

QUANTIFYING DISSIPATED POWER FROM WAKE FIELD LOSSES IN DIAGNOSTICS STRUCTURES

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Abstract

As a charged particle beam passes through structures, wake fields can deposit a fraction of the energy carried by the beam, as characterised by the wake loss factor. Some part of the deposited energy will be emitted into the beam pipe, some part can be coupled out of signal ports and some part will be absorbed by the materials of the structures. With increasingly higher stored currents, we require a better understanding of where all the energy deposited by wake losses ends up in order to avoid damaging components. This is of particular concern for diagnostics structures as they are often designed to couple a small fraction of energy from the beam, which makes them susceptible to thermal damage due to increased localised losses. We will detail the simulation and analysis approach which we have developed to quantify power deposition within structures. As an example the analysis of a beam position monitor pickup block of the Diamond storage ring is shown.

BASIC APPROACH

A single run of an electromagnetic simulation will allow the wake loss factor to be found. However this gives no information on the distribution of the losses within the structure. Ideally one would simply add up the energy loss over time at each mesh point in the simulation which would allow the energy loss spatial distribution to be computed. Unfortunately this is not possible with any of the currently available simulation tools.

The tool we chose to use was the wake field solver from the CST particle studio suite. A vital first step was to add ports to the models thus making it possible to record the time domain signals being emitted from the structure. Our approach is that any power deposited into the structure but not emitted from the ports is absorbed by the structure. This allows us to determine the fraction of the power lost from the beam which can cause local heating. However in order to localise the losses within the structure a further technique is required. This is to run multiple EM models with subtly different settings. The reference model is a full lossy model which contains all the material losses in the structure. Further models have sections or components switched to lossless parameters. A fully lossless model is also required to give a baseline, as a sanity check of the models and to verify that the simulation time is long enough. This is similar to the approach used by Nagaoka [1]. The difference between the full lossy and the selectively lossy models should, in principle, show the difference caused by the components whose properties were switched. This as-

sumes that the field distribution is not greatly perturbed by the change of material from lossy to lossless. An estimate of the validity of this assumption can be found by adding the component losses together and comparing it with the losses from the fully lossy model.

Our example case is a Diamond arc beam position monitor whose geometry is shown in Fig. 1. We initially investigated this structure in order to understand the higher than expected heating we observed.

The five specific features investigated were the block which the buttons were mounted in; the button itself; the ceramic, and the pin which connects the button to the rest of the structure. Additionally the effect of an annular slot, which was added to improve vacuum performance, was also investigated.

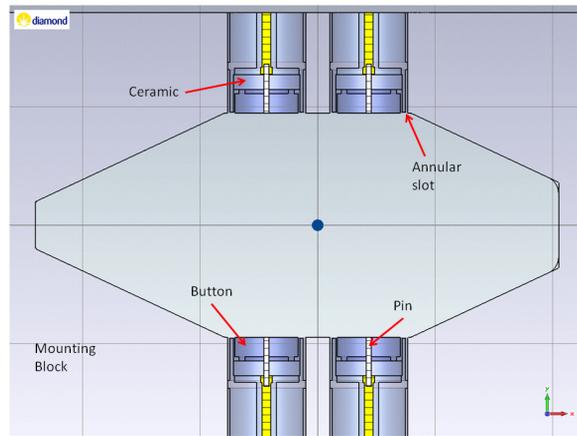


Figure 1: The geometry of an arc BPM.

Following is a description of the analysis used for each model. The results of these analyses are then combined to estimate the loss distribution within the structure and the total powers involved.

One major assumption that this work relies on is that the system being investigated is a linear system. This implies that power cannot be moved between frequencies. Therefore if we account for the power in the frequency domain then each frequency can be looked at separately.

ANALYSIS STEPS

Time Domain

Initially we are interested in the energy lost from the bunch which we get to via the wake loss distribution and the wake loss factor (k_z).

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The wake loss factor is the integral of the wake potential (W_z) combined with the normalised charge distribution ($\lambda_{q=1}$).

$$k_z = - \int \lambda_{q=1} \cdot W_z dt \quad (1)$$

In order to calculate the energy lost from a single bunch (E_{sb}), we scale the wake loss factor with the square of the bunch charge.

$$E_{sb} = k_z \cdot Q_{bunch}^2 \quad (2)$$

We now know how much energy is transferred from the bunch into the fields in the structure.

From each of the p ports we can get the time evolution for each of the m mode amplitudes $b_{p,m}$. The ports must only count the real part of the complex signal, as the real component corresponds to the transmitted signal rather than any evanescent signal moving around the structure and contacting the port boundaries. By combining the square of these signals we can account for the power which leaves the structure, and how it leaves it.

The integral will give the energies output on the ports.

$$E_{p,m} = \int \Re(b_{p,m})^2 dt \quad (3)$$

This can also be seen as the power of a 1 bunch per second train, and thus realistic powers can be found by using knowledge of the bunch spacing in the machine.

Additionally, by using a cumulative sum one can see the evolution of the energy deposition (see Fig. 2)

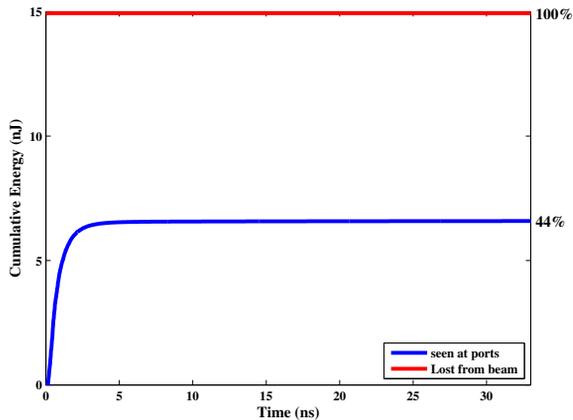


Figure 2: The time evolution of the energy leaving our example structure.

One would expect the curve to flatten out after some time as the energy which can escape does, leaving only that which is trapped. Thus, this flattening is a good indicator that the simulation has run for long enough, and will provide a realistic set of results.

Once one has the mode by mode, port by port signals they can be combined in different ways, for example, to find the fraction of power emitted down the beam pipe.

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Likewise one can find the power coming out of the signal ports. By adding up all the energy passing through all ports, we can get a measure of the total energy leaving the structure. We assume everything which is lost from the beam, but is not emitted by the ports is left in the structure. For our example this implies 56% of the power lost from the beam is trapped in the structure. This can be either power lost into the materials, or power which is trapped or very high Q modes and has not had time to radiate away at the time the simulation terminates. The assumption in this case is that all the trapped energy will eventually be absorbed by the material. We can then get a measure of the energy deposited into the structure, and thus the heating.

Frequency Domain

As before, we are looking to calculate the wake loss factor and the energy loss per bunch. Initially, we have to do the conversions into the frequency domain. (charge distribution (λ_q)¹).

$$S_{bunch} = \mathcal{F}\{\lambda_q\} \quad (4)$$

Where λ_q is the charge distribution, and S_{bunch} is the bunch spectrum

In order to get the wake impedance (Z_{wake}) the Fourier transform of the wake potential needs to be divided by the bunch spectrum

$$Z_{wake} = -\Re\left(\frac{\mathcal{F}\{W_z \cdot Q_{bunch}\}}{S_{bunch}}\right) \quad (5)$$

The bunch spectrum can also be used with the wake impedance to get power lost from the bunch (P_{bunch}) from which one can obtain the wake loss factor.

$$P_{bunch} = \int (|S_{bunch}|^2 \cdot Z_{wake}) df \quad (6)$$

The implementation of the Fourier transform is as a discrete transform, which implies that the bunch is repeated after each simulation time, so one initially has the power in an infinitely long bunch train. In order to get the energy in one simulation run, (i.e. 1 bunch) multiply the power for an infinite train by the simulation time (T)

$$E_{bunch} = P_{bunch} \cdot T \quad (7)$$

$$k_z = \frac{E_{bunch}}{Q_{bunch}^2} \quad (8)$$

As before, this gives us a measure of the energy lost from the beam.

By analysing in the frequency domain, in addition to accounting for the power passing through the ports on a port by port and mode by mode basis, it also allows us to separate the power on a frequency by frequency basis.

The frequency separation gives us the chance to identify the causes of various features, and so we can get an

¹We want the real component as this corresponds to resistive losses. The imaginary component by contrast corresponds to a reorganisation of the energy structure but generates no losses.

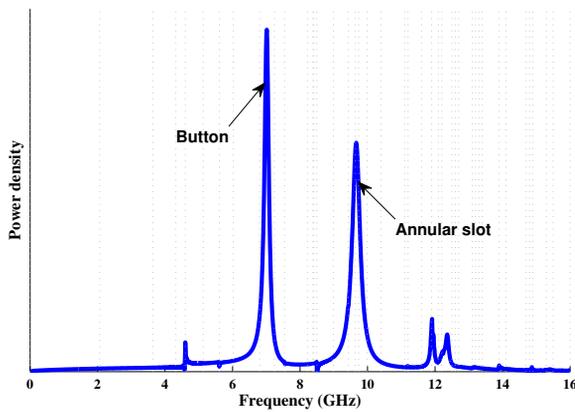


Figure 3: The frequency map of the power left in the structure.

idea of which section of the structure contributes most to the heating. By looking at the field distributions at the frequency of the peaks one can usually find the location of the resonance. In the example structure, we could identify the button as causing one strong resonance, while the other large contribution was tracked down to the annular slot slot (Fig. 3).

This view has similarities to the approach used by Günzel[2], Pinayev[3] and others where the Q factors of eigenmode resonances are used to estimate the relative losses.

As this is all in a frequency basis one can see what frequencies are important for the different outputs. This gives us the possibility to predict the output signal seen at a measurement port (Fig. 4). In principle one can now compare the simulation results with real world measurement data.

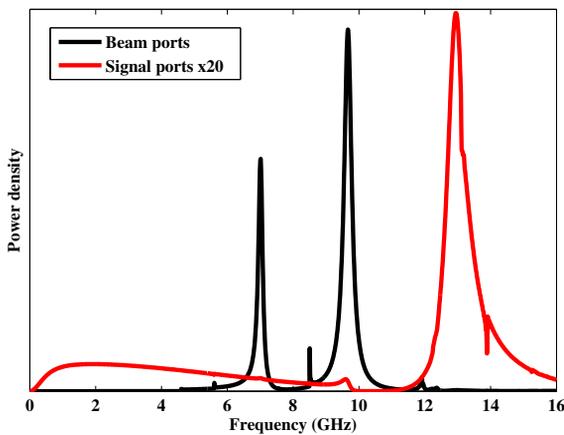


Figure 4: The frequency spectra emitted down the beam pipe, and out of the signal ports.

The wake loss factor and total port power loss results give a valuable cross check against the time domain approach, but we now have a much clearer understanding of which frequencies are emitted, where from, and which are trapped or absorbed by the structure.

EXTENSION TO DIFFERENT MACHINE CONDITIONS

All the previous analysis assumes a single bunch as that is usually what is modelled in the EM simulation. In a ring machine however, there will be multiple bunches passing through the structure over time.

As the wake impedance is a function of the structure only, then we can use it as a basis for investigating a range of machine and beam conditions.

By generating bunch spectra at a range of bunch lengths and fill patterns, and combining it with the simulated wake impedance, the wake loss factor for a range of machine conditions can be found from one set of simulations.

A similar approach can be taken with the port signals. In this case the 'impedance' is effectively a transfer function of the port. By doing this analysis on the port signals as well we can take into account the fact that the beam at different machine conditions has more or less power above the cut off frequency of the various port modes.

This post processing approach has a large time advantage over simulating each condition separately.

However, when investigating the effect of bunch train length, the limitations of the simulation length may become more apparent. The wake impedance, as we based on a time limited input, has by implication, a limit to the frequencies, it can represent. This means that a high Q resonance may not be truly represented. For a single bunch this will only cause a small error as the integrated energy is the same and is combined with a slowly changing bunch frequency spectrum. It can be seen as the envelope of the bunch power spectrum shown in Fig. 5. However for a bunch train the frequency response has sharp lines, thus the fine structure of the wake impedance becomes important (see Fig. 5).

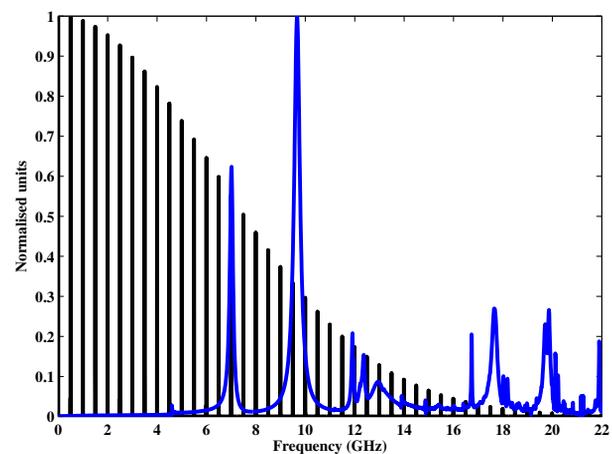


Figure 5: The overlap of the wake impedance and the power spectrum of a bunch train.

In order to validate this approach we simulated a structure at several values of longitudinal bunch length and com-

pared the results with the reconstruction using the shortest bunch length model. As one can see in Fig. 6, the agreement is very good.

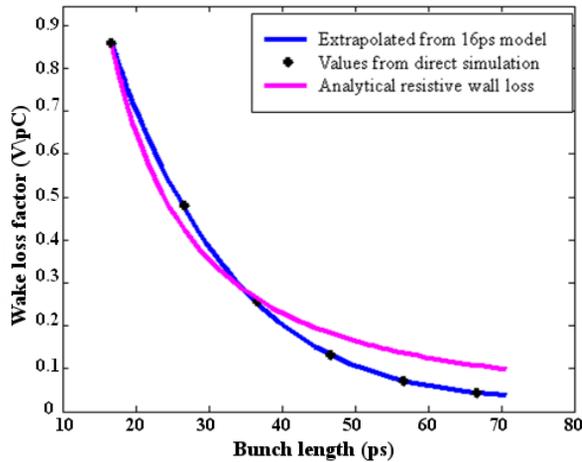


Figure 6: The effect of bunch length on the wake loss factor. For reference this is compared with the expected analytical resistive wall losses.

Another investigation is to calculate the expected bunch parameters for various operational conditions and see how things change when these are altered (raising the beam current for example).

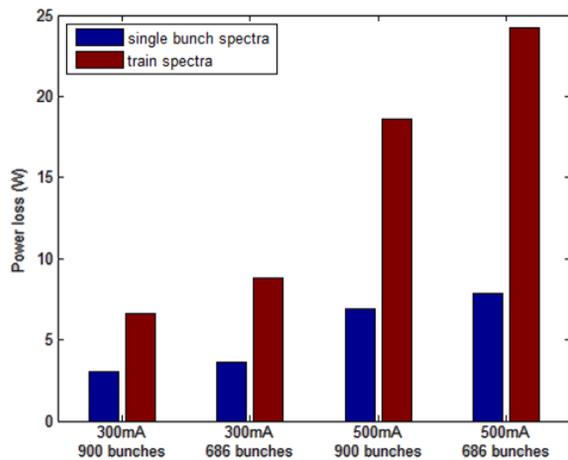


Figure 7: The effect of different machine conditions on power deposited into the structure.

Figure 7 shows how the power deposited into a structure can change markedly for differing machine running conditions. It also highlights the potential error which can be committed if only the pure single bunch case is considered.

Once the loss results from all the simulation runs are available, adjusted for the machine conditions of interest, one can combine them to discover which component contributes the most. By taking the difference between the

fully lossy model and each of the other models one can calculate the fractional contributions each component makes to the overall loss. The loss distribution for our example structure is shown in table 1. We found that the annular slot had the largest impact followed by the mounting block, and then the button. The button and the annular slot slot also showed up in the frequency spectrum of the power left in the structure as they were distinct resonances. The block response was much more broadband so only showed up as an increase in loss when it was not set to a perfectly conducting material.

Table 1: Fractional Loss Distribution Within Structure

Component	Fractional loss
annular slot	68%
mounting block	13%
button	10%
ceramic	~1%
pin	~1%

As is clear from table 1 this only accounts for ~93% of the losses within the structure. This discrepancy is put down to perturbations in the fields between different model configuration and could be improved by making smaller changes to each model. For example only changing a single button rather than all the buttons together. However even the current results have given us great insight into the causes of the observed heating.

CONCLUSIONS

From the realisation that we needed a better understanding of the heating effects due to wake losses we have been able to develop the tools to be able to more realistically assess the risk new machine parameters pose to the diagnostics systems. By combining the power of EM simulation with knowledge of the beam structure we have developed an approach which gives us a much better insight into the sensitivity to machine changes and to which component features are most prone to heating. This work also informs our designs going forward, where we will be able to make design decisions on a much firmer footing.

Although this analysis has been used primarily to investigate localised heat losses, it can be used more generally, for example to investigate the thermal effects of beam offsets.

REFERENCES

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