Non-linear RF feedback in ELSA accelerator

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Abstract

In order to decrease the electron energy spread in the ELSA accelerator, an RF feedback loop has been implemented. Because the klystron works close to the saturation regime, its response is non-linear, and the loop cannot be correctly optimised with the classical linear model. Thus, we changed the hypothesis of linearity to differentiability in a way to predict limitations and performance. This RF loop has been included in an adaptive feedforward system. This combination gives an amplitude stability of 0.05%. Theory, practical realisation and results are presented.

1. Introduction

The ELSA FEL [1] is constituted with a 18 MeV accelerator [2] driven by a single 433 MHz klystron which can deliver up to 6 MW during a maximum 200 μs pulse. As the stability of electron energy and phase is fundamental to obtain a low beam emittance [3] suitable for an FEL, an adaptive feedforward system [4] had been previously implemented to cancel RF-switching and beam-loading transient effects. Of course, such a system cannot deal with random pulse to pulse jitter. As this jitter was non-negligible in the ELSA accelerator, we decided to improve its stability by a direct RF loop.

The principle of direct RF feedback is simple: the source signal is combined with an opposed phase output signal. The resulting small signal is amplified and sent to the high-power amplifier (fig. 1).

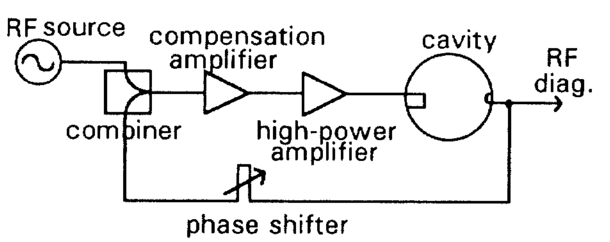

Fig. 1. Direct RF feedback on an accelerator.

2. Linear RF feedback model

In the linear model, the theoretical performance of such a loop is a noise reduction factor equal to the open loop gain plus one. Nyquist's theory shows that the main limitation of the open loop gain results from the quality factor of the cavity (Q) and the delay along the rest of the loop ($\tau = d\varphi/d\omega$) which results from cable length and amplifier bandwidth. If this delay is long compared to the filling time of the cavity ($\tau >> Q/\omega_0$), the open loop gain is then [5]:

$$G = mQ\pi / \omega_0\tau, \quad (1)$$

in which ω_0 is the RF angular frequency and m is the gain margin coefficient. This coefficient should not exceed 0.5 to insure robustness of the system.

3. Non-linear analysis

In the previous model, the high-power amplifier is assumed to work in its linear regime. But, because of their price, high power devices usually work close to their saturation point. In this regime, one can expect that the amplitude response is compressed, but that the phase is not (as the output phase must finally follow the input phase, at least for slow variation). Thus, if the low-level signal is phase <u>or</u> amplitude modulated, one can expect the high-power signal to be phase <u>and</u> amplitude modulated at the same frequency. In the frequency domain, this means intermodulation between sidebands on both side of the carrier.

Let us call T the transfer function of the RF chain, x and y being the input and output signals, respectively. This can be written as:

$$y = T(x), \quad (2)$$

in which the operator T may be non-linear. If the input signal is slightly modulated, x becomes $x+\Delta x$. Then, the output signal y becomes $y+\Delta y$. The hypothesis of differentiability is that Δy is linearly dependent on Δx; the linear operator involved is the Jacobian of the operator T at a given working point x:

$$\Delta y = Jac(T(x)) \times \Delta x. \quad (3)$$

For a given modulation angular frequency $\Delta\omega$, the Jacobian is a four complex coefficient matrix:

$$Jac(T) = \begin{bmatrix} \Delta A_y / \Delta A_x & \Delta A_y / \Delta\varphi_x \\ \Delta\varphi_y / \Delta A_x & \Delta\varphi_y / \Delta\varphi_x \end{bmatrix} = \partial T = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

in which ΔA and Δφ represent the relative amplitude and phase excursions of the RF signal, respectively. The matrix coefficients a, b, c, d, represent dynamic response of the RF chain, i.e. the way modulation is transmitted; these coefficients depend on modulation frequency.

Let us assume that the RF chain output amplitude and phase have been adjusted (with adequate attenuator and cable length) in a way that $x=T(x)$ for the given working point x. Let us also assume that the RF chain is looped through a perfect amplifier whose gain is $-k$, as shown in fig. 2.

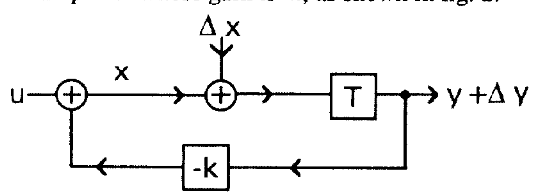

Fig. 2: Mathematical representation of the RF loop. The non-linear transfer function T has been adjusted in a way that $T(x)=x$ for the working point x.

Δy is then connected to Δx by :

$$\partial T\,\Delta x = (I + k\,\partial T)\,\Delta y\,, \qquad (5)$$

in which I is the identity operator. The stability of the loop is equivalent to imposing a finite quantity for Δy, which leads (analogously to Nyquist's theorem) to the condition:

The complex quantity q *must not surround the* (-1/k,0) *point, in which*

$$q = \left(\frac{a+d}{2}\right) \pm \sqrt{\left(\frac{a-d}{2}\right)^2 + bc}\,, \qquad (6)$$

a,b,c,d, *being the coefficients of the matrix* ∂T.

In the linear case, where the operator T is a constant for each angular frequency, no intermodulation occurs; so $a=d=t(\Delta\omega)$ and $b=c=o$. The above criterion becomes: *The quantity* $t(\Delta\omega)$ *must not surround the* (-1/k,0) *point*, which is Nyquist's theorem; k is then the open-loop gain.

4. Open loop measurement using an adaptive feedforward system

The above loop considered as an *RF device* has been included in an adaptive feedforward system [3], as shown in fig. 3. In this system, the output RF pulse y is analysed through an I/Q demodulator and digitised in a 2-channels acquisition board. The input RF pulse x is synthesised with an I/Q modulator commanded by a 2-channels arbitrary waveform generator. A personal computer deals with these different acquisition and generation waveforms in an amplitude/phase format. I/Q to A/φ and reciprocal transformations are performed by the computer; all linear defaults of the I/Q devices (offset, amplitude and phase unbalancing), are taken into account and corrected in both directions. Amplitude and phase of input pulse are corrected from pulse to pulse in a way to obtain the desired output pulse y_{target}, with the formula:

$$x' = H(x) + G(y - y_{target})\,, \qquad (7)$$

in which x' is the new input signal, G is a correction operator, and H is a damping operator which prevents the algorithm from divergence.

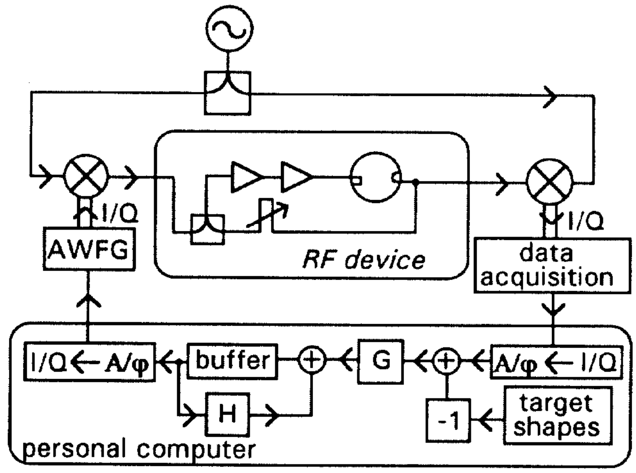

Fig. 3 Adaptive feedforward RF system.

The software can also work without correction, i.e. with $G=0$ and $H=Id$. In that case, it can be a good tool to study the transfer function of any *RF device*. Thus, a new possibility was added to the software in order to measure the Jacobian of the *RF device* constituted by the klystron and the accelerating cavities in an open-loop configuration.(fig. 4).

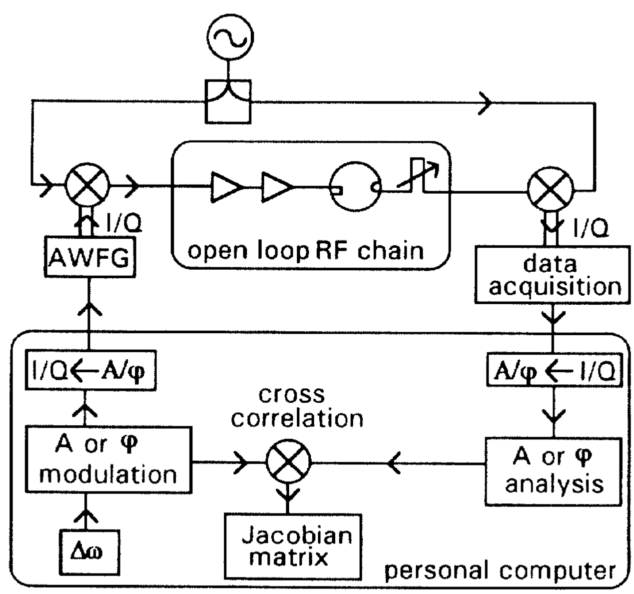

Fig. 4. Measurement of an RF device transfer function.

The input signal is successively phase and amplitude modulated; the output signal is analysed in terms of phase and amplitude modulation. Doing this operation with various modulation frequencies allows us to compute the Jacobian matrix of the *RF device* for each modulation frequency.

5. Open loop results

The Jacobian of the open loop RF chain has been measured between 10 and 300 kHz. The quantity q (as defined in (6)) has been derived and plotted versus frequency in fig. 5, and in the complex plane in fig 6. The contour crosses the negative real axis approximately on $(-0.07,0)$ for the worst determination of q. The choice of a 12 dB gain-margin sets the critical point 4 times further from the origin, i.e. on $(-0.28,0)$. This gives the value $k=3.6$ (i.e. 11 dB).

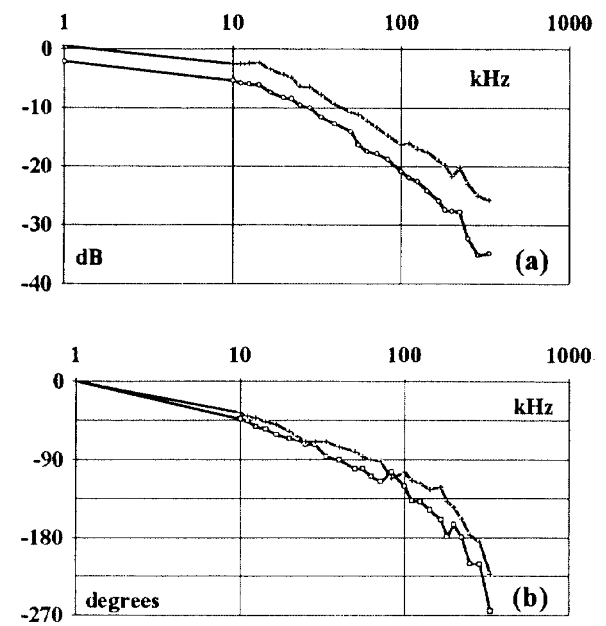

Fig. 5. Magnitude (a) and phase (b) of the complex quantity q vs. modulation frequency. The two curves are for the two determinations of the square-root.

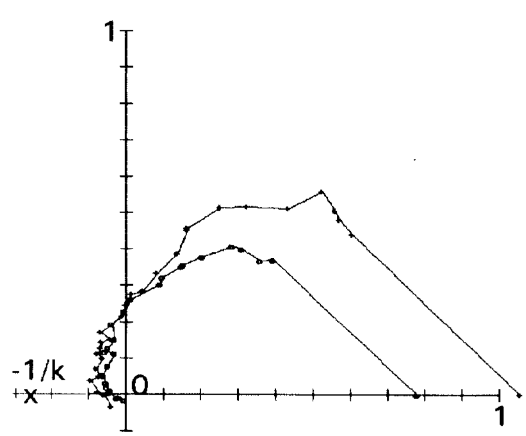

Fig. 6. Contour of complex quantity q. The critical point is not surrounded

6. Closed loop results and conclusion

Table 1 gives the stability without (open loop) and with (closed loop) feedback. Intra-pulse stability is defined as the r.m.s. noise around the mean value in a single pulse. Pulse-to-pulse stability is the r.m.s jitter of the mean value defined above.

Table 1. .R.m.s jitters without/with feedback loop.

	intra-pulse stability		pulse-to-pulse stability	
loop	amplitude	phase	amplitude	phase
open	0.08%	0.15°	0.15%	0.40°
closed	0.05%	0.15°	0.06%	0.15°

As expected, pulse-to-pulse jitter has been reduced by a factor compatible with the loop gain. Intra-pulse stability, which corresponds to faster phenomena, was only slightly improved for amplitude.

A similar system has been implemented for the 144 MHz-2 MW-2 MeV RF chain of the injector cavity [6-7]. In this case, the open loop gain was 20 dB, and the pulse-to-pulse jitter has been reduced from 0.050% to 0.015% in amplitude, and from 0.65° to 0.06° in phase.

The author thanks D.Dowell who convinced him of the necessity of such a loop.

7. References

[1] Ph.Guimbal et al., "First results in the saturation regime with the ELSA FEL", Nucl. Instr. and Meth., A341, p43-48, 1994.

[2] S.Joly et al., "The 433 MHz accelerator for the ELSA high-peak power FEL", in European Particle Accelerator Conference Proceedings, Berlin, Germany, May 1992, pp 563-565.

[3] A.Loulergue et al., "Transverse and longitudinal emittance measurements in the ELSA linac", these proceedings (EPAC, London, 1994).

[4] P.Balleyguier, "Adaptive feedforward control of amplitude and phase in a pulsed accelerator for FEL application", Nucl. Instr. and Meth., A332, pp 329-333, 1993.

[5] A.Gamp, RF Engineering for Particle Accelerator, Geneva: CERN Accelerator School, 1992, Vol. 2 p 408.

[6] P.Balleyguier, "Dead-time tuning of a pulsed RF cavity", in Particle Accelerator Conference Proceedings, Washington DC, USA, May 1993, Vol. 2 pp 1136-1138.

[7] S.Joly et al., "Progress report on the BRC photoinjector", in European Particle Accelerator Conference Proceedings, Nice, France, June 1990, Vol. 1 pp 140-142.