CONTROL OF SCRF CAVITIES IN HIGH POWER PROTON LINAC

A. Mosnier, DSM/DAPNIA, CEA-Saclay, France

Abstract

High intensity proton linacs are envisaged as drivers for numerous applications (neutron spallation source for condensed matter study, neutrino factories and muons colliders, hybrid systems for transmutation or energy production, etc). Energy and phase stability of the beam is of primary importance to avoid any beam loss along the linac and, for the applications using rings as compressor or accumulator, the tolerances are even more severe to allow a loss free injection into the rings. There is general agreement on the superconducting technology for the high-energy part, which offers some advantages, like higher gradient capabilities or operational costs reduction, as compared to room-temperature structures. However, due to the narrow bandwidth of superconducting systems and the inclination of the cavity walls to deform easily, various effects, like microphonics or Lorentz forces, could enhance the cavity field fluctuations and then spoil the energy stability of the proton beam. It is shown in this report that, provided a careful design of the RF feedback system, cavity fields can be very well controlled, even for the pulsed mode operation, by far the most complex one. On obvious grounds of cost savings, the “one klystron for multiple cavities” scheme can be considered but must be restricted to sufficiently high proton energy.

1 HPPA SPECIFICITIES

The forthcoming generation of High Power Proton Accelerators (HPPA), which have the potential to deliver beams of a few to several tens of MW, are envisaged as drivers for a large variety of applications. Furthermore, the superconducting (SC) technology, because of its higher gradient capabilities and lower operational costs with respect to normal-conducting structures, has been adopted in most of the designs for the major part of the linac. Table 1 gives the main parameters of the SC portion of typical new HPPA projects under construction or in planning.

The field in SC cavities has been successfully controlled in relativistic electron linacs (see [1] for example) even when using groups of multiple cavities driven by one common klystron. However, the non-relativistic nature of proton beam results in a larger sensitivity to cavity field fluctuations due to phase slippage along the linac (inside the cavities and from cavity to cavity). As a result, the requirements on the stability of the individual cavity fields among the different applications are very similar, of the order of 0.5% in amplitude and 0.5° in phase.

Another feature of the HPPAs is the non-zero synchronous phase, of the order of -30°, in order to maintain a sufficiently large stability of the synchrotron oscillations. The resulting reactive beam-loading has then to be compensated by a slight detuning of the cavities.

Last, the control of vector-sum of many cavities driven by one common klystron is more problematic due to the different dynamic properties of the individual cavities and to the beam phase slippage along the linac. This scheme can only be envisaged at sufficiently high energy.

This paper will focus on the pulsed mode operation, by far the most sensitive one. For illustration, numerical results will be given for the ESS project [2], which has the most fancy and complex beam pulse pattern (Figure 1). The pulse sequence, repeated at 50 Hz, consists of two short chopped beam pulses (0.48 ms), followed by one long unchopped beam pulse (2 ms), occurring once every 3 cycles. There is only one cavity filling at each cycle, thus maximising the RF-to-beam power efficiency.

Table 1: Main parameters of the SC portion of typical HPPA projects

	SNS	ESS SC version	Joint Project KEK/JAERI	SPL	KOMAC	RIA	Eurisol
Beam power [MW]	1.6	2 x 5	0.375	4	20	0.4	0.2 - 5
Final Energy [GeV]	1.	1.334	0.6	2.2	1.	0.4 / A	1.
Frequency [MHz]	805	704	972	352	700	805	704
Cavity beta	0.61/0.81	0.68/0.86	0.72/0.79	0.52/0.7/0.8	0.45/0.52/0.71	0.49/0.61/0.81	0.47/0.65/0.85
Gradient [MV/m]	10.2/16	10.5/12.5	9.7/11.1	3.5/5/9	1.7 av.	10.5/13/16	9/10.5/12.5
Rep. rate [Hz]	60	50 - 16.66	25	50	CW	CW	CW
Pulse duration [ms]	1.04	1.06 - 2	0.5	2.8	-	-	-
Beam current av. in macro pulse[mA]	26	79 - 112	50	13	20	-	0.2 - 5

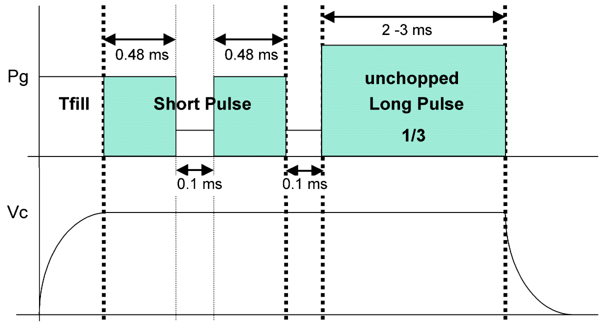

Figure 1: RF pulse pattern of the ESS project

The field in the cavity is kept constant between the current pulses thanks to the "feedforward" technique which applies a fast change of incident power (in-phase and in-quadrature), so that the pulsing rate of the cavity is kept to a maximum of 50 Hz, thus alleviating the Lorentz forces issue. The cavity forward power amounts to about the beam power during the filling and beam-on time, and about one quarter of this value between the pulses. The chopped beam gap required for proper injection into rings (about 30% of the revolution period) creates systematic amplitude and phase drops of the cavity field (Figure 2) of the order of 10^{-3}. In order to prevent the feedback from attempting a hopeless compensation, which would lead to systematic wasted power, it is better to sample the field measurement just before the beginning of each burst.

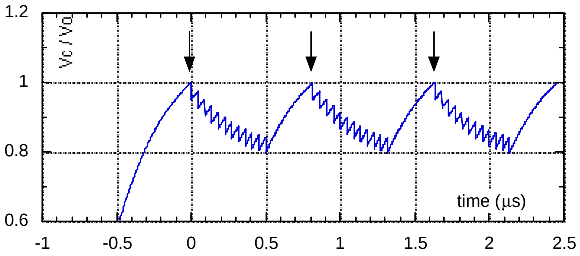

Figure 2: Cavity filling and voltage drop for a chopped beam pulse (accentuated beam-loading).

2 RF CONTROL ISSUES

The field control requirement depends on the following operational constraints:

- *High gradient* increases the Lorentz force detuning (proportional to the square of the field); active compensation by means of a special device, as a piezo-tuner, is needed for pulsed applications adopting very high gradients [3]
- *High loaded-Q* (low coupling) decreases the bandwidth of the system, giving a larger sensitivity to microphonics; fortunately, most of the HPPAs accelerate high beam currents, resulting in a low Q_{ex} for optimal transfer of the RF power
- *Pulsed RF* leads to transients induced by dynamic Lorentz force detuning and eventual resonant excitation of mechanical modes
- The "*one klystron for multiple cavities*" scheme gives different behaviours of the individual cavity fields, even though the vector-sum is perfectly controlled by the RF feedback system
- *Very low velocity* of the beam increases the detrimental phase slippage effect and makes the cavities more sensitive to Lorentz forces.

HPPAs call for the most advanced control systems, which should include very high-speed digital processors and gate arrays, feedback and feedforward, modelling and development tools. Various conceptual designs have been contemplated:

- Generator-Driven Resonator (GDR) or Self-Excited Loop (SEL)
- Amplitude/Phase or I/Q signal processing
- Analog or Digital system.

2.1 GDR vs. SEL

Figure 3 shows the basic scheme of any RF control system. In the SEL scheme, the loop frequency (equally the generator) continuously tracks the cavity frequency without the need for an external generator and is well suited for cavities prone to large frequency variations. For cw operation, it has been used for many years in heavy-ion accelerators. For pulsed operation, a seed signal is injected at start-up of the SEL to define properly the initial phase of the oscillations. The correct incident cavity power is then automatically generated, even in presence of non-linearity, Lorentz force or pre-detuning, whereas the proper incident power has to be pre-determined in the GDR scheme, which mimics exactly what a SEL does. With feedback loops, both schemes give similar performances and extra power. However, a pre-determined time-varying set point for the vector field has to be provided during cavity filling to guarantee a correct cavity field at the time of beam injection, especially under heavy microphonics conditions.

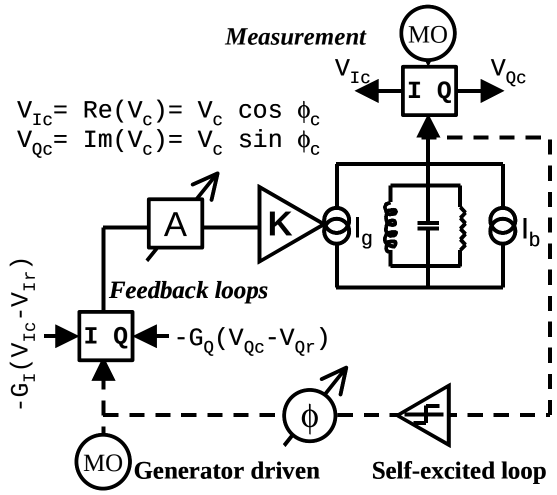

Figure 3: Generic RF control scheme

2.2 I/Q vs. A/ϕ signals

In-phase and in-quadrature (I/Q) signals are generally preferred for detection and control because they provide better performance than the classical amplitude and phase (A/ϕ) loops, mainly due to a best decoupling of control loops; the cavity detuning is simply recovered by the only Q-component instead of both A and ϕ components. While amplitude detectors with Shottky-diodes have lower noise, I/Q detectors and modulators are also well suited in digital systems for which commercial components are available with good linearity and without offset.

2.3 Control algorithms

The basic feedback algorithm is based on a proportional controller supplemented by a low-pass filter to guarantee sufficient stability margin but also to prevent from exciting the nearest mode of the fundamental passband of the cavity. Were this mode very close to the accelerating mode (for a large number of cells), the bandwidth and then the performance of the system could be strongly degraded. The nearest to fundamental mode distance is approximately identical for all applications (~ 0.8 MHz).

For repetitive and reproducible sources of perturbations as Lorentz force detuning, the feedforward technique will alleviate the control effort of the feedback. The repetitive errors are actually compensated from pre-determined tables such that the feedback has to correct the residual deviations from the predicted perturbations. Slow drifts of perturbations can be further compensated by a adaptive feedforward or learning procedure [4].

2.4 Analog vs. digital systems

Whereas analog systems have the lowest delay times and can achieve the highest feedback gains, digital systems provide a better flexibility in the control algorithms, natural and powerful diagnostics tools, and a precise calibration of the vector-sum in case of multiple cavities driven by one common klystron. Taking advantage of the most recent advances in fast DSP and PLD technology, the latency should not be any more a limitation and very fast digital feedback loops can now be implemented with time delays as short as 1µs. Larger time delays will spoil the performance of the feedback system, increasing both vector-field error and required extra-power (Figure 4). Aiming at extreme performance, a hybrid system employing analog technology for fast feedback loops and digital technology for adaptive feedforward could be a solution.

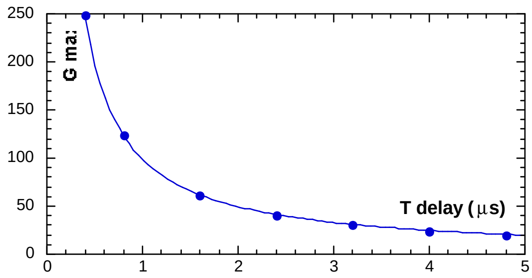

Figure 4: Maximum gain of feedback loops vs. delay time

The SNS low-level control system [5] is fully digital and includes a feedback based on I/Q modulation and a feedforward based on an iterative learning algorithm. In addition, a klystron loop controls phase and gain across the klystron and a slow loop stabilises the cavity frequency via mechanical tuners.

3 SOURCES OF PERTURBATIONS

Whereas microphonics is the main source of perturbation in CW machines, which have usually relatively low beam loading and then narrow cavity bandwidth, pulsed machines have other serious sources of significant phase and amplitude errors: Lorentz force detuning, resonant excitation of mechanical modes of the cavity and beam loading changes, which are induced by beam current fluctuations but also by any energy-phase error of the incoming beam. The great sensitivity of SC cavities to mechanical vibrations and gradient dependent Lorentz force comes from both the inclination of their walls to deform easily and the narrow cavity bandwidth.

For illustration, numerical results for the various perturbations are given for the ESS project. The low level RF system is based on the following design choices:

- Self-Excited Loop
- Fast digital system with a total time delay of 1.6 µs
- Feedback loops using I/Q devices with in-phase and in-quadrature gains of 30

3.1 Microphonics

The vibrations result generally from external excitations, such as cryogenic pressure oscillations, bubbles in the liquid helium or vacuum pumps. For elliptical cavities, typical phase fluctuations range from a few degrees for heavy loaded cavities (Qex ~ 10^5) to a few tens of degrees peak-to-peak for weakly loaded cavities (Qex ~ 10^7). For example, the microphonic noise leads to phase fluctuation up to 20° without feedback in the recirculating cw SC linac of Jefferson Laboratory [6] and to 4° in the pulsed Tesla Test Facility [1].

In case of pulsed operation, feedback loops must be closed during the filling time with a pre-determined time-varying set point for the vector field to guarantee a correct cavity field at the time of beam injection. Assuming a typical 400 Hz mechanical oscillation with an amplitude of 100 Hz (phase variations of 8°), the energy deviation at the ESS linac end remains very small (Figure 5).

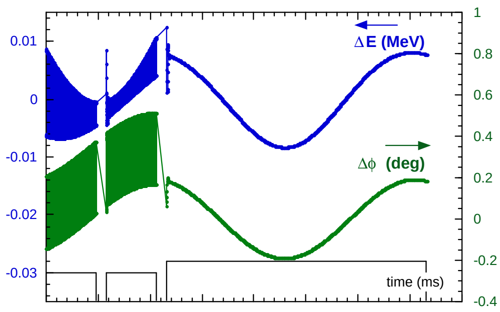

Figure 5: Energy and phase deviations of the multi-pulse beam at the ESS linac exit (microphonics effects).

We note that natural amplitude and phase drops due to beam chopping during the first two short pulses disappear during the last long pulse of unchopped beam.

3.2 Beam loading

Beam loading changes are generated by beam current fluctuations and any bunch oscillation induced by energy or phase offset of the incoming beam. In the latter case the beam loading variation results from the changes in energy gain per cavity, which depends on the beam velocity and time of arrival due to phase slippage with respect to the synchronous particle.

The feedback system efficiently controls the bunch charge fluctuations of frequency within the RF system bandwidth. A stochastic current fluctuation of 5% in the ESS linac gives quite acceptable bunch energy and phase deviations (0.4 MeV and 0.6 deg peak-to-peak).

Similarly, the control system is able to stabilise the cavity fields against sudden changes in beam-loading caused by energy-phase errors of the incoming beam. The phase space occupied by the beam at the linac output is very similar to the one that is obtained with perfectly constant cavity fields (Figure 6).

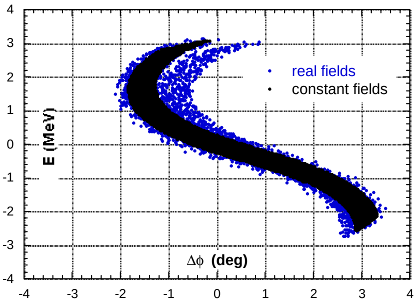

Figure 6: phase space at the ESS linac exit with incoming beam offset (±1 MeV ±1 deg input jitter)

3.3 Lorentz force

The pressure exerted by the RF fields on the cavity wall given by $P=(\mu_o H^2 - \varepsilon_o E^2)/4$ induces cell deformation and then resonant frequency shift. This cavity detuning is proportional to the square of the accelerating field and the sensitivity to the Lorentz force is defined by the *K* parameter: $\Delta f = -K\, E_{acc}^2$. Because of the higher peak surface fields and of the worse cavity stiffness, this parameter tends to strongly increase as the cavity beta decreases. One of the strategies for reducing the Lorentz force consists in welding rings between cells. This stiffening scheme has two beneficial effects: on one hand it tends to compensate the opposite effects of electric field in the iris region and of magnetic field in the equator region; on the other hand it tends to lower the frequency of the mechanical modes. However, the *K* parameter is very sensitive to the choice of the boundary conditions, which depends on the stiffness of the external structure including helium vessel and tuning system. Assuming an external stiffness of 100 kN/mm, which can be achieved without too much effort, one expects a *K*-value lower than 2 Hz/[MV/m]^2 for the medium-β cavity of the ESS linac. Furthermore, the frequency shift can be efficiently counteracted by a fast piezo-element, implemented onto the tuning system. The feasability of such an active compensation has been demonstrated on pulsed mode experiments made on a TESLA 1300 MHz cavity at DESY [3]and on a 500 MHz cavity at FZ-Jülich [7].

First, we assume that the individual mechanical modes are not significantly excited by the pulsed beam and are sufficiently damped between pulse cycles. Then, in addition to the two second order differential equations, the dynamics of each resonator can be well described by another first order one modelling the dynamic cavity detuning $\Delta\omega$ by the Lorentz forces:

$$\tau_m\, \Delta\dot{\omega} + \Delta\omega = -2\pi\, K\, E_{acc}(t)$$

In order to relax the feedback requirements, the cavity is pre-detuned, such that the resonance frequency equals the operating frequency at approximately half the beam pulse. The total detuning is set to the sum of detunings for Lorentz force and beam-loading compensation. Figure 7 shows, for example, the effect of realistic Lorentz forces (4 and 2 Hz/[MV/m]^2 for the medium- and high-β cavities) on the field of the last cavity of the ESS linac during the passage of the multi-pulse beam.

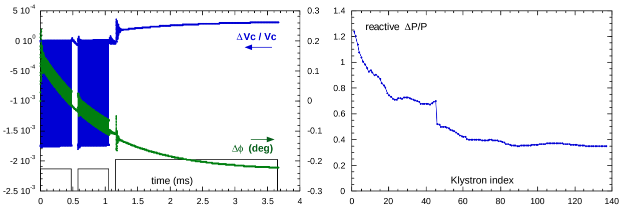

Figure 7: Field errors of the last cavity of the ESS linac and extra-power along the linac (Lorentz forces effects)

The extra-power required by the feedback loops (or the feedforward) is larger for the first sector of the linac because of the stronger Lorentz force effects but is decreasing as the energy gain of the cavities increases.

4 MECHANICAL MODE EXCITATION

For linacs of high repetition rate, the oscillations induced by the mechanical resonances could be not sufficiently damped so that resonant enhancement is possible. The contribution of each mode *k* to the cavity detuning can be described by a second order equation:

$$\Delta\ddot{\omega}_k + \frac{\omega_{mk}}{Q_{mk}}\Delta\dot{\omega}_k + \omega_{mk}^2 \Delta\omega_k = -2\pi\, K_k\, \omega_{mk}^2\, E_{acc}^2(t)$$

where ω_{mk}, Q_{mk} and K_k are the angular frequency, the mechanical quality factor and the dynamic Lorentz force parameter of the mechanical resonance *k*. The usual Lorentz force detuning is the sum of all individual mode detunings. As the detuning due to mode *k* in steady-state regime is proportional to the power spectrum of the RF pulses, which has generally a limited bandwidth, significant effects might come from only low frequency modes. Figure 8 shows for example the power spectrum of the ESS RF pulses.

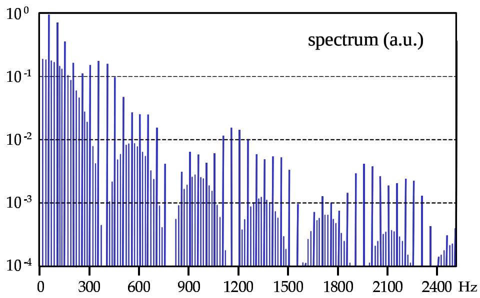

Figure 8: Power spectrum of the ESS RF pulses

The values of the K_m parameters of the cavity can be calculated with FEM mechanical codes by using the harmonic analysis [8]. It has been found that, when the stiffness of the cavity ends (tuner and He vessel) is not too small, the low frequency modes, those that could be excited by the RF field pulsing, have small K_m values and hence little impact on the cavity detuning. Consequently, there should be no dramatic increase of the oscillations due to cumulative effect from cycle to cycle. In order to observe discernible effects in the ESS linac, one is obliged at the same time to artificially amplify all K_m parameters (factor of 4) and to set the frequency of a low frequency mode in coincidence with an harmonic of the repetition rate (Figure 9).

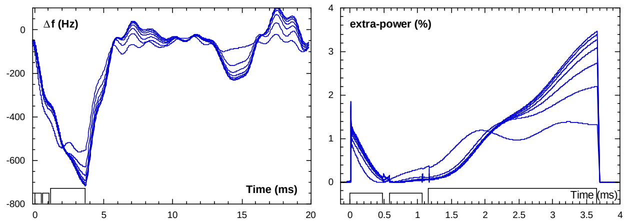

Figure 9: Evolution of frequency and extra-power of the 1st cavity (every 6 cycles) with all modes amplified (x 4), Qk = 100 for all modes, one mode set to 100 Hz.

Even with this pessimistic situation, the extra-power remains below 4% and the final cavity field errors are still within the tolerances during the passage of the beam. The steady-state regime, calculated for the entire linac with amplified (x 4) mechanical modes up to 1 kHz shows no significant cumulative effect and fluctuations are very similar to the one single cycle analysis. In conclusion, no serious trouble as regards mechanical modes is expected for the ESS pulsed mode operation, provided that the boundary conditions are stiff enough (~100 kN/mm).

5 MULTIPLE CAVITIES PER KLYSTRON

With relativistic electron beams, multiple cavities driven by a single power source can be easily controlled by the vector sum of the cavity voltages [1]. However for proton beams, since the dynamic behaviour of cavities depends on the beam velocity, even when the vector sum is kept perfectly constant, the individual cavity voltages can differ significantly. Besides, variations of loaded Q or Lorentz force parameters increase the differentials in cavity fields. One can however envisage this “one klystron for multiple cavities” scheme with very fast feedback loops at sufficient high energy, where the dynamic properties of the cavities are closer and the phase slippages are smaller. In the ESS SC linac, we assume for example groups of 6 and 4 cavities for the medium and high β sectors, respectively in order to equalize the klystron powers. Figure 10 shows the 4 cavity voltages of the last klystron during the beam pulses with Lorentz forces detuning effects, as well as the total energy and phase deviations at linac end, which are well below the tolerances. Besides, it was recently discovered that chaotic behavior could take place under certain circumstances [9]. Large frequency excursions can appear with very large K_m parameters and when the cavities are pulsed at a repetition rate close to one of their mechanical resonances. Among the pulsed projects planning to have more than one cavity per klystron, SPL could be the most sensitive to this phenomenon. The possible cures would be to implement piezo-electric tuners or to consider fast ferrite amplitude and phase modulators at the waveguide feeding each cavity or to increase the stiffness.

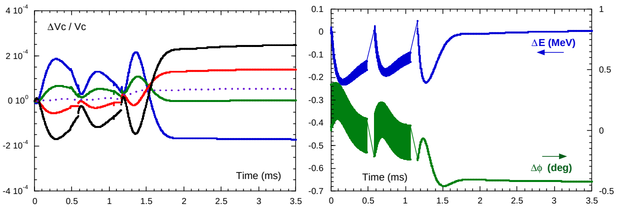

Figure 10: Amplitude of the 4 cavity voltages for the last groupand field deviations at linac end

6 ACKNOWLEGMENT

The author is most grateful to M. Luong and G. Devanz, who lent invaluable assistance and performed most calculations presented in this paper.

7 REFERENCES

[1] S. Simrock et al, “Design of the Digital RF Control System for the Tesla Test Facility”, Proc. of EPAC, Sitges, 1996.

[2] The ESS project, Vol. III, 2002, www.ess-europe.de

[3] M. Liepe et al, “Dynamic Lorentz Force Compensation with a Fast Piezoelectric Tuner”, Proc. of Part. Accel. Conf., Chicago, 2001.

[4] Sung-il Kwon et al, “SNS Superconducting Cavity Modeling Iterative Learning Control”, Proc. of Linac Conf., Monterey, 2000.

[5] A. Regan et al, “The SNS Linac RF Control System”, Proc. of Part. Accel. Conf., Chicago, 2001.

[6] C. Reece et al, “Refining and Maintaining the Optimal Performance of the CEBAF SRF Systems”, Proc. of Part. Accel. Conf., Chicago, 2001.

[7] R. Stassen et al, “Superconductive test cavity for the ESS”, Proc. of Part. Accel. Conf., Chicago, 2001.

[8] G. Devanz et al, “Numerical simulations of Dynamic Lorentz Detuning for SC Cavities”, these proceedings.

[9] J. Tückmantel, CERN NUFACT Note 082, 2001.