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CHARACTERIZATION OF THE BI-PHASE CO2 COOLING SYSTEM MARTA FOR QUALITY CONTROL IN THE ITK PIXEL DETECTOR PRODUCTION

Bachelorcolloquium presented by Dominik Hauner,
examined by
Prof. Dr. Klaus Desch and Dr. Matthias Hamer
24.10.2023

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OUTLINE

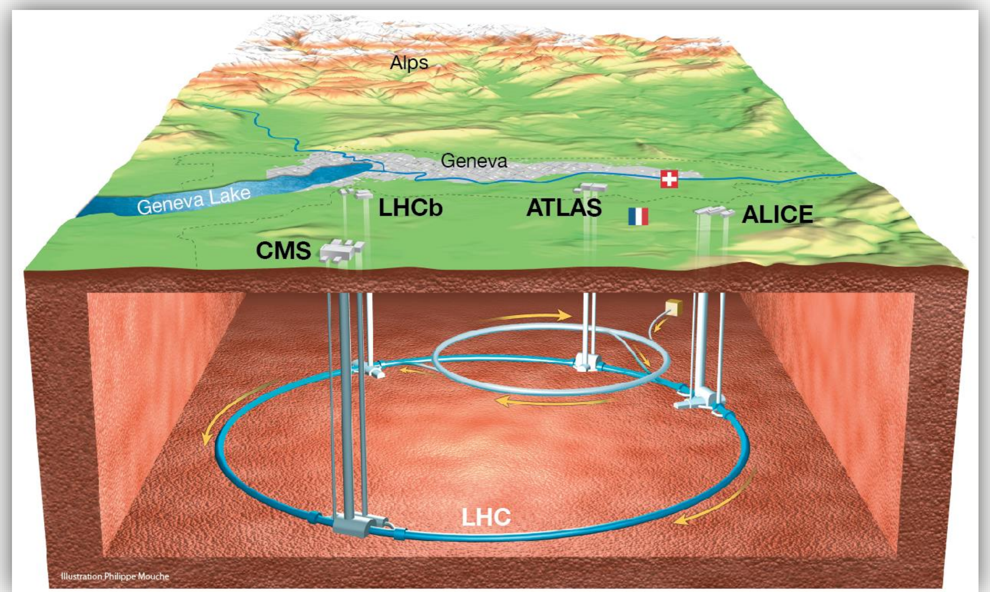
1. The ITk pixel detector
2. Cooling systems
3. **Characterization of MARTA**
4. Summary and outlook

PART 1

The ITk pixel detector

HIGH LUMINOSITY LHC

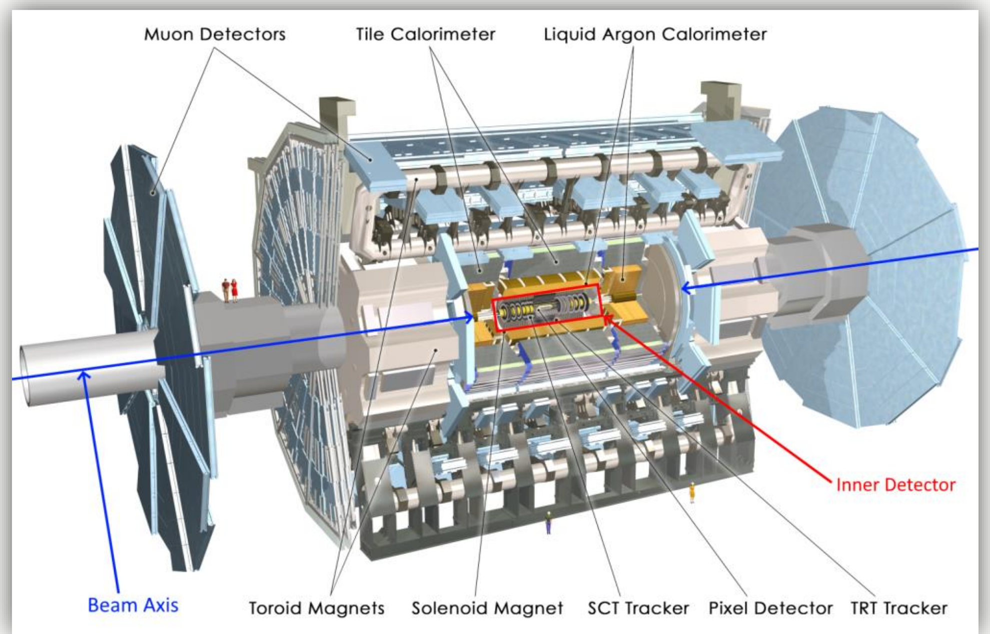
- HL-LHC will have **5 to 7 times the luminosity** of the current LHC
- Increased radiation and data collection rates
- **Replacement** of multiple **detectors** needed



https://cds.cern.ch/record/1708847 (09. 08. 23)

THE ATLAS DETECTOR

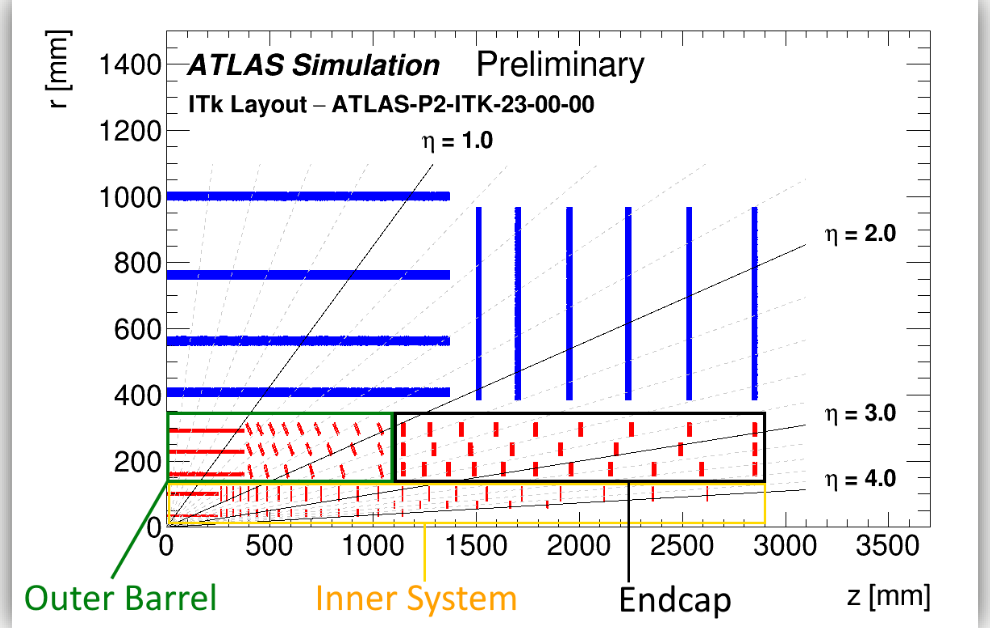
- Largest multi purpose detector in the LHC
- ATLAS will be upgraded for use in the HL-LHC
- Replacement of current Inner Detector with **new Inner Tracker detector**



https://cds.cern.ch/record/1095924 (25.07.23), modified

NEW ITK DETECTOR

- All-silicon particle detector
- **Improved** radiation tolerance, data collection rates, resolution and pseudorapidity coverage
- Assembly and **quality control** of **Local Supports** for the Outer Barrel at the University of Bonn



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2020-002/ (24.07.23), modified

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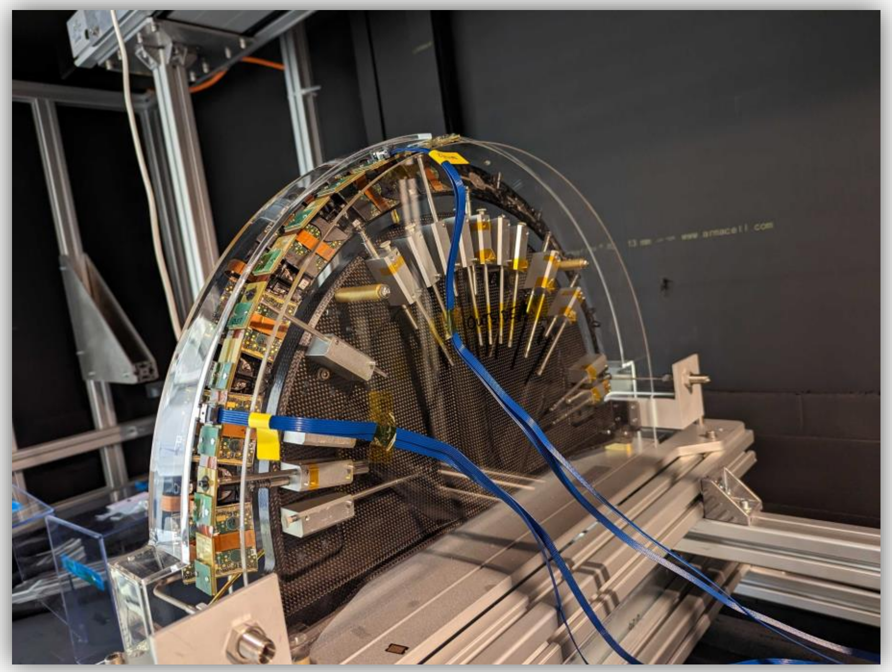
ITK LOCAL SUPPORTS



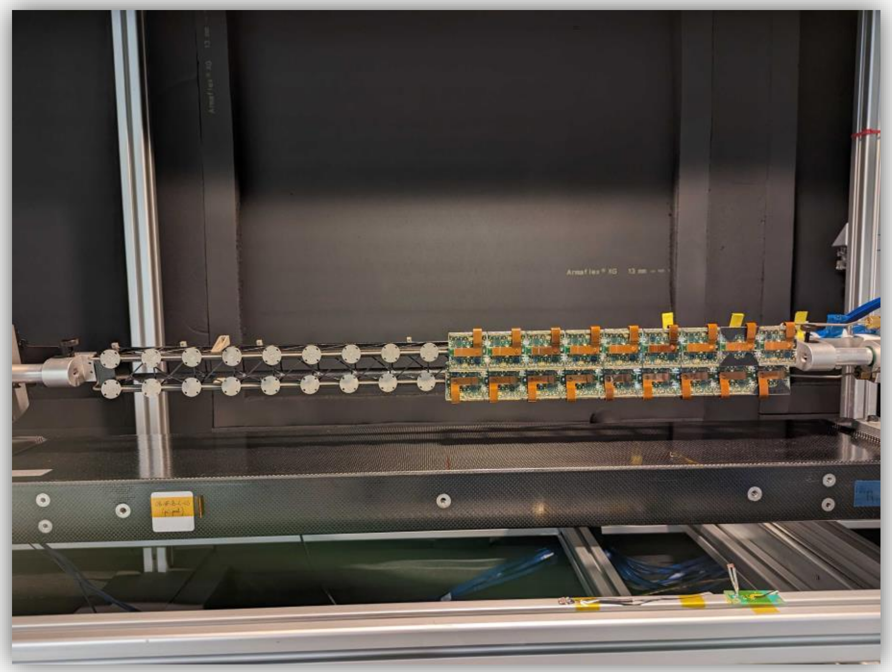
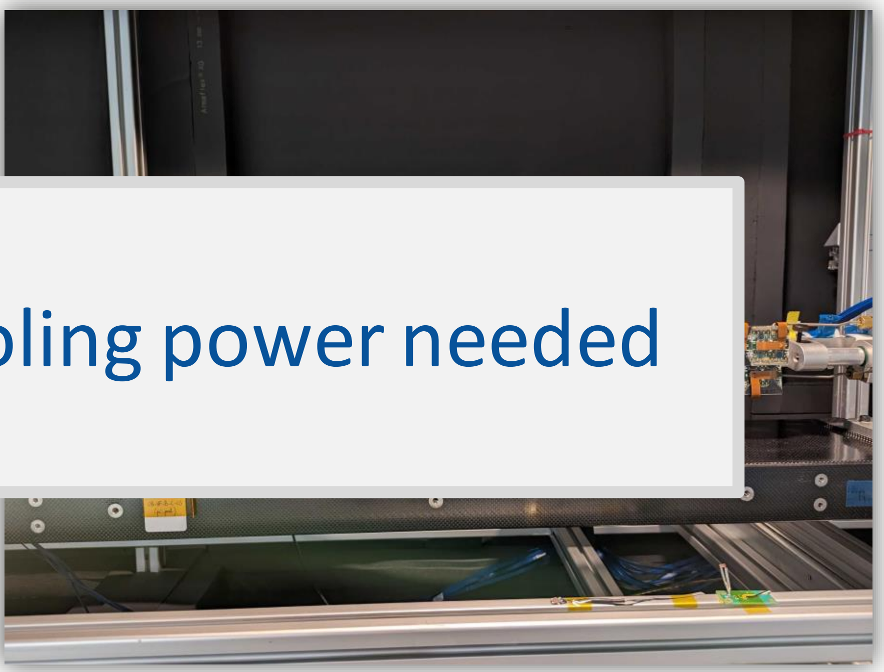


Image credit: Alexandra Wald

ITK LOCAL SUPPORTS



Approx. 400 W of cooling power needed

Image credit: Alexandra Wald

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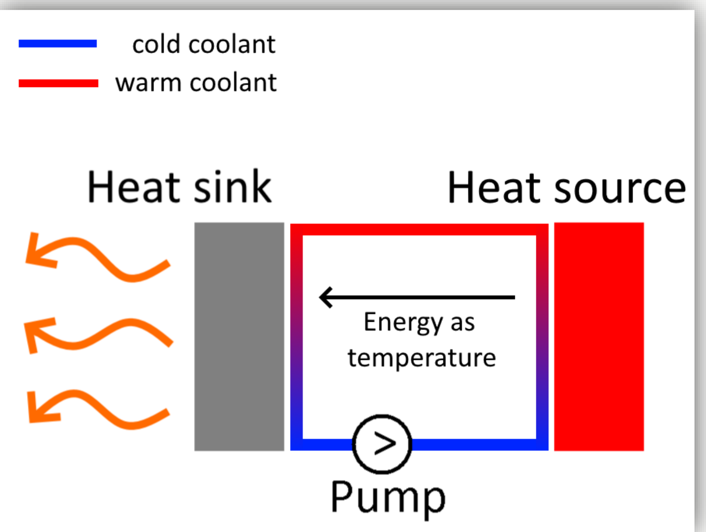
PART 2

Cooling systems

SINGLE-PHASE COOLING

- Fluid or gaseous coolant
- **Energy** from heat source **increases** the **coolant temperature**
- Coolant is cooled down in heat sink
- **Problem** for detectors: ENC $\propto T^2$



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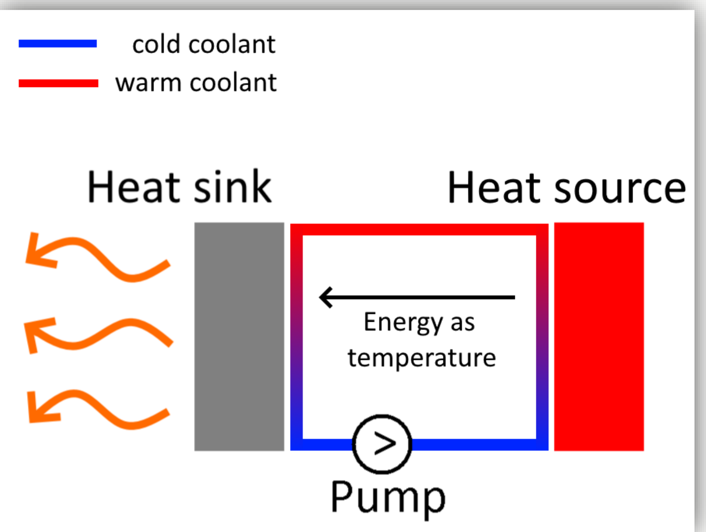
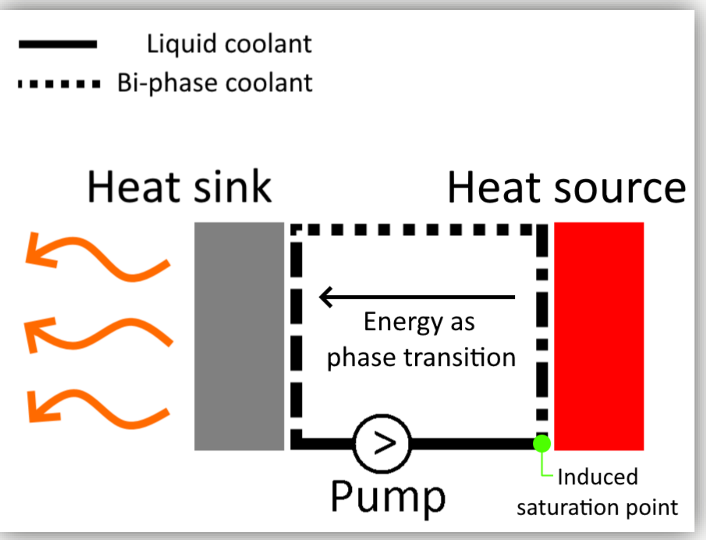


Advantage	Disadvantage
Very simple and cheap	Coolant temperature rises along heat source

BI-PHASE COOLING

- **Energy** from heat source causes coolant **phase transition**
- Coolant needs to be at **saturation point**
- **Risk of dry-out**



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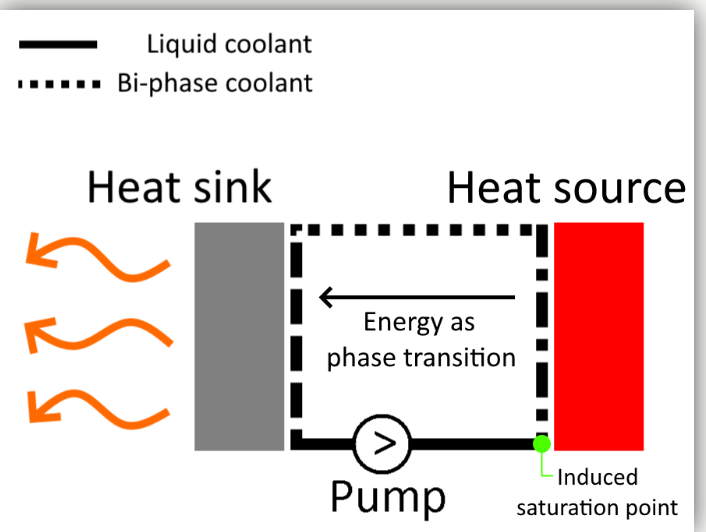

Advantage	Disadvantage
Constant coolant temperature along heat source	Difficult control of coolant temperature

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ACCUMULATOR CONTROLLED BI-PHASE COOLING LOOP (2PACL)

- Accumulator holds bi-phase coolant
- In bi-phase: **const. temperature = const. pressure**
- Regulate **temperature of accumulator** thus pressure
- Negligible pressure drop along cooling pipe between accumulator and heat source

->Control of coolant **temperature at heat source**

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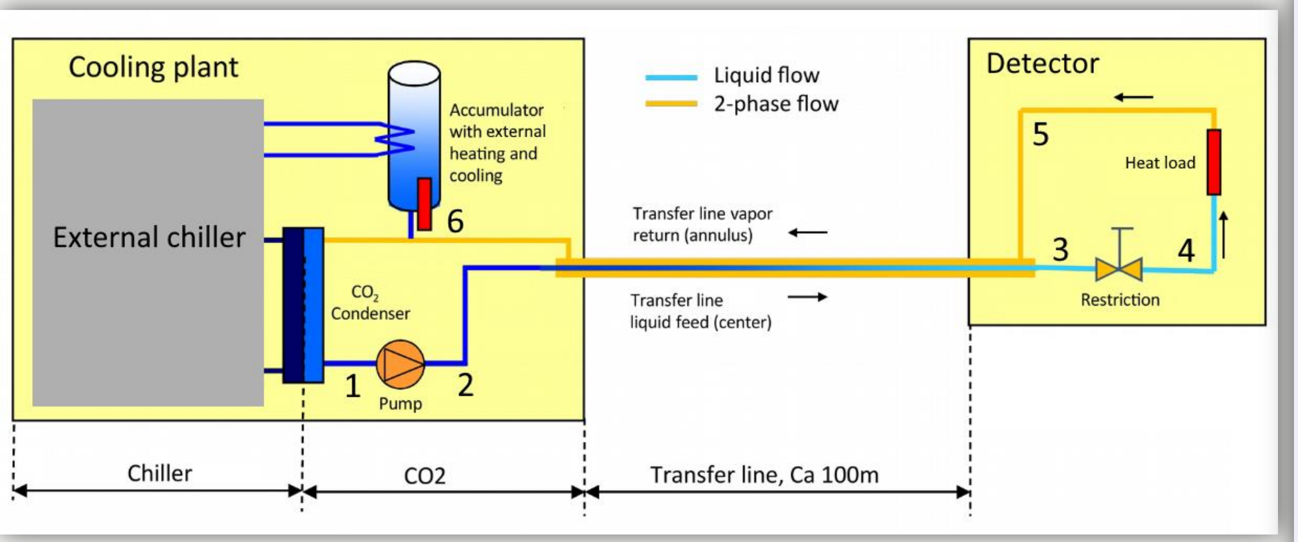
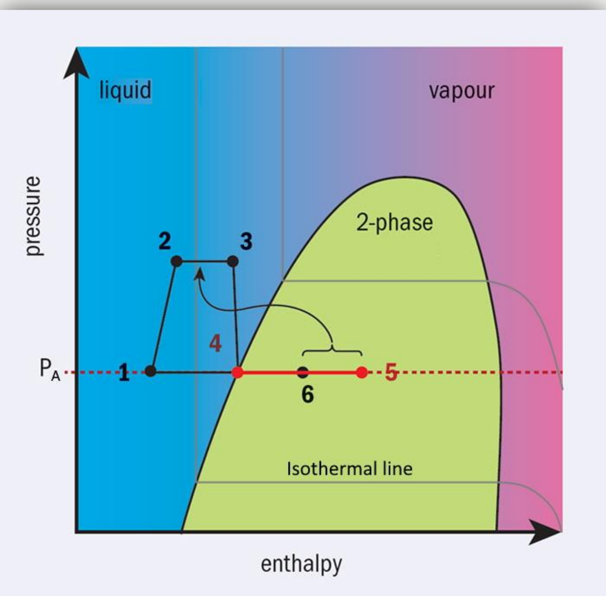
Advantage	Disadvantage
'Remote control' of temperature in detector	Complex and difficult to maintain

2PACL IN DETAIL

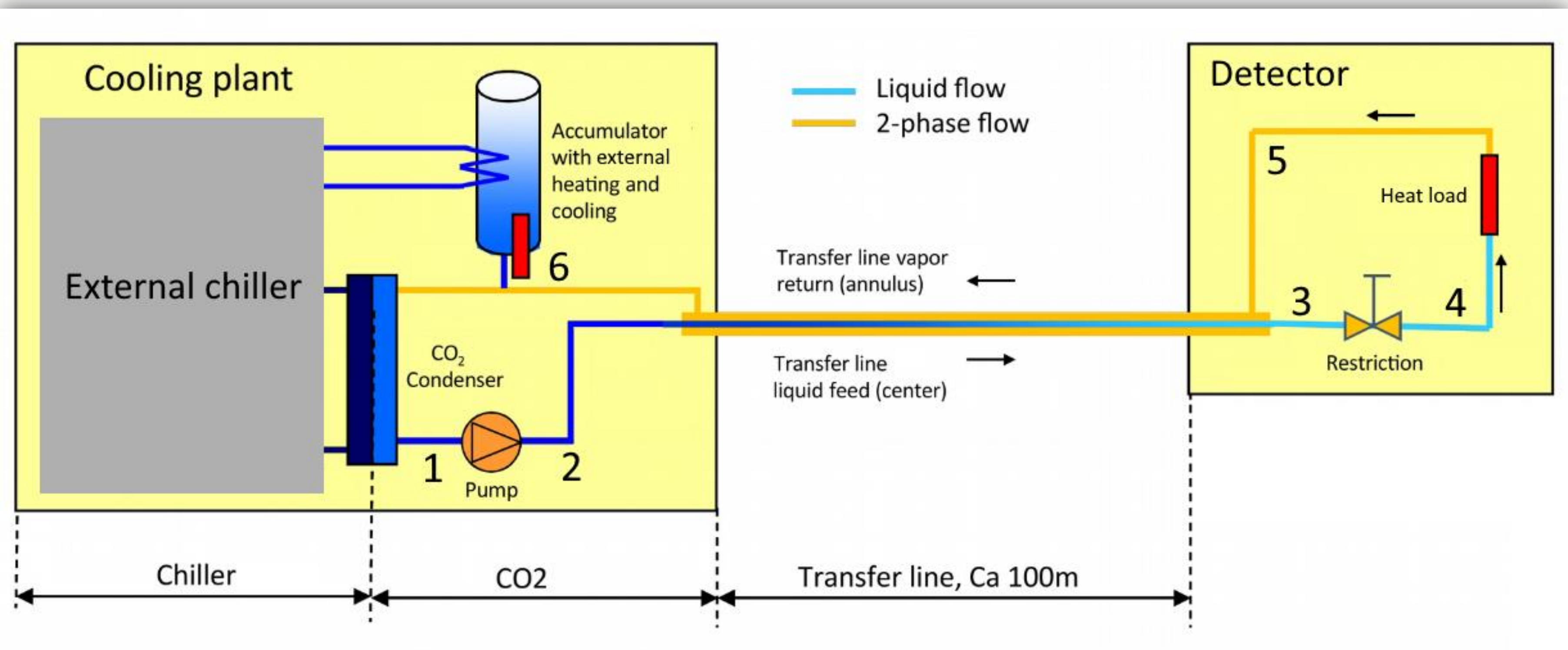




B. Verlaat u. a., *The ATLAS IBL CO2 cooling system*, modified

https://cerncourier.com/a/co2-cooling-is-getting-hot-in-high-energy-physics/ (19.10.23), modified

FROM 2PACL TO INTEGRATED-2PACL



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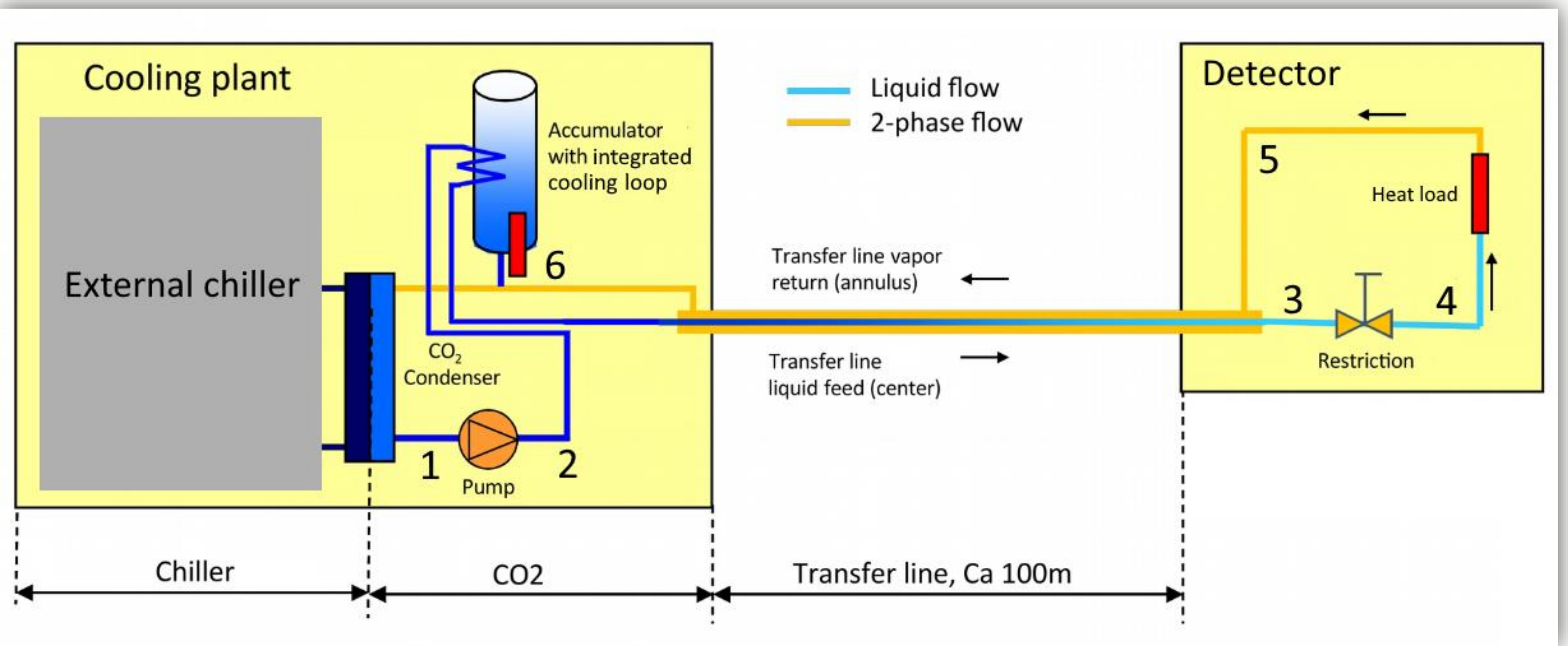

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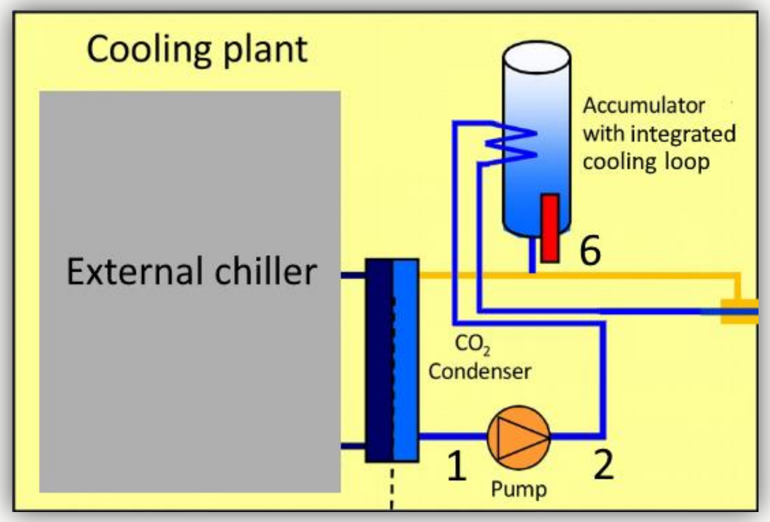
I-2PACL

- Accumulator is cooled by the coolant itself
- Coolant temperature in detector only controlled by a heater in the accumulator
- Reduced efficiency and **cooling power limited by chiller**
- When max. **cooling capacity is exceeded** system **heats up** to new stable temperature



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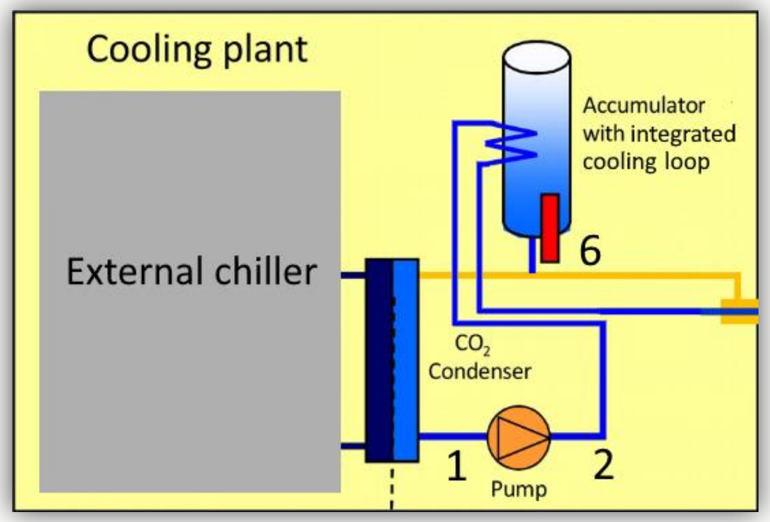

B. Verlaat u. a., *The ATLAS IBL CO2 cooling system*, modified

Advantage	Disadvantage
Simpler and cheaper, decreased risk of dry-out	Limited cooling power and efficiency

PART 3

Characterization of MARTA

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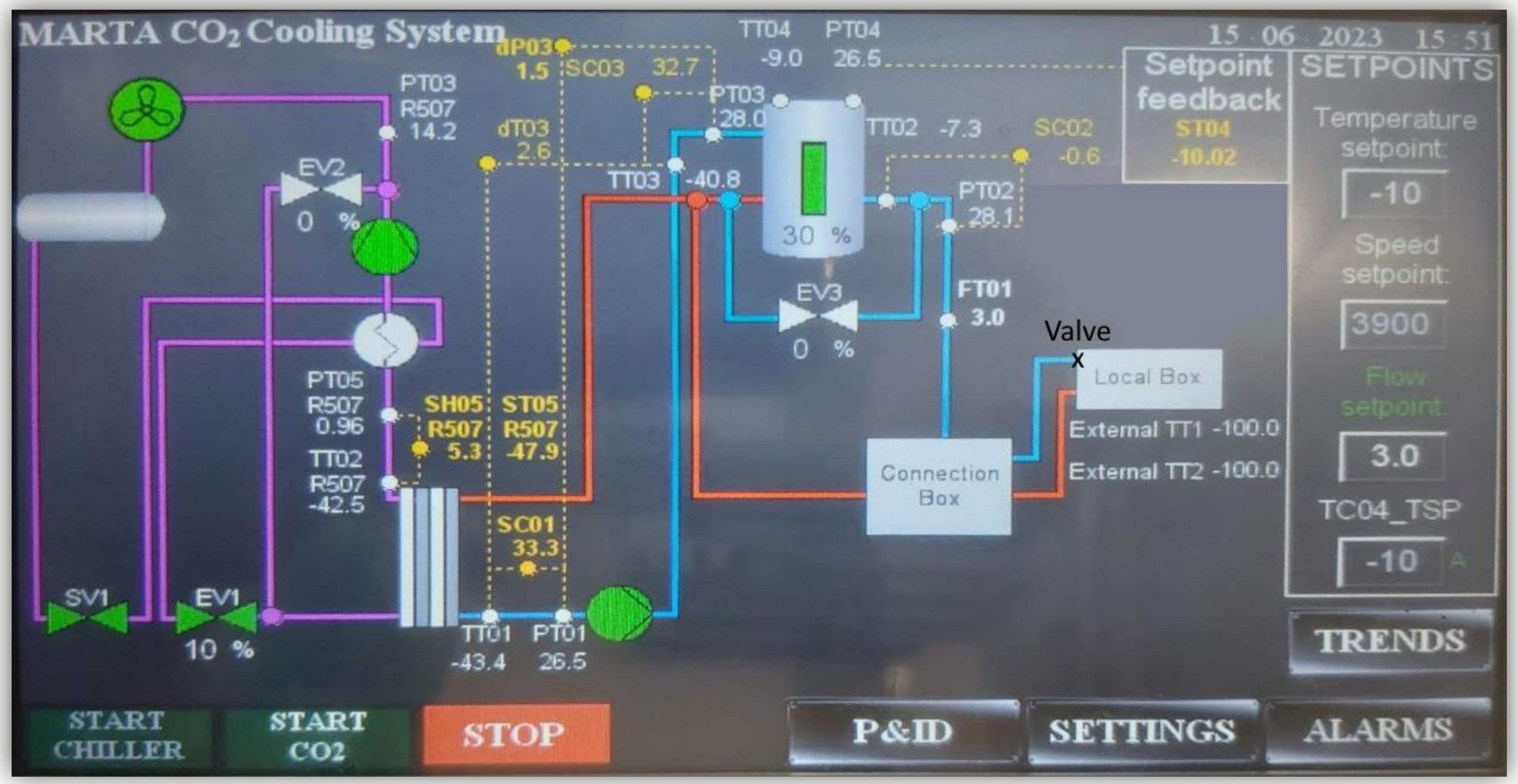
HOW TO OPERATE MARTA

Important parameters:

- Temperature set-point T_{set}
- Temperature feedback T_{fbk}
- CO_2-flow rate q_{CO2}
- CO_2-pump speed f_{pump}
- Pump delta pressure dP_{pump}

- Only CO_2**-flow rate or -pump speed** can be controlled at the same time
- dP_{pump} **must be** between 1 – 6 bar

HOW TO OPERATE MARTA



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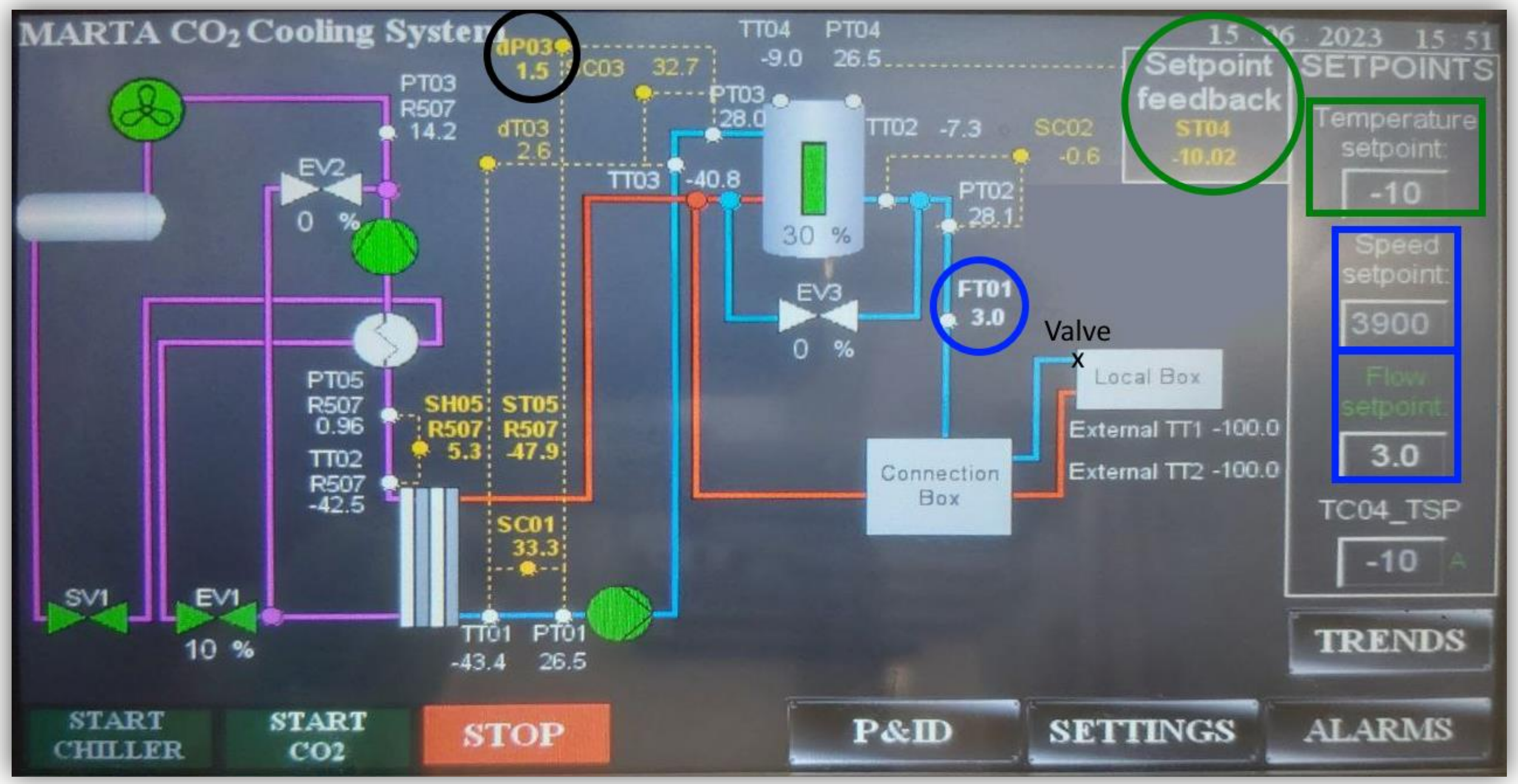

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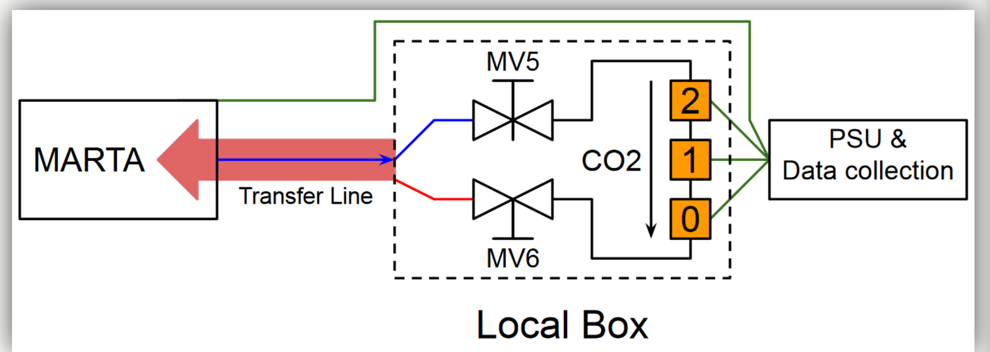
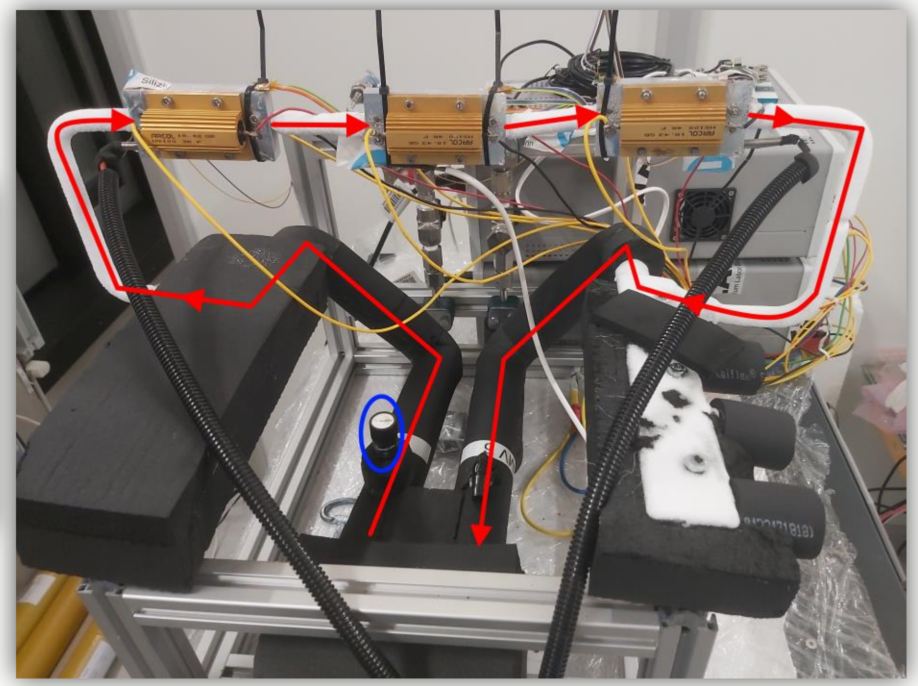
SETUP FOR MEASURING THE COOLING POWER

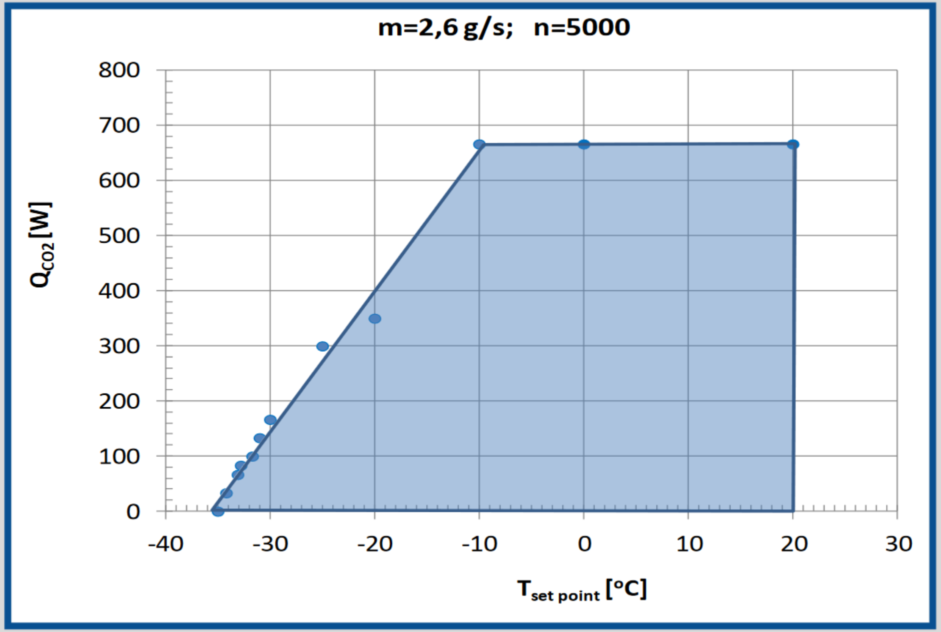




COOLING POWER OF MARTA

- For every heat load there is a **minimal stable T_{set}**
- This creates a **stable operating area**
- **Below** this temperature the system simply **heats up** to the operating area

MARTA First prototype operating area (blue)



https://indico.cern.ch/event/590227/contributions/2614149/attachments/1487980/2311754/MARTA_-_Monoblock_Approach_for_a_Refrigeration_Technical_Application.pdf (22.07.23)

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E.g. at 600 W heat load and T_{set} = -30 °C
T_{fbk} will simply rise to -12 °C

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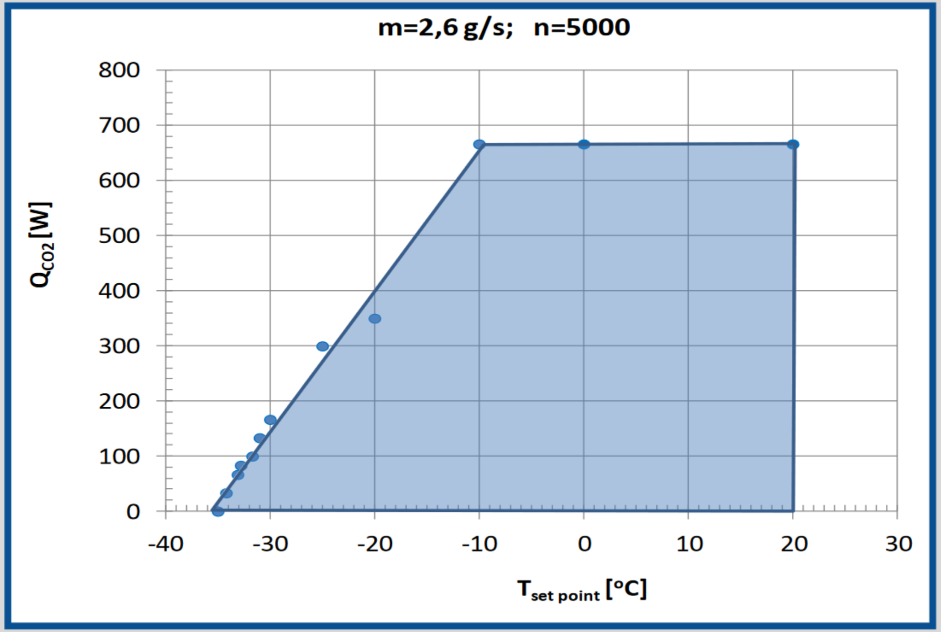

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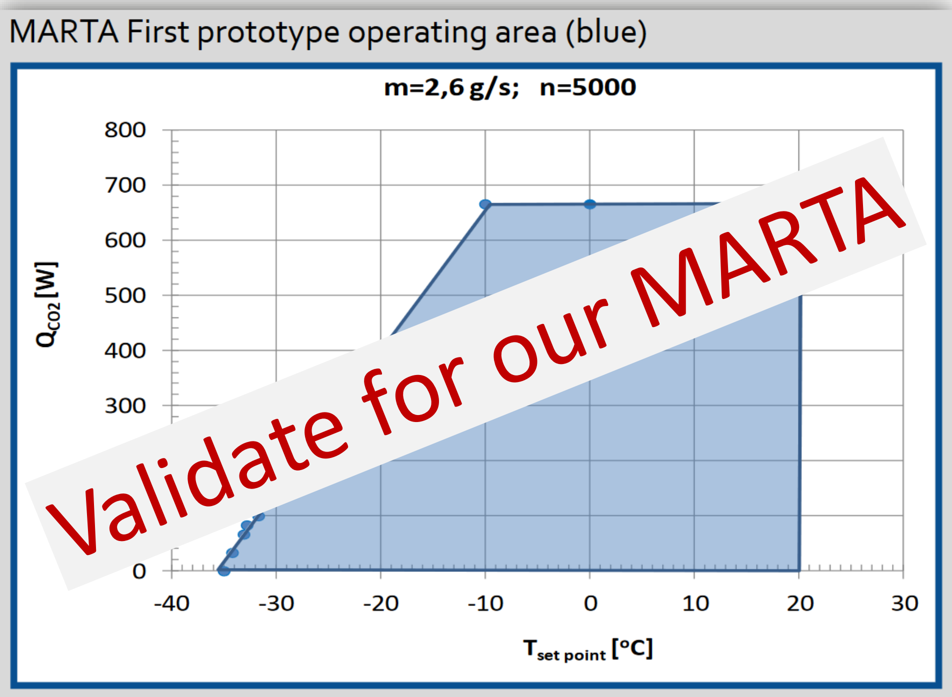

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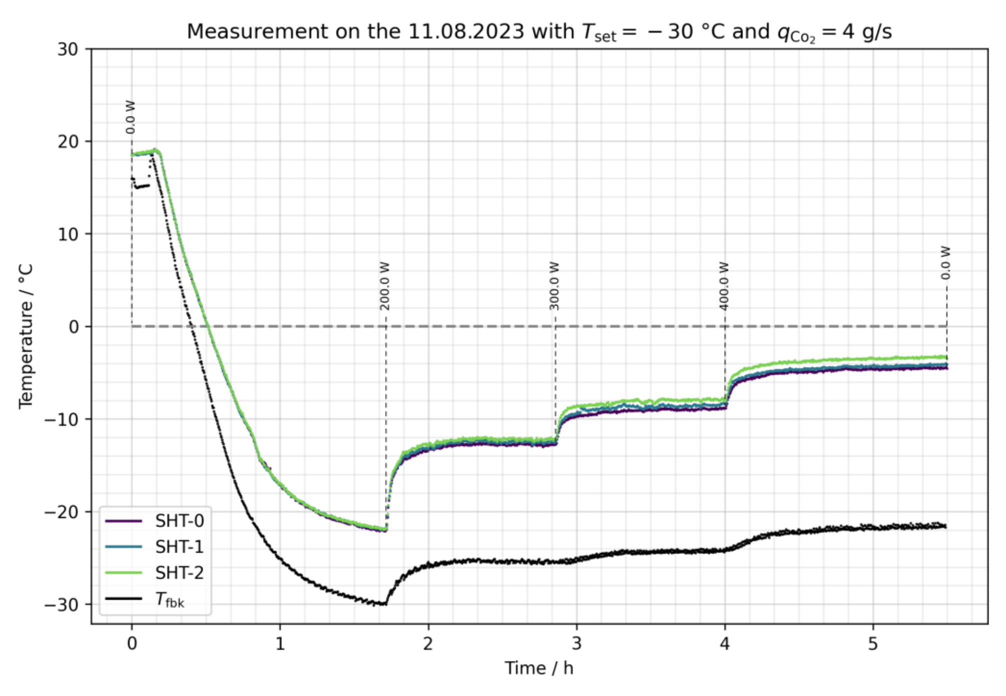
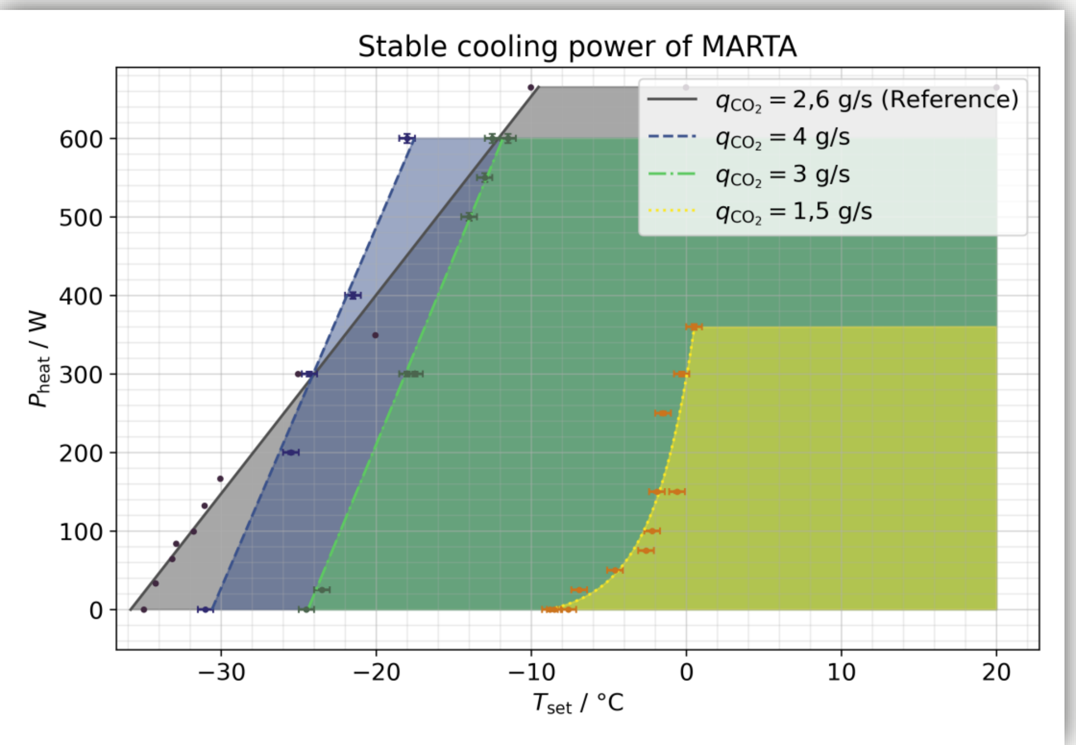
EXAMPLE MEASUREMENT

- System cools down with no heat load
- **Heat load is applied** until heat-up
- **Record T_{fbk}** when thermal equilibrium is achieved
- Increase heat load, repeat

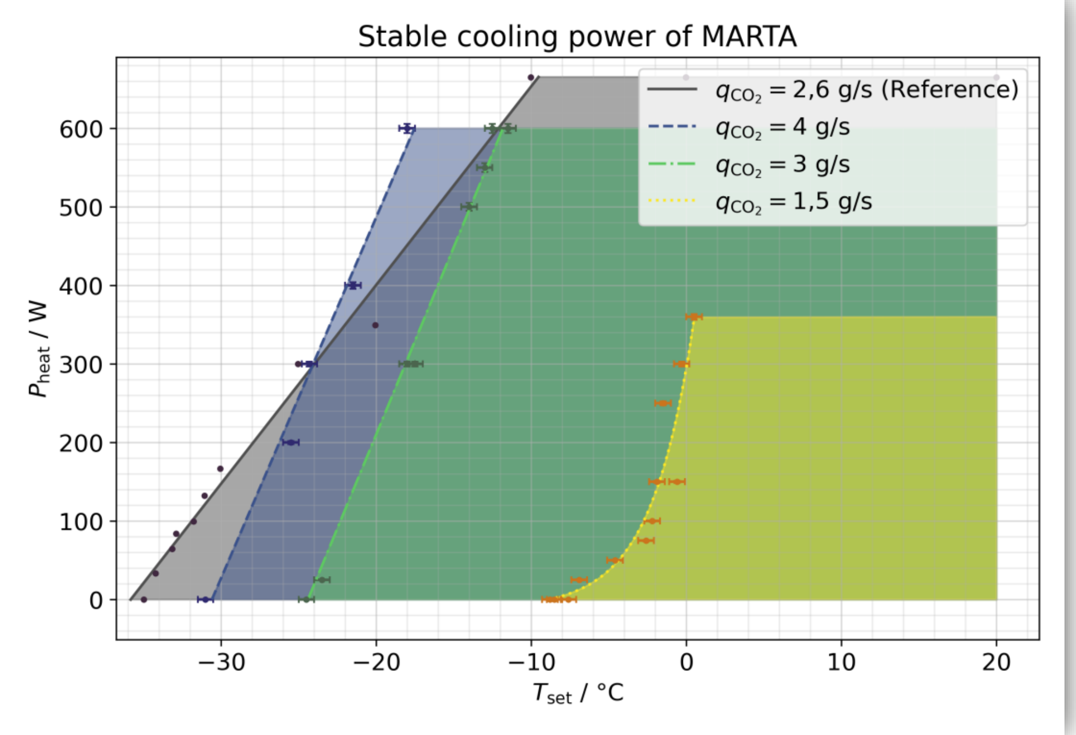


RESULTS FOR THE ITK-QC



RESULTS FOR THE ITK-QC

- Cooling power lower than anticipated
- At 400 W **CO_2 temperature** of below **-15 °C** possible
- Expected **max. pixel module temperature below 10 °C**



SUMMARY AND OUTLOOK

- Understanding the concept and operation of the cooling system in MARTA
- **Characterization of MARTA**
- Evaluation of cooling capabilities for ITk-QC
- Outlook:
  - Implementation of MARTA for the ITk-QC
  - **Further investigation of MARTA** edge case characteristics

IMPORTANT SOURCES

Technical Design Report for the ATLAS Inner Tracker Strip Detector, Techn. Ber., CERN, 2017, url: https://cds.cern.ch/record/2257755

P. Barroca, *Modelling CO2 cooling of the ATLAS ITk Pixel Detector*, Diss., 2019, url: https://cds.cern.ch/record/2703341

B. Verlaat, M. Van Beuzekom und A. Van Lysebetten, *CO2 cooling for HEP experiments*, 2008, url: https://cds.cern.ch/record/1158652

Conversations with M. Hamer, F. Hinterkeuser, K. Padeken

THANK YOU!

Any questions?

Detailed differences between ITk and ID

- ITk is just better!
- Also pseudorapidity increase from 2.5 to 4
- ITk needs a lot more cooling

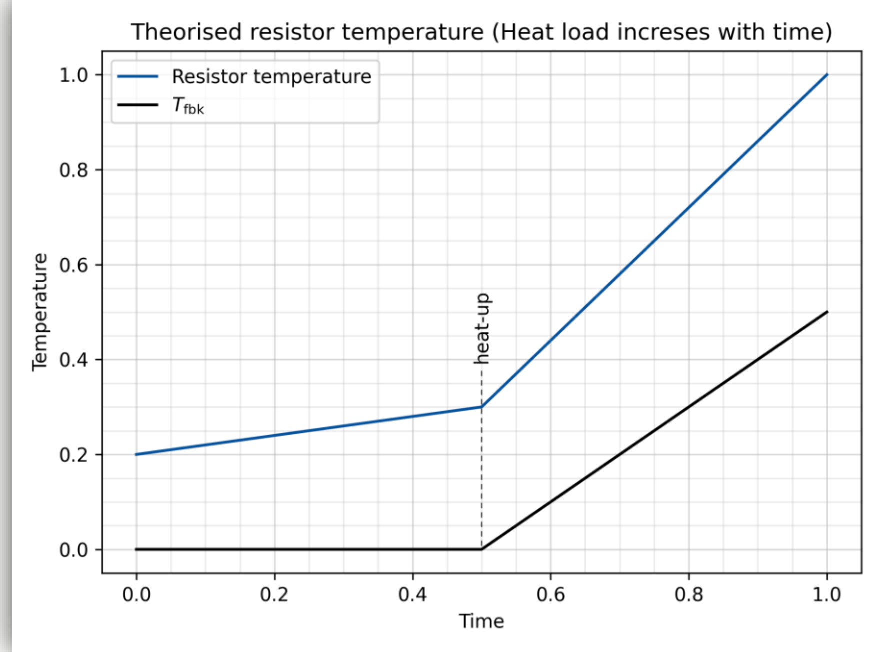
	ATLAS Pixel + IBL	ITk Pixel
Modules	2000	8500
Pixel Size	$50 \times 400\,\mu m^2$ or $50 \times 250\,\mu m^2$	$50 \times 50\,\mu m^2$
Readout channels	80 million	5 billion
Active area	$1.7\,m^2$	$14\,m^2$
TID	2.5 MGy	10 MGy
Fluence	$10^{15}\ n_{eq}/cm$	$1.4^{16}\ n_{eq}/cm$
Trigger rate	100 kHz	1 MHz
FE data rate	160 Mb s	5.12 Gb s
Powering	parallel	serial
Cooling budget	15 kW	100 kW

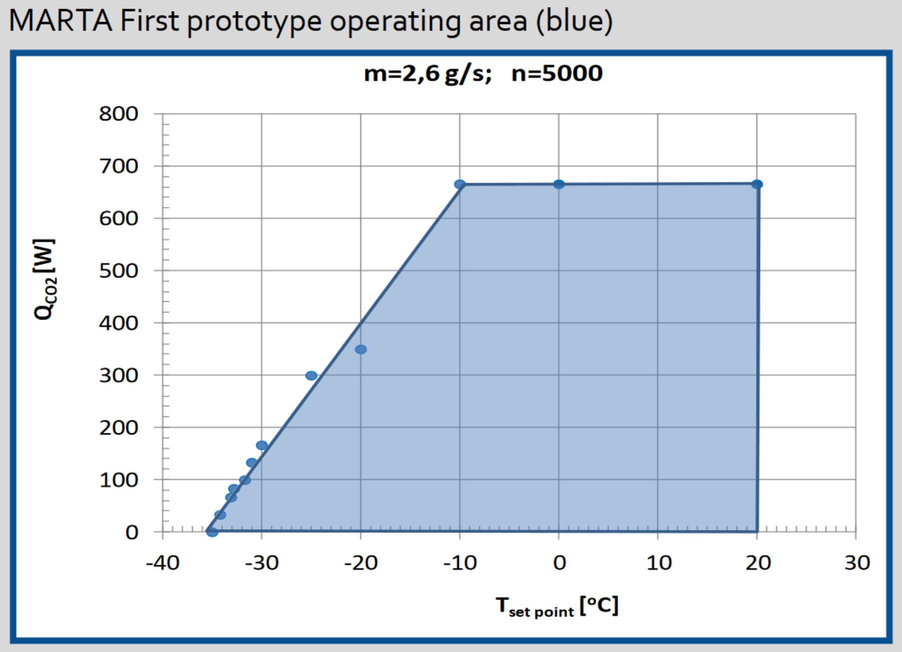
F. Hinterkeuser, *Evaluation of a Serial Powering Scheme and its Building Blocks for the ATLAS ITk Pixel Detector*

Methods for finding the max. cooling capacity

Method	**Resistor Temperature for the start of heat-up**	**T_{fbk} for the start of heat-up**	**Constant heat-up**
Description	Find sudden increase in resistor temperature	Increase heat load untill heat-up is observed	Start system in heat-up, measure T_{fbk} for selected heat loads
Evaluation	Temperature measurement too inaccurate	Takes a long time to stepwise increse heat load and wait for heat-up	Quickly measure along the line of max. cooling power

Methods for finding the max. cooling capacity

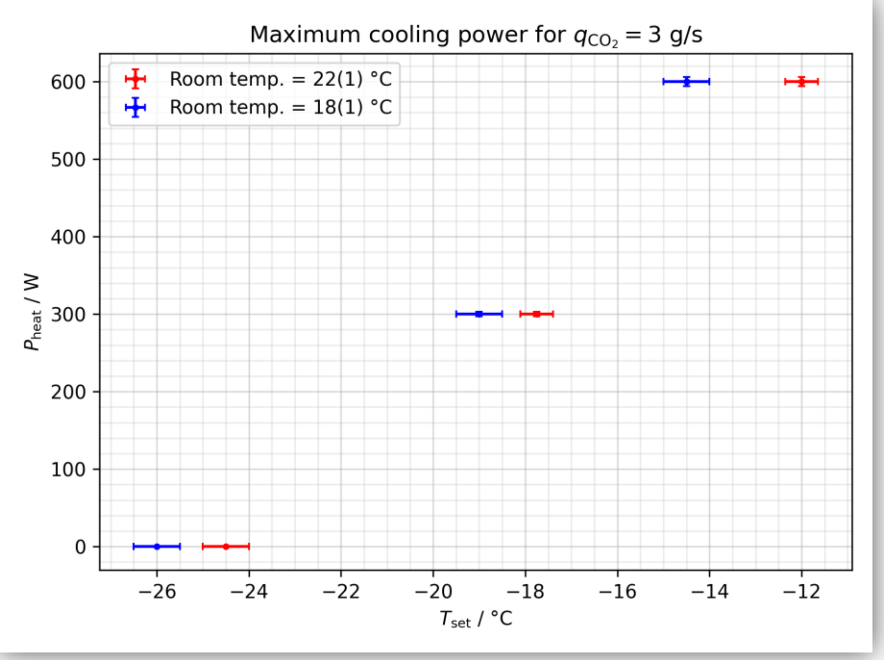




Does room temperature effect cooling power?

Lowering of room temperature by 4(1) °C

only improved cooling capacity by 1.8(4) °C



Why is the q_{CO2}= 1.5 g/s operating range limited?

- **Insufficient thermal connection** between the resistors and the cooling pipe **at higher temperature**
- The heat transfer suddenly collapses
- **Resistor quickly heats up** out of safe operating temperature
- No safe measurement possible