RF PULSE SHAPE CONTROL USING A RECCURENT ALGORITHM FOR A FEL RF-GUN CAVITY

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Abstract

FEL application requires a very constant RF accelerating field during the pulse. A classical feedback regulation loop cannot be very efficient when pulse duration is just a few times longer than the filling time of the cavity as the loop gain cannot be high enough.

For that reason, we decided to control the RF shape along the macropulse in a reccurent way : the pulse profile is corrected step by step by computation from the measurement of previous pulses and the desired shape.

The control algorithm is given and its performances will be presented.

Introduction

In the FEL-ELSA injector cavity[1], a very stable accelerating field is required during the macropulse, to achieve an energy spread in the 10^{-3} range. Moreover, in order to reduce the reflected power during the rising and the falling edges, the RF pulse should be trapezoid in shape. Since the frequency cavity is 144 MHz, and the unloaded Q value is 28000, the field raise/fall time constant is about 60 µs. Compared with the electron pulse duration (200 µs), that time is not small enough to allow a classical analog feedback system (fig.1) to be efficient during the pulse[2].

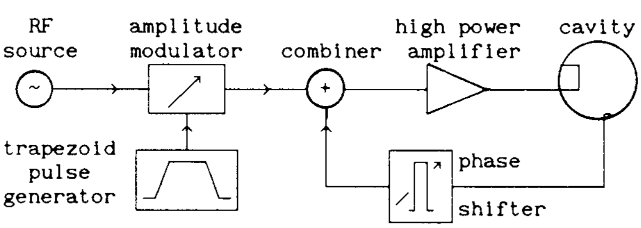

Fig.1. Analog RF feeback loop.

However, if a trapezoid shaped pulse is injected in the RF amplitude modulator, the electric field inside the cavity will not have this ideal time profile because of effects like: transient response of the amplifier, cavity filling time, beam loading and other non-linear effects. The used feedforward technique consists in synthesizing a particular shaped pulse and in injecting it into the low level RF modulator, in such a way that the measured time profile of the field inside the cavity fits the ideal trapezoidal curve.

Function feedback principle

The question is now how to guess what this particular shape should look like. This can be done by a "training" technique: in a typical feedback loop, the demanded output value of a transformer (in broad sense) is compared with its actual output value. The difference is then filtered and sent back to the transformer (fig.2). Studying the feedback system consists then in choosing the filter. In the linear modelization, the filter is fully characterized by its complex transmission coefficient, at each excitation frequency. In direct current (zero frequency), this coefficient is just a real number, usually called *loop gain*. In digital loops, the most simple and usual way is to use an infinite impulse response filter (IIRF), defined by:

$$\text{output}(i) = \alpha\ \text{output}(i-1) + \beta\ \text{input}(i-1),$$

where i is the reccurent indice.

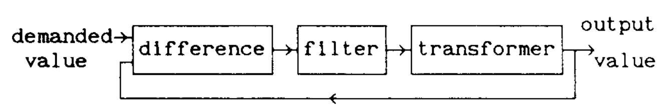

Fig.2. Typical feedback loop.

In our case, the principle is the same, apart from that the signal to be regulated is not a simple scalar but a function representing the pulse shape. This function can be seen as a mathematical vector, either in time or frequency domain; (from that point of view, the classical scalar feedback loop can be called a 1-D loop). Thus, the loop gain is no more characterized by a simple coefficient but by an operator $\mathcal{G}$ which will be chosen as linear.

The filter type will be the IIRF mentionned above. In other words, at each step, the pulse shape injected in the RF modulator, represented by te vector $\mathbf{e}(i)$, will be computed from the previous one $\mathbf{e}(i-1)$, the demanded shape $\mathbf{c}$, and the previous pulse profile $\mathbf{s}(i-1)$ measured inside the cavity, by the following formula:

$$\mathbf{e}(i) = \mathbf{e}(i-1) + \mathcal{G}\,[\mathbf{c} - \mathbf{s}(i-1)]. \qquad (1)$$

Stability

Classical stability criteria (Nyquist, for example) are helpless here because they deal with 1-D feedback loops. So, we have to find out another criterion.

Let us call $\mathcal{F}$ the transfer function of the RF chain, i.e.: modulator, power amplifier, cavity and detector. $\mathcal{F}$ transforms the vector $\mathbf{e}$ into the vector $\mathbf{s}$. We will assume $\mathcal{F}$ to be linear. Eq.(1) can be written as:

$$\mathbf{e}(i) = (\mathcal{I}-\mathcal{G}\mathcal{F})\,[\mathbf{e}(i-1)] + \mathcal{G}\,[\mathbf{c}], \qquad (2)$$

where $\mathcal{I}$ is the identy operator.

The classical *fixed point theorem*[3] of topology, says that the vectorial sequence $\mathbf{e}(i)$ will converge if the operator $(\mathcal{I}-\mathcal{G}\mathcal{F})$ is a contraction, i.e. it reduces distances:

$$\forall\mathbf{x},\forall\mathbf{y}, \quad \|(\mathcal{I}-\mathcal{G}\mathcal{F})[\mathbf{x}] - (\mathcal{I}-\mathcal{G}\mathcal{F})[\mathbf{y}]\| < \|\mathbf{x}-\mathbf{y}\|, \qquad (3)$$

or, simply:

$$\|\mathcal{I}-\mathcal{G}\mathcal{F}\| < 1. \qquad (4)$$

Since the operator $\mathcal{G}\mathcal{F}$ is fully characterized by its complex transmission coefficient $\gamma(\omega)$, the stability criterion (4) may be stated in the frequency domain as: for any angular frequency ω, $\gamma(\omega)$ has to be inside a disc of radius 1 and centered on 1 (fig.3).

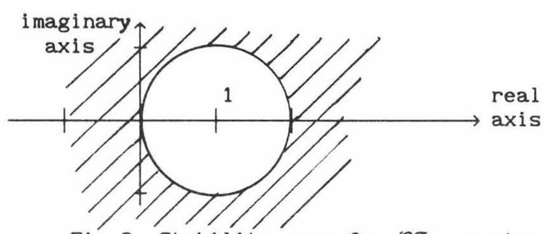

Fig.3. Stability aera for $\mathcal{G}\mathcal{F}$ operator.

So, the operator $\mathcal{G}$ has to be chosen correlated with $\mathcal{F}^{-1}$. In case of convergence, the limit vector $\mathbf{s}(\infty)$ will satisfy the following equation derived from eq.(1):

$$\mathbf{s}(\infty) = \mathbf{c} + \mathbf{r}, \qquad \text{where} \quad \mathcal{G}[\mathbf{r}]=\mathbf{0}.$$

The operator $\mathcal{G}$ should ideally be inversible, to insure the error output vector $\mathbf{r}$ to be nul. In any case, $\mathcal{G}$ has not to loose too much information.

Beam loading can be taken into acount by the addition of a constant term $\mathbf{f}$ in the transfer function $\mathcal{F}$, representing the RF signal induced by the beam inside the cavity:

$$\mathbf{s} = \mathcal{F}[\mathbf{e}] + \mathbf{f} = \mathcal{F}_1[\mathbf{e}].$$

It has to be noticed that substituting $\mathcal{F}_1$ into $\mathcal{F}$ in eq.(3) would not change it: beam loading should not perturb the loop stability, as long as the electron macropulses are repetitive.

Choice for operator $\mathcal{G}$

Since $\mathcal{F}$ is not exactly known, one cannot just decide to take $\mathcal{G} = \mathcal{F}^{-1}$. Let us call $\tilde{\mathcal{F}}$ the expected value for $\mathcal{F}$. With $\mathcal{G} = \tilde{\mathcal{F}}^{-1}$, the stability condition (4) would become:

$$\| \mathcal{I} - \tilde{\mathcal{F}}^{-1}\,\mathcal{F} \| < 1,$$

which would probably not be verified for every vector. As a matter of fact, if $\mathbf{x}$ is a vector for which $\|\mathcal{F}[\mathbf{x}]\|/\|\mathbf{x}\|$ is very small, $\|\tilde{\mathcal{F}}^{-1}[\mathbf{x}]\|/\|\mathbf{x}\|$ would probably be very large, and a small error on $\tilde{\mathcal{F}}$ would certainly lead to a value of $\|\tilde{\mathcal{F}}^{-1}\mathcal{F}\|$ much larger than unity.

A more suitable choice for $\mathcal{G}$ seems to be ${}^t\tilde{\mathcal{F}}$ ($\tilde{\mathcal{F}}$ transposed), which is somewhat correlated with $\mathcal{F}^{-1}$, but has not the same drawback. The limit vector $\mathbf{s}(\infty)$ will then differ from $\mathbf{c}$ by a vector $\mathbf{r}$ for which ${}^t\tilde{\mathcal{F}}[\mathbf{r}]=\mathbf{0}$ and then, $\mathcal{F}[\mathbf{r}]\simeq\mathbf{0}$. Then, a small error on the valuation of $\mathcal{F}$ would not have major consequence.

Since the RF chain transfer function is dominated by the filling time of the cavity τ, $\mathcal{F}$ will be represented by a simple low-pass filter $\tilde{\mathcal{F}}$, which gives, in the time domain:

$$s_j = \sum_{k=0}^{\infty} \exp(-k\;\Delta t/\tau)\; e_{j-k}\,,$$

where s_j and e_j are the samples of $\mathbf{e}$ and $\mathbf{s}$, respectively, and Δt is the sampling period. Then, the assumed matrix of the RF chain transfer function is, in the time domain:

$$\tilde{\mathcal{F}} = \begin{bmatrix} \alpha^0 & 0 & . & . & . & 0 \\ \alpha^1 & \alpha^0 & 0 & & & . \\ . & & . & & & . \\ . & & & . & & . \\ . & & & & . & 0 \\ \alpha^n & . & . & . & \alpha^1 & \alpha^0 \end{bmatrix},$$

with $\alpha = \exp(-\Delta t/\tau)$.

Upper right zeros are due to causality: s_j cannot be influenced by e_k if $k > j$. If a pure delay T occurs between $\mathbf{e}$ and $\mathbf{s}$, all the coefficients of $\tilde{\mathcal{F}}$ are translated $m=T/\Delta t$ times in lower-left corner direction, giving $\tilde{\mathcal{F}}'$. So, the operator $\mathcal{G}$ may be choosen as $\lambda\,{}^t\tilde{\mathcal{F}}'$, where λ is a coefficient to be adjusted experimentally.

Finally, three parameters have to be adjusted in $\mathcal{G}$. They may be interpreted as: feedback coefficient (λ), low-pass filter with negative time response (α), and negative pure delay (m). The application software described later allows the system user to change any of these parameters at any time, without stopping the reccurent algorithm.

Practical realization and results

The scheme of the actual feedback system is given in fig.4. The high power amplifier consists of a chain of amplifiers ended by a 2 MW tetrode. Both acquisition and restitution systems work at 0.5 MHz sampling frequency, with about four hundred 12-bits samples.

A convergence check-out algorithm has been implemented to avoid divergence in case of sudden RF chain cut-off: the residual output error (characterized by $\mathbf{s}$-$\mathbf{c}$) is computed at each step; if it grows, the feedback algorithm is automatically suspended.

In order to save time, calculations (feedback algorithm, convergence check-out, data curve display) are made on single precision integers, and the software was written in assembly language. This allowed the computer (PC AT 286 with a 10 MHz clock) to carry out its task in less than 30 ms.

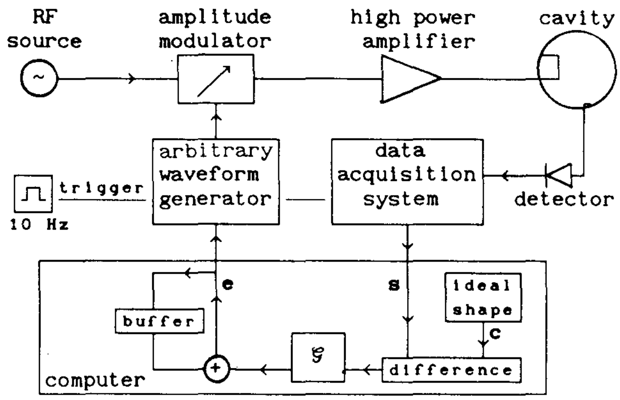

Fig.4. Function feedback loop.

Experiments showed that first and second order discontinuities on the demanded shape could generate instabilities: slowly growing ondulations on the pulse. For that reason, the demanded shape was smoothly designed (fig.5a), and the output data (s) was smoothed after each reccurence with a 1-2-1 pattern. Fig.5 shows experimental results after a few seconds, when a steady state has been achieved, without electron beam. The field amplitude stability (ΔP/2P) is about 0.3% in the flat part of the pulse. Fig.6 shows a preliminary result with 30% beam loading. The field stability was about 2.5%; this value should be improved in the future.

Conclusion

A quite constant RF amplitude field has been obtained during the pulse. Including an analog feedback loop for regulating the amplifier alone (which has a much shorter time response than the cavity) could improve the system performance. For the moment, the limitation seems to come from the reproductibility of the electron macropulse itself.

The next step will be to improve this regulation system in a way to stabilize also the RF the phase whithin the pulse.

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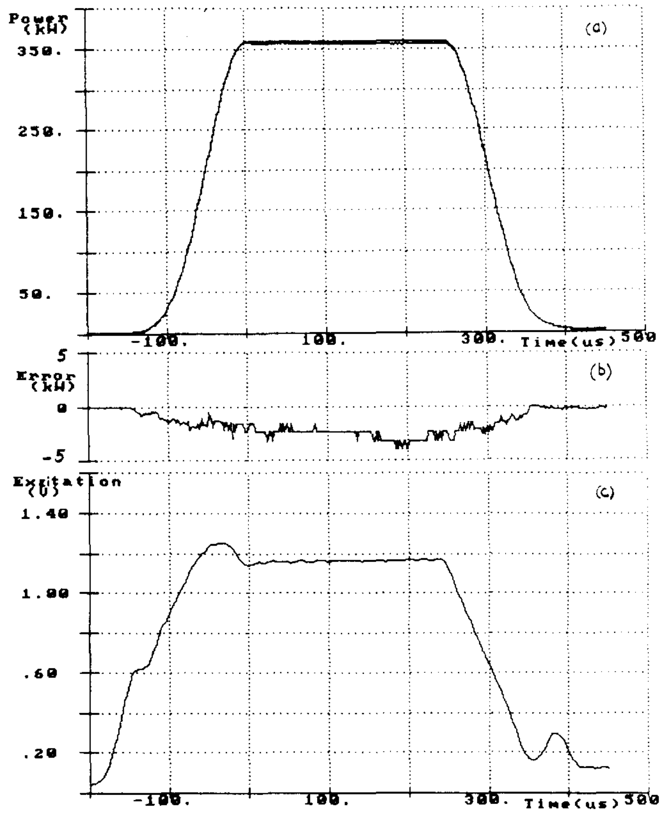

Fig.5. Results without beam.
(a) Demanded and actual power pulses (overlaping).
(b) Difference. (c) Corresponding input pulse.

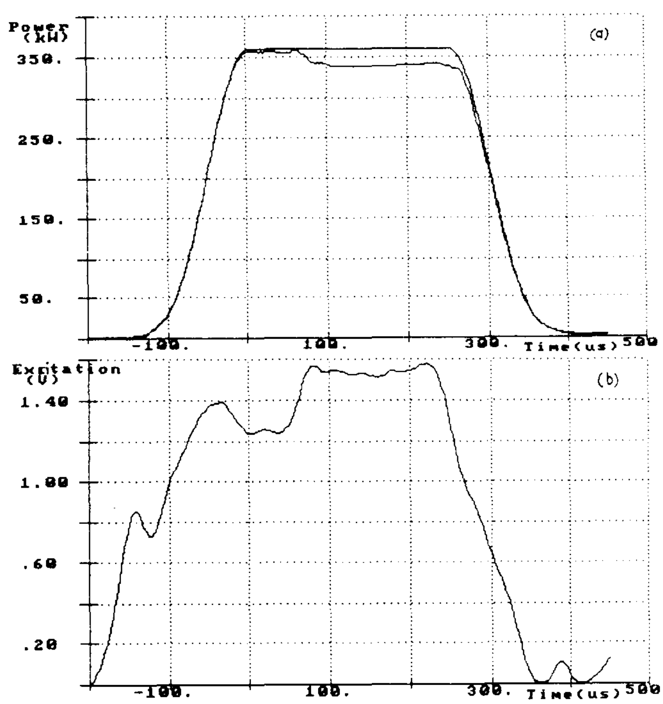

Fig.6. Results with 30% beam loading.
(a) Demanded and actual power pulses.
(b) Corresponding input pulse.