Transverse control and optimization for plasma wakefield acceleration

FACET-II

Facility for Advanced Accelerator Experimental Tests

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SLAC NATIONAL ACCELERATOR LABORATORY

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U.S. DEPARTMENT OF ENERGY

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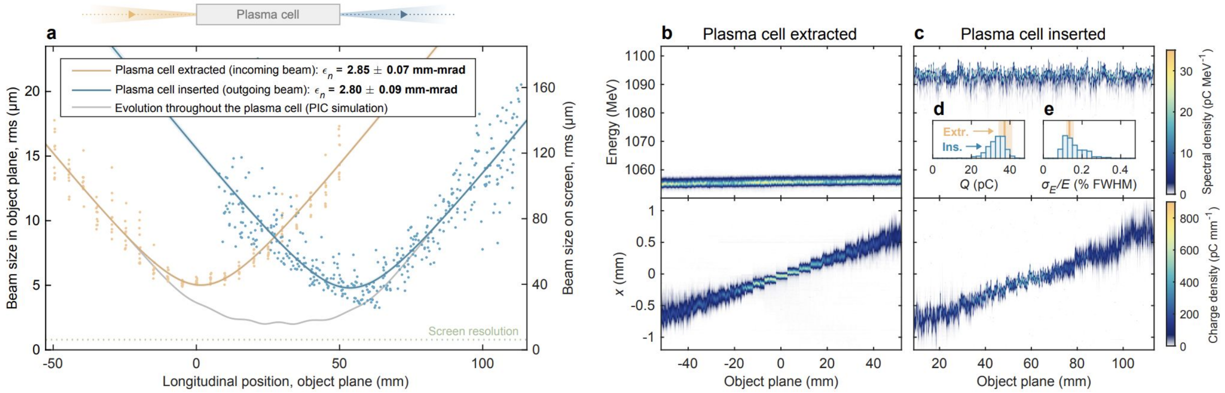
Emittance preservation in PWFA

- Emittance preservation in a high-gradient, high-efficiency PWFA has been demonstrated at FLASHForward, with a modest energy gain of ~4%

- Our goal is to achieve everything above but with ~100% energy gain

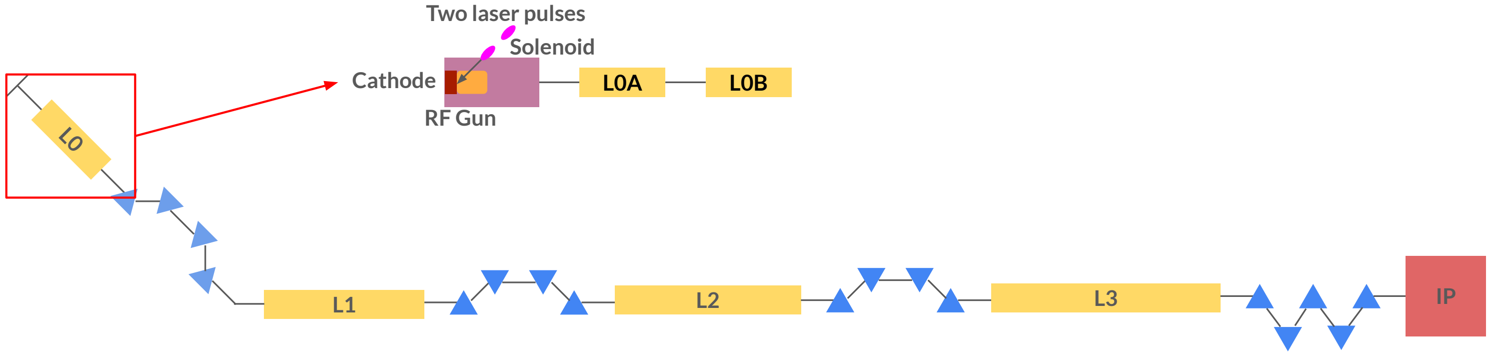


C. A. Lindstrøm et. al. (2024)

This is very hard because bad things scale up as you increase the energy gain

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

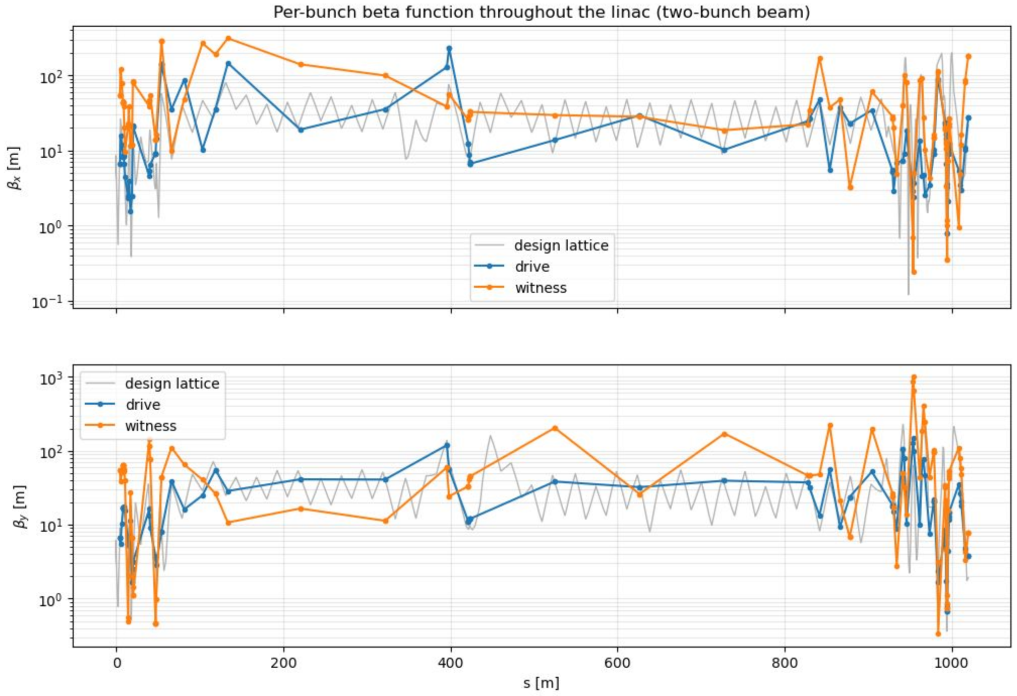


FACET-II generates two bunches from the photocathode; see my talk/poster at WG5.

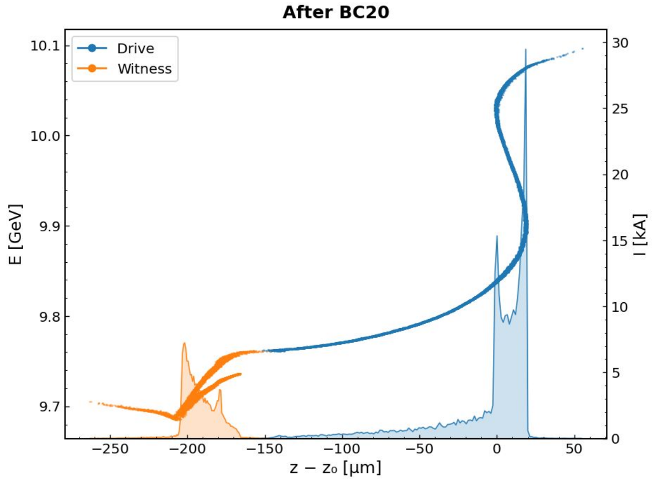
High-quality drive-witness pair with the right longitudinal and transverse properties

Challenge in transverse control

- Two-bunch mismatch throughout the linac due to asymmetric charge and energy offset
  - Charge-difference: difference space-charge effect in the injector → lattice mismatch even in the injector
  - Energy offset: chromatic focusing error, dispersion, and all that

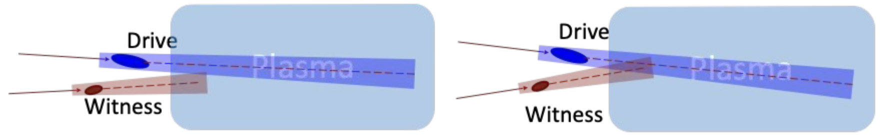


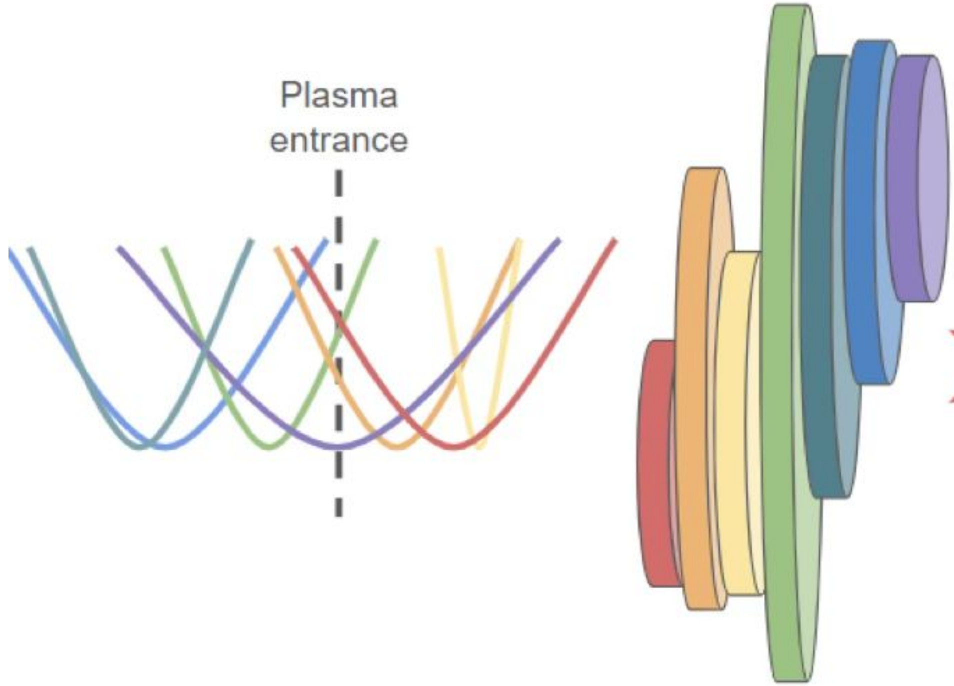
- Ultrashort electron beam (~10 um) with 10s of kA peak current: large energy spread and highly chromatic
  - Visualizing the beam using profile monitors almost impossible due to COTR



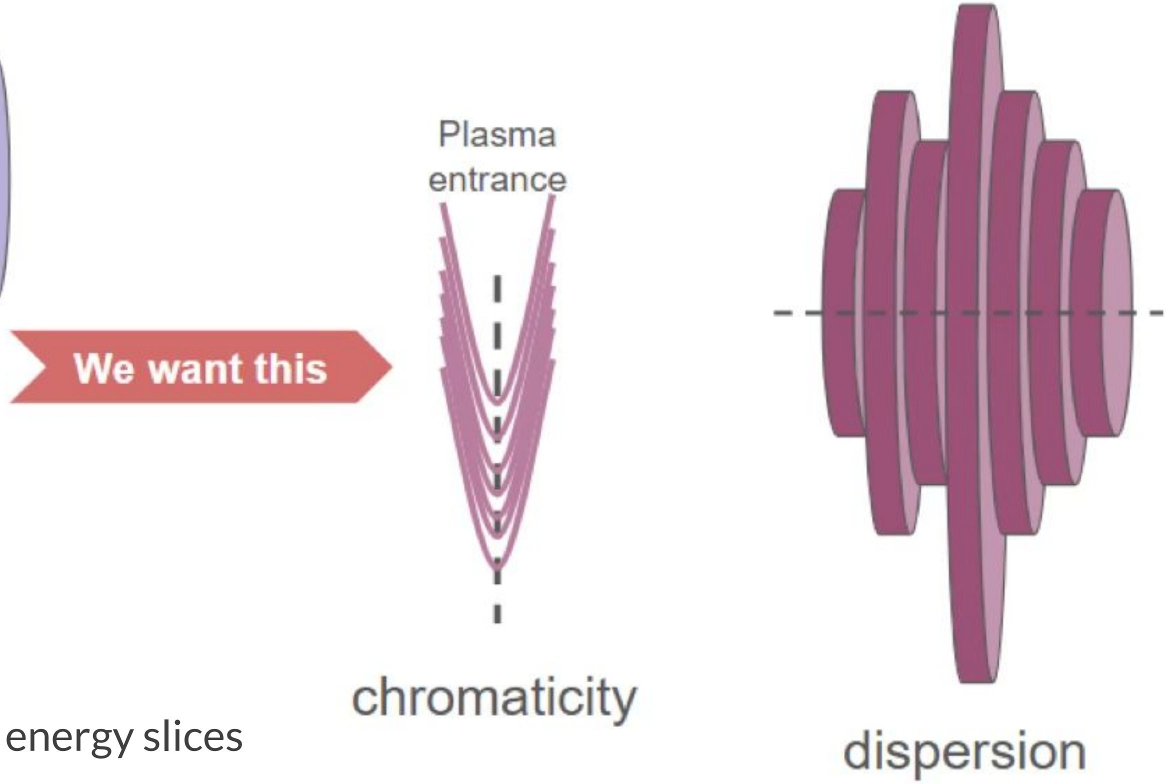
Diagnosing and controlling extreme beam is extremely challenging

Control of energy slices



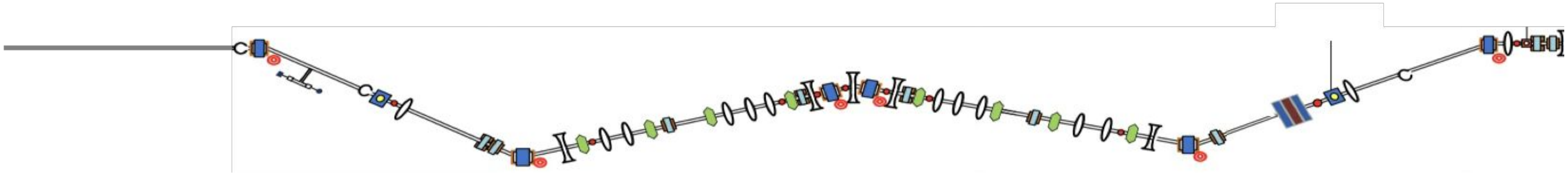


Different color = different energy slices

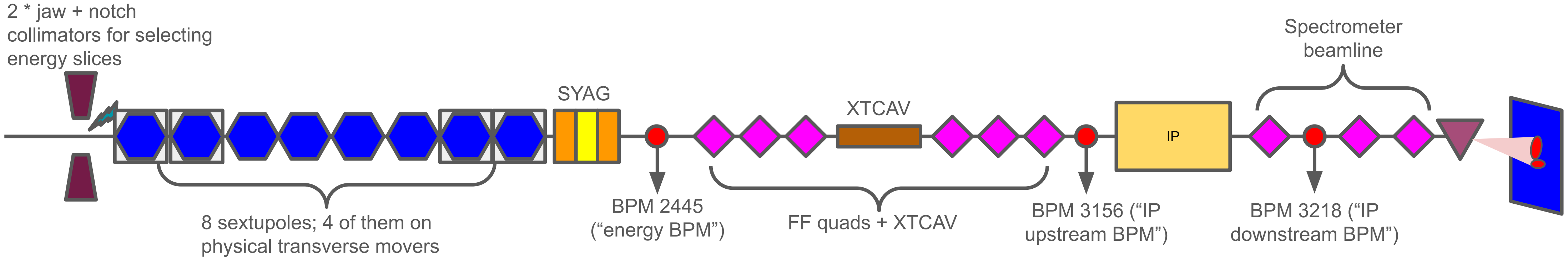


Control of the 6D phase space of the beam is needed

Transverse control using final BC and final focus



Final bunch compressor (“W-chicane”) with negative R56 to compress the wakefield-induced chirp in L3

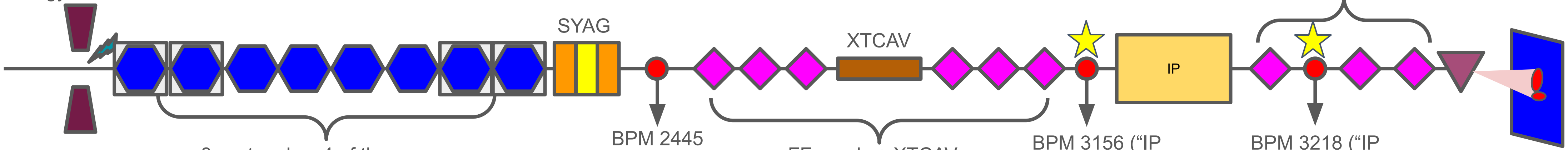


Sextupoles are used to correct dispersion and chromatic error; final focus quadrupoles are used to set the waist position and beta function

Highly coupled knobs to solve highly coupled problems

Energy slice trajectories reconstruction

- We measure slice dispersion (x/x'/y/y' vs energy) by scanning a collimator slit continuously through the dispersed beam and measuring two BPM readings beam-synchronously.



With the collimation system in the dispersive section, we can select an arbitrary energy slice

Energy BPM to measure slice energy and slice charge

$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}$$

$$x_1' = \frac{x_2 - M_{11} x_1}{M_{12}}$$

Using two BPMs and assume linear optics, we can compute x, x', y, y' at arbitrary locations between them.

The entire measurement takes 15 seconds

Chromatic virtual screen

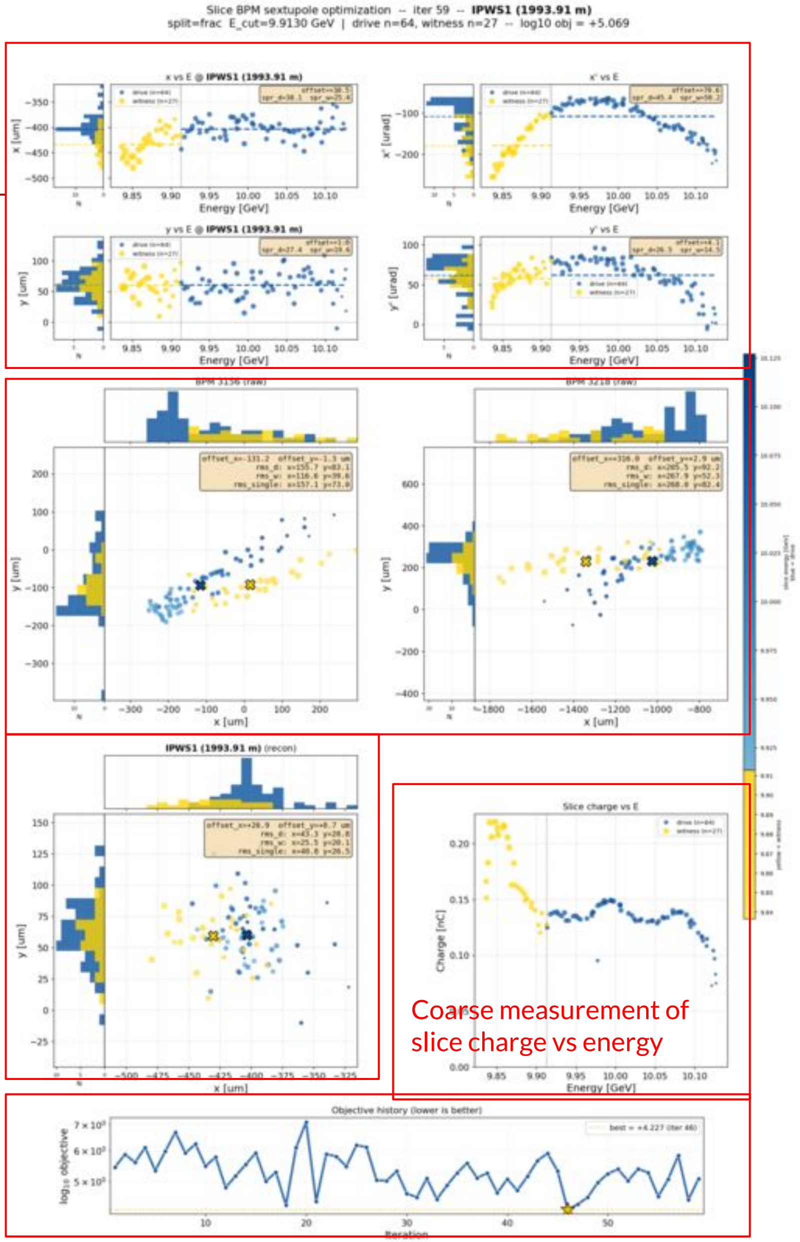
- Collimator+BPMs enable energy-resolved measurement of beam first moment
- Fast measurement enables iterative machine tuning to achieve minimal dispersion and dispersion prime
  - We observed persistent 2nd order x’
  - Need to better understand the highly coupled knobs
- Bayesian optimization explored to automate dispersion control
  - Results not yet satisfying; objective function is the key

x/x’/y/y’ vs energy

Raw BPM readings of different energy slices

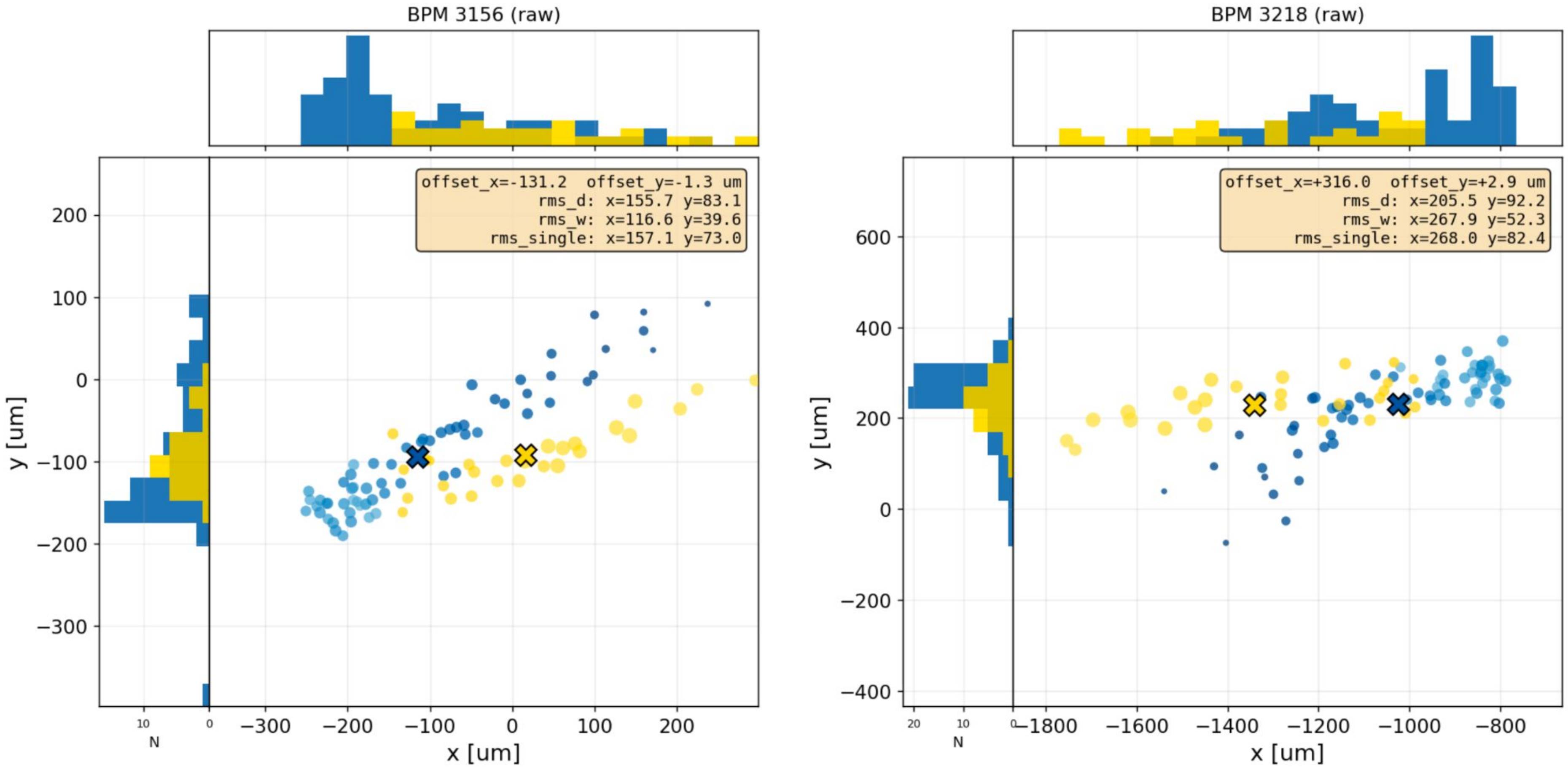
Reconstructed energy slices transverse centroid position at the plasma entrance

Bayesian optimization to minimize slice dispersion



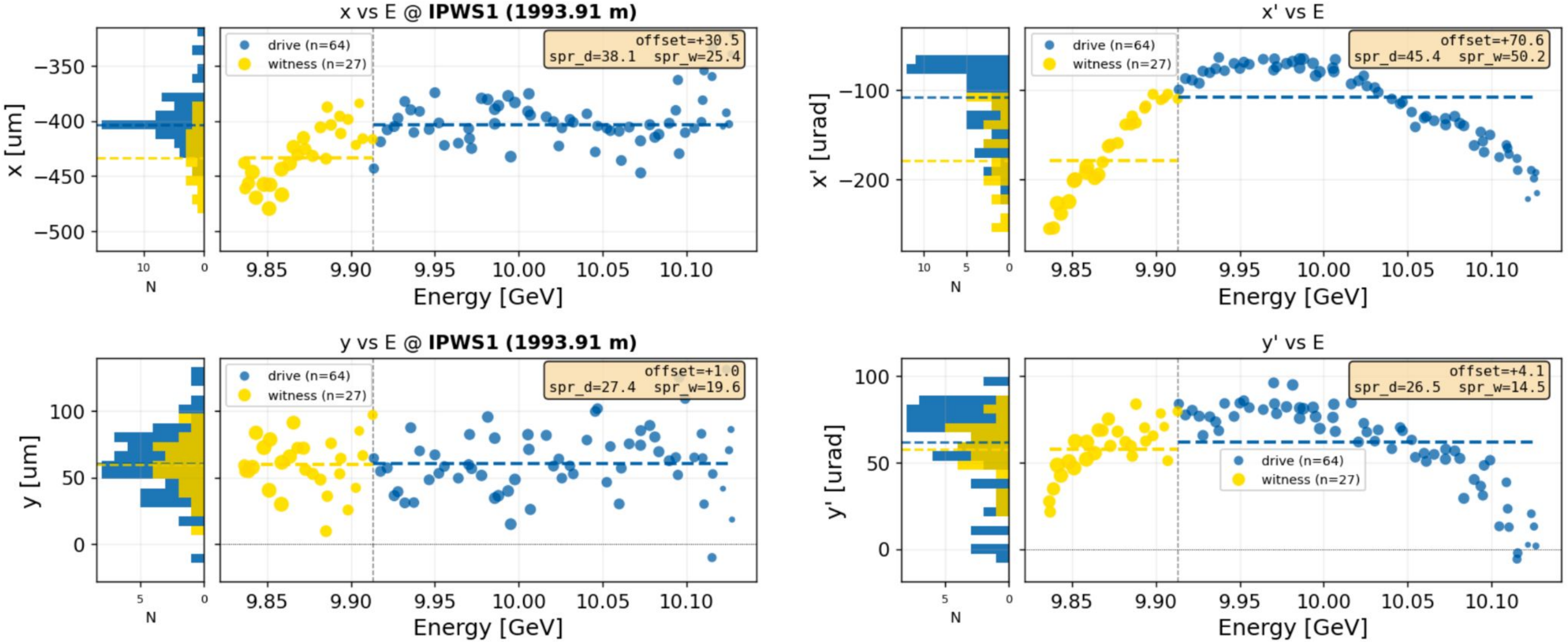
Chromatic virtual screen enables visualization and dispersion control of the beam

Chromatic virtual screen



Raw BPM readings resolving trajectories of different energy slices

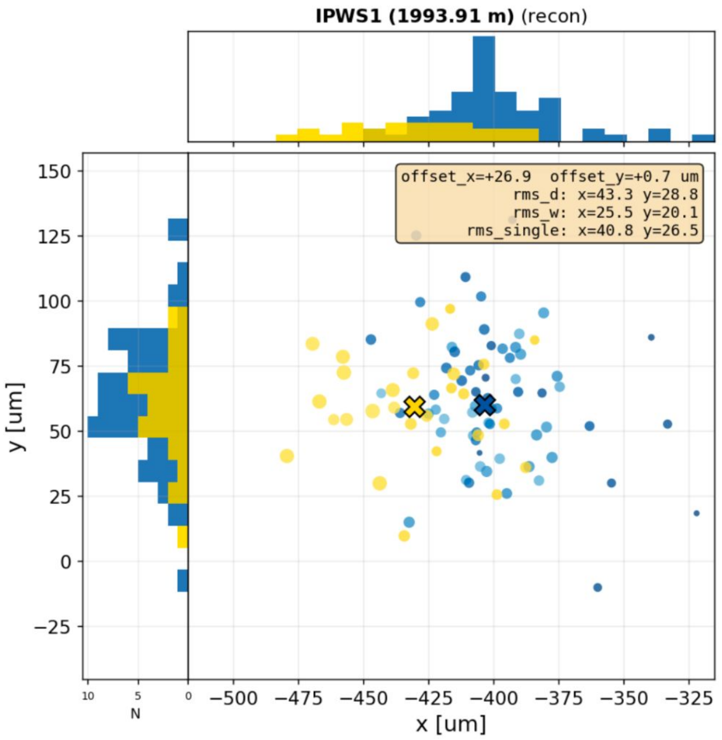
Chromatic virtual screen

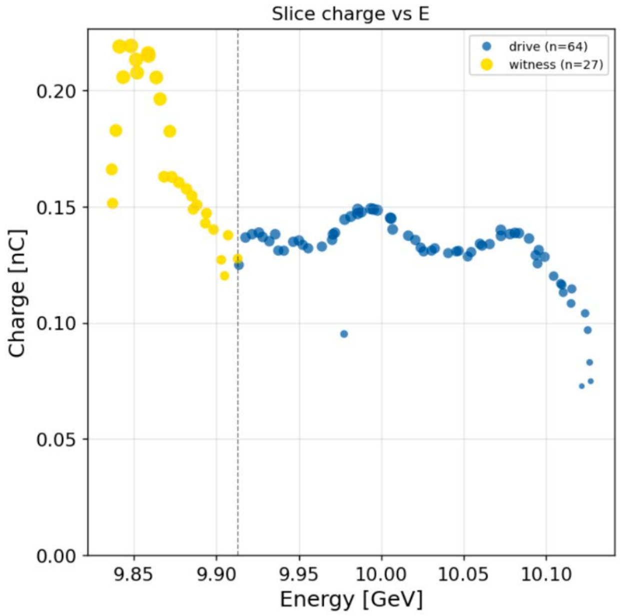


Reconstructed x/x'/y/y' vs Energy at the IP

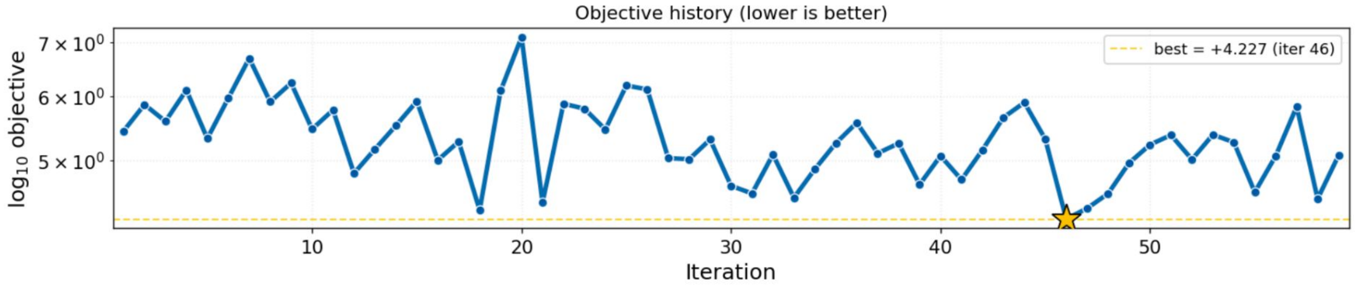
Chromatic virtual screen

Reconstructed energy slice centroid at the IP



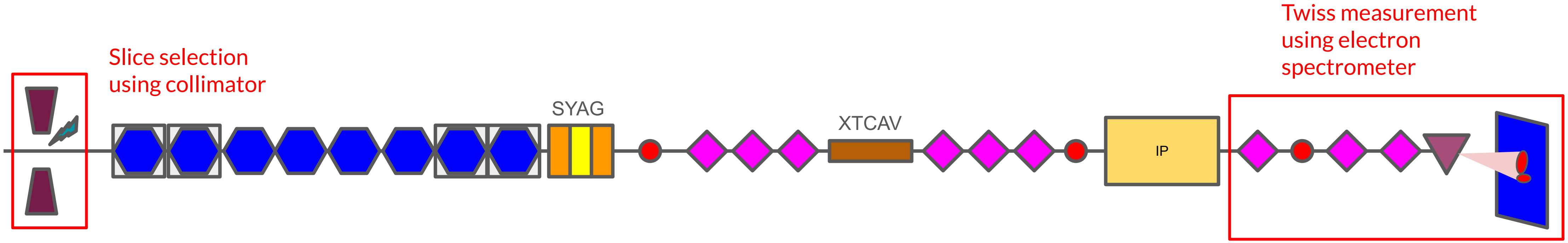


Slice charge vs energy

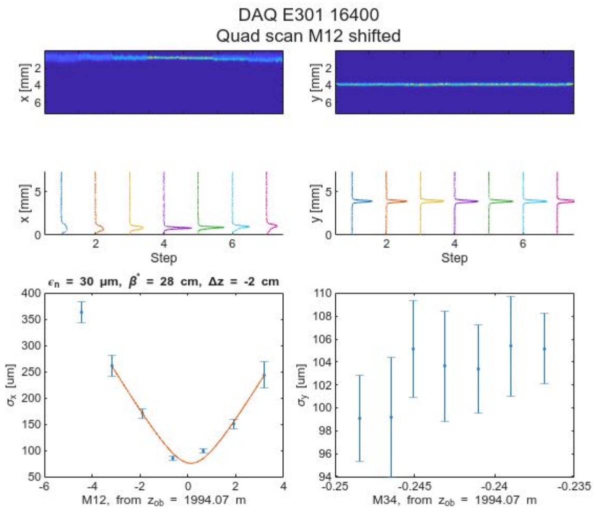


Bayesian optimization is being explored to tune on slice dispersion

Slice twiss parameter measurement



- Challenge of quad scan
  - COTR makes direct screen measurement almost impossible
  - Residual dispersion makes interpretation of projective profile nuanced
- Quad scan of a single energy slice
  - Use collimators to select a "representative" energy slice
  - Twiss backpropagation and waist shift are used to match the witness twiss
  - Energy spread small enough to do quad scan using electron spectrometer
  - Chromatic error hard to measure in an efficient manner

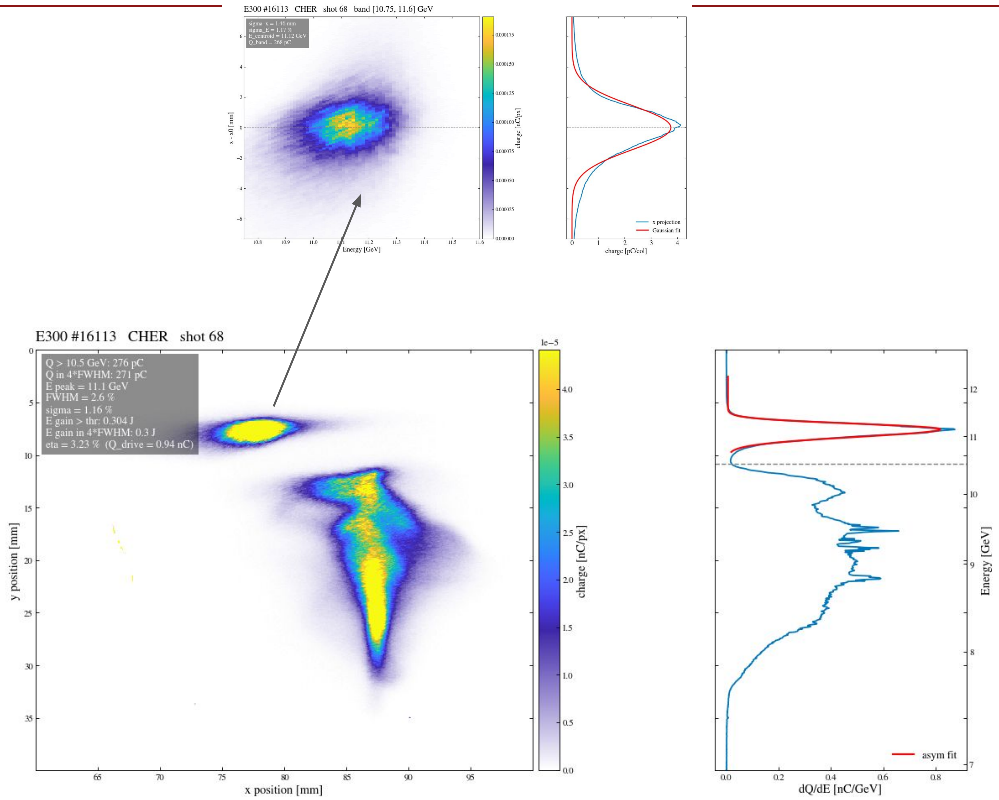


D. Storey

Twiss measurement for high energy spread beam is hard, slow, and subtle

First matching attempt

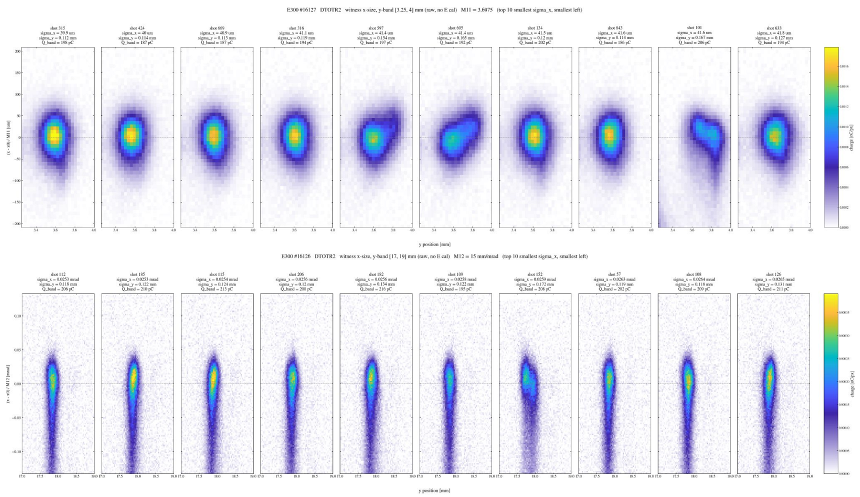
- Low density Li plasma, modest energy gain (~1 GeV, ~10%)
- Using electron spectrometer to measure the incoming & outgoing beam size and divergence
  - Spectrometer setting of M12=0 captures the x beam size
  - Spectrometer setting of M11=0, M12=big number (15 in our setting) to estimate the divergence



$$\sigma_{\mathrm{scr}}^2 = M_{11}^2 \langle x^2 \rangle + 2\, M_{11} M_{12} \langle x x' \rangle + M_{12}^2 \langle x'^2 \rangle + \eta^2\, \sigma_\delta^2$$

WARNING: EXTREMELY PRELIMINARY ANALYSIS

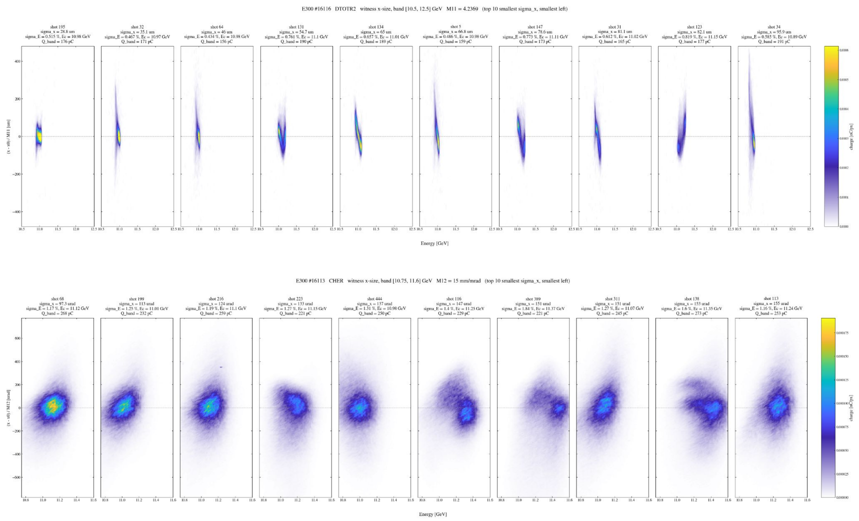
Incoming/outgoing emittance estimation



Incoming beam size

Incoming beam divergence

Incoming nor. emit. ~20 mm·mrad



Accelerated witness beam size (insufficient data taken, but good shots have similar beam size as incoming beam)

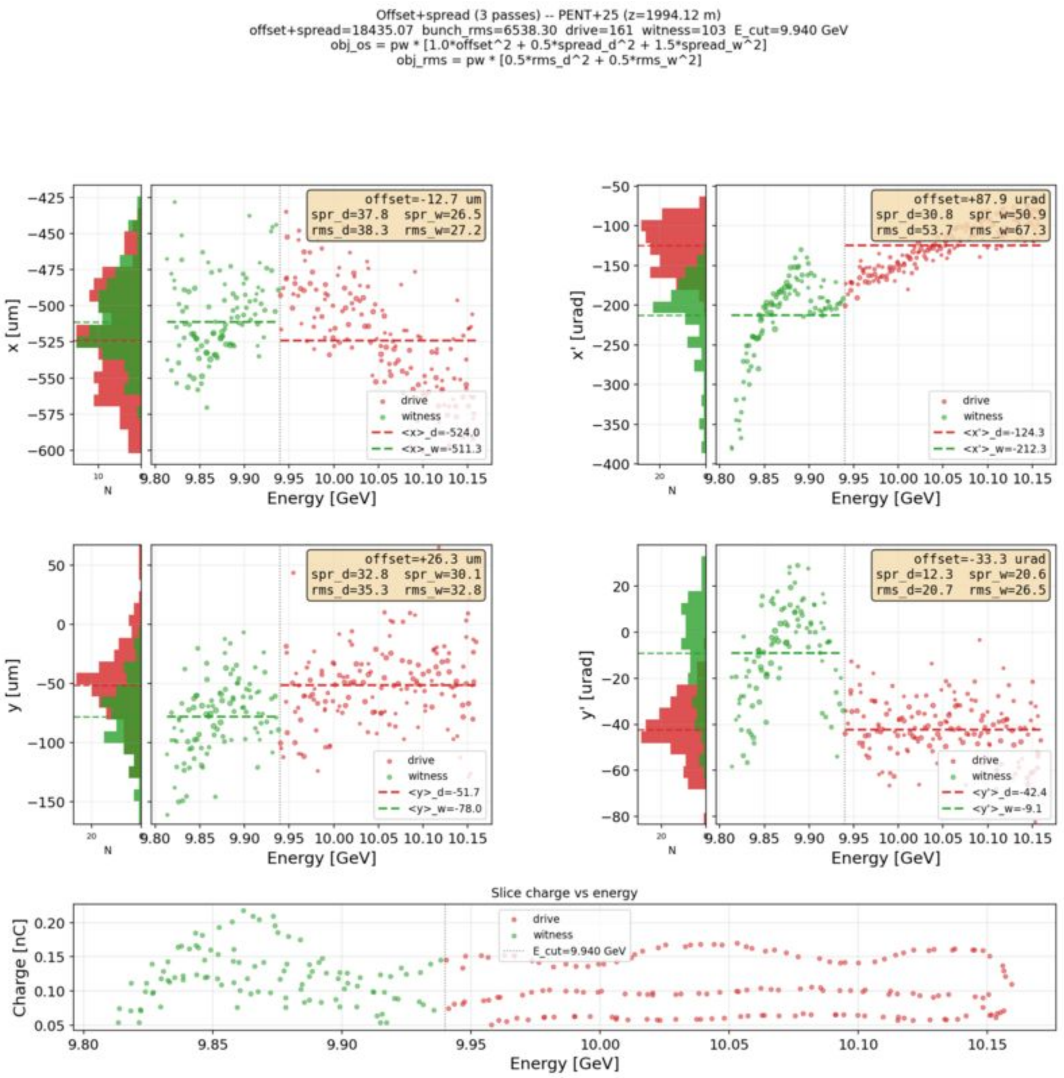
Accelerated witness beam divergence

We estimate a 5x growth in norm. emit. (upper bound)

WARNING: EXTREMELY PRELIMINARY ANALYSIS

Comment

- Very preliminary analysis (as you can see)
- We know that we are not matched
    - A FF quad was not functioning, so we did not achieve the matched beta function for our plasma density (matched beta ~15 cm; we achieved 25+ cm)
    - Angular mismatch is still large as measured by the chromatic virtual screen
- Better tools are being developed. We will try to do a better job next year.



Summary

- Fast chromatic virtual screen measurement enables slice dispersion control with hand- and ML-tuning

- Precise measurement and control of witness twiss parameters challenging

- Detailed reconstruction of the beam is the starting point

We are working towards matching and emittance preservation

Collaboration/Acknowledgements

E300 Collaboration: Erik Adli[4], Zack Buschmann[1], Sebastien Corde[5], Thamine Dalichaouch[3], Auralee Edelen[1], Claudio Emma[1], Ole G. Finnerud[4], Spencer Gessner[1], Juan Pablo Gonzalez-Aguilera[1], Claire Hansel[6], Carsten Hast[1], Mark Hogan[1], Chan Joshi[3], Daniel Kalvik[4], Peter Kicsiny[1], Anna Kinderman[1]7, Alexander Knetsch[1], Valentina Lee[6], Ching-En Lin[12], Carl A. Lindstrøm[8], Michael Litos[6], Ryan Loney[1], Nathan Majernik[1], Kenneth Marsh[3], Warren Mori[3], Brendan O'Shea[1], Jinseo Park[1]2, Marcellus Parker[1], Sharon Perez[1], Ivan Rajkovic[1], Sheldon Rego[5], Elena Ros[6], Ryan Roussel[1], Doug Storey[1], Kelly Swanson[1], Junzhi Wang[1], Gerald Yocky[1], Viktoriia Zakharova[5], Chaojie Zhang[3]

1. SLAC National Accelerator Laboratory; 2. Stanford University; 3. University of California Los Angeles; 4. University of Oslo; 5. Laboratoire d'Optique Appliquée (LOA); 6. University of Colorado Boulder; 7. UC Santa Cruz; 8. DESY

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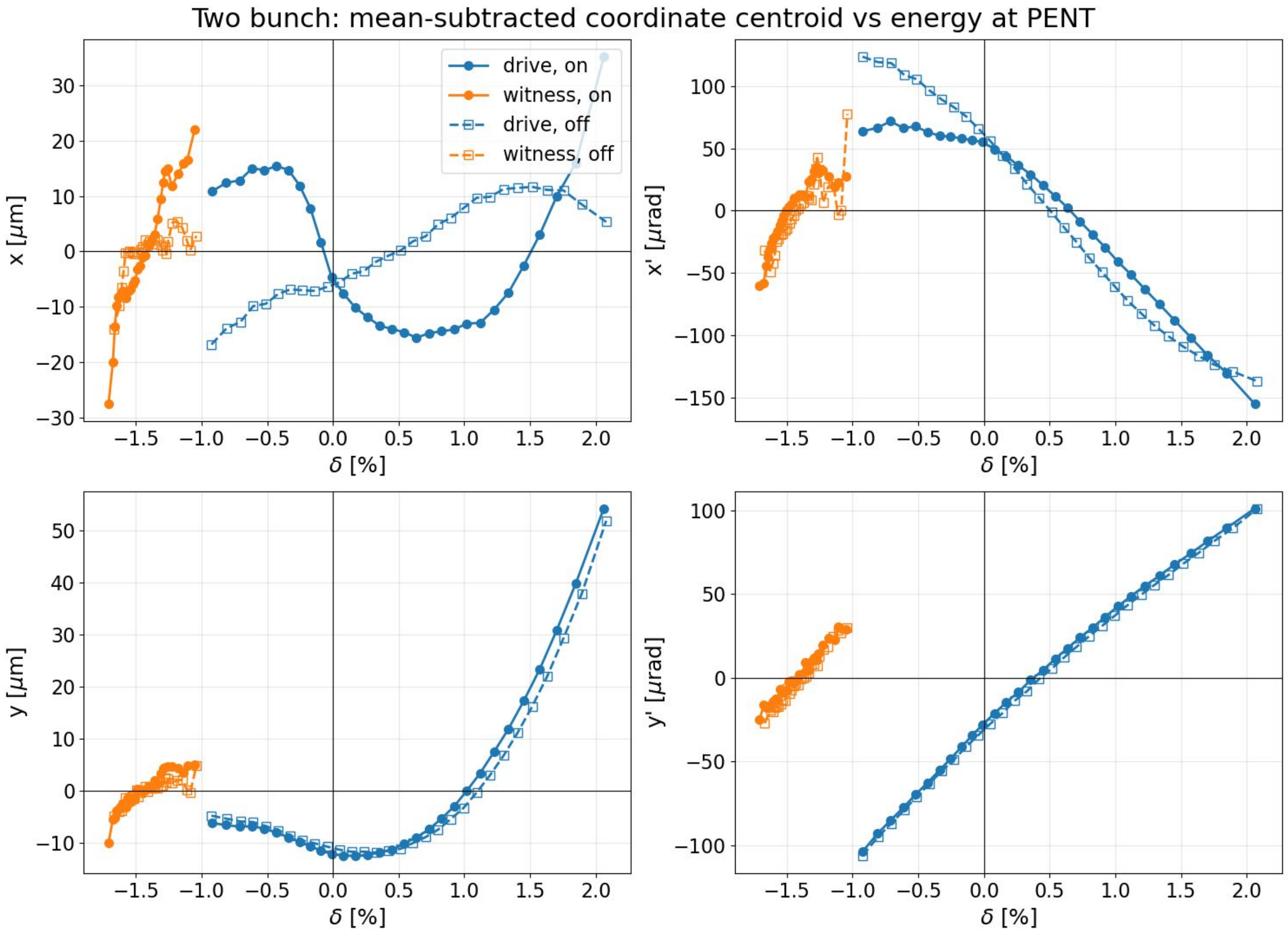
Backup slides

CSR effect in slice measurement



CSR hard to measure; first order seems OK