A High-Granularity Timing Detector for the Phase-II upgrade of the ATLAS Calorimeter system: beam test results

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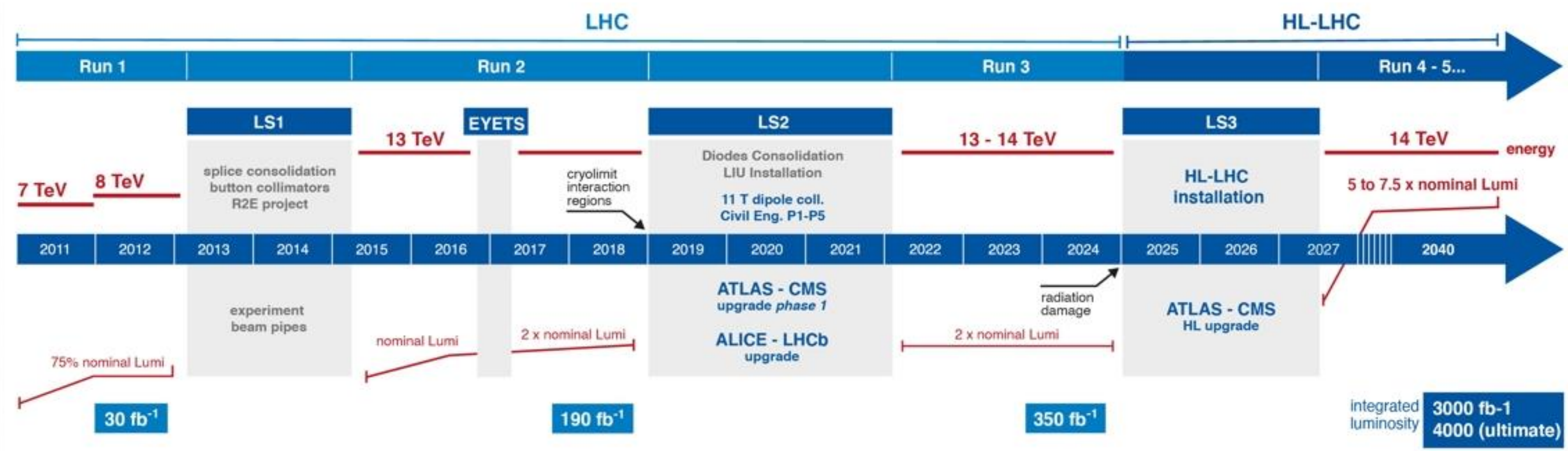
On behalf of the ATLAS High Granularity Timing Detector Group

Towards the High-Luminosity LHC

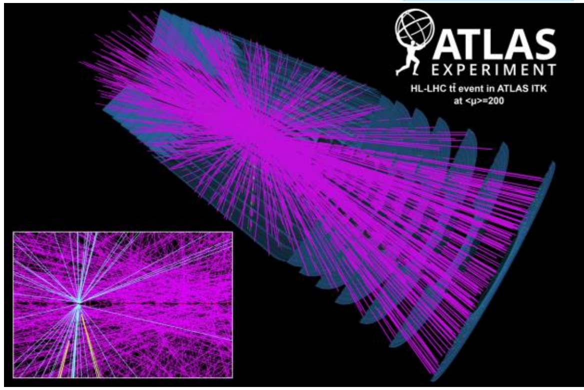
To extend the discovery potential, the LHC accelerator and experiments are scheduled for an upgrade.

The high-luminosity phase is expected to start in 2027 reaching 5-7.5 x the design luminosity



ATLAS detector will need major upgrades because of :

- ✓ Pile-up challenge : <μ> from ~ 30 in Run 2 to 200
- ✓ Radiation tolerance
- ✓ Trigger rates

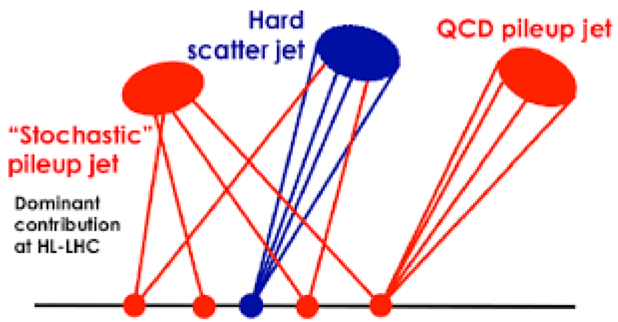


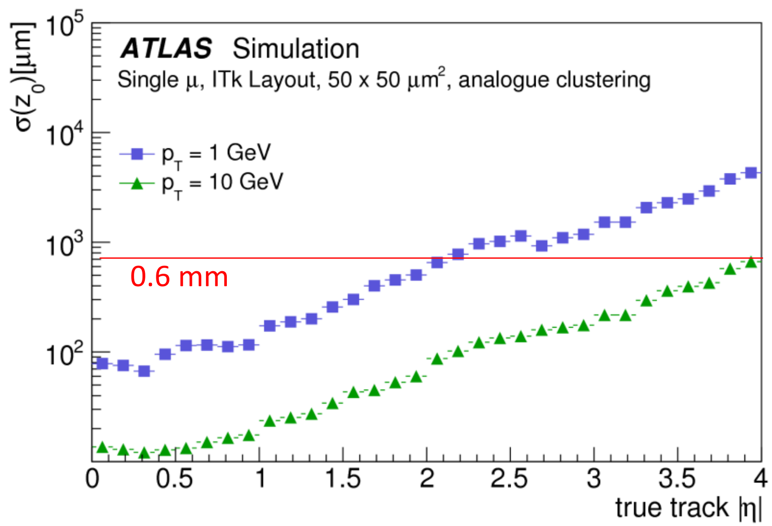
Among upgrades : a new **High-Granularity Timing Detector**

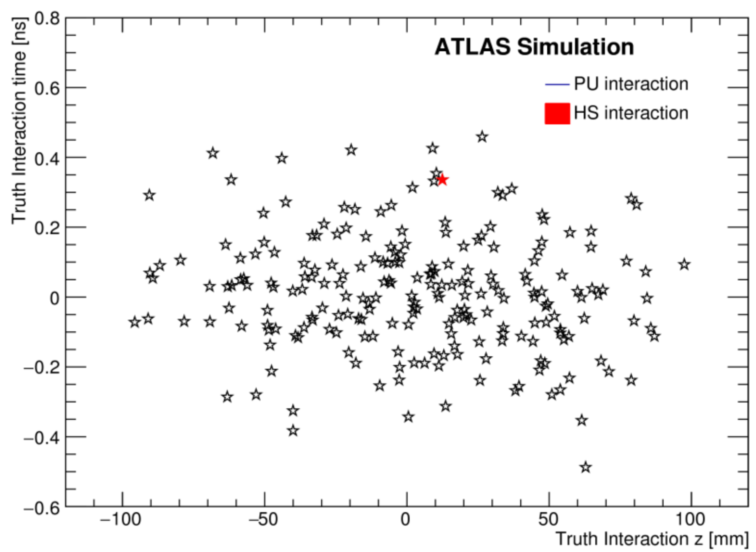
Pile-up challenge at HL-LHC

✓ At the HL-LHC, pile-up can add jets, create spurious jets, alter hard scattered jets and degrade physics performances

⇨ need a good tracking to reconstruct tracks and vertices. But at <μ> =200, average of 1.6 vertices/mm



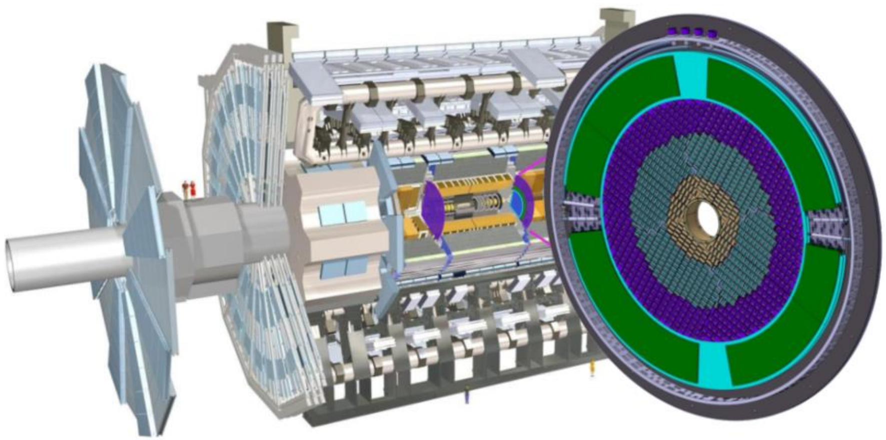




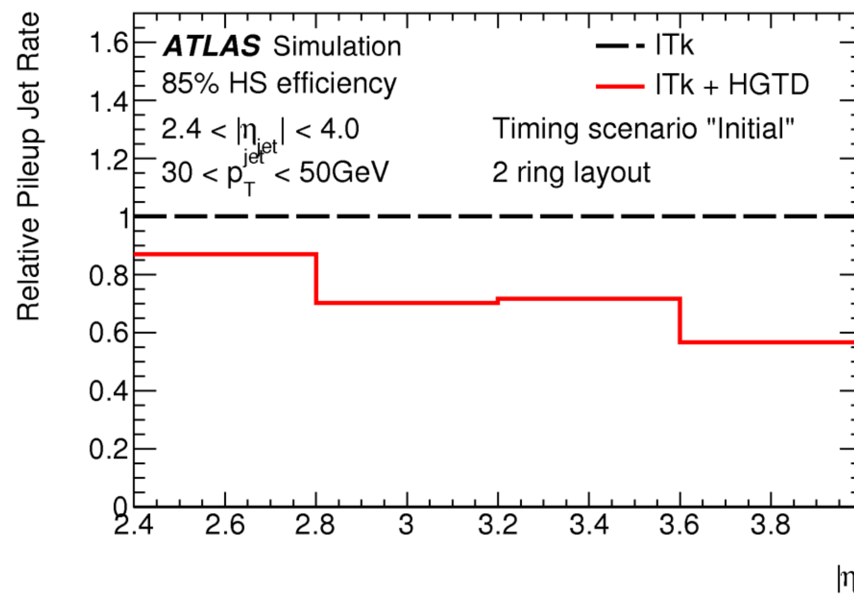
✓ New tracker ITk will provide good resolution on track impact parameters but will be completed **in forward region** by HGTD which will add **timing information** to mitigate pile-up effect

At a given z position, timing information helps to discriminate between pile-up and hard scattering interaction

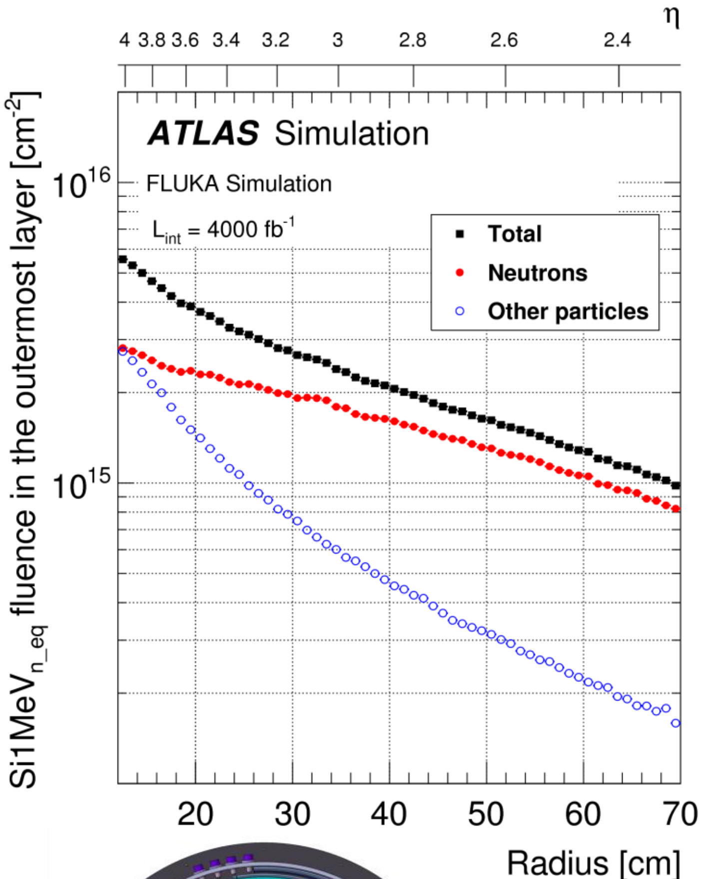
HGTD : a High-Granularity Timing Detector



- ✓ New detector constrained by the space available : thickness of 12.5 cm between barrel and endcap at |z|=3.5 m
- ✓ Two symmetric parts around the interaction point, each part made of two disks with double-side instrumentation
- ✓ Active area : 12 cm < R < 64 cm
  $2.4 < \eta < 4.0$
- ✓ Target time resolution :30-50 ps per track
- ✓ Impact on pile-up rejection, track and jet reconstruction, electron ID, b-tagging



HGTD radiation hardness

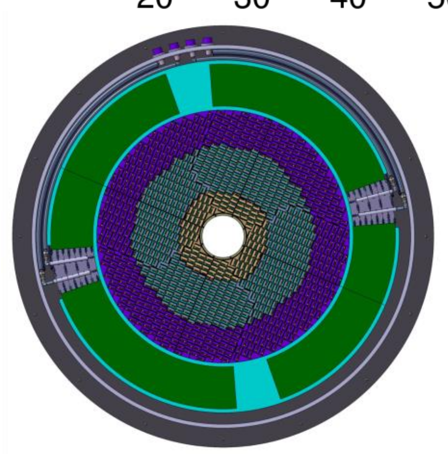


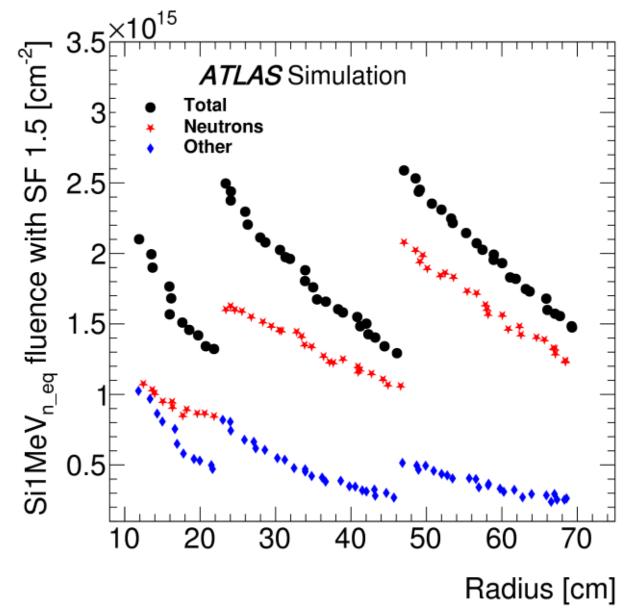
With FLUKA simulation, radiation level expected at R =12 cm: fluence > 5.6×10^{15} n_{eq}/cm^2
total ionizing dose ~ 3.3 MGy

But to achieve good time resolution with HGTD, the **maximum fluence** should be **2.5×10^{15} n_{eq}/cm^2** and TID **2 MGy**

⇨ Sensors will be operated at -30°C using a common CO_2 **cooling system** with ITk.

⇨ **Detector design optimized** (with a security factor of 1.5 for sensors and 2.25 for the electronics) segmentation into **3 replaceable rings.**





Replacement strategy:

- Inner (12-23 cm) every 1000 fb^{-1}
- Middle (23-47 cm) every 2000 fb^{-1}
- Outer (47-64 cm) never replaced

Constraints on sensors choice

Time resolution

Time resolution <70 ps/mip/sensor is beyond standard HEP silicon devices

$$\sigma^2_{tot} = \sigma^2_{Landau} + \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2 + \left(\frac{\mathrm{TDC}_{bin}}{\sqrt{12}}\right)^2 + \sigma^2_{clock}$$

Jitter *Time-walk* *(negligible)*

- $\sigma_{Landau} < 25$ ps (reduced for **thin sensors** 35-50 μm)
- $\sigma_{clock} < 15$ ps

- $\sqrt{\sigma^2_{Jitter} + \sigma^2_{TW}} < 25$ ps (70 ps at 4000 fb^{-1}) -> need **fast signal and excellent S/N**

Time-walk contribution can be corrected with the Time of Arrival (TOA) and the Time over Threshold (TOT)

Efficiency

High intrinsic single hit efficiency is essential. Can be achieved with :

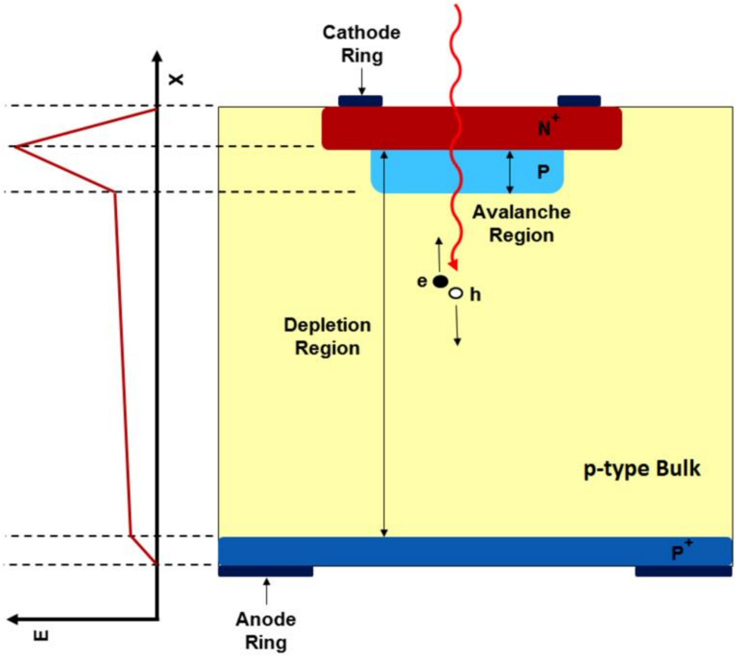
4 fC collected charge (for front-end functionality)

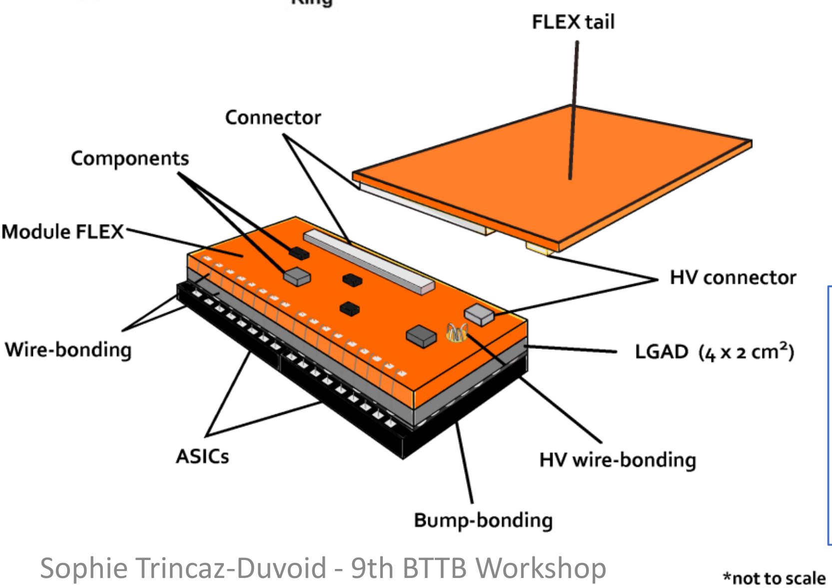
Threshold of the electronic discriminator is 2 fC.

S/N >7

low electronic noise

HGTD detection technology : LGAD





Low Gain Avalanche Detectors (LGAD)

- ✓ n on p sensors with a p-type multiple layer **thickness of 50 µm**
- ✓ Moderate internal **gain (8 - 50)**
  Large S/N ratio (larger than 7)
  Fast rise time (0.5-0.8 ns)
  Excellent time resolution (< 30 ps before irradiation)
  Lower impact from radiation
- ✓ Pixel size : 1.3x1.3 mm² (design for occupancy less than 10%). Total of 8032 modules of 15x30 pads
- ✓ Originally developed by CNM.
  Tested prototypes from CNM, HPK, BNL, FBK

Read out : front-end electronics ASICs ALTIROC

- ✓ Connected through bump bonding process
- ✓ 2 ASICS per modules (15x15 readout channels)

HGTD Test Beam campaigns

Program : ⇨ Measurement of collected charge, time resolution, efficiency, uniformity
⇨ Sensors provided by **different manufacturers**, with **different doping** and **irradiated at different fluences** up to $3x10^{15}$ n_{eq}/cm^2.

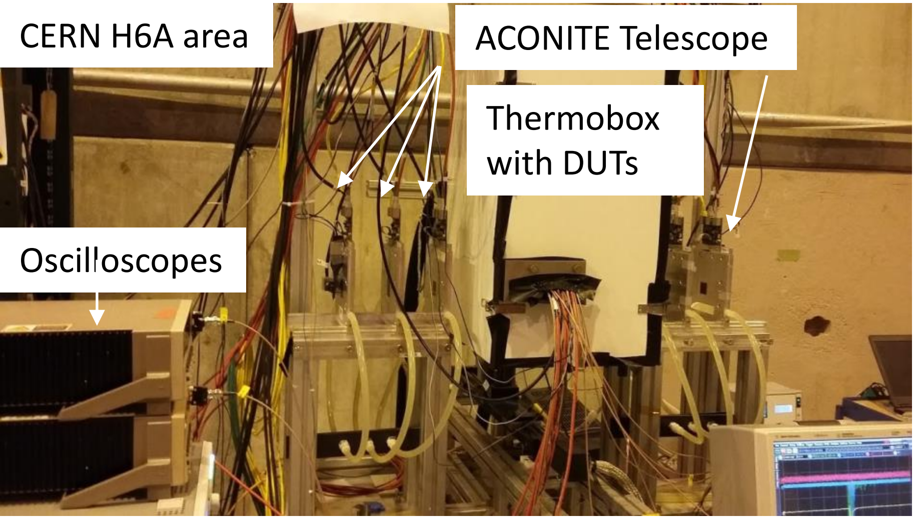
- **2016, 2017 and 2018 :**
  Test beams **at CERN** North Area SPS H6A & B beamlines with **120 GeV pions**
  ⇨2016+2017 : Unirradiated sensors and irradiated CNM sensors
  Unirradiated HPK sensors

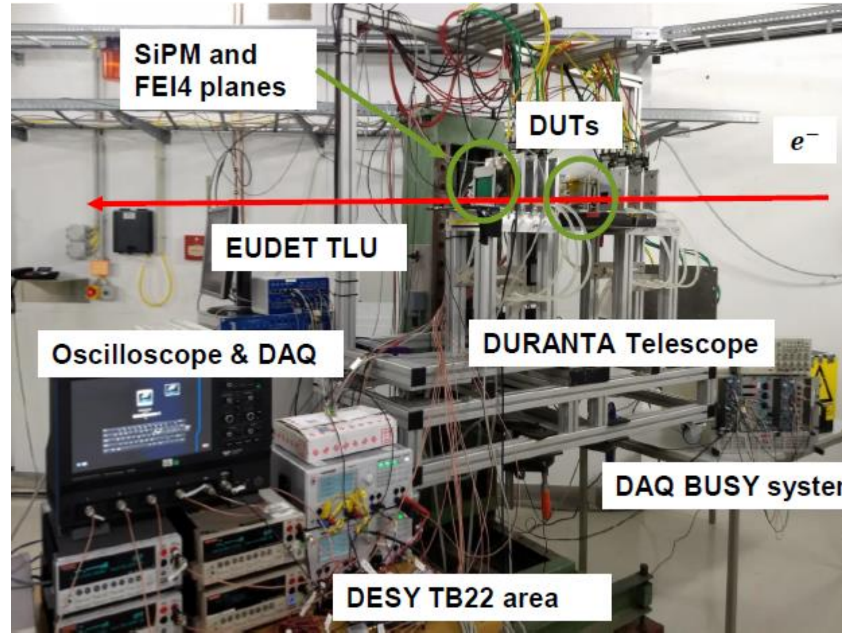
  ⇨2018 : Unirradiated CNM, HPK, BNL sensors irradiated with neutrons and protons :
  Boron implanted CNM sensors
  Boron with Carbon diffused CNM sensors
  Gallium implanted CNM sensors
  HPK sensors doped with boron
  2x2 array of ALTIROC 0

- **2019, 2020 :** Test beams at **DESY** T22 beamline with **5 GeV electrons**
  ⇨2019 : Unirradiated and **irradiated with neutrons and protons**
  single pad HPK,
  CNM sensors doped with Boron, Boron+Carbon and Gallium
  5x5 ALTIROC1 coupled to HPK 3.2 sensors

  ⇨ 2020 : only one campaign with HPK, NDL, FBK and CNM sensors
  Other campaigns were cancelled

Test beam setup

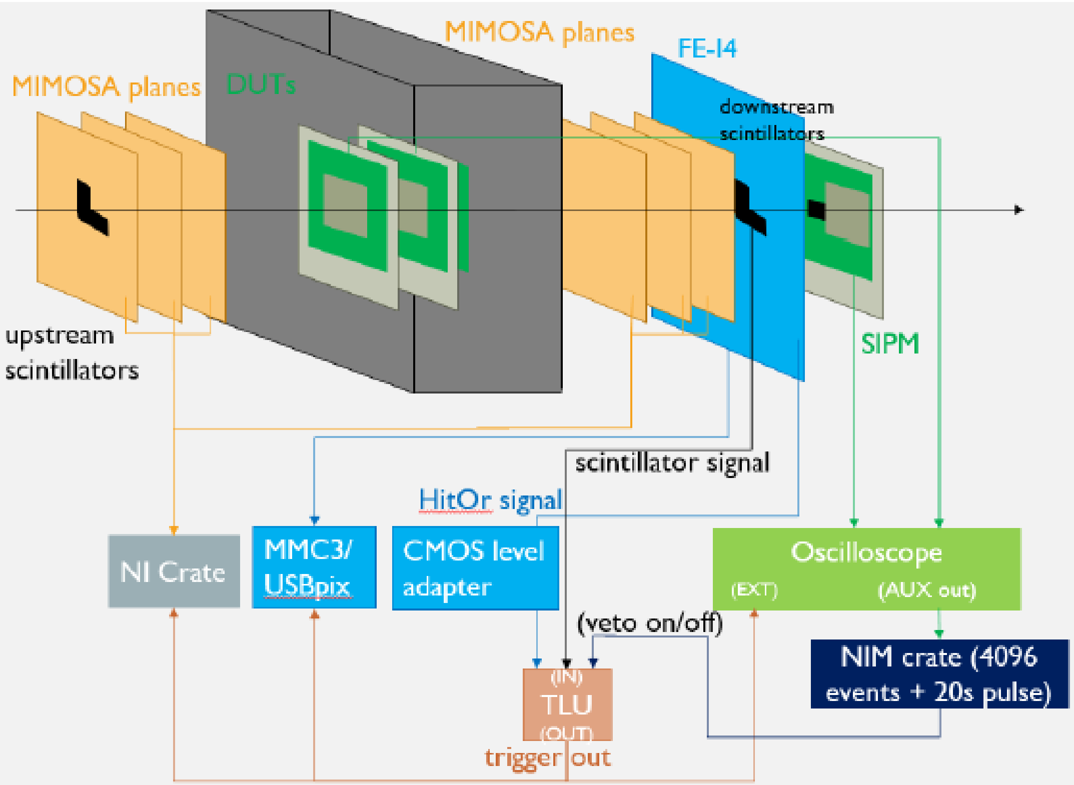




- ✓ **Sensors** - between 2 arms of a **TELESCOPE EUDET-type** (3 MIMOSA planes per arm)
  - inside a **cooling device** (Thermobox at CERN, Dry ice at DESY)
  - readout by **oscilloscopes** (2 oscilloscopes at CERN, 1 at DESY)
- ✓ On same oscilloscope, a Cerenkov light Quartz bar+SiPM provide **independent time reference**
- ✓ **FE-I4** plane with a **region of interest** geometrically optimized around sensors position is used as trigger reference (HitOr)
- ✓ Two plastic **scintillators** at each extremity of the telescope is also part of the TLU

DAQ and trigger scheme

DESY configuration



✓ Trigger Logic Unit (TLU) based on:
- scintillators
- FE-I4 HitOR signal
- Oscilloscope auxiliary output

✓ TLU triggers and synchronize :
- Telescope DAQ (NI-Crate using EUDAQ)
- Sensor DAQ (Oscilloscopes)

✓ Two independent sets of data recorded :
- from Telescope+FE-I4 for tracking
- from oscilloscope with sensor waveform signal

Oscilloscope needs time to empty the buffer
At CERN beam has a spill-structure (~ 4 s-long, every 16 s)
At DESY, continuous beam ⇨ busy signal implemented to simulate a spill-like beam (20 s paused)

Data analysis scheme

Data from telescope

Tracking program
Noisy pixels removal
Clustering
Telescope plane alignment
Tracks fitting
⇨ Hit position in DUT plane

Data from oscilloscope

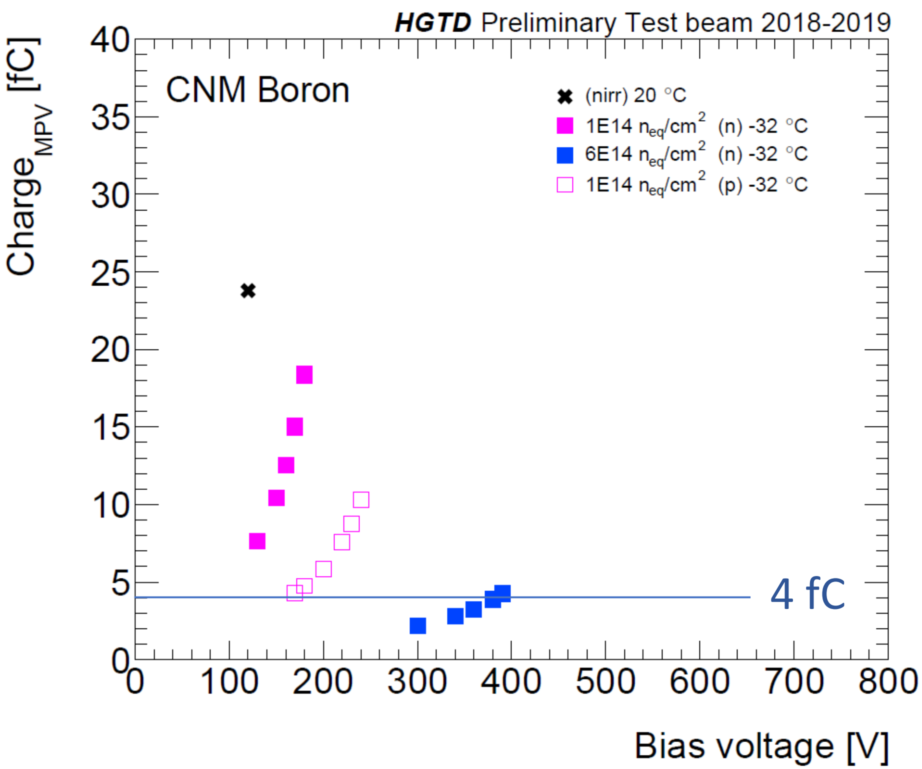
LGAD waveform processing
Pedestal substraction
Signal start and stop
Compute noise, charge, rise time, time at different CFD fraction or with CTD…

Root-tuple for user analysis
DUT signal information
hit position

Tracks reconstructed asking exactly one hit in FE-I4 plane.

Tracks fitting : - straight lines for CERN data (120 GeV Pions)
- multiple scattering for DESY data (5 GeV electrons) with EUTelescope v01-19-02 using GBL algorithm

Collected charge vs Bias voltage

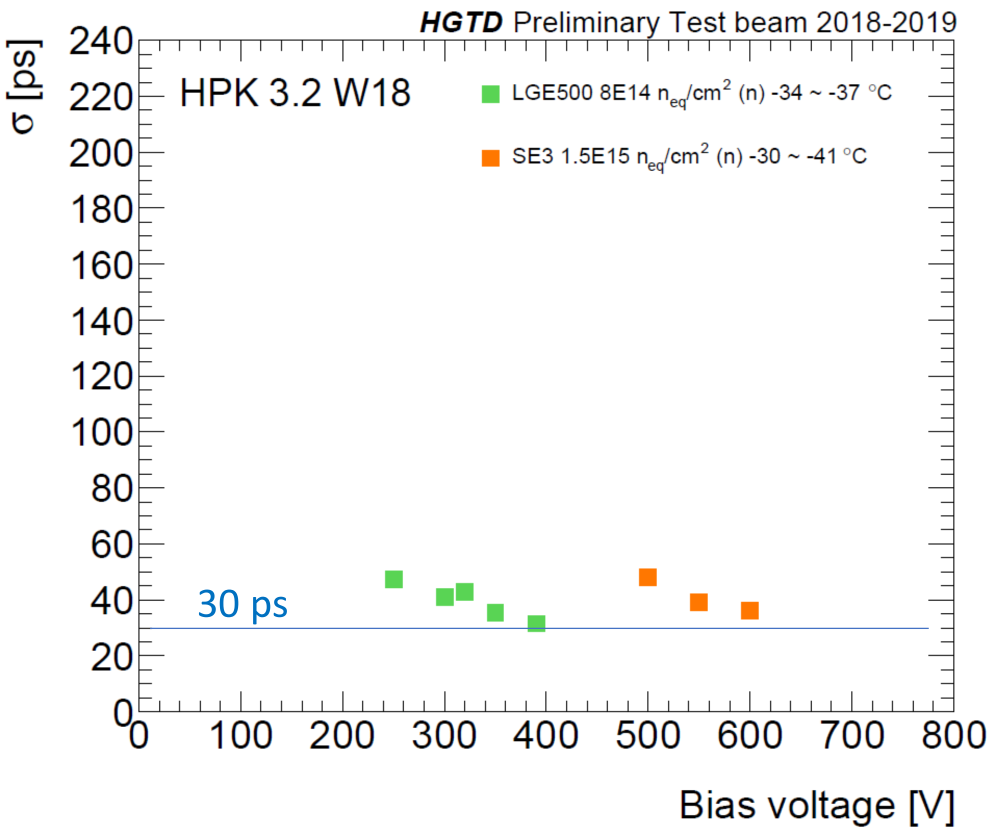


CNM sensors doped with Boron

- ✓ Charge computed as the integral of signal waveform divided by sensor transimpedance
- ✓ For each voltage point, the collected charge is given by the MPV of the Landau-Gauss fit of the events charge distribution
- ✓ For sensor irradiated with neutrons at **$6x10^{14}$ n_{eq}/cm^2, Q = 4.2 fC** for HV = 390 V

  For sensors doped with **Gallium** and irradiated with neutron at **$3x10^{15}$ n_{eq}/cm^2, Q=5.3 fC** for HV=740 V
- ✓ **Achieve the ALTIROC** requirement of 4 fC

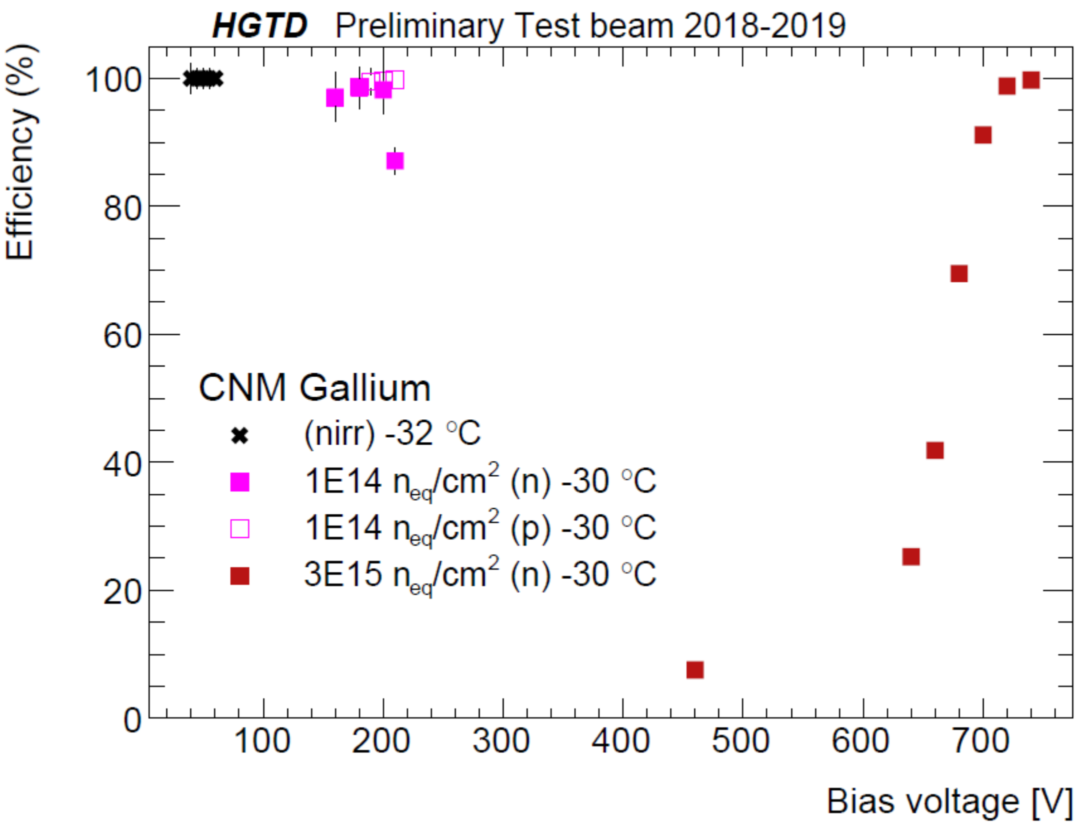
Time resolution vs bias voltage



HPK sensors doped with Boron and irradiated with neutrons

- ✓ Time resolution is computed from **time difference distribution** between the sensor and the SiPM or another sensor
- ✓ $\sigma^2(\Delta t) = \sigma^2(t_{sensor\ i}) + \sigma^2(t_{sensor\ j})$
  With 4 sensors, the system is constrained ⇨gives the resolution per sensor.
- ✓ For sensor HPK irradiated with neutrons at $1.5\text{x}10^{15}\ n_{eq}/cm^2$, time resolution is 36 ps at 600 V for a collected charge of 22.8 fC .
- ✓ Tested sensors that have a collected charge greater than 4 fC achieve the HGTD requirement: a time resolution better than 40 ps at higher bias voltage

Efficiency vs bias voltage



CNM sensors doped with Gallium

- unirradiated
- irradiated with neutrons or protons

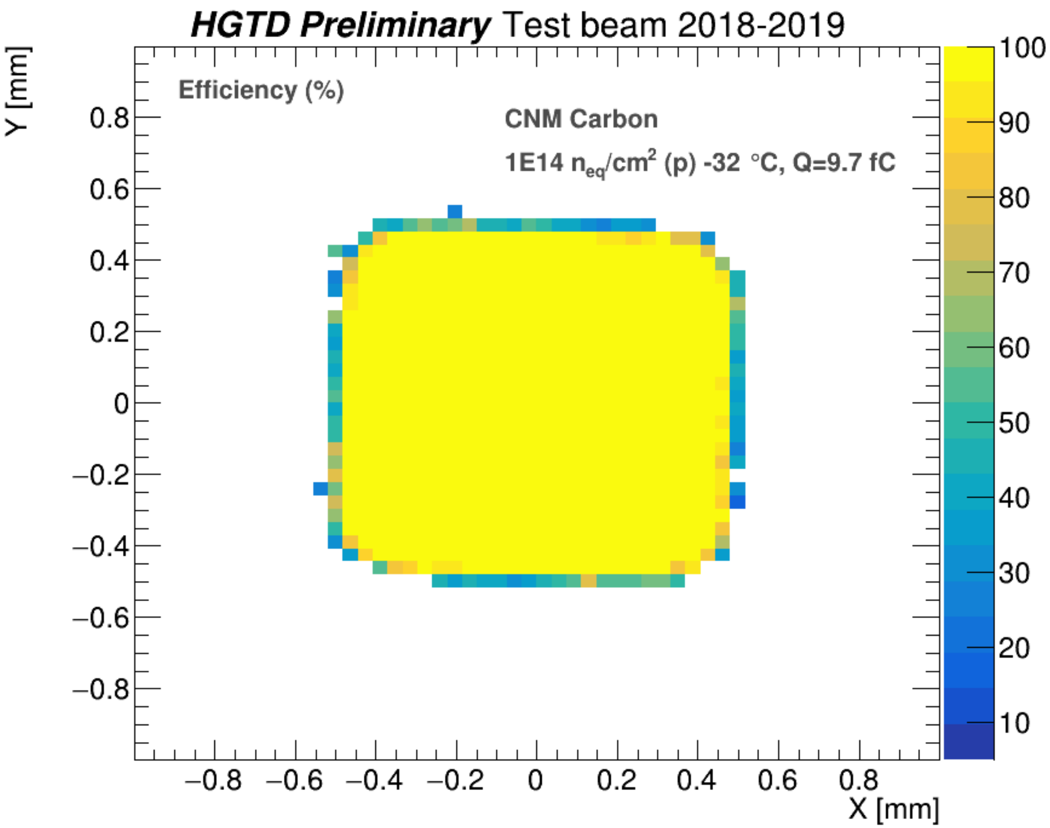
✓ For each bias voltage point, efficiency is defined as :

$$\varepsilon = \frac{\text{Tracks in the sensor center (0.5x0.5 mm}^2\text{) with Q>2fC}}{\text{Tracks in the sensor center}}$$

✓ The threshold at 2 fC for the collected charge corresponds to the threshold of the electronic discriminator

✓ For CNM sensor doped with Gallium and irradiated with neutrons at **3×10^{15} n_{eq}/cm^2**, efficiency reaches **99.7%** for a bias voltage of 740 V and a collected charge of **5.3 fC**

2D map efficiency



CNM sensor doped with Boron and Carbon diffused and irradiated with protons at $1x10^{14}$ n_{eq}/cm^2 :

- The collected charge is 9.7 fC.
- The time resolution is 34.7 ps
- Efficiency in central area (0.5x0.5 mm^2) is 99.8 %.

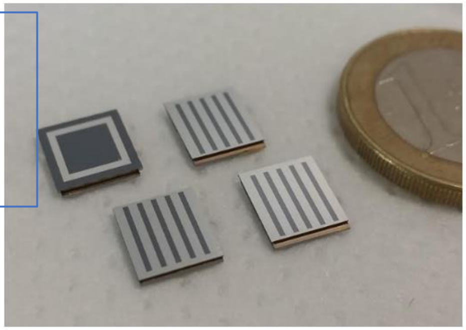
Other result : For CNM sensor doped with Gallium and irradiated with proton at $3x10^{15}$ n_{eq}/cm^2

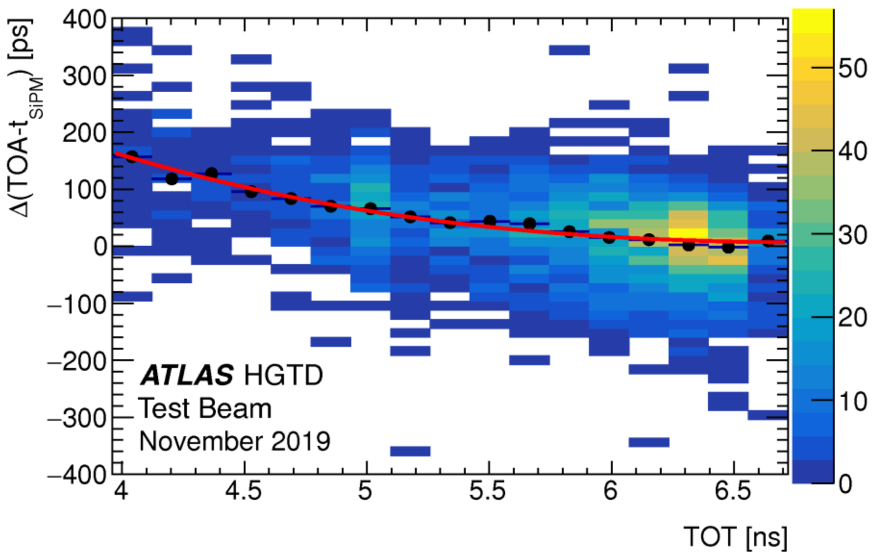
- The collected charge is 5.3 fC
- Time resolution is 37 ps
- Efficiency in central area (0.5x0.5 mm^2) is 99.7%.

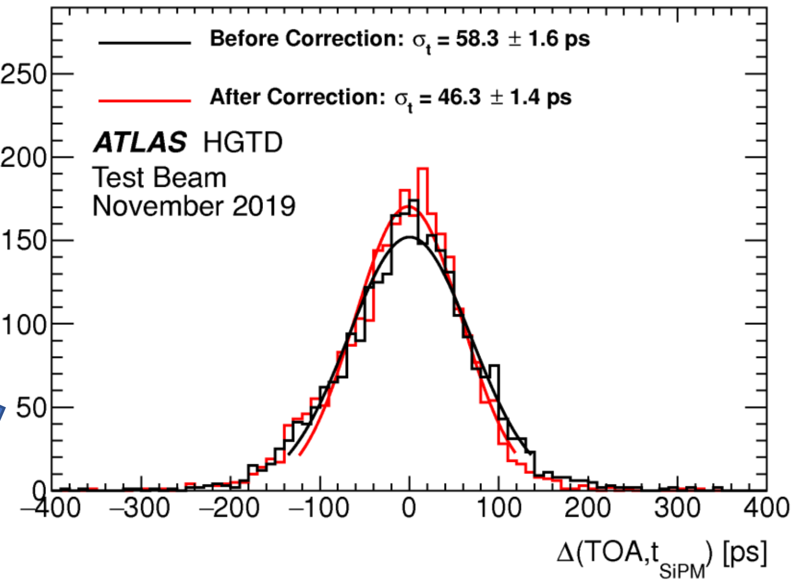
HGTD front end chip ALTIROC in Test beam

Test beam measurement at DESY in 2019
for Unirradiated ALTIROC1 modules
-> TOA corrected for time-walk

5x5 ATLIROC1 devices with HPK and CNM sensors







Estimated resolution of **46 ps** after time-walk correction and including Landau contribution (25 ps).
Estimated Jitter contribution of **39 ps**

In test beam configuration, improved DAQ (with FPGA) should improve jitter resolution by 35% achieving ~25 ps target

Summary

- ✓ At the HL-LHC, the pile-up will present an unprecedented challenge and the HGTD is expected to play a key role in ATLAS by adding timing information in the forward region
- ✓ The per-track timing resolution target is 30-50 ps up to the end of the detector (after recorded 4000 fb^{-1} of data).
- ✓ R&D for LGAD sensors and ALTIROC front end chip
- ✓ ALTIROC and LGAD sensors –irradiated or unirradiated – with different doping and from different vendors have been tested during test beam campaigns at CERN and DESY. They have shown to be able to reach the required performance
- ✓ Next test beam campaigns
  - ALTIROC test beams done at Strasbourg mid-January
  - Test beams planned at DESY for 2021 (will depend on sanitary situation)
  - Beam request procedure for test beams at CERN

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