Estimation of the Mode Losses in Complex RF Vacuum Devices

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Abstract

It is mandatory to reduce the mode losses in superconducting beam-tube structures due to the high costs of low temperature cooling. For the analysis of the HERA beam-position pick-up, as a complex three-dimensional rf vacuum device, the new 3D MAFIA code is used. Extensive checks with the 2D URMEL code as well as bench measurements in the frequency domain completed the estimation of the mode losses.

Introduction

The beam position in the HERA proton storage ring will be measured by about 250 directional-coupler pick-up stations [1]. They are build into the $4\,K$ cryostat of the superconducting magnets. Due to the high cost of the low temperature cooling it is important to minimize the introduced heat. For the HERA pick-up the losses have to be kept in the subwatt range. A considerable fraction of the heat losses is due to the so called *mode losses*, caused by excitation of electromagnetic field resonances in the pick-up by the beam[1]. This paper is concerned with the determination of these resonances.

The losses can be determinated in two complementary ways, in the time and in the frequency domain. Here the computation is done in the frequency domain, because wakefield effects can be estimated more easily and only a small number of resonances have to be considered[2]. The measurement is also done in the frequency domain, because this method determines each resonance separately with a high precision[3].

Power Losses of Resonance Modes

A particle beam excites resonance modes in a deformed section of the vacuum chamber. Number, type and quality factor of the possible modes are characteristic properties of the specific rf vacuum device. The excitation strength from a centered beam[4] is defined by the bunch spectrum.

Only a fraction of the modes has to be considered. In a cylindrically symmetrical device these are the TM monopole modes. Furthermore we used all relevant modes up to the beam pipe cutoff frequency, which is well above the $3\,dB$ frequency of our shortest bunch.

Next we describe the relation between the normalized power loss and the device parameters for a single mode. The normalized voltage across the RF-structure is given by [3]:

$$v_{n,\lambda}(t) \approx 2\, q_b\, k_{n,\lambda}\, \exp(-\frac{t}{Q_\lambda/\omega_\lambda})\, \cos(\omega_\lambda t) \tag{1}$$

Here ω_λ is the resonance frequency, Q_λ the quality factor and $k_{n,\lambda} = (\omega_\lambda/2)\,(R_\lambda/Q_\lambda)$ the normalized loss factor – with the shunt impedance R_λ – of an excited mode. Finally q_b is the test charge of a "dirac bunch".

For a bunch train with a time spacing T_b the voltages add up to

$$V_{n,\lambda} = 2\, q_b\, k_{n,\lambda}\, \frac{1-\exp(-\tau_\lambda)\cos(\omega_\lambda T_b)}{1-2\exp(-\tau_\lambda)\cos(\omega_\lambda T_b)+\exp(-2\tau_\lambda)}, \tag{2}$$

[1]The effect of the resonance modes on the stability of the beam was not our major concern.
[2]We consider only resonances below the beam pipe cutoff frequency.
[3]With stimulating pulse techniqes a resolution of only several watts was obtained [2].
[4]This simplification is valid for mode loss estimations.

	URMEL	MAFIA[a]
CPU time	$1\ldots3\,min$	$2\ldots4\,h$
elapse time	$10\ldots15\,min$	$20\ldots30\,h$
memory	$2\,MB$	$4\,MB$
meshpoints[b]	4000	30000

[a]In the MAFIA code set the E31 eigenvalue finder is used. R_λ and R_λ/Q_λ are computed interactively with P3.
[b]For URMEL problems we used a fourfold (except example No. IV) and for MAFIA an eightfold symmetry.

Table 1: Typical program data and computing performance

with $\tau_\lambda \approx \dfrac{T_b}{Q_\lambda/\omega_\lambda}$.

The $\omega_\lambda T_b$ term describes the phase between the bunch under test and the wakefields of the previous bunches. We get an upper limit of the mode losses by setting $\cos(\omega_\lambda T_b) = 1$:

$$V_{n,\lambda_{max}} = 2\, q_b\, k_{n,\lambda}\, \frac{1}{1-\exp(-\tau_\lambda)} \tag{3}$$

For the power loss per mode we get:

$$\begin{aligned} P_{n,\lambda_{max}} &= \frac{1}{2} V_{n,\lambda_{max}} I_0 \qquad , \text{with } I_0 = \frac{q_b}{T_b} \\ &= \frac{I_0^2}{2} R_\lambda \frac{\tau_\lambda}{1-\exp(-\tau_\lambda)} \\ &\approx \frac{I_0^2}{2} R_\lambda \qquad , \text{for small } \tau_\lambda \end{aligned} \tag{4}$$

The total power loss is given by the sum of the losses in every single mode n, where the normalized bunch spectrum ρ has to be taken into account:

$$P_{tot_{max}} = \sum_\lambda P_{n,\lambda_{max}} \cdot \rho^2(\omega_\lambda) \tag{5}$$

Computations for a practical RF Vacuum Device

The main task of the computation is to find all the relevant resonance modes of the structure. This is done by discretising the Maxwell equations and solving the eigenvalue problem. For cylinder symmetrical examples we used the URMEL code [4] and for three-dimensional ones the more general MAFIA codes [5].

The programs supply the modes with their resonance frequencies and electromagnetic fields. The Q_λ and R_λ/Q_λ values are computed from the field vectors. In the URMEL code this is done in a canonical way, in the MAFIA codes an integration path has to be specified – which is in our cases the symmetry axis.

Both codes run on the DESY central computer (IBM 3084–Q). Table 1 gives an impression of the typical program data of the examples under discussion and the computing performance. Practical experience shows that the eigenvalue finder SAP [7] of the codes is very sensitive to its main input parameter: the maximum resonance frequency of interest. Furthermore, closely spaced substructures lead to

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problems, which have to be tackled by fine tuning of the SAP parameters.

Next we explore the influence of geometry variations on the mode losses of the beam-position pick-up for the HERA proton storage ring [1]. For all comparisons a rather extreme HERA operation condition was chosen: a beam current of $0.163\,A$ and a bunch length of $0.3\,m$ with a parabolic shape in phase space[5] [6]. As a pessimistic approximation we used the envelope of the corresponding bunch spectrum $\rho(\omega_\lambda)$.

An inspection of different pick-up body structures (geometries I, II and III of Table 2) shows that a smooth – even though short – tapering reduces the mode losses by a factor up to two. The losses vary substantially for different antenna suspensions (Tab. 2, geometries IV, V and VI), where the antennas always enhance the dissipated power (II). The power losses are particularly high for structures with shorted antennas (geometry IV), due to a *coaxial transmission-line effect*. The best solution is simply hanging the antennas into the straight beam pipe (IV). For the HERA proton storage ring this is not possible due to the unavoidable reduction in acceptance. Therefore we used an antenna suspension in a beam pipe indentation (VI) with reasonably low power losses compared to the no antenna case (II).
The URMEL code, used for these cylinder symmetrical calculations, took neither our finite antenna width nor the complex shaped pick-up body structure into account[6]. In order to minimize the mode losses we used the smallest mechanically tolerable width. For the HERA beam-position pick-up (Tab. 2, geometry VIII) the maximum power loss is estimated to be:

$$\boxed{P_{tot_{max}} \approx 0.18\,W}$$

Detailed Comparisons of Power Loss Estimation Methods

For the relative simple rf vacuum structure II we compared the results of the different power loss estimation methods in detail. Two-dimensional – with the URMEL code – and three-dimensional calculations –with the MAFIA codes – as well as measurements for all relevant modes were performed (see Table 3).

The measurement of the resonance frequencies ω_λ and the corresponding Q-values Q_λ were done with the transmission method [8]. The shunt impedance R_λ is related in a simple way to the electric field component E_{z_λ} along the axis of interest: $R_\lambda/Q_\lambda = 1/2\,(\int (E_{z_\lambda}/\sqrt{P_\lambda Q_\lambda})\,dz)^2$, where P_λ is the power loss of the mode. The term $E_{z_\lambda}/\sqrt{P_\lambda Q_\lambda}$ is measured with the frequency shift method [9], and we get:

$$\frac{R_\lambda}{Q_\lambda} = \frac{2}{\omega_{p,\lambda}\,\epsilon\, c_E}\left[\left(\int_0^\ell \sqrt{\delta}\cos\frac{z\,\omega_{p,\lambda}}{c}\,dz\right)^2 + \left(\int_0^\ell \sqrt{\delta}\sin\frac{z\,\omega_{p,\lambda}}{c}\,dz\right)^2\right]$$

$\delta = \frac{\omega_{p,\lambda}-\omega_\lambda}{\omega_\lambda}$ relative frequency shift

c_E shape factor of the perturbing object

ϵ dielectric constant of the perturbing object

ω_λ frequency of the unperturbed resonance mode

$\omega_{p,\lambda}$ frequency of the perturbed resonance mode

Conclusion

In this paper we have presented frequency domain methods to compute and measure the power loss of vacuum devices. Mode losses in the *subwatt* range can be estimated. These methods can be applied to structures of almost any shape.

[5] In real space the shape has the form: $i_{norm}(t) = 16\,c\,[1-(2\,c\,t/\ell)^2]^{3/2}/(3\,\pi\,\ell)$

[6] Before the advent of 3D codes it was customary to take thewidth into account by scaling the cylindrically symmetrical result by the ratio of antennna-width to circumfence. For the Hera beam-position pick-up this crude method results in $P_{tot,max} \approx 0.7\,W$.

n_λ	$f_\lambda\,[MHz]$	Q_λ	$R_\lambda/Q_\lambda\,[\Omega]$
1	3059 [a]	29895	0.0859
	3044 [b]	31182	0.1114
	3072 [c]	19820	0.2
2	3101	29872	0.0680
	3086	31134	0.0477
	3110	23930	0.7
3	3169	29897	0.3304
	3152	31077	0.4520
	3179	23560	0.2
4	3265	30029	0.8859
	3248	31171	0.9432
	3277	23410	1.5
5	3387	30297	0.0724
	3370	31445	0.0621
	3397	17880	0.1
6	3531	30702	0.5309
	3515	31874	0.7157
	3543	21480	0.6
7	3696	31223	1.5633
	3680	32446	1.8835
	3708	20050	1.6
8	3878	31802	1.2152
	3863	33121	1.1626
	3891	19470	1.6
9	4070	32017	0.4529
	4055	33600	0.1808
	4085	13620	0.7

[a] 2D calculation
[b] 3D calculation
[c] rough measurement

Table 3: Comparison of the different estimation methods (results for geometry II of Tab. 2)

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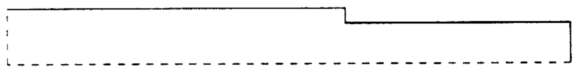
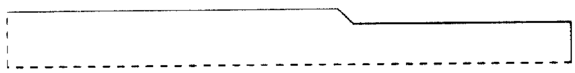
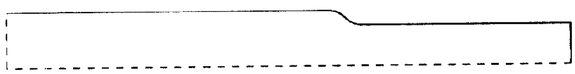
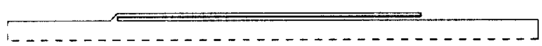
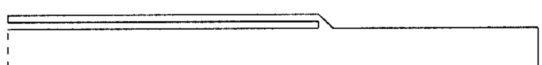
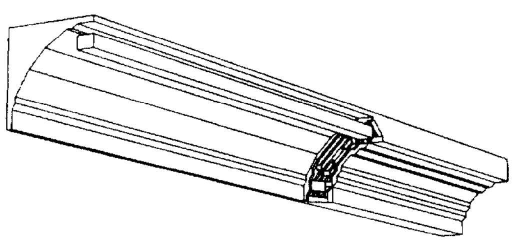
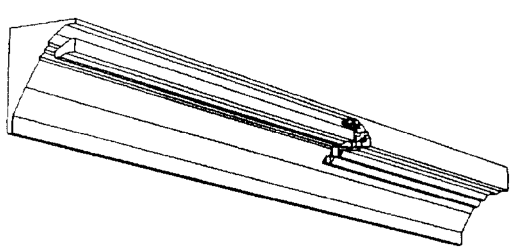
	geometry	program code used	power loss
I		URMEL	0.73 W
II		URMEL	0.50 W
III		URMEL-T	0.48 W
IV		URMEL	207 W
V		URMEL	1.02 W
VI		URMEL	2.87 W
VII		MAFIA	4.92 W
VIII		MAFIA	0.18 W

Table 2: Comparison of computed rf vacuum structures