Emittance and energy spread measurements of relativistic electrons from laser-driven accelerator

OUTLINE

- ALPHA-X Project
- Introduction on laser wakefield accelerator (LWFA)
- LWFA as a light source
- Electron beam characterization: emittance and energy spread

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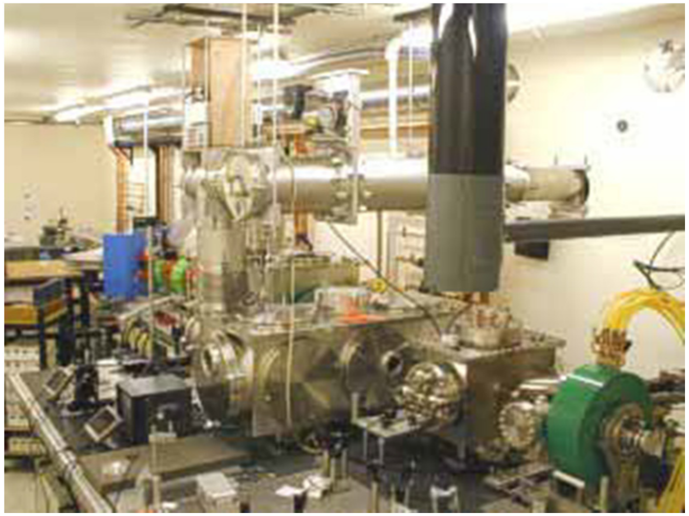
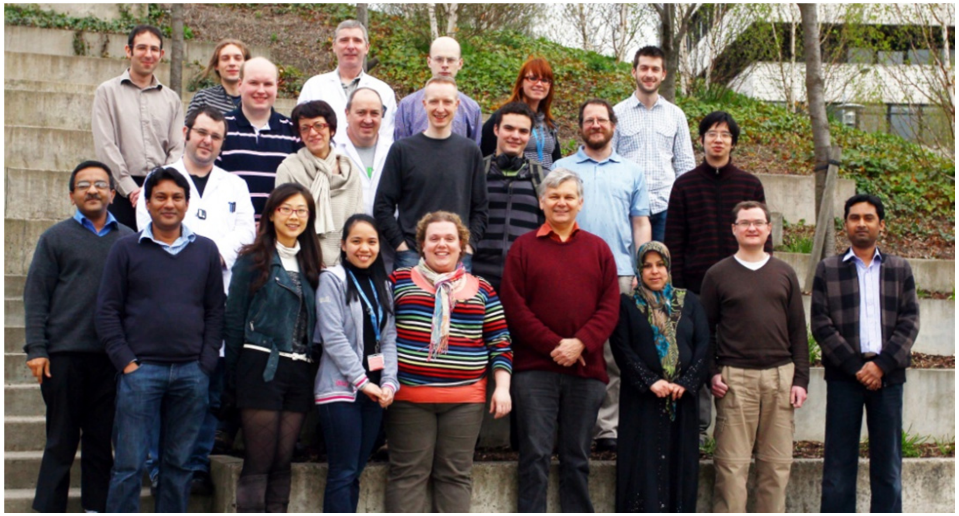
Advanced Laser Plasma High-energy Accelerator towards X-rays

- Collaboration of several universities and research centre in UK (Strathclyde, St. Andrews, Dundee, Abertay-Dundee, Cockroft Institute)
- Beam line is located at University of Strathclyde (Group Leader: Prof. Dino Jaroszynski)

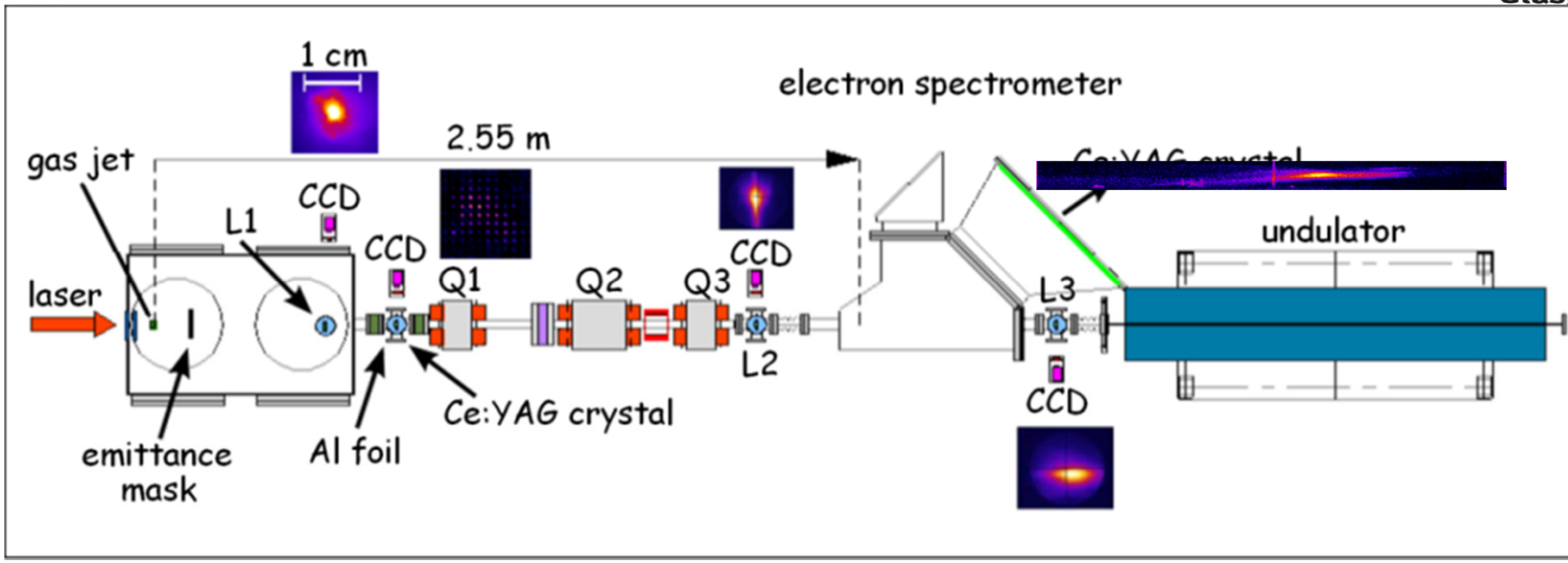


ALPHA-X beamline (~ 10m)



ALPHA-X Group in Strathclyde

ALPHA-X beamline



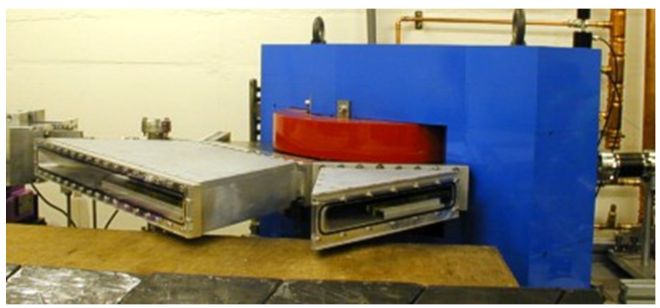
Laser:

900 mJ, 35 fs, 800 nm, initial $a_o \approx 1.0$

Plasma source:

2 mm He gas jet

$n_e \approx 10^{19}$ cm^{-3}

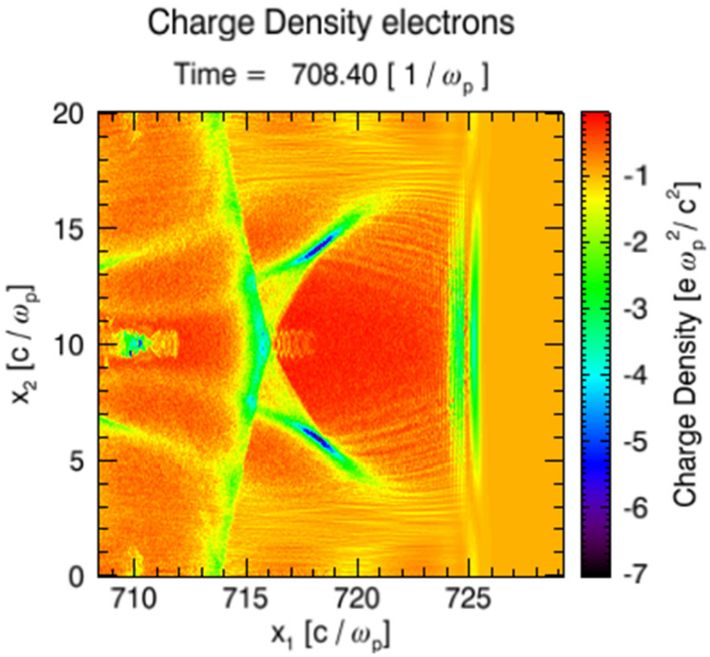


Electron spectrometer

- Uses quadrupole lenses to aid focusing
- Can measure electron energy up to 660 MeV (B=1.65 T)
- energy resolution is ~ 0.2-10% (energy dependent)

Electron characterization: emittance and energy spread

Laser wakefield accelerators (LWFA)



Conditions for bubble formation:

$$k_p R \approx 2\sqrt{a_o}$$

$$P > Pcrit \approx (\tau[fs]/\lambda[\mu m])^2 \times 30\,GW$$

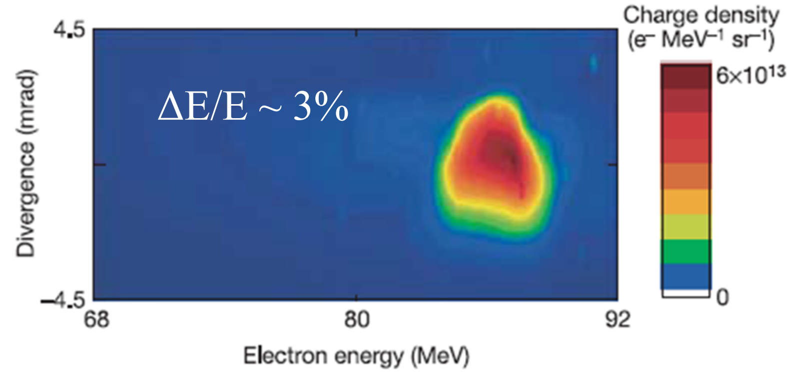
- Requires $I_{laser} \geq 10^{18}$ Wcm^{-2} ($a_o > 1$ for λ=1µm)
- Relativistic self focusing leads to plasma guiding
- Ponderomotive force leads to charge separation forming the plasma wakefield
- Electrons are self-trapped at the back of the bubble and accelerated to high energy
- Maximum electron's energy at the dephasing length:

$$\gamma_{max} \cong \frac{2a_o(\omega_{laser}/\omega_{plasma})^2}{3}$$

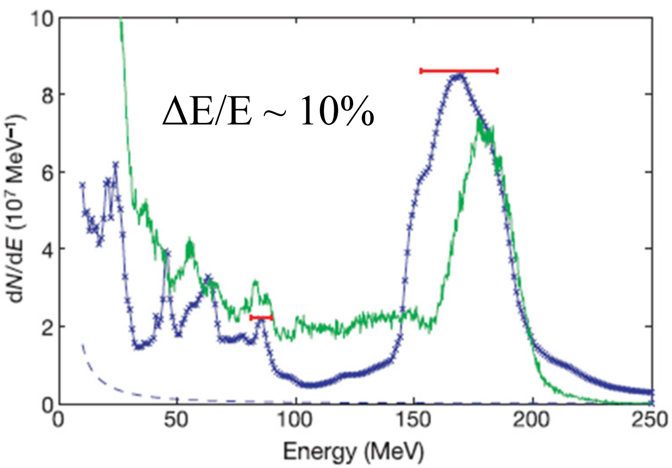
Laser wakefield accelerators (LWFA)

few mm-cm
acceleration length

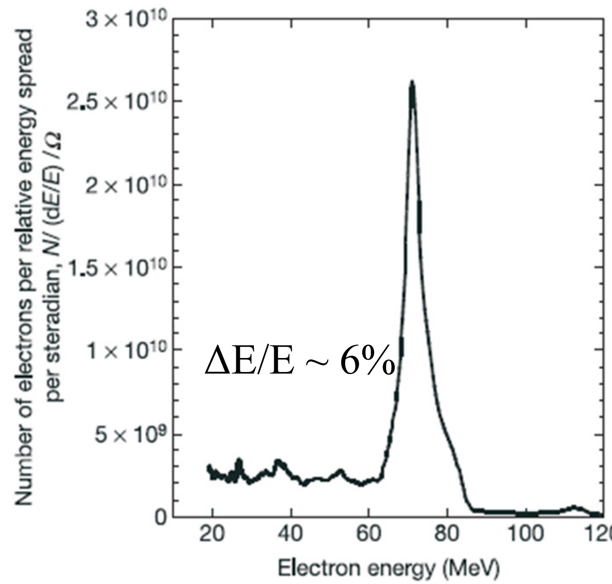
80 MeV – 1GeV
electron energy



G.R. Geddes et al.

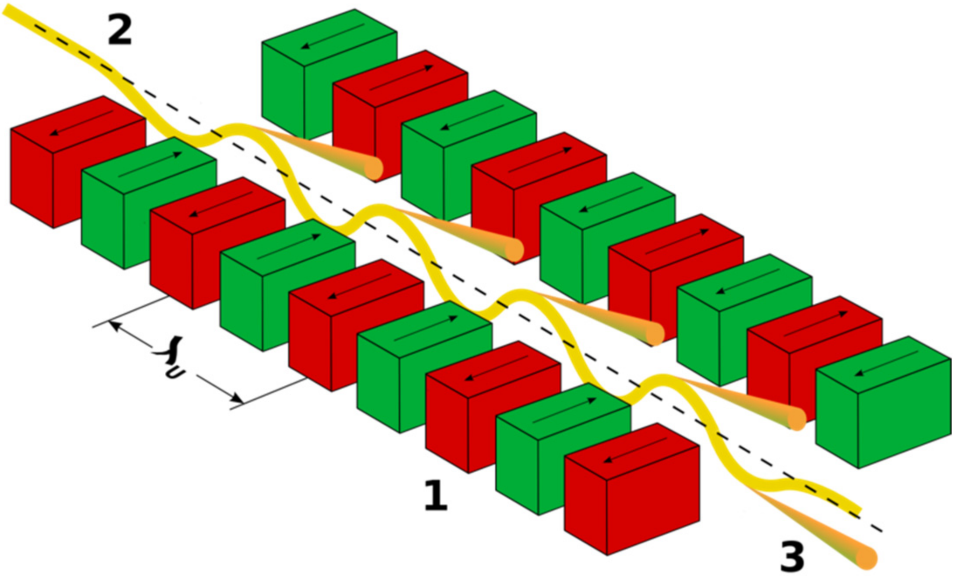


J. Faure et al.



S.P. D. Mangles et al.

LWFA as coherent radiation source?



Radiation brightness:

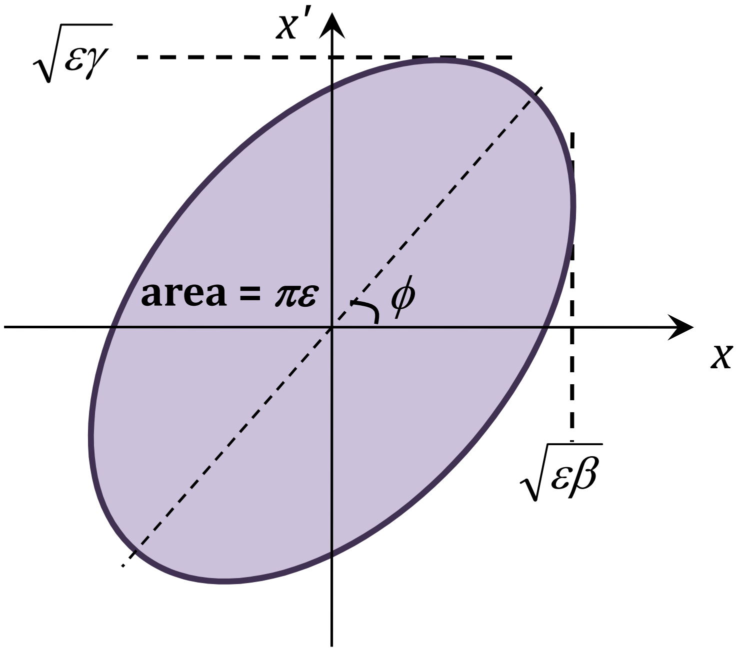
$$B = \frac{I}{4\pi^2 \varepsilon_x \varepsilon_y}$$

Radiation coherence:

$$\varepsilon_{x,y} \leq \frac{\lambda_{rad}}{4\pi}$$

Beam emittance

Phase space ellipse

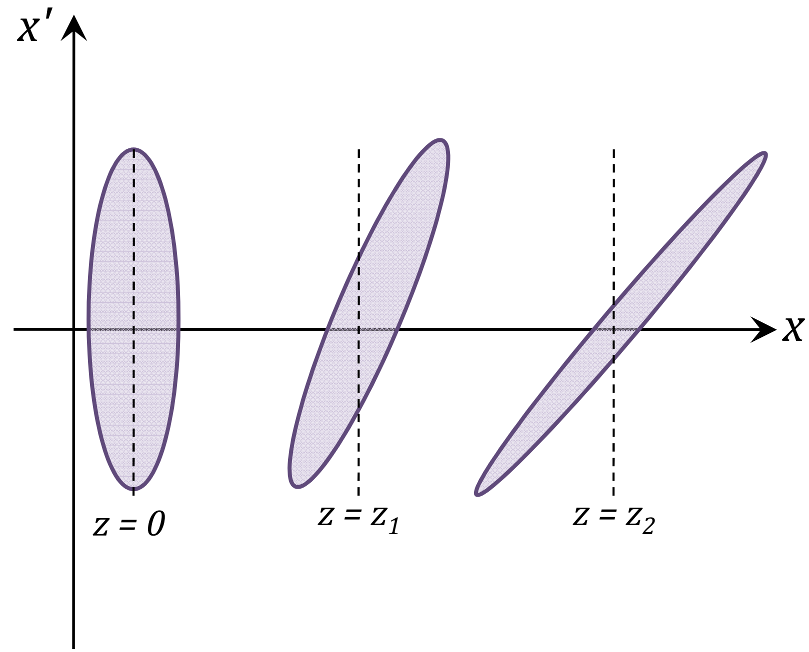


$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon$$

α, β, γ, ε → Twiss parameters

$$\tan(2\phi) = \frac{2\alpha}{\gamma - \beta} \qquad \gamma = \frac{1+\alpha^2}{\beta}$$

Transformation of phase ellipse for different locations in a drift space



The shape and orientation of the ellipse changes but the area is the same (Liouville Theorem)

Beam emittance

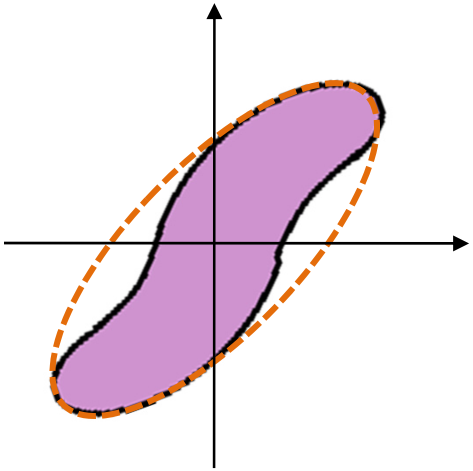
Emittance as the area of trace space:

$$\int_{ellipse} dx\,dx' = \pi\varepsilon$$

Emittance as a beam quality:

$$\varepsilon_{rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

- $\langle x^2\rangle$ → rms beam width
- $\langle x'^2\rangle$ → rms beam divergence
- $\langle xx'\rangle$ → correlation between x & x' (~zero at the beam waist)



Other definitions of emittance:

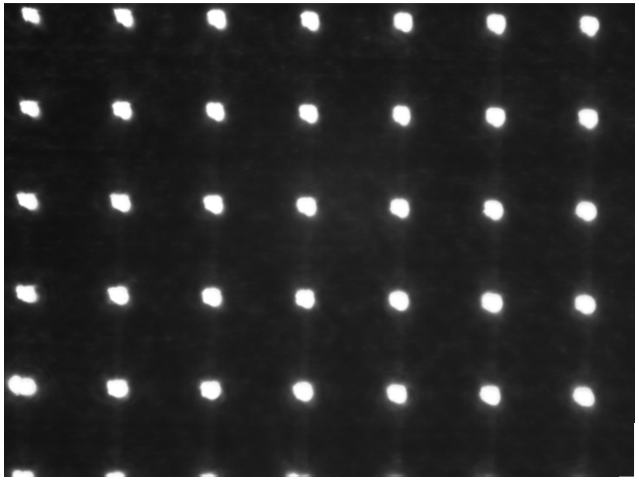
$$\varepsilon_{norm} = \gamma\beta_z\varepsilon$$

where: $\beta_z = v_z / c \qquad \gamma = \dfrac{1}{\sqrt{1-\beta_z^2}}$

$$\varepsilon_{rms} = 4\varepsilon$$

[Lapostelle's definition]

Pepper-pot emittance measurement

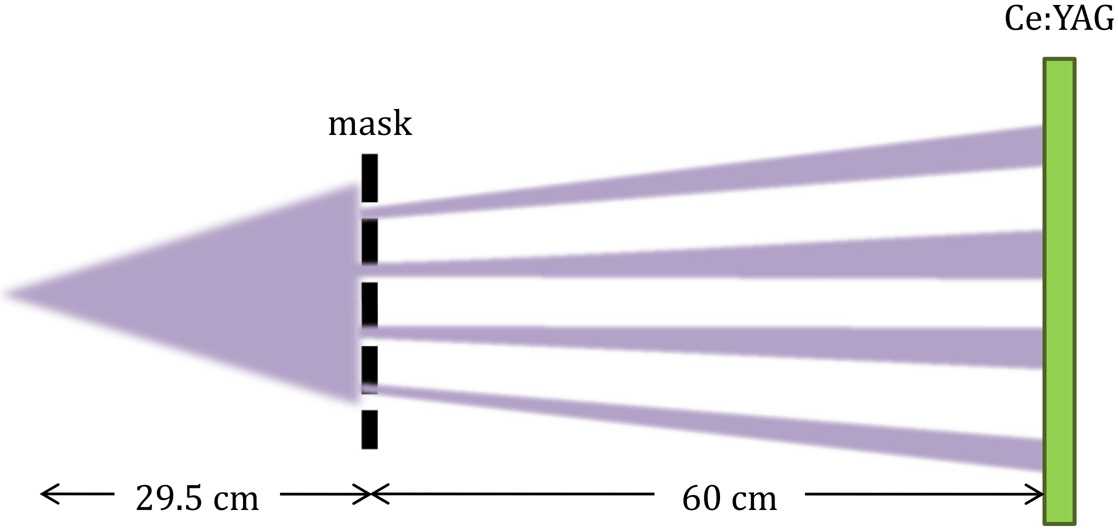

Transmission light image of the tungsten sheet

Pepper-pot mask:

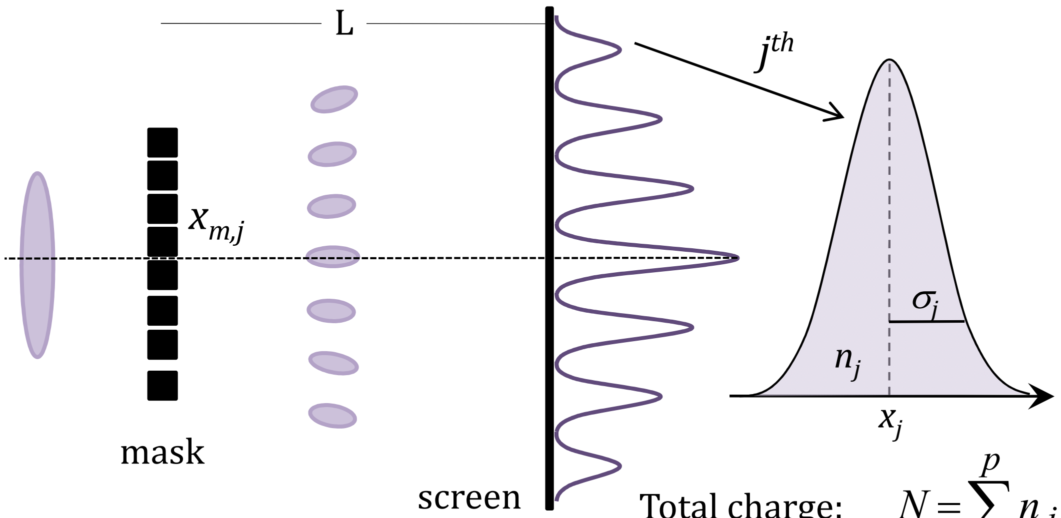
- tungsten sheet
- 27 x 27 grid
- 25 ±5 μm diameter
- 150 μm separation distance

Detector:

- Ce:YAG screen
- Coupled with a 14-bit CCD camera
- 10 μm resolution



Pepper-pot emittance measurement



Total charge: $N = \sum_j^p n_j$

$$\varepsilon_{rms} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

$$\langle x^2 \rangle = \frac{1}{N^2} \sum_j^p n_j (x_{mj} - \bar{x})^2$$

$$\langle x'^2 \rangle = \frac{1}{N^2} \sum_j^p n_j \left[\sigma_{j,x'}^2 + (x_{mj} - \bar{x})^2 \right]$$

$$\langle xx' \rangle^2 = \frac{1}{N^2} \left[\sum_j^p n_j x_j x'_j - N\bar{x}\bar{x}' \right]^2$$

In all beamlets:

Mean position:

$$\bar{x} = \sum_j^p n_j x_{m,j}$$

Mean divergence:

$$\bar{x}' = \sum_j^p n_j \bar{x}'_j$$

In j^{th} beamlet:

Mean divergence:

$$\bar{x}'_j$$

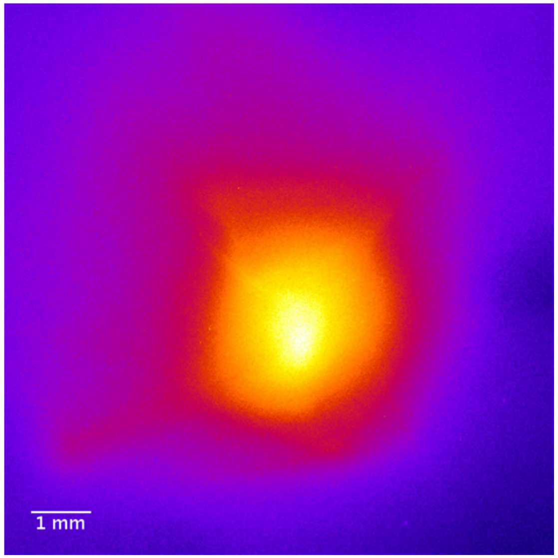
rms divergence:

$$\sigma_{j,x'} = \frac{\sigma_j}{L}$$

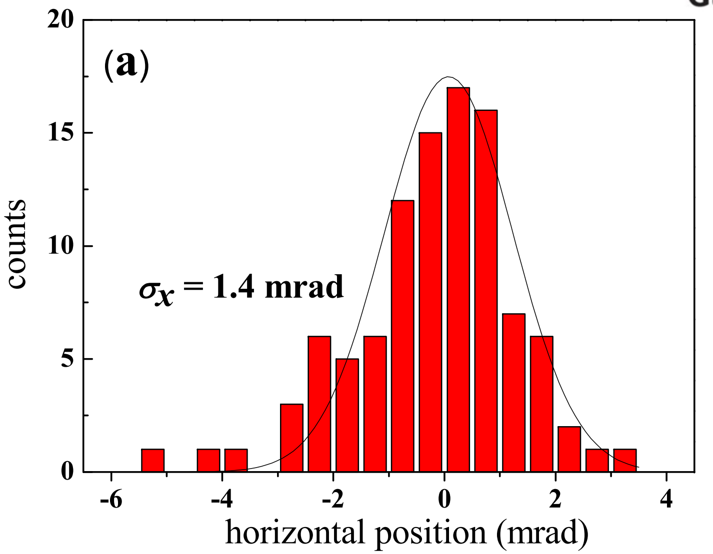
Advantages of pepper-pot method

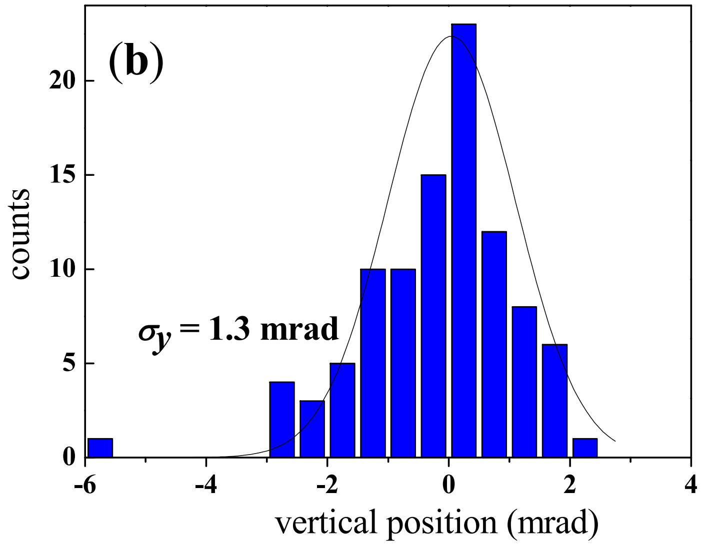
- Single shot measurement
- Less prone to space charge effect
- Can obtain x and y emittance at one measurement

Stability of the electron beam



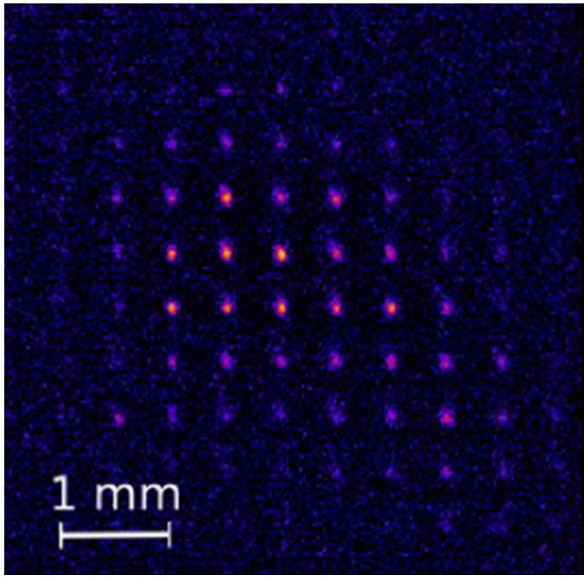
Electron beam as seen in the Ce:YAG screen



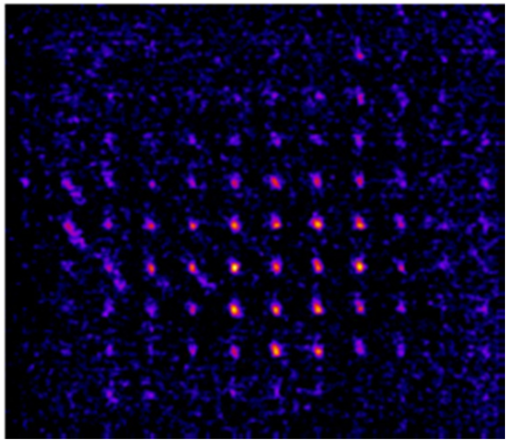


The electron beam has a good pointing stability (the deviation is less than one spot size)

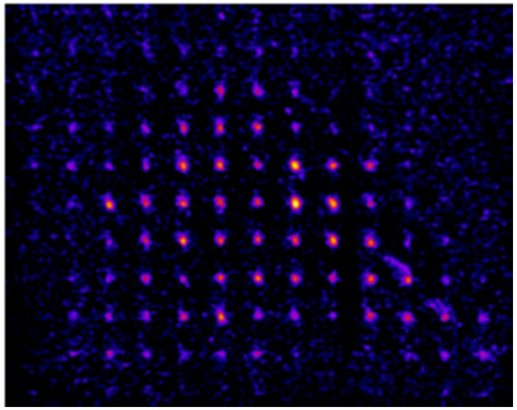
Transverse emittance measurement



$\varepsilon_{n,x}$ = 1.9 π-mm-mrad
$\varepsilon_{n,y}$ = 1.8 π-mm-mrad



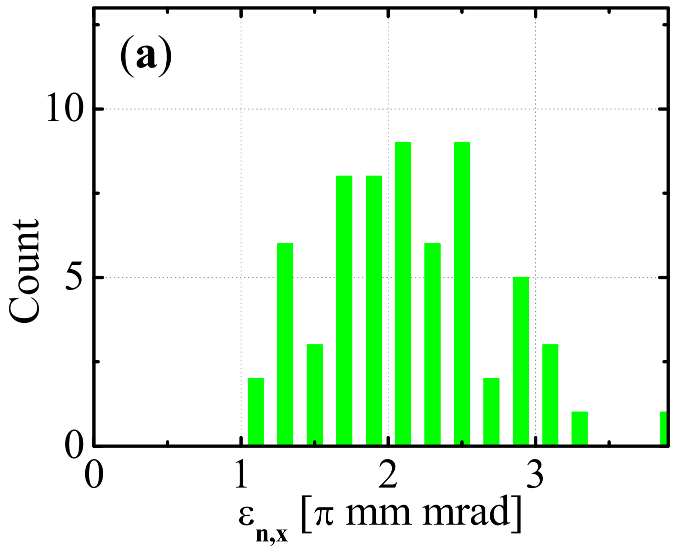
$\varepsilon_{n,x}$ = 1.3 π-mm-mrad
$\varepsilon_{n,y}$ = 1.5 π-mm-mrad

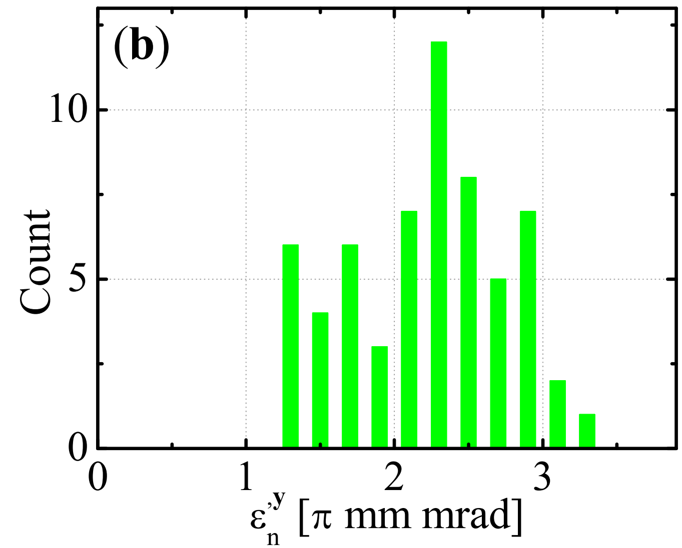


$\varepsilon_{n,x}$ = 2.2 π-mm-mrad
$\varepsilon_{n,y}$ = 2.5 π-mm-mrad

Transverse emittance measurement

- 64 out of 400 consecutive shots were measured



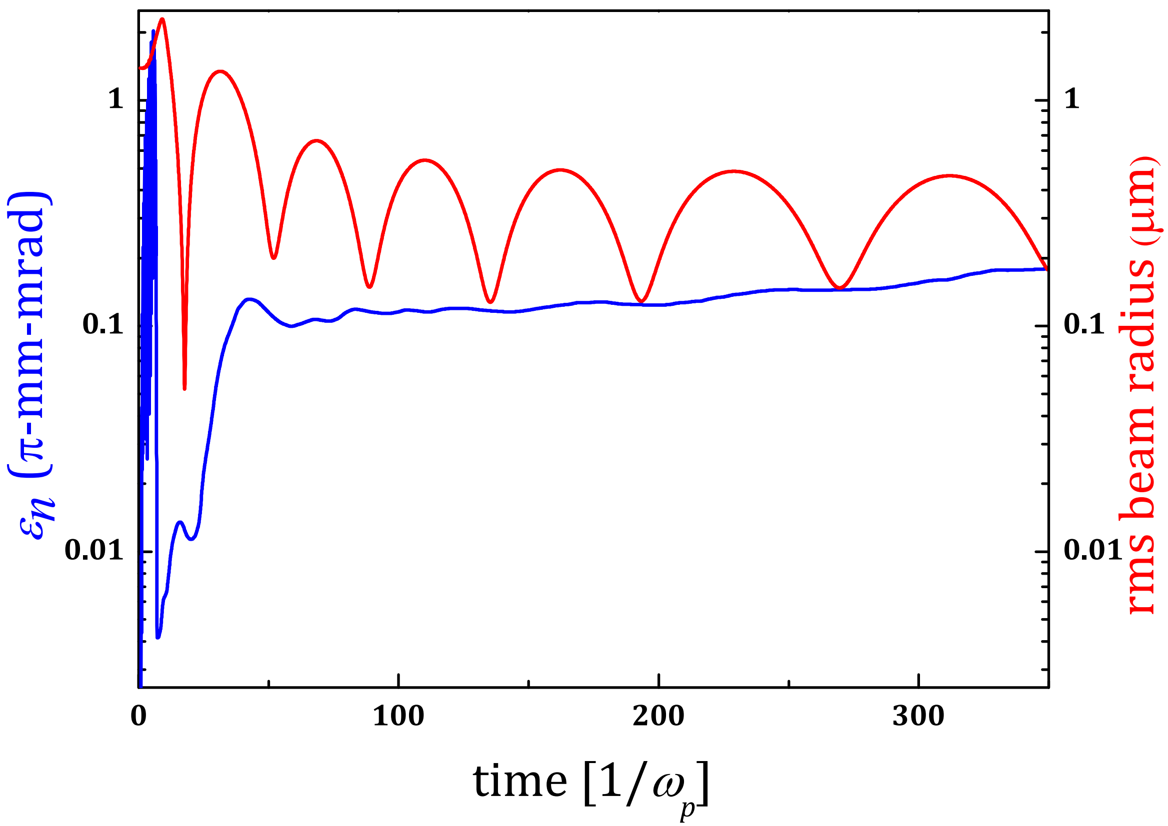


2.2 ± 0.7 π-mm-mrad

2.3 ± 0.6 π-mm-mrad

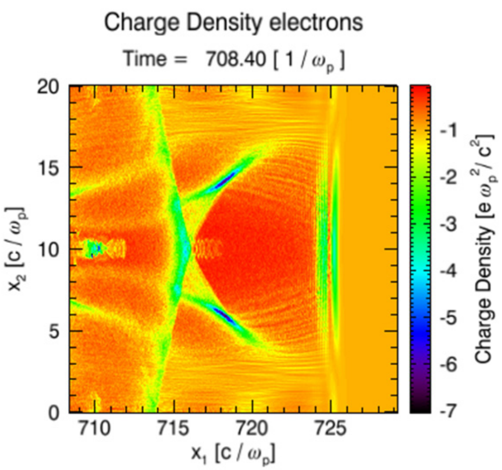
E. Brunetti et al. ***PRL****, 105, 215007(2010)*

2D PIC code OSIRIS simulation

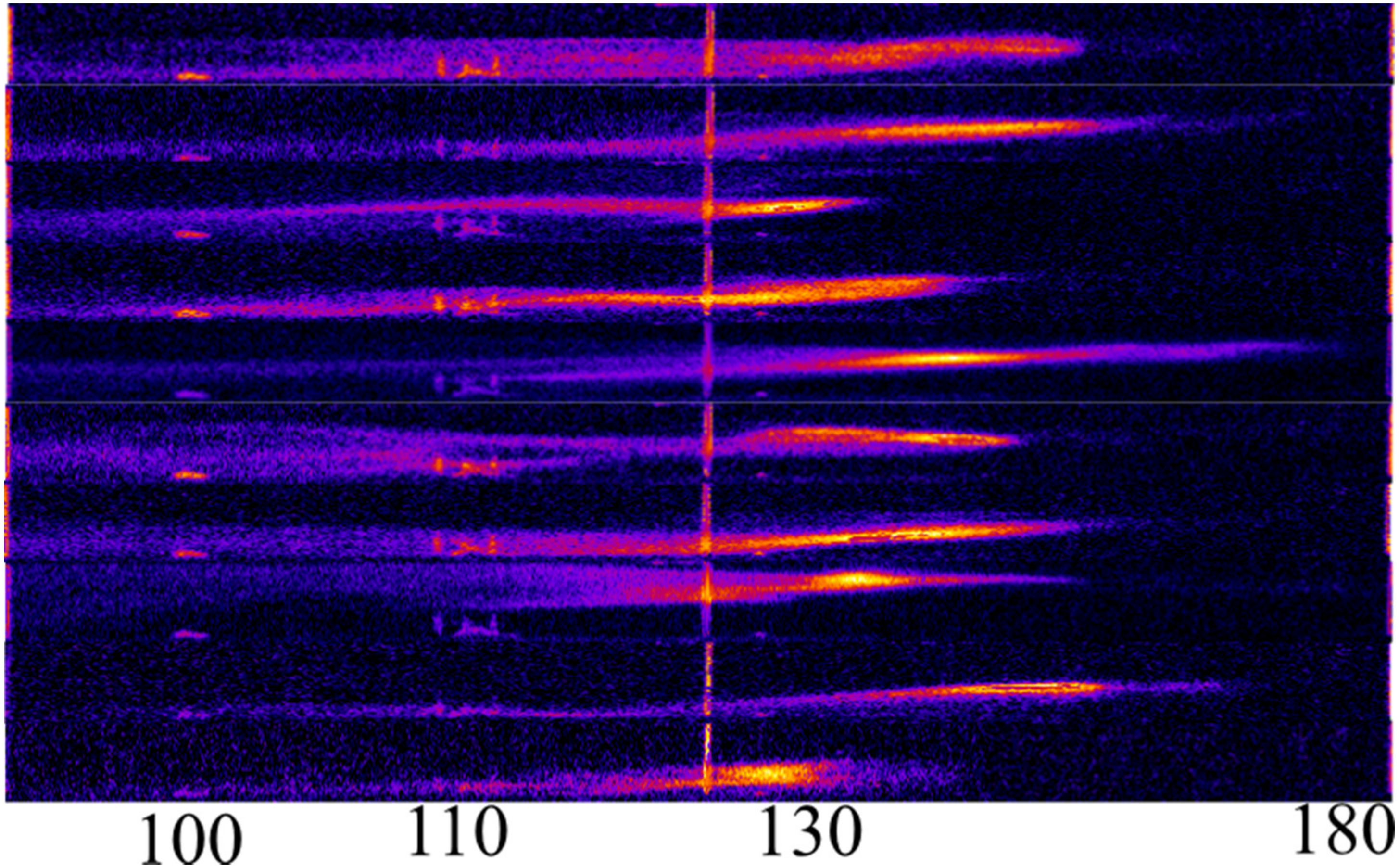


Time evolution of normalised transverse emittance and beam radius of the electron bunch

The emittance growth is dictated by the transverse forces acting on the electron before and during the capture in the plasma 'bubble.'

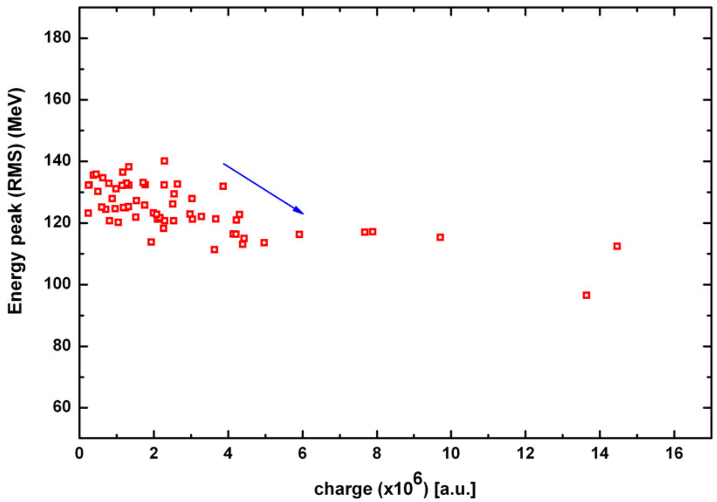


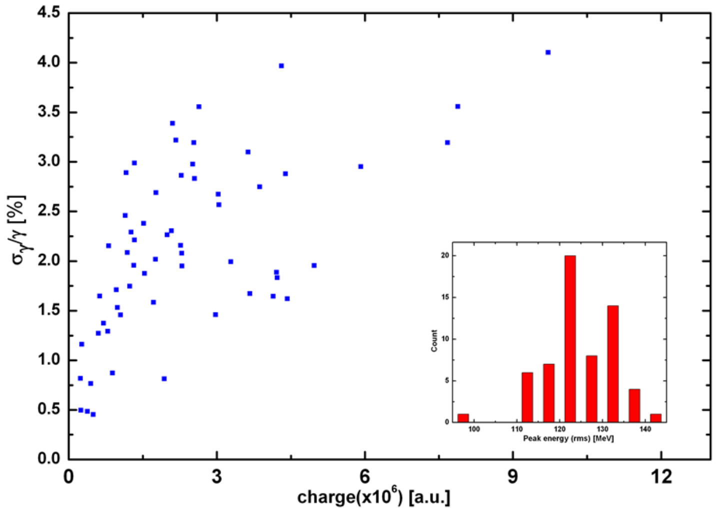
Electron beam's energy spectra



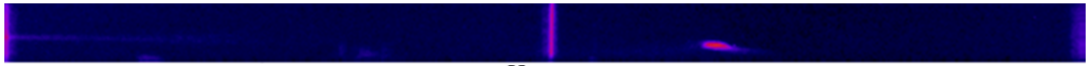
Electron's energy (MeV)

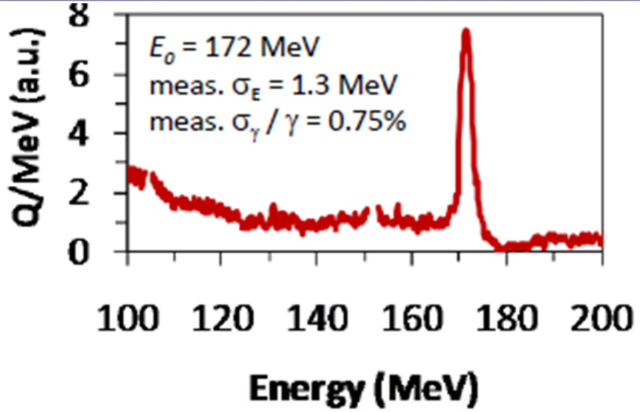
Electron beam's energy spectra

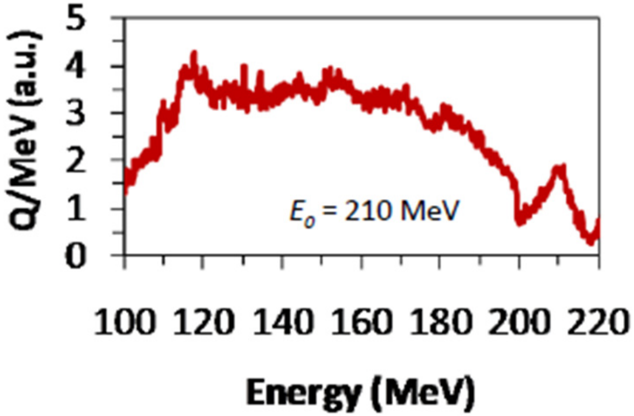


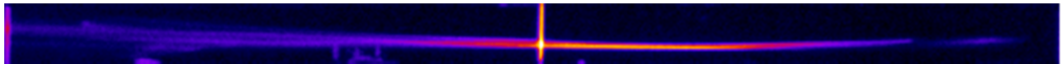


- Beam loading effect
- There seems to be scaling of energy spread and central energy to charge









M. Wiggins et al., ***PPCF*** *52, 124032 (2010).*

Summary

- Transverse emittance and energy spread were measured to characterised the electron beam from laser wakefield accelerator.
- The normalised emittance is $\varepsilon_{n,x,y}$ = 2.2 ± 0.7, 2.3 ± 0.6 π-mm-mrad, which is comparable to that of a linear accelerator (measurement was resolution limited).
- Central energy and energy spread shows scaling with the charge.
- The brightness for this accelerator is approximately equal to:

$$B \approx 5\times10^{15}\ \mathrm{Am^{-1}rad^{-1}}$$

which is suitable for driving a compact coherent radiation FEL .

EPSRC Engineering and Physical Sciences Research Council