# OPERATIONAL EXPERIENCE WITH THE ELETTRA RF SYSTEM

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*Abstract*

The ELETTRA RF System has been in operation since October 1993 and has now exceeded 20000 running hours. With four 500 MHz cavities powered by four 60 kW transmitters, ELETTRA has successfully delivered synchrotron light to the users with 300 mA of stored current at 2 GeV in multibunch mode, which is 1.5 times the initial target value ( 200 mA at 2 GeV). The RF system has worked very satisfactorily. Apart from the usual problems of debugging a new system, the main problem encountered during the operation period came from the coaxial power transmission line. The global operational experience gained during these years of operation and the performances of the various elements making up the ELETTRA RF system will be reported.

## 1 INTRODUCTION

The first beam was stored in ELETTRA in October 1993, just the second day of the commissioning. A full description of the system can be found in [1], but briefly it is composed of four bell shaped 500 MHz cavities, each one powered by an RF plant. Each plant can run completely independently of the others. Every power plant is composed of a 60 kW klystron amplifier derived from an UHF television transmitter, decoupled to the cavity by a power Y-junction circulator. Power transmission is performed by 6 1/8" coaxial cables. Two racks of low level and control electronics are installed for each plant. For fine regulation and stabilisation of the cavity fields, three feedback loops are installed: a frequency loop, an amplitude loop and a phase loop. An important feature of the system is the high precision stabilisation and setting (±0.05 °C) of the cavity reference temperature, which is used to control multibunch instabilities [2].

Protective equipments' interlocks of the unit act directly either on the power amplifier or to the switch which cuts the RF driving power to the plant. The RF system is completely remotely controlled from the storage ring control room. At the present time operating hours of the plants range from 21000 to 25000.

## 2 OPERATIONAL ASPECTS

Table 1 shows the operating parameters of the RF system during users' operation. Beam is injected at 1 GeV and then ramped to 2 GeV without acting on the RF system except for the change of the RF frequency required for orbit optimisation (from 499.654 to 499.649 MHz). The amplitude loop automatically adjusts the driving power to the amplifier to compensate for the increased beam loading. The coupling factor of the power feedthtrough was set during the installation to 1.5, which is the value required for 400 mA at 1.5 GeV. The amount of reflected power is always negligible (below 1.2 kW in the worst condition) and also the ratio between cavity and beam power is higher than 1.52, hence far from the Robinson instability limit. Therefore so far there is no need to change the coupling of the main couplers.

Table 1: RF System Operating Parameters

| Energy | 1 | 2 | GeV |
|---|---|---|---|
| Current | 300 | 300 | mA |
| Energy lost per turn without ID | 16 | 255.7 | keV |
| Energy lost per turn with ID | | 290.2 | keV |
| Power to the beam | 4.8 | 87.1 | kW |
| Number of cavities | 4 | 4 | |
| Total available RF power | 240 | 240 | kW |
| Peak cavity voltage | 630 | 630 | kV |
| Total eff. voltage | 1.76 | 1.76 | MV |
| Power wasted per cavity | 29.2 | 29.2 | kW |
| Beam power per cavity | 1.2 | 21.8 | kW |
| Total power per cavity | 30.4 | 51 | kW |
| Synchronous phase angle | 0.5 | 9.5 | deg |
| Overvoltage factor | 110 | 6.1 | |
| Synchrotron frequency | 16.1 | 11.3 | kHz |
| Cavity detuning | 41.3 | 41.3 | kHz |

By constant improvements to the equipment reliability the number of RF faults has constantly decreased. Statistics show that in 1997 the downtime due to the RF system amounted to 4 % of the total machine downtime [3]. It must be remembered that since each RF plant is independent, the machine can operate even with three RF plants, although in this case beam lifetime is consequently reduced. This allows in case of faults which cannot be fixed in a short time to repair them while the machine is in operation or, if not possible, to postpone the repair to a more convenient time. When the total RF voltage drops due to the trip of one RF plant, normally the beam is lost although this does not always happen. There are two possible reasons for this. The loss of one plant causes a fast increase of the stable phase angle. Due to the limited speed of the amplitude loop and the new combination of amplitude vectors, this provokes a voltage loss in the remaining operating cavities, leading to an avalanche effect and then to a complete beam loss, although not interrupting the operation of the remaining cavities [4]. Another explanation is that when a plant is lost, the related cavity cools down rapidly and if a strong coupled bunch instability is crossed, the beam is lost.

Coupled bunch instabilities are controlled by a careful setting of cavities' temperature and positioning of the movable higher order mode frequency shifters (HOMFS) installed on two cavities [2], [5]. A key factor for the success of this technique has been the good performance of the cooling rack, which keeps the cavity reference temperature stable to ± 0.05 °C. This parameter can be independently chosen for each cavity in a range between 40 and 80 °C. Coupling of the cavities via the beam has been sometimes observed. This normally appears as coupled oscillations in power and temperature of two cavities. The phenomenon is clearly due to higher order modes excited by the beam in one cavity. In fact to remove it, it is sufficient to shift the temperature of the cavity where the mode is excited to a value where the excitation is no longer present.

The RF system is completely remotely controlled and the procedures for switching on the plants and ramping the gap voltages have been completely automatised. Five minutes are required to get the amplifier ready and five minutes are needed to ramp the cavity gap voltage to the final value. Since the change of the RF frequency is now automatically performed by machine programs, the operator has no need to act on any setting or command of the RF system in standard machine operation. Only occasionally, for optimisation, small changes (some tenths of °C) of the cavity temperatures are required.

## 3 EQUIPMENT BEHAVIOUR

### *3.1 Cavities*

Prior to the installation in ELETTRA, all the cavities were baked at 150 °C and RF conditioned in the laboratory. Once installed in the ring, the cavities were re-baked and re-conditioned to 40 kW. Additional bake outs were performed each time the cavities were opened (installation of the HOMFS, substitution of the RF fingers on the vacuum valves). Due to the careful procedures which are followed during these operations, the re-conditioning of the cavities required only a few hours. This is also due to the good conditioning of the cavity walls reached after so many hours of operation with RF power and beam current. In fact also during operation, cavity vacuum interlock trips which happened during the first months of commissioning have disappeared. Vacuum in the cavities is now normally below 5 $10^{-10}$ mbar without beam at nominal RF power and below 5 $10^{-9}$ mbar with beam. Power input couplers have not given any problem. Visual inspections made on the occasion of the mounting of the HOMFS and during the substitution of the RF fingers did not show any degradation of the ceramic windows.

### *3.2 Power Plant*

On the whole, the 60 kW 500 MHz amplifiers have performed well. No klystron has been substituted so far. It is expected that the replacement of the klystrons will start at the end of this year, when all will have exceeded 25000 operating hours. The klystrons have not given any problems, no tube oscillations have ever been observed. With regard to the amplifiers, there has been only one major fault. On one of the amplifiers, the high voltage three phase transformer was recently damaged by an internal discharge in the low voltage part of the central winding and therefore had to be substituted. The operating hours of the plant were about 20200. From the measurements taken on the amplifier with the new transformer, it was clear that it was running at a much higher temperature compared to the remaining ones (146 °C instead of 130 °C). Although this value is below the threshold of the interlock thermoswitches installed inside the transformer, it is possible that working continuously at this temperature could have degraded the dielectric strength of the winding coating. There is no evident reason (absorbed power, mains harmonics, malfunctioning of the cooling, ambient temperature, etc.) for this anomalous behaviour of one amplifier and the problem is still under investigation.

The power circulators have performed very well. They are equipped with an arc detector and a regulation unit which compensates impedance variations in the circulator as a function of the cooling water temperatures and therefore of the RF power. The problem of spurious circulator arc trips happening during the first years of operation has been solved. This was simply due to a too sensitive control electronics, which was influenced by electronic noise.

Transmission of the RF power is performed by a 6 1/8" rigid coaxial line system, which is a suitable standard for the power levels and the RF frequency used. During these years of operation, we suffered from two main problems on the transmission lines. One came from the insulating supports of the inner conductor. Since part of the transmission line is in the tunnel, where it was expected to have a high radiation level, at the beginning it was decided to use a cross-linked polystyrene insulation which is advised for RF high power applications in areas where high radiation could be present. In May 96, the insulating support of one flexible joint was found to be almost completely melted causing repetitive faults on one plant. An immediate inspection of all the components showed that also other insulation supports had deteriorated to the same or lower extent. This problem was probably caused by a long term alteration of the characteristics of the insulating disks. This could be due to temperature effects, in fact this insulation material has a higher loss factor than teflon and it appeared clear that the degradation started at the points where, according to the calculations, the insulating disks reached the highest temperature. A further evidence of this was that the most damaged components were the flexible lines where a thicker dielectric disks is installed and which are mounted in a radiation free area. Measurements of the radiation levels inside the tunnel have shown that these are still below significant values [6], therefore it was concluded that all the insulation disks could be safely substituted either with ceramic or teflon ones. Lately at the end of 1997 a discharge damaged some components of one plant. The discharge started at the connection between the inner conductors of two coaxial components then, due to the contamination provoked by the first discharge, other components were partially involved. The discharge was due to the deterioration of the spring contacts, although it is not explained why it did not happen soon after the mounting of the line rather than after almost 6000 hours of operation from the last dismounting of the two components.

### *3.3 Low Level Electronics*

The low level electronics has proved to be very reliable. It is of modular construction, which eases installation and maintenance. After the initial debugging which involved also the choice of the fine settings of the loops, no problems came from this part of the RF system. All the required specifications have been met. The frequency loop keeps the cavity resonant frequency to ± 500 Hz or ± 100 Hz, according to the sensitivity chosen, so counteracting the reactive part of the beam loading. Actually the frequency loop sensitivity is normally set to ± 500 Hz, while the cavity resonant frequency is kept - 1 kHz below the generator frequency to avoid Robinson instabilities. The amplitude loop keeps the cavity gap voltage stable to ± 1 % at any beam loading, while the phase loop keeps the phase of the input power to the cavity within ± 0.5 degrees (at 500 MHz) at any power level. All the other components of the low level electronics (interlock switches, remotely controlled plant phase shifter, etc.) have performed well inside the required specifications. Actually no faults have happened in the low level electronics except a trivial one (malfunctioning of the fuses of one electronic board).

## 4 FUTURE UPGRADES

In parallel with the construction of the low level electronics for the synchrotron light sources ANKA and SLS, the low level electronics will be upgraded to add additional features to the system. The main ones will be to have a variable bandwidth of the amplitude and phase loop. The amplitude loop bandwidth will be adjustable in eight steps between 30 an 4000 Hz, while the phase loop bandwidth will be adjustable in eight steps from 100 to 5000 Hz. This will allow a further regulation of the system to conclude the studies on the effects of loop settings on beam quality. First tests were already performed during the characterisation of the loops [7].

The total available RF power is now 240 kW, which allows to store more than 330 mA at 2 GeV. Neglecting other factors which presently do not allow to increase the beam current in the machine, additional RF power is required to store 400 mA keeping the present total RF voltage. There is also a great interest to operate the machine at 2.4 GeV and already more than 100 mA have been stored at this energy. The maximum current which would be allowed by the available RF power at 2.4 GeV is 180 mA, with the same peak gap voltage (630 kV). Different scenarios can be envisaged to increase the RF power. The first one was already foreseen in the conceptual design of the machine: adding two 60 kW plants equal to the existing ones. This would allow to store more than 400 mA at 2 GeV and more than 250 mA at 2.4 GeV. There is however some concern in adding two more possible sources of multibunch instabilities due to the higher order modes of the additional cavities. Other possibilities would be to double the available RF power to each cavity by combining two similar RF amplifiers or installing completely new higher power plants. A hybrid scenario can also be thought, where only one or two plants will be upgraded to higher power. In this case a careful phasing of the plants is required, so that one or two cavities will deliver more power to the beam.

## 5 CONCLUSIONS

Reliability is a major concern for all the equipment installed in the synchrotron light source ELETTRA, where operating hours have been 6168 in 1997 and 6528 in 1998. The modular way the RF system has been built has been a key factor to assure the good performance of the system. Another important factor has been the choice to have as many components as possible that are more or less equal or derived from standard industrial components, therefore having the advantage of having been thoroughly tested.

## REFERENCES


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