3.1 Electronics Enclosure Design

Daniel Alfred

Requirements

The electronics enclosure for the MagAO-X Adaptive Optics instrument is designed according to the following requirements.

1. Operating temperatures shall be between -5°C and 25°C.
2. Storage temperatures shall be between -20°C and 50°C.
3. Maximum allowable heat leak from the electronics rack and instruments to the observatory is 60W.
4. Heat shall be removed with facility-supplied water/glycol coolant that can be assumed to be within 2°C of observatory ambient air.
5. The minimum usable depth of the rack shall be 30”. The minimum usable width shall accommodate 19” rack equipment.
6. Transmitted vibration shall be contained by using vibration isolation and minimizing the use of fans in the enclosure.
7. The rack shall provide the following interface capabilities:
    a. Manage cabling and hoses to minimize connecting and disconnecting effort
    b. Access ports for components
    c. Jack wheels
    d. Lifting eyes
    e. Bulkhead connections

Design

In order to meet the temperature and heat leak requirements, an electronics rack is designed that is based on a standard 19” electronics rack. However, 2” of rigid foam insulation encloses each side of the equipment rack. The rack and its dimensions are shown in figure 1.

To reduce transmitted vibration, the equipment rack will make use of direct liquid cooling for as many components as possible in order to minimize the use of fans. This includes the GPUs, CPUs, and motor controller components, which can be conductively sunk to a liquid cold plate. The rack, however, includes an air-liquid heat exchanger to remove heat from the components that are designed to sink heat convectively to ambient air. The rack is placed in line with the benchtop cameras that are liquid cooled. A diagram of the system cooling scheme is shown in figure 2.

The electronics rack waste heat is removed by the facility-supplied water/glycol coolant. The GPUs, CPUs, and motor controller components exchange heat conductively with packages and mounting plates that are directly liquid cooled. The DM drivers, computers (ICC and RTC), controllers, and other network devices and power supplies exchange heat with recirculating enclosure air that is driven and cooled by a Thermacore 5360 air-liquid heat exchanger with two axial fans. The rack thermal management scheme is shown in figure 3.

The components in the electronics rack that are directly liquid cooled include the GPUs, CPUs, and motor controller components and devices. Liquid coolant is plumbed to the RTC, ICC, PCIe expansion, and motor controller units. The RTC, ICC, and PCIe expansion units contain GPUs and CPUs that are packaged with EKWB water blocks. Based on thermal performance and flow data for the water blocks, the CPUs and GPUs will each be plumbed in parallel pairs in order to optimally balance thermal performance with pressure loss. For an expected minimum coolant flow rate of 1.5 GPM (346 L//h), the GPUs and CPUs will be sufficiently cooled and each GPU and CPU water block pair will represent a pressure loss of .61psi and .44 psi, respectively. This is shown in figures 4 and 5.

The motor controller components are mounted to a 19” wide, 26” deep aluminum plate. The plate will be liquid cooled with two Wakefield-Vette 4-pass cold plates. The components will be mounted on either side of the cold plates, which are sandwiched by aluminum mounting plates. The two cold plates are mounted in series, with all of the coolant flow passing through both. This design is shown in figure 6.

The maximum heat leak from the electronics rack is determined by considering the maximum temperature difference between the inside of the rack enclosure and ambient air, as well as the thermal resistances of the enclosure insulation and natural convection at the exterior of the rack. Unless it is shown to result in a violation of the requirement, it is sufficient to perform a calculation that is both relatively simple but addresses the problem at hand conservatively. In this case, the interior temperature of the wall of the enclosure is assumed to be very close to the maximum air temperature ($T_{hx.in}$), which is calculated from the following equation:

$$T_{hx,in} = T_{c,avg} + \frac{\dot{Q}}{TP}$$

$T_{hx,in}$ is the temperature of the air entering the heat exchanger, $T_{c,avg}$ is the average coolant temperature in the heat exchanger, TP is the stated thermal performance of the heat exchanger, and $\dot{Q}$ is the heat being removed by the heat exchanger. The heat flux (q”) through the rack enclosure can then be calculated from $T_{hx,in}$, T_{amb} (ambient temperature), enclosure insulation R value (R_{encl}), and the enclosure-ambient natural convection coefficient (h_{amb}) from the following equation:

$$q" = \frac{T_{amb} - T_{hx,in}}{R_{encl} + \frac{1}{h_{amb}}}$$

In order to calculate h_{amb}, a temperature difference between the exterior of the enclosure and ambient air must be assumed. This calculation is repeated until the assumed temperature difference and the calculated temperature difference match, since natural convection is driven by temperature difference and not ambient air conditions alone. For the worst-case hot condition, with the rack fully populated and operating at 100% duty cycle with ambient air at 25°C, the heat leak is 40W. For the worst-case cold condition, with the rack populated with the components it will be initially shipped with and ambient air at -5°C, the heat leak is 32W.

The operating temperatures of the air-cooled components can be determined from the temperature of the rack recirculating air that flows past it or over it. The operating temperatures of the liquid-cooled components are determined from temperatures of their mounting interfaces, which is a function of how much heat is added to the coolant, coolant properties, and coolant mass flow rate. The chip temperatures of the CPUs and GPUs are also determined from the thermal performance of the water blocks and the temperature of the coolant flowing through the water blocks. A summary of the temperatures for the worst-case hot condition (25°C ambient and 100% populated), as well as temperatures for the same condition but at 20°C is shown in table 1.

A summary of component operating temperatures is shown for the worst-case cold condition (-5°C ambient, rack populated in as-shipped condition, motors at 10% duty cycle), and the same condition but with ambient air at 0°C in table 2.

The temperature violations indicated for the worst-case hot and worst-case cold conditions can be addressed by opening up the doors of the rack when it experiences a daytime temperature higher than 20°C, or by turning off the heat exchanger fans when the outside ambient temperature drops below 0°C. This prevents the RTC and ICC motherboards from experiencing an operational temperature that is either hotter or colder than what they are rated for. This table also shows a temperature violation for the Andor cameras at ambient temperatures below 0°C. However, the risk to the Andor cameras and the motherboards is mitigated by the low probability that the observatory will actually experience these temperatures. A histogram of temperature data is shown in figure 7. The histrogram also shows the limiting ambient temperatures for the motherboards (labeled “mobo”) and the SMC100CC and C-863 motor controllers.

Additional testing of the motherboards can be performed in order to qualify them for operation in a larger temperature range than what they are currently rated for. The motherboards can be placed in a thermal chamber whose ambient temperature can be set to temperatures outside of the specified operating range of the motherboards (10°C-35°C) and functional tests can be performed to verify its operation at these temperatures. This would also reduce the risk carried by implementing off-the-shelf motherboards.

To further mitigate risk at worst-case cold operation, a heater can be placed on the motor controller plate, and can be temperature-controlled so that the plate does not drop below 5°C during periods when the heat exchanger fans are shut off. The minimum operating temperature of the motor controllers is 5°C, and the risk that the mounting interface for these components approaches this temperature increases when the heat exchanger fans are shut off, since the coolant stops carrying heat from the heat exchanger when that occurs. Also, the motor controllers are operating at a significantly reduced duty cycle (as low as 10%), thereby reducing the heat input to the mounting interface. Both of these effects can be easily counteracted with a temperature-controlled heater.

Each of the features indicated by the interfaces requirement (requirement 7) will be implemented in the design of the electronics rack, though those details are not presented here. This will include casters, removable sections or doors in the rack, proper cable management, lifting eyes attached to the top of the enclosure, and bulkhead connections for electronics and coolant hoses.

Figure 1

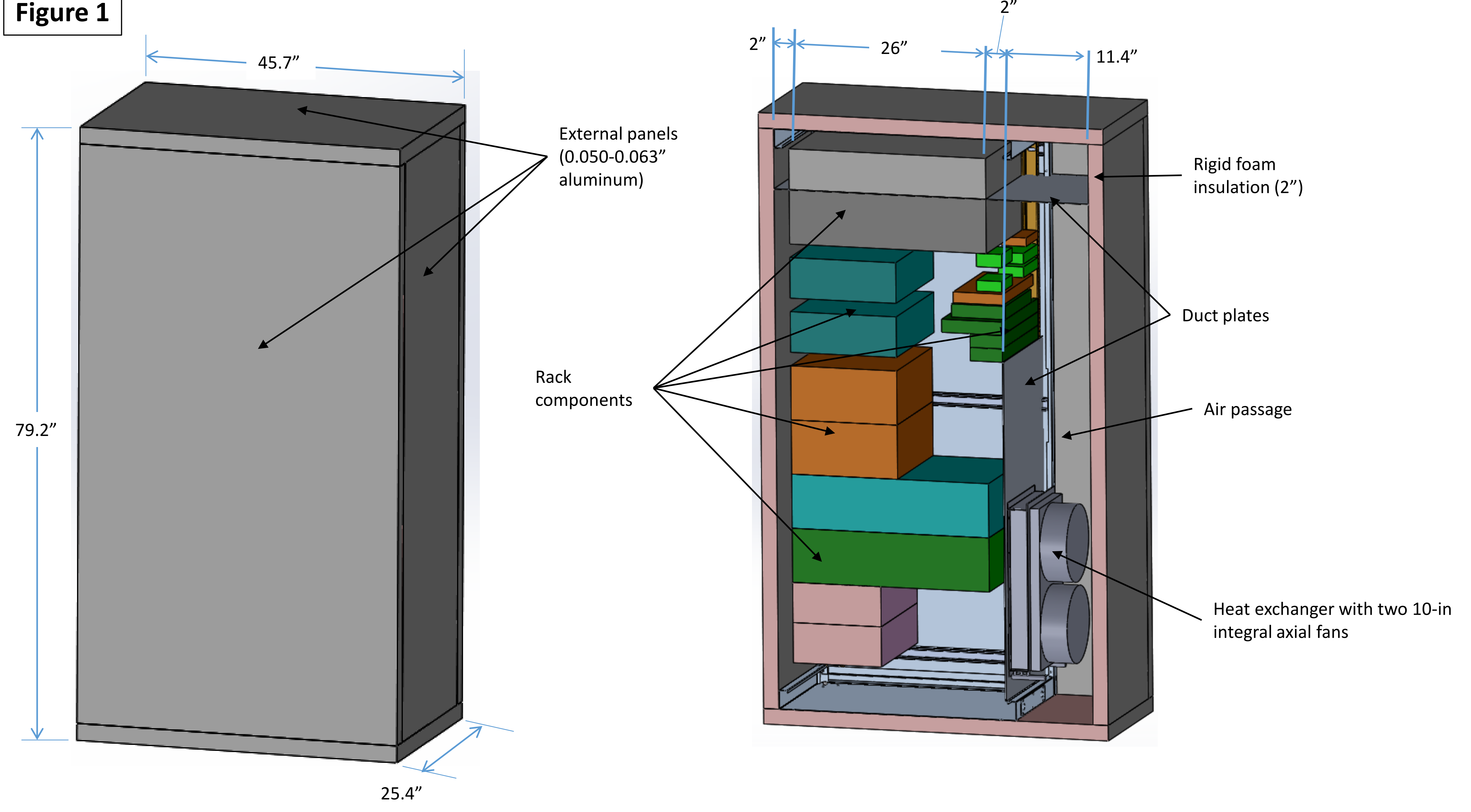
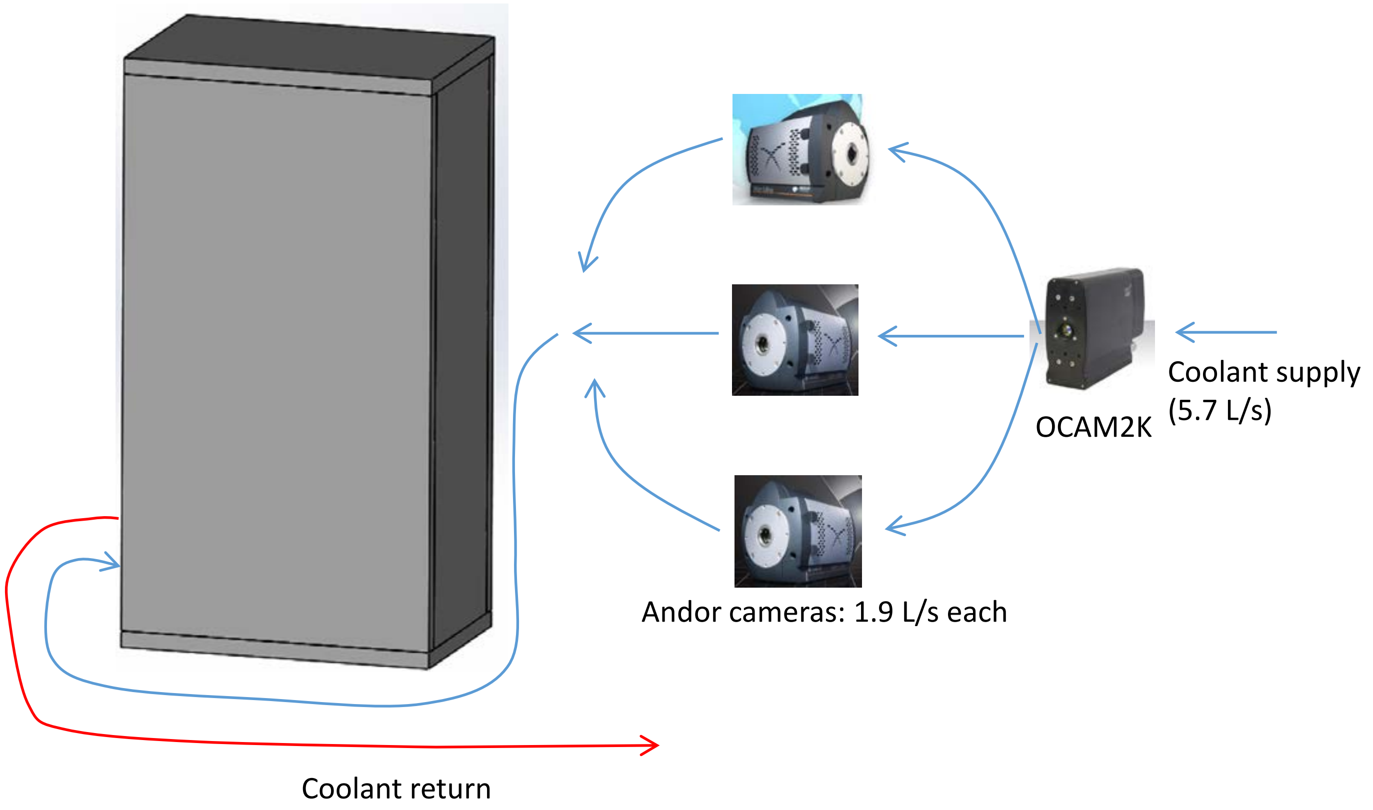

45.7”
79.2”
25.4”
External panels
(0.050-0.063”
aluminum)
2”
2”
26”
11.4”
Rigid foam
insulation (2”)
Duct plates
Rack
components
Air passage
Heat exchanger with two 10-in
integral axial fans

Figure 2



Coolant supply
(5.7 L/s)
OCAM2K
Andor cameras: 1.9 L/s each
Coolant return

Figure 3

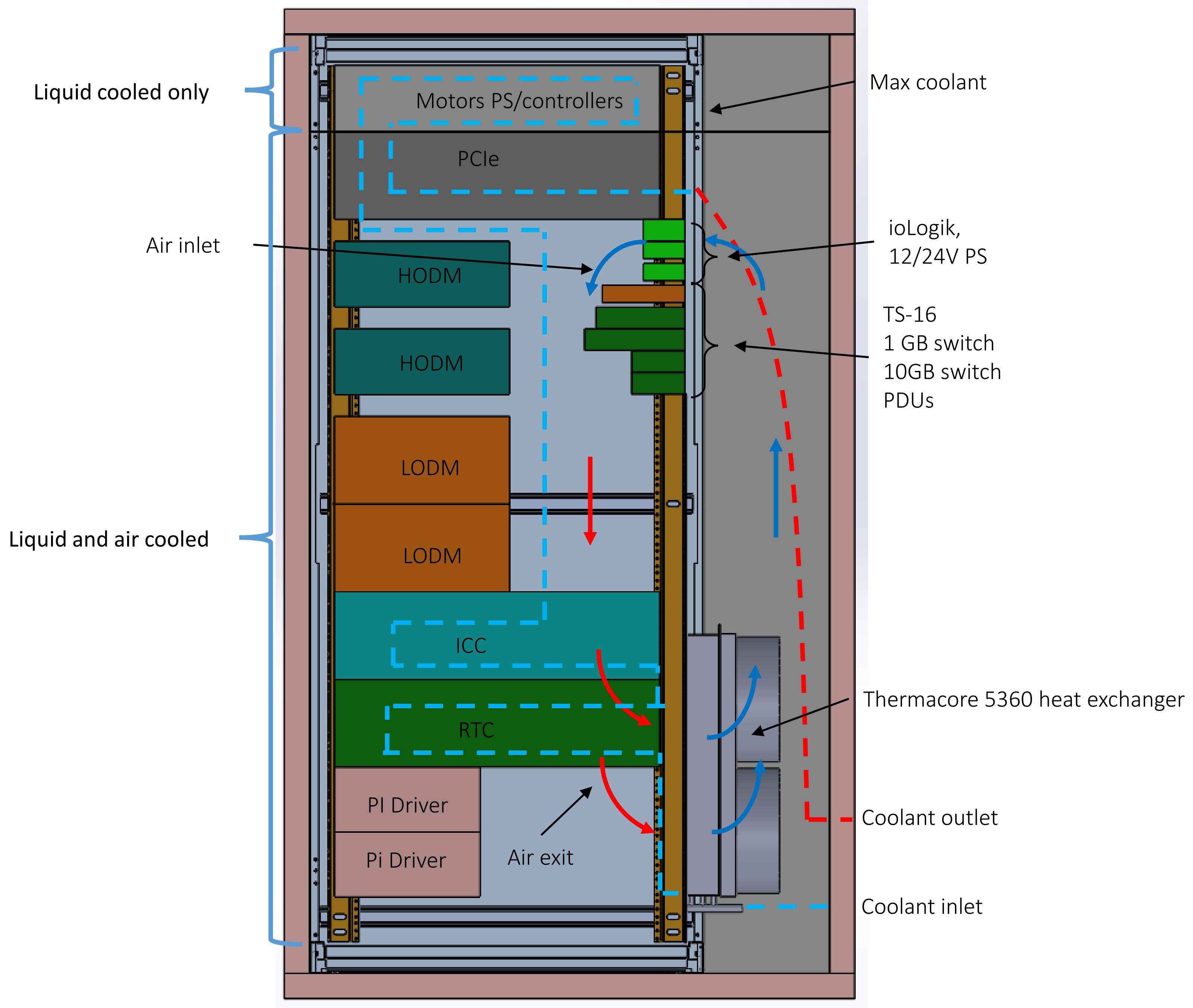
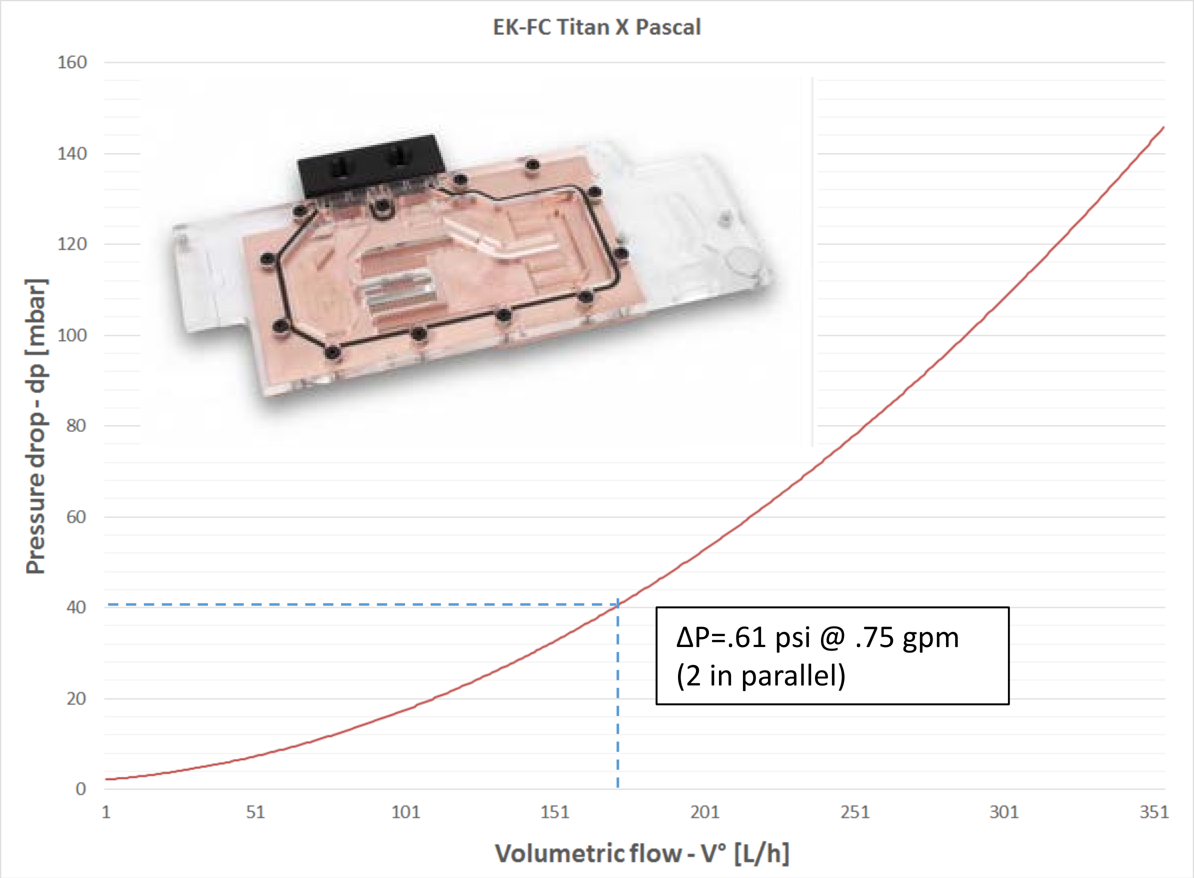
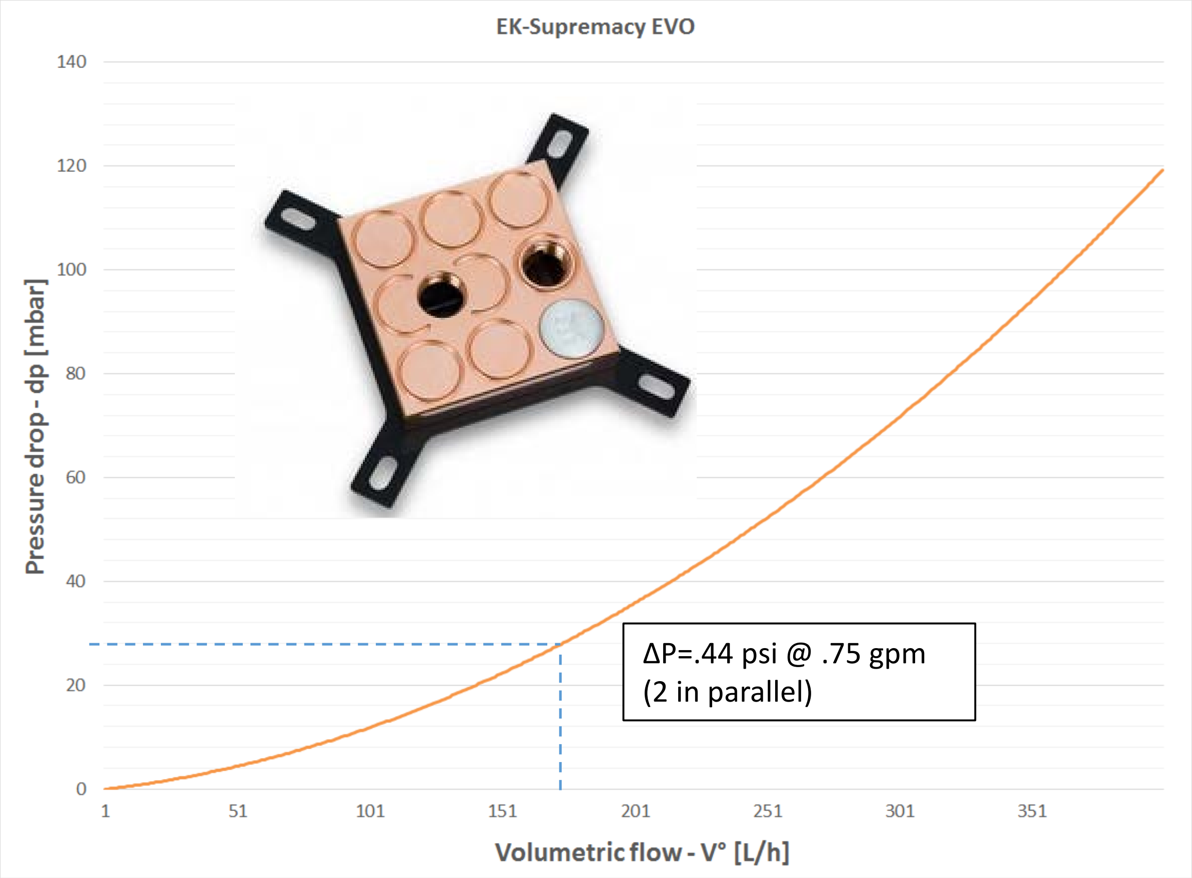

Liquid cooled only
Liquid and air cooled
Air inlet
Motors PS/controllers
PCIe
HODM
HODM
LODM
LODM
ICC
RTC
PI Driver
Pi Driver
Air exit
Max coolant
ioLogik,
12/24V PS
TS-16
1 GB switch
10GB switch
PDUs
Thermacore 5360 heat exchanger
Coolant outlet
Coolant inlet

Figure 4



GPU waterblock pressure vs. flow curve

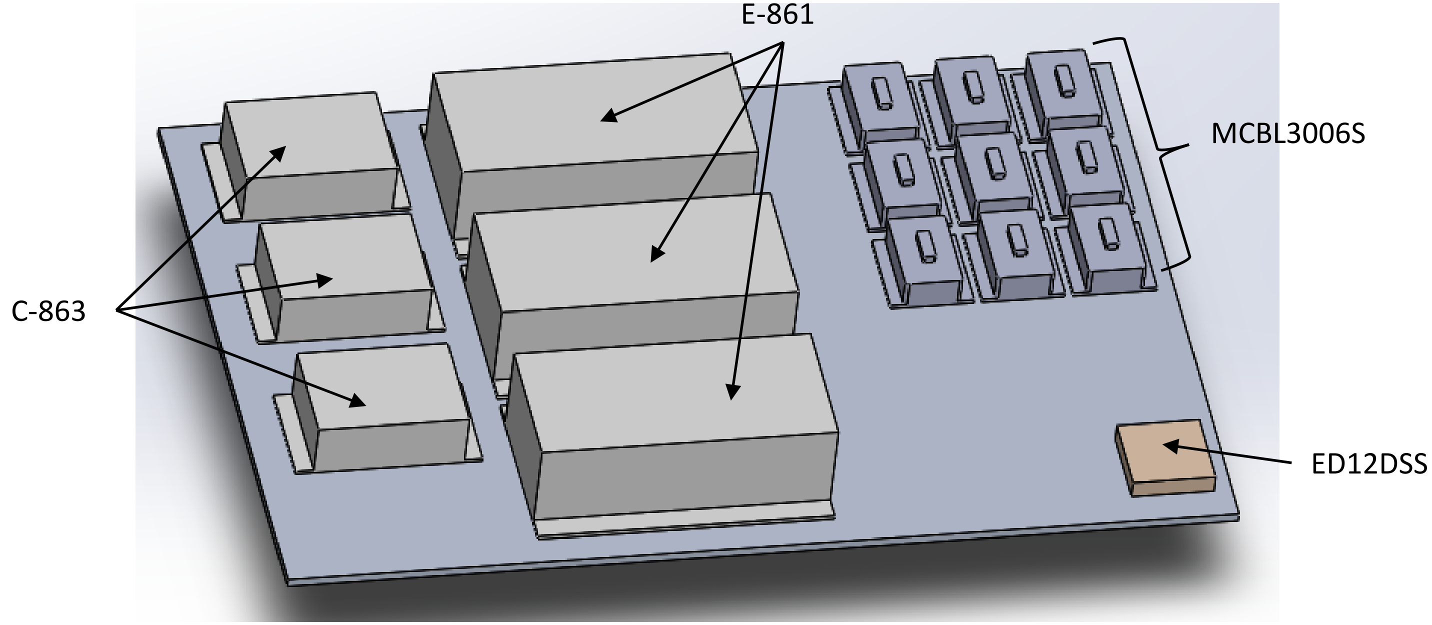
Figure 5



CPU waterblock pressure vs. flow curve

Figure 6

Motor Controllers and Drivers



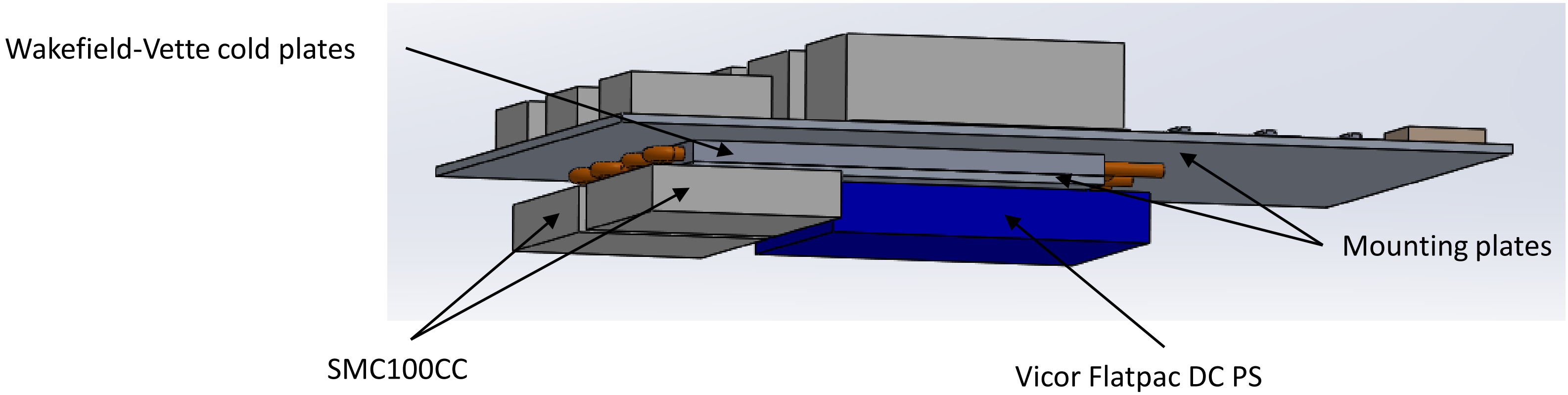


Table 1

	Component	Operating temperature (°C)		Max allowable temperature (°C)	Margin	
		@ 25°C	@ 20°C		@ 25°C	@ 20°C
Air-cooled	PCIe PSU	37	32	50	13	18
	ioLogik	37	32	75	38	43
	12/24 VDC PS	37	32	40	3	8
	TS-16	37	32	50	13	18
	1 GB Switch	37	32	40	3	8
	10 GB Switch	37	32	50	13	18
	PDU	37	32	50	13	18
	HODM	37	32	40	3	8
	LODM	40	35	50	10	15
	ICC PSU	40	35	50	10	15
	ICC Motherboard	40	35	35	-5	0
	RTC PSU	40	35	50	10	15
	RTC Motherboard	40	35	35	-5	0
	PI Driver	43	38	50	7	12
Liquid-cooled	OCAM2K	28	23	35	7	12
	Andor 897	25	20	30	5	10
	Andor 888	25	20	30	5	10
	RTC GPU (chip)	43	38	94	51	56
	RTC CPU (chip)	67	62	80	13	18
	ICC CPU (chip)	68	63	80	12	17
	PCIe GPU (chip)	51	46	94	43	48
	E-861	41	36	50	9	14
	C-863	41	36	50	9	14
	Vicor Flatpac	41	36	85	44	49
	SMC100CC	41	36	40	-1	4
	MCBL	41	36	85	44	49

Table 2

	Component	Operating temperature (°C)		Min allowable temperature (°C)	Margin	
		@ -5°C	@ 0°C		@ -5°C	@ 0°C
Air-cooled	PCIe PSU	3	8	0	3	8
	ioLogik	3	8	-40	43	48
	12/24 VDC PS	3	8	-10	13	18
	TS-16	3	8	0	3	8
	1 GB Switch	3	8	0	3	8
	10 GB Switch	3	8	0	3	8
	PDU	3	8	-15	18	23
	HODM	3	8	0	3	8
	LODM	5	10	0	5	10
	ICC PSU	5	10	0	5	10
	ICC Motherboard	5	10	10	-5	0
	RTC PSU	5	10	0	5	10
	RTC Motherboard	5	10	10	-5	0
	PI Driver	7	11	5	2	6
Liquid-cooled	OCAM2K	-4	1	--	--	--
	Andor 897	-5	0	0	-5	0
	Andor 888	-5	0	0	-5	0
	RTC GPU (chip)	9	14	0	9	14
	RTC CPU (chip)	33	38	0	33	38
	ICC CPU (chip)	33	38	0	33	38
	PCIe GPU (chip)	9	14	0	9	14
	E-861	4	9	0	4	9
	C-863	4	9	5	-1	4
	Vicor Flatpac	4	9	0	4	9
	SMC100CC	4	9	5	-1	4
	MCBL	4	9	0	4	9

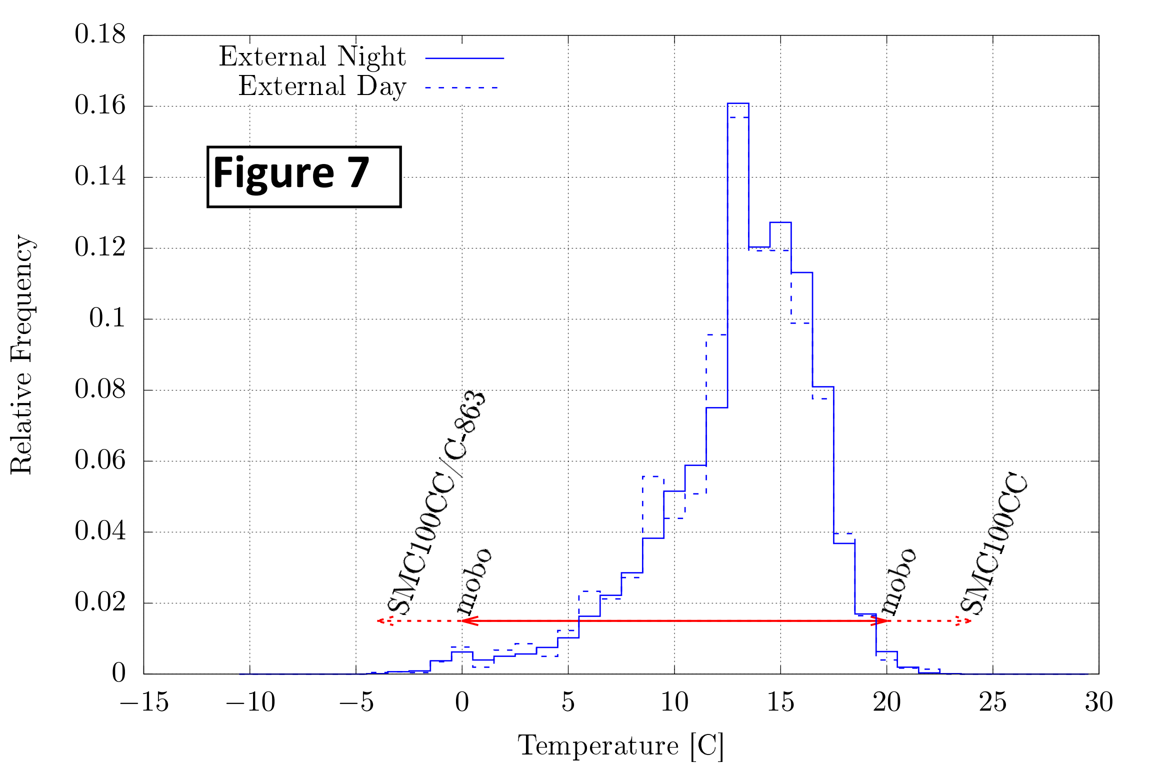


Figure 7
External Night
External Day
Relative Frequency
Temperature [C]
SMC100CC/C-863
mobo
mobo
SMC100CC
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
−15
−10
−5
0
5
10
15
20
25
30