LANDAU DAMPING OF LONGITUDINAL INSTABILITIES FOR THE OPERATION OF THE ESRF STORAGE RING

O. Naumann, J. Jacob, ESRF, Grenoble, France

Abstract

Landau damping of longitudinal coupled bunch instabilities with a bunch-to-bunch spread in synchrotron frequencies proved an effective tool in increasing the instability threshold current in the ESRF storage ring from the initial 60 mA to well beyond today's nominal intensity of 205 mA. This was first achieved using strong beam loading in fractional fillings, where the gap in the bunch train induces the necessary modulation of the accelerating voltage. The modulation obtained by operating two of the six cavities independently at one harmonic above the RF-frequency also made it possible to reach the same intensity in a homogeneous filling. Special care had to be taken of the $n = 1$ coupled bunch instability that can arise from the fundamental mode of the detuned cavities.

1 INTRODUCTION

The intensity limit of the ESRF is 205 mA in multi-bunch operation and 100 mA in few-bunch operation due to power limitations. However, longitudinal coupled bunch instabilities (LCBIs) due to higher order modes (HOMs) in RF-cavities have threshold intensities of as low as 60 mA. In this paper we discuss how we use Landau damping to fight these instabilities.

In section 2 we reiterate some of the theory necessary for the subject. Section 3 is dedicated to the two principal methods of how to produce the frequency spread necessary for Landau damping: fractional fillings and active modulation. In section 4 we explain how these methods are applied for operation.

Except where noted otherwise current ESRF parameters are used. Notably the revolution frequency is $f_0 = \omega_0/(2\pi) = 355$ kHz, the harmonic number $h = 992$, the energy $E_0 = 6$ GeV, the loss per turn $U_0 = 4.88$ MeV, the momentum compaction factor $\alpha = 1.8 \cdot 10^{-4}$, the natural damping constant $\delta_{\mathrm{n}} = 277$ Hz. The mean synchrotron frequency is $f_{\mathrm{s}} = \omega_{\mathrm{s}}/(2\pi) = 1.95$ kHz for a peak cavity voltage $\widehat{V} = 8$ MV and $f_{\mathrm{s}} = 2.4$ kHz for $\widehat{V} = 1.67$ MV. 5-cell cavities of the LEP-type used at the ESRF have important longitudinal HOMs with shunt impedances up to about 4 MΩ and resonance frequencies mainly clustered around 500 and 910 MHz.

2 THEORETICAL BACKGROUND

2.1 Landau damping of LCBIs

LCBIs arise due to the back-coupling of longitudinal particle oscillations via a feedback mechanism, usually a cavity HOM. The signal entering into the feedback can be attenuated by destroying the coherence of the participating particles by spreading out their natural frequencies. This phenomenon can be explained as Landau damping [1]. It is possible to achieve this by an intra-bunch spread, e.g. with a higher harmonic cavity, or by a spread in individual bunch frequencies, which is the focus of this paper.

The dispersion relation linking the complex coherent frequency ω and the beam current I_{b} is

$$\frac{1}{I_{\mathrm{b}} \frac{Z(\omega_{\mathrm{HF}})}{R_{\mathrm{HOM}}}} = \frac{1}{N} \sum_{i=1}^{N} \frac{\mathrm{j}k\omega_{\mathrm{HF}} R_{\mathrm{HOM}}}{\omega_{\mathrm{s}i}^2 - \omega^2 + 2\mathrm{j}\delta_{\mathrm{n}}\omega} = 1/f(\omega) \qquad \text{(DR)}$$

where the frequencies $\omega_{\mathrm{s}i}$ are the synchrotron frequencies of the N bunches in the machine and δ_{n} the natural damping due to synchrotron radiation. The impedance $Z(\omega_{\mathrm{HF}})$ is that of an HOM with shunt impedance R_{HOM}, that is driven at ω_{HF} near a multiple of ω_0. See [2] for a full derivation.

In the theoretical treatment of Landau damping authors generally use approximations which in our case amount to the following:

$$\omega^2 + 2\mathrm{j}\delta_{\mathrm{n}}\omega \approx (\omega + \mathrm{j}\delta_{\mathrm{n}})^2 \text{ for } \delta_{\mathrm{n}} \ll \omega_{\mathrm{s}i} \quad , \qquad (1)$$

$$\omega_{\mathrm{s}i}^2 - \omega^2 \approx 2\omega(\omega_{\mathrm{s}i} - \omega) \text{ for } \omega_{\mathrm{s}i} \approx \omega \qquad (2)$$

In this paper we include the study of cases where the ratio of the overall frequency spread, $\Delta\omega$, and the mean of all frequencies, $\overline{\omega_{\mathrm{s}i}}$, reaches values where the second approximation is no longer valid.

For a given distribution of frequencies, the current at the onset of the instability, the threshold current I_{th}, is determined by equation (DR) for real ω in the following way:

$$\mathrm{Im}\left[\frac{f(\omega)}{Z(\omega_{\mathrm{HF}})}\right] \stackrel{!}{=} 0 \quad , \quad \frac{R_{\mathrm{HOM}}}{Z(\omega_{\mathrm{HF}})} f(\omega) = I_{\mathrm{th}} \quad . \qquad (3)$$

I_{th} is larger than $I_{\mathrm{th},0}$, the threshold current for equal $\omega_{\mathrm{s}i}$, where the dispersion relation degenerates to the standard instability relation.

3 WAYS TO PRODUCE THE FREQUENCY SPREAD

3.1 Fractional Fillings

Fractional fillings can induce a bunch-to-bunch synchrotron frequency spread if the beam current is high enough. Beam loading by sidebands at harmonics of f_0 leads to a voltage modulation and a subsequent frequency spread.

The corresponding fix-point problem for the steady state synchronous passage times allows the calculation of the frequency spread numerically. The frequencies are distributed almost equidistantly, i.e. the corresponding frequency density is approximately constant within the range $\Delta\omega$: a rectangular pattern. As a result, the phase shifts by a constant amount from one bunch to the next. Yet, the frequency spread cannot be deduced directly from this phase spread, it was measured by exciting the beam externally and observing the response in the streak camera image, see figure 1.

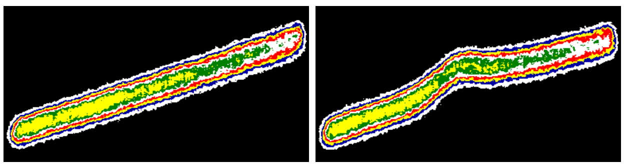

Figure 1: Bunch train in 1/3 filling at $I_\mathrm{b} = 150$ mA.
Sweep times: horizontal (position w.r.t. the revolution-phase): 0.9 μs.
vertical (position w.r.t. the RF-phase): 0.5 ns.
Left: steady state, right: response to an excitation at 1.8 kHz.

The frequency spread rising with current increases the instability threshold, as can be observed in figure 2, which depicts the case of a 2/3 filling and an HOM with $I_{\mathrm{th},0} = 100$ mA. The instability limit is reached at $I_\mathrm{th} = 230$ mA, where the two full lines intersect and (DR) has a real solution.

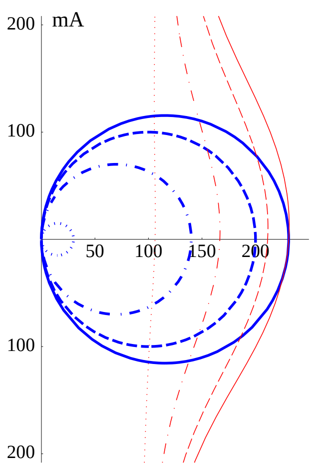

Figure 2:
Numerical evaluation of (DR) for a 2/3 filling and an HOM with $I_{\mathrm{th},0} = 100$ mA.

Circles: $I_\mathrm{b} Z(\omega_\mathrm{HF})/R_\mathrm{HOM}$ with ω_HF real.
Vertical Traces: $f(\omega)$ with ω real.

Varied Parameter: I_b
· · · · · · 40 mA,
— · — 140 mA,
— — 200 mA,
——— 230 mA.

3.2 *Landau damping from active modulation*

Driving one of the cavity units at $f_\mathrm{RF} + f_0$ leads to a modulation of the effective RF-voltage. This single sideband modulation is in fact both an amplitude and a phase modulation, but only the amplitude modulation enters into the values of the synchrotron frequencies.

An exact calculation of the synchrotron frequency distribution for such a homogeneous filling with modulation is possible [3]. It is not rectangular, as in the case of the fractional filling, but approximately hyperbolic, and becomes distorted for higher modulation levels. This shows up in figure 3, where the traces of real ω in the dispersion relation become asymmetric.

Our studies have shown that with active modulation a regulation of HOM thresholds is possible in a much wider range than with fractional fillings. For an HOM with a threshold current of $I_{\mathrm{th},0} = 75$ mA without Landau damping, the threshold current rises up to 350 mA with a modulation voltage of 2 MV. For an exact calculation of this limit it is important to solve the dispersion relation (DR) exactly, as the relative frequency spreads reach levels of up to $\Delta\omega/\overline{\omega_{si}} = 40\%$.

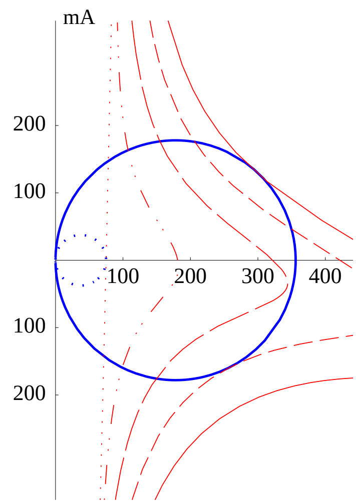

Figure 3:
Numerical evaluation of (DR) for a homogeneous filling and an HOM with $I_{\mathrm{th},0} = 75$ mA.

Circles: $I_\mathrm{b} Z(\omega_\mathrm{HF})/R_\mathrm{HOM}$ with ω_HF real and I_b:
· · · 75 mA, — 350 mA.

Vertical Traces: $f(\omega)$ with ω real.

Modulation Voltage :
· · · · · · 0 MV,
— · — 0.5 MV,
— — 1.0 MV,
- - - - - 1.5 MV,
——— 2.0 MV.

To achieve a sufficient voltage at $f_\mathrm{RF} + f_0$ the driven cavities have to be tuned close to the beam harmonic $h+1$. However, now the mode $n = 1$ can become instable, as can be seen in the streak camera images shown in figure 4.

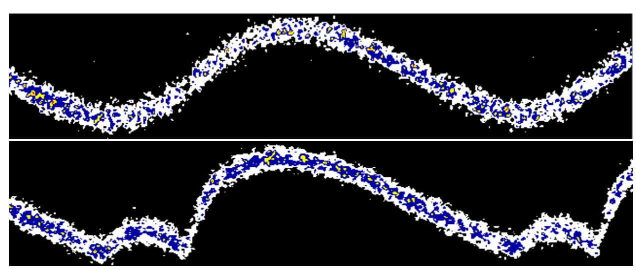

Figure 4: Bunch train in a homogeneous filling, $m = 13\%$.
Sweep times: horizontal: 4.3μs, vertical: 0.5 ns.
Above: beam current 20 mA, stable,
below: beam current 110 mA, snap-shot of $n = 1$ instability.

Figure 5 shows the threshold current for the $n = 1$ instability due to the fundamental mode of the cavities modulating the RF-voltage as a function of their resonance frequency. An appropriate choice of detune and modulation level allows escaping this instability; the tradeoff is between a sufficient level of m to fight the real HOM-instabilities and the reflected power due to the detuning.

4 LANDAU DAMPING IN OPERATION

4.1 *HOM-fighting strategy*

Due to the use of multi-cell cavities, the impedance spectrum of the ESRF is rich in high-Q HOMs. Figure 6 shows

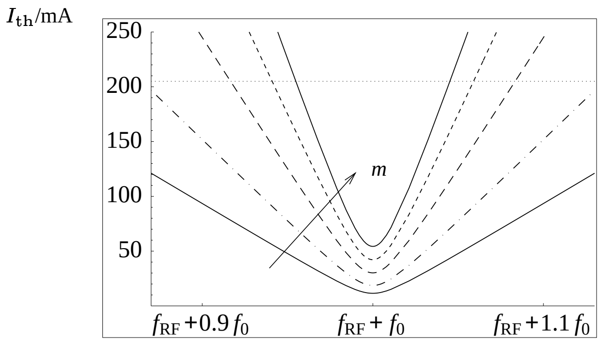

Figure 5: $I_{\rm th}$ of the $n = 1$ instability.
Variation of the modulation level m:
— 0, – · – 0.4, – – 0.8, - - - 1.2, — 1.6.

the impedance spectrum of one ESRF cavity transformed to $[0, f_0]$, which is appropriate for a global treatment of multi-bunch instabilities. With six cavities in operation [4] it becomes increasingly difficult to stay clear of the f_s spectral line.

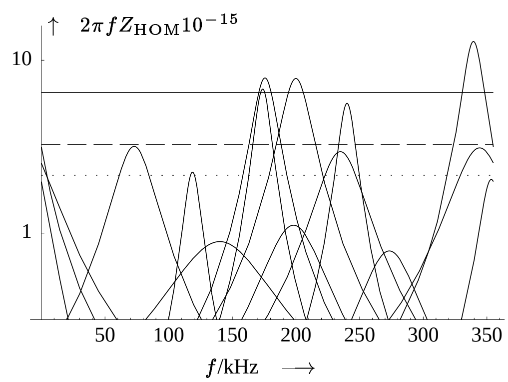

Figure 6: HOM spectrum of an ESRF cavity (measured).
The horizontal lines indicate the maximum impedance for stability with current I_b: — 100 mA, – – 200 mA, · · · 300 mA.

In principle it would be possible to fight all of these HOMs way beyond the present-day nominal intensity of 205 mA with active modulation and in a homogeneous filling, even with benefits for lifetime. However, the existing configuration of the cavity-transmitter system restricts the maximum current to about 170 mA with $\widehat{V} = 8$ MV, if two cavities are used for modulation.

Therefore, to reach 205 mA with $\widehat{V} = 11.67$ MV in multi-bunch operation, the somewhat weaker Landau damping due to fractional fillings is used in combination with a temperature control system which permits tuning away the HOMs with a very high R/Q. Then, the HOMs with a weaker R/Q are dealt with by the fractional filling induced Landau damping. The results presented in this paper have allowed the safe switching from a 1/3 filling ratio to a 2/3 filling ratio without compromises in the HOM stability and increasing the lifetime by 50%.

The situation is different for the few-bunch operation mode (16 or 32 bunches). Such a filling with equidistantly spaced bunches is similar to a homogeneous filling. As the energy acceptance is presently limited transversally, the lifetime has been maximized by switching off two cavities. As a result, they can no longer be controlled by the existent temperature control system and to avoid HOM instabilities the active modulation scheme is employed. The optimised operation parameters are 9 MV RF-voltage with a modulation voltage of 0.8 MV at a nominal intensity of 90 mA. Figure 7 shows a streak camera image of stable operation in this mode.

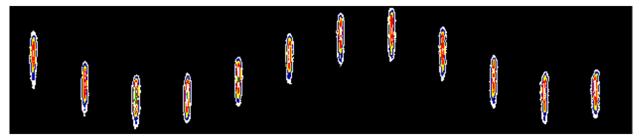

Figure 7: Bunch train in a 32-bunch filling, $m = 9\%$.
$I_b = 90$ mA, sweep times: horizontal: 4.3μs, vertical: 0.5 ns.

4.2 Outlook

For operation at lower energies actively induced Landau Damping becomes obligatory to enhance the then much weaker natural damping. It is already used for low energy studies.

The active modulation scheme would allow the HOM instability limit to be raised well beyond today's nominal intensity of 205 mA, should the need arise.

An active feedback would be another effective damping system, however, our investigation shows that the ESRF can safely do without.

5 SUMMARY AND CONCLUSIONS

We demonstrated the way Landau damping is used at the ESRF to fight HOM instabilities. The results of our investigations enable us choose the appropriate damping method to operate without limits from longitudinal coupled bunch instabilities.

Acknowledgements

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6 REFERENCES

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