Cryogenic Distribution System (CDS) for Eight HERA Superconducting RF Cavity Cryostats

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Abstract

The superconducting cavities in HERA are cooled by a separate LHe distribution system. It consists of one valve box for each cryostat (total 8), a 150 m transfer-line and a subcooler. LHe is supplied by the central HERA refrigerator [1]. The control system is based on the same computer arrangement as the HERA plant. We report about the system layout, the control and interlock philosophy and first operating experience.

Introduction

In 1986, it was decided to add 8 cryostats (nominal design voltage 5 MV/m at $Q_0 = 2 \times 10^9$) to the HERA main ring in the straight section north of Hall West. The LHe refrigeration supply source would be a valve box with LHe (4.3 K) and GHe (40-80 K) for shield circuits supplied from the HERA main refrigerator. Transfer line distance from the valve box source (Halle Versorgungsbox Hall West) is approx. 50 m in the Hall and approx. 80 m in the tunnel with 8 valve boxes and cryostats distributed in the tunnel 6.6 m apart (Fig. 1).

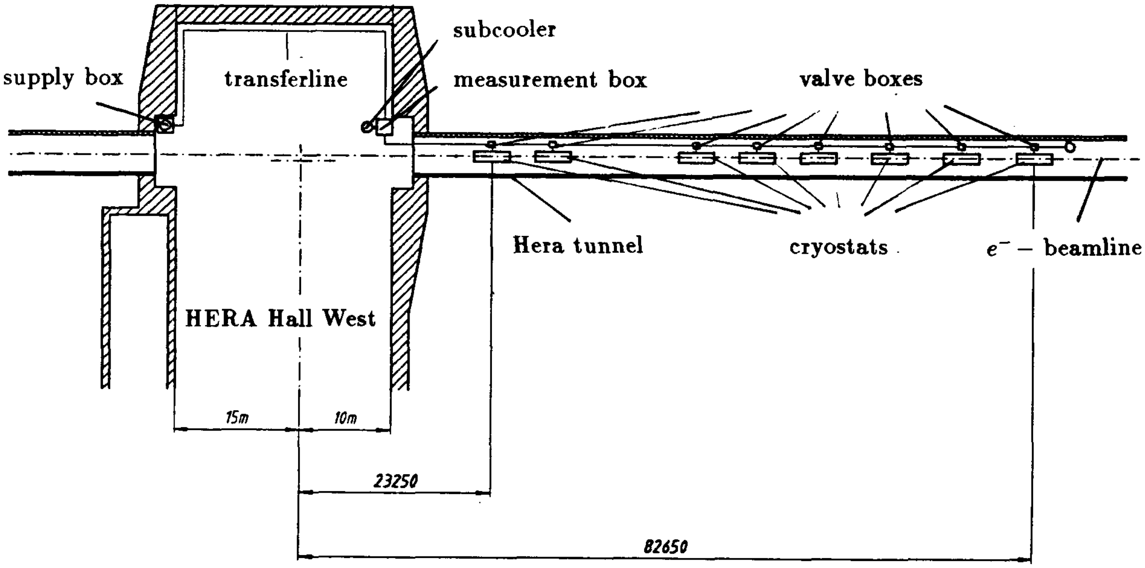

Fig. 1 HERA Hall West with transferline and 8 cryostats

The design operating conditions were fixed by the supply source, accelerator tunnel access, and the requirement that a single cryostat must be removed and replaced independently of all the others. This would permit a malfunctioning cryostat to be isolated, warmed up, removed and a new replacement made, cooled down and LHe filled, without disturbing the other 7 cryostats on line and cold. All normal operations including steady state transfer line temperature control and cryostat fill must be remotely controlled by a central computer control [2].

The extremely short fabrication, assembly and installation schedule, January, 1990 through October, 1990 necessitated multiple suppliers. Sulzer was the prime contractor; Leybold, Holland built and installed the approx. 50 m, 4 pass transfer line in the hall; Messer Griesheim, Germany, built the subcooler, Cryo Diffusion, France built the 32 "U" tubes for valve box connection to the 8 cryostats, and also 16 "U" tube jumper connections. Sulzer Winterthur built the measurement box, 8 valve boxes, and the tunnel transfer line. Even with this multiple effort, the job went amazingly well, due to extensive in-depth vendor experience.

Four cryostats were installed by April, 1991, two more by June, 1991, when the HERA e-beam started, and now (2/92) the final two are installed.

System Description

The flow sheet of the Cryogenic Distribution System (CDS) is shown in Fig. 2a and 2b. 40 K Helium gas and 4.5 K single-phase Helium start from supplybox HV-WL in HERA West Hall and travel to the components via a 4-pass transfer line. The first elements after approx. 50 m are the subcooler (400 l volume) and the measurement box containing the flowmeter and the heaters for calibration. The transfer line (about 80 m in length) in the HERA tunnel supplies 4.5 K and 40 K Helium to the eight cryostats. At every cryostat there is one valve box which contains temperature and level control valves as well as the isolating valves. A turnaround end contains a Joule-Thompson expansion valve for transfer line temperature control.

A warm gas circuit connected to each valve box and cryostat provides for purging, evacuation, cool-down and warm-up mixing. The safety vent is connected to the magnet-quench line for helium recovery.

Table 1. CDS Operating Conditions

	Temperature (K)	Pressure (bar)	Flow (g/s)
Single-Phase Supply	4.7	3.0 - 4.0	80 - 100
Two-Phase Return	4.35	1.15	80 - 100
Shield Supply	40	18.0	20
Shield Return	80	17.0	20
Purge GHe Supply	300	18.0	10
Safety Vent	100 - 300	1.2	

The liquid helium inventory of the CDS plus cryostats is approx. 2,100 l.

Radiation levels of up to 5 × 10^8 RAD (5 × 10^6 Gy) are possible in the HERA tunnel during operation. All materials (especially seals and electrical insulations) must be resistant to radiation.

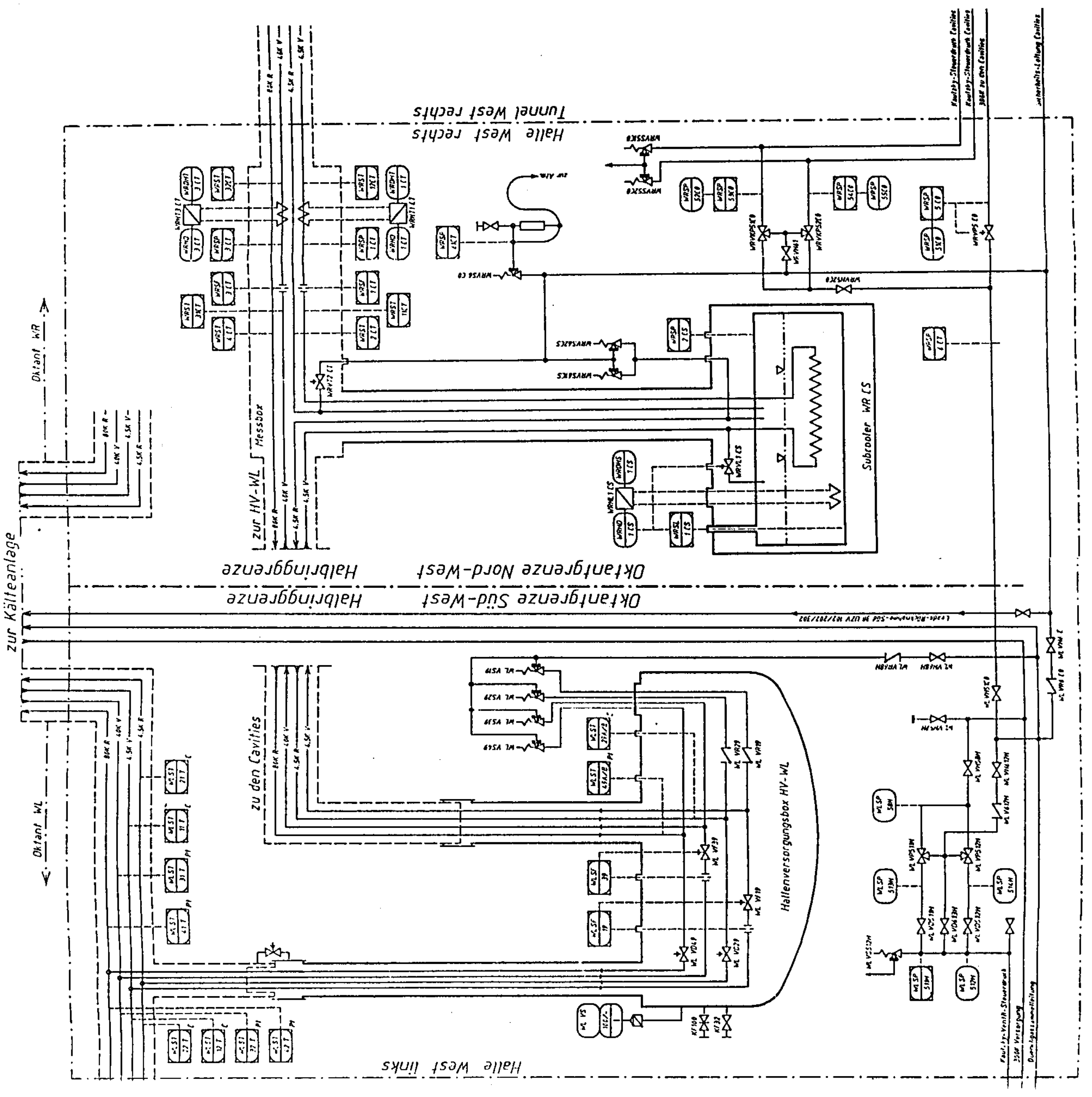

Fig. 2a Cryogenic flow scheme with supply box, subcooler and measurement box

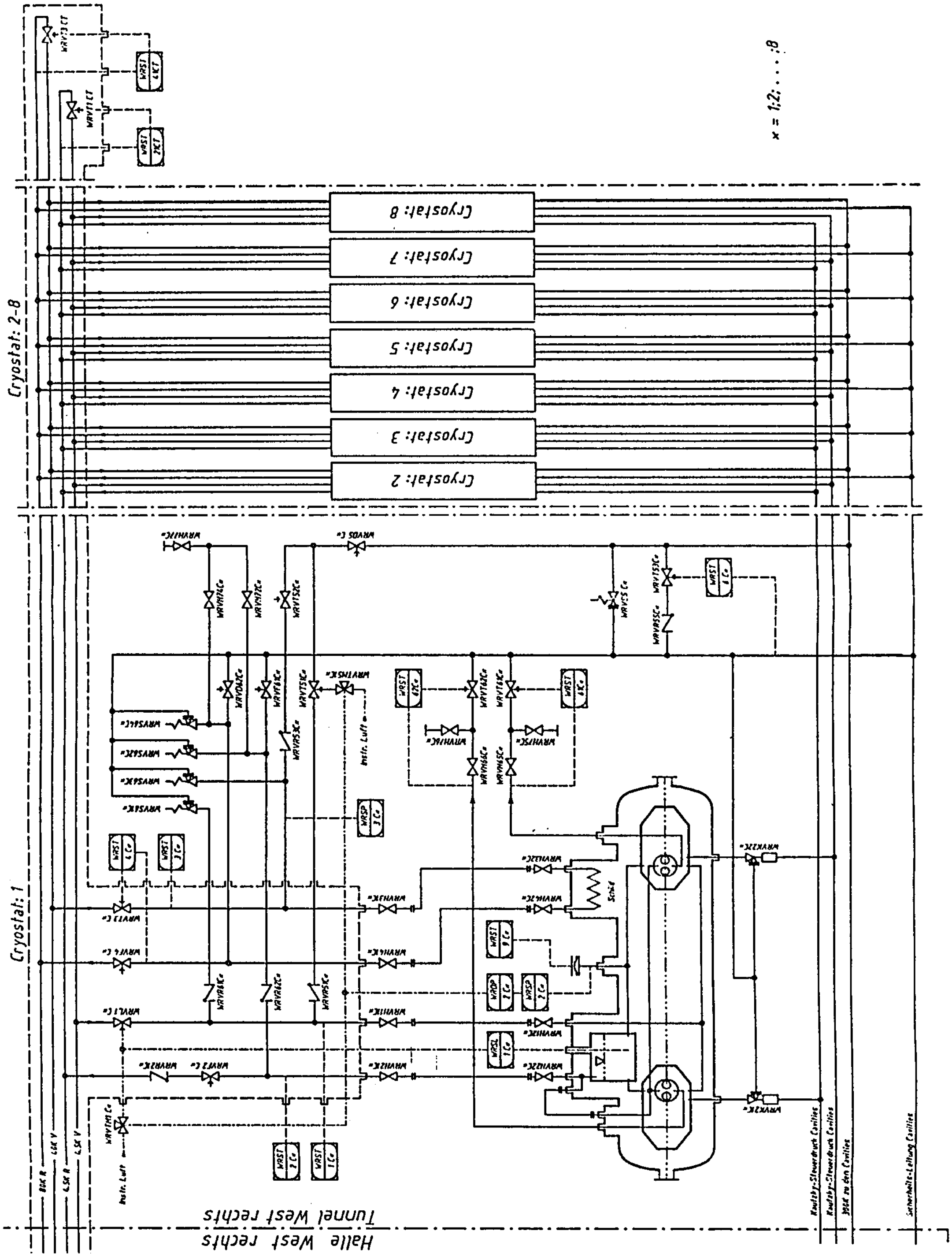

Fig. 2b Cryogenic flow scheme with valve boxes and cryostats

Transfer Line

The transfer line connects supply and return He refrigerant between the supply box HV-WL and the 8 cryostats. The main transfer line is about 130 m long and contains 4 cold He lines. Fig. 3 shows a cross section of the 4-channel Helium transfer line with a 256 mm diameter common vacuum jacket. A 182 mm diameter copper shield surrounds all four lines. There is a copper wire braid (24 mm in width) soldered with the 80 K line and coppershield every 300 mm along the transfer line. The shield is wrapped with 30 layers of superinsulation, the 4.5 K lines and the 40 K lines with 10 layers. The insulation vacuum is divided into 11 subunits by vacuum barriers for safety reasons and to make leak detection and installation easier. At the end of each subunit bellows are used to compensate for shrinkage of the cold tubes. The vacuum jacket is designed to tolerate 100 K in emergency. Every 2.30 m along the transfer line there is a low heat conductive support board (VETRESIT 300) 4.5 mm thick. The insulation vacuum at 300 K is better than $< 5 \times 10^{-5}$ mbar, improving when cold.

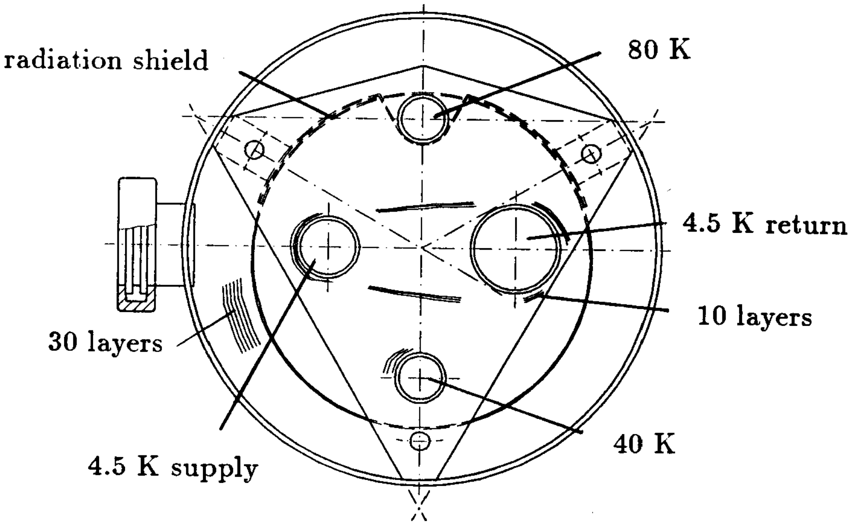

Fig. 3 Cross section of the transfer line

Table 2. Main Parameters of Transfer Line

	Pipe Size (mm)	Max Flow (g/s)
Vacuum Jacket	ø256 × 2	
Single Phase Supply	ø33.7 × 2	100
Two-Phase Return	ø48.3 × 2	100
Shield Supply	ø26.9 × 2	20
Shield Return	ø26.9 × 2	20

The Measurement Box

The measurement box contains line heaters, temperature probes and line orifice plates with pressure taps for flow measurements in both circuits. The heater is used to produce a Δ T in the stream to calibrate the flow meter.

Table 4. Main Parameters of Measurement Box

	4.5 K Line	40 K/80 K Line
Heater Power	250 W	250 W
Type of Flow Meter	Orifice	Orifice
Temperature Sensor	Carbon Resistance	PT-1000
Size (mm)	ø784 × 374 (thickness)	

Table 5. Parameters of Orifice-Type Flow Meter

Application Data:	Shield Line	4.5 K Line	
Medium Pressure	18.	3.	bar
Medium Temperature	40.	4.5	K
Medium Density	20.8	129.9	Kg/m^3
Flow Nominal Value	20.	100.	g/s
Tube Diameter "D"	21.7	28.5	mm
Dynamic Viscosity	5.8 E-06	3.6 E-06	Kg/ms
Sound Speed	394.	208.	m/s
Pressure Ratio P_2/P_1	0.9973	0.9967	
Isentropic Exponent	1.7938	18.7333	
Reynolds Number	2.0233E + 05	1.2410E + 06	
Calculation:			
Orifice Diameter "d"	9.6000	19.3000	mm
BETA = d/D	0.4424	0.6772	
Flow Coefficient "C"	0.6025	0.6025	
Prespeed Factor "E"	1.0197	1.1253	
Flow Number "ALFA"	0.6144	0.6779	
Expansion Number "EPSILON"	0.9994	0.9999	
Effect Pressure (Delta P-Orifice)	469.4161	99.7967	mmH_2O
Pressure Loss	389.8471	52.4602	mmH_2O

Subcooler

The first element (after approx. 60 m) is a subcooler of 400 liters volume. This serves to completely cool the supply He (low GHe content). It also acts as a gas ballast to help stabilize the pressure in the return flow to the central plant. This is extremely important for the cavity frequency stability. The subcooler is filled by the return two-phase Helium at 4.35 K. An expansion valve of 4.7 K inlet temperature and a heater, both connected with a LHe level indicator stabilize the level at 50 % (200 l) liquid Helium. The radiation shield consists of 50 layers of superinsulation (no cooled 80 K shield). The insulating vacuum is sealed.

Table 3. Main Parameters of Subcooler

	Outer container	Inner container
Working Pressure (Max)	0 bara	3.5 (20) bara
Working Temperature	20°	4.5 K
Diameter	1050 mm	900 mm
Medium	Vacuum	LHe
Volume	723 l	405 l

The Valve Box

The valve box has a single phase supercritical 4 K inlet supply valve controlled by a liquid level sensor in the cryostat. The 40 - 80 K shield circuit inlet valve is controlled by a return side temperature sensor. Both return line valves act as isolation valves. All four lines to the cryostat have indicating temperature sensors. In the 4 K return line there is a check valve to protect each cryostat from pressure increase in case of a coldbox or other cryostat mal function.

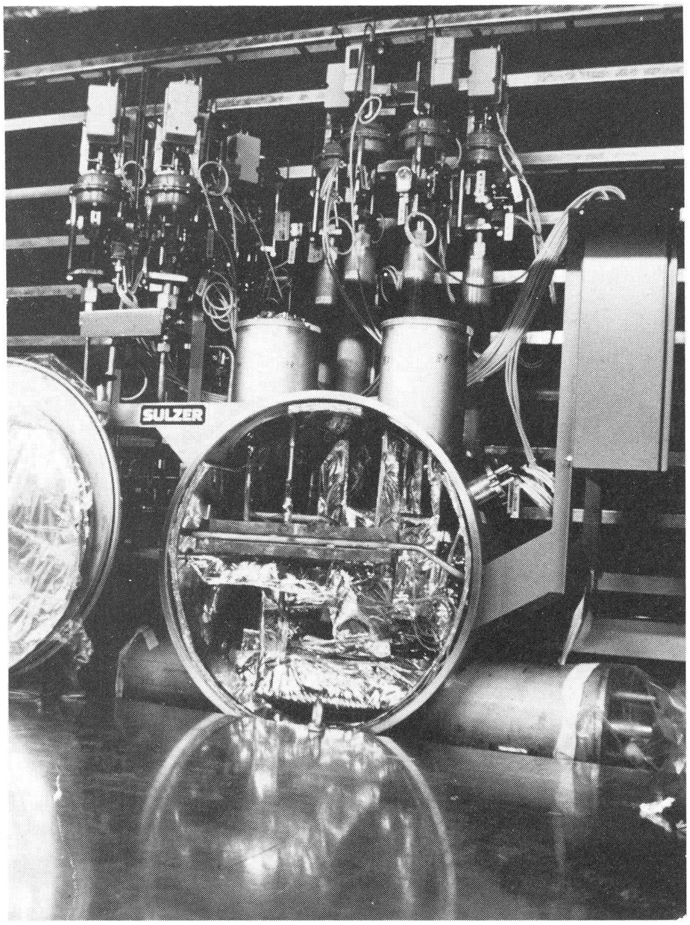

Fig. 4 Valve box in the tunnel (opened)

There is a warm gas circuit on each valve box for transient operations such as pumping, purging, cool down and warm up mixing.
The valve box is connected to the cryostat via four flexible "U" tubes. Ball valves on the bayonets allow removal of the cryostat when the CDS is still cold.
There are connections from the return lines to the safety vent for independent cool down and warm up of each cryostat. In order to preclude liquefied air on the safety line pipe surface a temperature controlled valve mixes warm gas if the temperature goes below 100 K.
There are 12 valves per box (96 valves in total) plus 3, one at the subcooler level and two at the transfer line end points, almost 100 valves for remote control. Figure 4 shows a valve box in the tunnel.

Cryostat

The cryostat is a vacuum container holding the superconducting radiofrequency cavities. Figure 5 shows the cryostat (4.5 m in length, 820 mm in diameter).

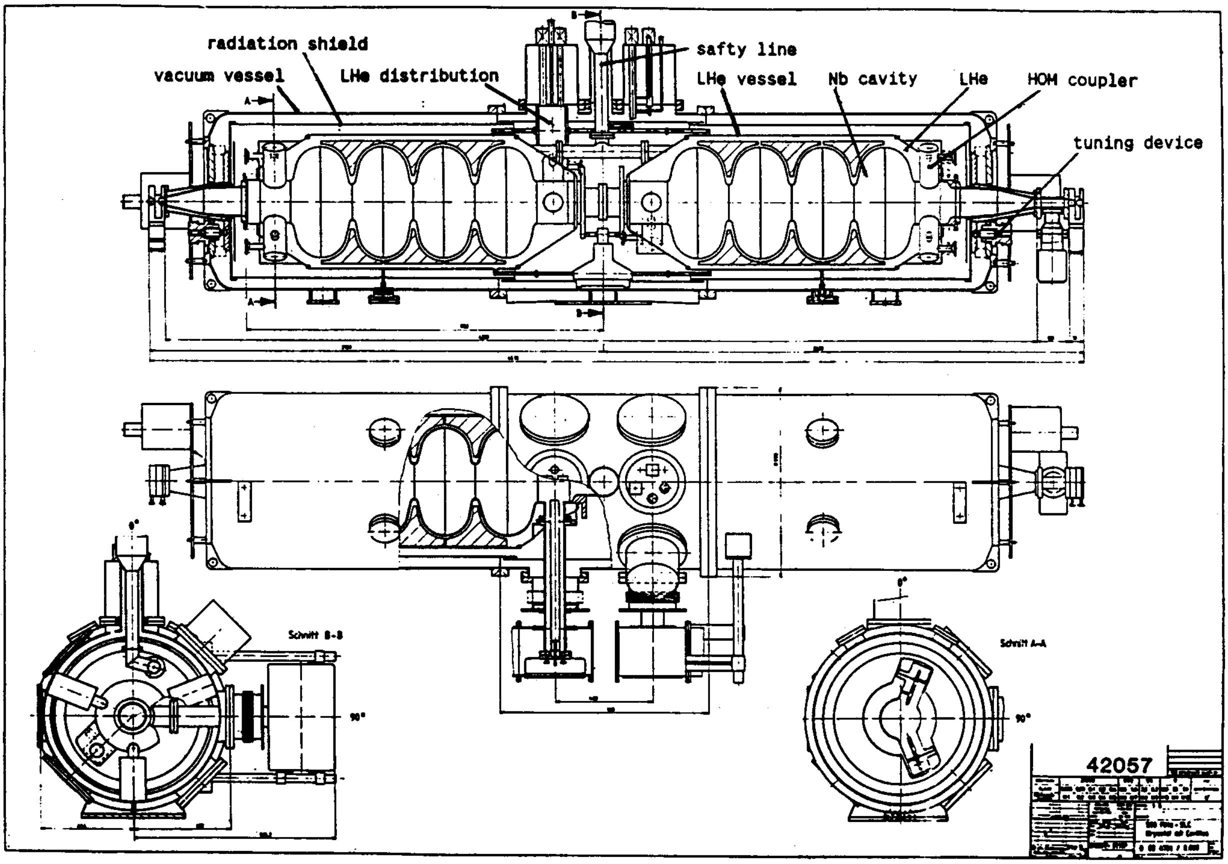

Fig. 5 View and cross section of the cryostat

The measured static losses of each cryostat are 12 W at 4.5 K and 120 W at 40 - 80 K. The cavity operates at a resonance frequency of 500 MHz. The RF losses per cryostat at an accelerating energy gradient of E_{acc} = 5 MV/m and a quality factor of Q = 2 $\times 10^9$ are 80 W. A cryostat needs 200 l LHe for normal operation. Aluminium fillers reduce the LHe inventory. Two 50 W heaters in the LHe simulate and compensate for the RF heat losses. There is a vapour liquid separator at the top of the cryostat.

The main coupler is cooled by boil-off helium which comes from the gas-liquid separator. GHe flow for each coupler cooling is about 0.1 g/s rising from 10 K to 290 K, passing through the warm control valves to the safety line which is connected to the magnet quench line. In order to keep the pressure in the safety line low enough (for a sufficient ΔP) we installed a direct line (100 m long, ø50 mm) to the low pressure side of the refrigerator. The cryostat is equipped with two relief (Kautsky type) valves and one burst disk for safety of the niobium cavity. The Kautsky valves are connected by the safety vent to the quench line for Helium recovery. The valve is opened at a bath-pressure of approx. 1.5 bara. The burst disk bursts at 2.0 bara into the tunnel as final protection.

Table 6. Main Parameters of Cryostat Valve Box

	Pipe Size (mm)	Flow (g/s)
Single Phase Supply	ø17.2 × 1.8	12.5
Two Phase Return	ø21.3 × 2	12.5
Shield Supply	ø17.2 × 1.8	2.5
Shield Return	ø17.2 × 1.8	2.5

Control System [3]

The main computer control system used for cryogenic controls is the EMCON D/3 system from REXNORD (now owned by TEXAS INSTRUMENTS). This system uses multibus standard and 8086/8087 cpu. A VAX computer has been added as the host. The communication between the D/3 system (PCM) and the actual cryogenic instrumentation involves 2 other systems as well, "SEDAC" and "PADAC".

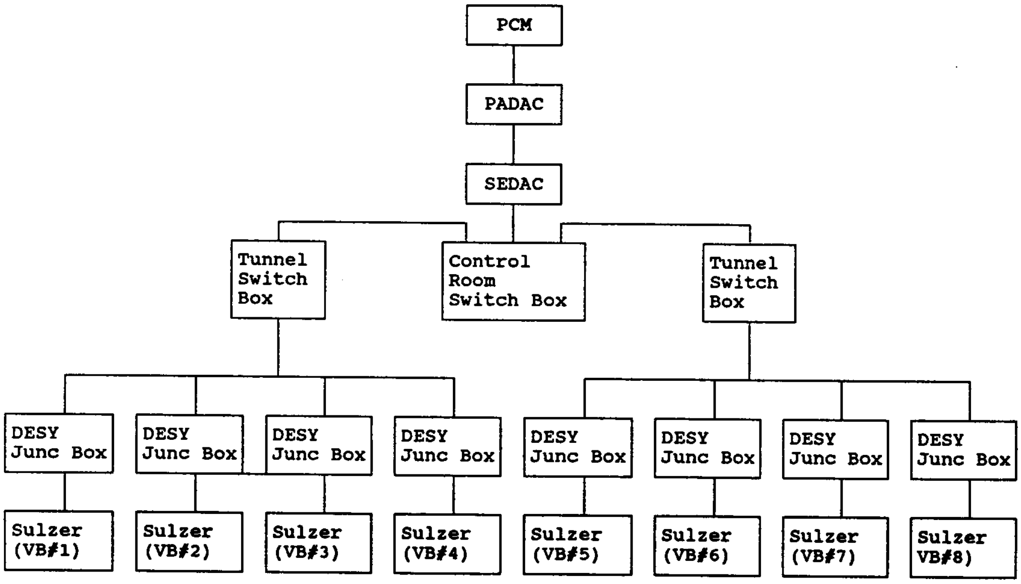

Fig. 6 Hardware layout of the computer control system

All signals are terminated into a set of SEDAC crates (DESY design) used to acquire data and send signals to output devices. SEDAC crates have analog input, analog output, digital input, digital output, temperature sensor, and liquid level board control functions. The second system, PADAC (also designed at DESY), retrieves and sends data in parallel format to and from the SEDAC crates and passes information on or from the D/3 system. Note that temperature conversions (from electrical signal to temperature) are done at the PADAC level.

The actual hardware layout including all "terminal" or "junction" boxes is shown in Fig. 6.

Safety System

The thin niobium cavity (approx. 2 mm wall thickness) can only tolerate a pressure difference of 2.5 bar, otherwise it will be permanently deformed. This means a maximum of 2 bar abs. is permissible against the beam vacuum in the cavity. This small operating window requires accurate pressure control, precisely working low pressure relief valves (Kautsky) and burst discs as a final protection. The different pressure levels for hardware are shown in Tab. 7.

A "Cryo OK" output signal is used to communicate between the cryocontrol system and the RF klystron in a way such that the cryogenic parameters of each cryostat are either good or bad (Tab. 7).

The pressure sensor on each cryostat is used as a quench detector. If the pressure in the He-bath is 30 mbar higher than under normal operation the RF will be switched off and the beam will be dumped.

Table 7. Different Safety Levels

Hardware:		
Pressure Switch:	P $\geq$ 1.3 bara	→ close supply valves (WRVL1C*, WRVT51C*) → RF off
Kautsky Valves:	P $>$ 1.5 bara	→ blow in safety line
Burst Disc:	P $>$ 2.0 bara	→ blow in the tunnel
Software:		
Pressure Sensor:	P_0 +30 mbar	→ RF off (quench detector) → beam dump
Cryogenic OK:		
if	liquid level	$>$ 98 %
	He pressure	$<$ 1.2 bara
	shield temp.	$<$ 150 K
	2 power couplers	cooled
	burst disc	ok
	SEDAC	runs
	cryo ok program	runs
		→ RF unblocked

Acceptance Test

Warm Test

Warm gas pressure and vacuum tests as well as TÜV inspection were successfully completed in December, 1990. An acceptance test for the whole system at 22 bar was required. The other conditions were: no leaks in the insulating vacuum (1×10^{-8} mbar l/s) and across the seats of the valves. During this test we found no leaks from the Helium main components into the insulating vacuum. Two valves (out of 100) had a leak (1×10^{-3} mbar l/s) across the seat. After replacing the seal on the first one and readjusting the stroke of the second they were tight.

Heat Load Test

For the heat load test without cryostats we used jumpers on the "U" tubes of valve boxes 1 through for the 4 K and 40 - 80 K circuits.
In the 40 - 80 K circuit we measured the heat load between the temperature sensors WRST32CT and WRST4CT, i.e. the part between (and including) the measuring box and valve box No. 8, including "U" tubes and jumpers on box 1 to 4. The calculations are based on measured temperature increase and mass flow in the circuit. Five measurements with different mass-flows gave an average of $Q = 667.0 \pm 26$ W loss in the shieldline. This is a factor of 2 higher than specified. Temperature measurements at the surface of the vacuum jacket indicate that at some locations the radiation shield is insufficient. It is planned to verify and possibly repair the defect during the coming shut down.

In the 4 K circuit the pressure taps to the orifice plate flow meter produce thermo-acoustic oscillations and the temperature sensor WRST2CT was broken. Heat load measurements are planned after repair of the components.

Power consumption of the whole system is shown in Tab. 8.

Tab. 8 Measured Cold Power Consumption of the CDS Plus Cryostats

	40 - 80 K	4.5 K
Cryogenic Distribution System	670 W	* 120 W
8 Cryostats	960 W	96 W
Total Static	1630 W	
RF Losses		
16 Cavities (3.3 MV/m, $Q_0 = 8 \times 10^8$)		640 W
Total (Static and Dynamic)	1630 W	856 W
	4.5 - 300 K	
RF input coupler cooling	1.6 g/s	

* specified

Operating Procedures

Usually the CDS and the cavities are cooled down after the main ring is stable at 4.2 K. During the first sequence of the cool down procedure the return gas enters the quench line of the magnet system for recovery. The regular cooling circuits are closed if the temperature of the return gas is low enough. In the following paragraphs this procedure is described in detail.

Transfer Line Cooldown

40 - 80 K line:

Cold GHe enters from the 40 K supply line and goes through the end valve WRVT3CT back to valve box No. 1, passing valve WRVF4C1 and WRVD62C1 to the safety line. If the temperature in this part is below 100 K, the 80 K return line will be cooled backwards by 80 K GHe also passing through the valves WRVF4C1 and WRVD62C1 in the safety line. If temperature sensor WRST4CT is below 100 K, we close both valves in box No. 1 and connect the circuit to the hall box HVWL.

4.5 K Line

Single phase helium enters from the 4.5 K supply line and goes through the end valve WRVT1CT back to the return line passing the cool down valve WRVT2CT to the safety line. When the temperature sensor WRST2CT shows less than 10 K, we close the valve WRVT1CT. We cool down the TL return line and the subcooler by means of GHe return line via WRVT2CT. There is no temperature indication, i.e. after 45 min we close the cool down valve WRVT2CT and connect the circuit to the hallbox HVWL. The subcooler inlet valve (WRVL1CS) and the heater control circuits can be closed.

Cryostat Cooldown

40 - 80 K

After opening the supply valve WRVT3C* (* = 1 to 8) and the cooldown valve WRVD62C* we wait until the temperature sensor in the return line shows less than 100 K. Then the return valve (WRVF4C*) can be opened (close WRVD62C*) and the control circuit of the supply valve can be activated.

4.5 K

Because of the so-called Q_0-degradation effect of the cavities the cooldown procedure has to be executed very fast in the temperature range of 150 - 20 K [4]. According to this rule we cool down the cavities with a mixture of LHe and warm GHe: The supply valve WRVL1C* is opened a little and the warm gas valve WRVL51C* is controlled by the supply temperature WRST1C*. The return gas passes by WRVF61C* to the safety line. After approx. 48 h the return temperature is 150 K and the fast cooldown procedure can start: close the warm gas valve and open the 4.5 K supply valve as far as possible. This procedure is limited by the pressure in the cavity (see Table 7). Within 2 h the cavity temperature is at 4.5 K and normal operation can start: close WRVF61C*, open WRVP2C*, WRVL1C* level controlled. It takes 15 min to fully fill the cavity with LHe. Fig. 7 shows a cooldown curve.

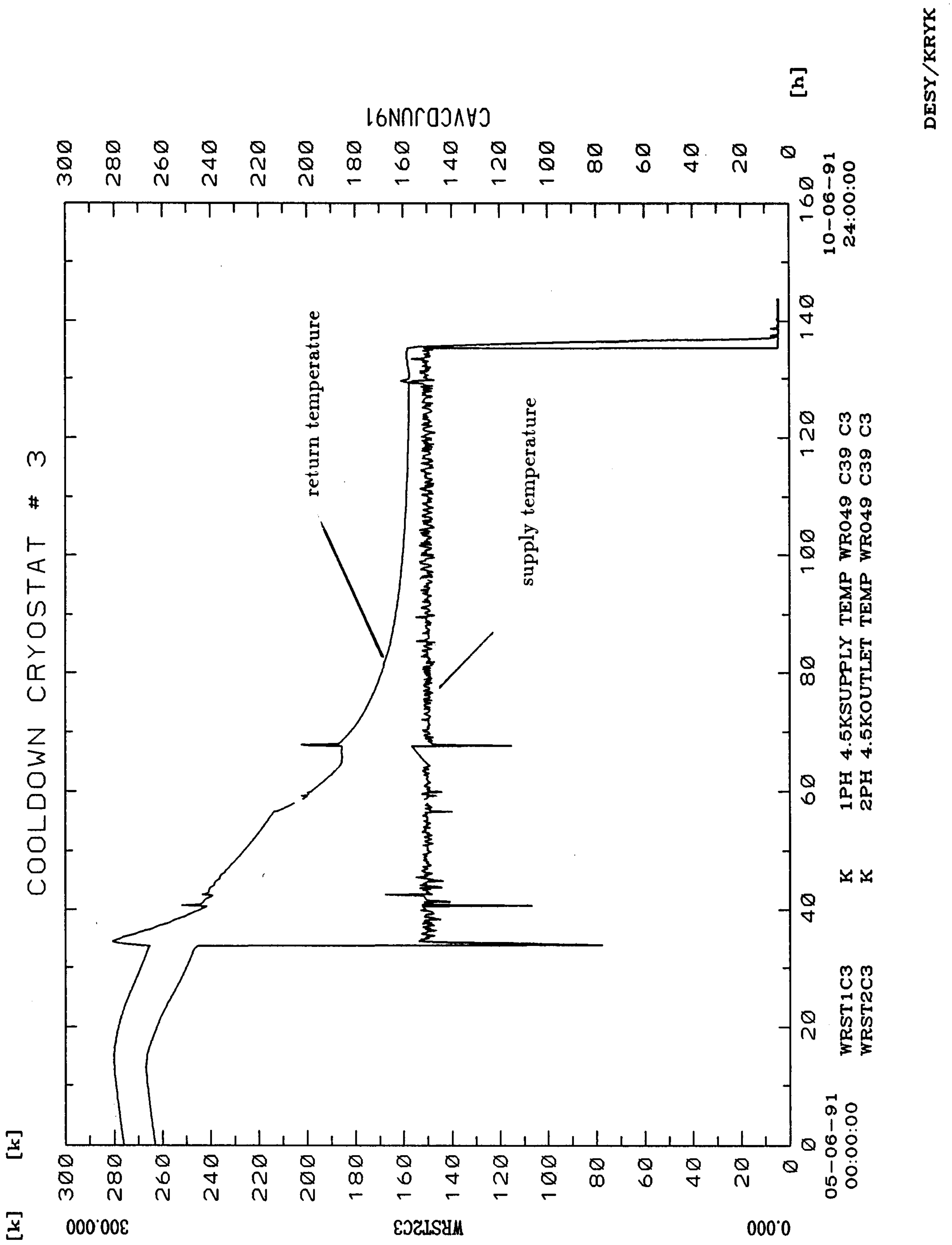

Fig. 7 Typical cooldown curve for a cryostat (4.5 K circuit)

Operational Experience with the CDS

During the first commissioning period of HERA in 1991 twelve cavities (6 cryostats) were operated for 3,000 h at 4.3 K. For one third of this time (1,000 h) the cavities were in RF operation. The CDS with cavities has made 12 cooldown/warm up cycles.
During operations we have had 12 cryogenic interruptions of the CDS caused by problems with the HERA refrigerator:

- hardware problems in control system,
- loading new program during operation,
- manipulation in control electronics during operation.

In all cases there were no hardware failures of the HERA plant. The refrigerator was operational again typically within 10 h.

Operating status recovery of the CDS was achieved by:

- standard handling: 8 times,
- emergency handling: 3 times.

Due to a computer hardware failure we had one major event: A warm He-gas valve opened to the He-bath and three (out of 6) burst disks were broken. A warm up was required to assemble new burst disks and pump/purge the system. Fortunately this happened at the beginning of a 6 weeks shut down period.
In steady state operation of the cavities it is possible to stabilize the LHe level in the cryostat within a range of less than ± 2 cm. The liquid level is measured in a phase seperator of 3.5 l volume (i.d. = 15 cm). Thus the level control on the cryostat bath is extremely precise.
Electric heater switch on in the cryostats makes up for the heat load so that in the event of a sudden RF switch off the volume change of the bath is less than 2 %.
Due to thermo-acoustic oscillations in the pressure taps to the flow meter the pressure oscillations in the cryostat baths Δ P were approx. ± 4 mbar with a wavelength of 0.6 sec. This is a frequency shift of 280 Hz for the cavities and too fast for the cavities' slow tuning system. After eliminating the thermo-acoustic oscillations the Δ P in the bath is ± 5 mbar and the wavelength is 16 min, which can be handled easily by the tuning system.

Conclusion

Twelve 4-cell cavities housed in 6 cryostats installed in HERA were cooled successfully by the CDS. The liquid level controls as well as the pressure controls have performed very accurately. Up to now the system has made 12 cooldown/warm up cycles and has operated for 3,000 h. Part of this time (1,000 h) the system has run with the dynamic heat load of the RF power and the cavities in accelerator mode.

Acknowledgement

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