Cryogenics for Large & Very Large Accelerators

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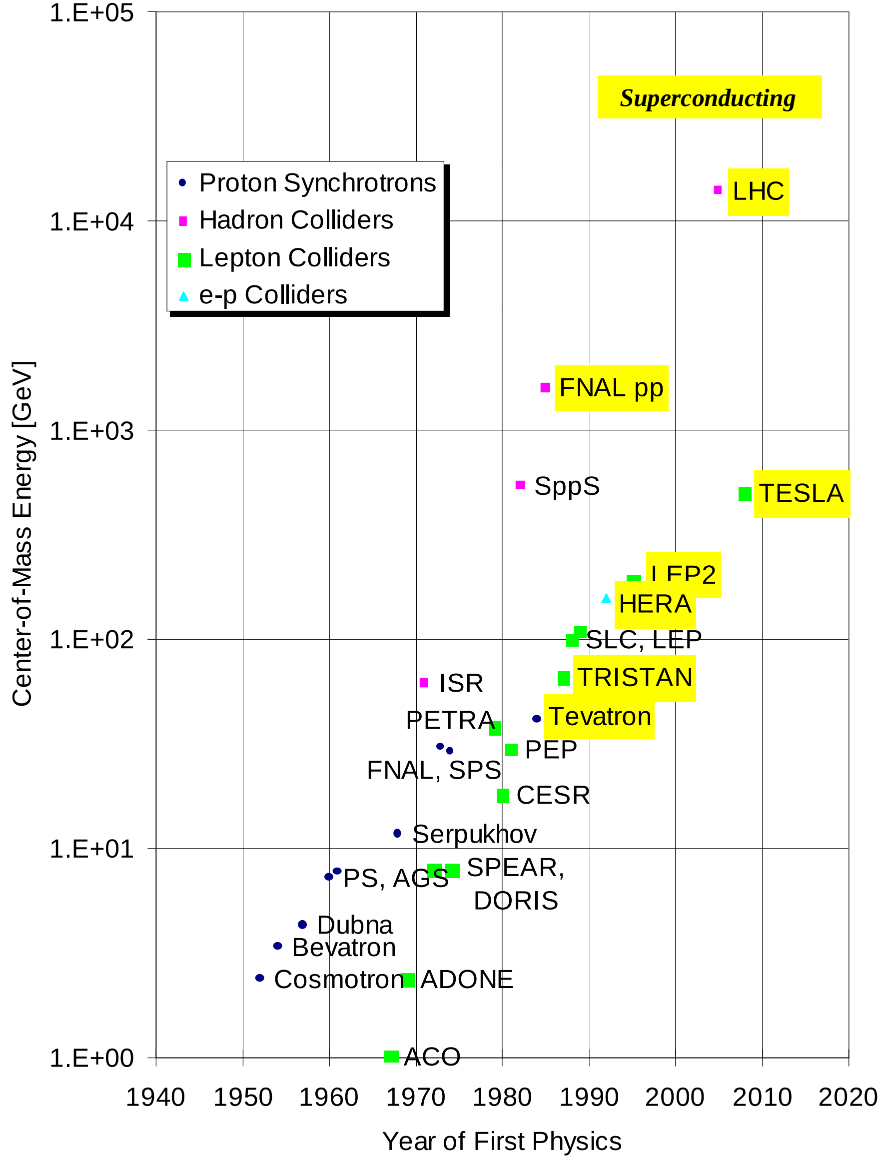

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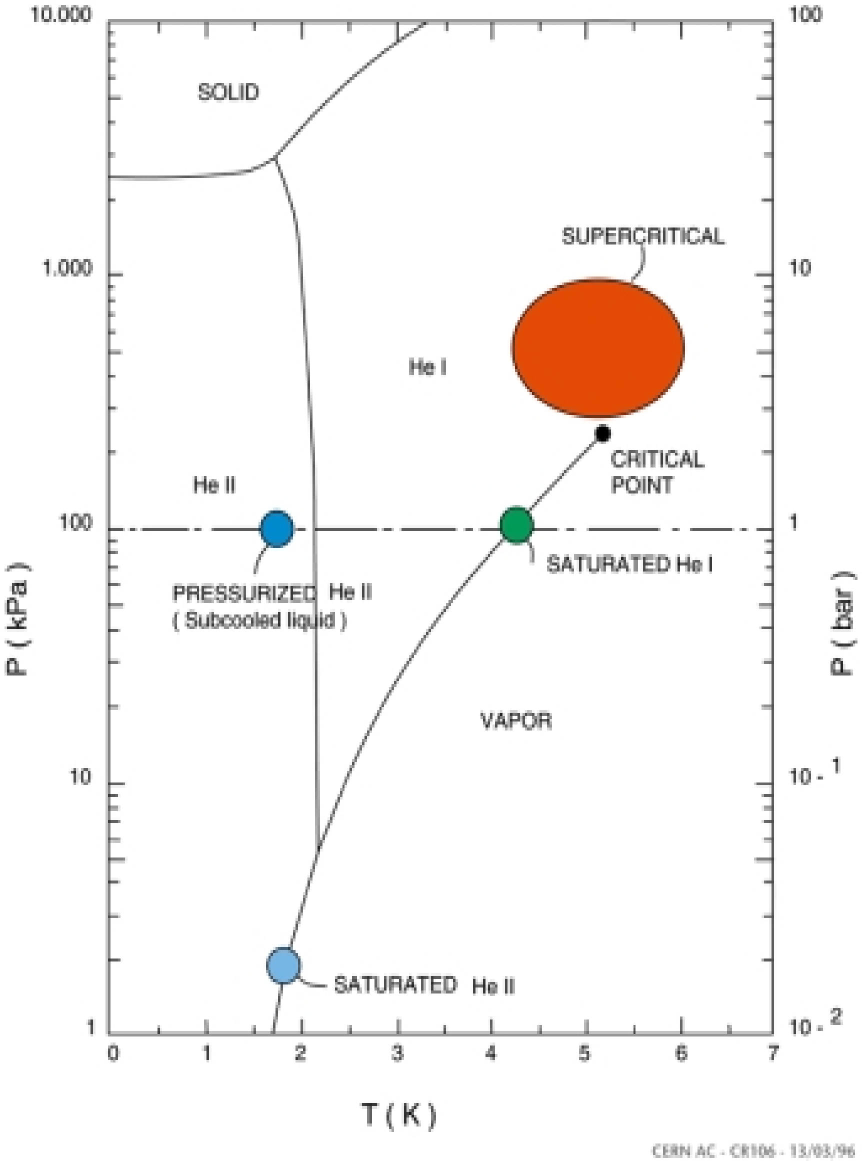
Characteristic Temperatures of Cryogens

Cryogen	Triple point [K]	Normal boiling point [K]	Critical point [K]
Oxygen	54.4	90.2	154.6
Argon	83.8	87.3	150.9
Nitrogen	63.1	77.3	126.2
Neon	24.6	27.1	44.4
Hydrogen	13.8	20.4	33.2
Helium	2.2 (λ point)	4.2	5.2

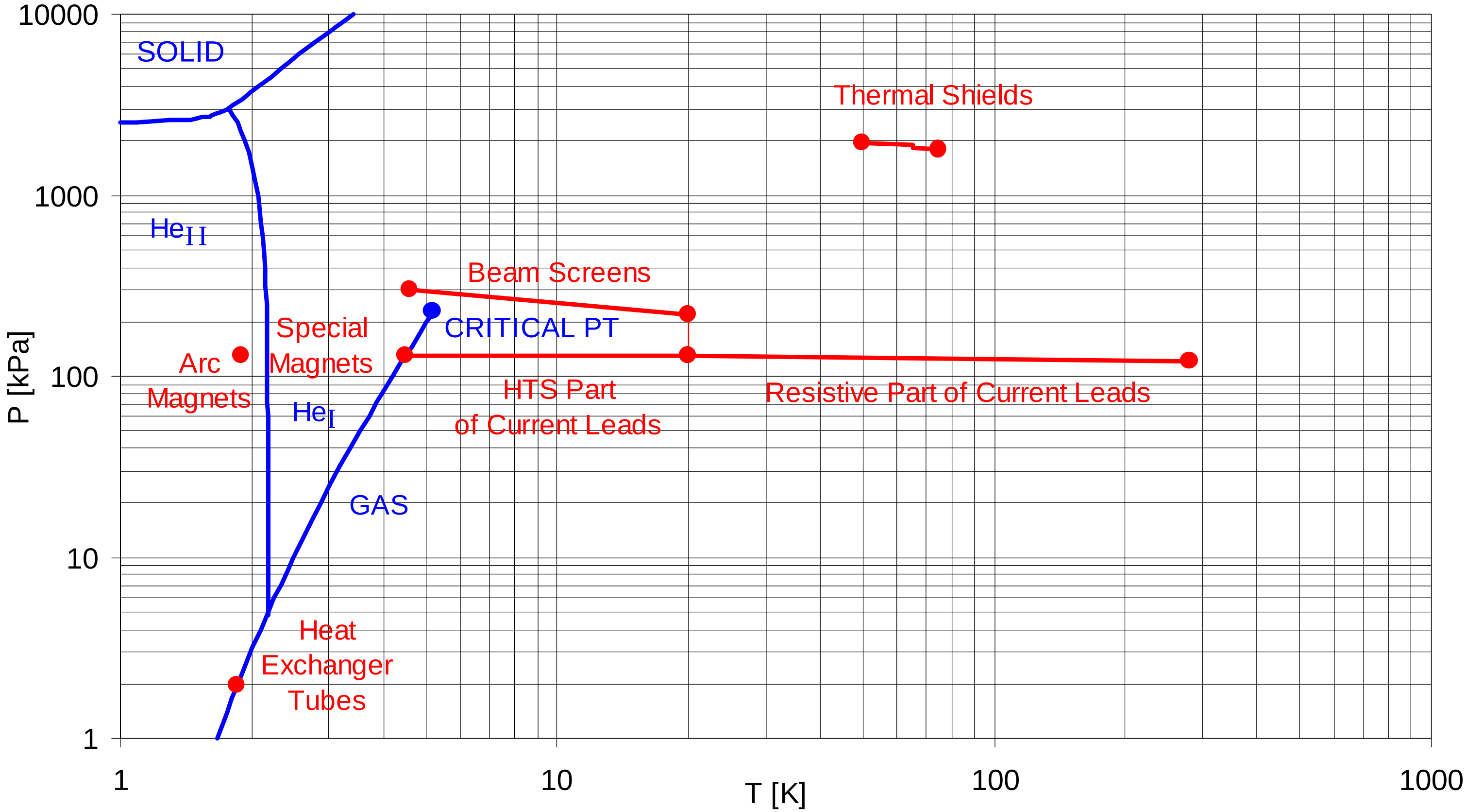
Phase diagram of helium



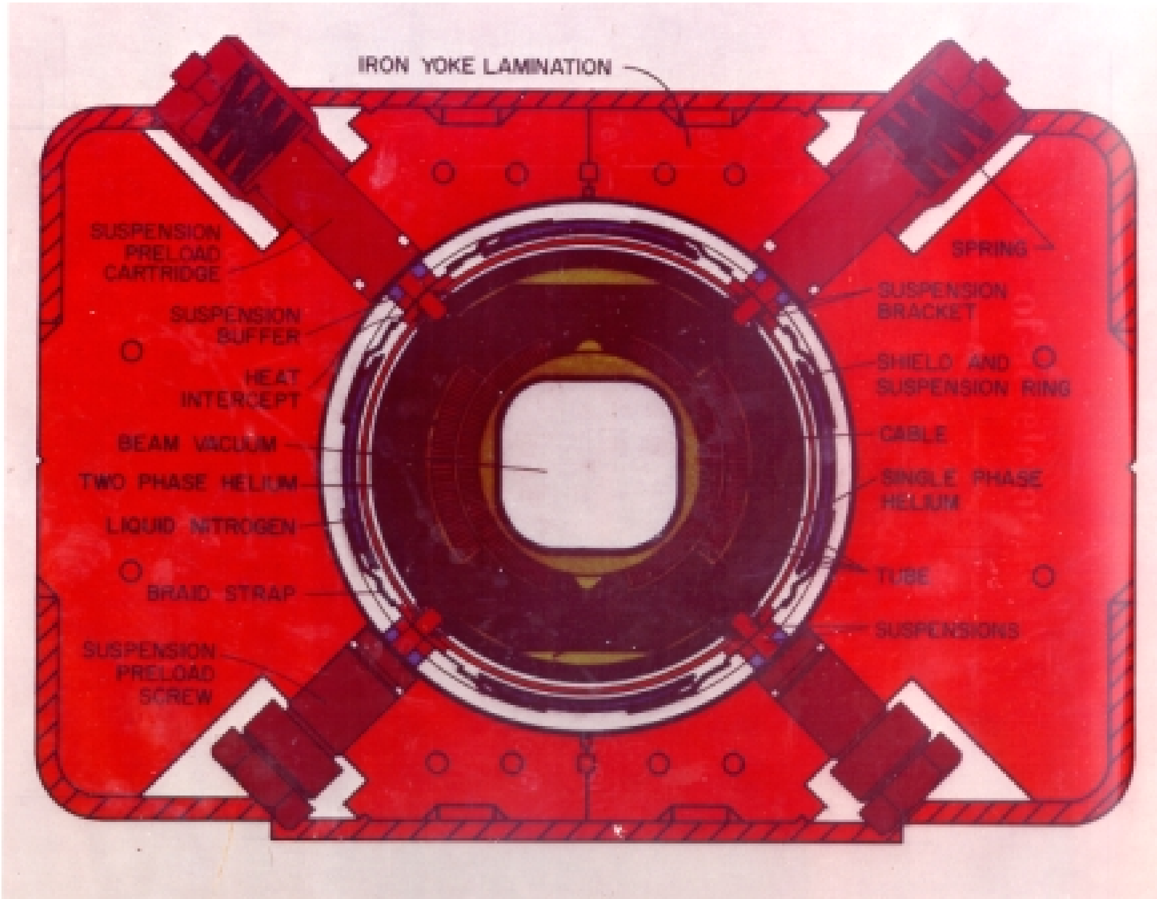
Helium as a cooling fluid

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

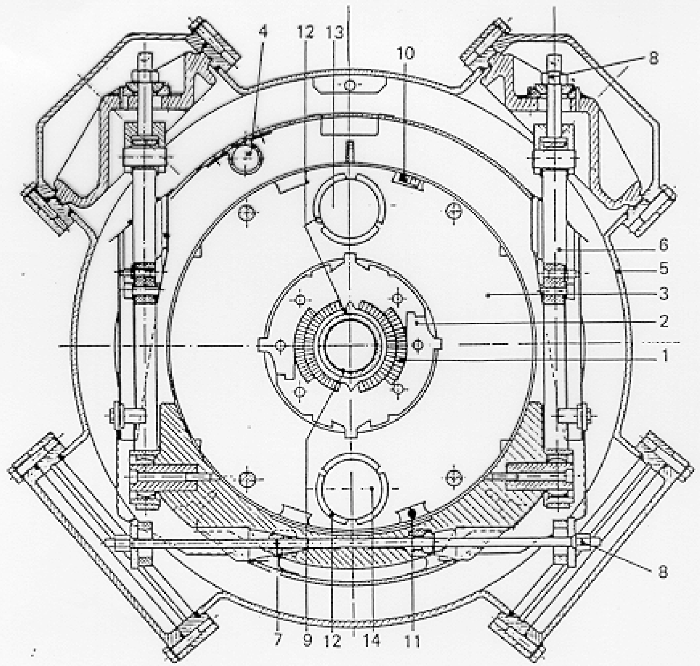
Thermodynamic states of He in the LHC



Tevatron Cryomagnet Cross-section



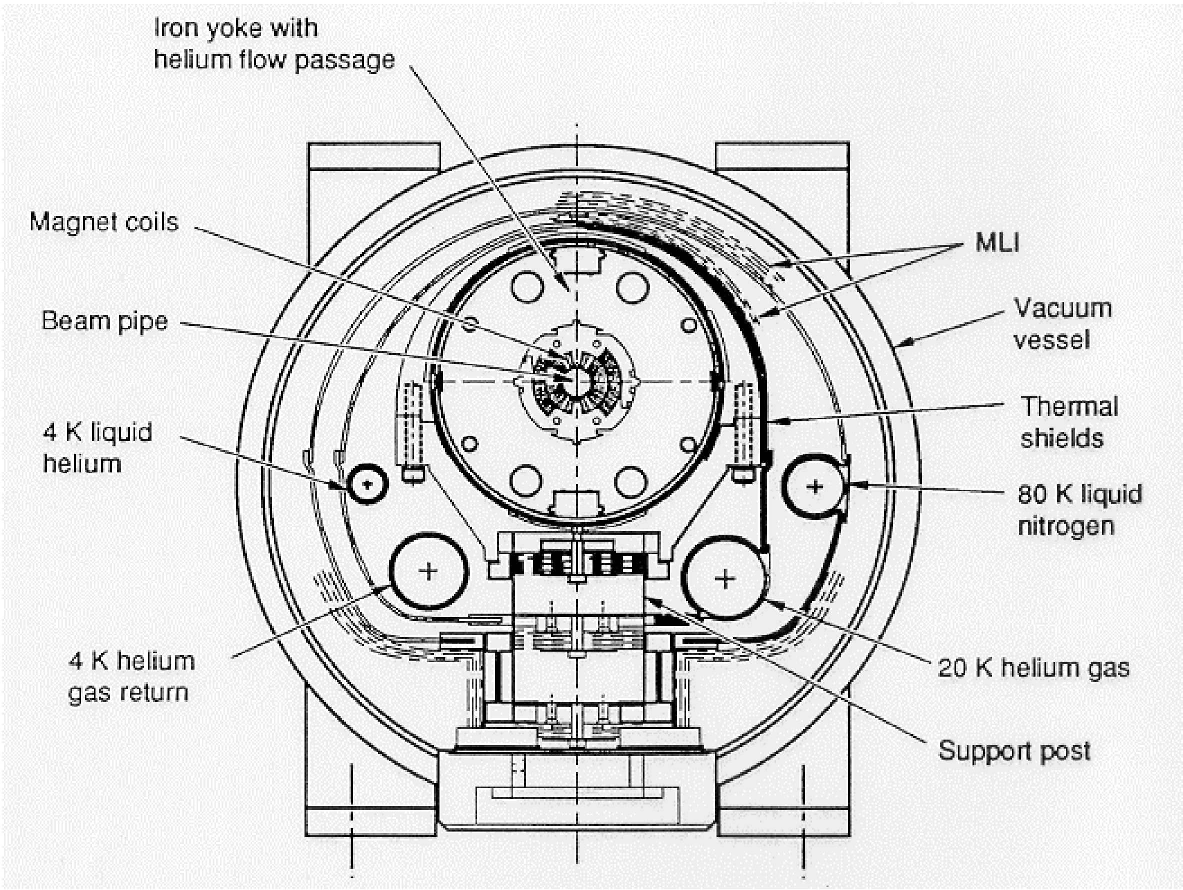
HERA Cryomagnet Cross-section



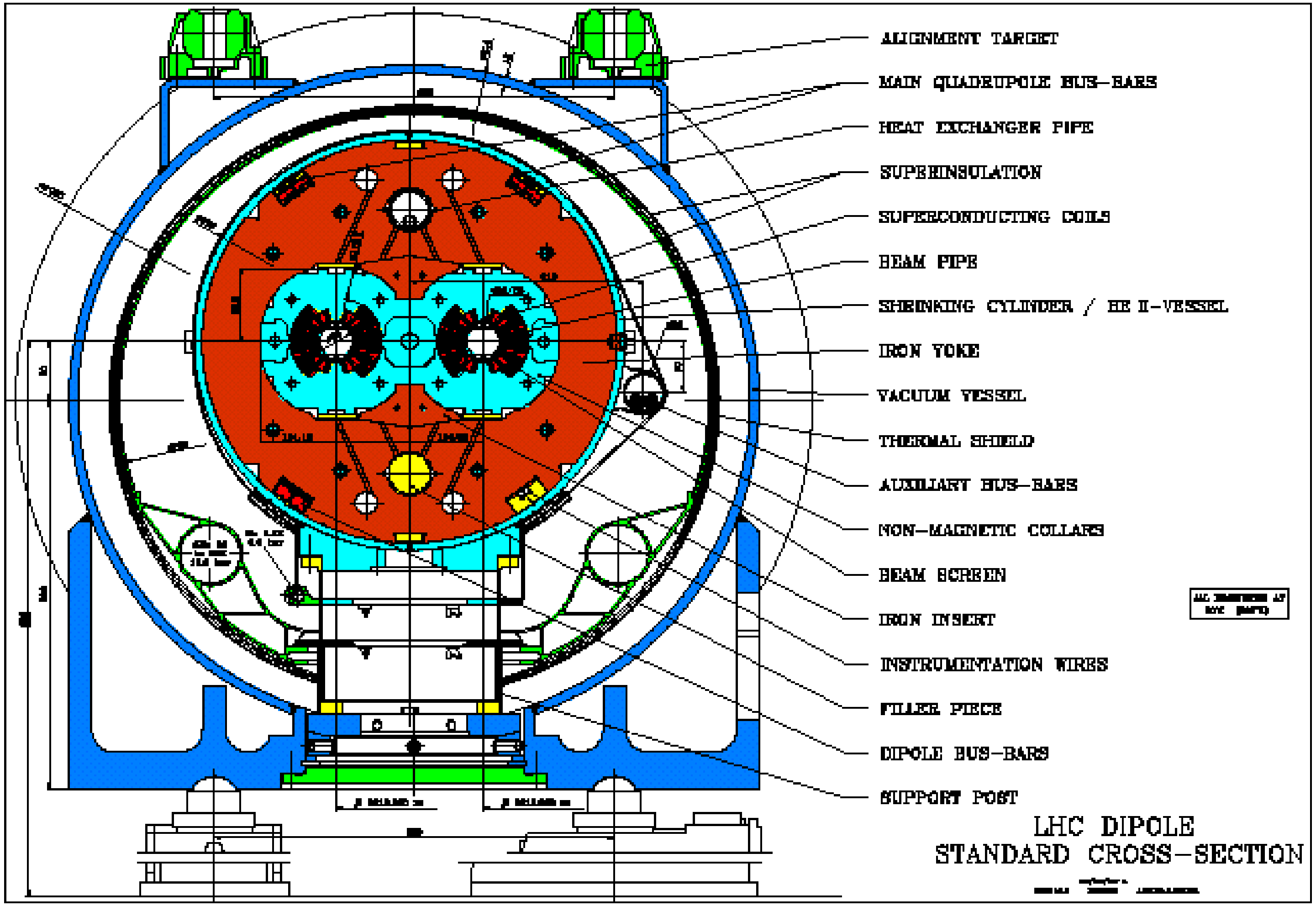
HERA Dipole Cross Section

(1) Two layer coil
(2) Laminated aluminum collars
(3) Laminated yoke
(4) Shield coooling tube
(5) Vaccum container
(6) Glass fiber tape
(7) Glass fiber rod
(8) Adjustment
(9) Beam tube with correction Coils
(10) Forward and return bus
(11) Correction coil bus
(12) One-phase helium
(13) Two-phase helium
(14) Aluminum filler

SSC Cryomagnet Cross-section



LHC Cryomagnet Cross-section



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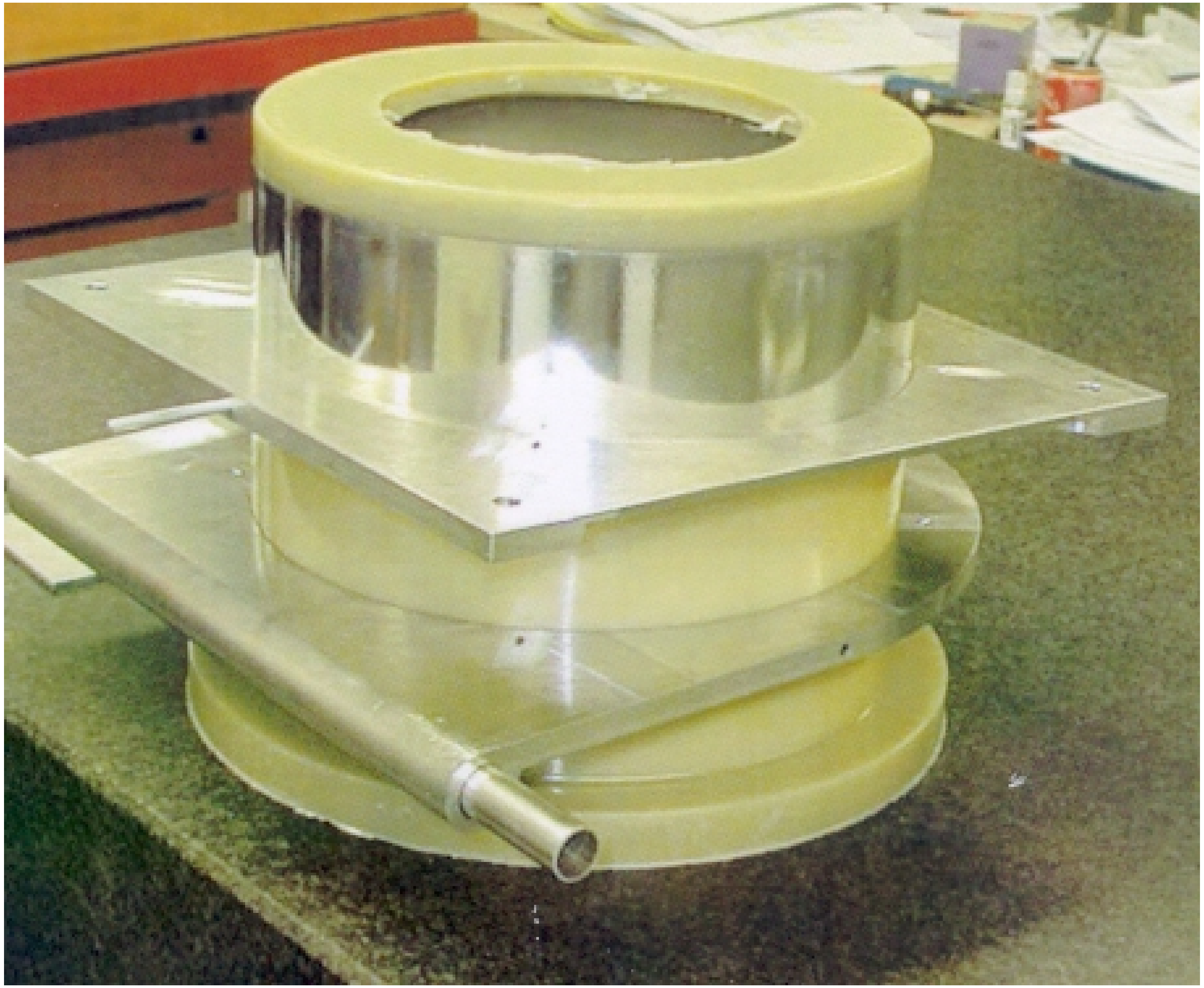
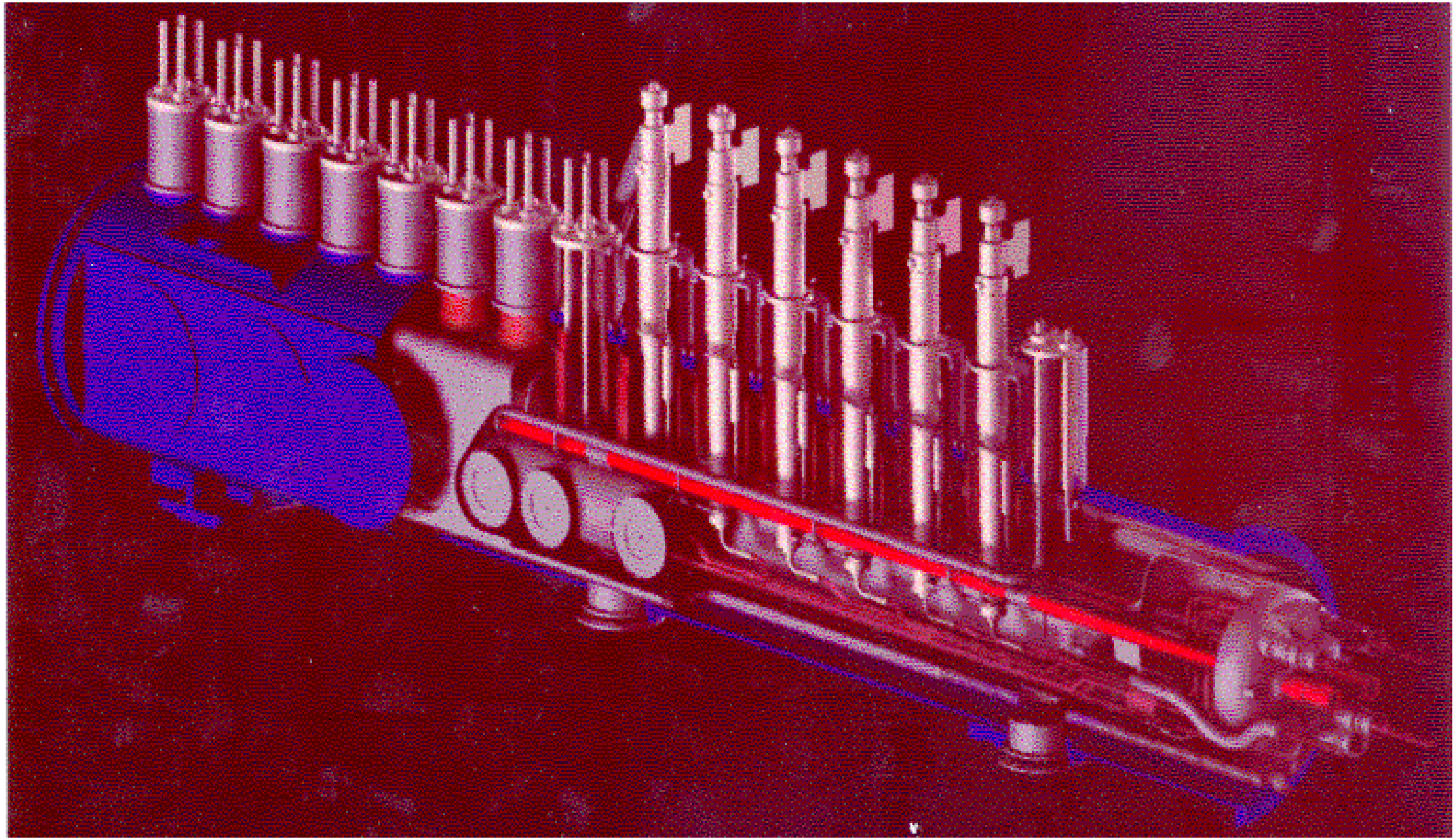
Heat Load Management in the LHC

- 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
  - Current leads — HTc superconductors
- Beam-induced heating
  - Synchrotron radiation }
  - Beam image currents } 5-20 K beam screens
  - Acceleration of photoelectrons }

GFRE Support Post for LHC Cryomagnet



LHC Electrical Feedbox



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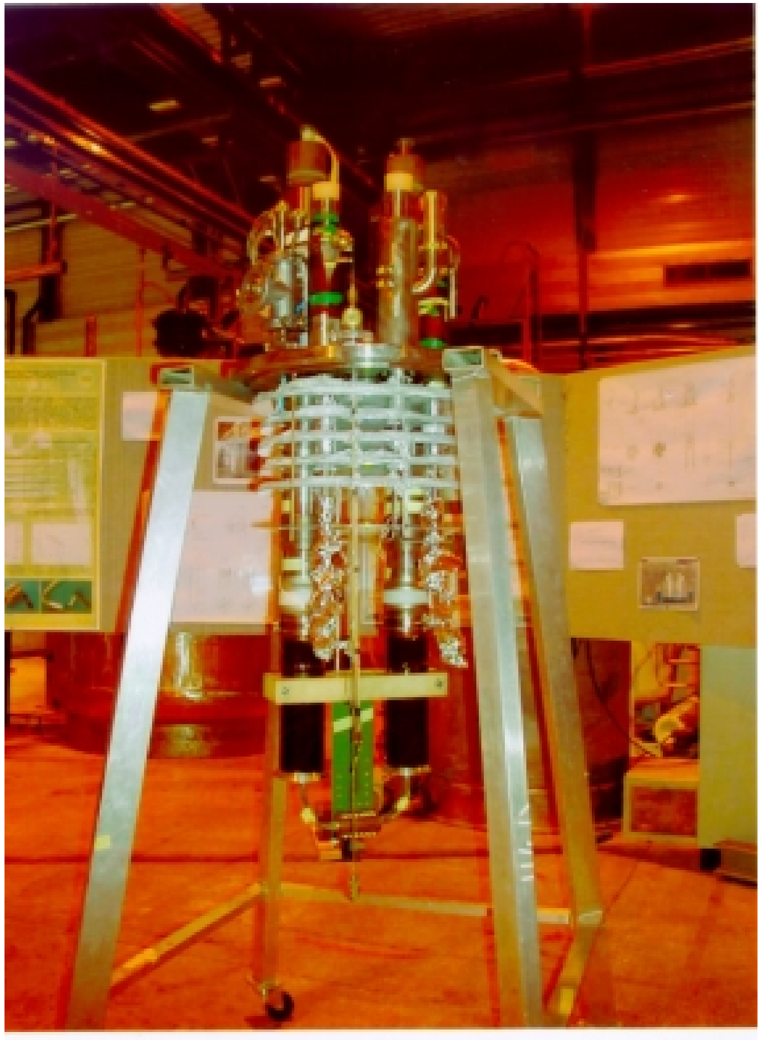
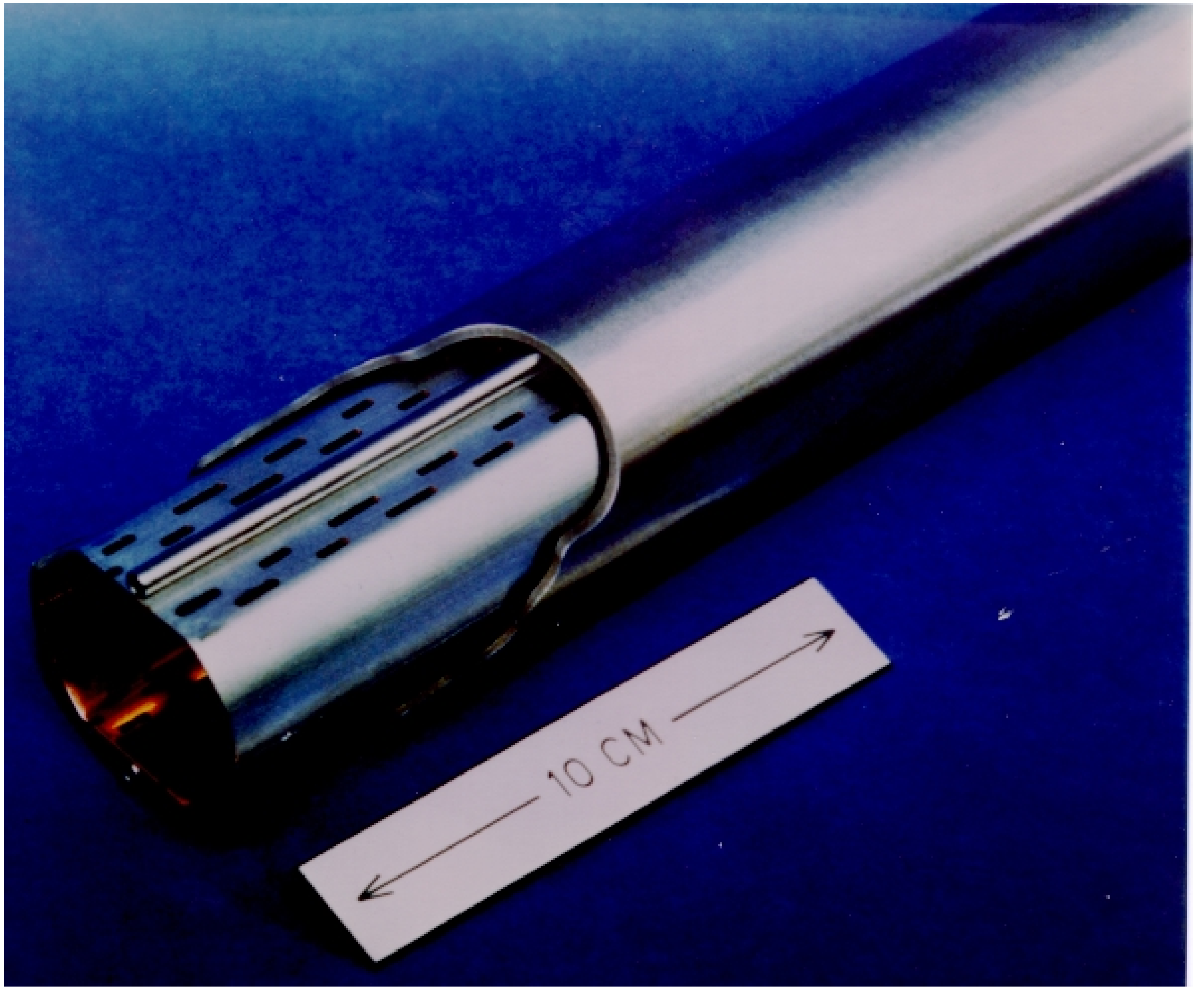
Prototype 13 kA HTS Current Leads



HTS vs. Resistive Current Leads

Type	Resistive	HTS (4 to 50 K) Resistive (above)
Heat into LHe	1.1 W/kA	0.1 W/kA
Total exergy consumption	430 W/kA	150 W/kA
Electrical power from grid	1430 W/kA	500 W/kA

LHC Beam Screen



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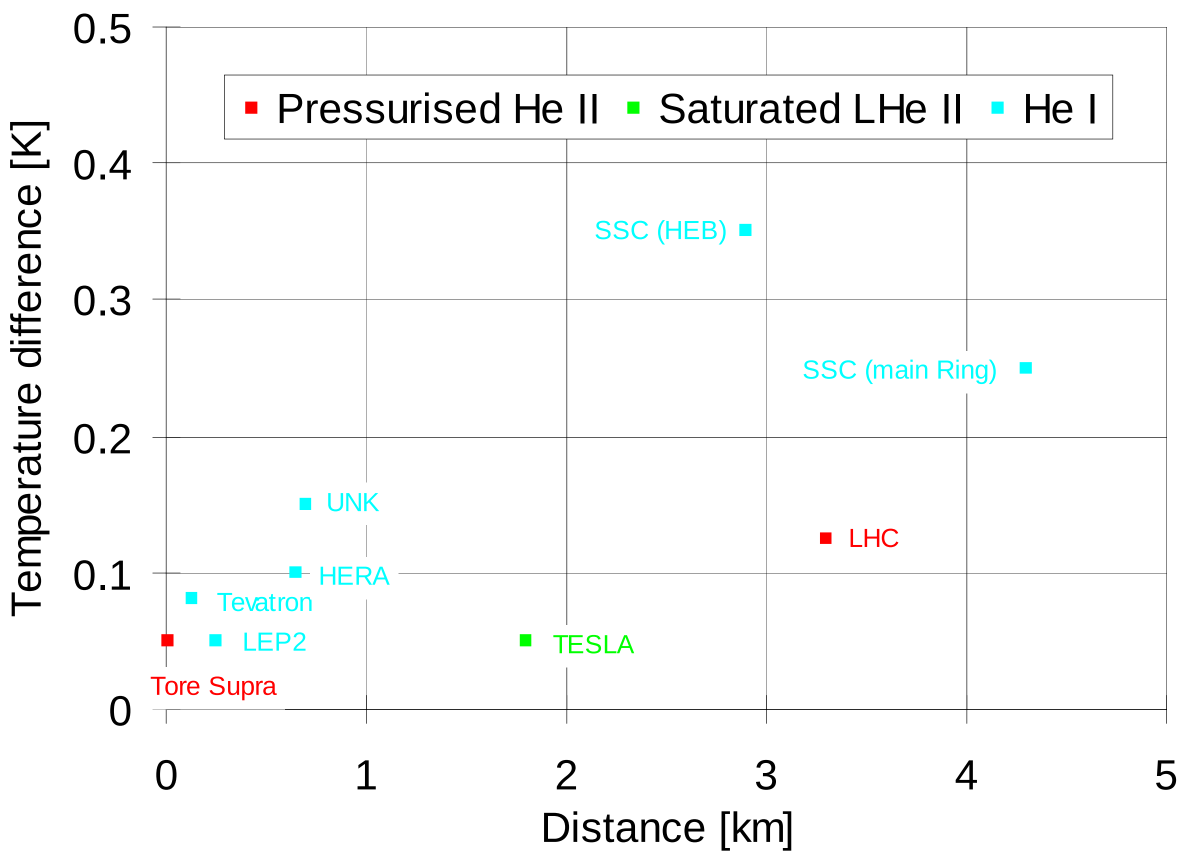
Transport of Refrigeration in Large Distributed Cryogenic Systems



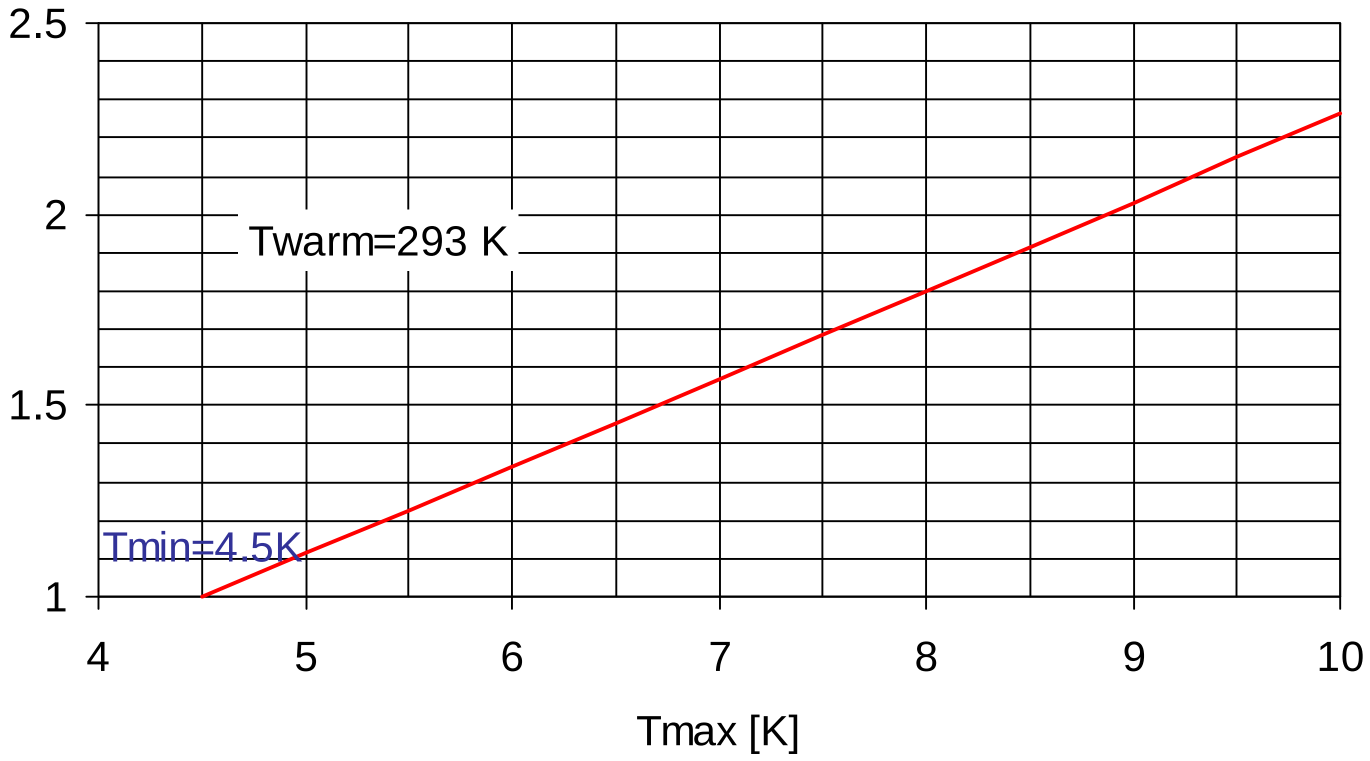
Cryogenic distribution scheme: design considerations

- Accelerator geometry & site topography
- Heat transport performance
  - temperature range & allowable ΔT
  - temperature stability vs. applied heat load
  - ultimate cooling power transported
  - flow & pressure drop
- Sectorisation & redundancy
- Capital & operation costs
- Installation & maintenance

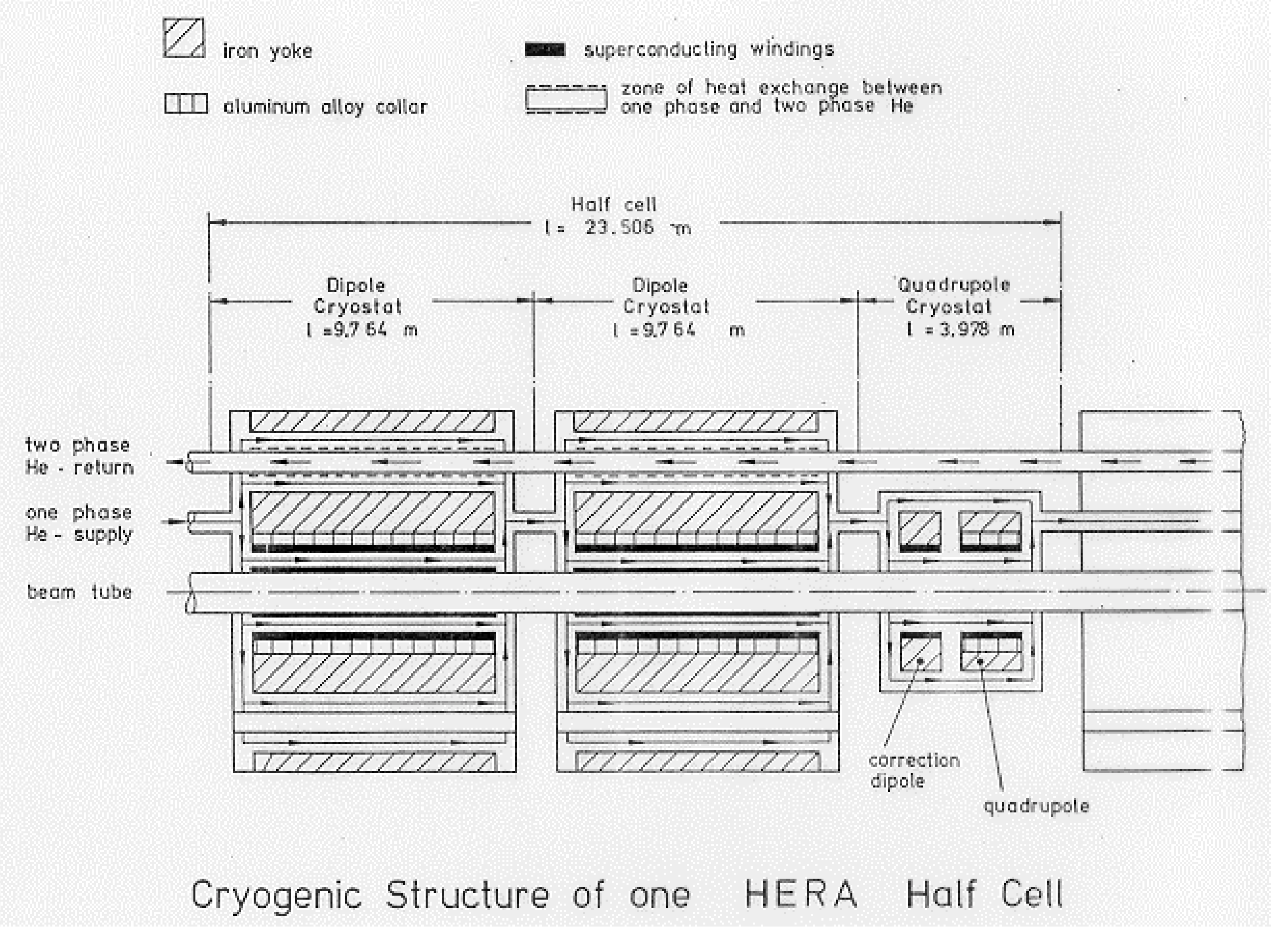
Cryogenic Distribution Scheme: Design Issues

- Monophase vs. two-phase
  - temperature control
  - hydrostatic head & flow instabilities
- Pumps vs. no pumps
  - efficiency & cost
  - reliability & safety
- LN2
  - capital & operating costs of additional fluid
  - safety in underground areas (ODH)
- Separate cryoline vs. integrated piping
- Series vs. parallel cooling loops
- Number of active components (valves, actuators)

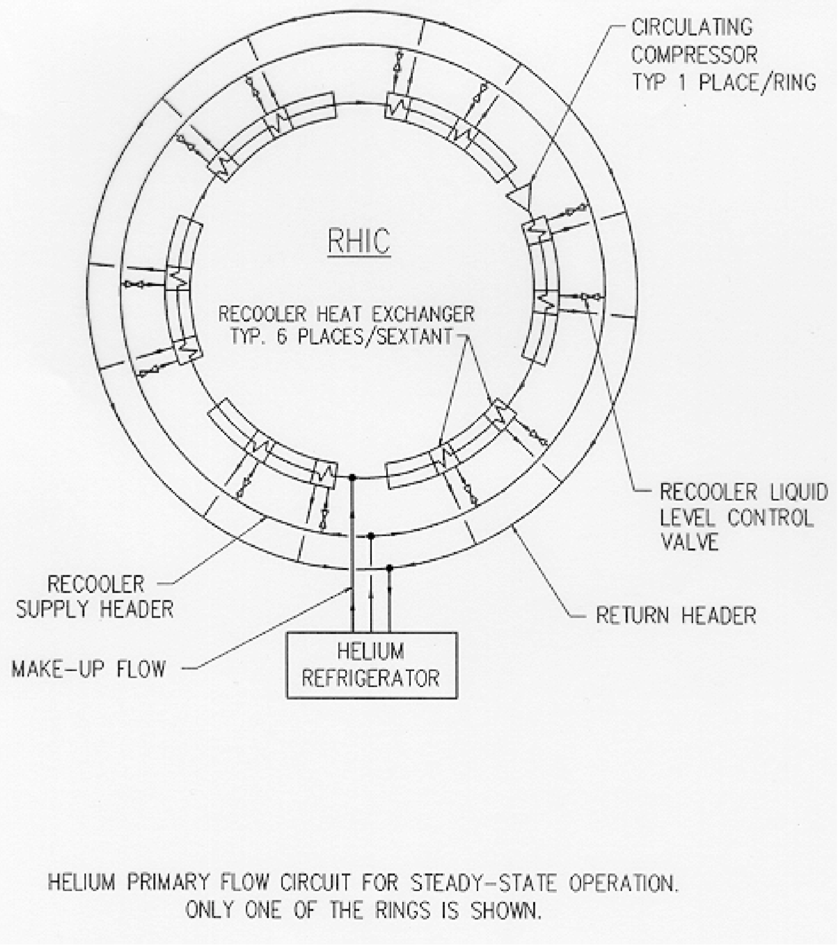
Relative Exergy of Refrigeration in Non-isothermal Cooling



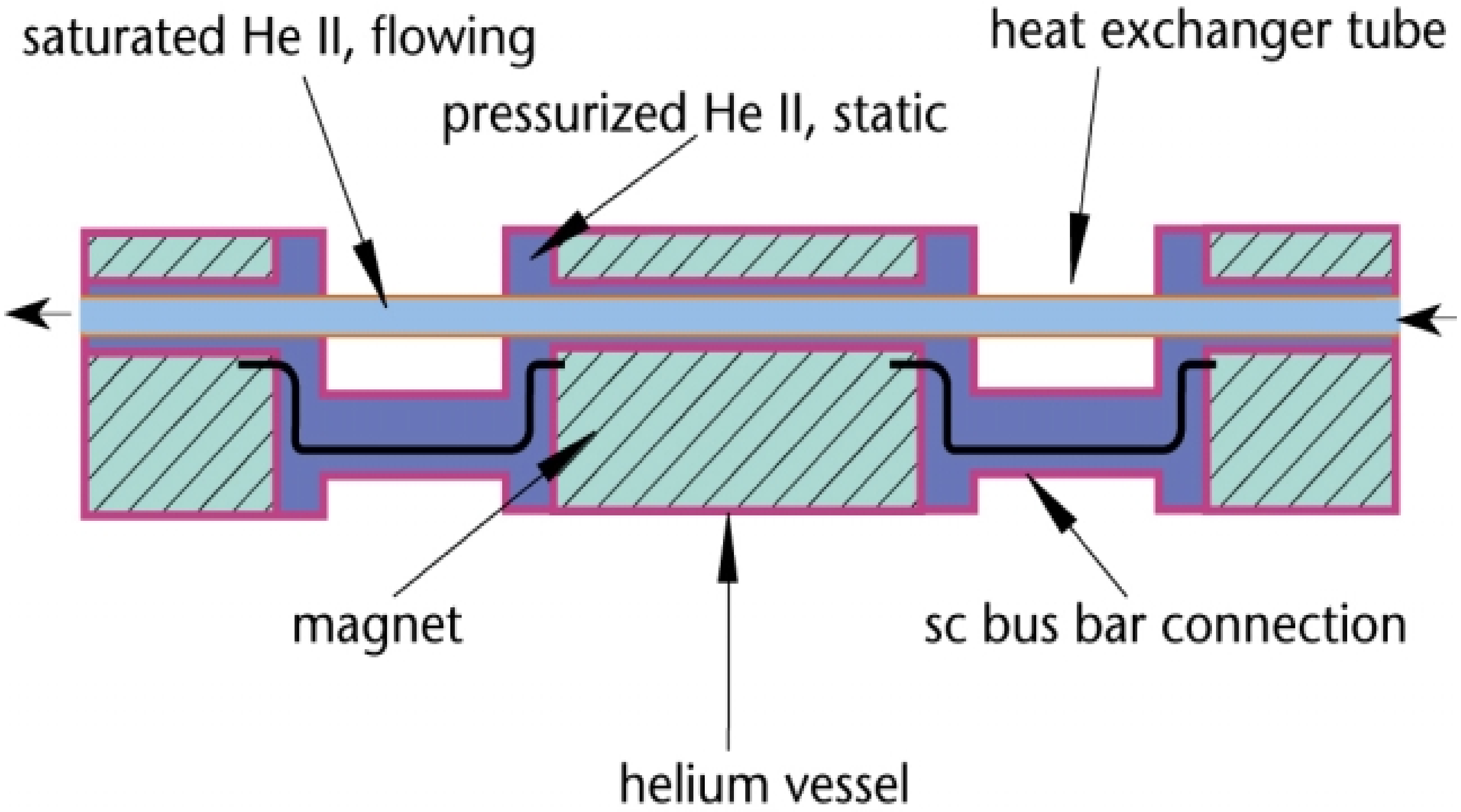
HERA Magnet Cooling Scheme



RHIC Magnet Cooling Scheme



LHC magnet string cooling scheme



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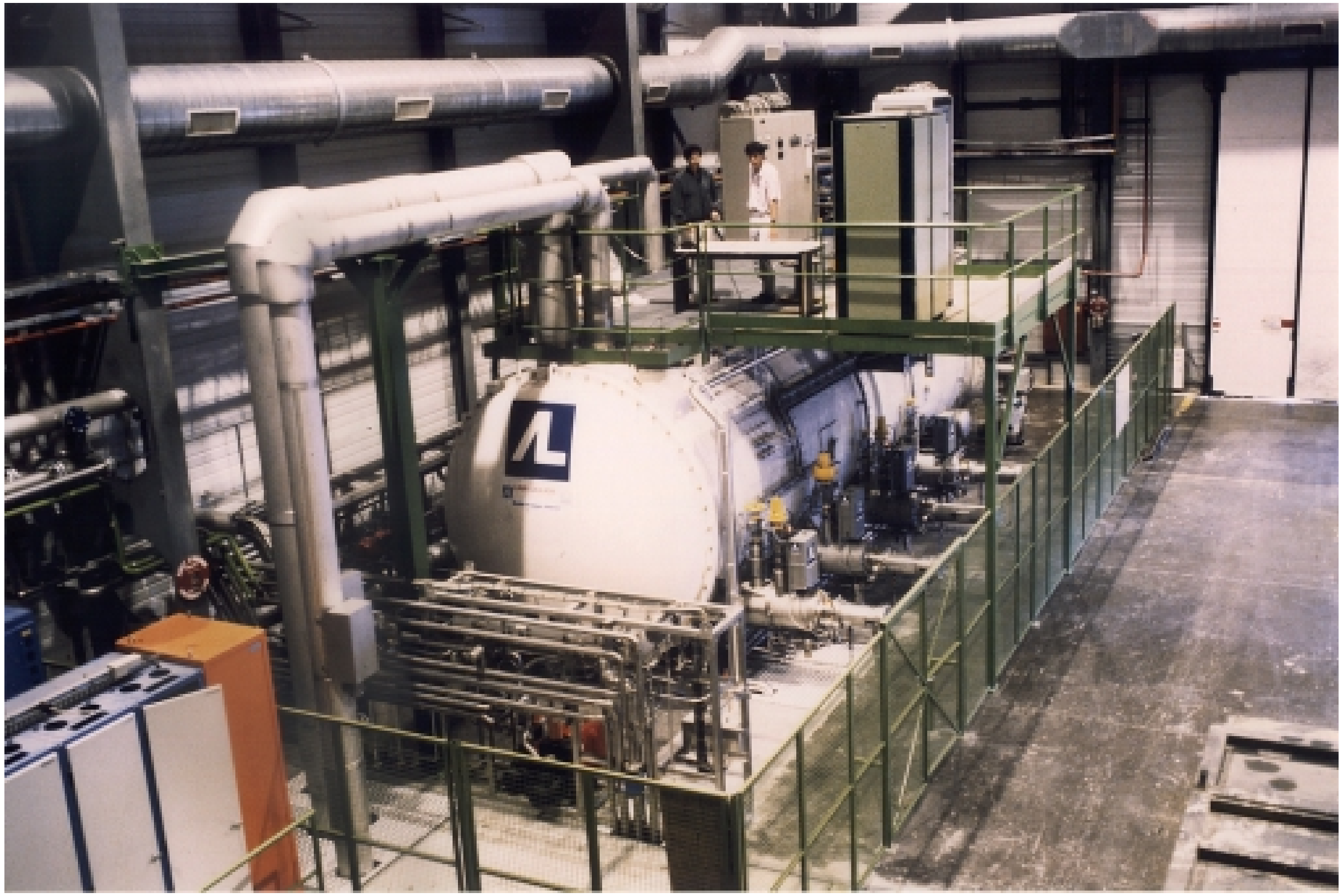
Large-capacity He Refrigerators: State of the Art

- Thermodynamics: modified Claude cycle
- Maximum unit size about 20 kW@4.5 K
  - limited by size of main heat exchangers
  - transportability of coldbox
- Efficiency 220-230 W/W (about 30 % of Carnot cycle)
  - essential operating cost driver
  - also increases compactness and reduces investment
- Turn-down capability to 50% of nominal
- Coldbox specific volume down to 5 m^3/kW@4.5 K
- Full automatic control
  - incl. automatic restart after utility failure
- Available turnkey from specialised industry
- Cost of base units well documented

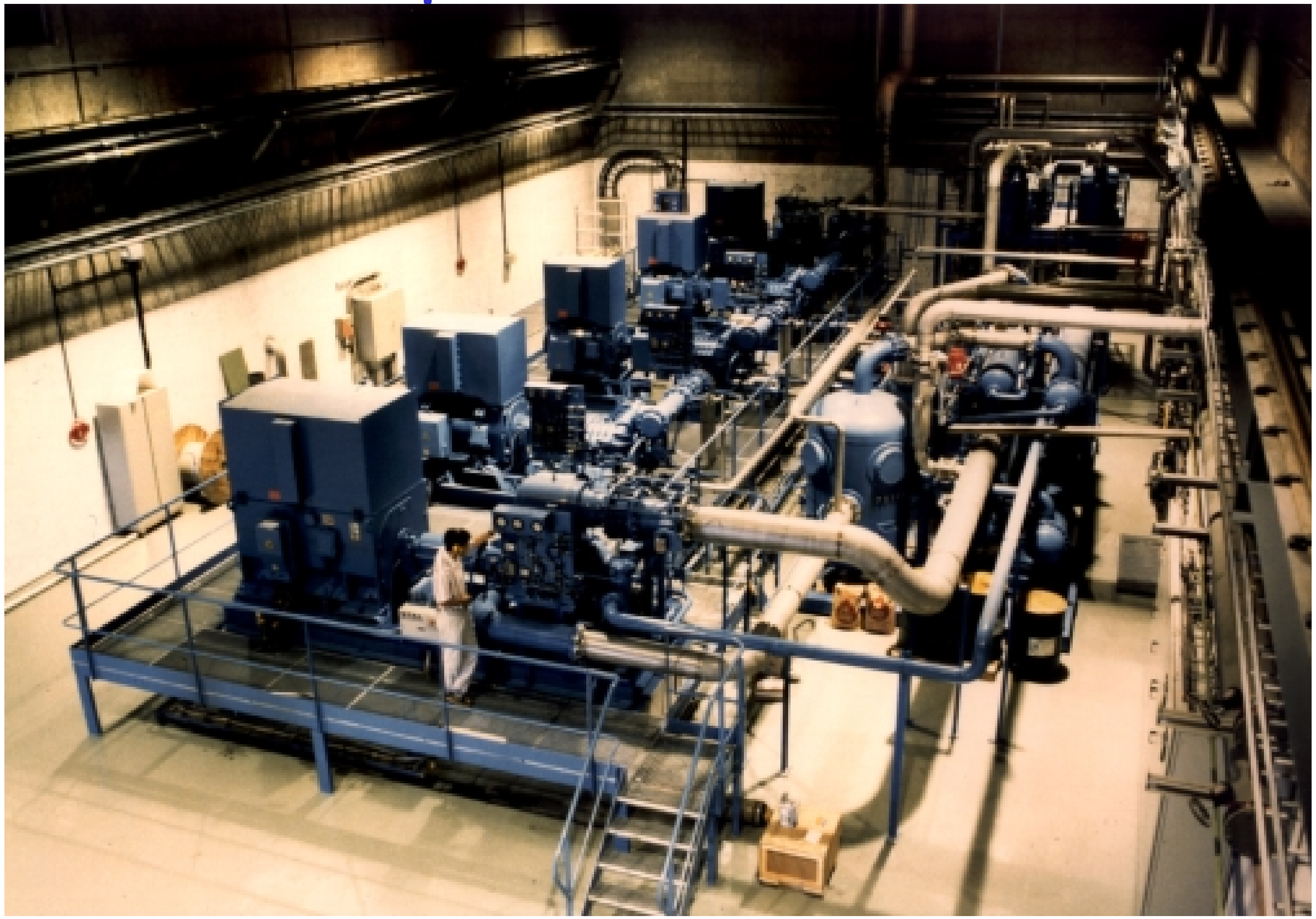
Large-capacity He Refrigerators: Technology

- Compressors
  - oil-injected screws, multistage
  - capacity adjustment by slide valve
  - maximum unit size 10'000 m^3/h, power 2 MW
  - isothermal efficiency 50 to 55 % at full capacity
- Oil removal
  - 3 stages of coalescing filters -> aerosols
  - charcoal bed adsorber -> volatile compounds
- Heat exchangers
  - brazed aluminium alloy, plate-and-fin
- Cold turbo-expanders
  - static & dynamic He bearings, maintenance-free
  - maximum unit capacity 200 kW
  - adiabatic efficiency up to 80%

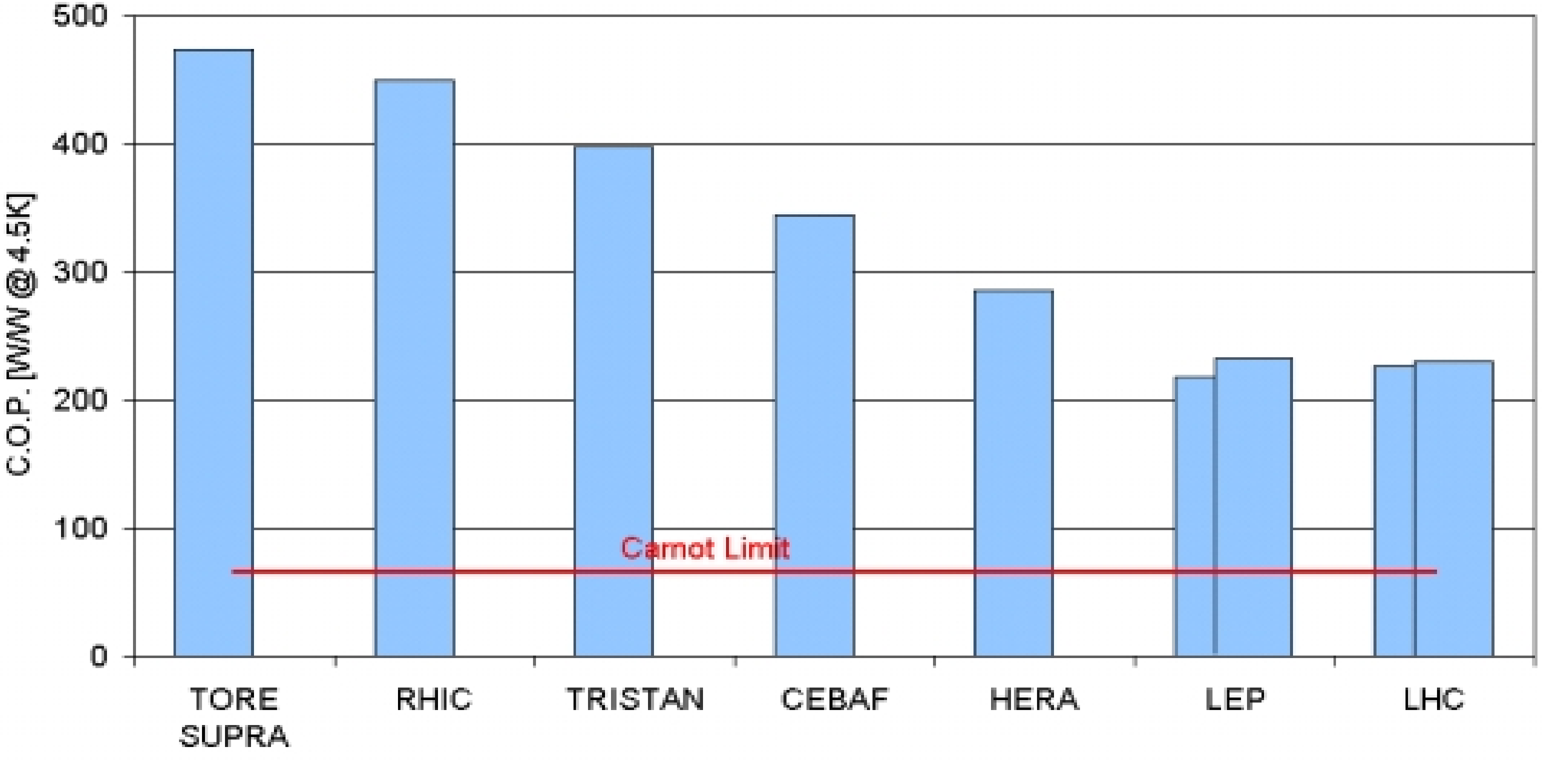
LEP/LHC Helium Refrigerator Coldbox
12/18 kW @ 4.5 K



LEP/LHC Helium Refrigerator Compressor Station



Efficiency of Large Cryogenic Helium Refrigerators



Cryogenic He Refrigerators
Capital Cost

- Covering
  - Modified Claude cycle, no permanent LN2 precooling
  - Capacity range 0.8 to 18 kW @ 4.5 K equivalent
  - Iso-exergetic assessment of mixed cooling duties
- Not included
  - LN2 precooler for cooldown of load
  - Coldbox interconnection lines & pipework
  - Process control hardware & software
- Best practical fit

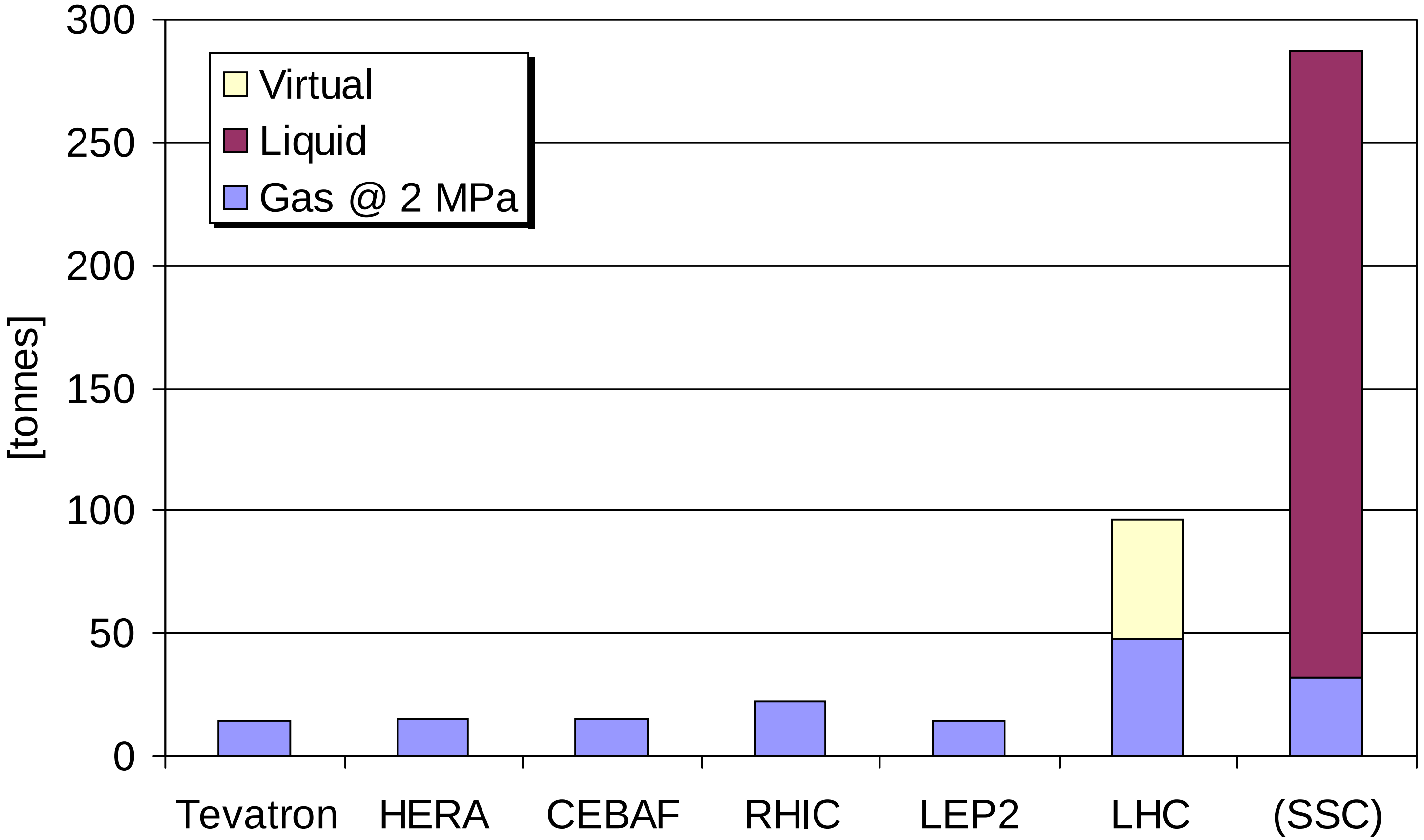
$$\text{Cost} = 2.2 \times \text{Capacity}^{0.6}$$

[MCHF 1998]   [kW @ 4.5 K]

Cryogenic He Refrigerators Operation Cost Ingredients

- Thermodynamic efficiency (C.O.P.)
- Annual hours of operation
- Amortization time
- Mix of operating modes
- Marginal cost of electricity, incl. externalities
- Preventive maintenance
- Helium losses
- Manpower

Helium 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

Instrumentation, automation & process control

- Thermometry
  - precision over large range -> single sensor?
  - stability over time, thermal cycles
  - radiation resistance
  - individual calibration and non-linear conversion
- Advanced control techniques
  - cryogenic processes non-linear, control of pure delays
  - Model-Based Predictive Controllers vs. PID
- Field buses & “intelligent” positioners
- PLC-based SCADA systems

Conclusions

- Large-scale cryogenics for accelerators operational for cold lengths of a few km, and unit cryogenic plants of about 20 kW@4.5 K capacity
- Extension to larger projects by multiplying number of refrigerators and cooling loops
- Efficient system design requires integrated approach (SC device, cooling scheme, cryogenic plant) from early project stages
- Components & subsystems available turnkey from specialised industry, at market prices

Some References

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