Tunable photocathode two-bunch mode for advanced accelerator application

FACET-II

Facility for Advanced Accelerator Experimental Tests

AAC 2026

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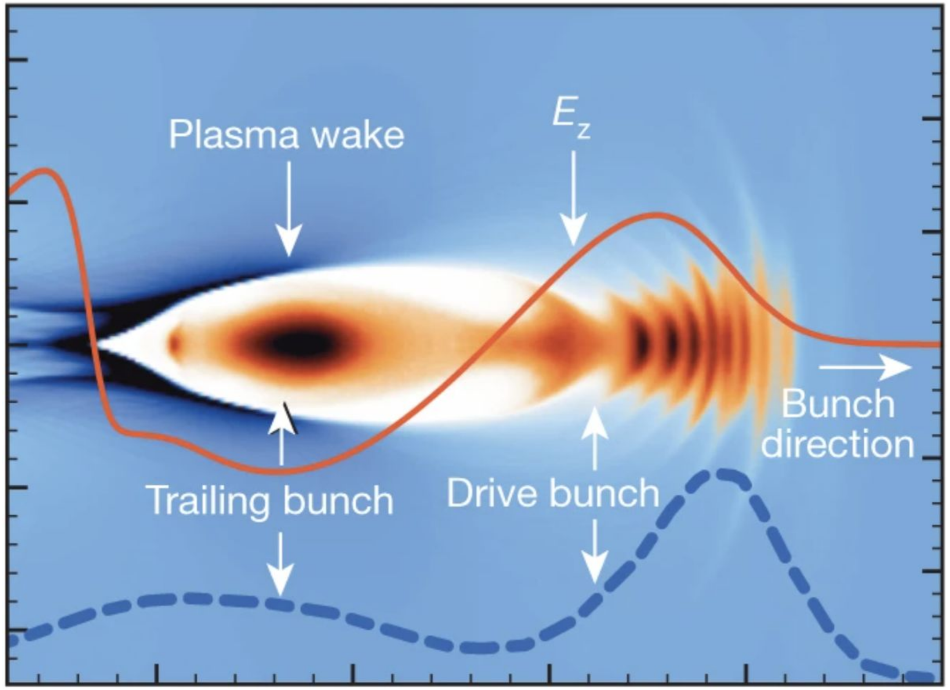
July 30, 2026

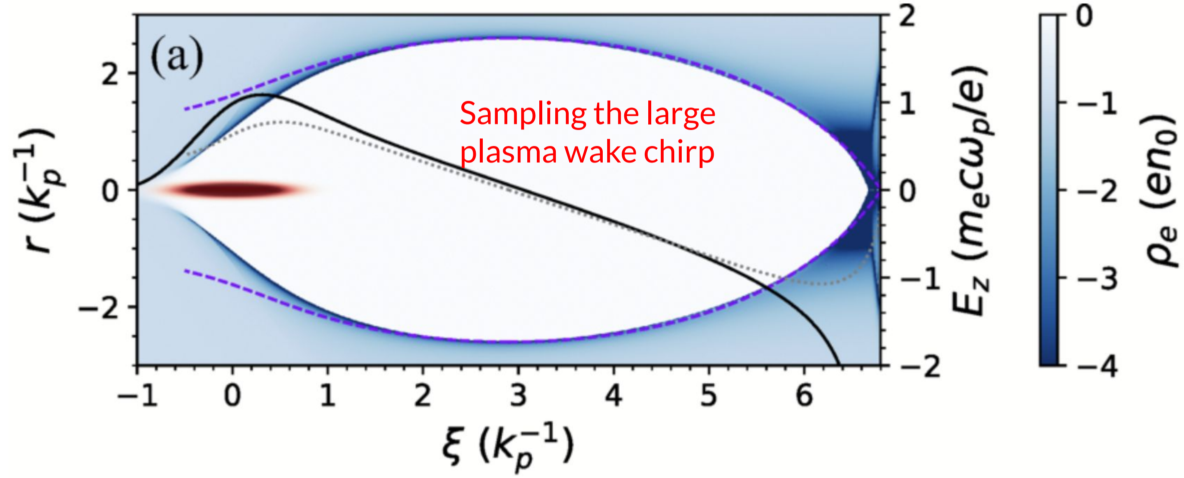
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Two-bunch PWFA experiments



“Standard” PWFA experiments operating at plasma density 1e16 - 1e17, corresponding to an optimal bunch separation from 50 to 250 um. Figure adapted from M. Litos et. al. (2014).



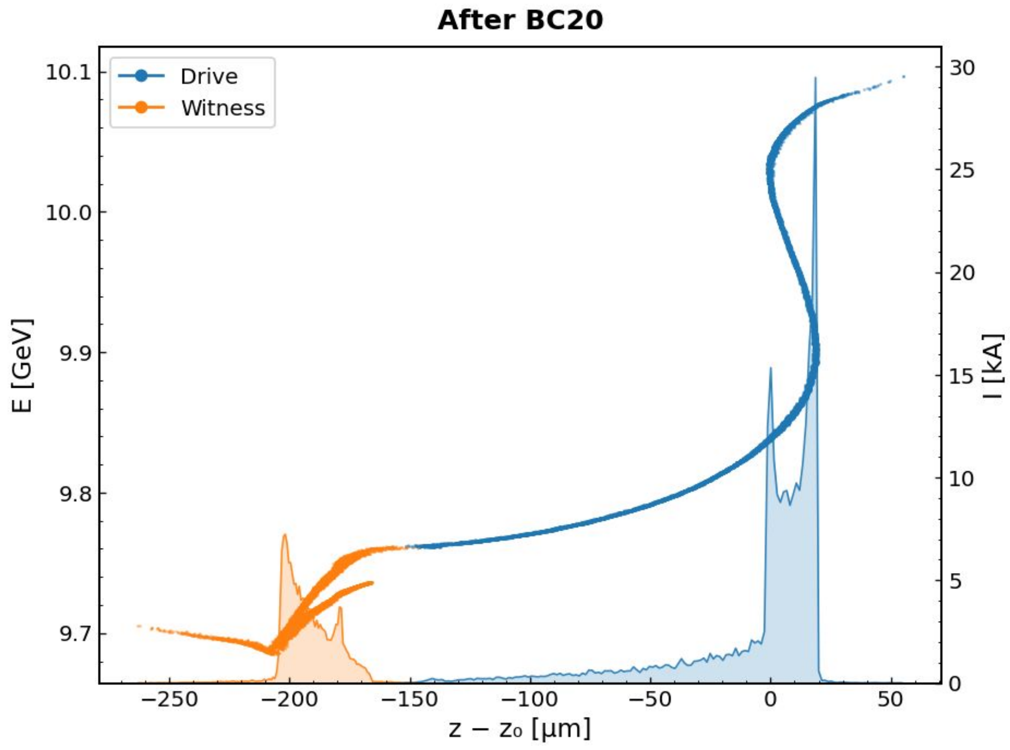
Plasma-based compression demand short bunch separation (50-150 um) with large drive to witness current ratio. Figure adapted from K. Swanson et. al. (2026)

How do we deliver two bunches with desired spacing and current profile?

Different PWFA experiments demand different beams

We want to deliver two bunches with

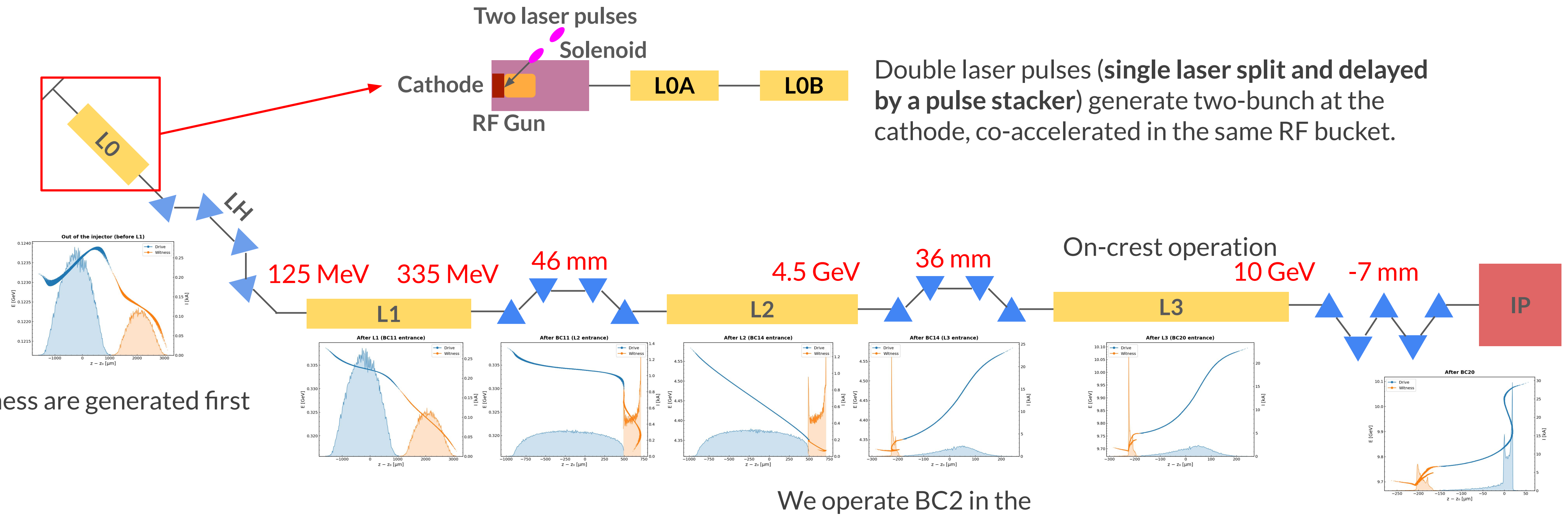
- High current, short bunch length
- **Controllable** bunch spacing from 50 um to 300 um
- **Controllable** Energy offset
- **Individually controllable** bunch length/current



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 (**single laser split and delayed by a pulse stacker**) generate two-bunch at the cathode, co-accelerated in the same RF bucket.

Witness are generated first

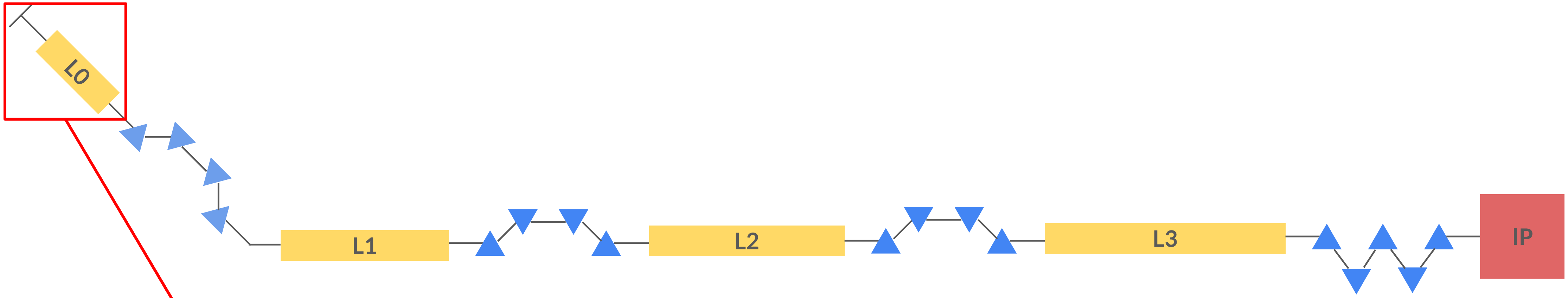
We operate BC2 in the overcompress regime to swap the position of drive and witness.

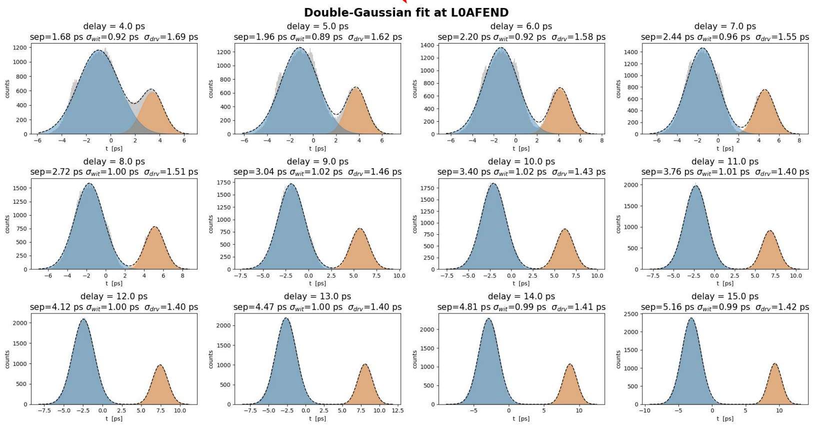
Nominally, **3:1 charge ratio with a total charge of 1.6-2.1 nC**

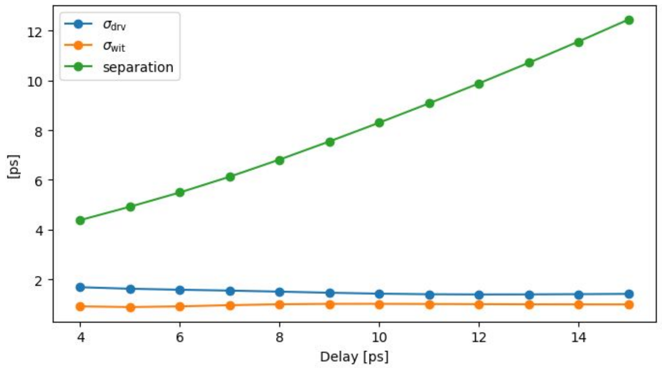
Three main longitudinal knobs: Injector pulse stacker (delay, arm power ratio), L1 and L2 phase

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

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 treat injector setting as a boundary condition and study the dynamic downstream

Longitudinal dynamics with compression

- We want to deliver two bunches with
  - High current, short bunch length
  - **Controllable** bunch spacing
  - **Controllable** Energy offset
  - **Individually controllable** bunch length/current
- 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 (~500 fs)
    - Different bunch experience very different RF phase

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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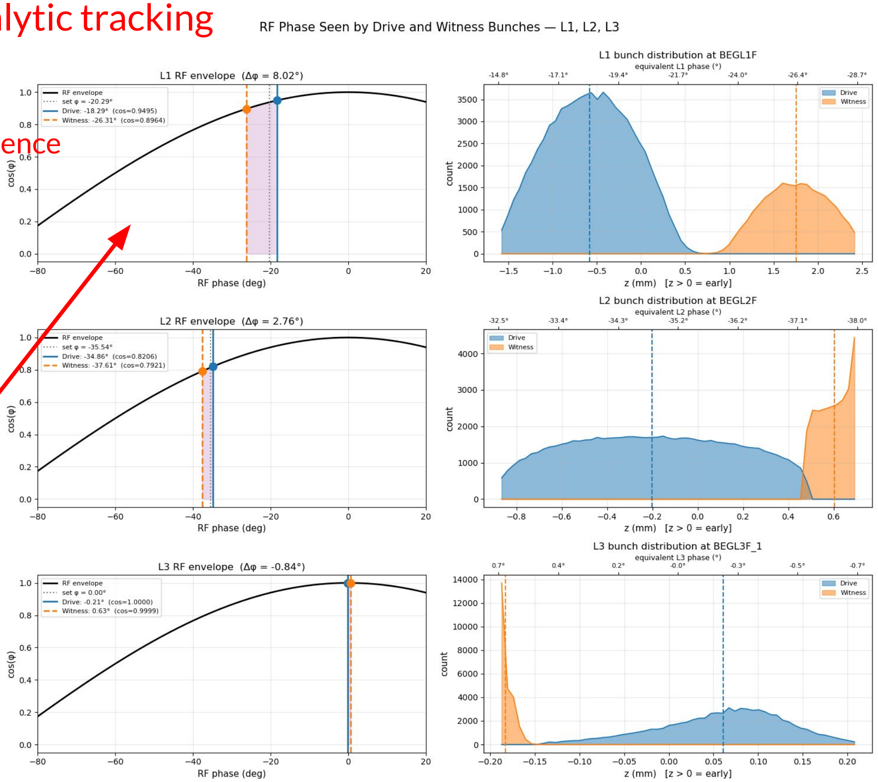
(Received 18 December 2014; published 2 March 2015)

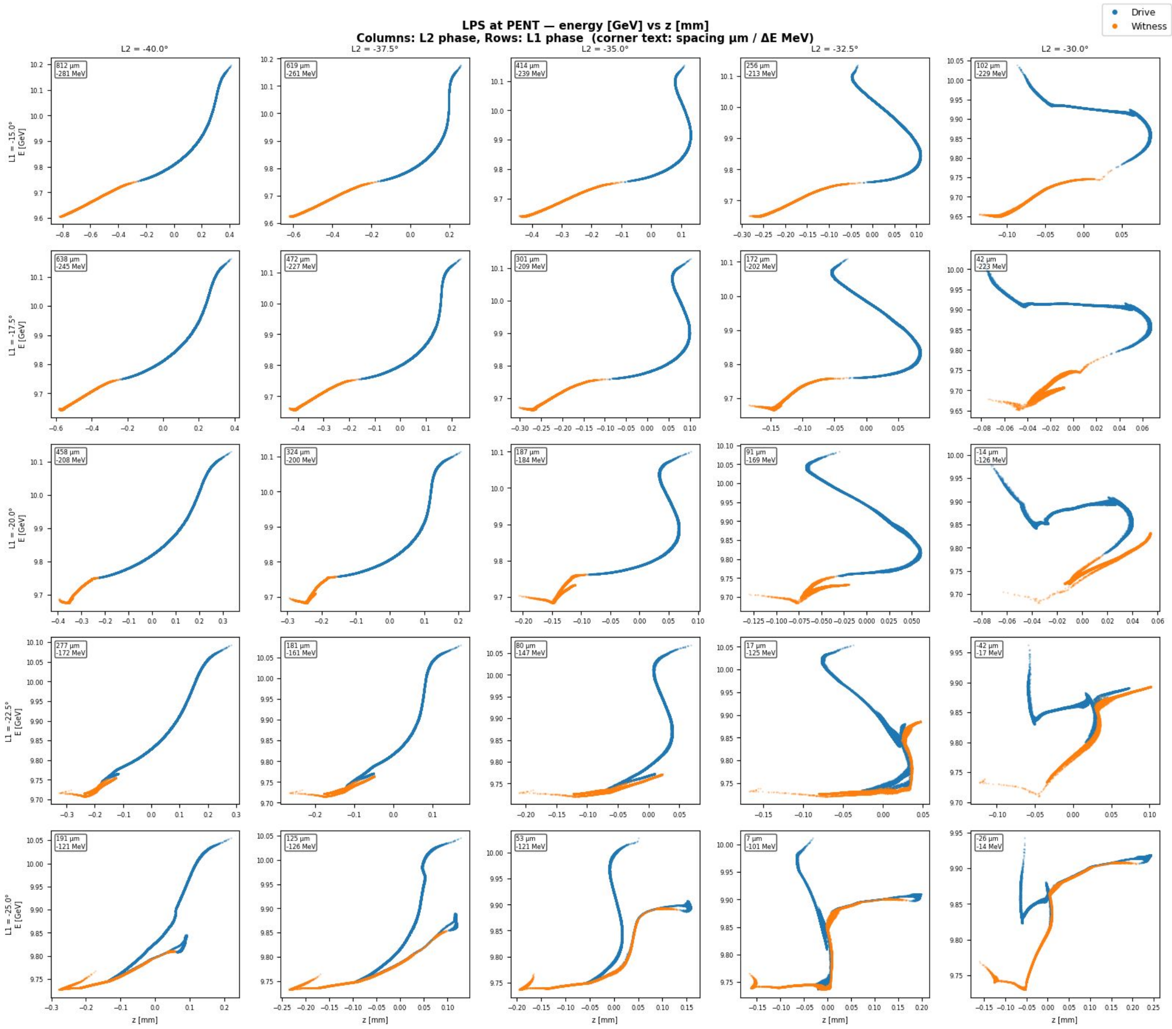
We partially adapt the formalism in Z. Zhang et. al. for analytic tracking

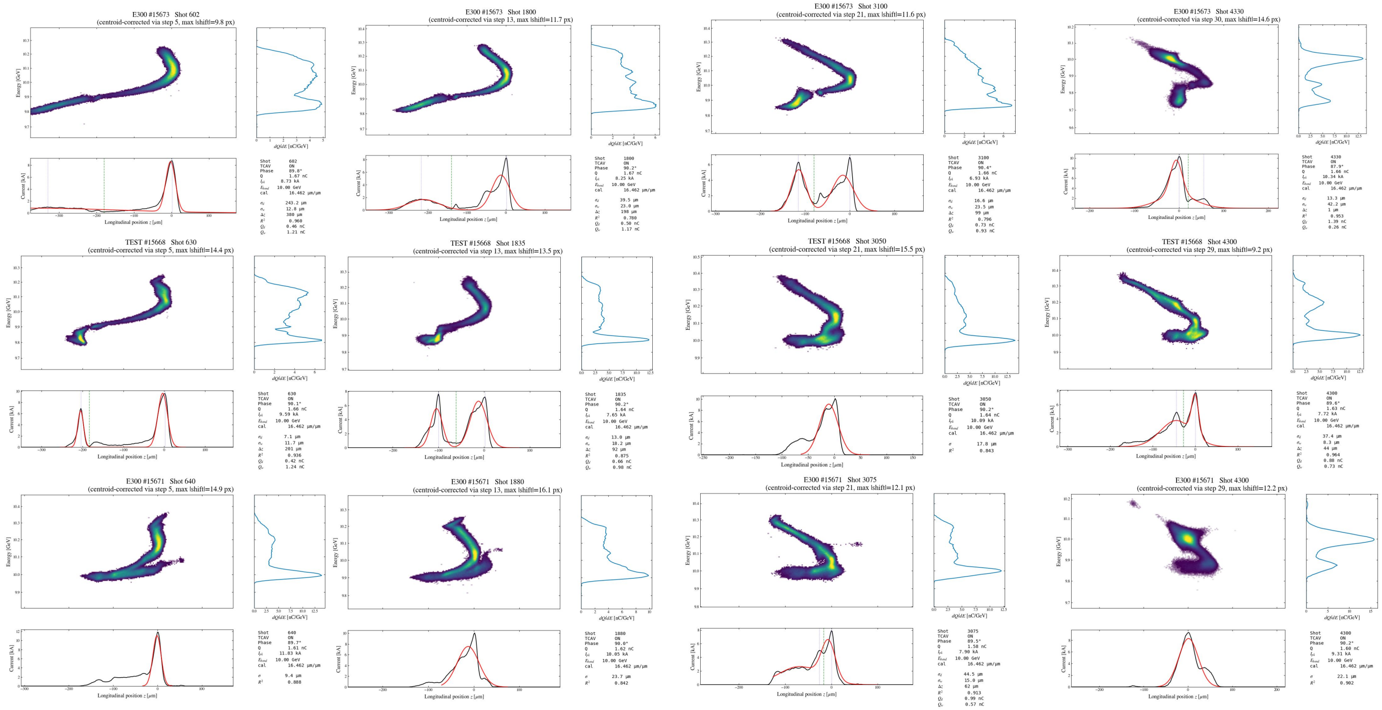
Two-bunch experience ~10 deg RF phase difference in L1



RF phase tracking and longitudinal wakefield is the key

Measurement of two-bunch LPS using XTCAV

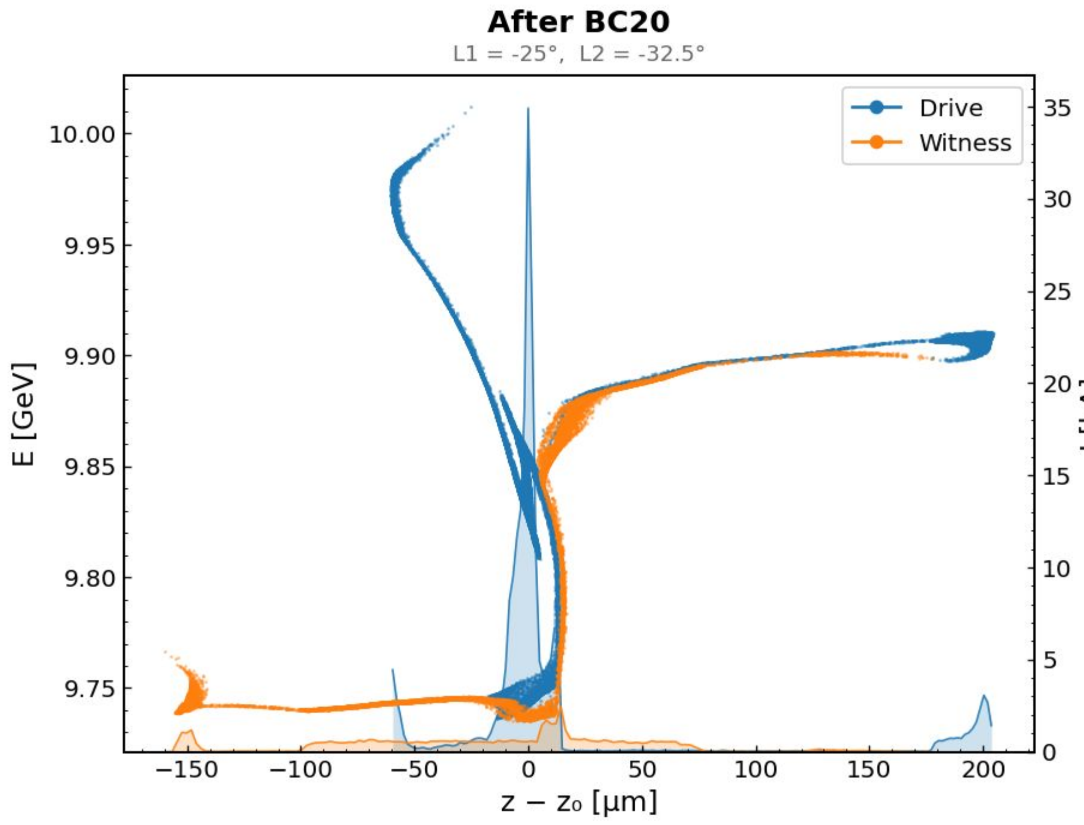


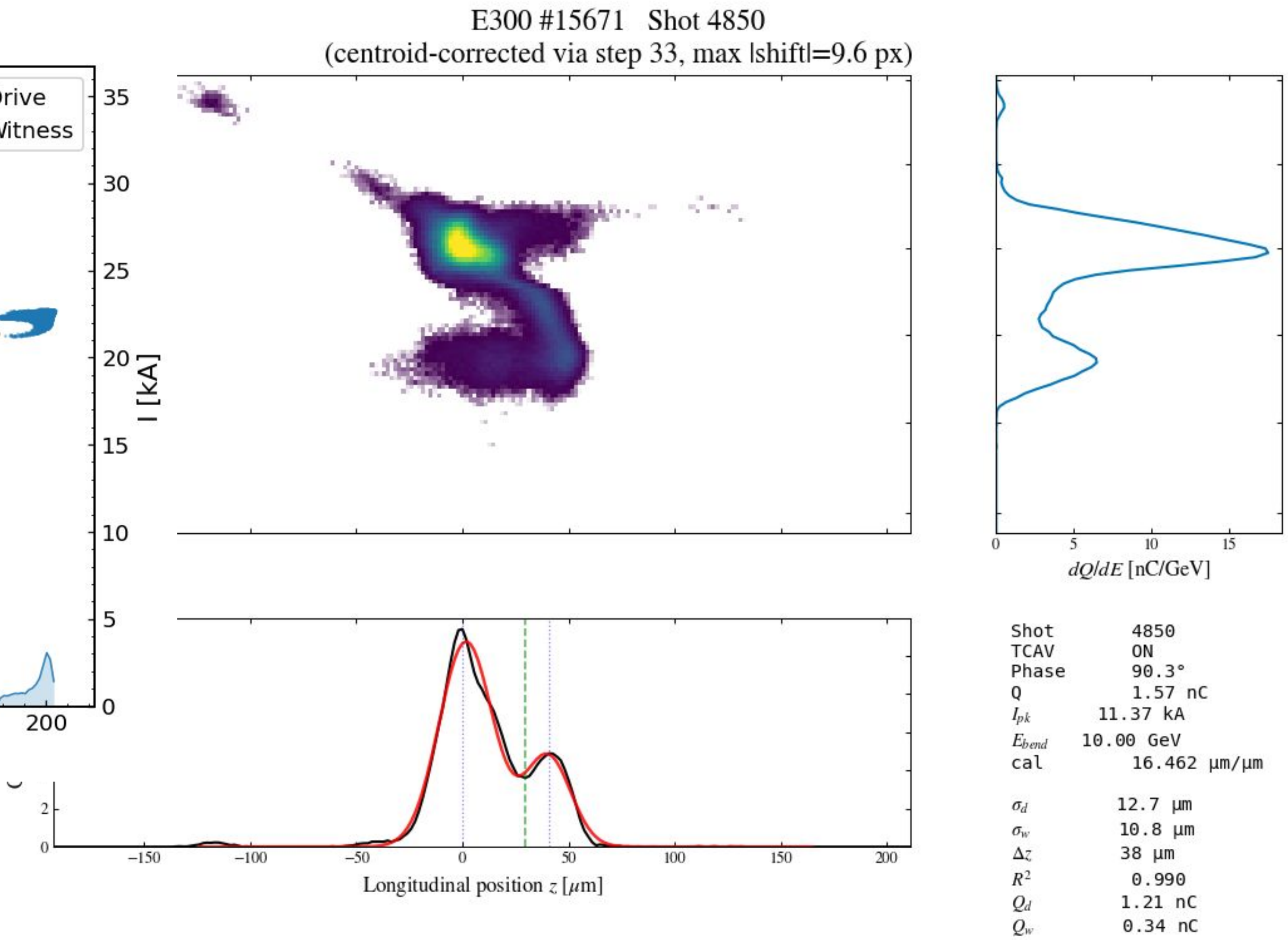


Simulations are done using **Impact-T** (injector) + **Bmad** within the **FACET2-S2E framework (N. Majernik et. al. 2026)**

Excellent agreement between simulation and experiment!

Measurement of LPS with XTCAV





…even for very wild configuration

Analytic tracking

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

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

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

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

(Chirp)

- inherited: Chirp inherited from a previous linac+compressor stage, diluted by acceleration
- RF: RF phase chirp for individual bunches at a given bunch separation and centroid RF phase
- self-wake: Chirp evaluated at the bunch centroid using BNC wake for uniform current profile and SLAC S-band acceleration structure

Idea:
- Uniform current profile
- Linear compression
- Bunch-dependent RF tracking
- Chirp comes from RF+self-wake
- Centroid energy kick from self-wake + leading bunch wake to the trailing bunch

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

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

(Energy offset)

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

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

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

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

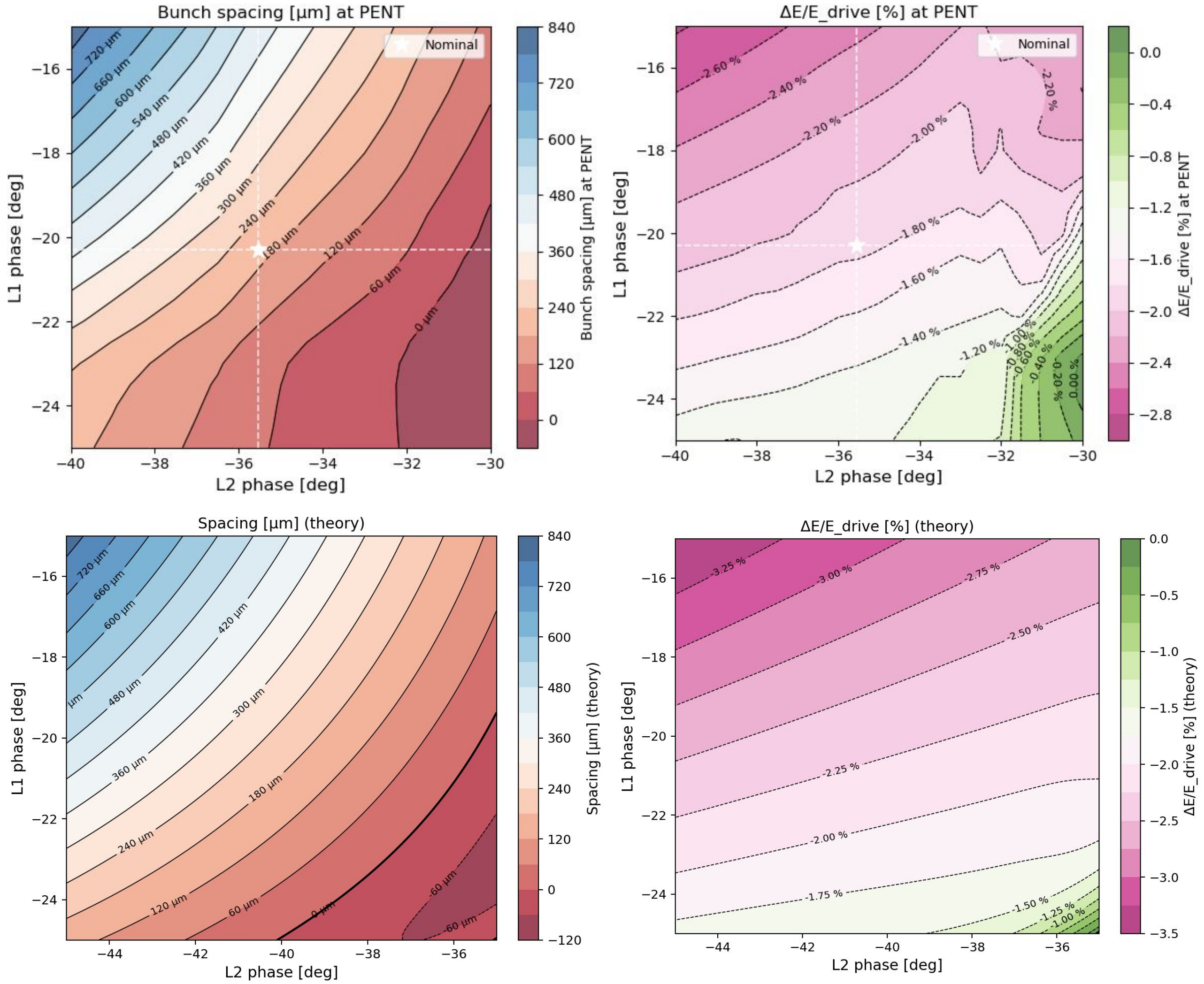
(Bunch length and spacing)

Bunch separation and energy offset

- Starting from the same injector LPS, bunch spacing and energy offset analytic tracking exhibit good agreement with simulation

- Spacing:
  - L1/L2 both talk strongly to spacing; so you can achieve the same spacing with a wide range of phase combinations

- Energy offset:
  - L1 phase talks more to energy offset
  - For PWFA we don't really care about energy offset to 1st order; but energy difference talk strongly to transverse



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

$$\left|\frac{\partial\Delta E/\partial\varphi_1}{\partial\Delta E/\partial\varphi_2}\right| = \frac{R_{56}^{(1)}\kappa_1}{\mathcal{C}^{(1)}} \cdot \frac{\sin 2\varphi_2}{2} \approx \frac{2.0}{0.34} \times 0.47 = 2.8$$

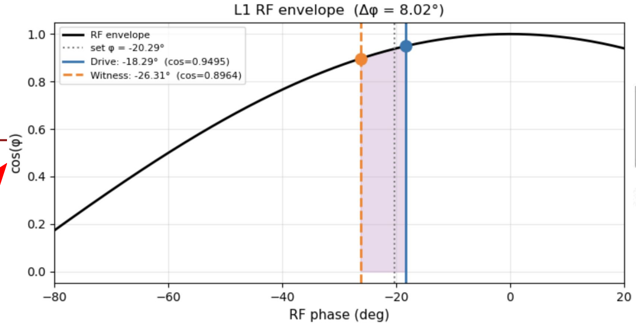
SLAC

Individual bunch length

- **Quasi-orthogonal bunch length control**
  - L2 phase talks strongly to drive bunch length
    - 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
  - 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

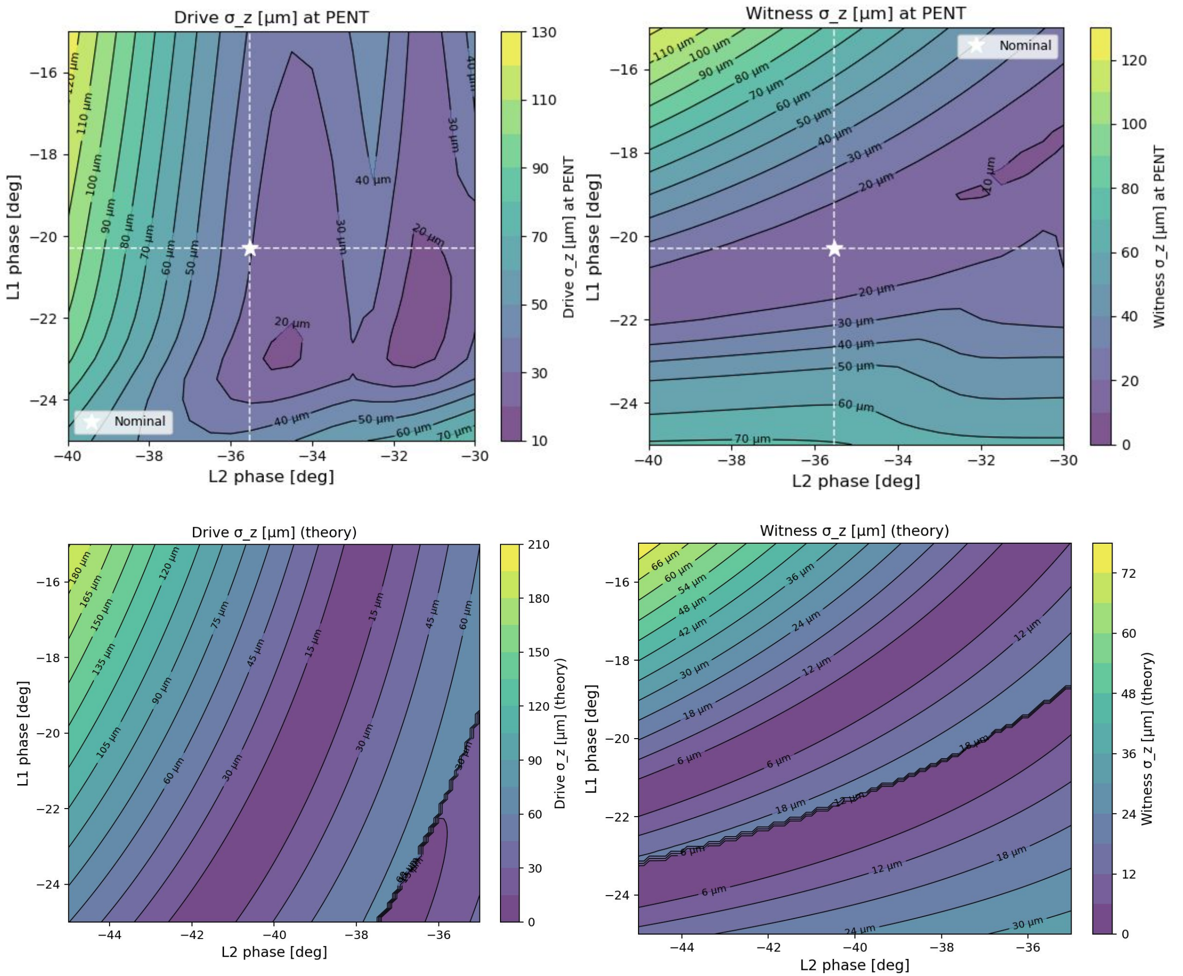
- The combination of the bunch spacing control and quasi-orthogonal bunch length control enables **customization of current ratio at a given bunch spacing**

- For a given current requirement (e.g. drive and witness both at peak compression), the bunch spacing is uniquely determined by injector bunch spacing (this tells us **WHEN** do we need to go back to the injector to achieve a desired LPS profile)

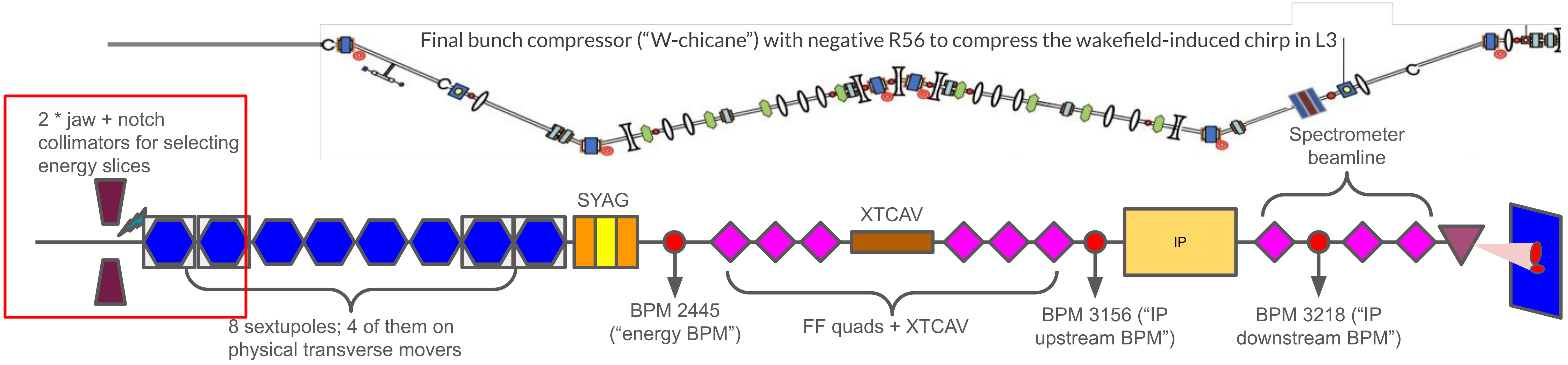


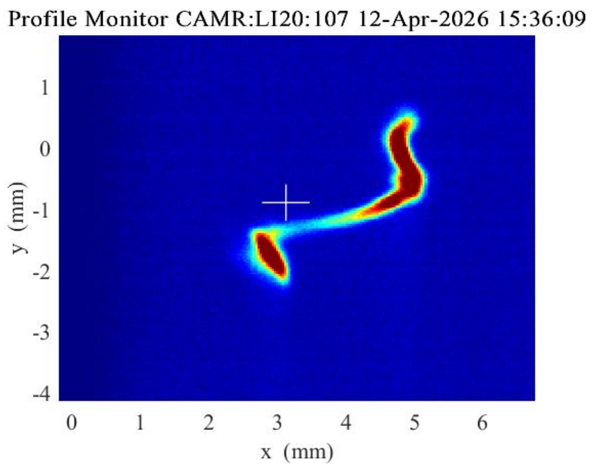
$$g_d^{(1)} = \underbrace{+2.1}_{\text{inherited}} \underbrace{-12.8}_{\text{RF}} \underbrace{+6.2}_{\text{self-wake}} = -4.5\ \text{m}^{-1} \quad (\text{tracked} \ -4.5)$$

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

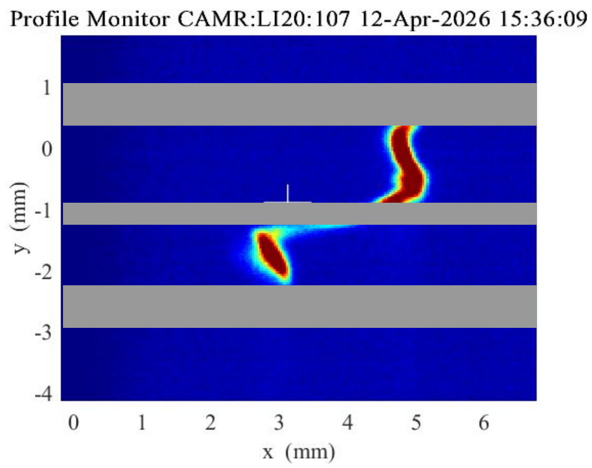


Collimation system





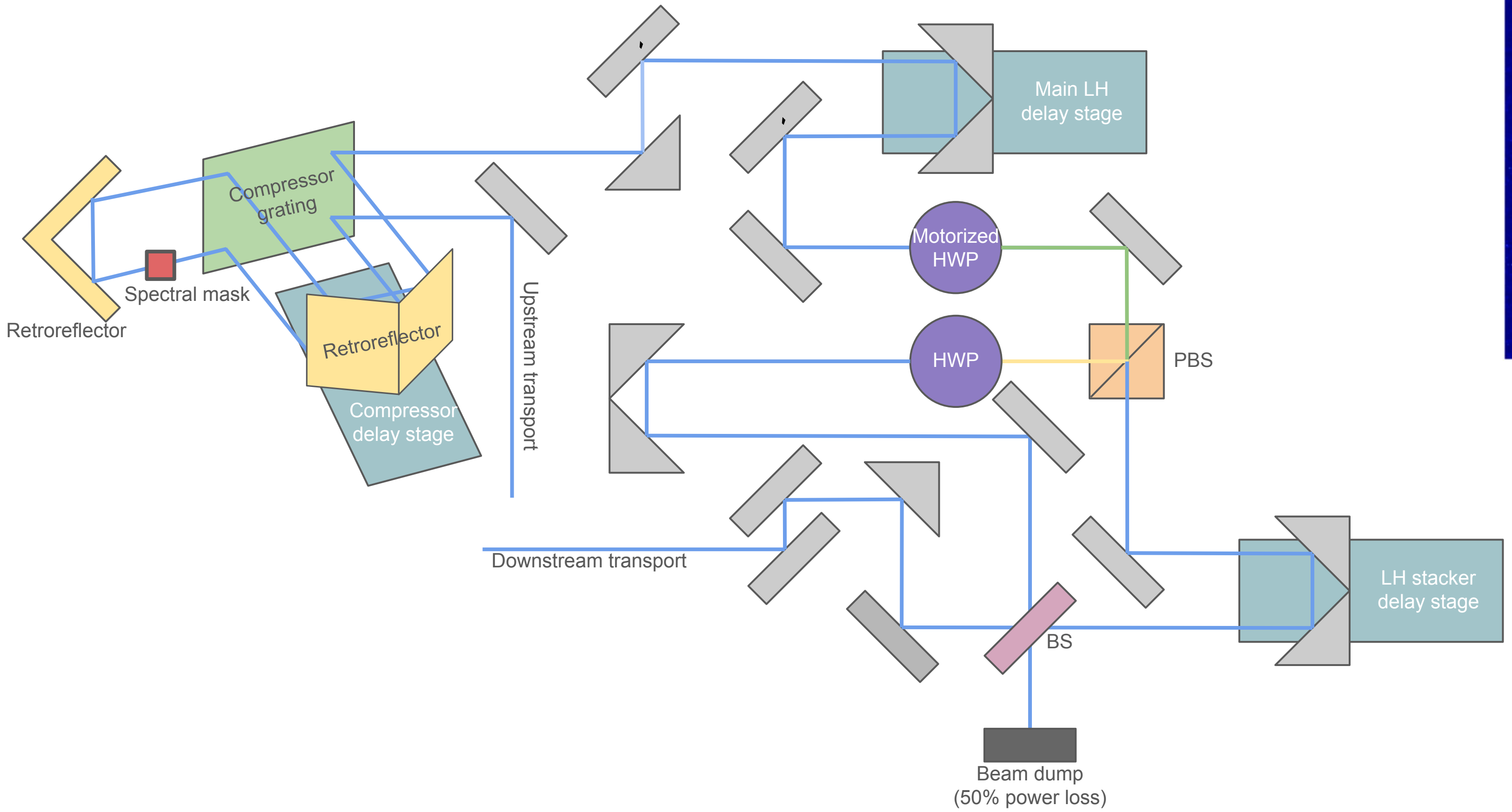
Jaw and notch collimators to optimize beam loading

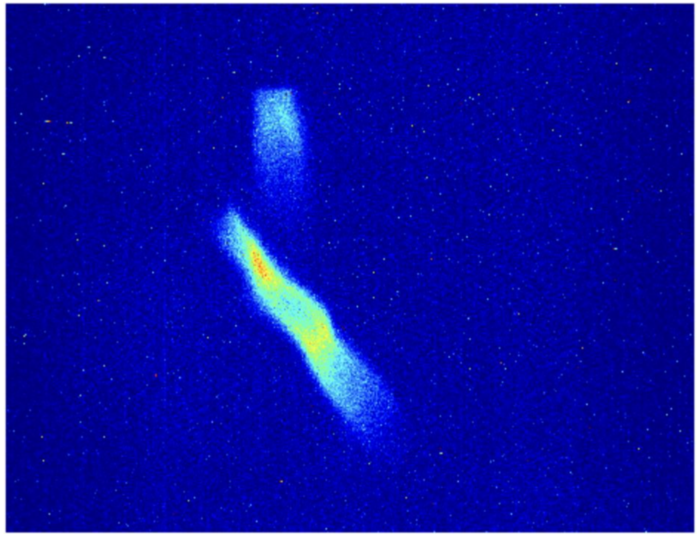


Collimators are used to "clean up/fine tune" the longitudinal phase space

LPS customization using laser heater

Spectral shaper + pulse stacker schematics:



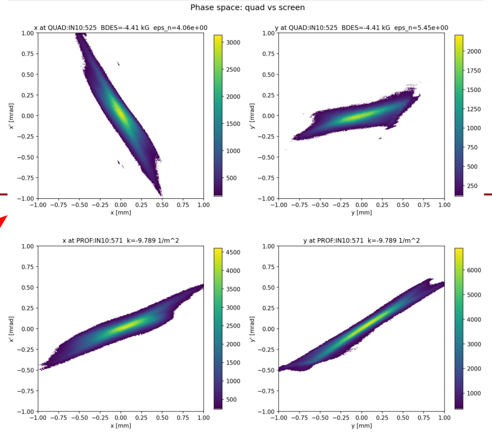


Customized two-bunch LPS in the injector measured by S-band TCAV. LH imprinted bumps on the drive using chirped-pulse beating technique. LH energy modulation is then transformed into current modulation via compression.

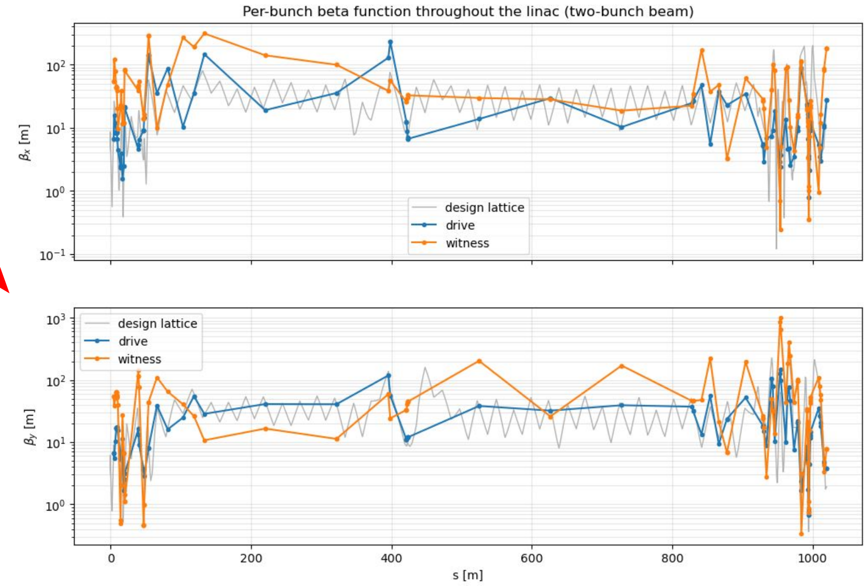
Laser heater with shaped temporal profile enables further customization of LPS

Challenge in transverse control

- Extreme(ly short) beam comes with large energy spread
  - Energy offset of drive and witness lead to lattice mismatch throughout the linac
- Asymmetric bunch charge lead to mismatch starting from the injector due to space-charge
- COTR makes beam visualization and diagnostics very hard
- More details in my other [talk]



Tomographically-reconstructed two-bunch TPS in the injector showing features of non-overlapping ellipses



Comment

- Photocathode two-bunch mode is fully customizable, enabling various needs of different experimental program

- Sometime pencil and paper theory works quite well

- Transverse control is challenging

Acknowledgements

SLAC AD AARD & APBO group: Zack Buschmann, Claudio Emma, Spencer Gessner, Mark Hogan, Alexander Knetsch, Ryan Loney, Nathan Majernik, Brendan O'Shea, Marcellus Parker, Sharon Perez, Ivan Rajkovic, Doug Storey, Kelly Swanson, Junzhi Wang, Gerald Yocky

This work is supported by the U.S. Department of Energy under contract DE–AC02–76SF00515.

Understanding individual bunch length control

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

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

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

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

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

Clean drive orthogonality; subtle witness orthogonality

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