Tracker Data Rate Studies for FCC-hh

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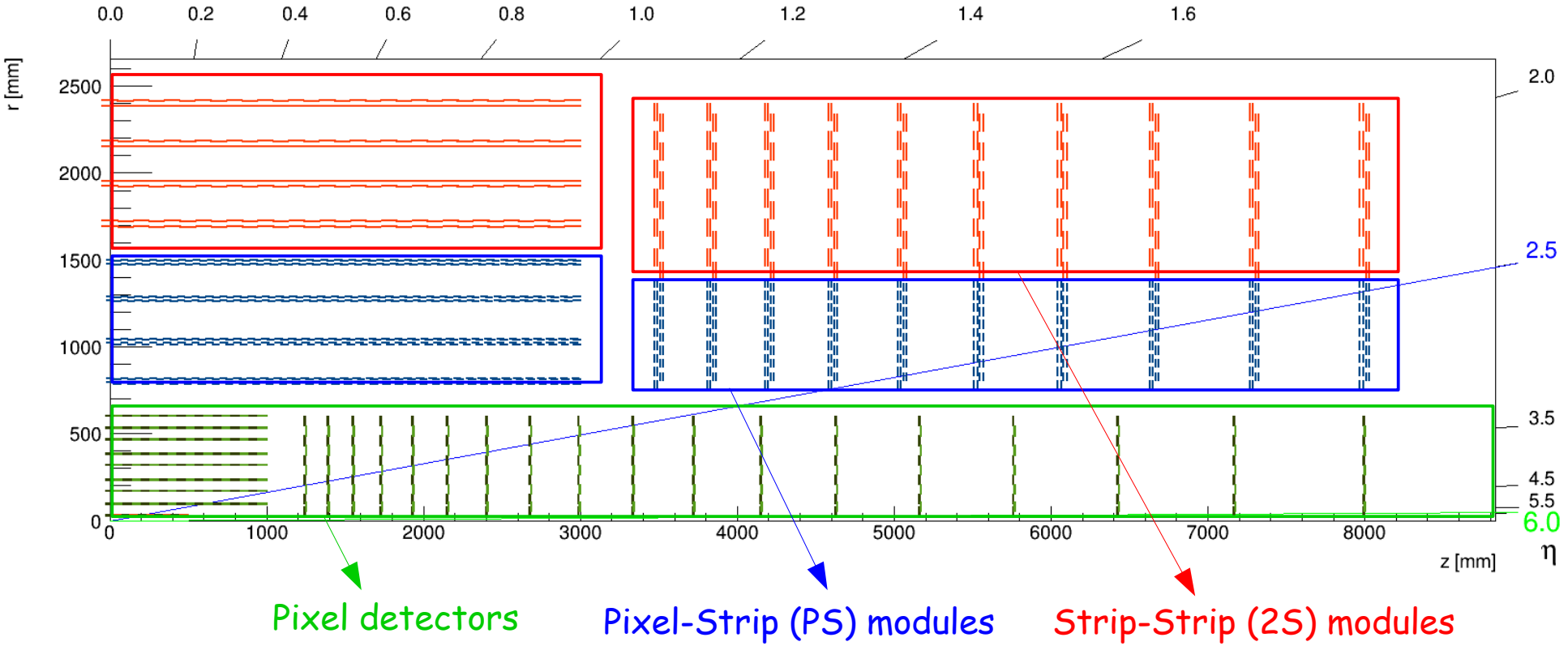
Overview

- **Data rate studies:**
  - FCC-hh tracker model based on CMS phase 2 upgrade design – pixel, PS, 2S modules
  - Fluka irradiation map (F. Cerutti & M.I.Besana) & hit occupancy estimation
  - Data addressing scheme
  - Results & conclusions

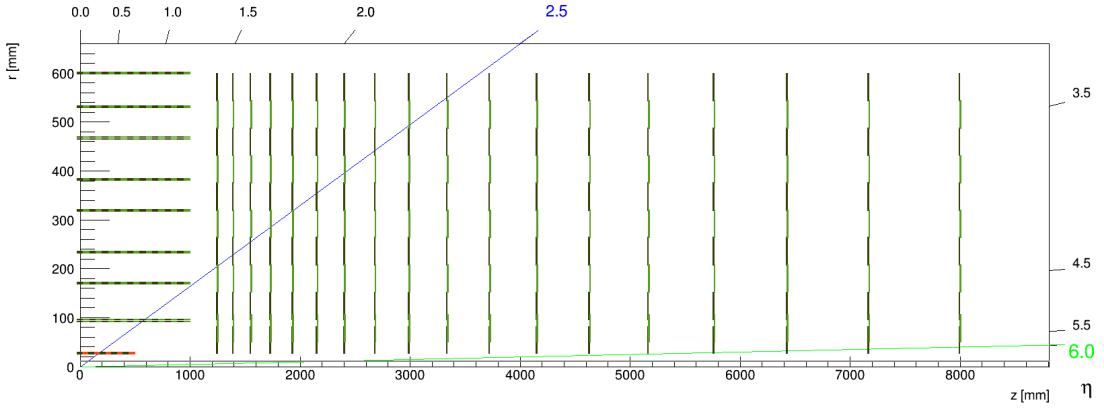
FCC-hh Tracker Model

- Let me "extrapolate" the CMS phase 2 upgrade layout to FCC dimensions



FCC-hh Tracker Model – Inner Geometry

- Geometry parameters of the inner tracker with pixel modules



Tag	PXBL01 PXBL02	PXBL03 PXBL04 PXBL05 PXBL06 PXBL07 PXBL08 PXBL09	PXER01 PXER02 PXER03	PXER04 PXER05 PXER06 PXER07 PXER08 PXER09 PXER10 PXER11	
Type	pixel	pixel	pixel	pixel	
Sensor area (mm^2)	969.0	1938.0	969.0	1938.0	
Total area (m^2)	1.4	34.7	4.0	43.8	**84.0**
Number of modules	1488	17920	4176	22608	**46192**
Number of sensors	1488	17920	4176	22608	**46192**
Number of channels (M)	195.04	2348.81	547.36	2963.28	**6054.48**
Number of channels per sensor	131072	131072	131072	131072	

Total area [m2] = 84

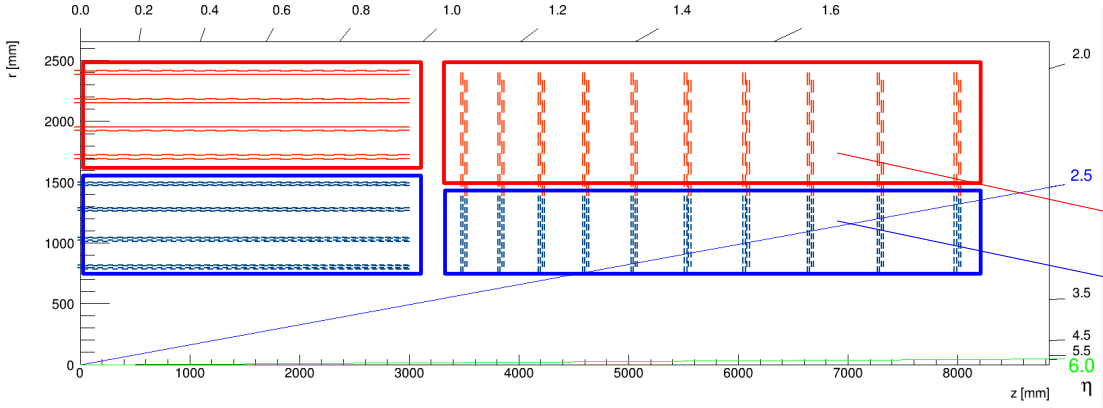
Number of channels (M) = 6054

Layer no :	1	2	3	4	5	6	7	8	9	Total
Radius [mm] :	25.0	93.3	169.2	232.9	317.9	381.6	466.5	530.1	600.0	
Z-min [mm] :	-500.0	-1000.0	-1000.0	-1000.0	-1000.0	-1000.0	-1000.0	-1000.0	-1000.0	
Z-max [mm] :	500.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	
Number of rods :	12	36	32	44	60	72	88	100	116	
Number of modules per rod :	19	35	35	35	35	35	35	35	35	
Number of modules :	228	1260	1120	1540	2100	2520	3080	3500	4060	19408

Disk no :	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
Radius-min [mm] :	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	
Radius-max [mm] :	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	
Average Z pos. [mm] :	1250.0	1394.2	1555.1	1734.5	1934.6	2157.9	2406.8	2684.5	2994.3	3339.7	3725.1	4154.9	4634.2	5168.9	5765.3	6430.5	7172.5	8000.0	
Number of rings :	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	
Number of modules per disk :	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	13392

FCC-hh Tracker Model – Outer Geometry

- Parameters of the inner tracker with PS (pixel-strip) & 2S (strip-strip) modules



Tag	TBL05 TBL06 TBL07 TBL08	TBL03 TBL04	TBL01 TBL02	TEDDR18 TEDDR19 TEDDR20 TEDDR21 TEDDR22 TEDDR23 TEDDR24 TEDDR25 TEDDR26 TEDDR27 TEDDR28 TEDDR29	TEDDR01 TEDDR02 TEDDR03 TEDDR04 TEDDR05 TEDDR06 TEDDR07 TEDDR08 TEDDR09 TEDDR10 TEDDR11 TEDDR12 TEDDR13 TEDDR14 TEDDR15 TEDDR16 TEDDR17	
Type	pt2S	ptPS	ptPS	pt2S	ptPS	
Sensor area (mm^2)	9189.7	4441.0	4441.0	9189.7	4441.0	
Total area (m^2)	639.1	219.7	156.9	599.9	225.2	**1840.8**
Number of modules	34770	24738	17662	32640	25360	**135170**
Number of sensors	69540	49476	35324	65280	50720	**270340**
Number of channels (M)	141.31	807.45	576.49	132.65	827.75	**2485.64**
Number of channels per sensor	2032	30720, 1920	30720, 1920	2032	30720, 1920	

Layer no :	1	2	3	4	5	6	7	8	Total
Radius [mm] :	800.0	1028.0	1272.3	1485.2	1704.5	1936.1	2167.7	2400.0	
Z-min [mm] :	-3000.0	-3000.0	-3000.0	-3000.0	-3000.0	-3000.0	-3000.0	-3000.0	
Z-max [mm] :	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0	
Number of rods :	54	68	84	98	118	134	150	168	
Number of modules per rod :	147	143	137	135	61	61	61	61	
Number of modules :	7938	9724	11508	13230	7198	8174	9150	10248	77170

Disk no :	1	2	3	4	5	6	7	8	9	10	Total
Radius-min [mm] :	756.6	756.6	756.6	756.6	756.6	756.6	756.6	756.6	756.6	756.6	
Radius-max [mm] :	2400.0	2400.0	2400.0	2400.0	2400.0	2400.0	2400.0	2400.0	2400.0	2400.0	
Average Z pos. [mm] :	3500.0	3836.7	4205.8	4610.4	5054.0	5540.2	6073.2	6657.4	7297.9	8000.0	
Number of rings :	29	29	29	29	29	29	29	29	29	29	
Number of modules per disk :	2900	2900	2900	2900	2900	2900	2900	2900	2900	2900	29000

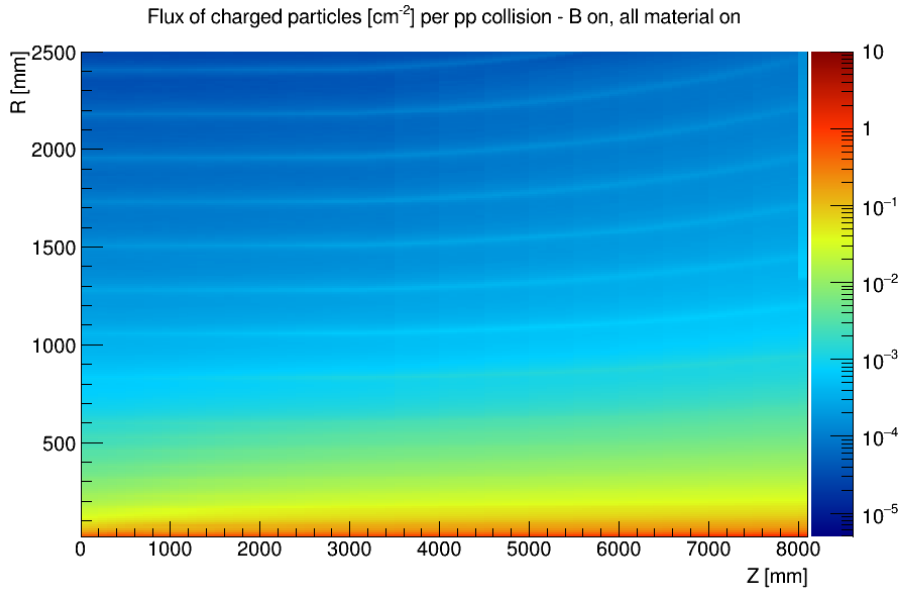
Ring no :	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
R-min [mm] :	756.6	803.2	833.8	880.5	909.7	956.5	984.5	1031.4	1058.0	1105.1	1130.5	1177.6	1201.8	1249.0	1271.9	1319.3	1341.0	1388.5	1462.3	1564.3	1635.1	1737.4	1805.1	1907.7	1972.5	2075.4	2137.3	2240.4	2299.5
R-max [mm] :	802.9	849.5	880.0	926.7	956.0	1002.8	1030.7	1077.7	1104.3	1151.4	1176.7	1223.9	1248.0	1295.3	1318.2	1365.6	1387.3	1489.0	1562.8	1664.8	1735.6	1837.9	1905.6	2008.2	2073.0	2175.9	2237.8	2340.9	2400.0
Number of modules per ring :	56	56	60	64	64	68	68	72	76	76	80	84	84	88	88	92	92	104	108	116	120	128	132	140	144	152	156	164	168

Total area [m2] = 1841

Number of channels (M) = 2485

Fluka Simulations & Hit Occupancy

- **How to estimate the occupancy & hit-rates?**
  - Use Fluka simulated fluence of charged particles [particles/cm^{-2}] per pp collision



  - Scan detector module by module → find corresponding fluences
  - Scale these numbers to expected **max pile-ups = 1000** → i.e. get fluence per bunch crossing
  - Calculate hit-rates:
    - Non-triggered data → f = 40 MHz
    - Triggered data → f ~ 1 MHz (value given by hardware limits, e.g. FPGA etc.)

Data Bandwidth & Data Rates

- **How to calculate the required bandwidth from hit rates?** Two options how to address the data:

  1) Sparsified data:

  → address each channel: nBits = $\log_2$(nRows) + $\log_2$(nColumns)

  → add data block for cluster width: assuming avg cluster-size~3 → 2bits

  → add data block for pulse-height: 0bits (binary read-out), 4-8bits (analog read-out)

  2) Unsparsified data:

  → address tho whole matrix: nBits = 1bit/channel x nRows x nColumns (x 4-8bits for analog)

Inner barrel: 1st layer (binary read-out)

#Hit-channels per module per BX :	5224	→ Hit rate/collision/module * nPileUps=1000
Module avg occupancy (max[sen1,sen2])[%] :	3.99	
Module bandwidth/(addr+clsWidth=2b[b] :	19	→ Sparsified data: 17bits (address) + 2bits (clsWidth)
Mod. bandwidth(#chnls*(addr+clsWidth)[kb] :	96.93	→ Module bandwidth → sparsified data, binary read-out
Mod. bandwidth (matrix*1b/channel) [kb] :	128.00	→ Module bandwidth → unsparsified data, binary r-o
Data rate per layer - 40MHz,spars [Tb/s] :	823	
Data rate per layer - 1MHz,spars [Tb/s] :	20	
Data rate per ladder - 40Mhz,spars [Gb/s] :	70257	
Data rate per ladder - 1Mhz,spars [Gb/s] :	1756	
Data rate per module - 40Mhz,spars [Gb/s]:	3697.74	→ Data rate per module for untriggered data (40MHz)
Data rate per module - 1Mhz,spars [Gb/s]:	92.44	→ Data rate per module for triggered data (1MHz)

Results: Inner Barrel (Binary read-out)

Pixel detector

Total data flow from inner barrel

Number of pile-up events: 1000										
Layer no :	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total [TB/s]**
Radius [mm] :	25.0	93.3	169.2	232.9	317.9	381.6	466.5	530.1	600.0	
Min flux in Z [particles/cm^-2] :	480.9	52.6	20.8	12.5	6.9	4.9	3.1	2.4	1.7	
Max flux in Z [particles/cm^-2] :	605.7	75.5	27.7	16.7	8.5	6.1	3.6	2.9	2.0	
Z position [mm] related to max flux :	500.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	
Max cell area in Z (1% occupancy) [mm^2] :	0.0017	0.0133	0.0361	0.0600	0.1170	0.1631	0.2740	0.3455	0.4892	
#Hits per BX (bunch crossing) :	1191126	782118	520512	427240	306090	262404	195096	173950	143898	
#Hit-channels per BX :	1191126	782118	520512	427240	306090	262404	195096	173950	143898	
#Hit-channels per module per BX :	5224	620	464	277	145	104	63	49	35	
Module avg occupancy (max[sen1,sen2])[%] :	3.99	0.47	0.35	0.21	0.11	0.08	0.05	0.04	0.03	
Module bandwidth/(addr+clsWidth=2b[b] :	19	19	19	19	19	19	19	19	19	
Mod. bandwidth(#chnls*(addr+clsWidth)[kb] :	96.93	11.52	8.62	5.15	2.70	1.93	1.18	0.92	0.66	
Mod. bandwidth (matrix*1b/channel) [kb] :	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	
Data rate per layer - 40MHz,spars [Tb/s] :	823	540	359	295	211	181	134	120	99	345
Data rate per layer - 1MHz,spars [Tb/s] :	20	13	8	7	5	4	3	3	2	8
Data rate per ladder - 40Mhz,spars [Gb/s] :	70257	15377	11513	6872	3610	2579	1569	1231	878	
Data rate per ladder - 1Mhz,spars [Gb/s] :	1756	384	287	171	90	64	39	30	21	
Data rate per module - 40Mhz,spars [Gb/s]:	3697.74	439.35	328.95	196.37	103.17	73.70	44.83	35.18	25.09	
Data rate per module - 1Mhz,spars [Gb/s]:	92.44	10.98	8.22	4.91	2.58	1.84	1.12	0.88	0.63	

9.5 (1.1) Gb/s/cm^2

0.05 (0.03) Gb/s/cm^2

Comment: To get a 4b analog data output, use conversion factor → f=((19+4)/19)

Results: Inner End-cap (Binary read-out)

Pixel detector

Total data flow from inner end-cap

Number of pile-up events: 1000												
Ring no :	1	2	3	4	5	6	7	8	9	10	11	Total [TB/s]
Average radius [mm] :	53.5	78.5	123.5	179.5	235.5	291.5	347.5	403.5	459.5	515.5	571.5	
Min flux in R [particles/cm^-2] :	113.4	62.0	39.3	20.5	12.8	9.1	6.9	4.6	3.4	2.7	2.2	
Max flux in R [particles/cm^-2] :	1169.2	317.8	131.3	61.7	37.3	25.6	17.4	12.5	9.5	7.0	5.3	
Z position [mm] related to max flux :	7996.0	8004.0	7996.0	8004.0	7996.0	8004.0	7996.0	8004.0	7996.0	8004.0	7996.0	
Max cell area in R (1% occupancy) [mm^2]:	0.0009	0.0031	0.0076	0.0162	0.0268	0.0390	0.0575	0.0799	0.1058	0.1430	0.1873	
#Hits per BX (bunch crossing) :	1431460	1770732	1324020	1000360	845416	673728	518976	442680	385632	305136	256360	
#Hit-channels per BX :	1431460	1770732	1324020	1000360	845416	673728	518976	442680	385632	305136	256360	
#Hit-channels per module per BX :	1988	1366	612	694	451	292	200	146	111	81	61	
Module avg occupancy (max[sen1,sen2]) [%] :	1.52	1.04	0.47	0.53	0.34	0.22	0.15	0.11	0.09	0.06	0.05	
Module bandwidth/(addr+clsWidth=2b[b] :	19	19	19	19	19	19	19	19	19	19	19	
Mod. bandwidth(#chnls*(addr+clsWidth)[kb] :	36.89	25.35	11.37	12.89	8.38	5.43	3.72	2.72	2.07	1.51	1.14	
Mod. bandwidth (matrix*1b/channel) [kb] :	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	128.00	
Data rate per ringLayer-40MHz,spars [Tb/s]:	989	1223	915	691	584	465	358	305	266	210	177	773
Data rate per ringLayer- 1MHz,spars [Tb/s]:	24	30	22	17	14	11	8	7	6	5	4	19
Data rate per ring - 40Mhz,spars [Gb/s] :	28144	34814	26031	19668	16621	13246	10203	8703	7582	5999	5040	
Data rate per ring - 1Mhz,spars [Gb/s] :	703	870	650	491	415	331	255	217	189	149	126	
Data rate per module - 40Mhz,spars [Gb/s]:	1407.21	967.08	433.86	491.71	319.65	206.97	141.72	103.61	78.98	57.69	43.45	
Data rate per module - 1Mhz,spars [Gb/s]:	35.18	24.18	10.85	12.29	7.99	5.17	3.54	2.59	1.97	1.44	1.09	

3.6 (2.5) Gb/s/cm^2

0.07 (0.06) Gb/s/cm^2

Comment: To get a 4b analog data output, use conversion factor → f=((19+4)/19)

Results: Outer Barrel (Binary read-out)

Pixel-strip or strip-strip detector

Total data flow from outer barrel

Layer no :	1	2	3	4	5	6	7	8	Total [TB/s]
Radius [mm] :	800.0	1028.0	1272.3	1485.2	1704.5	1936.1	2167.7	2400.0	
Min flux in Z [particles/cm^-2] :	0.7	0.4	0.3	0.2	0.1	0.1	0.1	0.1	
Max flux in Z [particles/cm^-2] :	0.9	0.5	0.4	0.2	0.1	0.1	0.1	0.1	
Z position [mm] related to max flux :	3000.0	3000.0	3000.0	3000.0	2900.0	2600.0	3000.0	2500.0	
Max cell area in Z (1% occupancy) [mm^2] :	1.11	2.18	2.70	5.04	7.37	8.88	10.33	12.27	
#Hits per BX (bunch crossing) :	562950	357136	286272	215600	176764	160666	138750	108864	
#Hit-channels per BX :	562950	357136	286272	215600	176764	160666	138750	108864	
#Hit-channels per module per BX :	70	36	24	16	24	19	15	10	
Module avg occupancy (max[sen1,sen2])[%] :	1.85	0.96	0.65	0.42	0.60	0.48	0.37	0.26	
Module bandwidth/(addr+clsWidth=2b[b] :	30	30	30	30	26	26	26	26	
Mod. bandwidth(#chnls*(addr+clsWidth)[kb] :	1.04	0.54	0.36	0.24	0.31	0.25	0.19	0.13	
Mod. bandwidth (matrix*1b/channel) [kb] :	31.88	31.88	31.88	31.88	3.97	3.97	3.97	3.97	
Data rate per layer - 40MHz,spars [Tb/s] :	307	194	156	117	83	75	65	51	131
Data rate per layer - 1MHz,spars [Tb/s] :	7	4	3	2	2	1	1	1	3
Data rate per ladder - 40Mhz,spars [Gb/s] :	5825	2934	1904	1229	725	580	447	313	
Data rate per ladder - 1Mhz,spars [Gb/s] :	145	73	47	30	18	14	11	7	
Data rate per module - 40Mhz,spars [Gb/s]:	39.63	20.52	13.90	9.11	11.89	9.52	7.34	5.14	
Data rate per module - 1Mhz,spars [Gb/s]:	0.99	0.51	0.35	0.23	0.30	0.24	0.18	0.13	

Comment: To get a 4b analog data output, use conversion factor → f_1=(34/30) for the first 4 layers & f_2=(30/26) for the second 4 layers

Results: Outer End-cap (Binary read-out)

Pixel-strip or strip-strip detector

Total data flow from outer end-cap

Ring no :	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Total [TB/s]
Average radius [mm] :	779.8	826.3	856.9	903.6	932.9	979.7	1007.6	1054.5	1081.2	1128.2	1153.6	1200.8	1224.9	1272.2	1295.1	1342.5	1364.1	1438.8	1512.5	1614.6	1685.3	1787.6	1855.4	1958.0	2022.8	2125.7	2187.6	2290.7	2349.8	
Min flux in R [particles/cm^-2] :	0.96	1.00	0.71	0.57	0.50	0.48	0.47	0.50	0.38	0.32	0.29	0.29	0.28	0.29	0.27	0.21	0.19	0.18	0.16	0.13	0.13	0.10	0.09	0.10	0.07	0.07	0.07	0.05	0.05	
Max flux in R [particles/cm^-2] :	1.92	1.61	1.44	1.40	1.36	1.18	0.96	0.79	0.73	0.72	0.73	0.70	0.67	0.50	0.46	0.64	0.50	0.64	0.50	0.47	0.37	0.38	0.26	0.31	0.24	0.24	0.20	0.21	0.15	
Z position [mm] related to max flux :	7981.5	8018.5	7981.5	6675.9	7981.5	8018.5	7981.5	8018.5	5521.7	6091.7	7279.4	8018.5	7981.5	8018.5	7981.5	8018.5	7981.5	8018.5	7981.5	8018.5	7981.5	8018.5	7981.5	8018.5	7981.5	8018.5	7981.5	8018.5	7981.5	
Max cell area in R (1% occupancy) [mm^2]:	0.5	0.6	0.7	0.7	0.7	0.8	1.0	1.3	1.4	1.4	1.4	1.4	1.5	2.0	2.2	1.6	2.0	1.6	2.0	2.1	2.7	2.6	3.8	3.2	4.1	4.2	5.0	4.7	6.8	
#Hits per BX (bunch crossing) :	127568	122080	124680	105984	92032	79832	72896	77904	80560	67488	64960	59136	54264	55792	60368	57408	51520	106288	104544	92568	79200	86272	72072	75880	69120	60192	62400	57072	48048	
#Hit-channels per BX :	127568	122080	124680	105984	92032	79832	72896	77904	80560	67488	64960	59136	54264	55792	60368	57408	51520	106288	104544	92568	79200	86272	72072	75880	69120	60192	62400	57072	48048	
#Hit-channels per module per BX :	113	109	103	82	71	58	53	54	53	44	40	35	32	31	34	31	28	51	48	39	33	33	27	27	24	19	20	17	14	
Module avg occupancy (max[sen1,sen2]) [%] :	2.97	2.84	2.71	2.16	1.87	1.53	1.40	1.41	1.38	1.16	1.06	0.92	0.84	0.83	0.89	0.81	0.73	1.26	1.19	0.98	0.81	0.83	0.67	0.67	0.59	0.49	0.49	0.43	0.35	
Module bandwidth/(addr+clsWidth=2b[b] :	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	26	26	26	26	26	26	26	26	26	26	26	26	
Mod. bandwidth(#chnls* (addr+clsWidth)[kb] :	1.67	1.60	1.52	1.21	1.05	0.86	0.79	0.79	0.78	0.65	0.59	0.52	0.47	0.46	0.50	0.46	0.41	0.65	0.61	0.51	0.42	0.43	0.35	0.34	0.30	0.25	0.25	0.22	0.18	
Mod. bandwidth (matrix*1b/channel) [kb] :	31.88	31.88	31.88	31.88	31.88	31.88	31.88	31.88	31.88	31.88	31.88	31.88	31.88	31.88	31.88	31.88	31.88	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	
Data rate per ringLayer-40MHz,spars [Tb/s]:	69	66	68	57	50	43	39	42	43	36	35	32	29	30	32	31	28	50	49	43	37	40	34	35	32	28	29	26	22	146
Data rate per ringLayer-1MHz,spars [Tb/s]:	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	3
Data rate per ring - 40Mhz,spars [Gb/s] :	3564	3410	3483	2961	2571	2230	2036	2176	2250	1885	1814	1652	1516	1558	1686	1603	1439	2573	2531	2241	1917	2089	1745	1837	1673	1457	1510	1381	1163	
Data rate per ring - 1Mhz,spars [Gb/s] :	89	85	87	74	64	55	50	54	56	47	45	41	37	38	42	40	35	64	63	56	47	52	43	45	41	36	37	34	29	
Data rate per module - 40Mhz,spars [Gb/s]:	63.65	60.91	58.06	46.27	40.18	32.80	29.95	30.23	29.62	24.81	22.69	19.67	18.05	17.71	19.17	17.43	15.65	24.75	23.44	19.32	15.98	16.32	13.22	13.12	11.62	9.59	9.69	8.43	6.93	
Data rate per module - 1Mhz,spars [Gb/s]:	1.59	1.52	1.45	1.16	1.00	0.82	0.75	0.76	0.74	0.62	0.57	0.49	0.45	0.44	0.48	0.44	0.39	0.62	0.59	0.48	0.40	0.41	0.33	0.33	0.29	0.24	0.24	0.21	0.17	

Comment: To get a 4b analog data output, use conversion factor → f_1=(34/30) for the first 17 rings & f_2=(30/26) for the second 12 rings

Summary

- **Summary & comments:**
  - **Data rates estimated for a CMS phase 2 upgrade design extrapolated to FCC-hh dimensions**

    → not an optimized design

    → results need to be taken at the order of magnitude, but still good approximation!
  - **The triggered (1MHz) first 2 layers in the inner barrel region and the first 2 "ring-layers" in the inner end-cap with data flows >> 10Gb/s per module**

    → 1st (2nd) layer in inner barrel: 9.5 (1.1) Gb/s/cm^2

    → 1st (2nd) ring-layer in inner end-cap: 3.6 (2.5) Gb/s/cm^2

    → out of scale for the current technology → need for trigger & special technology!
  - **For comparison the triggered (1MHz) outermost layers in the inner detector:**

    → 8th (9th) layer in inner barrel: 0.05 (0.03) Gb/s/cm^2

    → 10th (11th) ring-layer in inner end-cap: 0.07 (0.06) Gb/s/cm^2

    → compatible with the current technology ~ 10Gb/s, **when triggered**
  - **Outer tracker from R~140cm compatible with the current technology even untriggered!**

Summary Cont.

- **Comment:**
  - **CMS phase2 upgr. experience:** optical link converters for pixel tracker need to be positioned out of radiation hard region (i.e. on the pixel support envelope ~ R=200mm) → all data need to be transmitted through twisted-pair cables (with limited bandwidth) to converters

    → for FCC-hh design that would mean significant increase in material budget!

    → need for optical link technology, which can deal with significant increase in bandwidth & increased tolerance to radiation