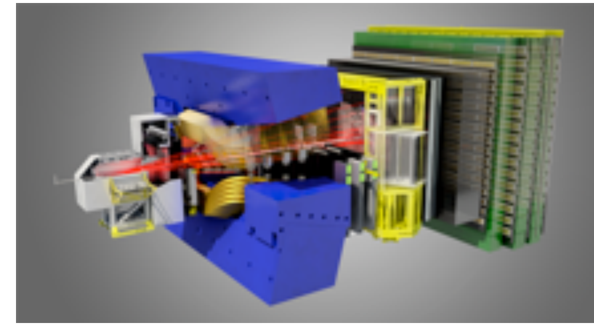


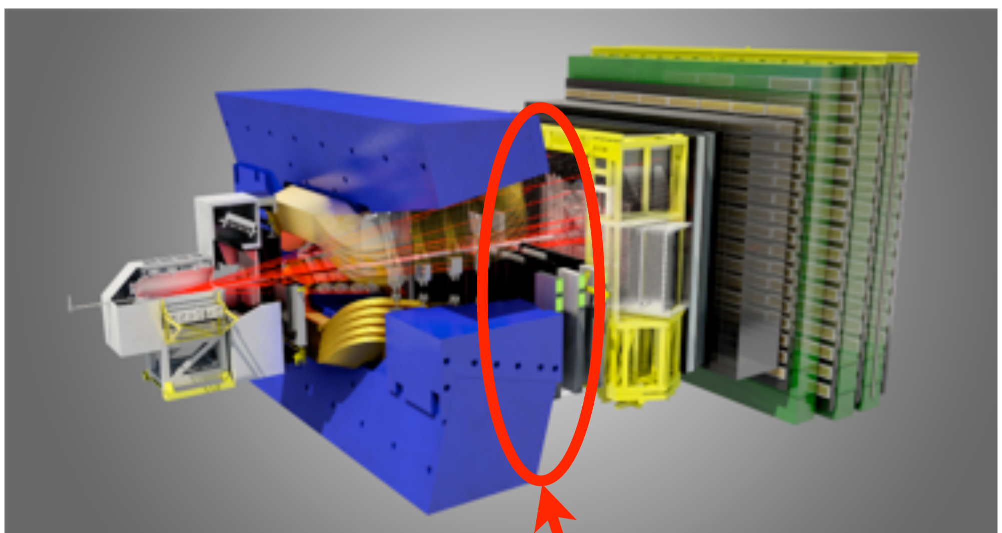
A scintillating fiber tracker for the LHCb upgrade

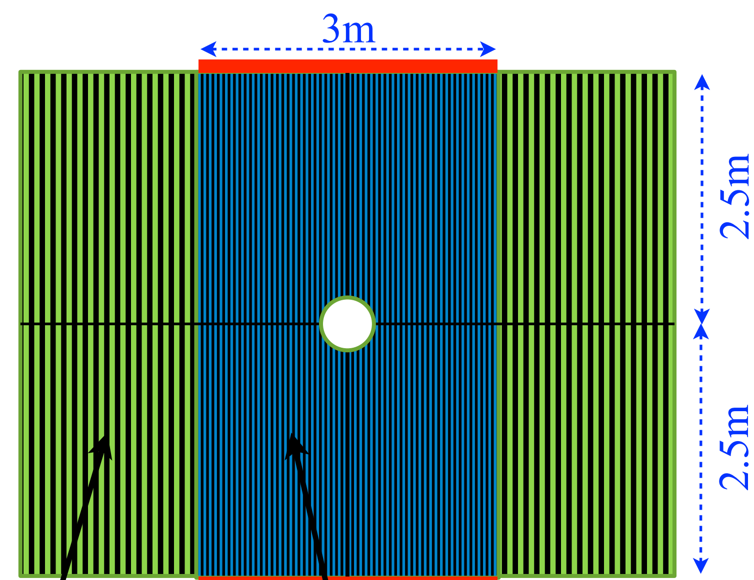
Fred Blanc (EPFL)

Clermont-Ferrand
23/05/2013

Proposed tracker

- 3 tracking stations downstream of the LHCb magnet
- 250 μm scintillating fibers
- readout with multi-channel Silicon photo-multipliers (SiPM)

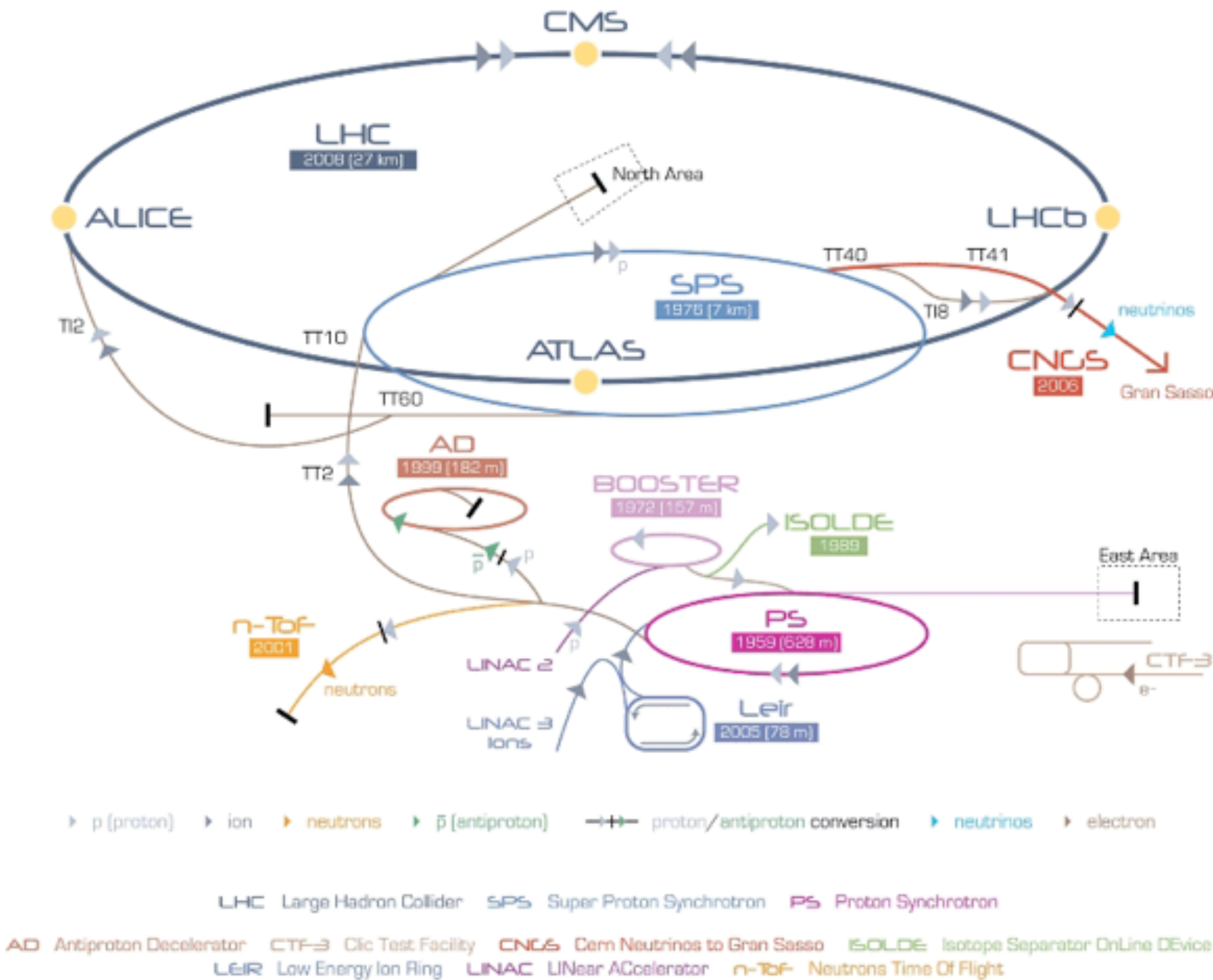




LHC and the LHCb experiment

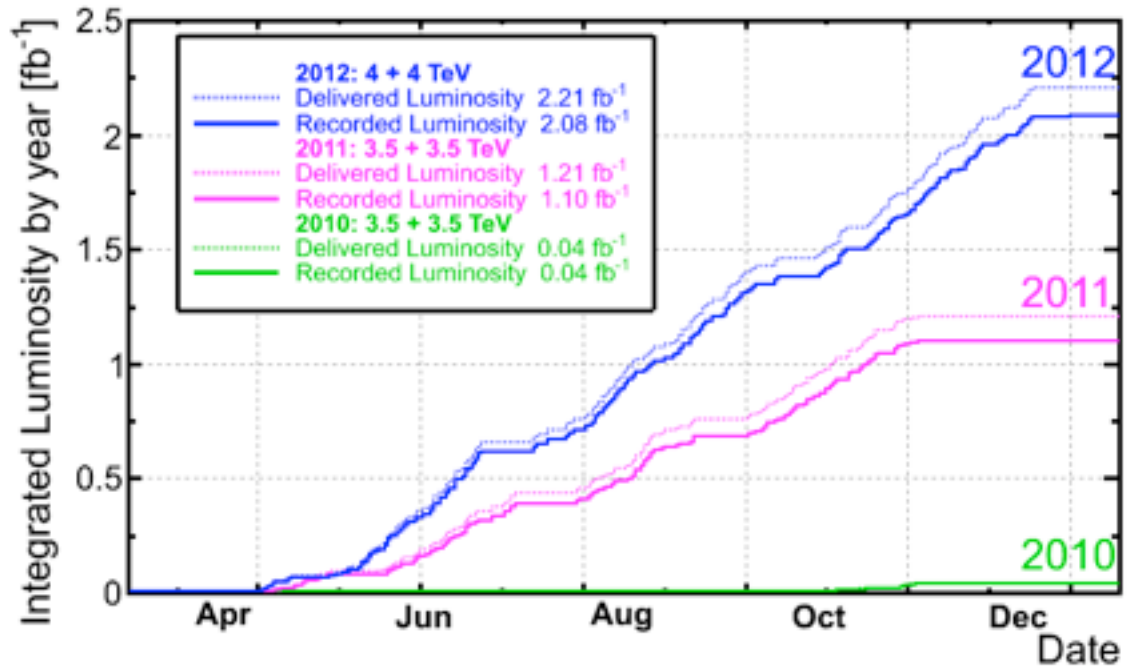
The CERN accelerator complex

The CERN accelerator complex



The LHC accelerator at CERN

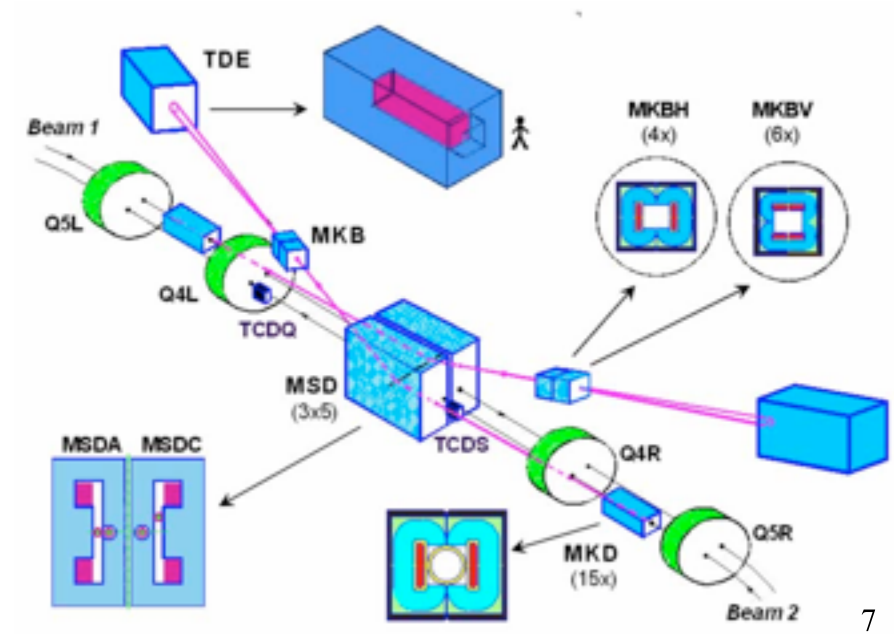
- The LHC is installed in the old 27km circular LEP tunnel
- Accelerates protons to a maximum energy of 7TeV
  - 3TeV in 2011; 4TeV in 2012; expect 6.5-7TeV in 2015
- Interaction rate: (up to) 40MHz ⇒ 25ns bunch crossings
- Revolution frequency: 11kHz
- Main operation since 2010
- Currently stopped to bring the beams to nominal performance by 2015



LHC: beam energy

- 7 TeV protons ⇒ 2×7 TeV center of mass energy
  [1TeV = 10^{12} eV with 1 eV = 1.6×10^{-19} Joules]
  ⇒ kinetic energy of a 1mg mosquito at 1.5m/s
- 10^{11} protons per bunch
- ~1400 bunches per beam in 2012 data taking period
- Total beam energy
  - $E_{beam} = 1400 \times 10^{11} \times 7\times10^{12}$ eV
    $\simeq 10^{27}$ eV = 1.6×10^{8} J
  - equivalent to the kinetic energy of a 40-ton truck at 300km/h
    $E_{kin} = 1/2mv^2 \Rightarrow v = (2E_{kin}/m)^{1/2} =$
    $(3.2 \times 10^8 / 40000)^{1/2}$ = 90m/s = 324km/h

Beam dump system



Les particules du “modèle standard”

LEPTONS

Composants de la matière

Électron Un des composants de l’atome, avec le nucléon.	**Neutrino-Électron** Particule sans charge électrique et avec une très petite masse. Des milliards de ces particules traversent votre corps à chaque seconde.
Muon Très proche de l’électron, mais plus lourd ; il a une durée de vie de 2 millionièmes de secondes.	**Neutrino-Mu** Créé en même temps que les muons quand certaines particules se désintègrent.
Tau Encore plus lourd ; il est légèrement instable. Il a été découvert en 1975.	**Neutrino-Tau** Découvert en 2000.

Les particules du "modèle standard"

QUARKS

Composants de la matière

Up Sa charge électrique est + 2/3 *e* ; les protons en contiennent deux, les neutrons en contiennent un.	**Down** Il a une charge électrique de -1/3 *e* ; les protons en contiennent un, les neutrons en contiennent deux.
Charmé Un proche du « Up », mais plus lourd. Découvert en 1974.	**Étrange** Un proche du « Down », mais plus lourd.
Top Encore plus lourd ; découvert en 1995.	**Beauté** Encore plus lourd ; mesurer les quarks beauté est un test important de la théorie électro-faible.

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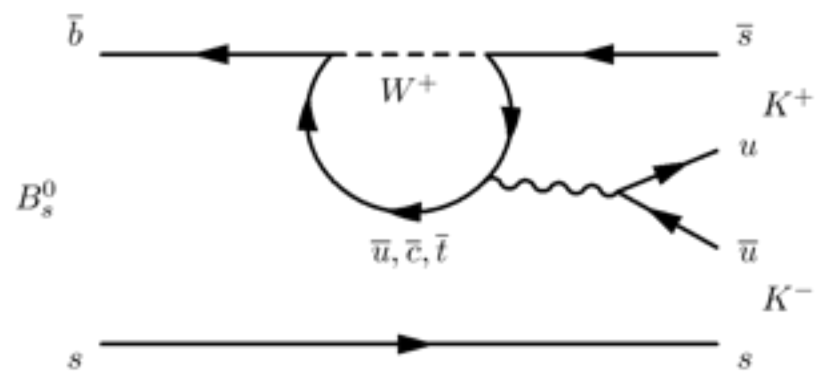
LHCb: the physics goals

- Main LHC experiments (ATLAS & CMS)
  - search for new heavy particles ($M \simeq 100-1000 GeV/c^2$)
  - candidate Higgs particle observed at $126 GeV/c^2$
    ⇒ confirmation of the standard model of particle physics
- LHCb
  - study the matter-antimatter asymmetry and rare processes
  - precision measurements in heavy-flavor systems
    - particles containing heavy quarks (*beauty* or *charm*)
  - new physics (i.e. heavy particles) can enter loops and modify the behaviour of the standard model predictions



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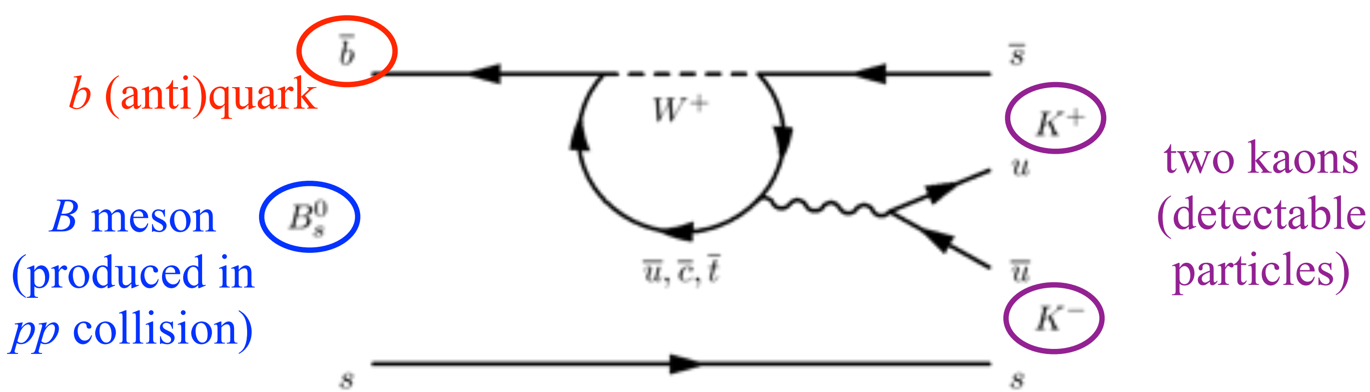
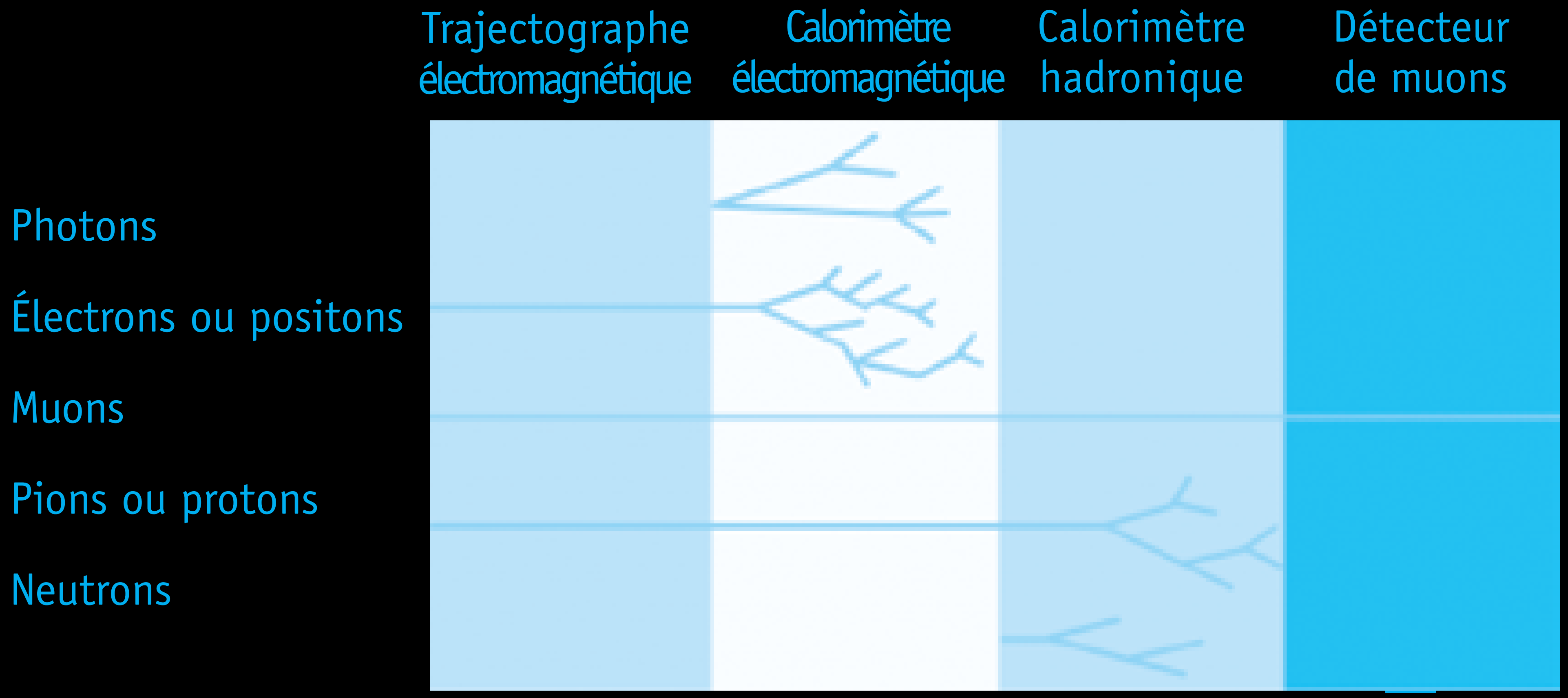


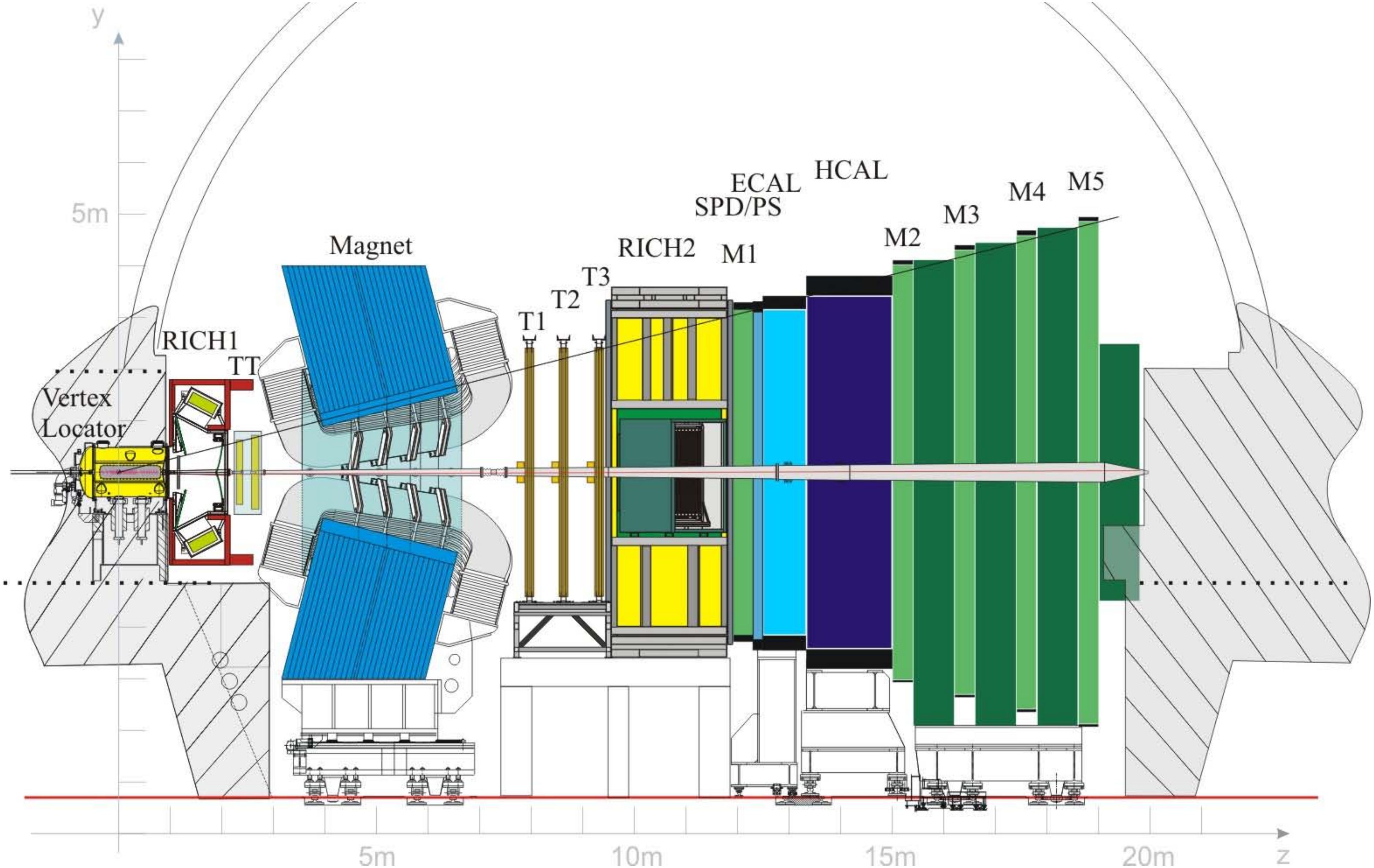
Comment détecte-t-on les particules

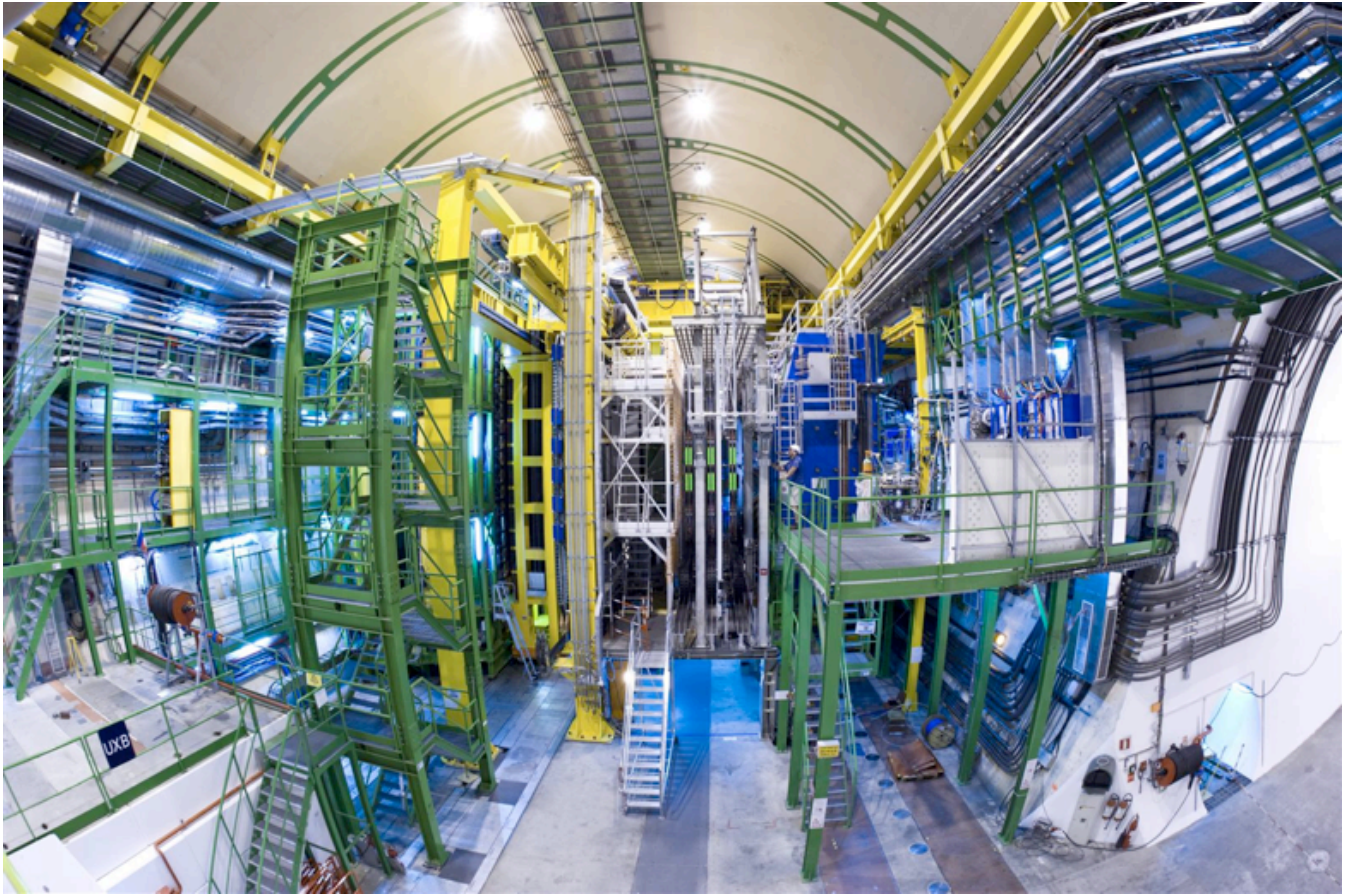


LHCb: the detector

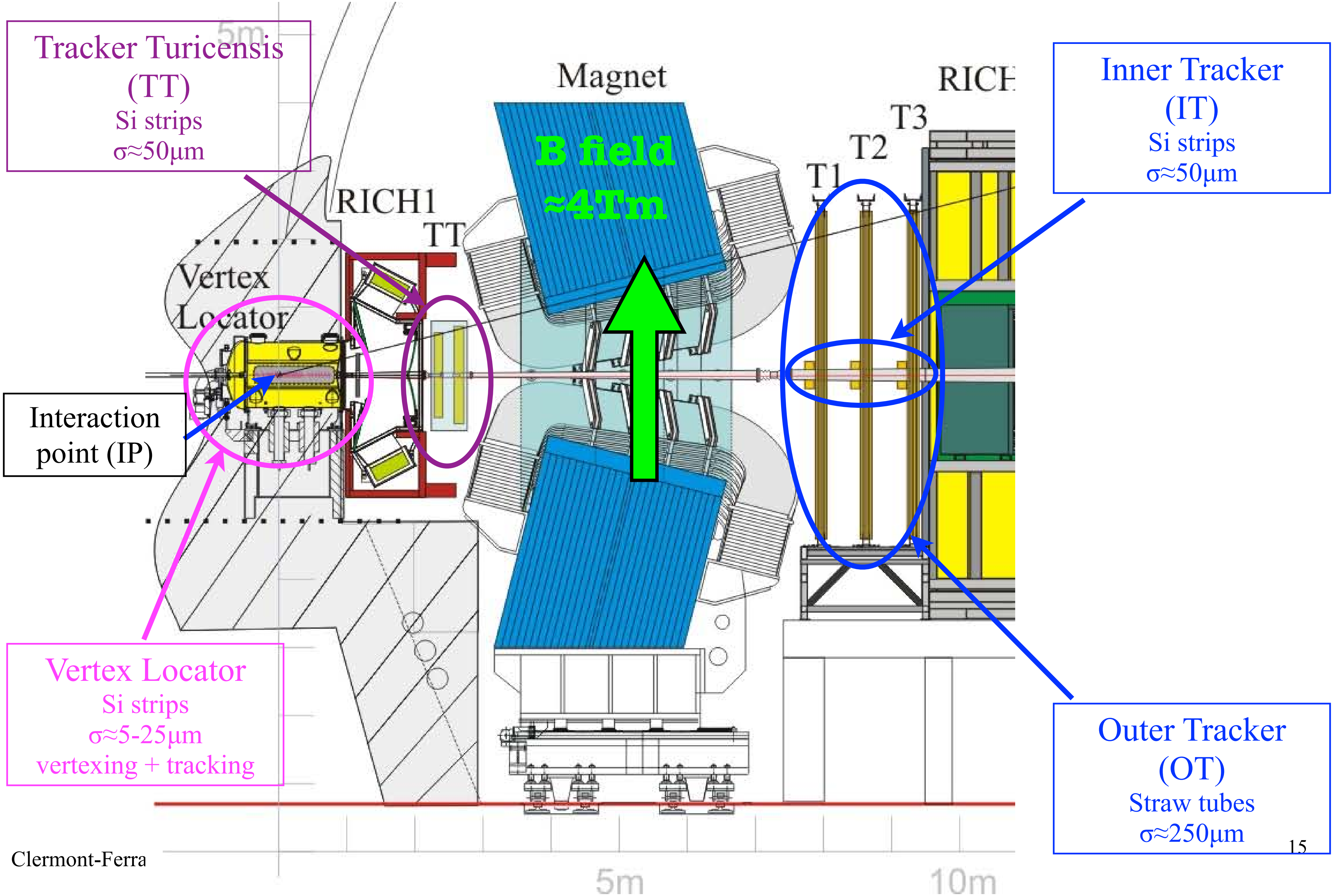
- In proton-proton collisions, the B mesons are predominantly produced the in direction of the beams
  ⇒ build the detector along the beam line (forward spectrometer)
- Short B meson lifetime
  ⇒ high precision vertex detector near interaction point
- Kinematics reconstruction of the processes
  ⇒ tracking system with bending magnet
- Multiple types of detected charged particles ($\pi^{\pm}$, $K^{\pm}$, p, $e^{\pm}$, $\mu^{\pm}$)
  ⇒ particle identification (Cherenkov + calorimeters)
- Detection of neutral particles (photons)
  ⇒ electromagnetic calorimeter
- Muon ($\mu^{\pm}$) identification
  ⇒ muon detectors placed after the calorimeters

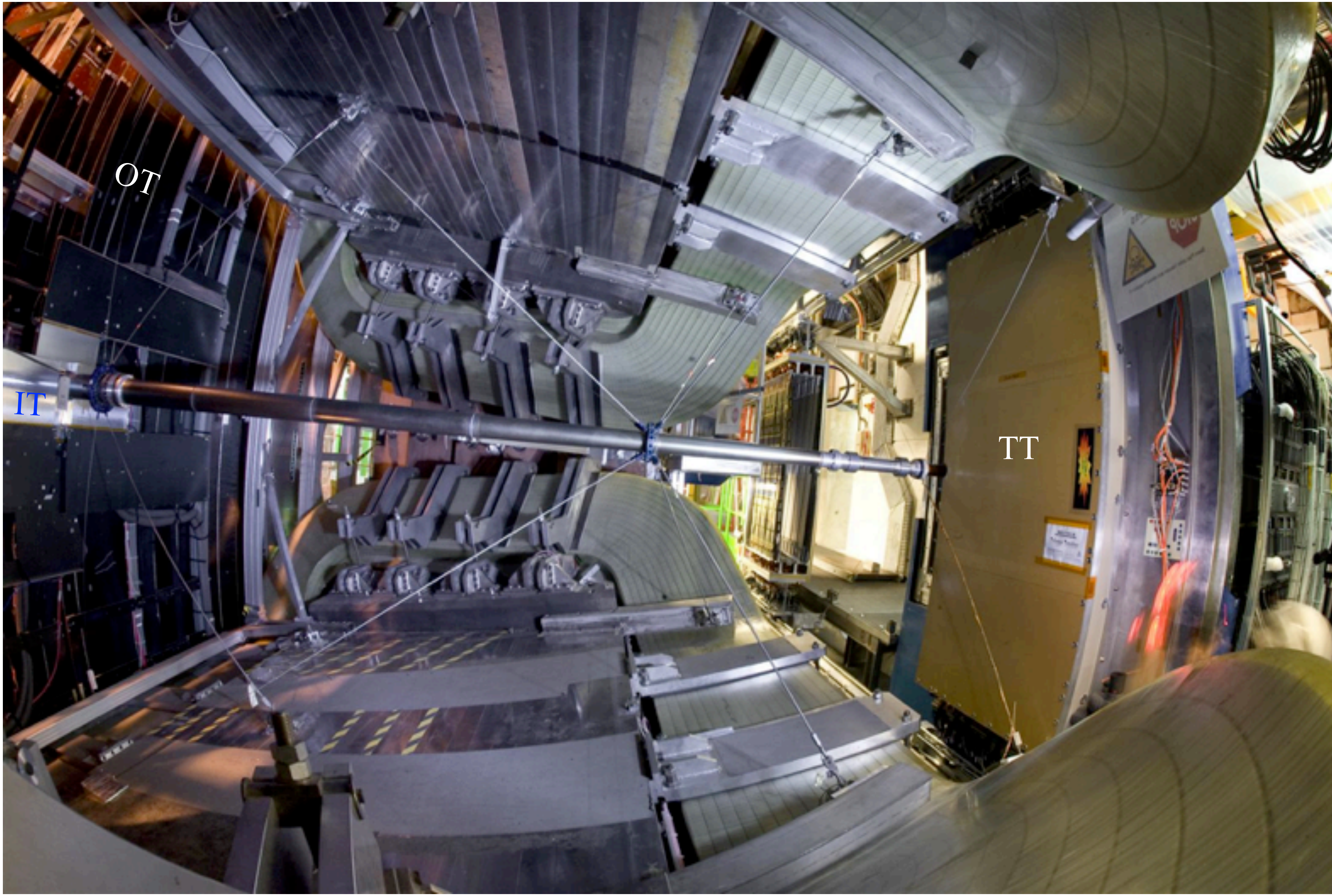
LHCb detector



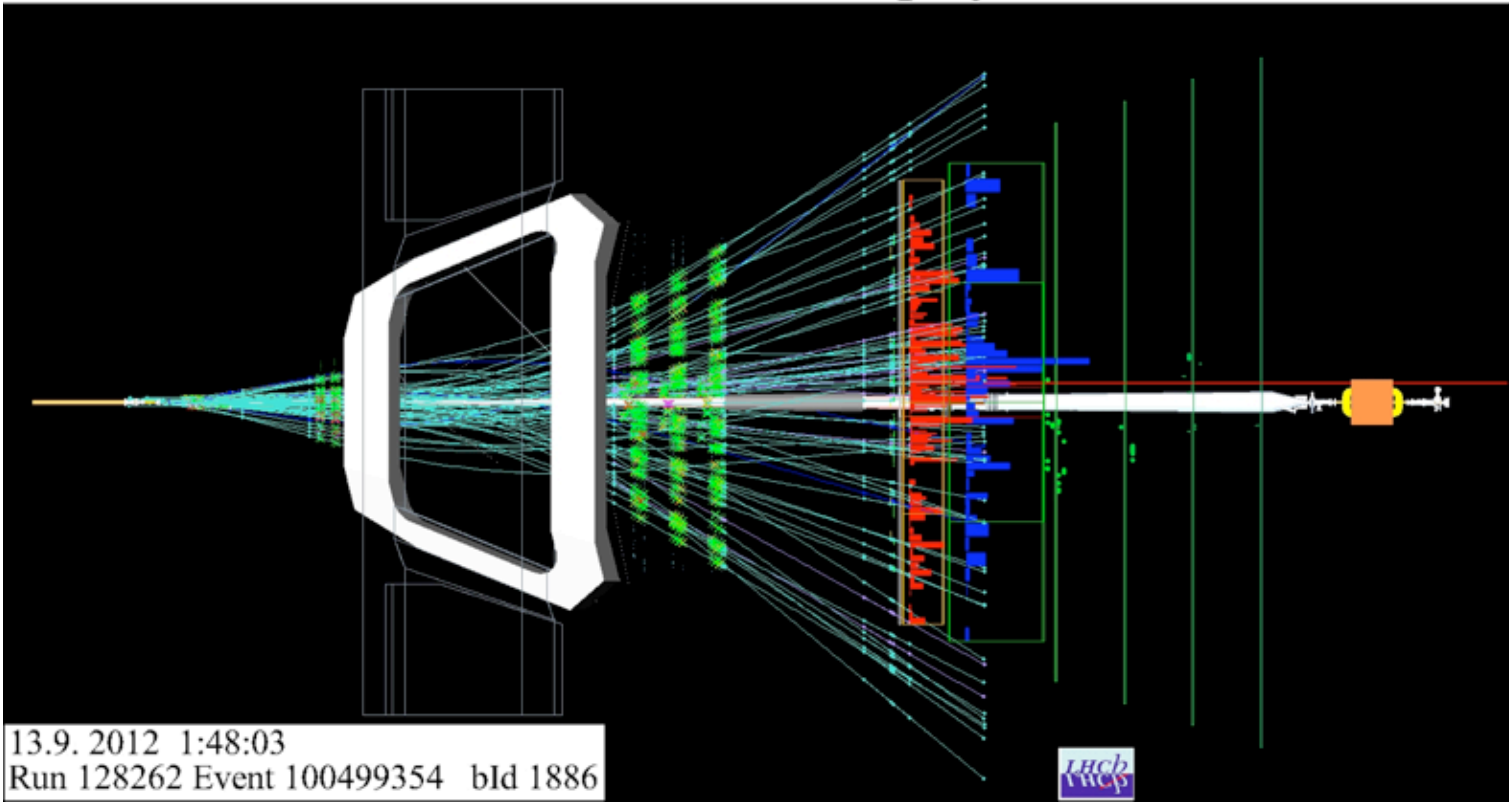

UXB

...zoom on the tracker



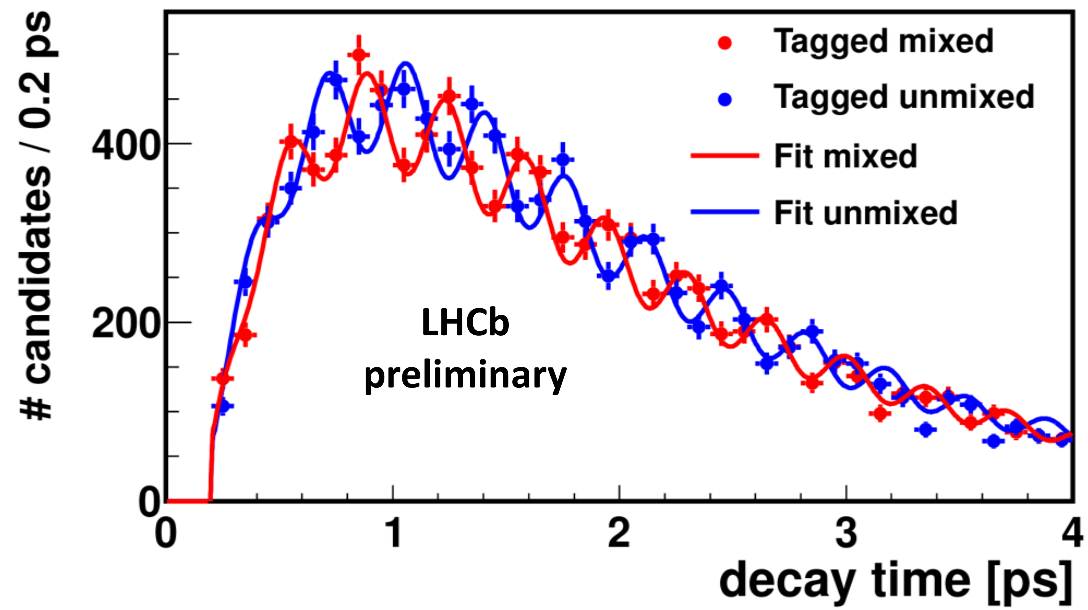

OT
IT
TT

LHCb Event Display

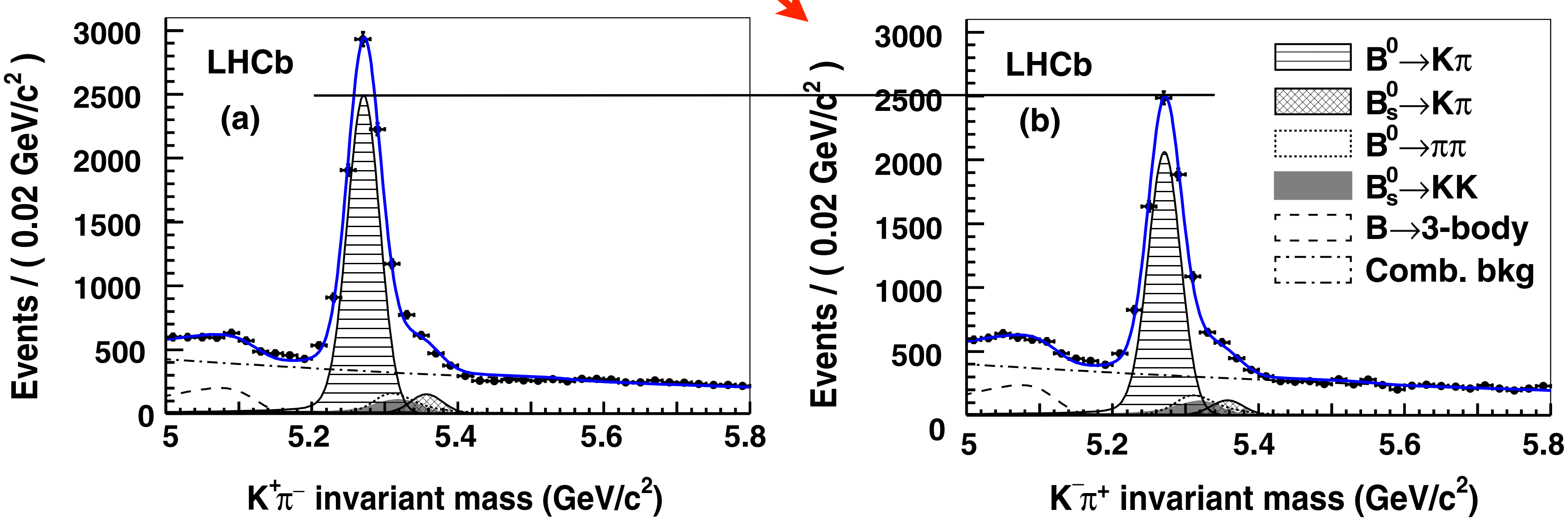


LHCb: selected physics results

- Measurement of the oscillations of B_s^0 mesons



- Observation of the CP (matter-antimatter) asymmetry in B_d^0 decays



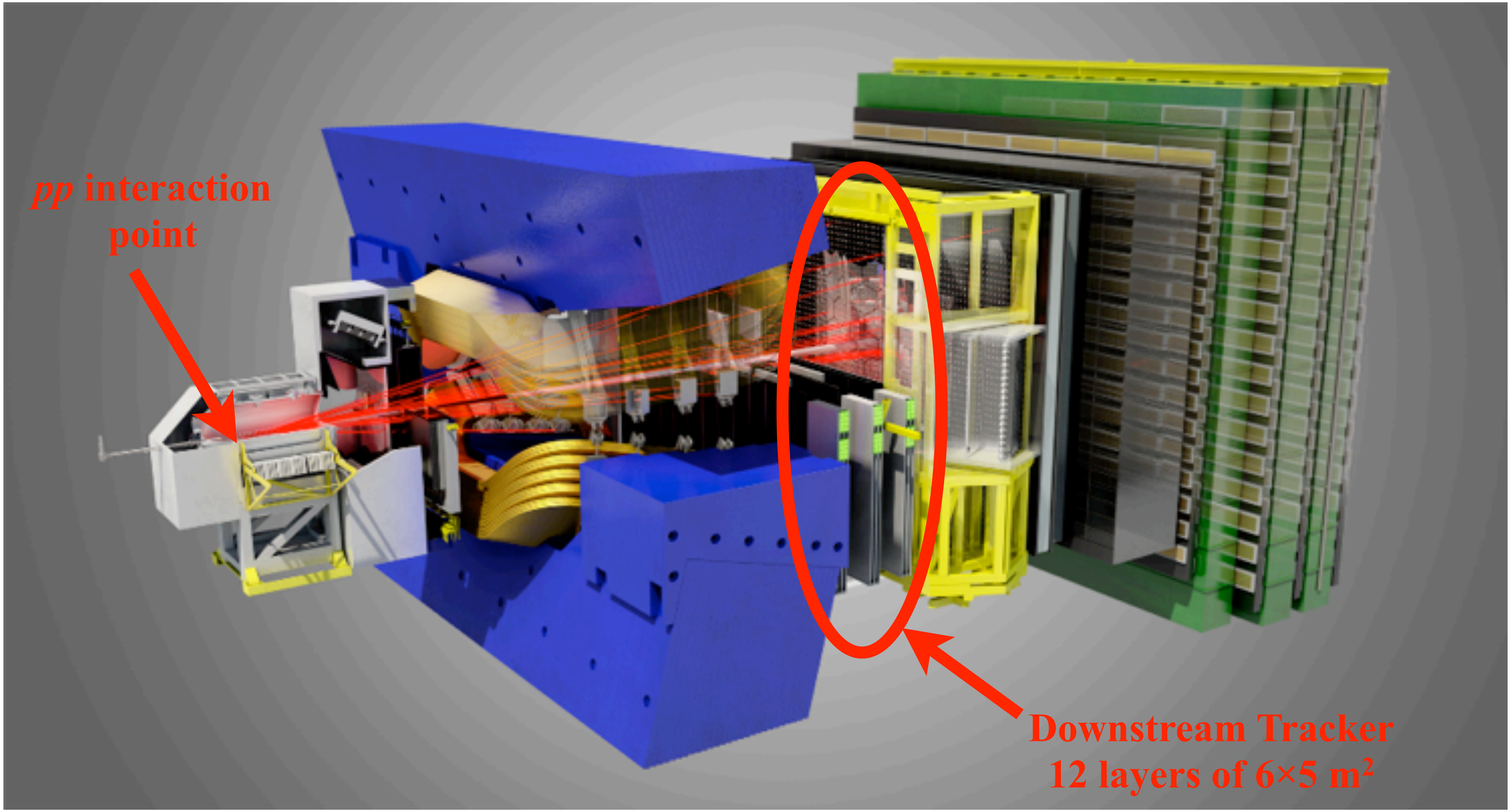
LHCb: the need for an upgrade

- Adding $2fb^{-1}$ of data every year is significant in the first years
  - statistical uncertainties are proportional to the square root of the integrated luminosity $\sim (L)^{1/2}$
- Expect $\sim 7fb^{-1}$ by 2016; 2017 will add 30%
  $\Rightarrow$ only ~13% improvement on the statistics
- A significant increase is necessary to justify the effort of operating the detector
  $\Rightarrow$ upgrade of the LHCb detector
- LHCb upgrade plans:
  - replace several sub-detectors
  - change all electronics to allow 40MHz readout
  - install new detector during the 2018 LHC shutdown

LHCb tracker upgrade

LHCb detector upgrade

- LHCb upgrade: replace several detectors, and R/O electronics
- Discuss here the replacement of the tracker, downstream of the magnet



Tracking detector requirements

- High hit detection efficiency ($\geq$ 98−99%)
- Spatial hit resolution at the level of 60−100μm
- Minimize material in the acceptance
  - to limit the effects of multiple scattering and energy loss
- Readout electronics to operate at 40MHz
- Rate of reconstructed noise clusters < ~ 2MHz / 128-channels

- **The above requirements must be fulfilled over the full lifetime of the experiment (up to 50fb^{-1})**

Comments on the hit resolution

- Hit resolution is driven by multiple scattering
  - each station (TT, IT, OT): $x/X0 \approx 3\text{-}4\%$
    $\Rightarrow$ multiple scattering angle θ_{ms} (cf. PDG)

$$\theta_{\rm ms} = \frac{13.6\,{\rm MeV}}{\beta c p}\sqrt{x/X_0}\left[1+0.038\ln(x/X_0)\right]$$

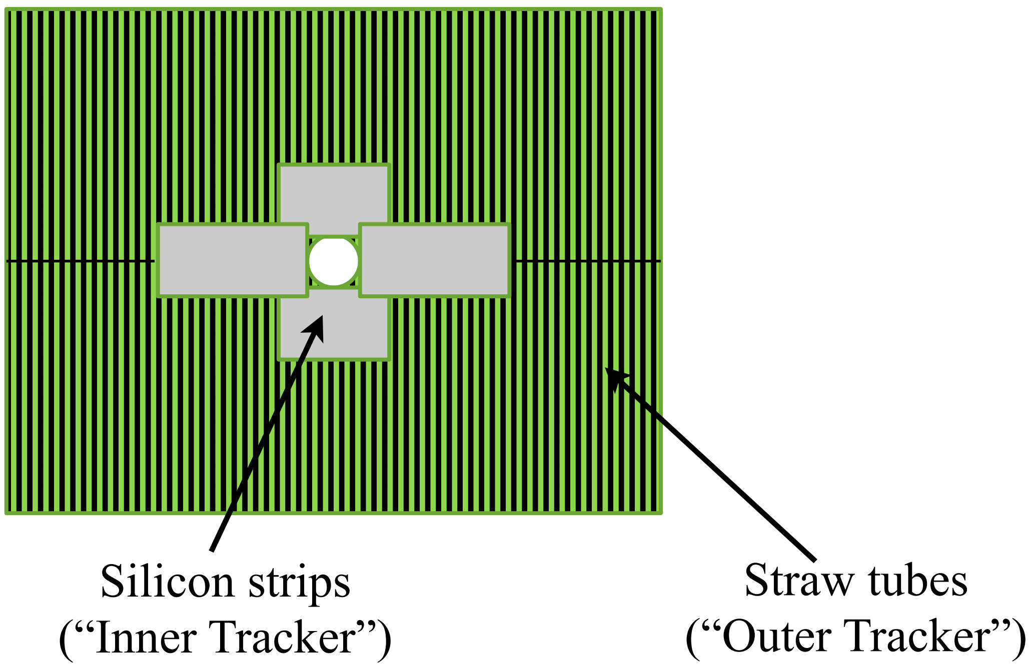
  - $p \approx 20\text{GeV}/c$; $\beta \approx 1$ $\Rightarrow \theta_{ms} \approx 0.12\text{mrad}$
  - $0.12\text{mrad} \times 0.6\text{m} = 72\mu\text{m}$
    $\Rightarrow$ uncertainty due to multiple scattering from a tracking station to the next
    $\Rightarrow$ do not need better than $\approx 60\mu\text{m}$ measurement accuracy
  - effect across the magnet: $0.12\text{mrad} \times 5.5\text{m} = 660\mu\text{m}$

$\Rightarrow$necessity to minimize the material in the acceptance!

Options for the LHCb tracker upgrade

- Two options are being considered:

Silicon strips + Straw tubes

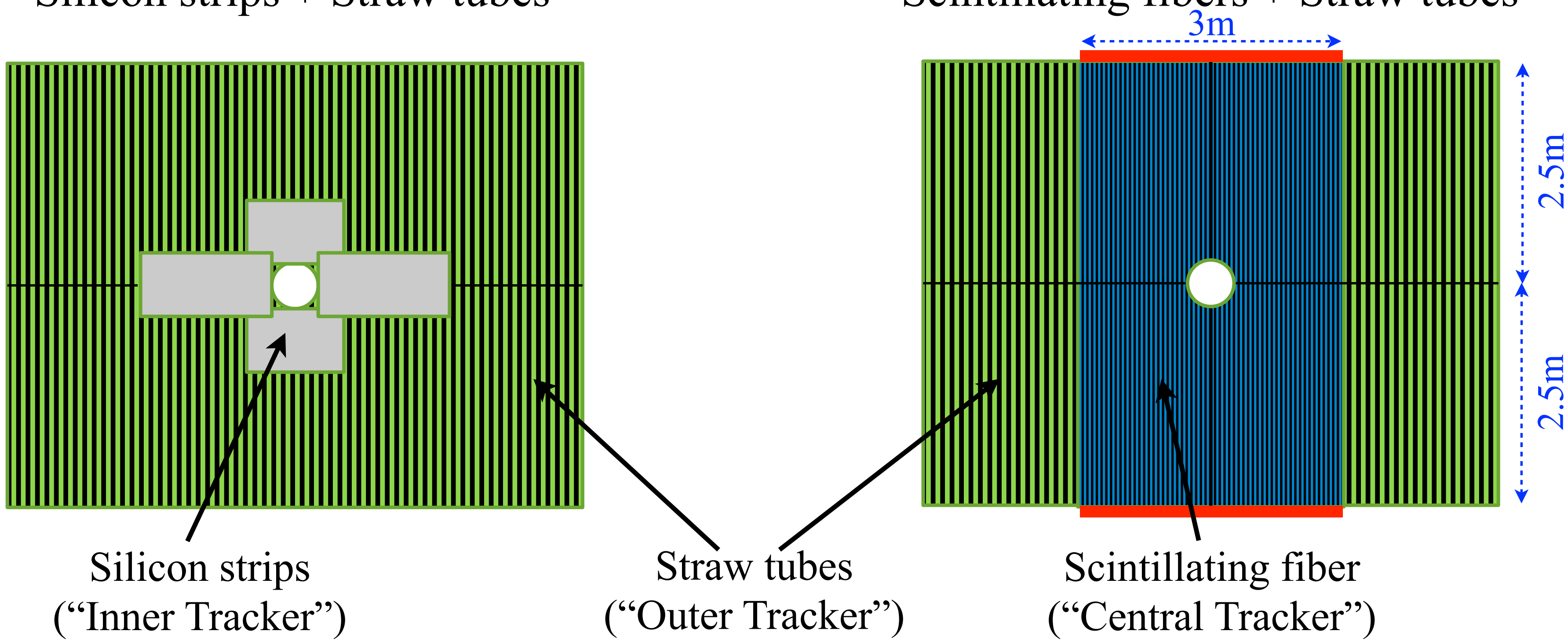


Options for the LHCb tracker upgrade

- Two options are being considered:

Silicon strips + Straw tubes

Scintillating fibers + Straw tubes



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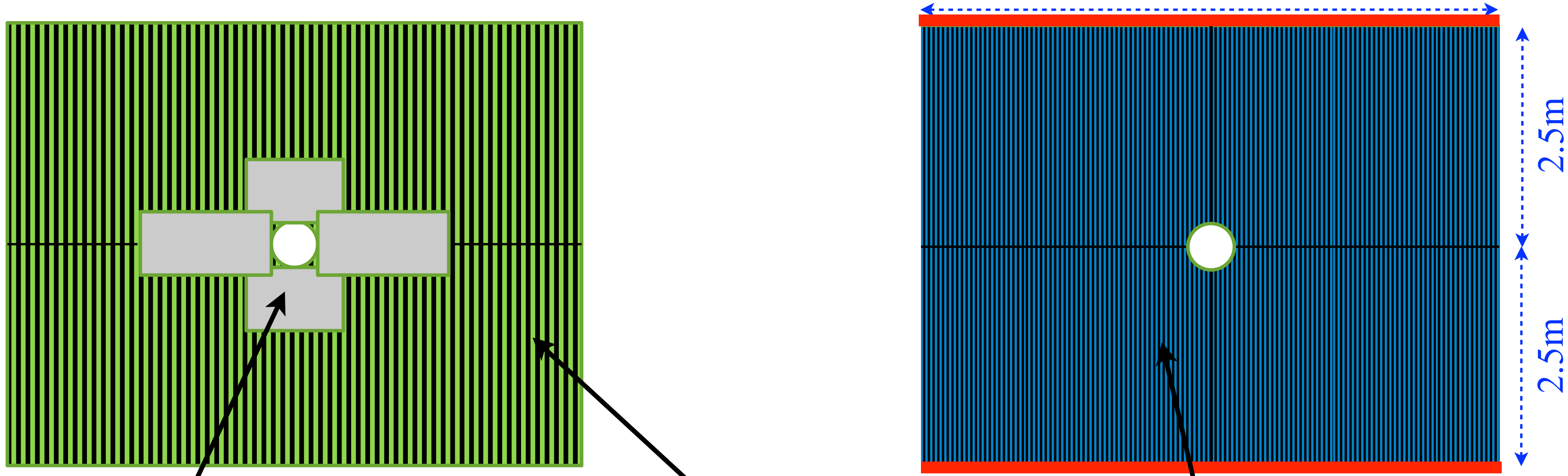


Silicon strips
("Inner Tracker")

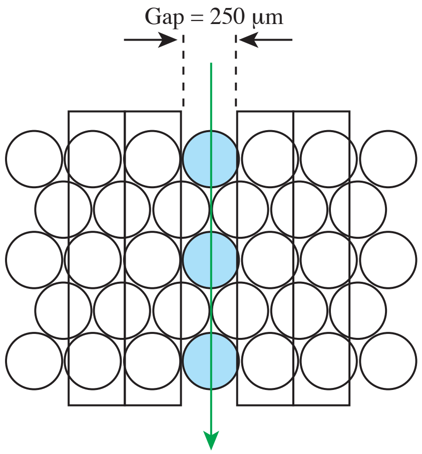
Straw tubes
("Outer Tracker")

Scintillating fibers

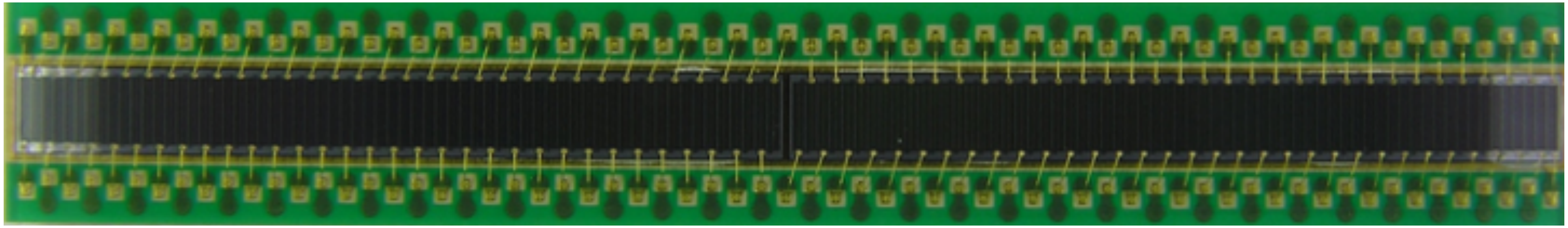
- Scintillating fiber (SciFi) is a new technology in LHCb
  ⇒ can a SciFi tracker fullfil the performance requirements?
  ⇒ will the SciFi technology perform as required after the radiation dose received in the LHCb upgrade ($50fb^{-1}$)?

Main SciFi detector features

- 250μm diameter scintillating fibers
  - arranged in multiple layers for sufficient light collection
- Cover the acceptance with 2.5m long fibers
  - mirror at the center (beam pipe height)
  - light detected outside the acceptance
    ⇒ minimize "inactive" material in the acceptance
  - vertical (x) and stereo (u&v) ⇒ 12 layers



- readout with multi-channel Silicon photo-multipliers (SiPM)



- Readout: 40MHz front-end electronics

The SciFi tracking in numbers

- 12 layers of $5\times6m^2$

  $\Rightarrow 360m^2$

- 250μm diameter fibers arranged in 5 layers

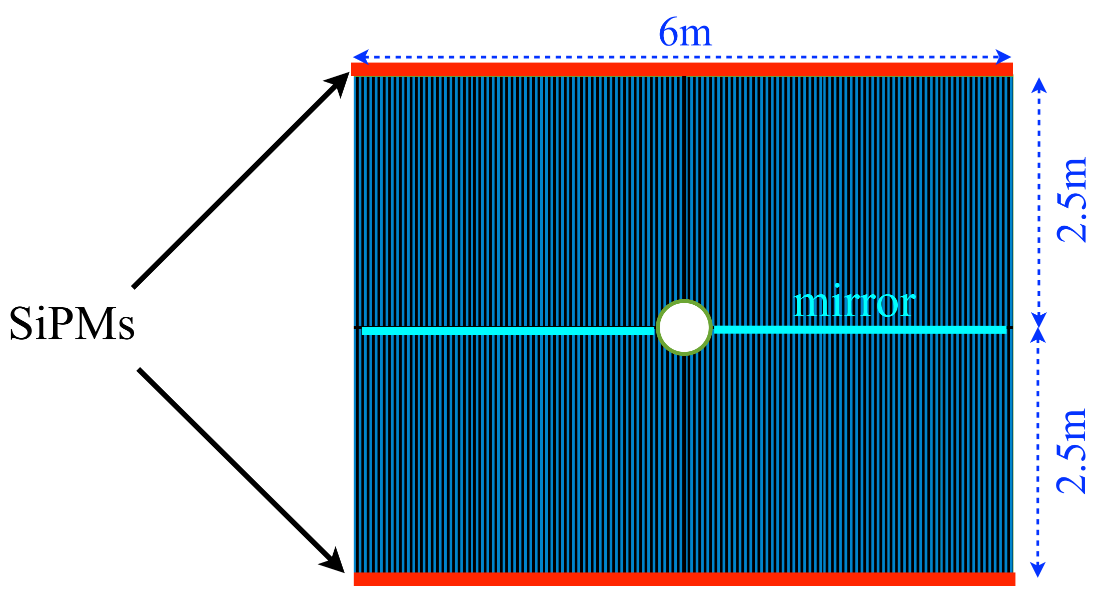
  $\Rightarrow$ 7200km

- readout at top and bottom of the detector stations

  $\Rightarrow$ 144m instrumented with 250μm channels

  $\Rightarrow$ 576k channels

  $\Rightarrow$ 4500 SiPMs

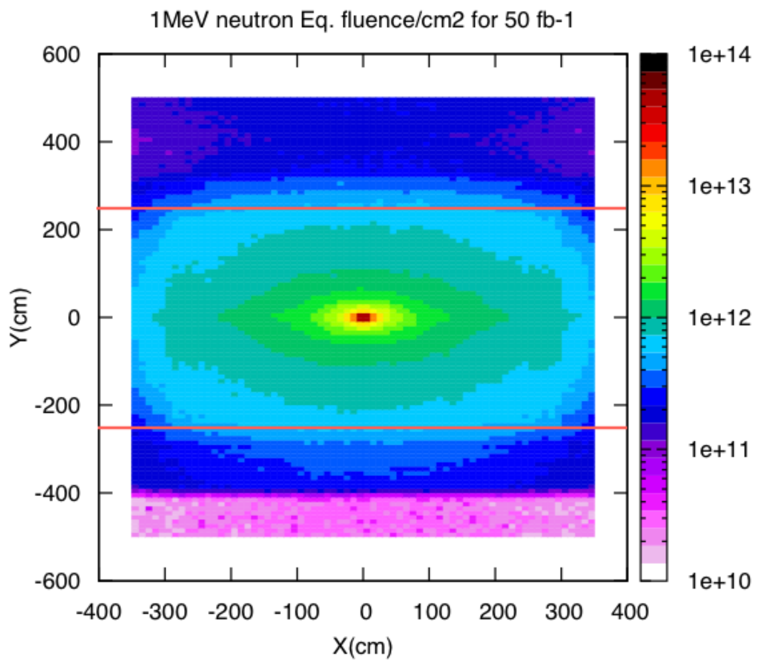


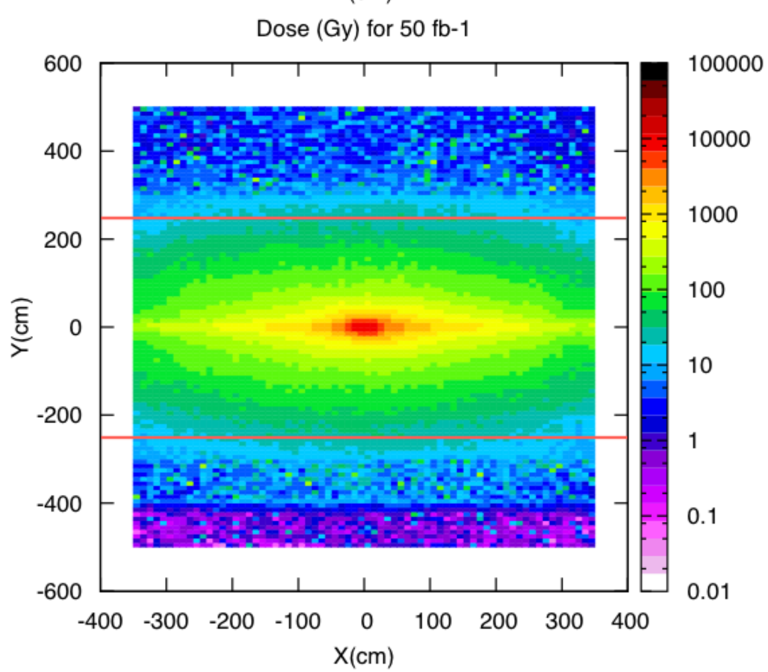
SciFi technology challenges

- Development needed for the LHCb SciFi tracker
  - fibers and SiPM radiation hardness studies
  - fiber module construction
    - how to produce 2.5m long fiber mats
    - how to obtain the necessary mechanical precision and rigidity
  - cooling for the SiPMs down to −50ºC
    - what cooling system
    - how to control the mechanical stress
  - readout at 40MHz

SciFi R&D

LHCb upgrade: radiation environment





FLUKA simulations

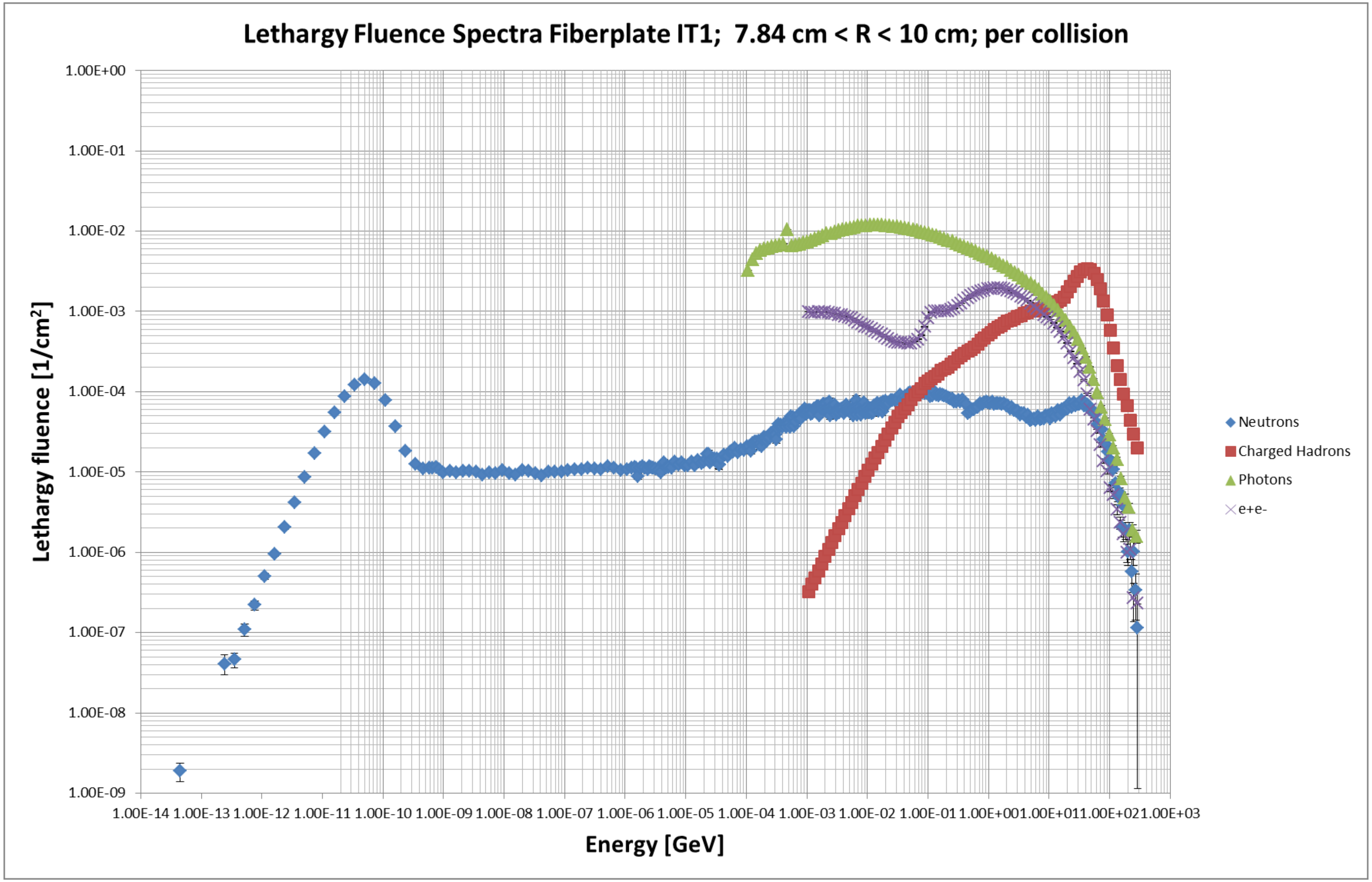
SiPM rad. environment

- **1MeV neutron-equivalent fluence**: At a position of ±250cm, the n_{eq} fluence is $6x10^{11}$ per cm^2
- **Neutron fluence** could be reduced by a factor more than two for 1MeV neutrons using a shielding 10cm-thick

Fibers rad. environment

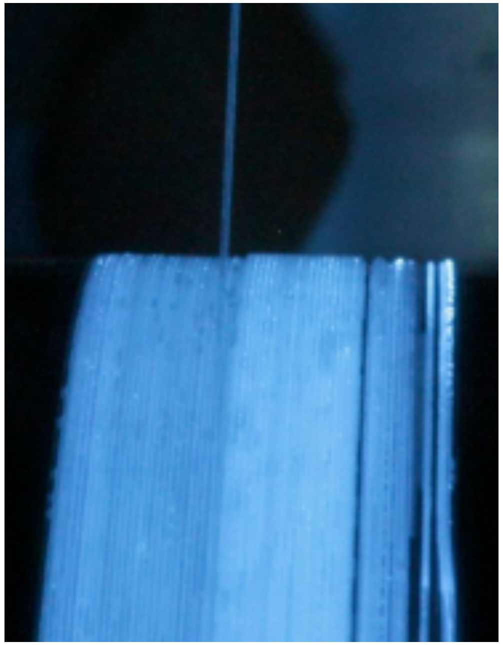
- **Ionizing DOSE**: At a position of 9cm aprox. from the beam axis, the peak dose is about **26kGy** and average dose over the second and first rings gives **23kGy** (10% stat. error)

Spectra close to the beam pipe at Fiberplate in front of IT1



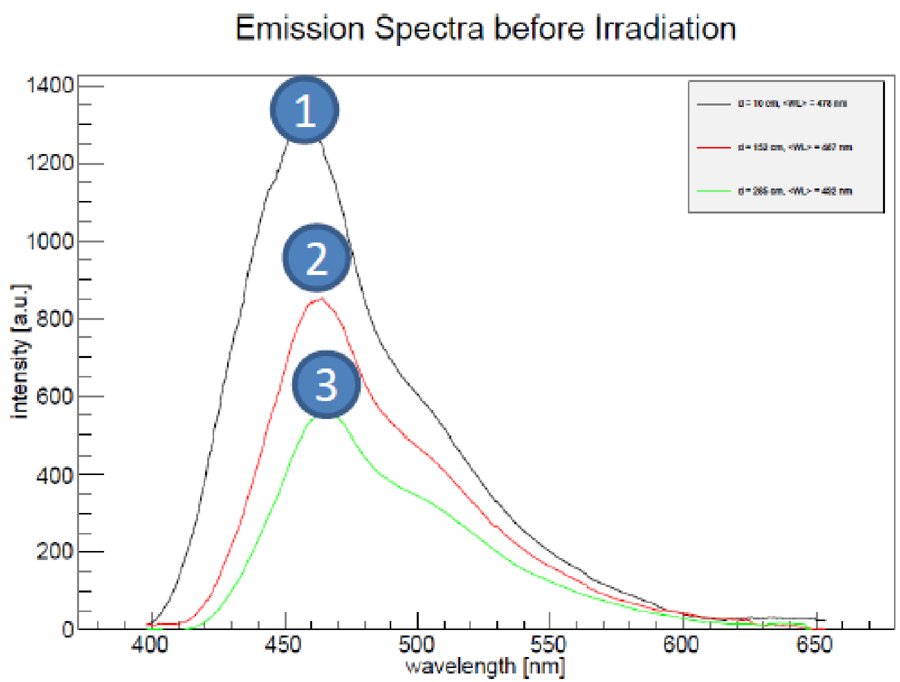
Careful: Lethargy means multiplying fluence with Energy bin values in order to get more detail out of high energy regions in a logarithmic binning. Integration below the curve is no longer possible!

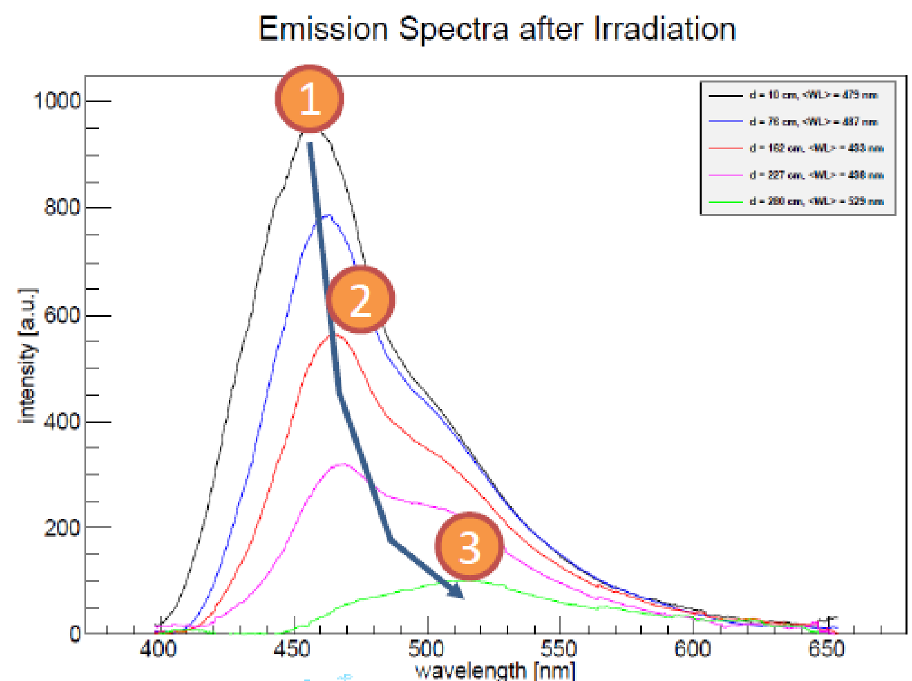
Scintillating Fibers



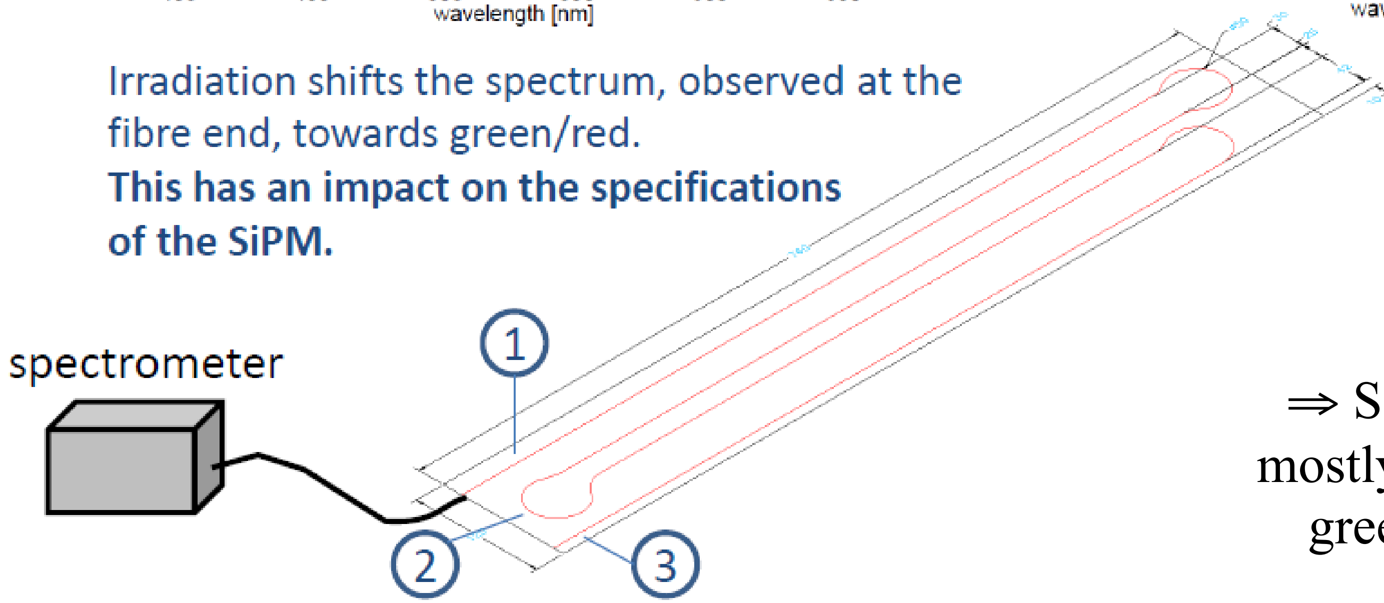
- Baseline fiber: Kuraray SCSF-78MJ
- The fibers have two roles:
  1. act as scintillator
     - 2.8ns scintillation decay time
     - light yield: ~1600 photons/mm/MIP×5.35% capture $\Rightarrow$ 10's of photons
     - scintillating dye is expected to be radiation hard
  2. transport the light to the SiPM
     - 5.3ns/m propagation time
     - attenuation length is an issue (radiation hardness)
- Alternative fiber: 3HF
  - expected to be more radiation hard
  - ...but slower decay time and lower light yield

Fiber emission spectrum after irradiation





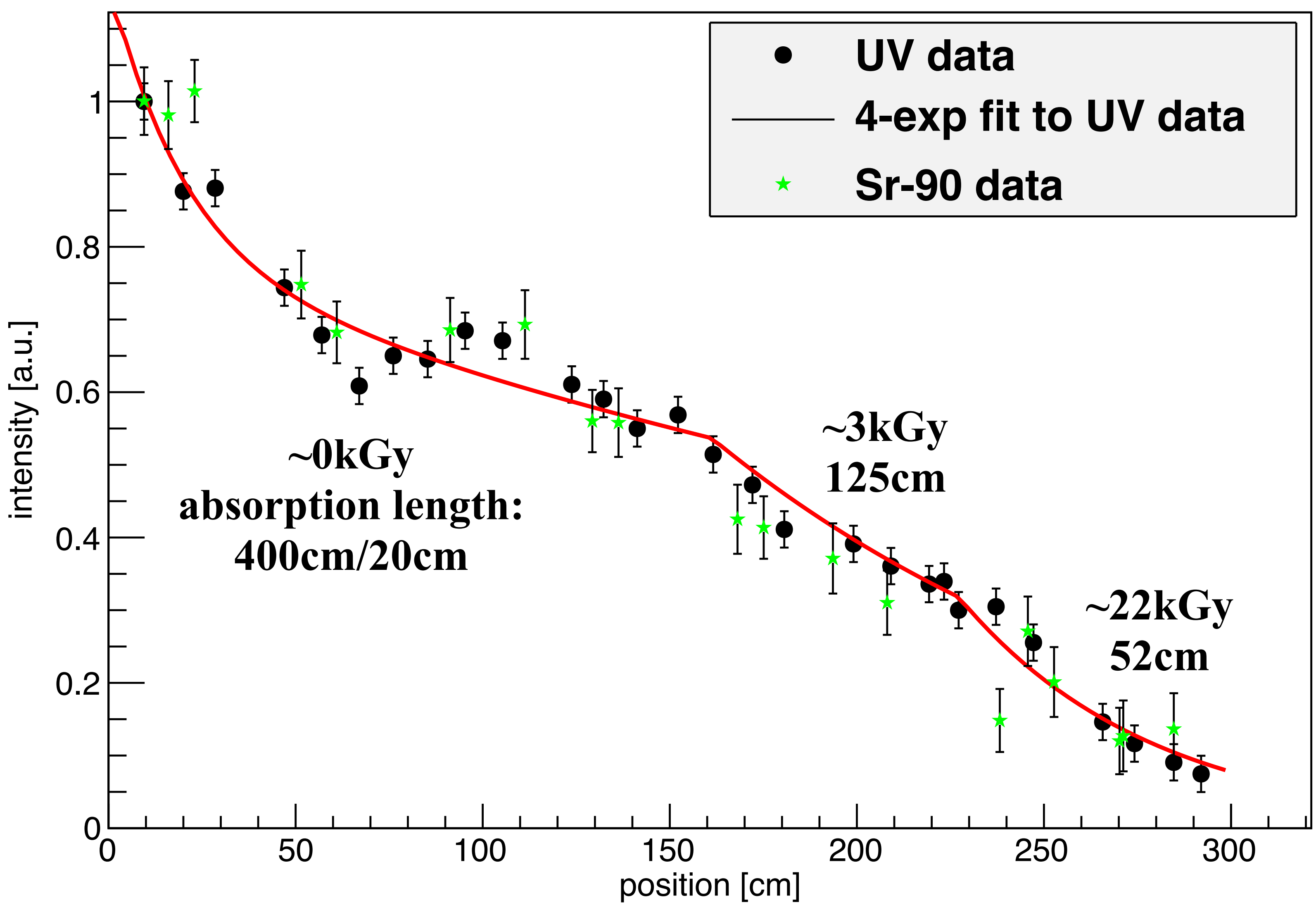
Irradiation shifts the spectrum, observed at the fibre end, towards green/red.
This has an impact on the specifications of the SiPM.



⇒ SiPM preferably mostly sensitive in the green wavelength

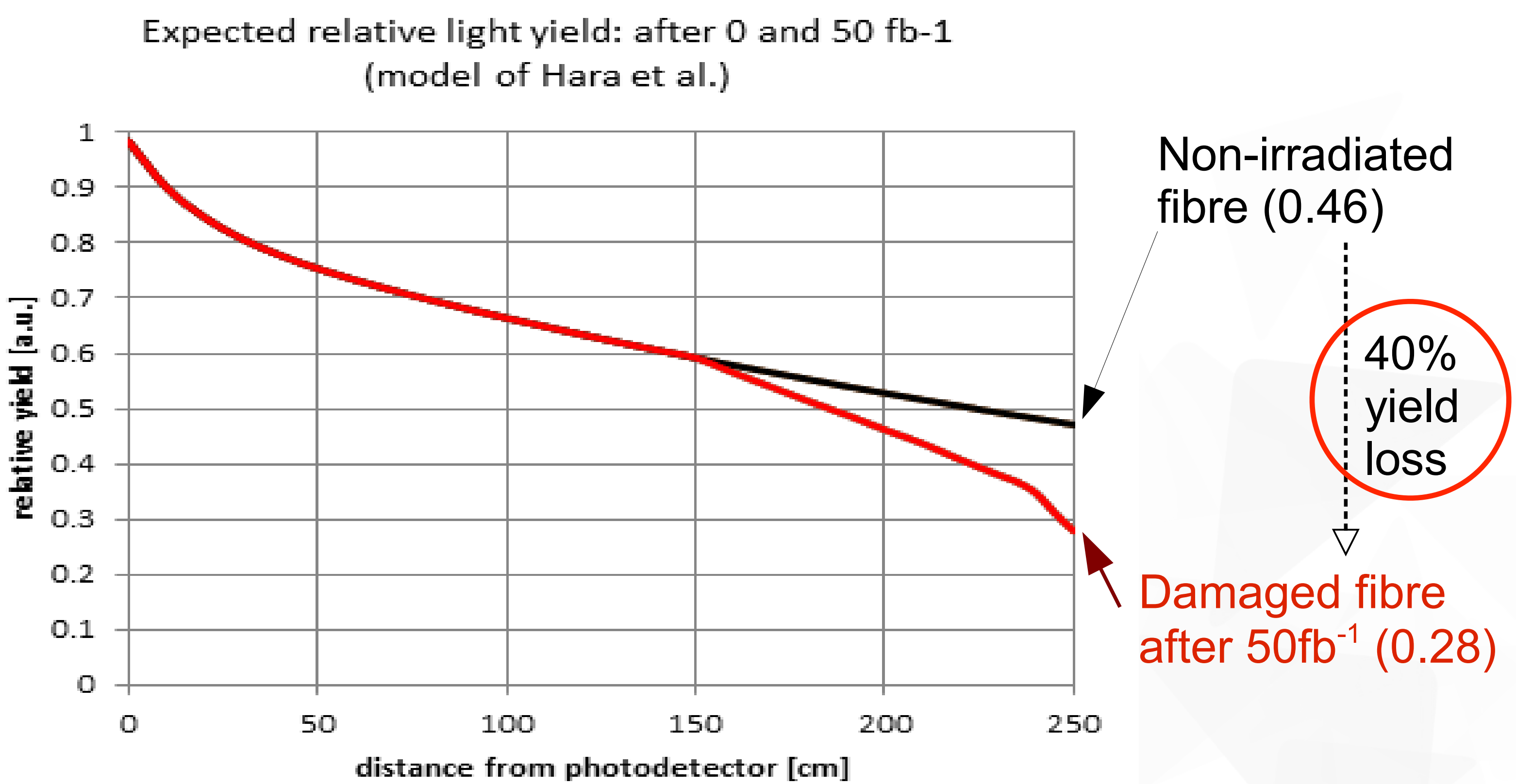
Attenuation length of irradiated fibers

- Irradiated fibers at the CERN PS with 24GeV/c protons

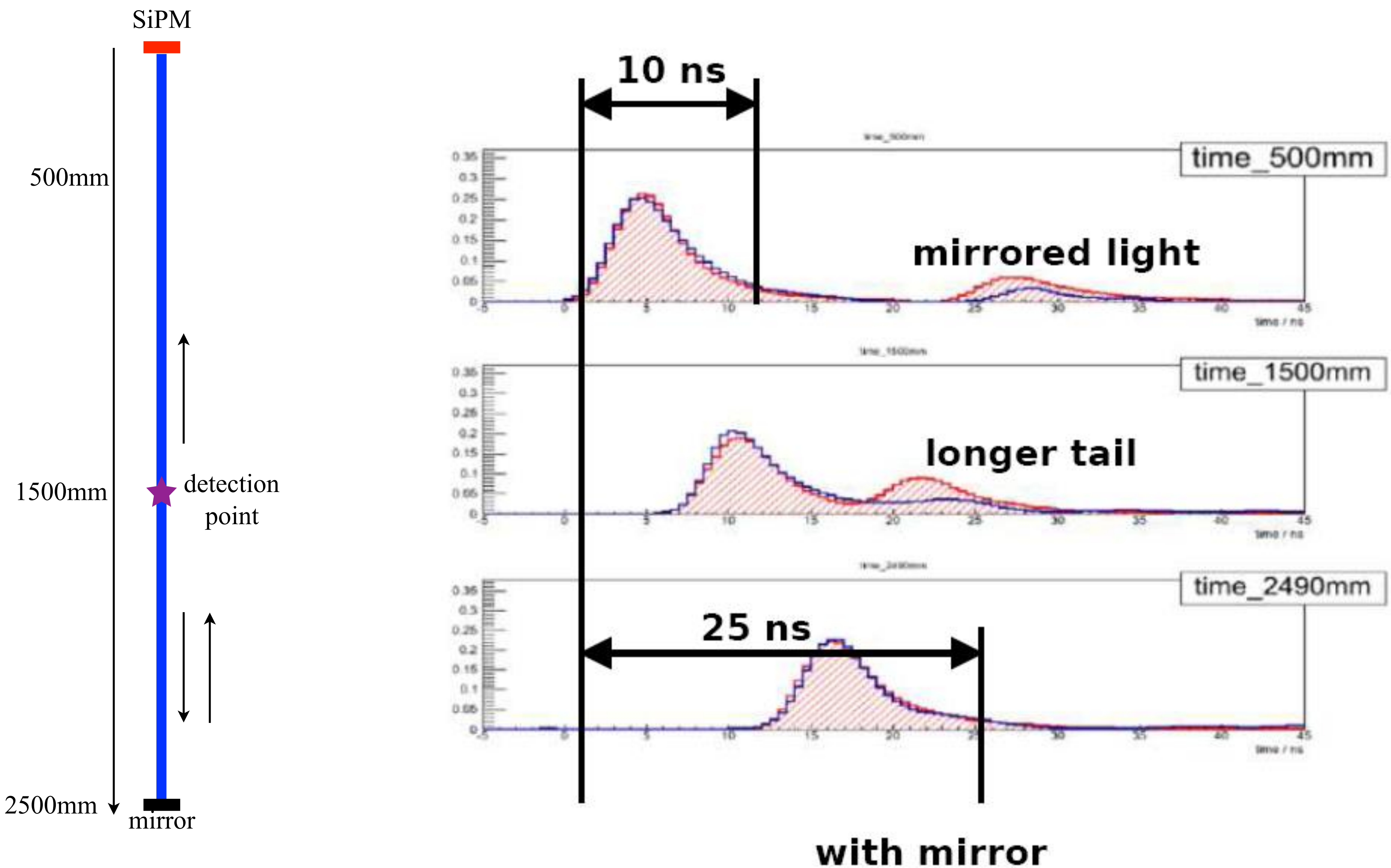


Scintillating fiber radiation hardness

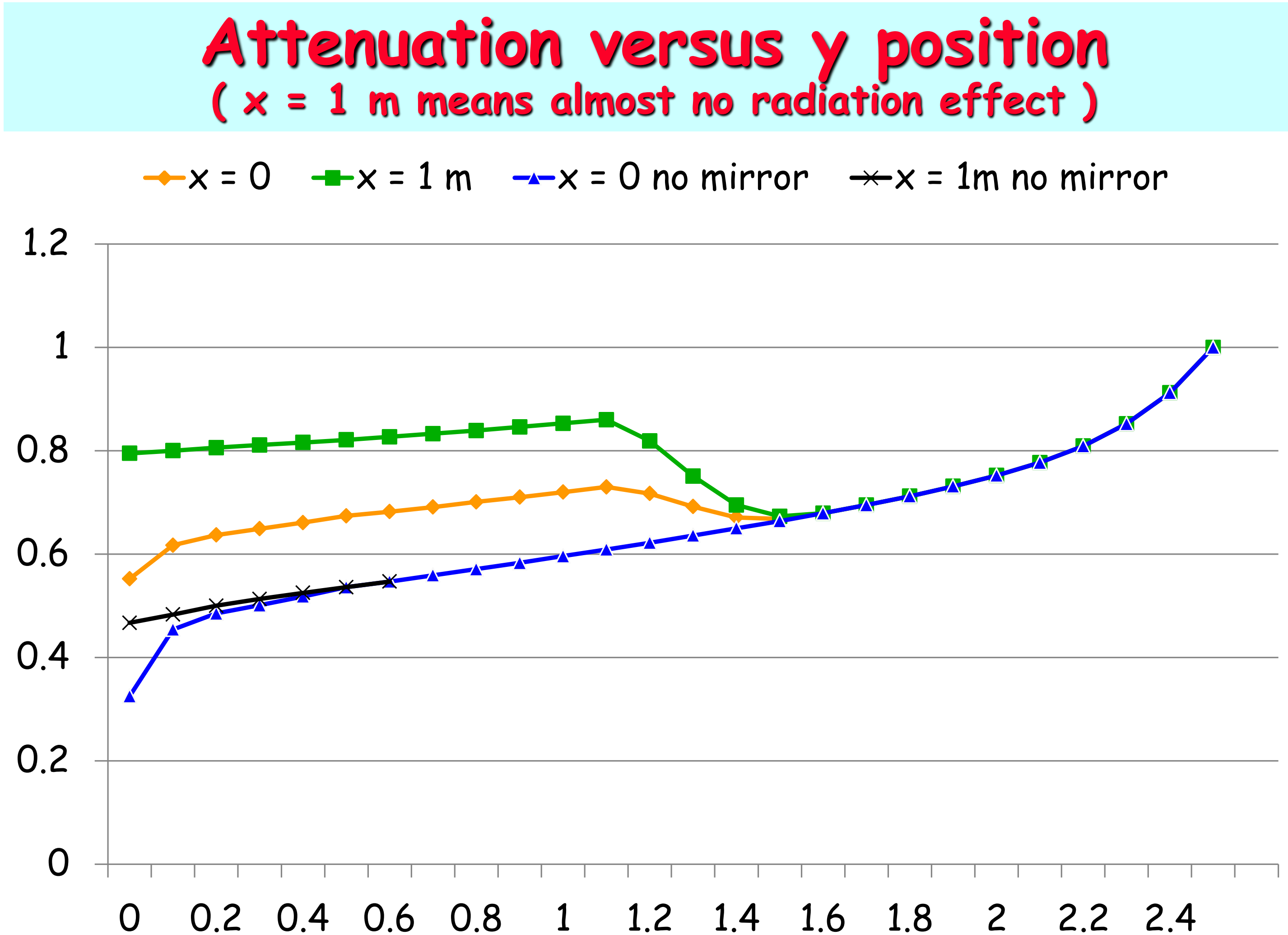
- Damage due to radiations found to increase logarithmically with the dose
- Projected relative light yield loss:
  (without mirror & without timing cut)



Light detection time



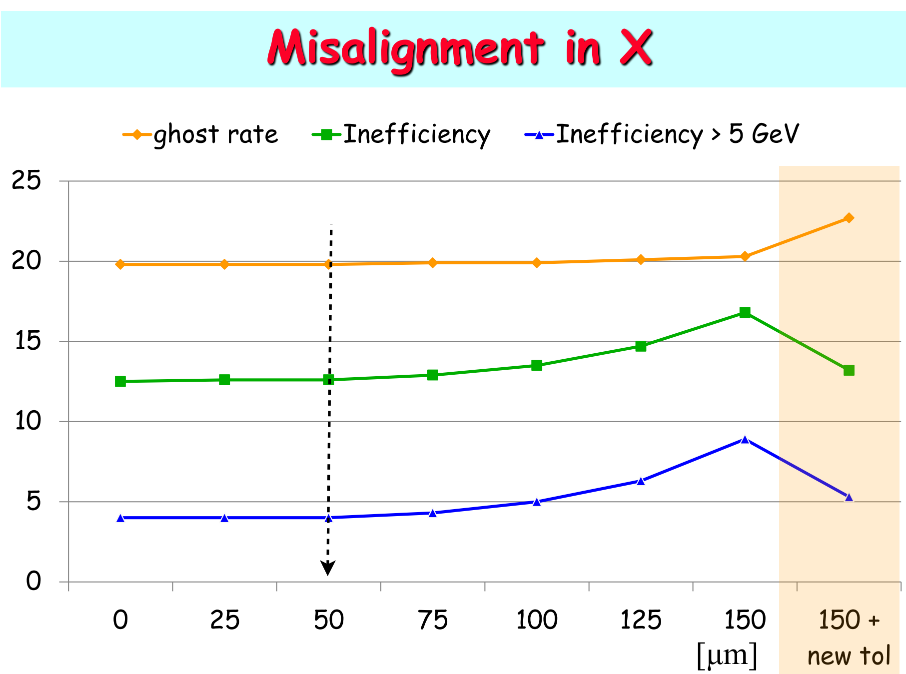
Light yield loss: with mirror and timing cut

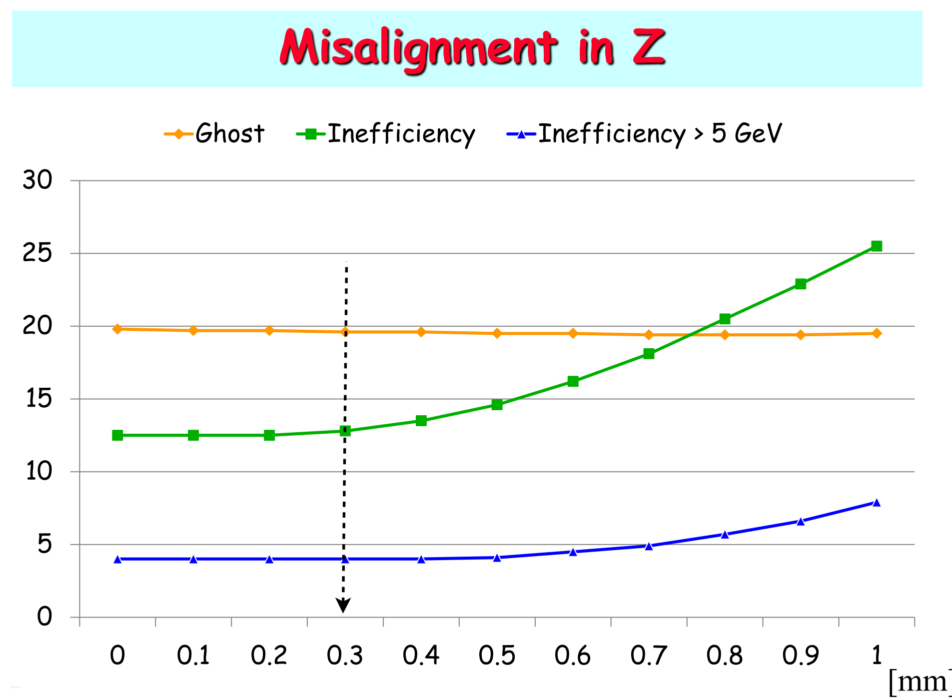


- Effect of mirror and timing cut is to reduce light yield spread for all hits along the 2.5m long fiber

Detector performance from simulation

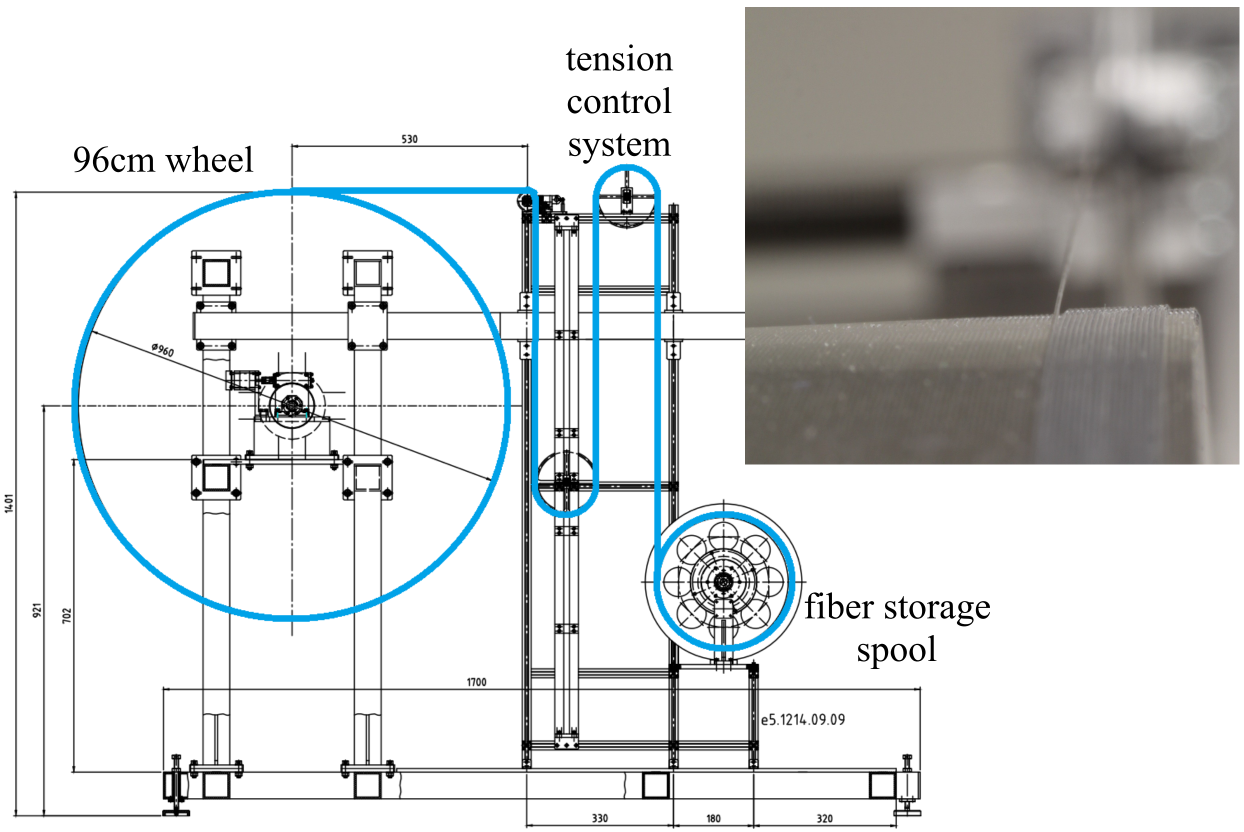
- Tracking on simulated data has been used to evaluate the performance of the SciFi tracker:
  - similar performance to current LHCb, even with ×5 luminosity!
  - faster thanks to single technology
- Estimated level of acceptable noise clusters: ~2MHz / SiPM
- Fibers must be straight over their full length



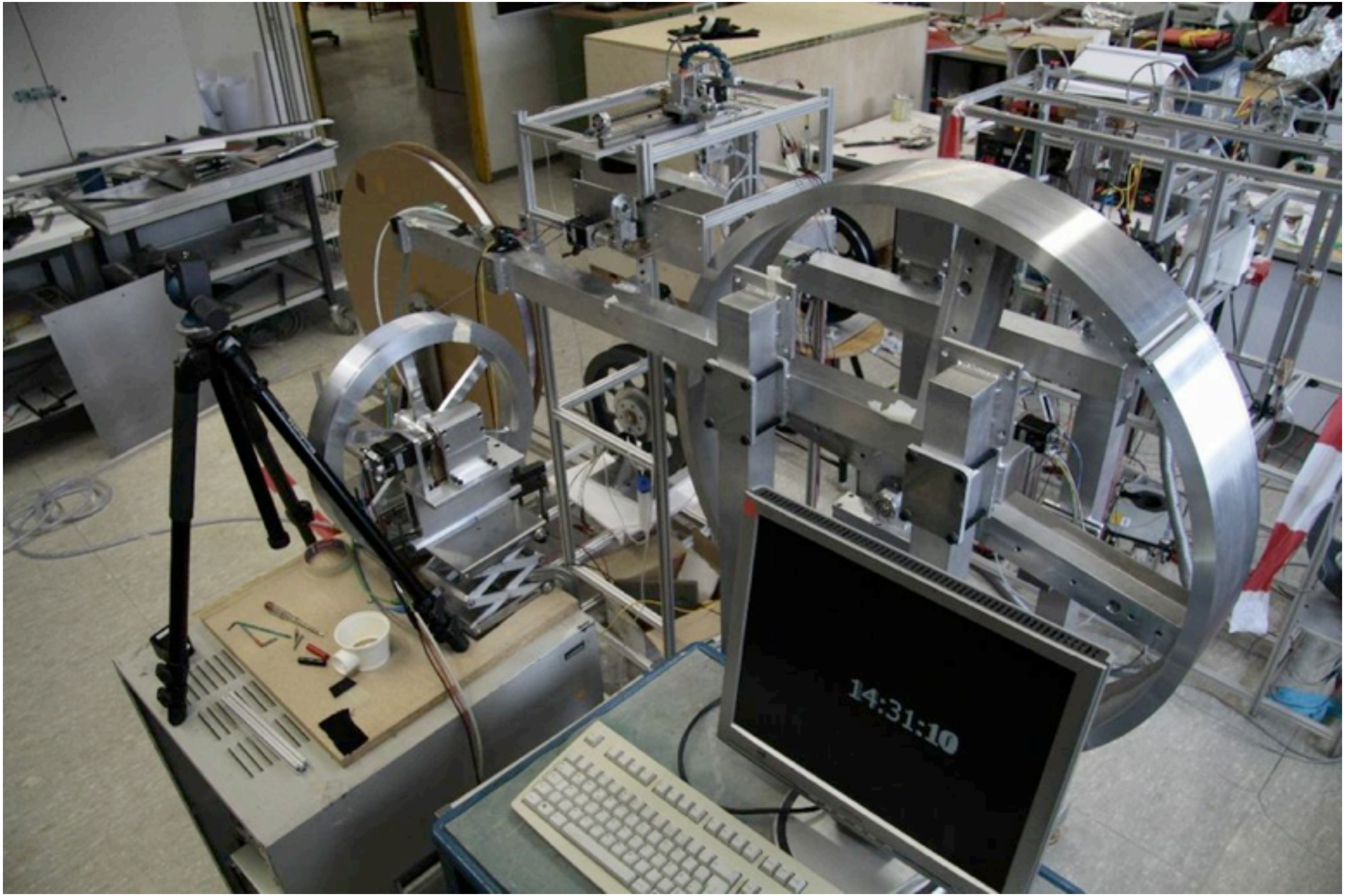


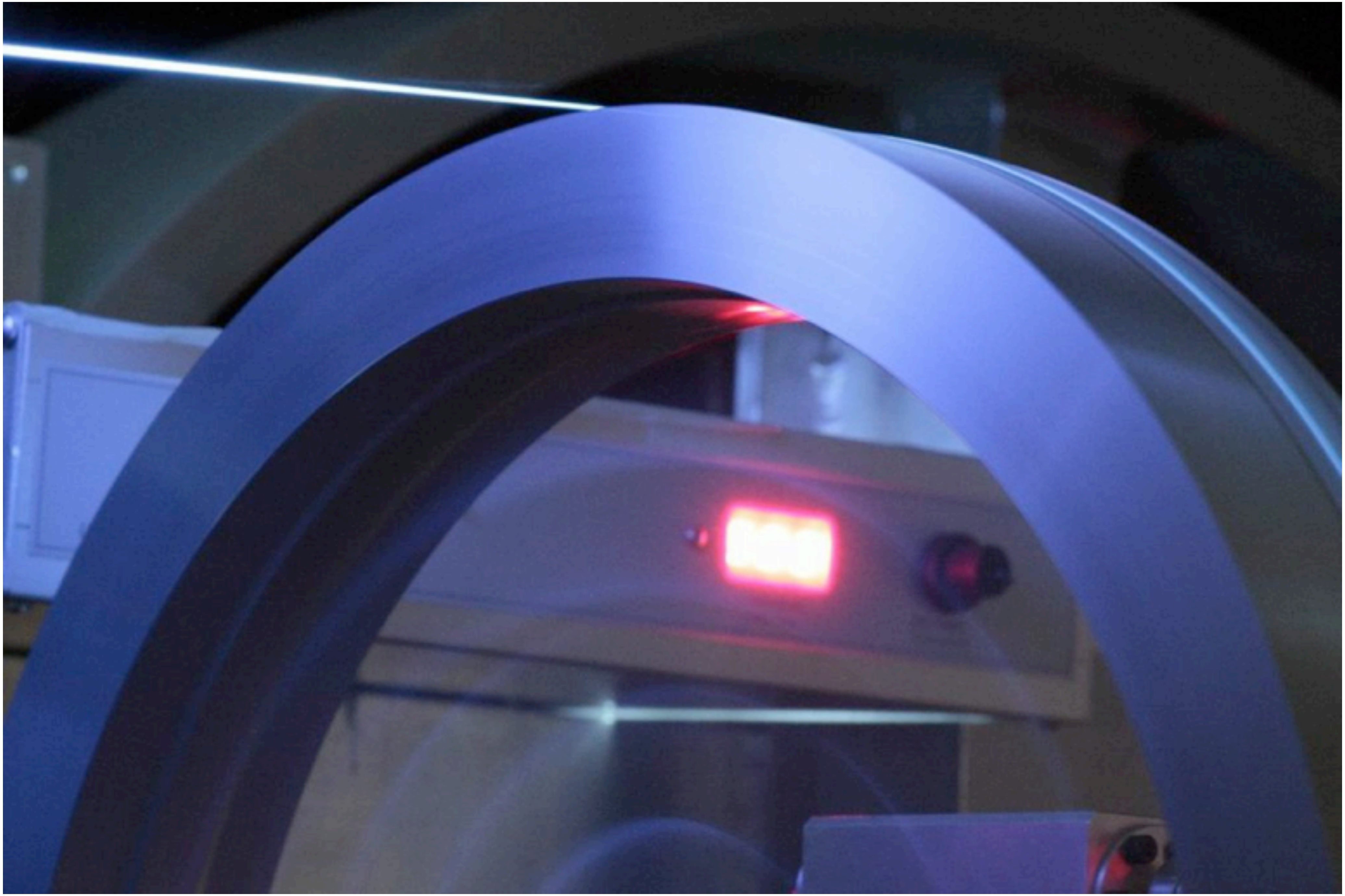
Fiber mat production

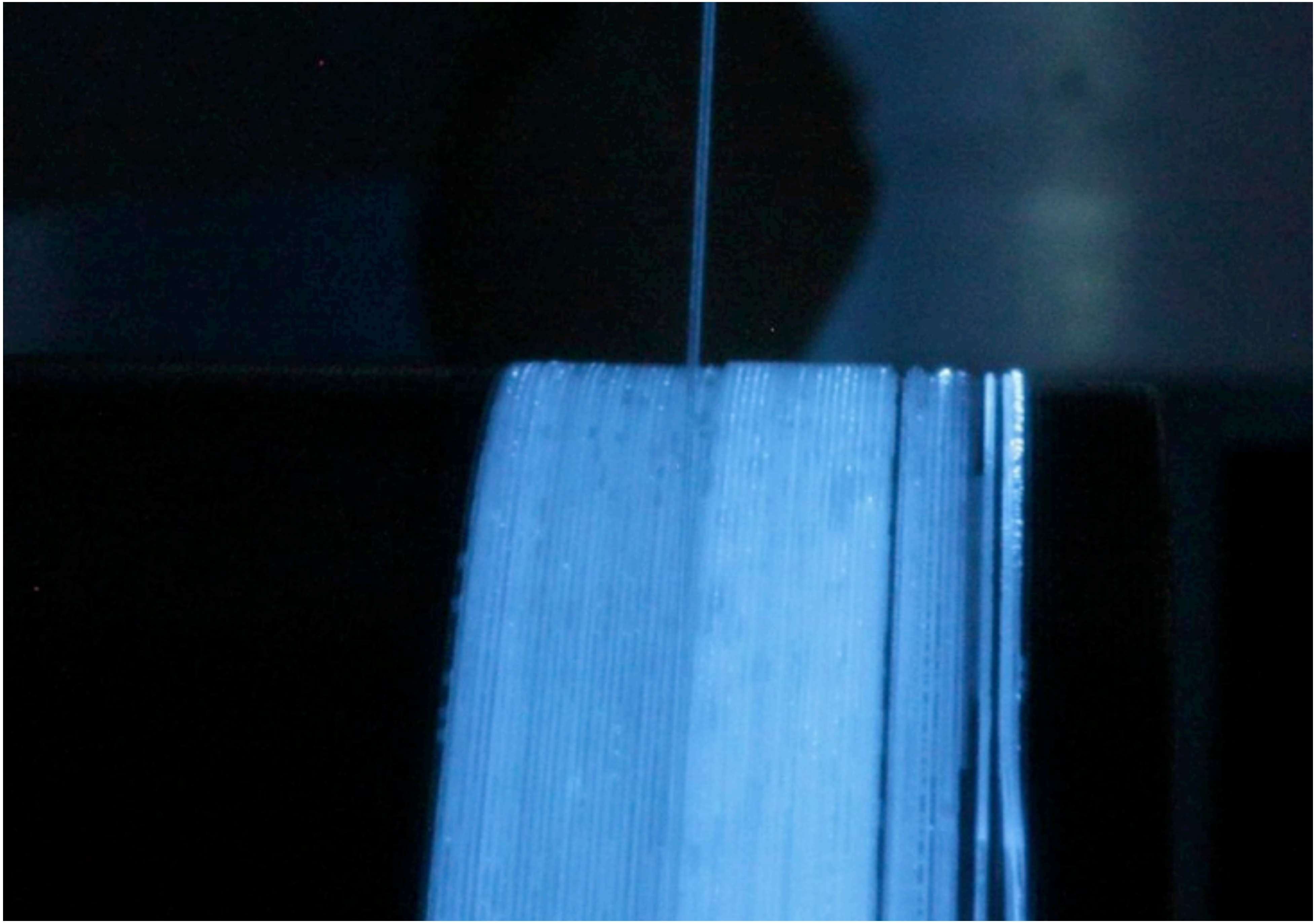
- Lay down fibers on a 96cm diameter cylinder
  - grooves give fibers 280μm pitch
  - each layer is glued to the previous layer (total = 5 layers)
- Fiber mat is cut and taken off the wheel before the glue is dry



Fiber quality is tested (diameter, cracks) before use

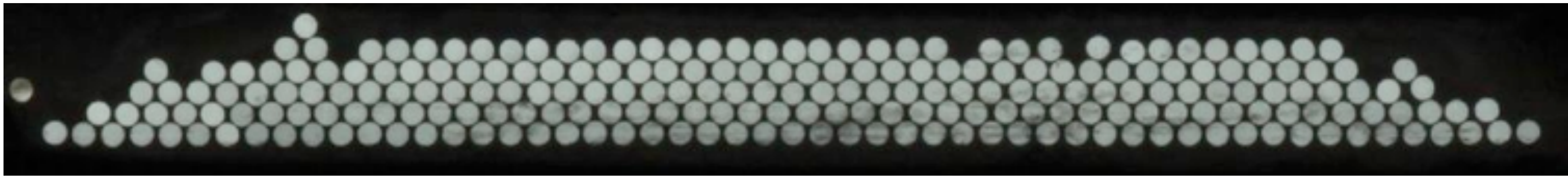

14:31:10





Fiber mats

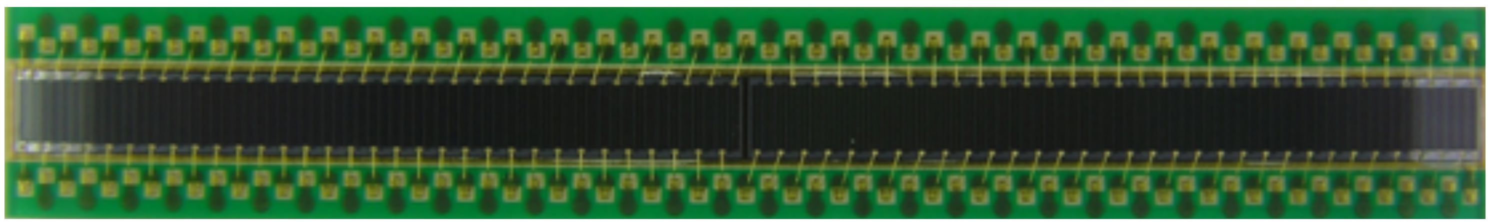
- Fiber mat prototype

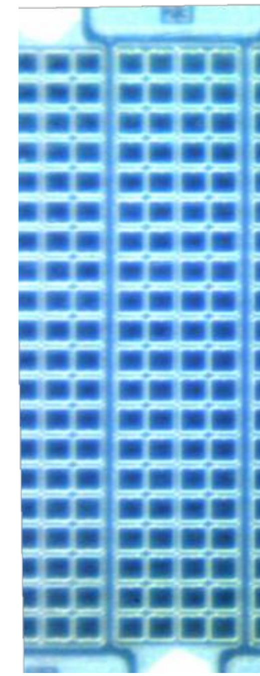


- Next steps:
  - improve fiber mat quality
  - R&D for cutting 2.5m long mats (sides and ends)
  - casting into a precise shape

Silicon Photo-Multipliers (SiPM)

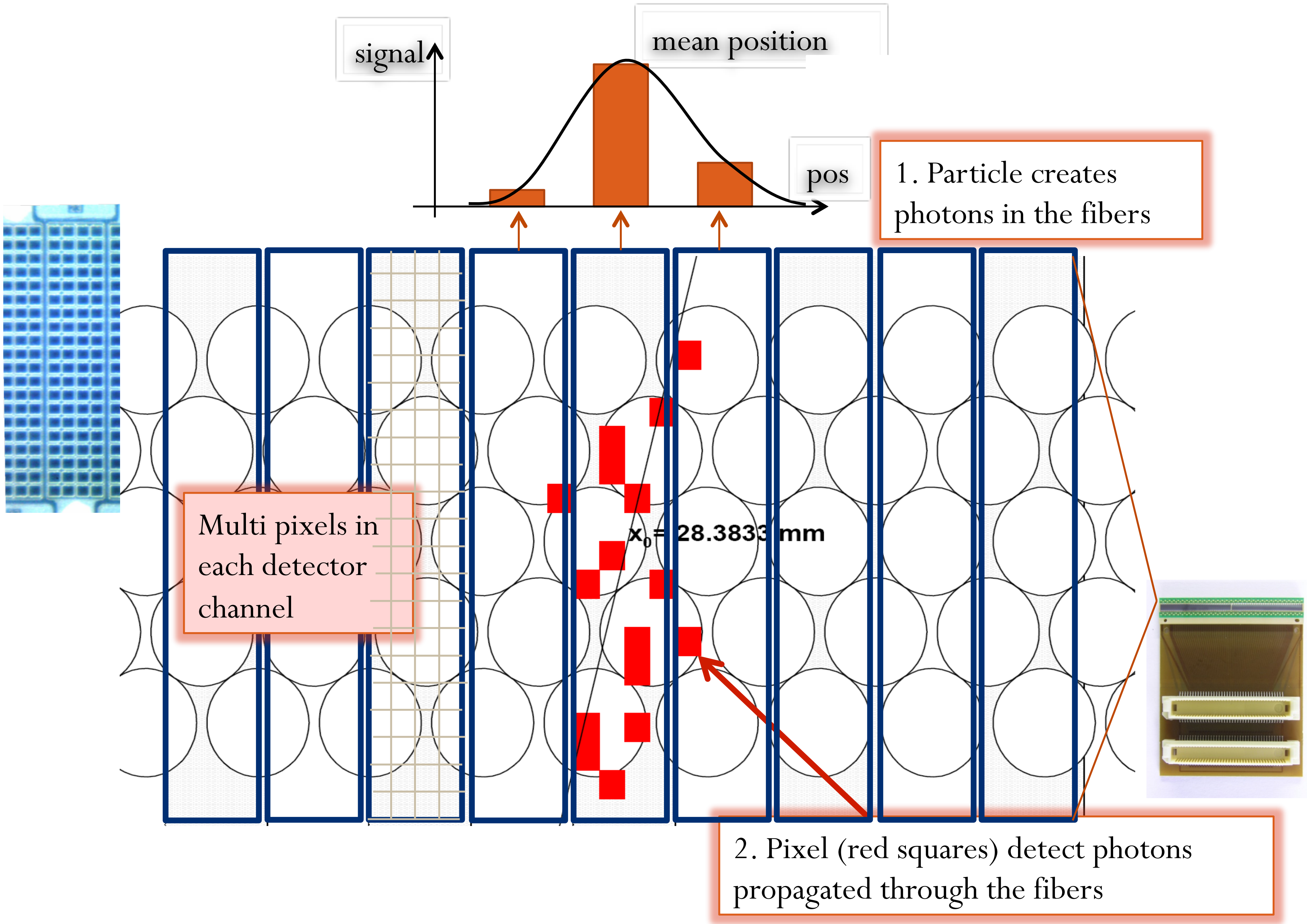
- 0.25×1.3 mm^2 channels of 4×20 pixels
- pixel size = 55µm
- 128 (2×64) channels grouped in a an 32mm array





- Two manufacturers: Hamamatsu and Ketek
- Development in progress

Signal cluster detection with SiPM



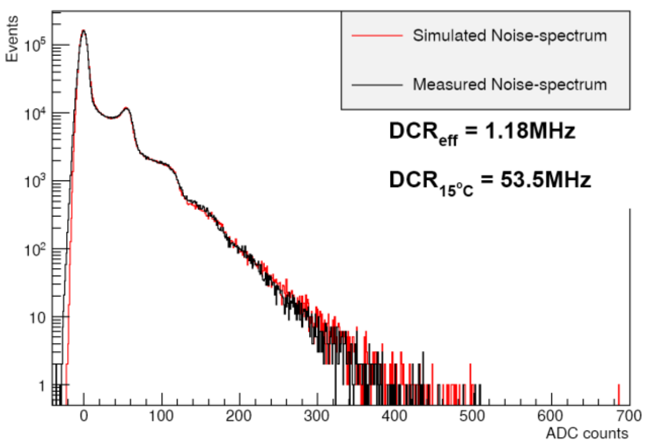
SiPM noise studies

- The thermal noise is the primary source of noise
- The noise cluster rate depends on
  - the primary noise frequency f_p (thermal noise)
  - temperature T (f_p is reduced by a factor 2 every 10ºC)
  - neutron dose: f_p increases linearly with the dose
  - pixel-to-pixel cross talk probability $P_{x\text{-}talk}$
  - after pulse probability P_{after}
  - integration and shaping time Δt
  - clustering algorithm A, which depends on selection thresholds
- A simulation was developed on this model

$$f_C = f\left(f_P(\Delta V, T, Dose), A(th_{seed}, th_{neigh.}, th_{sum}), p_{x-talk}(\Delta V), p_{after}(\Delta V), \int^{\Delta t} \right)$$

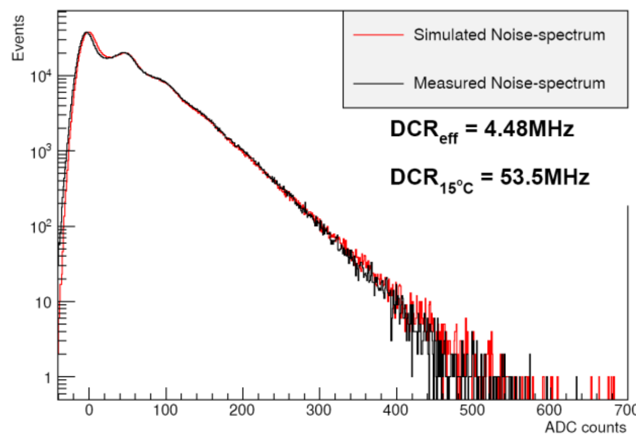
Simulation of the dark noise spectrum

- Irradiation $8fb^{-1}$
- T=-40°C
- Slow shaping



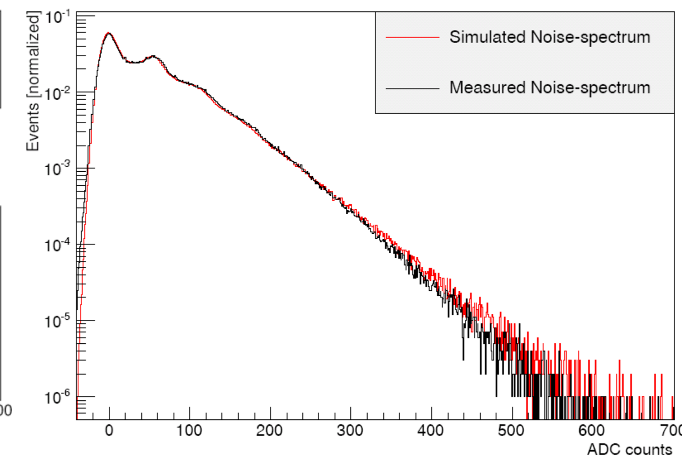
Very good agreement for the dark noise spectrum. Dark count rate can be compared with measured dark.

- Irradiation $8fb^{-1}$
- T=-20°C
- Slow shaping



Change only the primary noise (higher T) . Very good prediction of the dark noise spectrum.

- Irradiation $50fb^{-1}$
- T=-44°C
- Slow shaping



Too slow readout, pile-up of random events create large noise.

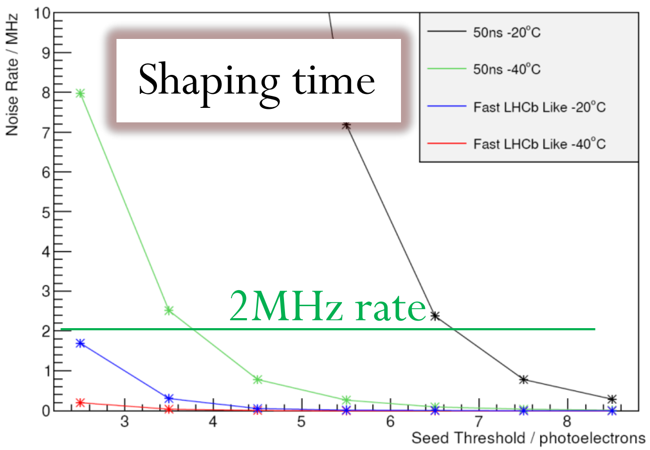
Good predictive power ⇒ can be used to extrapolate to LHCb upgrade conditions

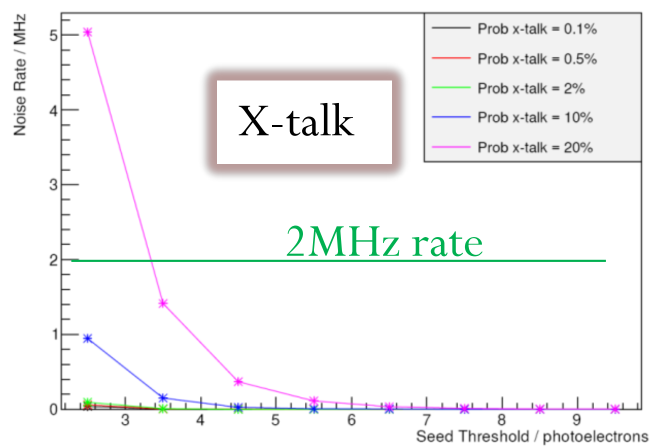
Simulation of the cluster noise rate

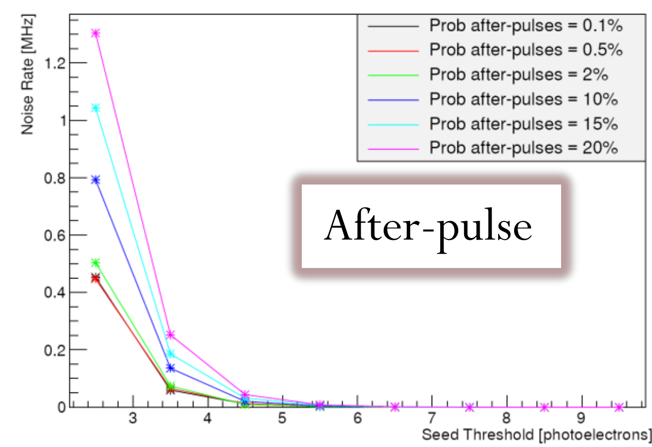
- Irradiation $8fb^{-1}$
- T=-20°C , -40°C
- Slow and fast shaping

- Irradiation $25fb^{-1}$
- T=-40°C
- Fast shaping

- Irradiation $25fb^{-1}$
- T=-40°C
- Fast shaping







Shorten the shaping time by a factor 8!
Cluster noise is dominated by random pile-up of noise pulses.

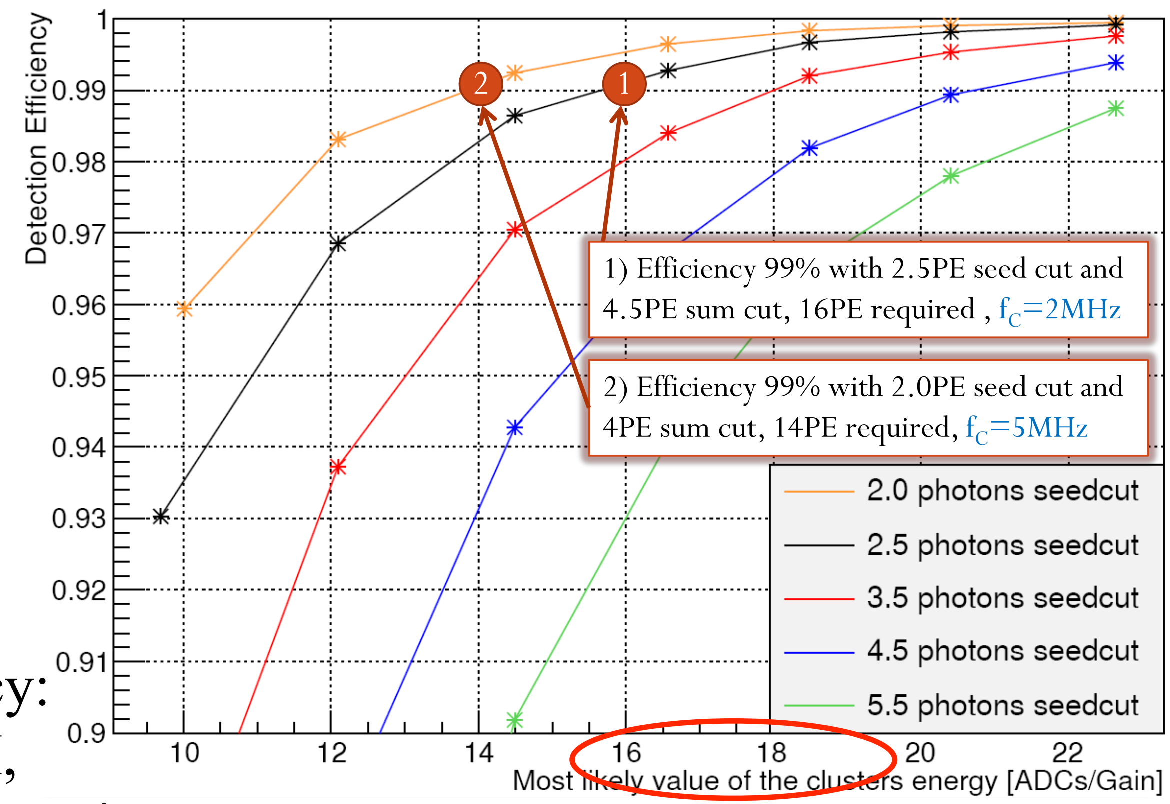
Keep x-talk probability below 2% to allow for a low noise cluster rate.

Keep after-pulse probability below 2% to allow for a low noise cluster rate.

SiPM radiation hardness

- Maximize the hit detection efficiency, while keeping the cluster noise at an acceptable level (< ~2MHz / 128-channels)
- Noise controlled by:
  - shielding, cooling, pixel-pixel cross-talk, integration time

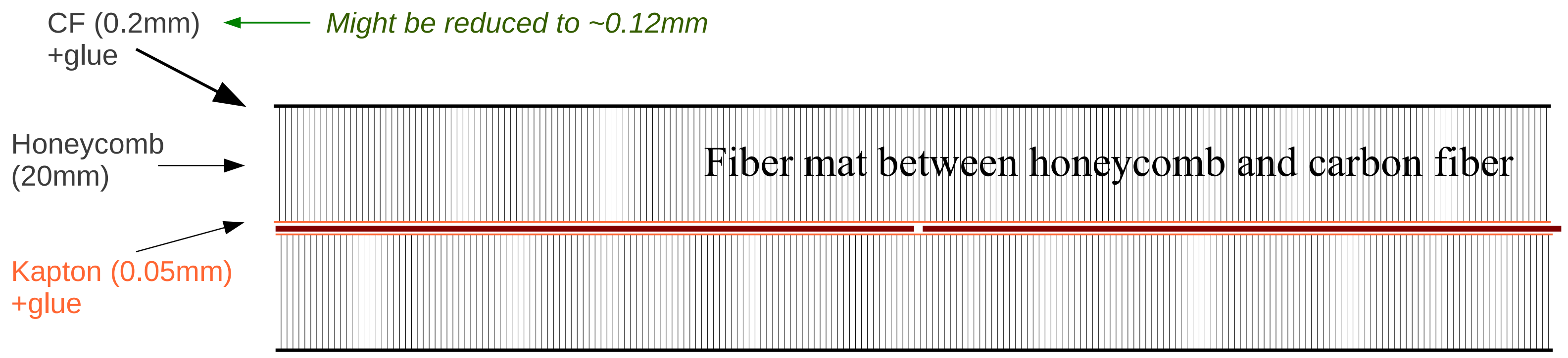
Simulation of the hit detection efficiency



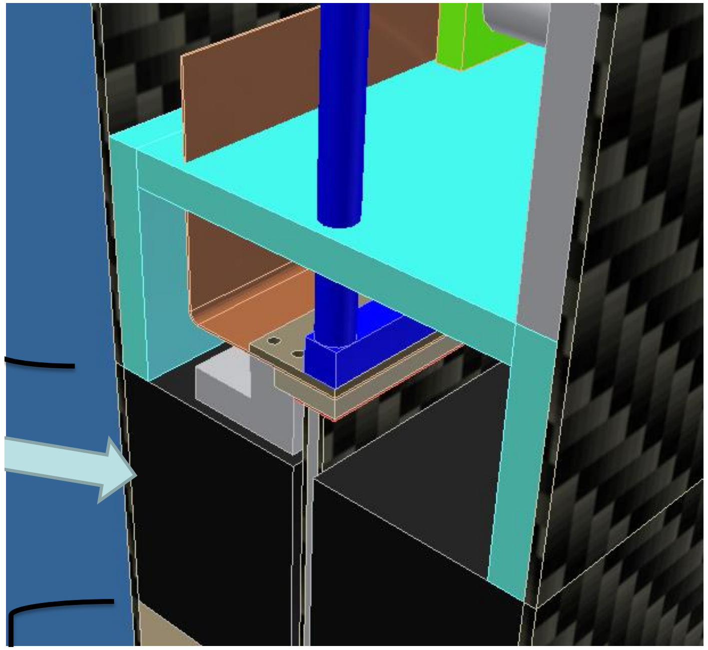
- Results:
  - noise can be kept below 2MHz
  - photon detection efficiency: OK for the KETEK SiPM, and too low for Hamamatsu SiPM
- On-going R&D is expected to improve significantly the performance of the Hamamatsu detector

Detector modules

- Plan to build 16 SiPM wide modules (~52cm)
- Single or double fiber layers



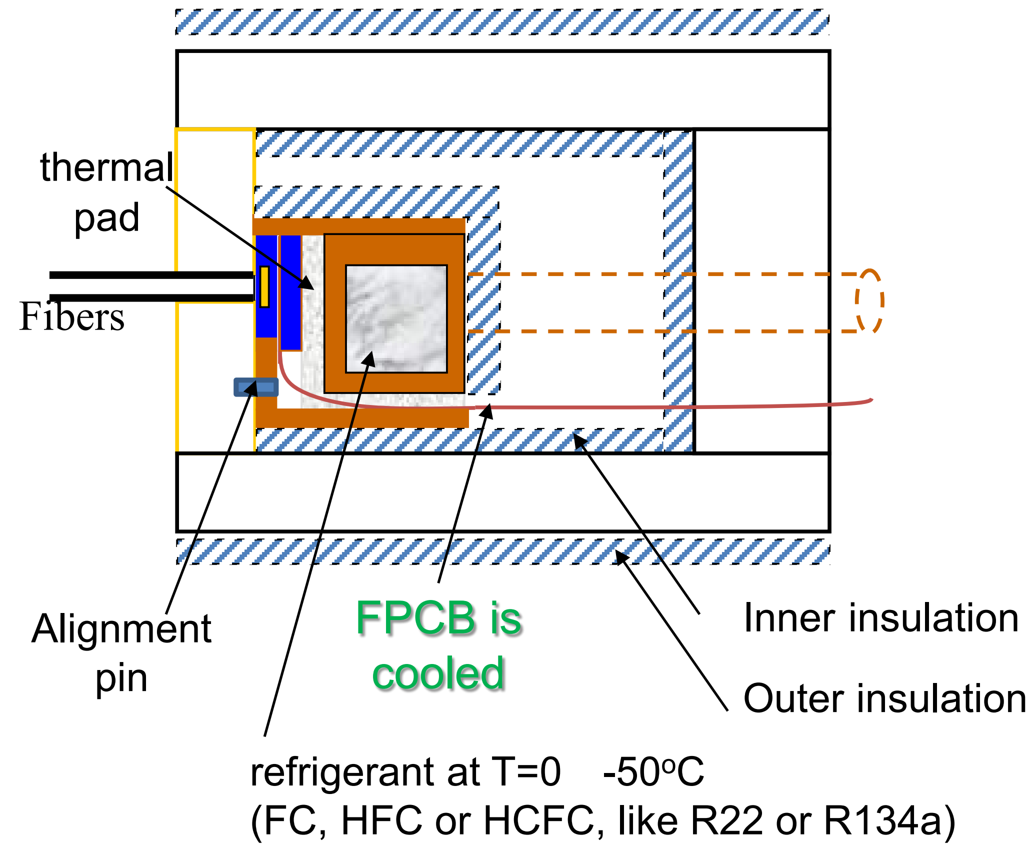
- Development of a service box to hold
  - the SiPMs
  - the cooling system for the SiPMs
  - the readout electronics
  - the mechanical support



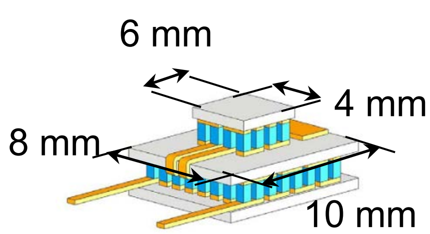
SiPM cooling (−50ºC)

- Considering several cooling systems for SiPMs

  1. **liquid (single- or 2-phase)**



  2. **thermoelectric cooling**



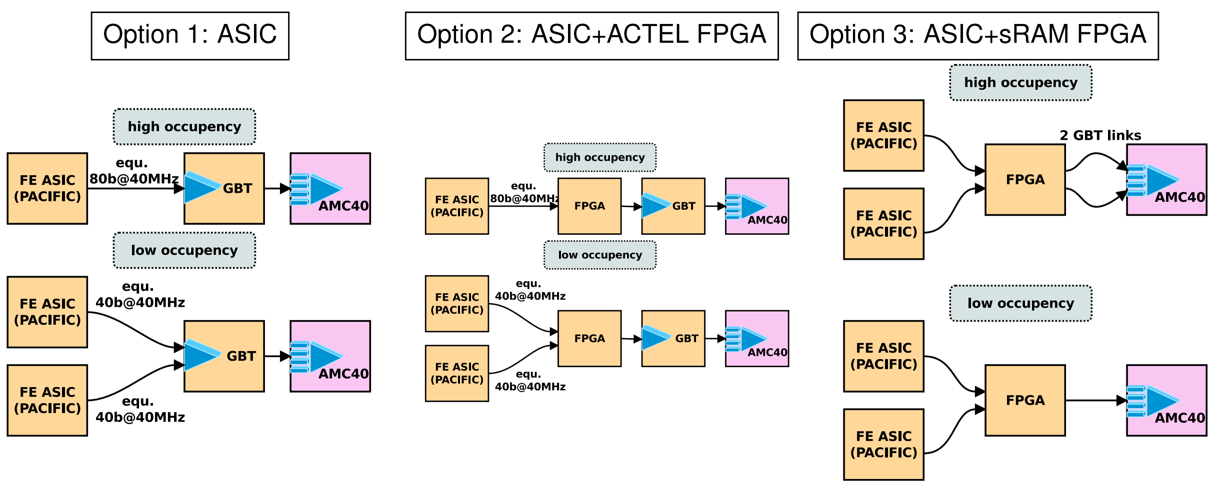
  3. **chilled air cooling**

  4. **cooling through the PCB**

- Thermal analysis of the various options in progress

Front-end electronics

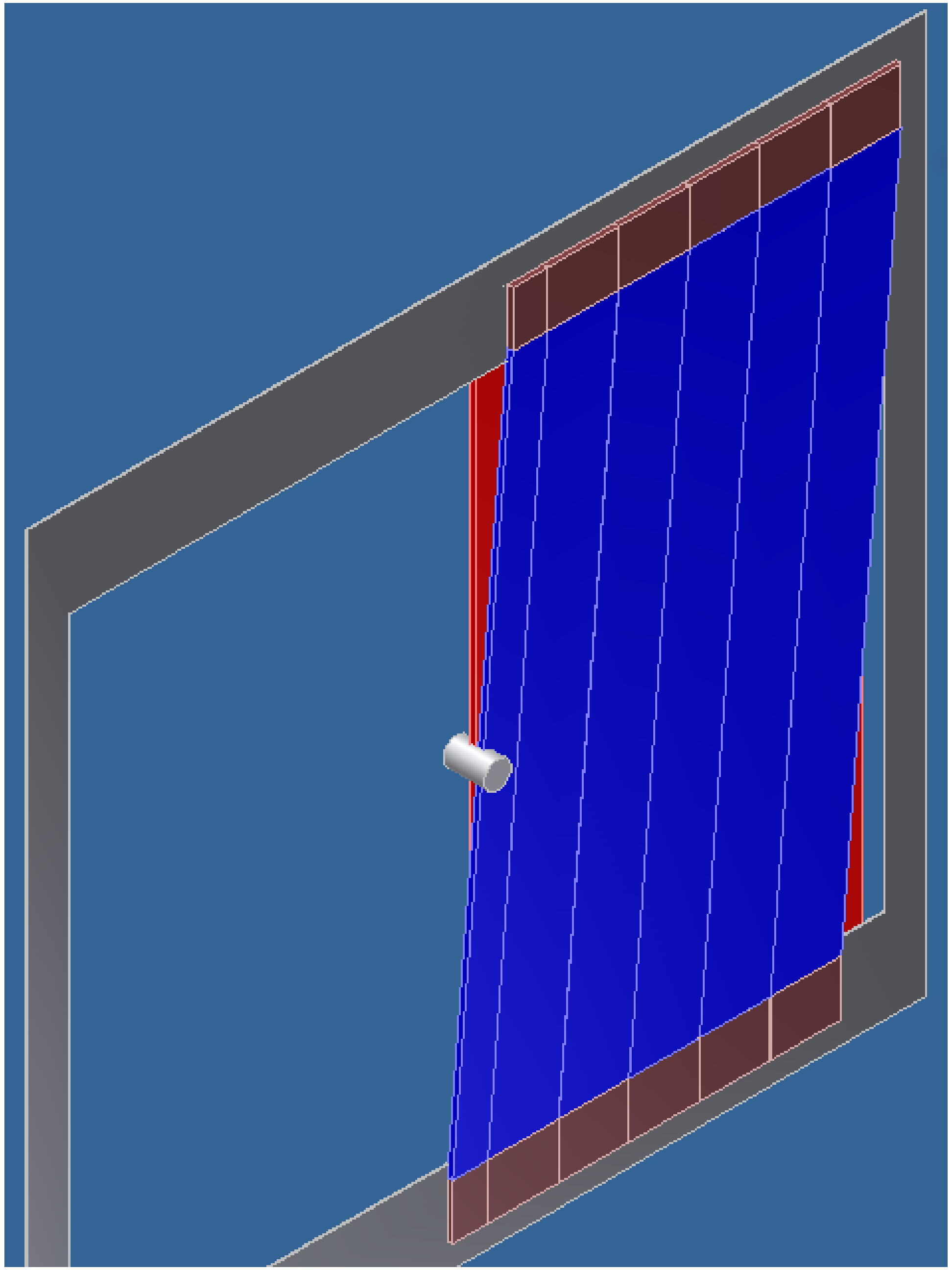
- 40MHz readout electronics
  - development in Clermont-Ferrand and Barcelona to meet the SciFi detector requirements
  - considering various options

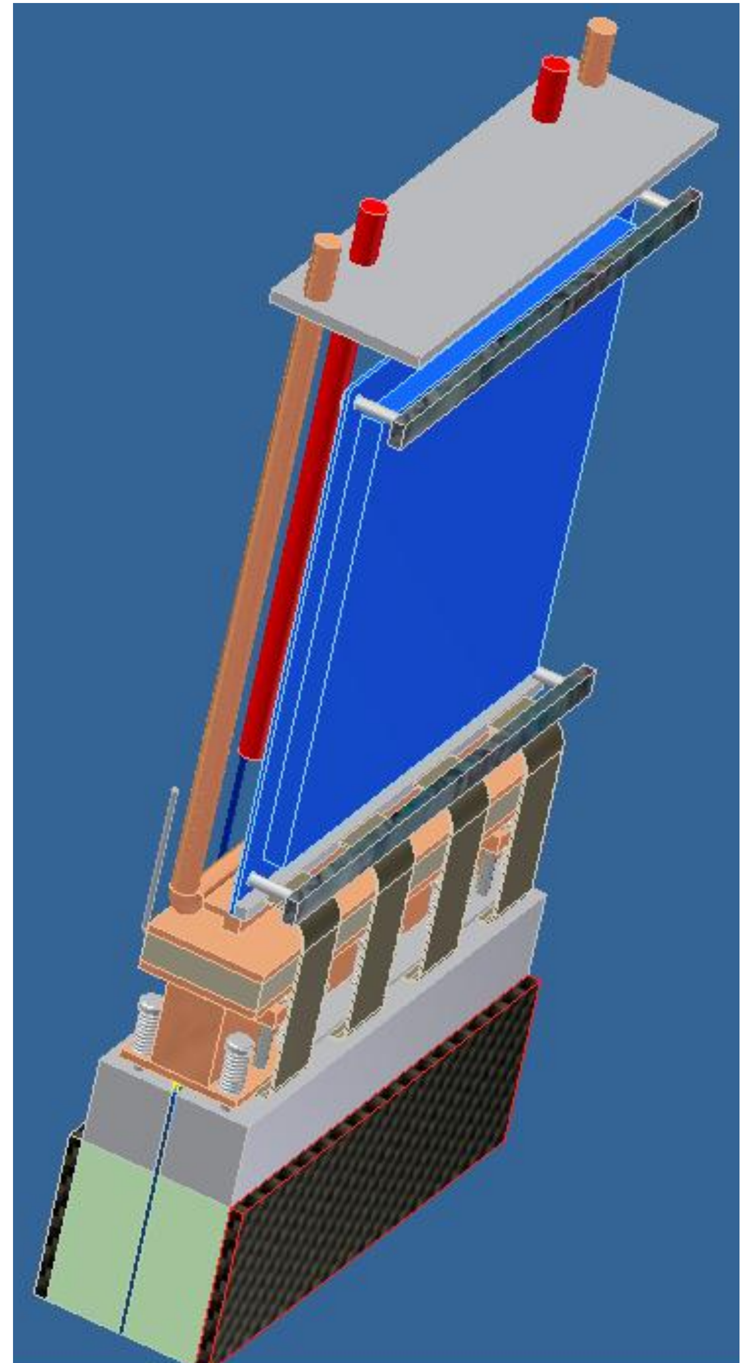


- Choice between the options in September 2013

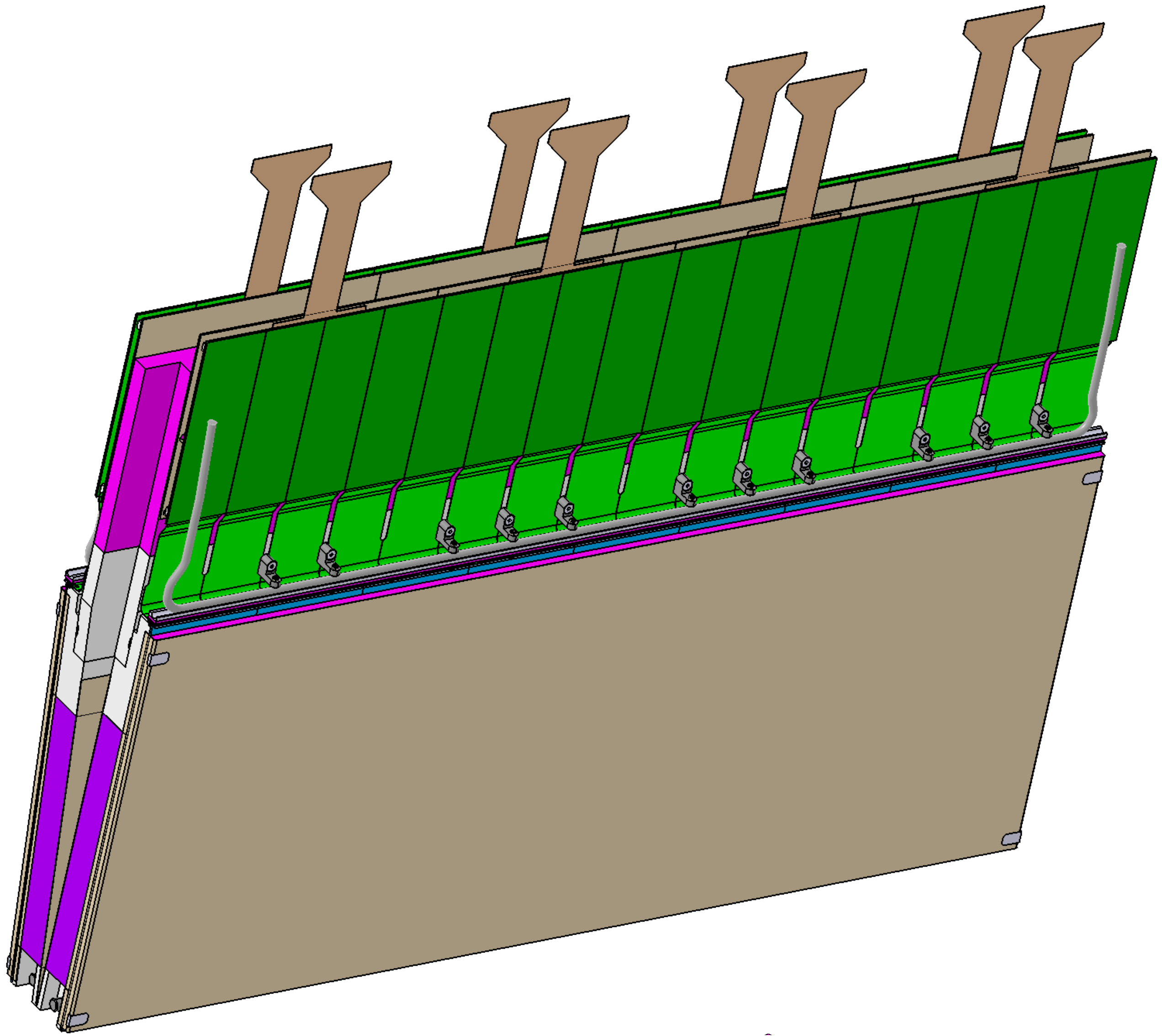
  - take into account SiPM response, occupancy distribution, etc...
- Short term testing with existing 40MHz *beetle* chip (LHCb)

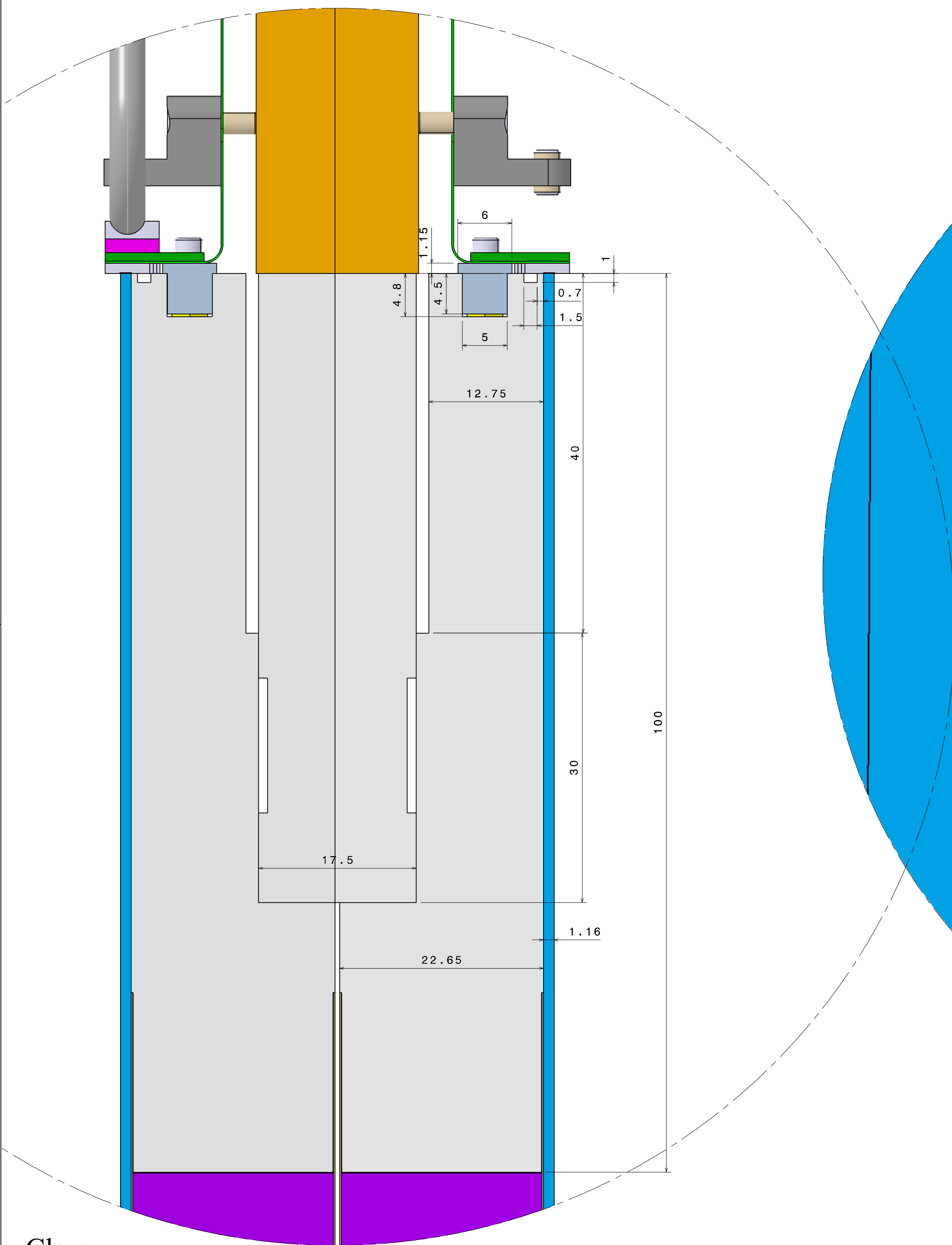
Detector layout and integration (in progress)

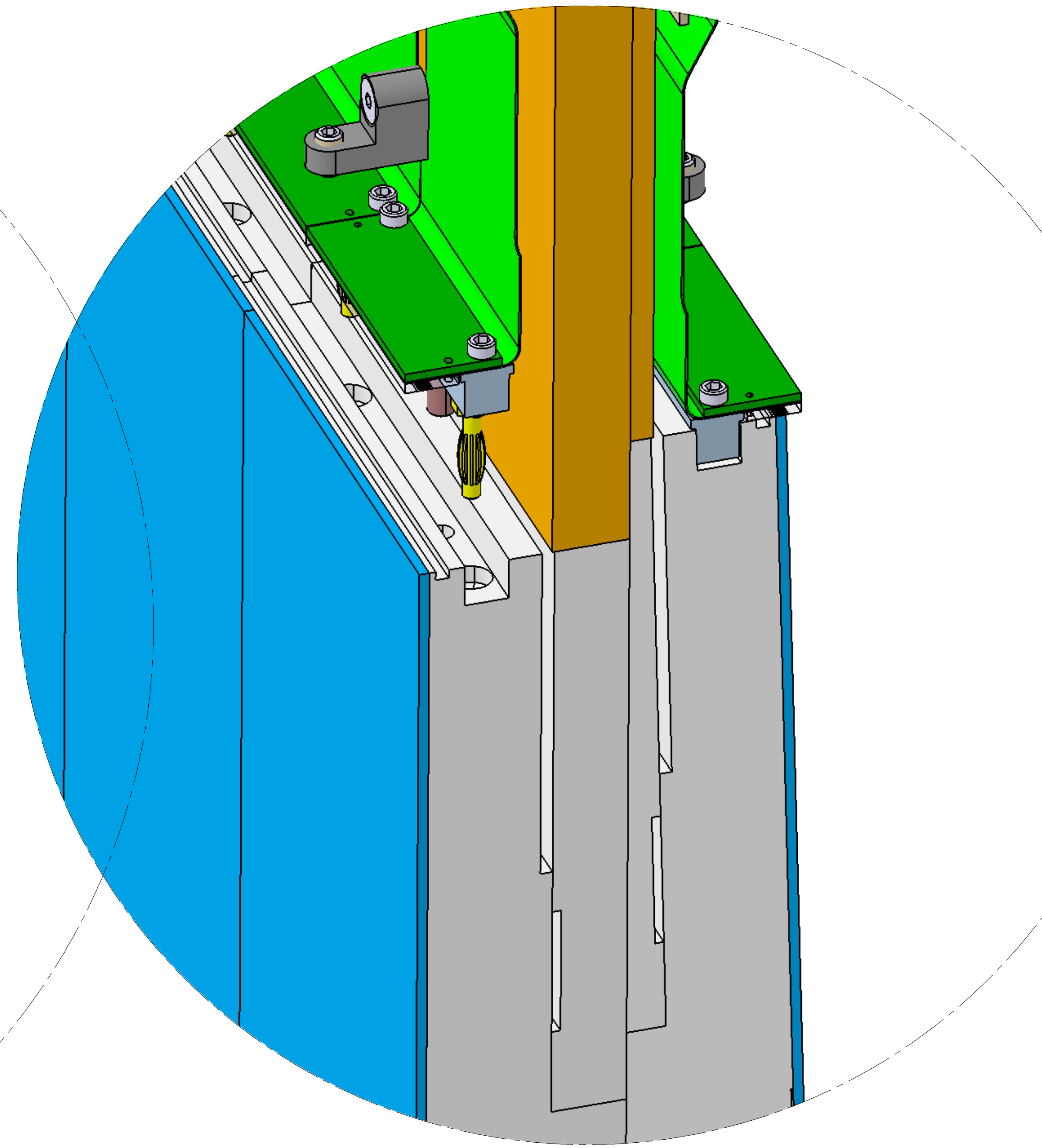




Prototype engineering drawings for a double fiber layer design







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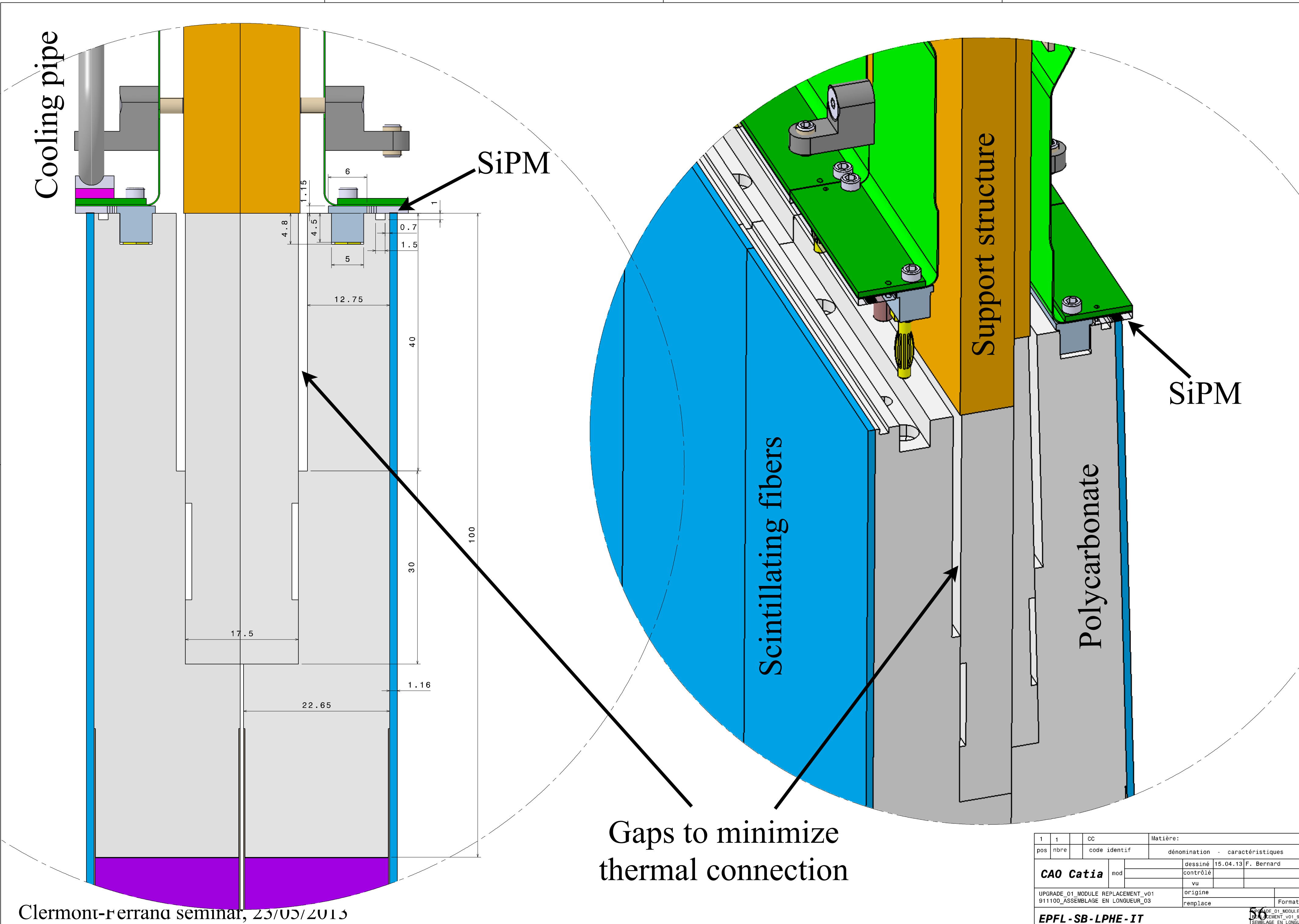
Cooling pipe
SiPM
6
1.15
1
4.8
4.5
0.7
1.5
5
12.75
40
100
30
17.5
1.16
22.65
Support structure
SiPM
Scintillating fibers
Polycarbonate
Gaps to minimize thermal connection
1
1
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Conclusion (and next steps)

- A scintillating fiber detector readout with SiPMs is being developed for the upgrade of the LHCb experiment
- It is the first time this technology would be used at this size and in the high radiation environment of the LHC
- The next steps towards a Technical Design Report by the end of 2013 are in preparation:

1. continuation of the SciFi and SiPM R&D
2. construction of a demonstrator detector module with all functionalities
   - challenging engineering R&D
     (e.g. fiber mat production, integration of the cooling, ...)
3. design of the front-end electronics
   - multiple solutions are being considered
4. design of the global detector layout
5. planning until installation and cost evaluation