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.

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

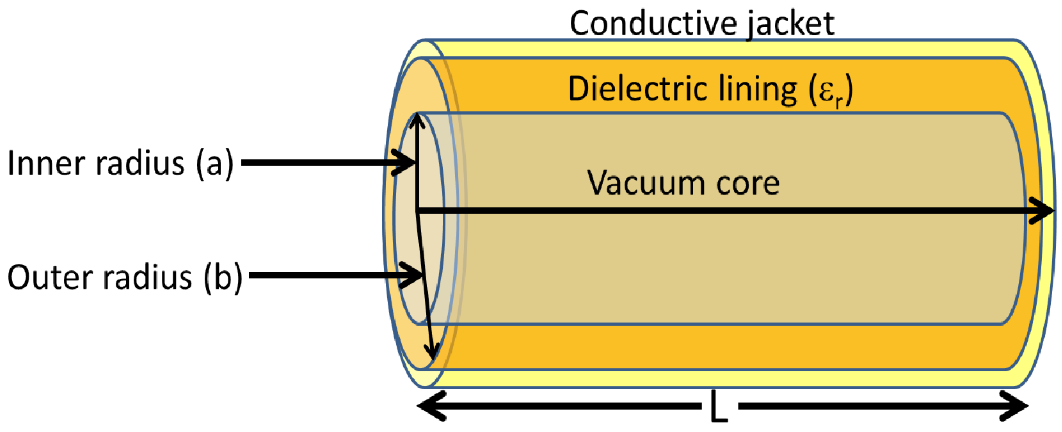
$$k_2 = \omega\sqrt{\frac{\epsilon_r}{c^2} - \frac{1}{v_p^2}}$$

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

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

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

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

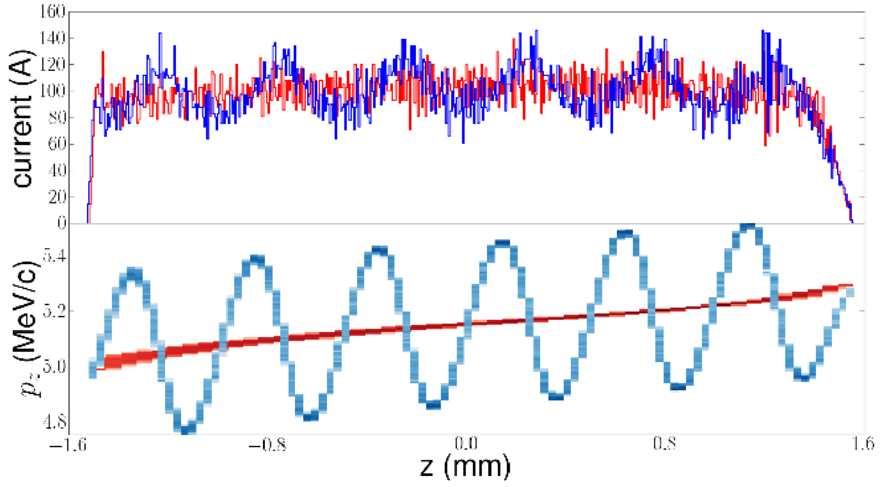


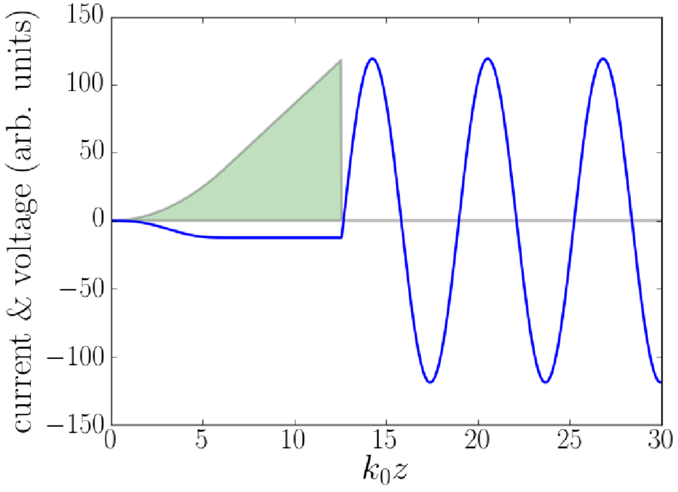
Beam-driven Wakefields

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

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

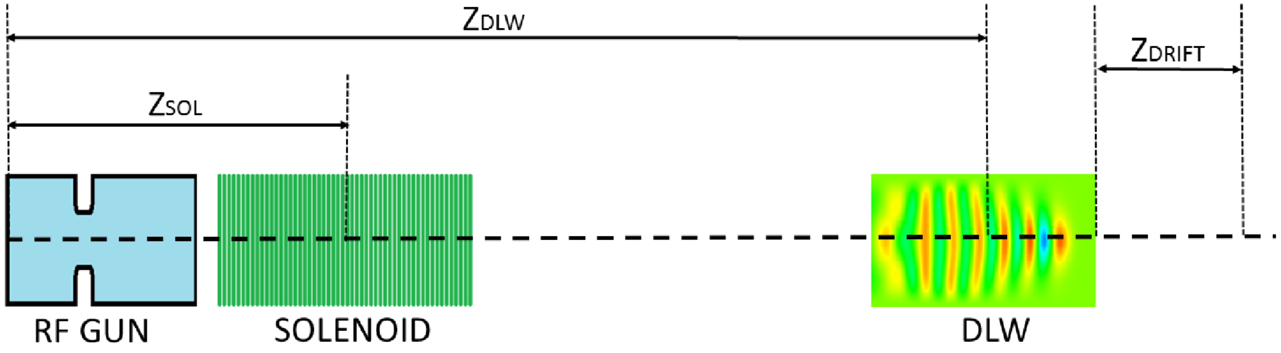
- Charged particles can excite modes in DLWs.
- Assuming an on-axis electron bunch, the excited TM (accelerating mode) can be calculated with the convolution of the current profile with the Green's function of the structure.
- The spectral content of the electron bunch determines the mode coupling and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





Self-Wake Interactions at Low Energy

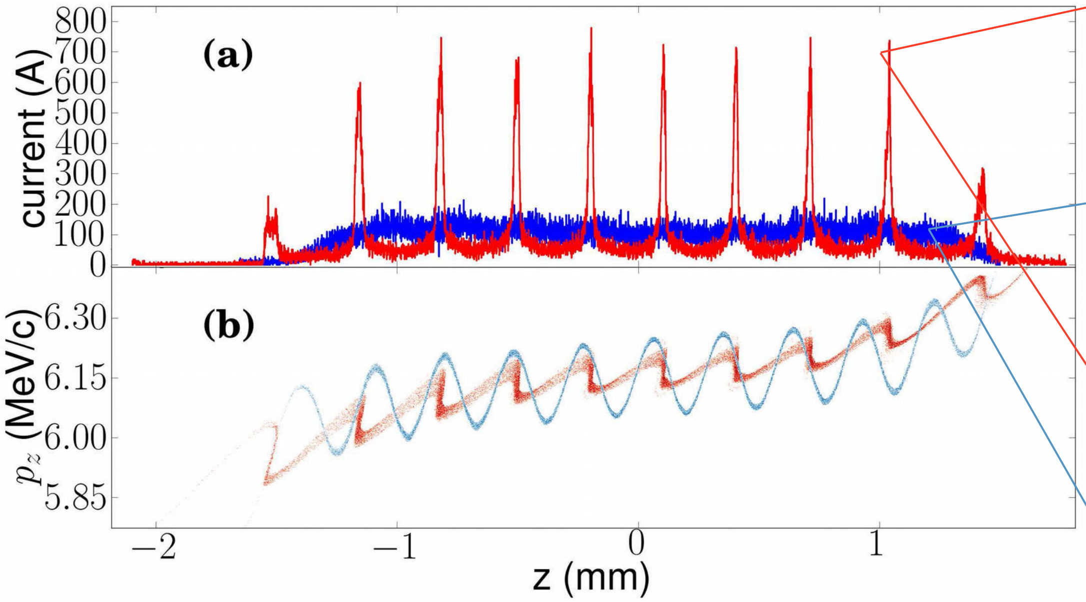
- Photo-Injector Source:
  - ~ 100 Amp currents.
  - < 10 MeV energy out of gun (L-Band(1.3GHz - 60 MV/m) vs S-Band(2.856 GHz – 140 MV/m), X…)
  - Emittance at μm-level. Brightness effectively determines the
- Ballistic bunching, shaping+



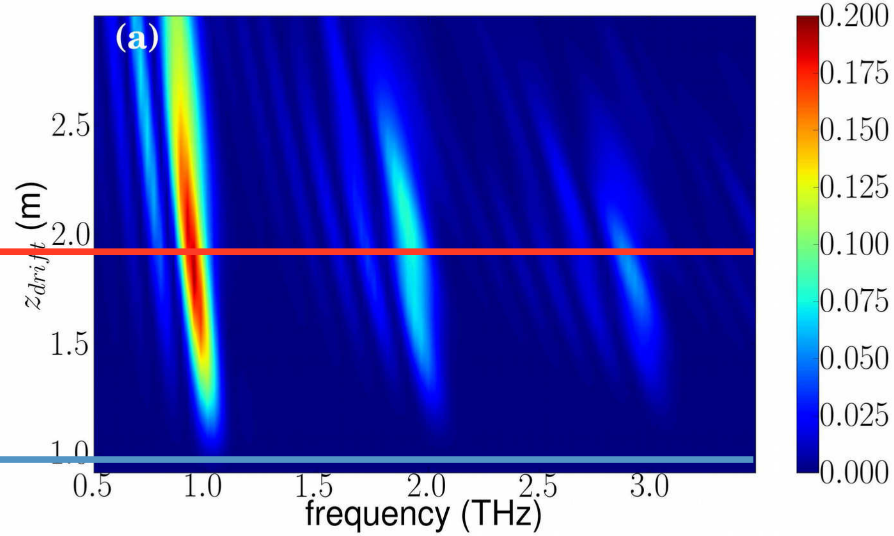
$$R_{56} \simeq -\frac{D}{\gamma^2}$$

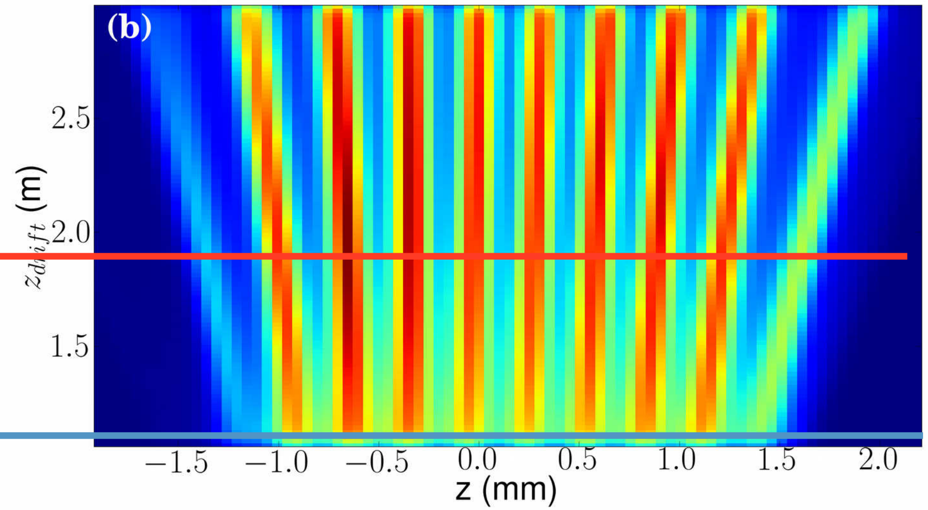
Density modulation at 1 THz

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

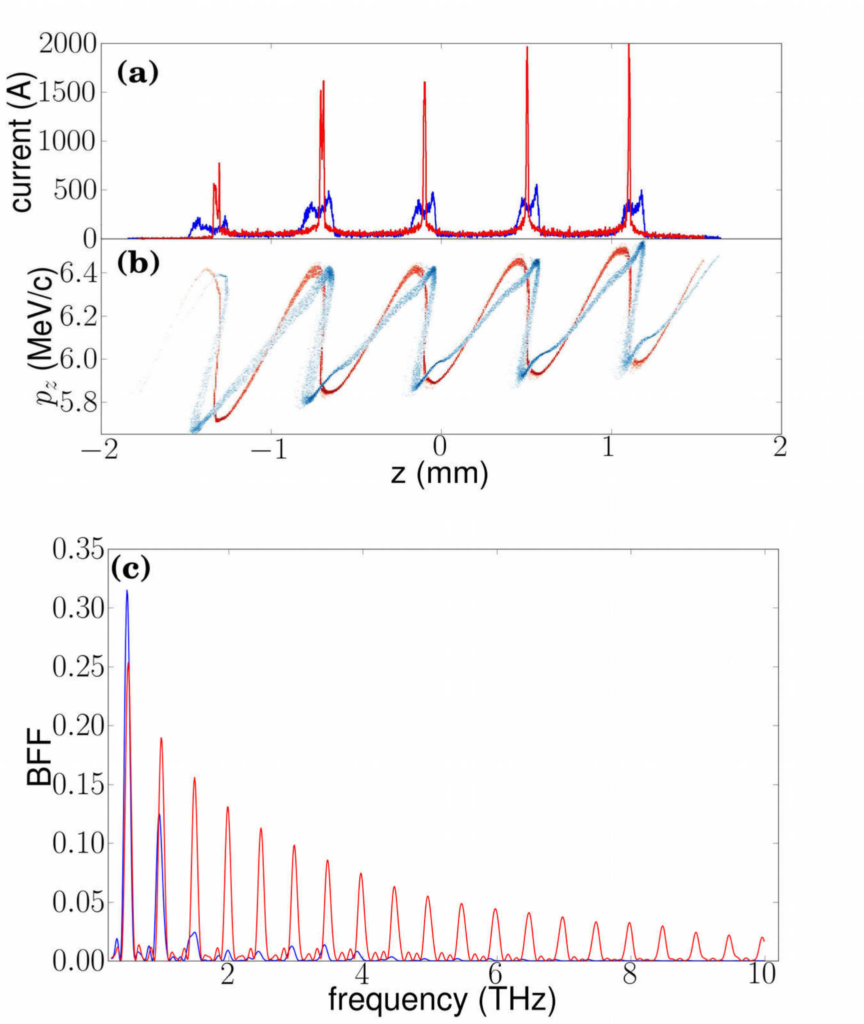


*F. Lemery and P. Piot, PRST **17,** 112804 (2014).*





500 GHz DLW – (350 μm, 393 μm, 5.7)

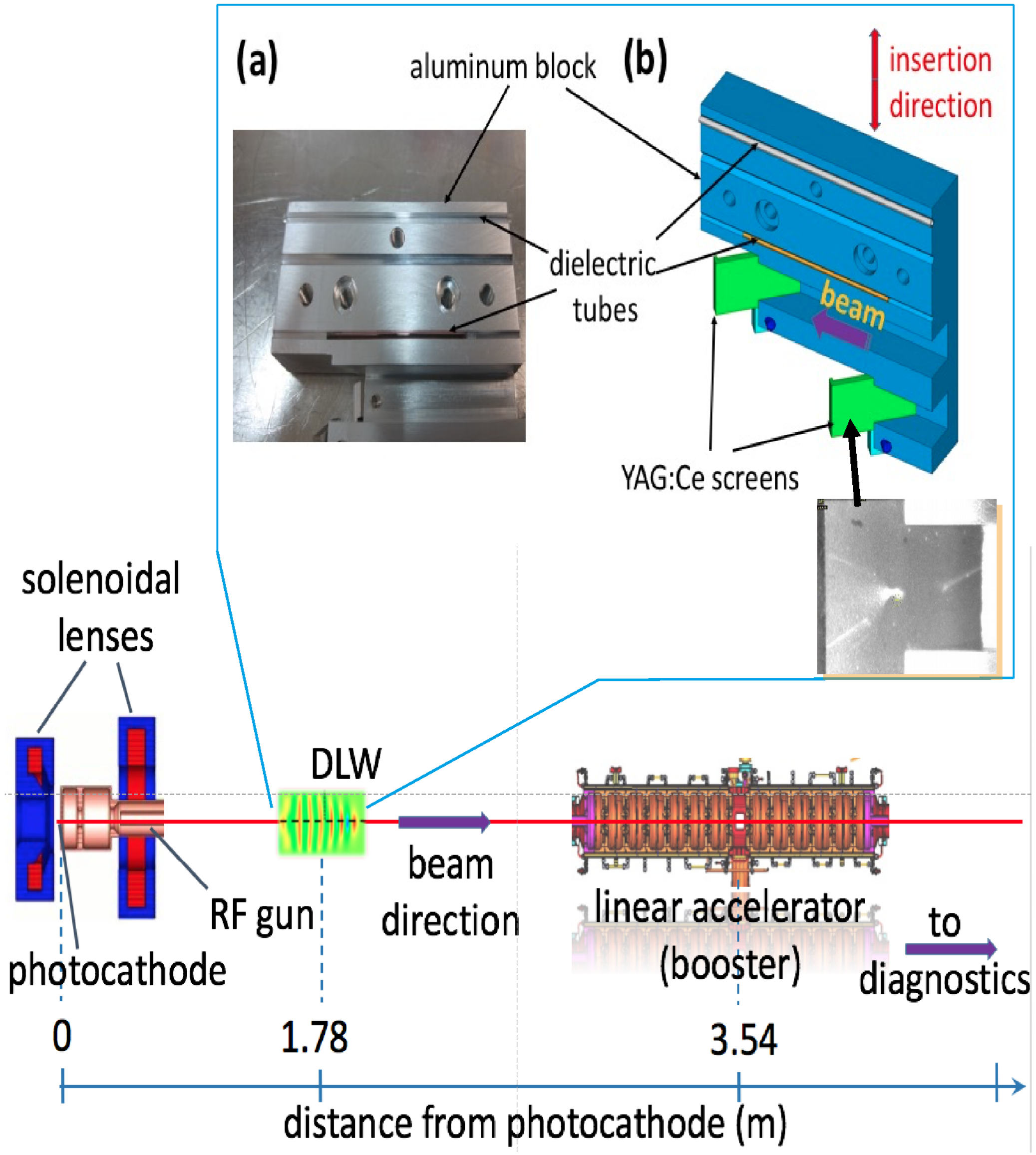


- Much larger wakes for lower frequency- from spectral content of the beam.
- Large harmonic content at maximum compression.
- Higher mode suppression by under/over compressing the bunches.

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.



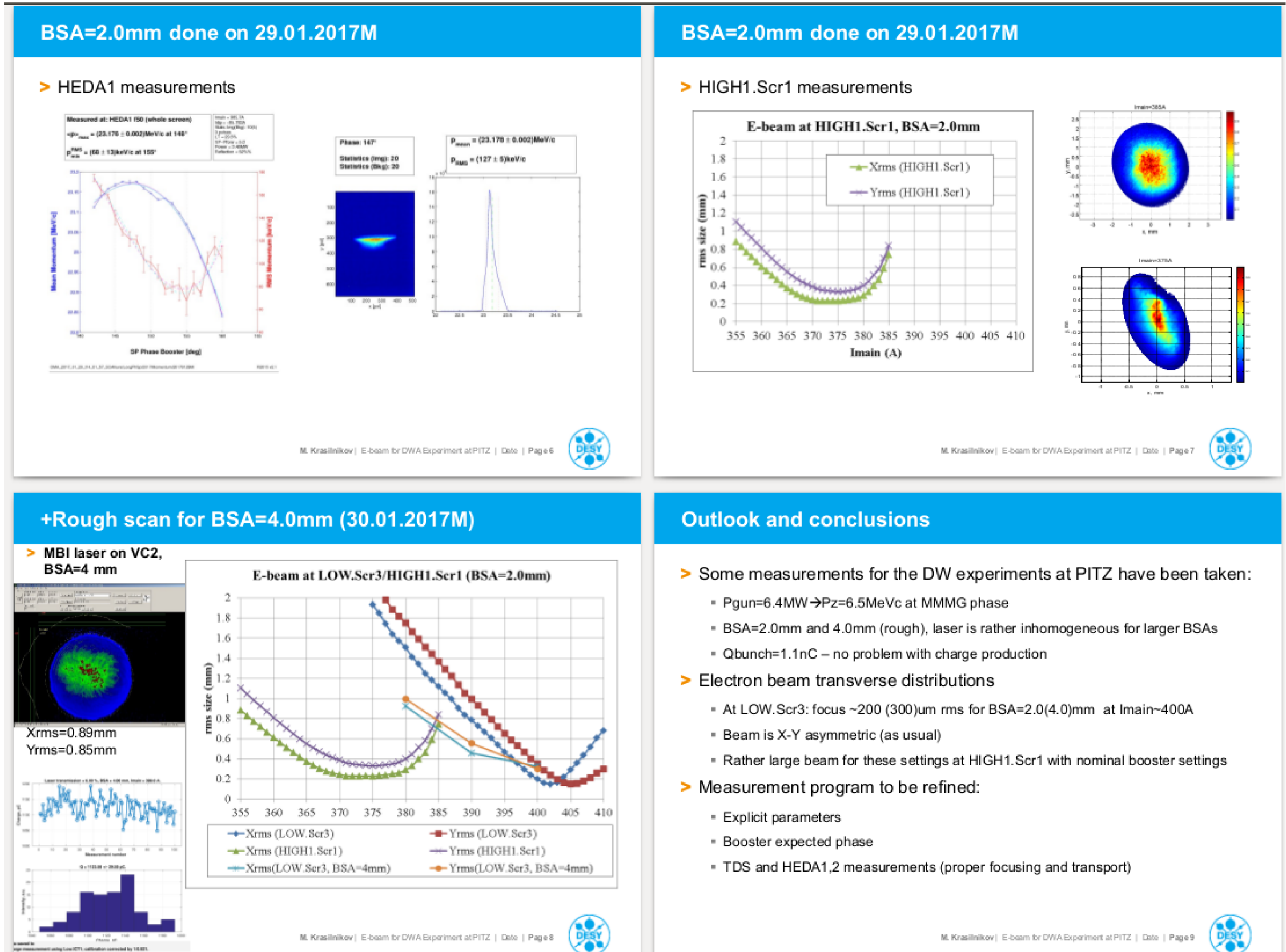
- Coated DLW ($\lambda = 1.03\ mm$)

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

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

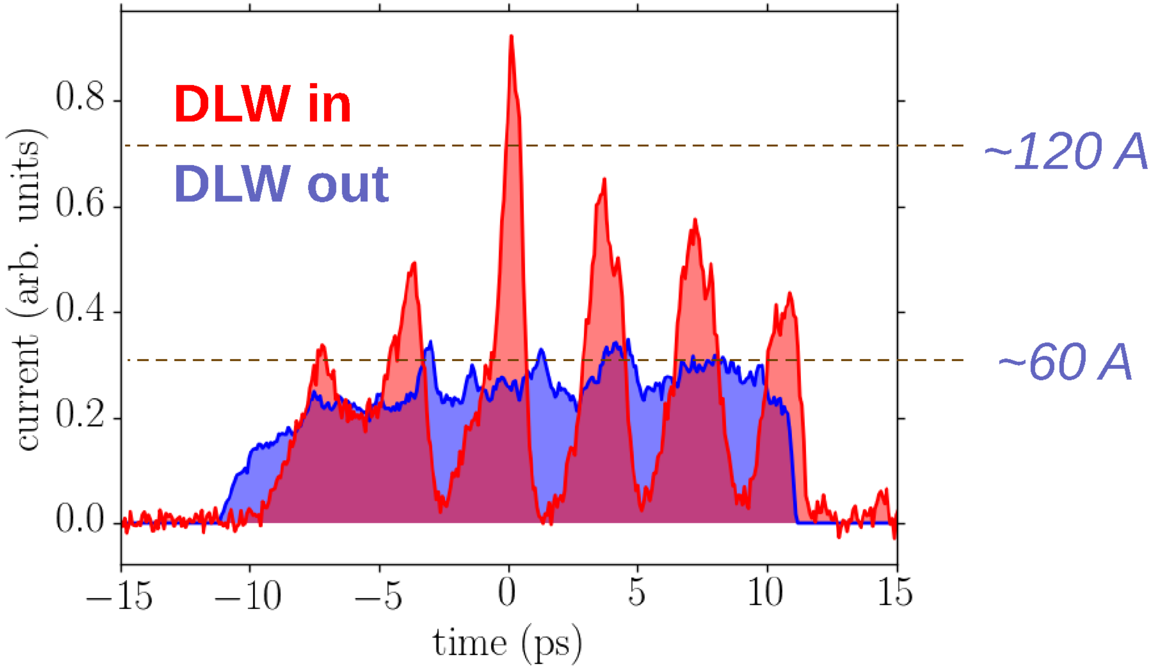
Experiment at PITZ

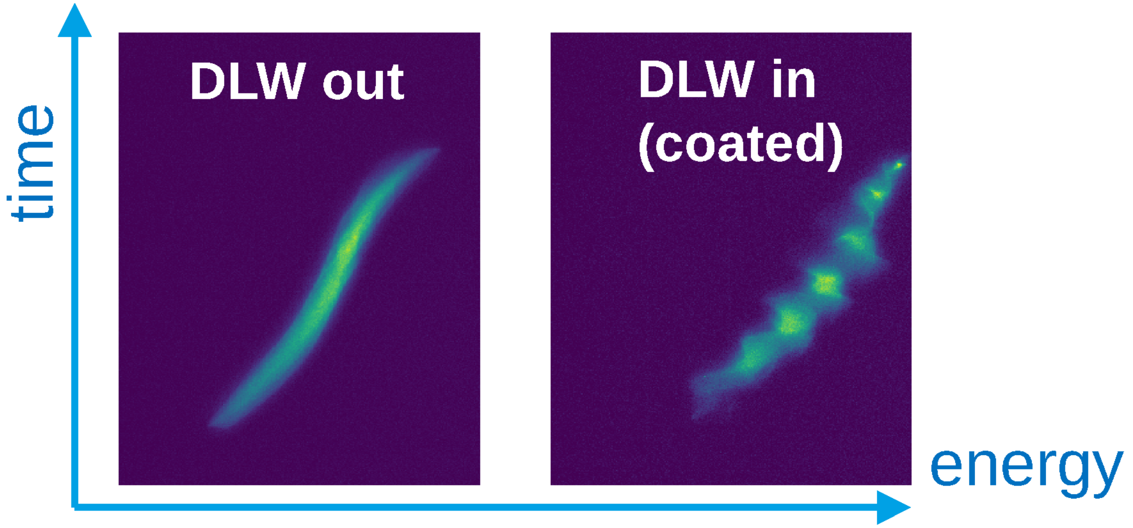
- Excellent machine preparation before experimental run.
- Characterized the beam at Low.Scr3 well in advance.
- Engineering support was fantastic, simple DLW mount was placed in actuator holder.



Experiment at PITZ

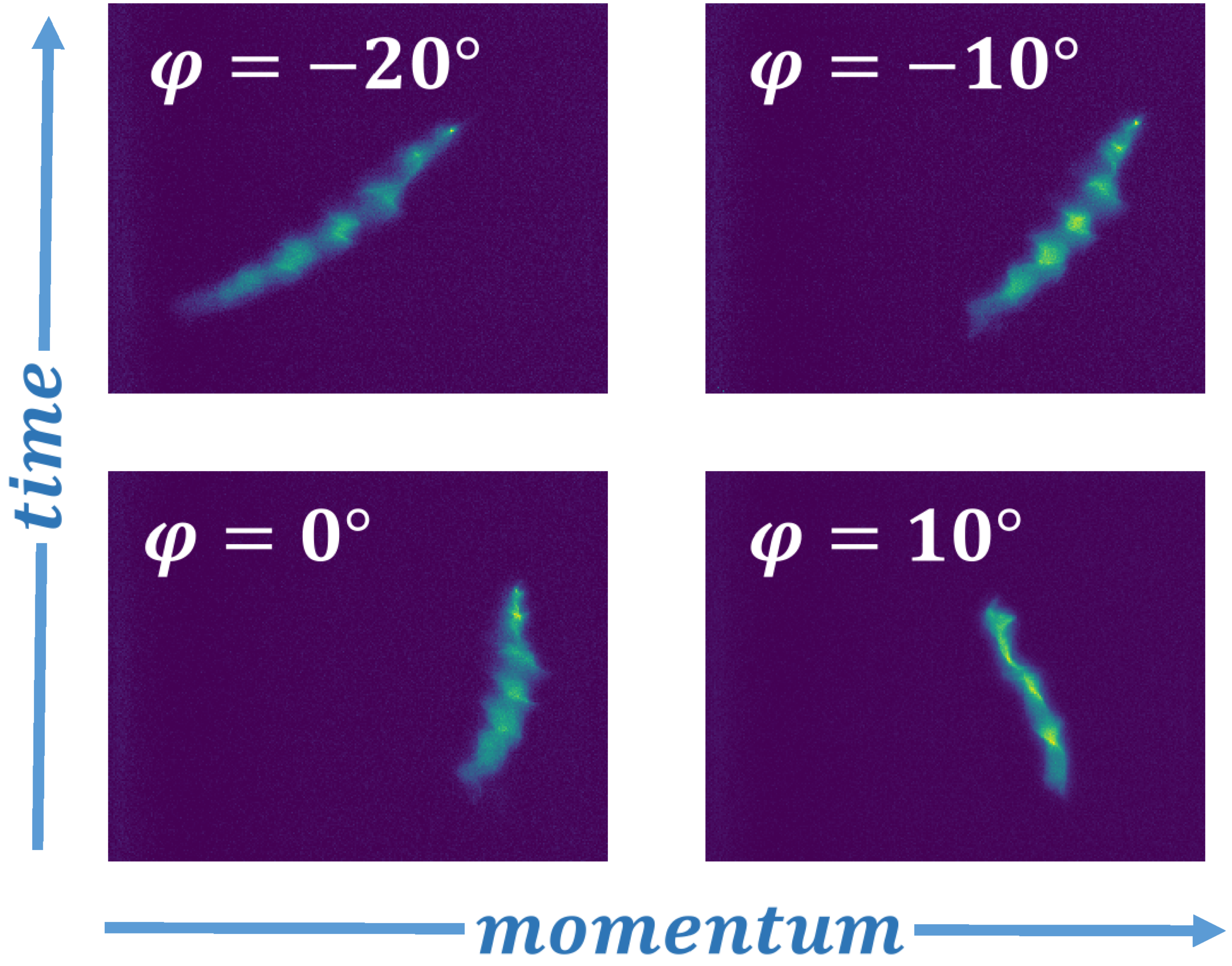
- Demonstrated the formation of ~ps bunch trains at ~6 MeV with resolution limited peak currents up to **~150 A**
- Directly measured the longitudinal phase space downstream of the DLW structure
- Passed a bunch train with up to 200 bunches per pulse through the structure and monitored energy modulations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





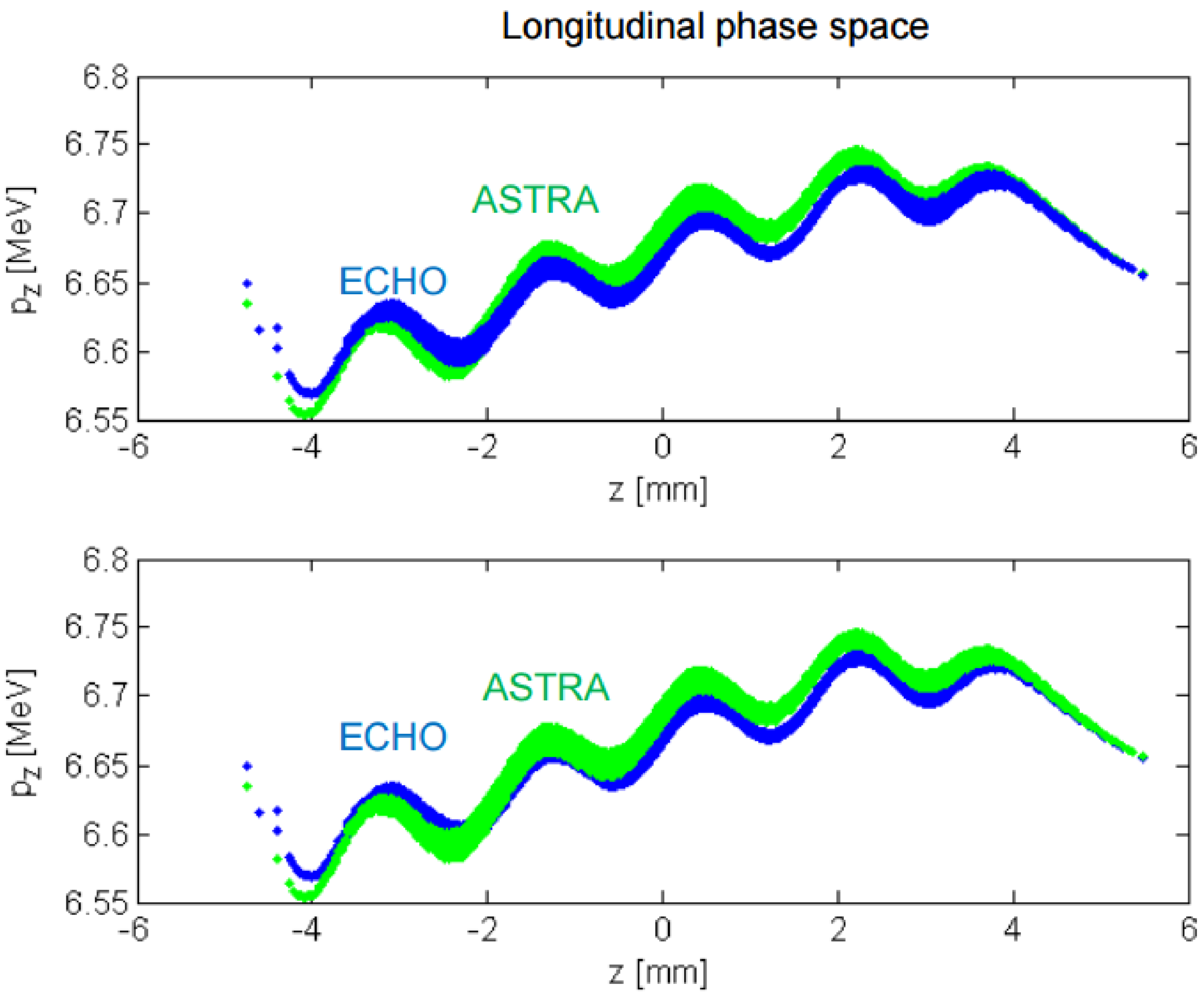
Control of longitudinal phase space

- 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!



Test 4. Full simulation of dielectric insert.

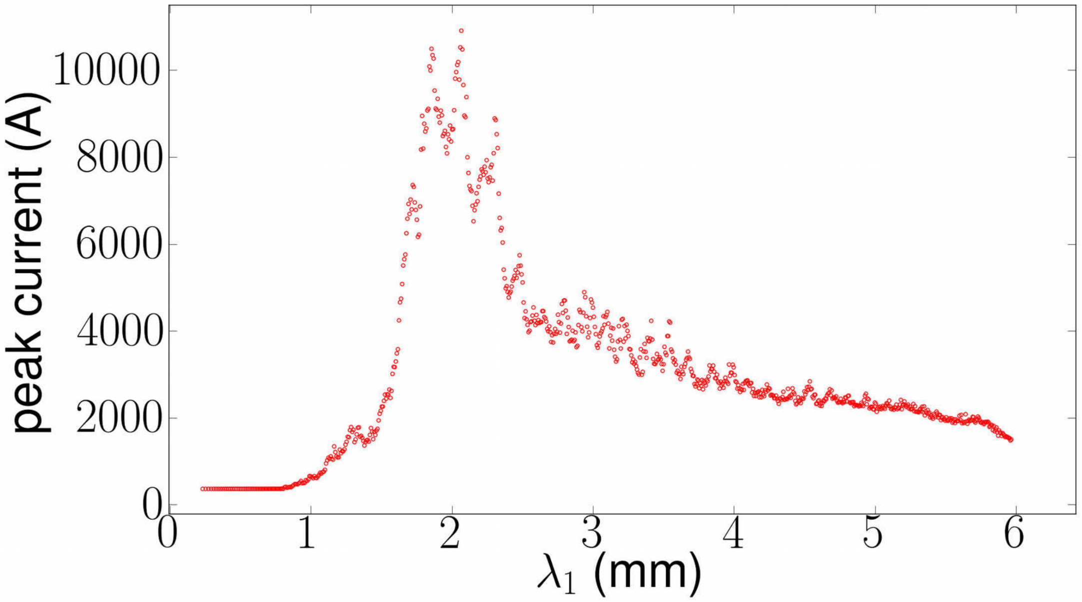
Comparison with ASTRA by Igor Zagorodonov

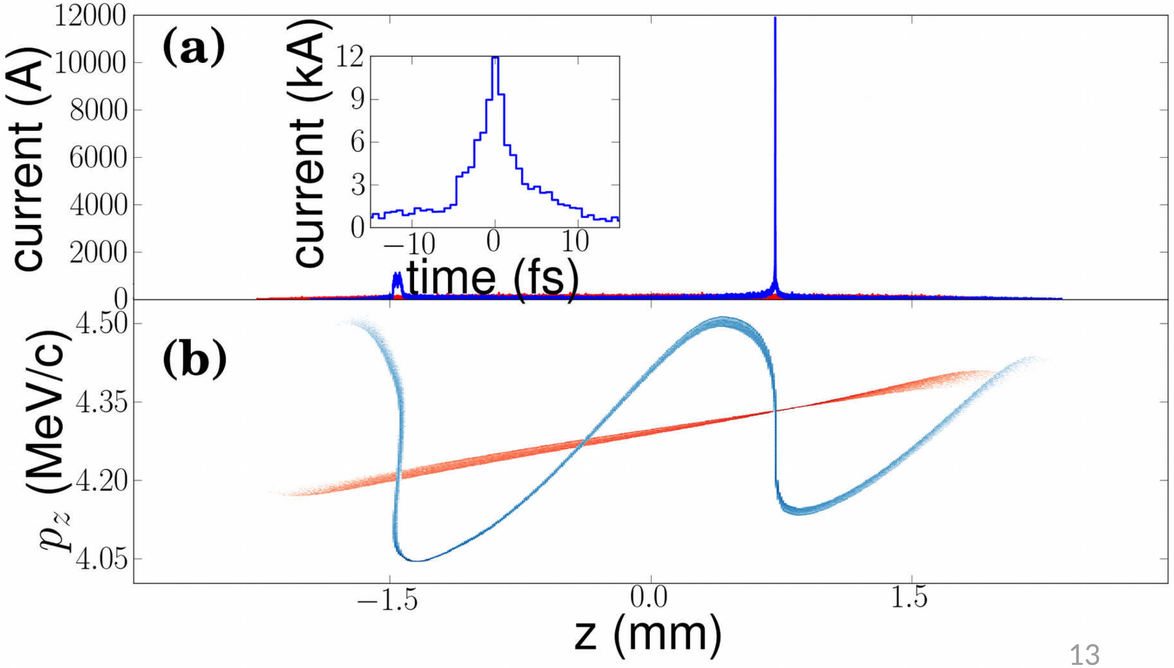


Future DLW possibilities at PITZ

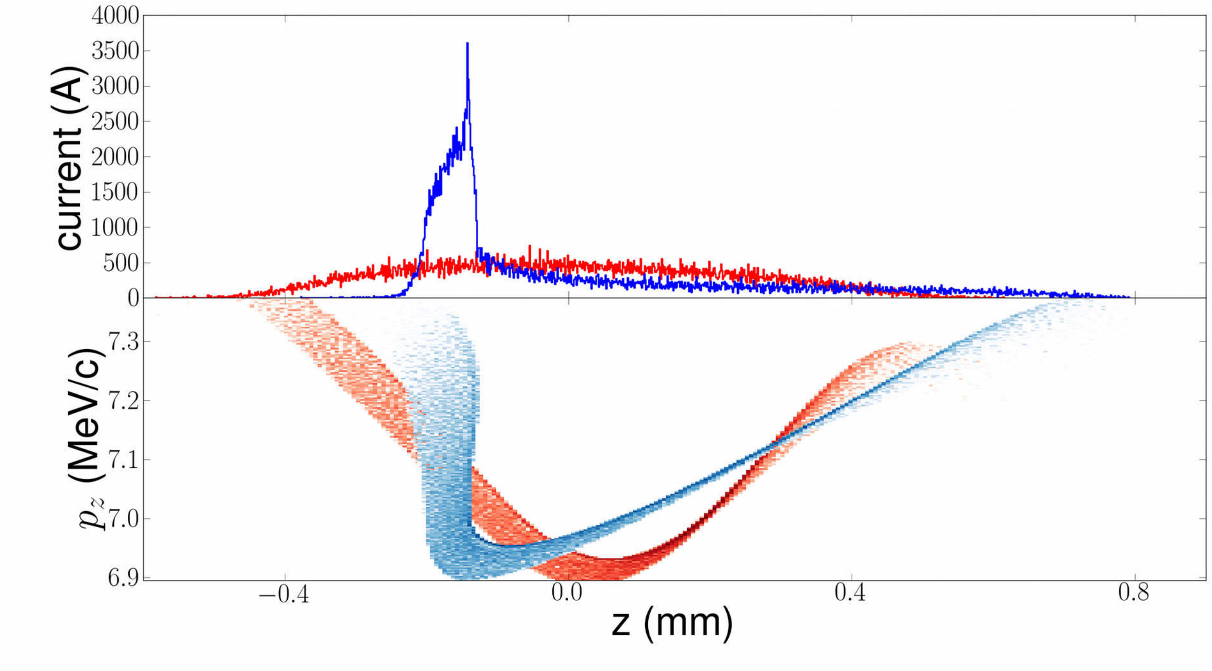
Passive Compressor

- 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

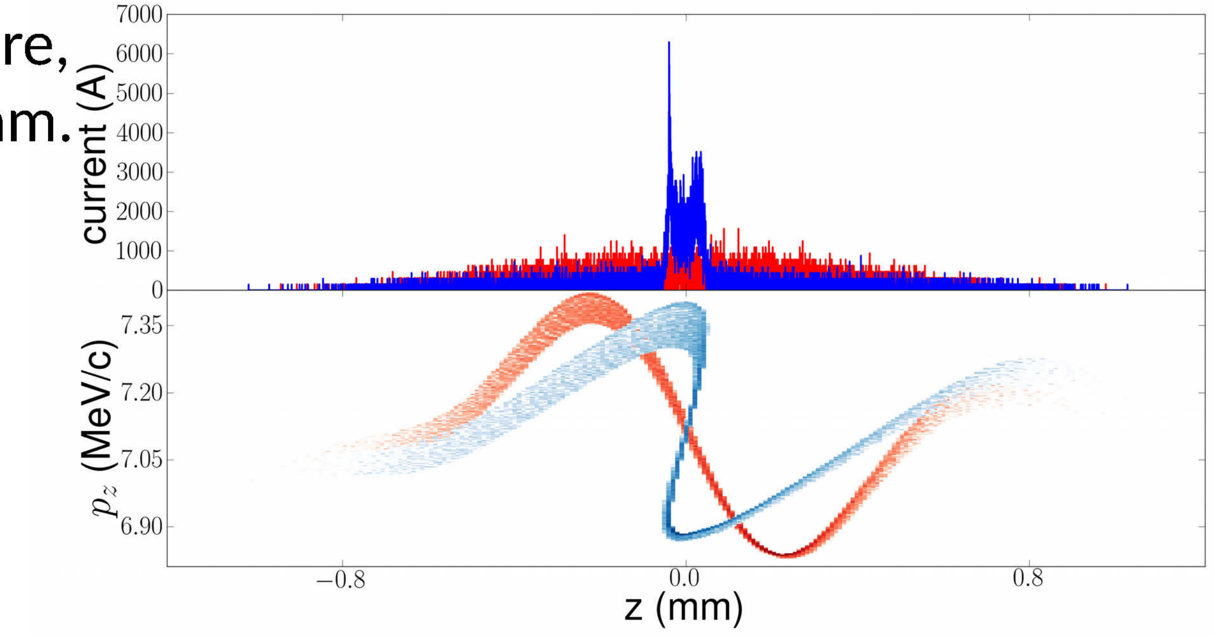




Passive Compressor for beam-driven applications

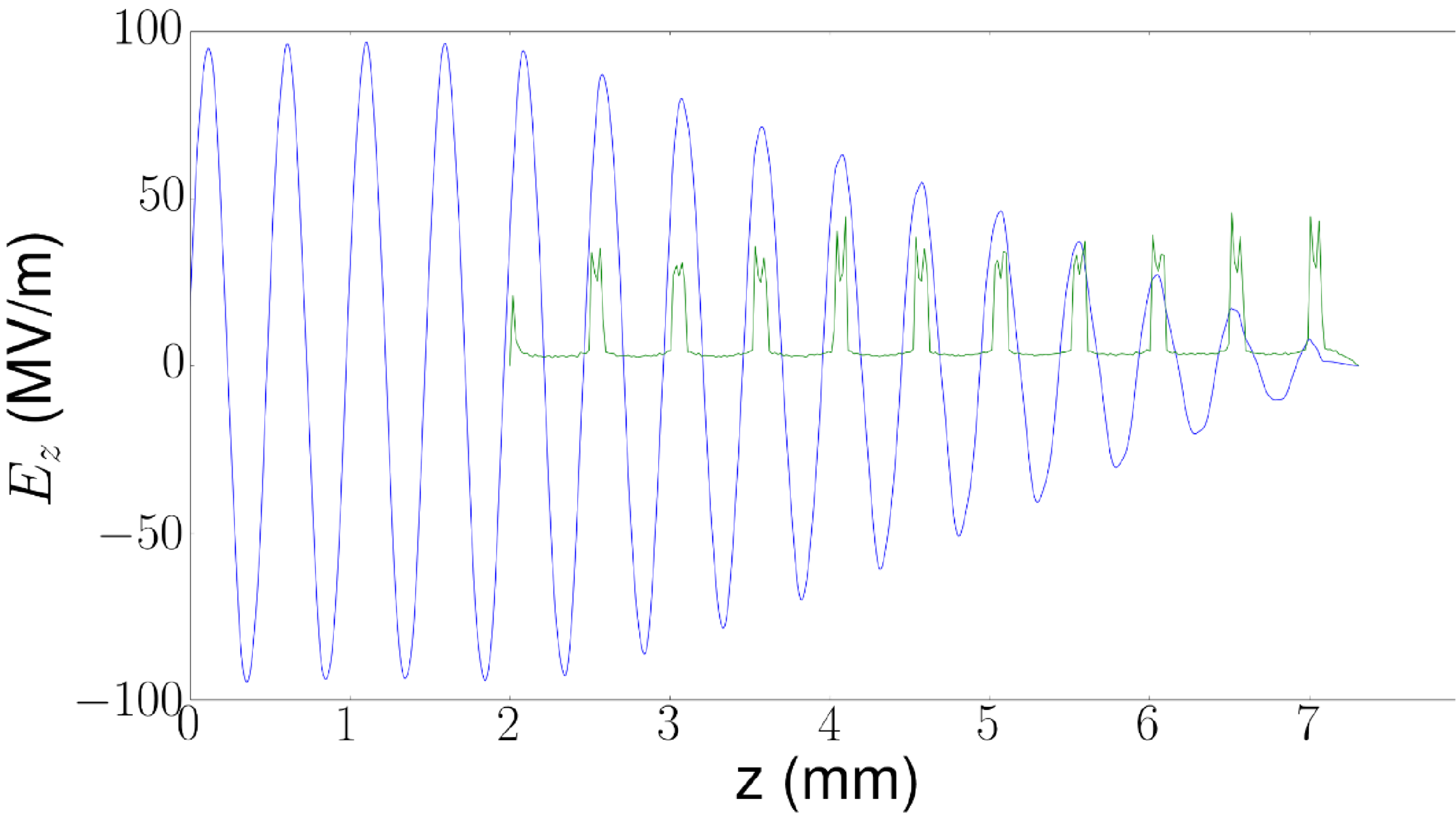


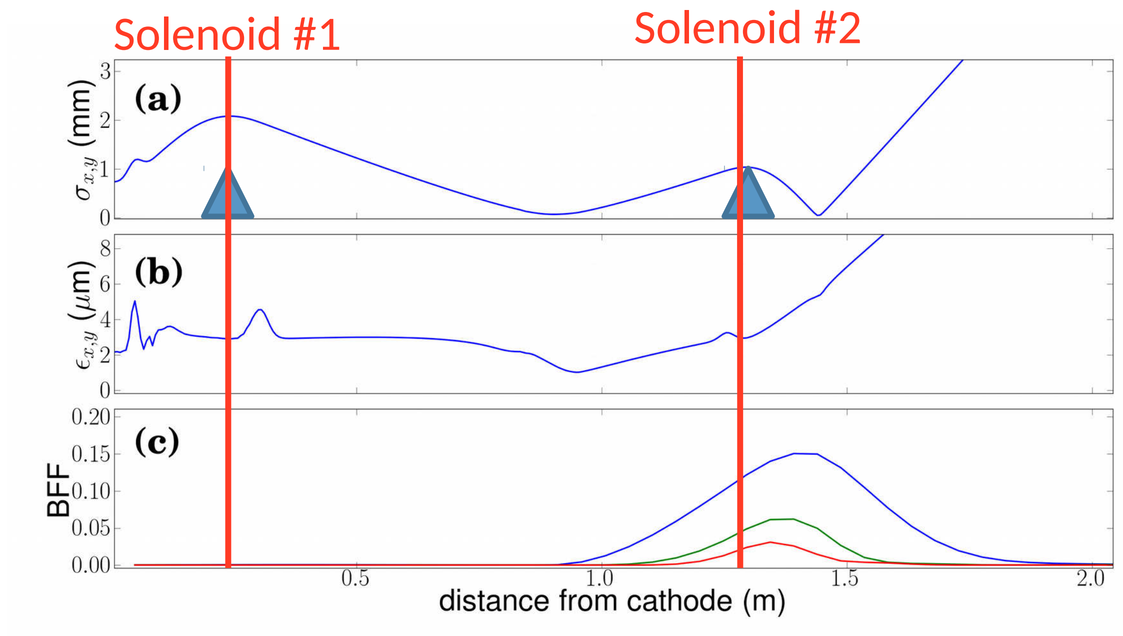
- Bunch larger portion of the bunch (50%)
- Extremely scalable: higher charge → longer bunches → larger structures.
- Details: Red trace: immediately after structure, blue trace 1.2 m (1.13 m bottom) downstream.
- (a, b, e, L) = (1 mm, 1.05 mm, 5.7, 5 cm) corresponding to λ0 = 1.948 mm

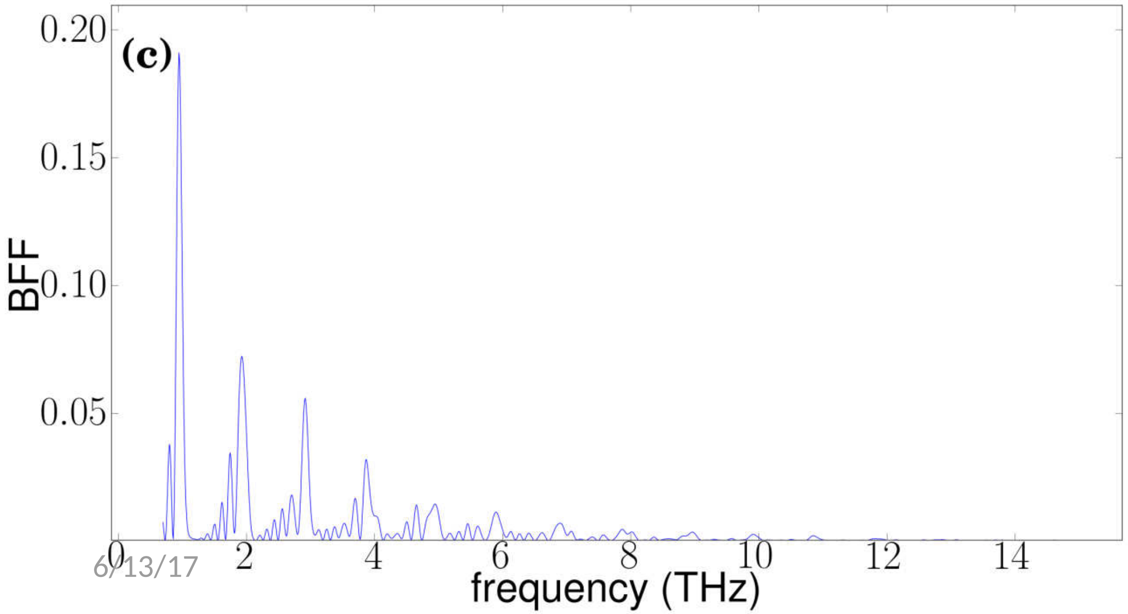


THZ RADIATION

- Microbunched beams have excellent bunch form factors ~ 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.





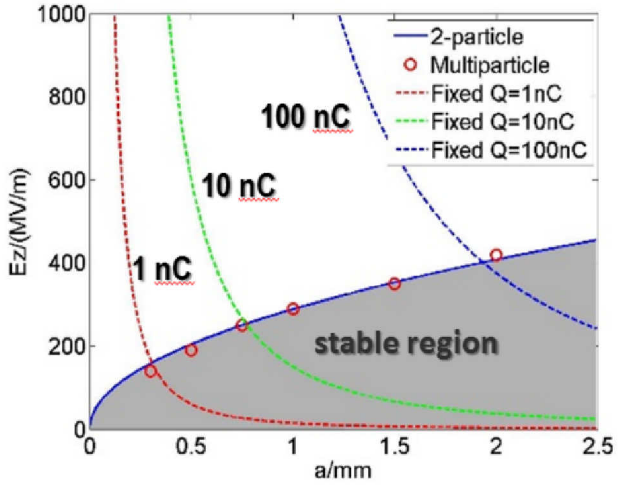


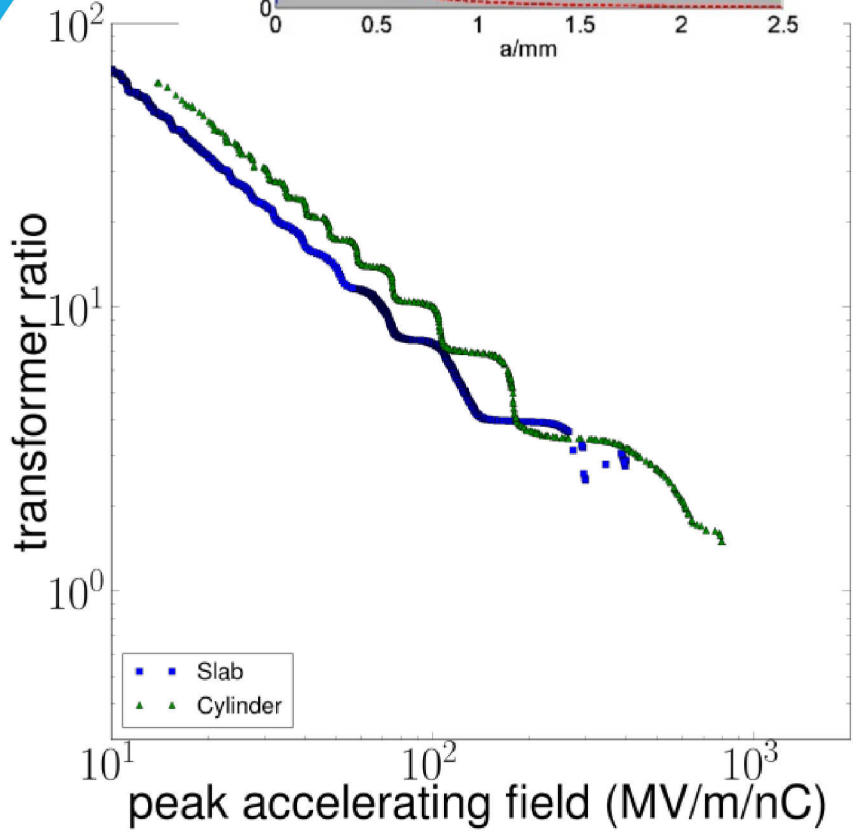
THz Source cont.

- 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.