Mixed cooling solutions for the Belle II vertex detector

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On behalf of Belle II VXD Collaboration

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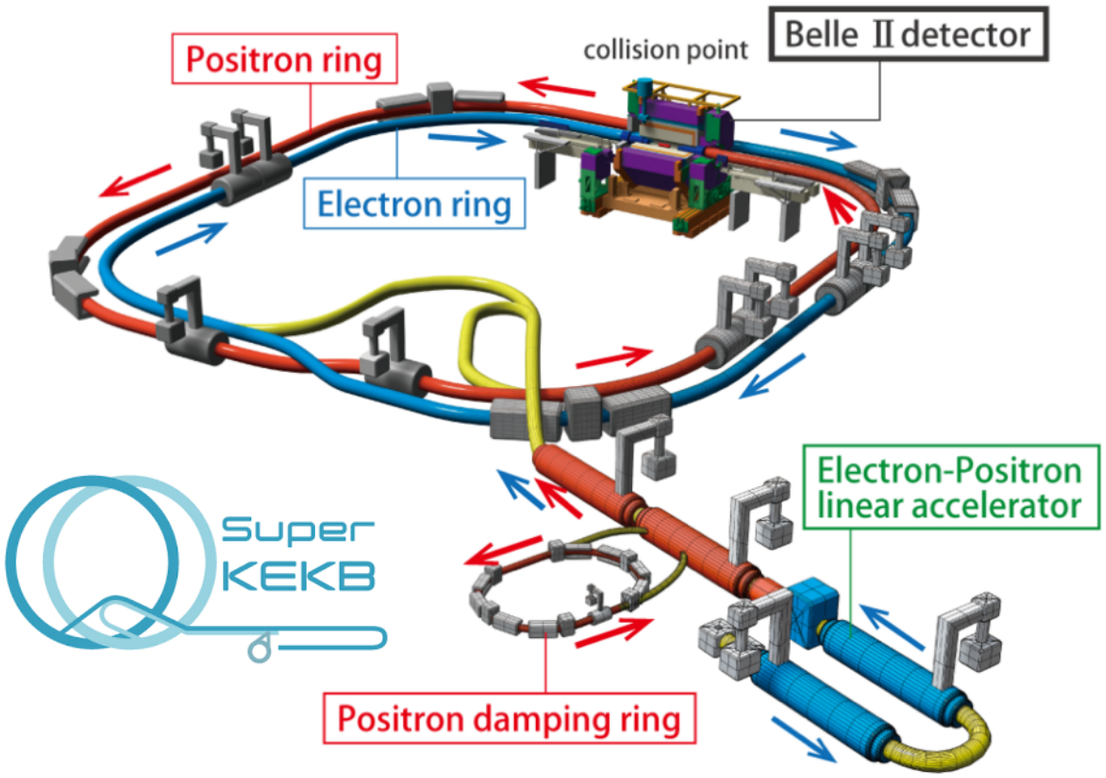
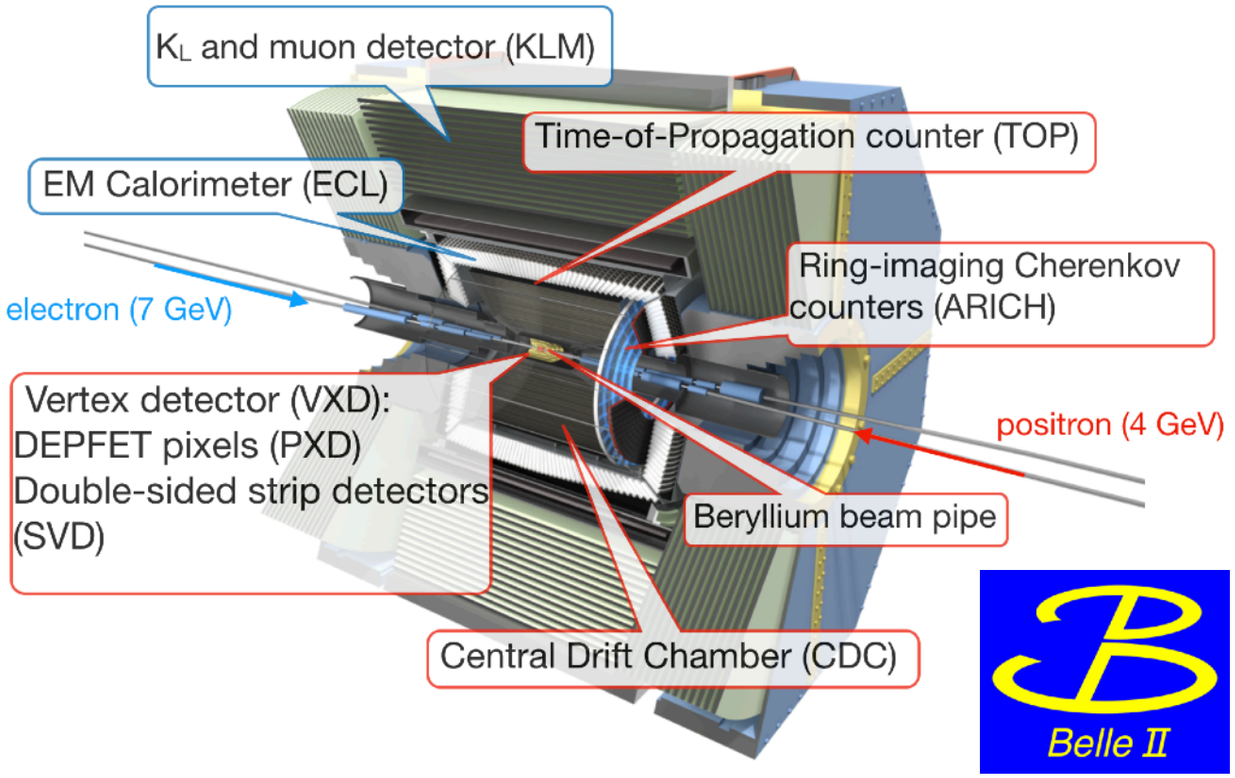
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Belle II

DESY.

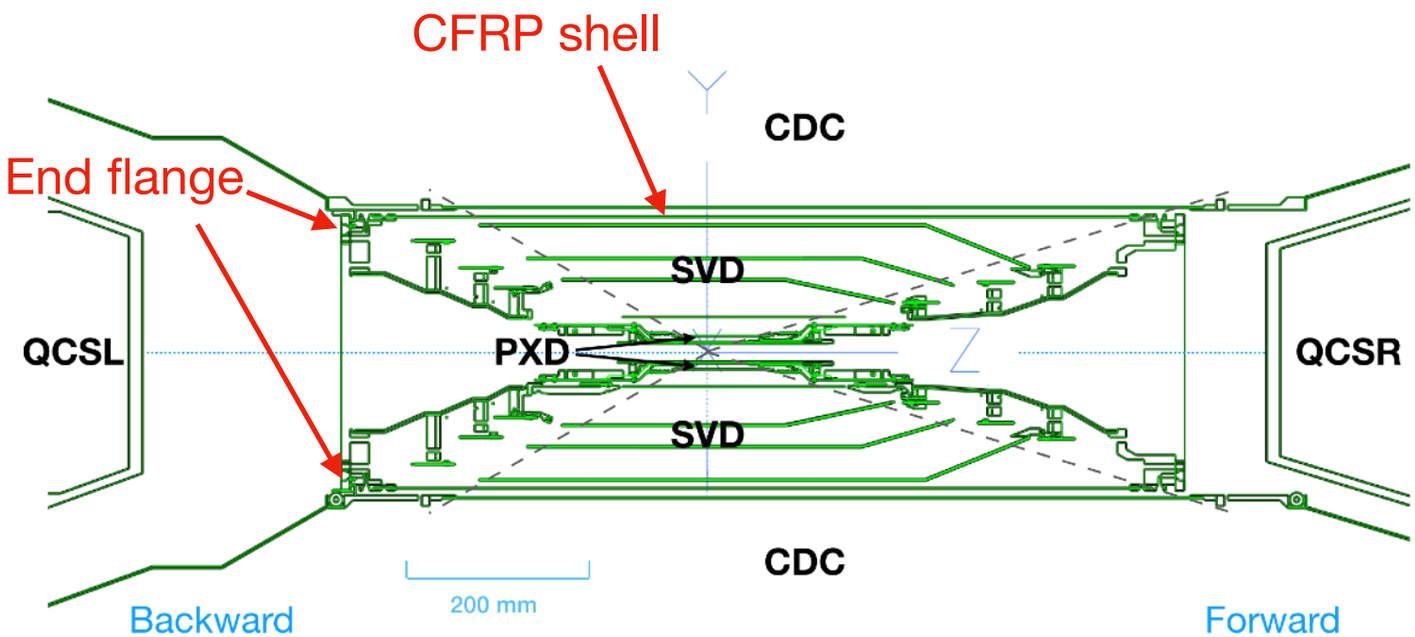
SuperKEKB and Belle II

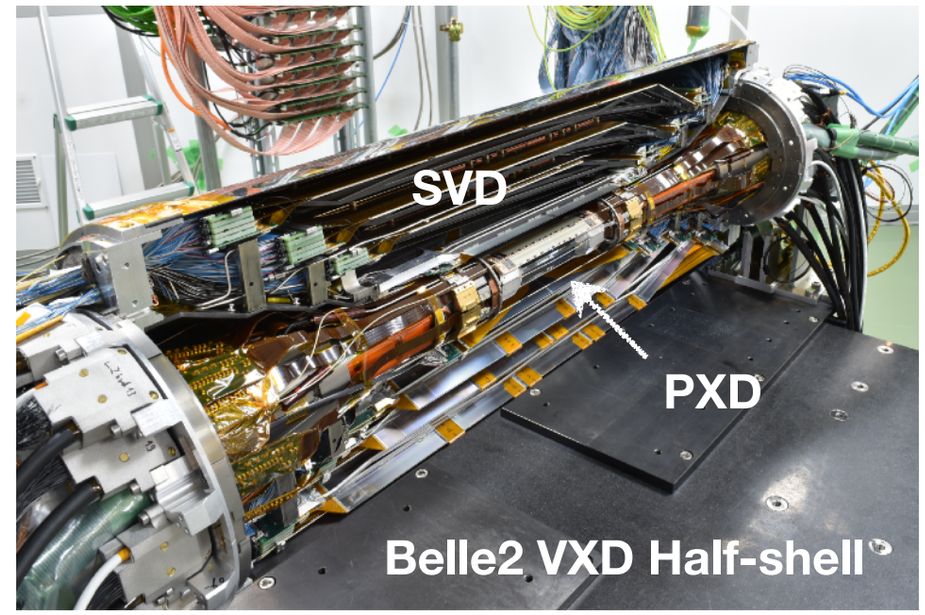




- SuperKEKB delivers e^+e^- collisions at 10.58 GeV ($M_{\Upsilon(4S)}$), with a target peak luminosity of 8×10^{35} $cm^{-2}s^{-1}$, 40 times larger than that of KEKB.
  - Increase beam currents twice
  - Reduce vertical beam spot size by a factor of 20
- Belle II detector has accomplished a series of upgrades to
  - Improve the overall performance
  - Cope with the increased background and high trigger rate.
- Physics data taking started in March 2019, aiming to accumulate a dataset of 50 ab^{-1} by ~2027, to study flavour physics and explore new physics beyond the standard model.

Belle II Vertex Detector (VXD)





- The Belle II VXD (PXD + SVD) is a mechanically combined unit, dimensions defined by the cylindrical CFRP shell and the end flanges.

Pixel Detector (PXD)

- 2 layers of DEPFET sensors
- r=1.4cm, 2.2cm; Length ~12cm
- ~0.027m^2

Silicon Vertex Detector(SVD)

- 4 layers of double-sided silicon strip detectors (DSSDs)
- r=3.9cm, 8.0cm, 10.4cm, 13.5cm; Length ~60cm
- ~1m^2

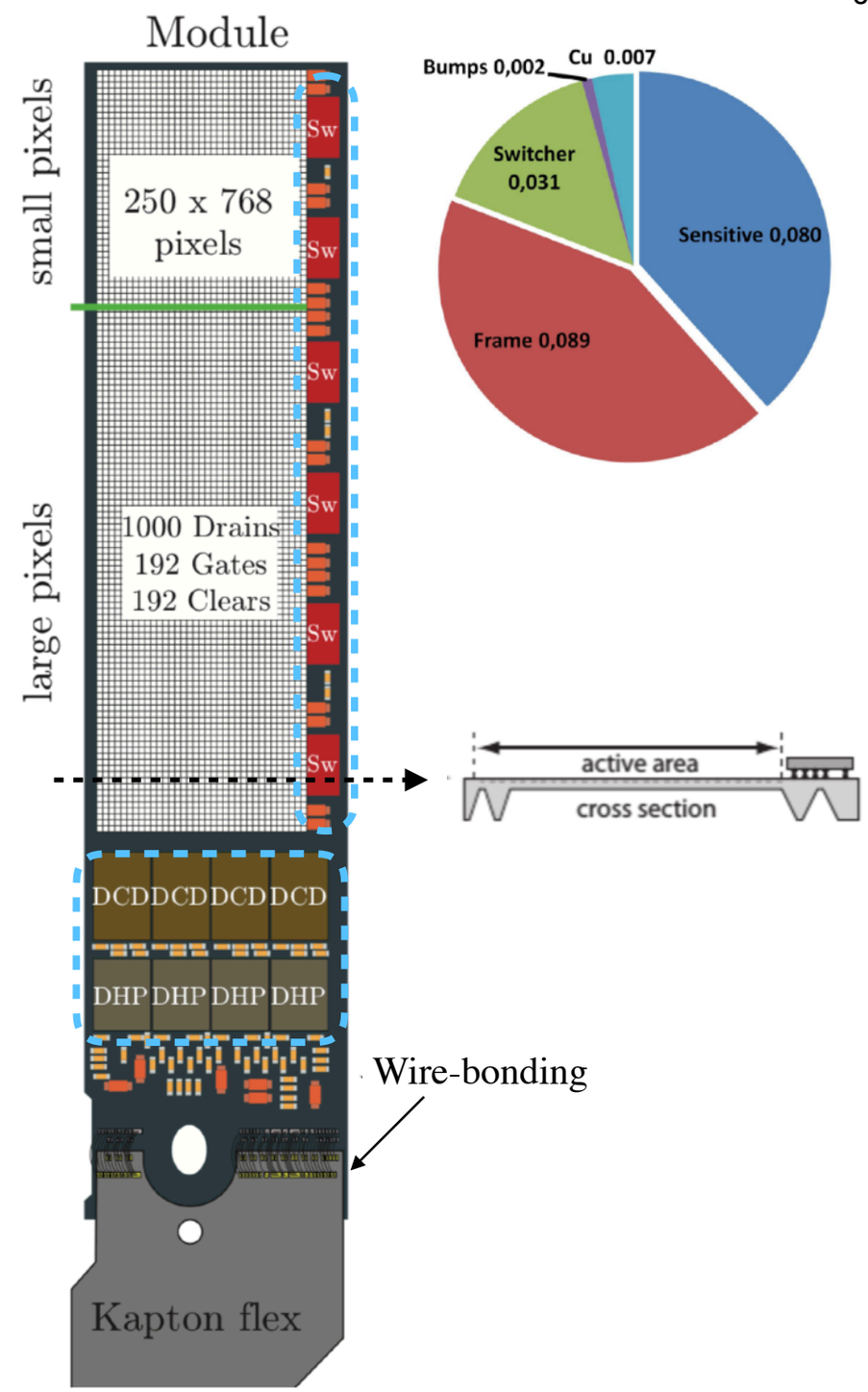
DEPFET based PXD module

- Matrix of 250x768 pixels, pitch size of 50x55-85 μm²
- Sensitive area per module:
  - Layer.1: 12.50x44.80 mm²
  - Layer.2: 12.50x61.44 mm²
  - thinned down to 75 μm.
- Mechanically self-supporting device.
  - frame thickness: 525 μm.
- DEPFET matrix consumes 0.5W of power (~ 60-90 mW/cm²).
- Power consumption dominated by the ASICs (~ 9W) at the end of stave (EOS).

Three different ASICs on the sensor

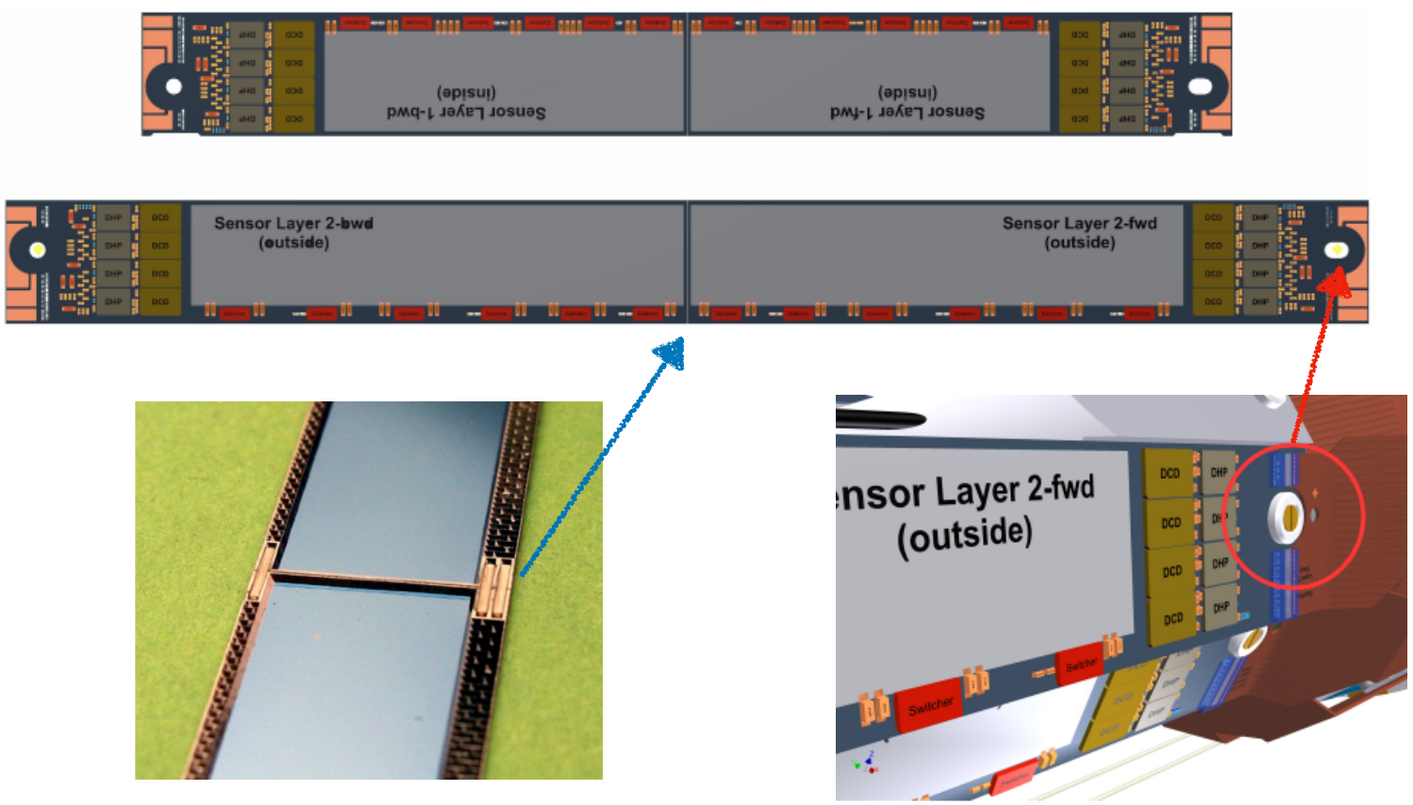
ASIC	Purpose	Position	Power consumption
Switcher	Row addressing	along the sensor	1W
DCD	Signal digitization	end of stave	7 W
DHP	Digital signal processing	end of stave	1.5 W

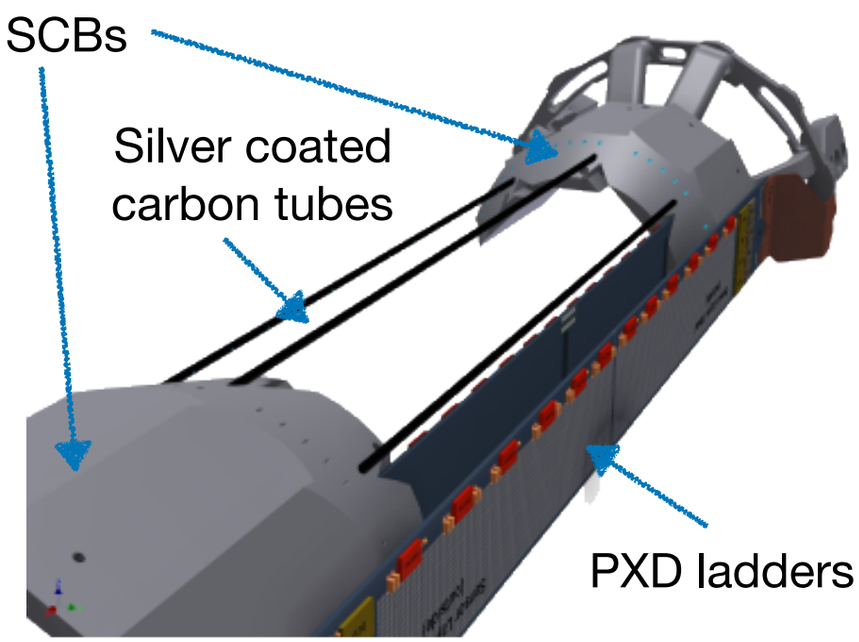
PXD module: 0.21% X_0



PXD Layout

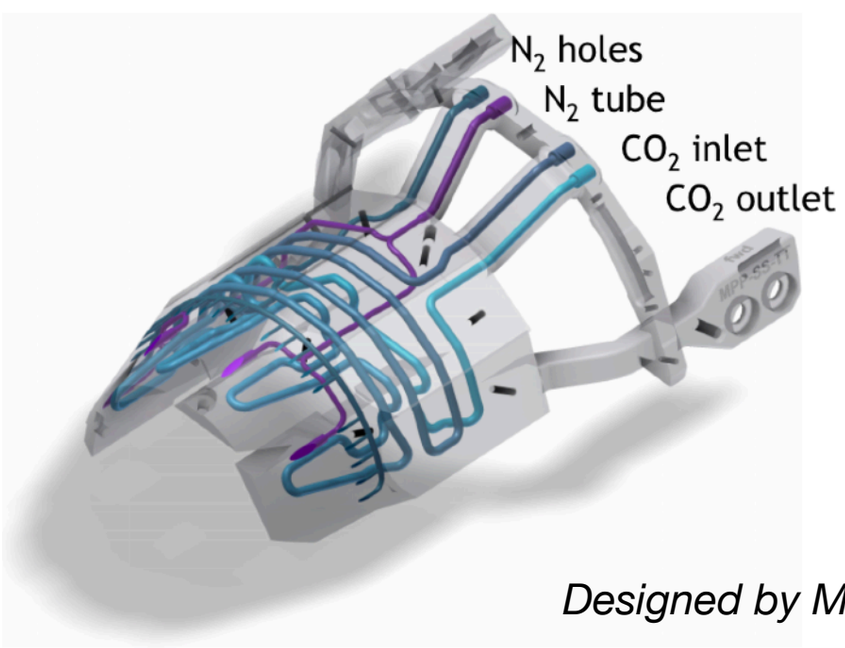
- Ladder formed from 2 sensors
  - End-to-end joint gluing, ceramic mini-rods embedded in the rim of sensor.
- Common support for both layers → support and cooling blocks (SCBs)
  - Ladders are directly mounted on SCBs, the torque for fastening screws is accurately controlled (7-15 mN·m).
  - Elongated holes on the forward module allow for compensating thermal expansions.
- Ladders are electrically isolated from SCBs and screws.



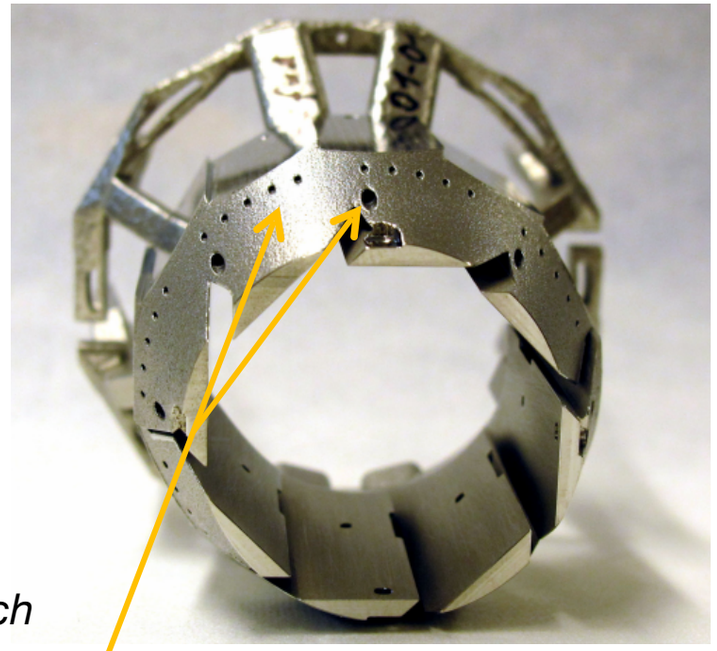


Cooling Scheme for PXD

- Active cooling is required at EOS → 2-phase CO_2 cooling
  - Enclosed CO_2 channels integrated in SCBs.
- Forced gas (N_2) flow is used for cooling the matrix → minimise the material budget in physics acceptance of detector.
  - Open holes on SCB provide forced gas flow between the two PXD layers.
  - N_2 is guided through the holes along the carbon tubes for local cooling of the L.1 Switchers.



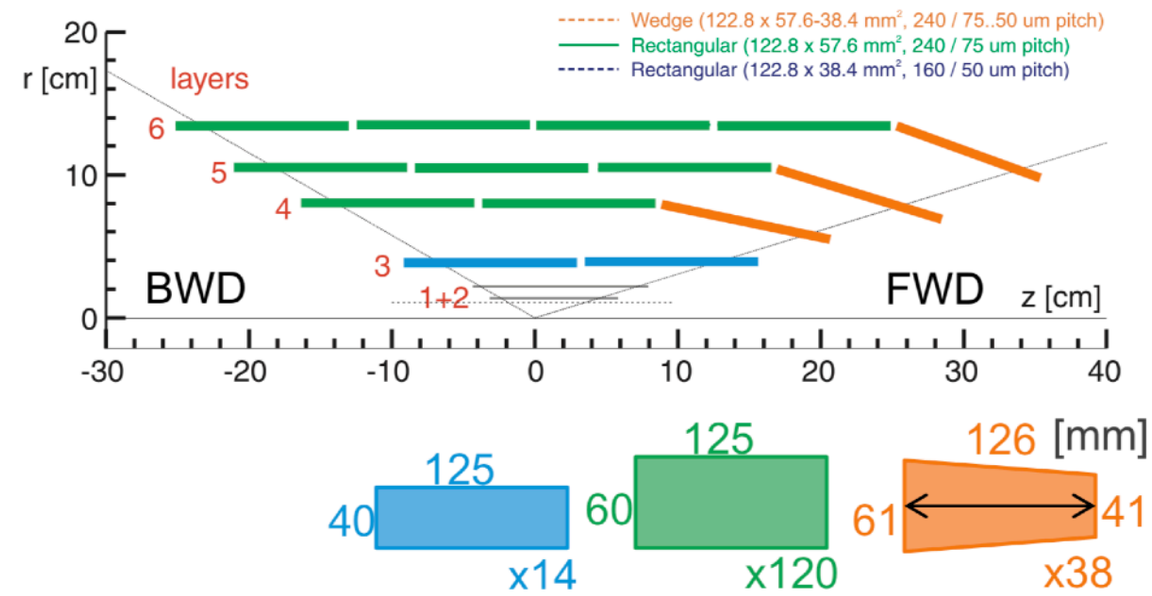
Designed by MPP, Munich

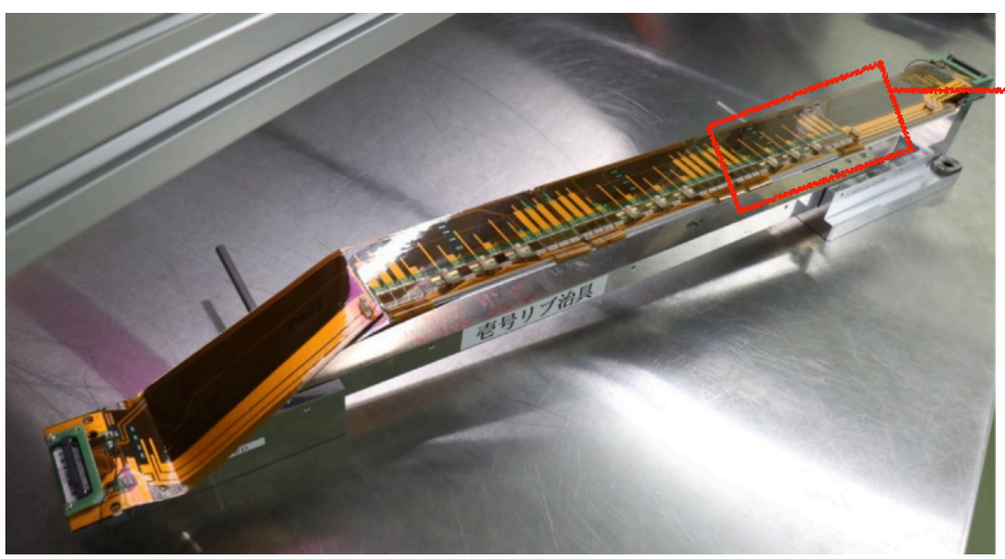


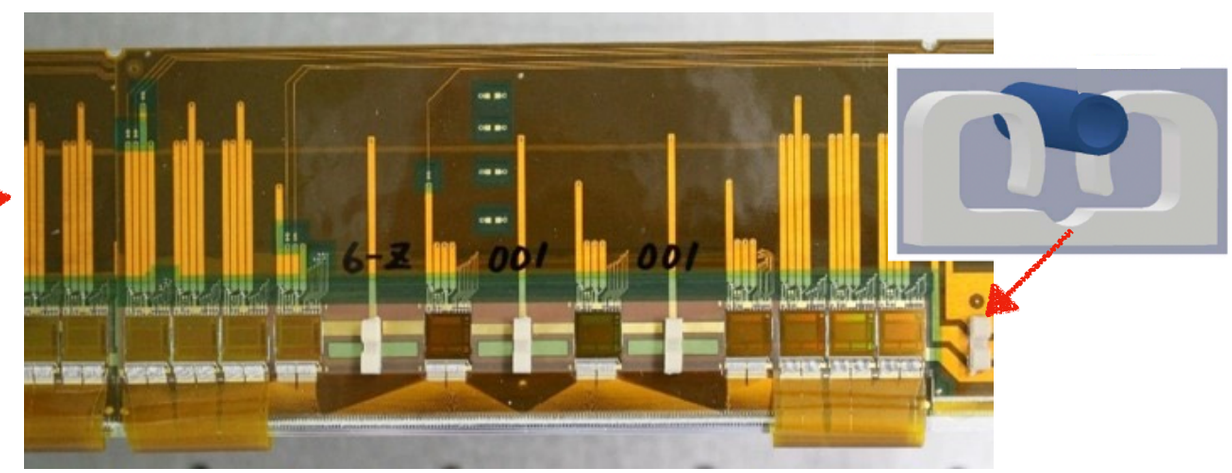
SCB, manufactured from stainless steel using 3D printing technology, with enclosed CO_2 and open N_2 channels inside.

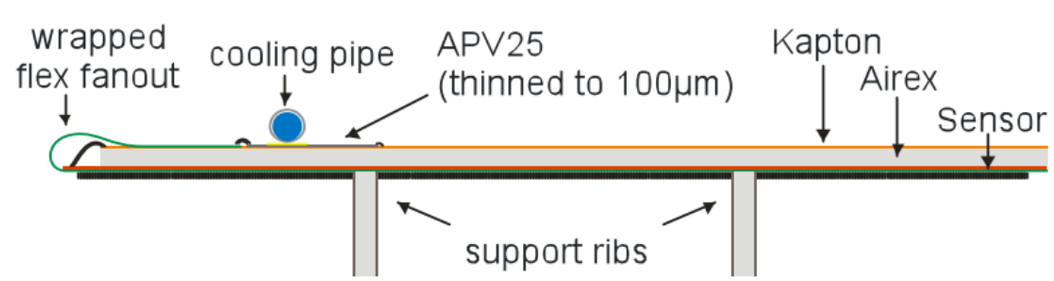
Belle II SVD

- Four layers of ladders with up to 5 DSSD sensors in a row.
  - 768 strips on p-side, 768(512)strips on n-side.
  - p-strip pitch: 50-75μm, n-strip: 160-240μm
  - Sensor thickness: 300-320μm.
- Supported by two ribs and Airex foam core sandwich.
- APV25 readout chip are thinned down to 100 μm.
- Origami concept: all APV25 are aligned in a row on p-side.



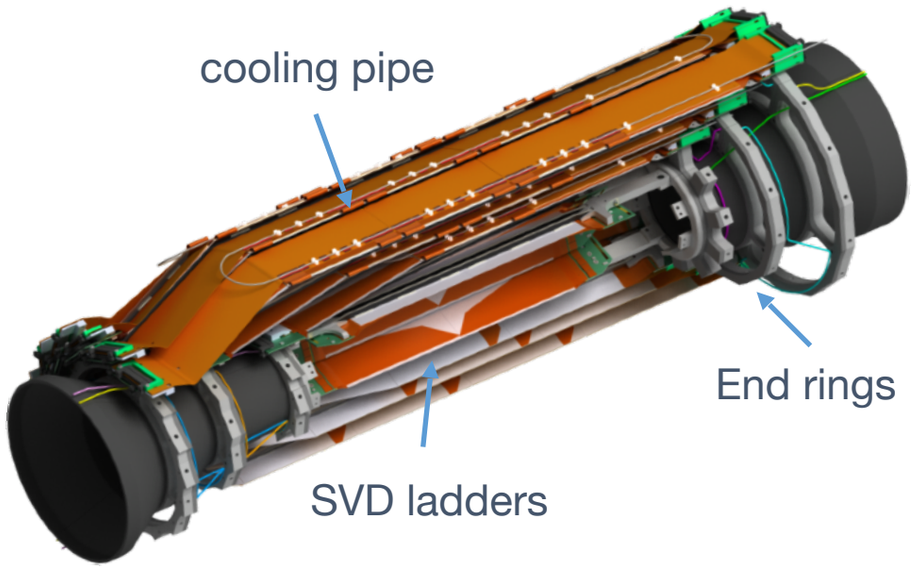


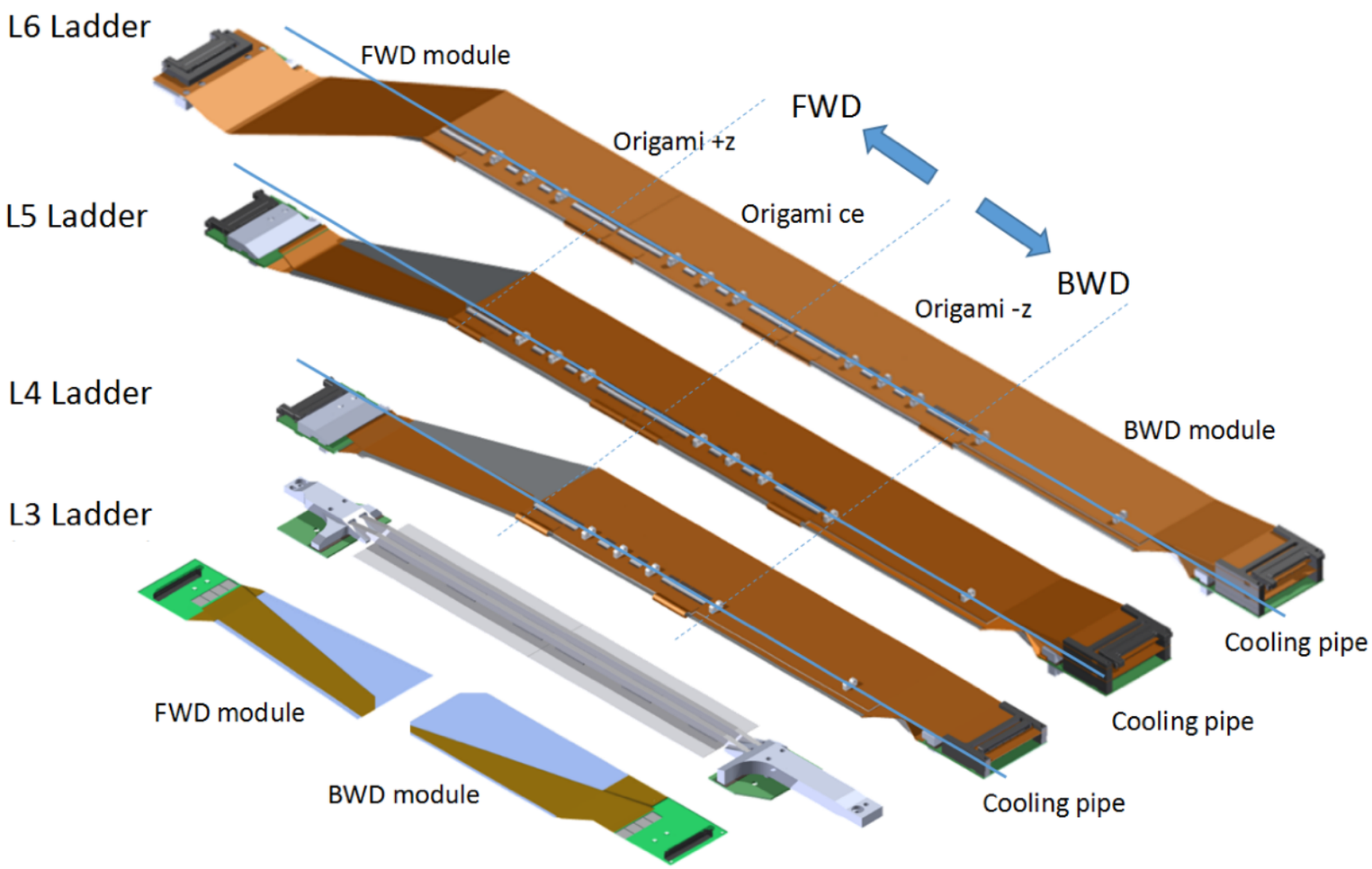




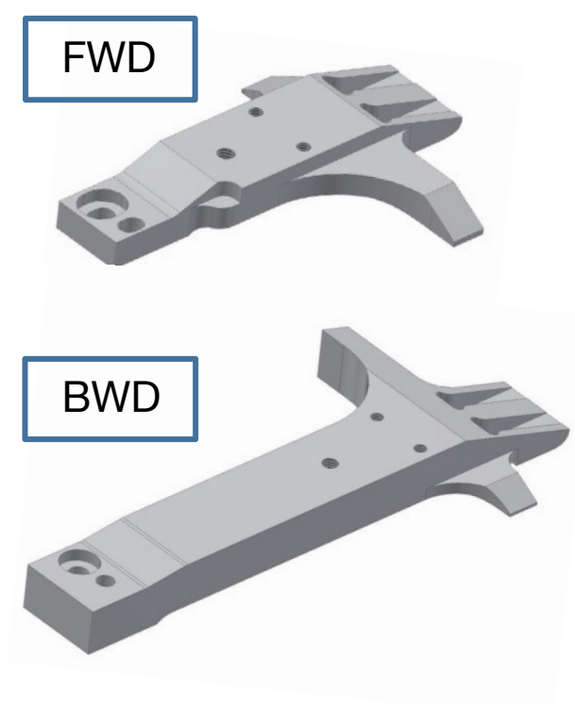
Structure of SVD

- SVD ladders are mounted on end-rings which are glued on CFRP support cones.
- Barrel modules of L.4-6 are cooled with meandering stainless steel cooling pipes.
- APV25s of L.3 and L.4-6 FWD/BWD sensors at the end of the ladder, which are cooled by end-rings (embedded with cooling channels).

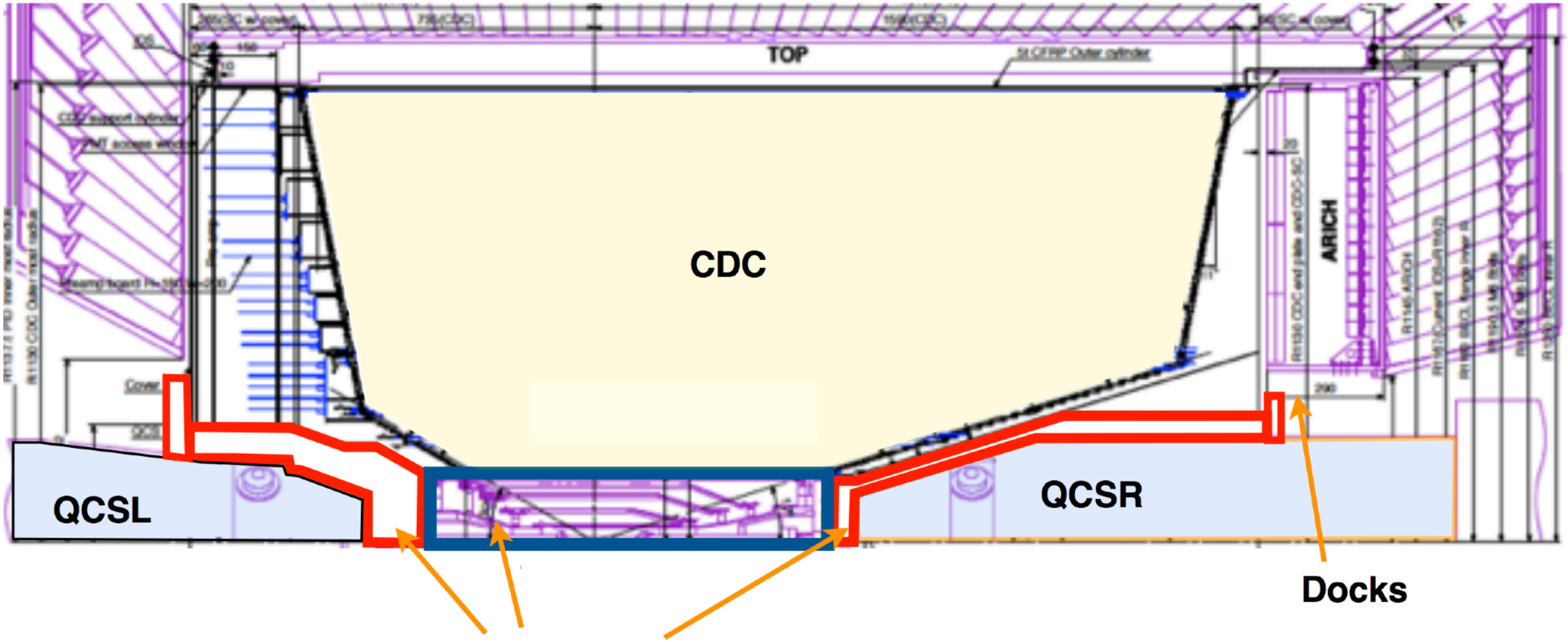




L3 bridge



Cooling Requirement of VXD



"Cold" VXD and "warm" Dry Volumes

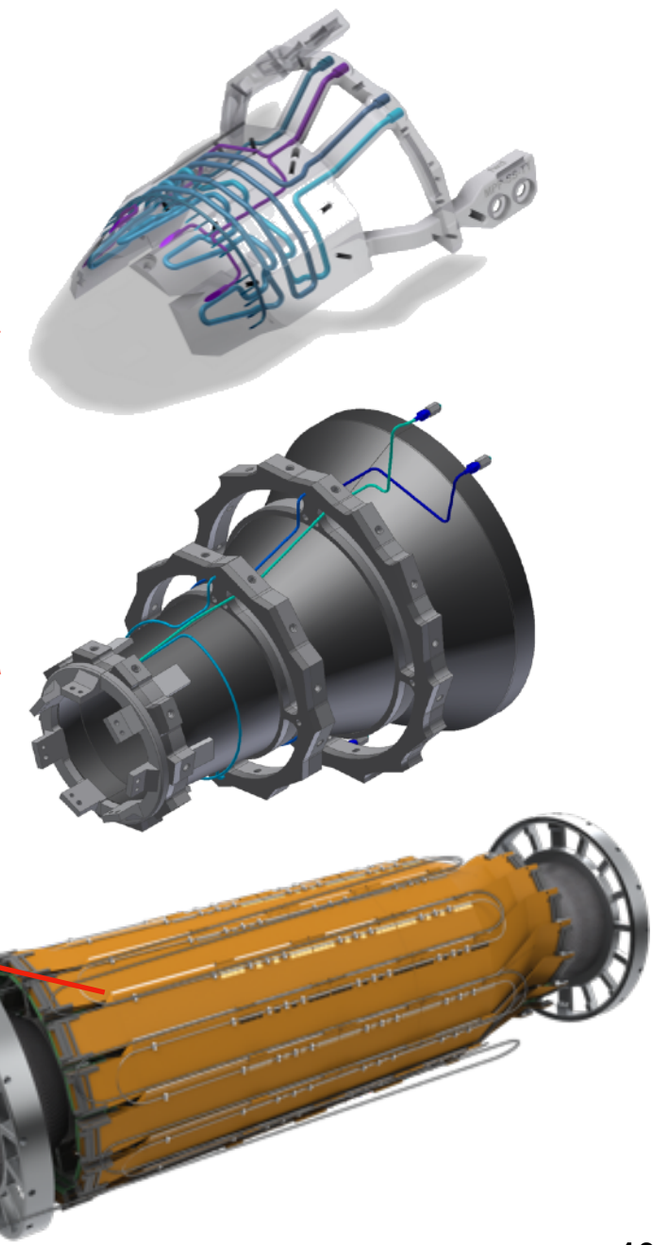
- The goal is to achieve a stable and homogeneous thermal environment in the dense VXD volume with minimised material in acceptance region .
  - The temperature on sensors and ASICs need to be well controlled for S/N improvement.
    - Low temperature, low gradient.
  - Thermal impact to outer tracker needs to be minimised.

Cooling Requirement of VXD

- VXD power consumption ~ 1.1kW (PXD: 400W + SVD:700W), together with the parasitic heat load from the environment, the cooling capacity of 2-3kW is required.
  - Forced N_2 flow + 2-phase CO_2 cooling
  - Balanced heat load and CO_2 mass flow in each cooling circuit.
    - ~ 1g/s in each circuit.
  - CO_2 set point < -20°C is required.

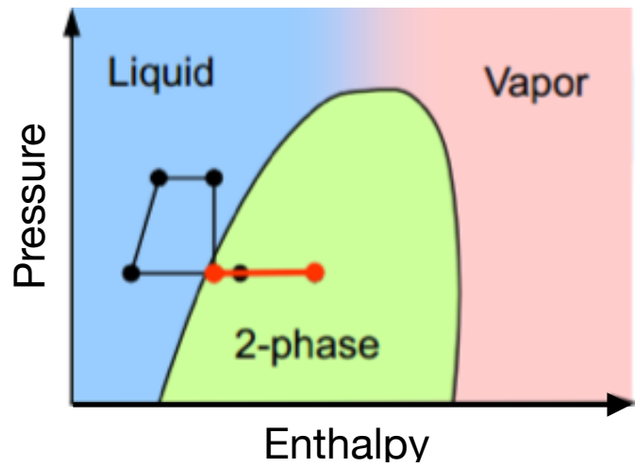
VXD cooling scheme for the power consumption.

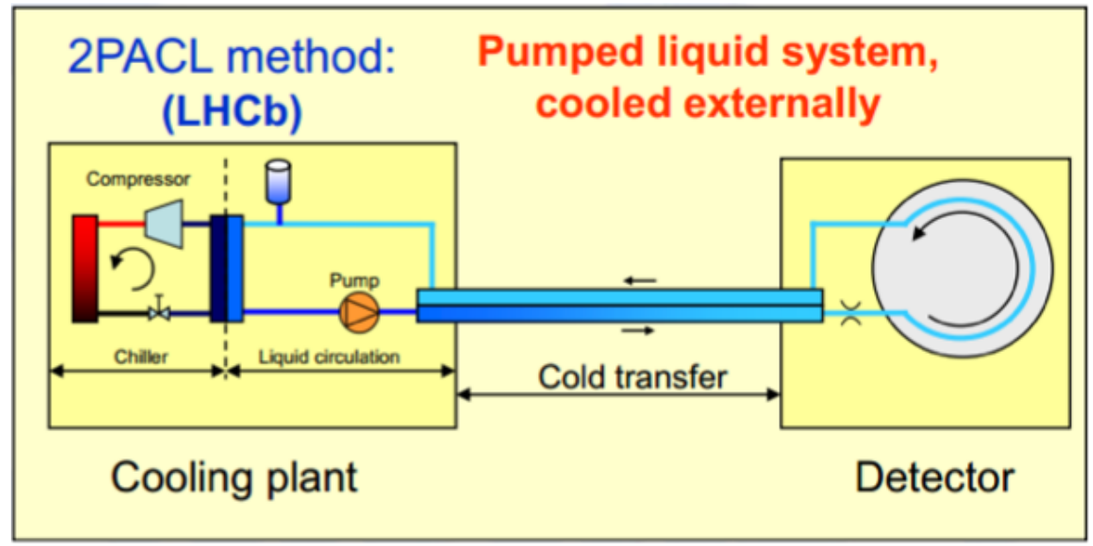
Circuit	Half shell	Side	Layers	Cooling type	$\varnothing_{inner}$ [mm]	Power [W]
1	+y	−z	1&2	SCB	1.2	105
2		+z	1&2	”	1.2	105
3	−y	−z	1&2	”	1.2	105
4		+z	1&2	”	1.2	105
5	+x	−z	3–6	End-ring	1.5	93
6	−x		3–6	”	1.5	93
7	+x	+z	3–6	”	1.5	93
8	−x		3–6	”	1.5	93
9	+x	−z	4&5	Origami cooling pipe	1.4	68
10	−x		4&5	”	1.4	68
11	+x		6	”	1.4	96
12	−x		6	”	1.4	96



2PACL Cooling Method

The 2-Phase Accumulator Controlled Loop (2PACL) is an efficient cooling concept especially for the low-mass vertex detector in dense volume close to IP.





Advantages:

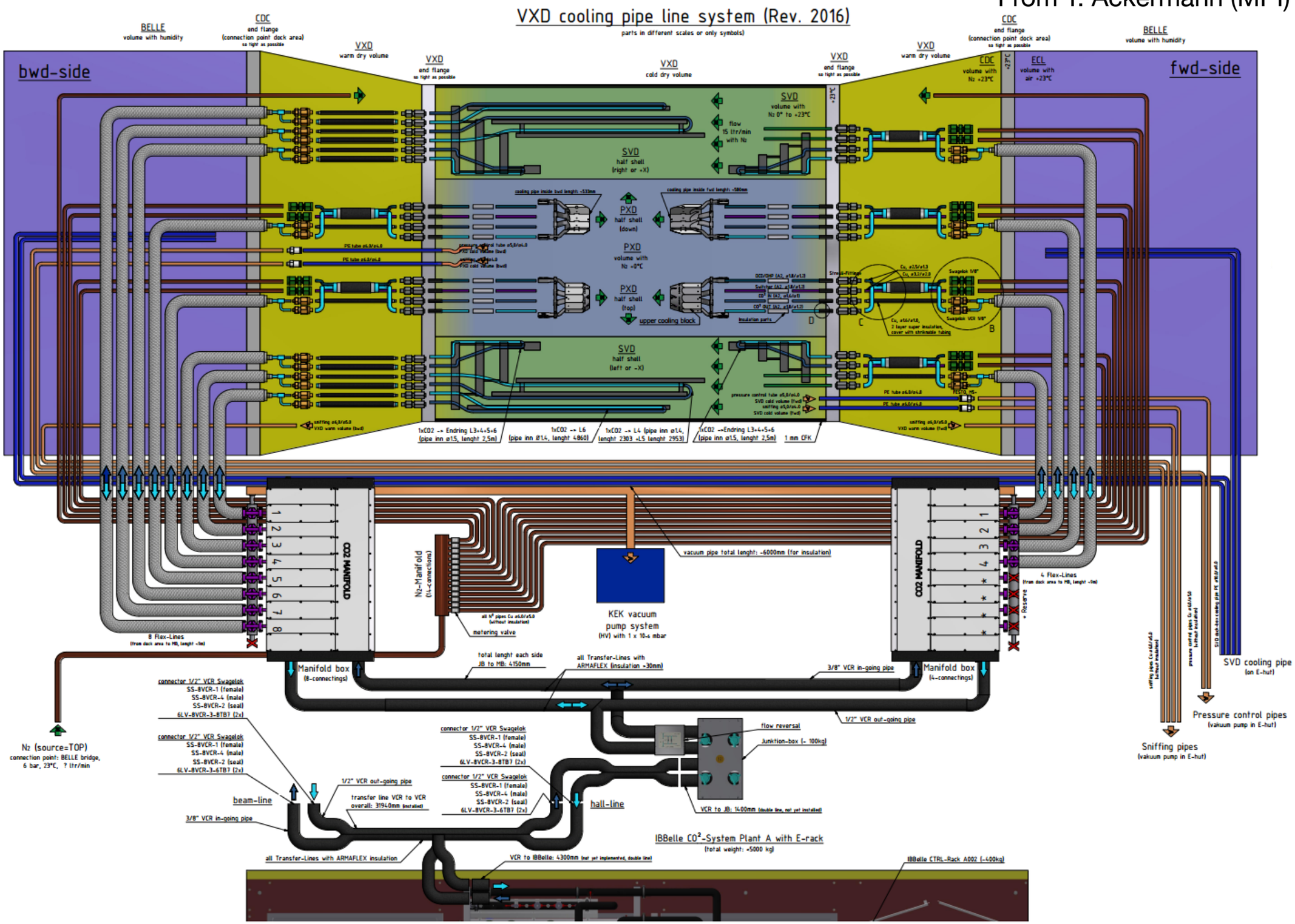
- Reduced on-detector cooling pipe diameter → reduction in material budget and space consumption.
- Radiation tolerant and excellent thermo-mechanical behaviour.
- All control hardware in a distant accessible cooling plant. Evaporator pressure (→temperature) controlled with a 2-phase vessel, no local control nor sensing needed on-detector.

Challenges:

- Operating pressure is high,
  - Fragile connectors, leakages.
- need to guarantee the 2-phase state, otherwise “dry-out”.

VXD Cooling Pipe System

From T. Ackermann (MPI)



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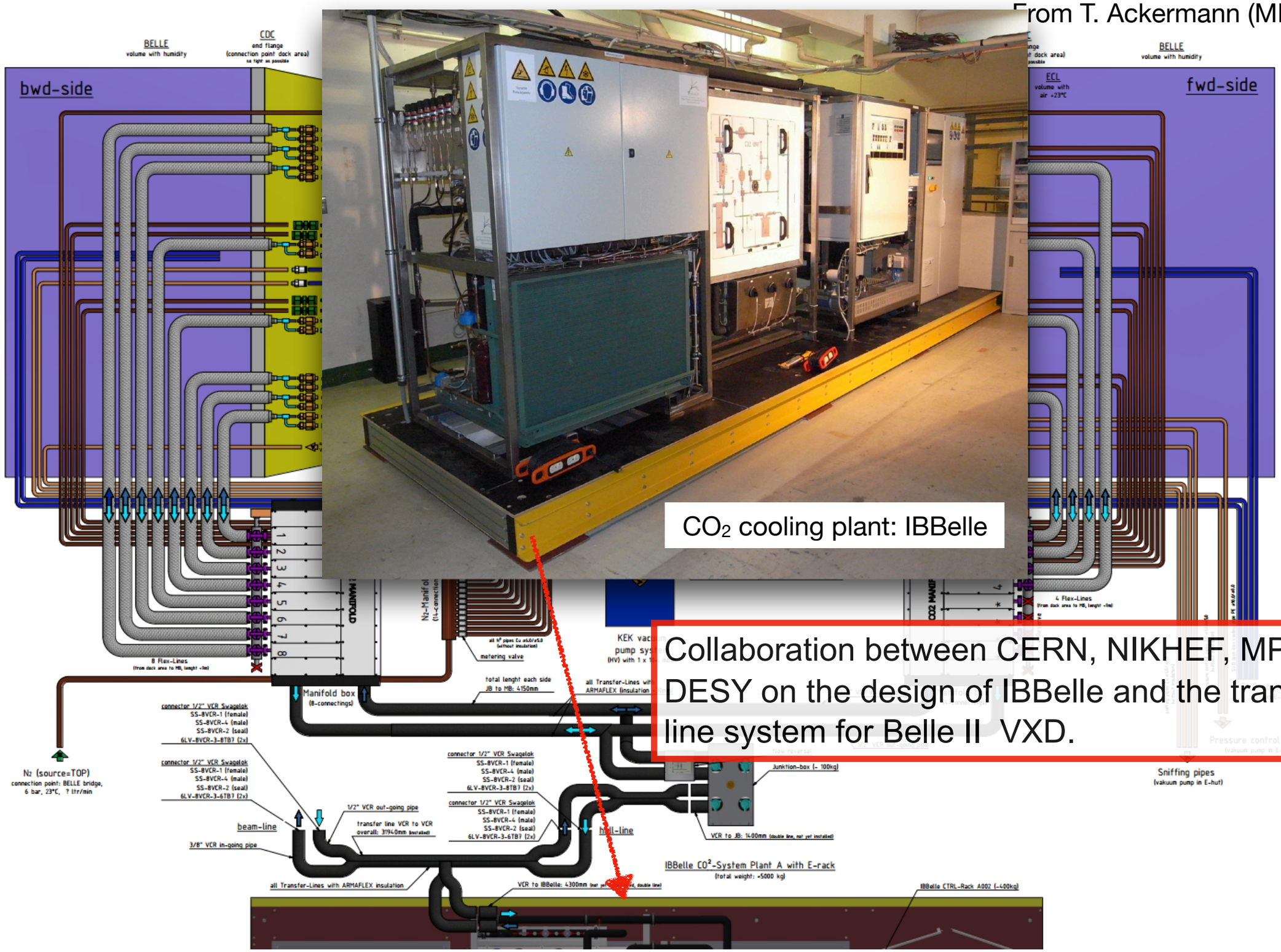
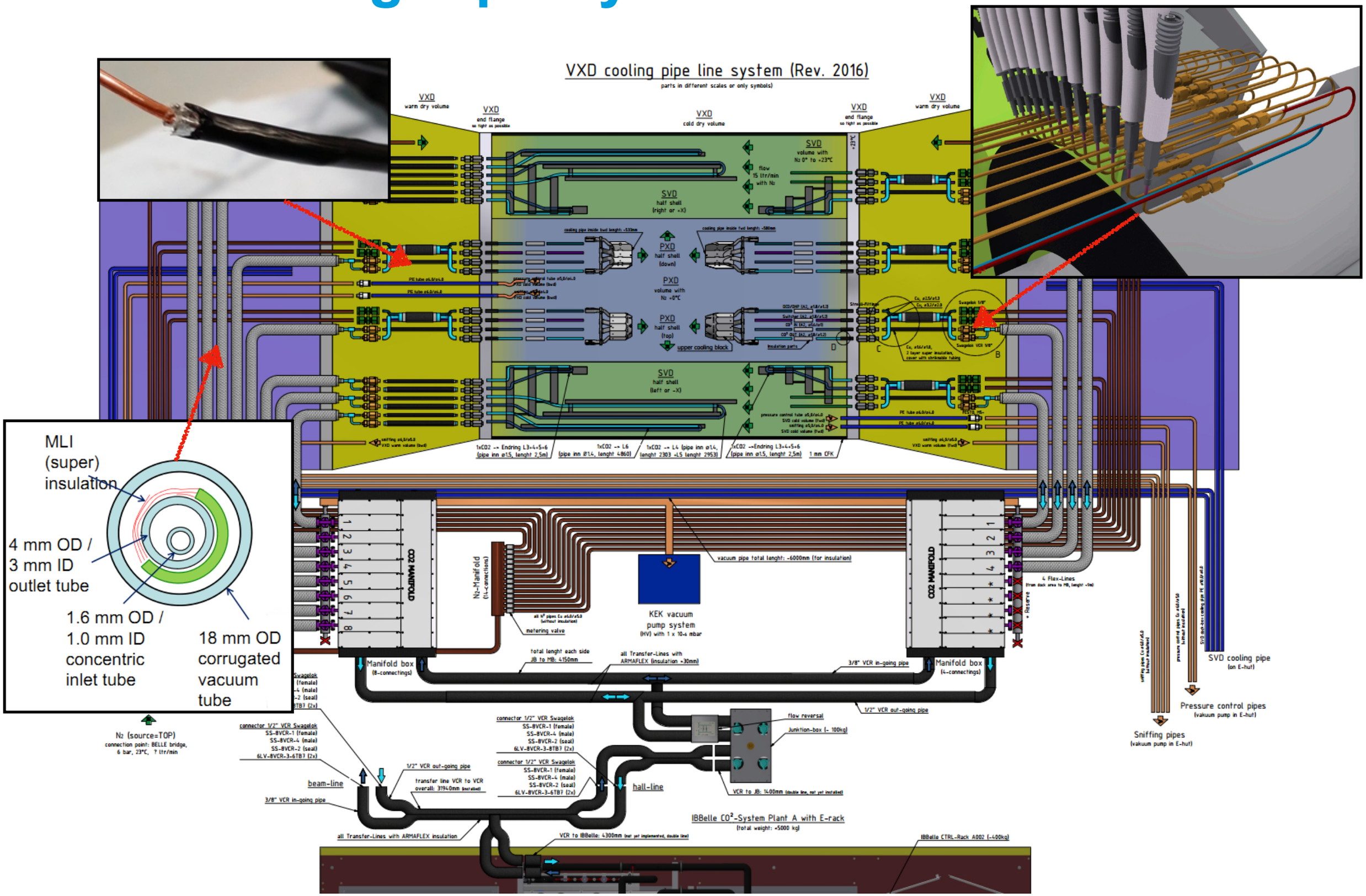


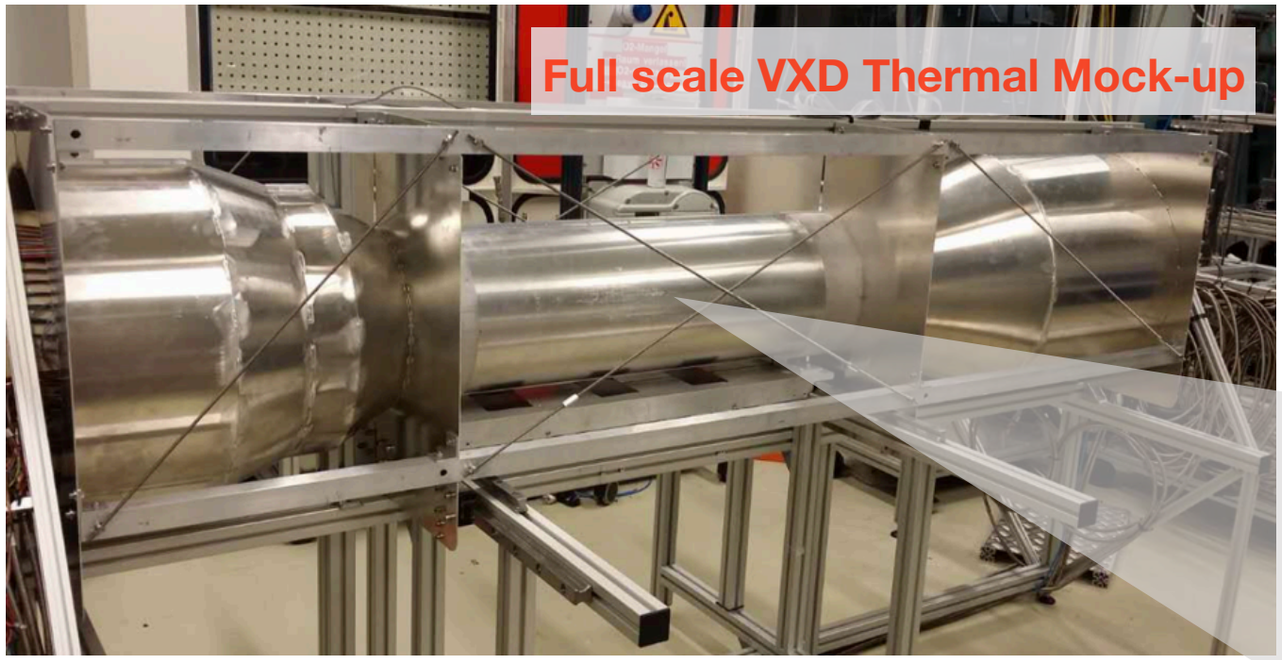
Collaboration between CERN, NIKHEF, MPI and DESY on the design of IBBelle and the transfer line system for Belle II VXD.

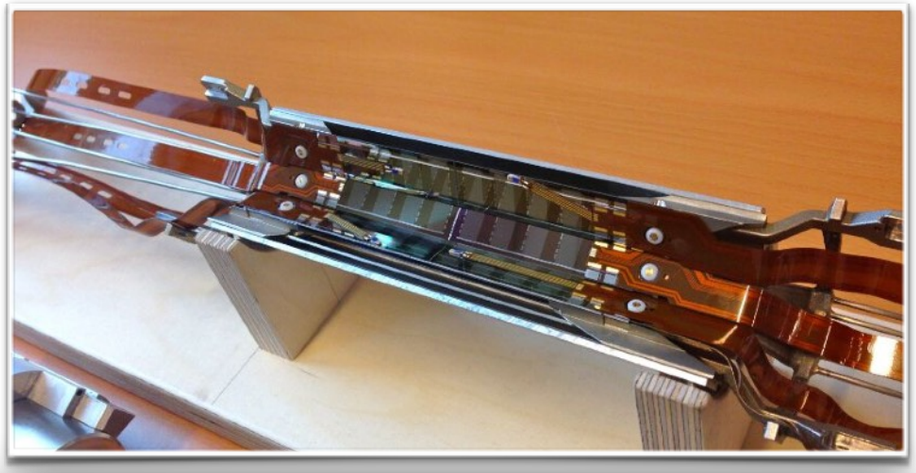
VXD Cooling Pipe System

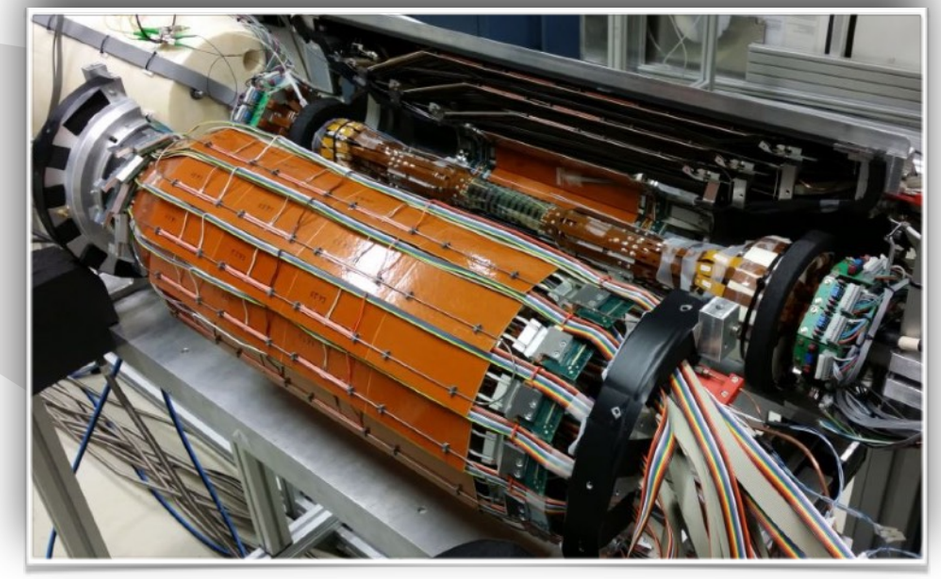


VXD Thermal Mock-up @ DESY

- Dummy sensors with the same thermo-mechanical properties as in the final system are equipped with resistors that simulate the heat load of the frontend ASICs.
- Study the thermal/mechanical properties of VXD as well as the integration procedures.
- Verify the performance of the 2-phase CO_2 cooling system.

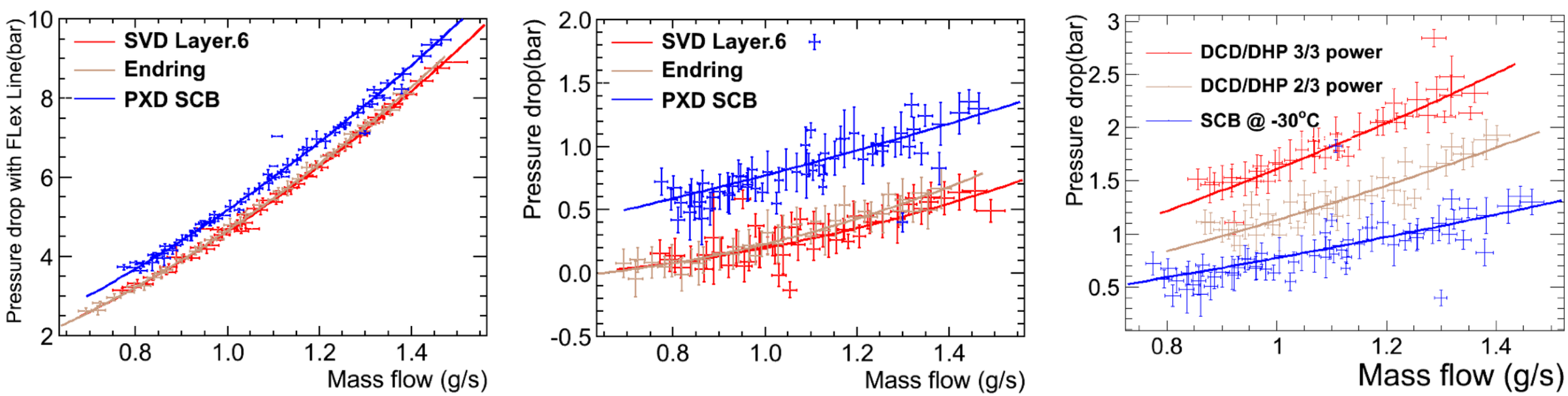






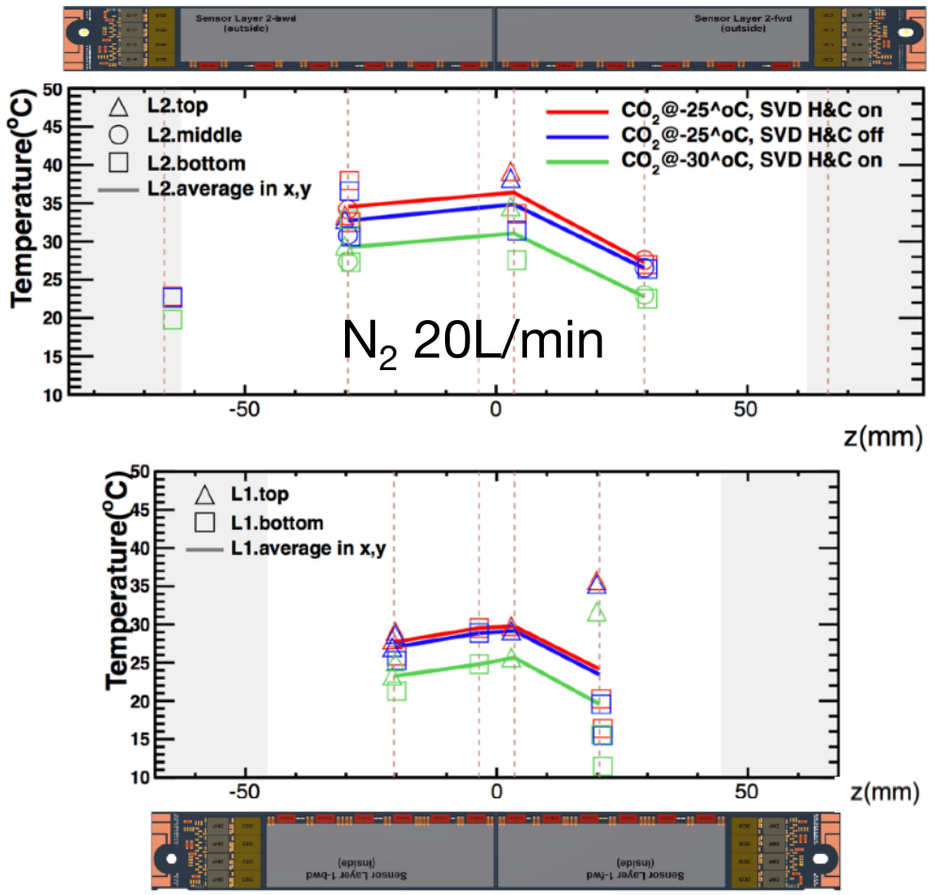
Pressure drop in Different Cooling Circuit

- The long and thin cooling lines cause pressure drops, which result in temperature gradients.
- Relatively big contribution of pressure drop in transfer flex line, to ensure balanced CO_2 mass flow in each circuit.
- Additional pressure drop results from the heat load from detector.
- In Belle II VXD, 14g/s mass flow is provided from IBBelle, which results in ~5bar pressure drop.

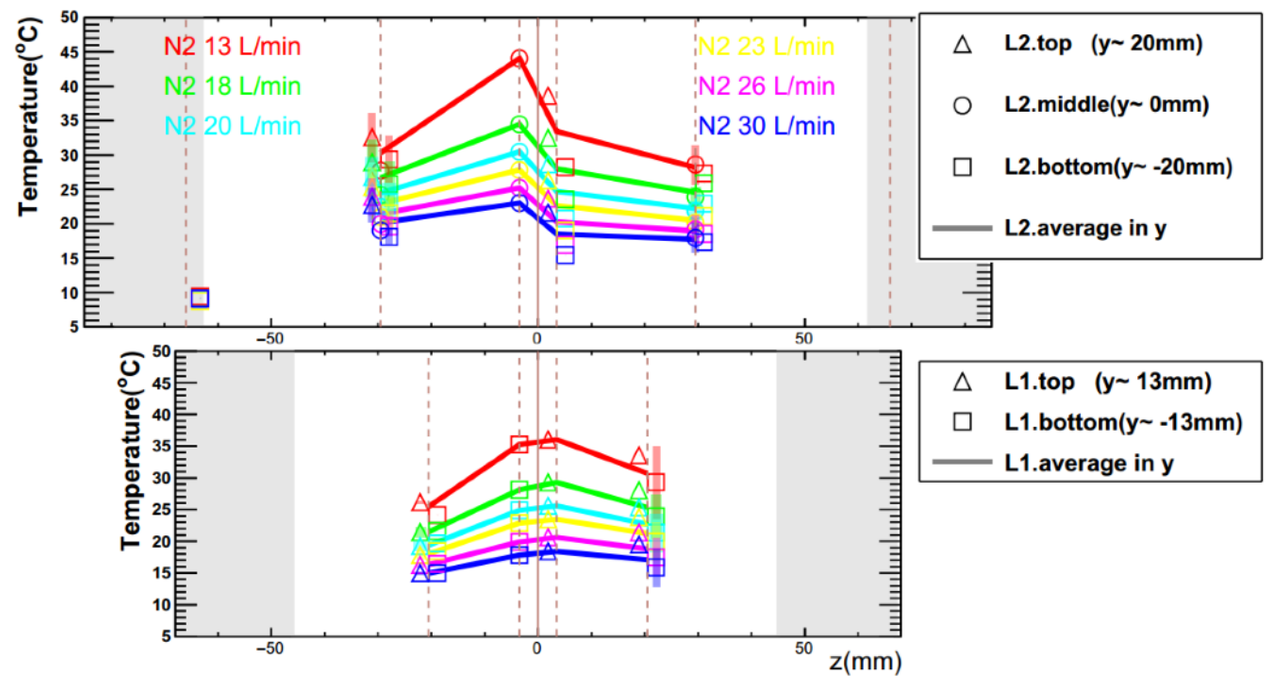


Temperatures in VXD

❖ PXD

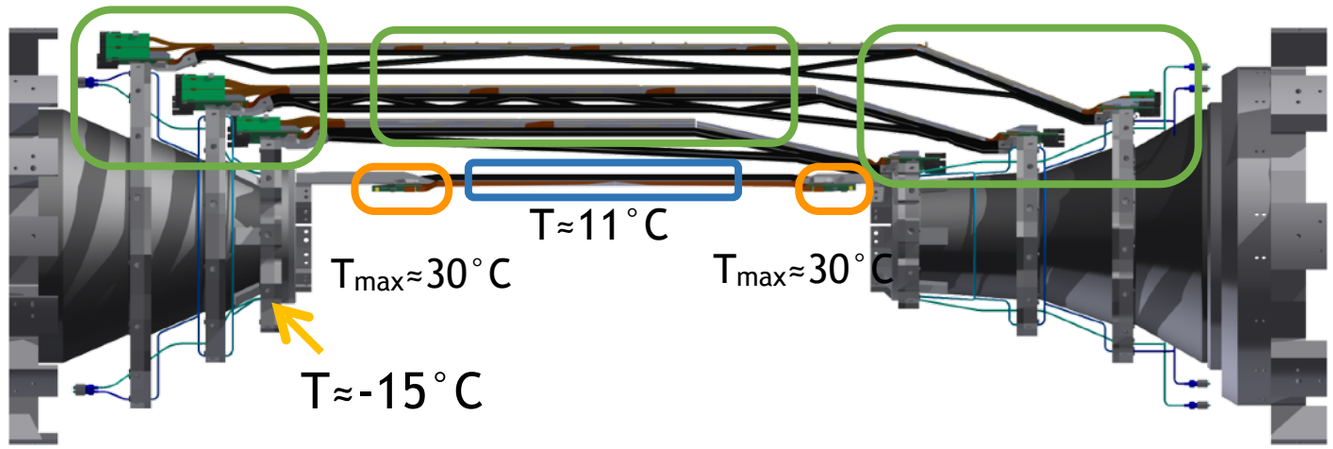


CO_2@-30°C, different N_2 flow



❖ SVD

CO_2@-25°C

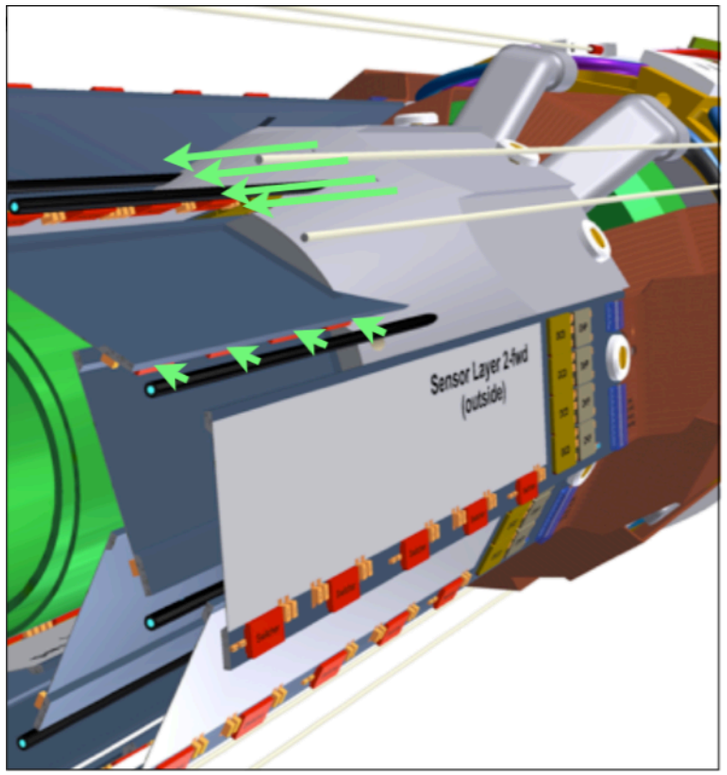


Temperatures in VXD

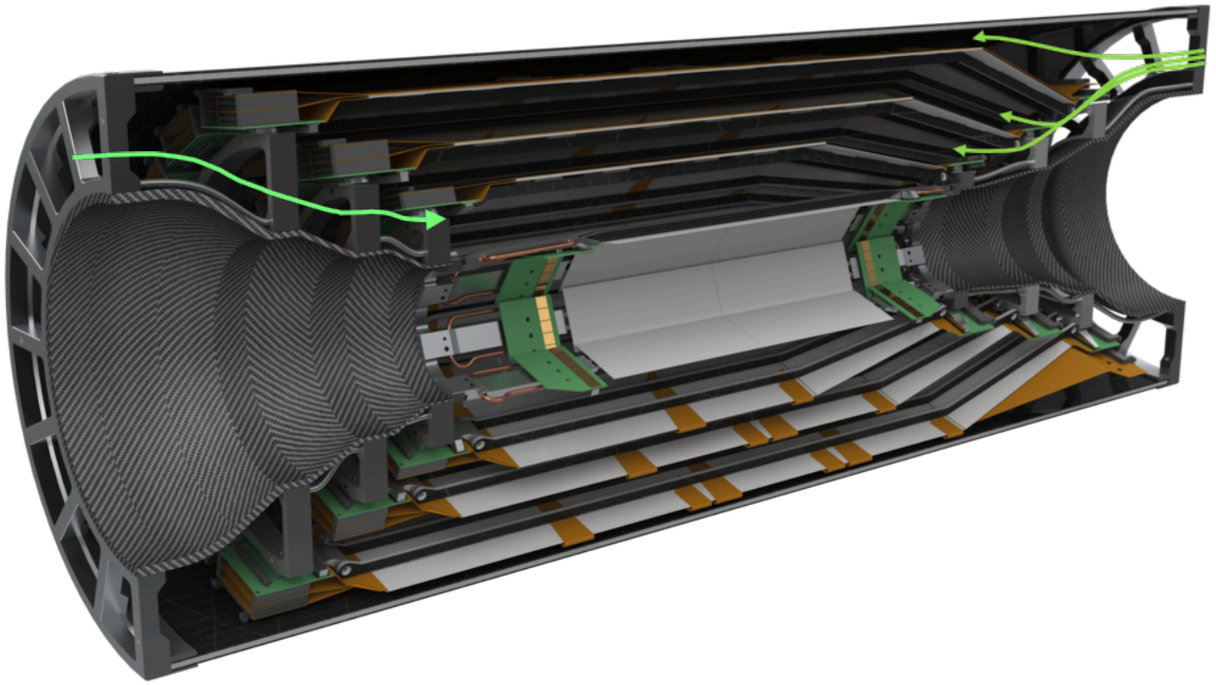
- PXD:
  - By reducing the CO_2 set point, the temperature on PXD ladder decreases, while the gradient along the ladder stays.
  - By increasing the N_2 flow, the gradient gets improved.
  - More than 40°C's gradient between SCB and ASICs.
  - N_2 temperature is ~0°C when realised from SCB.
- SVD:
  - temperature on SVD is well under control at <30°C.
- Small thermal interference between PXD and SVD.
- Dry volume
  - Local dew point: ~ 70 (-50)°C in cold (warm) dry volume.
  - Temperature on CDC inner cylinder is under control.

N_2 flow in VXD Volume

- PXD



- SVD

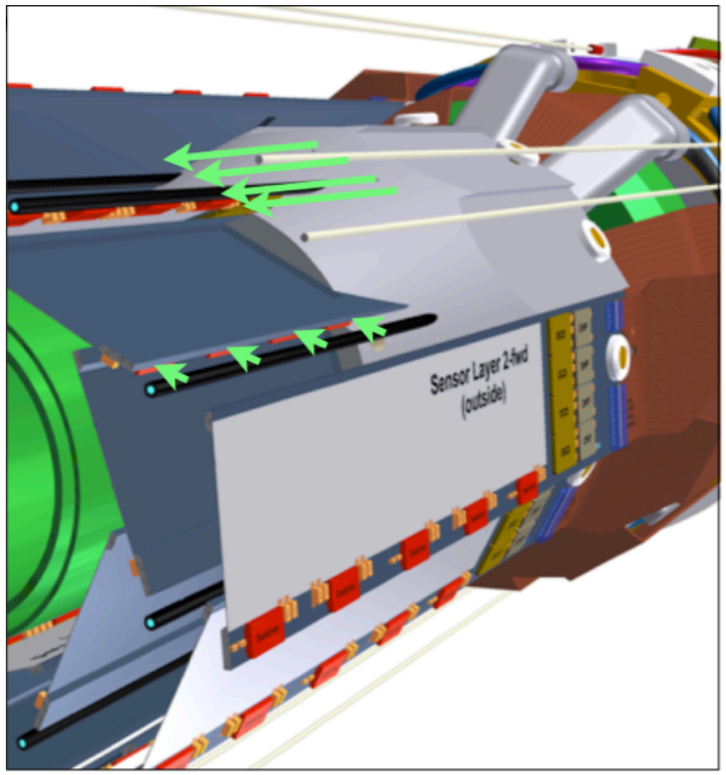


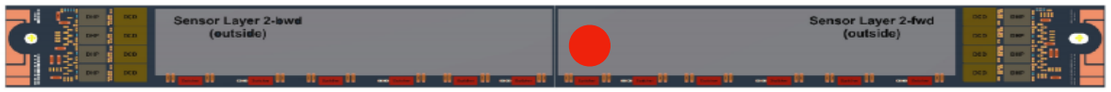
Dry gas flow through entire VXD volume

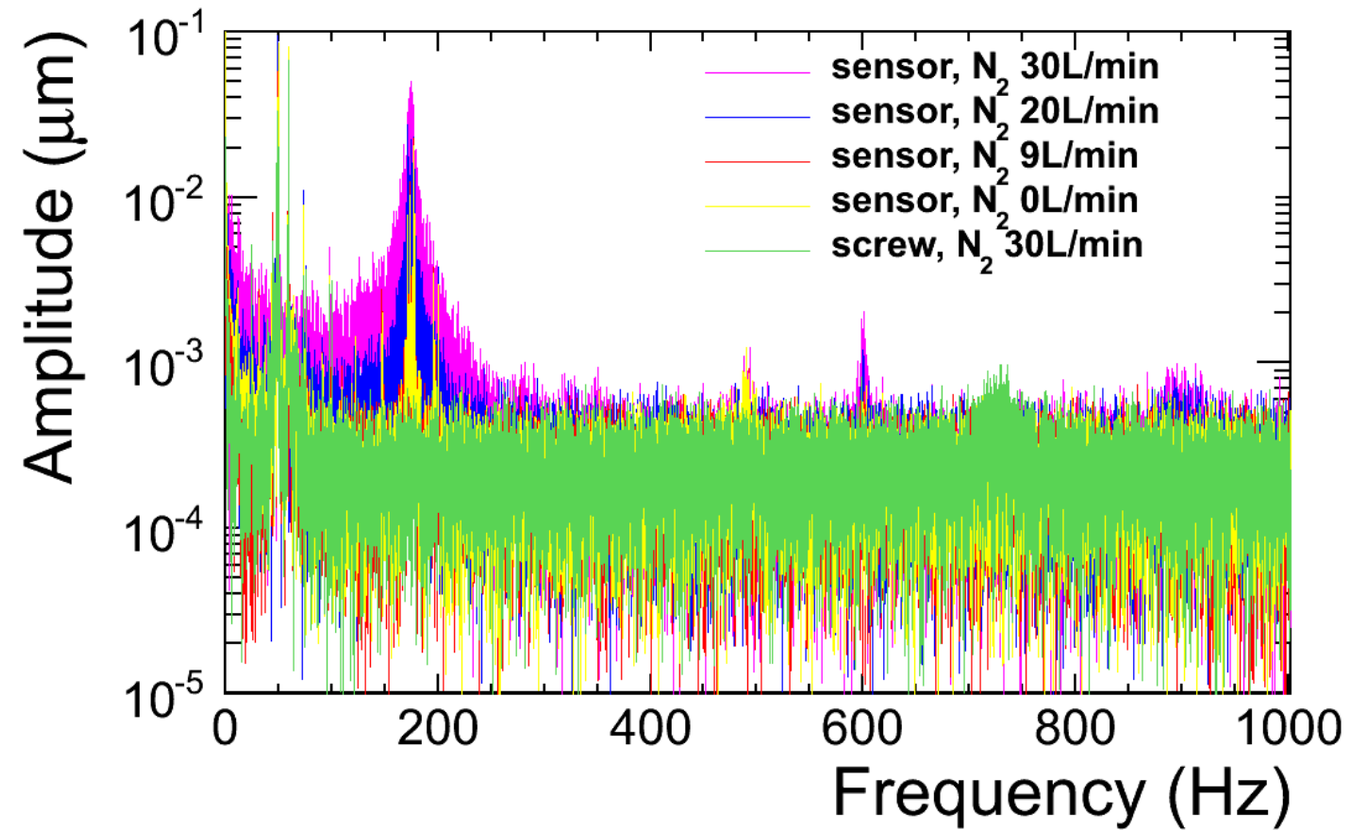
- to obtain homogeneous thermal environment and avoid condensation

- PXD: T~0°C, N_2 flow also gets cooled from SCBs.
  - For air cooling of DEPFET sensors.
- SVD: ambient temperature (minimise impact to CDC).

Possible Vibration from N_2 flow







- Largest vibration in the ladder center.
- The amplitude of vibration increases with the flow rate.
  - negligible comparing to the resolution.

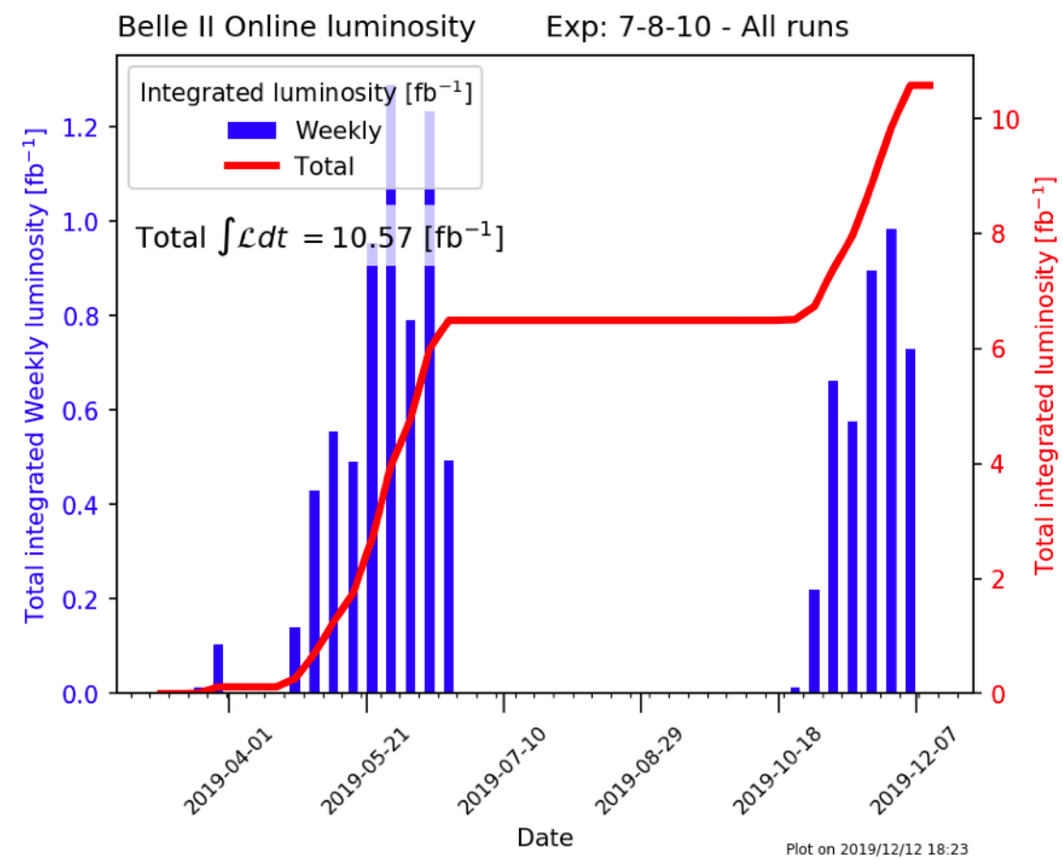
Summary

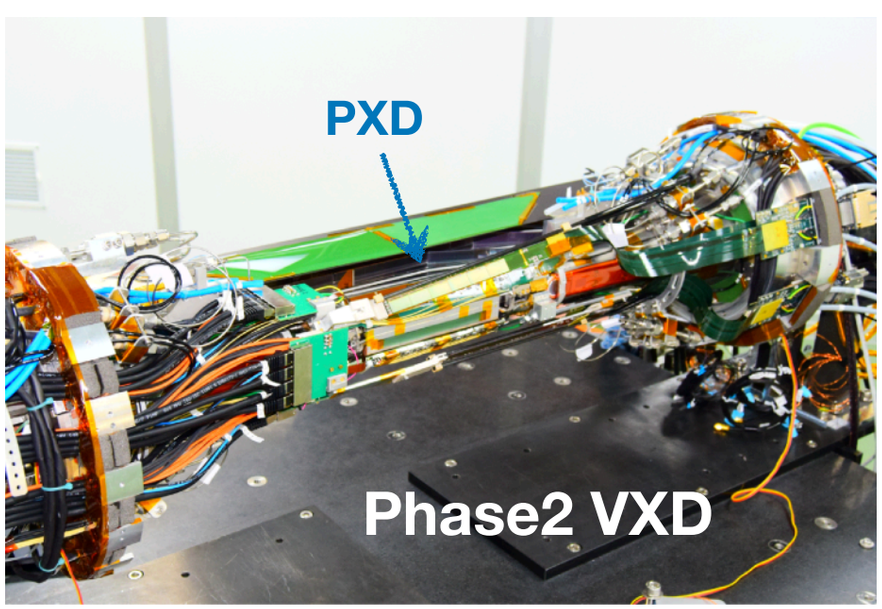
- Mixed cooling method is chosen for Belle II VXD, which has compact detector layout in the dense volume close to the interaction point.
  - 2-phase CO_2 cooling of the VXD is essential for Belle II VXD operation
  - Considering material and performance, air cooling (N_2) is used for the PXD sensors inside of physics acceptance.
- Active collaboration in design, construction of VXD cooling system and verification of its performance.
- The VXD cooling system has been running stably since Belle II experiment started. Excellent performance is achieved.

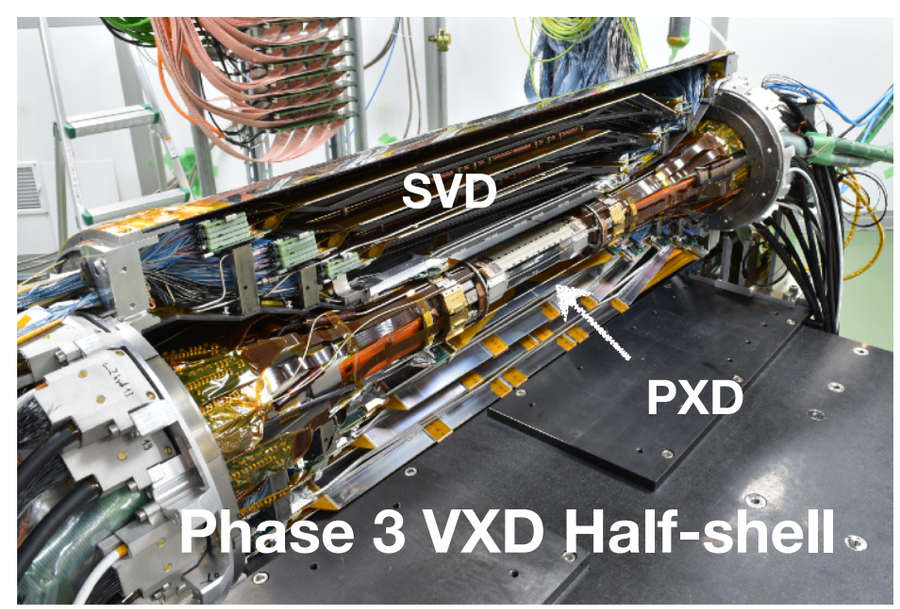
Backup

Highlights of Belle II Status

- Collisions started in Spring 2018, “Phase 2”.
  - Mainly for beam commissioning,
  - with a dedicated vertex detector to study beam background.
  - **0.5 fb^{-1} data recorded.**
- Physics data taking has started in March 2019, “Phase 3”.
  - With Belle II VXD
  - **10 fb^{-1} data recorded.**
  - Aim to collect 200 fb^{-1} by summer 2020.
- On Dec.3, Belle II achieved to record data at luminosities in excess of 10^{34} cm^{-2}s^{-1} (KEKB design luminosity)

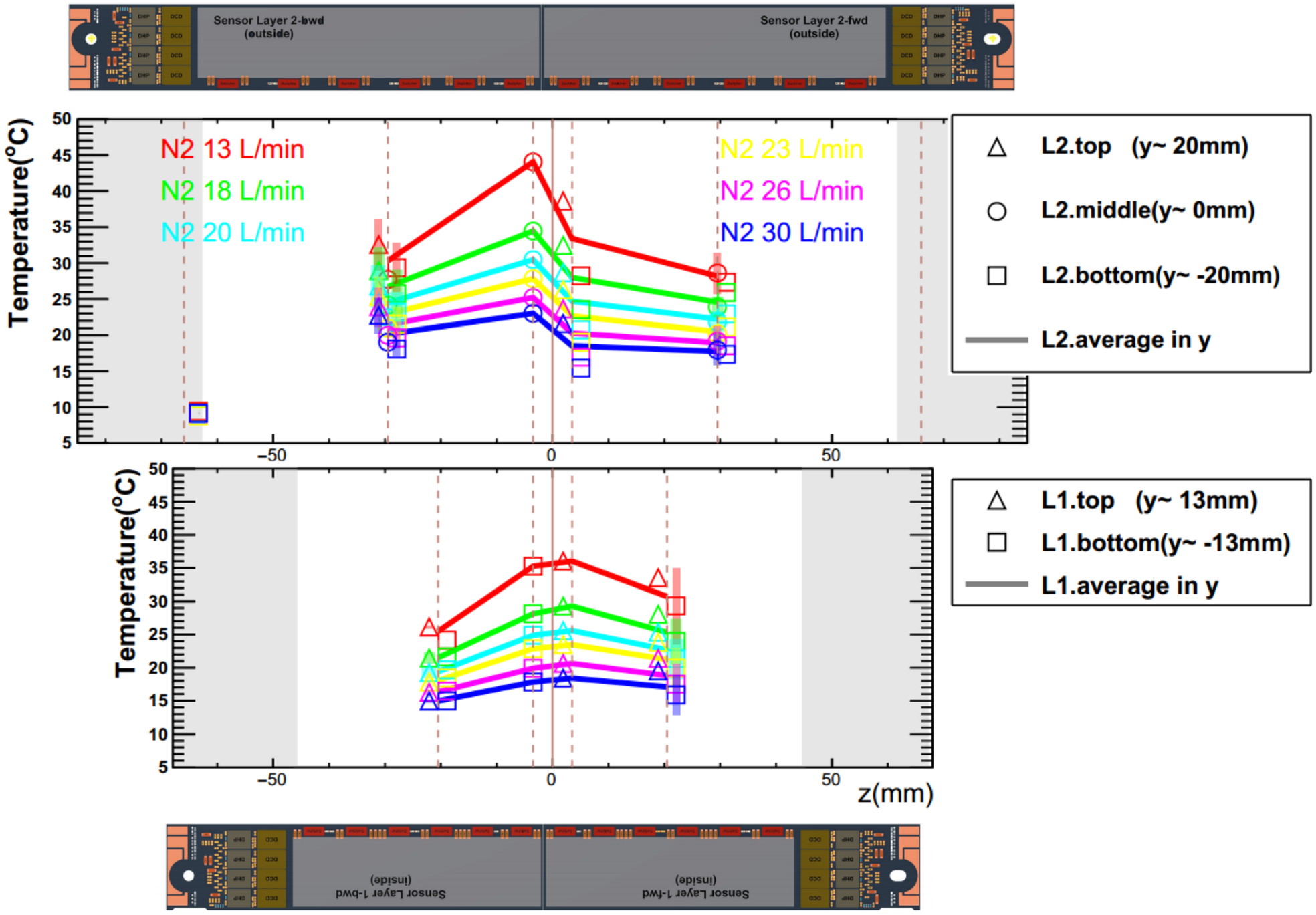






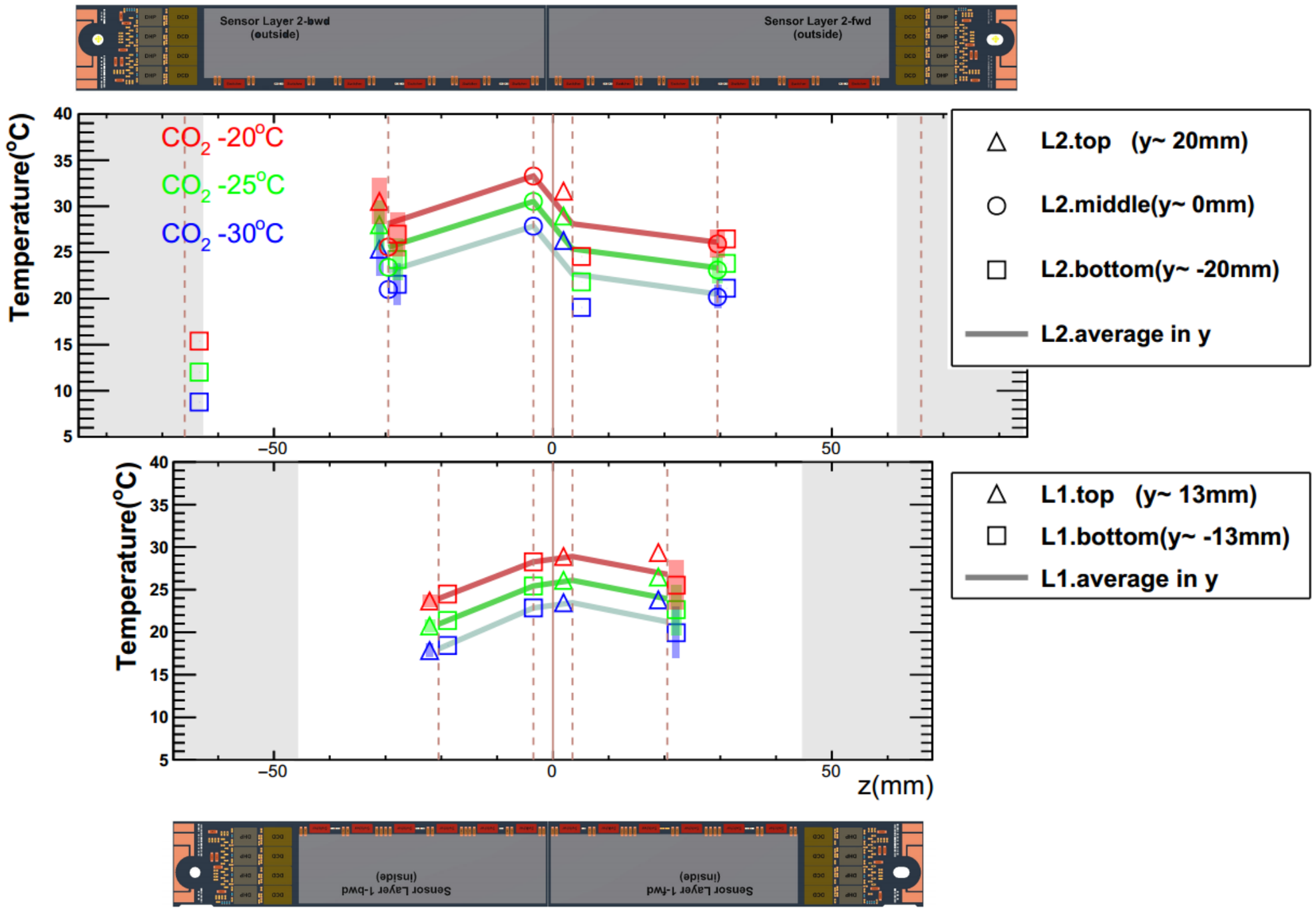
Comparison between different N_2 flow

CO_2@-30°C, full heat load to PXD.



Comparison between different CO_2 temperature

N_2 flow 23L/min; full heat load to PXD.



PXD Ladder Deformation

Deformation measurement, Layer 2, sensitive area 35°C, DCD/DHP 28°C.