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EVALUATION of DIFFERENT VERSIONS of SHIELDING for the PROTON BEAM in the HERA-B VERTEX TANK

S.G.Wipf,
Deutsches Elektronen Synkrotron, DESY, Hamburg, Germany.

DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY HAMBURG

1 Introduction

The goal of the HERA-B experiment is to study CP violation in decays of B Mesons. The halo of the HERA proton beam is brought into collision with internal target wires inside the Vertex detector. The Vertex tank also contains silicon detectors which can be moved into the vicinity of the beam by means of cylindrical supports.

The HERA-B Vertex tank presents a resonant cavity for the proton beam. Resonant modes excited by the passage of the proton beam through the Vertex tank could have very undesirable consequences for the operation of HERA and hence also for the data taking of the experiments H1 and ZEUS.

Three methods are available to control the resonant modes.

- Modes can be coupled out of the cavity.
  For Hera-B this is not very practical, as the number of modes which could possibly be excited in such a tank is very high.
- Modes could be damped by the introduction of absorbing material into the vertex tank thus reducing the quality factor and the coupling between the beam and the tank.
  This method would be preferable from the point of view of data-taking for Hera-B as, even though cooling of the absorbing material would then be necessary, there would be no loss of events through the prescence of shielding material. However this method only combats multi-bunch effects, where the wake fields created by one bunch act on later bunches, single bunch instabilities such as head-tail effects would still remain.
- The third method, which has been investigated here, is to physically shield the proton beam.

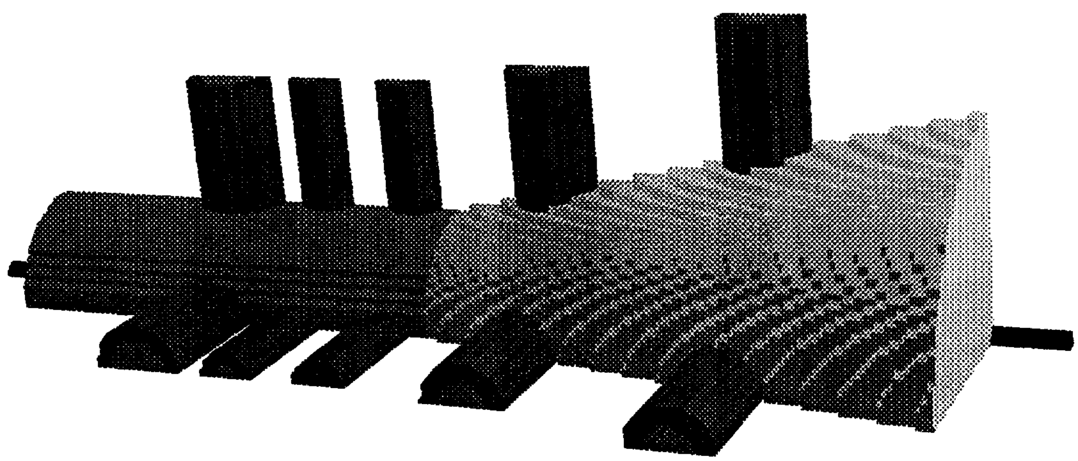

Figure 1. The calculation model for the vertex tank, seen from the outside.
One quarter of the geometry was modelled.

The wake fields and modes have been calculated for three different methods of shielding and for the unshielded tank. A half-size model of the Vertex tank has been built at INFN, Napoli. An experimental study is in progress to measure the effect of various shieldings. The calculations, in parallel with this experimental study, were carried out for this half-size model. All the results presented here have been scaled to full size. The full-size tank is $2.5m$ long and the radius is $24cm$ at the beginning and $52.6cm$ at the end, the beam tube radius is $16mm$.

2 Geometry

The Hera-B vertex tank consists of a cylindrical section, radius $24cm$ joining to a conical section which terminates at the exit window with radius $52.6cm$, the first calculation model used a length of $2.4m$ (later calculations use $2.5m$). Within the tank are the detector paddles, mounted on movable cylindrical manipulators, see figures 1 and 2. The distance along the beam axis between the horizontal and vertical paddles was $5.2mm$ and they were $30mm$ from the axis.

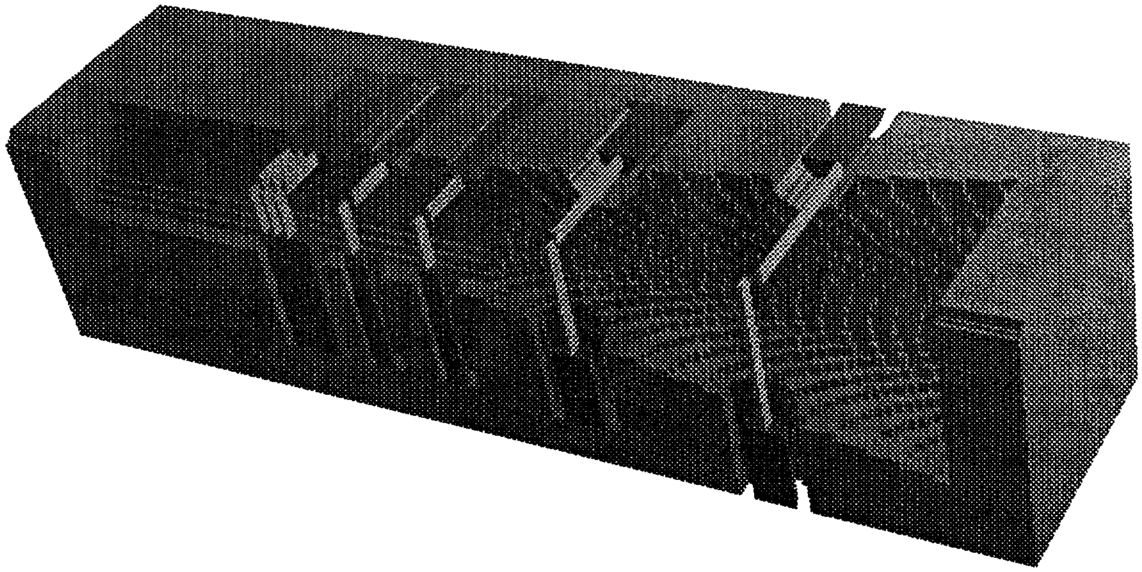

Figure 2. The model of the unshielded tank seen from the inside.

Three versions of possible shielding were calculated, in addition to the vertex tank with no shielding:

1. Unshielded tank.
2. 12 wires stretched parallel to the beam axis at a radial distance of 16 mm.
3. 4 metal strips, $26mm$ wide, mounted similarly to the wires.
4. A beam tube, radius $20mm$, with holes for the paddles and the target. There would be no break in the beam tube so that mirror charges could flow unhindered.

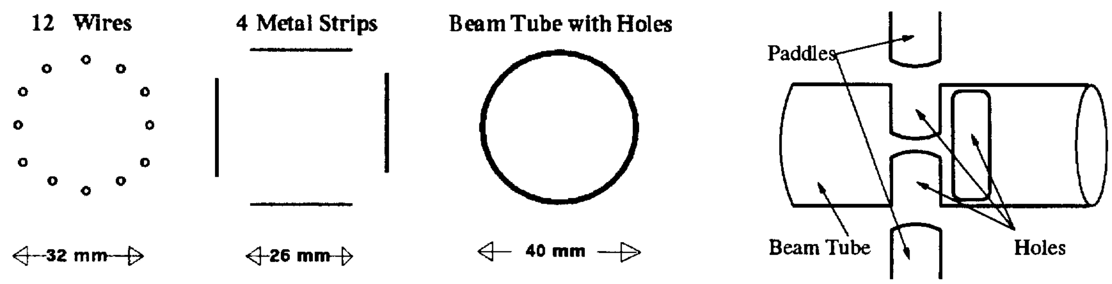

Figure 3. Cross section of the three different shielding models, the beam tube with holes is also shown from the side.

The first calculations were carried out in two dimensions with cylindrical symmetry. However, as it is not possible to represent the paddles realistically in 2 dimensions, three dimensional calculations were very soon necessary. 600,000 mesh points were needed to represent a quarter of the vertex tank. In order to discretise the geometry for calculation many simplifications had to be made, as the tank is so large and contains so many fine details.

- A quarter of the tank was calculated. Thus the paddle positions were symmetrical with respect to the horizontal and vertical axes, not shifted in the horizontal and vertical planes as in Figure 4. In the beam direction (z) the paddles were staggered in pairs so that the 2 vertical paddles were in the same plane while the 2 horizontal paddles were $5.2mm$ behind. In the actual design all four paddles are staggered and the separation between them is only $2mm$.

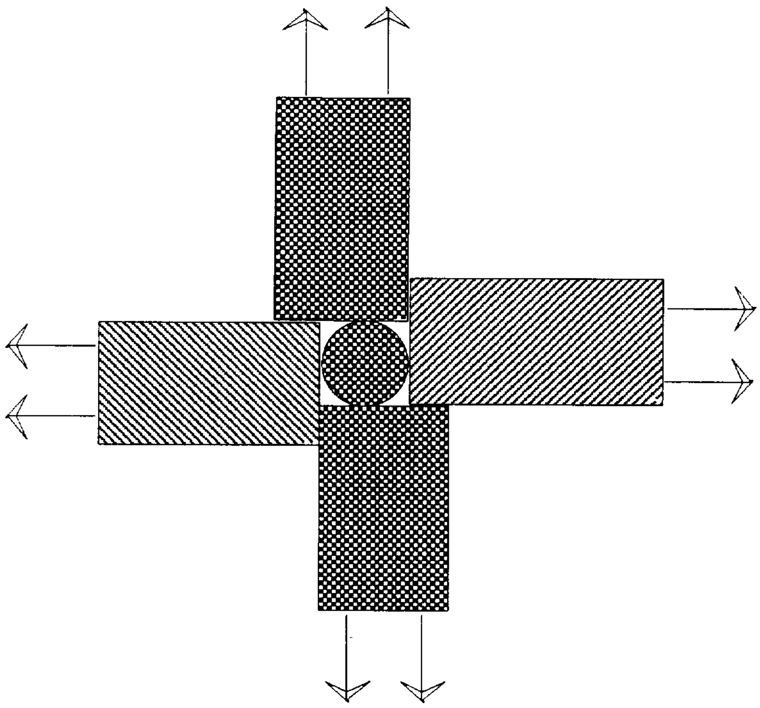

Figure 4. Diagram of the paddles showing the direction of motion. The paddles are shifted sideways and are positioned one behind another in the beam direction, separated by a distance of 2 mm.

- The gap in the shielding for the target was not included in the first model.
- The paddles were $5.2mm$ thick instead of $2mm$.
- The paddles were simple rectangular wafers, without shaping.
- The manipulators were represented as simple cylinders with no fine detail.
- It was not possible to reproduce the fine gap between the paddles and the holes in the shielding, the holes had the same dimensions as the cross section of the paddles.
- The pumping holes in the shielding were not modelled.
- The target was not modelled.

3 Definitions

3.1 Time Domain

The quantities which are calculated to assess the effect of the shielded or unshielded HERA-B Vertex tank on the HERA proton beam are the wake potential and the impedance.

The wake potential of a point charge, q, travelling at the speed of light, c, as seen by a test charge at a distance, s, behind it, is defined as,

$$W(s) = \frac{1}{q}\int_{-\infty}^{\infty} E_z(x, y, z - s, t = z/c)dz \qquad (1)$$

In the MAFIA time domain calculation the source point charge is replaced by a rigid bunch of finite length with Gaussian charge distribution. The current distribution, $I^\sigma(t)$, is given by

$$I^\sigma(t) = cq\frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{1}{2}(ct/\sigma)^2} \qquad (2)$$

The superscript σ will be used to designate the quantities produced by this bunch e.g. the wake field, $W^\sigma(s)$, as defined in equation 1.
Thus the single bunch energy loss can be calculated as

$$U^\sigma = -q\int_{-\infty}^{\infty} W^\sigma(ct) \cdot I^\sigma(t)dt \qquad (3)$$

When T_b is the time between successive bunches and if the wake fields from the previous bunch have died away by the time the next bunch arrives i.e. when

$$W^\sigma(c \cdot T_b) \approx 0 \qquad (4)$$

then the power loss, P^σ, is given by

$$P^\sigma = \frac{U^\sigma}{T_b} = -\int_{-\infty}^{\infty} \frac{W^\sigma \cdot I^\sigma(t)dt}{T_b} \qquad (5)$$

As condition (4) is not fulfilled in the case of the HERA-B vacuum vessel, it must be kept in mind that there will be a remanent field acting on succeeding bunches in addition to the wake fields induced by the bunch itself. Thus the power loss may actually be much higher than the calculated value as the wake fields from each bunch can reinforce each other but it may also be much lower as there could be a cancellation effect.

3.2 Frequency Domain

In the frequency domain the wake fields can be separated into the contribution from trapped modes, $W'(s)$, where $\omega < \omega_{cutoff} \approx 4.6GHz$ and a residuum which can dissipate in the beam tubes. In the case of the HERA proton ring this residuum is negligible.

$$W'(s) = \sum 2k_\nu \cdot cos\frac{\omega_\nu s}{c} \cdot e^{-(\omega_\nu t/2Q_\nu)} \qquad for\ t > 0 \qquad (6)$$

where the subscript ν represents a particular mode with frequency, f_ν, and $\omega_\nu = 2\pi f_\nu$, k_ν is the loss parameter

$$k_\nu = \frac{\left(\int_{-\infty}^{\infty} E_{z_\nu}(z) \cdot dz \cdot e^{i\omega_\nu z/c}\right)^2}{4 \cdot TotalEnergy_{(\nu)}} \qquad (7)$$

and Q_ν the quality factor.

$$Q_\nu = \frac{\omega_\nu \cdot StoredEnergy_{(\nu)}}{TotalLosses_{(\nu)}} \tag{8}$$

These quantities are all obtained from the MAFIA eigenmode calculation. As there are many sharp resonances, ω_ν will depend on the exact positions of the paddles. To make a full calculation in the frequency domain all the modes would need to be calculated up to $\approx 2GHz$ which means at least 200 modes.

In general, the impedance is defined as,

$$Z(j\omega) = \frac{1}{j}\int W(ct)e^{-j\omega t}dt \tag{9}$$

so the impedance of a gaussian bunch is given by

$$Z'(j\omega) = \frac{1}{j}\sum_\nu 2k_\nu \frac{j\omega + \frac{\omega_\nu}{2Q_\nu}}{({\omega_\nu}^2 - \omega^2) + (\frac{\omega_\nu}{2Q_\nu})^2 + j\omega\frac{\omega_\nu}{Q_\nu}} \tag{10}$$

The beam spectrum is given by, where the subscript μ indicates a particular harmonic of the periodic signal,

$$I(t) = Re\left\{\sum_\mu e^{j\omega_r\mu} I_\mu\right\} \tag{11}$$

where ω_r is the frequency of revolution. Then the dissipated power can be written as

$$P_d = \sum_\mu \frac{1}{2}|I_\mu|^2 \cdot Im\left\{Z'(j\omega_r\mu)\right\} \tag{12}$$

The worst case for a single mode occurs when that mode coincides with one of the lines of the beam spectrum, $\bar{\mu}$. In this case, when $\omega_\nu = \bar{\mu}\cdot\omega_r$, the total power dissipation of the νth mode becomes

$$P_d = \sum_{\mu\neq\bar{\mu}} \frac{1}{2}|I_\mu|^2 \cdot Im\left\{Z'(j\omega_r\mu)\right\} + \frac{1}{2}|I_{\bar{\mu}}|^2 \cdot Im\left\{Z'(j\omega_\nu)\right\} \tag{13}$$

If one assumes that only the resonance ν is excited, the first term can be neglected,

$$P_d \approx \frac{1}{2}{I_{\bar{\mu}}}^2 Im\left\{Z'(j\omega_\nu)\right\} \tag{14}$$

also, when $\omega \approx \omega_\nu$, the imaginary part of $Z'(j\omega_r\mu)$ from equation (10) can be approximated by

$$Im\left\{Z'(j\omega_r\mu)\right\} \approx \frac{2k_\nu Q_\nu}{\omega_\nu} = R_{shunt_\nu} \tag{15}$$

where R_{shunt_ν} represents the maximum value of the shunt impedance at a resonant frequency. In addition, as $I_{\bar{\mu}} \leq I_0$, $I_{\bar{\mu}}$ can be replaced by I_0, where the beam current, I_0, is the amplitude of the first spectral line. Thus

$$P_\nu = \frac{1}{2}\cdot I_0^2 \cdot R_{shunt_\nu} \tag{16}$$

This quantity can easily be calculated and is, in addition, only weakly dependent on changes in frequency caused by small geometrical changes such as the positions of the paddles. The maximum shunt impedances occur mainly at lower frequencies. In this discussion it has been assumed that the probability, that the frequency of more than one mode coincides with a line of the beam spectrum at any one time, is very small, so that one is justified in using values for the mode with the highest shunt impedance for the worst case estimate. For more details see [?].

4 Calculation

The wake fields were calculated using the time domain module, T3, of the MAFIA [?] programs. In addition the effects of individual modes were investigated using the eigenvalue solver, E.

The design value for the σ of the proton bunch in HERA is $85mm$. In order to be able to scale the calculated values for the full-size tank, a bunch length of $42.5mm$ had to be used for the wake field calculation. As the frequency of a mode varies inversely with the length of the tank, the frequencies and the loss parameter were scaled with a numerical factor of 0.5 whereas, for the Quality Factor, Q, and the Shunt Impedance, Rs, the factor was $\sqrt{2}$.
The tank was assumed to be of Steel with conductivity of $1.0 \cdot 10^6$ and the paddles of aluminium with conductivity of $3.3 \cdot 10^7$. Due to the limitations of disc space and memory, it was not possible to calculate all the modes up to the cut-off frequency of the beam pipe.

An additional four calculations were made at a later date with updated dimensions for the tank (10 cm longer), this gives a slightly lower frequency for the fundamental mode, so that they are not directly comparable with the first four calculations. The later calculations for the "beam tube with holes" shielding also included holes for the target, in addition more modes were calculated up to a frequency of $772MHz$.

Table 1: **Values for the full-size tank of the Loss Parameter and Power loss from the Transient calculations and of the Shunt Impedance from the calculation of the Resonant modes (20 modes calculated)**

	klong $Volt/C$	Power Loss $Watt$	Max. Shunt Impedance for a single mode (Ohm)
Beam pipe with holes	$-4.6045 \cdot 10^9$	11.8	613
Metal strips	$-1.0301 \cdot 10^9$	2.6	60
Wires	$-3.5941 \cdot 10^8$	0.9	2.3
No Shielding	$-5.9566 \cdot 10^{11}$	1525	307573.72
Wires(2nd model, with contact)	$-3.818839 \cdot 10^9$	10	82.2
Wires(2nd model, without contact)	negligible	negligible	241
Beam pipe (with extra hole for target)	$-3.11579 \cdot 10^9$	7.97	2226(in 80 modes)
Beam pipe (paddles moved in)	$-5.621605 \cdot 10^{10}$	143.9	negligible

4.1 No Shielding

The time domain calculation, for a rigid gaussian bunch, gave a loss parameter of $-2.57789 \cdot 10^{11} Volt/C$. This was first scaled for the full-size tank and then, assuming the design parameters for the HERA proton beam,

total beam current = $160mA$ in 210 bunches with a revolution time of $21\mu sec$ and using $\sigma = 85mm$,

the maximum non-resonant power which could be deposited in the vertex tank is 1525 Watt.

The frequencies and electromagnetic fields for the first twenty modes were also calculated in the frequency domain. Table 2 lists the frequency, Q-value, k-parameter, shunt impedance and resonant power loss for each mode. This power is only lost when a particular mode is excited by the beam. This can happen when the frequency of that mode is an exact multiple of the bunch repetition frequency. Although this is not normally the case, it is certainly possible that changes in the paddle positions or temperature variations could tune one of the many modes to such a value.

4.2 Wires and Metal Strips

For the three types of shielding, it was not possible to model the very thin material (a few μm) which would actually be used. In the case of wires, due to the limitations of the mesh, they had a cross section of $4mm \cdot 4mm$ thus the shielding appears to be considerably more effective than in reality. On the other hand the shunt impedance and Q factor are higher as the losses in the wires are underestimated due to the thickness.

Table 2: **Results from the eigenvalue calculation for the unshielded tank, scaled for the full size tank**

Mode	f/MHz	Q	kz [V/C]	Rs(Ohm)	P(Watt)
1	104.097	2729	$0.332553 \cdot 10^{8}$	277	3.55
2	131.151	2068	$0.574639 \cdot 10^{8}$	288	3.69
3	141.384	884	$0.374494 \cdot 10^{8}$	74.6	0.955
4	143.781	843	$0.194905 \cdot 10^{8}$	36.4	0.465
5	163.905	1997	$0.270482 \cdot 10^{11}$	$1.049 \cdot 10^{5}$	1343
6	177.898	800	$0.186433 \cdot 10^{10}$	$2.668 \cdot 10^{3}$	34.1
7	182.767	968	$0.698927 \cdot 10^{10}$	$1.178 \cdot 10^{4}$	151
8	184.537	1703	$0.294893 \cdot 10^{10}$	$8.663 \cdot 10^{3}$	111
9	193.268	1537	$0.178739 \cdot 10^{11}$	$4.524 \cdot 10^{4}$	579
10	250.804	5917	$0.446341 \cdot 10^{11}$	$3.352 \cdot 10^{5}$	4290
11	254.803	2171	$0.199970 \cdot 10^{9}$	542	6.94
12	295.811	2145	$0.392950 \cdot 10^{9}$	907	11.6
13	301.182	2040	$0.300306 \cdot 10^{9}$	647	8.29
14	304.341	3847	$0.391121 \cdot 10^{11}$	$1.574 \cdot 10^{5}$	2014
15	312.035	2193	$0.206292 \cdot 10^{9}$	461	5.91
16	329.459	3986	$0.294254 \cdot 10^{10}$	$1.133 \cdot 10^{4}$	145
17	358.340	5184	$0.945886 \cdot 10^{10}$	$4.356 \cdot 10^{4}$	558
18	377.460	4210	$0.697070 \cdot 10^{11}$	$2.475 \cdot 10^{5}$	3168
19	417.274	7663	$0.312170 \cdot 10^{10}$	$1.825 \cdot 10^{4}$	234
20	423.250	2497	$0.731323 \cdot 10^{11}$	$1.373 \cdot 10^{5}$	1758

The transient loss parameter was only $-7.18827 \cdot 10^{8} Volt/C$ which implies a negligible power loss of $\tilde{1} Watt$. It is however possible to define metal sheets in a coordinate plane with no thickness, and additional calculations were made with 12 wires of $2mm \cdot 0mm$ cross section. This gave a loss parameter of $-3.81884 \cdot 10^{9} Volt/C$ and power loss of $10 Watt$, which is well within the tolerable limits.

In the eigenmode calculation, the maximum shunt impedance within the first 20 modes up to a frequency of $246.7 MHz$ was 82 Ohm, thus it is unlikely that there are dangerous modes which could be excited in this case. The first five eigenmodes had lower frequencies than were present in the unshielded tank.

The calculation was then repeated with no contact between the wires and the paddles, in this case the loss parameter was of the order of the numerical error which implies a negligible power loss. Here the first five eigenmodes had lower frequencies than were present in the unshielded tank. These were modes in which resonances of the wires or strips were involved. Among the higher frequencies one can also expect resonances of the paddles and the tank to be included.

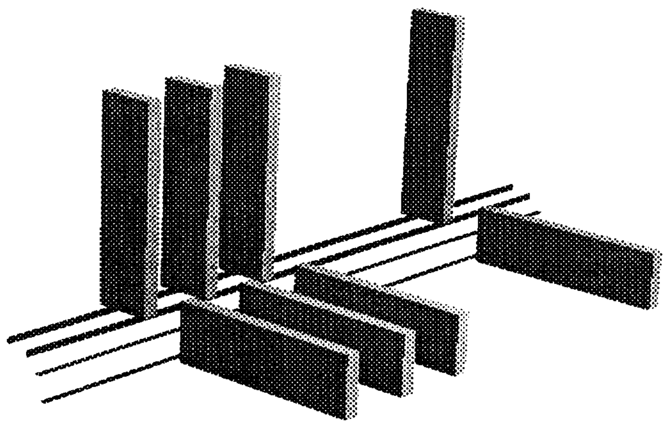

Figure 5. Shielding with 12 wires, represented as narrow strips.

Using the option of metal sheets with no thickness, the modelling of the metal strips was more realistic. However there is another factor which must be considered which is the thickness of the shielding with respect to the skin depth. If the thickness is greater than the skin depth then this model of the metal strip shielding works very well, however if this is not the case then fields can penetrate the metal strips and the effectiveness of the shielding will be greatly reduced. The four strips were $26mm$ wide ($13mm$ in the quarter model). The wake field calculation gave a loss parameter of $-1.03014 \cdot 10^9 Volt/C$ and power loss of 2.6 $Watt$. The maximum shunt impedance from the frequency domain calculation up to a frequency of $370 MHz$ was 159 Ohm.

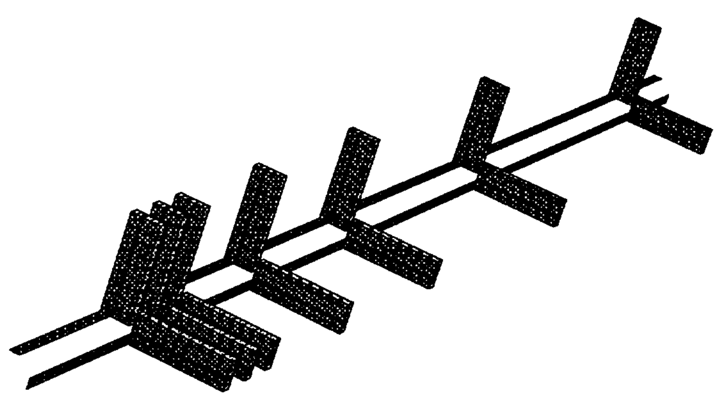

Figure 6. Metal strip shielding.

4.3 Beam Pipe with Holes

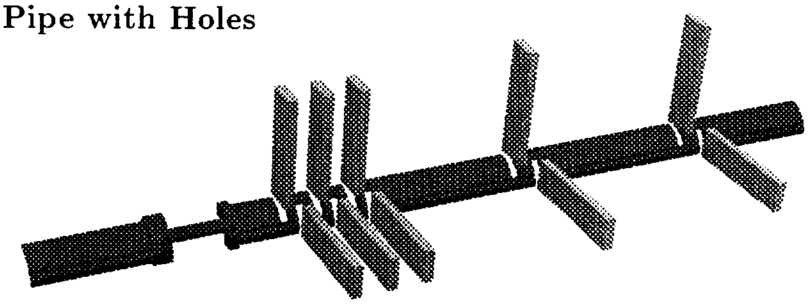

Figure 7. Close-up view of the holes in the beam tube, showing the mesh and the thickness of the beam pipe.

Again the thickness of the shielding which could be modelled was much above that which would be used. Similar values were obtained for the loss parameter, $-4.60453 \cdot 10^9\ Volt/C$ and a power loss of 11.8 $Watt$. The maximum shunt impedance up to a frequency of $311 MHz$ was 613 Ohm. Additional calculations were made including the hole for the target, both with the paddles in their outer position for injection and in the inner position for data taking, see Table 1. The loss parameter for the outer position was $-3.11579 \cdot 10^9\ Volt/C$ with a power loss of 8 $Watt$. As the former configuration is closest to that which is actually built into the Vertex tank for the first year of HERA-B operation, more modes were calculated for this case. 80 modes were calculated up to a frequency of 781.4 MHz. This produces a 1 $GByte$ data file and needs an additional 1.5 $GByte$ disc space for temporary files. The maximum shunt impedance was 2226 Ohm for the 59th mode at 739.8 MHz. Table 3 lists the parameters for all the modes with impedances above 200 Ohm. There are regions of the vertex tank where local cavities are formed and electro-magnetic fields can oscillate, especially round the paddle supports. Figure 8 shows the electric field of two modes which could resonate in such a cavity. The modes with the highest shunt impedances all had a maximum field in the region between a paddle and the hole underneath it.

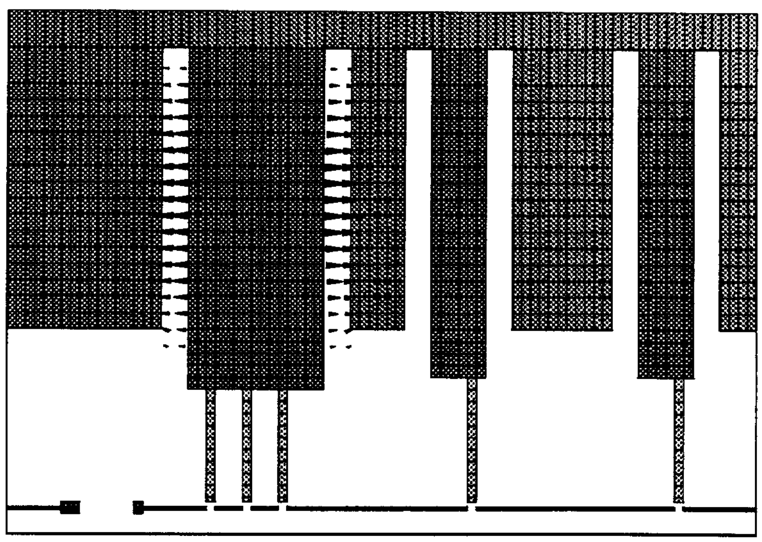

Figure 8. E-Field of the 437.4 MHz mode showing the first 5 paddles in the x=0 plane.

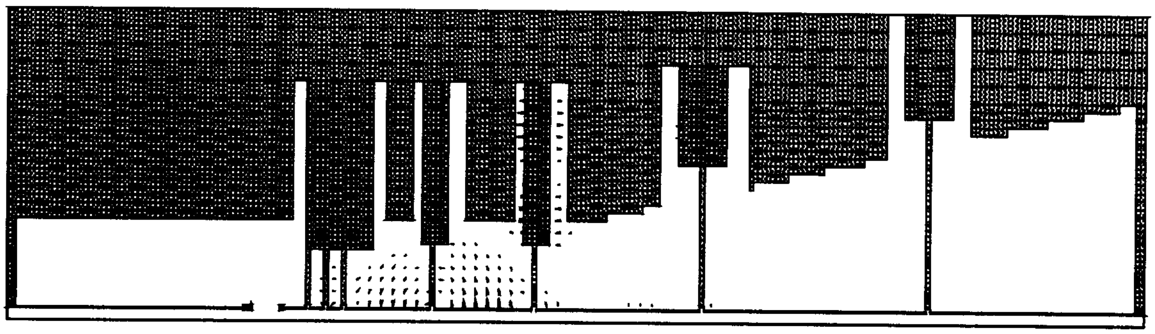

Figure 9. E-Field of the 739.8 MHz mode in the y=0 plane.

Table 3: **Results from the eigenvalue calculation, scaled for the full size tank, for a beam tube with holes for the paddles and for the target**

Mode	f/MHz	Q	kz [V/C]	Rs(Ohm)	P(Watt)
24	352.752	2847	$0.684699 \cdot 10^9$	1759	22.5
26	408.829	5095	$0.507429 \cdot 10^8$	201	2.58
29	436.924	5178	$0.800116 \cdot 10^8$	302	3.86
37	509.652	2437	$0.140517 \cdot 10^9$	214.	2.74
38	511.935	4897	$0.725357 \cdot 10^8$	221.	2.83
40	552.456	2771	$0.161497 \cdot 10^9$	258	3.30
42	579.628	5465	$0.126541 \cdot 10^9$	380	4.86
45	607.997	5436	$0.259127 \cdot 10^9$	737	9.44
53	644.935	5967	$0.126334 \cdot 10^9$	372	4.76
56	660.121	5436	$0.495139 \cdot 10^9$	1298	16.6
59	679.890	2932	$0.162141 \cdot 10^{10}$	2226	28.5
63	695.370	4534	$0.208428 \cdot 10^9$	433	5.54
66	708.361	3357	$0.599413 \cdot 10^9$	904	11.6
69	723.678	3980	$0.360889 \cdot 10^9$	632	8.09
72	739.784	4632	$0.421944 \cdot 10^9$	841	10.8
78	772.327	5763	$0.254436 \cdot 10^9$	604	7.74

5 Conclusion

All the shielding models produced a reduction of at least a factor 100 in the loss parameter and hence also in the power loss. Thus the important considerations in choosing and constructing an effective shielding for the proton beam will be in the engineering. The problems of building and supporting a stable shielding which will not be in danger from injection oscillations and which will not sag are considerable especially for the material thicknesses which would be desirable from the HERA-B point-of-view. For the wire and strip shieldings, one has to take skin depth into account as it is possible that one or two wires or one strip must carry all the induced current when the beam is off axis. More detailed calculations are also needed for the beam pipe with holes, as it would be thinkable that in this case, in spite of a good overall shielding effect, that particular modes could still be excited. It is also important that the contact between the paddles and the shielding be well defined (i.e. that there is either always contact between paddles and shielding or that they are insulated from each other), to avoid induced effects and local heating.

Acknowledgement

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[2] The MAFIA Collaboration, CST GmbH, Lautenschlägerstr. 38, 64289 Darmstadt, Germany.