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Measuring the beam-breakup instability in beam-driven plasma-wakefield accelerators

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SLAC NATIONAL ACCELERATOR LABORATORY

University of Colorado Boulder

loa

Stony Brook University

UCLA

Motivation

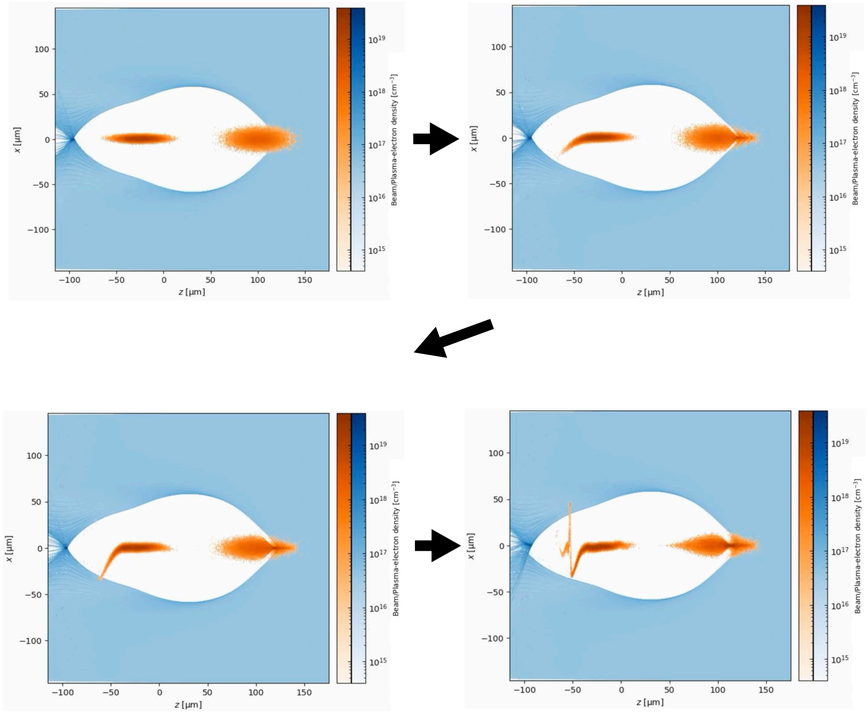
- Beam-breakup instability ⇒ emittance growth, oscillation amplitude growth and charge loss.
- Transverse instabilities limit conventional colliders such as CLIC in terms of charge, gradient etc.
- The small acceleration cavities in plasma accelerators offer higher gradients, but also much stronger instabilities.
  - For next generation colliders, such as HALFH (hybrid, asymmetric, linear Higgs factory) [Foster et al., New J. Phys. 9, 093037 (2023)] transverse instabilities must be suppressed to achieve desired parameters.

Our goals

- Full parameter mapping [Uni. Oslo]
  - Using PIC simulations to map out the entire parameter space that impacts the size of transverse instabilities to find an optimum working point.
- Experimentally verify the amplitude increase and methods to suppress the instability [FACET-II/SLAC and Uni. Oslo] : The E302 experiment
  - Developing methods to quantify the amplitude increase due to transverse instabilities (topic of this talk and poster).
  - We are currently testing these methods using data from the E300 experiment at FACET-II facility at SLAC National Accelerator Laboratory.
  - Eventually look at methods to suppress transverse instabilities.

Transverse instabilities

- Drive bunch (**hose instability**):
  - Large bunch size — [Martinez de la Ossa et al., PRL 121, 064803 (2018)]
  - Induced energy chirp — [Mehrling et al., PRL 118, 174801 (2017)]
- Trailing bunch (**beam-breakup instability**):
  - Operation in the quasilinear regime — [R. Lehe et al., PRL 119 244801 (2017)]
  - Suppression of beam-breakup instability with Ion Motion —[Mehrling et al., PRL 121 264802 (2018)]



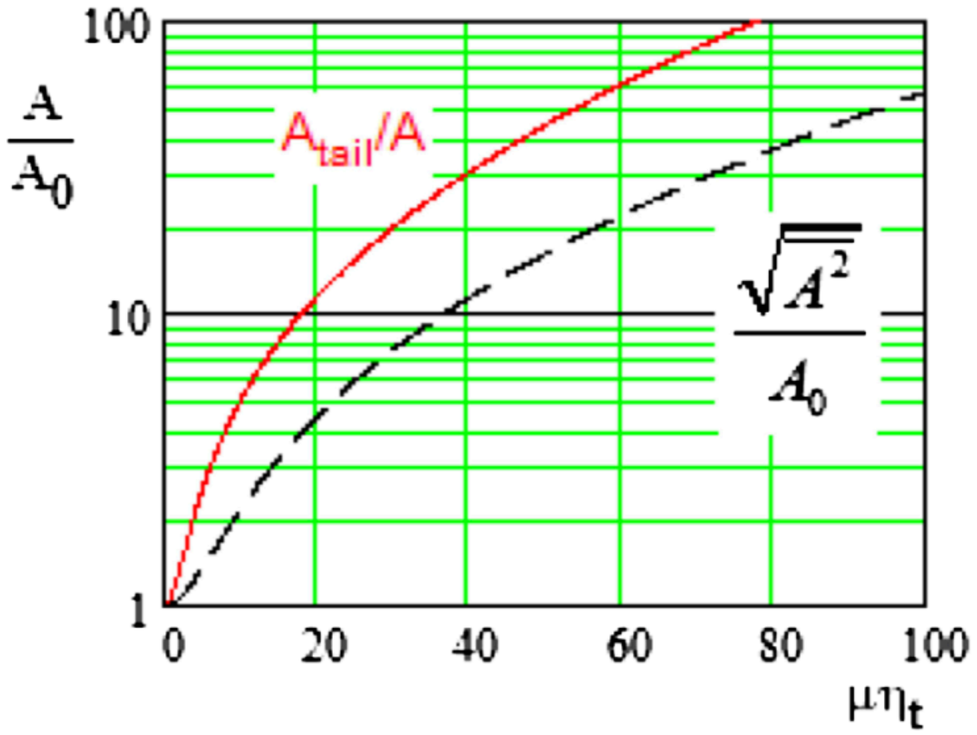
Evolution of a trailing bunch with large beam-breakup instability

Fundamental relation between efficiency and transverse instability?

- Relationship between instability and efficiency proposed “limits” the achievable efficiency.
  - Efficiency versus instability in plasma accelerators PRAB 20, 121301 (2017)

$$\eta_t \approx \frac{{\eta_P}^2}{4(1-\eta_P)}$$

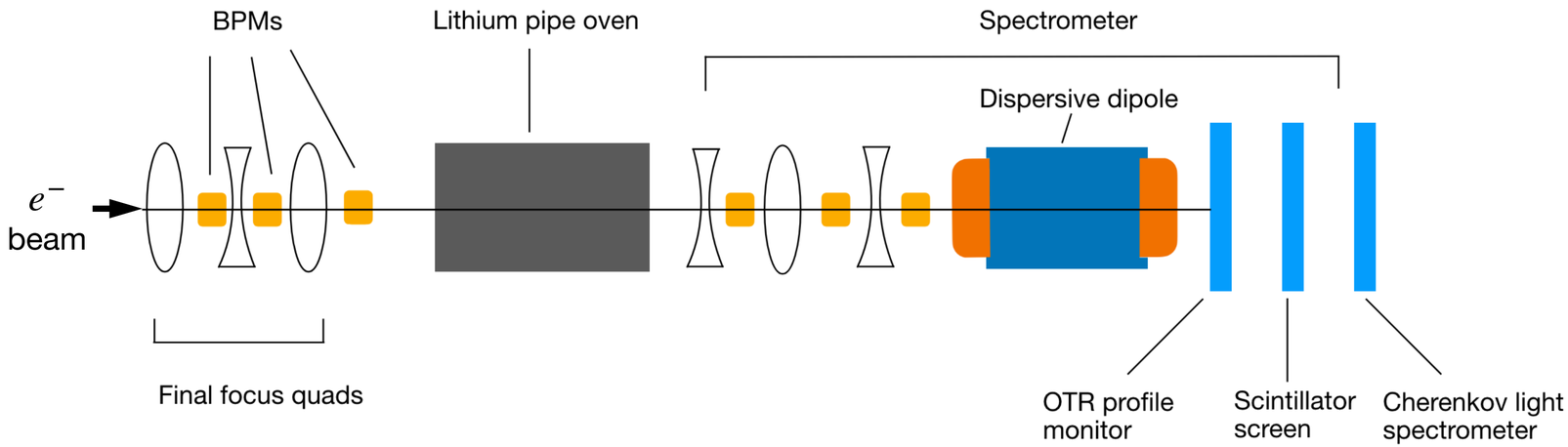
  - Transverse wakefields blow up at high efficiencies.
  - This leads to an exponential increase in amplitude of the trailing bunch.



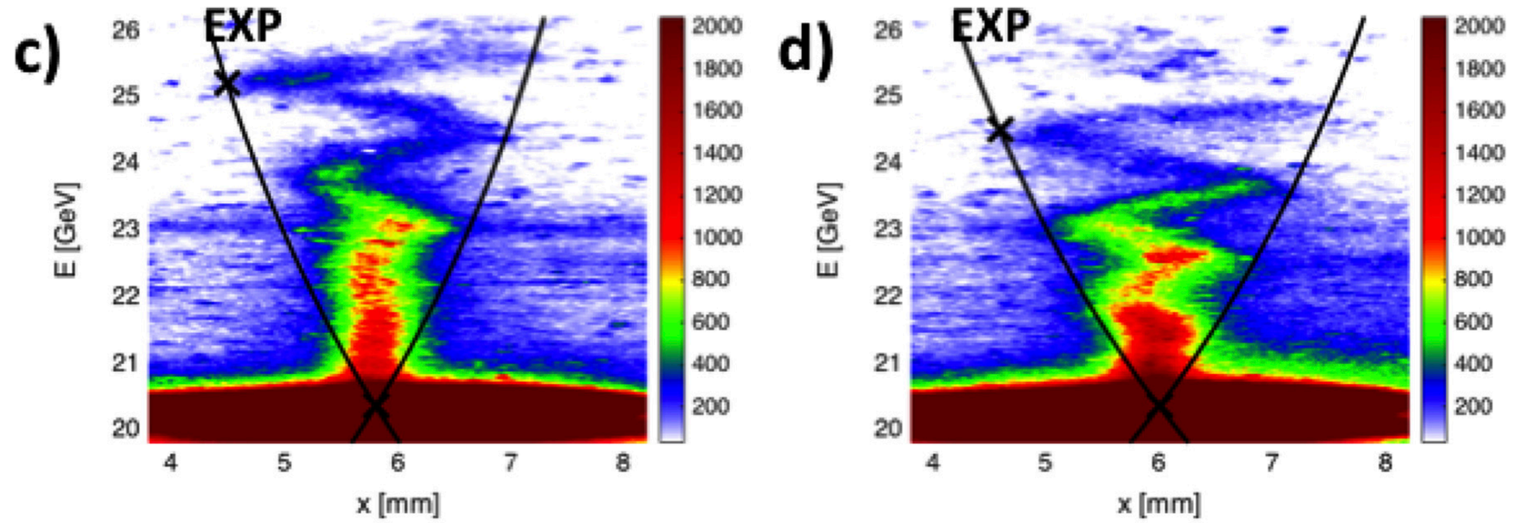
Source: Lebedev et al., PRAB 20, 121301 (2017).

Experimental setup at FACET-II

- Imaging spectrometer with three quadrupole magnets and a dispersive dipole.
- Quadrupole imaging increases energy resolution, but complicates transverse phase-space.
- Consequently real data is hard to interpret.



Source: https://arxiv.org/pdf/2402.10325.pdf



Source: Adli et al., Nucl. Instrum. Methods Phys. Res. Sect. A 829, (2016)

Simulating the experiment

- We use a start-to-end python framework to simulate the FACET-II beam with an initial transverse offset.
  - HiPACE++ for the plasma interaction [Computer Physics Communications 278, 108421, (2022)]
  - OCELOT for FACET-II spectrometer [Nucl. Instrum. Methods Phys. Res. Sect. A 768, 151-156, (2014)]

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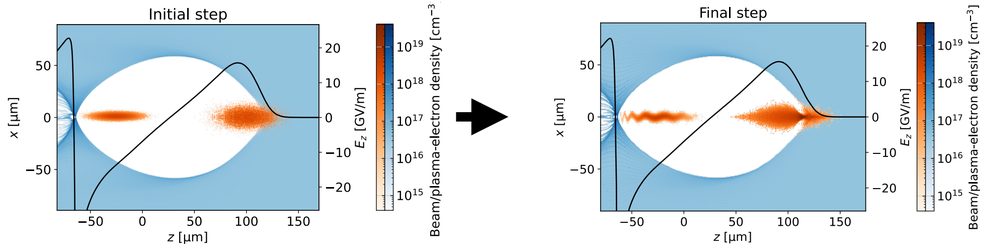

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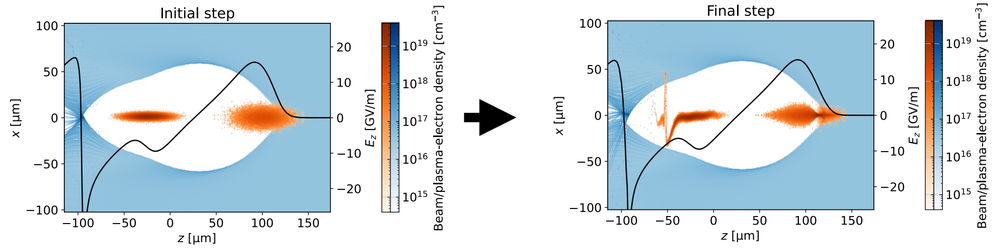

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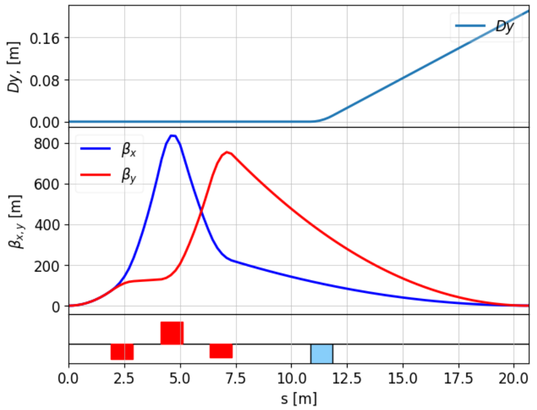

Simulated spectrometer images

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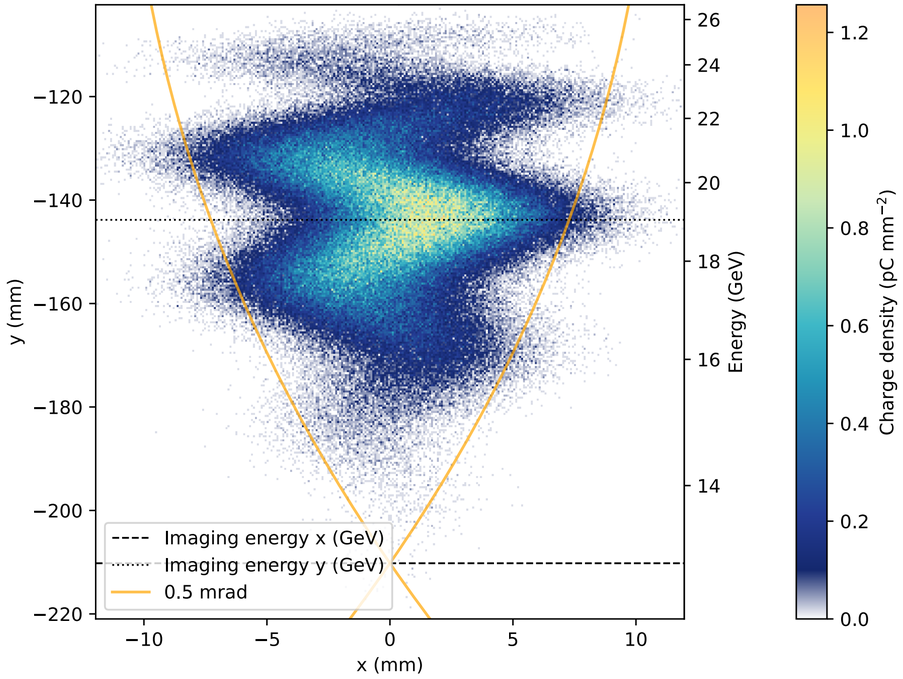

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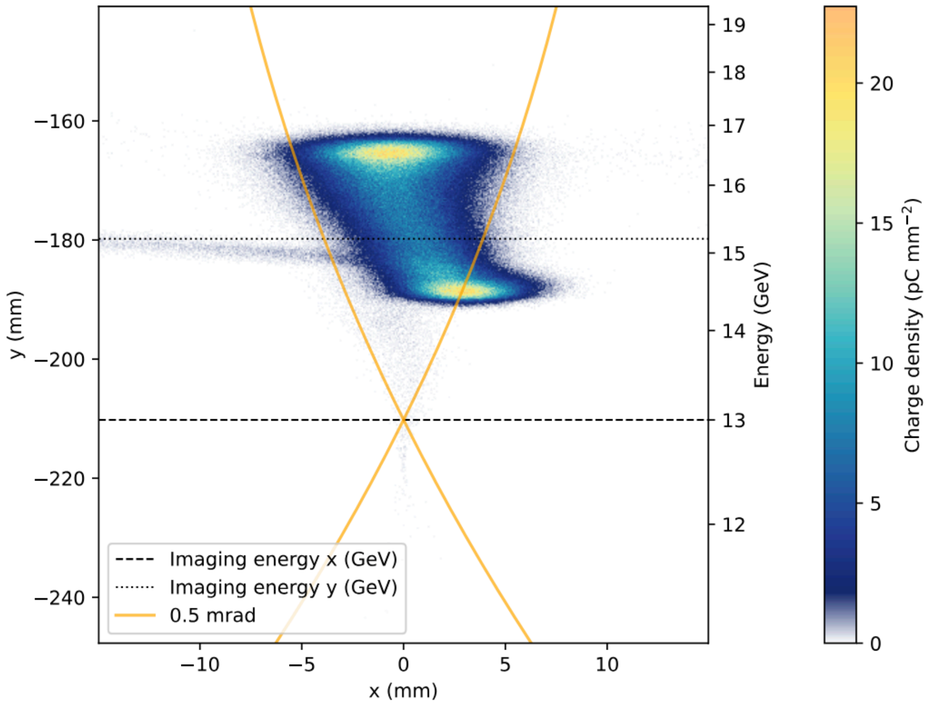

Converting spectrometer image to x'-E distribution

- $x_{\text{screen}} = m_{11}(E)x_0 + m_{12}(E)x_0'$
- $m_{12}(E)$ scales more strongly than $m_{11}(E)$ with bunch energy
- $x_0' = \dfrac{x_{\text{screen}}}{m_{12}(E)}$ (Valid away from imaging energy)
- $\sigma_{x',\text{error}} = \dfrac{\sigma_x m_{11}(E)}{m_{12}(E)}$
- $\dfrac{d^2Q}{dx'dE} = \dfrac{d^2Q}{dxdy} \cdot \dfrac{dx}{dx'} \cdot \dfrac{dy}{dE} = \dfrac{d^2Q}{dxdy} \cdot m_{12}(E) \cdot \dfrac{dy}{dE}$

Converted x’-E distributions—easier to interpret

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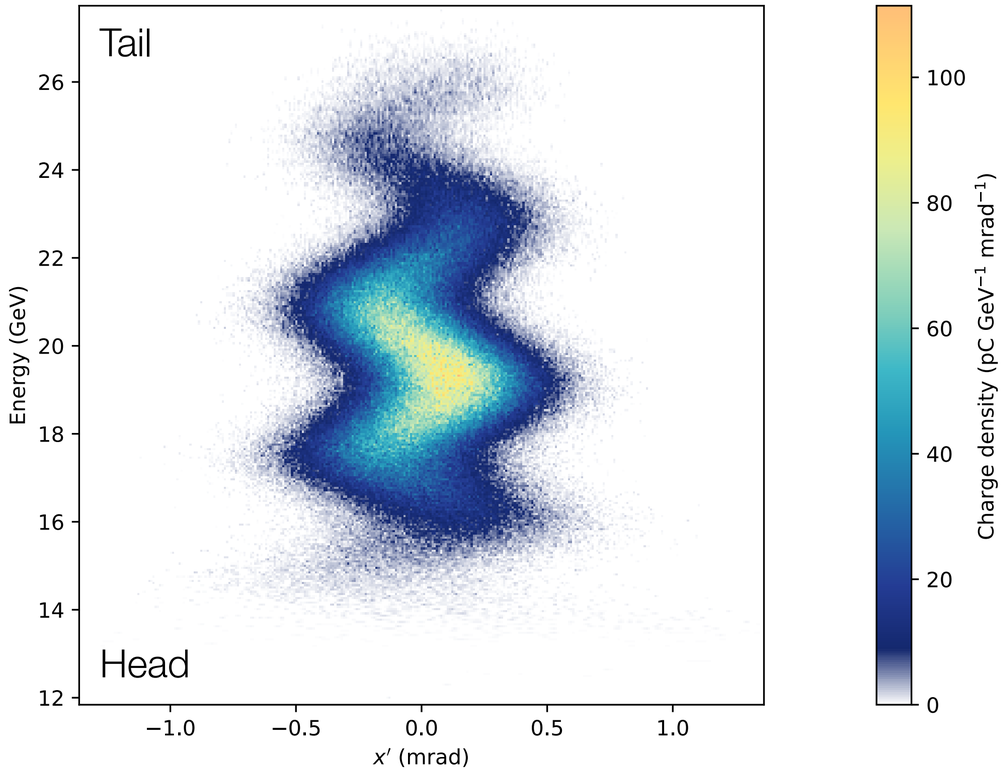

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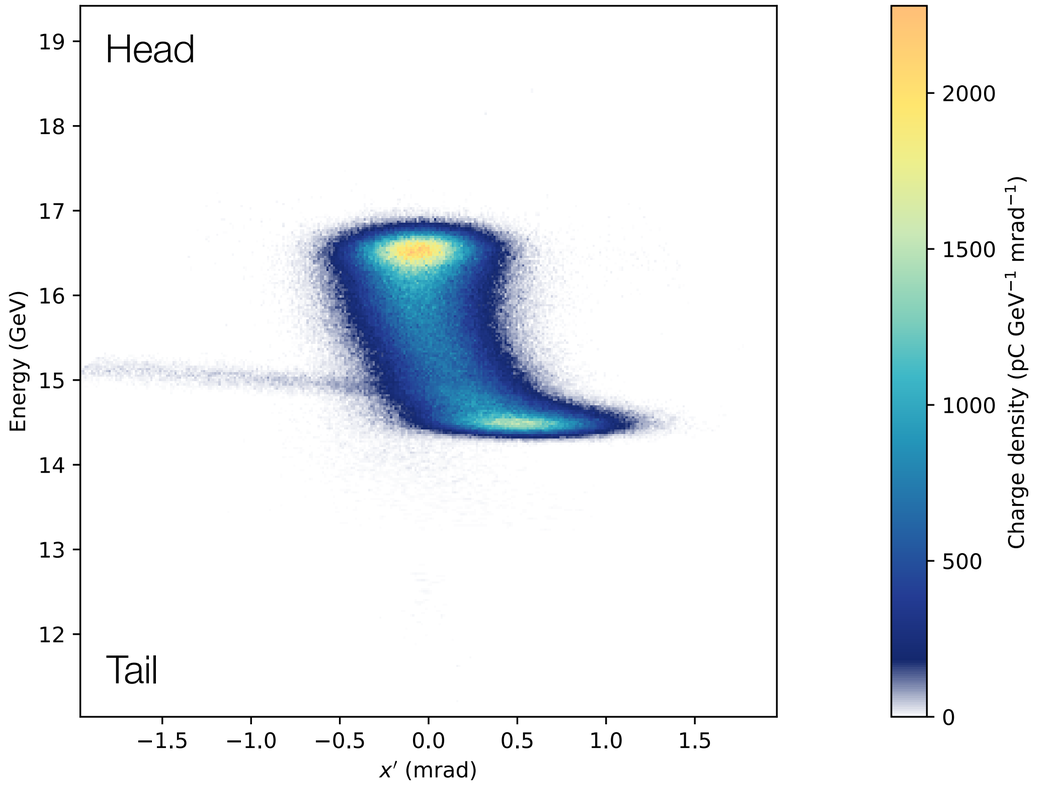
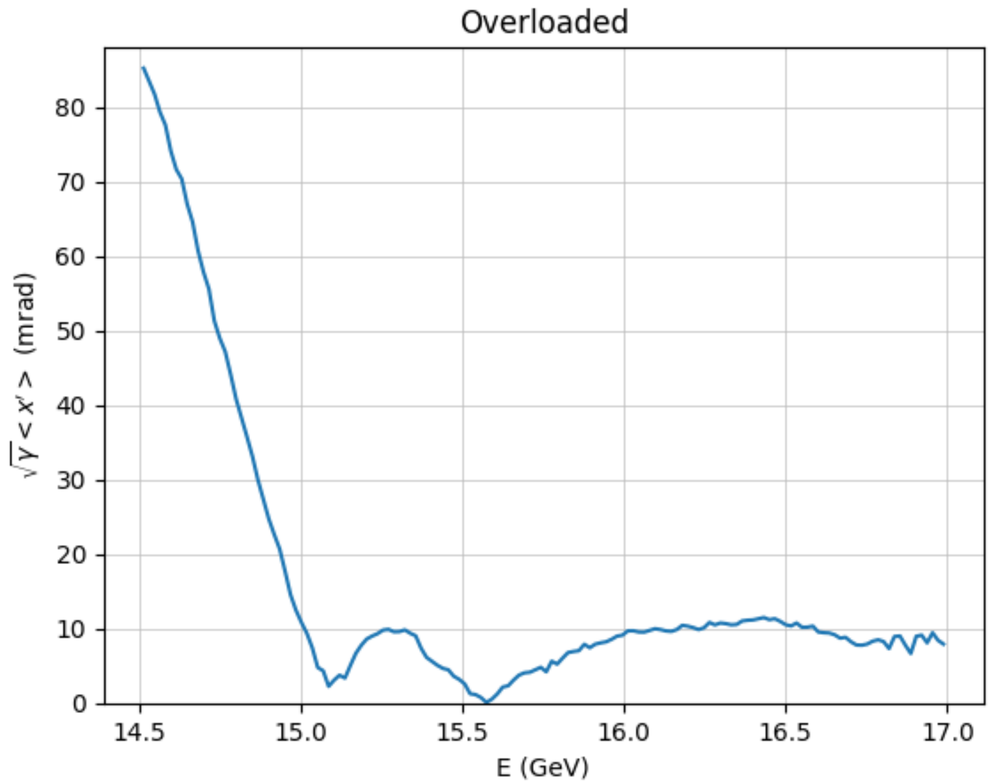
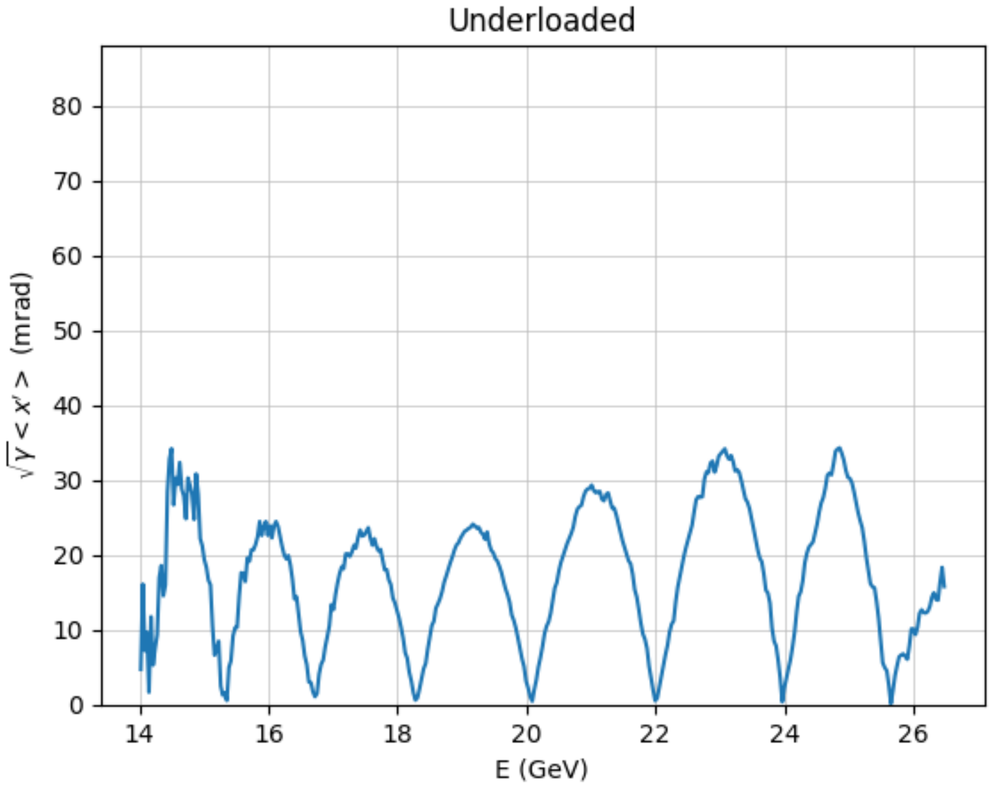


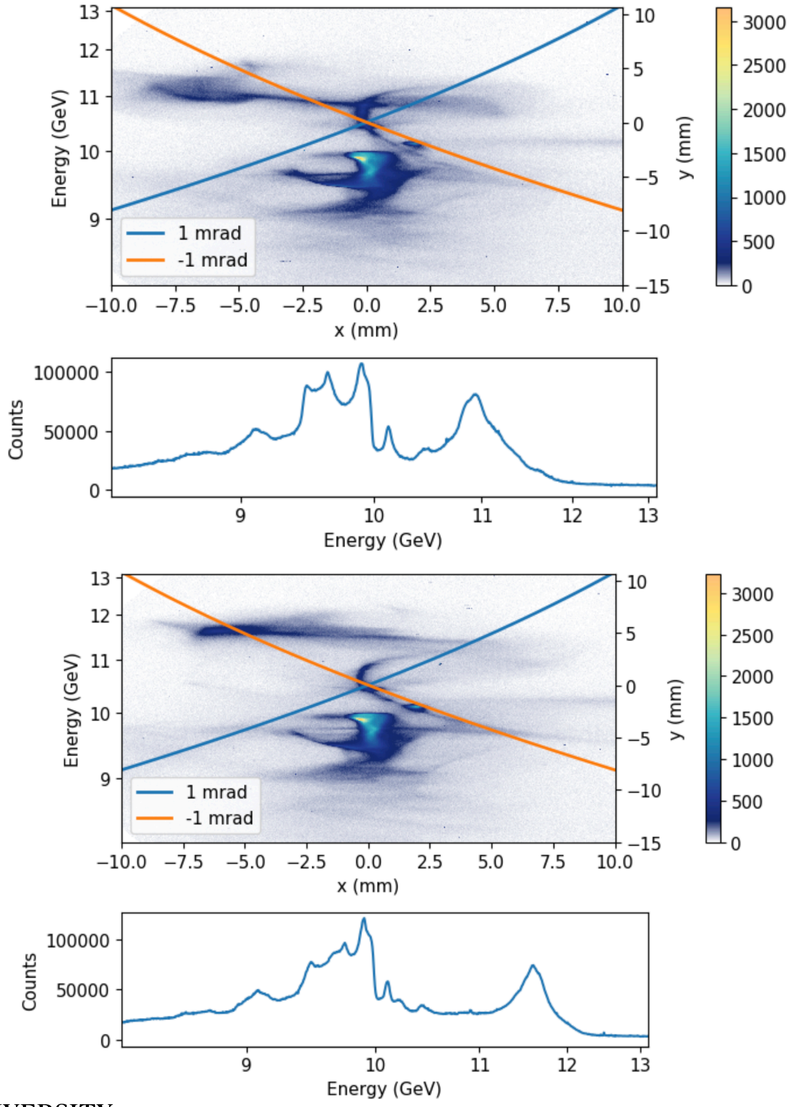
Ultimate goal—amplitude increase from head to tail

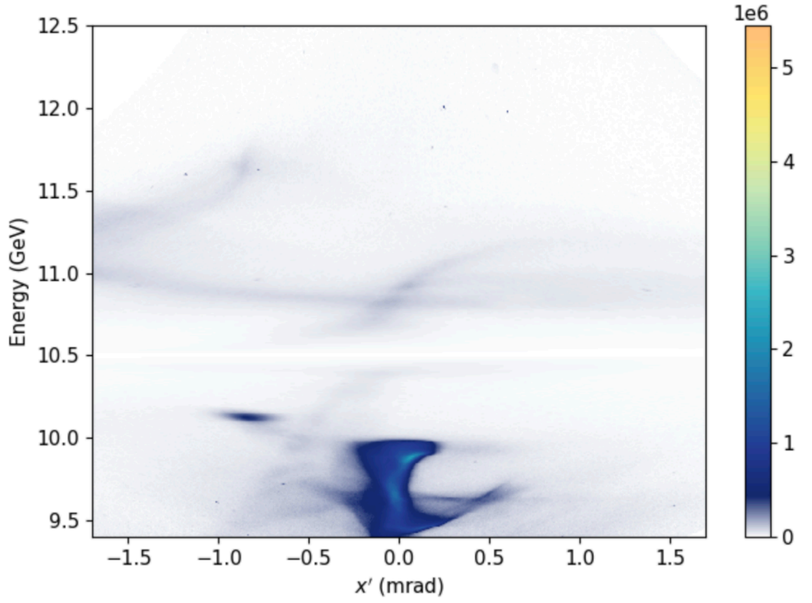


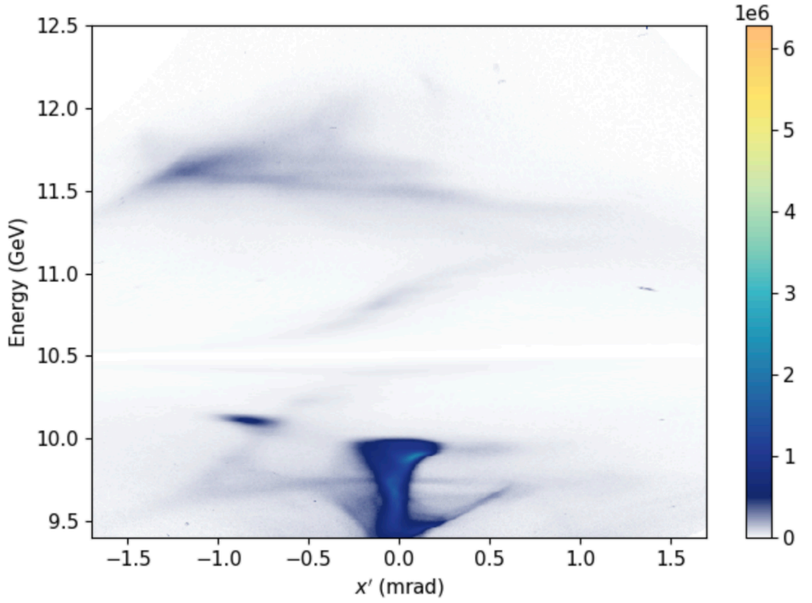


Testing the methodology on preliminary E300 experimental data

Non-ideal imaging condition in lithium plasma

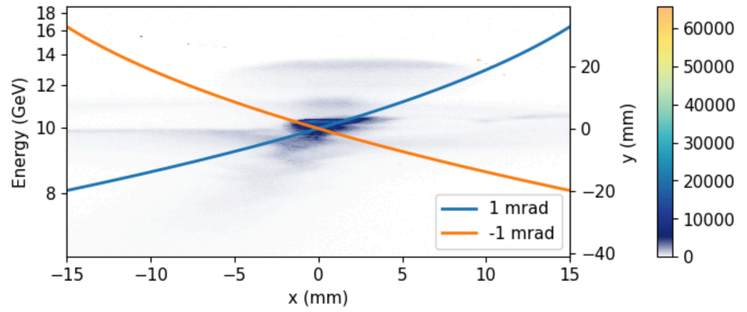


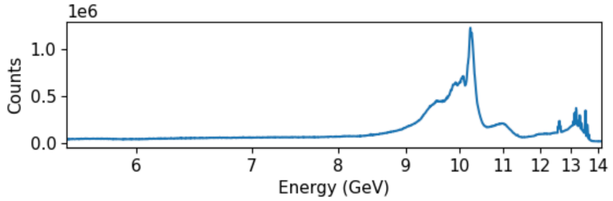


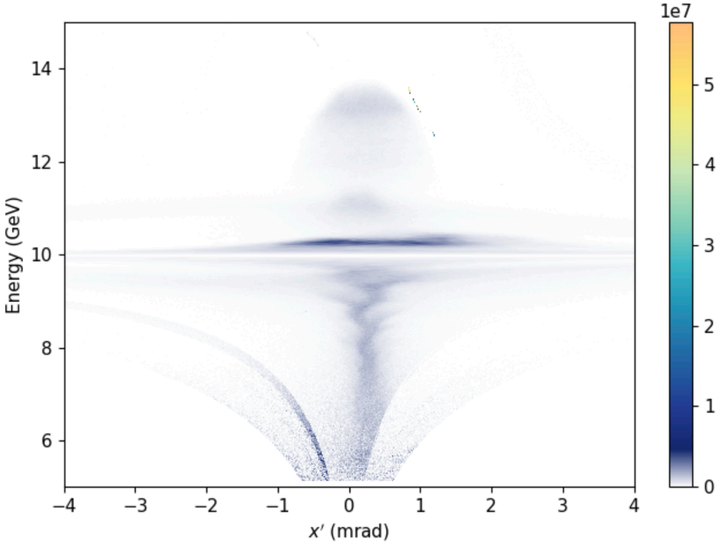


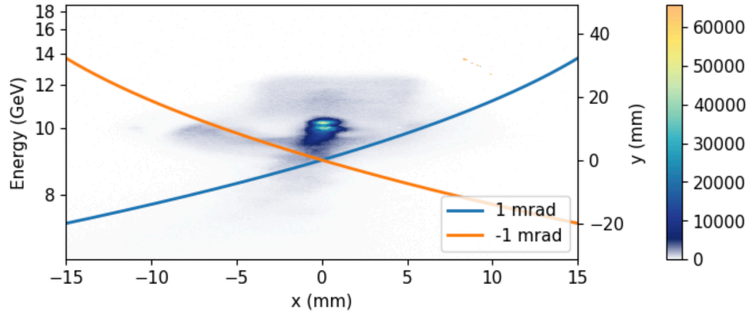
Different imaging energy in x and y (hydrogen fill)

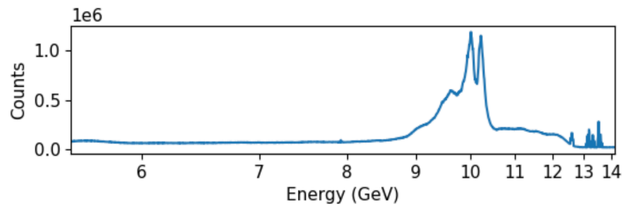
- Implemented new feature that let's us image different energies in x and y.
- This gives improved energy resolution, while avoiding asymptotic behaviour near imaging energy.

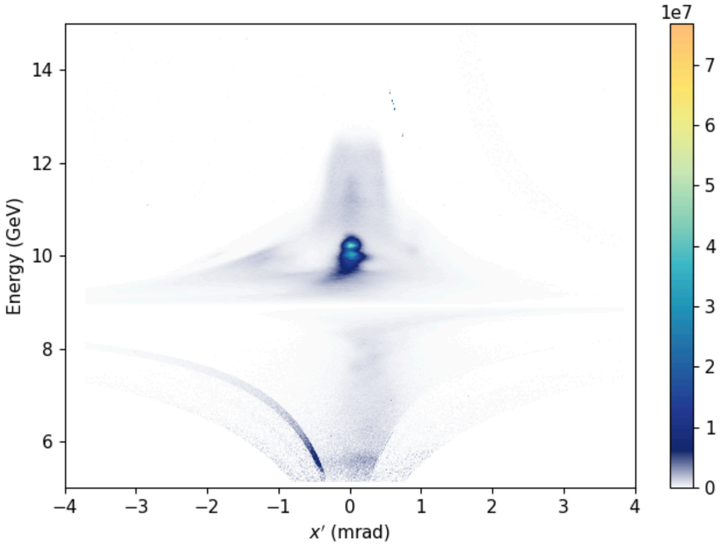












Summary and Outlook

- Transverse instabilities are important for plasma accelerator applications such as colliders and FELs.
- E302 experiment will study this at FACET-II.
- We are developing methods previously used at FACET to measure oscillation amplitudes due to transverse instabilities.
- We are testing these methods using E300 data taken at FACET-II.
  - We see indication of transverse sub-structure, expect stronger signals in future experimental shifts.
- In future work, we look to compare configurations with different amount of witness charge to probe strength of instability as a function of efficiency.