TECHNOLOGY OF CRYOGENICS FOR STORAGE RINGS

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Abstract

Large scale refrigeration systems as installed or planned for big hadron colliders or lepton storage rings are used as examples to describe the technology of cryogenics for accelerators. The different principles used, the different helium properties utilized, the technologies employed, the different components needed and the different schemes being realized to assure uninterrupted and efficient cooling together with a flexible use of the systems for cool down, warm up and steady state operation are described in the most essential points.

1 INTRODUCTION

Superconducting magnets and superconducting cavities represent the key technology for modern high energy particle accelerators. Existing and planned (or discarded) large hadron accelerators and storage rings like RHIC[1], TEVATRON[2], HERA[3], (UNK)[4], LHC[5], (SSC)[6] use superconducting magnets to guide and focus the beams up to energies in the TeV region. Lepton accelerators and storage rings like CEBAF[7], TRISTAN[8], HERA-e[9], LEP200[10] or the planned linear collider TESLA[11] use superconducting cavities. These accelerators are examples for large scale cryogenic systems showing the application of well developed cryogenic technology in different cooling schemes and representing the state of the art at the time of their design. Common to all designs is the use of big helium refrigerators or liquifiers together with large scale cryogenic distribution systems. The continuous efforts of laboratories together with industry rendered it possible to adapt this technology to the individual needs of the accelerators. Cryogenic systems have to allow for a flexible operation to cope with the different requirements like cool down, warm up, stable operation, cooling of static and dynamic heat loads, quench recovery and standby modes to allow for maintenance, repairs etc.. High efficiencies (e.g. 30% of carnot) reduce operational costs and high reliability and a high degree of availability (99%) is necessary for an uninterrupted accelerator operation. With the increase of beam energies the growing size of new accelerators and correspondingly that of the cryogenic systems set new limits to refrigeration systems in terms of size, refrigeration power, temperature ranges, operational modes, efficiencies, flow conditions and cooling principles. Triggering impulses for new developments and experience with large scale refrigeration is coming also from large experimental fusion projects like e.g. Tore Supra, Wendelstein, LHD or ITER which are described elsewhere [12]. Fig.1 shows the increase of cooling power for the biggest hadron accelerator projects. Though the amount of cold mass increases with the size of the accelerator the installed refrigeration power per ton of cold mass tends to decrease with new generations of cryosystems. This may be the reflection of improved cryostats with minimized heat loads together with higher efficiencies of new refrigerators and cooling circuits. Refering to the existing or planned refrigeration systems of the above mentioned accelerators this paper describes the different cooling principles used, their differences, the underlying technology, the present status and the envisaged developments. There are a lot of detailed papers and lectures describing the same topics [13], [14].

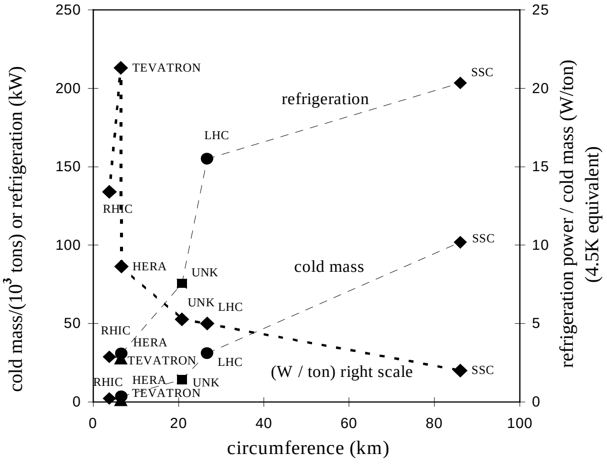

Figure 1: Refrigeration at different big accelerators

2 TASKS OF THE CRYOGENIC SYSTEM

The main tasks of a cryogenic system and the corresponding devices and procedures needed are the following: *Production of refrigeration power* (compressors, refrigerators / liquifiers), *distribution of the cryogen* (transfer lines, dewars, distribution valve boxes*), supply and cooling* of components or groups of them (precooler, dewars, heat exchangers, supply valve boxes, cryostats, warm tubing and gas supply), *variability and flexibility* of refrigeration to handle different modes of operation, *process control and monitoring* of temperatures, pressures, mass flow rates, stability control (sensors, computers, network, software, operating procedures, alarming, data aquisition, visualisation and archieving), *cryogen recovery* (closed circuits, gas collection lines, leak tightness), *storage* of helium as liquid or gas (dewars, bags, tanks, pressure vessels), *helium purification* (filters, separators, adsorbers, purifiers, gas analysers), handling of *safety aspects* (pressure relieve, safety concept, material certification, safety rules, technical examinations), *accommodation* to accelerator buildings and tunnels. These tasks and installations are common to all cryogenic systems. Differences can be

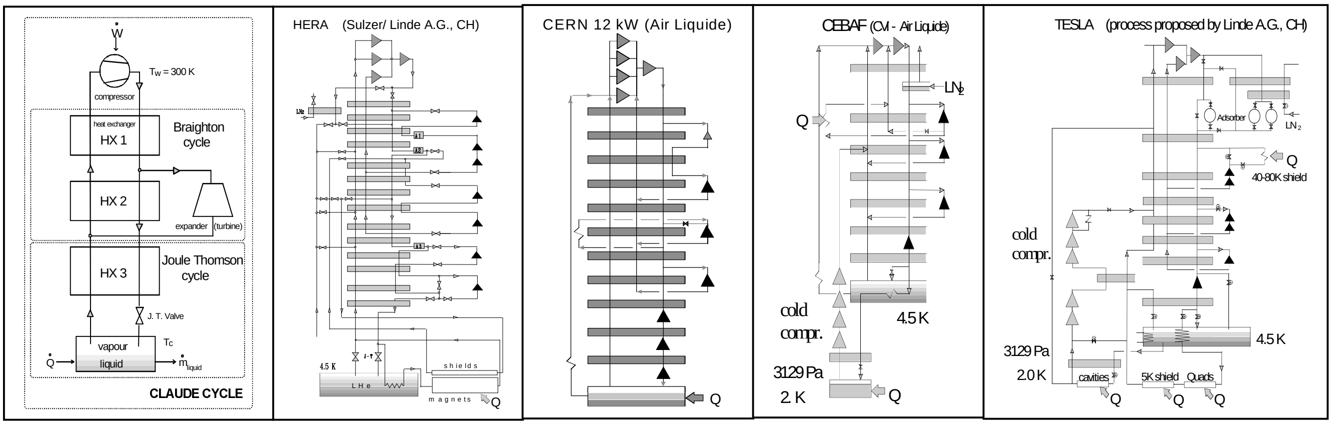

Figure 2: Layout of Coldboxes

found in the choice of cooling principles, optimization of operating conditions, sectorisation and redundancy concepts and the choice of machine components like compressors, turbines etc. which use different technologies.

3 REFRIGERATORS

Modern and high power helium refrigerators are using a modified Claude cycle which is a combination of a Joule Thomson and a Braighton cooling cycle (fig.2). Since for helium the Joule-Thomson effect sets in below its inversion temperature at about 40K (real gas behaviour) effective cooling by isentropic expansion through a nozzle or throttle valve starts only below 10K and $20*10^5$ Pa and is thus reserved to the low temperature end of a cryogenic cycle. So the helium temperature of the main flow has to be lowered by a series of heat exchangers which are cooled by a separated stream delivered at $\approx 20*10^5$Pa from a helium compressor system. The cooling is produced by the extraction of mechanical work during an adiabatic expansion in an expansion machine. Nowadays oil lubricated screw compressors and turboexpanders with friction free gas bearings (static or dynamic) became standard technology. Both components have a high intrinsic reliability. Compressors run more than 25000 hours without maintenance, turboexpanders running at high rotational speed (>100000 rpm) more than 40000 hours. For more than 1 kW refrigeration power at 4.5K, 2 to 7 turbines are arranged at different temperature levels which at the end expand to the suction pressure of the main compressors either at their first (atmospheric pressure) or second (2 to $4*10^5$Pa) compression stage. High purity helium (few ppm impurities) is required in order not to disturb expander wheels or block flow channels in the standard plate fin aluminum alloy heat exchangers by frozen particles of contaminating gases. Figure 2 shows the layout of existing or proposed coldboxes for different accelerators. The large amount of expansion turbines and heat exchangers reflects the optimization of the cryogenic cycles with respect to flexible cooling demands at high efficiencies. Special optimizations were performed at the low temperature ends of the coldboxes. The maximum theoretical cycle efficiency is the carnot efficiency $\eta = T_{cooling}/(T_{ambient} - T_{cooling})$ which is 1.49% at $T_{cooling}$= 4.4K. Practical efficiencies are $\eta_{total} = \eta_{compressors} * \eta_{coldbox} * \eta_{carnot}$. They are determined by the compressor and coldbox efficiencies which are typically slightly above 50% each (55% for LEP2 and LHC). Their product (% of carnot of a cycle) has reached for best machines up to30%. The inverse (specific power consumption) expresses the amount of primary power which has to be invested for 1Watt of refrigeration and is a direct measure of the cost factors to produce 1 Watt of refrigeration. Typical values are 25W/W at $T_{cooling}$=60K, 250W/W at 4.4K, 800W/W at 1.8K. Figure 3 shows the efficiency improvement achieved in the last years.

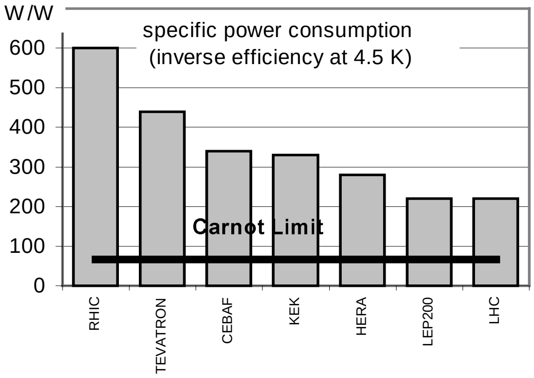

Figure 3: Specific power consumption of refrigerators

Refrigerators operating at 2 K (CEBAF, TESLA) or lower (LHC: 1.8-1.9K) need to pump on a liquid helium bath to lower the saturation vapour pressure down to values below 31 hPa. The pumping (helium compression to atmospheric pressure) can be done at warm or at cryogenic temperatures or in a mixed mode. Warm pumping stations like roots pumps (high compression ratios), rotary vane pumps (limited volume flow), liquid ring pumps (good cooling, high compression ratio) or combinations of them are being used e.g. at CERN and DESY for test facilities. Operating with warm tubing at subatmosheric pressures makes the system sensitive to air inleaks. The large size of such pumping systems (very high volumetric flow rates at low gas density) and the large and expensive heat exchangers with low pressure drops which are necessary to recover the enthalpy of the pumped cold helium vapour are reasons to better use cold compressors. The techniques developed for expansion turbines can preferably also be used for cold centrifugal compressors. They deliver compression ratios of 2.5 to 3. Because of the high total compression ratio of >60 (at 1.8K, 16 hPa) which is needed to exhaust to the suction of the warm compressors, a series of e.g. 4 to 5 compression stages is necessary (fig. 2). Cold compressors with active magnetic bearings are industrially available[15] and are running at Tore Supra [16] and CEBAF (4 compressors). At the TEVATRON 24 (+3) cold compressors with gas foil bearings are being used to lower the magnet temperatures from 4.6K down to 3.9K [17]. At HERA the temperatures could be lowered to 4K just by lowering the suction pressure of warm compressors to subatmospheric values [18]. The need for LHC will be 24 to 40 and for TESLA $\approx$70 cold compressors. Further development of industrially produced cold compressors is necessary (see section 8).

4 LAYOUT OF CRYOGENIC SYSTEMS

The cooling stations and refrigeration plants can be located as central plants (RHIC, CEBAF, HERA), as distributed systems (SSC, LEP200, LHC, TESLA) or as a mixture with a central liquifier and distributed satellite refrigerators (TEVATRON, UNK) as described in ref. [19]. At central plants maintenance and local checks can easily be performed at a single location and a pool of redundant machinery and spare parts can be installed there. Disadvantages are the long distribution systems with unwanted pressure drops or long cold tubings (transfer lines) with large diameters. Distributed satellite systems need access to the tunnel at several locations (24 at TEVATRON and UNK). The helium can be compressed near to the accelerator components because it returns warm from the satellite refrigerators. Thus pressure drops in the helium return header which increase the temperatures in the accelerator components can be lowered. A cryogenic transfer line is needed to supply the satellites with pressurized liquid from the central liquifier. Large accelerators with lengths of some tens of kilometers like SSC, LHC or TESLA do not suggest central plants. The total cooling power needed in these accelerators, (fig.1), is larger than single cryogenic plants can deliver nowadays (<20kW at 4.5K). The refrigeration stations are located at several locations along the accelerators to supply the cooling power to strings of magnets or cavities (SSC design: 10 locations with 2 coldboxes, each supplying 2 strings of 4.3 km length; LHC: 3*2 + 2 stations supplying 8 sectors of 3.3km length, TESLA: 7 locations, each with 2 coldboxes supplying 12 unit sections of 2.5 km length)

5 COOLING PRINCIPLES

The cooling principles used to cool the accelerator components (magnets or cavities) are mainly determined by the temperature range of operation, the heat loads (dynamic and static), the helium flow conditions (single or two phase helium, accelerator slope), the heat exchange and heat transport conditions (precooling, recooling, heat extraction), the allowed pressure levels (magnets: $\approx 20*10^5$ Pa, cavities: $\approx$ 2 to $3*10^5$ Pa) and the spatial distribution of the cold components (accelerator length, accessability to the tunnel etc.). The properties of helium [20] naturally define four ranges of operation which are indicated in figure 4:

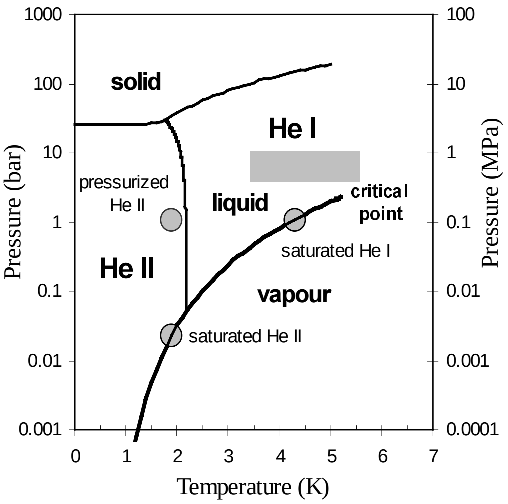

Figure 4: Helium phase diagram: p vs. T

Saturated HeliumI at about atmosheric pressure with a temperature of 4.35K is used for bath cooling (pool boiling) with the following characteristics: heat fluxes of 20 W per 1 g/s of helium flow is absorbed by the latent heat of helium. The helium is boiling at constant temperature, defined by the equilibrium vapour pressure in the cooling loop (normally established by the suction pressure of the helium compressors). High heat transfer at small temperature differences (up to 1 W/cm^2 in the nucleate boiling region). S*upercritical, single phase Helium I*: Above the critical pressure (2.275_*10^5Pa) supercritical liquid helium behaves like a standard fluid, it appears only in a single phase, vapour bubbles cannot occur, since the saturation line will never be crossed with temperature rises. Flow instabilities like those in two phase flow conditions are excluded. Heat is absorbed by the sensible heat of the helium with a corresponding increase in temperature (0.5 Watt / g/s, $\Delta T= 0.1$K). This is a factor of 40 less than in the two phase cooling mode at the same helium mass flow rate (fig.5). Higher mass flow rates lower the temperature rise. Normally the maximum allowed temperature rise is about 0.1 to 0.2K and limits the maximum length of accelerator components to be cooled in series with single phase helium. The single phase helium flow has to be recooled with boiling saturated helium (heat exchangers in a liquid helium bath). For lower temperatures one has to pump on the helium bath (moving down the saturation line). Below the lambda point (2.17K) helium changes its properties by occupying new quantumstates (Bose condenstion). Outstanding properties of s*aturated Helium II* are: low viscosity (superfluidity) and extremely high apparent thermal conductivity. Whereas the latent heat nearly does not change, the thermal capacity has a pole-like peak at the lambda point, Fig 5. Cooling systems using saturated helium II operate at subatmospheric pressures between 16 and 50 hPa. Because of the extremely high thermal conductivity (≈ 10^3 x of copper) no overheating of vapour bubbles occurs (totally “quiet“ boiling) and heat can be removed without mass transport by evapouration at the surface. Together with the advantages to operate superconducting devices at lower temperatures (higher current densities in s.c. magnets, lower BCS losses in s.c. cavities) helium II offers the best properties to be used in accelerators despite it is about three times more expensive than producing refrigeration at 4.4 K. To overcome two phase flow instabilities and problems of subatmospheric operation within the accelerator components (dielectric breakdown, air contamination) *pressurized helium II* is used. It can be operated at any but comfortably at atmospheric pressure by subcooling it with saturated helium II.

For other temperature levels like shield cooling between 4.6 and 20 K or cooling of current leads, helium I is used. Thermal intercepts and shields at temperatures between 40 and 80 K are normally cooled by cold high pressure helium gas extracted from an intermediate temperature level of the refrigeration cycle. The enthalpic heat which can be absorbed by the cold helium gas is shown in Fig.5 also in comparison with an alternate shield cooling by liquid nitrogen (TEVATRON, KEK). Figure 6 shows the cooling principles used at different accelerators. Cavities are normally cooled in a saturated liquid helium bath with He I (4.4K, LEP, KEK, HERA-e) or with He II (< 2.1K, CEBAF, TESLA). Bath cooling for magnets is used for compact devices or single magnets only. Two phase flow problems like blockage of vapour flow by the liquid or blockage of liquid flow by the vapour phase (high flow speeds of vapour in countercurrent flow conditions) and local overheating (e.g. at magnet coils) by formation of vapour bubbles are reasons not to use direct bath cooling for long strings of accelerator magnets. They are preferably cooled with single phase supercritical helium. The necessary recooling of the single phase flow is optained at distinct recooler positions (SSC every 180m, RHIC every ≈105m with a recirculating single phase helium centrifugal pump). At HERA, UNK and the TEVATRON the magnets are recooled continuously by a heat exchanger tube within the magnets or a concentric tube which contains backflowing two phase helium, produced at the end of the magnet string by Joule-Thomson expansion of the supercritical helium. In the LHC design the heat exchanger tube operates at 1.8K and the magnets are filled with static pressurized helium II. Extensive studies and modelling were performed to understand heat conduction and heat transfer in static and forced flow helium II (see references in [21]).

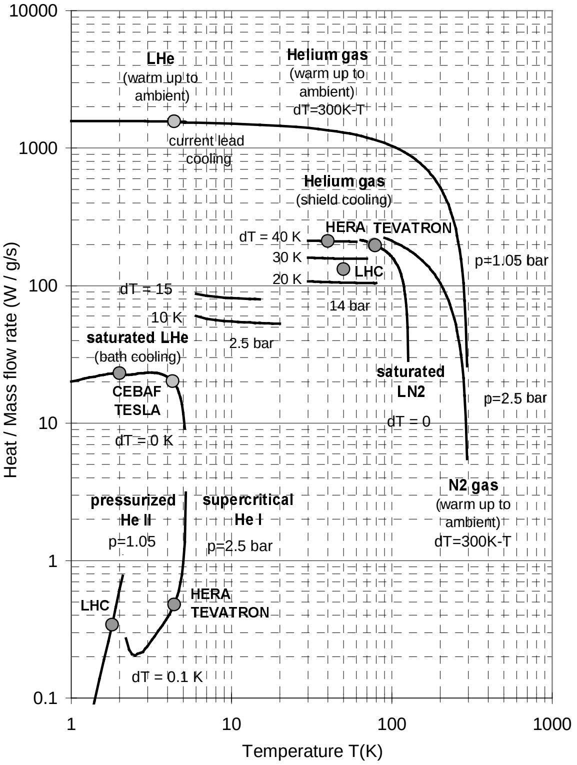

Figure 5: Enthalpy differences of helium (absorbable heat at different temperatures)

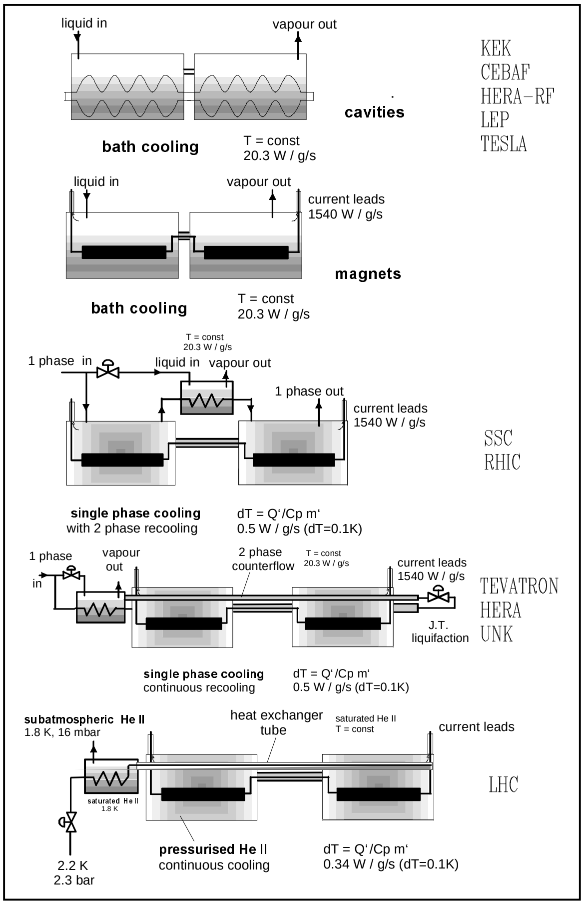

Figure 6: Cooling principles used at different accelerators

6 Cryostats

The minimisation of heat inleaks to the accelerator components in their cryostats is only one of the many *functionalities* of the cryostats. The most important of them and the standard techniques are: *Thermal insulation* (vacuum insulation at pressures: warm 10^{-4}hPa, cold 10^{-5}-10^{-7}hPa; choice of low heat conductivity materials with optimized geometries; use of multi layer reflective superinsulation: 20-30 layers between 300K and 80K, 5-10 layers below 80K, density:10-20 layers/cm; use of heat shields with active cooling to absorb heat inleaks at the highest possible temperature level resulting in about: <1.5W/m^2 from 300K to 80K, 0.1 – 1W/m^2 from 80 to 4.5K, depending on vacuum), *container for helium* (leak tightness: 10^{-9} hPa l/sec), *support of accelerator components* (precise positioning, survey, mechanical stability), *electrical connections* (current leads, s.c. connections, cold diodes, rf coupler etc.), *monitoring* (sensors, tuners), *safety* (gas relieve), *sectorisation* (vacuum barriers, plugs, valves and tube connections), *assembly* (repairs, cleanness). Different techniques are used to support the cold masses with e.g. posts (SSC, RHIC, LHC, TESLA) or fiber reinforced tapes (HERA, UNK). The same standard techniques are being applied to cryogenic transfer lines and cryogenic supply and valve boxes. Cryogenic supply and return lines can be integrated into the vacuum container of the cryostat (SSC, RHIC, TESLA, partially LHC) whereas seperate transfer lines allow for a choice of larger diameters for the cold vapour return lines (LHC, HERA).

7 Sectorisation and Redundancies

The length of s.c. accelerators is cryogenically sectorised in order to handle the sections seperately, distribute the heat loads to parallel cooling loops, cool down and warm up small sections to enable a fast intervention, repair or replacement of cryostats and components. Sections are separated by valves, vacuum barriers and plugs (LHC) or “u“-tubes (CEBAF, SSC). The section lengths are individually chosen at different accelerators and depend on the heat loads, cool down/warm up time, accepted accelerator downtime for interventions and repairs, expected reliability of components and effordable redundancies. The choice of sector lengths is a compromise between the available cooling power, reduced repair downtimes, number of separating elements (which can fail themselves), simplicity of the system and costs. Figure 7 shows the choice of sector lengths at different accelerators. The sectorisation at hadron machines is mainly determined by their cooling loops whereas at lepton machines with s.c. cavities often single cryostat modules are cooled. An exception will be TESLA where - because of cost reasons and reduction of warm/cold transitions - not single modules but strings of cavity modules (147m) or accelerator units (2.5km) are supplied with liquid or by one refrigerator, respectively. The tubing of units should be dimensioned such that neighboured refrigerators can deliver their spare capacities to a failing section.

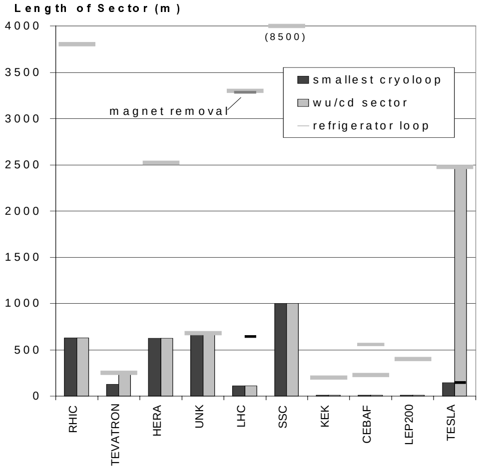

Figure 7:Sector lengths, cooling loops and refrigerator sections

8 Trends and Developments

The following trends and developments are being observed and commented [22]: <u>Coldboxes</u>: There is no principal limitation in refrigeration power given by the coldbox size. The size is limited by transport constraints, but there are ideas to develop and use helium filled air lifters (up to150 t?). Computer aided designs, modelling and optimization of cycles can produce higher efficiencies. There is a tendency to split coldboxes into modules at the following temperature levels: >80K: (LN_2 precooler module, eventually perlite insulated [23]), >20K: coldboxes at the surface, <20K coldboxes installed on tunnel level [10], < 2.1K: seperate cold compressor boxes. Heat exchanger, made from brazed plate fin Al-alloy became mass produced standards with high efficiencies at low temperature differences. Coldbox sizes envisaged by industry are: 30 kW (4.4K) or 10000 l/h (=340g/s) or 5 kW (1.8K). For comparison: LHC: 18kW, TEVATRON 6200 l/h (with LN2 precooling), TESLA (3.6 kW at 2K).

<u>Turboexpanders</u>: There is no development in sight: Existing types are very reliable. Standard machines use static or dynamic gas bearings. There is a tendency to use more efficient wet turbines (<10K) instead of Joule-Thomson expansion valves (recover 1 to 2J/g i.e. 500-1000W with 500 g/s at 4.5K). <u>Cold Compressors [24]:</u> Industrial cold centrifugal compressors are available, running at CEBAF and TORE SUPRA. They use highly sophisticated and expensive active magnetic bearings. The foil gas bearing cold compressors running at the TEVATRON needed maintenance which was not negligable. New developments are necessary. Prototypes are developed. They use either the technology of turbines with static gas bearings [25] or new developed ceramic ball bearings [26]. Tests were performed at CERN. Ideas coming up to use HTSC magnetic bearings. There is a

market from big projects which will use cold compressors: NIFS(50g/s), LHC (120g/s, 24 to 40 machines), TESLA (170g/s, ≈70 machines), advanced tritium production ATP (USA): (500g/s). Compressors: The use of oil lubricated screw compressors (reliability: >40000h) became standard technolgy. There are demands to increase the efficiencies above 55% (e.g. using no slide valves; stiffer housings, smaller clearences). Oil free screw compressors have less chance (too much heat development, clearence problems). Oil free turbo compressors can be more efficient, but more stages will be necessary (expensive). Helium storage: Less investments at high flexibility are wished for helium storage at accelerators. A way out may be an organized liquid helium exchange forth and back between consumer and vendor.

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