Reprints available directly from the publisher
Photocopying permitted by license only

Amsterdam B.V. Published in The Netherlands under
license by Gordon and Breach Science Publishers SA
Printed in Malaysia

OPERATING EXPERIENCE WITH SUPERCONDUCTING CAVITIES IN THE HERA E-RING

B. DWERSTEG, A. MATHEISEN, W.-D. MÖLLER, D. PROCH, D. RENKEN and J. SEKUTOWICZ

Deutsches Elektronen Synchrotron DESY,
Notkestrasse 85, 22603 Hamburg, FRG

(Received 22 January 1996; in final form 22 January 1996)

In this paper a short description of SRF part of the HERA electron ring is given. Statistics of beam loss due to the failures of the superconducting cavities and discharging in the fundamental mode couplers is discussed. Computed and measured effects of wrong phasing on cavity performance is presented.

Keywords: Superconducting cavities

1 INTRODUCTION

Superconducting RF installation in the HERA e-ring has been completed in April 1992. The installation itself and the operation experience till mid of 1994, have been presented already in the Proceedings of former SRF Workshops[1] and Proceedings of the European Particle Accelerator Conferences.[2] The installation is made of:

- sixteen sc cavities,
- two klystrons and distribution system of the microwave power,
- interlock and control electronics,
- cryogenic and vacuum systems.

A brief description of the RF part of the installation, interlocks and controls circuits is given below.

1.1 Cavities and Cryostats

Superconducting, 4-cell, 500 MHz cavities of the HERA e-ring are made of bulk niobium. Each cavity is equipped with one fundamental mode coupler and three HOM couplers. All couplers are made in coaxial line technique. Cavity and HOM couplers are dipped in 4.2 K LHe bath. Two cavities are assembled in one cryostat, symmetrically with respect to the mid plane of the cryostat. These cavities are connected by 3/2 λ long beam tube, to which both fundamental mode couplers are attached. Since the nominal Q_{ext} of all FM couplers has been fixed to 2.5×10^5, frequency adjustment of each cavity can be performed by means of slow mechanical tuner, which corrects the length of the cavity.

1.2 RF Source and the Distribution System

Microwave power is generated by two klystrons and guided down to the tunnel by WR1800 type waveguide. Both klystrons deliver maximum power of $P_k = 1.1$ MW under cw operation (0.55 MW each). The nominal value of $P_k = 1.5$ MW (0.75 MW per klystron) was not achievable due to the limitation in the power supply. Recently, problem has been solved and in the future we will try to operate cavities with more power. The maximum input power per cavity was, up to now, 64 kW (waveguide losses are 7%). Equal distribution of the power is done in the tunnel, by 9 directional couplers and 6 magic T's. In front of each cavity, 3-stub waveguide transformer is placed, to make possible:

- change of the Q_{ext} in the range from 5×10^4 to 1.25×10^6,
- phase adjustment of the cavity in the range $\pm 50^\circ$.

1.3 Interlocks and Control Electronics

To avoid damage of the system, several signals from each cavity and each cryostat are monitored during the operation. Interlocks signals are listed in Table I. In addition to the interlock electronics, the SRF system is equipped with voltage and phase control loops to provide proper operation of the system for various beam loading conditions. The three most important control loops are as follows:

- Cavity Phase Lock Loop which compensates for the beam induced voltage by changing the resonant frequency of the cavity,
- Voltage Control Loop (VCL), which adjusts the power of both klystrons, to keep a constant sum of all 16 voltages, $V_\Sigma = \Sigma V_n$, for different beam loading and thus makes the efficiency of the system higher for the broader I_b range,
- RF Phase Control Loop which keeps constant the phase between V_Σ and the reference phase.

The profit of using the VCL can be seen in the computed example shown in Figures 1 and 2. The total voltage V_Σ = 34 MV, as required, stays constant for the different beam current I_b and the fixed synchrotron phase $\varphi_s = 45^\circ$. The klystron power delivered to the cavities is adjusted and the reflected power is minimized. Without the VCL we would observe a drop of the V_Σ for $I_b \geq$ 25 mA or a change of the synchrotron phase and increase of the V_Σ and of the reflected power, for $I_b \leq 25$ mA. The second situation would happen at the end of every luminosity run, when I_b is reduced due to the finite life time of the beam. The VCL makes the efficiency $\eta = P_{\text{beam}}/P_{\text{klystron}}$ vs. I_b higher than 75% already for $I_b > 22$ mA, although the system has been matched for the beam current of I_b = 45 mA.

TABLE I Interlocks

Kind of interlock	*Measured value*	*Measured by*
Fundamental Mode Coupler	temperature of the ceramic window	infrared detector
	multipacting current	pickup probe
	light intensity at the vacuum side	light detector
	light intensity in the doorknob region	light detector
	pressure of air cooling ceramic window	pressure sensor
	temperature of He gas cooling the inner conductor	temperature sensor
Higher Order Mode Couplers	temperature of all 3 feedthroughs placed between the iso-vacuum and air	PT100
Cryogenic Interlock	quench detector LHe level in each cryostat	
Vacuum Interlock	pressure in the beam line	current of ion pump and vacuum gauge
RF distribution system	forward and reflected power at the input of all absorbers	

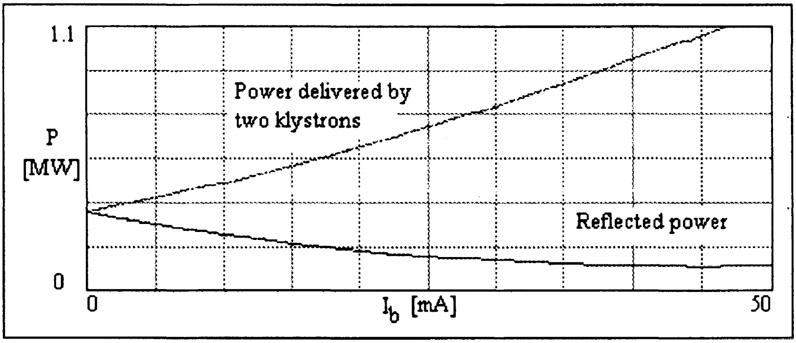

FIGURE 1 Forward and reflected power vs. I_b with VCL.

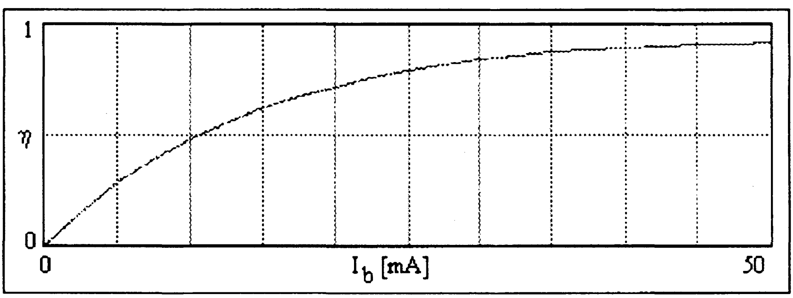

FIGURE 2 Efficiency $\eta = P_{\text{beam}} / P_{\text{klystron}}$ vs. I_b with VCL.

2 LUMINOSITY RUNS, HIGH CURRENT EXPERIMENTS AND STATISTICS

The operating time of the SRF system since June 1991 till October 1995 is in total about 23000 hours. The system was cooled down and warmed up 22 times without mechanical or any other kind of damage. Table II contains a brief history of the system. Figure 3 shows the increase of the average stored current (1991) and the average stored current at the beginning of luminosity runs (1992 ÷ 1995) vs. years of operation. Maximum klystron power delivered to the sc cavities vs. years of operation is given in Figure 4.

TABLE II

Date		*Comment*
June 1991	12 sc and 84 nc cavities installed in the HERA e-ring. Upgrade of energy from 28 GeV to 30.4 GeV	polarization measurements
April 1992	Starting of the operation of all 16 cavities	
Oct. 1992	begin of the luminosity runs	
Nov. 1992	max. accelerating voltage $V_\Sigma = 76$ MV achieved after system has been assembled in the tunnel	limited by global heating of two cavities
June 4, 1995	max. stored $I_b = 47$ mA at 27 GeV	machine study
June 6, 1995	max. stored $I_b = 52$ mA at 12 GeV	machine study

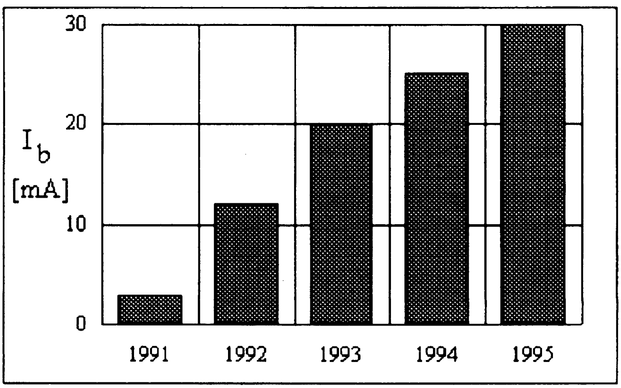

FIGURE 3 I_b vs. years of operation for the luminosity conditions.

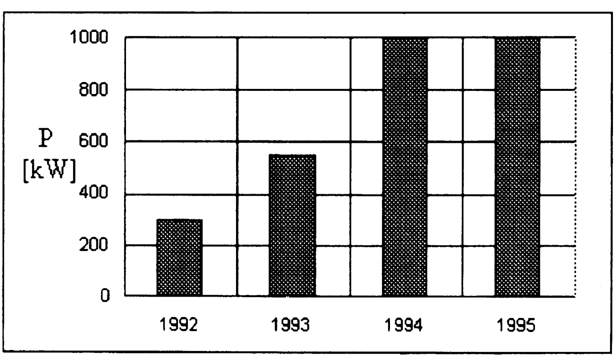

FIGURE 4 Maximum klystron power delivered to sc cavities vs. years of operation for the luminosity conditions.

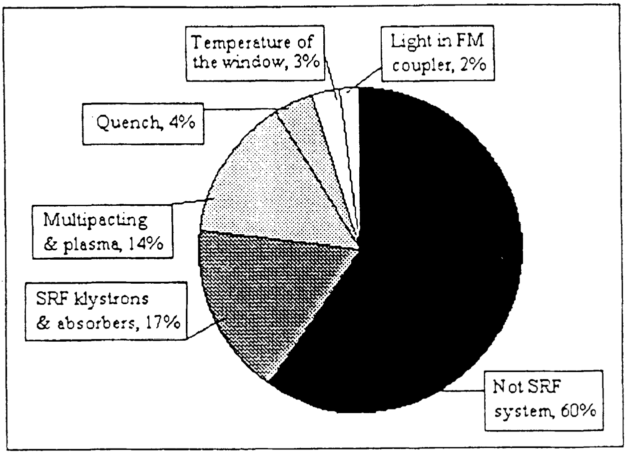

FIGURE 5 Beam loss statistics July–September, 1995.

2.1 Reliability of the SRF System

The recent statistics for the period from July to September 1995 says that 40% of all losses of the e^+ beam are caused by the SRF system (Figure 5). There are two dominating problems:

- loss of the beam caused by the failure of klystrons or absorbers,
- loss of the beam caused by multipacting or plasma discharging in FM couplers.

One more phenomenon has been observed during the high current experiments in November 1994:

- loss of the beam caused by strong detuning of cavities with the wrong phasing.

3 SRF SYSTEM FAILURES

3.1 Multipacting and Plasma Discharging in Fundamental Mode Couplers

To investigate these phenomena several signals are continuously recorded by the fast data logging program. If the beam is lost, all signals from 75 ms before to 25 ms after the loss of the beam are stored on the computer hard disk. Monitored signals are listed below:

Interlock signals:

- multipacting current I_e of each cavity*,
- input power P_{abs} of each absorber in the tunnel*.

Additional signals:

- voltage V_n of each cavity*,
- phase lock signal of each cavity V^*_{ph},
- total klystron power P_{kly},
- beam current I_b,
- amplitude of V_Σ.

Signals marked with * are measured by the multiplexer. Sixteen values of the I_e, V_n, P_{abs} and V_{ph}, are sent to the computer and re-measured every 2 ms.

The typical event of the multipacting and plasma discharging in the FM couplers is presented in Figures 6a–c. The electron current I_e (Figure 6a), measured by the electron probe, has a high amplitude and triggers the interlock loop. Since the delay time of all interlock loops has been fixed to 50 ms, the SRF system continues operation and the beam stays still in the ring for this time. At $t = 0$, klystrons are switched off (Figure 6b) and the beam is lost (Figure 6c), but discharging in the coupler remains until the input power decreases to a quarter of the initial value. The observed hysteresis is characteristic for the plasma discharging. It is very probably started by the multipacting, since its initialization happens only at some levels of the input power. Two periods of multiplexed I_e and V_n signals, at the beginning of the discharging, are shown in Figures 7a,b. The first period on both diagrams shows 16 I_e signals and 16 V_n signals, just before discharging occurs. In the second period we can see discharging in the coupler of cavity 3 and 4. The voltage in both cavities drops very fast. It gives an indication that the input power is reflected by the "short" produced by the discharging while the still circulating beam takes out the energy from the cavities. The plasma discharging decouples cavities from the waveguide and causes increase of the external Q. It was observed very often that during the plasma discharging the cavity was firstly emptied and then filled again by the beam, to the higher energy, such that the induced voltage reaches a value much bigger than $Ib \times (R/Q) \times Q_{\mathrm{ext}}$ (Figure 8). In addition, in many cases we observed

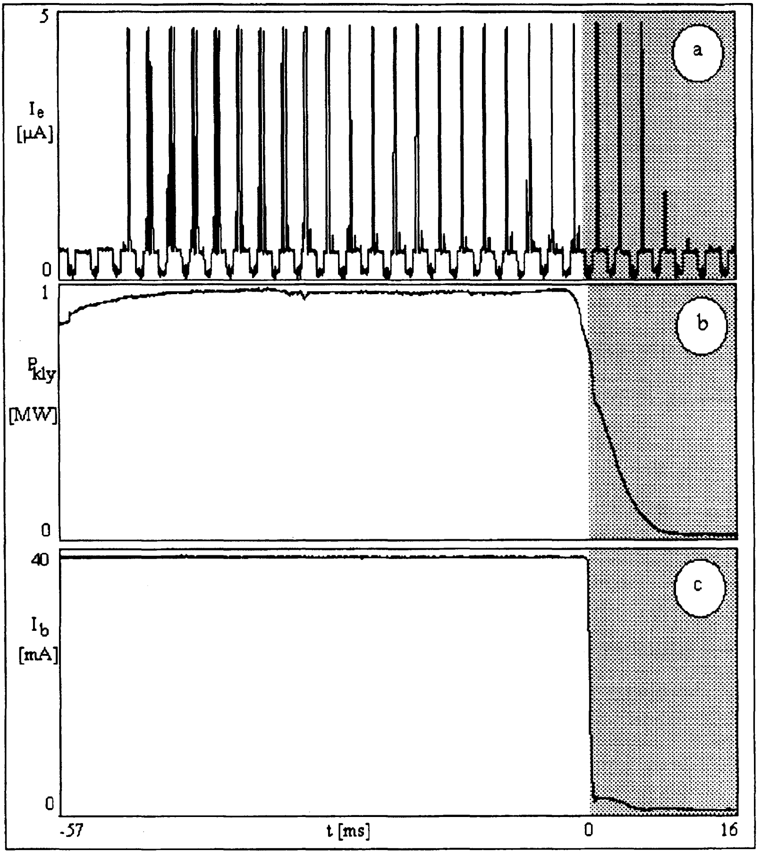

FIGURE 6 Multipacting and plasma discharging in FM couplers.

that discharging spreads to the coupler of the neighboring cavity, housed in the same cryostat. This can be explained by the rather short, 60 cm, distance between two couplers. To prevent FM couplers from multipacting and plasma discharging phenomena, pulse conditioning of the system has been applied. The processing is performed with a pulse length of 5 ms and a klystron power $P_{\mathrm{kly}} = 1.2$ MW. To enlarge part of the surface in the FM couplers, cleaned during processing, all cavities are simultaneously detuned by $\pm 45^{\circ}$, to move standing wave pattern in the couplers. This way of conditioning turned out to be extremely effective in suppressing of multipacting and plasma discharging.

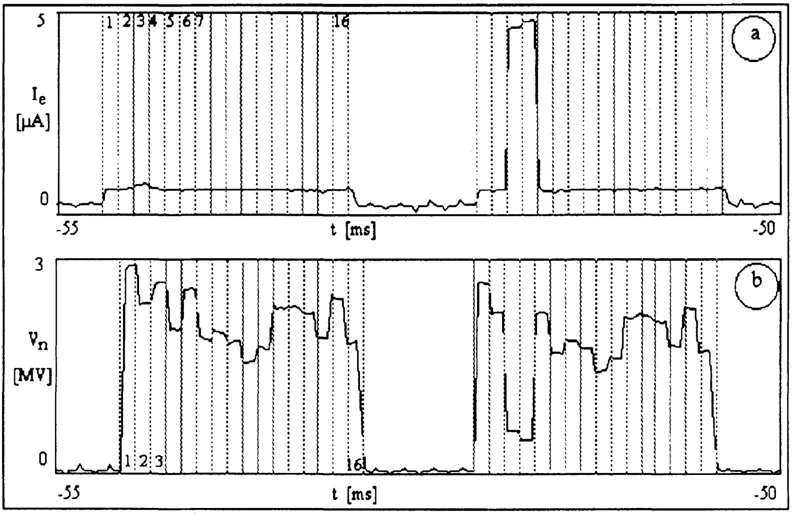

FIGURE 7 Beginning of the discharging in the FM coupler.

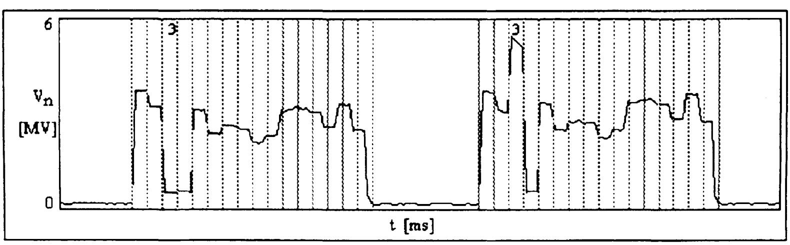

FIGURE 8 The empty cavity No. 3 is re-filled by the circulating beam and 2 ms later, voltage of this cavity reaches 5 MV.

3.2 Cavity Trips Caused by Phasing Errors

The strongest detuning of the cavities by the beam takes place during injection when the average synchrotron phase $\langle\phi\rangle$ is near to 90°. The measured phasing errors of the individual cavities were in the range of ±20°. There are two main contributions to them: limited accuracy in the phase adjustment and thermal effects in the power distribution system, occurring at the operation. The phasing errors and the strong beam loading cause big

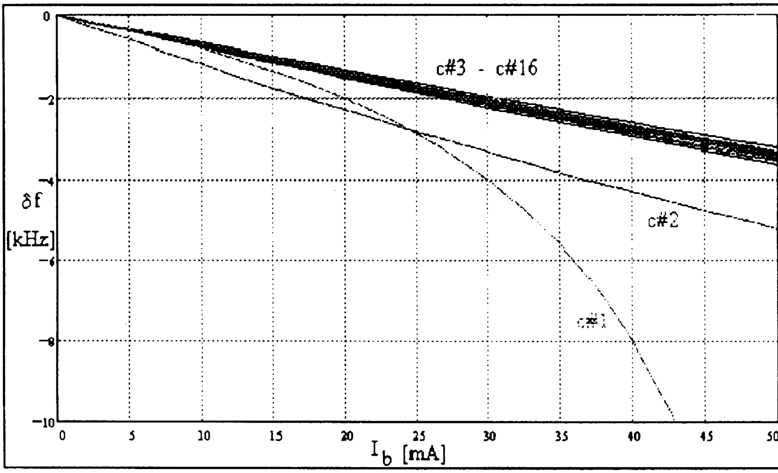

FIGURE 9a Detuning δf_n vs. I_b. Phase of cavity No. 1 $\phi_{s1} = 70°$ and $\phi_{s2} \div \phi_{s16} = 85°$.

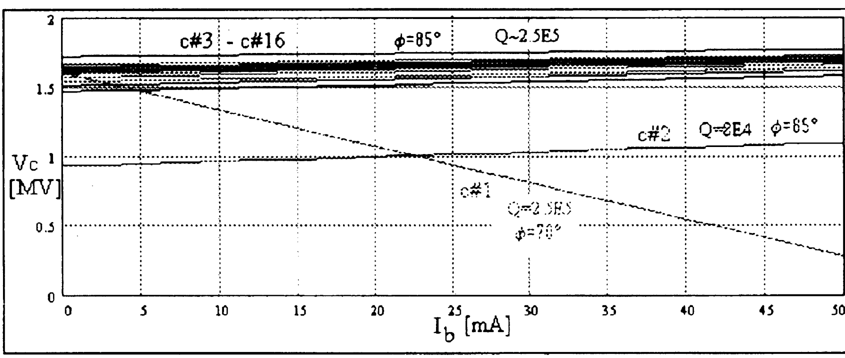

FIGURE 9b Voltage Vc vs. I_b. Phase of cavity No. 1 $\phi_{s1} = 70°$ and $\phi_{s2} \div \phi_{s16} = 85°$.

differences in the detuning of individual cavities. This has been observed during the high current experiments, in November 94.[3] As the VCL keeps V_{Σ} constant and does not control V_n of the individual cavities, voltages of cavities with smaller ϕ_s drop while voltages of cavities with bigger ϕ_s increase. The first group of cavities is detuned by many kHz towards the lower frequency. Spectral lines of the HERA e-ring are separated only by 47 kHz,

TABLE III Measured and re-calibrated values of V_n

NO.	Cavity Q_{ext} [10^5]	I_b = 0 [mA] V_n [MV]	I_b = 47 [mA] V_n [MV]
1	2.39	1.7	2.2
2	0.81	0.9	0.7
3	2.20	1.6	2.3
4	2.45	1.7	1.5
5	2.30	1.7	1.5
6	2.13	1.6	1.2
7	2.50	1.7	0.8
8	2.41	1.7	2.0
9	2.37	1.7	**3.2**
10	2.47	1.7	1.1
11	2.57	1.8	2.7
12	2.76	**1.9**	2.7
13	2.46	1.7	1.5
14	2.52	1.7	0.6
15	2.44	1.7	0.9
16	2.01	**1.6**	**0.5**
	V_{max}/V_{min}	1.19	6.40

thus strong detuning may cause the induced voltage by the lower spectral line to be comparable with the voltage of the fundamental mode. Figures 9a,b show computed detuning and voltage for individual cavities vs. I_b, when the whole SRF system is operated at V_Σ = 25 MV. In this computer simulation, cavity No. 1 has a synchrotron phase $\phi_{s1} = 70°$. Other cavities have phases $\phi_{s2} \div \phi_{s16} = 85°$. We can see here, that even for the smaller phase errors of $\pm 7.5°$, strong beam loading causes that the voltage of cavity No. 1, for I_b = 50 mA, drops to 20% of its value at the beginning of the injection. The measured results are presented in Table III. Voltages without beam are listed in column 3. Column 4 contains V_n measured with 47 mA beam, at an injection energy of 12 GeV. In both cases, the system was operated at a total voltage V_Σ = 25 MV. The ratio of the maximum voltage V_{max} to the minimum voltage V_{min} (bottom row)[a] changes here from 1.2 without the beam to 6.4 with the beam. To keep the system less sensitive to phasing errors, Q_{ext}'s of all cavities, except cavity No. 2, have been changed to half of the values listed in Table III. In 1995 cavities were mostly operated with the total voltage V_Σ higher than 30 MV. Under these new operation conditions cavity trips

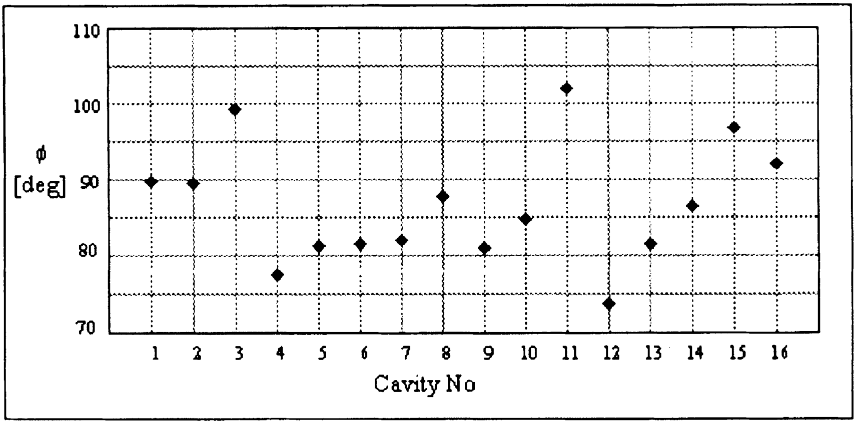

FIGURE 10 Phases of 16 sc cavities measured at the injection.

have not been observed in this year, even for the maximum stored current of 52 mA, although the phasing errors, after the last correction, are still in the range of $\pm 14^\circ$ (Figure 10).

4 CLOSING REMARKS

The last two years of operation have shown that the SRF system is able to:

- transfer nearly 1 MW power to the beam,
- produce total voltage of $35 \div 40$ MV for luminosity runs,
- store and accelerate up to 39 mA beam for the luminosity runs and store up to 52 mA beam for the machine studies (high current experiments).

In addition, high current experiments performed during the machine studies showed that HOM power induced by the beam does not exceed the expected value of 120 W/cavity and can be transferred outside cryostats to the external loads by the coaxial cables and feedthroughs. Two times (once 1993 and once in 1994) the beam was dumped by the feedthrough temperature interlock. In both cases, the feedthrough has been replaced and no temperature

[a] Ratio is computed without cavity No. 2, because Q_{ext} of this cavity is low for quench reason.

increase has been measured after the exchange. No quenching and no change in FM rejection filter performance have been observed for all 48 couplers during the five years of operation.

4.1 Klystron Power

The electron beam current, stored for the luminosity runs, still does not reach the design value of 58 mA but increases in average by 6.6 mA/year. To enable operation at $35 \div 40$ MV for the design current, one should make use of the nominal klystron power of 1.5 MW. As it was mentioned before, very recently, limitations in the power supply have been solved and we will operate both klystrons in the next year at the nominal power of 1.5 MW. The first attempt to increase the power has been carried out right after this Workshop. The operation with the klystron power 1.35 MW and 39 mA beam at 27.5 GeV was successfully performed.

4.2 Multipacting and Conditioning of the System

Last two months of operation showed that 2 hours of pulse conditioning once a day (during the injection of the proton beam, no additional time needed) suppresses very efficiently the multipacting and the plasma discharging in the couplers. The only one beam loss, caused by this phenomena, has happened in that time.

We have to proceed this way of conditioning for a longer time to be sure that no other means like the bias voltage or the baking will be necessary to increase the reliability of the system.

4.3 Phasing of the Cavities

Phase adjustment for the high current operation plays an important part. With the present values of Q_{ext}, the SRF system is less sensitive to phasing errors. Nevertheless, the injection of 58 mA beam and/or operation at 1.5 MW, will require higher accuracy in the phasing and better compensation for the dynamic errors, coming from the heating of the power distribution system. For this reason, we plan to build new waveguide transformers, with the stubs driven by stepping motors, to enable phase correction during operation.

References

[1] D. Proch, *et al.*, *DESY Laboratory Report* (Proceed. of the 6th Workshop on RF Superconductivity, October 4–8, 1993, CEBAF).

[2] B. Dwersteg, *et al.*, *Operating Experience with Superconducting Cavities in HERA* (Proceed. of EPAC94, 27 June–1 July, 94, London).

[3] J. Sekutowicz, *et al.*, *Beam Loading for 16 SC HERA Cavities with Voltage Control Loop* (HERA Seminar '95, March 1995, Bad Lauterberg).