LHC Project Note 118

July 1997
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RF Losses in the FELIX Experimental Chamber

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Keywords: Coherent losses, FELIX vacuum chamber, RF-screen

Summary

The aim of this note is to analyse the coherent losses in the FELIX experimental chamber. Because of the large number of bunches in the LHC, the coherent loss factor can reach rather large values and a careful analysis of the bunch frequency spectrum and the frequency spectrum of the trapped modes in the FELIX experimental chamber is necessary. The analysis shows that an additional RF-screen can reduce the coherent losses.

1 Introduction

For a broad band impedance the wake fields extend only over a short range behind the bunch and the wake fields of two consecutive bunches can not interfere. Thus, for a broad band impedance, the total power loss of all bunches is given by the product of the number of bunches and the power loss per bunch. For a narrow band impedance, the wake fields extend over a long range behind each bunch and the wake fields of successive bunches can overlap. Depending on the distance of the successive bunches, this overlap of the wake fields can lead to a coherent power loss which is proportional to the square of the total number of bunches. An analysis of the longitudinal trapped modes in the FELIX vacuum chamber shows that the experimental chamber has a rich spectrum of modes with Q-values larger than 20,000, indicating the significance of coherent losses. Because of the large number of bunches in the LHC (2835 bunches) the coherent power loss can be significantly larger than the incoherent one, reaching values larger than a few kWatts.

2 Incoherent Losses

Fig. 1 and 2 show the upper half of the FELIX experimental chamber. It should be pointed out that the radial and longitudinal dimensions are not identical. The maximum radius of the experimental chamber is only 70 cm, whereas the total length of the chamber is 20 m. Fig. 1 shows the vacuum chamber without RF-screen and Fig. 2 shows the same layout but with an additional RF-screen at a radius of 8 cm. This screen can be either made out of a solid tube with pumping slots for the vacuum or by stretched wires or ribbons.

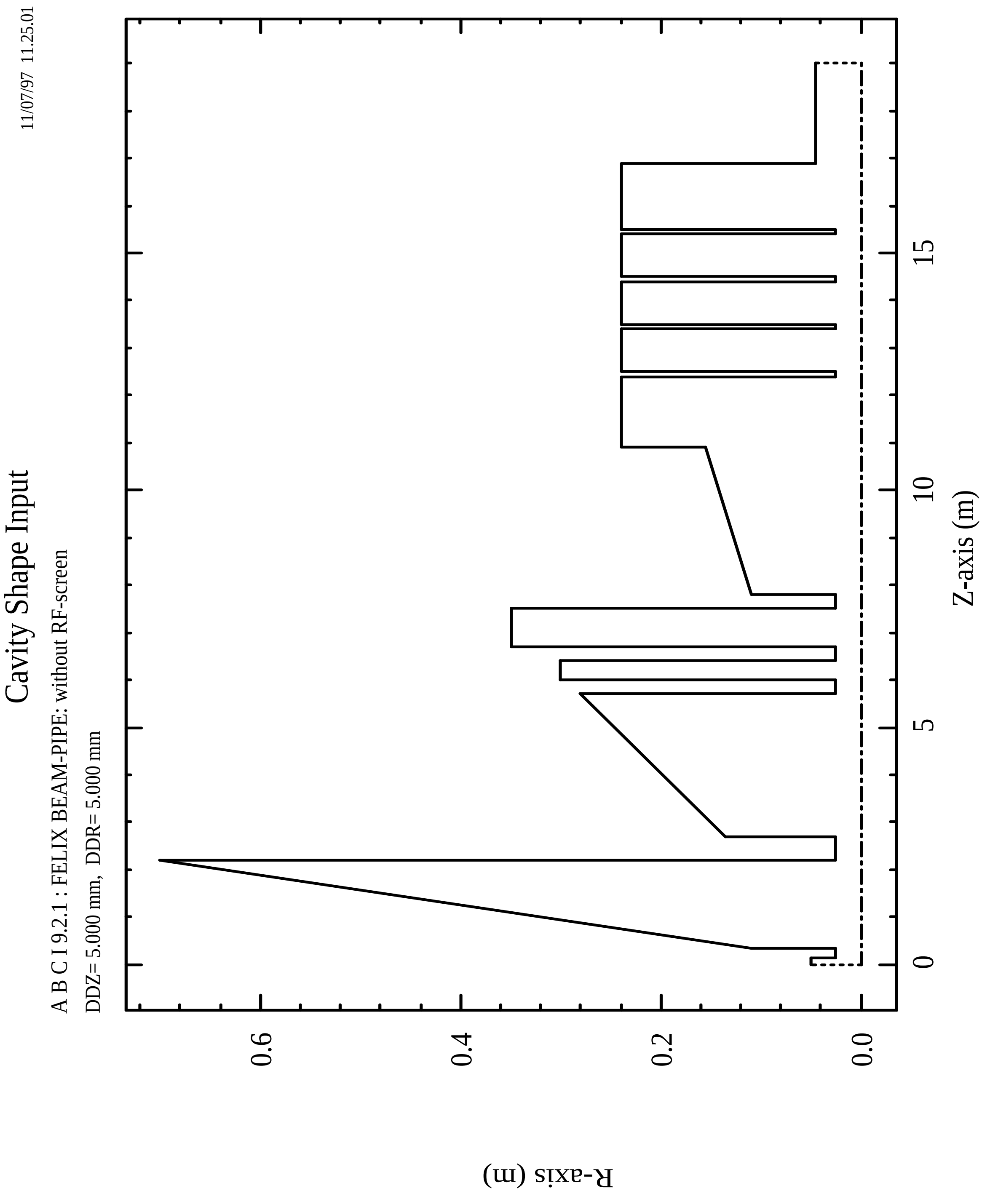

Figure 1: *The FELIX vacuum chamber without RF-screen. The vacuum chamber has rotational symmetry along the longitudinal axis and mirror symmetry at the IP. The picture shows only the upper half of the right half of the chamber. Note the different radial and longitudinal dimensions.*

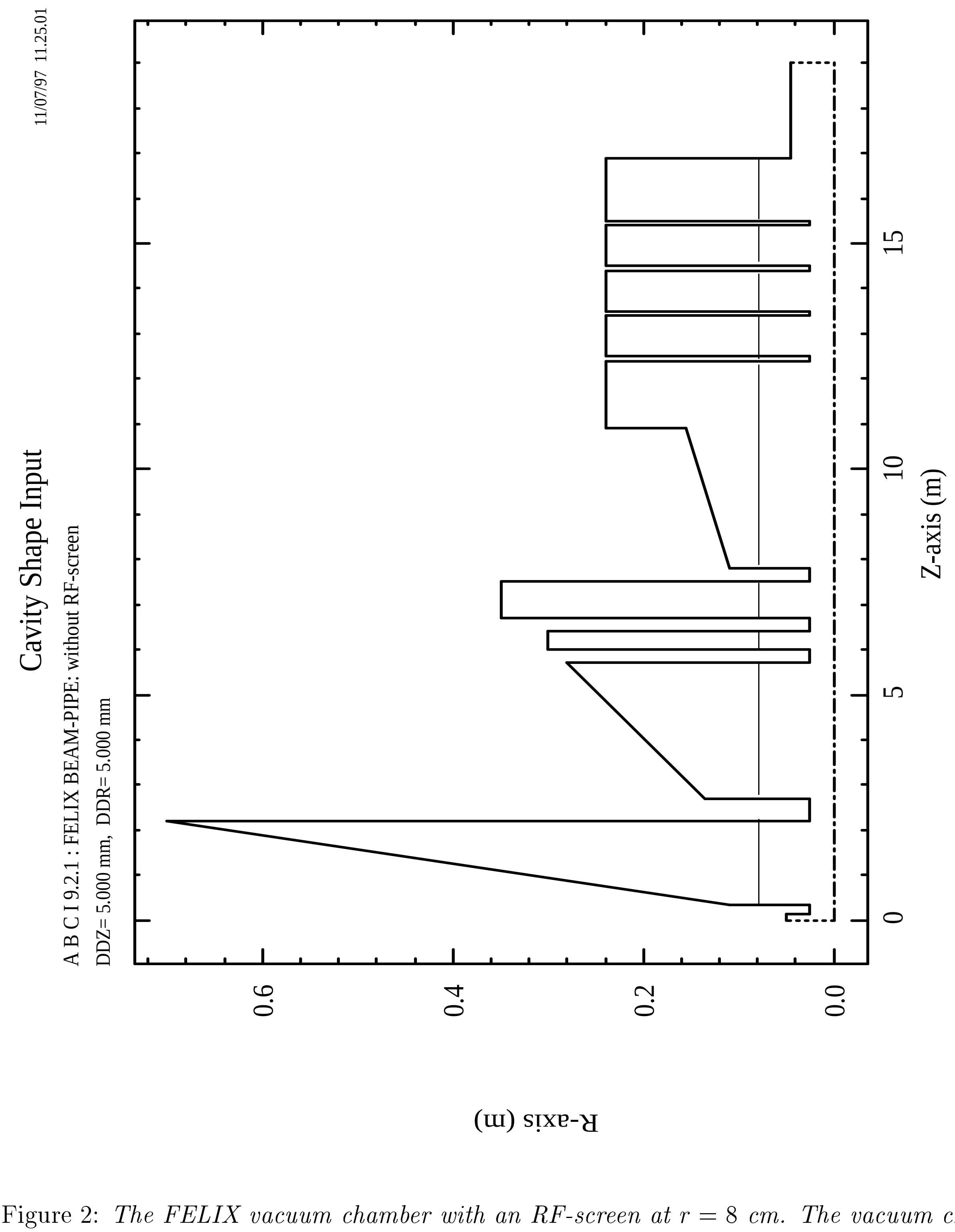

Figure 2: *The FELIX vacuum chamber with an RF-screen at* $r = 8$ *cm. The vacuum chamber has rotational symmetry along the longitudinal axsis and mirror symmetry at the IP. The picture shows only the upper half of the right half of the chamber. Note the different radial and longitudinal dimensions.*

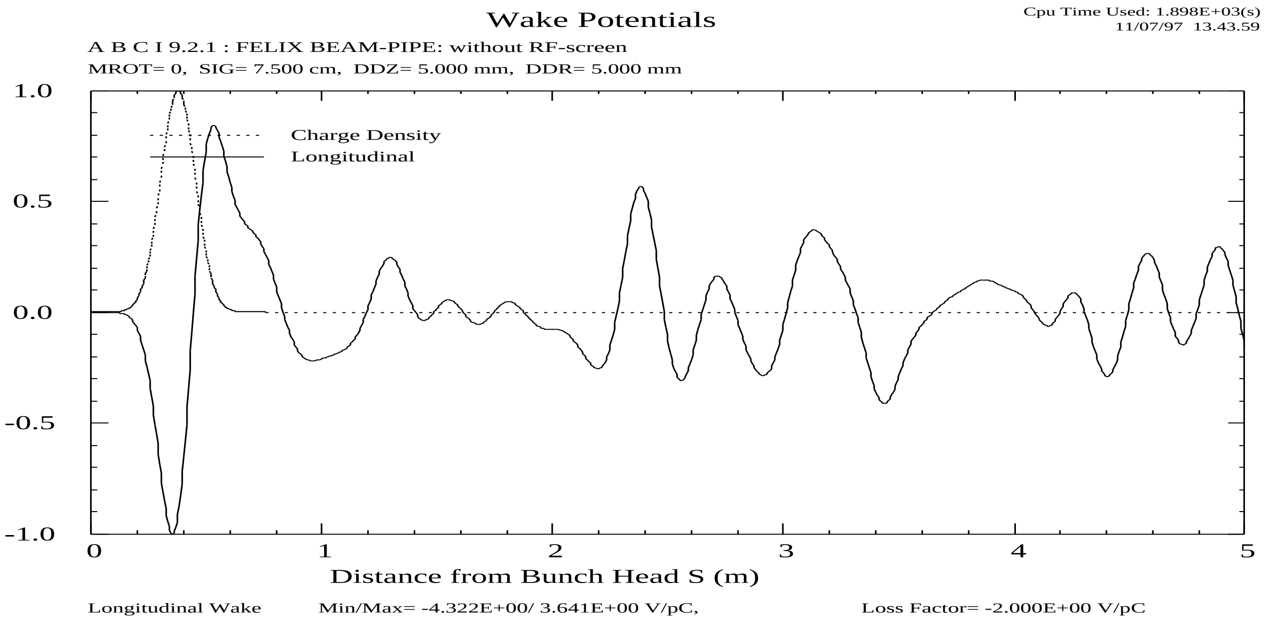

Figure 3: *The longitudinal wake potential for the FELIX vacuum chamber without RF-screen and a bunch length of 7.5 cm (luminosity operation).*

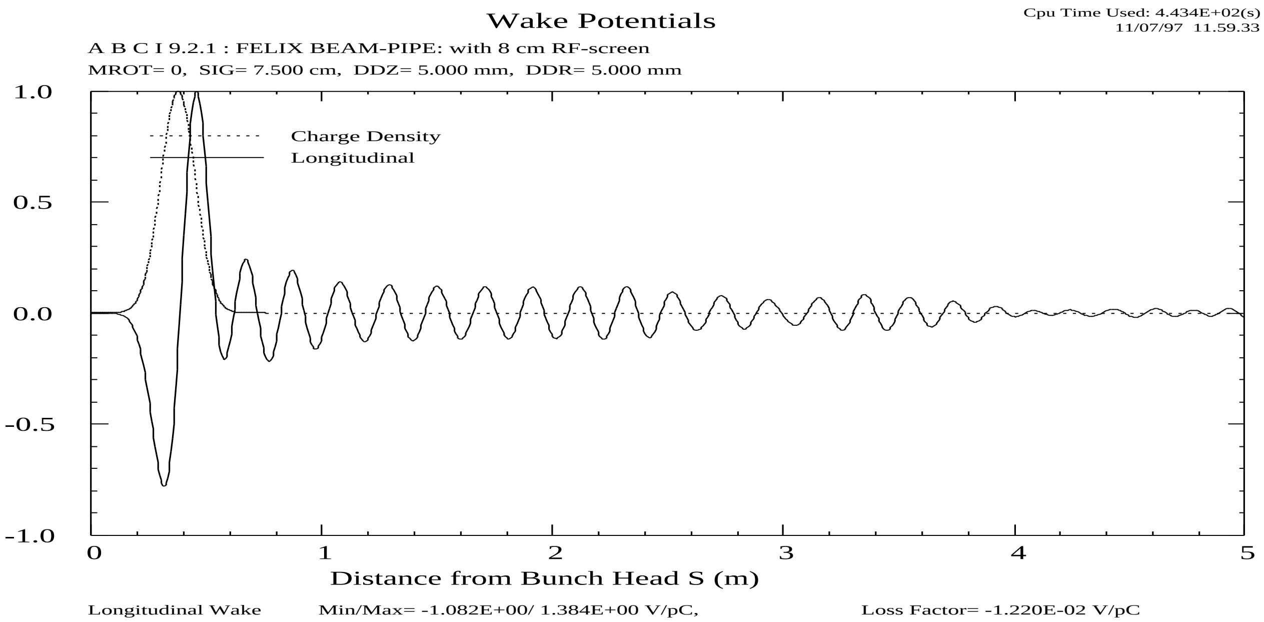

Figure 4: *The longitudinal wake potential for the FELIX vacuum chamber with an RF-screen at $r = 8$ cm and a bunch length of 7.5 cm (luminosity operation).*

Q_b [C]	N_b	f_{rev} [KHz]	k_L [V/pC]	$k_{L,scr}$ [V/pC]	$k_{L,tap}$ [V/pC]	σ_i	σ_l
$1.6 \cdot 10^{-8}$	2835	11.245	-2.000		-0.012 -0.0051	13.0 cm	7.5 cm

Table 1: *Parameters for the LHC. Q_b is the total charge per bunch, N_b the total number of bunches in the machine, f_{rev} the revolution frequency, k_L the loss factor for the experimental chamber without RF-screen, $k_{L,scr}$ the loss factor for an experimental chamber with RF-screen at an radius of 8 cm, and $k_{L,tap}$ the loss factor for an experimental chamber with an RF-screen which has an additional tapering over 20 cm at the begining and end of each screen section, and σ_i and σ_l are the bunch lengths at injection and luminosity energy respectively.*

The detailed geometry of the RF-screen is not of essential relevance for the following calculations. The aim here is not to present a final design for such a screen, but rather to a estimate weather is is feasible to reduce the RF-loads generated in the vacuum chamber by means of an RF-screen. Assuming for the moment a screen with a copper surface one needs at least a copper thickness of 17.5 μm in order to screen frequencies above 40 MHz (bunch frequency for the nominal bunch separation).

The incoherent loss factor is given by

$$k_L = -\frac{1}{Q_b^2} \int_{-\infty}^{+\infty} dz' \rho(z') \int_{-\infty}^{+\infty} dz \rho(z) W_L(z' - z), \tag{1}$$

where Q_b is the total charge per bunch, $\rho(z)$ the longitudinal charge distribution, and W_L the longitudinal wake potential of a point charge. Fig.3 shows the wake potential for a vacuum chamber without RF-screen and Fig.4 shows the corresponding wake potential for a vacuum chamber with an RF-screen with a radius of 8 cm.

The total power loss associated with the incoherent loss factor is given by

$$P_{incoh.} = N_b \cdot k_L \cdot Q_b^2 \cdot f_{rev}, \tag{2}$$

where N_b is the number of bunches in the machine, Q_b the total charge per bunch, and f_{rev} the revolution frequency. The parameters for the LHC are given in Table 1.

Inserting the values from Table 1 into Equation 2, one obtains a total incoherent power loss of

$$P_{incoh.} = 16.32\mathrm{kW} \tag{3}$$

for the structure without RF-screen,

$$P_{incoh.} = 97.93\mathrm{W} \tag{4}$$

for a structure with RF-screen and

$$P_{incoh.} = 41.62\mathrm{W} \tag{5}$$

for a structure with RF-screen and an additional tapering over 20 cm at the beginning and end of each screen section.

There is no resonance condition associated with the incoherent losses and in all cases the vacuum chamber/RF-screen must be capable to dissipate the heat of the incoherent losses. The values given in Equations (3), (4) and (5) are per beam. Thus, during luminosity operation, the chamber must dissipate twice these values.

The incoherent losses for a vacuum chamber without RF-screen reach intolerable values of more than 16 kW. Compared to these large losses, the vacuum chamber with RF-screen has rather moderate incoherent losses of less than 2×100 W. However, the RF-screen will be in vacuum and it can dissipate the accumulated heat only at the end points where it is connected to the outer vacuum chamber. It still remains to be examined whether a heat load of about 200 W can be tolerated in such an environment and whether the resulting temperature increase on the screen is compatible with the vacuum requirements. In any case, the required minimum thickness of the screen will probably be determined by the heat load produced.

3 Coherent Losses

For the coherent power loss associated with a narrow band impedance, one has to include the bunch distribution and a sum over multiple revolutions in Equation 1. Assuming for the sake of simplicity an equidistant bunch distribution one can write the coherent power loss as [1]

$$P_{coh.} = -f_{rev}^2 \cdot N_b^2 \cdot Q_b^2 \cdot \sum_{p=-\infty}^{+\infty} \cdot \exp\left(-[p \cdot N_b \cdot \omega_0 \sigma_z]^2 / 2c^2\right) \cdot Z_0^{||}(p \cdot N_b \cdot \omega_0). \tag{6}$$

Assuming a resonator impedance of the form

$$Z(\omega) = \frac{R_S}{1 + iQ\left(\frac{\omega_R}{\omega} - \frac{\omega}{\omega_R}\right)}, \tag{7}$$

where R_S is the shunt resistance, Q the quality factor, and ω_R the resonance frequency of the impedance, the sum in Equation 6 can be evaluated analytically [5]. Assuming further a narrow band resonator impedance with

$$\triangle \equiv \frac{\pi f_{rev}}{2Q f_b} \tag{8}$$

and satisfying

$$\triangle \ll 1 \quad \text{and} \quad Q \gg 1, \tag{9}$$

one gets [5]

$$P_{coh.} = -2 \cdot f_{rev}^2 \cdot N_b^2 \cdot Q_b^2 \cdot R_S \cdot \frac{\triangle^2 e^{-(\omega_R \sigma / c)^2}}{\sin^2(\pi f_R / f_b) + \triangle^2} \tag{10}$$

(f_b is the bunch frequency). Both assumptions are satisfied by the HOM spectrum of the FELIX vacuum chamber.

Because both beams of the LHC share the same vacuum tube at the interaction points, the wake fields of both beams will contribute to the coherent loss factor. Assuming two identical counter rotating beams with the same bunch spectrum, the wake fields of the two beams will cancel each other. However, if the two beams are not identical, the wake potentials will not cancel and the beam spectrum seen by the impedance consists of the sum of the beam spectra of both beams. Because all vacuum chambers should be able to tolerate the operation with one beam only, we will assume in the following only one beam. Furthermore, we will consider a worse case scenario, where one of the beam spectrum lines lies right on one of the resonance frequencies of the vacuum chamber. This assumption is motivated by the uncertainty of the exact HOM spectrum. Even small mechanical tolerances in the final geometry of the vacuum chamber can produce rather large mode frequency shifts. For example, a change of the maximum radius at the first cone in Fig. 1 by 1 mm can shift the mode frequency by more than 1 MHz. However, one might argue in the end that when the difference between the HOM frequency and an integer multiple of the bunch frequency is larger than 10 MHz it will be unlikely that the beam will excite this HOM.

Table 2 shows data for the first 30 longitudinal modes for the FELIX experimental chamber without RF-screen calculated with the MAFIA program [3]. Table 3 and 4 show the corresponding modes for a structure with an RF-screen at a radius of 8 cm. All trapped modes in Tables 2 and 3 satisfy the criterion (9) of a narrow band impedance. The calculations for the data in Tables 2, 3 and 4 assumed a Cu vacuum chamber.

Assuming that the resonance frequency of the impedance is right on a frequency line of the bunch spectrum we find for the vacuum chamber without RF-screen a rich spectrum of HOM with a coherent power loss of more than 500 kW.

For a structure with RF-screen we find 13 HOM with a coherent power loss of

$$P_{coh.} > 200 \text{ W}. \tag{11}$$

Even a heat load of 200 W per mode is rather large and one either has to avoid that the resonance frequency of the trapped modes lies right on one of the frequency lines of the bunch spectrum or one has to reduce the shunt resistance of the trapped modes in the FELIX vacuum chamber. The first method seems to be difficult because the bunch spectrum of the two counter rotating beams changes during the filling procedure or when only part of the beams are lost. Furthermore, as we mentioned already above, even small mechanical deformations of the vacuum chamber can lead to a significant shift of the mode frequencies. Even after installation, the geometry of the chamber could change slightly due to temperature changes. A scheme that aims at avoiding the overlap of any of the trapped mode frequencies with the beam spectrum has to consider all possible bunch distributions in the machine and a reasonable tolerance for the calculated mode frequencies.

The second method is referred to as 'de-Qing'. By putting a resistive material or an antenna in the structure, one can reduce the shunt resistance and the Q-values of the trapped modes while keeping the ratio R_S/Q constant. Unfortunately, resistive materials have a small free path length for particles penetrating through the material. Thus, the introduction of resistive materials into the vacuum chamber is excluded due to restrictions from the experiment. The introduction of antennas in the experimental chamber does not require resistive materials and thus is a feasible option. However, it does imply a non-uniform distribution of objects inside the experimental chamber and additional components and cabling outside the experimental chamber. Furthermore, a large number of HOM modes might also require a large number of antennas, each optimised for one mode. A reduction of the coherent loss to less than 10 W per trapped mode requires a 'de-Qing' to the point that $Q \sim 250$ and a scenario using antennas for this purpose requires further studies.

Mode #	$\omega_R/2\pi$ [Hz]	R_s/Q [Ω/m]	Q	$(\omega_R - \omega_b)/2\pi$ [Hz]	RF-loss [W]
1	1.952913e+08	111.29900000	36451	-3.53e+07	2493427.20
2	2.916767e+08	27.64000000	51364	-1.17e+07	765833.27
3	3.278493e+08	16.11510000	39754	-7.85e+06	325684.68
4	3.679997e+08	12.45160000	52536	-8.00e+06	310940.96
5	3.776386e+08	190.63700000	32784	-1.76e+07	2970742.42
6	3.825453e+08	186.86000000	30259	-2.25e+07	2687613.41
7	4.212772e+08	25.96880000	46023	-2.13e+07	526988.48
8	4.324361e+08	53.60390000	34493	-3.24e+07	815270.60
9	4.456595e+08	33.32970000	55948	-5.66e+06	756719.50
10	4.781349e+08	47.06030000	37256	-3.81e+07	711492.15
11	4.798314e+08	21.60850000	41237	-3.98e+07	361601.99
12	4.829656e+08	41.25710000	39963	-2.97e+06	610923.69
13	4.902006e+08	22.04950000	36081	-1.02e+07	294786.52
14	4.917328e+08	27.83930000	41690	-1.17e+07	430051.38
15	4.979011e+08	108.25100000	37635	-1.79e+07	1509572.91
16	5.063876e+08	0.71402100	31724	-2.64e+07	8393.24
17	5.113160e+08	7.08541000	55641	-3.13e+07	146079.67
18	5.241033e+08	35.83990000	37220	-4.10e+06	447765.65
19	5.263218e+08	46.32940000	39117	-6.32e+06	608316.71
20	5.352870e+08	26.16420000	33012	-1.53e+07	289925.98
21	5.412494e+08	15.00180000	64874	-2.12e+07	326678.78
22	5.707988e+08	29.64640000	40082	-1.08e+07	358486.17
23	5.757687e+08	15.73070000	39433	-1.58e+07	187136.70
24	5.826325e+08	1.36748000	38905	-2.26e+07	16050.09
25	6.101431e+08	6.84998000	44081	-1.01e+07	81227.17
26	6.230057e+08	0.77398400	65320	-2.30e+07	13599.97
27	6.336256e+08	25.70510000	41131	-3.36e+07	284412.94
28	6.460256e+08	22.49390000	43325	-6.03e+06	231920.91
29	6.536640e+08	50.50100000	48835	-1.37e+07	586904.38
30	6.796653e+08	3.25565000	43806	-3.97e+07	33939.69

Table 2: *Parameters for* **the first 30 longitudinal modes** *in the FELIX experimental chamber* **without RF-screen**. *The mode parameters are calculated with* **MAFIA**. *For the data in the fourth column we assumed a bunch length of* $\sigma_z = 7.5$ *cm.*

Mode #	$\omega_R/2\pi$ [Hz]	R_s/Q [Ω/m]	Q	$(\omega_R - \omega_b)/2\pi$ [Hz]	RF-loss [W]
1	1.4345111e+09	0.00497984	27193	-3.45e+07	0.69
2	1.4345112e+09	0.00518708	27193	-3.45e+07	0.72
3	1.4348873e+09	0.02175921	27084	-3.49e+07	3.02
4	1.4348881e+09	0.02196114	27083	-3.49e+07	3.05
5	1.4353457e+09	1.64289398	26680	-3.53e+07	224.81
6	1.4353459e+09	1.63126604	26681	-3.53e+07	223.23
7	1.4359967e+09	3.88032367	25744	-3.60e+07	512.23
8	1.4359980e+09	3.87115618	25740	-3.60e+07	510.94
9	1.4367749e+09	0.51110363	26839	-3.68e+07	70.36
10	1.4367784e+09	0.47656519	26848	-3.68e+07	65.63
11	1.4379893e+09	3.65809400	25920	-3.80e+07	486.22
12	1.4380639e+09	3.61548444	25834	-3.81e+07	478.95
13	1.4387458e+09	1.83293399	23522	-3.87e+07	220.94
14	1.4387556e+09	1.94143119	23591	-3.88e+07	234.71
15	1.4401181e+09	1.18583785	26058	-1.18e+05	119.38
16	1.4401247e+09	1.20782548	26037	-1.25e+05	121.50
17	1.4426214e+09	0.19102573	25878	-2.62e+06	19.10
18	1.4427610e+09	0.26611687	25876	-2.76e+06	26.60
19	1.4452549e+09	1.55923612	26791	-5.25e+06	161.43
20	1.4452560e+09	1.56946474	26791	-5.26e+06	162.49
21	1.4476902e+09	4.24273368	24193	-7.69e+06	396.28
22	1.4476904e+09	4.24655472	24194	-7.69e+06	396.65
23	1.4508967e+09	5.73036896	25122	-1.09e+07	555.98
24	1.4508976e+09	5.73143822	25129	-1.09e+07	556.24
25	1.4541489e+09	1.55050046	26698	-1.41e+07	159.96
26	1.4541608e+09	1.47150407	26705	-1.42e+07	151.85
27	1.4562186e+09	1.71484742	26204	-1.62e+07	173.61
28	1.4565112e+09	1.94352951	26228	-1.65e+07	196.95
29	1.4591024e+09	0.26369784	26452	-1.91e+07	26.95
30	1.4591092e+09	0.28966511	26455	-1.91e+07	29.61

Table 3: *Parameters for* **the first 30 longitudinal modes** *in the FELIX experimental chamber* **with an RF-screen at a radius of 8 cm**. *The mode parameters are calculated with* **MAFIA**. *For the data in the fourth column we assumed a bunch length of σ_z = 7.5 cm.*

Mode #	$\omega_R/2\pi$ [Hz]	R_s/Q [Ω/m]	Q	$(\omega_R - \omega_b)/2\pi$ [Hz]	RF-loss [W]
31	1.4659952e+09	0.01287400	26686	-2.60e+07	1.33
32	1.4660184e+09	0.01284559	26687	-2.60e+07	1.32
33	1.4684944e+09	3.06620410	26338	-2.85e+07	312.03
34	1.4685174e+09	3.11420997	26330	-2.85e+07	316.82
35	1.4730907e+09	2.28133007	26740	-3.31e+07	235.73
36	1.4731313e+09	2.40412563	26713	-3.31e+07	248.17
37	1.4766960e+09	0.11988499	23933	-3.67e+07	11.08
38	1.4767512e+09	0.12548190	23940	-3.68e+07	11.60
39	1.4799987e+09	0.60267101	26456	-4.00e+07	61.61
40	1.4800277e+09	0.55563839	26445	-2.77e+04	42.40
41	1.4878999e+09	2.07805864	24803	-7.90e+06	148.61
42	1.4879305e+09	2.23442304	24823	-7.93e+06	159.92
43	1.4925589e+09	1.22941202	25320	-1.26e+07	89.78
44	1.4926370e+09	1.08249029	25344	-1.26e+07	79.12
45	1.497107e+09	0.18172788	26528	-1.71e+07	13.91
46	1.497132e+09	0.18178805	26535	-1.71e+07	13.92
47	1.505680e+09	3.45233080	26616	-2.57e+07	265.17
48	1.506149e+09	2.50431127	26803	-2.61e+07	193.72
49	1.508800e+09	2.24144024	26198	-2.88e+07	169.43
50	1.509463e+09	3.01190217	26101	-2.95e+07	226.81
51	1.520001e+09	0.91419751	26671	-1.30e+03	52.08
52	1.520135e+09	0.96201217	26628	-1.34e+05	54.71
53	1.527988e+09	0.98673684	26908	-7.99e+06	56.72
54	1.528067e+09	1.29239959	26969	-8.07e+06	74.46
55	1.532459e+09	10.02582170	26108	-1.25e+07	558.85
56	1.533149e+09	9.09144548	26127	-1.31e+07	507.14
57	1.543630e+09	7.26927526	24533	-2.36e+07	380.33
58	1.543876e+09	7.43105120	24432	-2.39e+07	387.17
59	1.549998e+09	4.44478200	26344	-3.00e+07	250.03
60	1.550537e+09	4.20730162	26427	-3.05e+07	237.43

Table 4: *Parameters for* **the subsequent 30 longitudinal modes** *in the FELIX experimental chamber* **with an RF-screen at a radius of 8 cm**. *The mode parameters are calculated with* **MAFIA**. *For the data in the fourth column we assumed a bunch length of* $\sigma_z = 7.5$ *cm.*

Using the same formalism as in [1] we recalculate the shortest rise times for the higher order modes of the structure with RF-screen in Tables 3 and 4. For the following calculations we considered the first 20 longitudinal modes. For each longitudinal mode we considered the first 20 radial modes and diagonalize the interaction matrix using a numerical routine from the EISPACK library. For the longitudinal case we find the lowest rise times for

$$R_s = 10.03 \text{ M}\Omega, \quad \omega_R/2\pi \approx 1.53 \text{ GHz}, \quad \text{and} \quad Q = 26108 \tag{12}$$

with

$$\tau_{inj} \geq 2.16 \; s \qquad \text{for l} = 7 \quad \text{and} \qquad \tau_{lum} \geq 4.28 \; s \qquad \text{for l} = 4. \tag{13}$$

The index l specifies the longitudinal mode number for which we found the smallest rise time. For l = 1 we get

$$\tau_{inj} \geq 18.1 \; s \qquad \text{for l} = 1 \text{ and} \qquad \tau_{lum} \geq 16.9 \; s \qquad \text{for l} = 1. \tag{14}$$

In the short bunch approximation (bunch length $\ll$ wavelength of the mode), we get for the l = 1 mode

$$\tau_{inj} \geq 0.05 \; s \qquad \text{and} \qquad \tau_{lum} \geq 0.72 \; s. \tag{15}$$

4 Summary

The analysis of the coherent losses in the FELIX vacuum chamber showed that a design without RF-screen leads to very large incoherent losses (more than 15 kW). With RF-screen, the incoherent losses can be reduced to less then 50 W. Without RF-screen, the coherent losses can be larger than a few kW if the bunch frequency is in resonance with on one of the trapped mode frequencies and the vacuum chamber has a rich spectrum of more than 40 modes with such large losses. With RF-screen, the coherent losses are of the order of 200 W per trapped mode and the vacuum chamber has only 3 HOM which are sufficiently close to the nominal bunch spectrum.

A reduction of the coherent loss to less than 10 W per trapped mode requires a 'de-Qing' to the point that $Q \sim 250$. A scenario using antennas for this purpose requires further studies.

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