RF FEEDBACK SYSTEMS FOR SC CAVITIES

A. Mosnier, SOLEIL, Gif/Yvette (France)

Abstract

During the past decade, RF superconductivity expanded successfully and has become an important technology for particle accelerators for high energy physics and nuclear physics. A key component of any high performance accelerator (high intensity ring, low emittances linac, ...) is the RF feedback system that will determine, in particular, the longitudinal phase space and the stability of the multibunch beam. However, the RF system, designed for SC cavities, will differ significantly from the one, designed for copper cavities. Due to their high Q, they operate generally with much higher beam loading and will be much more sensitive to microphonic effects. Concerning operation with pulsed RF, special care must be taken because of dynamic cavity deformation due to radiation pressure. In this paper, the design and performance of RF feedback systems for existing or planned accelerators are reviewed and the challenging tasks for c.w. and pulsed mode operation are discussed.

1 INTRODUCTION

Higher and higher precision control of the accelerating field is required from the RF system. Since the involved RF time constants are large, RF systems using superconducting (SC) cavities look at first sight better suited than room temperature sections from the field stability point of view. However, owing to the much smaller bandwidth, this assessment is mitigated as soon as we consider detuning effects, driven by microphonic noise for instance. Furthermore, to achieve the desired field quality, the low level RF control system must face not only various external perturbations (beam loading, beam current fluctuations, mechanical vibrations , ripple on high voltage power supplies…) but also potential instabilities, which are driven by internal positive feedback loops. More specifically, these unwanted loops are caused by the deformation of the cavity wall or by the circulating beam dynamics in non-isochronous machines, leading to ponderomotive[1] or Robinson[2] instabilities.

2 ROBINSON INSTABILITY

For the sake of clearness, we assume hereafter that the operation energy is above transition energy. For minimizing the RF power required from the klystron, the cavity frequency is normally detuned to compensate the reactive component of the beam loading. Cavity voltage and generator current are in phase and the optimal detuning angle, defined by $\tan\psi = 2Q\,(\omega_o - \omega_{rf})/\omega_o$, is

$$\tan\psi = -Y\sin\phi_S$$

where $Y = R\,I_b/V_c$ is the beam-loading parameter, ratio of the beam-induced voltage on resonance to the cavity voltage, and R is the shunt impedance, including the generator impedance. In addition, assuming a matched generator, the cavity coupling is $\beta = 1 + P_b/P_d$, where P_b is the beam power and P_d is the cavity wall dissipation, meaning that all RF power is transfered to the load. The detuning angle and the beam-loading parameter become

$$\tan\psi = -\frac{\beta-1}{\beta+1}\tan\phi_S, \qquad Y = \frac{\beta-1}{\beta+1}\,\frac{1}{\cos\phi_S}$$

For SC cavities, where the dissipated power is much smaller than the beam power ($\beta >> 1$), the detuning angle should be set just to the opposite of the synchronous phase and $Y \to 1/\cos\phi_S$, for optimal power transfer.

Robinson instabilities describe the coupling of stored energy to beam oscillations through the accelerating field. A phase modulation of the beam $\delta\phi_b$ will induce a cavity voltage modulation, in phase $\delta\phi_c$ and in amplitude δv_c, which in turn will modulate the beam (Fig.1).

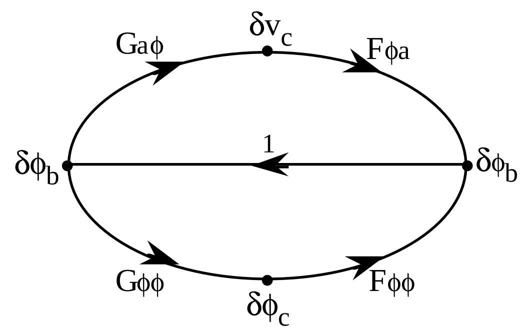

Fig. 1 : Flow graph related to Robinson instabilities

The loop is closed and growing oscillations can start, according to phase conditions. The stability of the beam-cavity system, without and with external feedback loops, can be analysed in frequency domain : instability occurs when some poles of the closed-loop transfer function have positive real parts. The poles are the roots of the characteric equation $1+H(p)$, where $H(p)$ is the open-loop transfer function, which is recalled below without external feedback [3], with somewhat different notation

$$H(p) = \frac{\omega_s^2}{p^2 + \omega_s^2} \times \frac{\tan\psi}{(1+\tau\,p)^2 + \tan^2\psi} \times \frac{Y}{\sin\phi_s}$$

Stability can then be determined by Routh's or Nyquist's criterion, leading to the Robinson stability limits [2]

$$\tan\psi < 0 \quad (1) \qquad Y < \frac{2\sin\phi_S}{-\sin 2\psi} \quad (2)$$

2.1 First Robinson stability limit

First condition is automatically satisfied (resonance frequency below the RF frequency) in normal operation, once the cavity tuning has been adjusted for reactive beam loading compensation : according to the bunched beam instabilities theory, longitudinal dipole oscillations are damped when the resistive part of the resonator at the upper synchrotron sideband is smaller than at the lower sideband. However, with very high beam loading, the necessary detuning frequency can be very large for copper cavities, and even exceed the revolution frequency (see for example [4] and [5] for the KEK-B and PEP-II B-factory rings). As the fundamental mode impedance at the upper synchroton sidebands of the revolution harmonic frequencies becomes high, several coupled-bunch modes can be strongly excited. Different approaches to cope with these instabilities have been proposed: by using an additionnal energy storage cavity or by direct RF feedback with parallel comb filters, which reduces selectively the impedance at the upper synchrotron sidebands. For SC cavities, however, which have usually lower R/Q and larger voltage, the detuning frequency is much smaller and generally less than the revolution frequency.

2.2 Second Robinson stability limit

Second inequality prescribes a current threshold, which is reached when the beam sits on the crest of the generator voltage, leading to a vanishing longitudinal focusing for the dipole mode. Unlike copper cavities, SC cavities operating at matched conditions, i.e. at optimal tuning and coupling factor (β>>1), are just at the high-intensity Robinson limit ($Y \rightarrow 1/\cos\phi_S$). The straightforward way of coping with this Robinson type instability would be to run the cavities “on tune“, but at the expense of an increased incident power

$$\Delta P_{inc} = \frac{1}{4} P_b \tan^2 \phi_s$$

This “on tune“ solution is defavourable for large ϕ_s rings and sets challenging demands to the main coupler, owing to the higher peak fields, even for moderate ϕ_s values, like the LEP machine [6], obliged to run “on tune” for ponderomotive instability reasons. The other, more elegant, remedy consists in reducing the impedance seen by the beam by using the RF feedback scheme [7].

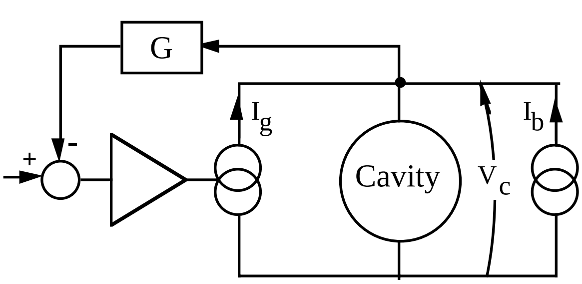

Fig. 2 : Schematic of the direct RF feedback

The principle is to reduce significantly the fundamental mode impedance seen by the beam by reinjecting the RF signal coming from the cavity pick-up back into the power amplifier. With a loop gain G, the apparent Q of the resonator, which is seen by the beam, is now divided by the factor 1+G (and all the quantities containing it, τ, $\tan\psi$ and Y). Assuming a constant loop gain G over the bandwidth of concern, the open-loop transfer function $H(p)$ and the 2nd Robinson stability limit become

$$H(p) = \frac{\omega_s^2}{p^2 + \omega_s^2} \times \frac{\tan\psi}{(1 + G + \tau\, p)^2 + \tan^2\psi} \times \frac{Y}{\sin\phi_s}$$

$$Y < \frac{(1+G)^2 + \tan^2\psi}{-\tan\psi} \sin\phi_S$$

With a matched generator, the beam-loading limit is simply increased by the factor 1+G. Fig.3 shows for example the root locus - plot of the roots of the characteristic equation in the complex plane - as a function of the beam-loading parameter Y for the RF system of the SOLEIL Light Source project. Without external feedback (top plot), the absolute value of the synchrotron frequencies (given by the imaginary part of the complex conjugate roots) increase with the beam current, while one of the other two roots, which are wandering along the real axis in opposite direction, reach the origin and makes the system unstable.

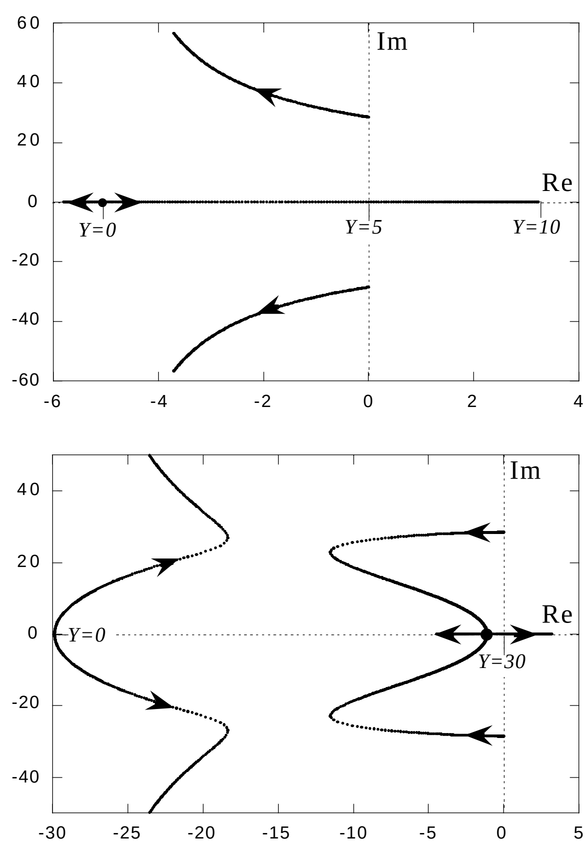

Fig. 3 : Root locus (variable is Y), without (top) and with (bottom) RF feedback (G=5).

With RF feedback (bottom plot), even for modest gain values (G=5 in that case), all four roots are complex and the synchrotron frequencies fall down. When the real axis is reached, these two roots become purely real (the coherent frequency vanishes) and the stability is lost again as soon as one of them goes beyond the origin. In fact, the apparent impedance cannot be reduced indefinitely, and one limitation of the maximum gain comes from the overall delay of the feedback loop, including klystron, waveguides and cables. The stability study of a system containing a dead time is more tedious because of its nonlinear characteristic. In any case, the system must be stable even without beam. Taking the loop around cavity and amplifier only and allowing for a 45° phase margin, the gain limit is $G < \pi\tau/4T$ [7], where T is the total delay time and τ is the filling time of the cavity. It is worthwhile noting that, unlike copper cavities, SC cavities have filling times (a few hundred µs) much larger than usual delay times and RF feedback performance will be generally limited by other effects.

2.3 RF feedback implementations

The RF feedback technique was successfully applied to multicell SC cavities first in the **SPS** at CERN [8]. Beam instabilities could then be avoided during the high intensity proton cycle (200 mA), while low intensity e^+e^- beams were accelerated during the lepton cycle (0.5 mA). The modes of the fundamental passband of the SC cavity were damped by means of a direct RF feedback system, acting on the four cavity modes. Separate notch filters allow individual adjustments of the loop gains. For the two higher frequency modes, which are very close, further reduction is achieved thanks to an additional digital feedback loop, which consists of a digital comb-filter and one-turn delay, ensuring maxima at every harmonic of the revolution frequency and 2π phase rotation between them. **LEP** is on the way of the 100 GeV energy and is now fully equipped with 272 SC cavities. RF feedback is being implemented on all modules to stabilize the relatively 14 mA beam, especially at injection, where the RF voltage is low (high beam loading), and at high energy, where the synchronous phase goes closer to zero (with respect to the crest) with almost all RF power transferred to the beam. As a group of 8 cavities are driven by a single klystron, the total RF voltage must be reconstructed from the pick-up signals of each cavity. The loop gain of about 26 dB makes pushes the Robinson limit away, but the performance of the system depends on the accuracy of the vector sum reconstruction due to calibration errors (in amplitude and in phase). At KEK, experiments with high beam currents were carried out on TRISTAN Accumulation Ring to test a prototype of SC cavity developed for the B-Factory **KEK-B**. It was shown that the use of the RF feedback could suppress efficiently a strong coherent synchrotron oscillation and a stable beam current of 573 mA could be stored [9]. For the synchrotron light source **SOLEIL** project, considering a high stored current of 500 mA, the SC solution was chosen to cope with multibunch instabilities. RF feedback will be directly implemented by means of two fast amplitude and phase feedback loops (Fig.4). These loops are anyhow necessary to provide a very good time stability (of the order of 1 ps) of the photon flux to the users. The nominal RF drive signal is modulated by quantities proportional to cavity amplitude error (in phase) and cavity phase error (in quadrature) through I-Q modulators. When the gains of both loops are identical, the dynamic behaviour of the system is similar to the one controlled by the direct RF feedback scheme.

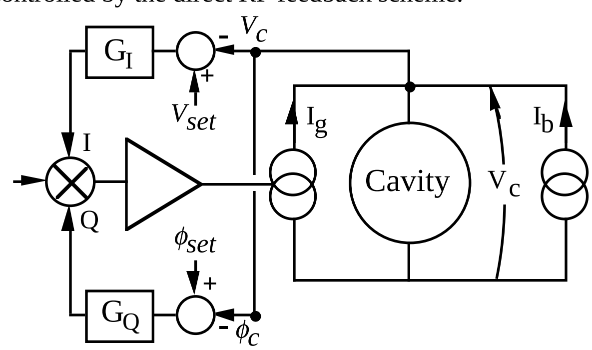

Fig. 4 : Schematic of the SOLEIL feedback system.

3 MICROPHONICS

The great sensitivity to microphonics noise comes from the poor mechanical stiffness of the cavities and from their narrow bandwidth (generally around ±100 Hz). From the beginning of the history of SC acceleration, the designers have had to do their utmost to fight the microphonic effects : heavy-ion SC accelerators were the first to suffer for it and clever solutions had to be found to keep the accelerating wave in phase with the beam (see [10] for example). For relativistic beam SC structures, typical phase fluctuations range nevertheless from a few degrees for low loaded Q cavities (like KEK-B prototype) to 20° peak-to-peak for higher Q cavities (low intensity beam) and are generally driven by the cryogenic system. For example, to produce the high energy electron beam with the tight required energy spread (2.5 10^{-5} rms) the recirculating c.w. SC linac of **Jefferson Laboratory** uses RF control modules [11], with 50-70 dB loop gains. Without feedback, the resonance frequency modulation, induced by microphonic noise, lead to phase fluctuation up to 20°, and even up to 100° for very noisy cavities, associated with nearby vacuum pumps. Moreover, when one single klystron drives multiple cavities, the feedback system controls the measured total voltage, analog or digital recontruction of the vector-sum, and not the real one. Thus, any time-varying perturbation, like microphonics, will induce jitter in the voltage seen by the beam. Great care must be taken in the vector sum calibration : for example better than ±10% for the amplitude and ±1° for the phase in TESLA proposal.

4 PONDEROMOTIVE INSTABILITY

Due to their small bandwidth and to the strong inclination of their walls to get out of shape, SC cavities suffer from the so-called "ponderomotive oscillations", which originate in a coupling between the RF stored energy and mechanical oscillations through the force exerted on the cavity walls (so-called Lorentz force or "radiation pressure"). As the accelerating field proceeds to grow, the peak of the resonance curve moves towards negative frequencies $\Delta f_c = -k\,E_a^2$, where k is the radiation detuning parameter. A 1st "static" instability occurs with a positive tuning angle ψ, when the resonance function becomes multivalued. The mechanism of the 2nd "dynamic" instability is the following: the resonance frequency modulation by a mechanical vibration will result in an amplitude modulation of the cavity field (with a function transfer *Ge*), which, in turn, will modulate the resonance frequency (with a function transfer *Gm*), via the radiation pressure. The loop is closed and the amplitude of the mechanical vibration will be amplified or damped, according to the relative phase. The expressions of the transfer functions, relative to the cavity and mechanical modes are given by

$$G_e(p) = \frac{\delta v_c}{\delta \omega_c} = \frac{-\tau \tan\psi}{(1+\tau\, p)^2 + \tan^2\psi}$$

$$G_m(p) = \frac{\delta \omega_c}{\delta v_c} = -4\pi\, k_m\, E_a^2\, \frac{\omega_m^2}{p^2 + 2/\tau_m\, p + \omega_m^2}$$

where τ and τ_m are the e.m. and mechanical time constants, ω_m and k_m are the angular frequency and the radiation detuning parameter of the mechanical mode *m*.

The system is unstable if some roots of the characteristic equation $1\text{-}G_eG_m$ have positive real parts, occuring at frequencies close to the resonance frequency of the mechanical mode. The root locus of one of the two conjuguate roots, responsible for the exponential growth of the oscillations, is plotted on Fig. 5, with the detuning angle ψ as variable (from $+\pi/2$ to $-\pi/2$). Ponderomotive ocillations are excited at negative detuning angle values and the limit is rapidly reached (a couple of degrees) even at moderate accelerating gradients for RF systems of small bandwidth (high Q). However, as soon as some external feedback is introduced, the system can be stabilized, even with low loop gains.

Unfortunatly, RF systems, using a single klystron for several SC cavities and thus a vector sum feedback, cannot avoid this ponderomotive instability, because the cavities are not totally identical and can "breathe" with different phases [6]. At **Jefferson Laboratory**, where each klystron feeds one single cavity, the cavities start to oscillate at only a few MV/m, but are extremely stable once the amplitude control loop is turned on. In **LEP** at CERN, where 8 cavities are powered by one klystron, ponderomotive oscillation can be observed when the detuning is increased under higher beam loading. The present remedy is to run the cavities "on tune" for suppressing the instabilities, at the expense of extra incident power, but remaining acceptable for the LEP parameters (less than 10% at high energy).

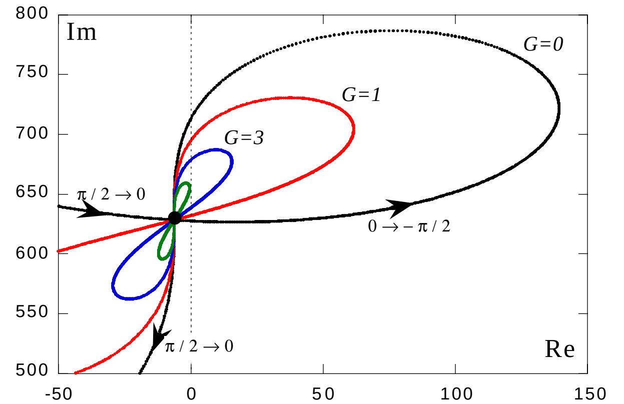

Fig. 5 : Root locus with ψ asvariable for different loop gains *G* (Q=5 10^6, Ea=6MV/m, fm=100Hz, Qm=50, km=2 Hz/$(\text{MV/m})^2$)

5 PULSED OPERATION IN LINACS

Owing to their very low RF power dissipation, SC linacs operate normally in c.w. mode with a very high stability level (see for example Jefferson Laboratory: better than 0.02% in amplitude and 0.1° in phase). Pulsed mode operation, however, is necessary for very high energy SC linacs (large number of cavities with high accelerating gradient), like the proposed linear collider TESLA, to maintain the cryogenic load within reasonable limits. This opens new challenging RF control issues, especially when low multi-bunch beam energy spread is required all along the beam pulse.

5.1 Cavity voltage error sources

Transient beam loading is ideally suppressed by injecting the bunch into the cavity at the time $\tau\,Log2$ (for a beam on-crest), resulting in a constant total cavity voltage during the whole beam pulse. Residual field variations due to various pertubations (RF mismatch, current fluctuations, power source ripple, Lorentz forces and microphonics detuning) are then compensated by fast feedback and feedforward techniques. The feeding of multiple cavities (16 to 32) by one single klystron, however, makes the task more tricky.

Since Lorentz forces ("radiation pressure") detune the cavity by more than one cavity bandwidth during the filling time, the RF frequency must track the decreasing cavity frequency to insure minimum power requirement. Unfortunatly, due to the finite response time of the cavity walls, the resonance frequency goes on to shift during field flat-top (Fig. 6), with a mechanical time constant of the order of the beam pulse duration. Thanks to a positive pre-detuning of the cavity, such that operating ω_{RF} and cavity ω_c frequencies are equal in about the middle of the beam pulse, minimal amplitude and phase errors can be achieved, relaxing the feedback requirements. However, since the cavity voltage must be at the correct phase when the first bunch arrives, it is better to lock the cavity phase on a pre-determined phase law $\phi(t)$ during the filling time, insuring a minimal amount of peak power required for control, in the presence of microphonics.

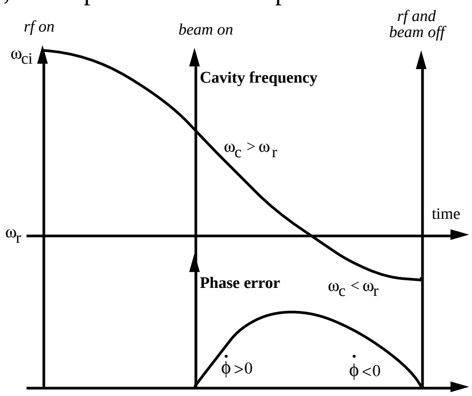

Fig. 6 : cavity frequency and phase error during filling time and beam pulse

The dynamics of the pulsed RF system can be simply modelled by a set of 3 non-linear 1st order differential equations for each cavity

$$\tau \dot{A}_c = A_g \cos(\phi - \phi_g) - A_b \cos(\phi - \phi_b) - A_c$$

$$\tau \dot{\phi}_c = - A_g / A_c \sin(\phi - \phi_g) + A_b / A_c \sin(\phi - \phi_b) - \tau \Delta\omega_c$$

$$\tau_m \Delta\dot{\omega}_c = -\Delta\omega_c - 2\pi K A_c^2$$

Numerous simulations [12] by Runge-Kutta integration, including realistic spreads in cavity parameters (on electric and mechanical time constants τ and τ_m, radiation detuning parameter K), errors in setting points (cavity pre-detuning $\omega_c(0)$, vector-sum calibration) and assuming reasonable feedback loop gains (30-40dB), brought out the following conclusions: heavy beam-loading, detuning due to systematic Lorentz forces or erratic microphonics were not any more serious problems for the pulsed operation in SC linacs and beam energy spreads of a few 10^{-4} could be achieved even for accelerating gradients as high as 25 MV/m. However, when multiple cavities are powered by one single drive, two challenging issues remain.

- Vector-sum calibration
- Spread in loaded Q

With different Qs (coupling error due to fabrication tolerance or on purpose, aiming at reaching the maximum gradients in each of the SC cavities), the filling times will differ, resulting in a non flat accelerating field profile. Even with optimization of incident power and beam injection time, the Q-spread tolerance will be limited by the extra power required for feedback we can tolerate (≈15% for 20% extra power).

5.2 RF control systems implementation

Feedback is usually applied to in-phase and quadrature component of the cavity voltage by means of I/Q modulators (the main pertubations coming from cavity detuning - Lorentz forces or microphonics - RF field is automatically corrected by an out-of-phase signal, solely). While fast analog feedback systems are well suited (fast, simple, swift to bring into operation) when a small number of units are concerned [13], digital control is preferred for large RF systems, because it provides flexibility, easier reconstruction of the vector-sum and extensive diagnostics [14]. Very fast DSP (≥50 Mhz) must be selected to reduce the additional loop delay caused by the computation time of the feedback algorithms. Digital I/Q detectors, based on sampling of the IF down-converted probe signals have been developed for the vector-sum calculation. Besides, in order to reduce the control effort due to systematic error sources (like the Lorentz forces), feedforward can be added, from learning tables, which are adaptively updated.

6 ACKNOWLEDGMENTS

I would like to express my gratitude to K. Akai, D. Boussard, L. Doolittle, D. Graef, H. Padamsee, S. Simrock, who kindly provided updated and detailed informations about KEK, CERN, Jefferson Laboratoty , S-DALINAC, CESR, and TTF RF systems.

REFERENCES

[1] V.E. Shapiro, Sov. Phys. JETP, Vol.28, No2 ,1969.
[2] K.W. Robinson, CEAL-1010, Feb. 1964.
[3] F. Pedersen, IEEE Trans. Nucl. Sci. NS-32, p.2138, 1985.
[4] Y. Yamazaki and T. Kageyama, Particle Accelerators 44 p.107 (1994).
[5] P. Corredoura et al., “RF Feedback Development for the PEP-II B Factory”, Proc. EPAC 94, June 1994, London.
[6] D. Boussard, “Impact of Superconducting Cavities on LEP2 Design”, CAS Superconductivity.
[7] D. Boussard, IEEE Trans. Nucl. Sci. NS-32, p.1852, 1985.
[8] D. Boussard, H.P. Kindermann, V. Rossi, “RF Feedback applied to a Multicell Superconducting Cavity”, Proc. EPAC 88, June 1988, Rome.
[9] Y. Funakoshi and K. Akai, “High Beam Current Experiments for the KEKB conducted at the TRISTAN Accumulation Ring”, Proc. PAC’97, 1987, Vancouver.
[10] D. Schulze et al., IEEE Trans. Nucl. Sci., NS-26, No. 3, p. 3748 (1979).
[11] S.N. Simrock, “RF Control System for CEBAF”, Proc. PAC’91, San Francisco, p.2515, 1991.
[12] A. Mosnier and J.M. Tessier, “Field Stabilization in a Superconducting Cavity Powered in Pulsed Mode”, Proc. EPAC 94, June 1994, London.
[13] A. Mosnier et al, “RF Control System for the SC Cavity of the Tesla Test Facility Injector”, Proc. PAC’97, Vancouver, 1997.
[14] S. Simrock et al, “Design of the Digital RF Control System for the Tesla Test Facility”, Proc. EPAC’96, June 1996, Sitges.