Cryogenic refrigeration for the LHC

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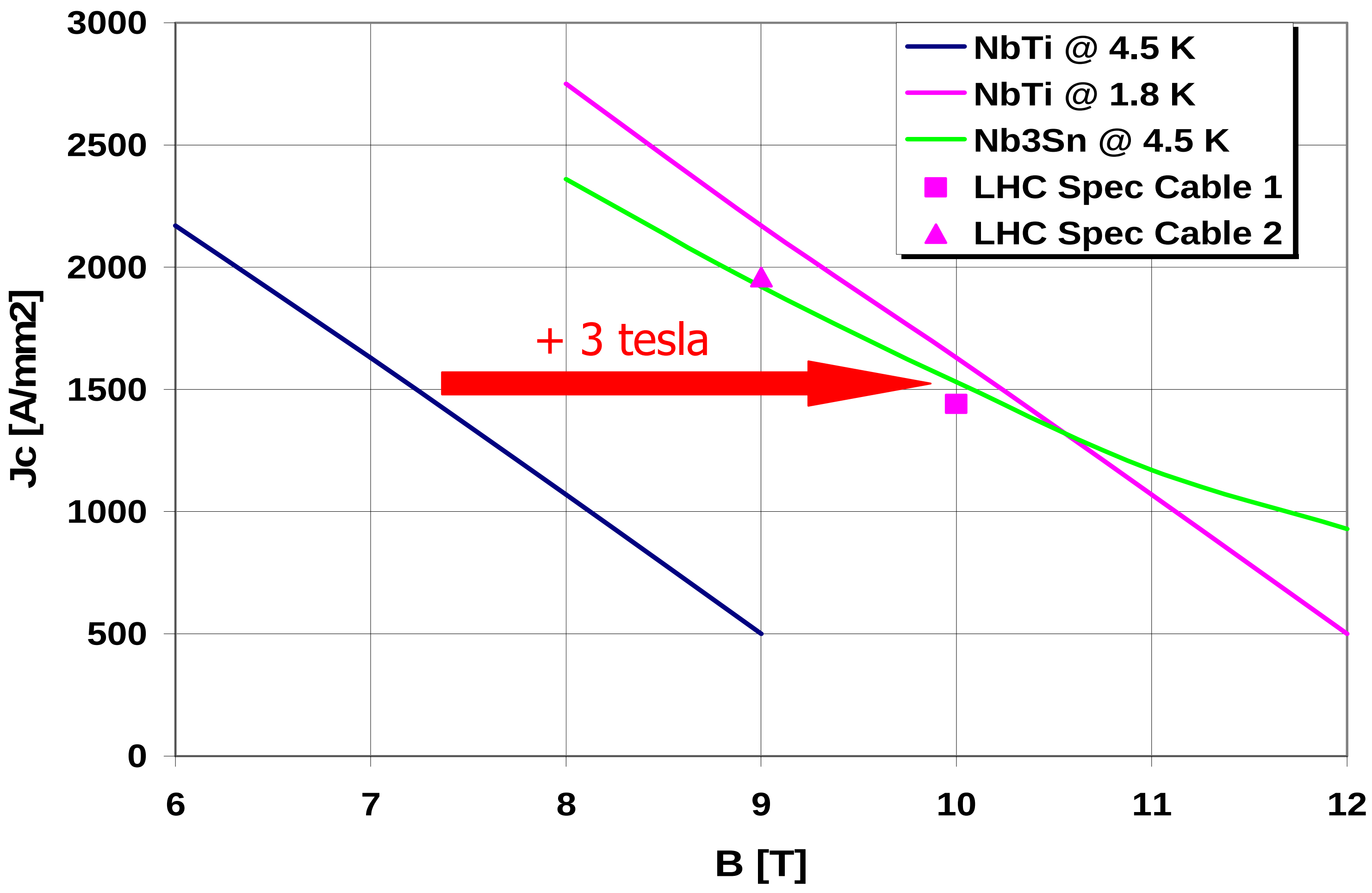
The largest scientific instrument in the world…

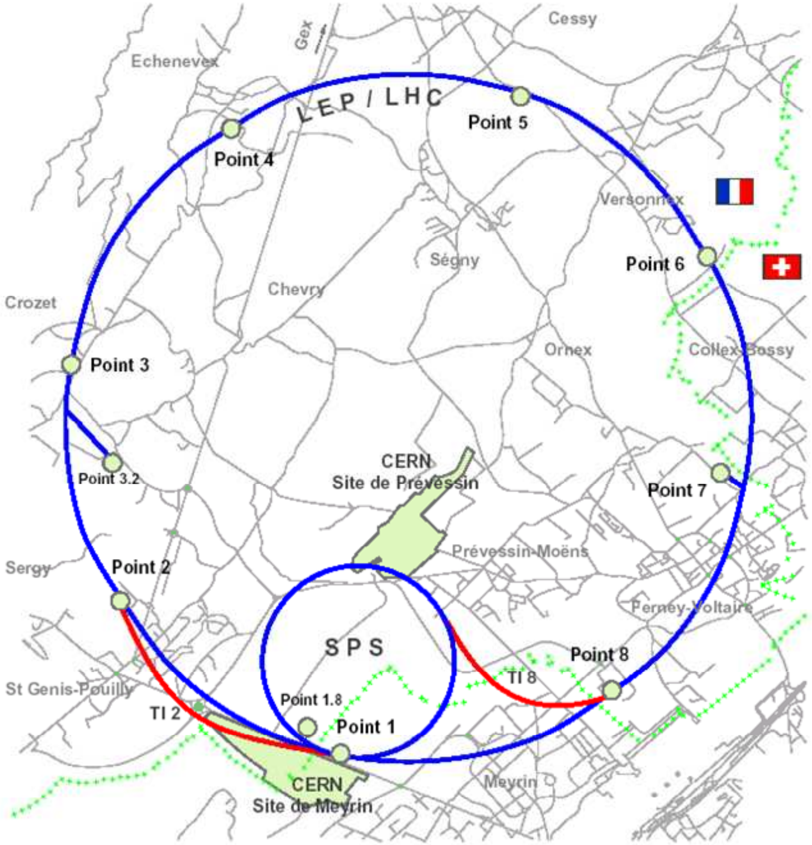
…based on advanced technology

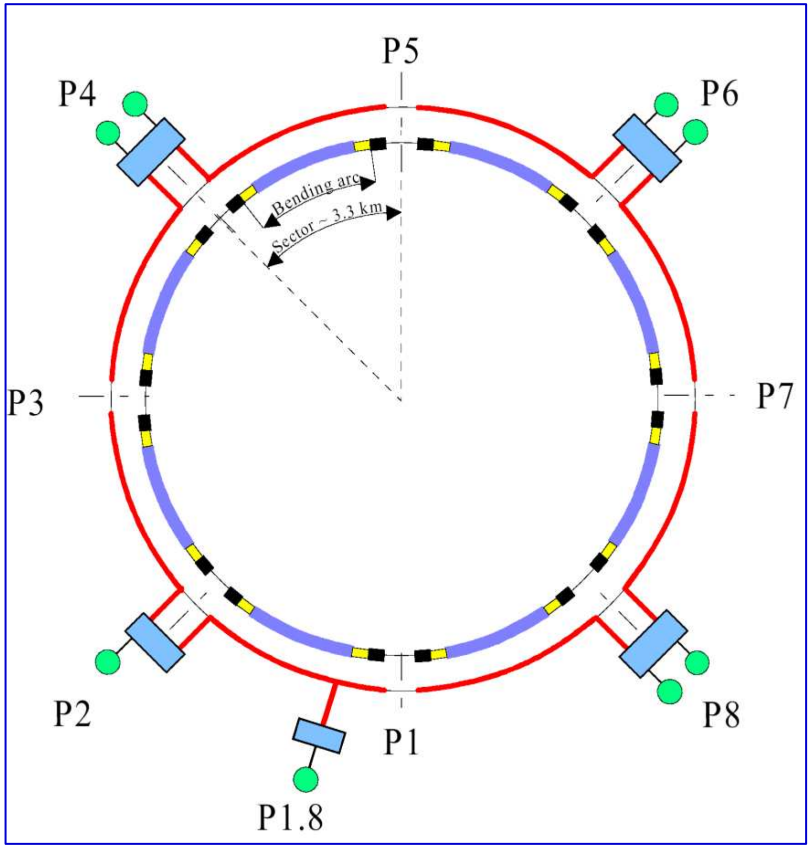
23 km of high-field superconducting magnets operating in superfluid helium at 1.9 K

Superconductors for high-field magnets



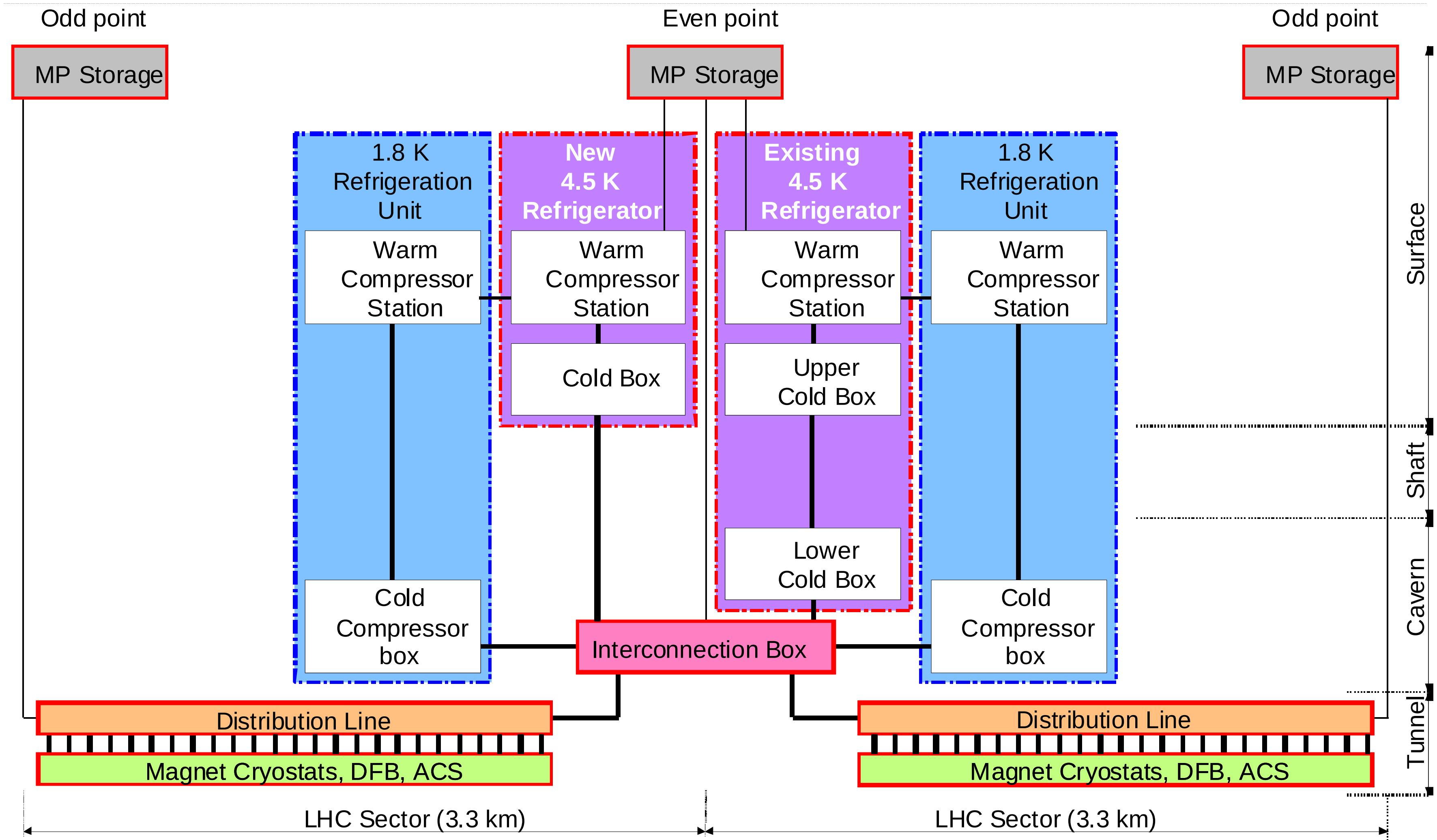
Cryogenic system layout





- 5 cryogenic islands
- 8 cryogenic plants, each serving adjacent sector, interconnected when possible
- Cryogenic distribution line feeding each sector

Configuration of cryogenics at LHC even point



Cryogenic plants

4.5 K refrigerators
(18 kW @ 4.5 K)

1.8 K refrigeration units
(2.4 kW @ 1.8 K)

Cryogenic storage and distribution

GHe storage

LIN storage

Vertical transfer line

Cryo-magnet string

Distribution line

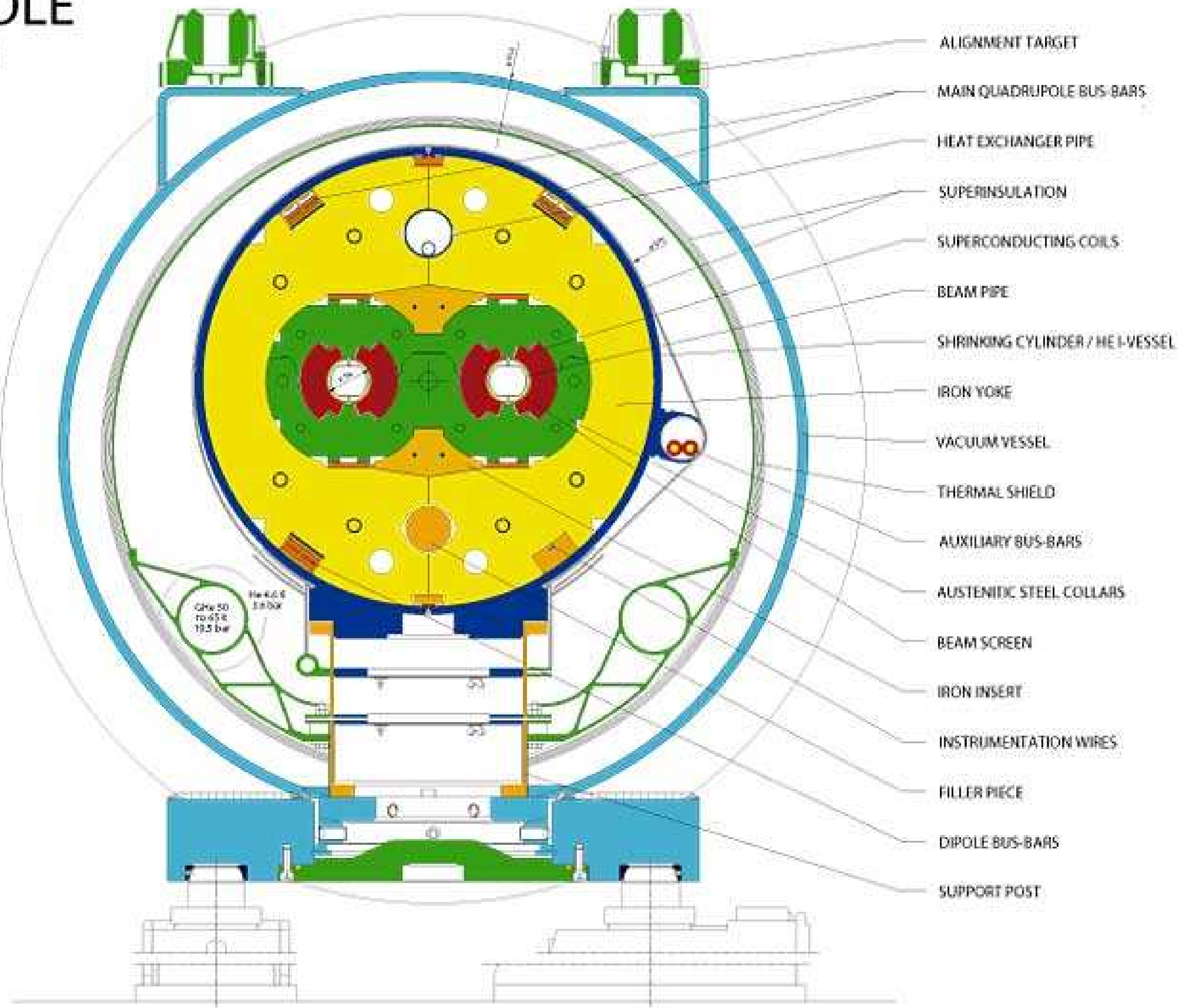
Interconnection box

Analysis & management of heat loads

Analysis	*Management*
• <u>Heat inleaks</u>	
– Radiation	70 K shield, MLI
– Residual gas conduction	Vacuum < 10^{-4} Pa
– Solid conduction	Non-metallic supports Heat intercepts
• <u>Joule heating</u>	
– Superconductor splices	Resistance < a few nΩ
• <u>Beam-induced heating</u>	
– Synchrotron radiation	}
– Beam image currents	} 5-20 K beam screens
– Acceleration of photoelectrons	}
– Beam halo	absorbed in cold mass

LHC DIPOLE

CROSS SECTION



Steady-state heat loads [W/m]
(Cryomagnets and distribution line in LHC arcs)

Temperature	50-75 K	4.6-20 K	1.9 K LHe	4 K VLP
Heat inleaks*	7.7	0.23	0.21	0.11
Resistive heating	0.02	0.005	0.10	0
Beam-induced nominal**	0	1.58	0.09	0
Beam-induced ultimate**	0	4.36	0.11	0
Total nominal	7.7	1.82	0.40	0.11
Total ultimate	7.7	4.60	0.42	0.11

* no contingency

** Breakdown	nominal	ultimate
Synchrotron radiation	0.33	0.50
Image current	0.36	0.82
Beam-gas Scattering	0.05	0.05
Photoelectron	0.89	3.07

Scaling laws for LHC dynamic loads

Beam parameter	Energy E	Bunch current I_{bunch}	Bunch number n_{bunch}	Bunch length σ_z [r.m.s.]	Luminosity L
Resistive heating	E^2	-	-	-	-
Synchrotron radiation	E^4	I_{bunch}	n_{bunch}	-	-
Image current	-	I_{bunch}^2	n_{bunch}	$\sigma_z^{-3/2}$	-
Photo-electron cloud	-	I_{bunch}^3	n_{bunch}	-	-
Beam gas scattering	-	I_{bunch}	n_{bunch}	-	-
Random particle loss		I_{bunch}	n_{bunch}		
Secondaries	E	-	-	-	L
RF losses	-	I_{bunch}^2	n_{bunch}	-	-

Uncertainty & overcapacity factors

- Uncertainty factor F_{in}
  - Lack of reproducibility in construction (e.g. MLI wraps)
  - Variance of thermal processes at work (e.g. insulation vacuum)
  - Evolution in time (ageing, contamination of reflective surfaces)

  ⇒ *applied to static loads only, dynamic loads and their scaling known from first principles*
- Overcapacity factor F_{oc}
  - Cooldown in finite time
  - Refrigerator loading < 100 %
  - Variability of machine performance

  ⇒ *applied to sum of static load with uncertainty and dynamic load*

  ⇒ *no overcapacity applied to ultimate conditions*

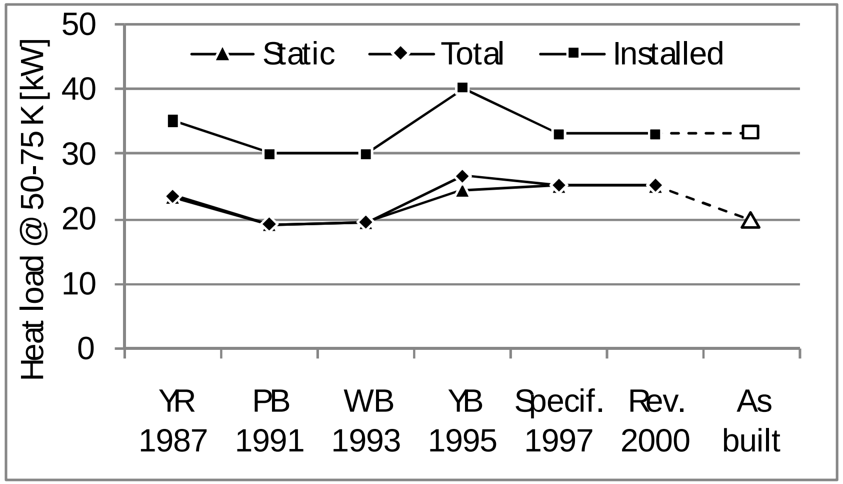
Overall factor on installed refrigeration

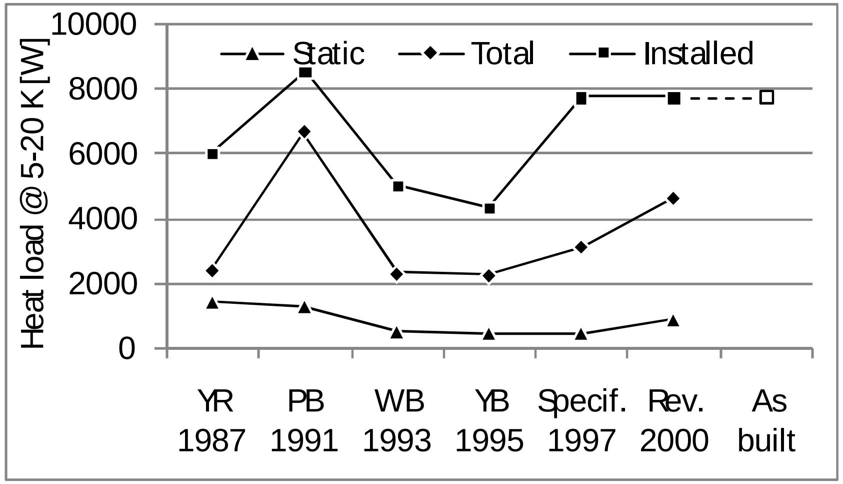
- Installed refrigeration power

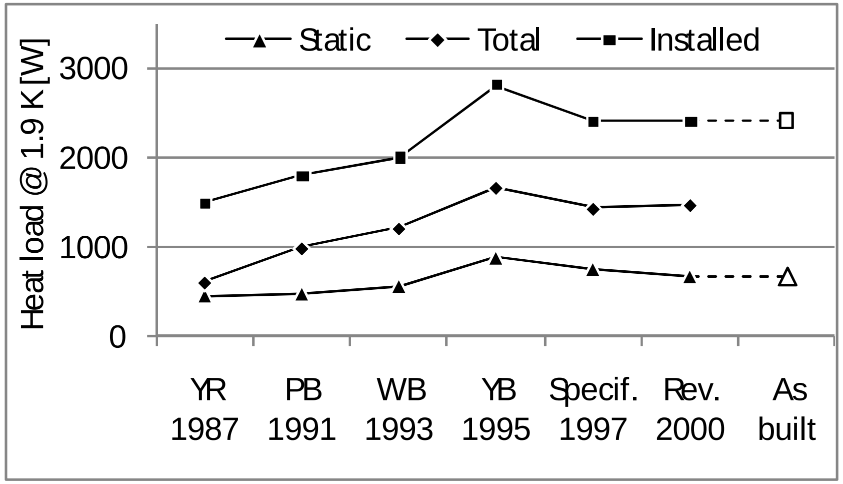
$$Q_{installed} = \mathrm{Max}\ [F_{oc}\,(F_{in}\,Q_{stat} + Q_{dyn\ nom});\ (F_{in}\,Q_{stat} + Q_{dyn\ ult})]$$

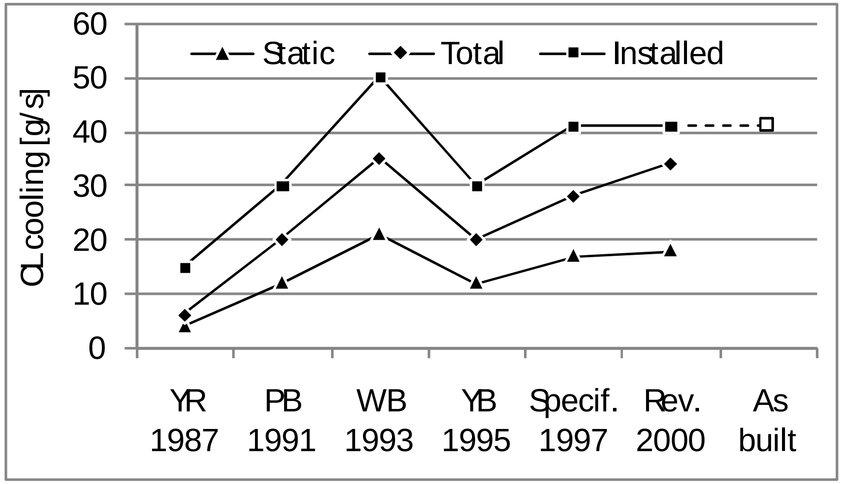
- Values of uncertainty & overcapacity factors
  - F_{in} = 1,5 at beginning of project
  - F_{oc} = 1,5
  - F_{in} gradually lowered following refinement of project configuration and improved knowledge of component thermal performance

Evolution of estimated heat loads & installed refrigeration capacity per LHC sector





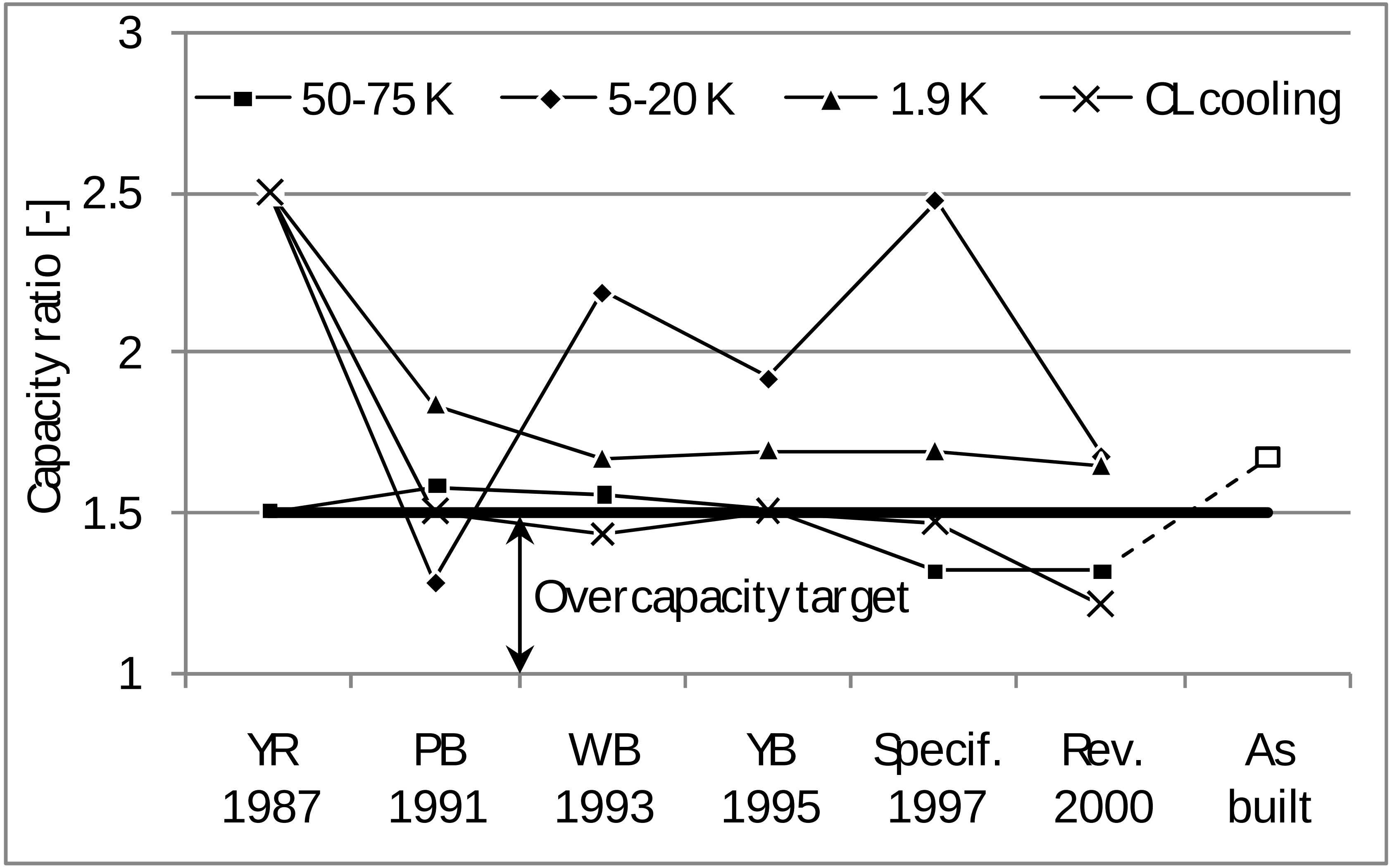




Installed cooling duties in the LHC sectors

Temperature level	High-load sector	Low-load sector	
50-75 K	33000	31000	[W]
4.6-20 K	7700	7600	[W]
4.5 K	300	150	[W]
1.8 K	2400	2100	[W]
3-4 K	430	380	[W]
20-280 K	41	27	[g/s]

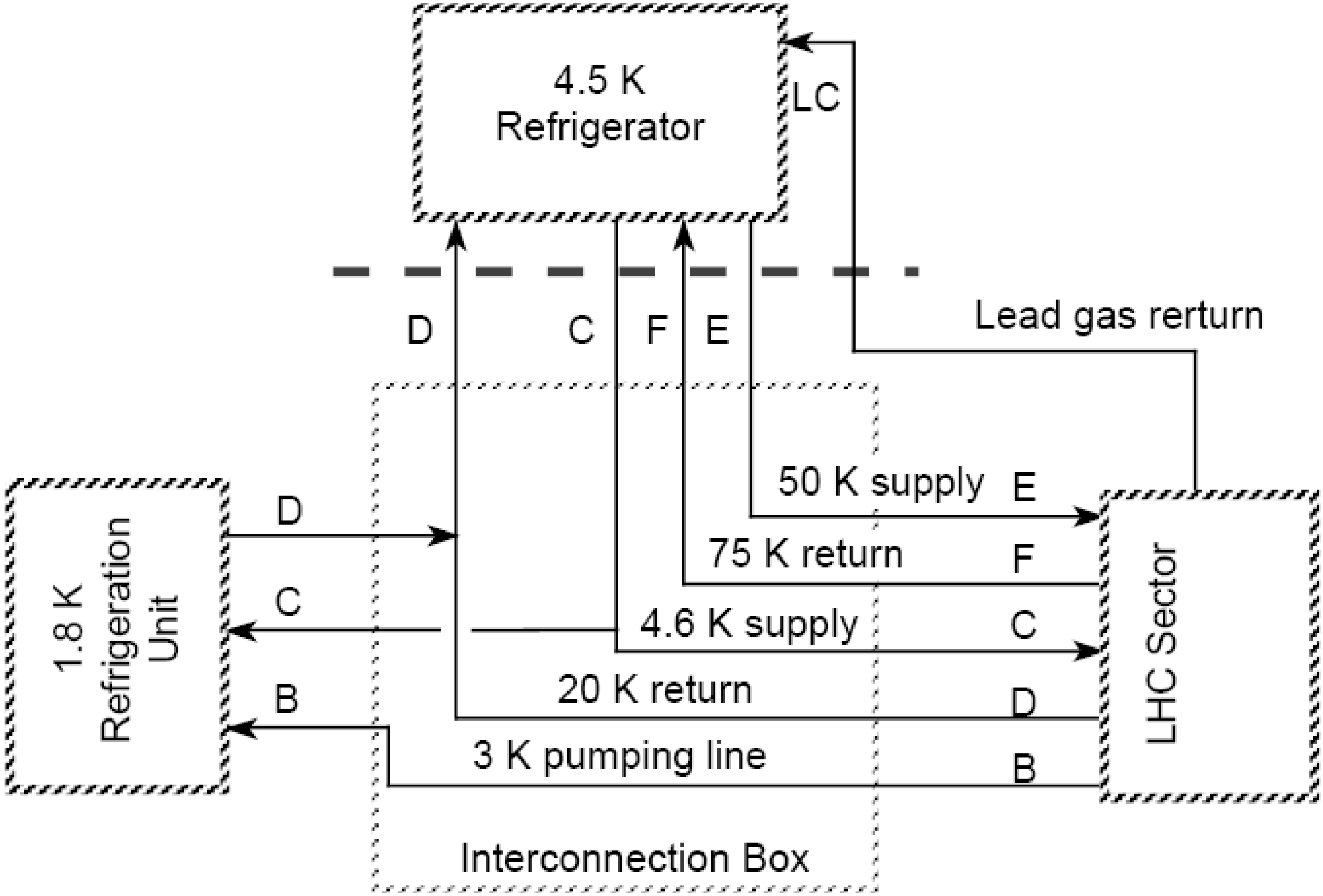
Evolution of installed power to heat load ratio



Procurement from industry

- European industry (Air Liquide & Linde Kryotechnik) had demonstrated their competency and know-how in manufacturing turnkey helium refrigerators of medium or large capacity
  - HERA (10 kW)
  - LEP2 (6 kW, 12 kW)
- Most efficient approach was therefore to procure via a functional and interface specification
  - Transform sector cooling requirements into refrigeration duties which can be reception-tested at cryoplant interface
  - Clearly define interfaces to cryogenic and other systems
  - Promote energy-efficient solutions
- Oligopolistic nature of market & desire to balance industrial returns among Member States led to split procurement under constraints
  - Align prices to satisfy CERN lowest-bidder purchasing rule
  - Impose convergence of non- or less-proprietary part of supply, i.e. compressor station and control system

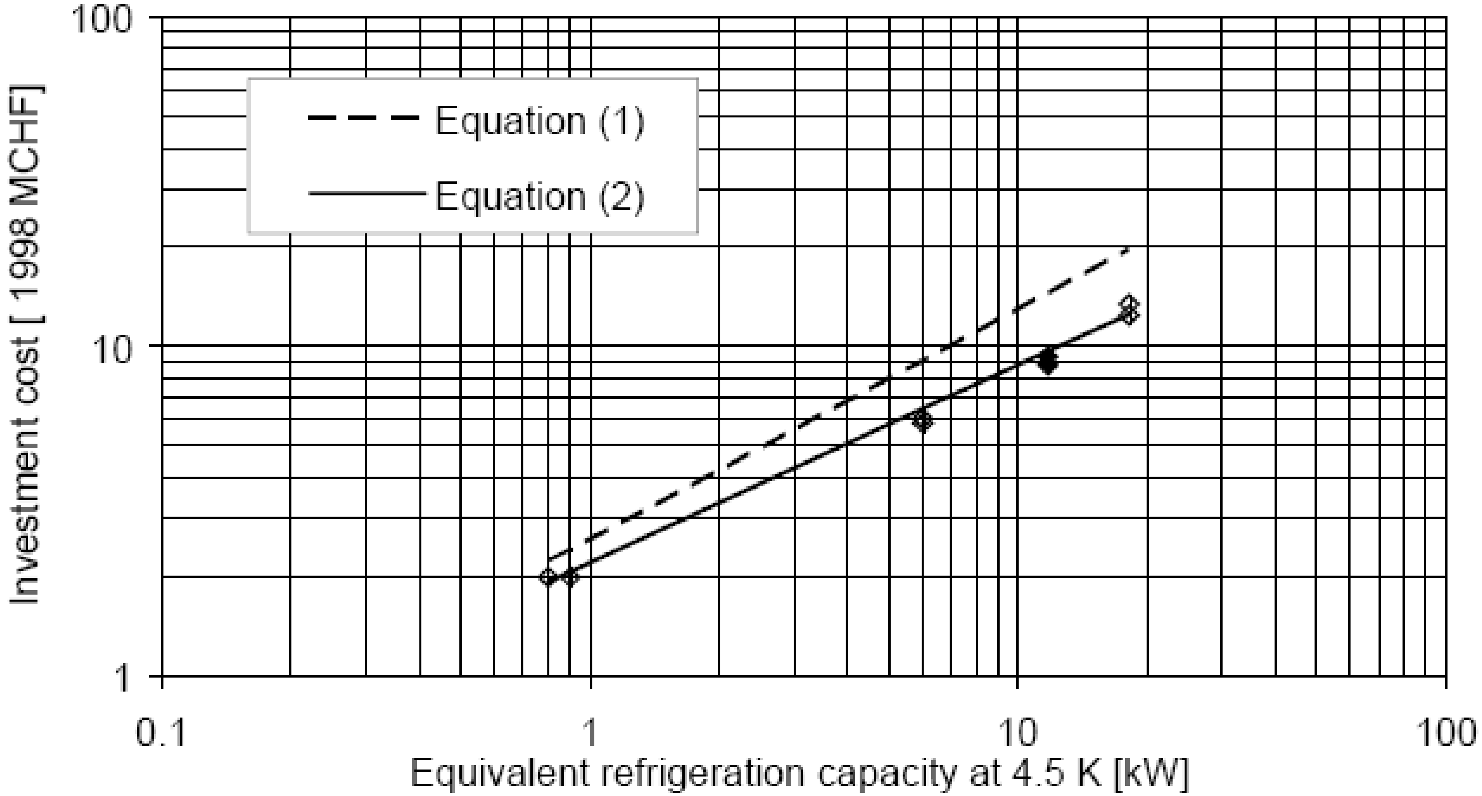
Conversion of cooling duties from LHC sector to 4.5 K refrigerator



Specified refrigeration capacity for the LHC 4.5 K refrigerators

Temperature level	Unit	New refrigerator	Upgraded refrigerator
50-75 K	[W]	33000	31000
4.5-20 K	[W]	20700	19500
4.5 K	[W]	4400	4150
20-280 K	[g/s]	41	27

Scaling laws for cost of cryogenic He refrigerators
(single cold box, no LIN precooling, controls excluded)



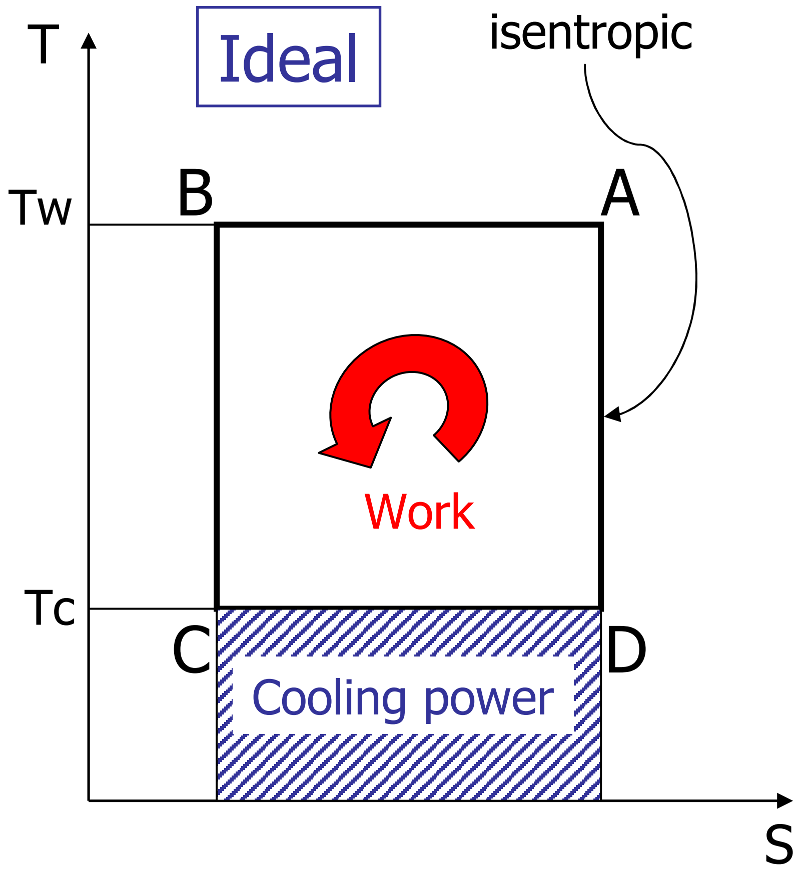
$$\text{Cost[1998 MCHF]} = 2.6 * (\text{Capacity[kW@4.5K]})^{0.7} \quad (1)$$

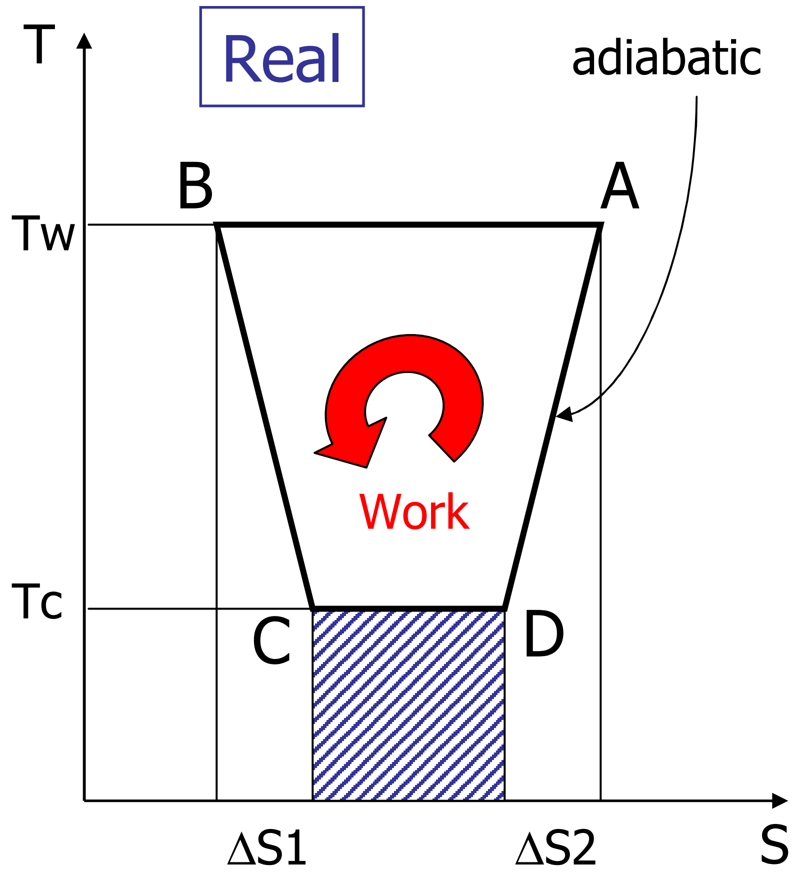
$$\text{Cost[1998 MCHF]} = 2.2 * (\text{Capacity[kW@4.5K]})^{0.6} \quad (2)$$

How to specify an efficient He refrigerator

- Include capital & operating costs over amortization period *(10 years)* in adjudication formula
- Operating costs dominated by *electricity*
- Include externalities in electricity costs *=> 60 CHF/MWh*
  - distribution & transformation on CERN site
  - heat rejection in aero-refrigerants
- Establish shared incentive in the form of *bonus/malus* on measured vs. quoted electrical consumption
- Break *"high efficiency = high investment" pseudo-rule:* for given (specified) output, a more efficient plant is smaller, resulting in lower investment (direct & indirect) as well as cheaper operation

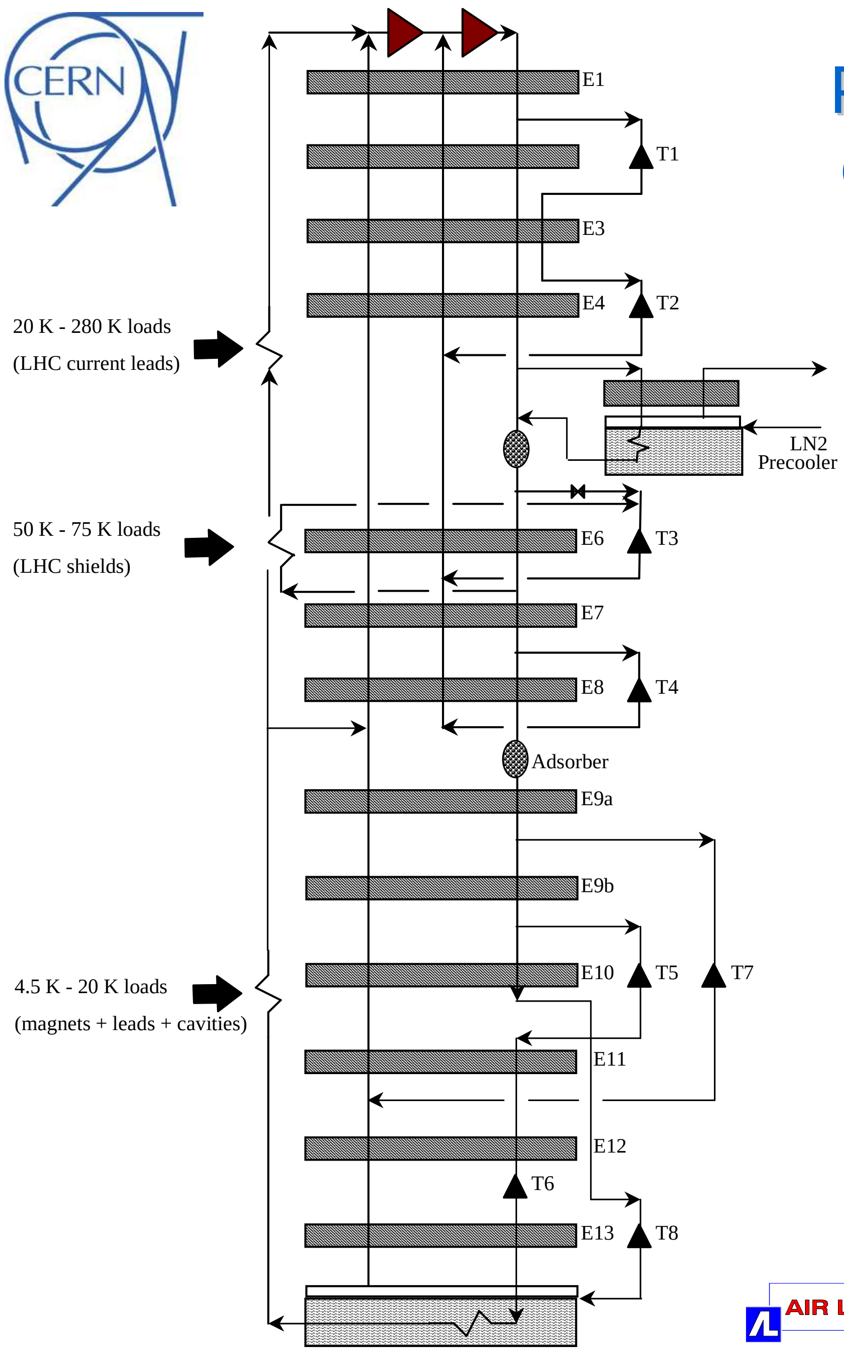
How to make an efficient refrigerator
(exemplified on Carnot cycle schematic)

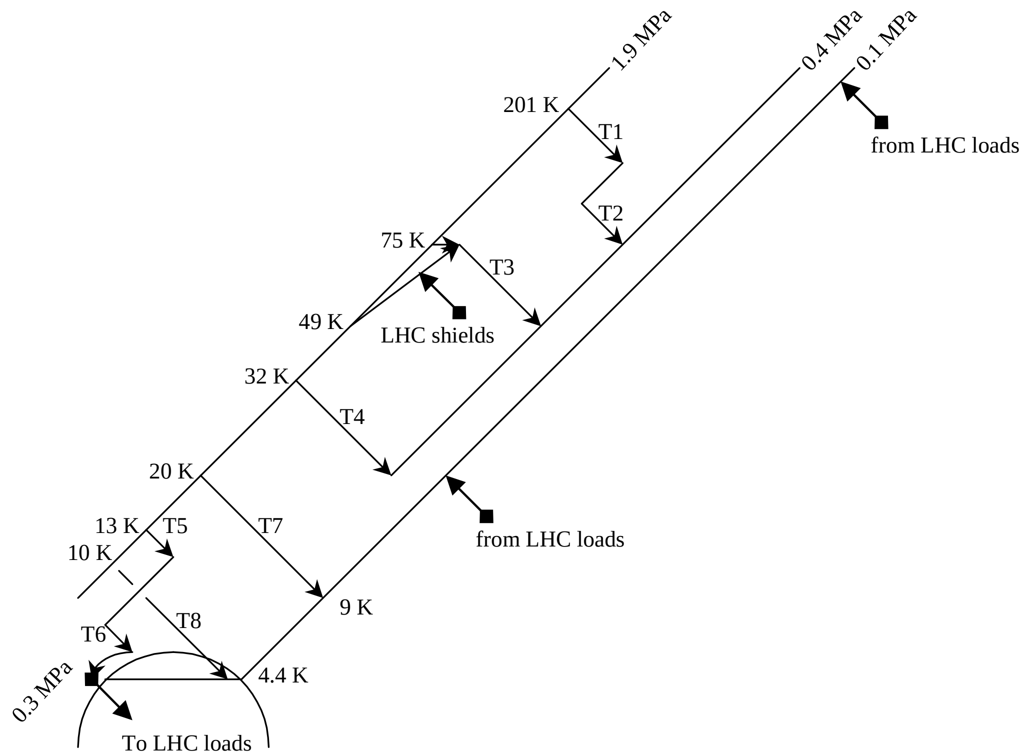




Widen the low-temperature end of the cycle as shown in the T-S diagram

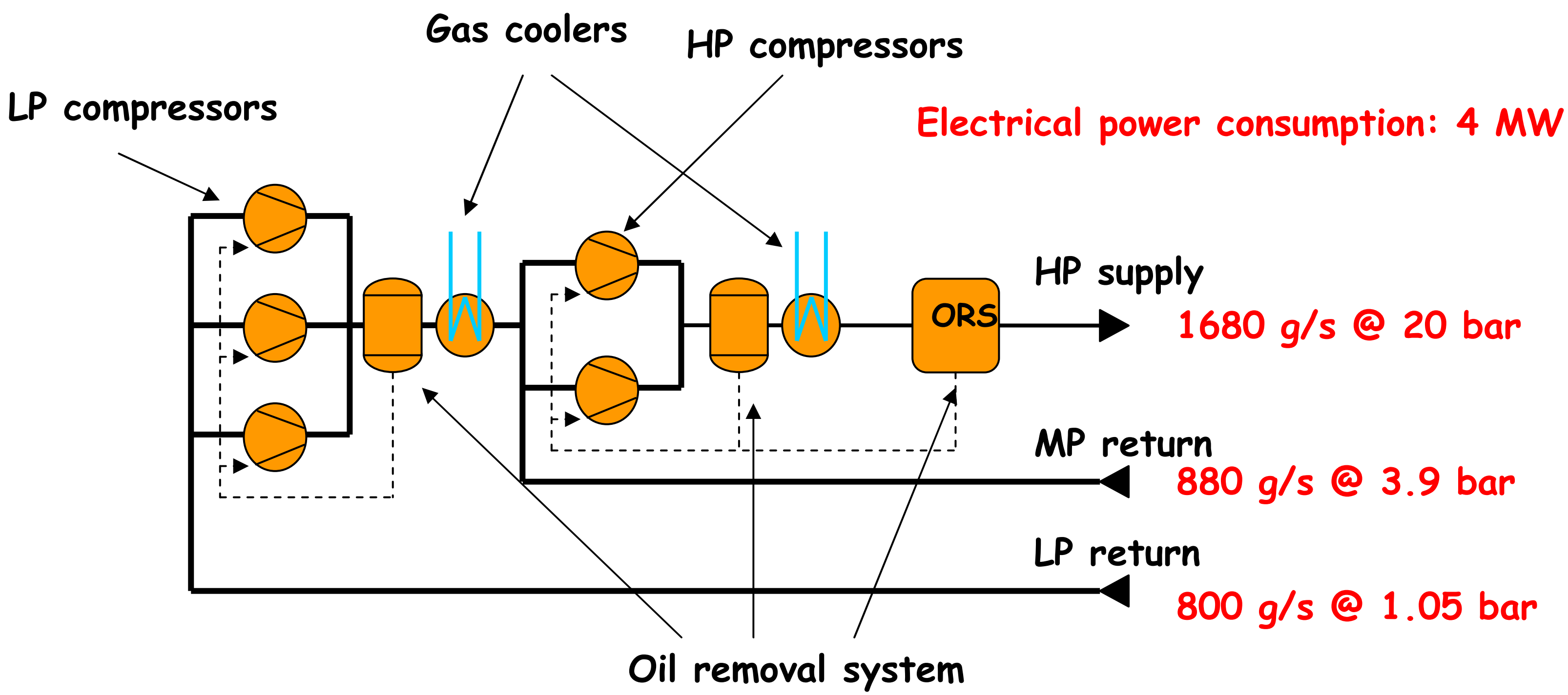
Process cycle & T-S diagram of 18 kW @ 4.5 K cryoplant





AIR LIQUIDE

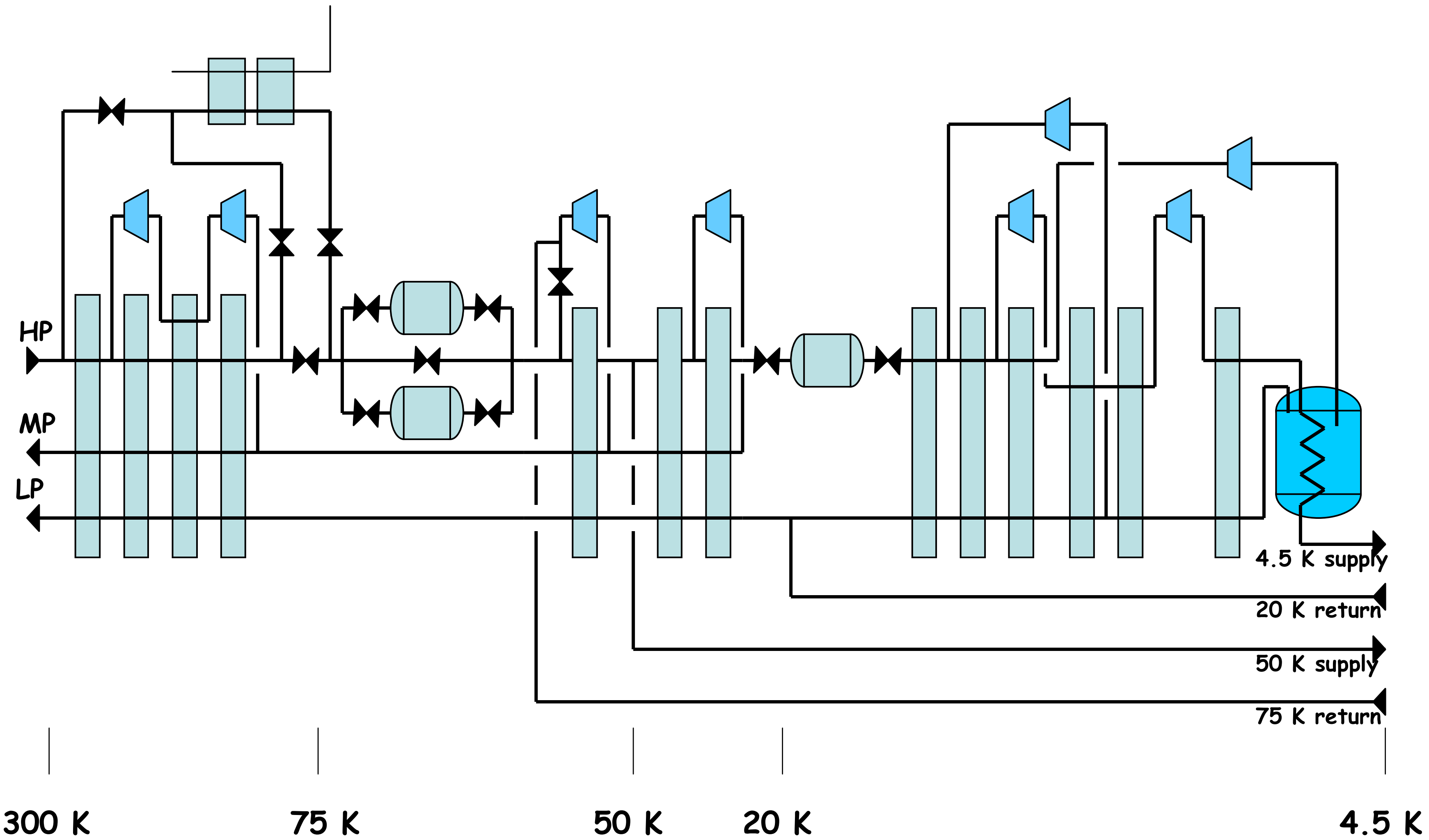
Compressor station of 4.5 K refrigerator



Identical installation for both suppliers

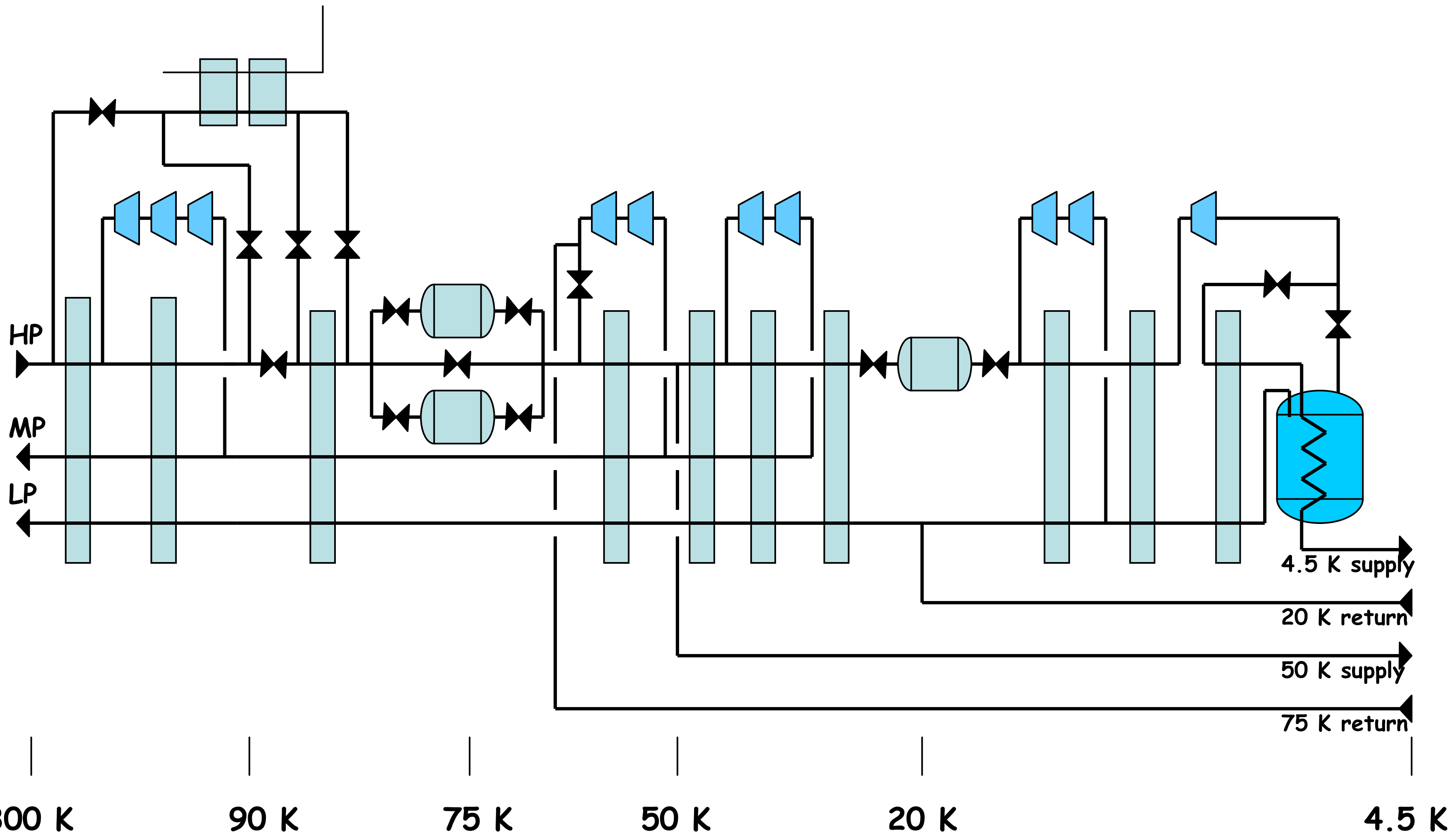
Compressor station of 4.5 K refrigerator
(Power input ~ 4 MW)

Cold box of Air Liquide 4.5 K refrigerator



Cold box of Air Liquide 4.5 K refrigerator

Cold box of Linde 4.5 K refrigerator

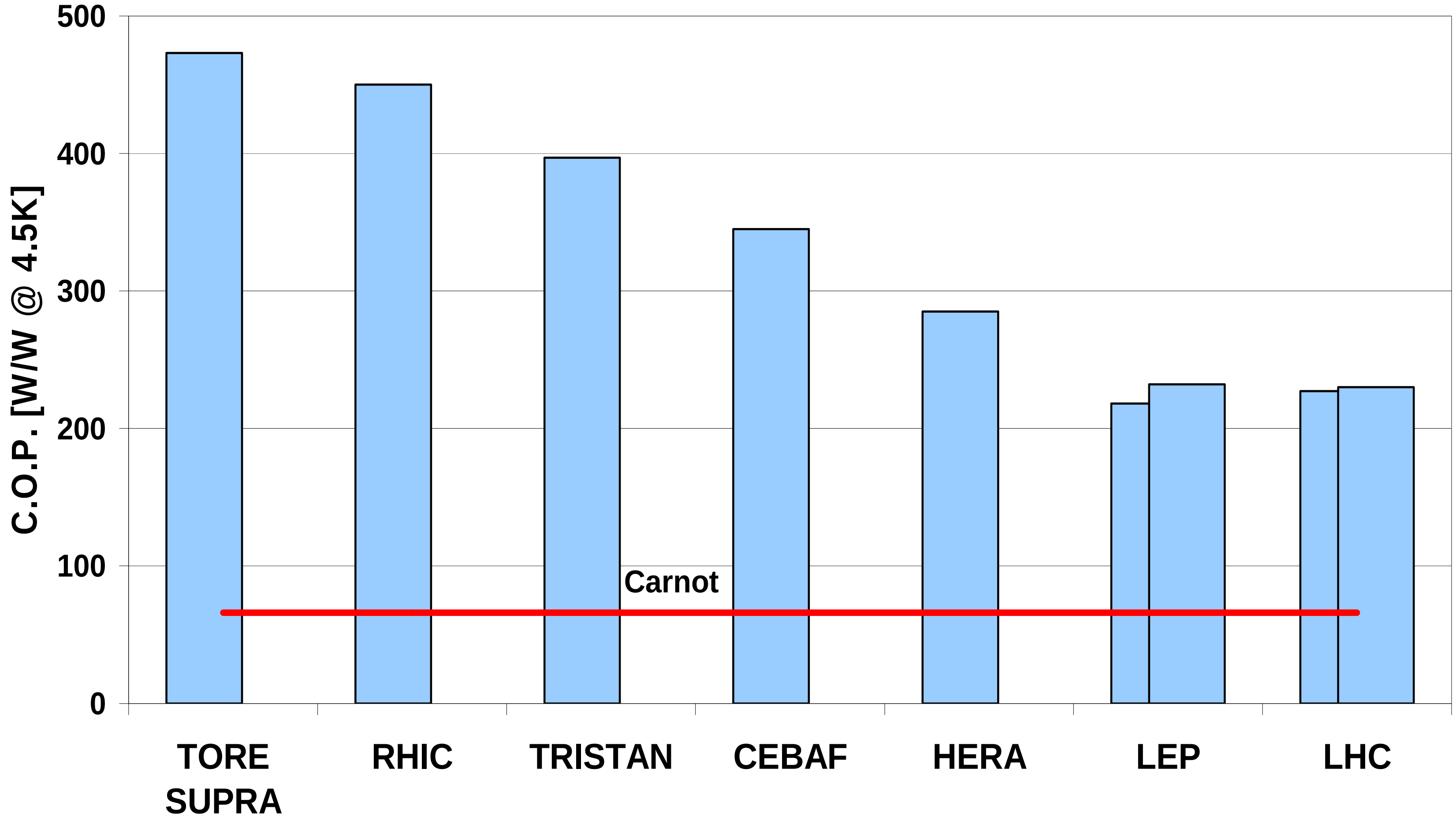


Cold box of Linde 4.5 K refrigerator

Guaranteed vs measured performance of the new LHC 4.5 K refrigerators

LHC location	PA18	PA4	PA6	PA8
Supplier	Air Liquide	Air Liquide	Linde	Linde
Guaranteed energy consumption [kW]	4204	4204	4275	4275
Measured energy consumption [kW]	4297	4474	3964	4095
Measured cryogenic capacity [% of specified]	97.3	101.5	100.1	99.3
COP [W/W]	248	247	222	231

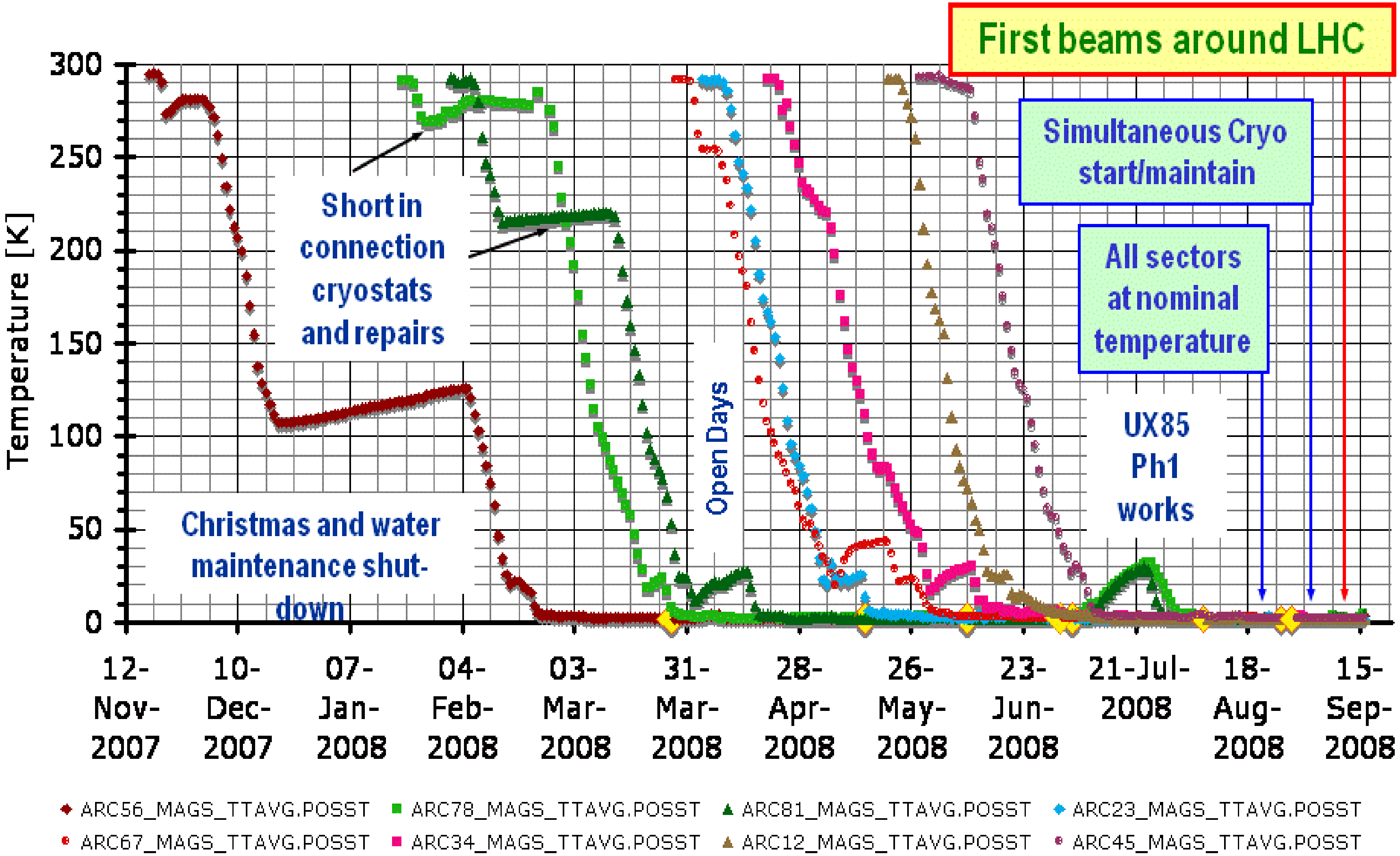
C.O.P. of large cryogenic helium refrigerators



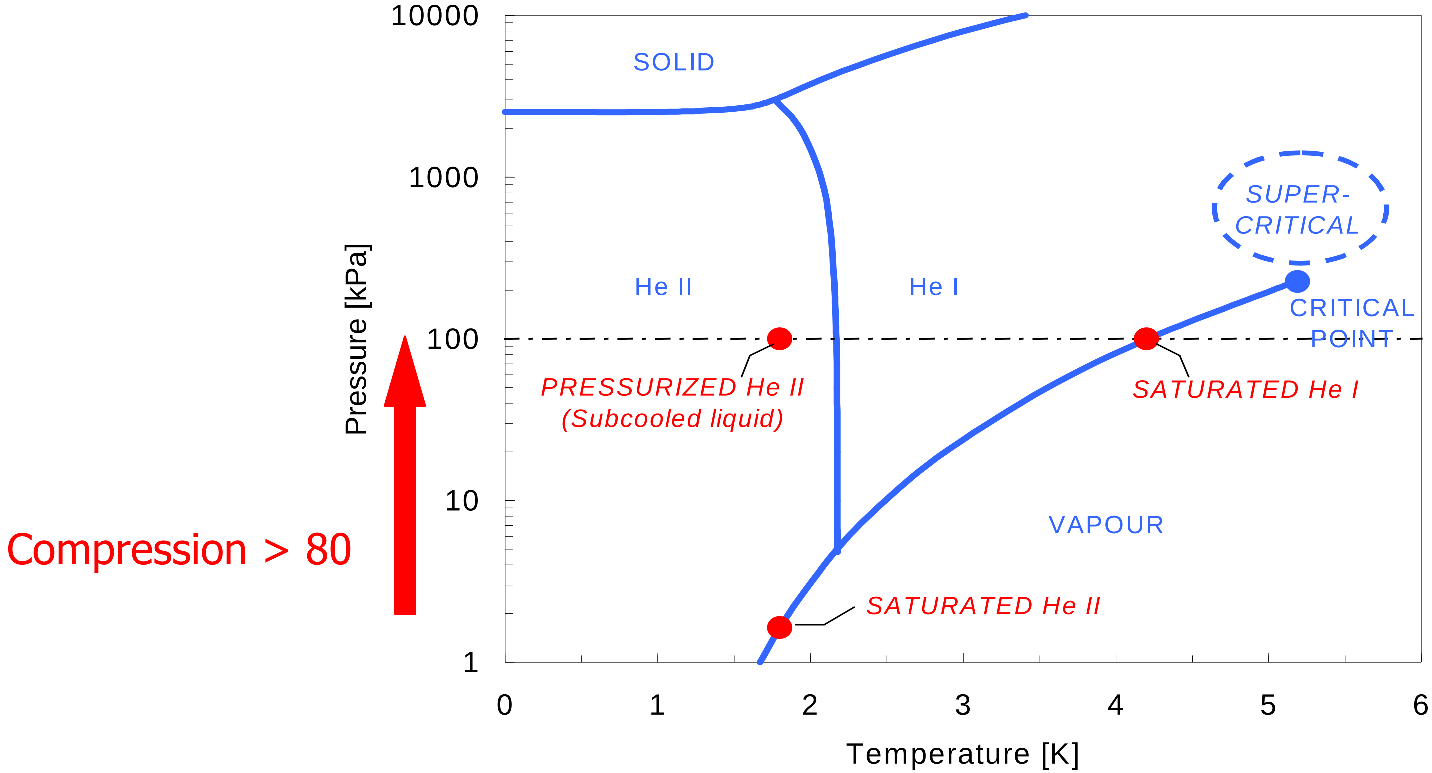
Liquid nitrogen precooling

- Each 3.3 km sector has a mass of 4625 t to be cooled in few weeks
- Corresponding power 600 kW, must be generated by vaporization of 1250 t LIN at rates of up to 5 t/h
- LIN precooling not foreseen for steady-state operation, but may also be used to boost helium liquefaction

First cooldown of LHC sectors



Challenges of power refrigeration < 2 K

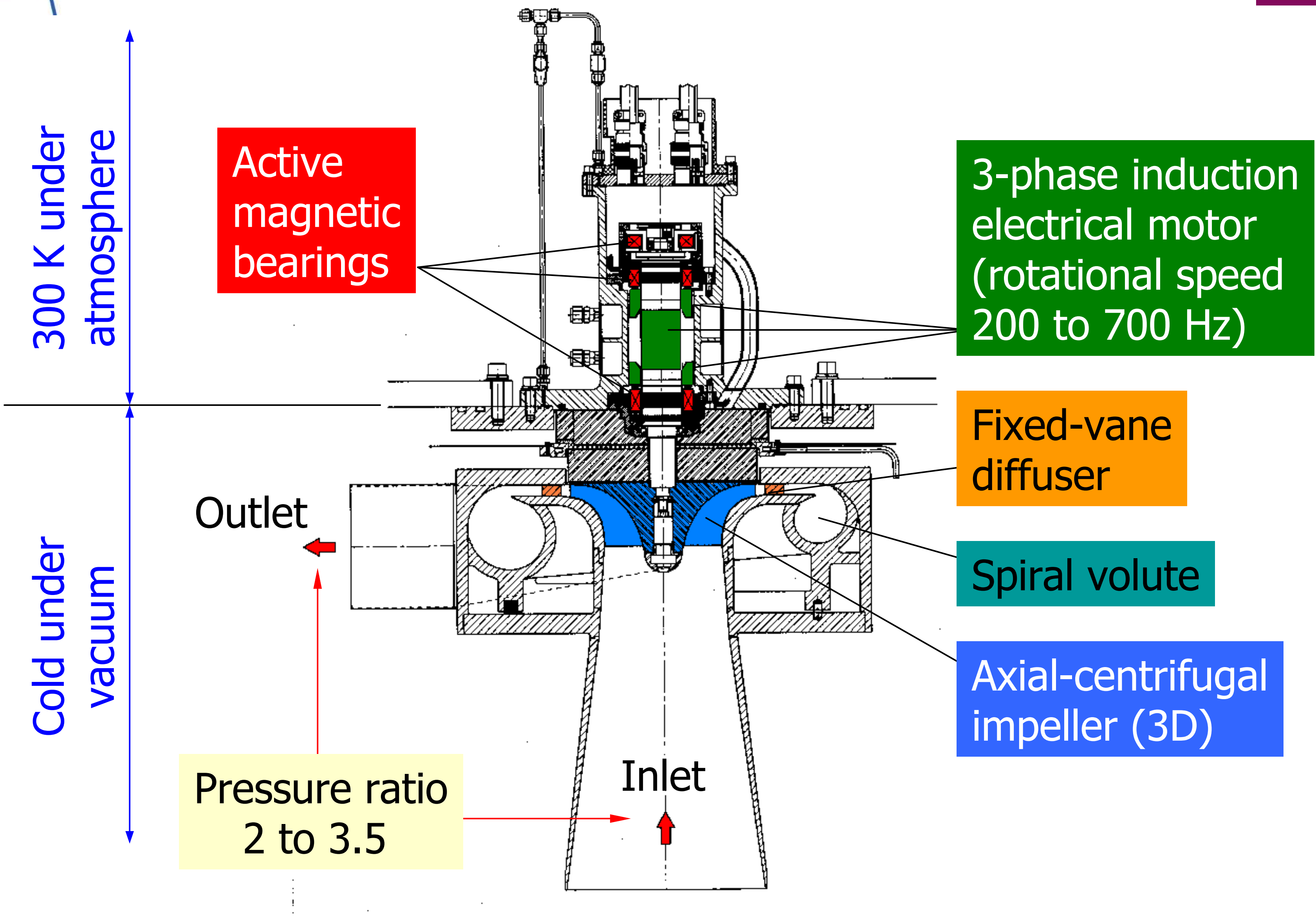


- Compress large mass-flow rate of gaseous helium across high pressure ratio

⇒ maximum density at suction, i.e. cold

- Non-lubricated, contact-less machinery *⇒ hydrodynamic compressor, multistage*
- Heat of compression rejected at low temperature *⇒ high thermodynamic efficiency*

Main Features of LHC Cold Compressors

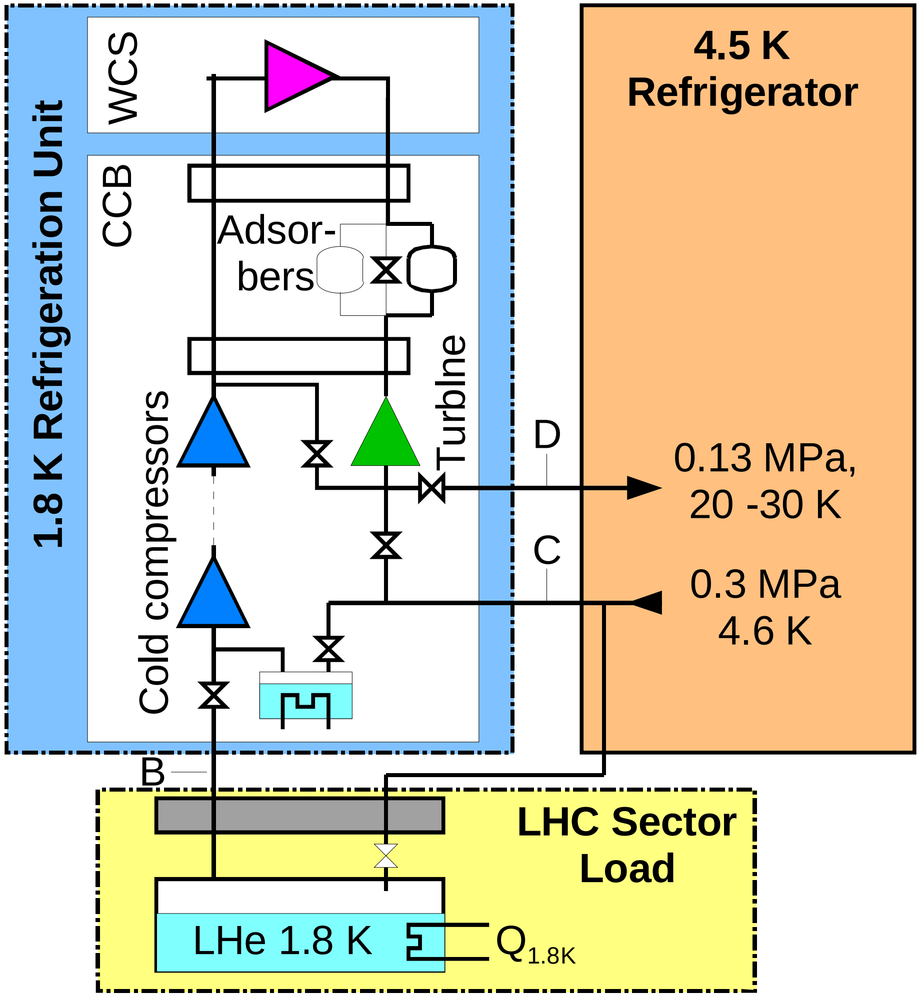


Cold hydrodynamic compressors for the LHC

IHI-Linde

Air Liquide

Specification of LHC 1.8 K refrigeration units

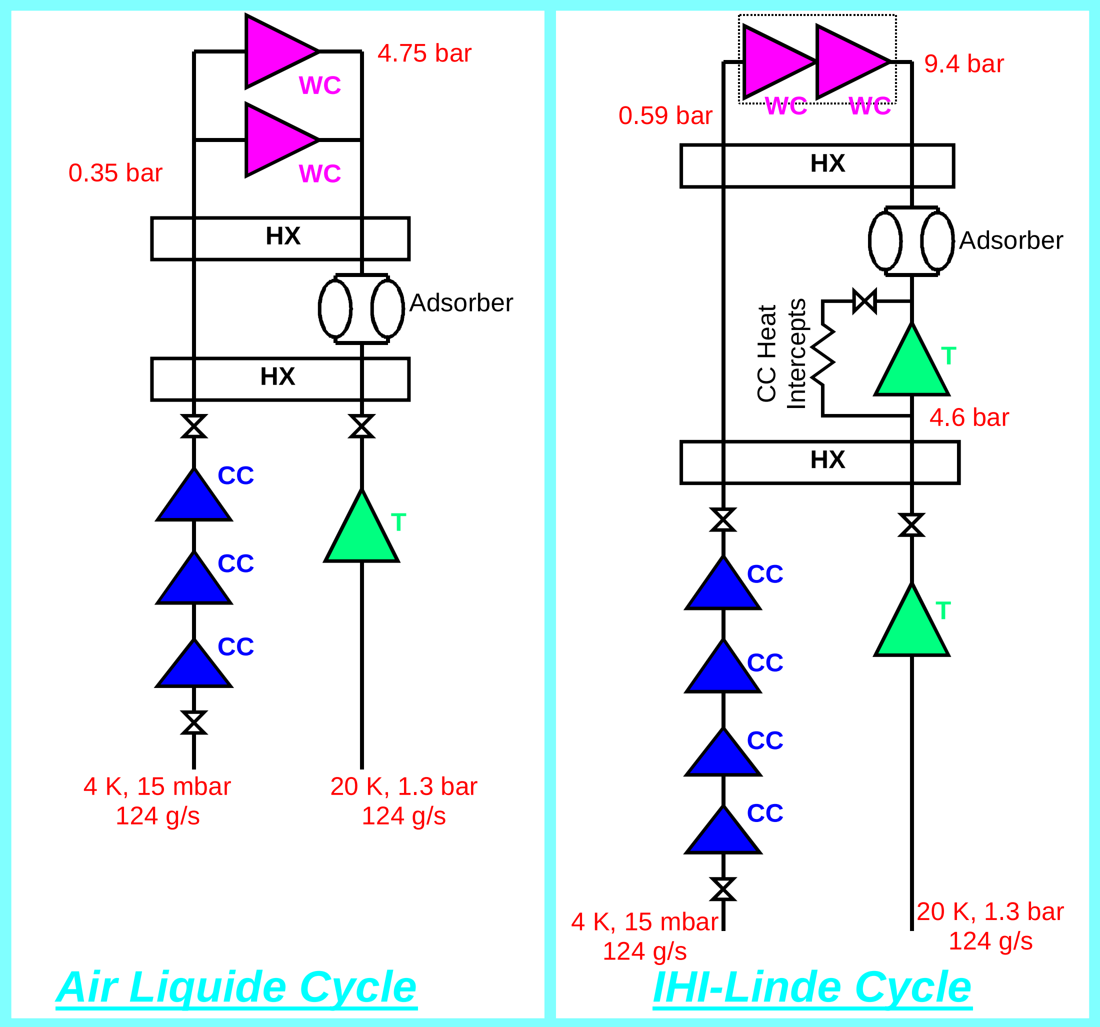


Steady state operation modes:

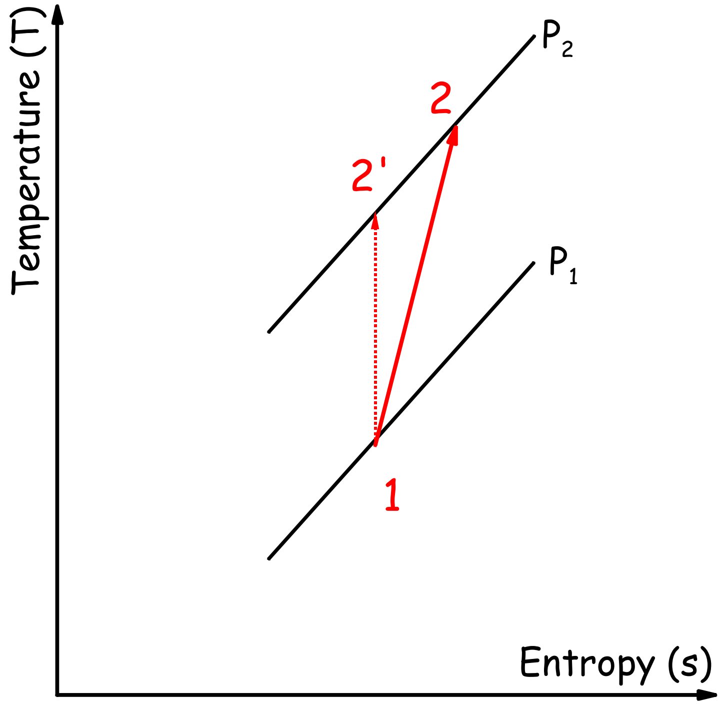
- Installed pumping capacity 125 g/s at 15 mbar (i.e. ~2.4 kW @ 1.8 K)
- Turndown capability: 1 to 3 without extra liquid burning
- Cold return temperature to the 4.5 K refrigerator below 30 K (reduced capacity) to 20 K (installed capacity).
- Capacity check in standalone mode (Interface B closed)

1.8 K refrigeration cycles for the LHC

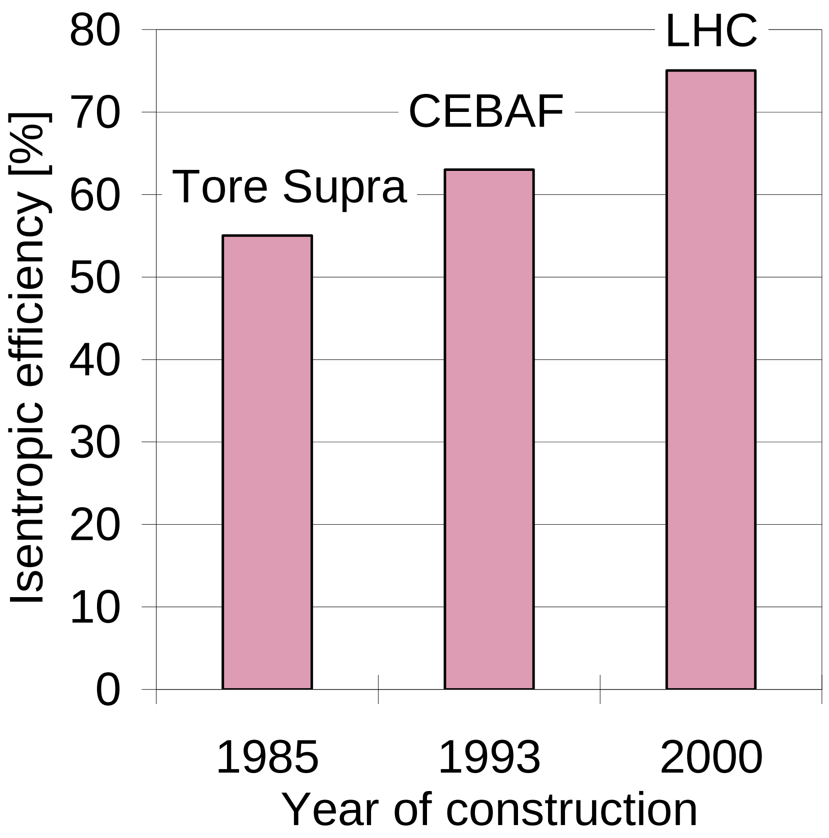
1.8 K Refrigeration Unit Cycles



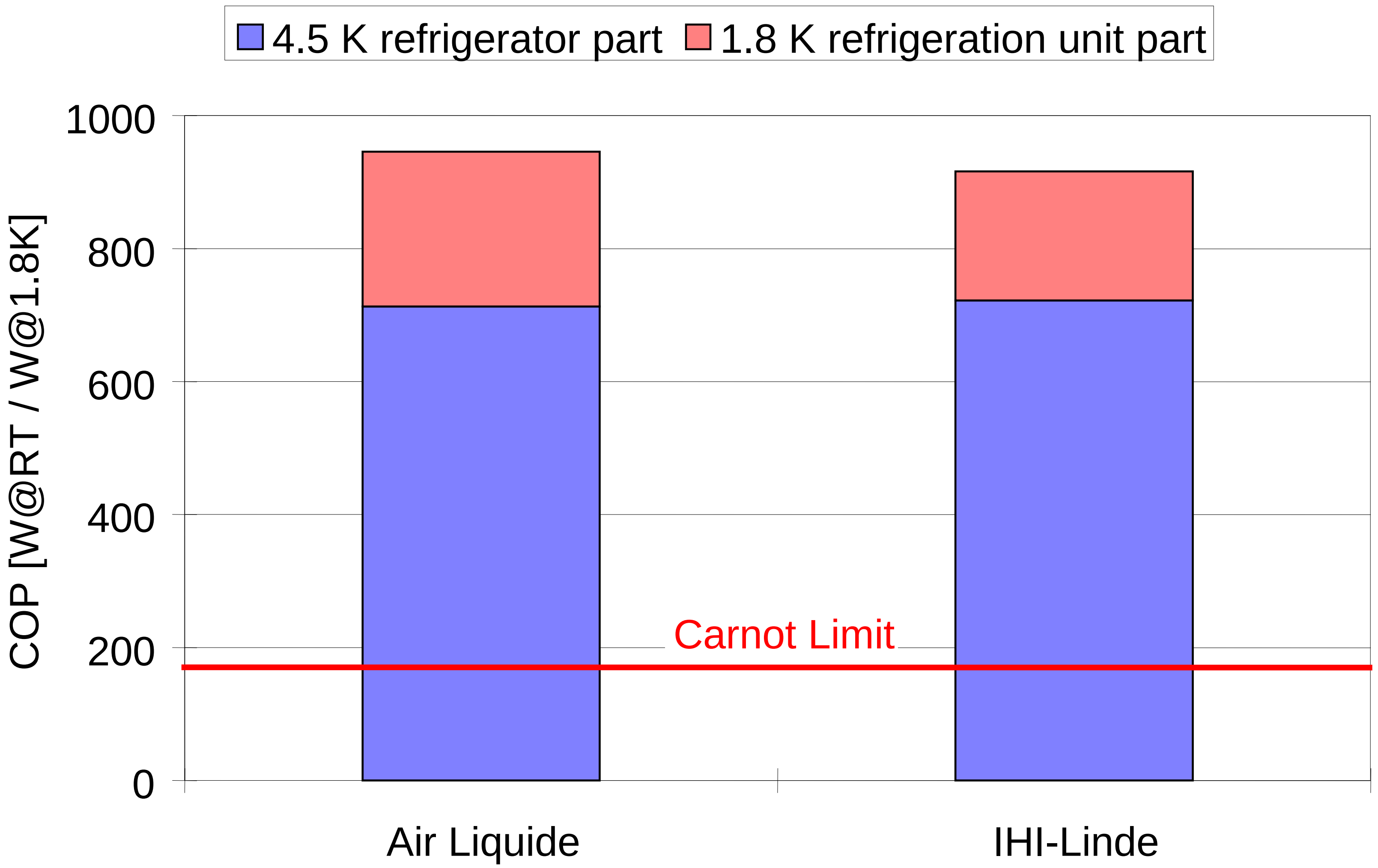
Isentropic efficiency of cold compressors



$$\eta_{is} = \frac{H_{2'} - H_1}{H_2 - H_1}$$



C.O.P. of LHC 1.8 K refrigeration units



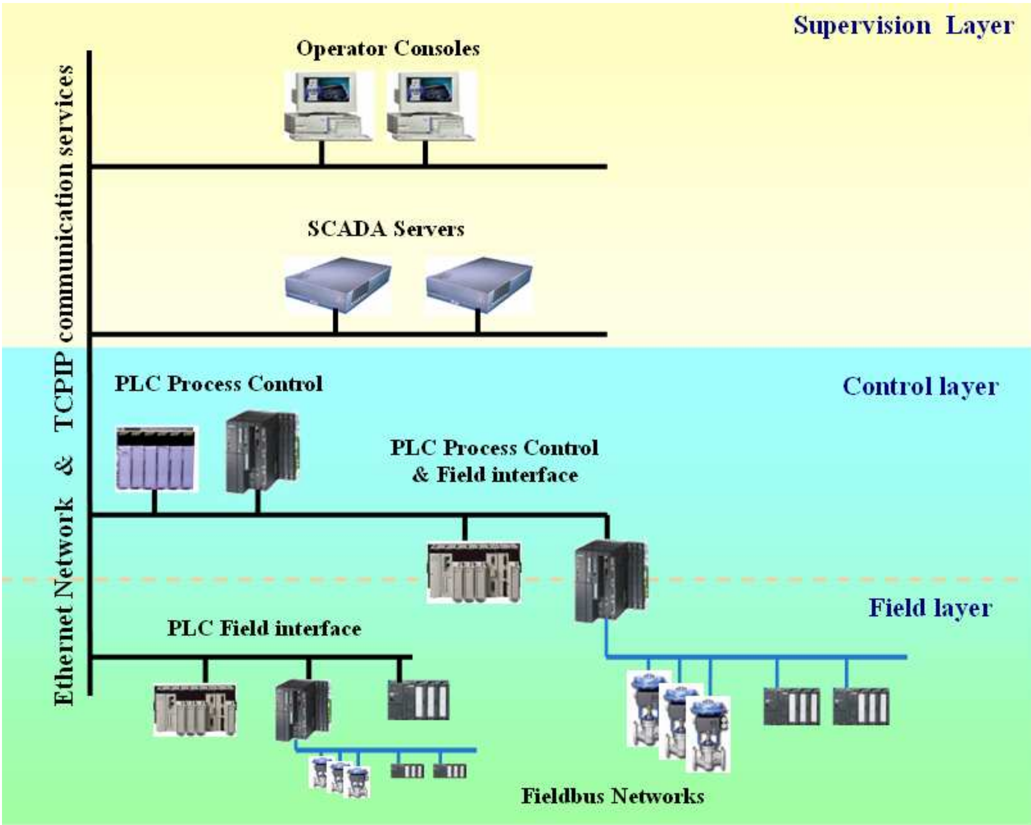
Controls for LHC cryogenics
Challenges & solutions

	Tunnel	4.5 K refrigerators	1.8 K units	QUI	Common	TOTAL
Analog Inputs	12136	5216	2640	1128	216	21336
Analog Outputs	4856	1140	608	292	112	7008
Digital Inputs	4536	8100	3984	1144	592	18356
Digital Outputs	1568	956	1184	232	272	4212
Closed Loop Controllers	3680	548	328	100	48	4704

UNICOS framework providing

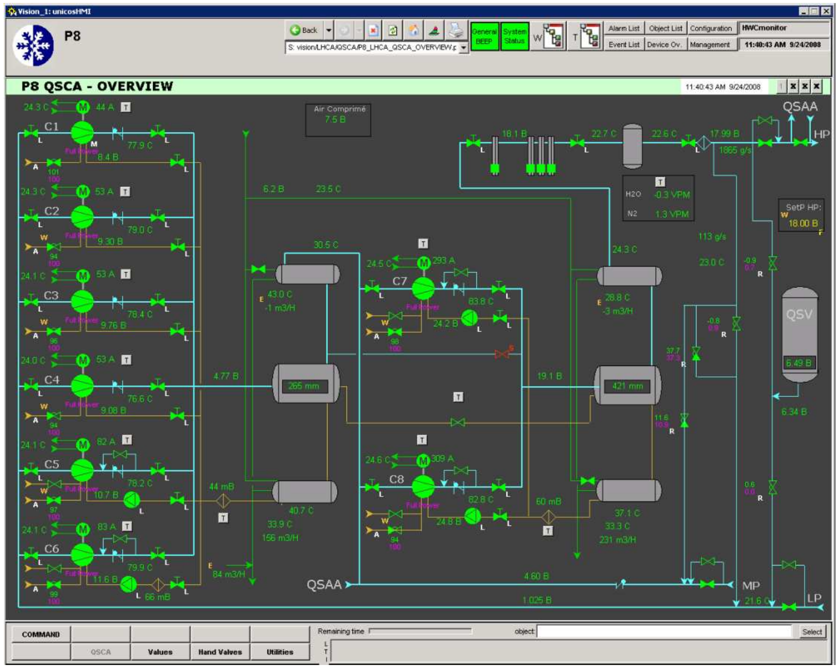
1. Programmable logic controllers (PLC) and associated hardware
2. Programming rules and code library for common objects
3. Automated tools for writing control code
4. Gateways based in industrial PC for WorldFIP-based signal conditioners
5. Communication via Ethernet gateways <-> PLC and PLC <-> PLC
6. Event-driven communication protocol between PLC <-> SCADA
7. SCADA based in PVSS with generic widgets, look-and-feel and shared data server

Control system architecture

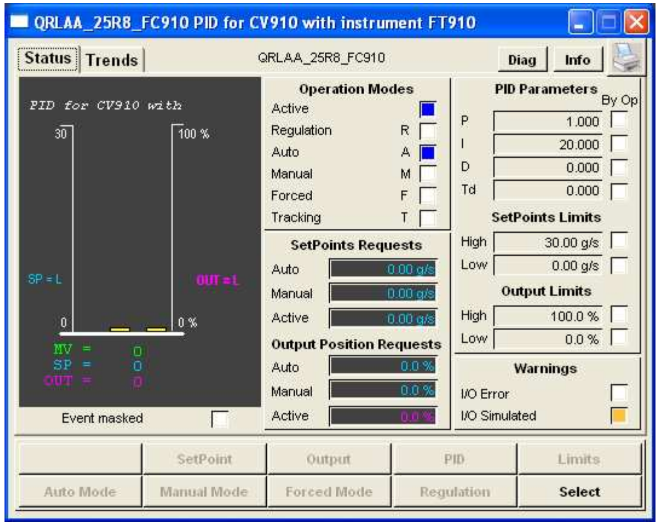


- Supervision layer
  - Interface for operation team
  - All operators action are taken from this level
- Process control layer
  - PLC : the control logic is performed at that level
  - Programmers act on that Level
- Field layer
  - Interface to process direct I/O Boards, Fieldbuses

Operator-friendly SCADA

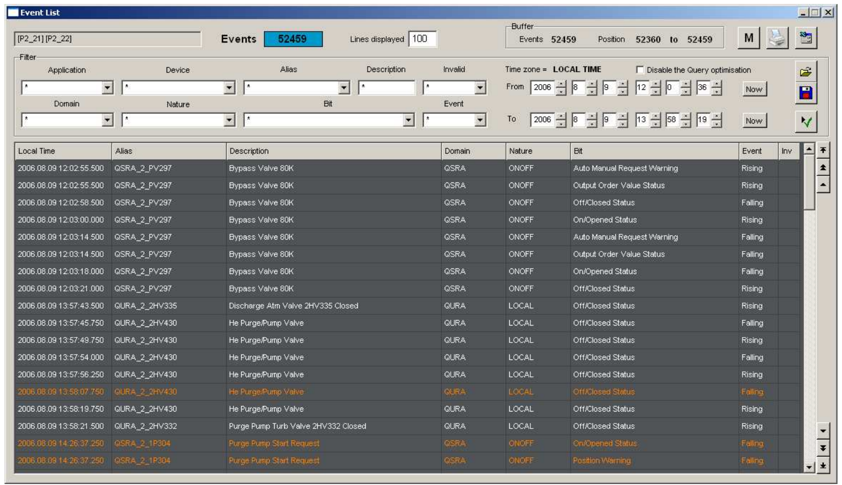


Animated synoptics

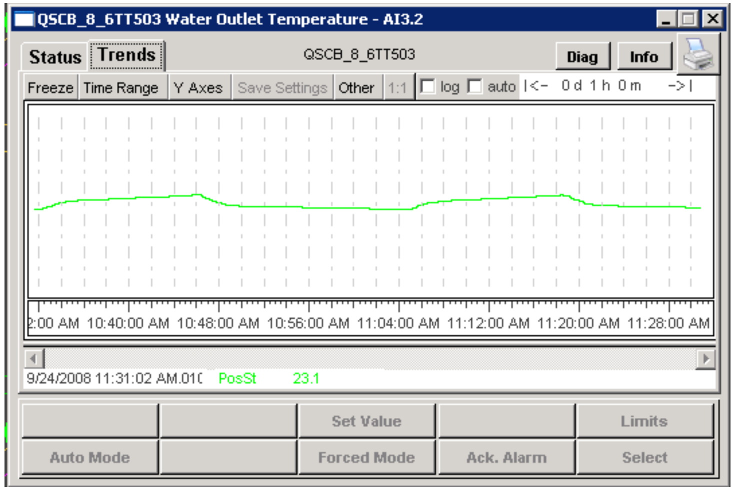


PID controllers

Alarm & event lists



Trend charts



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