Lessons learned from the HGTD sensor R&D

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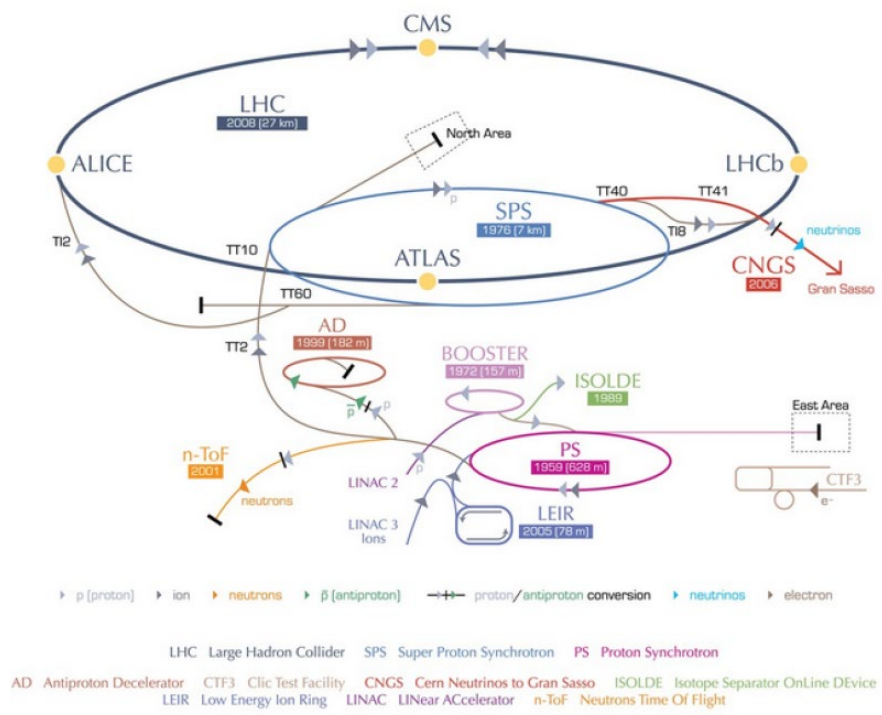
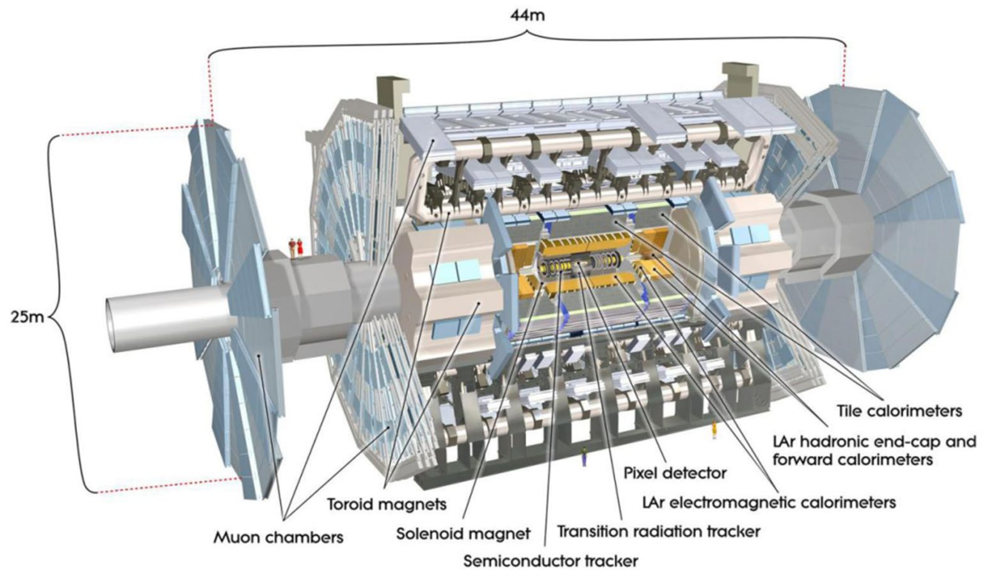
LHC high luminosity and ATLAS

- **LHC** had very successful runs since the start of collisions in 2010
  - Discovery of the Higgs boson, SM measurements, search for SUSY and exotic particles
- It will be upgraded in 2027 to High Luminosity LHC (HL-LHC)
  - Instantaneous luminosity will be ~3 times past run conditions
  - From L = 2.5E34 $cm^{-2}s^{-1}$ to L = 7.5E34 $cm^{-2}s^{-1}$

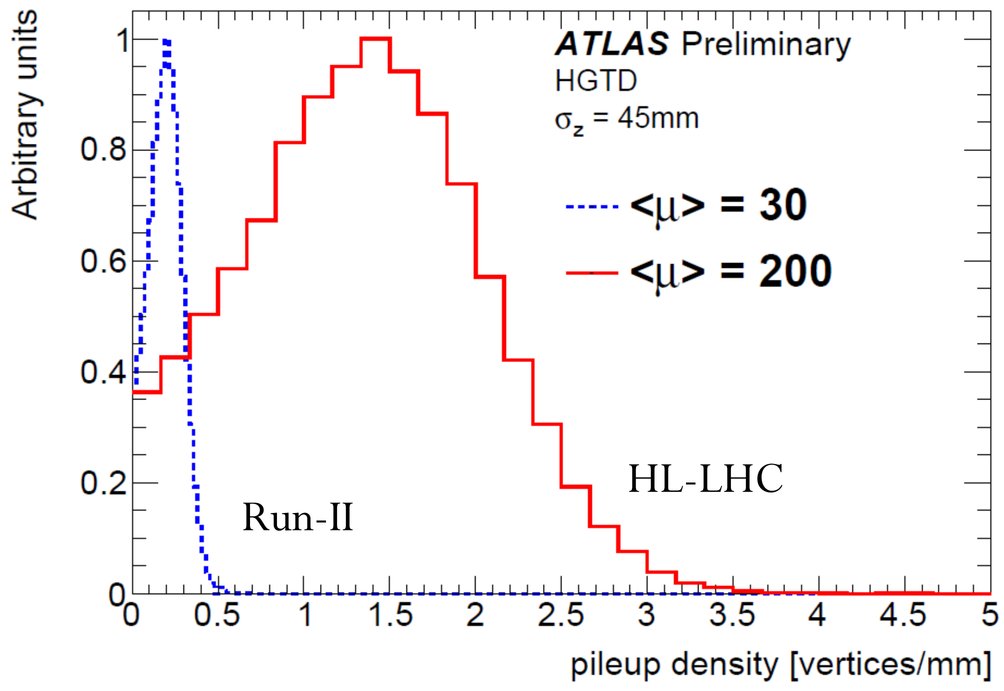
- To maintain performance the ATLAS detector will be upgraded (phase-II upgrade) for HL-LHC
  - The inner detector will be replaced (ITk project)
  - New readout electronics for EM and Hadronic calorimeters
  - Upgraded muon spectrometer
  - TDAQ system will be completely re-worked
- **New end-cap pixel timing detector**
  - High granularity timing detector, **HGTD**
  - HGTD TDR

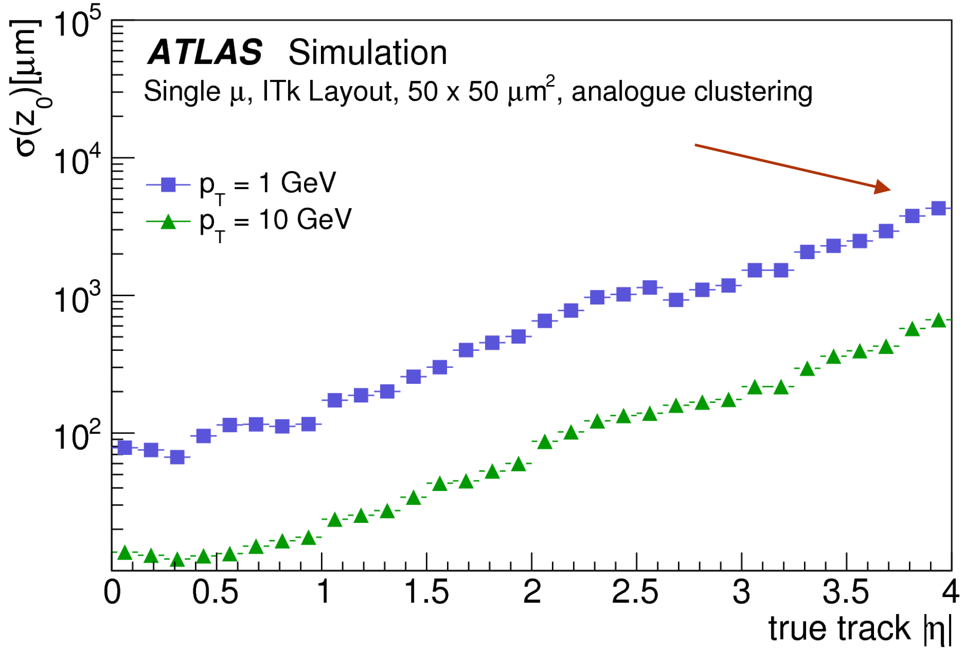




HGTD motivation

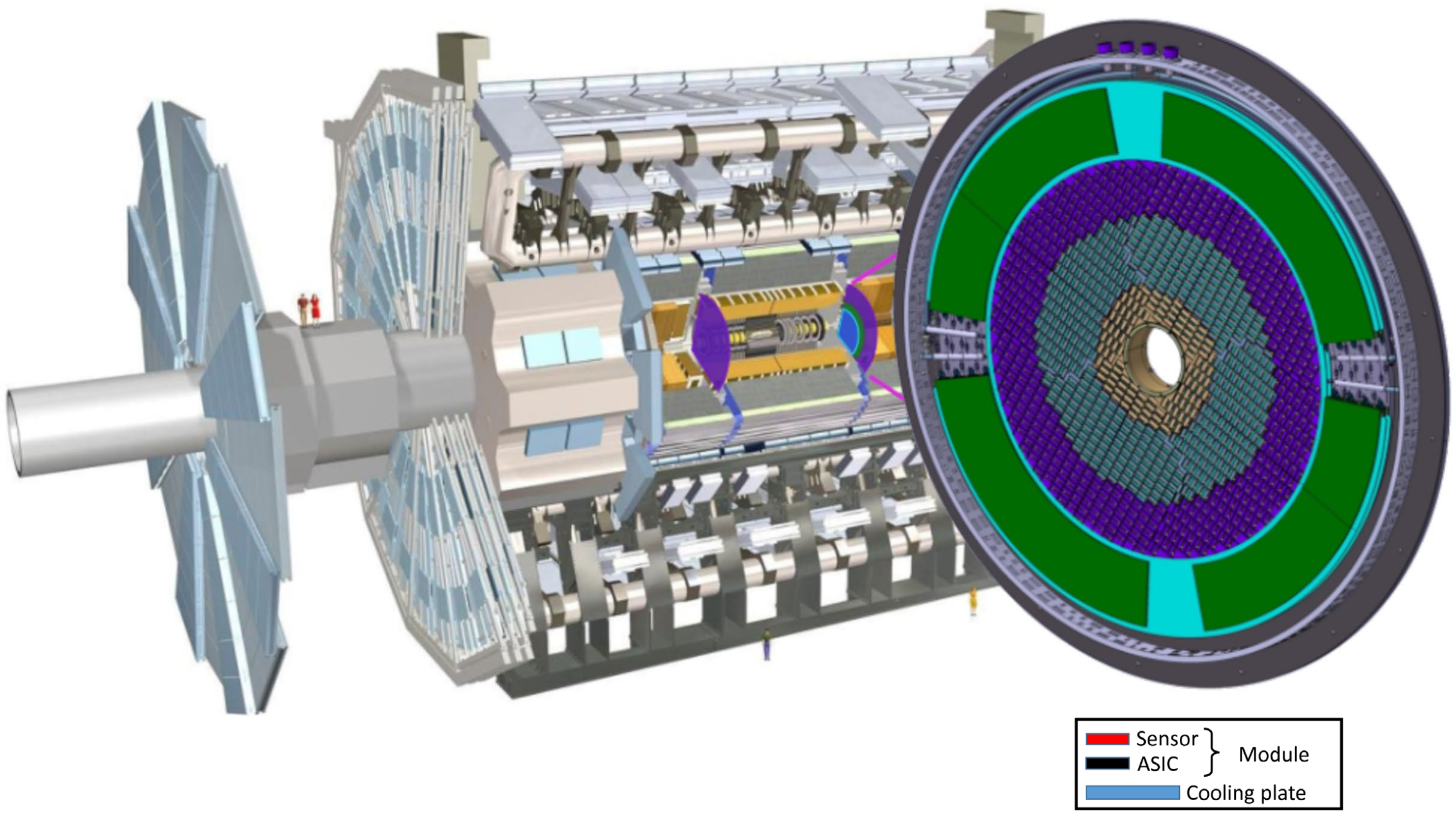
- With increased instantaneous luminosity the biggest challenge will be the **Pileup**
  - Beam profile σ_z = 50 mm, σ_t = 180 ps, 1.44 vertex/mm
  - Pileup will be ~6 times higher than current pileup
  - Especially troublesome in the forward region
- The new ITk tracker will have a better position resolution and extended pseudo-rapidity
  - However Z0 (impact parameter) resolution for end-cap tracks at $\eta > 3$ is order of ~mm
- **With timing information** from HGTD the **pileup effects can be reduced**

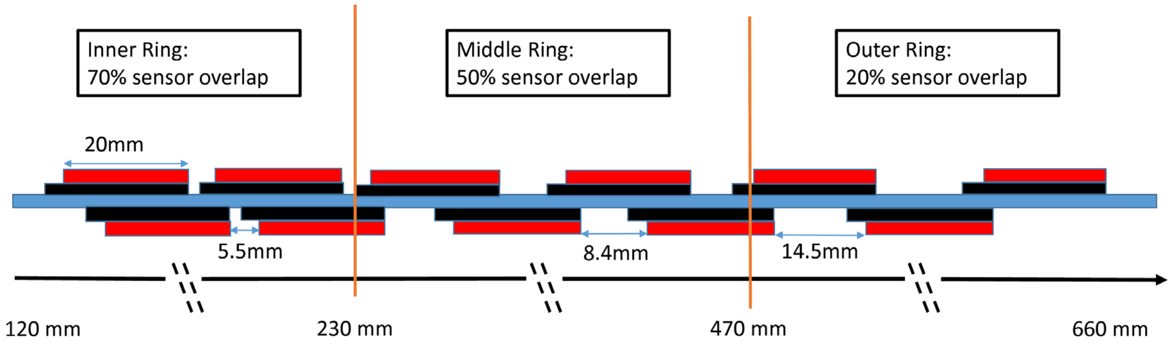




ATLAS HGTD TDR

HGTD layout





Structure

- Two double-instrumented disks in the end-cap
- Rotated by 15° in opposite directions to avoid gaps
- $2.4 < |\eta| < 4$, $120\text{ mm} < r < 640\text{ mm}$
- Structure is divided in concentric 3 rings with different active sensor overlap (70%, 50%, 20%)
- Number of hits per tracks: 2.6, 2.4, 2

Requirements

- Time resolution < 30-50 ps per track, < 35-70 ps per hit (start-finish)
- Occupancy < 10%
- Fill factor > 85%
- Total power dissipation < 500 $^{mW}/_{cm^2}$
  - <100 $^{mW}/_{cm^2}$ sensor-only
- Radiation damage: 2.5E15 N_{eq}/cm^2 and 2 MGy

HGTD - EPIC comparison

HGTD

Pseudo-rapidity coverage	$2.4 < \|\eta\| < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	± 3.5 m
Weight per end-cap	350 kg
Radial extension:	
Total	110 mm $< r <$ 1000 mm
Active area	120 mm $< r <$ 640 mm
Pad size	1.3 mm $\times$ 1.3 mm
Active sensor thickness	50 µm
Number of channels	3.6 M
Active area	6.4 m^2
Module size	30 x 15 pads (4 cm $\times$ 2 cm)
Modules	8032
Collected charge per hit	$>$ 4.0 fC
Average number of hits per track	
$2.4 < \|\eta\| < 2.7$ (640 mm $> r >$ 470 mm)	$\approx$2.0
$2.7 < \|\eta\| < 3.5$ (470 mm $> r >$ 230 mm)	$\approx$2.4
$3.5 < \|\eta\| < 4.0$ (230 mm $> r >$ 120 mm)	$\approx$2.6
Average time resolution per hit (start and end of operational lifetime)	
$2.4 < \|\eta\| < 4.0$	$\approx$ 35 ps (start), $\approx$ 70 ps (end)
Average time resolution per track (start and end of operational lifetime)	$\approx$ 30 ps (start), $\approx$ 50 ps (end)

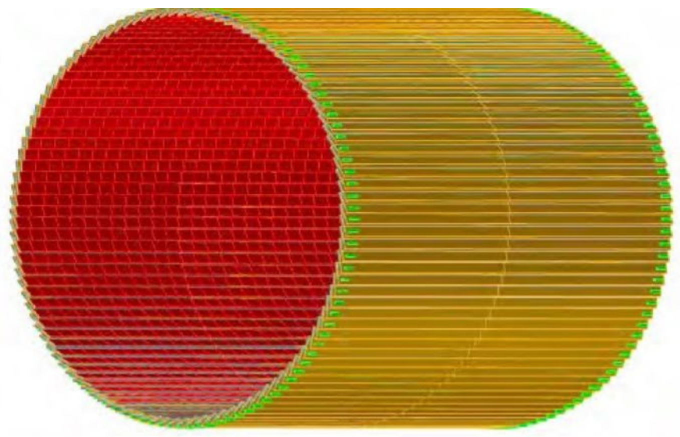
Table 2.1: Main parameters of the HGTD.

Active Area EPIC /HGTD = 2
Linear Pixel size EPIC/HGTD = 0.4 to 0.8
Electronic channel density EPIC/HGTD = 3.4 to 6.8
Position resolution requirement EPIC/HGTD = 1/30
Time resolution EPIC/HGTD = 0.5 to 1

EPIC

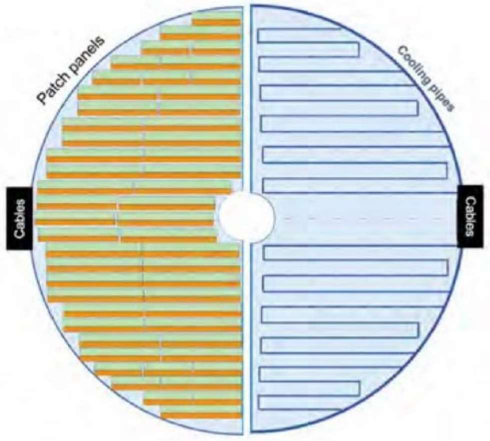
Barrel AC-LGAD tracker (ToF):

Pixel size 0.5mm by 1.0mm. 10.9 m^2 active area.



Hadron endcap AC-LGAD tracker (ToF):

Pixel size 0.5mm by 0.5mm. 2.22 m^2 active area.



EPIC is more ambitious than HGTD

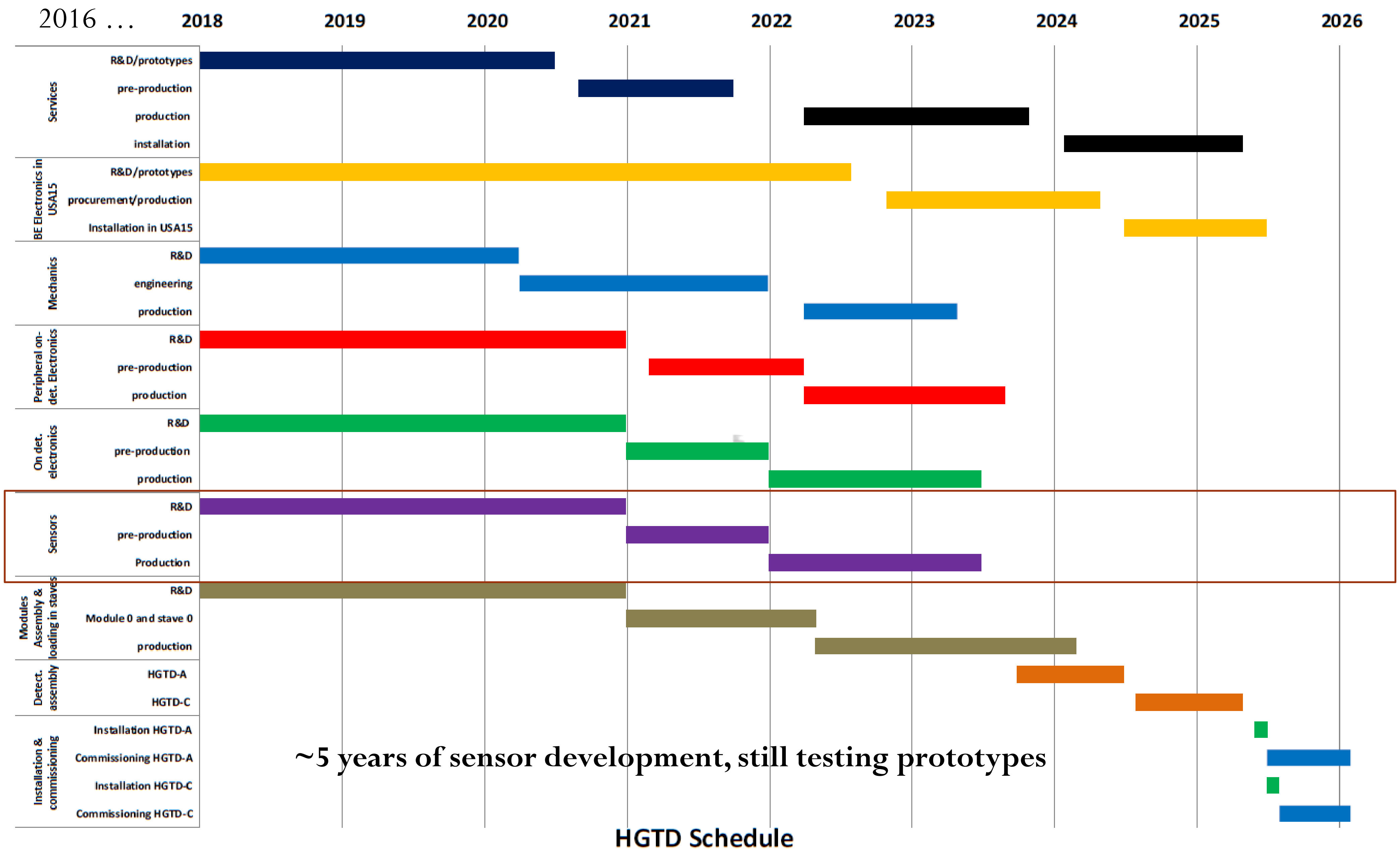


Figure 6.1: Gantt chart showing the schedule of the various activities in the HGTD project.

HGTD sensor prototype runs

- Several HGTD LGAD R&D runs from different vendors
  - Total of 7 vendors, most responded to the market survey
  - Multiple production per vendor (4x HPK, FBK, 3x CNM, NDL, IMEI, etc…)
- Many different types tested: Boron + Carbon, deep gain layer, Gallium, thin (30um) substrate
  - **Some solutions worked some didn't**
- Prototype arrays size up to full size (15x15)

Manu-facturer	Wafer Size [inch]	Thick-ness [μm]	C Implant	Array 5×5	Array 15×15	Array 30×15	UBM
CNM	4-6	30 - 300	x	x	(x)	(x)	
FBK	6	(50) 60 - 300	x	x			
HPK	6	20 - 80		x	x	(x)	x
BNL	4	50					
Micron	4	100 - 300					
NDL	6	33 (50)		x			

IMEI…

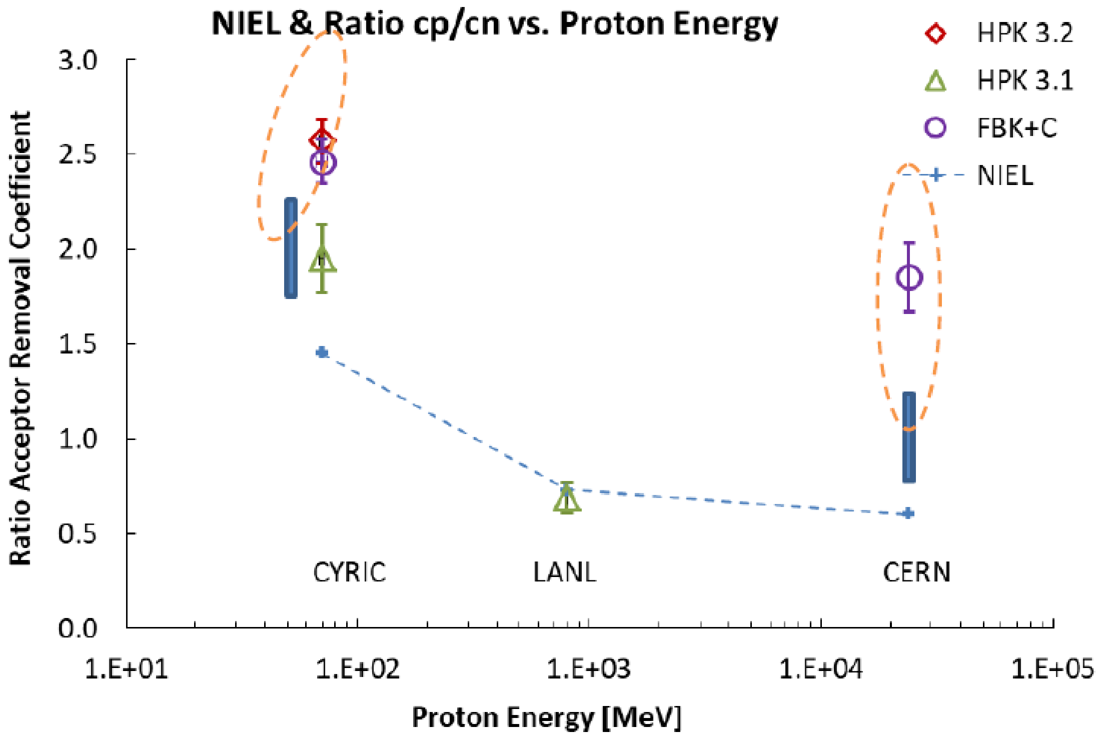
Manu-facturer	Name	Thickness [μm]	Gain layer dopant	C implant	Gain layer depth [μm]	Gain layer depletion [V]
HPK	HPK-3.1	50	Boron	No	1.6	40
HPK	HPK-3.2	50	Boron	No	2.2	55
FBK	FBK-UFSD3-C	60	Boron	Yes	0.6	20
CNM	CNM-AIDA1/2	50	Boron	No	1.0	45
NDL	NDL-33μm	33	Boron	No	1.0	20
Manu-facturer	**Name**	**Full depletion [V]**	**V_{BD} −30 °C [V]**	**Nominal IP [μm]**	**Nominal SE [μm]**	**Max. Array Size**
HPK	HPK-3.1	50	200	30-95	200-500	15×15
HPK	HPK-3.2	65	70	30-95	200-500	15×15
FBK	FBK-UFSD3-C	25	170	37	200-500	5×5
CNM	CNM-AIDA1/2	50	220/50	37-57	200-500	5×5
NDL	NDL-33μm	35	70	55	450	15×15

HGTD sensor irradiations

- Irradiation campaigns done for most prototype runs
- Irradiation with neutrons, protons of different energies and gammas
- Discovered that **NIEL factor do not work** for acceptor removal in LGADs

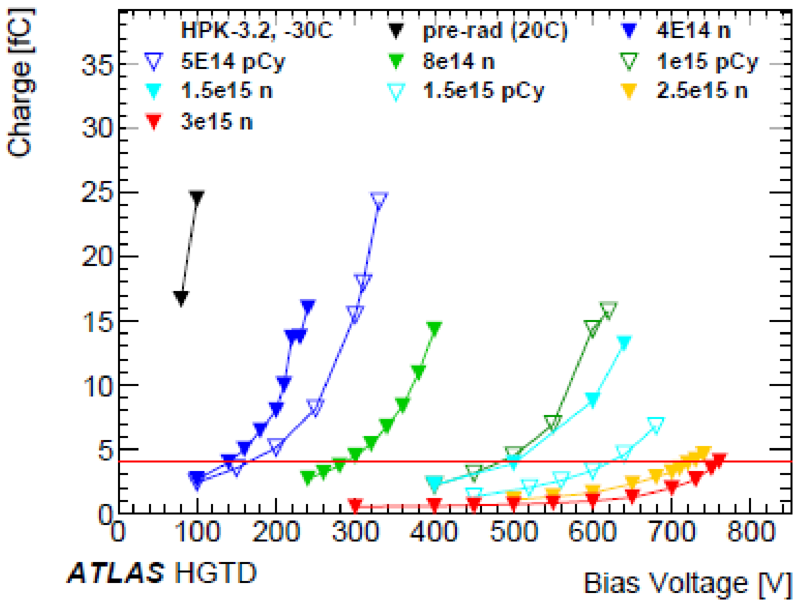
Facility & Abbreviation	Particle Type	Hardness Factor	TID [MGy] / 10^{15} n_{eq} cm^{-2}	Max. Fluence [10^{15} n_{eq} cm^{-2}]	Max. TID [MGy]	LGAD Types Irradiated
JSI Ljubljana (*n*)	≈1 MeV n	0.9	0.01	6	0.06	all
CYRIC (*pCY*)	70 MeV p	1.5	0.81	2.5	4.0	HPK-3.1/3.2, NDL FBK-UFSD3-C
Los Alamos (*pLA*)	800 MeV p	0.7	0.43	6	0.4	early prototypes
CERN PS (*pPS*)	23 GeV p	0.6	0.44	6	2.7	early prototypes

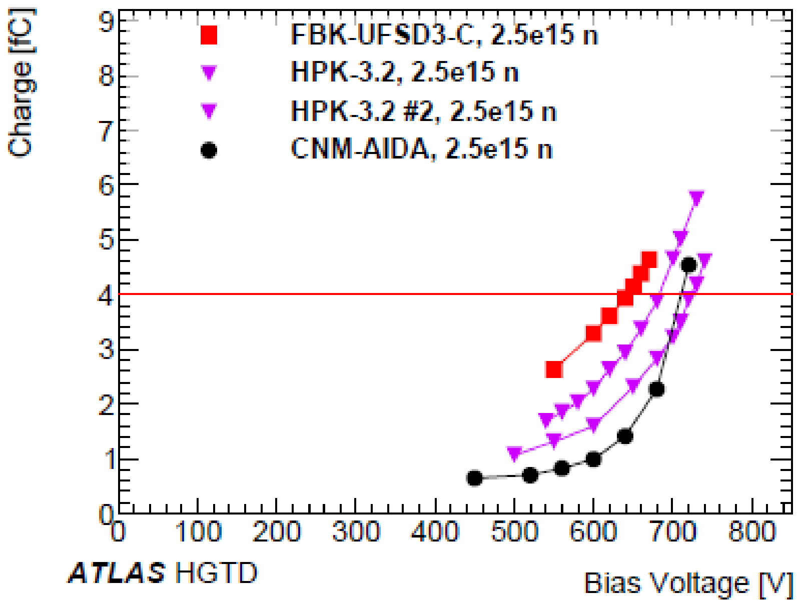
Table 5.4: Irradiation facilities and parameters and maximum achieved fluence and TID, as well as LGAD types irradiated.

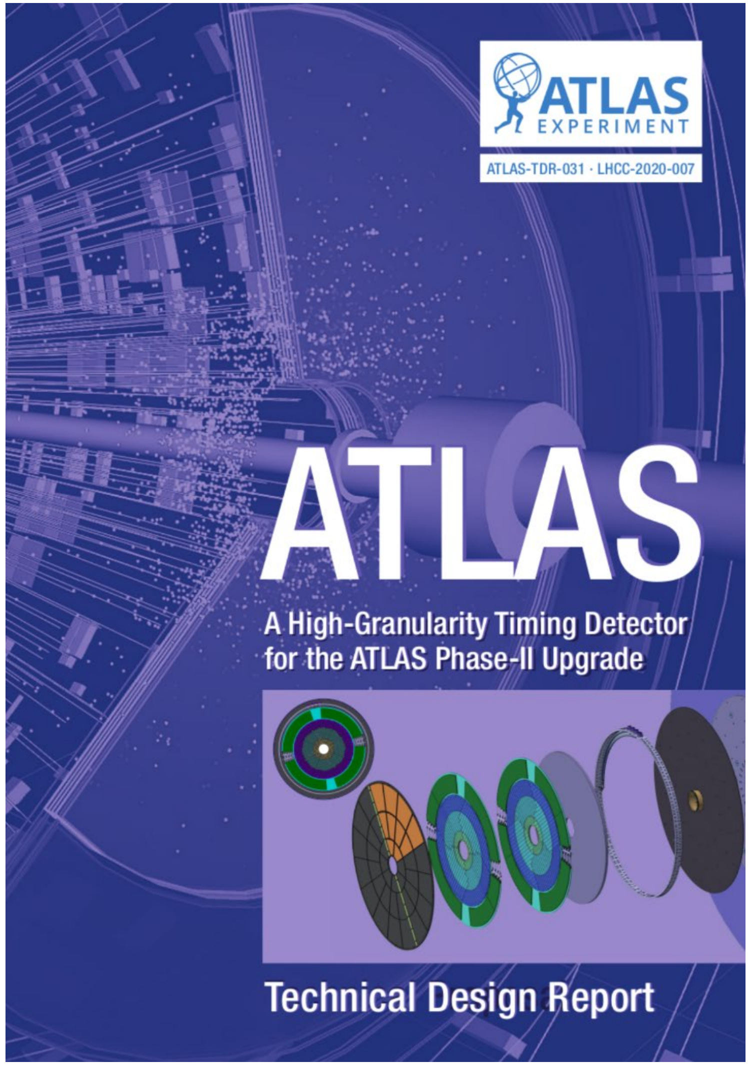


HGTD TDR and sensor R&D status

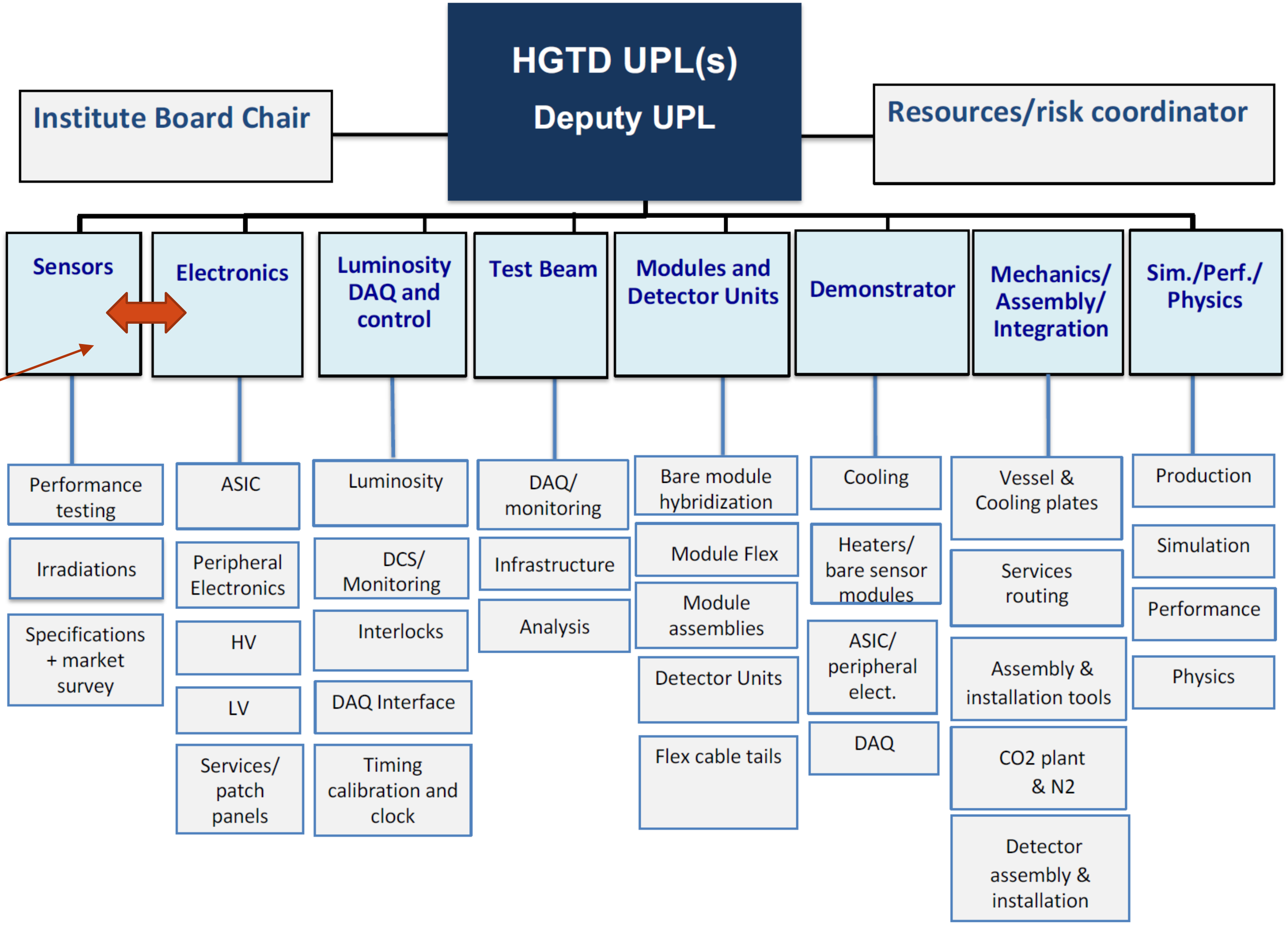
- HGTD TDR published in 2020
  - Was already delayed 1 year because of issues with power consumption and radiation damage
- 3 vendors fully characterized (+1 not added, NDL, because of last minute results), each fulfilling HGTD requirements
  - HPK most promising since it could cover all production
  - Many plots comparing CC, time resolution, power, current etc…
- **However issues arose after the TDR**: single event burnout and higher damage from proton irradiation







HGTD organization



Communication between groups is crucial!

Conclusions

- **HGTD** relies on a new technology (LGADs) that took a long time to characterize
  - Over 5 years of R&D phase, one could say it is still ongoing
- Many setbacks along the way that were solved thanks to diversifying efforts
  - **TDR contained quite detailed studies, after it we still encountered crucial issues**
- Several group involved in the sensor R&D, at least 3 actively testing sensors at the beginning and more now
  - Advantage of shared R&D with CMS ETL
- Multiple vendors, several productions per vendor, twice a year TB campaign

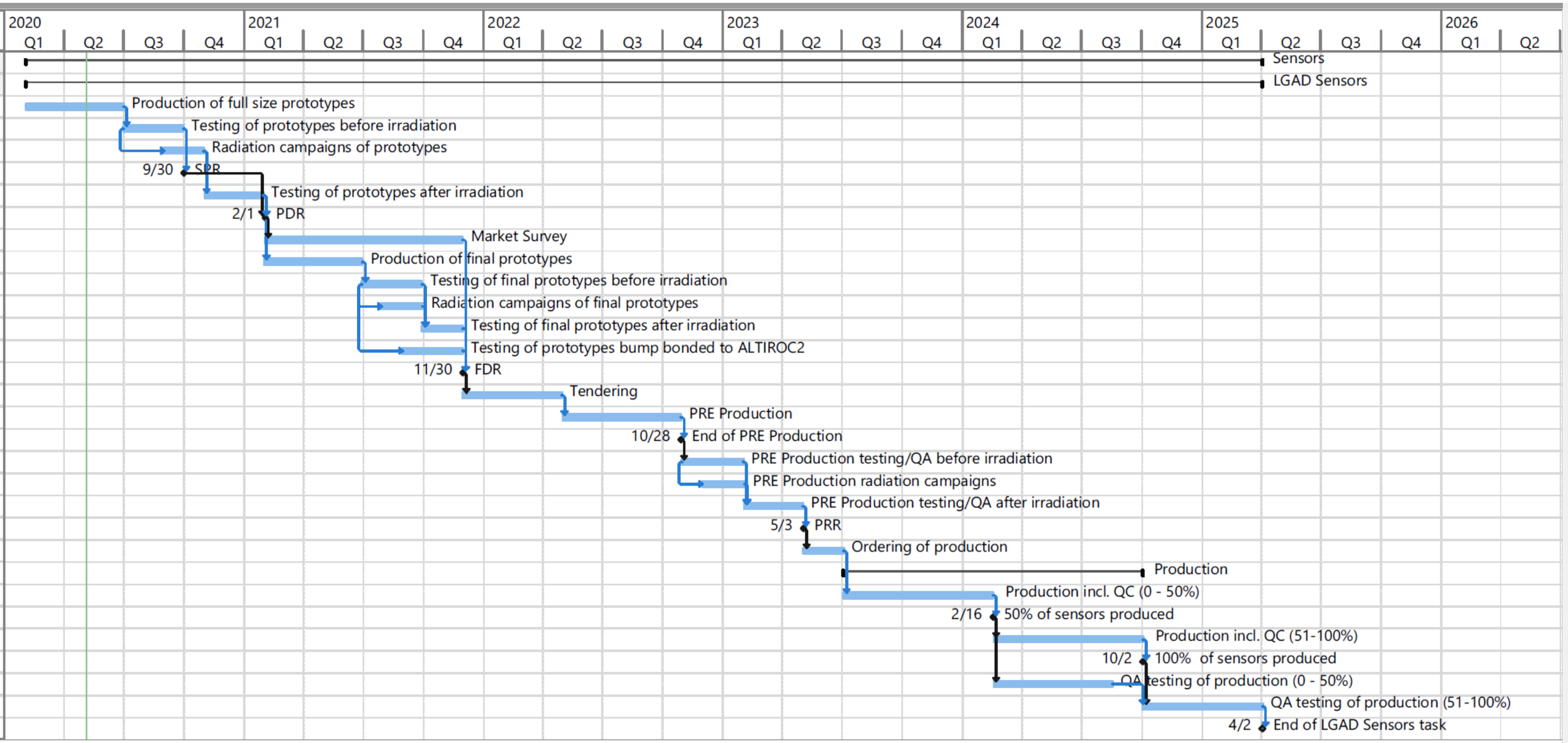
- **EPIC relies on a new technology as well** (AC-LGADs)
  - LGAD part quite understood but **AC readout still to be fully characterized**
  - **Many more variables to optimize than in LGADs**
  - Need comparisons and full picture to take decisions on parameters → there's progress but not quite there yet!
  - Strip sensors studied twice at TB (barrel), not much on pixels (end-cap)
- **Diversification** (more vendors, more technologies) might solve **future deal breaker issues** (e.g. for HGTD was SEB)
- **Yield and uniformity** of productions to be addressed
- Irradiation is much lower in EPIC and not a source of concern, but it's stills something to check: we don't completely understand the effect in AC-LGADs. Especially if not homogeneous and with protons.

Backup

Sensors market survey and production

- Market survey will start Q1 2021 and end in Q4 2021 (FDR due Q4 2021)
  - SPR Q4 2020 and PDR in Q1 2021
- Then pre-production will start in Q2 2022 until Q4 2022
  - Following pre-production testing and Q/A before and after irradiation
  - PRR in Q2 2023
- Production Q3 2023 to Q4 2024
  - First half of production ready Q1 2024, Q/A during second part of production

Task ID	WBS	Task Name	Duration	Start	End	ID	Predecessors	Successors
	8.1	**Sensors**	**1313 days**	**2020/2/3**	**2025/4/2**	**1**		
	8.1.1	**LGAD Sensors**	**1313 days**	**2020/2/3**	**2025/4/2**	**2**		
SEN-1		Production of full size prototypes	102 days	2020/2/3	2020/6/30	3		4
SEN-2		Testing of prototypes before irradiation	64 days	2020/7/1	2020/9/29	4	3	6FS+1 day,5SS+44 days
SEN-3		Radiation campaigns of prototypes	43 days	2020/9/1	2020/10/30	5	4SS+44 days	7
SEN-M1		SPR	0 days	2020/9/30	2020/9/30	6	4FS+1 day	8
SEN-4		Testing of prototypes after irradiation	61 days	2020/11/2	2021/1/29	7	5	8FS+1 day,10
SEN-M2		PDR	0 days	2021/2/1	2021/2/1	8	7FS+1 day,6	9
SEN-5		Market Survey	211 days	2021/2/2	2021/11/29	9	8	15
SEN-6		Production of final prototypes	104 days	2021/2/1	2021/6/29	10	7	11
SEN-7		Testing of final prototypes before irradiation	64 days	2021/6/30	2021/9/28	11	10	12SS+22 days,13,14SS+44 days
SEN-8		Radiation campaigns of final prototypes	43 days	2021/7/30	2021/9/29	12	11SS+22 days	13
SEN-9		Testing of final prototypes after irradiation	43 days	2021/9/30	2021/11/29	13	12,11	15
SEN-10		Testing of prototypes bump bonded to ALTIROC2	64 days	2021/8/31	2021/11/29	14	11SS+44 days	15FS+1 day
SEN-M3		FDR	0 days	2021/11/30	2021/11/30	15	9,13,14FS+1 day	16
SEN-11		Tendering	105 days	2021/12/1	2022/4/29	16	15	17
SEN-12	**8.1.1.1**	**PRE Production**	**129 days**	**2022/5/2**	**2022/10/28**	**17**	**16**	**18**
SEN-M4		End of PRE Production	0 days	2022/10/28	2022/10/28	18	17	19,345
SEN-13		PRE Production testing/QA before irradiation	66 days	2022/10/31	2023/1/31	19	18	20SS+23 days,21
SEN-14		PRE Production radiation campaigns	45 days	2022/12/1	2023/2/2	20	19SS+23 days	21
SEN-15		PRE Production testing/QA after irradiation	60 days	2023/2/3	2023/5/2	21	20,19	22FS+1 day
SEN-M5		PRR	0 days	2023/5/3	2023/5/3	22	21FS+1 day	23
SEN-16		Ordering of production	42 days	2023/5/4	2023/7/3	23	22	25
SEN-17	**8.1.1.2**	**Production**	**320 days**	**2023/7/4**	**2024/10/2**	**24**		
SEN-17a		Production incl. QC (0 - 50%)	161 days	2023/7/4	2024/2/16	25	23	26
SEN-M6		50% of sensors produced	0 days	2024/2/16	2024/2/16	26	25	27,29,350,352
SEN-17b		Production incl. QC (51-100%)	159 days	2024/2/19	2024/10/2	27	26	28
SEN-M7		100% of sensors produced	0 days	2024/10/2	2024/10/2	28	27	30,354,356
SEN-18		QA testing of production (0 - 50%)	127 days	2024/2/19	2024/8/16	29	26	30
SEN-19		QA testing of production (51-100%)	125 days	2024/10/3	2025/4/2	30	29,28	31
SEN-M8		End of LGAD Sensors task	0 days	2025/4/2	2025/4/2	31	30	



Country/FA	Institutes involved in HGTD R&D
Brazil	USP
CERN	CERN
China	IHEP, NJU, USTC, SINANO, SJTU
France	IJCLab, LPC, LPNHE, OMEGA
Germany	Mainz, Giessen, Goettingen*
JINR	JINR
Morocco	UIT, UH2C, UM5R, UMP
Russia	MEPhI
Slovenia	JSI
Spain	IFAE
Sweden	KTH
Taiwan	AS, NTHU
USA*	BNL, SLAC, SMU, UCSC, SUNYSB

Table 15.1: List of countries/Funding Agencies and corresponding Institutes contributing to HGTD R&D. OMEGA and SINANO are ATLAS Technical Associate Institutes. *Goettingen and USA Institutes will only be involved in the R&D phase.

R&D Activities/WG	Institutes
Sensors	BNL, CERN, Goettingen, IFAE, IHEP, JINR, JSI, USTC, USP, UCSC
Electronics	AS, Giessen, IFAE, IHEP, IJCLab, JINR, KTH, LPC, NJU, NTHU, Omega, SLAC, SMU, SUNYSB, UIT, UH2C, UM5R, UMP, USTC
Luminosity, DAQ and Control	IHEP, KTH, Giessen, UCSC, UIT, UH2C, UM5R, UMP
Test beams and demonstrator	All Institutes
Module assembly and loading	BNL, IFAE, IHEP, IJCLab, JINR, LPNHE, Mainz, UIT, UH2C, UM5R, UMP, USTC, SINANO
Mechanics, assembly and installation	CERN, IHEP, IJCLab, JINR, LPNHE, MEPhI
Simulation/Performance/Physics	All Institutes

Table 15.2: List of R&D activites and participating Institutes. OMEGA and SINANO are ATLAS Technical Associate Institutes. US groups will only be involved in the R&D phase. Goettingen is only involved in the Sensors R&D phase.

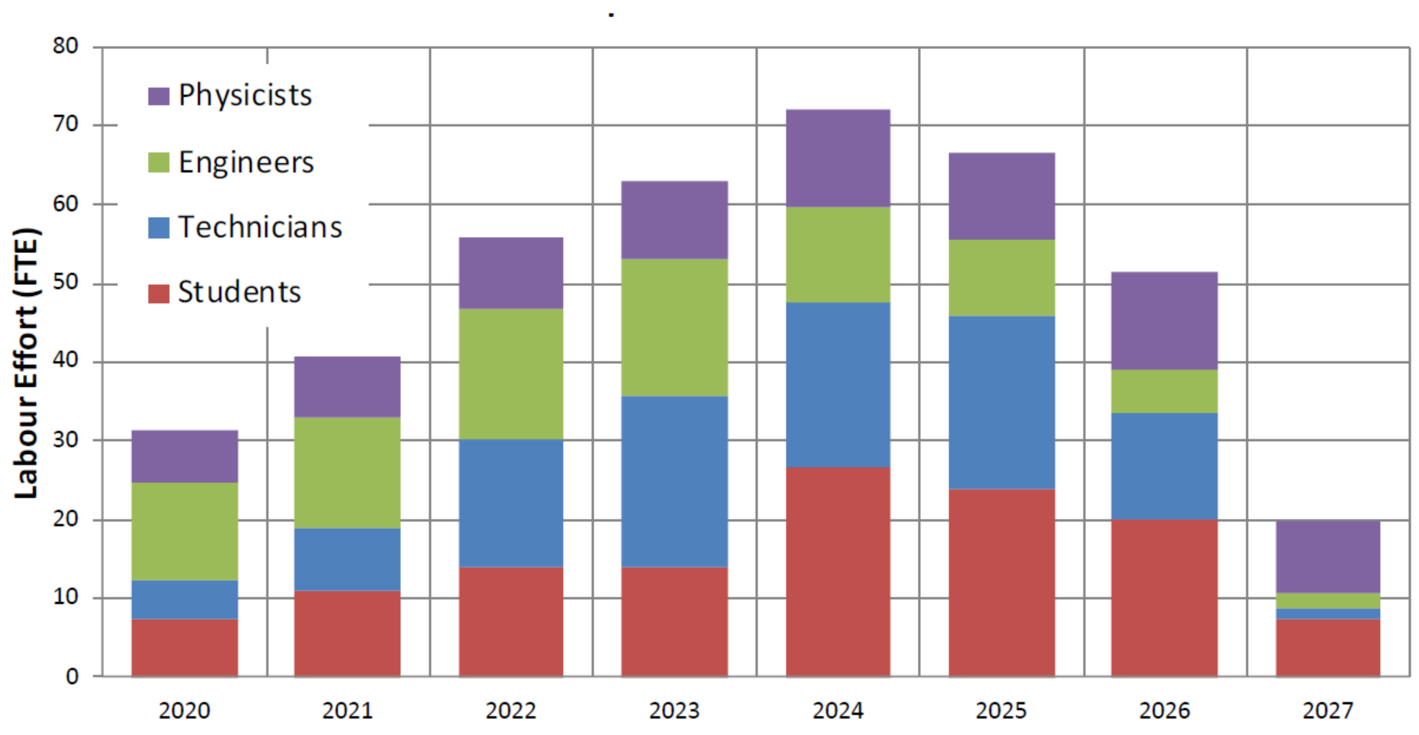


Figure 15.11: Required effort (in FTE) needed per labour type (physicists, engineers, students, technicians) over the lifetime of the project.

Critical issues and setbacks in HGTD (non-complete)

- Power dissipation
  - Lead to **TDR 1 year delay** and restructuring of the wheels (3 rings instead of 2)
- Collected charge needed for the ASIC
  - CC not enough after irradiation, 3 rings structure needed. 30um devices (less base CC) not feasible even though the time resolution was better
- Yield from full sensor production
  - Yield was too low for 30x15 arrays, needed to reduce the sensor size to 15x15
- Irradiation gradient
  - Irradiation difference between one edge and the other of the sensor, fine for 15x15 (not for 30x15)

After the TDR

- Damage from proton was higher (up to factor 3) than neutron damage
  - Discovered late because of beam line availability
- Single event burnout (SEB), lowering voltage limits → **HPK is not a viable vendor anymore**
  - Several **new prototype runs with HPK (still ongoing)** to try and find a solution