Cryogenics for LHC Experiments

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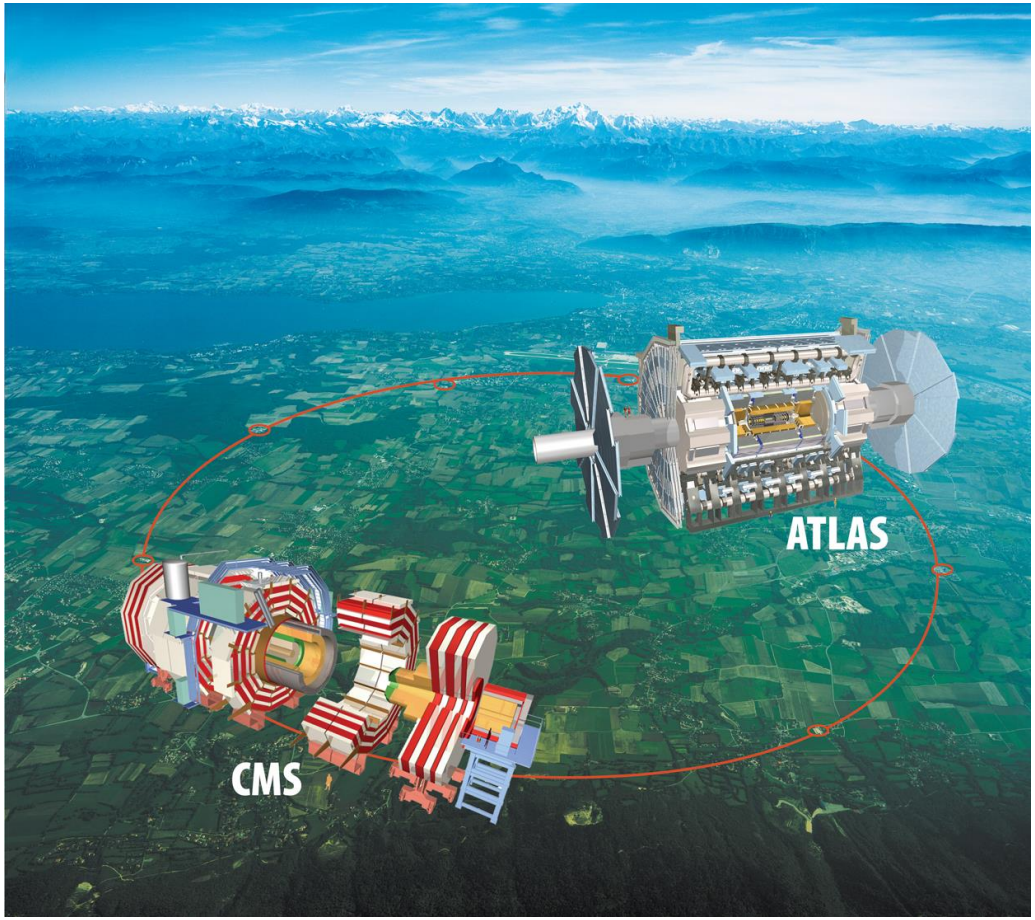
LHC experiments: ATLAS and CMS

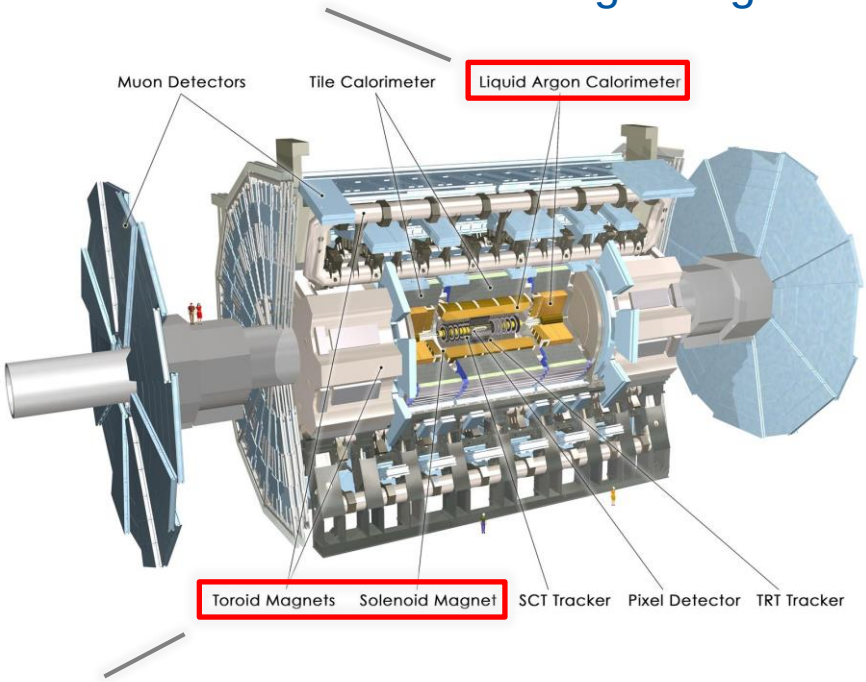


- general-purpose particle physics experiments
- run by international collaborations
- installed at the CERN LHC
- 100 m underground

Source: © CERN / BUL-PHO-2009-064-3

ATLAS: A Toroidal LHC ApparatuS

Calorimeters for measuring energies



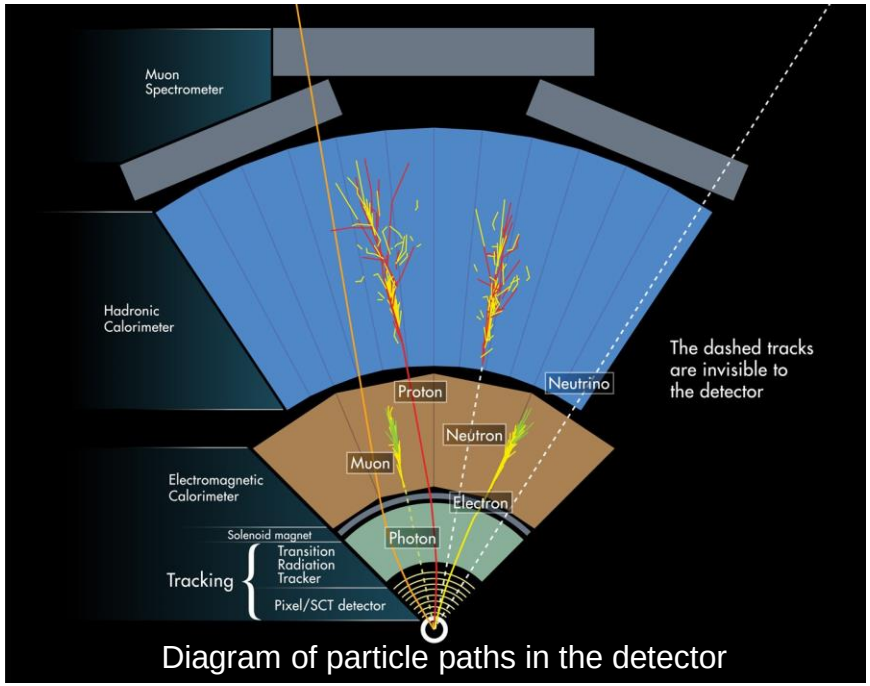
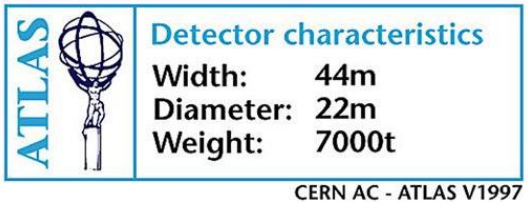


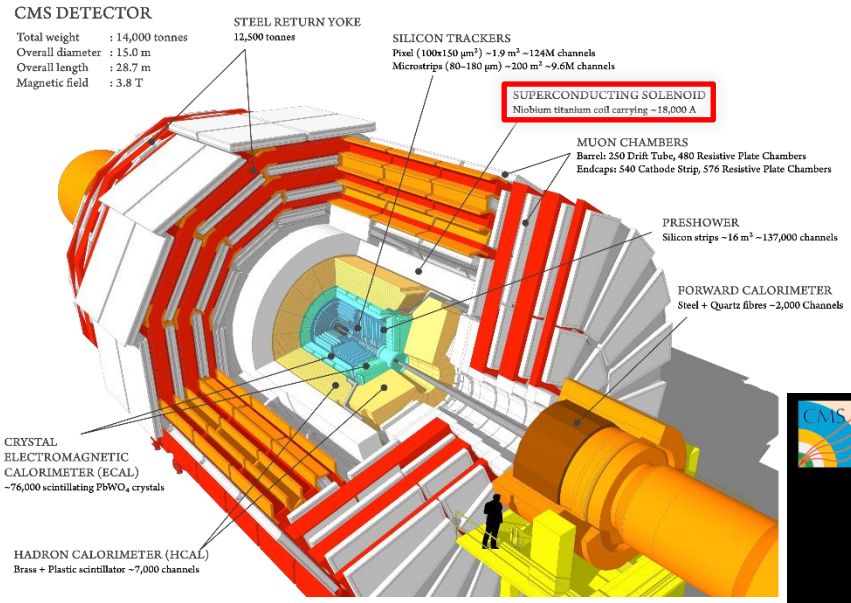
Diagram of particle paths in the detector

Large superconducting magnets for bending charged particles trajectories and measuring momenta



Source: © CERN-GE-0803012-05, CERN-EX-1301009

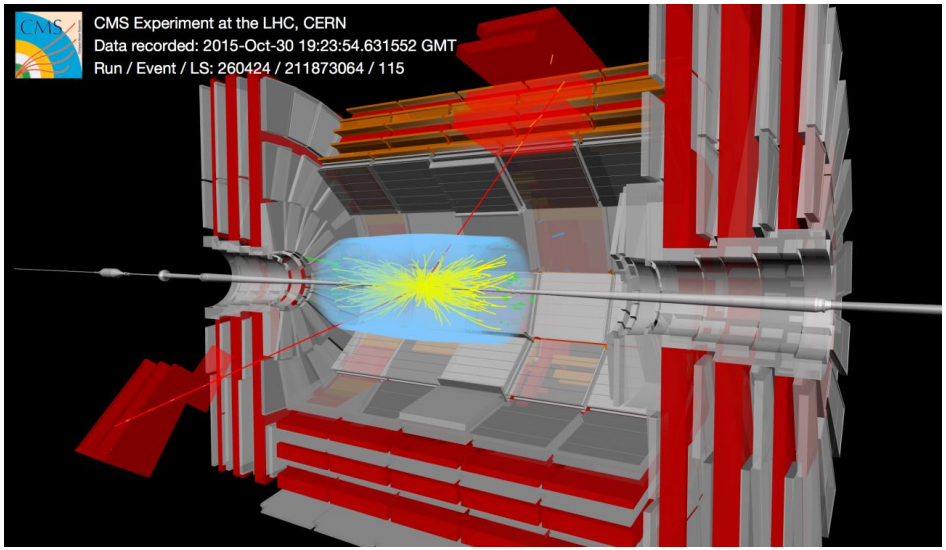
CMS: Compact Muon Solenoid



Detectors common requirements: compactness, transparency, maintainability

Tracker and Calorimeters placed inside the coil

15 separate «slices»



Source: © CERN / CMS-OUTREACH-2019-001, MS-PHO-EVENTS-2015-005-4, Detector model in SketchUp by Tai Sakuma

Where to find cryogenics in LHC experiments

- as a cooling source for detector superconducting magnets
- as active “medium” of detectors

  for particles energy measurements

  like Liquid Ionization Chambers

  (liquefied rare gases detectors)

Content

- The ATLAS and CMS experiments
- Cryogenics for detector superconducting magnets
  - Magnets characteristics
  - Cryogenic system requirements
  - CMS solenoid: thermosyphon cooling scheme CMS
  - ATLAS toroids: forced flow cooling scheme
  - Operational experience
- Cryogenics for rare liquefied gases detectors
  - ATLAS liquid argon calorimeter
  - Requirements
  - Cryogenic system
  - Operational results
- References

Cryogenics for detector superconducting magnets

Detector superconducting magnets

- What is special about detector magnets:
  - have often to deliver a magnetic field in a large volume

    (sensitive volume CMS solenoid: 370 m^3);
  - are often enclosed in the experiment. In this case the magnet system shall be made as “transparent” as possible, to diminish the possibility that particles will be adsorbed in the magnet “mass”;
  - are non-series magnets

Detector superconducting magnets

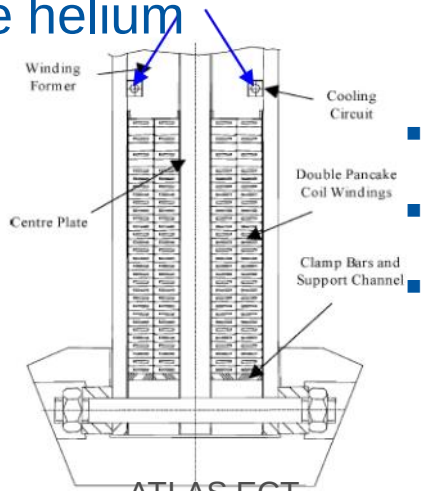
Common characteristics

- Coil support, thermal shield, cooling channels made out of Aluminum
- Al-stabilized NbTi-Cu conductors

- Operating temperature 4.5 - 4.8K
- Indirect cooling w 2-phase helium

CMS

LHe cooling circuit



ATLAS ECT

Cryo requirements

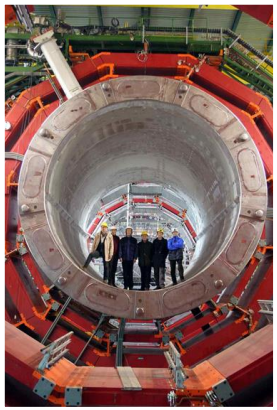
- Cool-down with a max. temperature gradient of 40K
- Cool cold mass, current leads and thermal shields
- Accomodate static and dynamic heat loads
- Ensure slow dumps
- Limit fast dumps
- Limit thermal cycling

Solenoid magnets

with thermosyphon cooling

- ATLAS central solenoid
  - ✓ 5.3 m length, 2.4 m diameter
  - ✓ 5 t cold mass
  - ✓ 2 T field, 7.73 kA nominal current
  - ✓ 38 MJ stored energy
  - ✓ Shares the calorimeter insulation space volume
- CMS solenoid
  - ✓ 12.5 m length, 7 m o.d.
  - ✓ 225 t cold mass
  - ✓ 4 T field @ IP , 2 T @ iron yoke
  - ✓ 18 kA nominal current
  - ✓ 2.7 GJ stored energy
  - ✓ the largest of its kind

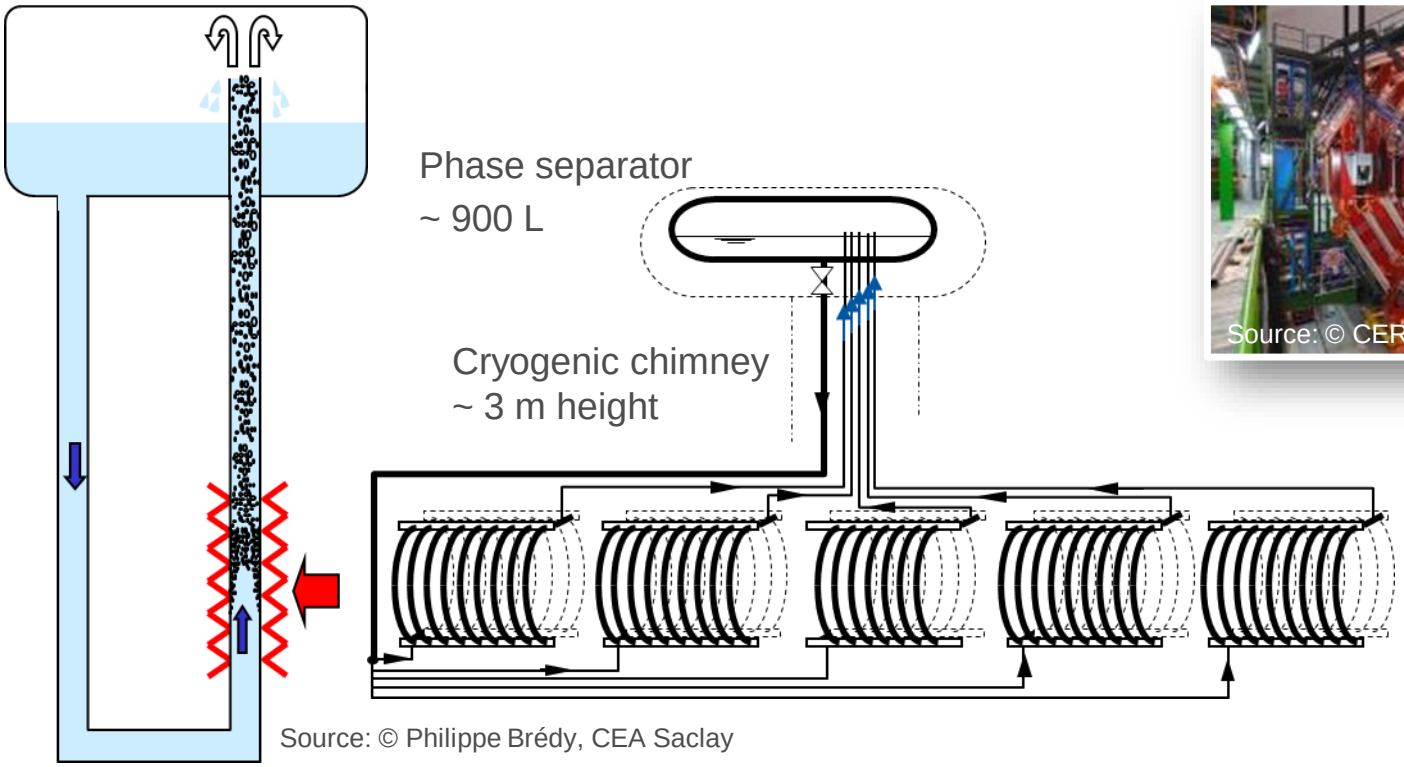

ATLAS central solenoid




CMS solenoid

Source: © CERN

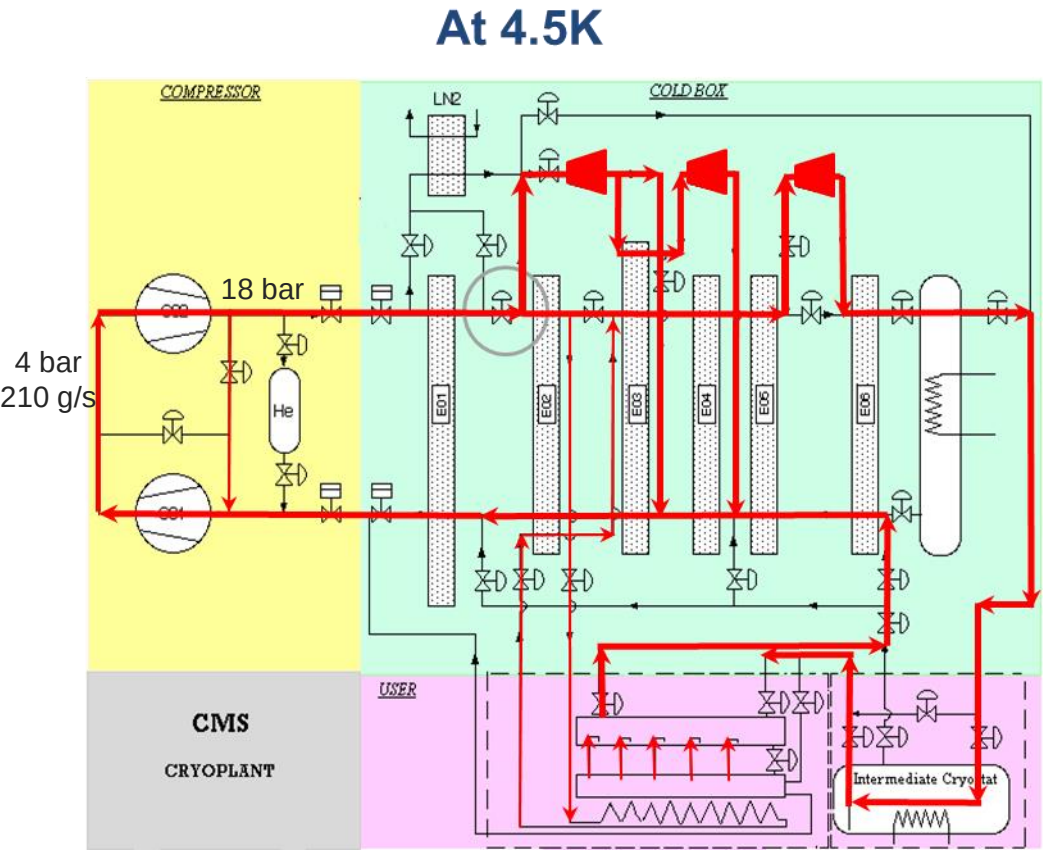
CMS thermosyphon cooling



Source: © Philippe Brédy, CEA Saclay

- Possible with a geometry allowing sufficient pressure head to drive the flow & avoiding high points with risk of vapour lock
- Driving force created by the difference in density between the liquid supply and the two phase return column: self sustained natural boiling convection
- Natural circulation, no cold mechanical pump needed
- When sufficient liquid available: magnet system can go into slow-dump in case of power failure

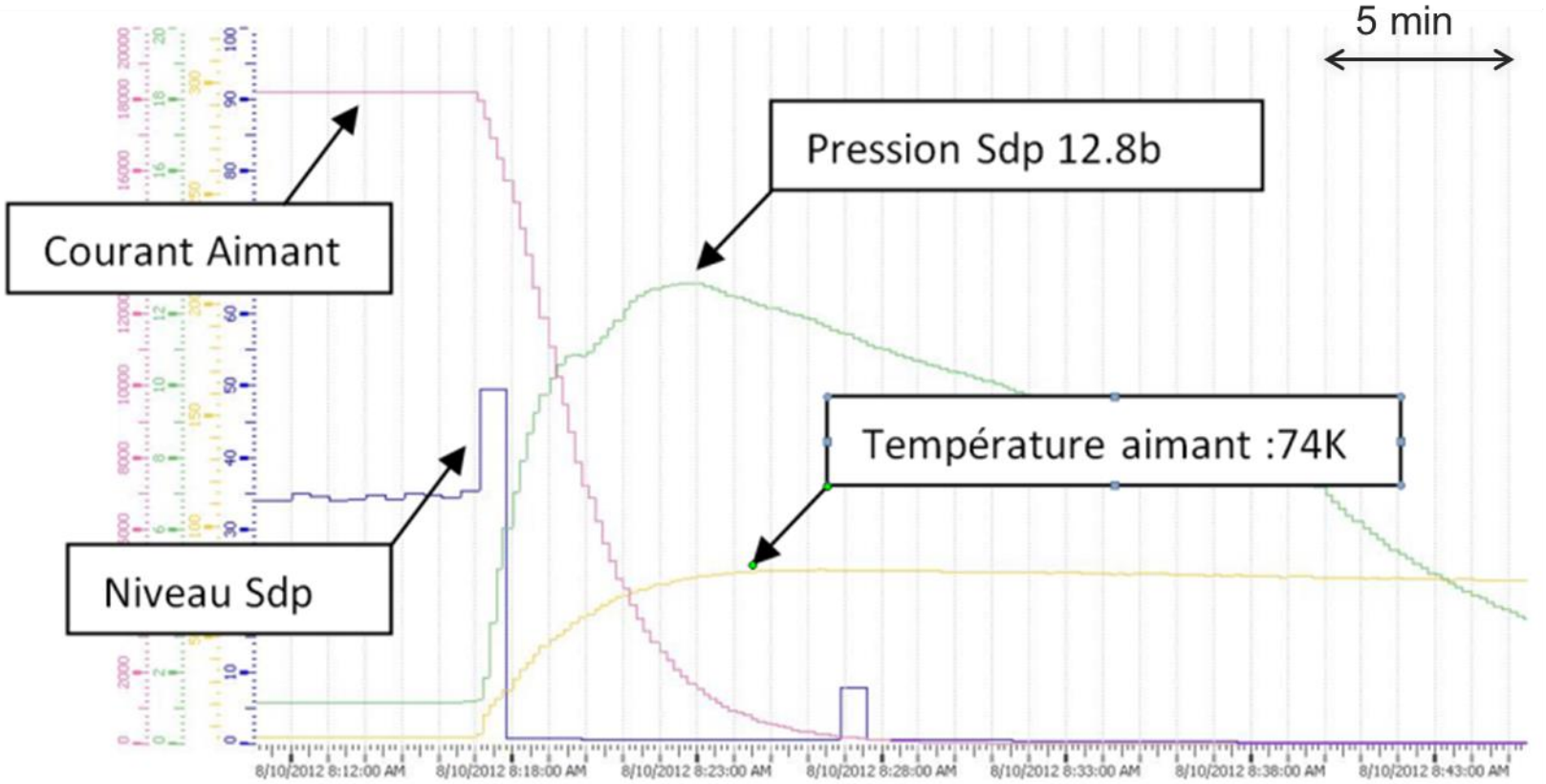
CMS refrigeration scheme



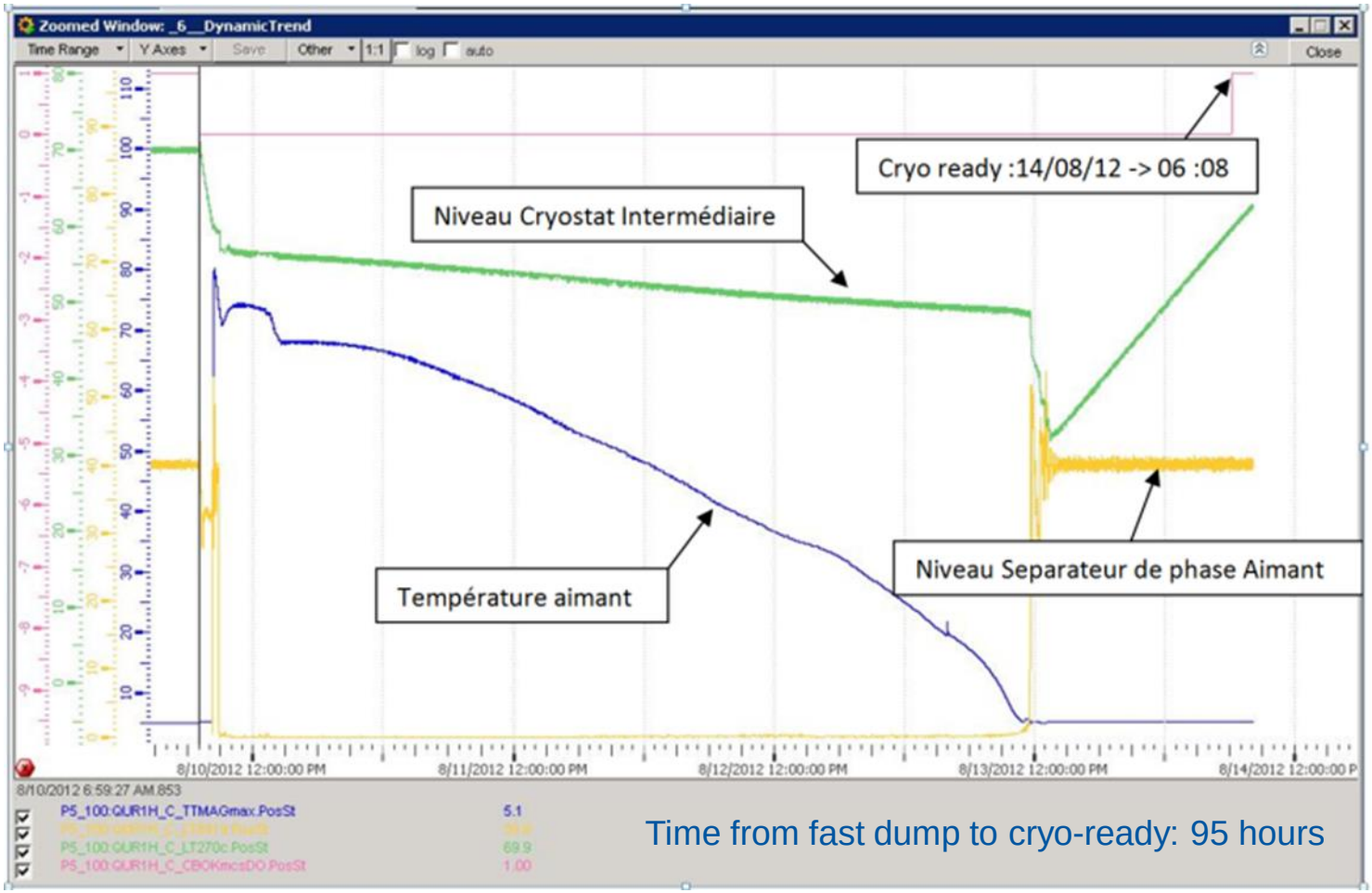
Refrigerator data - 1.5 kW @ 4.5 K equivalent:
800 W @ 4.5K
4.5 kW @ 70K for thermal shield
4 g/s liquefaction load for current leads

CMS fast dump

Helium loss: 180 kg



CMS fast dump recovery



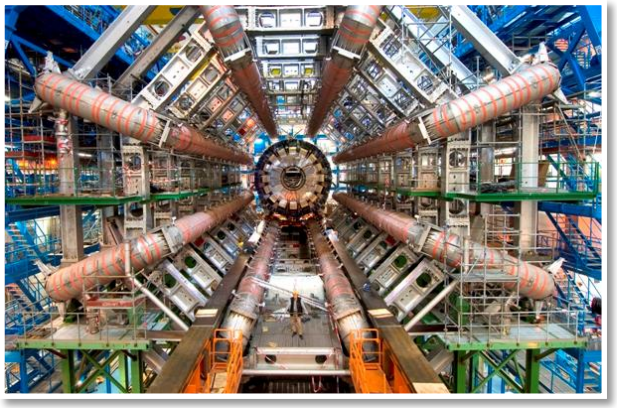
Time from fast dump to cryo-ready: 95 hours

Toroid magnets

with forced flow cooling

ATLAS:

- Barrel Toroid
  - ✓ 8 separate race track flat coils
  - ✓ 25.3 m length, 20.1 m o.d.,
  - ✓ 370 ton cold mass,
  - ✓ 1T (4 T on superconductor),
  - ✓ 20.5 kA nominal current;
  - ✓ 1.08 GJ stored energy;
- 2 End-cap Toroid
  - ✓ 8 coils in common cryostat each
  - ✓ 5.0 m length, 10.7 m o.d.,
  - ✓ 160 ton cold mass,
  - ✓ 1T (4 T on superconductor),
  - ✓ 0.25 GJ stored energy



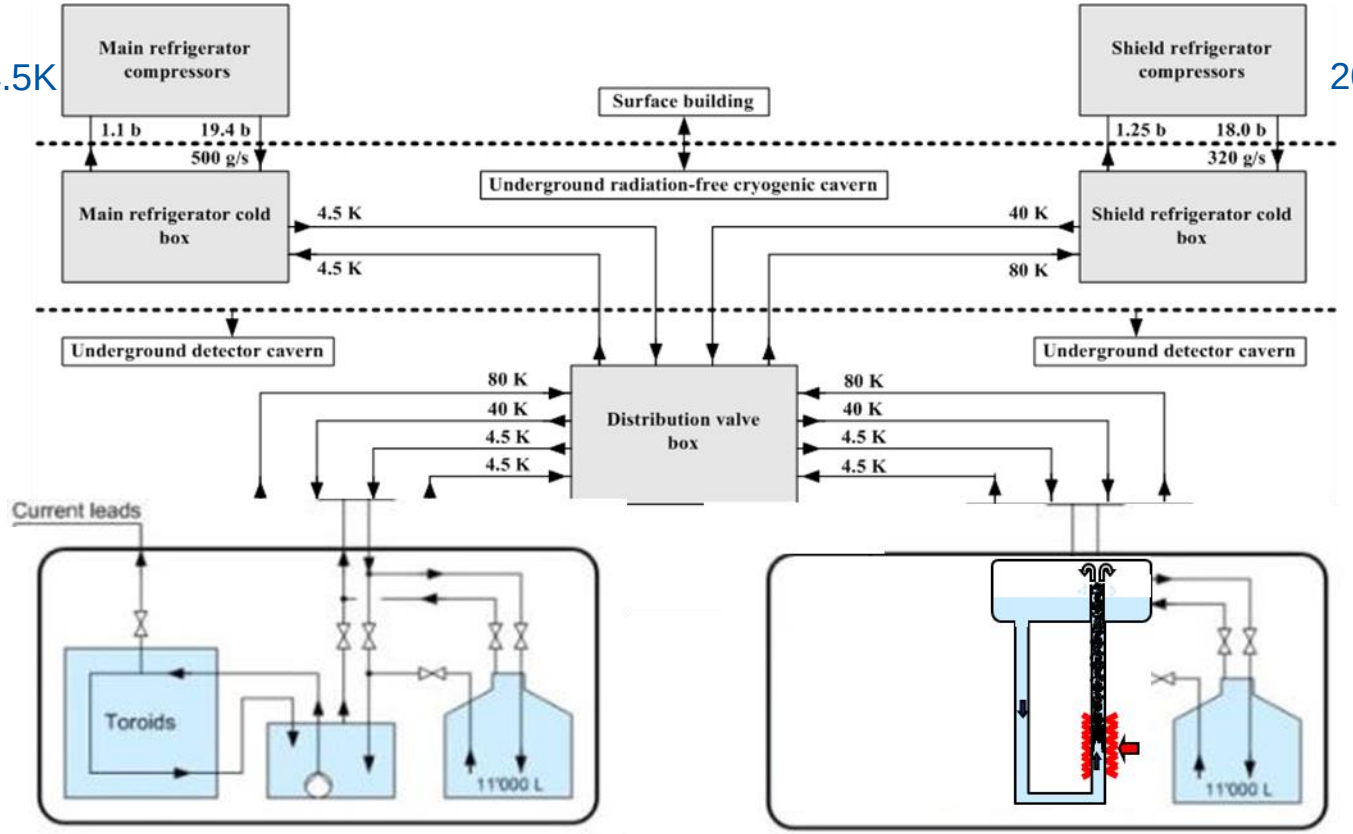
Source: © CERN

ATLAS Toroid forced flow cooling

refrigeration scheme

6 kW @ 4.5K

20 kW @ 60K



Toroid proximity cryogenics

Solenoid proximity cryogenics

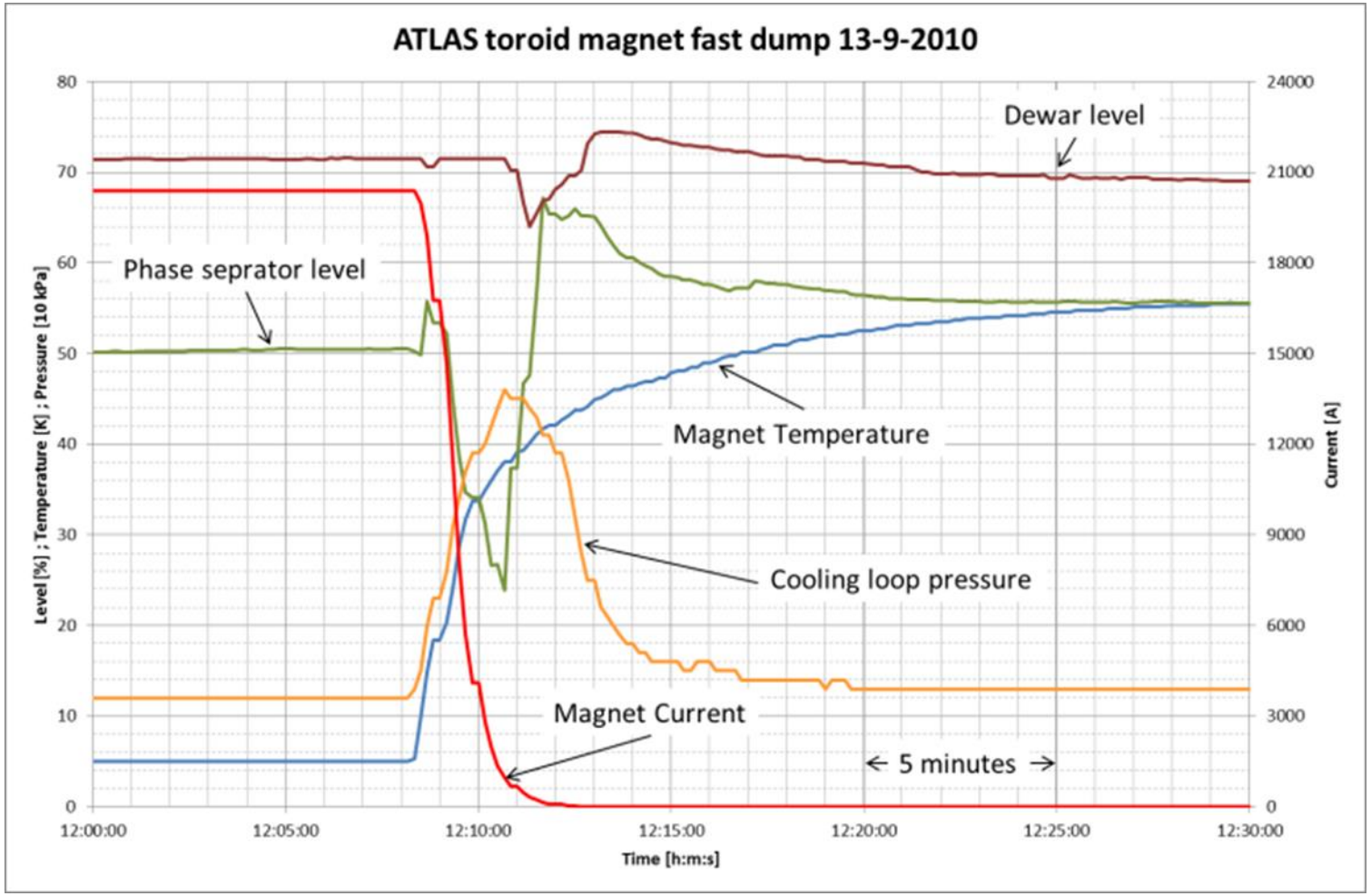
Centrifugal pump

~~1.2~~ 0.7 kg/s / 300 mbar

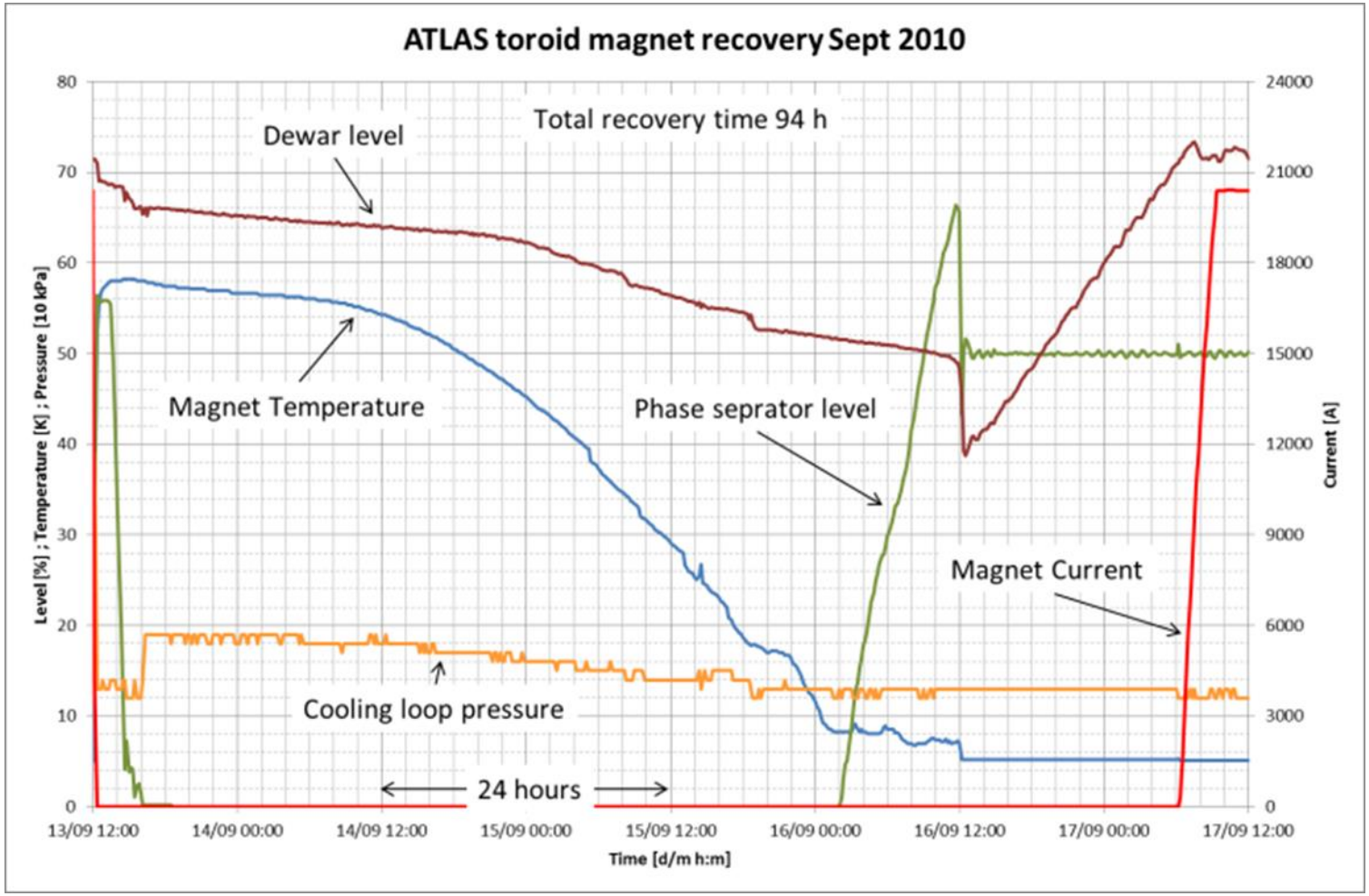
Buffer volume covering slow dump

Buffer volume for decoupling from toroid

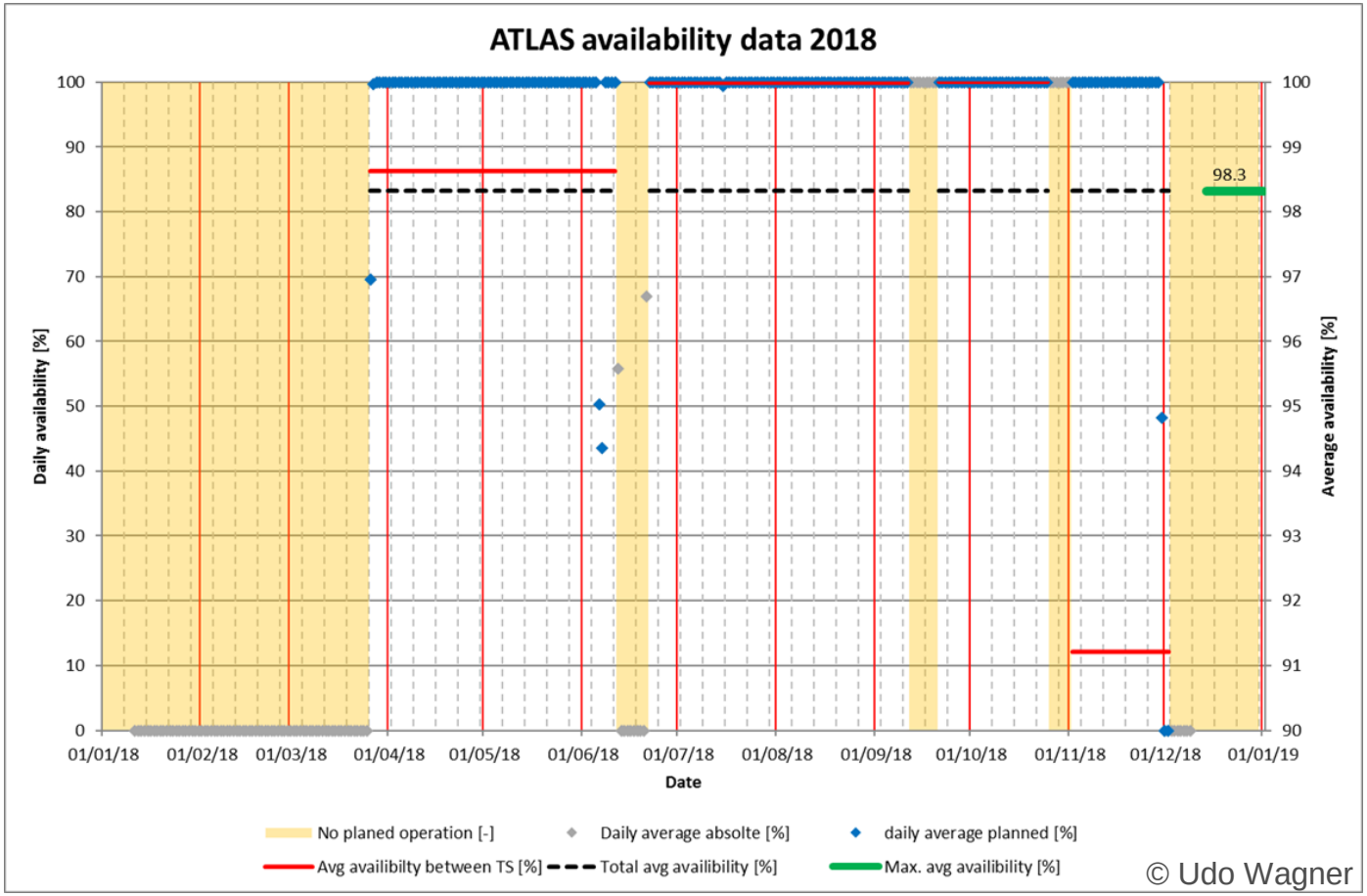
ATLAS toroid fast dump



ATLAS toroid fast dump recovery



Performances of ATLAS cryogenics

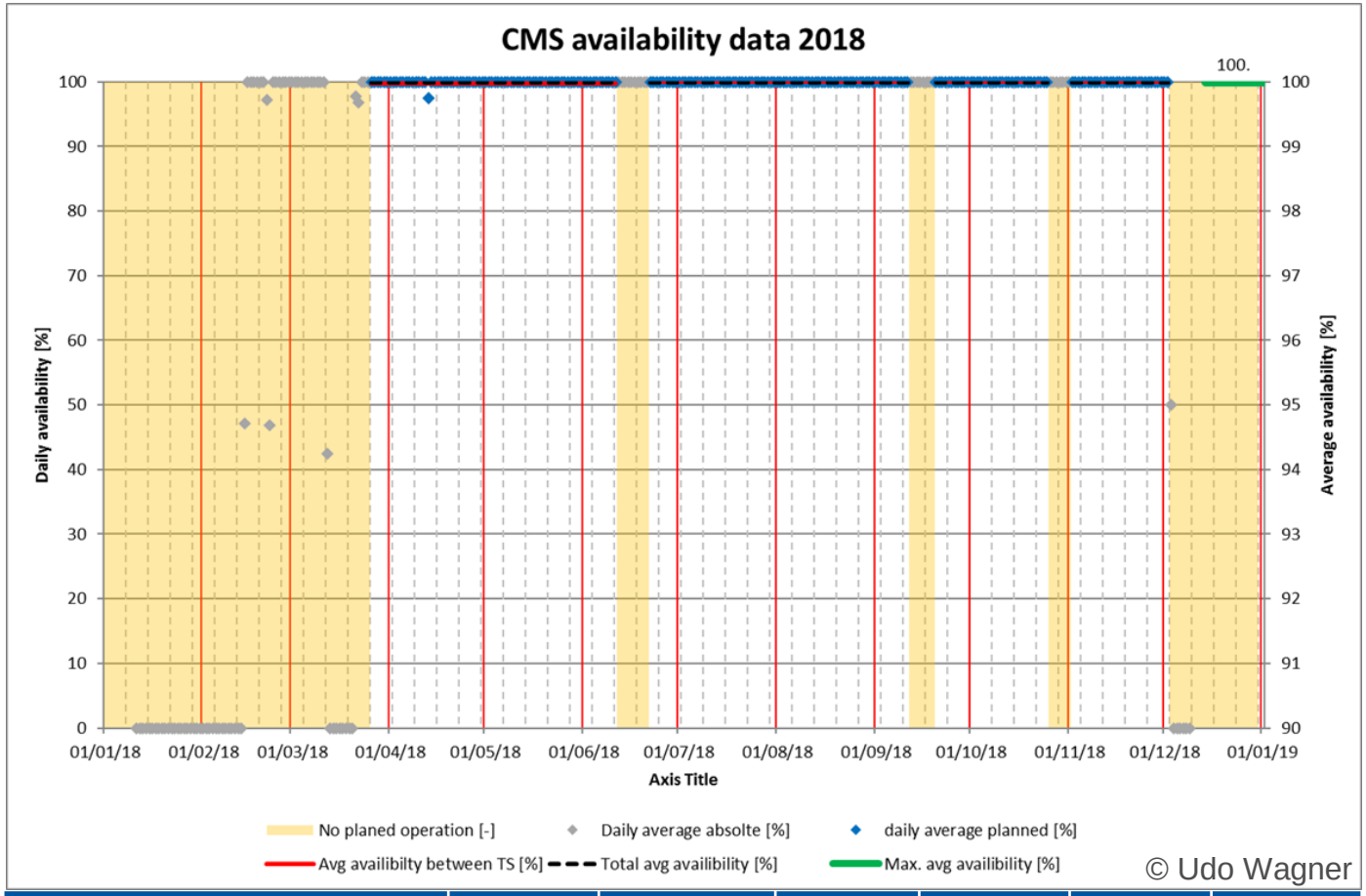


© Udo Wagner

Helium losses < 2 kg/d

Year	2011	2012-13	2015	2017	2018
Total average availability (%)	96.5	98.3	92.5	97.1	98.3

Performances of CMS cryogenics



© Udo Wagner

Helium losses < 0.2 kg/d

Year	2011	2012-13	2015	2016	2017	2018
Total av. availability (%)	98.3	96	52.7	97.9	98.9	99.989

Operational experience ~10 y

Main causes for down-time	Main consolidations
Sensitivity to power cuts: ▪ “Glitches”, typically <120 ms ▪ Long term cuts, typically >300 ms to black-out	Detailed fault chain analysis Readjustment of hard and soft safety to be tolerant to power losses of < 120 ms. Now most of the glitches are seen by the client system
Control& instrumentation ▪ Electrical contact error, element failure ▪ Mistakes or shortfalls in programmed controls	Modification of hard wired safety chain Replacement of aging electrical cabinets (ATLAS), aging elements, aging PLCs, standardization,

Operational experience ~10 y

Main causes for down-time	Main consolidations
Oil contamination 2015: Installations with well performing oil separators and coalescers suffered little Major impact on CMS availability (52%!) Cumulated effect: ▪ Change of coalescers cartridges brand during 2013-14 preventive maintenance ▪ bad choice of the adsorbent material of the final oil adsorber during 2013-14 preventive maintenance ▪ Under-sizing of the final oil separator of CMS	YETS 2015-16: 1. Exchange the final oil separator (generous design) 2. Exchange the coalescer stages (generous design) 3. Exchange the oil adsorbent material 4. Exchange the high pressure piping between compressor station and cold-box 5. Clean the cold box circuits 6. Exchange the 20 K and 80 K adsorbers Better prevent than cure!

*YETS: year end technical stop ~3 months

Operational experience ~10 y

Main other limitations	Main improvements
Gaseous impurities and regular filter clogging: ▪ due to temperature excursions, accumulated gaseous impurities migrate to the 80K adsorber outlet, desorb, and clog the turbine inlet filters ▪ Single 80K adsorber without bypass	Improved procedures. We live with periodic warm-up of turbine inlet filters (on-line, no down-time) and regeneration of adsorber / cold box (stop during TS)
1st heat exchanger clogging twice a year (CMS): intervention in TS, no down time: ▪ Water from top up oil ▪ We rely on purges and oil adsorber heating to remove water during a start-up phase.	Install dryer units at both CMS and ATLAS in order to live 1 full year run without cold-box warm up

And more improvements

- Installed redundancy of all compressor stages
  - diminish down-time in case of large equipment failure
- de-coupling of ATLAS toroid and solenoid system with added 11000 liter dewar to solenoid system
  - diminish the effect of an eventual toroid fast-dump on the physics measurements

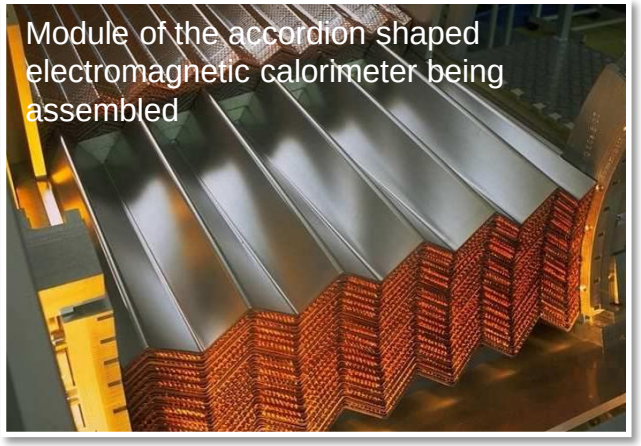
Cryogenics for liquefied rare gas detector

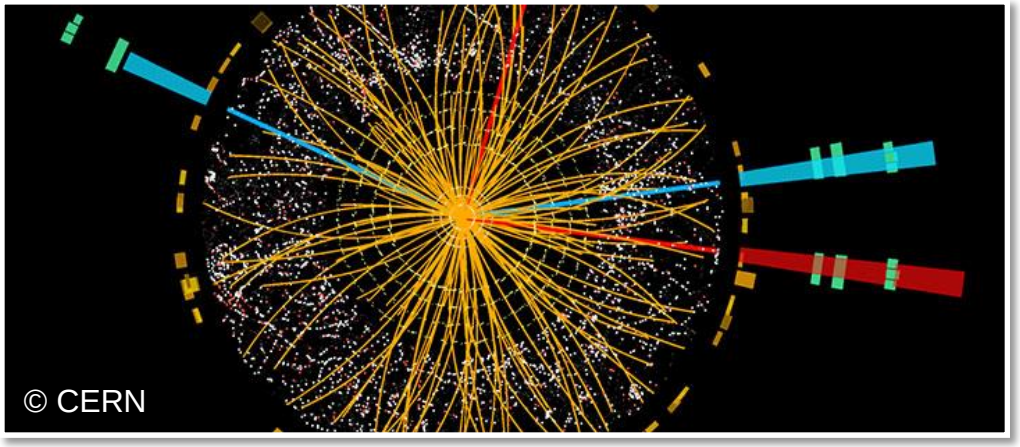
the ATLAS Liquid Argon Calorimeter

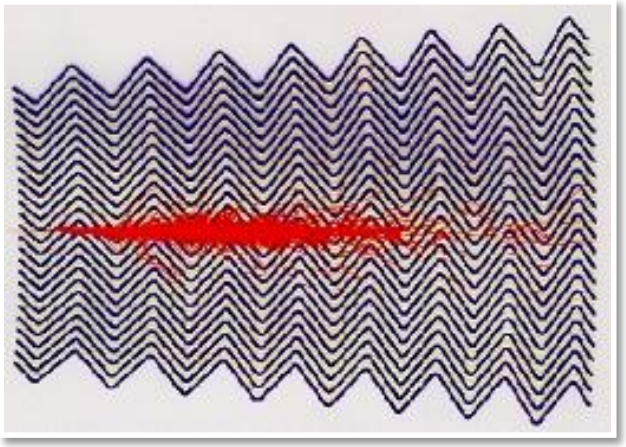
The ATLAS liquid argon calorimeter

A noble liquid ionization chamber

- Accordion shaped lead adsorber plates alternating with HV copper electrodes immersed in liquid argon bath
- Interactions with the adsorbers transform the incoming particule energy into a shower of secondary particules which in turn ionize the liquid argon
- The electrons created are accelerated in the HV field and this electrical “current” is measured by the electrodes.
- This allows to establish both the position and the energy of the incoming particle.

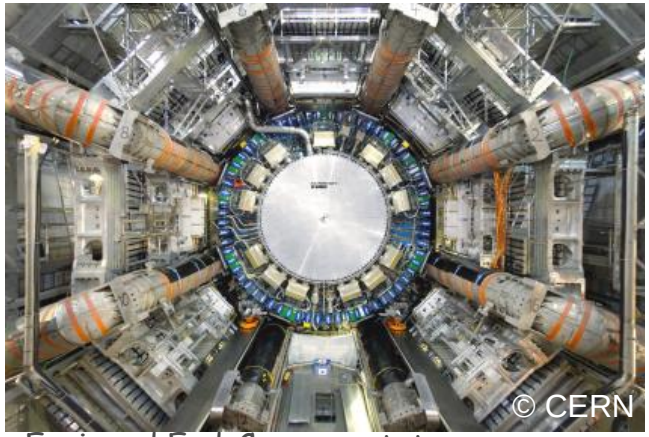




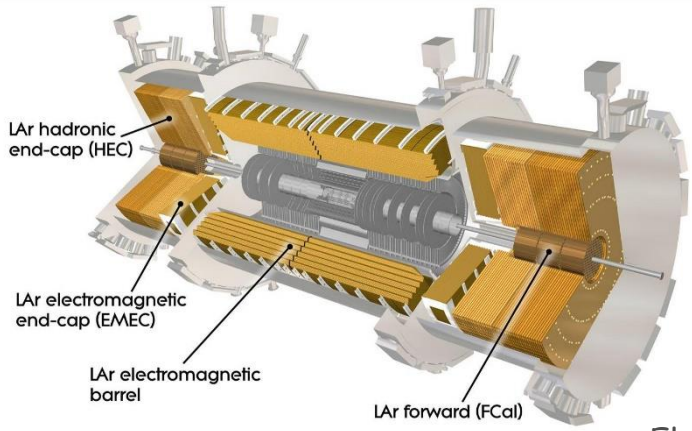


Electrons shower in the calorimeter

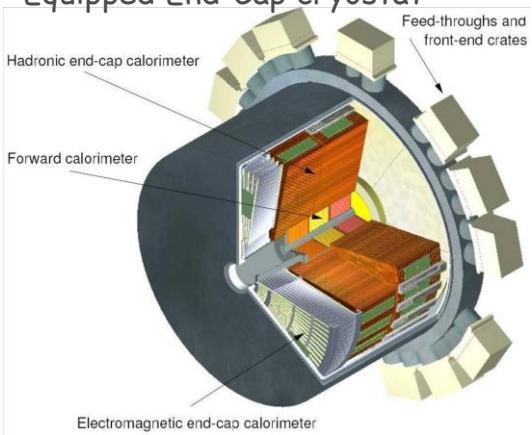
The ATLAS liquid argon calorimeter



Equipped End-Cap cryostat

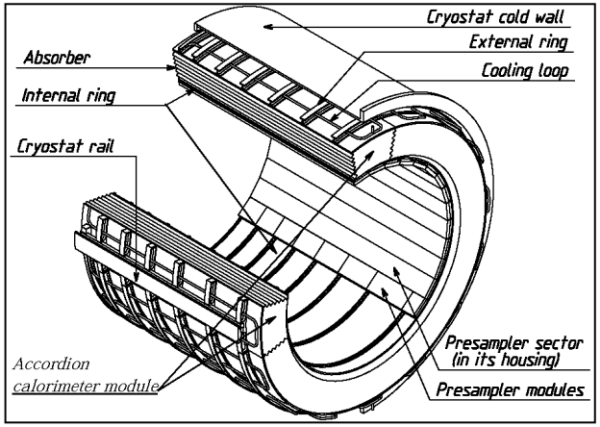


Electromagnetic barrel half-wheel



diameter 4.3 m
length 3 m
heat load 2.5 kW
(~ 25 % cold electronics)

- three Al cryostats
- total cold mass 550 t
- total liquid argon volume 100 m^3 in underground
- temperature around 88.3 K
- cooled by forced flow evaporating liquid nitrogen
- 228000 signal wire feed-through
- operational 365/365 since 2005



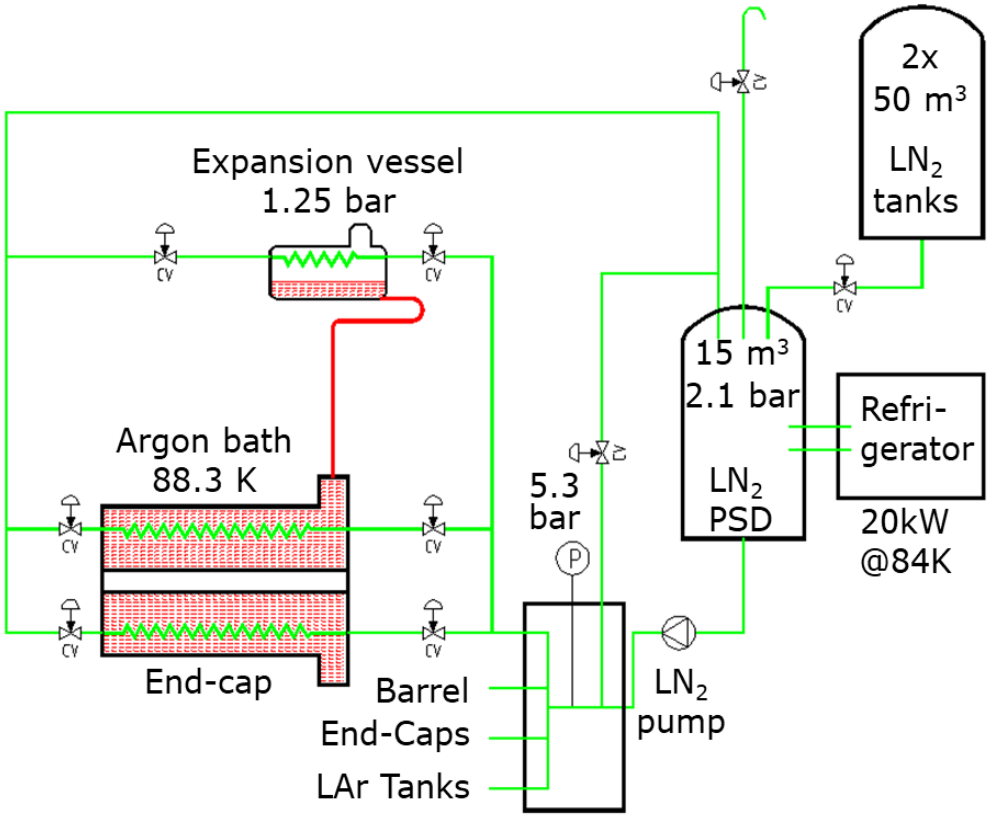
diameter 4.3 m
length 6.5 m
heat load 1.9 kW
(~ 50 % Feedthroughs)

Requirements

- Cool-down
  - keep ΔT within strict T° dependant limits (<6K..45K) to avoid any excessive stresses or displacements of the detector composite structure
- Steady-state
  - No gas bubble formation in liquid bath
  - Liquid argon bath temperature constant at about 88.4 K (Temperature stability not well defined in TDR)
  - Temperature gradient across bath < 0.7 K
  - Argon purity < 2 ppm(v) of O2-equivalent
  - Safe and uninterrupted functioning over the life-time of the experiment
  - Prevent any condensation of water on the electrical feed-throughs

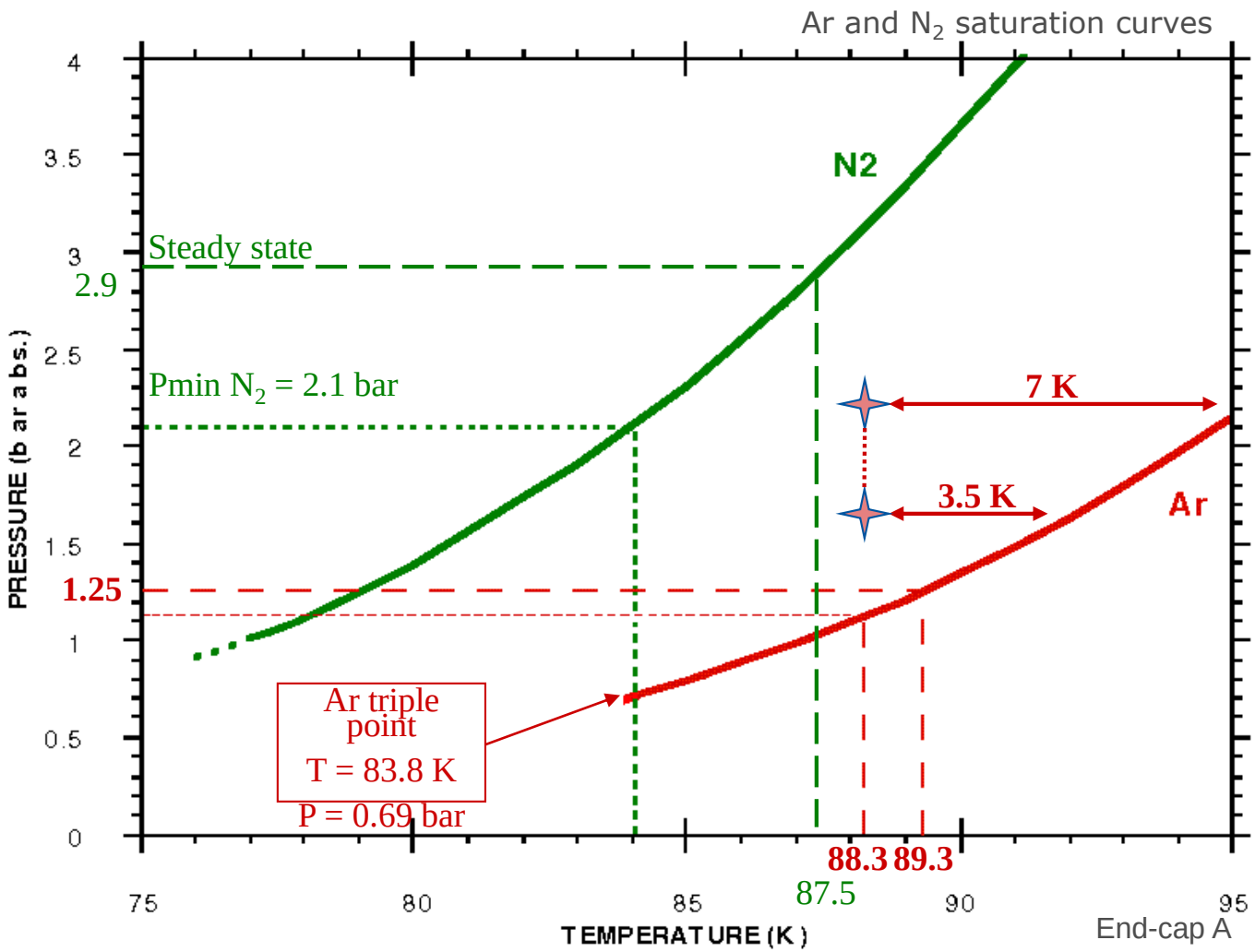
Energy measurement sensitivity: 2 % per K

Forced flow of evaporatring liquid nitrogen



- Nitrogen circulated through heat exchangers via a centrifugal pump;
- 2-phase nitrogen flow regulated to the same pressure in all 12 heat exchangers placed in the baths;
- Wetting of heat exchanger ensured
- Nitrogen re-liquefied by refrigerator;
- System backed up by 100 m3 N2 storage at the surface;

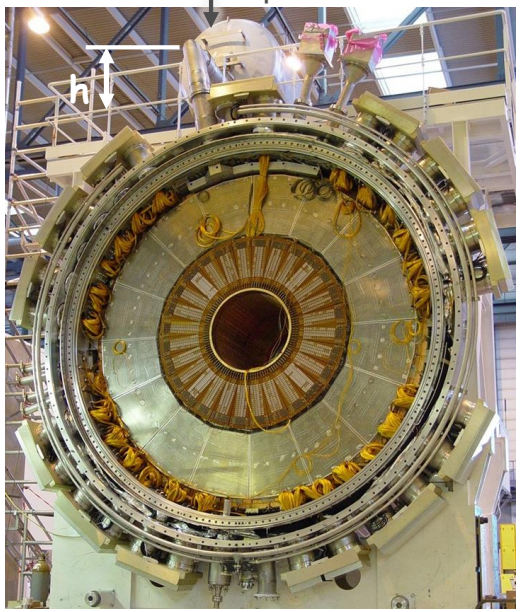
LAr bath sub-cooled with 4 K to 7 K



h barrel ≈ 3.4 m

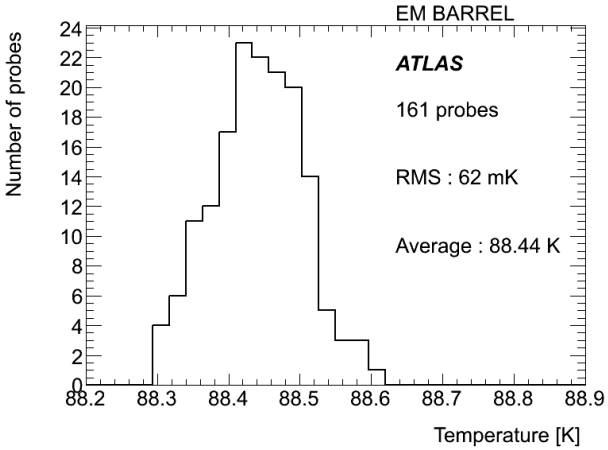
h end-cap ≈ 2.4 m

expansion vessel

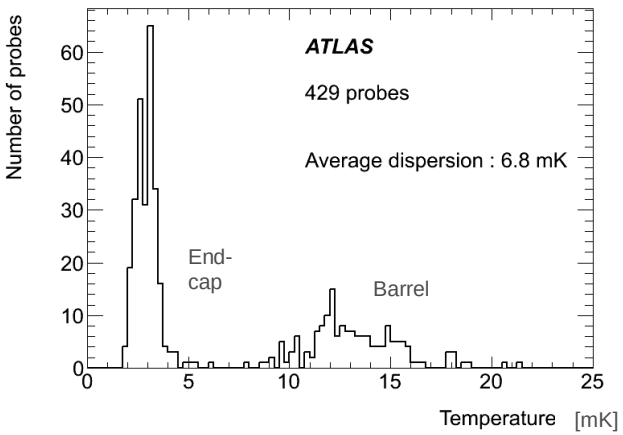


No boiling (no gas production, no noise)
Time to recover from cooling failure

Result 2010 data taking period

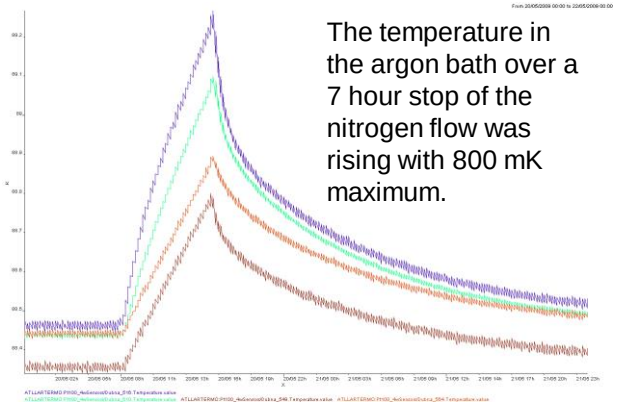


Temperature uniformity over detector volume: < 70 mK rms



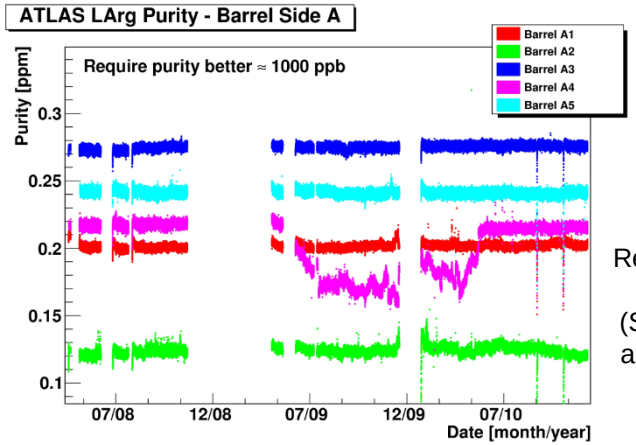
Barrel: due to a 50 mK step caused by switch of LN2 supply service (~5 mK without this 2 weeks)

Temperature stability: < 5 mK rms



The temperature in the argon bath over a 7 hour stop of the nitrogen flow was rising with 800 mK maximum.

LAr bath sub-cooled with 4.2 K to 7.7 K. No argon gas bubble



Results over more than 2 years (Systematic error approx. 100 ppb)

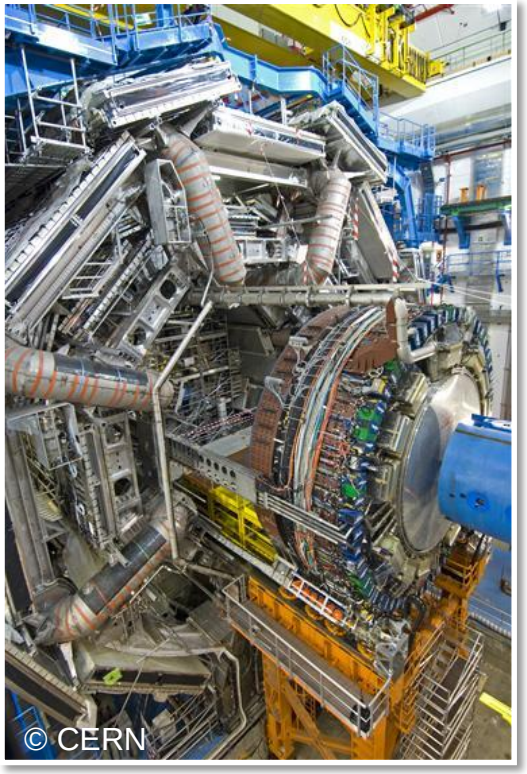
Argon purity: between 0.1 and 0.3 ppm of O2-equivalent

Un-interrupted functioning

Redundancies:

- LN2 pumps (x3)
- LN2 supply services (x3)
- all essential devices on backed-up electrical power system: EDF/EOS network, diesel generators, UPS
- compressed air and cooling water backed up
- Warm back-up for each of the PLCs (not really redundant)

Displacement of end-caps over 12 m for access to inner part



Safety aspects

Special features related to safe handling of large volume of cryogenic liquids in underground area:

- Argon volume of the three cryostats can be emptied into 2 x 50 m^3 argon storage tanks by:
  - gravity
  - cryogenic pump
- Argon tanks are equipped with LN2 condenser and kept cold
- Items containing large volumes are:
  - equipped with safety valves collected to a dedicated DN 500 pipe going to surface
  - placed above retention pits
- Gas constantly renewed from the retention pits by surface extraction system
- Insulation vacuum levels are monitored
- Oxygen detectors

Conclusion

These cryogenic systems have been designed, constructed and installed by international collaborations:

- CMS cryogenics: CEA-SACLAY,CERN
- ATLAS magnet cryogenics: CEA-SACLAY,CERN, INFN, KEK, RAL
- ATLAS calorimeter cryogenics: BNL, CEA, CERN, LAL, LPSC and NTNU

Some references

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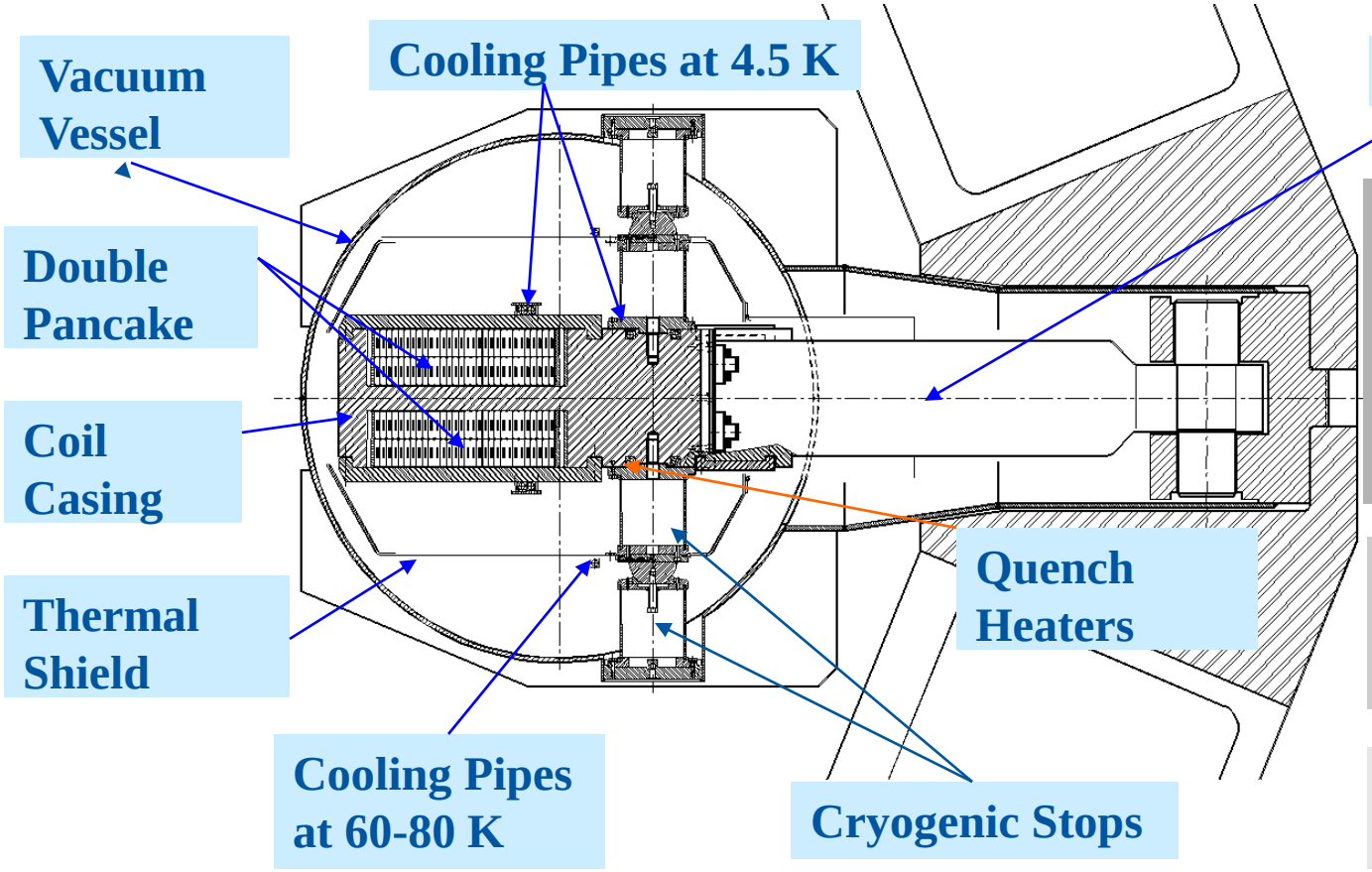
Back-up slides

ATLAS Barrel toroid cross section → Slow dump



When the current changes in the coil **eddy currents** are induced and the heat load of the cold mass increases

Slow dump is always preferred to fast dump

Slow dump is at constant dI/dt

Source: © Ruggero Pengo

ATLAS design & measured heat loads

Thermal loads at 4.5 K

	design		measured
		static	
Barrel toroid	660 W		510 W
Both End-Cap toroid	360 W		290 W
Central solenoid	50 W		17 W
Pump	650 W		670 W
infrastructure	450 W		215 W
Total	2170 W		1702 W
		dynamic	
Barrel toroid (2 hr)	350 W		360 W
Both End-Cap toroid (2 hr)	220 W	140 W	
Central solenoid (20 min)	20 W		25 W
Total	590 W		525 W

Liquefaction load (1.6 x 6 + 1.2) g/s = 10.8 g/s (design)
(1.85 x 6 + 1.2) g/s = 12.3 g/s (measured)

Source: © Giorgio Passardi

Operation of LHC detectors cryogenics

365 day operation
3 Technical Stops (~1 week) per year run for planned interventions
1 Year End Technical Stop for maintenance and improvements

- Detectors dedicated operation 2008 to 2016
  - Dedicated team of 5 CERN staff operators/team leader ensuring
    - ✓ Daily site operation
    - ✓ On-call service for outside of working hours interventions
  - back- up by 2nd line “Best Effort” support :
    - ✓ for operational or expert support in exceptional situation
    - ✓ for assistance of other support services (controls, electricity, maintenance…)
- LHC and its detectors common operation 2017 to 2019
  - Common team of 15 CERN staff operators/team leaders ensuring
    - ✓ Daily site operation
    - ✓ 24h Shift service from the Cern Central Control room for monitoring and 1st line interventions
  - 10 industrial support operators ensuring:
    - ✓ Daily operation
    - ✓ On-call service for outside of working hours 2nd line interventions
  - back- up by 2nd line “Best Effort” support

Helium losses 2012

	Nominal inventory (kg)	Strategic inventory (kg)	Total losses 2012 (kg)	Permament losses (kg)	Losses due to stops (kg)	Others
CMS	900	1200	-1600	330 (~27% of SI) (0.9 kg / day)	660 (~ 80 kg / stop)	610 (purges)
ATLAS	2600	3500	-3350	1095 (~30% of SI) (3 kg / day)	740 (~185 kg / stop)	1515 (purges + CP6 installation)

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