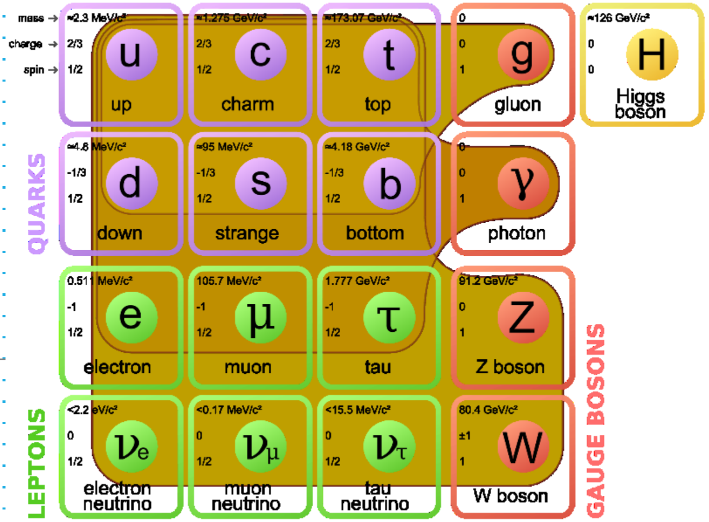
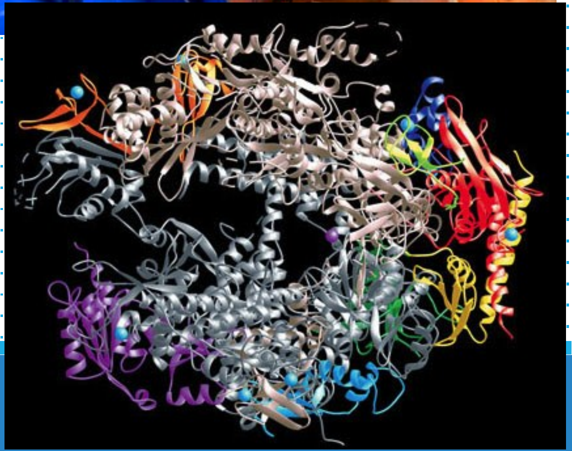
Beam-driven acceleration and manipulation using high-impedance mediums

FRANÇOIS LEMERY, PHILIPPE PIOT

Motivation for Accelerators



- Cockroft+Walton 1930-split the atom
- Colliders led to standard model (and beyond?)
  - Higgs found hiding @125 GeV/c² LHC Run #1 2012
  - New physics in Run2 $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$
    - Pentaquark (2.1 σ LHCb)
    - 2 TeV bump (3.4 σ ATLAS & CMS)
  - IceCube 1.7 PeV neutrinos from northern sky (PhysRevLett.115.081102)
  - “OMG particle” e.g. ultra-high-energy cosmic rays E> 10^20 eV
  - BSM searches (DM, DE, extra dimensions, SUSY?) require high energies
- Light sources for other scientific frontiers
  - SASE-based e.g. FLASH, LCLS, XFEL revolutionizing our biophysics
  - Chemical and drug development advancements
  - Possible future coherent gamma-ray sources for nuclear physics (need more energy!)
- Limitations
  - Cost ($13+ BN for LHC, $1 BN LCLS)
  - Magnet strength in circular machines
  - Acceleration gradients and length in linear accelerators (LINACs) < 100 MV/m

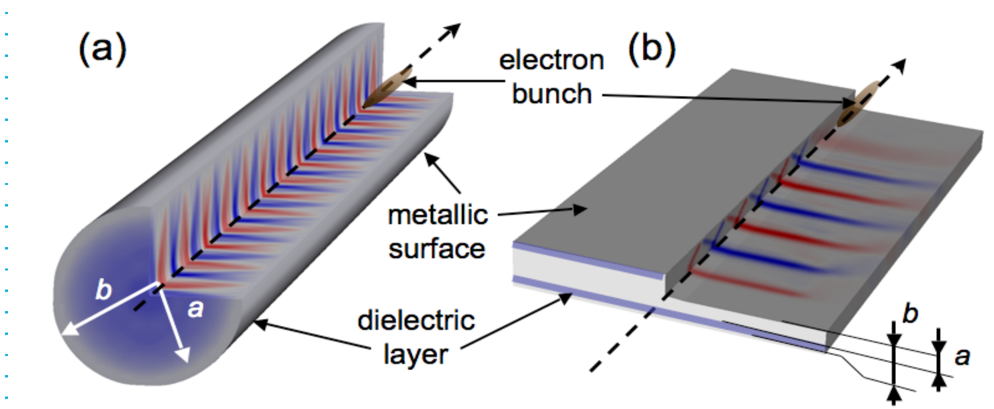


Beam-driven Wakefield Acceleration

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

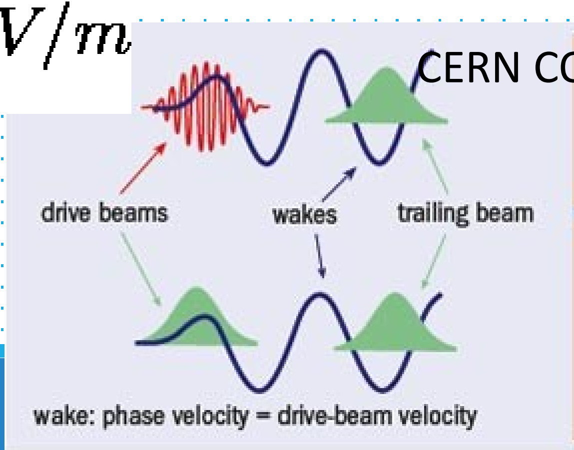
$$E(z) = \int_{-\infty}^{z} I(z-z')G(z')dz'$$

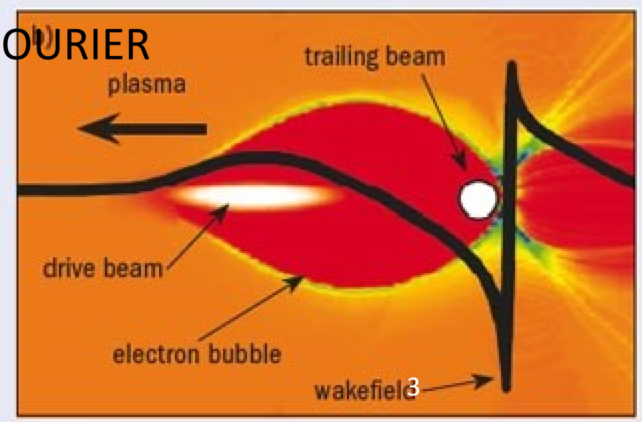
$$G(z) = \sum_{n} \kappa_n cos(k_n z)$$



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

CERN COURIER





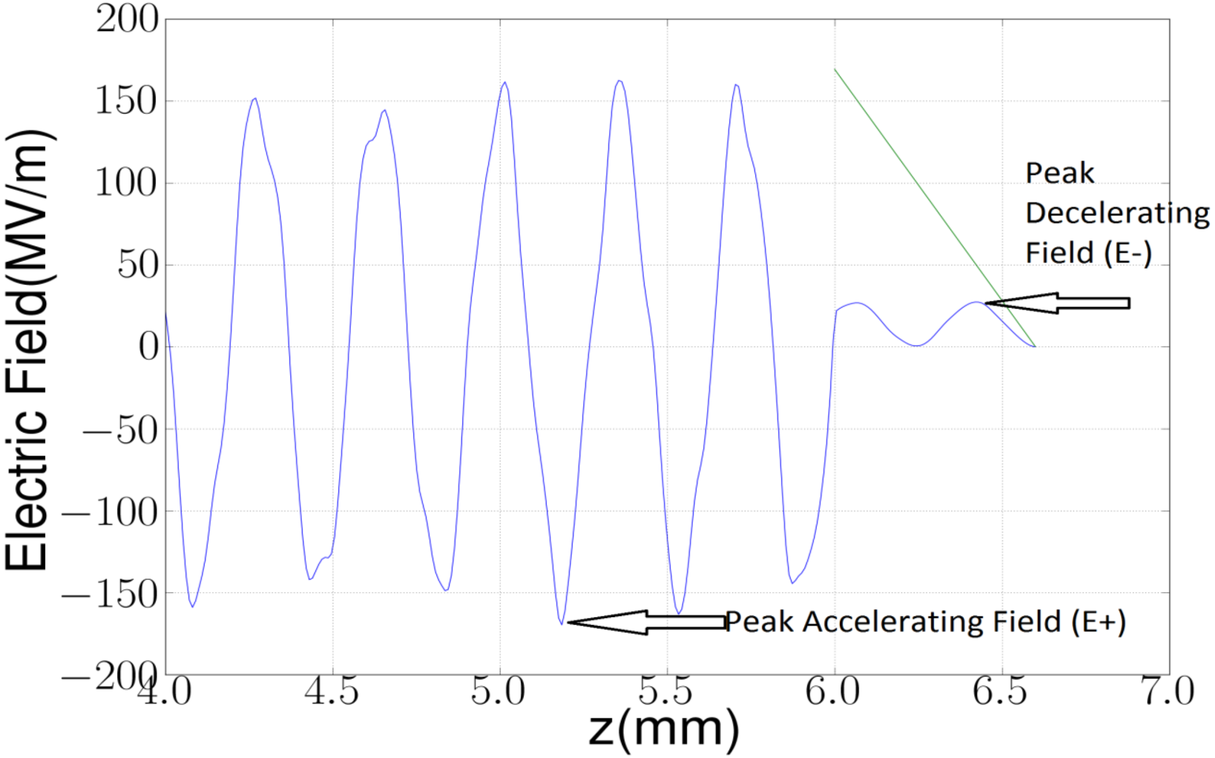
Wakefields and the Transformer Ratio

$$E(z) = \int_{-\infty}^{z} I(z - z')G(z')dz' \quad G(z) = \sum_{n} \kappa_n cos(k_n z)$$

- Transformer Ratio $\mathcal{R} \equiv \left| \frac{E_+}{E_-} \right|$

- Fundamental wakefield theorem: symmetric bunches R < 2.

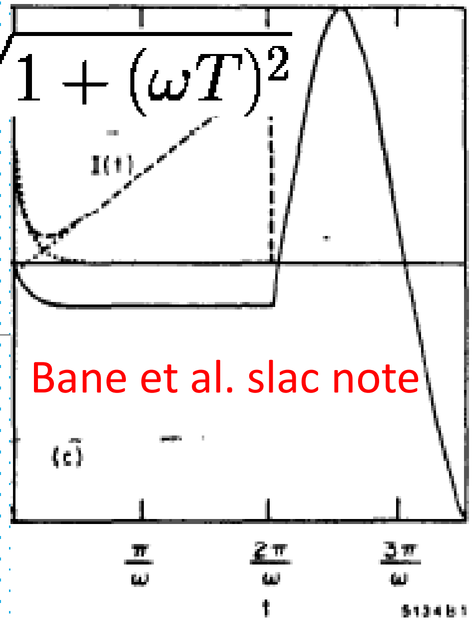
- Interested in large accelerating fields (E+) *and* efficient energy transfers (R)



"Ideal" Transformer Ratio

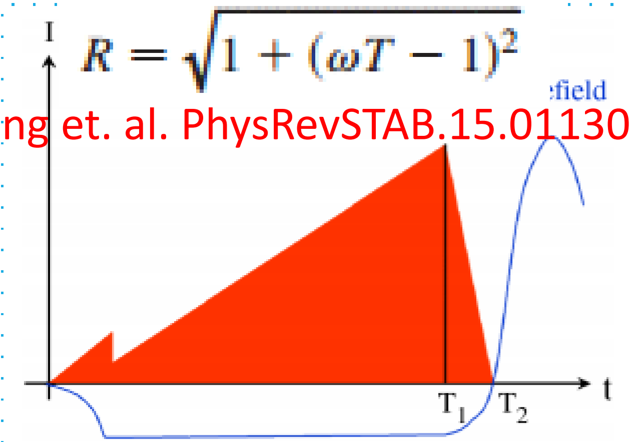
Constant decelerating fields lead to the largest R and E+

- Bane '85 exponential ramp
- Jiang '12 double triangle
- Bunch trains of varying charge (Tsakanov)
- Difficult to generate such distributions – generally require masks + transverse to longitudinal EEX.



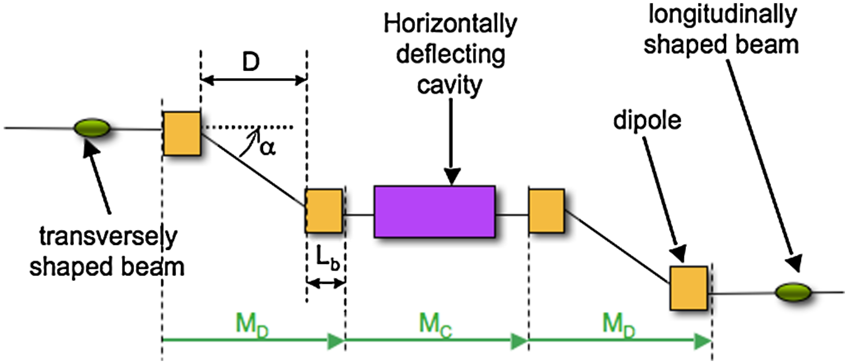
$$R = \sqrt{1 + (\omega T)^2}$$

Bane et al. slac note

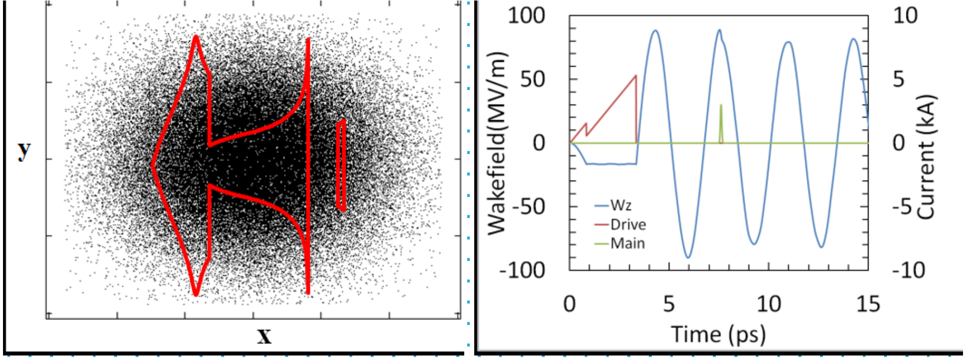


$$R = \sqrt{1 + (\omega T - 1)^2}$$

Jiang et. al. PhysRevSTAB.15.011301



P. Piot, PhysRevSTAB.14.022801



A. Zholents, FEL14 (FRB02).

Search for Continuous/Smooth shapes

- Smooth shapes are generally easier to produce
- Coulomb force (space charge) naturally produces smooth shapes.

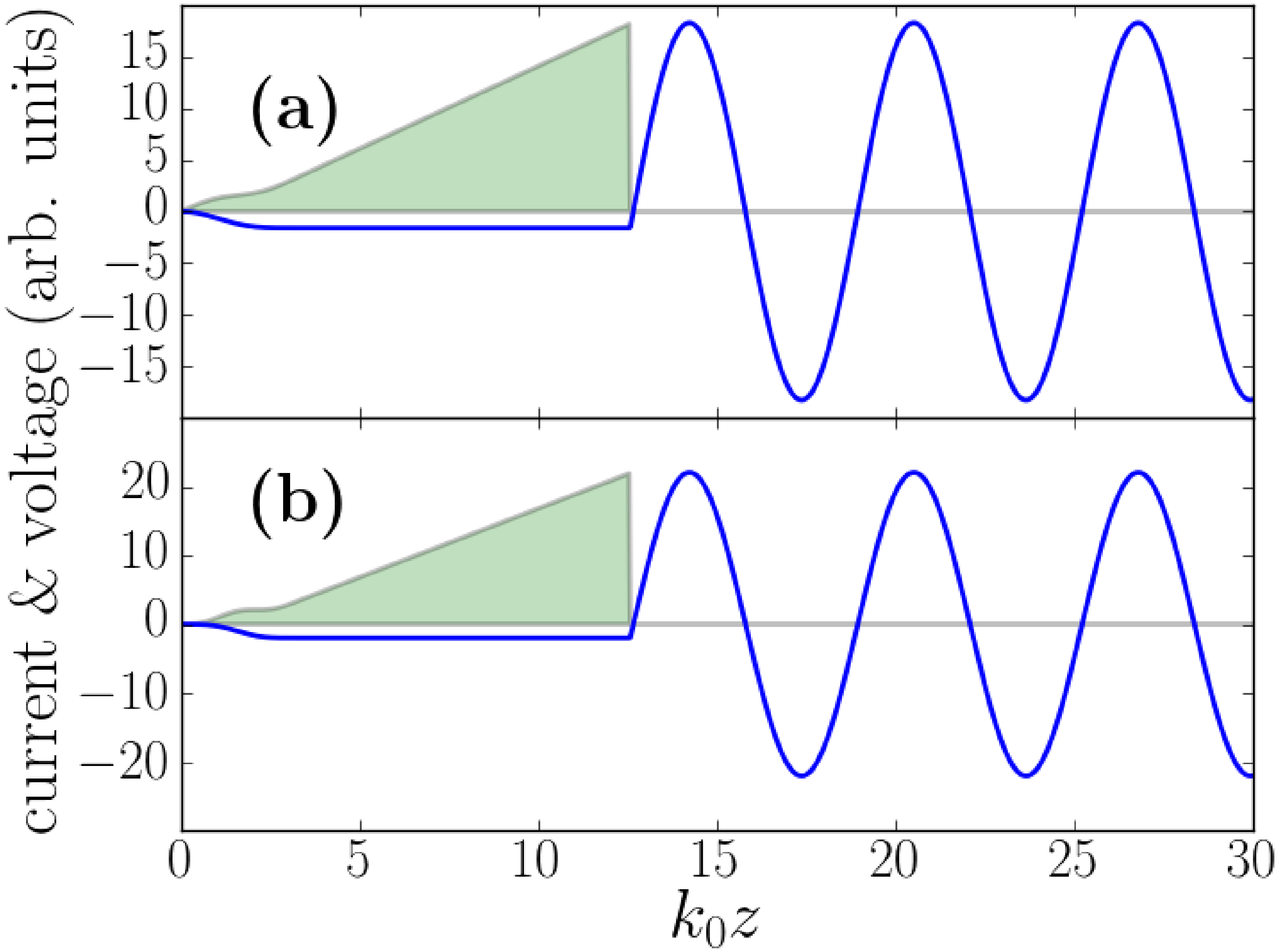
$$s(z) = \begin{cases} f(z) & z < \frac{\lambda}{n} \\ f'(\lambda/n)z - f'(\lambda)\lambda/n + f(\lambda/n) & x \geq \frac{\lambda}{n} \\ 0 & elsewhere \end{cases}$$

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

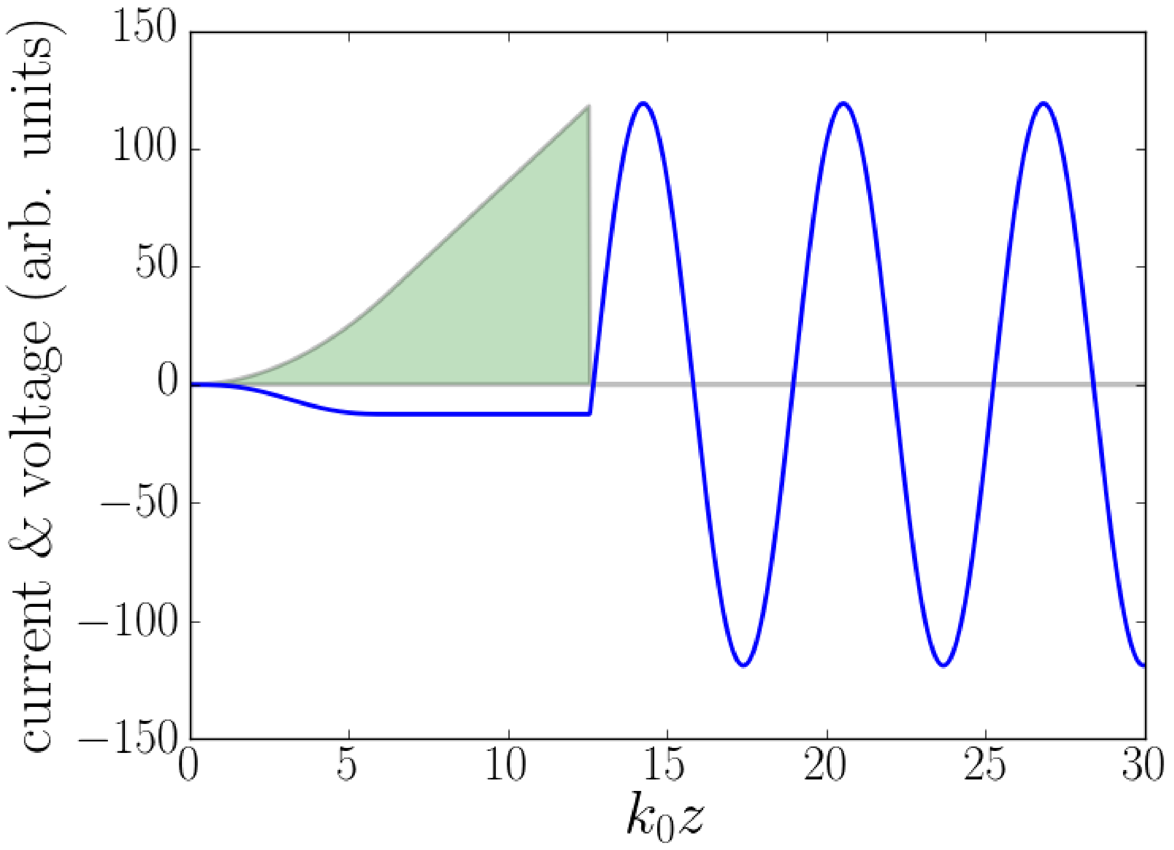


Quadratic Ramp

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

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

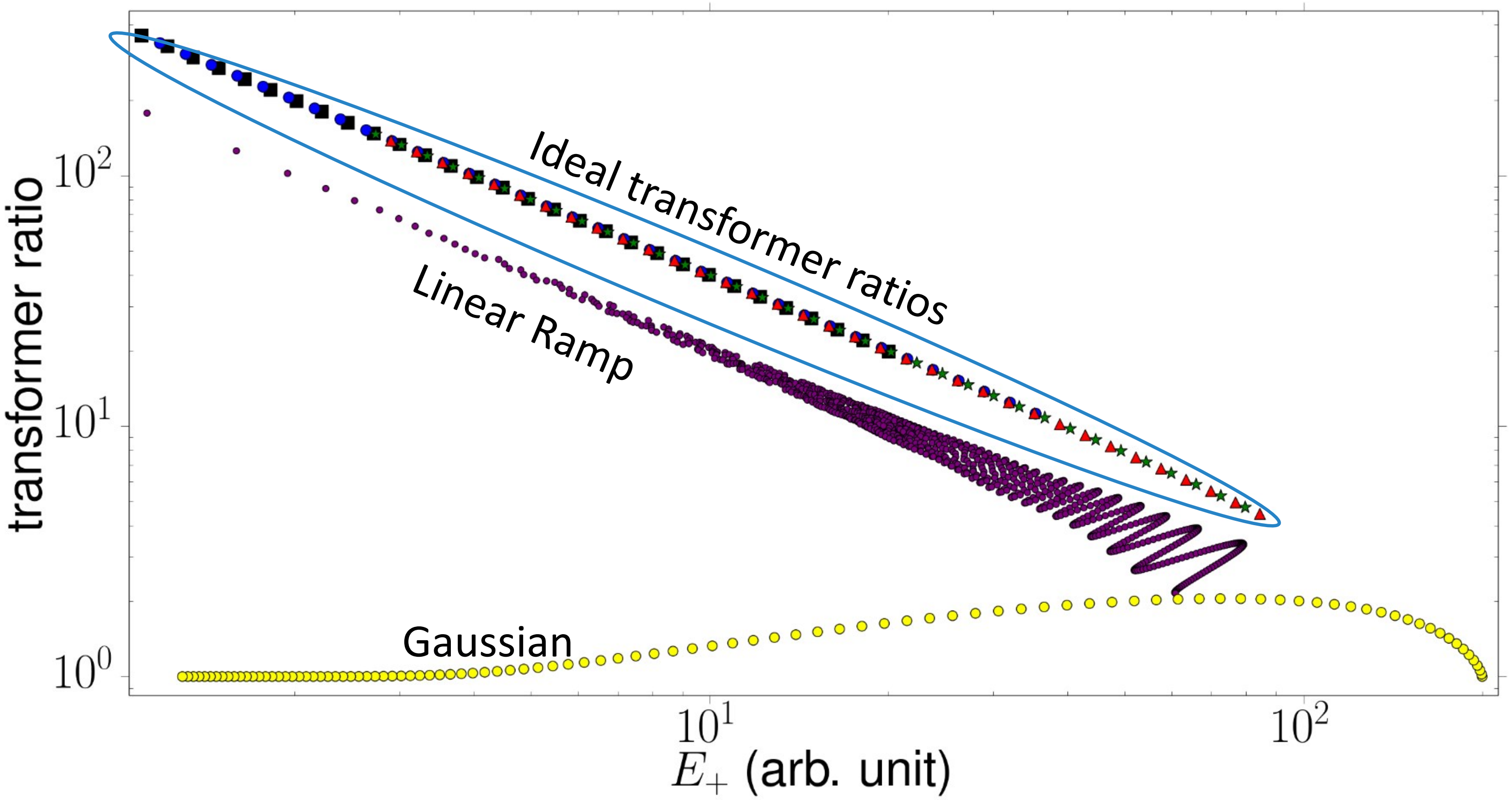
- Simplest known shape to generate constant decelerating field



Benchmarking

- Previous descriptions of R were not normalized to a specific charge.
- Normalizing each proposed shape yields interesting results:

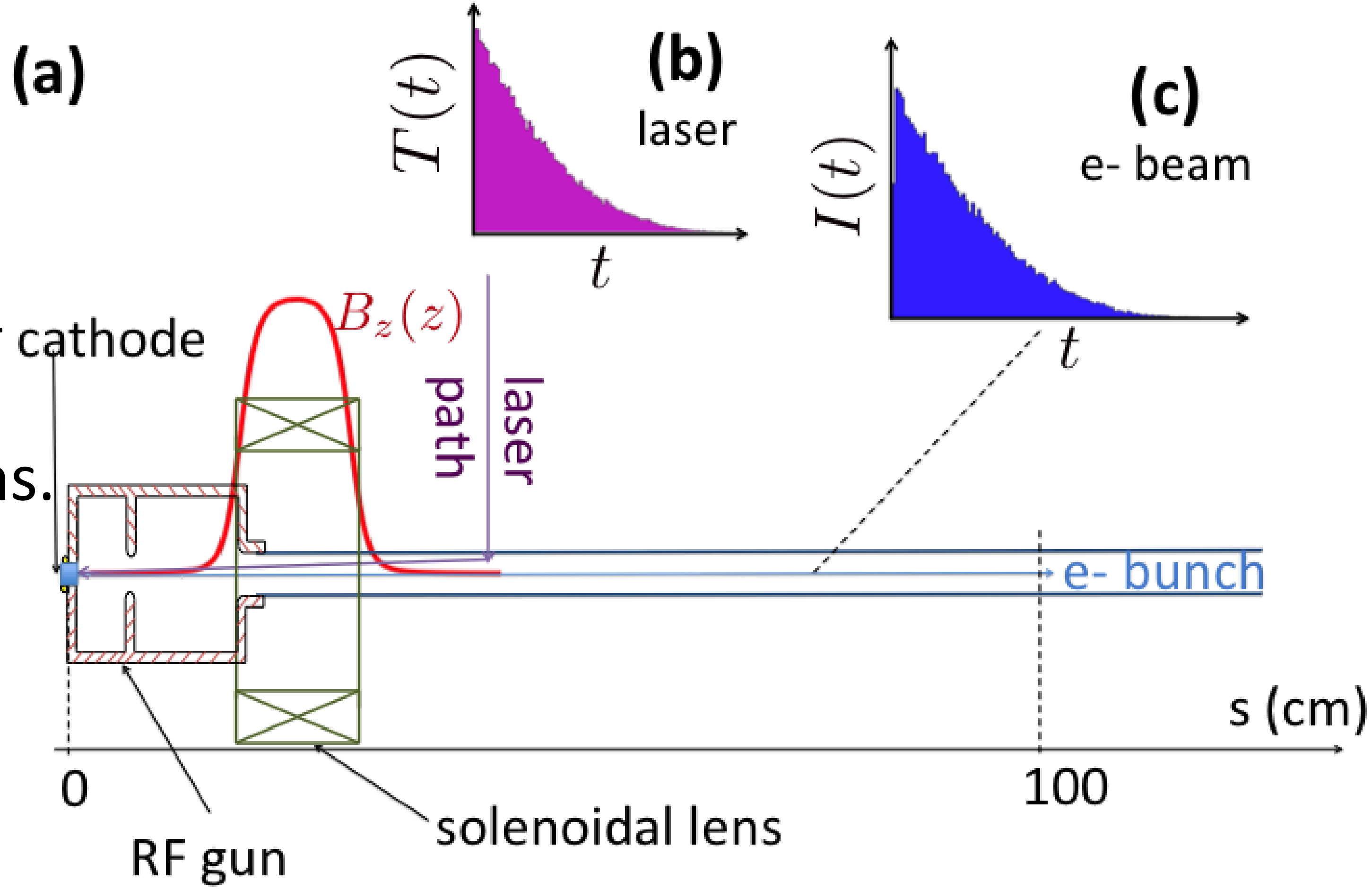
$$Q = \frac{1}{c}\int_0^{N\lambda} dz I(az),$$



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	$\sqrt{1+\pi^2(2N-1)^2}$	$\sqrt{1+\pi^2(\frac{4Q}{a\lambda^3}-\frac{1}{3})}$	$\frac{a\lambda^3}{\pi^2}$

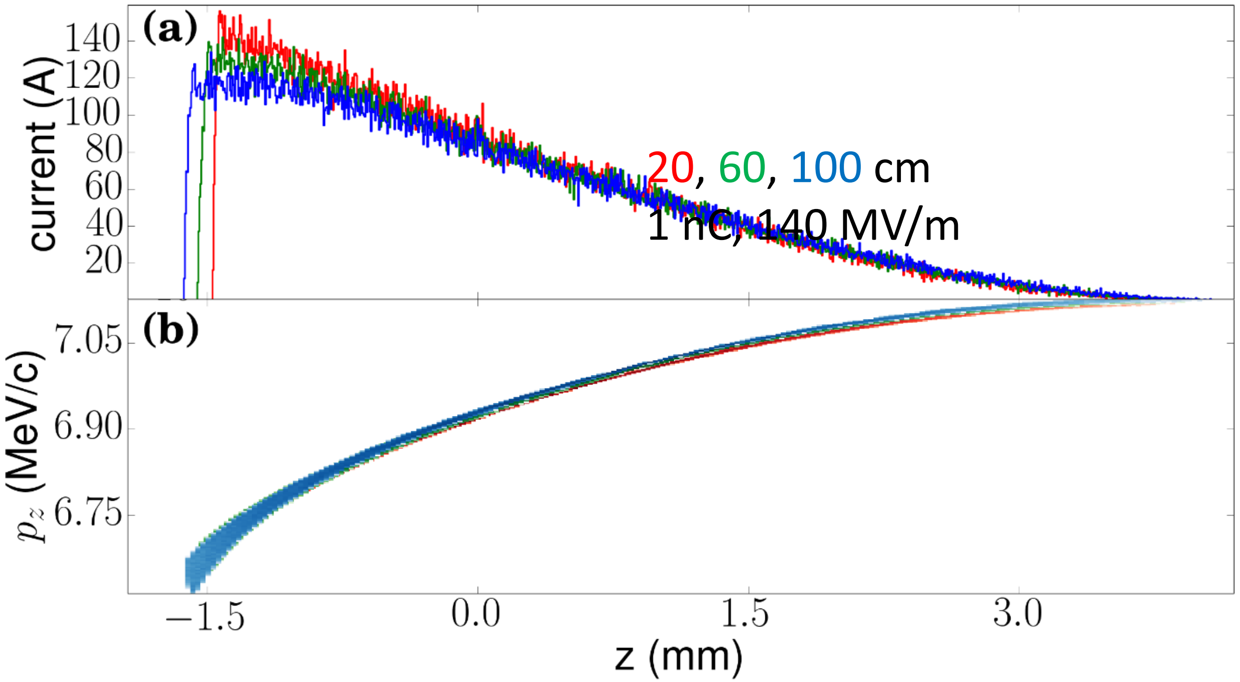
Temporal Laser Shaping

- 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.

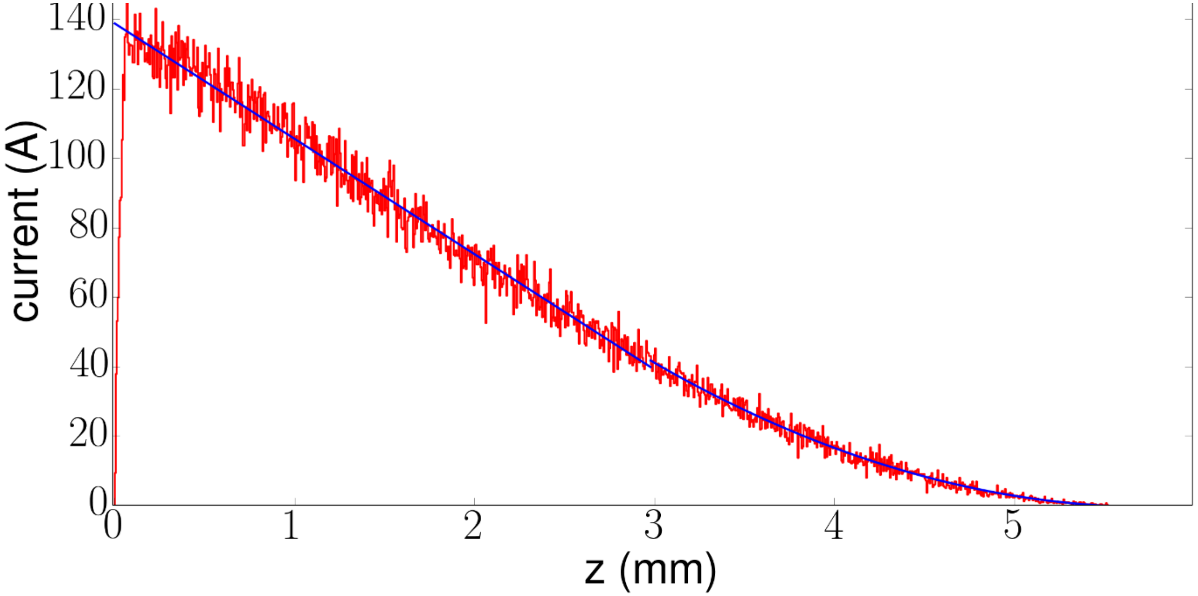


Laser Shaping Continued

- Quadratic ramp relatively simple to generate using a polynomial laser shape (e.g. $\alpha\tau^n$) see evolution (right)
- Tunable parameters
  - Laser (length, shape, spotsize)
  - Charge
  - Acceleration gradient



20, 60, 100 cm
1 nC, 140 MV/m



Simulations including additional effects

- Investigate effect of Dazzler bandwidth limitations
- Image charge effect on cathode
- Space charge washes out high-frequency ringing.

- Additional simulations for compression of 5 nC bunch in paper

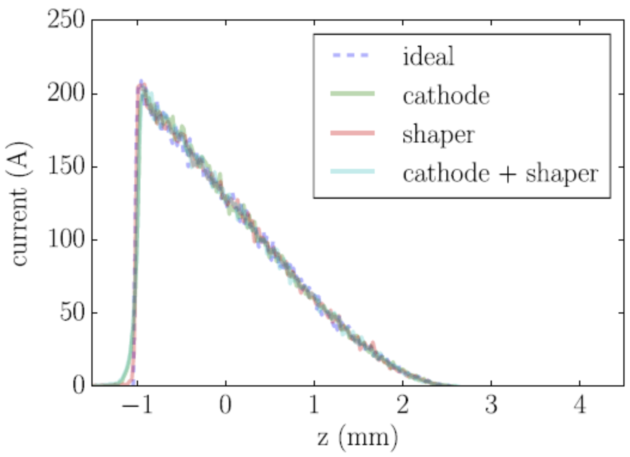


FIG. 7. Comparison of the final electron-bunch current at $s = 50$ cm from the cathode surface for the four cases considered in Fig. 6. The "cathode" and "shaper" respectively correspond to the inclusion of the cathode response time and shaper bandwidth limitation in the initial particle distribution at $s = 0$ while the ideal case is given by Eq. (19) with $\alpha = 2$ and $\tau = 15$ ps. The head of the bunch corresponds to $z > 0$.

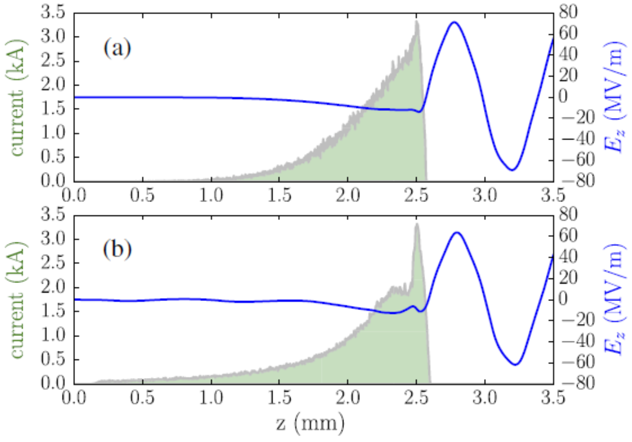
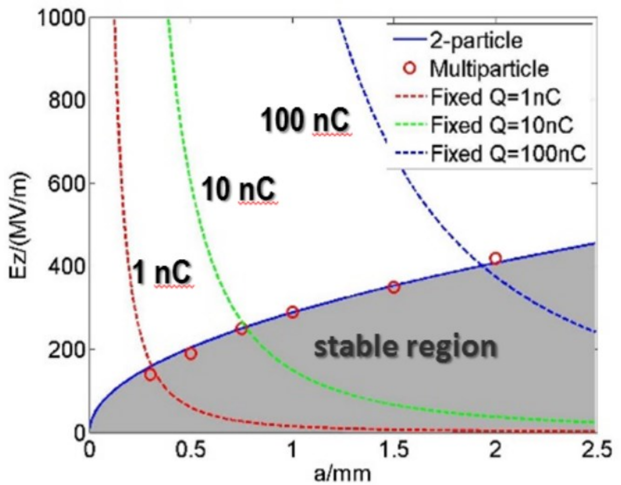
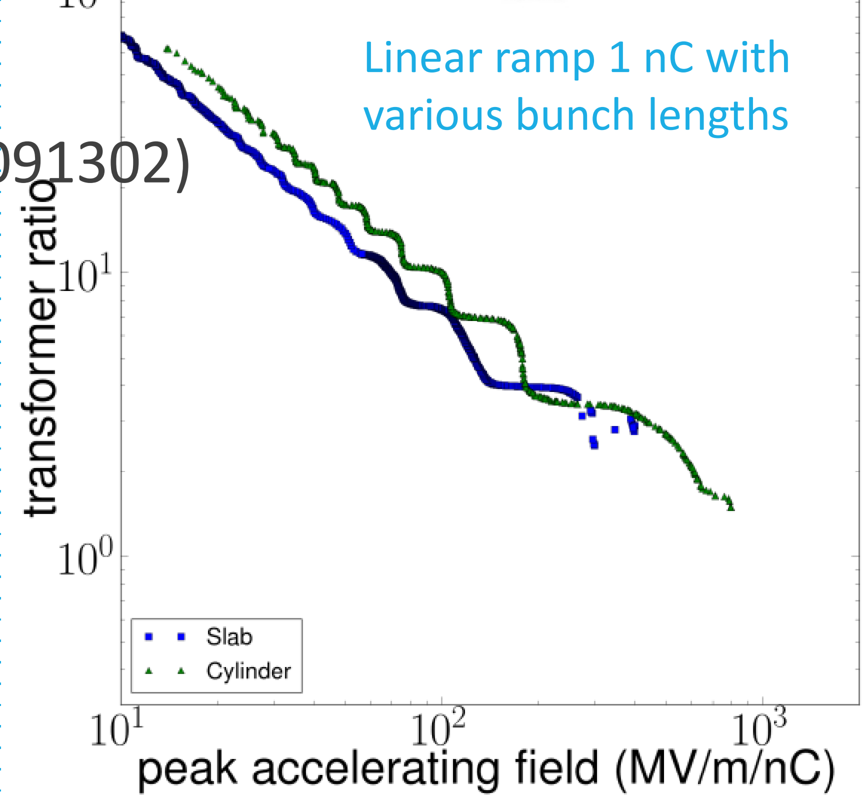


FIG. 9. Final current distribution (green shaded area) and associated wakefield (blue traces) for the "ideal" (a) and "realistic" (b) cases of compression discussed in the text. The head of the bunch corresponds to $z = 0$.

Choice of Structure

- Cylindrical DLW
  - Largest gradients
  - Cylindrically symmetric (round beams)
  - Beam breakup (BBU) (C. Li et. al PhysRevSTAB.17.091302)
- Slab DLW
  - Slightly less gradient ~ (80 % cylindrical)
  - Cylindrically symmetric (round beams)
  - Significant dipole suppression
    - A. Tremaine et al., Phys. Rev. E 56, 7204 (1997).
  - TUNABLE GAP!





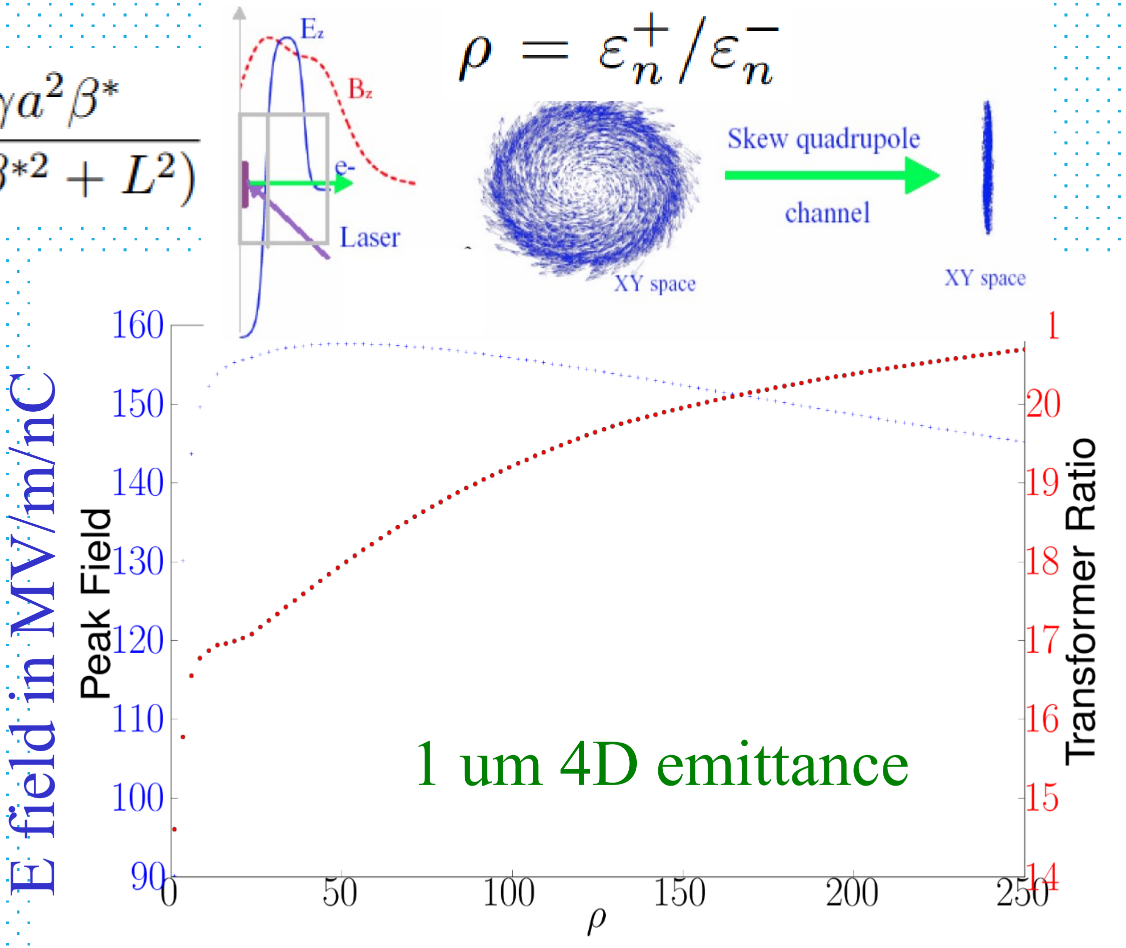
Linear ramp 1 nC with various bunch lengths

Flat-beams in Slab-symmetric Structures

- Flat-beams reduce betatron requirements
- Variable aperture to tune to specific frequency.
- Smaller apertures with flatter beams lead to larger accelerating fields AND transformer ratios!!! (Linear ramp (right))
- Easier alignment

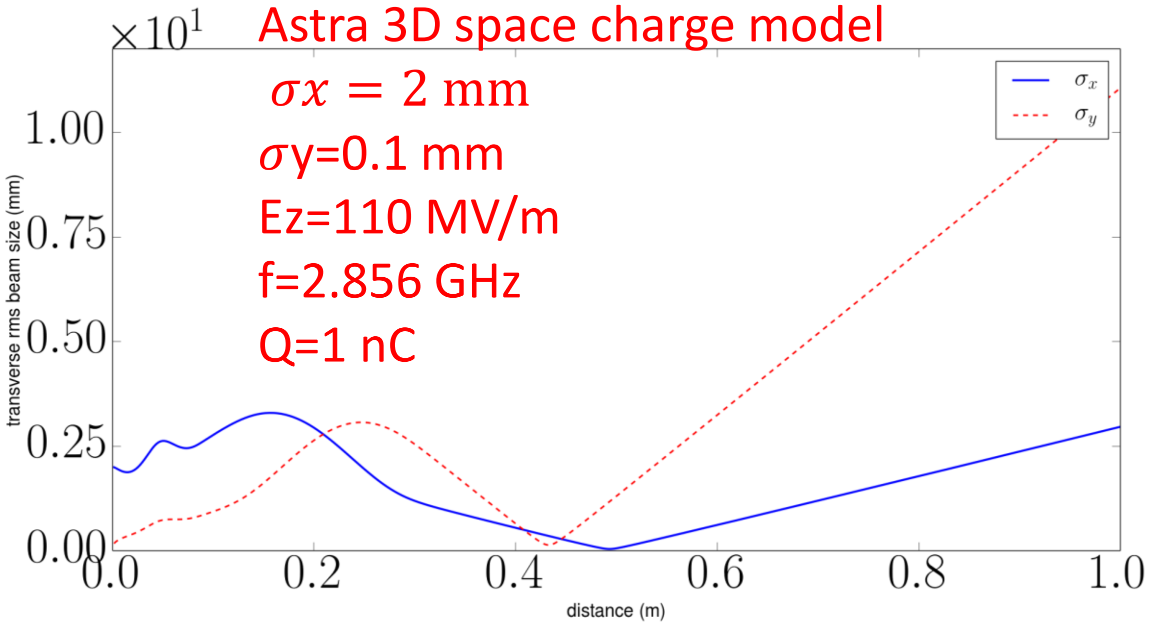
$$\varepsilon_\perp \leq \frac{4\gamma a^2 \beta^*}{9(4\beta^{*2} + L^2)}$$

$$\rho = \varepsilon_n^+ / \varepsilon_n^-$$



Flat-beams from Transverse Laser Shaping

- Use transverse-asymmetric laser pulse onto cathode
- Space charge influences emittance asymmetric emittance growth
- Account Larmor rotation with solenoid strength
- More work needed to find limits of technique


Astra 3D space charge model

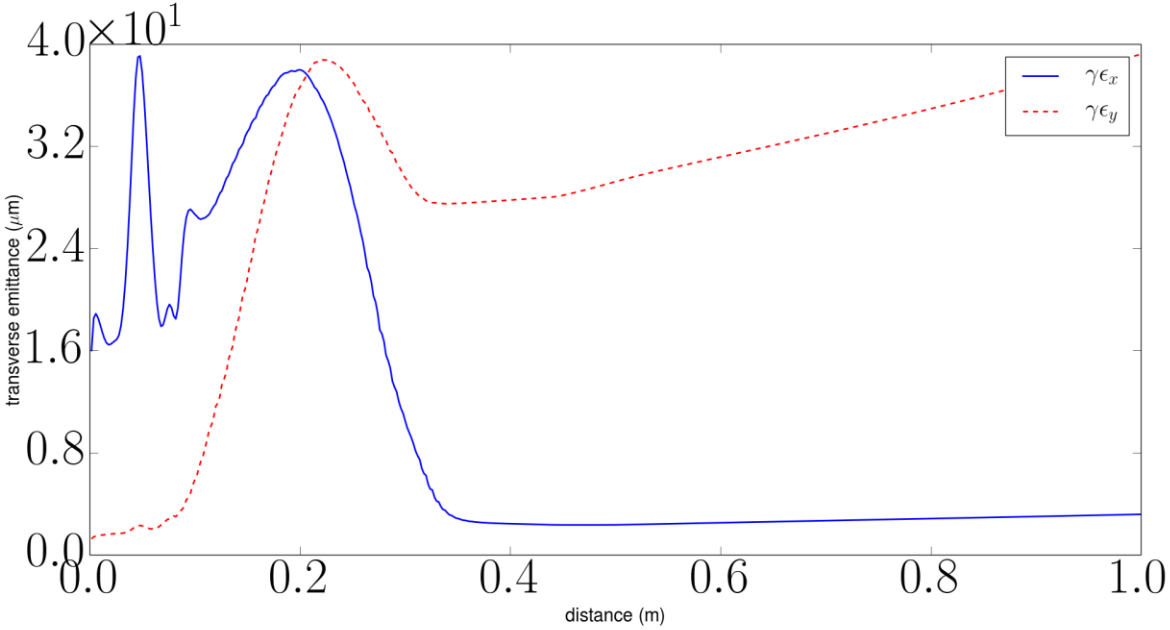
$\sigma x = 2$ mm

σy=0.1 mm

Ez=110 MV/m

f=2.856 GHz

Q=1 nC

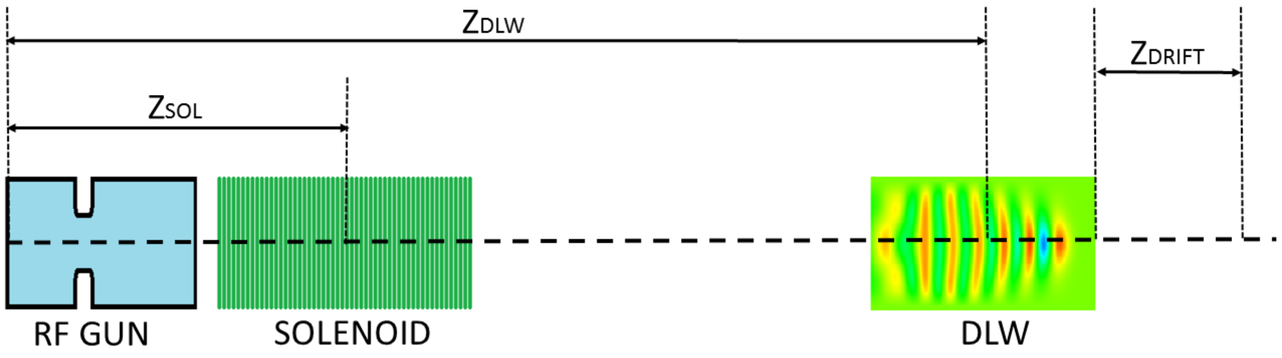


Ballistic bunching + manipulation with DLWs

USING SELF-WAKE INTERACTION TO BUNCH BEAMS VIA DRIFTS AT LOW ENERGY

Ballistic bunching with self-wake

- Is it possible to ballistically bunch with self-wake? (remove jitter from conventional ballistic bunching)
- Photo-Injector source capable of generating :
  - < 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.
  - Large charge densities capable of exciting strong self-wakes
- Explore effects of various structures and combinations

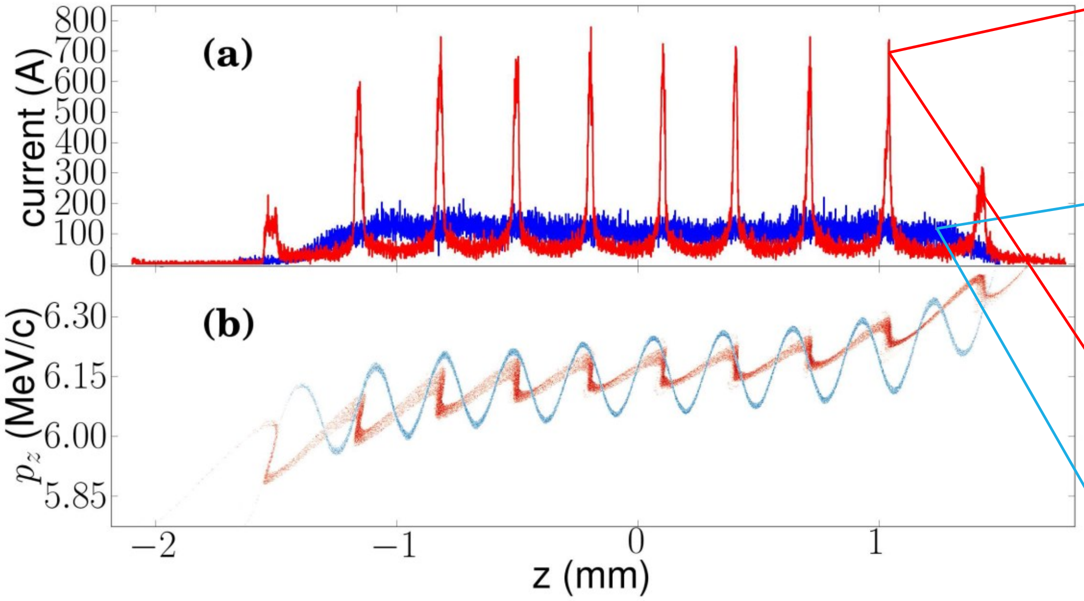


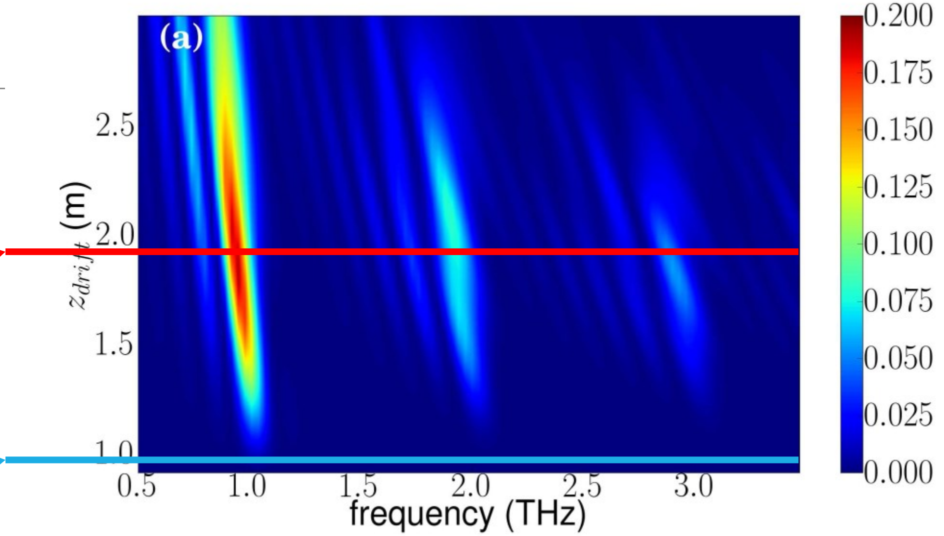
$$R_{56} \simeq -\frac{D}{\gamma^2}$$

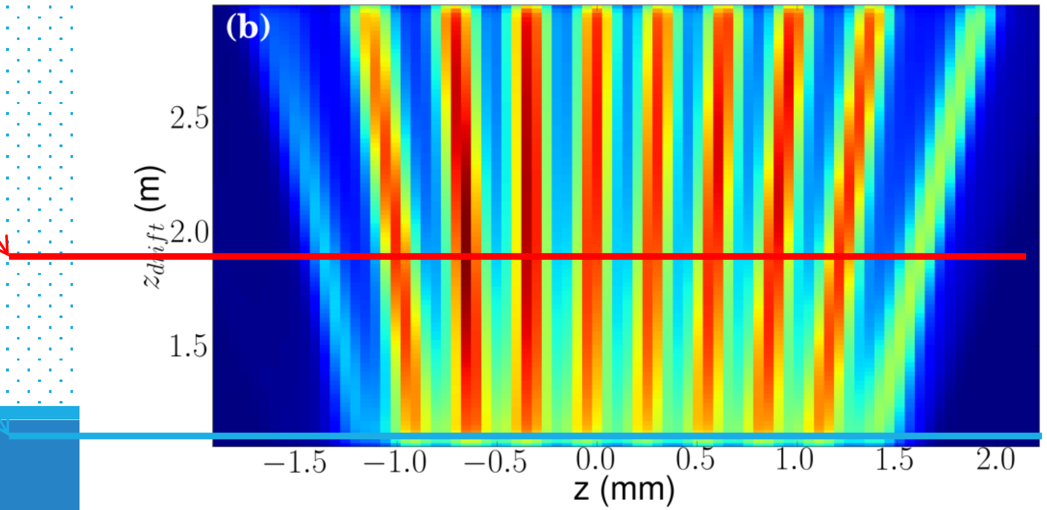
Ballistic bunching with 1 THz DLW

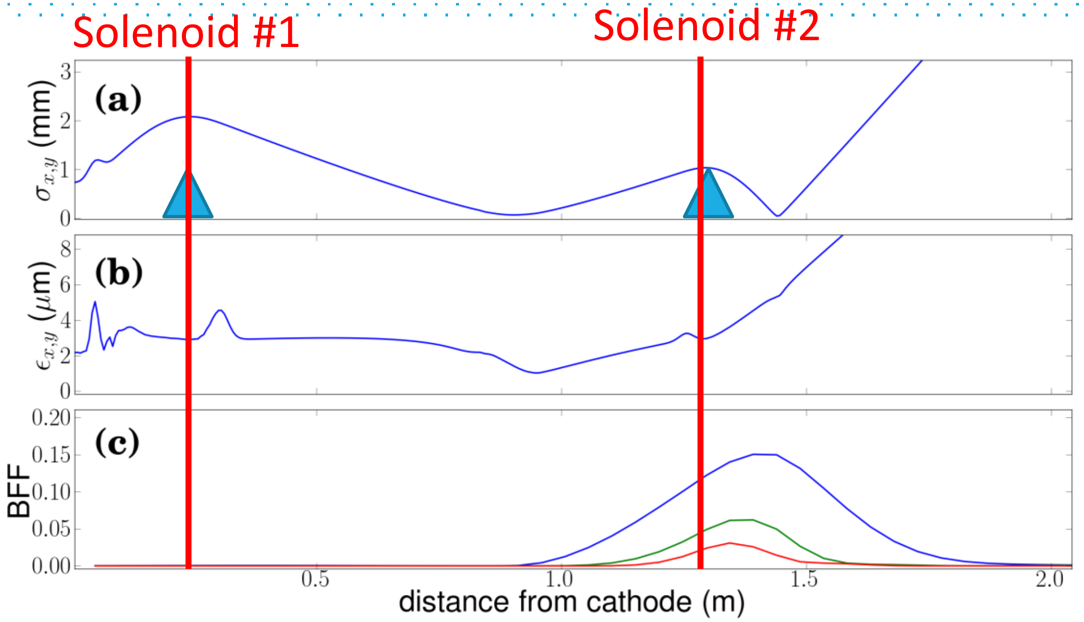
S-Band Gun

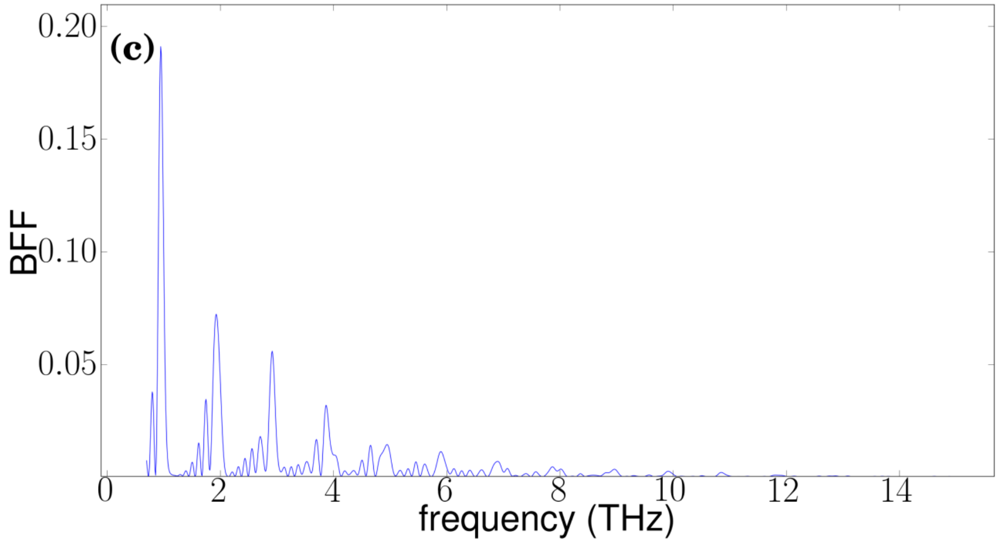
DLW parameters (a, b, ε, L) =(350 μm, 363 μm, 5.7, 11 cm)











1THz Continued..

Fitting into 11 cm structure OK (84 % transmission).

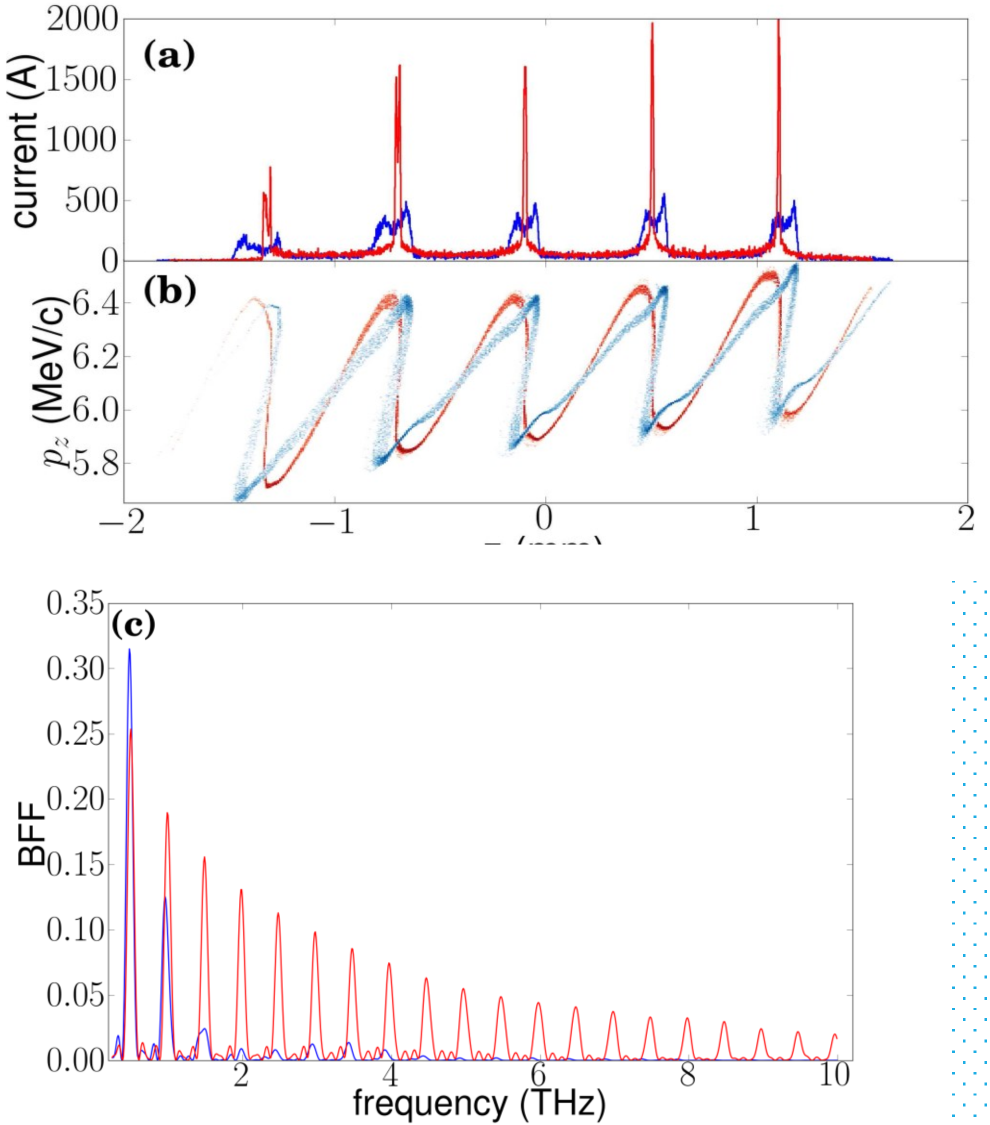
DLW length change impact.

Can we do better than BFF=0.2?

- Energy correlation in LPS
  - Solution 1: Longer bunch
  - Solution 2: Lower the frequency

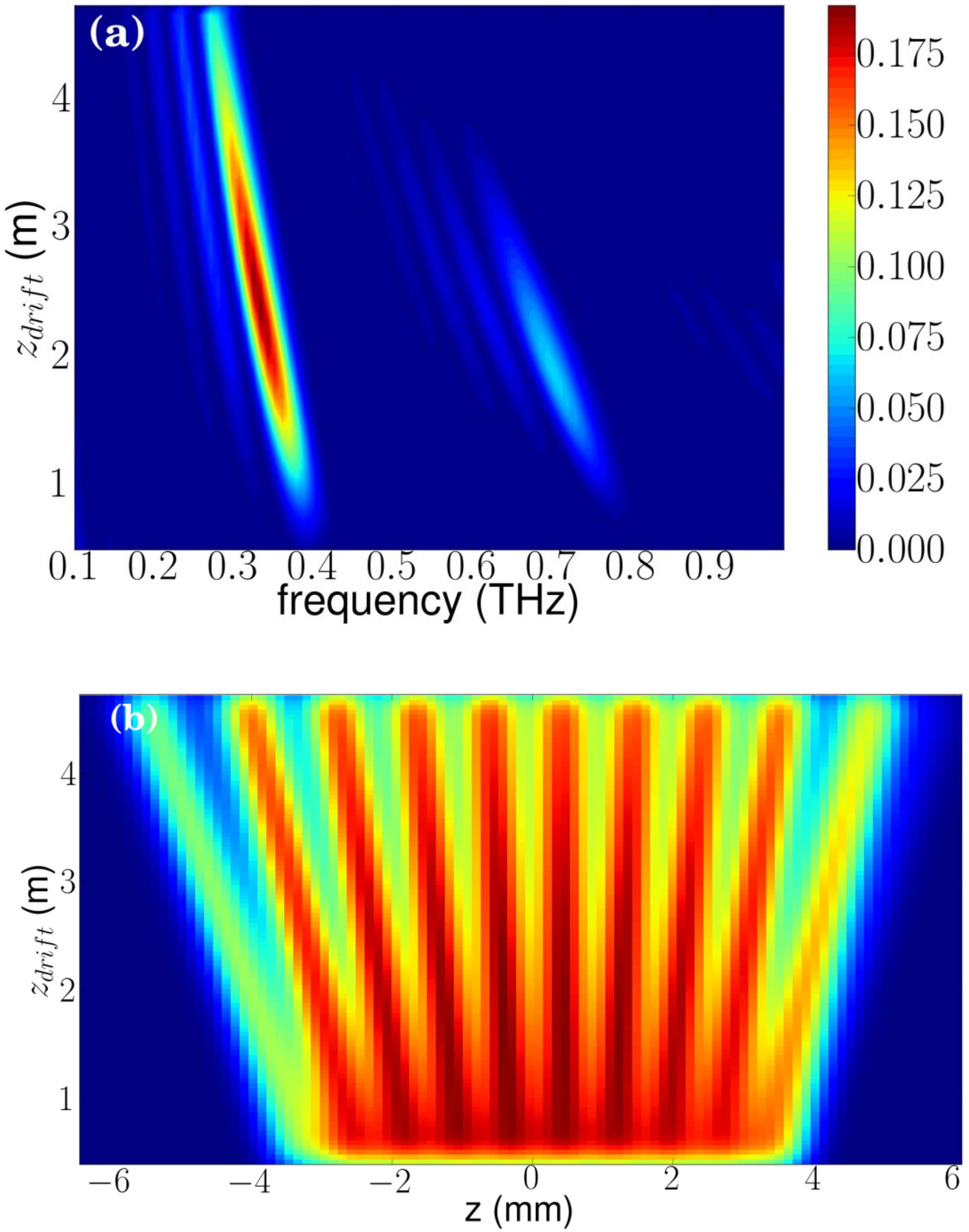
500 GHz DLW – (350 µm, 393 µm, 5.7)

- Lower frequency (e.g. longer wavelength) traps more electrons
- Smaller influence from initial LPS chirp for BFF
- “Easier” to do (e.g. larger inner radius structure, spectral content)
- Higher mode suppression by under/over compressing the bunches.



L-Band case study

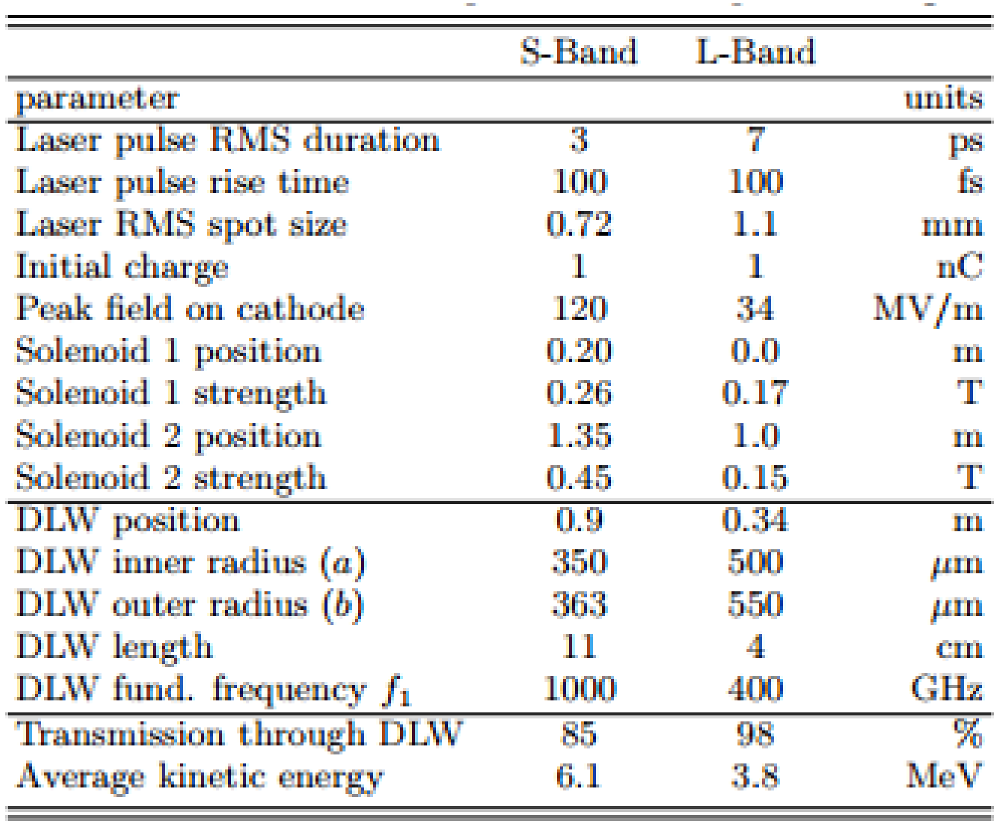
- Larger emittance
  - Larger structures
  - Lower frequencies
- Lower energy
  - Shorter bunching length for same energy modulation
  - More space charge effects



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)

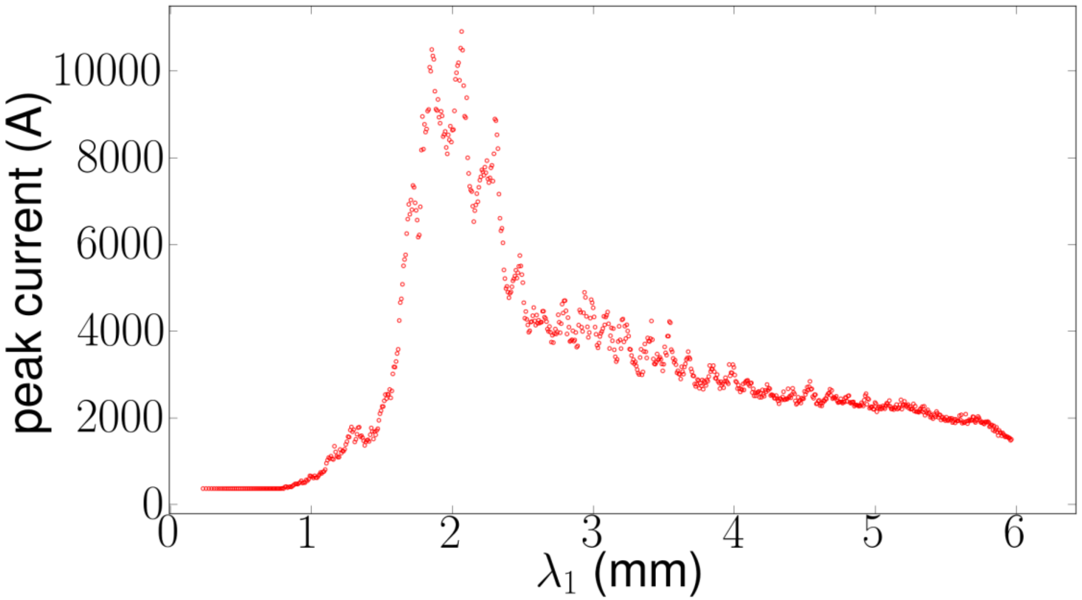
$$\widetilde{F}|(\omega) = \frac{1}{N^2}\left(\left|\sum_i^N \cos\frac{\omega z_i}{c}\right|^2 + \left|\sum_i^N \sin\frac{\omega z_i}{c}\right|^2\right)$$

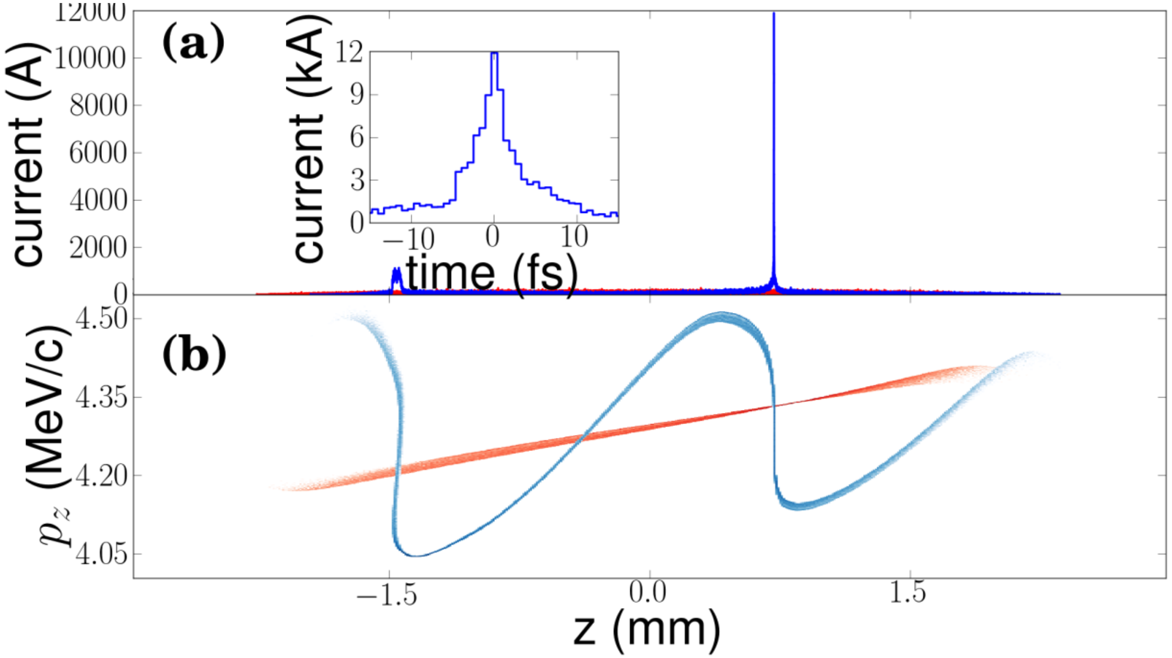


	S-Band	L-Band	
parameter			units
Laser pulse RMS duration	3	7	ps
Laser pulse rise time	100	100	fs
Laser RMS spot size	0.72	1.1	mm
Initial charge	1	1	nC
Peak field on cathode	120	34	MV/m
Solenoid 1 position	0.20	0.0	m
Solenoid 1 strength	0.26	0.17	T
Solenoid 2 position	1.35	1.0	m
Solenoid 2 strength	0.45	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

Passive Compressor

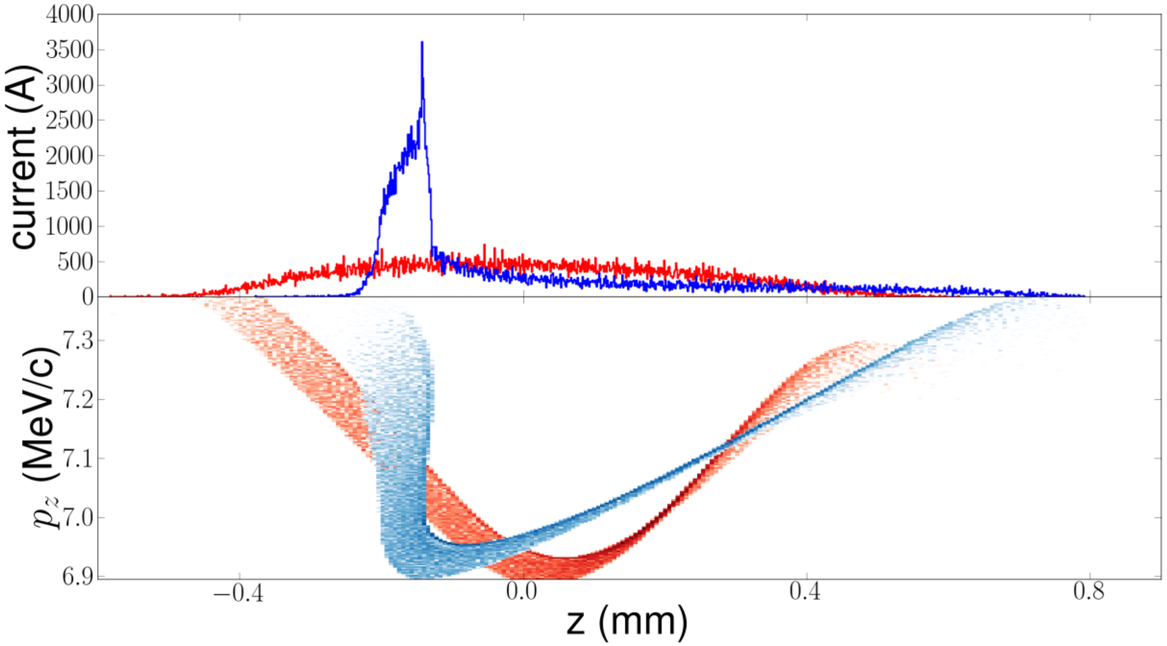
- L ~ λ – Single peak.
- Peak current limited by energy spread.
- Scan various wavelengths and record peak current.
- For L-Band case, this corresponds to a peak current of ~ 12 kA (7.1%).
- Scalable for higher charge / large structures a=650 µm
- Limited by slice energy spread

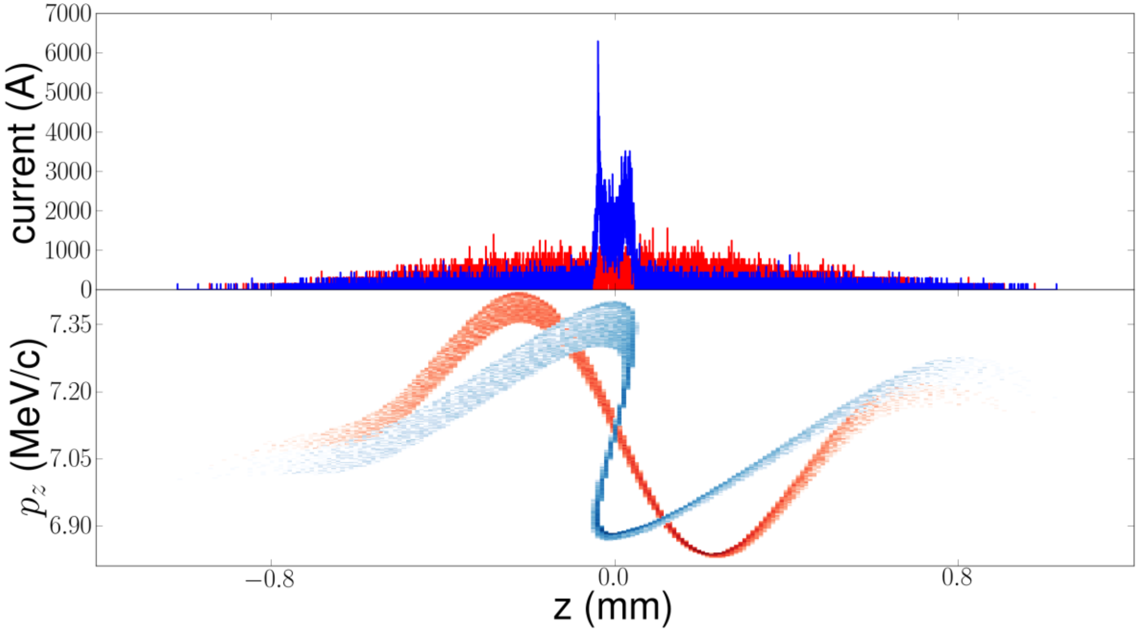


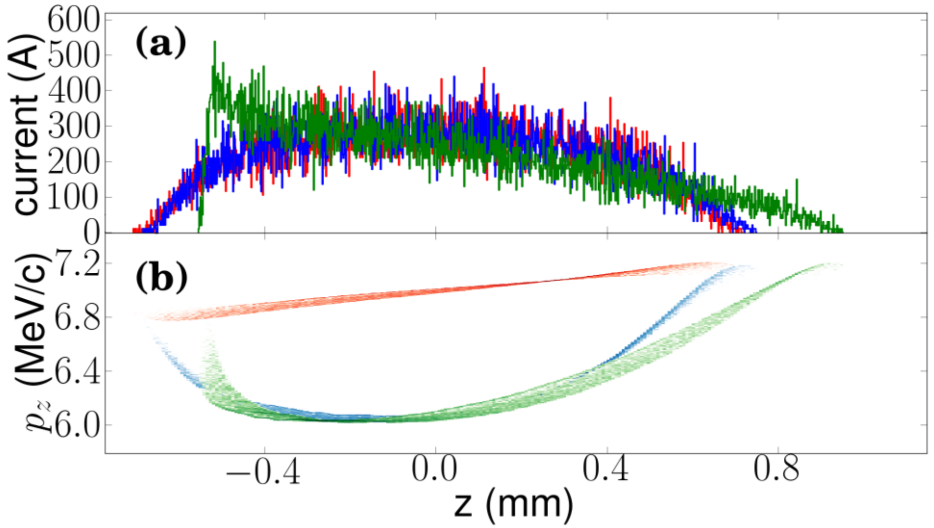


Passive Compressor for beam-driven applications

- 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



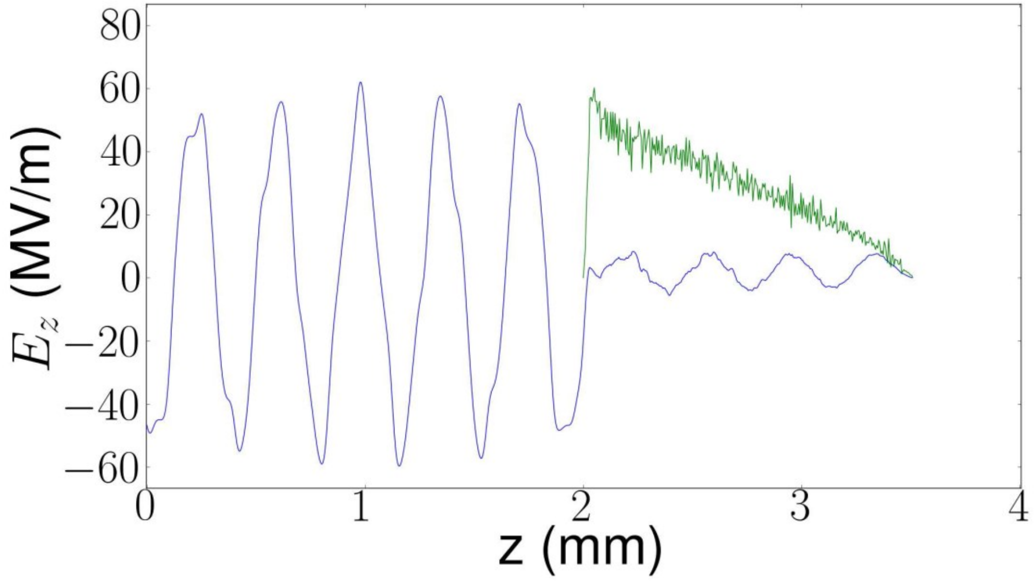




Longitudinal Shaping with DLW

Larger wavelengths (λ>>L)

- Bunch shaping
- Passive bunching
- De-chirper/Linearizer

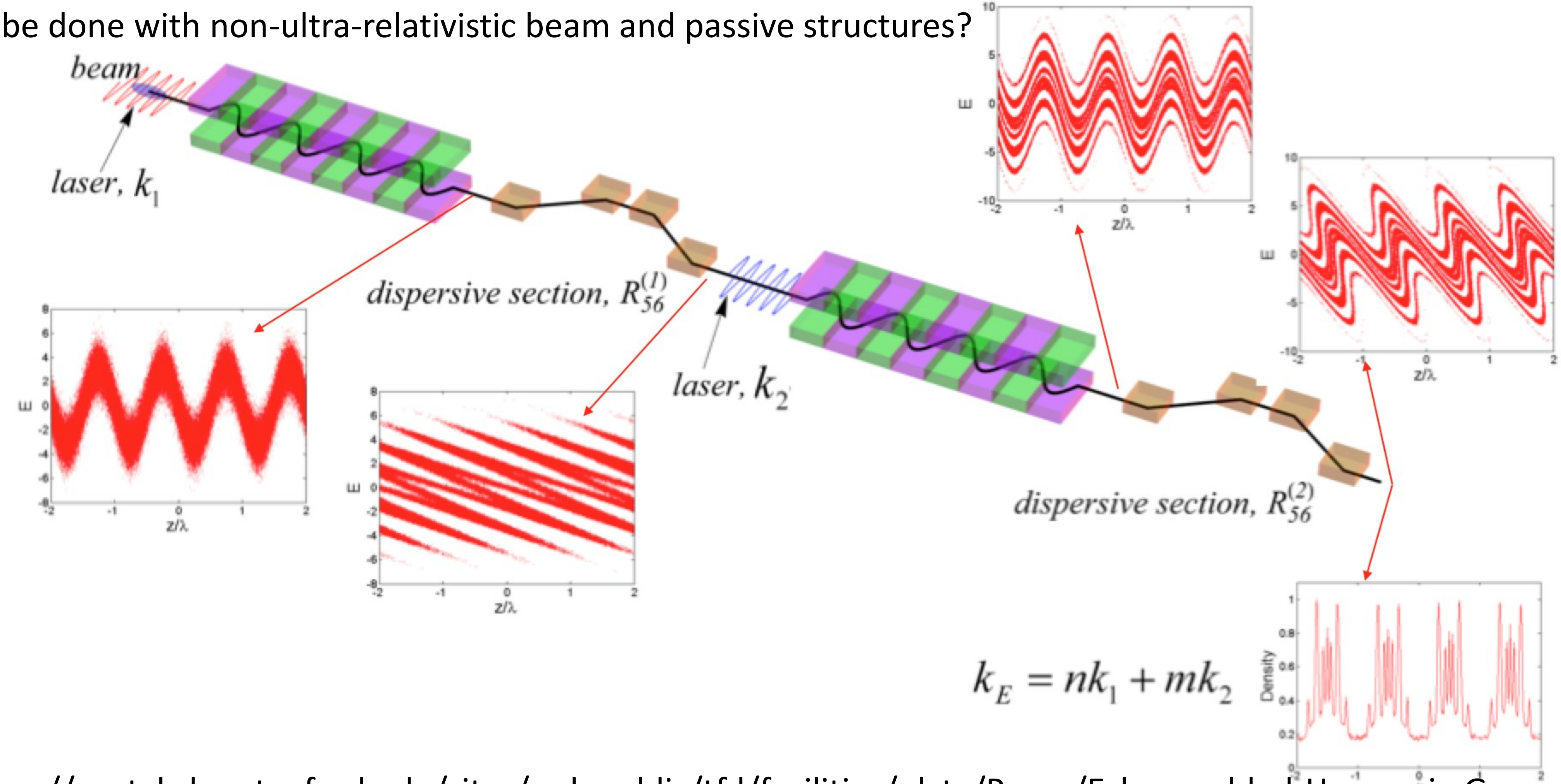


Ramped bunch for high transformer ratio acceleration.

- Here for (165 μm, 197 μm, 5.7)
- R = 7.3 (Theoretical max 9.3)

Cascaded Passive Manipulation

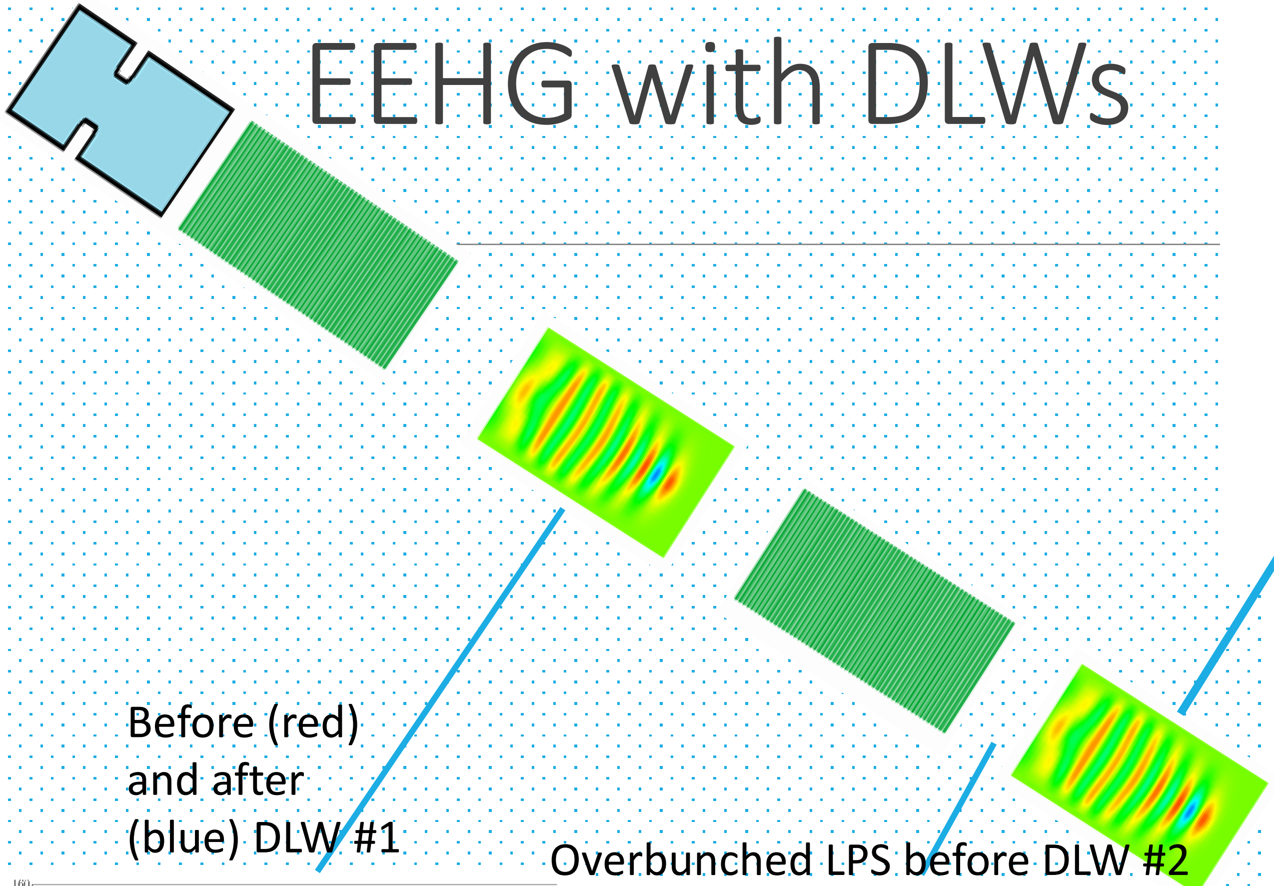
- Can this be done with non-ultra-relativistic beam and passive structures?

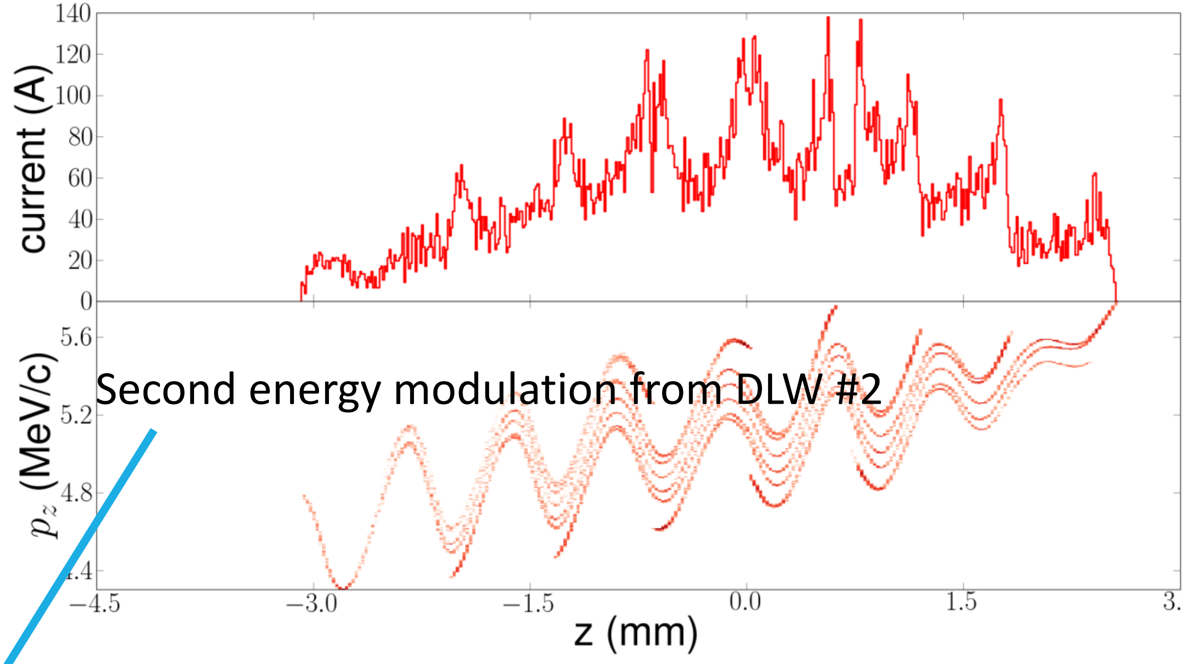


$$k_E = nk_1 + mk_2$$

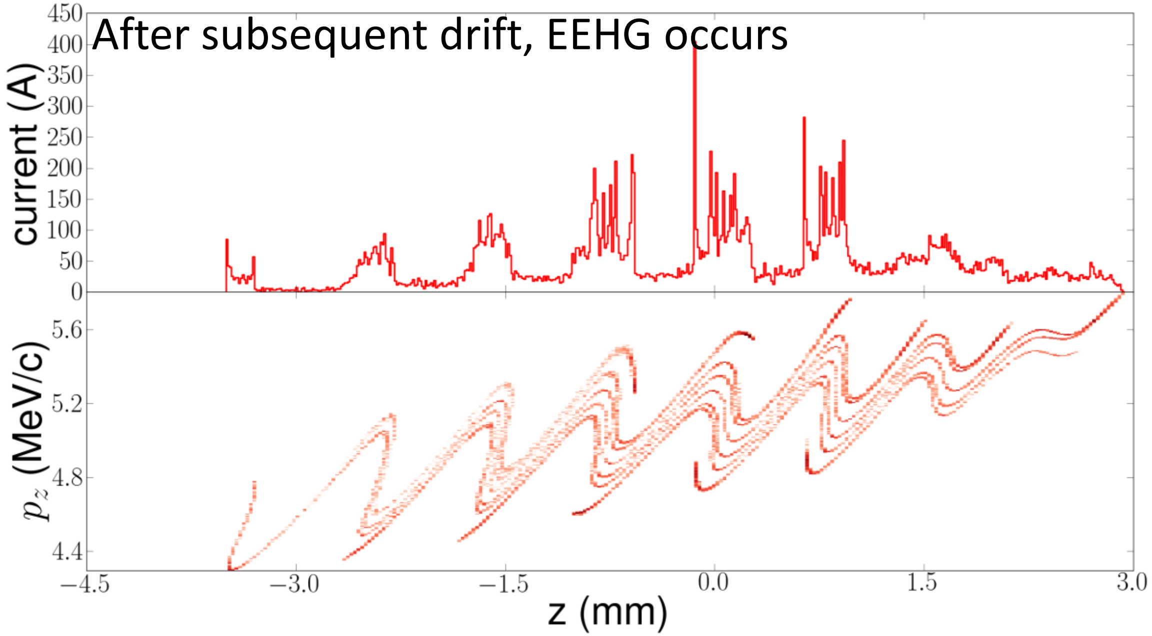
https://portal.slac.stanford.edu/sites/ard_public/tfd/facilities/nlcta/Pages/Echo-enabled-Harmonic-Generation.aspx

EEHG with DLWs



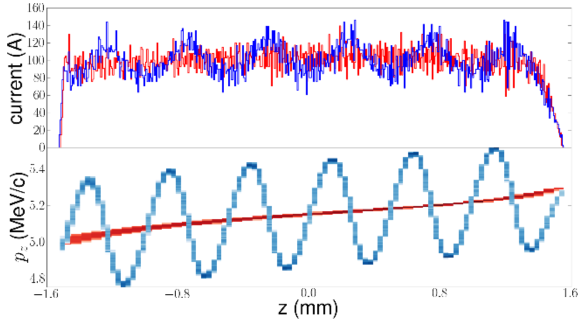


Second energy modulation from DLW #2

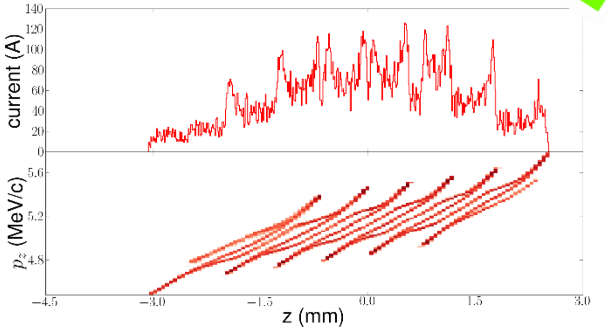


After subsequent drift, EEHG occurs

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

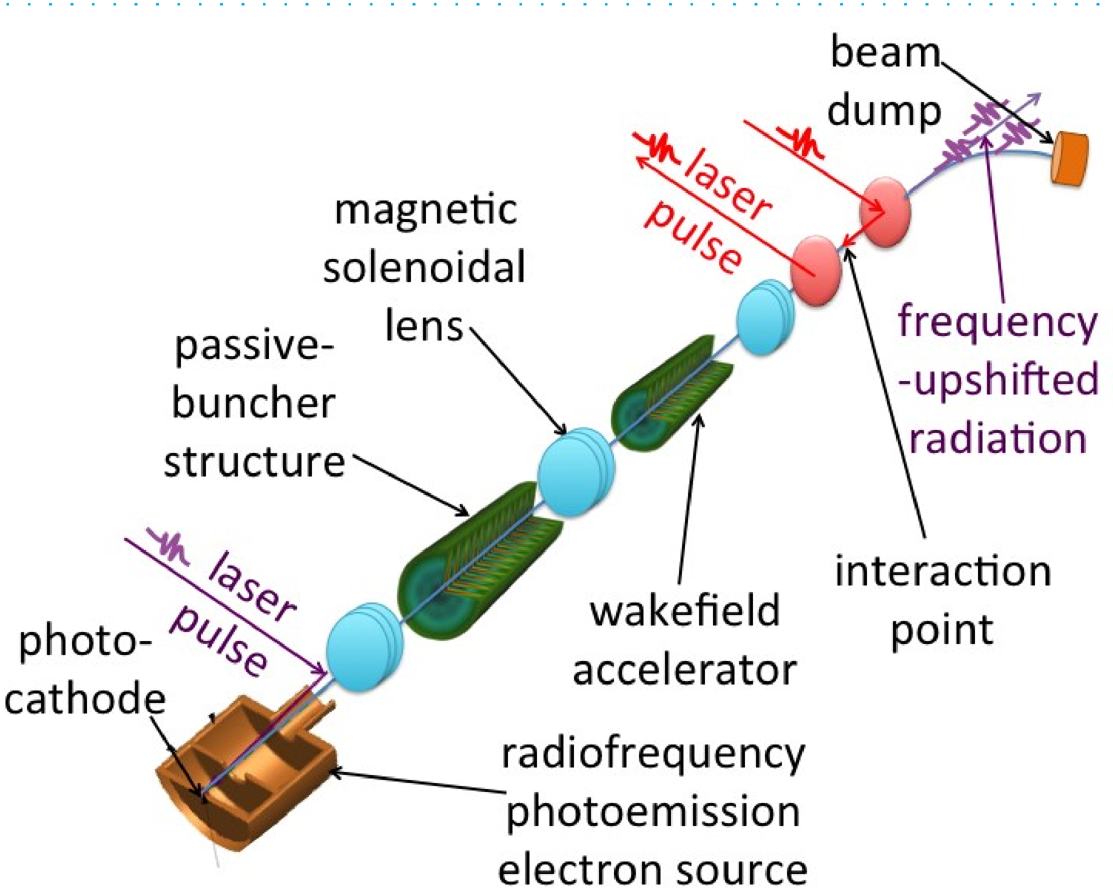


Overbunched LPS before DLW #2



Merging concepts for Acceleration

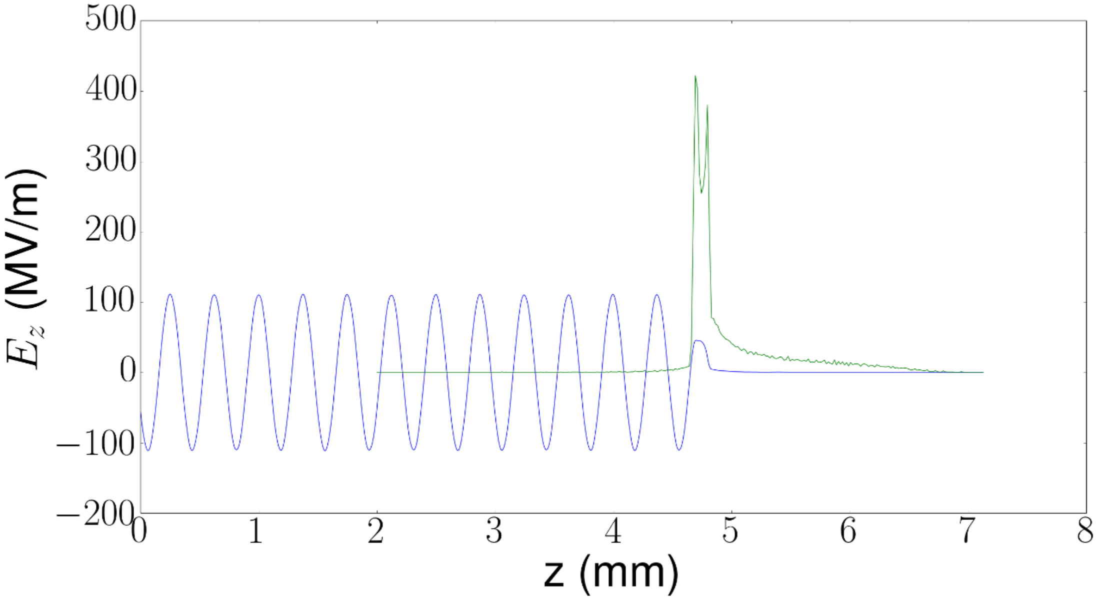
- DLWs in series, bunch and accelerate
- DLW dimensions limited by beam
- Total energy gain limited by transformer ratio

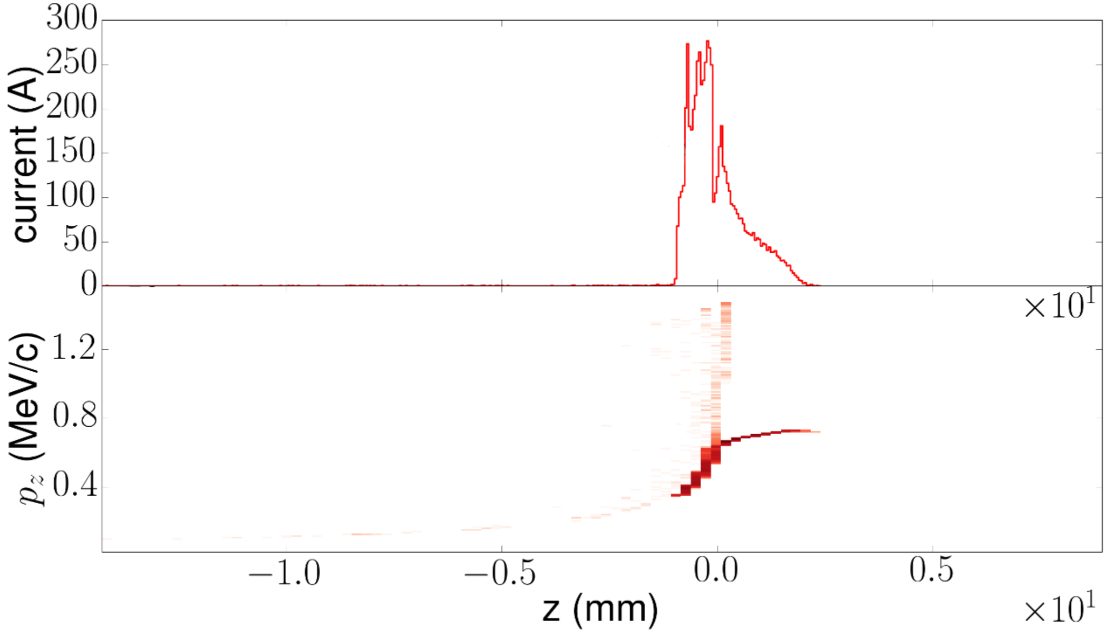


Compact X-Ray source

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

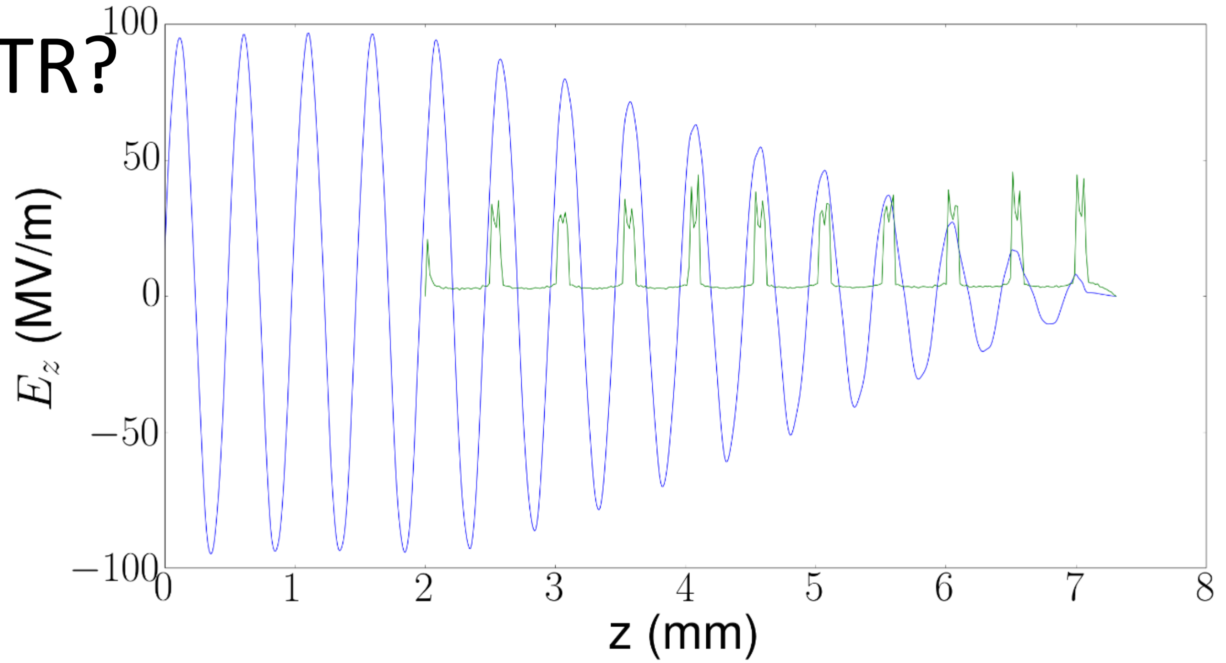
- Dynamic processes at large gradients
  - Will require full PIC simulations
  - Look at emittance growth





Coherent THz extraction

- Cherenkov radiator
  - Using second DLW to extract DLWs of same (or higher harmonic) frequency.
- Efficiency enhancement over CTR?
  - CTR scales with energy/BFF
  - Fields in DLW scale with
    - BFF/charge
    - Structure parameters



Current work on AXSIS

- Recently joined F. Kaertner group at CFEL
- AXSIS is an ERC project for generating coherent 12.4 KeV X-rays on a tabletop
- Use of laser-based THz generation to accelerate/bunch electrons
- Inverse Compton scattering for X-Ray generation.
- Everything synchronized from a single oscillator/seed

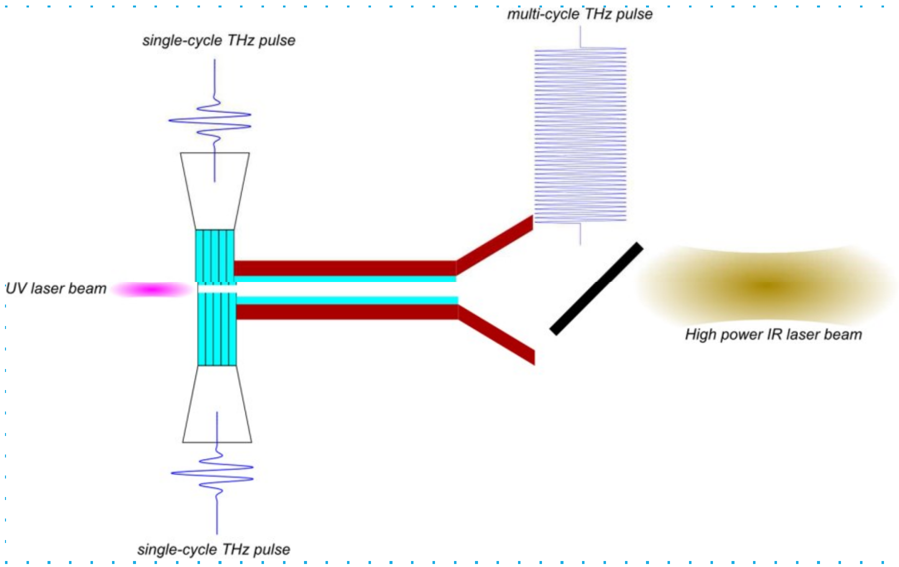


Photo courtesy A. Fallahi

Thanks

Philippe Piot – Adviser from NIU/Fermilab who made this work possible, and fun.

Daniel Mihalcea—Useful discussions and simulation help.

Jun Zhu—Useful discussions and help with flat-beams.

Peter Stoltz/ Tech-X for Vorpal (VSIM) help.

Looking forward to exciting opportunities at DESY!