



# Ballistic Bunching Experiment at PITZ

François Lemery, Philippe Piot and PITZ team

# DLW overview

- 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.

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

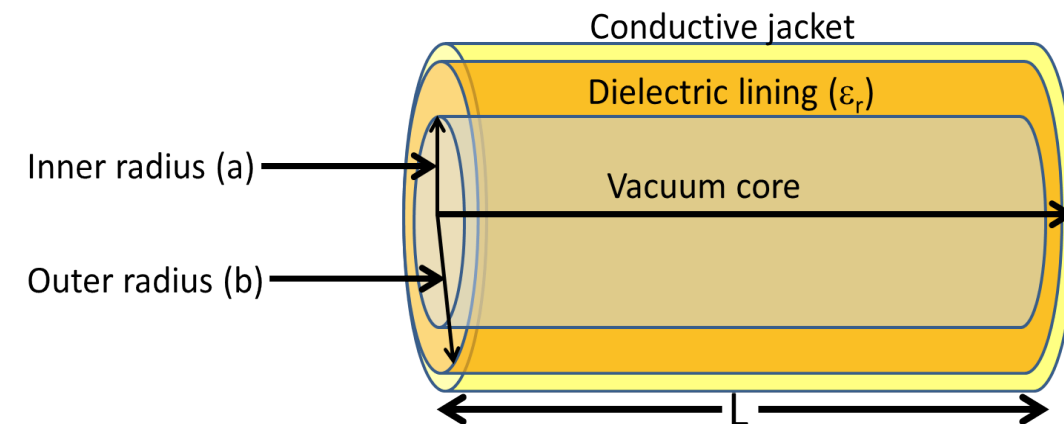
$$k_2 = \omega \sqrt{\frac{\epsilon_r}{c^2} - \frac{1}{v_p^2}}$$

$$k_z = \frac{\omega}{v}$$

$$E_z = \begin{cases} B_1 J_0(k_1 r) e^{i(\omega t - k_z z)} & 0 \leq r < a \\ B_2 F_{00}(k_2 r) e^{i(\omega t - k_z z)} & a \leq r \leq b \end{cases}$$

$$E_r = \begin{cases} \frac{-ik_z}{k_1} B_1 J'_0(k_1 r) e^{i(\omega t - k_z z)} & 0 \leq r < a \\ \frac{-ik_z}{k_2} B_2 F'_{00}(k_2 r) e^{i(\omega t - k_z z)} & a \leq r \leq b \end{cases}$$

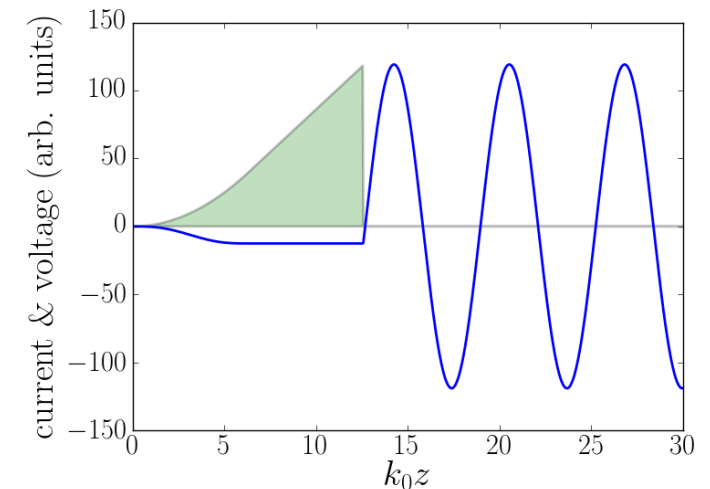
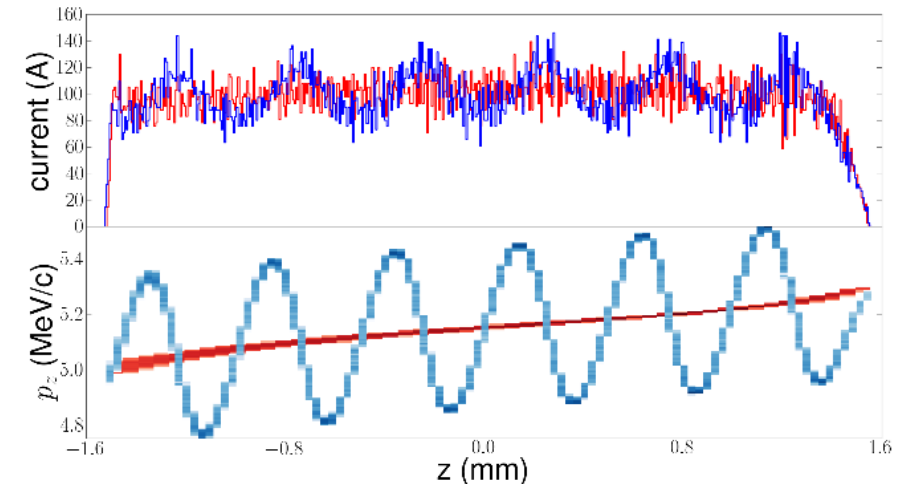
$$H_\phi = \begin{cases} \frac{-i\omega\epsilon_0}{k_1} B_1 J'_0(k_1 r) e^{i(\omega t - k_z z)} & 0 \leq r < a \\ \frac{-i\omega\epsilon_r\epsilon_0}{k_2} B_2 F'_{00}(k_2 r) e^{i(\omega t - k_z z)} & a \leq r \leq b \end{cases}$$



# Beam-driven Wakefields

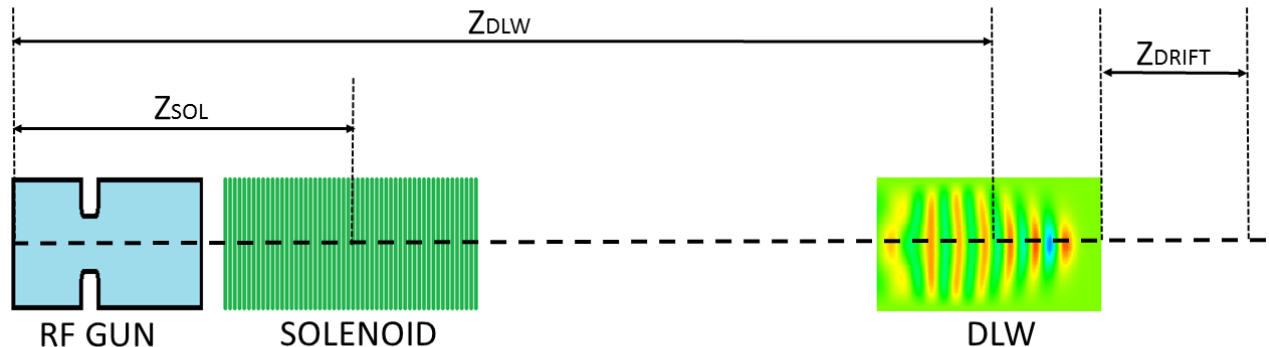
- Charged particles can excite modes in DLWs.
- Assuming an on-axis electron bunch, the excited TM (accelerating mode) can be calculated with the convolution of the current profile with the Green's function of the structure.
- The spectral content of the electron bunch determines the mode coupling and i.e. wakefield amplitude to a particular mode.

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



# Self-Wake Interactions at Low Energy

- Photo-Injector Source:
  - $\sim 100$  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...)
  - Emittance at  $\mu\text{m}$ -level. Brightness effectively determines the
- Ballistic bunching, shaping+



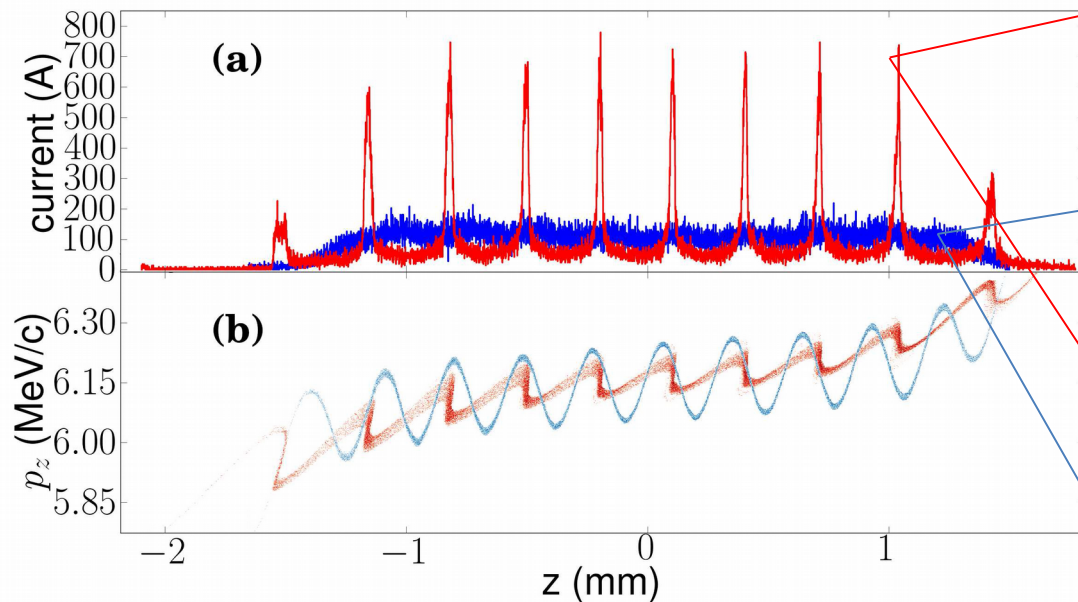
$$R_{56} \simeq -\frac{D}{\gamma^2}$$



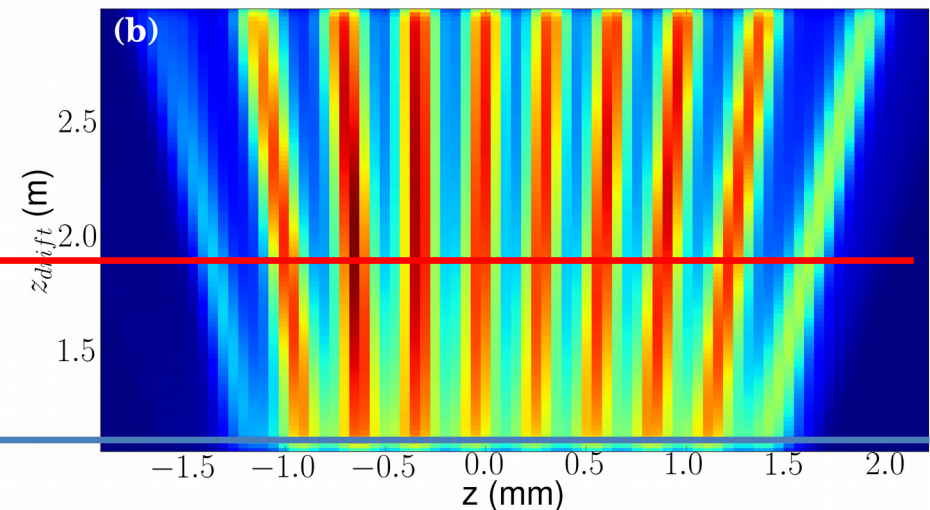
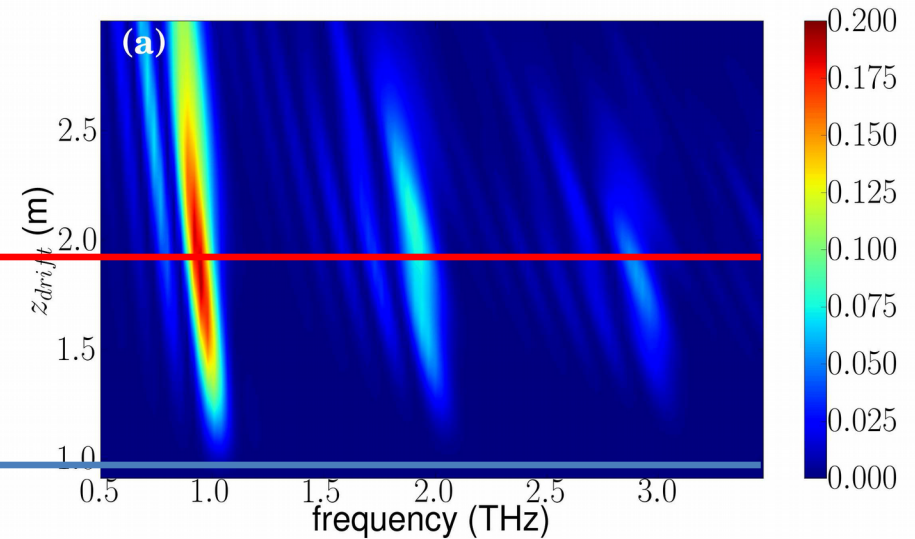


# Density modulation at 1 THz

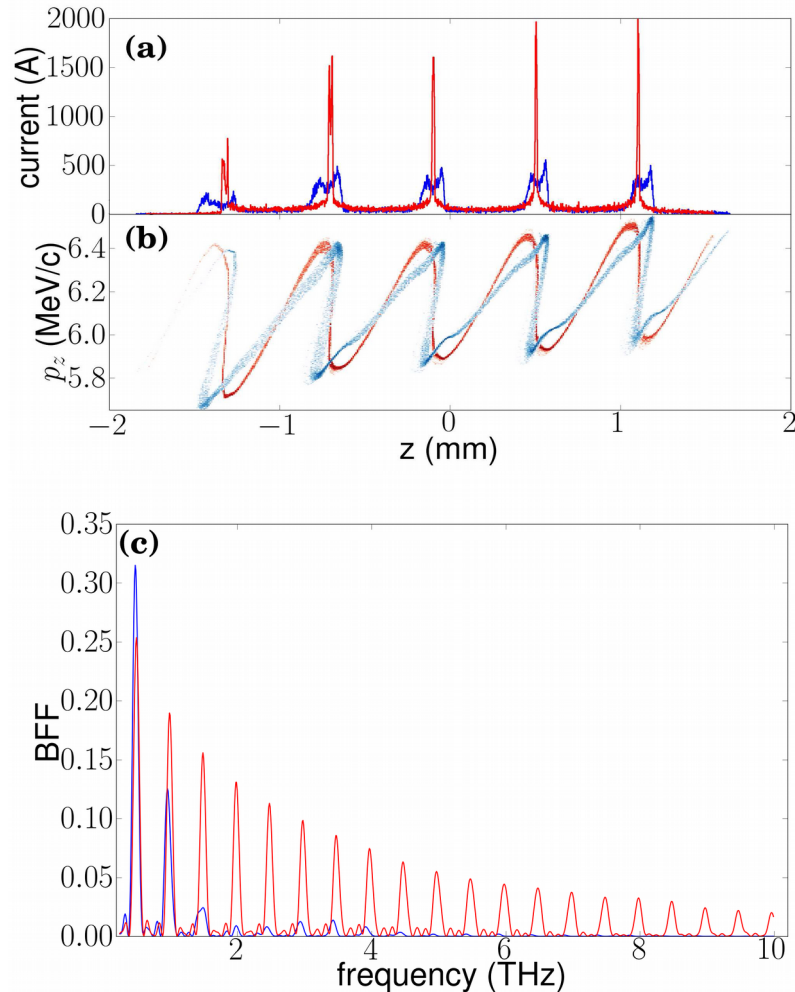
- S-Band Gun
- DLW parameters ( $a$ ,  $b$ ,  $\epsilon$ ,  $L$ ) = (350  $\mu\text{m}$ , 363  $\mu\text{m}$ , 5.7, 11 cm)



*F. Lemery and P. Piot, PRST 17, 112804 (2014).*



# 500 GHz DLW – (350 $\mu\text{m}$ , 393 $\mu\text{m}$ , 5.7)



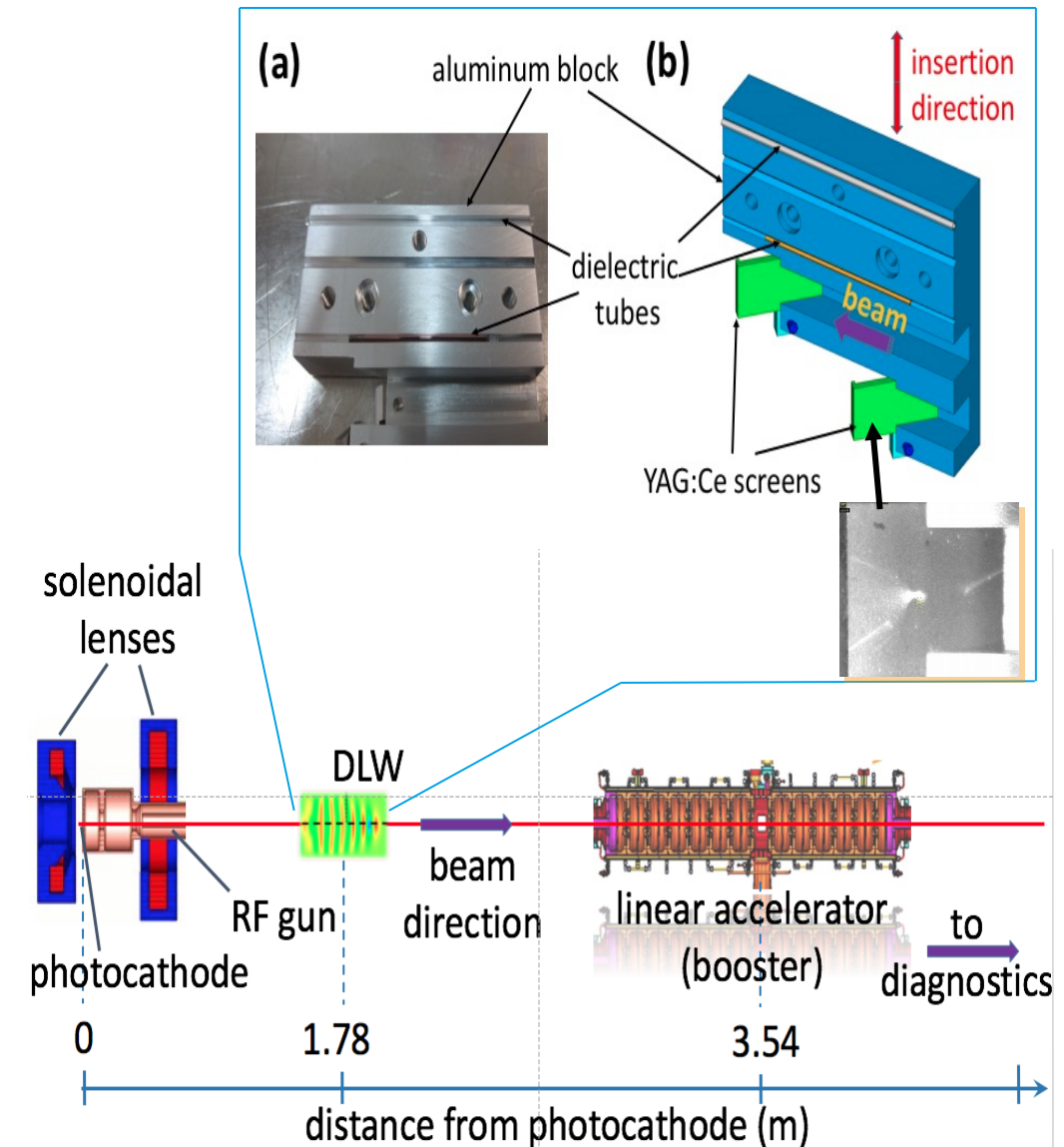
- Much larger wakes for lower frequency- from spectral content of the beam.
- Large harmonic content at maximum compression.
- Higher mode suppression by under/over compressing the bunches.

# Experiment at PITZ

> Setup allowed for precise beam alignment and transmission through DLWs:

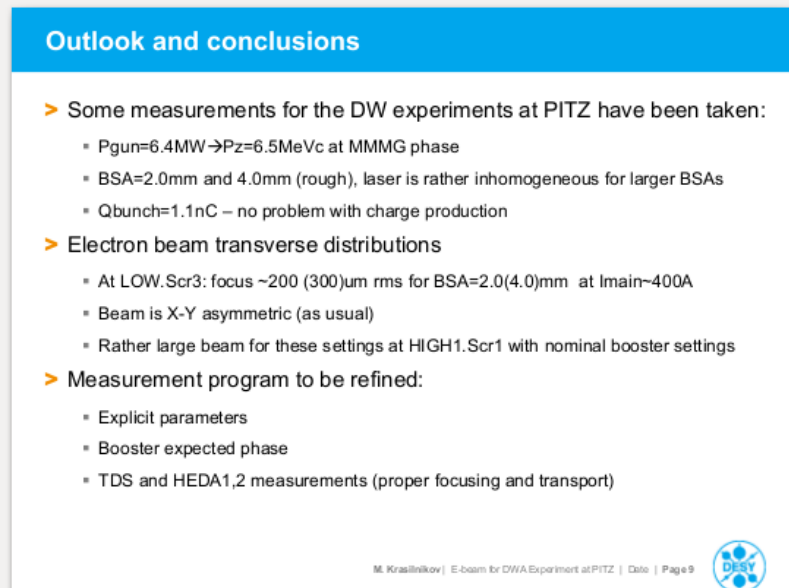
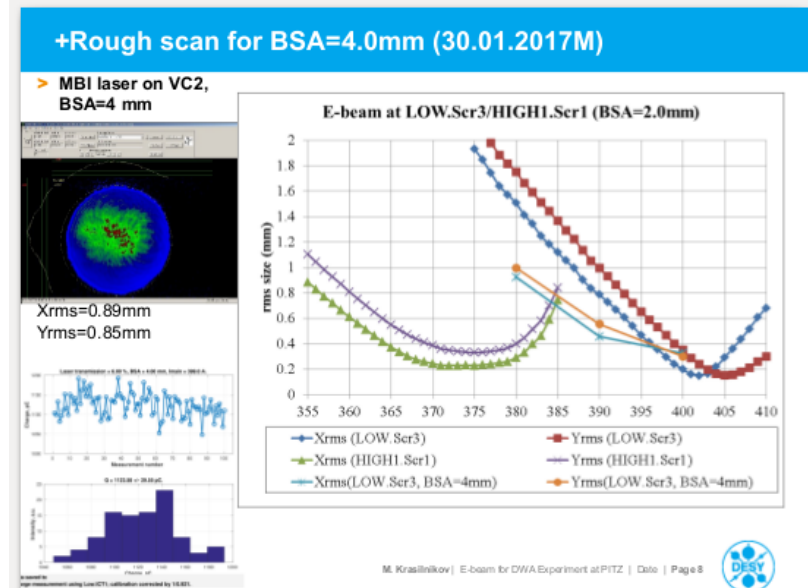
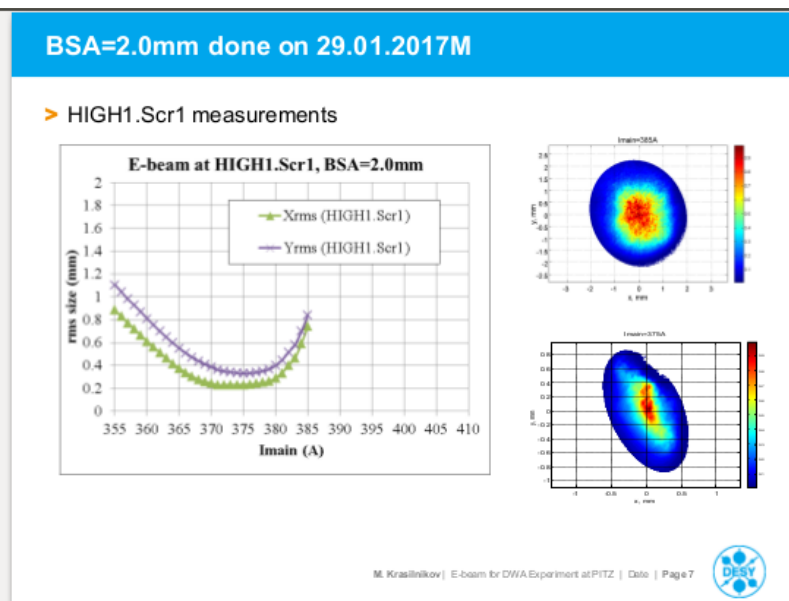
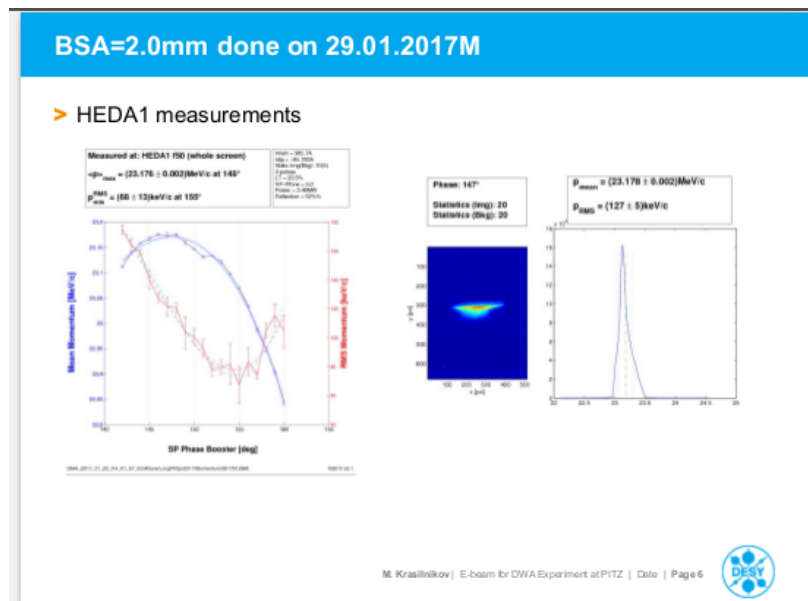
- DLWs holder equipped with YAG:Ce screens
- Gun quad system improved beam symmetry and enabled full transmission
- Two steerers between gun and DLW.
- PITZ' flat-top pulses improved results significantly.

- Coated DLW ( $\lambda = 1.03 \text{ mm}$ )  
 $(a, b, L, \epsilon_r) = (450 \text{ }\mu\text{m}, 550 \text{ }\mu\text{m}, 5 \text{ cm}, 4.41)$
- Uncoated DLW ( $\lambda = 1.60 \text{ mm}$ )  
 $(a, b, L, \epsilon_r) = (750 \text{ }\mu\text{m}, 900 \text{ }\mu\text{m}, 8 \text{ cm}, 4.41)$



# Experiment at PITZ

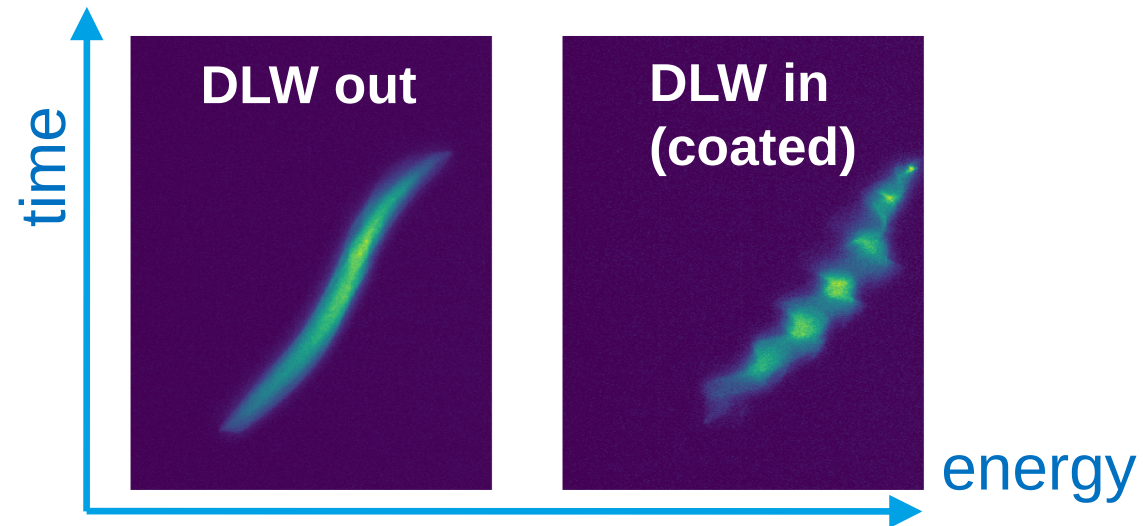
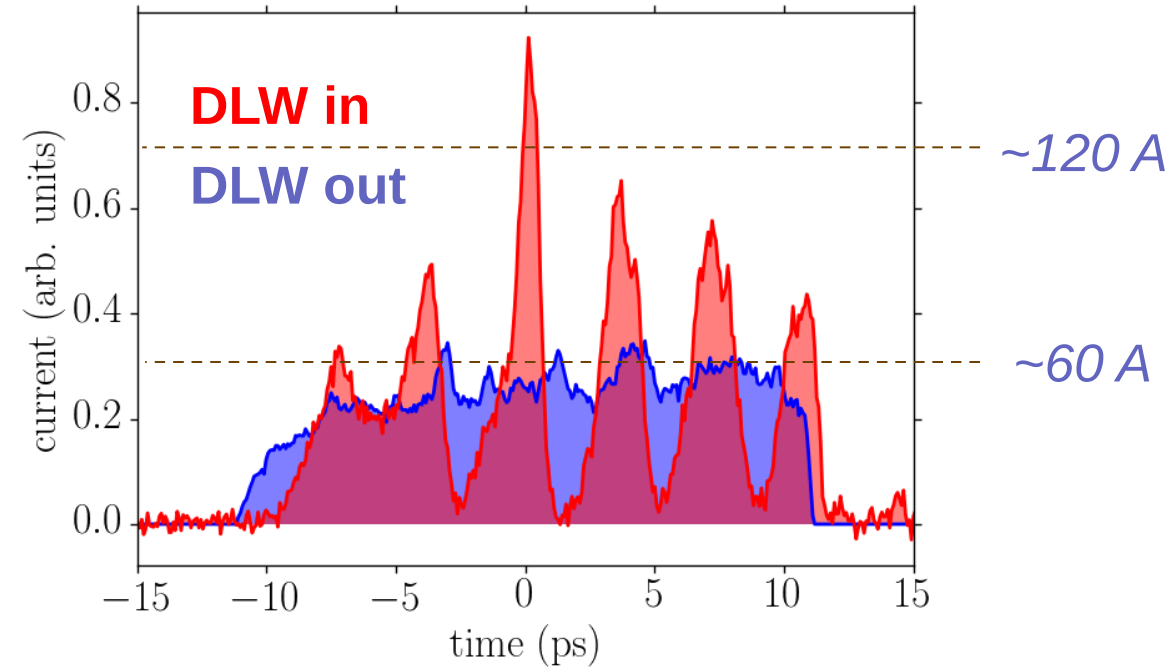
- Excellent machine preparation before experimental run.
- Characterized the beam at Low.Scr3 well in advance.
- Engineering support was fantastic, simple DLW mount was placed in actuator holder.





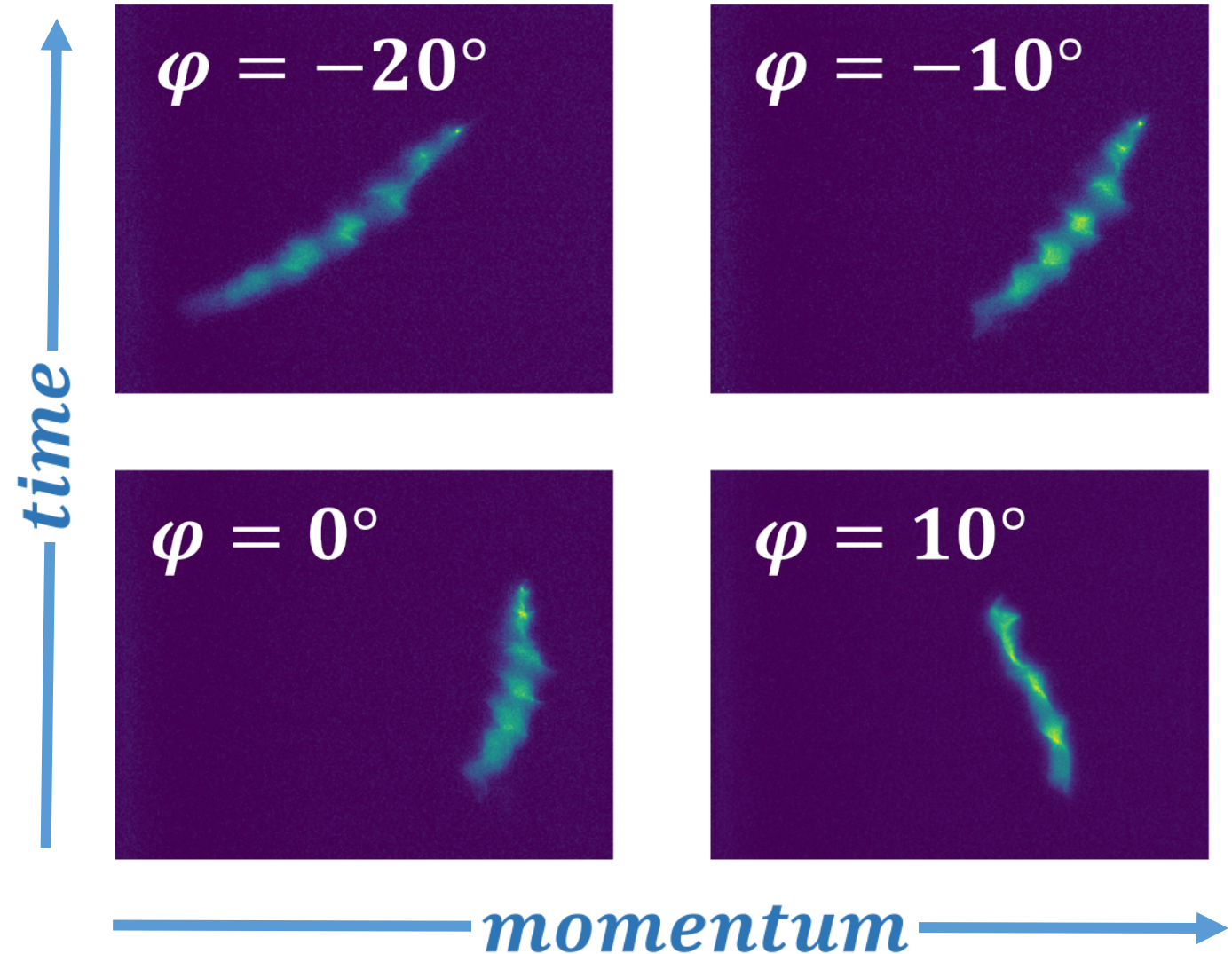
# Experiment at PITZ

- > Demonstrated the formation of  $\sim$ ps bunch trains at  $\sim$ 6 MeV with resolution limited peak currents up to  **$\sim 150$  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.



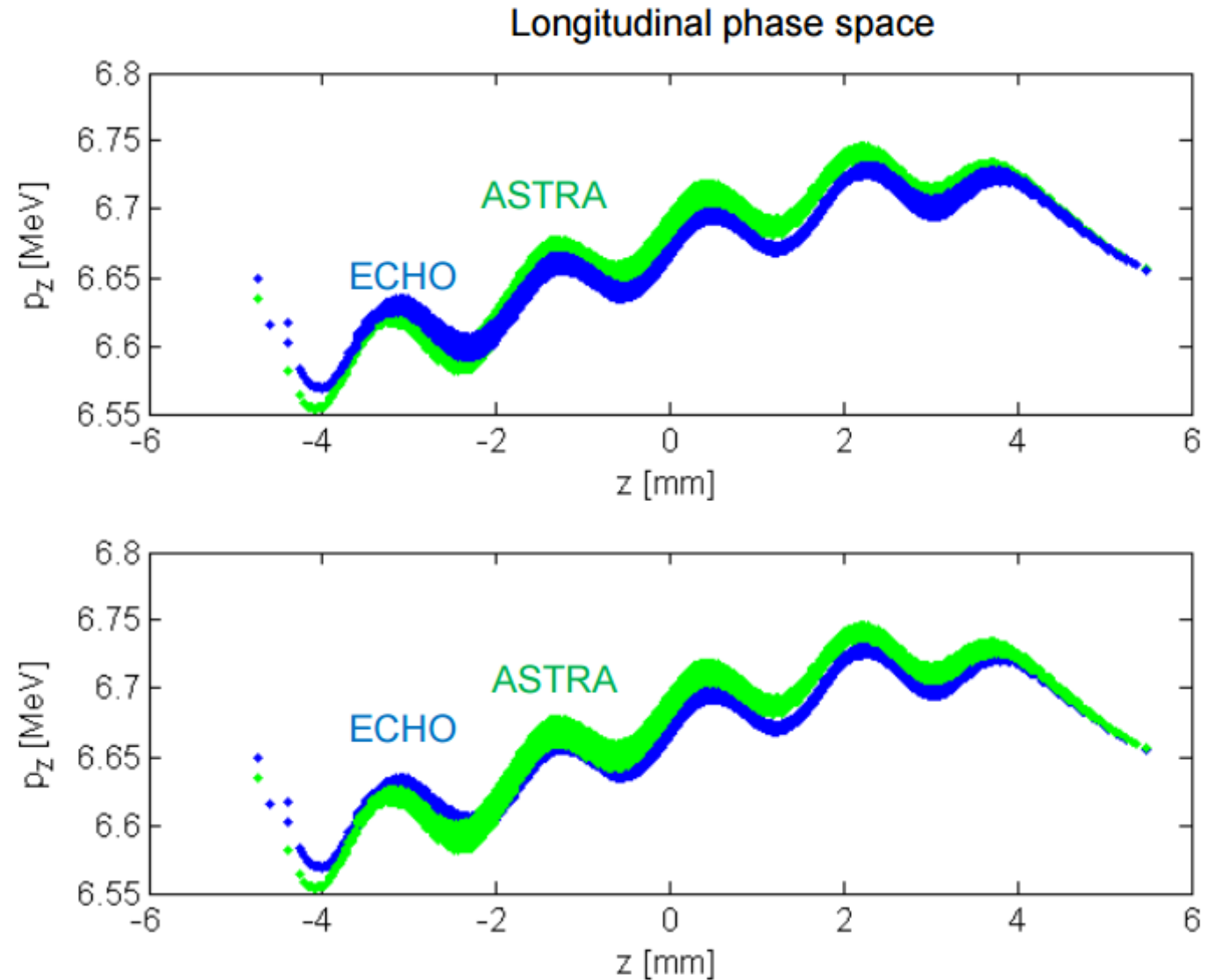
# Control of longitudinal phase space

- 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!



# Test 4. Full simulation of dielectric insert.

Comparison with  
ASTRA by Igor  
Zagorodnov

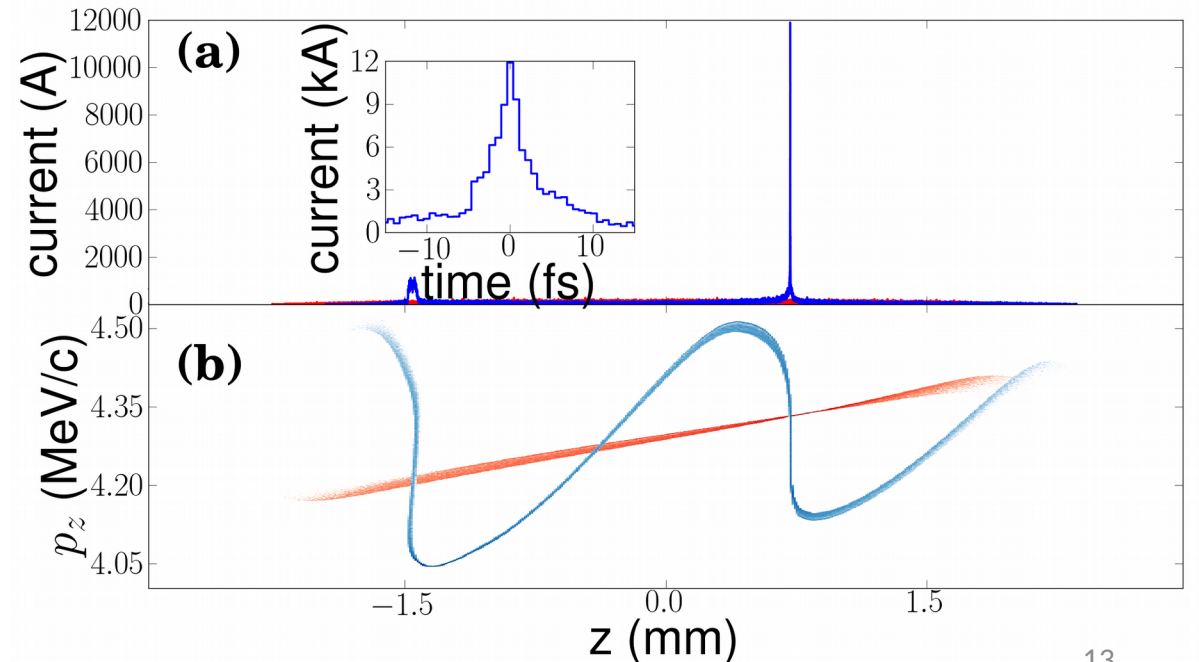
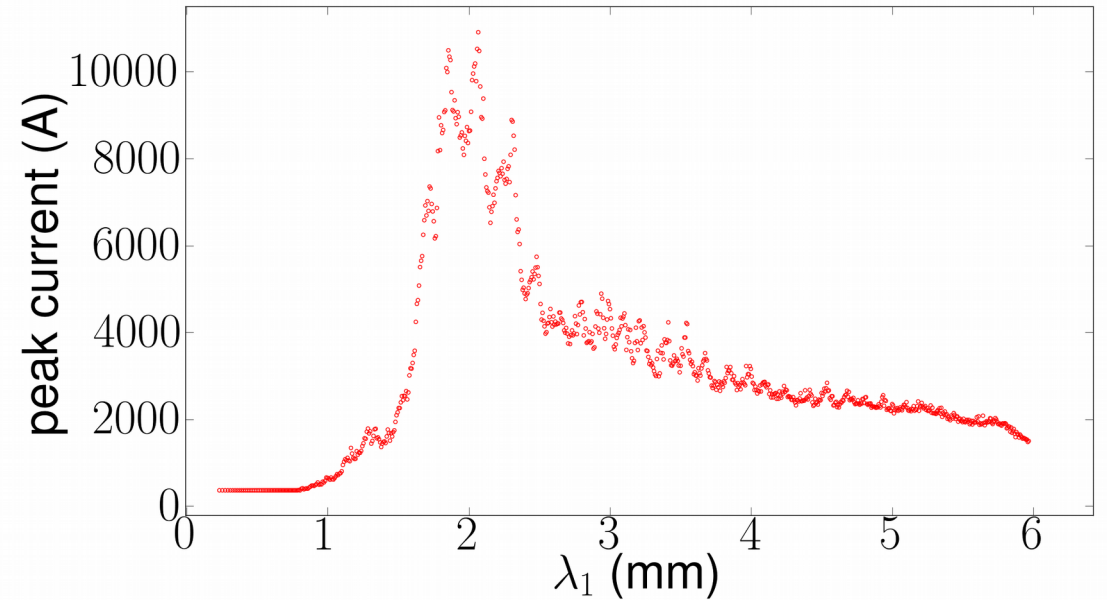


Future DLW possibilities at PITZ



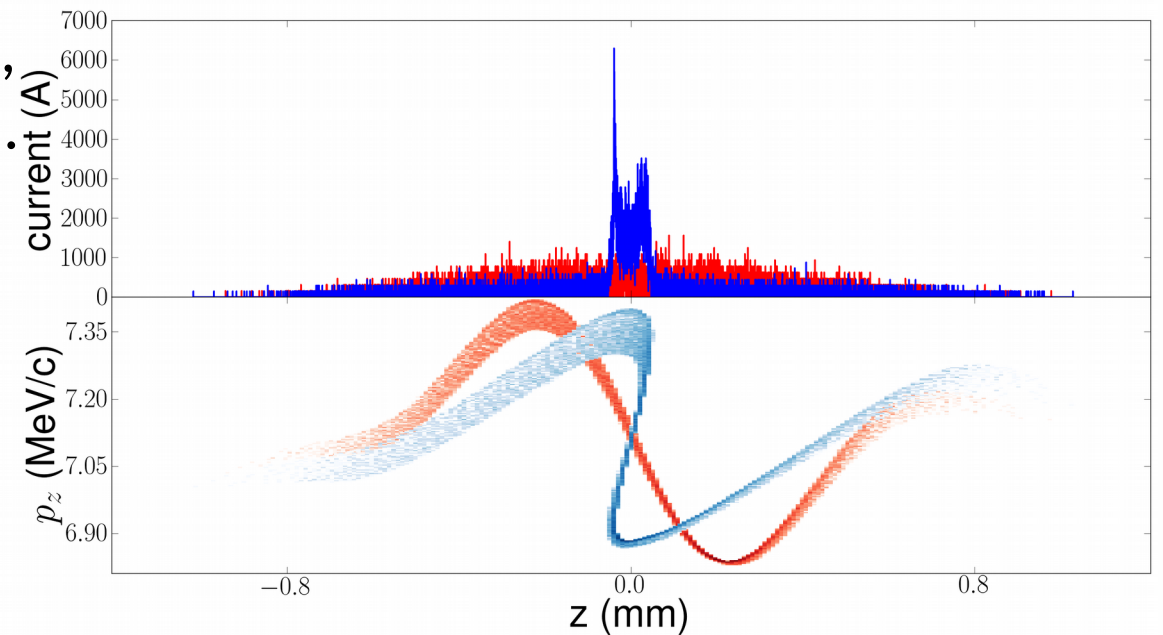
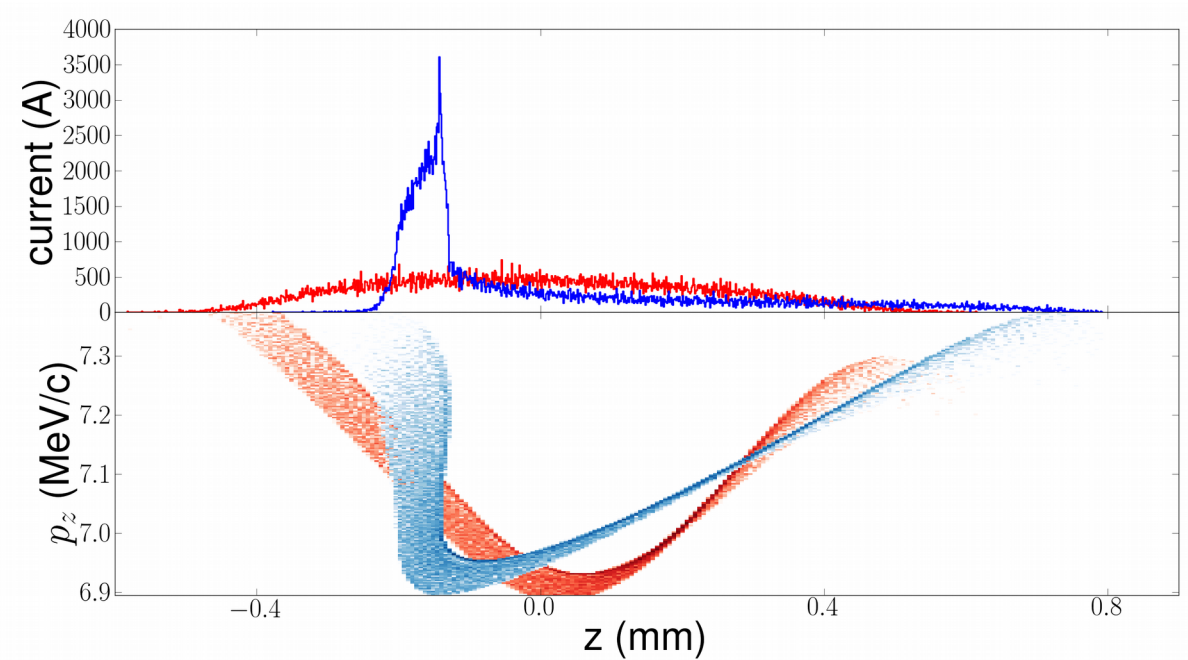
# Passive Compressor

- $L \sim \lambda$  – 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  $\sim 12$  kA (7.1%).
- Scalable for higher charge / large structures  $a=650 \mu\text{m}$



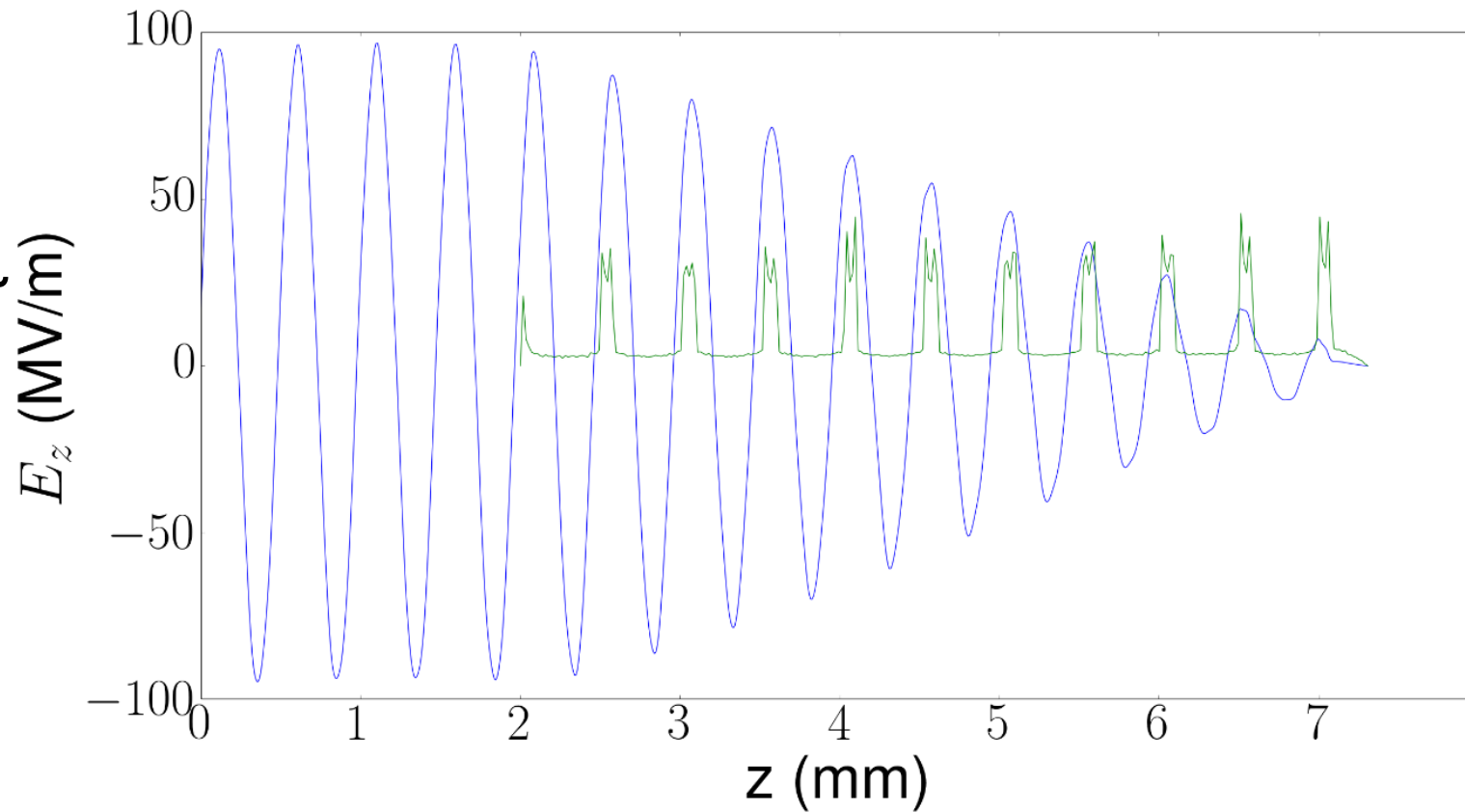
# Passive Compressor for beam-driven applications

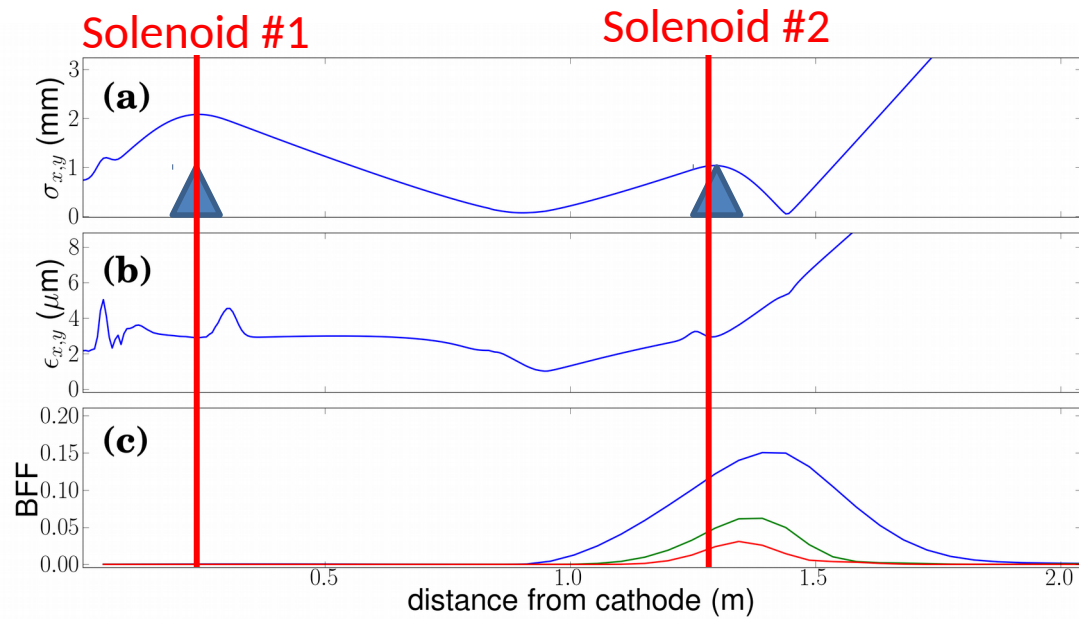
- Bunch larger portion of the bunch (50%)
- Extremely scalable: higher charge  $\rightarrow$  longer bunches  $\rightarrow$  larger structures.
- Details: Red trace: immediately after structure, blue trace 1.2 m (1.13 m bottom) downstream.
- $(a, b, e, L) = (1 \text{ mm}, 1.05 \text{ mm}, 5.7, 5 \text{ cm})$  corresponding to  $\lambda_0 = 1.948 \text{ mm}$



# THZ RADIATION

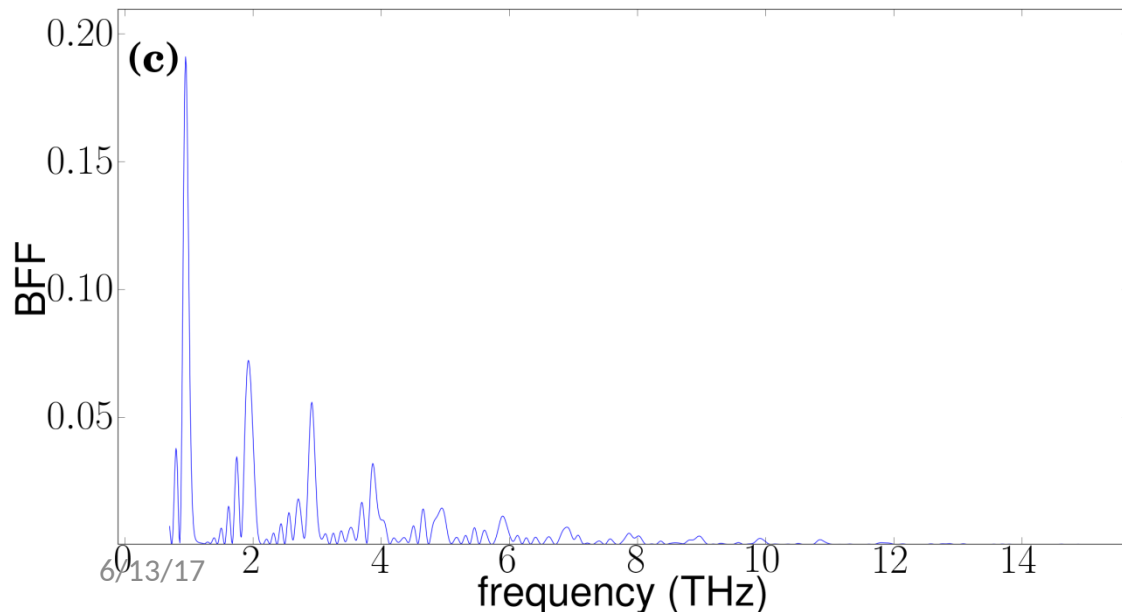
- Microbunched beams have excellent bunch form factors  $\sim 0.3$ - therefore are a good candidates to generate CEP stable THz radiation.
- Radiation extraction
  - Using two DLWs of same (or higher harmonic) frequency.
  - Or undulator.





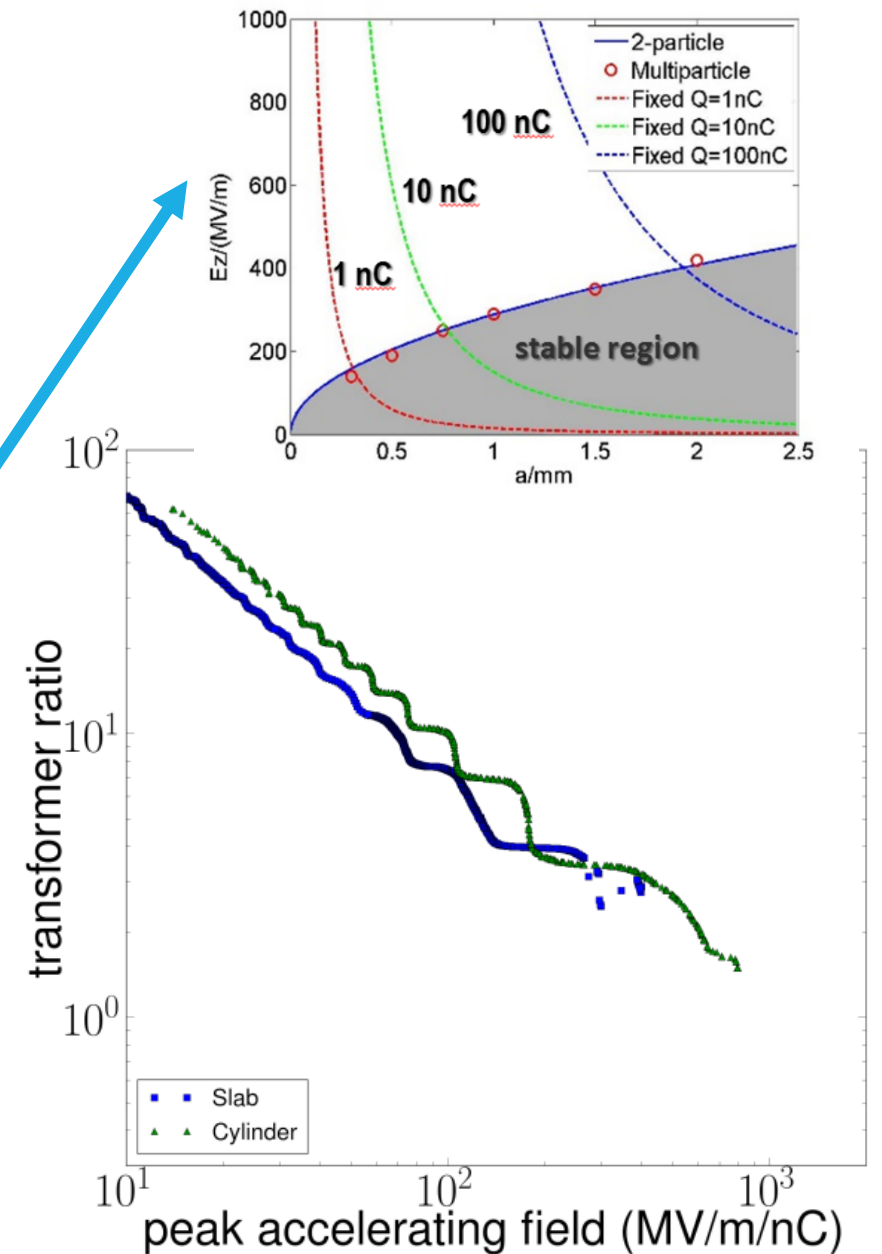
# THz Source cont.

- Previous study for THz generation shown; PITZ could use similar approach with bunched beam.
- A solenoid between the DLW and booster could help reduce the beam size for easier transmission in a structure downstream.



# 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!



# THANKS!

- Thanks to the fantastic support of the PITZ team ! Your hard work and smart minds made this experiment go very smoothly.
- Papers in preparation, intend to submit to PRL.