*Particle Accelerators*, 1995, Vol. 51, pp. 53–61
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# LOW IMPEDANCE VACUUM CHAMBERS

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*(Received 15 December 1995; in final form 14 June 1995)*

The impedance of vacuum chambers has for long been the subject of many theoretical and experimental investigations. After impedance issues have been properly addressed by accurate three dimensional wake field computations, beam dynamics simulations showed that the effects of impedance of the vacuum chamber in $e^+e^-$ storage rings can be very important for both single bunch and multibunch operation. Comparison with measured data have proven that the impedance can be predicted rather accurately.[1] We analyze here a method to suppress the impedance of pumping slots in vacuum chambers by orders of magnitude by applying models and numerical computations with MAFIA.[2] While basically simple, the scheme of *hidden slots* is extremely efficient in suppressing both narrow-band and broad-band impedances by orders of magnitude. This technique was first used in the design of the HERA electron ring vacuum chamber components.[3] Although developed for $e^+e^-$ accelerators, the same technique may be used to suppress the impedance in high current proton machines such as the LHC.

KEY WORDS: Impedance, instabilities, vacuum chambers

## 1 LOW IMPEDANCE SLOTS – THE BASIC PRINCIPLE

Investigation of vacuum chamber impedances is a never ending subject in accelerator design and many different approaches can be found in the literature. The two main approaches are either by numerical solution of Maxwell's equations e.g.[2,4–6] or analytical methods introducing in or the other way a perturbation technique e.g.[8–10]

It is known that the transverse electromagnetic field of an ultra relativistic bunch of charged particles in an infinitely long vacuum pipe of constant cross section is solution of a simple two dimensional Poisson equation for a scalar potential.[5–7,11]

Wake fields are excited whenever the cross section of a pipe changes. We assume that the strength of these parasitic wake fields is proportional to the transverse electric field strength facing the discontinuity. Thus one obvious method to lower these wake fields and the impedance is to *hide* discontinuities from the primary beam electromagnetic field.

In order to describe the technique of *hidden slots*, we will demonstrate here the effects for a generic vacuum chamber, which was used to study the effects of the slots and their particular dimensions in the context of the PEP-II[12] project.

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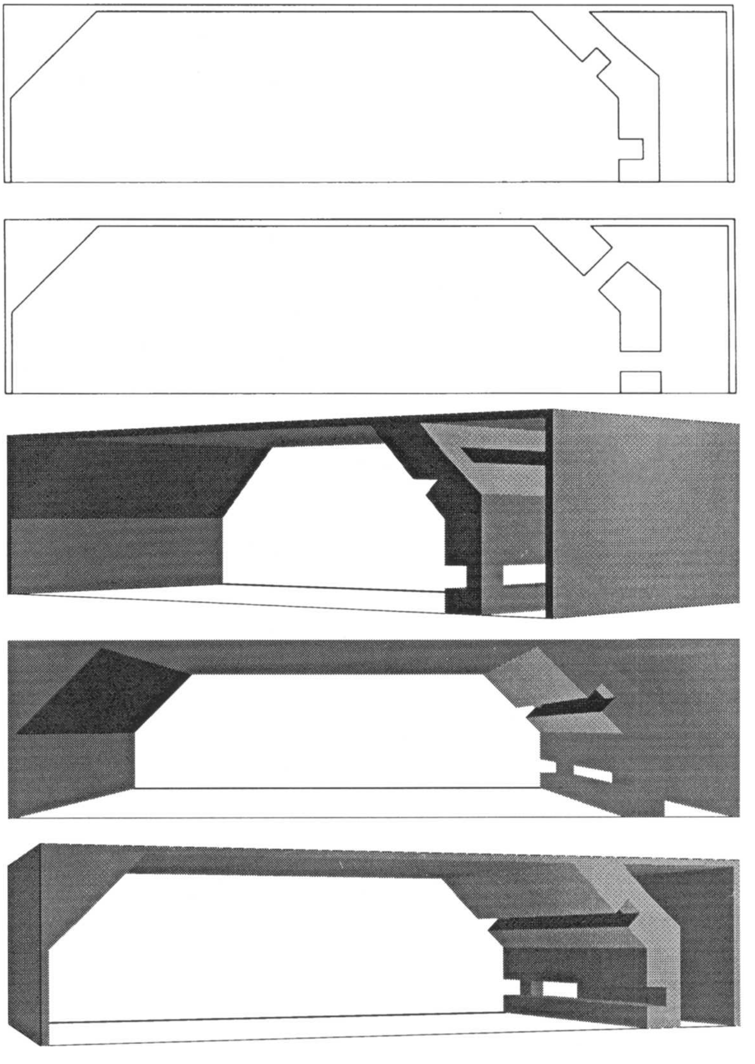

FIGURE 1: Cross sections and three dimensional views of a generic vacuum chamber with *hidden slots*. Four pumping slots connect the beam chamber with a side chamber. The side chamber houses vacuum pumps. For the purpose of impedance analysis the pumps are replaced by a conducting wall. The upper plot shows the cross section at the center of a hidden slot. The lower plot shows the cross section in the middle between two slots. The slots seen from the pumping chamber appear as ordinary slots. From the beam chamber side the slots are seen only on the bottom of a valley. Unless stated otherwise we use the following dimensions for our numerical analysis: chamber width 9 cm, chamber height 5 cm, groove depth 6 mm, groove width 6 mm, slot length 4 cm and slot width 6 mm.

The geometric size of the generic chamber used here for demonstration purposes is very similar to most chambers used in other large scale $e^+ e^-$ storage rings, such as PETRA, PEP, LEP and HERA-$e^-$.

The basic idea is to move the location of wake field excitation from the inner surface of the chamber downwards into the slot. Or in other words, the goal is to avoid strong transverse electromagnetic fields facing longitudinal discontinuities.

For demonstration purposes we assume that the location of excitation is moved just half way from the inner surface of the chamber down towards the end of the slot in horizontal direction.

As a result of deepening the slots, the fields of the beam will not be able to reach down into the groove where the slots begin to interrupt the longitudinal wall currents from flowing. However, it is assumed here that the length of the groove is infinite or very long compared to the length of one slot so that the effects of the beginning and ending of the groove can be neglected. Figure 1 shows a generic vacuum chamber with the actual slots moved from the inner surface down into the groove.

There are three possible ways to approach the analysis and to estimate the possible reduction in overall impedance. These will be discussed in the following.

### *1.1 A simple analytical model*

The transverse electromagnetic field in an infinitely long vacuum chamber of constant cross section is a solution of a Laplace equation for a scalar potential.[5–7,11]

If we assume that the wake field of discontinuities is proportional to the field at the location of the discontinuity, we can estimate the effect of hiding the slots by estimating the field strength being solution of a Laplace equation.

Let us consider the slot region only. For a width $w$ and a coordinate system $(x, y)$ at the beginning of the slot, the solution for the scalar potential inside the slot can be expressed as

$$\Phi(x, y) = \sum_n a_n \phi_n(x, y),$$

with $a_n$ as unknown coefficients and

$$\phi_n(x, y) = e^{-n\pi x/w} \sin(n\pi y/b),$$

as solution of

$$\Delta\phi = 0,$$

$$\vec{E} = -\nabla\phi.$$

We (over-)estimate the field at a depth equal to the width ($x = w$) by taking only the first element of the sum into account. This yields a reduction factor of:

$$e^{-\pi} = 0.043.$$

The wake field is in fact lowered by this factor squared, thus approximately by **536**, for the following reasons. The wake potential in the transverse plane for any given position $s$ inside the bunch is also a solution of a Laplace equation with $s$ as parameter:[5–7,11]

$$\Delta_{xy} w_{\|}(x, y, s) = 0$$

with

$$w_{\|}(x, y, s) = w^{*}(x, y, s)$$

on the boundary.

Thus the Green function can be applied twice in this model, once for the reduction in field generation and a second time for the effect of electric field created at the boundary on the beam sitting in the middle of the chamber.

### *1.2 Electrostatic model*

A more accurate modeling of the situation may be obtained by actually calculating the detailed electrostatic field distribution in a chamber with infinitely long slots. Such a refined model requires a two dimensional electrostatic field solver as it is part of MAFIA.

The horizontal field in the middle of the lower slot (Point **C**) is 40 times lower than on the inner surface of the chamber if there were no hidden slots (Point **A**) and 17 times smaller as the horizontal field in the entry of the valley (Point **B**), see Figures 2 and 3. Thus this model predicts a gain of $17^2$ up to $40^2$ assuming that the wake field is proportional to the field facing a discontinuity.

### *1.3 Electromagnetic model*

Finally, the true answer is obtained by solving the fully electromagnetic problem in time domain for obtaining the wake potential. Figure 4 shows these two wake potentials. As can be seen, the shape of the wake potentials is almost identical, in fact within a percent level. However, the amplitude is drastically reduced as expected by (accidentally) exactly a factor of 1000.

A narrow-band analysis by means of the periodic eigenmode analysis module in MAFIA for traveling wave periodic solutions in frequency domain yields a set of synchronous modes and their associated coupling impedances. By comparing the coupling impedance with and without hidden slots we find exactly the same reduction factor.

Thus the overall impedance is lowered by three orders of magnitude, if the chamber were infinitely long.

In a real machine, the chamber is of finite length and the slot hiding valley must begin and end at some place, reducing the overall reduction factor.

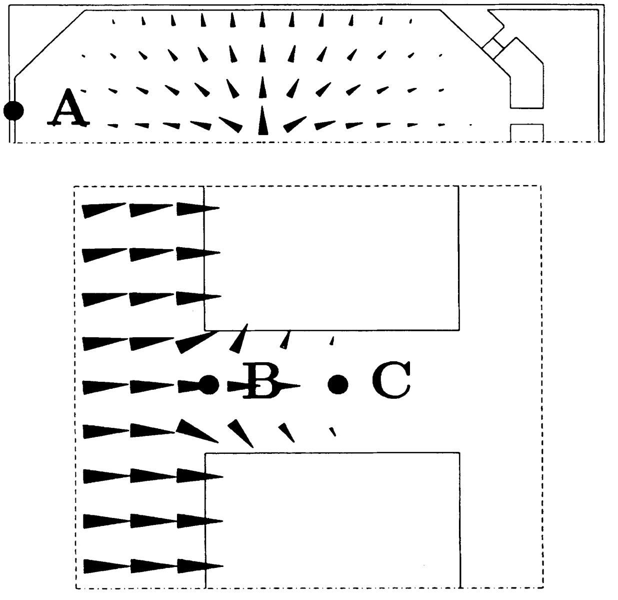


FIGURE 2: Transversal electrostatic field of a beam in the vacuum chamber with hidden slots in logarithmic scale. Note the exponential decay of the field in the inner slot region.

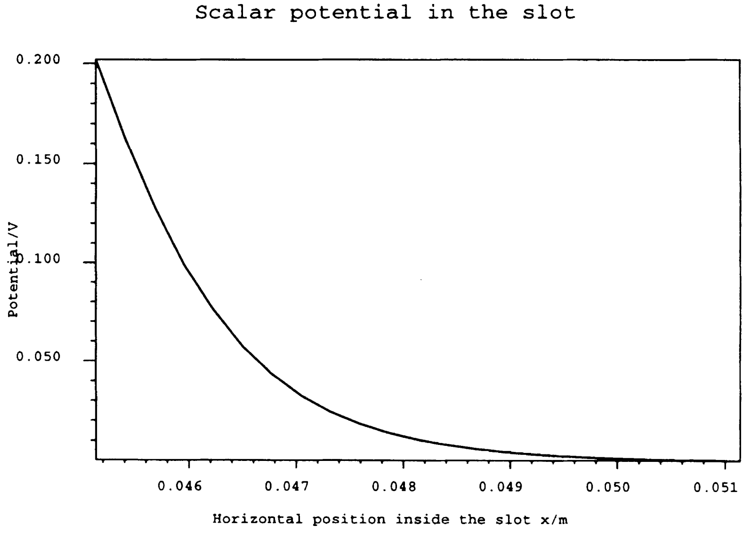


FIGURE 3: The nearly exponential decay of the scalar potential inside the slot. The slot width was chosen to 6 mm.

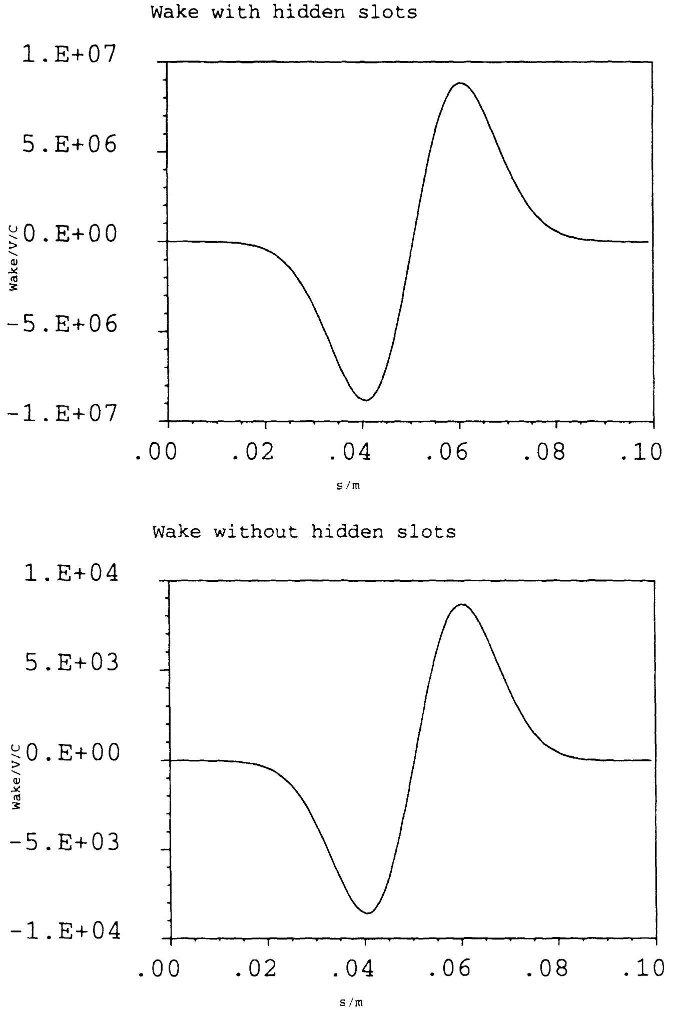


FIGURE 4: Longitudinal wake potential of a normal vacuum chamber section with visible slots (top) and one with hidden slots (bottom) showing the almost identical shape and reduction in amplitude by three orders of magnitude. The chamber dimensions are: chamber width 9 cm, chamber height 5 cm, groove depth 6 mm, groove width 6 mm, slot length 4 cm and slot width 6 mm.

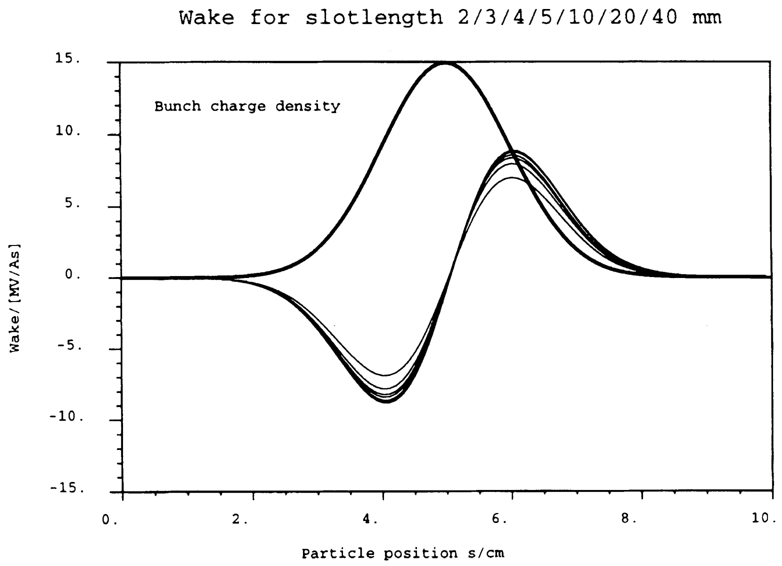


FIGURE 5: The wake potential for different lengths of the slot. The bunch charge density (fat line) is plotted for reference. It is seen that the wake potential converges very rapidly with the slot length.

## 2 IMPEDANCE OF A FINITE LENGTH CHAMBER

The impedance of a long chamber with $N$ slot sections will not be reduced by the ideal factor observed before because the slot hiding groove is itself a long slot that begins and ends near the ends of the real chamber. Thus the question remains how the impedance of such a long slot changes with its length.

Figure 5 shows the wake potential for various slot lengths. As can be seen, when the length is greater than a few centimeters, the impedance stays constant. The physical picture confirms this result. Once the wall currents have overcome the changes at the beginning of the long slot, no wakes are generated until the end of it. This effect is known from earlier computer simulations[13] and semi-analytical models.[10]

In a chamber with $N$ hidden slot sections the total impedance will thus be the summation of the $N$ hidden slots and the groove as one long slot. For these parameters and geometries we thus obtain a reduction factor $R$:

$$R = \frac{N}{1 + \dfrac{N-1}{1000}}.$$

For chambers of 5–10 m length and slots of 5–10 cm length the reduction still remains of the order of 100 or higher if the two unavoidable ends were smoothly tapered.

## 3 SUMMARY

The technically simple technique of *hiding* discontinuities in a vacuum chamber is explained by simple models and exact computations. The overall reduction in impedance may be as large as several orders of magnitude. This new technique was first used in the design of all critical components in the vacuum system of the HERA electron ring. The price to pay is an increase in manufacturing cost and a decrease in mechanical stability.

Although *hidden slots* reduce the beam impedance, they do not reduce radiation from TE-like fields excited by other objects in the ring by the same amount. For shielding other than directly beam excited fields from the pumps, the slot length must be kept short. Short slots would increase the total impedance but on the other hand they do this on a level orders of magnitude lower than in ordinary chambers. Thus *hidden slots* not only allow to reduce the beam impedance but also allow (indirectly) effective shielding of the pumps from TE and TM-like radiation by allowing shorter slots.

## ACKNOWLEDGEMENTS

This work was started during my sabbatical at the Stanford Linear Accelerator Center in the context of the PEP-II project. The author wishes to thank all members of the ATSP group for making this period very comfortable and productive. Cho Ng deserves my thanks for many helpful discussions and careful reading of the manuscript.

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