Measurement of wakefields in hollow plasma channels

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in collaboration with Spencer Gessner (CERN)
presented by Erik Adli (University of Oslo)

FACET-II Science Workshop
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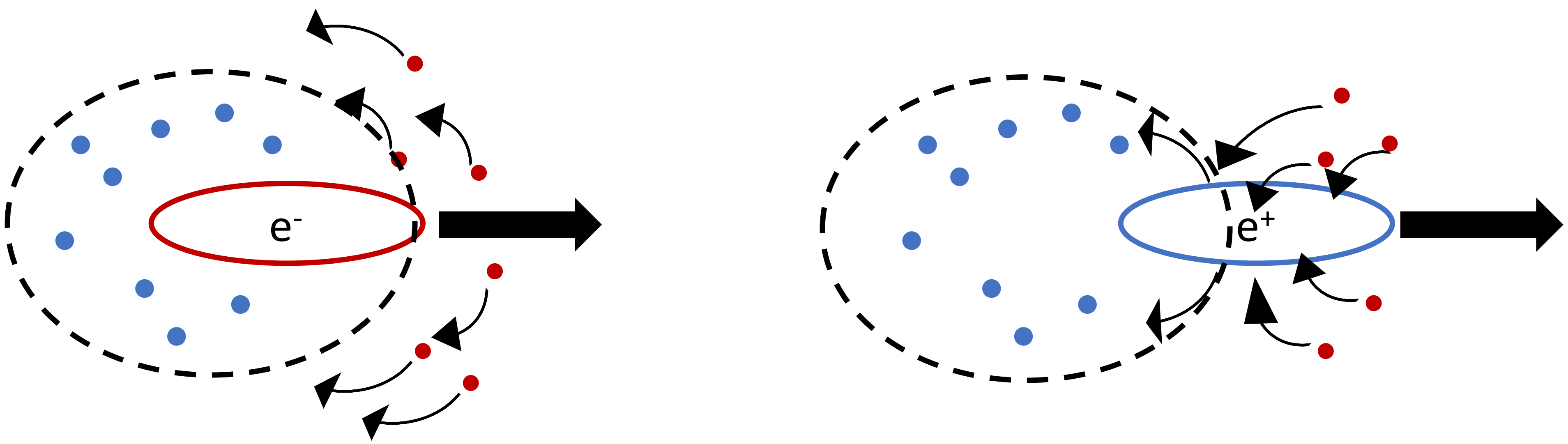
EAAC
2017

Motivations for the hollow plasma channel

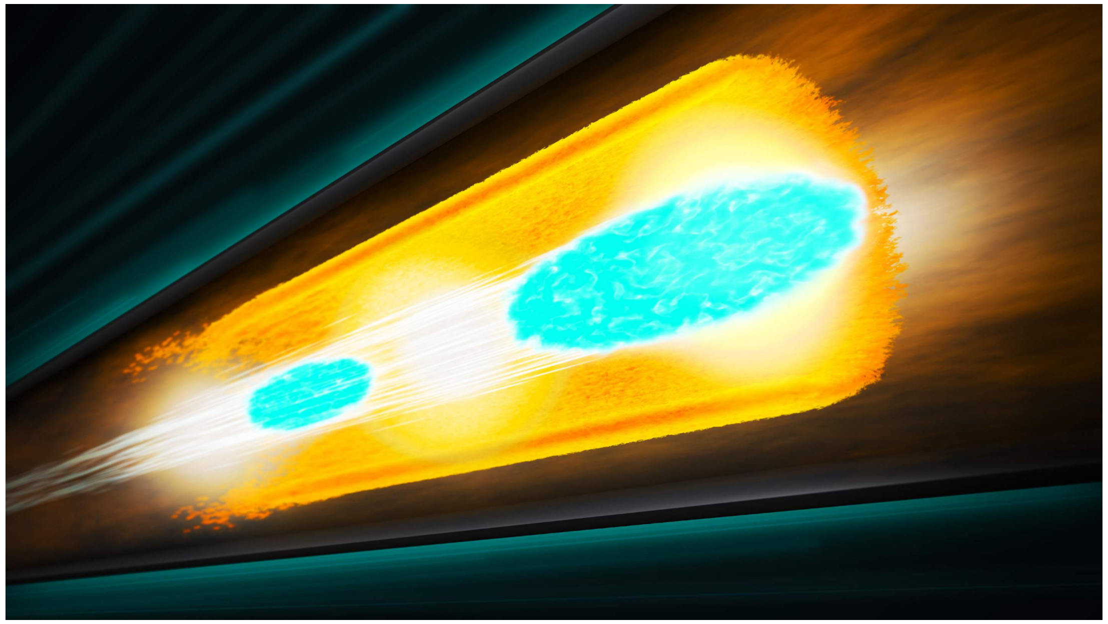
An intrinsic charge asymmetry

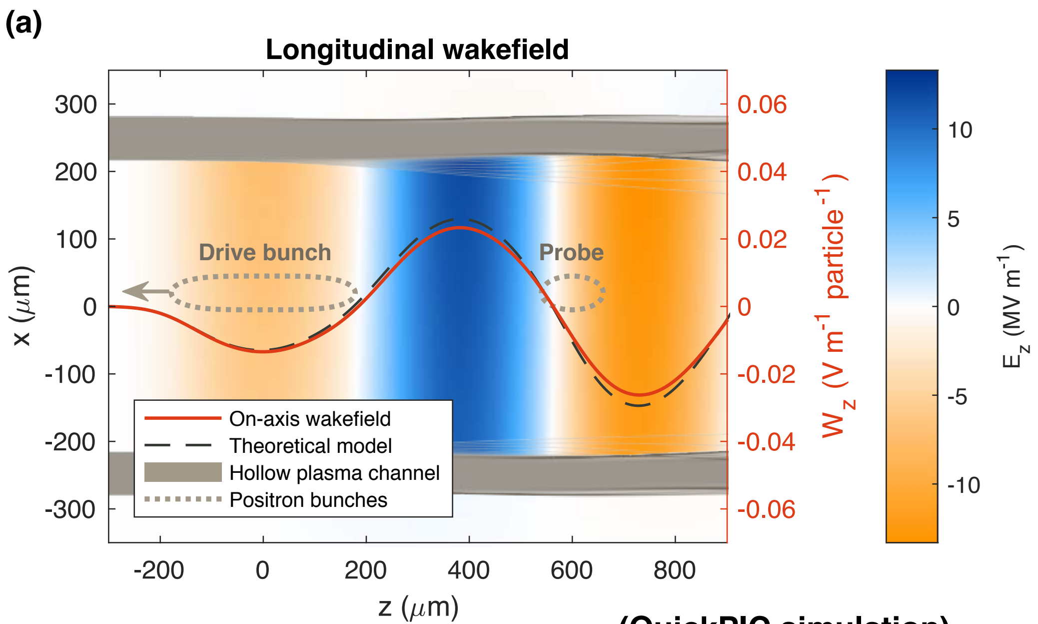


$m_i >> m_e$

- Plasmas have a problem that conventional accelerating structures do not: an intrinsic charge asymmetry.
- Even if we have a mechanism for accelerating electrons, this does not extend to positrons.

Hollow plasma channels





(QuickPIC simulation)

- A hollow plasma channel is a proposed method to symmetrize the charge response and allow high gradient positron acceleration.

- Principle:
  – A positron bunch propagates <u>in the centre</u> of the hollow plasma channel
  – The channel wall is perturbed, driving an oscillating longitudinal wakefield
  – A trailing positron bunch is placed in the <u>accelerating</u> phase of the wakefield

- Benefit of hollow plasma channels: In principle, <u>no focusing forces</u> inside

Analytical expressions for hollow channel modes exist

m=0, longitudinal mode

$$W_{z0}(z) = \frac{ek_p\chi_{\parallel}^2}{2\pi\epsilon_0 a}\frac{B_{00}(a,b)}{B_{10}(a,b)}\cos(\chi_{\parallel}k_p z)\Theta(z). \qquad (1)$$

m=1, transverse dipole mode

$$W_{x1}(z) = -\frac{e\Delta x\chi_{\perp}}{\pi\epsilon_0 a^3}\frac{B_{11}(a,b)}{B_{21}(a,b)}\sin(\chi_{\perp}k_p z)\Theta(z), \qquad (3)$$

S. Gessner, PhD thesis, SLAC-R-1073 (2016) ,
earlier work by C. Schroeder (1999)

Misalignment leads to transverse wakefields

- Drive bunches perfectly aligned to the channel axis will give zero transverse force everywhere.
- However, misaligned drive bunches will drive **strong dipole-like (transversely uniform) oscillating transverse wakefields**.
- First discussed by C. Schroeder in 1999 ("Multimode Analysis of the Hollow Plasma Channel Accelerator").
- This leads to beam deflection and beam loss.
- This problem gets rapidly worse with stronger accelerating fields (transverse force scales faster with smaller channel radius):

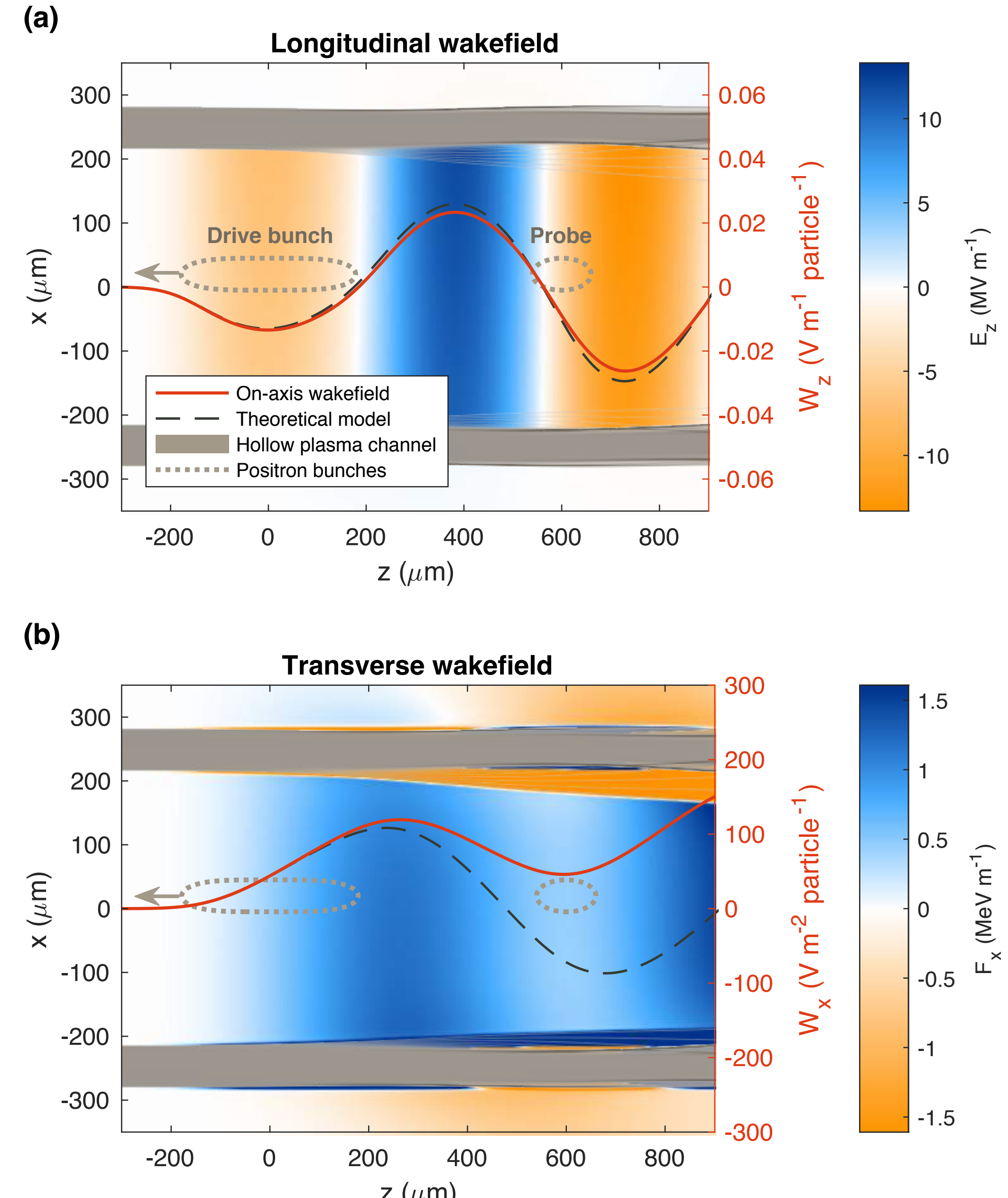
Accelerating field per particle

$$W_{||} \propto \frac{1}{a^2}$$

Transverse force per particle

$$W_{\perp} \propto \frac{1}{a^{3-4}}$$

(a: channel inner radius)



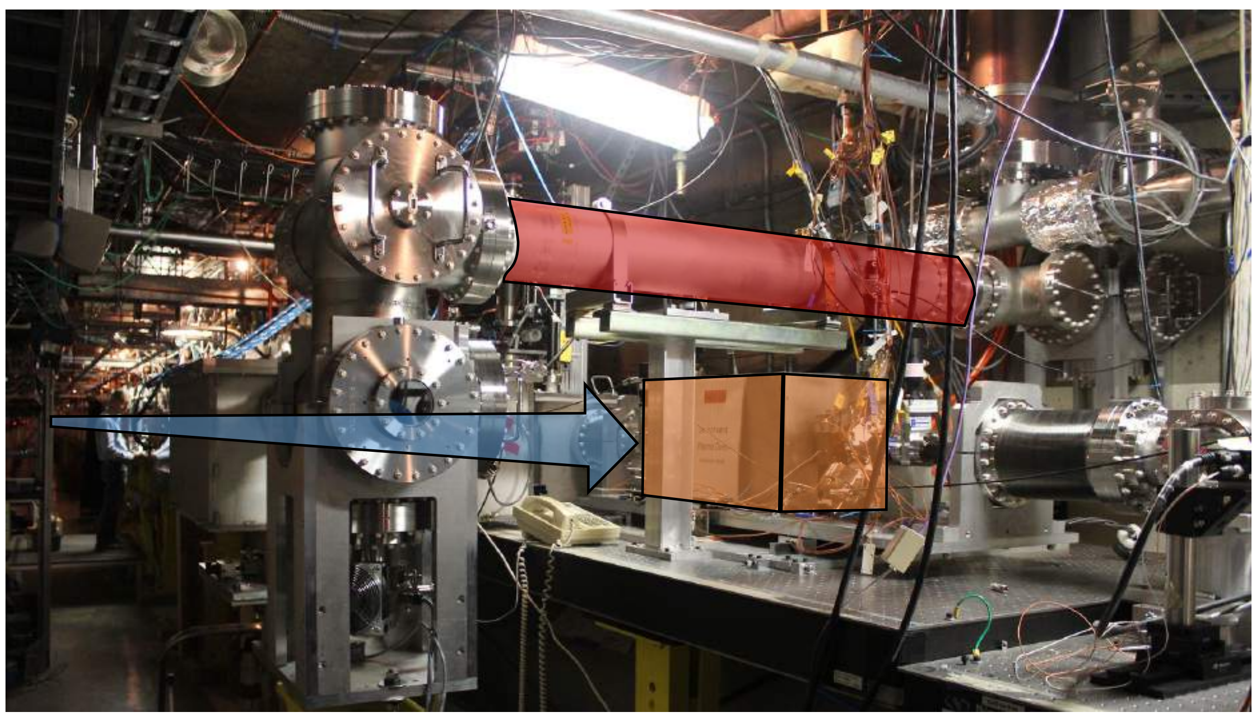
(QuickPIC simulation)

- Many orders of magnitude stronger wakefields compared to CLIC
  - Hollow channel (500 μm diameter, 3x1015 cm-3): ~1 000 000 V/pC/m/mm
  - CLIC (8 mm diameter, copper): ~10-100 V/pC/m/mm

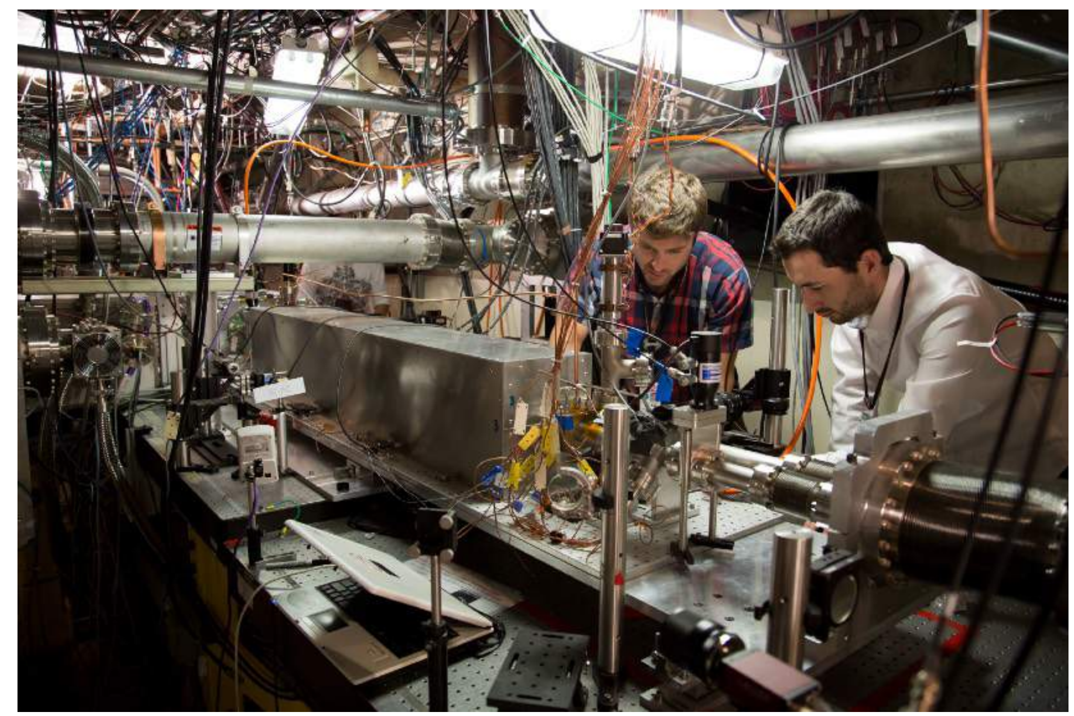
Experiments at FACET

The E225 experiment

- FACET hosted the dedicated hollow plasma channel E225 experiment, lead by Spencer Gessner
- The main aim was to demonstrate positron acceleration in a hollow channel, but also to investigate transverse wakefields



FACET experimental area, showing positron beam (blue), ionising laser (red) and lithium vapor oven (orange).
Image source: Spencer Gessner

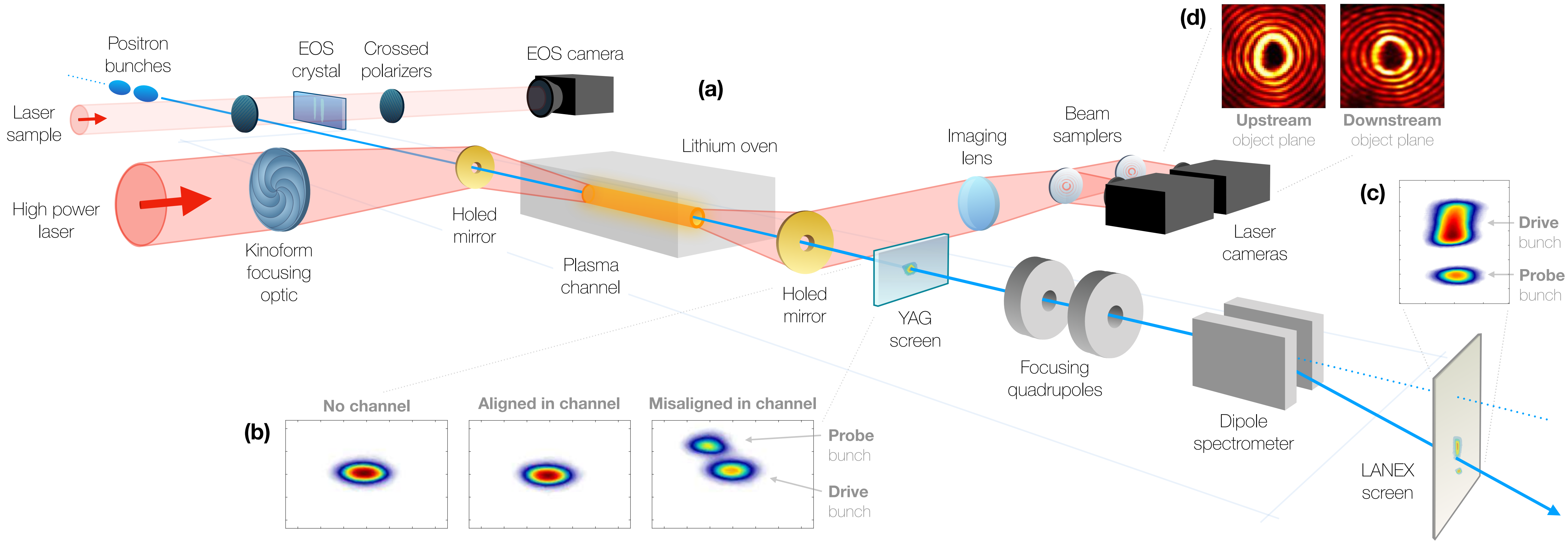


Spencer Gessner (left) and Sebastien Corde (right) at FACET.
Image source: SLAC National Accelerator Laboratory

FACET

SLAC NATIONAL ACCELERATOR LABORATORY

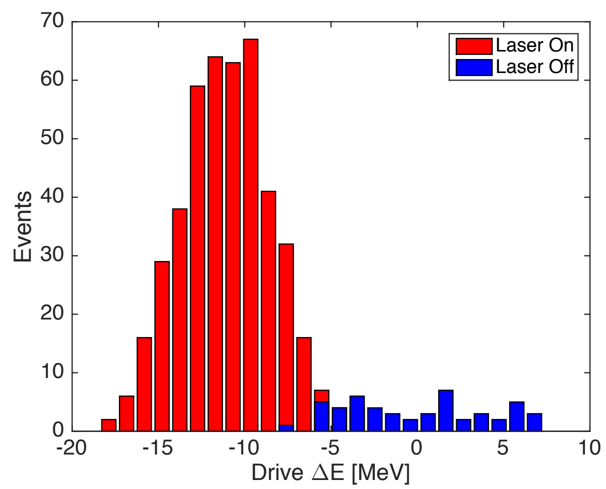
E225 – Experimental setup

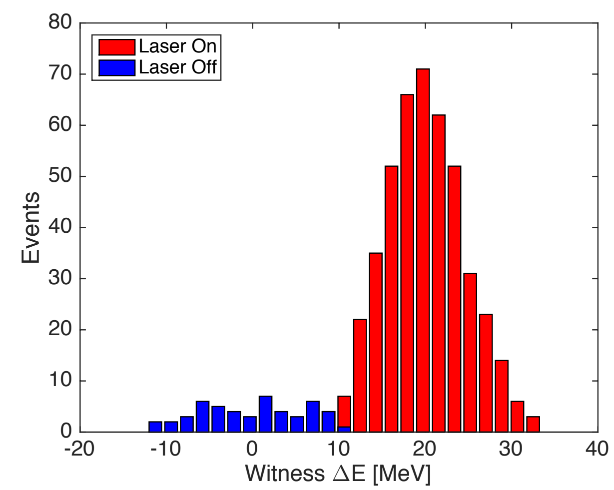


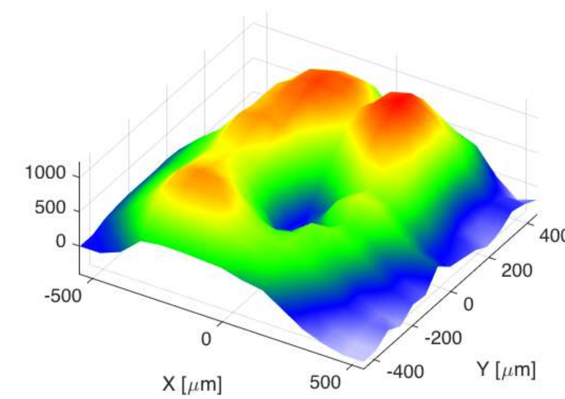
- The SLAC linac provided **two 20 GeV bunches**, made from one bunch using a beam notching device.
- The FACET laser (up to 10 TW, 60 fs pulses) was adjusted down to ensure **no ionisation in the channel**.
- A lithium oven was set to give a neutral gas density of $3\text{x}10^{16}$ cm^{-3} (but was necessarily fully ionized).

Positrons successfully accelerated in a hollow channel

- Clear evidence of energy gain for the positron witness bunch, while there is energy loss for the positron drive bunch.

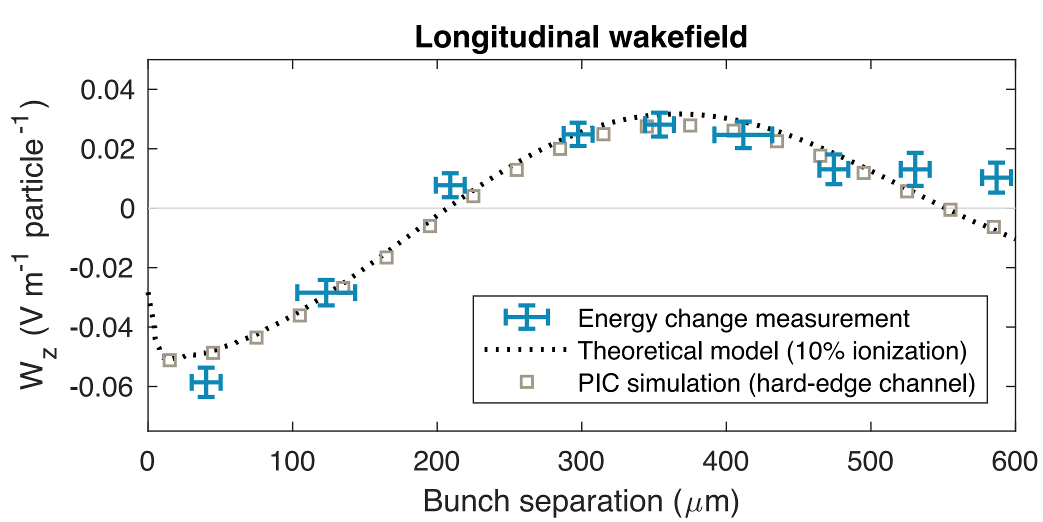






Reconstruction of the plasma channel based on kick measurements

- A scan of bunch separations shows the energy gain (or loss) depends on the phase.



The transverse wakefield experiment

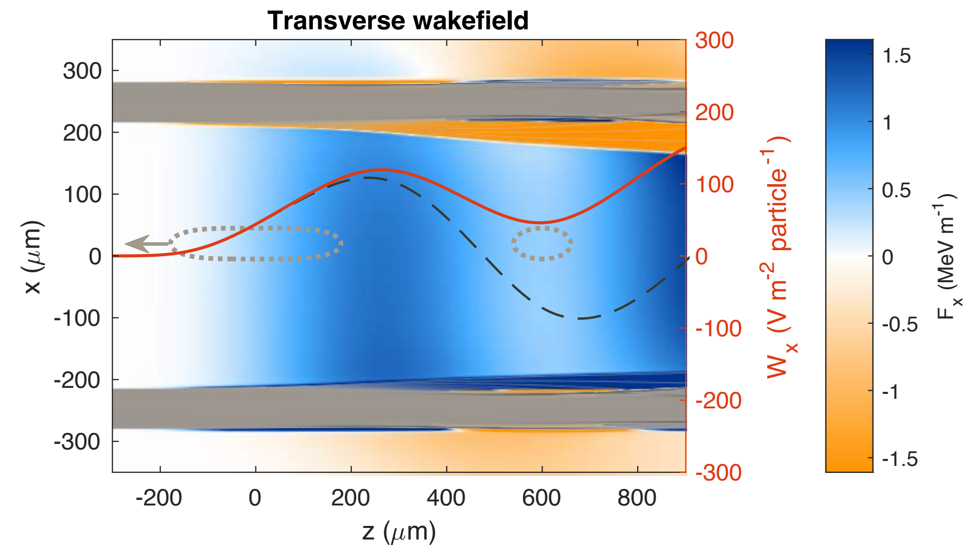
- Our **goal** was to **measure the how the transverse wakefield varied longitudinally**.

- The probe bunch observing the wakefield is deflected angularly (kicked) when the channel and the drive bunch are relatively offset.

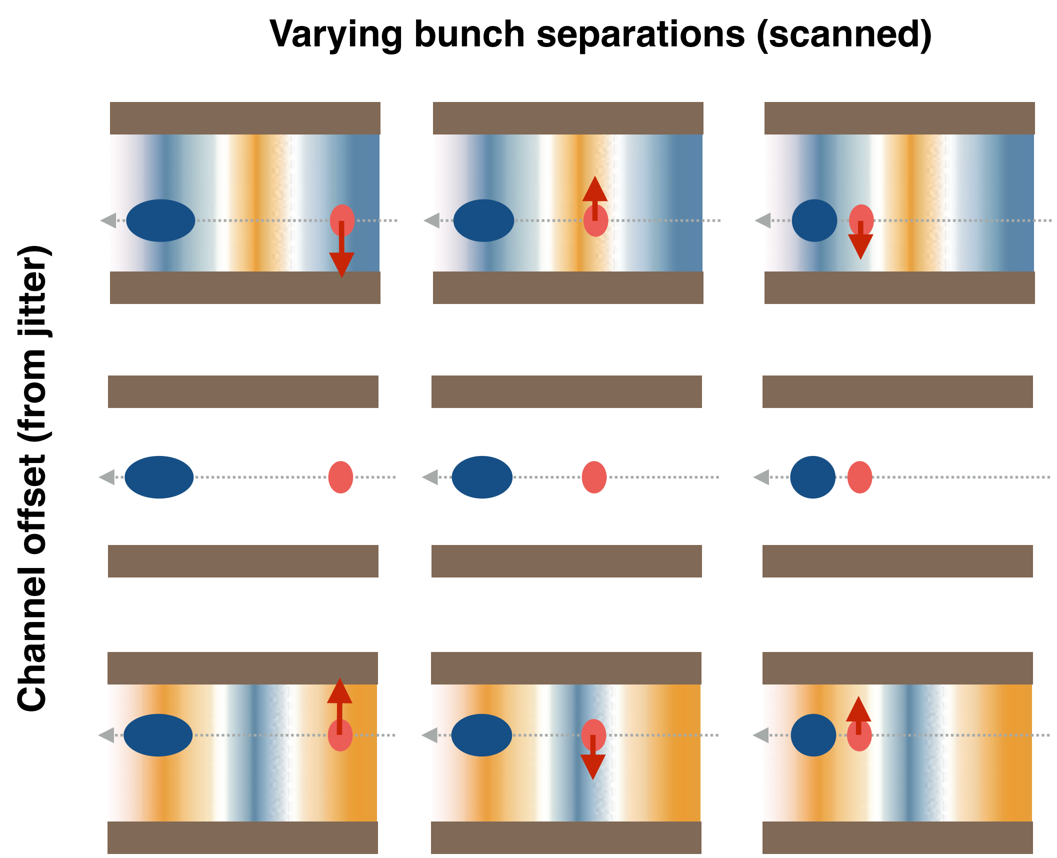
- The experiment performed was:
  Transverse channel offsets for various bunch separations
  – The channel (250 μm radius) was offset by transverse laser jitter (20-40 μm rms)
  – The bunch separation was varied by stretching the bunch and adjusting the notching device.

- Diagnostics:
  – Laser offset imaged downstream (**laser cameras**).
  – Probe kick measured on a **spectrometer** (in the non-dispersed plane).
  – Bunch separation measured using an **electro-optical sampler**.

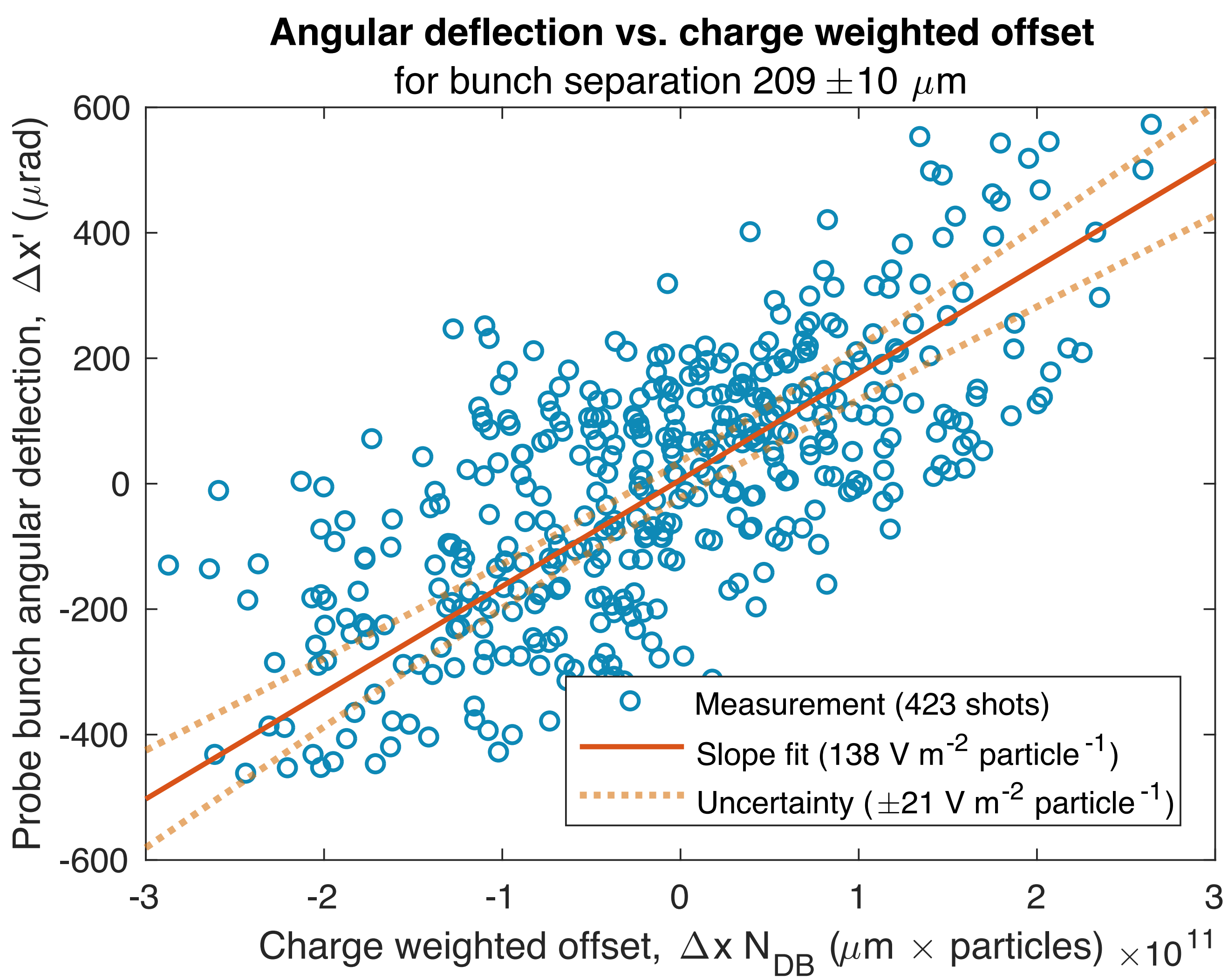
Prediction:



Experiment (2D “scan”):



Observed data (deflection vs. channel offset)



- For each bunch separation, a correlation between channel offset and probe bunch angular deflection was observed.
- The **slope of this correlation is proportional to the transverse wakefield per offset** at the z-location of the probe bunch.

Another independent measurement

- An independent measurement is beneficial (due to high complexity).
- It is possible to estimate the transverse wakefield per offset from the measured longitudinal wakefield, via the Panofsky-Wenzel theorem and the linear model.

Panofsky-Wenzel theorem:

$$\frac{\partial W_x}{\partial z} = \frac{\partial W_z}{\partial x}$$

Integrate (++) →

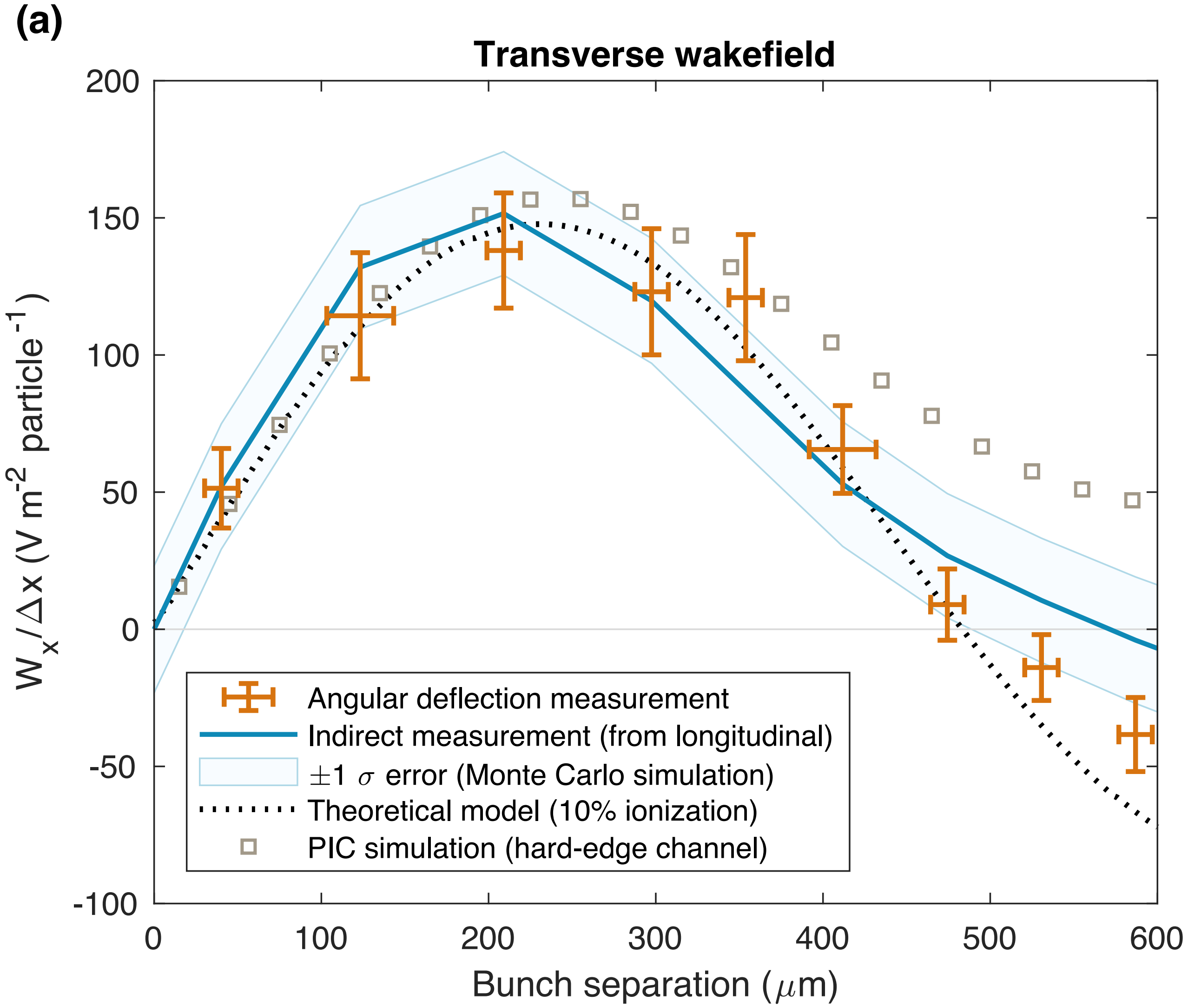
Estimate of transverse from longitudinal wakefield:

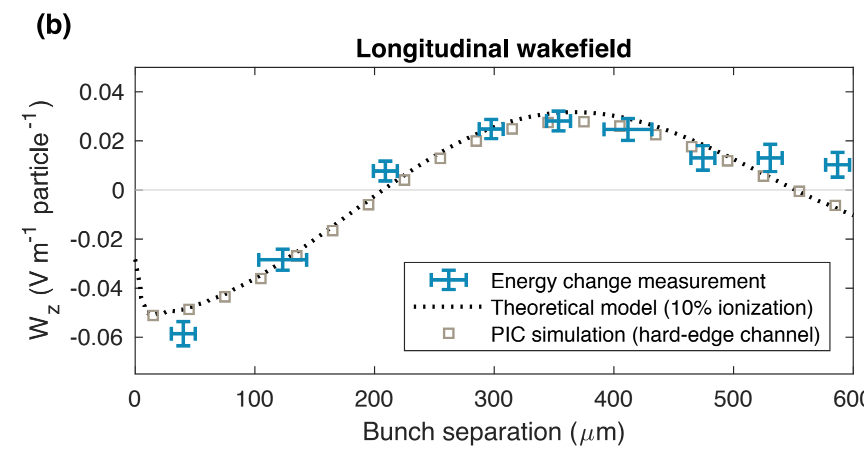
$$\frac{W_x(z)}{\Delta x} \approx -\frac{\kappa(a,b)}{a^2} \int_0^z W_z(z') dz'$$

where $\kappa(a,b) = \frac{4\chi_\perp^2 - 2}{\chi_\parallel^2 - 1}$

- Not perfect: Assumes linear model, breaks down far behind the drive bunch.
- Provides verification of numerical calibrations, etc.
- The longitudinal wakefield was measured by the energy change of the probe bunch (on a spectrometer).

Final experimental results





- Plasma density determined by a wavelength fit (10% ionization = 3×10^{15} cm^{-3})
- Good fit, largely consistent with theory. Some discrepancy at larger separations.

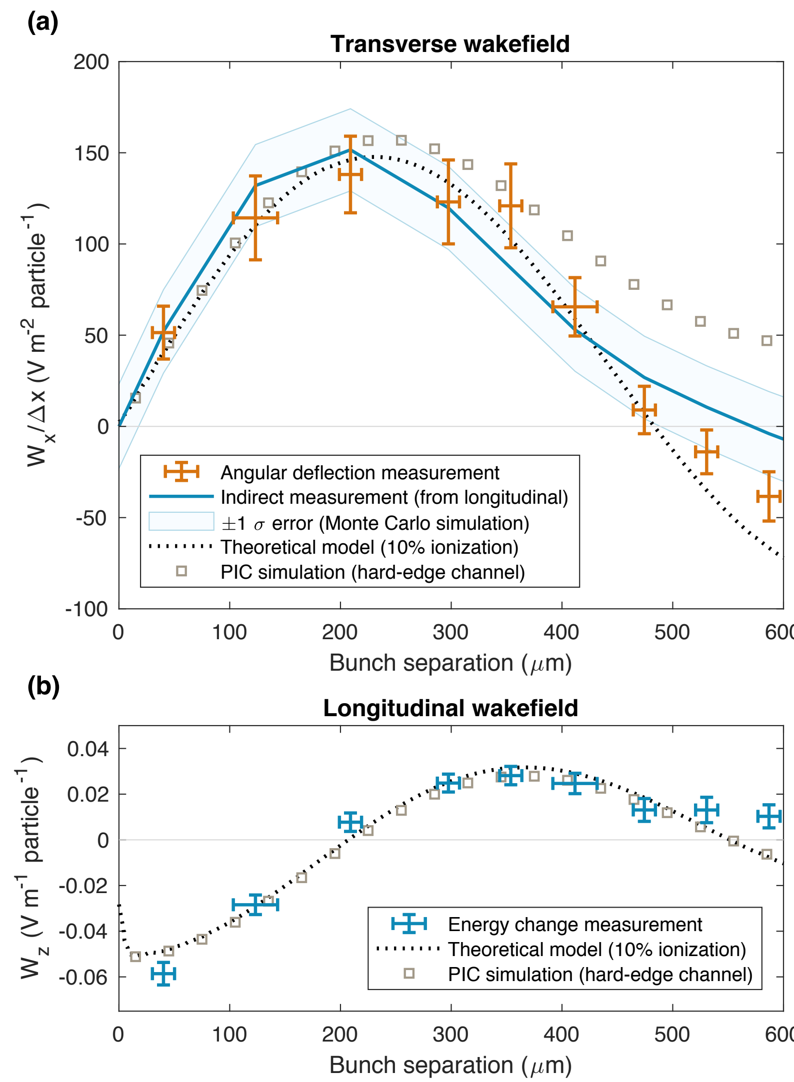
Implications

- **Overall, the measurement agrees with the theoretical models.**

- Simulation-based parameter scans indicate that the discrepancy at large separations can possibly be explained by using a more complex radial plasma shape (not possible to exclude with our diagnostics).

- Implication:
  – There is indeed a strong transverse wakefield, as expected.
  – This needs to be mitigated for the hollow channel to be useful.

- Submitting these results to Physical Review Letter.

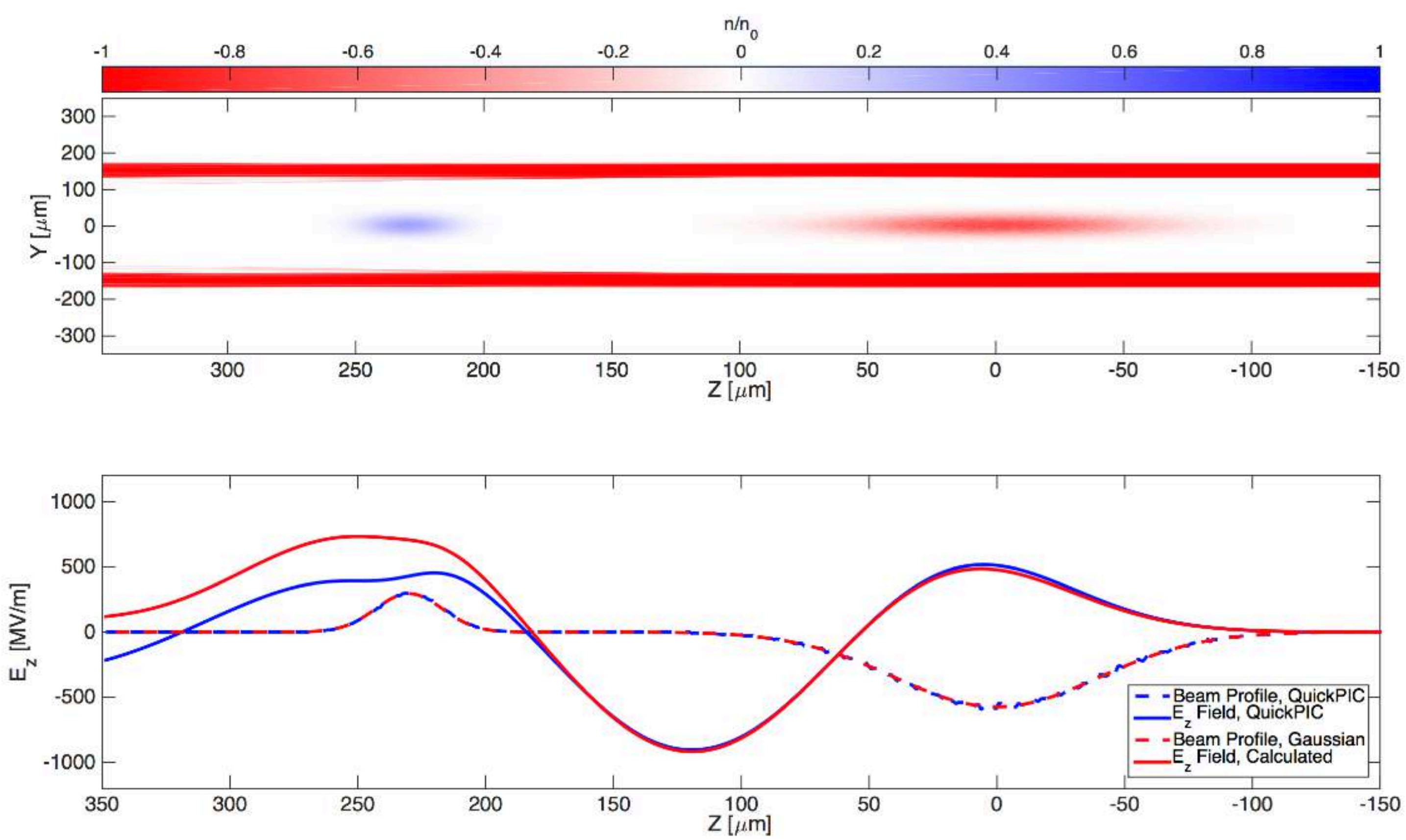


Future directions

Positron acceleration should be electron driven

- Wall plug-to-beam efficiency is key to high energy colliders

- Therefore, ideally a plasma-based linear collider is electron driven (or proton driven) because positrons are energy intensive to produce.



Electron driven positron acceleration in a hollow plasma channel.
Image source: ***S. Gessner thesis, SLAC-R-1073***

Two big challenges for hollow plasma channels

Problem #1 (fundamental)

Suppressing the transverse wakefield

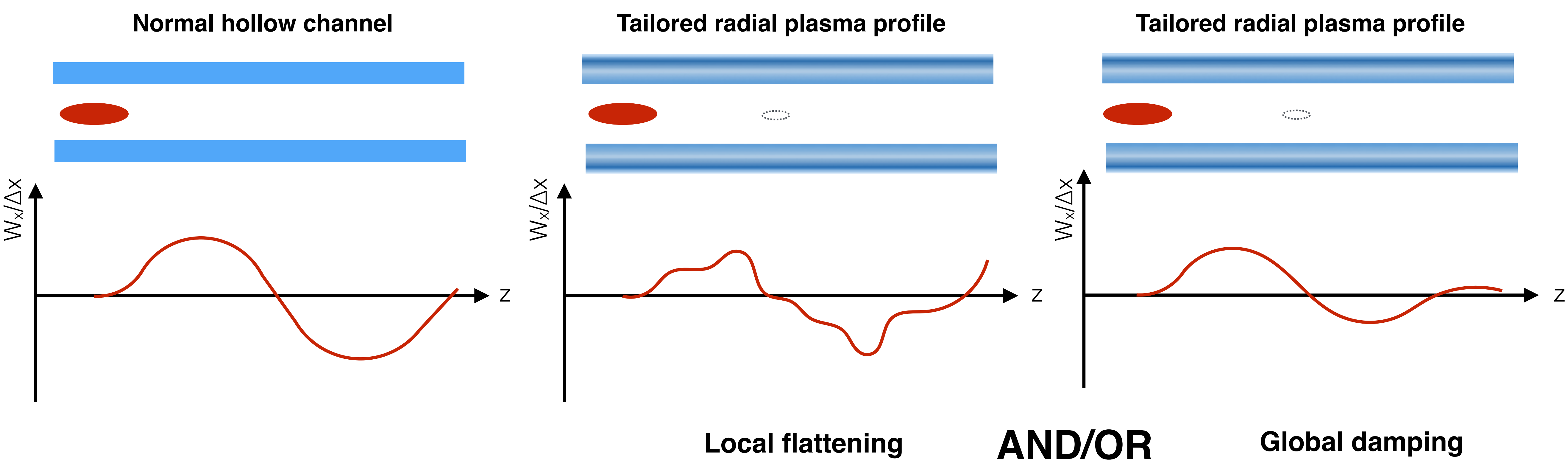
Problem #2 (technical)

Creating an on-axis vacuum

Suppressing the transverse wakefield (one interesting pathway)

- The wakefields are determined in part by the radial plasma profile n(r).
- Speculation: A suitably tailored radial profile may damp (locally or globally) the transverse wakefield, while sustaining a non-zero accelerating field

  (ref. G. Shvets "Excitation of Accelerating Wakefields in Inhomogeneous Plasmas", 1996)



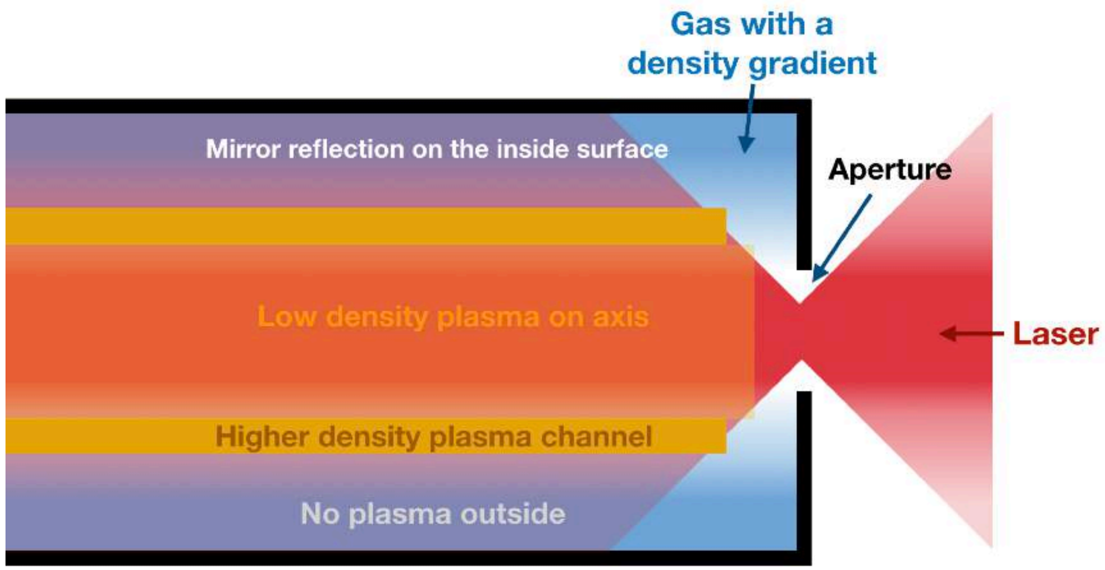
Creating a vacuum on axis

- Eventually, we need to have a vacuum on axis, to avoid beam ionisation.

- **Centrifuge technique**, where the gas density is approximately exponentially decaying towards the axis.

- **Cryo-cooled gas cluster** technique (used for corrugated plasma channels by H. Milchberg)

- These ideas can potentially be tested in the laser labs at UCLA or UC Boulder.



Gas centrifuge

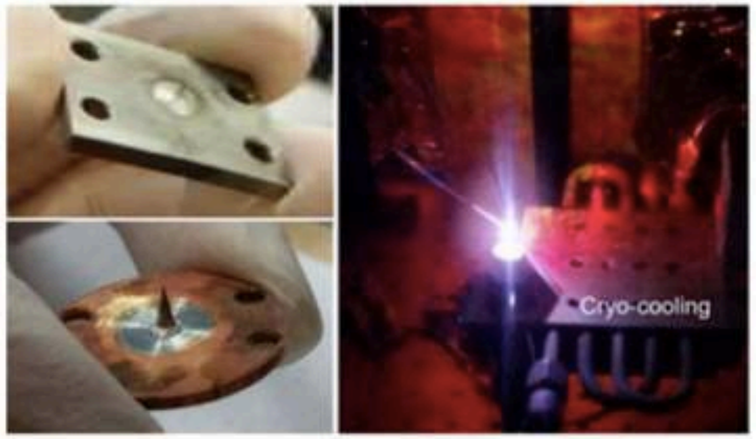


Image source:
H. Milchberg (Uni Maryland), EAAC2017 talk

Conclusion

- Hollow channels are promising, supporting very strong longitudinal wakefields.
- However, they also support very strong well as transverse wakefields (leading to beam loss)
- Positrons were accelerated in a hollow plasma channel!
- The transverse wakefield was measured experimentally, and found largely consistent with theory.
- Suppression mechanisms for the transverse wakefield is key to the survival of the hollow channel.

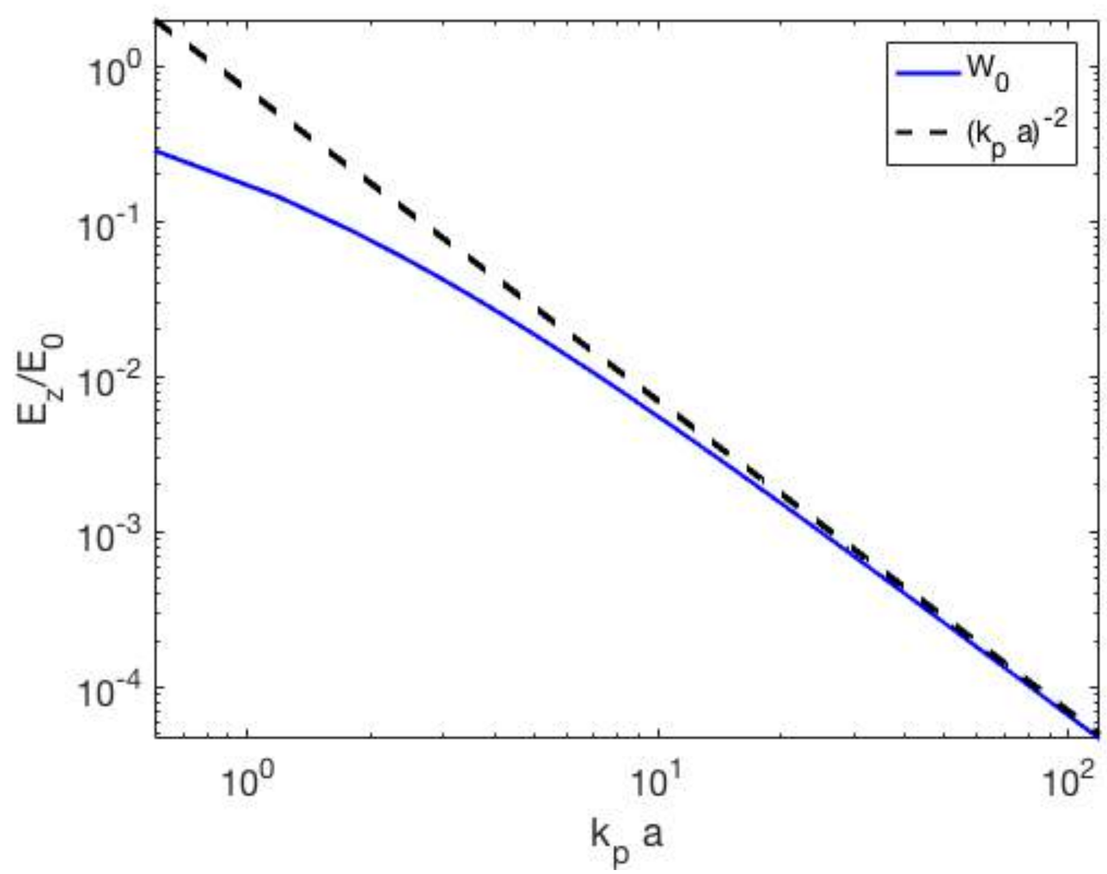
Ideas for FACET-II hollow channel experiments

- Radial tailoring of the hollow channel profile (laser shapes, time delays, etc.)
- On-axis vacuum (centrifuges, cryo-cluster flow, etc.)
- Electron-driven hollow channel positron acceleration.

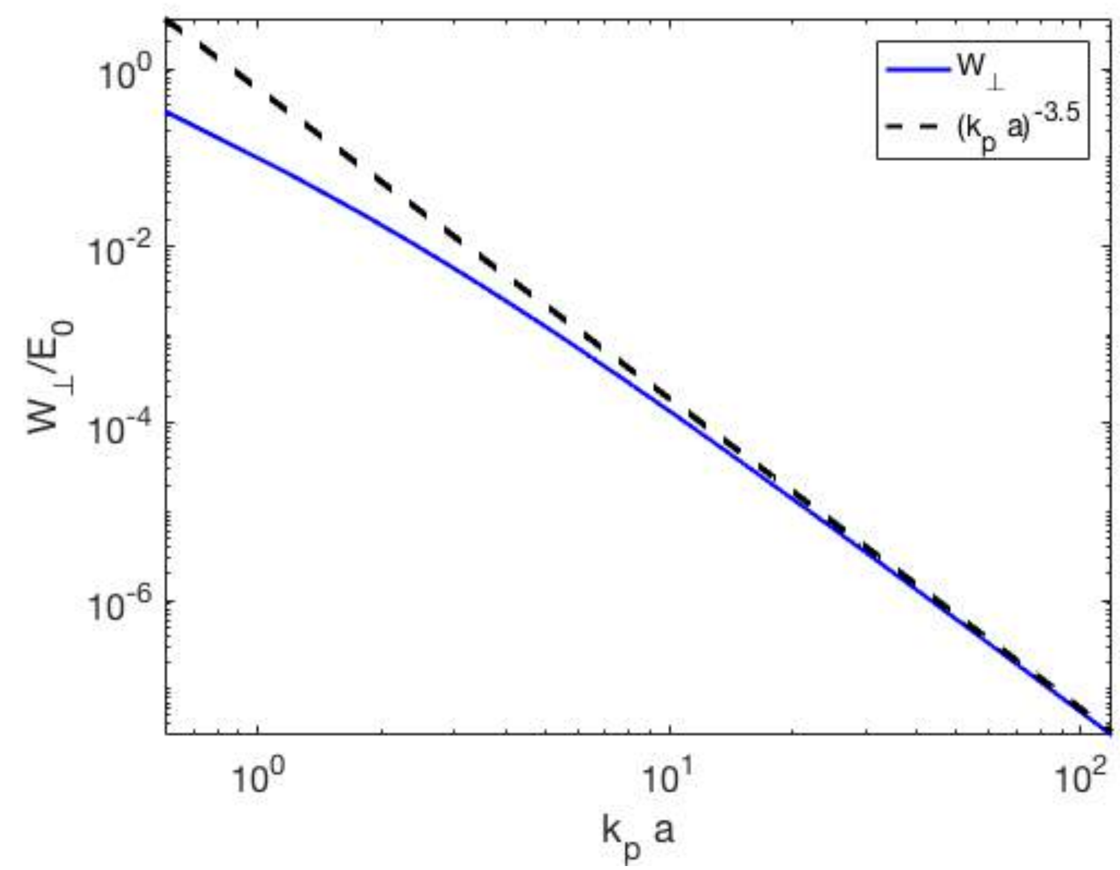
Thank you for your attention!

Dependence on channel radius

Longitudinal wakefield



Transverse wakefield



by Spencer Gessner