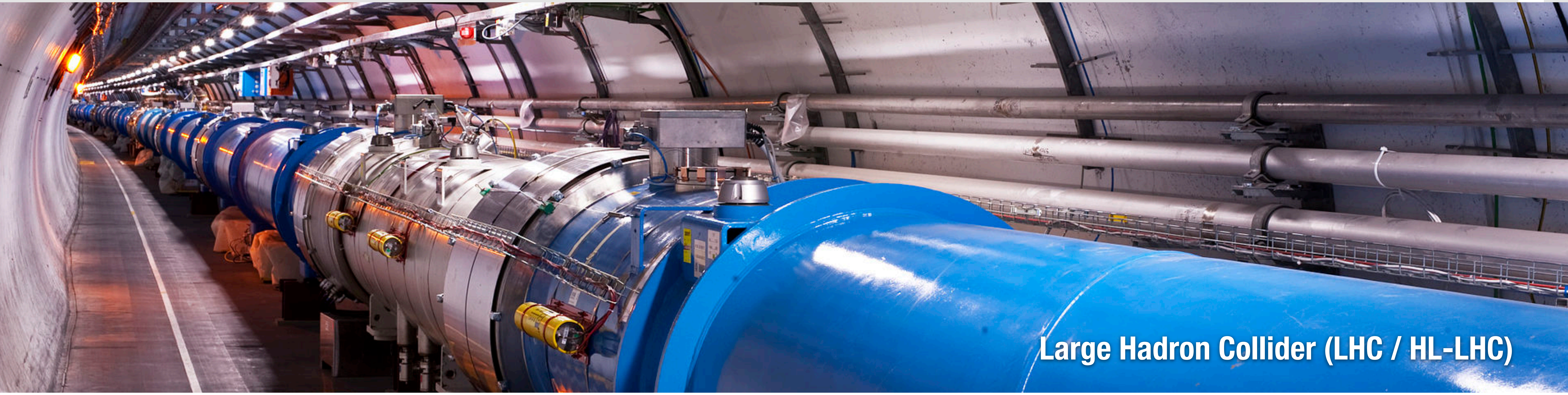
Upgrading the ATLAS tracker detectors for the High-Luminosity LHC era

First meeting of the Planes Complementarios AstroHEP

June 6, 2024 — Zaragoza

Carlos Escobar Ibáñez on behalf of the IFAE's and IFIC's ITk teams



High Luminosity LHC

- Introduction to the LHC upgrade
- The upgrade of the ATLAS tracker detector
- Outline and conclusions

In this presentation will talk just about ATLAS ITk upgrade work in the framework of the PPCC

IFAE Institut de Física d'Altes Energies

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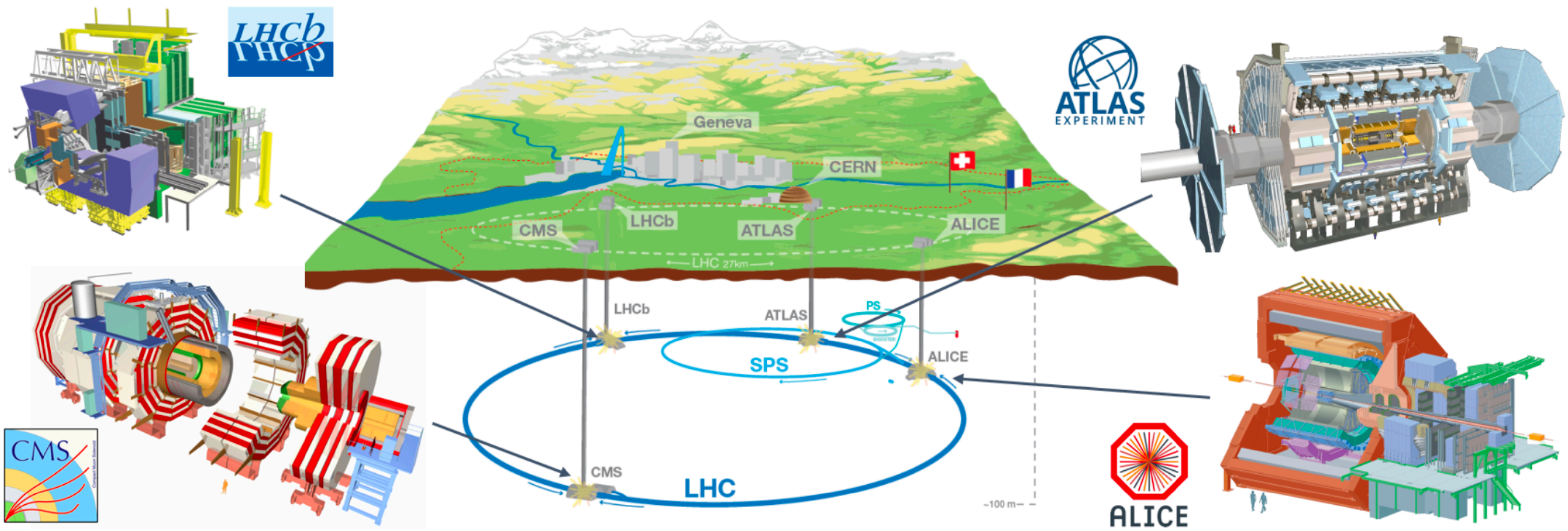
For a general overview see S. Grinstein's talk: Status of the Spanish contribution to the HL-LHC detector upgrades

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator

- Exploring the energy frontier since 2008
- Located at CERN, 100 m underground
- 27 km collider where two beams go in opposite directions
- Proton-proton collisions @ 40 MHz



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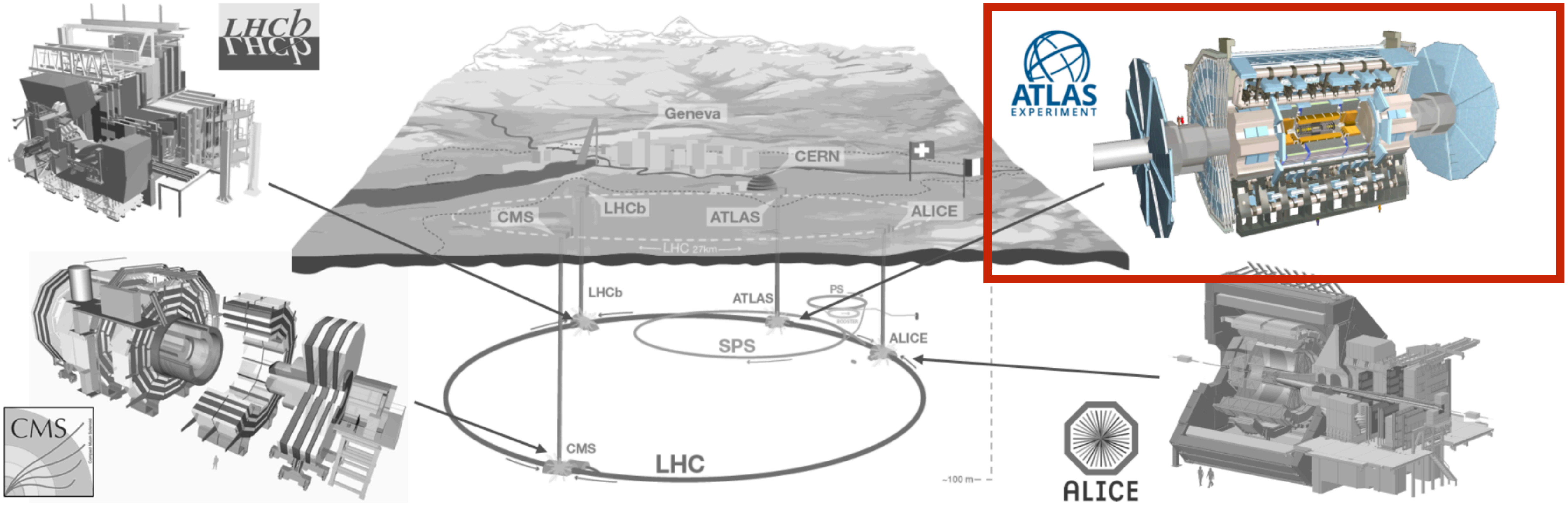


The High-Luminosiy LHC

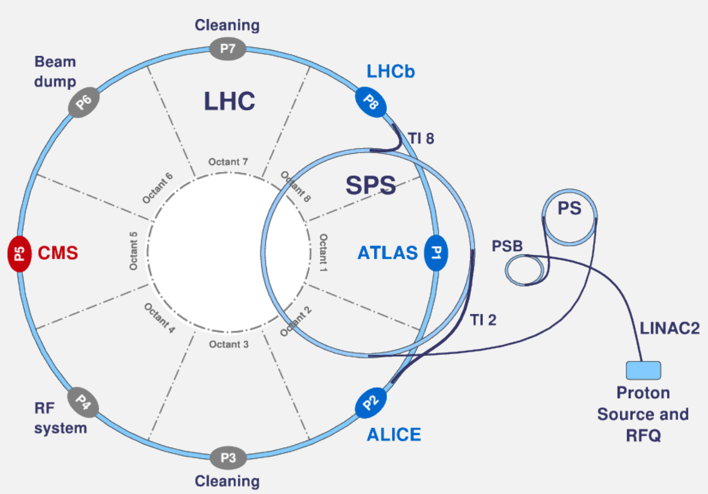
The High-Luminosity LHC (HL-LHC) is an upgraded version of the LHC

- HL-LHC is the next step to explore the energy frontier!
- Upgrading the CERN's accelerator complex would provide a **higher "useful luminosity"** to the detectors
- HL-LHC **installation (physics) phase** currently scheduled to start in **~2026 (~2029)**
- Major interventions on more than 1.2 km of the LHC tunnel
- Challenges: new IR-quads Nb3Sn (inner triplets), New 11T Nb3Sn (short) dipoles, Collimation upgrade, Cryogenics upgrade, Crab Cavities, Cold powering, Machine protection, etc

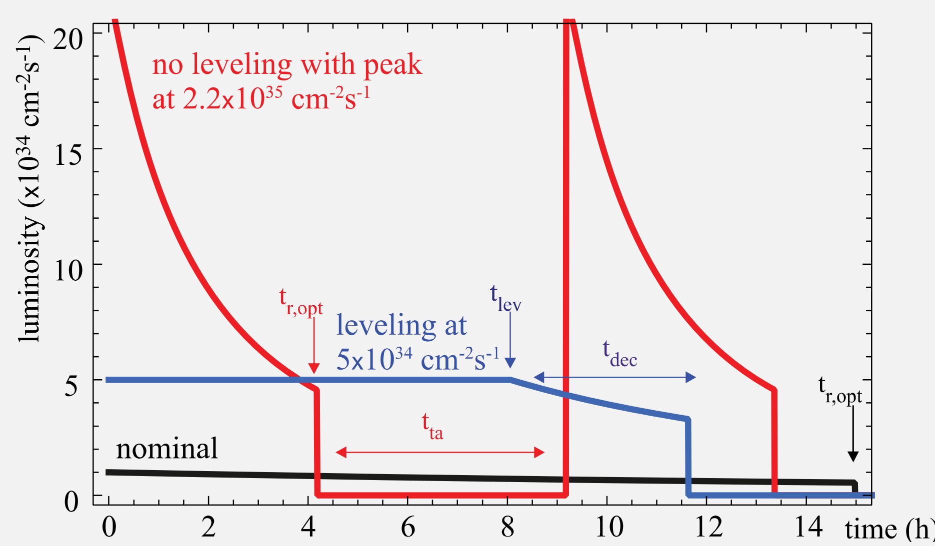
Beam current and brightness

(number of protons in beam)

New/better injectors
LIU (LHC Injector Upgrade)



Luminosity leveling (interaction point)



Useful luminosity.
Reduce radiation damage on IP and keep pile-up under control.
For efficiency it is better to have a constant luminosity for a longer time.

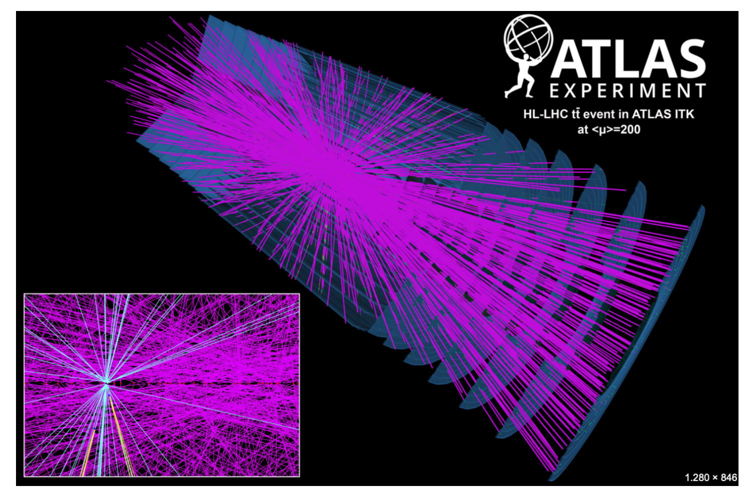
Goal of the HL-LHC:

- ~5 times the nominal LHC luminosity (5×10^{34} cm^{-2} s^{-1})
- Increase pile-up from ~50 to ~200 collisions per beam crossing
- Deliver >10x the integrated luminosity (3000-4000 fb^{-1}) of LHC Runs 1-3 combined
- The high luminosity offers the opportunity for a wealth of physics measurements but **presents significant challenges** to the detector and to the trigger and data acquisition systems in the form of **increased trigger rates, detector occupancy and radiation hardness**

↓

Need to **upgrade ATLAS experiment** to deal with more radiation damage, more “messy” events...

LHC event

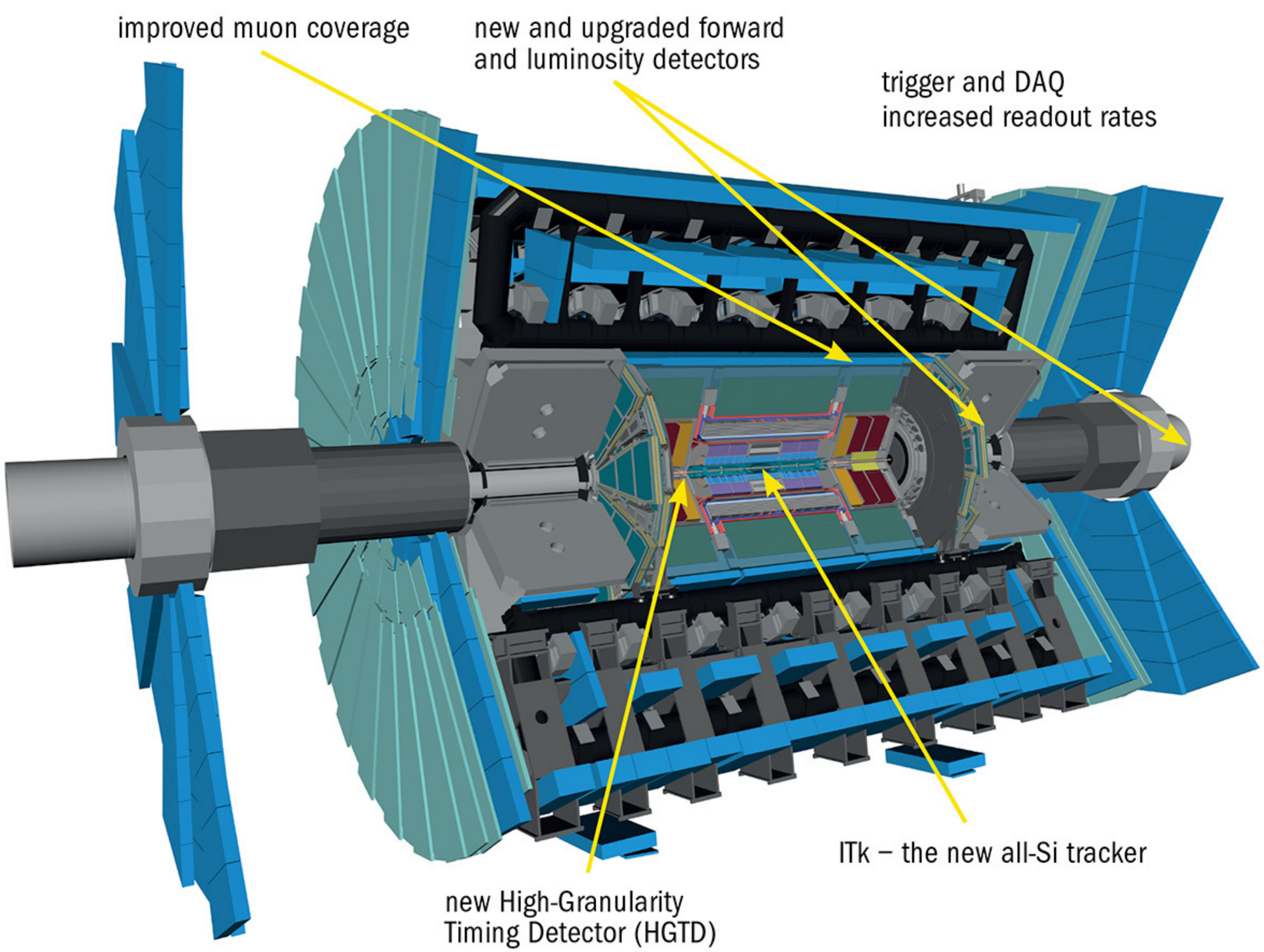


HL-LHC simulation

Goal of the detectors: keep similar performance in harsher environment than in the current detector

- Increased radiation levels and detector occupancy (higher granularity)
- Tracking performance is critical
- Maintaining (even improve) physics sensitivity is very challenging for the trigger

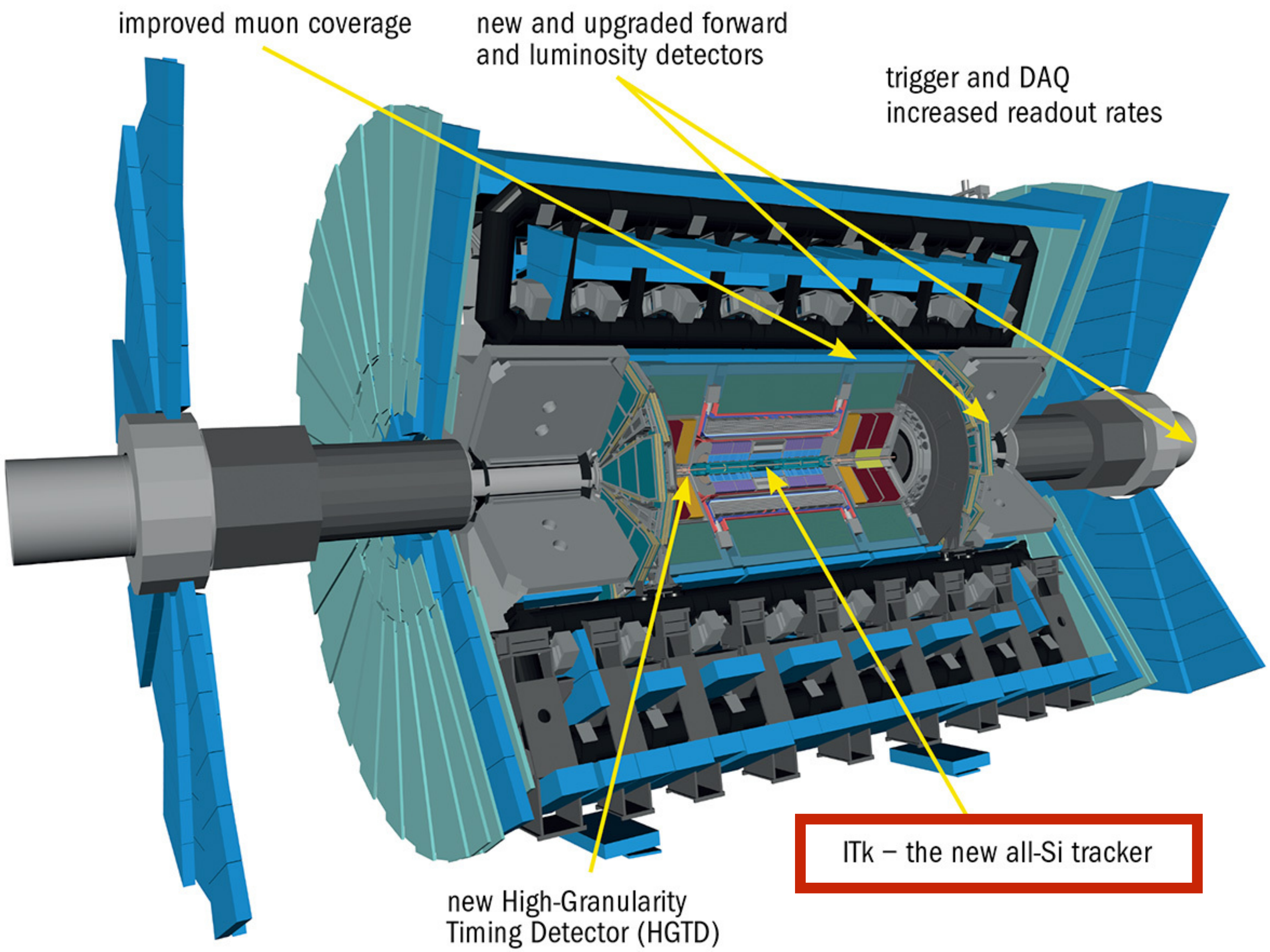
The upgrade of the ATLAS detector



- **Inner tracker replacement with all pixel and strip silicon design**
  - improved momentum resolution and added coverage from η 2.5 to 4.0 with low material budget
- **Calorimeters**
  - LAr: new full-digital FE and RO electronics with active PU corrections techniques
- **Muons**
  - additional muons chambers to increase trigger acceptance (under discussion η < 4) and suppress random coincidences
- **Trigger**
  - Upgrades L0 hardware trigger with RO of 1MHz and HLT of 10kHz
  - Hardware Tracker that provides HLT with tracks
  - (Evolution with track based triggers at 4 MHz)
- **(High-Granularity Timing Detector:**
  - precise timing (30ps) measurement of tracks 2.4<η<4.9 to reconstruct primary vertex)

- **Tracking**
  - Extended tracking up to η 4 with higher granularity
  - Provide L1 trigger with tracks
- **Calorimeter**
  - Increased granularity by switching read-out to silicon photomultipliers in hadronic/ endcap calorimeters
- **Muon**
  - Enhanced coverage of forward region up to η 2.8
- **Trigger**
  - L1 rate of 750kHz and 12.5μs latency and HLT with 7.5kHz
- **Minimum ionising particle timing detector**
  - up to η = 3.0 and timing resolution of 30ps to reconstruct primary vertex

The upgrade of the ATLAS detector



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In this presentation will talk just about ATLAS ITk upgrade work in the framework of the PPCC

The ATLAS tracker is designed to reconstruct the momentum of the charged particles traversing it

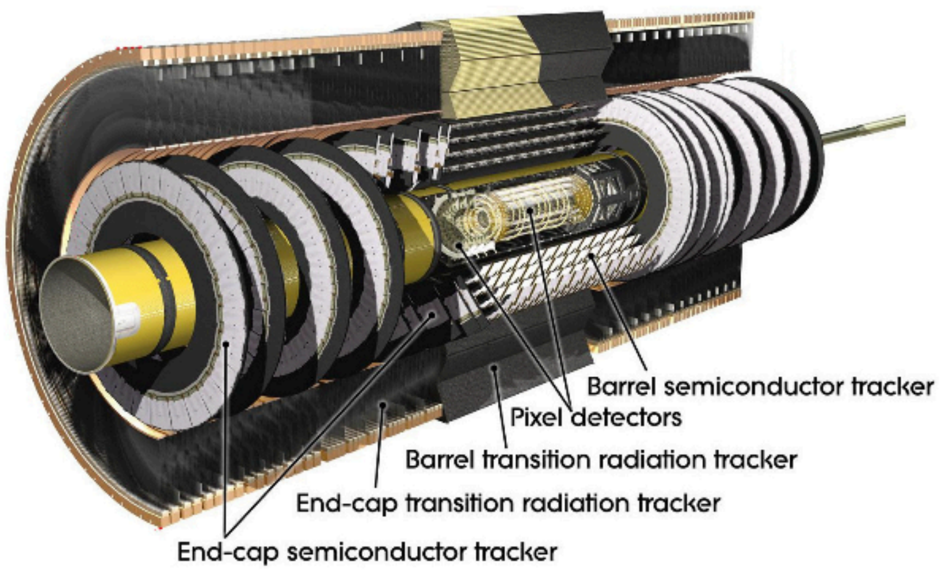
- Barrel + two end-caps
- Current trackers will not withstand radiation beyond 500 fb^{-1} → **change of silicon technology**
- **Reduced material and finer granularity** (space/time) needed for pattern recognition at pile-up of ~200
- **Increase bandwidth** to readout the higher volume of data
- At least 9 silicon hits per track

LHC (Inner detector (ID))

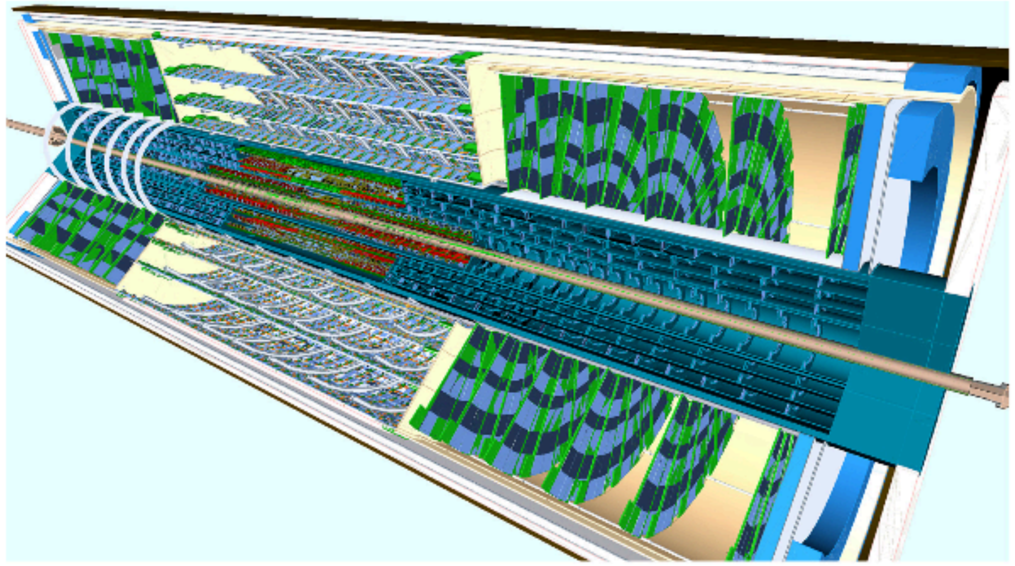
- IBL and Pixels (Si-pixel)
- SCT (Si μ-strip)
- TRT (straw tubes)
- Coverage of $|\eta| < 2.5$

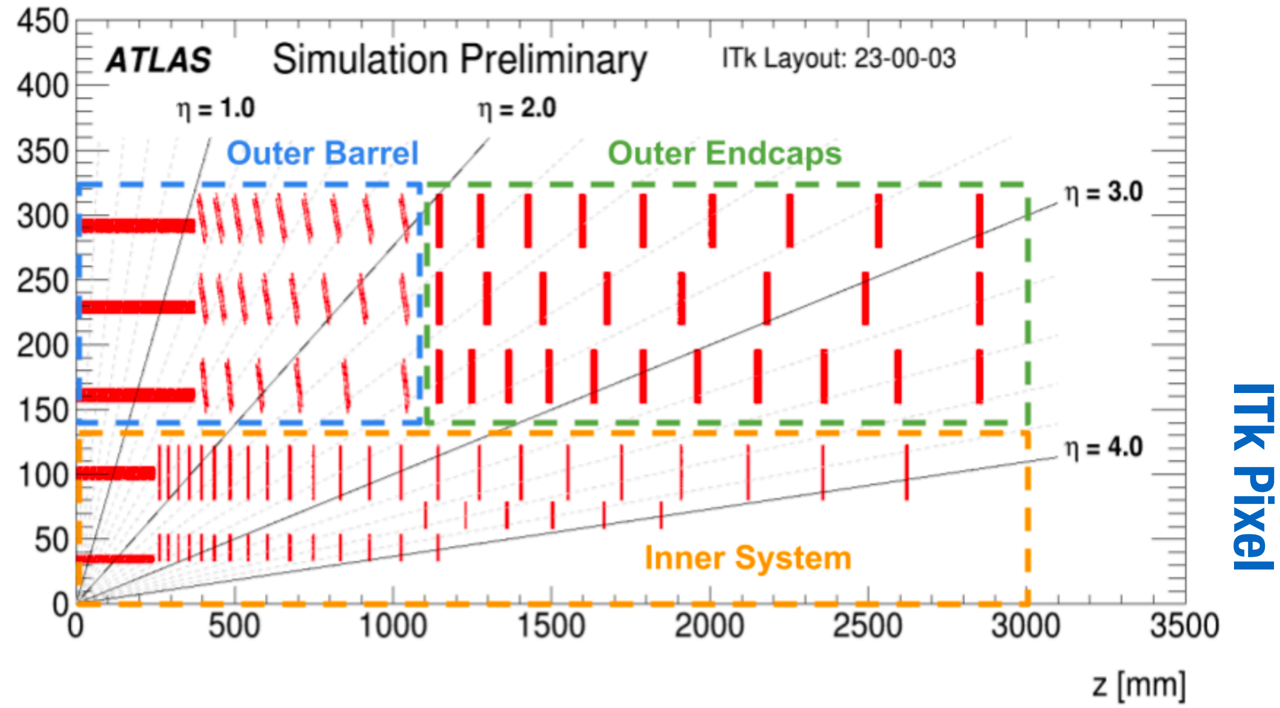
HL-LHC (Inner Tracker (ITk))

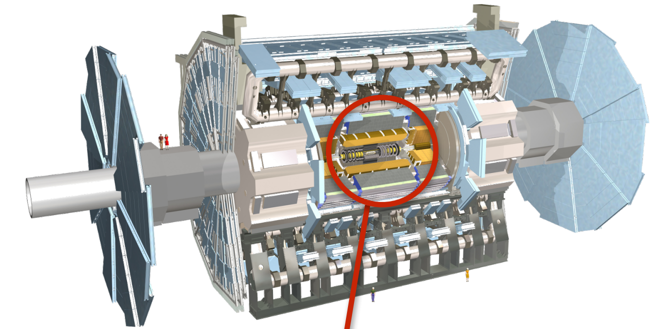
- **ITk Pixel (Si-pixel)**
- **ITk Strip (Si μ-strips)**
- High Granularity Timing Detector (HGTD)
- Coverage of $|\eta| < 4.0$ (μ-strips $|\eta| < 2.5$)

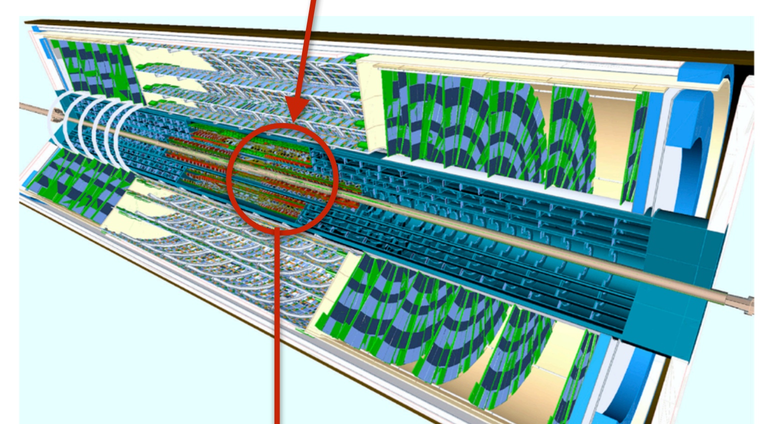


Full replacement →





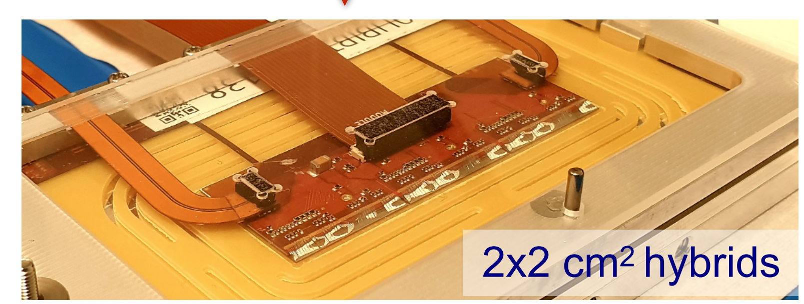




- ITk-Pixel has more than 5 G Pixels (~10 k modules)
  - Active area: 13 m^2
- Three systems (inner, outer, outer end-caps) → $\eta < 4$
- Inner system replaceable (radiation damage)
- Serial powering and carbon fiber supports

Sensors:

- Pixel sizes
  - 25 x 100 µm^2 (innermost barrel)
  - 50 x 50 µm^2 (everywhere else) →
- 3D sensors in innermost barrel/disks
- Planar sensors in the other layers
- 3 or 4 FE chips/module (triplets, quads)

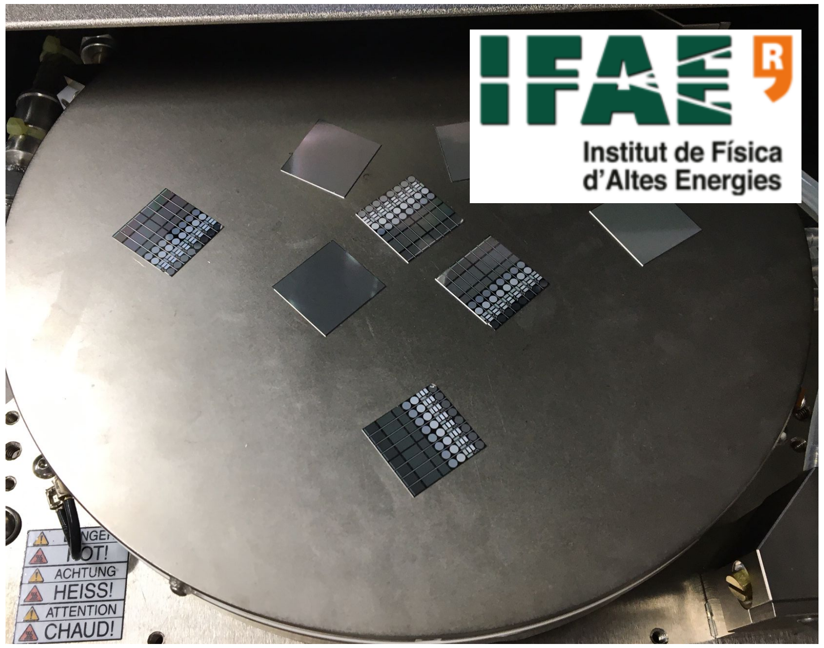


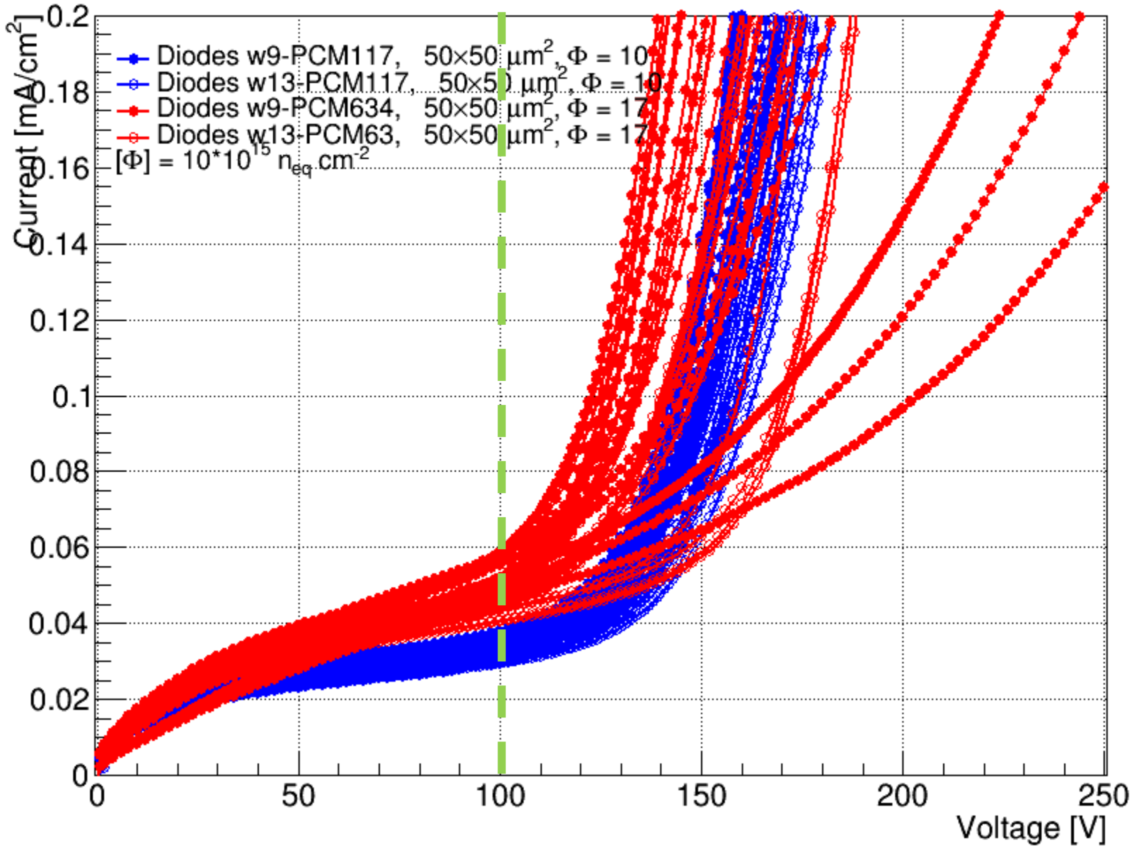
IFAE-Barcelona contribution:

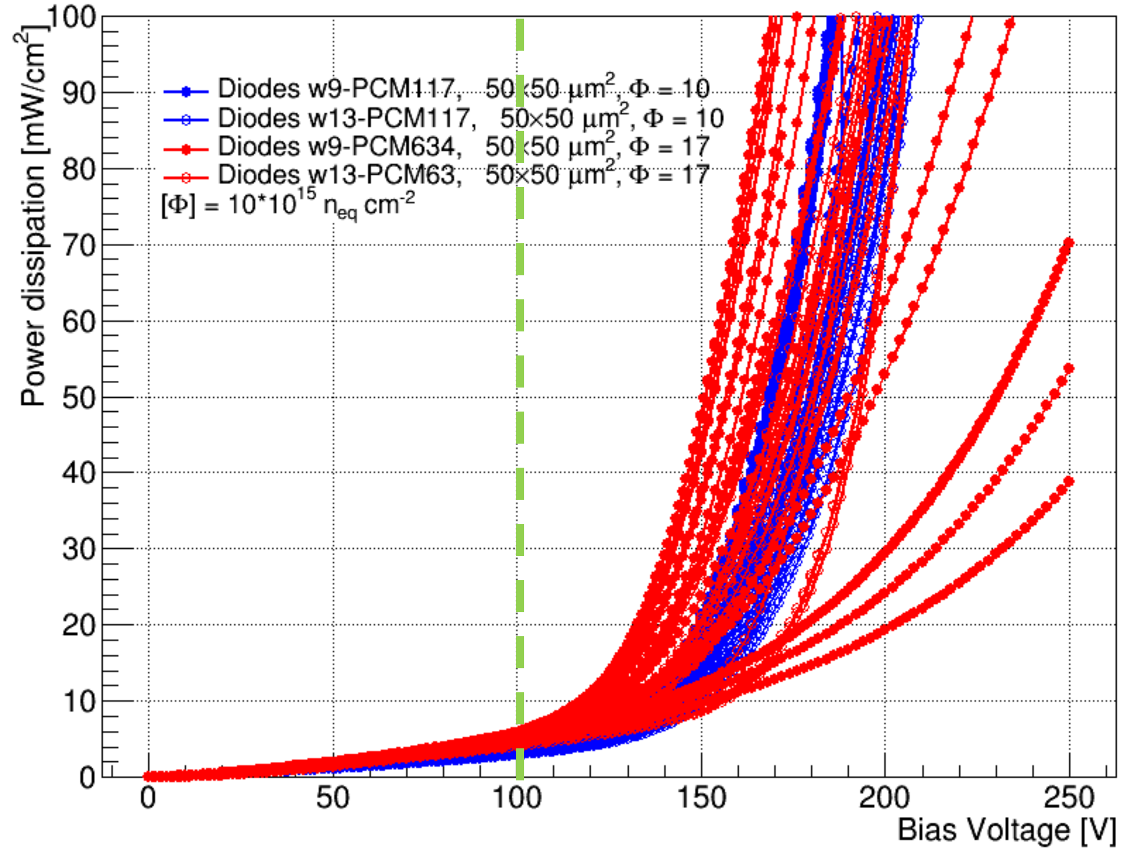
- Assembly and testing of **innermost** triplet pixel modules of barrel section (L0)

ITk Pixel sensor quality assurance

- Verify electrical properties of test diodes and 3D sensors with Temporary Metal before and after irradiation
  - Irradiations at JSI, Ljubljana with reactor neutrons and at CYRIC, Japan with protons
- Probe station with cold chuck at IMB-CNM
  - IV measurements at 20 ˚C (before irrad.) and -25˚C (after irrad.)
- **Sensors should be able to operate at 100 V after irradiation to 1.7^{16} n_{eq}/cm^2**



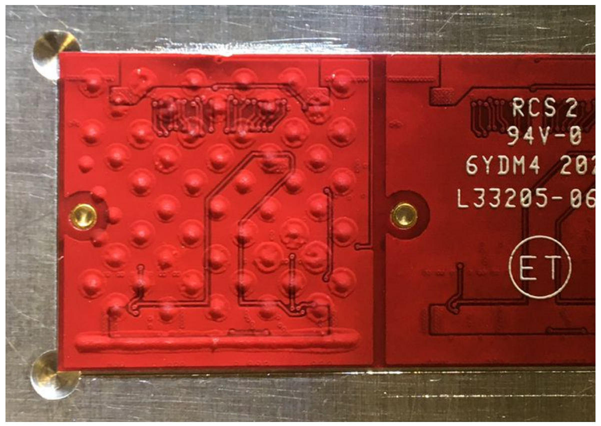




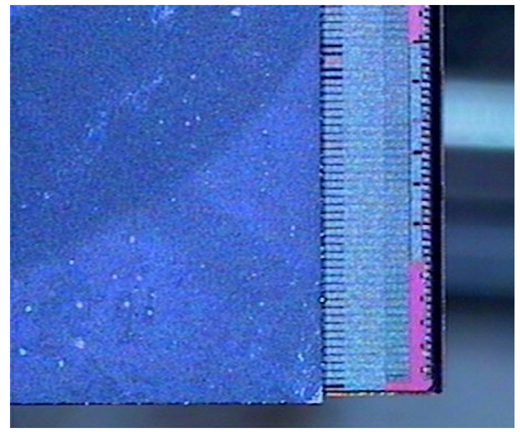
Low power dissipation is a critical feature of 3D sensors

Triplet module: three front-ends bump-bonded onto three sensor dies

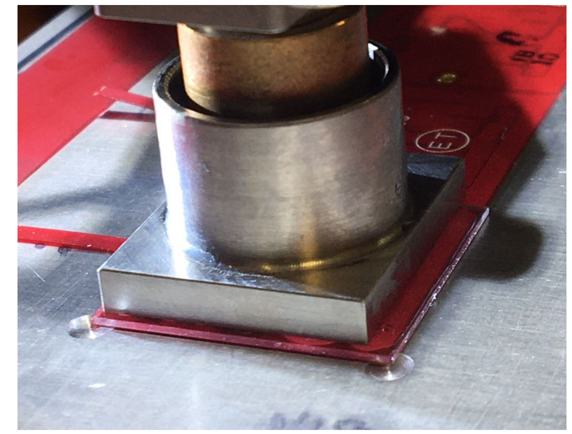
(1) Deposit glue on flex



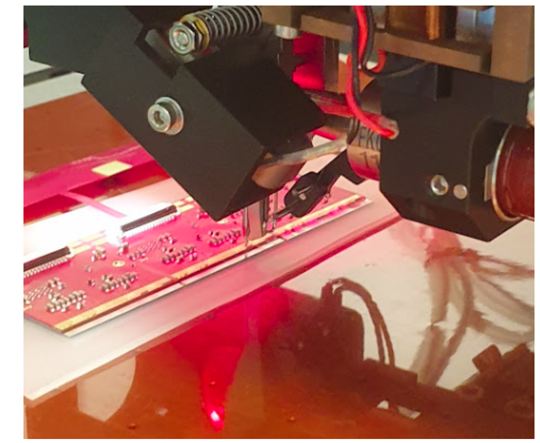
(2) Align hybrids and flex



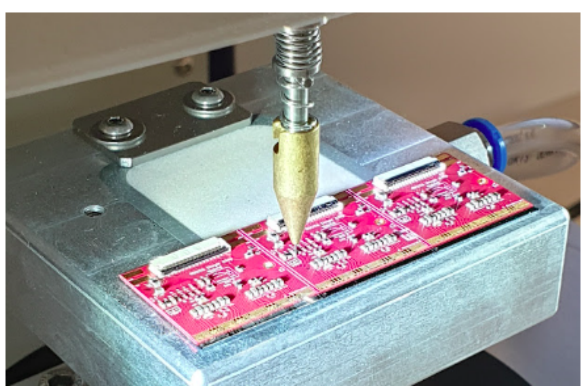
(3) Place hybrid on flex



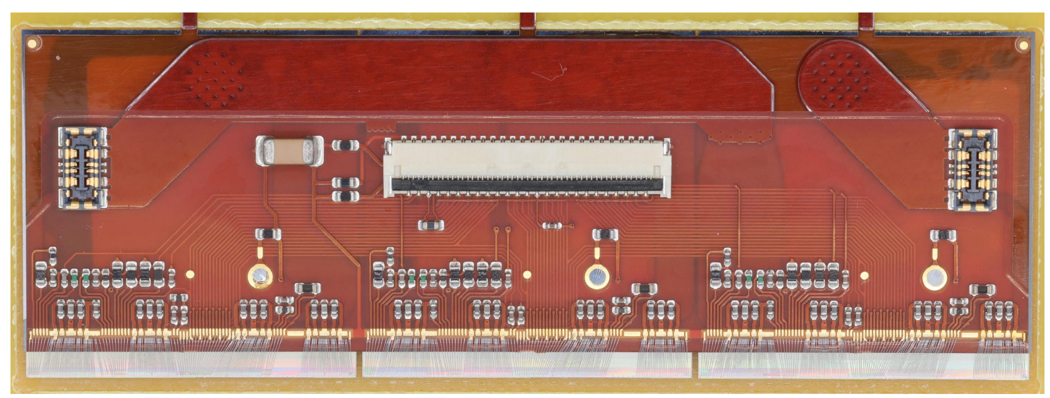
(4) Wire-bond

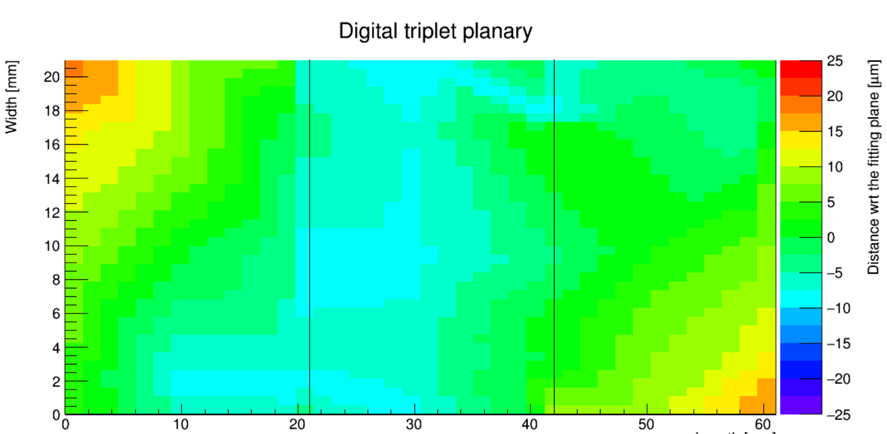


(5) Wire-bond



(6) Metrology



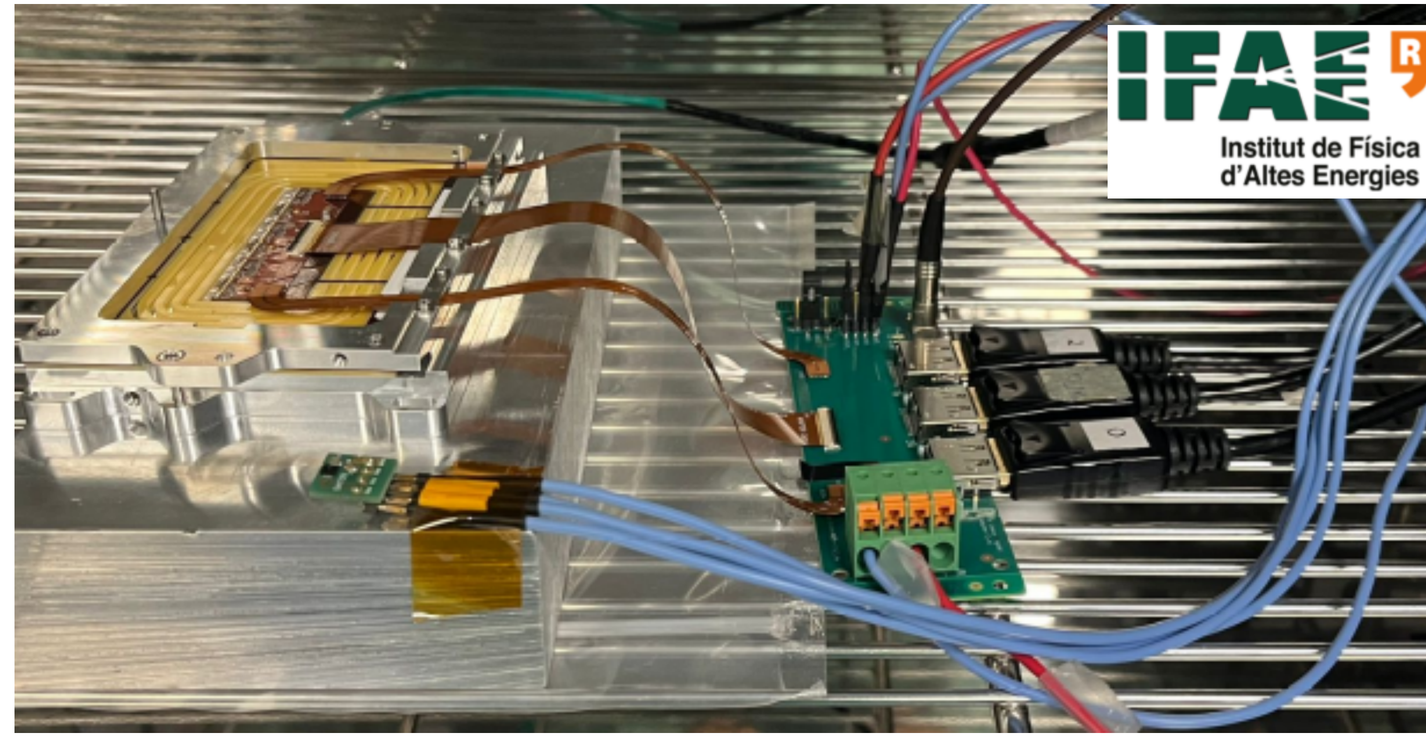


Several metrology steps

- Length
- Rotation
- Flatness
- Glue coverage (in glass dummies)
- Glue weight
- …

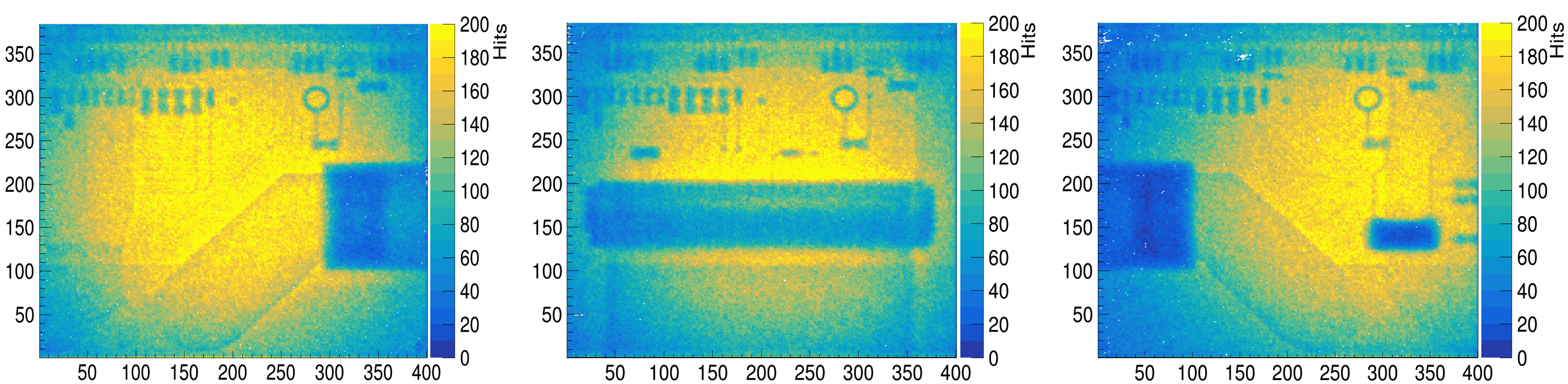
Full process currently takes several days… will need to speed up assembly and testing process towards production!

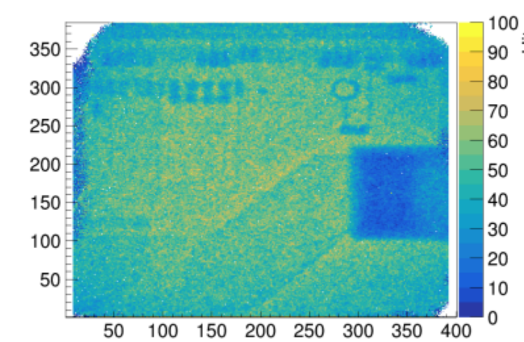
- **Electrical characterization**
  - Basic chip functionalities
  - Tuning
  - Sensor IV
- **Thermal cycling:**
  - From -45°C to +40°C
  - Climate chamber with dry air flushing (RH ~10%)



- **Check for disconnected bumps**
  - Dedicated disconnected bump scan
  - Sr90 β-source scan

The good...





The bad…

Still tuning hybridization process!

ITk Pixel triplet module pre-production

- Triplet pre-production well underway at IFAE
- Out of **9 triplets assembled** so far only 1 has currently has a critical failure

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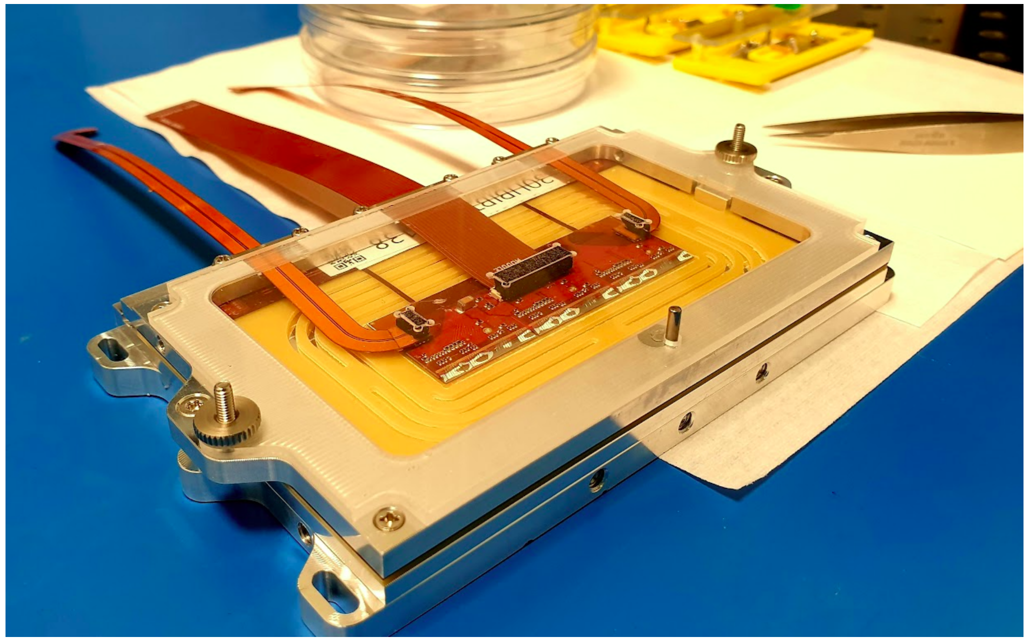
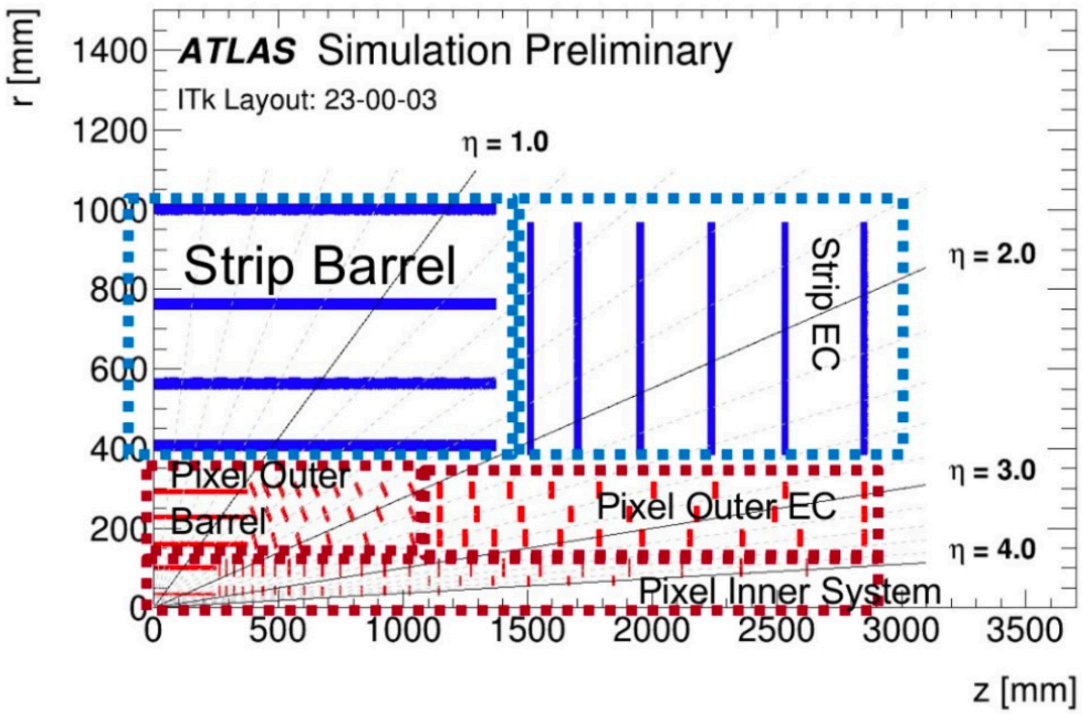
	SN	BMs	Part Rec.	Assembly	WB	Warm	Cold	TC+PFA	Sta+PFA	F. Warm	F. Cold	Comments
Pre-0	20UPIMS2102138	Sin50-IZM	DONE	DONE	DONE	DONE	DONE	DONE	Not Yet	Not Yet	Not Yet	Some disc. areas (expected)
Pre-1	20UPIMS2102134	FBK25-LND	DONE	DONE	DONE	FAIL	NO	NO	NO	NO	NO	No communication (Ship to Berkeley)
Pre-2	20UPIMS2102133	FBK25-LND	DONE	DONE	DONE	DONE	DONE	DONE	Not Yet	Not Yet	Not Yet	Disc areas. Increased after TC
Pre-3	20UPIMS2102132	FBK25-LND	DONE	DONE	DONE	DONE	DONE	DONE	Not Yet	Not Yet	Not Yet	Disc areas. Increased after TC
Pre-4	20UPIMS2102141	FBK25-LND	DONE	DONE	DONE	DONE	DONE	DONE	Not Yet	Not Yet	Not Yet	So far, OK
Pre-5	20UPIMS2102142	FBK25-LND	DONE	DONE	DONE	DONE	DONE	NO	Not Yet	Not Yet	Not Yet	Source scan crash // LPmode error
Pre-6	20UPIMS2102143	FBK25-LND	DONE	DONE	DONE	DONE	DONE	NO	Not Yet	Not Yet	Not Yet	Source scan crash
Pre-7	20UPIMS2102144	FBK50-IZM	DONE	DONE	DONE	DONE	DONE	Not Yet	Not Yet	Not Yet	Not Yet	So far, OK
Pre-8	20UPIMS2102146	FBK50-IZM	DONE	DONE	DONE	DONE	On going	Not Yet	Not Yet	Not Yet	Not Yet	
Pre-9	20UPIMS2102147	FBK50-IZM	DONE	DONE	DONE	DONE	On going	Not Yet	Not Yet	Not Yet	Not Yet	
Pre-10	?	?	Not Yet	Not Yet	Not Yet	Not Yet	Not Yet	Not Yet	Not Yet	Not Yet	Not Yet	

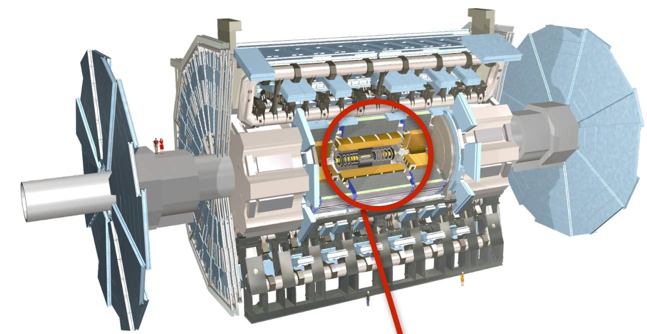


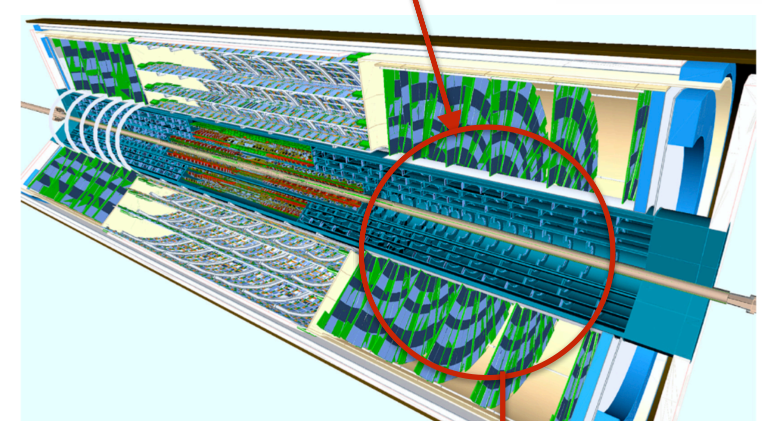
- Modules to be shipped to SLAC (USA) for loading
- Triplet production (i.e. final modules) to start end of 2024
- Target is to built **130 triplet modules** at IFAE

ITk Strip detector



ITk Pixel + ITk Strip

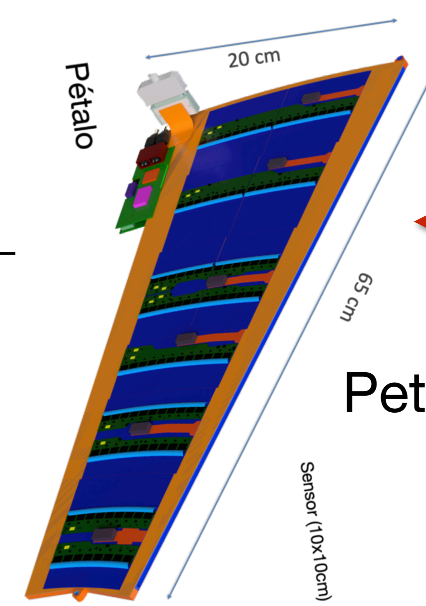




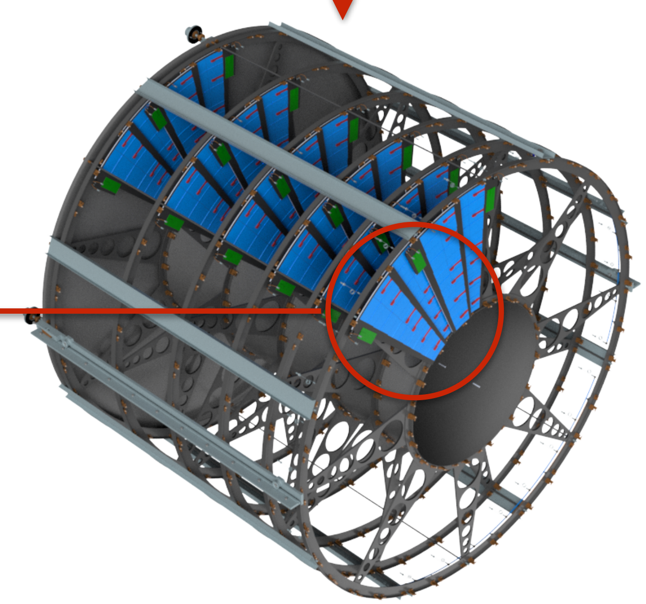
- ITk-Strip has ~165 m^2 of silicon micro-strip
- Each end-cap has 6 disks
- Each disc has 32 wedge-shaped carbon fiber supports (petals)
- Each petal houses 18 sensors, 9 on each side

IFIC-Valencia contribution: ←

- Assembly and testing of global structures, petals and modules for the ITk end-caps



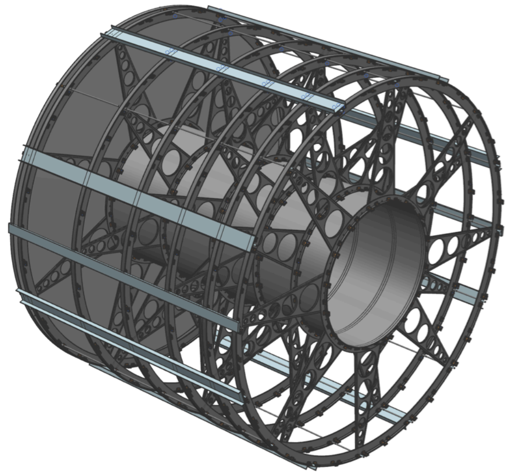
Petal

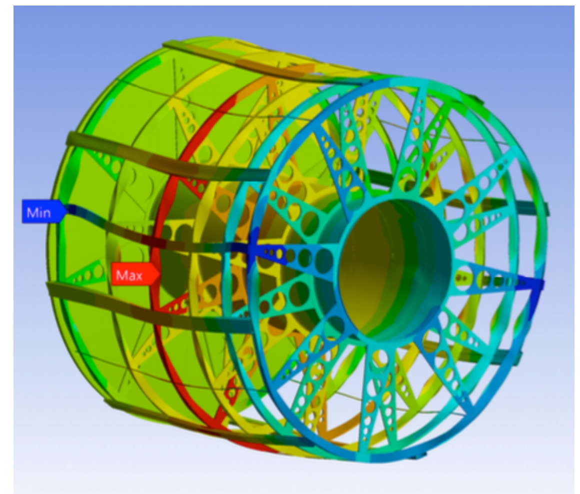


ITk Strip end-cap

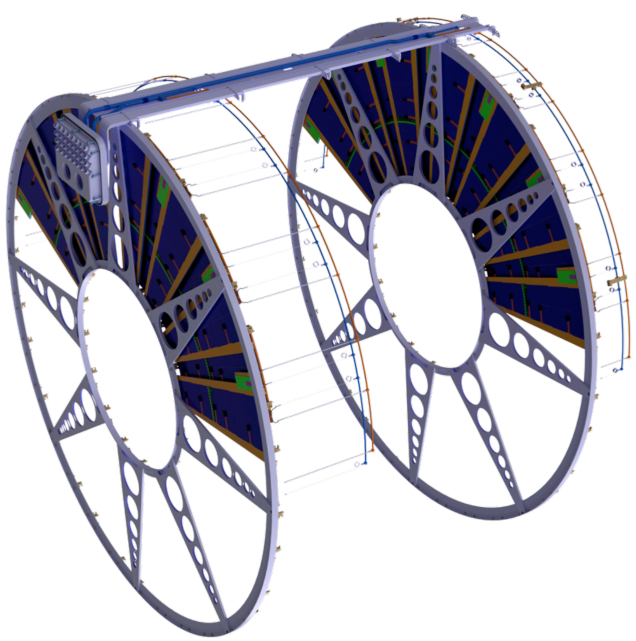
ITk Strip Global Support and Integration and Services

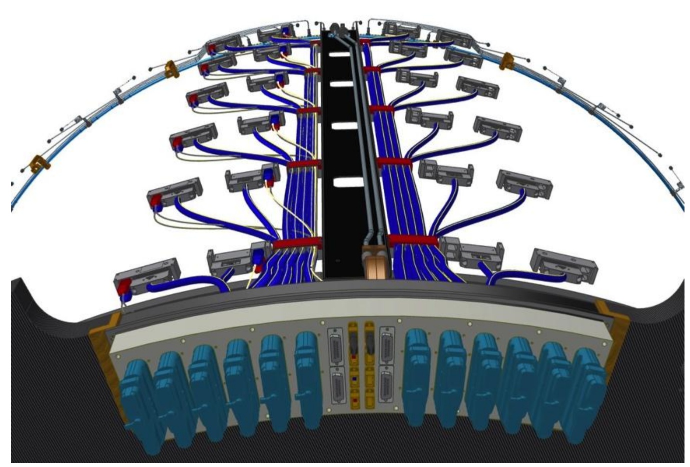
- Design of the **global support structure** and petal fixation to the structure (in collaboration with NIKHEF and DESY)
- Finite Element Analysis to optimize the structural stability of the system

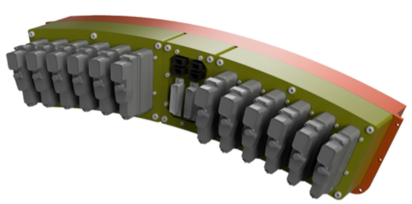




- Design of the **service module** bringing power, control signals and cooling to the petals
  - Service patch panel in the structural bulkhead to connect to services beyond the ITk volume
  - Design of customized cables and connectors for both detector and off-detector connections
  - Assemble and test the 16 service modules and install them in the end-cap mechanical structures







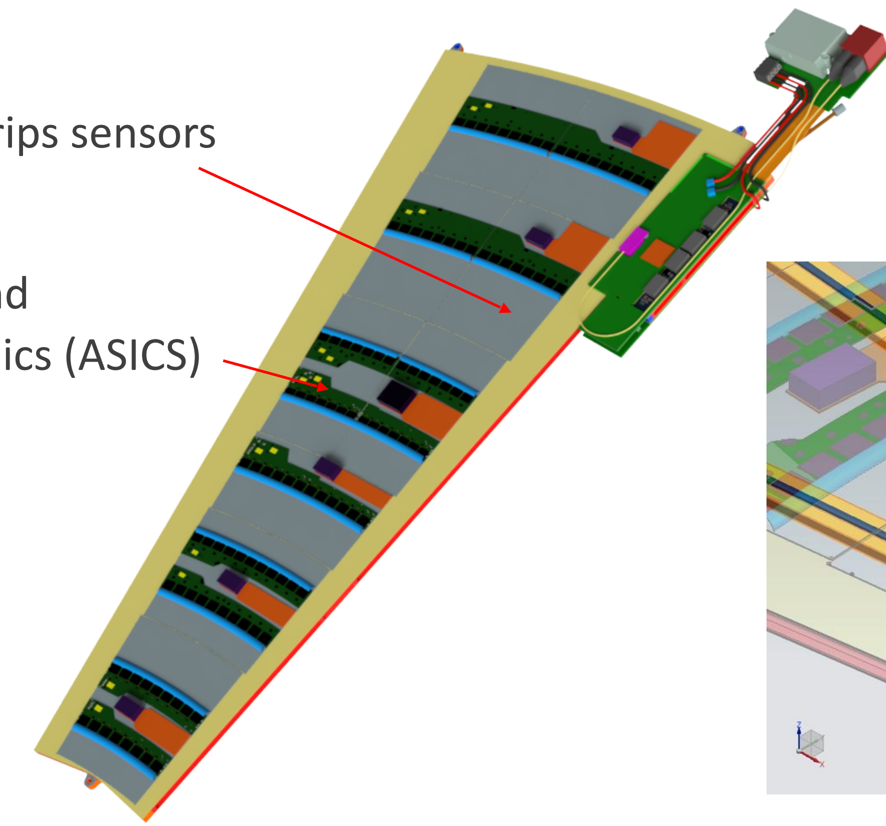
Real size mock-up to check envelopes and train connection of services

ITk Strip petals assembly and design

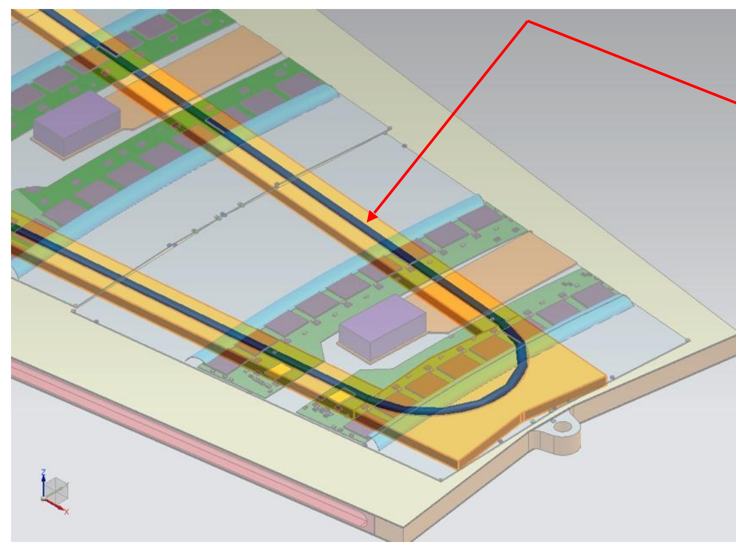
- **Sensors are glued on local supports (Petals).** This is the building block of the EC system
  - It is a carbon fibre sandwich with integrated cooling and electronics
- Double sided object with 18 sensors, 70 cm height, 10-20 cm width

Silicon μ-strips sensors

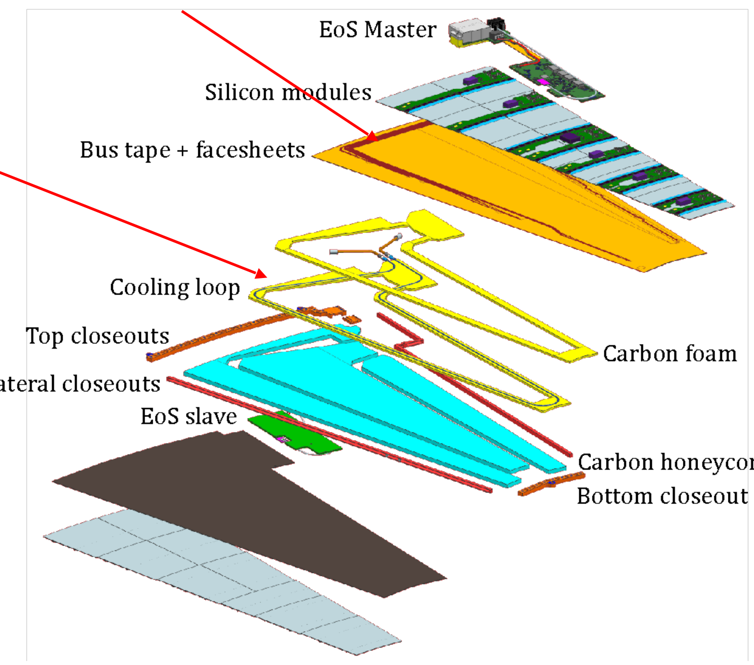
Front End electronics (ASICS)



Cooling pipes



Bus tape to distribute power and signals



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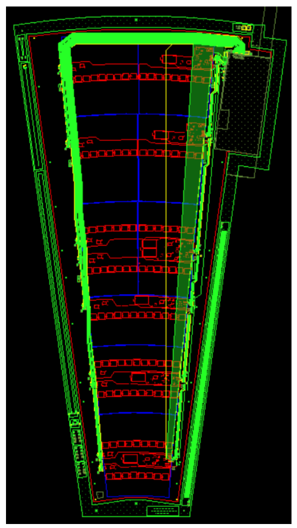
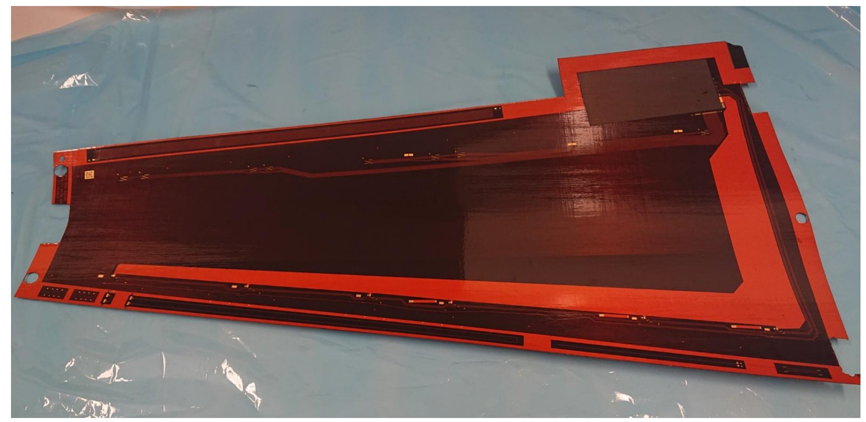
Design of the petal bustapes

- The different signals and voltages get to the modules in the petal via the traces on a polyimide tape (bustape) which is co-cured with the carbon fiber pre-pregs that make the petal facing, where modules are glued onto



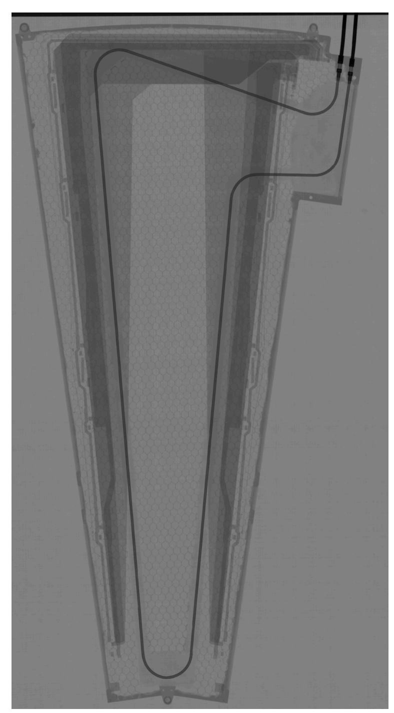


Tapes designed in IFIC-Valencia (front and back) and fabricated in Slovenia

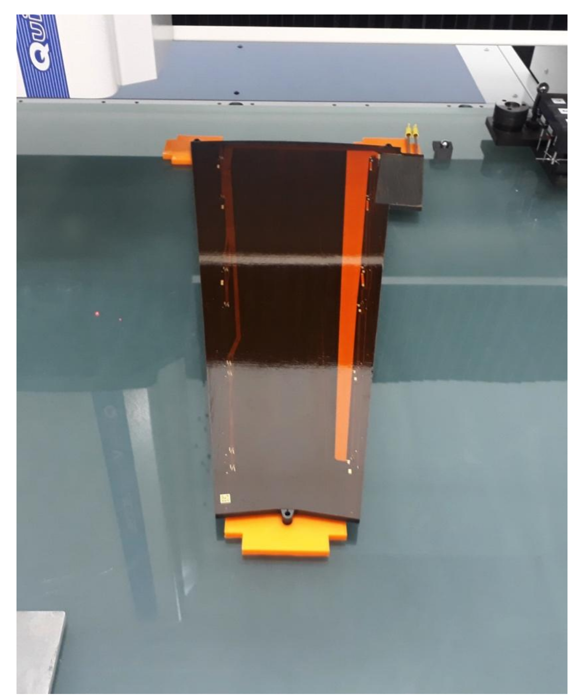
Petal cores: Quality Assurance (QA) and Quality Control (QC)

- In charge of the QC of 200 core petals during production phase

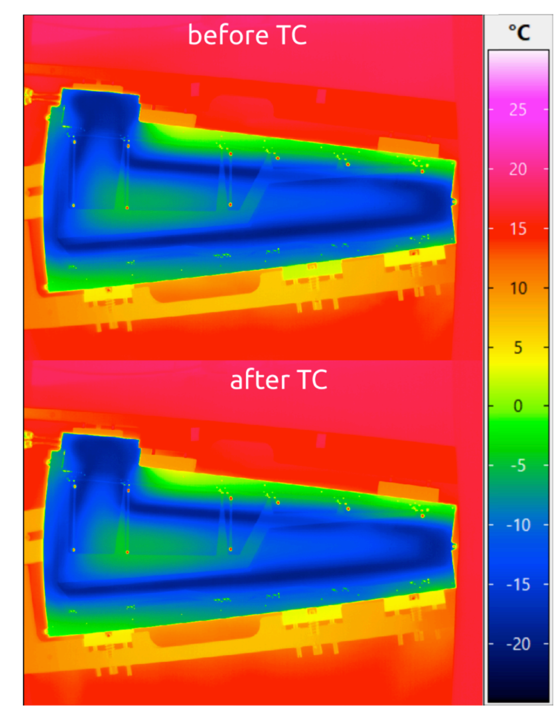
X-ray scan



Metrology

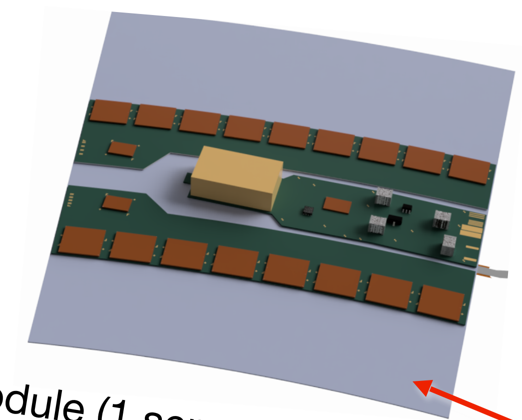


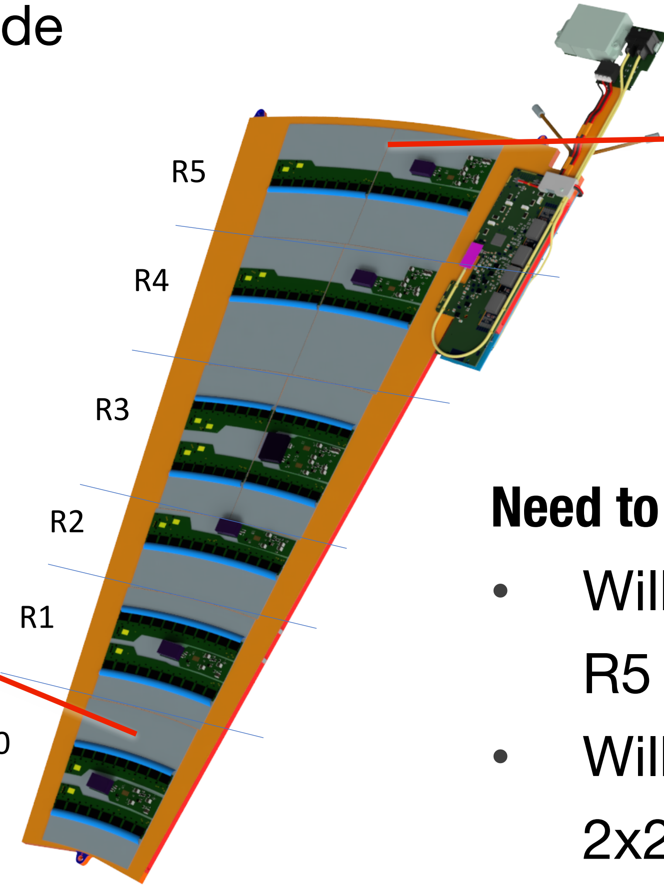
Thermal cycling + Infrared image

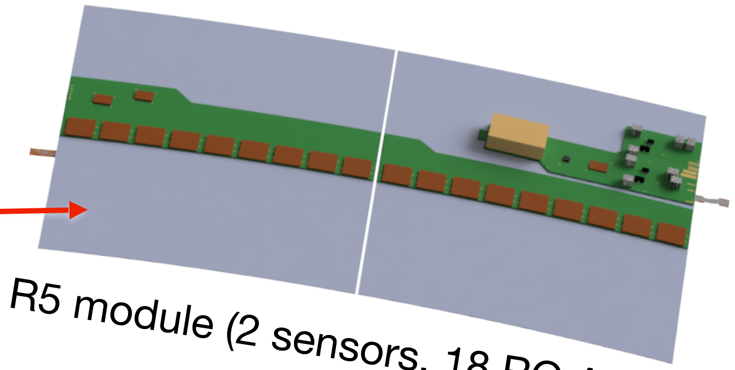


ITk Strip modules

- Each petal has 6 rings of sensors with one sensor shape per ring
- 3 upper radius rings have 2 sensors
- In total, 18 modules, 9 on each side



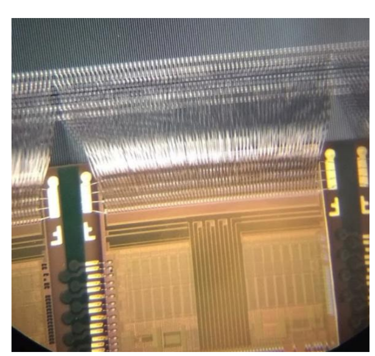




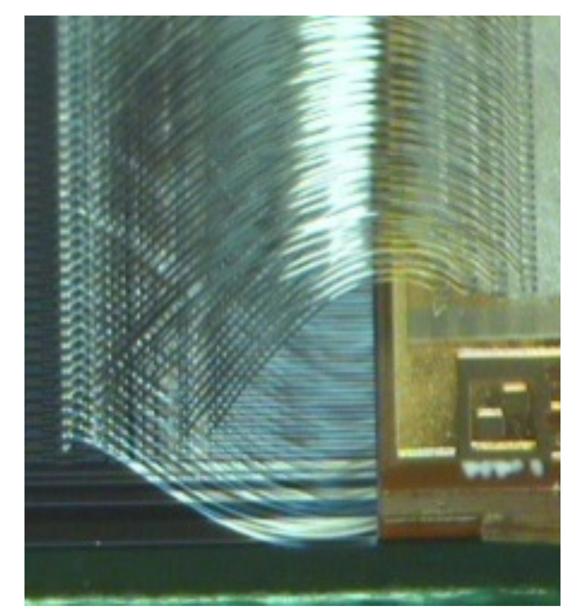
Need to populate 100 of those petals

- Will assemble all the required R0 (200) and R5 (2x200) modules. In total 600 modules
- Will receive 200 R1, 200 R2, 2x200 R3 and 2x200 R4. In total 1200 modules

- **Wire bonding** R/O ASICs to sensors is probably the lengthiest part of the process
- 256 bonds/chip in 4 rows and approx. 1.4 m of wire
- Have to bond 7000 chips, i.e. ~1.8 million wirebonds and about 10 km of wire



4 row wire-bonding →



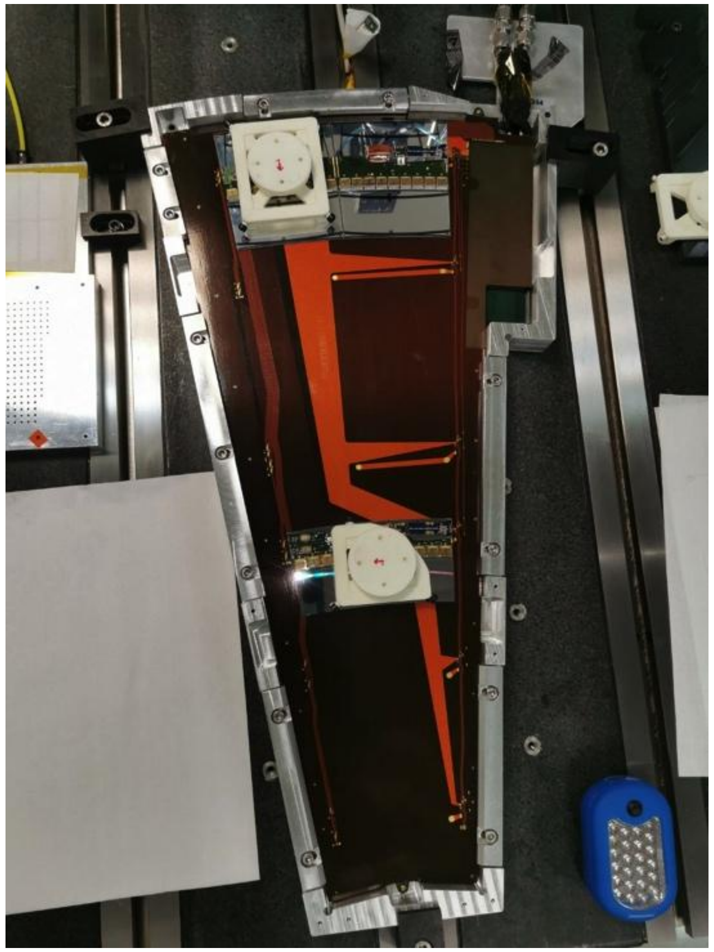
ITk Strip module loading

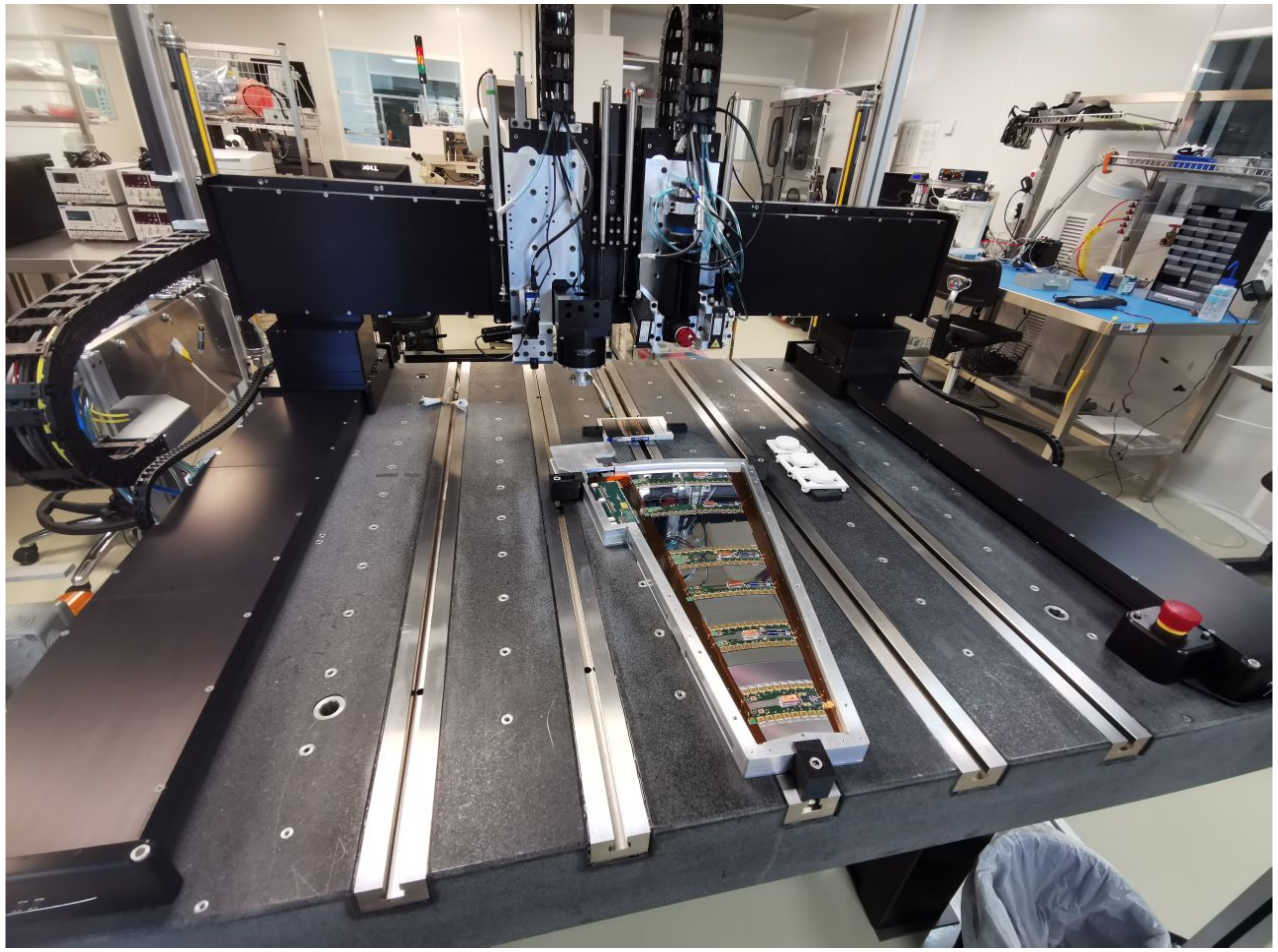
- **Have to "populate" 100 petals** (we build 600 of 1800 modules), using a "very-large" pick-and-place machine that
  - Dispenses the glue on the petal
  - Positions the module with 20 μm precision
  - And does the final metrology

Currently 8 (pre-production) +15 (production) petals fully loaded

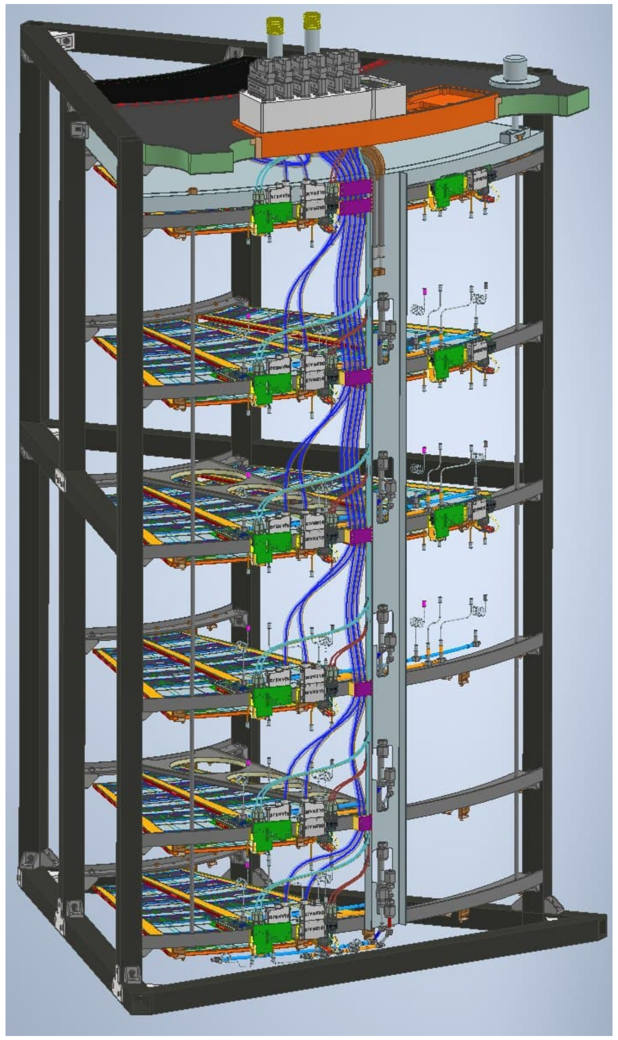
Post-loading process

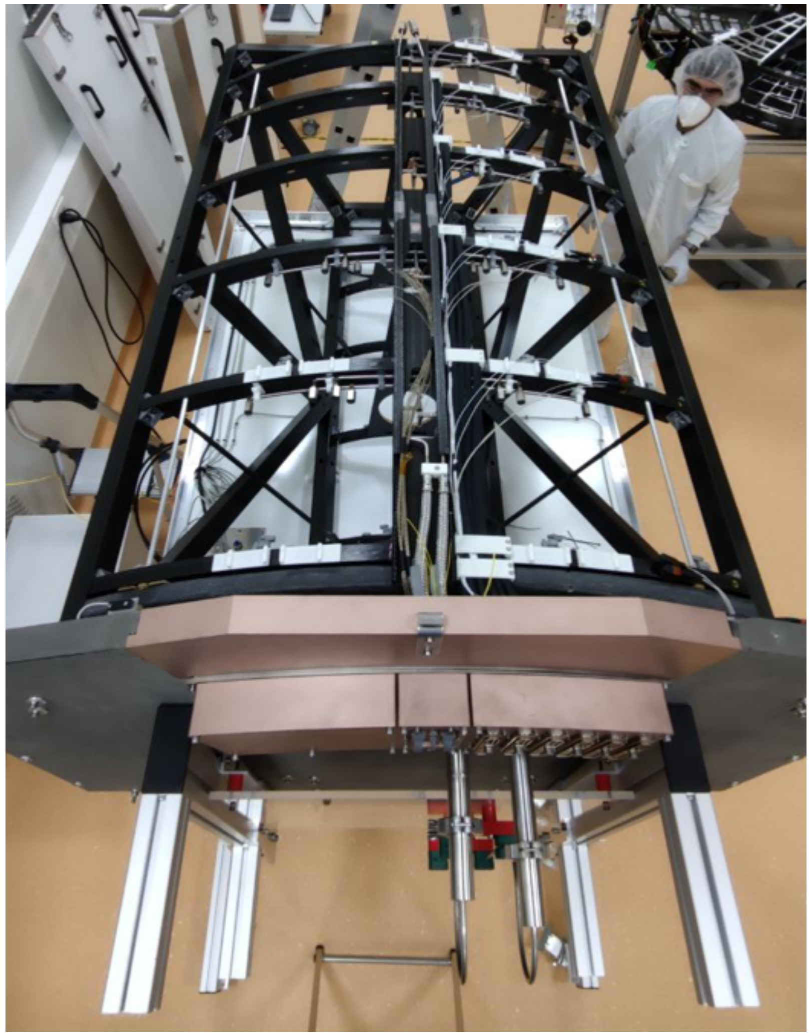
- Fully loaded petals have to be bonded, electrically tested and operated at -35 (done with CO_2 cooling)



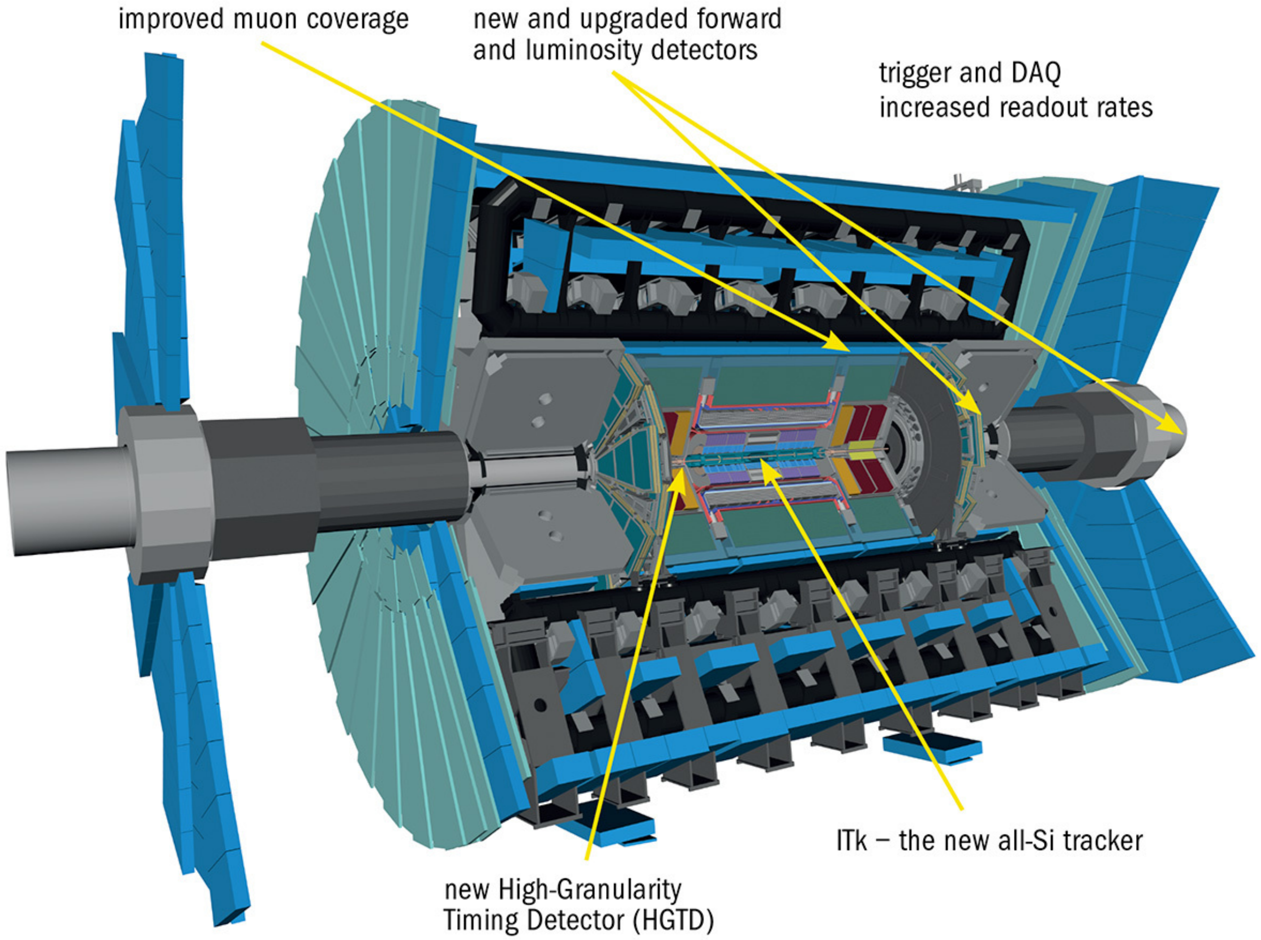


- **Design of the mechanical structure for a system tests setup** that will be operated first at DESY and later at CERN
  - The setup will operate more than one petal a a time and will serve to test several aspects of the system
- Participate in the preparation and operation of such system





- The HL-LHC will continue exploring the energy frontier
  - Significant challenges: detector, trigger and data acquisition systems
  - Increased trigger rates, detector occupancy and radiation hardness challenges
- Major upgrades of all experiments needed to cope with these requirements!
  - GOAL: keep similar performance in harsher environment than in the current detector
- IFAE and IFIC groups playing a critical role in the ITk upgrade activities of the ATLAS experiment thanks to the PPCC



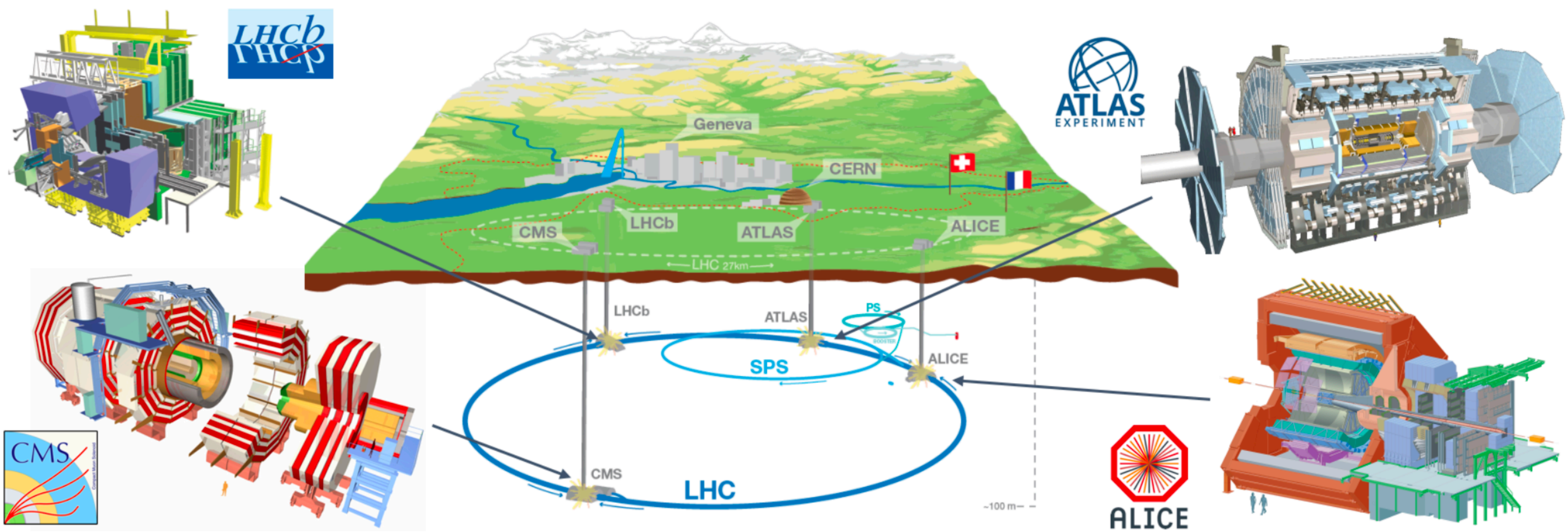
BACKUP

The Large Hadron Collider

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator

- Exploring the energy frontier since 2008
    - First beam circulated through the collider (September 2008)
    - First collisions with low-energy beams up to 1.18 TeV circulated in the tunnel (November 2009)
        - *The world's highest-energy particle accelerator!*
    - First proton beams at 3.5 TeV and first high-energy collisions at 7 TeV (March 2010)
    - First lead-ion beams (November 2010)

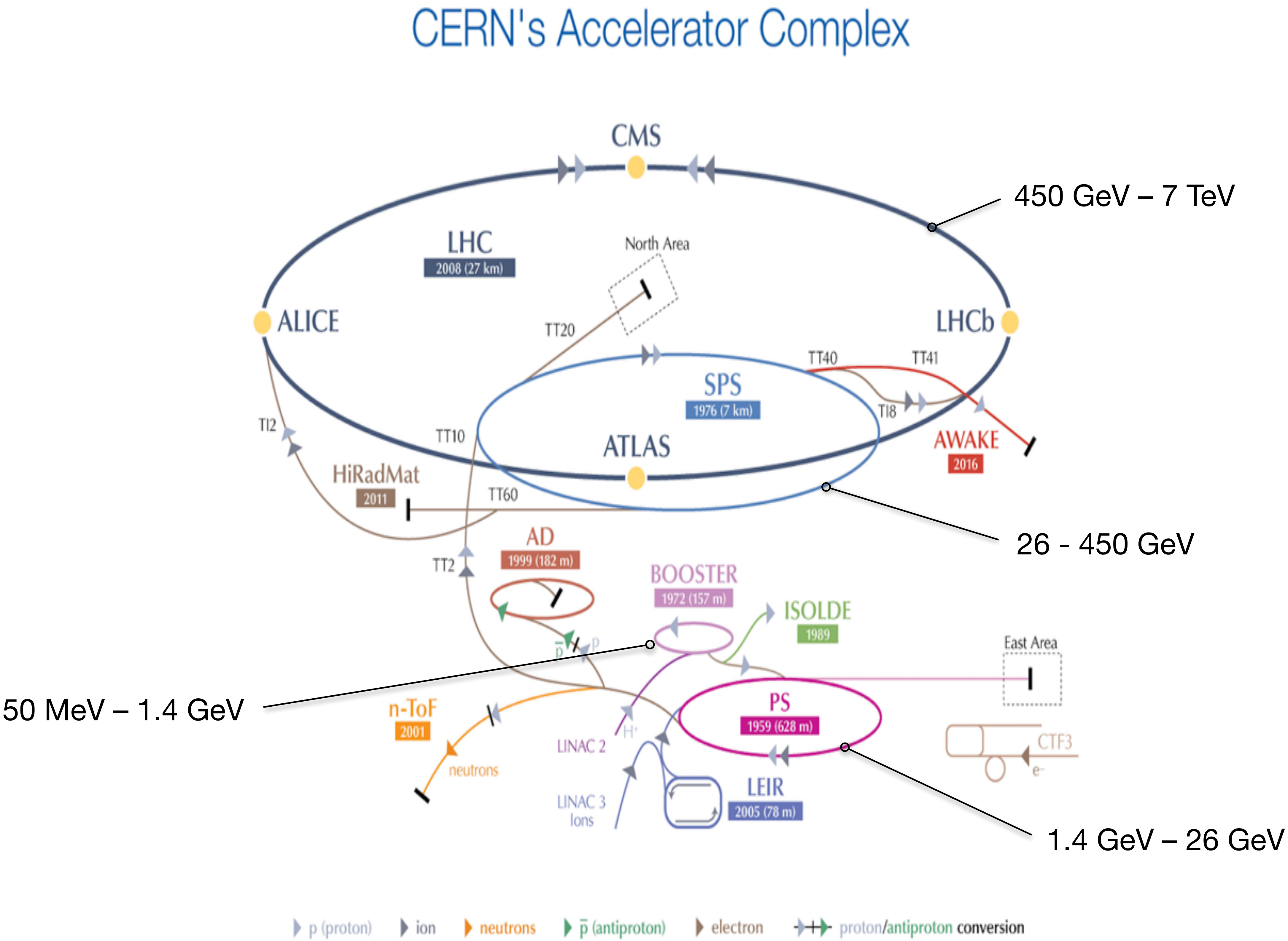
- Located at CERN, 100 m underground
- 27 km collider where two beams go in opposite directions
- Collison rate: 40 MHz



There are 4 main experiments placed in the LHC ring:

- **LHCb:** flavour physics of the SM
- **ALICE:** physics of strongly interacting matter at extreme energy densities (quark-gluon plasma)
- **ATLAS and CMS:** General-purpose detectors exploring a wide range of physics topics
- Some other smaller experiment : TOTEM, MoEDAL, LHCf, FASER and SND@LHC

- Higgs boson was observed in 2012, validating the last missing piece of the SM
- Search for New Physics: SUSY, dark matter, and other theories beyond the SM


CERN's Accelerator Complex
CMS
450 GeV – 7 TeV
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
26 - 450 GeV
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
50 MeV – 1.4 GeV
n-ToF
2001
PS
1959 (628 m)
LINAC 2
CTF3
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)
1.4 GeV – 26 GeV
p (proton)
ion
neutrons
p̄ (antiproton)
electron
proton/antiproton conversion

The High-Luminosiy LHC

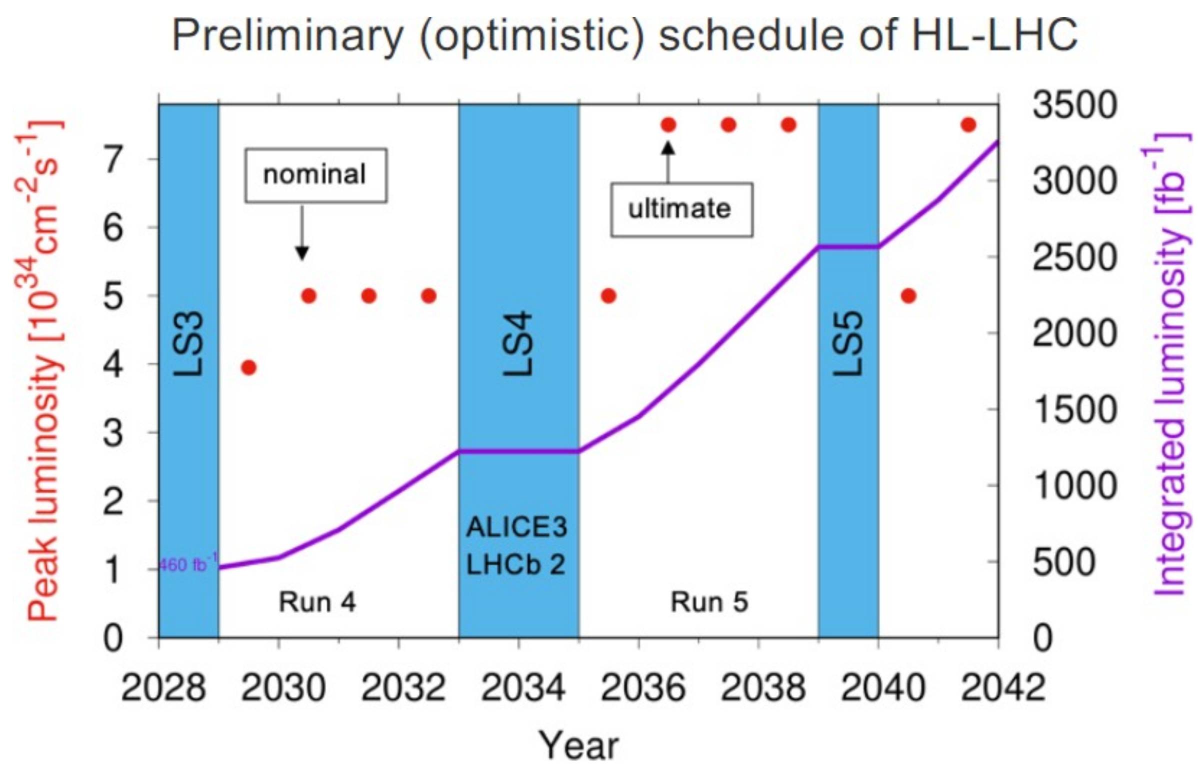
Parameter	Design	Run 1	Run 2	Run 3	HL-LHC
Beam energy	7	3.5 - 4	6.5	6.8	7
Centre-of-mass energy ($\sqrt{s}$) [TeV]	14	7 - 8	13	13.6	14
Bunch spacing [ns]	25	50	25	25	25
Bunch Intensity [10^{11} ppb]	1.15	1.6	1.2	up to 1.8	2.2
Number of bunches (n_b)	2800	1400	2500	2800	2800
Transverse emittance (ϵ) [μm]	3.5	2.2	2.2	2.5	2.5
Amplitude function at the interaction point (β^*)[cm]	55	80	30→25	30→25	donw to 15
Crossing angle [μrad]	285	-	300→260	300→260	TBD
Peak Luminosity [10^{34} $cm^2 s^{-1}$]	1.0	0.8	2.0	2.0	5.0
Peak pileup	25	45	60	55	150
Nominal magnetic field (B) [T]	8.73	4.16 - 7.76	7.73	8.73	11
Injection energy [GeV]	450				
Circumference length [km]	26.7				
Radius [km]	4.24				
Number of dipole magnets	1232				
Length of dipole magnets [m]	14.3				
Number of quadripole magnets	395				
Total mass [tons]	27.5				

Despite the great progress in the HL-LHC project and the upgrades of ATLAS and CMS, delays have accumulated due to COVID-19 and technical challenges.

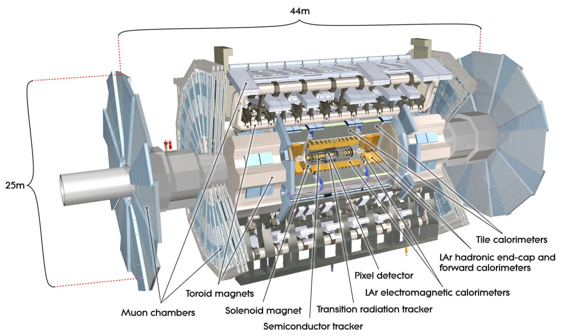
CERN very recently (Jan. 2022) decided to extend Run 3 by 1 year and LS3 by 6 months.

No further extensions of Run3 nor LS3 are possible, for technical and political reasons.

Current HL-LHC end date (2038) implies only 2500 fb^{-1} will be provided to ATLAS and CMS.
The goal of providing 3000 fb^{-1} will not happen before 2041.
Final decision on the HL-LHC long term schedule will have to be taken in the next (or next to next) European Strategy Update



The ATLAS upgrade

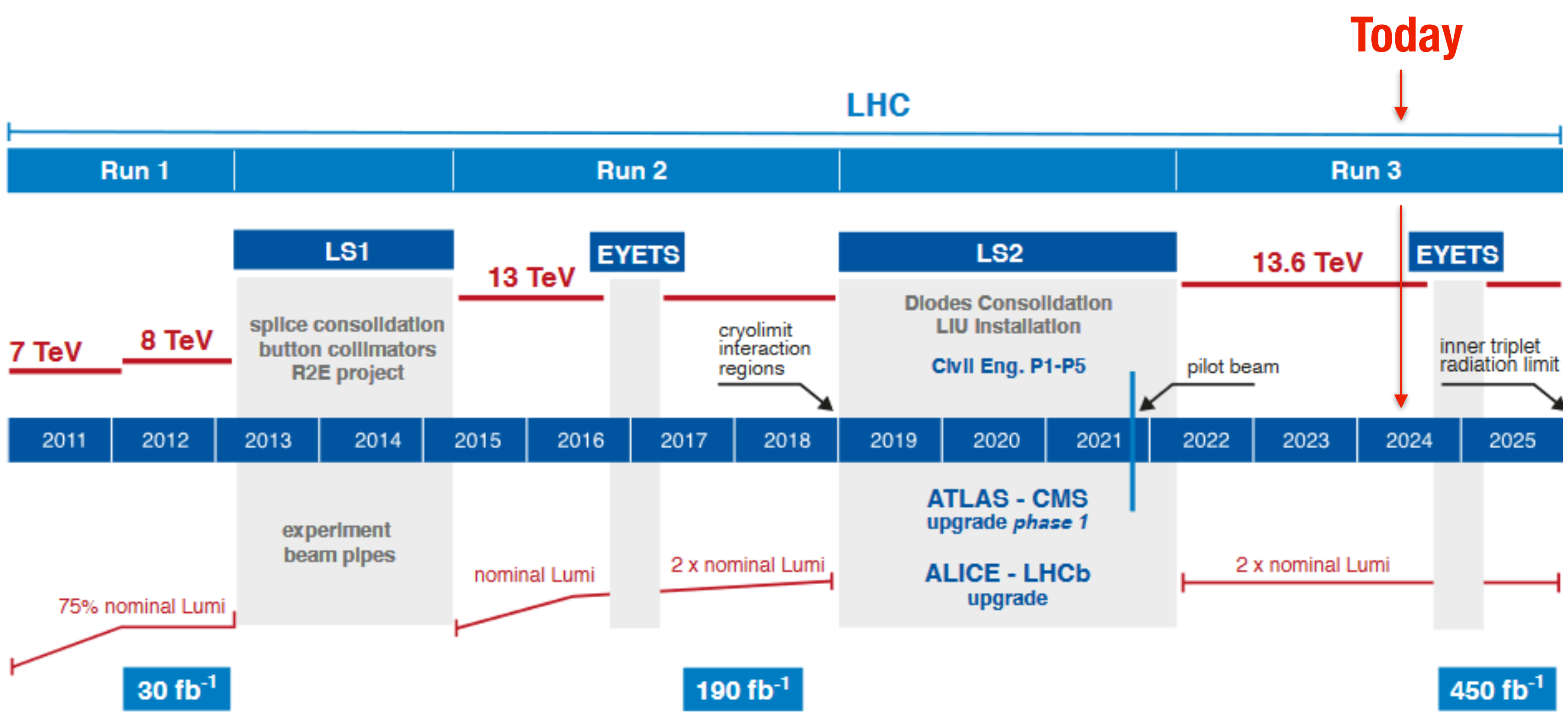


- **Inner tracker replacement with all pixel and strip silicon design**
  - improved momentum resolution and added coverage from η 2.5 to 4.0 with low material budget
- **Calorimeters**
  - LAr: new full-digital FE and RO electronics with active PU corrections techniques
- **Muons**
  - additional muons chambers to increase trigger acceptance (under discussion η < 4) and suppress random coincidences
- **Trigger**
  - Upgrades L0 hardware trigger with RO of 1MHz and HLT of 10kHz
  - Hardware Tracker that provides HLT with tracks
  - (Evolution with track based triggers at 4 MHz)
- **(High-Granularity Timing Detector:**
  - precise timing (30ps) measurement of tracks 2.4<η<4.9 to reconstruct primary vertex)

- **Tracking**
  - Extended tracking up to η 4 with higher granularity
  - Provide L1 trigger with tracks
- **Calorimeter**
  - Increased granularity by switching read-out to silicon photomultipliers in hadronic/endcap calorimeters
- **Muon**
  - Enhanced coverage of forward region up to η 2.8
- **Trigger**
  - L1 rate of 750kHz and 12.5μs latency and HLT with 7.5kHz
- **Minimum ionising particle timing detector**
  - up to η = 3.0 and timing resolution of 30ps to reconstruct primary vertex

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator

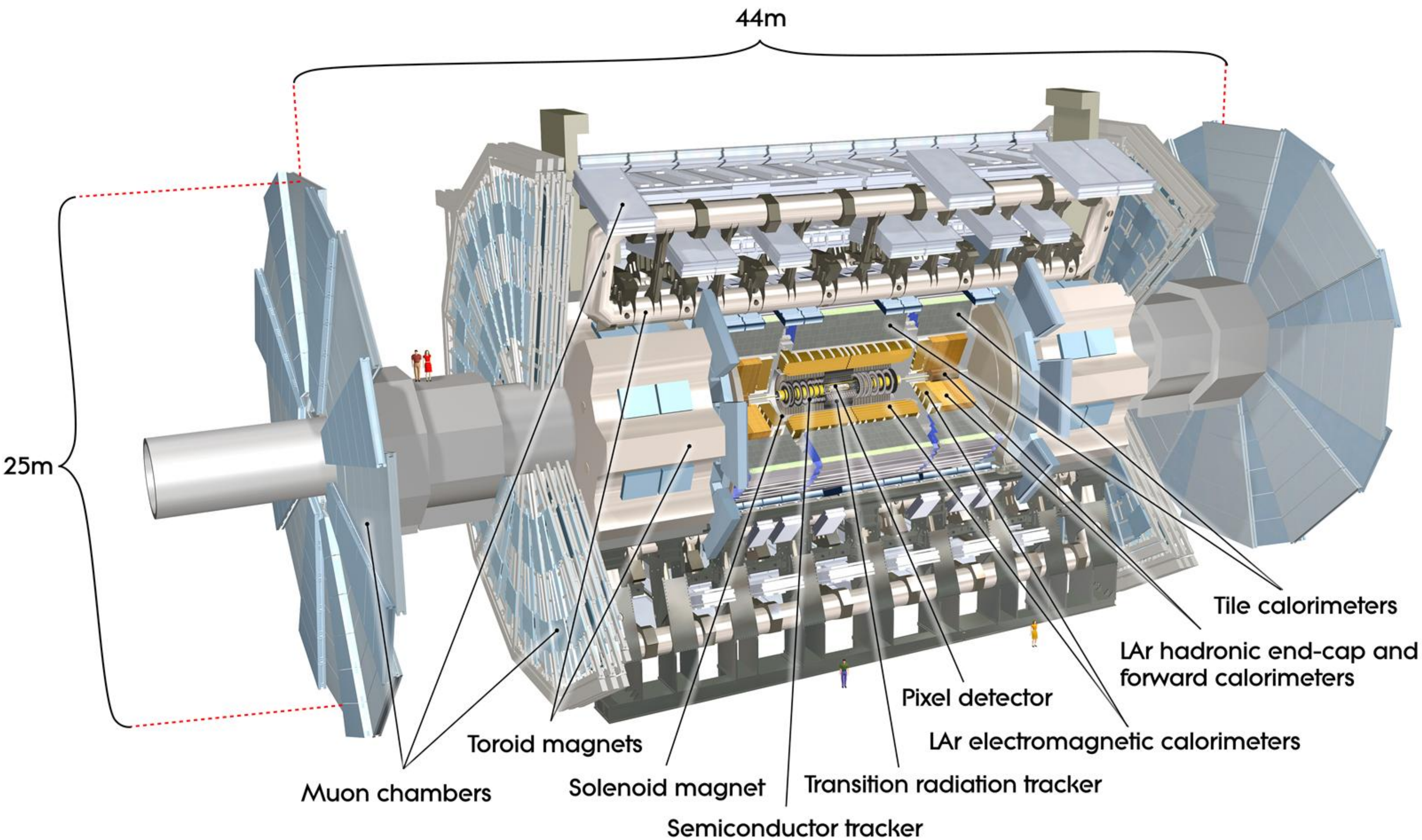
- Data taking periods: Run 1 (2011,2012), Run 2 (2015-2018) and Run 3 (2022-nowadays)



The ATLAS detector

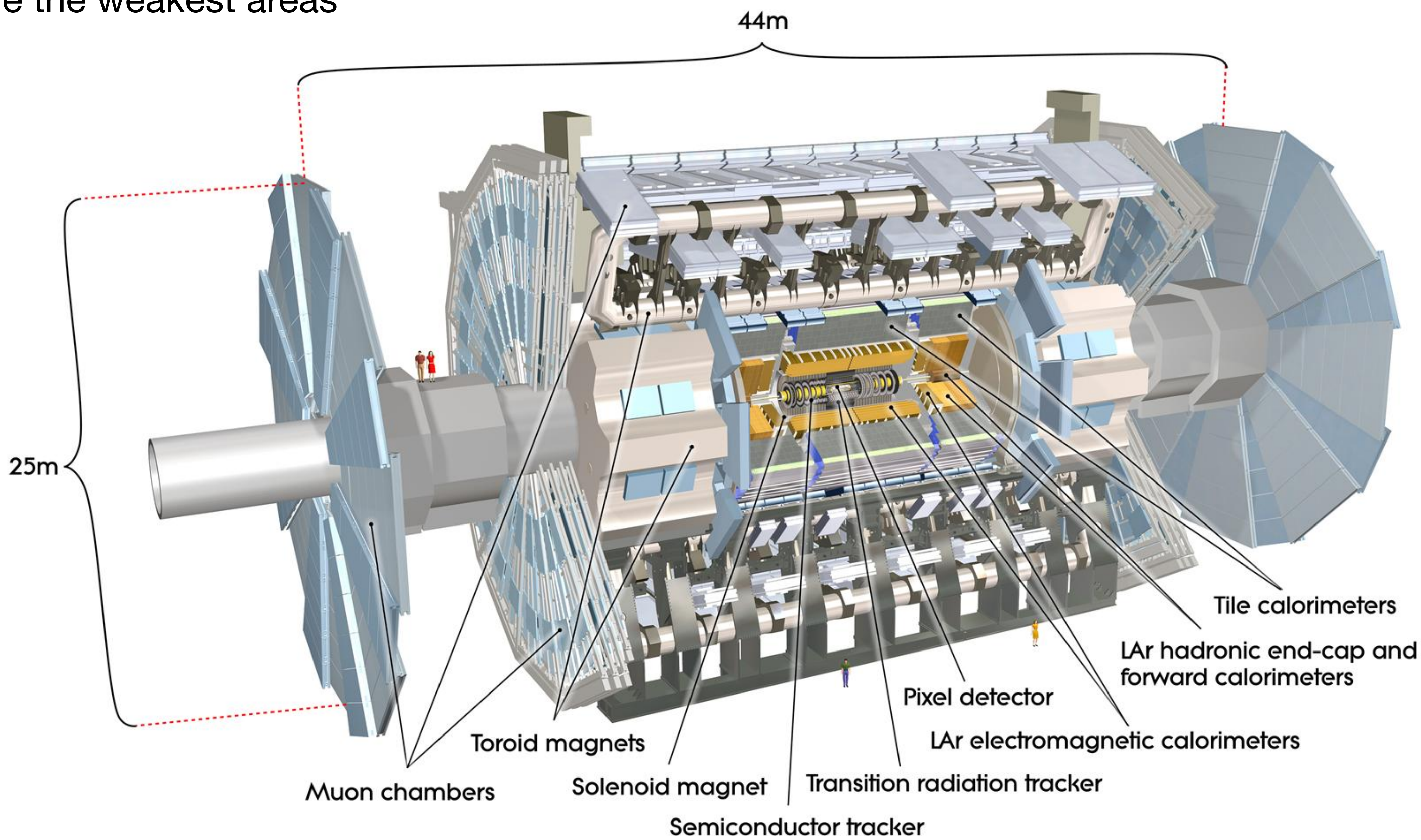
ATLAS (A Toroidal LHC ApparatuS) is a general-purpose detector

- Forward/backward-symmetric cylindrical detector and covers almost the entire solid angle
- The largest detector located at the LHC: 44m in length and a diameter of 25m
- Embebed in a Magnetic system (max. 2T) and composed of several layers with a specific goal



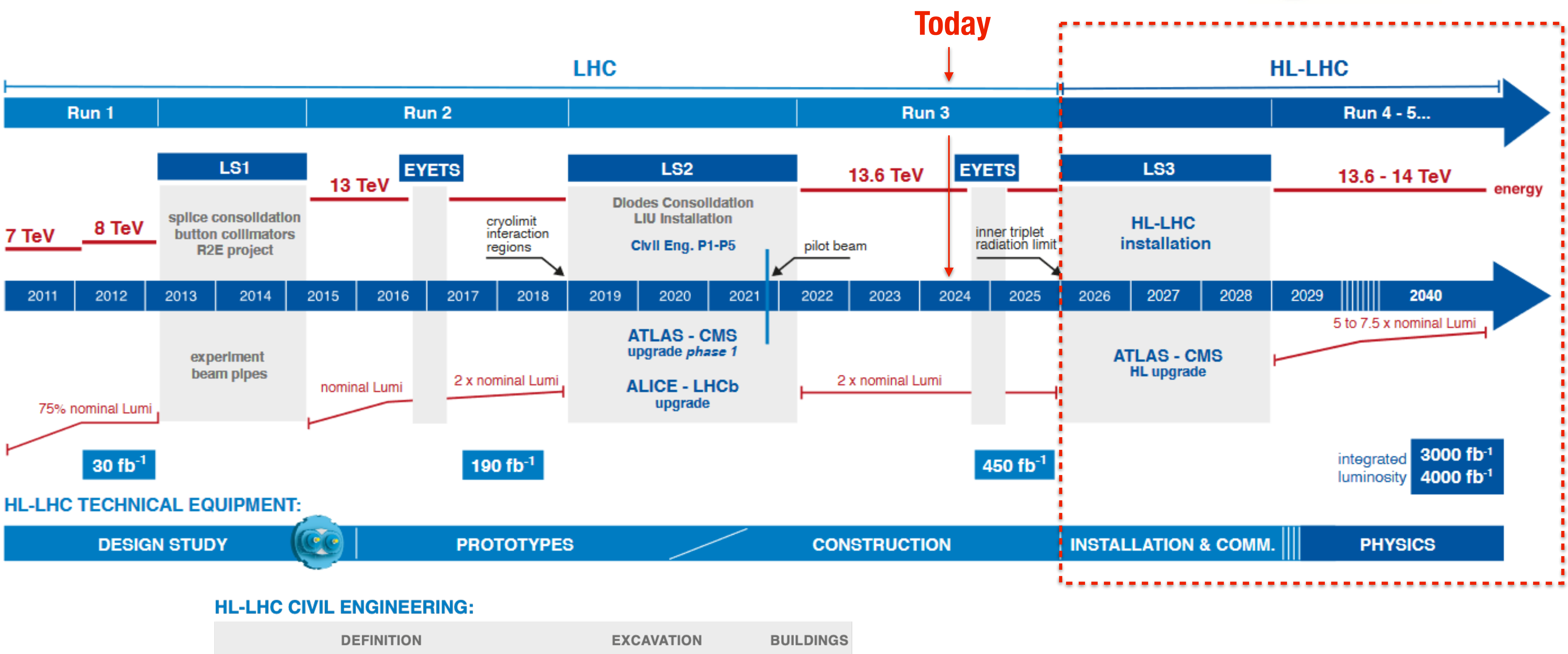
ATLAS detector at the HL-LHC

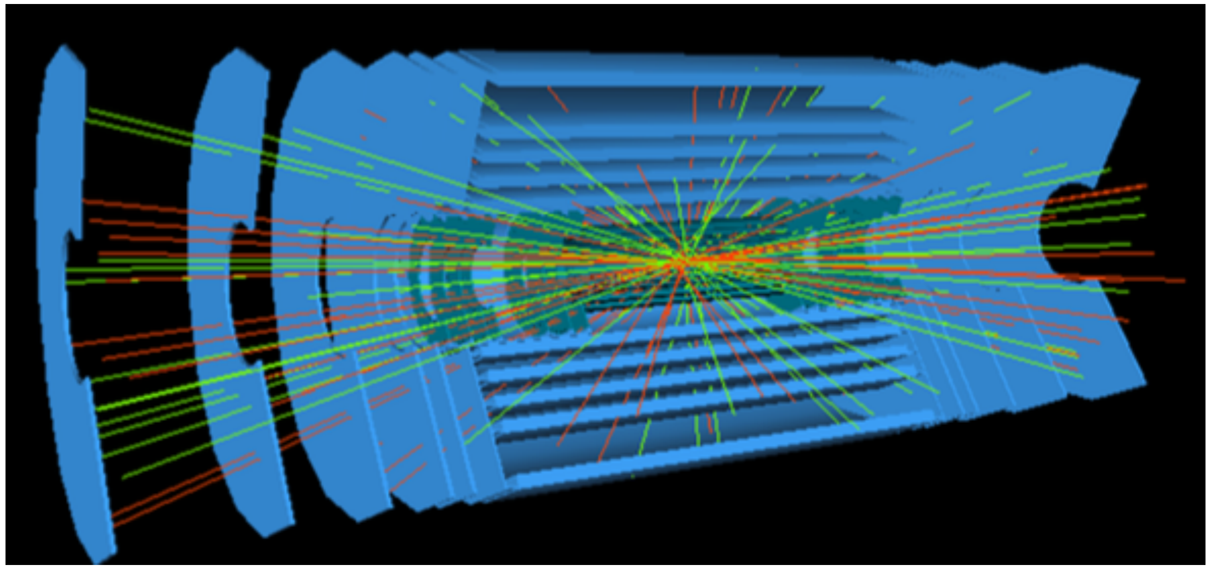
- Maintain (improve) today's performance at 5-10 times higher pile-up and luminosity
- Survive ~10 years of extreme radiation
- Many systems need upgrading, but most importantly the tracker
- Calorimeters and Muon detectors need to upgrade the readout electronics, trigger system and improve the weakest areas



LHC/HL-LHC upgrade timeline

- HL-LHC **installation phase** currently scheduled to start in ~**2026**
- HL-LHC **physics phase** currently scheduled to start in ~**2029**



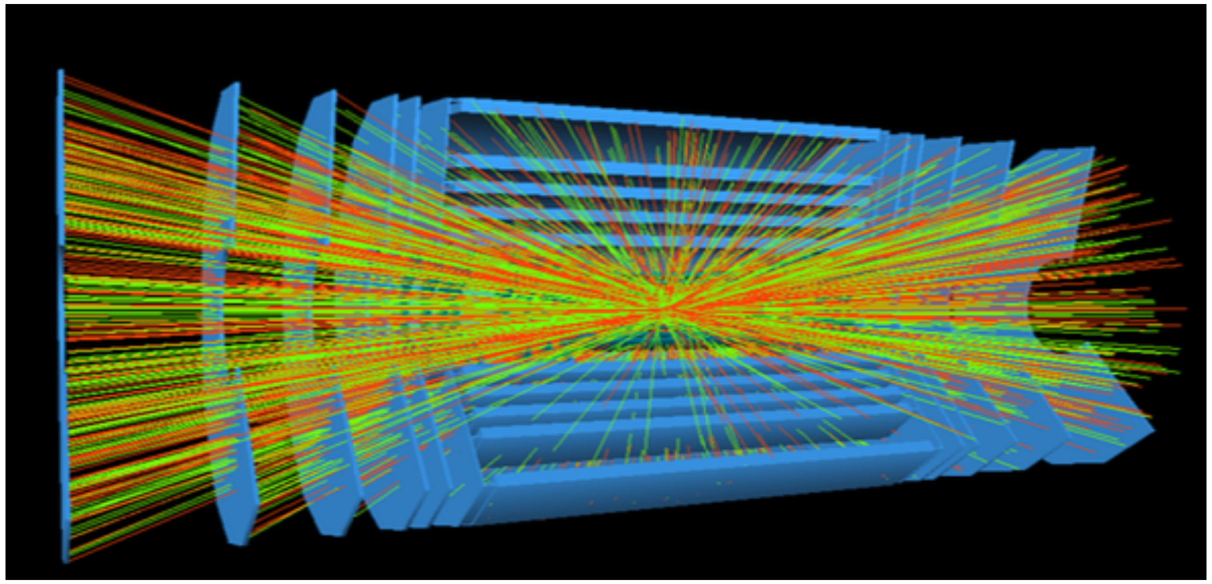


LHC

- Pile-up: ⟨μ⟩ ~ 33
- Trigger: single HW trigger signal (L1) running at a peak rate of 100 kHz

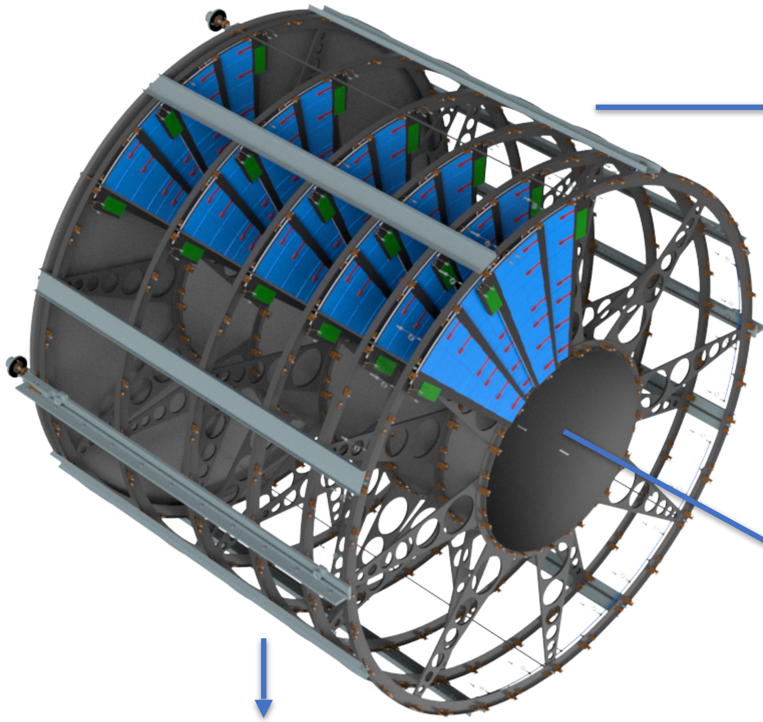
HL-LHC

- Pile-up: ⟨μ⟩ ~ 140-200
- L0 trigger rate of few MHz → L1 trigger below 1 MHz

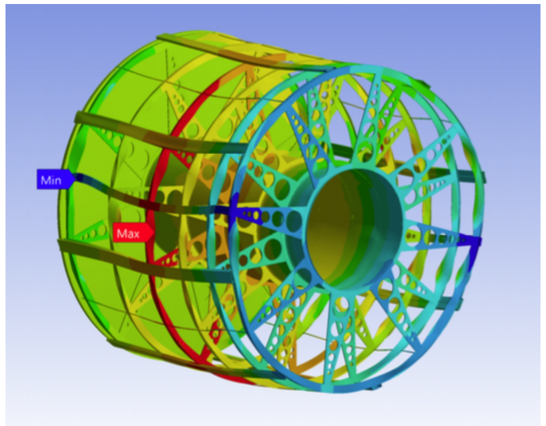


ITk Strip activities and responsibilities

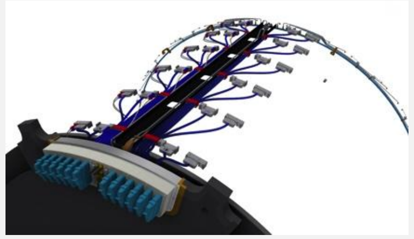
Global support structure

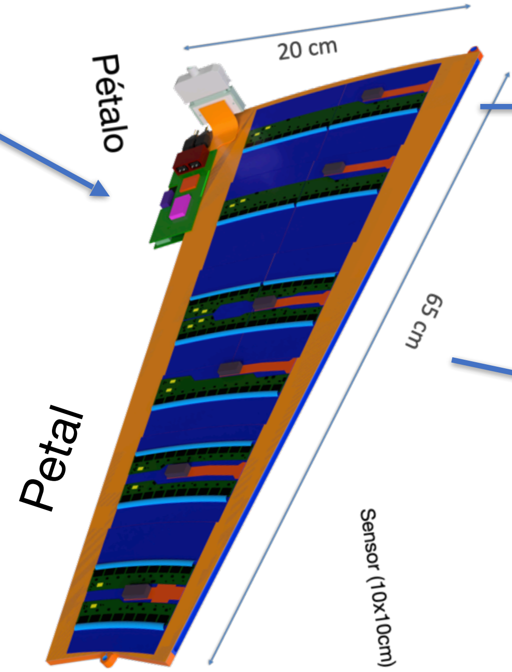


Finite Element Analysis simulations



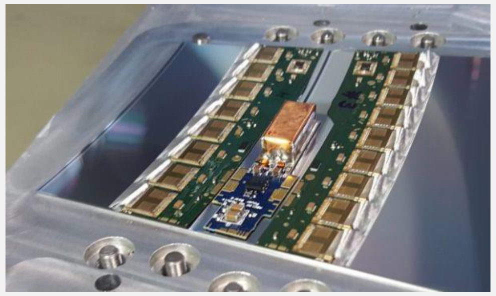
Services

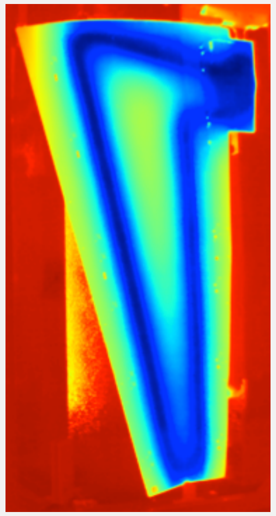




Petal loading

Modules



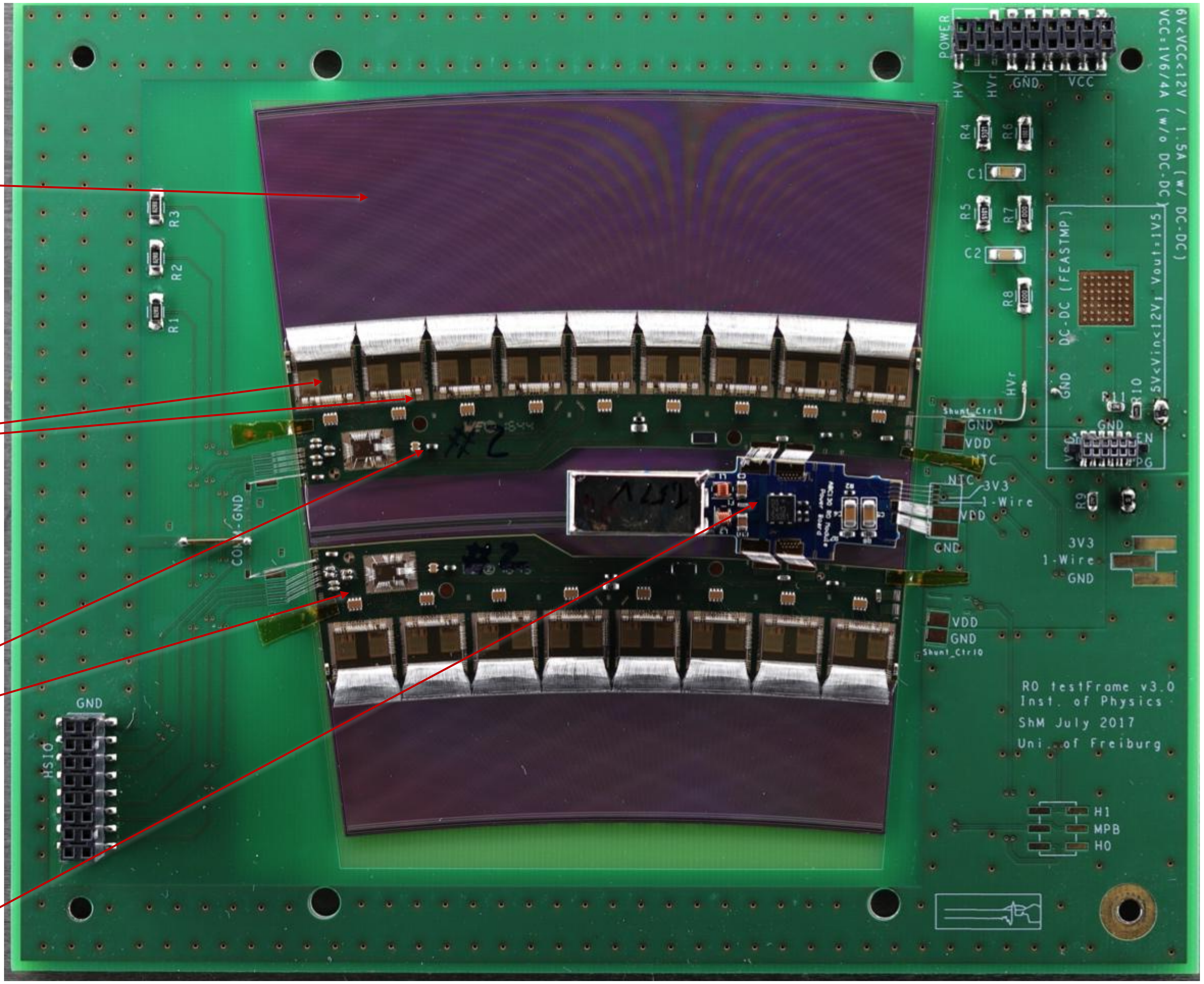


Cores + Bus tapes

First R0 module built in Valencia

Sensor

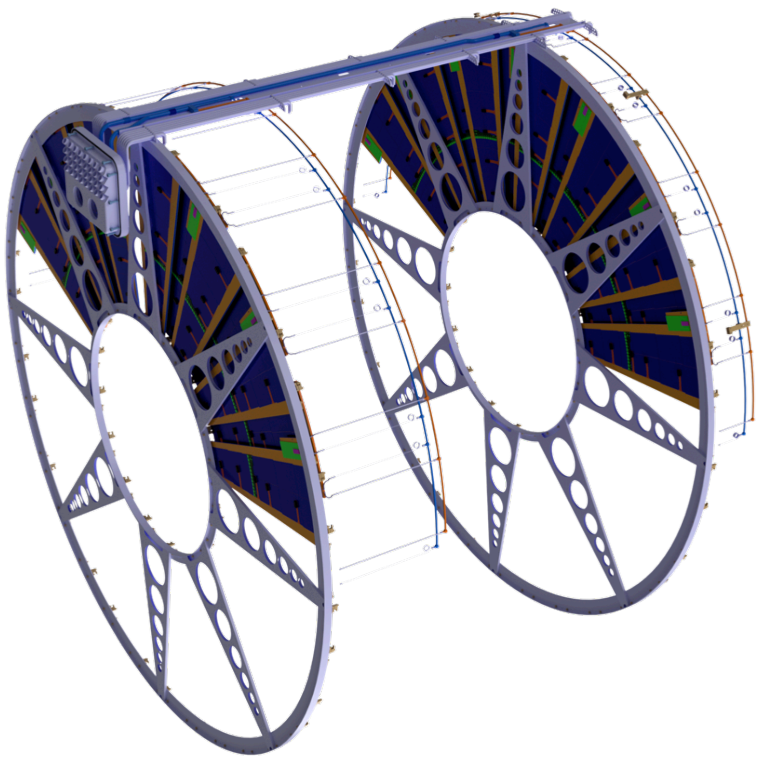
R/O ASICs

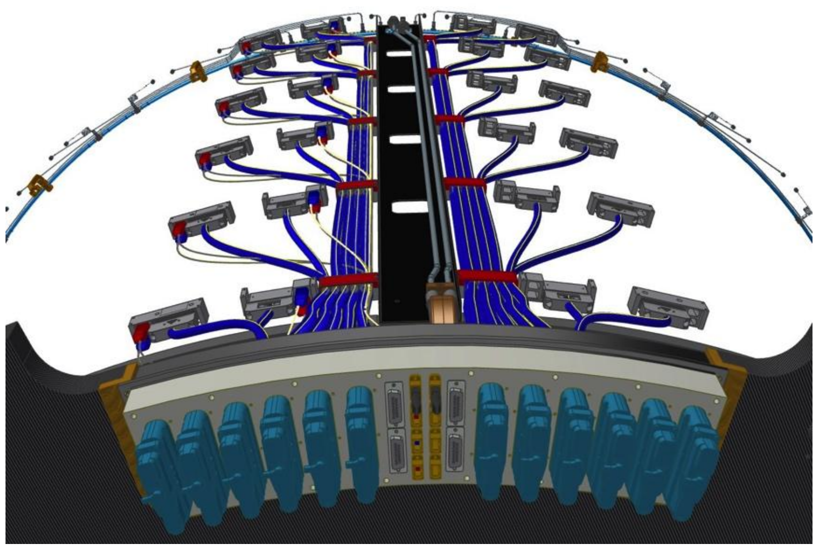


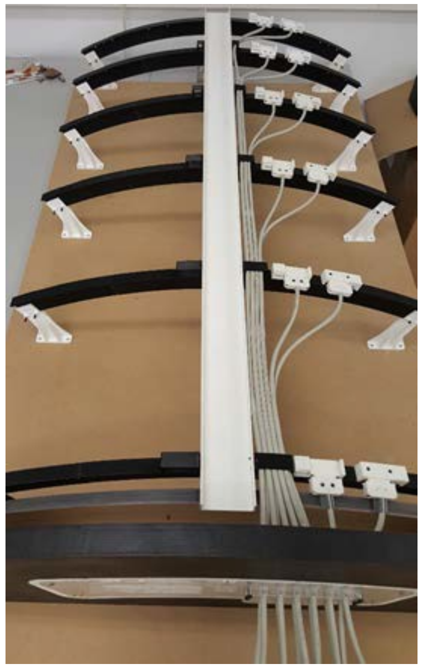
Hybrid

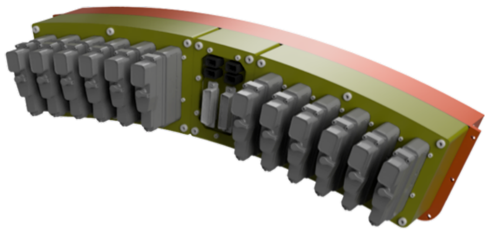
Power board

- Design of the service module bringing power, control signals and cooling to the petals
  - Service patch panel in the structural bulkhead to connect to services beyond the ITk volume
  - Design of customized cables and connectors for both detector and off-detector connections
  - Assemble and test the 16 service modules and install them in the EC mechanical structures









Real size mock-up to check envelopes and train connection of services