# INVESTIGATION OF THE IMPEDANCE AND HIGHER ORDER MODE LOSSES FOR PROPOSED BEAM PIPE CONFIGURATIONS FOR THE HERA LUMINOSITY UPGRADE PROJECT

M. Dohlus, S. G. Wipf
Deutsches Elektronen Synchrotron (DESY)
Notkestrasse 85, 22607 Hamburg, Germany

*Abstract*

The impedance and wakefield effects and higher order mode losses have been investigated for the Luminosity Upgrade Project at HERA for three regions where only minimal heating can be tolerated. These are two versions of the beam pipe configuration at the interaction region of the experiment Zeus and also for a region where superconducting magnets are to be installed. As the structures are very long (up to 4.9m) it was not possible to calculate all modes up to the cut-off frequency directly, thus long term wake calculations (100nsecs) in the time domain were used to pinpoint potentially dangerous modes. The frequency and band-width information thus obtained could be used to obtain the impedance of these modes in the frequency domain. The calculations were carried out using the MAFIA [1] programs.

## 1 IMPEDANCE CONSIDERATIONS

Impedance calculations were carried out for the beam tube of the interaction region at ZEUS and also in the adjoining region of the superconducting magnets, using the MAFIA programs [1]. Both wakefield (time domain), and resonant field (frequency domain) calculations were made. In the frequency domain the resonant fields were calculated for as many modes as possible, these fields can then be used to obtain the loss parameter, shunt impedance and power loss. Assuming that only one mode will be excited exactly on resonance at any one time, the maximum values give a good worst case estimate of the potential power loss.

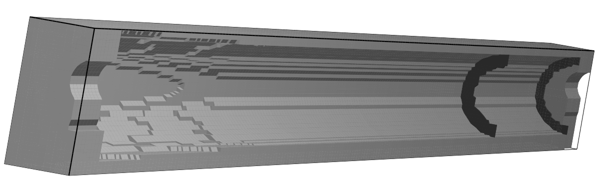

Figure 1: Version I: A foreshortened view of the interaction region at Zeus, the absorbers are shown as dark arcs.

As the damping time of the wakefields is longer than the time between bunches, the single pass loss, calculated from wakefields, does not give an *absolute* value of the power loss which can be expected. It is possible that the wakefields from each bunch accumulate and that the final figure is higher than the calculated transient losses, however this figure has been used as a measure of comparison for different beam tube geometries and for different longitudinal bunch lengths.

The Version II design entails considerable geometrical alterations. A much smoother beam tube, with tapers at either side of the collimators helps to reduce the losses due to wakefields and an asymetrical absorber at $z = 1.65m$ has the effect that many fewer modes are actually trapped in the interaction region. However the change from normal to superconducting magnets reduces the tolerance to heating due to resonant and transient losses further along the beam pipe. Thus it was necessary to consider the impedance in the region of the superconducting magnets in addition to that in the interaction region.

## 2 DEFINITIONS

### 2.1 Time Domain

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 [2],

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

Provided that the wake fields from one bunch have died away when the next bunch arrives, then the power loss, $P$, is given by

$$P = \frac{U}{T} = -\frac{1}{T}\int_{-\infty}^{\infty} W(s)\cdot c\lambda(s)ds \qquad (2)$$

where $T$ is the time between successive bunches, $U$ the energy and $\lambda(s)$ the charge distribution (usually Gaussian).

### 2.2 Frequency Domain

In the frequency domain it is unusual for modes where $\omega > \omega_{cutoff}$ to be trapped. The loss parameter $k_\nu$ for a particular mode, $\nu$, with frequency, $f_\nu$ and $\omega_\nu = 2\pi f_\nu$ is given by

$$k_\nu = \frac{|\int_{-\infty}^{\infty} E_{z_\nu}(z)\cdot dz \cdot e^{i\omega_\nu z/c}|^2}{4\cdot TotalEnergy_{(\nu)}} \qquad (3)$$

and $Q_\nu$ the quality factor.

$$Q_\nu = \frac{\omega_\nu \cdot StoredEnergy_{(\nu)}}{TotalLosses_{(\nu)}} \qquad (4)$$

Thus the worst case power loss for a single mode is given by

$$P = 2 \cdot I_0^2 \cdot R_{shunt} \tag{5}$$

where $R_{shunt} = 2kQ/\omega$ represents the shunt impedance at a resonant frequency with $I_0$ = DC beam current and $2\pi\sigma \ll c/f_\nu$.

These quantities are all obtained from the MAFIA eigenmode calculation and are, in addition, only weakly dependent on changes in frequency caused by small geometrical changes. The maximum shunt impedances occur mainly at lower frequencies.

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.

## 3 GEOMETRY

### *3.1 Version I:*

A 3.2 meter long section was modeled around the ZEUS Interaction Point ($z = 0.0m$), which formed a resonant cavity due to the changes in cross section at either end. It was only necessary to model half the structure as it is symmetrical with respect to the x-z plane. The electron (or positron) beam travels in the positive z-direction.

The geometry consisted of, from left to right, (see Figure 1):

- keyhole beam pipe, an elliptical beam tube inside the combined function magnet with lateral extension for synchrotron light;
- opening up into a conical section with an entry radius of $54mm$ at $z = -1.3m$ and an exit radius of $46.25mm$ at $z = -0.62m$;
- this is followed by a long cylindrical central beam pipe from $z = -0.62$ to $1.3m$;
- at $z = 1.3m$ there is a sudden change in cross section to an elliptical beam tube inside the other combined function magnet with a wider extension than on the left hand side.
- Two synchrotron radiation absorbers were positioned at $z = 0.75m$ and $1.3m$.
- keyhole beam pipe

A second configuration was also investigated using an elliptical central beam pipe from $z = -1.3m$ to $1.3m$. The height of the beam tube at the interaction point was $20mm$ as opposed to $46.25mm$ for the cylindrical cross-section, the width remained unchanged.

### *3.2 Version II - Interaction Region:*

A 3.9m stretch of beam tube was calculated. The geometry consisted of, again starting from the left, (see Figure 2):

- an elliptical beam tube 30mm high with a small post or "finger" absorber on one side of the horizontal axis at $z = -1.75m$;
- a step-wise increase in width from 91 to 123mm at $z = -1.7m$, masked by r.f. shielding, is followed by an elliptical cone which continues until $z = -0.6m$ where the height is $21mm$;
- this is followed by a long elliptical central beam pipe, width $108mm$ from $z = -0.6m$ to $1.55m$;
- at $z = 1.55m$ there is an assymetrical tapered absorber;
- a pair of tapered synchrotron radiation absorbers were positioned either side of the horizontal axis at $z = 0.8m$ and a single absorber at $z = 1.4m$.

The symmetry with respect to the x-z plane could also be taken advantage of here.

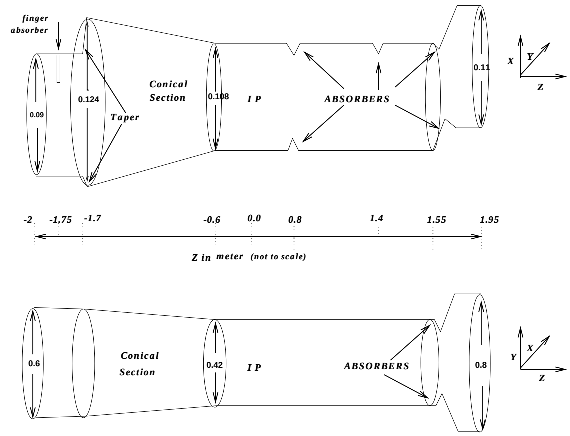


Figure 2: Version II: A diagram of the Interaction Region.

### *3.3 Version II - Superconducting Magnets:*

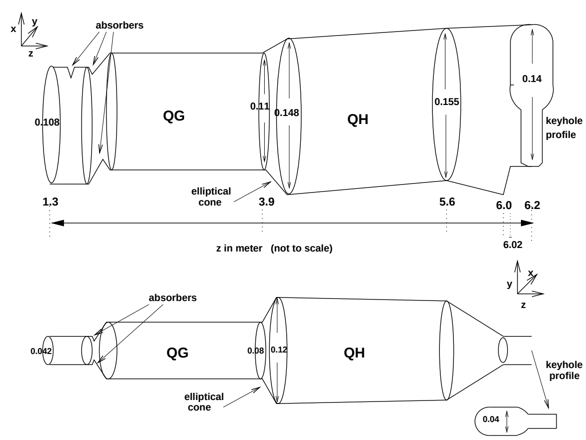


Figure 3: Version II, Superconducting Magnets: A diagram (not to scale) of the beam tube at the Superconducting Magnets . (The last 2 absorbers at the end of the interaction region can be seen at the beginning of this section.)

For the superconducting magnets the section from $1.3m$ to $6.2m$ was modelled, from left to right (see Figure 3):

- the rightmost end of the interaction region beam tube including the absorber at $1.4m$ and the staggered absorbers between $1.55m$ and $1.66m$
- the elliptical beam tube in right hand side magnet with vertical height of $40mm$
- the conical connection between the magnets, where the vertical height changes from $40mm$ to $60mm$ between $z = 3.9m$ and $4m$
- the larger elliptical beam tube continues through the second magnet to $z = 5.6m$. As the path of the beam is curved in this section, slight shifts were included in the geometry so that the distance of the beam from the walls remained correct.
- a gradually tapering section starting at $5.6m$ connects to the keyhole chamber of next magnet at $6m$ where extra space is needed to accomodate the synchrotron radiation

## 4 TIME DOMAIN - INTERACTION REGION

For the Version II configuration, the damping time for a typical mode trapped in the Interaction Region with frequency $3954MHz$ and Q-factor $14000$ is given by

$$\tau = 2Q/\omega \approx 1\mu sec\ (11 bunches).$$

As the bunch separation time is only 96 nanoseconds, this means that the wakefields from one bunch are still present when the next bunch arrives. The two extreme cases are when these fields are either in phase or out of phase by $\pi$ with the wakefields from the next bunch. In the former case the fields accumulate while in the latter case they cancel. The losses drop dramatically with increasing bunch length, so that maximum losses can be expected at injection. In HERA the longitudinal bunch length of the electrons or positrons (in contrast to the protons) is shortest at injection and longer at higher energies. The longitudinal $\sigma$ for positrons or electrons varies with beam energy as shown in Table 1.

Table 1: Variation of Longitudinal $\sigma$ for positrons/electrons with beam energy

| | | | |
|---|---|---|---|
| Energy: | 12 GeV | 27.5 GeV | 29.8 GeV |
| Voltage: | 90 MV | 110 MV | 140 MV |
| Sigma: | 3mm | 12.3mm | 13.4mm |

In order to simulate the beam, the time domain program represents the bunch as a rigid longitudinal Gaussian charge distribution. For Version I, 4mm was the smallest value of the $\sigma$ of the distribution which could be calculated directly, as the extreme ratio of height to length of the beam tube begins to cause computational problems. The 3mm bunch length was calculated in two sections. For the left hand side section it was necessary to take the group velocity of the wakefields into account and to calculate to the point where the tail of the bunch has outstripped the wakefields, $z = 0.9m$.

These very lengthy calculations were only repeated for the Version II geometry for a $\sigma$ of 4mm, all other Version II calculations were carried out with a bunch $\sigma$ of $8mm$. The Version I values which are included in Table 2 indicate the relationship between bunch length and transient losses and the effect of reducing the height of the beam tube. The steep increase of transient losses with a 3mm bunch length is expected to be similar for the Version II configuration. The Version II single pass transient losses were calculated to be 47 Watt for a $\sigma$ of $8mm$. The bunch spectrum for a 3 $mm$ and an 8 $mm$ $\sigma$ bunch only differ in their high frequency content, for frequencies well above 5 $GHz$. The increased transient losses need not be trapped in the interaction region, although there will be reflections at absorbers and other changes in cross-section. Thus only a small portion of the losses are deposited in the walls.

Table 2: Summary of the Single Pass Losses and of the Maximum Single Mode Resonant Power Losses

| Beam Tube | Bunch Length | Single Pass Power Loss | Resonant Power Loss |
|---|---|---|---|
| **Version I:** | mm | Watt | Watt |
| *Cylindrical* | 3 | 1870 | 1993 |
| | 4 | 1338 | 1978 |
| | 7 | 597 | 1910 |
| | 8 | 493 | 1881 |
| | 13 | 203 | 1684 |
| *Elliptical* | | | |
| | 3 | 873 | |
| | 8 | 138 | 420 |
| **Version II:** | | | |
| *Interaction Region* | 4 | 187 | |
| | 8 | 47 | 3 |
| *s.c. magnets* | 8 | 108 | 10 |
| **Present Set-up** | | | |
| | 8 | 395 | 1212 |

## 5 FREQUENCY DOMAIN - INTERACTION REGION

The first 75 modes which lie between 2.2 and 4.14 $GHz$ could be calculated. The majority are not trapped and the energy can flow away and dissipate in the rest of the ring, however one trapped mode was identified which resonated at the "finger" absorber at $2.58GHz$. If this mode were to be excited, $94Watt$ would be dissipated at that position. Two variations of this absorber were calculated, the first extending it to the walls on both sides so that it could not so easily resonate and the second adding an additional taper on the down-stream side. In the former case a similar mode was found at 2.83 GHz, reducing the losses to

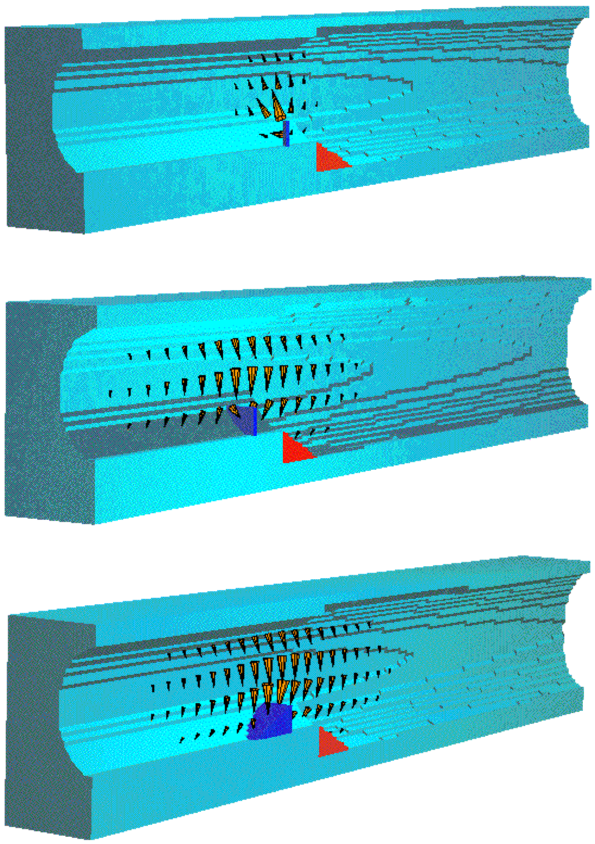

Figure 4: Three versions of the absorber at z=-1.75m. Top: the original "finger" design - resonant loss=94.5 Watt, frequency=2.58 GHz. Middle: "sector" design - resonant loss=17 Watt, frequency=2.83 GHz. Bottom: "sector with taper" - resonant loss=3 Watt, frequency=2.82 GHz.

17 Watt, while the taper produced a further reduction to 3 Watt at a frequency of $2.82GHz$ (see Figure 4). The long range wake was calculated for 80 $nsecs$. Examination of the fourier transformation showed no sharp resonances beyond the range of frequencies which could be calculated in the frequency domain, so no trapped modes are expected at higher frequencies.

### 5.1 *Time Domain - Superconducting Magnets*

It was possible to calculate the longitudinal wake fields with reasonable accuracy, although, with an over $4m$ section, one enters a regime where the step size has to be chosen much smaller in relation to $\sigma$ in order to keep the numerical dispersion error small, on account of the asynchronisation of the bunch and the wakefields. For $\sigma = 8mm$ a transient loss of 108 Watt was calculated.

### 5.2 *Frequency Domain - Superconducting Magnets*

As the beam tube is only $21mm$ high at the right hand side of the IP region and $20mm$ in the keyhole section, the superconducting magnet section forms a quasi-cavity for the beam. Table 3 shows the chamber heights and cut-off frequencies for the various sections. Due to the greater vertical height of the beam tube in the right hand side superconducting magnet and the small opening of the keyhole vacuum chamber beyond, a large range of modes can be trapped in this region. Thus the 80 modes which can be calculated without overstepping the file and memory limitations lie below $2.5Ghz$ and another 200 modes can be expected to lie between $2.5Ghz$ and the cut-off frequency, $4.39Ghz$. Within these 80 modes all resonant losses were very moderate, ($< 4Watt$).

Table 3: Vertical chamber height and cut-off frequency from IP to the keyhole vacuum chamber

| | | |
|---|---|---|
| IP beam pipe, (-2, -1.6): | 2.97Ghz | .0295m |
| IP beam pipe, (-0.6,1.55): | 4.19Gh | .021m |
| first s.c.magnet beam pipe: | 2.2Ghz | .04m |
| second s.c.magnet beam pipe: | 1.46Ghz | .06m |
| Keyhole: | 4.39Ghz | .02m |

Modes can be calculated at higher frequencies but the reliability of the results depends on knowing the number of modes which lie in a particular bandwidth. Thus there is no guarantee that *all* modes have been found, whereas when the whole frequency range is used modes are only rarely missed. 10 modes spanning 70 $MHz$ were calculated at 4 Ghz using this method and a maximum resonant loss for a single mode was found to be 10 Watt, this is the figure which is entered in Table 4 but the possibility of higher resonant losses cannot be excluded.

Table 4: Superconducting Magnets: Resonant Losses for 10 modes near 3950 $MHz$

| Frequency (MHz) | Q-factor | Kz (V/C) | Rshunt (Ohm) | Loss (Watt) |
|---|---|---|---|---|
| 3942.351 | 4540 | 1.035E+09 | 379.0 | 2.73 |
| 3944.285 | 6143 | 3.595E+08 | 178.0 | 1.28 |
| 3945.393 | 4265 | 2.653E+08 | 91.3 | 0.657 |
| 3947.076 | 8359 | 1.031E+08 | 69.5 | 0.500 |
| 3950.215 | 5345 | 2.807E+09 | 1209.0 | 8.71 |
| 3951.592 | 4810 | 3.288E+08 | 127.0 | 0.917 |
| 3960.004 | 6958 | 3.850E+08 | 215.0 | 1.55 |
| 3963.570 | 5705 | 1.311E+09 | 600.0 | 4.32 |
| 3965.430 | 5136 | 1.456E+09 | 600.0 | 4.32 |
| 3979.007 | 4415 | 5.219E+07 | 18.4 | 0.133 |
| 4012.014 | 5312 | 3.420E+09 | 1441.0 | 10.4 |

To aid in the analysis of the resonant losses in the superconducting magnets at higher frequencies, a long range wake calculation was carried out. A similar method was used in reference [3]. The wake potential was calculated

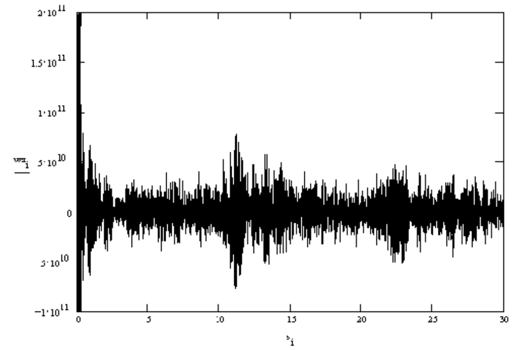

Figure 5: Left: The wake potential, calculated for $30m$ after the bunch head, plotted against distance from the head of the bunch, abscissa: 0 to $30m$.

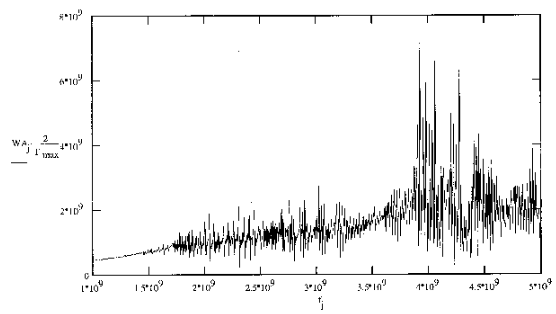

Figure 6: Superconducting magnet beam tube: Long term wake calculation for 100 $nsecs$. Fourier transformation of the long term wake in the frequency domain, ordinate: $2 \cdot k$-parameter, 0 to $8 \cdot 10^9$, abscissa: 0 to 5 $GHz$.

for $100nsecs$ and the amplitudes of the fourier transformation were analysed. The wake potential is shown in Figure 5 while Figure 6 shows the fourier transformation of the long range wake. The first 80 modes, which were directly calculated in the frequency domain, can be seen as distinct peaks in the frequency range up to $2.5GHz$, while there is also a band of sharp resonances which can be seen at $4GHz$.

The wake potential is given by

$$W(s) = \sum_{\nu} 2k_{\nu} \cdot cos\frac{\omega_{\nu} s}{c} \cdot e^{-(\omega_{\nu}/2Q_{\nu}) \cdot s/c} \quad for\, t > 0 \tag{6}$$

The amplitude normalisation in Figure 6 is chosen so that the ordinate corresponds to the amplitude of an undamped oscillation. Assuming that the damping ($\exp(-\omega/2Q \cdot s/c)$) can be neglected for the calculation range (s= $0 \ldots 30m$), the spectral peaks can be taken as $2 \cdot k_{\nu}$ ($V/C$). An approximate shunt impedance can be calculated for a mode with a sharp peak in the frequency spectrum. For example the highest peak of the spectrum at 3.9 $GHz$ has an amplitude of $\approx 7.3 \cdot 10^9$. The shunt impedance is given by $2kQ/\omega$ so using Q $= 5500$ (obtained from the frequency domain calculations for this band mentioned above) gives a shunt impedance of 1683 $Ohm$ and a power loss of 12 Watt, for the HERA design current of $60mAmp$ for electrons. This value is of the same order of magnitude as that obtained from the frequency domain calculations and thus one would expect the maximum resonant mode loss to be not greater than 12 $Watt$ per excited mode.

## 6 COMPARISON WITH THE PRESENT CONFIGURATION

Similar calculations were made for a change in the beam tube at the interaction region at the end of 1994, the configuration which is now in place. Modes were then trapped in the region from $z = -2.24m$ and $z = 2.5m$. The Version I calculations showed an increase in single pass impedance of approximately 20% for a bunch length of 8 mm. For Version II these losses have been reduced to a third of the value which was calculated for the Version I configuration with an elliptical beam tube.

## 7 CONCLUSION

The resonant losses are caused by modes which are completely trapped in the part of the beam pipe with the largest cross-section and therefore with the lowest cutoff frequency. The losses of higher spectral components (e.g. above 10 GHz) are estimated by the 'single pass power loss'. This quantity describes the power loss of the beam, but only a fraction of this energy is absorbed in the walls of the interaction region. Most of the energy propagates upstream and downstream into the beam pipe and is dissipated over a great length. The intersection of absorbers can be tolerated, if their surfaces are small compared to the pipe cross-section. The following modifications could reduce the transient losses in the superconducting magnets

- A more gradual taper into the keyhole section,
- A reduced vertical dimension in the right hand side section
- A more gradual taper between the sections
- Breaking the x-z symmetry so that fields can couple to lower waveguide modes.

The main problems are likely to occur at injection when the electron or positron bunch is shortest.

## 8 REFERENCES


[1] The MAFIA Collaboration, CST GmbH, Lauteschlägerstr. 38, 64289 Darmstadt, Germany.

[2] 'Wake Fields and Impedances', by T.Weiland, R.Wanzenberg, DESY M-91-06, May 1991.

[3] 'HOM Heating at the PEP-II B-Factory IR Beryllium Vacuum Pipe', X.Lin, C.-K.Ng, K.Ko, SLAC-PUB-7658, Sept 1997.