

Corrugated Pipe for Generating Terahertz Radiation

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Introduction

- It has been noted in the past, in the study of wall-roughness impedance, that a beam passing through a metallic pipe with small-scale corrugations excites a high-frequency mode that propagates with the beam
- Propose driving such a structure with a short, ~ 1 nC beam, in order to generate THz radiation (~ 0.1 – 3 THz) with total energy a few mJ
- Generates narrow-band, multi-cycle pulses
- Wall losses are important and need to be considered in the design
- Analytical formulas give good approximations for the important parameters. For numerical calculations we employ I. Zagorodnov's program ECHO, a time-domain Maxwell equation solver

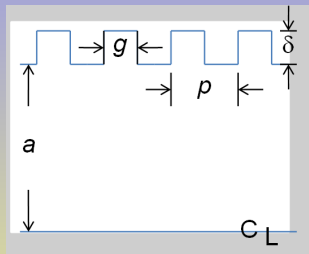
Introduction Cont'd

- Will describe TPIPE, a 5-cm-long copper structure being fabricated for testing at FACET at SLAC
- Calculate effect of driving TPIPE with long, modulated beam (cf. D. Xiang's talk) using APS beam parameters
- Using a corrugated metallic pipe for generating THz radiation is similar to using a metallic pipe with a thin dielectric layer

For a detailed report on the theory, see K. Bane, G. Stupakov, *Nucl. Inst. Meth. A677* (2012) 67–73

Theory

A short, relativistic bunch generates a strong synchronous mode in a pipe with rough surfaces (A. Novokhatski & A. Mosnier, 1997; K. Bane & A. Novokhatski, 1999)



A short bunch passes through a corrugated pipe, with $p \lesssim \delta \ll a$ (for simplicity let $p = 2g$). A dominant mode is excited, with:

- Frequency far above cutoff, $k = \frac{2}{\sqrt{a\delta}}$
- Group velocity $\left(1 - \frac{v_g}{c}\right) = \frac{2\delta}{a} \ll 1$

⇒ • Radiation pulse length at end of pipe

(L is pipe length)

$$\ell = 2 \frac{\delta L}{a}$$

- Mode loss factor

$$\kappa = \frac{Z_0 c}{4\pi a^2}$$

Theory Cont'd

- The wake at the origin for any round, periodic structure of minimum aperture a is $W_0 = 2\mathcal{K} = Z_0 c / (\pi a^2)$
- What makes the corrugated pipe attractive as a THz generator is that (almost) all interaction is in one mode, with

$$W(s) \approx W_0 H(s) \cos(ks)$$

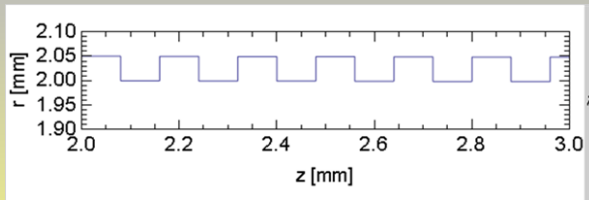
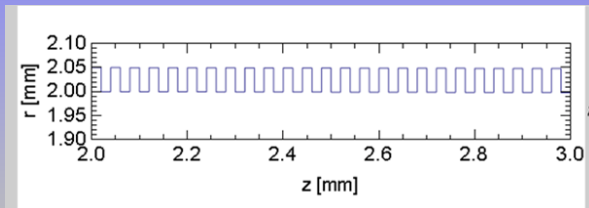
- Energy lost by bunch $U_w = Q^2 \mathcal{K}_\lambda L$

$$\mathcal{K}_\lambda = \frac{Z_0 c}{2\pi a^2} e^{-k^2 \sigma_z^2};$$

for good interaction need $k\sigma_z \ll 1$

- Energy in pulse, $U = U_w - U_{rw}$, with U_{rw} resistive losses in wall; optimize by adjusting corrugation depth to period ratio, δ/p

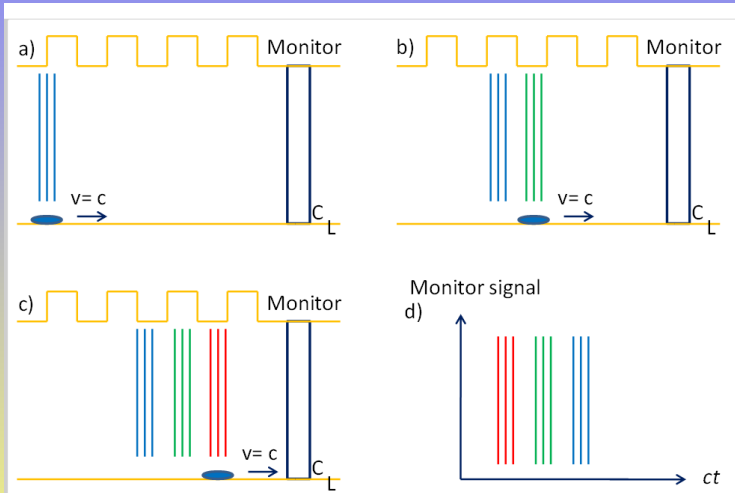
Resistive Wall Losses



Two structures with different δ/ρ . The distance along the wall per unit length in z , $\alpha = 3.5$ (top), $\alpha = 1.6$ (bottom)

- Losses get bigger for smaller $a^{6/15}$

Pulse Generation



Schematic of pulse generation by bunch in corrugated beam pipe (a-c); schematic of signal measured at monitor (d).

Comparison to CTR Source

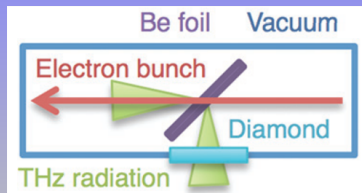


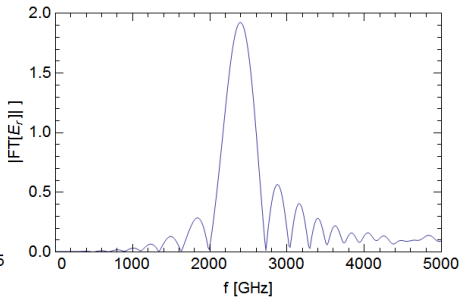
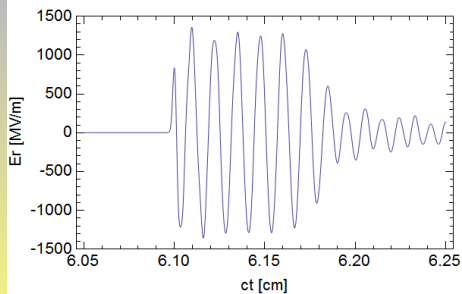
Table: Characteristic differences in radiation scaling from a foil and from a corrugated pipe; k is typical wave number, U is pulse energy

	CTR	Pipe
Type	Broadband	Narrow band
k	$1/\sigma_z$	$1/\sqrt{a\delta}$
U	$1/\sigma_z$	L/a^2

2.4 THz Example (Cu)

Pipe radius, mm	0.5
Pipe length, cm	6
δ , μm	4
Period p , μm	12
Bunch charge, nC	1
Bunch length σ_z , μm	10

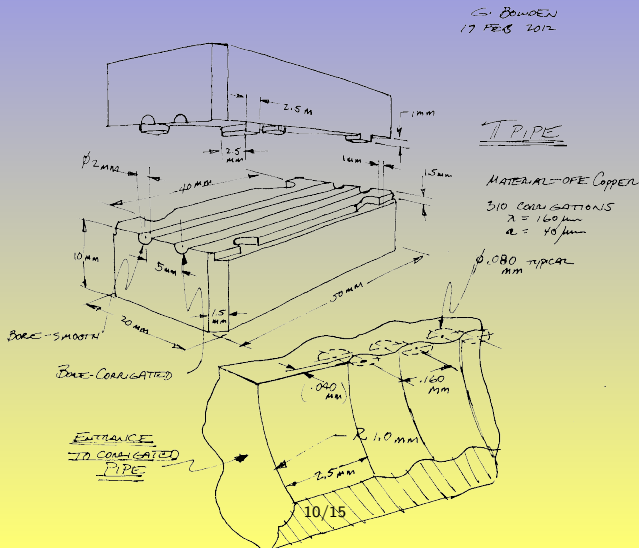
Frequency, THz	2.4
Pulse length, ps	2.7
Wake energy, mJ	3.5
Pulse energy, mJ	2.4



Parameters (tables); E_r near wall⁽¹⁶⁾ (left), $|\tilde{E}_r|$ (right)

Test structure

- We are making a structure to test at FACET, that we call TPIPE (G. Bowdon sketch)



Test Structure

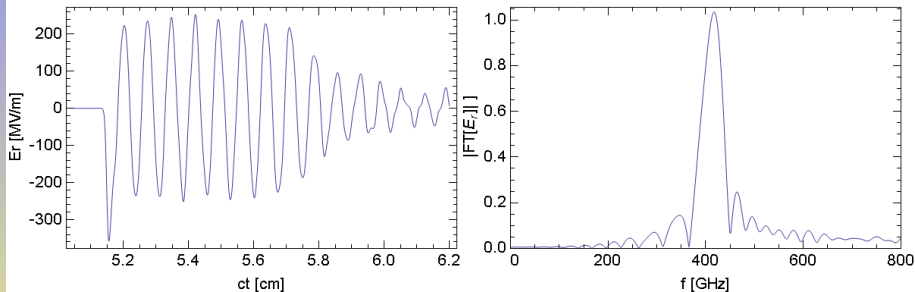
Expected beam: $eN = 3.2$ nC, $\sigma_z = 50$ μm

- Structure: $a = 1$ mm, $L = 5$ cm, $\delta = 60$ μm , $p = 160$ μm

Yielding frequency $f = 420$ GHz, pulse length $\ell = 6.5$ mm (14 cycles), wake energy $U_w = 5.8$ mJ, pulse energy $U = 4.8$ mJ, peak field at wall $E_r = 300$ MV/m

- We will measure frequency and energy in pulse. We will see if fields damage structure

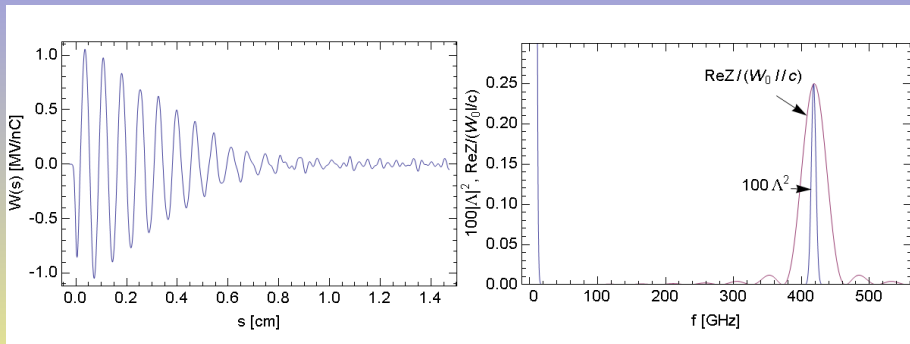
Test Structure Cont'd



E_r at wall (of the radiation pulse) expected for FACET test (left),
Fourier Transform of E_r (right)

Modulated APS Beam and TPIPE

- Wake of short bunch $W(s) \approx W_0 H(1 - s/\ell)(1 - s/\ell) \cos ks$
- $U_w = Q^2 W_0 L \varkappa$, with $\varkappa = \frac{1}{\pi} \int_0^\infty |\Lambda(\omega)|^2 \text{Re}Z(\omega) d\omega$



Wake of short bunch in TPIPE (left), overlap of Λ^2 and $\text{Re}Z$ (right)

- For APS in single bunch mode: $Q = 18 \text{ nC}$, $\sigma_z = 1 \text{ cm}$, and taking modulation strength 10% \Rightarrow THz pulse energy $U \sim 100 \mu\text{J}$

Conclusion

- The metallic pipe with small corrugations can be used to generate narrowband pulses of THz radiation with high energies (on the order of mJ's)
- When excited by modulated storage ring-type bunches, energies of 100's of μJ can still be achieved
- Using flat instead of round geometry would allow for some tuning, giving similar results (not discussed here)
- Metallic pipe with thin dielectric layer (which has been studied at Argonne for many years now) should give similar results. Which is better for THz generation depends on many practical issues such as breakdown, ease of manufacturing, etc

Addendum

At the end of the talk a question was asked: for the example of the modulated APS beam used with TPIPE, what is the average power loss?

Answer: the energy in the pulse $U = 100 \mu\text{J}$, and the energy lost in the walls $U_{rw} = 22 \mu\text{J}$. For the APS, the revolution frequency $f_{rev} = 2.7 \times 10^5 \text{ Hz}$. Therefore, the average resistive wall losses $P_{rw} = U_{rw} f_{rev} = 6 \text{ W}$