E200 quad scans at FACET

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Outline

• Dumpline experimental set-up

• Quad scans for energy spectrum measurements

• Multishot quad scan emittance measurements

• Possible improvements for FACET-II
To properly characterize the beam coming out of the plasma, one needs to re-focus the beam onto the detectors.

The beam coming out of the plasma has a complex and broad energy spectrum, i.e. is not monoenergetic.

A quadrupole doublet (QS1 and QS2) and a dipole is used in the dumpline to address these issues.
Dumpline experimental set-up

What do we see on the detector?

Plasma On
Dipole Off

FACET e-beam

Final Focus

Be

Plasma
(laser-ionized or self-ionized)

Quadrupole Doublet

Be

QS1 QS2

Dipole

Vacuum pipe

Deflected electrons

Open air

Beam dump

CCD

Cherenkov or Scintillator detector

y
(vertical axis)
What do we see on the detector?

Plasma On
Dipole Off

Quad scans don’t provide meaningful emittance measurements

What do we see on the detector?
Dumpline experimental set-up

What do we see on the detector?

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Dipole On

FACET e-beam
Final Focus
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Quadrupole Doublet
Dipole
Vacuum pipe
Deflected electrons
High energy
Focused energy
Low energy
Open air
Beam dump
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y (vertical axis)
Dumpline experimental set-up

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Messages?

- Spectral measurement is only accurate over a finite energy bandwidth
- Emittance can be measured in a single shot ("butterfly" method, see next talk)
- Can deduce the exit position of the beam
- Emittance can be measured with a multishot quad scan, if the transport matrix is properly adjusted
• For large energy loss, it is difficult to measure the decelerated spectrum in a single shot.

• Measured decelerated spectrum is dependent on the quadrupole doublet setting, because particles are defocused away from the focus energy set point and signal goes below noise level.

• How to properly determine the energy transferred to the plasma by the drive beam (energy loss)?
Spectral measurements

• How to properly determine the energy transferred to the plasma by the drive beam (energy loss)?

  Multishot piecewise spectral measurement

  ![Graph showing dQ/dE (pC GeV⁻¹) vs E (GeV) for different values of E_image: 10.35 GeV, 12.85 GeV, 15.35 GeV, 17.85 GeV, and 20.35 GeV.]

• This was necessary to determine energy loss and energy extraction efficiency (from the plasma wake to the accelerated bunch) in the letter “Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield” [Nature 524, 442 (2015)].
Quad scan emittance measurements

\[
\langle x^2 \rangle_{\text{im}} = M_{11}^2 \langle x^2 \rangle_{\text{ob}} + 2M_{11}M_{12} \langle xx' \rangle_{\text{ob}} + M_{12}^2 \langle x'^2 \rangle_{\text{ob}}
\]

3 unknowns, related to the beam parameters:
\[\alpha_x, \beta_x, \epsilon_x\]

Area of interest, the rest of the image is disregarded

- \(M_{11}\) and \(M_{12}\) are known.
- \(M_{11}\) and \(M_{12}\) can be scanned for a target energy.
- The 3 unknowns can then be determined.
- \(M_{34} = 0\) is necessary to minimize chromaticity in the vertical direction, i.e. to minimize the energy bandwidth contributing to the signal in the area of interest.
Quad scan emittance measurements

\[ \langle x^2 \rangle_{\text{im}} = M_{11}^2 \langle x^2 \rangle_{\text{ob}} + 2M_{11}M_{12} \langle xx' \rangle_{\text{ob}} + M_{12}^2 \langle x'^2 \rangle_{\text{ob}} \]

- Quad scan: QS1 and QS2 integrated gradient are set to satisfy a required \( M_{12} \) value and the additional condition \( M_{34}=0 \). \( M_{11} \) is calculated from the deduced QS1 and QS2 values in order to perform the fit over the experimental data.
- The scanned parameter is therefore \( M_{12} \).

\[ M_{12} < 0 \quad M_{12} = 0 \quad M_{12} > 0 \]
Quad scan emittance measurements

- Data from April 2016
- Two-bunch positron acceleration in uniform plasma
- Quad scan to characterize witness bunch emittance at an energy gain of +1.25 GeV

\[ \gamma \epsilon_x = 750.4 \text{ mm.mrad} \]
Quad scan emittance measurements

- Data from April 2016
- Witness bunch characterized in the absence of plasma

![Graph showing the relationship between $M_{12}$ (m) and $\sigma_x$ (m) with the data and fit, and normalized emittance $\gamma\epsilon_x = 49.8$ mm.mrad]
Quad scan emittance measurements

Pros:

• Precise measurement, no assumption on energy dependence of beam parameters.

• Can resolve very low divergence beams because the transport matrix can be scanned over a very wide range (typically $M_{12}$ from -20 m to +20 m). Same beam size resolution than “butterfly” method, limited by the scintillator resolution and $M_{11}$.

• Can be used to validate “butterfly” method, which is a single shot measurement.

Cons:

• It is a multishot measurement. Cannot detect rare shots with extremely small emittance. Needs relatively stable outcoming beams.

• Works for the x dimension, not for the y dimension. Shouldn’t be a problem with more symmetric input beams.
Possible improvements for FACET-II

- Remove windows downstream of the plasma (Be window).

- Increase $M_{11}$ as much as possible, to increase beam size resolution in the object plane.

- Improve beam size resolution in the image plane.

- If more quadrupoles are considered in the dumpline, optimization can be performed to reduce chromaticity in the $y$ dimension over a wider energy bandwidth.
• Quad scans are usually necessary to properly characterize decelerated energy spectrum and energy transferred to the plasma by the drive beam

• Emittance measurement is possible with a quad scan in a dispersed region
  - Was demonstrated at FACET.
  - Can be very promising for FACET-II emittance preservation studies with normalized emittance down to a few micrometers.
  - An excellent complement to “butterfly” measurements.

• Several improvements possible:
  - Remove Be window.
  - Increase $M_{11}$.
  - Improve scintillator/profile monitor resolution.