Operation of the RF System During the Commissioning of ELETTRA.

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Abstract

Due to the very short time needed to achieve multiturn operation, the RF system of ELETTRA was switched on already on the second day of the first commissioning phase of the machine (October 6, 1993). The first beam accumulation was then observed on the same day. Since the beam energy was limited to 1.1 GeV, one cavity was sufficient. In fact with only one cavity operating at 530 kV peak gap voltage, it was possible to store up to 400 mA at the end of the first commissioning phase (December 1993). At the beginning of the second commissioning phase (January 1994), a second cavity was switched on. The performance of the RF system during the commissioning is discussed here.

1. INTRODUCTION

The RF system of ELETTRA is composed of four 500 MHz cavities distributed along the ring [1]. Each cavity is fed by an independent 60 kW RF plant. A temperature control, a tuning loop and an amplitude loop are installed on each plant. A phase loop is foreseen, the prototype tested on one plant with beam during the commissioning and it will be installed in the next months.

The RF system was switched on already the second day of the commissioning. In fact 2000 turns (which was roughly the maximum number of turns calculated for operation without RF) were achieved on the second day. Since the injection energy was limited to 1.1 GeV, only one cavity was switched on, at the beginning without amplitude loop. All over the first phase of commissioning (October-December 1993), only one cavity was used which was sufficient to reach 410 mA at the end of this phase [2,3].

In January, a second cavity was switched on and in the following months the remaining two. Energy ramping of the machine was performed up to a maximum energy of 2.3 GeV, without acting on the RF parameters [4].

2. ONE CAVITY OPERATION

For the first three months, the machine was operated with only one active cavity, whereas the remaining three were detuned in order to avoid harmful interaction with the beam. Since the machine operated at 1.1 GeV during this first period and no ID were used, the loss to restore were only the ones due to the bending magnets which are 23.3 keV/turn. This means that for the design beam current (400 mA), the total required RF power for the beam is about 9.3 kW. Being 60 kW the available RF power per each plant and the measured cavity shunt impedance equal to 7 MΩ, it is clear that one cavity is sufficient to restore the beam losses.

The driving signal for the RF plant could be synchronous or asynchronous to the machine main clock. The cavity resonant frequency was set to 1 kHz below the generator frequency to prevent Robinson instabilities. The vacuum trip level was set at 10^{-7} mbar. Since it was not expected to reach high currents in the first period of commissioning, the main coupler of the cavity was adjusted to critical coupling without beam. Therefore the reflected power was increasing proportional to the beam current. The amount was a few percent of the forward power, in any case staying far below values which could be critical for a safe operation of the RF plant. At the beginning no amplitude loop was installed. It must be noted that the amplifier and all the components of the plant were designed to have an amplitude stability of ± 1% and a phase stability of ± 0.5°. Therefore the amplitude loop and the phase loop are meant only to cope with beam related effects. Without amplitude loop, the gap voltage was decreasing due to the beam loading effect with the stored current. In this case, in fact, being the total power delivered by the amplifier constant, the power dissipated on the cavity walls decreased with increasing beam current. In some occasions, particularly for high injection rates, this caused fast changes of the cavity temperature and consequently a detuning of the cavity. This caused a phase rotation and a decrease of the cavity gap voltage which resulted in sudden beam losses probably related to Robinson instability. Anyhow a maximum current of 212 mA at 1.1 GeV was reached. The total power delivered by the amplifier was kept to 20 kW. For a radiation loss of 23.3 keV/turn, about 5 kW of RF power was required for the beam and therefore the gap voltage was 450 kV. This means, taking into account the transit time factor (0.7 for our cavities) that the stable phase angle was about 4.2°.

The amplitude loop was set into operation at the end of October. After an optimisation of the parameters of the loop, a satisfactorily operation of the loop was reached. The gap voltage was kept constant to ± 1 % at any current and the power delivered by the amplifier was seen to increase in good agreement with the stored current. Actually the variation of the input power was used as a cross check of the current measurement.

With the amplitude loop and the cavity operated at 530 kV gap voltage, a maximum current of 410 mA was stored. Under these machine conditions, the power delivered by the amplifier was 32 kW (20 kW in the cavity, 10 kW to the beam, 2 kW reflected to the circulator and insertion loss of the coaxial line). The stable phase angle was 3.6°.

3. MULTICAVITY OPERATION

At the end of the first phase of the commissioning, the main coupler of each cavity was set to the correct position in order to obtain matched line conditions at 1.5 GeV 400 mA (coupling factor=1.5). The second cavity was switched on in January 94. The phasing between the two cavities was quite easily performed by balancing the input power to the cavities. For this purpose a remotely controlled variable phase shifter was installed for each plant. Finally the gap voltage of the cavities was set to 500 kV, thus giving a total gap voltage of 1.0 MV and hence a total accelerating voltage of 0.7 MV. With two cavities sufficient RF power was available to perform ramping of of small beam current from the injection energy (1.1 GeV) to 2.3 GeV, which was actually performed without varying the gap voltage but acting only on the magnets of the machine. It must be noted that there was no need to optimise the phases between the two plants and the linac in synchronous mode. Setting into operation of the third cavity (April 94) and of the fourth one (May 94) was quite directly performed based on the experience with two cavities balancing the input power to all the working cavities, so that the beam receives the same amount of power in each cavity. The gap voltage of each cavity is set to 500 kV, giving a total voltage of 2.0 MV and it is not varied during the energy ramping of the machine. At 1.1 GeV this results in a stable phase angle of 1°, while at 2.0 GeV this is equal to 10.5°. For all the cavities, the resonant frequency is set 1 kHz below the generator frequency to prevent Robinson instability. The working reference temperature of the cavities is set in the 50÷60 °C range. Up to now with three cavities operating in these conditions, a record stored current of 530 mA has been reached at 1.1 GeV and 226 mA were successfully ramped up to 2.0 GeV.

4. CAVITY OPERATING TEMPERATURE AND H.O.M. DISTRIBUTION

The cavity reference temperature is held constant better than ± 0.05 °C by the water cooling system. Being the temperature dependence of the cavity equal to 8.5 kHz/°C, this means that for constant gap voltage (and hence constant wasted power on the cavity walls), the frequency of the cavity is kept in a 850 Hz range by the temperature loop. The cavity reference temperature is set in the 50÷60 °C range. At the beginning of operation the reference temperature is set at 55 °C for each cavity. At this nominal temperature value, the resonance frequency is the nominal one (499.654 MHz) with external tuning system in the central position. For other temperature values or generator frequencies, the mechanical tuning system adjusts itself in order to maintain the relation between cavity fundamental mode and generator frequencies. On the contrary, the H.O.M frequencies are free to vary with the temperature. Therefore moving the reference temperature of the cavities allows to change the H.O.M. resonance frequencies, while the fundamental frequency is kept constant by the mechanical tuning loop. In this way a simple method to move dangerous H.O.M modes is possible. Obviously, due to minor mechanical differences, the H.O.M. distribution of the cavities is slightly different and therefore the optimum operating temperature can be different from cavity to cavity. A mapping of the H.O.M. of the cavities up to the cut-off frequency of the vacuum chamber has been performed at different temperature in the 50÷60 °C range with a network analyzer. For example fig.1 gives the behaviour with temperature of the frequency of the first six longitudinal H.O.M. for one cavity. Since the frequency distribution in the cavities with RF power and beam loading can be different compared to the "cold cavities", the frequency vs temperature measurements were verified under operating conditions. This was possible by measuring the amplitude variation of beam harmonics when the reference temperature of the cavity is changed. The signal was picked up on the cavity gap voltage measuring loop and the measurements were performed with a spectrum analyzer. The agreement between the data taken on the "cold cavities" and those taken in operating conditions is fairly good. Based on the results of these investigations, an optimisation of the reference temperature of each cavity will be performed. A detailed description of these measurements is given in [5].

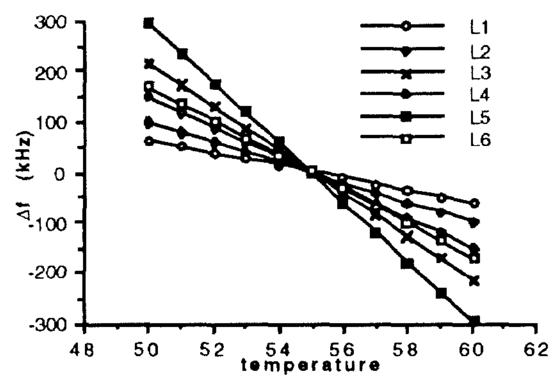

Fig. 1 Variation of the resonance frequency of the first six longitudinal modes vs. temperature (55°C taken as the reference). At 55 °C: L1=950.056 MHz, L2=1055.017 MHz, L3=1419.029 MHz, L4=1513.440 MHz, L5=1598.314 MHz, L6=1877.001 MHz

The idle cavities were detuned by more than 300 kHz above the nominal RF frequency in order to avoid interaction between the beam and the fundamental mode of the not unpowered cavities. The detuning was obtained by keeping the temperature of the cavities around 25 °C, that is more than 30 °C below the working reference temperature. The voltage induced in the fundamental mode of these cavities has been measured and found to be negligible.

5. VACUUM IN THE CAVITIES

The pressure in the cavities is normally in the range between 5 10^{-10} and 5 10^{-9} mbar depending on the intensity of beam current. In the passive cavities the vacuum pressure does not differ substantially from the values measured in the active ones. Thus the pressure in the cavities results to be, at the gap voltage levels used, almost independent of the RF power. This is due to the careful RF power conditioning. The vacuum pressure depends obviously on the beam intensity, and a deterioration of the vacuum conditions has been observed in case of very high injection rates (some tens of mA/sec). On some occasions this caused a pressure trip (level of 1.0 10^{-7} mbar) and consequently RF was switched off. Anyway, the number of interruptions is very low and decreases with operating time, which demonstrates that a certain number of operating hours with beam is fundamental for the complete reliability of the system.

During a shutdown an inspection of the inner surface of the cavities and of the ceramic windows was done. No trace of metalization was observed on the cavity power feedthroughs. Although the operating hours were still limited, this seems to be a good indication for the reliability of the power coupler.

6. POWER PLANT PERFORMANCE

Each power plant is composed of a 60 kW 500 MHz amplifier using a klystron as final stage, followed by a circulator equipped with temperature compensating system and arc detector. Each plant can be switched on independently from the others, so the operation can be adapted to the needs. Of course this could also be useful in case of faults, since it allows to operate the machine, even if at a reduced available RF power. Usually the power plants have operated at an output power in the 18 ÷ 40 kW range. The stability of the cavity voltage has been measured for operating conditions with beam and it is better than 1 % in amplitude and 1.4° in phase even without phase loop (fig. 2). The RF generator frequency was usually the nominal one (499.654 MHz) and it was varied in a maximum range of ± 20 kHz for machine physics measurements.

No failures occurred on the power plants except the substitution of a faulty fan due to a failure of a protection thermostat. The operating hours for the most used plant (the one which has been switched on just at the beginning of the commissioning) are more than 2500 hours. Even if this is not a long operating time, a first positive conclusion on the reliability of the power plants can be drawn. All the low level implemented circuits did not have any failure and their performance has been well in the required specifications. One prototype of the phase loop has been tested on one RF plant during the last months of the commissioning. The prototype showed a satisfactory behaviour. The phase was kept well within the ± 0.5° range and the whole system worked properly. Hence the production of the four definitive phase loop circuits has started and they will be installed during the next months.

7. CONCLUSIONS

Up to now all the RF cavities have been set into operation. The whole system has worked reliably. A study on the working reference temperature of the cavities and its relation with H.O.M. has been carried on. This will allow to optimise the operation of the system in order to minimise or avoid the excitation of H.O.M. by the beam and eliminate related instabilities.

Still no complete tests have been performed on the mutual interaction among all the control loops of the plants, even if for the moment the operation of the whole system is satisfactory. It must be noted that on each RF plant four loops are foreseen: the control of the reference temperature, the tuning loop, the amplitude loop and finally the phase loop. An extensive study will be performed when all the loops are installed in order to further optimise the performance of the whole system.

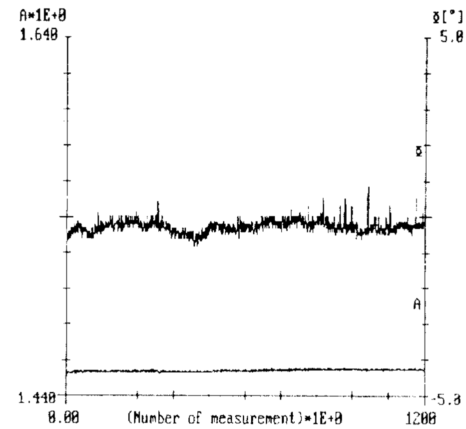

Fig.2 Measurement of phase (upper curve) of gap voltage on one cavity (no phase loop installed) with respect to the reference signal. The lower curve shows the ratio between the amplitudes of the two signals.

8. ACKNOWLEDGMENTS

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