NOTE ON PERFORMANCE OF THE RF SYSTEM IN THE HERA E-RING

J. Sekutowicz, MHF-SL Group, DESY, Hamburg, FRG

Abstract

The design value of the electron beam current in the HERA e-ring is I_b = 60 mA. For such high current, stable operation of superconducting and normal conducting cavities requires high phasing accuracy. The aim of this note is: to describe observed beam loss caused by phasing errors and to discuss the influence of the wrong phasing on the cavities' performance.

1 INTRODUCTION

The total beam power, required to store the design current at the collision energy of 27.5 GeV, is 5.2 MW. The circumferential voltage U_{cir}=125 MV, needed at that energy for stable operation, is provided by the RF system built of 16 superconducting, 500 MHz, bulk Nb cavities [1] and 82 normal conducting copper cavities (50 five-cell and 32 seven-cell cavities). Seven RF power stations, two klystrons each, supply microwave power to the cavities. One RF power station serves a group of 16 sc cavities. Other stations deliver RF power to six groups of nc cavities (five groups of 14 cavities and one group of 12 cavities). For the reliability and economical reasons one has to find out, what part of the U_{cir} should be supplied by the sc cavities (U_{sc}) and by the conventional cavities (U_{nc}). Fig. 1 shows RF power required for sc and nc cavities and sum of both powers vs. U_{nc} (lower scale) and vs. U_{sc} (upper scale), when I_b = 60 mA is stored at 27.5 GeV. Obviously, if voltage of sc cavities gets higher the whole system becomes more efficient, but there are three limits of U_{sc}.

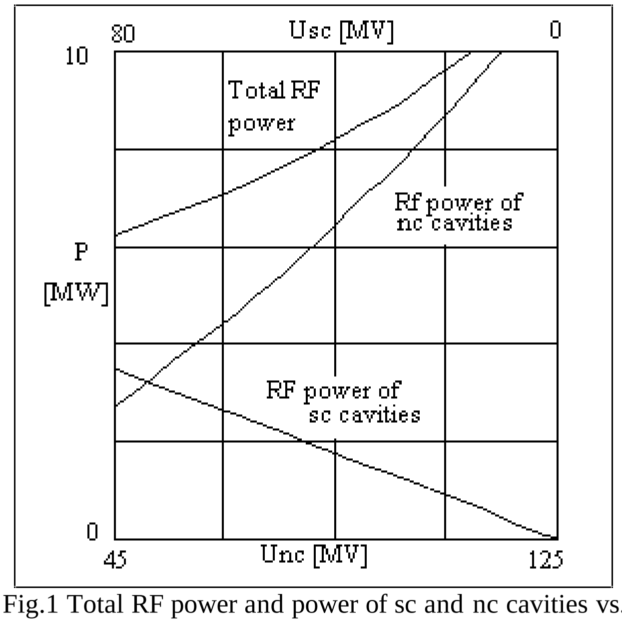

Fig.1 Total RF power and power of sc and nc cavities vs. U_{nc} , as required for I_b=60mA. U_{sc} = 125-U_{nc} .

Firstly, each RF power station cannot deliver more than 1.3÷1.4 MW. The maximum available power per sc cavity, reduced by losses of the RF distribution system, is about 82 kW. Since the mean value of the synchrotron phase at 27.5 GeV should be $<\varphi_s>$=45°, maximum U_{sc} cannot exceed 31 MV when I_b = 60 mA. Additionally, reliability of sc system goes down when the RF power increases. This is caused by plasma discharging in input couplers, initialized by multipacting phenomenon. Pulse conditioning, once a day, improved performance of sc cavities but does not give a safety margin for operation with maximum power. As a remedy against multipacting it is planned during shut down 1996/97, to put bias voltage between inner and outer conductor of each input coupler, to destroy resonant conditions for the multipacting phenomenon. The way it will be done is similar to that applied at CERN.

Secondly, the sc system can be operated only with U_{sc} smaller than 44 MV, due to quenching of some cavities. In opposite to both above mentioned upper limits, the third limitation, coming from phasing errors, determines a lower limit of the voltage U_{sc}. This will be discussed in the next sections for the group of 16 sc HERA cavities driven by one power station, but the conclusion applies to any kind of cavities if a group of them is driven by one power source.

2 VOLTAGE CONTROL LOOP

Each group of cavities in HERA is equipped with a Voltage Control Loop (VCL), which adjusts the RF power, to keep constant the voltage of the whole group for different beam loading and increase the efficiency of the system for the broader I_b range. The profit of using the VCL in case of sc cavities can be seen in the computed example shown in Fig. 2 a, b. The total voltage U_{sc}= 25 MV, as required, stays constant for the different beam current I_b and the fixed synchrotron phase φ_s = 45°. The RF power delivered to the cavities is adjusted and the reflected power is minimized. Without the VCL we would observe a drop of the U_{sc} for $I_b \geq$ 36 mA or a change of the synchrotron phase, increase of the U_{sc} and increase of the reflected power for $I_b \leq$ 36 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

$\eta = P_{beam} / P_{station}$ vs. I_b higher than 75% already for I_b>16 mA, although the system has been matched for a beam current of I_b = 36 mA.

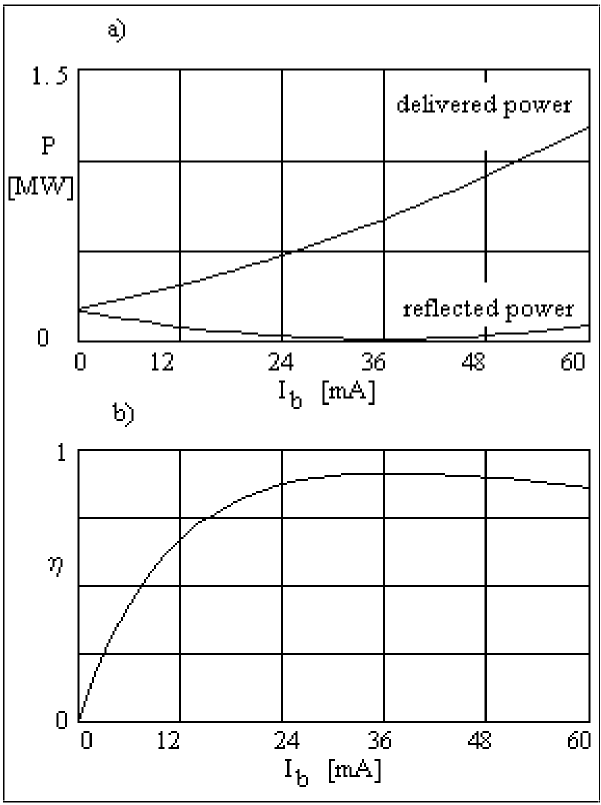

Fig. 2 a) Power delivered to sc cavities and the reflected power vs. I_b when U_{sc}=25 MV. b) efficiency of sc system.

3 CAVITY TRIPS CAUSED BY PHASING ERRORS

It was observed very often during an injection that voltages V_n of individual sc cavities with beam differed very strong from those without beam, however, sum $U_{sc} = \Sigma V_n$ stayed constant for both cases. That effect was associated with loss of the beam. An example observed during the high current experiments in November 94 [2] is given in Table 1. Maximum and minimum values of V_n have been underlined. Looking for an explanation we came to the following one. The strongest detuning of the cavities by the beam takes place during injection when the average synchrotron phase $<\varphi_s>$ is near to 90°. The phasing errors and the strong beam loading cause big differences in the detuning of individual cavities. As the VCL keeps U_{sc} constant and does not control V_n of the individual cavities, voltages of cavities with smaller φ_s (beam passes near to the crest of the V_n) drop while voltages of cavities with bigger φ_s increase. The range of phase deviations we have measured was ±15° (see Fig. 3). There are two main contributions to measured phasing errors: limited accuracy in the phase adjustment and thermal effects in the power distribution system occurring during operation, which are rather hard to foresee.

Table 1. Measured and re-calibrated values of V_n.

Cavity		I_b = 0 [mA]	I_b= 47 [mA]
No.	Qext[10^5]	V_n [MV]	V_n [MV]
1	2.39	1.7	2.5
2	0.81	0.9	0.6
3	2.20	1.6	2.3
4	2.45	1.7	1.7
5	2.30	1.7	1.7
6	2.13	1.6	1.1
7	2.50	1.7	0.5
8	2.41	1.7	2.2
9	2.37	1.7	<u>3.9</u>
10	2.47	1.7	1.0
11	2.57	1.8	2.9
12	2.76	<u>1.9</u>	2.2
13	2.46	1.7	1.5
14	2.52	1.7	<u>0.5</u>
15	2.44	1.7	0.9
16	2.01	<u>1.6</u>	0.6
V_{max} / V_{min} *)		1.19	7.80

*) ratio is computed without cavity No. 2, because Qext of this cavity is low for quench reason.

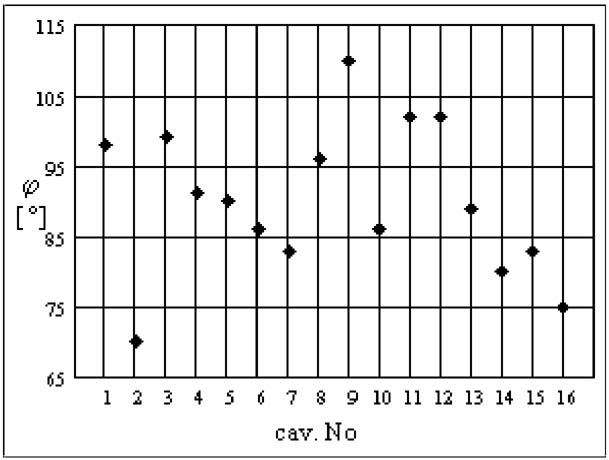

Fig. 3 Phases of sc cavities measured at injection

All cavities with smaller φ_s are detuned by many kHz towards the lower frequency. Since spectral lines of the HERA e-ring are separated by 47 kHz, strong detuning may cause the induced voltage by the lower spectral line to be comparable with the voltage of the fundamental mode what usually yields to loss of the beam.

Fig. 4 a, b show computed voltage V_n and detuning δf_n of individual cavities vs. I_b , when the whole sc system is operated at U_{sc} = 25 MV. In this computer simulation, cavity No. 1 has phase φ_{s1} = 70°. Other cavities have phases $\varphi_{s2} \div \varphi_{s16}$ = 85°. We can see here, how the beam loading causes that the voltage of cavity No. 1 drops to zero when the injected beam reaches 60 mA. Notice that in the computed example the phase deviation range was only ±7.5°, a half of what we have measured. The situation can be improved if U_{sc} gets higher. This is shown in Fig. 5, which gives δf_n for U_{sc}= 31 MV

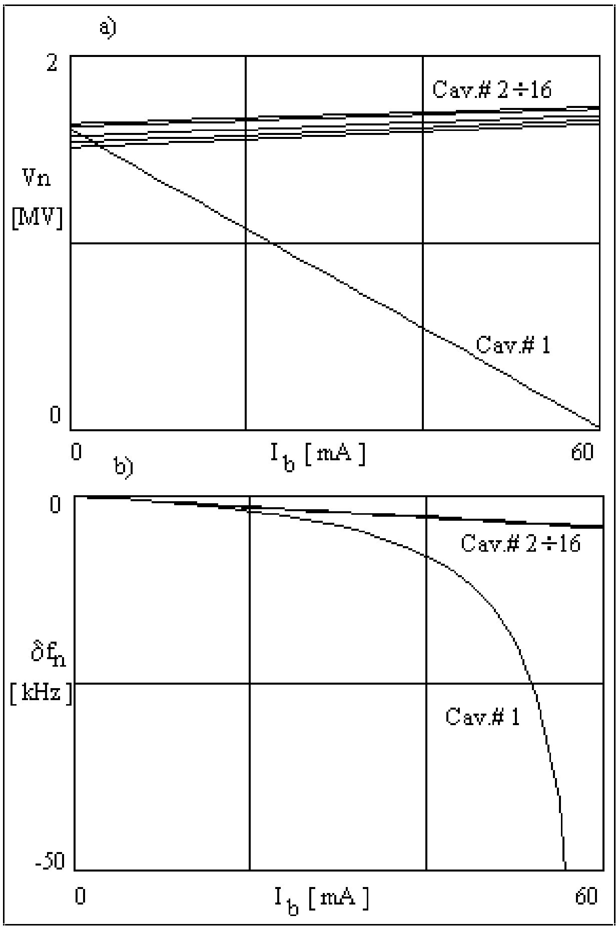

Fig. 4 V_n (a) and δf_n (b) during injection. Both diagrams are done for U_{sc}=25 MV, φ_{s1} = 70° and $\varphi_{s2} \div \varphi_{s16}$ = 85°.

instead of U_{sc}=25 MV. Detuning of a cavity with impedance (R/Q) and loaded quality factor Q_L is given by the following expression [3]:

$$\delta f_n = -\frac{\tan(\zeta)}{2 \cdot Q_L} \cdot f_o \qquad (1)$$

where:

$$\tan(\zeta) = \frac{I_b \cdot (R/Q) \cdot Q_L}{V_{gr} - I_b \cdot (R/Q) \cdot Q_L \cdot \cos(\varphi_s)} \sin(\varphi_s) \qquad (2)$$

or

$$\tan(\zeta) = \frac{I_b \cdot (R/Q) \cdot \sin(\varphi_s)}{\sqrt{\frac{4}{Q_{ext}} P_{inp} \cdot (R/Q)} - I_b \cdot (R/Q) \cdot \cos(\varphi_s)} \qquad (3)$$

V_{gr} is the source induced voltage and P_{in} is the cavity input power. To avoid strong detuning one needs to make denominator in (2) or (3) big, by increasing of V_{gr} or decreasing of $Q_L \cong$ Qext. For an ideal phased group VCL makes denominator simultaneously constant for each cavity. If φ_s errors are significant increase of Pin vs. I_b is not sufficient for cavities with smaller φ_s and V_n drops. This explains why phase errors limit lower value of U_{sc}. To keep the sc system less sensitive to phasing

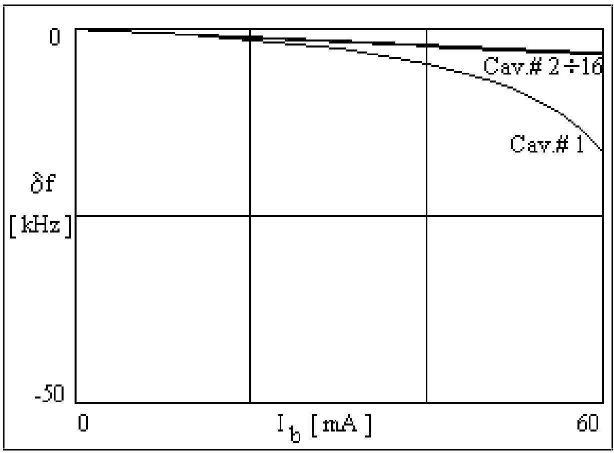

Fig. 5 δf_n during injection, U_{sc}=31 MV, phases as before.

errors, Q_{ext}`s of all cavities, except cavity No. 2, have been changed to half of the values listed in Table 1. Additionally, in 1995 cavities were mostly operated with the total voltage U_{sc} higher than 30 MV. Under these new operation conditions cavity trips have not been observed in this year, even for the maximum stored current of 52 mA, although the phasing errors, after the last correction, were still in the range of ± 14°. During the last shut down phase shifters have been installed to enable proper cavity phasing.

Measurements performed in December 95, showed that groups of nc cavities have a phasing errors range as listed in Table 2. They may lead to similar problems for the high intensity beam.

Table 2 Phasing errors range of nc cavities

Group	$\delta\varphi_s$ [deg]
NL (north-left)	± 7.3
NR (north-right)	± 7.6
OL (east-left)	± 19.2
OR (east-right)	± 14.2
SL (south-left)	± 10.1
SR (south-right)	± 26.2

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