Review of Large-Scale Cryogenic Systems for Accelerators

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Abstract

High energy accelerators close to the TeV region or beyond require in the case of protons high magnetic fields with inductions of several Tesla respectively high electric field gradients in the case of electrons. Both types of fields can be realized only by means of superconductivity. Problems of production of refrigeration and its transportation over long distances are discussed. Different cooling possibilities are described. Solutions for existing machines as well as for future projects being in the stages of construction, planning or proposition are presented.

1. INTRODUCTION

Progress in high energy physics is closely related to the development of high energy accelerators. The access to smaller dimensions to be investigated requires higher and higher energies of particles, i.e. any progress in submicroscopic investigation of matter is strongly related to the possibilities for increasing the energies of particle accelerators.

The most powerful accelerators with conventional iron magnets require about 50 MW for particle energies between 300 and 400 GeV. A next mile stone in accelerator progress was the application of superconducting magnets.

The largest accelerators, using liquid helium refrigeration, are listed in Tab. 1.

Tab. 1 List of Large Superconducting Accelerators

Name	Particle Type	Length (km)	magn.field (Tesla)	Energy (TeV)
TEVATRON	p	6.3	4.4	0.9; 2x1[1]
HERA	e^-p	6.4	0.18/4.7	0.03/0.82
UNK	p	20	5.0	3/2x1.2[2]
SSC	p	86	6.6	2x20
LHC	p	26.7	10	2x7.7
RHIC	heavy ions	3.8	?	?
			electr.field (MV/m)	
CEBAF	e^-	1.7	1.3	0.004
TESLA [3]	$e^- e^+$	28	25	2x0.25

remarks: [1] to be realized with lower operating temperature (cold compressor to be installed)
[2] option for 2 x 3 TeV with 2. ring foreseen
[3] in early study stage

The TEVATRON of FNAL was the first machine producing protons close to 1 TeV, followed by HERA at DESY with nominal 820 GeV.

The acceleration of electrons in circular machines is limited by energy losses due to synchrotron radiation. At a given energy and magnetic field, in order to maintain the particle energy at a constant level, these losses have to be compensated permanently by alternating electrical fields being produced in RF-resonators, presently made out of copper. The resistivity of the copper is limiting the maximal attainable voltage gradient and a large fraction of the RF power is dissipated in the cavaties.

Superconducting cavities made of pure Niobium enable much higher voltage gradients and a reduction of power losses, both by a factor of about ten.

2. REFRIGERATION SYSTEM ALTERNATIVES

Any refrigeration system has to perform the following basic requirements:

2.1 Generation of sufficient refrigeration power at different temperature levels and transfer of refrigeration from the sources to a wide spread system

2.2 Supply of individual components or groups of components from the distribution system.

2.3 Handling of different modes of operation

- cool down
- warm up
- transition states (filling with liquid, dynamic losses during acceleration)
- steady state operation
- quench problems

2.4 gas recovery and storage

2.5 process controls

2.6 safety problems for personal and equipment

2.1 Generally the amount of refrigeration required for large accelerator systems exceeds the capacity of presently existing individual refrigerators. There are practical limitations for the maximum size of refrigerator components as dimensions of cold boxes and heat exchangers (transportation problems!), turbine powers, compressor sizes, flow areas etc. These require a subdivision of cooling production into several individual units. The refrigeration capacity requirements for the largest accelerators are listed in Tab. 2.

Tab. 2 Refrigeration Capacities of Accelerators of Tab.1

Name	Temp. (K)	Refrig. (KW)	Liquef. (g/s)	el. Power (MW)
TEVATRON	4.6	23		11.3
	80.0	130		
HERA	4.4	20.2	61.5	8.1
	40/80	60		
UNK	4.4	60	55.6	54.4
	80.0	220		
SSC	4.0	110	540	69.0
	20.0	180		
	80.0	600		
LHC	1.8	14.4		?
	4.5/10	68.0		
	50/75	240		
	4.5		240	
CEBAF	2.0	4.8		?
	45.0	12.0		
	4.5		10	
TESLA	1.8		80.0	129.0
	4.5	32.4		
	40/80	230		
RHIC[1]	3.8	19.0		16.0
(ISABELLE)	55.0	35.0		

[1] RHIC uses the ISABELLE refrigerator

There are different possibilities of subdivision:

2.1.1 Central refrigeration station

All refrigeration is produced at one place by means of a few units. The coolant is fed to the parts to be cooled by means of a long transferline going all around the accelerator tunnel. Local subcoolers and small supply boxes perform the supply and control of individual units. RHIC/ISABELLE, CEBAF and HERA are examples for this solution. The cooling scheme of HERA is shown in Fig. 1. The concentration of all machinery in one central building is an advantage, but the transferline contributes remarkably to the costs of the system.

2.1.2 Distributed point stations

For very long distances the large flow areas in a transferline, necessary especially for the vapor return flow, become too expensive. Individual refrigeration stations have to be installed along the accelerator.
Each station supplies only a fraction of the whole ring

(1/10 for SSC, 1/8 for LHC, 1/8 for TESLA). Additional stations may be necessary for the supply of detectors, booster machines or detector equipment.

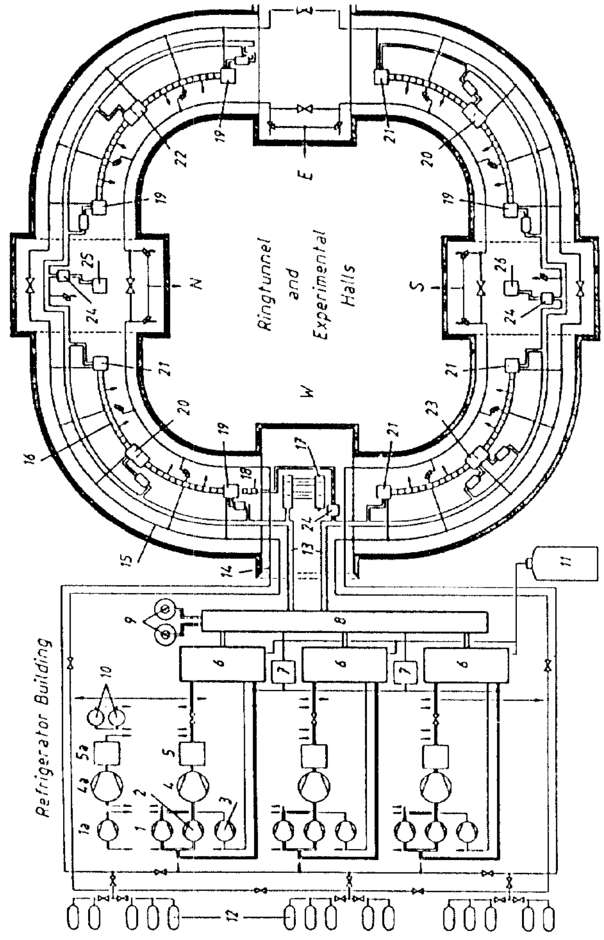

Fig. 1 Cooling Scheme of HERA

compressors, first stage (1:2;3;1a), second stage (4;4a), gas purification (5;5a), cold boxes (6), return gas heater (7), distribution valve box (8), LHe tanks (2 x 10 m^3) (9), cryogenic purifiers (10), LN2 tank (150 m^3) (11), warm gas storage tanks (15 x 267 m^3, 20 bar)(12), 4 channel cryogenic transferline (13), quench gas collection line (14), 300 K/20 bar He supply line (15), superconducting magnet strings (16), 2 reference magnets (17),8 superconducting e$^-$ ring HF cavaties (18), precooler endboxes EC (19), middle box MJC (20), Joule-Thomsen valve endbox EJ (21), middle box MJJ (22), middle box MCC (23) detector supply box HV (24), detectors H1 (25), ZEUS (26)

2.1.3 Central Liquefier with distributed satellites

For mean size dimensions it is still preferable to produce a large fraction of refrigeration in a central liquefier and bring it through a transferline to local small refrigerators.

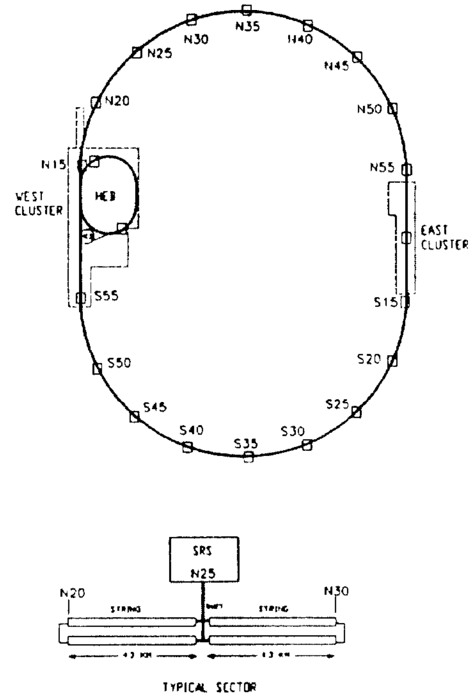

Fig. 2 Segmentation of SSC

The liquid injection increases the capacity of them. The cold vapor is warmed up to room temperature and recompressed by local heat exchangers and compressors. The gas returns to the central liquefier through a simple warm tube and the cost for the circumferential transferline can be kept low due to the absence of a large diameter vapor return tube. A system of this type has successfully been working for about 8 years in the TEVATRON (Fig. 3) and a similar one is in construction for UNK in Serpukhov. Their numbers of satellites are 24 and 12 respectively.

2.2 Supply and Control of local subunits

From local points in the system (this may be either a branching in the transferline or a local station) a number of magnets has to be cooled. In case of magnets with operating temperatures around 4 K a one phase cooling has been chosen for all systems.

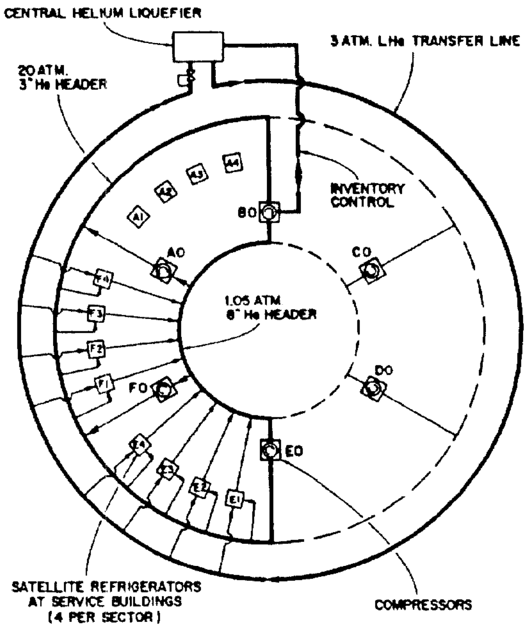

Fig.3 The TEVATRON Cooling Scheme

A typical arrangement for one section, cooling two adjacent strings of magnets is shown in Fig. 4. It represents one substation of UNK. At a certain temperature level the helium passes precoolers and enters the magnets at T ≈ 4.4 K, P ≈ 3 bar. After having passed all magnets of the string, the helium is expanded and partially liquefied.
It returns through a separate channel in the magnets where it absorbes the heat from the one phase coolant by evaporation. Excess liquid is collected in the precooler and the total flow rate is balanced to a constant liquid level.

In the case of HERA the precoolers are directly connected to the transferline, the upper part of the satellite does not exist. Since the coolant temperature increases due to the absorbed heat, it has to be recooled either continously in the magnets (Fig. 5) or periodically in special recoolers being placed after a certain number of magnet units (Fig. 6).

In any case the heat sink for re-cooling will be 2 phase helium boiling at a pressure defined by the vapor return system.

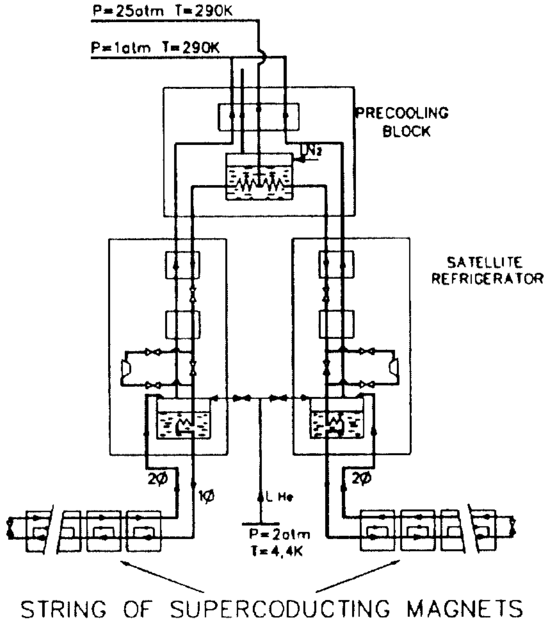

Fig.4 Scheme of UNK Subunit

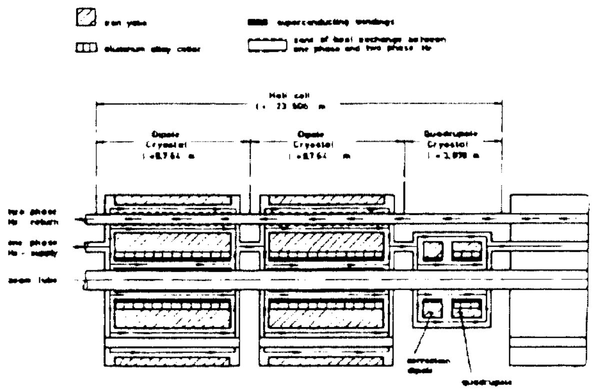

Fig.5 The HERA Continous Cooling

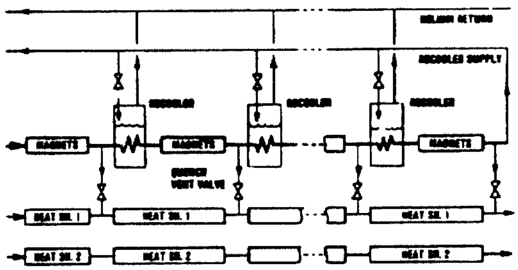

Fig.6 The SSC Periodic Cooling

The pressure drop along this return system defines the maximum temperature in the cooling loop.

For a continous recooling the two phase helium has to flow over the whole distance of a magnet string. (About 120 m for The TEVATRON, 650 to 700 m for HERA and UNK).

Another handicap is the fact, that for geological and other reasons most of the large accelerators cannot be oriented exactly in a horizontal plane - they are tilted and non planar. This may cause instabilities in the two phase flow which can be avoided by the application of extra recoolers (Fig. 6). By controlling the level in the bath, the inlet flow rate is matched to the evaporation rate and no liquid or two phase flow will enter the transferline. With this arrangement SSC can operate with a string length of more than 4 km.

The temperature in the magnets is limiting the maximum particle energy of any superconducting accelerator. To reduce the operating temperature, the vapor return pressure has to be lowered. In order to avoid large room temperature pumping systems and huge heat exchangers, cold compressors at the end of the vapor return line are preferred.

While the TEVATRON and SSC have limited their minimum temperatures to values between 3.5 and 4 K, there are reasons for other accelerators (LHC, CEBAF, TESLA) to go below 2.1 K, i.e. to cool with superfluid He II.

Due to the extremely good heat transfer between He II and the surfaces to be cooled LHC favorizes a bath cooling system over very short distances of the sub units (50 m only)(Fig. 7). Of course, a large number of precoolers and JT valves is necessary. That might be the price for obtaining 10 Tesla with Nb/Ti wires.

The electron linacs CEBAF and TESLA will be cooled with two phase helium II. at a temperature of 2 K. Fig. 8 represents a 145 m module string of TESLA cavities.

The high dynamic HF losses in the cavaties will produce high flow rates and consequently very powerful cold compressors are required. At present the cold compressors for CEBAF are the largest ones being built for this temperature.

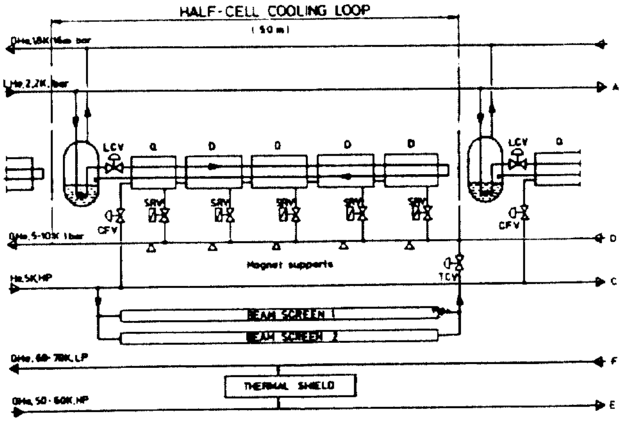

Fig.7 The LHC Cooling with 2 Phase/1.8 K Helium

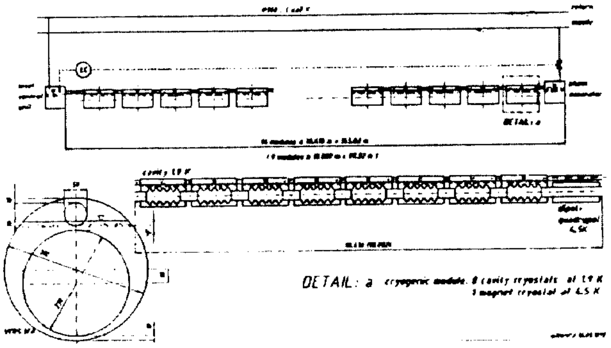

Fig.8 The TESLA Cooling with 2 Phase/1.8 K Helium