ELECTROMAGNETIC DESIGN OF THE HERA e^- VACUUM SYSTEM.

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Abstract

The most serious limitation of the current in a single bunch in large e^- and e^+ linacs or storage rings is due to transverse single bunch instabilities that are the result of the beam-environment interaction. Such interaction is proportional to the number of particles in the bunch and is mainly caused by changes in the cross section of the vacuum chamber along the accelerator. For long bunches the corresponding transverse impedance is generally localized in the cavities. For short bunches, however, the contributions from small discontinuities of the vacuum chamber become more and more significant; and this can become the dominant part of the transverse impedance for large machines. To minimize this part in the HERA e^--ring, we have used the 3-D version of BCI of the MAFIA group of codes to design and redesign several components of the vacuum system, such as vacuum chamber junctions and various parts of the vacuum chamber. By designing according to these computations, we were able to keep the contribution of the entire vacuum system below that due to the accelerating cavities.

INTRODUCTION

Why electromagnetic design of the vacuum system? For many years computational tools have been used in accelerator physics to design and optimize r.f. structures, mainly cavities [1]. In the beginning, the main design goal was only to maximize the shunt impedance of the accelerating mode in order to lower the necessary power input for a required gradient; however it became more and more evident that parasitic collective effects caused mainly by the cavities led to serious limitations in achieving the maximum possible beam current. For PETRA, it was found that this limitation was given by a transverse single bunch instability due to beam environment interaction [2,3]. To understand this phenomenon, we have to consider a bunch of charged particles passing an accelerator structure. Each change in the cross section of this structure excites electromagnetic fields, whose strength is proportional to the number of particles inside the bunch. The corresponding Lorentz force consists of decelerating and deflecting components, which will act back on the particles inside the bunch. While the first component is responsible for an energy spread of the bunch, the second one simply kicks the particles in the transverse direction which can lead to a blow up of the bunch. The calculation of this effect requires the solution of Maxwell's equation in the time domain. This was done by the TBCI [4,5,6] program, which is used to minimize the deflecting forces for cylindrically symmetric structures. Beside this, a lot of effort was made for PETRA to localize so-called 'missing' transverse impedance (corresponding to these deflecting forces) to explain the fundamental head-tail mode tune shift [6]. Due to the fact that contributions of the cavities agreed with the measurements only for longer bunches, we concluded that for shorter bunches, the transverse impedance was no longer localized within the cavities, but that small discontinuities of the vacuum chamber became more and more dominant. For example, for Gaussian bunches with a rms length of around one centimeter, the contribution from 60 cavities had the same order of magnitude as the contribution from 232 vacuum chamber junctions in PETRA. This was the starting point for the development of 3D-BCI [7] (member of the MAFIA [8,9] code family), because most of the components which must be examined no longer have cylindrical symmetry. Large machines like HERA require more attention to transverse impedance outside the cavity sections due to the enormous length of the vacuum chamber. Thus we made an excessive effort in designing the vacuum system such that the transverse impedance is minimized.

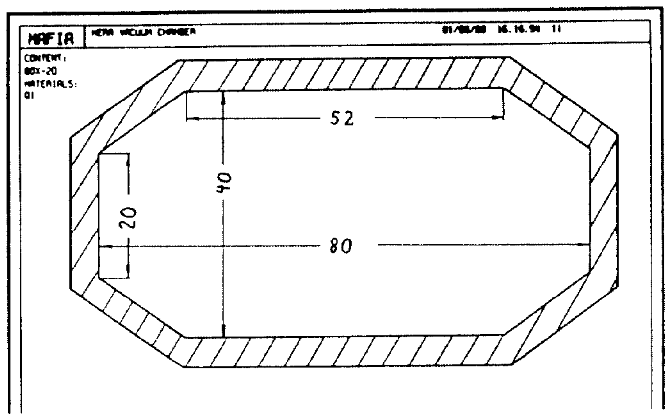

Figure 1: Dimensions of the HERA vacuum chamber.

THE WAKEFIELD FORMALISM

Lorentz forces due to scattered electromagnetic fields acting back on the bunch are also called *wake fields* and are space and time dependent. If a bunch is moving in the z-direction with velocity βc, we can write down the wake fields in a comoving frame (with relative bunch coordinate $s = \beta ct - z$ and charge distribution $\rho = \lambda(s)\delta(x-x_0)\delta(y-y_0)$ with $\lambda(s)$ given as longitudinal line density of ρ):

$$\begin{aligned}\vec{F}_{co}(x,y,s,t) &= \vec{F}(x,y,z=\beta ct-s,t) \\ &= e(\vec{E}(x,y,\beta ct-s,t)+\beta ct\vec{e}_z\times\vec{B}(x,y,\beta ct-s,t))\end{aligned} \tag{1}$$

Compared with the slow variation of particle motion, this force is a rapidly oscillating function so that only the averaged force acting on the bunch during the passage through the structure has to be taken into account, giving the change of momentum for each particle position inside the bunch. These integrated forces define the wake potential:

$$\vec{W}(x,y,s) = \int_{-\infty}^{\infty} \vec{F}_{co}(x,y,s,t)d(\beta ct) \tag{2}$$

For those more familiar with the concept of impedance, we will shortly summerize the relationship between wake potentials and impedances. The longitudinal wake potential is related to the longitudinal impedance by the Fourier transformation:

$$Z_\rho(x_0,y_0,\omega) = \int_{-\infty}^{\infty} W_{\parallel}(x_0,y_0,s)\, e^{i\omega s}\, ds \tag{3}$$

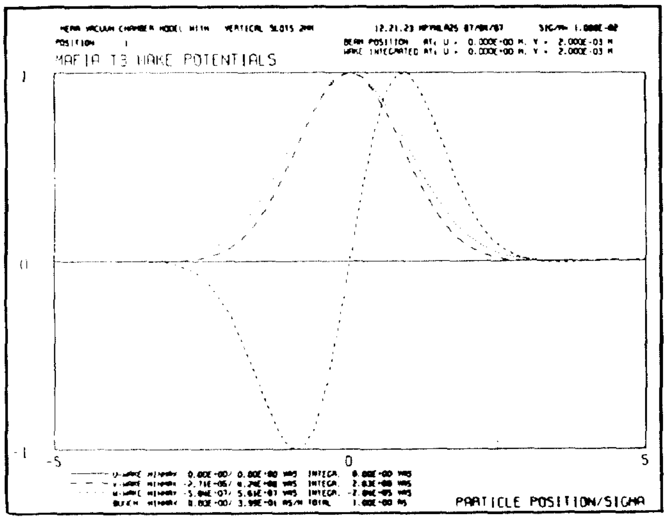

Figure 2: Wake potential calculated by 3D-BCI for the HERA vacuum chamber type with vertical slots.

The above impedance depends on the charge distribution ρ, although the impedance is usually defined using $\lambda(s) = \delta(s)$. Numerical reasons prohibit the calculation of wakes for a δ-pulse[11], but both impedances are related by

$$Z_\rho(x_0, y_0, \omega) = Z_\delta(x_0, y_0, \omega)\beta c\tilde{\rho}(x_0, y_0, \omega) \tag{4}$$

where $\tilde{\rho}$ is the Fourier transformation of the charge distribution. This can be easily seen from the fact that:

$$W_\rho = W_\delta * (\beta c \rho) \tag{5}$$

which is the convoluton of the δ-wake with the current distribution. Via the Panofsky-Wenzel theorem[12] longitudinal and transverse impedance are coupled by

$$\vec{Z}_\perp(x_0, y_0, \omega) = -\nabla_{x,y}\frac{i}{\omega}Z_{||}(x, y, \omega) \quad {}_{x=x_0, y=y_0} \tag{6}$$

which reflects the relationship between the longitudinal and the transverse wake potential in the time domain. Because we are only interested in the relative size of the transverse impedance of the vacuum system compared with the cavity section, we will directly compare the averaged tranverse kick seen by the bunch:

$$\vec{k}_\perp(x_0, y_0) = -\frac{\int_{-\infty}^{\infty} \lambda(s)\vec{W}_\perp(x_0, y_0, s)ds}{(\int_{-\infty}^{\infty} \lambda(s)ds)^2} \tag{7}$$

which simply corresponds to the average voltage seen transversely by the bunch normalized to a charge of one coulomb. The reason for this is that $k_\perp$ is a single characteristic number, that yields directly the measurable betatron tune shift [4]. The main contribution is given by the dipole moment in the Taylor expansion in x and y of this function, because we are only considering small variations from the beam position (x_0, y_0), which means that we are only interested in a quantity like:

$$k_\perp = \max(|\nabla_{(x_0,y_0)}\vec{k}_x(x_0, y_0)|, |\nabla_{(x_0,y_0)}\vec{k}_y(x_0, y_0)|) \tag{8}$$

The shape of the vacuum chamber may vary along the structure. The variation of that part of the vacuum chamber closest to the beam has the greatest effect. Therefore, to predict the maximum contribution, the beam position is varied towards that part. The final design kept the sum of these values for different parts of the vacuum system in the order of a few percent compared with the one given by the cavity section for a Gaussian bunch with a rms length of 1 cm.

THE VACUUM SYSTEM FROM AN ELECTROMAGNETIC POINT OF VIEW

Several types of vacuum chamber cross sections are used in HERA due to requirements of the vacuum pumps and the different magnet types. A compromise had to be found between effencity of the pumps which requires bigger slots in the vacuum chamber and the averaged vertical kick (here measured in $V/pC/m$) which minimization requires no slots at all or at least far away from the beam position. The averaged vertical kick caused by the cavity section (56 5-cell and 28 7-cell PETRA cavities) has a value of around $1700V/pC/m$ which will be compared with the vacuum system.

In the dipole section two rows of 75 horizontal slots each 100mm long and 2mm wide (with 20mm distance between two slots) are used for getter pumps (figure 3).

In the next case it is required to use vertical slots due to the layout of the quadrupols. This section consists of 4 rows with 6 slots each (on top and bottom of the vacuum chamber) and same dimension as in the dipole section. Several versions of this type were examined (figure 4). Because these slots are much nearer to the beam position we decide for so-called hidden slots (figure 4). 460 of these dipole and quadrupole section are used for HERA.

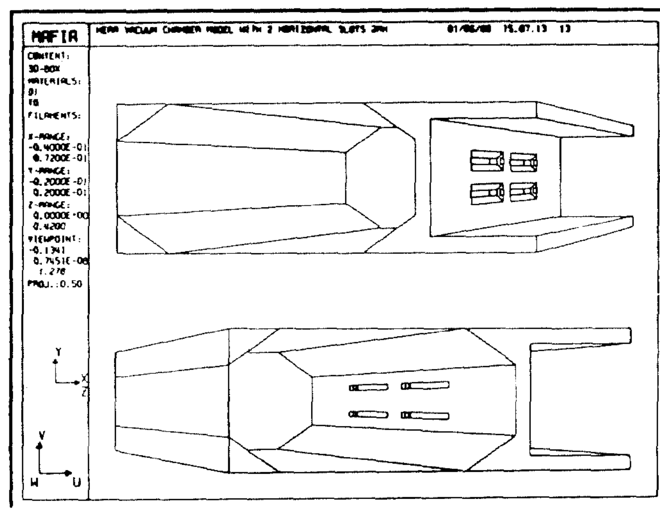

Figure 3: HERA vacuum chamber dipole section with horizontal slots.

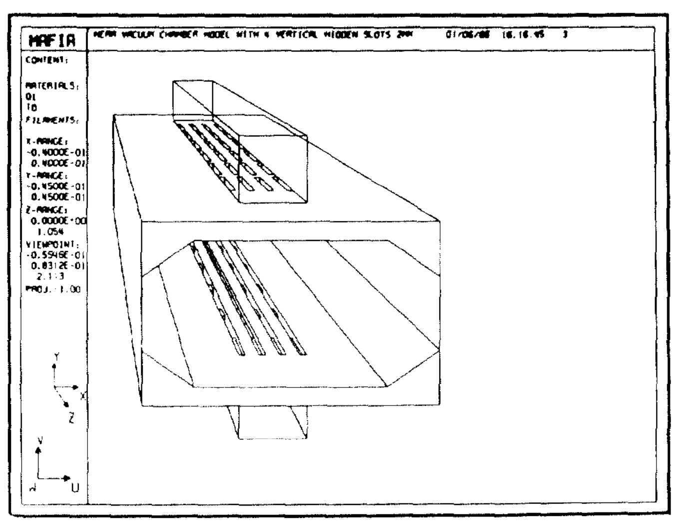

Figure 4: HERA vacuum chamber quadrupole section with vertical slots.

A third type of vacuum chamber was required for the turbo pump section (figure 5) which was made of six slots each of 120mm long and 4mm wide. In order to make the transverse force symmetric pseudo slots had been added on top of the vacuum chamber. 230 units of this type are installed.

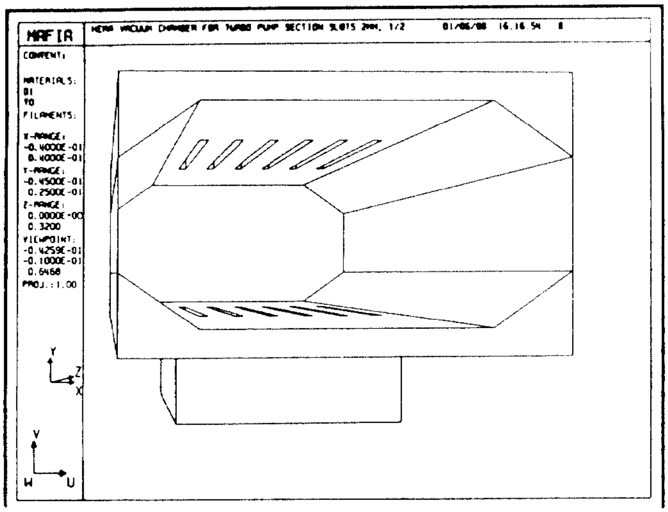

Figure 5: HERA vacuum chamber turbo pump section with vertical slots.

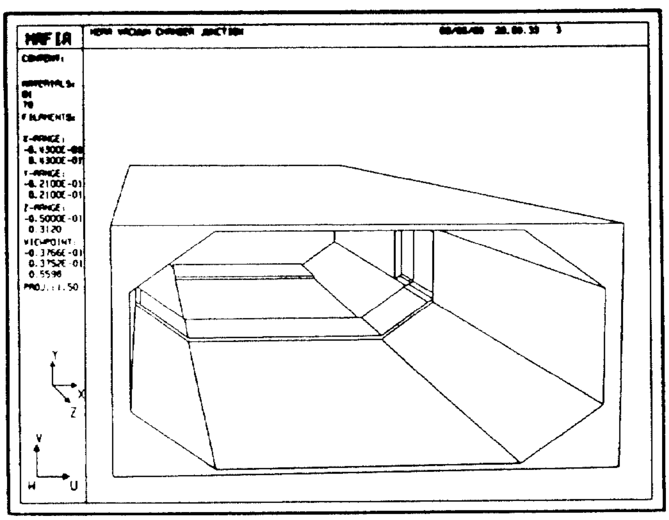

Figure 6: HERA vacuum chamber junctions.

A further component is the vacuum chamber junction chamber junction (figure 6), which causes in PETRA as much transverse impedance as the cavities. By a careful design it was possible to reduce the transverse impedance by a factor of 3.5. 460 units are required. The following table will give the results of the design procedure:

TYPE OF VACUUM CHAMBER	FIGURE	$k_\perp/(V/pC/m)$
dipole section (horiz.)	3	7.5
quadrupole section (vert.)	4	8.1
turbo pump section (vert.)	5	17.7
vacuum chamber junction (vert.)	6	257.0
all cavities (vert. + horiz.)	-	1700.0

Table 1: Maximum transverse kick parameter for HERA vacuum system components.

CONCLUSION

All major vacuum systems of HERA have been studied with respect to their transverse broad band impedance. By means of a three dimensional wake field code the kickparameters were computed and the vacuum system designed such that sum of its contribution is significantly lower than the unavoidable cavity impedance. Some runs were done with more than 800000 meshpoints needing more than 3 hours CPU on a IBM3084Q. This however seems more than adequate despite the importance of the transverse impedance.

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References

[1] T.Weiland, Design of R.F. cavities, Lecture Notes in Physics, vol. 215, pp21-32, 1983.

[2] R.Kohaupt, Transverse Instabilities in PETRA, in Proceedings of XI Internat. Conf. on High Energy Accel. , Geneva, 1980, pp562-565.

[3] D.Degèle, PETRA, in Proceedings of XI Internat. Conf. on High Energy Accel. , Geneva, 1980, pp16-25.

[4] T. Weiland, Transverse beam cavity interaction part 1: Short range forces , NIM, Vol. 212, pp 13 - 21, 1983.

[5] T. Weiland, Comment on wake field computation in the time domain , NIM, Vol. 216, pp 31 - 34, 1983.

[6] R.Klatt, T.Weiland, Theoretical prediction of head tail tune shift in PETRA , in IEEE Trans. Nucl. Sci., NS - 32, pp 2356-2358, 1985.

[7] R.Klatt, T.Weiland, Wake Field Calculations with Three-Dimensional BCI Code, in Proceedings of Linear Accelerator Conference, SLAC, 1986, pp. 282-285.

[8] T.Weiland, On the numerical solution of Maxwell's equations and applications in the field of accelerator physics, Part.Acc. 15 (1984) , pp245-292 and references therein.

[9] R.Klatt, F.Krawczyk, W.-R.Novender, C.Palm, T.Weiland, B.Steffen, T.Barts, M.J.Browman, R.Cooper, C.T.Mottershead, G.Rodenz, S.G.Wipf, MAFIA - A three-dimensional electromagnetic CAD system for magnets, RF structures and transient wake-field calculation, in Proceedings of Linear Accelerator Conference, SLAC, 1986, pp. 276-278.

[10] T.Weiland, RF cavity design and codes, in Proceedings of Linear Accelerator Conference, SLAC, 1986, pp. 243-248.

[11] T.Weiland, On the Computation of Electromagnetic Fields Excited by Relativistic Bunches of Charged Particles in Accelerating Structures, CERN/ISR-TH/80-07, January 1980 and in Proceedings of XI Internat. Conf. on High Energy Accel. , Geneva, 1980, pp570-574.

[12] W.K.H.Panofsky, W.A.Wenzel, Some Considerations Concerning the Transverse Deflection of Charged Particles in Radio-Frequency Fields, Rev. Sci. Instrum., vol. 27, p967, 1956.