SLS-TME-TA-1998-0012
September 14, 1998

Possible upgrading of the SLS RF system for improving the beam lifetime

Patrick Marchand

PSI

Contents:

Possible upgrading of the SLS RF system for improving the beam lifetime

1. Introduction

For the RF system of the SLS storage ring different alternatives have been considered and compared [1,2]. The solution which was adopted for the starting phase is based on the use of conventional, already well-proven equipment that should be available and operational within relatively short times, compatible with the SLS schedule. It consists of four 500 MHz plants, each comprising a normal conducting (nc) single-cell cavity of the ELETTRA type, powered with a 180 kW CW klystron amplifier via a WR1800 waveguide line.
In spite of the lower power requirement, one similar plant will be used for the booster with the intention of standardizing.
The use of superconducting (sc) cavities has been ruled out as a starting solution. However, combining “HOM free” sc cavities with the initial nc system is regarded as a possible future option for improving the beam lifetime in the storage ring when operating at very high brightness [3]. Either the energy acceptance could be increased using one 500 MHz sc cavity [4,5], or the bunches could be lengthened using one (possibly two) 2nd or 3rd harmonic sc cavity (ies) [6]. Within both schemes, the sc cavities could be operated in an entirely idle mode (no external RF source). A description of this possible further upgrading is reported here.

2. The initial normal conducting RF system

The RF system which was adopted for the SLS starting phase is described in details in [7]. For the storage ring, it consists of four 500 MHz plants, each comprising a nc single cell cavity similar to that used in ELETTRA [8,9], powered with a 180 kW CW klystron amplifier via a WR1800 waveguide line. The cavity input coupler is of the coaxial type, terminated by a coupling loop. For coping with the cavity HOM impedances, the parasitic frequencies will be tuned such that to avoid resonant excitations by the beam. This can be achieved by combining three tuning means [10,11]: temperature control of the cooling water, elastic mechanical deformation and a plunger tuner. In addition, each plant will be equipped with standard amplitude and phase regulation loops.
According to the main ring parameters [12] which are listed in Table 1, one can expect from such a system operating conditions as described in Table 2. These data show that the SLS nominal requirement can be fulfilled with relatively conservative performance levels. Besides, would one of the four cavities be out of use, the operation at full beam current is still possible with an RF voltage of about 2 MV.
In spite of the lower power requirement, a RF plant similar to those of the storage ring will be used for the booster [32] with the intention of standardizing.

3 Possible further upgrading

The SLS brightness could be further improved following different approaches. Unfortunately, this is generally at the expense of a strong reduction in beam lifetime [3,26]. Enlarging the energy acceptance with a significant increase of the RF voltage is one of the possible solutions for recovering the lifetime. Doubling the RF voltage while maintaining relaxed operating performance would require twice the number of nc cavities. Replacing the nc cavities by sc cavities would be another alternative. Instead, complementing the initial nc

system with a fully idle (no external RF source) 500 MHz sc cavity is regarded as a more attractive solution.
Another method for improving the beam lifetime consists of lengthening the bunches with a higher harmonic RF system (1 or 1.5 GHz). Within this scheme, using an idle sc cavity would be also very attractive.

3.1 Superconducting RF cavities

A sc system, as compared to a nc one, has the obvious advantage of limiting the wall dissipation to a negligible amount; it also permits to reach higher accelerating gradient: 10 MV/m in a 500 MHz sc cavity is considered nowadays as a rather common performance and the higher is the frequency, the higher is the achievable accelerating gradient [24,27]. However, the minimum number of needed cavities is essentially dictated by the limitation in cavity input power: typically 100 kW for the systems already operating in other laboratories [13,14,15]. Input couplers, capable of handling higher power, are presently under development at different places [15,16,17]. Nevertheless, due to the huge ratio of beam-to-cavity power, ensuring stable operating conditions remains a critical issue and this involves the use of feedback systems [33]. The proposed hybrid "powered nc and idle sc" system, which is described in the next section should solve the power related problems and allow full profit of the sc cavity accelerating gradient.
Concerning the coupled bunch instabilities, with a sc system there is no other alternative cure than a strong de-Qing of all the cavity HOM resonances. The required amount of de-Qing for the SLS is well above the capability of the existing systems. However, there are different technical approaches presently developed for the B-Factories [15,18,19] or other Light Sources [20,21] which could be applied to the SLS.
More generally, the higher degree of complexity of a sc system makes the design, fabrication and operation more delicate. It is also worthwhile to mention that at PSI there is a lack of expertise in the various fields which are associated to the RF sc technology. The acquisition of this "new culture" together with the development program would be hardly compatible with our time schedule. For these reasons, the use for the SLS of a sc RF system as a starting solution has been ruled out. Nevertheless, we will attentively follow the developments carried out elsewhere on the "HOM free" sc cavities in view of possible further upgrading as described next.

3.2 The hybrid "powered nc and idle sc" RF system

Detailed studies of such a system were previously reported in [22,23] for the bunch shortening case. The basic idea is to separate the functions of the two RF systems in order to optimize their respective performance: the nc system supplies the power for replacing the losses per turn; the beam-driven sc system only contributes to the potential well.

3.2.1 Beam induced voltage in an idle cavity

The power deposited by the beam passing through an idle (no external RF source) cavity is:

$$P_b = V\, I_b \cos\psi = -\, V\, I_b \sin\phi_s = V^2 / (2\, R_s)$$

where, $V = 2\, R_s\, I_b \cos\psi$, is the cavity voltage induced by the beam;

I_b is the beam average current; R_s is the cavity shunt impedance; $\phi_s = \psi - \pi / 2$, is the synchronous phase and ψ is the cavity tuning angle defined as : $\mathrm{tg}\, \psi = 2\, Q\, \delta f / f_r$ where Q is the cavity quality factor and $\delta f = h\, f_o - f_r$; f_o , f_r and h are the revolution frequency, the cavity resonant frequency and harmonic number, respectively. The corresponding phasor representation is shown in Figure 1.

One can also express the beam induced voltage as:

$$V = I_b \sin\psi \,(R/Q)\, f_r / \delta f$$

and if the cavity is detuned sufficiently far from the resonance ($\delta f >> f_r / Q$) , one gets :

$$\psi \approx \pi / 2 \,,\ \ \phi_s \approx 0 \,,\ P_b \approx 0$$

$$\text{and } V \approx I_b \,(R/Q)\, f_r / \delta f \,.$$

The above results point out that the induced RF voltage which is proportional to the beam current can be controlled via the cavity frequency detuning (linear dependence). Note also that the sign of the induced voltage (focusing or defocusing) depends on the direction of the detuning.

A sc cavity with its very high Q is the ideal component for making use of the induced voltage while keeping the beam energy losses at negligible level : assuming a typical R/Q value of 50 Ω * and the SLS nominal beam current (I_b = 0.4 A), one finds that 2.6 MV are induced when the cavity is detuned by 4 kHz at 500 MHz. This amount of detuning - which corresponds to several thousands of sc cavity bandwidths (a few Hz) and remains much smaller than the revolution frequency - well fulfills the required conditions, $\delta f >> f_r / Q$. The induced voltage could be easily maintained even at extremely low current by controlling the detuning, still within the previous limit. The beam power deposited into the sc cavity, equal to the wall dissipation (~ 50 W), is negligible as compared to the radiation losses.

All the above results also apply to a higher harmonic cavity.

Obviously, an idle cavity has to be complemented with another RF system which will provide the power necessary to compensate the beam radiation losses. The beam dynamic equations for such a system are derived in Appendix 1.

3.2.2 Increase of the energy acceptance using a 500 MHz idle sc cavity

If one combines the previously described 500 MHz nc system with an idle sc cavity of same frequency, the total RF accelerating voltage "seen" by the beam can be expressed as:

$V(t) = V_T \sin(\phi(t) + \phi_s)$, where, for $\phi_{sc} \approx 0$ (idle sc cavity),

$V_T = (V_{nc}^2 + V_{sc}^2 + 2\, V_{nc} V_{sc} \cos\phi_{nc})^{1/2}$ and $\mathrm{tg}\, \phi_s = V_{nc} \sin\phi_{nc} / (V_{nc} \cos\phi_{nc} + V_{sc})$.

Figure 2 shows the RF voltages (nc, sc and nc+sc) versus phase in the SLS case with $V_{nc} = V_{sc}$ = 2.6 MV; one gets for the overall RF voltage an amplitude, V_T of 5.2 MV and a synchronous phase, ϕ_s of 6.5°. The associated RF buckets (nc and nc+sc), computed from the beam dynamic equations (Appendix 1), are also shown in Figure 2. As compared to the initial situation with only the nc system, this corresponds to an enhancement factor of 1.6 in terms of energy acceptance. Concurrently, since the sc cavity is here detuned such as to produce additional focusing, the bunches are shortened by a factor of 1.4. Taking into account both effects, the beam life time can theoretically be improved by a factor of about 2.5 [25]. A further reduction might come from the effective lattice acceptance whose final value is expected to be slightly lower than initially anticipated [5,26].

Concerning the Robinson's criterions for the stability of synchrotron oscillations, the presence of the idle sc cavity is beneficial since it reinforces the oscillation damping strength while keeping the instability current threshold unchanged (see Appendix 3).

During the injection, the RF voltage in the sc cavity will build up with the current and the induced transients should always remain quite tolerable. Note also that, during the injection, the detuning of the sc cavity is a free parameter that can be set at will.

---

* 50 Ω is a typical R/Q value for a "HOM free" single cell sc cavity with large beam aperture [15,27].

In the storage regime the RF voltage of the sc cavity is controlled via its frequency tuning system. The stability constraints on this voltage are relatively relaxed since it only marginally affects the beam dynamics which is essentially determined by the powered nc system.
For the operation modes where the lifetime is less critical, the presence of the sc cavity will permit to save a significant amount of the power dissipated in the nc cavities by operating them at reduced voltage and larger synchronous phase.

3.2.3 Lengthening of the bunches using a 2nd or 3rd harmonic idle sc cavity

An alternative method of improving the beam lifetime consists in producing longer bunches with less density. Again, this could be advantageously realized using a hybrid system as described before but with a higher harmonic cavity detuned in the other direction (de-focusing case). Figure 3 shows the RF voltages (nc, sc and nc+sc) versus phase, as well as the associated RF buckets and bunch profiles, in the SLS case with a 2^{nd} harmonic (1 GHz) idle sc cavity. The beam induced voltage of about 1.2 MV, required to have a quasi zero slope over the phase domain covered by the bunch, is obtained with a detuning of 16 kHz (for R/Q ≈ 50 Ω, as before). One finds that the bunches are lengthened by a factor of about four ($\sigma_z \approx 4.\sigma_{zo} \approx$ 15 mm), the energy acceptance is nearly unaffected and the phase acceptance is even enlarged as compared to the single nc system. Consequently, the beam lifetime should be improved by about a factor four as the bunch length. Although the phase acceptance is slightly reduced, quite similar results are obtained with a 3rd harmonic system (see Figure 4). The required voltage of about 0.85 MV at 1.5 GHz is obtained for a detuning of 36 kHz, again assuming a R/Q of 50 Ω.
Concerning the Robinson stability, the condition is more delicate than in the focusing case since the harmonic sc cavity is now detuned such that it contributes to anti-damping. However, provided that its resonant frequency is not set such that it presents a too high impedance at the first satellites of the synchrotron frequency (side-bands), the overall effect should be dominated by the damping coming from the nc system. In principle, this is not a critical issue since the sc cavity naturally has an extremely narrow bandwidth (see Appendix 3).
Although the required performance is fully compatible with the use of a single sc cavity, adding a second one could present significant advantages:

- lower accelerating gradient and cryogenic losses for the same voltage;
- higher voltage capability;
- extension of the operating beam current range down to lower values (doubled detuning for the same voltage and current);
- possibility of applying the two-cavity HOM damping technique developed for SOLEIL [21]; as mentioned before, for coping with the HOM, different approaches could be adopted.

The previous results tend to demonstrate that, in order to improve the beam lifetime of the SLS, the bunch lengthening technique is more efficient than increasing the fundamental RF voltage. Moreover, with the former solution, one can expect a significant amount of Laudau damping - due to the nonlinearity of the RF waveform - which should help in fighting the coupled bunch instabilities. Another benefit is that the resulting decrease in peak current should raise the threshold for single bunch instabilities. Note also that the harmonic cavity could easily be detuned in the other direction shortening the bunches by a factor 1.5, if needed. Furthermore, one could cumulate the benefits of both methods in implementing three idle sc cavities: one 500 MHz and two harmonic cavities. The beam life time would then be theoretically improved by an order of magnitude or alternatively, the bunches shortened by a factor two.

Idle harmonic nc cavities are also being operated in other laboratories [28]. Applied to the SLS case, this solution would require about ten cavities in order to keep at a reasonable level the amount of power to be restored by the main RF system and ensure safe conditions for Robinson's stability (see Appendix 2 and 3). An effective cure to the HOM impedances would have to be found as well and that could be the tuning technique which is used for the 500 MHz system. An alternative idle nc system for the SLS is described in Appendix 3 and the main features of the two versions are compared in Table 3. Although the sc option appears to be more convenient, the idle nc system remains a possible alternative for the bunch lengthening application. Further investigations are needed for weighting up the respective advantages and drawbacks of the nc and sc versions.

4 Conclusions

The nominal RF power and voltage requirement for the SLS storage ring are quite modest and achievable with conventional, already well-proven equipment that can be available and operational within relatively short times. It is planned to use four 500 MHz plants, each consisting of a nc single cell cavity similar to that used in ELETTRA, powered with a 180 kW CW klystron amplifier via a WR1800 waveguide line. The cavity input coupler is of the coaxial type, terminated by a coupling loop. For coping with the cavity HOM impedances, the parasitic frequencies will be detuned to avoid resonant excitations by the beam. This can be achieved by combining three tuning means: temperature control of the cooling water, elastic mechanical deformation and a plunger tuner. In addition, each plant will be equipped with standard amplitude and phase regulation loops.

This system - while operating at relatively conservative performance levels - should be capable of fulfilling the SLS nominal requirement.

The use of superconducting cavities has been ruled out as a starting solution. However, for improving the beam lifetime the initial nc system could be further complemented with idle (no external power source) sc cavities. Within this scheme, the beam power is entirely supplied by the nc system while one takes full profit of the beam induced voltage in the sc cavities. Such a system could be used either to double the fundamental RF voltage with one 500 MHz sc cavity, or to lengthen the bunches by a factor three to four with one (possibly two) 2nd / 3rd harmonic sc cavity (ies). The computer simulations indicate that the latter solution would be more efficient for our purpose. Furthermore, we could cumulate the benefits of both methods in implementing three idle sc cavities: one 500 MHz and two harmonic cavities. This would theoretically result in improving the beam life time by about one order of magnitude and alternatively offer the possibility of shortening the bunches by a factor two.

A priori, the *hybrid "powered nc and idle sc" system* should not pose any special problem. On the contrary, it appears to be particularly flexible and easy to control; moreover, the difficulties related to the transmission of large power through the sc cavities and the associated technological problems are eliminated. The main challenge for the use of a sc cavity in such a high current machine certainly resides in the damping of the parasitic HOM impedances which can drive coupled bunch instabilities. Programs of development aimed at solving this problem, have been launched at several laboratories. We will attentively follow their advancement in view of a possible application in the SLS.

For the bunch lengthening purpose, an idle 3rd harmonic nc system (~ 10 cavities) remains an attractive alternative. Further investigations are necessary for weighting up the respective advantages and drawbacks of the sc and nc versions.

5 References

[1] P. Marchand, RF for Synchrotron Radiation Sources (1.5-2.5 GeV), SLS-Note 6/95, presented at the first RF Workshop of the New European Light Source Projects, Karlsruhe Research Center, October 1995.

[2] P. Marchand, RF system for the SLS, PSI SLS Note 14/96, September 1996.

[3] SLS Design Handbook, Version 30. November 1996, section 2.7.

[4] P. Marchand, Use of an idle superconducting cavity for improving the energy acceptance in the SLS storage ring, PSI SLS Note 19/96, October 1996.

[5] J. Bengtsson et al, Increasing the energy acceptance of high brightness synchrotron light storage ring, NIM A404, p. 237-247, 1998.

[6] P. Marchand, Foils of the SLS MAC meeting, December 1996 and Presentation at the 4th RF workshop of the New European Light Source Projects, Daresbury, UK, April 1997.

[7] P. Marchand, RF System for the SLS Booster and Storage Ring, PSI Note SLS-TME-TA-1998-0011, September 1998.

[8] A. Massarotti et al, 500 MHz Cavities for the Trieste Synchrotron Light Source ELETTRA, Proceedings of the EPAC90, Nice, France, p. 919-921, June 1990.

[9] A. Massarotti et al, The RF System of ELETTRA, Proceedings of the EPAC94, p. 1853-1855, London, June 1994.

[10] M. Svandrlick et al, Improved Methods of Measuring and Curing Multibunch Instabilities in ELETTRA, presented at the EPAC96, Sitges, Spain, June 1996.

[11] M. Svandrlick et al, Simulations and Measurements of Higher Order Modes of the ELETTRA RF Cavities in view of Coupled Bunch Instability Compensation by Temperature Variation, presented at the EPAC96, Sitges, Spain, June 1996.

[12] M. Böge et al, The Swiss Light Source Accelerator Complex: An Overview, presented at the EPAC98, Stockholm, June 1998.

[13] B. Dwersteg et al, Operating Experience with Superconducting Cavities in HERA, Proceedings of the EPAC94, p. 2039-2041, London, June 1994.

[14] S. Noguchi et al, Recent Status of the TRISTAN Superconducting RF System, Proceedings of the EPAC94, p. 1891-1893, London, June 1994.

[15] J. Kirchgessner, Review of the Development of RF Cavities for High Currents, Proceedings of the IEEE PAC, p. 1469-1473, Dallas, May 1995.

[16] M. Pisharody et al, High Power Window Tests on a 500 MHz Waveguide Window for the CESR Upgrade, Proceedings of the IEEE PAC, p. 1720-1722, Dallas, May 1995.

[17] J. Tückmantel et al, Improvements to Power Couplers for the LEP2 Superconducting Cavities, Proceedings of the IEEE PAC, p. 1642-1644, Dallas, May 1995.

[18] T. Tajima et al, Development of HOM Damper for B-Factory (KEKB) Superconducting Cavities, Proceedings of the IEEE PAC, p. 1469-1473, Dallas, May 1995.

[19] W. Hartung et al, Measurement of the Interaction between a Beam and a Beam Line Higher-Order Mode Absorber in a Storage Ring, Proc. of the IEEE PAC, p. 3294-3296, Dallas, May 1995.

[20] A. Fabris et al, Design of a 3rd harmonic superconducting cavity for bunch lengthening in ELETTRA, presented at the EPAC98, Stockholm, June 1998.

[21] A. Mosnier et al, HOM damping in SOLEIL superconducting cavity, presented at the EPAC98, Stockholm, June 1998.

[22] P. Marchand, Hybrid Normalconducting / Superconducting RF System for High Luminosity Circular e+ e- Colliders, Particle Accelerators, Vol 36, Numb. 1-3 (1991), p. 205-222, March 1991.

[23] P. Marchand and L. Rivkin, Idle Superconducting RF Cavities for Bunch Focusing, Proceedings of the IEEE PAC, p. 780-782, San Francisco, May 1991.

[24] E. Kako et al, Thermal quench phenomena on the 1.3 GHz high gradient superconducting cavities, Proceedings of the EPAC96, p. 2124-2126, Sitges, Spain, June 1996.
[25] P. Marchand, SLS: beam lifetime and bunch lengthening versus RF voltage, PSI SLS-Note 17/96, October 1996.
[26] A. Streun, Momentum acceptance and Touschek lifetime, PSI SLS Note 18/97, November 1997.
[27] T. Furuya et al, A prototype module of a superconducting damped cavity for KEKB, Proceedings of the EPAC96, p. 2121-2123, Sitges, Spain, June 1996.
[28] A. Anderson et al, Landau cavities at MAX II, presented at the EPAC98, Stockholm, June 1998.
[29] R.A. Rimmer et al, A third-harmonic RF cavity for the Advanced Light Source, presented at the EPAC98, Stockholm, June 1998.
[30] K. Robinson, CEA-II (1956) and CEAL 1010 (1964).
[31] P. Marchand, Robinson's stability criterion for narrow band resonators in large accelerators and storage rings, CERN/EF/RF 84-5, July 1984.
[32] C. Gough et al, The SLS Booster Synchrotron, presented at the EPAC98, Stockholm, June 1998.
[33] A. Mosnier, RF feedback systems for sc cavities, presented at the EPAC98, Stockholm, June 1998.

Appendix 1

Beam dynamic equations for a double RF system

In presence of two RF systems, an electron at phase ϕ - with respect to the synchronous electron - experiences an overall RF accelerating voltage that can be expressed as:

$$V(\phi) = V_1 \left[\sin(\phi + \phi_{s1}) + a \sin(k\phi + k\phi_{s2})\right],$$

where V_1, $V_2 = aV_1$, $h_1 = h$, $h_2 = kh$, ϕ_{s1}, ϕ_{s2} are the peak accelerating voltage, the harmonic number and the synchronous phase for each system, respectively.
In the particular case of the hybrid "nc powered and sc idle" system one gets:

$$\phi_{s2} = \phi_{sc} = 0,\ \phi_{s1} = \phi_{nc},\ V_1 = V_{nc} \text{ and}$$
$$V(\phi) = V_{nc} \left[\sin(\phi + \phi_{nc}) \pm a \sin(k\phi)\right],$$

where the sign of the 2nd term depends on which direction the sc cavity is detuned (focusing or defocusing).
The electron synchrotron motion can be derived from the Hamiltonian as follows:

$$d\phi / dt = \delta H / \delta W, \quad dW / dt = - \delta H / \delta\phi$$

where $H(W, \phi) = (h\, \alpha\, \omega_o^2\, W^2) / (2\, E) + e\, P(\phi) / (2\, \pi)$,

$P(\phi) = - \int_0^{\phi} [V(\phi) - V(0)]\, d\phi$,

$W = \Delta E / \omega_o$,

ΔE is the electron energy deviation,

$\omega_o = 2\, \pi\, f_o$,

and the other parameters are defined in Table 1.

Since the electron trajectories in the longitudinal phase space (ϕ, W) are contours of constant Hamiltonian, one can compute from the above equations the boundary of the stable region ("RF bucket"), the energy and phase acceptance as well as the equilibrium bunch profile which is given by:

$$I(\phi) = A \exp\left[P(\phi) / (V_1\, \sigma_{\phi o}^{\ 2} \cos \phi_{s1})\right],$$

where A is the normalization constant and $\sigma_{\phi o}$ is the RMS bunch length (in RF phase unit) when only the first system is active ($V_2 = 0$).
It is worthwhile to note that the product of the bunch length and the synchrotron frequency remains constant for any value of the overall RF voltage:

$$\sigma_{\phi o}\, f_{so}\ (@\ V_2 = 0) = \sigma_{\phi}\, f_s,\ (@ \text{ any value of } V_2).$$

The above theory is still applicable to the bunch lengthening case - with nonlinear RF waveform - as far as the RF voltage slope is not too much distorted within the phase domain covered by the bunches; that is valid for the SLS numerical examples shown in Figures 3 and 4. The effect of strong non-linearity on the bunch shape becomes visible if the slope of the RF voltage at the bunch location approaches too much zero, as illustrated in Figure 5. The electron distribution within the bunches is then largely distorted and extremely sensitive to the variations of the RF voltage.

Appendix 2

Harmonic idle nc system for bunch lengthening

For the nc version, we chose a 3rd harmonic system (f_r = 1.5 GHz) that is a quite good compromise between shunt impedance, ratio of wave length over bunch length and equipment size.
The main requirements for the design of the system are the following:

1) the maximum power lost by the beam and to be restored by the main 500 MHz RF system must not exceed P_{max} = 40 kW;
2) the derivative of the overall voltage must be close to zero at the bunch phase;
3) the RF wave-form should not present too much non-linearity over the phase range covered by the bunches;
4) the Robinson stability should be insured for the overall system;
5) the four above conditions must be fulfilled for a stored beam current, I_b ranging between 0.15 A and 0.4 A.

The beam induced voltage and power lost in an idle RF system are (see section 3.2.1):

$$V = 2\, R_s\, I_b \cos\psi = I_b \sin\psi\, (R/Q)\, f_r / \delta f$$

$$P = V\, I_b \cos\psi = -\, V\, I_b \sin\phi_s = V^2 / (2\, R_s).$$

Combining the above equations with requirements 1) and 2) leads to:

$$\tan\psi = 2Q\, \delta f / f_r \geq I_b\, V_1 \cos\phi_{s1} / (k\, P_{max}),$$

$$V \geq P_{max} / (I_b \cos\psi),$$

$$R_s \geq V^2 / (2\, P_{max}).$$

Applied to the SLS case, one finds that the required shunt impedance is about 10 MΩ and then, with this value, conditions 3) and 4) are also satisfied for operation at the full beam current of 0.4 A. Besides, the stability analysis (see Appendix 3) pointed out that another constraint was requirement 4) at the lowest stored beam current: a R/Q value of about 600 Ω is necessary to insure a stable operation at 0.15 A.
In practice, this could be achieved using 10 pill-box cavities similar to that used at MAX II (R/Q ≈ 65 Ω, Q ≈ 15000) [28]. With nose-cone type cavities optimised for higher impedance as in ALS [29], one could reduce the number of required cavities down to 8. In order to cure the HOM problem, the temperature tuning technique could be applied as for the 500 MHz system.
Typical operating parameters for such a system are listed in Table 3 and compared to the sc version. The nc system presents a few drawbacks:

- large number of cavities;
- significant amount of power to be restored by the 500 MHz system;
- any variation of current or cavity frequency leads to a change in power loss which is directly reflected back to the 500 MHz system; troubles could possibly result from this coupling between the two systems through the beam;
- making the harmonic system “invisible for the beam” requires an unpractical amount of detuning;
- slight degradation of the energy acceptance.

These inconveniences are eliminated when using sc cavities.

Appendix 3

Robinson stability for a double RF system

The condition for the stability of coherent electron bunch synchrotron oscillations in the presence of a single accelerating RF system was first derived by K. Robinson [30]. The so-called “Robinson’s criterion” consists in fact of two stability conditions that can be expressed:

a) $i_b < 2\, V \cos \phi_s / (R_s \sin 2\psi)$;

b) $\psi > 0$;

where i_b is the Fourier component of the beam current at the RF frequency (twice the DC component for short bunches), ϕ_s is the synchronous phase; ψ, V, Rs are the cavity tuning angle, peak RF voltage and effective shunt impedance, respectively.

The two stability conditions are naturally satisfied for the 500 MHz system, matched at full beam loading: $\Delta f = \Delta f_m$ and $\beta = \beta_m$ (see Table 2).

The extension of the Robinson’s criterion to a double RF system [22] pointed out that the current limit given by a) is unchanged when adding an idle cavity or, in other words, the first Robinson’s stability criterion is automatically fulfilled for the overall system provided that it is fulfilled for the powered system. This can be interpreted as follows: the restoring force for *coherent* phase oscillations is proportional to the slope of the *RF generator voltage* at the bunch phase (negative for stability); the inequality a) is simply an expression of this condition and consequently it is unaffected by the presence of an idle cavity. Obviously the powered system has to restore the losses in the idle system and the phase, ϕ_s corrected accordingly. While losses are negligible in sc cavities, they can become significant in nc cavities and the resulting phase change may lead to a critical reduction of the stability margin.

Requirement b) means that the detuning must be such as to provide oscillation damping, a condition which is strictly valid for a single system and when neglecting the other sources of damping (radiation damping, Landau damping, …). An idle cavity, detuned in the direction for focusing, naturally contributes to damping and conversely to antidamping for bunch lengthening. In the latter case, the stability will be ensured if the damping from the powered system compensates the antidamping from the idle system. Therefore, the resonant frequency of the harmonic system must not be set so that it presents a too high impedance at the first satellites of the synchrotron frequency ($m*f_s$).

A computer code was written for evaluating the overall damping or growth rate factors in the presence of two RF systems. The computed data are listed in Table 4 for the SLS case with a 3rd harmonic idle system operating in the bunch lengthening regime. These results correspond to the nc and sc versions, as described in Table 3. Note that the incoherent synchrotron frequency of 2.2 kHz assumed here corresponds to a bunch lengthening factor of about 3.5. One can see that in both cases the net effect at the significant side bands is a damping and when antidamping starts for higher values of m the instability growth rate is lower than the radiation damping rate by several orders of magnitude. The stability is easily ensured in both cases with full stored beam current. Although the conditions become less favorable - especially for the nc system - when maintaining the same voltage at lower stored beam current (smaller detuning), the stability is always ensured down to 0.15 A* . Below this value, in the nc case the growth rate of modes m = 1 and m = 2 approaches the radiation damping rate. In the sc case, the resonant excitation of one side-band could lead to trouble, even at relatively large values of m; on the other hand, due to the extremely narrow bandwidth, this is

---

* Provided that the R/Q value is larger than 600 Ω in the nc case.

easy to avoid: changing the cavity frequency by a fraction of a kHz should be sufficient to re-establish stable conditions without affecting too much the operating parameters.

We assumed here - as usually - that the instability growth rate was proportional to the real part of the impedance. While this is certainly valid for the nc case, it could be slightly different for a sc cavity of very high Q, due to a possible “broadening process” as described in [31]. This effect - which in principle shall act favorably - should not affect too much the preceding results.

Note that the addition of a second sc cavity would improve the conditions for the operation at reduced beam current (doubled detuning at same voltage and current) and also offer a few other advantages (see section 3.2.3).

Revolution frequency, f_o [MHz]	1.04	
Momentum compaction, α	7. E - 4	
Beam current, I_b [A]	0.4	
Energy, E [GeV]	2.4	
Radiation loss / turn, ΔU [MeV]	0.6	
Momentum spread, σ_p [%]	0.09	
Longitudinal damping time τ_s [ms]	4.5	
Transverse damping times, $\tau_x \approx \tau_y$ [ms]	9.	
RF frequency, f_{RF} [MHz]	499.652	
Harmonic number, $h = f_{RF} / f_o$	480	
RF power into the beam, P_b [kW]	240.	
RF voltage, V_{RF} [MV]	2.0	2.6
Overvoltage, q	3.3	4.3
RF acceptance, ε_{RF} [%]	± 3.0	± 3.7
Bunch length, σ_s [mm]	4.4	3.8
Synchrotron frequency, f_s [kHz]	6.8	7.8
Synchrotron tune, $Q_s = f_s / f_o$ [E-3]	6.5	7.5
Synchronous phase, ϕ_s [degree]	17.5	13.3

Table 1 : Basic parameters for the SLS storage ring.

I_b [mA]	V_{RF} [MV]	P_d (1c) [kW]	P_b (1c) [kW]	P_t (1c) [kW]	β_m	Δf_m [kHz]	nb of cav.
400.	2.0	37.	60.	97.	2.6	32.	4
400.	2.6	60.	60.	120.	2.0	27.	4
400.	2.0	65.	80.	145.	2.2	24.	3

Table 2 : SLS possible operating conditions with 4 or 3 (out of 4) nc cavities in use.

- V_{RF} is the accelerating voltage “seen” by the beam (transit time factor included);
- P_d (1c), P_b (1c) and P_t (1c): wall dissipation, power delivered to the beam and total RF power per cavity;
- β_m, Δf_m : optimum coupling factor and detuning (zero reflected power at full beam current).

	idle nc sytem	idle nc system
f_r	1.5 GHz	1.5 GHz
n_{cav}	8 - 10	1
$R_s * n_{cav}$	10 MΩ	7.5 GΩ
Q_o	15000 - 20000	1.5 E8
V	0.85 MV	0.85 MV
P_d	36 kW*	50 W
I_b	0.4 A	0.4 A
ϕ_s	6 °	~ 0 °
δf	470 kHz	35.3 kHz
ε_{RF}	3.45 %	3.65 %
σ_z	15 mm	15 mm
f_s	2.2 kHz	2.2 kHz

Table 3

3rd harmonic idle RF system for bunch lengthening: typical operating parameters (nc and sc versions).

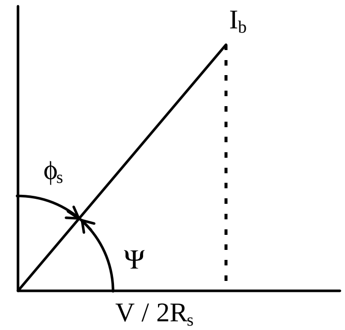
* Power to be restored by the 500 MHz system ($\Delta\phi_s$ of 2°).

mode number ($m*f_s$)	τ_{nc} / τ_{rad} (@ I_b = 0.4 A)	τ_{sc} / τ_{rad} (@ I_b = 0.4 A)	τ_{nc} / τ_{rad} (@ I_b = 0.15 A)	τ_{sc} / τ_{rad} (@ I_b = 0.15 A)
m = 1	D	D	D	D
m = 2	D	D	0.3	D
m = 3	3.5 E -3	D	0.1	D
m = 4	8 E - 4	D	6 E - 3	3 E - 4
m = 5	4 E - 5	5 E - 7	3 E - 4	5 E - 5

Table 4

Ratio of the instability growth rates over the radiation damping rate for the nc and sc cases as defined in Table 3 at two values of the beam current (“D” is for Damping).

Figure 1 : Phasor representation of the beam induced voltage in an idle cavity.



$V = 2\ R_s\ I_b \cos\psi = I_b \sin\psi\ (R/Q)\ f_r / \delta f$;
$P = V\ I_b \cos\psi\ = -\ V\ I_b \sin\phi_s\ = V^2 / (2\ R_s)$;
$\phi_s = \psi - \pi / 2$;
ϕ_s is the synchronous phase;
ψ is the cavity tuning angle defined as:
$\mathrm{tg}\ \psi = 2\ Q\ \delta f / f_r$.

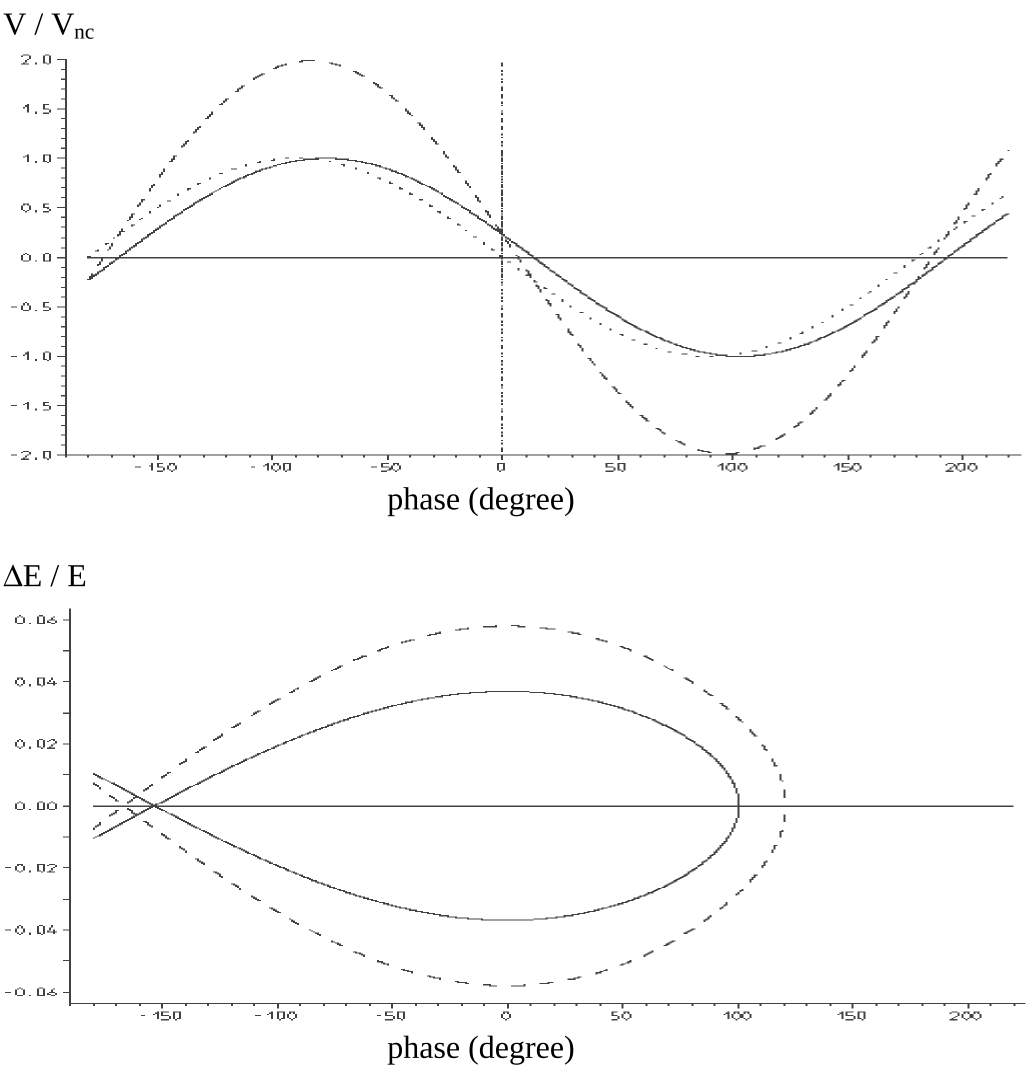


Figure 2 : Normalised voltages (nc, sc, nc+sc) versus phase and "RF buckets" (nc and nc+sc) for $V_{nc} = V_{sc} = 2.6$ MV and $f_{nc} = f_{sc} = 500$ MHz.

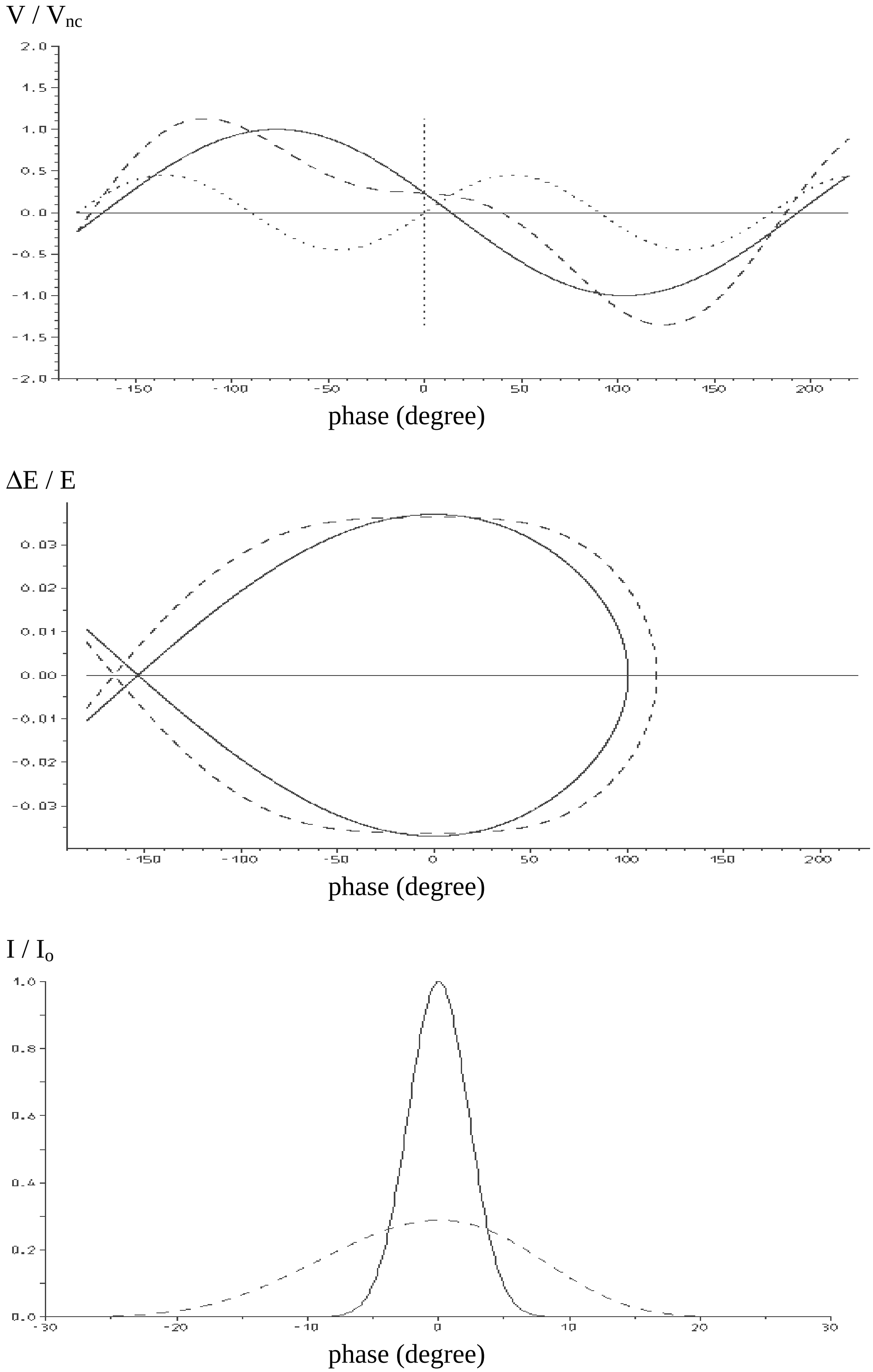


Figure 3 : Normalised RF voltages (nc, sc, nc+sc) versus phase, “RF buckets” and bunch profiles (nc, nc+sc) for V_{nc} = 2.6 MV, V_{sc} = 1.2 MV and $f_{sc} = 2.f_{nc}$ = 1 GHz.

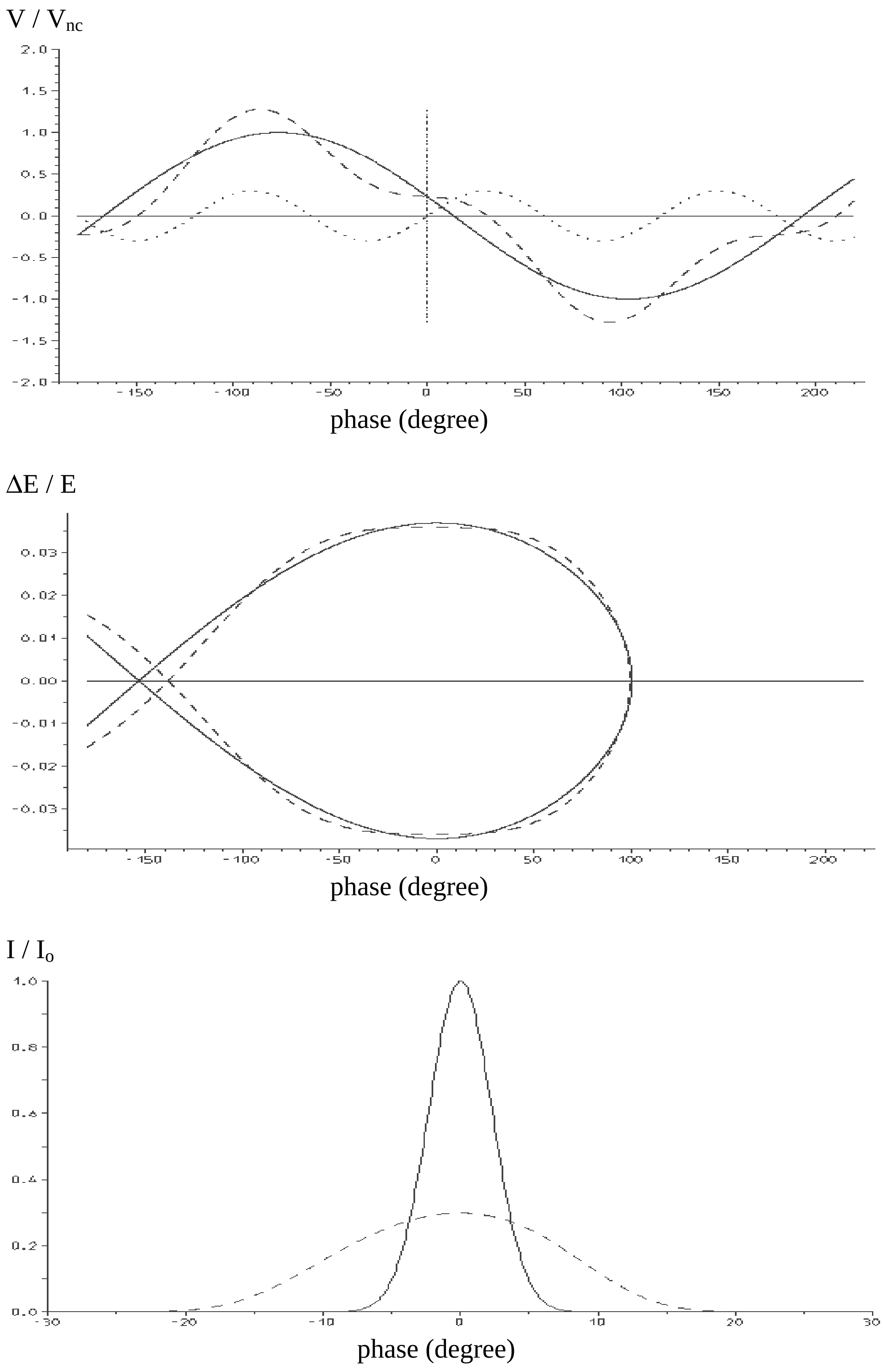
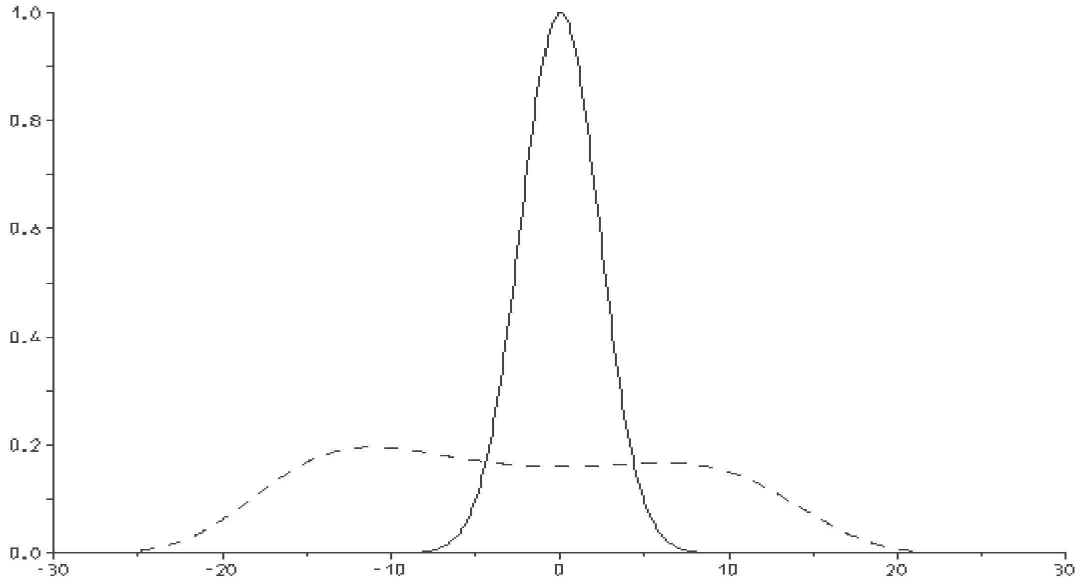


Figure 4 : Normalised RF voltages (nc, sc, nc+sc) versus phase, "RF buckets" and bunch profiles (nc, nc+sc) for V_{nc} = 2.6 MV, V_{sc} = 0.8 MV and $f_{sc} = 3.f_{nc}$ = 1.5 GHz.

I / I_o



phase (degree)

<u>Figure 5</u> : Distortion of the bunch profiles due to strong non linearity of the RF voltage (V_{nc} = k*V_{sc}).