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U.S. DEPARTMENT OF ENERGY
Office of Science

Cooling system design and humidity management

ePIC SVT Working Meeting at Oxford
2025-12-18
Joe Silber (LBNL) - mechanical engineer, presenting
Jaime Cruz Duran (LBNL) and Nick Payne (formerly LBNL) - CFD analyses
Nicole Apadula (LBNL) - thermal tests
Elaine Buron (LBNL) - CAD design

ePIC

gement

High level cooling requirements

From draft Preliminary Design Report (PDR):

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

Design process from high level req'ts to detailed specs

High level requirements

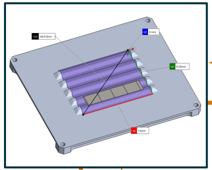
Table 9.2: SVT component temperature requirements (N/S is not specified).

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

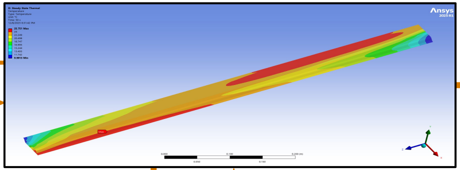
Req't on Tmax

Constraints on ΔT, ΔP, air speed

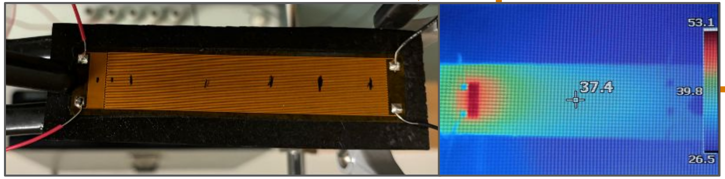
CAD design



Local supports heat transfer analysis



Local supports physical test



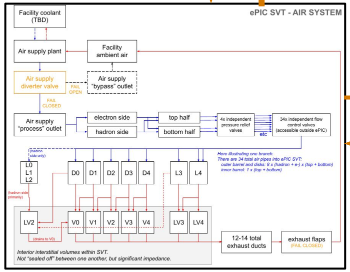
End-to-end system performance calculation

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	$Re = 4 \dot{m} / (\pi D \mu_1)$	-	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
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
stream temperature rise due to external heat input	[illegible]	K	0.0	0.0	0.0	0.0	0.0	0.0	9.4	0.0	0.0

System architecture

Temperatures, pressures, flow rates

System layout

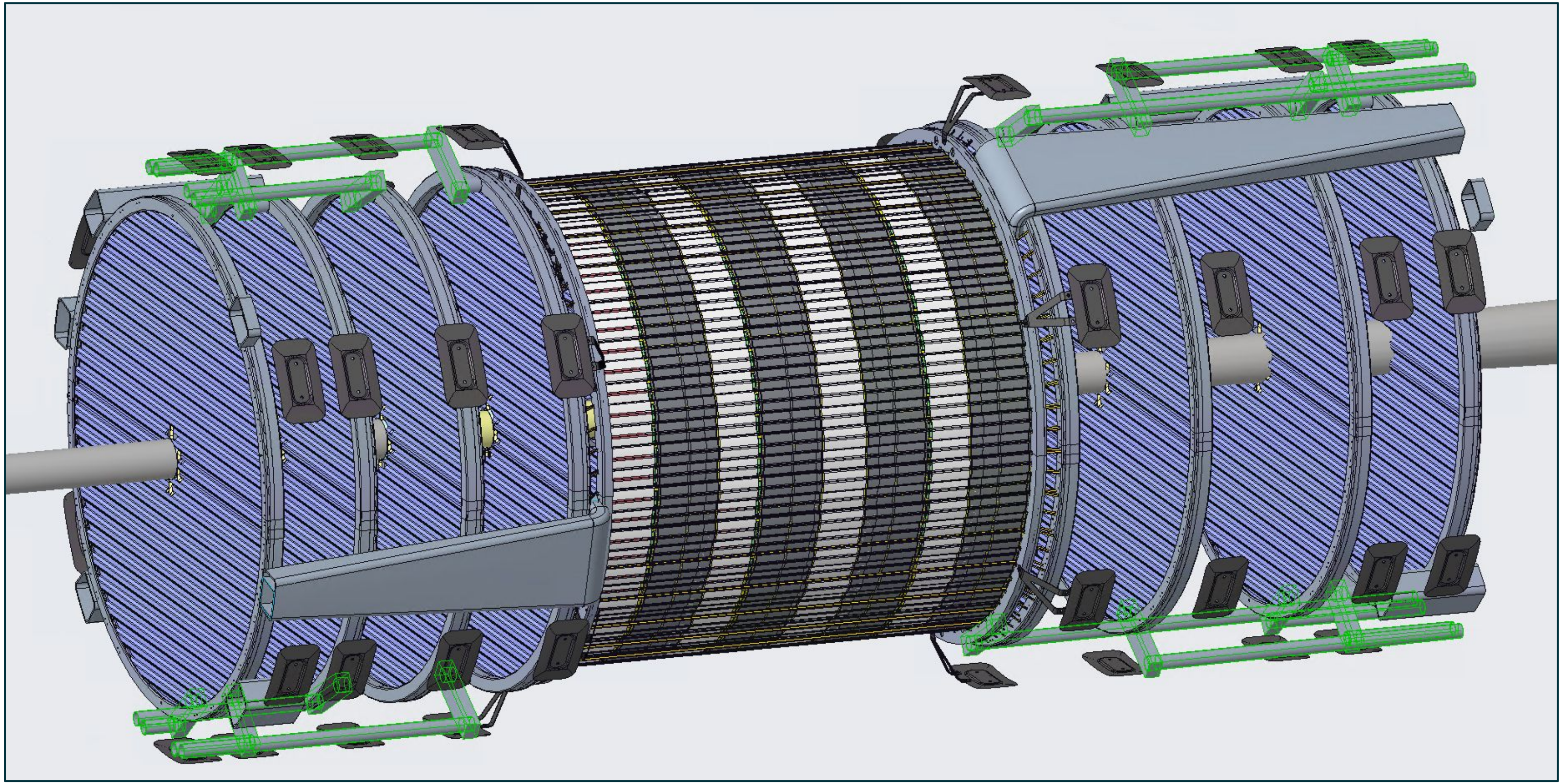


Operational logic

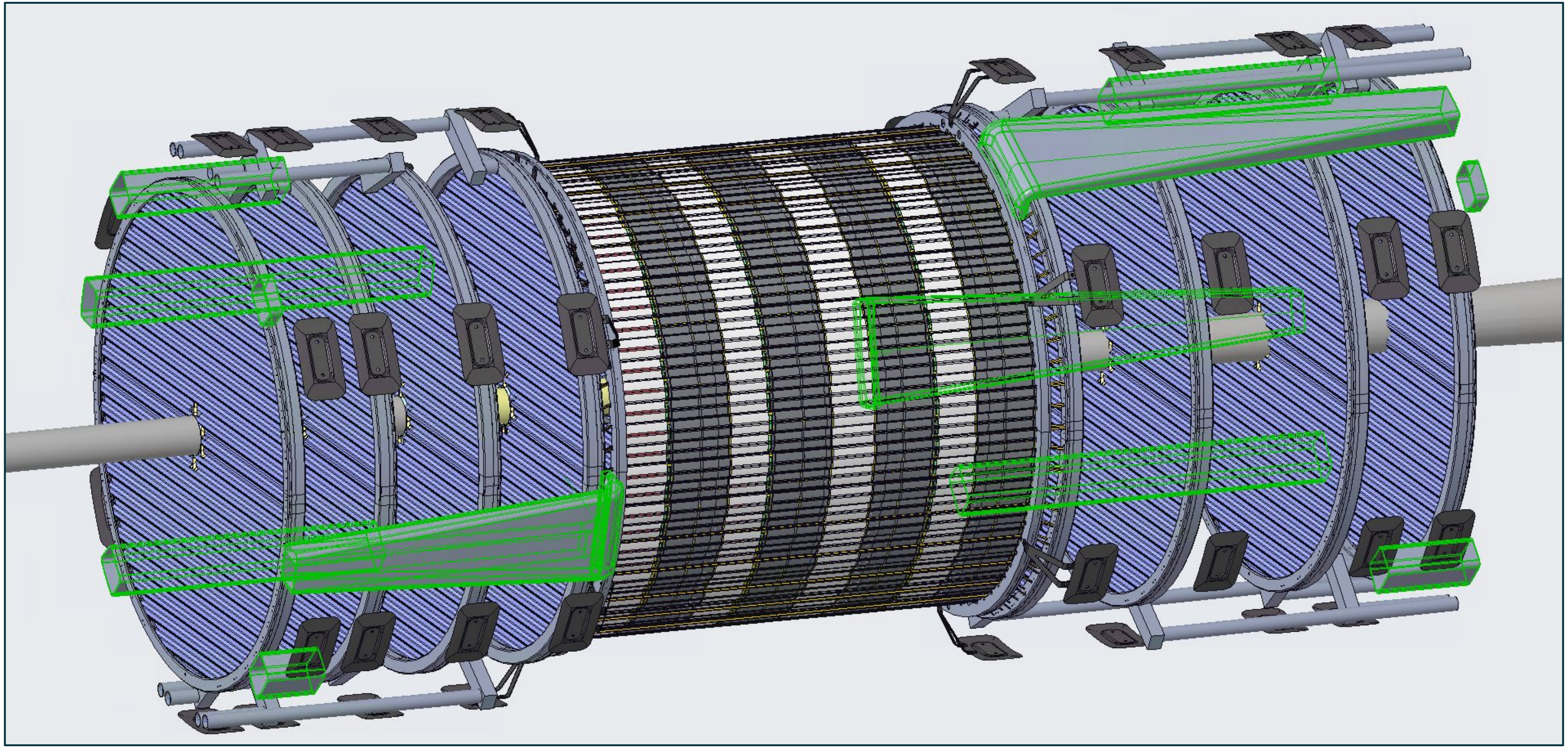
Detailed specs on cooling plant

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

Air supply pipes



Air exhaust ducts



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

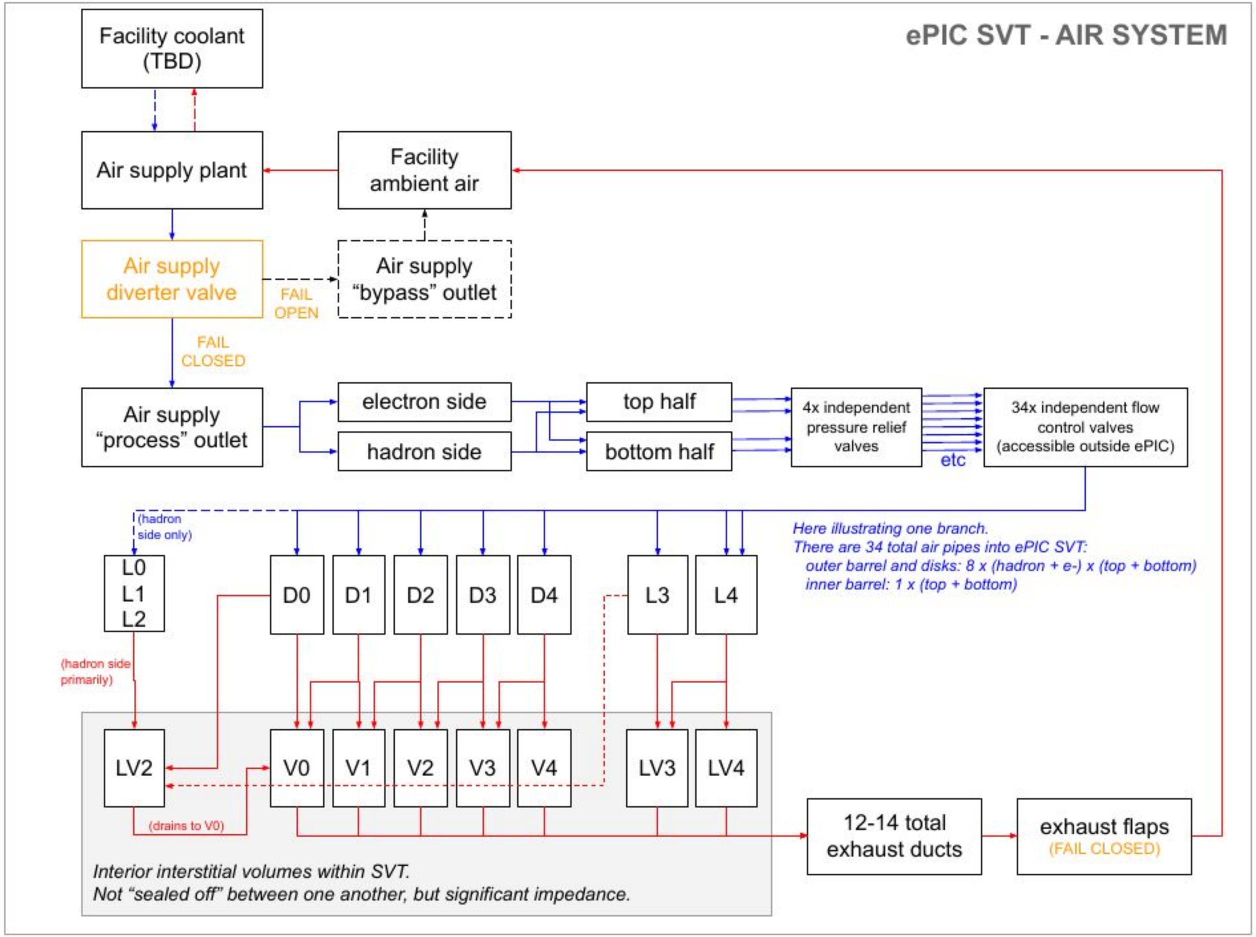
Nomenclature

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



Air exhaust

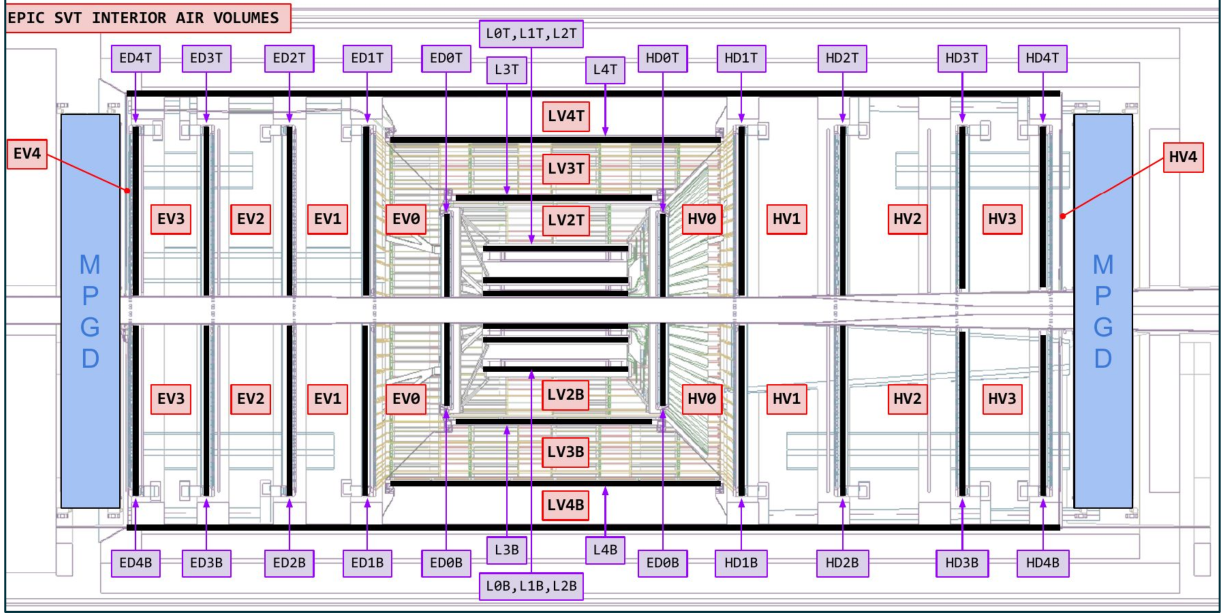
- Exhaust via 12-14 ducts
- Duct hydraulic ∅62 mm
  - I.e. much greater cross-section than input pipes (4 x ∅50 mm)
- Ducts draw from interior volumes (see diagram)
- These volumes aren't "sealed" from each other, but significant impedance
- Suction could be done but probably not necessary
- Flapper valves at outlets to prevent ingress when flow off

ePIC SVT - interior air volumes diagram

Rev	Date	Author	Description
v1	2025-12-11	Joe Silber (LBNL)	initial release

Notes
1.

References
1. Live editable version of this document
2. ePIC SVT cooling system diagram
3. ePIC SVT cooling air flow stages



Link: ePIC SVT interior air volumes diagram - v1.pdf

System calculator inputs: local supports geometry

	A	B	C	D	E	F	G
51	***Disk geometry***						
52	corrugation pitch	xc	mm	34.7			
53	corrugation height	hc	mm	6			
54	corrugation cross-sectional area	Ac ~ xc * hc / 2	mm²	104.1			
55	corrugation hydraulic diameter	Dc = √(4 Ac / π)	mm	**11.5**			
56	large disk diameter (D1-D4)	Dd14	mm	870			
57	small disk diameter (D0)	Dd0	mm	488			
58	num large disks (per side)	nd14	-	4			
59	num small disks (per side)	nd0	-	1			
60	avg disk diameter (areally weighted)	Dd = √((Dd14²*nd14+Dd0²*nd0)/(nd14+nd0))	mm	808.2			
61	avg large disk corrugation length	Lc14 ~ π / 4 * Dd14	mm	683.3			
62	avg small disk corrugation length	Lc0 ~ π / 4 * Dd0	mm	383.3			
63	avg corrugation length	Lc ~ π / 4 * Dd	mm	**634.7**			
64	avg num corrugations (per half disk)	ncd ~ (Dd/2) / (xc/2)	-	23.3	<-- non-integer is ok, it's averaging large and small disks		
65							
66	***Layers geometry***						
67	stave channel width (this is one side)	ws	mm	20.65			
68	stave channel height at edge	hs1	mm	2.92			
69	stave channel height at center	hs2	mm	7.49			
70	stave channel avg height	hs = (hs1 + hs2)/2	mm	5.2			
71	stave channel cross-sectional area	As ~ ws * hs	mm²	107.5			
72	stave channel hydraulic diameter	Ds = √(4 As / π)	mm	11.7			
73	variation from disk corrug hydraulic diameter	Ds / Dc - 1	-	1.6%	<-- this is pretty similar to disk corrugation hydraulic diameter		
74	L4 stave length	Ls4	mm	793			
75	L3 stave length	Ls3	mm	503			
76	num L4 staves (per top/bottom half)	ns4	-	35			
77	num L3 staves (per top/bottom half)	ns3	-	22			
78	avg stave channel length	Ls = (Ls4*ns4+Ls3*ns3)/(ns4+ns3)	mm	681.1			
79	variation from disk corrug avg length	Ls / Lc - 1	-	7.3%	<-- this is pretty similar to disk average corrugation length		
80	Note: given geometric similarity of average barrel staves to average disk corrugation channels, I treat them all as basically the same in flow calcs below.						
81	num half disks equivalent to an OB half	nds_equiv = Ls * (ns4 + ns3) / (Lc * nc)		**2.6**	<-- non-integer is ok, it's averaging lots of things		

System calculator inputs: internal volumes and exhaust

	A	B	C	D
89	***SVT internal volume geometry***			
90	approx percent of internal volume which is ambient air	vf_amb	-	90%
91	PST diameter	D_pst	mm	1076
92	PST length	L_pst	mm	2540
93	SVT total internal ambient air volume	v_svt = vf_amb * π/4 * D_pst² * L_pst	mm³	2.08E+09
94	number of internal ambient air subvolumes	n_v	-	12
95	average SVT internal subvolume's volume	v_{va} = v_svt / n_v	mm³	1.73E+08
96	num subvolumes between large disks	n_{vl}	-	6
97	typical gap between large disks	g_{vl}	mm	423.2
98	rough equiv hydraulic diameter between large disks	D_{vl} = √(4 / π * D_pst * g_{vl})	mm	761.4
99	L4 diameter	D_L4	mm	840
100	L3 diameter	D_L3	mm	540
101	rough equiv hydraulic diameter outside L4	Dh_L4 = √(D_pst² - D_L4²)	mm	672.4
102	rough equiv hydraulic diameter between L3/L4	Dh_L34 = √(D_L4² - D_L3²)	mm	643.4
103	average SVT internal subvolume's hydraulic diameter	D_{va} = (n_{vl} * D_{vl} + D_L3 + Dh_L34 + Dh_L4) / (n_v	mm	**713.8**
104	average SVT internal subvolume's length	L_{va} = v_{va} / (π/4 * D_{va}^2)	mm	**432.8**
105				
106	***Exhaust duct geometry***			
107	exhaust duct width	w_{ex}	mm	55
108	exhaust duct height	h_{ex}	mm	70
109	exhaust duct cross-sectional area	A_{ex} = w_{ex} * h_{ex}	mm²	3850
110	exhaust duct perimeter	P_{ex} = 2 * (w_{ex} + h_{ex})	mm	250
111	exhaust duct hydraulic diameter	D_{ex} = 4 A_{ex} / P_{ex}	mm	61.6
112	number of exhaust ducts per internal ambient subvolume	n_{ex}	-	1

System calculator inputs: module power loads

	A	B	C	D	E	F	G
114	***Module power loads***						
115	reference link for power loads	Copy of EIC-LAS Power - 2025-10-22	*Also see adjoining sheet where RSUs are counted in an alternate way.*				
116	power per LEC	Q_1lec	W	0.208			
117	power per RSU	Q_1rsu	W	0.208			
118	typical num RSU per module	n_rsu_per_mod	-	5.652	<-- average, calculated on adjoining sheet		
119	typical EIC-LAS power	Q_eiclas = n_rsu_per_mod * Q_1rsu + Q_1lec	W	1.38			
120	AncASIC power multiple of EIC-LAS	qf_aa	-	45%			
121	typical power per AncASIC	Q_1aa = qf_aa * Q_eiclas	W	0.62			
122	FPC power multiple of EIC-LAS	qf_fpc	-	30%			
123	typical power per FPC	Q_1fpc = qf_fpc * Q_eiclas	W	0.42			
124	length per RSU	L_rsu	mm	21.6			
125	num rsu per avg corrug length (exact coverage)	n_rsu = Lc / L_rsu	-	29.4	<-- non-integer is ok, it's averaging stuff		
126	num modules per avg corrug length	n_mod = n_rsu / n_rsu_per_mod	-	5.2			
127	total RSU power per avg corrug	Qc_rsu = Q_1rsu * n_rsu	W	6.11			
128	total LEC power per avg corrug	Qc_lec = Q_1lec * n_mod	W	1.08			
129	total AncASIC power per avg corrug	Qc_aa = Q_1aa * n_mod	W	3.24			
130	total FPC power per avg corrug	Qc_fpc = Q_1fpc * n_mod	W	2.16			
131	total power per avg corrug	Qc = Qc_rsu + Qc_lec + Qc_aa + Qc_fpc	W	**12.59**			
132	total power per avg module	Q_mod = Qc / n_mod	W	2.42	<-- cross-check this against others' current-best-estimates		
133	total modules modeled below	n_mod_system = L_4 * N_4 * n_mod	-	3693.8	<-- cross-check this against others' current-best-estimates		

System calculator inputs: boundary conditions

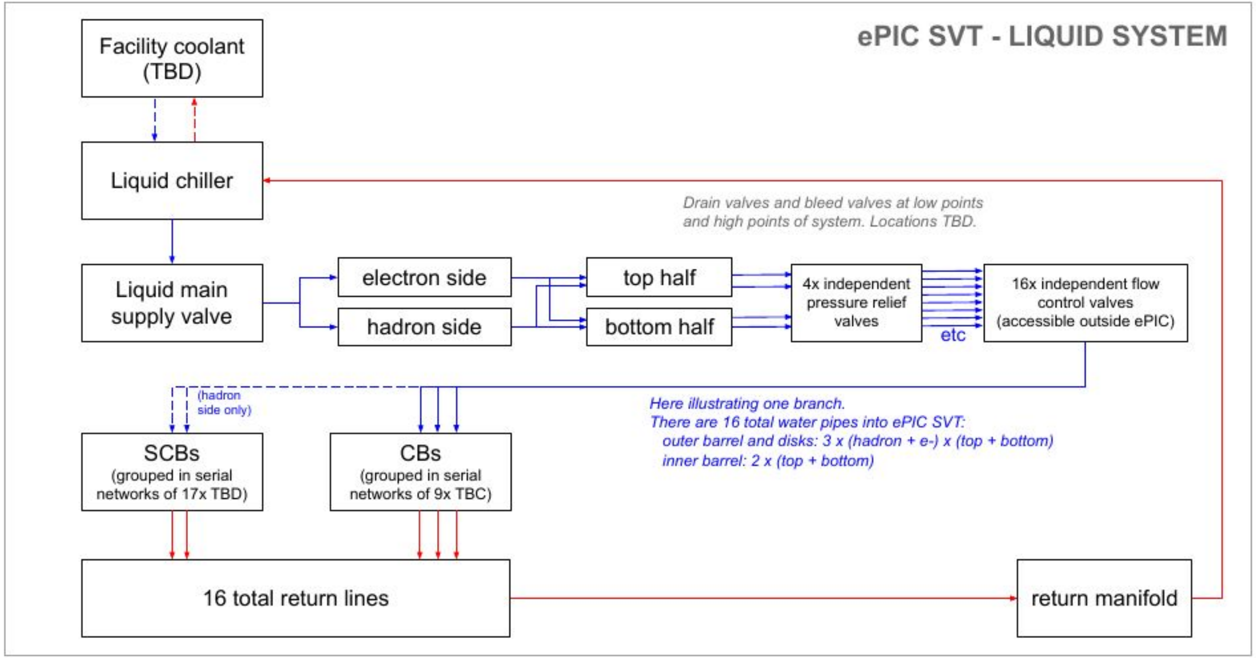
	A	B	C	D	E	F	G
135	***Boundary conditions***						
136	source temperature	T_s	°C	2.8	276.0	K	
137	source pressure	P_s	bar	1.427	0.413	bar (gauge)	Iteratively solved
138	"	"	Pa	142,654	41,329	Pa (gauge)	
139	"	"	psi	20.7	6.0	psi (gauge)	
140	source mass flow rate	$\dot{m}_s$	kg/s	0.95			
141	SVT internal ambient volume's positive pressurization	ΔP_+	bar (gauge)	0.03	must be >= 0		
142	"	"	in H_2O (gauge)	12.0			
143	SVT internal ambient volume's pressure	P_β	bar	**1.043**	must be >= 1.01325 (external atmospheric)		
144	"	"	atm	1.030			

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

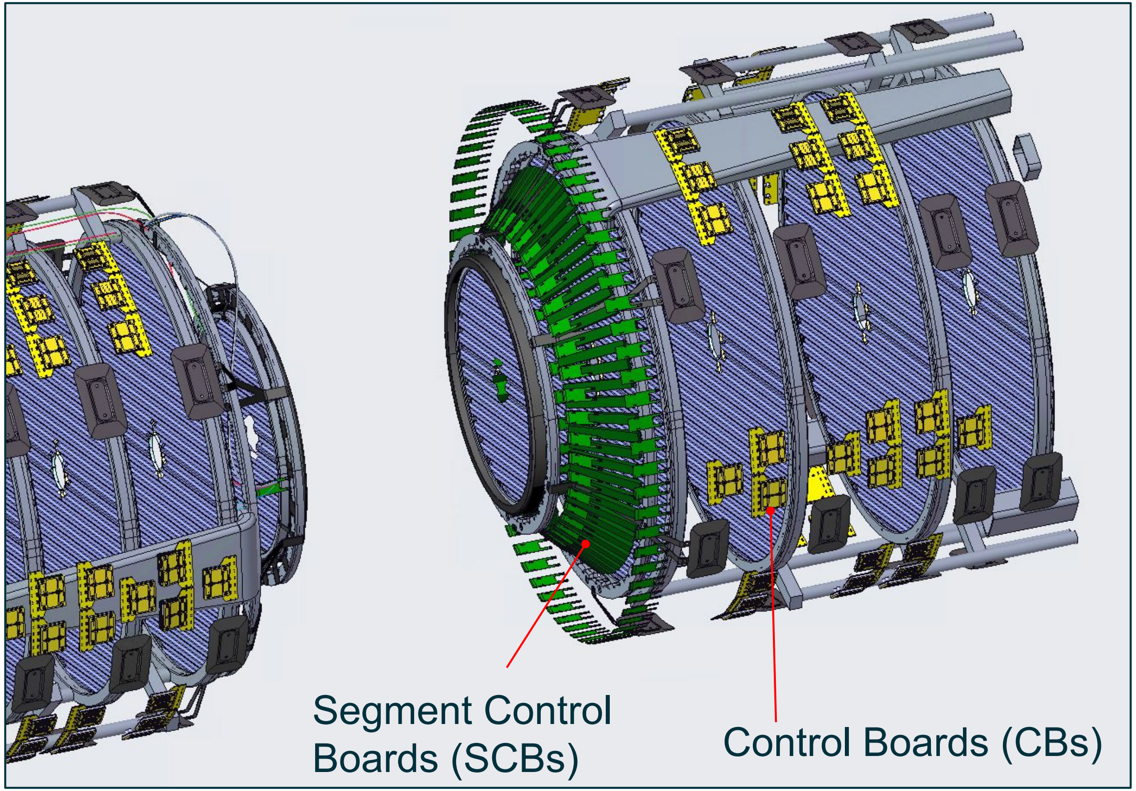
	A	B	C	D	E	F	G	H	I	J	K	L
150	stage description	-	-	*source --> ePIC*	*branches to hadron + electron sides*	*branches to top + bottom halves*	*pipes into ePIC to half disks and half barrels*	*pipes within SVT to half disks and half barrels*	*manifold*	*disk channels and staves*	*SVT internal ambient volumes*	*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	$N_i = \text{product}(n_i)$	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	$A_{12} = \pi D^2 / 4$	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
160	all channels total cross-sectional area	$\Sigma A_{12} = A_{12,i} * N_i$	cm²	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	$V_a = \dot{m} / \rho_a$	m³/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)	$\Sigma V_a = V_a * N_i$	m³/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%

Link: ePIC SVT cooling air flow stages - v15.xlsx


ePIC SVT - LIQUID SYSTEM
Facility coolant (TBD)
Liquid chiller
Drain valves and bleed valves at low points and high points of system. Locations TBD.
Liquid main supply valve
electron side
hadron side
top half
bottom half
4x independent pressure relief valves
etc
16x independent flow control valves (accessible outside ePIC)
(hadron side only)
Here illustrating one branch.
There are 16 total water pipes into ePIC SVT:
outer barrel and disks: 3 x (hadron + e-) x (top + bottom)
inner barrel: 2 x (top + bottom)
SCBs (grouped in serial networks of 17x TBD)
CBs (grouped in serial networks of 9x TBC)
16 total return lines
return manifold

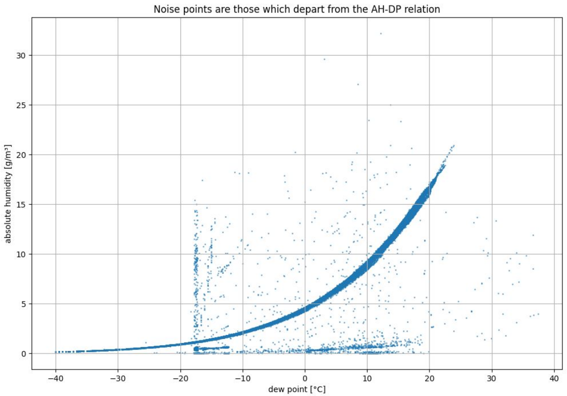
Liquid cooling of CBs and SCBs

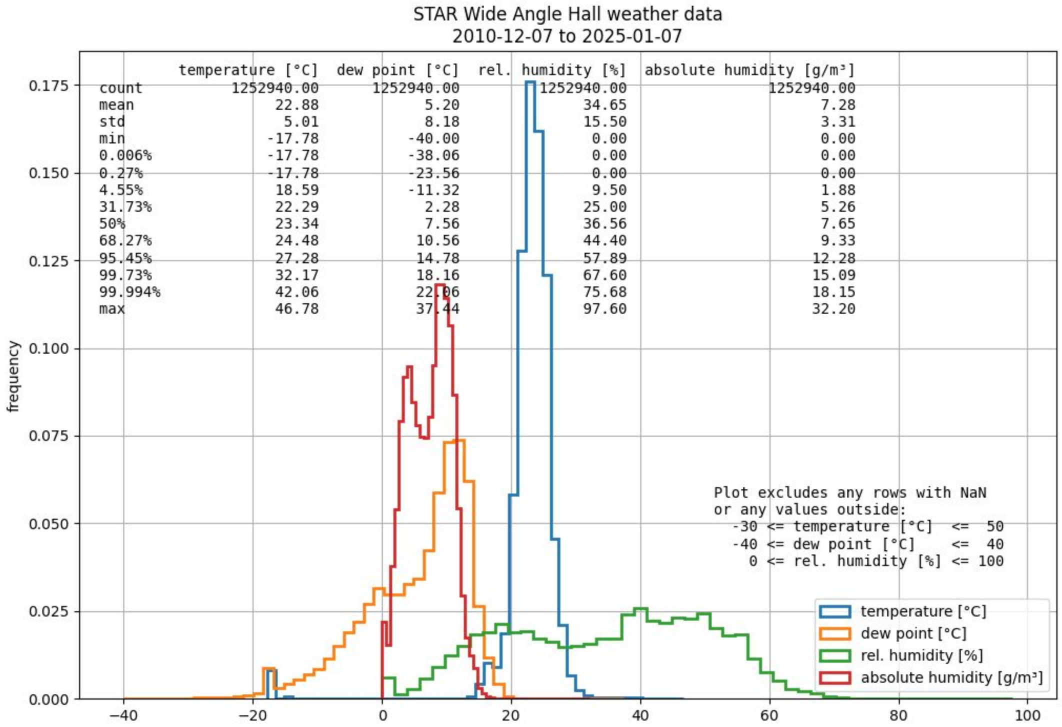
- Current thought is to group CBs into serial cooling chains of ~9x
  - i.e. 12x such networks
  - assemble and test a network outside detector, prior to assembly
  - still working on patterning
  - might make sense to unify multiple CBs into fewer cold plates
- And group SCBs into networks of 17x
- Very much a work in progress



STAR WAH environmental data over 14 years

- extreme hot/wet condition:
  - **dew point ~ 22.1 C**
  - **ambient temp ~ 35.0 C**
- Some noise in the WAH data
- Especially early in time history
- But I'm pretty confident the hot/wet condition stated above was a real event – see abs humidity vs dew point (these are physically correlated)





System calculator inputs: humidity and insulation

	A	B	C	D	E
39	**Insulation properties, boundary conditions, and assumptions**				
40	insulation material thermal conductivity	k_insul	W/(m*K)	0.02	<-- 0.05 for typical insulation wraps, ATLAS uses silica aerogel ~ 0.02 W/(m*K)
41	"	"	US R-value @ 1"	7.2	
42	insulation thickness design factor	t_design_factor	-	2.0	
43	typical convection coefficient outside insulation	h_insul	W/(m^2 * K)	5.0	
44	exterior hot/wet dew point	Td_humid	°C	22.1	4σ (99.994% envelope) value in WAH data 2010-2025
45	exterior hot/wet temperature	Tamb_humid	°C	35.0	corresponding ambient temperature in WAH data 2010-2025
46	SVT interior average air temperature	Tamb_svt	°C	14.4	from calculations below
47	air supply relative humidity	RH_supply	%	30%	
48	SVT interior dewpoint calc intermediate term	y_svt = ln(RH_supply * exp((17.62 * T_amb_svt) / (243.12 + T_amb_svt)))	-	-0.2192	using Magnus model
49	SVT interior dew point	Td_svt = (243.12 * y) / (17.62 - y)	°C	-3.0	assuming 100% displacement of by supply (i.e. supply input >> moist air back flow or effusion from outside ambient)

This assumed -3°C dew point value is used to size the insulation (next slide). It assumes an HVAC-like supply (30% RH). I expect it will end up being quite conservative because we more likely will buy a compressed air system with Class 2 (-40°C) or Class 3 (-20°C) pressure dew point.

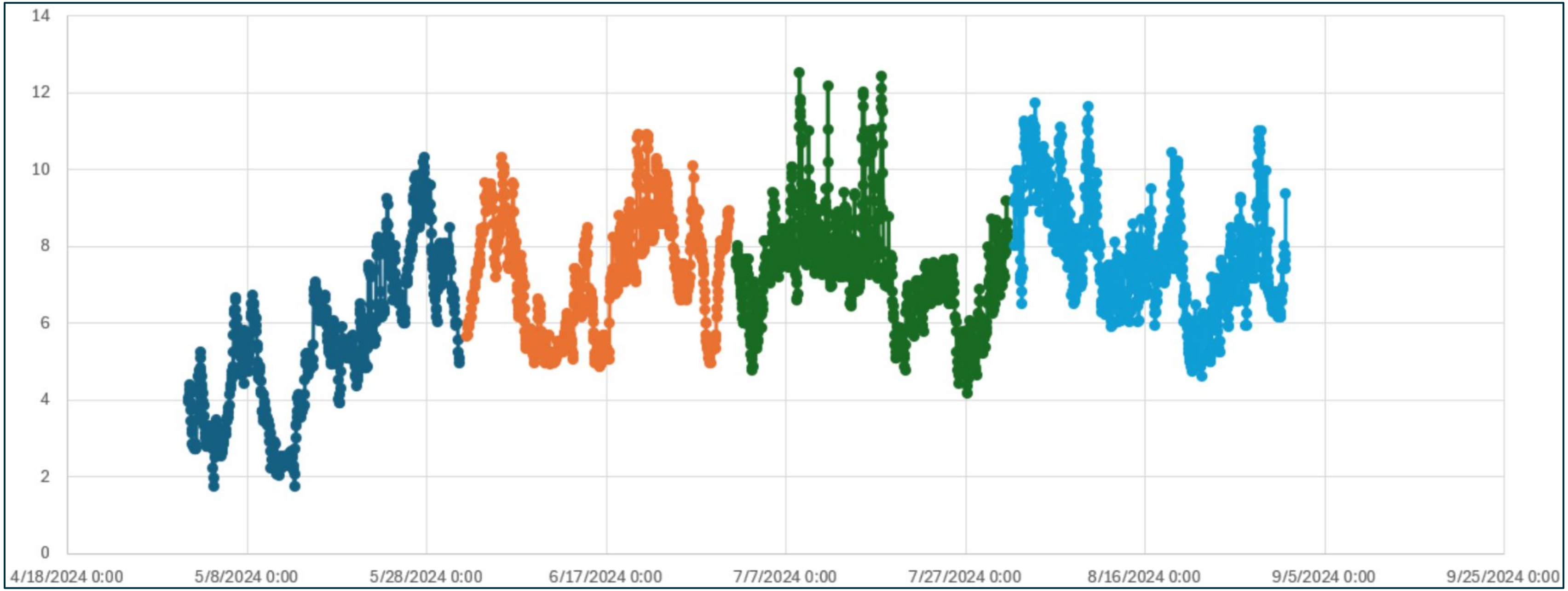
Baseline calculations of insulation thickness

	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
219	is exterior? (fully or partially)	-	boolean	1	1	1	1	0	0	0	n/a	1
221	min temperature this stage	Tmin = min(T_1, T_2)	°C	2.7	3.0	1.6	3.7	3.5	3.5	5.0	-	14.2
222	air stream temperature relative to the local dewpoint	ΔTd = Tmin - select(Td)	°C	-19.4	-19.1	-20.5	-18.4	6.5	6.5	8.0	-	-7.9
223	temperature difference needing insulation	ΔTinsul = abs(min(0, ΔT_insul))	°C	19.4	19.1	20.5	18.4	0.0	0.0	0.0	-	7.9
224	temperature diff from a condensating surface to local ambient	ΔTcond2amb = select(Tamb) - select(Td)	°C	12.9	12.9	12.9	12.9	17.4	17.4	17.4	-	12.9
225	iterative thickness calc intermediate value	λ = k * ΔTinsul / (h_insul * ΔTcond2amb)	mm	6.0	5.9	6.4	5.7	0.0	0.0	0.0	-	2.5
226	insulation minimum outside diameter (neglects pipe wall)	Dmin_insul = 2 * λ / ln(D_insul / D)	mm	111.4	86.1	61.5	32.7	23.0	23.0	11.5	-	66.3
227	insulation minimum thickness (no margin)	tmin_insul	mm	5.7	5.5	5.7	4.8	0.0	0.0	0.0	-	2.4
228	insulation design thickness	t_insul = t_design_factor * tmin_insul	mm	**11.4**	**11.1**	**11.5**	**9.7**	**0.0**	**0.0**	**0.0**	-	**4.7**
229	pipe + insulation outer diameter (pipe wall neglected)	D_total_no_wall	mm	**122.9**	**97.1**	**72.9**	**42.3**	**23.0**	**23.0**	**11.5**	-	**71.1**

With respect to either the exterior extreme dew point value (22.1°C) or the interior (-3°C).

This 10 mm thick insulation around the hydraulic ∅23 mm air pipes occurs in the region of uncertain dryness within ePIC but outside SVT. May be challenging to cross-sectional area.

sPHENIX Hall (IR) dewpoint data May-Aug 2024



(courtesy Dan Cacace)

Same insulation calcs as before, but assuming:

1. max exterior dew point in the Wide Angle Hall is 13°C rather than 22.1°
2. interlock stops operation when DP > 13°C (i.e. WAH HVAC goes down)

	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
219	is exterior? (fully or partially)	-	boolean	1	1	1	1	0	0	0	n/a	1
221	min temperature this stage	Tmin = min(T_1, T_2)	°C	2.7	3.0	1.6	3.7	3.5	3.5	5.0	-	14.2
222	air stream temperature relative to the local dewpoint	ΔTd = Tmin - select(Td)	°C	-10.3	-10.0	-11.4	-9.3	6.5	6.5	8.0	-	1.2
223	temperature difference needing insulation	ΔTinsul = abs(min(0, ΔT_insul))	°C	10.3	10.0	11.4	9.3	0.0	0.0	0.0	-	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	17.4	17.4	17.4	-	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	0.0	0.0	-	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	23.0	23.0	11.5	-	67.8
227	insulation minimum thickness (no margin)	tmin_insul	mm	2.2	2.8	2.0	1.6	0.0	0.0	0.0	-	3.1
228	insulation design thickness	t_insul = t_design_factor * tmin_insul	mm	**4.4**	**5.6**	**4.0**	**3.2**	**0.0**	**0.0**	**0.0**	-	**6.2**
229	pipe + insulation outer diameter (pipe wall neglected)	D_total_no_wall	mm	**108.8**	**86.1**	**58.0**	**29.4**	**23.0**	**23.0**	**11.5**	-	**73.9**

Insulation thickness at the entrance pipes is much reduced

Humidity management strategy

- Supply air quality: water content
  - ≤ Class 3 (i.e. -20°C pressure dew point)
  - per ISO 8573-1:2010
- Insulate exterior cold pipes
  - from air supply plant to ePIC: efficiency, good housekeeping
  - from exterior to SVT: prevent condensation on detectors
  - once inside SVT we have guarantees on air dryness
- Interlock if WAH HVAC fails and/or exterior dew point above insulation design value (e.g. 13°C TBC)
- If air flow shuts down while interior structures are cold…
  - must prevent significant backflow into system from exterior
  - i.e. provide high impedance (not an airtight seal) against moisture effusion
    - flapper valves on exhaust duct outlets
    - closeouts elsewhere
- Air supply diverter valve
  - vents air to bypass outlet if fault condition
  - during startup no air flow to SVT until guaranteed dry
  - supply plant can be tested / operated / fixed without running air to SVT

Air quality strategy

- ISO 8573-1:2010 defines compressed air purity classes
- Supply air quality
  - solid particulate: Class 1
  - total oil: Class 1
  - water: ≤ Class 3
- Air supply diverter valve
  - vent supply air to bypass outlet for startup, air quality test, etc
- Additional air filters at manifolds just outside ePIC
  - extra line of defense

CLASS	SOLID/DIRT Particle size 0.1-0.5 µm	0.5-1.0 µm	1.0-5.0 µm	WATER @7 bar/100 psi Pressure Dewpoint		OIL Including vapor
	Maximum number of particles per m³			°C	°F	mg/m³
0	As specified by the equipment user or supplier					
1	≤ 20 000	≤ 400	≤ 10	-70	-94	≤ 0.01
2	≤ 400 000	≤ 6 000	≤ 100	-40	-40	≤ 0.1
3	-	≤ 90 000	≤ 1 000	-20	-4	≤ 1
4	-	-	≤ 10 000	+3	+38	≤ 5
5	-	-	≤ 100 000	+7	+45	> 5
6	-	-	-	+10	+50	-

Source: Atlas Copco

System calcs + humidity management + air quality + control considerations → detailed specs on air supply plant

ePIC SVT Air Supply Plant - Requirements

Contact
Joe Silber <jhsilber@lbl.gov>
Lawrence Berkeley National Laboratory

Color key:
INPUT
CALCULATED
LINKED

Version history
```
v1 - 2025-11-11 - JHS - initial version
v2 - 2025-11-19 - JHS - wider T_stability, diverter, moisture in terms of DPs, possible enclosure, add'l comments
```

Abstract
The Silicon Vertex Tracker (SVT) is a key subsystem of the Electron-Proton/Ion Collider (ePIC) detector. It will probe the smallest internal building blocks of visible matter -- quarks and gluons -- and help us understand the underlying laws that govern the strongest force in nature.

The SVT is composed of thousands of custom silicon sensors. They will be cooled by a steady supply of cleaned, conditioned, cooled air. This specification is for the plant which will generate that cooling air. This specification does not include the transmission of that air to the SVT.

ID	Category	Description	Name	Value (SI)	Units (SI)	Value (US)	Units (US)	Comments
00	process air	temperature - nominal	T_nom	3	°C	37.4	°F	Possible future relaxation of T_nom to +12°C (TBD)
01	output air	temperature - adjustment range - min	T_min	-5	°C	23.0	°F	Possible future relaxation of T_min to +7°C (TBD)
02	output air	temperature - adjustment range - max	T_max	30	°C	86.0	°F	
03	output air	temperature - stability about setpoint	T_stability	±2	°C	±3.6	°F	
04	output air	pressure dew point - max allowable	PDP_max_allow	-10	°C	14.0	°F	Pressure dew point shall never exceed this value when output stream is flowing through the process outlet. Possible future relaxation of PDP_max_allow to +3°C (TBD).
05	output air	pressure dew point - stability	PDP_stability	±2	°C	±3.6	°F	
06	output air	pressure dew point - setpoint adjustment	PDP setpoint	Pressure dew point shall be settable within a range defined by the AQ_water class (at low end) to PDP_max_allow (at high end).				
07	output air	pressure - nominal	P_nom	0.44	bar (gauge)	6.4	psi (gauge)	
08	output air	pressure - adjustment range - min	P_min	0.03	bar (gauge)	0.4	psi (gauge)	
09	output air	pressure - adjustment range - max	P_max	0.75	bar (gauge)	10.9	psi (gauge)	
10	output air	pressure - stability about setpoint	P_stability	±0.02	bar (gauge)	±0.29	psi (gauge)	
11	output air	mass flow rate - nominal	ṁ_nom	1.0	kg/s	132	lbm/min	
12	output air	mass flow rate - adjustment range - min	ṁ_min	0.1	kg/s	13	lbm/min	
13	output air	mass flow rate - adjustment range - max	ṁ_max	1.5	kg/s	198	lbm/min	
14	output air	density - nominal	ρ_nom	1.82	kg/m^3	0.11	lbm/ft^3	at P_nom, T_nom
15	output air	density - min	ρ_min	1.18	kg/m^3	0.07	lbm/ft^3	at P_min, T_max
16	output air	density - max	ρ_max	2.27	kg/m^3	0.14	lbm/ft^3	at P_max, T_min
17	output air	volumetric flow rate - nominal	V_nom	0.55	m^3/s	1166	ft^3/min	at P_nom, T_nom
18	output air	volumetric flow rate - min	V_min	0.08	m^3/s	179	ft^3/min	at P_min, T_max
19	output air	volumetric flow rate - max	V_max	0.66	m^3/s	1398	ft^3/min	at P_max, T_min
20	output air	air quality - solid particulate	AQ_particulates	Class 1	per ISO 8573-1:2010		-	
21	output air	air quality - total oil	AQ_oil	Class 1	per ISO 8573-1:2010		-	Oil-free compression or high-end filtration is critical to prevent oil contamination
22	output air	air quality - humidity / water	AQ_water	≤ Class 3	per ISO 8573-1:2010		-	Class 2 PDP = -40°C, Class 3 = -20°C, might consider Class 4 (PDP=+3°C) if significant cost savings and if T_min could be increased to ~ +10°C (TBD)
23	output air	output diverter	diverter_valve	Plant shall have an integrated 3-way diverter valve on the output stream. Outlets are to "process" (goes to SVT instrument) and "bypass" (exhaust). Fail-safe state (e.g. upon loss of power) shall be to the bypass outlet.				
24	facility	hose inner diameter - process air	Dh_process	100	mm	4	in	Connects to the SVT
25	facility	hose inner diameter - bypass air	Dh_bypass	TBD	mm	TBD	in	Connects to facility exhaust
26	facility	hose fitting type - process air	fitting_process	TBD	-	-	-	
27	facility	hose fitting type - bypass air	fitting_bypass	TBD	-	-	-	
28	facility	electrical - plug form	e_plug	TBD	-	-	-	
29	facility	supply voltage	V_supply	TBD	-	-	-	
30	facility	supply frequency	f_supply	60	Hz	-	-	
31	facility	heat rejection - coolant	coolant	TBD	-	-	-	
32	facility	heat rejection - coolant temperature	Tc	TBD	°C		K	
33	facility	heat rejection - coolant flow rate limit	Vc	TBD	L/min		?	
34	facility	heat rejection - coolant pressure	Pc	TBD	?		?	
35	environment	ambient temperature during operation - avg	T_amb_avg	23	°C	73.4	°F	Based on 15 year STAR WAH data 99.73% (3σ) envelope
36	environment	ambient temperature during operation - min	T_amb_min	18	°C	64.4	°F	Based on 15 year STAR WAH data 99.73% (3σ) envelope
37	environment	ambient temperature during operation - max	T_amb_max	32	°C	89.6	°F	Based on 15 year STAR WAH data 99.73% (3σ) envelope
38	environment	ambient dewpoint during operation - avg	DP_amb_avg	5.2	°C	41.4	°F	Based on 15 year STAR WAH data 99.994% (4σ) envelope
39	environment	ambient dewpoint during operation - max	DP_amb_max	22.1	°C	71.8	°F	Based on 15 year STAR WAH data 99.994% (4σ) envelope
40	control	fault condition on process air	process_fault	System shall have a process_fault condition, based on measured state of the output air. The state is logically TRUE when any of the key parameters (temperature, pressure, or pressure dew point) falls outside either its user-configured allowable range or the limit values listed here (whichever is more restrictive).				
41	control	output diverter control	diverter_ctrl	System shall automatically direct output air to the bypass outlet during startup, shutdown, or process_fault state.				
42	control	control interface - local	ctrl_local	Plant shall have a local user-interface panel by which it can be operated.				
43	control	control interface - remote	ctrl_remote	Plant shall have an API allowing customer to integrate it into our facility's control system, for configuring, monitoring, and real-time control.				
44	control	emergency shut-off - local	shutoff_local	Emergency shut-off shall be readily achievable by pressing an easily-identifiable hardware button, by any person physically stationed near the plant.				
45	control	emergency shut-off - remote	shutoff_remote	Emergency shut-off shall be readily achievable by a simple electrical interlock signal.				
46	maintenance	uptime during normal operations	uptime	99.5	%			
47	package	max width	W_max	TBD	m	TBD	in	
48	package	max length	L_max	TBD	m	TBD	in	
49	package	max height	H_max	TBD	m	TBD	in	
50	package	max weight	M_max	TBD	kg	TBD	lbm	
51	package	enclosure	enclosure	TBD, possibly enclose loud components (e.g. compressor) for moderate sound dampening.				

Link: ePIC SVT air supply plant reqts - v2.xlsx