SVT Power Estimates and Cooling Design

Ernst Sichtermann (LBNL)

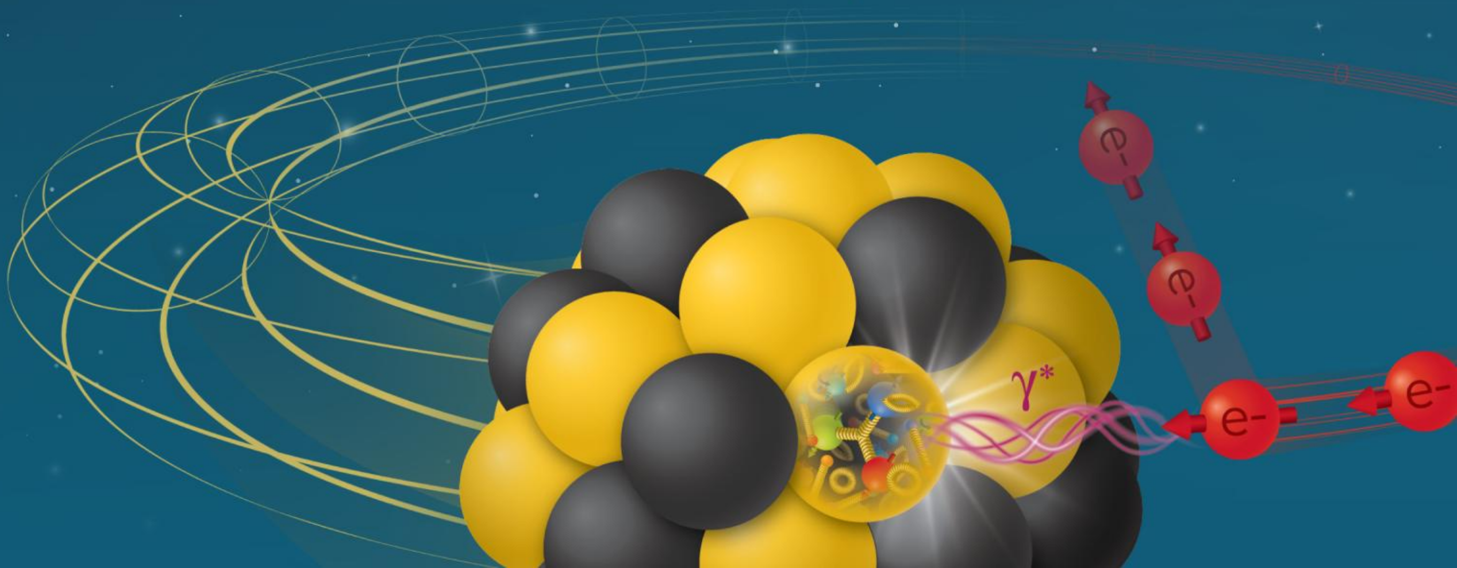
Based on the work by many! Errors my own.

ePIC Collaboration Meeting

Brookhaven National Laboratory

January 21, 2026

Electron-Ion Collider

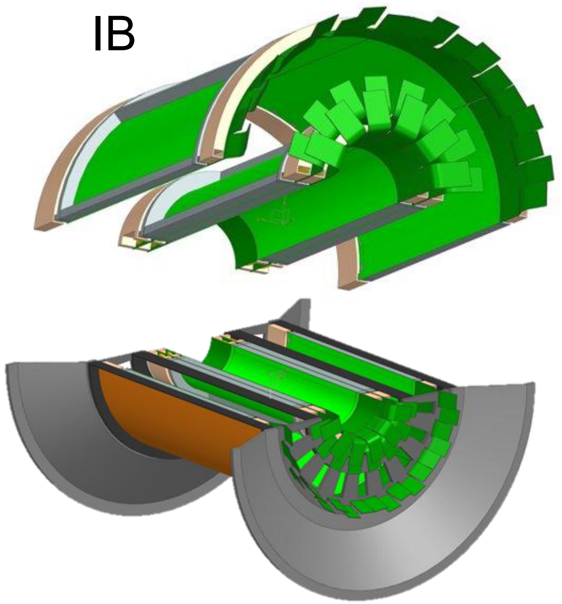


Outline

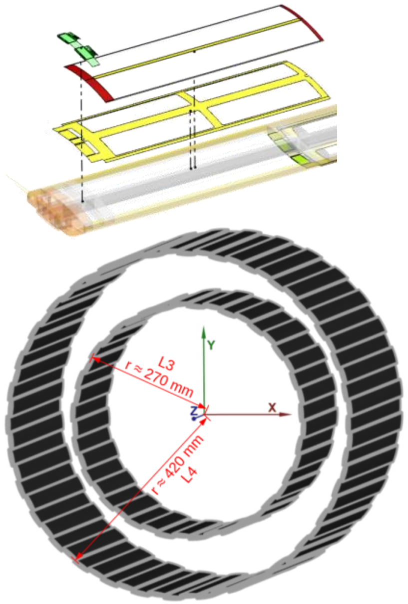
- Introduction
- Power dissipation
- Cooling
  - Air cooling of sensitive layers, disks
  - Humidity management
  - Liquid cooling of RDOs
- Summary

Silicon Vertex Tracker – SVT

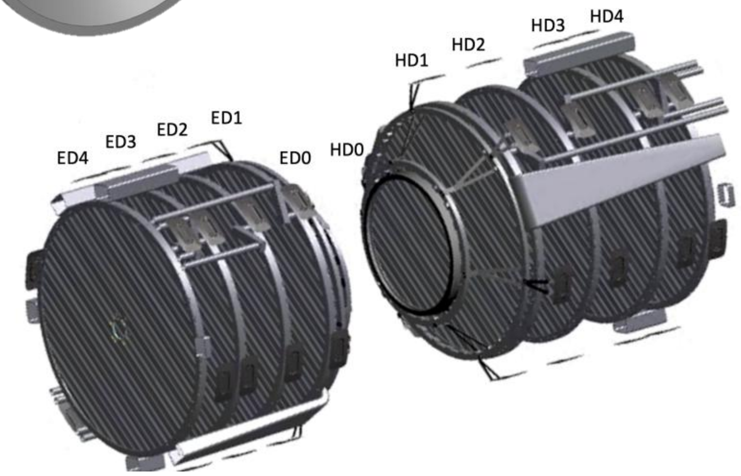
IB



OB



Disks



- SVT is the innermost subsystem of the ePIC central detector,
- Most or all of us will have seen various visualizations, but as a reminder:
- **Barrel**
  - **Inner Barrel (L0, L1, L2 Layers):** Curved, thinned, wafer-scale ITS3 sensors, called MOSAIX
  - **Outer Barrel (L3-L4 Layers):** based on EIC Large Area Sensor (LAS), which is derived from MOSAIX with a focus on large-area coverage in layers and disks (formfactor, yield, etc.)
- **Endcap**
  - 5 Hadron Disk (HD0-4) and 5 Lepton Disks (ED0-4) with EIC-LAS Sensors
- Overall dimensions r ~ 0.4 m, l ~ 2.2 m.

Outer Barrel and Disks – Schematic Layout

ePIC SVT - disk and barrel power and readout architecture
Sichtermann, Glover, Silber

Rev	Date	Author	Description
v1	2025-10-09	Joe Silber (LBNL)	imported original diagram from Ernst, added details on sizes, counts, and connection interfaces
v2	2025-10-15	Joe Silber (LBNL)	visual cleanup, approx dims on furcation tubes, power wire pairs, and CB-FIB ribbon
v3	2025-10-16	Joe Silber (LBNL)	incorporated comments from Nikki on barrel vs disk variations; made MFPC and bridge connections more visually clear
v4	2025-12-16	Joe Silber (LBNL)	Added ref links

Nomenclature

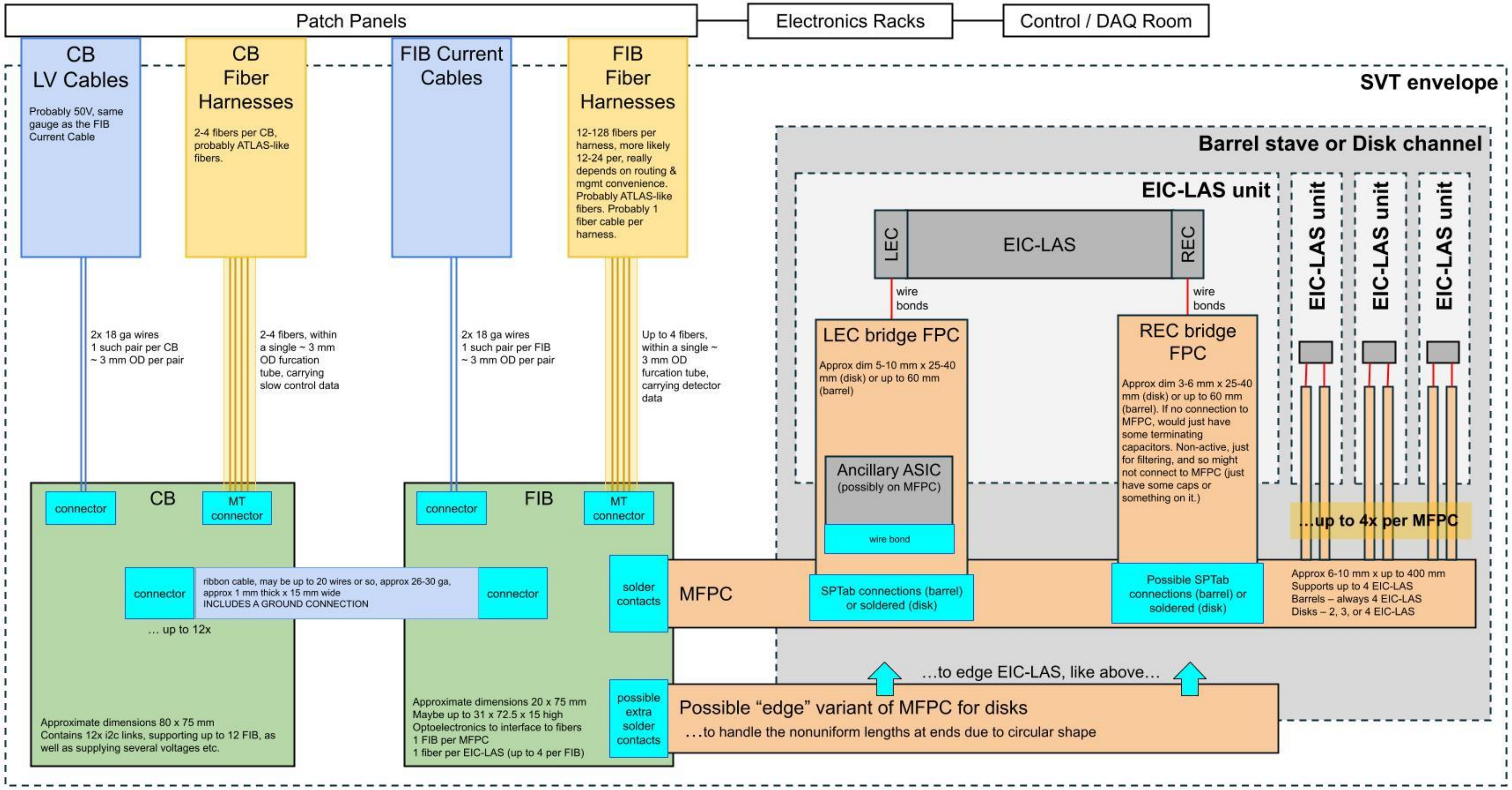
FPC … Flexible Printed Circuit
CB … Control Board
FIB … FPC Interface Board
LV … Low Voltage
MFPC … Main FPC
BFPC … Bridge FPC
SPTab … bonded overlapping Al/Kapton

Notes

1. Not to scale.
2. Color-coding consistency not guaranteed.

References

1. Live editable version of this document
2. module drawing from Nikki 2025-08-22

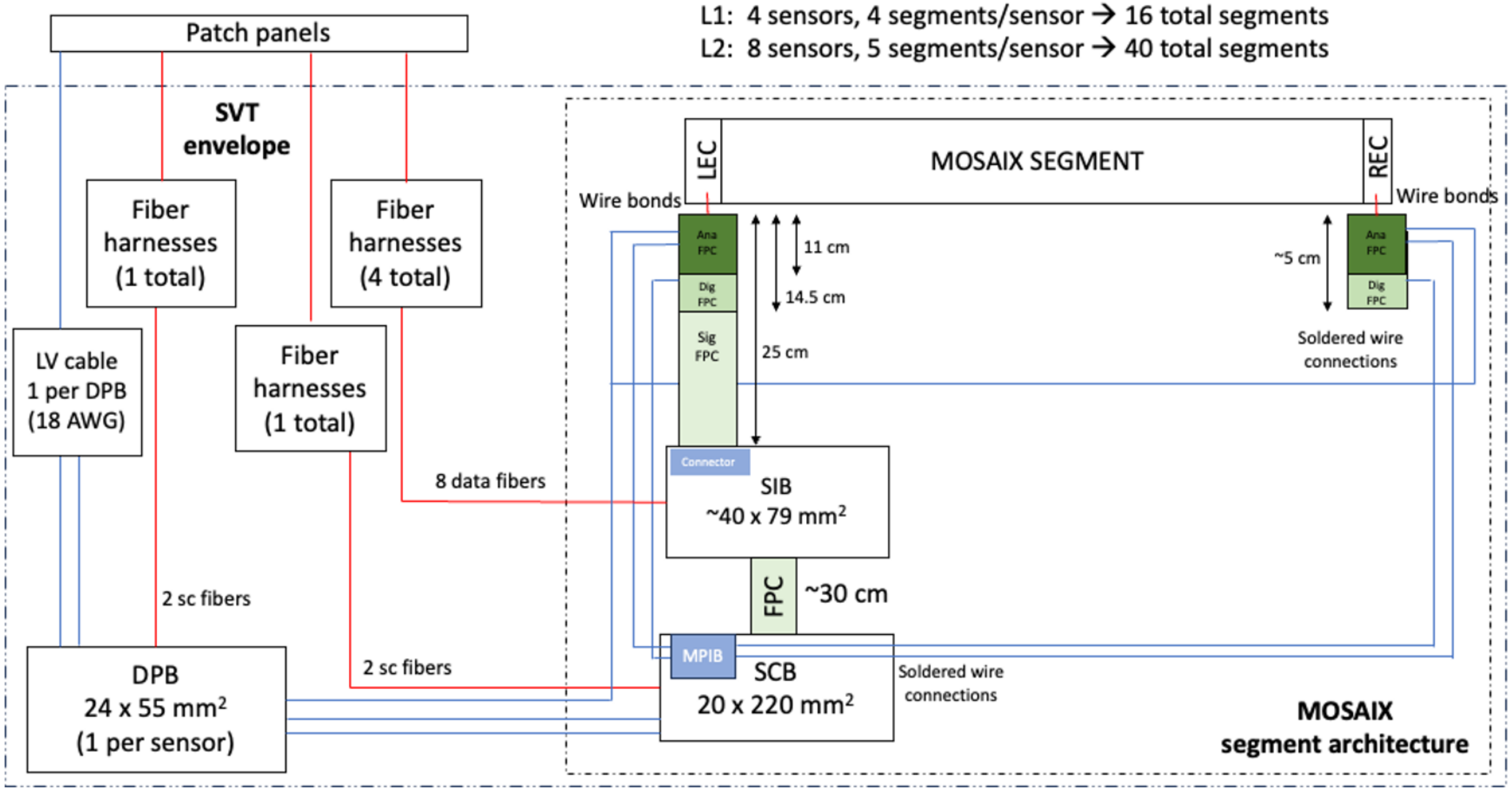


Power dissipators in envelope: **sensor** and ancillary ASIC, FPCs (resistive), FIBs (VTRx+), FIB-CBs.

Inner Barrel – Schematic Layout

IB Connections
NA - Version 2, 11/5/25

L0: 4 sensors, 3 segments/sensor → 12 total segments
L1: 4 sensors, 4 segments/sensor → 16 total segments
L2: 8 sensors, 5 segments/sensor → 40 total segments



DPB: Detector Power Board
SCB: Segment Control Board
SIB: Segment Interface Board

Fiber harness: up to 144 fibers

Power and Cooling

- Power dissipation driven by the sensor(s),
- Sensors continue to be developed,
- We know quite a bit and use up-to-date insights with conservative assumptions, but power dissipation is not and cannot now be final.

Power Analysis Overview

- **Actual case (160MHz)**: Revised estimates
  - **EIC-LAS: Total Power**
    - The most recent revised power estimates show a 1.3x improvement.
    - Applying a slower clock (40MHz) to the tiles could significantly reduce power dissipation (further analysis ongoing).

Supply	Voltage	RSU Power (mW)	LEC Power (mW)	EIC-LAS Power (mW)	RSU Power (mW)	LEC Power (mW)	EIC-LAS Power (mW)
GAVDD	1,32	36,96	0	221,76	59,4	0	356,4
GDVDD	1,32	106,932	68,805	710,397	145,086	81,246	951,762
GSVDD	1,32	2,112	25,08	37,752	3,168	35,772	54,78
TXVDD	1,2	0	66	66	0	91,2	91,2
Total Power		146,004	159,885	1035,909			1454,142
AncASIC (+35%)				1398,47715			1963,0917
AncASIC (+45%)				1502,06805			2108,5059

TYP: 1.3x improvement

MAX: 1.2x improvement

Total Power	168,432	371,76	1382,352			1791,18
AncASIC (+35%)			1866,1752			2418,093
AncASIC (+45%)			2004,4104			2597,211

Conservative values currently in use

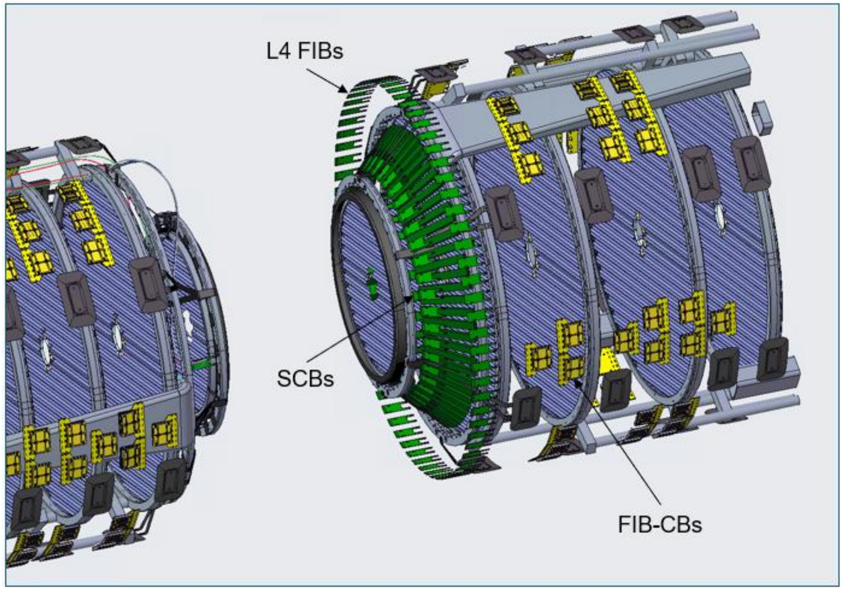
ePIC SVT DSC meeting (Sept 2025)

Electron-Ion Collider
ePIC SVT PDR2, January 27 and 28, 2026 João de Melo 20

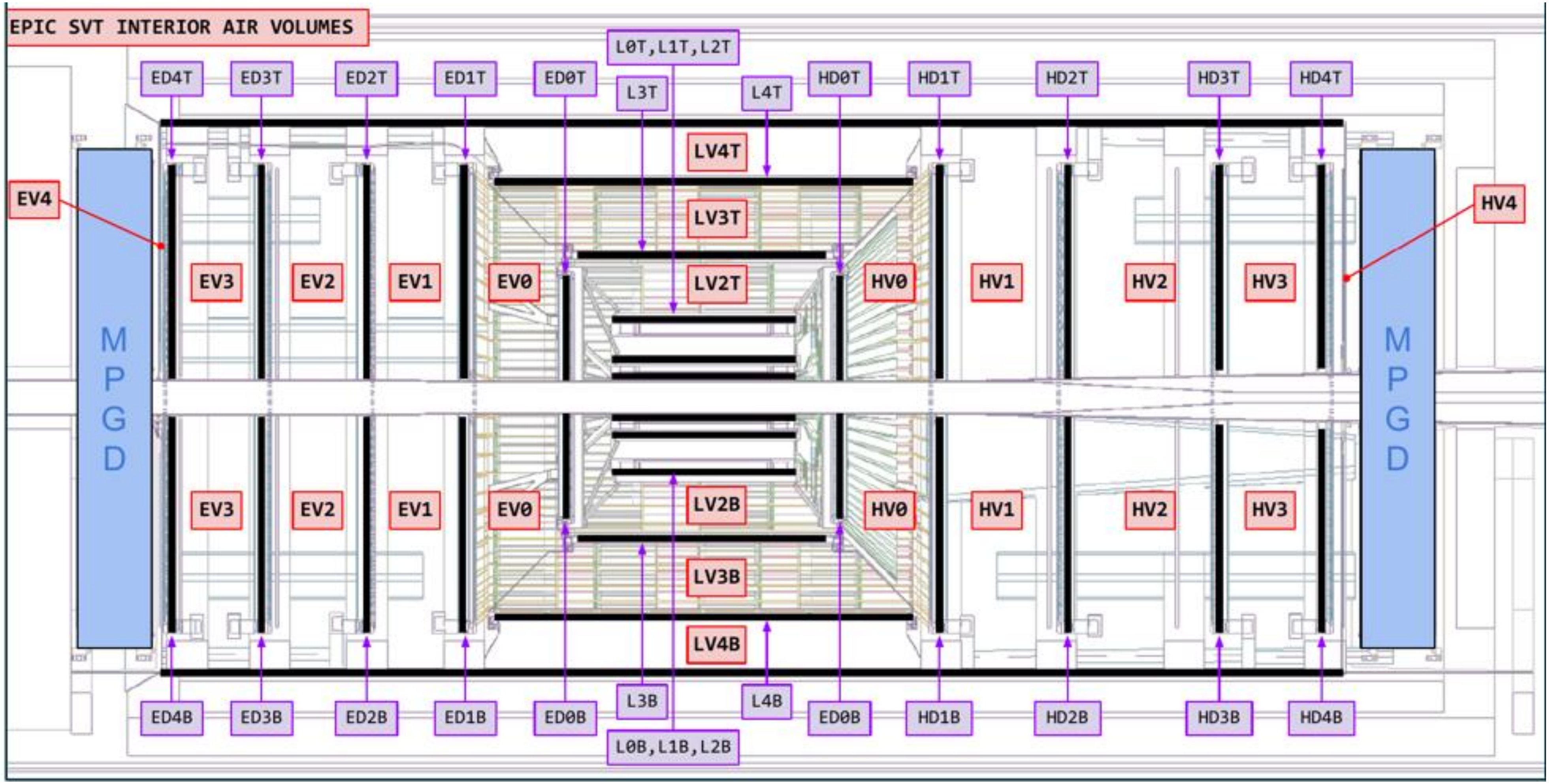
Power and Cooling

- Air cooling of sensitive areas,
  - Required for innermost barrel and disk layers to meet resolutions,
  - Uniformity of design,
- Liquid cooling of RDOs – grouped layout,
- 5.9 (9.3) kW – typical (max) dissipation of sensors, ancillary ASIC, FPCs
- 1.2 kW – RDOs

	Total air-cooled power/system [W]	
	typical	max
L0	30	37
L1	40	50
L2	101	124
L3	514	776
L4	1545	2442
Disks	3670	5819
Total power [kW]	5.90	9.25



Cooling – geometrical air volumes



Cooling – Schematic layout air cooling

ePIC SVT - cooling system diagram

Rev	Date	Author	Description
v1	2025-12-11	Joe Silber (LBNL)	initial release
v2	2025-12-12	Joe Silber (LBNL)	add liquid system
v3	2025-12-16	Joe Silber (LBNL)	space out e-/hadron & top/bottom

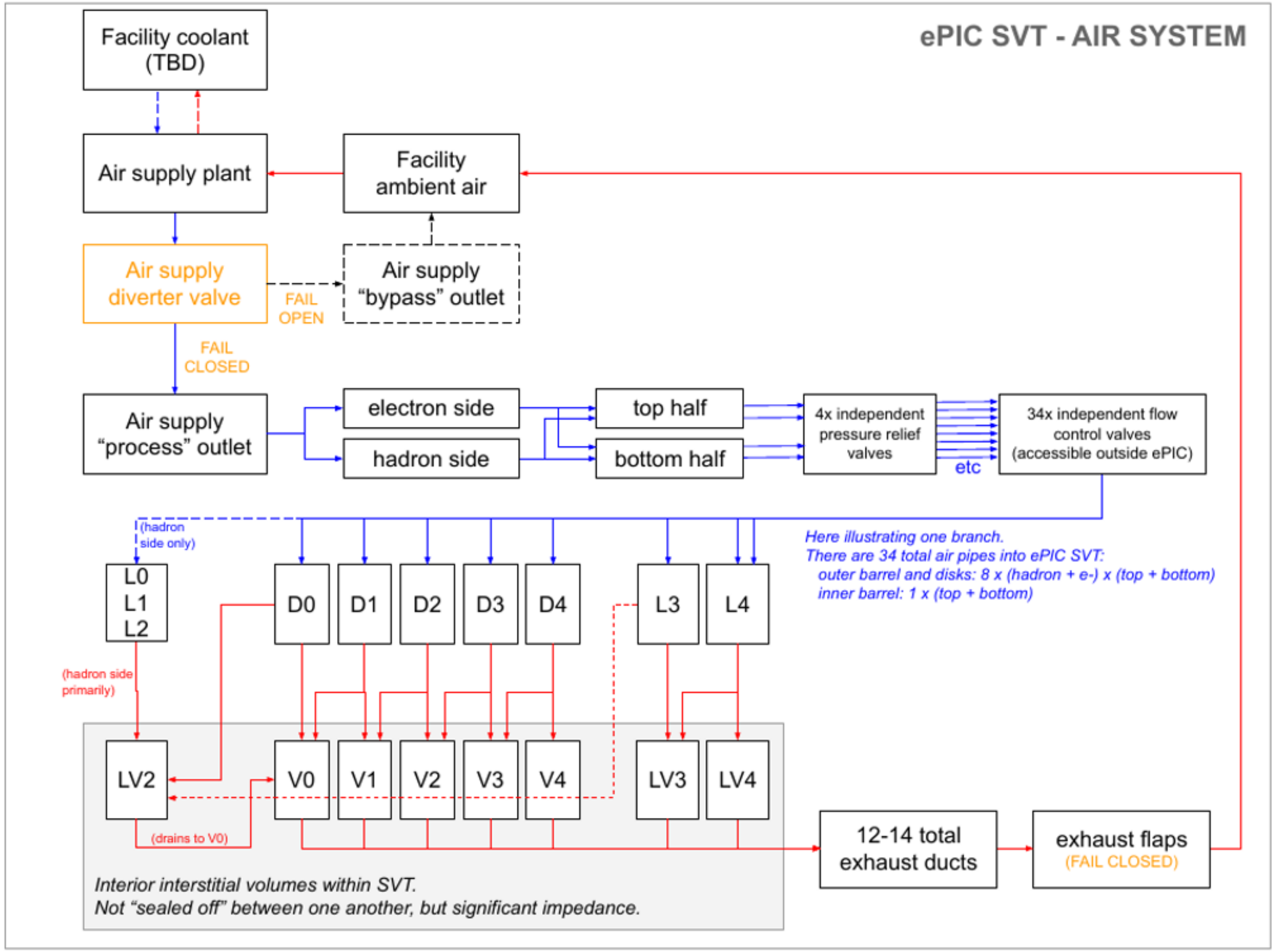
Nomenclature

SVT … Silicon Vertex Tracker
TBD … To Be Determined
L# … Barrel layer IDs
D# … Disk IDs
V# … Disk interstitial volume IDs
LV# … Barrel layer interstitial volume IDs
SCB … Segment Control Board
CB … Control Board

Notes

1. Graphical elements not intended to follow any standard.
2. Color-coding consistency not guaranteed.

Link:
ePIC SVT cooling system diagram - v3.pdf



Cooling – Approach

High level requirements

Table 9.2: SVT component temperature requirements (N/S is not specified).

Requirement	LEC	RSU	REC	AncASIC
Maximum T [°C]	65	40	N/S	80
Maximum T variation [°C]	10	1 over 3 mm 10 over full length	N/S	10

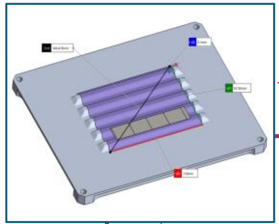
Req't on Tmax

informs ΔT, ΔP, air speed

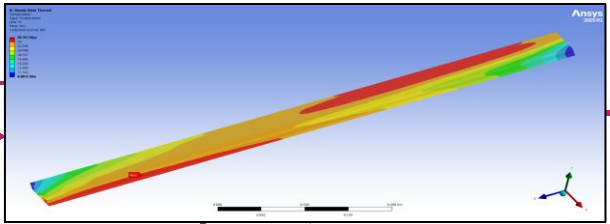
End-to-end system performance calculation

stage description	-	-	source --> ePIC	branches to hadron + electron sides	branches to top + bottom halves	pipes into ePIC to half disks and half barrels	pipes within SVT to half disks and half barrels	manifold	disk channels and staves	SVT internal ambient volumes	exhaust ducts
stage index	-	-	0	1	2	3	4	5	6	7	8
num channels (per parent channel)	n_i	-	1	2	2	8	1	1	22.2	0.0169	1
total num channels in system	N_i = product(n_i)	m	1	2	4	32	32	32	710	12	12
mass flow per channel	$\dot{m}$ = ($\dot{m}_s$ or previous stage $\dot{m}$) / n_i	kg/s	0.950	0.475	0.238	0.030	0.030	0.030	0.001	0.079	0.079
length	L	m	10.000	10.000	15.000	7.000	3.000	0.100	0.635	0.433	10.000
hydraulic diameter (mm)	D_mm	mm	100	75	50	23	23	23	11.5	713.8	61.6
hydraulic diameter	D	m	0.100	0.075	0.050	0.023	0.023	0.023	0.012	0.714	0.062
single channel cross-sectional area along length L	$A_{12} = \pi D^2 / 4$	m²	7.85E-03	4.42E-03	1.96E-03	4.15E-04	4.15E-04	4.15E-04	1.04E-04	4.00E-01	2.98E-03
all channels total cross-sectional area	$\Sigma A_{12} = A_{12,i} * N_i$	m²	7.85E-03	8.84E-03	7.85E-03	1.33E-02	1.33E-02	1.33E-02	7.40E-02	4.80E+00	3.58E-02
"	"	cm²	78.5	88.4	78.5	133.0	133.0	133.0	739.6	48,024.7	357.6
entrance temperature	$T_1 = T_s$ or previous stage T_3	K	276.0	276.32	275.59	277.01	276.80	276.68	278.12	287.54	287.32
"	"	°C	2.8	3.2	2.4	3.9	3.7	3.5	5.0	14.4	14.2
entrance pressure	$P_1 = P_s$ or previous stage P_3	Pa	142,654	139,043	132,457	117,849	108,409	104,014	104,437	104,325	103,929
"	"	bar	1.427	1.390	1.325	1.178	1.084	1.040	1.044	1.043	1.039
entrance density (ideal gas law)	$\rho_1 = P_1 / (R * T_1)$	kg/m³	1.801	1.753	1.675	1.482	1.365	1.310	1.308	1.264	1.260
entrance dynamic viscosity	$\mu_1 = \mu_0 * (T_1/T_0)$^0.76	Pa*s	1.73E-05	1.73E-05	1.73E-05	1.73E-05	1.73E-05	1.73E-05	1.74E-05	1.78E-05	1.78E-05
Reynold's number	Re = 4 $\dot{m}$ / (π D μ_1)	-	6.99E+05	4.66E+05	3.50E+05	9.48E+04	9.48E+04	9.48E+04	8.50E+03	7.91E+03	9.18E+04
friction factor (Blasius)	f = 64/Re, Re < 2300 = 0.316/Re^0.25 otherwise	-	0.011	0.012	0.013	0.018	0.018	0.018	0.033	0.034	0.018
friction pressure drop (Darcy-Weisbach)	$\Delta P_{12} = -f * (L/D) * \dot{m}^2 / (2\ \rho_1\ A_{12}^2)$	Pa	-4,438	-5,317	-17,025	-9,440	-4,394	-153	-114	0	-825
downstream pressure	$P_2 = P_1 + \Delta P_{12}$	Pa	138,216	133,727	115,432	108,409	104,014	103,862	104,323	104,325	103,104
"	"	bar	1.382	1.337	1.154	1.084	1.040	1.039	1.043	1.043	1.031
ambient pressure in the downstream area of this stage	P_local_ambient	bar	1.013	1.013	1.013	1.043	1.043	1.043	1.043	1.043	1.013
downstream pressure relative to local ambient	description(P_2 - P_local_ambient)	-	positive	positive	positive	positive	approx neutral	approx neutral	approx neutral	approx neutral	positive
module power input to stream	Q = Qc * N_i if channel or stave else 0	W	0.0	0.0	0.0	0.0	0.0	0.0	8943.9	0.0	0.0

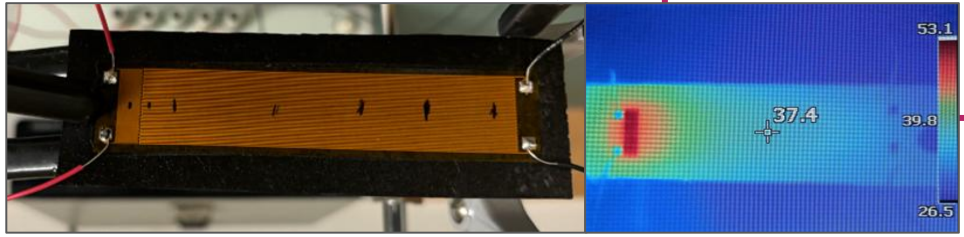
CAD design



Local supports heat transfer analysis



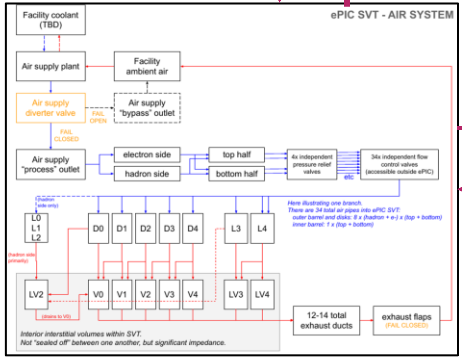
Local supports physical test



System architecture

Temperatures, pressures, flow rates

System layout



Operational logic

Detailed specs on cooling plant

ID	Category	Description	Name	Value (SI)	Units (SI)
00	process air	temperature - nominal	T_nom	3	°C
01	output air	temperature - adjustment range - min	T_min	-5	°C
02	output air	temperature - adjustment range - max	T_max	30	°C
03	output air	temperature - stability about setpoint	T_stability	±2	°C
04	output air	pressure dew point - max allowable	PDP_max_allow	-10	°C
05	output air	pressure dew point - stability	PDP_stability	±2	°C
06	output air	pressure dew point - setpoint adjustment	PDP setpoint	Pressure dew point shall defined by the AQ_water PDP_max_allow (at high	
07	output air	pressure - nominal	P_nom	0.44	bar (gauge)
08	output air	pressure - adjustment range - min	P_min	0.03	bar (gauge)
09	output air	pressure - adjustment range - max	P_max	0.75	bar (gauge)
10	output air	pressure - stability about setpoint	P_stability	±0.02	bar (gauge)
11	output air	mass flow rate - nominal	ṁ_nom	1.0	kg/s
12	output air	mass flow rate - adjustment range - min	ṁ_min	0.1	kg/s
13	output air	mass flow rate - adjustment range - max	ṁ_max	1.5	kg/s
14	output air	density - nominal	ρ_nom	1.82	kg/m³
15	output air	density - min	ρ_min	1.18	kg/m³

Cooling – Air

Cooling system performance baseline

- source temperature = 2.8°C
- total mass flow = 0.95 kg/s
- total volume flow = 1135 cfm @ source pressure, 1604 cfm @ exhaust
- source pressure = 1.43 bar → 1.03 bar positive pressure @ exhaust
- channel/stave entrance temperature = 5.0°C
- channel/stave air speed = 10.0 m/s
- total power extracted = 8.9 kW
- SVT internal ambient temperature = 14.4°C

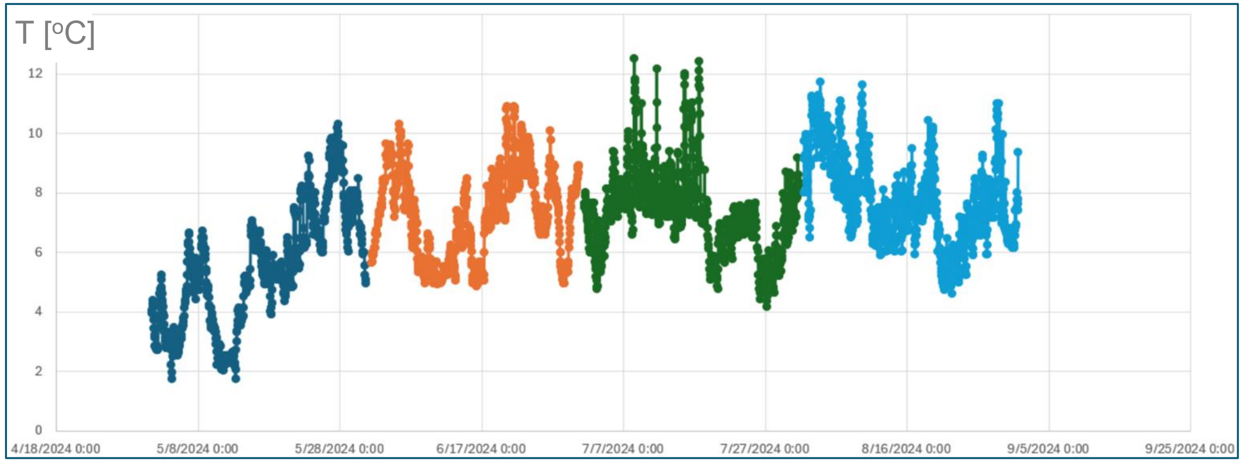
	A	B	C	D	E	F	G	H	I	J	K	L
150	stage description	-	-	*source --> ePIC*	*branches to hadron + electron sides*	*branches to top + bottom halves*	*pipes into ePIC to half disks and half barrels*	*pipes within SVT to half disks and half barrels*	*manifold*	*disk channels and staves*	*SVT internal ambient volumes*	*exhaust ducts*
151	stage index	-	-	0	1	2	3	4	5	6	7	8
152	num channels (per parent channel)	n_i	-	1	2	2	8	1	1	22.2	0.0169	1
153	total num channels in system	N_i = product(n_i)	m	1	2	4	32	32	32	710	12	12
154	mass flow per channel	$\dot{m} = (\dot{m}_s$ or previous stage $\dot{m}) / n_i$	kg/s	0.950	0.475	0.238	0.030	0.030	0.030	0.001	0.079	0.079
155	length	L	m	10.000	10.000	15.000	7.000	3.000	0.100	0.635	0.433	10.000
156	hydraulic diameter (mm)	D_mm	mm	100	75	50	23	23	23	11.5	713.8	61.6
158	single channel cross-sectional area along length L	$A_{12} = \pi D^2 / 4$	m^2	7.85E-03	4.42E-03	1.96E-03	4.15E-04	4.15E-04	4.15E-04	1.04E-04	4.00E-01	2.98E-03
160	all channels total cross-sectional area	$\Sigma A_{12} = A_{12,i} * N_i$	cm^2	78.5	88.4	78.5	133.0	133.0	133.0	739.6	48,024.7	357.6
162	entrance temperature	$T_1 = T_s$ or previous stage T_3	°C	**2.8**	**3.2**	**2.4**	**3.9**	**3.7**	**3.5**	**5.0**	**14.4**	**14.2**
164	entrance pressure	$P_1 = P_s$ or previous stage P_3	bar	**1.427**	1.390	1.325	1.178	1.084	1.040	1.044	1.043	1.039
167	Reynold's number	$Re = 4 \dot{m} / (\pi D \mu_1)$	-	6.99E+05	4.66E+05	3.50E+05	9.48E+04	9.48E+04	9.48E+04	8.50E+03	7.91E+03	9.18E+04
169	friction pressure drop (Darcy-Weisbach)	$\Delta P_{12} = -f * (L/D) * \dot{m}^2 / (2 \rho_1 A_{12}^2)$	Pa	-4,438	-5,317	-17,025	-9,440	-4,394	-153	-114	0	-825
171	downstream pressure	$P_2 = P_1 + \Delta P_{12}$	bar	1.382	1.337	1.154	1.084	1.040	1.039	1.043	1.043	1.031
172	ambient pressure in the downstream area of this stage	P_local_ambient	bar	1.013	1.013	1.013	1.043	1.043	1.043	1.043	1.043	1.013
173	downstream pressure relative to local ambient	description(P_2 - P_local_ambient)	-	positive	positive	positive	positive	approx neutral	approx neutral	approx neutral	approx neutral	positive
174	module power input to stream	$Q = Qc * N_i$ if channel or stave else 0	W	0.0	0.0	0.0	0.0	0.0	0.0	**8943.9**	0.0	0.0
175	stream temperature rise due to external heat input	$\Delta Tq_{12} = Q / (N_i * \dot{m} * c_p)$	K	0.0	0.0	0.0	0.0	0.0	0.0	9.4	0.0	0.0
181	downstream temperature	$T_2 = T_1 + \Delta Tq_{12} + \Delta Tk_{12}$	°C	**2.7**	**3.0**	**1.6**	**3.7**	**3.5**	**3.5**	**14.3**	**14.4**	**14.2**
185	average volumetric flow	$V_a = \dot{m} / \rho_a$	m^3/s	0.536	0.276	0.151	0.021	0.022	0.023	0.001	0.063	0.063
187	total volumetric flow (all channels)	$\Sigma V_a = V_a * N_i$	m^3/s	0.536	0.552	0.605	0.667	0.710	0.726	0.738	0.751	0.757
188	"	"	cfm	**1134.9**	1170.2	1282.8	1414.1	1505.3	1537.9	1564.8	**1592.3**	1603.5
189	average air speed	$u_a = V_a / A_{12}$	m/s	68.2	62.5	77.1	50.2	53.4	54.6	**10.0**	0.2	21.2
194	pressure ratio calculated with non-choked eqn	$\beta_{3n} = P_{3n} / P_2$	-	**1.006**	**0.993**	**1.028**	**1.000**	**1.000**	**1.018**	**1.001**	**0.997**	**1.003**
195	is choked?	$\beta_{3n} < \beta_x$	boolean	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
214	system energy balance error	$\dot{E}$_err = ($\dot{E}_2 - \Sigma Q_i$) - $\dot{E}_1$_stage0	W	-2	-4	-24	-26	-27	-27	-24	-24	-24
215	system energy balance error fraction (w.r.t. total energy)	$\dot{E}$_err_frac = $\dot{E}$_err / $\dot{E}_1$_stage0	-	-0.001%	-0.002%	-0.009%	-0.010%	-0.010%	-0.010%	-0.009%	-0.009%	-0.009%
216	system energy balance error fraction (w.r.t. total input pov	$\dot{E}$_err_frac = $\dot{E}$_err / ΣQ_i		-0.027%	-0.049%	-0.274%	-0.293%	-0.307%	-0.307%	-0.272%	-0.272%	-0.272%

Cooling – Humidity management

- Humidity must be managed, since cooling air will usually be below the ambient dew point,

- Approach:
  - Supply dried air, class 3 ISO 8573-1:2010 or better,
  - Insulate exterior cold pipes,
  - Interlock SVT operation and divert supply air if supply air conditions are not met, e.g. as the cooling system settles during startup,
  - Interlock SVT operation if ambient conditions are not met, e.g. if WAH HVAC is not operational,
  - Limit backflow and moisture effusion into SVT if air flow shuts down while interior structures are cold.

Dewpoint data May – August 2024, sPHENIX Hall – courtesy Dan Cacace



	A	B	C	D	E	F	G	L
150	stage description	-	-	source --> ePIC	branches to hadron + electron sides	branches to top + bottom halves	pipes into ePIC to half disks and half barrels	exhaust ducts
151	stage index	-	-	0	1	2	3	8
152	num channels (per parent channel)	n_i	-	1	2	2	8	1
153	total num channels in system	N_i = product(n_i)	m	1	2	4	32	12
154	mass flow per channel	$\dot{m} = (\dot{m}_s$ or previous stage $\dot{m}) / n_i$	kg/s	0.950	0.475	0.238	0.030	0.079
155	length	L	m	10.000	10.000	15.000	7.000	10.000
156	hydraulic diameter (mm)	D_mm	mm	100	75	50	23	61.6
219	is exterior? (fully or partially)	-	boolean	1	1	1	1	1
221	min temperature this stage	Tmin = min(T_1, T_2)	°C	2.7	3.0	1.6	3.7	14.2
222	air stream temperature relative to the local dewpoint	ΔTd = Tmin - select(Td)	°C	-10.3	-10.0	-11.4	-9.3	1.2
223	temperature difference needing insulation	ΔTinsul = abs(min(0, ΔT_insul))	°C	10.3	10.0	11.4	9.3	0.0
224	temperature diff from a condensating surface to local ambient	ΔTcond2amb = select(Tamb) - select(Td)	°C	22.0	22.0	22.0	22.0	22.0
225	iterative thickness calc intermediate value	λ = k * ΔTinsul / (h_insul * ΔTcond2amb)	mm	1.9	1.8	2.1	1.7	0.0
226	insulation minimum outside diameter (neglects pipe wall)	Dmin_insul = 2 * λ / ln(D_insul / D)	mm	104.4	80.6	54.0	26.2	67.8
227	insulation minimum thickness (no margin)	tmin_insul	mm	2.2	2.8	2.0	1.6	3.1
228	insulation design thickness	t_insul = t_design_factor * tmin_insul	mm	**4.4**	**5.6**	**4.0**	**3.2**	**6.2**
229	pipe + insulation outer diameter (pipe wall neglected)	D_total_no_wall	mm	**108.8**	**86.1**	**58.0**	**29.4**	**73.9**

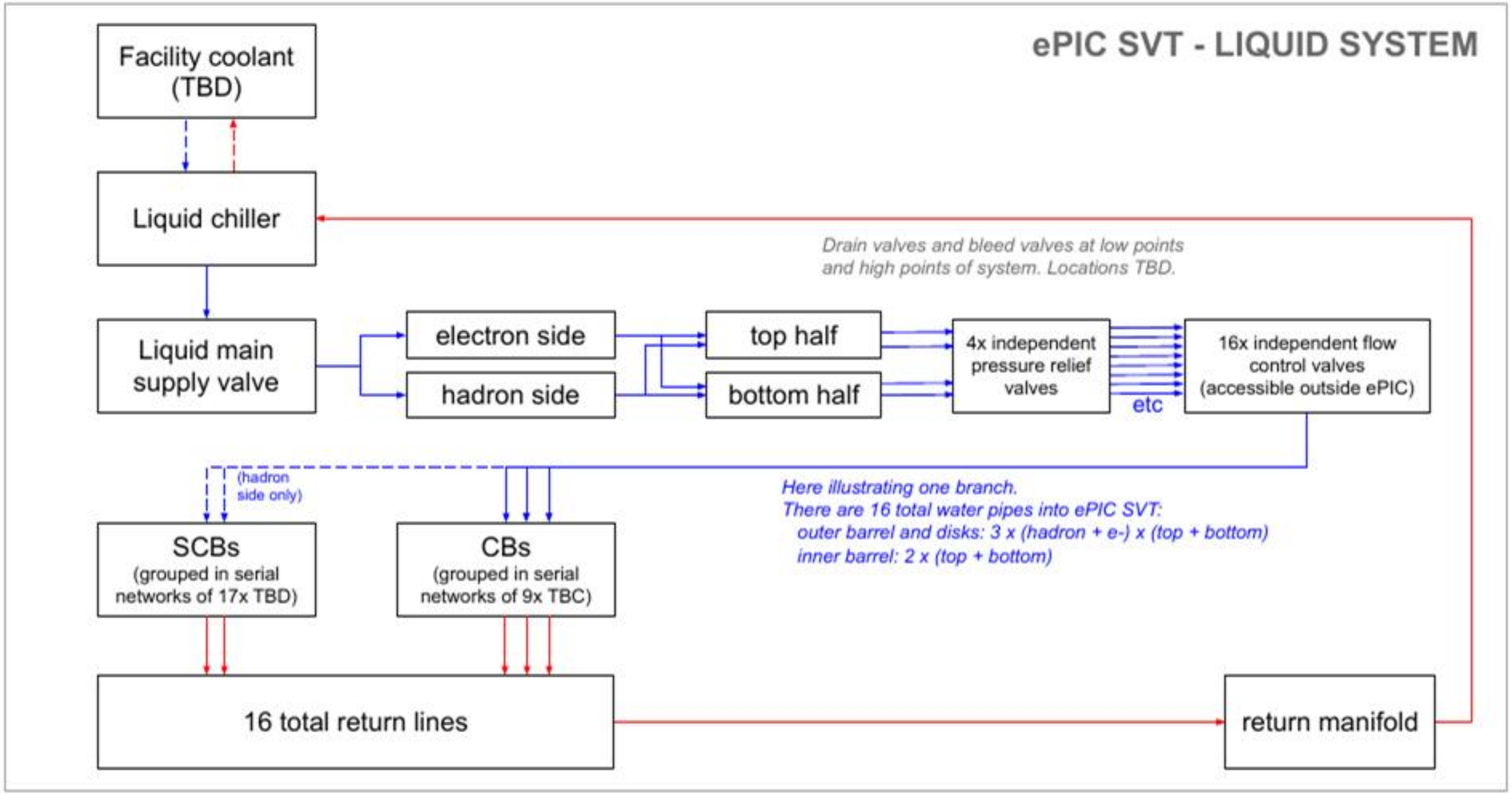
Services

- SVT
  - IB services are primarily in forward region,
  - OB and disk services are evenly split between forward and backward region,
  - Cross section needs for power dominate over signal by an order of magnitude,
  - Power conductor size driven by voltage drop; lower gauge (thicker conductors) between disconnect and racks,
  - **Services include cooling air outlets,** as well as all inlets, and liquid lines.

Backward region

Subsytem	Type	Item	Material	Cable Specifics	Quantity	Diameter (cm)	Cross Area (cm^2)	Notes
Inner Barrel	Power	LV	Multi-Conductor Cable	4 Al conductors, 18AWG	16	0.9	NA	All on the hadron side; none on the electron side
	Signal	Data	144 Fiber Cable		4	0.89	NA	All on the hadron side; none on the electron side;harnesses TBD
	Cooling	cooling	Air		2	2.54	NA	All on the hadron side; none on the electron side
	Cooling	Exhaust	Air				40.54	Preliminary estimate, not subject to packing & misc.
Outer Barrel	Power	LV	Multi-Conductor Cable	4 Al conductors, 18AWG	93	0.9	59.16	
	Signal	Data	144 Fiber Cable		6	0.89	3.73	
	Cooling	cooling	Air		8	2.54	40.54	
	Cooling	Exhaust	Air				162.15	Preliminary estimate, not subject to packing & misc.
Disks	Power	LV	Multi-Conductor Cable	4 Al conductors, 18AWG	185	0.9	117.69	
	Signal	Data	144 Fiber Cable		12	0.89	7.47	
	Cooling	Cooling	Air		10	2.54	50.65	
	Cooling	Exhaust	Air				202.60	Preliminary estimate, not subject to packing & misc.
Outer Barrel / Disks FIB	Signal	Read out Fibers			NA	NA	NA	part of the fiber counts above (OB, disks) insofar external
	Power	Ext Current Source			NA	NA	NA	powered by CB (i.e. internal services, but not external)
	Cooling	cooling	Air / convection		NA	NA	NA	VTRx+ can be cooled convectively per its manual
Outer Barrel / Disks CB	Signal	Slow Control Fibers FIB	144 Fiber Cable		1	0.89	0.62	
	Signal	Slow Control Fibers FPC	144 Fiber Cable		1	0.89	0.62	
	Power	Ext Voltage Source		4 Al conductors, 18AWG	26	0.9	16.54	16 OB control boards, 36 disk control boards
	Cooling	Cooling	Water		28	0.63	8.73	Approx. 1.3 kW to be cooled
Inner Barrel SCB	Signal	Control Fibers	144 Fiber Cable		1	0.89	NA	All on the hadron side; none on the electron side;harnesses TBD
	Cooling	Cooling	Water		4	0.63	NA	All on the hadron side; none on the electron side
Inner Barrel DPB	Signal	Control Fiber	144 Fiber Cable		1	0.89	NA	All on the hadron side; none on the electron side;harnesses TBD
	Power	Bulk Power	Multi-Conductor Cable	4 Al conductors, 18AWG	16	0.9	NA	All on the hadron side; none on the electron side
	Cooling	Cooling	Water		4	0.63	NA	All on the hadron side; none on the electron side
Ground(s)							0.70	Preliminary estimate
Interlocks							4.00	Preliminary estimate; more of a "space allocation"
Environmental sensors							4.00	Preliminary estimate; more of a "space allocation"
						TOTAL X1.5	876.97	Exhaust not 1.5x, only 1.0x

Cooling – Liquid (RDOs)



Mass needs to be minimized within the SVT envelope – “modified chilled water.”

Summary

- SVT cooling
  - based on up-to-date knowledge of continuing sensor and ancillary ASIC development,
  - system design incorporates heat transfer tests and analyses of layers, staves, and disks,
  - plant design and specifications developed, including humidity management,
  - to be done:
    - CFD analyses of the SVT internal volume in its entirety,
    - moisture effusion at close-outs as services are finalized,
    - adjustments, as needed, towards final sensor and ancillary ASIC designs,
    - complete layout in CAD of liquid cooling loops for RDOs (mainly control boards)
    - (incorporate external heat in-/out-flux)