Beam Dynamics with Self-Wakes in Dielectric-Lined Waveguides

François Lemery, Philippe Piot and PITZ team:

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Acknowledgments

EAAC17: “A conference so nice that it doesn’t make sense!”

Thanks to:

Franz Kaertner for useful discussions and support.

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And most importantly the fantastic PITZ team for their beyond excellent experimental efforts to realize this work! We are indebted!

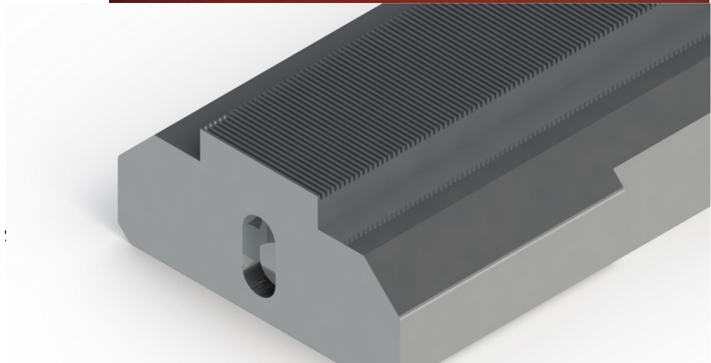
Introduction

- Charged particle beams interact with their environment and produce wakefields, generally in accelerators wakefields are bad, but sometimes they can be good, too.

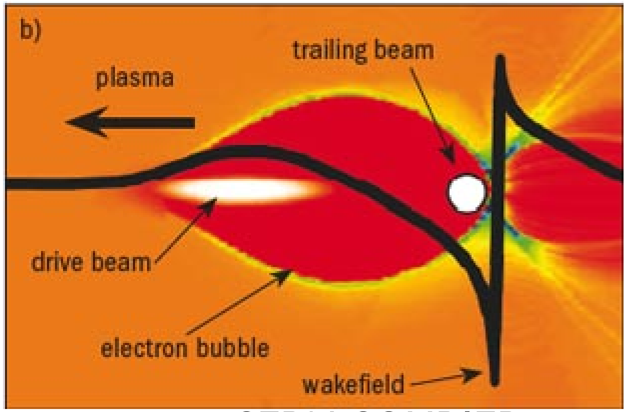
  High impedance mediums e.g. dielectric-lined waveguides, corrugated structures, and plasmas are used to generate large wakefield amplitudes.

  The wakefield can be calculated from the convolution of the current profile and the Green's function:

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

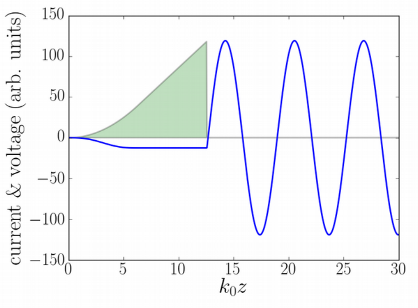


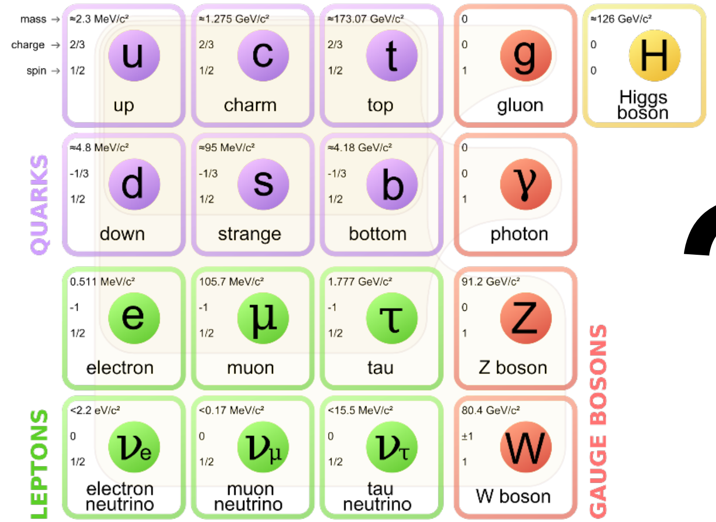
LCLS dechirper



CERN COURIER

Applications





?

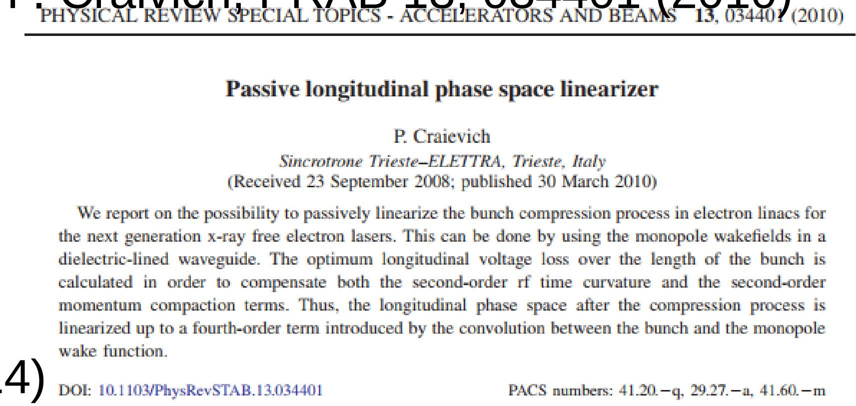
- Efficient beam-driven acceleration between drive and witness bunch, Voss&Weiland 1972. May be useful in future TeV colliders with enhanced transformer ratios.

  -Beam manipulation applications:

  -Linearizer/dechirper for improving peak currents orreducing energy spreads

  -Multibunching for e.g. THz generation applications

P. Craivich, PRAB 13, 034401 (2010)


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 13, 034401 (2010)

Passive longitudinal phase space linearizer

P. Craievich

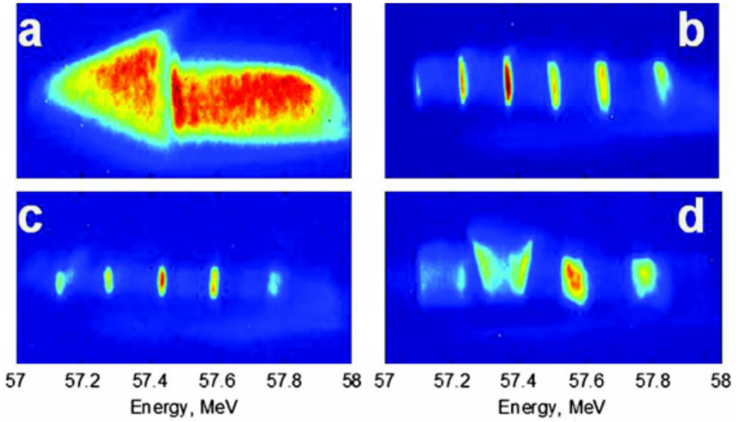
Sincrotrone Trieste–ELETTRA, Trieste, Italy

(Received 23 September 2008; published 30 March 2010)

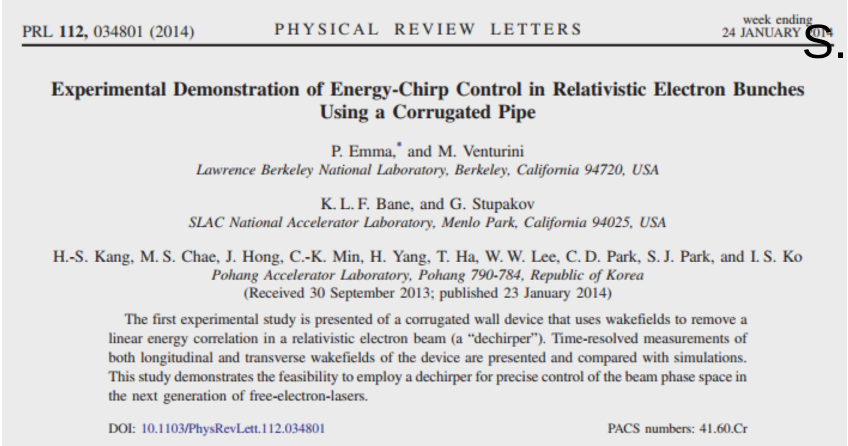
We report on the possibility to passively linearize the bunch compression process in electron linacs for the next generation x-ray free electron lasers. This can be done by using the monopole wakefields in a dielectric-lined waveguide. The optimum longitudinal voltage loss over the length of the bunch is calculated in order to compensate both the second-order rf time curvature and the second-order momentum compaction terms. Thus, the longitudinal phase space after the compression process is linearized up to a fourth-order term introduced by the convolution between the bunch and the monopole wake function.

DOI: 10.1103/PhysRevSTAB.13.034401 PACS numbers: 41.20.−q, 29.27.−a, 41.60.−m

S. Antipov et al PhysRevLett.108.144801



P. Emma et al. PRL 112, 034801(2014)


PRL 112, 034801 (2014) PHYSICAL REVIEW LETTERS week ending 24 JANUARY 2014

Experimental Demonstration of Energy-Chirp Control in Relativistic Electron Bunches Using a Corrugated Pipe

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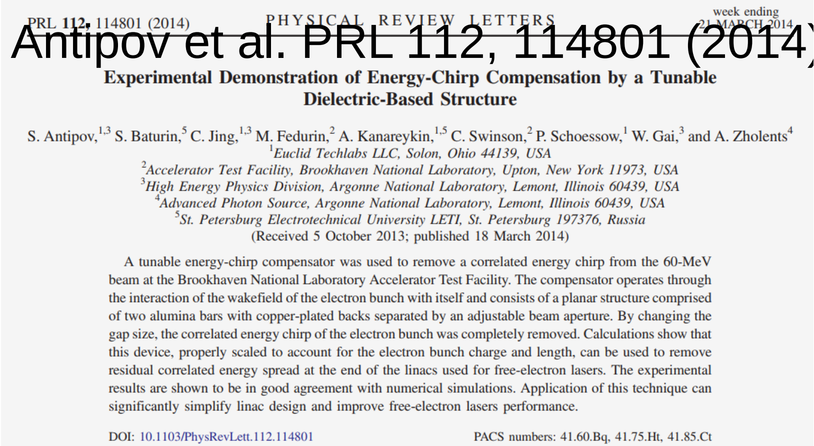
(Received 30 September 2013; published 23 January 2014)

The first experimental study is presented of a corrugated wall device that uses wakefields to remove a linear energy correlation in a relativistic electron beam (a "dechirper"). Time-resolved measurements of both longitudinal and transverse wakefields of the device are presented and compared with simulations. This study demonstrates the feasibility to employ a dechirper for precise control of the beam phase space in the next generation of free-electron-lasers.

DOI: 10.1103/PhysRevLett.112.034801 PACS numbers: 41.60.Cr

S. Antipov et al. PRL 112, 114801 (2014)


PRL 112, 114801 (2014) PHYSICAL REVIEW LETTERS week ending 21 MARCH 2014

Experimental Demonstration of Energy-Chirp Compensation by a Tunable Dielectric-Based Structure

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(Received 5 October 2013; published 18 March 2014)

A tunable energy-chirp compensator was used to remove a correlated energy chirp from the 60-MeV beam at the Brookhaven National Laboratory Accelerator Test Facility. The compensator operates through the interaction of the wakefield of the electron bunch with itself and consists of a planar structure comprised of two alumina bars with copper-plated backs separated by an adjustable beam aperture. By changing the gap size, the correlated energy chirp of the electron bunch was completely removed. Calculations show that this device, properly scaled to account for the electron bunch charge and length, can be used to remove residual correlated energy spread at the end of the linacs used for free-electron lasers. The experimental results are shown to be in good agreement with numerical simulations. Application of this technique can significantly simplify linac design and improve free-electron lasers performance.

DOI: 10.1103/PhysRevLett.112.114801 PACS numbers: 41.60.Bq, 41.75.Ht, 41.85.Ct

DLW overview

In high energy regime, k1→ 0
and fields are uniform.

$$k_1 = \omega\sqrt{\frac{1}{c^2} - \frac{1}{v_p^2}}$$

$$k_2 = \omega\sqrt{\frac{\epsilon_r}{c^2} - \frac{1}{v_p^2}}$$

$$k_z = \frac{\omega}{v_p}.$$

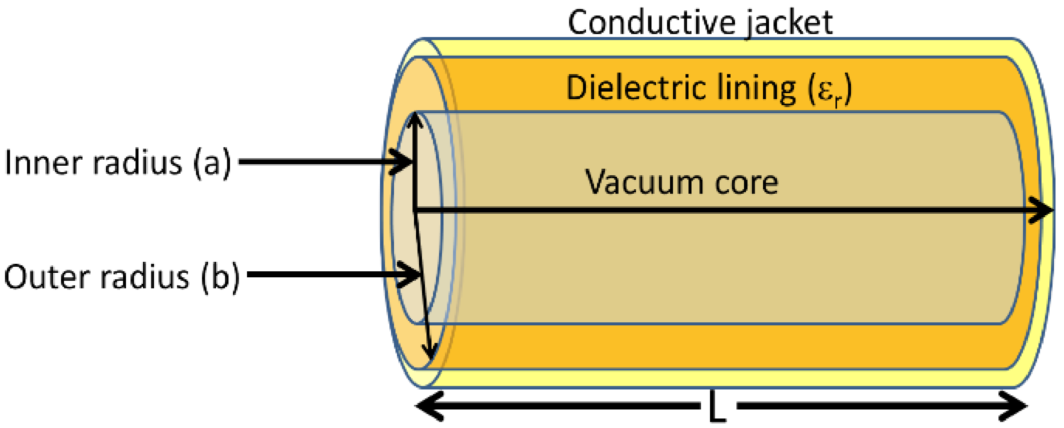
- Dielectric-lined waveguides (DLW)
  - Around since 60s, applications to communication and data transfer.
  - Wakefield application came in mid-to-late 1980s, see W. Gai.
  - First experiments in early 90s.
  - Fundamental mode is a deflection mode which has limited their use for e.g. collider applications.

$$E_z = \begin{cases} B_1 J_0(k_1 r) e^{i(\omega t - k_z z)} & 0 \le r < a \\ B_2 F_{00}(k_1 r) e^{i(\omega t - k_z z)} & a \le r \le b \end{cases}$$

$$E_r = \begin{cases} \frac{-ik_z}{k_1} B_1 J_0'(k_1 r) e^{i(\omega t - k_z z)} & 0 \le r < a \\ \frac{-ik_z}{k_2} B_2 F_{00}'(k_2 r) e^{i(\omega t - k_z z)} & a \le r \le b \end{cases}$$

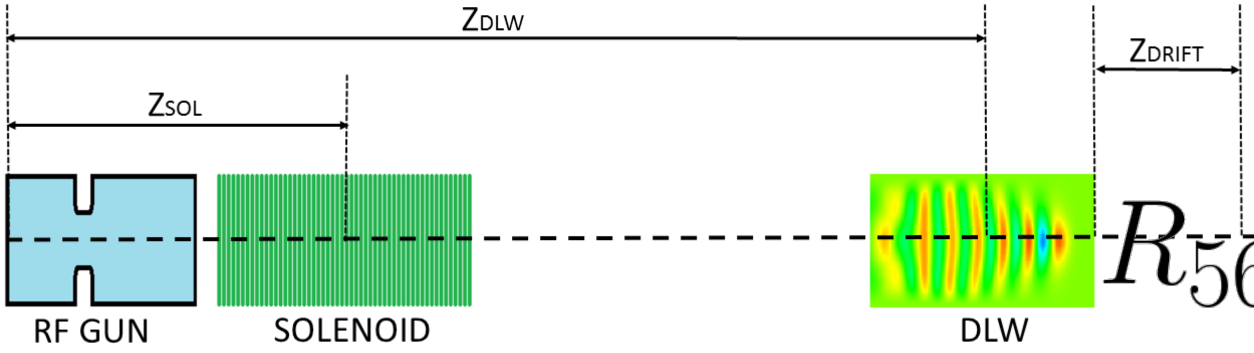
$$H_\phi = \begin{cases} \frac{-i\omega\epsilon_0}{k_1} B_1 J_0'(k_1 r) e^{i(\omega t - k_z z)} & 0 \le r < a \\ \frac{-i\omega\epsilon_r\epsilon_0}{k_2} B_2 F_{00}'(k_2 r) e^{i(\omega t - k_z z)} & a \le r \le b \end{cases}.$$

-Argonne National Lab recently demonstrated 100 MV/m from drive to witness beam ! See M. Conde talk.



Self-Wake Interactions at Low Energy

- Photo-Injector Source:
  - ~ 100 Amp currents.
  - < 10 MeV energy out of gun (L-Band(1.3GHz - 60 MV/m) vs S-Band(2.856 GHz – 140 MV/m), X…), energy spread.
  - Emittances < 1 μm for S-Band. Ideal for fitting into smaller structures.
- Ballistic bunching, shaping+
- No CSR

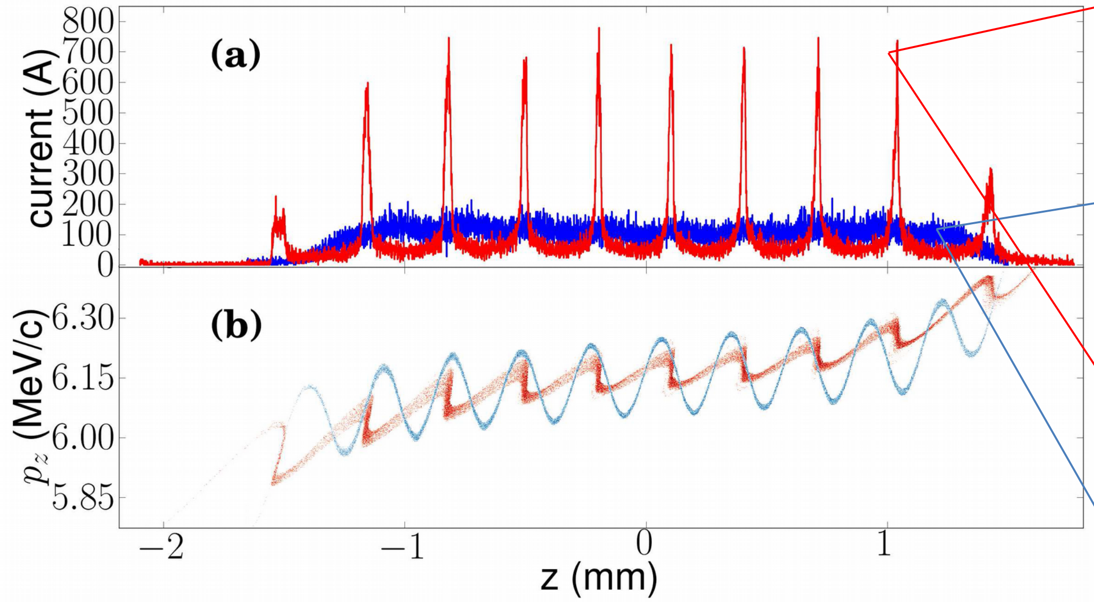


$$R_{56} = \frac{Z_{drift}}{\gamma^2}$$

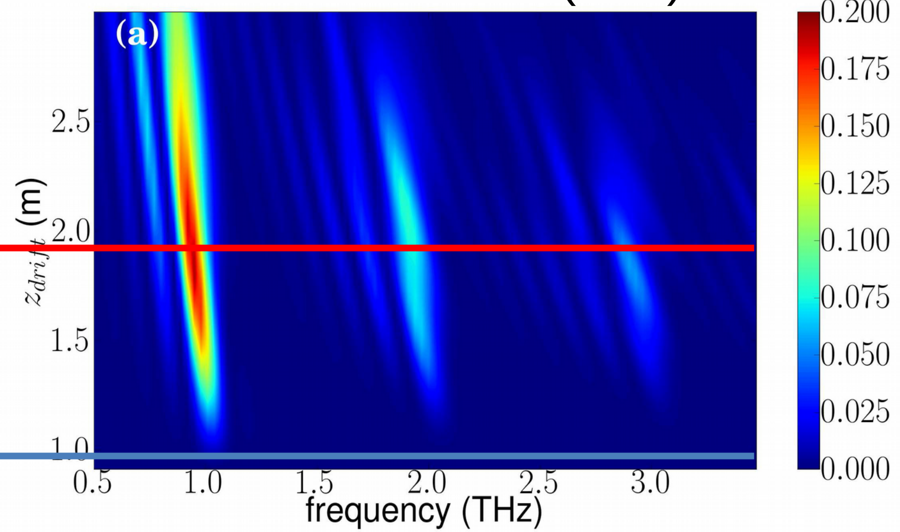
Density modulation at 1 THz

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

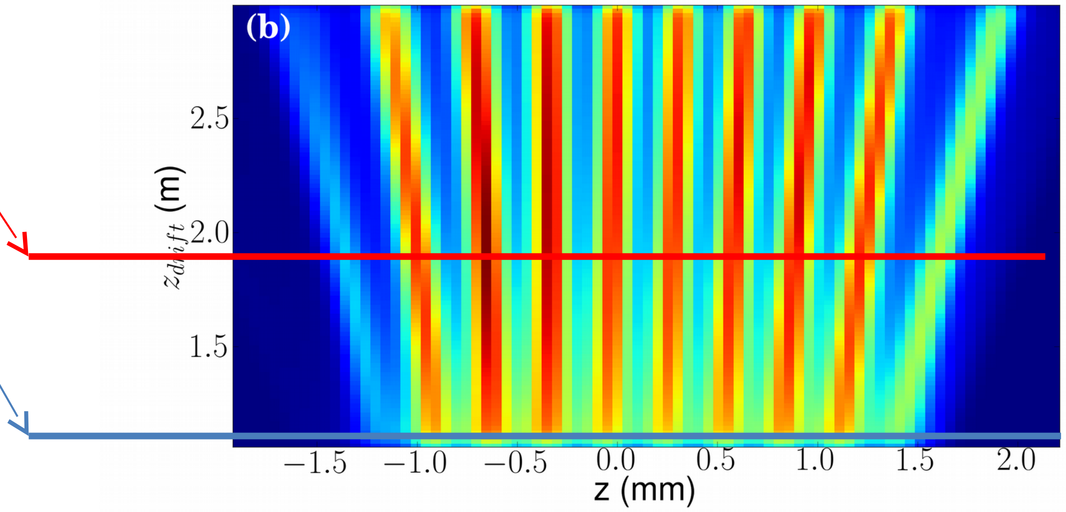
- S-Band Gun
- DLW parameters (a, b, ε, L) =(350 μm, 363 μm, 5.7, 11 cm)

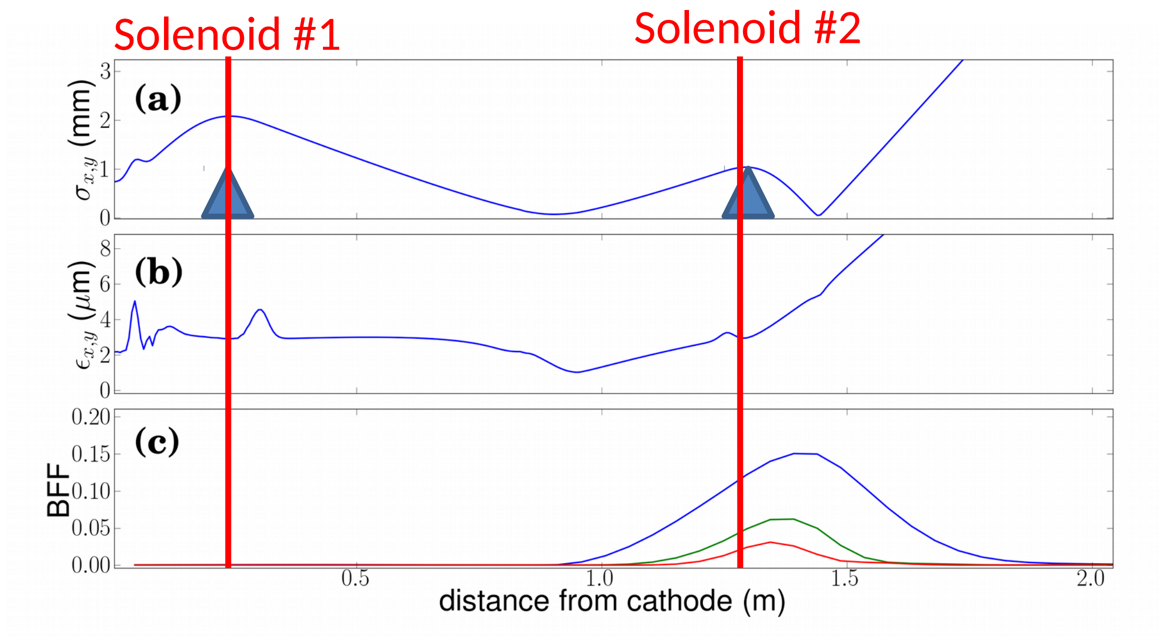


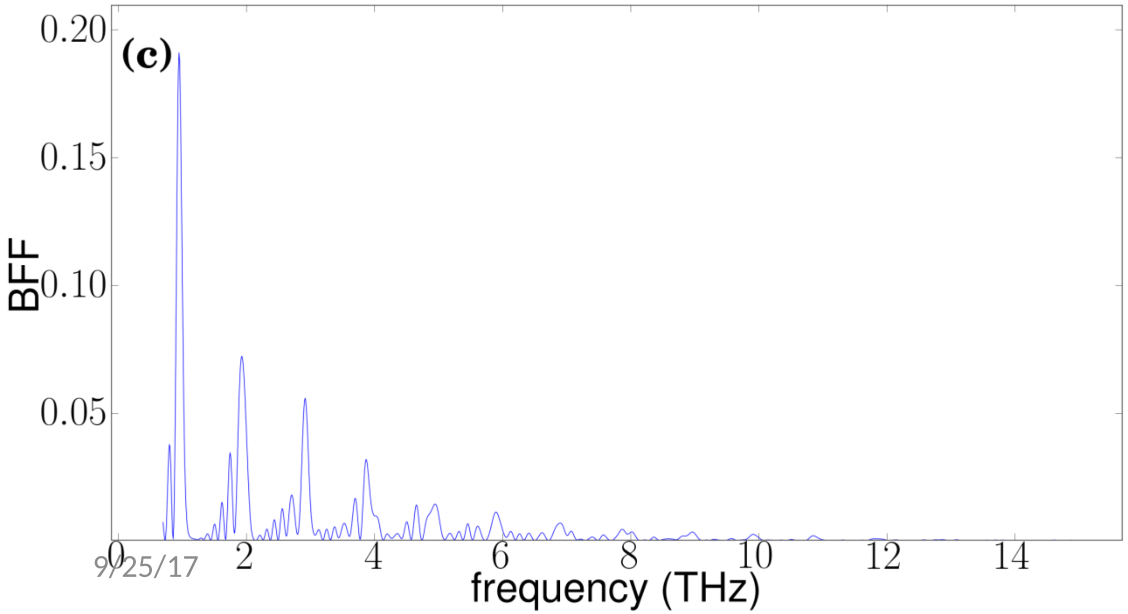
Bunch form factor (BFF)



Density contour plot



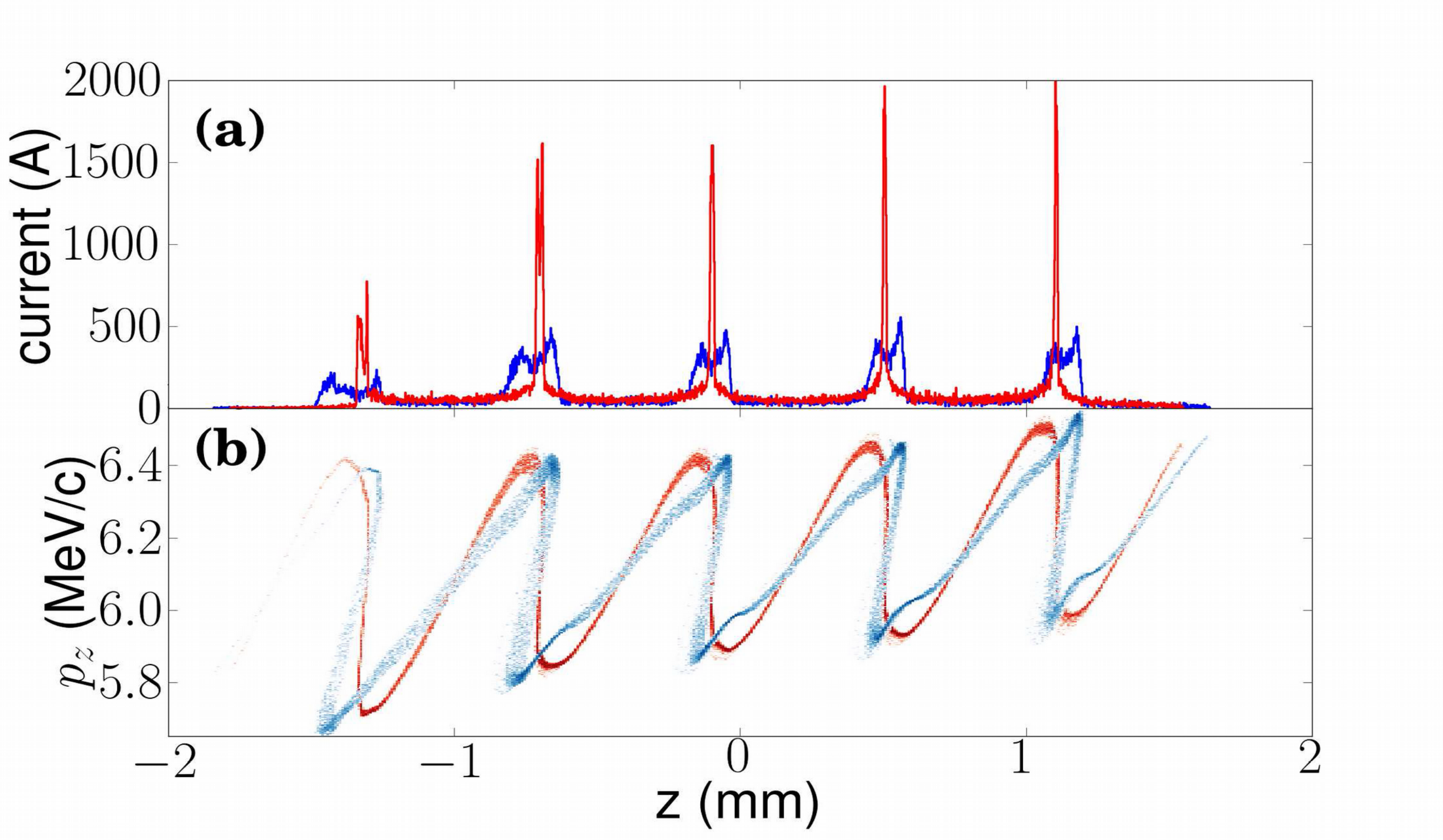




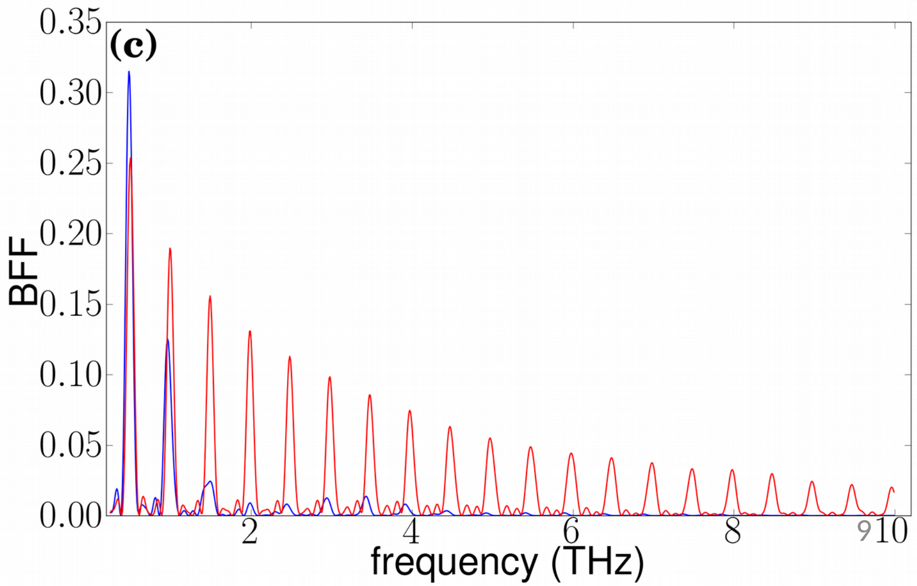
1THz Continued..

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

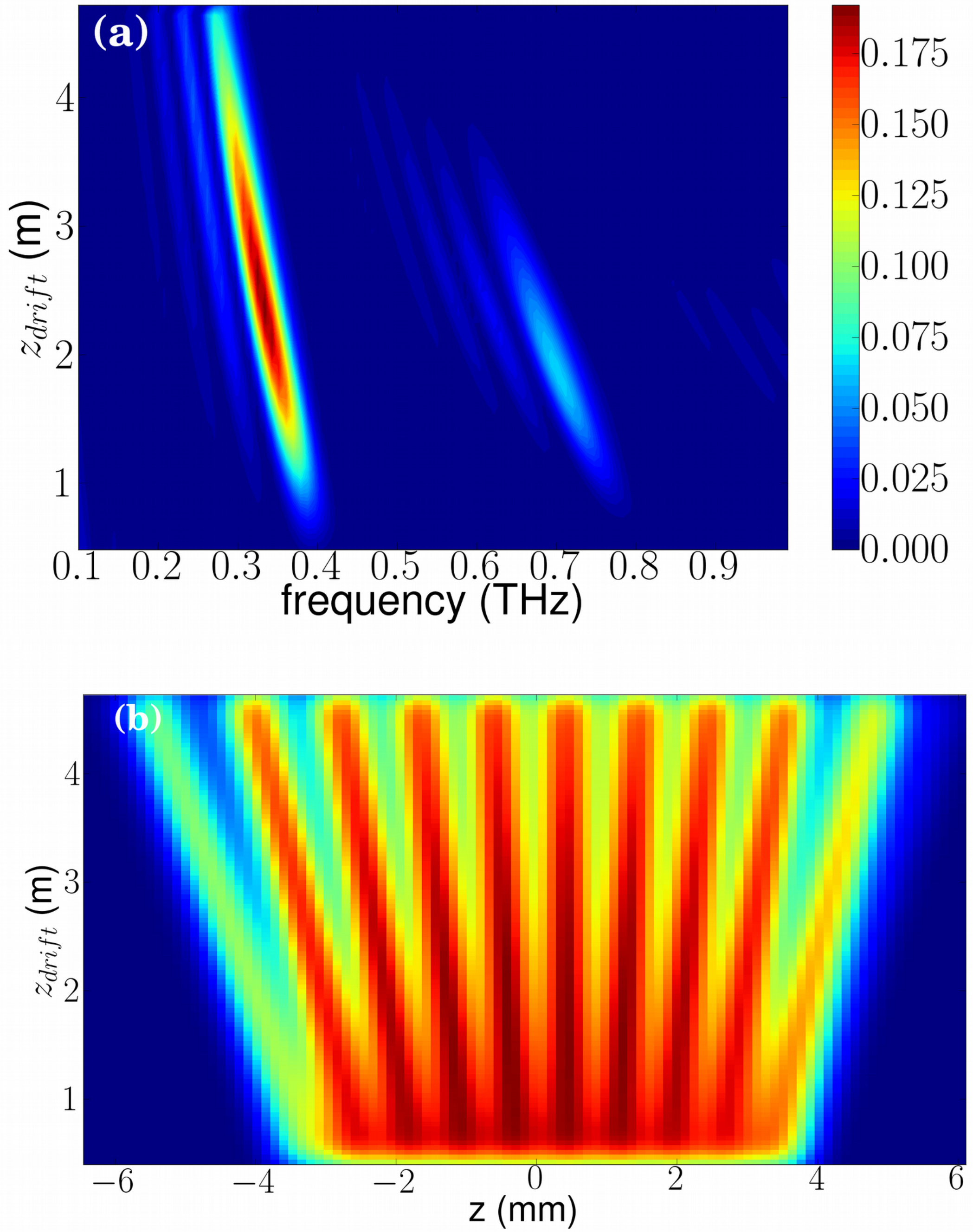


- Large harmonic content at maximum compression.
- Higher mode suppression by under/over compressing the bunches.



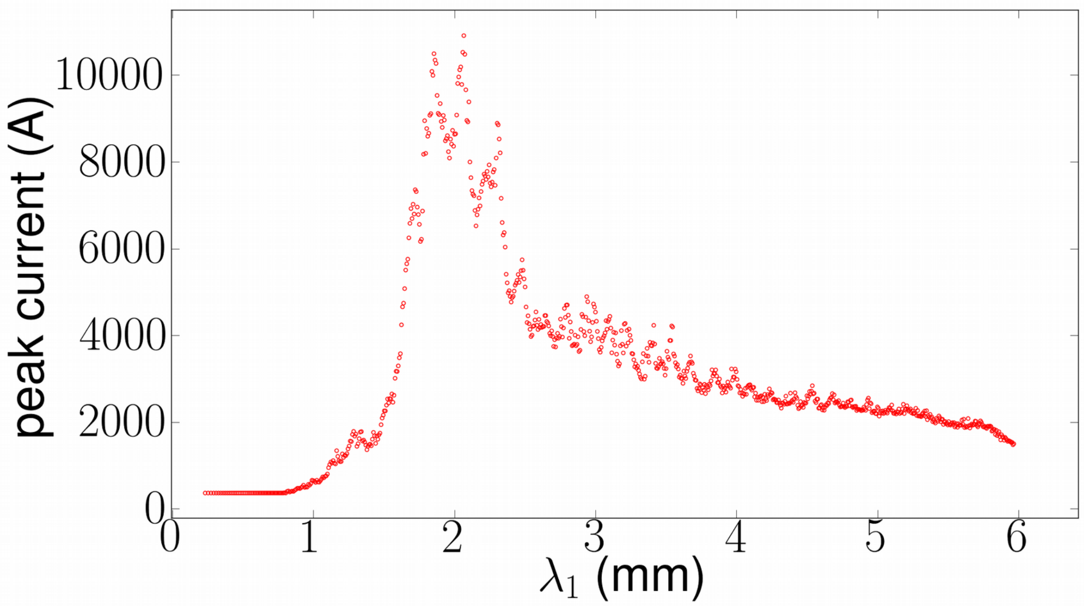
L-Band case study

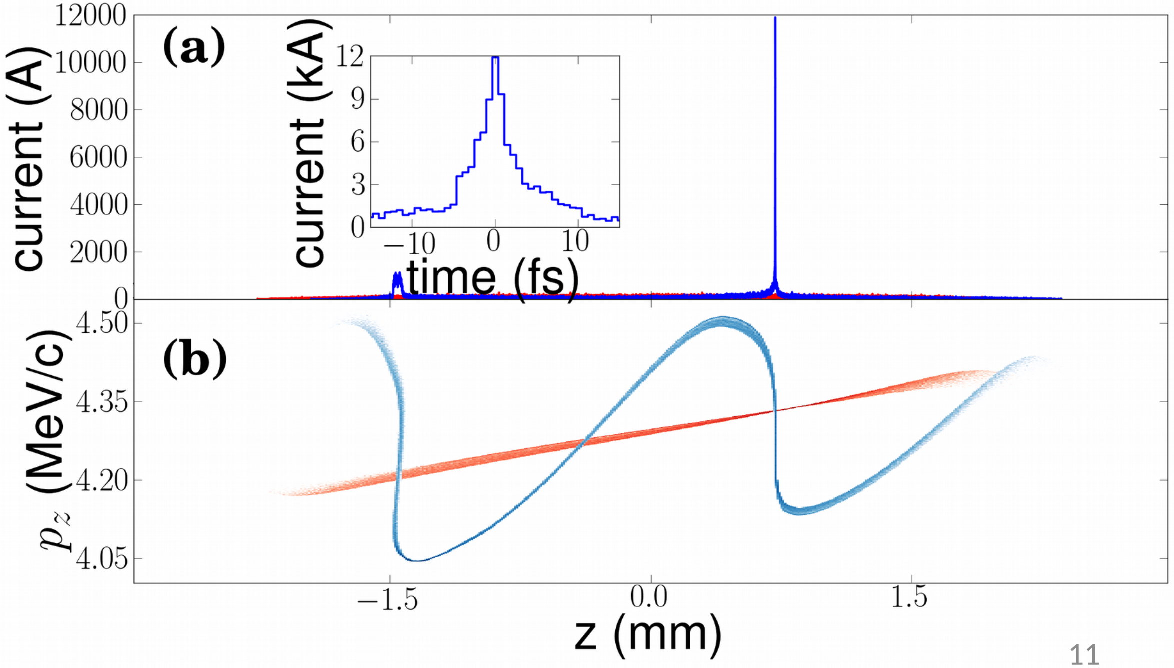
- Larger emittance
  - Larger structures
  - Lower frequencies
- Lower energy
  - Shorter bunching length for same energy modulation
  - More space charge effects



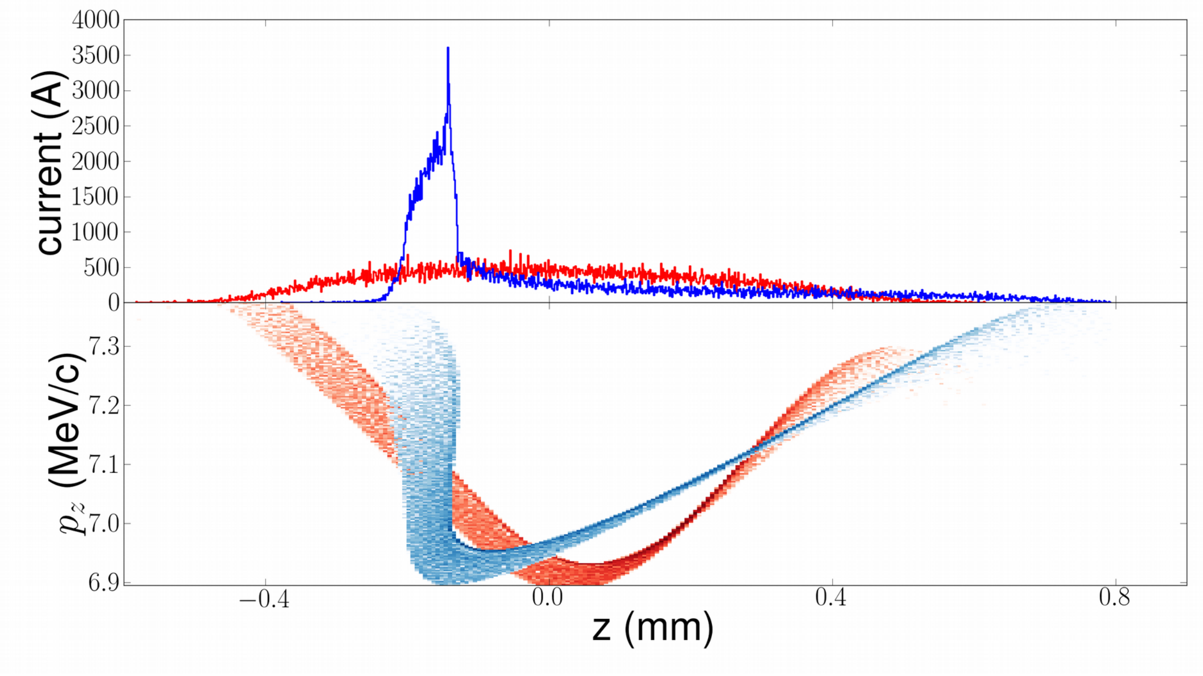
Passive Compressor

- 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

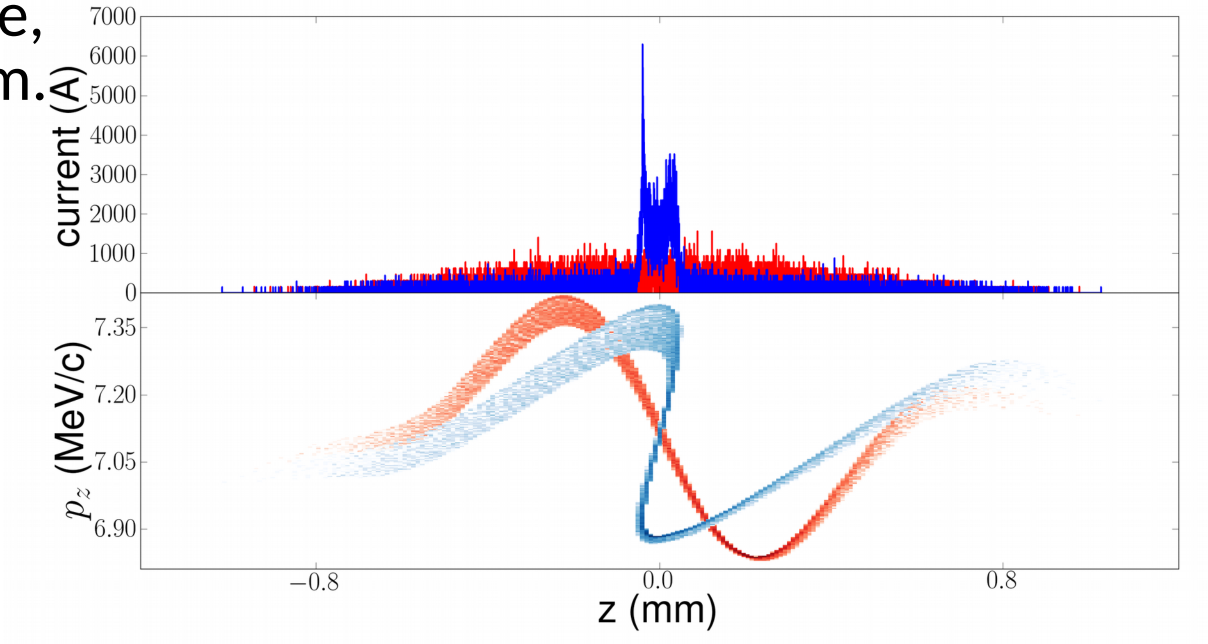




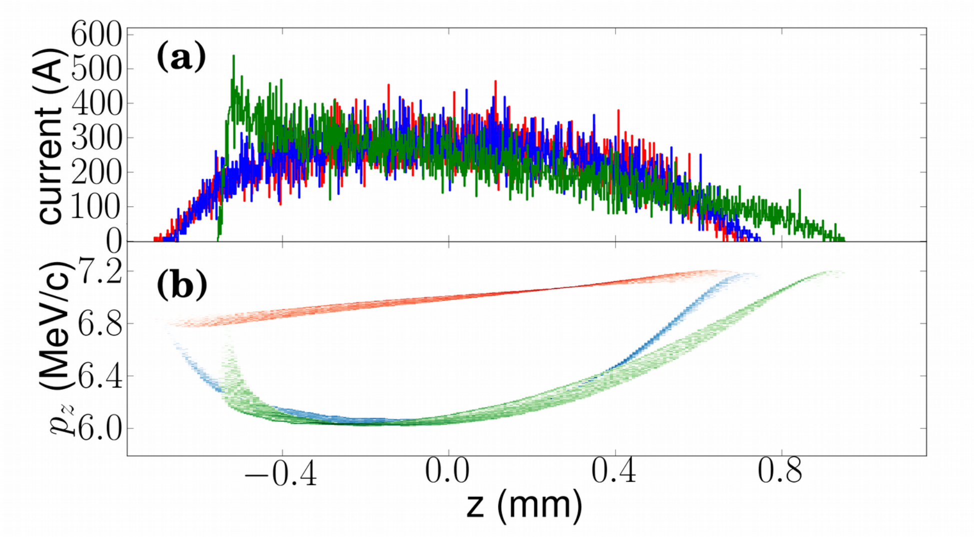
Passive Compressor for beam-driven applications

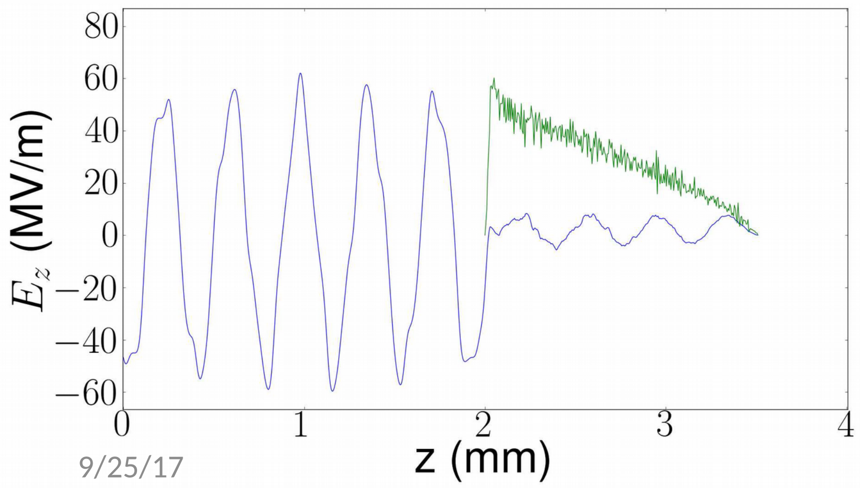


- Bunch larger portion of the bunch (50%)
- Extremely scalable: higher charge→ longer bunches→ larger structures.
- Details: Red trace: immediately after structure, blue trace 1.2 m (1.13 m bottom) downstream.
- (a, b, e, L) = (1 mm, 1.05 mm, 5.7, 5 cm) corresponding to λ0 = 1.948 mm



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)

PRL 118, 054802 (2017) PHYSICAL REVIEW LETTERS week ending 3 FEBRUARY 2017

Generation of Ramped Current Profiles in Relativistic Electron Beams Using Wakefields in Dielectric Structures

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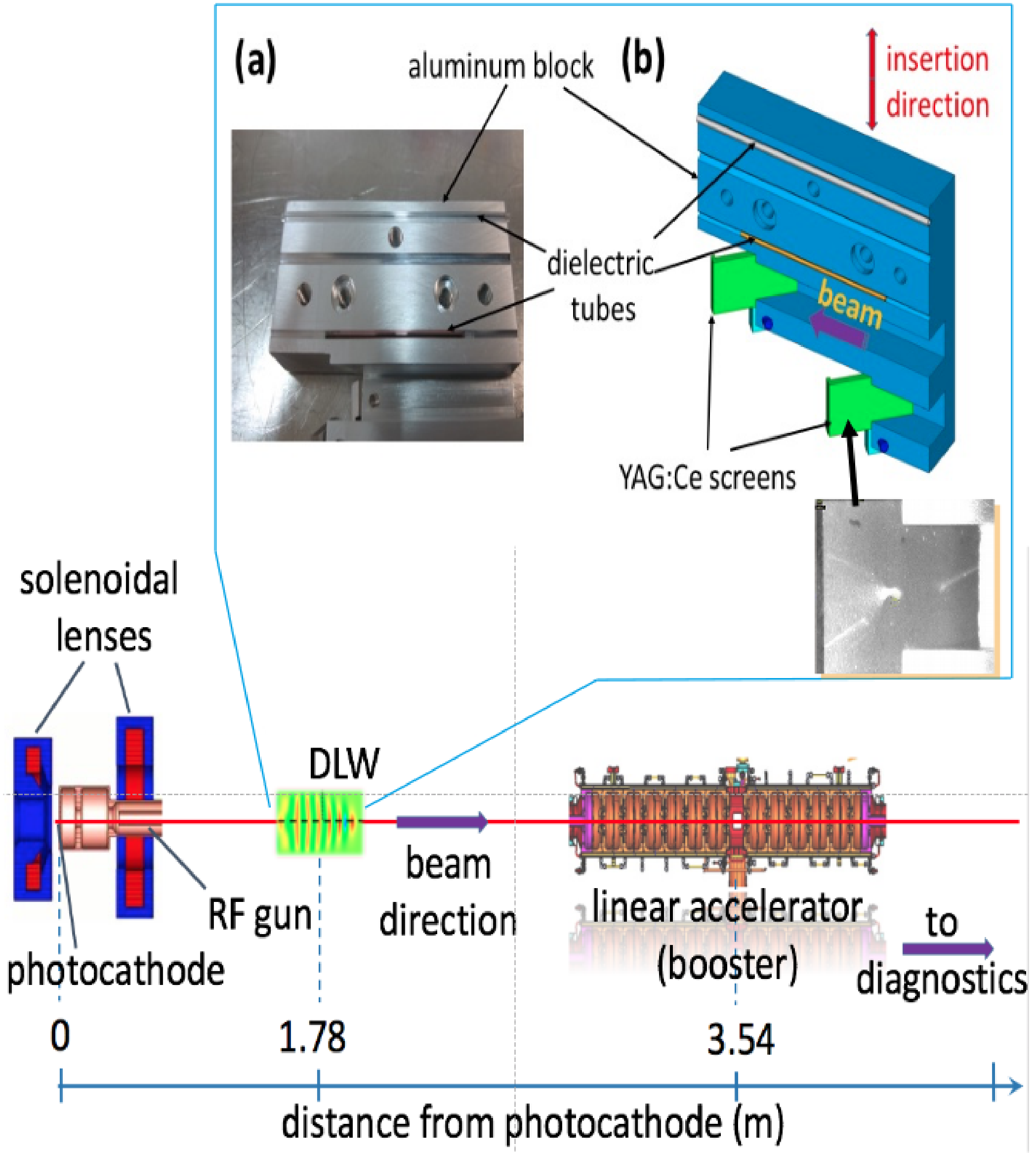
Temporal pulse tailoring of charged-particle beams is essential to optimize efficiency in collinear wakefield acceleration schemes. In this Letter, we demonstrate a novel phase space manipulation method that employs a beam wakefield interaction in a dielectric structure, followed by bunch compression in a permanent magnet chicane, to longitudinally tailor the pulse shape of an electron beam. This compact, passive, approach was used to generate a nearly linearly ramped current profile in a relativistic electron beam experiment carried out at the Brookhaven National Laboratory Accelerator Test Facility. Here, we report on these experimental results including beam and wakefield diagnostics and pulse profile reconstruction techniques.

Experiment at PITZ

> Setup allowed for precise beam alignment and transmission through DLWs:
  - DLWs holder equipped with YAG:Ce screens
  - Gun quad system improved beam symmetry and enabled full transmission
  - Two steerers between gun and DLW.
  - PITZ' flat-top pulses improved results significantly.



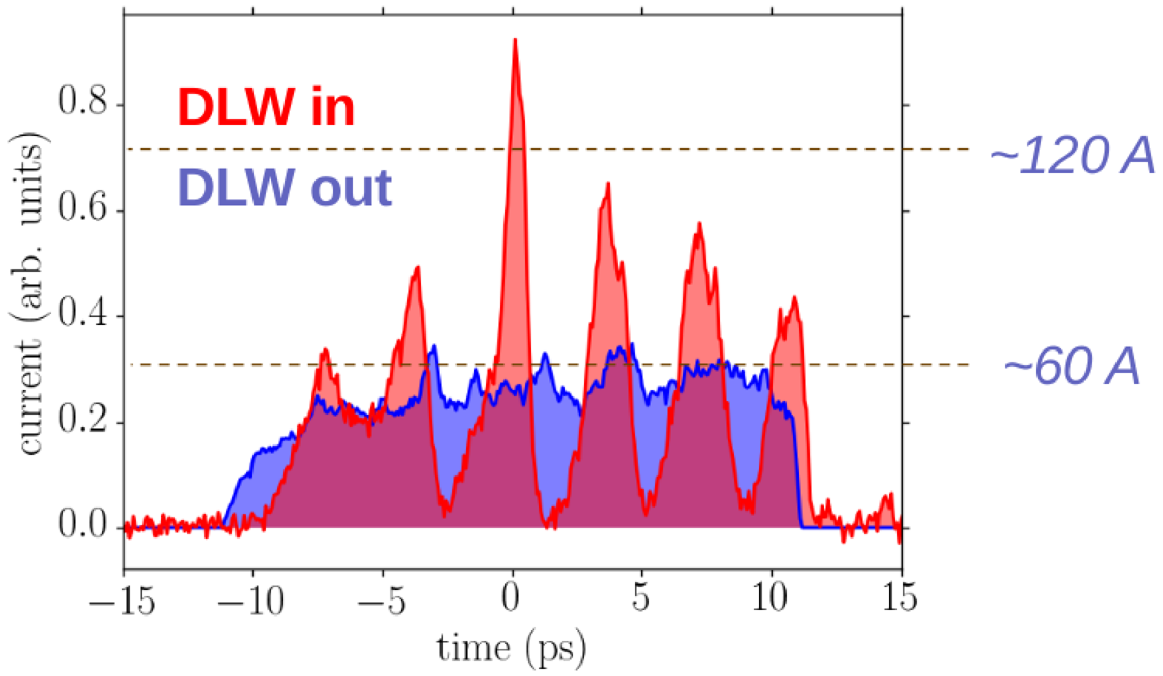
- Coated DLW ($\lambda = 1.03\ mm$)

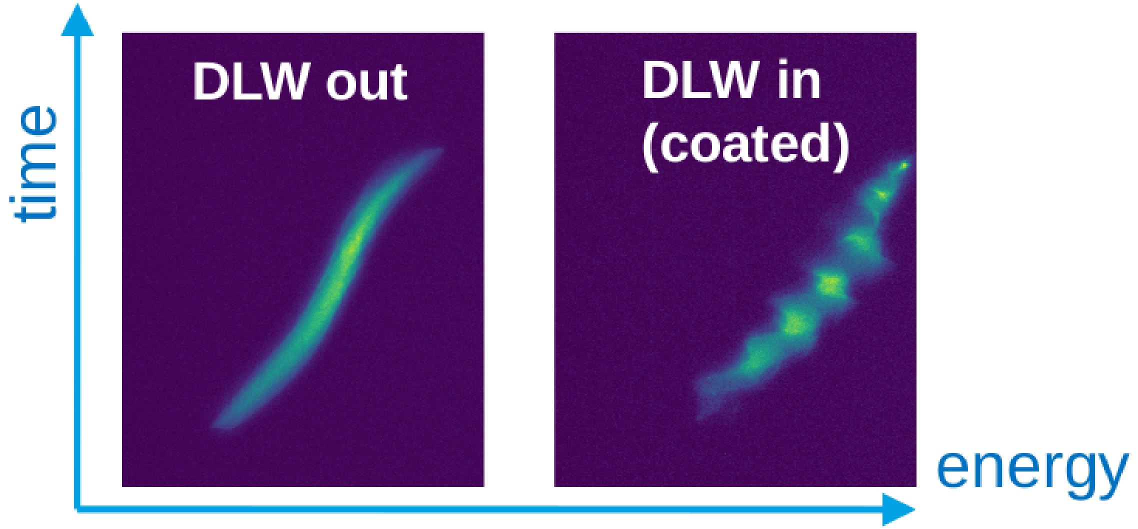
  $(a, b, L, \epsilon_r) = (450\ \mu m, 550\ \mu m, 5\ cm, 4.41)$
- Uncoated DLW ($\lambda = 1.60\ mm$)

  $(a, b, L, \epsilon_r) = (750\ \mu m, 900\ \mu m, 8\ cm, 4.41)$

Experiment at PITZ

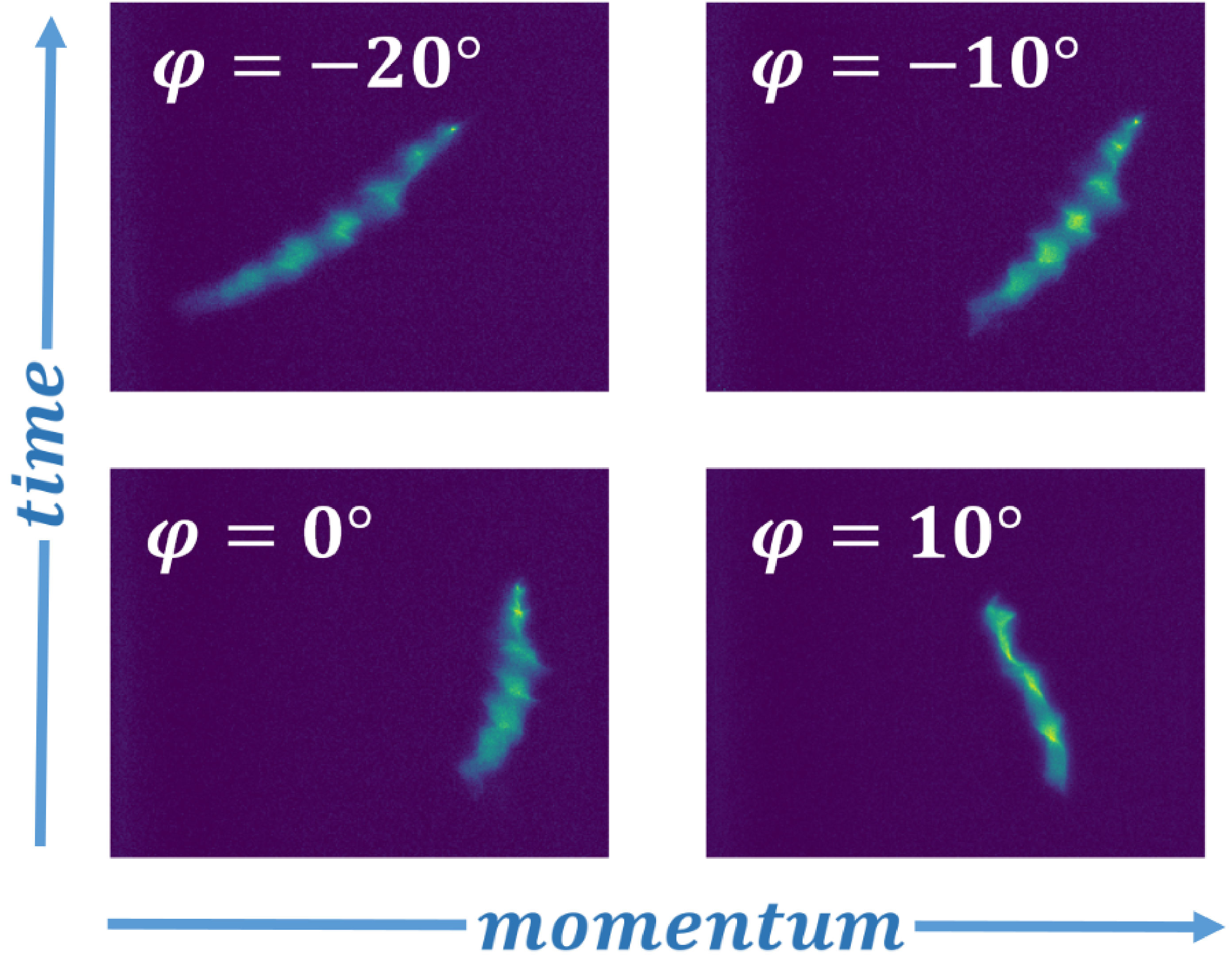
- Demonstrated the formation of ~ps bunch trains at ~6 MeV with resolution limited peak currents up to **~150 A**
- Directly measured the longitudinal phase space downstream of the DLW structure
- Passed a bunch train with up to 200 bunches per pulse through the structure and monitored energy modulations
- no dynamical effects observed.





Control of longitudinal phase space

- Booster phase provides a knob to control the longitudinal phase space correlation
- Possible applications as:
  - an injector for multicolor radiation source (e.g. FEL)
  - Time resolved ultrafast electron diffraction (UED) single-shot!



Grazie per l'attenzione!