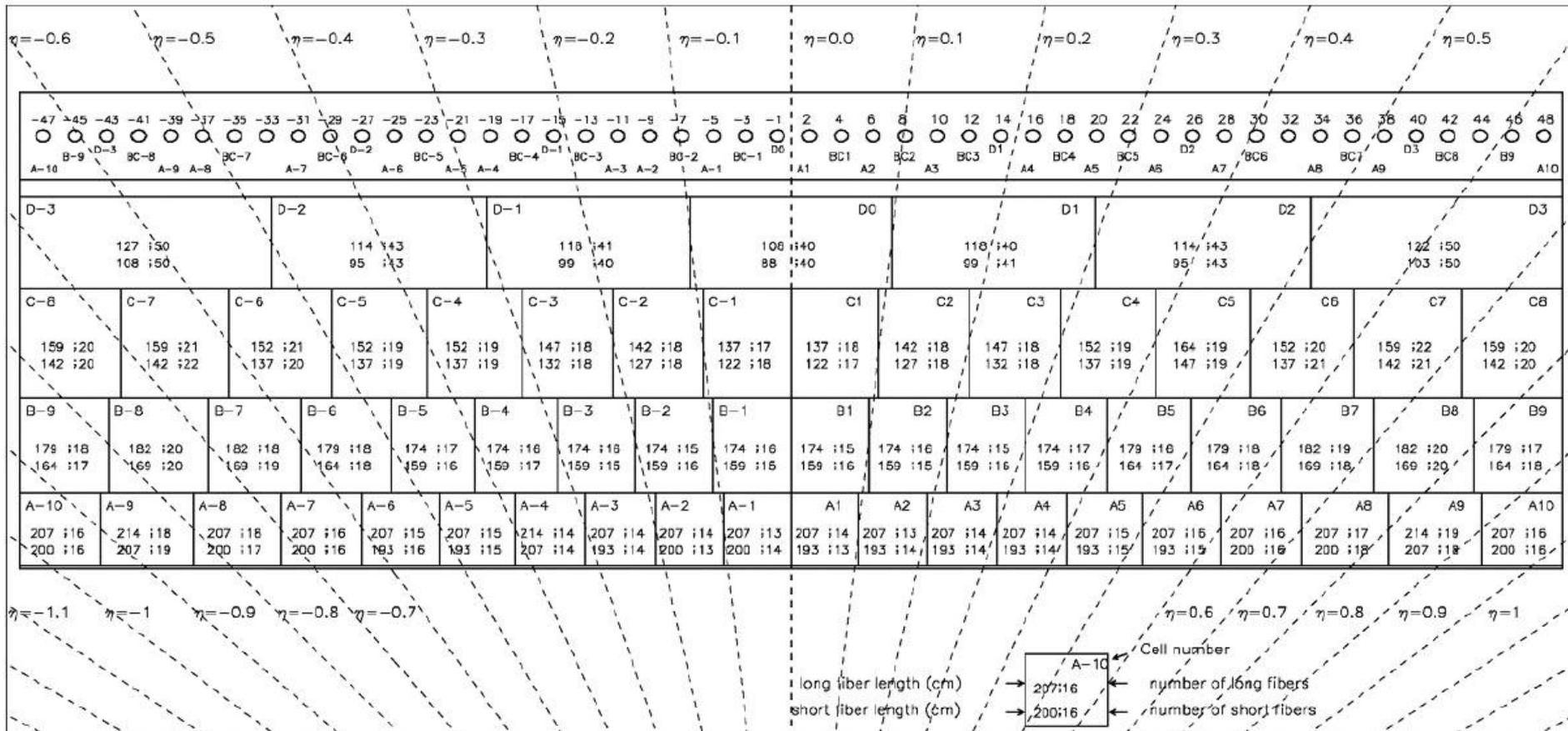
gluing the fibers: not automatic



guiding a fiber inside the profile

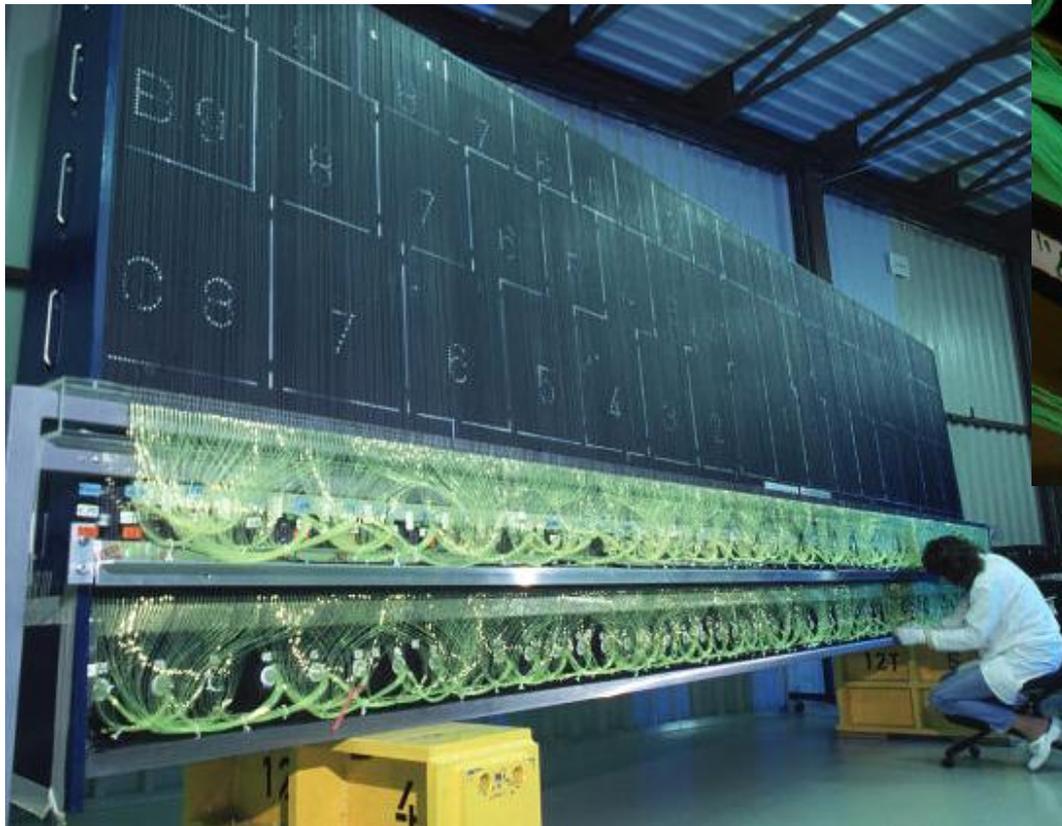
Tilecal cell structure - central barrel map

Cells obtained grouping many fibers in front of one PMT



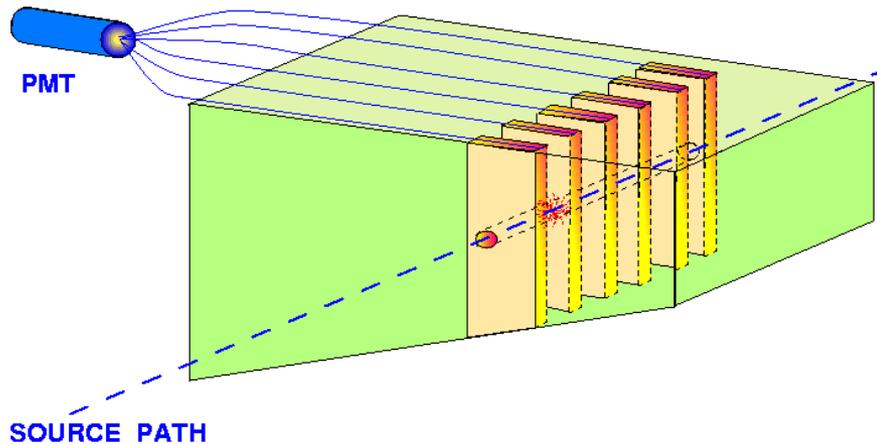
Cell structure - making the fiber bundles

Fibers converging to a plastic tube making a bundle corresponding to a cell



A mock up needed to make the fiber bundles

Intercalibration using ^{137}Cs radioactive source



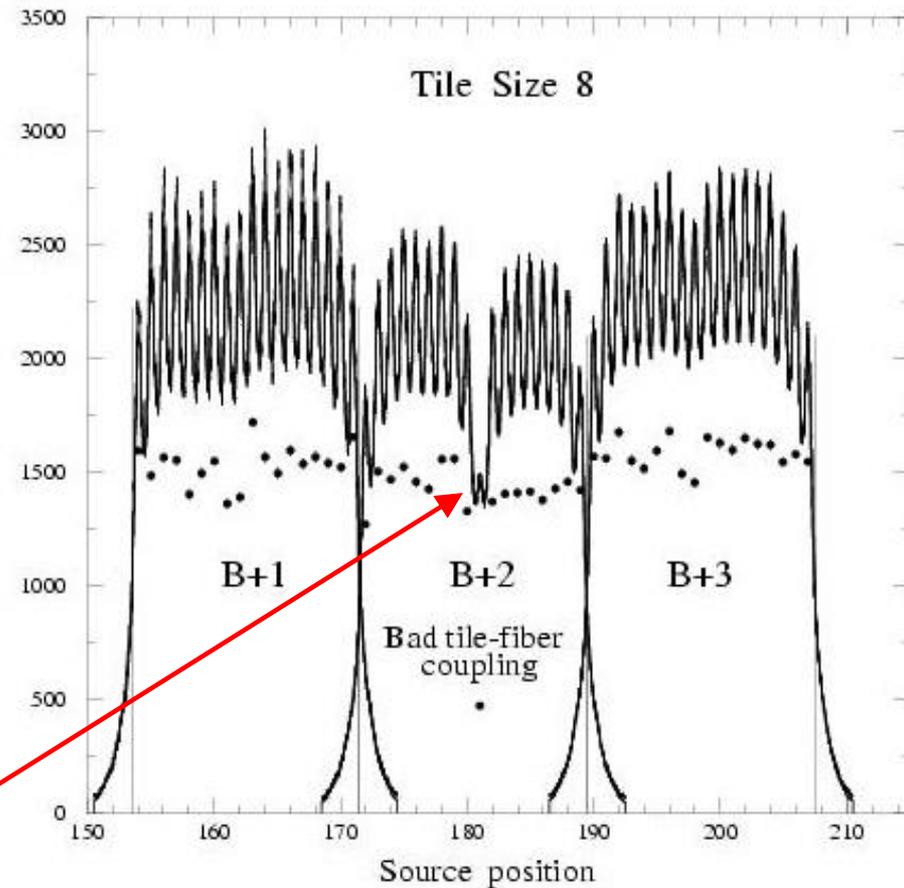
Peaks - tile response

Dots - adjusted response from each individual tile (calculated taking into account the distribution of the cesium radiation through the several neighbour tiles)

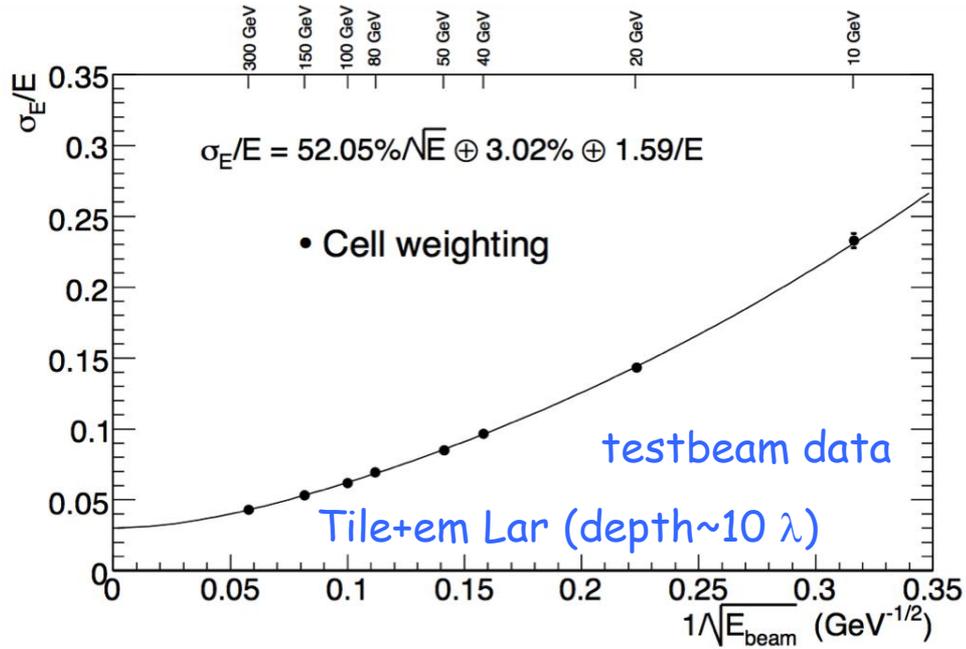
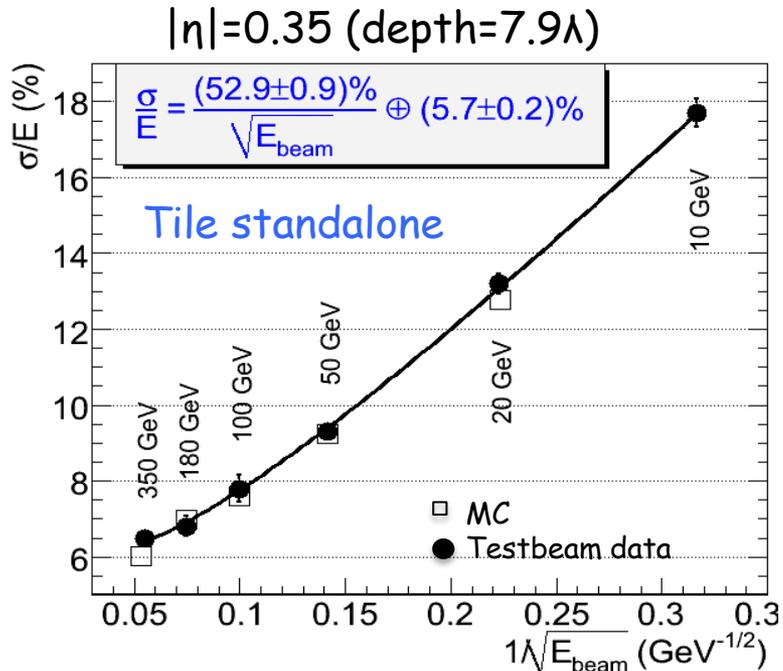
Calibration - equalization of the average response of each cell

Cesium source also used for quality control of the modules

Moveable cesium source crosses each scintillator perpendicularly



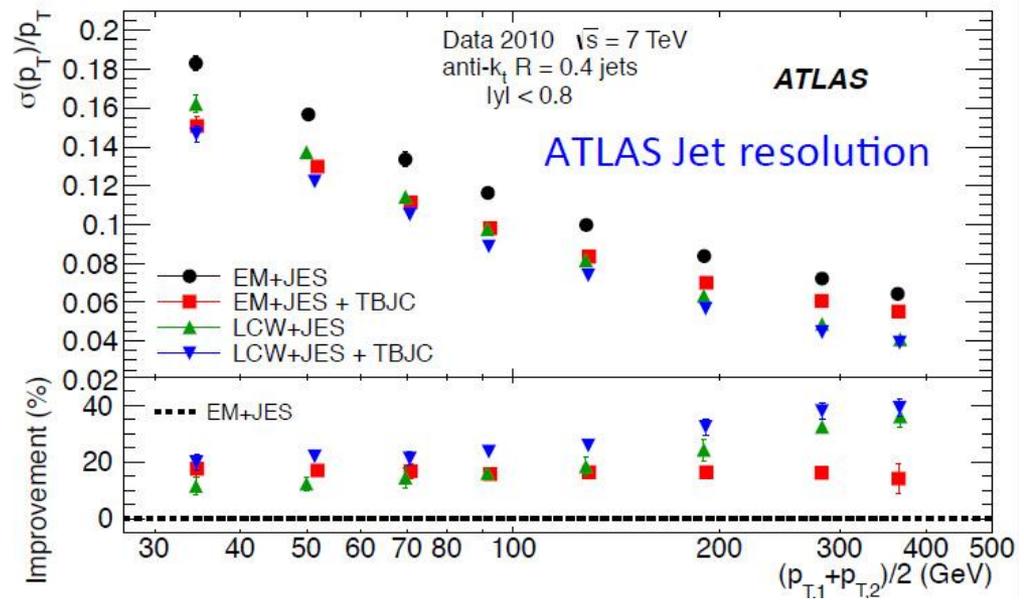
π resolution in testbeams \rightarrow jet resolution in ATLAS



Good performance thanks to >10 years R&D, test-beams, MC tuning, cosmics

Jet resolution close to design:

- constant term ~3%
- Pile-up worsens low p_T resolution
- Improvements after pile-up corrections for in-time/out-time bunches/noise threshold tuning, etc.

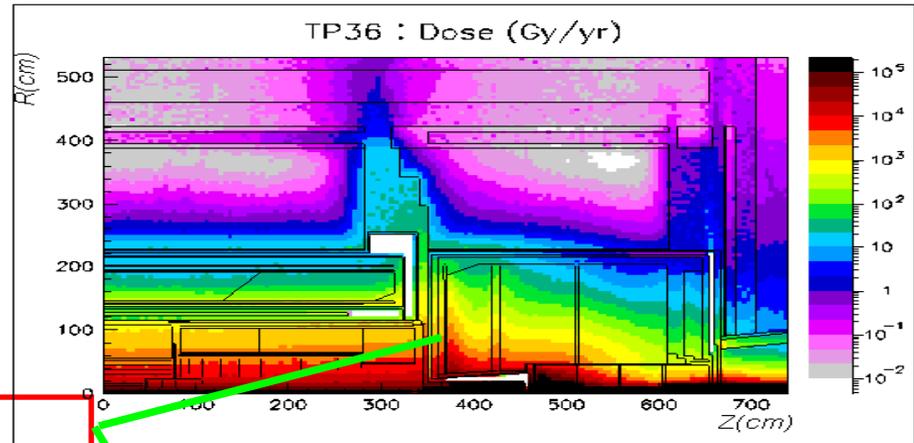


Upgrades

Tilecal upgrades for Long shutdown 2019

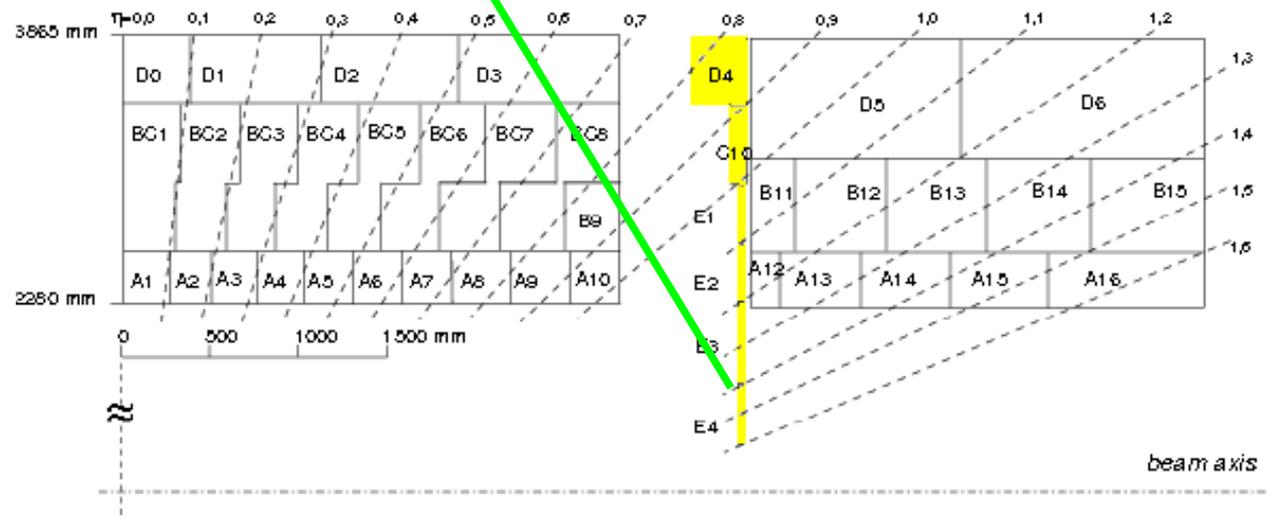
Tilecal scintillators and WLS fibers do not need replacement.

Exception: long scintillators in the gap/crack region that suffer significant radiation damage causing light loss

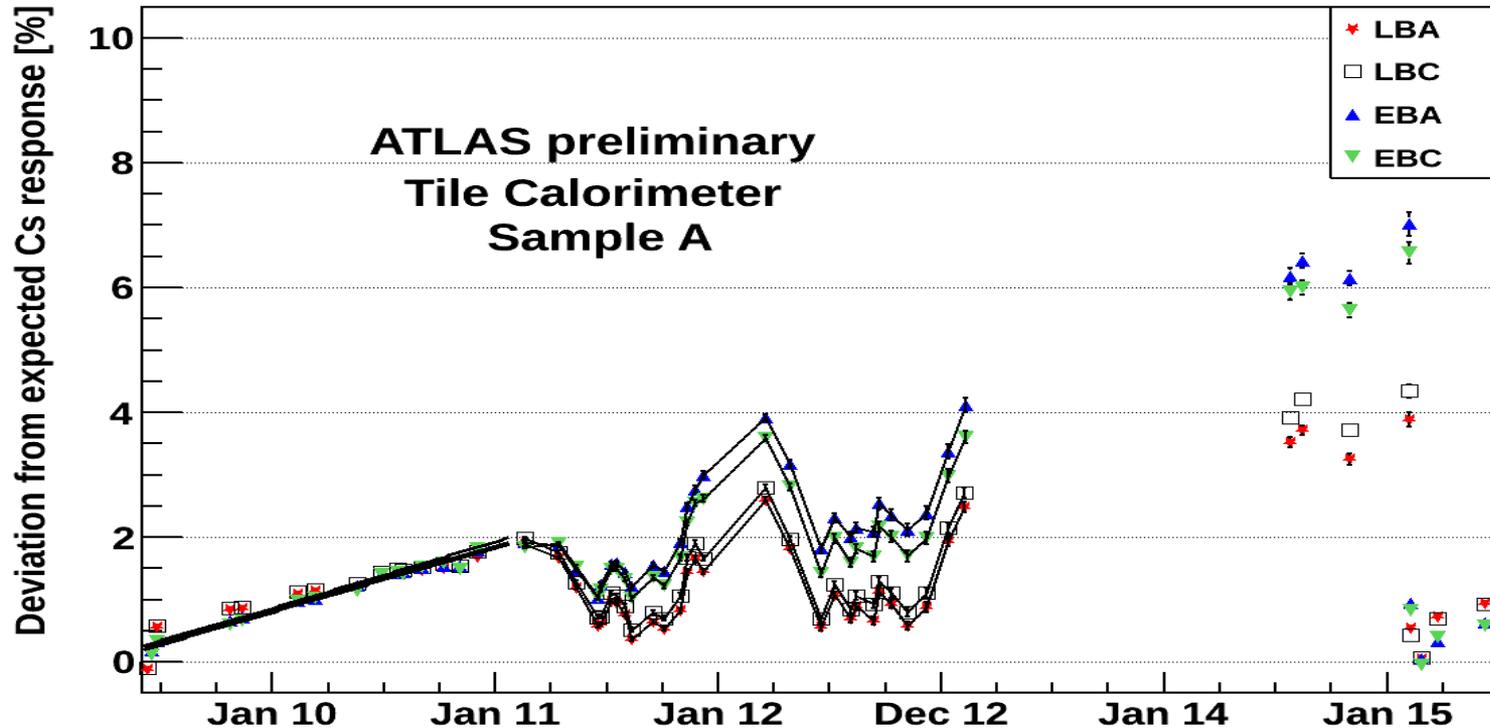


Cryostat scintillators covering the rapidity range from 1.2 - 1.6 are in a high radiation environment, 1 kGy/year

Need to investigate radiation hard scintillators and WLS fibers and replace them



Tilecal PMTs response along the years



Triggered discussion on possible need to replace PMTs in the future

Take the opportunity to improve granularity using MAPMTs?

If replacement needed why not MultiAnode PMTs?

MAPMT

2x2mm,

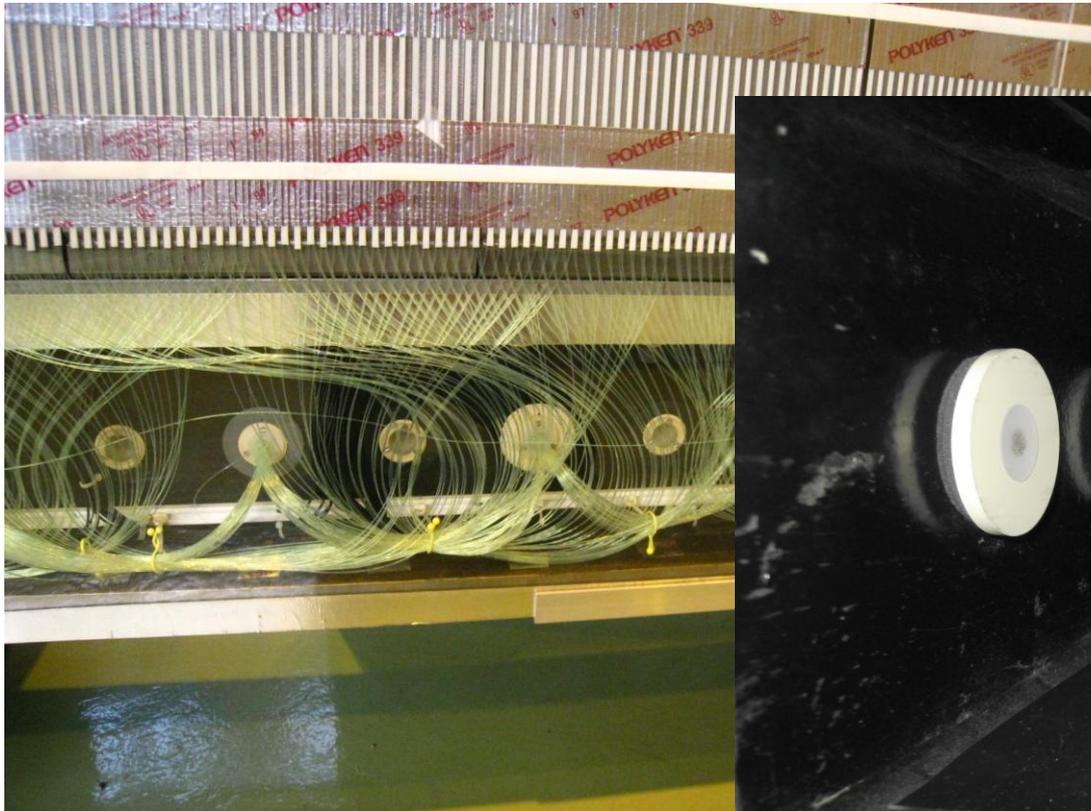
0,3mm dead zone channel to channel



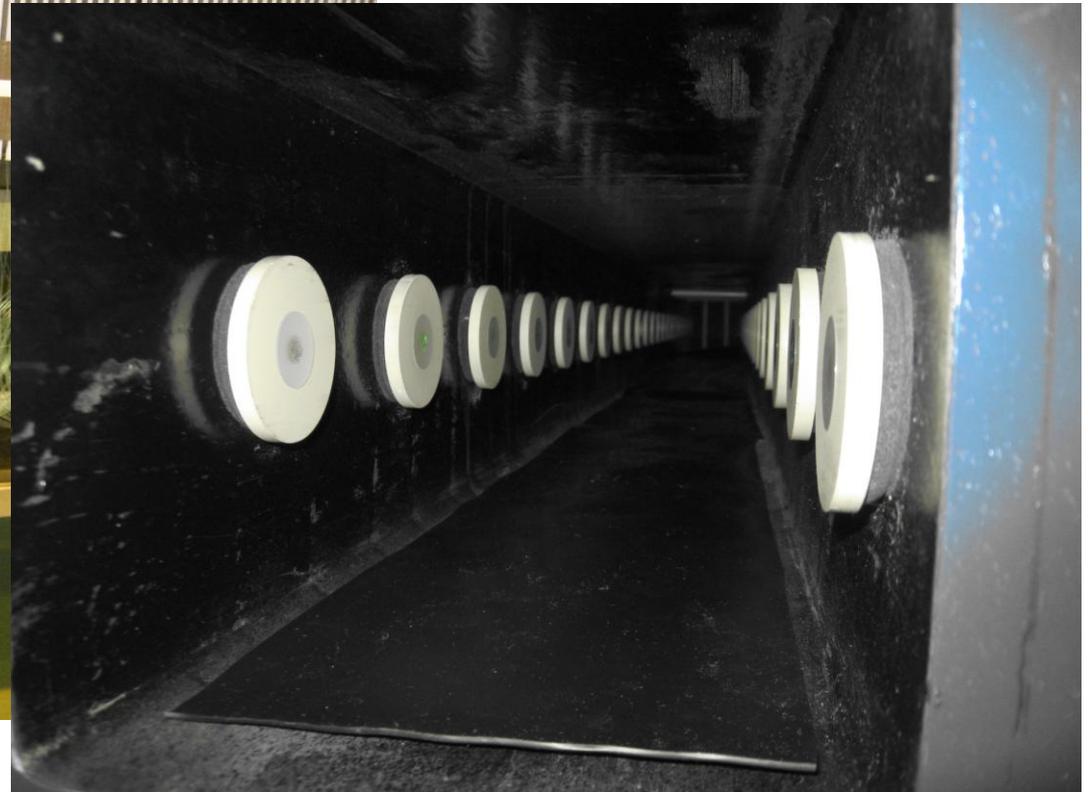
Would it allow better granularity?

How to play with the fibers to improve Tilecal granularity?

Redo fiber bundles? Not possible.



Single fiber output available inside girder in fiber bundles

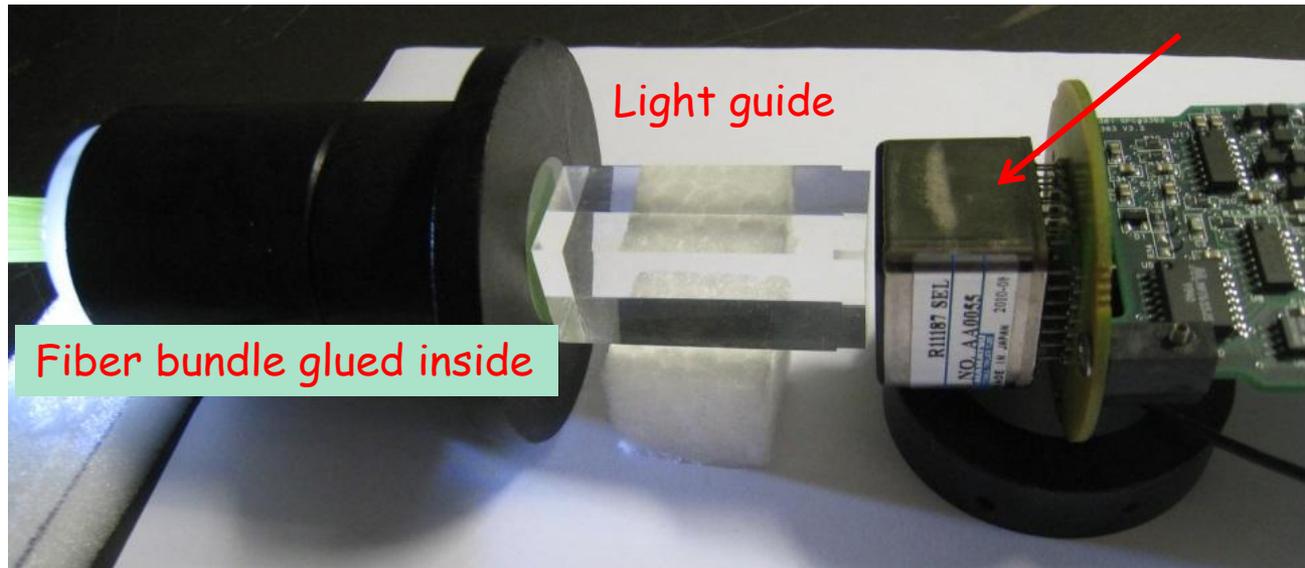


Fiber bundles

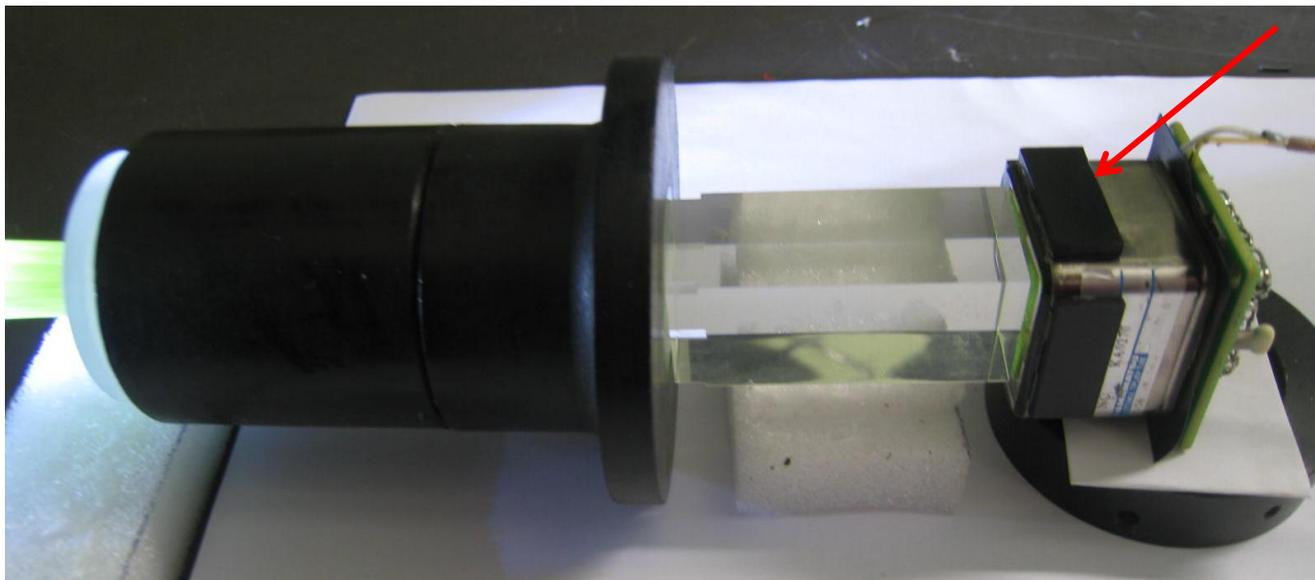
Each bundle is unique. The fibers are randomly positioned.



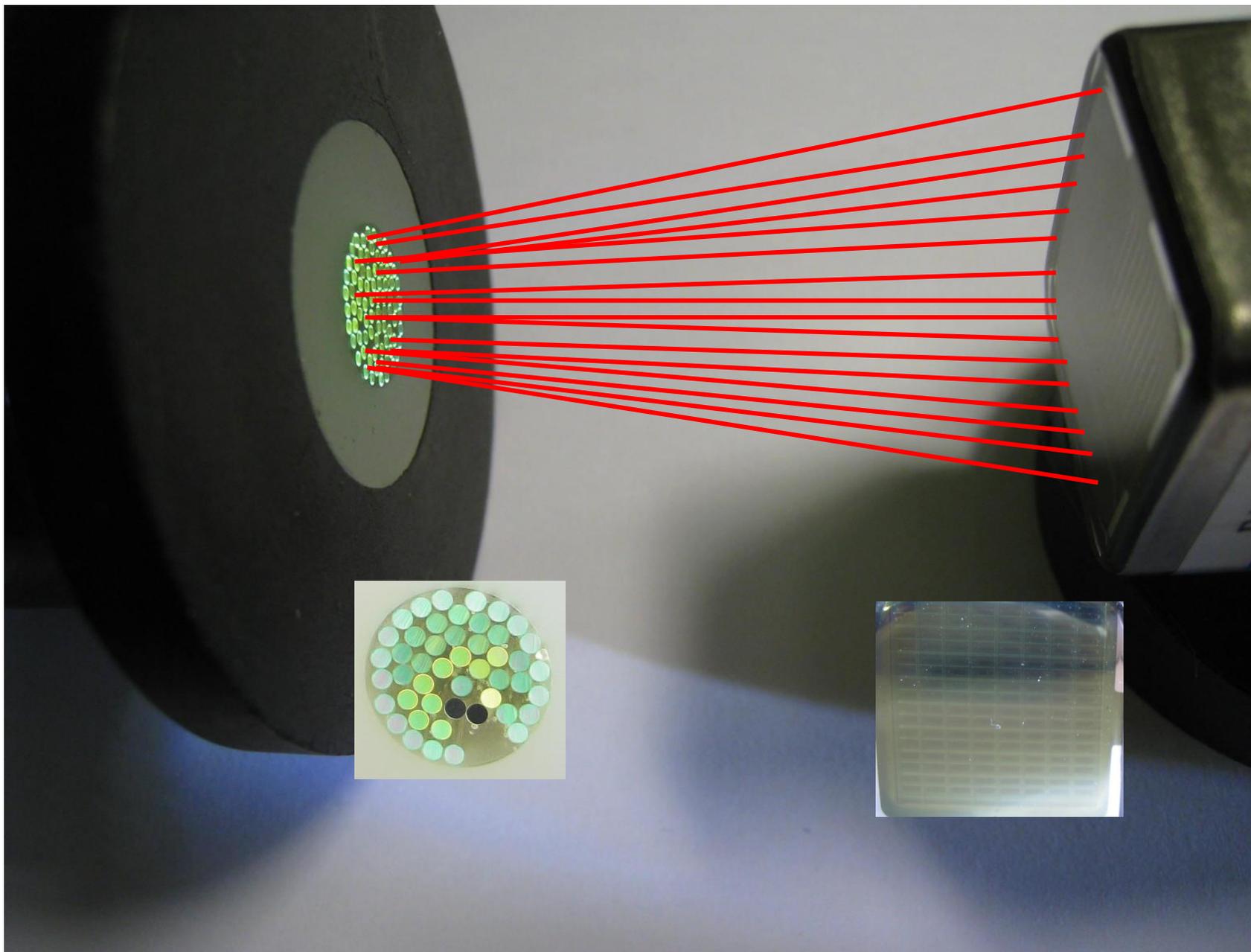
Tilecal PMT



MAPMT

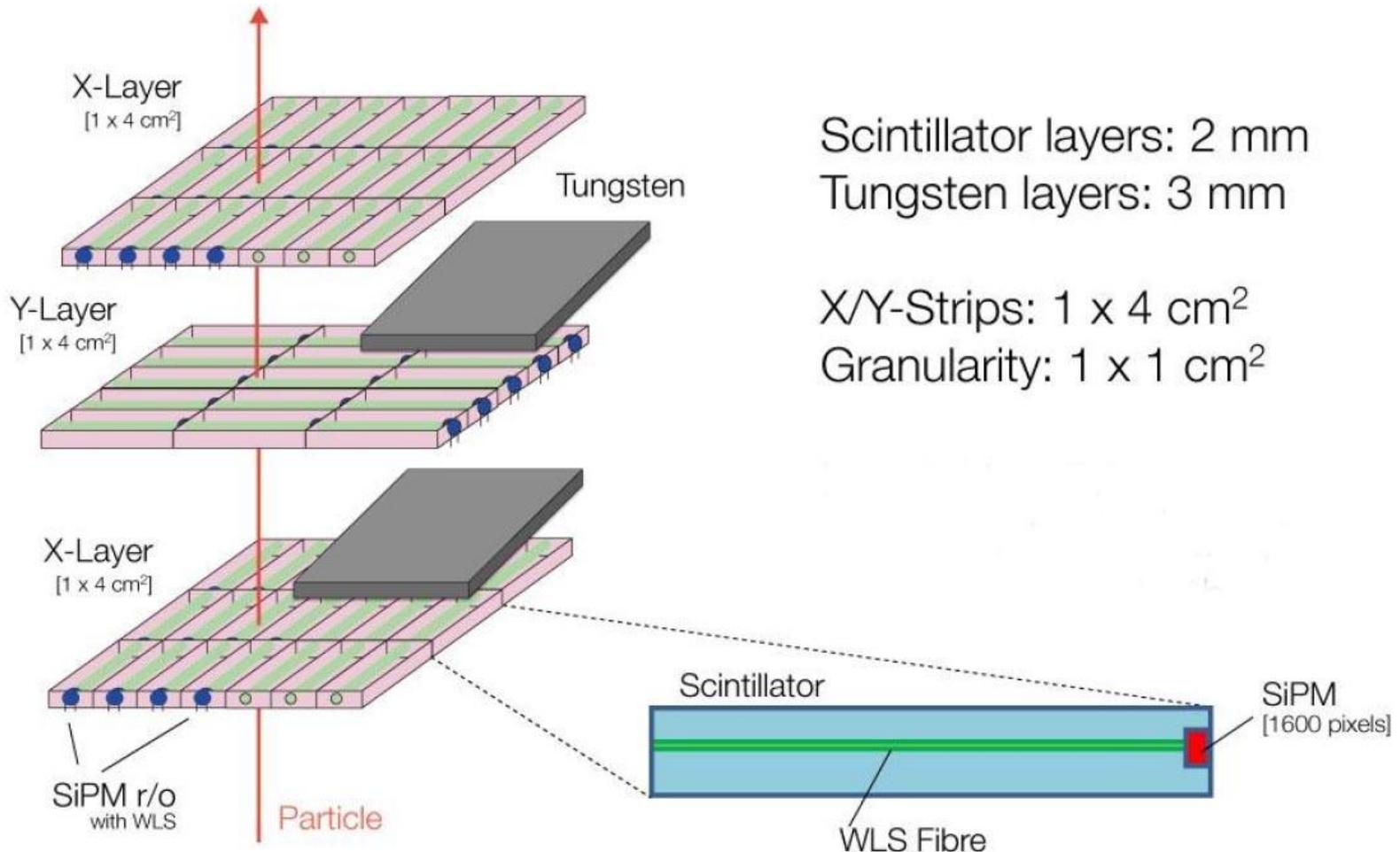


Special light guide to guide the light to the MAPMT?



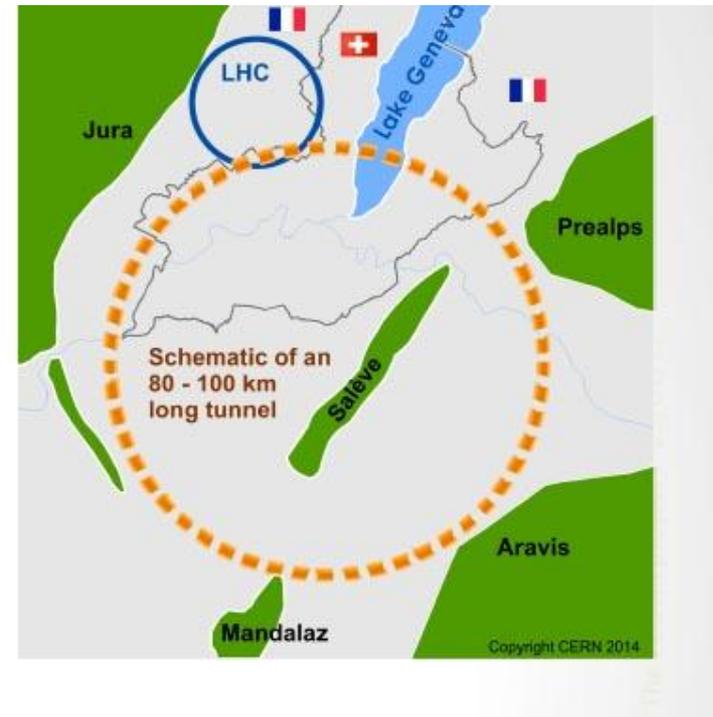
Calorimeters with scintillators and WLS fiber for the future

CALICE - example of a very high granularity ECAL



Future Circular Collider (FCC)

- Possible to host FCC-hh in Geneva area
 - Centre mass $E = 100\text{TeV}$ (x7 LHC)
 - 83-100 Km tunnel (x 3-4 LHC)
- (If NiTi 8.3 Tesla (LHC dipoles) $\Rightarrow v_s=42\text{ TeV}$ in 100km ...) \Rightarrow
- $\sim 16\text{ T dipoles (NbSn}_3) \Rightarrow 100\text{ TeV } pp$ in 100 km
 - $\sim 20\text{ T (HST)} \Rightarrow 100\text{ TeV } pp$ in 83 km
- Use LHC as injector
 - Strong support from CERN
 - e^+e^- collider (*FCC-ee*) as potential intermediate step
 - $p-e$ (*FCC-he*) option
 - China also interested to host the project



FCC-hh	Phase 1	Phase 2
C.M Energy	100TeV	100TeV
Luminosity	$5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	$3 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ *
Integrated <u>Lumi</u>	3 ab^{-1}	30 ab^{-1} *
Bunch spacing	25ns \rightarrow 5ns	5ns

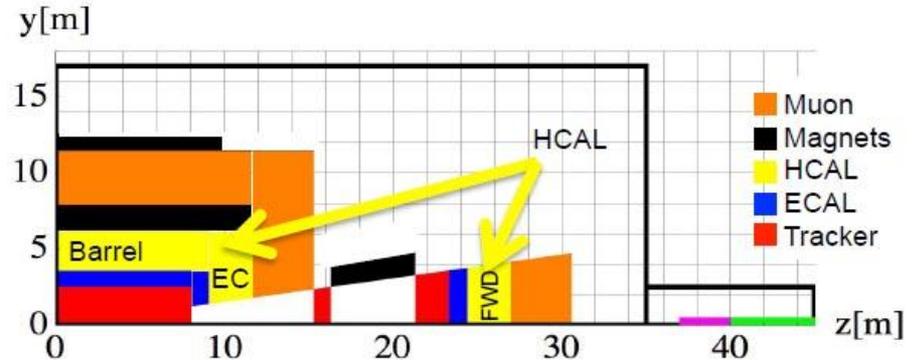
* NB upper values used for detector R & D + radiation studies

A high granularity Tilecal for FCC ?

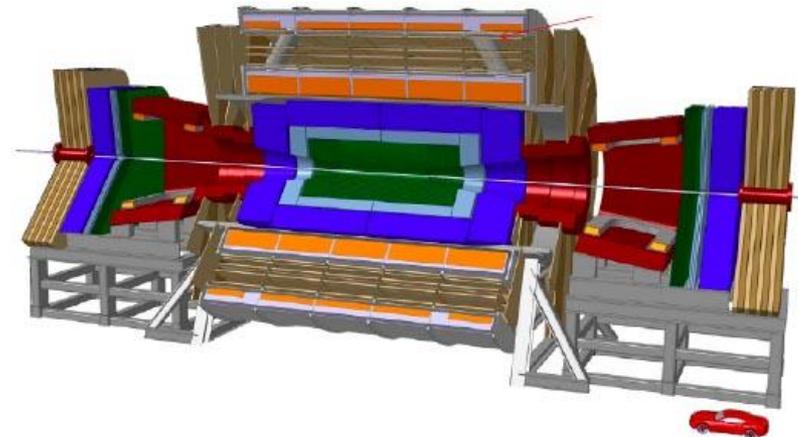
- We expect large energy of decay products at the FCC
 - Large jet P_T
 - Missing E_T signatures
 - High-mass, long-lived particles
 - Tau decays
 - Veto on photons / electrons / jets

- Requirements for HCAL

- Depth
- Resolution
- Segmentation
- Dynamic range
- Coverage



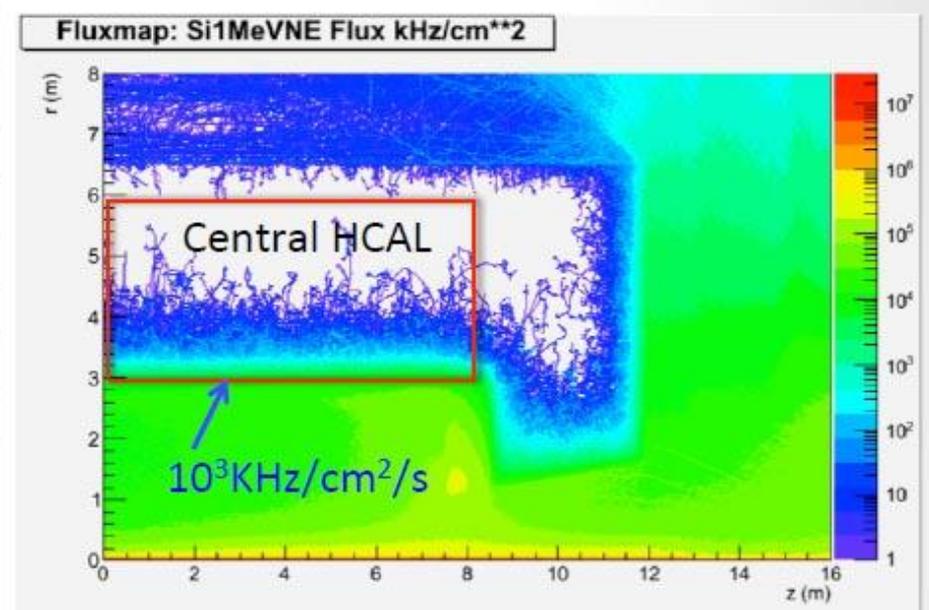
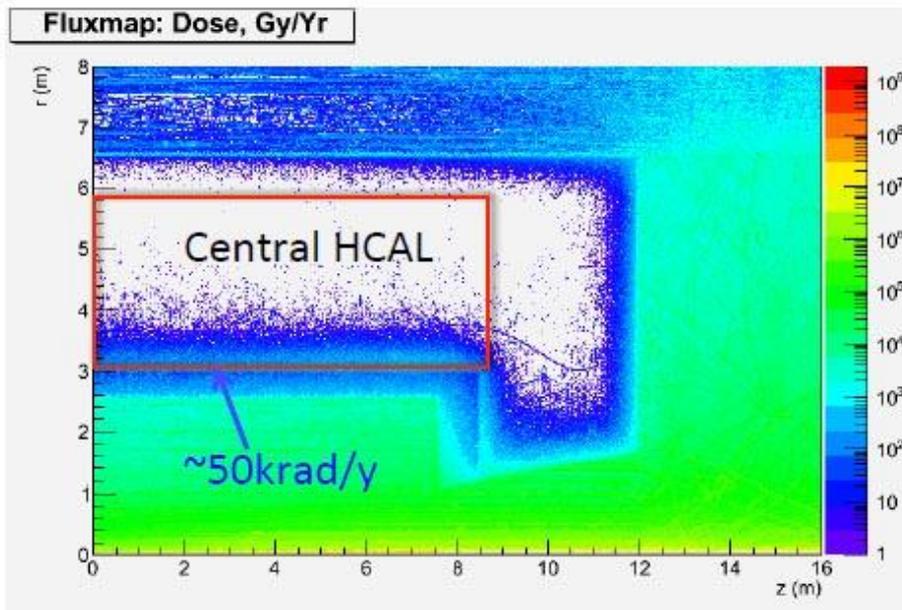
Baseline barrel calorimeter:
 80% Fe, 20% Polystyrene
 λ of this mix = 20.6 cm



Radiation levels in FCC

Assuming luminosity $L=10^{36}\text{cm}^2\text{s}^{-1}$

Dimensions: inner tracker 2.5m, em calo 3m, had calo 6m, Zmax 8.5m



Central HCAL protected by ECAL, max dose $\sim 50\text{krad/year}$ at $L=10^{36}\text{cm}^2\text{s}^{-1}$
For 10 years $\sim 0.5\text{ Mrad}$

Today commercial scintillators (BC408, EJ200) are radiation harder by a factor $\sim 1.5-2$ than current Tilecal scintillators

The use of organic scintillators in the central region $\eta < 1.5$ seems to be possible

Optics for FCC

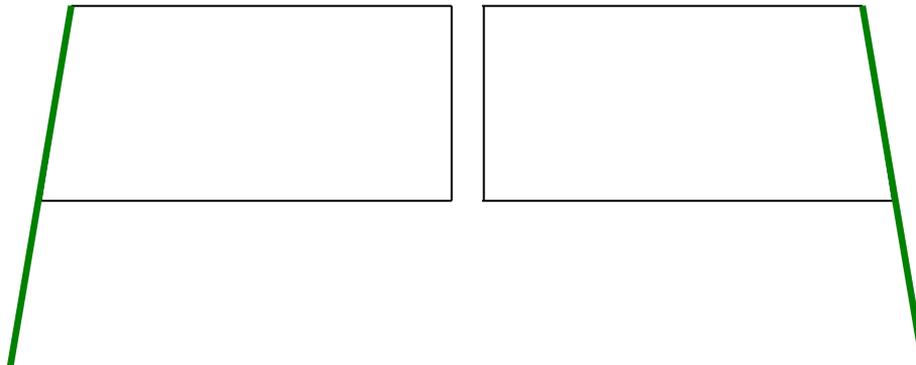
R&D on radiation harder scintillators/fibers to increase safety factors

Improve ϕ granularity

Move outer radius. R_{min} goes from 2.2 to 3m. Allows more modules of similar size (64 \rightarrow 87 modules)

Half-trapezoidal tiles: readout by a single fiber. \Rightarrow Light loss and less uniformity.

Reduce modules/tiles ϕ dimension (87 \rightarrow 122 modules)



Half size semitrapezoidal tiles with single fiber readout

Summary

- Scintillators and fibers are versatile for hadronic calorimeters
- ATLAS Tilecal is a very successful calorimeter
- Equipments for R&D and QC of scintillators and fibers in the lab
- Used in production for Tilecal
- For High Luminosity LHC Tilecal will upgrade only a few special scintillators, and is studying possibilities to increase granularity of existing cells
- Much better granularity is needed for FCC but preliminary studies for a Tilecal for FCC show it seems feasible