Advances in Two-Bunch Plasma Wakefield Acceleration at FACET-II

FACET-II

Facility for Advanced Accelerator Experimental Tests

AAC24 Advanced Accelerator Workshop

Doug Storey | Associate Staff Scientist | FACET-II

On behalf of the E300 Collaboration

July 23, 2024

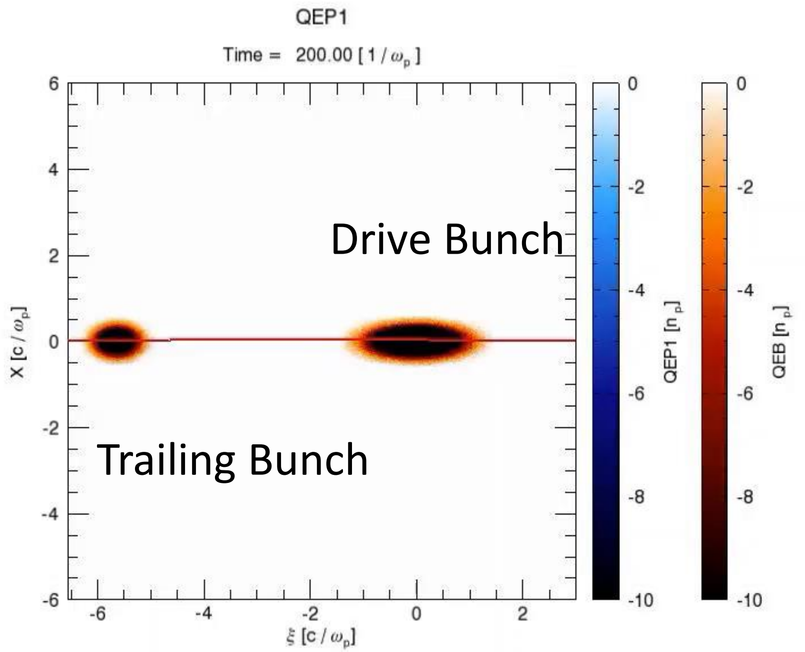
E300 collaboration

- PI's: C. Joshi (UCLA) and M. Hogan (SLAC)
- SLAC team:
  - R. Ariniello, C. Emma, S. Gessner, A. Knetsch, N. Majernik, B. O'Shea, S. Perez, I. Rajkovic, D. Storey, K. Swanson, R. Watt, M. Hogan
  - Z. Buschmann, S. Kalsi, R. Loney, M. Parker, G. Yocky
    - *FACET-II is supported in part by the U.S. Department of Energy under contract number DE-AC02-76SF00515*
- Collaborators:

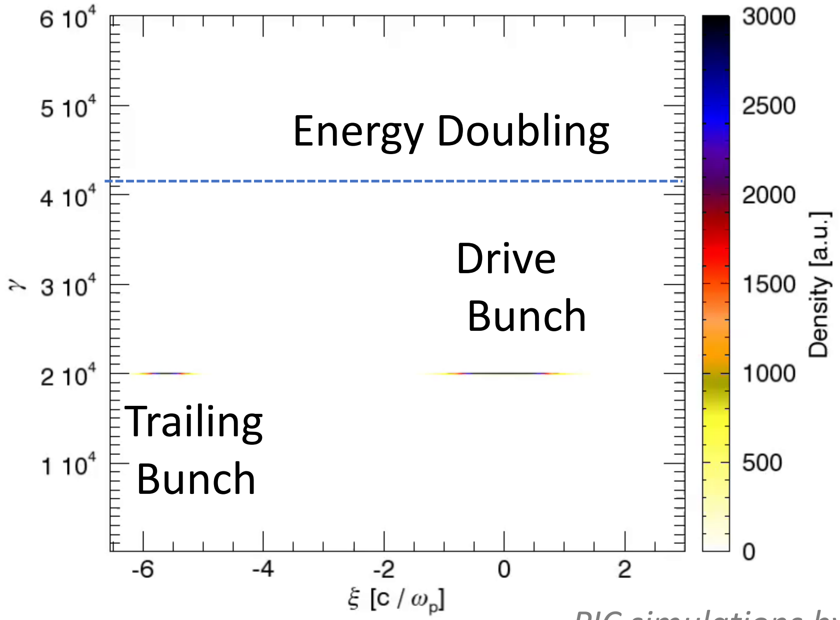
Two-Bunch PWFA: E300 goals at FACET-II

- To demonstrate energy doubling of a trailing bunch (from 10 to 20+ GeV) with:
  - <1% Energy Spread, and
  - Drive bunch pump depletion and > 40% drive to trailing bunch energy transfer efficiency,
  - while minimizing emittance growth

- Plasma and beam density with on-axis, E_z profile:

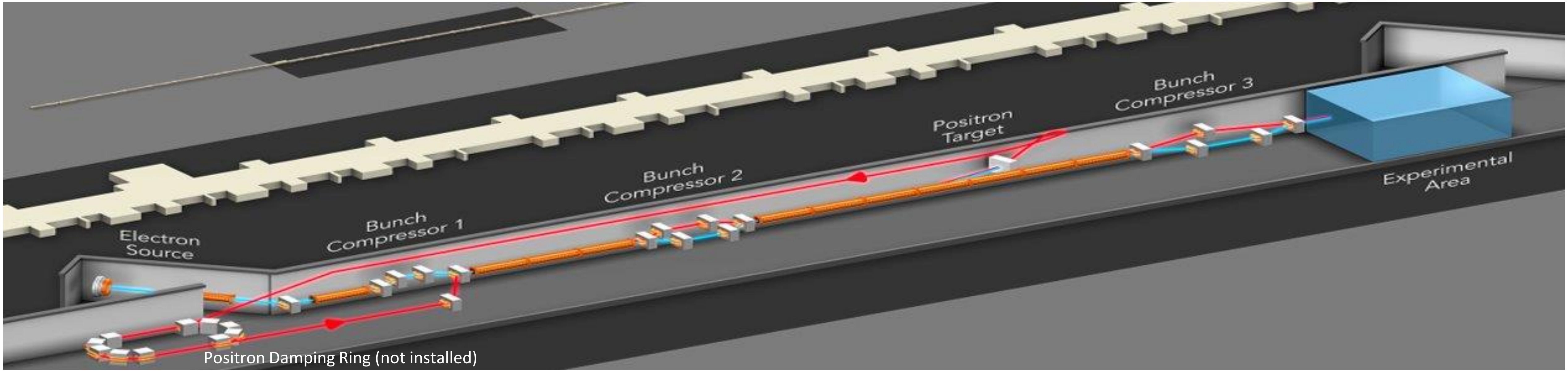


- Energy evolution of drive and trailing bunches:



PIC simulations by W. An

Overview of the FACET-II National User Facility



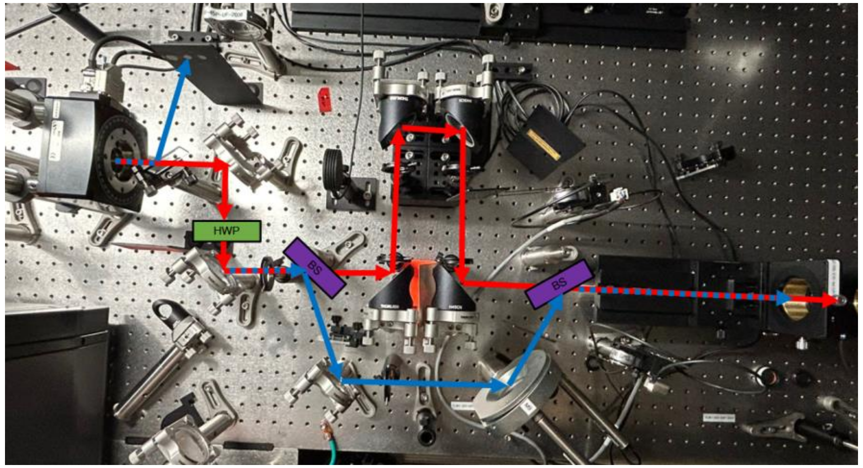
- Hosts experiments in beam-driven PWFA and those that take advantage of intense electron and laser beams
- First experimental run in 2022 – single bunch configuration
- First two-bunch commissioning in 2024
- Positron capabilities do not yet exist, but the plans do

Two bunch generation

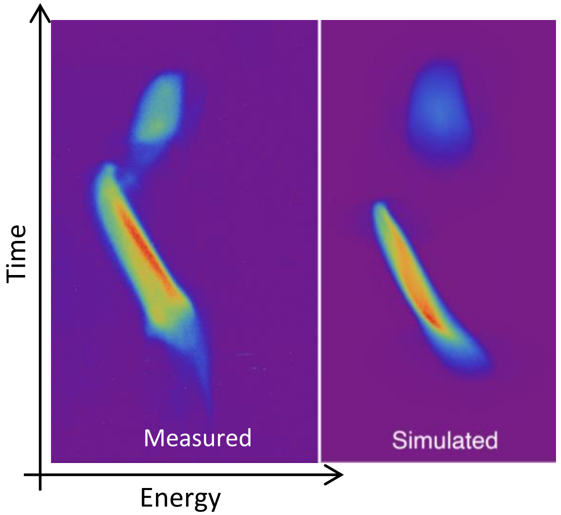
Two bunch generation at the cathode

- 2 UV pulses aligned with 9ps separation
- Nominal configuration:
  - 1.2 nC drive – 10 x 8 µm emittance
  - 0.4 nC witness – 4 x 5 µm emittance
- Excellent agreement with simulation out of the injector

UV pulse stacking



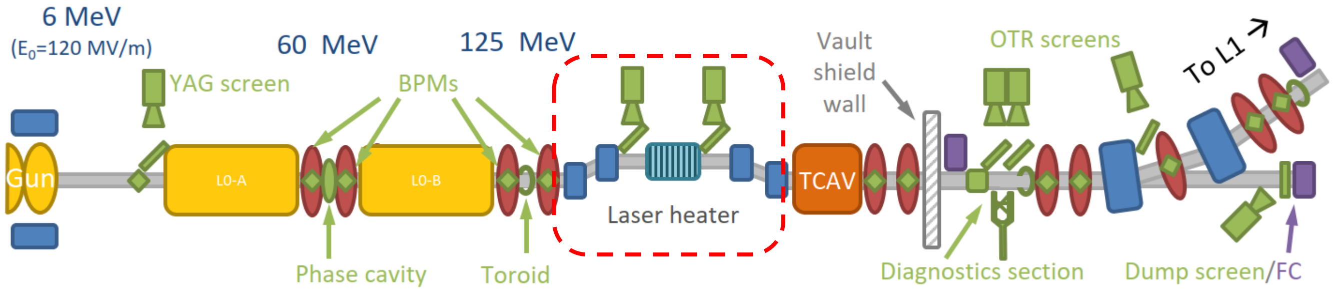
Injector long. phase space



Laser heater

- Increases uncorrelated energy spread
- Effective tool for limiting microbunching, CSR, and ionization of buffer gas
  - *See* ***C. Emma's talk in WG5*** *on Thurs.*

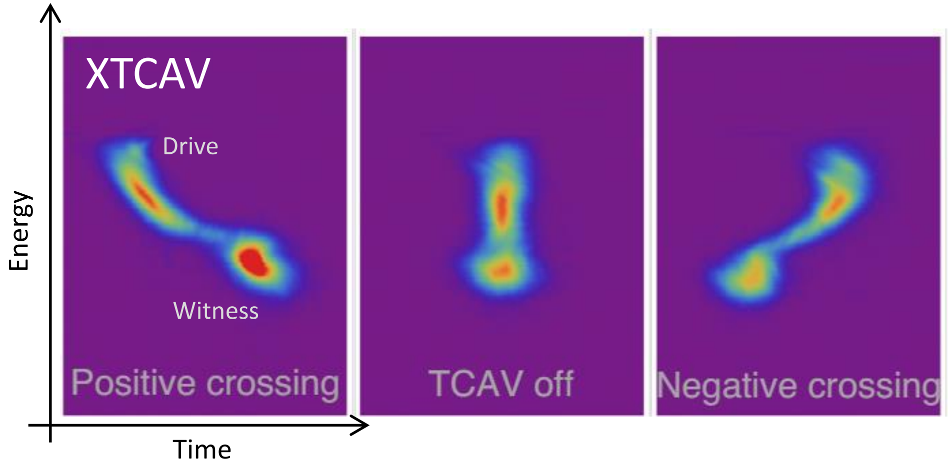
Injector schematic



Longitudinal diagnostics at the IP

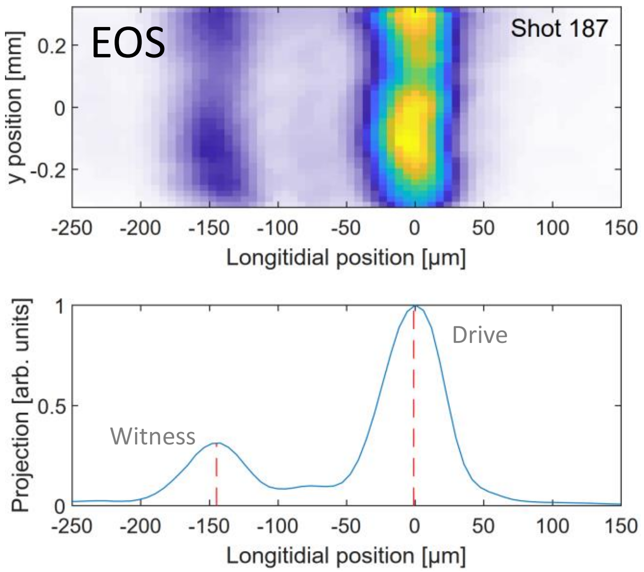
X-band transverse deflected cavity

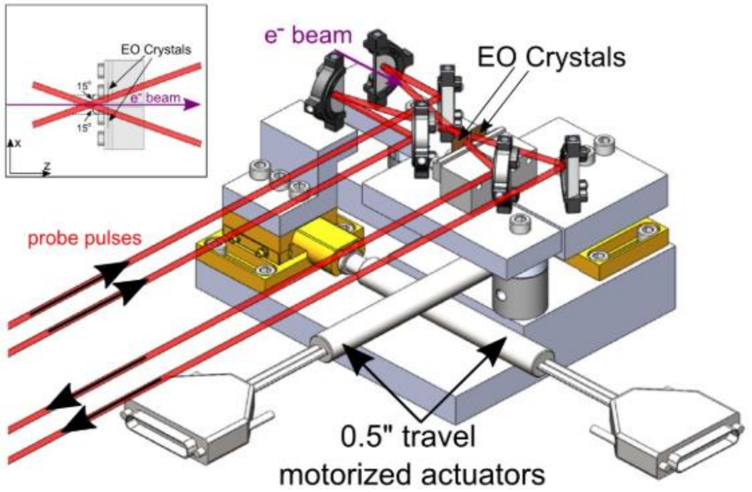
- Single-shot longitudinal phase space measurements
  - Nominal bunch separation of ~140 µm
  - Drive bunch ~10.1 GeV, Witness ~9.9 GeV
- Upgrades to XTCAV RF are ongoing to improve resolution



Electro-Optical Sampling (EOS)

- Non-destructive bunch separation measurement
- Extension to EOS-BPM under development
  - *See **C. Hansel's** talk in **WG5** (now!)*



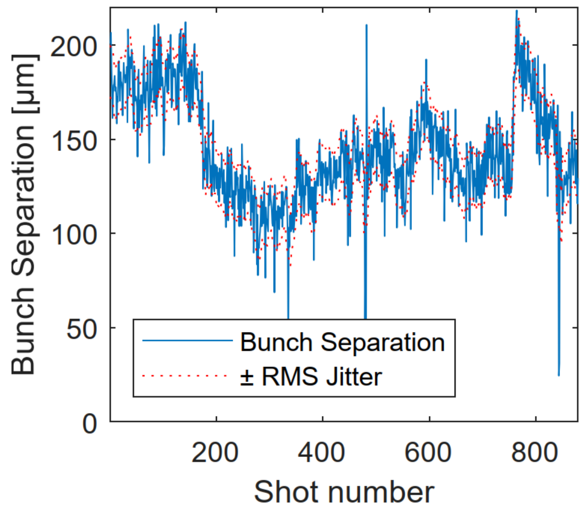


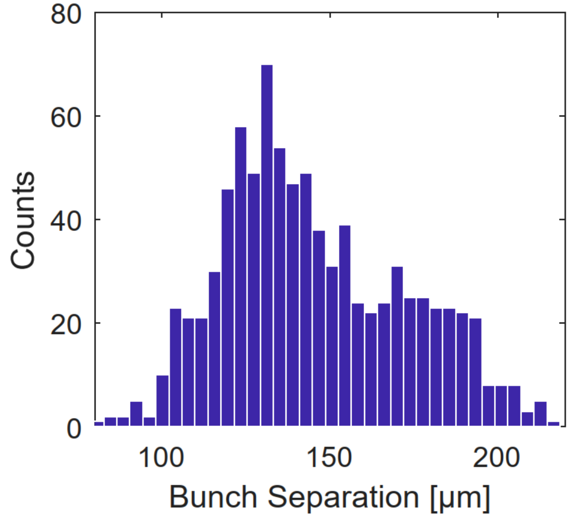
Two-bunch delivery to the IP

EOS measurements of bunch separation

  - Drift of order 100 µm
  - Jitter ~ 13 µm

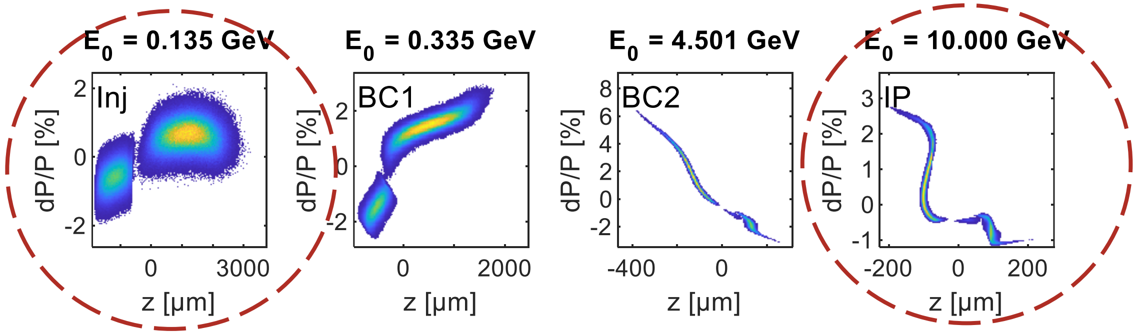
- Strong correlation with energy at the second bunch compressor



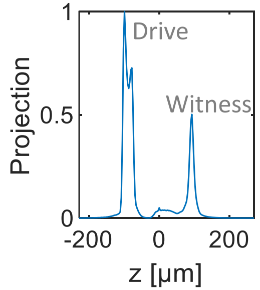


Longitudinal feedback systems

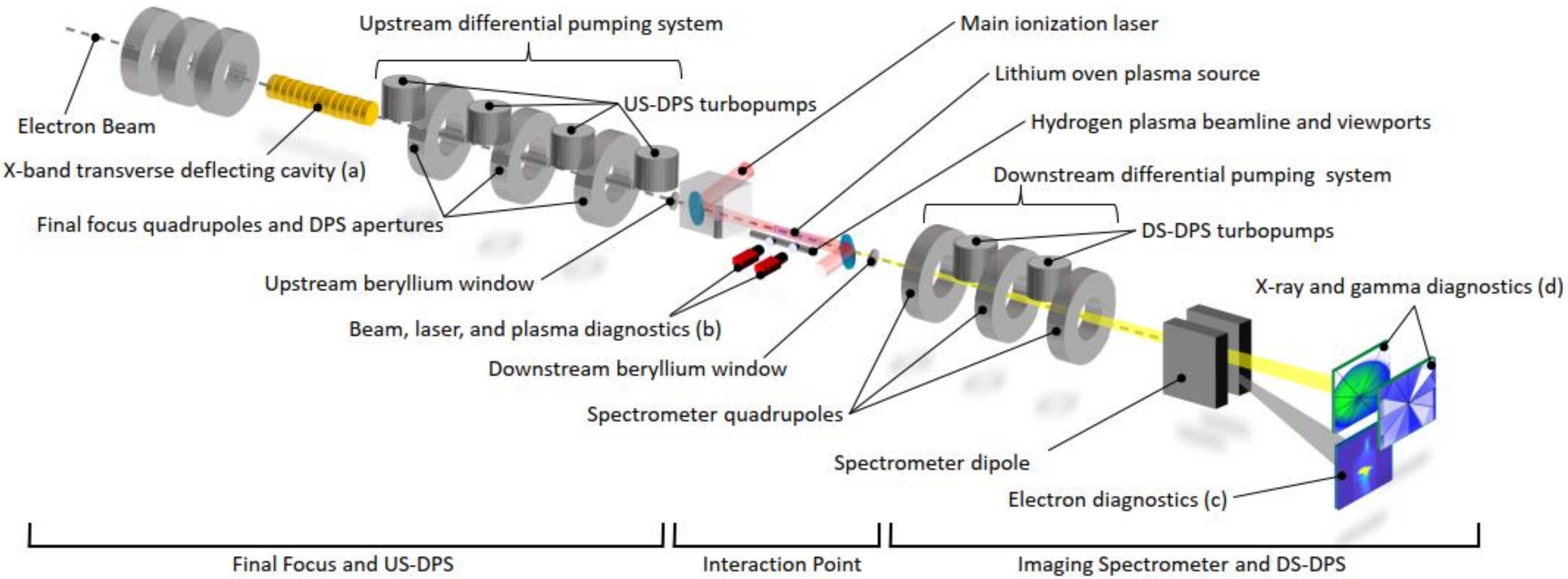
- Feedbacks need to work on both bunch separation and compression
  - Few knobs, and even fewer diagnostics
    - Laser pulse separation, linac phases
- Much more work to be done!



Simulated LPS along the linac:

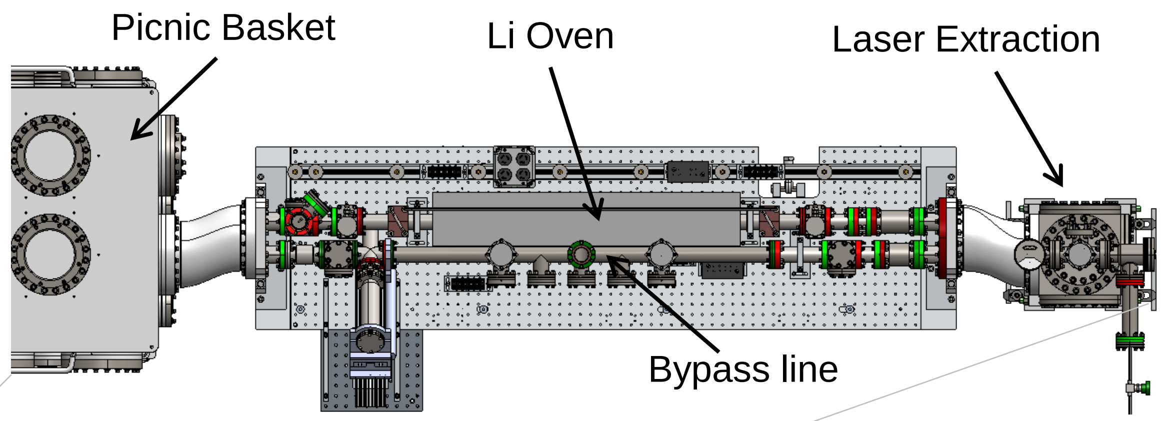


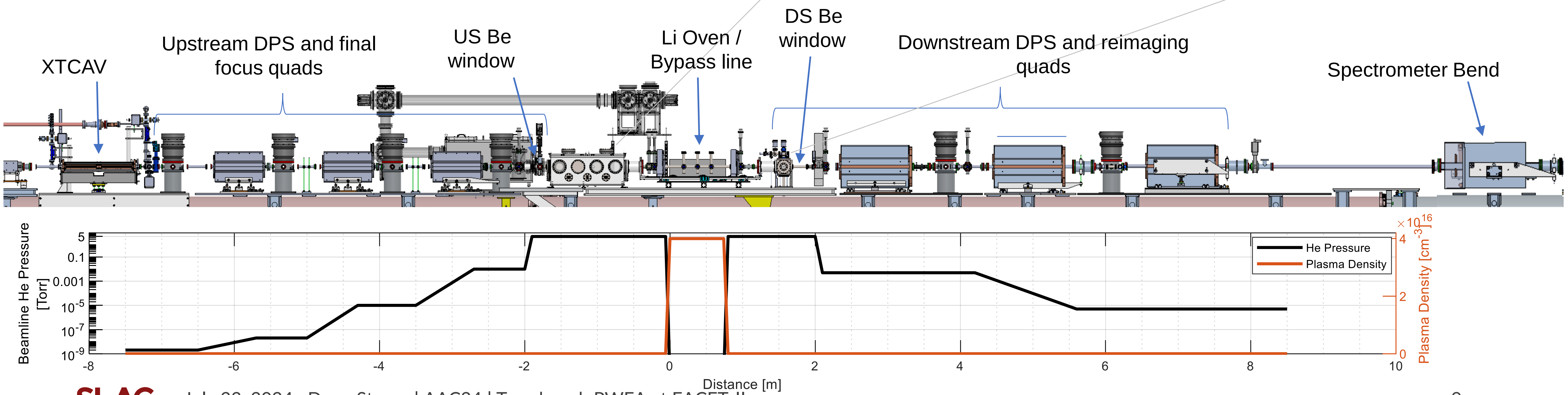
FACET-II experimental area overview



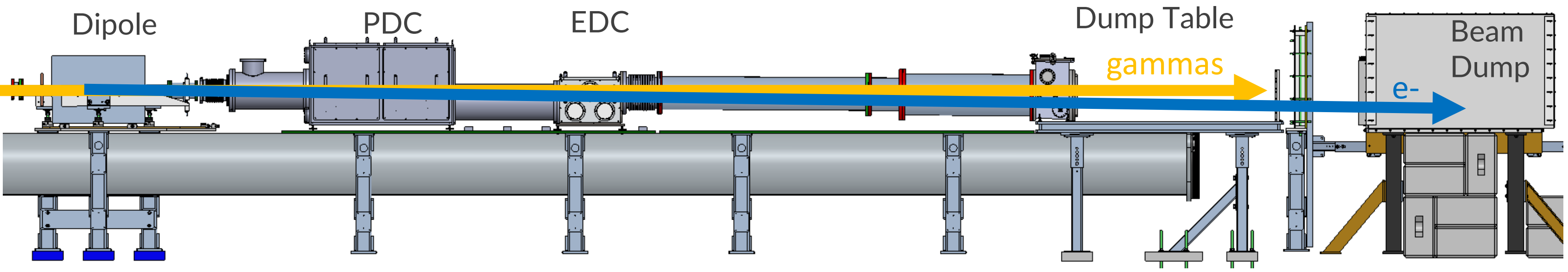
Plasma sources – Lithium oven and hydrogen gas

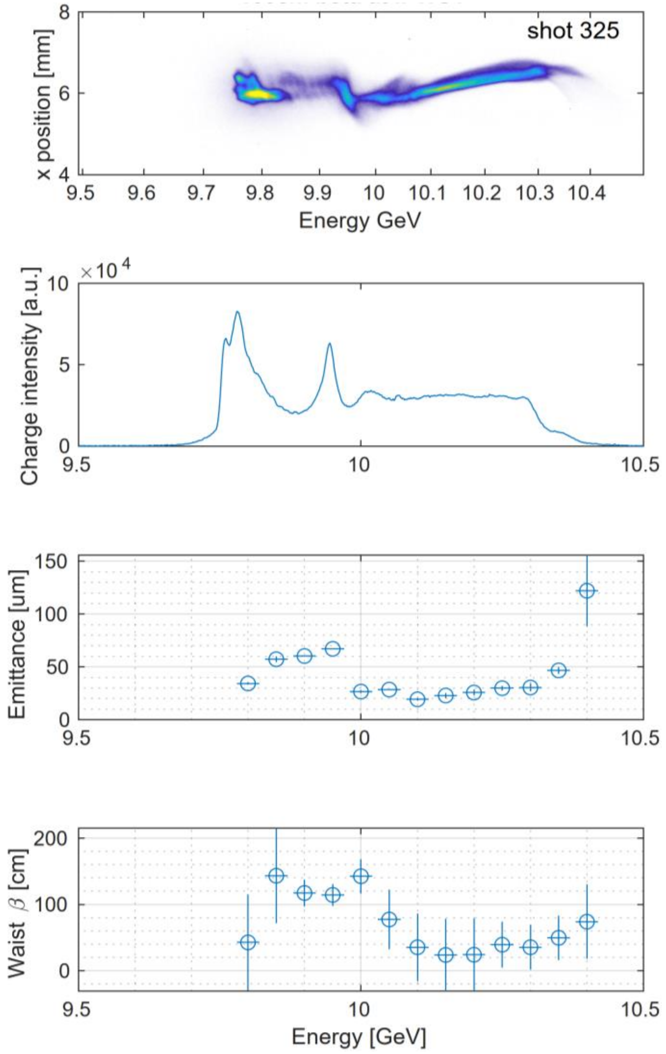
- Main plasma source is the lithium oven - hot lithium vapor contained by He buffer gas
  - Nominal 4×10^{16} cm^{-3} density over 40cm length
  - ~10 cm density ramps defined by lithium/helium boundary
- Second plasma source is static fill of 4 meters of hydrogen gas





Spectrometer diagnostics





Imaging spectrometer beamline

- Broadband, large field of view electron spectrometers
- High resolution electron profile monitors
- X-ray/Gamma-ray screens for measuring betatron radiation

Dispersive quad scan measurements of two-bunch system

- Witness emittance ~50µm, energy spread ~1% FWHM
- Drive emittance < 50 µm

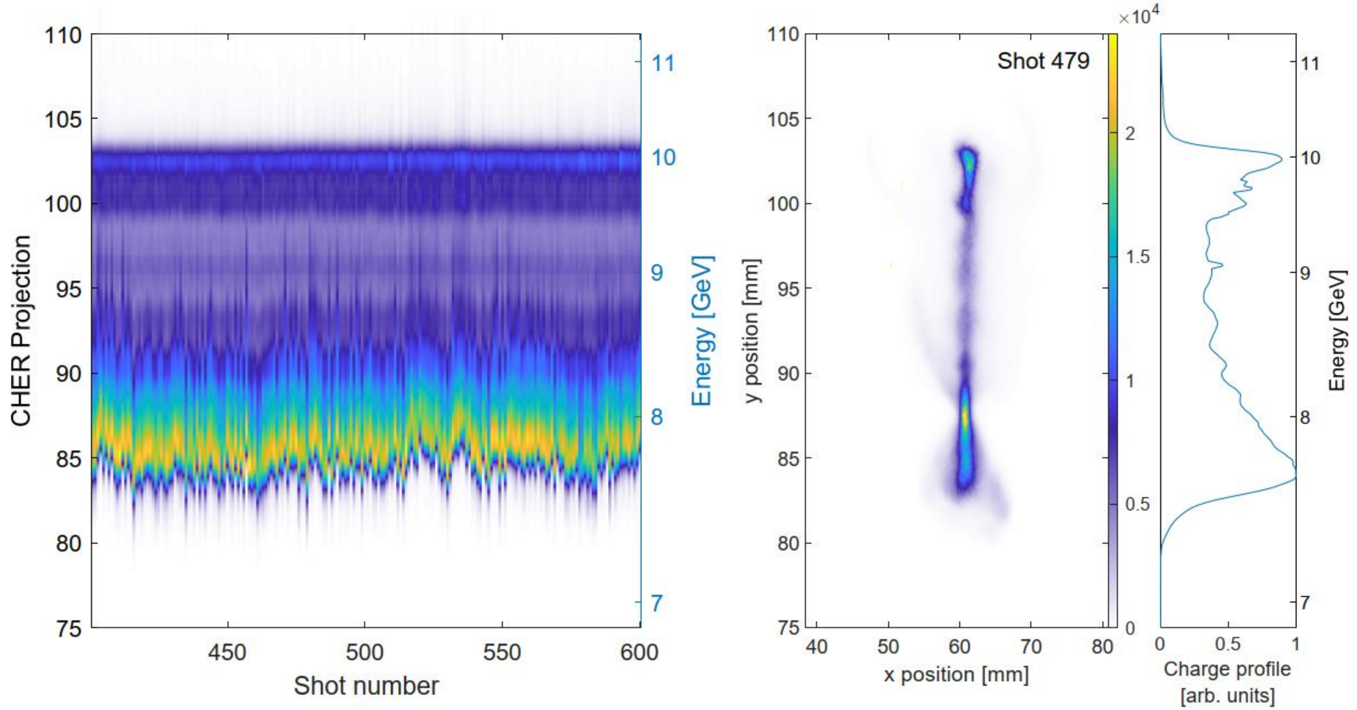
Drive to wake energy transfer with two bunches

- In previous single bunch runs we demonstrated ~40% energy transfer to the wake in the Li oven
  - *See **R. Ariniello's** talk in **WG3** (next!)*
  - However – the Li oven was damaged in these runs, leading to loss of Li
  - In the two-bunch studies we were working with an unknown plasma density profile

Drive only energy transfer

- Witness collimated at the end of linac
- Max energy loss of ~2.5 GeV
- >85% of charge participating
- Total energy transfer = 1.4 ± 0.1 J (~13%)

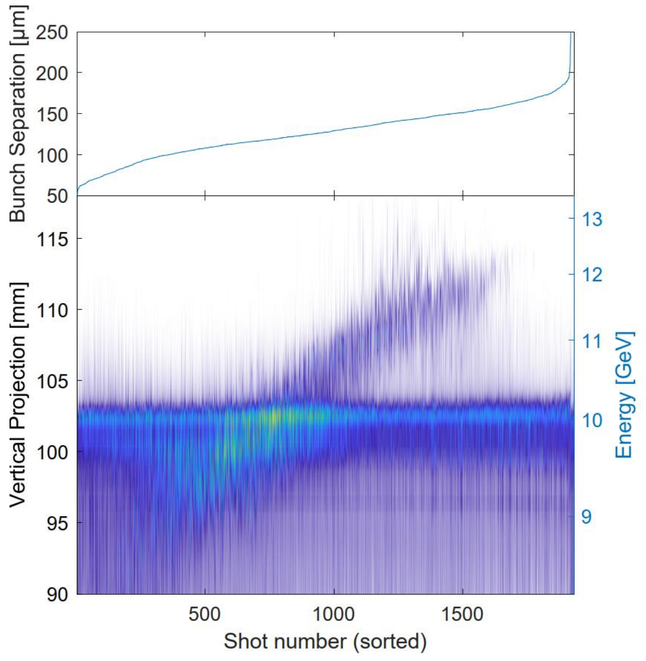
Relatively small energy loss, but high participating charge → **oven in poor state**

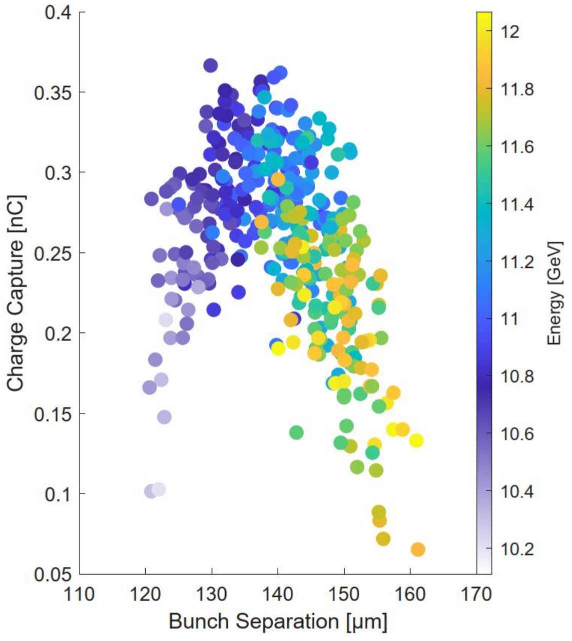


Witness acceleration

Acceleration of the witness by up to ~2 GeV

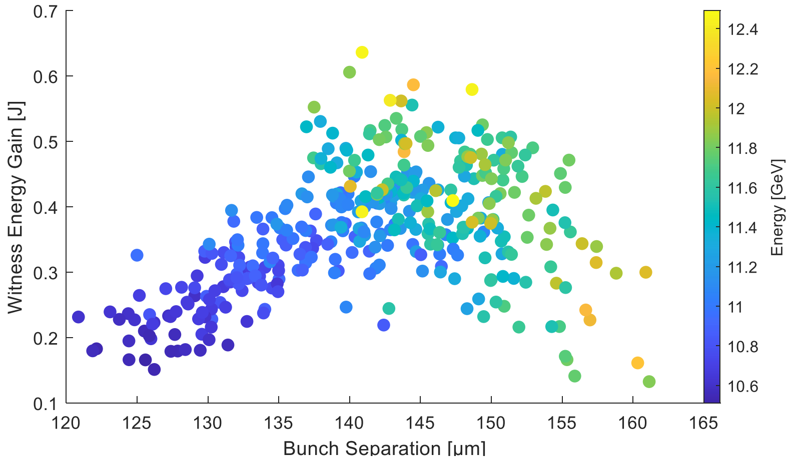
- Near complete capture of the witness at the optimal bunch spacing
  - Max witness capture at bunch separation ~ 138 um
  - FWHM of distribution ~ 25 um
  - 5 Torr Li oven → λ_p ~ 160 um





Estimate of energy transfer efficiency

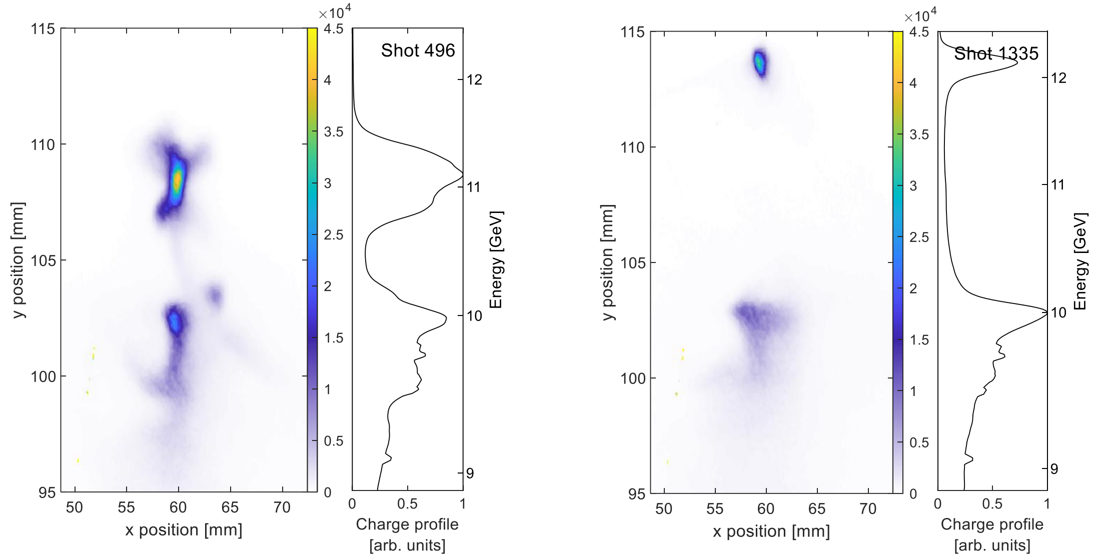
- 0.3 to 0.5 J energy transfer to witness
- Maximum 35% wake-to-witness energy transfer efficiency



Beam quality of the accelerated witness charge

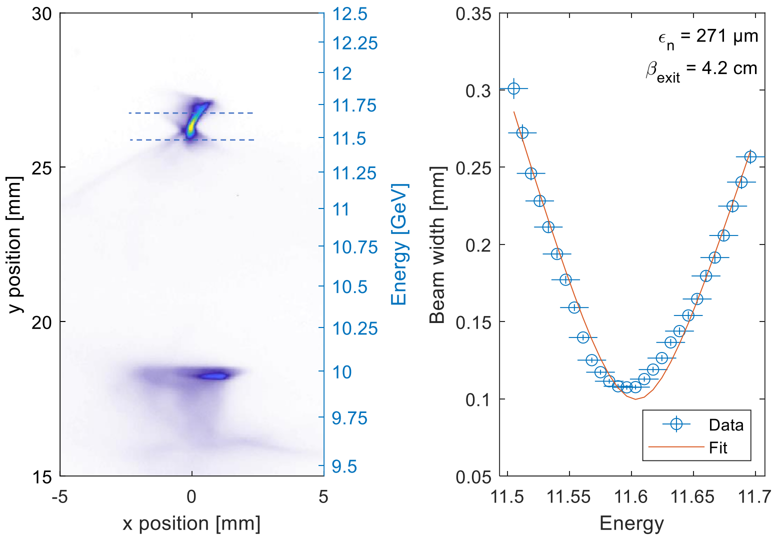
Energy spread

- Order 1-2 GeV of acceleration at optimal bunch separation
- Energy spread of 1-4% of accelerated witness
  - Shot 496: 320 pC at 11 GeV, 3% energy spread
  - Shot 1355: <100 pC at >12 GeV, 1% energy spread

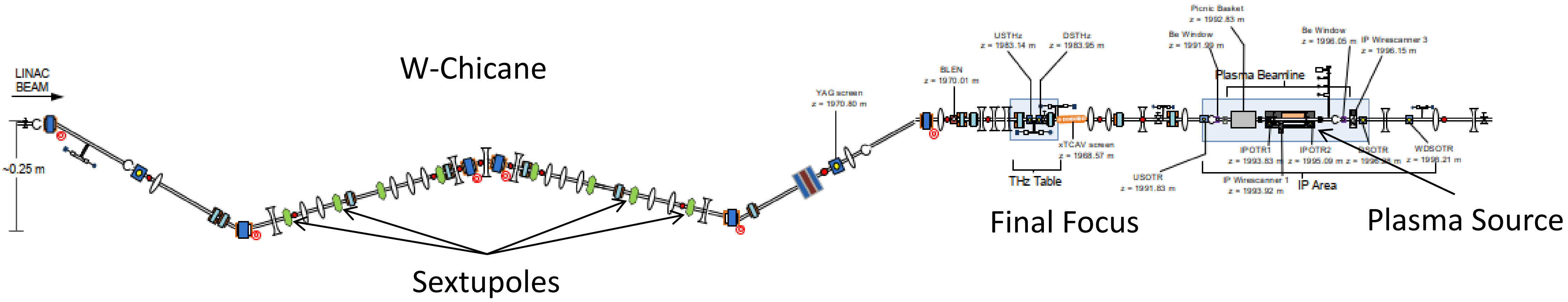


Single shot emittance measurements

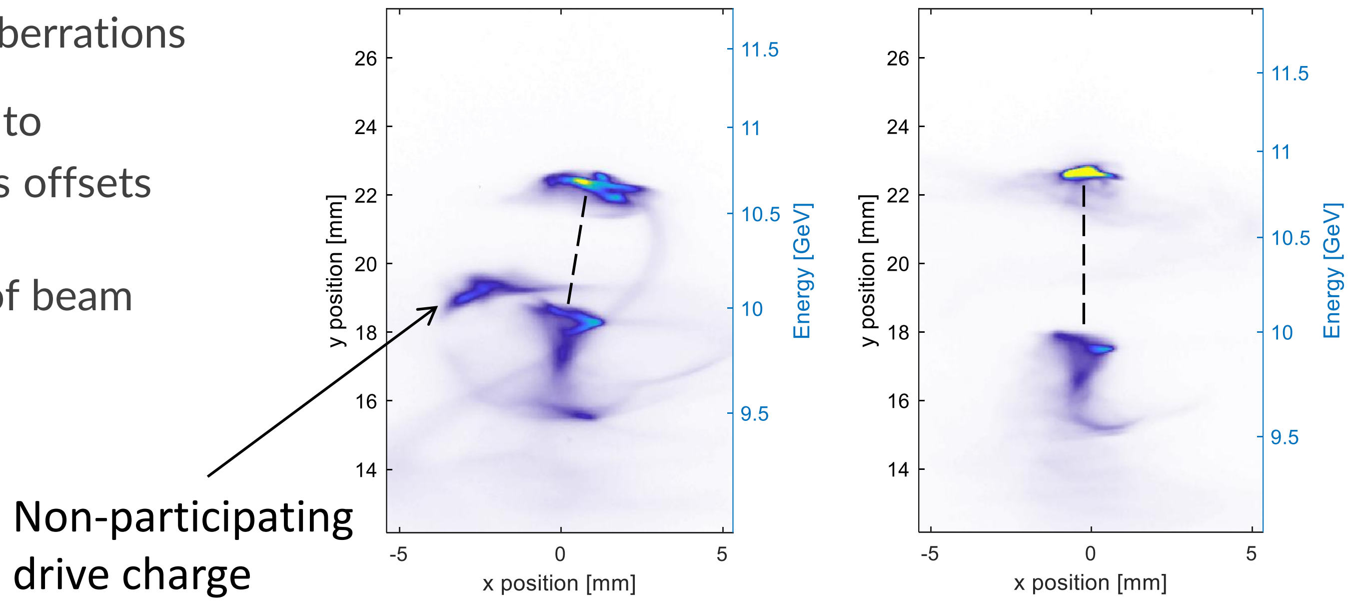
- Minimum accelerated witness emittance of ~ 250 µm
  - Beam not matched to plasma
  - Large fluctuations due to long. and transverse jitter
- Alignment of the two bunches into the plasma is critical!
  - *See **O. Finnerud's** talk in **WG3** on Mon.*



Beam alignment into the plasma



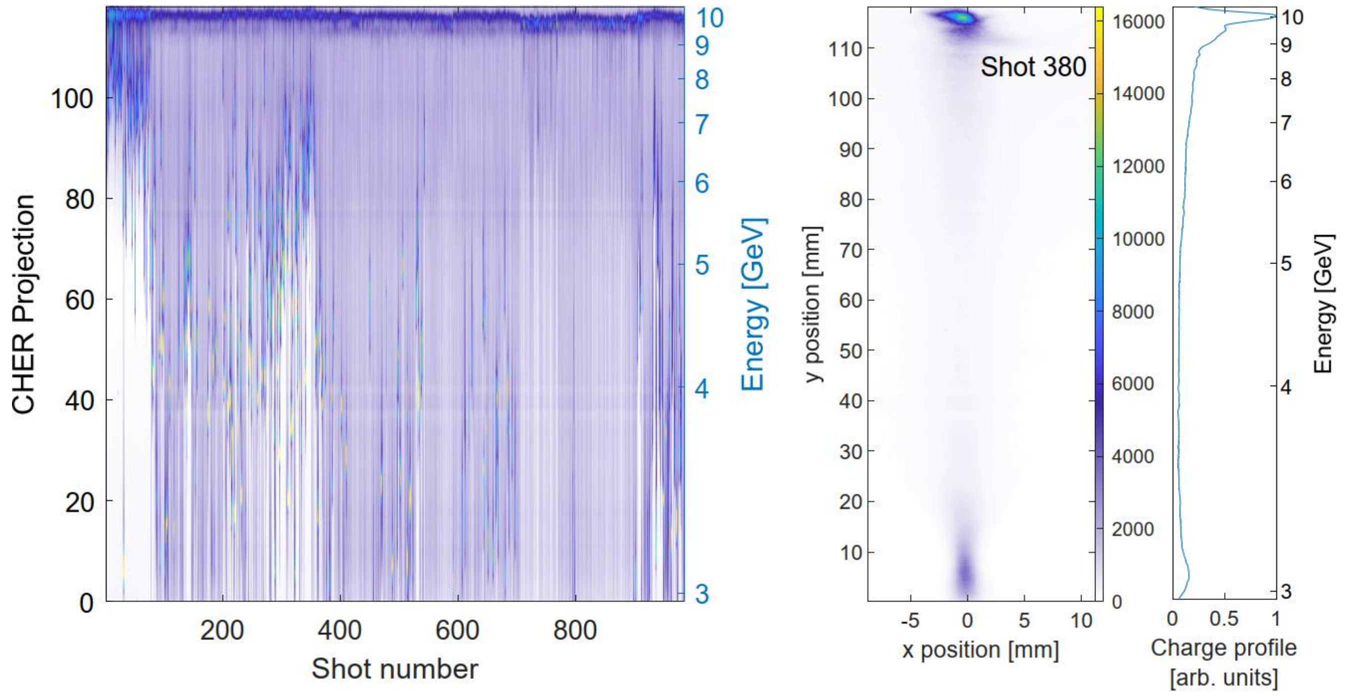
- Sextupoles are included to correct chromatic aberrations
- Tuning of their transverse position was critical to minimize dispersion at the IP and drive/witness offsets
- It is very tricky to make direct measurements of beam profile at the IP
- Opportunity for ML/AI optimization based on PWFA performance



Two bunches in H_2 plasma – Drive-to-wake energy transfer

~3 meter long beam-ionized hydrogen plasma

- Static fill pressures up to 1.5 Torr
- Single bunch characterization:
  - C. Zhang, *et al.*, "Generation of meter-scale hydrogen plasmas..." PPCF (2024)
  - D. Storey, *et al.*, "Wakefield generation in hydrogen and lithium plasmas...", PRAB (2024)
- Laser heater used to optimize beam ionization



Drive to wake energy loss

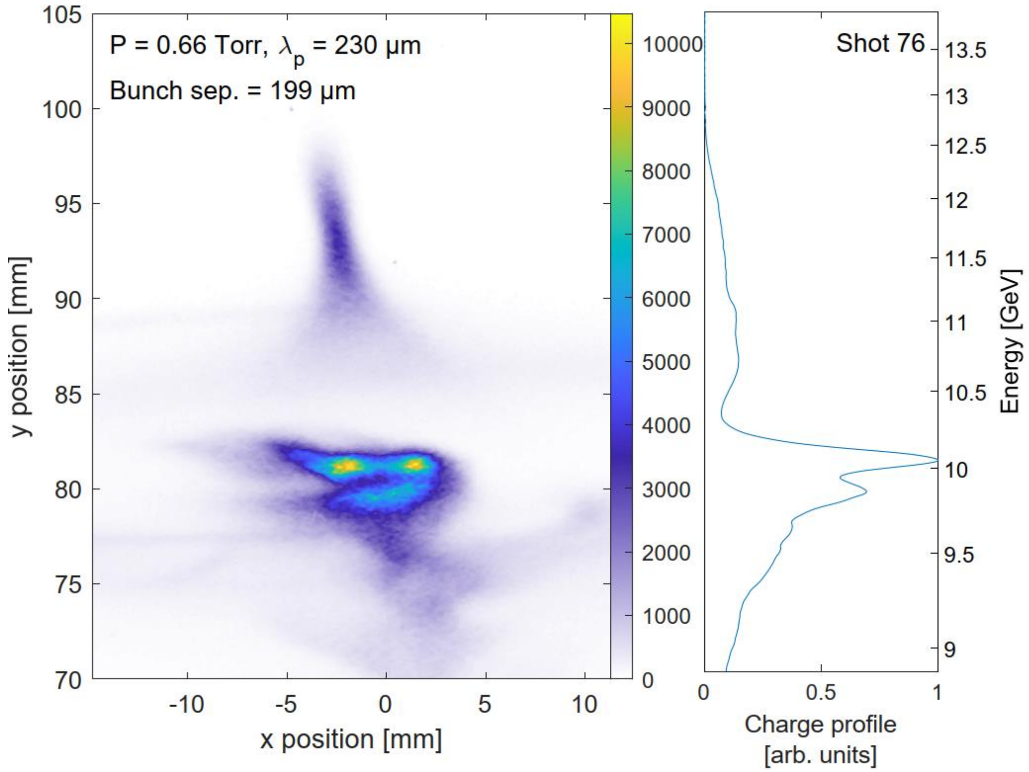
- Maximum energy loss down to ~1.5 GeV in two bunch configuration
- Maximum energy transfer to the wake > ~30%

Two bunches in H_2 plasma – Witness acceleration

- Pressure adjusted to maximize witness capture and acceleration
  - Pressure ~0.6 Torr → λ_p~230 µm
  - Optimal bunch separation ~200 µm

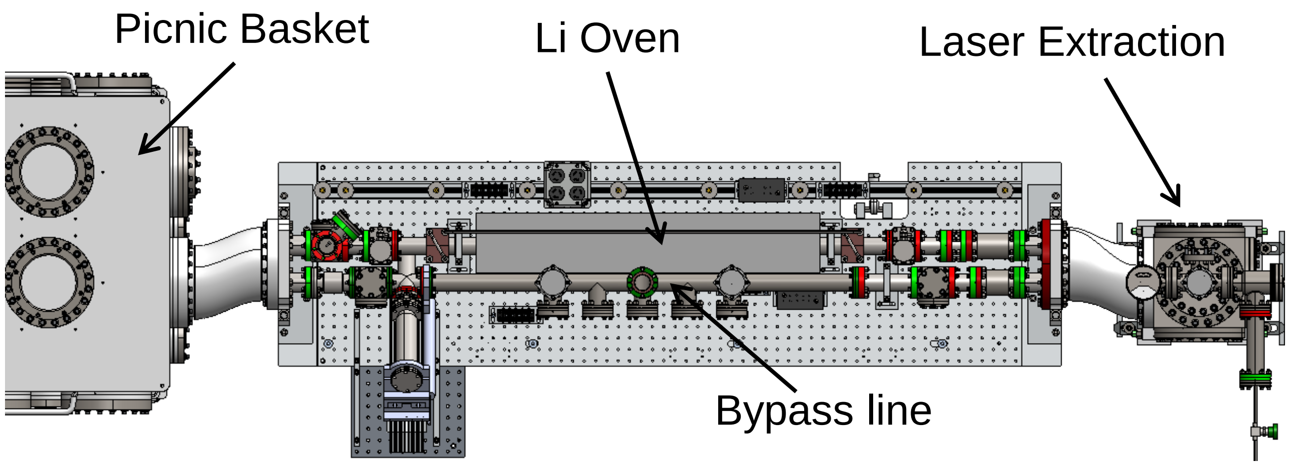
- Bunch quality:
  - ~100 pC witness charge transported through the full plasma column
  - ~1 GeV acceleration with large energy spread

- Less stability and control with beam-ionized H_2 plasma



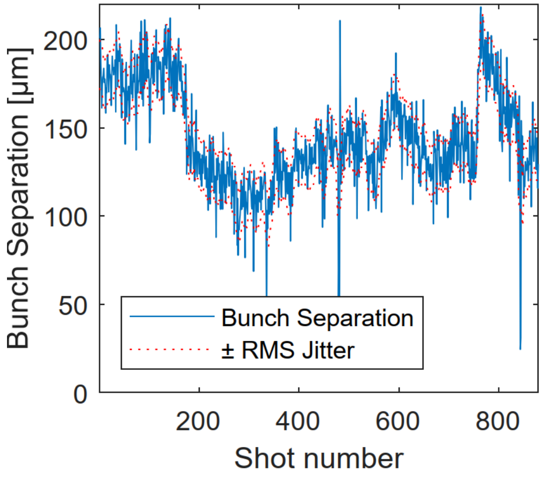
Future prospects

- Lithium oven is being replaced for 2024/25 run
- Improvements to longitudinal feedbacks, stability, and matching the machine to the linac model
- Improved sextupole characterization and tuning
- Developing improved tools for minimizing dispersion at the IP
- Improved reliability – vacuum system, diagnostics, etc



Goals for the upcoming run:

- Demonstrate pump depletion and >60% drive-to-wake energy transfer in two-bunch configuration
- Stable two-bunch delivery to the IP
- Parameter scans to optimize witness acceleration and quality



Summary

- First demonstration of **both** two-bunch delivery **and** witness bunch acceleration at FACET-II
- Achieved 1-2 GeV witness acceleration
  - Limited by the degraded Lithium plasma source
- Near full capture of the witness bunch in the wake
- Few-% level energy spread of accelerated witness
- Relatively large emittance growth – for now