Thermal Management for Silicon Detectors

Introduction: importance of cooling and overview of heat sources.
Electronics Heat Sources
External Heat Sources
Silicon Sensor Heat Production
What do we mean by thermal management?
Brief overview of CO2 cooling
FEA and Prototyping
Summary

Introduction

- Silicon detectors have many heat sources; this heat has to be removed by a cooling system
- Stable temperature for stable position; needed to benefit from the ~20 micron resolution of the detectors.
- As well as removing the heat, we need to cool below room temperature to avoid "thermal runaway" in sensors.
- Spare cooling capacity needed to cover uncertainties in our predictions, but costs %X0. So good FEA modelling requires less safety margin and less material, while minimising chances of failure.

Thermal Management – Cooling++

- The process of understanding and minimising heat sources; local as well as system-wide effects such as convection; removing that heat (cooling); providing dry atmospheres (N2) to avoid condensation; heaters outside to avoid condensation during maintenance and to avoid cooling our neighbours
- Safety: monitoring of temperatures, humidity, flow rates, pressures
  - Warn in time for corrective action if something is going wrong
  - Cut power if cooling fails
- Requirements:
  - Maintain a steady temperature (e.g. < 2 degC)
    - For good position stability
  - Keep cold (e.g. < -20 degC)
    - To avoid thermal runaway and high leakage currents (electronic noise)
  - Low material budget (%X0)
  - High reliability: thousands of tubes need very high joint reliability
  - Avoid ice/condensation

Overview of heat sources

- Silicon Sensor
  - Diode, reverse biased to give full depletion depth
  - Small leakage current, but significant after radiation damage
  - Also the bias has to be raised after radiation damage, both to fully deplete and to give efficient fast charge collection – minimising the time for electrons to get trapped at radiation damage sites
  - This current times voltage gives a significant heat load (25 % pixels, 10 % strips) at end of HL-LHC.
- Readout chips
  - Most of the heat (~60 %) is produced in the front-end amplifier and data handling chips
    - (FE-I4, ABC)
  - Several other chips are important too: HCC, SPP, GBT, lasers…
- Powering
  - Local point-of-load powering units are not 100 % efficient.
  - The inefficiency (~20 %) appears as heat in the DC-DC or serial power unit.
- Cables
  - To minimise %X0 we use narrow cables, leading to heat production.
    - We design for 5 – 10 % of total power produced in the cables.

Other heat sources

- External:
  - Inward heat leaks. Especially beam-pipe bake-out. But also just because we run colder than outside.
- Convection:
  - Typically sensors at the top have a higher heat-load than those at the bottom
- Radiation:
  - Tends to be small since driven by temperature differences which we keep small.

Overview of cooling methods

- Gas (Air, N2, CO2, He...)
  - The atmosphere around our electronics will conduct heat away. But it is a very poor conductor, and has low heat capacity (by volume)
  - We cannot flow a high rate: vibrations
  - Temperature rise if a future endcap strip detector is air cooled at 1 vol exchange per hour:
    - dT = power / C_p / vol flow rate / density
    - ~ 4,000 K (!)
  - But the atmosphere can have significant effects by convection
  - And there are possibilities with new materials (carbon foams)
- Monophase liquid cooling
  - Used in Alice. Low pressure (below atmospheric) prevents leaks into detector and allows very thin-walled cooling pipes (40 μm)
  - But low conductivity of heat into the liquid needs large tube-wall surface, and temperature of fluid depends on heat input
- Biphase evaporative cooling
  - Used in current ATLAS pixel and strips
  - Heat removed by latent heat of evaporation (i.e. you boil the liquid into gas)
  - More on this later

Electrical Heating – Chips and Cables

An object (chip, resistor, silicon sensor, ...) with a voltage V across it carrying a current I develops a power

$$P = VI$$

Chip developers give us I and V (we need to take the maximum values given)

Using Ohm's Law $V = IR$ gives a useful form for a cable:

$$P = I^2R$$

And the cable resistance is given by its length l, cross-sectional area A, and resistivity of the material ρ by

$$R = l\rho/A \quad \text{so } P = I^2\rho l/A$$

...we should choose low resistivity, fat cables for low power
But this gives high percent radiation length:

$$\%X0 = lA/(X0 \text{ x sensor area})$$

So we have to compromise between power loss in cable and $\%X0$
Somewhere in the region 5 – 10 % of total power in cables in the inner tracker volume is OK

Silicon Sensor Heating

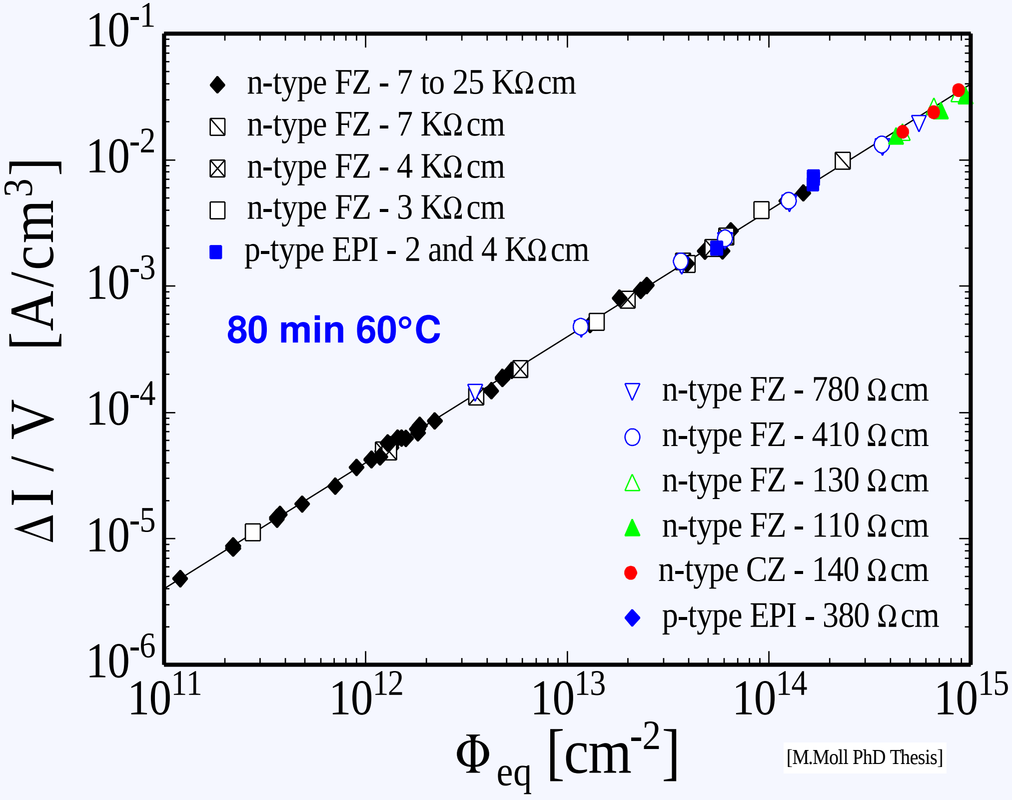
Same formula, $P = VI$. But now:

V has to be increased with radiation damage ~500 V for strips.
I depends on both radiation damage and temperature
Michael Moll et al show leakage current at high doses is very independent of detector type, and is linear over several orders of magnitude.

Plot leakage current per unit volume of detector vs. how much dose the detector received (in number of 1 MeV neutron equivalent per cm^2)
Straight line:

$$I = \alpha \Phi V$$

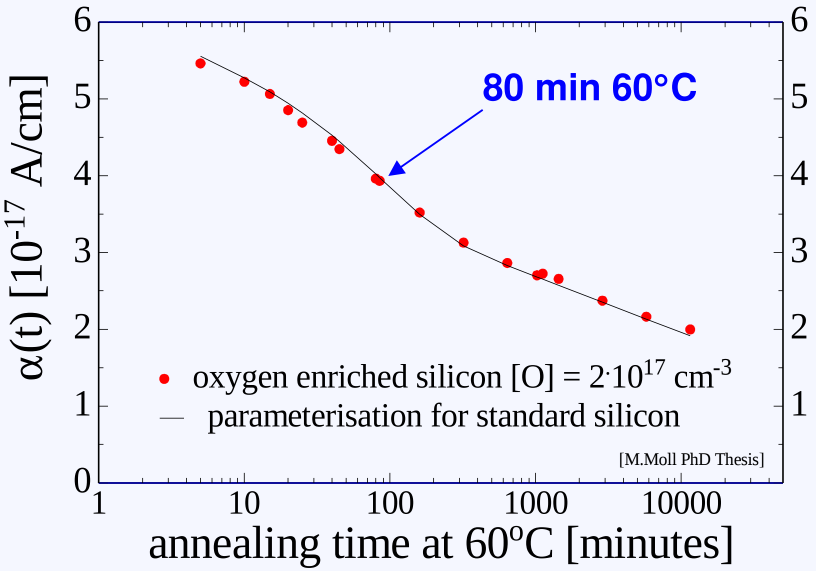
α depends on heat history of detector: warming it up repairs some of the damage, reduce leakage current
Plot is for 80 min at 60 degC
$\alpha \sim 4x10^{-17}$ A/cm



[M.Moll PhD Thesis]

Temperature dependence of α

- Annealing changes α:
  - 2 – 5 x 10^{-17} A/cm
- But also leakage current is temperature dependent
  - At higher temperatures, more electrons get shaken in to the conduction band
  - How many depends on the band-gap E_g of Si
  - Roughly every 7 °C rise doubles the leakage current.
- So we have to specify the temperature at which α is given. Plot is for $T_0 = 20$ °C = 293.15 K



Temperature dependence of leakage current:

$$I(T) = I(T_0)\ (T/T_0)^2 \exp(-E_g / 2k_B(1/T - 1/T_0))$$

K_B is Boltzman's constant, converts from eV to K. T, $T0$ in K.

Temperature dependence of band gap E_g

- As the silicon cools, the atoms get closer together due to thermal contraction.
- This affects the band gap energy.
- While there are models to understand this (e.g. Varshni relation), it is usually better to take measured values:
  - E_g = 1.136, 1.131, 1.126 eV at -20, 0, +20 degC.
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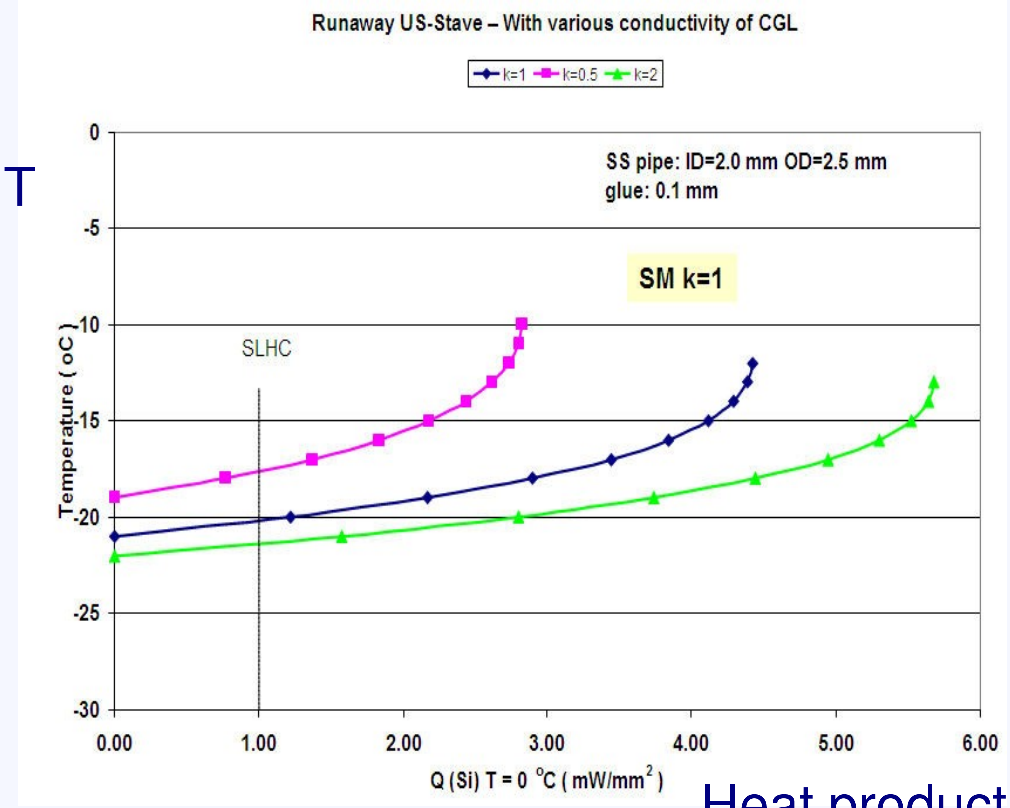
- This then gives a model for heat production that can be fed into calculations (hand or FEA modelling) for heat production.

Thermal Runaway

- Model is quite complicated because of the feed back: higher leakage --> higher temperature --> higher leakage current.
- But also higher temperature drives a higher cooling rate
  - At low enough temperatures, these balance, and you reach a stable cooling point
- But at a certain point, the cooling is insufficient, and the sensor goes in to "thermal runaway", eventually tripping the bias voltage supply.

Typical thermal runaway curves (Graham Beck)
As sensor radiation damage increases the heat production in mW/mm^3 at T_0 = 0 °C increases.
Initially there is a stable sensor temperature which slowly rises.
But at a certain point, this "runs away".



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Heat production

Convection

- Our cooling design keeps the sensors, which cover a large fraction of the surface area, cold: colder than the readout chips.
- The nitrogen atmosphere around the sensors cools to somewhere close to the silicon temperature.
- The chips are hotter: they therefore loose some heat to the nitrogen.
- In fact, the nitrogen temperature comes to equilibrium roughly where the heat into it from hot things like chips, equals the heat out of it into cold surfaces like silicon sensors and cooling pipes.
- But this heat transfer is not necessarily *local:* by convection, modules at the top can get quite a heat load.
- The heat flow per module into the gas is a small fraction – most goes into the CO2 coolant.
- But if this heat convects to the top of the detector, the heat from a large number of detectors can be absorbed by a small number:
  - It can be very significant!
- This needs some care. Modelled with computational fluid dynamics, CFD.
- Also inward heat leaks can be small per module, but have a large impact on some modules due to convection

Mitigating Convection Effects

- Reduce inward heat leaks with insulation
- Reduce the difference between hottest objects and coldest:
  - If every thing is at the same temperature, the atmosphere will cool to that temperature and then there will be no further heat transfer to the gas
- In practice, this means that we need well-cooled chips, even though chips can quite happily run hot.
- Finally, if needed, we can add extra cooling circuits at the top of the detector to absorb the convected heat instead of it going in to sensors.

Radiation

- Radiation is another heat transfer mechanism driven by temperature differences.
- However, I think it is not very important:
  - We do not have large temperature differences
  - There is no mechanism which concentrates the radiated heat of a large number of sensors onto a small number of sensors
- It does affect all our prototyping measurements:
  - We need to minimise radiative losses by e.g. running in a freezer or insulating very well

Beam Pipe Bake-out

- LHC vacuum pipe through ATLAS
- Has "getter" on inside
- Has to be heated (to ~300 ^{0}C) to refresh the getter properties (drive off the molecules attached to it) each time the beam pipe has been opened
- This procedure puts a large heat-load on the innermost pixel layer
- It is a driving factor in the design of the cooling plant and IBL
- (It is an example where radiation and convection are very important)

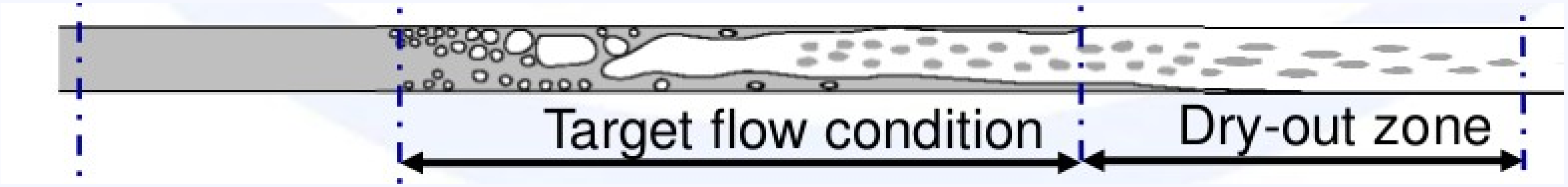
Heat Leaks

- ATLAS Rule:
  - Thou shalt not cool nor heat thy neighbours
  - I.e. all systems should be thermally neutral.
- Inner Tracker is cold (below ambient)
  - Heat flows in!
  - Can reduce with insulation, but not eliminate
- Fixed by adding heaters!
  - Seems bizarre: we want to minimise heat sources, and then go add heaters.
  - But there is no other way.
- We also need heaters outside to prevent condensation and ice build up
- This heat then flows in to our detectors giving an extra heat load. Or:
  - We can also add cooling on the inside of our thermal enclosure to absorb this heat
  - "Active thermal barrier"
    - Can be very thin, low insulation, yet have a high temperature drop without any heat flow from our neighbours or into our detectors
  - In practice, it is a lot of effort and risk (leaks) and we avoided it in the current inner tracker

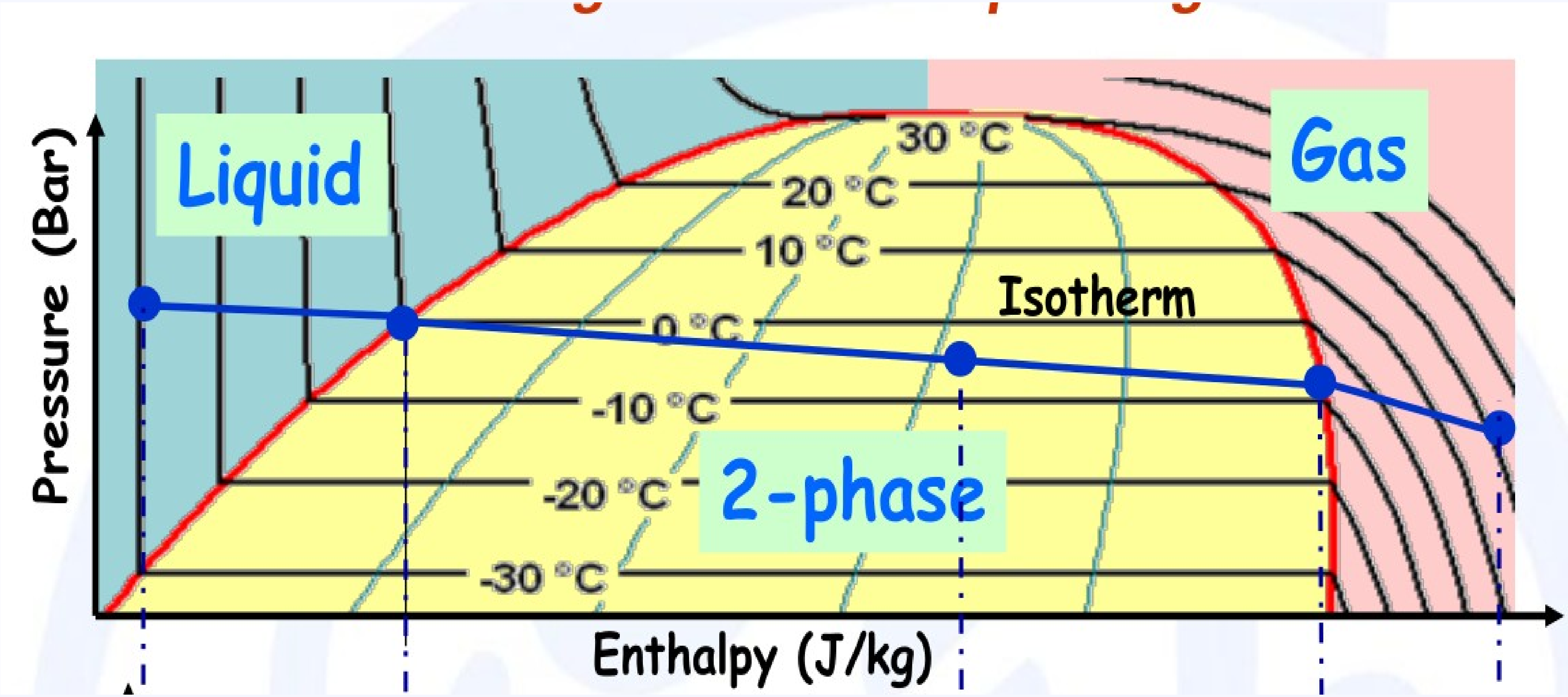
Cooling

Evaporative Cooling

- Pictures and info from talks by Bart Verlaat, Nikhef, CO2 expert.
- Liquid in, gas (and left-over liquid) out
- Latent heat of evaporation absorbed by the liquid is provided by the thing we want to cool
- Latent heat of evaporation is "big": e.g. water has heat capacity 4.2 J/gK but latent heat of evaporation of 130 J/g: so boiling ~ heating by 30 deg C
- No temperature change with heat input – very useful for uniform temperatures along a stave
- The boiling process is very violent: bubbles of steam form and float very fast through the liquid, transfering heat rapidly into the bulk
  - Gives very high heat transfer coefficient ($W/m^2/K$)
  - Allows small tubes – low material; easy bending; low forces due to CTE mismatch



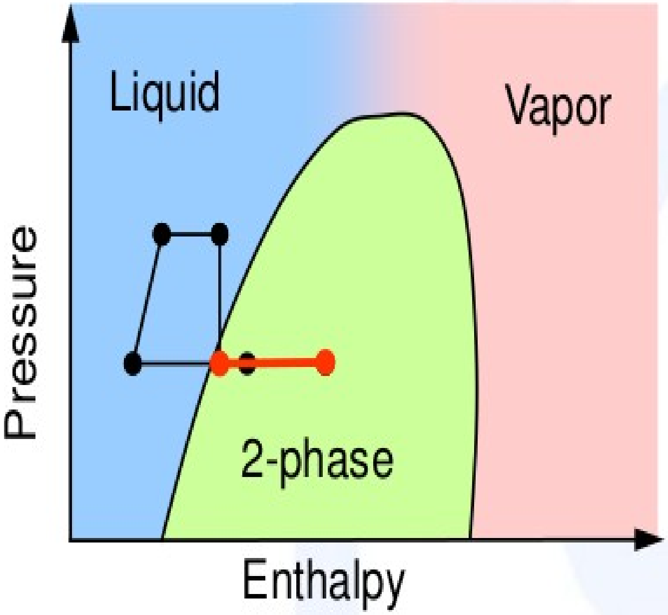
Pressure – Enthalpy Diagram

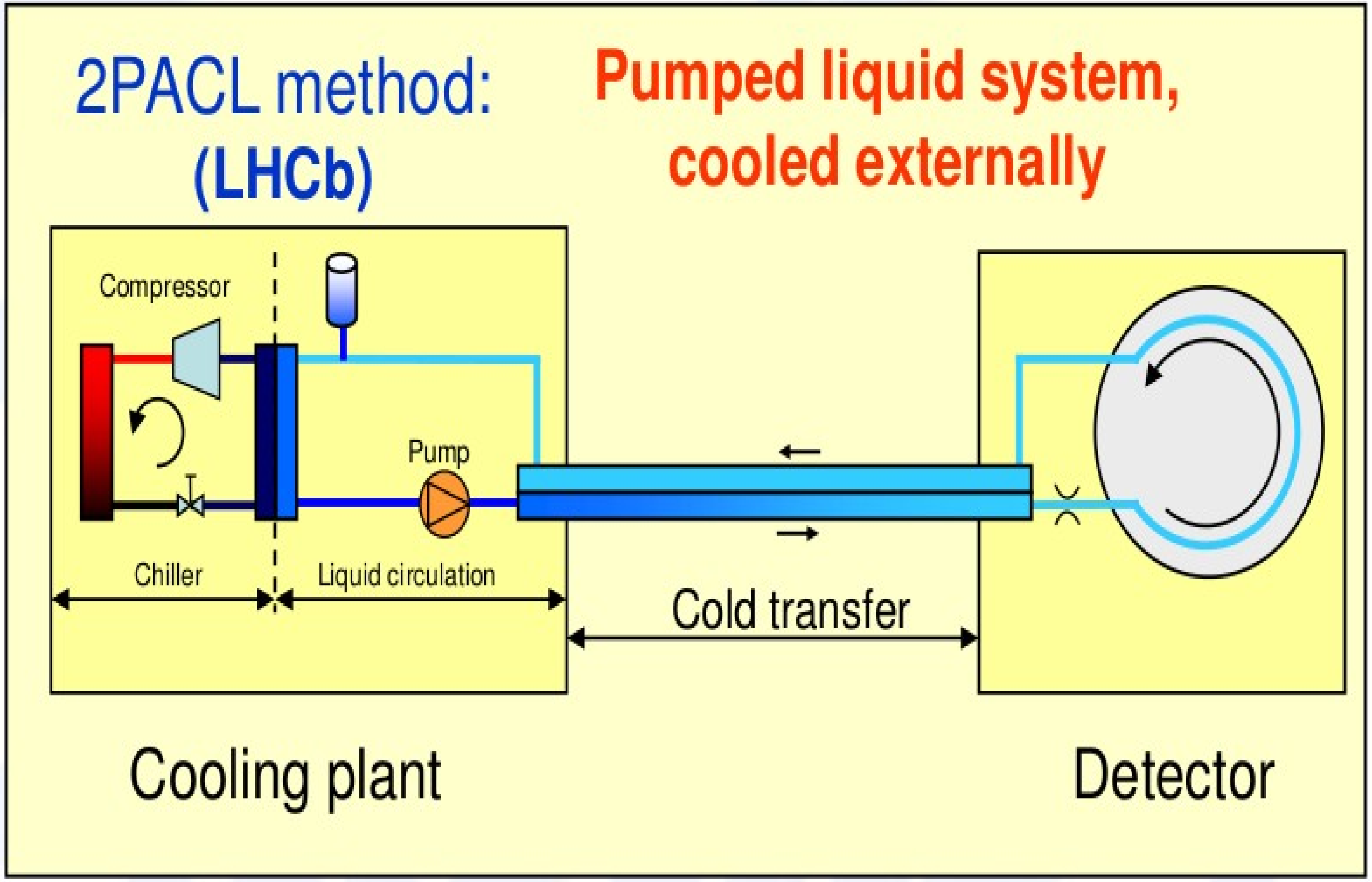


CO2 as coolant

- CO2 has high latent heat, low viscosity, and liquifies at high pressure (compared to many other fluids we could consider): 70 bar at room temperature. It has very high heat transfer coefficient. And it can cool well below -40 C – cold enough for us.
- These make it very good for us.
- The high pressure needs some care, and makes difficulties finding standard parts etc.
  - But it is the main reason for the high heat transfer coefficient: high pressure keeps the vapour dense, so it transfers "more heat per bubble"
  - This allows narrow diameter tubes
  - Which can have narrow walls despite the high pressure
  - Hence good for %X0 (despite what everyone's gut reactions say)
  - The high pressure also means that small pressure drops due to flow along narrow tubes have very little temperature effect
    - Note another bizarre property: The pressure drop due to flow along a tube gives a temperature fall – boiling point is lower at lower pressure. This is despite putting heat into the fluid.

IBL Cooling Plant

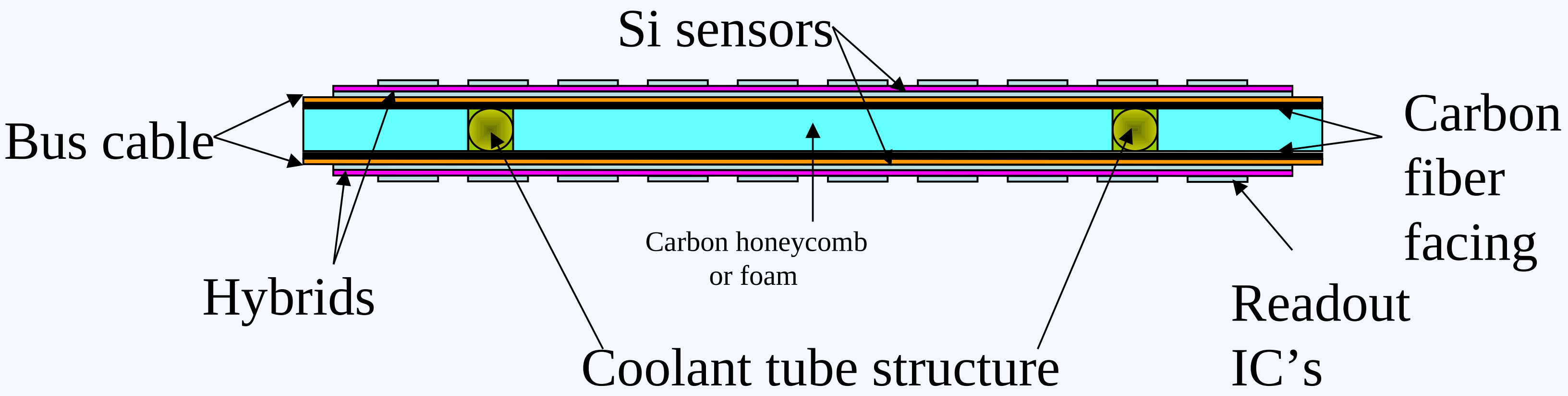




2PACL method: (LHCb)

Pumped liquid system, cooled externally

Staves and Petals



- Combine mechanical support and cooling functions in one
- Use carbon fibre reinforced plastics (CFRP)
  - High Young's Modulus
  - High thermal conductivity
  - Very long radiation length (so low %X0)
- Titanium cooling tube ~2 mm diam., ~0.1 mm wall thickness – low %X0
- Carbon foam to get heat in to tube
  - Low density, hence low %X0

FEA

- Many heat sources
- Many different materials (different thermal conductivities) in 3D arrangement
- Distributed heat production – many individual sources
- Temperature dependent heat production of sensor
    - All makes it unrealistic to make direct calculations
    - Instead, we use Finite Element Modelling
- Also the CO2 fluid is very difficult to model
    - Models do exist, e.g. Prof. J. Thome from EPFL Lausanne
    - But mostly, we just treat the tube wall as a constant temperature
- We verify the FEA with prototype measurement
- We can then trust our model, and optimise the stave design

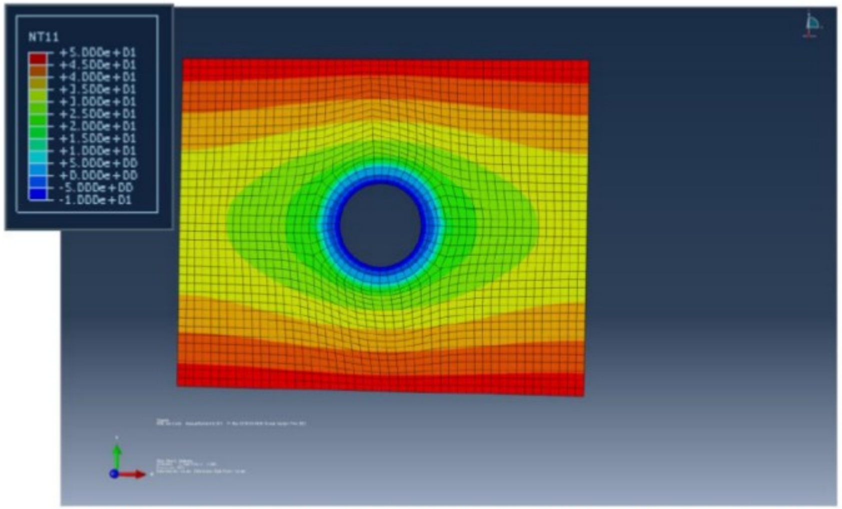
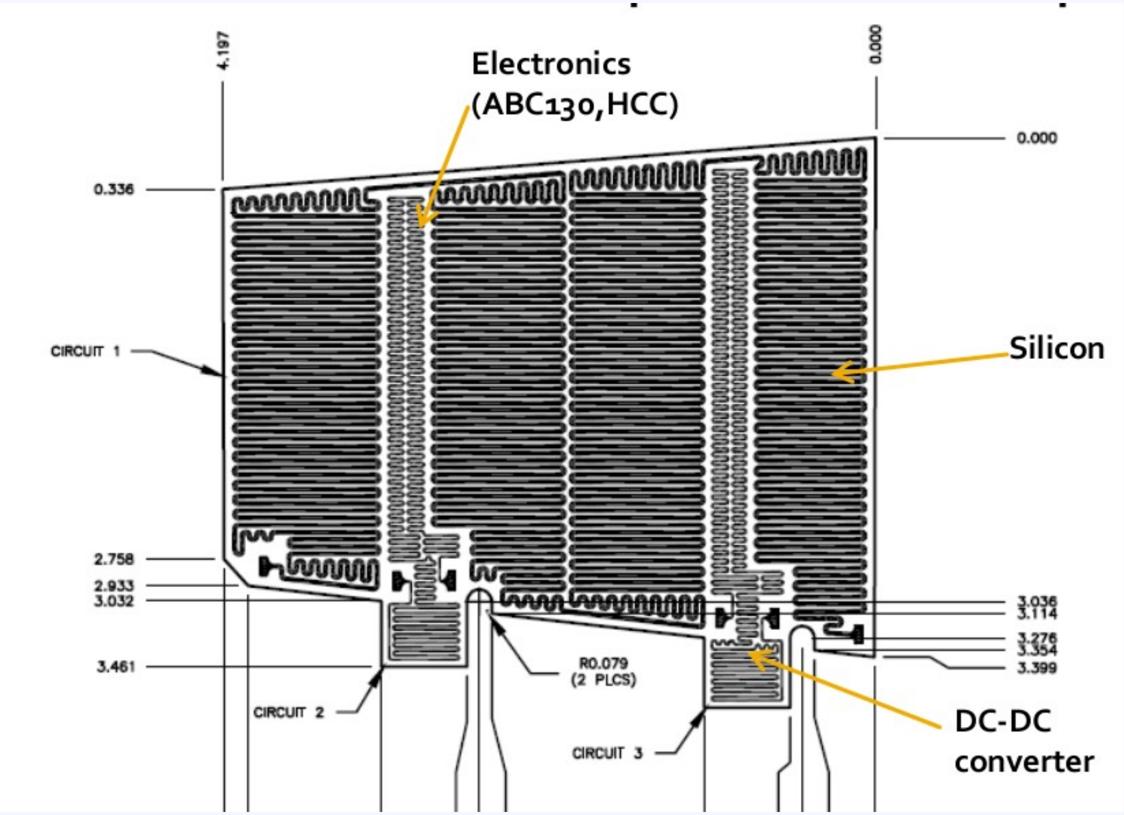


Figure 10: Figure 3: Simple 3D planar shell with hole consisting of 3 different materials(starting from the top: k1x=135, k1y=60,k1z=60, k2=10, k3=60 [W/mK]) and boundary conditions Ttop=50°C, Ttube=-10°C, Tbottom=50°C

Prototyping

- Make a stave (cooling pipes, foam, support)
- But: rather expensive to use real sensors (irradiated!) and electronics etc.
- So we glue on dummy silicon sensors (just plain Si metal) with correct glue pattern
- Add heaters to the silicon
  - Heaters deal with sensor, readout chips, module controller chips, DC-DC converter inefficiency heat sources
- Heat and cool with a CO2 plant
- Measure silicon temperatures and compare with FEA predictions



Summary

- Main heat source: the readout chips
- Sensor heating after radiation damage is significant (especially at end of HL-LHC)
- Several other sources must also be allowed for: heat leaks, radiation and convection; cables; power converter inefficiency...
- Cooling system must have enough margin to be guaranteed to work, while minimising material (%X0).
- FEA is an important tool for thermal management. It needs correct input to give meaningful results, as well as verification with prototypes.

References

- ATLAS upgrade ID cooling system requirements, G. Viehhauser et al, https://edms.cern.ch/document/986779
- B. Verlaat, Evaporative CO2 cooling for thermal control of scientific equipments
  - SLAC Advanced Instrumentation Seminars