Simulating the Measurement of the Electron Beam Emittance at AWAKE

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The AWAKE project

- Scaling RF accelerators is impractical:
  - synchrotron radiation
  - cost
- Plasma wakefield acceleration is an alternative
  - Larger EM gradients (up to the GV/m scale)
  - Electrons will be accelerated in the wakefield of a proton beam
- AWAKE is a proof-of-concept

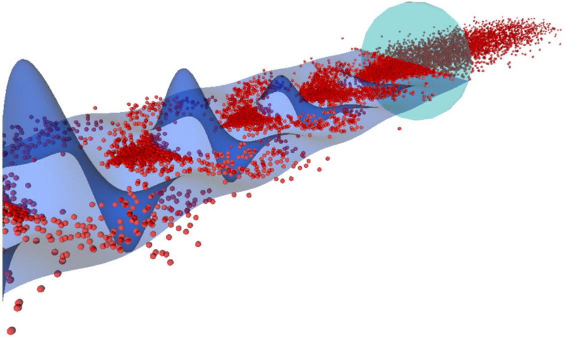


Figure: Artists impression of the AWAKE witness beam electrons (red) captured and accelerated by the plasma wakefield (blue). Credit: Alexey Petrenko / CERN. `https://www.hep.ucl.ac.uk/awake/`

The Spectrometer

Goals:

1. Measure the energy of the beam
2. Determine the quality of the beam

Objective:

Investigate the effect on the emittance measurement of experimental parameters:

- mean energy and energy spread
- background photons
- emittance

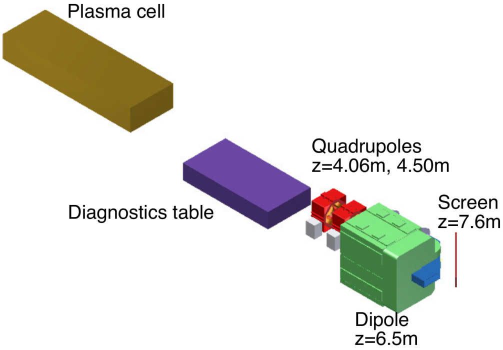


Figure: 3D schematic of the spectrometer downstream of the plasma cell. Source: Deacon, Lawrence, et al. "Development of a spectrometer for proton driven plasma wakefield accelerated electrons at AWAKE." (2015): WEPWA045.

The Simulation

To simulate the shape of the beam on the screen the following transport matrix $\mathcal{M}$ is applied to the input beam matrix $\boldsymbol{\sigma_0}$

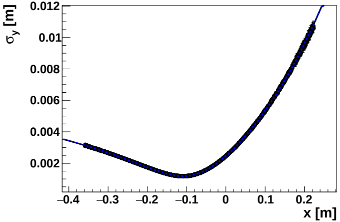
$$\boldsymbol{\sigma}_1 = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} = \mathcal{M}\, \boldsymbol{\sigma}_0\, \mathcal{M}^T, \quad \epsilon = \sqrt{\det \boldsymbol{\sigma}}, \quad \beta\gamma - \alpha^2 = 1, \quad \tan 2\varphi = \tfrac{2\alpha}{\gamma - \beta}$$

$$\mathcal{M} = \underbrace{\begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}}_{\text{drift}} \cdot \underbrace{\begin{pmatrix} \cos\varphi_1 & \frac{\sin\varphi_1}{\sqrt{k_1}} \\ -\sqrt{k_1}\sin\varphi_1 & \cos\varphi_1 \end{pmatrix}}_{\text{vertically focusing quadrupole}} \cdot \underbrace{\begin{pmatrix} 1 & g_2 \\ 0 & 1 \end{pmatrix}}_{\text{gap}} \cdot \underbrace{\begin{pmatrix} \cosh\varphi_2 & \frac{\sinh\varphi_2}{\sqrt{|k_2|}} \\ -\sqrt{k_2}\sinh\varphi_2 & \cosh\varphi_2 \end{pmatrix}}_{\text{horizontally focusing quadrupole}} \cdot \underbrace{\begin{pmatrix} 1 & g_1 \\ 0 & 1 \end{pmatrix}}_{\text{gap}}$$

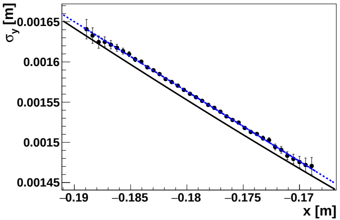
where quadrupole strength k_1 and k_2 and drift distance to screen d are functions of energy. From this we are able to derive a function $\sigma_y\,(x; \beta, \gamma, \epsilon)$ where

$$\sigma_y = \sqrt{\boldsymbol{\sigma}_{1,11}} = \sqrt{\epsilon\beta} \qquad \text{rms beam envelope}$$

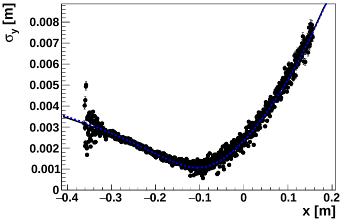
Beam Reconstruction Examples



$\bar{E}$	1.3 GeV
σ_E	0.4 GeV
ϵ	1×10^{-6} m rad
bg density	0.01 /pixel



$\bar{E}$	1.3 GeV
σ_E	0.013 GeV
ϵ	1×10^{-6} m rad
bg density	0.01 /pixel

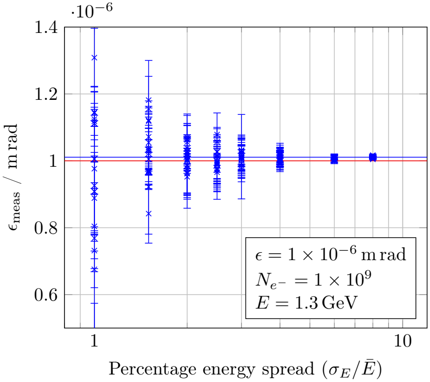


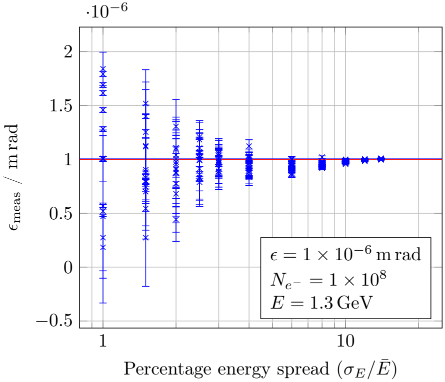
$\bar{E}$	1.3 GeV
σ_E	0.4 GeV
ϵ	1×10^{-6} m rad
bg density	80 /pixel

- Black line: the function $\sigma_y\,(x; \beta, \gamma, \epsilon)$ of the shape of the simulated beam
- Black points: measured σ_y value for each vertical strip of pixels
- Blue line: the function $\sigma_y\,(x; \beta, \gamma, \epsilon)$ fitted (χ^2) to the black points

Results Energy Spread

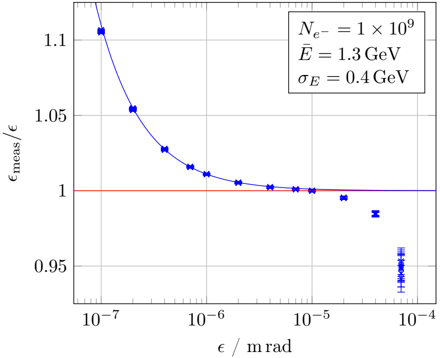
The effect of the energy spread of the electron beam on the simulated emittance measurement.

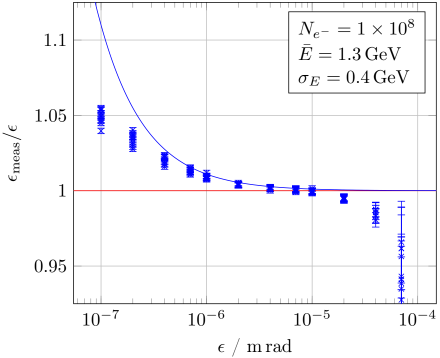




For lower energy spreads, the electron beam is spread much smaller accross the screen.

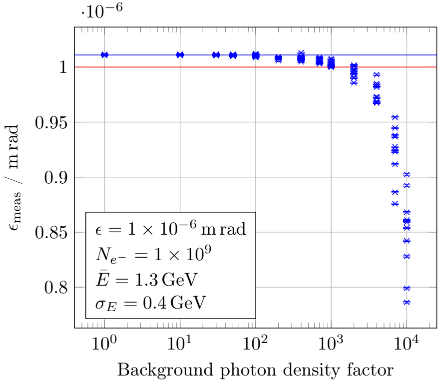
The effect of the emittance on the simulated emittance measurement.

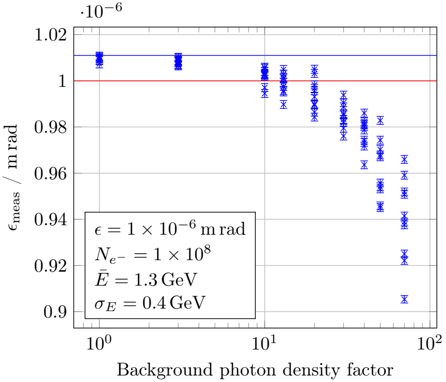




For large emittances, many of the electrons completely miss the screen so we arrive at a lower value for the transverse momenta of the beam.

The effect of background photons on the simulated emittance measurement.





The number of photons per bin is expected to be in the order of magnitude of 1×10^{-2}.

Conclusion

- Shown how the energy spread, background and emittance affect the emittance measurement.
- Graphs are quite specific and are only accurate when keeping certain parameters constant.
- Give a general idea as to how the emittance measurement should behave with respect to each parameter.