EFFECT OF VACUUM CHAMBER TAPERING ON IMPEDANCE BUDGET IN STORAGE RINGS

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Abstract

It is well-known that wakefield effects due to steep vacuum chamber transitions can be decreased by tapering the steps with small angles. However, even very long taper transitions can give rise to harmful high frequency resonators and contribute to the microwave instability. Time domain calculations were carried out on various transitions, like the ones needed at both ends of RF accelerating cavities or insertion devices. The effects of these tapers on longitudinal dynamics are found sizeable and results are discussed in the case of the SOLEIL storage ring light source.

1 INTRODUCTION

With the aim of estimating the overall impedance of the vacuum chamber of storage rings, the effects of reduction or enlargement of the beampipe diameter were first studied. Large jumps in transverse size originate mainly from insertion devices and accelerating structures. Whereas the former give rise to pipe reduction and behave mostly like inductive collimators, the latter give rise to pipe enlargement and lead to significant resistive impedance. Since the SOLEIL insertions are nearly axisymmetric, simulations have been carried out with the time domain code NOVO [1], which can compute accurately and very quickly, even with very long tapers. Lastly, the effect of the cavity assembly, terminated in long tapers at both ends, on the threshold of the microwave instability was calculated from the point-like wake potential.

2 INSERTION DEVICES

We consider first the transition of the beampipe to insertion devices, which will be installed on 13 straight sections of the SOLEIL storage ring. The cross section of the vacuum chamber - octogonal through the quadrupoles and rectangular through the insertion devices - has been modelled by a round symmetric beampipe, with a variation of the radius from b=12.5 mm to a=6.5 mm. The wakefield effects are usually decreased by tapering the transition with a small angle. In our case, the length of the taper was chosen equal to 100 mm, giving a taper angle of about θ=3.4°.

The interaction mechanism has been abundantly analysed (see [2-4] for instance) and is brievely recalled below. If we drop the energy gain of a bunch entering a narrowing pipe ('step-in') or the energy loss of a bunch exiting into a broadening pipe ('step-out'), due to the change of the self-field moving with the bunch (the 'Log term' of pipes of different radii), we can directly compare the impedances of the two steps (in and out) and when they are linked together. For long enough bunches ($\sigma > a/\pi$), i.e. for frequencies below the cut-off frequency, there is no outgoing waves and the impedance is hence purely inductive, given approximatively by

$$L \approx \frac{\mu_o}{4\pi} \frac{(b-a)^2}{l}$$

For time domain calculations with the code NOVO, a bunchlength of 1 mm and a step-size smaller than 0.1 mm were chosen, in order to get a high enough frequency bunch spectrum and to get rid of step corner effects at high frequency. The wakefield is calculated over 200 mm behind the bunch to achieve a proper frequency resolution. Separate calculations for isolated "taper-in" and "taper-out" transitions gave rigourously identical results, when the 'Log-term' is omitted, as expected. The real and imaginary parts of two times the impedance of a single transition (taper-in or -out) are shown on Fig.1 (solid and dashed thick lines). At low frequency, the impedance is purely inductive and the inductance, inferred from the slope at the origin, is 0.046 nH per transition, in agreement with the previous formula, about 30% larger. A resistive component appears clearly for high frequencies (above 20 GHz), also in agreement with the previous condition.

The cross-talk between the two inverted transitions of the insertion device was last studied, by varying the length of the connecting tube. Interferences tend to modify slightly the wakefield effects and the minimal distance, above which the total loss factor is constant (k=0.325 V/pC) is about 200 mm. The impedance of the two transitions, linked by a 300 mm long pipe, is also shown on Fig.2 (thin lines) and is exactly the sum of the impedances of both separate tapers at low frequency. However, resonant modes are excited at higher frequency and add up to the inductive impedance, even when the transitions seem "independant". Of course, if the beampipes were interchanged (larger diameter for the connecting tube and smaller diameter for the end-tubes), the resonances would have been more pronounced. One can conclude that the net effect of these 13 pairs of transitions on the longitudinal dynamics of the SOLEIL ring is not significant: inductive impedance smaller than Z/n = 6.5 mΩ (roughly half this value if we take into account the azimuthal filling factor) and resonances at very high frequencies only.

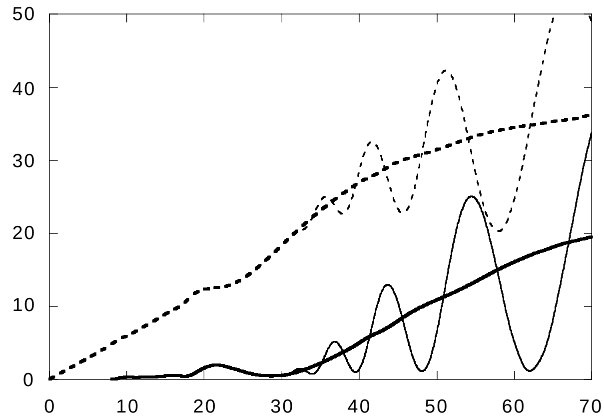

Fig.1 : Real (solid lines) and imaginary parts (dashed lines) of the impedance (Ω) for two isolated (thick) and connected (thin) transitions vs. frequency (Ghz).

3 CAVITY ASSEMBLY

However, the situation is less favourable for the RF accelerating system, which must include a pair of transitions of much larger beampipe reduction, with the pipe of biggest diameter in-between. As we will see, the wakefields are actually dominated by the transitions and not by the cavities.

Two superconducting 350 MHz cavities are presently developed [5] to provide an rf voltage of 4 MV and a power of 400 kW to the beam. A single cryostat contains both cavities, a large middle beamtube of around $3\lambda/2$ length and of 200 mm radius, and two end-tubes of smaller 130 mm radius. Finally, two 500 mm long tapers (limited by space) form the transitions between the radius b=130 mm of the cavity tube and the radius a=15 mm of the ring vacuum chamber. The three structures, the sole cavities (a), the sole transitions (b) and the total assembly, cavity with transitions (c), have been separately studied and are drawn on Fig.2. The total length of the cavity assembly is about 5 meters.

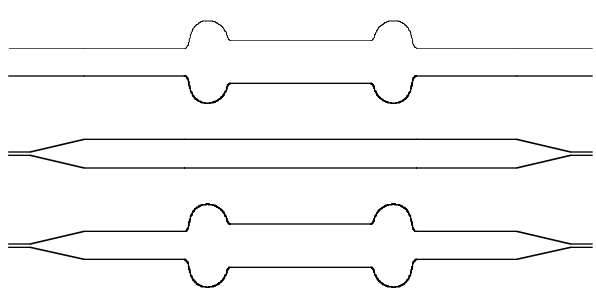

Fig.2 : Geometry of the 3 structures, the sole cavities (top), the sole transitions (middle), the cavities with tapers (bottom).

The wake potentials for the SOLEIL design bunchlength of 4 mm are plotted on Fig. 3 for the 3 structures. We notice that the wake induced by the sole tapers is very close to the wake induced by the total assembly, the cavity contribution being very weak. Besides, from the wake behaviour (delta function most of the bunch duration with small reflection at the tail) we can infer that, at these frequencies, the bunch experiences mainly the resistive component with a small inductive component of the impedance.

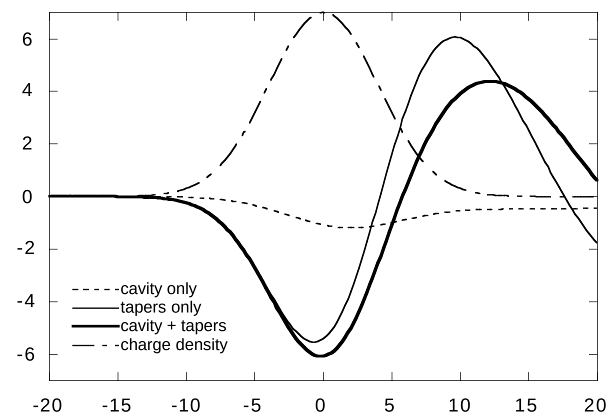

Fig.3: Wake potentials (V/pC) along the 4 mm bunch (mm) for the 3 structures.

Since the lossfactors are roughly inversely proportional to the bunchlength and to the quare root of the bunchlength for cavity and transitions, respectively, we expect a negligible cavity contribution below some small bunchlength value. The computed lossfactors, given on Fig. 4 for bunchlengths between a few tenths of mm to 10 mm, show that the lossfactors, induced by the tapers and by the total assembly, are practically superimposed below a bunchlength of around 3 mm.

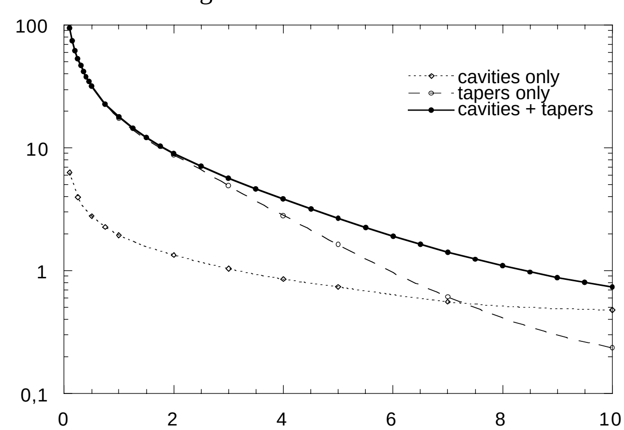

Fig.4 : Lossfactors (V/pC) vs. bunchlength (mm) for the 3 structures.

The impedances for the sole tapers were computed, separately and with the big connection tube, from wakefields induced by a 1 mm long bunch (up to 200 mm behind). Contrary to the transition of the insertion device (Fig.1), the impedance is inductive only at very low frequency and a finite real part comes very soon. Once both tapers are connected, the strong crosstalk (cavity-like behaviour) induces resonances at low frequencies, with a large broadband resonance at 10 Ghz.

Lastly, Fig.5 shows the net impedance of the total assembly (cavities with tapers). Small and sharp resonances rise from the cavities at low frequency, but the general behaviour is dictated by the tapers: large broadband resonance around 10 GHz and constant resistive component at higher frequencies.

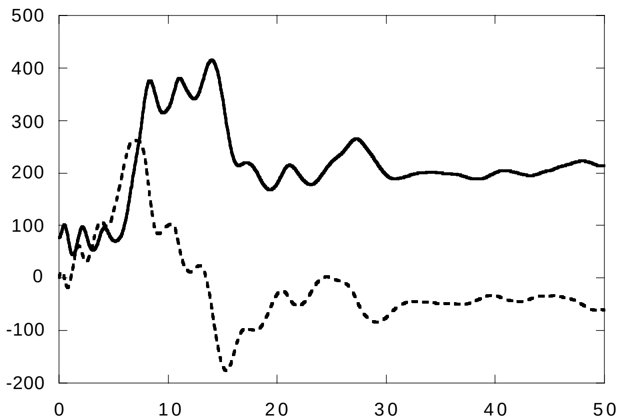

Fig.5 : Real (solid line) and imaginary part (dashed line) of the impedance (Ω) for the total assembly (cavities + tapers) vs. frequency (Ghz).

4 MICROWAVE INSTABILITY

With the aim of appraising the effect of the cavity assembly impedance on the bunch-lengthening and the microwave instability threshold, tracking simulations for the SOLEIL ring were carried out. However, microwave instability studies require the knowledge of the point-like wake function at very short distance (about one order of magnitude smaller than the natural bunchlength of 3.6 mm), while time-domain wakefield codes provide bunch wake potentials for bunches of finite distribution. Moreover, it is unreasonable to consider bunchlengths much smaller than 1 mm for a structure of total length 5 m ! The point-like wake was then inferred from a fit of the lossfactors, computed for different bunchlengths. When the lossfactor, as a function of σ, can be splitted up into a sum of exponantial functions, the delta-wake is then also a sum of exponential functions of the distance s.

$$k(\sigma) = \sum a_n \sigma^{\alpha_n} \quad \Rightarrow \quad W(s) = \sum a_n F(\alpha_n) s^{\alpha_n}$$

with $F(\alpha_n) = \sqrt{\pi}\, 2^{1-\alpha_n} \big/ \Gamma((\alpha_n + 1)/2)\,, \quad \alpha_n < 0$

Five terms were sufficient to fit perfectly the total lossfactor curve of Fig.4 between 1 and 10 mm and to calculate precisely the wake at short distance from the previous expression. The validity of the reconstructed wake was checked by comparing the results of convolutions with gaussian charge distributions with the bunch wakes computed directly with the NOVO code.

Numerical simulations, performed with the parameters of the 2.5 GeV SOLEIL ring and using **only** the wake of the cavity assembly (tracking of 400,000 particles), revealed a threshold around 40 mA. Fig.6 shows the evolution of the relative rms bunchlength (top) and energy spread (bottom) as a function of the number of turns, when the current is first linearly increased from 0 to 50 mA before the flat-top starting at turn 10,000. A sudden energy widening can be observed before the final current. The charge density is plotted on Fig.7, showing a bunch more populated at the head, due to the resistive character of the impedance. Finally, a broadband resonator (R=450Ω, Q=2) with a center-frequency of 11 GHz gave very similar results.

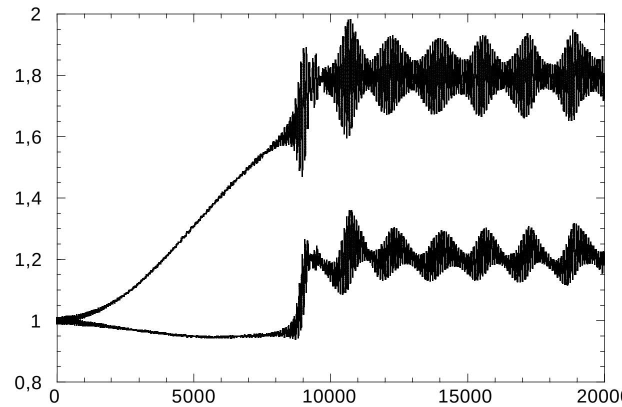

Fig.6 : Evolution of the relative rms bunchlength (top) and energy spread (bottom) for a current of 50 mA (flat-top at 10,000 turns).

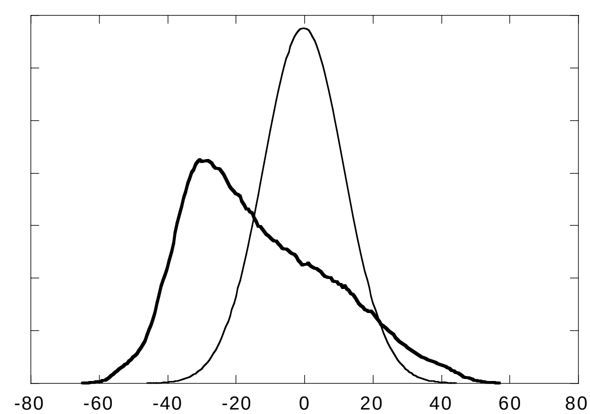

Fig.7 : Initial gaussian (thin) and final (thick) charge densities at 50 mA.

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