CMS TRACKER
PHASE 2 UPGRADE
IT SERVICES V1.4

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Version notes:

V1.4 wrt to V1.3 : fixed baseline for optomodules, fixed typo in pg 17 (#mod for R4)

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INTRODUCTION TO GEOMETRY

The purpose of this document is to describe the services, the guidelines, the geometry constraints and suggest possible architectures of the cabling for powering and readout of the CMS Inner Tracker modules for Phase II Upgrade (the ones selected for the TDR). **It is a first draft overview of the services and should not be taken as a final version**.

The official Layout webpage for the CMS Phase II Tracker can be found under this link.

The geometry version of IT4025 has been selected for the TDR. The acceptance of this layout extends to $|\eta| \backsimeq 4$. The Inner Tracker part is shown in the picture below and will be equipped with pixel modules. It is composed of a barrel part (TBPX) with four cylindrical layers (L1, L2, L3, L4), a forward part (TFPX) with eight small disks per end and an extension part (TEPX) with four larger disks per end.

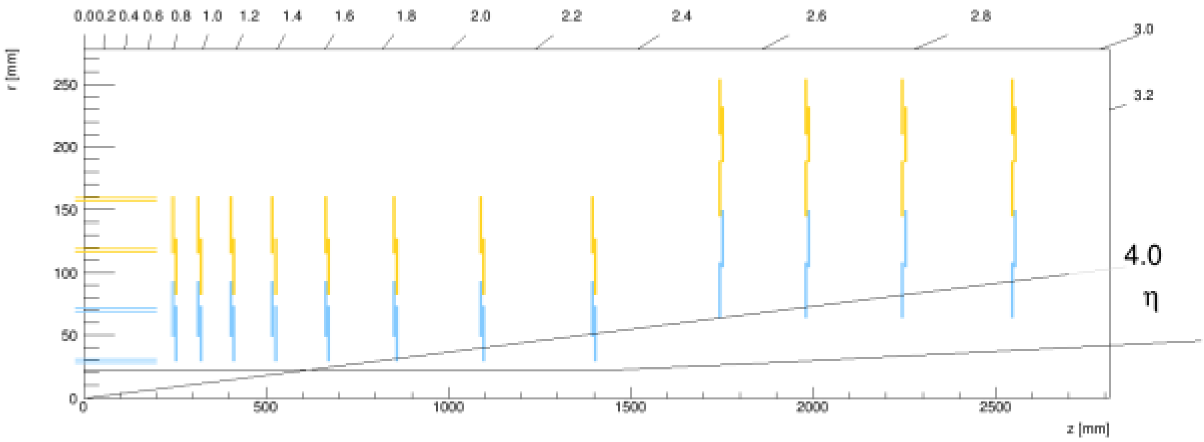

Figure 1. The IT geometry presented in the TDR.

The TBPX pixel modules are arranged in "ladders". Each ladder is split in z into two parts, one long (5 modules) and one short (4 modules). The two inner layers of the TBPX use 2x1 chip modules whereas the two outer ones use 2x2 chip modules (see Table 1).

The TFPX and the TEPX are arranged in concentric rings (4 for TFPX, 5 for TEPX). Each disk is physically made out of two disks; one that supports the odd rings and one that supports the even rings. Each of these disks are split in half into D-shaped structures known as Dees (see Figure 2).

The barrel, forward and endcap will be mounted in half cylinders that will hold their services. There will be four Inner Tracker structures to be inserted at installation time. Two of them are depicted in the Figure 3. There is no mixing of services among the four half-cylinders. **Therefore, the design of the services for the IT has to always be considered per quarter of the detector (per end, per side). All the tables, plots etc shown in this document refer to a quarter of the detector unless stated otherwise.***

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* *Side note: At CMS, "per end" is used for the two +Z, -Z and "per side" is used for the far, near side (split in phi). There has not been any decision on which end will be the long (5 modules in each barrel ladder) or the short (4 modules per ladder). It does not make any difference. The two sides (far, near) are identical so there is no reason to distinguish among them. From now on, the document will describe the services for a quarter of the detector.*

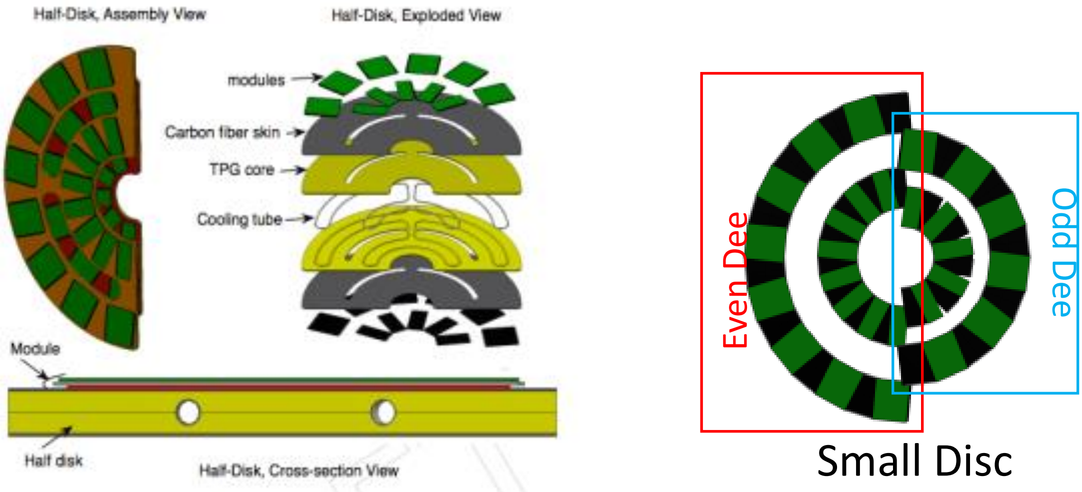


Figure 2. Sketches showing details of the dee structures. A ½ double-disc consists of two dees. Modules are arranged on both sides of the dees. (tdr reference fig 4.12)

Figure 3. (Left) CAD drawings showing the split of the IT into two half cylinders per end (tdr reference fig 4.10). (Right) the two parts of the barrel split in +-z (tdr reference fig 4.11)

Table 1. Type of modules and multiplicities of ladders and disks for a quarter of a detector.

QUARTER OF IT		Multiplicity (#ladders, #disks)	#modules per ladder/ half ring (short/long)	Type of modules	Number of modules (short/long)	Number of chips (short/long)
TBPX	L1	6	4/5	2x1	24/30	48/60
	L2	14	4/5	2x1	56/70	112/140
	L3	12	4/5	2x2	48/60	192/240
	L4	16	4/5	2x2	64/80	256/320
				SUM	**192/240**	**608/760**
TFPX	R1	8	10	2x1	80	160
	R2	8	16	2x1	128	256
	R3	8	12	2x2	96	384
	R4	8	16	2x2	128	512
				SUM	**432**	**1312**
TEPX	R1	4	20	2x1	80	160
	R2	4	28	2x1	112	224
	R3	4	18	2x2	72	288
	R4	4	20	2x2	80	320
	R5	4	24	2x2	96	384
				SUM	**440**	**1376**
				QUARTER OF TBPX+TFPX	**624/672**	**1920/2072**
				QUARTER OF TEPX	**440**	**1376**
				QUARTER OF IT	**1064/1112**	**3296/3448**
				ONE END OF IT	**2128/2224**	**6592/6896**
				ENTIRE IT	**4352**	**13488**

The following illustrations (Figures 4, 5, 6) will be used to facilitate the understanding of the routing of the services. The modules in green are 2x1 modules used in the two inner layers of TBPX and two inner rings of the disks, whereas the ones in orange are 2x2 modules used in the two outer layers of TBPX and the outer rings of the disks.

TBPX

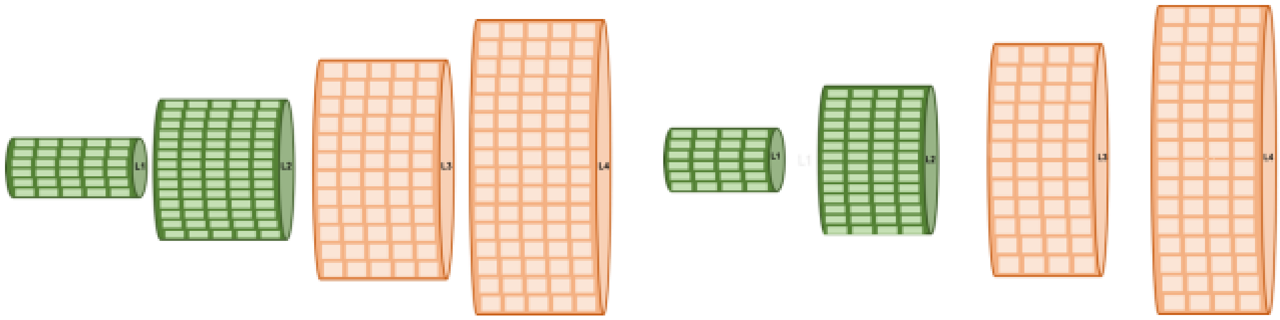


Figure 4. Illustration of the TBPX ladders (rows) and modules (cells) for the short (left) and the long (right) for a quarter of the detector.

TFPX/TEPX

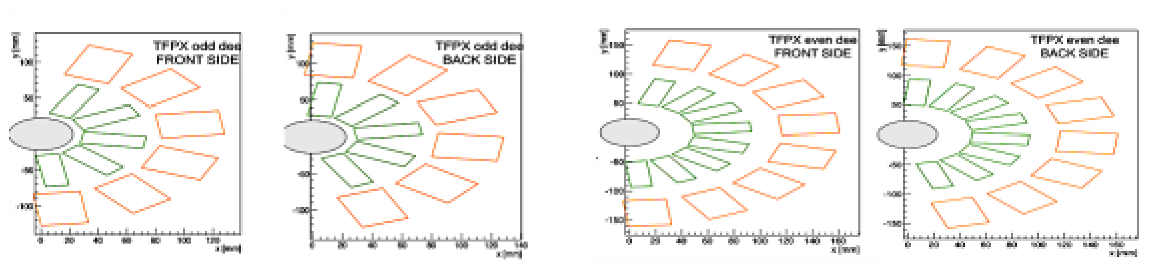


Figure 5. Illustration of two TFPX dees, an odd (R1, R3) and an even (R2, R4), which form a double disk.

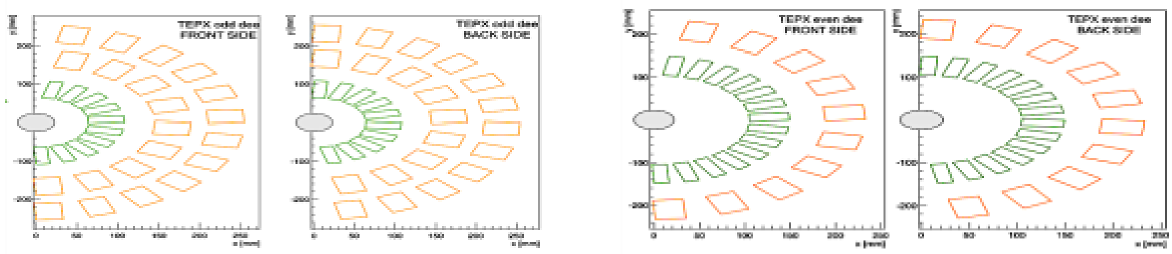


Figure 6. Illustration of two TEPX dees, an odd (R1, R3, R5) and an even (R2, R4), which would form half disk.

SERIAL POWERING OF THE MODULES

Each pixel chip will consume about ~2 A and need a supply voltage of 1.4 V. The use of DC-DC power conversion has been excluded due to radiation hardness and material budget reasons. Therefore, a serial power distribution system has been proposed. This scheme fulfils the requirements of high current power distribution with acceptable power cable losses, radiation hard and within the material limitations being based on a custom-made regulator embedded on the chip. The CMS pixel chip size will be 22 mm x (16.4 mm + 2 mm) = 360 mm^2 pixel array area/ (the extra 2 mm are there for the periphery). Below there is a picture of the RD53A demonstrator with chip size 20 mm x 11.8 mm. The power consumption of the chip at max. hit/trigger rate, including any SLDO losses (meaning current shunted by the SLDO) is expected to be < 1 W/cm^2.

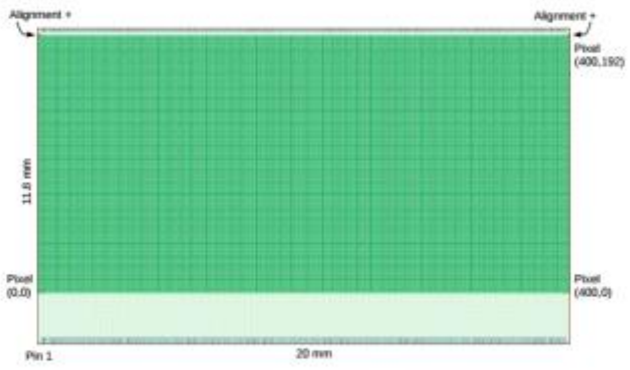


Figure 7. Top view of RD53A pixel array. The width is 20 mm and 400 pixels and the height is 11.8 mm and 192 pixels. The final CMS chip will be an enlarged version of this.

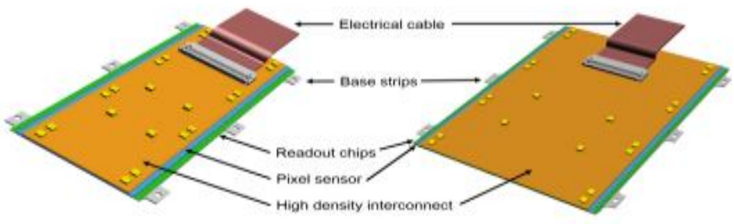


Figure 8. Sketch of the 1x2 and 2z2 pixel modules (tdr reference fig. 4.3)

Serial power loops feed the required supply current to chains of 5-10 pixel modules, with the two or four pixel chips on each module connected in parallel. For the moment, the maximum number of modules in a chain is set to 10. However, if in the future it is demonstrated that we can have more than that, this improvement might allow for reduction in the number of chains, probably better occupancy in some cases of the LpGBT input links on the expense of losing more modules when losing a chain. Future tests with the RD53A chip will show if power chains of more than 10 modules is a viable option.

TBPX

The guideline of max. 10 modules per chain is translated into TBPX by serially powering every two ladders leading to 8-module chains for the short end (left side of Figure 9) and 10-module chains for the long end (right side of Figure 9). It is straightforward to calculate the chains in the barrel #SPchains= #ladders/2.

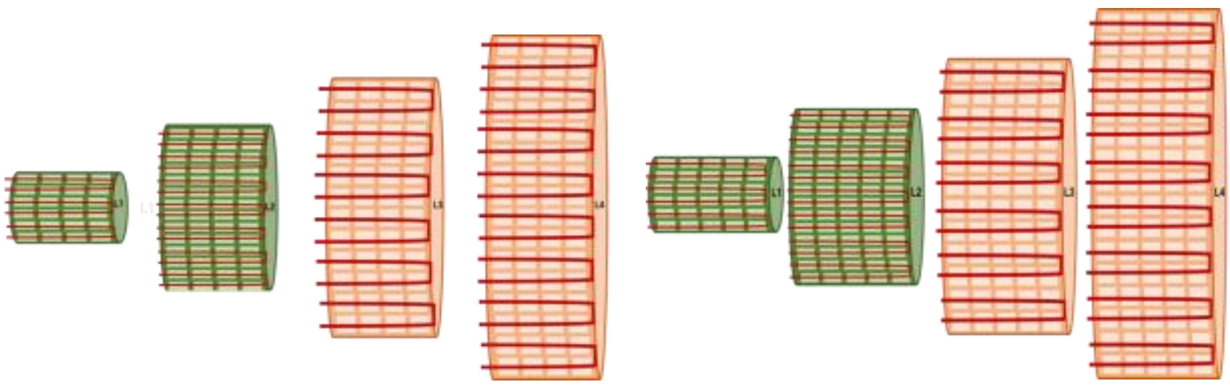


Figure 9. Serial power chains for TBPX short (top) and long (bottom) end. Every SP chain runs along two consecutive ladders: each layer needs #ladders/2 chains to get powered.

TFPX- TEPX

There is no practical way to combine the chains between rings of a dee in the TFPX since the inner rings of dees will host 1x2 chip modules while the outer 2x2 chip modules. In the TEPX case, in the odd dee, R3 and R5 can be combined nicely in chains of 7 modules (which will later be readout by one LpGBT each) [†]. The rest of the chains have followed the simple rationale of keeping it neat, simple and symmetric with max 10 modules per chain. For R1 of TFPX, after discussing with the TFPX engineers the number of chains was updated from 1 (of 10 modules) to 2 (of 5 modules) to avoid complications during assembly (such that a SP chain does not run from the front to the back side of the dee). A summary of the power chains in the IT per part of the detector is presented in Table 2.

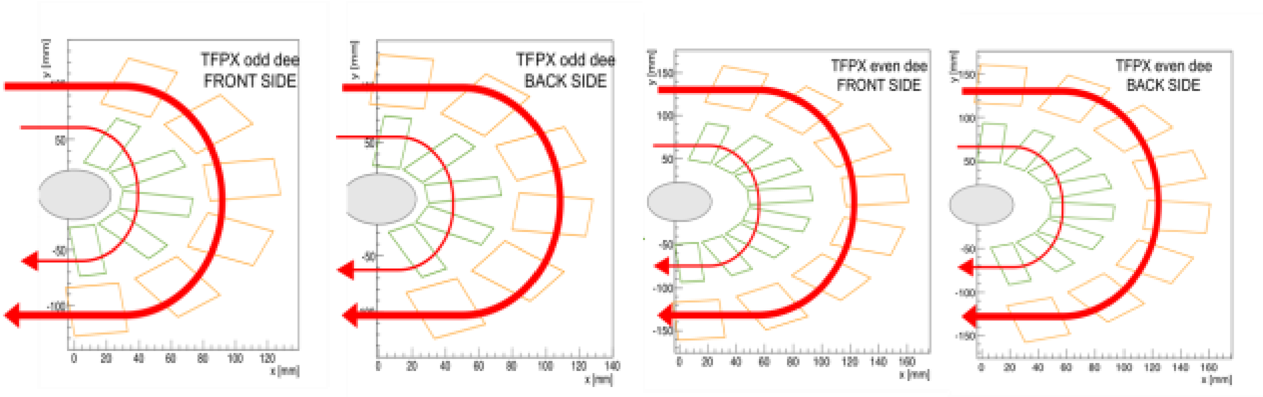


Figure 10. Serial powering of TFPX dees: 8 serial power chains per half double-disk.

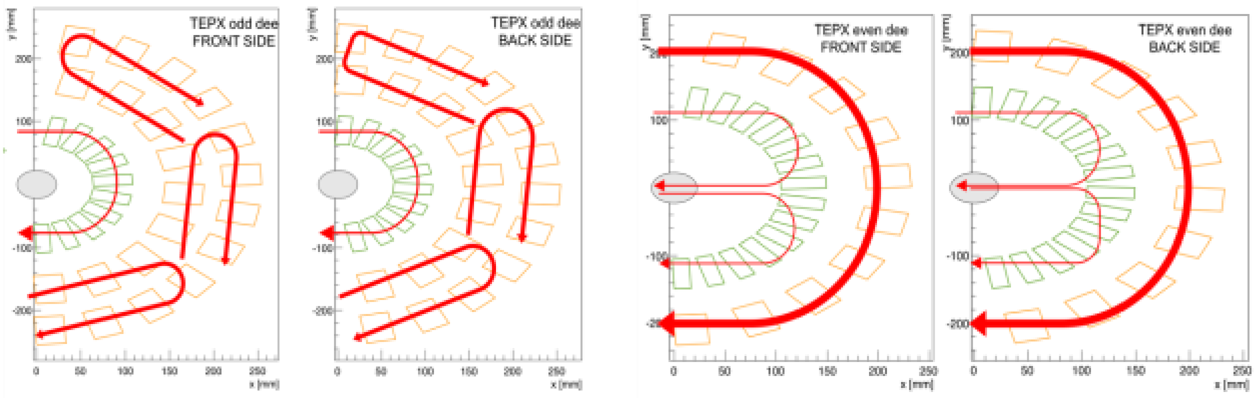


Figure 11. Serial powering of TEPX dees: 14 serial power chains per half double-disk.

[†] Alternative powering scheme for R3-R5 TEPX (separate chains per ring) results to same number of chains (2 for r3, 4 for r5) but would need 8 LpGBTs instead of 6 for the readout.

Table 2. Summary of SP chains needed to power the IT.

QUARTER OF IT		SP Chains 1x2 modules	SP Chains 2x2 modules	SP Chains SUM
TBPX	L1	3		3
	L2	7		7
	L3		6	6
	L4		8	8
	SUM	**10**	**14**	**24**
TFPX	Odd Dee	2	2	4
	Even Dee	2	2	4
	Disk	4	4	8
	SUM	**8*4 = 32**	**8*4= 32**	**64**
TEPX odd dee		2	6	8
TEPX even dee		4	2	6
TEPX disk		6	8	14
TEPX SUM		**4*6 = 24**	**4*8 =32**	**56**
QUARTER OF TBPX+TFPX		**42**	**46**	**88**
QUARTER OF TEPX		**24**	**32**	**56**
QUARTER OF IT		**66**	**78**	**144**
ONE END OF IT		**132**	**156**	**288**
ENTIRE IT		**264**	**312**	**576**

HIGH VOLTAGE DISTRIBUTION

There has not been a decision on the HV distribution scheme yet. The decision can only be taken after extensive tests with modules serially powered with sensors (with RD53A) for noise coupling and EMC (end of 2017). The most conservative approach regarding the high voltage distribution would be to use a HV wire per module and a separate return. This option could be supported by using coaxial cables for the HV distribution. This option would eliminate the noise coupling among modules of a serial power chain but would be more expensive in terms of material-budget (cables) and power supply channels. Below two options regarding the high voltage distribution are presented. Option A is the one that has been used for the cable description as it is more pessimistic in terms of space allocation while option B is the most favourable solution for the final system.

Option A) The approach of the cable description is based on 10 HV individual wires per SP chain plus one common return wire. Since there will be a difference of potential among the outputs of the modules, the common return wire is shown to be connected to the "AC-gnd" of the modules. This wire could be used for filtering purposes. A noise coupling problem though would still be present. This option doesn't really seem to serve the purpose of isolating the noise of a module but would only allow to compensate for the ΔV differences of the sensors (especially in the case of the 3D sensors). In this document, option A has been chosen as baseline for the design of the cables, although the preferred so-far HV scheme for the final system is option B (to be demonstrated).

Option B) A more realistic approach is that HV will follow the serial power architecture, i.e. a HV wire would be used per SP chain (up to 10 modules). An implication of that solution would be that if there is a HV problem on any of the sensors, the whole chain will suffer. Regarding the grounding of the system; each module in a SP chain sits in a different potential and have local grounds. This "local ground" potential can reach for the first module in a chain of ten, as high as ~10 * 1.4V=14V with respect to the "local ground" of the last module which will be ~2-3V (assume also some voltage drop on wires). If a single wire of HV is used to power a chain then the effective HV voltage seen by the modules in a chain will be varying by up to max 20V. A HV filter will be needed to avoid any noise coupling between the pixel sensor signal and the pixel chip. If the sensors are planar, the ΔV difference should not cause any problems since its minor w.r.t. to the absolute value of HV. A more problematic case is the use of 3-D sensors that require much smaller bias voltage and in this case this ΔV becomes significant.

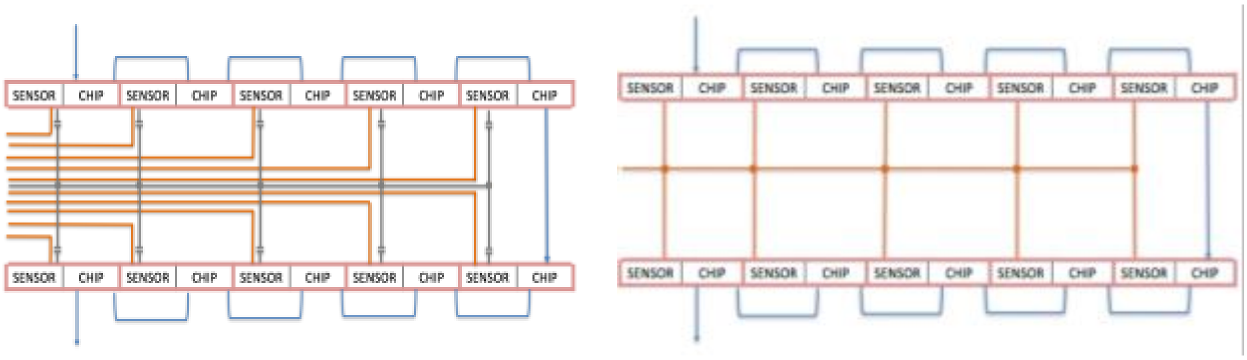


Figure 12. High Voltage distribution options with serial powering of the chip. Left (option A) used as the basis for the cable assumption, right (option B) the scheme that is the most probable for the final system.

READOUT

E-LINKS

Triggered event data collected from the pixel array will be collected by the end of column of the pixel chip where pixel array data will get re-organized by on-chip data processing and are sent out after a lossless data compression algorithm has been applied. Chip data are sent over a configurable (1-4) number of differential electrical links (E-links) at 1.28 Gbps to the opto-modules that accommodate the LpGBT chip that converts the readout data to optical. Data from up to seven E-links are merged into 10 Gbps upstream optical links to the DAQ. Every module will also receive command, trigger and configuration data via a downstream 160 Mbps E-link originating from the LpGBT, which receives the data via a 2.5 Gbps downstream optical link. The number of E-links used to readout a chip depends on the location on the detector since there is a strong dependence on hit rates vs location. For outer pixel layers and rings, where the hit rates are low, the data from all the chips of the module are merged into a single E-link that comes out of the module. Notice also that for the disks, because of the $1/r^2$ dependence, the rate across a module is not uniform. The rates among disks of the same part of the detector are similar (small Z dependence).

A proposed lossless data compression has been presented during a RD53 meeting by K. Androsov. This algorithm was applied in CMSSW data by Yang-Yang and was presented during Phase 2 days. The results of this study are shared in this link and present the data rates per subdetector part using the single-hit data format of 9*2+4 bits per hit (pixel address = 9+9, TOT=4 bits) and the respective results after the delta-compression. The mean values (and not the 99%) of bits per chip per event are used to determine required number of E-links. Derandomizer buffers will smoothen out the tail of the distribution. Table 3 shows these rates (before and after compression) and the readout rate in Mbps for a trigger rate of 750 kHz per pixel chip per location, while Table 4 calculates the number of readout E-links needed per module per location such that a maximum bandwidth occupancy of 75% is achieved in the 1.28Gbps links (keeping 25% headroom). Tables 5 and 6 summarize the total estimated bandwidth and the total number of links for every subdetector part.

Table 3. Date Rates before and after on-chip data compression per chip per event.

Rate presented as bits per chip per event, calculated for Pixel4021 using ttbar_200PU relval samples				
	Mean	Delta_byColumn Mean	Compression Factor	Chip RO rate in Mbps for 750KHz
TBPX _L1 (PR4x1)	6286.23	3529.39	1.8	2647
TBPX _L2	1535.3	695.036	2.2	521
TBPX L3	717.343	308.774	2.3	232
TBPX L4	487.302	202.568	2.4	152
TFPX_R1_lowCol	1552.8	901.184	1.7	676
TFPX_R1_highCol	3029.77	1909.14		1432
TFPX_R2_lowCol	1000.75	543.93	1.8	408
TFPX_R2_highCol	1584.78	928.937	1.7	697
TFPX_R3_lowCol	626.029	309.292	2.0	232
TFPX_R3_highCol	814.019	428.119	1.9	321
TFPX_R4_lowCol	451.207	205.549	2.2	154
TFPX_R4_highCol	559.914	267.455	2.1	201
TEPX R1_lowCol	787.409	463.59	1.7	348
TEPX R1_highCol	1171.64	710.774	1.6	533
TEPX R2_lowCol	495.509	274.883	1.8	206
TEPX R2_highCol	630.577	359.083	1.8	269
TEPX R3_lowCol	417.228	222.738	1.9	167
TEPX R3_highCol	433.137	236.155	1.8	177
TEPX R4_lowCol	317.742	161.522	2.0	121
TEPX R4_highCol	350.807	184.045	1.9	138
TEPX R5_lowCol	274.477	136.242	2.0	102
TEPX R5_highCol	310.51	158.583	2.0	119

Table 4. Estimated number of E-links per subdetector part and E-links bandwidth occupancy.

		CHIP			MODULE			
		RO rate in Mbps for 750KHz	RO 1.28 Gbps Links per chip	Elink Occupancy per chip	#chips per module	Module Rate Mbps	RO 1.28 Gbps Links per module	Elink Occupancy per module
TBPX	L1	2647	3	69%	2	5294	6	69%
	L2	521	1	41%	2	1043	2	41%
	L3	232	0.25	72%	4	926	1	72%
	L4	152	0.25	47%	4	608	1	47%
TFPX	R1_lowCol	676	1	53%	1	2108	3	55%
	R1_highCol	1432	2	56%	1			
	R2_lowCol	408	1	32%	1	1105	2	
	R2_highCol	697	1	54%	1			43%
	R3_lowCol	232	0.5	36%	2	1106	2	
	R3_highCol	321	0.5	50%	2			43%
	R4_lowCol	154	0.25	48%	2	710	1	
	R4_highCol	201	0.25	63%	2			55%
TEPX	R1_lowCol	348	0.5	54%	1	881	1	69%
	R1_highCol	533	0.5	83%	1			
	R2_lowCol	206	0.5	32%	1	475	1	37%
	R2_highCol	269	0.5	42%	1			
	R3_lowCol	167	0.25	52%	2	688	1	54%
	R3_highCol	177	0.25	55%	2			
	R4_lowCol	121	0.25	38%	2	518	1	40%
	R4_highCol	138	0.25	43%	2			
	R5_lowCol	102	0.25	32%	2	442	1	35%
	R5_highCol	119	0.25	37%	2			

Table 5. Estimated bandwidth in Mpbs per subdetector part.

Quarter of IT		Module RO rate Mbps for 750KHz	Mod per ladder/Dee		Rate per ladder/ring		#phi per half cyl / #disks	RATE for Half cyl /Dee [Mbps]	
			short	long	short	long		short	long
TBPX	L1	5294	4	5	21176	26470	6	127058	158823
	L2	1043	4	5	4170	5213	14	58383	72979
	L3	926	4	5	3705	4632	12	44463	55579
	L4	608	4	5	2431	3039	16	38893	48616
	SUM							**268'797**	**335'997**
TFPX	R1	2108	10		21077		8	168619	
	R2	1105	16		17674		8	141395	
	R3	1106	12		13273		8	106187	
	R4	710	16		11352		8	90817	
	SUM				**63377**			**507019**	
TEPX	R1	881	20		17615		4	70462	
	R2	475	28		13313		4	53253	
	R3	688	18		12390		4	49560	
	R4	518	20		10367		4	41468	
	R5	442	24		10617		4	42467	
	SUM				**64303**			**257210**	
								READOUT RATE [Gbps]	
Quarter of TBPX+TFPX								**776**	**843**
Quarter of TEPX								**257**	
Quarter of IT								**1033**	**1100**
One end of IT								**2066**	**2200**
Entire IT								**4267**	

Table 6 Summary of number of links needed per subdetector part.

QUARTER OF IT		Multiplicity (#ladders, #disks)	#modules per ladder/ half ring	#Links per module	Total #Links (short)	Total #Links (long)
TBPX	L1	6	4 (short)/ 5 (long)	6	144	180
	L2	14	4 (short)/ 5 (long)	2	112	140
	L3	12	4 (short)/ 5 (long)	1	48	60
	L4	16	4 (short)/ 5 (long)	1	64	80
	SUM				**368**	**460**
					Total #Links for N*half disks	
TFPX	R1	8	10	3	240	
	R2	8	16	2	256	
	R3	8	12	2	192	
	R4	8	16	1	128	
	SUM				**816**	
TEPX	R1	4	20	1	80	
	R2	4	28	1	112	
	R3	4	18	1	72	
	R4	4	20	1	80	
	R5	4	24	1	96	
	SUM				**440**	
Quarter of TBPX+TFPX					**1184**	**1276**
Quarter of TEPX					**440**	
Quarter of IT					**1624**	**1716**
One end of IT					**3248**	**3432**
Entire IT					**6680**	

LPGBTS

The conversion of the readout data to optical links at 10 Gbps by LpGBTs and the Versatile Links (VL+) is constrained to a maximum total dose 100 Mrad and to a fluence of 3 x 10^{15} n_{eq}/ cm^2 (see presentation by Jan Troska https://indico.cern.ch/event/626258/). Therefore, the LpGBT modules of TBPX will arranged on the support cylinders, while for TFPX and TEPX the LpGBT modules will be located at the periphery of the dee structures.

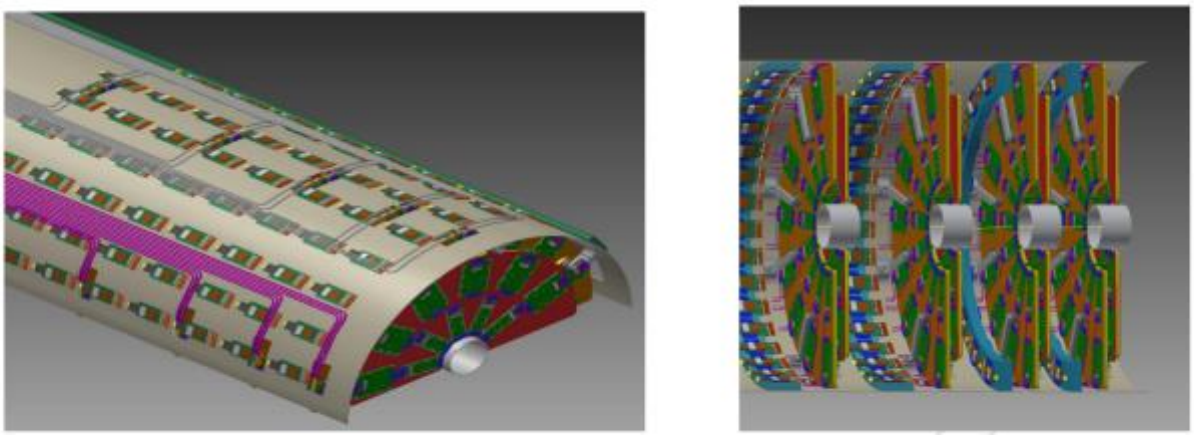


Figure 13. The placement of the LpGBT modules as presented in the TDR (tdr fig 4.13)

E-links originating from nearby chips and modules can be arriving in the same LpGBT (up to 7 inputs). The constraints of the elinks to LpGBTs grouping are the following:

- Max inputs of LpGBT is 7
- All links of a module connects to the same LpGBT (cannot split modules in multiple LpGBTs)
- A LpGBT can be shared amongst modules that belong to the same power chain.
- No front-to-back connection is allowed for the E-links.

Below Figures 14-16 show how these rules apply for the detector parts. The number in each cell corresponds to the E-links per module. Each cell corresponds to a module. Each row corresponds to a ladder. Each rectangular frame shows a group of links readout by a LpGBT (done only for one SP as an example for barrel). Each yellow line is a SP chain. Figure 17 is an illustration of the groups of the total number of LpGBTs needed for each part of the detector for a quarter of IT.

TBPX

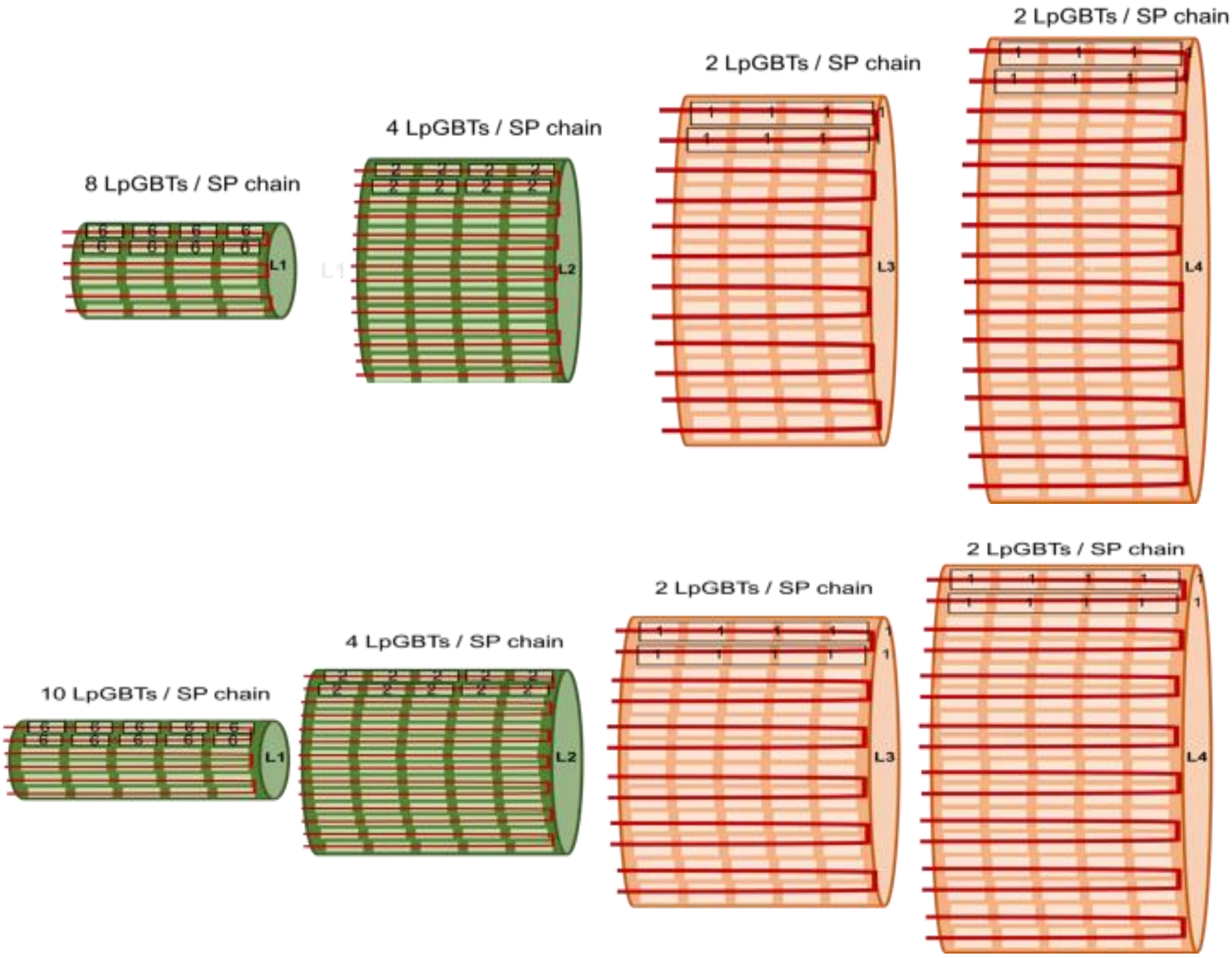


Figure 14. LpGBTs needed per TBPX Serial Power chain for the short(top) and long (bottom) end of the barrel.

DEES (TFPX- TEPX)

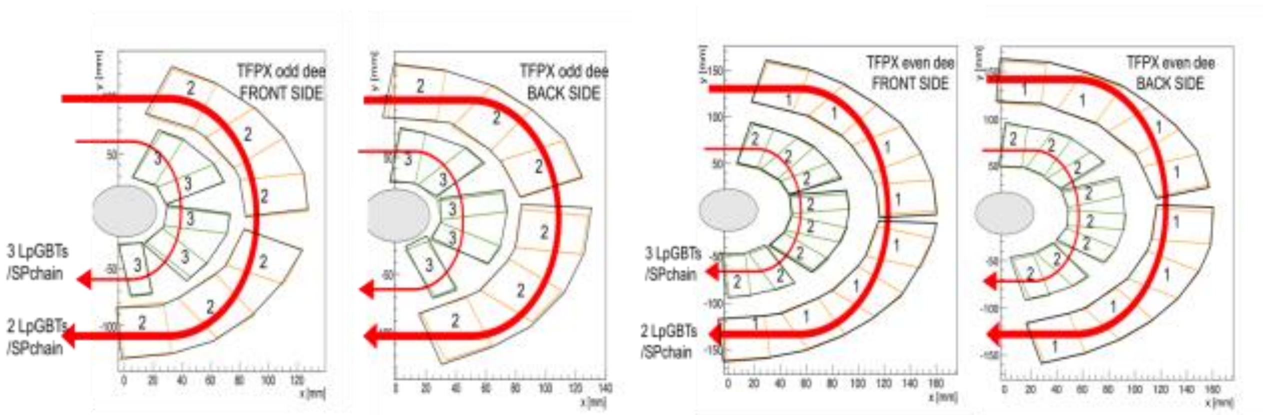


Figure 15. LpGBTs needed per TFPX Serial Power chain.

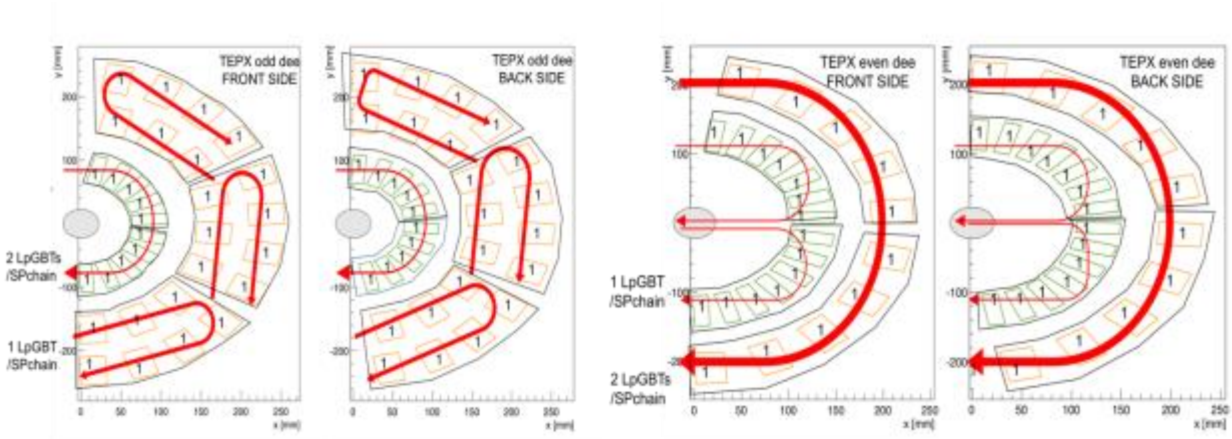


Figure 16. LpGBTs needed per TEPX Serial Power chain.

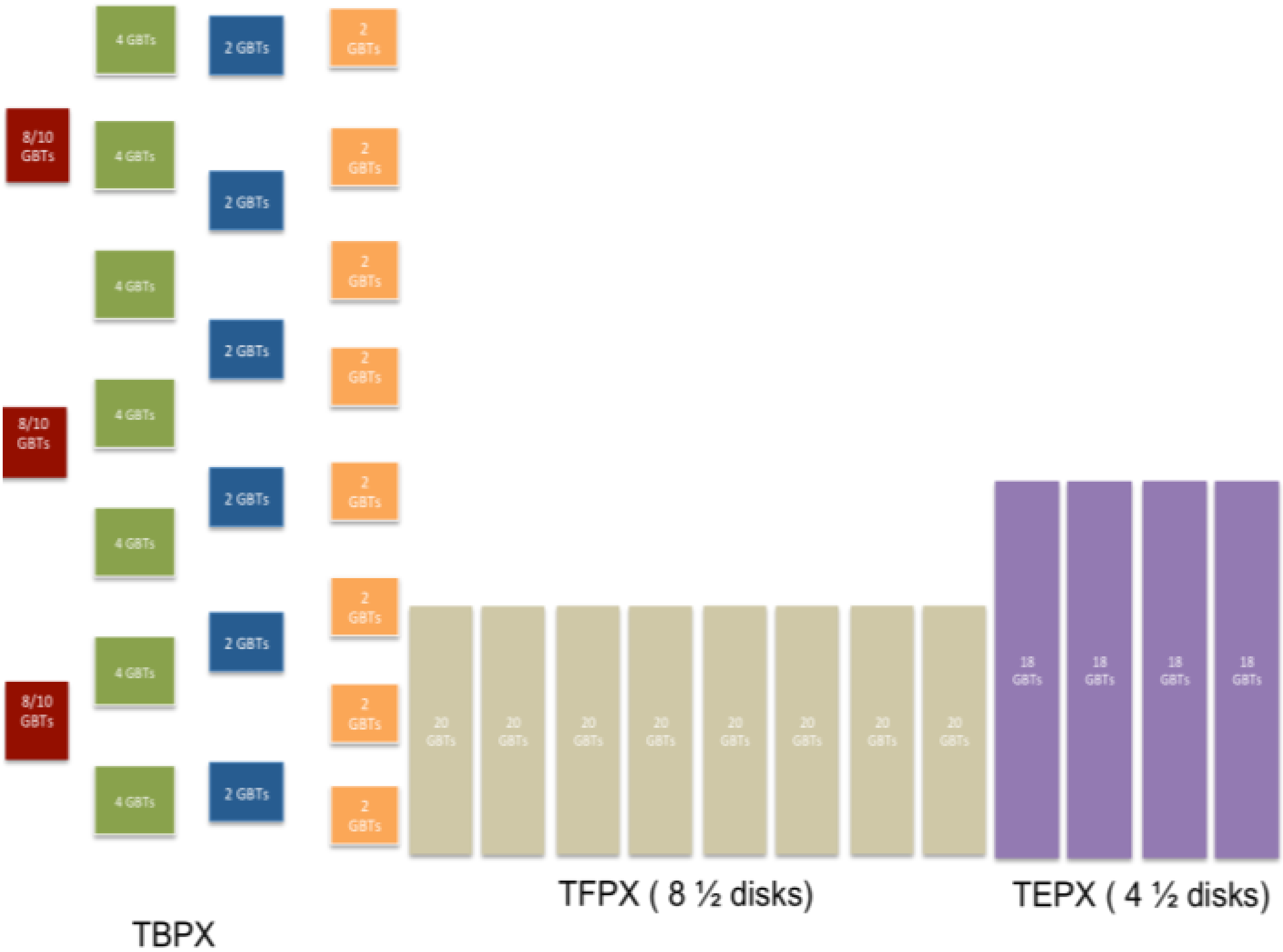


Figure 17. A map of the groups of the LpGBTs needed for each part of the IT for a quarter of the detector.

MULTIFIBRE BUNDLES

At Patch Panel 0 (PP0) the fibers originating from nearby LpGBTs will be grouped together in multi-fiber bundles of 24 fibers (MFB). The grouping of the LpGBT links to multi-fiber bundles follows the constraints:

- One MFB serves 12 LpGBTs (24 fibers, 12 upstream-12 downstream).
- One MFB should serve LpGBT that are sitting close to each other (following similar routing).
- No mixing of TEPX services with the TFPX-TBPX allowed.

The following summary Table 7 uses the information presented in Table 6 and Figure 17 and presents how the LpGBT links can be grouped in bundles of 12 pairs and the percentage of fibers used in the bundles.

Table 7 Summary table for #GBTs/MFBs per sub-detector

Quarter of IT		LpGBTs (short-long)	Bandwidth [Gbps]		MFB (all disks)	MFB usage (short-long)
			Short	Long		
TBPX	L1	24 - 30	127	158	2 - 3	24/24 - 30 /36 = 100% - 83%
	L2	28	58	73	3	28 /36 = 78%
	L3	12	45	55	1	12 /12 = 100 %
	L4	16	39	49	2	16 /24 = 67 %
	SUM	80/86	269	336	8-9	
TFPX	Odd Dee	10				
	Even Dee	10				
	8 disks	160	8* 63.4 = 507		16 (2/half disk)	160 /192 = 83%
TEPX	Odd Dee	10				
	Even Dee	8				
	4 disks	72	4*64.3 = 257		6	72/72 =100%
Quarter of TBPX+TFPX		240/246	776	843	24/25	
Quarter of TEPX		72	257		6	
Quarter of IT		312/318	1033	1100	30/31	312/360 =87% - 318/372=85%
One end of IT		624/636	2066	2200	60/62	
Entire IT		1260	4267		122	

MULTIFIBRE CABLES

At Patch Panel 1 (PP1) multi-fibre bundles will be grouped together to multi-fibre cables (MFC) (144 fibres each). Grouping the MFBs here was done keeping in mind that it would be nice to mix data from the TBPX layers and the TFPX disk such that a DTC failure would not cause complete loss a big part of the detector.

- One MFC serves 6 MFBs (72 GBTs).
- Each MFC will be serving one DAQ module with 72 inputs.
- One MFC can combine different regions.
- The services for TEPX are completely separated by the rest of the IT.

The following summary table shows the grouping of the MFBs to MFC and the respective input bandwidth for a DTC module. The 6 MFBs will be served by 1 MFCs, hence 1 DTC. The rest of the 25 MFBs for TBPX and TFPX can be served by 5 DTCs/MFCs.

Table 8. Mapping of the multifibre bundles to multifibre cables and DAQ modules.

#MFC	**Quarter of IT**	MFBs	MFC usage	DTC Input Bandwidth [Gbps]
1	TBPX L1+ 1* ½ TFPX disk	3 (2) +2 = 5 (4)	5/6 (4/6)	206
2	TBPX L2+ 1* ½ TFPX disk	3+2 = 5	5/6	129
3	TBPX L3+ 2* ½ TFPX disks	1+2*2 = 5	5/6	177
4	TBPX L4+ 2* ½ TFPX disks	2+2*2 = 6	6/6	171
5	2* ½ TFPX disks	2*2 = 4	4/6	127
6	4* ½ TEPX disks	6	6/6	257
	Quarter of IT	31 (30)	31 (30) /36 = 86 (83) %	1067

POWER CABLES FOR THE PIXEL MODULES

A multi-service cable will serve two serial power chains. Figure 18 shows a proposed distribution scheme for a SP chain. In this illustration, the power supplies (PS) are located in the counting room (USC), and up to 10 modules of a chain are supplied. Each multi-service cable consists of

- 2*2 thick LV conductors carrying 4A/8A for powering two serial power chain (LV SP)
- (10+1)*2 HV wires: 10 to provide high voltage to max 10 modules and 1 for a common return as described in option B in the Section High Voltage distribution per serial power chain
- 2 smaller LV conductors (similar to the LV wires used for OT) used for preheating the cooling lines
- 8 wires for two hardwired temperature sensors (assuming the two SP chains served by the cable belong to the same cooling loop)
- a copper braid (at least 85% shield) and a jacket compliant to safety rules.

The copper resistivity used for the calculations is 1.72e-8 Ωm and the copper cladded aluminium 2.7e-8 Ωm.

Table 9. Number of multiservice cables used.

QUARTER OF IT	SP Chains 1x2 modules	Power Cables	SP Chains 2x2 modules	Power Cables	SP Chains TOTAL	Power Cables TOTAL
TBPX+TFPX	42	22	46	23	88	45
TEPX	24	12	32	16	56	28
QUARTER OF IT **SUM**	**66**	**34**	**78**	39	144	73
ENTIRE IT	**264**	**136**	**312**	156	576	292

A total of 292 multi-service cables for powering the entire IT will run from the power supply racks to the Patch Panel 1 (PP1) boards located inside the solenoid. Their length depends on the location of the power supplies (PS). If the PS sit in USC then the distance would be around 85 m while if the PS sit in the balconies of UXC it would be 30 m.

For the first 85 m (up to PP1), a multiservice cable with Cu conductors similar to the one proposed for the OT is proposed. For the next 6 m (PP1-PP0) the LV SP cables and the drain wire change to a smaller cross-section of copper because of space constraints in the services channels. This change leads unavoidably to higher power losses. The multi-services cables used up to PP0 will be the same for 4A and 8A chains unless space limitations dictate otherwise. From PP0 and further on towards the modules, there will be no more cables but single copper cladded aluminium wires of different Al cross-section for the 4A ($0.8 mm^2$) and the 8A ($1.6 mm^2$) chains will be routed to reach individual modules. More details of the cables are shown in the following sections.

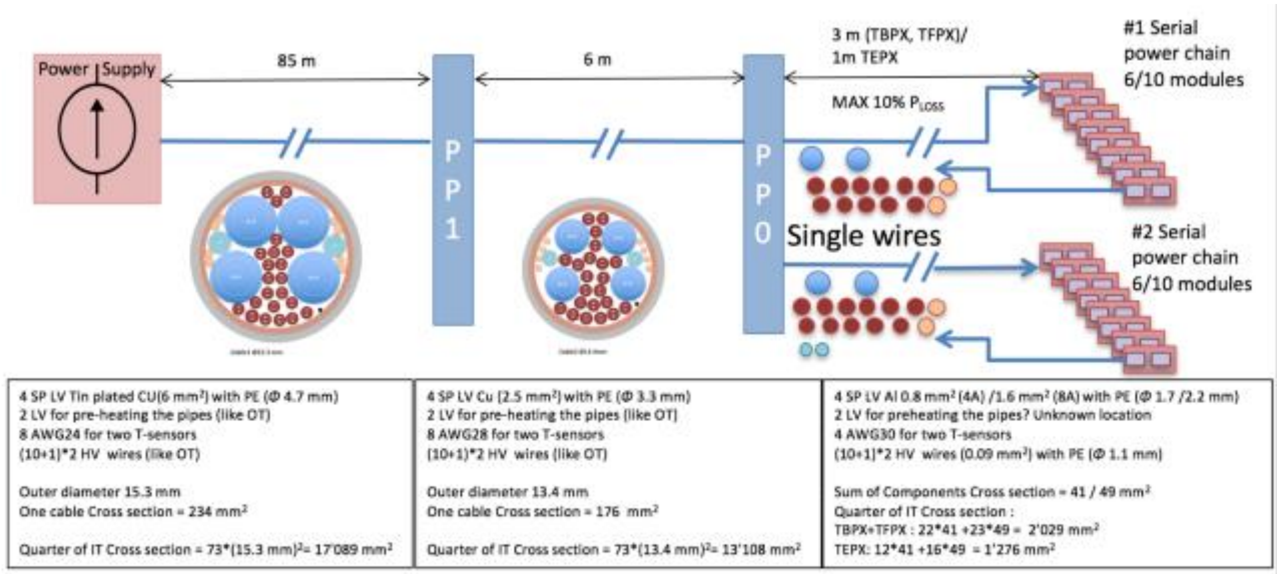


Figure 18. Proposed distribution scheme for a SP chain using two multiservice cables till PP0 and then switching single wires.

Table 10. Voltage drops on a SP cables for 6mm² wires between PS-PP1, 2.5mm² for PP1-PP0 and 0.8 mm² (4A)/1.6mm² (8A) inside the detector.

Current @PS (A)	Voltage @PS (V)	Single wire Vdrop Cable1 (V)	Voltage @PP1 (V)	Single wire Vdrop Cable2 (V)	Voltage @PP0 (V)	Single wire Vdrop Cable3-4 (V)	Module Chain Vin (V)	Single wire Total Vdrop LVPS to modules (V)
4	17.09	0.97	16.11	0.17	15.95	0.41	15.54	1.54
8	5.37	1.95	3.42	0.33	3.09	0.41	2.68	2.68

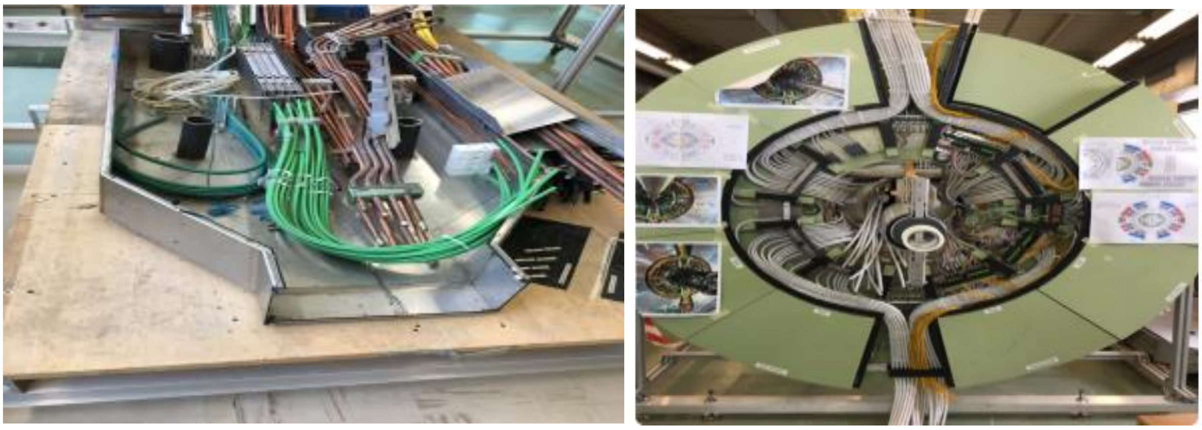


Figure 19. Pixel Phase 1 mock-up patch panels at B187. On the left, a tracker channel PP1-PP0. On the right, a picture of PP0.

POWER CABLE PS-PP1 (CABLE 1)

The LV SP conductors' cross-section was optimized for carrying 4A/8A over the long 85 m distance. Below one might see a table where the use of different cross-sections (starting from 1.5mm² similar to the one used for OT) show the Vdrop, the current density and the cable losses. The case of 6 mm² was chosen as baseline since it has modest current density and power losses. The voltage drop in the case of IT is not a problem as it uses serial powering.

The HV conductor cross-section is similar to the one used by OT (0.6mm²). These wires will be used to provide high voltage to the sensors (up to 1kV) and low current of up to 40 mA. One wire is used per module while one single return wire is used for a full chain (as described in option B in HV distribution section). Similarly, the LV wires for preheating the cooling pipes and the ones for the T-sensor are identical to the ones used by OT.

Table 11. Comparison of cross-sections for the serial power conductors for the PS-PP1 multi-service cable.

Cu Xsection	Length	Current per chain	Number of chains (Full detector)	Total Chip Power	20C Resistance	Vdrop	Single wire power loss	J	Vdrop	P	Total cable loss
(mm²)	(m)	(A)		(W)	(Ω)	(V)	(W)	(A/mm²)	(V/m)	(W/m)	(W)
1.50	85.00	4.00	264	14784	0.97	3.90	15.59	2.67	0.05	0.18	8233.98
1.50	85.00	8.00	312	34944	0.97	7.80	62.38	5.33	0.09	0.73	38924.29
2.50	85.00	4.00	264	14784	0.58	2.34	9.36	1.60	0.03	0.11	4940.39
2.50	85.00	8.00	312	34944	0.58	4.68	37.43	3.20	0.06	0.44	23354.57
4.00	85.00	4.00	264	14784	0.37	1.46	5.85	1.00	0.02	0.07	3087.00

4.00	85.00	8.00	312	34944	0.37	2.92	23.39	2.00	0.03	0.28	14596.00
6.00	**85.00**	**4.00**	264	14784	**0.24**	**0.97**	**3.90**	**0.67**	**0.01**	**0.05**	**2058.50**
6.00	**85.00**	**8.00**	312	34944	**0.24**	**1.95**	**15.59**	**1.33**	**0.02**	**0.18**	**9731.07**
10.00	85.00	4.00	264	14784	0.15	0.58	2.34	0.40	0.01	0.03	1235.10
10.00	85.00	8.00	312	34944	0.15	1.17	9.36	0.80	0.01	0.11	5838.64

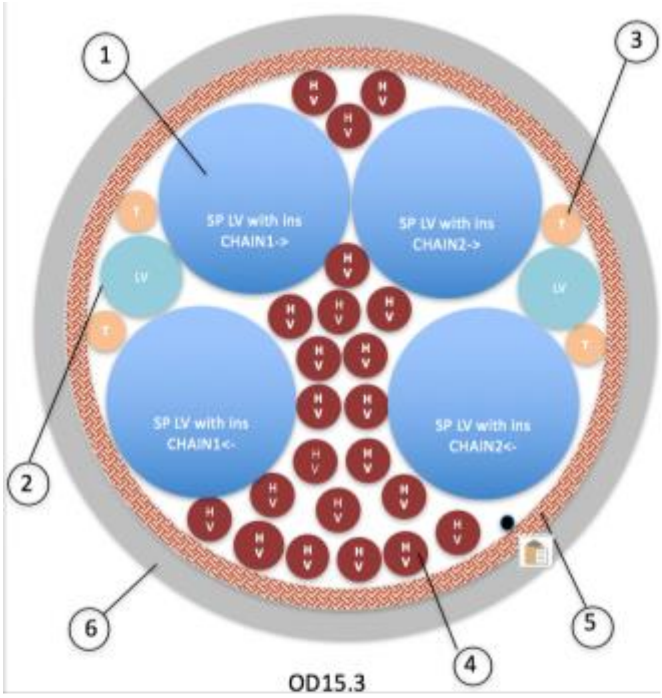


Figure 20. Illustration of a multiservice cable for PowerSupply-PP1 part.

Table 12. List of components of the PS-PP1 cable and dimensions

	Description	**Al Xsection of one wire [mm²]**	**Diameter of conductor [mm]**	**Thickness of insulation [mm]**	**External Diameter [mm]**	**#wires**	**Remarks**
1	Tin plated copper conductor with PE-insulation (LV SP)	6	3.3	0.8	4.7	4	50x0.39 Serial powering
2	Tin plated copper conductor with PE-insulation (LV OT) Preheating pipes	1.5	1.5	0.25	2.0	2	Type 2 in OT LVPS-PP1
3	T-Sensor	0.20	0.6	0.1	0.8	8	AWG 24
4	Tin plated copper conductor with PE-insulation (HV)	0.24	0.6	0.25	1.1	22	Type 3 in OT LVPS-PP1
5	Al-PR-foil+Copper braid			0.5	13.8		
6	Jacket of PE			0.75	15.3		

Table 13. Description of a wire type 1 used for SP powering in cable 1.

Type 1 wire description in Cable 1	filament diameter [mm]	filament cross section [mm^2]	#N filaments	Total cross section [mm^2]	Equivalent diameter [mm]	Diameter after taking into account bundling factor [mm]	Diameter incl. insulation [mm]
Copper	0.35	0.10	50	4.81			
Tin clad copper	0.39	0.12	50	5.98	2.76	3.3	4.7

POWER CABLE PP1-PP0

At the path PP1 to PP0, space is a concern as the service channels are limited in number and dimensions. Therefore, the conductors of LV SP should decrease in cross-section even if the power losses increase, while the rest remain the same. Table 14 below shows how the losses and Vdrop change if 4mm^2 or 2.5mm^2 Cu conductors are used for the LV SP cable for the PP1 -PP0 part. We decided to use the Cu 2.5mm^2 as baseline unless there are objections due to the high heat dissipation in the service channels. Mechanics FEA simulation with the copper plates and water pipes have to confirm or not if these numbers are acceptable. Table 15 shows the power dissipated in two channels where the services will be routed for a quarter of IT. Especially in the case of an “only-cable” channel the W/m can reach 60 W/m.

Table 14. Comparison of Al cross-sections for the serial power conductors for the PP1-PP0 multi-service cable.

Material	Cond. Xsection	Length	Current per chain	# chains	Total Chip Power	20°C Resistance	Vdrop	Single wire power loss	J	Vdrop	P	Total cable loss
	(mm^2)	(m)	(A)		(W)	(Ω)	(V)	(W)	(A/mm^2)	(V/m)	(W/m)	(W)
Al	**2.50**	6.00	4	264	14784	0.06	0.26	1.04	1.60	0.04	0.17	547.43
	2.50	6.00	8	312	34944	0.06	0.52	4.15	3.20	0.09	0.69	2587.85
Al	**4.00**	6.00	4	264	14784	0.04	0.16	0.65	1.00	0.03	0.11	342.14
	4.00	6.00	8	312	34944	0.04	0.32	2.59	2.00	0.05	0.43	1617.41
Cu	**2.50**	6.00	4	264	14784	0.04	0.17	0.66	1.60	0.03	0.11	348.73
	2.50	6.00	8	312	34944	0.04	0.33	2.64	3.20	0.06	0.44	1648.56

Table 15 Power dissipated in the service channels by the Serial power cables along the PP1-PP0 path.

		QUARTER OF THE DETECTOR (one end half cyl - 180deg)				
	Cu Xsection (mm^2)	SPCHAINS	SP chains in a channel of 75% cables	SP chains in a channel of 25% cables	W/m in a channel of 75% cables	W/m in a channel of 25% cables
4A chains	2.50	**66**	**50 (26 cables)**	**16 (8 cables)**	**11.01**	**3.52**
8A chains	2.50	**78**	**58 (29 cables)**	**20 (10 cables)**	**51.08**	**17.61**
SUM		**144**	108	36	62.09	21.14

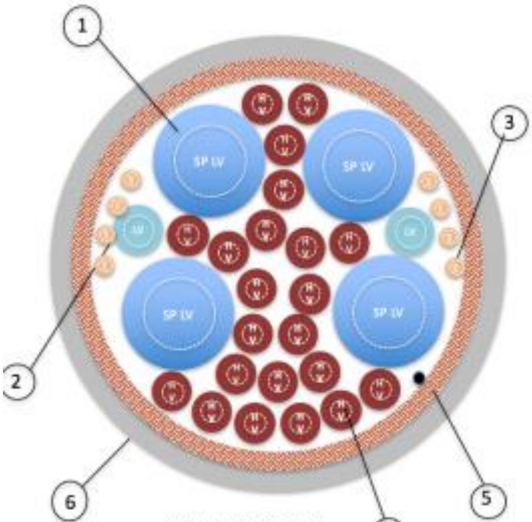


Figure 21. Illustration of a multiservice cable for PP1-PP0 part. The outer diameter decreases from 13.4 mm to 11.1 mm due to the decrease of the diameter of the SP cables.

Table 16 List of components of the PP1-PP0 cable and dimensions

Pos	Description	Cu Xsection of conductor [mm^2]	Diameter of conductor [mm]	Thickness of insulation [mm]	External Diameter [mm]	#wires	Remarks
1	Tin plated copper conductor with PE-insulation (LV SP)	2.5	2.1	0.6	3.3	4	21x0.39 Serial powering
2	Tin plated copper with PE-insulation (LV OT) Preheating pipes	0.5	0.9	0.275	1.45	2	Type 2 in OT PP1-PP0 but with copper
3	T-Sensor	0.080	0.4	0.1	0.6	8	AWG 28
4	Tin plated copper with PE-insulation (HV)	0.24	0.6	0.3	1.2	22	Type 3 in OT PP1=PP0 but with copper

5	Al-PR-foil+Copper braid			0.5	12.1		
6	Jacket of PE			0.65	13.4		

Table 17 Description of a wire used for SP powering in cable 2

Type 1 wire description in cable 2	filament diameter [mm]	filament cross section [mm²]	#N filaments	Total cross section [mm²]	Equivalent diameter [mm]	Diameter after taking into account bundling factor [mm]	Diameter incl. insulation [mm]
Copper	0.35	0.0962	21	2.03			
Tin plated copper	0.39	0.1195	21	2.51	1.8	2.1	3.3

POWER CABLES PP0-MODULES

The 13.4 mm diameter cables at PP1 will be converted to single Al wires at PP0. Only the SP LV cables will switch to smaller diameter Al cables (0.8 mm^2 for 4A chains and 1.6 mm^2 for 8A chains) at the expense of higher current density and losses for material budget reasons. The space allocated for TBPX+TFPX should be calculated separately from the TEPX space. The cables for pre-heating of the pipes will not be needed further than PP0. The length of these wires is estimated around 3 m for the TFPX/TBPX case and 1 m for the TEPX. The transition from cables to wire bundles might require the presence of an intermediate step a fan-out pcb as done currently in the pixel detector.

Table 18. List of single wires for PP0-modules part for two 4A chains

Description	Al Xsection of one conductor [mm²]	Diameter of conductor [mm]	Thickness of insulation [mm]	Diameter with insulation [mm]	External Xsection [mm²]	#wires	Total Xsection [mm²]
Copper cladded Al conductor with PE-insulation (LV SP)	0.8	1.3	0.2	1.7	2.89	4	11.56
Copper cladded Al conductor with PE-insulation (LV OT) Preheating pipes	0.13	0.5	0.2	0.9	0.81	2	1.62
Two T-Sensors AWG 30	0.05	0.3	0.1	0.5	0.25	4	1
Copper cladded Al conductor with PE-insulation (HV)	0.09	0.4	0.35	1.1	1.21	22	26.62
TOTAL							~41

Table 19. List of single wires for PP0-modules part for two 8A chains

Description	Al Xsection of one conductor [mm²]	Diameter of conductor [mm]	Thickness of insulation [mm]	Diameter with insulation [mm]	External Xsection [mm²]	#wires	Total Xsection [mm²]
Copper cladded Al conductor with PE-insulation (LV SP)	1.6	1.8	0.2	2.2	4.84	4	19.36
Copper cladded Al conductor with PE-insulation (LV OT) Preheating pipes	0.13	0.5	0.2	0.9	0.81	2	1.62
Two T-Sensors AWG 30	0.05	0.3	0.1	0.5	0.25	4	1
Copper cladded Al conductor with PE-insulation (HV)	0.09	0.4	0.35	1.1	1.21	22	26.62
TOTAL							~49

Table 20 Copper Cladded Aluminium wires for the PP0-modules connection

PP0-module 4 A	filament diameter [mm]	filament cross section [mm²]	#N filaments	Total cross section [mm²]	Equivalent diameter [mm]	Diameter after taking into account bundling factor [mm]	Diameter incl. insulation [mm] (1.5 the diameter of the conductor)
Aluminum	0.3	0.07	10	0.71			
Copper clad alu	0.32	0.08	10	0.81	0.9	1.3	1.7
PP0-module 8A	filament diameter [mm]	filament cross section [mm²]	#N filaments	Total cross section [mm²]	Equivalent diameter [mm]	Diameter after taking into account bundling factor [mm]	Diameter incl. insulation [mm] (1.5 the diameter of the conductor)
Aluminum	0.49	0.19	8	1.51			
Copper clad alu	0.5	0.20	8	1.58	1.26	1.8	2.2

SUMMARY OF POWER LOSSES FOR SERIAL POWERING

Table 21. Summary of the power loss for the entire IT detector.

Xsection	Length	Current per chain	Number of chains (Full detector)	Total Chip Power	20C Resistance	Vdrop	Single Wire Power loss	J	Vdrop	P	Total cable losses (Full detector)	Power Loss percentage wrt to chip power
(mm^2)	(m)	(A)		(W)	(Ω)	(V)	(W)	(A/mm^2)	(V/m)	(W/m)	(W)	%
LVPS-PP1: Cu												
6	**85**	**4**	**264**	**14784**	0.24	0.97	3.90	0.67	0.01	0.05	2058.50	14 %
6	**85**	**8**	**312**	**34944**	0.24	1.95	15.59	1.33	0.02	0.18	9731.07	28 %
PP1-PP0: Cu												
2.5	**6**	**4**	**264**	**14784**	0.04	0.17	0.66	1.60	0.03	0.11	348.73	2%
2.5	**6**	**8**	**312**	**34944**	0.04	0.33	2.64	3.20	0.06	0.44	1648.56	5%
PP0-Mods (TBPX,TFPX): Al												
0.8	**3**	**4**	**168**	**9408**	0.10	0.41	1.62	5.00	0.14	0.54	544.32	6%
1.6	**3**	**8**	**184**	**20608**	0.05	0.41	3.24	5.00	0.14	1.08	1192.32	6%
PP0-Mods (TEPX): Al												
0.8	**1**	**4**	**96**	**5376**	0.03	0.14	0.54	5.00	0.14	0.54	103.68	2%
1.6	**1**	**8**	**128**	**14336**	0.02	0.14	1.08	5.00	0.14	1.08	276.48	2%
ENTIRE IT POWER LOSSES SUM 4A chains											3055.23	
ENTIRE IT POWER LOSSES SUM 8A chains											12848.43	
TOTAL POWER LOSSES ENTIRE IT											15903.66	

LPGBT POWERING

There has not been an official solution suggested for the power of the LpGBTs. Each opto-module will host a LpGBT chip (1.25V, 0.6A) and a VTRx (2.55V, 0.12A). A cascaded DC-DC conversion scheme similar to the one used to power the OT is being considered. This scheme is based on two step-down DC-DC buck converters, where the power is supplied at a higher voltage, Vin, and smaller feed current for the same consumed power. In the first conversion stage, upFEAST DC-DC converter receives 11V and converts this

voltage to 2.55V which can directly power the VTRx. The second stage is based on the DCDC2S converters which are used to convert 2.55V into 1.25V to power the LpGBT chips.
A scheme of combining 2 LpGBTs in on opto-module is proposed in this document (scheme i) called the 'Pair' option, although many other combinations might be also possible. Another one (scheme ii) goes towards the direction of grouping LpGBTs served by one upFEAST and DCDC2S converters in between them with the current ratings of the OT case. The other one (scheme iii) uses the same converters but with smaller coils for smaller current ratings such that one pair of upFEAST and DCDC2S would power one LpGBT. From now on, the pair of upFEAST and DCDC2S will be called DC-DC-DC. A few more words on the two schemes can be found below.

i) The '**Pair**' option:
A version of the DC-DC converters should be able to power **TWO** LpGBT+VTRx. This option seems to serve well the balance between adding too many opto-modules as in the granular solution (see iii) and still have gained in reliability in case of loss of an opto-module. Plus, the number of installed LpGBTs that would be installed but not be used is significantly less than in the more "grouped" option (see ii) without the need of mixing[‡] the powering of the optomodules and the serial power chains. (Installing 2*692= 1384 LpGBTs when 1260 wil be used). More details can be found in the following section and Figure 22 and Table 22.

ii) The '**Grouped**' option
A version of the DC-DC converters should be able to power **FOUR** LpGBT+VTRx. This scheme means that a failure of an upFEAST converter will result on a loss of data by 4 LpGBTs. In addition, having a board with that will serve 4 means that the granularity of the LpGBTs will now be constrained to a multiple of 4 which will result in an increase on the numbers of LpGBTs, since many of them will not be used (or could be used but then more elinks and fibers will be needed!) (see Appendix for more details). (Installing 4*592= 2368!!!!! LpGBTs when half of them (1260) will be used if not mixing the powering chains and 4*358=1472 if mixing the LpGBTs serving different chains is allowed. This means that not only something significantly bulkier than the other options should be installed but also the number of these optomodules would be significantly increased wrt to (i) and (ii)).

iii) The '**Granular**' option:
A very small version of the DC-DC converters should be able to power a **SINGLE** LpGBT+VTRx. This option has the advantages of losing less data in case of a DC-DC failure and also having a granularity of one LpGBT so no-used LpGBTs will be installed. This scheme will result to a higher number of cables installed to serve the 1260 opto-modules but in case of a failure only the data of one LpGBT will be lost (see Appendix for more details).

INVESTIGATING 'PAIR' LPGBT POWERING SCHEME:

[‡] Mixing the chains here means that a optomodule with a DC-DC-DC powers N LpGBTs serving different power chains. The rule of a LpGBT serving modules of the same chain is never broken. This is taking a step further the separation of the two powering schemes used in the IT.

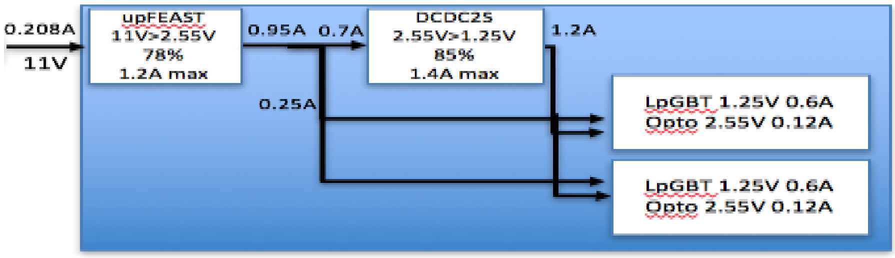


Figure 22 The "PAIR" LpGBT powering scheme using 1 DC-DC-DC for each 2 LpGBTs. (Current rating for upFEAST part reduced to 35%, and to ~50% for the DCDC2S part).

Table 22 Powering LpGBTs with the "PAIR" option.

	Quarter of IT	LpGBTs (short/ long)	DC-DC-DC		'1 wire to 1 optomodule to 2 LpGBTs' Cables with 48 single wire pairs serving 48 DC-DC-DC (0.28A)	'1 wire to 6 optomodules to 24 LpGBTs' Cables with wires able to power 16 groups of 4 DC-DC-DC
			Not mixing SP chains (short/ long)	Mixing SP chains (short/ long)		
TBPX	L1	24 /30	12/15	12/15		
	L2	28	14	14		
	L3	12	6	6		
	L4	16	8	8		
	SUM All Layers	**80/86**	**40/43**	**40/43**	**1**	**1**
	Respective number #LpGBTS	**80/86**	**80/86**	**80/86**		
TFPX	Odd dee	10	6	5		
	Even dee	10	6	5		
	SUM 8 disks	**160**	**96**	**80**	**2**	**1**
	Respective number #LpGBTS	**160**	**192**	**160**		
TEPX	Odd dee	10	5	5		
	Even dee	8	4	4		
	SUM 4 disks	**72**	**36**	**36**	**1**	**1**
	Respective number #LpGBTS	**72**	**72**	**72**		
SUMMARY OF LpGBTS						
Quarter of TBPX+TFPX		**240/246**	**272/278**	**240/246**		
Quarter of TEPX		**72**	**72**	**72**		

Quarter of IT	312/318	344/350	312/318		
Entire IT	1260	1388	1260		
SUMMARY OF DCDCs and cables					
Quarter of TBPX+TFPX		136/139	120/123	6	2
Quarter of TEPX		36	36	2	1
Quarter of IT		172/175	156/159	8	3
Entire IT		692	630	32	12

COOLING

The table below shows a proposed cooling architecture for the IT. A maximum limit of 330 W/ cooling loop (CL) has been set (close to the OT one). The distribution of power per cooling loop has the following characteristics: maximum 327 W/CL, average 264 W/CL, minimum 193 W/CL. Three transfer lines out of five per quarter of the detector are used for TBPX/TFPX. These 3 transfer lines serve the following: 1 CL/ L1, 2 CL / L2, 3 CL/ L3, 4 CL/ L4, 1 CL per TFPX Dee, meaning 1+2+3+4+8*2*1 = 26 cooling loops. For a quarter of TEPX, 2 transfer lines are needed serving 16 cooling loops (2 CL per TEPX Dee). It has to be investigated/confirmed that the LpGBTs do not require separate cooling loops as the LpGBTs do not need to operate @ -20^{o}C. In addition, the presence of the carbon fiber support and cold air around them should be sufficient to keep them at a normal operating temperature. For the moment, the presence of preheaters for the cooling pipes is foreseen, to be investigated whether the power of the LpGBT and the cable losses could be used to replace them.

Table 23 Proposed cooling architecture for a quarter of IT detector.

QUARTER OF IT			Estimated Power [W] (chip, sensor, cables, LpGBT)	Cooling Loops	Power per Cooling Loop [W]	Transfer lines	Power per transfer line [W]
TBPX	Short	L1	218	1	218		
		L2	408	2	204		
		L3	640	3	213		
		L4	845	4	211		
		SUM	2111	10		1	2111
	Long	L1	275	1	275		
		L2	498	2	249		
		L3	787	3	262		
		L4	1039	4	260		
		SUM	2422	10		1	2422
TFPX		Odd Dee	252	1	259		
		Even Dee	322	1	334		
		8 half disks	4590	16			2372
TEPX		Odd Dee	626	2	331		

	Even Dee	408	2	215		
	4 half disks	4136	16			2185
SUMMARY						POWER [kW]
QUARTER OF TBPX+TFPX			26		3	6.8/7.2
QUARTER OF TEPX			16		2	4.4
QUARTER OF IT			42		5	11.2/11.5
ONE END OF IT			84		10	22.4/23.1
ENTIRE IT			168		20	45.5

PP1 - SERVICE CHANNELS

There will be four service channels per end allocated for IT services. To further facilitate access, the IT services will be routed to the service channels closest to the horizontal plane (contrary to previous experience where they were close to the vertical plane) such that they are reachable from the IT installation platforms. The phi-distribution of the tracker channels can be seen in Figure 23 below. Note also that the maximum allowed occupancy of the channels is 75% and that out of the two channels per quarter, one will be filled 75% with cables (eg IT1 channel) and the other one 25% cables and 50% all the cooling of that part of the detector (eg IT4 channel). Therefore, ¾ of cables are allocated in one service channel and ¼ of cables in the one with the cooling. Assumed channel size 262.3 cm^2. A maximum of 8 cables per quarter of the IT needed to power the LpGBTS is assumed.

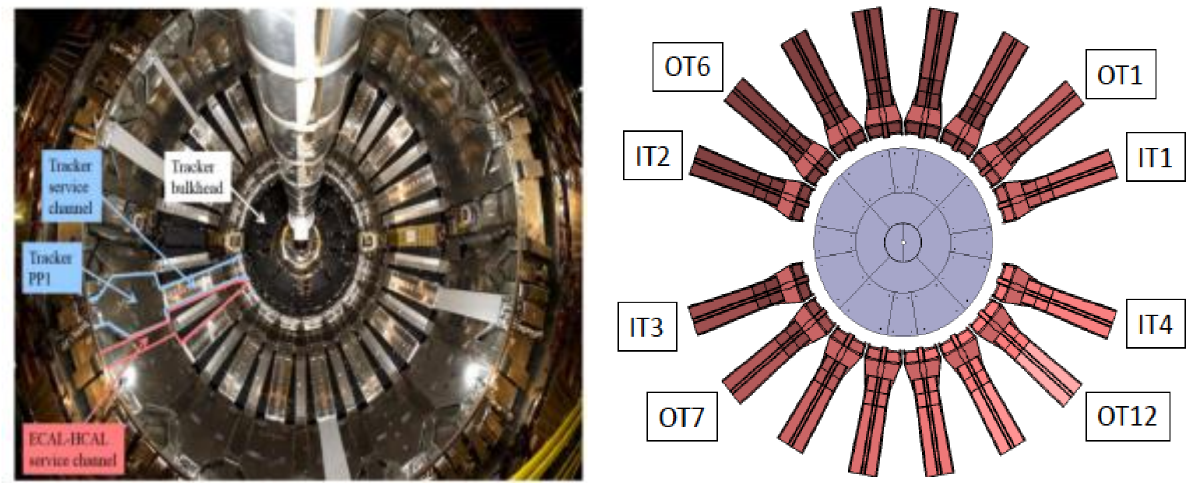


Figure 23. (Left) photo highlighting in blue one of the tracker service channels and PP1s, and in pink one of the neighbouring ECAL+HCAL service channels (taken from TDR fig 5.2). (Right) The phi distribution of the four IT channels per end.

From Axel's workbook the services in a IT channel at PP1 will be :

Table 24. List of services arriving at PP1 channels and dimensions of the cables.

Service type	IT	IT+	IT+, HALF	IT CHANNEL 1	IT CHANNEL 4	Diameter of a cable (mm)	Area of one cable (cm^2)
Power cables IT 2 chips	136	68	34	26	8	13.4	1.8

Power cables IT 4 chips	156	78	39	29	10	13.4	1.8
Power cable LpGBTs	40	20	10	6	2	13.4	1.8
MFB	124	62	31	15	16	3.6	0.1
Inlet cooling pipes	20	10	5	0	5	8	0.6
Outlet cooling pipes	20	10	5	0	5	14	2.0
Dry gas injection pipes	24	12	6	3	3	6	0.4
Sniffing pipes	10	5	2.5 §	1	1	6	0.4
Environment sensors	72	36	18	9	9	3	0.1
Channel water pipe	16	8	4	2	2	10	1.0

Table 25 Estimation of occupancy of two IT channels per quarter (one 75% cables, one 50% cooling and 25% cables) using Axel's workbook template.

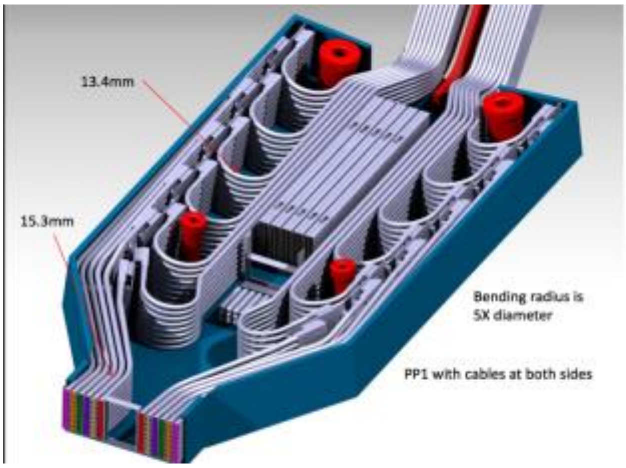
	Service channel #	**2**	**18**
	Name	**IT1**	**IT4**
POWER CABLES	Power cables IT 2 chips	26	8
	PC IT2 area (cm^2)	**46.7**	**14.4**
	Power cables IT 4 chips	29	10
	PC IT4 area (cm^2)	**52.1**	**18.0**
	Power cables LpGBTs	6	2
	PC LpGBT area (cm^2)	**10.8**	**3.6**
OPTICAL FIBERS	MFB	16	15
	MFB area (cm^2)	**2.1**	**1.9**
COOLING BUNDLES	Inlet cooling pipes	0	5
	Outlet cooling pipes	0	5
	BUNDLE area (cm^2)	**0.0**	**82.5**
SENSORS AND DETECTOR ENVIRONMENT	Dry gas injection pipes	3	3
	Remaining DGIP area (cm^2)	**1.1**	**0.7**
	Sniffing pipes	1	1
	SP area (cm^2)	**0.4**	**0.4**
	Environment sensors	9	9
	ES area (cm^2)	**0.8**	**0.8**
	Channel water pipes	2	2
	CWP area (cm^2)	**2.0**	**2.0**

§ 5 sniffing pipes per end are distributed as 1 sn.p. per channel for 3 channels and 2 sn.p. for one channel eg. channel 2.

RESULTS	Total area of services (cm^2)	**115.8**	**124.2**
	Channel fill	44.1%	47.4%

The service channels will be redesigned according to the need of Pixel Phase 2. The current preliminary design for Phase 2 Tracker channels foresees each side of PP1 hosting 6 stacks of 8 parallel power connections. So 48 connections per side of PP1, equal to 96 connections per PP1, equal to a maximum of 96 power cables per channel for a “only cable” channel and 48 power cables for a “cables+cooling” type of channel. IT and OT service channels will be kept as similar as possible. Some preliminary drawings of the PP1 are shown in Figures 24 and 25. Based on this design, the constraint on the bending radius of the power cables is min. 70 mm.

As far as the cooling of the cable bundles are concerned, before there was one water cooling loop per channel with copper pipes used to warm the pipes/ cool the cables. For the moment, it is desired that two cooling loopes per channel (one per side) in order to lower the impedance of the circuit and increase also the cooling capacity of it.



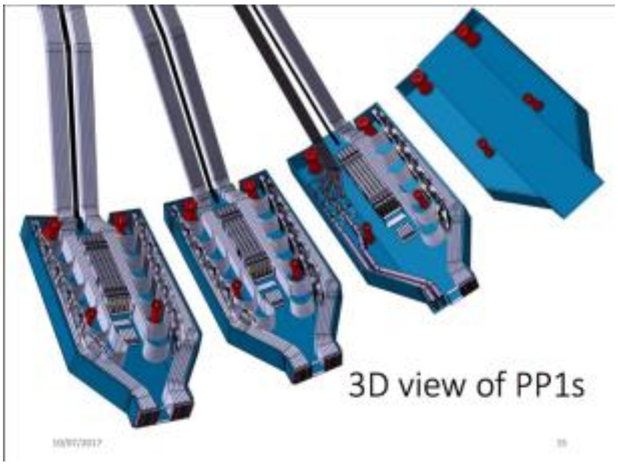


Figure 24 Tracker service channels are under design (last drawing presented by Axel Filenius Nicola Bacchetta Karol Rapacz https://indico.cern.ch/event/649173/)

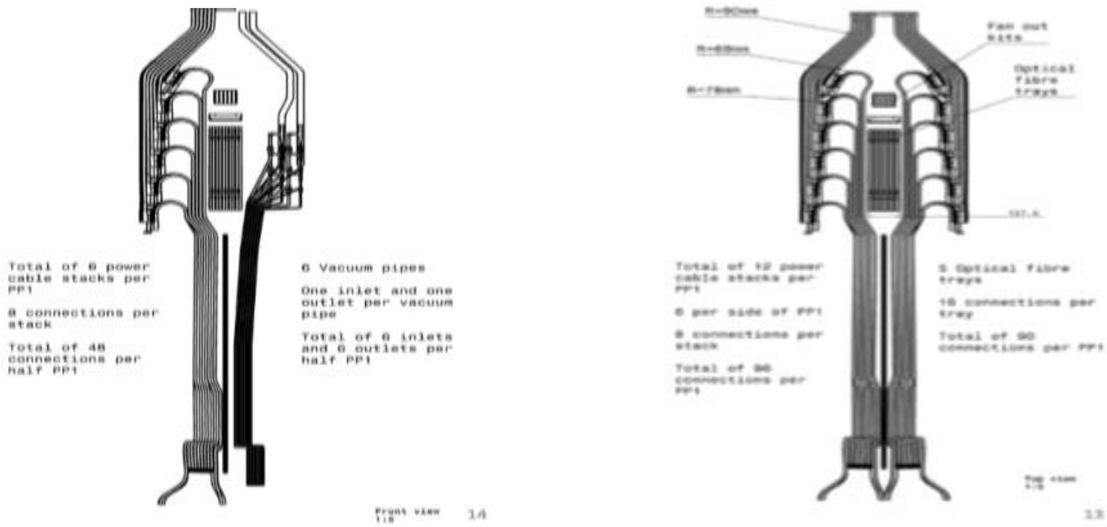


Figure 25 Tracker services Axel Filenius Nicola Bacchetta Karol Rapacz https://indico.cern.ch/event/649173/

PP0 - COLLECTION OF PHOTOS MOCK-UP PHASE 1 DETECTOR

For a quarter of TBPX/TFPX the space needed for the services is around 26 cm^2, while for the TEPX around 15 cm^2. No appropriate arrangement has been done in a C-shape way. This is just an estimation for the engineers to consider when designing the laying of the services on the support tubes. Some picture of the C-shapes used to distribute in phi the services for Pixel phase 1 are shown as an example in Figure 26.

Figure 26 PP0 mock-up of Pixel Phase 1 detector services at B187.

<u>**At PP0 to the PP1 side**</u> the cross-section of the power wires for serial powering and LpGBT powering will be for a quarter of IT:

for TBPX+TFPX : (45 for SP + 6 for LpGBT) * $(13.4\ mm)^2$ = 92 cm^2

for TEPX: (28 for SP + 2 for LpGBT) * $(13.4\ mm)^2$ = 54 cm^2

These numbers do not include cooling cross section.

<u>**At PP0 to the detector side**</u> the cross-section of the power wires will be for a quarter of IT:

for TBPX+TFPX : Cross Section for 4A chains+ Cross Section for 8A chains+ LpGBT powering=

22 * 41 mm^2+ 23 * 49 mm^2 + 6*80*1.0*1.0 mm^2 ~ 26 cm^2

for TEPX: Cross Section for 4A chains+ Cross Section for 8A chains+ LpGBT powering=

$12 * 41 \text{ mm}^2 + 16 * 49 \text{ mm}^2 + 2*80*1.0*1.0 \text{ mm}^2 \sim 15 \text{ cm}^2$

These numbers do not include cooling cross section.

In case the space in the service cylinder is not sufficient to host all the above-mentioned cables, one could consider to drop the multiple HV wires and keep only one for each serial power chain.

SUMMARY

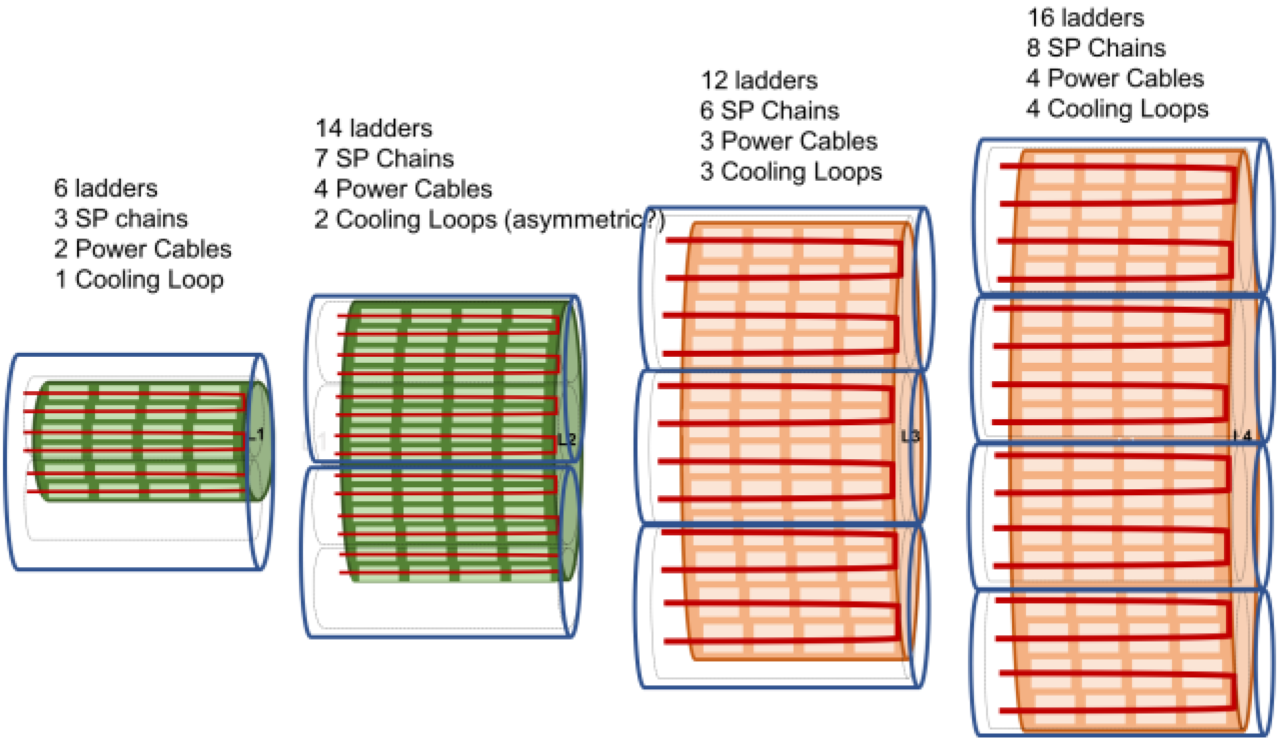
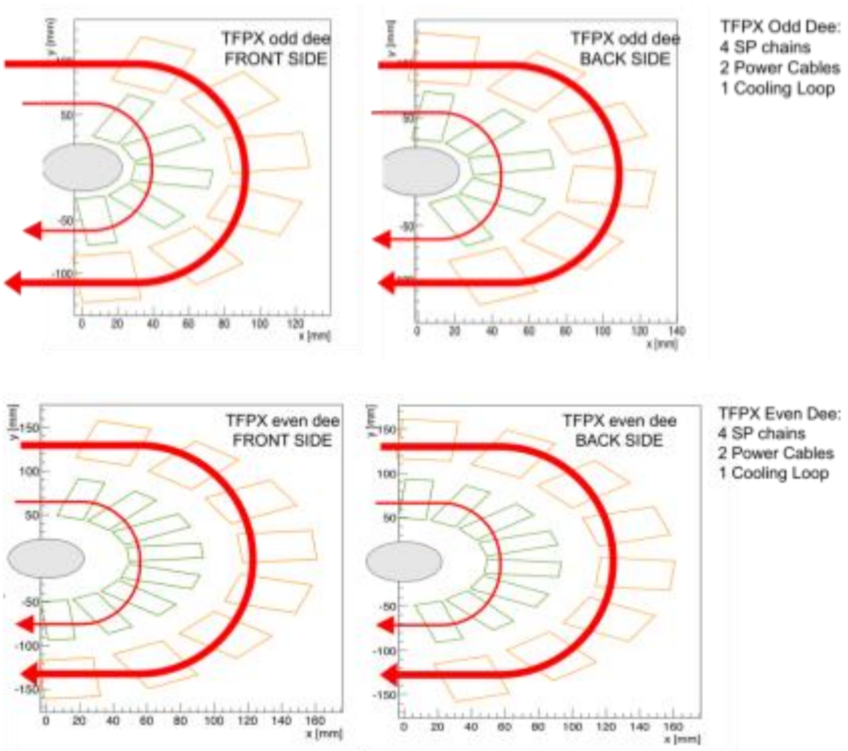


Figure 27 TBPX Cooling Loops and Power Cables for the long end (short end architecture is similar).



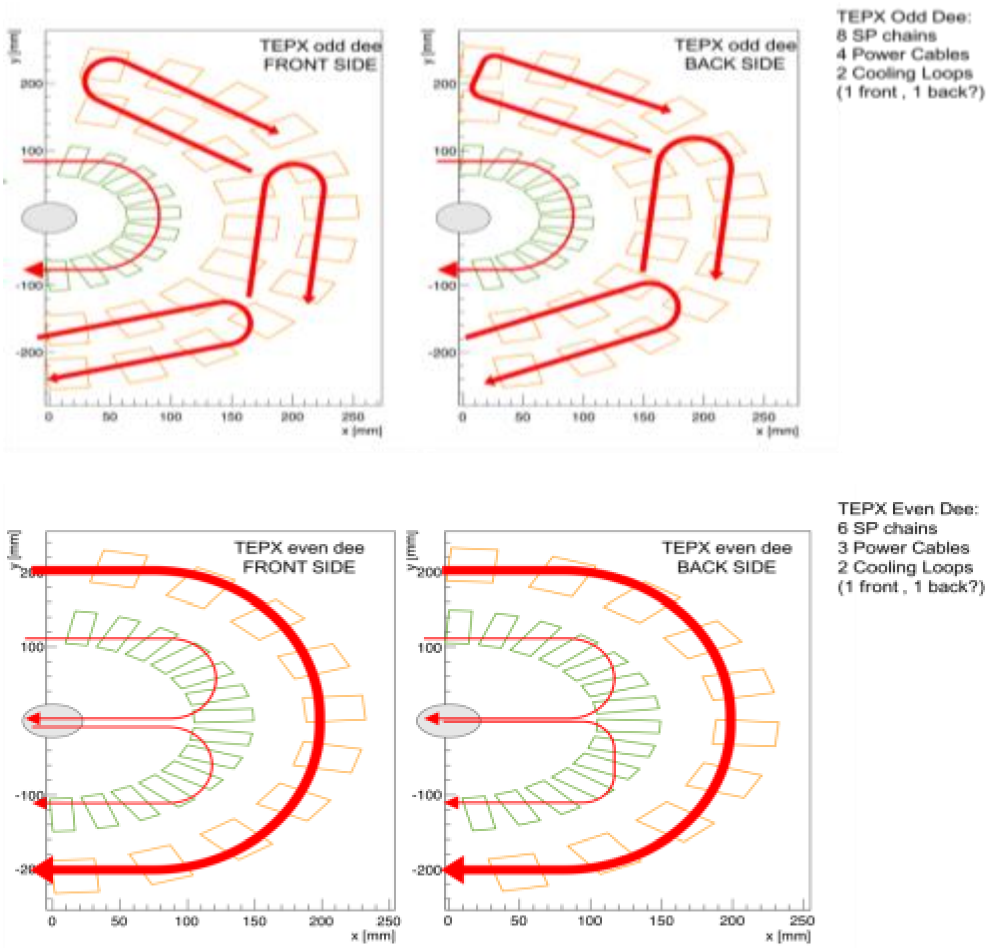


Figure 28 SP chains, cables and loops summary for the disks

Keeping the sum numbers from Tables from previous sections (referring to a quarter of the IT), we can now extract the numbers shown in the TDR table 4.3.

Table 26. TDR Table of 4.3

TDR table 4.3 (full detector)	**TBPX**	**TFPX**	**TEPX**	**Total**
E-links (readout)	1656	3264	1760	6680
E-links (control)	864	1728	1760	4352
Optical links	332	640	288	1260
Power chains	96	256	224	576
Front-end power [kW]	8	16	16	40

Table 27 Power Summary for the Inner Tracker, used as basis for cooling calculation.

QUARTER OF IT		Number of chips		Chip Power [W]		SP chains		Serial Power Cable Losses at the PP0-modules part [W]	Number of LpGBTs		LpGBT power [W]		Sensor losses (tk layout)		TOTAL POWER	
		short	long	short	long	4A chain	8A chain		short	long	short	long	short	long	short	long
TBPX	L1	48.0	60.0	142.6	178.2	3.0	0.0	9.7	24.0	30.0	25.2	31.5	41.0	56.0	218.5	275.4
	L2	112.0	140.0	332.6	415.8	7.0	0.0	22.7	28.0	28.0	29.4	29.4	23.0	30.0	407.7	497.9
	L3	192.0	240.0	570.2	712.8	0.0	6.0	38.9	12.0	12.0	12.6	12.6	18.0	23.0	639.7	787.3
	L4	256.0	320.0	760.3	950.4	0.0	8.0	51.8	16.0	16.0	16.8	16.8	16.0	20.0	845.0	1039.0
	SUM	608.0	760.0	1805.8	2257.2	10.0	14.0	123.1	80.0	86.0	84.0	90.3	98.0	129.0	2110.9	2599.6
TFPX	Odd dee	68.0		202.0		2.0	2.0	19.4	10.0		10.5		27.0		258.9	
	Even dee	96.0		285.1		2.0	2.0	19.4	10.0		10.5		19.0		334.1	
	Disk	164.0		487.1		4.0	4.0	38.9	20.0		21.0		46.0		593.0	
	SUM	1312.0		3896.6		32.0	32.0	311.0	160.0		168.0		368.0		4743.7	
TEPX	Odd dee	**208.0**		**617.8**		**2.0**	**6.0**	**15.1**	**10.0**		**10.5**		**18.0**		**661.4**	
	Even dee	**136.0**		**403.9**		**4.0**	**2.0**	**8.6**	**8.0**		**8.4**		**10.0**		**431.0**	
	Disk	**344.0**		**1021.7**		**6.0**	**8.0**	**23.8**	**18.0**		18.9		**28.0**		**1092.3**	
	SUM	**1376.0**		**4086.7**		**24.0**	**32.0**	**95.0**	**72.0**		**75.6**		**112.0**		**4369.4**	
QUARTER OF TBPX+TFPX		1920.0	2072.0	5702.4	6153.8	42.0	46.0	434.2	240.0	246.0	252.0	258.3	466.0	497.0	6854.6	7343.3
QUARTER OF TEPX		1376.0		4086.7		24.0	32.0	95.0	72.0		75.6		112.0		4369.4	
QUARTER OF IT		3296.0	3448.0	9789.1	10240.6	66.0	78.0	529.2	312.0	318.0	327.6	333.9	578.0	609.0	11223.9	11712.7
ONE END OF IT		6592.0	6896.0	19578.2	20481.1	132.0	156.0	1058.4	624.0	636.0	655.2	667.8	1156.0	1218.0	22447.8	23425.3
ENTIRE IT		13488.0		40059.4		264	312	2117	1260		1323.0		2374.0		45873.2	

Table 28 Cable summary

Cable 1	Voltage at the source [V]	Current [A]	Constraint	#wires	Remarks
1	18	8 (or 4)	max P /wire = 0.2 W/m	4	Serial powering LV
2	14	0.7	Vdrop 3V (from 14V to 11V)	2	Preheater LV
3			max resistance 90mOhm/m	8	T-sensor
4	1000	0.001	max 400mOhm/m	22	HV
5				1	drain for LV
			max outer diameter 15.3mm	Copper braid 85%+jacket	
Cable 2	Voltage at the source [V]	Current [A]	Constraint	#wires	Remarks
1	16	8 (or 4)	max P /wire = 0.8 W/m	4	Serial powering LV
2	11	0.7	Vdrop 1V (from 11V to 10V)	2	Preheater LV
3			max resistance 250mOhm/m	8	T-sensor
4	1000	0.001	max 400mOhm/m	22	HV
5				1	drain for LV
			max outer diameter 13.4mm	Copper braid 85%+jacket	
Group of wires, 8A case	Voltage at the source [V]	Current [A]	Contraint	#wires	Remarks
1	15	8	max P /wire = 1.7 W/m	2	Serial powering LV
2			max resistance 400mOhm/m	2 or 4	T-sensor
3	1000	0.001	max resistance 400mOhm/m	11	HV
			max outer diameter 4-5mm	Kapton tape protection	
Group of wires, 4A case	Voltage at the source [V]	Current [A]	Contraint	#wires	Remarks
1	15	4	max P /wire = 0.85 W/m	2	Serial powering LV
2			max resistance 400mOhm/m	2 or 4	T-sensor
3	1000	0.001	max resistance 400mOhm/m	11	HV
			max outer diameter 4-5mm	Kapton tape protection	
Summary	Length [m]	material	#cables	Total length [m]	driving parameter
Cable 1	100	Copper	292	29200	total power losses
Cable 2	6	Copper	292	1752	power dissipation per meter and space
Group of wires 3 (4A)	3	CCA	272	816	weight+space+rad hard
Group of wires 4 (8A)	3	CCA	312	936	weight+space+rad hard

APPENDIX: INVESTIGATING MORE OPTIONS FOR THE OPTO-MODULES

INVESTIGATING ‘GROUPED’ LPGBT POWERING SCHEME:

Below in Figure 29 shows the distribution of the power in this case. Assuming one cable could power one upFEAST converter which could power 2 DC-DC2S converters and each DC-DC2S converter a group of 4 LpGBTs. The number of opto-modules needed are calculated in Table 29.

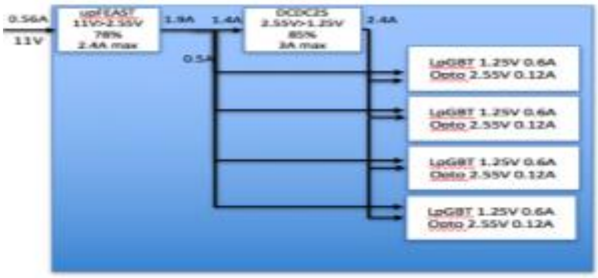


Figure 29 The “GROUPED” LpGBT powering scheme using 1 DC-DC-DC for each 4 LpGBTs. (Current rating for upFEAST part reduced to 60%, stayed the same for DCDC2S part).

Table 29 Powering LpGBTs with “GROUPED” option.

Quarter of IT		LpGBTs (short/ long)	DC-DC-DC Not mixing SP chains (short/ long)	DC-DC-DC Mixing SP chains (short/ long)	‘1 to 1 to 4’ Cables with single wires serving 42 optomodules (0.56A) (mixing SP chains)	Groups of 4 DC-DC-DC (2.24A) (only with mixing)	‘1 to 4 to 4’ Cables with 32 wires able to power 16 groups of 4 optomodules
TBPX	L1	24 /30	6/9	6/8		2	
	L2	28	7	7		1	
	L3	12	6	3		1	
	L4	16	8	4		1	
	SUM All Layers	**80/86**	**27/30**	**20/22**	**1**	**5**	**1**
	Respective number #LpGBTS	**80/86**	**108/120**	**80/88**			
TFPX	Odd dee	10	4	3		1	
	Even dee	10	4	3		1	
	SUM 8 disks	**160**	**64**	**48**	**2**	**16**	**1**
	Respective number #LpGBTS	**160**	**256**	**192**			
TEPX	Odd dee	10	8	3		1	

Even dee	8	6	2		1	
SUM 4 disks	**72**	**56**	**20**	**1**	**8**	**1**
Respective number #LpGBTS	**72**	**224**	**80**			
SUMMARY OF LpGBTS						
Quarter of TBPX+TFPX	**240/246**	**364/376**	**272/280**			
Quarter of TEPX	**72**	**224**	**80**			
Quarter of IT	**312/318**	**588/600**	**352/360**			
Entire IT	**1260**	**2376**	**1414**			
SUMMARY OF DCDCs and cables						
Quarter of TBPX+TFPX		**91/93**	**68/71**	**3**	**21**	**2**
Quarter of TEPX		**56**	**20**	**1**	**8**	**1**
Quarter of IT		**147/149**	**88/91**	**4**	**29**	**3**
Entire IT		**592**	**358**	**16**	**116**	**12**

Individual powering option: A pair of wires for each DC-DC-DC

To power every DC-DC-DC independently, a conductor with total Vdrop< 3V should be chosen to carry 0.56A. Up to 84 wires can fit in one cable of similar dimension with the mult-service cables.

Table 30. Voltage drops calculated for the wires used to power the upFEASTs for the '1 to 4' powering scheme.

Material	Cond. Xsection	Length	Current	Number of DC-DC-DC (max/min)	20ºC Resistance	Vdrop	Single wire power loss	J	Vdrop	P	Total power loss on wires (max/min)
	(mm^2)	(m)	(A)		(Ω)	(V)	(W)	(A/mm^2)	(V/m)	(W/m)	(kW)
Copper	0.41	85	0.56	592/358	3.566	2.00	1.12	1.37	0.02	1.3E-02	1.32/0.80
Copper	0.102	6	0.56	592/358	1.012	0.57	0.32	5.49	0.09	5.3E-02	0.38/0.23

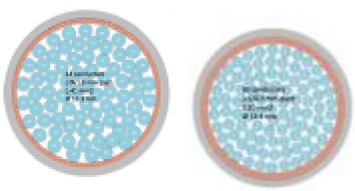


Figure 30 Cables used for the individually wired 'Grouped' LpGBT power scheme. On the left, Cable 3 for the LVPS-PP1 part, with 15.3mm outer diameter, can power 42 DC-DC-DC converters. Right, Cable 4 for PP1-PP0 part, with 13.4 mm outer diameter can host min. 84 smaller conductors (the sketch above shows 90 wires).

Table 31. Description of Cables 3 and 4 for individual powering of the DC-DC-DCs with the "Grouped" scheme

Description Cable 3	**Cu X-section [mm²]**	**Diameter of conductor [mm]**	**Thickness of insulation [mm]**	**External Diameter [mm]**	**#wires**
Tin plated copper conductor with PE-insulation (LV SP)	0.41	0.9	0.2	1.3	84
Al-PR-foil+Copper braid			0.5	13.8	
Jacket of PE			0.75	15.3	
Description Cable 4	**Cu X-section [mm²]**	**Diameter of conductor [mm]**	**Thickness of insulation [mm]**	**External Diameter [mm]**	**#wires**
Tin plated copper conductor with PE-insulation (LV SP)	0.102	0.5	0.2	0.9	90
Al-PR-foil+Copper braid			0.5	12.1	
Jacket of PE			0.65	13.4	

Parallel powering option: A pair of wires for each group of four DC-DC-DCs

To power groups of four DC-DC-DCs, a pair of conductors with total Vdrop< 3V should be chosen to carry 2.24A. Up to 32 conductors of 1.3 mm² can fit in one cable of similar dimension with the mult-service cables.

Table 32. Voltage drops calculated for the wires used to power four DC-DC-DCs for the 'Grouped powering scheme.

Material	Cond. Xsection	Length	Current	Groups of 4 DC-DC-DCs	20°C Resistance	Vdrop	Single wire power loss	J	Vdrop	P	Max Total power loss on wires
	(mm²)	(m)	(A)		(Ω)	(V)	(W)	(A/mm²)	(V/m)	(W/m)	(kW)
Copper	1.3	85	2.24	116	1.125	2.52	5.64	1.72	0.030	0.0664	1.3
Copper	0.7	6	2.24	116	0.147	0.33	0.74	3.20	0.055	0.1233	0.17

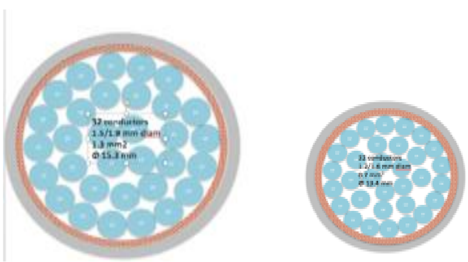


Figure 31 Cables used for the individually wired 'Grouped' LpGBT power scheme. On the left, Cable 5 for the LVPS-PP1 part, with 15.3mm outer diameter, can power 42 DC-DC-DC converters. Right, Cable 6 for PP1-PP0 part, with 13.4 mm outer diameter can host min. 84 smaller conductors (the sketch above shows 90 wires).

Table 33. Description of Cables 5 and 6 for parallel powering the DC-DC-DCs with the "Grouped" scheme

Description Cable 5	**Cu X-section of one wire [mm²]**	**Diameter of conductor [mm]**	**Thickness of insulation [mm]**	**External Diameter [mm]**	**#wires**
Tin plated copper conductor with PE-insulation (LV SP)	1.3	1.5	0.2	1.9	32
Al-PR-foil+Copper braid			0.5	13.8	
Jacket of PE			0.75	15.3	
Description Cable 6	**Cu X-section of one wire [mm²]**	**Diameter of conductor [mm]**	**Thickness of insulation [mm]**	**External Diameter [mm]**	**#wires**
Tin plated copper conductor with PE-insulation (LV SP)	0.7	1.2	0.2	1.6	32
Al-PR-foil+Copper braid			0.5	12.1	
Jacket of PE			0.65	13.4	

INVESTIGATING "GRANULAR" LPGBT POWERING SCHEME:

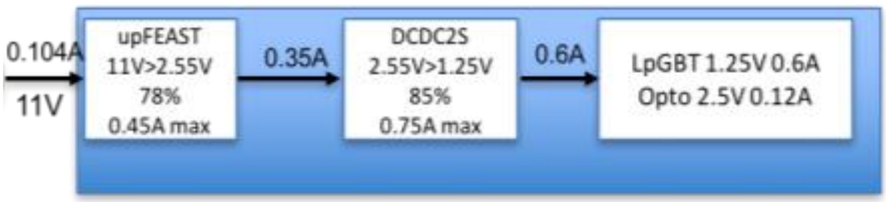


Figure 32. The "Grabular" LpGBT powering scheme using coils reduced to 20nH? (10% of that used for 4A upFEAST) and 50nH? (25% of that used for 3ADCDC2S)

A voltage supply per LpGBT would be needed in the second case where smaller DC-DC converter would be used. The cross-section of such a cable would be much smaller than the one in the case described above. Assuming a max allowed voltage drop of 3V (as in OT) and a current of 0.5 A needed the cross-section could be minimized to 0. 3 mm^2 (diameter 0.8/1.2 mm with PE insulation). Up to 90 conductors could fit in a 13.4 mm cable like the one presented earlier meaning they could serve up to 45 LpGBTs. In this scenario, 8 cables of 15.3 mm per quarter of IT would be needed (instead of 5 or 4 from '1 to 4' scheme).

Table 34 LpGBT powering cables needed for the "GRANULAR" option.

Quarter of IT		LpGBTs (short/long)	Cables with 90 wires serving 45 DC-DC-DCs	Groups of 20 DC-DC-DCs (mixing chains)	Cables with 32 wires serving 16 groups of 20 DC-DC-DCs
TBPX	**L1**	24 /30		2	
	L2	28		2	

	L3	12		1	
	L4	16		1	
	SUM	**80/86**	**2**	**6**	
TFPX	**Odd dee**	10			
	Even dee	10			
	8 disks	**160**	**4**	**8**	
TEPX	**Odd dee**	10			
	Even dee	8			
	4 disks	**72**	**2**	**4**	
Quarter of TBPX+TFPX		**240/246**	**6**	**14**	**1**
Quarter of TEPX		**72**	**2**	**4**	**1**
Quarter of IT		**312/318**	**8**	**18**	**2**
Entire IT		**1260**	**32**	**72**	**8**

Individual powering option: A pair of wires for each DC-DC-DC

To power every DC-DC-DC independently, a conductor with total Vdrop< 3V should be chosen to carry 0.102A. Up to 90 wires can fit in a cable of similar dimensions with the multi-service cables. The cable would be similar to Cable 4 presented previously.

Table 35 Calculating voltage drop and power losses for individual conductors for the "GRANULAR" powering scheme of the LpGBTs.

Material	Cond. X-section	Length	Current	Number of DC-DC-DC	20^{o}C Resistance	Vdrop	Single wire power loss	J	Vdrop	P	Total power loss on wires
	(mm^2)	(m)	(A)		(Ω)	(V)	(W)	(A/mm^2)	(V/m)	(W/m)	(kW)
Copper	0.102	85	0.104	1260	14.333	1.49	0.16	1.02	0.02	1.8E-03	0.39
Copper	0.102	6	0.104	1260	1.012	0.11	0.01	1.02	0.02	1.8E-03	0.03

Parallel powering option A: A pair of wires for each group of four DC-DC-DCs

To power groups of up to twenty DC-DC-DCs, a pair of conductors with total Vdrop< 3V should be chosen to carry 2.08 A. Up to 32 conductors of 1.3 mm^2 and 0.7 mm^2 can fit in a cable of similar dimension with the multi-service cables. The cables used would look similar to cables 5 and 6 presented previously.

Table 36 Calculating voltage drop and power losses for parallel powering of the DC-DC-DCs for the "GRANULAR" powering scheme.

Material	Cond. X-section	Length	Current	Groups of 20 DC-DC-DC	20°C Resistance	Vdrop	Single wire power loss	J	Vdrop	P	Total power loss on wires
	(mm^2)	(m)	(A)		(Ω)	(V)	(W)	(A/mm^2)	(V/m)	(W/m)	(kW)
Copper	1.3	85	2.08	72	1.125	2.34	4.87	1.60	0.028	0.0572	0.70
Copper	0.70	6	2.08	72	0.147	0.31	0.64	2.97	0.051	0.1063	0.09

Parallel powering option B: A pair of wires for each group SP chain. Adding four conductors to the existing multi-service cables.

Similarly, groups of up to 10 DC-DC-DCs, but this time powering groups of DC-DC-DCs serving LpGBTs that readout modules belonging to the same SP chain. In this case, 4 conductors able to carry up to 1A have to fit in the multi-service cables that will serve 2 SP chains. If the HV conductors are reduced to 4 (option C and most probable), there should be sufficient space to add the LpGBT powering conductors. In this case, no extra cables would be needed to power the LpGBTs. There would be no mixing of the SP chains and the readout powering BUT there should be some kind of fan-out at PP0 where the thick conductors will be converted to single wires able to power in parallel from 1 up to 10 DC-DC-DCs depending on the location. This option could also be used in the "Grouped" case.