IDLE SUPERCONDUCTING RF CAVITIES FOR BUNCH FOCUSING

P. Marchand, L. Rivkin
Paul Scherrer Institut, CH-5232 Villigen PSI

I. INTRODUCTION

In the feasibility study for a B-Meson Factory using the CERN ISR tunnel and the LEP injection system (BFI) [1], a combination of normal conducting (n.c.) and superconducting (s.c.) RF cavities has been proposed as an alternative in the context of upgrading the luminosity towards 10^{34} cm^{-2} s^{-1} [2,3]. In such a hybrid n.c./s.c. system, both systems may contribute to the compensation of the beam energy losses as well as to the longitudinal focusing of the bunches. Another possibility is to limit the role of the s.c. system to a pure focusing task by setting its synchronous phase to zero (no acceleration). In this latter scheme, the s.c. cavities might be operated in a completely idle mode (i.e., no external RF source). The RF power required for the compensation of the beam energy losses would be entirely provided by the n.c. system. A proper detuning of the s.c. cavities should permit use of the beam induced voltage as the focusing voltage.

The steady state and dynamic behaviour of a single RF system, in the presence of beam loading, has been already largely treated [4,5,6,7]. Extending the analysis to the more general case of two RF systems coupled through the beam was the subject of a previous note [8]. No major critical issues, as compared to conventional methods, were encountered in the context of the BFI. On the contrary, the partial or complete separation of functions, powering and longitudinal focusing, characteristic of this system, makes it particularly flexible. The main results of this study and examples of applications are presented. The possibility of testing the bunch shortening provided by idle s.c. cavities in an existing storage ring is also discussed.

II. STEADY STATE DESCRIPTION

Only the beam-RF system interactions at the fundamental frequency will be considered. The higher order modes (HOM) of the RF cavities are supposed to be sufficiently damped and are taken into account only as extra beam energy losses. In addition, we will assume short e^- (or e^+) bunches above the transition energy and $T_b/T_f \ll 1$ (T_b : time between bunch passages, T_f : cavity filling time). The fundamental interaction between the beam and an RF system can be then described by the phasor diagram of figure 1.

V, cavity voltage (phase reference)
R, cavity shunt impedance
β, input coupling factor
i_b, fundamental beam current
(twice the average value, I_b)
$2i_g$, generator short circuit current[1]
Φ_g, phase of the generator current
Φ_S, synchronous phase
Ψ, cavity detuning angle

$tg\Psi = \dfrac{2\ Q\ \delta f}{(1+\beta)\ f_r}$ $\qquad \delta f = h f_0 - f_r$

Q, cavity quality factor	h, RF harmonic number
f_0, revolution frequency	f_r, cavity resonant frequency

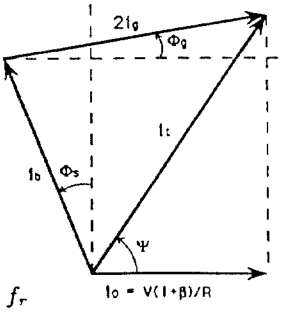

Fig. 1 : Phasor representation of the beam-cavity interaction

An equilibrium or steady state condition is defined by

$$\Delta U/e = V\ sin\Phi_S\ ,$$
$$\sigma_s \propto (h\ V\ cos\Phi_S)^{-1/2}\ ;$$

ΔU is the energy loss per turn and σ_s, the RMS bunch length. At a given RF frequency, the specification of ΔU and σ_s leads to a unique solution for both V and Φ_S. The power delivered to the beam is then $P_b = V\ I_b\ sin\Phi_s$ and the cavity dissipation, $P_d = V^2/2R$. The minimum power requirement, $P_g = P_b + P_d$, corresponds to the matched case (no reflection), obtained when the reactive current is compensated by the proper detuning, δf and the coupling factor set such $\beta = 1 + P_b/P_d$.

In the presence of two different RF systems, each of them may be described as before[2] and the steady state definition becomes

$$\Delta U/e = V_1\ sin\Phi_{S1} + V_2\ sin\Phi_{S2}\ ,$$
$$\sigma_s \propto (h_1\ V_1\ cos\Phi_{S1} + h_2\ V_2\ cos\Phi_{S2})^{-1/2}\ .$$

For fixed RF frequencies ($h_1 \leq h_2$), a specified stationary condition can now be obtained from different combinations of both RF system parameters ($V_1, \Phi_{S1}, V_2, \Phi_{S2}$).

In the particular case where the second RF system is idle, the equivalent phasor diagram is reduced to that of figure 2.

$i_{g2} = 0$
$\beta_2 = 0$
$\Phi_{S2} = \Psi_2 - \pi/2$
$V_2 = 2\ R_2\ I_b\ cos\Psi_2$

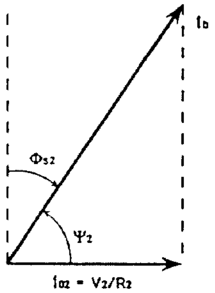

Fig. 2 : Phasor representation for idle cavities

The beam-cavity interaction corresponds to a power lost by the beam, equal to the cavity dissipation:

$$P_{b2} = V_2\ I_b\ sin\Phi_{S2} = -P_{d2} = -V_2^2/2R_2\ .$$

With s.c. cavities and large enough I_b, $\Phi_{S2} \simeq 0$, $\Psi_2 \simeq \pi/2$ ($cos\Psi_2 \simeq 1/tg\Psi_2$) and the induced voltage is then

$$V_2 = (R/Q)_2\ I_b\ f_{r2}\ /\ \delta f_2\ ,\ \text{where}\ \delta f_2 \gg f_{r2}/Q_2\ .$$

A steady state is now defined by

$$\Delta U/e = V_1\ sin\Phi_{S1}\ ,$$
$$\sigma_s \propto (h_1\ V_1\ cos\Phi_{S1} + h_2\ V_2)^{-1/2}$$

and can be obtained from different operating points within the range $0 < \Phi_{S1} \leq \pi/2$. Thus, σ_s is adjustable, without other interference, by simply varying δf_2 and, for a specified σ_s, there is still a degree of freedom available.

The power requirement is minimum if the n.c. system is matched and $V_1 = \Delta U/e$ (or $\Phi_{S1} = \pi/2$). This corresponds to a complete separation of functions: powering by the n.c. system ($P_b = V_1 I_b$), focusing by the s.c. one ($\sigma_s \propto V_2^{-1/2}$).

The preceding situations are generally met for e^- or e^+ in storage regime ($\sigma_s \ll c/f_{r2}$, $I_b = I_{bmax}$). Now it happens that, during the accumulation, one passes through different operating states while I_b varies from zero to I_{bmax}, in successive steps ΔI_b. The value of δf_2, which can then be freely set, determines the increasing rate of V_2 versus I_b. It has to remain larger than a few s.c. cavity bandwiths and such that the resonance does not approach too closely the next beam spectrum line (typically, $\delta f_2 < f_0/2$). At low I_b, as long as $V_2 \ll V_1$, a proper

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[1] value "seen" by the beam (i.e., transformed by the coupling circuit).
[2] index 1 and 2 used for the n.c. and s.c. system, respectively.

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trapping of the injected bunches necessitates $V_1 > \Delta U/e$. This constraint may determine the operating point. It is also possible to make use of the power reserve existing at low beam loading for varying V_1 during the accumulation.

The stability of the system in presence of perturbations, the subject of the next section, is another important consideration.

III. DYNAMIC BEHAVIOUR

A. Stability criterion

In the presence of a single RF system, the stability condition is defined by the well known Robinson criterion [5] which, in our notations, can be expressed as:

$$0 < sin2\Psi < 2\ cos\Phi_S\ /\ Y\ , \quad \text{where}\ \ Y = i_b/i_0\ .$$

We found in ref. 8 that, extended to the more general case of a double RF system, the upper stability limit, becomes:

$$sin2\Psi_1 < \frac{2\ cos\Phi_{S1}}{Y_1} + \frac{h_2 V_2}{h_1 V_1 Y_1}\ (2\ cos\Phi_{S2} - Y_2\ sin2\Psi_2)\ . \quad (1)$$

If the second RF system is idle, the second term of the right hand side in (1) cancels ($\Phi_{S2} = \Psi_2 - \pi/2\ , Y_2 = 1/cos\Psi_2$) and we once again obtain the classical Robinson limit for the first RF system, as if it was alone:

$$sin2\Psi_1 < 2\ cos\Phi_{S1}\ /\ Y_1\ . \quad (2)$$

This result states that the stability condition for the hybrid n.c./idle s.c system is met as soon as the Robinson criterion is fulfilled for the n.c system; in particular, (2) will be automatically satisfied if the n.c cavities operate in the matched case at maximum beam current and $0 < \Phi_{S1} < \pi/2$.

B. Stability margin and transient effects

In practice, a sufficient safety margin is necessary to cope with departures from the ideal conditions previously assumed. Generally, for e^- or e^+ in a normal storage regime (constant or slowly variable i_b), the parameters can be precisely set by means of "slow" amplitude and tuning servo controls. The main source of perturbation then results from the accumulation, when I_b increases from zero to I_{bmax} in successive injections, ΔI_b. The sudden changes of beam loading temporarily destroy the steady state equilibrium and induce transient oscillations of the RF voltage. Emittance blow up or even beam losses may occur if the safety margin is not sufficient.

According to our preceding results, the stability region increases when the operating point moves away from the condition $\Phi_{S1} = \pi/2$. The presence of "fast" compensation (phase loop, feedforward, RF feedback, external coupling of the two systems) would significantly modify the situation.

The transient effects directly produced in the n.c. system should be negligible compared to the s.c. one. If the latter could be considered individually, as a "free oscillator", the frequency of the transient oscillations would be δf_2, its damping rate, T_{f2} (natural s.c. cavity filling time), and its amplitude, expressed in terms of instantaneous power [8],

$$\Delta \hat{P}_2 = \Delta V_2\ I_b\ , \ \text{with}\ \ \Delta V_2 = (R/Q)_2\ \Delta I_b\ f_{r2}\ /\ \delta f_2\ . \quad (3)$$

However, the s.c. system cannot be treated independently since it is coupled to the n.c. system through the beam. A correct analysis requires considering the global system response (in particular, its slowest damping rate) which depends on the steady state operating conditions of both systems. Equation (3) should nevertheless give a good idea of the real maximum transient amplitude; conversely, as we will see in a following example, the damping time may be much shorter than T_{f2}.

Due to the high degree of freedom available with this system, a general analytic approach is quite complex. In the next section, we estimate the effects for particular applications.

IV. EXAMPLES OF APPLICATIONS

The n.c/idle s.c. system provides an economical way of generating very high RF voltage, with additional degree of freedom available, due to the separation of longitudinal focusing and energy loss compensation functions.

This seems to be particularly well suited for the needs of flavor factories (Tau-charm, B-meson) where short bunches together with high design current are required.

Achieving very short bunches and high peak currents is also important in synchrotron light sources, storage ring drivers for short wavelength FELs as well as in the damping rings for future linear colliders. With very short bunches, we enter a regime where the effective impedance seen by the beam decreases with bunch length, resulting in the increase of the threshold peak current for the turbulent bunch lengthening instability. Such dependence of the threshold on bunch length has been observed experimentally (e.g. SPEAR, LEP) [9,10]. In LEP, the threshold current is ten times higher than what one would expect in the long bunch regime.

Two examples of possible applications are described in the following section.

A. B-meson factory

We now consider the use of a n.c./idle s.c. system in the high energy ring of the L = 10^{34} cm^{-2} s^{-1} BFI proposed in ref. [1]. The main design parameters of the ring and characteristics of the RF system [2,3] are listed below.

- **ring parameters :**
  - E = 8 GeV, ΔU = 6 MeV , mom. comp. fact. = 0.005
  - I_b = 1.12 A , n_{bunch} = 320 , σ_s = 4.8 mm
- **n.c. RF parameters :**
  - $Q_1 \simeq 50000$, $(R/Q)_1 = 73\ \Omega$/cav , $n_{cav1} = 32$
  - 8 MW of installed RF power
- **s.c. RF parameters :**
  - $Q_2 \simeq 10^9$, $(R/Q)_2 = 40\ \Omega$/cav , $n_{cav2} = 40$
  - 120 MV of total voltage

The number of cavities is adjusted for practical values of the accelerating gradient, input coupler power, HOM and fundamental dissipation. Instability thresholds have also been taken into account. The frequency of both systems is 500 MHz. Higher harmonic s.c. cavities would lead to an intolerable reduction of the longitudinal acceptance during the accumulation.

The following table presents a set of typical operating conditions for the n.c. system.

Φ_{S1} [°]	V_1 [MV]	P_{d1} [kW]	P^{RF}_{total} [MW]	β_1	δf_1 [kHz]
25.	14.4	920.	7.7	8.4	80.
35.	10.6	500.	7.3	14.6	97.
45.	8.6	330.	7.1	21.6	103.
55.	7.4	240.	7.0	27.8	97.

In all cases, a matched condition at full beam current is assumed. The 8 MW available power, allows operation at Φ_{S1} as low as 25° which corresponds to a quite comfortable stability margin. With less power, it is still possible to achieve an efficient capture of the 8 cm injected bunches, by varying V_1 during the accumulation.

For a total filling time of a few minutes and injection pulses around 3 mA, the transients directly produced in the n.c cavities should be negligible. However, those induced by the idle s.c. system must be considered more carefully. An estimate of their maximum effects is given below, for $\Phi_{S1} \simeq 30°$ and different values of δf_2.

δf_2 [kHz]	ΔV_2 [kV]	$\Delta \hat{P}_2$ [kW]	$\Delta \hat{P}_2/P_1$ [%]	$\Delta\Phi_{S1}$ [°]	τ [ms]
8.2	320.	350.	5.0	1.7	5.2
25.	100.	115.	1.7	0.6	0.4
50.	50.	60.	0.9	0.3	1.7
150.	17.	20.	0.3	0.1	100.

ΔV_2 and $\Delta \hat{P}_2$ are defined in (3); $\Delta\Phi_{S1}$ is the equivalent phase variation in the n.c. system and τ, the slowest damping rate obtained by solution of the characteristic equation [8]. The first line corresponds to the value of δf_2 required for $\sigma_s \simeq 5$ mm ($V_2 = 110$ MV) in the storage regime; $\tau \simeq 5$ ms. In the next line, δf_2 is set for minimum damping time ($\tau \simeq 400\mu s$). This is not necessarily the optimum condition: the two last examples show higher τ, but lower amplitude. In the search for the best compromise, amplitude, damping rate and eigenfrequency values must be simultaneously taken into account.

The above results seem quite compatible with the expected safety margin. Thus, the n.c. system could be equipped with only conventional "slow" amplitude and tuning controls; for the s.c. cavities, a servo mechanism controlling their voltage, via the action of a tuner, would be sufficient. If it were necessary, "fast" compensation methods could be added.

B. Synchrotron light source

In the context of a parameter study for a possible future Swiss Light Source (SLS) we have considered the use of idle s.c. cavities to obtain bunches as short as $\sigma_s = 1$ mm .

Operated at 1.5 GeV, a 200 m long ring with momentum compaction factor around 0.002 and using a 500 MHz RF system (1 MV voltage), would produce 6 mm long bunches.

Introducing idle s.c. cavities that would provide 30 MV induced voltage, would shorten the bunch to 1 mm. Due to the expected slow filling rate of the ring, the problem of injection transients should not be critical. Both 500 MHz and 1.5 GHz were considered, and while the higher harmonic system results in some saving of space needed for the cavities, the HOM problem may become more serious.

It should be possible, by careful design, to build a ring with broad band impedance $Z/n < 1\Omega$. For short bunches, the effective impedance seen by the beam could be much smaller, resulting in higher achievable peak currents. However, some theoretical considerations [11] suggest that the lowest limit of the effective impedance is the so-called "free space" impedance, which in our case would be around 0.2 Ω. If this were confirmed, the impedance constraints on the vacuum chamber and RF cavities could be relaxed by the use of short bunches.

A test of the effective impedance scaling with bunch length, down to this limit, should be possible in the proposed experiment at EPA ring which is described below.

V. TEST ON AN EXISTING MACHINE

Electron Positron Accumulator (EPA) is a part of the LEP preinjector complex. Operated at 500 MeV, the 126 m long ring provides eight e^- or e^+ bunches with σ_s from 20 to 40 cm. Up to 40 KV is produced with a single 19 MHz cavity.

A higher harmonic n.c. RF cavity (the convenient choices could be 114 MHz PS, 200 MHz SPS or 350 MHz LEP) with a voltage around 1 MV would shorten the bunch to about 1 cm.

An idle 500 MHz s.c. cavity, prototype of a single cell cavity considered in the designs for the B-factory, could provide an additional 3 MV induced voltage that would shorten the bunch further to a few millimeters. Such a cavity would be equipped with an efficient HOM damping system assuring the multibunch stability control. During normal operations, it could be tuned very far from the resonance, lowering the induced voltage to value much less than the main RF voltage.

The broad band impedance in EPA, dominated by the contribution from the kicker magnets, is about 16 - 20 Ω. The added RF cavities will not increase the overall impedance by much. Conversely, with the 1 cm long bunches, the effective impedance should be approximately twenty times smaller than the low frequency limit quoted above.

Already with 1 mA, the induced 3 MV in the idle s.c. cavity, will make the bunch 4 mm long and reduce the effective impedance below the "free space" impedance estimate for EPA. In these conditions, we expect a ratio coherent-to-incoherent synchrotron radiation of about two and it should grow linearly with current. Thus, a test at EPA would provide plenty of signal to check the calculations that take into account the shielding effects of the vacuum chamber [12].

Bunch shortening provided by idle cavities could be preliminarily tested in the CERN SPS: on the one hand, by idling a part of the existing 200 MHz n.c. cavities, in the 300 mA proton beam, on the other hand, by combining this system with the two installed 350 MHz s.c cavities, in the e^- beam. In the first case, the idle n.c. cavities are less sensitive to transient effects; in the second case, the voltage induced in the idle s.c. cavities by the available e^- current of 0.5 mA will remain low compared to the accelerating voltage. However, these experiments should bring much information concerning the practical operation of such a system.

VI. CONCLUSION

A hybrid n.c./idle s.c system is particularly well suited for the needs of $e^-(e^+)$ storage rings or colliders where short bunches together with intense beam are required. The study of its application for two possible future machines, the B-meson factory in the CERN ISR and the Swiss Light Source, did not point out any further difficulties as compared to conventional systems. On the contrary, the additional degree of freedom available, due to the separation of functions, powering and longitudinal focusing of the beam, makes it very flexible.

We propose testing the principle with the existing equipment and the available beams of the CERN SPS as well as in a further experiment at CERN EPA, with a prototype of a 500 MHz s.c. cavity considered in the designs for the B-meson factory.

In addition, the EPA test would permit to study the scaling of the effective ring impedance with bunch length, down to the "free space" limit and to experimentally check the coherent radiation level over a large range of bunch length.

If this system were confirmed to be operational, it could be attractive for a wide domain of other applications.

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