# RF System Developments for High Current Accumulation in the ESRF Storage Ring

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*Abstract*

The radiofrequency system, in operation on the ESRF storage ring for more than two years, has recently been upgraded to allow the accumulation of 200 mA. Coherent multibunch beam oscillations are damped by filling only one third of the storage ring: in this mode, 175 mA have already been achieved.

Despite the increasing reliability and performances of the RF system, recent cavity window failures have slowed down the program for higher stored beam intensity. The analysis of the window failures, however, indicates that too slow vacuum interlock triggering rather than high intensity operation are to be incriminated. The implementation of very fast triggering of the RF pin switch after a cavity pressure burst will free the way towards 200 mA of stored beam.

## 1. INTRODUCTION

Four 352.2 MHz five-cell LEP-type cavities, initially coupled with $\beta = 3$ to the power source, provide the accelerating voltage of 7 to 9 MV required to compensate for the synchrotron radiation loss in the ESRF Storage Ring (SR), [1, 2]. Although two transmitters are available, the initial scheme of feeding RF power from only one transmitter to all the four cavities has been kept until now: we could store 156 mA of beam using a 1 MW klystron, i.e. more than the nominal design current of 100 mA.

As a consequence of the good experience at high intensity operation, the system has been upgraded in January 94 with a 1.3 MW klystron and an increased coupling $\beta = 4$ of the accelerating cavities which together principly push the current limit to 200 mA. In this configuration already **175 mA** of stored beam have been achieved.

Besides the available RF power, the maximum power ratings of the cavity input couplers and beam instabilities are key issues for high intensity operation : our experience and corresponding developments are also briefly presented.

## 2. RF PARAMETERS FOR HIGH BEAM CURRENTS

In the modified ESRF version of the five-cell LEP design, each cavity is powered through two coaxial input couplers since high beam loading $P_b$ adds to the power $P_c$ dissipated in the 4 cavities to produce the required accelerating voltage [1,2]. Fig. 1 shows that for a typical accelerating voltage $V_c$ = 7.5 MV, the power incident on each coupler reaches the nominal LEP test power of $P_g/8$ = 140 kW at about 160 mA. ($P_g$ being the total RF power incident on the 4 SR cavities).

The coupling of the cavities had initially been set to $\beta$=3 in order to operate the cavities under matched conditions around the nominal current of 100 mA: zero of the computed reflected power $P_r$ in fig. 2.

The ceramic RF window is at a quarter wavelength from the coupling loop, i.e. at a E-field maximum. In fig. 2 is plotted the calculated equivalent incident power $P_w$ corresponding to the sum E-field from the actual forward and reflected waves. It turns out that up to the matching condition, the E-field in the ceramics and therefore also the dielectric losses are independent from the beam current: the increase of the incident wave field being compensated by the decrease of the reflection when ramping the current. However, above the match, the E-field increases strongly. In addition, for $\beta$=3 and lower values of $V_c$ the strong Robinson instability (no more stable RF bucket) occurs for beam currents below 200 mA (e.g. at 180 mA for $V_c$ = 7.0 MV).

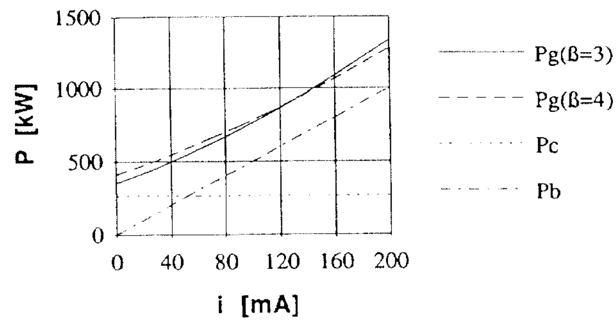


Fig.1 Computed RF power required for $V_c$ = 7.5 MV.

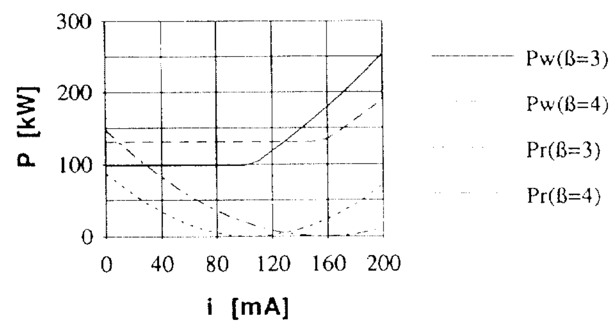


Fig. 2 Equivalent window power for $V_c$ = 7.5 MV.

No problem was encountered when ramping the current to 156 mA with the initial RF configuration in automn 93. With 200 mA as the ultimate goal, it was then decided to upgrade the RF systems in order to allow further ramping of the current. The cavity couplers were turned to the maximum achievable coupling $\beta$=4 in order to:

◊ shift the matching condition close to 200 mA (fig..2),
◊ thus reducing the window power load $P_w$ at 200 mA to a value close to the one achieved for $\beta$=3 at 156 mA,
◊ lowering the maximum required klystron power Pg for 200 mA to a value slightly below 1300 kW (fig. 1).

## 3. RF TRANSMITTERS

### *3.1 Klystrons*

Four 1.1 MW klystrons were purchased in order to guarantee the operation of the 3 transmitters (2 for the storage ring, SR, and 1 for the booster). The ESRF run time experience is now 6 000 hours. Over this period, there were 2 klystron failures. The first one was a loss of filament connection and this was attributed to a 15 g shock received during tube shipment. The second one was due to Barium evaporation from the impregnated cathode to the gun whenelt. A " filament stand by " scheme, at reduced heating power, has been implemented in order to avoid cathode over heating. In order to guarantee the high ESRF run time (7 000 hours per year), two more spare klystrons are being purchased.

Even if not disturbing the ESRF operation, another problem encountered on the klystrons was the occurence of instabilities seen as sidebands at $f_{rf} \pm 2$ MHz on the RF output spectrum. These tube oscillations are attributed to back scattered electrons coming back from the last cavity output gap and producing intermodulation signals. This phenomenon being present when the tube works at high efficiency, it was possible to get a stable operation by choosing good working ranges.

In order to allow a higher stored beam current while working with only one transmitter, one klystron was upgraded to 1.3 MW. The corresponding power upgrade was implemented on the 3 High Voltage Power Supplies.

### *3.2 Improved reliability of operation*

During the first 2 years of transmitter operation, several problems had to be cured, mainly : anode modulator instabilities, crowbar pre-firing (about one per 24 h), controller crash, too sensitive interlocks. Most of these problems were cured by improving electronics. For instance, the crowbar pre-firings were coming from the triggering electronics and not from the ignitron stack itself (we now only got 2 crowbar pre-firing over 15 weeks of operation ).

Since September 1993, the average RF availability is better than 90 % except for the 2 runs during which cavity couplers had to be changed and conditioned (availability was then about 75 % over these 3 weeks long runs).

### *3.3 Organisation for equipment testing and development*

A cavity test stand is being installed. It will allow new component testing or conditioning (e.g. cavity couplers, HOM dampers). It will be powered by the SR2 transmitter which should only be connected to 2 SR cavities for the ESRF X-beam delivery at current larger than 170 mA . For lower beam, the SR1 transmitter will be sufficiant to feed the 4 cavities. Since SR2 is not a real spare transmitter which can be fully dedicated to testing, waveguide switches are being procured in order to allow a faster SR2 transmitter switching onto the different loads : SR cavities or cavity test stand or klystron waveguide load.

## 4. BEAM INSTABILITIES

### *4.1 HOM driven coherent multibunch oscillations*

Although the Higher Order Modes (HOM) of the cavitiy cells with nose cone drift tubes do in principle strongly couple to coherent multibunch oscillations, it turns out that the HOM impedances of the 5-coupled-cell cavity are of the same order as for a single cell [1]. The cavities were installed in low ß, zero-dispersion straight sections in order to maximize the transverse instability thresholds. On the SR, only longitudinal HOM coupled oscillations have been observed so far at current levels in the order of the predicted 60 mA [1]: typically around 70 mA in mutlibunch operation with the 992 buckets homogenously filled (fig.3), and around 50 mA in 16 equally spaced bunches for one given cavity temperature.

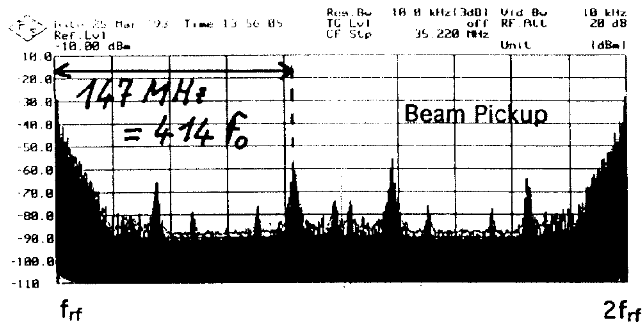


Fig. 3 Homogenous mutlibunch filling: 146.99 MHz side band of a longitudinal oscillation coupling to a 909.61 MHz longitudinal HOM of SR cavity number 3.

A regulation of the cooling water output temperature to ≈0.1°C via the control of the flow rate has been installed on each cavity. Changing e.g. the setpoint for cavity 3 by only +0.2°C allowed to suppress the 146.99 MHz side band of fig. 3 belonging to multibunch mode n=578=992-414 coupling to a 910 MHz passband HOM. But now mode n=419 coupling to a 500.96 MHz longitudinal HOM produced a 148.76 MHz side band. A further increase of the setpoint by 2 °C then killed also this beam-HOM resonance and allowed to ramp the beam from 70 to 120 mA. With standard cavity cooling the 16 bunch filling is limited to 80 mA by the single bunch limit of 5 mA rather than by multibunch oscillations.

A much more simple means to avoid HOM coupled instabilities, however, consists of filling only 1/3 of the SR. This is achieved by the synchronous injection from the booster into the SR. This filling pattern leads to a strong Amplitude and Phase modulation of both the cavity voltage and the beam signal, giving sufficient spread of the synchrotron frequencies to damp any coherent longitudinal oscillation. A remarkable feature of the 1/3 filling mode is that the damping effect increases with the beam current. The highest beam intensities up to the 175 mA achievement have therefore been obtained with 1/3 filling. Also for the standard service to the X-ray users, the SR is operated in this very stable 1/3 filling mode.

Finally, HOM damping to lower their coupling impedance and increase the instability thresholds, which requires special selective antennas, is still under investigation.

*4.2 Resistive wall impedance driven transverse instability*

For sake of completeness, we mention also the occurence of coherent transverse oscillations excited by the vertical resistive wall impedance of the stainless steel vacuum chambers. For homogenous filling, the instability threshold can be pushed beyond 100 mA with a +0.4 chromaticity over-compensation. However, the impedance will increase with the on-going installation of normal and narrow gap insertion devices and a further raise of the chromaticity will start to affect the lifetime for values above ≈+0.7.

Here again the 1/3 filling of the SR turned out to be a very effective cure, since the 175 mA of stored beam were achieved with the standard chromaticity of only +0.2. This may be explained by the fact that the resistive wall impedance has a bandwidth of several revolution frequencies (355 kHz) and has consequently a "memory" shorter than the 2 μs long gap between two passages of the 1μs long bunch train: the loop gain is therefore significantly reduced in the 1/3 filling mode.

*4.3 Single bunch transverse mode coupling instability*

The single bunch current is limited by the transverse mode coupling instability to 5 mA. The threshold can be increased up to 10 mA by changing the chromaticity, but the highest value of 17 mA per bunch was reached with a fast transverse feedback. During this fast feedback tests, the current was still limited by outgasing in the cavities, and higher ultimate currents are expected after further conditioning [3].

## 5. CAVITY INPUT COUPLER FAILURES

*5.1 History of the window failures*

During the first 2 years of operation the SR cavity couplers gave no sign of power limitations. It appeared later that their initial RF conditioning at the low speed dictated by the initial cavity conditioning, and the slow ramping of the beam governed by the progress of the SR commissioning were essential to operate them under safe conditions. After the January 94 shut down, when the cavities had been opened to set the coupling to ß=4, the reconditioning with RF first and then with beam up to 100 mA was performed within less than 3 days only. The 175 mA were achieved in march 94, without any sign of overloading.

Four days later, while the SR was operated with a nominal 100 mA beam to serve the users, suddenly a window on cavity 2 started to heat and broke after a few minutes. One month later another window broke during a 16 bunch operation at 80 mA. Finally, two days later, while ramping the RF voltage with the standard conditioning procedure after the last repair, a strong pressure burst occured on cavity 4, followed by a severe heating of one of its windows.

*5.2 Analysis of the window failures and protective measures*

The observations of the events preceding a window failure lead to the following explanation:

1. Electron multipactor in the high E-field region of the coupler provokes degassing of non- or badly conditioned zones *(explains the strong pressure bursts observed for the smallest steps in RF power during conditioning)*.

2. The strongest pressure bursts in the volume contained by the ceramics can reach locally as much as $10^{-3}$ mbar *(bad conductance towards the well pumped cavities)*.

3. Up to May 94, the RF was tripped only about 200 to 400 ms later by a standard ESRF Penning gauge controller. This means that the full RF power fed the gas cloud and could initiate a glow discharge *(a very bright glow discharge has been observed with a CCD camera looking to a window)*.

4. The RF had time to feed several tens of kJ into the glow discharge and to sputter off a large quantity of copper *(explains the pits observed at the surface of the coupler conductors)*.

5. The sputtered copper metallized the ceramic windows *(explains the thick copper layer observed on the vacuum side of the broken ceramics)*.

6. While becoming metallized, the ceramics were more and more heated by the increasing RF power loss until they broke.

In May 94, 3 couplers showing abnormal heating were exchanged. A fast vacuum interlock was installed with a response time of a few ms to reduce the RF energy fed into a glow discharge. At the same time, the vacuum interlock thresholds were lowered by one decade. As a result, it took about 150 hours, instead of 10 hours with the old interlocks, to recondition the cavities to only 7.25 MV and 100 mA in multibunch / 80 mA in 16-bunch operation.

Since May 94 the SR has again been operated for already 6 weeks at nominal intensities without any sign of coupler deterioration. And a further improvement of the window protection is in preparation: a fast light detection interlock (arc detector) looking at each cavity window, that will trip the RF some μs after a glow discharge has been started.

## 6. CONCLUSIONS

The available RF power and the means to control beam instabilities have permitted to store already 175 mA in the ESRF storage ring. The analysis of the window failures indicates that with the implementation of new very fast vacuum interlock triggering, the windows should be sufficiently well protected to keep the 200 mA objective as one parameter to increase the brilliance of the X-ray source.

## 7. REFERENCES


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[3] J.-L. Revol and E. Plouviez: " Diagnostics and Equipments for Single Bunch Operation at ESRF", these Proceedings.