Northern Illinois University

Fermilab

Dielectric Lined Waveguides for Beam Acceleration and Manipulation

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Outline

- Beam driven acceleration
  - Longitudinal shaping
    - Alternative shapes for enhanced transformer ratios
    - Investigate temporal laser-shaping to generate such distributions
- Beam manipulation
  - Longitudinal phase space manipulation with self-wake at low energy
    - Microbunching, passive compressor, longitudinal shaping
  - Multiple structures
    - EEHG, acceleration, radiators
- Toward dispersion controlled acceleration in a DLW
  - Tapered dielectric lined waveguides to control phase velocities

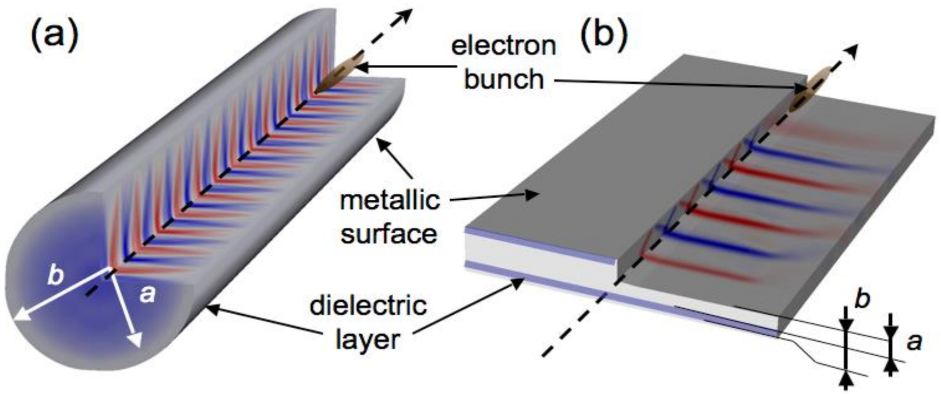
Beam Driven Wakefield Acceleration

$$E(z) = \int_{-\infty}^{z} I(z - z')G(z')dz'$$

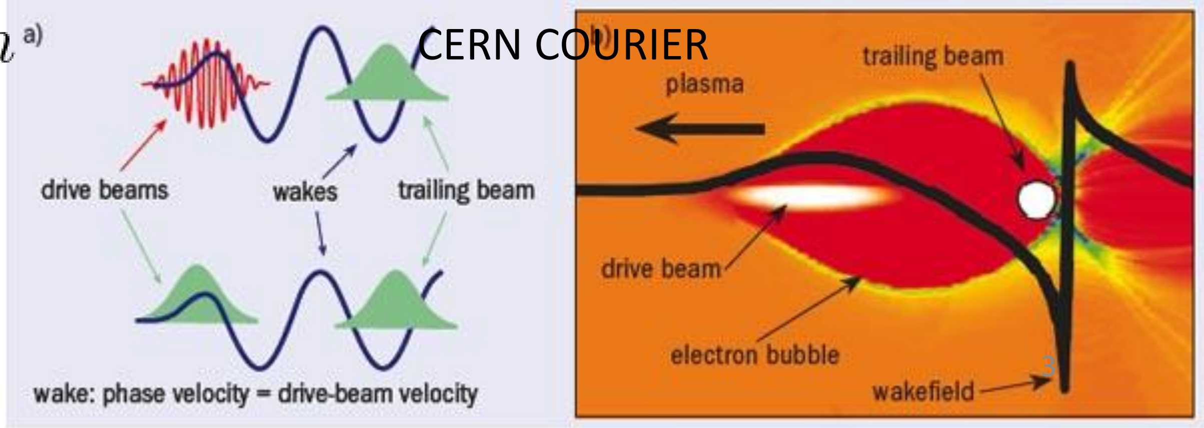
$$G(z) = \sum_{n} \kappa_n cos(k_n z)$$

- Voss-Weiland DESY 1982
- High-impedance medium
  - Dielectric Lined Waveguides (DLW)
    - Cylindrical/Slab symmetric
    - Transmission concerns
    - Low cost
    - Relatively clean (vacuum wise)
  - Plasmas
    - Gas (ionized)/ vacuum concerns
    - Collisions + emittance growth
    - Ease of beam transmission

$$E+ = 96 * \sqrt{\frac{n_e}{cm^3}} V/m$$

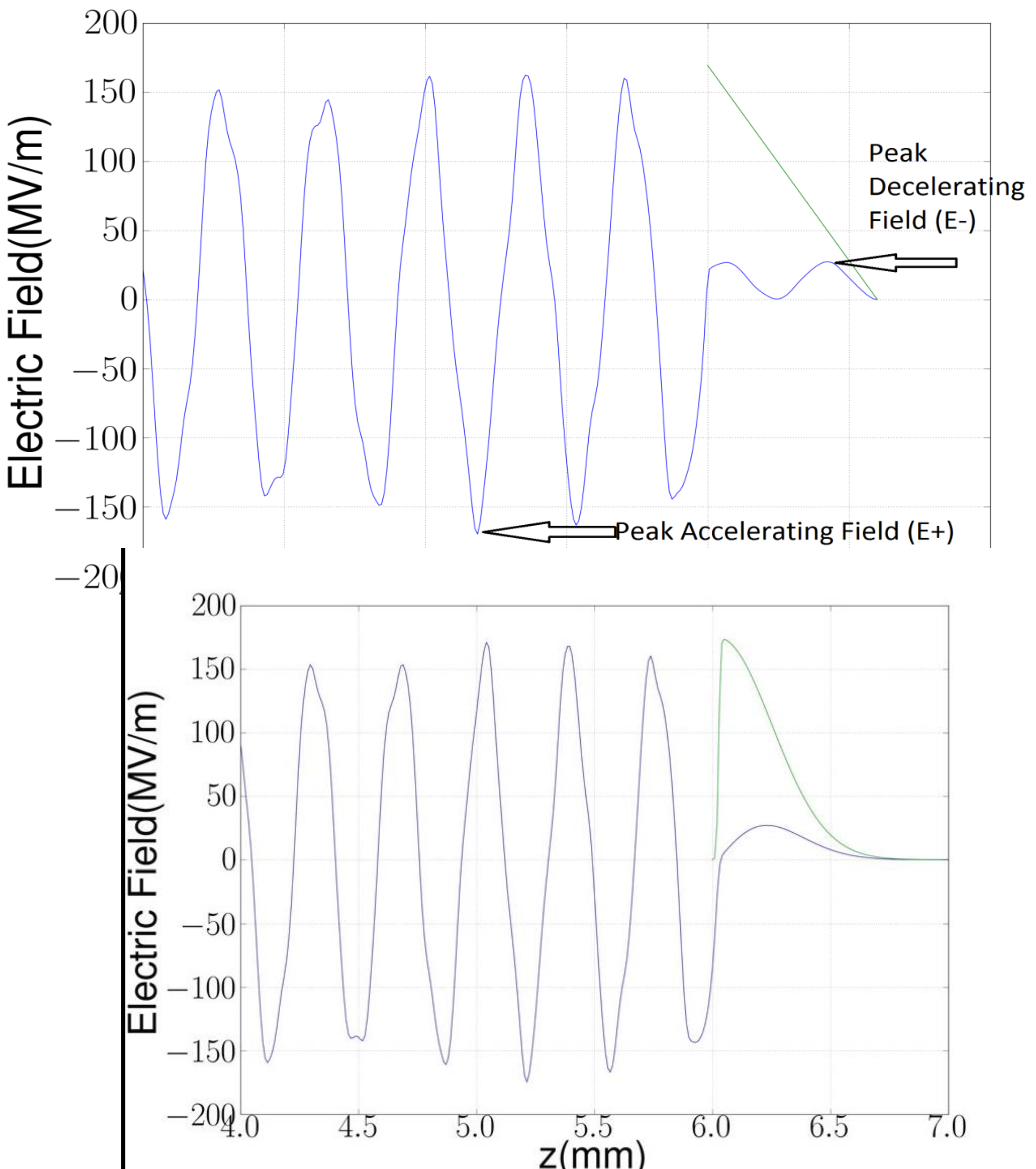


CERN COURIER



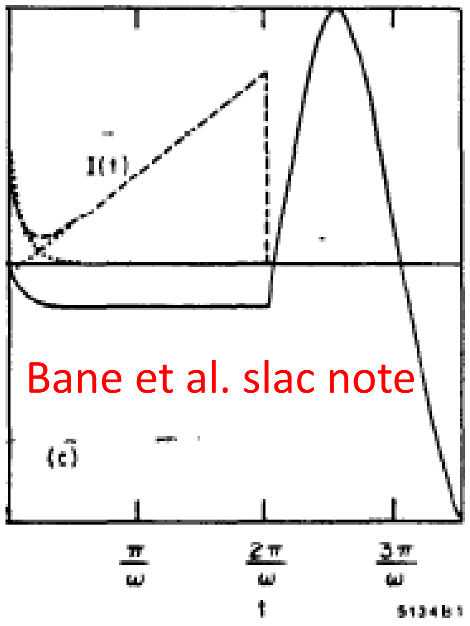
Wakefields and the Transformer Ratio

- Fundamental wakefield theorem: symmetric bunches R = E+/E- < 2.
- Interested in large accelerating fields *and* efficient energy transfers

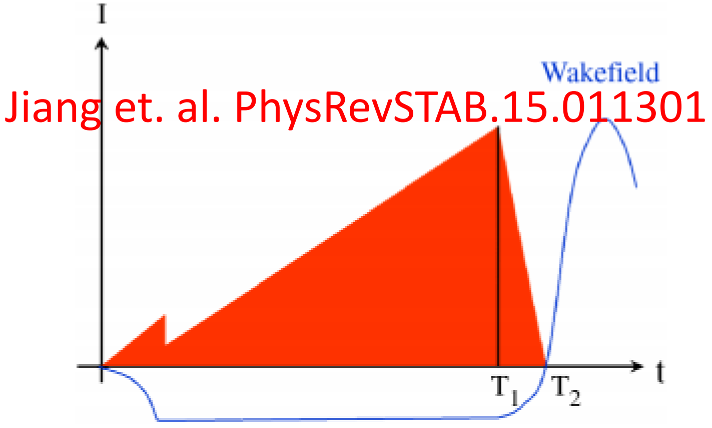


Overview: Ultimate Transformer Ratio

- For persistent acceleration- require flat decelerating field.
  - Bane '85 exponential ramp $R = \sqrt{1 + (\omega T)^2}$
  - Jiang '12 double triangle $R = \sqrt{1 + (\omega T - 1)^2}$
  - Difficult to generate such distributions – generally require masks + transverse to longitudinal EEX.
  - Search for smooth/continuous shape with flat decelerating field.



Bane et al. slac note



Jiang et. al. PhysRevSTAB.15.011301

Search for Continuous/Smooth shapes

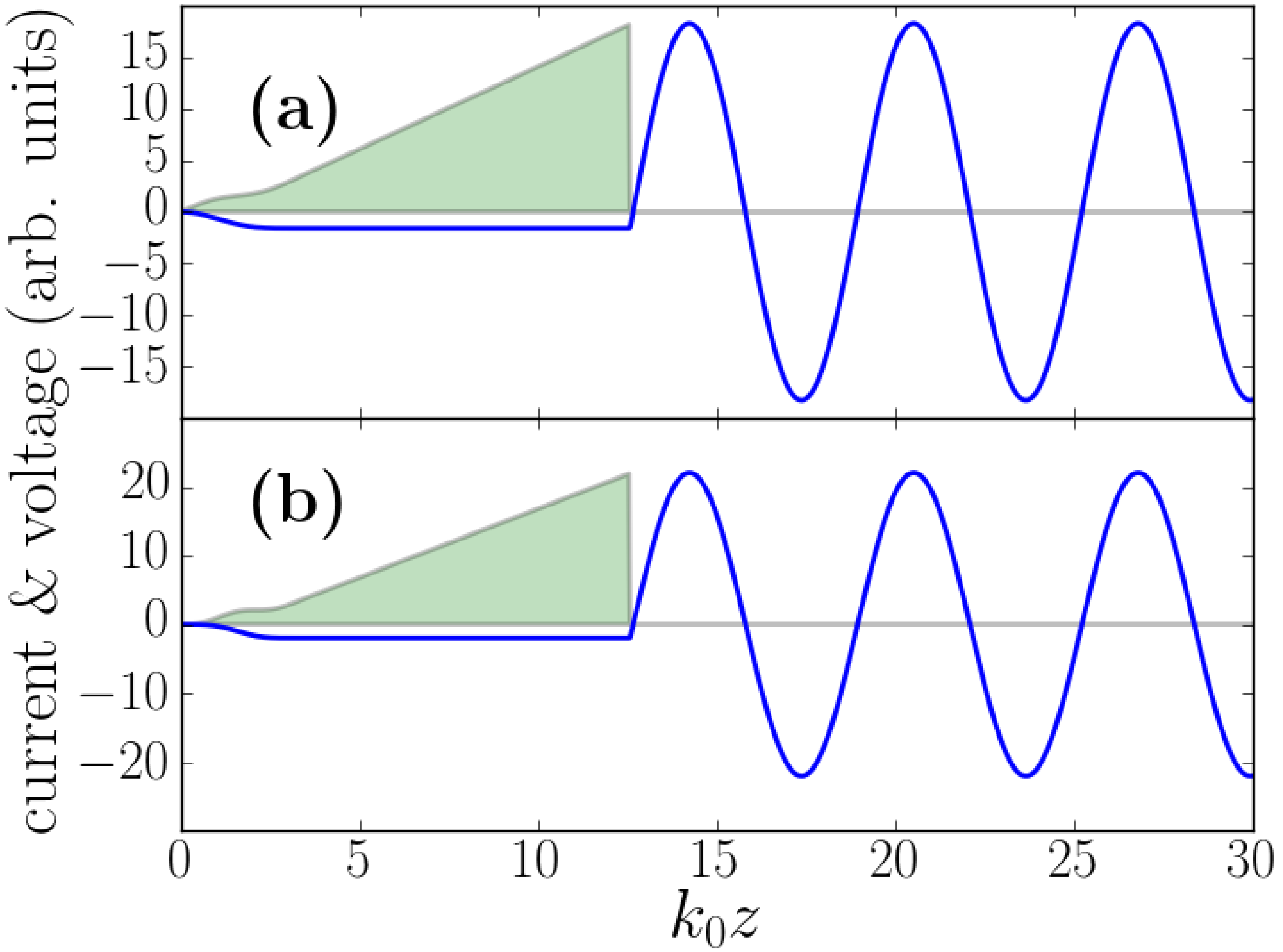
- Smooth shapes lower emittance requirements in proposed longitudinal shaping techniques
- Coulomb force (space charge) naturally produces smooth shapes.

$$s(z) = \begin{cases} f(z) & z < \frac{\lambda}{n} \\ f'(\lambda/n)z - f'(\lambda)\lambda/n + f(\lambda/n) & x \geq \frac{\lambda}{n} \\ 0 & elsewhere \end{cases}$$

Sinusoidal Ramp

$$f(z) = az + b\sin(qkz)$$

$$\mathcal{R} = \begin{cases} \frac{1}{8}\sqrt{\pi^2(3-16N)^2+64} \\ \\ \frac{1}{2}\sqrt{\pi^2(1-4N)^2+4}. \end{cases}$$

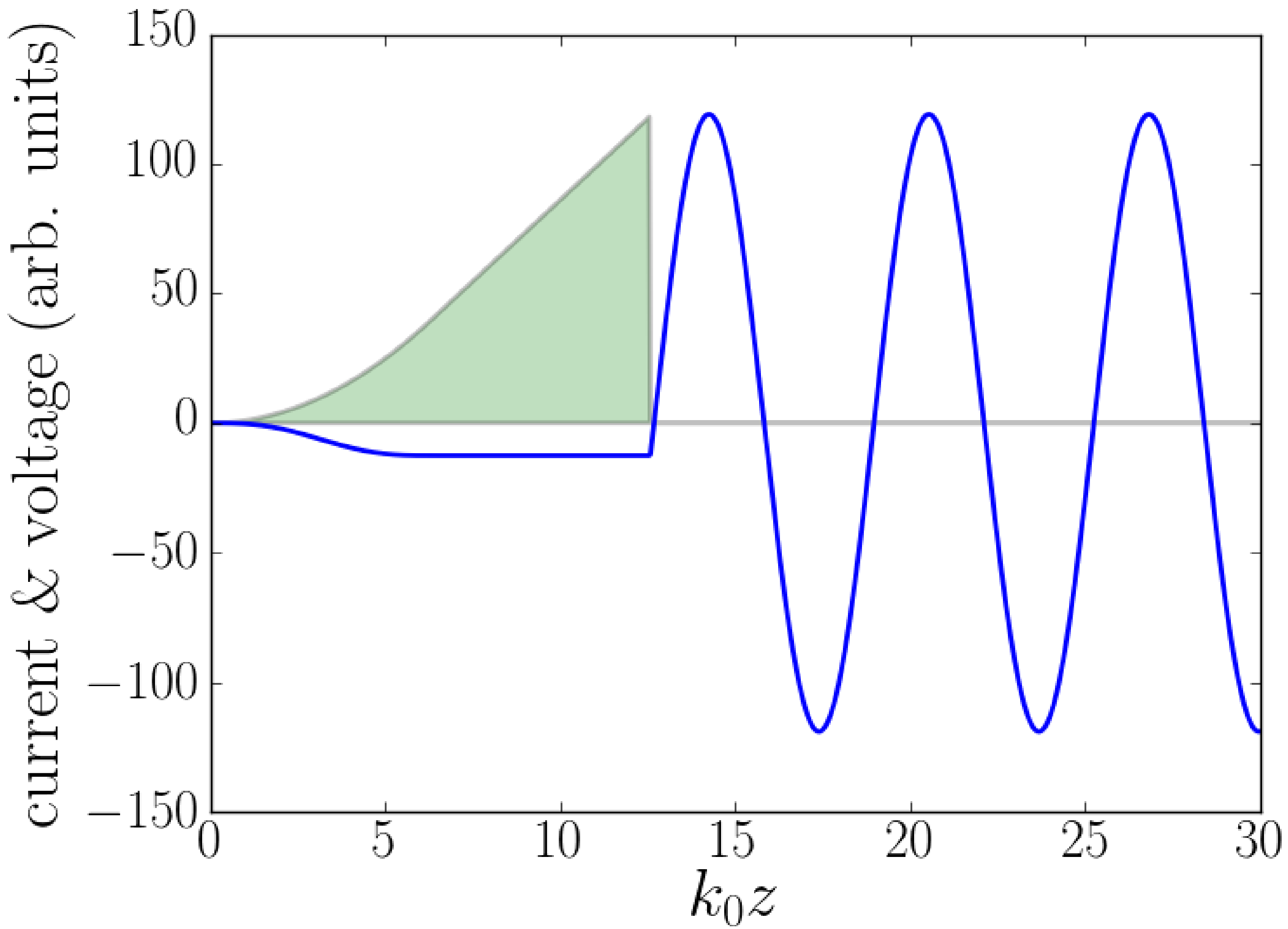


Leads to 2 solutions:
When c is even, top solution
When c is odd, bottom solution

Quadratic Ramp

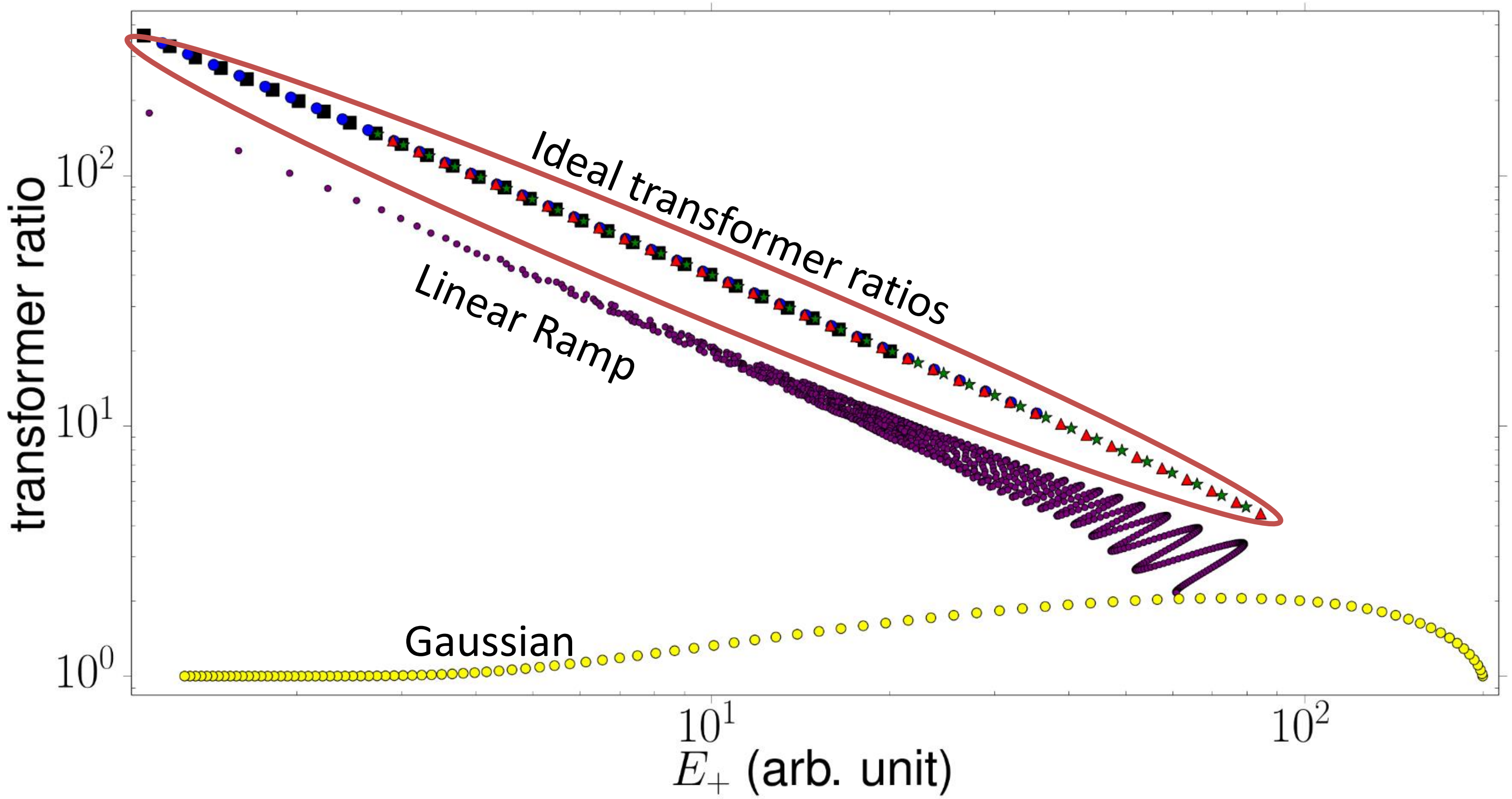
$$f(x) = ax^2,$$

$$\mathcal{R} = \sqrt{1 + \pi^2(2N - 1)^2}.$$



Benchmarking

- Previous description of R are usually not normalized to a specific charge.
- Normalizing each proposed shape yields interesting results:

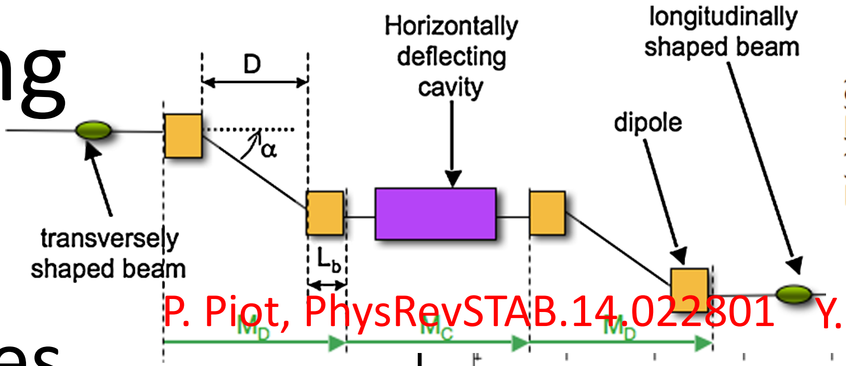


distribution	R(N)	R(Q)	V_-^m
doorstep	$\sqrt{1+(1-\pi/2+2\pi N)^2}$	$\sqrt{2+\pi(\frac{4Q}{a\lambda}-1)}$	$\frac{a\lambda}{\pi}$
d-triangle	$\sqrt{1+(2\pi N-1)^2}$	$\sqrt{2+\pi(\frac{4Q}{a\lambda}-1)}$	$\frac{a\lambda}{\pi}$
sin-rampU	$\frac{1}{2}\sqrt{\pi^2(1-4N)^2+4}$	$\frac{1}{6}\sqrt{44-9\pi^2+\frac{24\pi Q}{a\lambda}}$	$\frac{6a\lambda}{\pi}$
sin-rampD	$\frac{1}{8}\sqrt{\pi^2(3-16N)^2+64}$	$\frac{1}{8}\sqrt{64-15\pi^2+\frac{48\pi Q}{a\lambda}}$	$\frac{16a\lambda}{3\pi}$
quadratic	$\sqrt{1+\pi^2(2N-1)^2}$	$\sqrt{1+\pi^2(\frac{4Q}{a\lambda^3}-\frac{1}{3})}$	$\frac{a\lambda^3}{\pi^2}$

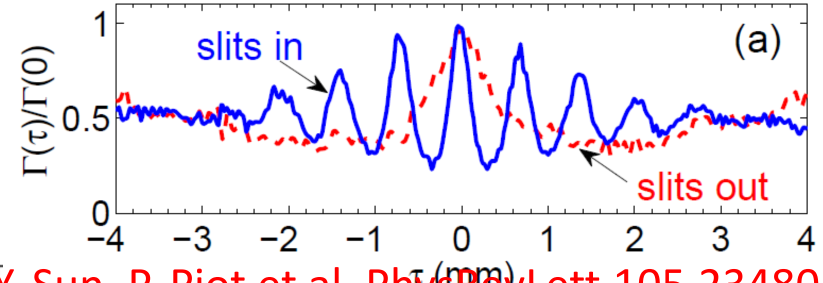
$$Q = \int_0^{N\lambda} dz I(az),$$

Longitudinal Shaping Techniques

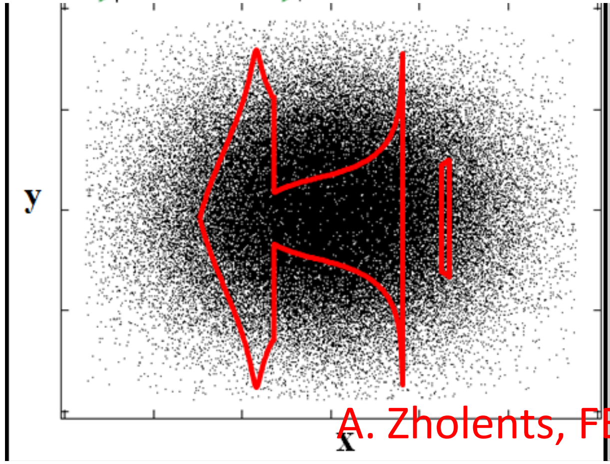
- Mask-based techniques
  - Transverse to longitudinal
    - Emittance exchange (EEX)
    - Chicane based
- Beam manipulation with RF
  - Experiment done at FLASH
- Investigate alternative techniques

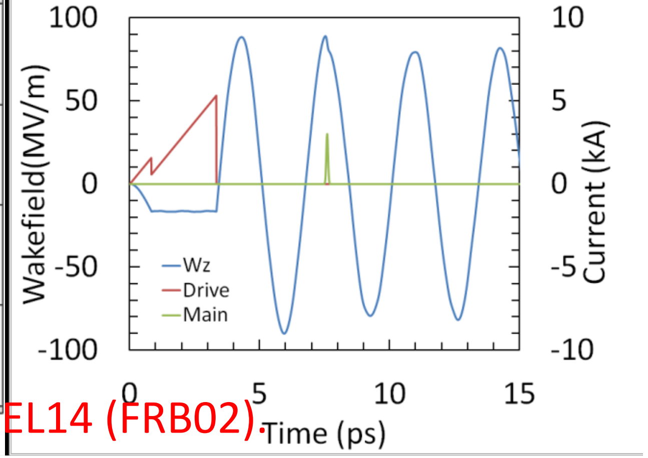


P. Piot, PhysRevSTAB.14.022801



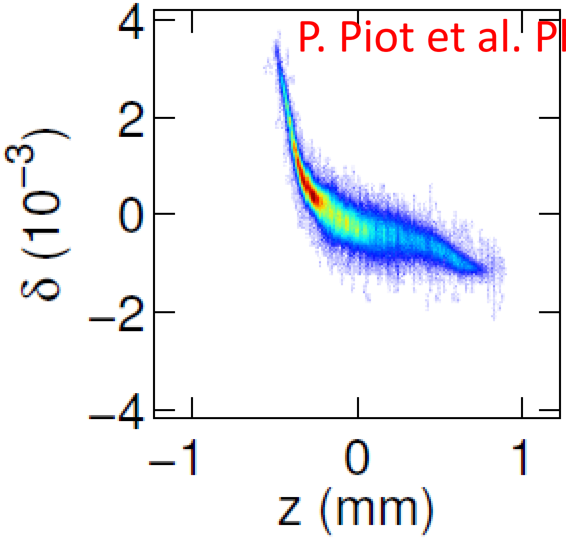
Y. Sun, P. Piot et al. PhysRevLett.105.234801

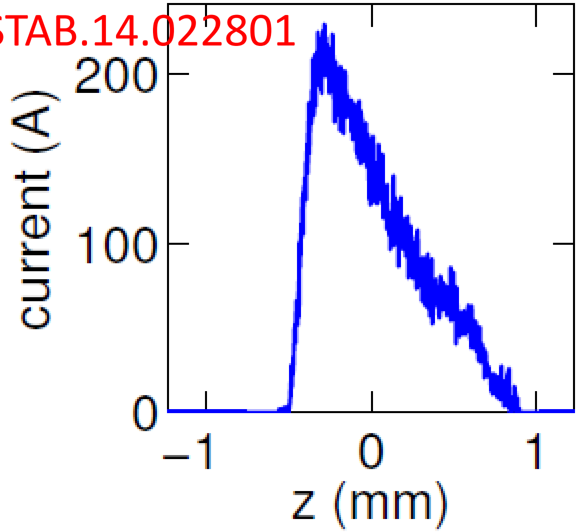




A. Zholents, FEL14 (FRB02).

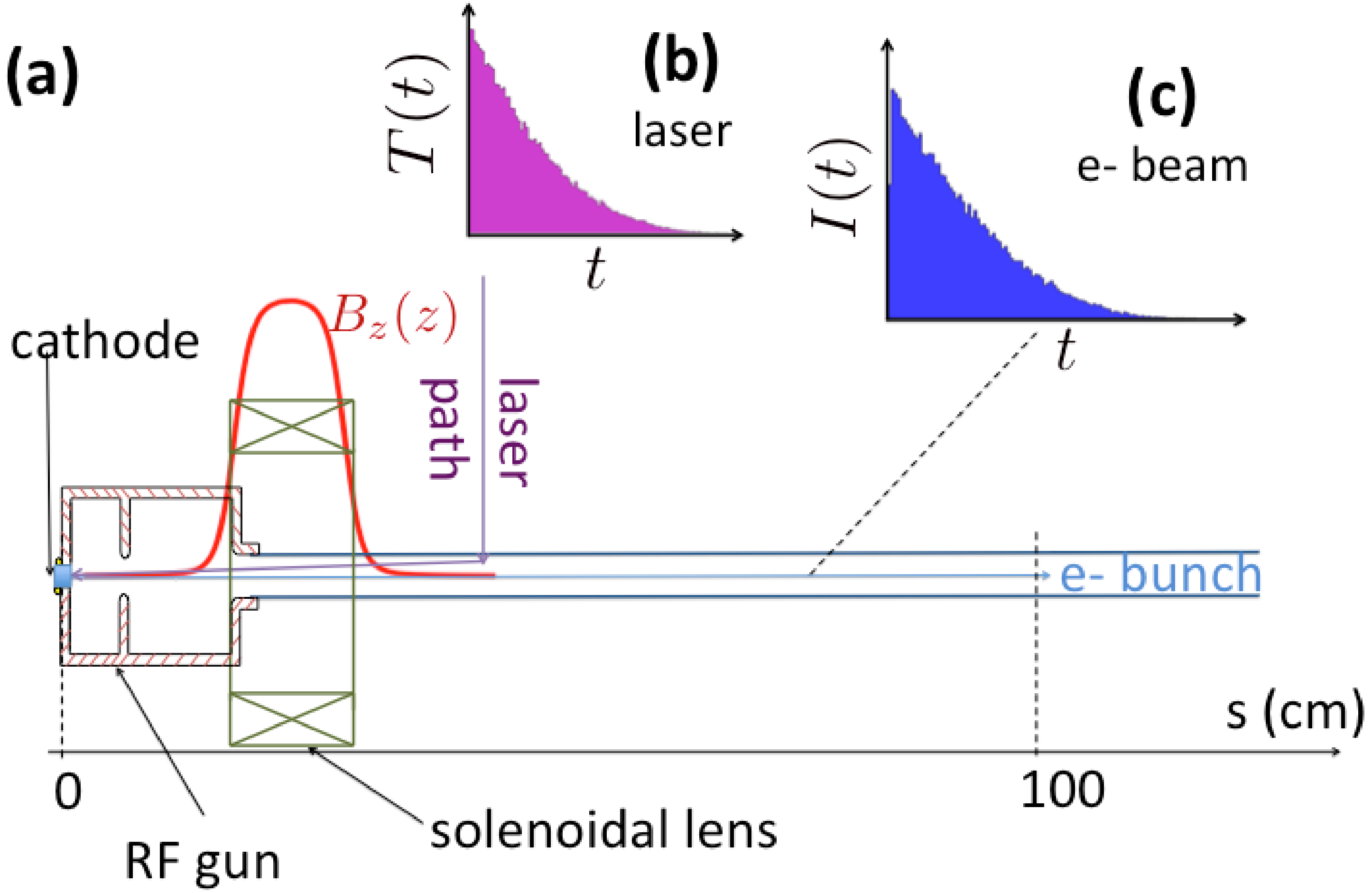
P. Piot et al. PhysRevSTAB.14.022801





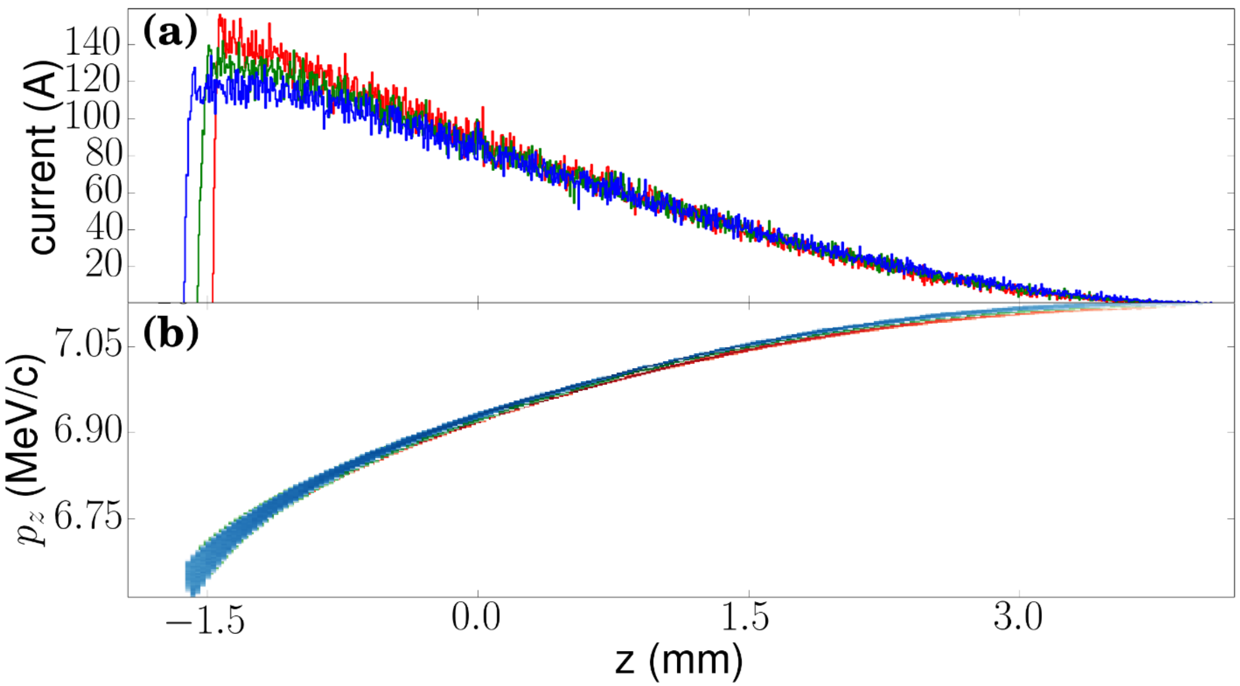
Temporal Laser Shaping

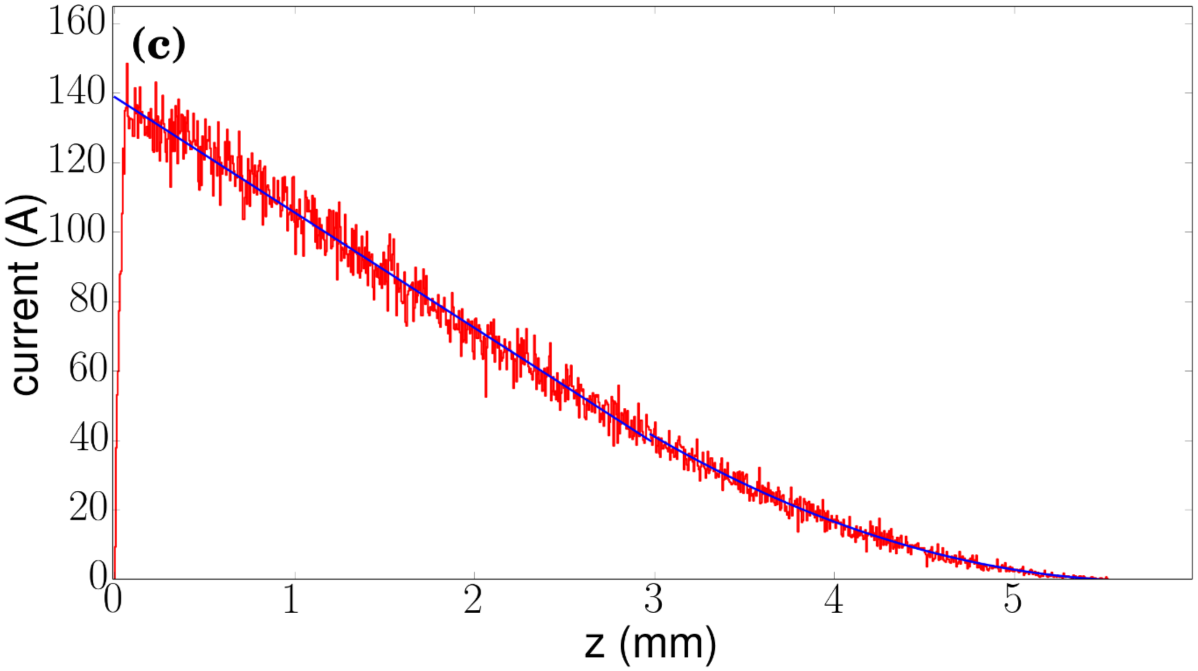
- Longitudinal laser-shaping
  - Generate longitudinal electron distribution out of RF gun.
  - Large accelerating fields (e.g. S-Band) can preserve relatively high charge density distributions.
  - Support high-repetition rates
  - Use compressor at high-energy to scale the distribution if necessary.



Laser Shaping Continued

- Investigate polynomial (right $I=az^2$) and exponential laser profile pulses
- Tunable parameters
  - Laser (length, shape, spotsize)
  - Charge
  - Acceleration gradient



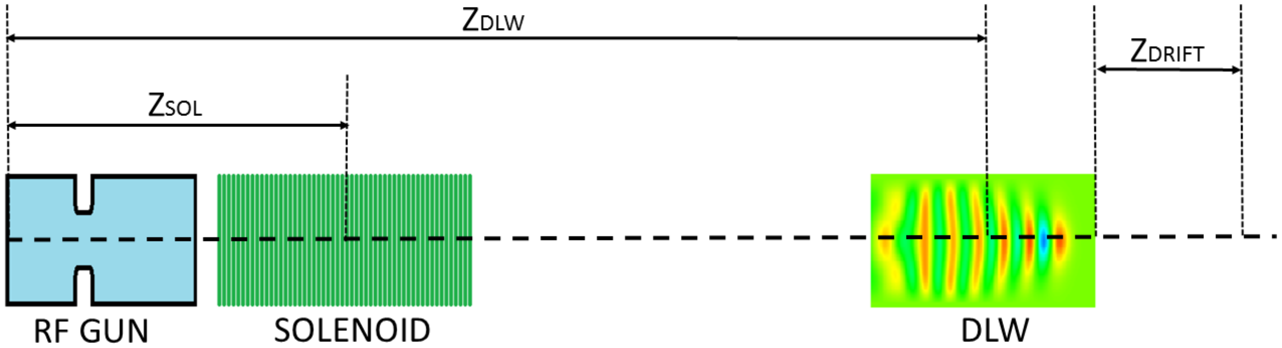


Passive manipulation: Recent results

- Recently proposed/demonstrated passive applications:
  - Linearizer: P. Craievich Phys. Rev. ST Accel. Beams **13**, 034401
  - De-chirper
    - P. Emma et al. PhysRevLett.112.034801
    - S. Antipov et. al. PhysRevLett.112.114801
  - Multi Bunching: S. Antipov et. al. PhysRevLett.111.134802

Self-Wake Interactions at Low Energy

- Photo-Injector Source:
  - ~ 100 Amp currents.
  - < 10 MeV energy out of gun (L-Band(1.3GHz - 35 MV/m) vs S-Band(2.856 GHz – 140 MV/m), X…), energy spread.
  - Emittances < 5 µm for S-Band. Ideal for fitting into smaller structures.
- Ballistic bunching, shaping+



$$R_{56} \simeq -\frac{D}{\gamma^2}$$

Numerical Simulations with ASTRA

- Particle tracking code with space charge
- Use 2+1/2 D – cylindrical symmetry.
- 100k macro particles,
- 200 long. bins, 7 rad. bins.
- Use Green's function "WAKE"

ASTRA module.

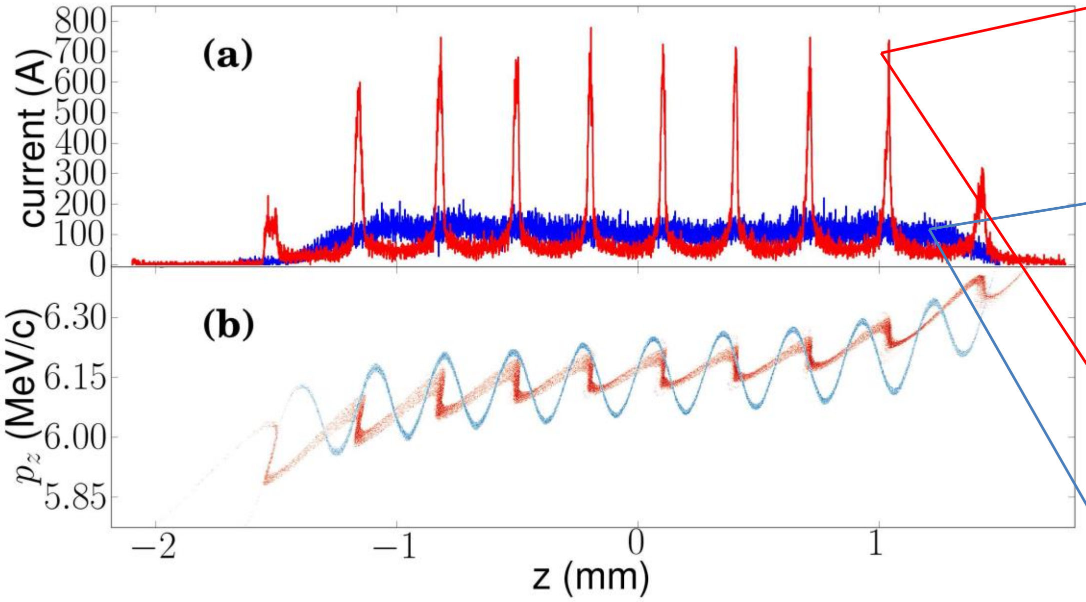
- Use offline software to calculate the bunch form factor (BFF)

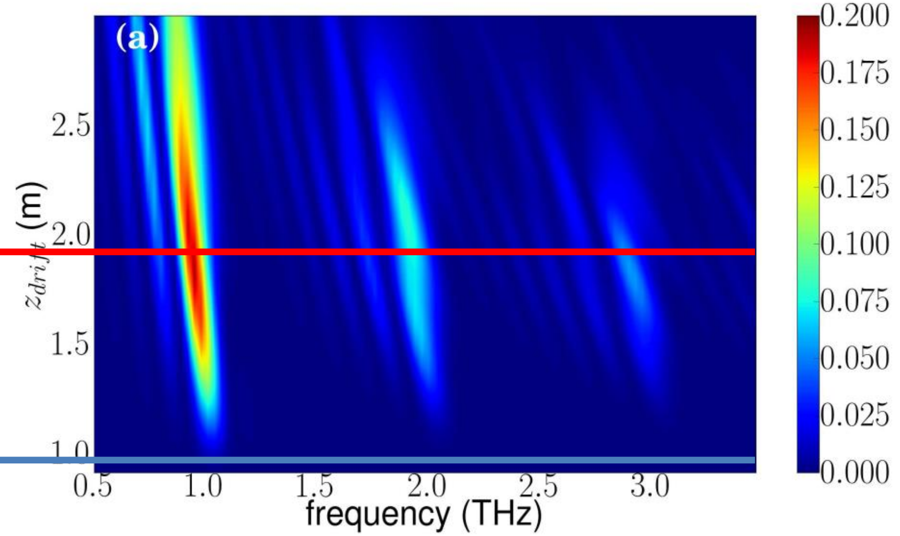
$$\widetilde{F}(\omega) = \frac{1}{N^2}\left(\left|\sum_i^N \cos\frac{\omega z_i}{c}\right|^2 + \left|\sum_i^N \sin\frac{\omega z_i}{c}\right|^2\right)$$

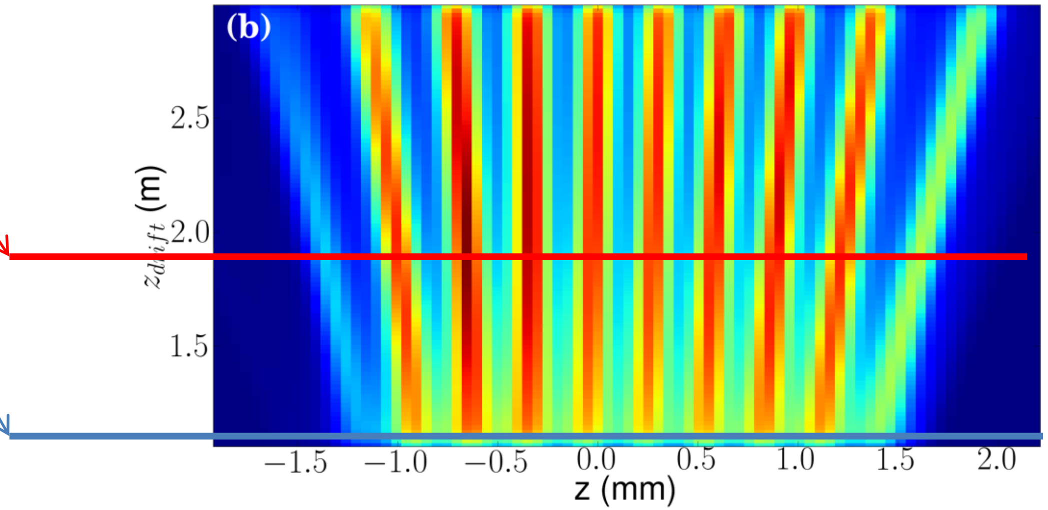
	S-Band	L-Band	
parameter			units
Laser pulse RMS duration	3	7	ps
Laser pulse rise time	100	100	fs
Laser RMS spot size	0.72	1.1	mm
Initial charge	1	1	nC
Peak field on cathode	120	34	MV/m
Solenoid 1 position	0.20	0.0	m
Solenoid 1 strength	0.26	0.17	T
Solenoid 2 position	1.35	1.0	m
Solenoid 2 strength	0.45	0.15	T
DLW position	0.9	0.34	m
DLW inner radius (a)	350	500	μm
DLW outer radius (b)	363	550	μm
DLW length	11	4	cm
DLW fund. frequency f_1	1000	400	GHz
Transmission through DLW	85	98	%
Average kinetic energy	6.1	3.8	MeV

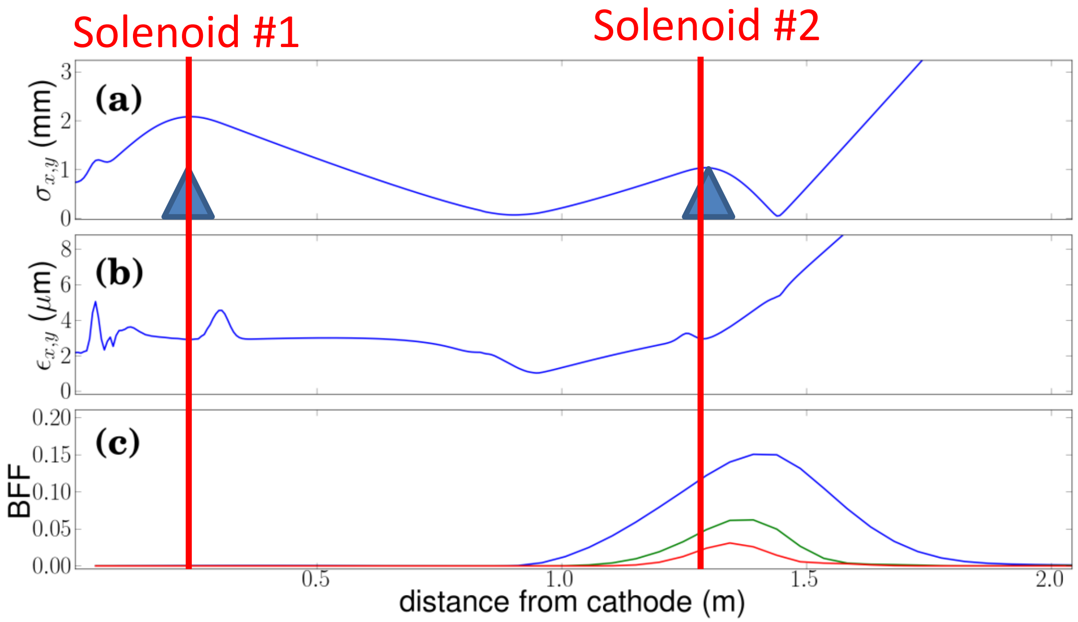
Density modulation at 1 THz

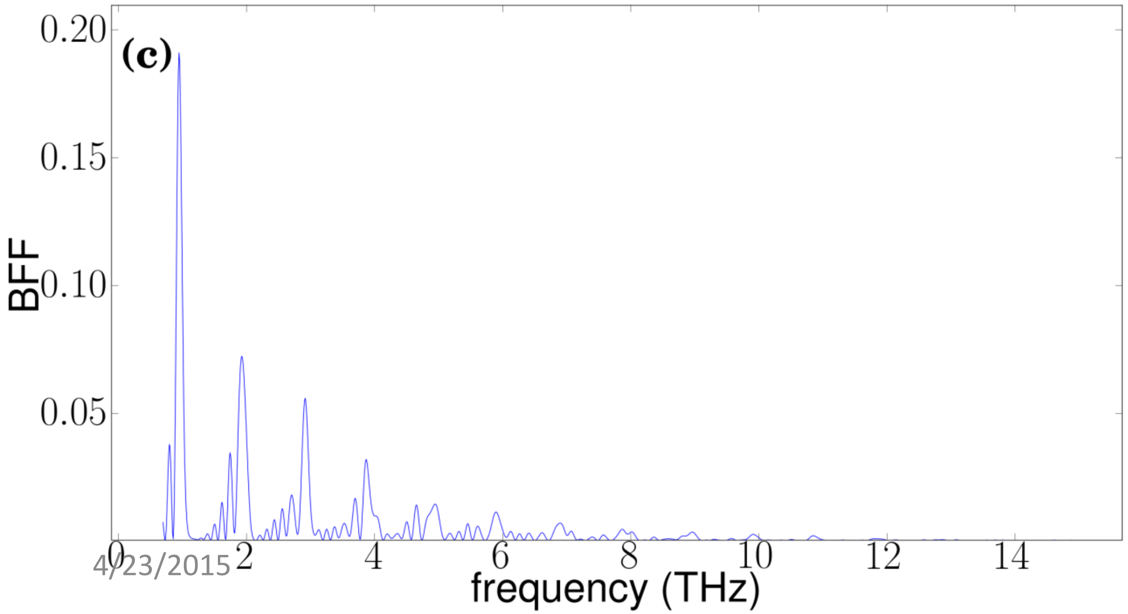
- S-Band Gun
- DLW parameters (a, b, ε, L) =(350 μm, 363 μm, 5.7, 11 cm)







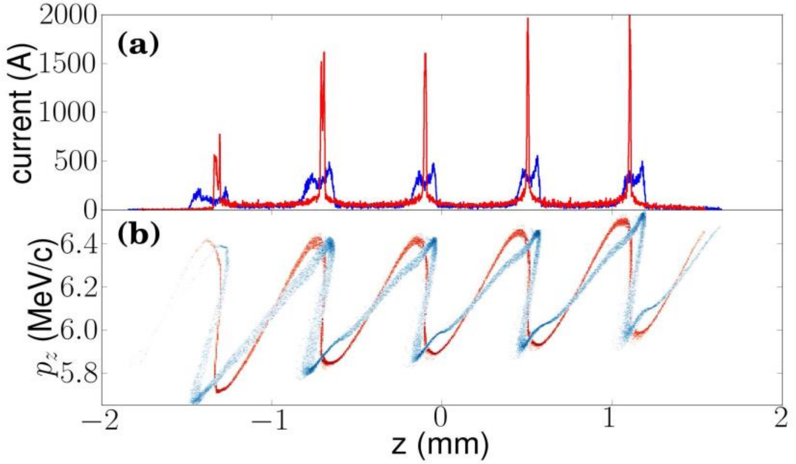


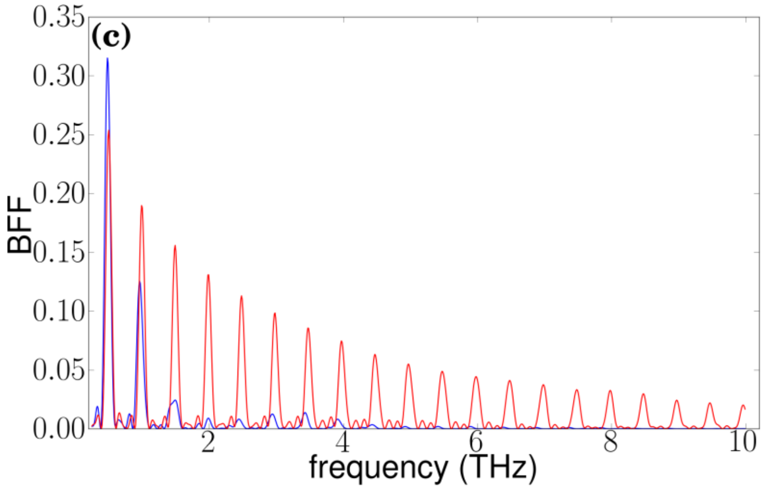


1THz Continued..

- Fitting into 11 cm structure OK (84 % transmission).
- DLW length change impact.
- Can we do better than BFF=0.2?
  - Energy correlation in LPS
    - Solution 1: Longer bunch
    - Solution 2: Lower the frequency

500 GHz DLW – (350 μm, 393 μm, 5.7)

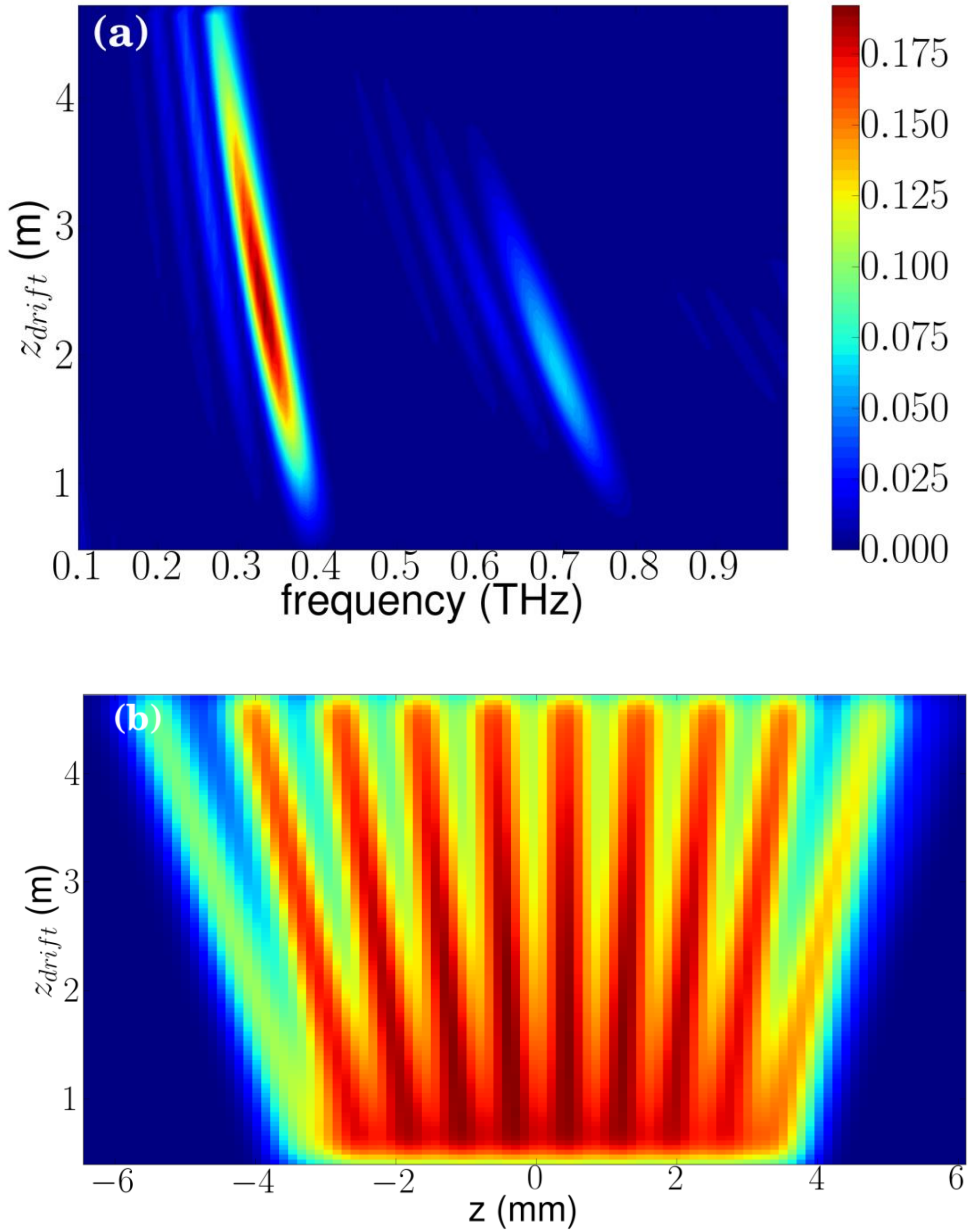




- Large harmonic content at maximum compression.
- Higher mode suppression by under/over compressing the bunches.

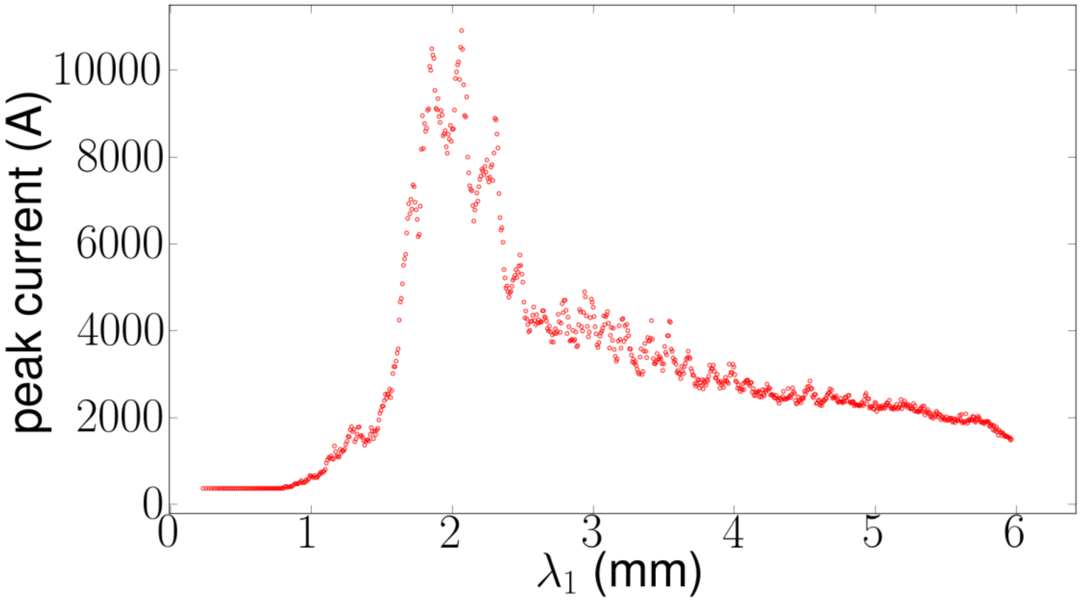
L-Band case study

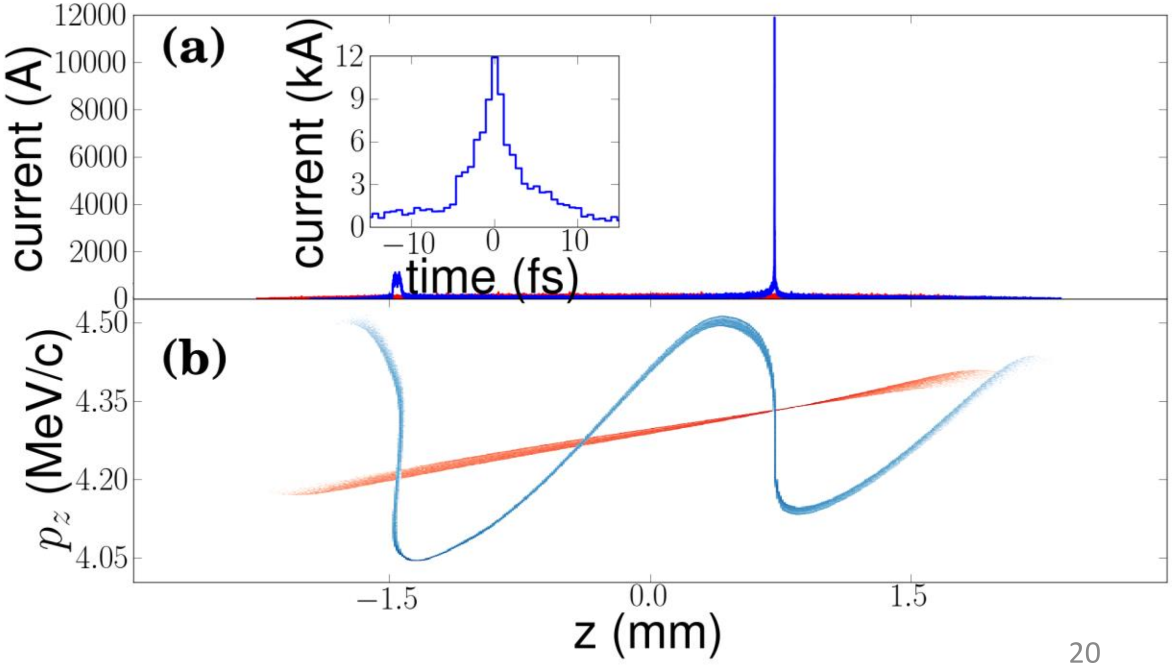
- Larger emittance
  - Larger structures
  - Lower frequencies
- Lower energy
  - Shorter bunching length for same energy modulation
  - More space charge effects



Passive Compressor

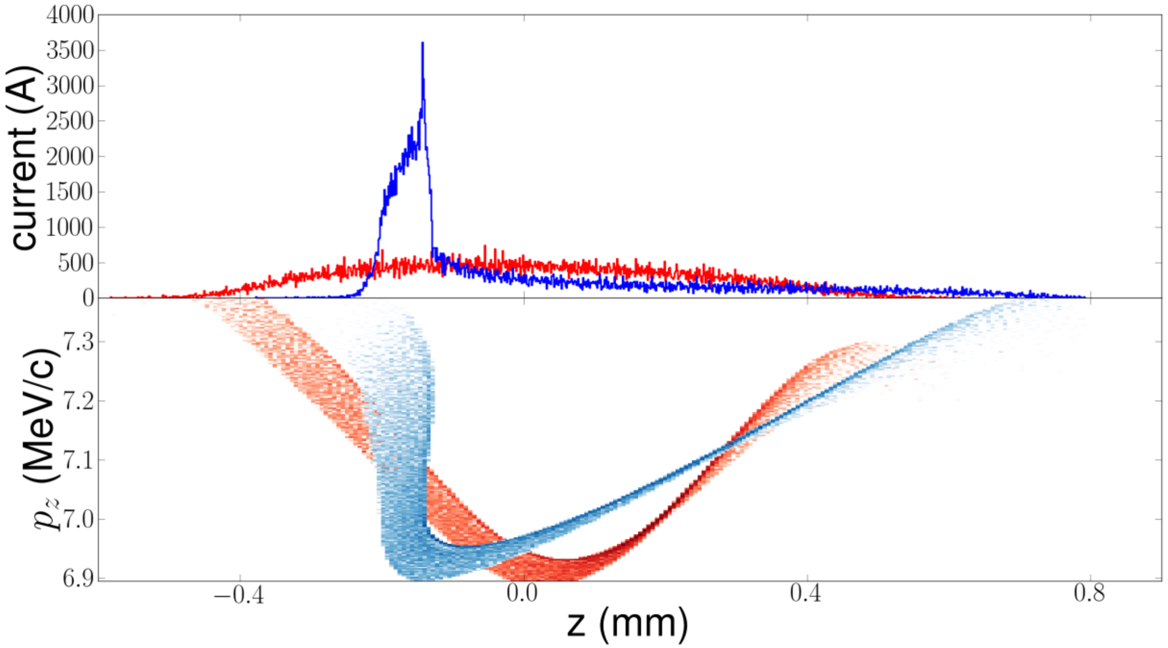
- L ~ λ – Single peak.
- Peak current limited by energy spread.
- Scan various wavelengths and record peak current.
- For L-Band case, this corresponds to a peak current of ~ 12 kA (7.1%).
- Scalable for higher charge / large structures a=650 μm

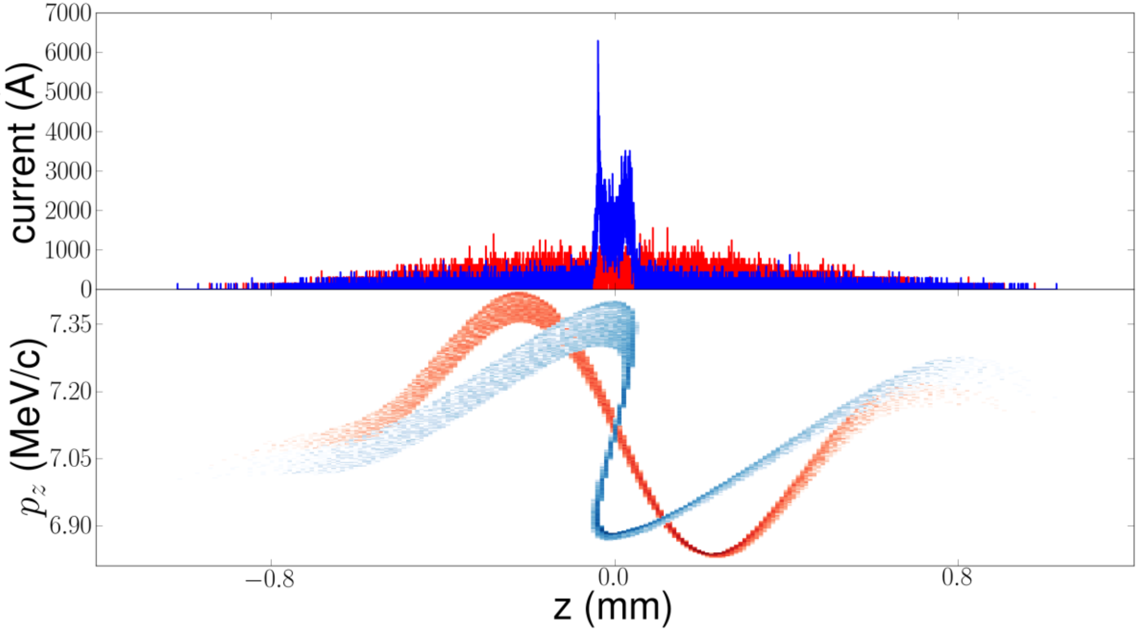




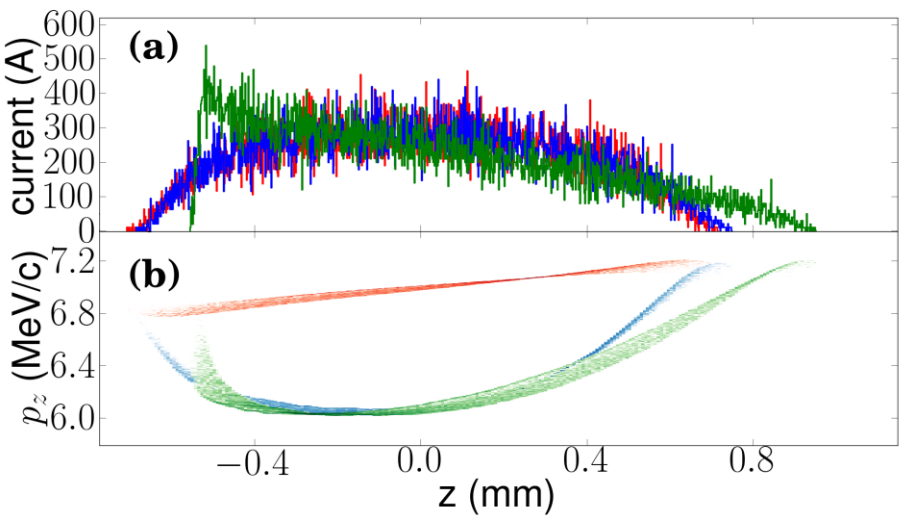
Passive Compressor for beam-driven applications

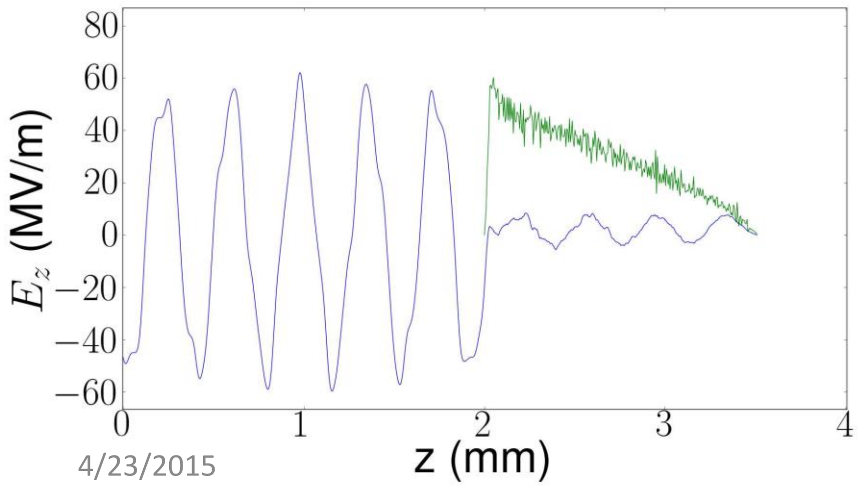
- Bunch larger portion of the bunch (50%)
- Extremely scalable: higher charge→longer bunches→ larger structures.
- Details: Red trace: immediately after structure, blue trace 1.2 m (1.13 m bottom) downstream.
- (a, b, e, L) = (1 mm, 1.05 mm, 5.7, 5 cm) corresponding to λ0 = 1.948 mm





Longitudinal Shaping with DLW

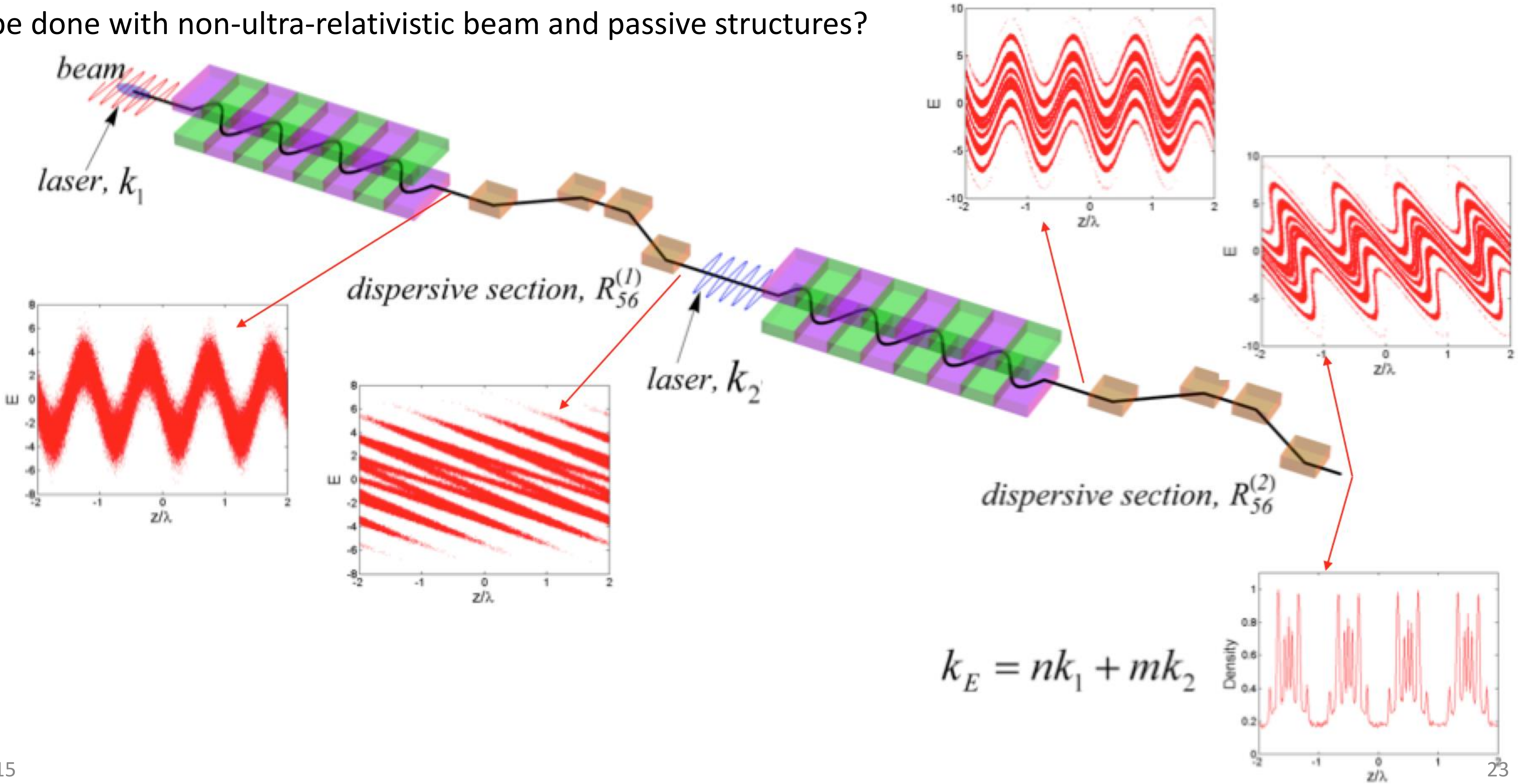




- Larger wavelengths (λ>>L)
  - Bunch shaping
  - Passive bunching
  - De-chirper/Linearizer
- Ramped bunch for high transformer ratio acceleration.
  - Here for (165 µm, 197 µm, 5.7)
  - R = 7.3 (Theoretical max 9.3)

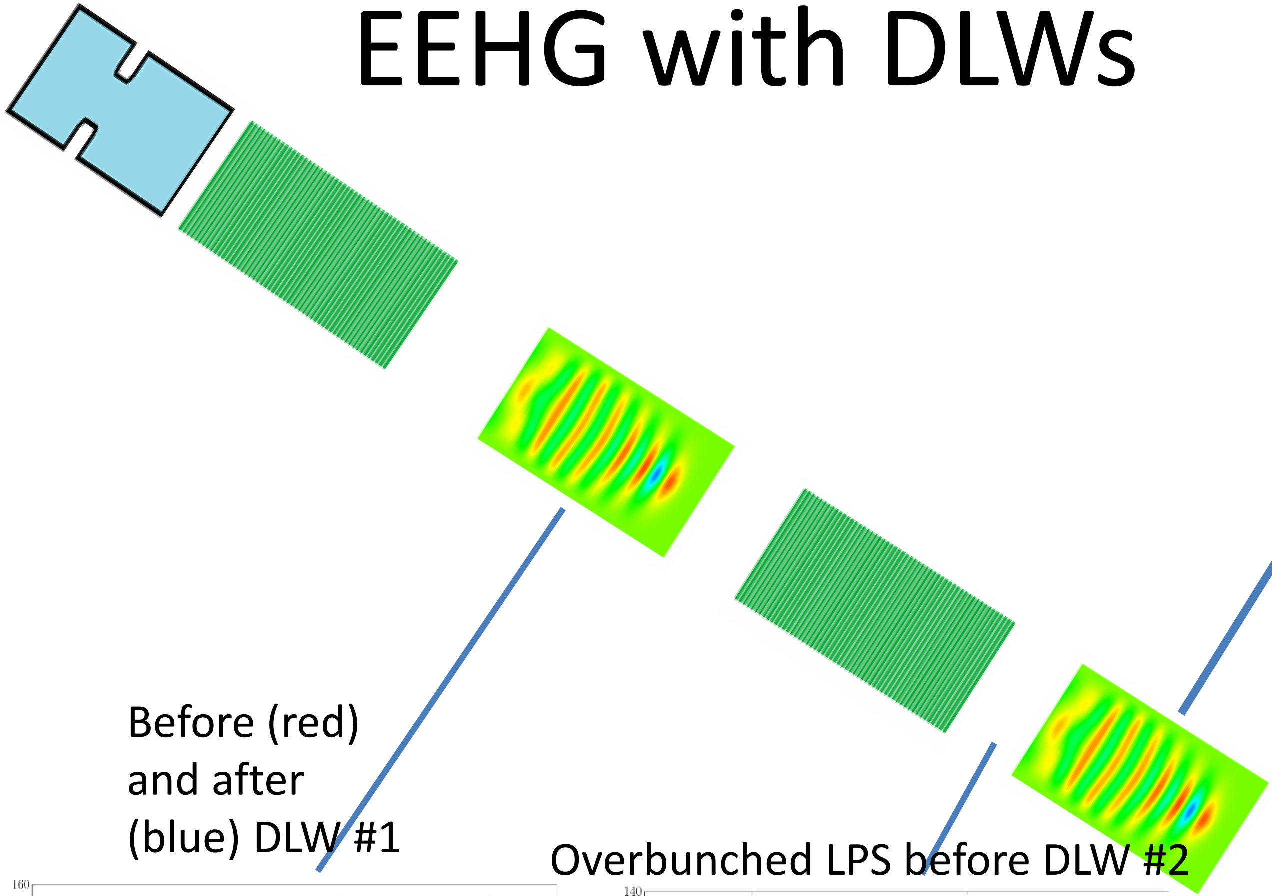
Cascaded Passive Manipulation

- Can this be done with non-ultra-relativistic beam and passive structures?

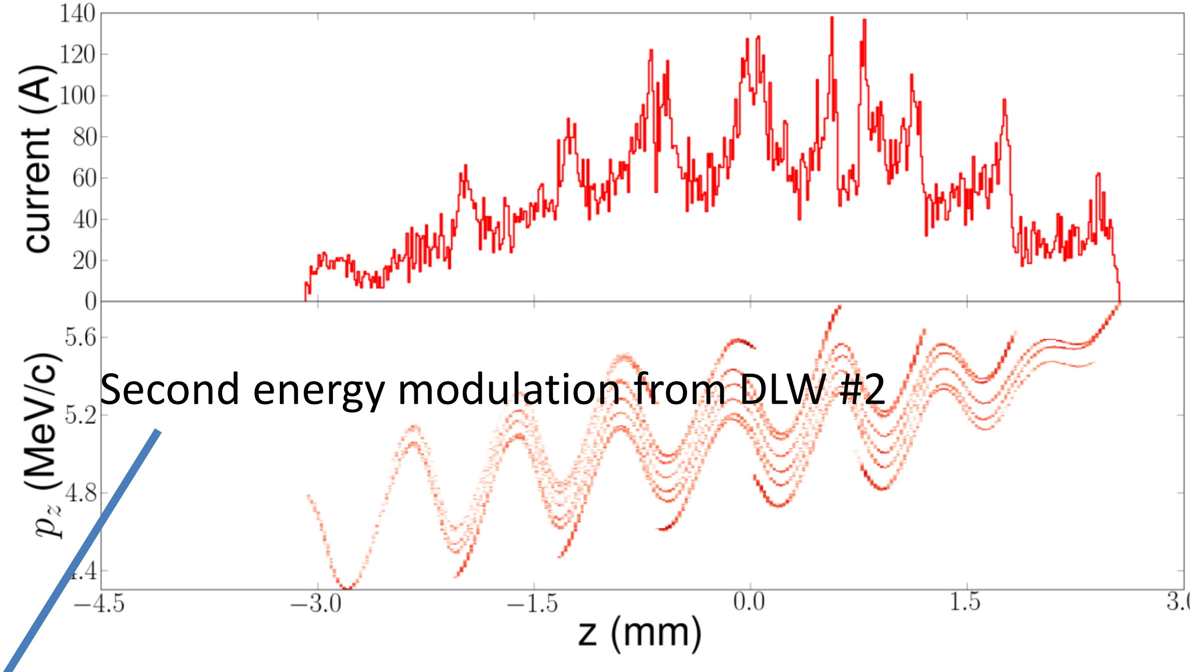


https://portal.slac.stanford.edu/sites/ard_public/tfd/facilities/nlcta/Pages/Echo-enabled-Harmonic-Generation.aspx

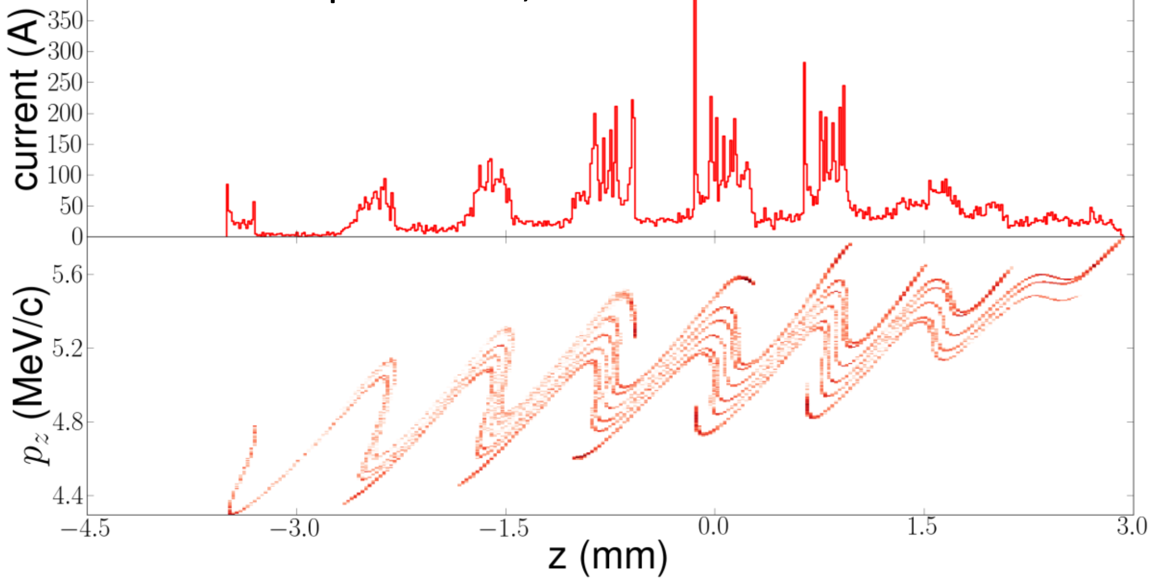
EEHG with DLWs



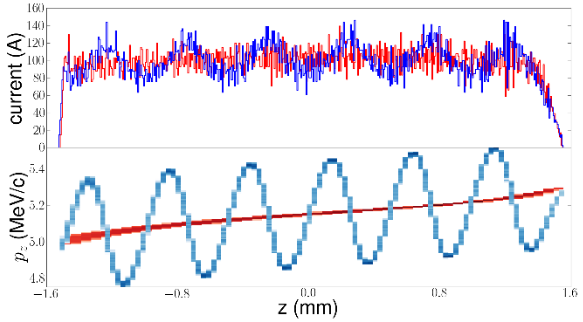
Second energy modulation from DLW #2



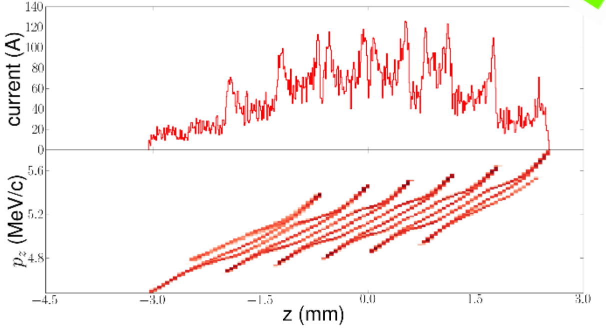
After subsequent drift, EEHG occurs



Before (red) and after (blue) DLW #1



Overbunched LPS before DLW #2

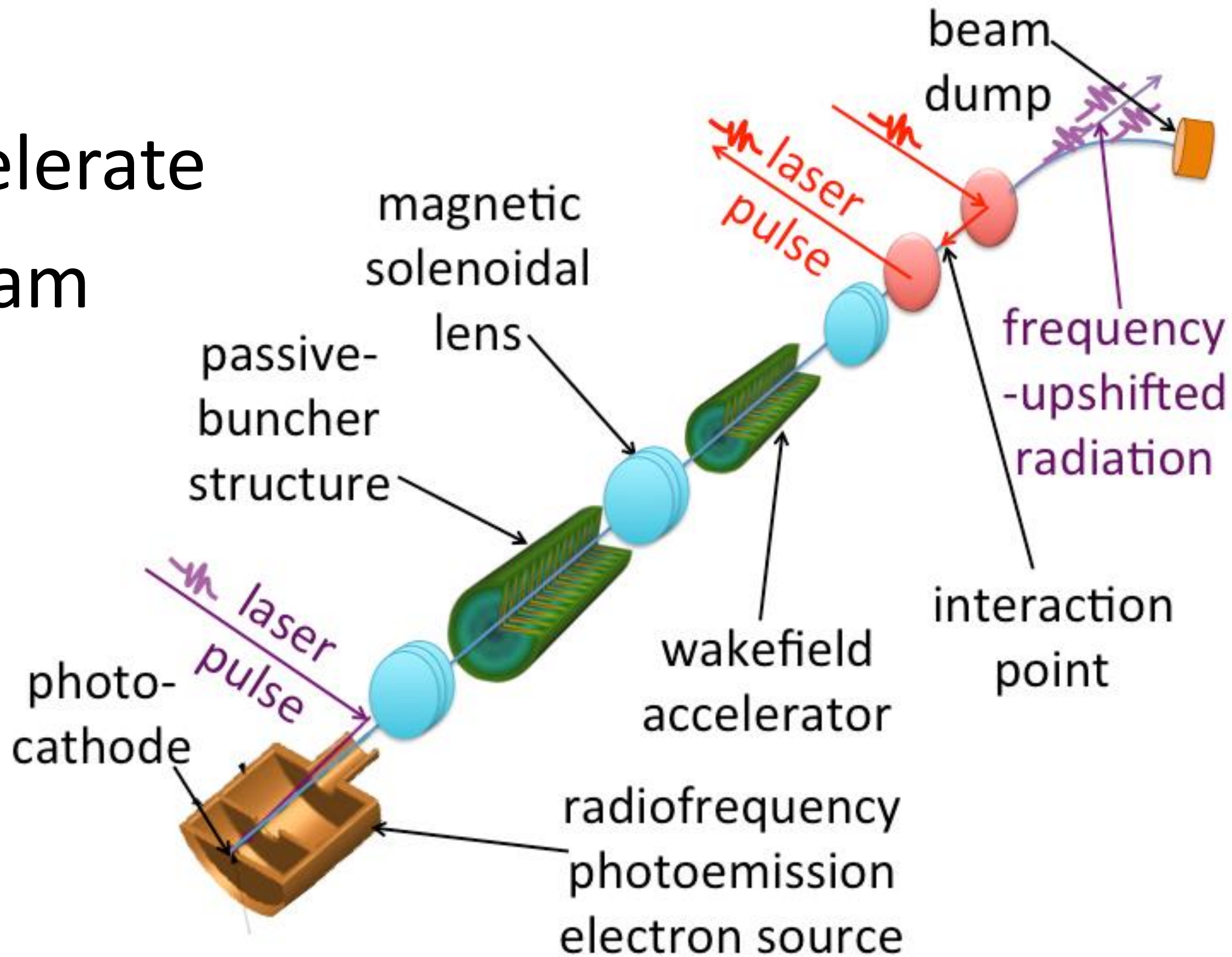


DLW-EEHG outlook

- Relatively cheap
- Capable of < 50 fs electron bunch formation
- Second structure frequency limited by first.
- Self wake requires relatively large bunch charge/currents
- Technique could do better at higher energy (IPAC15).

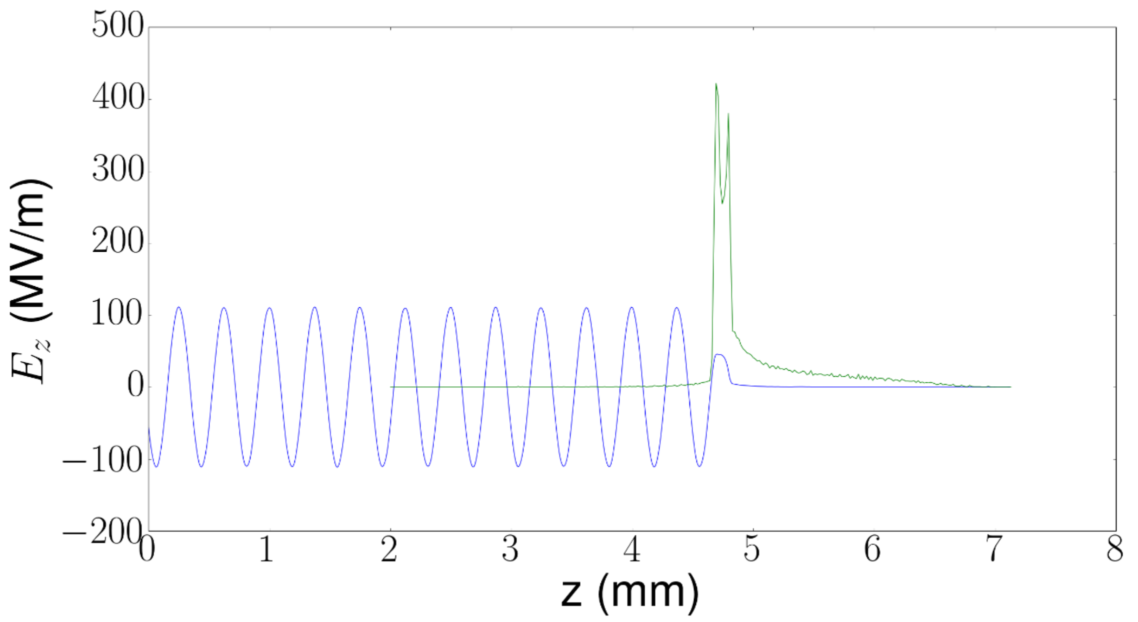
Merging concepts for Acceleration

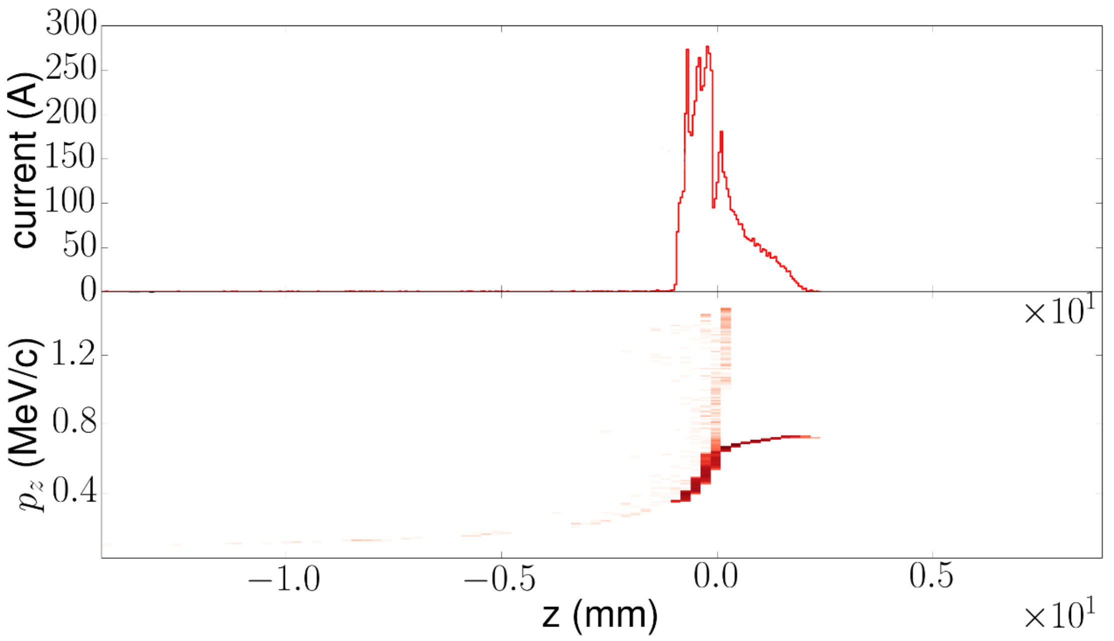
- DLWs in series, bunch and accelerate
- DLW dimensions limited by beam
- Total energy gain limited by transformer ratio



Compact X-Ray source

- S-band test case:
  - E+ = ~ 111 MV/m
  - E- = ~ 43 MV/m
  - R = ~ 2.6





Dispersion Controlled Acceleration in DLW

- Acceleration in free space
  - Lawson-Woodward overcome with a_0>>1 (S. Carbajo et al. 2015).
- THz acceleration in DLW
  - Sustains modes with phase/group velocities < c
  - Capable of large acceleration gradients (E. Nanni et al. 2014)

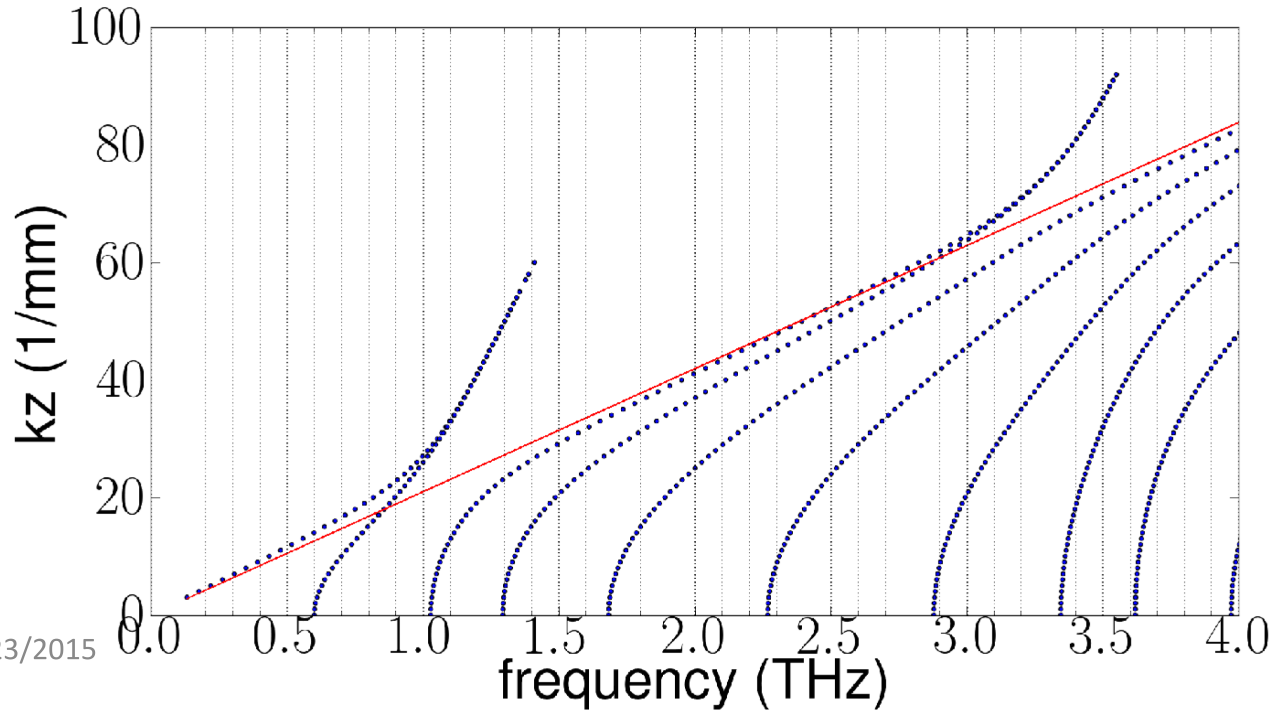
Primitive look at DCA

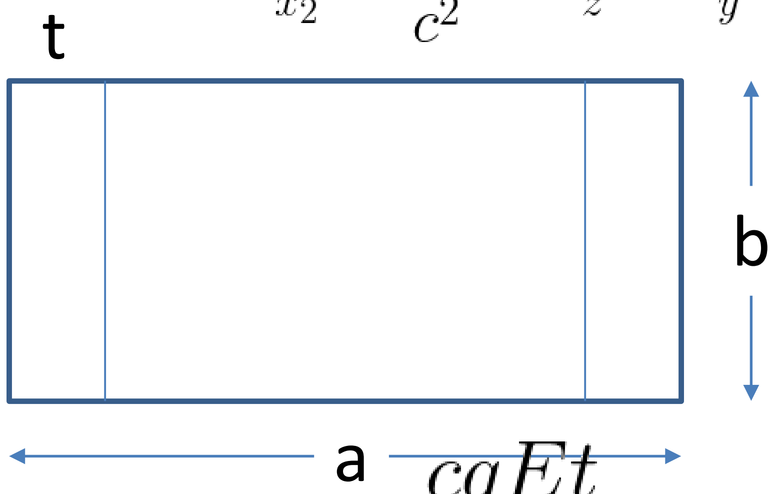
$$0 = k_{x_1}^2 sin^2(k_{x_1}t)sin(k_{x_2}(a-2t)) - \epsilon^2 k_{x_2}^2 cos^2(k_{x_1}t)sin(k_{x_2}(a-2t))$$
$$-2\epsilon k_{x_1}k_{x_2}sin(k_{x_1}t)cos(k_{x_1}t)cos(k_{x_2}(a-2t))$$
$$0 = k_{x_1}sin(k_{x_1}t)sin(k_{x_2}(\frac{a}{2}-t)) - \epsilon k_{x_2}cos(k_{x_2}(\frac{a}{2}-t))cos(k_{x_1}t)$$

LSM Modes

$$k_{x1}^2 = \frac{\omega^2}{c^2}\epsilon - k_z^2 - k_y^2$$
$$k_{x2}^2 = \frac{\omega^2}{c^2} - k_z^2 - k_y^2$$

- 1 electron experiencing constant acceleration gradient of 100 MV/m.
- Solve dispersion relations backwards (v→a).

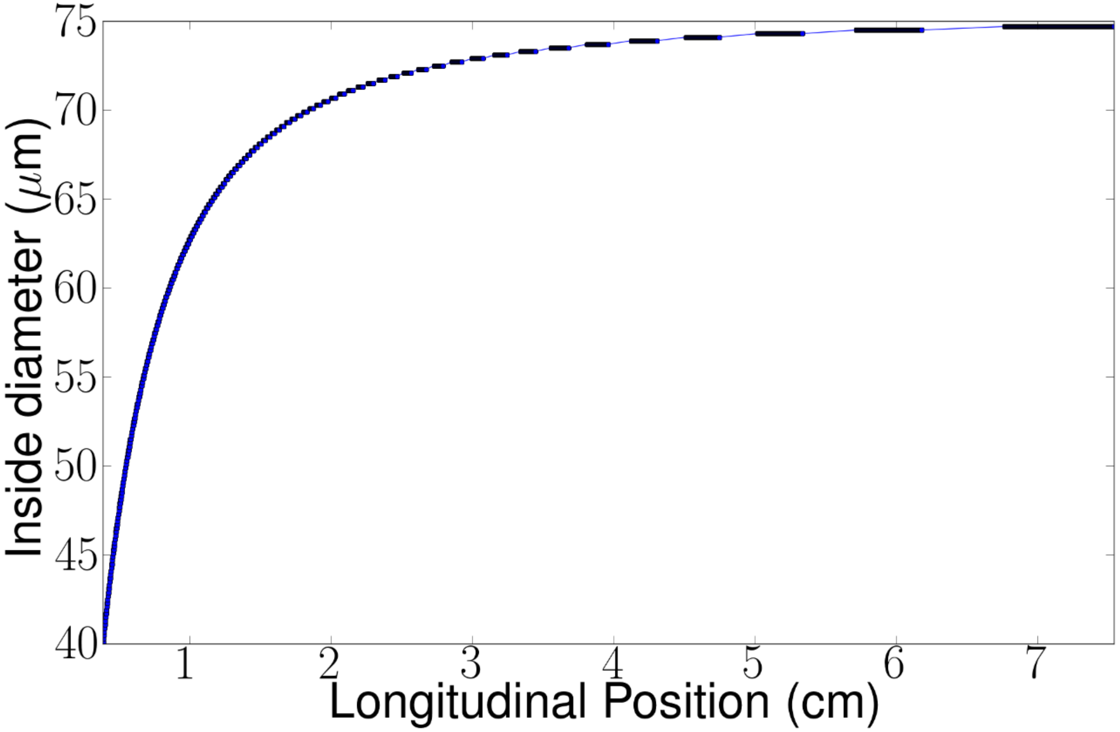




$$\beta_z = \frac{cqEt}{\sqrt{(cqEt)^2 + E_0^2}}$$

$$z(t) = \frac{1}{qE}\sqrt{(cqEt)^2 + E_0^2}$$

Primitive look at DCA cont.



- Hyperbolic-like diameter
  - Analytical solution?
- Additional things to consider:
  - Cylindrical geometry
  - Mode coupling
  - Group *and* phase velocity matching?
  - Full simulation required (PIC?)
  - Machineable (CNC) or 3D print?

Summary

- Beam driven techniques
  - Investigated alternative smooth ideal transformer ratio shapes
  - Proposed laser-shaping technique to generate quadratic-ramp
- Beam manipulation at low energy
  - Passive compression (large peak currents, charge densities, scalable)
  - EEHG
  - Acceleration at low energy for X-ray source
- Dispersion controlled acceleration
  - Can we mitigate phase slippage in a low energy THz-based accelerator with a tapered DLW? –THz Gun

Thank you to Daniel Mihalcea, Harsha Panuganti, and especially Philippe Piot for support.

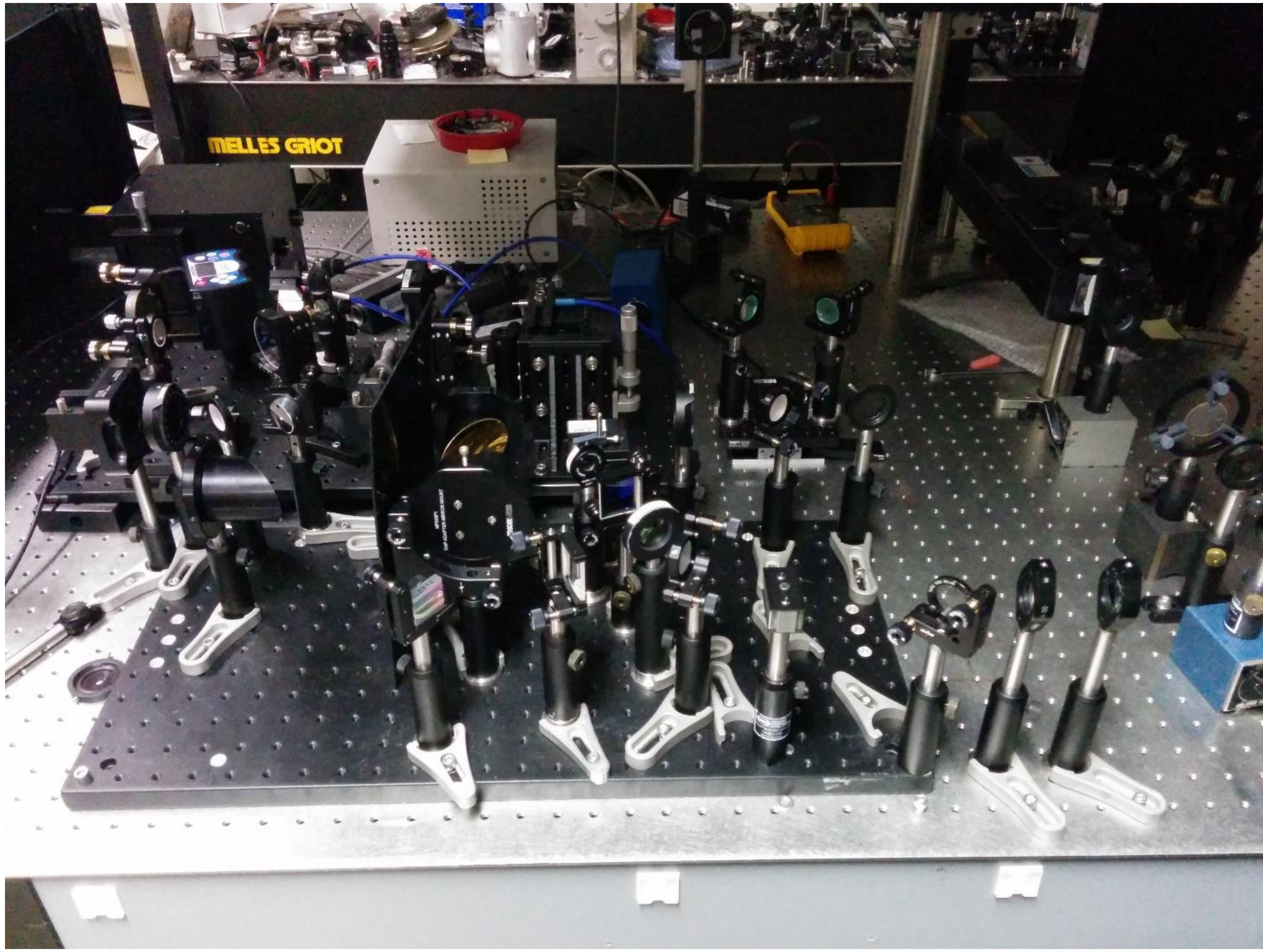
Thank you to NIU for fellowship awards and stipend support.

This work was supported by the Defense Threat Reduction Agency, Basic Research Award # HDTRA1-10-1-0051, to Northern Illinois University and by the Department of Energy contracts No. DE-FG02-08ER41532 and No. DE-SC0011831 with Northern Illinois University.

QUESTIONS & DISCUSSION

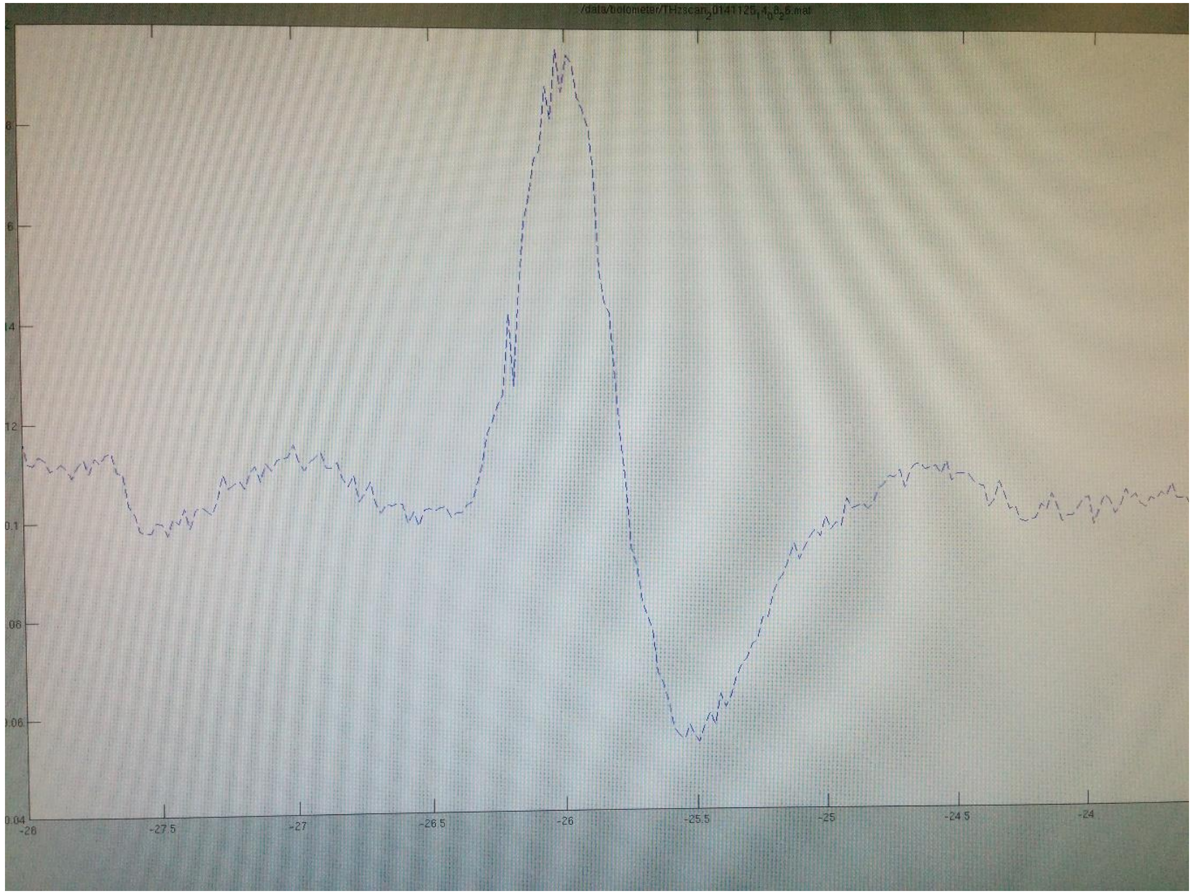
Experimental setup

- Tilted wavefront THz generation using LiNbO with EO detection
- Setup allows for a target (DLW)
- Currently investigating slab-symmetric DLW in preparation for ASTA experiment.
- First results promising; comparing with simulation for IPAC15.



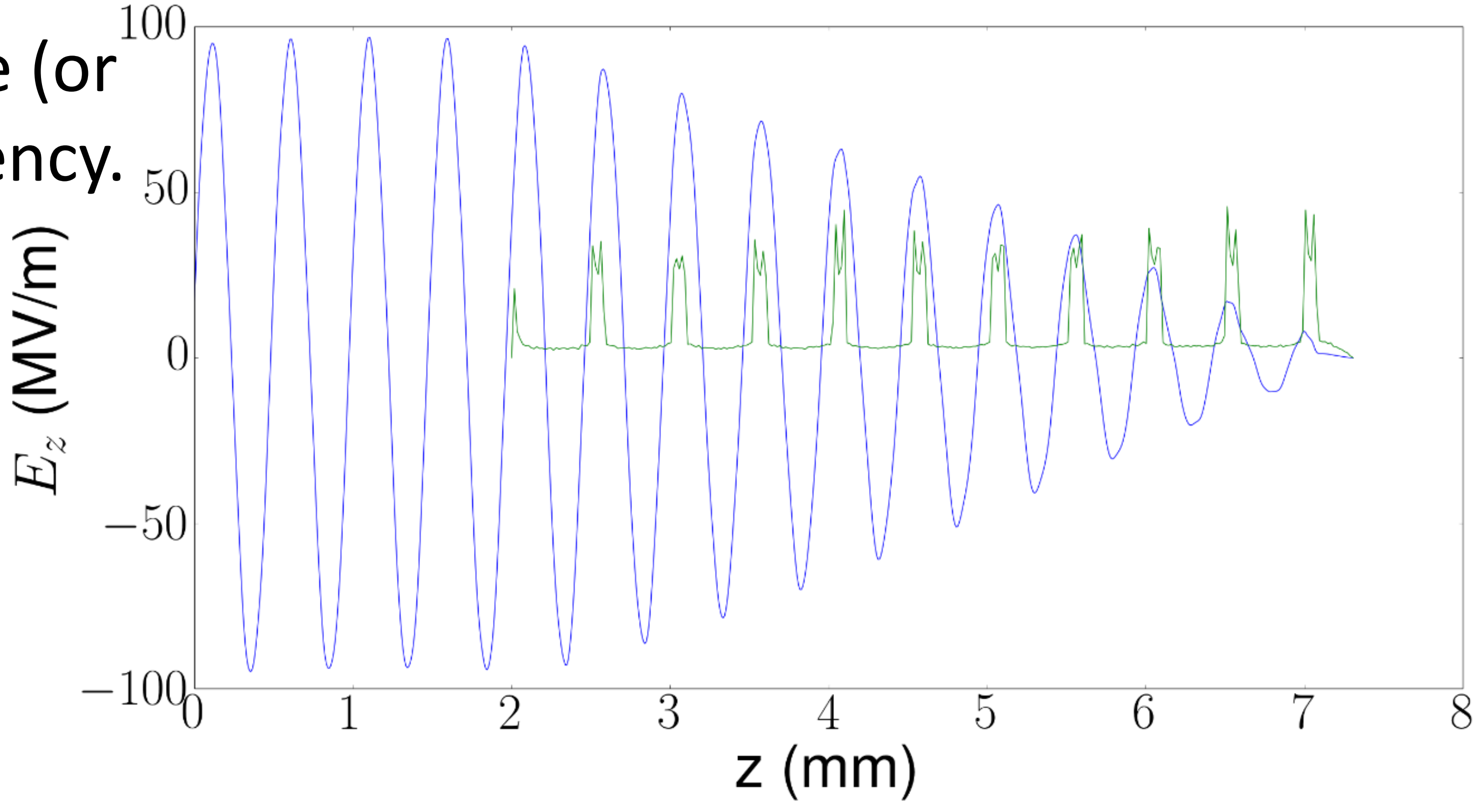
THz experiment continued

- First data recently taken, experiment in progress.
- Goals: investigate THz dispersion in DLWs with various geometries (possible applications to acceleration and beam manipulation).



RADIATION

- Radiation extraction
  - Using two DLWs of same (or higher harmonic) frequency.
  - Efficient



$$V_{-}(z) = \int_0^z s(z')\omega(z-z')dz' = \begin{cases} \frac{\lambda\left(\left(c^2-1\right)(a\lambda+2\pi b(-1)^c c)+\cos\left(\frac{2\pi z}{\lambda}\right)\left(2\pi bc\left((-1)^c c^2+1\right)-a\left(c^2-1\right)\lambda\right)\right)}{2\pi^2(c^2-1)} & z > \lambda/2 \\ \frac{\lambda\left(a\lambda\sin^2\left(\frac{\pi z}{\lambda}\right)+\frac{\pi bc\left(\cos\left(\frac{2\pi z}{\lambda}\right)-\cos\left(\frac{2\pi c z}{\lambda}\right)\right)}{c^2-1}\right)}{\pi^2} & z < \lambda/ \end{cases}$$

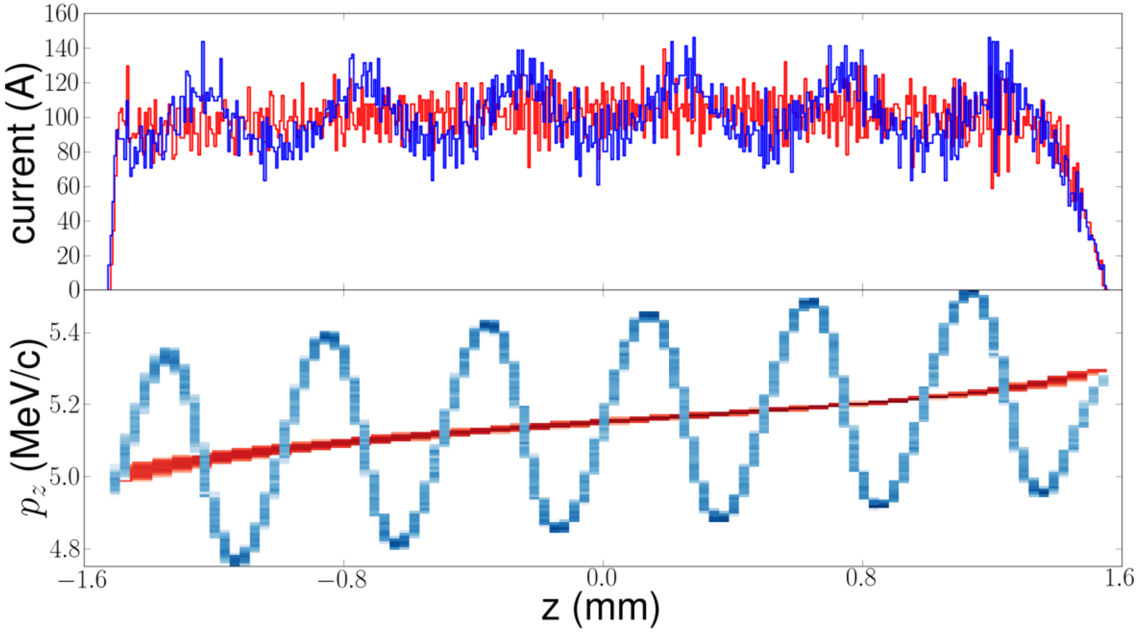
$$V_{-}(z) = \int_0^z s(z')\omega(z-z')dz' = \begin{cases} \frac{a\lambda^2\left(2\pi z-\lambda\sin\left(\frac{2\pi z}{\lambda}\right)\right)}{2\pi^3} & z < \lambda/n \\ \frac{a\lambda^3\left(2\pi-n\left(\sin\left(2\pi\left(\frac{1}{n}-\frac{z}{\lambda}\right)\right)+\sin\left(\frac{2\pi z}{\lambda}\right)\right)\right)}{2\pi^3 n} & z > \lambda/n. \end{cases}$$

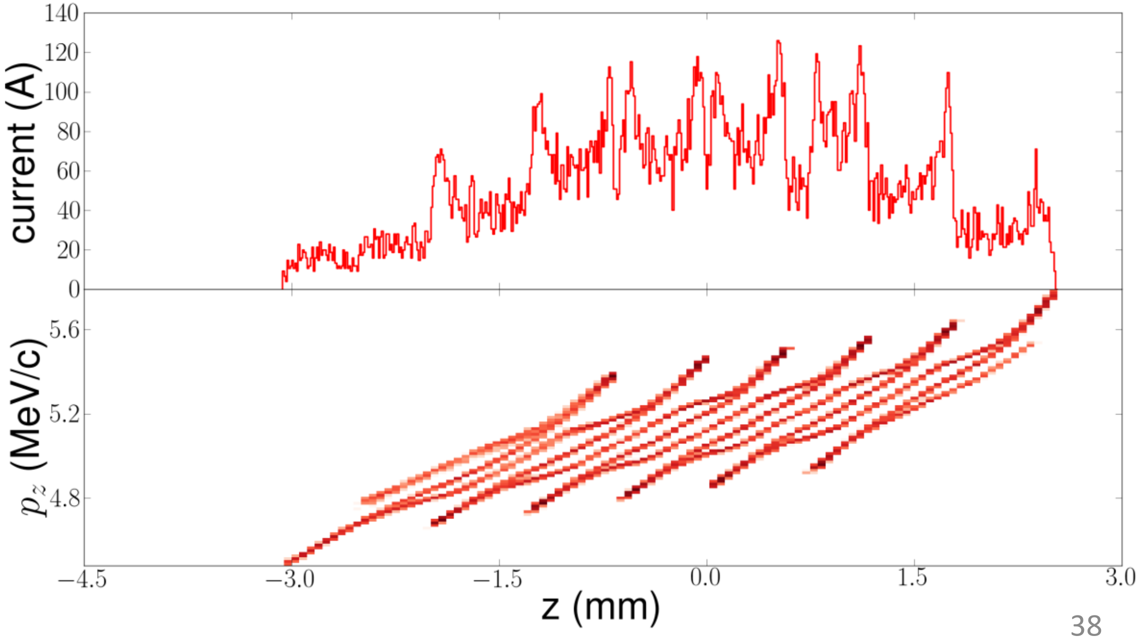
Passive Compressor (Central Bunching)

- L = λ → "Central-bunching"
- High-charge compression
- For S-Band case, this corresponds to ~55.8% of the bunch in ~100 µm.
- Extremely scalable: higher charge → longer bunches→ larger structures.
- Details: Red trace: immediately after structure, blue trace 1.13 m downstream.
- (a, b, e, L) = (0.8 mm, 0.85 mm, 5.7, 10 cm) corresponding to λ0 = 1.774 mm

EEHG with DLWs

- Undulator+Laser ➔ DLW
- Chicane ➔Drift
- Simulation:
- (top) bunch before (red) and after DLW (a, b, e, L) = (0.4 mm, 0.43 mm,5.7, 10 cm) (0.6 THz)
- (bottom) overbunched before DLW2 (a, b, e, L) = (0.5 mm, 0.55 mm, 5.7, 5 cm) (0.4) THz





EEHG with DLWs Cont.

- (top) after DLW2
- (bottom) At maximum bunching BFF ~0.08