CRYOGENICS FOR SUPERCONDUCTING MAGNETS

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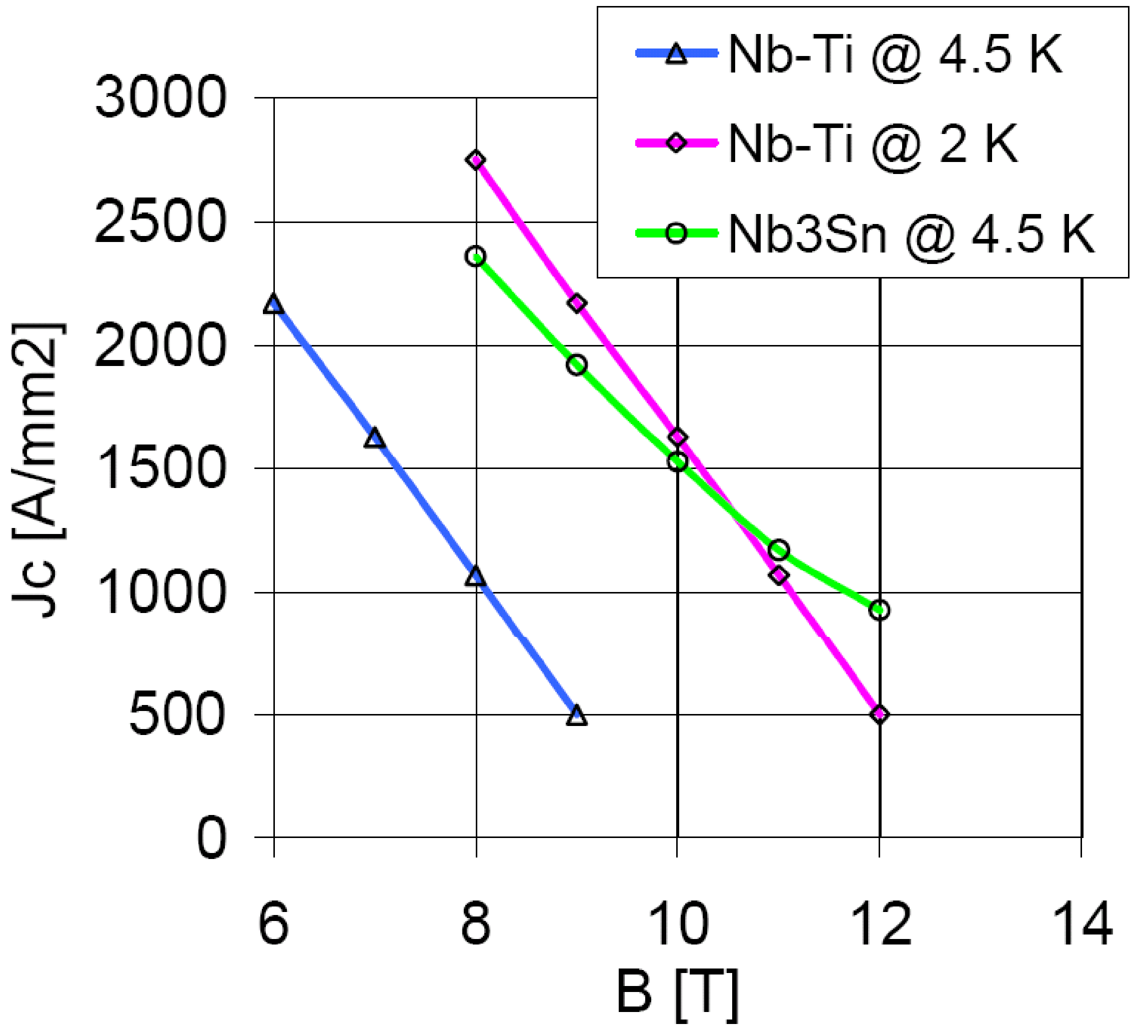
Contents

Contents

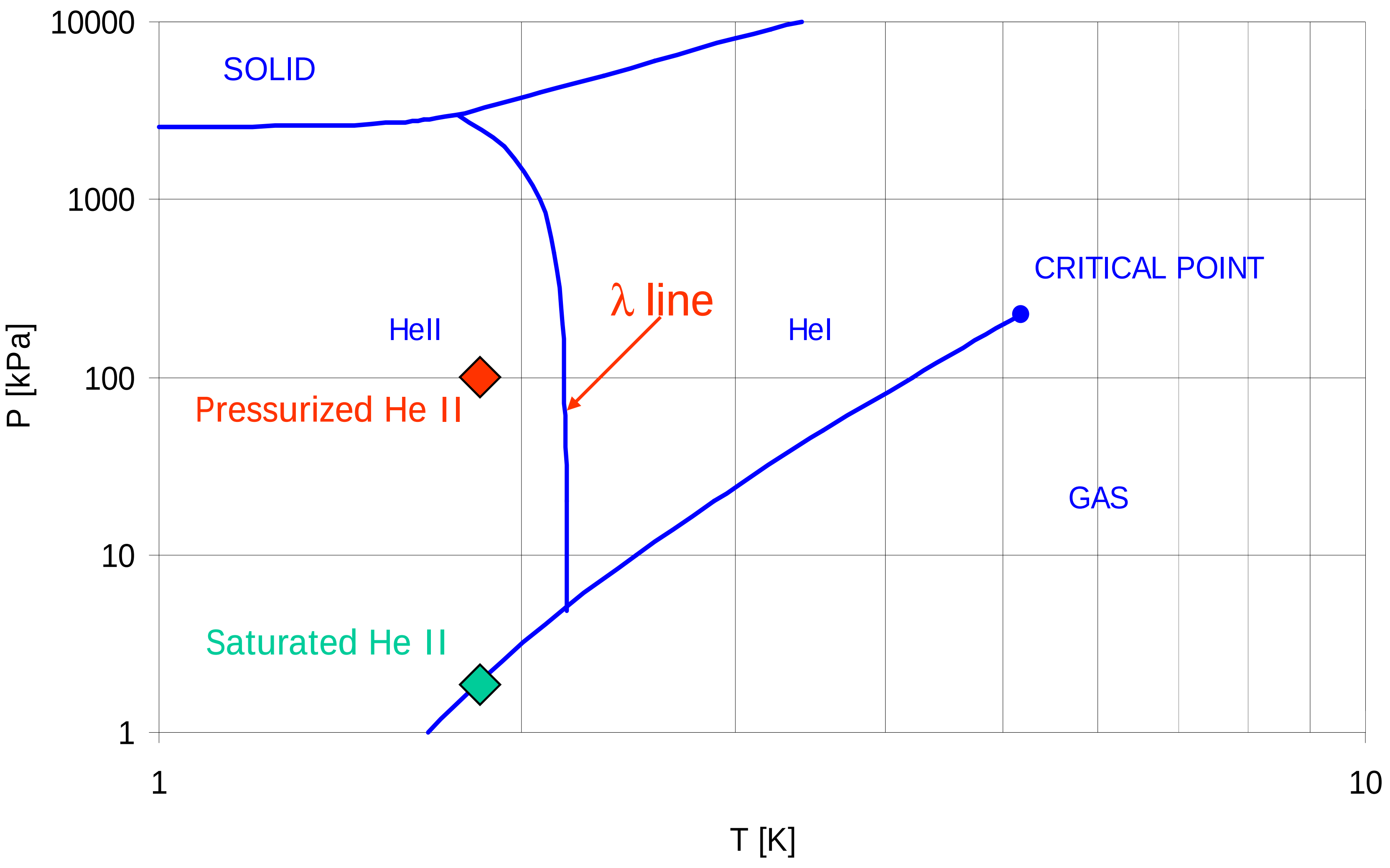
Role of cryogenics

- Compactness through higher fields
  - superconducting bending and focussing magnets for circular accelerators.
  - superconducting acceleration cavities for linear accelerators
- Reducing of specific project cost
- Saving energy
  - in electromagnets
  - in acceleration cavities
- Improvement of environment conditions
  - cryogenic pumping
  - low resistive wall in high intensity accelerators

Critical current density of superconductors



Phase Diagram of Helium



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- Role of cryogenics
- Helium as a cooling fluid
- Layout and requirements of large cryogenic systems
- Main equipments and features
  - Heat loads and cryostat design
  - Power refrigeration at 4.5 and 1.8 K
  - Specific developments:
    - » Current leads, heat exchangers, rotating machines, safety valves
  - Helium inventory management and storage
- Future perspective for large cryogenic systems
- Conclusions

Helium as a cooling fluid

Phase domain	Advantages	Drawbacks
Saturated He I	Fixed temperature High heat transfer	Two-phase flow Boiling crisis
Supercritical	Monophase Negative J-T effect	Non-isothermal Density wave instability
He II	Low temperature High conductivity Low viscosity	Second-law cost Subatmospheric

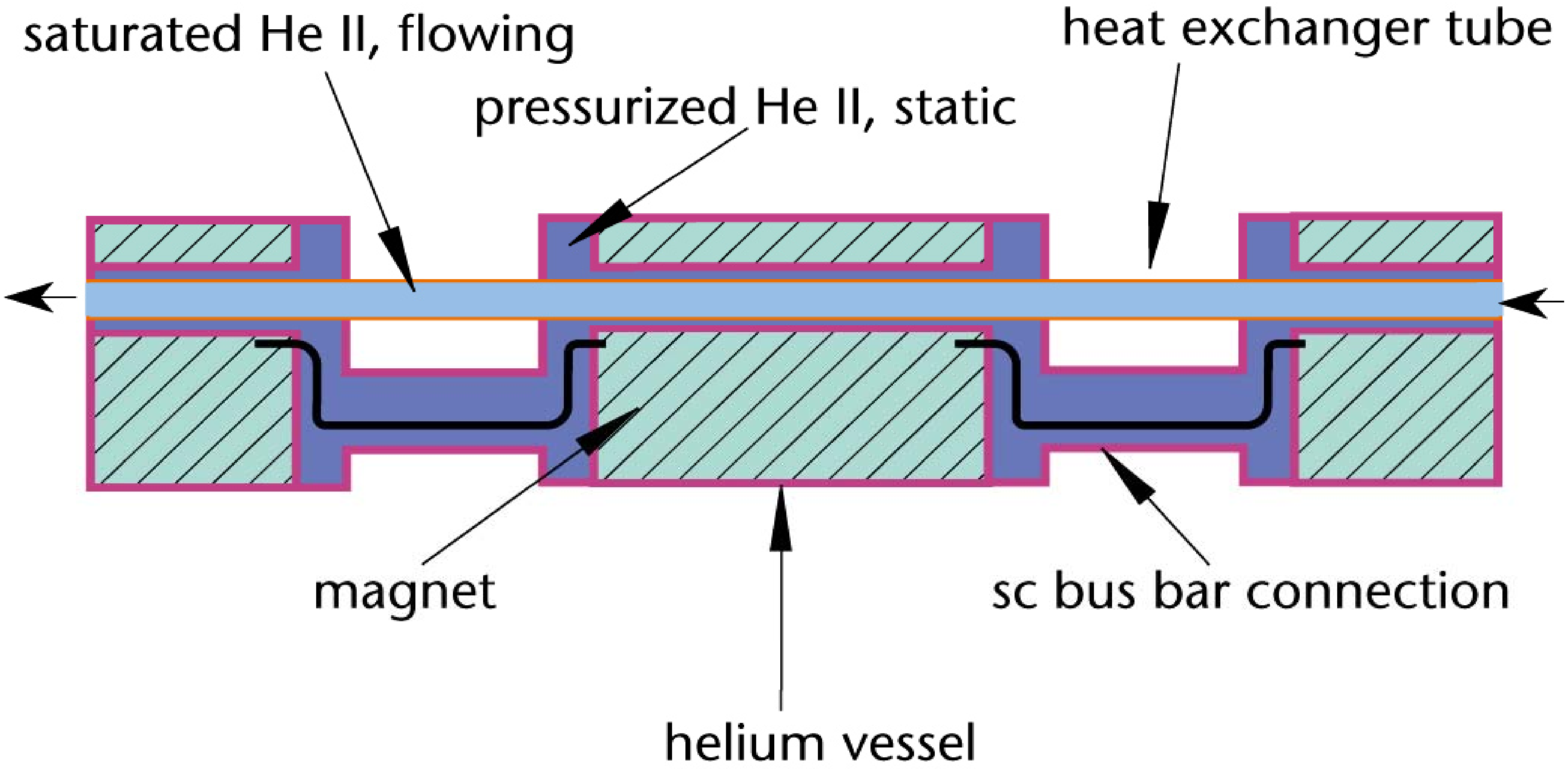
Superfluid Helium as a Magnet Coolant

- Temperature below 2.17 K
- Low bulk viscosity
- Very large specific heat
  - 10^5 times that of the conductor per unit mass
  - 2×10^3 times that of the conductor per unit volume
- Very high thermal conductivity
  - 10^3 times that of cryogenic-grade OFHC copper
  - peaking at 1.9 K
  - still, insufficient for long-distance heat transport

Pressurised vs. Saturated Superfluid Helium

+ Mono-phase (pure liquid)
+ Magnet bath at atmospheric pressure
  - no air inleaks
  - higher heat capacity to the lambda line
+ Avoids bad dielectric strength of low-pressure gaseous helium
– Requires additional heat exchanger to saturated helium heat sink

LHC magnet string cooling scheme



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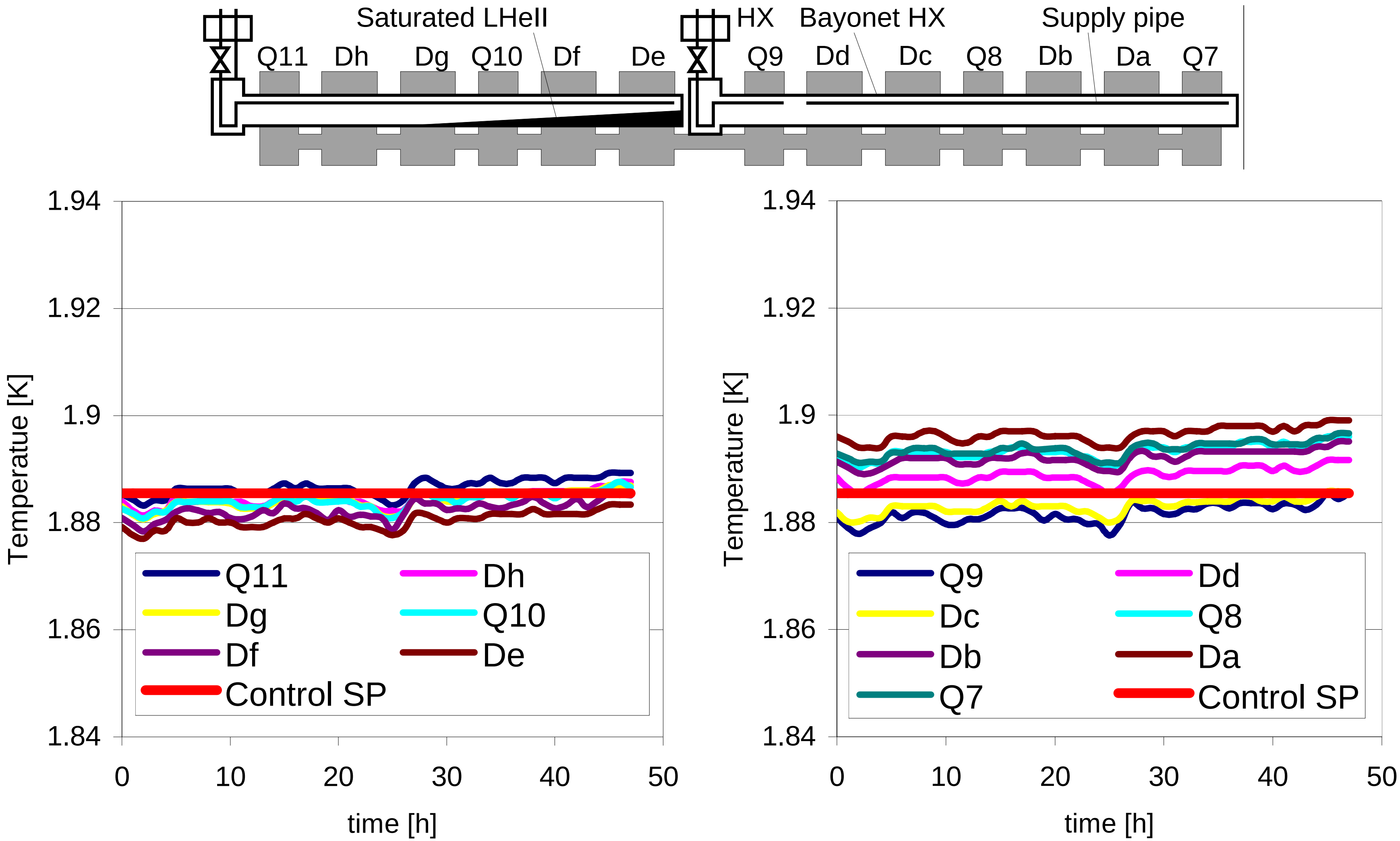
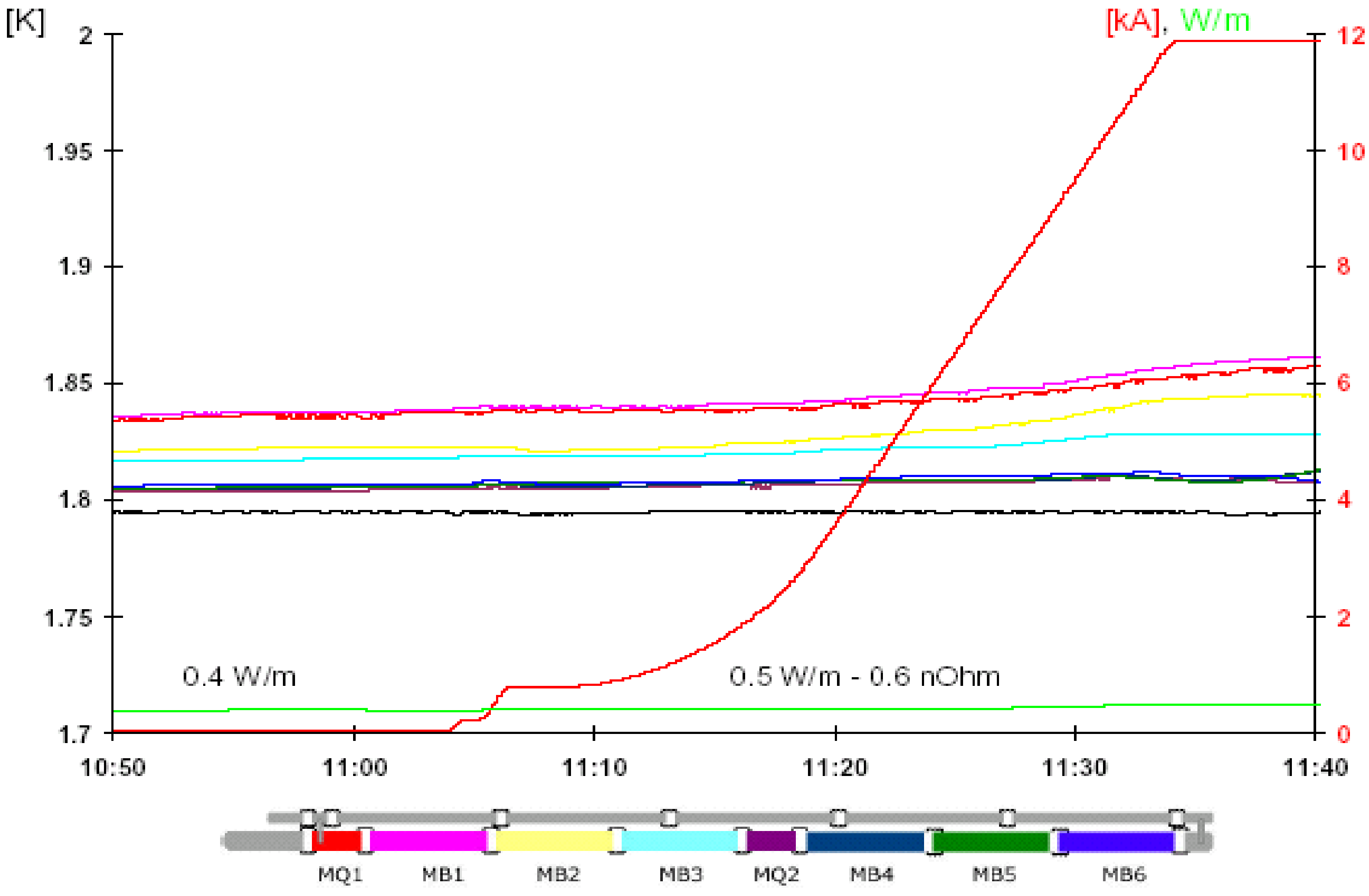
Steady-state magnets cooling in LHC string



Magnet temperature in string upon current ramp



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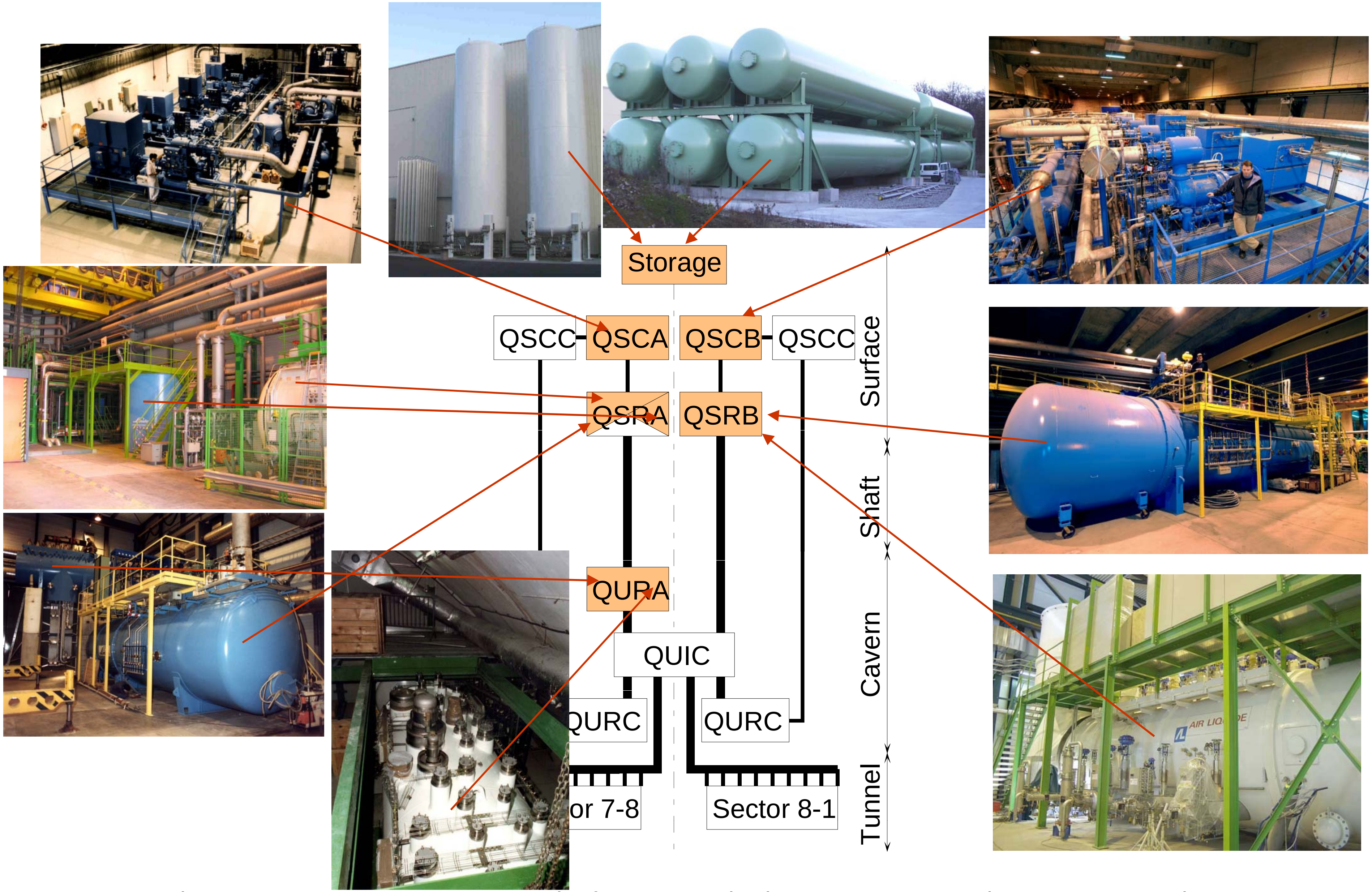
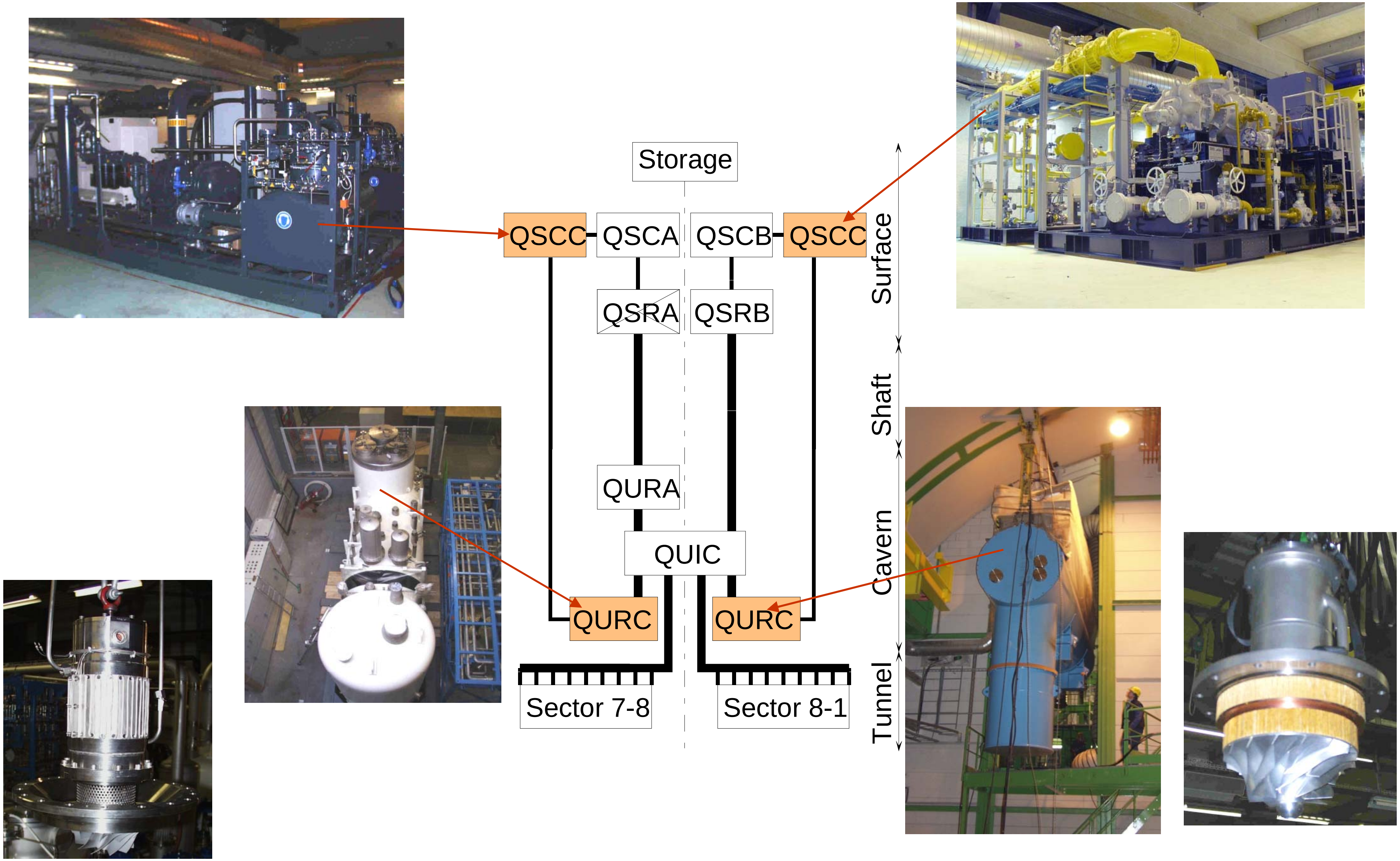
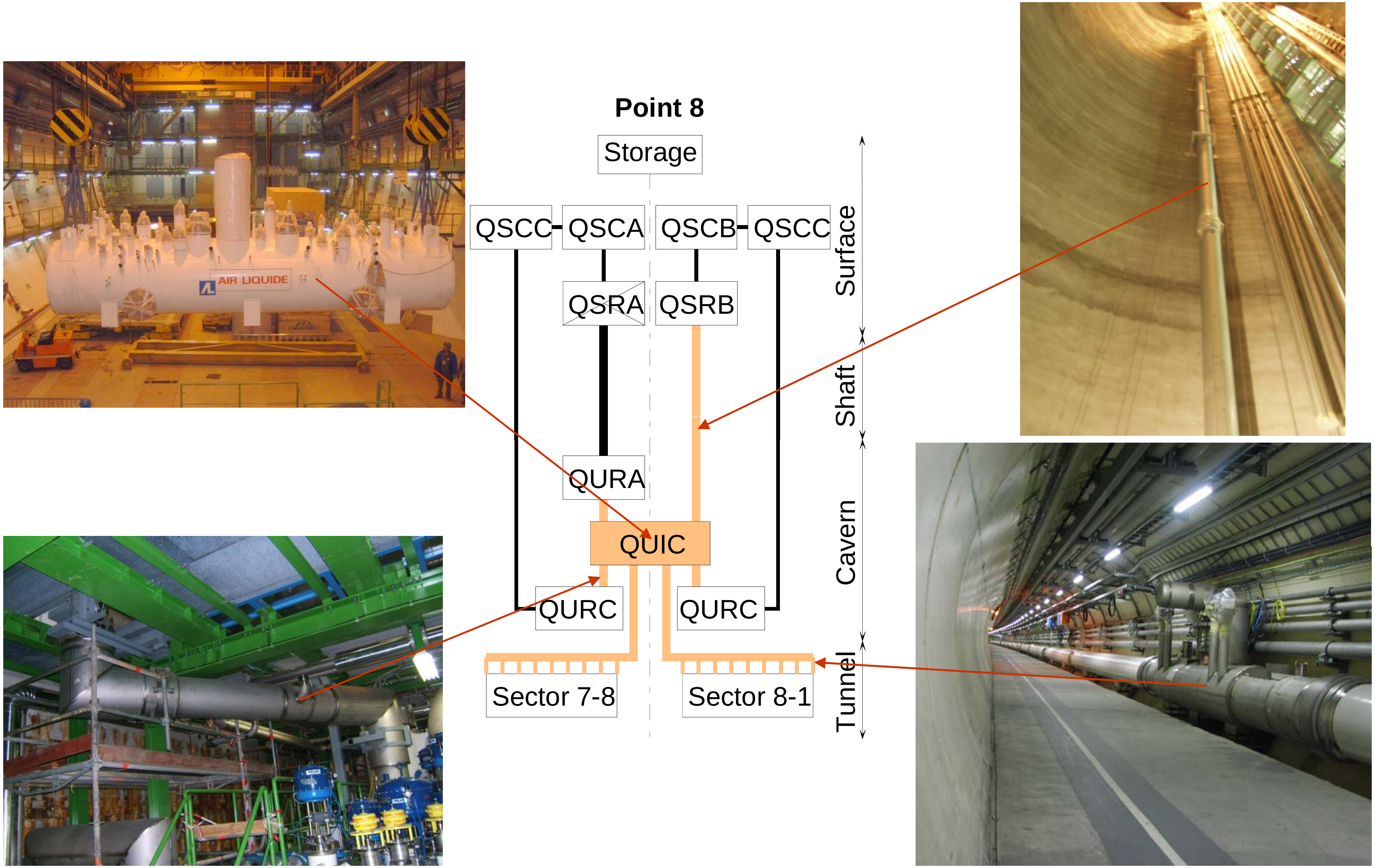
LHC infrastructure and 4.5 K refrigerators



LHC 1.8 K refrigeration units



LHC cryogenic distribution system

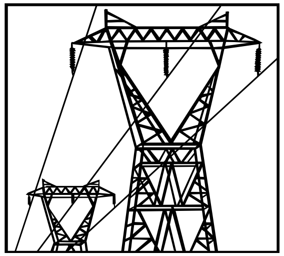


What does the LHC cryogenic system need ?

✓ Electric power

about 32 MW; 24 GWh/month

1.2 MCHF/month

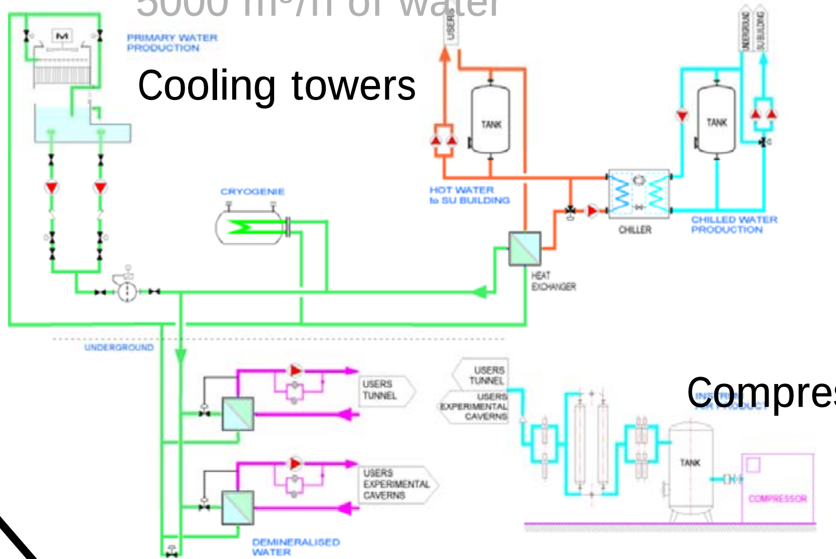


✓ Cooling and ventilation

5000 m³/h of water

Cooling towers

Compressed air



✓ Helium and nitrogen

120 t of He – 4 MCHF

10’000 t of LN2 – 1.6 MCHF

CRYO

144 kW @4.5 K

✓ Vacuum

10^{-2} mbar

✓ Controls:

Networks, fieldbuses, PLC, SCADA

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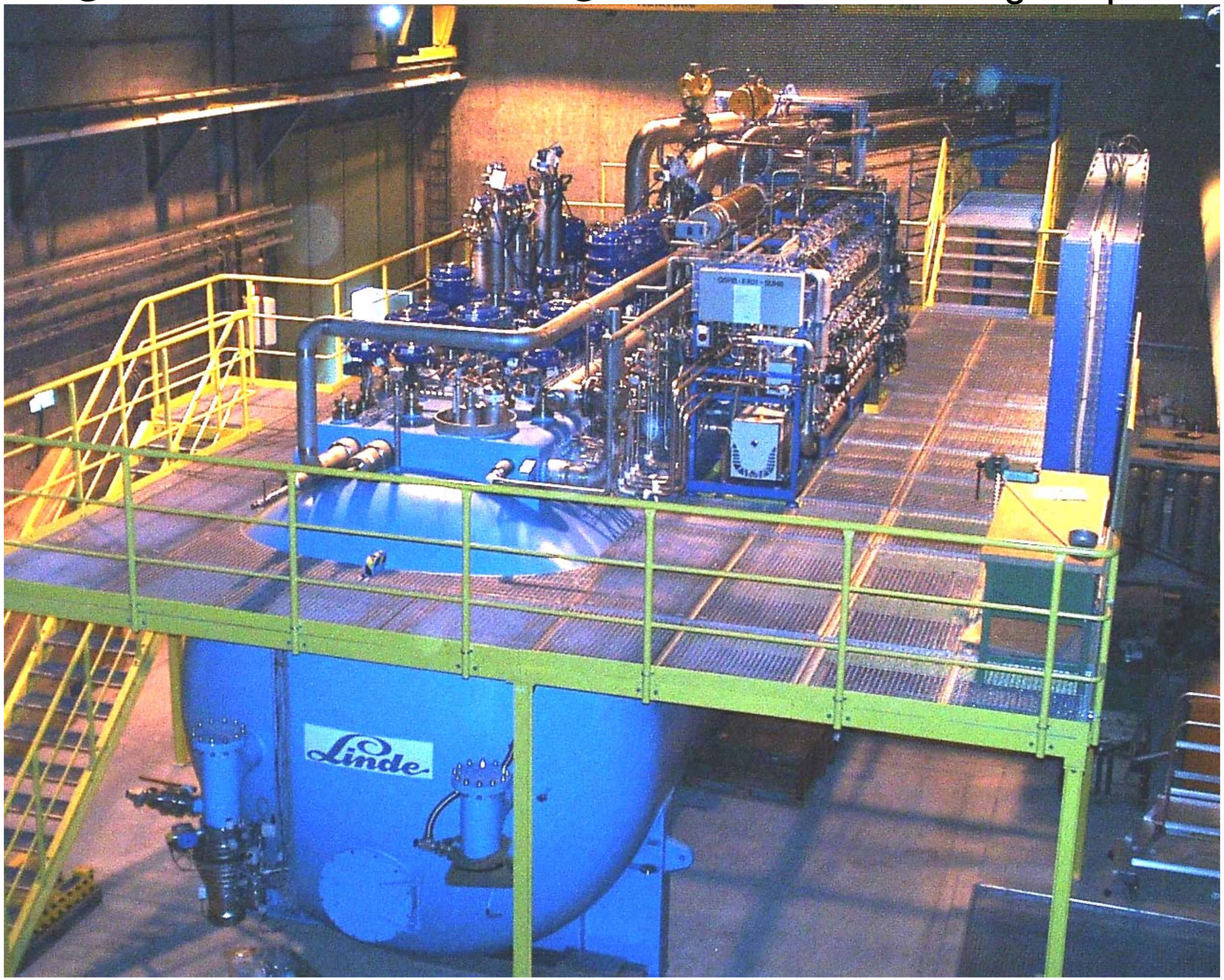
Cryostat Design & Heat Load Management

- Heat inleaks
  - Radiation — 70 K shield, MLI
  - Residual gas conduction — Vacuum < 10^{-4} Pa
  - Solid conduction — Non-metallic supports
Heat intercepts
- Joule heating
  - Superconductor splices — Resistance < a few nΩ
- Beam-induced heating
  - Synchrotron radiation }
  - Beam image currents } 5-20 K beam screens
  - Acceleration of photoelectrons }

LHC 18 kW @ 4.5 K Cold Box

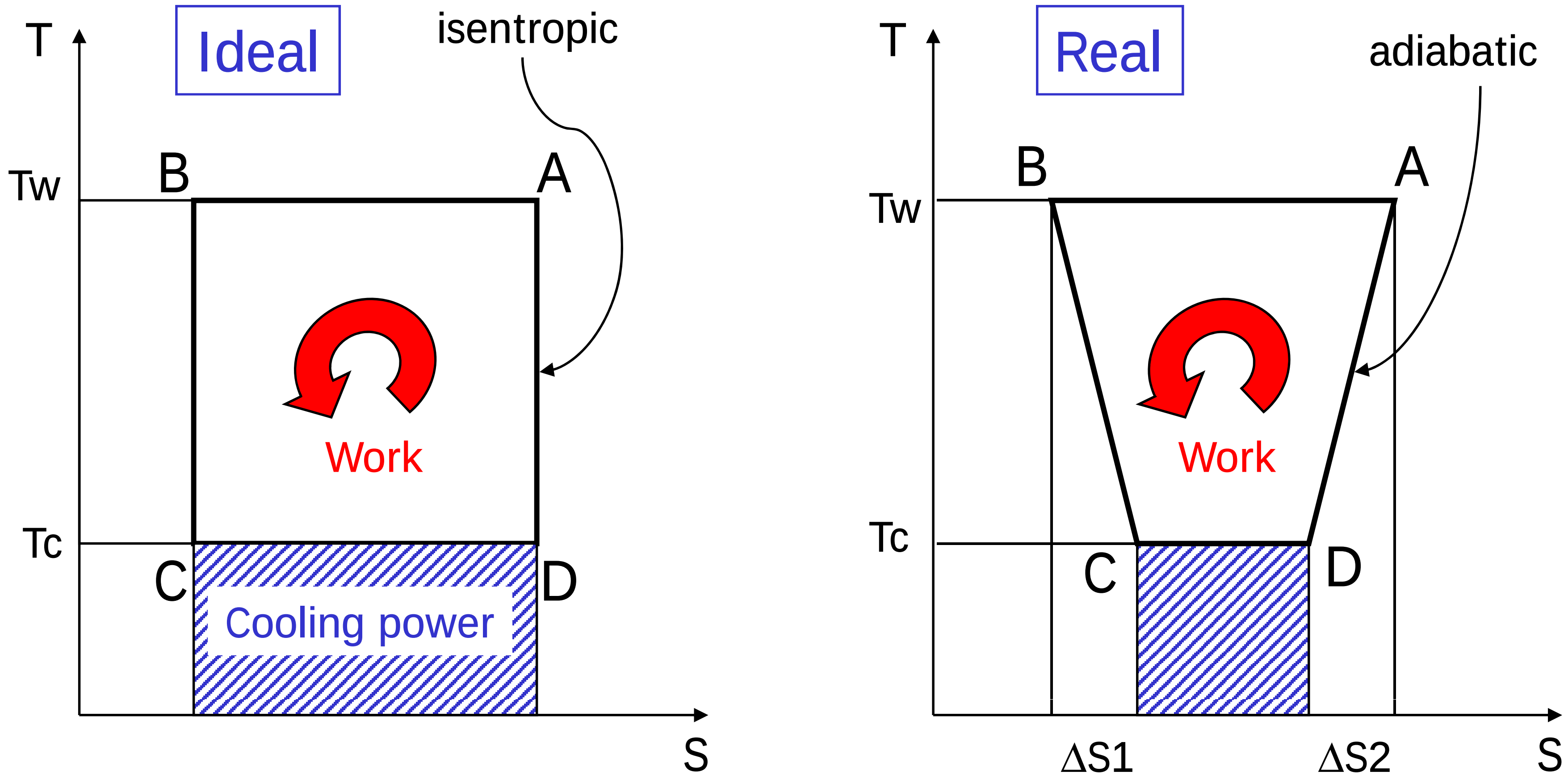
33 kW @ 50 K to 75 K   23 kW @ 4.6 K to 20 K   41 g/s liquefaction



How to Specify an Efficient He Refrigerator

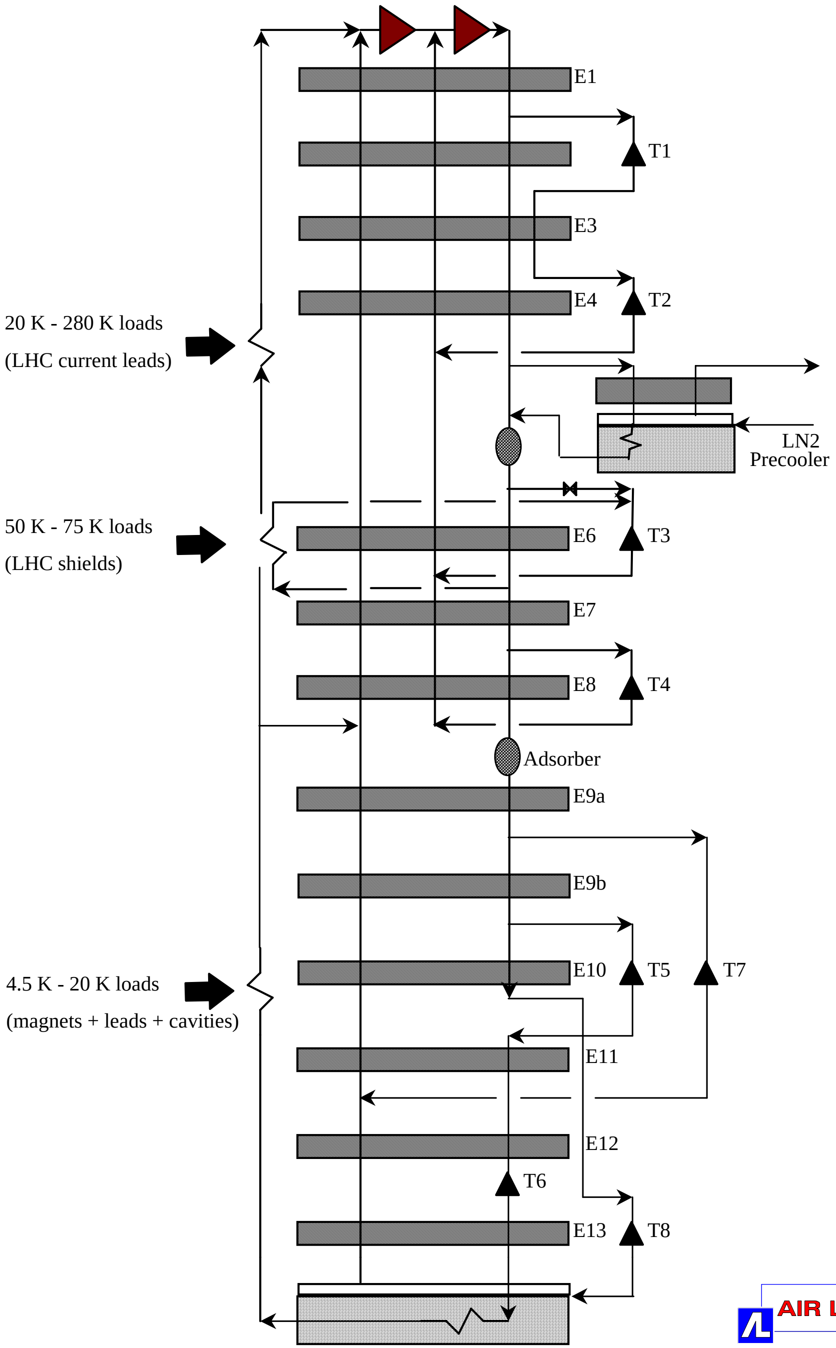
- Include capital & operating costs over amortization period *(10 years)* in adjudication formula
- Operating costs dominated by *electricity*
- Include externalities in electricity costs *=> 60 CHF/MWh*
  - distribution & transformation on site
  - heat rejection in aerorefrigerants
- Establish shared 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

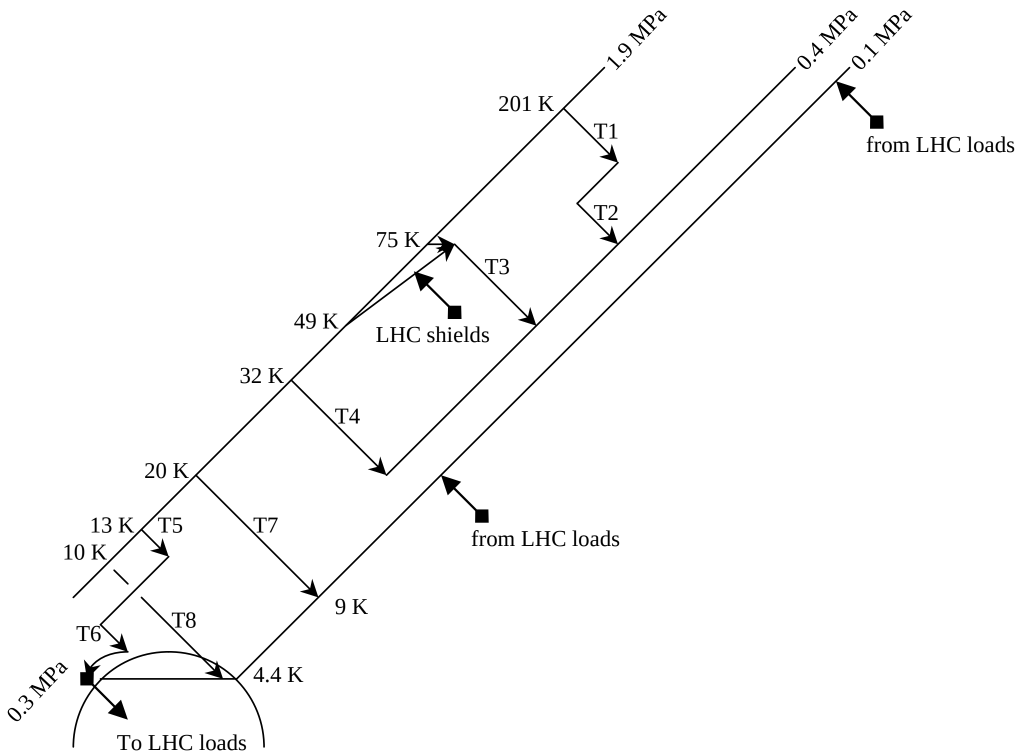
How to make an efficient refrigerator
(Carnot cycle schematic)



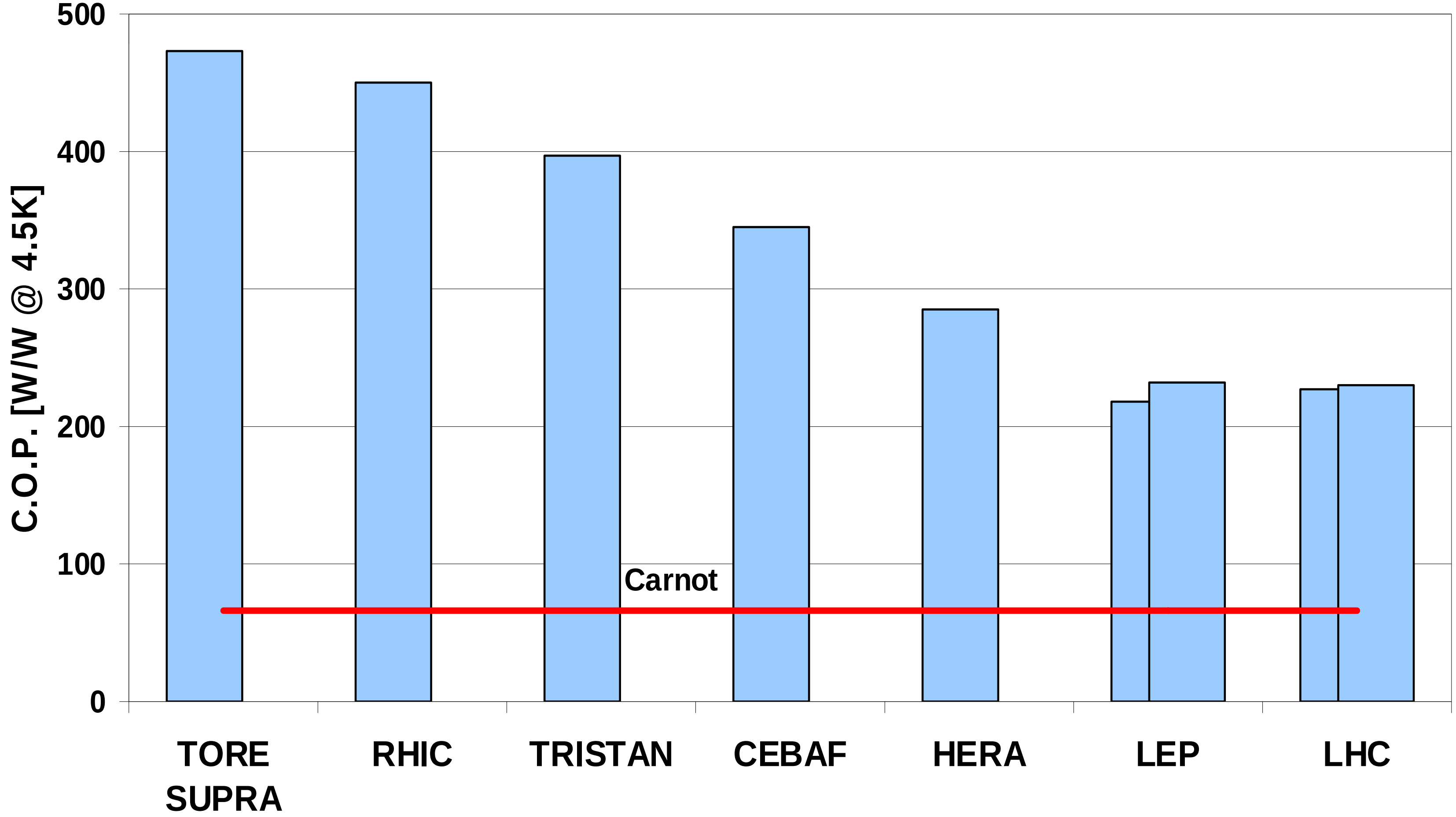
Widen the low-temperature end of the cycle as shown in the T-S diagram

Process Cycle & T-S Diagram of 18 kW @ 4.5 K Cryoplant





C.O.P. of Large Cryogenic Helium Refrigerators



Challenges of Power Refrigeration Below 2 K

- Maintain saturation pressure < 2 kPa on cold source

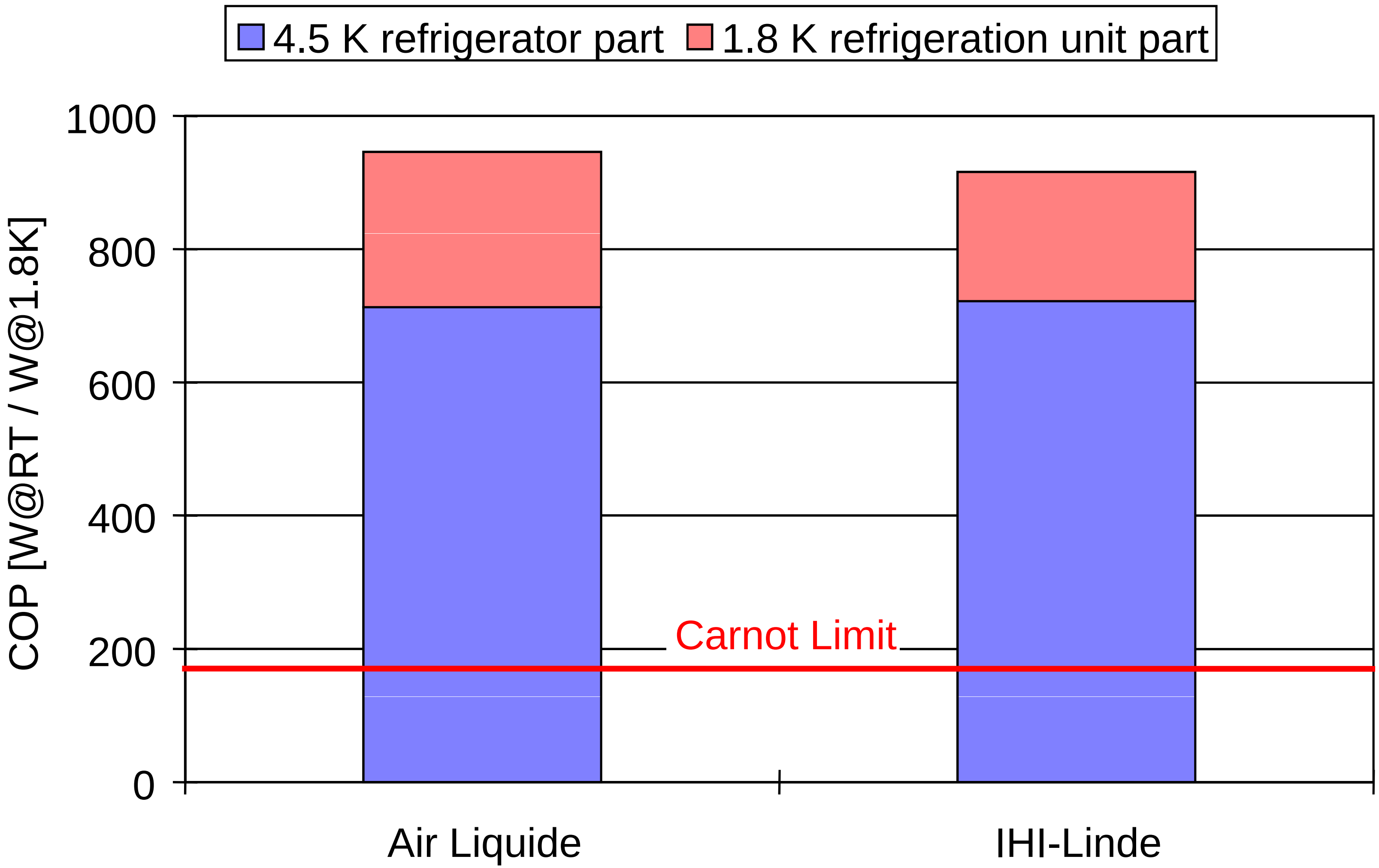
=> compress GHe across pressure ratio of ~80

- Warm volumetric pumps are limited in capacity *(10 g/s at 1kPa i.e. 200 W at 1.8 K)*
- Cold compressors handle gas with increased density but
  - need *non-lubricated, contact-less* solutions,
  - only acceptable with *good isentropic efficiency* (heat of compression is rejected at low temperature)
- Cold hydrodynamic compressors exhibit limited pressure ratio of ~3 per stage

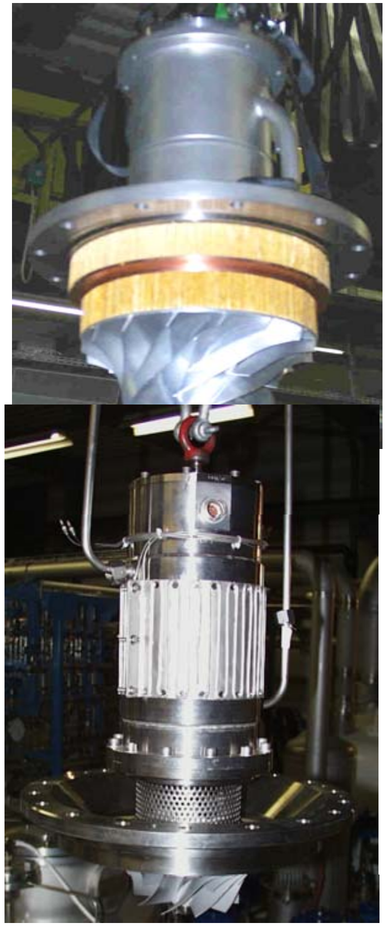
=> five stages in series to achieve overall pressure ratio

- Irreversibilities in VLP heat exchangers
  - thermal: axial heat conduction, wall thermal resistance
  - hydraulic: frictional pressure drop, uneven flow distribution

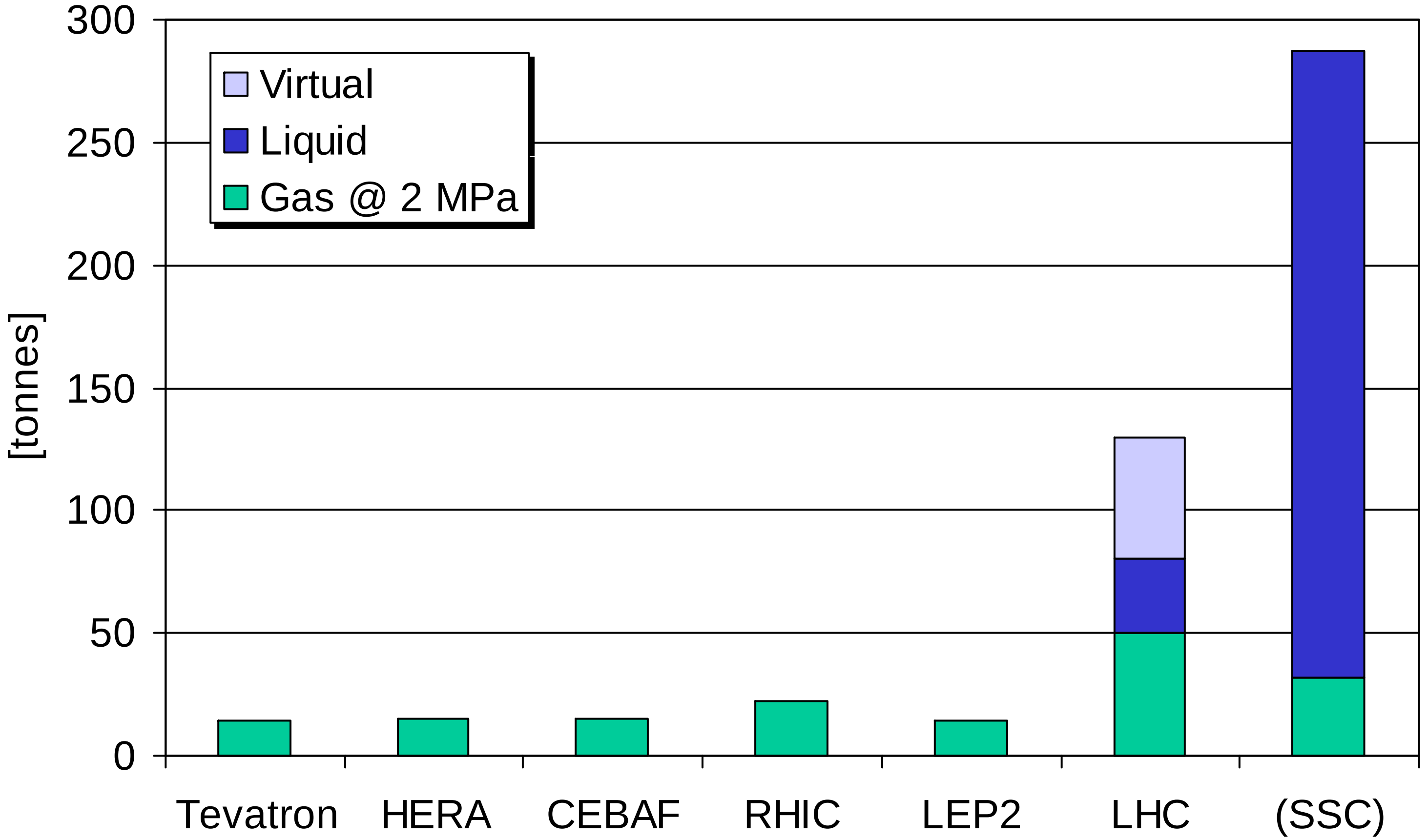
C.O.P. of LHC 1.8 K Refrigeration Units



Specific developments

Subcooling heat exchangers	HTS current leads	Rotating machine (warm and cold)	Safety valves (quench)
 			

He Inventory of Large Cryogenic Systems



Specific Cost of Bulk He Storage

Type	Pressure [MPa]	Density [kg/m^3]	Dead volume [%]	Cost [CHF/kg He]
Gas Bag	0.1	0.16	0	300(1)
MP Vessel	2	3.18	5-25	220-450
HP Vessel	20	29.4	0.5	500(2)
Liquid	0.1	125	13	100-200(3)

(1) Purity non preserved
(2) Not including HP compressors
(3) Not including reliquefier

Liquid and gaseous storage tanks

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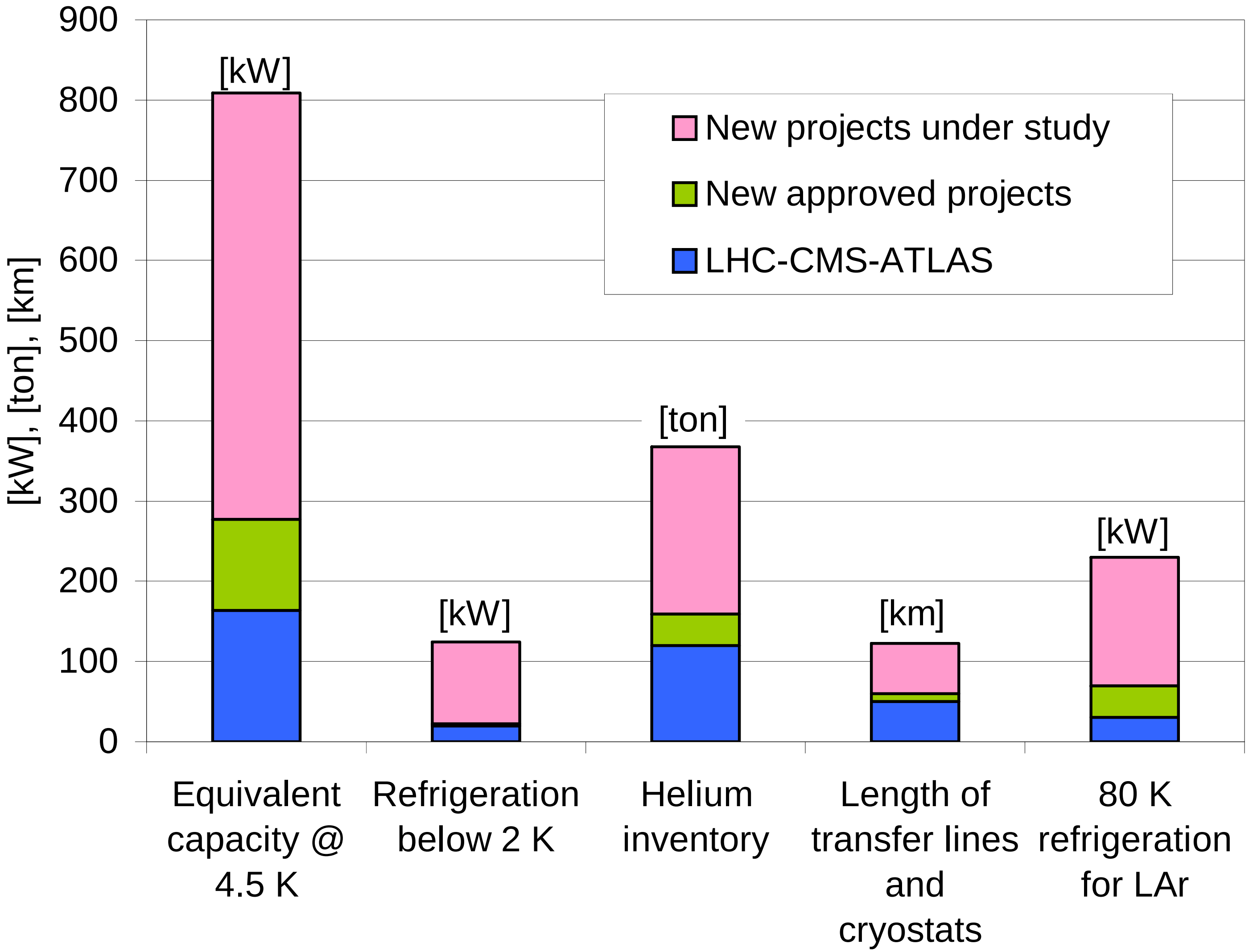
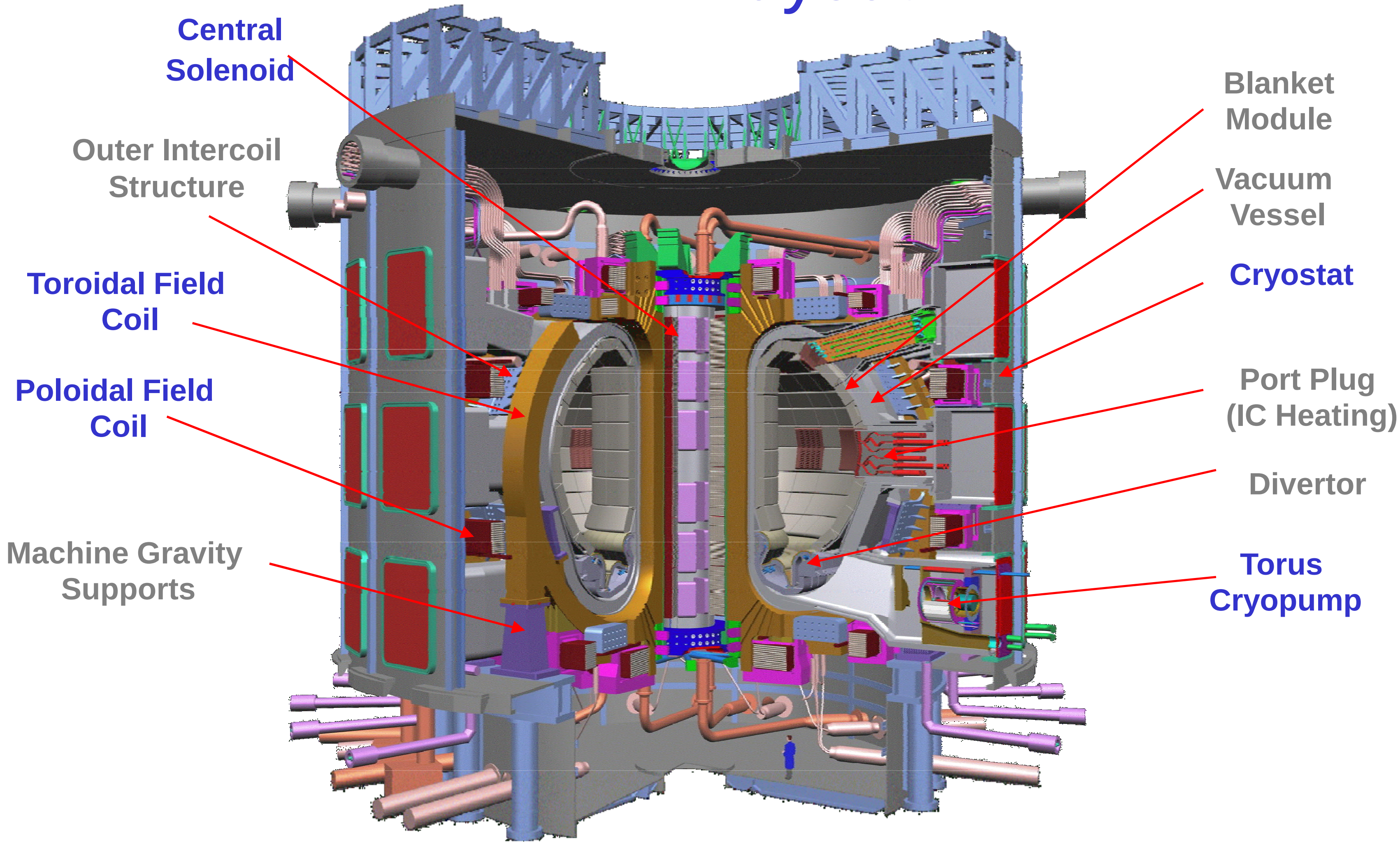
New project requirements



ITER layout



International Collaboration: Europe – Japan - Russia – Canada - USA – China - India

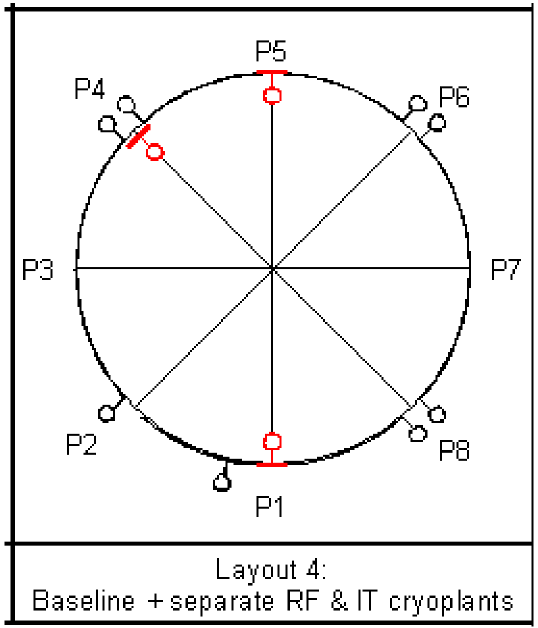
Cryogenic capacity & Thermal loads

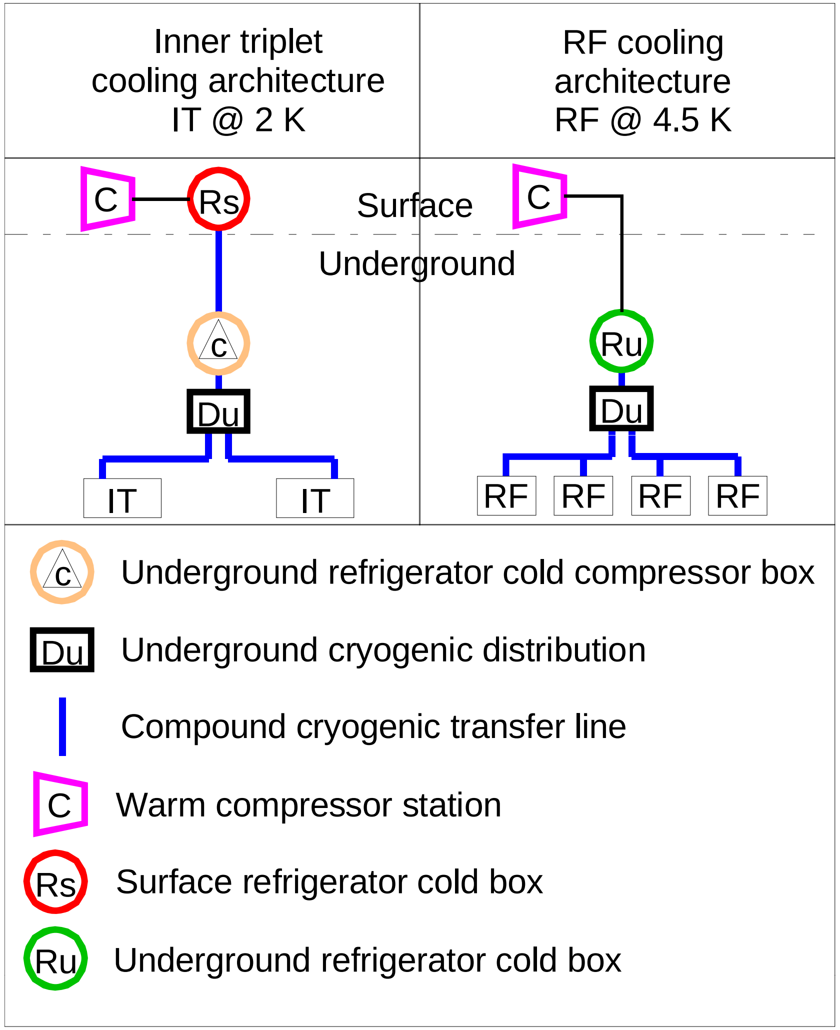
- LHe cryoplants: 60 kW equivalent @ 4.5 K
  - Cooling of the superconducting magnet system (Toroidal and poloidal coils):
    - 31 kW @ 4.5 K including 13 kW of pulsed heat loads and 6 kW of cold pump heat loads.
  - Cooling of current leads:
    - 100 g/s of LHe liquefaction
  - Cooling of cryo-pumps with high regeneration frequency:
    - 4 kW @ 4.5 K and 60 g/s of LHe liquefaction

- LN2 cryoplants: 1120 kW @ 80 K
  - Thermal shielding:
    - up to 830 kW @ 80 K during chamber baking
  - LHe cryoplant pre-cooling:
    - Up to 280 kW @ 80 K during normal operation

- Helium inventory: 20 t

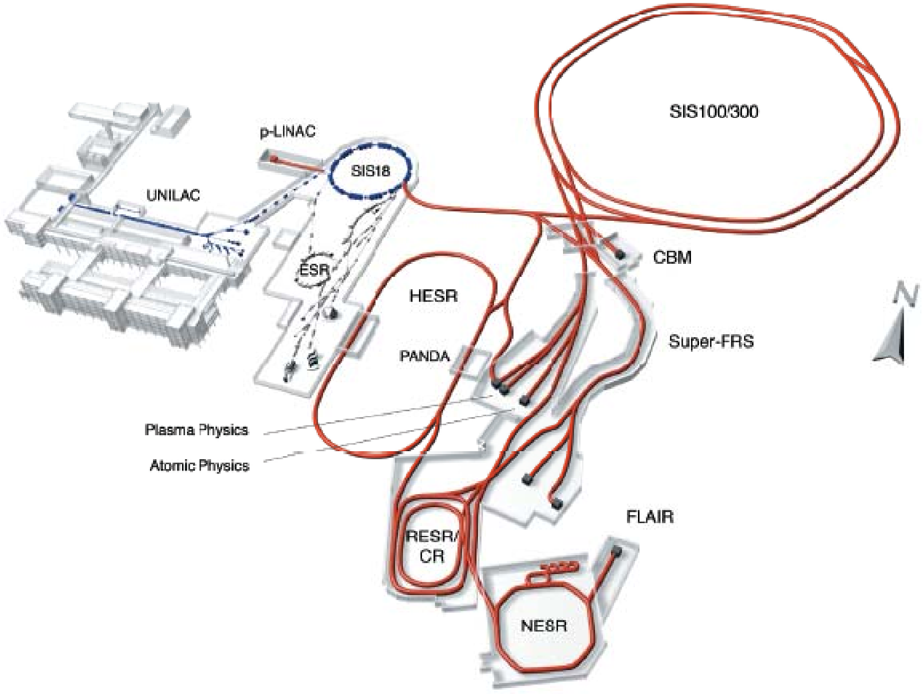
LHC luminosity upgrade study

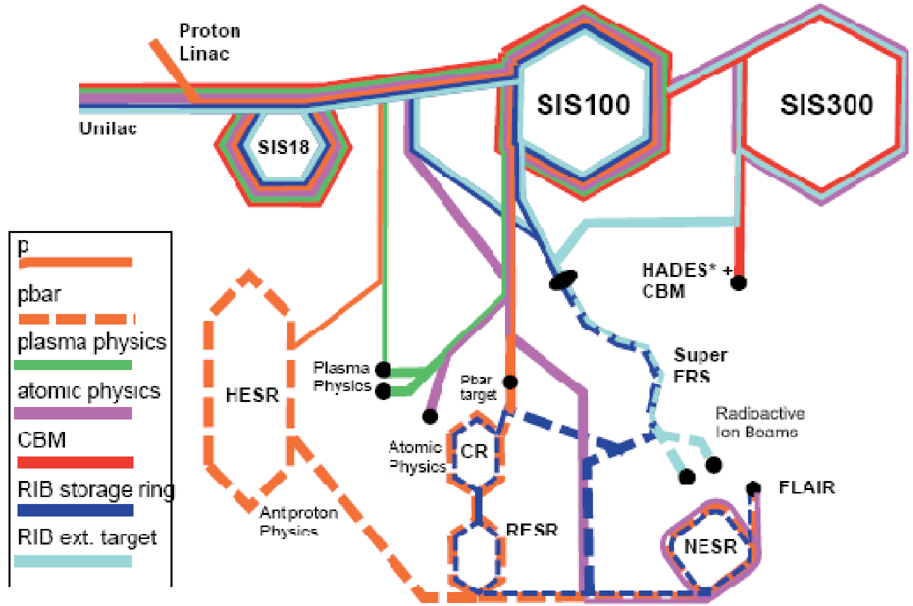




- Cryoplants: Two 2 K cryoplants
  and one 4.5 K cryoplant
  - Total installed power: 39 kW @ 4.5 K including 10 kW @ 2 K
  - Size of largest plants: 16 kW @ 4.5 K including 5 kW @ 2 K
- Distribution
  - 3 distribution boxes and 500 m of compound transfer lines

FAIR at GSI, Darmstadt (Germany)





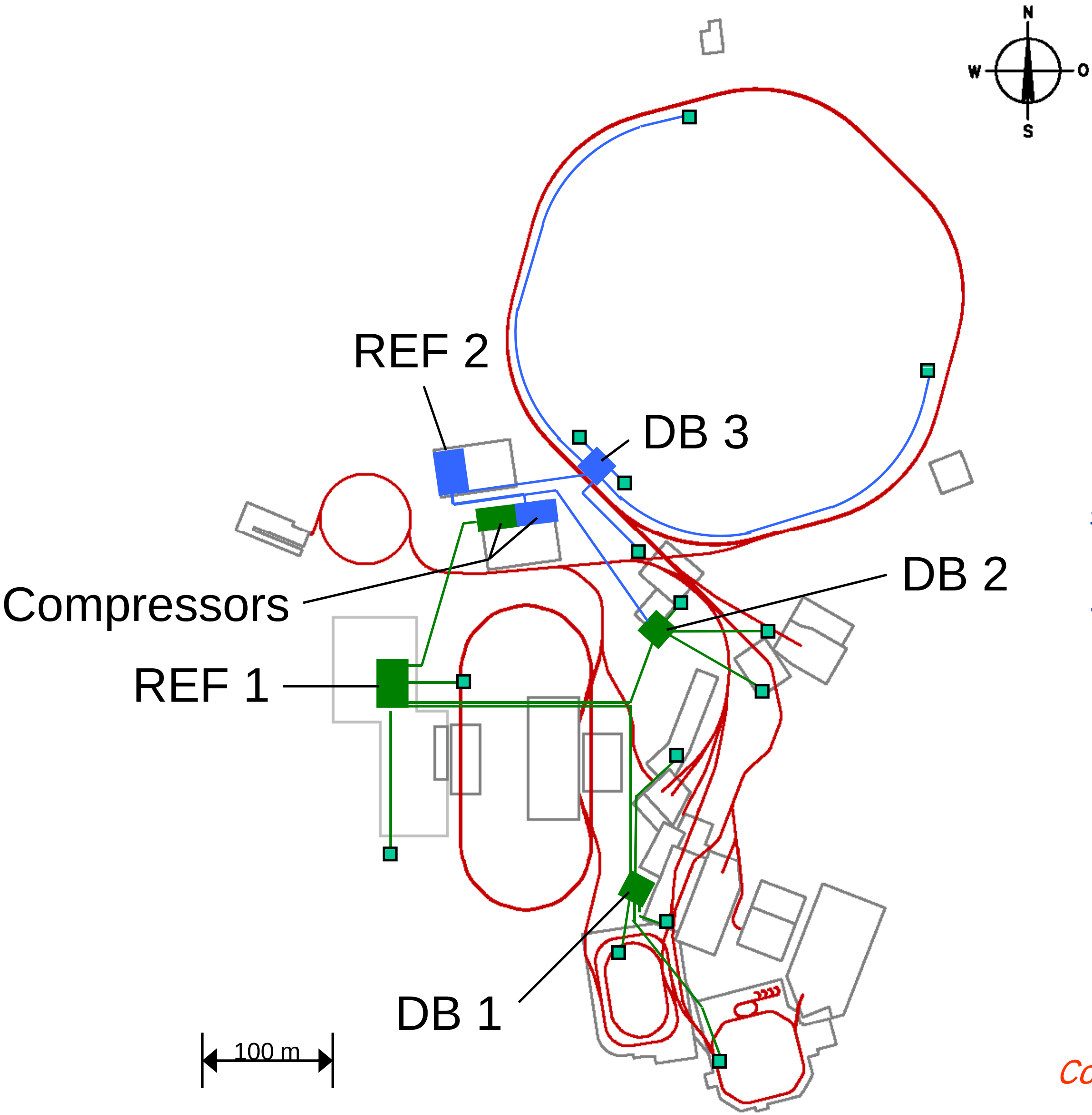
Facility for Antiproton & Ion Research

Complex of synchrotrons and storage rings using superconducting magnets

Production: up to 2012
Installation and commissioning: 2011 to 2013
Operation: from 2012

Subproject	Numbers of sc magnets
SIS 100	449
SIS 300	444
HEBT	187
SuperFRS	180
CR	48
HESR	320
MTF	2*

FAIR cryogenic system



Refrigeration @ 4.4 K

Heat load: 27.8 kW
Design capacity: 41.7 kW

Length of transfer lines: 1.7 km
# of distribution boxes: 3

Total helium inventory: 11 t

Courtesy G. Moritz & M. Kauschke

Contents

Conclusions

- Significant advances in cryogenic engineering of large helium – particularly helium II – systems.
- Technology industrially available.
- Newly approved projects (ITER, European X-FEL, FAIR) are already demanding efforts from the cryogenic community.
- Large cryogenic refrigerators with multi-kW capacities down to 2 K as well as complex cryogenic distribution systems will be required for future projects.
- There are many similarities between the different projects devices, cooling methods and cryogenic refrigeration.

Acknoledgements

- The work presented here is essentially that of the ACR group of the Accelerator Technology department
- Thanks to Ph. Lebrun and L. Tavian for some of the slides presented