PERFORMANCE OF PLANAR RADIATOR IN THE RADIABEAM-IAC EXPERIMENT*

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Abstract

Planar gratings structure for generation of mm-sub-mm wavelength long-range wakefields is analysed. The rugged, side-open, slow wave structure can sustain substantial beam loading including long multi-bunch trains up to CW operation. Electromagnetic performance of the structure is characterized numerically vs. experiment with emphasis to application to flat beams. It is shown that such an electrically wide, wavelength-gap structure can operate at significantly reduced tolerances whereas substantial flatness of the wakefield can be obtained at essentially non-flat eigenmode profile.

INTRODUCTION

In the experiment [1] conducted at Idaho Accelerator Center (IAC) a side-open gratings planar structure (see Fig. 1) was used to generate and partially extract mm-sub-mm wave radiation induced by wakefields. Since the structure is relatively new the radiator performance needs more detailed characterization as well as to substantiate the measurements made and to support other potential applications such as compact THz sources [2], energy dechirping [3] and collinear wakefield acceleration.

We analyse here the structure performance with GdfidL code [4] in eigen- and time domains. The side opening has been modelled as a large space enclosed by low conductivity walls (see Fig. 1) with negligible influence on the frequencies of the modes of our interest.

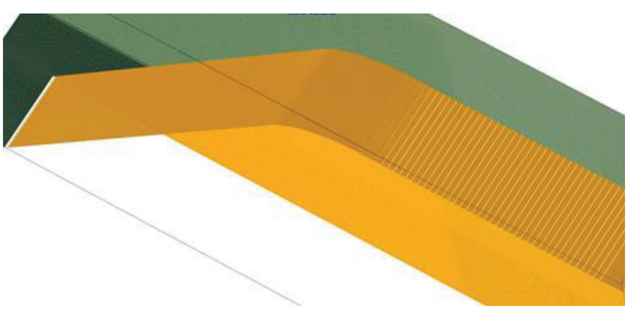

Figure 1: GdfidL model of one-quarter structure with horn antenna. Interaction gap: 1.26 mm, width: 6.3 mm, grating length L=30.4 mm (130 periods), period: 0.23 mm, and groove depth: 0.081 mm.

EIGENMODES

We analyse here eigenmodes that are in synchronism with the relativistic beam (v/c=0.996) using only one period of the regular part of the structure. Several modes with different horizontal variations can potentially interact with the beam in such an oversized structure. Field patterns for lowest modes are shown in Fig. 2. Side opening provides modal selection for the wakefield energy radiated forward [2,5] due to the side radiation losses via the factor $F = \left(\left(1-\exp(-\alpha L)\right)/\alpha L\right)^2$, where $\alpha = \pi f / Q v_{gr}$ is the modal attenuation. Simulation results for the first few eigenmodes are shown in Table 1.

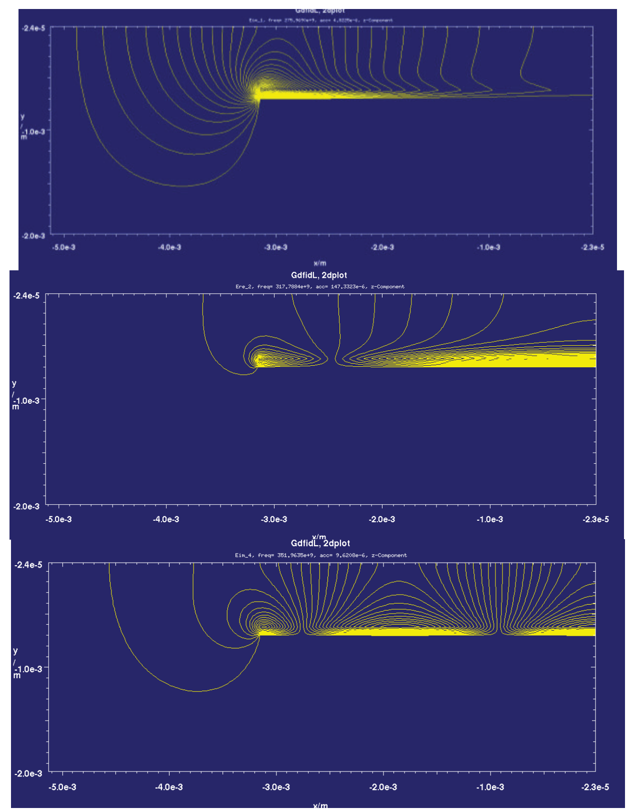

Figure 2: Contour plots in transverse XY plane for the Ez field for three lowest modes which are synchronous to 5MeV beam at 276, 312 and 352 GHz (one quarter model).

Table 1: F, group velocity, and r/Q [Ω/m] for different widths w [mm] of the beam filling the vertical gap.

f, GHz	F	r/Q, w=0	r/Q, w=2	r/Q, w=4.76	βgr
276	0.05	11	14.3	94	0.81
312	0.53	2450	2201	1343	0.844
352	0.27	1076	721	112	0.72
401	5e-4	459	180	23	0.79

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One can see from Table 1 that with the absorbing periphery (having as low as 1 Sm/m surface conductivity) the factor F reduces fast as the modal order increases. This effect is similar to the spectrum rarefaction in open cavities and waveguides. One can see that mode #2 (at 312 GHz) strongly dominates in beam interaction due to radiation losses and higher r/Q at finite beam width.

TIME DOMAIN SIMULATIONS

Wakefield simulations have been performed here for filament and ribbon bunches having 30 pC charge at 500 and 700fs rms durations in various configurations: grating structure only, with horn attached, horn only (without the structure), and also in the structure with randomized geometrical parameters:

Wakefields induced by flat (ribbon) and filament bunches are illustrated in Fig. 3. Note the radiation patterns seen in Figs 3, 7 is significantly modified ("flattened") by the beam width.

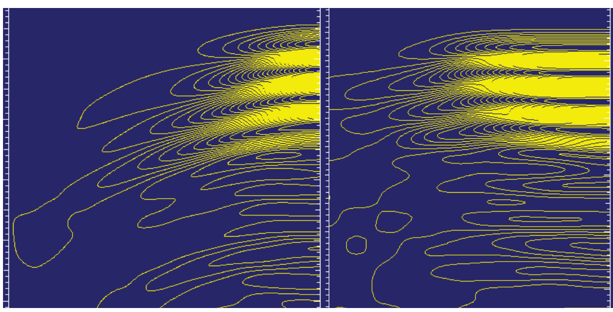

Figure 3. Ez field pattern in median XZ plane induced by a σz=150 μm bunch along 40 periods structure at t=31 ps for filament (left) and 4.8 mm wide (right) bunch filling the vertical gap.

Field spectra shown in Figs. 4, 5 confirm the dominant mode at ~300 GHz. Line splitting is caused by partial reflection of the power from the horn.

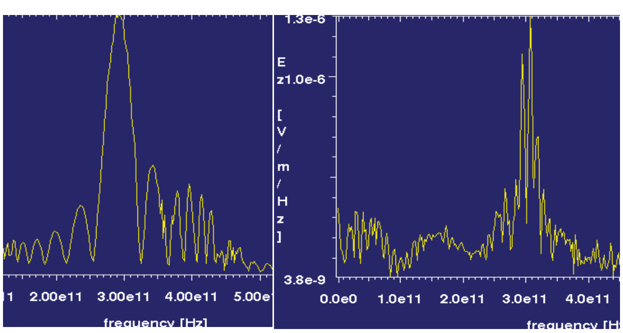

Figure 4: Ez field spectra on the output edge of the gratings (left) and on the horn opening (right) forσz=150 μm and w=2 mm bunch.

Longer bunch causes appearance of spectrum lime at lower frequencies (tens of GHz, see Fig. 5, right) and magnitude reduction at 300 GHz (compare to Fig. 4, right). We observed very similar behaviour experimentally [1], when we obtained signals from fast oscilloscope (~20 GHz bandwidth) whereas the pyrodetector signal was weak or not registered yet. That occurs when the chicane and RF phases were tuned incompletely.

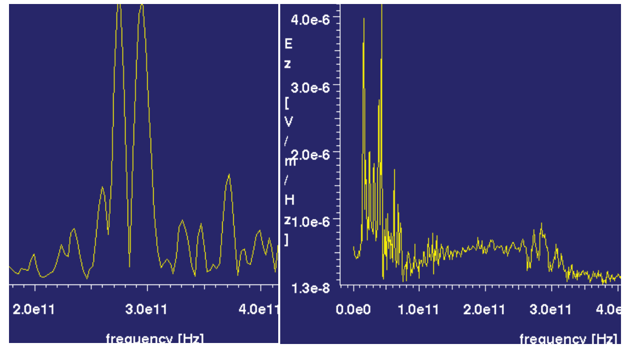

Figure 5: Ez field spectra on the output edge of the gratings (left) and on the horn opening (right) for a σz=210 μm, w=2 mm bunch.

Flux integral that determines radiated energy is plotted in Fig. 6 for full system and horn only. One can see that the radiated energy without gratings is negligible compared to that with gratings that occurs at ~ 310 GHz (see Fig. 4, right).

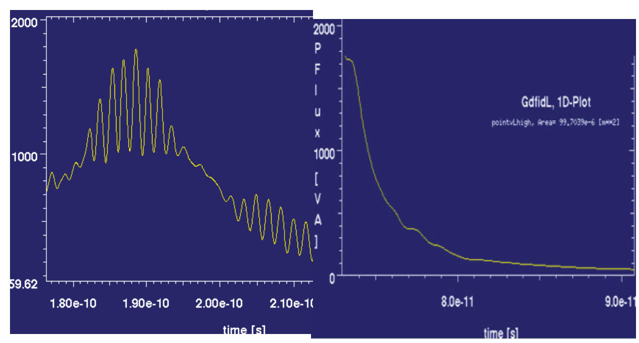

Figure 6: Total flux integral [W] (including quasi-static charge-induced fields) vs. time on the horn output with (left) and without the gratings (right) for a σz=150 μm, w=2 mm bunch.

From Fig. 6, left one can estimate the radiation micropulse time ~20 ps which corresponds well to the 18ps drain time determined as difference between slow wave structure filling time and time-of-flight. The tail of the plot corresponds to the bouncing caused by partial reflection.

One can also estimate from Fig. 6, left, ~40 nJ energy radiated by a 500 fs microbunch. For 1.3 GHz RF frequency and 2 μs pulse length it corresponds to ~100 μJ energy radiated per macropulse or ~3mW average power at 30 Hz rep rate. That corresponds well to pyrodetector measurements [1] and previous analytical estimations. From the analytical model and the simulations above we also estimate the rms bunch duration about 600-700 fs.

Wider bunches change field because of generation of higher and lower order modes (see Figs 7, 8).

From the field pattern induced by the bunch in the horn (Fig. 9) one can assume lobe direction angle about half of the opening angle. This is in agreement with preliminary far-field simulations.

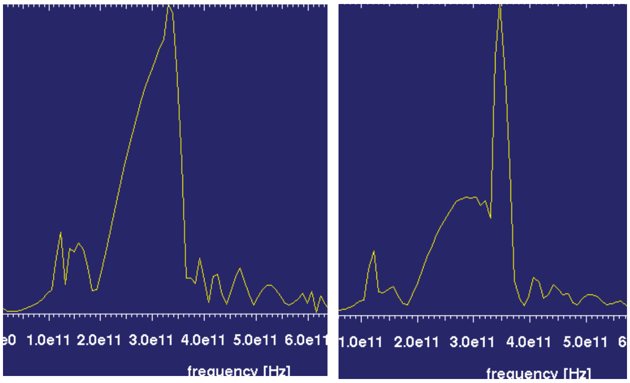

Figure 7: Ez field spectra induced in the 40-period gratings for 2 mm (left) and 4.76 mm (right) wide bunch at σz=150 µm.

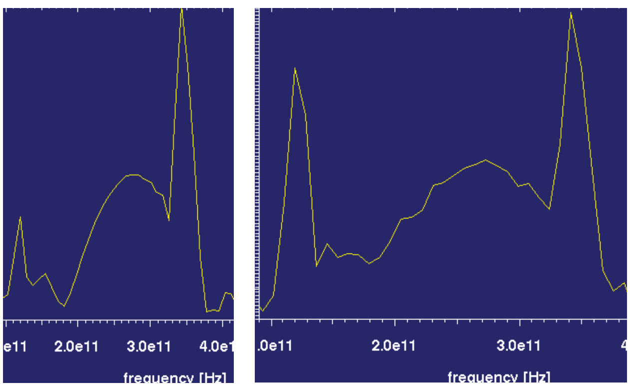

Figure 8: Ez field spectra induced in the 40-period gratings for 4.76mm (left) and 7 mm (right) wide bunch at σz=210 µm.

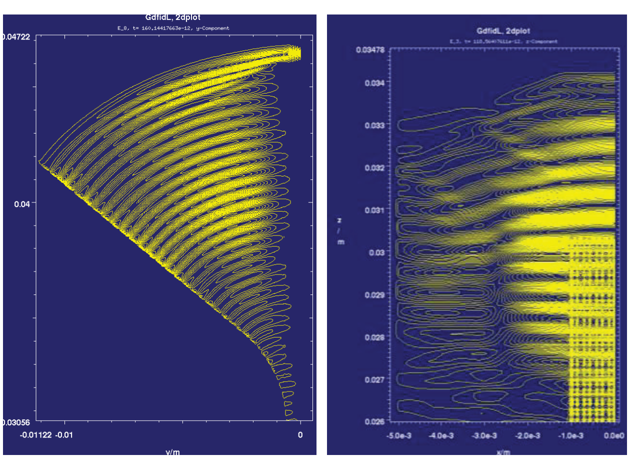

Figure 9: Ey in YZ (left, t=160ps) and Ez field plotted in XZ plane (right, t=118ps) forσz=150 µm bunch. The rectangular region on the right corresponds to the 2mm bunch width.

To model effect of CNC milling tolerances we introduced 0.5 mill randomization into the gratings parameters (period, groove depth, and thickness) in the full-length model (with the horn). The results for power and spectrum shown in Fig. 10 to be compared to Figs 4, 6.

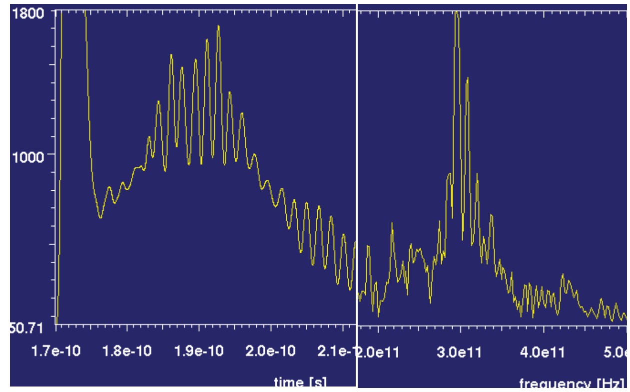

Figure 10: Full power [W] (left) and Ez field spectrum (right) for radiator with randomized gratings for 2 mm wide, σz=150 µm bunch.

CONCLUSION

Simulation confirmed ~mW power radiated from the insertion device at sub-THz frequency estimated earlier from measurements at negligible contribution of geometric wake induced by the antenna horn.

Flat beam considerably modifies wakefield pattern and can make it "flat" even if the eigenmode is not flat.

Wider beam (>5 mm) also results in appearance of ~120 GHz line and shift of the main peak to higher frequency (340 GHz at 7 mm width).

Radiation from longer bunches (≥650 fs) is dominated in the insertion device by lower frequencies (10-100 GHz) that was effectively used in the experiment for the pre-tuning of the beam compression system with fast oscilloscope.

At shorter bunches the radiation is strongly dominated by a single mode at ~310 GHz. That validates analytical simulations made previously to design the experiment [1].

Gratings randomization (~a mill) does not change much the coherent part of the wake making the high group velocity structure exceptionally attractive for applications.

ACKNOWLEDGMENTS

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