Cooling Design Update

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ePIC Detector Electronics ASIC & FE Board Electronics Power Summary

Detailed Estimate of LV Power (example Si MAPS)

18 AWG, 4 cond. Cable Ø 9.0mm

Detector Layers(s)	# Sensors	series (arrays)	No. sensor arrays in parallel	Cable load Amps	18 AWG AL Ampacity @30˚C enviorment	Cable Derated Ampacity	Cable% Ampacity	LV cables from dist. panel to detector (4-cond.)	pairs	PDB Type (channels)	No. of PWR dist. Panels	No. of power feed cables	Amps Used	Supply Amps	% Amps Used	Supply Voltage / channel	V-Drop/ 25' cable	Power(W)	Power Estimate (used) Watts	LV Modules req.	LV Crates req.	19" Equipment rack space %
sagitta L3	450	2	2	1.7	4.5	2.88	59.03%	57	2	8	8	16	194	320	60.56%	2.4	1.1	465.1	621	8		
sagitta L4	1092	4	2	1.7	4.5	2.88	59.03%	69	2	8	9	18	235	360	65.17%	4.8	1.1	1127.0	1,503	9		
E disk	1100	3	2	1.7	4.5	2.88	59.03%	92	2	8	12	24	313	480	65.17%	3.6	1.1	1127.0	1,503	6		
H disk	1100	3	2	1.7	4.5	2.88	59.03%	92	2	8	12	24	313	480	65.17%	3.6	1.1	1127.0	1,503	6		
Total	3742							310			41	82	1,054	1,640	64.27%	N/A		3,846.1	5,130	29	3	70%

Si Disk Power Summary

	# Sensors Electron + Hadron	Voltage Required	Current (A)	Power(W)	Power Total + Losses	Cable count from LV distribution	Cable type/ PN	Cable Rating	No. of LV Dist Panels	PS Model	LV Module Qty.	LV System Ampacity	%Ampacity Used	PS Location	Rack space required(u)	Rack Cooling
Low Voltage distribution	2,200	3.6V	630	2.3kW	3kW	184	2 pair 18AWG/ AL	VW-1	24	MVP800L	12	960	66%	s.Platform	19u	1u MCW Heat Ex + 1u fan

Detector Heat Dissipation

Detector	Type	Front End LV Power	HV Bias	LV Power Supply Type	HV Power Supply Type	Power Supply Location	LV Power Feed	LV Feed Cables (Tray Rated)	Cooling (Board Electronics)
EE HCAL BACKWARDS	SiPM	200W	50W@ 50V	MPV 4016I	Wiener MPV 8120I	W. Platform, 19" rackmount	10V @ 30A	4x 14 AWG	Heatsink Convection
EE EMCAL ENDCAP	SiPM	500W	500W@50V	MPV 4016I	Wiener MPV 8120I	W. Platform, 19" rackmount	10V @ 60A	4x 12AWG	Liquid
pf-RICH	HRPPD	310W	70W@3kV	MPV 4018I	CAEN A1515BV	S. Platform, 19" rackmount	1.2V@ 330A	14x 12AWG	Liquid/ Neg. pressure
EE MPDG Disk	uRWELL	300W	1.5W@1.5kV	PL500	CAEN A1515BV	S. Platform, 19" rackmount	10V @ 40A	2x 10AWG	Liquid
Outer Barrel MPGD	uRWELL	1.7kW	1.5W@1.5kV	PL500	CAEN A1515BV	S. Platform, 19" rackmount	10V @ 200A	12x 12AWG	Liquid
Inner Barrel MPGD	uRWELL	700W	1.5W@1.5kV	PL500	CAEN A1515BV	S. Platform, 19" rackmount	10V@ 80A	15x 12AWG	Liquid
MAPS Disk	EIC-LAS	3kW	Derived from LV system	MPV 4008I	N/Applicable	S. Platform, 19" rackmount	3.6V@ 960A	48x 10AWG	Liquid
MAPS Sagitta Layer3	EIC-LAS	650W	Derived from LV system	MPV 4008I	N/A	S. Platform, 19" rackmount	2.4V@ 320A	16x 12AWG	Liquid
MAPS Sagitta Layer4	EIC-LAS	1.5kW	Derived from LV system	MPV 4008I	N/A	S. Platform, 19" rackmount	4.8V @ 360A	18x 12AWG	Liquid
MAPS Vertex	EIC-LAS	100W	Derived from LV system	MPV 4008I	N/A	S. Platform, 19" rackmount	1.2V @ 100A	4x 12 AWG	Liquid

Note: Power estimates include power conversion losses and added contingency

Detector Heat Dissipation

Detector	Type	Front End LV Power	HV Bias	LV Power Supply Type	HV Power Supply Type	Power Supply Location	LV Power Feed	LV Feed Cables (Tray Rated)	Cooling (Board Electronics)
Barrel HCAL	SiPM	220W	1.6W @50V	MPV 8016I	MPV 8120I	S. Platform, 19" rackmount	10V @ 30A	8x 16AWG	Liquid
Barrel ECAL	SiPM AstroPix	1.6kW	1W @50V & 100W @ 400V	MDH-07/16	MPV 8120I & EHS F005p	S. Platform, 19" rackmount	10V @ 200A	16x 12AWG	Liquid
DIRC	HRPPD	330W	70W@3kV	MPV 4018I	CAEN A1515BV	S. Platform, 19" rackmount	1.2V@ 350A	16x 12AWG	Liquid
Barrel TOF	AG-LGAD	7.2kW	4W@400V	PL506	CAEN A1625	S. Platform, 19" rackmount	10V @ 900A	30x 8AWG	Liquid
HE TOF	AG-LGAD	16.0kW	4W@400V	PL506	CAEN A1625	S. Platform, 19" rackmount	10V @ 2,000A	60x 8AWG	Liquid
dRICH	SiPM	300W	23W@70V	MPV 4016I	MPV 8120I	S. Platform, 19" rackmount	10V @ 40A	4x14AWG	Liquid
FWD ECAL	SiPM	2.8kW	750W@ 50V	PL506	MPV 8120I	E. Platform, 19" rackmount	10V @ 350A	20x 12AWG	Liquid
HE HCAL	SiPM	1.7kW	3kW@ 50V	PL506	MPV 8120I	E. Platform, 19" rackmount	10V @ 200A	12x 12 AWG	Heatsink Convection

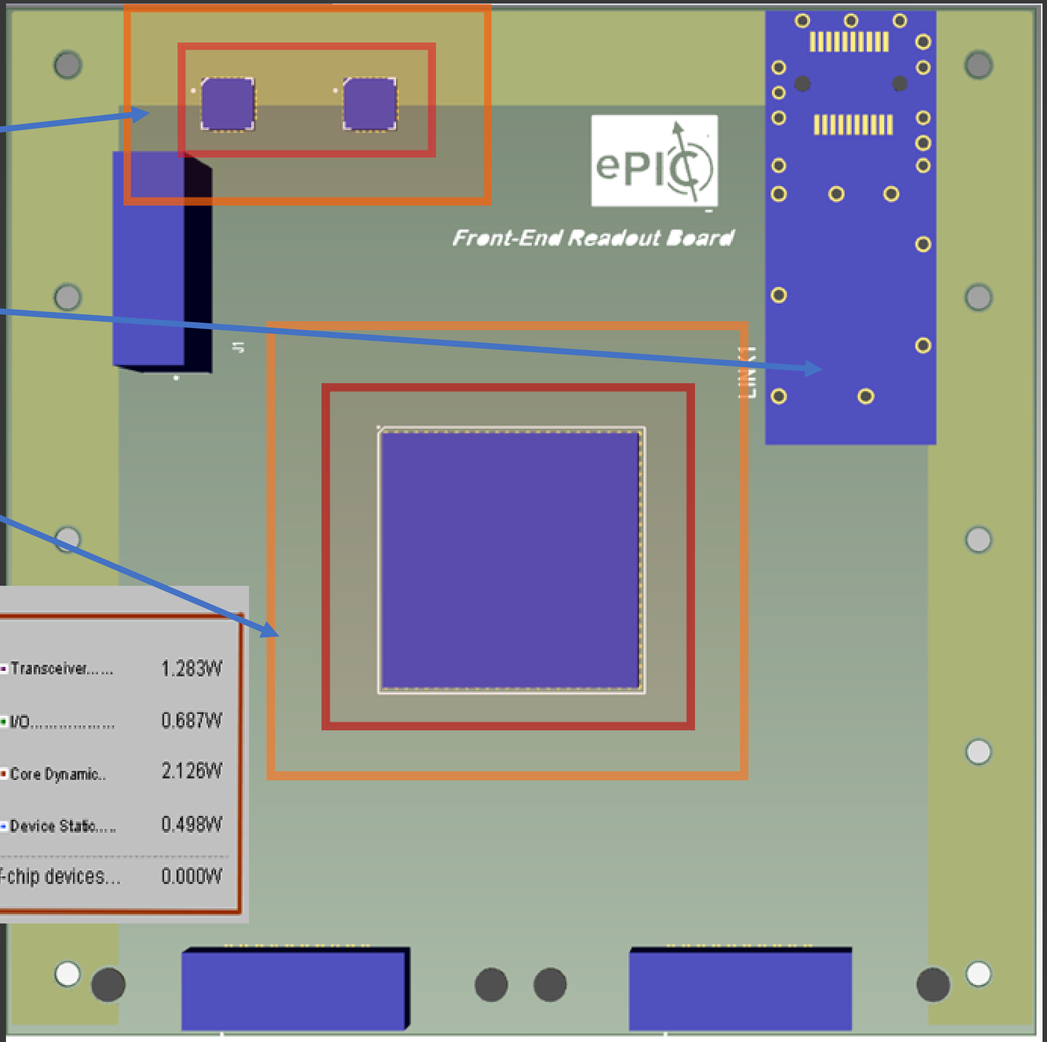
Note: Refer to ePIC Services on-line Spreadsheet for details of power distribution
August 2023, T.Camarda for BNL EE Group
REV-02

Estimated Power + Heat-Dissipation in RDO CCA
PCB Pre-Design Analysis

Power Regulators
2.5W Power Dissipation 20 °C Rise
Based on ~70.0% efficiency

Gigabit media-converter transceiver: ~ 750mw

5W Power Dissipation (BGA)~ 26°C Rise
Based on Xilinx PE simulation



Summary

Total On-Chip Power	4.594 W		28%	Transceiver......	1.283W
Junction Temperature	77.4 °C		15%	I/O................	0.687W
Thermal Margin	22.6°C	1.7W	46%	Core Dynamic..	2.126W
Effective ΘJA	10.3 °C/W		11%	Device Static.....	0.498W
				Power supplied to off-chip devices...	0.000W

BOARD POWER TOTAL => 8.5W

PCB Basic Specifications
8x Layer PCB with Power & Ground Planes
PCB Material: FR-4 TG-180 with 1oZ Copper
2.0mm thick board
PCB Area: 4.0" x 4.0"
FR-4 thermal conductivity 0.25 W / m-K
Decoupling capacitors => multi-terminal low ESL

Conditions:
PCB placed in still air
Ambient environment 30°C
This analysis is for FPGA without top-mounted heat-sink
Psi-JT thermal model => component junction to PCB

- The bulk of the heat generation is from the FPGA power dissipated in the BGA package plus the 2.5W power losses from the Voltage Regulators (~70% efficiency)
- In this scenario, with 0 CFM airflow and no top-mounted heat-sink attached to the device. Heat is removed from the device through the power & GND vias. Thermal stitching vias connecting the copper planes help to distribute heat. The PCB material and copper thus absorb heat generated by the devices.
- Based on the copper weight and layer + copper plane count, we can estimate an overall (power reg + FPGA) 25°C rise in the PCB with a bulk of the heat rise located in a 1.0-inch^2 area around the heat generating component . *This is illustrated by the orange and red boxes around the components.*

The temperature of the PCB is then ~(26°C + 30°C = 56°C)

TARGET PCB OPERATING TEMPERATURE
- To lower PCB temperature to ~35°C => (Δt/ 8W) => Cooling capacity / PCB => (21°C/8W) = 2.63 °C/W

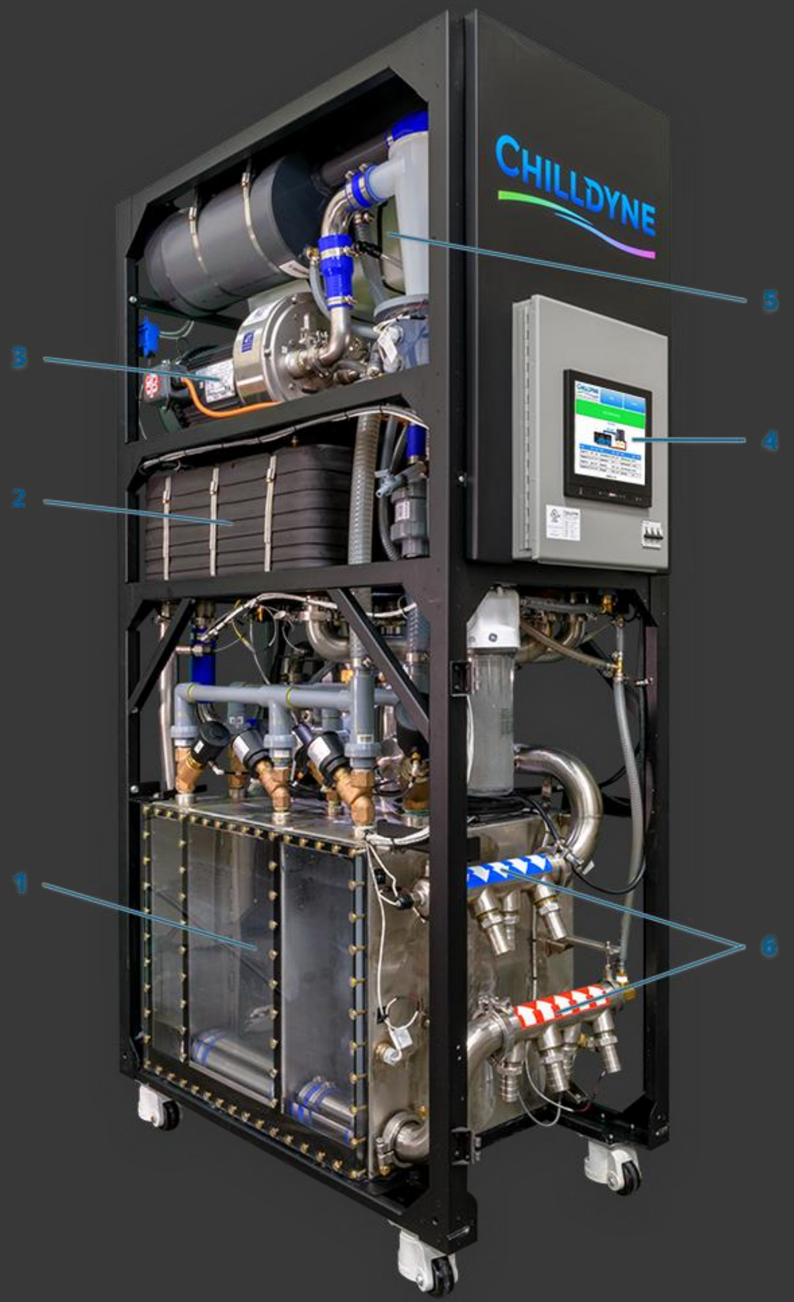
General Cooling Requirements

- Minimize potential damage from cooling system (inner detectors are going to be hard to service)
  - Run all detectors at about room temp or slightly higher to mitigate condensation concerns (known exceptions: dRICH).
  - Use negative pressure water circulators to mitigate leak concerns (draws air into lines instead of leaking water out).
    - Alternatively, Novec can be used with a positive pressure system to mitigate leak concerns as it's not electrically conductive.
- Minimize the space taken by cooling services, specifically where there is too much congestion (between the EEEMCal and DIRC and between the dRICH and HCal).
- Make manifolds and cooling services disconnects as accessible and serviceable as possible.

Cooling Circulator – Negative Pressure Water

CF-CDU300 Components

1. **Pump Chambers**
   The pump chambers control the flow of fluid into and out of the CDU. The proprietary three-chamber arrangement allows the CDU to pull fluid through the loop while maintaining a steady flow.
2. **Heat Exchangers**
   The heat exchangers move heat from the technology cooling system to the facility water system. The two series heat exchangers allow the CDU to move up to 300 kW of heat even on hot and humid days.
3. **Liquid Ring Pump**
   Liquid ring pumps use water as a seal that never needs to be replaced. The CDU's liquid ring pump provides the vacuum used to pull the coolant through the load.
4. **Microprocessor Control**
   The intelligent, network-enabled core of the CDU automatically manages coolant temperatures, flow rates, water quality, and more. The Cool-Flo Software allows the CDU to be easily integrated into popular DCIM and BMS systems.
5. **Water Quality Control**
   The CDU automatically monitors and controls the quality of the water in the technology cooling system. The water quality system dispenses coolant additives as-needed to prevent corrosion and biological growth.
6. **Coolant Handling Manifolds**
   Up to 4 cooling loops exit either the top or bottom of the CDU to support both raised floor and overhead configurations.



Product Line: CF-CDU300

- **Input Power:** 208, 380/415, and 480 VAC configurations available
- **Cooling Capacity:** Up to 300kW with 15 °C rise.
- **Approach:** Delivery at 7 °C above facility water temperature at 300 kW; 2 °C at 200 kW
- **Flow Rate:** Up to 300 LPM at 0.5 bar differential
- **System ΔPressure:** Maximum 22 inHg, minimum 10 inHg
- **Manifold to CDU Tubing**: 1 1/4" ID, up to 30 ft, 4 circuits, 36 racks or more
- **Network Connections:** 1x Fast Ethernet, RJ45 / 8p8c
- **User Interfaces:** Touchscreen GUI, local web-based GUI and local web API, Telnet and RS-232 command lines, SNMP and Modbus TCP/IP, Syslog (UDP), FTP file transfer.

Facility Specifications:

- **Cooling Water:** 2°C to 45°C at 350 LPM (92 GPM), ASHRAE W4, 15 psi (1 bar) differential
- **Fill Water:** 2 GPM, 20 to 100 PSI, filtered, RO recommended
- **Drain Capacity:** 4 GPM, 50 mm (2 in) recommended
- **Electrical Power:**
  - 480 VAC, 60 Hz, 3-phase WYE or Delta, 5 Amps
  - 208 VAC, 60 Hz, 3-phase WYE, 10 Amps
  - 380/415 VAC, 50/60 Hz, 3-phase WYE, 7 Amps

https://chilldyne.com/cooling-distribution-unit/

Cooling Calculation

Heat Transfer Equation

$$\dot{Q} = \dot{m} c_p \Delta T$$

$\dot{Q}$ – Heat Flow
$\dot{m}$ – Mass Flow
c_p – Specific Heat
ΔT – Temp Change

Pressure-loss Equation

$$\Delta p = L f_D \frac{\rho}{2} \frac{v^2}{D}$$

Δp – Pressure Loss
L – Tube Length
f_D – Friction Factor
ρ – Fluid Density
v – Fluid Velocity
D – Tube Diameter

Pressure-loss Equation, Bend

$$\Delta p = f_D v^2 \frac{\rho}{2} \frac{R_b}{D} \frac{\pi\theta}{180} + k_b v^2 \frac{\rho}{2}$$

Δp – Pressure Loss
f_D – Friction Factor
ρ – Fluid Density
v – Fluid Velocity
R_b – Bend Radius
D – Tube Diameter
θ – Bend Angle
k_b – Bend Coefficient

Reynolds Number Equation

$$Re = \frac{\rho v D}{\mu}$$

Re – Reynolds Number
ρ – Fluid Density
v – Fluid Velocity
D – Tube Diameter
μ – Dynamic Viscosity

Friction Factor Equation – Churchill-Bernstein Approximation (non-implicit)

$$f_D = 8\left(\left(\frac{8}{Re}\right)^{12} + \frac{1}{(A+B)^{3/2}}\right)^{1/12} \quad A = \left(2.457 \ln\left(\frac{1}{\left(\frac{7}{Re}\right)^{9/10} + 0.27\frac{\epsilon}{D}}\right)\right)^{16} \quad B = \left(\frac{37530}{Re}\right)^{16}$$

Cooling Calculation Results – Detectors

Detector	Total Heat	QTY		Temp Change	Pressure Drop	Length	Bends		Flow Rate	Total Flow	OD	Area	Area Packing	Area Safety
Units	W	12.00		C	psi	m	4.00		L/min	L/min	in	cm2	cm2	cm2
MAPS Vertex	100	12		2	0.25	6	4		0.12	1.43	0.25	3.80	6.48	7.96
MAPS Sagita Layer3	700	120		2	0.25	6	4		0.08	10.00	0.25	38.00	64.83	79.58
MAPS Sagita Layer4	1400	236		2	0.25	6	4		0.08	20.00	0.25	74.74	127.49	156.52
MAPS Disk	3000	550		2	0.25	6	4		0.08	42.86	0.25	174.18	297.12	364.76
Inner Barrel MPGD	700	33		2	0.25	6	4		0.30	10.00	0.31	16.33	26.36	32.54
Barrel TOF	7200	144		2	0.25	6	4		0.71	102.86	0.38	102.61	159.52	197.65
HE TOF	16000	8		2	0.25	6	4		28.57	228.57	1.50	91.21	122.30	153.91
Outer Barrel MPGD	1700	40		2	0.25	6	4		0.61	24.29	0.38	28.50	44.31	54.90
MPDG Disk	300	16		2	0.25	6	4		0.27	4.29	0.31	7.92	12.78	15.78
pfRICH	350	9		2	0.25	6	4		0.56	5.00	0.38	6.41	9.97	12.35
EEEMCAL	500	30		2	0.25	6	4		0.24	7.14	0.31	14.84	23.96	29.58
DIRC	350	12		2	0.25	6	4		0.42	5.00	0.31	5.94	9.59	11.83
dRICH	6000	24		2	0.25	6	4		3.57	85.71	0.63	47.50	68.34	85.36
EEHCAL	200	36		2	0.25	6	4		0.08	2.86	0.25	11.40	19.45	23.88
Barrel ECAL	1600	96		2	0.25	6	4		0.24	22.86	0.31	47.50	76.68	94.65
Barrel HCAL	200	12		2	0.25	6	4		0.24	2.86	0.31	5.94	9.59	11.83
HE ECAL	2800	36		2	0.25	6	4		1.11	40.00	0.44	34.92	52.82	65.63
HE HCAL	1700	12		2	0.25	6	4		2.02	24.29	0.50	15.20	22.52	28.04
Total	44800	1426								640.00		726.95	1154.12	1426.76

Cooling Calculation Results – RDOs

Detector	Total Heat	QTY		Temp Change	Pressure Drop	Length	Bends		Flow Rate	Total Flow	OD	Area	Area Packing	Area Safety
Units	W	12.00		C	psi	m	4.00		L/min	L/min	in	cm2	cm2	cm2
Inner Barrel MPGD	960	12		2	0.10	6	4		1.14	13.71	0.50	15.20	22.52	28.04
Barrel TOF	2144	24		2	0.10	6	4		1.28	30.63	0.50	30.40	45.05	56.09
HE TOF	1072	24		2	0.10	6	4		0.64	15.31	0.44	23.28	35.21	43.75
Outer Barrel MPGD	2304	48		2	0.10	6	4		0.69	32.91	0.44	46.55	70.42	87.50
MPDG Disk	256	12		2	0.10	6	4		0.30	3.66	0.38	8.55	13.29	16.47
pfRICH	136	6		2	0.10	6	4		0.32	1.94	0.38	4.28	6.65	8.24
EEEMCAL	96	3		2	0.10	6	4		0.46	1.37	0.44	2.91	4.40	5.47
DIRC	192	6		2	0.10	6	4		0.46	2.74	0.44	5.82	8.80	10.94
dRICH	9920	48		2	0.10	6	4		2.95	141.71	0.75	136.81	192.96	241.52
EEHCAL	144	6		2	0.10	6	4		0.34	2.06	0.38	4.28	6.65	8.24
Barrel ECAL	2096	48		2	0.10	6	4		0.62	29.94	0.44	46.55	70.42	87.50
Barrel HCAL	72	3		2	0.10	6	4		0.34	1.03	0.38	2.14	3.32	4.12
HE ECAL	512	24		2	0.10	6	4		0.30	7.31	0.38	17.10	26.59	32.94
HE HCAL	664	12		2	0.10	6	4		0.79	9.49	0.44	11.64	17.61	21.88
All RDOs	20568	24		2	0.10	6	4		12.24	293.83	1.25	190.02	257.42	323.58
Total	20568	276								293.83		355.51	523.89	652.68

Detector Requirements

- Heat Dissipation – Total heat dissipated by the detector.
- Heat Stability – Changes in heat dissipation over time.
- Temperature – Desired operating temperature.
- Tolerance – Allowable deviation from the desired temperature.
- Gradient – Allowable difference in temperature across the detector.
- Stability – Allowable deviation from the desired temperature over time.
- Segmentation – The number of detector components there are that require cooling, we can determine the number of parallel or series lines, manifolding, etc.
- Additional Requests?

Summary / Next Steps

- Power dissipation estimate calculated
- Corresponding tube and flow rate estimate calculated

- Refine power and cooling calculations
- Confirm power numbers are reasonable with detector groups.
- Work on determining more reasonable RDO quantities.
- Determine appropriate RDO locations and cooling scheme.
- Decide manifolding sizes and locations.
  - Sensors, interlocks, controls, etc.
- Work with detector groups to determine temperatures, tube sizes, flow rates.
- Consider cooling interface details.

Questions?