Corrugated Structures for Terahertz Generation and Beam Dechirping

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Introduction

- There is a need for a source of short, intense pulses of THz radiation. One beam-based source of broad-band radiation has an short electron beam hitting a foil to generate coherent transition radiation (CTR). Laser-based sources can generate narrow-band radiation of intensities that keep improving. We study here the possibility of using a beam and a corrugated pipe to generate intense narrow-band THz radiation
- In linac-based X-ray FEL's, after the last bunch compressor, the beam is short and has an energy chirp. By running the beam off-crest in a following linac this chirp can be removed before the undulator. We consider the use of a corrugated pipe as a passive, inexpensive alternative method of "dechirping"

Outline

Corrugated pipe for:

- THz generation
- Proof-of-principle experiment
- Dechirping
- Demonstration experiment
- Conclusion

Theory describes work performed with G. Stupakov; see *Nucl. Inst. Meth.* A677 (2012) 67–73 and A690 (2012) 106–110

THz measurement performed at Brookhaven's ATF (paper not yet finished); Dechirping measurements at Pohang's ITF (paper submitted for publication)

Dielectric-Lined Pipes

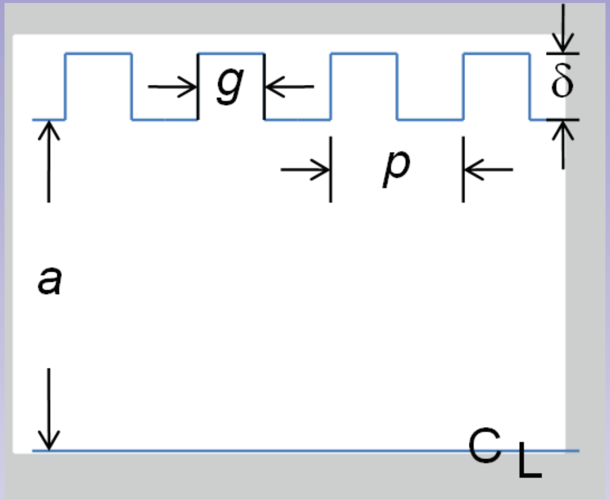
There has been lots of activity in using a dielectric-lined pipe for both THz generation and dechirping. The physics of the two types of structures—pipes with small metallic corrugations or with a thin dielectric liner—is the same. Mainly three groups: W. Gai et al at ANL, J. Rosenzweig et al at UCLA, S. Antipov et al at Euclid Labs are active

Experimental activity on dielectric-lined pipes for THz, e.g.: A.M. Cook et al, PRL 103, 095003 (2009); S. Antipov et al, PRL 108, 144801 (2012); S. Antipov et al, PRL 111, 134802 (2013)

See also S. Antipov's talk on Thursday at 11:30 on "Dielectric acceleration and tests in the BNL ATF and SLAC FACET Facilities"

Corrugated Structure: THz Generation

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



Consider short bunch excites mode in corrugated pipe, with $p \lesssim \delta \ll a$; for simplicity let $p = 2g$:

- Frequency far above cutoff, $k = \dfrac{2}{\sqrt{a\delta}}$ and small compared to $1/\delta$
- Group velocity $\left(1 - \dfrac{v_g}{c}\right) = \dfrac{2\delta}{a} \ll 1$

$\Rightarrow$ radiation pulse length at end of pipe

(L is pipe length)

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

- Mode loss factor

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

THz Generation Cont'd

- The wake at the origin for any round, periodic structure of minimum aperture a is $W(0^+) = 2\sum_n \varkappa_n = Z_0 c/(\pi a^2)$, where $\varkappa_n$ is the loss factor of mode n. What makes the corrugated pipe attractive as a THz generator is that all interaction is in one mode

- Final energy in pulse, U, can be estimated from wake loss of bunch: *bunch* loss factor

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

(wake) energy lost by bunch in pipe, $U_w = Q^2 \varkappa_\lambda L$

(For good interaction need $k\sigma_z \ll 1$)

- Resistive wall losses are important and can easily be calculated. We shall see from simulations that $U \approx U_w - U_{rw}$

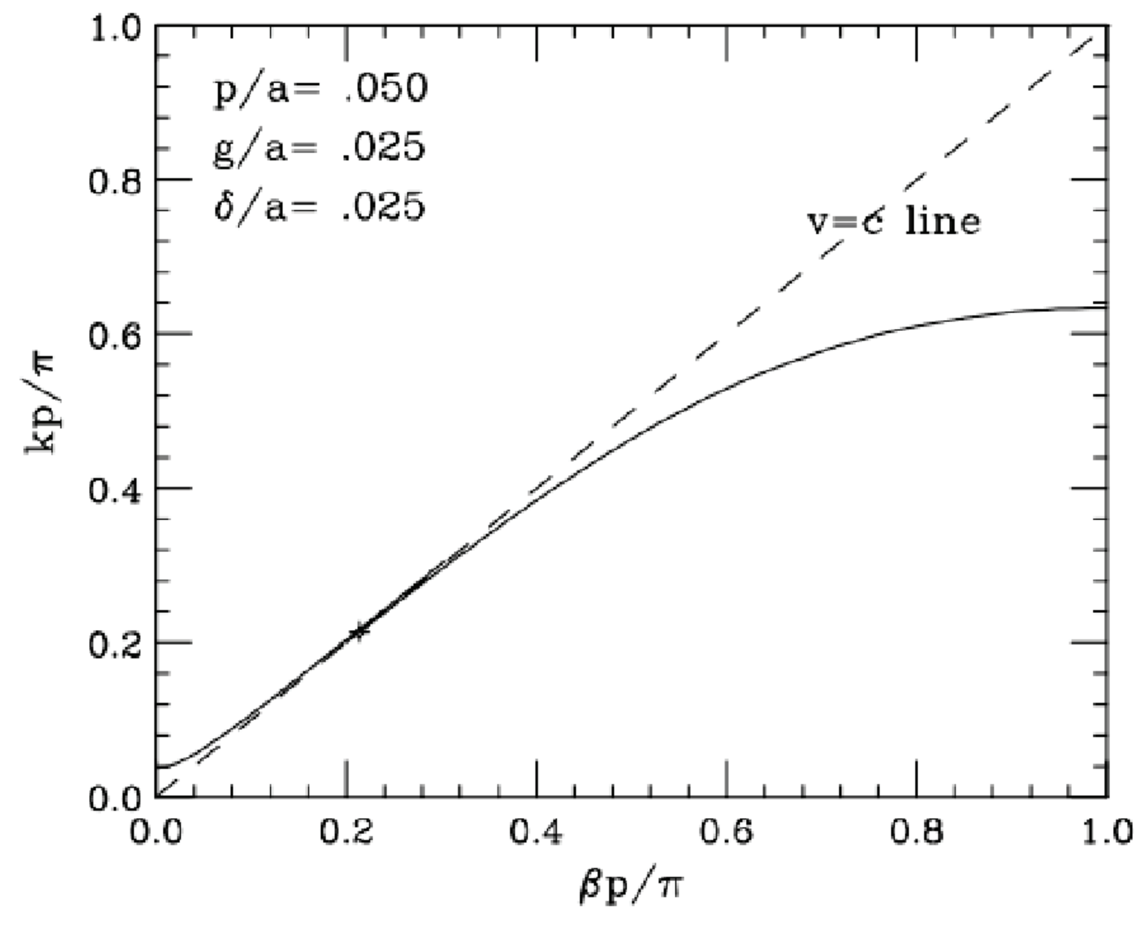
- Power in pulse, $P = cU/\ell$

THz Cont'd

Note:

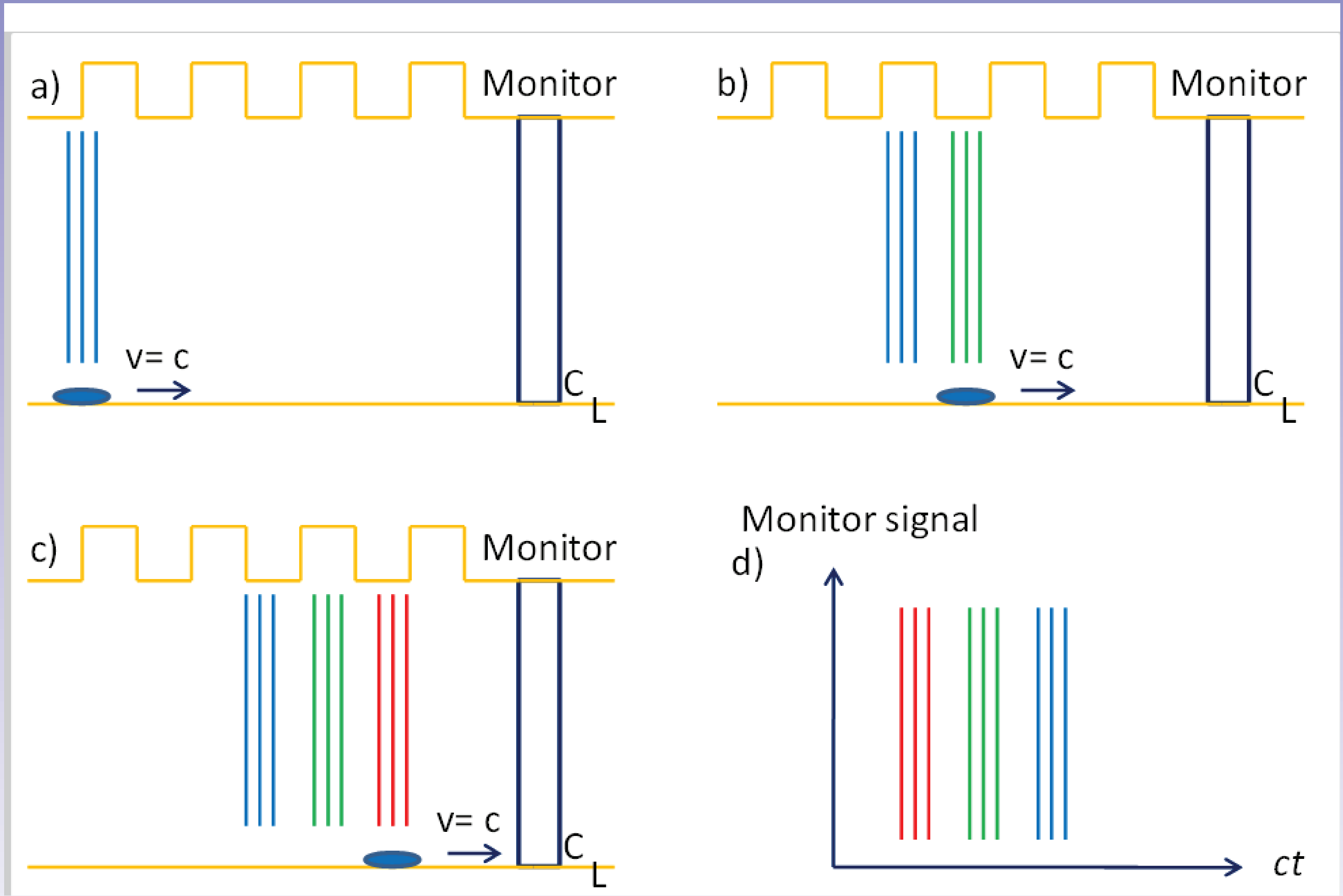
- Analytical results valid for $\delta \gtrsim p$. If this is slightly violated, then frequency k will be higher and excitation $\varkappa$ lower. In opposite regime, $\delta \ll p$, dominant mode is gone, and structure behaves completely differently
- There is a dominant dipole mode at nearly the same frequency

Dispersion Curve



Brillouin diagram of a corrugated pipe with a strong synchronous mode

Pulse Generation



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

Analytical Estimates

For $a = 2$ mm, $\delta = 50$ μm, $p = 40$ μm, $L = 50$ cm, $\sigma_z = 100$ μm, $Q = 1$ nC, **analytical** values of:

- frequency $f = kc/2\pi = 0.3$ THz
- $k\sigma_z = 0.63$, bunch energy loss $U_w = 1.5$ mJ (for point charge $U_w = 2.25$ mJ)
- peak power P= 30 MW
- pulse length $\ell/c = 80$ ps

To allow us to shorten the pulse, we could taper the structure to introduce a frequency chirp and then compress (cf. Chirped Pulse Amplification [CPA] in lasers). In simulations, for above example, could reduce pulse length to $\ell/c = 9$ ps

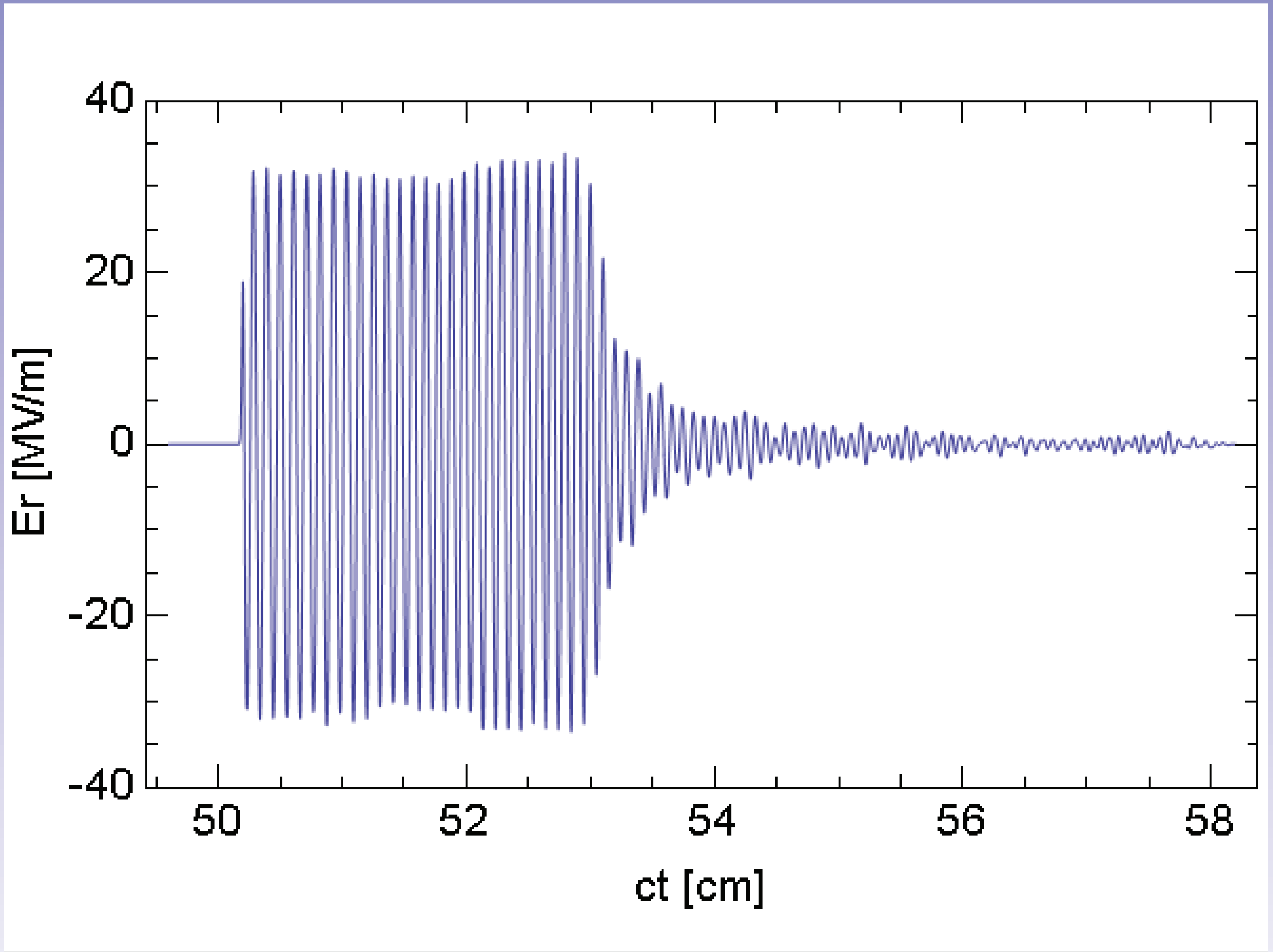
Simulations

- We use I. Zagorodnov's program ECHO, a time domain Maxwell equation solver, to simulate the generation of the THz pulse.
- A speed of light Gaussian bunch generates fields in the structure. We monitor E_r and H_ϕ as functions of time at a location at the end of the structure. The outgoing power is given by

  $$P(t) = \frac{c}{2}\int_0^a E_r(r,t)H_\phi(r,t)r\,dr\,.$$

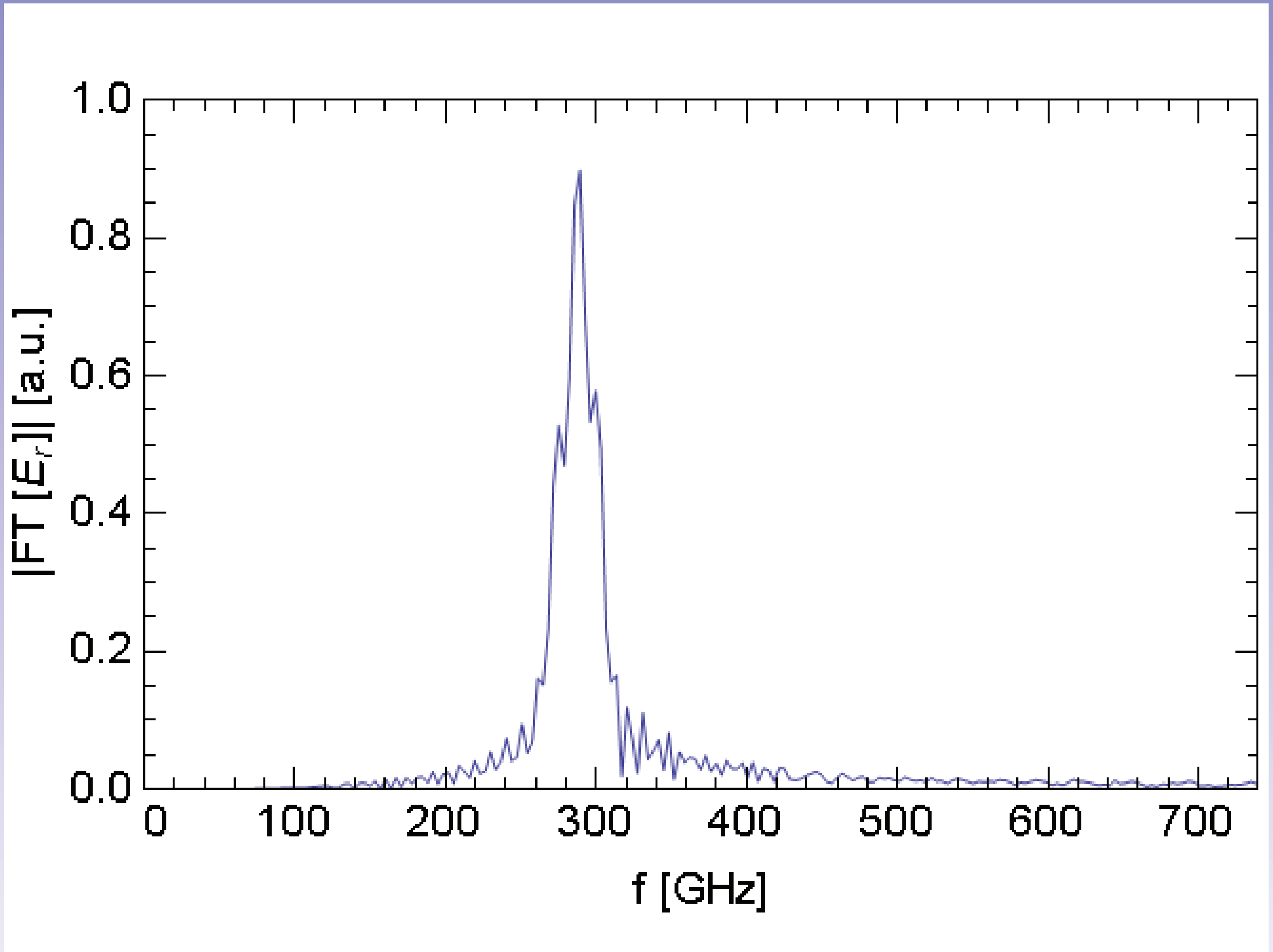
  The energy in the pulse, $U = \int P(t)\,dt$.

Simulations: E_r at monitor



E_r as function of time at $r = 1.5$ mm. Note that the pulse length $\ell \sim 2.7$ cm, or 90 ps.

Fourier transform

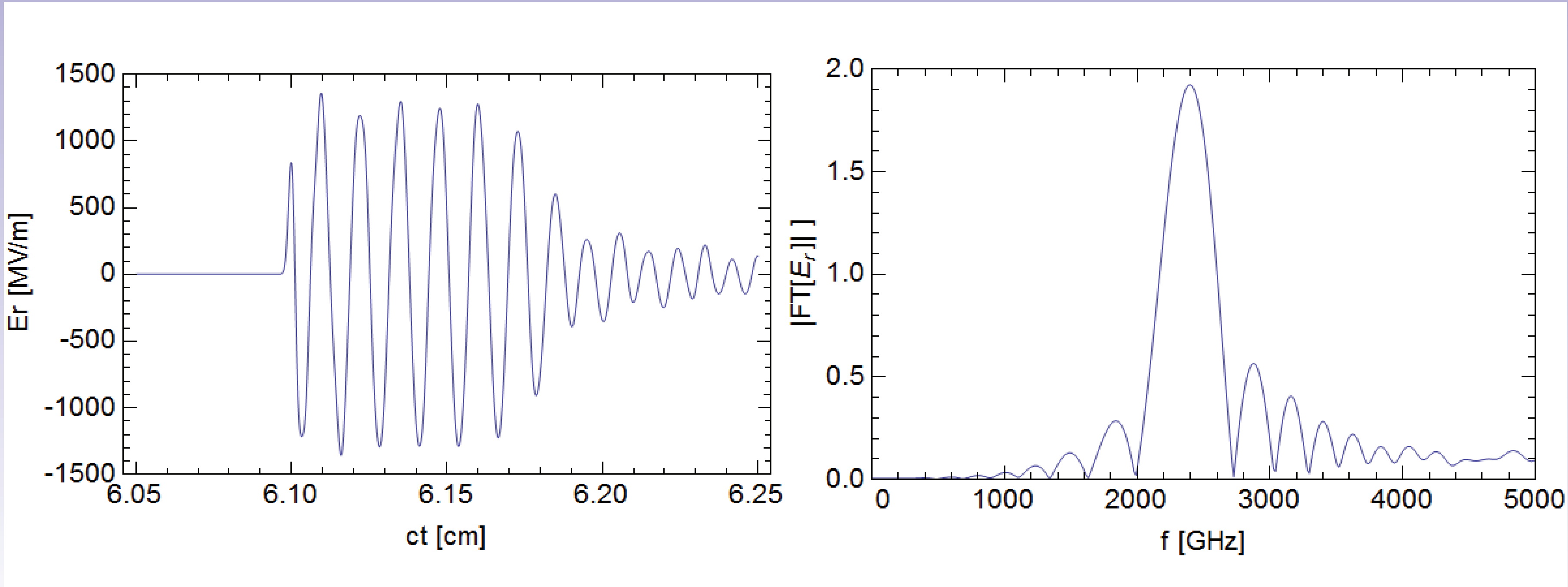


Absolute value of Fourier transform of E_r at $r = 1.5$ mm for the untapered structure. The peak is at 290 GHz.

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

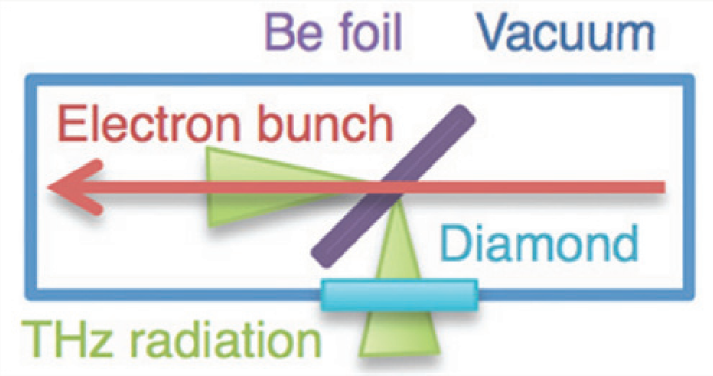
Frequency, THz	2.4
Pulse length, ps	2.7
Wake energy, mJ	3.5
Pulse energy, mJ	2.4
η	0.69



Parameters (tables); E_r (no losses) near wall (left), $|\tilde{E}_r|$ (right)

Comparison of Corrugated Pipe to CTR Source

At the end of the LCLS, the electron bunch can pass through a Be foil to generate THz radiation (D. Dranciang et al, Appl Phys Lett **99**, 141117 (2011))



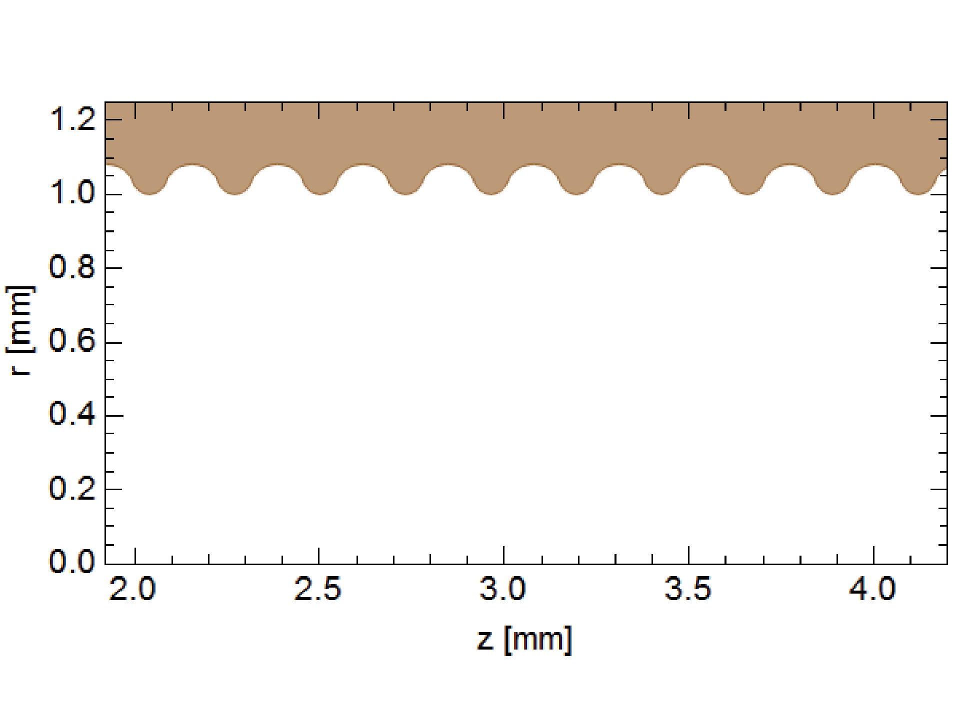
- Bunch charge $eN = 350$ pC, uniform distribution of length 50 fs. Calculated energy in backward direction $U = 1.4$ mJ; including losses, $U = 560$ µJ (H. Loos); measured 140 µJ. Calculation for 2.4 THz corrugated pipe gives 290 µJ.

- CTR radiation is broadband, single cycle; corrugated pipe radiation is narrow band, multiple cycle

Test Device: TPIPE

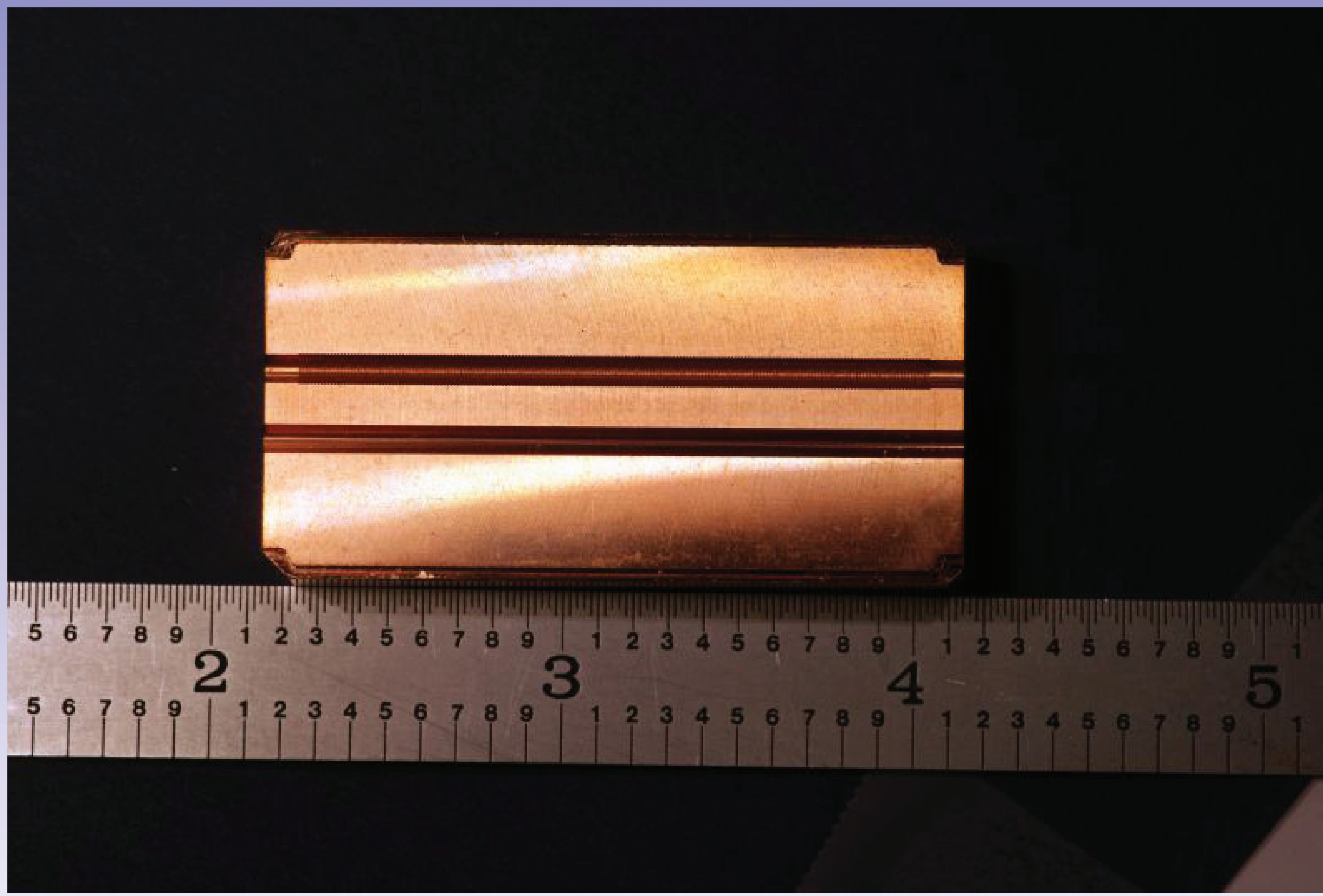
- We have had a test device machined out of copper, with $a = 1$ mm, $L = 5$ cm, $\delta = 50$ µm, $p = 160$ µm

If driven by a short bunch, it should yield frequency $f = 430$ GHz and pulse length $\ell = 1$ cm (14 cycles)



A sketch of the corrugation geometry of TPIPE

TPIPE Cont'd

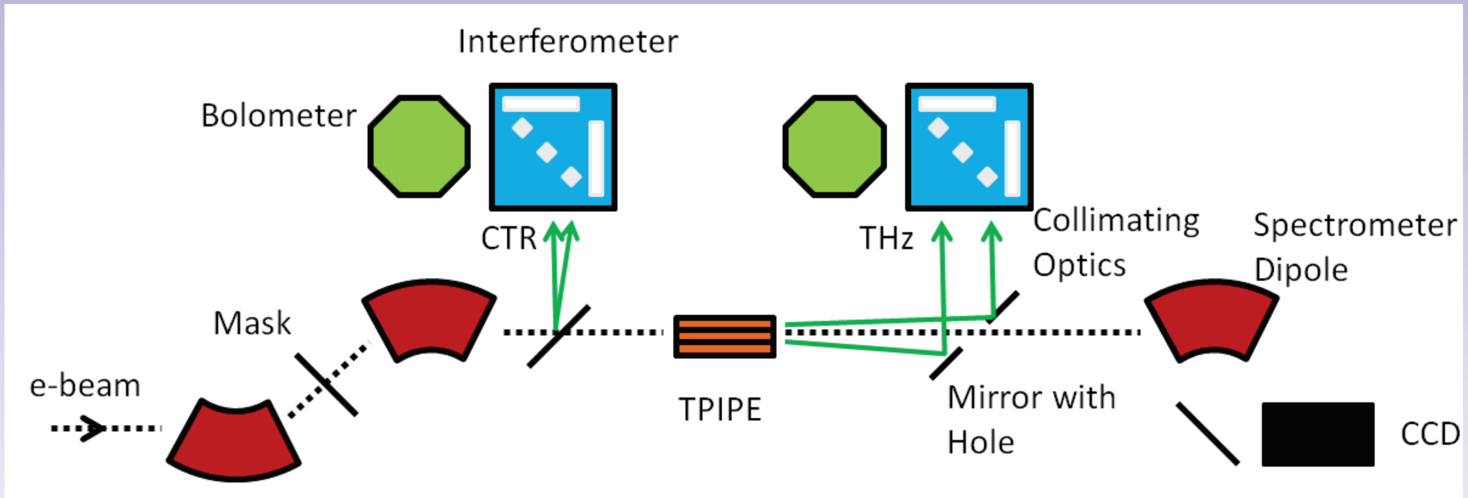


Half of TPIPE, before diffusion bonding. Corrugations have been machined in the top groove; the bottom one is smooth–for null test

Measurement at BNL's ATF: Some Results

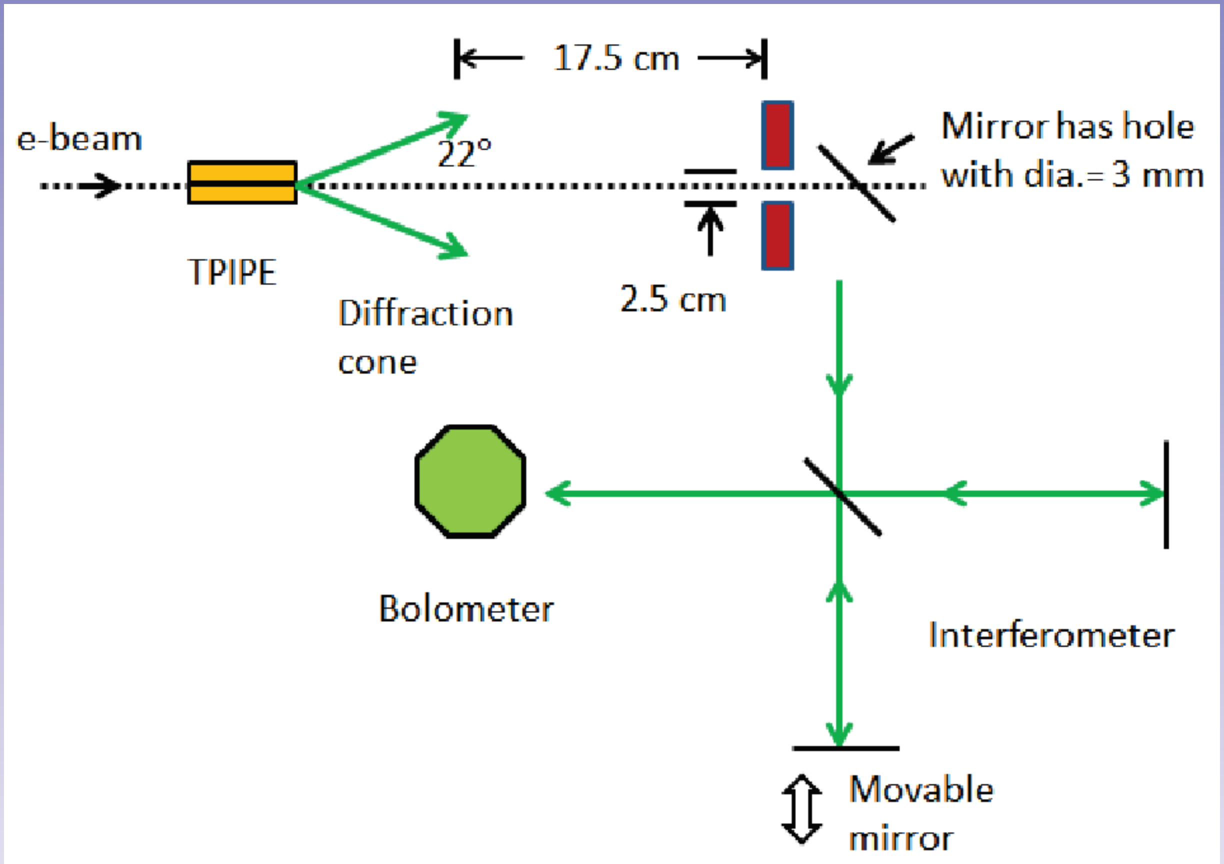
A *proof-of-principle* measurement was performed at Brookhaven's Advanced Test Facility (ATF) with S. Antipov, K. Kusche, ...

- The beam energy is 60 MeV; the beam peak current is 100 A, and the bunch length can be adjusted with the use of masks
- (1) THz pulse is measured with an interferometer and a liquid He bolometer, (2) effect on the beam is measured with a spectrometer



Experimental layout. The first interferometer is used as a diagnostic for the bunch shape; the second one, to measure the THz signal (adapted from Andonian et al, App Phy Lett, 2011)

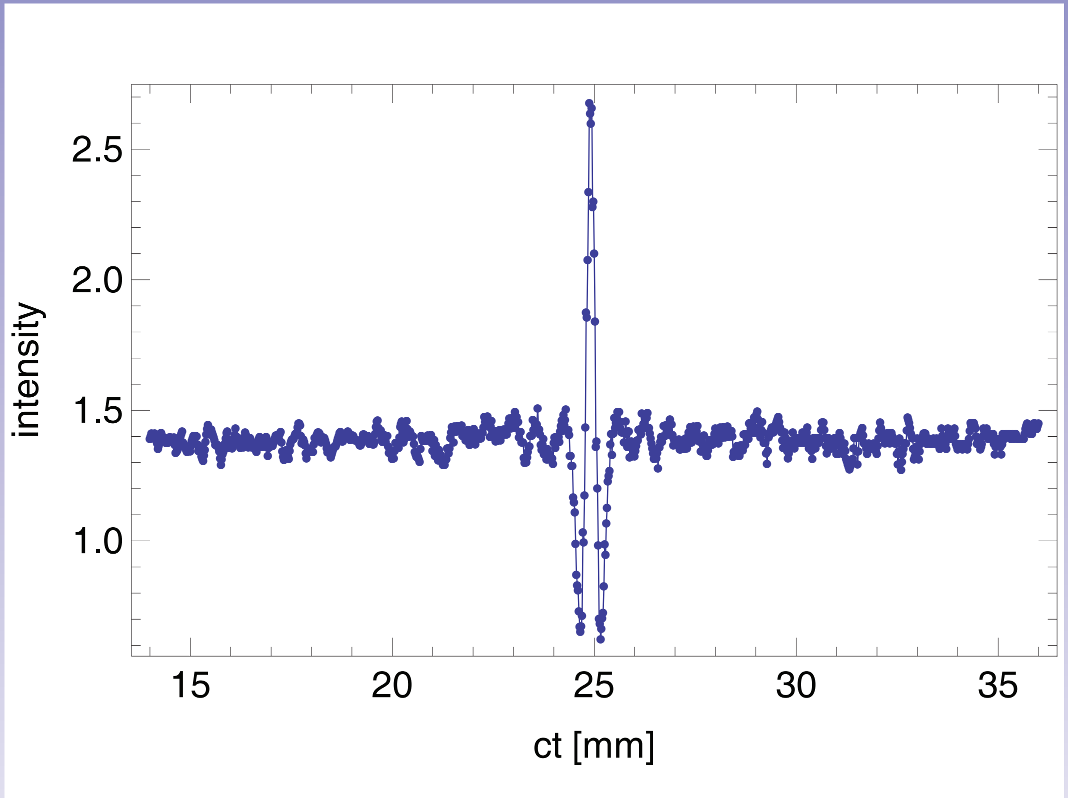
Measurements Cont'd



Detail of experimental layout

- Because of diffraction angle and distance to mirror, portion of THz collected is small (could improve using cone horn). Also expect a diffraction radiation signal due to hole in mirror.

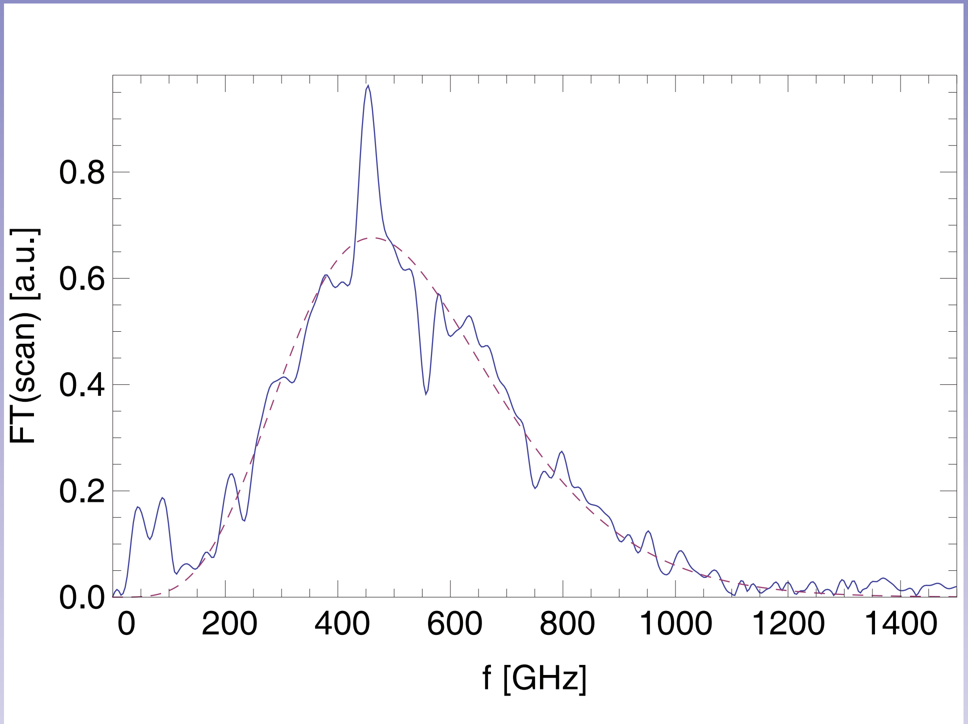
Interferometer Scan



A fine, 20-mm interferometer scan of the radiation generated by TPIPE

- $eN = 68$ pC, $\ell = 2\sqrt{3}\sigma_z = 200$ μm

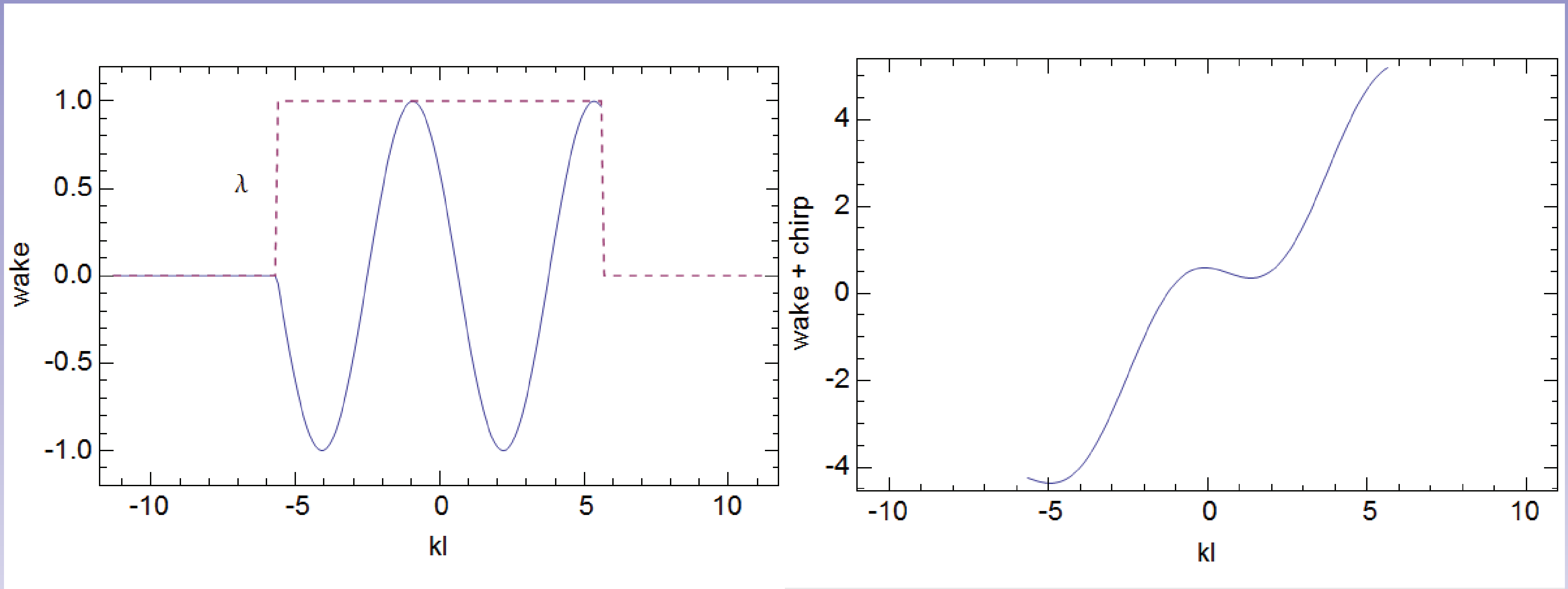
Interferometer Scan Cont'd



Fourier transform of the scan of previous slide (blue). A broad-band background to the narrow-band spike is indicated by the dashed red curve

- Narrow-band signal (10% BW) at 450 GHz is seen above broad-band background (probably due to diffraction radiation at mirror hole). Note: interferometer cuts out low frequencies

Spectrometer Measurement of Wake Effect on Beam

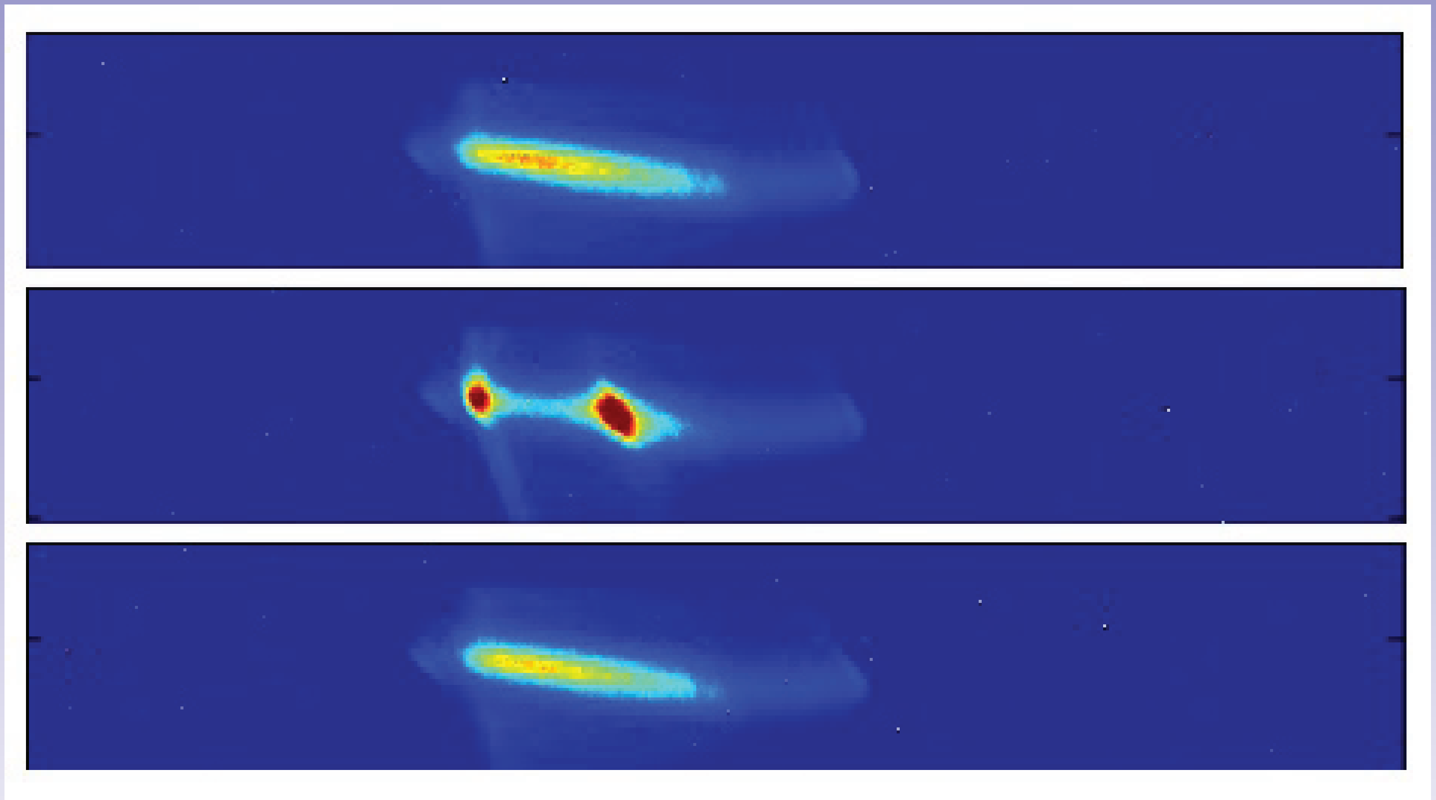


Sketch showing: wake of long, uniform bunch (left); wake + chirp (right)

- With a long uniform bunch with an energy chirp, one can measure the period of the wake in the spectrometer

Spectrometer Measurement

- Take a long uniform bunch, place it off-crest on the rf to induce a known chirp



Spectrometer images of long (1.2 mm), chirped bunch, with no structure (top), TPIPE (middle), smooth pipe (bottom)

- Spacing of density spikes gives frequency, $f \approx 450$ GHz

Corrugated Pipe as Dechirper

- In LCLS, after 2nd bunch compressor the beam is left with a positive chirp (the beam tail is at higher energy than the head). The wakefield in the 550 m of Linac 3 is used to passively cancel the chirp—to "dechirp"
- Some linac-based FEL's use a lower RF frequency (*e.g.* NGLS in Berkeley), and the wake in the last linac is too weak to cancel the chirp. The chirp can be canceled by running off-crest in the linac, but this is expensive, inefficient. Also, some XFELs have a soft-xray line, where they need no acceleration after the last bunch compressor (e.g. NGLS, PAL XFEL)
- Therefore, there is interest in developing a simple, inexpensive device that can be used as a dechirper

Dechirper Cont'd

Dielectric structures fans have also been studying dechirpers, e.g.:

• On reducing energy spread of beam using a dielectric-lined tube: Rosing, J. Simpson, "Passive momentum spread reduction, the wakefield silencer," ANL internal report WF–144, April 1990

• Proof of principle experiment performed at BNL's ATF using dielectric tube with L = 5 cm. Reduced σ_E from 250 keV to 70 keV. S. Antipov et al, IPAC12

• S. Antipov et al, "Demonstration of energy chirp compensation by a tunable dielectric based structure," submitted to PRL

Theory

- Point charge wake $W(s) = 2\varkappa \cos ks$, with loss factor $\varkappa = Z_0 c/2\pi a^2$ and wave number $k = 2/\sqrt{a\delta}$

Bunch wake $W_\lambda(s) = -\int_0^\infty W(s')\lambda(s-s')\,ds'$

- With tail of beam at higher energy than head, want dechirper that is capacitive $\Rightarrow k\sigma_z$ small

If $k\sigma_z \ll 1 \Rightarrow W_\lambda(s) \approx -2\varkappa \int_{-\infty}^{s} \lambda(x)\,dx$

- If uniform distribution of length l (with $kl/3.5 \sim k\sigma_z \ll 1$):
$\lambda(s) = H(s + l/s)H(l/2 - s)/l \Rightarrow$
$W_\lambda(s) = -2\varkappa \sin[k(s + l/2)]/kl \approx -2\varkappa s/l$

Chirp at end of pipe of length L: $h = -2\varkappa eNL/l$.

Theory Cont'd

- Can only be used to induce a negative chirp
- What makes the corrugated pipe attractive as a dechirper:

(i) it has only one significant mode, with the maximum possible $\varkappa$ for a given aperture

(ii) one can have aperture a small, for strong interaction, and still choose corrugation parameters to give a relatively low k

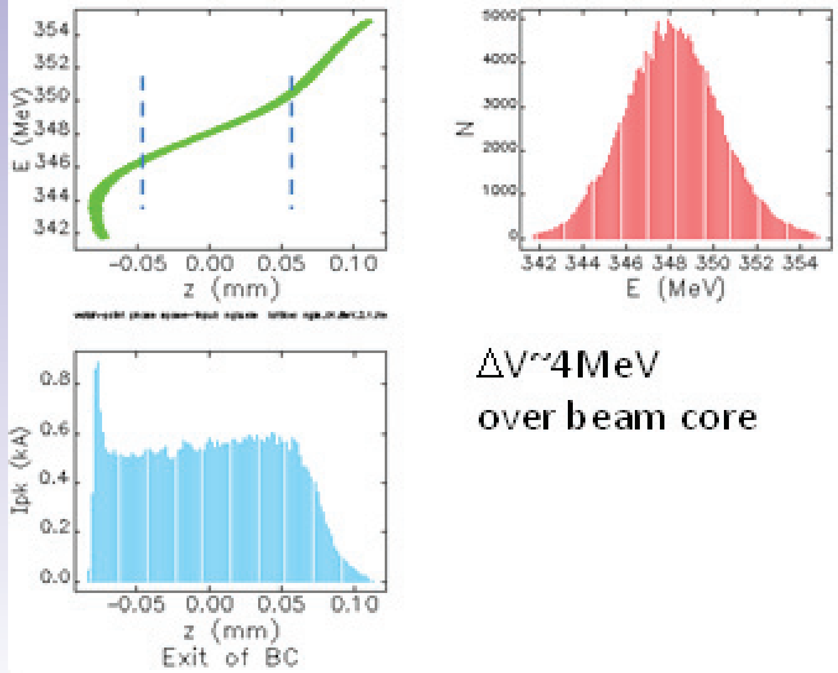
Slide from M. Venturini

Removing the energy chirp after BC

BERKELEY LAB

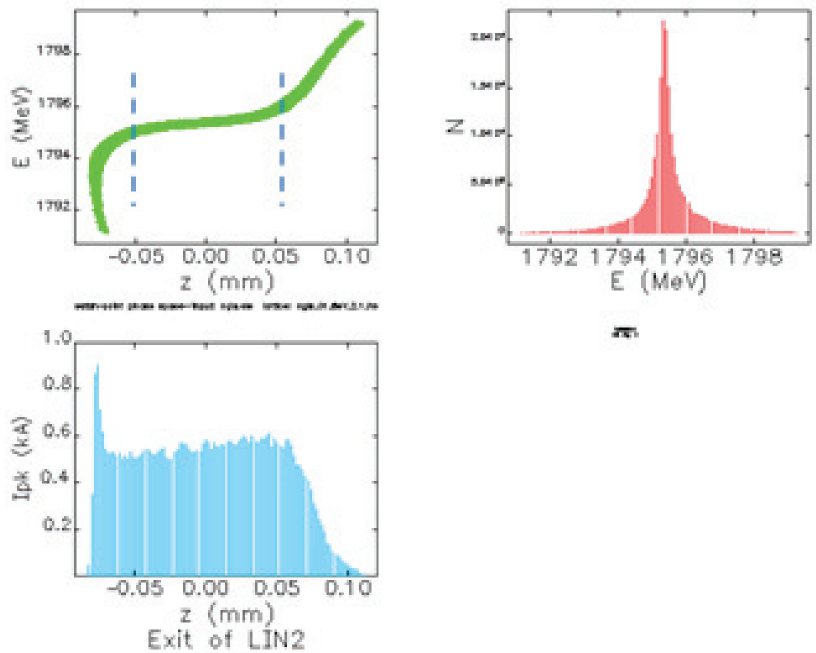
- For ngls wakes in rf structures are insufficient to remove energy chirp (in particular if operated at modest 500-600 A currents)
- Need to run linac after BC off crest (in example below, about 25 deg, ~10% acceleration efficiency loss)
  - Inefficient, expensive

Long. phase space after compressor



ΔV~4MeV over beam core

Long. phase space at exit of linac



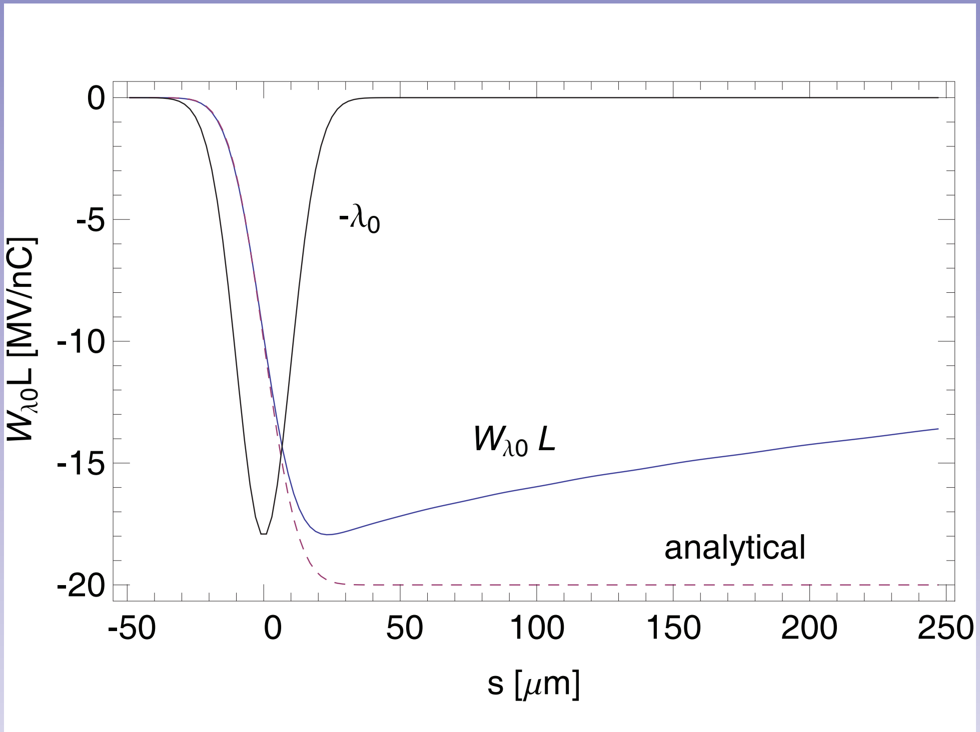
Berkeley NGLS Example

- For NGLS, required chirp is $h = -40$ MeV/mm over 150 μm. For uniform λ, can achieve this with ($h \approx -2\varkappa eNL/l$): $eN = 300$ pC, $l = 150$ μm; $a = 3$ mm, $L = 5$ m, $\delta = 450$ μm, $p = 1000$ μm, $g = 750$ μm; yielding $k = 1.7$ mm^{-1}, $\varkappa = 2$ MV/nC, $U_w = 0.9$ mJ
- Ran ECHO for this structure for Gaussian bunch with $\sigma_z = 10$ μm, to generate a "Green function" wake
- Then convolved this wake with toy model of NGLS bunch shape:

$$\lambda(s) = A \begin{cases} 1 & : \quad |s| < 75 \ \mu\mathrm{m} \\ e^{-s^2/2\sigma_0^2} & : \quad |s| > 75 \ \mu\mathrm{m} \end{cases}$$

where A is a normalization constant and $\sigma_0 = 20$ μm

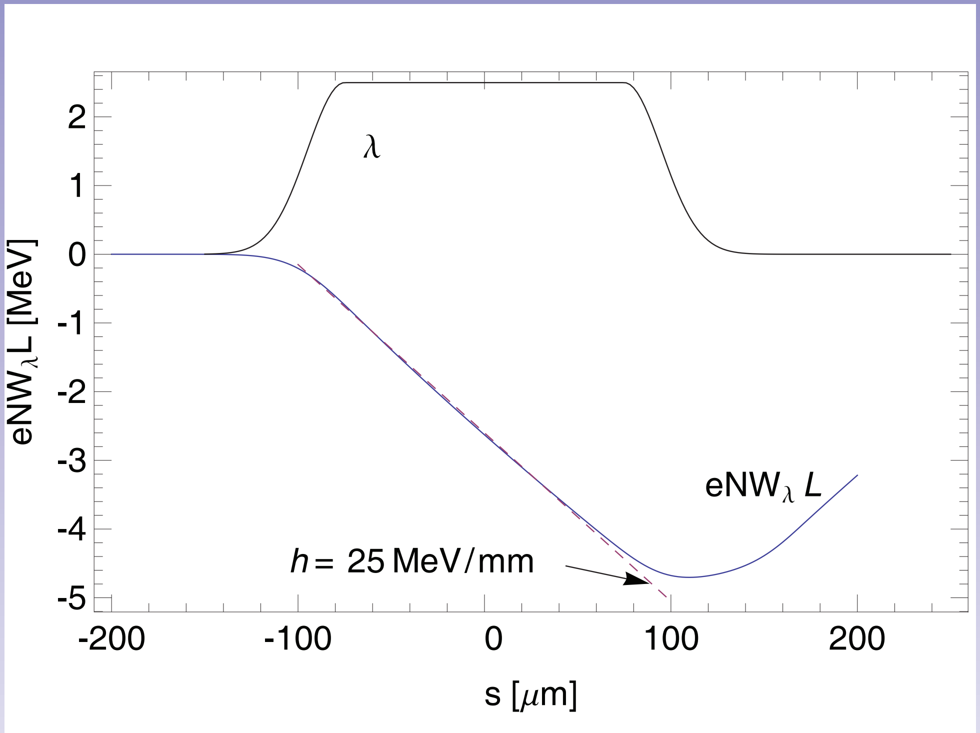
Green Function Wake of Dechirper



Dechirper for NGLS: wake of $\sigma_z = 10$ μm long bunch (blue). Dashed, red curve gives analytical approximation $W_{\lambda 0}L = -2\varkappa L(1 + \mathrm{erf}(s/\sqrt{2}\sigma_z))$. Driving bunch shape λ_0 is given in black.

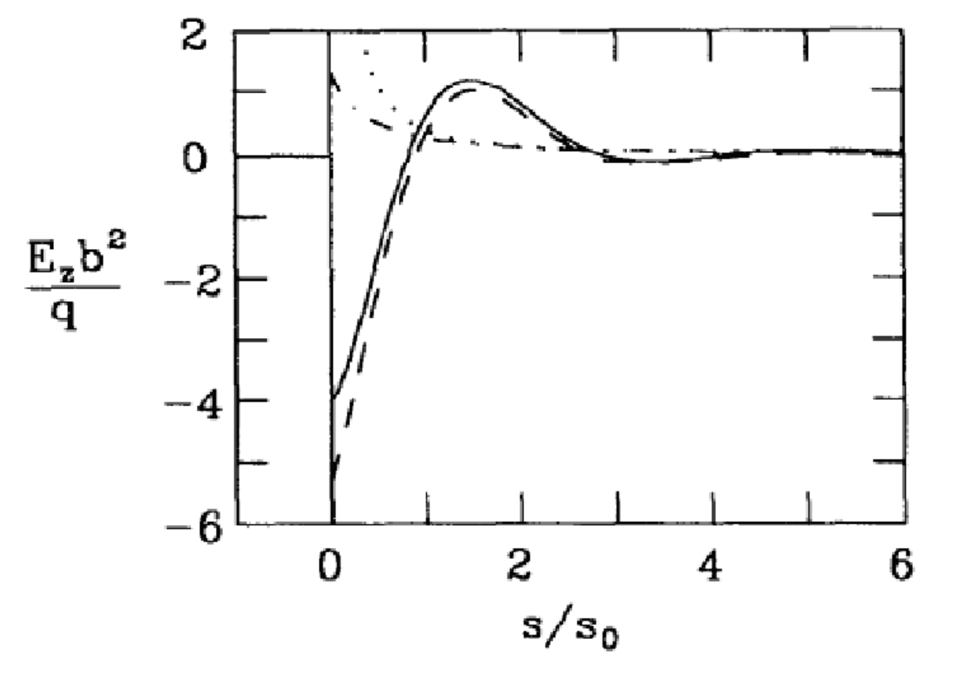
- Almost perfect agreement of wake over bunch. Disagreement behind

Wake for Model of NGLS Bunch



Dechirper for NGLS: wake of toy model of NGLS bunch (blue). Dashed, red curve represents a chirp $h = -25$ MeV/mm. Bunch shape is given in black.

Comparison with a Resistive Pipe



Short range resistive wall wake for metallic pipe of radius b. Wake at $s = 0$ is the same as for a corrugated pipe of radius b

- The zero crossing of the corrugated pipe wake is at $\pi/2k = 900$ μm. For resistive wall wake, $s_0 = (cb^2/2\pi\sigma)^{1/3}$, with σ the conductivity. If $b = 3$ mm, $s_0 = 9$ μm (Cu), $s_0 = 32$ μm (SS)

Dechirper Cont'd

- Can do dechirping using a metallic pipe with a thin dielectric liner—the wake effect is equivalent. With δ the thickness of dielectric layer, same formula for $\varkappa$, and $k = \sqrt{2\epsilon/(\epsilon-1)a\delta}$. Which is cheaper, more reliable, easier to implement?

- For dechirper of adjustable strength, can consider planar geometry with adjustable separation

Dechirper Test Experiment at Pohang (PAL) in Korea

Experiment was performed August 5-10, 2013 at the Injector Test Facility (ITF) of the Pohang Accelerator Laboratory (PAL). H.-S. Kang gave an invited talk on the dechirper and the experiment at the FEL conference in New York this August

- Experiment performed by H.-S. Kang and his team. Invited to participate were K. Bane, P. Emma, G. Stupakov, M. Venturini

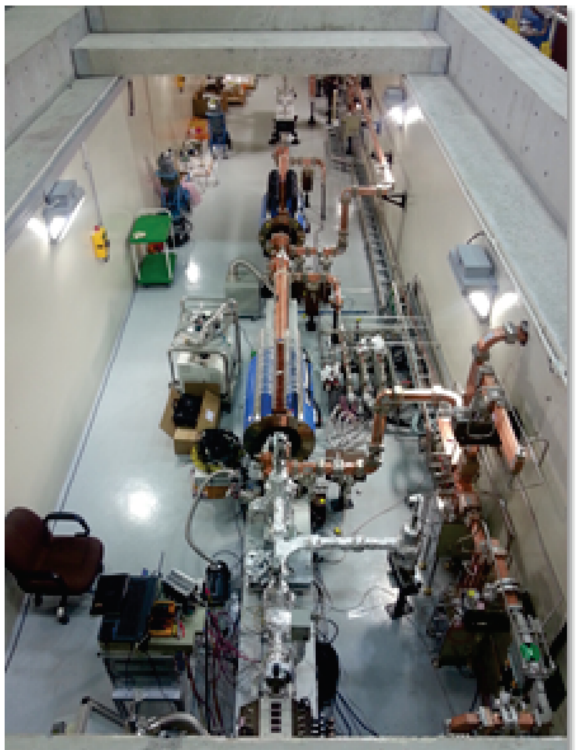
- Report submitted for publication

- Beam properties: $eN = 200$ pC, energy 70 MeV, $\sigma_z = 0.45$ mm. 1-m long dechirper with adjustable vertical aperture. Diagnostics include an S-band deflecting cavity and a spectrometer.

Dechirper Test Experiment Cont'd

PAL-XFEL

Injector Test Facility



ITF Tunnel

ITF Modulator / Klystron

August 26, 2013
FEL 2013

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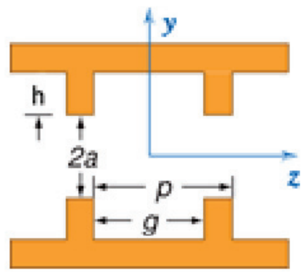
Slide from H.-S. Kang

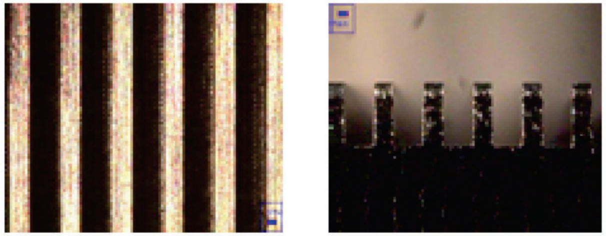
Test Experiment Cont'd

Corrugation Parameters for Dechirper



	A Test module at PAL-ITF	PAL-XFEL Soft XFEL line
Beam energy, GeV	0.07	3.15
Half gap, a [mm]	4	2.5
corrugation period, p [mm]	0.5	1.0
corrugation depth , h [mm]	0.6	0.5
corrugation gap, g [mm]	0.3	0.5
Width of plate [mm]	50	50
Length [m]	1	20

After Chemical Cleaning



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Slide from H.-S. Kang

Test Experiment Cont'd

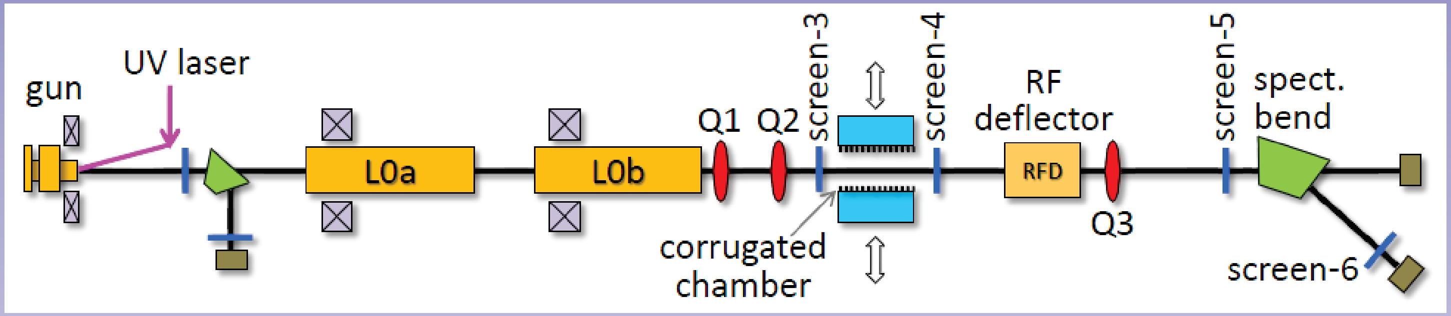
- Flat geometry was chosen for flexibility. In flat geometry, if gap is $2a$, then compared to round case: (1) k is smaller by $1/\sqrt{2}$, (2) $w_z(0)$ reduced by factor $\pi^2/16$

For leading and trailing particles 1 and 2

$$w_y(s) = y_1 w_d(s) + y_2 w_q(s) \ , \quad w_x(x) = (x_1 - x_2) w_q(s) \ ;$$

$w_z(s)$, $w_d(s)$, $w_q(s)$, slightly damped oscillating functions; we have analytical and numerical (field matching) solutions for flat geometry

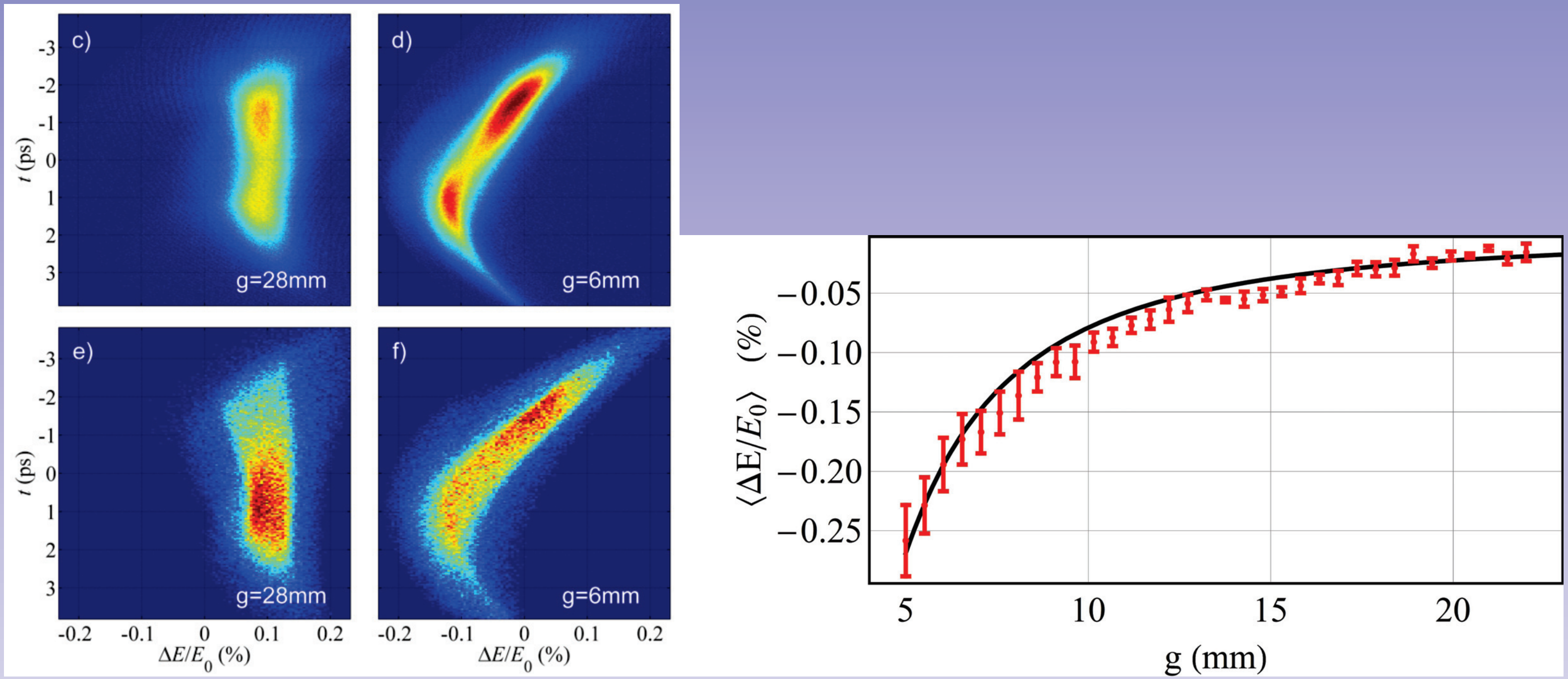
Test Experiment Cont'd



Layout of PAL ITF wakefield experiment

- At PAL ITF, performed time-resolved measurements of longitudinal, dipole, and quadrupole wakes, and also of averaged wake effects as functions of collimator gap or beam offset
- Results give measurements in reasonable agreement with theory (scale factor question, $\sim 25\%$)

Test Experiment Cont'd



Screen 6: (Left) images of $\Delta E/E$ vs t, measured (top two), simulated (bottom two), for gap $g \equiv 2a = 28$ mm (left two), 6 mm (right two). Bunch head is at the top of each frame

(Right) Average of beam energy change vs gap, measured (symbols) and simulated (line)

Conclusions

- The corrugated structure is unique in that (nearly) all the impedance is in one mode. In addition, one can have both an aperture that is small—for a strong wake amplitude—and a relatively long wavelength, for coherent excitation by a beam
- We have shown that—with reasonable parameters—one can generate a radiation pulse with frequency ~ 1 THz and a total energy ~ 1 mJ
- The corrugated pipe may be a passive, inexpensive way of removing residual energy chirp in a linac-based FEL
- A proof-of-principle experiment at BNL's ATF has measured THz pulses of the proper frequency and bandwidth. A test measurement of the wake of a flat dechirper seems to be in agreement with theory