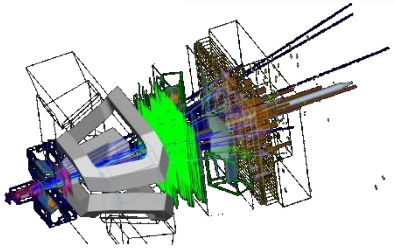


Scintilator Fiber Tracker,

Review of the SiPM cooling system

20 February 2015

Bart Verlaat, Petr Gorbounov

SciFi Tracker cooling Infrastructure

SiPM Cooling
(single-phase liquid)
$T_{SiPM} \leq -40°C$

Cooling plant for (fluorinated) the fluid coolant, low-loss transfer lines ($L_{plant\text{-}detector} \approx 100$ m)

New project (CERN EN/CV)

Electronics Cooling
(DI Water, $T_{PACIFIC} \approx 50°C$)

Upgrade/refurbishing of existing OT cooling facility
(23 kW -> ~30 kW)

Upgrade project (?)

Dry Gas Supply
(flushing/purging/venting)
Normal dew point ≤ -60°C

Class 1 or 2 desiccant compressed air dryer + low-P pipes (technical compressed air supply or a local ~30 m3/h compressor)

Minor work package (CERN EN/CV)

Optional: Vacuum system for thermal insulation

Pressures $<10^{-4}$ mbar needed for thermal resistance

Separate project or integrated in SiPM cooling plant?

SiPM Cooling

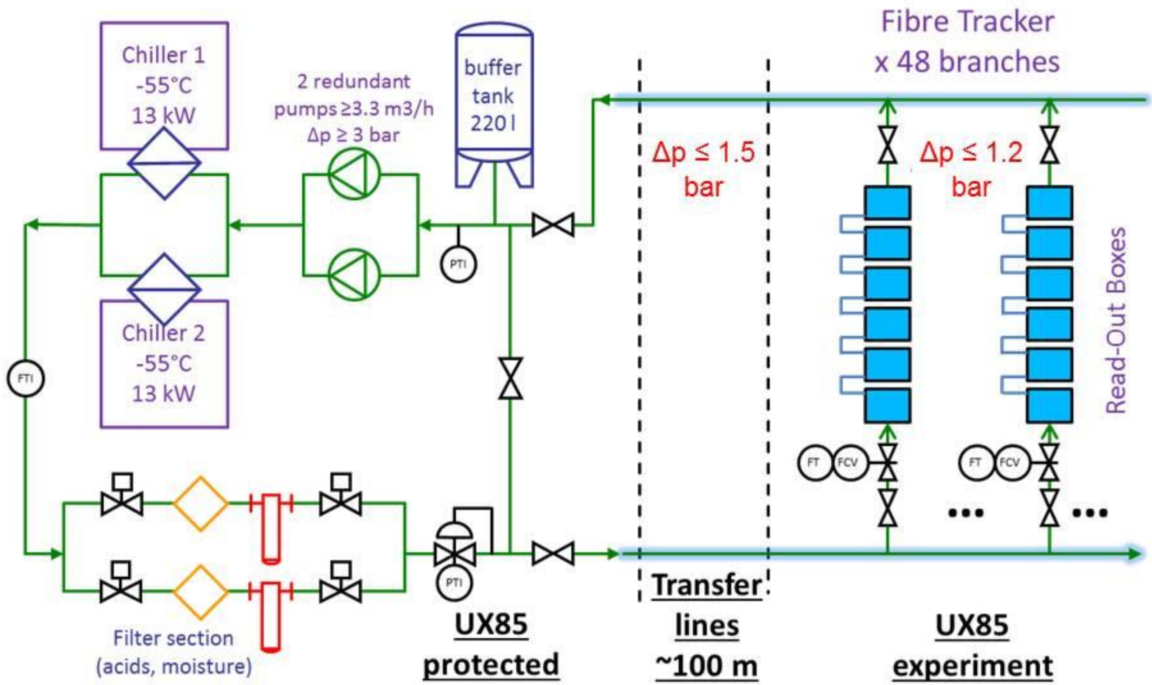
Gross features:

- Conventional single-phase liquid cooling
- Use of environmentally-friendly and safe coolant (zero ODP, low GWP)
- Relatively low SiPM working temperature: down to -40°C
- Large detector extent (total length of SiPM arrays: ~150 m)
- Estimated heat load at the tracker side, excluding local interconnections : ≤ 20 W x 288 ≈6 kW

Major cooling plant design input parameteres (subject of interest for this WS!):

- $\dot{Q}$, required useful cooling power (proper detector and local interconnections heat loads)
- $\dot{V}$ and $\dot{M}$, Volume and Mass flows
- T and P, coolant Temperature and Pressure at the distribution point
- ΔP, expected pressure drop at the detector side
- Temperature stability and accuracy
- Coolant:
  - Total amount
  - thermo-physical properties as functions of T (density, viscosity, boiling point; to a lesser extent - specific heat, thermal conductivity)
  - chemical properties (compatibility with materials, reactivity, requirements on purity etc)

Infrastructure
(TRD concept, pioneer work by Petr Gorbounov)



$\dot{Q}$ = 13 kW (assuming 20 W/coldbox)

$\dot{V}$ = 3.3 m3/h

T ≈ 54°C

P = 2.3 bar

ΔP = 1.2 bar (incl. interconnections)

Coolant: Novec 649 (fluoroketone)
or C6F14 as backup
≈330 kg (213 l @ 40°C)

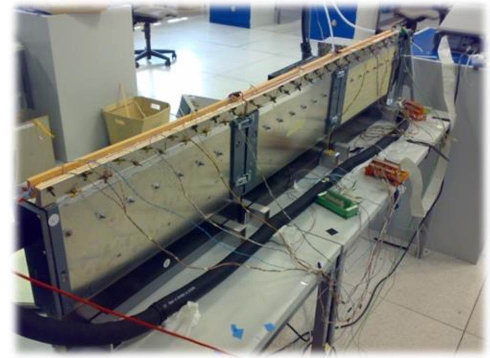
Dry gas: air, ≈ 35 m3/h (all services)
normal DP < -60°C

Temperature stability and accuracy:
±0.1K

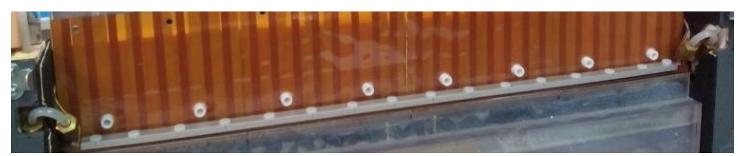
6 ROB's in serie

- Commercial chiller
- Temperature control: built in the chiller or by external heater (not shown)
- Moisture and acid filters
- Chiller, pump, filter group: duplicated (hot spares)
- Transfer lines: ≤12 W/m pick-up
- Cost: 300-330 kCHF

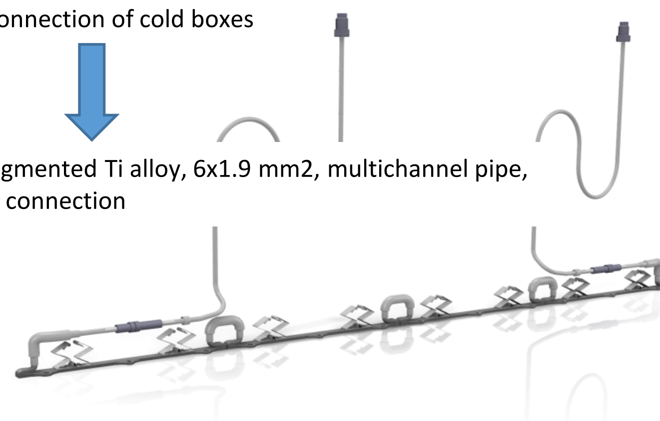
Post-TDR developments



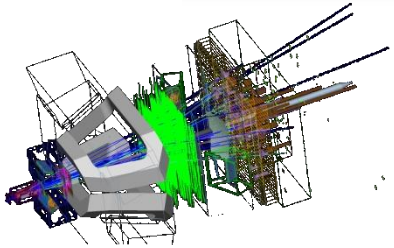
- **Thermal tests** with real-size mock-up CB at CERN (see Orsay'2014)
  - dummy SciFi mats, SiPM arrays and flex cables
  - real TDR-style cooling and insulation structures
  - C6F14 and Novec 649 coolants
  - Linear heaters simulating r/o electronics
  - measured heat load at the average T_{SiPM}=-40°C and $T_{PACIFIC}$=50°C: **14.2 W/CB** (*cf* 20 W in TDR)
  - ΔP per branch @ T_{SiPM}=-40°C : 1.4 bar (incl. ~0.3 bar in the inlet and outlet connections)
  - TDR assumptions have been validated
- Work on the **coolant validation** initiated (October 2014). Work package started (end January 2015)
  - 2 types of candidate fluids are under test: commercial fluoroketons (GWP=1) and segregated HFEs (GWP≈300); compared with perfluorocarbon C6F14 (GWP >10^4)
- **Engineering design of the ROB** at NIKHEF
  - Design studytaking into account modularity, serviceability and design Integration
  - Main problem is fitting inside the tight volume insulated cooling lines. Vacuum insulation seems the only option.
  - baseline option: parallel ROB connection to the cooling, segmented cooling bar for thermal expansion
  - New design considerations have impact on the previous mentioned TDR numbers. Larger flow



TDR: straight copper square 7x7 mm2 pipe with round inner bore 4 mm; serial connection of cold boxes

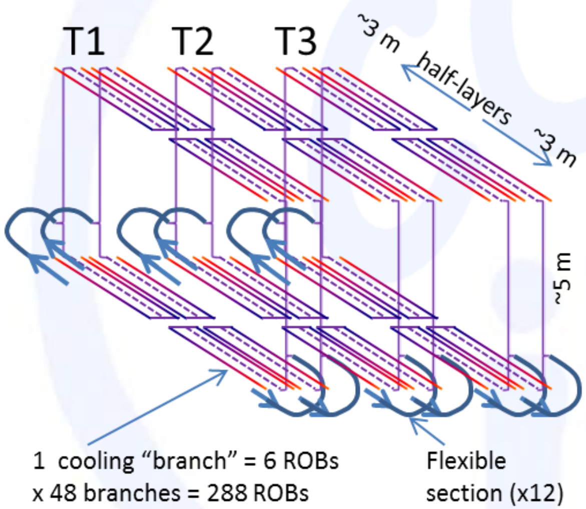


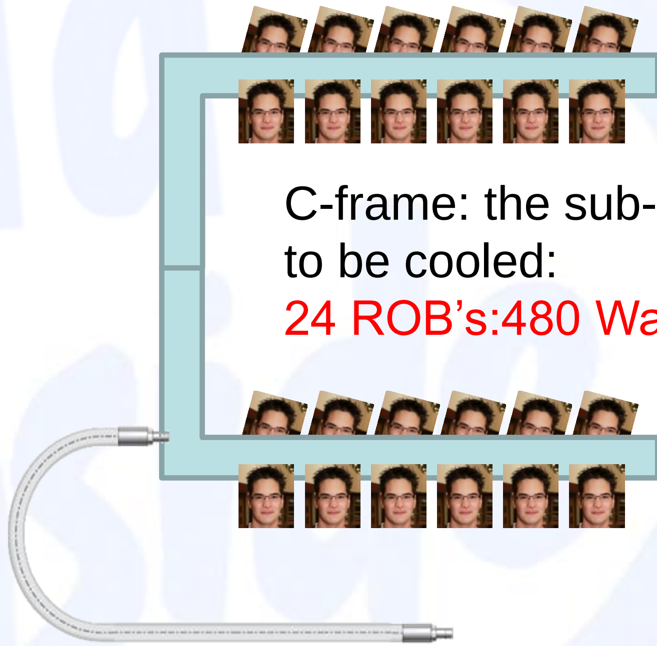
EDR: segmented Ti alloy, 6x1.9 mm2, multichannel pipe, parallel connection



SciFi cooling optimization

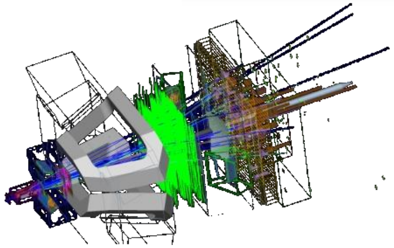
- The SciFi modularity is similar than the current OT.
  - 2x3 C-frames per side = 12 C-frames
  - 12 C-frames x 24 ROB's = 288 ROB's
  - 288 Robs x 20Watt = 5760 Watt



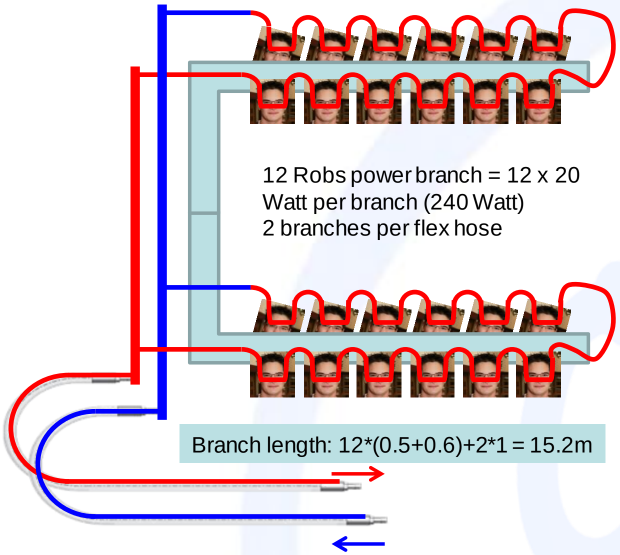


1 flex hose pair per C-frame

- How to connect all ROB's to the cooling?
  - Option 1: All upper (or lower) ROB's in series (12x per loop, 2 loops per C-frame)
  - Option 2: All Robes of 1 side in series (6x per loop, 4 loops per C-frame)
  - Option 3: All ROB's parallel (1x per loop, 24 loops per C-frame)

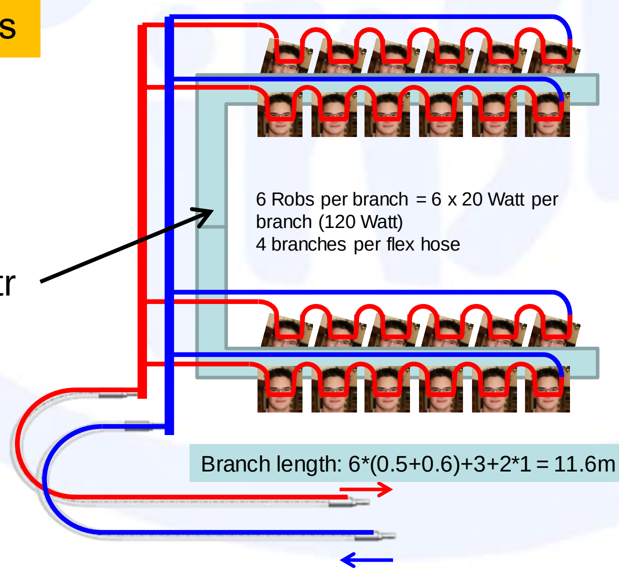


Different cooling layouts

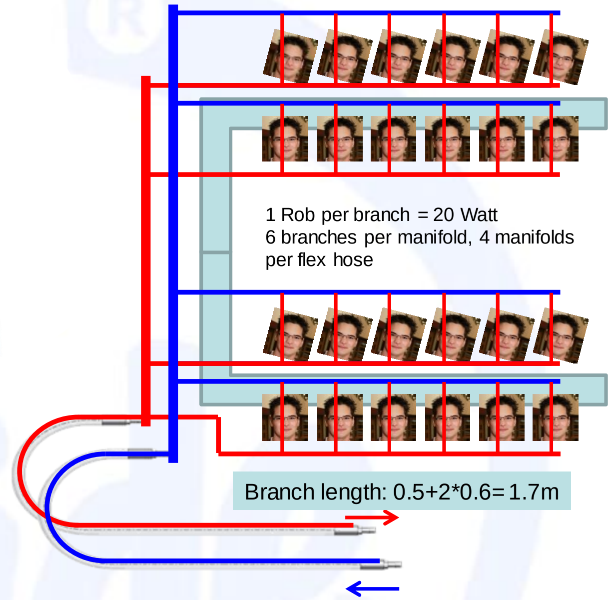


Option 1: 12 Rob's in series

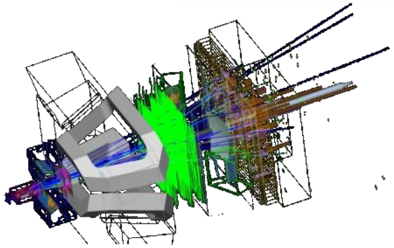
Option 2: 6 Rob's in series



Option 2 tested by Petr



Option 3: All Rob's parallel



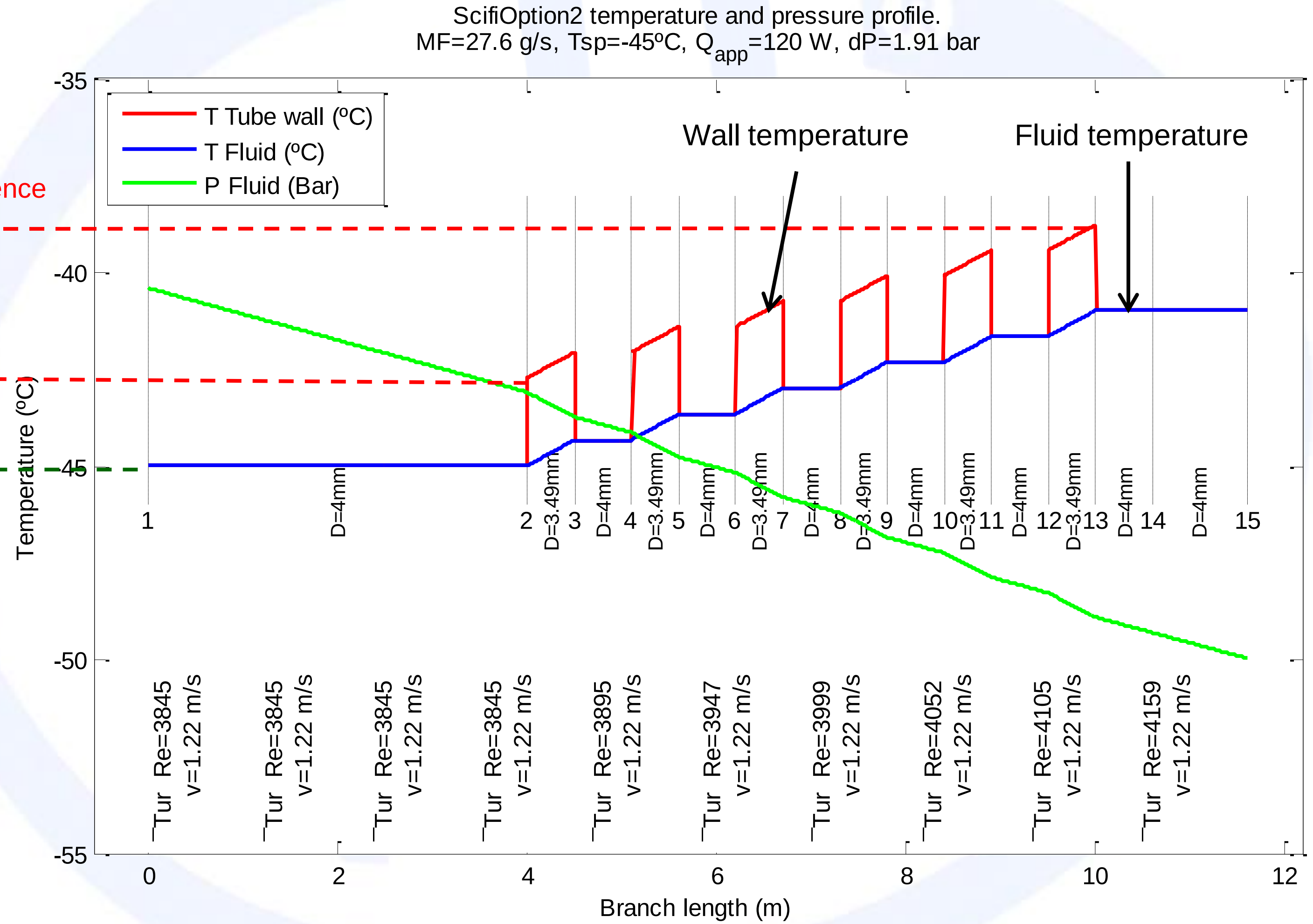
Temperature gradients modelled by CoBra

Important for SiPM gradients

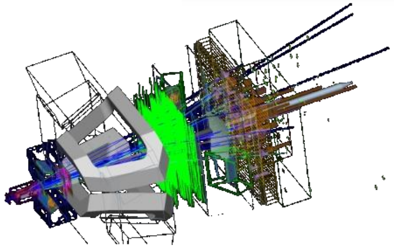
Maximum SiPM temperature difference

Maximum temperature gradient

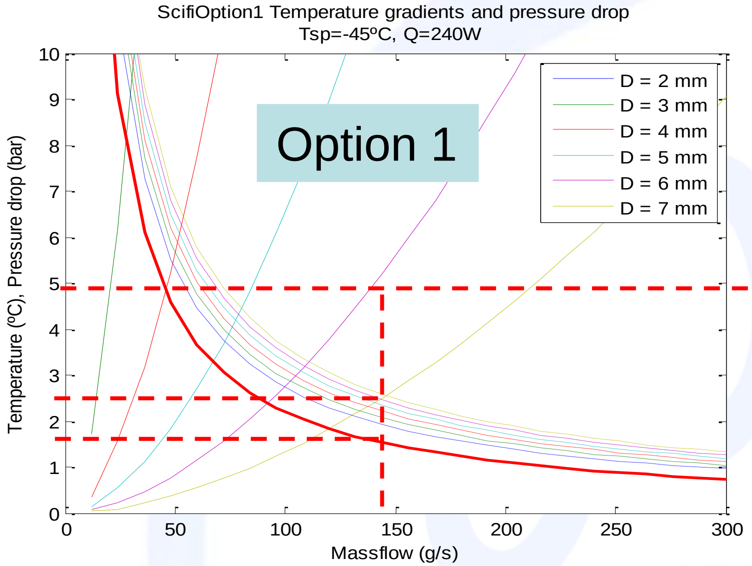
Important for cooling temperature

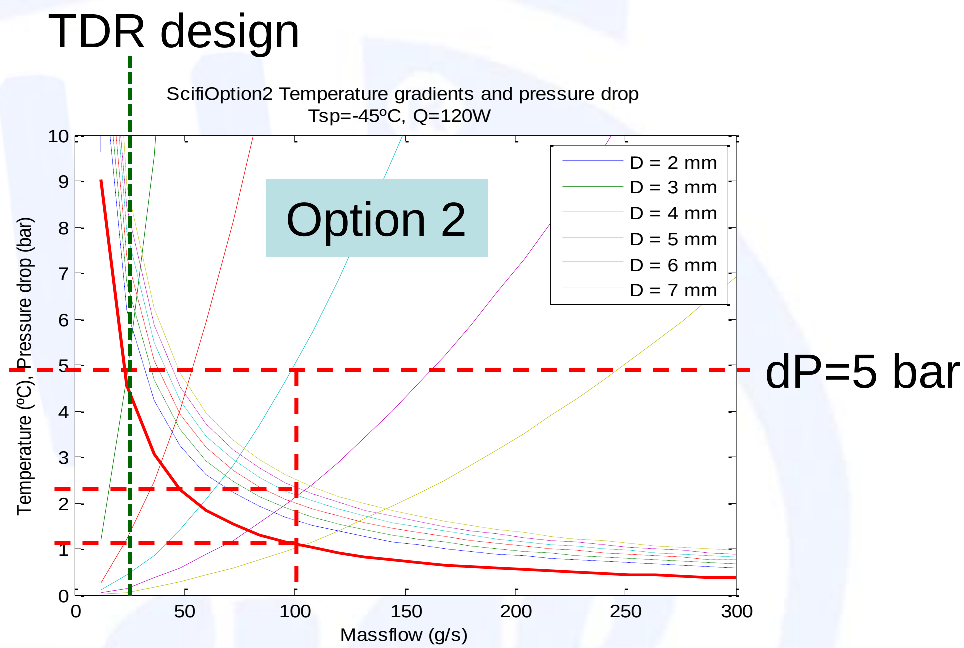


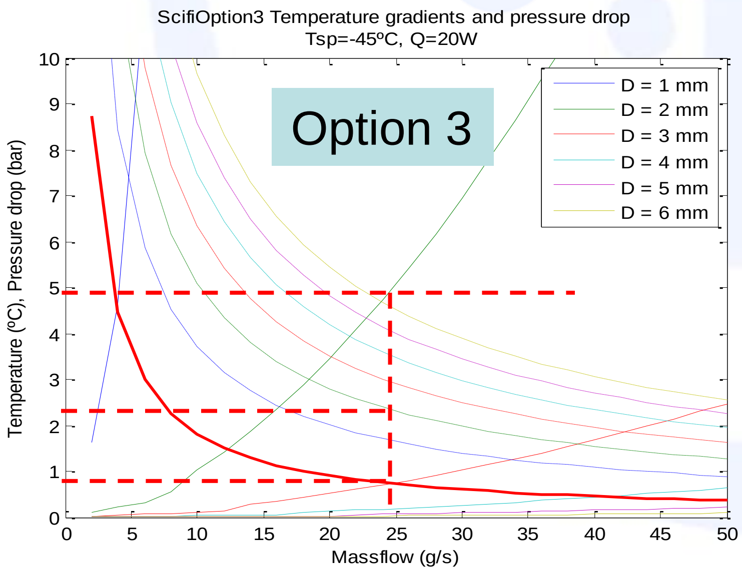
CoBra is a model calculating temperature profiles in tubes, developed originally for CO_2.



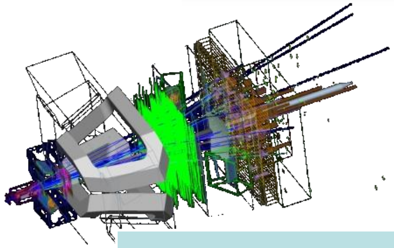
Selecting diameters





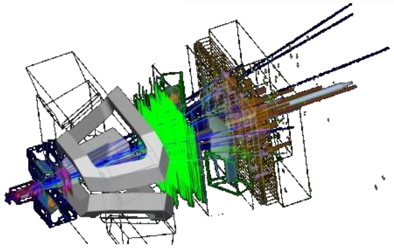


- Diameter selection:
  - Choose allowable dP (eg. 5 bar)
  - Draw a vertical line in the section where the lines are flattening out horizontally. (-> Low dP)
  - Find the desired diameter
    - Option 1: ca. 6mm
    - Option 2: ca. 5mm
    - Option 3. ca. 2mm



Summary table including prediction for connection lines

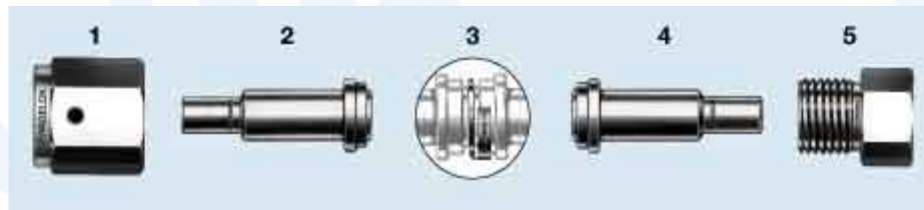
	Option 1	Option 2	Option 3
Cooling branch inner diameter	6 mm	5 mm	2 mm
Temperature gradient between SiPMs	1.5°C	1°C	0.8°C
Temperature gradient between coldest cooling and warmest SiPM	2.2°C	2.4°C	2.2°C
Pressure drop per branch (Bar)	5 bar	5 bar	5 bar
Mass flow per branch	140 g/s	100 g/s	25 g/s
Total C-frame mass flow	280 g/s	400 g/s	600 g/s
Flex line inner diameter based on 0.2 bar dP	12mm	14mm	16mm
Environmental heat pick-up in flexlines with 40mm foam	12x52 W = 624 W	12x54 W = 648 W	12x56W = 672 W
Total system mass flow	3360 g/s	4800 g/s	7200 g/s
Transfer line inner diameter based on 1.5 bar dP	37mm	42 mm	50 mm
Environmental heat pick-up in transfer line with 40mm foam (5.8kW in SciFi)	1.59 kW	1.7 kW	1.87 kW

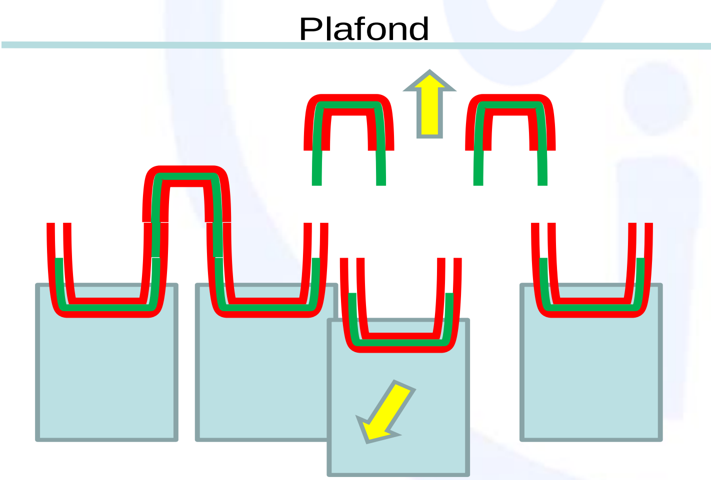


SciFi fluid connections

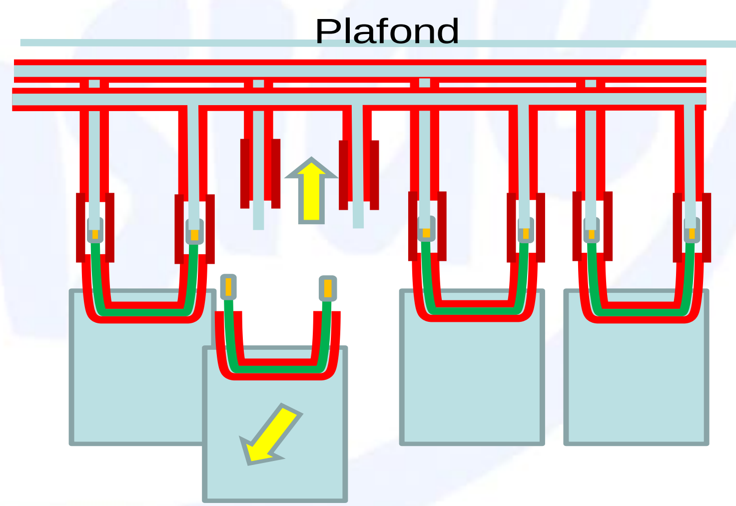
- With a parallel option diameters around 2mm are feasible.
  - This gives the option of using 1/8” VCR connectors which are small enough to fit inside ½” VCR connectors for a possible vacuum connector.
    - ½ “ VCR connectors for vacuum fit in Scifi geometry!
- The serial option needs larger vacuum connectors and we have no solution to make it fit in SciFi

D_{max} 1/8“VCR=12.8mm
D_{max} 1/2”VCR=31.2mm

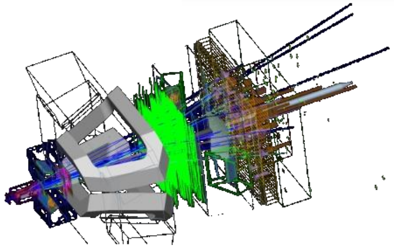




Serial option with Johnson type connectors

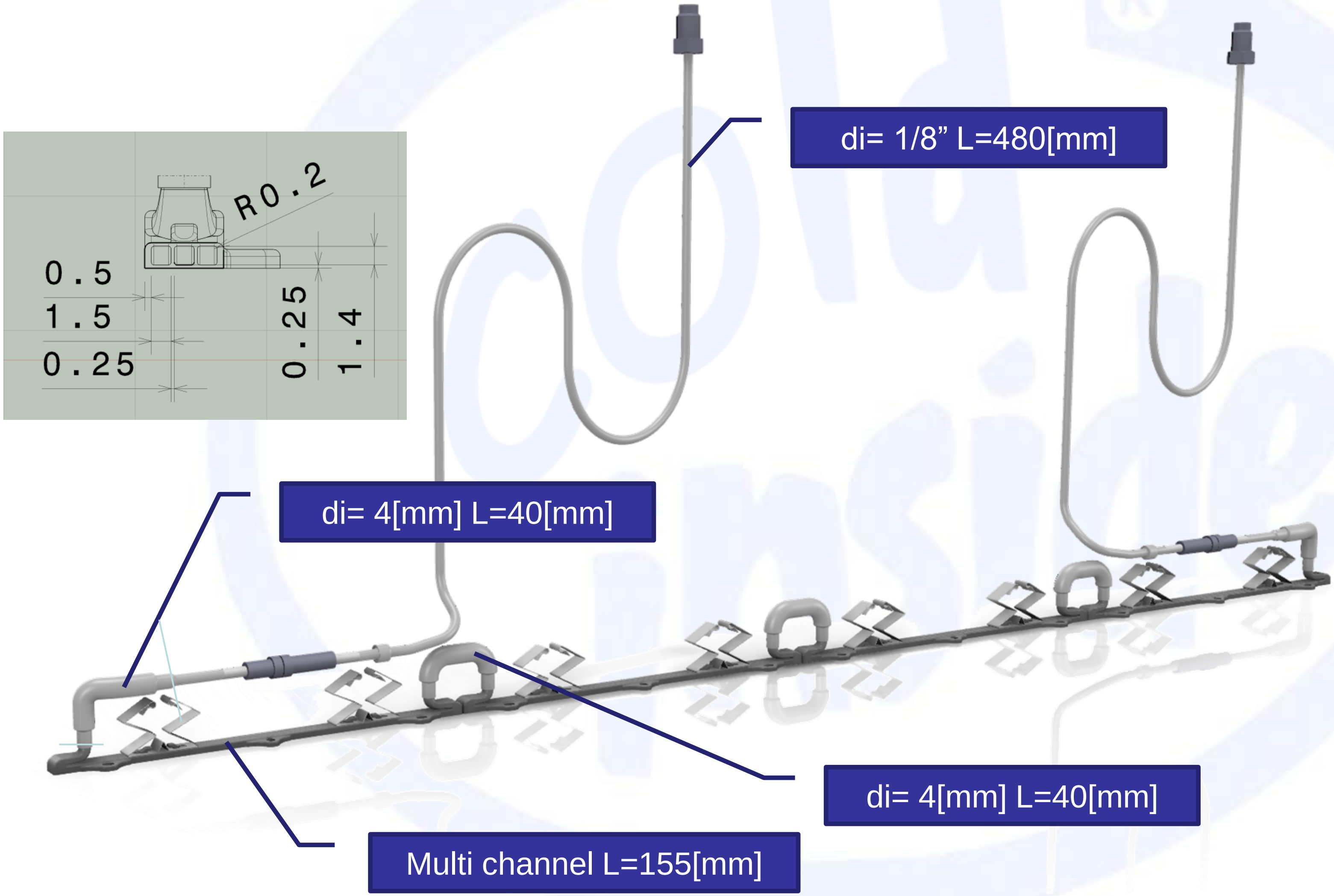


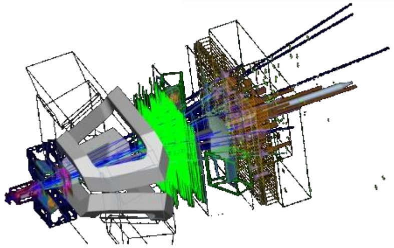
Parallel option with vacuum connectors



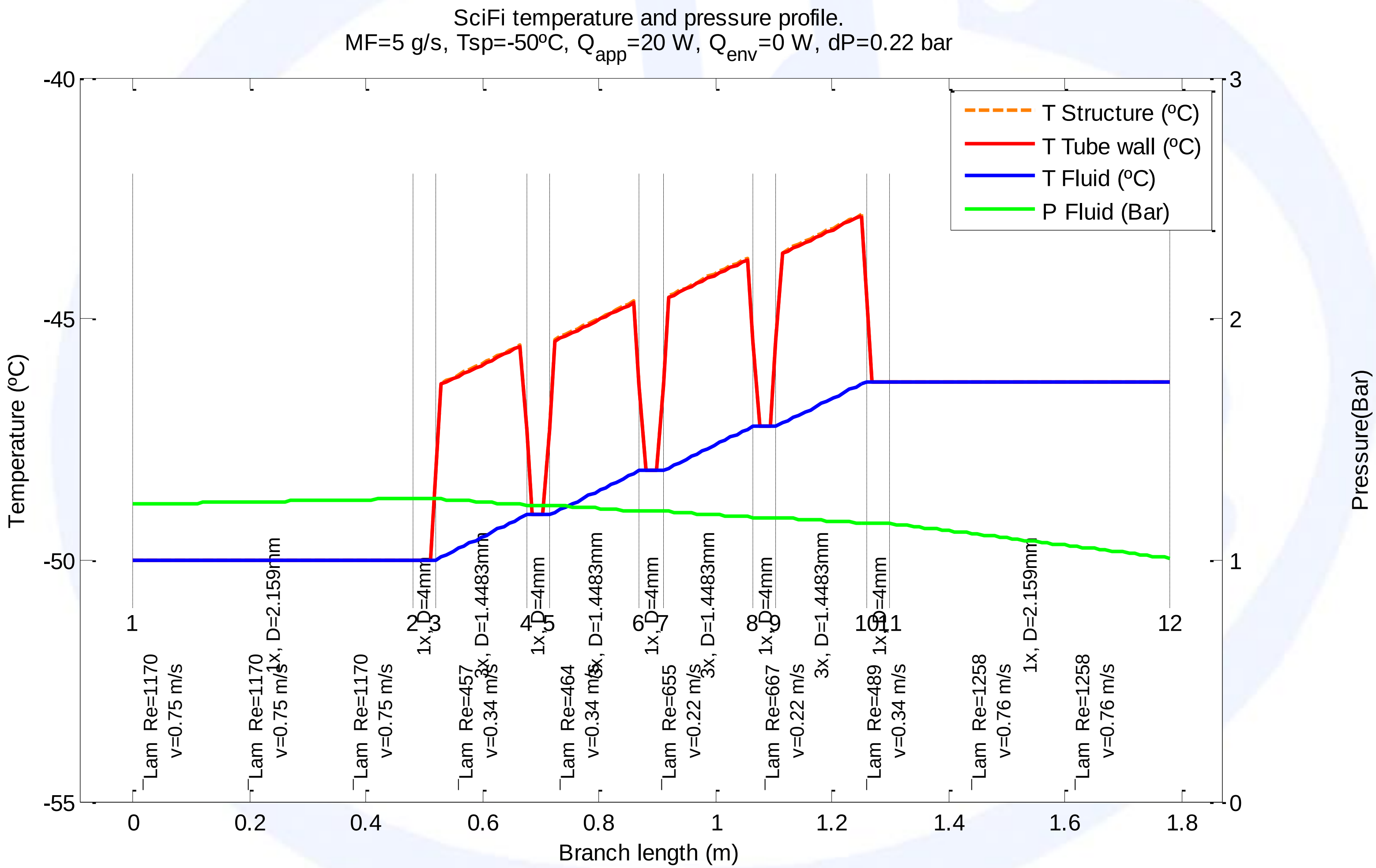
Analyses of new parallel cooling design

Based on 1/8” VCR dimensions

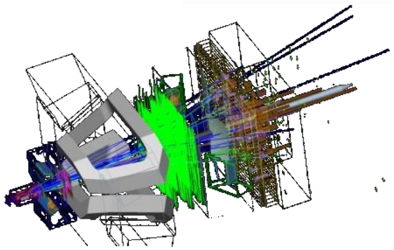




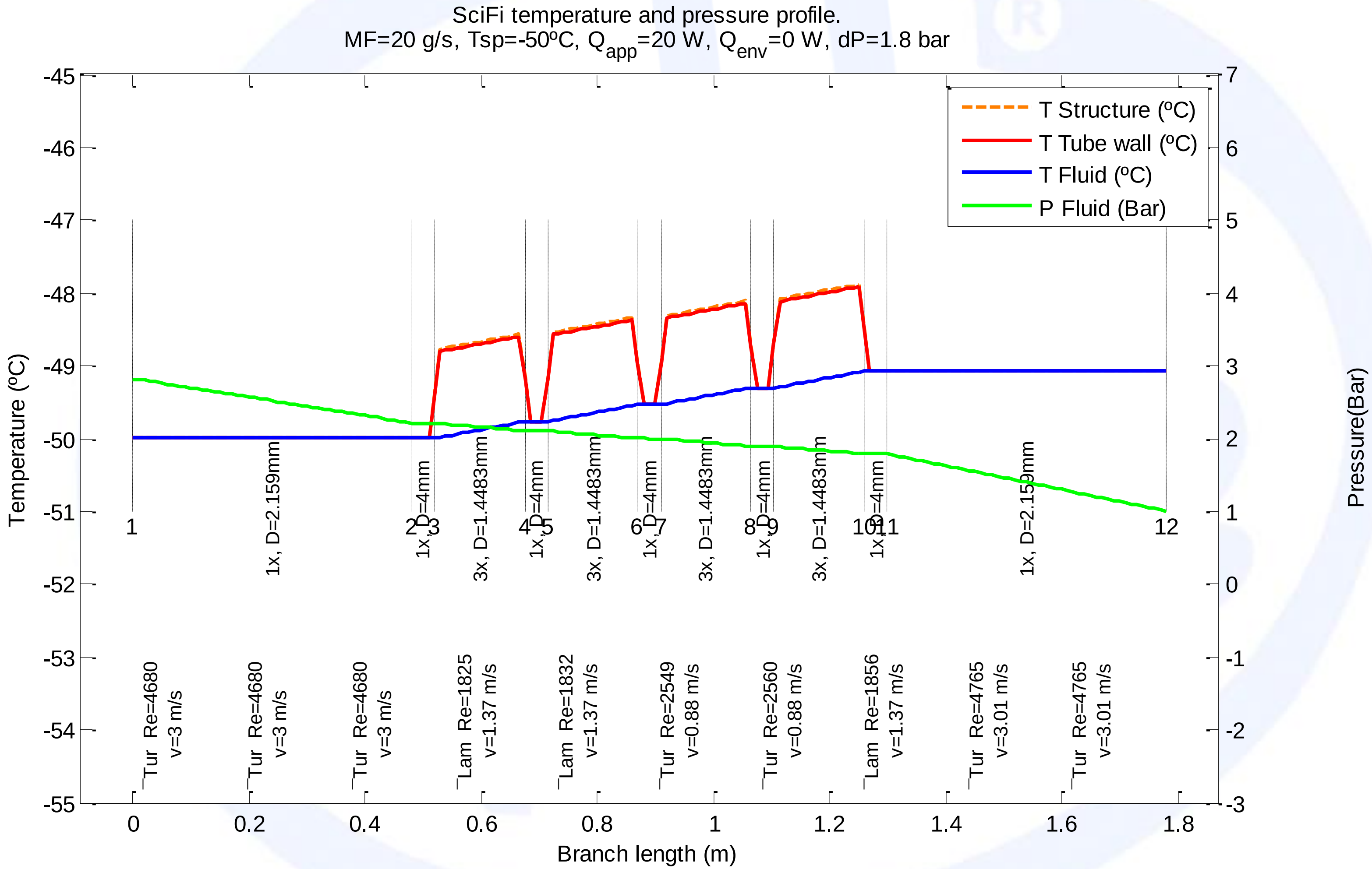
New parallel design
5 g/s flow



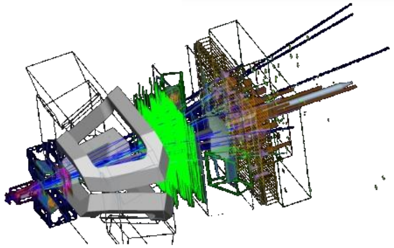
HTC=667 W/m2K



New parallel design
20 g/s flow



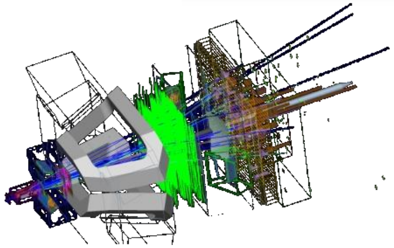
HTC=2008 W/m2K



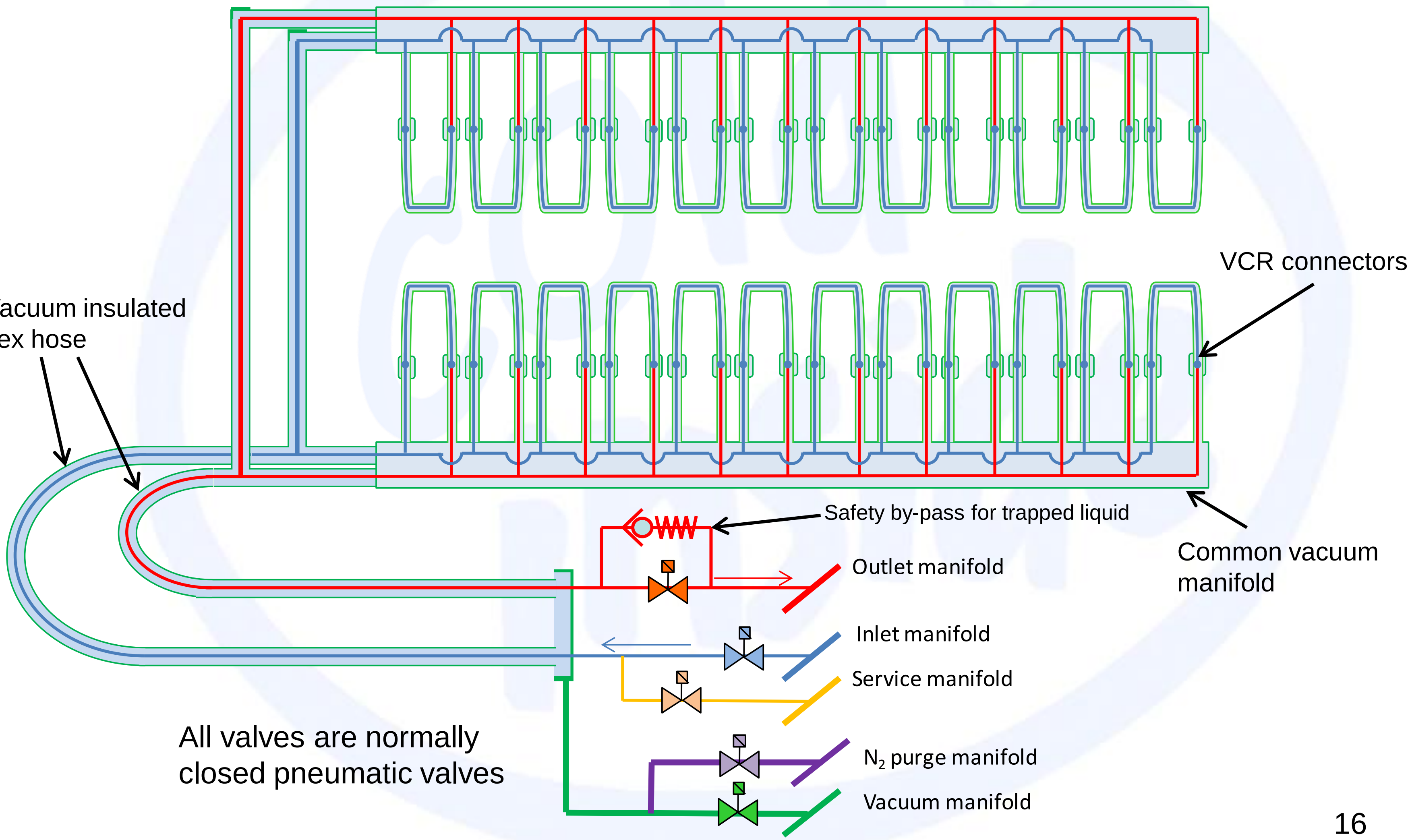
What are functionalities of the cooling system at C-frame level?

- Cooling 
- Insulation 
- Modularity (1 ROB can be removed) 
- Fluid draining.. 

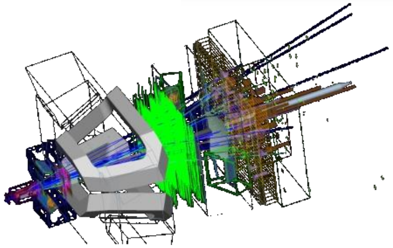
  - Novec draining by gravity is hard. There are lots of local low spots.
  - Novec may not get in contact with water so air exposure is critical
- Can we drain Novec by evaporation as we do with CO_2?
  - Most likely yes, Novec has a saturation pressure of 0.32 bar @ +20°C, this means if we can lower the pressure below 0.32 bar the Novec evaporates out of the cooling loops if a colder reservoir is present. Vacuum insulation needs purging for necessary heat transfer.



P&ID at C-frame



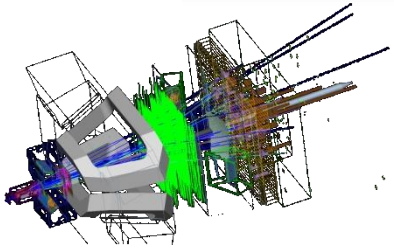
All valves are normally closed pneumatic valves

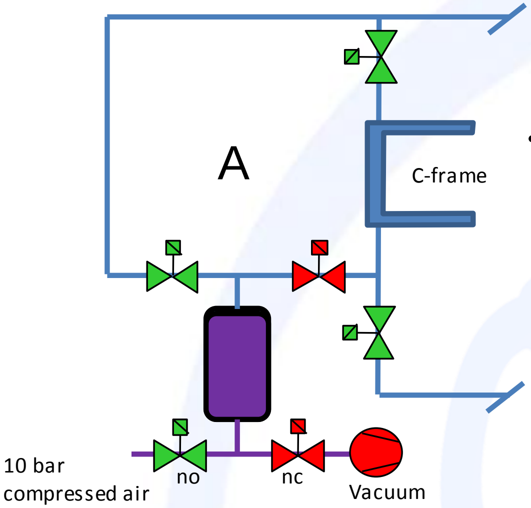


Liquid draining by evaporation

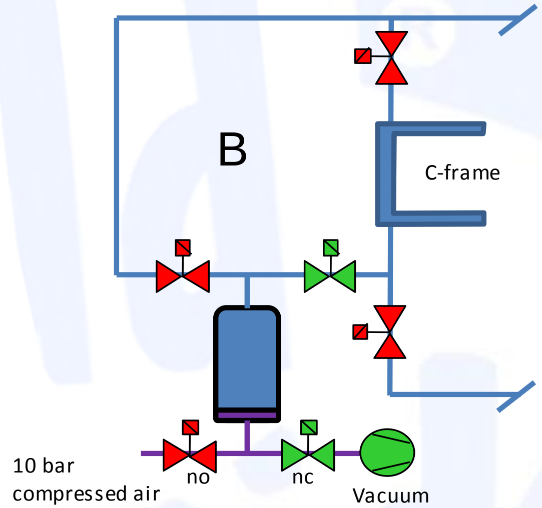
- When the volume containing a pure liquid is enlarged, the homogeneous density is lowered and a 2-phase mixture evolves.
  - Estimation of buffer volume: >1.5x C-frame volume
- Pressure of the system need to be below 0.32 bar for Novec.
- When an pressure controllable expansion vessel is used (0-10 bar) this can be achieved.
- Vessel need some cooling to be colder than C-frames. All liquid is collected in the expansion vessel.
- Once stabilized, the loops contain only warm Novec gas and can be disconnected from the system. Only loss is gaseous Novec, no liquid dripping!
  - Estimation: 2-5 g/liter C-frame volume lost (density of Novec gas)

C-Frame emptying procedure by evaporation

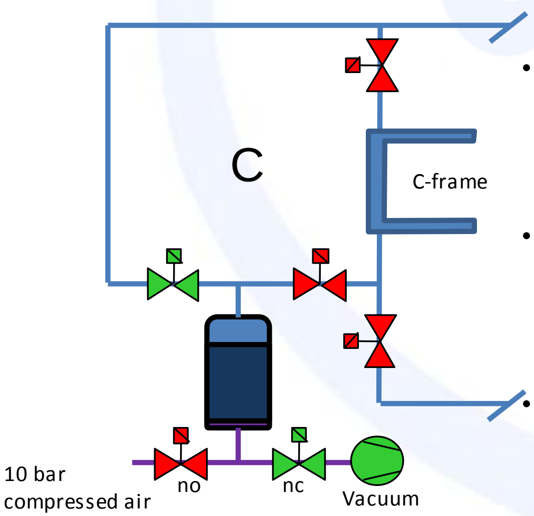




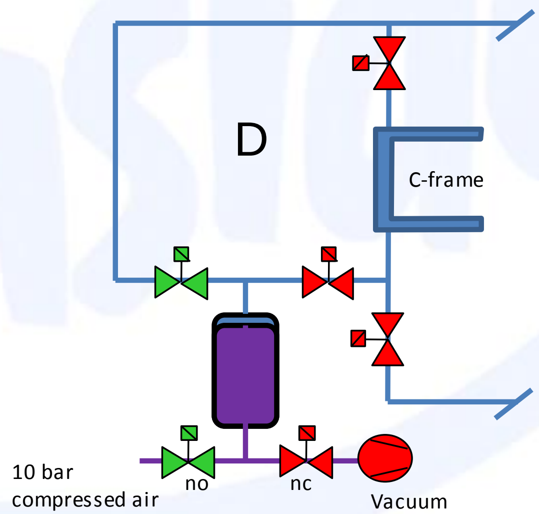
- Normal situation: C-frame is circulated with cold Novec. Receiver vessel is pressurized with compressed air.



- C-frame loop is closed off by in and outlet valves.
- Valve to receiver is opened and receiver secondary volume is vacuumed.

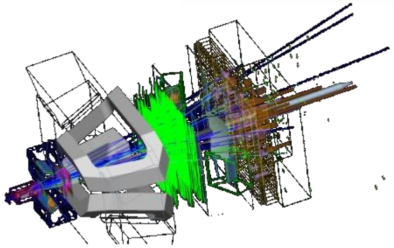


- Due to the larger volume and hence lower density the Novec starts to evaporate.
- When the accumulator is cooled (a few ºC below ambient) the Novec condenses in the receiver.
- Cooling can be achieved by water or the Novec loop itself.



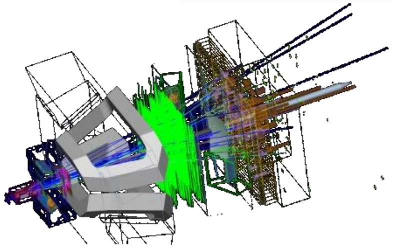
- When all liquid is collected in the receiver, the C-frame loop can be closed off and opened for maintenance. Only a few gram of novec is lost, no liquid dripping!
- The compressed air in the secondary volume of the receiver pushes all the liquid back into the system.

Receiver should be around 1.5x the volume of the C-frame to empty it.

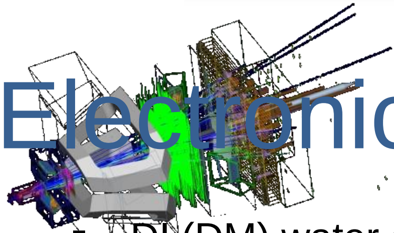


Conclusions

- For integration reasons we (Nikhef) believe that the best way to go is cooling parallel ROB's.
  - Small (ca 2mm) pipes, allow vacuum insulation in the tight available space.
- Novec 649 is thermally okay for SciFi.
  - Checked by tests and simulations
  - Radiation hardness must be investigated (Petr Gorbounov)
- Larger plant flows are needed than foreseen in the TDR (ca. 4x)
  - But it will enhance the thermal stability a lot.
    - Maximum gradient in the cooling foreseen ca. 2ºC
- A new concept for draining Novec by evaporation is proposed.



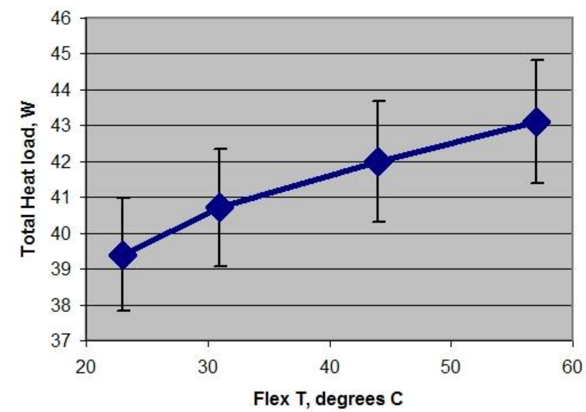
Back-up slides.



Electronics Cooling

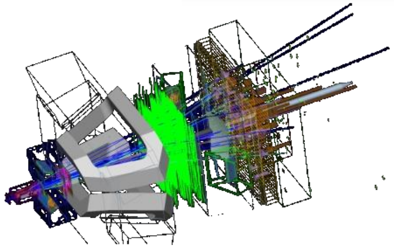
- DI (DM) water cooling. Existing OT cooling capacity: 23 kW. Estimated for SCiFi (W. Vink): 30 kW (FE boards) + 5 kW (power distribution)
- Upgrade of the existing facility is required
- SiPM cooling and Electronics cooling are largely decoupled. The mockup tests demonstrated that thermal bridge between the FE and the ColdBox is not a critical factor

Heat Load (3 modules)
as function of outer flex temperature

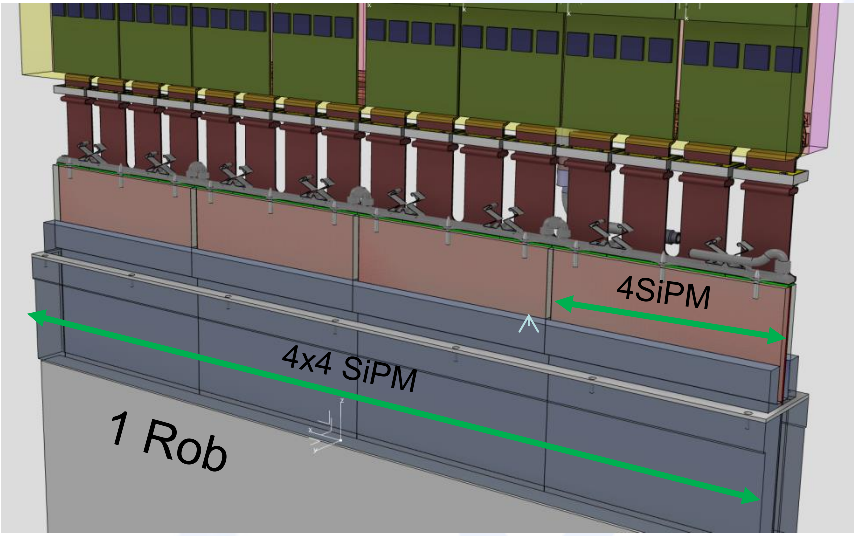


Dry Gas Supply

- Flushing inner CB cold volumes to remove the humidity penetrating through the vapor barriers (< 5 m3/h)
- Venting cold communication cabinets and critical open manifolding elements
- (Optionally) purging the liquid cooling circuits
- **Dry air** is a natural and least expensive option; no re-circulation
- Commodity desiccant air dryer (class 1 or 2, pDP of -70°C or -40°C, resp.):
  - compact, complete system including prefilter with auto-drain, regenerated adsorption dryer and afterfilter
  - required facility: compressed air (central or local compressor), 8-16 bar

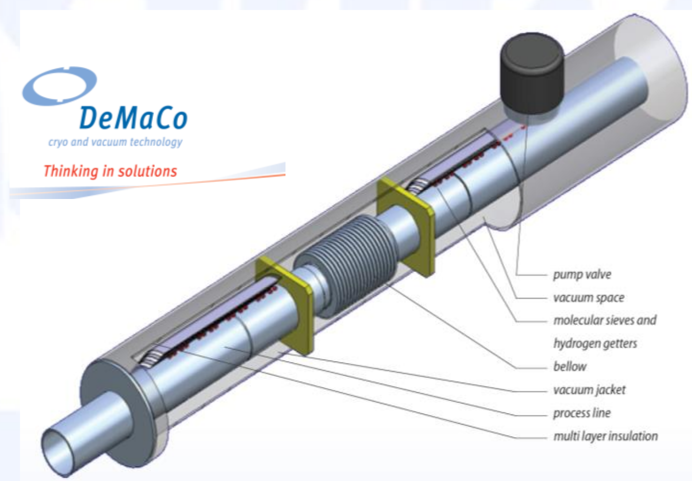


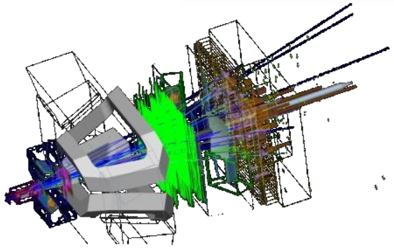
Thermal and environment requirements



- The cold lines of SciFi need insulation. Foam type of installation for -50°C temperatures need to be ~30mm thick.
- Insulated bundle diameter >70mm.
- There is no space for these foam thicknesses and applying insulation to be vapor tight seems impossible
- We assume only feasible insulation candidate:
  -> Vacuum insulation.
- Vacuum insulation applied successfully in Atlas and CMS:
  - CMS: 12mm -> 28mm vacuum
  - Atlas: 4mm -> 16mm vacuum (flexible)
  - Atlas: 21mm -> 50mm vacuum
  - Large sizes are standard industrial solutions (>63mm vacuum)

- 4 SiPM’s form 1 group. Max dT per group=1°C
- Each Rob has 4x4 SiPM’s. Max dT per Rob = 4°C
- Max temp for warmest SiPM=-40°C
- Estimated dT SiPM to Cooling is 5°C => Max cooling fluid = -45°C
- Per C-frame 480 W. Cp=1084 J/kg*K, dT= 4°C => 110.6 g/s Novec as minimum flow
- Novec flows per branch for dT=4°C max
  - Option 1: 12 robs in series: 12*110.6/24=55.3 g/s
  - Option 2: 6 robs in series: 6*110.6/24=27.65 g/s
  - Option 3: 1 rob (al parallel): 110.6/24=4.6 g/s

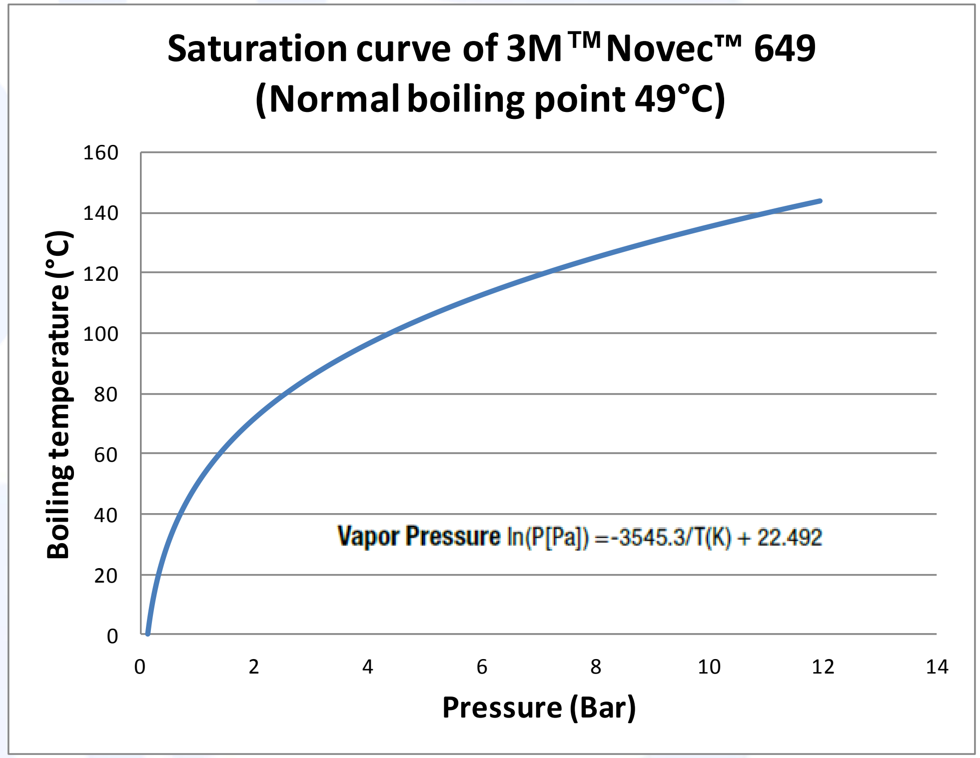


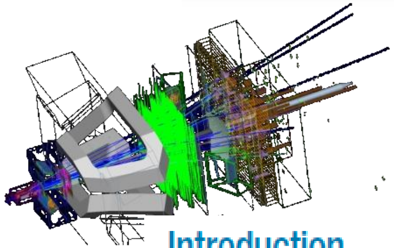


3M™ Novec™ 649 physical properties

Typical Physical Properties

	3M™ Novec™ 649 Fluid
Boiling Point(°C)	49
Pour Point (°C)	-108
Molecular Weight (g/mol)	316
Critical Temperature (°C)	169
Critical Pressure (MPa)	1.88
Vapor Pressure (kPa)	40
Heat of Vaporization (kJ/kg)	88
Liquid Density (kg/m^3)	1600
Coefficient of Expansion (K^{-1})	0.0018
Kinematic Viscosity (cSt)	0.40
Absolute Viscosity (cP)	0.64
Specific Heat (J/kg-K)	1103
Thermal Conductivity (W/m-K)	0.059
Surface Tension (mN/m)	10.8
Solubility of Water in Fluid (ppm by wt)	20
Dielectric Strength, 0.1" gap (kV)	>40
Dielectric Constant @ 1kHz	1.8
Volume Resistivity (Ohm-cm)	10^{12}
Global Warming Potential (GWP)	1





3M™ Novec™ 649 Engineering Fluid

Introduction

3M™ Novec™ 649 Engineered Fluid is a clear, colorless and low odor fluid, one in a line of 3M products designed as replacements for ozone depleting substances (ODSs) and compounds with high global warming potentials (GWPs) such as sulfur hexafluoride (SF_6) and hydrofluorocarbons (HFCs), such as HFC-134a and HFC 245fa.

3M Novec 649 Engineered Fluid is an advanced heat transfer fluid, balancing customer needs for physical, thermal and electrical properties, with desirable environmental properties.

Features

The environmental profile, margin of safety, low viscosity, high molecular weight, low pour point and heat transfer performance of 3M™ Novec™ 649 Engineered Fluid make it an ideal candidate for a variety of heat transfer applications.

Novec 649 fluid is compatible with a wide range of materials of construction and requires no special piping or handling systems, and is very stable in storage. Its high dielectric constant makes it safe for direct contact in most electronics/computing applications.

Typical Applications

Novec 649 fluid is an effective heat transfer fluid with a boiling point of 49°C. Novec 649 fluid is useful in heat transfer particularly where non-flammability or environmental factors are a consideration.

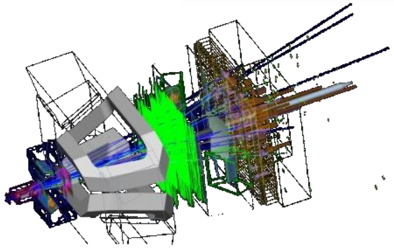
Examples of systems which benefit from use Novec 649 fluid include:

- Organic Rankine Cycle
  - Diesel Engines
  - Generators
  - Geothermal Applications
  - Solar Applications
- Electronics Cooling (Single or Dual Phase)
  - Power Electronics such as IGBTs or inverters
  - Transformers and other equipment (SF6 replacement)
- Computer/Data Center Cooling

Physical Properties

Properties	3M™ Novec™ 649 Fluid	SF_6	HFC-245fa	HFC-134a
Ozone Depletion Potential (ODP)[1]	0.0	0.0	0.0	0.0
Global Warming Potential[2]	1	23900	1030	1,300
Atmospheric Lifetime (years)	0.014	3200	7.6	140

[1] World Meteorological Organization (WMO) 1998, Model-Derived Method.
[2] Intergovernmental Panel on Climate Change (IPCC) 2007 Method, 100 Year ITH.



3M™ Novec™ 649 Engineering Fluid

Environmental, Health and Safety

Studies by a third party laboratory (Massachusetts Institute of Technology) have shown that Novec 649 fluid has an estimated atmospheric lifetime of five days due to photolysis in sunlight.[1]

The potential for Novec 649 fluid to impact the radiative balance in the atmosphere (i.e., climate change) is limited by this very short atmospheric lifetime. [Using a measured IR cross-section and the method of Pinnock et.al., the instantaneous radiative forcing for Novec 649 fluid is calculated to be 0.50 Wm-2ppbV-1.] This radiative forcing and a 5-day atmospheric lifetime result in a GWP value of about 1 [using the WMO 1999 method over a 100-year integration time horizon].

The photolysis of Novec 649 fluid is expected to rapidly produce fluorinated alkyl radicals similar to those produced by other fluorochemicals. Studies of the atmospheric chemistry of these radical species and their degradation products have concluded that they have no impact on stratospheric ozone. This combined with its very short atmospheric lifetime, leads to the conclusion that Novec 649 fluid has an ozone depletion of zero.[1]

Before using this product, please read the current product Material Safety Data Sheet (available online or through your 3M sales or technical service representative) and the precautions and directions for use on the product package. Follow all applicable precautions and directions for use.

[1] N. Taniguchi, T.J. Wallington, M.D. Hurley, A.G. Guschin, L.T. Molina and M.J. Molina, *Atmospheric Chemistry of $C_2F_5C(O)CF(CF_3)_2$: Photolysis and Reaction with Cl Atoms, OH Radicals and Ozone*. J Phys Chem A, 2003, 107, 2674 – 2679.

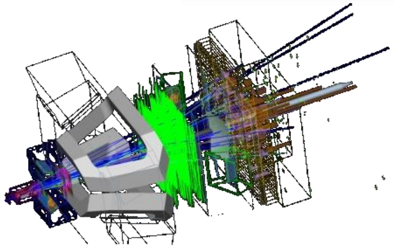
Wikipedia
The Free Encyclopedia

Photo dissociation, **photolysis**, or **photodecomposition** is a chemical reaction in which a chemical compound is broken down by photons. It is defined as the interaction of one or more photons with one target molecule. Photo dissociation is not limited to visible light. Any photon with sufficient energy can affect the chemical bonds of a chemical compound. Since a photon's energy is inversely proportional to its wavelength, electromagnetic waves with the energy of visible light or higher, such as ultraviolet light, x-rays and gamma rays are usually involved in such reactions.

Properties Description

Composition of 3M™ Novec™ 649 Fluid	
Dodecafluoro-2-methylpentan-3-one	9.0 mole %, minimum
Chemical Formula	$CF_3CF_2C(O)CF(CF_3)_2$

R&D is needed to evaluate Novec radiation hardness



3M™ Novec™ 649 Engineering Fluid

Stability

Novec 649 fluid should be used in a sealed system to prevent interaction with water. Fluoroketones like Novec 649 fluid, though reactive with liquid water (ie. a separate water phase), are remarkably stable in its absence to over 300°C. 3M's applications engineers are available to discuss system design and trade-offs for Novec 649 fluid vs. alternative heat transfer fluids or solutions.