Measuring low emittances at FACET

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Introduction (a little history)

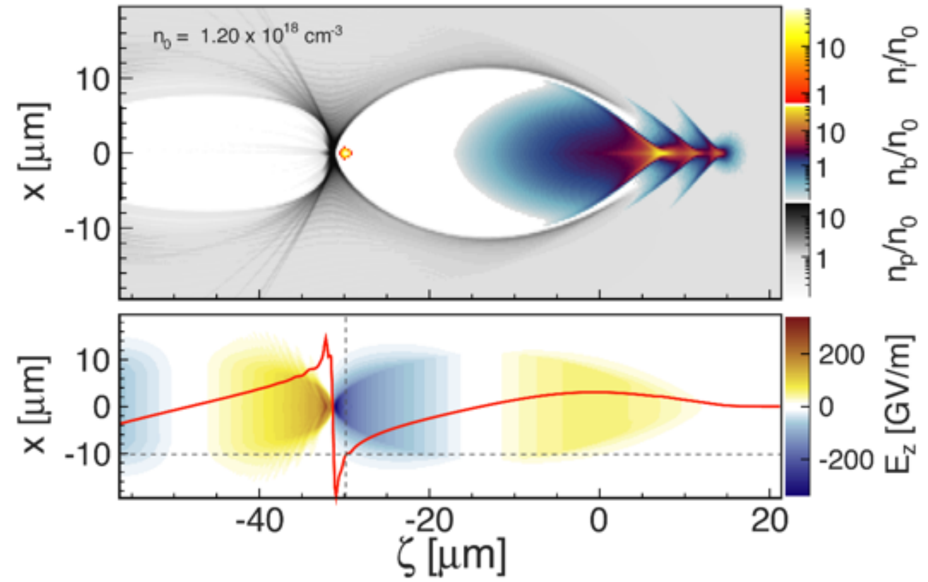
- FACET hosted multiple experiments on electron beam injection, including:
  – E210 (Trojan Horse-injection experiment)
  – E217 (Ionization injection experiment)

- Their emittance was expected to be very low: O(1 mm mrad) or lower.

- Measuring such low emittances is very challenging, especially at low energies.

- However, we (Carl and Navid, independently) came up with a method for extracting the available emittance information.

Image credit: DESY (vi-pwfa.desy.de)



LOW EMITTANCE
↓
HARD TO MEASURE

Imaging spectrometers (how they work)

- FACET had an imaging spectrometer for dispersing the beam.
- This is useful for detection of beams with:
  – **High divergence**
  – **High energy** (long drifts for dispersion)
- Two quadrupoles are used to focus a particular range of energies.
- "Imaging" refers to **"point-to-point imaging"**:
  – The position of a particle in the imaging plane (the screen) depends only on its position in the object plane (the plasma exit), and not the angle.

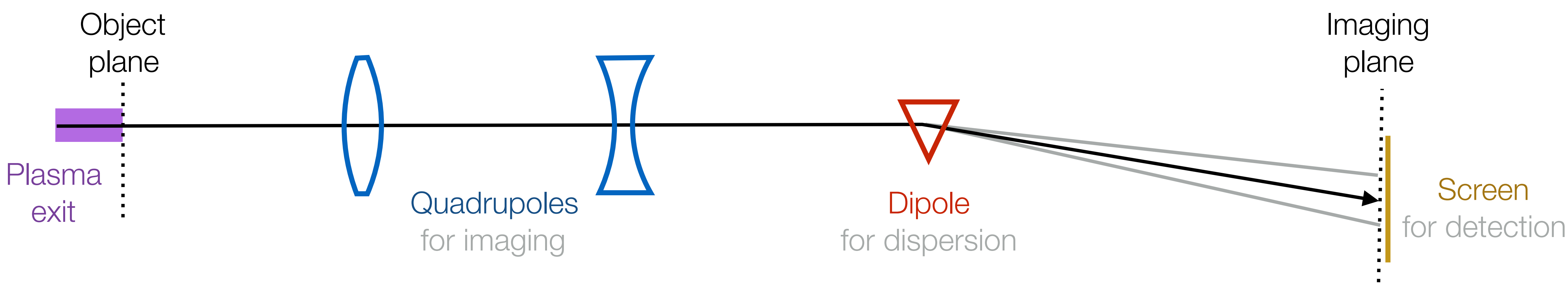
Linear beam transfer:

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix}$$

$$\begin{pmatrix} y \\ y' \end{pmatrix} = \begin{pmatrix} m_{33} & m_{34} \\ m_{43} & m_{44} \end{pmatrix} \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix}$$

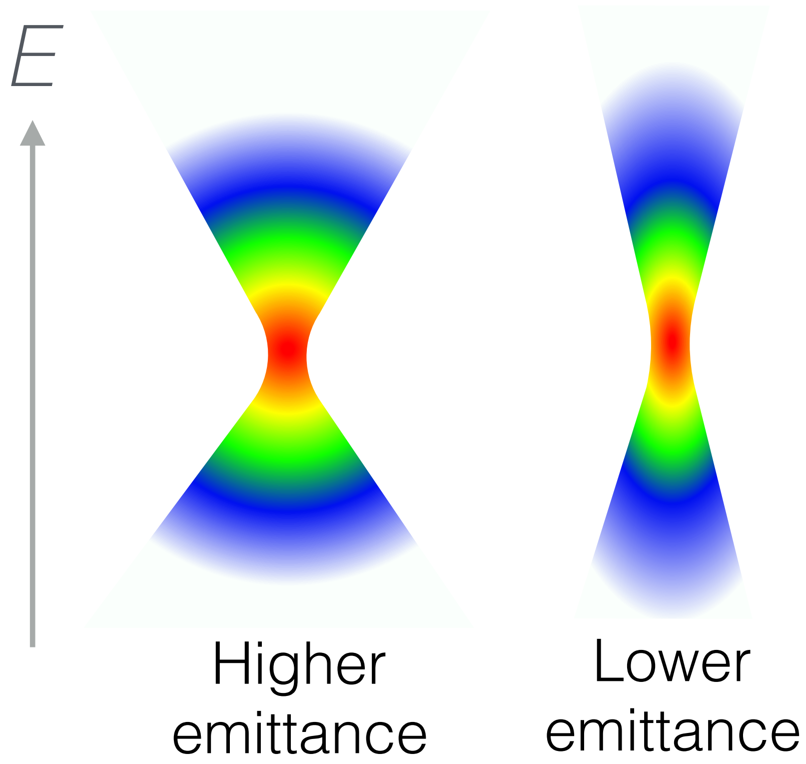
Imaging condition (x and y):

$$m_{12} = 0$$
$$m_{34} = 0$$



The Butterfly (what we usually see)

- A typical high-energy (~20 GeV), high-emittance (~0.1-1 mm) image:



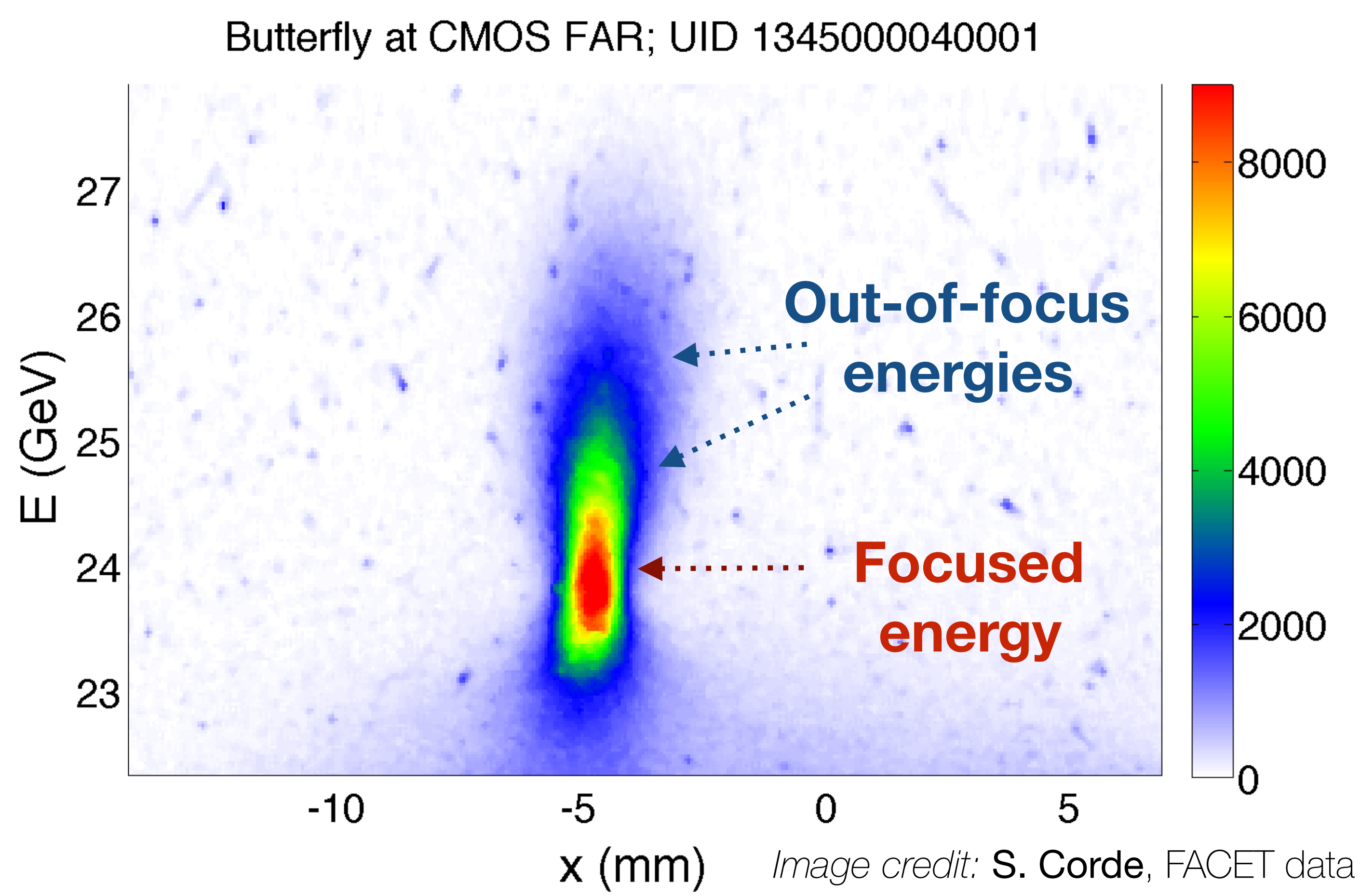


Image credit: S. Corde, FACET data

- 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.
- Robust method for high emittance beams, but not ideal for low emittance beams.

Low emittance beams and windows (a complication to the model)

- For low-energy or low-emittance beams, windows lead to significant **emittance growth** through multiple scattering.

- Lower energies are scattered more:

$$\sqrt{\langle \theta^2 \rangle} = 13.6\, z \frac{1}{\beta p} \sqrt{\frac{x}{X_0}} \left\{ 1 + 0.038 \ln \frac{x}{X_0} \right\}$$

θ: scattering angle
p: momentum
x: window thickness
X_0: radiation length

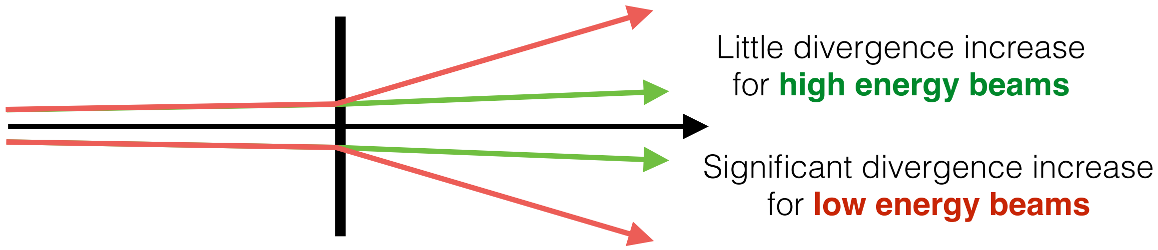
- FACET had two windows downstream of the plasma:
  – A beryllium/diamond window (~70-100 μm)
  – An aluminum beam line dump window (5 mm)

- These windows result in emittance growth: this sets the "emittance resolution".

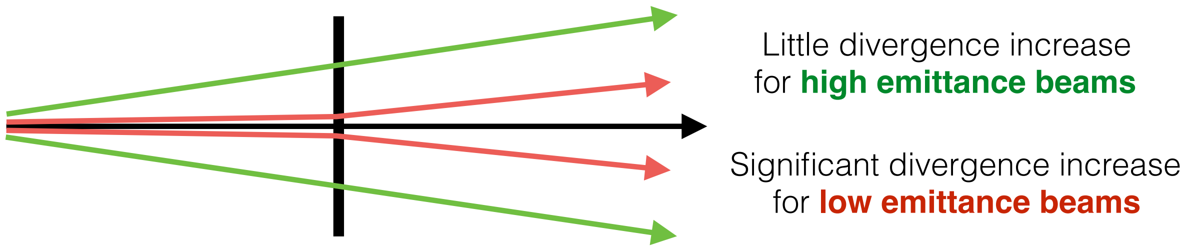
Diamond window

Beryllium windows

Windows are bad for low energy beams



Windows are bad for low emittance beams



Question:

Can we still measure emittances around or below this "emittance resolution"?

Answer:

Yes, at least partly, if we have an exact model of the spectrometer.

Our method (model including effect of windows)

1. Do gaussian fits to find beam width (σ_x) of each energy.

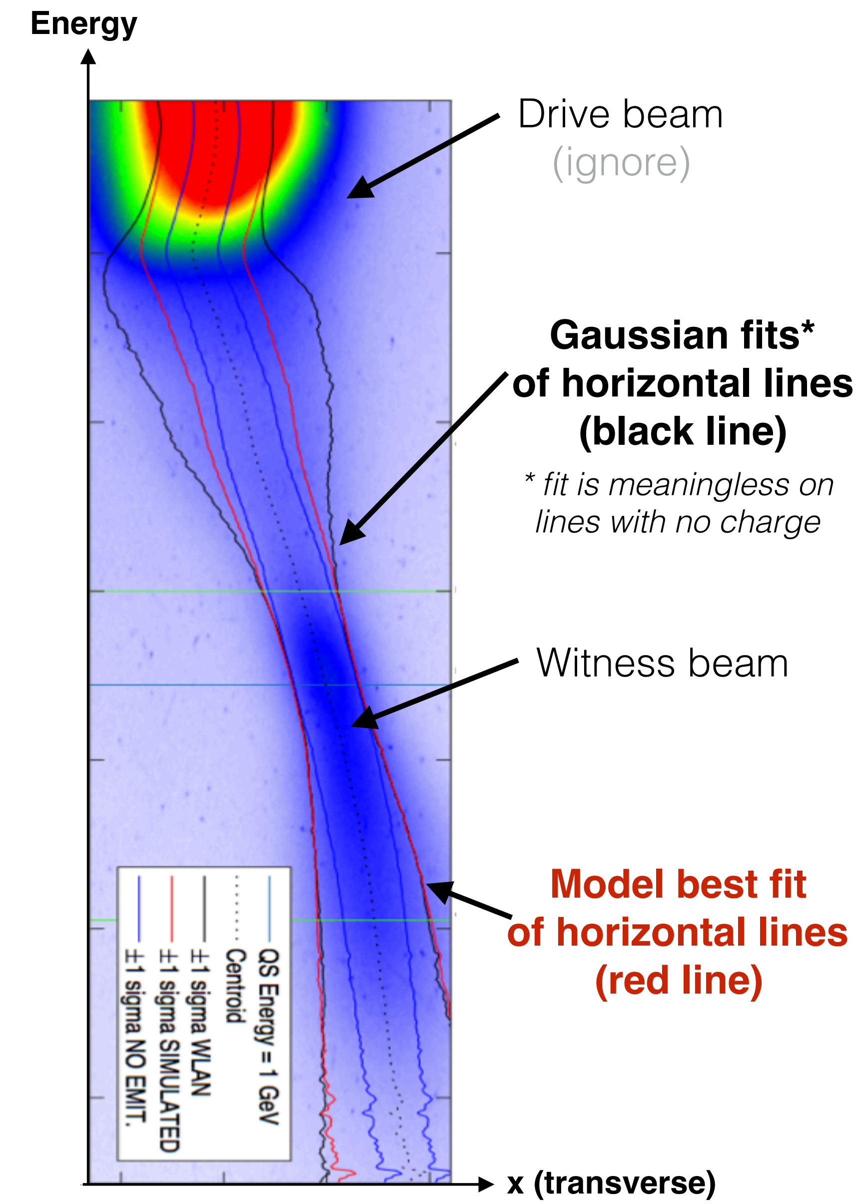
2. Find best fit of parameters (β, ϵ_N, s^*) by comparing the modelled beam widths to the measured beam widths.

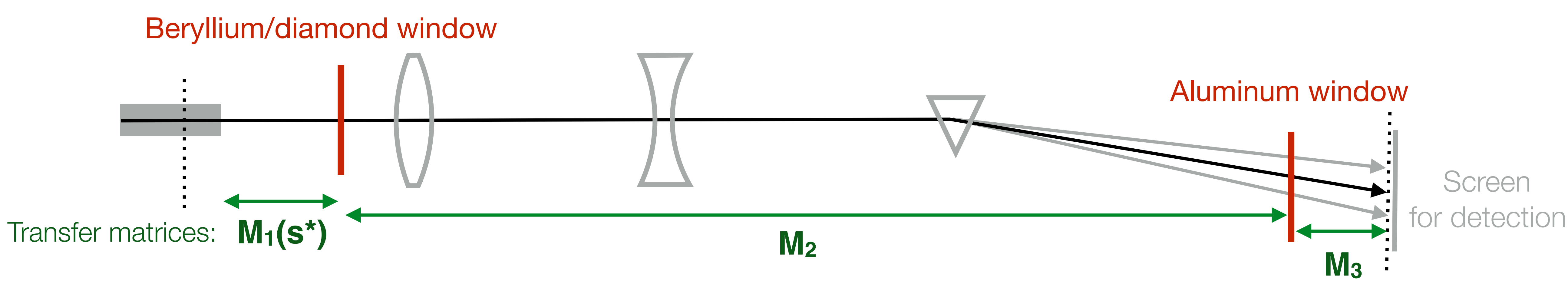
Model (final beam matrix given: β, ϵ, s*) :

$$\Sigma_{\text{end}}(\beta^*, \epsilon, s^*) = M_3(M_2(M_1(s^*)\Sigma_0(\beta^*, \epsilon)M_1(s^*)^\dagger + \Sigma_{Be})M_2^\dagger + \Sigma_{Al})M_3^\dagger)$$

$$\Sigma_{\text{window}} = \begin{pmatrix} 0 & 0 \\ 0 & \Delta\theta^2 \end{pmatrix} \quad \Sigma_0 = \epsilon \begin{pmatrix} \beta^* & 0 \\ 0 & \frac{1}{\beta^*} \end{pmatrix}$$

Main point: You can predict the beam at the screen given a three parameters only (computationally cheap)

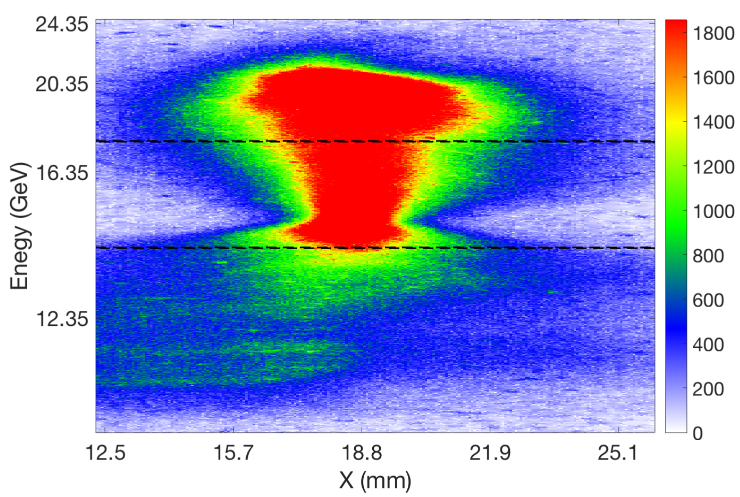


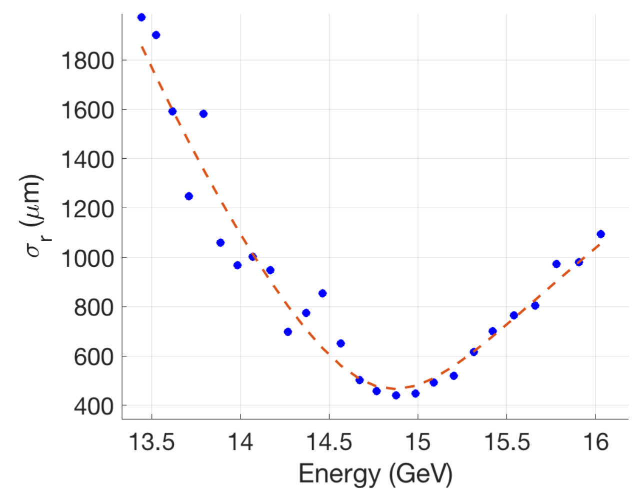


E217 examples (ideal case: high energy, low emittance)

Credit: **Navid Vafaei-Najafabadi** (analysis and images)

High emittance, high energy shot (normal butterfly method):

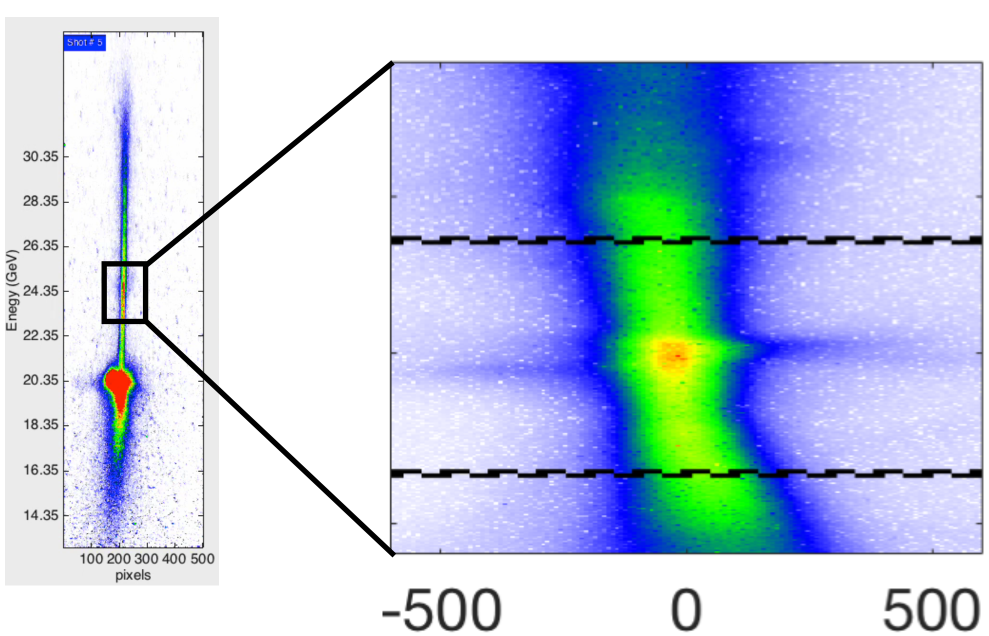


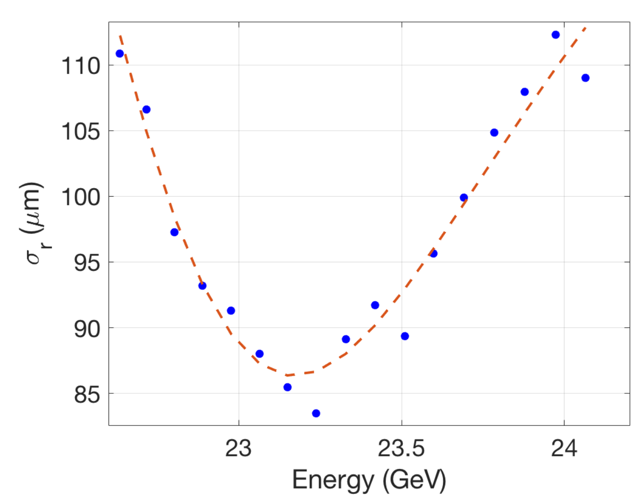


ϵ_N = 584 mm-mrad

σ_r = 56 μm

Low emittance, high energy shot (needs the new method):





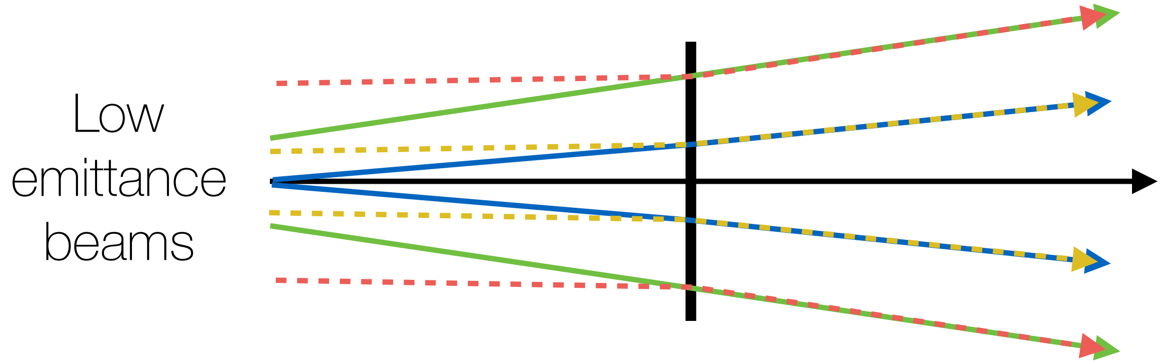
ϵ_N = 5 mm-mrad

σ_r = 1 μm

Limitations / opportunities for low energy beams (be clever: get estimates)

- Method works best around and above the emittance resolution.

- However, below the emittance resolution, it is also possible to gain information.



Windows wash out information about incoming divergence, but not the incoming beam size

- **Make assumptions about the divergence** before window (upper/lower bounds)
→ **Get estimates for emittance** before window (upper/lower bounds)

- This method is used for the E210 Trojan Horse injection experiment.

E210-examples (non-ideal: low energy, low emittance)

Work in progress (yet unpublished) for the E210 collaboration.

High emittance, low energy:

Low emittance, low energy:

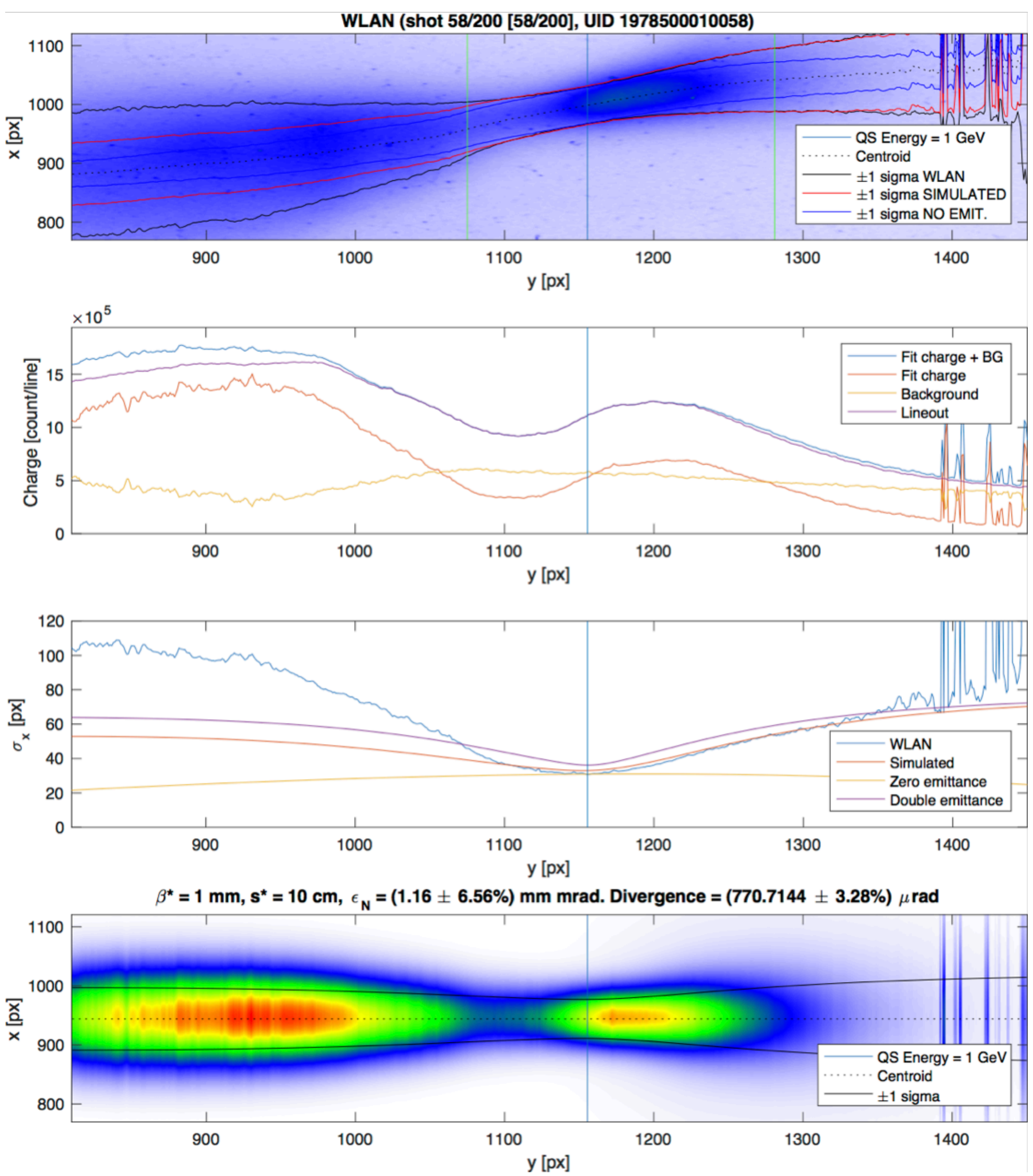
fit is meaningless on lines with no charge

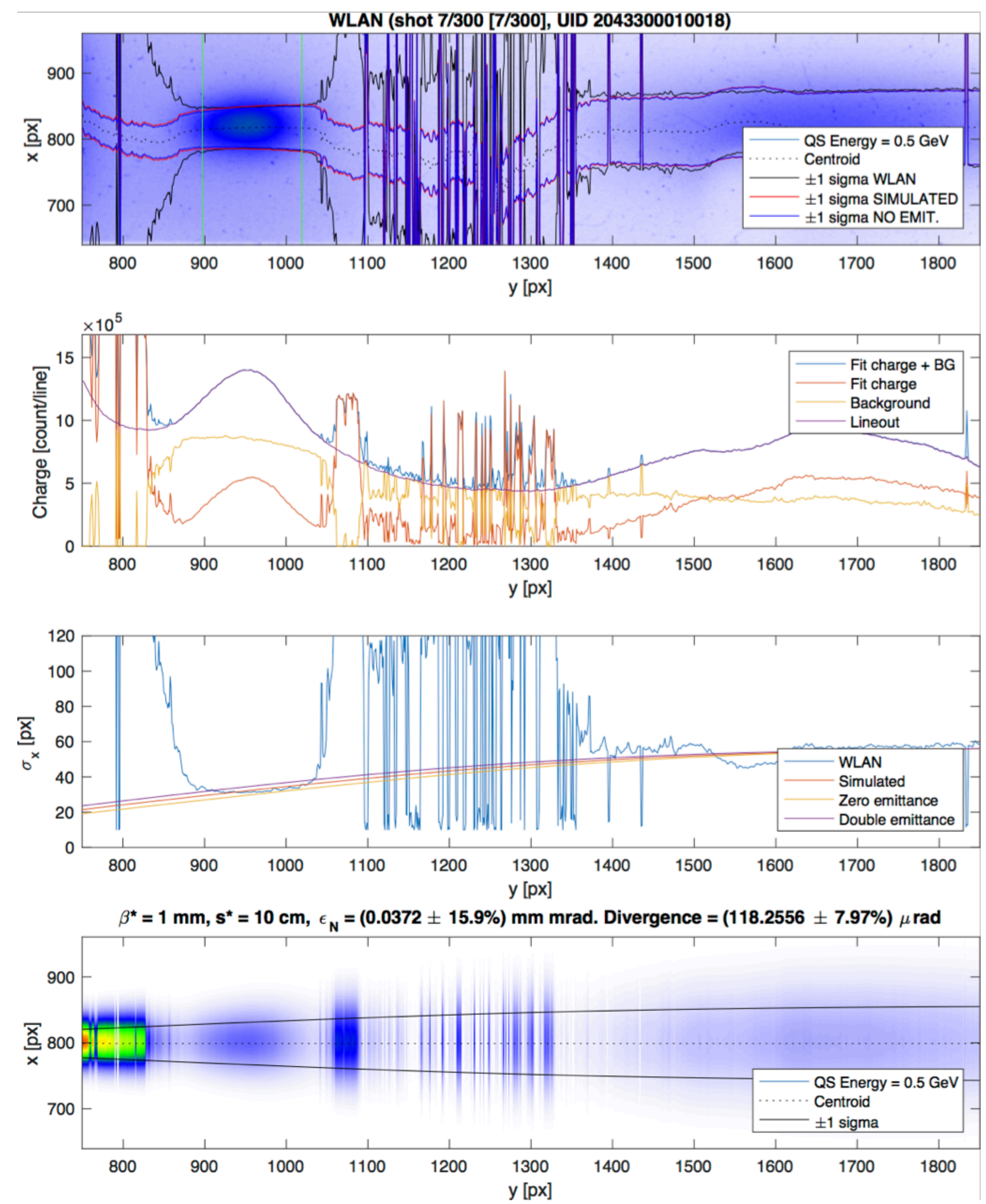
Spectrometer image
(energy axis: horizontal)

Charge distribution
(energy axis: horizontal)

Transverse beam size
(energy axis: horizontal)

Best fit simulation
(energy axis: horizontal)





- *Note: The method does not need a butterfly to work, in fact it works better further away.*

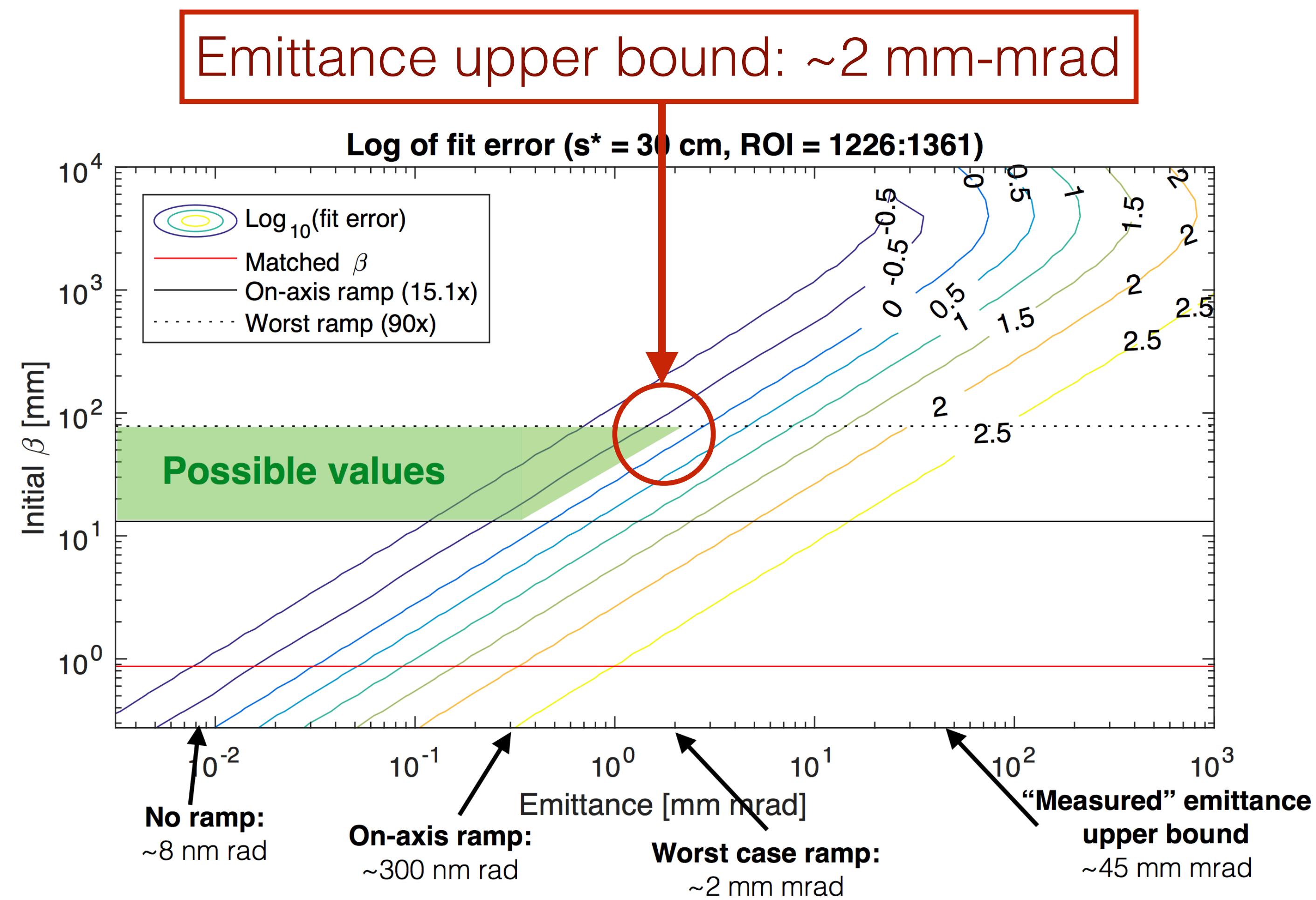
E210-example in-depth (one shot where the method worked great)

- Looking at one particularly good (suspected Trojan Horse injection) shot.

- Reasonable assumptions for E210:

  – Injected charge has a matched beta function (1 mm scale)

  – A plasma density ramps can maximally increase beta to ~length of ramp (10 cm scale)



Confidence interval plot
with indicated possible values for emittance

- Result:
  – Upper bound estimate for emittance: ~2 mm-mrad
  (given worst case density ramp: **likely much lower**)

Summary and recommendation for FACET-II (screw the windows!)

- Measuring emittances for low emittance, low energy beams is challenging!
- We have shown it is possible to gain some/all emittance information even with windows. However, this is very complicated and a source of errors.
- One main goal for FACET-II is to demonstrate low emittance PWFA beams.
- This will require reliable low-emittance measurement techniques.
- Recommendation for FACET-II:

  Avoid beam windows downstream of the plasma,
  at least when searching for low emittance beams.