MODELLING AND SIMULATION OF THE RF SYSTEM FOR SPIRAL2

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Abstract

The acceleration of non relativistic particles, with a velocity lower than light velocity, in an RF cavity is more complex than for relativistic particles. Non-linear behaviours appear on the accelerator voltage because of the phase slippage inside the cavity. Moreover, a superconducting RF cavity is sensitive to various perturbations like mechanical vibrations (microphonics) and Lorentz force detuning. These perturbations produce a significant detuning of the cavity, leading a strong instability for the amplitude and phase of the field because of the narrow bandwidth of the accelerating mode. We will present a simulation approach of the cavity and its LLRF system control in order to ensure proper cavity operation under perturbations in the framework of the SPIRAL2 project.

INTRODUCTION

The SPIRAL 2 LINAC should accelerate beam with different characteristics: a 5 mA deuteron beam (Q/A=1/2), a 1 mA ion beam (Q/A=1/3) or a 5 mA proton beam. The injector, which is equipped with two different sources, includes a RFQ and three rebuncher cavities. The injector cavities are operated at room temperature. A superconducting LINAC follows the injector with a total of 26 cavities of two types (12 cavities: β=0.07 and 14 cavities: β=0.12). As a project option, six rebuncher could equip the high energy beam transport line (Figure 1).

Each LLRF system must control the amplitude and phase of one cavity field at 88.05 MHz (except for the RFQ, which is fed by 4 separate power amplifiers and requires 4 synchronized LLRF systems) and the frequency tuning of the cavity. The architecture of the SPIRAL2 system is based on the VME64X standard with a common analog/RF front-end and digital signal processing unit for all the different cavities [1,[2] in order to be cost effective and ensure easy maintenance. The maximum amplitude and phase error allocation are of the order of ±1% and ±0.5 degree respectively.

RF CONTROL SYSTEM MODELING

The simulation of an RF control loop consists in solving numerically a set of coupled differential equations describing the dynamic behaviour of the cavity, beam loading, feedback loop and perturbations [3].

Cavity equations

Denoting Q_L the loaded quality factor of the cavity, V_c the cavity voltage, ω_0 the angular resonant frequency, and I_g the generator current, the equivalent RLC model provides a differential equation characteristic of a cavity driven by a current generator in the absence of any beam:

$$\tau \frac{d\tilde{V}_c}{dt} + (1 + j\,y)\,\tilde{V}_c = R_L \tilde{I}_g ,$$

$$\textit{with } \tau = \frac{2Q_L}{\omega_0} \textit{ and } \; y = -\tan\psi \approx 2Q_L \frac{\omega - \omega_0}{\omega_0}$$

where R_L is given by:

$$R_L = \left(\frac{R_s}{Q}\right) Q_L$$

Then, expanding the phasor into real and imaginary part, denoted with subscript *r* and *i*, a set of two coupled differential equations is obtained:

$$\begin{cases} \tau \dfrac{dV_{cr}}{dt} + V_{cr} - yV_{ci} = R_L I_{g0r} \\ \tau \dfrac{dV_{ci}}{dt} + V_{ci} + yV_{cr} = R_L I_{g0i} \end{cases}$$

Beam loading

The beam is represented by a succession of bunches characterized by an energy and a phase leading to an instantaneous effect on the cavity voltage.

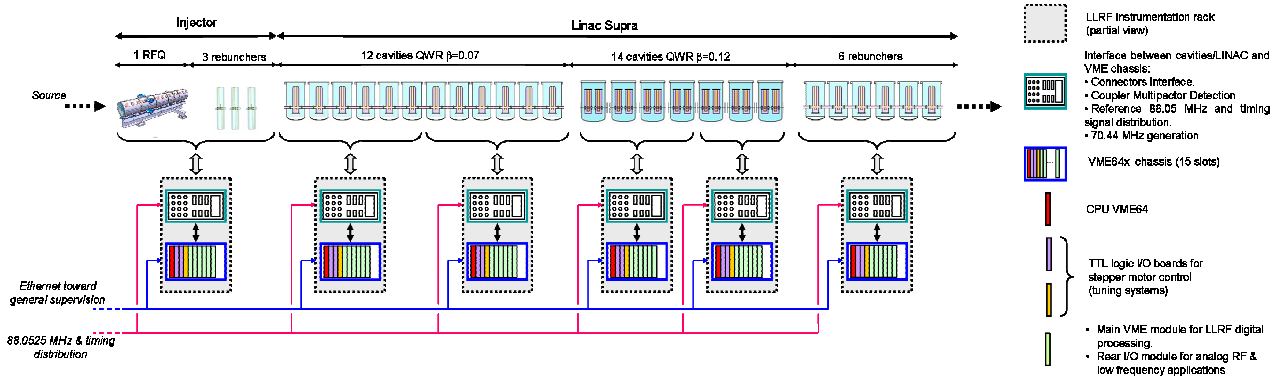

Figure 1: SPIRAL2 Linac synoptic (Courtesy P. Galdemard)

Since the travelling time of a bunch across a cavity is very short compared to the filling time, the beam loading action may be seen as an instantaneous effect. The cavity voltage just after the crossing of a bunch is given by the beam loading theorem [4]:

$$\begin{cases} V_{cr}^{+} = V_{cr} - \omega \dfrac{R_s}{Q} q_b \cos\left[\phi_c + \phi_s + \Delta\phi_{inj}\right] \\ V_{ci}^{+} = V_{ci} - \omega \dfrac{R_s}{Q} q_b \sin\left[\phi_c + \phi_s + \Delta\phi_{inj}\right] \end{cases}$$

Where $\tan \phi_c = V_{ci}/V_{cr}$, ϕ_s is the synchronous phase and $\Delta\phi_{inj}$ is the injection phase error. In the case of non-relativistic particles, this representation is the only one capable of tracking energy gain error and phase slippage for every bunch crossing the cavity.

Perturbations

Since SPIRAL 2 is a CW accelerator, the main perturbations of the superconducting cavities are microphonics which correspond to mechanical deformations due to external forces like the liquid helium bath pressure or structure resonances. This perturbation can be described by a sum of slowly modulated harmonic oscillations.

$$\Delta\omega_{\mu}(t) = \sum_{i}^{N} \overline{\Delta\omega_i}(t) \sin(\omega_i t + \varphi_i)$$

But Lorentz forces can be also taken into account in the simulations [3]. A detuning of a cavity generates a request for additional power to maintain the amplitude of the accelerator field.

Implantation with Simulink

A Matlab[tm] and Simulink[tm] based simulation tool has been developed. Figure 2 gives an overview on the simulation scheme. The cavity voltage phasor is described in real and imaginary component.

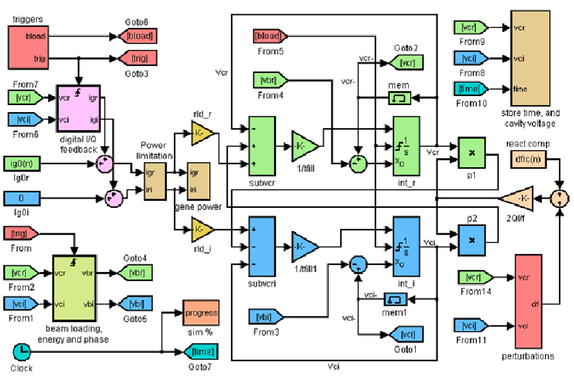

Figure 2: Architecture for cavity simulation.

Amplifier characteristics (like bandwidth and non-linearity of the gain), ADC quantization and sampling are easily modeled thanks to the flexibility of Simulink.

A PI-controller based feedback loop maintains the cavity voltage phasor constant in order to provide the same energy gain and phase shift to any bunch of the beam.

SIMULATIONS

Calculations are done for the cavity 10 of the superconducting linac and for 5 mA deuton beam. Cavity is firstly detuned at the nominal detuning which minimizes reflected power. Figure 3 shows the behavior of the amplitude and phase of the cavity field without feedback. In order to assess the effect of microphonics, an harmonic modulation (220 Hz) of the cavity resonant frequency with a magnitude of 20 Hz is used in the simulation. Calculations start in an already stationary regime for the nominal generator current.

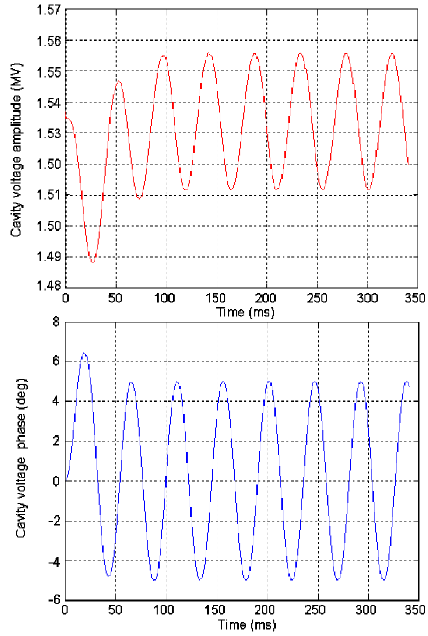

Figure 3 :Amplitude and phase error induced by microphonics (without feedback)

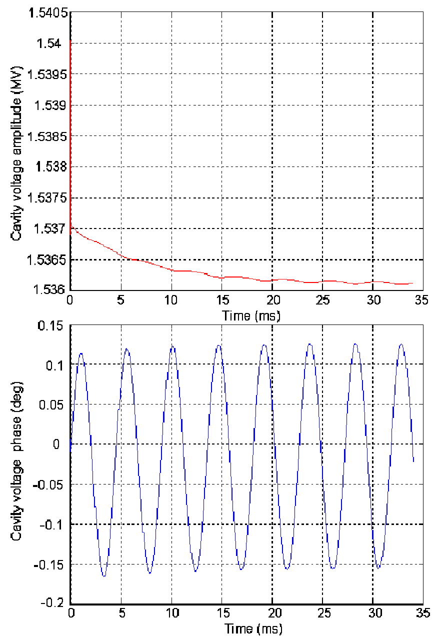

Figure 4: Residual errors with a PI feedback.

Figure 4 shows the action of the regulation loop closed with the proportional gain of 100 and an integrator gain of 1/64. The amplitude and phase error are of the order of ±0.1% and ±0.15 degree respectively. As expected, the feedback regulation of the cavity requires an extra power for the amplifier of about 8% (Figure 5).

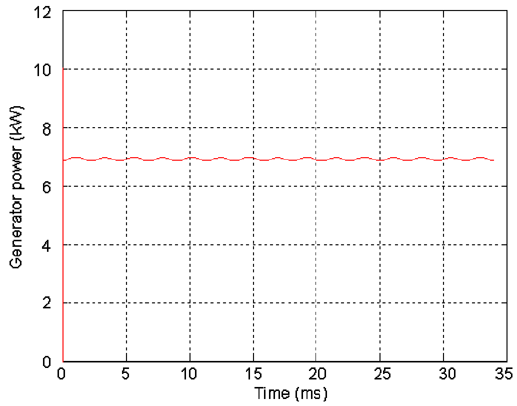

Figure 5: Generator power with feedback compensation.

The simulator also enables to verify the cavity operation for the commissioning mode where the beam is pulsed at different duty cycles. In this case, we could check the stability of the feedback system in presence of beam holes; despite the large power variation of amplifier needed to maintain the stability of the cavity field. The next simulations are realized for a 50% duty cycle and a 80ms pulse length.

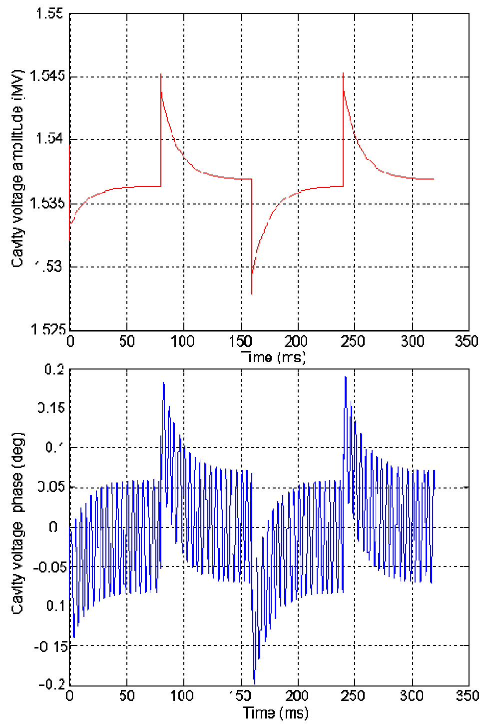

Figure 6: Amplitude and phase stability with feedback in pulsed beam mode.

With the same regulation parameters as used previously, the amplitude and phase error are a maximum error of ±0.8% and ±0.2 degree respectively at the beginning of the pulse (Figure 6). Figure 7 shows the power variation needed for the regulation of the voltage cavity.

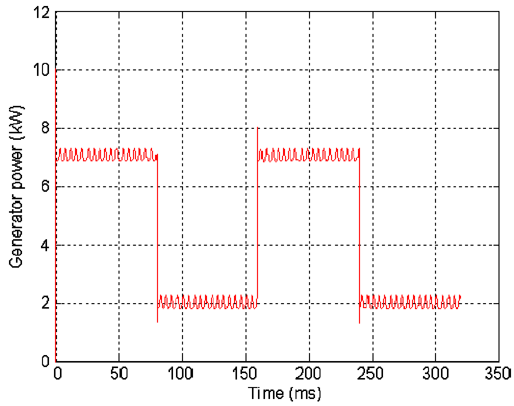

Figure 7: Generator power with feedback compensation.

CONCLUSION

This simulator is a helpful tool to model different kinds of perturbations, and how to compensate for them. It permits to test different system of control and to evaluate their performances in different machine configurations. The efficiency of the feedback loop in the cavity detuning compensation should be paid with an increase of the generator power. The RF control system modelling is an attempt to simulate such a multi-loops system to predict the beam energy spread at the output of one cavity.

REFERENCES

[1] M. Di Giacomo, B. Ducoudret, M. Tripon, G.l Le Dem, P. Barret, P. De Antoni, P. Galdemard, M. Luong, O. Piquet, Status of the RF Systems for the SPIRAL2 Linac at the Beginning of the Construction Phases, LINAC06.

[2] P. De Antoni, P. Galdemard, O. Piquet, S. Sube, Y. Mariette, M. Luong, M. Di Giacomo : The architecture of the low level RF electronics for Spiral 2, Low Level Radio Frequency Workshop, October 22-25, 2007- Knoxville, TN, USA

[3] M. Luong, O. Piquet, RF control System Modeling, report for IP-EUROTRANS/DM1/WP1.3.

[4] P. B. Wilson, « High Energy Electron Linacs: Applications to Storage Ring RF Systems and Linear Colliders », SLAC-PUB-2884, July 1981