# Diagnostics for a Plasma Wakefield Accelerator

WP13 EuPRAXIA electron and photon diagnostics workshop

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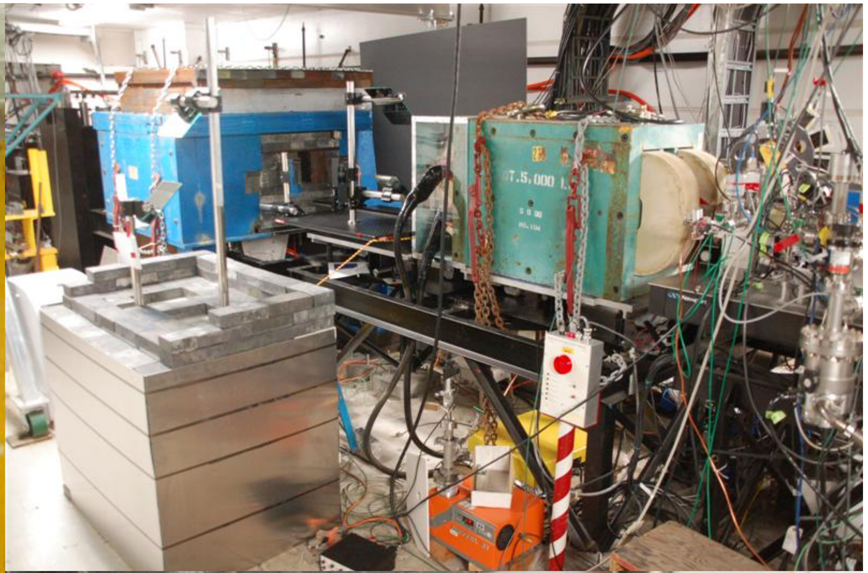
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

# Why am I here giving this talk?



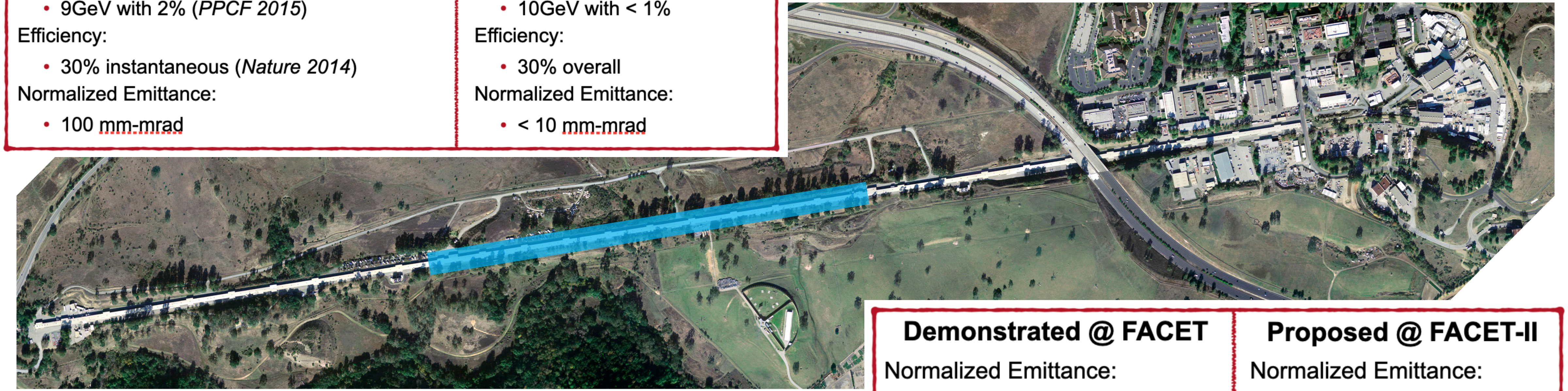
Rasmus and I have been discussing these topics for twenty years!

# FACET-II: a National User Facility with a Portfolio of PWFA Experiments

## Beam-driven plasma wakefield acceleration with electrons (now) and positrons (future)

| Demonstrated @ FACET | Proposed @ FACET-II |
|---|---|
| Gradient:<br>• >100GeV/m (*Nature Communications 2016*) | Gradient:<br>• >10GeV/m |
| Energy Gain & Energy Spread:<br>• 9GeV with 2% (*PPCF 2015*) | Energy Gain & Energy Spread:<br>• 10GeV with < 1% |
| Efficiency:<br>• 30% instantaneous (*Nature 2014*) | Efficiency:<br>• 30% overall |
| Normalized Emittance:<br>• 100 mm-mrad | Normalized Emittance:<br>• < 10 mm-mrad |

**FACET-II experiments are focused on 10GeV stage with high-energy extraction, high-efficiency and preserving beam emittance ~10$\mu$m level**



| Demonstrated @ FACET | Proposed @ FACET-II |
|---|---|
| Normalized Emittance:<br>• 1.5 mm-mrad | Normalized Emittance:<br>• 0.01 mm-mrad |
| Bunch Charge & Duration:<br>• 20pC & 100fs | Bunch Charge & Duration:<br>• 20pC & 20fs |
| Energy & Energy Spread:<br>• 0.5 GeV with 2% | Energy & Energy Spread:<br>• > 1 GeV with 1% |

## Development of high-brightness plasma-based injectors

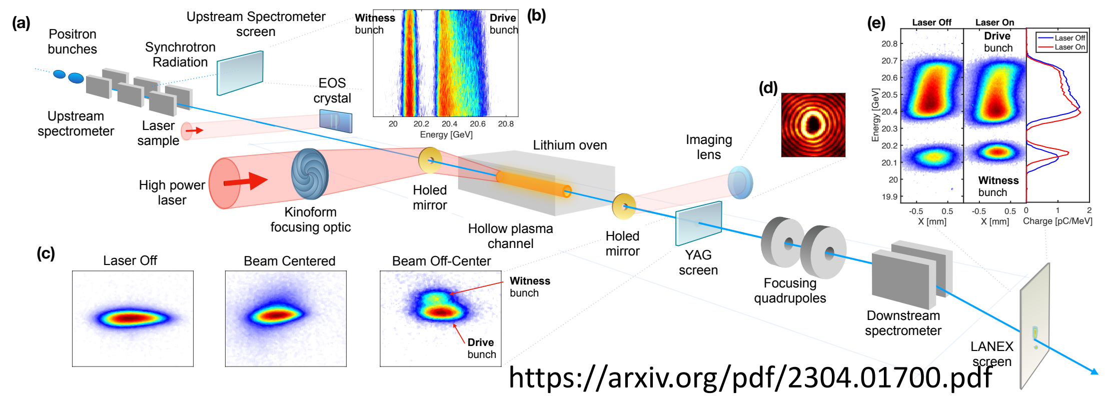
**Beam Brightness scales with plasma density. Short FACET-II bunches are predicted to enable collider level emittance beams**

# Approach of this presentation

- I will give an overview of diagnostics that I have found to be useful for PWFA experiments over the years
- I will correlate types of diagnostics with the goal or problem being addressed but I will not delve into specific design details such as resolution – these depend on detailed requirements of specific experiments (beam energy, peak current, emittance…)
- I will cite examples from my own work and collaborations as well as that of other groups and give references where available

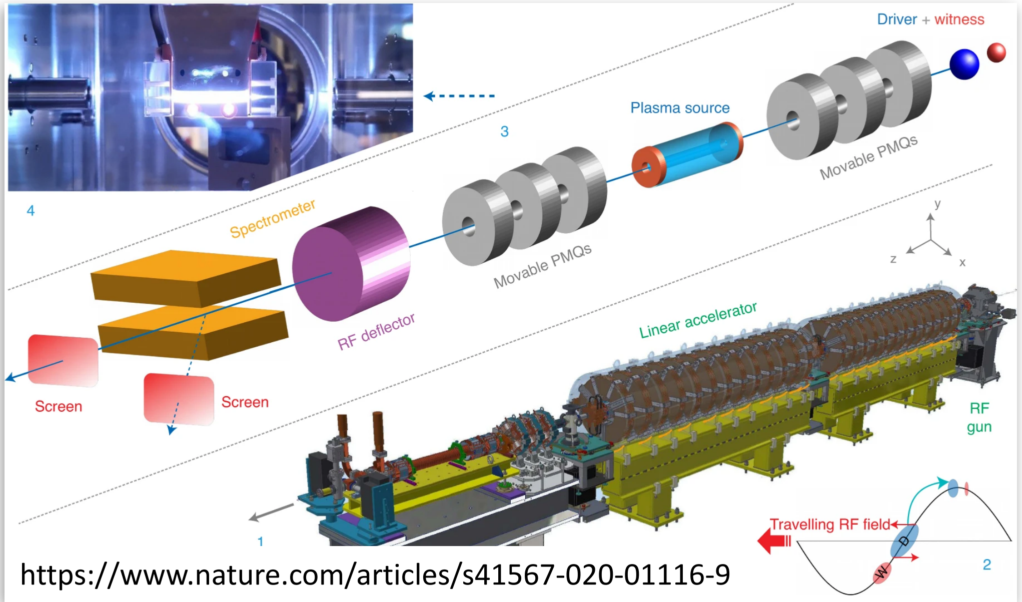
# Beamlines of Three Active PWFA Facilities Have Many Similarities

## FACET-II @ SLAC



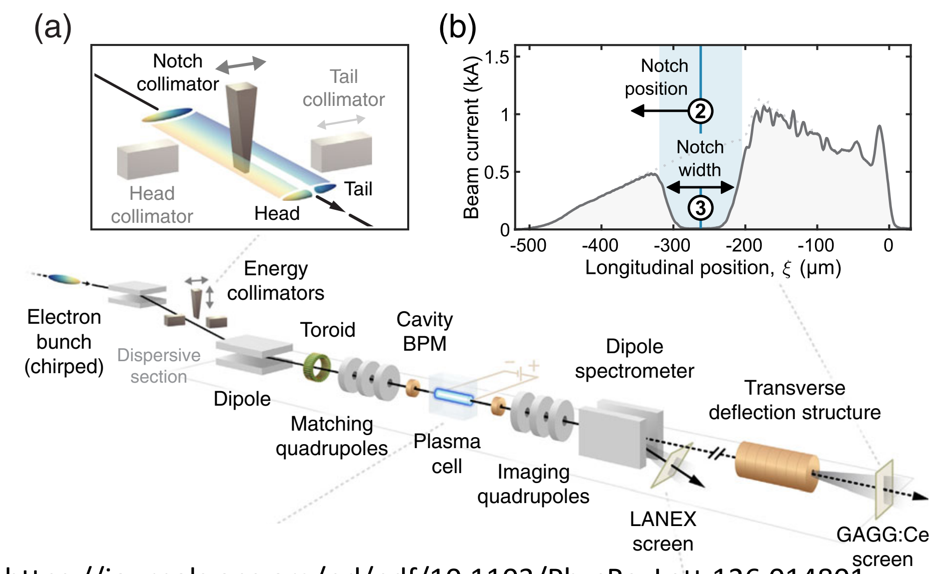

https://arxiv.org/pdf/2304.01700.pdf

## SPARC_LAB @ INFN




https://www.nature.com/articles/s41567-020-01116-9

## FLASHForward @ DESY

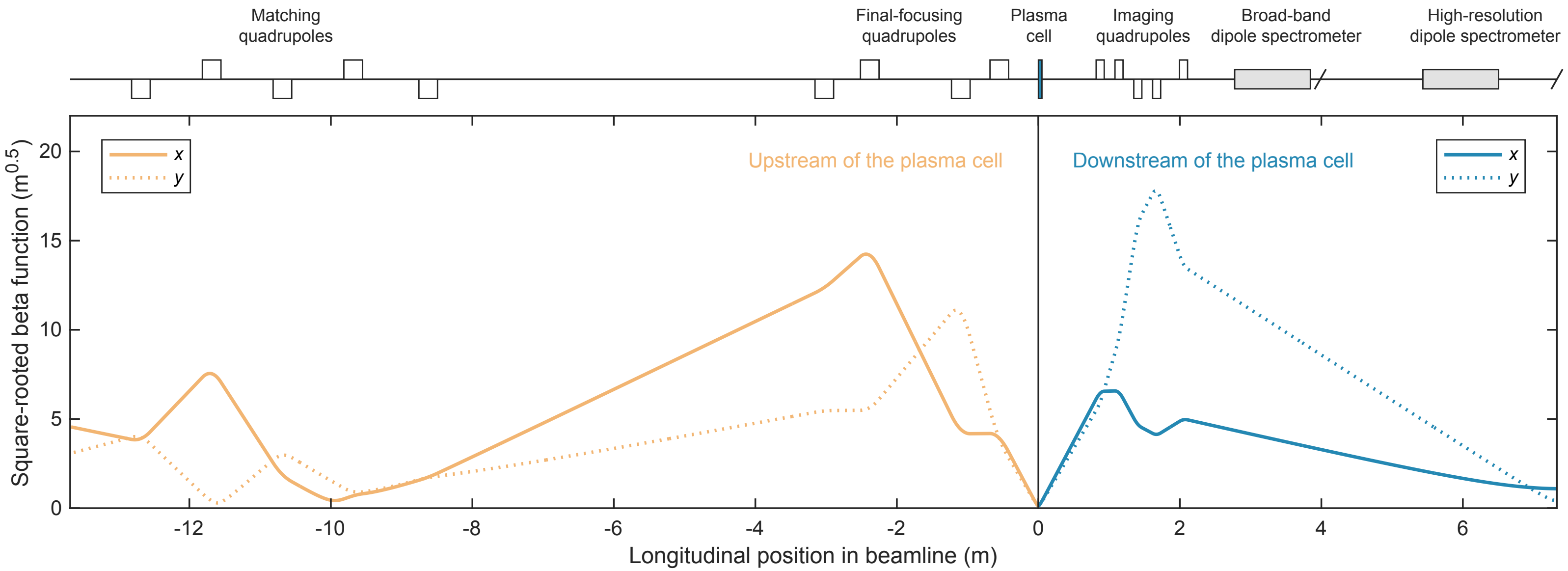


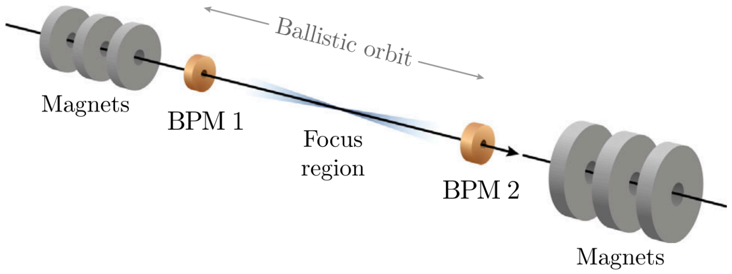

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.126.014801

Common ingredients:

- Final focus and **Imaging spectrometer magnets**
- Collimation systems
- Plasma targets and lasers
- **BPMs and Toroids**
- **Bunch length monitors: TCAVs, EOS, Pyro**
- **Profile monitors: OTRs, YAG, LANEX, Cherenkov**

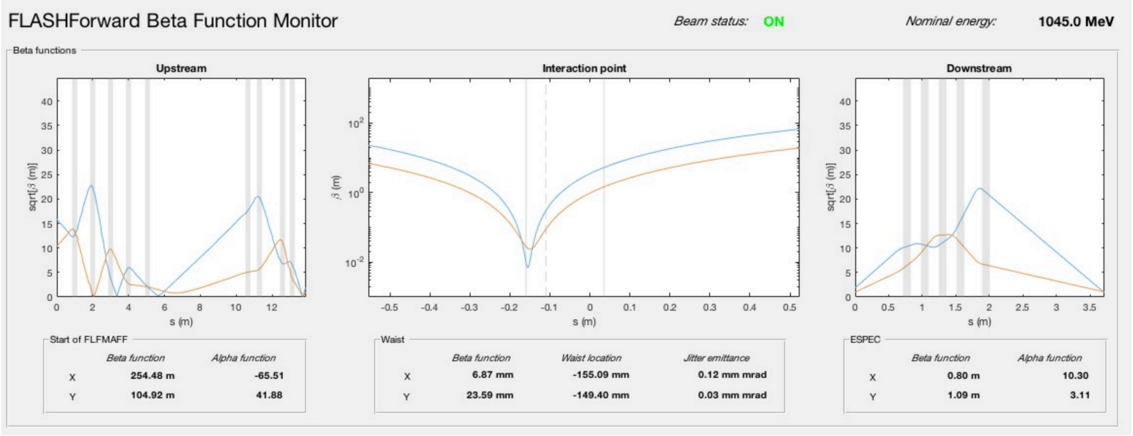
# Emittance Preservation Requires Understanding Optics at per-mille Level




Source: Lindstrøm et al., PRAB 23, 052802 (2020).

- **The waist beta function is ~10 x 10 mm.**
- mm-level movements required 0.1%-level changes in quad currents.
- Online beta-function monitor (Hz updates) using two BPMs.
  - ~mm precision in placing the beta function.
- Online tool was crucial in placing the focus precisely (no time for quad scans for every 0.1% change in final-focus quads.)
- We never used in-waist screens (CTR makes it impossible to use).




Online beta-function GUI (measured live with 2-BPM technique)

In use at ATF2, FACET-II and FLASHForward – slide courtesy of Carl Lindstrøm

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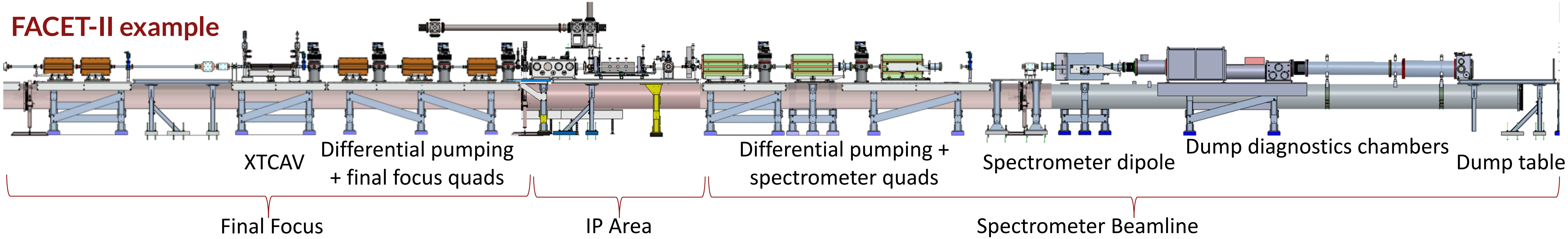
# Imaging Spectrometer After the Plasma Performs Many Functions

**FACET-II example**

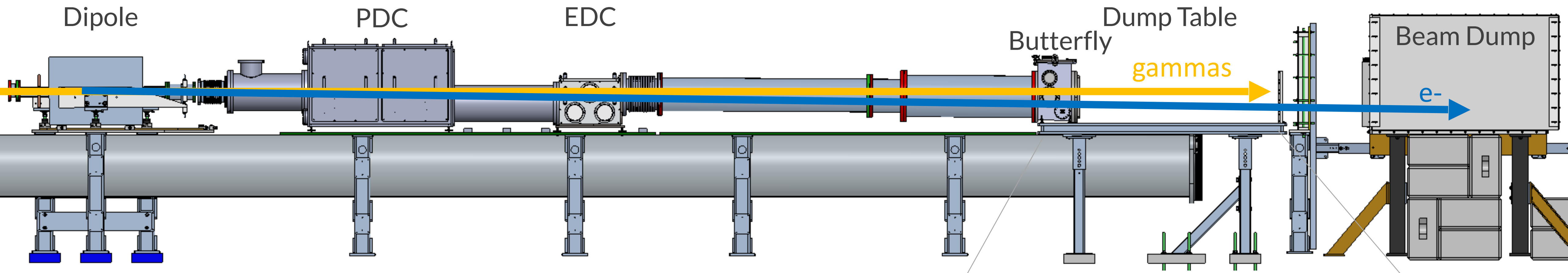



- Measure energy spectrum after the plasma (point to point imaging R12 = R34 = 0)
- Typically combined with dual imaging systems:
  - Lower-resolution with higher acceptance (wakefield amplitude, affect on drive beam, quantifying efficiency…)
  - Higher-resolution with limited energy acceptance (precision measurements of witness bunch energy and energy spread)
- Through dispersion can access drive and witness beams independently
- May be scanned to stitch together spectrum, change imaging planes, perform quad scans
- Screens can be calibrated for charge measurement

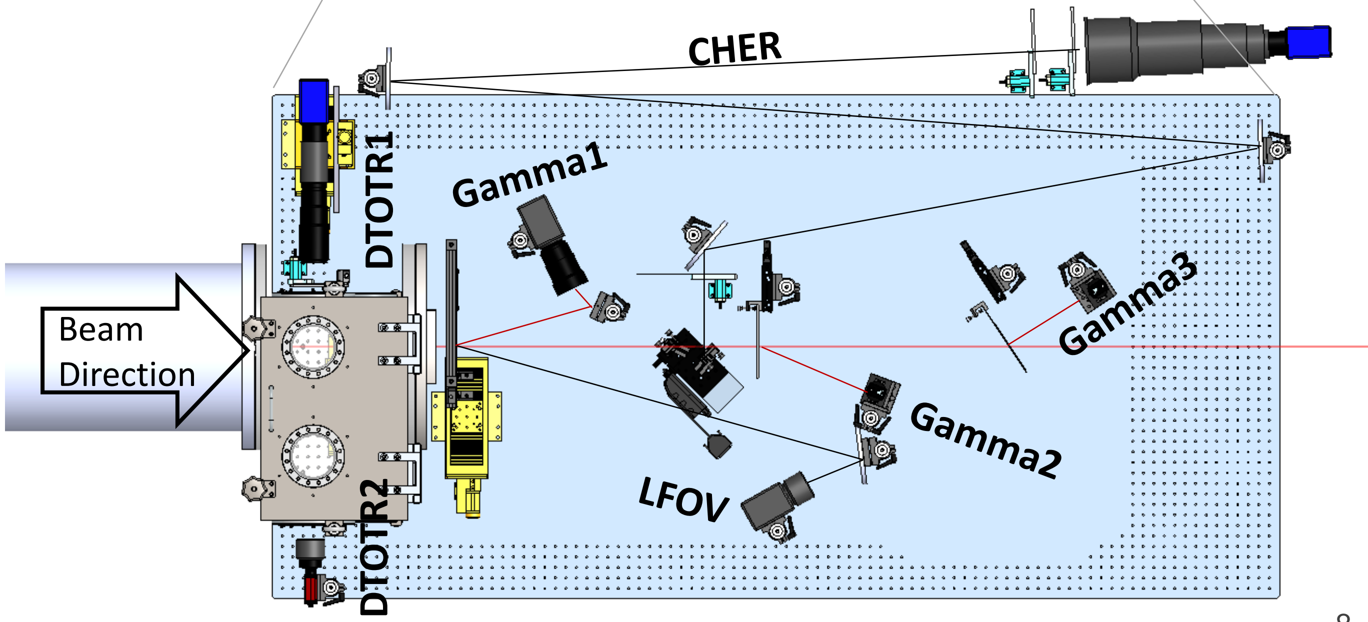
https://www.nature.com/articles/nature05538

https://arxiv.org/pdf/2305.09581.pdf

# Spectrometer Diagnostics Overview



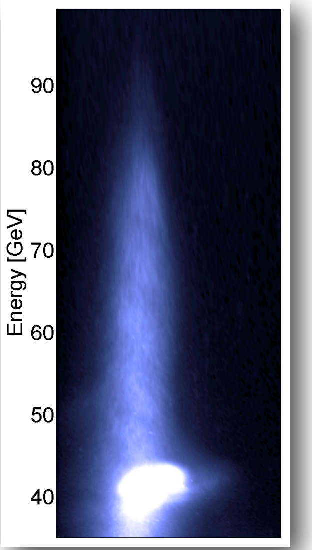

- Dump table contains main electron and gamma diagnostics
  - DTOTR1/2 – in vacuum OTR+YAG high resolution, single shot emittance and TCAV measurements
  - LFOV and CHER – DRZ and Cherenkov spectrometers with large field of view
  - Gamma1/2/3 -> photon profile, spectral information from <100keV to 10's of MeV
- PDC/EDC added for low energy electron and positron diagnostics

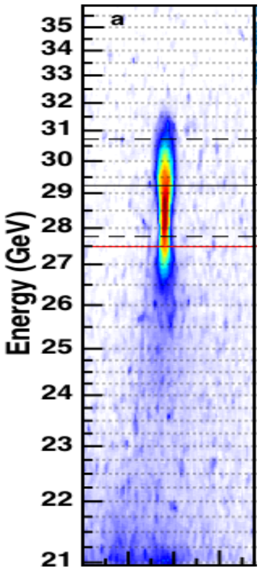


# Energy Spectrum Reveals Details of the PWFA Interaction

https://www.nature.com/articles/nature05538

Wakefield amplitude and energy gain

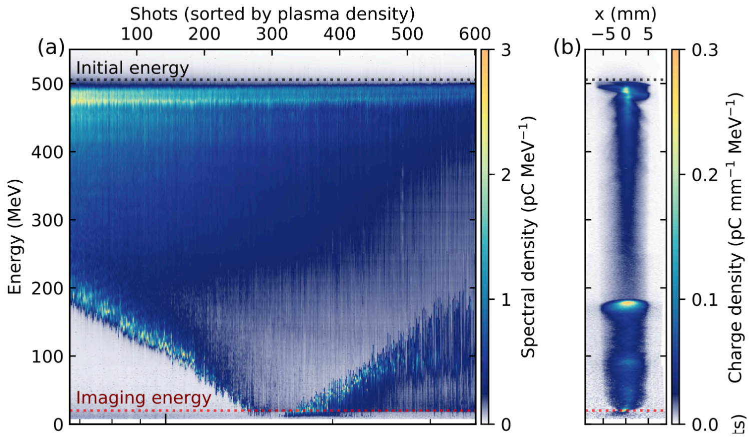



https://iopscience.iop.org/article/10.1088/0741-3335/58/3/034017

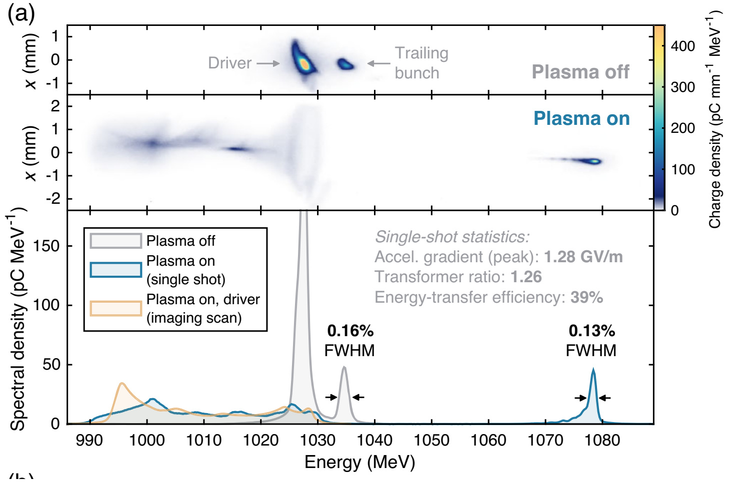
Energy and energy spread

Energy gain and loss – Efficiency



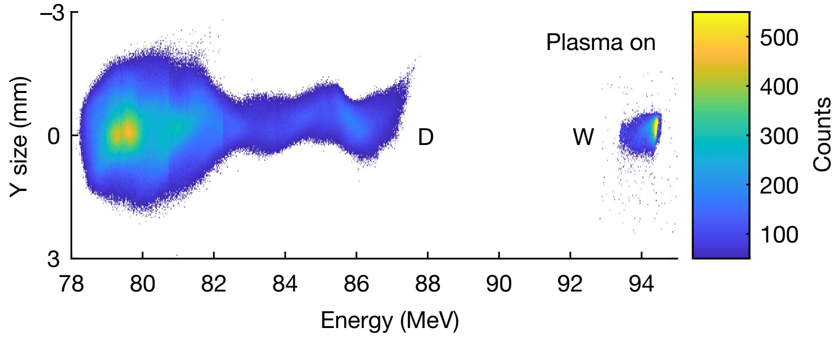

https://arxiv.org/pdf/2305.09581.pdf

Optimal beam loading



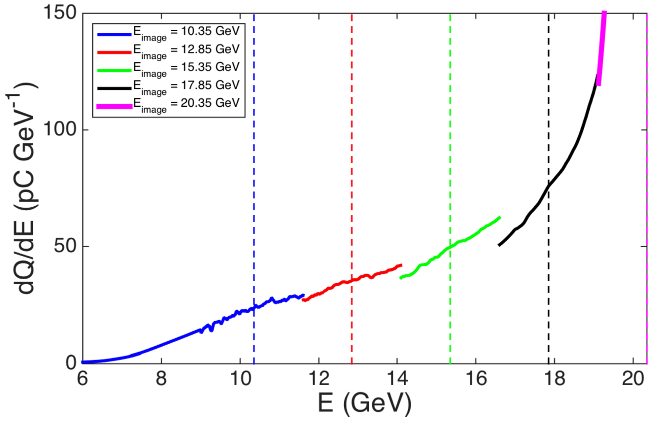

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.014801

Energy boost before FEL




https://www.nature.com/articles/s41586-022-04589-1

Multishot piecewise spectral measurement

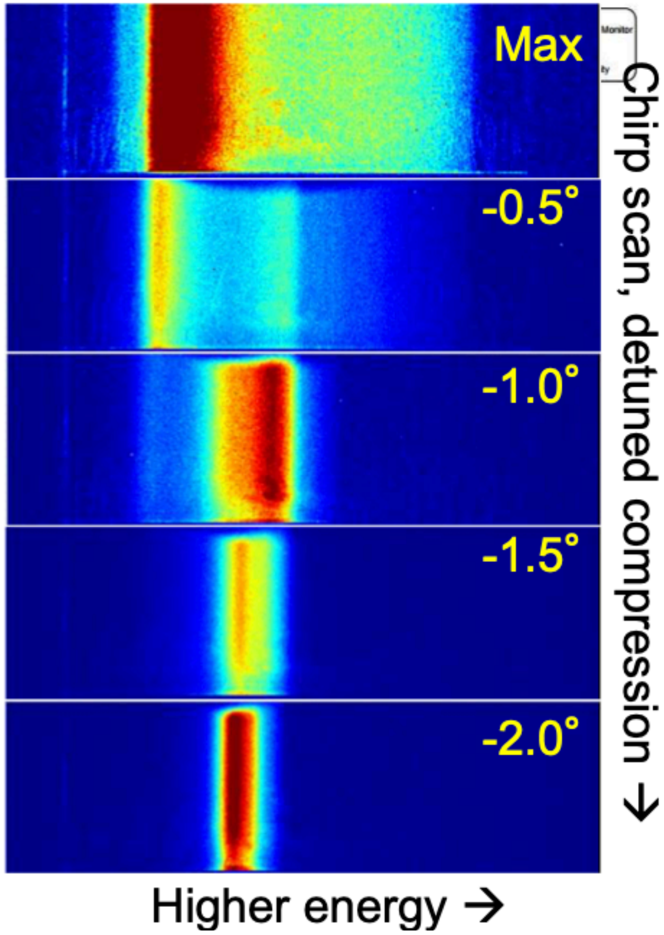


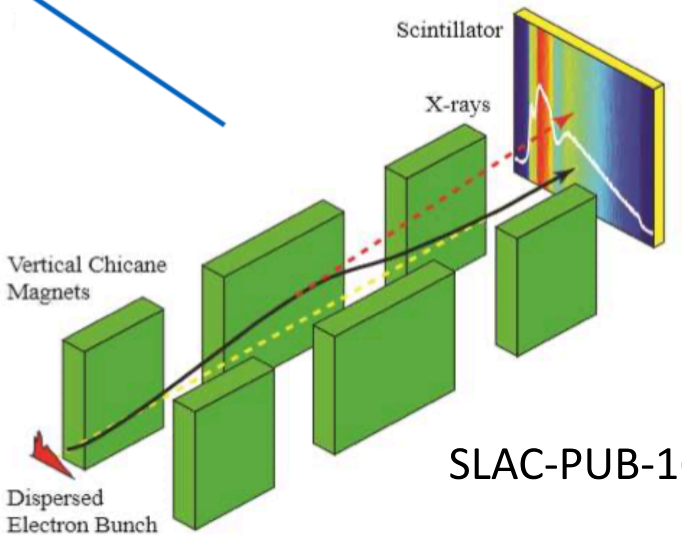

https://www.nature.com/articles/nature14890

- Need to BBA the quads to avoid steering and added dispersion
- Calibrate energy axis carefully
- Charge calibration (counts/e-)
- Be careful with saturation in camera or material
- Be mindful of synchrotron and betatron backgrounds

# Non-invasive Energy Spectrometer at FACET/FACET-II

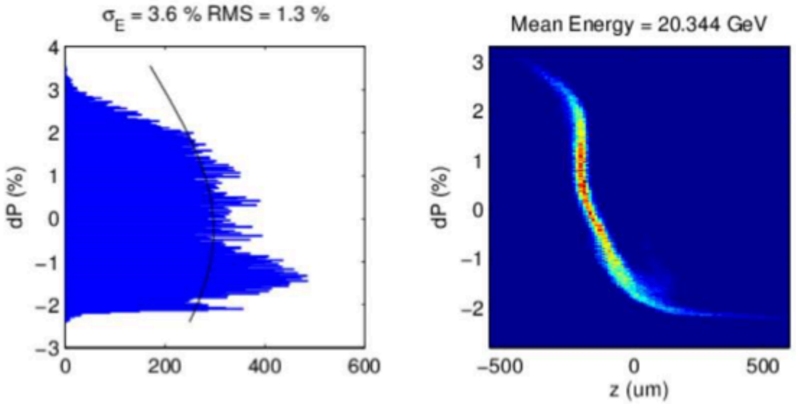
- With strongly compressed beams energy-spectrum correlates with compression
- Enables shot-to-shot comparison of before and after plasma for systems with drift and/or jitter
- Non-invasive single shot




SLAC-PUB-16310

- Vertical chicane in region of large horizontal dispersion
- Intercept X-rays off axis with YAG screen



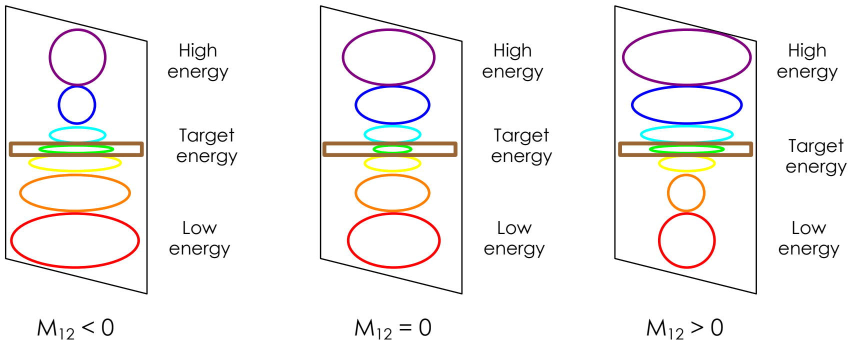

Scheinker, Gessner, PRSTAB **18** 102801 (2015)

# Emittance Measurement with Dispersive Quad Scan in Spectrometer

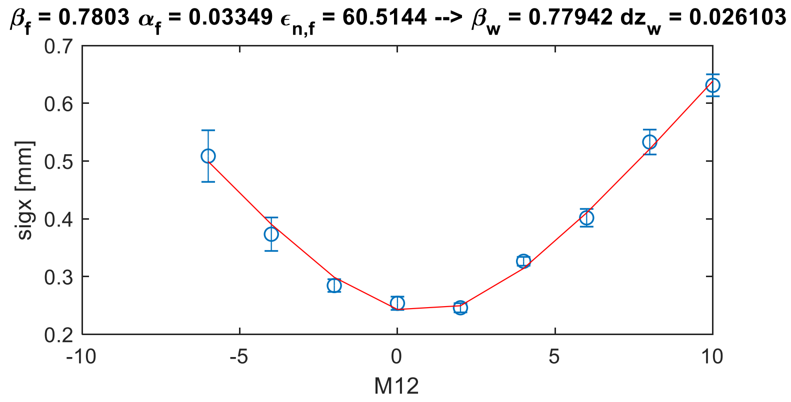
« Dispersive » quad scan

Scan $M_{12}$, keep $M_{34}$=0.

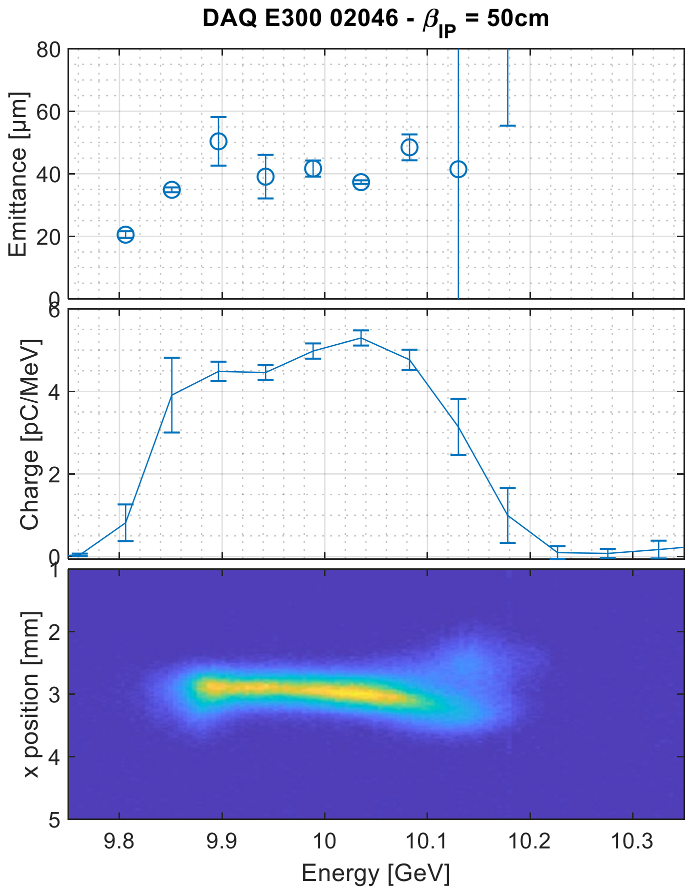
$$\langle x^2\rangle_{\rm im} = M_{11}^2\langle x^2\rangle_{\rm ob} + 2M_{11}M_{12}\langle xx'\rangle_{\rm ob} + M_{12}^2\langle x'^2\rangle_{\rm ob}$$




Projected Measurement




Dispersive Measurement




**Advantages**:

- No assumption on Twiss/emittance vs energy
- Measure energy-slice emittance
- Can resolve lower emittance than butterfly (M12 range vs energy spread used to fit butterfly)
- Can measure no plasma case and beams with very low energy spread

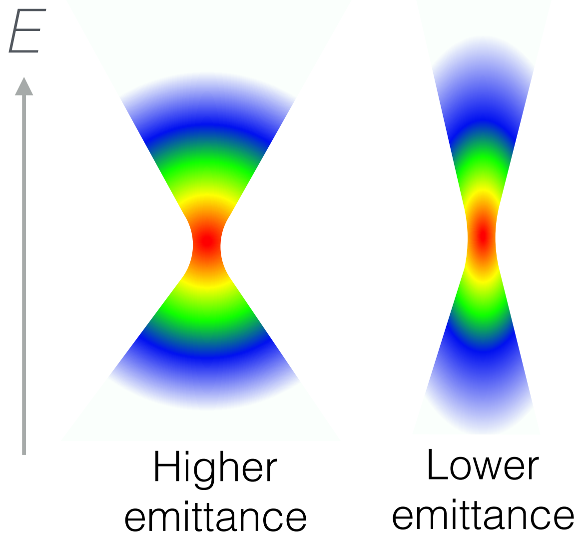
**Disadvantages**:

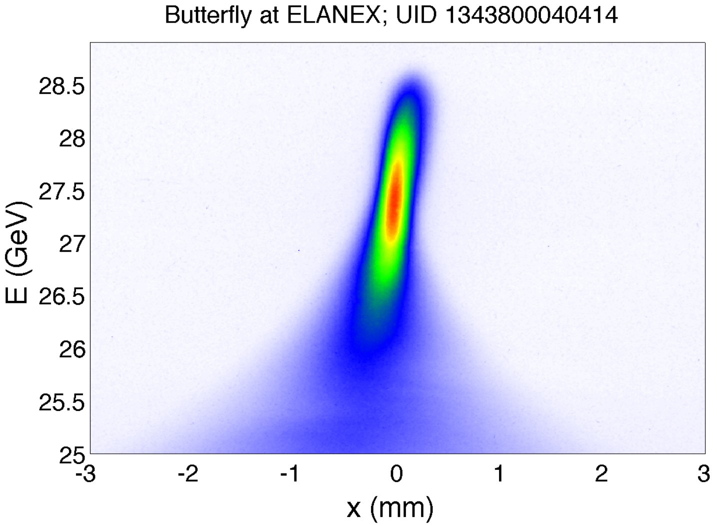
- Multishot
- Only for non-dispersed plane

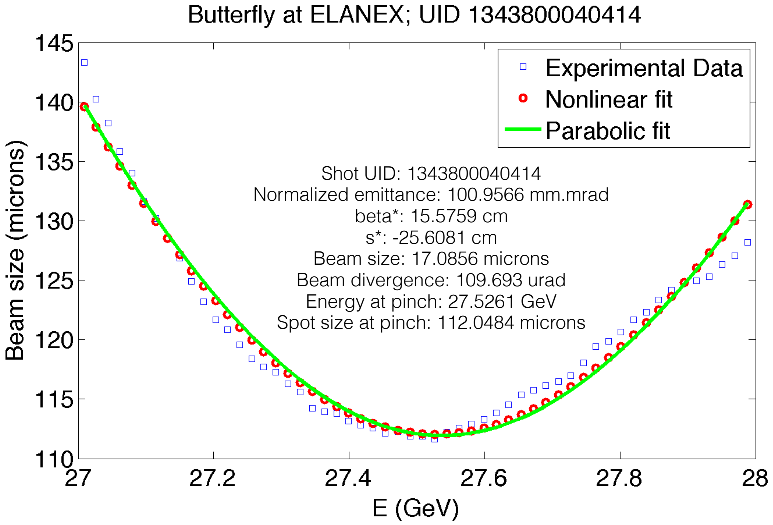
FACET-II data courtesy Doug Storey

# Butterfly Emittance Measurement

- First developed at LWFA Facilities and successfully implemented at FACET and FACET-II
- Energies further from the focus → Increasing contribution from divergence → Wider on image
- Divergence angle and position of the butterfly determines the emittance, exit beta function and the exit plane




FACET data courtesy Sebastien Corde

**Advantages:**

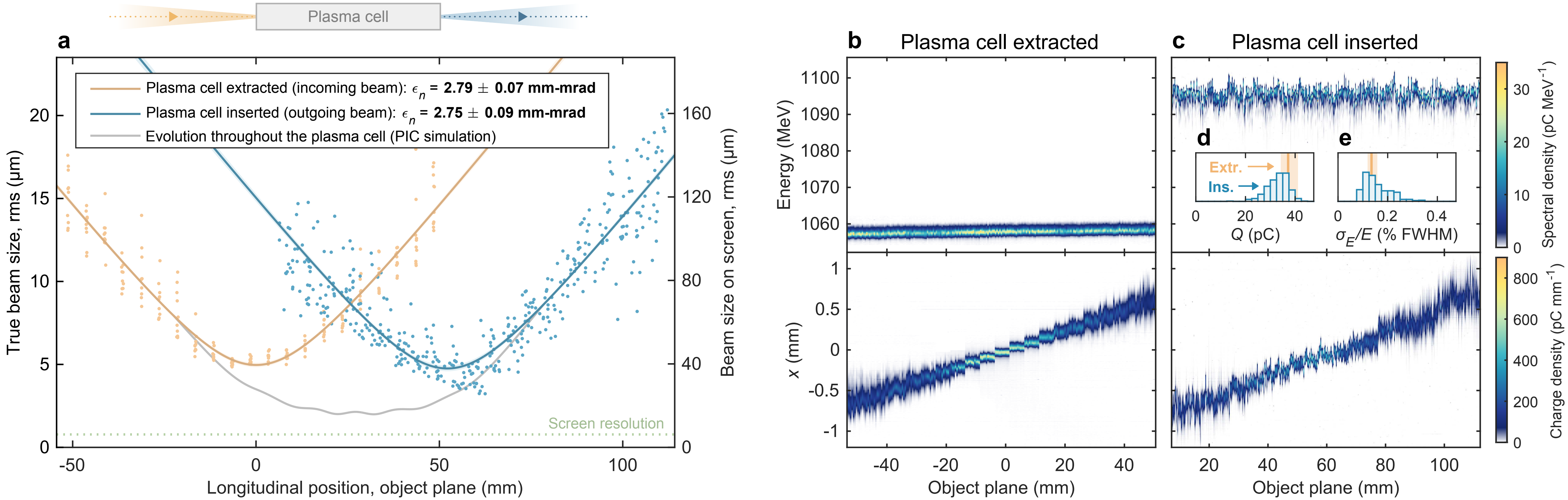
- Single shot

**Disadvantages:**

- Assume $\alpha$, $\beta$ and $\varepsilon$ independent of $\gamma$
- This is wrong when there is a mismatch, which is expected to happen when emittance growth occurs
- Only for non-dispersed plane

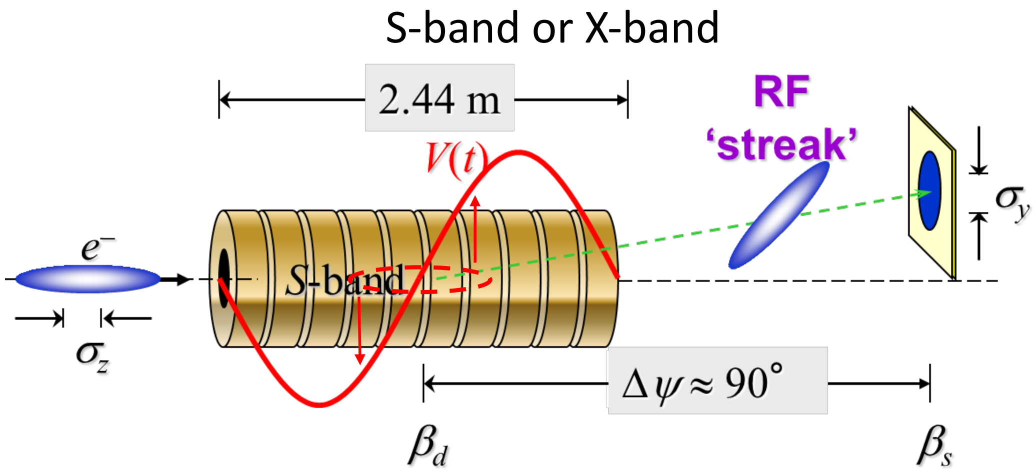
# Emittance Measurement by Scanning Spectrometer Object Plane

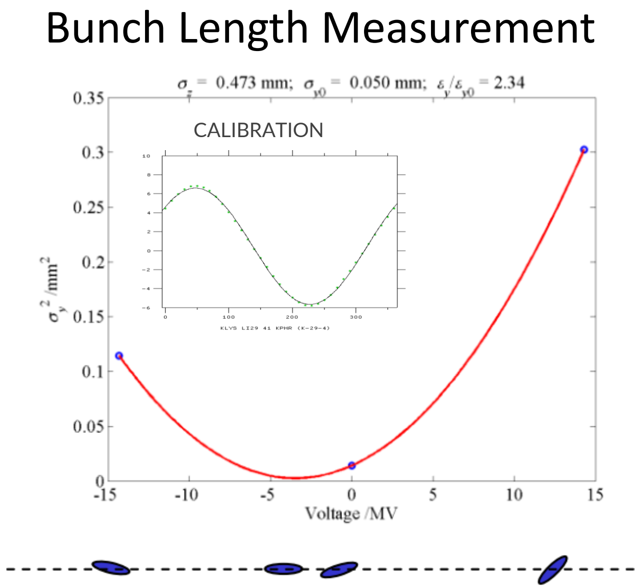
- The imaged beam size is shown for a range of object planes around the plasma cell, measured with the plasma cell extracted (orange points) and inserted into the beam path (blue points)
- Fits of the virtual-waist evolution (orange and blue lines) demonstrate that the normalized emittance, εn, was preserved to within the fit error
- The measurement was performed by scanning the object plane of a point-to-point imaging spectrometer, first with the plasma cell extracted (b, 210 shots) and subsequently inserted (c, 420 shots)



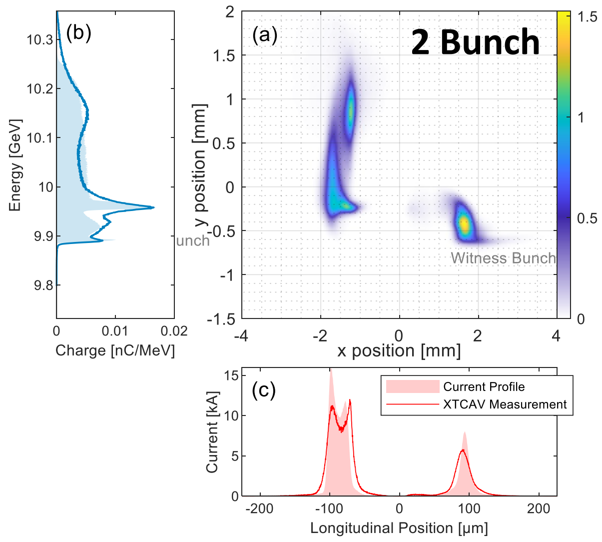

Source: Lindstrøm et al., submitted (2022)

# Transverse Deflecting Cavities



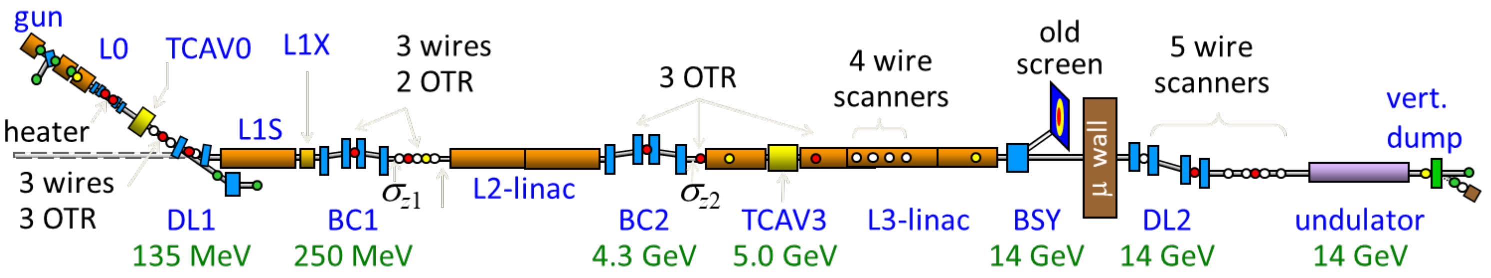

- Deflecting structure produces a time-varying transverse kick to the bunch
- The bunch is not timed to sit at the crest of the RF wave, but at the zero-crossing
- The net deflection of the centroid of the bunch is zero, but the head and the tail of the bunch are streaked in opposite directions
- Calibrated, single shot, femtosecond resolution

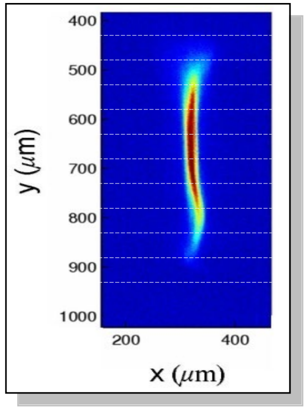



Combined with spectrometer can get full longitudinal phase space

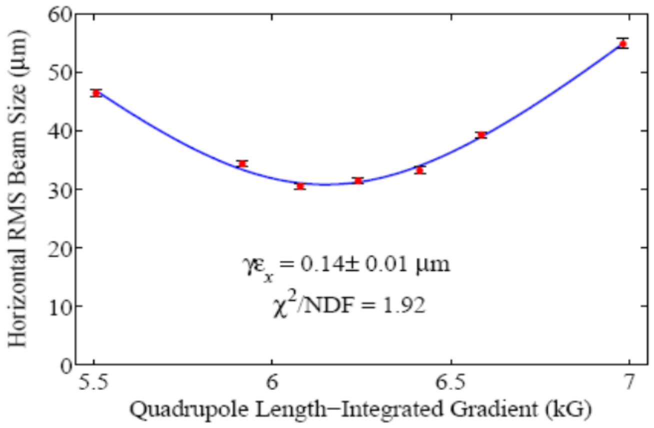
# TCAVs Are Powerful and Versatile Diagnostic Tools

e.g. study slice emittance with TCAV0 in LCLS Injector

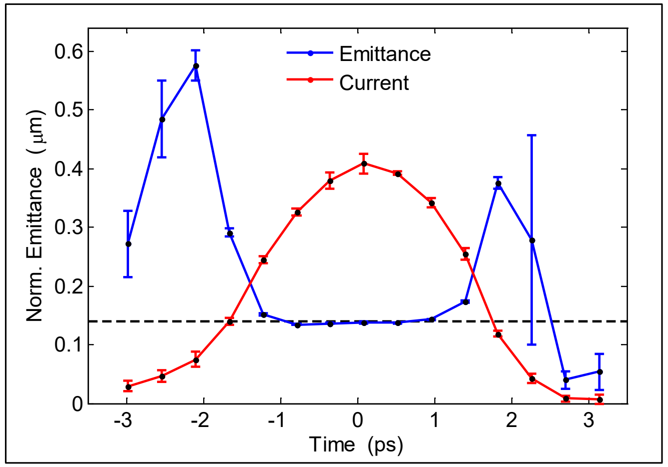



Screen measurement




Quad Scan



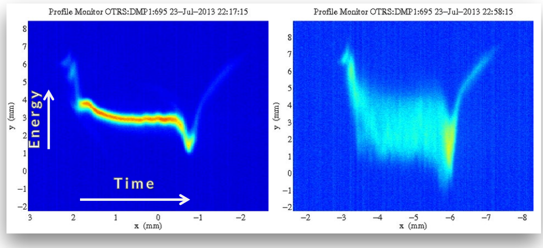

Slice Emittance (x-plane only)

https://cds.cern.ch/record/556141/files/wpah116.pdf

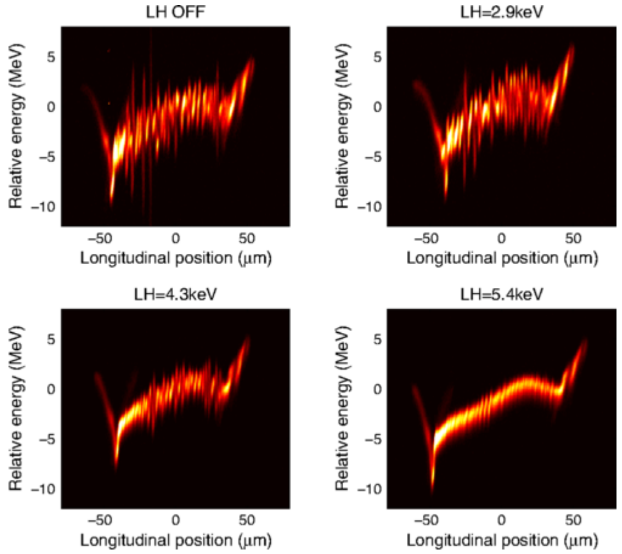
https://www.nature.com/articles/ncomms4762

https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.030704

…also used in dumpline spectrometer for characterization of FEL Lasing




…and studying suppression of the micro bunching instability

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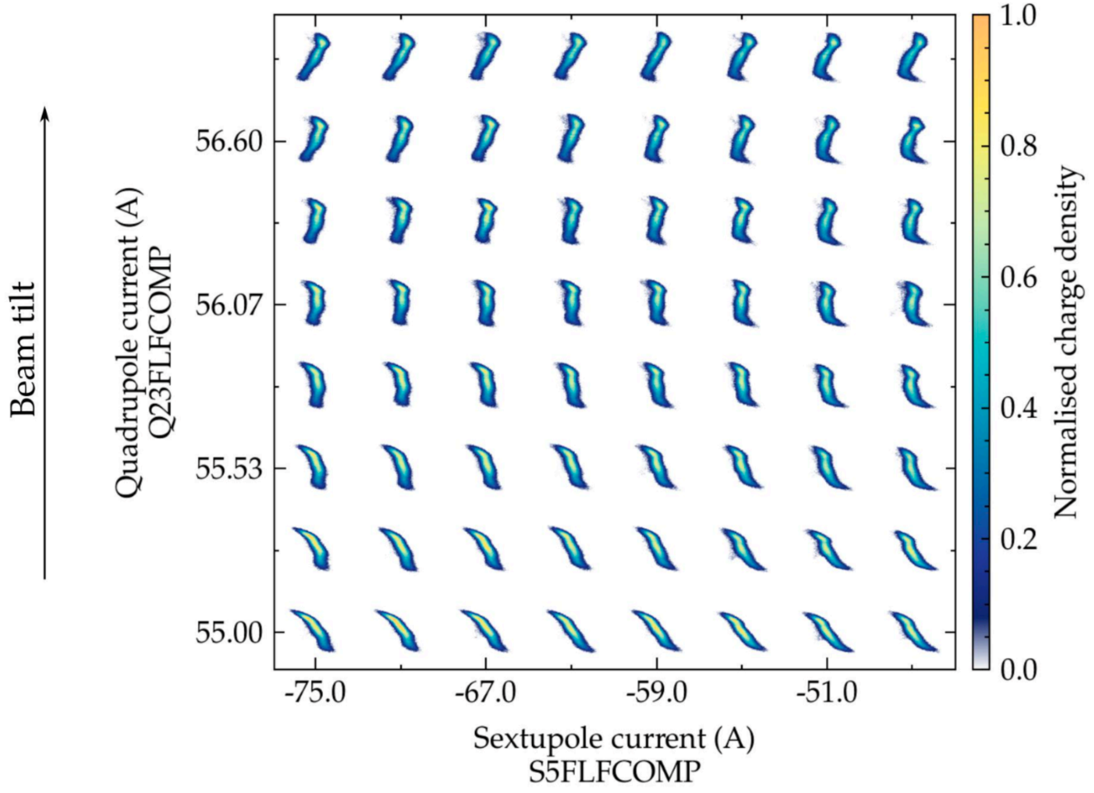
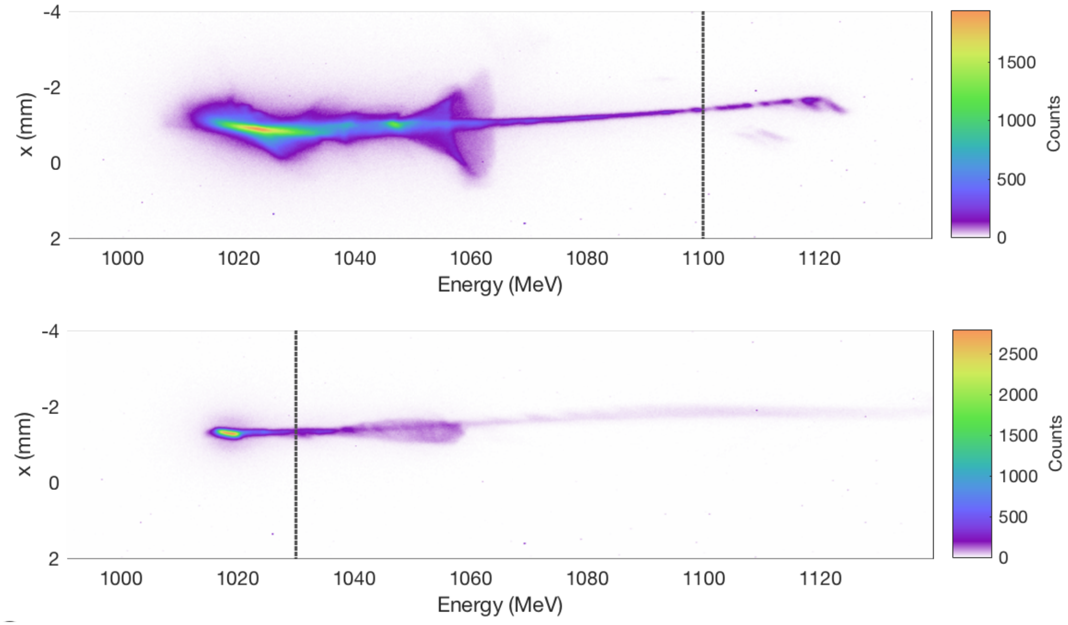
# For Good PWFA Performance – “Straighten the Beam!”

- Hosing instability is predicted for low emittance beams in strongly loaded PWFA when beams have large tilts or offsets
- TCAV diagnostic facilitates correcting head-tail correlations before the plasma




Pau Gonzalez (PhD thesis, Uni. Hamburg, 2022

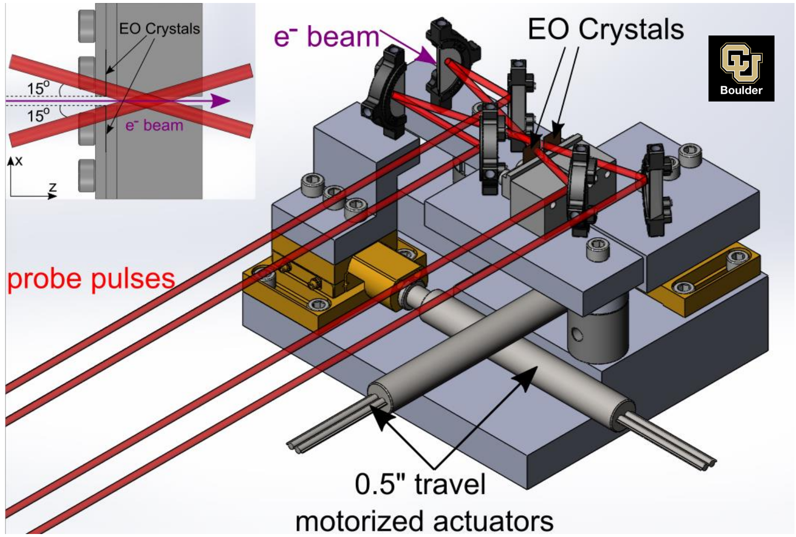


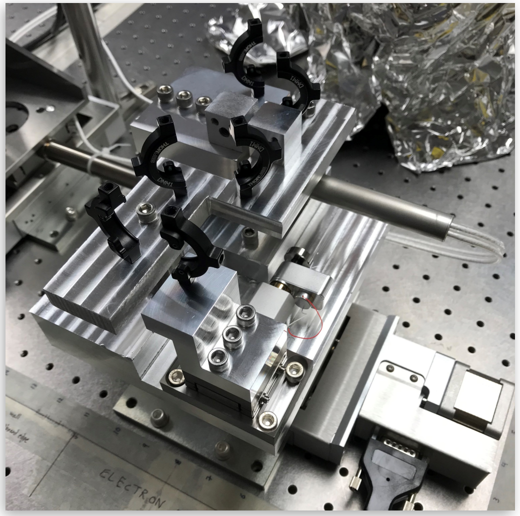

> In the end, the plasma tells you if the bunch was straight or not (final straightening is in-situ).

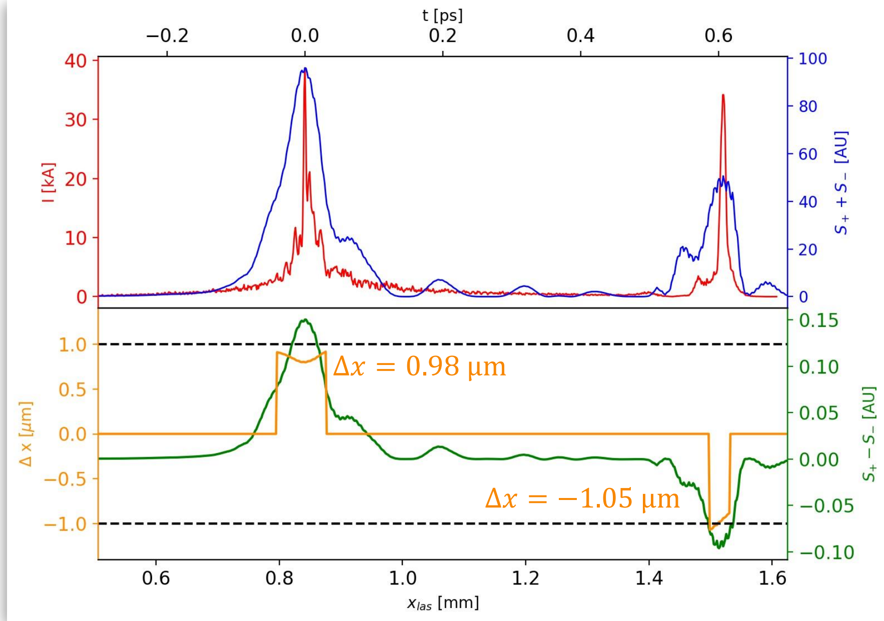
PolariX TDS: [https://www.nature.com/articles/s41598-021-82687-2](https://www.nature.com/articles/s41598-021-82687-2)

# Litos Group at CU Boulder is Developing a New Generation of Diagnostics for Transverse Wakefield Studies at FACET-II

- Single crystals provide standard measurement of longitudinal spacing
- Difference signal provides horizontal offset
- First generation will measure one transverse direction
- Calibrated with stage translation






An Electro-Optic Sampling Beam Position Monitor (EOS BPM)

Simulations predict longitudinal bunch-to-bunch separation resolution of ~10 fs and relative transverse offset resolution of ~1μm for realistic FACET-II PWFA beams.

**Use single shot information to correlate emittance growth vs witness beam offset**



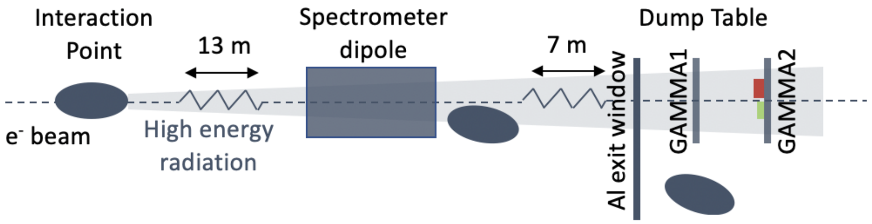
https://doi.org/10.1016/j.nima.2021.165210 and https://www.osti.gov/servlets/purl/1852444

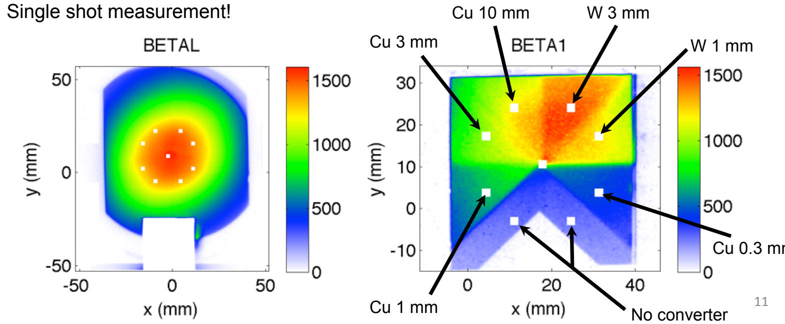
https://royalsocietypublishing.org/doi/full/10.1098/rsta.2018.0173
and P. San Miguel Claveria AAC2022 Proceedings

# Betatron Gamma-ray Measurements at FACET & FACET-II

Information can be obtained from spatial and spectral gamma-ray measurements

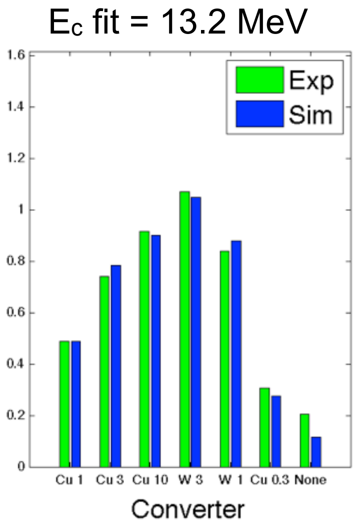
- Self-focusing
- Beam symmetrization
- Matching
- Emittance diagnostic

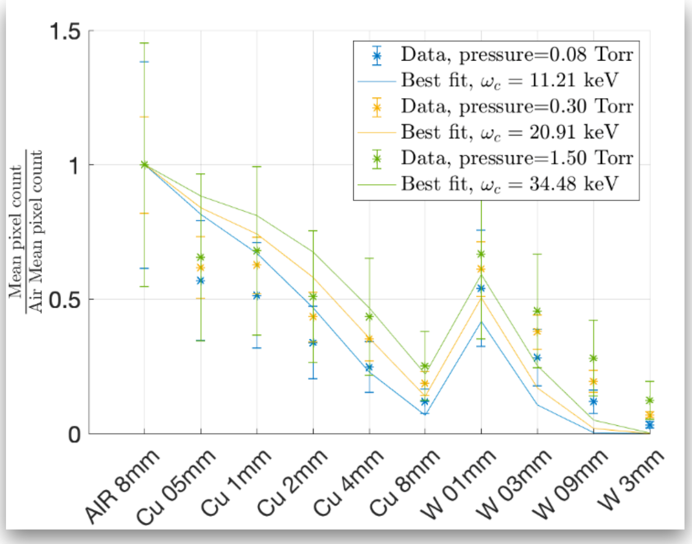



$$\theta \approx K/\gamma = 1.33 \times 10^{-10}\sqrt{n_0[\mathrm{cm}^{-3}]/\gamma}\sigma[\mu\mathrm{m}]$$

$$E_c[\mathrm{eV}] = 5.24 \times 10^{-21}\gamma^2 n_0[\mathrm{cm}^{-3}]x_0[\mu\mathrm{m}]$$




FACET-II PWFA with Beam Ionized H2
$E_c$ fits give $x_0$: 0.3, 1, 2µm

## FACET-II:

- Need detectors for keV and MeV photons
- Angularly-resolved spectrum can be very important

**Next steps are to transition from qualitative to quantitative diagnostic**

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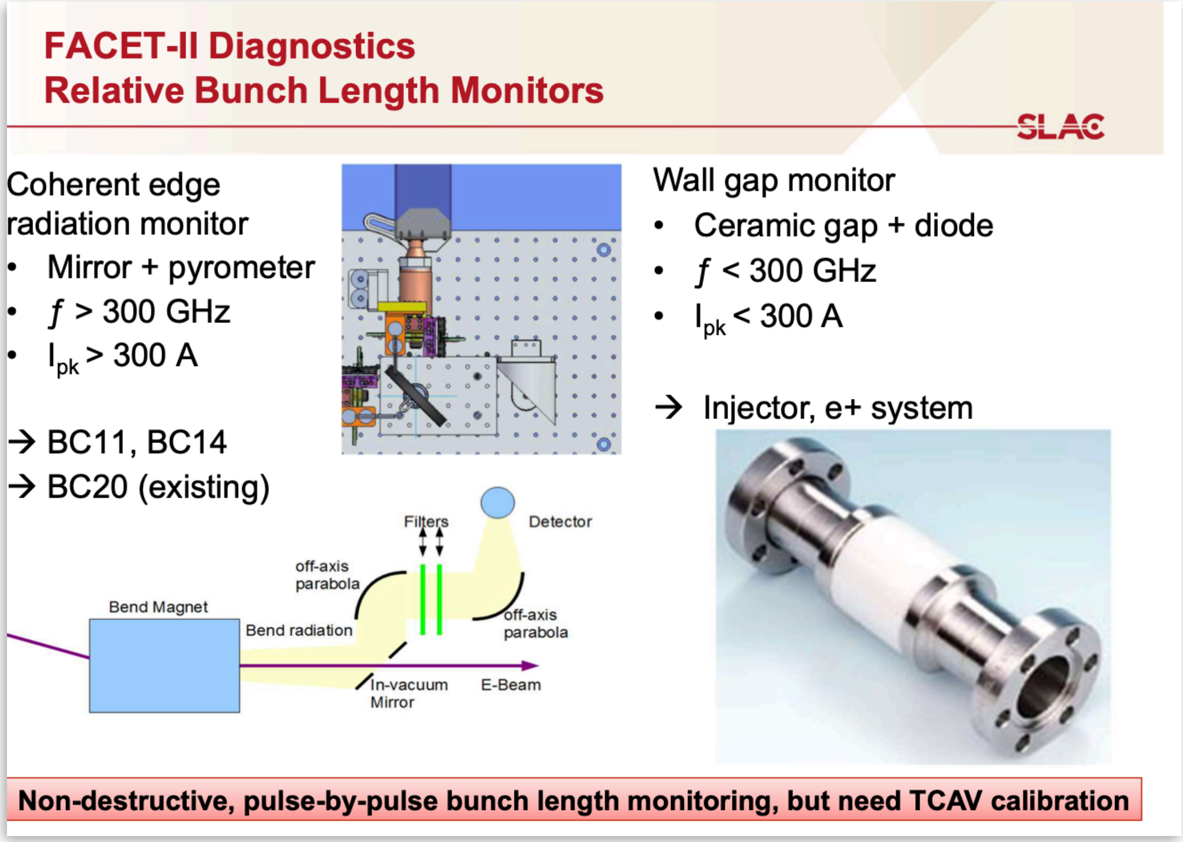
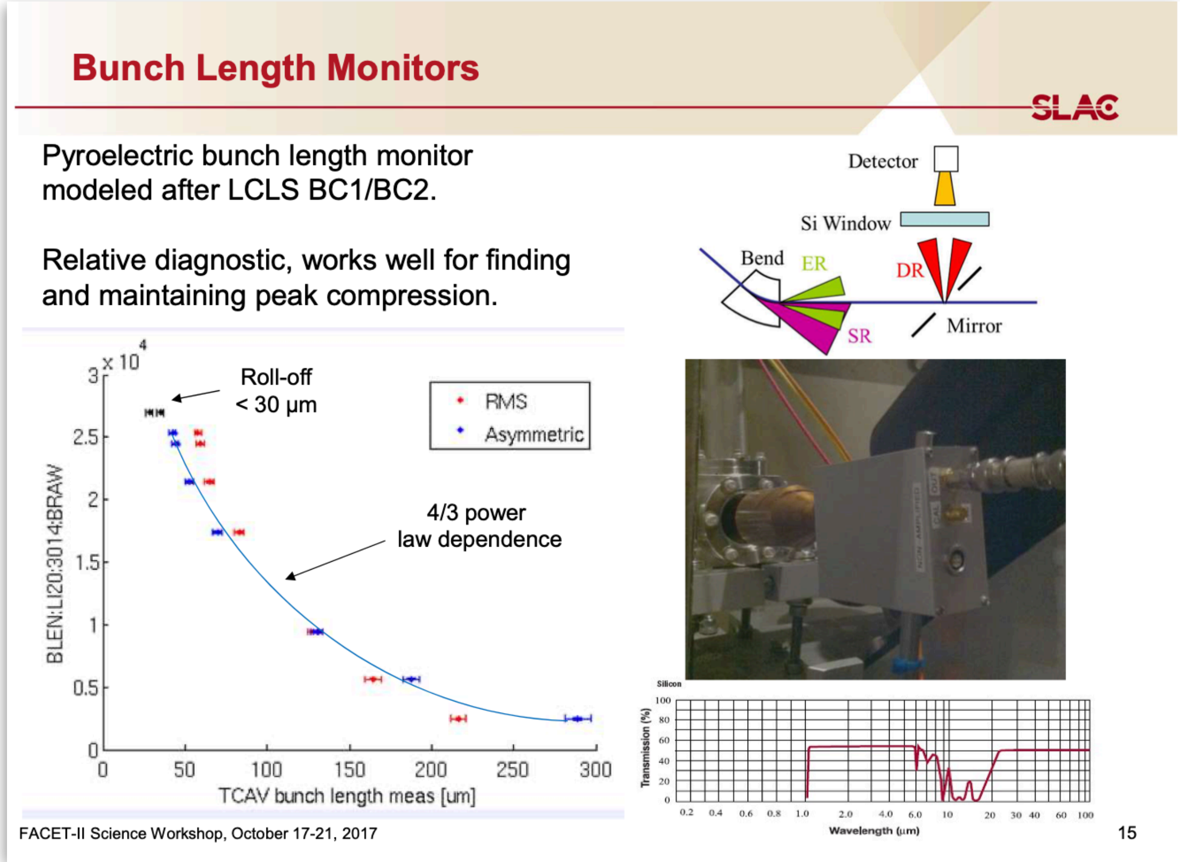
# Relative Bunch Length Monitors



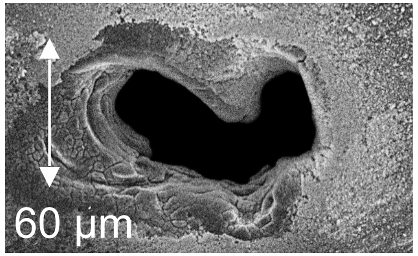

Great for feedbacks and quick correlations when you just want a scalar value

# Extreme Beams Can Be Challenging

Be vacuum window damage at FACET expected for 2nC with

$$\sigma_x = \sigma_x = \sigma_x = 20\mu m$$

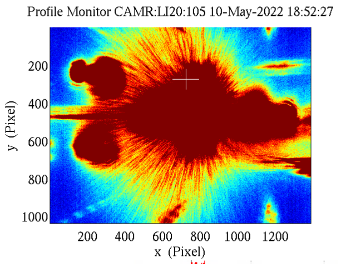
$$P \propto \frac{Q^2}{\sigma_r^2 \sigma_z^2} F\left({}^{\sigma_r}/_{\sigma_z}\right)$$



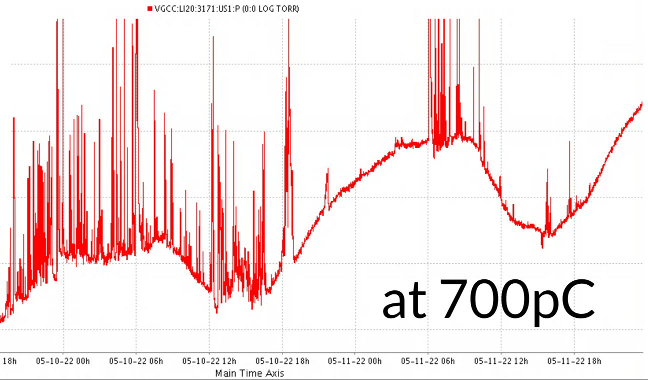

[SLAC-PUB-15729]

New threshold for micro bunched beams at FACET-II?

COTR

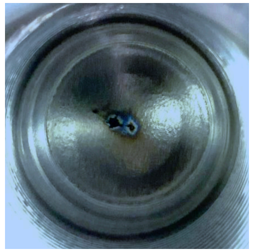



Vacuum activity

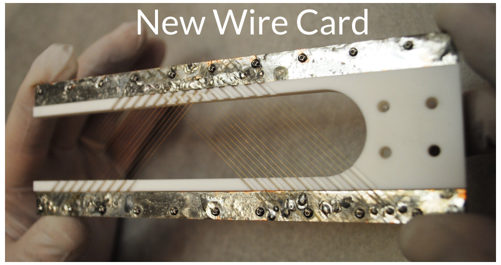



at 700pC

Be window damage



Traditional diagnostics become consumables

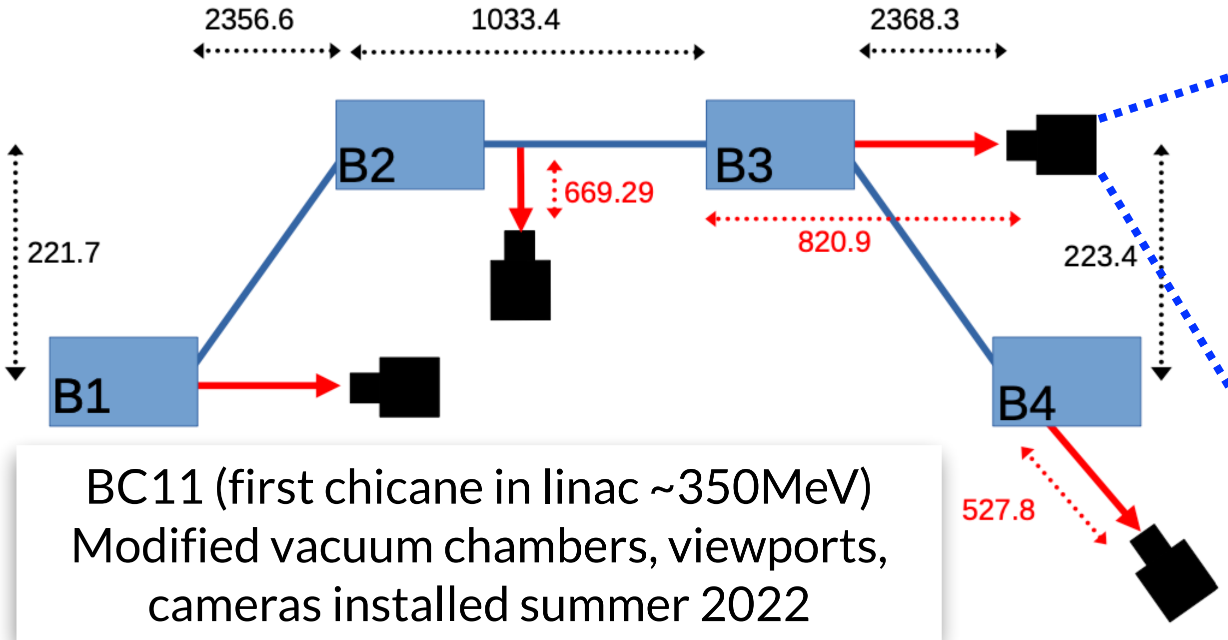




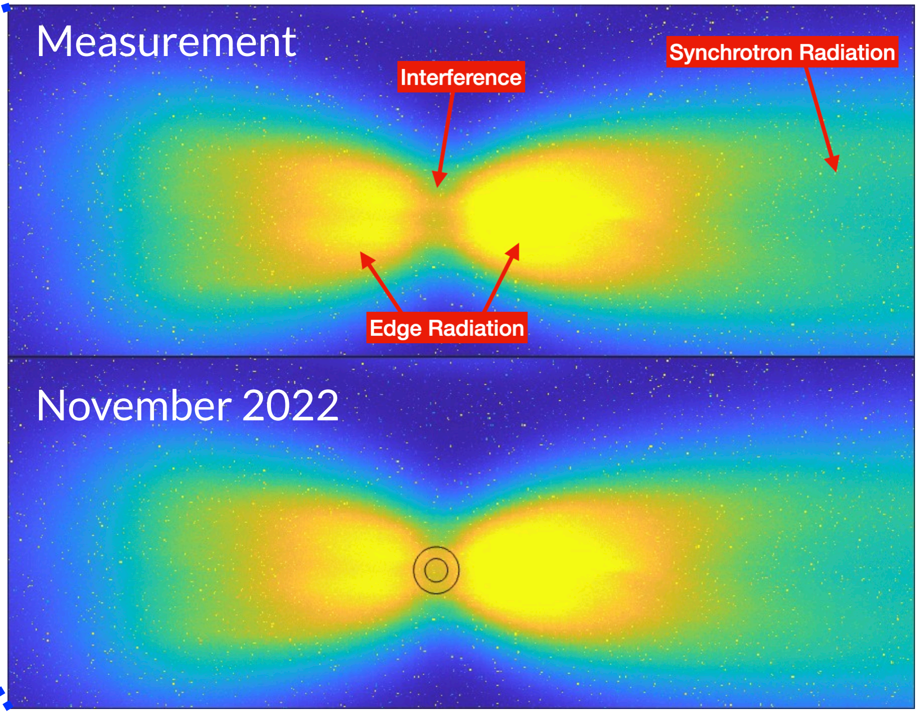
- Laser heater is installed and awaiting commissioning to mitigate microbunching
- Differential pumping system removed vacuum windows from experimental area

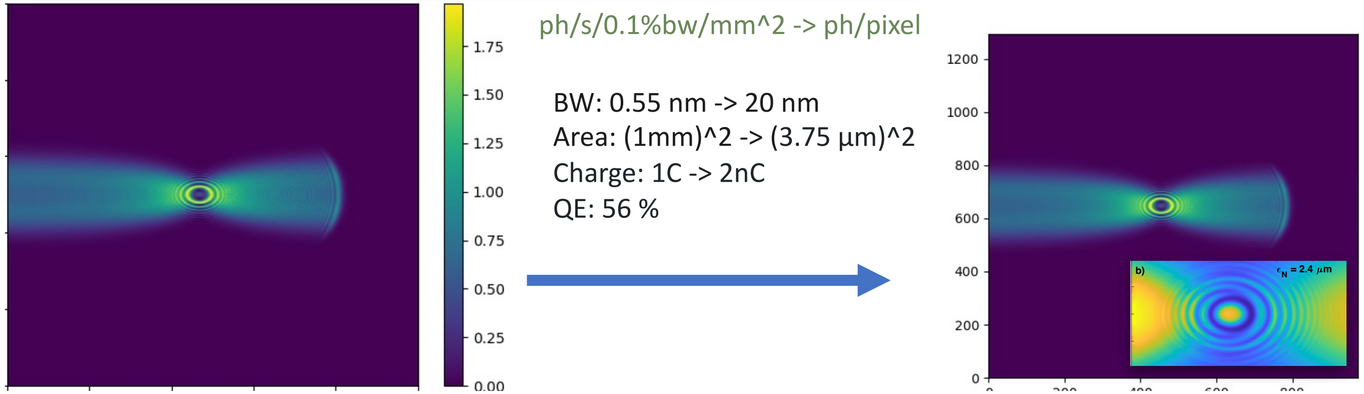
**FACET-II has unique challenges related to high intensity beams that require new approaches**

# ML/AI Based Virtual Emittance Diagnostic Under Development




BC11 (first chicane in linac ~350MeV)
Modified vacuum chambers, viewports, cameras installed summer 2022



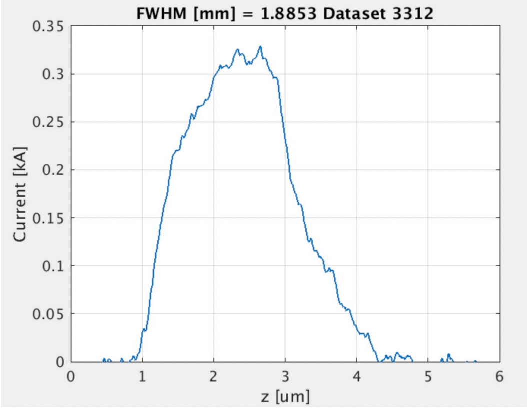

Spectral filters installed in December downtime to enhance interference fringes needed for emittance quantification

**Steady progress on O'Shea ECA for non-destructive emittance measurement along the FACET-II linac**

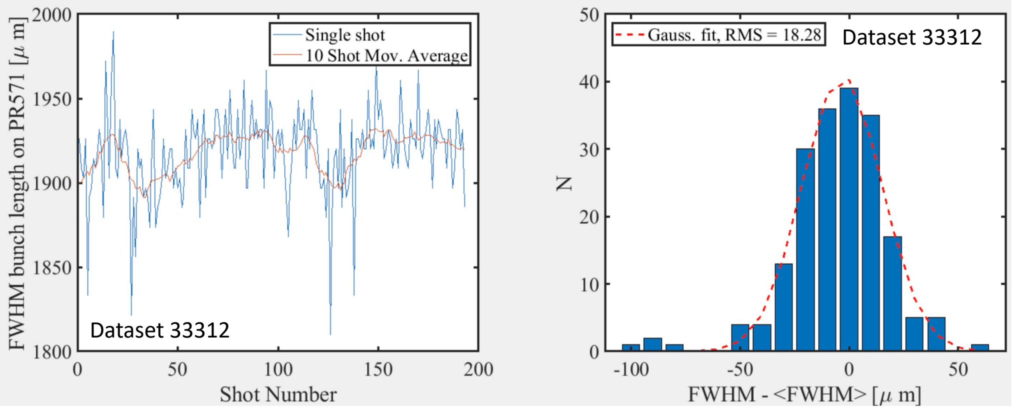
# Injector TCAV Commissioning with ML-based Bunch Length Prediction

- TCAV used to measure current profile and characterize shot-to-shot current/bunch length variations in the injector
- Bunch length variations correlated with injector RF, magnet, laser parameters.
- ML model used to predict changes in the bunch length from non-destructive inputs
- Non-destructive LPS diagnostic to be used for tuning/data analysis in upcoming runs

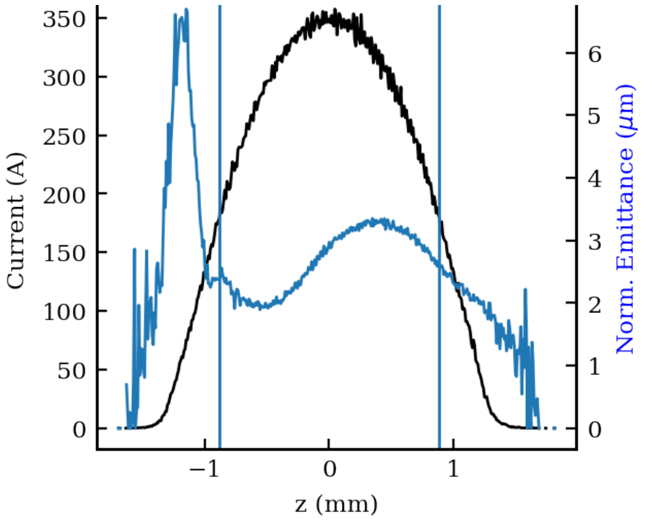
Current profile (measured)



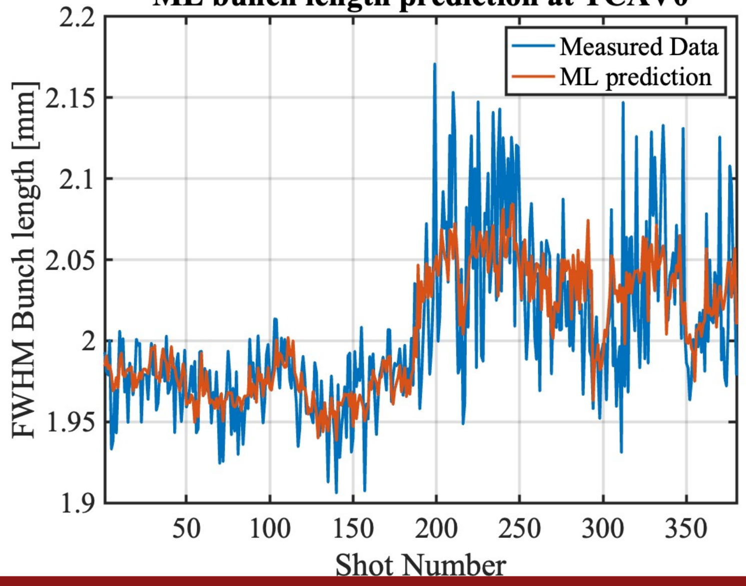

Bunch length variation (measured)




Current profile (simulation)




ML bunch length prediction at TCAV0



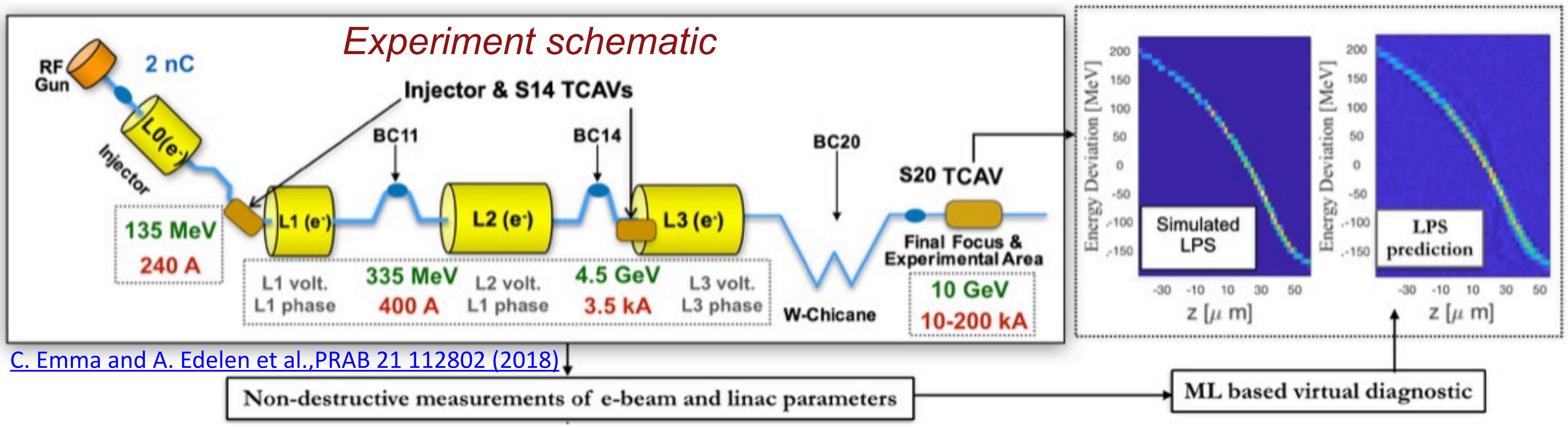

**ML based diagnostic successfully predicts bunch length at the injector exit. Extension to 2D LPS to follow.**

# E327 - Virtual diagnostic for longitudinal phase space prediction and optimization

### *Science Goals*

Implement a single-shot non-destructive ML diagnostic to predict the e-beam LPS along the linac.

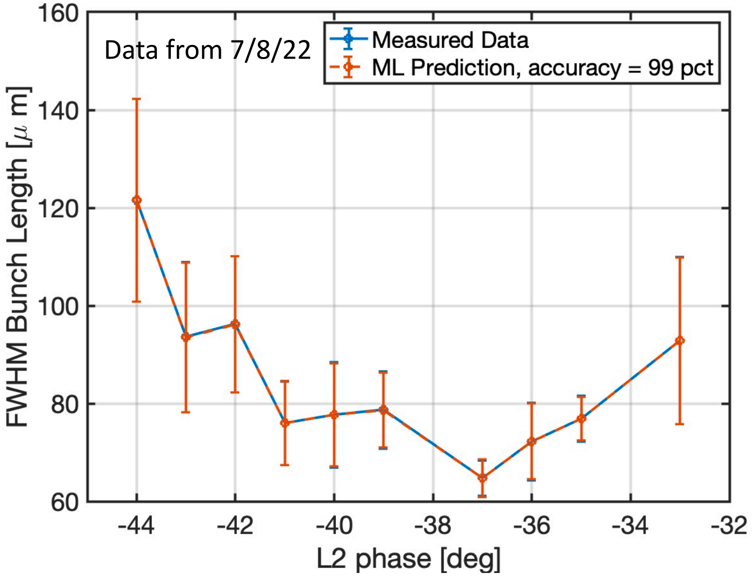
Use the ML-diagnostic to customize/ control the LPS for different experiments.

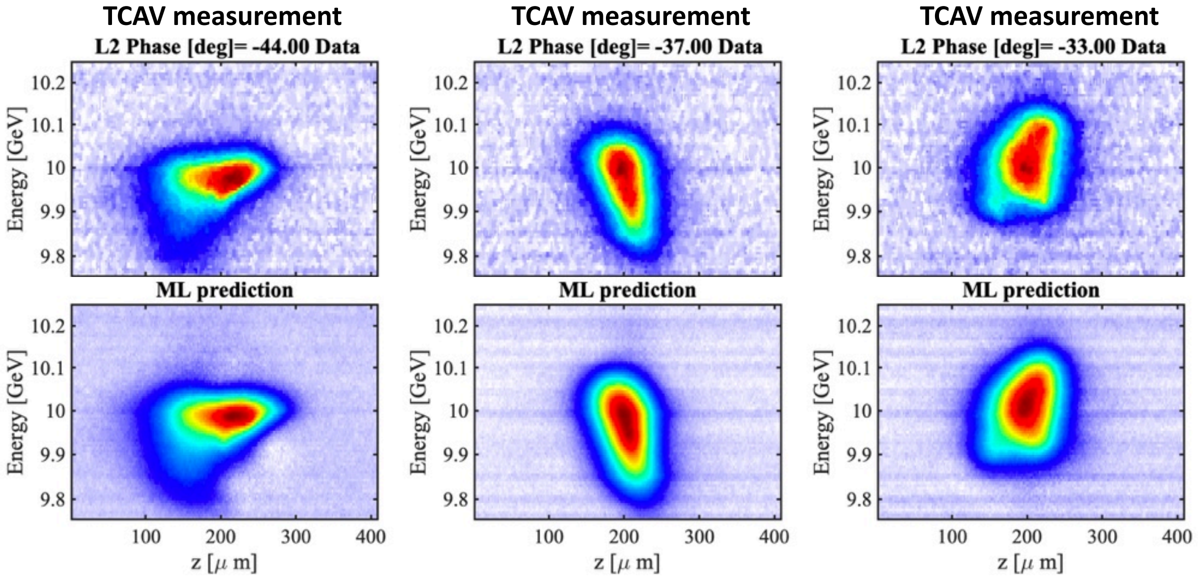



C. Emma and A. Edelen et al.,PRAB 21 112802 (2018)

## *First results*

Neural network prediction of FWHM bunch length and LPS in FACET experimental area




ML based LPS diagnostic feasibility demonstrated at FACET-II.
Upcoming work focused on robustness + multiple locations/beam configurations

# Summary

- Decades of PWFA experiments have employed a wide variety of conventional and novel diagnostics to address various physics challenges
- Recent experiments focussed on beam quality and emittance preservation at SPARC_LAB, FLASHForward and FACET-II provide a good template for EuPRAXIA to draw from:
  - A well designed spectrometer to characterize energy, energy spread and emittance
  - High resolution BPMs upstream and downstream of the plasma for precise waist location and matching to strong focussing at the entrance of the plasma up-ramp
  - A transverse deflecting structure and appropriate downstream screens to measure the current profile and ensure the beams are straight entering the plasma
- ML/AI tools are showing promise and may provide virtual diagnostics for long term stability
- Thank you to Riccardo Pompili, Carl Lindstrøm and my FACET-II colleagues for their helpful comments and contributions