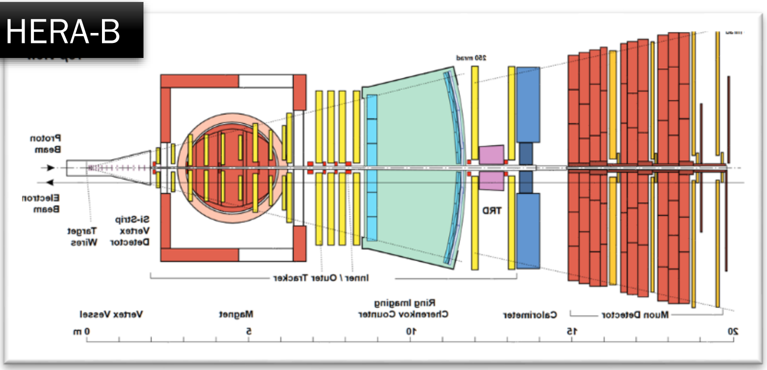
Germany in LHCb Upgrade 2: The Mighty Tracker

B. Leverington,
Universität Heidelberg,
On behalf of the Mighty Tracker group.

Forward Flavour Physics Detectors

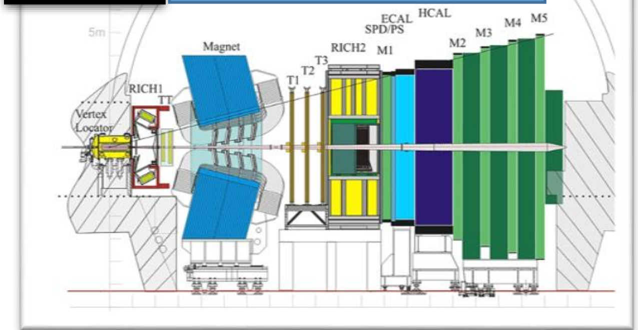
at hadron colliders

HERA-B

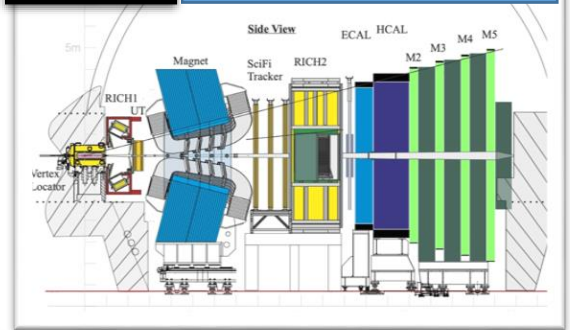


0.5 fb-1 per year at DESY, fixed target,
Didn't meet its performance goals ;
20 physics and 23 detector papers

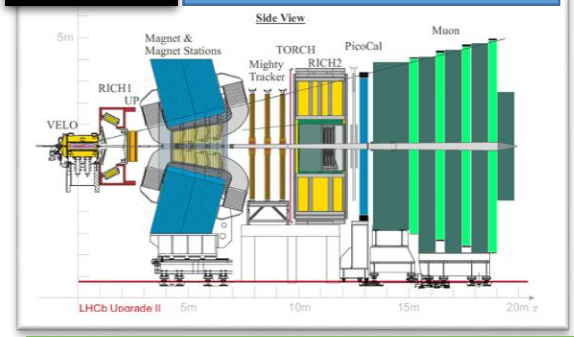
LHCb | L0 Hardware Trigger



LHCb-U1 | 30 MHz Software trigger



LHCb-U2 | 30 MHz Software trigger



Design:

$L = 0.4\ 10^{33}$ Goal: 10 fb^{-1}
1 to 2 fb^{-1} per year ; mu = 1.1

$L = 2\ 10^{33}$ Goal: +45 fb^{-1}
~7-9 fb^{-1} per year; mu = 5.3

$L_{peak} = 10\text{-}15\ 10^{33}$; +200-300 fb^{-1}
~40-50 fb-1 per year; mu = 42

FSP LHCb Erforschung von Universum und Materie

BMBF

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Forward Flavour Physics Detectors

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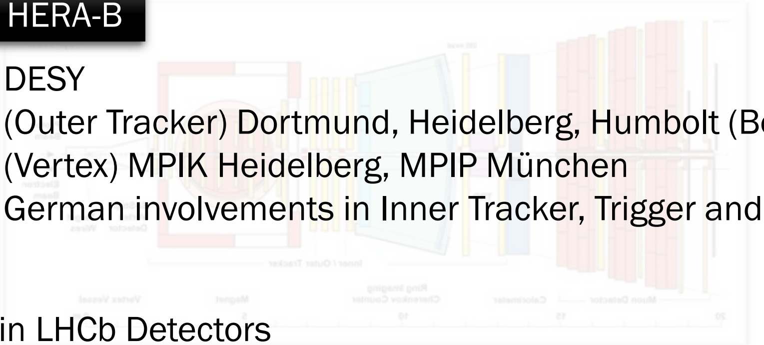
HERA-B



DESY
(Outer Tracker) Dortmund, Heidelberg, Humbolt (Berlin), Rostock
(Vertex) MPIK Heidelberg, MPIP München
German involvements in Inner Tracker, Trigger and RICH as well

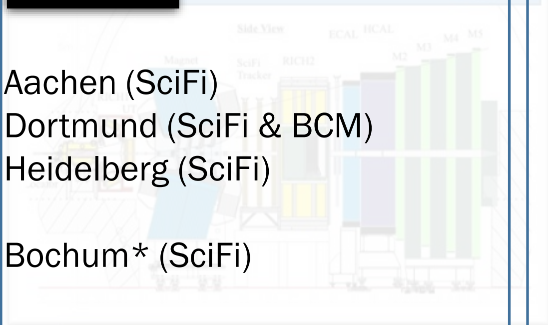
German involvement in LHCb Detectors

MT = Pixel + SciFi

LHCb

Dortmund (Outer Tracker & BCM)
Heidelberg (Outer Tracker)

LHCb-U1



Aachen (SciFi)
Dortmund (SciFi & BCM)
Heidelberg (SciFi)

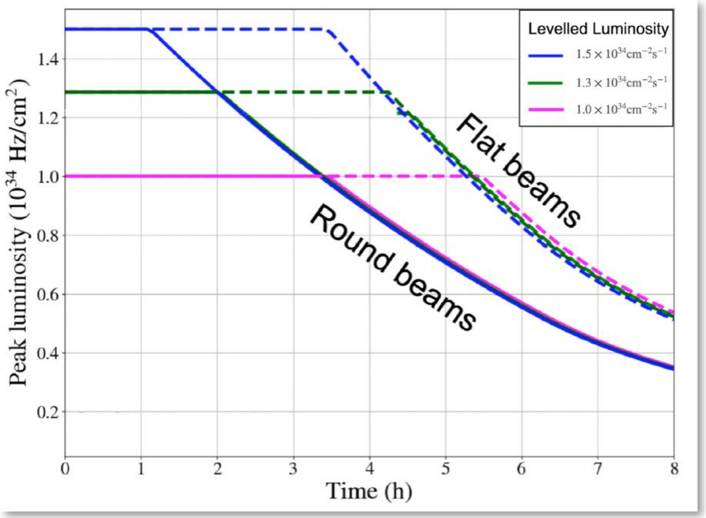
Bochum* (SciFi)

LHCb-U2

Aachen (MT)
Bochum (MT)
Bonn (MT)
Dortmund (MT & BCM)
Freiburg (MT)
Heidelberg (MT)

Theory: MPIK and Siegen

(Integrated) Luminosity

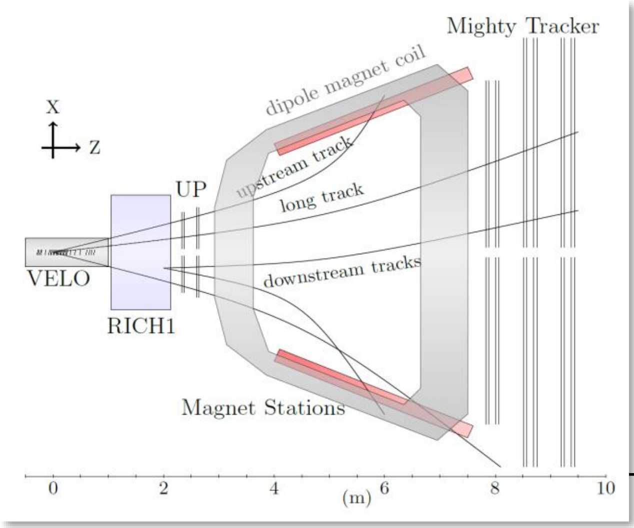


	Round optics			Flat optics		
Levelled $\mathcal{L}_{peak}$ ($10^{34}\,cm^{-2}\,s^{-1}$)	1.0	1.3	1.5	1.0	1.3	1.5
Run 1–6 recorded $\mathcal{L}_{int}$ (fb^{-1})	262	287	297	294	340	367
New recorded:	208	233	243	240	286	313

Run 1 to 4 assumes 54 fb-1 collected

Tracking in increased Pile-up

~ mu=25-35 visible interactions per BX in Upgrade 2
~ 2000 charged particles within the LHCb acceptance



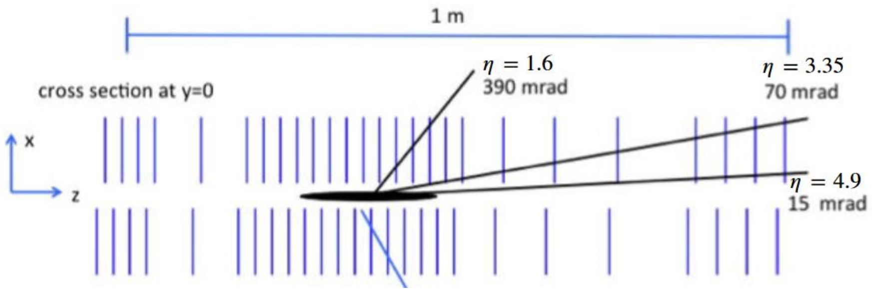
Requirements:

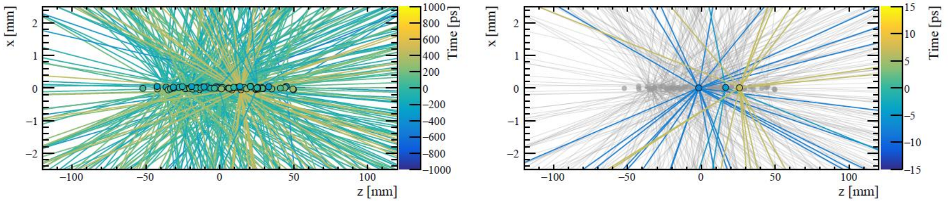
- Upgrade 1: Higher Spatial Granularity to prevent overlapping hits in the same channel in all trackers
- Upgrade 2:
  - VELO: adding sub-bx timing granularity (50 ps per hit) to match tracks and vertices
  - UT: increased spatial granularity with pixels instead of strip detectors (only BX timing)
  - T : pixels in the inner region, still scintillating fibres in the outer regions behind the magnet (only BX timing planned for Tracks)
  - Timing for downstream tracks will be provided by the particle identification systems.

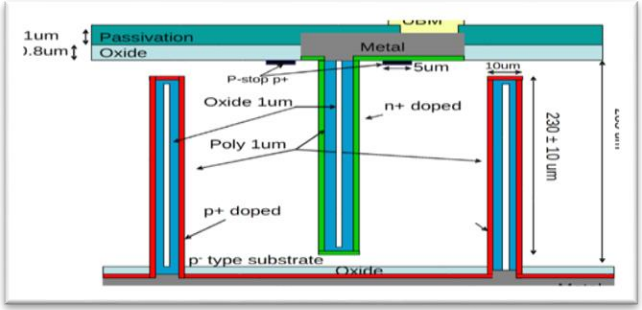
New tracking detectors!

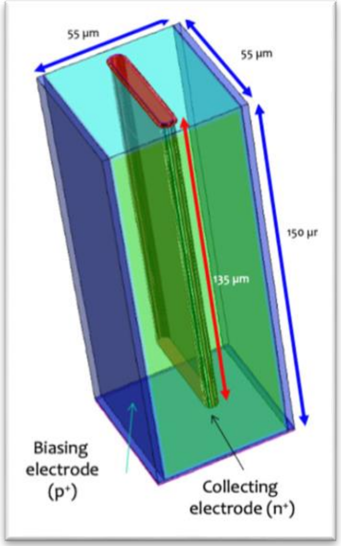
3D sensors are promising

- VELO Pixels with Timing (TV)





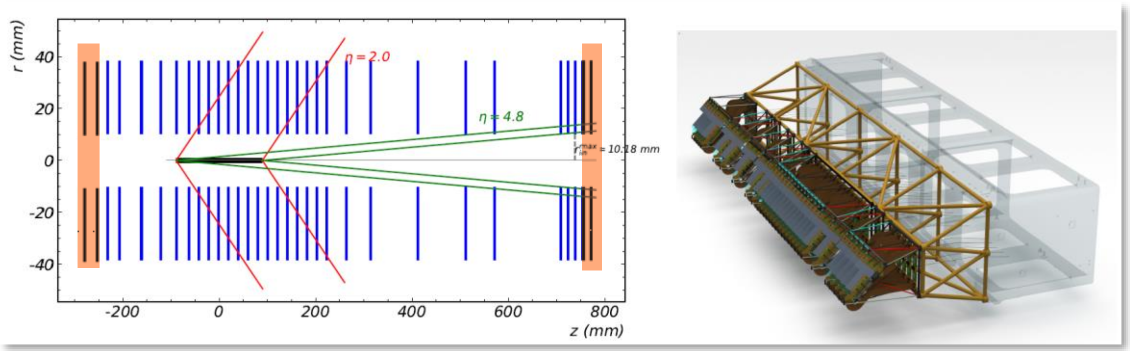




Trench geometry

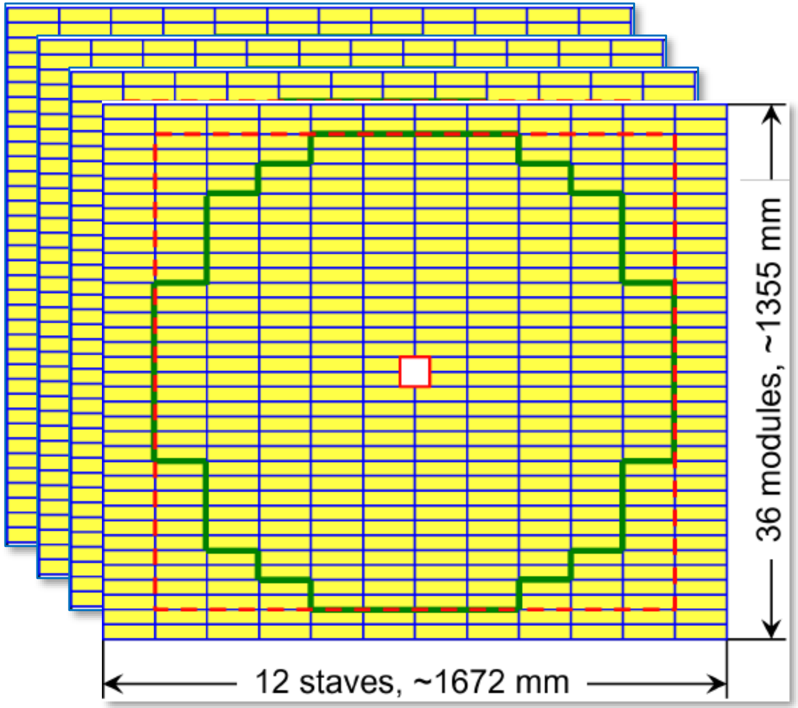
- nu = 42 (left) with no timing, (right) with 30ps time window
- 150 µm thick sensors with 10 µm spatial resolution.
- 28 nm pixel technology.

VELO in the Scoping Document



- Middle scenario:
  - Same geometry and construction
  - fewer data links from the lower luminosity
- Low scenario:
  - by removing the first two and last two stations, by adopting a more conservative corrugated design for the RF shield, with 150 μm thickness,
  - by using a heavier cooling substrate, increasing by **a factor of two** the material of the detector modules.

Upstream Pixel Tracker in the Scoping Doc.



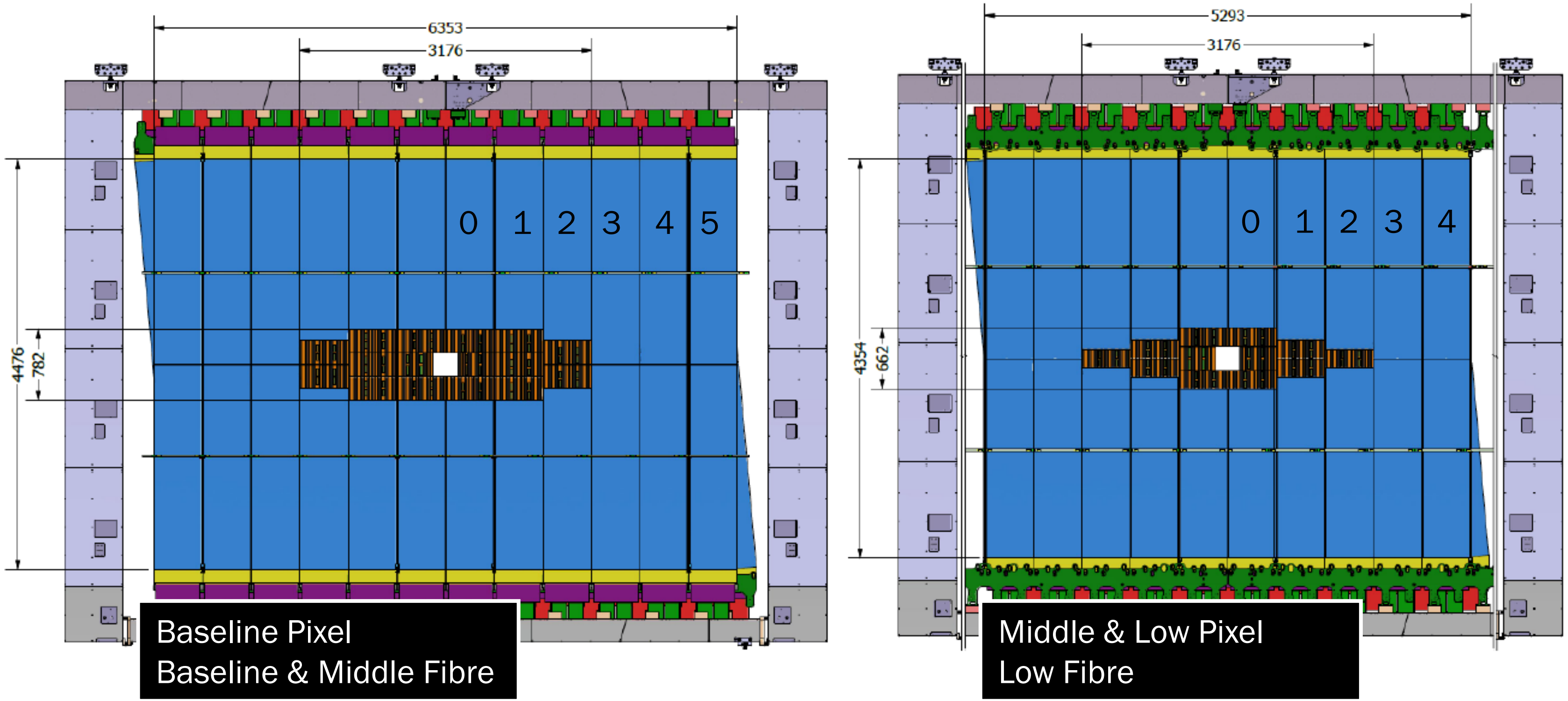
- four planes of silicon pixels based on DMAPS technology
- New baseline (red box)
- Middle scenario saves cost with fewer data links from the lower luminosity
- Lower cost (green outline) removes the lower occupancy regions

Could likely to be a flavor of the same DMAPS technology as the Mighty-Pixel

The Mighty Tracker in the Scoping Doc.

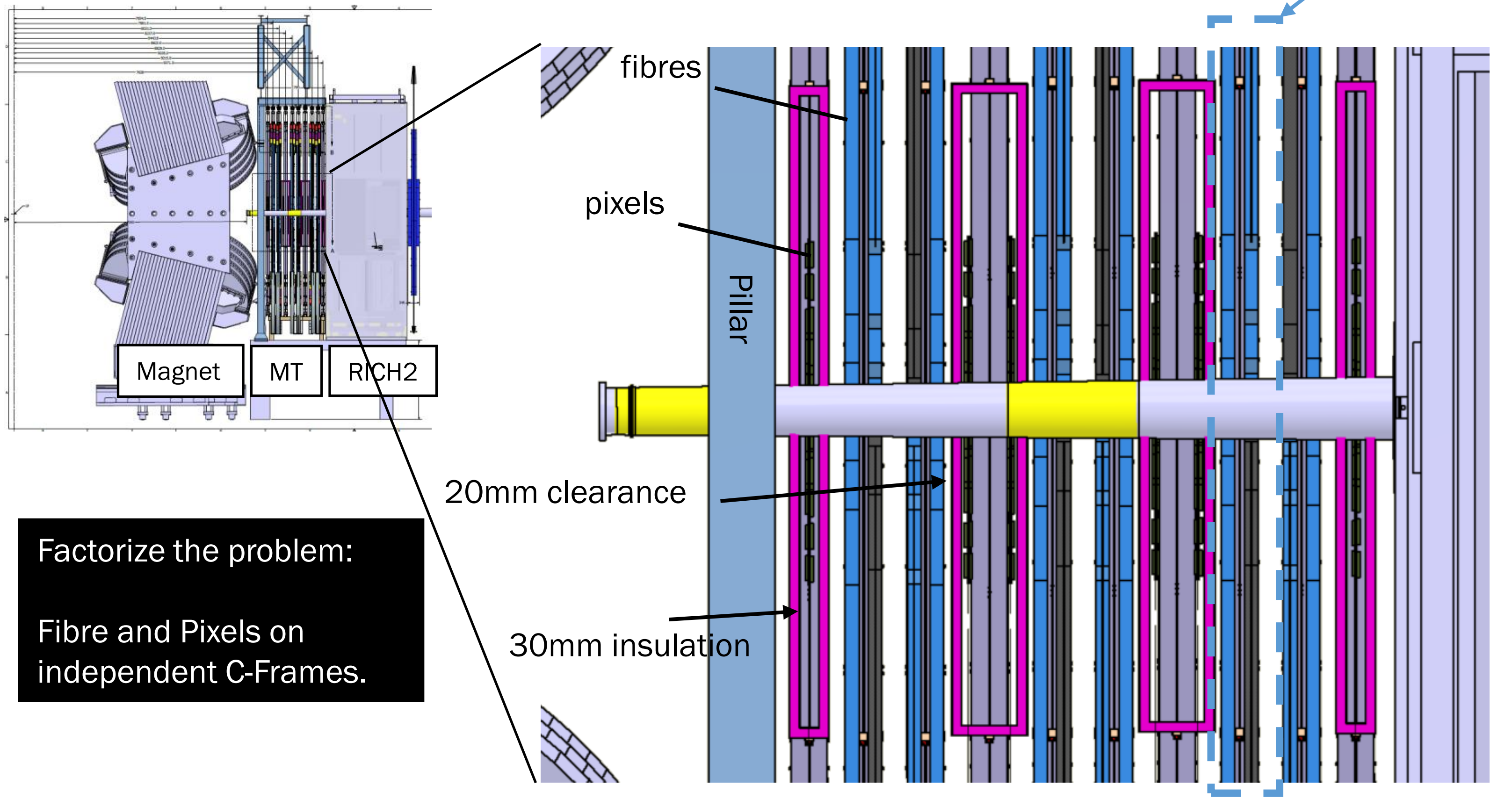
Mighty-SciFi: scintillating fibres for the majority of the area

Mighty-Pixel: a high-granularity silicon (DMAPS) pixel detector around the beampipe



C-Frames & Integration

We need to remove 2nd row of pillars!



Factorize the problem:

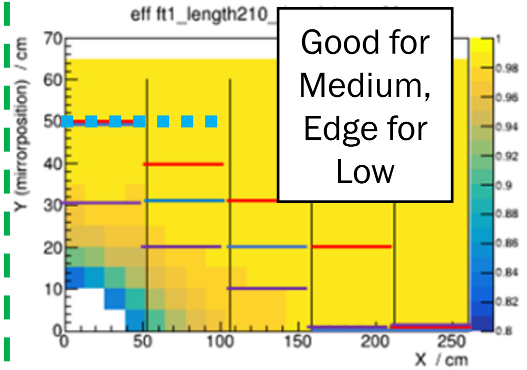
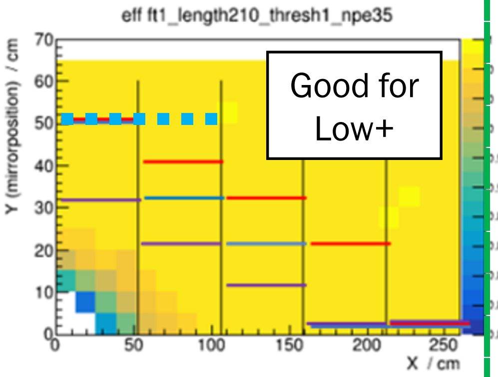
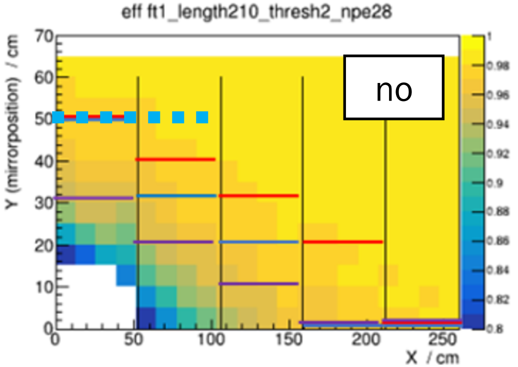
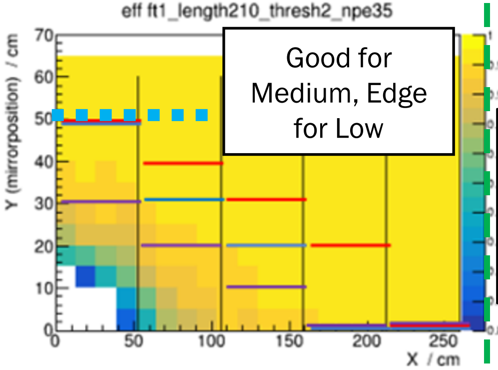
Fibre and Pixels on independent C-Frames.

Toy Studies of Hit Efficiency

*NB: fast parametric MC

Hit Efficiency of 6-layer fibre mats

U1 * 7 radiation map (350fb-1)

	H2017 +3.5V PDE	x1.25
1.5pe. Sum threshold		
2.5pe. Sum threshold		

*Old Names
- High
- Medium
- Low

Pixel Geometry

Occupancy

Pixels are nice, great performance, but expensive.
Put fibres where they can do the job.

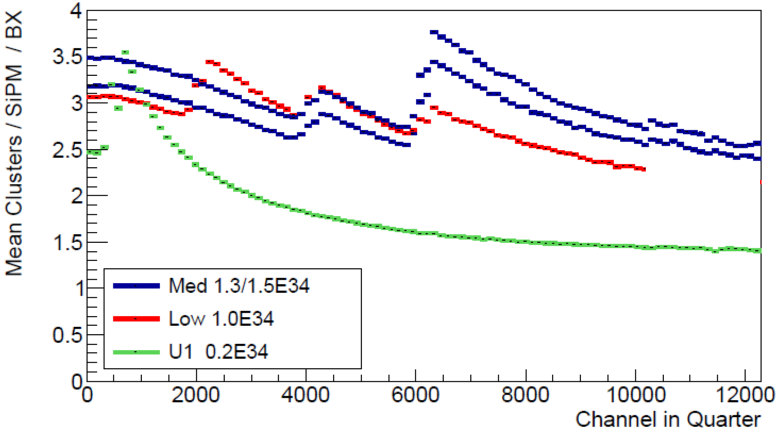


Figure 63: Single hit (cluster) occupancy distribution for the Mighty-SciFi for the Baseline scenario of the Mighty-Pixel, labelled as Med in figure, at peak luminosity 1.3 and 1.5 $\times 10^{34}$ cm^{-2}s^{-1}, and for the Middle/Low scenarios, labelled as Low. The Upgrade I SciFi occupancy is also shown for comparison.

Don't forget to add spillover cluster/hits from late particles in the previous BX (detector also creates a hit in the next BX). The plot above underestimates the real occupancy.

Relative Scoping Performances

Channel	Relative acceptance %	
	Middle	Low
$B_s^0 \to \mu^+\mu^-$	99.3 ± 0.1	95.3 ± 0.1
$B_s^0 \to \phi(\to K^+K^-)\phi(\to K^+K^-)$	99.4 ± 0.1	90.6 ± 0.2
$D^0 \to K_S^0(\to \pi^+\pi^-)\pi^+\pi^-$	99.7 ± 0.1	84.8 ± 0.8

Largely an effect of removing the outer SciFi modules

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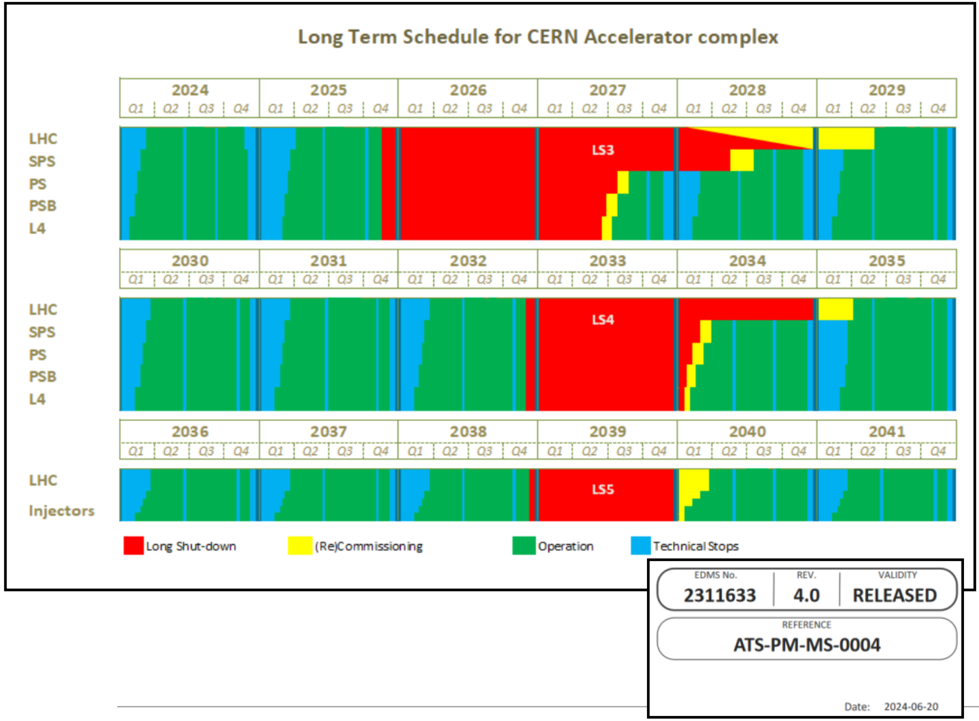
More about the Mighty Tracker

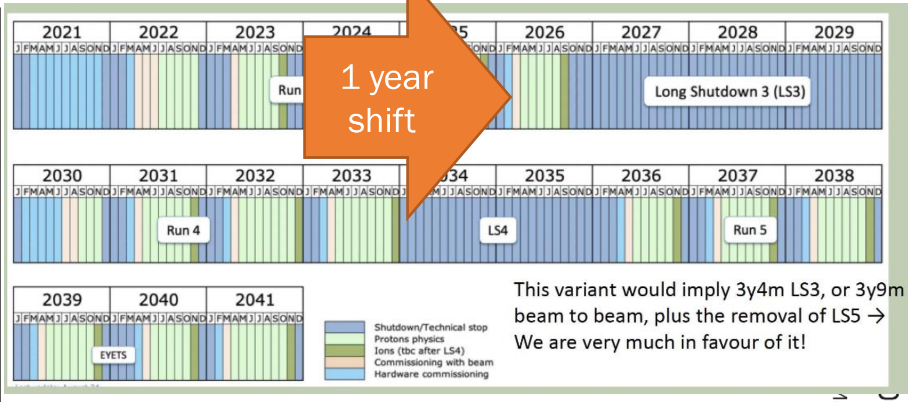
What, when, and where.

U2 Installation in LS4

Official released schedule as June 2024



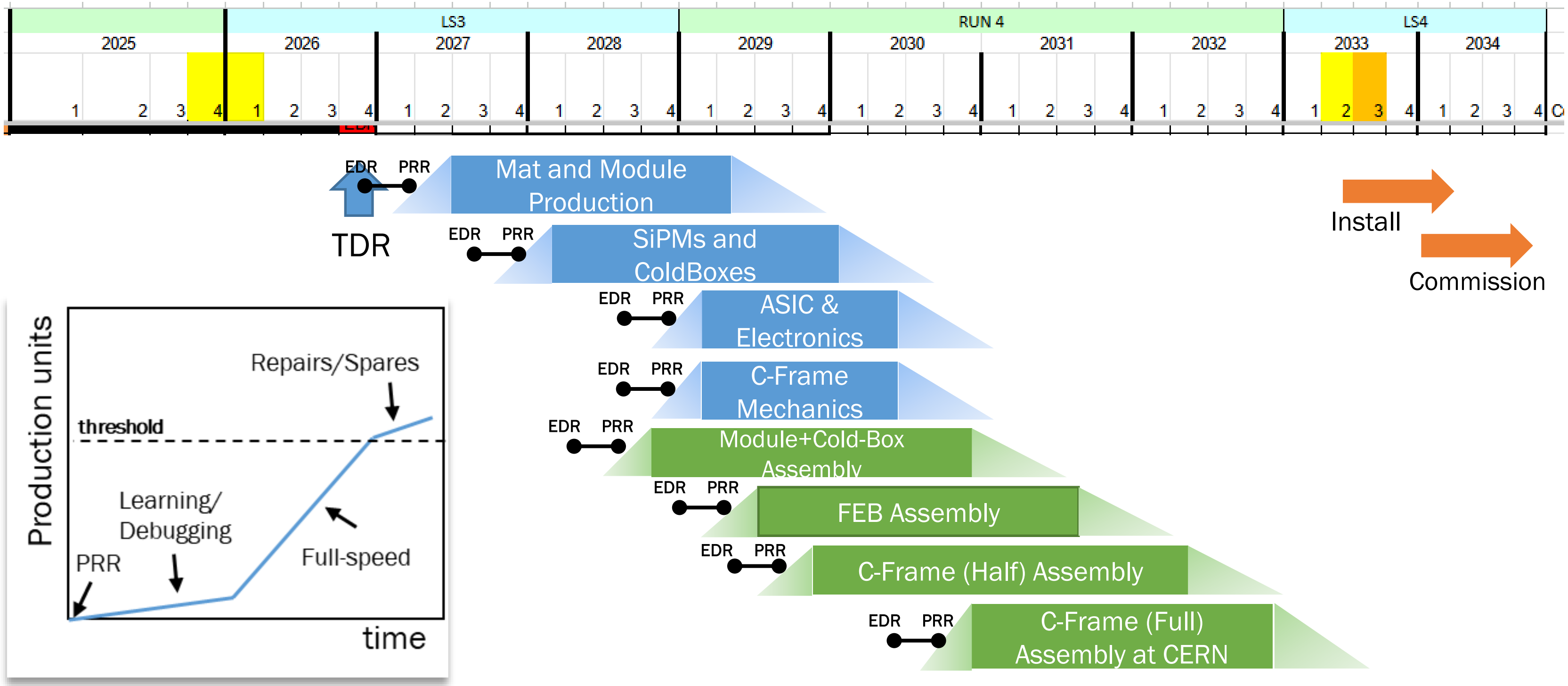
Shown in the LHCb Tuesday meeting
Sept 17, 2024 (not official)



Might seem like a buffer is added for us, but I've never seen reality meet a schedule. We'll need it for commissioning in any case.
Plan for Assembly in 2032 and pre-commissioning in 2033, install in 2034.

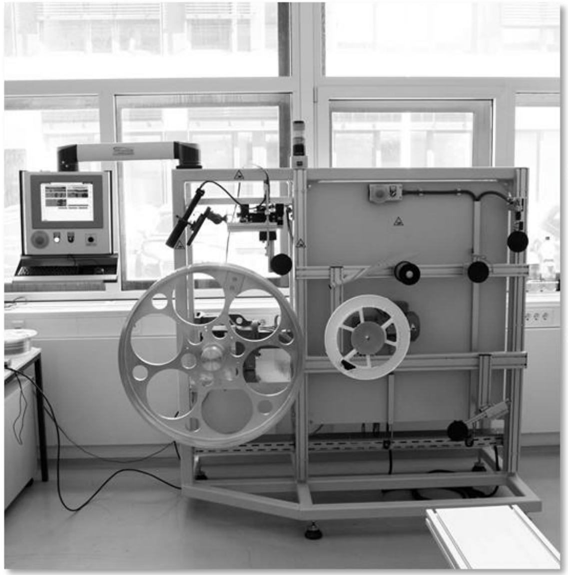
Mighty-SciFi Production Plan

We'll take an Everything-as-Early-as-Possible philosophy (EEP!).
The schedule can only get delayed. If enough components are available, start the next step. Provide enough dummies or prototypes for testing and commissioning assemblies.

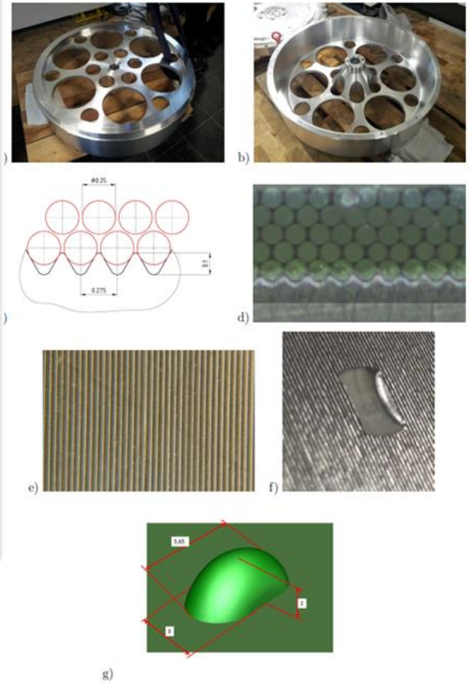


Production of the Mighty-SciFi

- Winding of ~1080 Fibre Mats
  +spares
- Baseline is Kuraray 78MJ like in U1
  - Fibre QA machine needs to be supported at CERN or moved
- Winding centres
  - Aachen
  - Dortmund
  - EPFL
  - ? (needs a new winding machine)
- Serial Production:
  - Order fibre Q1 2027 (directly after the TDR is accepted)
  - Mats in Q3 2027 – Q1 2030

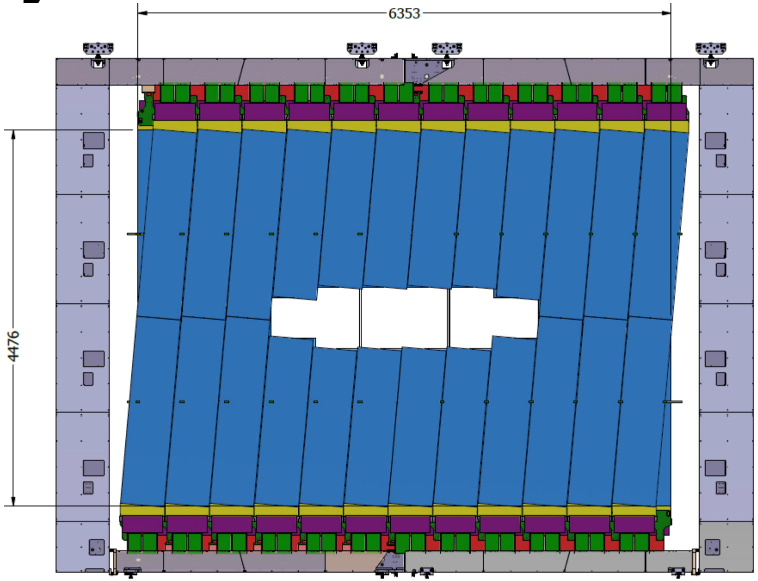


Fibre mat winding machine and wheel

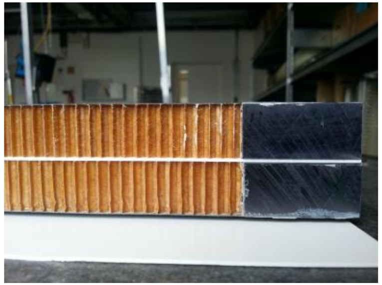


Production of the Mighty-SciFi

- Production of 256 modules
  +spares
  - 4 different lengths (~2.4m long)
  - "Cut-out" removes the extra material in the pixel region
  - Shorter modules should be easier to handle and produce.
  - Vacuum-tight interface at one end for the cold box
- Similar production schedule as the mats
  - At least 2 assembly sites with 1 or more in Germany

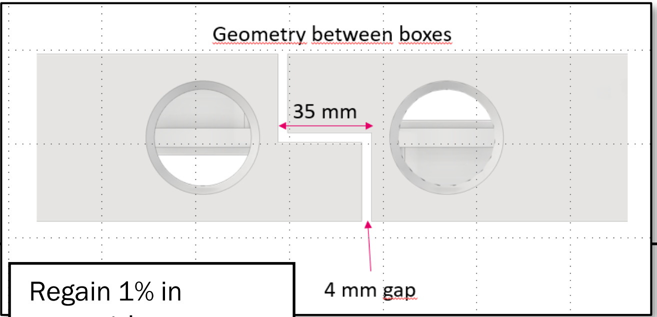


Honeycomb-carbon fibre composite panels with fibres in the middle

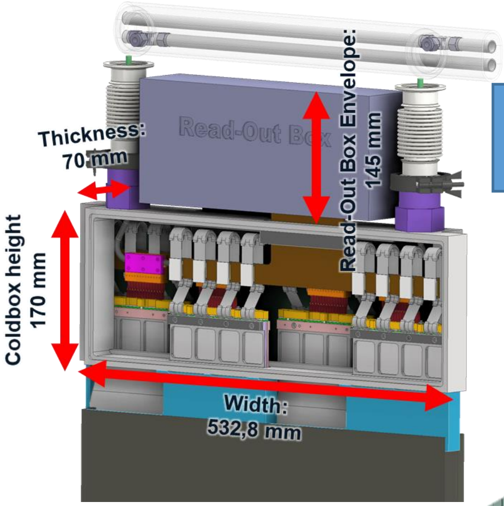


Production of the Mighty-SciFi

- Cryo Cold-boxes
  - Prototypes in development by Aachen and EPFL
  - Slight bend out of plane in Z to accommodate the cryo cooling bar
  - Introduces a module overlap to remove gaps between modules
  - Introduces a vacuum tightness requirement on the module interface and box.
  - Production Q3 2027 to Q1 2030

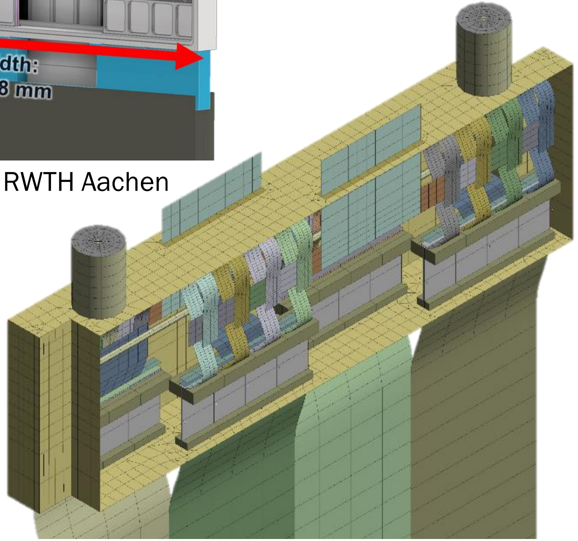


Regain 1% in geometric coverage.



CAD model from RWTH Aachen

Talk on Tuesday from Thomas Oeser

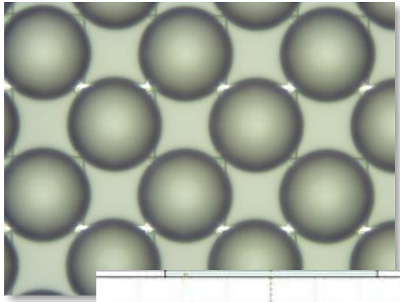


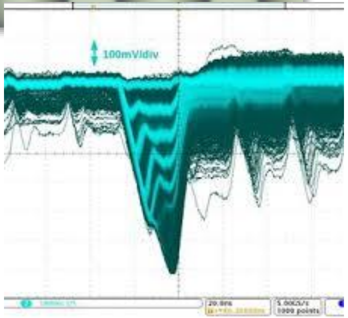
Production of the Mighty-SciFi

- SiPM developments at EPFL
  - Microlenses show gains in light yield of 10-30% depending on the overvoltage
  - Production needed in time to add to the cold-boxes and fix to the modules.
    - 2028-2029

- PACIFIC++ and the Front-end electronics (Poland, Brazil, Spain, Costa Rica,++)
    - Digital parts can be tested in an FPGA, but need to be baked into the (an) ASIC because of the higher radiation levels
    - Likely to have additions of a TDC and ADC .
    - Analog parts will need to be tuned to a cryo-sipm
    - Q4 2029 - Q4 2030

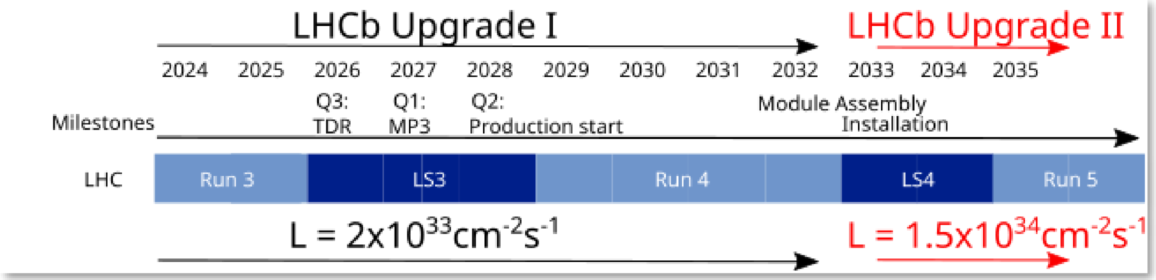
- Light-injection System for SiPM Calibration
  - Optical parts need to be included in the module+cold-box (2028-2029)





Production of the Mighty-Pixel

- It's a fresh technology for LHCb with all the teething problems and learning curve to go with it.
  - And we want to build 12.6m^2 of it.
- MightyPix1 and TelePix show the technology seems viable for MT.
- Take the experience from ALICE and some Atlas/Mu3e developments as input for production estimates of DMAPS detectors.



- **MightyPix2 to be submitted in Q1-Q2 2025 to AMS Foundry**
  - **will qualify LFoundry-150nm as an alternative foundry**
- **MightyPix3 in hand for an EDR in 2027**
- **MightyPix4 for Production in Q2 2028**

Talks on Tuesday from Hannah Schmitz and Lucas Dittmann on MightyPix status

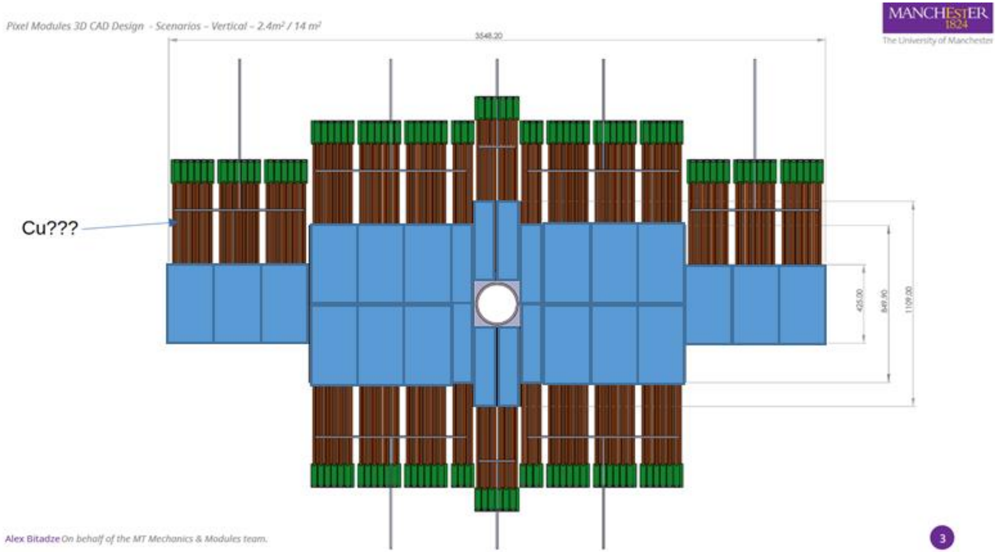
Production of the Mighty-Pixel

- Maintain Left-Right symmetry for LHCb

Move material away from the beamline (Y=0cm)

  - Some more secondaries in SciFi…

- Modular structure to accommodate chip size, assembly, and maintenance.



Production of the Mighty-Pixel

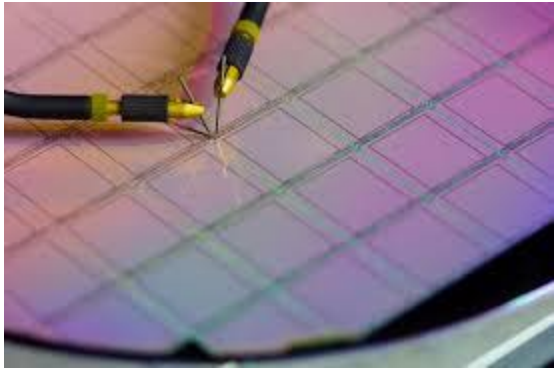
Production Chain

- Chip Production — Mpix 4: Q4 2027
- Wafer Probing → 60-70%
- Thinning/Dicing
- Chip Probing → Has to be >99%
- Chip to Flex — 2028 – Q3 2031
- Flex testing → 80%
- Flex to Module — 2029- Q1 2032
- Module testing → 85-90%

We need 34k Sensors for the baseline option ⟶ 100k sensors to be ordered (assume 40% pass)

This means 2.5k wafers.

We estimated (so far) that we would have 2 sites doing the wafer probing in 1.5 years with 200 workdays per year ⟶ 4.2 wafers per day



Material borrowed from Klaas Padeken

Production of the Mighty-Pixel

Production Chain

Chip Production		Mpix 4: Q4 2027
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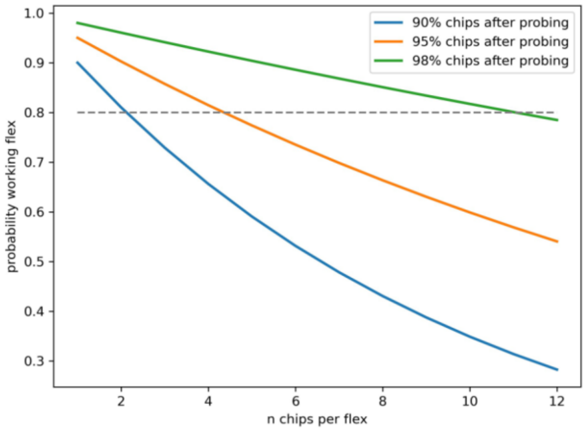
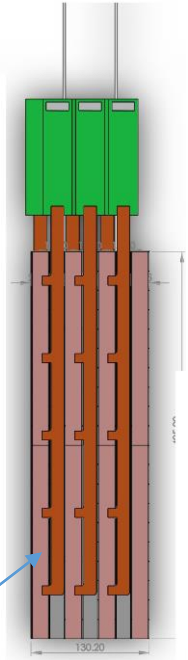
Thinning/Dicing		
Chip Probing	→ Has to be >99%	
Chip to Flex		2028 – Q3 2031
Flex testing	→ 80%	
Flex to Module		2029- Q1 2032
Module testing	→ 85-90%	

Chips per flex



To be roughly at 80% → 4 or 6 chips/flex with more than 95% chips working

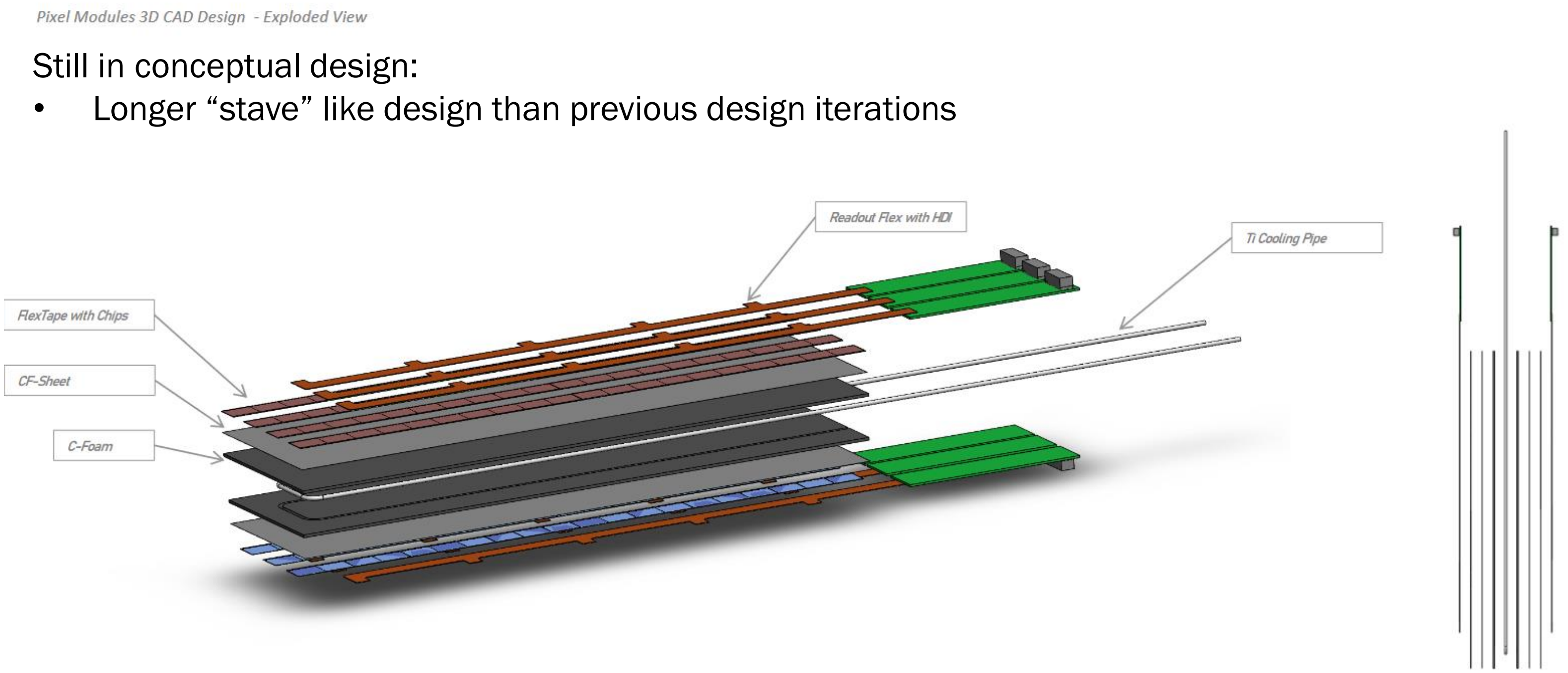
Flex with 6 chips



Material borrowed from Klaas Padeken

Production of the Mighty-Pixel

2029- Q1 2032



Still in conceptual design:

- Longer “stave” like design than previous design iterations

Alex Bitadze *On behalf of the MT Mechanics & Modules team.*

Material Budget

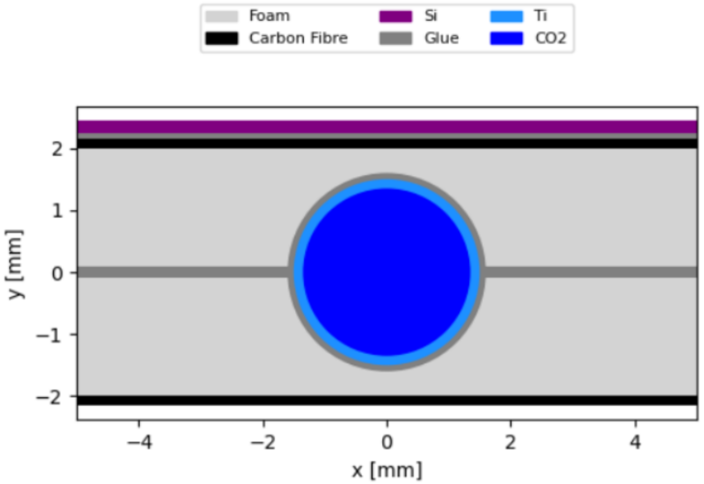
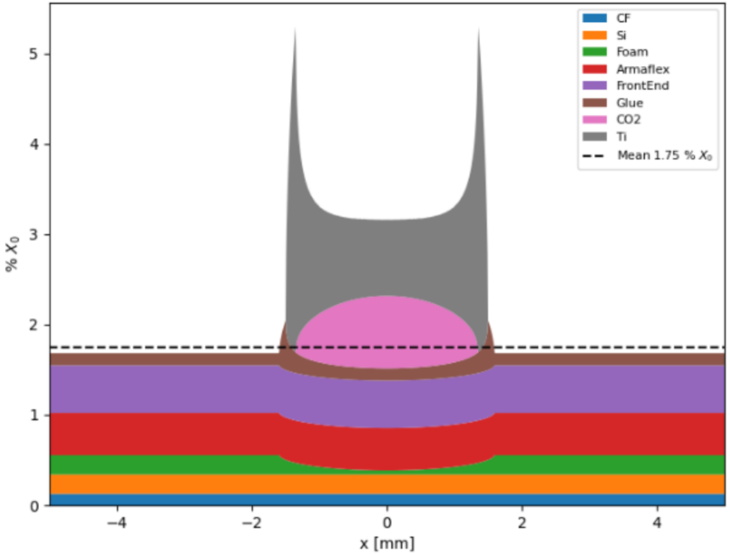


Figure 3: Cross-section of the module design, highlighting its different components.



1.75% X0 average per module;
Includes insulated box and electronics
(internal note in progress)

Radiation Damage and Maintenance

- Remember that Recorded Luminosity is lower than Delivered Luminosity (~85-90%)
  - End-of-life means +10-15% more than that

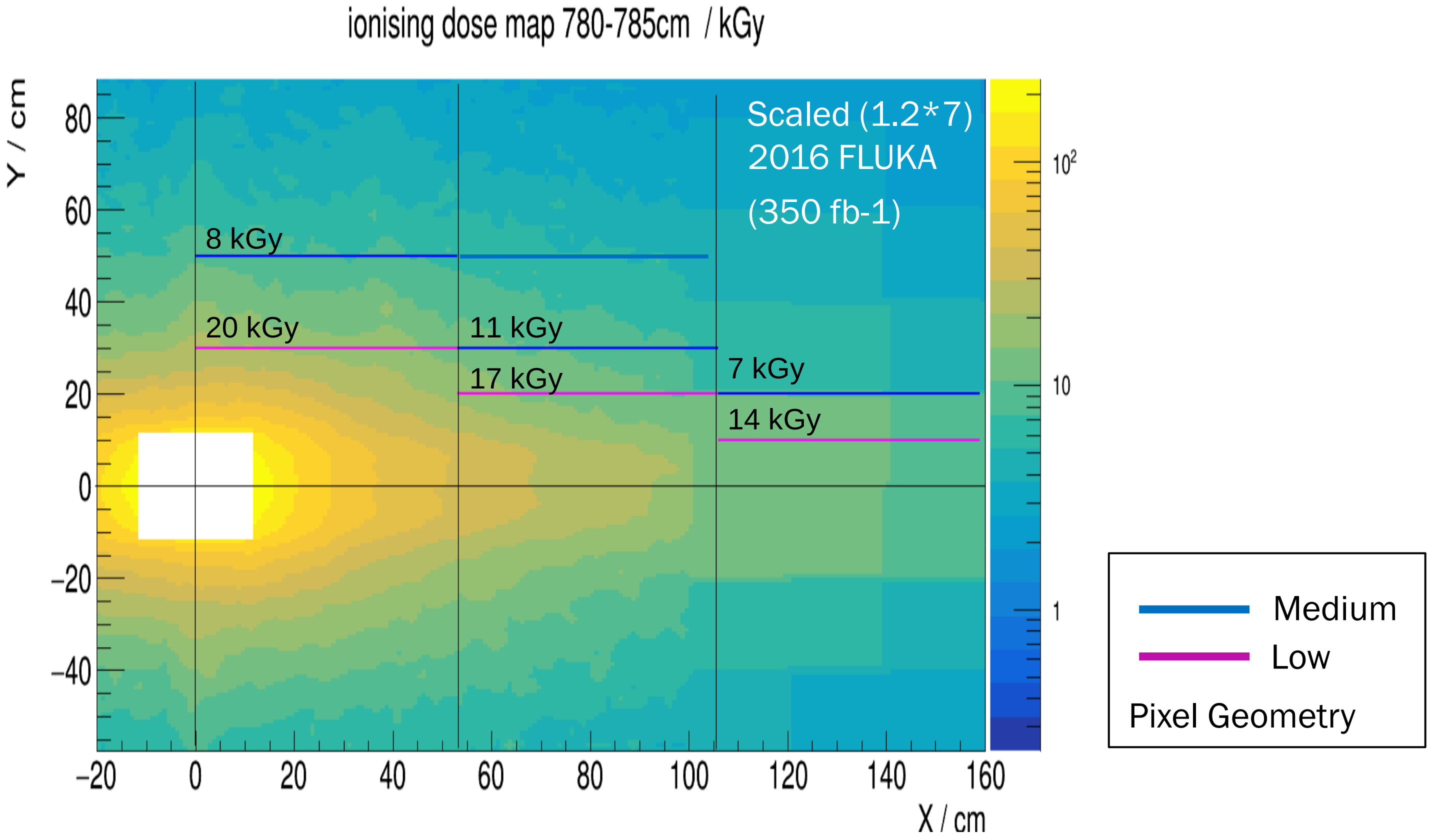
- ~2/3rds of the particle hits in the MT will come from secondaries from material interactions upstream [LHCb-PUB-2022-003]
  - Upstream material budgets will have an effect here , but also the beampipe flange.

- Like the SciFi in U1, little redundancy means high requirements on detector performance: in hit efficiency and operational efficiency.
  - Difficult to replace components during operation (once per year for major operations)
  - The pixel tracker will be next to a beryllium beam pipe under vacuum.
  - **Understand how the detector ages, and how components and systems behave in edge cases, what happens when they fail.**
  - **Test early and at scale with installation-like prototypes or production**

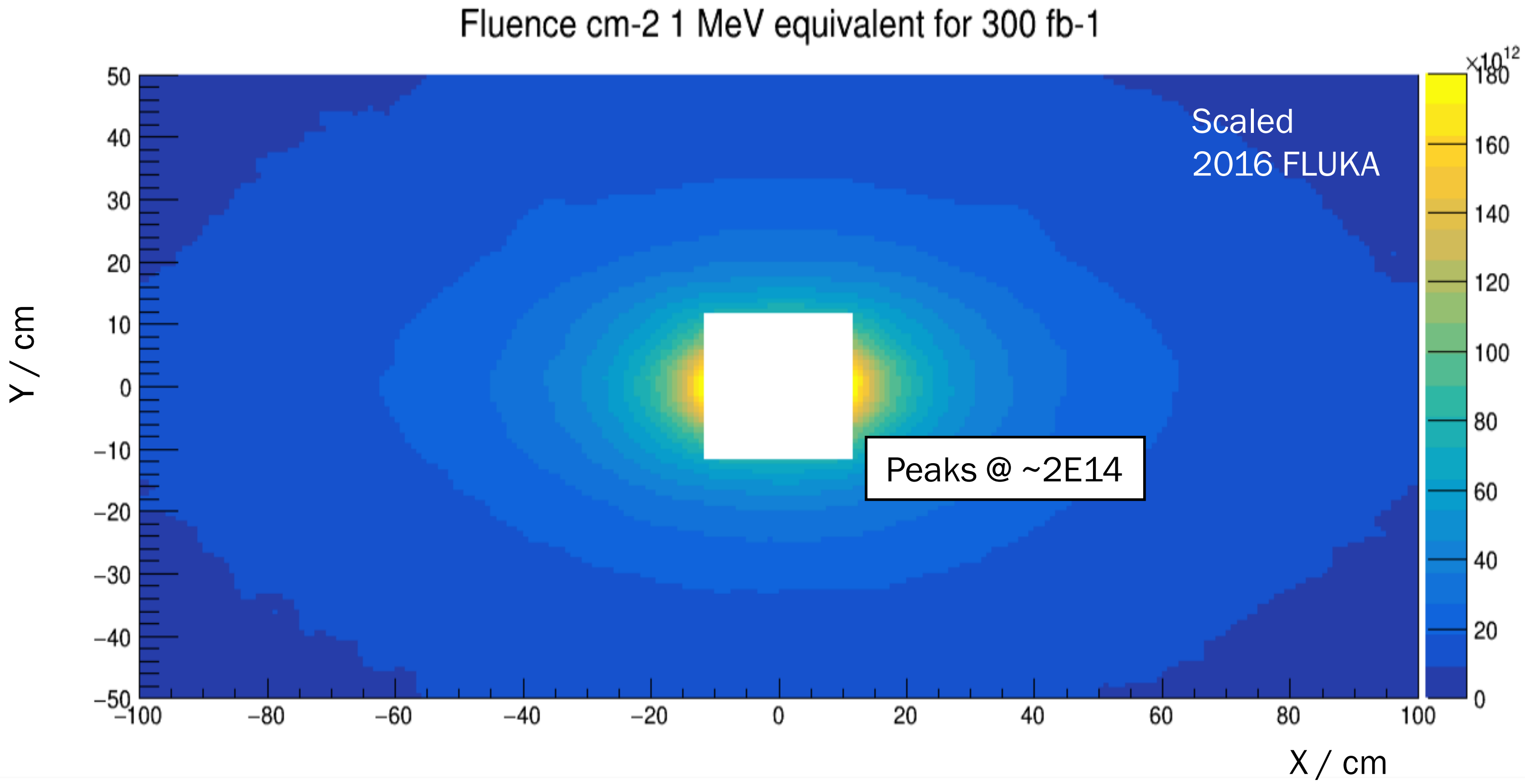
Ionising Radiation Dose (J/kg = Gy)

Find the boundary limits for hit <u>efficiency and occupancy</u>

Peak Dose is reduced for SciFi, but the **average dose is higher** outside in U2

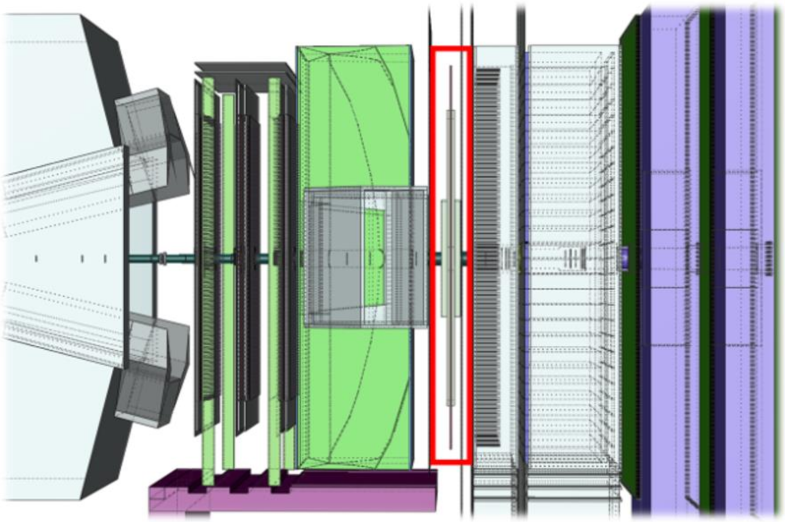


Non-Ionising Energy Loss (NIEL) Fluence



RP recommends to take x2 as safety factor.

Neutron Shielding



Required to have a SciFi in U2

Might also benefit the RICH 2 if they use SiPMs.

		(2016 FLUKA) No Shielding (1 MeV n.eq. 10^{12}) T3	(2016 FLUKA) Shielding (1 MeV n.eq. 10^{12}) T3	(2024 FLUKA*) No Shielding (1 MeV n.eq. 10^{12}) T3	(2024 FLUKA*) Shielding (1 MeV n.eq. 10^{12}) T3
	Upgrade 1 (50 fb-1)	1.4	0.4	2.1	0.6
Low-lumi	Upgrade 2 (284 fb-1)	8.0	2.4	12.0	3.6
Stated as high end	Upgrade 2 (350 fb-1)	9.8	2.9	14.7	4.4

I've put 2024 FLUKA as 1.5x 2016 FLUKA Fluences.

No Upgrade2 geometries like tungsten ECAL yet...

Conclusion

- The Mighty-SciFi and the Mighty-Pixel will perform as a tandem tracking system, sharing a common envelope

- The fibre part of SciFi is still waiting for the results from Run 3, but the production is understood. The system is running well in 2024.
  - The cryo-cooling will be critical for Run 5. See the talk from Thomas tomorrow.

- The pixel development is well underway to be one of the largest pixel trackers ever built.
  - For more details, stay tuned for talks on Tuesday from Hannah and Lucas

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