Vertex Detector and Silicon Tracker Power and Cabling Considerations

Bill Cooper
Fermilab

Sensor Requirements

- Early evaluations for an outer silicon tracker assumed a power dissipation of 17.4 μW per channel averaged over a pulsed power cycle.
- Measurements of KPIX prototypes suggested a slightly high value, 20 μW per channel.
- Power dissipation to be expected in a vertex detector was less well known.
  - R&D on pixel sensors has been ongoing.
- To provide guidance, heat removal from a pixel barrel with a sensor layout similar to that of SiD was calculated.
- To avoid the need for studies of vibrations associated with forced-flow gas cooling, the calculations assumed that flow along the length of the barrel would be laminar with dry air as the cooling gas.
  - Maximum Reynolds number = 1800
  - That led to a total power for five barrel layers of 20 watts and a power dissipation of ~ 0.0131 W/cm^2.
- More recent estimates suggest that a power dissipation in the range 0.1 to 0.13 W/cm^2, or higher by a factor of 7.5 to 10, is more likely.

~2 W/sensor for SiD VTX L2-5

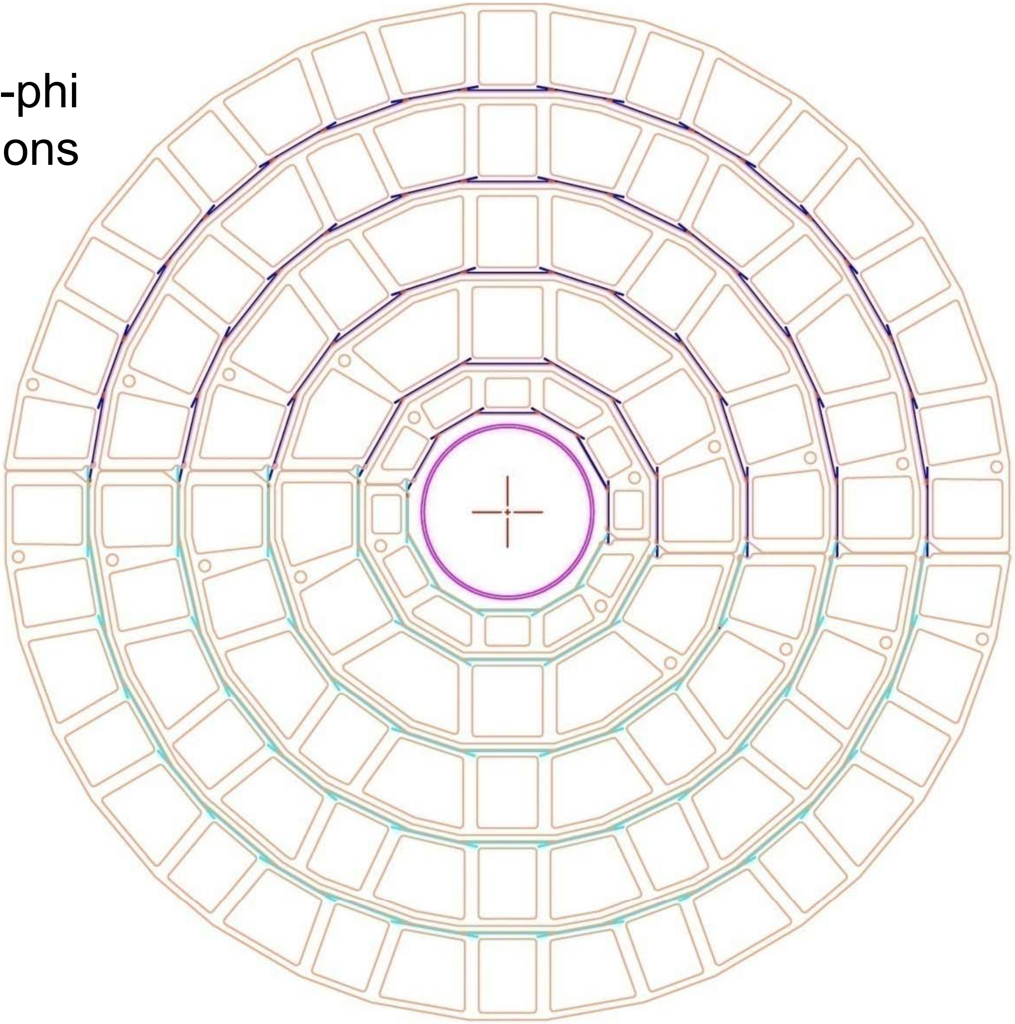
Vertex Barrel Cooling

- Calculations have been repeated with an appropriately higher power dissipation per unit area, 0.13 W/cm^2.
  - The same general barrel geometry was assumed.
  - Layers were approximated by cylinders.
  - Flow was along the barrel length between barrel layers.
  - The cooling gas was assumed to be dry air.
  - Barrel power = 180 watts.
- Results
  - Adequate cooling can no longer be achieved with laminar flow, so Reynold's numbers were allowed to increase.
    - 14300 on the exterior of L1, 41700 on the exterior of other layers
  - The temperature difference between silicon and cooling air is uncomfortably large, 14^{o}C to 17^{o}C for one set of conditions.
  - Under those conditions, the pressure difference from one end of the barrel to the other is 28.6 Pa = 0.0041 psi = 0.115" H_2O.
  - That corresponds to a net longitudinal force on the silicon region of the barrel = 230 gram = 0.104 lb, a challenge for a low-mass structure.
  - Total air flow for the barrel = 424 g/s = 0.326 m^3/s = 691 acfm for 0^{o}C air.
  - Flow and ΔP are well within the range of standard HVAC blowers.
  - The need for an air dryer encourages the use of a compressor and air delivery via piping.

Vertex Detector Barrel End View

- Two sensor active widths: 8.6 mm (L1) and 12.5 mm (L2-L5)
- Carbon fiber end rings provide support and control out-of-round

108 r-phi locations



Sensor active widths:
L1: 8.6 mm
L2 - L5: 12.5 mm
Cut - active width: 0.08 mm
Inner radii:
A-layer: 14, 21, 34, 47, 60 mm
B-layer: 14.4593, 21.4965, 34.4510, 47.3944, 60.3546 mm
Sensors per layer:
12, 12, 20, 28, 36
Sensor-sensor gap: 0.1 mm
Sensor thickness: 0.075 mm
7 June 2007, 14 August 2007

- Sensors are glued to one another near their long edges to form half-cylinders.
- Top and bottom halves allow installation around the beam pipe.
- Hermeticity is good.

Silicon and Air Temperatures

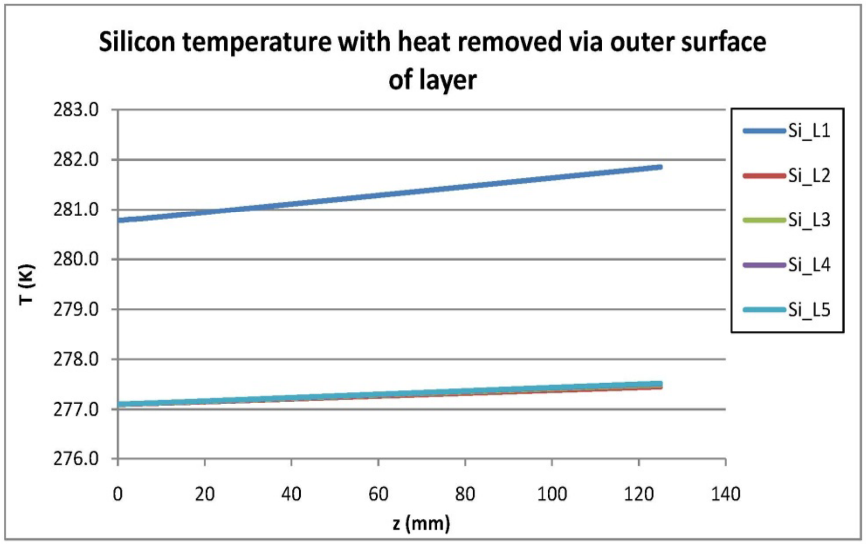
- Heat removal from one silicon surface (outer surface)

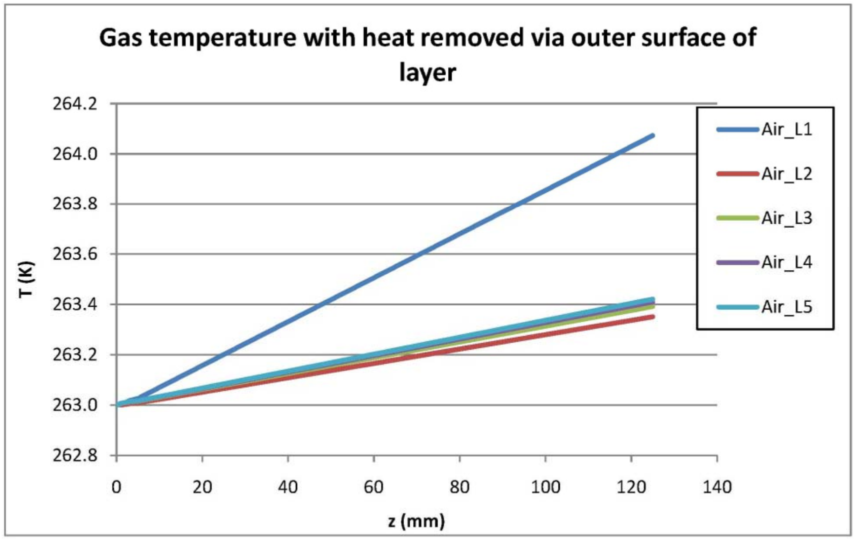
End-to-end pressure	28.58 Pa 0.00415 psi					
Gap	Flow g/s	Reynold's number	Flow velocity m/s	Heat removed W	Average T_silicon - T_gas K	T_rise of gas K
Beam pipe to L1	0.79	1137	4.39	0.00		
L1 to L2	13.11	14293	12.76	14.37	17.78	1.09
L2 to L3	60.00	41661	19.92	21.52	14.10	0.36
L3 to L4	88.32	41661	19.92	34.79	14.10	0.39
L4 to L5	116.65	41661	19.92	48.06	14.10	0.41
L5 to outer shell	144.97	41661	19.92	61.34	14.10	0.42
Totals	423.85			180.08		

Initial air temperature was taken to be 263 K.

Flow between the beam pipe and L1 is too low for significant heat removal.

L1 behaves differently from L2-L5 due to the smaller gap from L1 to L2.





Silicon and Air Temperatures

- Heat removal from both silicon surfaces

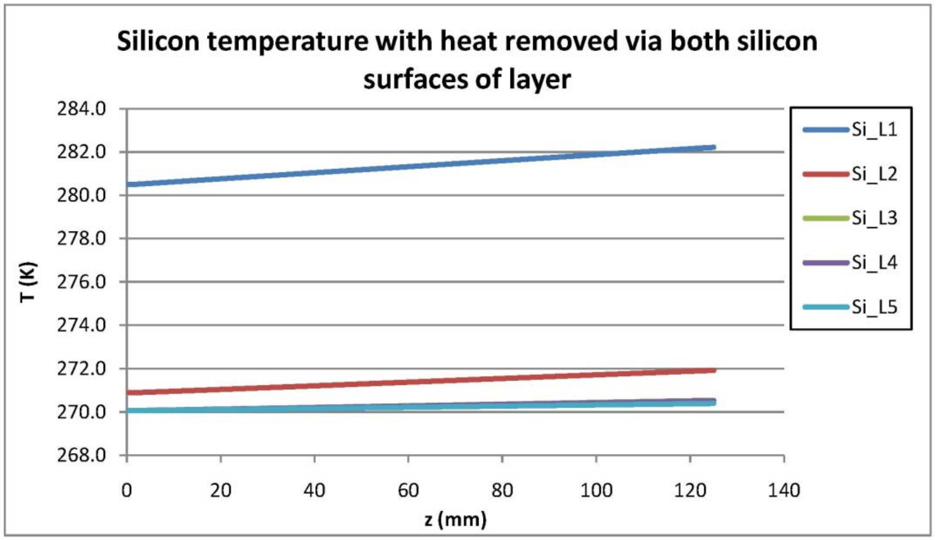
End-to-end pressure	28.58	Pa
	0.00415	psi

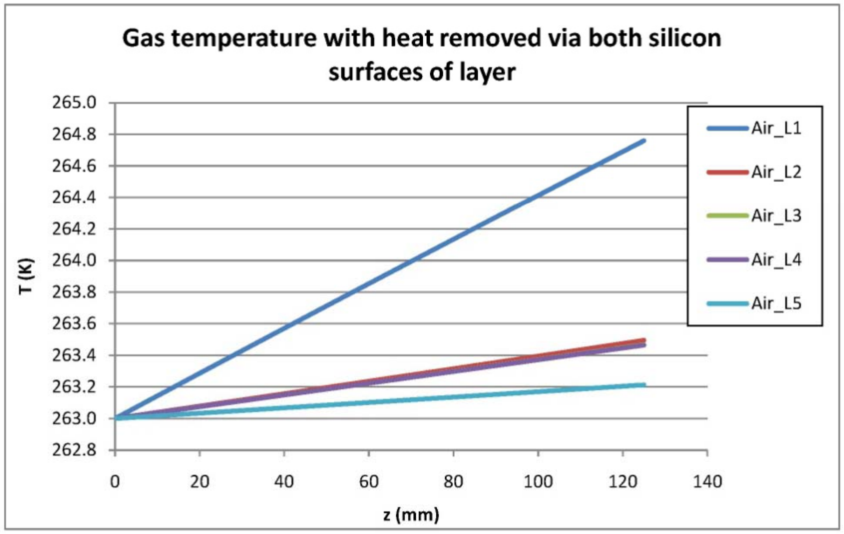
Gap	Flow g/s	Reynold's number	Flow velocity m/s	Heat removed W	Average T_silicon - T_gas K	T_rise of gas K
Beam pipe to L1	0.79	1137	4.39	0.25	18.18	0.32
L1 to L2	13.11	14293	12.76	23.19	17.47	1.76
L2 to L3	60.00	41661	19.92	29.80	8.14	0.49
L3 to L4	88.32	41661	19.92	41.44	7.06	0.47
L4 to L5	116.65	41661	19.92	54.43	7.06	0.46
L5 to outer shell	144.97	41661	19.92	30.96	7.12	0.21
Totals	423.85			180.08		

Initial air temperature was taken to be 263 K.

Flow between the beam pipe and L1 is too low for significant heat removal.

L1 behaves differently from L2-L5 due to the smaller gaps to L2 & the beam pipe.





Comments

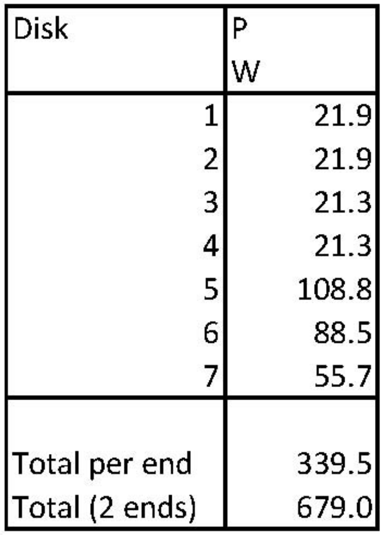
- Flow velocities are high.
  - The implications of turbulent flow and high velocity on vibrations will need to be investigated.
- Heat removal from the innermost layer is difficult with that layer close to the beam pipe.
  - That issue might be addressed by actively cooling the beam pipe.
  - A primarily motivation for the high air flow rate is the L1 silicon temperature.
- All layers benefit from removing heat from both surfaces.
  - L1 benefits minimally, since flow along its inner surface is small.
  - Other layers show roughly a factor of two benefit (as expected from doubling the heat removal area).
- The extent to which both surfaces participate is determined by thermal resistance of the sensor support structures.
  - If foam were used, it would be helpful if it were thermally conductive.
- Volumetric flow is high.
  - 424 g/s corresponds to ~746 scfm.

Cooling Equations

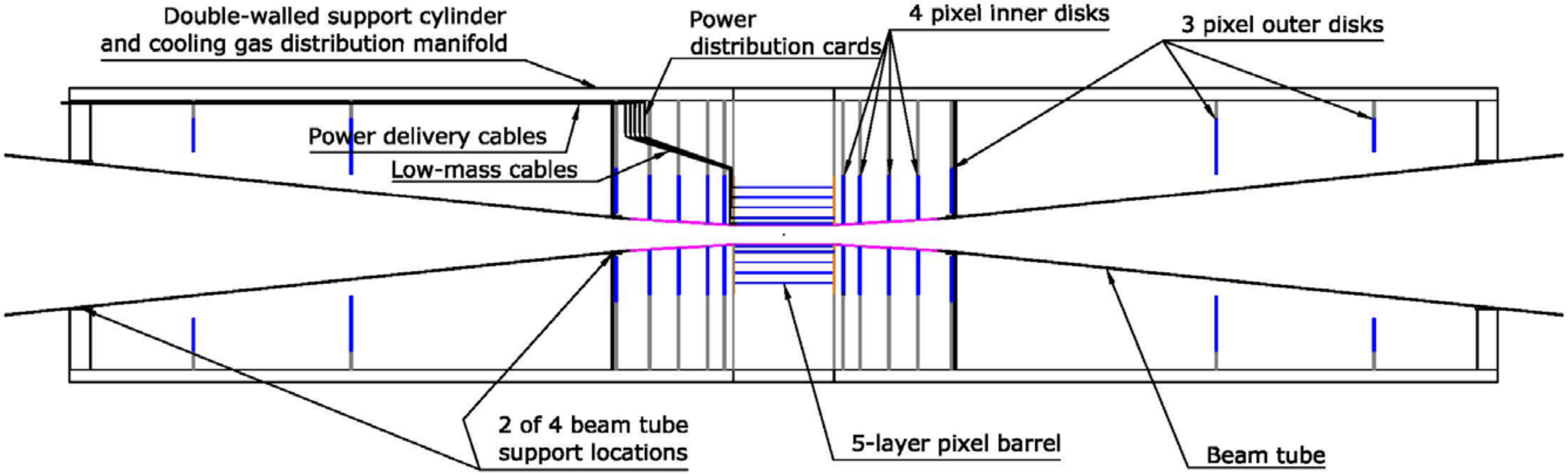
- Hydraulic diameter = $D_h = 2*(R_2 – R_1)$
- Flow area = $A = \pi*(R_2^2 – R_1^2)$
- Flow rate = dm/dt
- $N_{Re} = D_h*G/\mu$, where $G = 1/A*dm/dt$ and μ = viscosity
- Friction factor = $f = 0.316*N_{Re}^{-0.25}$
- Colburn j-factor = $j_h = 0.023*N_{Re}^{-0.2}$
- $h = j_h*C_p*G/N_{Pr}^{2/3}$, where C_p is the specific heat at constant pressure and N_{Pr} is the Prandtl number (of dry air)
- $dP/dL = f*G^2/2/g_c/\rho/ D_h$, where ρ = density and g_c = gravitational constant
- $T_{Air}(z+dz) = T_{Air}(z) + Q*(dz/L)/c_p/(dm/dt)$
- $T_{Si} = T_{Air} + Q/A/h$
- For a more detailed description of heat transfer, please see chapter 2.4 at http://www.wlv.com/products/databook/databook.pdf.

Disk Cooling

- Assume the same power dissipation per unit area as in the barrels, 0.13 W/cm^2.
- 340 W per end isn't small, but one can still imagine cooling with air.
- Air temperature rise from the 180 Watts of the barrel is modest, ~0.42^{o}C (with relatively high flow rates).
- The barrel flow "sees" the heat input of disks at one end of the VTX region.



Disk	P W
1	21.9
2	21.9
3	21.3
4	21.3
5	108.8
6	88.5
7	55.7
Total per end	339.5
Total (2 ends)	679.0

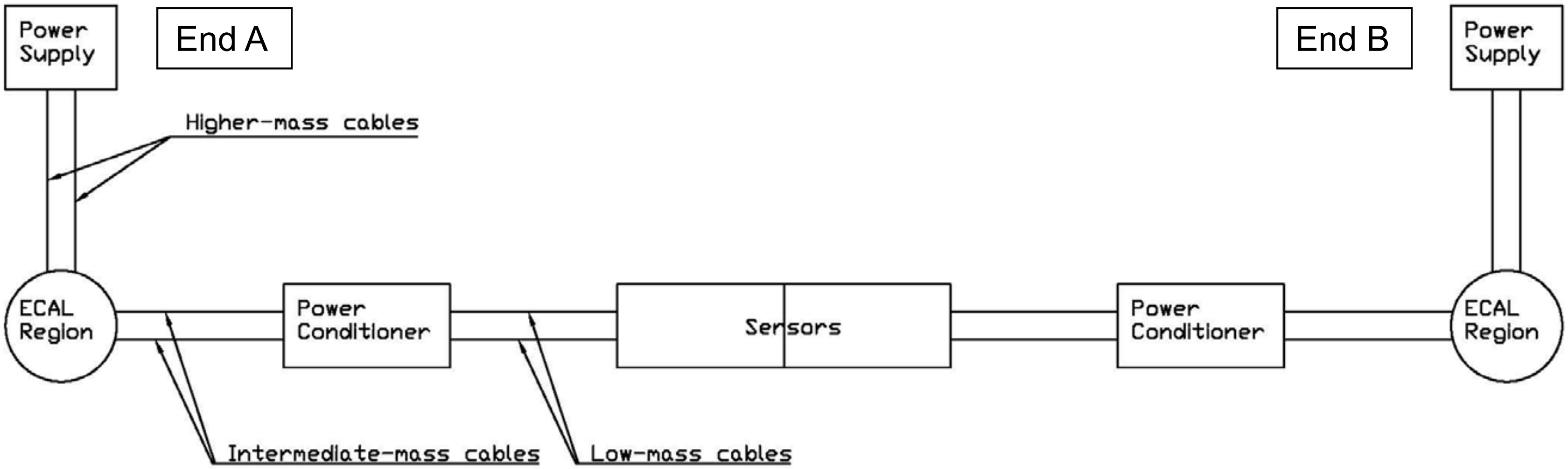


Disk Cooling

- The total sensor power to be removed increases to 859 watts, a factor of 4.77 increase.
  - With the same air flow, 424 g/s, and assuming all the disk power is extracted via air flow, that corresponds to a net ΔT_{air} of approximately 2.02^{o}C, still acceptable.
- In addition, heat dissipated by cabling and power conditioning within the vertex detector region will need to be removed.
  - That corresponds to a factor of approximately 1.45 in heat to be removed, but still leads to an acceptable increase in air temperature.
- The issue which remains to be addressed is heat transfer from the disks into the air flow stream with acceptable disk temperatures.
  - So far, a suitable flow path to ensure that isn't evident.
- An option, particularly for the three outermost disks at each end, may be to cool actively with evaporative CO2.
  - Then the surfaces of those disks could cool the air for other disks and for the barrel.
- A final issue is temperature uniformity from the bottom to the top of the VTX region.
  - We need to check convective heat transfer coefficients and their impacts on bottom to top ΔT.

Power Delivery

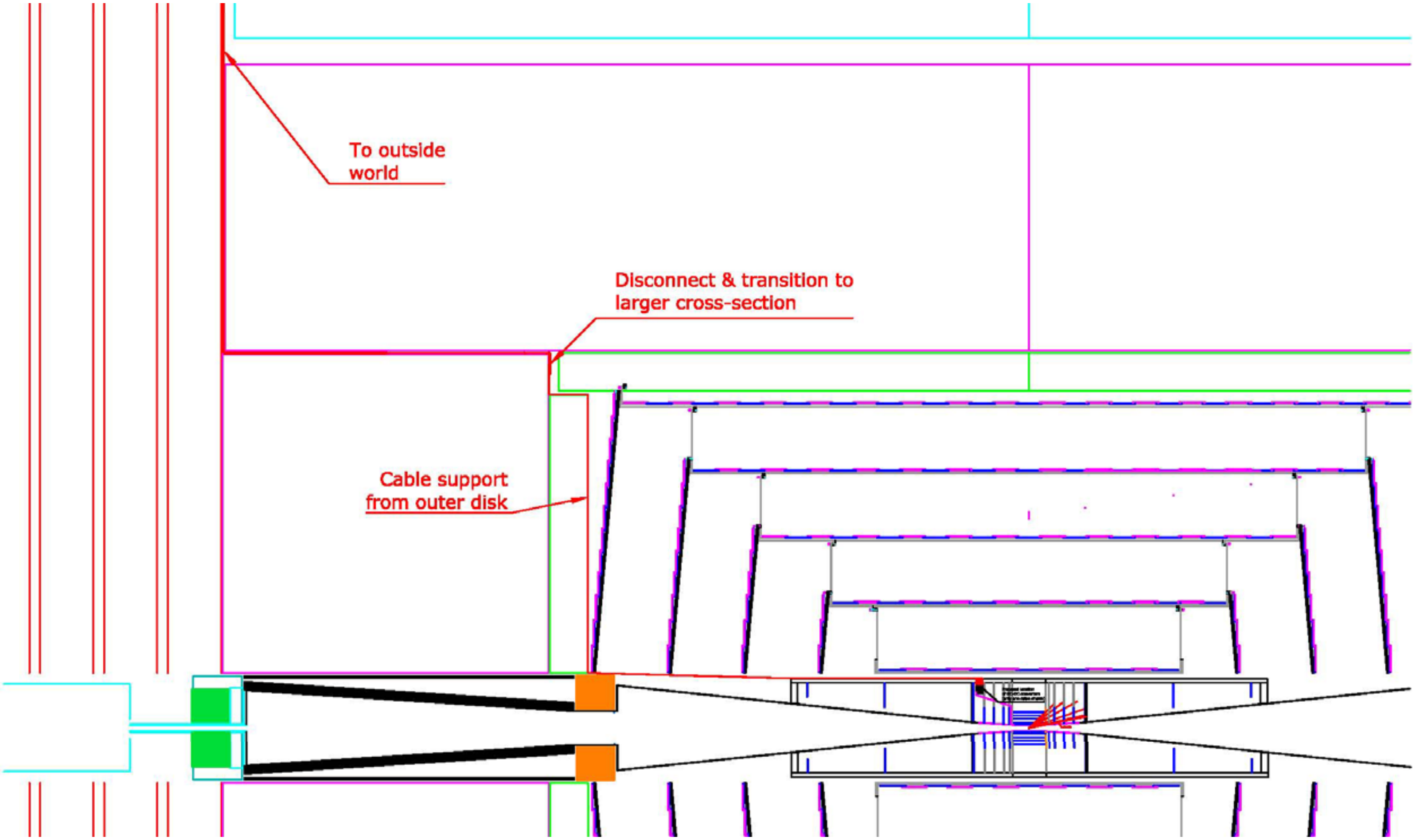
- Power supplies are expected to be located on the exterior of the detector or at another exterior location to be identified.
- The basic paths from the power supplies to the silicon sensors of either the tracker or the vertex detector are shown schematically below.



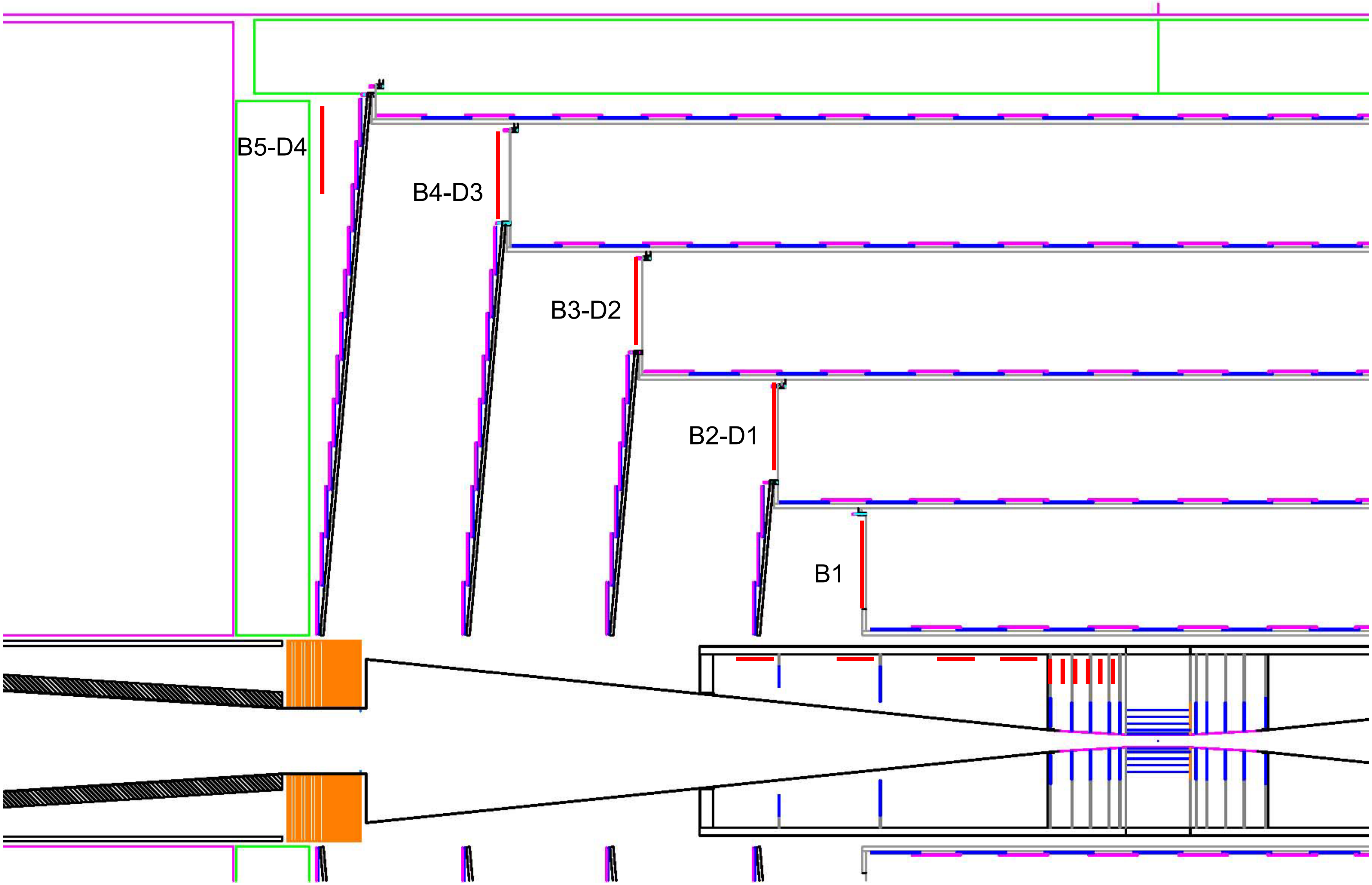
- In principle, splitting can occur at the power supplies, at the conductor size transition in the ECAL region, at the power conditioners, and at the sensors.
- Care should be taken that ground loops do not occur from one end of the solenoid to the other.

Possible VTX Cable Path for SiD

- Cables run on outer surface of VTX support cylinder.
- VTX disk cables could follow a similar path.
- Cable power is dissipated into the outer tracker region.

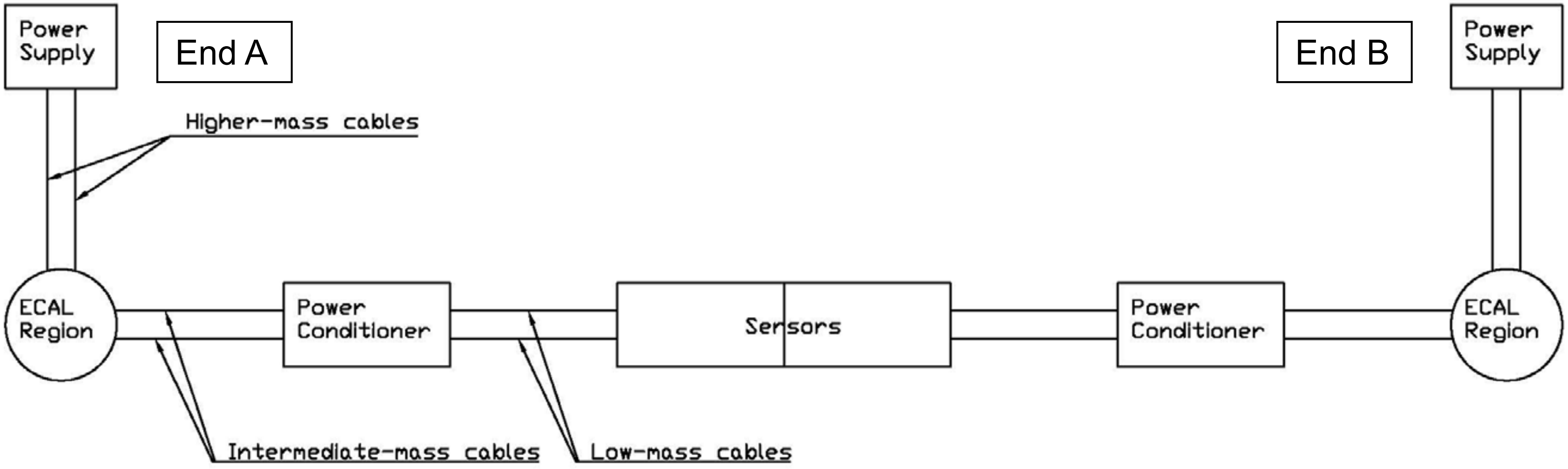


Tentative Power Conditioner Locations



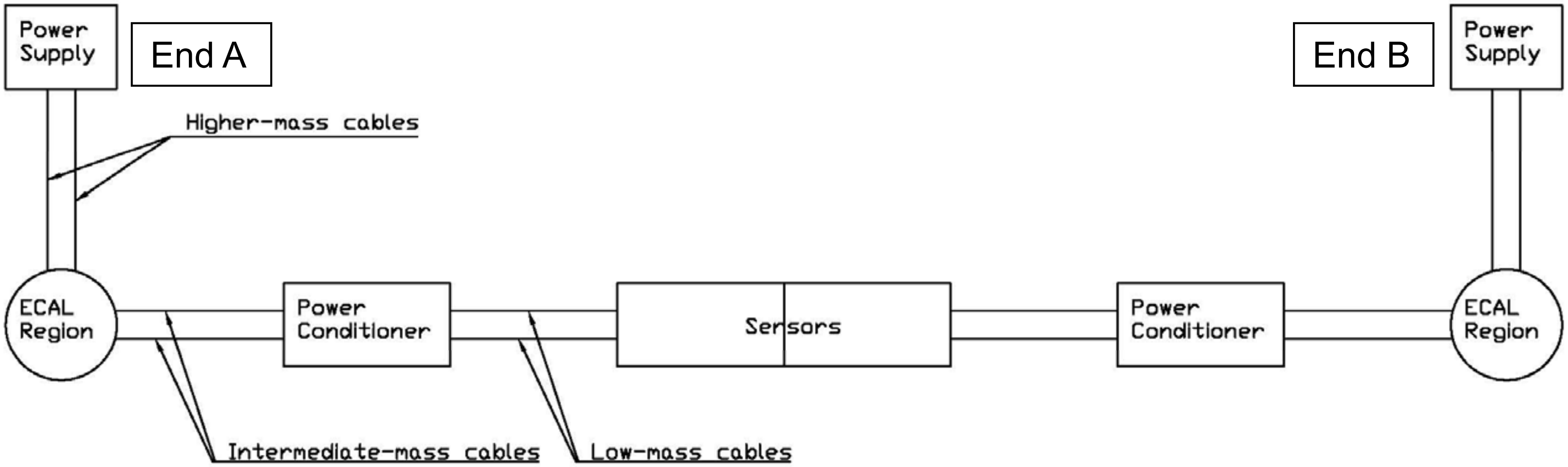
Pulsed Power

- The spill structure of the accelerator, roughly a1 ms spill every 200 ms, allows sensor power to be reduced between spills.
- Although the reduction of average power with respect to peak power could be as much as 200, a power reduction factor if 80 is assumed to allow the power to be ramped up and down at a convenient rate and to allow sensors to remain partially powered in the "down" state.
- Power cycling devices could be located anywhere along the supply chain provided acceptable ramp rates were achieved.
- In practice, they are expected to be relatively close to the sensors in the boxes labeled "Power Conditioner".



Pulsed Power

- If a battery (or sufficiently large capacitor) were present at the input to a power conditioner, then the relevant voltage drop in cables leading to the conditioner would be close to the average voltage drop over an accelerator cycle.
- The analysis which follows assumes no such buffering, that is, the relevant voltage drop is the instantaneous drop with power ramped up (conservative). That directly reflects the voltage available to sensors in the ramped up state.
- Power dissipation from those cables is the average dissipation over a cycle.
- Fail-safe design is an issue for pulsed power.



DC-DC Converters

- Please see the talk by Satish Dhawan.
- DC-DC converters are under active investigation as a means to allow the cross-section of conductors to be reduced before the converters.
- For the same power, less current (and hence less conductor cross-section) is needed if the voltage is higher.
  - The DC-DC converters reduce voltage from the higher value to the value that is needed.
  - A step-down ratio of 8 is assumed in the subsequent analysis.
  - DC-DC converters are assumed to be located in the boxes labeled “Power Conditioner”.
  - They should be located close to the sensors for maximal benefit, but their material needs to be taken into account in selecting a location.
  - Fail-safe design is an issue.
- Serial powering represents another approach to providing the same benefits.
  - Fail-safe design is an issue.

VTX Power Delivery

- Cable contributions appear to be dominated by power delivery.
- SiD barrel with 0.13 W/cm^2:
  - 90 watts average power dissipated at the barrel and a power cycling factor of 80 (14400 watts dissipated at the barrel when ramped up)
  - Power distributors located 0.3 m from sensors.
    - Serial powering of ladders occurs at the distributors.
    - Serial powering within ladders as well.
  - 0.4 volt drop in cables to ladders and back
  - 2.9 volts at distributors (2.5 volts at ladders)
  - Ladder length = 125 mm.
  - Current per ladder is proportional to the ladder width (8.6 mm for layer 1, 12.5 mm for layers 2-5).
- Then when powered "up"
  - 40.5 watts dissipated in cables and DC-DC converters for the barrels (45% of barrel power)
  - 153 watts dissipated in cables and DC-DC converters for the disks (45% of disk power)
- Additional power is dissipated by cabling outside the VTX region.

Power Delivery to VTX Barrel

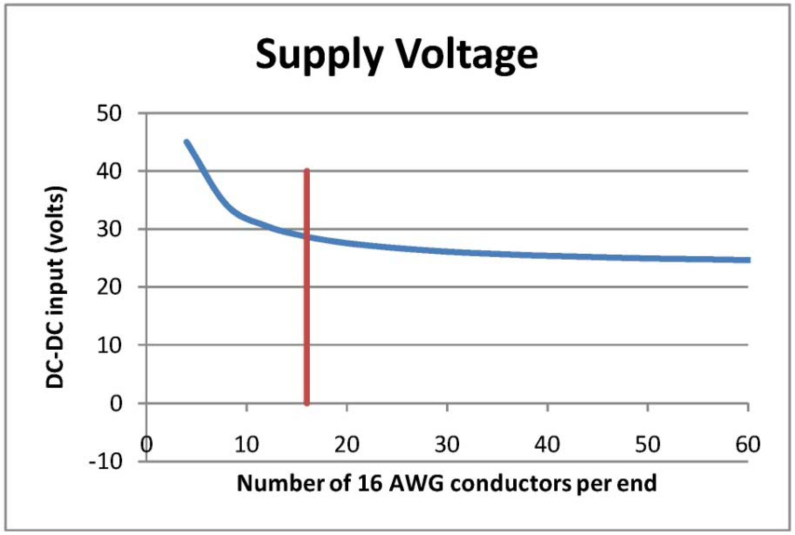
One end of VTX	**Ramped up**	**Average**		
P_barrel	7200	**90**	**watts**	
Pulsed power factor	80	80		
DC-DC converter out	2.9		volts	
Sensors	2.5		volts	
I_sensors	2880		amp	
P_cables	1152	**14.4**	**watts**	**VTX Region**
R_cables	0.000139		ohms	
P_total	8352	**104.4**	**watts**	
P_cables/P_total	0.138			
DC-DC converter eff.	0.8			
P_into_DC-DC	10440	**130.5**	**watts**	**1.45 P0**
Step-down ratio	8			
V_DC-DC_in	23.2		volts	
I_DC-DC_in	450		amp	
# conductors per end (supply + return)	18			
I_conductor	50		amp	
Conductor AWG	16			**Tracker region**
Conductor diameter	1.29032		mm	
R/L	13.17248		Ohms/km	
L	3		m	
R_conductor	0.03952		ohms	
P_cables	1778	**22.2**	**watts**	
V_cable	2.0		volts	
V_total	27.2		volts	
P_total	12218	**152.7**	**watts**	**1.70 P0**

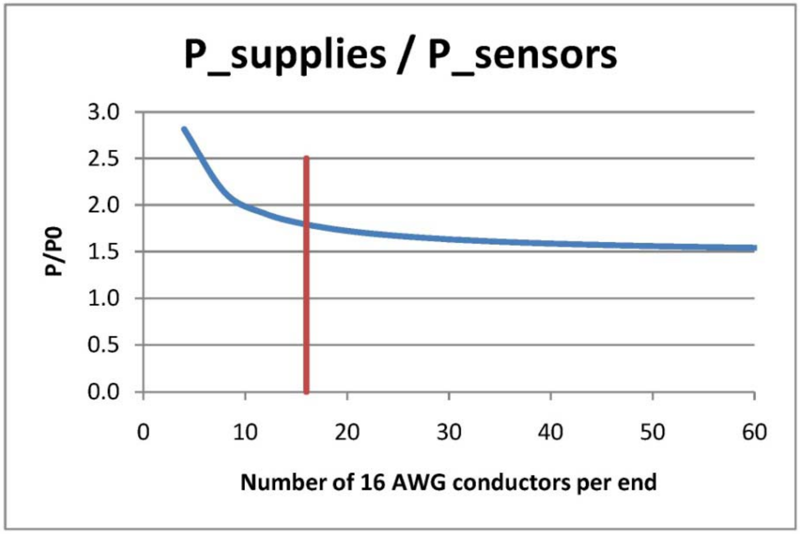
0.13 W/cm^2 sensor power dissipation

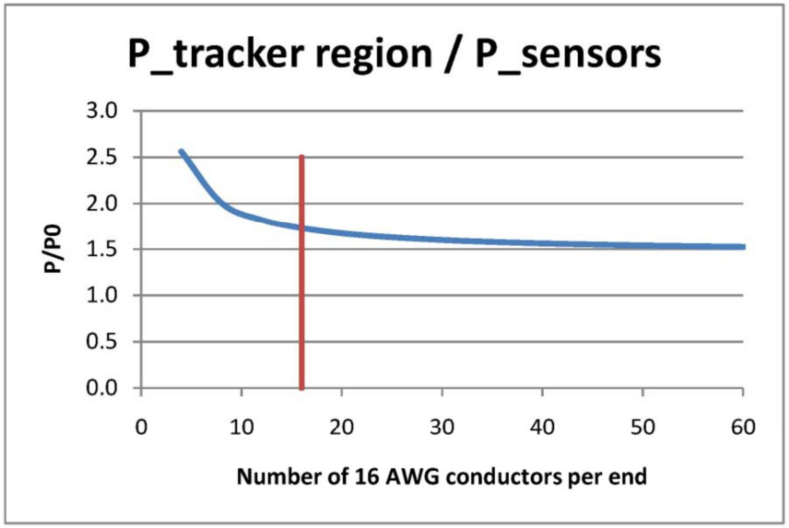
	Ramped up	**Average**		
# conductors per end (supply + return)	18			
I_conductor	50		amp	
Conductor AWG	6			
Conductor diameter	4.11		mm	**Calorimeter + Muon**
R/L	1.29593		Ohms/km	
L	7		m	
R_conductor	0.00907		ohms	
P_cables	408.2	**5.1**	**watts**	
V_cable	0.45		volts	
V_total	28.06		volts	
P_total	12627	**157.8**	**watts**	**1.75 P0**

Power Delivery to VTX Barrel

- DC-DC converters are within the cooled silicon region.


Supply Voltage

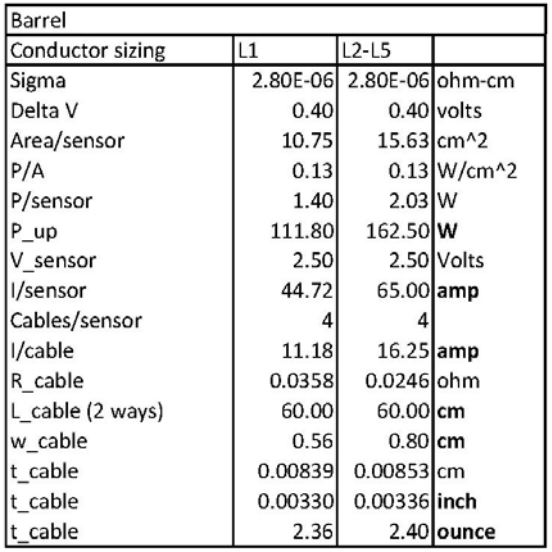

P_supplies / P_sensors


P_tracker region / P_sensors

P_VTX_region /P_sensors = 1.45

VTX Barrel Power Conductor Sizing

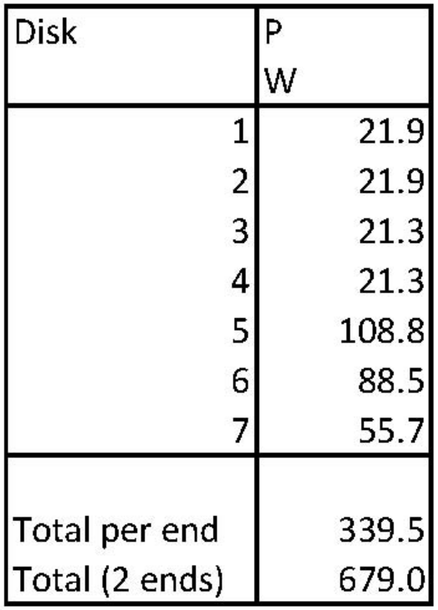
- From the DC-DC converters to the sensors, assume aluminum conductor with ρ = 2.8 x 10^{-6} ohm-cm.
- Assume a conductor length of 60 cm and that 16% of sensor power is dissipated over the 30 cm cable length.
- Width available = 6.4 mm (Layer 1), 8 mm (Layers 2-5)
- Assume width used = 4 mm (Layer 1), 5.6 mm (Layers 2-5).
- Then conductor thickness = ~ 85 μm (84 μm for Layer 1).
  - Relatively thick with a bad impact on the material budget
  - Could try more serialization or voltage regulation at the sensor



Barrel			
Conductor sizing	L1	L2-L5	
Sigma	2.80E-06	2.80E-06	ohm-cm
Delta V	0.40	0.40	volts
Area/sensor	10.75	15.63	cm^2
P/A	0.13	0.13	W/cm^2
P/sensor	1.40	2.03	W
P_up	111.80	162.50	**W**
V_sensor	2.50	2.50	Volts
I/sensor	44.72	65.00	**amp**
Cables/sensor	4	4	
I/cable	11.18	16.25	**amp**
R_cable	0.0358	0.0246	ohm
L_cable (2 ways)	60.00	60.00	**cm**
w_cable	0.56	0.80	**cm**
t_cable	0.00839	0.00853	cm
t_cable	0.00330	0.00336	**inch**
t_cable	2.36	2.40	**ounce**

Power Delivery to VTX Disks

- The same power dissipation per unit area was assumed as for the barrels: 0.13 W/cm^2.
- Since pixel size might be lower for the outer three disks, final power dissipation might be significantly lower, 150 watts per end rather than the 340 watts per end which was assumed.



Disk	P W
1	21.9
2	21.9
3	21.3
4	21.3
5	108.8
6	88.5
7	55.7
Total per end	339.5
Total (2 ends)	679.0

Power Delivery to VTX Disks

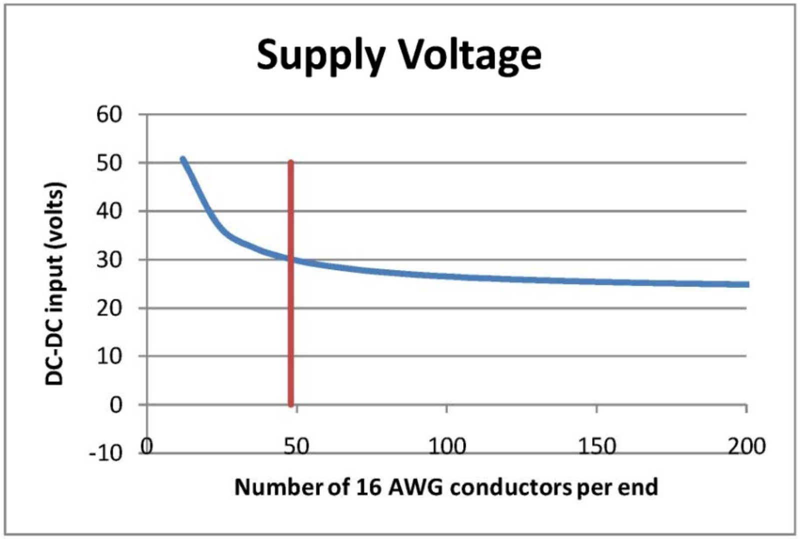
One end of VTX	**Ramped up**	**Average**		
P_disks	27200	**340**	**watts**	
Pulsed power factor	80	80		
DC-DC converter out	2.9		volts	
Sensors	2.5		volts	
I_sensors	10880		amp	
P_cables	4352	**54.4**	**watts**	**VTX Region**
R_cables	0.000037		ohms	
P_total	31552	**394.4**	**watts**	
P_cables/P_total	0.138	0.138		
DC-DC converter eff.	0.8			
P_into_DC-DC	39440	**493**	**watts**	**1.45 P0**
Step-down ratio	8			
V_DC-DC_in	23.2		volts	
I_DC-DC_in	1700		amp	
# conductors per end (supply + return)	48			
I_conductor	70.83333		amp	
Conductor AWG	16			**Tracker region**
Conductor diameter	1.29032		mm	
R/L	13.17248		Ohms/km	
L	3		m	
R_conductor	0.03952		ohms	
P_cables	9517	**119.0**	**watts**	
V_cable	2.8		volts	
V_total	28.8		volts	
P_total	48957	**612.0**	**watts**	**1.80 P0**

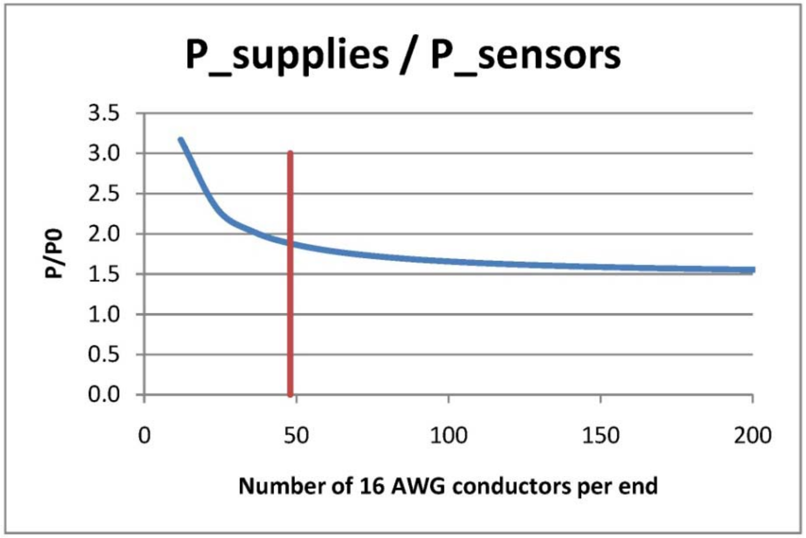
0.13 W/cm^2 sensor power dissipation

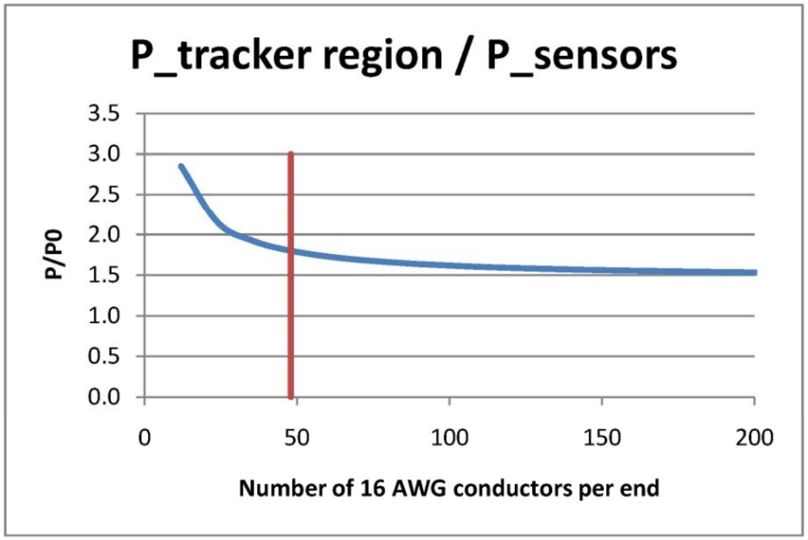
	Ramped up	**Average**		
# conductors per end (supply + return)	48			
I_conductor	70.83333		amp	
Conductor AWG	6			
Conductor diameter	4.11		mm	**Calorimeter + Muon**
R/L	1.29593		Ohms/km	
L	7		m	
R_conductor	0.00907		ohms	
P_cables	2184.7	**27.3**	**watts**	
V_cable	0.64256		volts	
V_total	30.08		volts	
P_total	51142	**639.3**	**watts**	**1.88 P0**

Power Delivery to VTX Disks

- DC-DC converters are within the cooled silicon region.


Supply Voltage

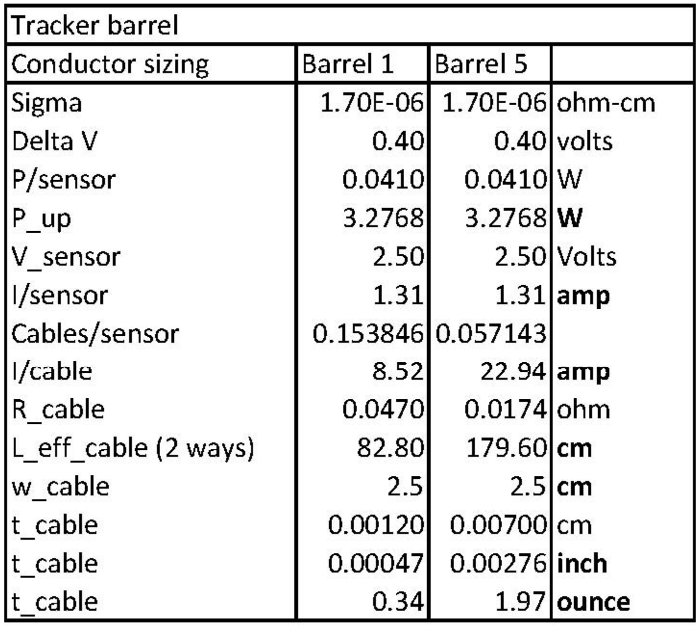

P_supplies / P_sensors


P_tracker region / P_sensors

P_VTX_region /P_sensors = 1.45

Tracker Barrel Power Conductor Sizing

- From the DC-DC converters to the sensors, assume copper conductor with $\rho = 1.7 \times 10^{-6}$ ohm-cm.
- Assume a conductor length of twice the raw cable length and that 16% of sensor power is dissipated over the cable length.
- Assume width available = 25 mm
- Then minimum conductor thickness varies from 12 µm to 70 µm.
  - Relatively thick in the outer barrels



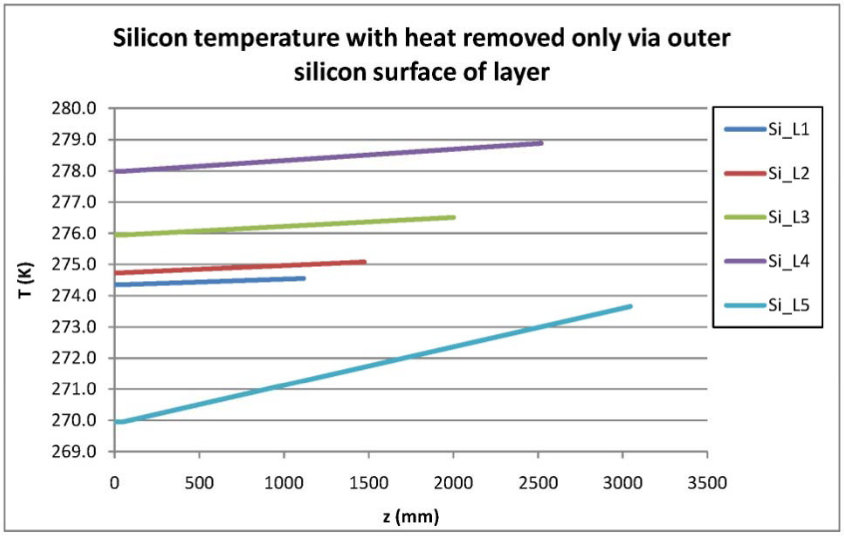
Tracker barrel			
Conductor sizing	Barrel 1	Barrel 5	
Sigma	1.70E-06	1.70E-06	ohm-cm
Delta V	0.40	0.40	volts
P/sensor	0.0410	0.0410	W
P_up	3.2768	3.2768	**W**
V_sensor	2.50	2.50	Volts
I/sensor	1.31	1.31	**amp**
Cables/sensor	0.153846	0.057143	
I/cable	8.52	22.94	**amp**
R_cable	0.0470	0.0174	ohm
L_eff_cable (2 ways)	82.80	179.60	**cm**
w_cable	2.5	2.5	**cm**
t_cable	0.00120	0.00700	cm
t_cable	0.00047	0.00276	**inch**
t_cable	0.34	1.97	**ounce**

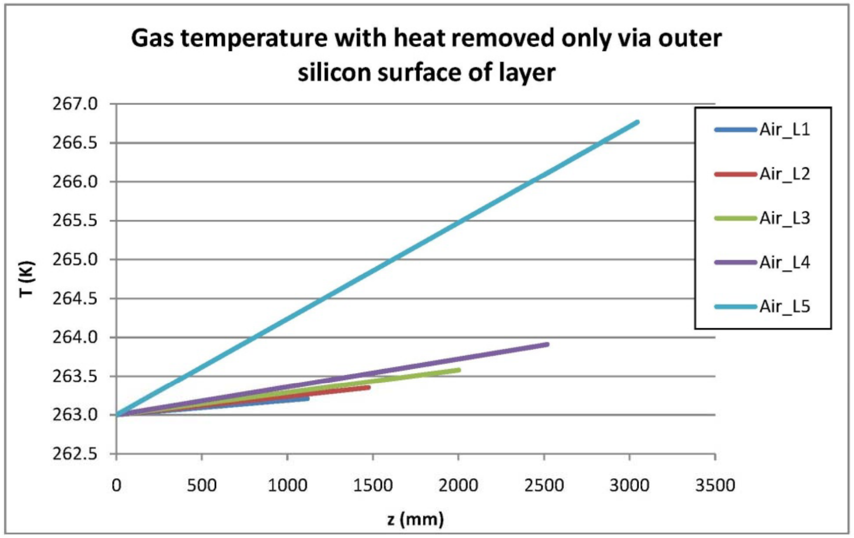
Tracker Barrel Heat Removal

- Average sensor power to be removed = 333 W ignoring power delivery losses.
- The plots which follow assume an initial air temperature of 263 K and a flow of 377.9 g/s.
- A more complete heat transfer correlation was used.
  - The two correlations gave essentially the same answer for the VTX barrel.
- The ΔT_{air} averages 0.88 K.
- One difficulty is that the majority of flow bypasses the silicon and picks up little heat.
- A second difficulty is that the gap from barrel 5 to the ECAL is much smaller than gaps between other barrels.
- A third difficulty is that, for reasonable flow rates, Reynold's numbers range from 1900 to 2700, a region of transition flow.
  - Reynold's number = 615 for flow outside barrel 5 (laminar).
  - In the transition region, flow is unstable and can be either laminar or turbulent.
  - The two flow regimes have significantly different heat transfer coefficients and friction factors.
- These issues will need to be addressed, perhaps by adding flow guides, before credible flow and heat transfer calculations can be made.
- The disks have similar, but more difficult, issues.

Tracker Barrel Heat Removal

- These plots should be taken with a grain of salt and are, at best, preliminary.
- Z is measured from one end of the silicon region for each barrel.





- Serious calculations remain to be done for the tracker disks.

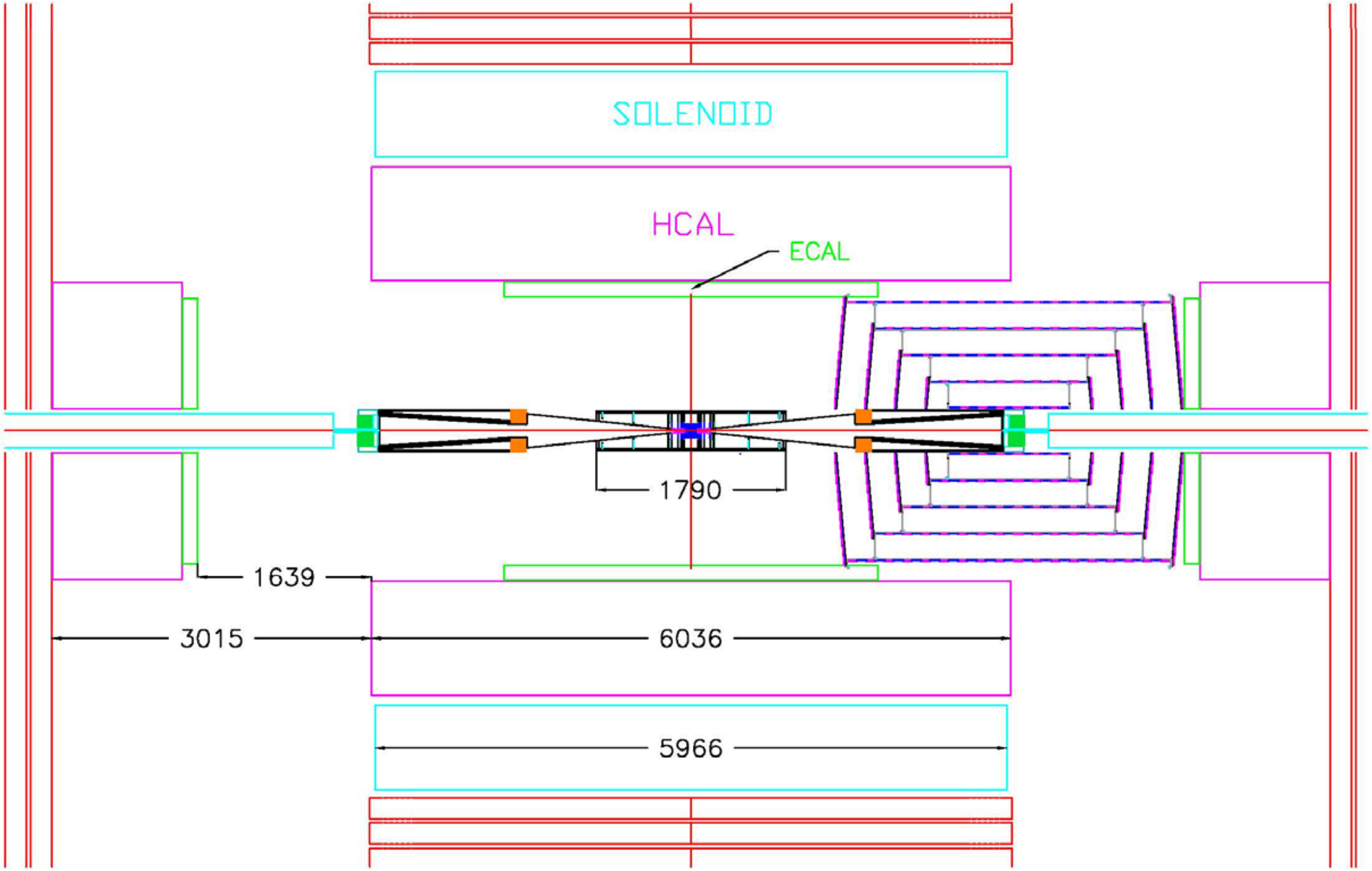
In Conclusion

- Air cooling still works with higher power dissipation in the VTX barrel.
  - We should work to improve L1 cooling in the VTX barrel.
  - We should understand how to cool the VTX disks.
  - We will need to investigate vibrations.
- The outer tracker presents its own issues.
  - Barrel air flow needs to be directed more effectively.
  - The disks need attention.
- Power cycling and DC-DC converters work (in principle), but will require R&D.
  - Systems should be designed with high reliability and fail-safe operation in mind.
  - Serial powering is an option.

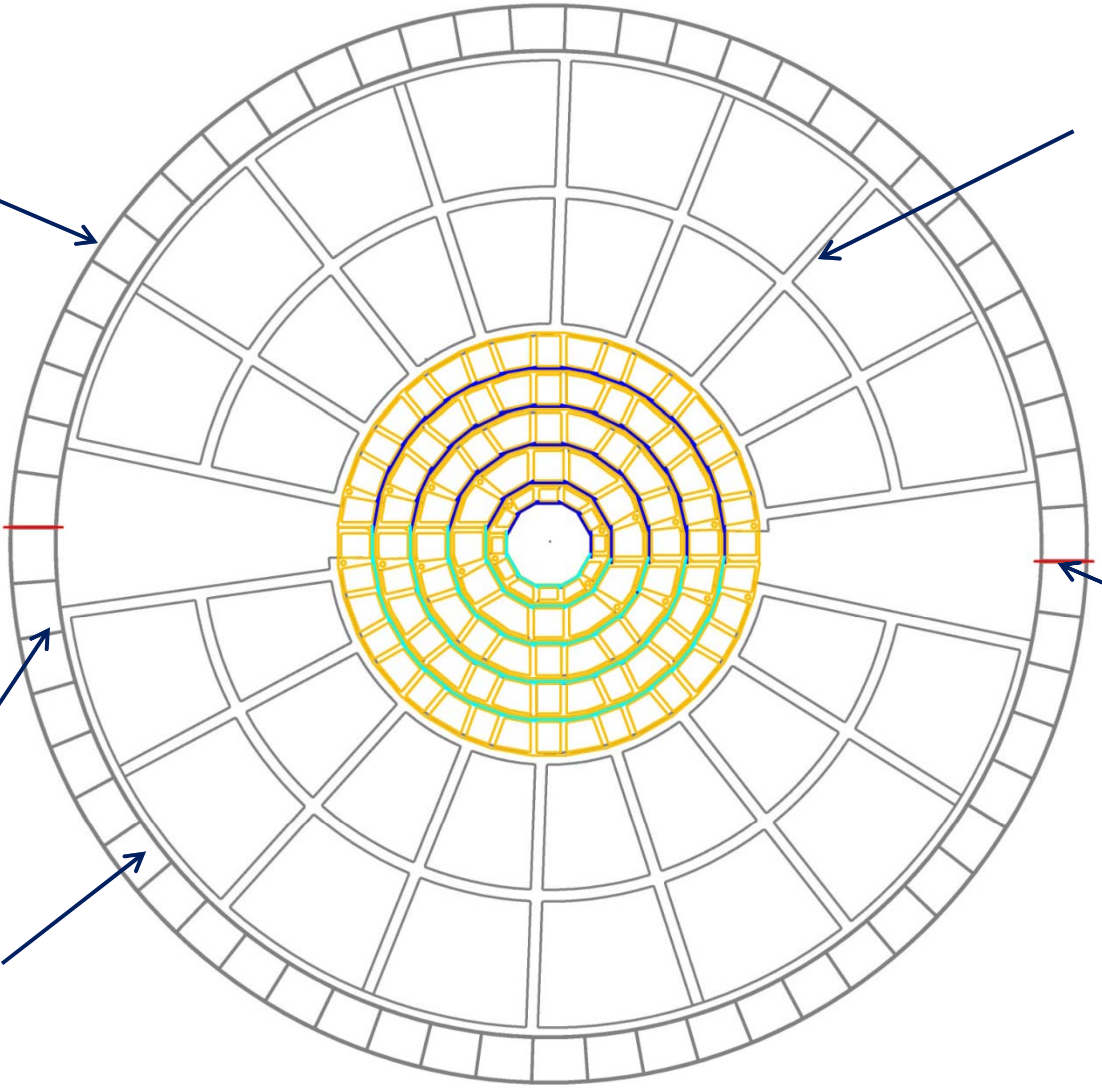
Extra Slides

SiD Open for Servicing the VXD

- Detector opening distances, the transition radius from VXD to outer tracker, and the dimensions and support of the VXD and beam line elements were chosen with servicing the VXD in mind.



End View of VXD Barrel and Supports



Double-
walled,
carbon fiber,
outer support
cylinder

Web structure
would probably
be conical to
improve Z-
stiffness

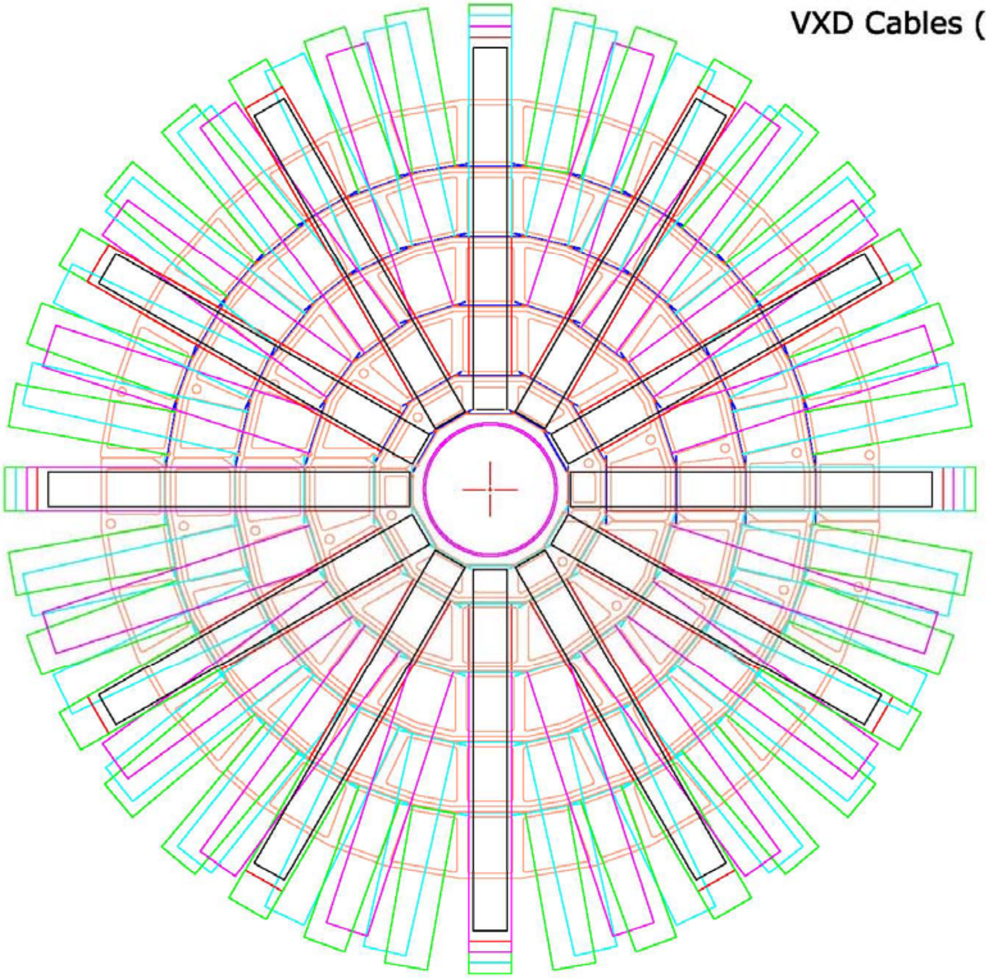
Longitudinal
strips ("ribs")
separate the
walls

Cooling gas
flow passage
(60 total)

Separation
line between
upper and
lower half-
cylinders

Barrel End View with Cables

- Cable contributions to material are significant.
- The original goal of 0.1% X0 per layer did not include cables.



VXD Cables (two per "ladder" end)

Sensor active widths:
L1: 8.6 mm
L2 - L5: 12.5 mm
Cut - active width: 0.08 mm
Inner radii:
A-layer: 14, 21, 34, 47, 60 mm
B-layer: 14.4593, 21.4965, 34.4510,
47.3944, 60.3546 mm
Sensors per layer:
12, 12, 20, 28, 36
Sensor-sensor gap: 0.1 mm
Sensor thickness: 0.075 mm
7 June 2007, 14 August 2007