Toward a Cherenkov FEL experiment at AREAL

Ideas on developing Thz generation in collaboration with CANDLE and DESY

Francois Lemery
Ultrafast Beams and Applications

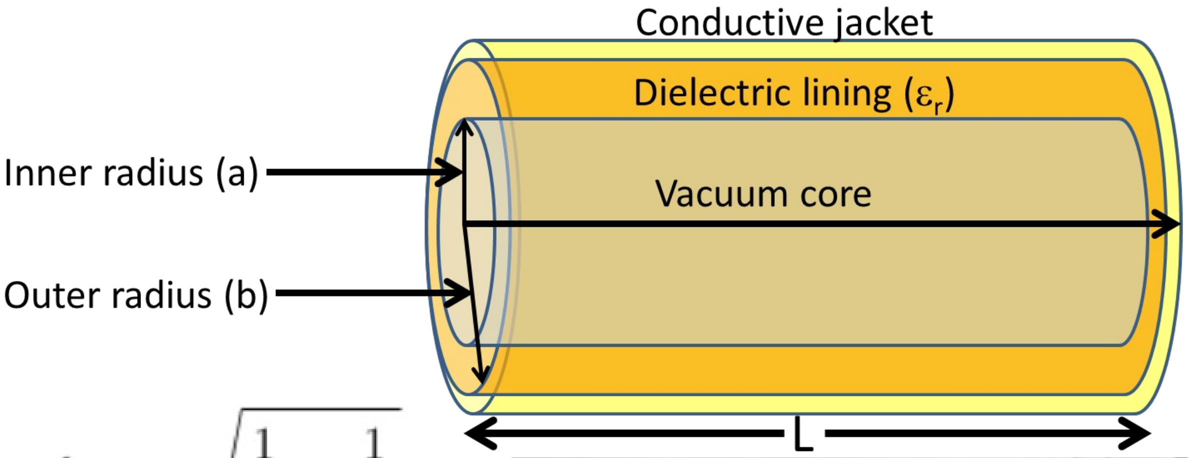
Overview of the talk

- Cherenkov FEL introduction
- Results at PITZ
- Simulations on multi-bunch
- 3D printing dielectric structures

Overview

Dielectric-lined waveguides

- Dielectric-lined waveguides (DLW), corrugated metallic structures, two-layer metallic structures are high-impedance mediums - leading to a wide variety of beam-related applications:
  - Acceleration
  - Beam manipulation
    - De-chirping
    - Microbunching
    - THz generation
    - Streaking
  - The basis for these techniques relies primarily on the TM mode
  - *Note: The fundamental mode is a deflecting mode!



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

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

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

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

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

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

Cherenkov Free Electron Laser

Brief history and introduction

- The wakefield generated from a charged bunch passing through a structure can be calculated with the convolution the current profile and the Green's function:
-
$$V(z) = \int_{-\infty}^{z} G(z-\zeta)S(\zeta)d\zeta.$$
-
- Gerate 1987- demonstrates the principle of a CFEL with a microtron source.
  - They report up to 200 kW of ~1 mm radiation with 0.2% conversion efficiency.
  - Beam qualities have drastically improved with modern photoinjectors

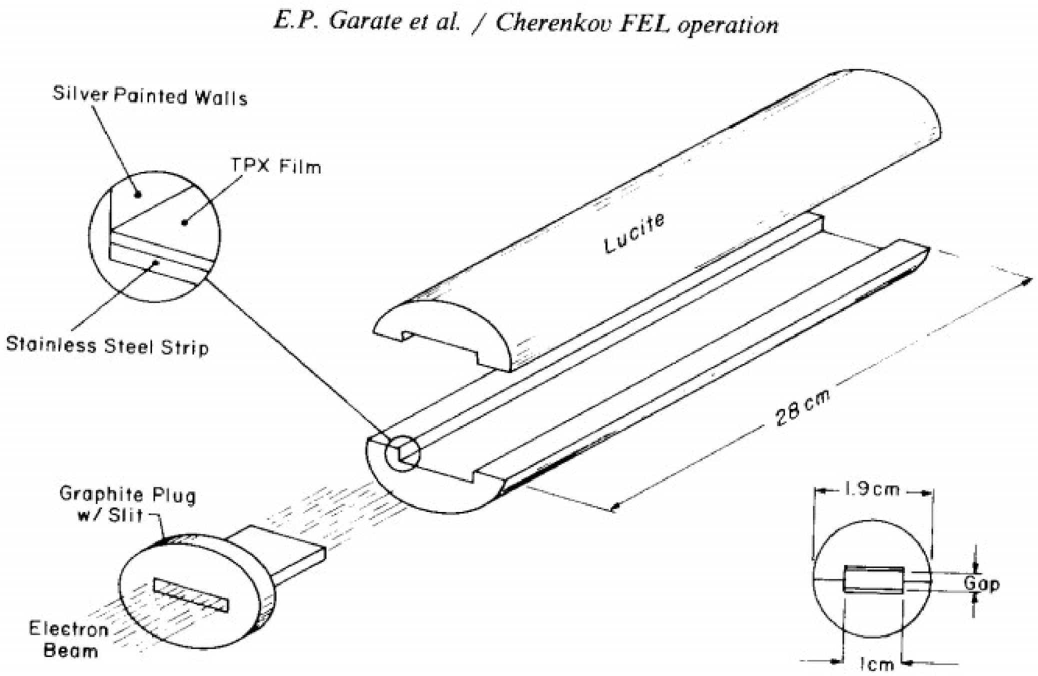
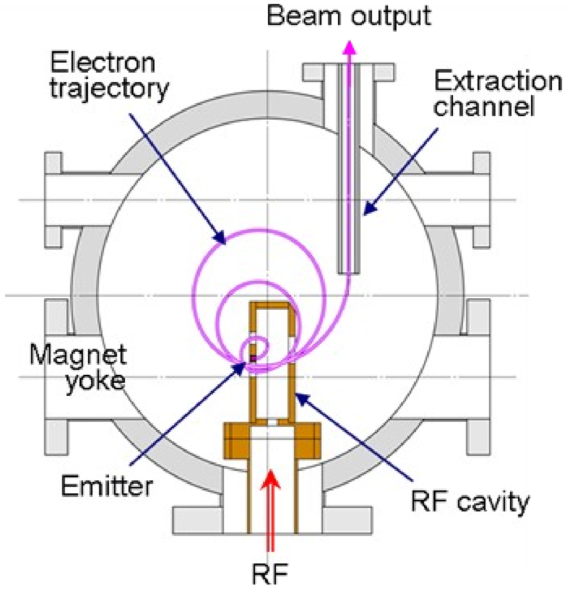
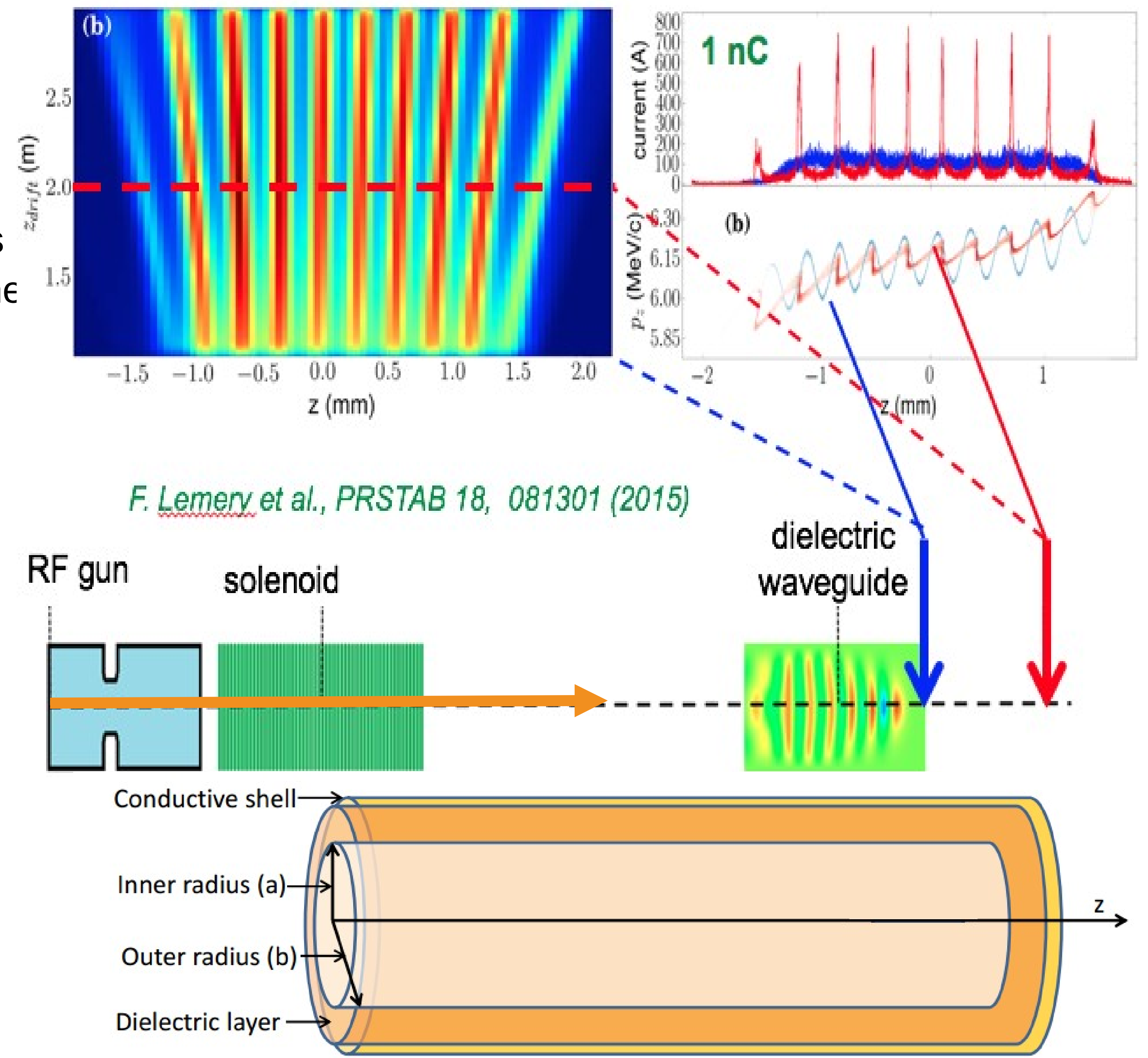


Fig. 1. The slow wave supporting structure.



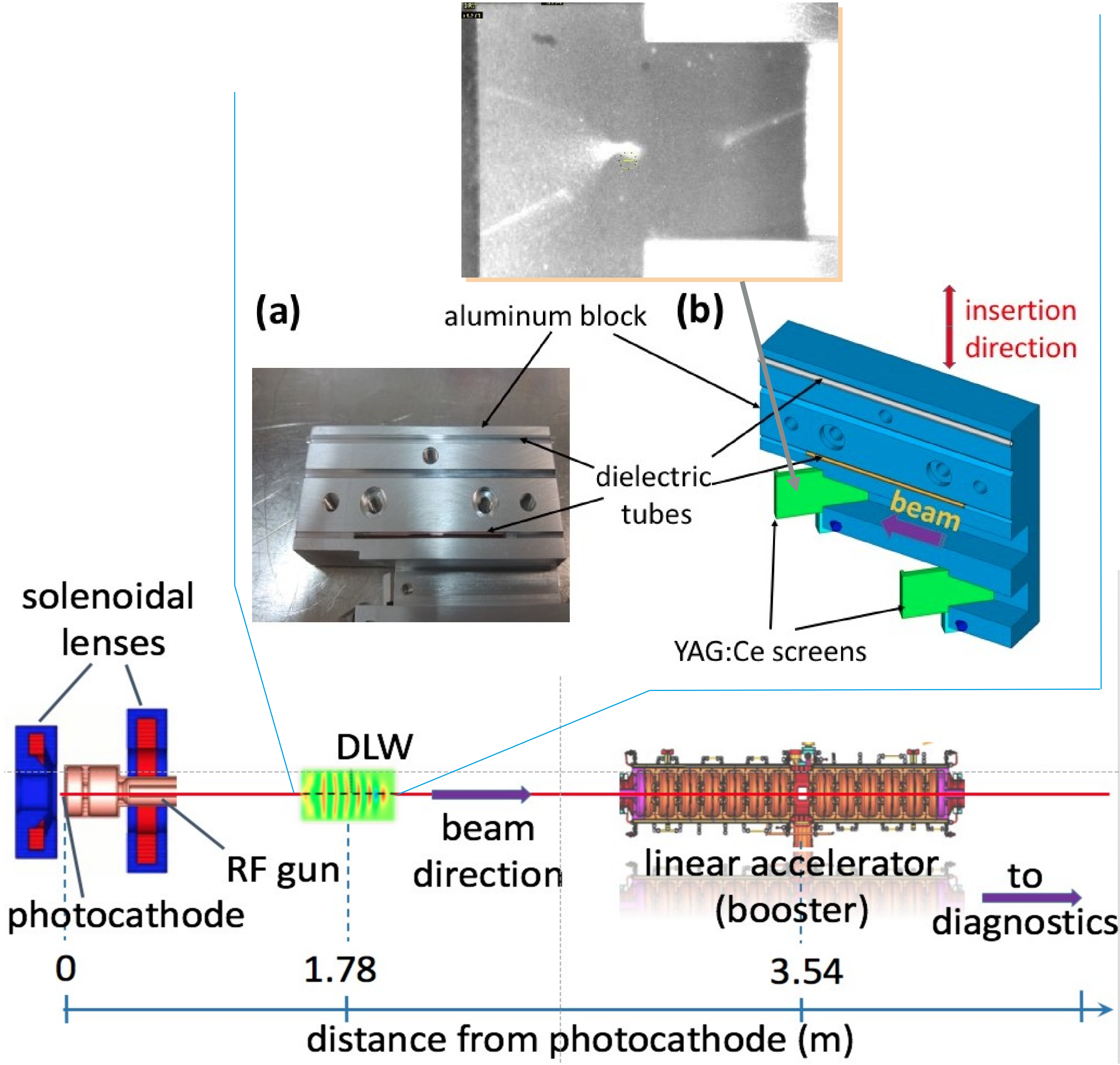
Principle of wakefield-assisted bunching at PITZ

- A bunch passes through a DLW and generates a wakefield which energy modulates itself at the structure wavelength.
- Because the bunch is non-ultra-relativistic, the energy modulation converts into a density modulation after a drift.
- Experiment performed at PITZ uses dielectric lined waveguides (DLWs) to excite the wakefields.
- FLAT-TOP bunches *



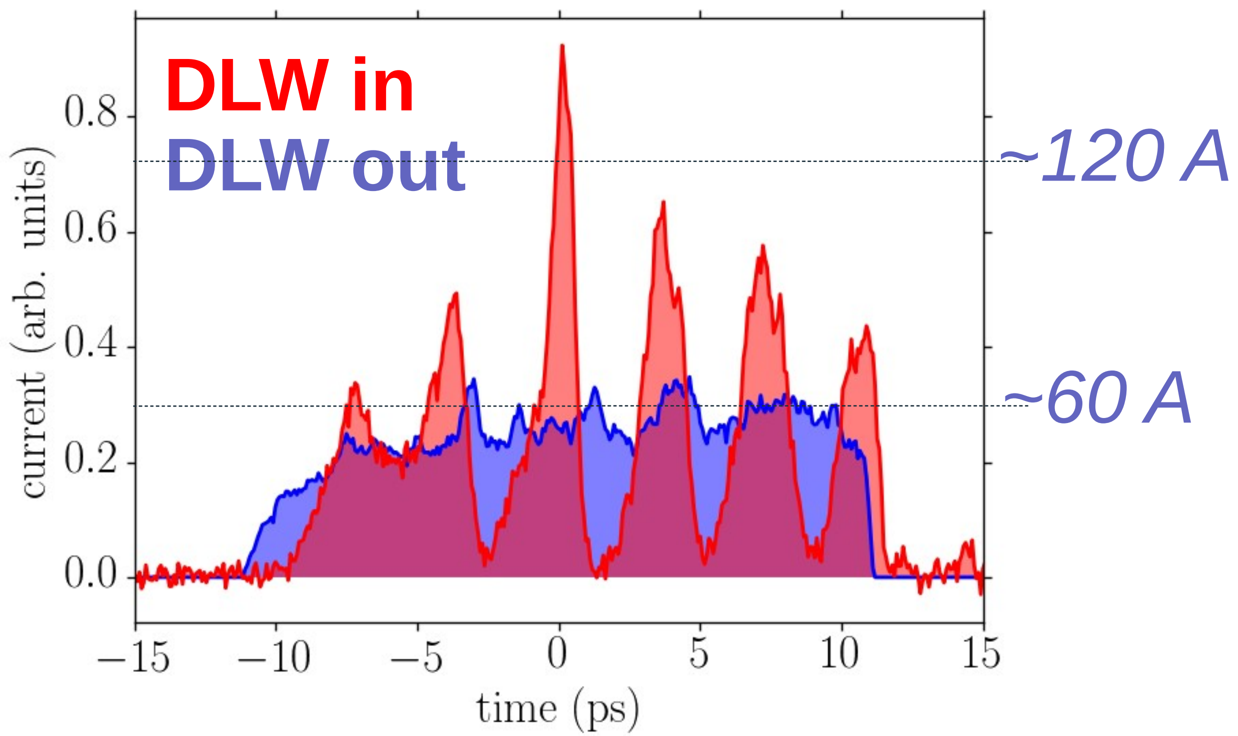
Experimental setup at PITZ

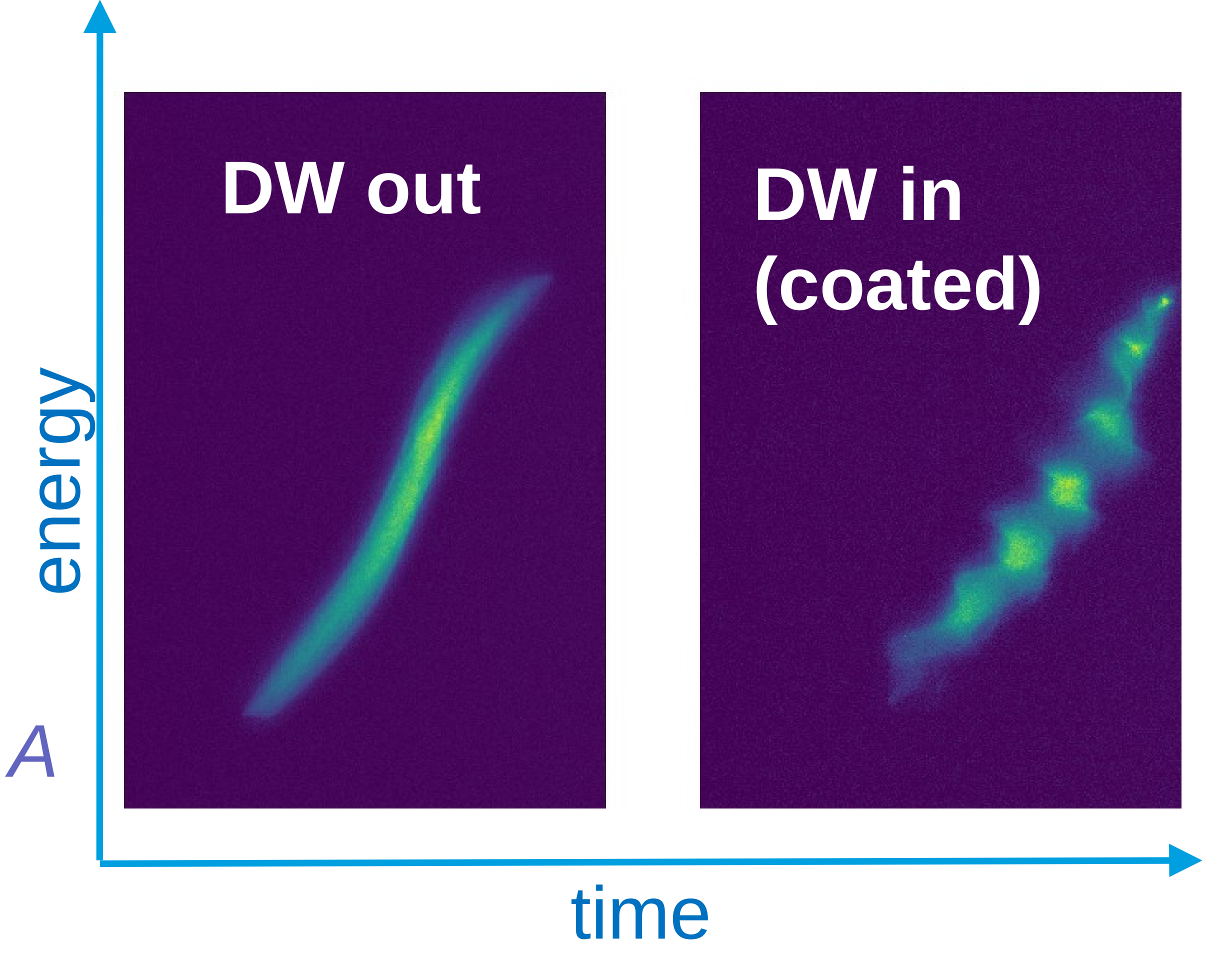
- Two DLWs were used with dimensions selected to excite wakes at THz wavelengths
- Setup allowed for precise beam alignment and transmission through DLWs:
  - DLWs holder equipped w. YAG:Ce screens,
  - Added quad. corrector to improve beam symmetry enabled full transmission
- PITZ' flat-top pulses improved results significantly.



Main Achievements

- Demonstrated the formation of a sub-ps bunch train at ~6 MeV with peak current up to ~150 A



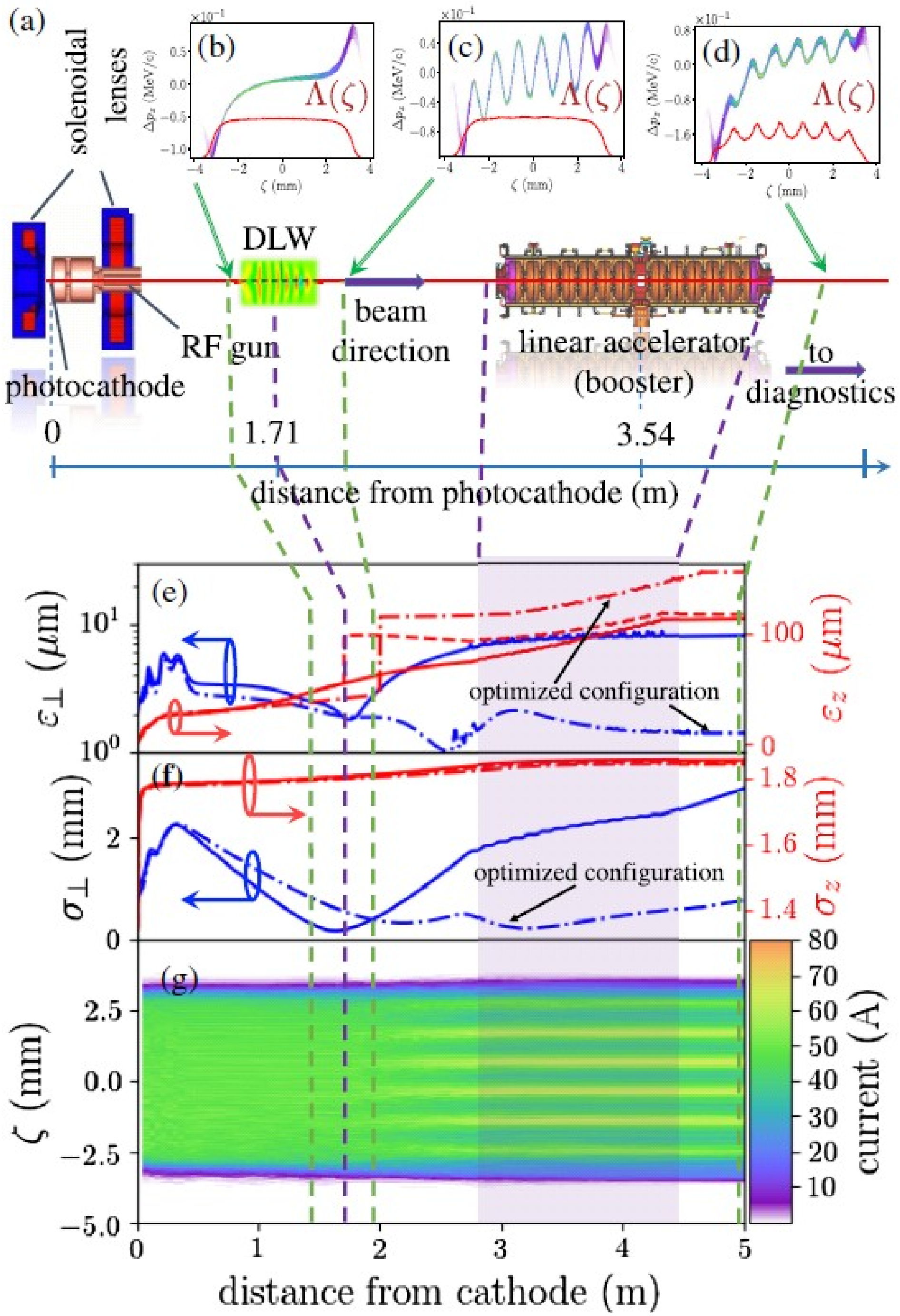


- Directly measured the longitudinal phase space downstream of the DLW structure

Main Achievements

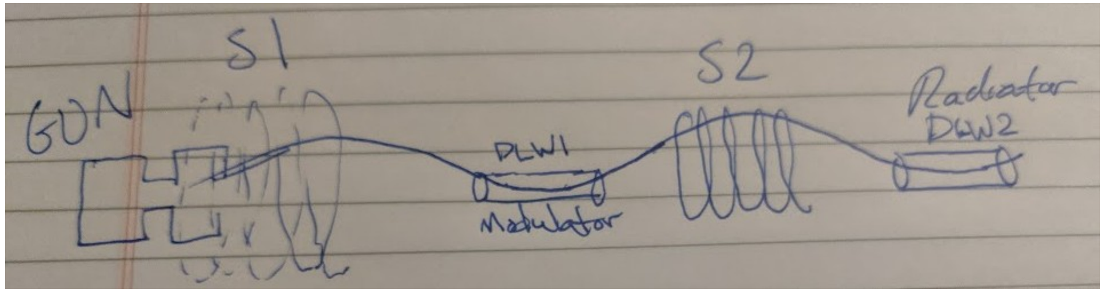
- Non optimal configuration
- Simulations results show emittance compensation is possible.
- Estimated gain length to be 1.5 cm.

$$\ell = \frac{1}{\sqrt{3}}\gamma\left(\kappa k_w \frac{I}{I_A}\right)^{-1/3}.$$

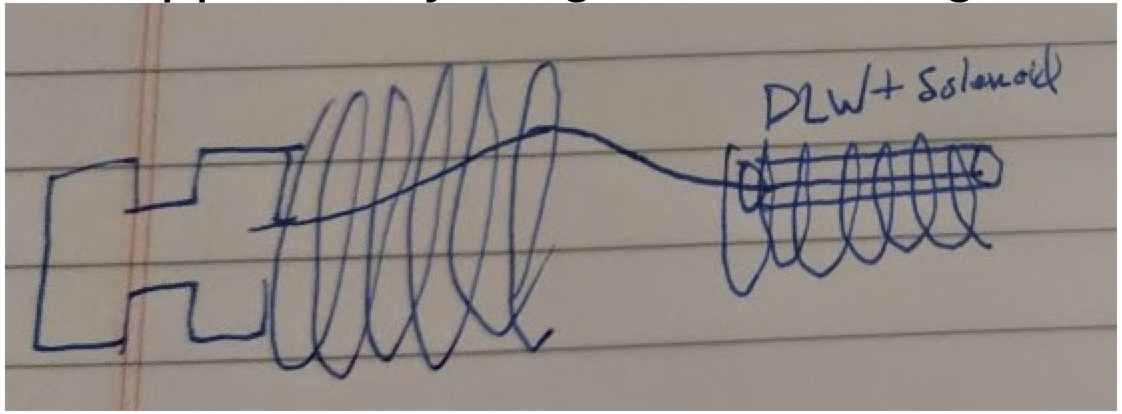


How do we gain something…
on a compact scale?

- Saturation typically occurs on 10-20 gain lengths
- Possible approaches:
  - Allow beam to bunch ballistically, then use second structure as radiator.



  - Use longer structure supported by magnetic focusing.

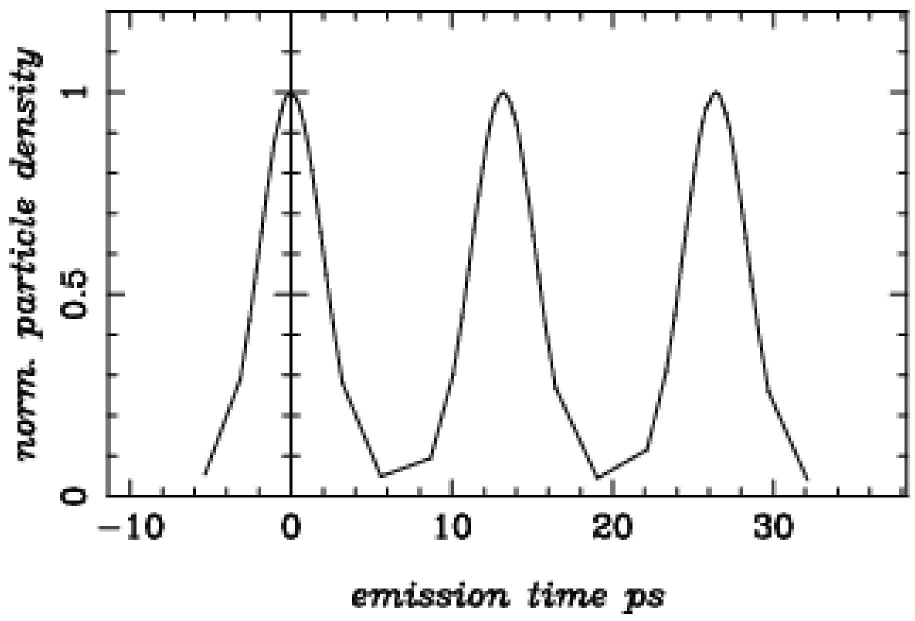


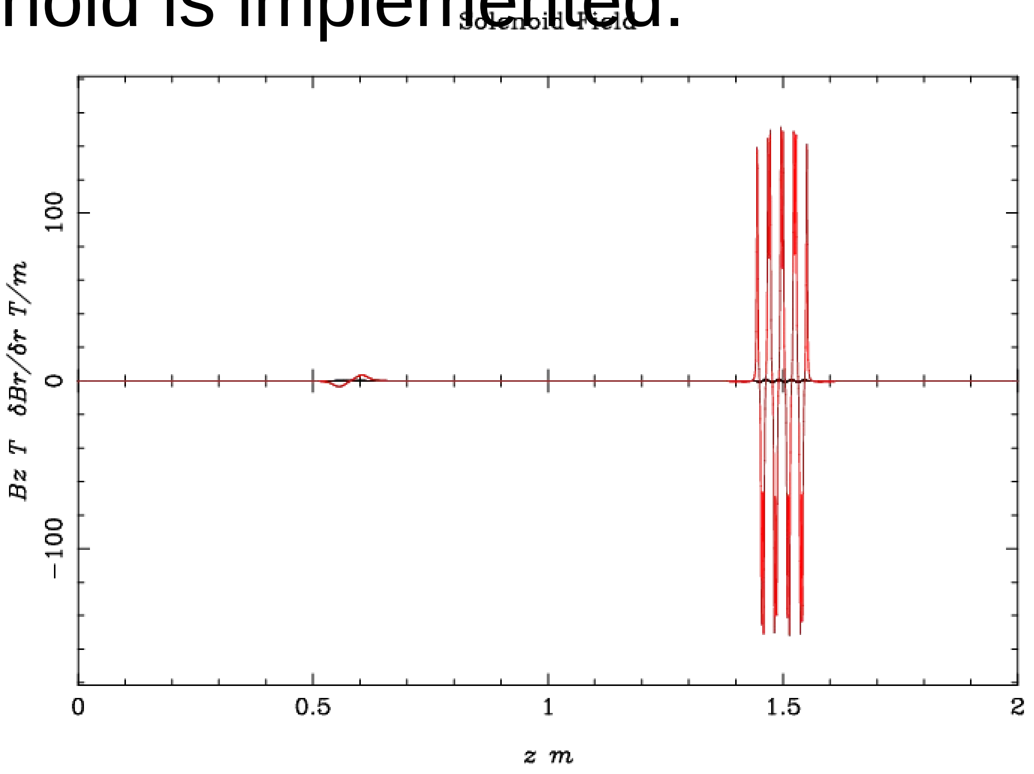
Bunching from the cathode

- Gain comes form the microbunching process with FEL interaction.
- Gain can lead to large bunch form factors >0.3 but this is probably more challenging at lower energies with space charge.
- The large wavelengths (~1 mm) of Thz is much longer than conventional fs-class lasers used in photoinjectors.
- We can then imagine producing a bunch train from the cathode using e.g. beam splitters (Arsham), BBO crystals, etc.
- This approcah could in principle yield much higher BFF.

Preliminary simulation

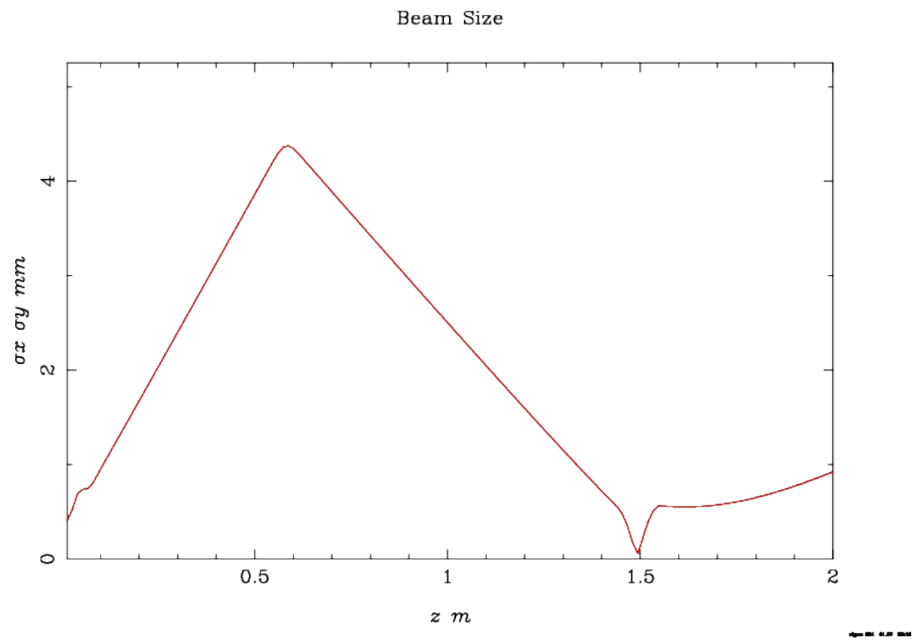
- Here we begin with the AREAL astra deck, with 3 bunches of 100 pC each.
- The wavelength of the structure is 2.7 mm, giving bunch separation of 13.2 ps
- Alternating permanent magnetic solenoid is implemented.

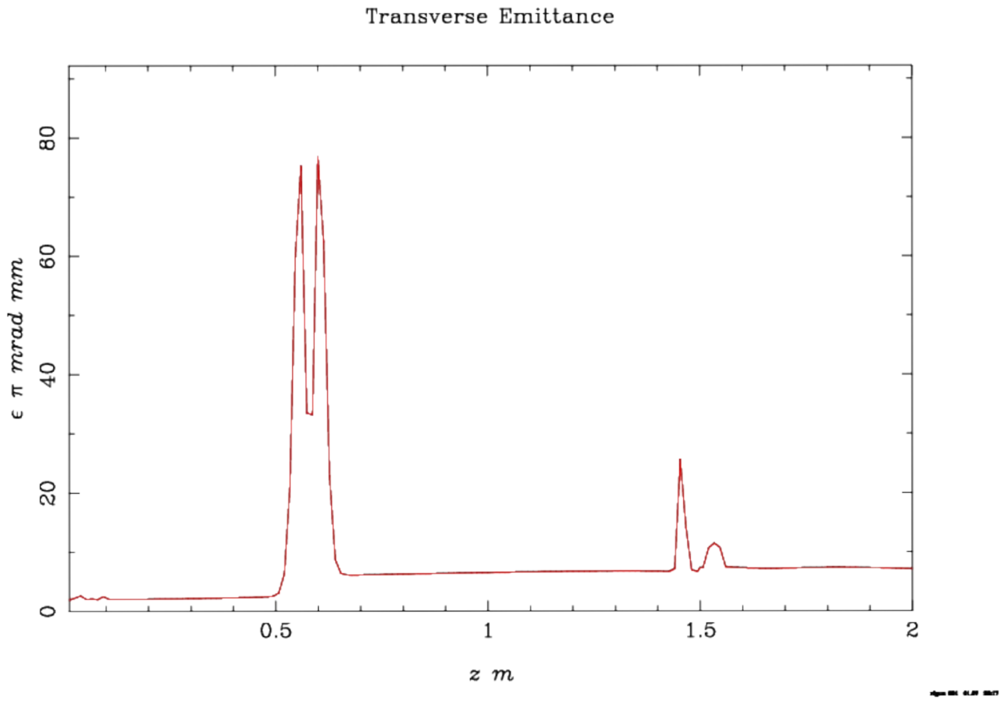




Preliminary simulation

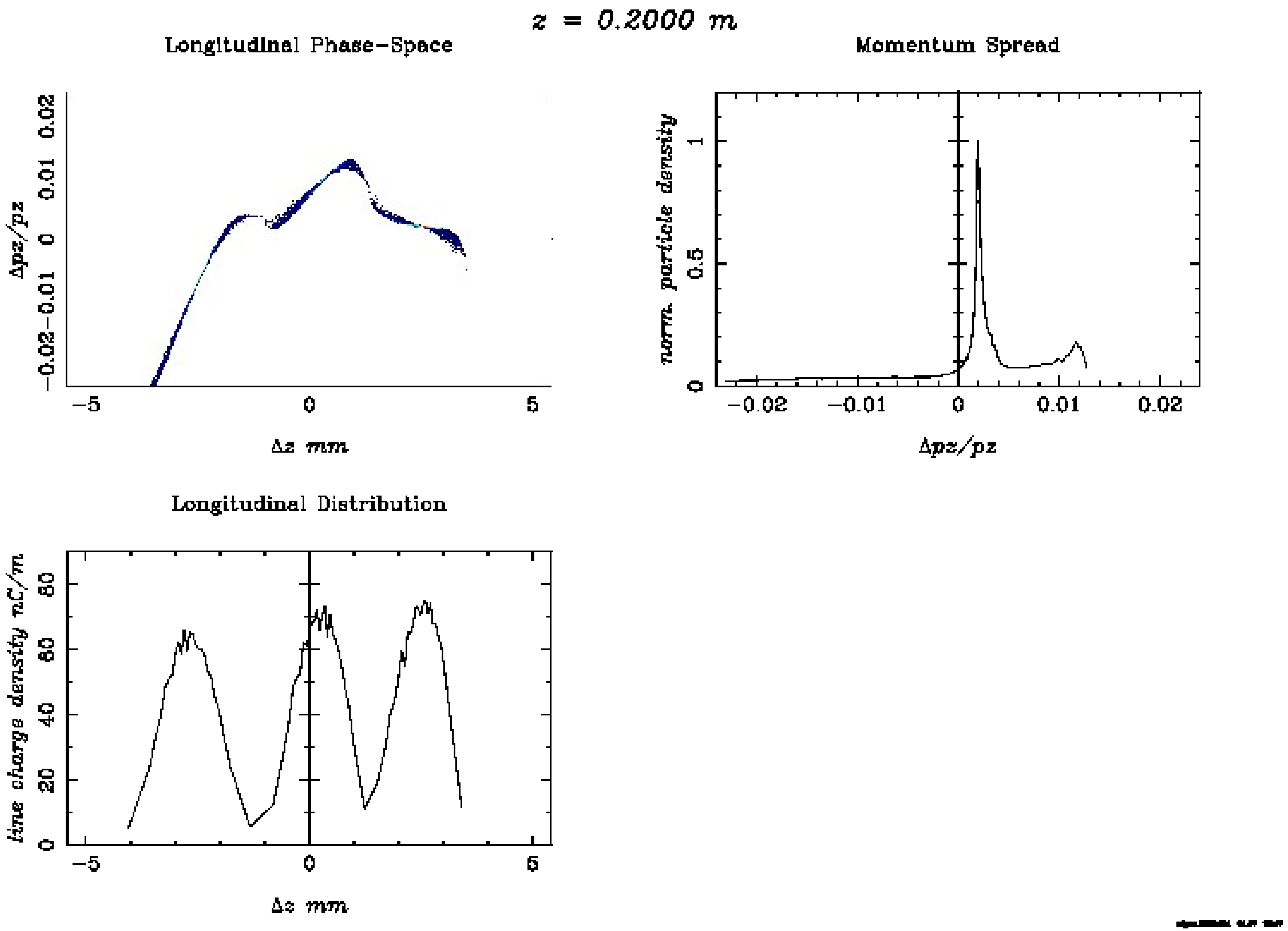
- Beam size is a little large at the first solenoid and leads to some emittance growth.
- It is generally well maintained over ~50 cm.
- Needs futher optimiziation.





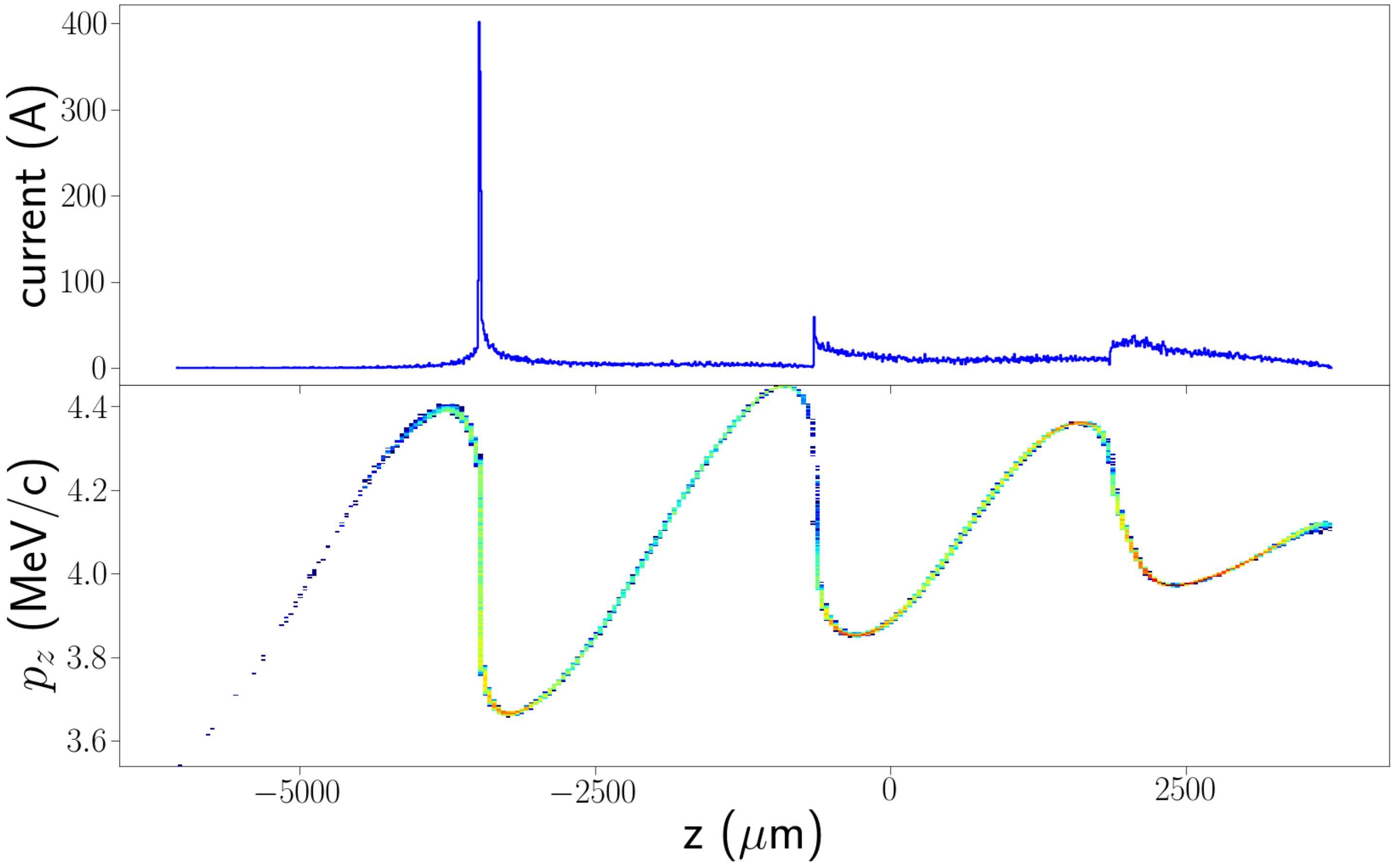
Preliminary simulation

- Beam exits gun with total of 300 pC.
- Space charge effects are noticable but not destructive.



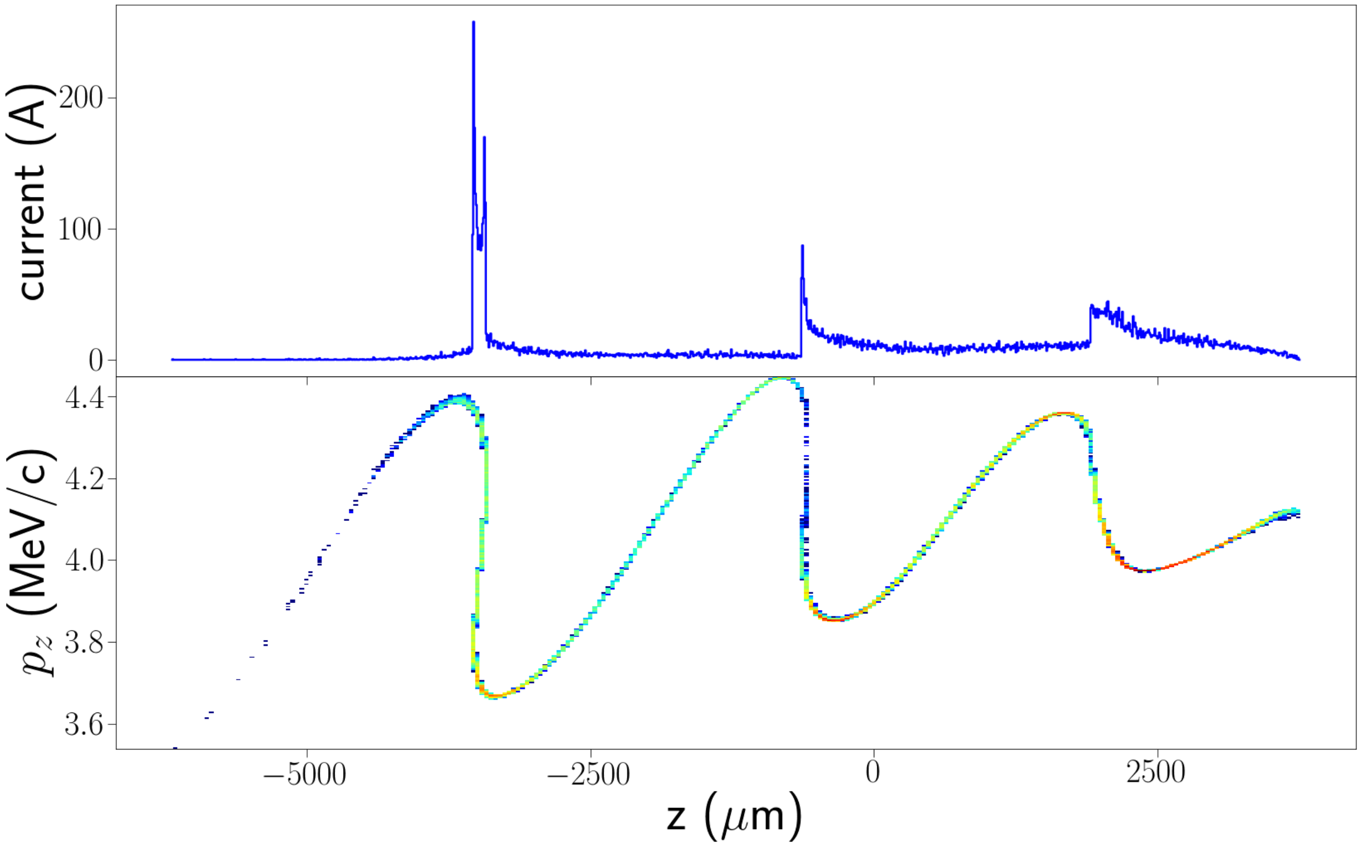
Preliminary simulation

- Subequently in the DLW the fields add up and generate a strong wake.
- Currents are evolving rapidly.
- Here multiple kicks (3) are implemented in ASTRA



Preliminary simulation

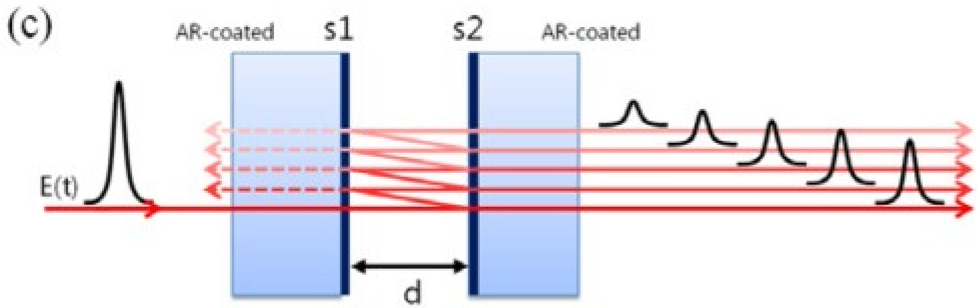
- At the end of the structure, the beam is we bunched.
- The last peak has a peak current of ~300-400 A.



Preliminary simulation - outlook

- The scheme has potential to generate high power Thz radiation.
- However there are limits.
  - Here the maximum number of bunches was 3 due to 3 Ghz curvature (particle loss, focusing problems etc. With 4)
  - Less charge, with shorter bunches could improve things, but it is generally a challenging optimization problem.
  - Alternatively in the many pulse case we could use a Fabry Perot interferometer

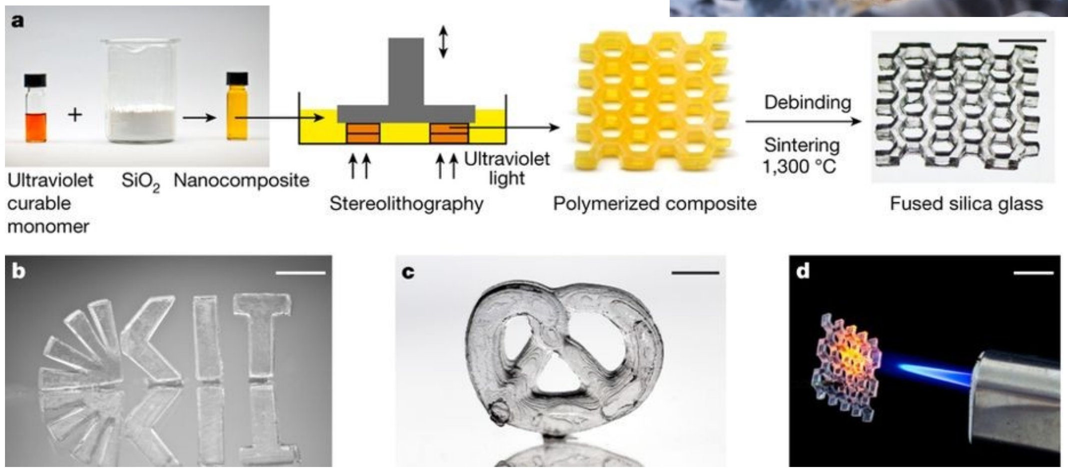
https://doi.org/10.1364/OE.21.000070



ASIGA 3D printer

A leading high-performance printer used for various applications

- ASIGA offers the best resolution entry-level printer with a laser spot size of 27 um. This defines the minimum feature size.
- The laser spot size location is controlled with automated optics, allowing for additive printing which yields smooth macroscopic features.
- The MAX X 27 model provides 4 encoders to obtain the distances between the source and target to obtain a 1 um resolution in the plane of depth.
- The printing material is flexible; there are many existing materials but, as demonstrated by K.I.T., quartz and other exotic recipes are possible (see bottom right).



Nature **volume 544**, pages 337–339 (20 April 2017)

First samples under a microscope

First look at low-end SLA, Formlabs 2 printer

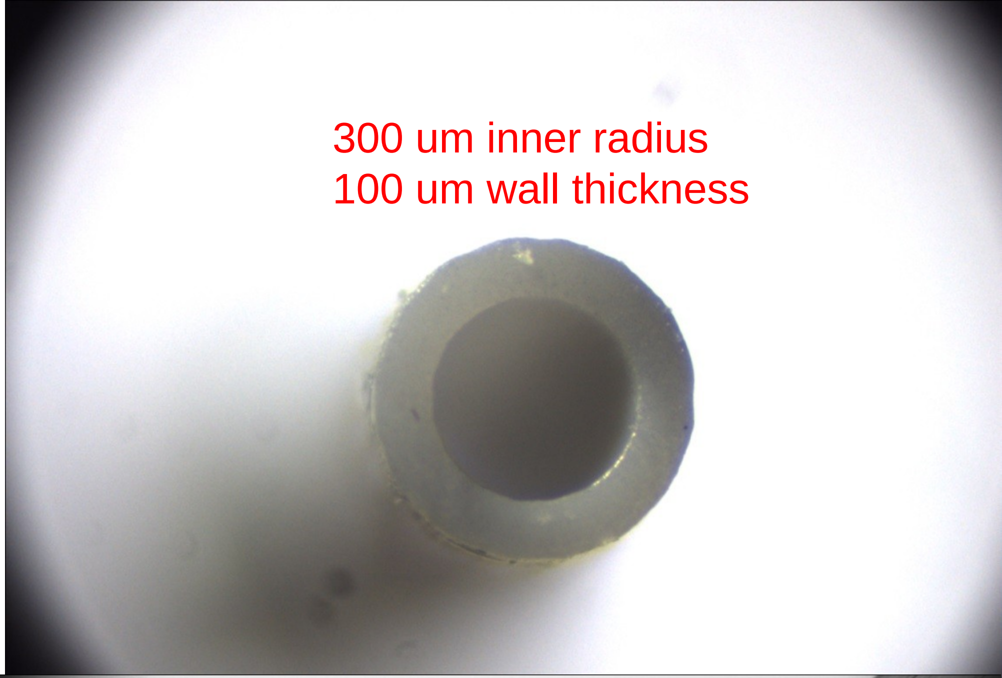
- A Formlabs 2 (140 um) is at DESY in the uTCA group, used primarily to print component cases etc.
- Johannes Zink was kind enough to print some samples for us.
- Some sample defects are apparent in the cases the DLW are not printed vertically.

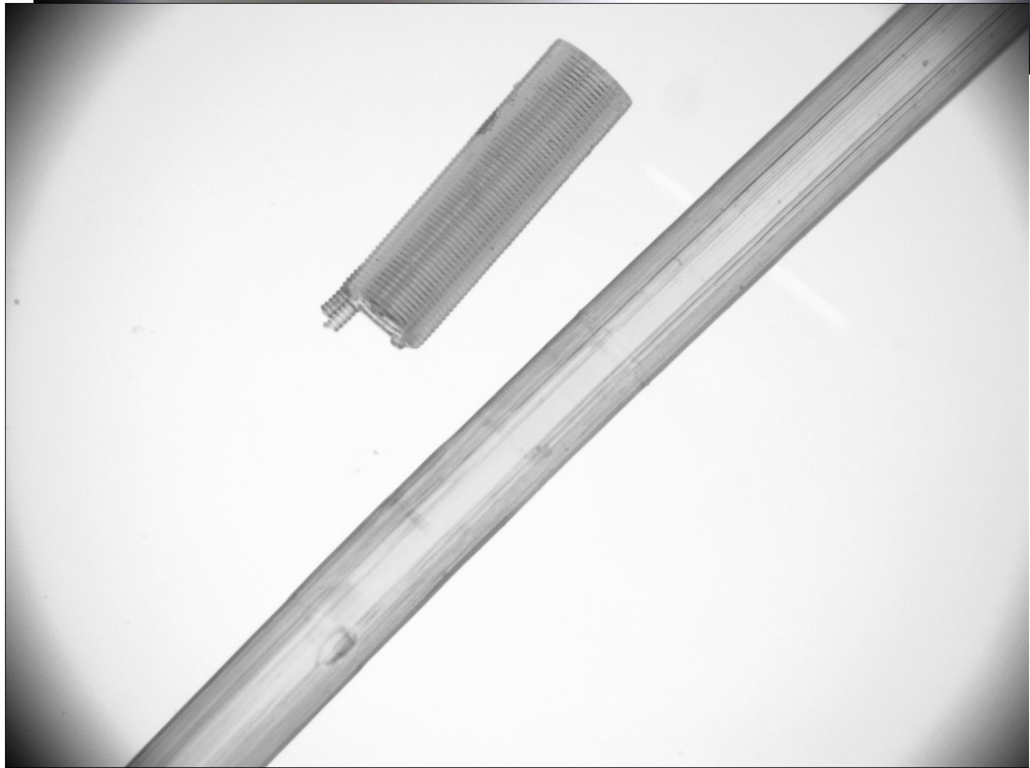
300 um inner radius
100 um wall thickness

First samples under a microscope

Looking at the ASIGA 27 um MAX X

- We reached out to ASIGA, they put us in contact with a local German host and they were kind enough to send us samples.
- Shown top right is a head on view of the vertically printed DLW.
- Shown bottom right are two DLWs printed vertically and horizontally (top, bottom respectively).
- We used a calibration mask to analyze the size of the structure (see next slide). We measured the outer diameter to be 801 um, by averaging the two depth of field measurements. We ordered a DLW with 800 um outer diameter, there is of course some associated error in our measurement from the depth of field but we would rather measure the spectroscopic properties of the DLW in more detail.





Conclusion

- Dielectric lined waveguides have tremendous potential in accelerator science.
- They have been shown to manipulate and accelerate electron beams, and also have applications in radiation generation.
- Now testing 3D printed structures with THz EOS setup.

Acknowledgements

Vasili , Michael, Arsham, Bagrat and the entire CANDLE team for fruitful discussions.

Klaus, Martin, Igor

Philippe Piot,

Frank Mayet, Thomas Vinatier, Ulrich Dorda, Dongfang Zhang, Moein Fakhari, Max Hochman, Ralph Assmann, Max Kellermeier, Luca Genovese,

Frank Stephan, Mikhail Krasilnikov and the PITZ team.

Thank you, questions?