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Cooling experience with the LHCb VELO and spin-offs

Forum on Tracking Detector Mechanics

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(Nikhef/CERN)

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Acknowledgements to Eddy Jans, Martin Van Beuzekom and Marco Kraan for the provided information

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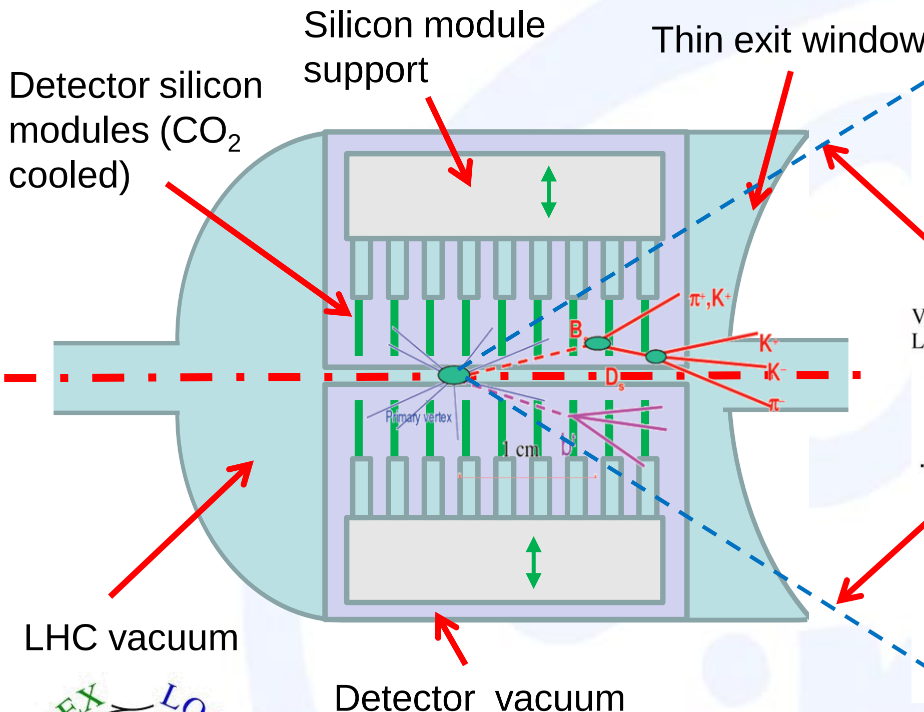
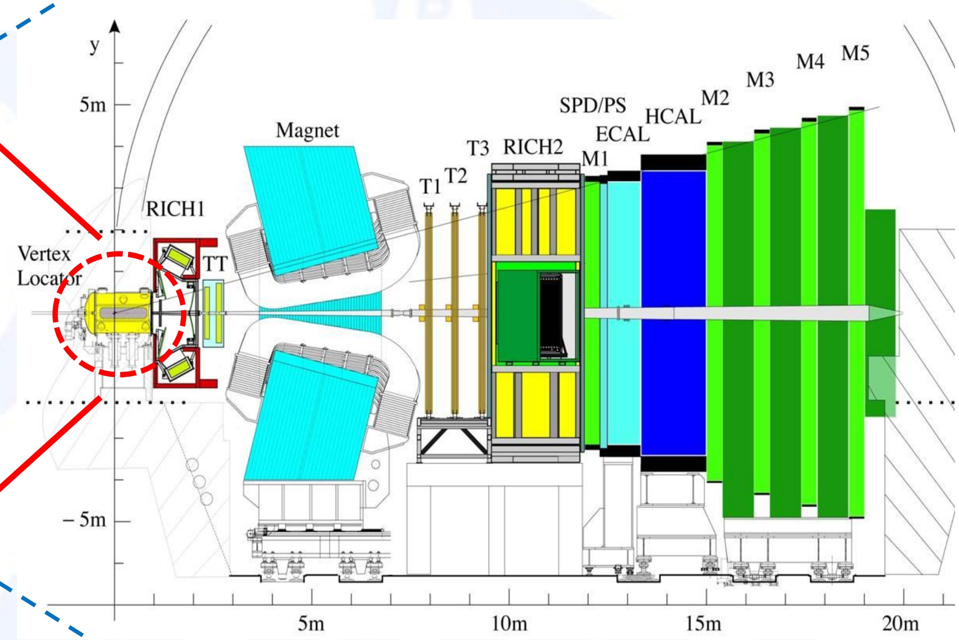
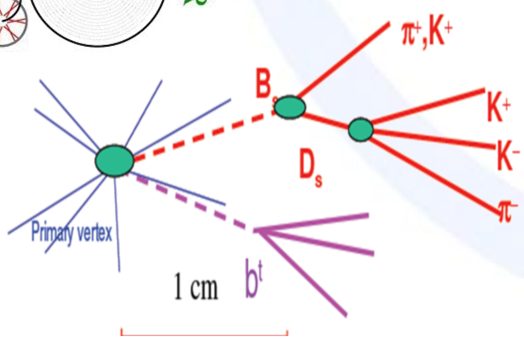
Introduction to the LHCb Velo







- LHCb is a forward focused detector (0.6 to 14.3 degree)
- Velo task: Locate secondary vertices of B-mesons
  - Silicon detector close to beam (8mm)
  - Located inside a vacuum volume separated from LHC vacuum by a 0.3mm aluminum foil (detector has too much out gassing)
- Complex detector from a mechanical point of view
  - 2 vacuums (<10mbar dP) separated by a thin foil RF-box
  - Motion system to move detector ~30mm away from the beam during injection
  - CO2 cooling system inside the vacuum
  - Thin wall vacuum vessel for minimum particle distortion

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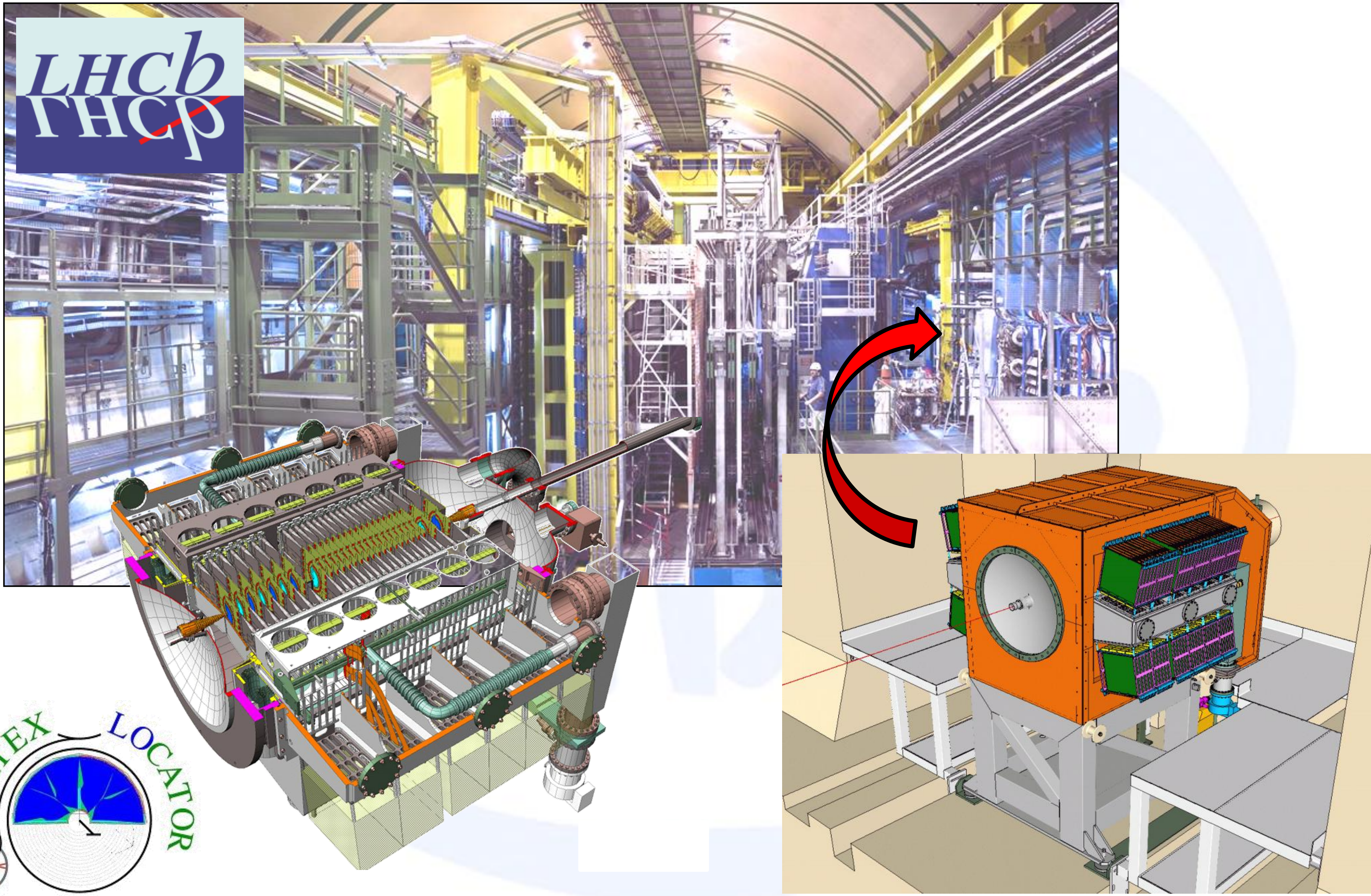
LHCb Detector



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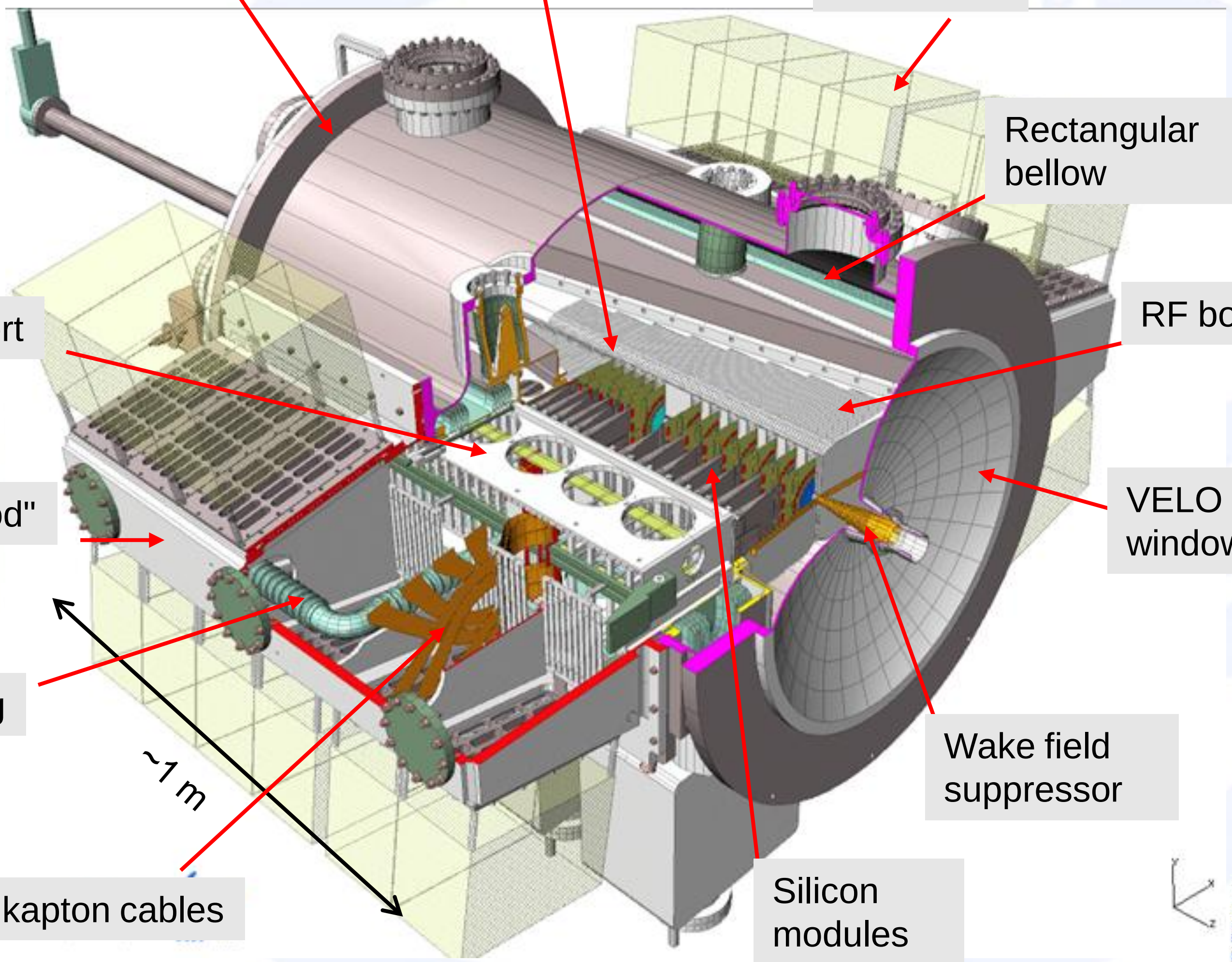
Velo overview



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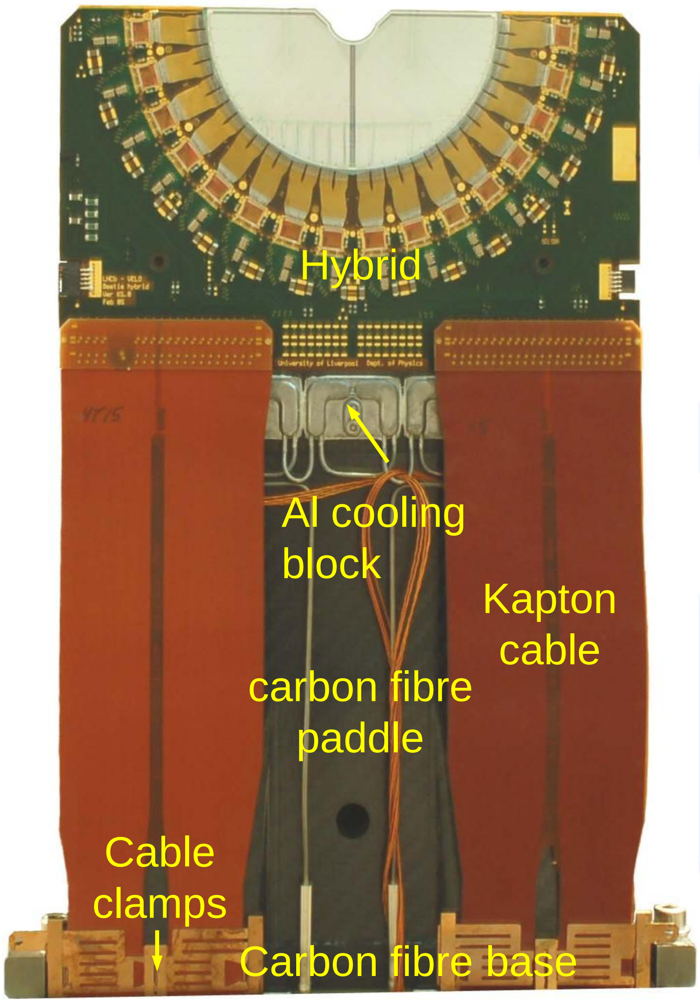
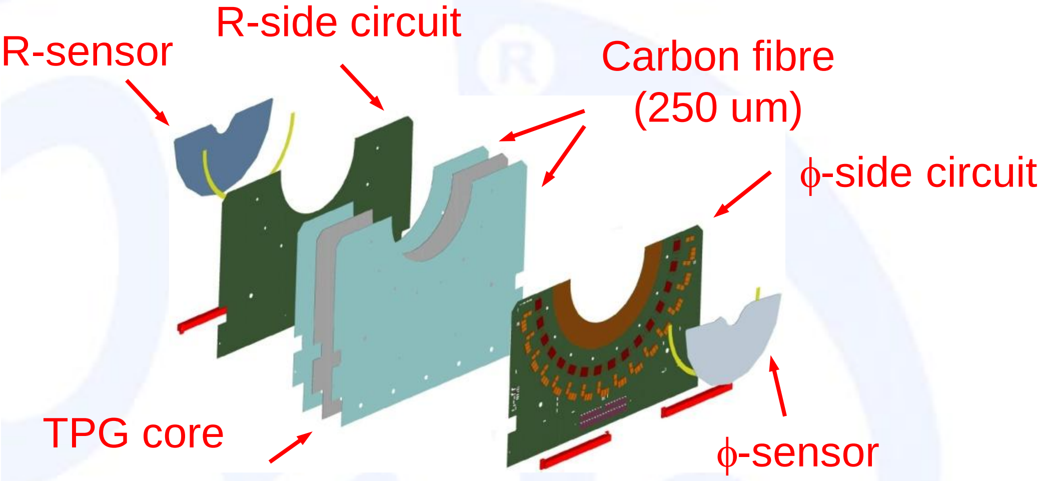
VELO Module





- Double-sided symmetric build to balance stresses due to “bi-metallic” effects.
- N-on-n sensors (300um).
- Thermal pyrolitic graphite (400um)
- Analogue read-out asic’s : 2 x 16 Beetle chips (~18 Watt)
- Cooling: 2-phase CO_2 [silicon tip @ -7° C]
- 3 layer kapton cable for signals and power.

Slide from Jan Buytaert

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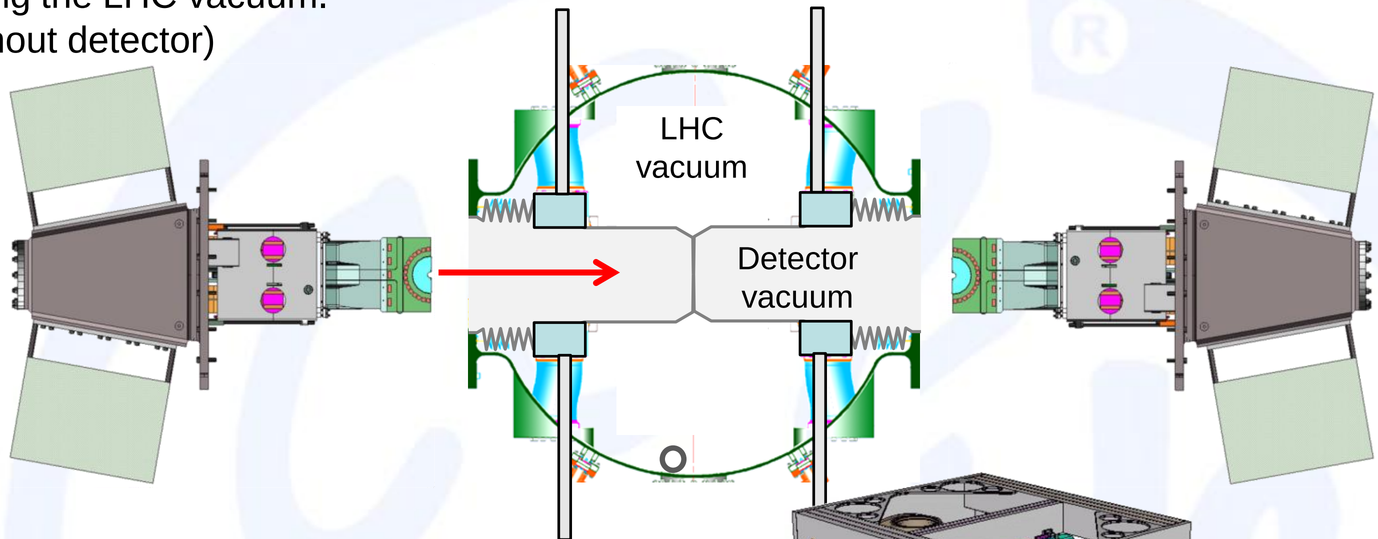
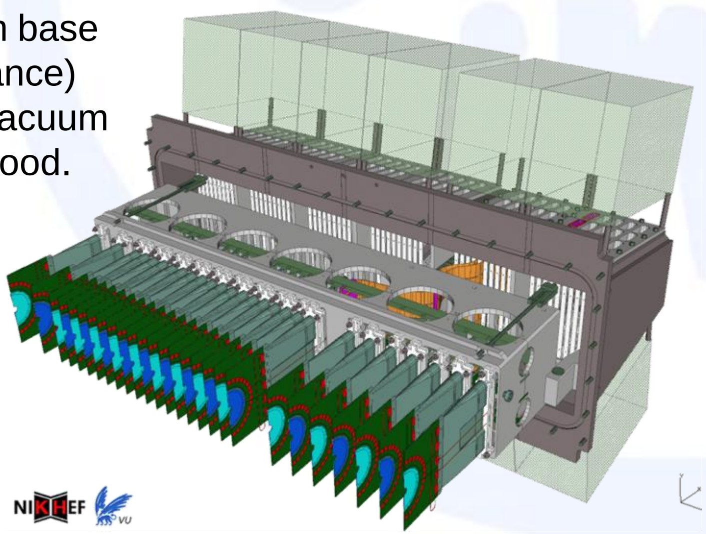
Velo configuration
Detector halves

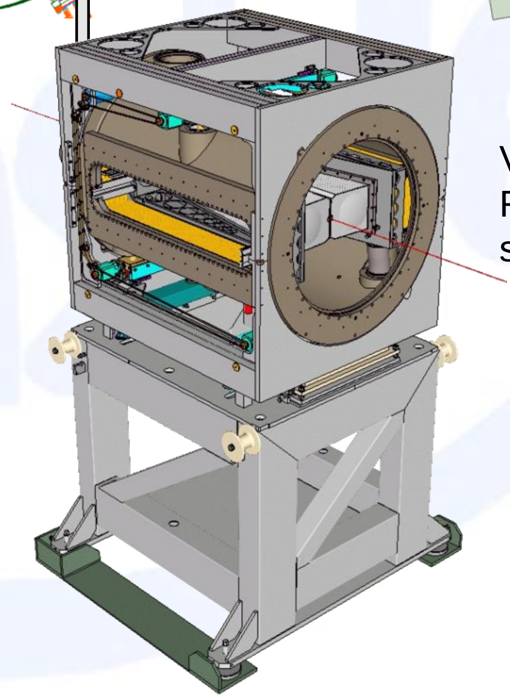
Detector halves can be installed without opening the LHC vacuum. (Back-out without detector)



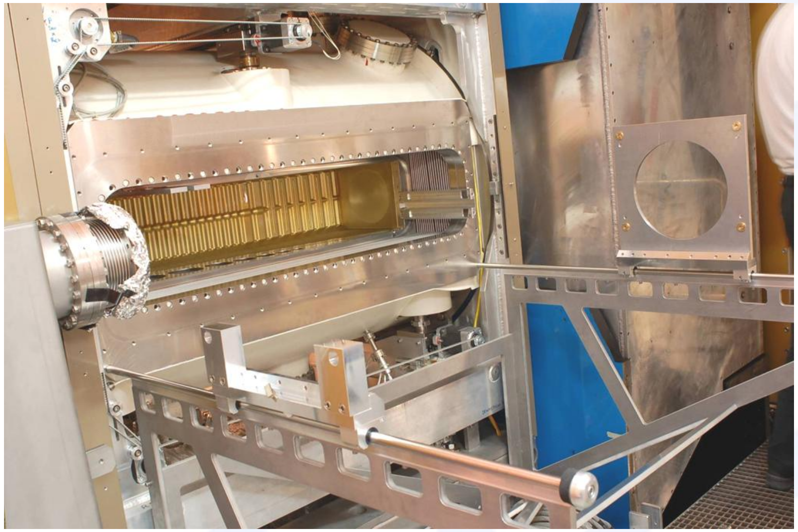
Modules mounted on a solid aluminum base (not in acceptance) including the vacuum feed through hood.

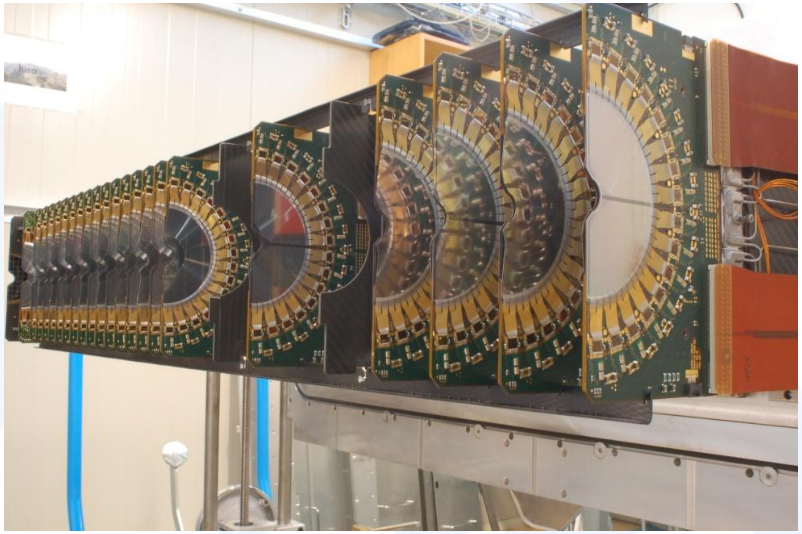


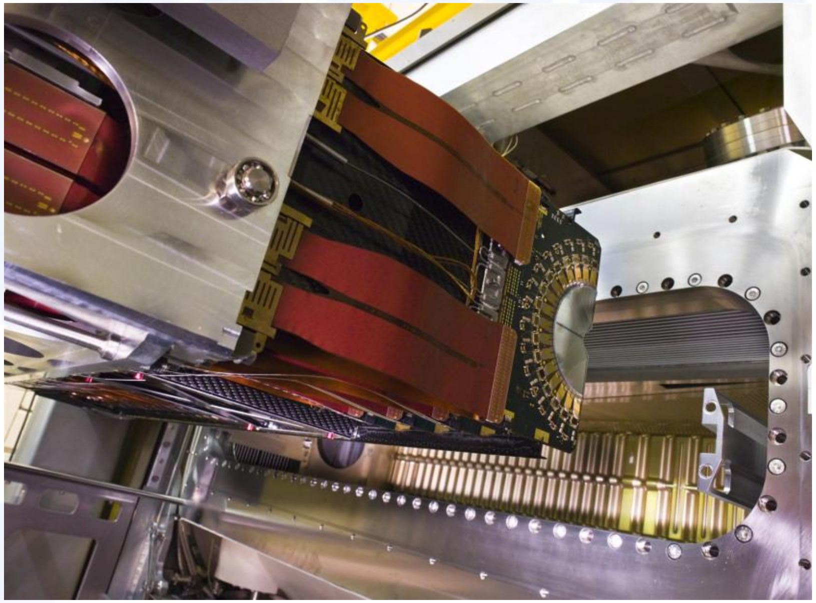
Vacuum vessel with RF-boxes and motion system



Velo detector half installation







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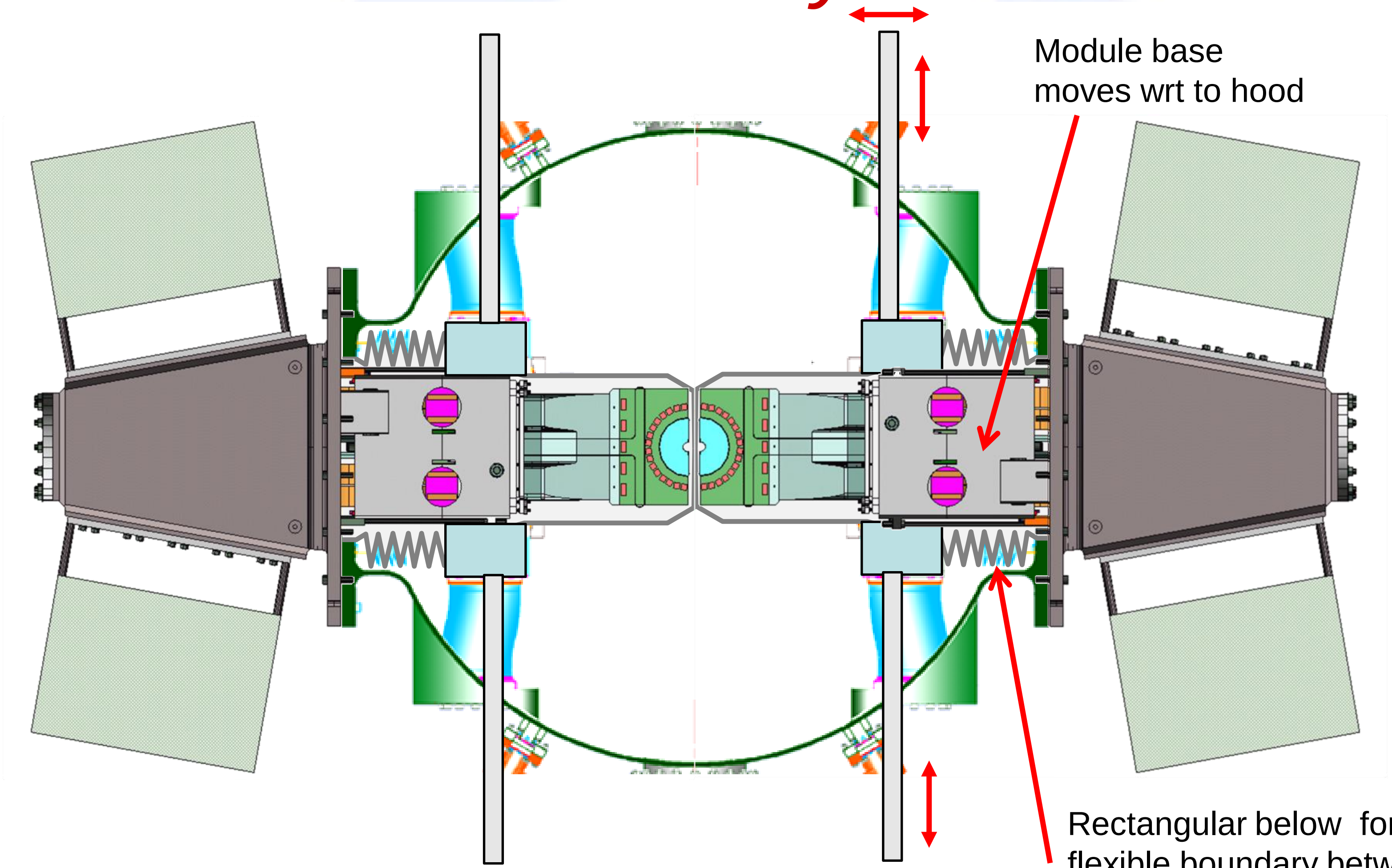
Velo configuration
Motion system

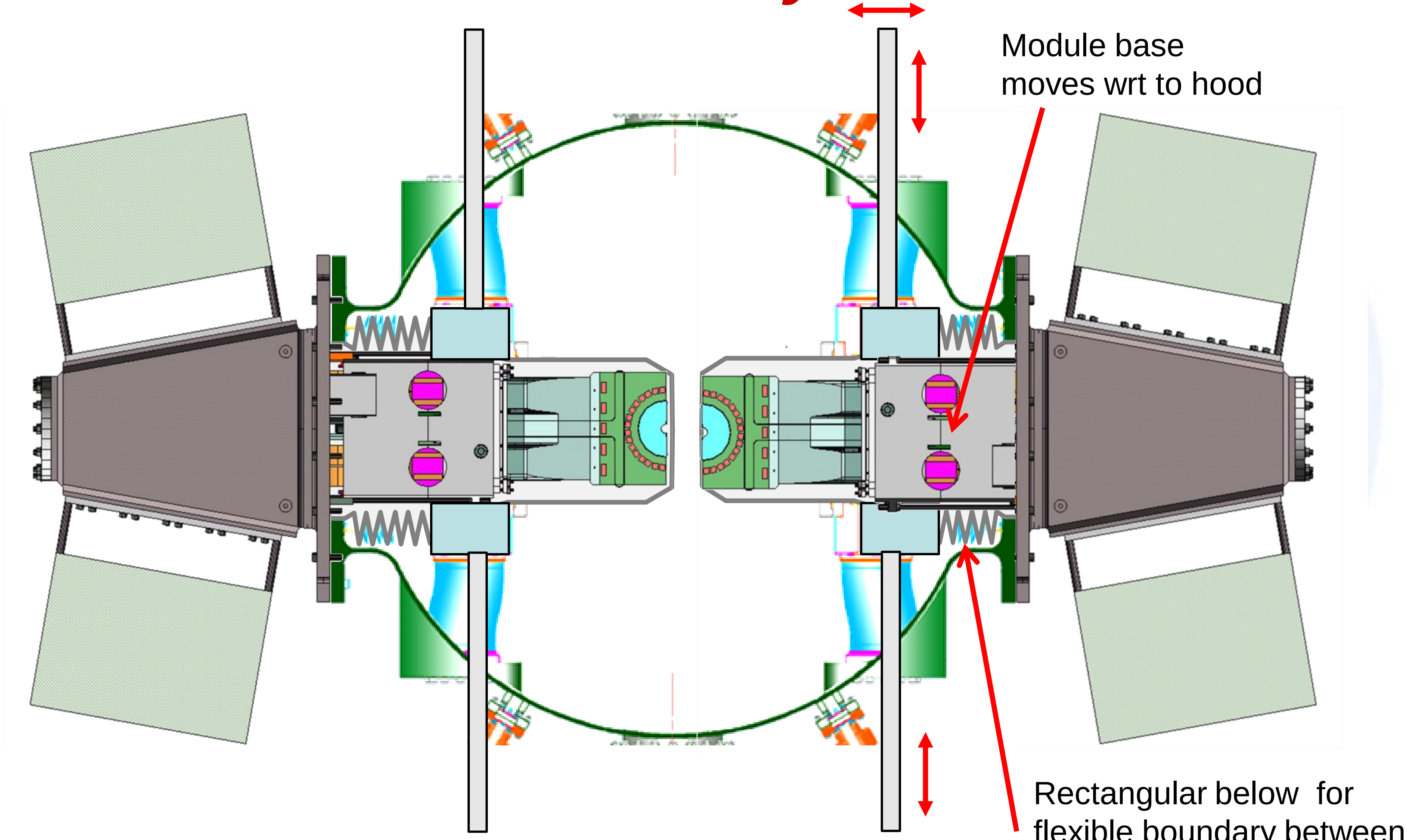


Module base moves wrt to hood

Rectangular below for flexible boundary between detector and LC vacuum

Motion of detector from the outside through bellows

Velo configuration
Motion system



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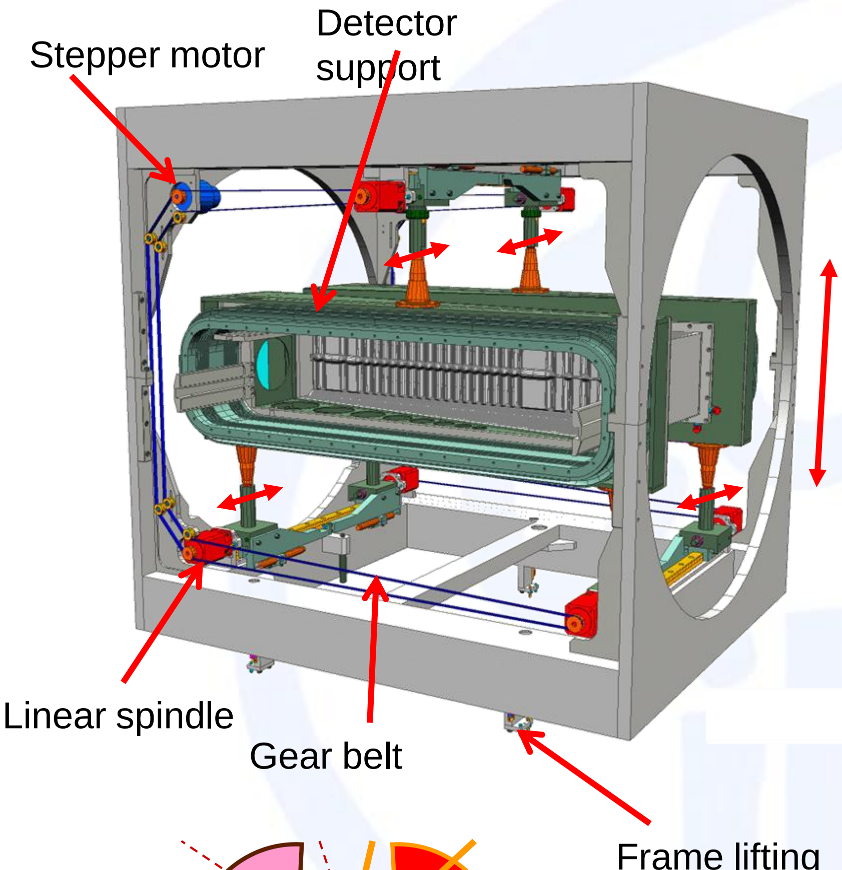
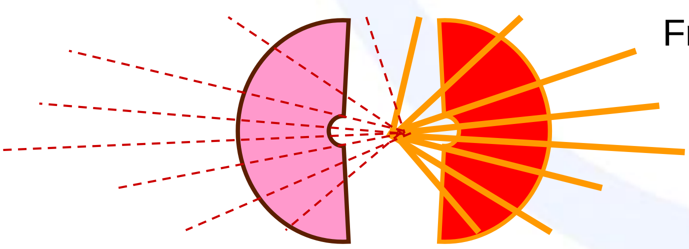
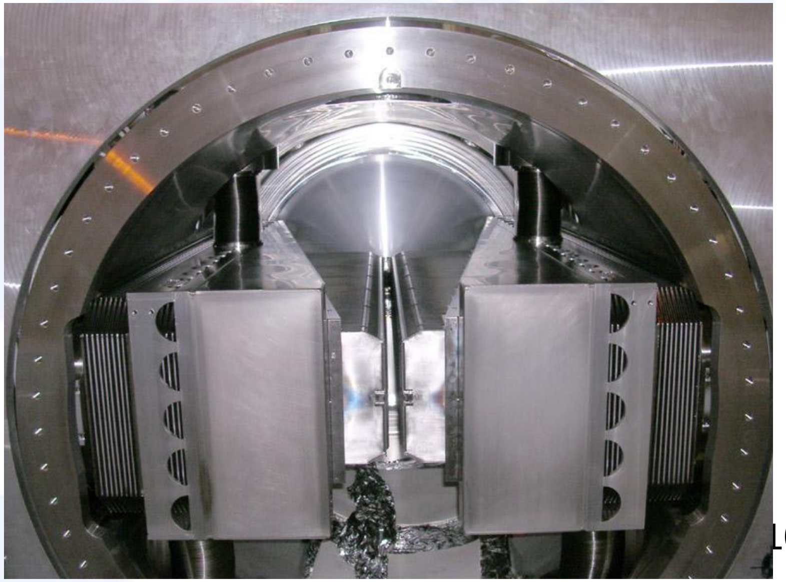
Velo Motion system





Detector positioned around the beam by tracking

- Moves the detector halves away by 30mm each to make place for beam injection
- Reproducibility <10μm
- Up and down movement by frame lifting
- Able to centre around the displaced beam (±5mm). Positioned with tracks
- Motion system components
  - Stepper motor
  - Gear belt
  - Linear spindles
- All motion hardware outside vacuum
- Vacuum bellows to allow motion



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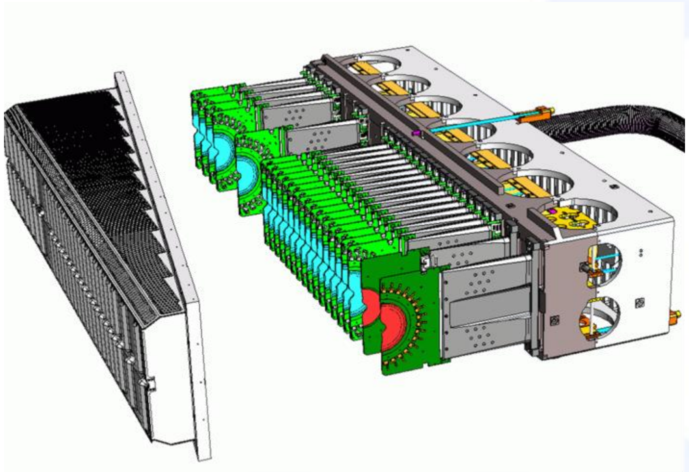
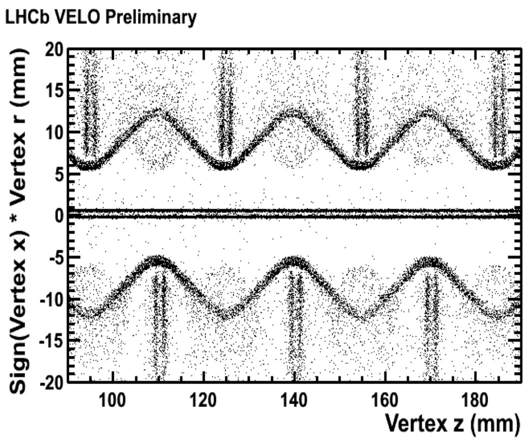
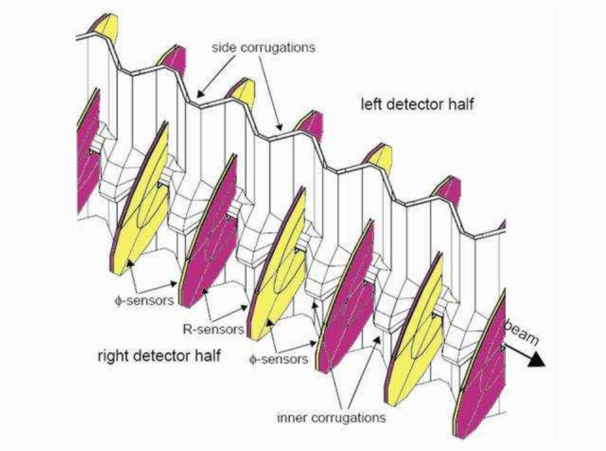
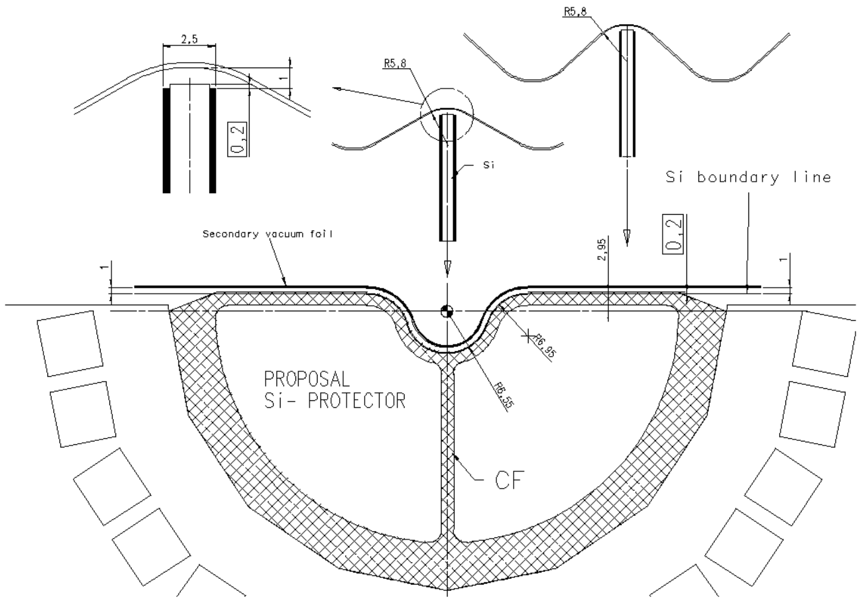
The Detector Vacuum box ("RF Box")







- 0.3mm thick plastic deformed aluminum
- Corrugated foil to make sensors of 2 halves overlapping (ca. 5mm)
- Distance foil-sensor: 1mm
- Foil serves 2 purposes:
  - RF-shielding
  - Beam / detector vacuum boundary
  - Torlon coating inside (HV-isolation, thermal emissivity)
  - NEG coating outside (Vacuum pumping)



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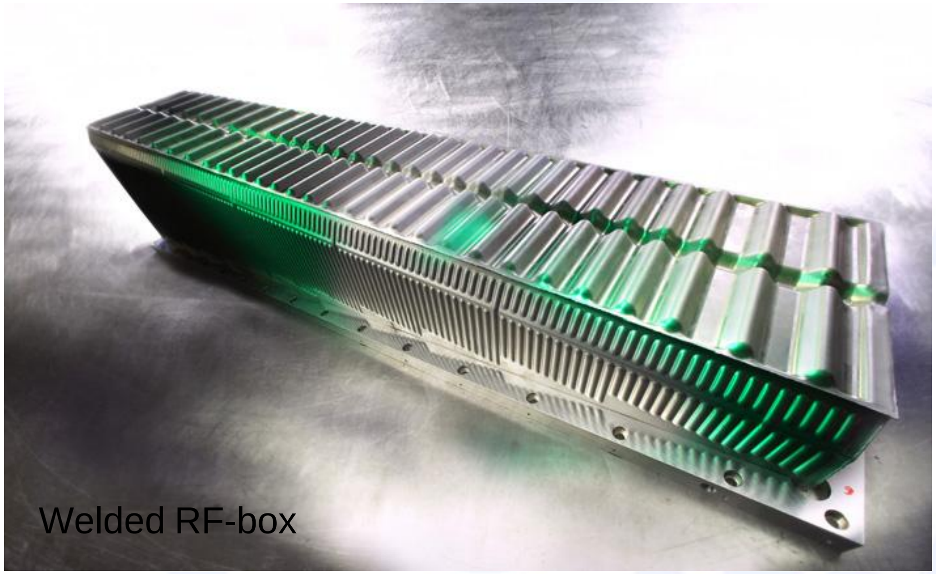
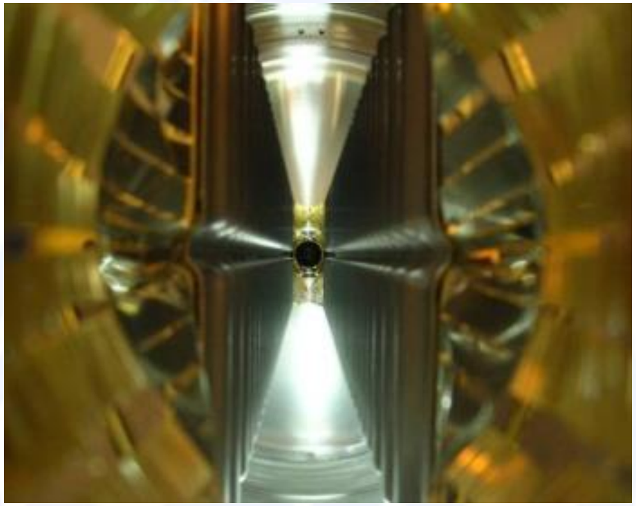
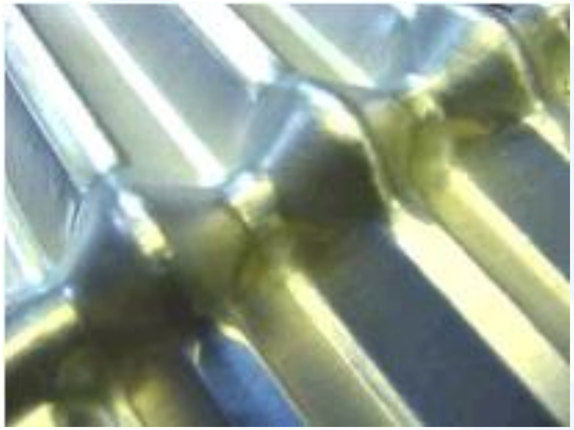
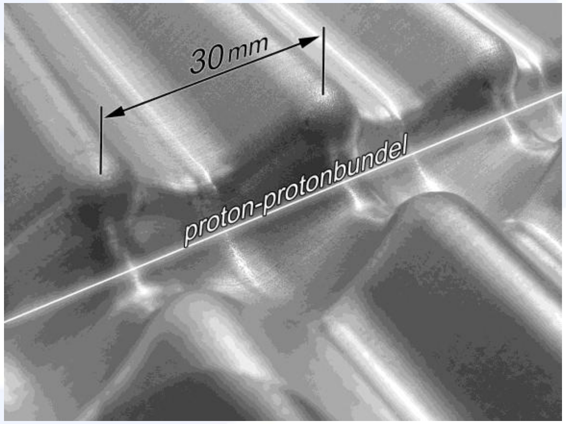




View from inside detector in open position



Detector side of the foil with silicon pockets



Beam side of the foil with beam passage space

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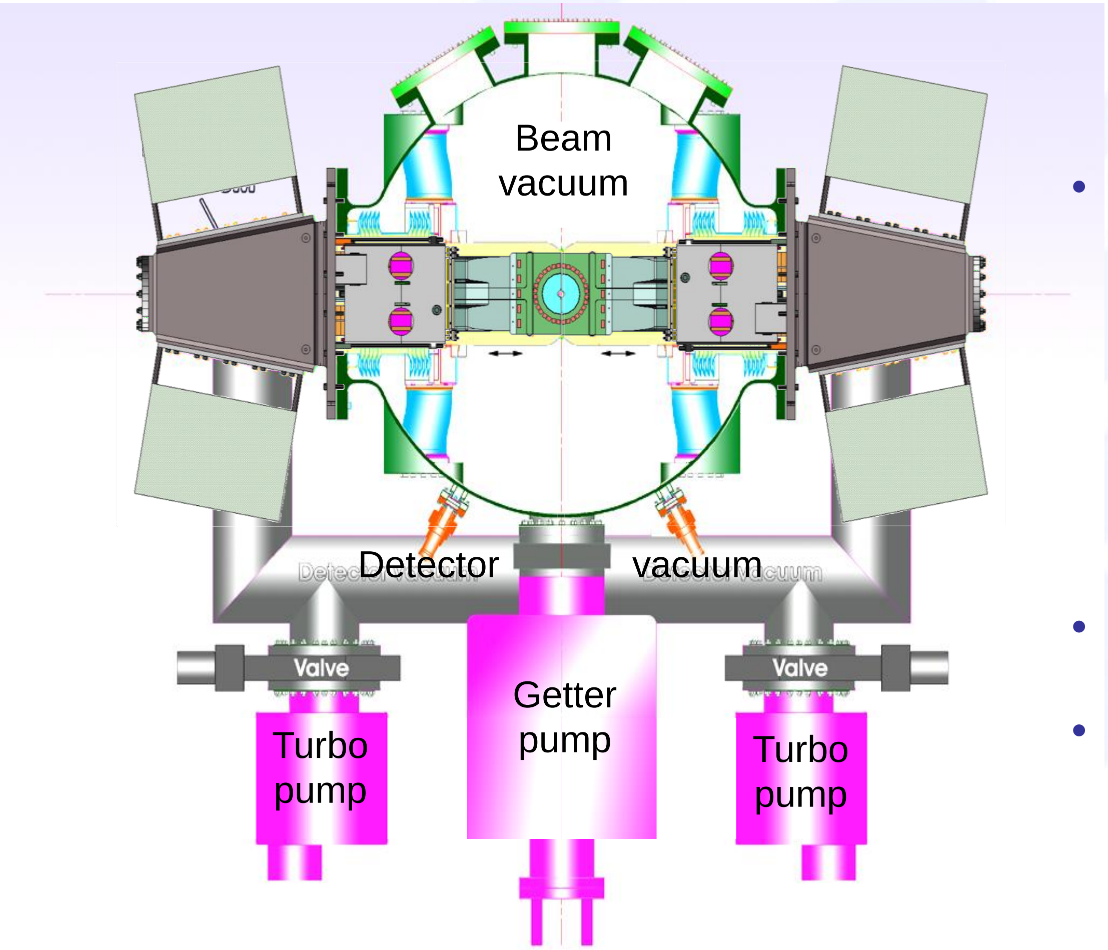
Vacuum system



- 2 vacuum systems separated by the RF-Box.
  - Detector vacuum 10^{-5} mbar (Detector outgases)
  - Beam vacuum 10^{-9} mbar
- Only 10mbar pressure difference allowed
  - Remember: silicon distance 1mm!
  - Complex pumping of 2 systems simultaneously via restrictions (-5mbar<dP<+2mbar)
  - When absolute pressure lower than 2 mbar achieved, then full pumping on both volumes.
- Vented with ultra pure neon during venting
- Able to install detector halves when beam vacuum is vented with neon.
  - Complex balancing of neon pressure in beam vacuum versus atmospheric pressure in detector volume (<2 mbar!)

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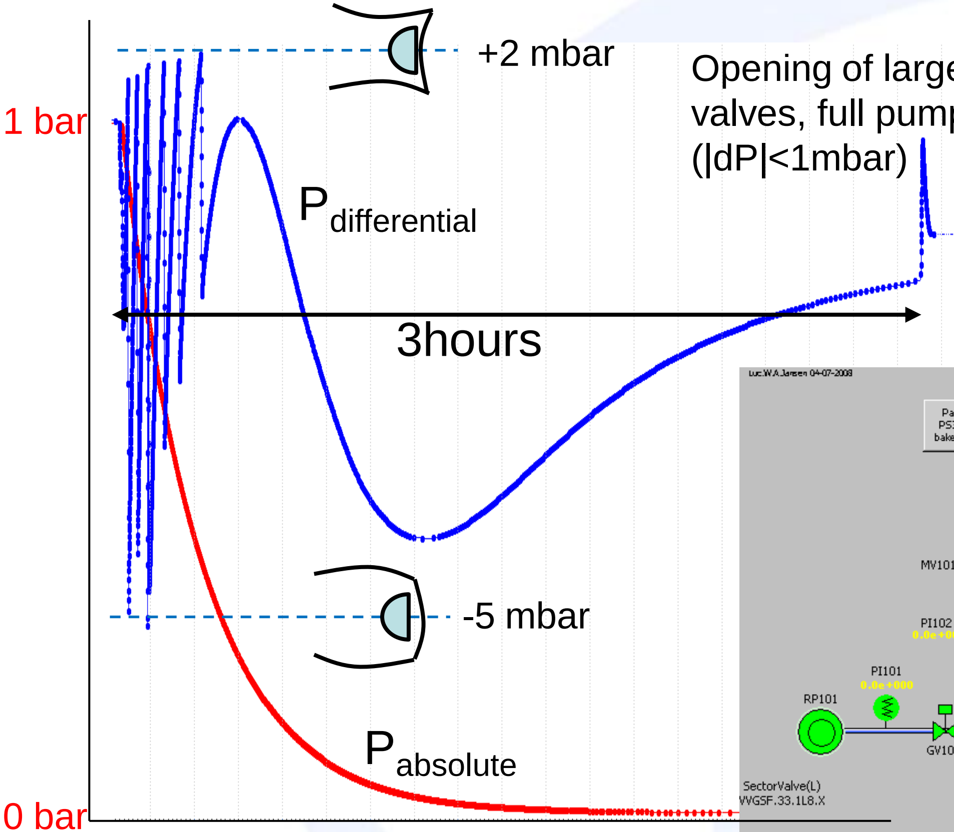
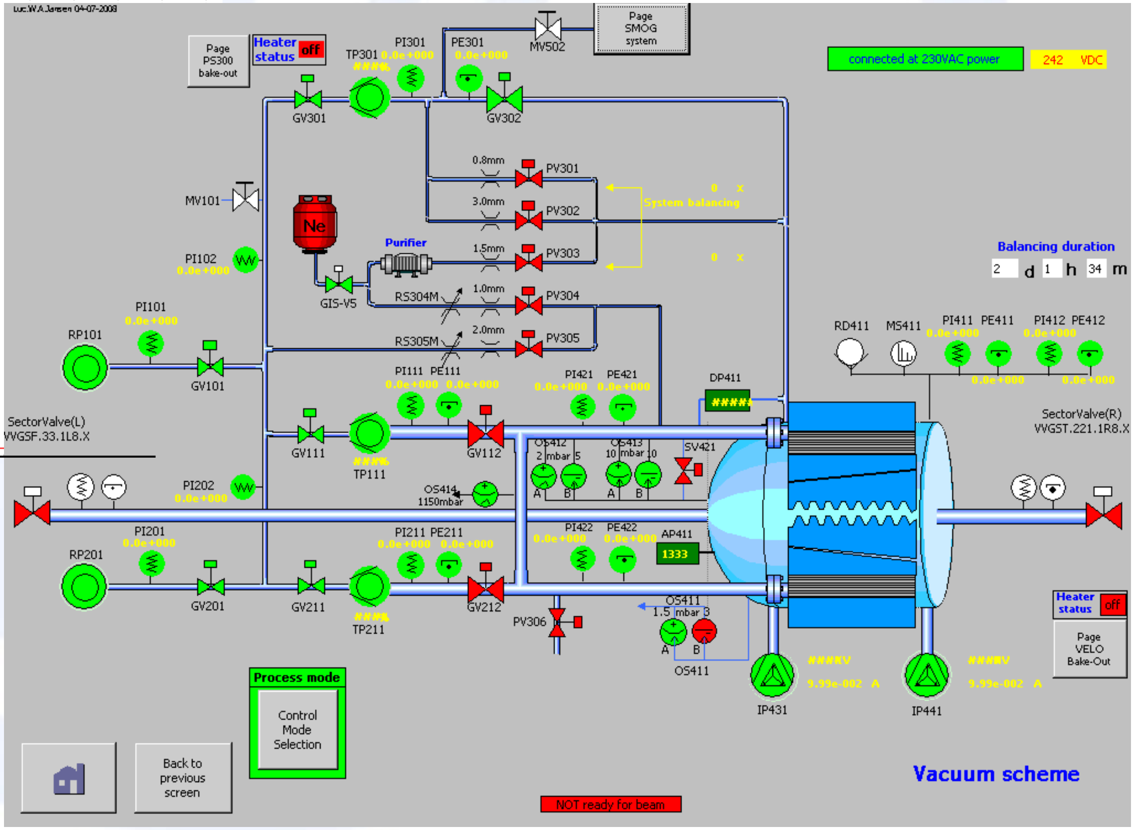
Vacuum pumping



After 2 months of pumping:
Detector vacuum: $2x10^{-6}$ mbar
Beam vacuum: $3x10^{-9}$ mbar



dP pressure switching
by membrane switches
(-5 to +2 mbar)

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Velo Thermal Control System (VTCS)

- The VTCS is a CO_2 based thermal control system (It cools and it heats)
- VTCS is inside the detector vacuum system
  - Extreme leak tightness requirements
  - Heat removal by conductance only
  - Inaccessible
  - Flexible to follow the 30mm detector movement

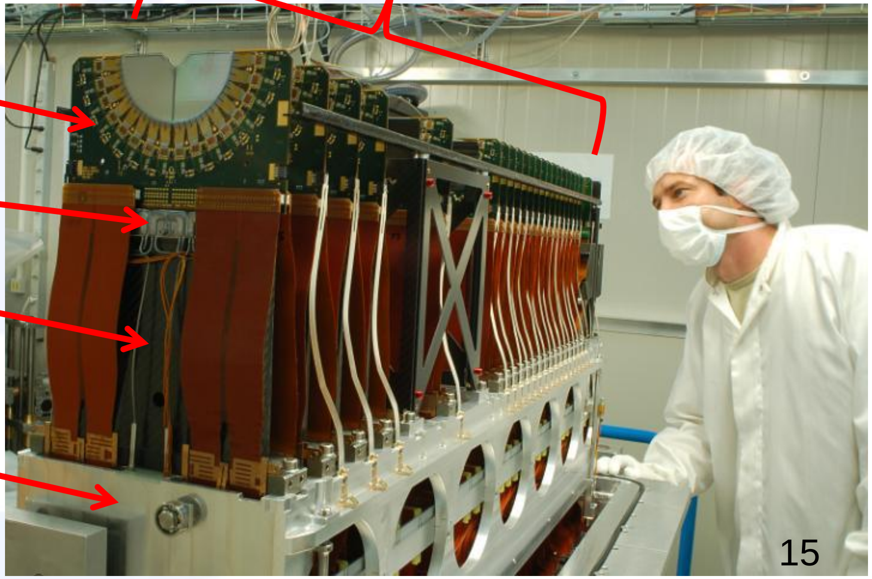
400 Watt (750 max)

Maintain silicon and hybrid at cold temperatures (<-5ºC)

CO_2 cooling(-30ºC)

Thermal isolating paddle

Maintain base at room temperature for correct module position (Heater controlled)



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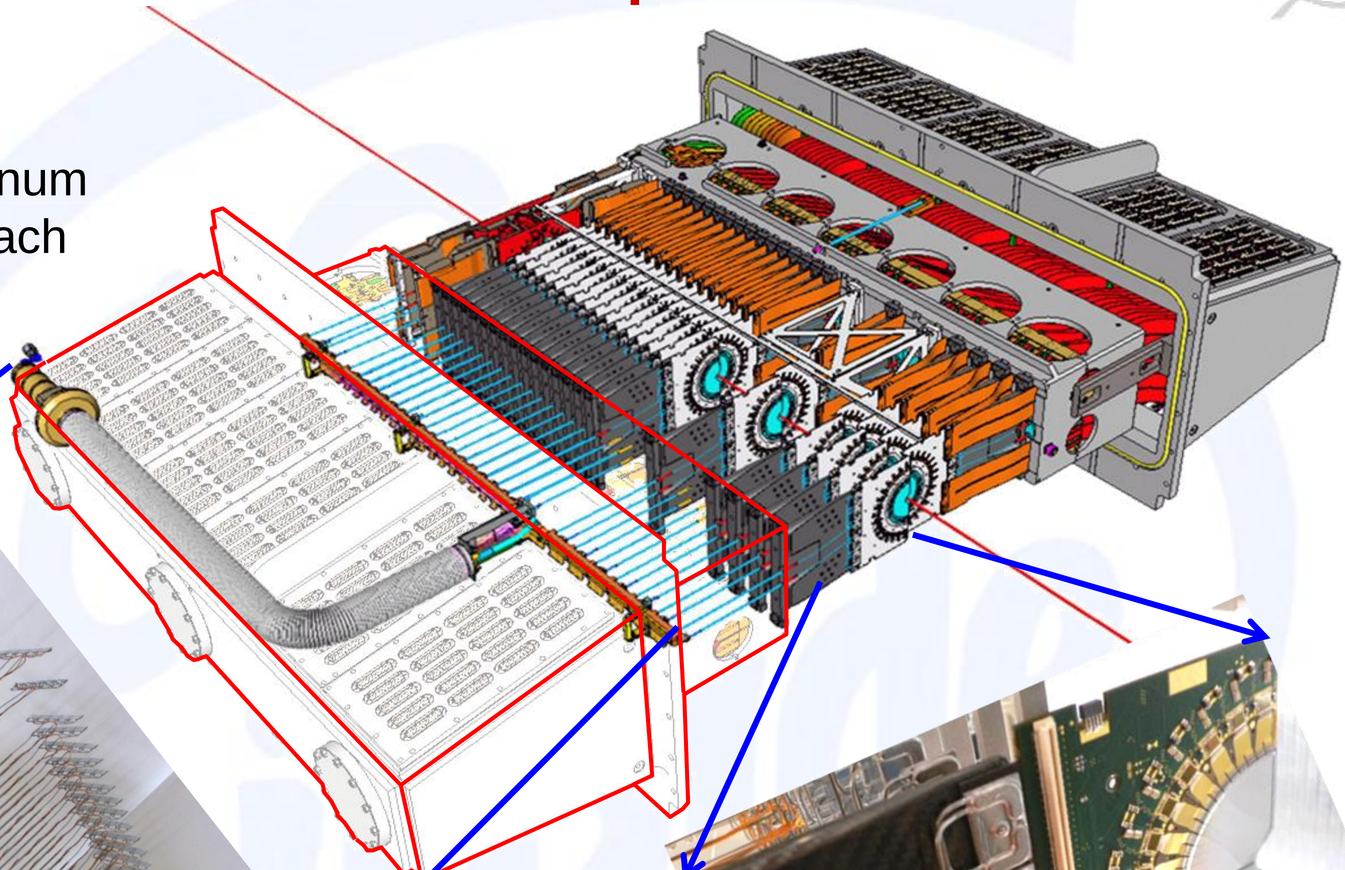
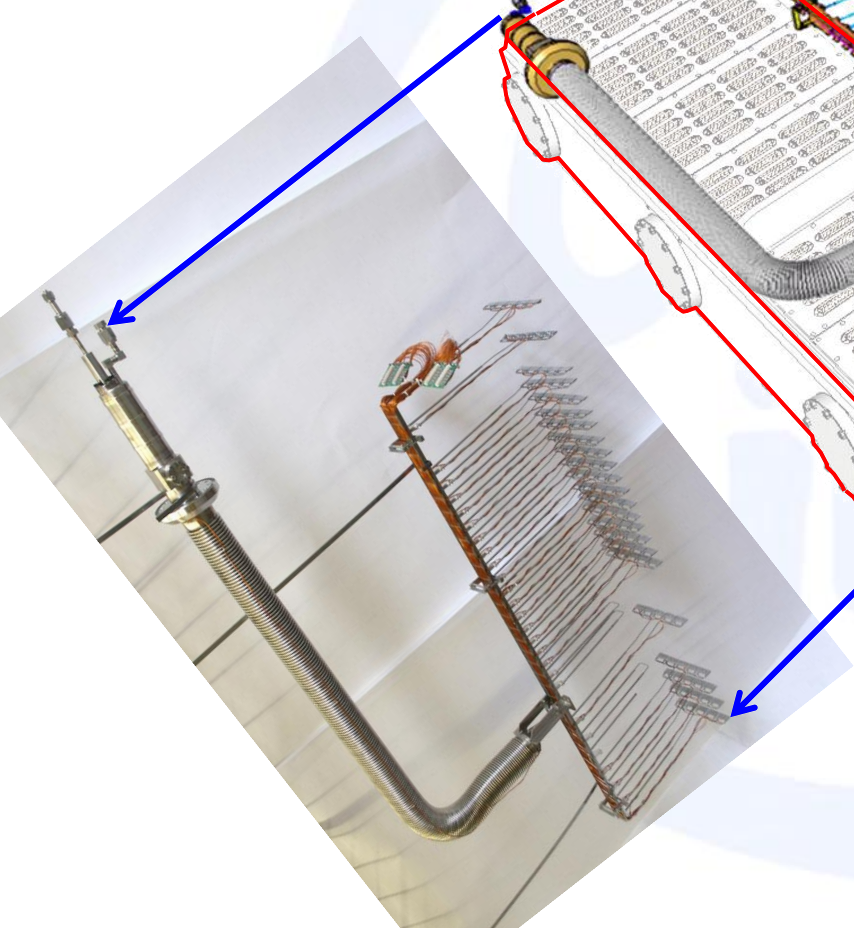
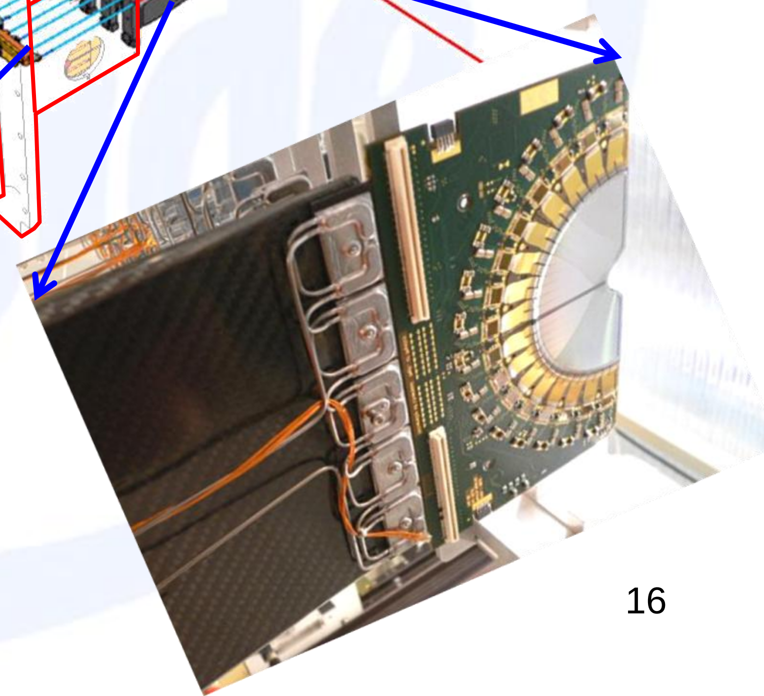
VTCS Evaporator

A parallel supply of evaporative CO_2 to dismountable aluminum cooling blocks on each silicon module







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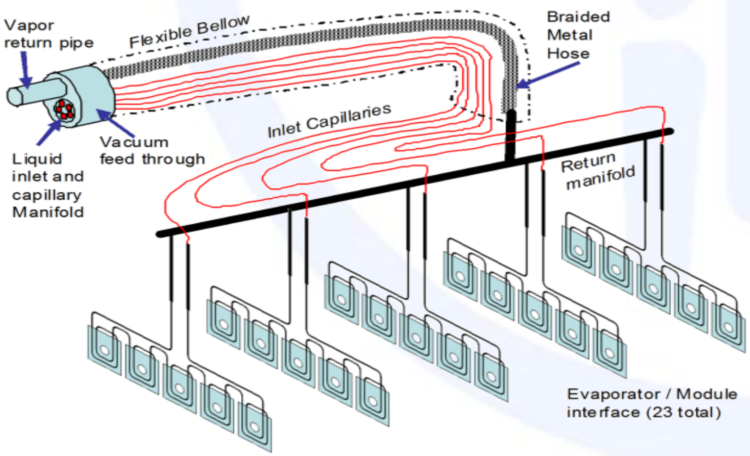
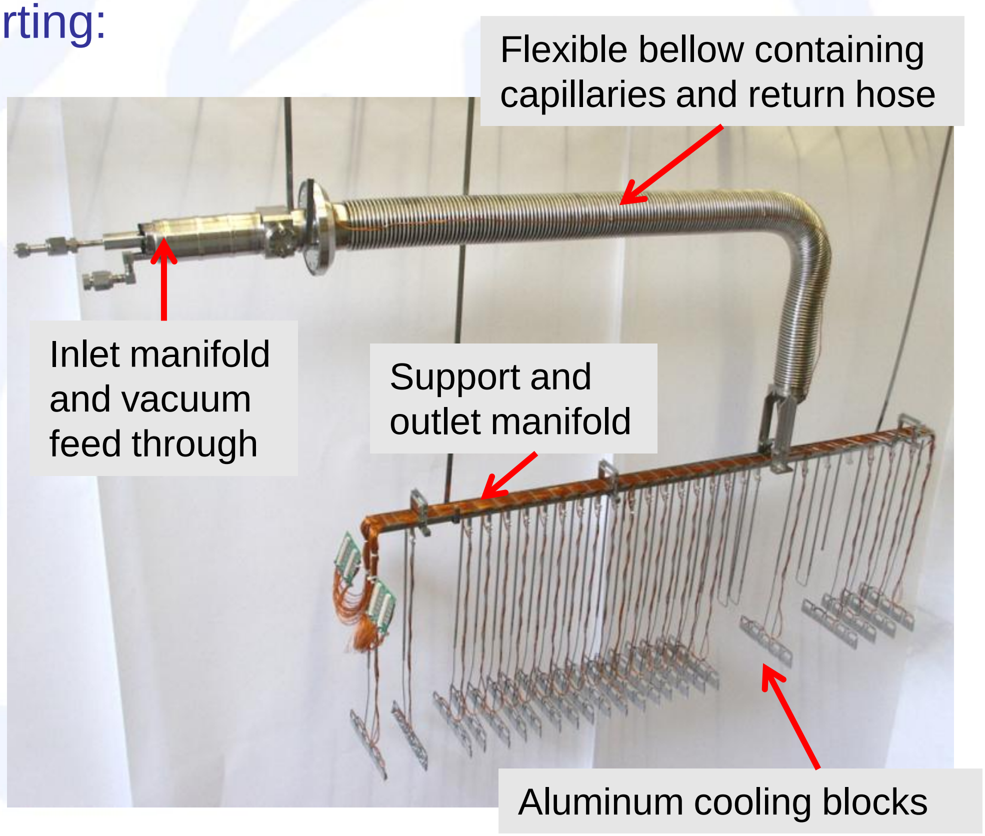
VTCS evaporator

- 23 parallel cooling channels (1mmID x 1115mm (457mm heated))
- 0.5mmID x 2038mm inlet capillaries accessible from outside.
- 1 return manifold
- Inlet capillaries + 3/8" metal bellow hose as flexible assembly for detector movement
  - Inside a separated vacuum bellow for extra safety
- Manifold is main assembly supporting:
  - 23 paralell evaporators
  - Oversized capillary lengths
  - Temperature sensor cables
  - Interface to module base





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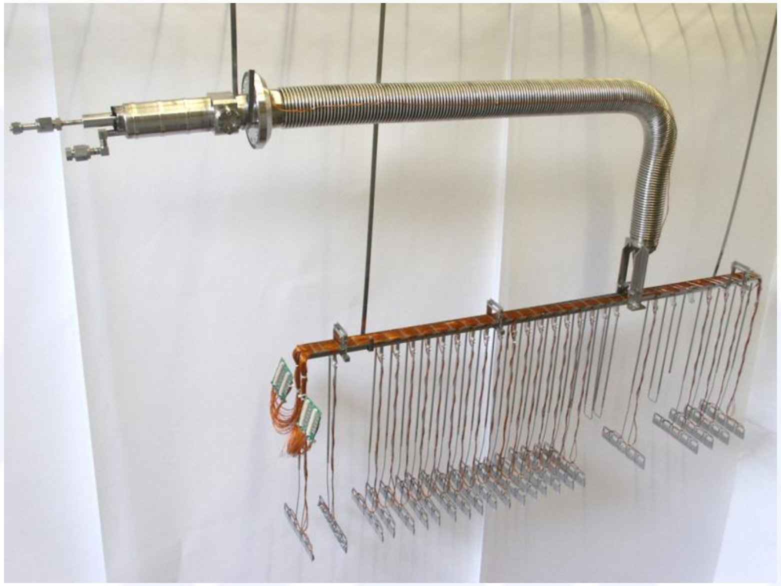
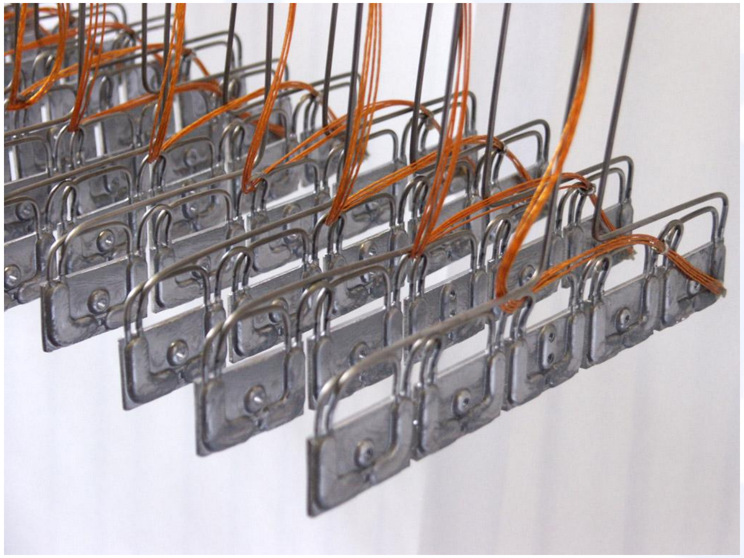
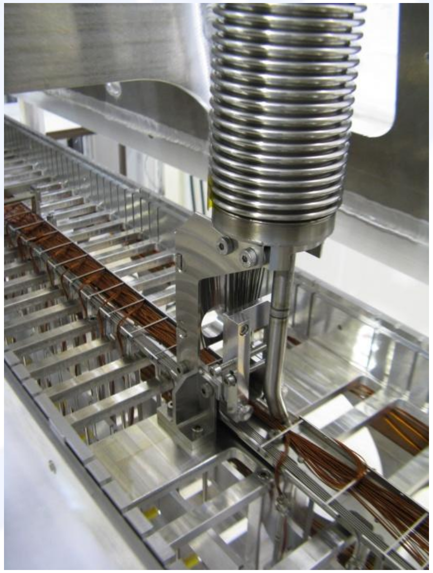
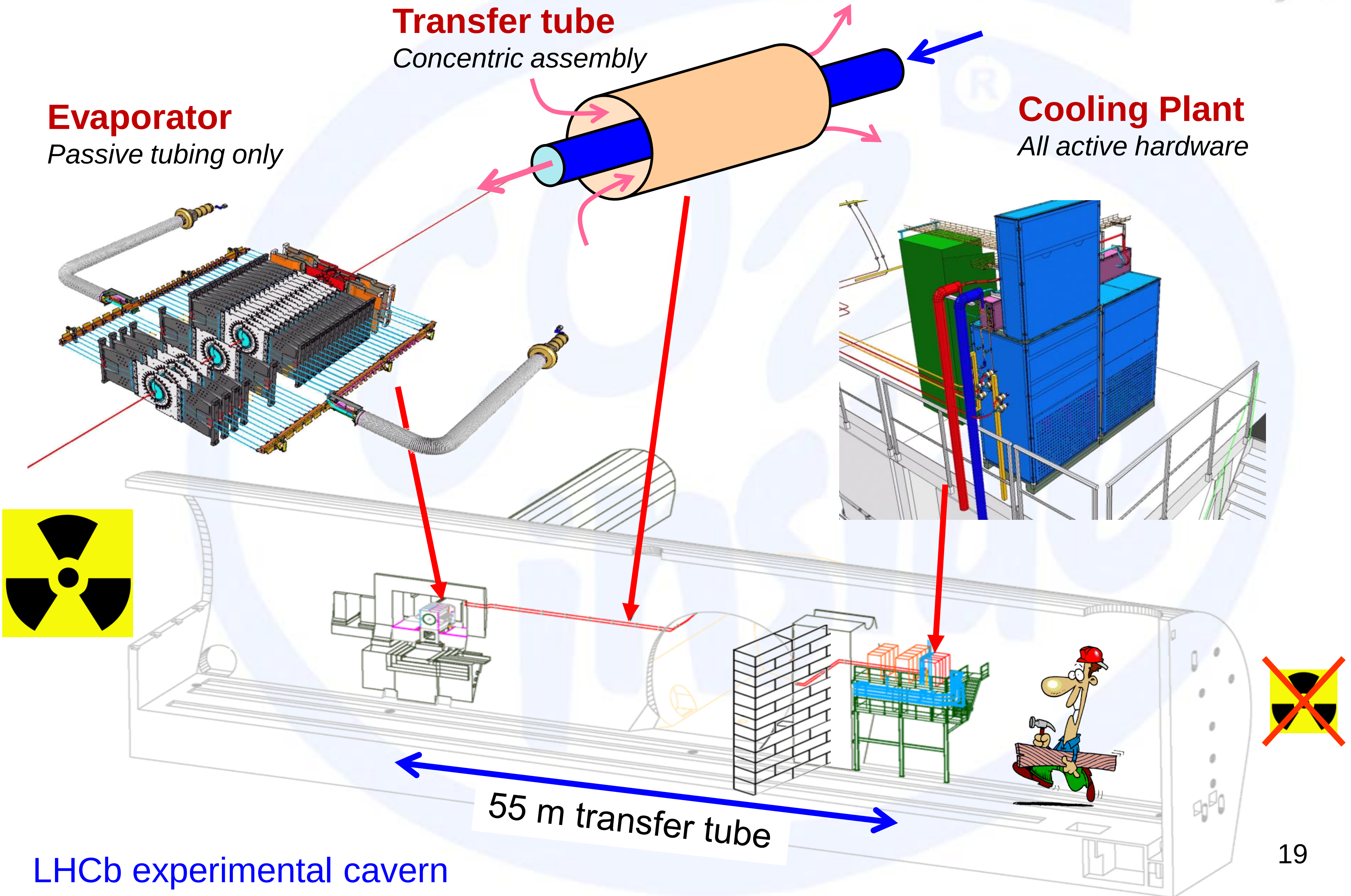
VTCS Evaporator



VTCS Locations



LHCb experimental cavern

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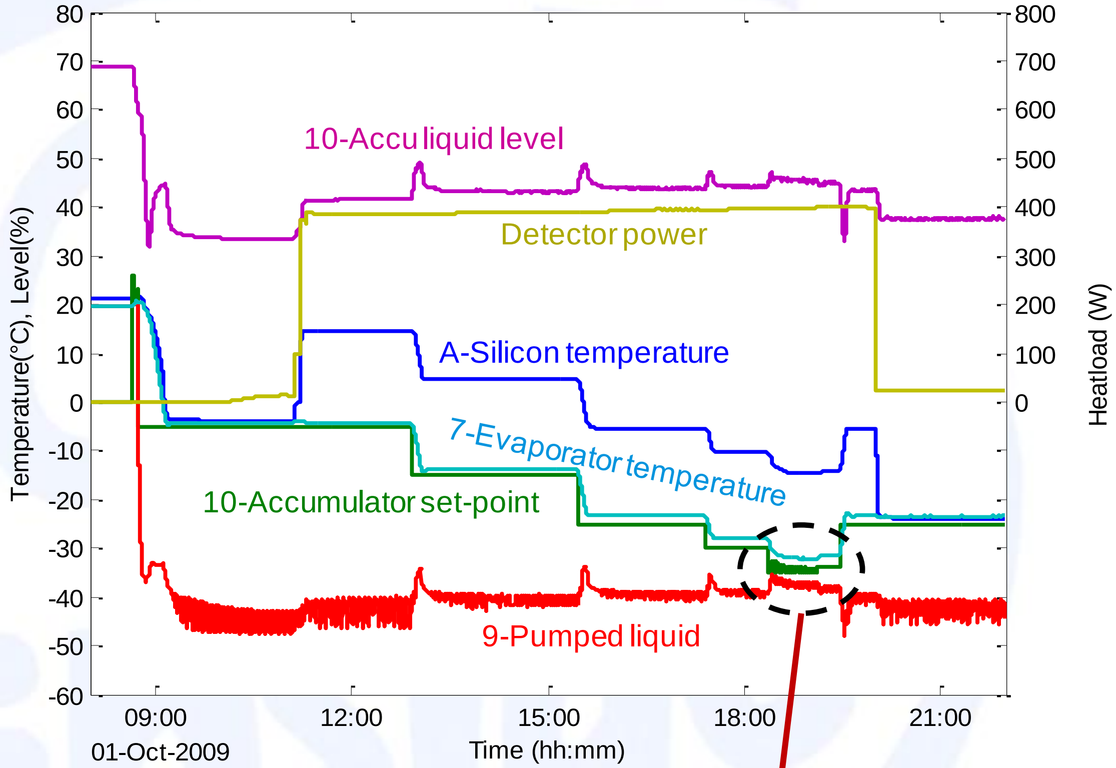
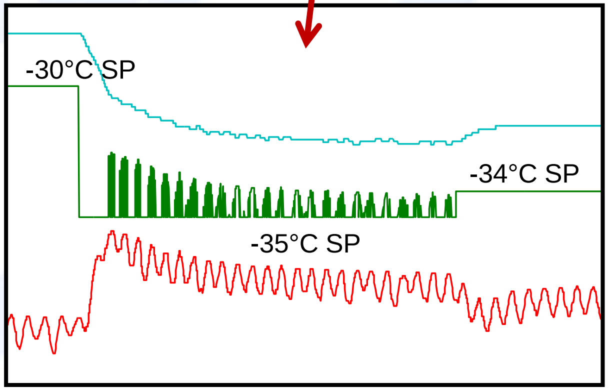
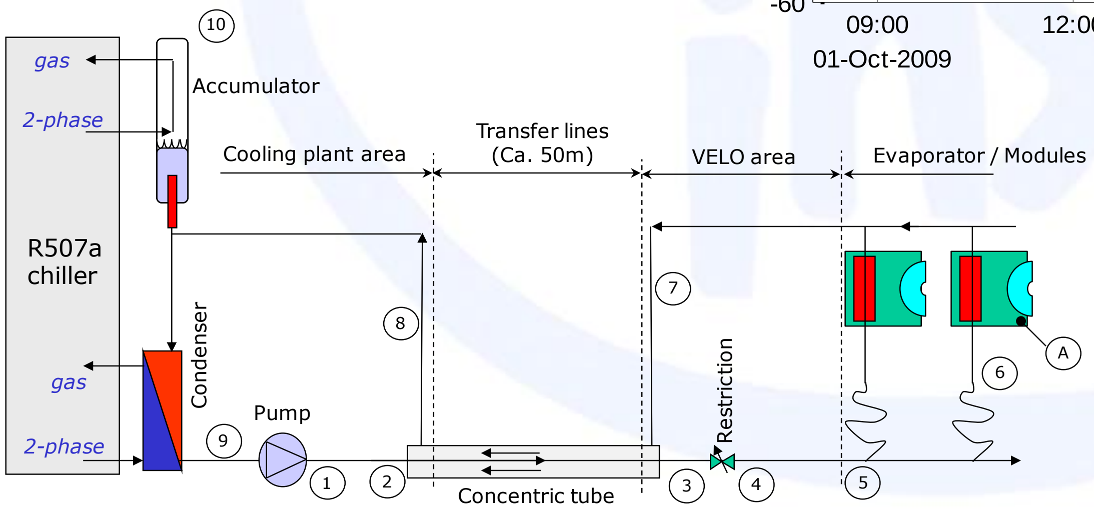
VTCS Commissioning results:
Start-up and operation

Start–up of the VTCS during October 2009 commissioning:

8:40 - Start-up with set-point -5°C
11:10 - Detector switched on
12:50 – Set point to -15°C
15:30 - Set point to -25°C
17:10 - Set point to -30°C
18:20 - Set point to -35°C (System Limit)
19:10 - Set point to -34°C
19:30 - Set point to -25°C
20:00 - Detector Switched off







VTCS Commissioning results:

Start-up and operation in the PH-diagram

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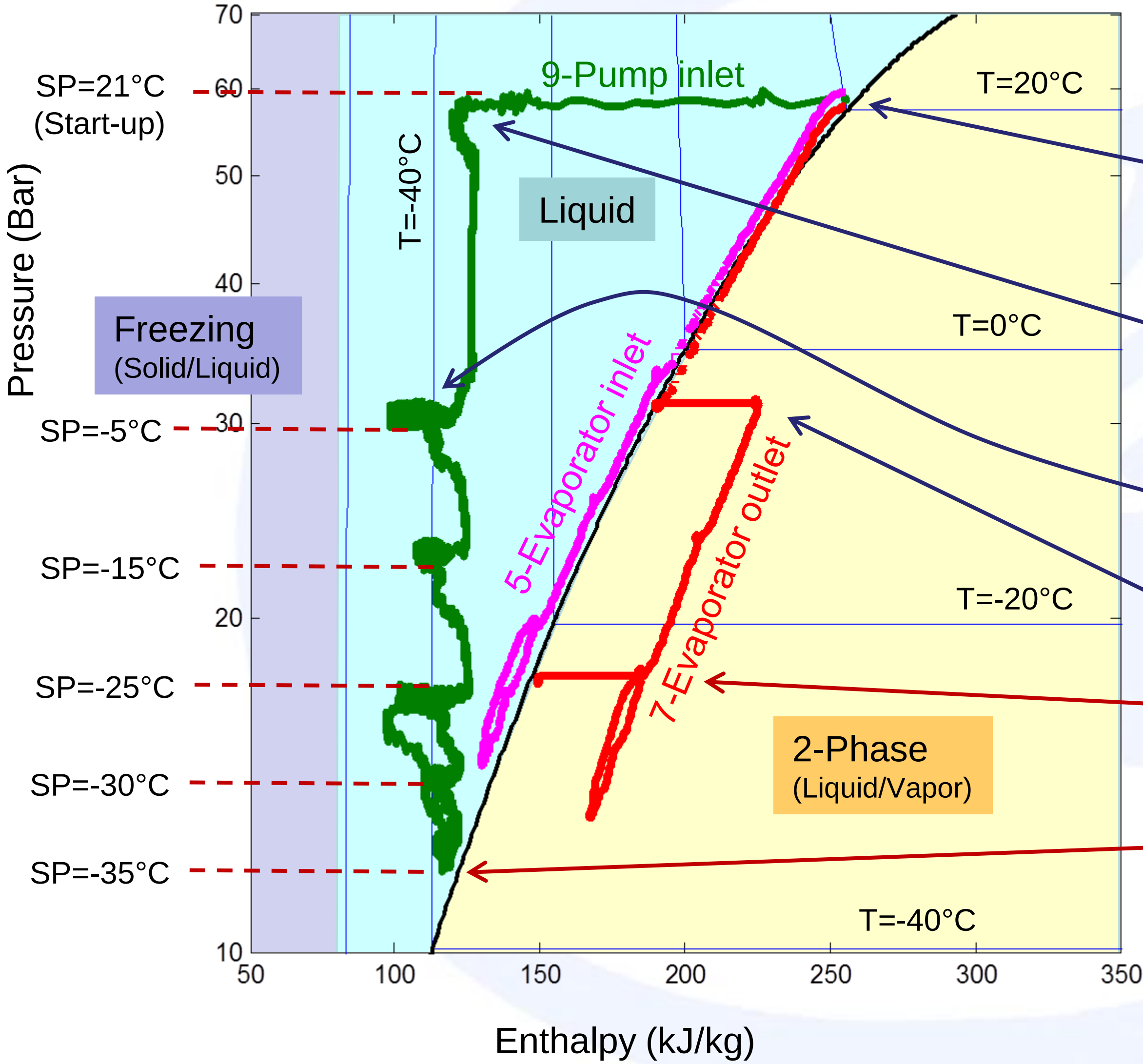

Start-up sequence

1. Increase pressure to make liquid.
2. Pump at high pressure and cool down in liquid mode
3. Lower pressure to desired set-point
4. Power-up detector

Switch-off detector

Lowest possible set-point (liquid approaches saturation line)

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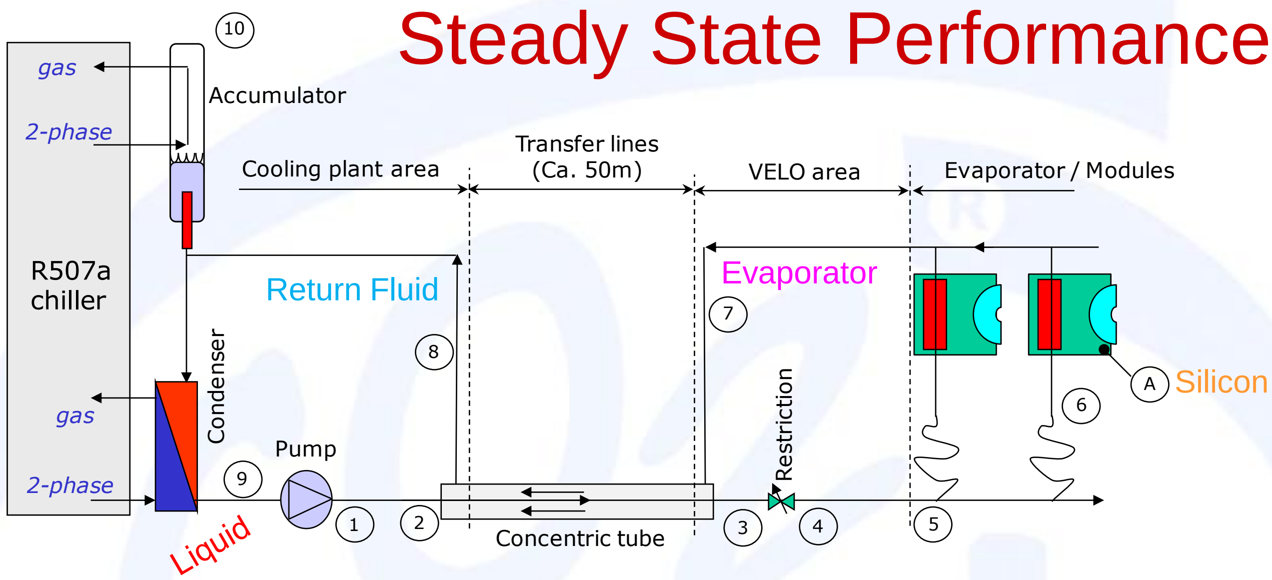
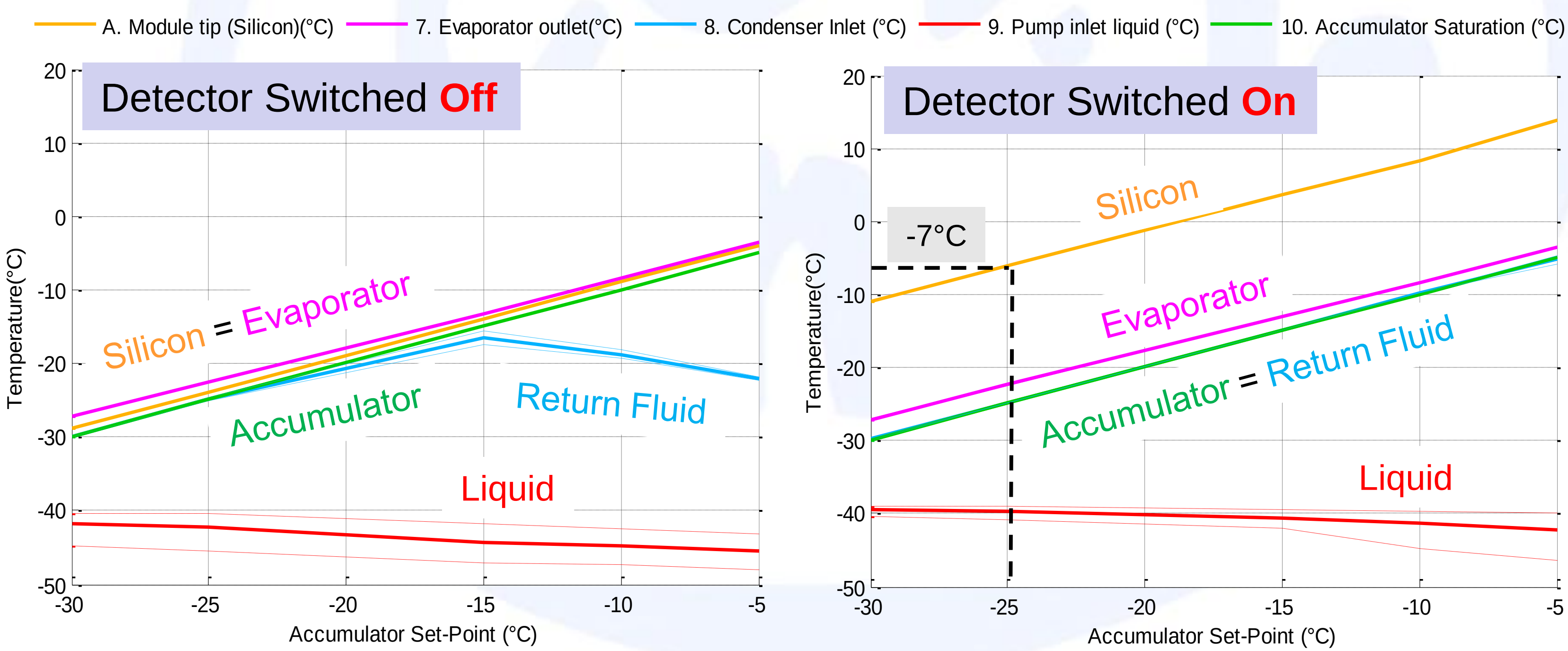
VTCS Commissioning results:
Steady State Performance





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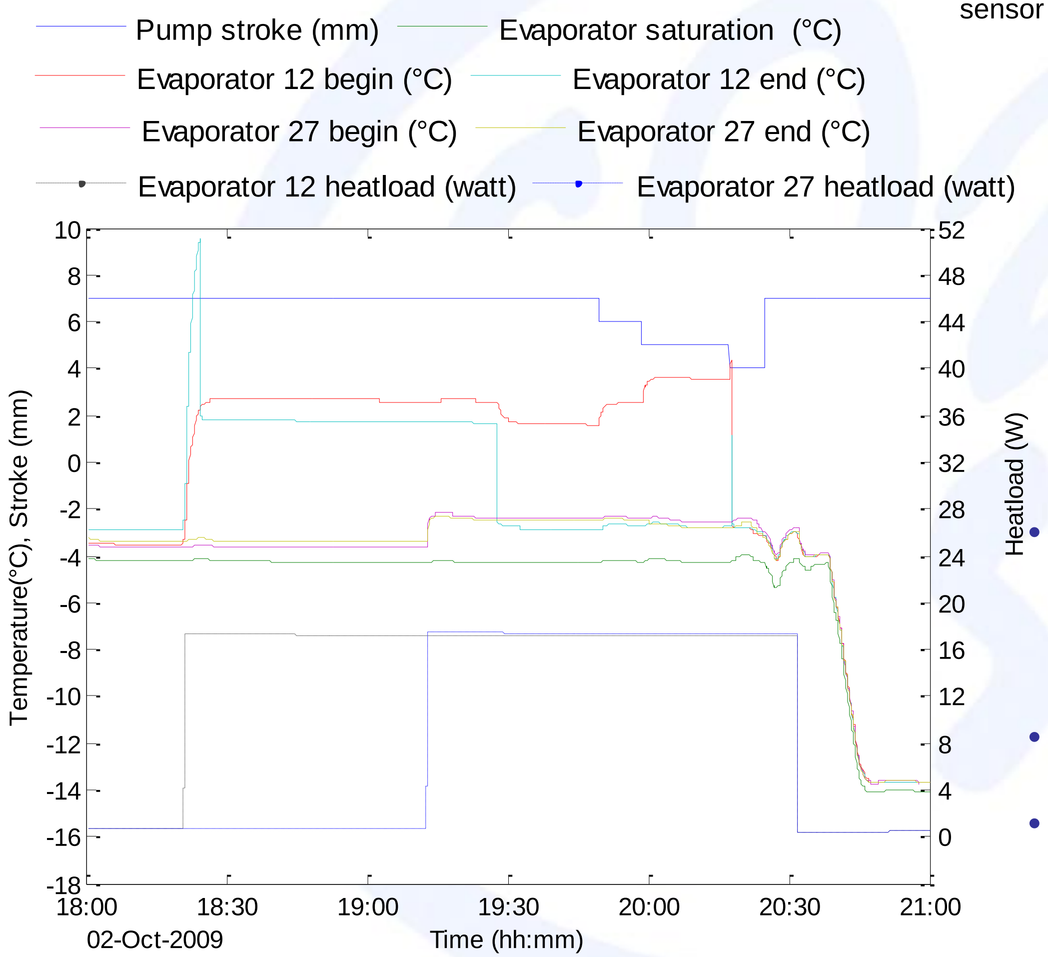
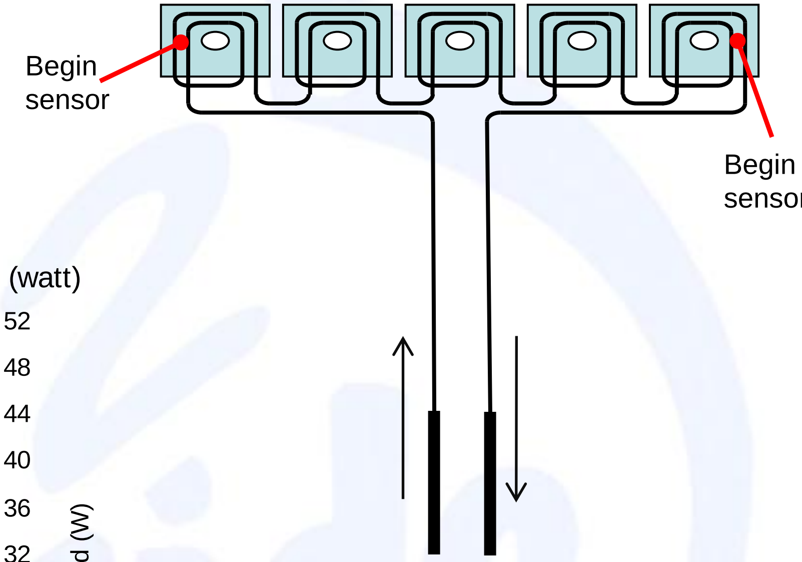
Boiling start-up problems





- Some evaporators have problems getting boiling started. This phenomena seemed to get worse in time.
  - Cleaner CO_2 (No nucleation triggers)
- Disappears after a while, no mayor problem, sometimes annoying
- Layout of evaporator with multiple passes is believed to be a bad concept.
  - Boiling section suppresses boiling in other section due to the increased heat transfer. (The winner takes it al, ……. the heat.)

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Evaporator construction

- The evaporator design is a complex assembly
  - Tight space requirements
  - Flexible in and outlet
  - Reliable connection methods
    - No connectors in vacuum!
    - Orbital welding
    - Nicrobraz EL-36 vacuum brazing
  - The absence of hydraulic connectors resulted in a dismountable thermal interface at the cooling to module interface.
    - Thermaflow T710, adhesive phase change material (45°C)
- Connection methods outside vacuum
  - Swagelok VCR connectors
  - Orbital welding
- Paper about the VTCS evaporator:
  - "*Design, manufacture and test results of the VTCS CO_2 evaporator for the LHCb experiment at CERN*", HEFAT2010, 7th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, 19-21 July 2010, Antalya, Turkey

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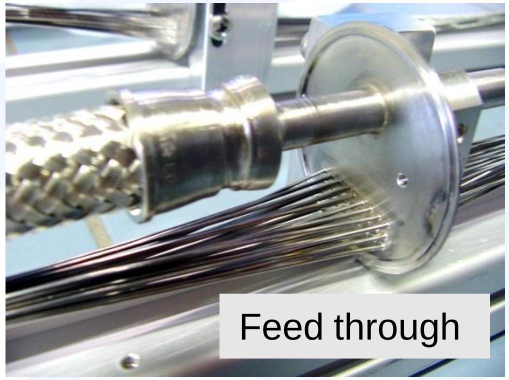
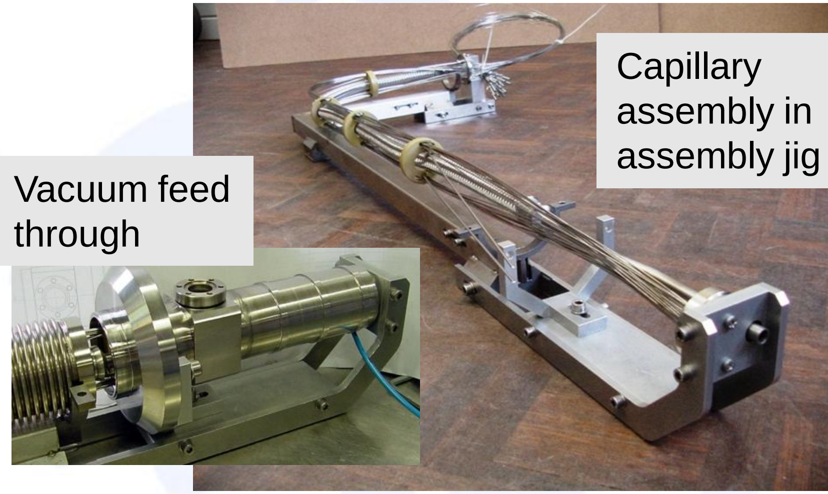
VTCS assembly
Flexible in and outlet below


Brazed capillary assembly

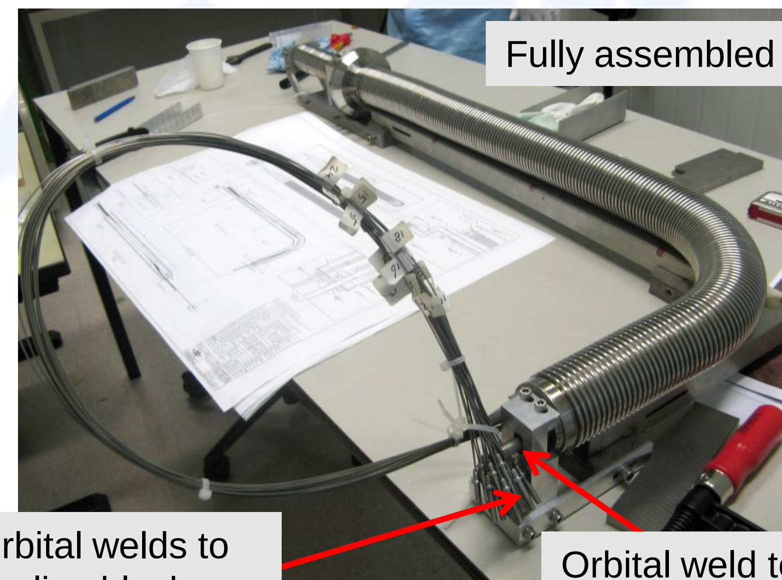

Feed through


Vacuum brazing


Brazed inlet manifold


Vacuum feed through

Capillary assembly in assembly jig


Fully assembled hose

Orbital welds to cooling blocks

Orbital weld to outlet manifold

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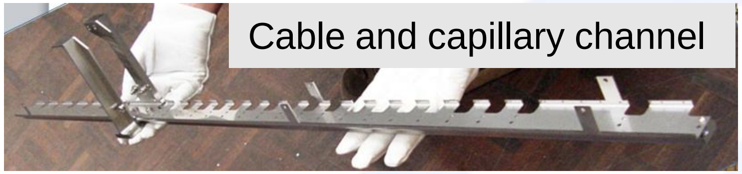
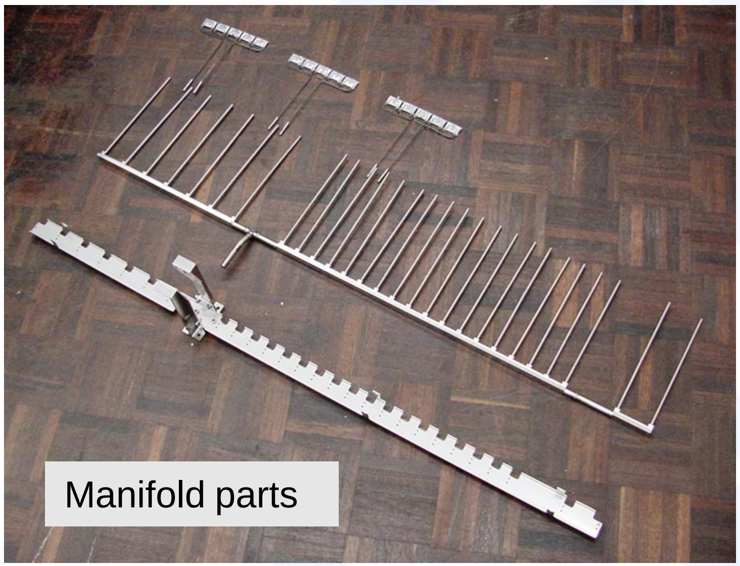
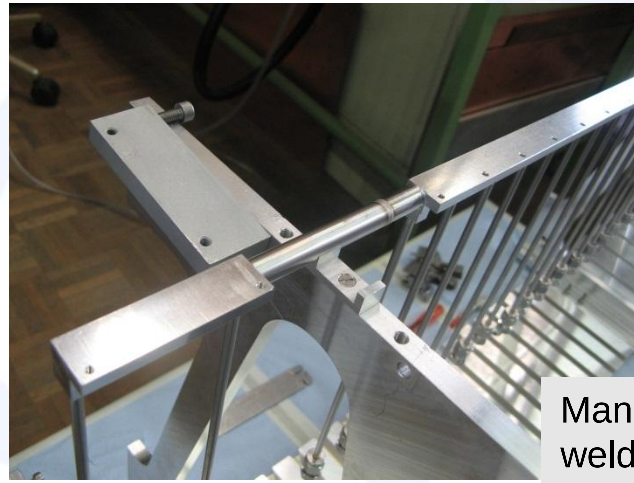
CERN

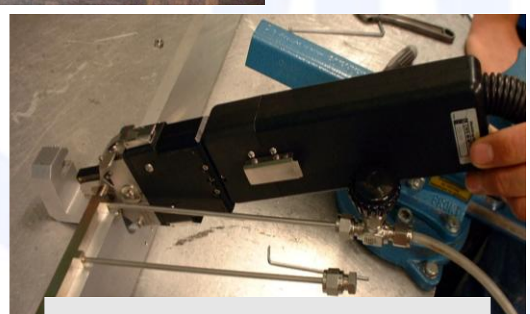
VTCS assembly
Support manifold

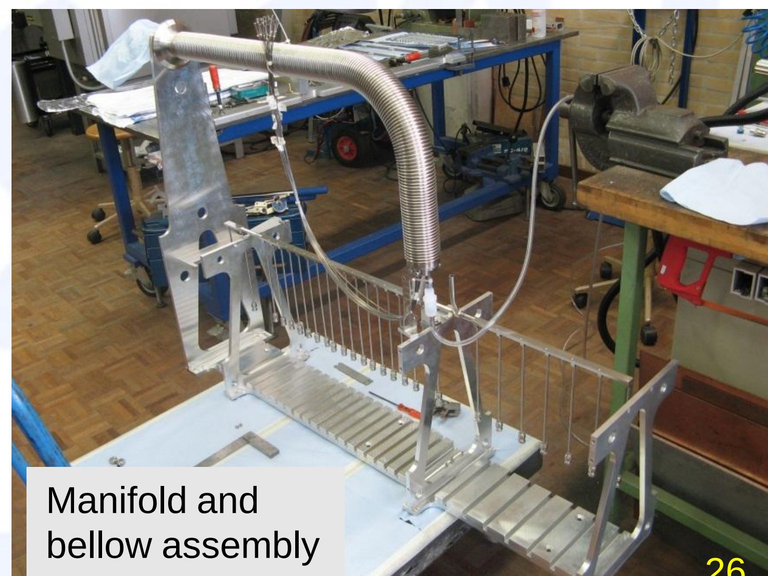

Cable and capillary channel


Manifold parts


Manifold welds


Machined manifold section


Manifold orbital welding (Swagelok series 8)


Manifold and bellow assembly

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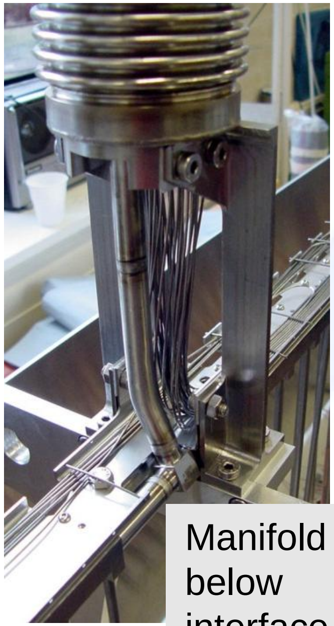
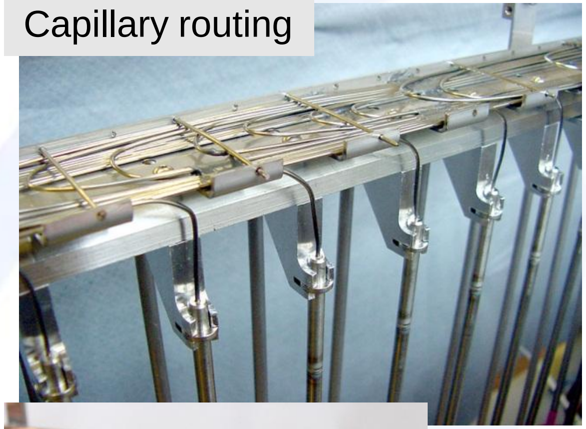
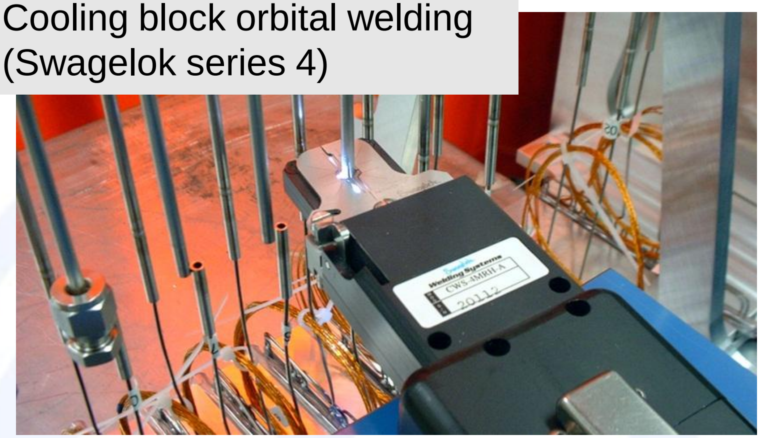
VTCS assembly
Evaporator block assembly



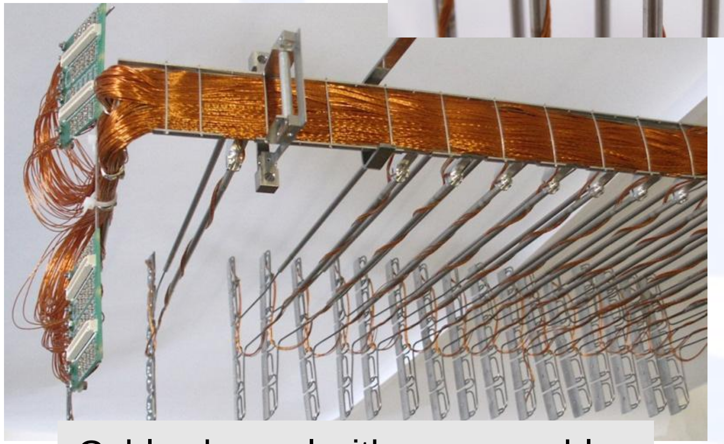
Manifold below interface



Capillary routing

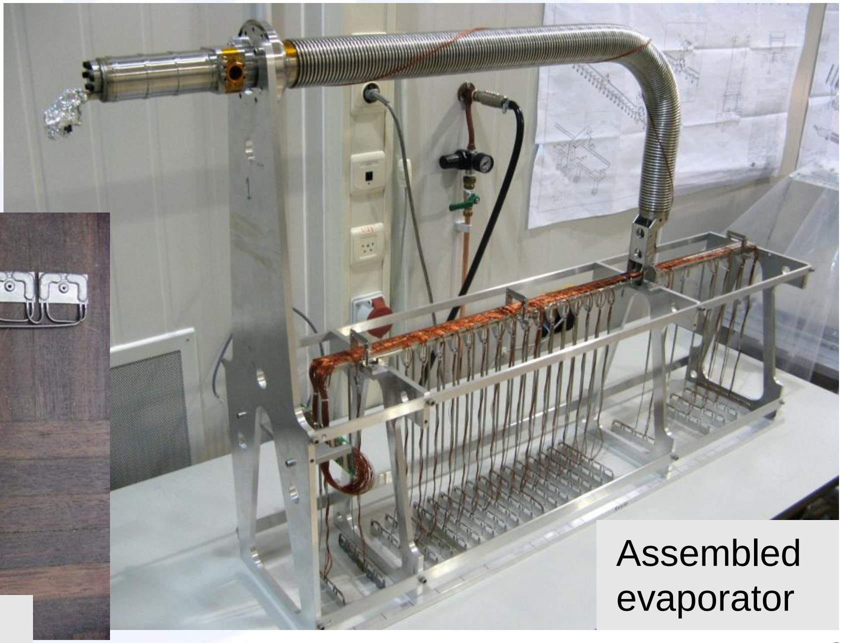


Cooling block orbital welding (Swagelok series 4)



Cable channel with sensor cables

Aluminum cooling block



Assembled evaporator

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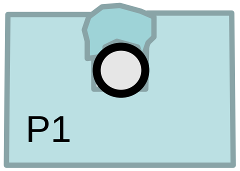
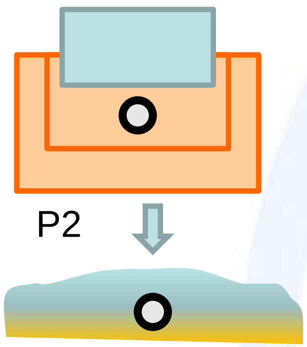
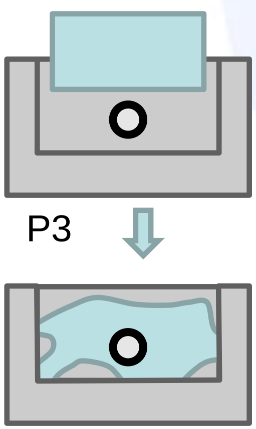
The biggest fun we had: *"Baking cookies"*



Welding tube inside



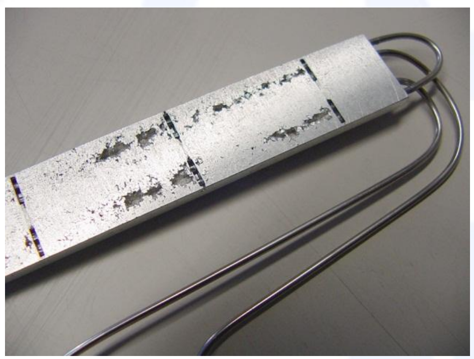
Melting in a copper mold



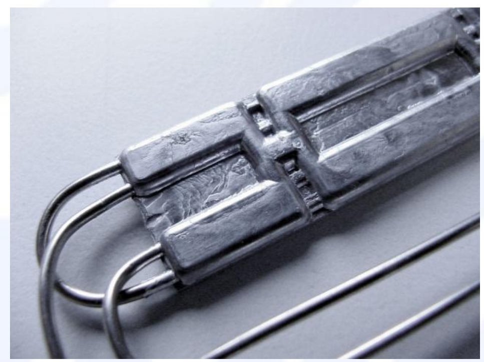
Melting in a SS mold with inert gas

- Question was: Can we melt aluminum cooling blocks around a stainless steel pipe?
  - As Aluminum crimps more we must get a nice crimp contact though?

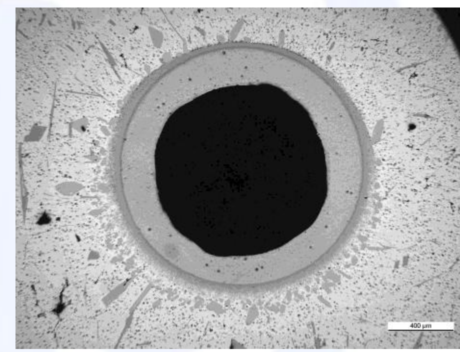
Prototype 4: Mg vapor bubbles due to vacuum



Prototype 5: Vacuum melting / pressurized freezing.. Perfect!



Applied vacuum method bonded SS to Alu by diffusion of Fe into Al



Result of vacuum baking:
A: Perfect contact around the pipe, B: perfect contra shape of the mold

- Aluminum cookie recipe:
  - Take a stainless steel tin and fill with aluminum blocks or bars (AlMg4,5Mn)
  - Melt aluminum under vacuum <1e-3 mbar at 700ºC for 1.5 hour
  - Apply 1 bar Argon pressure for 10 minutes
  - Switch of oven and let cool down.
  - Remove cookies from the mold and machine

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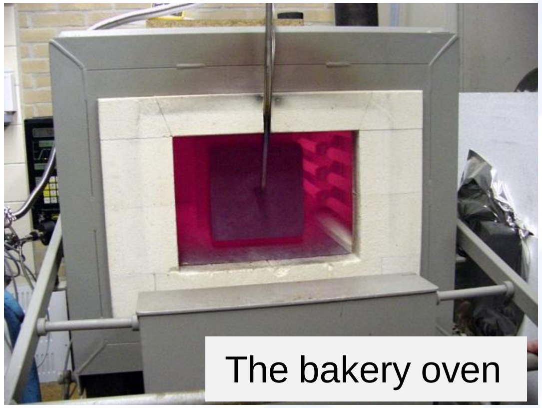
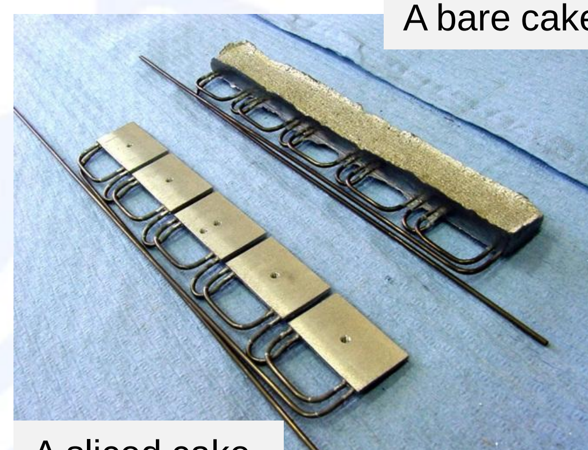
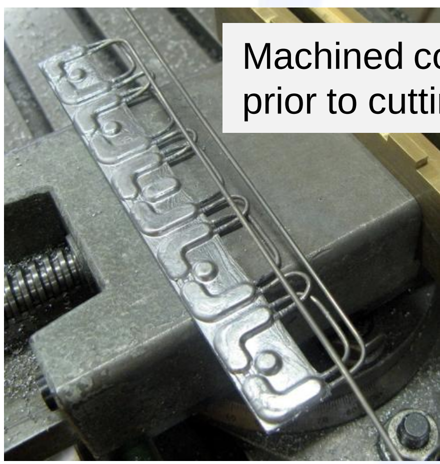
“The cookie bakery”


The bakery oven


Serial production baking


A bare cake

A sliced cake


Machined cookie prior to cutting


Tube bend jig


Mold detail

Magic pen to stop “super fluid aluminum”


A delicious aluminum cake!

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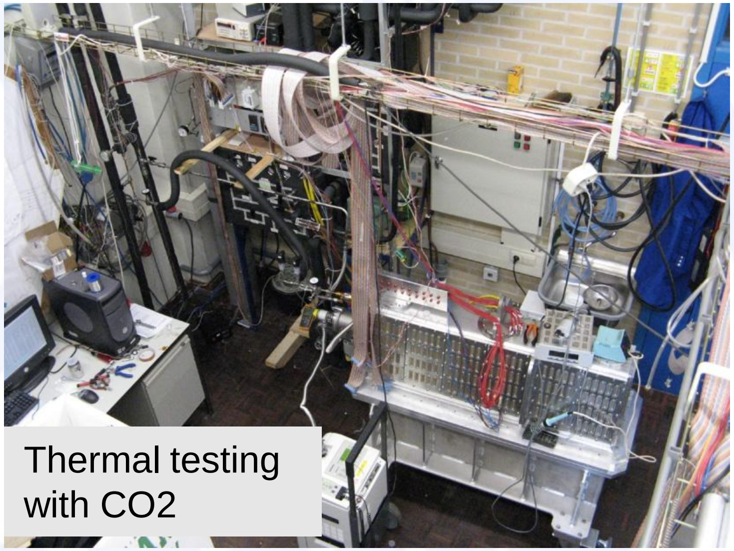
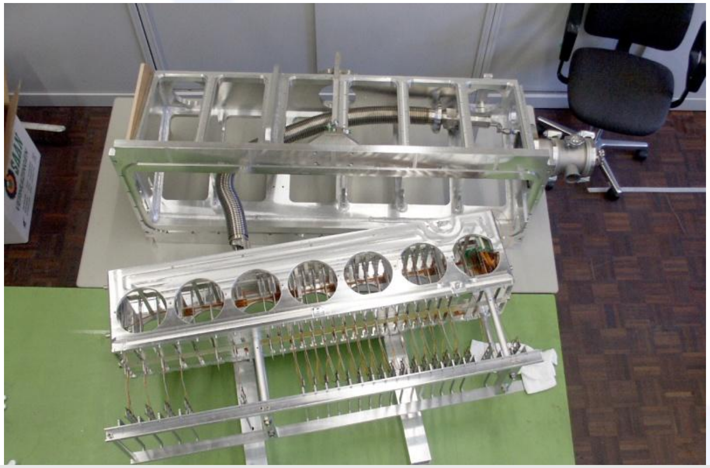
VTCS assembly
Detector half assembly

Insertion of evaporator into module base

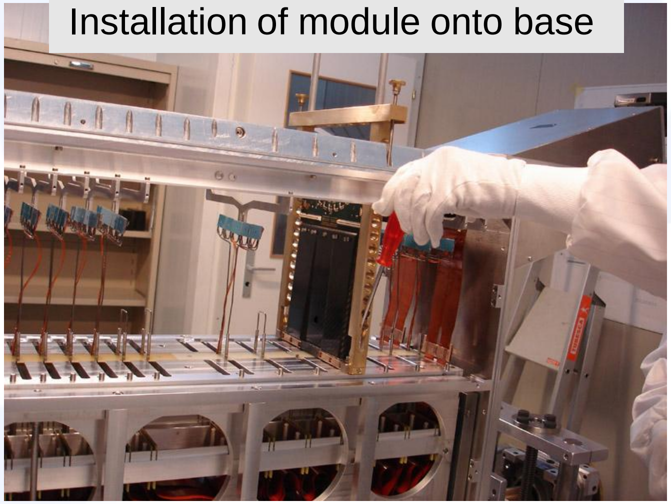


Thermal testing with CO2



Insertion of evaporator and base into hood

Installation of module onto base



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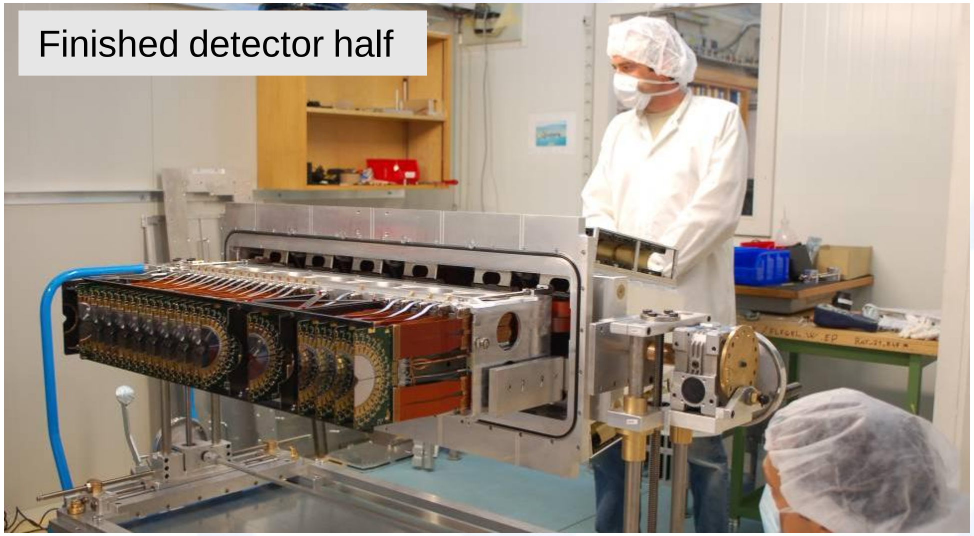
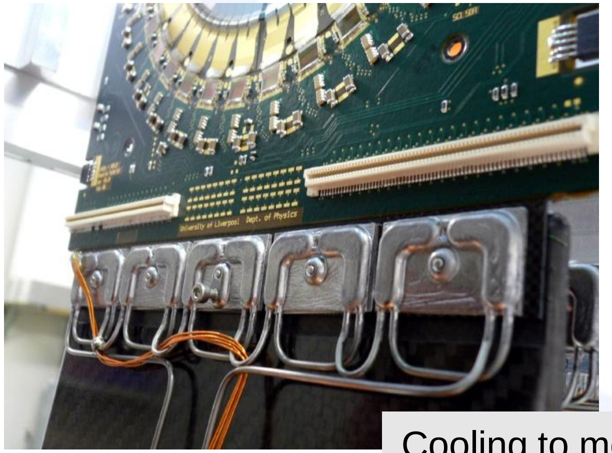
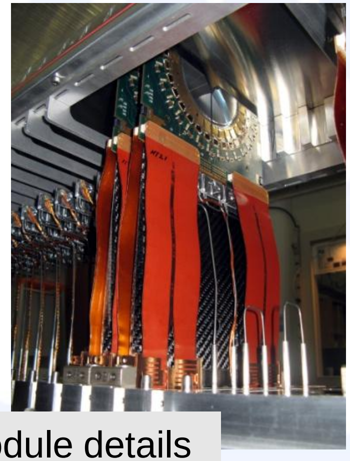
VTCS assembly
Detector half finished

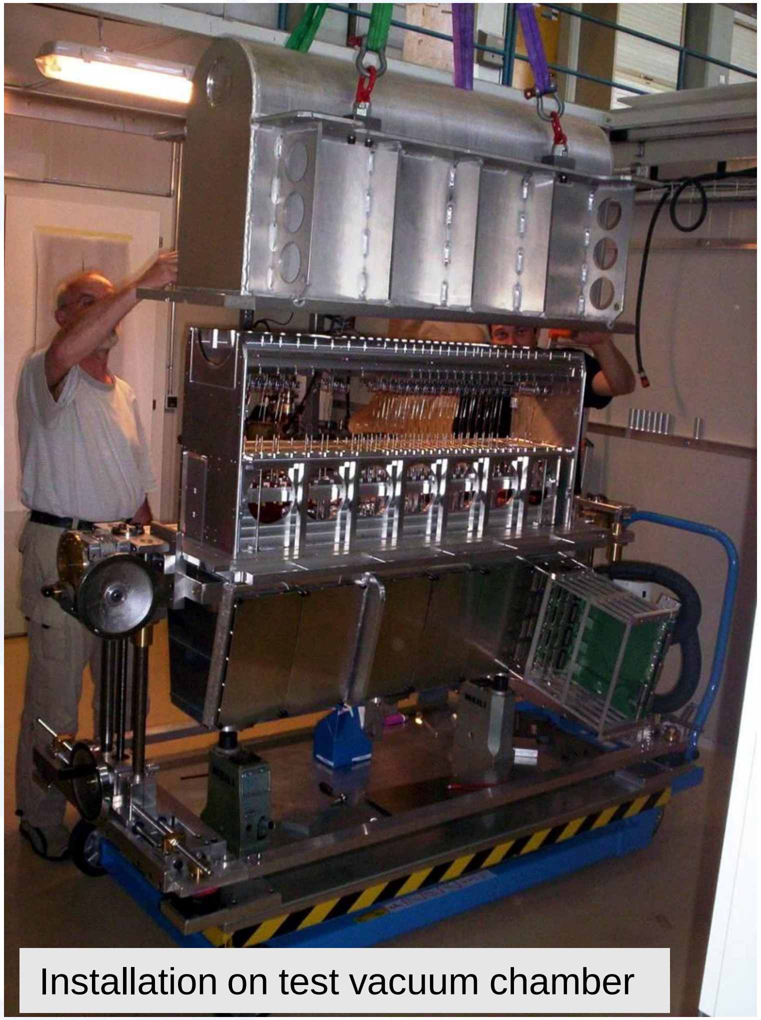


Finished detector half





Cooling to module details



Installation on test vacuum chamber

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Spin-off

- The 1st spin-off of CO_2 cooling is the application in AMS-02. All the other spin-offs we know
  - Atlas, CMS, Belle, etc……..
- But the LHCb Velo system is by itself also a spin-off of the AMS system
- So, in fact the LHCb is a spin-off of it's own spin-off…….

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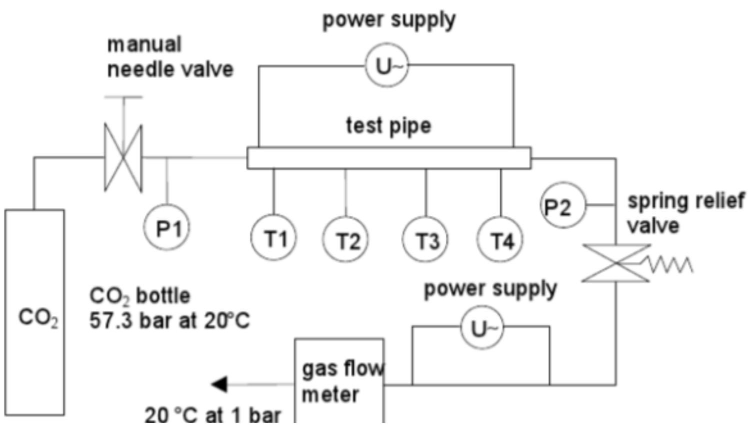
Some history:
LHCb-Velo

- In 1999 Herman Boer Rookhuizen @ Nikhef proposed CO2 cooling for the Velo.
- A demonstration was given 1st with a fire extinguisher, later with a decent blow system set-up

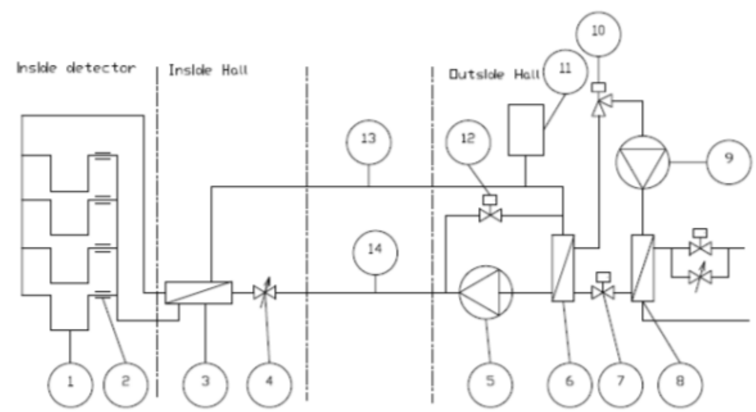
Blow system set-up anno 1999



Power [W]	p_1 [bar]	p_2 [bar]	T_1 [°C]	T_2 [°C]	T_3 [°C]	T_4 [°C]	Mass flow [g/s]
20	15.2	16.4	-27.3	-25.7	-25.8	-28.1	0.07
40	15.9	16.9	-26.7	-25.7	-24.9	-26.2	0.13
100	14.7	16.1	-28.4	-28.0	-26.4	-29.2	0.33
200	14.8	16.1	-27.9	-27.4	-26.2	-29.0	0.66

Table 1: *Test results for the 2.5 mm diameter pipe.*

First plant concept anno 2000



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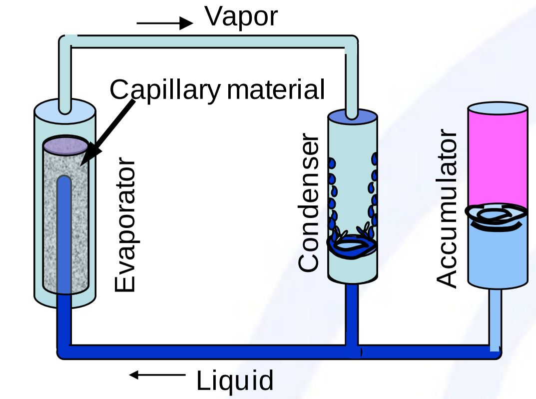
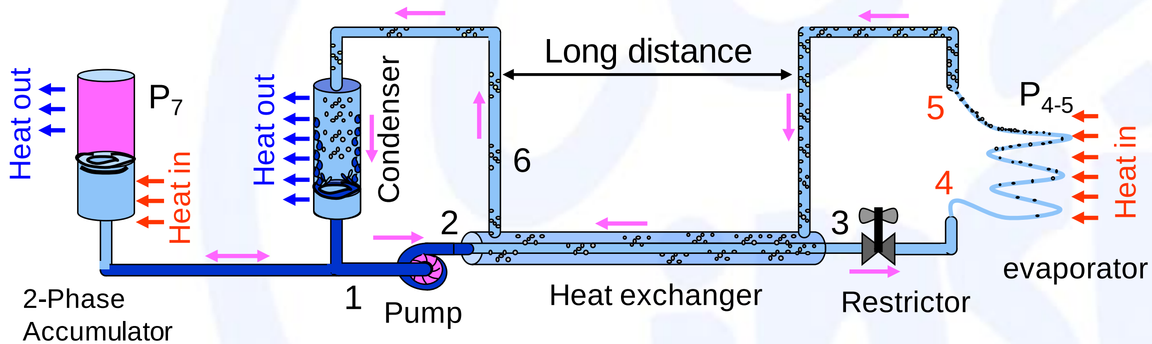
Some history: *AMS-Tracker*

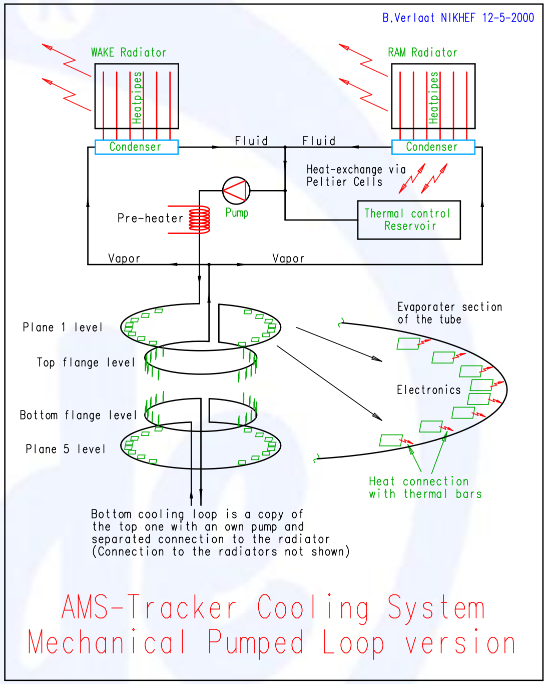
Capillary Pumped Loop



2PACL System



1st proposed 2PACL concept for AMS (2000)



- In space a Capillary Pumped Loop (CPL) systems were used using a 2-phase accumulator for pressure control
- This option was explored for AMS but the wide spread heat sources required long thin tubing…aha…CO_2!!!
- A mechanically pumped loop system was developed taking only the accumulator as heritage of the CPL
- The 2PACL system was born and later applied in both AMS and LHCb.

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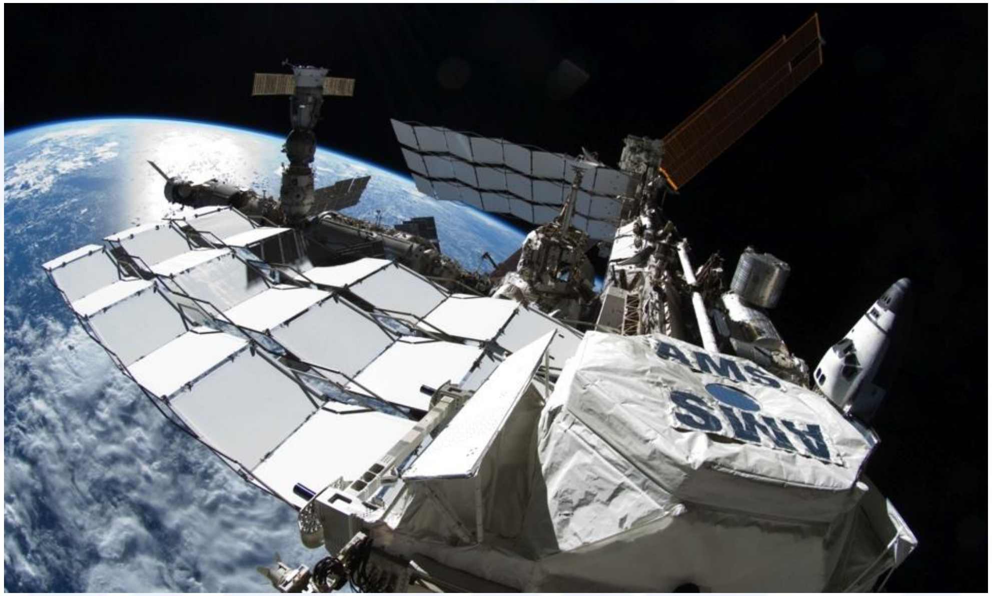
Current CO_2 cooling status



- CO_2 cooling is now operational in 2 HEP experiments:
  - LHCb-Velo (since 2009)
  - AMS-Tracker (on orbit since may 2011)
- Both cooling systems have the same technologies and the same lessons learned

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Lessons learned

- Both AMS and LHCb were designed for extreme circumstances:
  - Vacuum environment
  - In accessible
- Extreme leak tightness requirements
  - Orbital welding of standard 316L tubing
  - Capillary tubing: Vacuum brazing (LHCb) / Laser welding (AMS)
  - Connectors: Swagelok VCR (LHCb) / Dynatube (AMS)
- Keep it simple approach:
  - Let the thermodynamics do the work!
  - No “too” fancy controls
  - Simple redundancy is the best redundancy
- All of above is not difficult to apply, one just have to do it.