Tunable photocathode two-bunch mode for advanced accelerator application

FACET-II

Facility for Advanced Accelerator Experimental Tests

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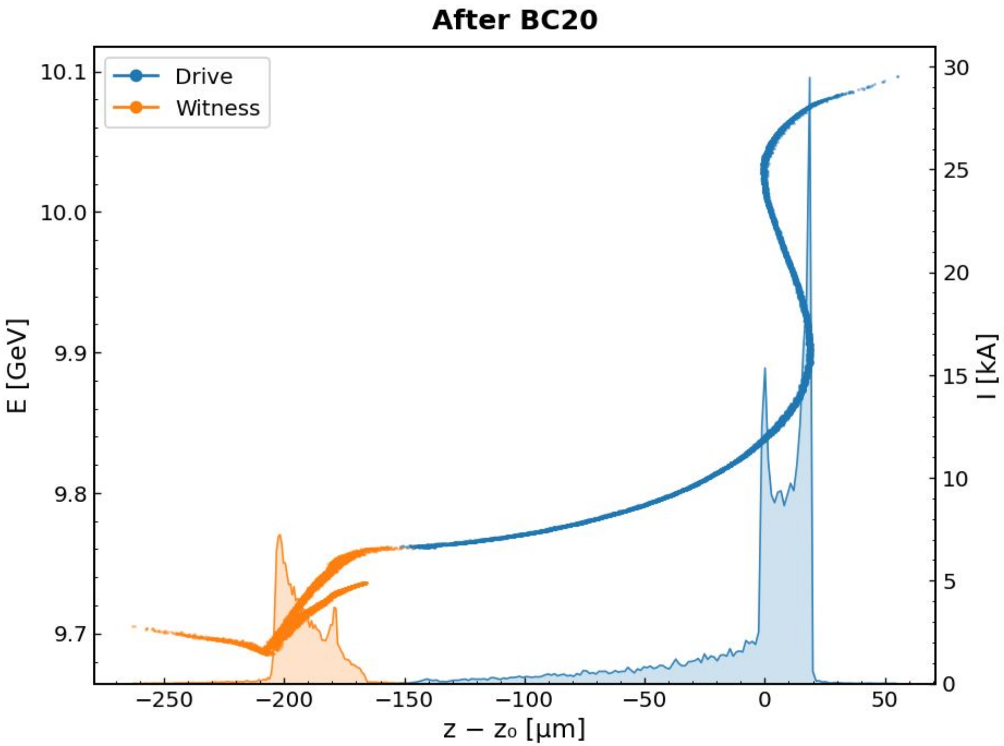
Two-bunch PWFA experiment at FACET-II

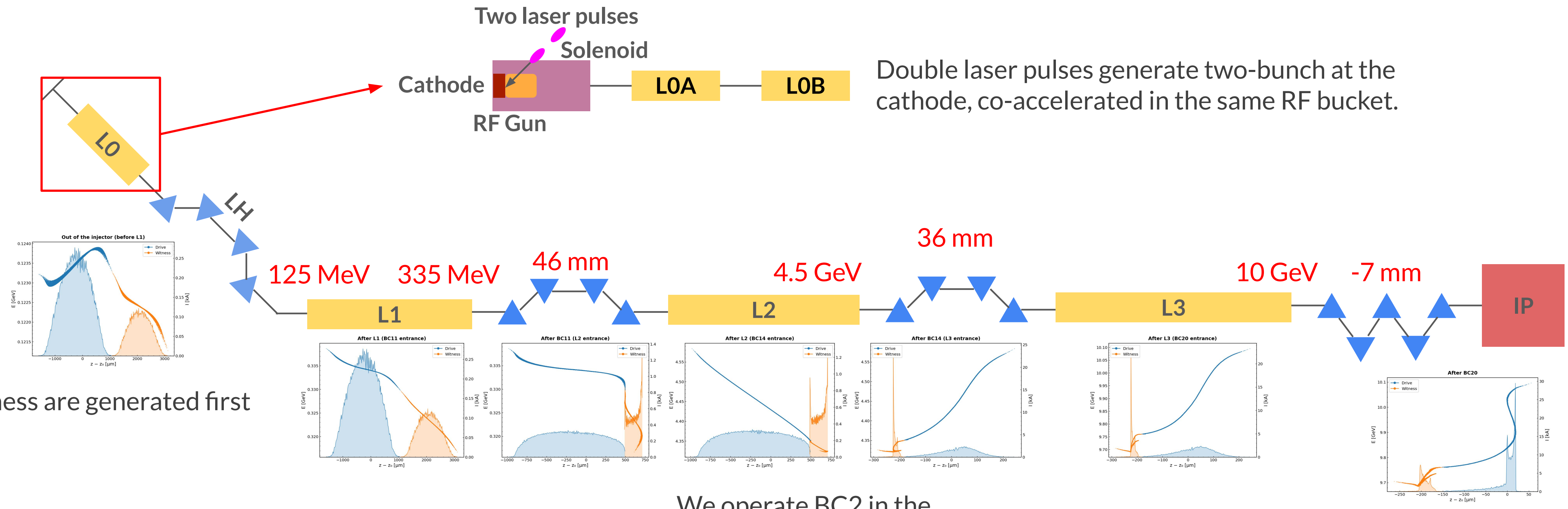
- One of the primary goals of PWFA at FACET-II (E300)
  - Demonstration of a single stage with the beam parameters required for a future plasma-based collider or light source
    - >30% energy transfer efficiency
    - multi-GeV/m energy gain (10+ GeV)
    - maintaining <1% energy spread
    - minimal emittance growth
- Drive bunch requirements
  - High current
  - Good transverse properties
- Witness bunch requirements
  - Correct spacing behind the drive
  - Correct current profile to beam-load the wake
  - Matched spot size to the plasma



Typical simulated LPS for two-bunch PWFA experiments at FACET-II

High-quality drive-witness pair with the right longitudinal and transverse properties

Two-bunch from the photocathode



Double laser pulses generate two-bunch at the cathode, co-accelerated in the same RF bucket.

Witness are generated first

We operate BC2 in the overcompress regime to swap the position of drive and witness.

Nominally, 1.2 nC driver+0.4 nC witness

Longitudinal dynamics of two-bunch with multi-stage compression is complicated

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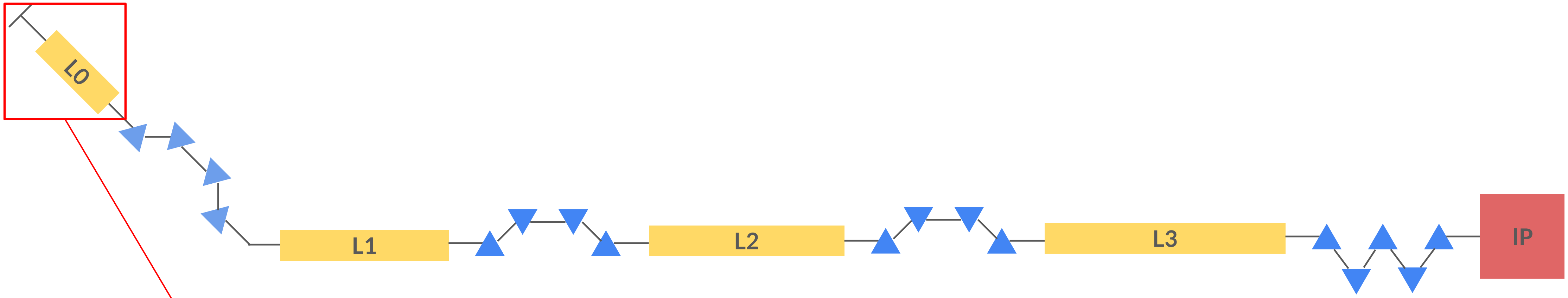
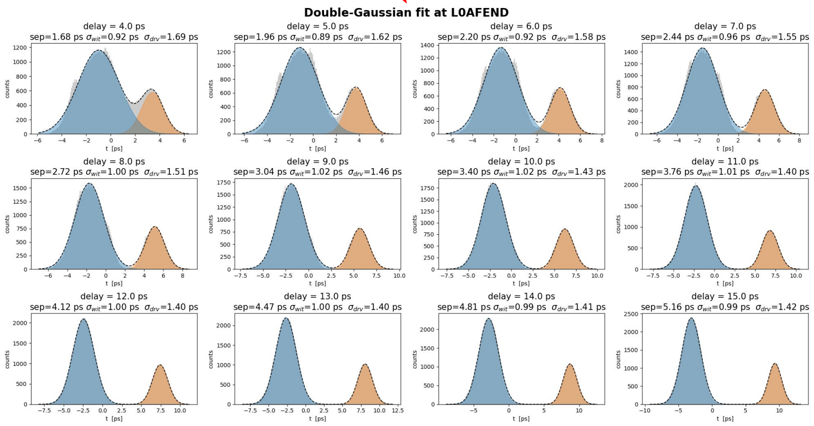
Longitudinal dynamics of two-bunch mode

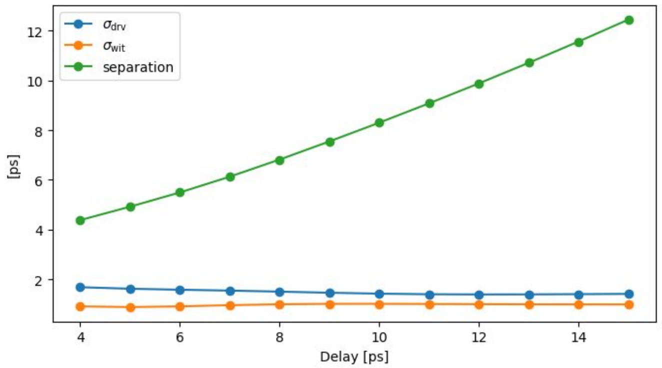
- Different experiments demand different beam
  - PWFA at different plasma density (100-250 um)
  - Plasma-based compression needs short separation to sample the wake (50-100 um)
  - How do we deliver two-bunch mode for various experiments?
- Longitudinal control knobs
  - Photocathode laser two-pulse separation (controlled by a pulse stacker)
  - L1 and L2 phase (we keep the chicane R56 fixed)
  - L3 operated on crest

Understanding the longitudinal dynamics is the key for beam delivery

Injector dynamics







- Injector dynamics dominated by velocity bunching + space-charge
- Bunch separation out of the injector roughly grows linearly as initial pulse stacker delay
- Detailed dynamics to be understood

We will treat two-bunch out of the injector as a boundary condition and understand the dynamic downstream

Longitudinal dynamics with compression

- Things we want to track
  - Bunch separation
  - Energy offset
  - Individual bunch length
    - This is extremely important for PWFA

We adapt the formalism in Z. Zhang et. al. for analytic tracking

Article | Open access | Published: 06 March 2015

High-intensity double-pulse X-ray free-electron laser

A. Marinelli, D. Ratner, A.A. Lutman, J. Turner, J. Welch, F.-J. Decker, H. Loos, C. Behrens, S. Gilevich, A.A. Miahnahri, S. Vetter, T.J. Maxwell, Y. Ding, R. Coffee, S. Wakatsuki & Z. Huang

Nature Communications **6**, Article number: 6369 (2015) | Cite this article

Longitudinal dynamics of twin electron bunches in the Linac Coherent Light Source

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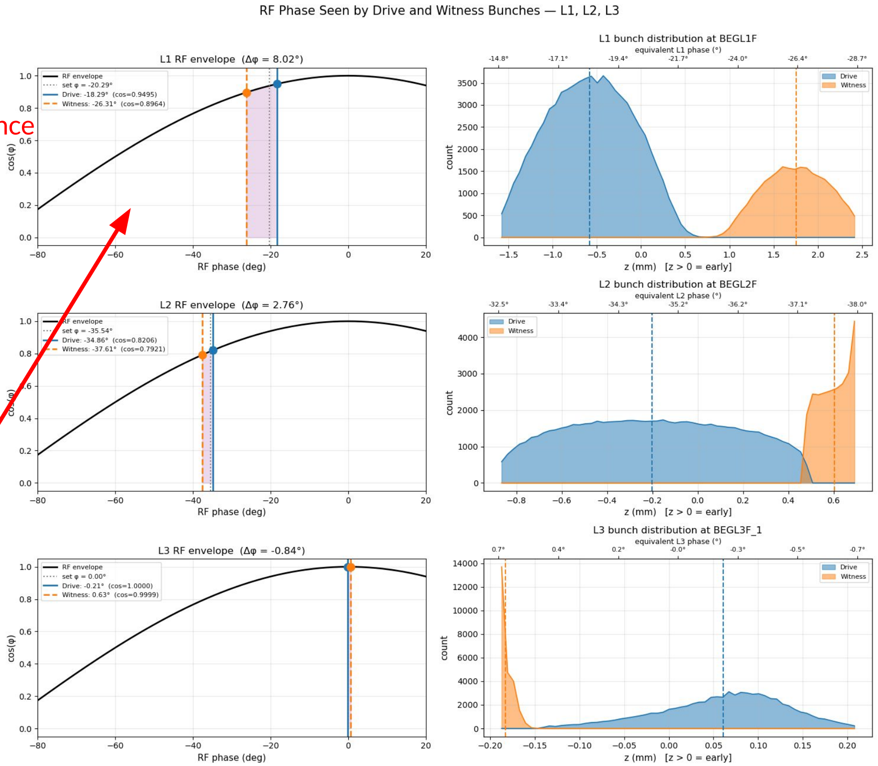
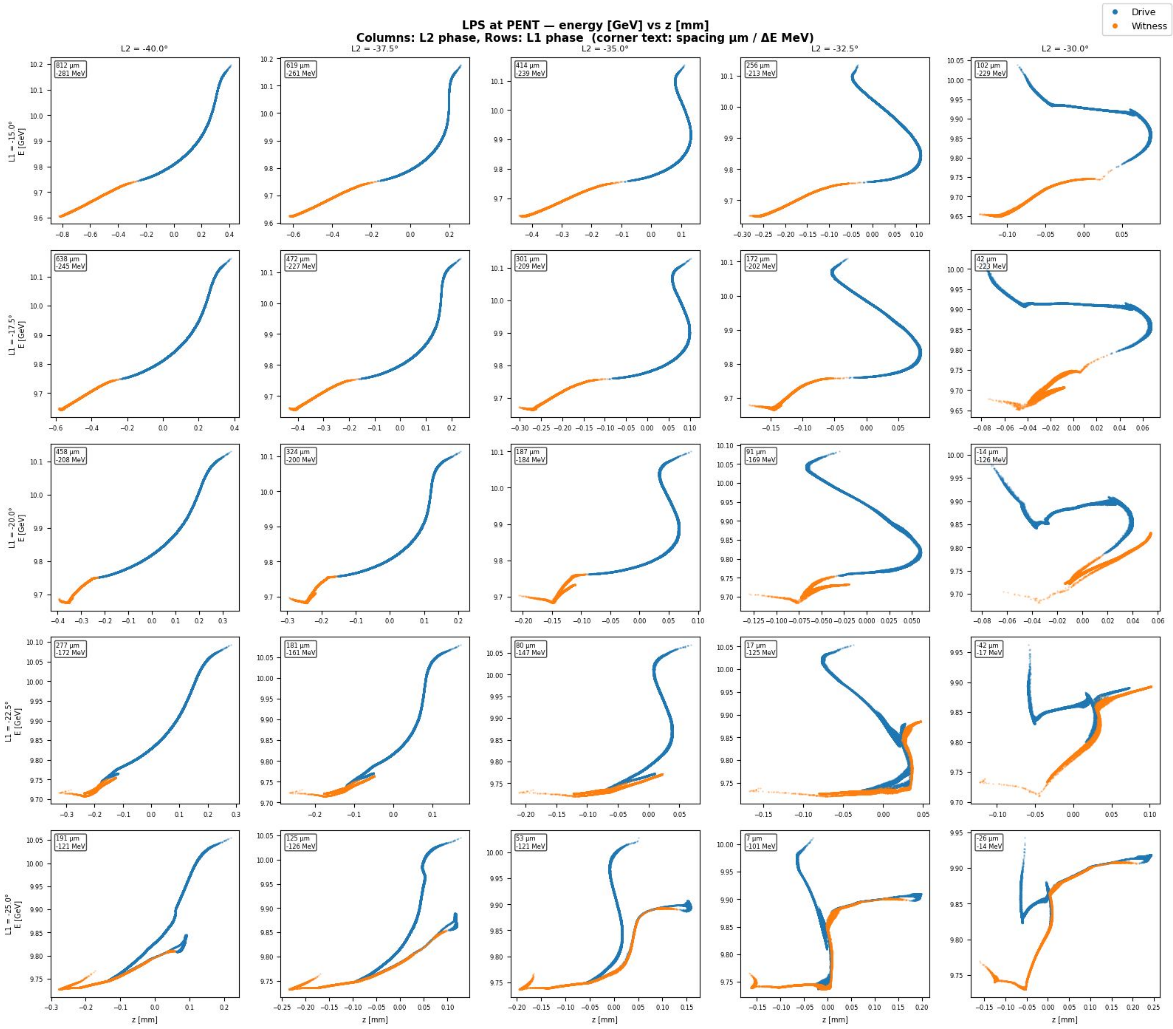
Two-bunch experience ~10 deg RF phase difference in L1

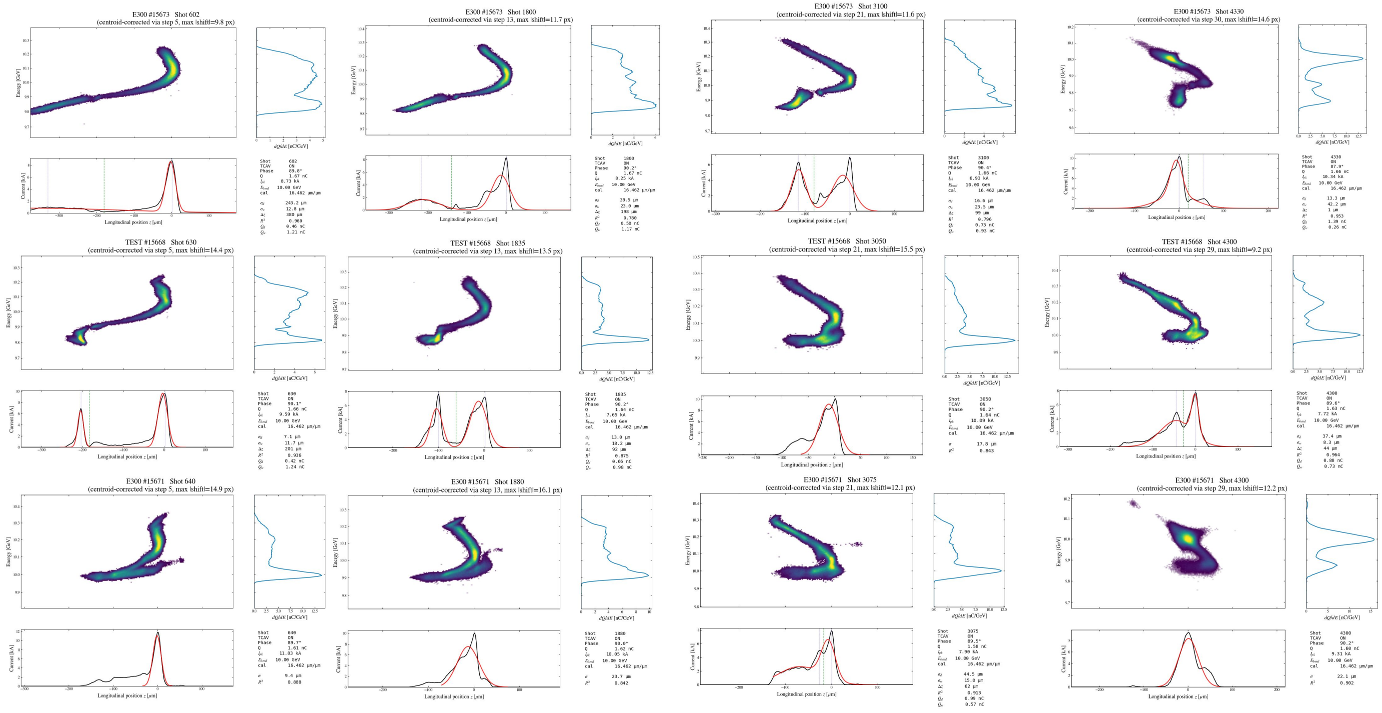


- Main difference from LCLS two-color mode
  - Asymmetric charge
    - We typically operate at 3:1 charge ratio
  - Bunch charge an order of magnitude higher
    - Much stronger collective effect e.g. longitudinal wakefield
  - Targeting larger bunch separation
    - Different bunch experience very different RF phase

RF phase tracking and longitudinal wakefield is the key

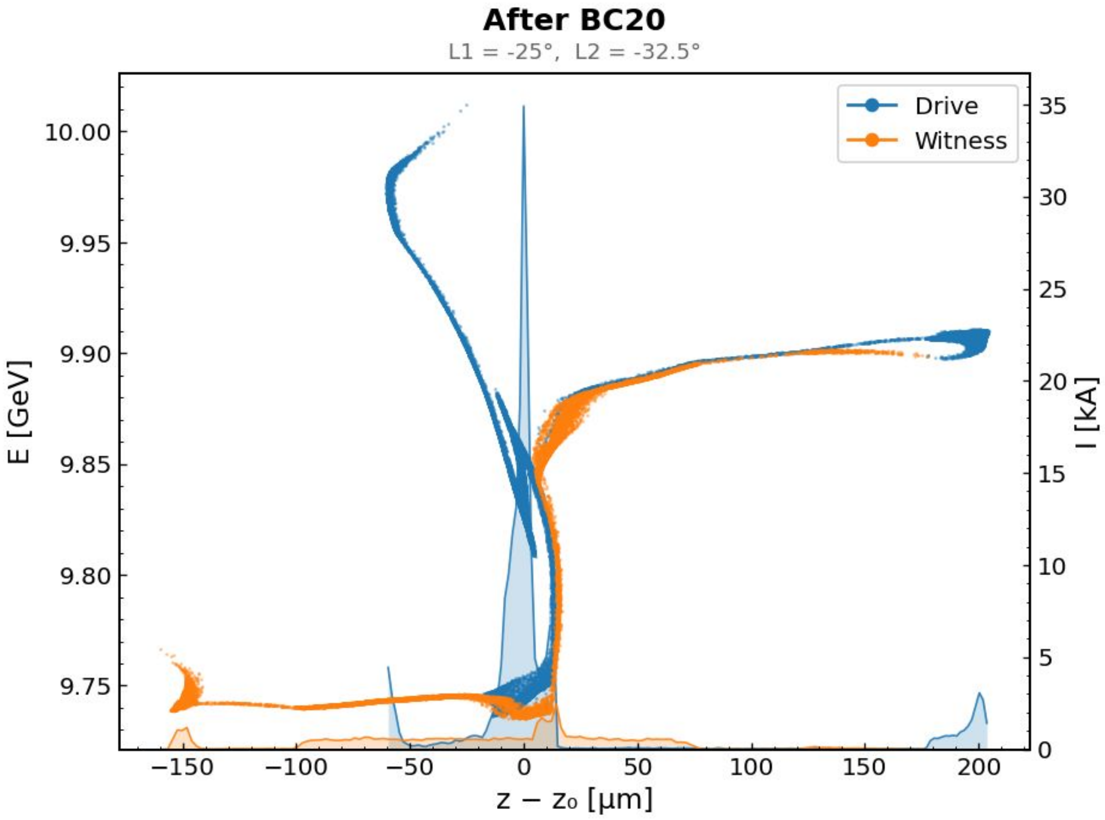
Measurement of LPS using XTCAV

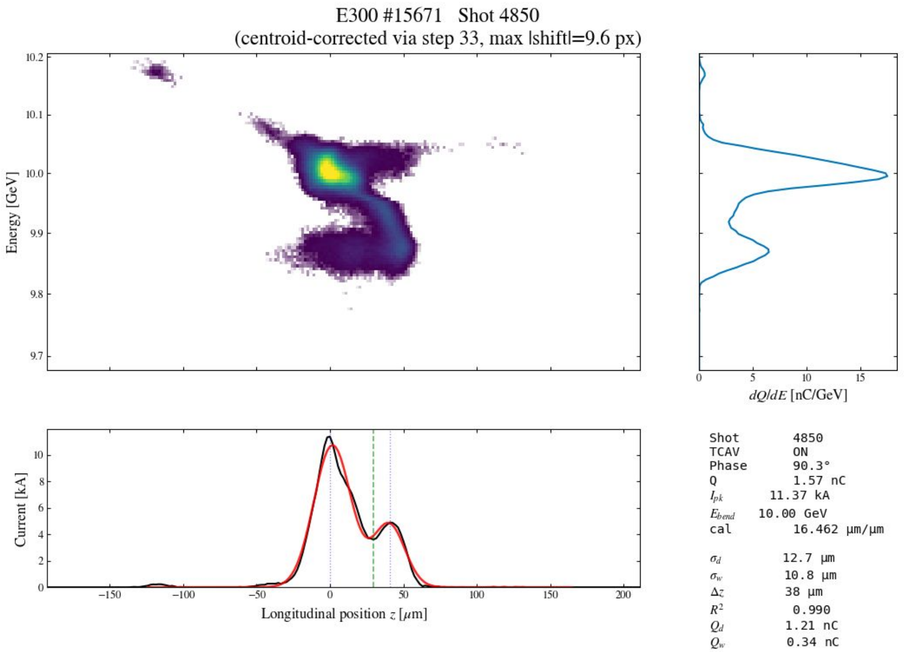




Excellent agreement between simulation and experiment!

Measurement of LPS with XTCAV





…even for very wild configuration

Analytic tracking

$$W(s) = W_0 \, e^{-\sqrt{s/s_0}}, \qquad W_0 = \frac{Z_0 c}{\pi a^2}, \qquad a = 11.6 \text{ mm}, \quad s_0 = 1.5 \text{ mm}$$

$$B \equiv e^2 W_0 = \frac{4 \, r_e \, mc^2}{a^2}$$

- Main idea:
  - Assume uniform current profile
  - Track the chirp to the linear order at bunch centroid
  - Linear compression
- Collective effect
  - We mainly track longitudinal wakefield
    - Short-range geometric wakefield using BNC formula for SLAC s-band acceleration structure
    - Each bunches only chirp itself
    - Leading bunch gives an approximately constant energy kick to the trailing bunch

Chirp tracking

- We track the chirp at the centroid of each bunches assuming a uniform current profile

$$\varphi_i^{(n)} = \varphi_n - k\, z_{c,i}^{(n-1)}$$

$$g_i^{(n)} = \underbrace{\frac{E_{n-1}}{E_n} \frac{g_i^{(n-1)}}{C_i^{(n-1)}}}_{\text{inherited}} + \underbrace{k \left(1 - \frac{E_{n-1}}{E_n}\right) \frac{\sin \varphi_i^{(n)}}{\cos \varphi_n}}_{\text{RF}} + \underbrace{\frac{B\ell_n}{E_n} \frac{N_i}{L_i^{(n-1)}} e^{-\sqrt{L_i^{(n-1)}/2s_0}}}_{\text{self-wake}}$$

Chirp inherited from a previous linac+compressor stage, diluted by acceleration

RF phase chirp for individual bunches at a given bunch separation and centroid RF phase

Chirp evaluated at the bunch centroid using BNC wake for uniform current profile and SLAC S-band acceleration structure

Energy offset tracking

Inherited energy offset | RF phase energy offset | Wake-induced energy offset

$$\Delta E^{(n)} = \Delta E^{(n-1)} + (E_n - E_{n-1})\, k\Delta z^{(n-1)} \tan\varphi_n + \Delta E_w^{(n)}$$

$$\Delta E_i^{\text{self}} = -B\,\ell_n\,N_i\,\Lambda_i, \qquad \Lambda(\sigma) \simeq \frac{1}{2} - \frac{1}{2}\sqrt{\sigma/s_0}$$

$$\Delta E_w^{(n)} = \underbrace{\text{sgn}(\Delta z)\, B\ell_n N_L\, e^{-\sqrt{|\Delta z|/s_0}}}_{\text{cross kick}} - \underbrace{B\,\ell_n \big(N_d\Lambda_d - N_w\Lambda_w\big)}_{\text{loss differential}}$$

Centroid energy kick due to leading bunch's wake (point-source approximated, evaluated at trailing bunch centroid)

Centroid energy kick due to self-wake

Bunch compressor tracking

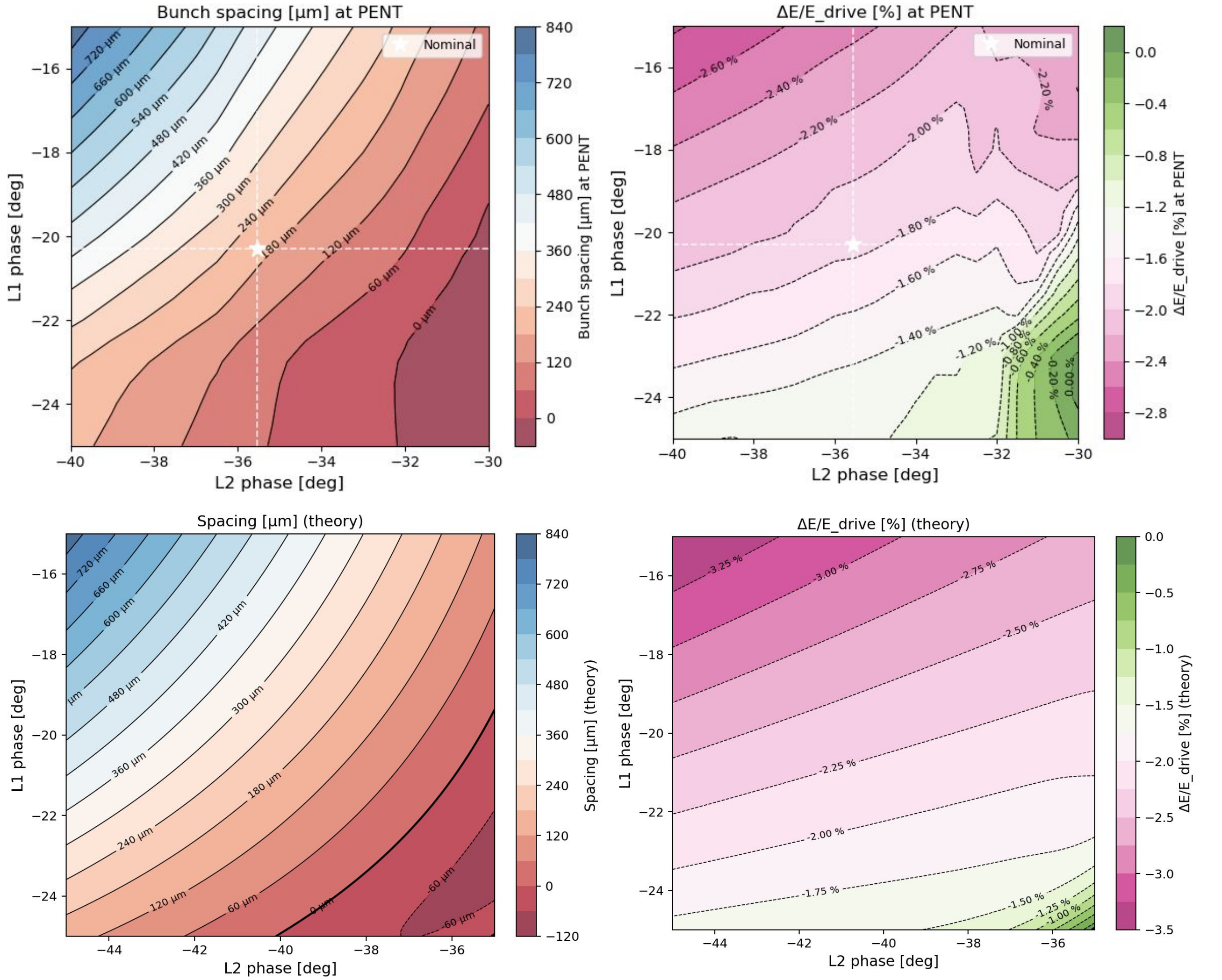
- Bunch compressor translate chirp into bunch length compression, and translate energy difference into spacing difference
  - Entirely 1st order tracking; non-linear effect completely ignored.

$$C_i^{(n)} = 1 + g_i^{(n)} R_{56}^{(n)}, \qquad \sigma_i^{(n)} = \left|C_i^{(n)}\right| \sigma_i^{(n-1)}$$

$$\Delta z^{(n)} = \Delta z^{(n-1)} + \frac{R_{56}^{(n)}}{E_n} \Delta E^{(n)}$$

Bunch separation and energy offset

- Bunch spacing and energy offset analytic tracking exhibit good agreement with simulation
- Note that since we operate BC2 in the overcompress regime, the bunch spacing is a fine cancelation of large initial spacing and strong compression; even a few percent of error in chirp tracking will lead to large difference in spacing



Both L1 and L2 are strong knobs to changes final bunch spacing

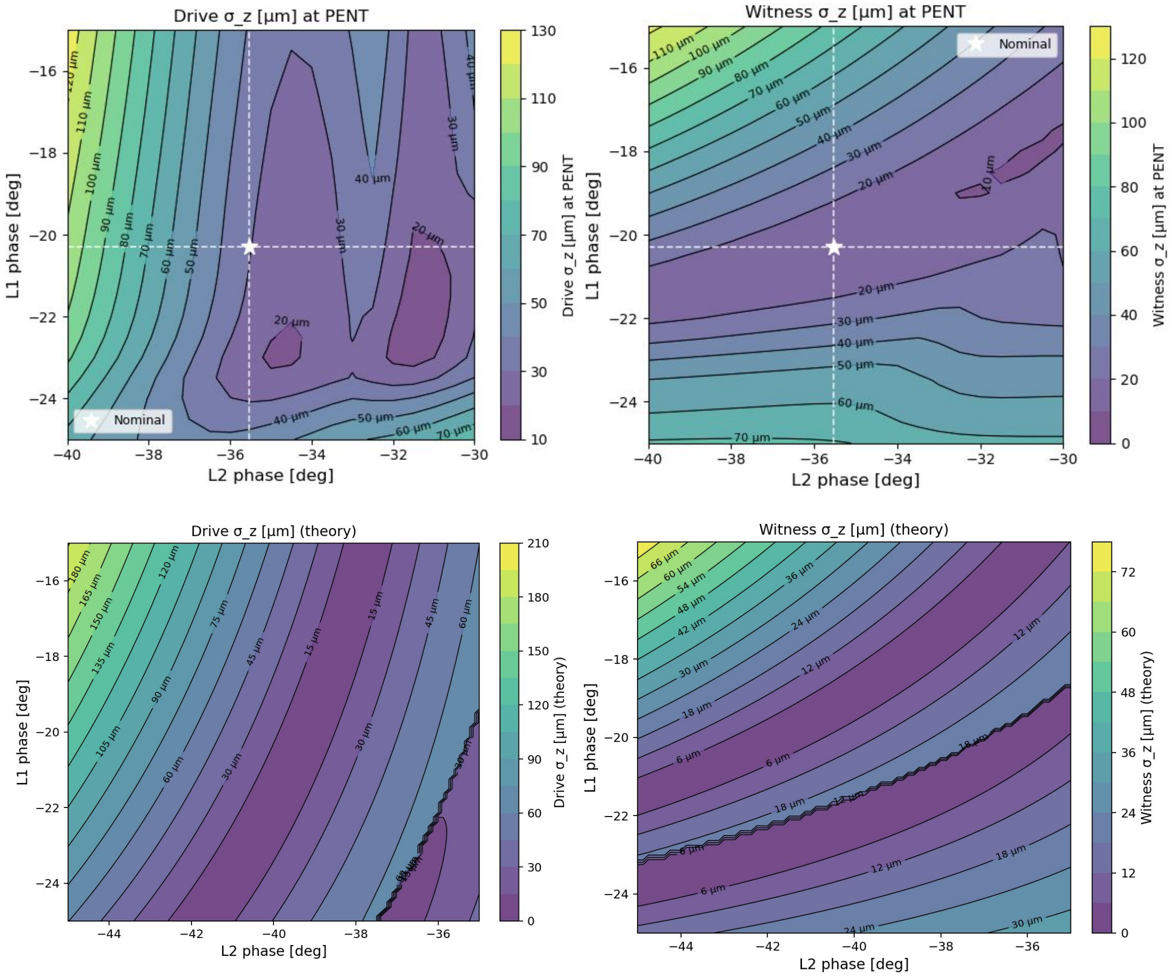
Individual bunch length

- Quasi-orthogonal control
  - In L1, drive chirp is almost cancelled out by much closer-to-crest RF chirp and wakefield; it is therefore barely compressed in BC1, and thus almost entirely controlled by L2

$$g_d^{(1)} = \underbrace{+2.1}_{\text{inherited}} \underbrace{-12.8}_{\text{RF}} \underbrace{+6.2}_{\text{self-wake}} = -4.5\ \text{m}^{-1} \quad (\text{tracked } -4.5)$$

$$g_w^{(1)} = \underbrace{-1.3}_{\text{inherited}} \underbrace{-18.0}_{\text{RF}} \underbrace{+3.0}_{\text{self-wake}} = -16.4\ \text{m}^{-1} \quad (\text{tracked } -16.3).$$

  - Witness length therefore controlled by L1 in closed loop
  - At a fixed bunch separation, wide range of current ratio can be achieved via wiggling linac phases



Understanding individual bunch length control

$$\kappa_j \equiv k\left(1-\frac{E_{j-1}}{E_j}\right)\sec^2\varphi_j \qquad \left(k=\frac{2\pi f_{\rm rf}}{c}\right) \qquad \varepsilon \equiv \frac{E_1}{E_2}, \qquad \rho \equiv \frac{R_{56}^{(2)}}{R_{56}^{(1)}}$$

$$\boxed{\frac{\partial \ln \sigma_i}{\partial \varphi_1} = \frac{R_{56}^{(1)}\kappa_1}{C_i^{(1)}}\left[1+\frac{\rho\,\varepsilon}{C_i^{(1)}C_i^{(2)}}\right], \qquad \frac{\partial \ln \sigma_i}{\partial \varphi_2} = \frac{R_{56}^{(2)}\kappa_2}{C_i^{(2)}}}$$

Bunch length sensitivity

$$\varepsilon = \frac{E_1}{E_2} \ll 1 \quad (\text{L2 gain} \gg \text{L1 energy};\ 0.073), \qquad \rho,\ \frac{\kappa_2}{\kappa_1},\ R_{56}^{(j)}\kappa_j = O(1)$$

$$C_d^{(1)} = O(1), \quad \left|C_d^{(2)}\right| \ll 1,\ C_d^{(2)} < 0; \qquad C_w^{(1)} \ll 1, \quad C_w^{(2)} = O(1)$$

Near operating point

$$r_d \equiv \left|\frac{\partial_{\varphi_1} \ln \sigma_d}{\partial_{\varphi_2} \ln \sigma_d}\right| \sim \left|C_d^{(2)}\right|,$$

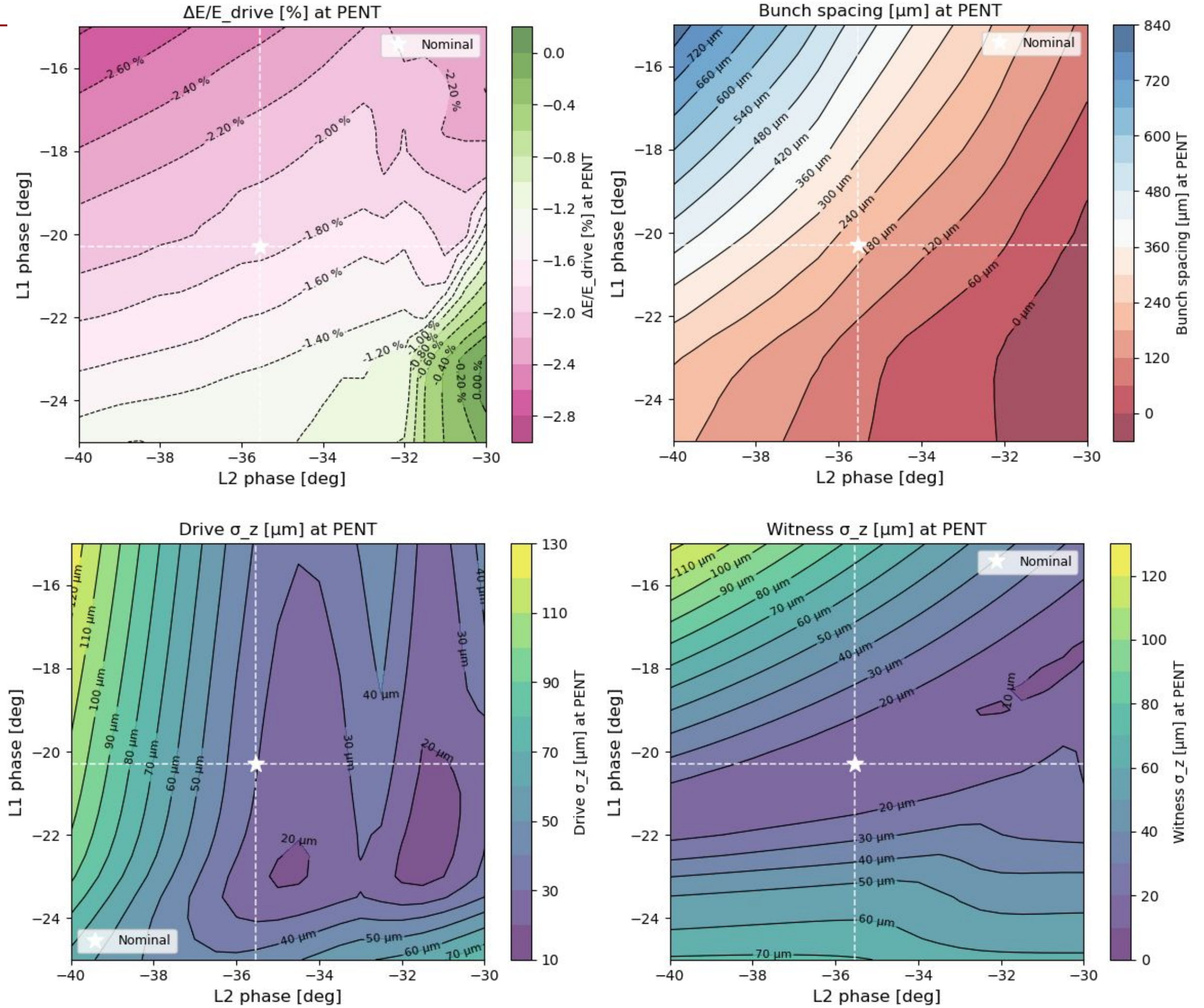
Clean drive orthogonality; subtle witness orthogonality

$$r_w \equiv \left|\frac{\partial_{\varphi_2} \ln \sigma_w}{\partial_{\varphi_1} \ln \sigma_w}\right| \sim O(1)\,\frac{\left(C_w^{(1)}\right)^2}{\varepsilon}.$$

Drive entirely gated by L2; witness controlled by L1 in closed loop

Tunability of two-bunch mode

- The combination of the bunch spacing control and quasi-orthogonal bunch length control enables fine tuning of two-bunch current ratio at a fixed final bunch spacing
- For a given current requirement (e.g. drive and witness both at peak compression), the bunch spacing is uniquely set by injector bunch spacing



Understanding two-bunch dynamic enables delivery of such mode with the required individual current profile and bunch spacing

Summary

- We demonstrate the quasi-independent tunability of drive-witness pair in photocathode two-bunch mode with nano-Coulomb, asymmetric bunch charge

- We use analytic theory to understand the RF chirp offset+wakefield dominated longitudinal dynamics

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