The Production of High Quality Electron Beams in the ALPHA-X Laser Wakefield Accelerator

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- ALPHA-X project
- Motivation: quality electron beams and light sources
- The ALPHA-X beam line: experimental setup
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  energy stability, charge, energy spread, transverse emittance

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- Summary

ALPHA-X Project

Advanced Laser Plasma High-energy Accelerators towards X-rays

- Basic Technology grant (2002) and EPSRC grant (2007)
- Consortium of U.K. research teams (Stage 2)

ALPHA-X

U. Strathclyde
D. Jaroszynski
B. Bingham
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P. McKenna

U. St. Andrews
A. Cairns

U. Dundee
A. Gillespie

U. Abertay Dundee
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Cockcroft Institute
M. Poole
R. Tucker

Science & Technology Facilities Council
ASTeC
LANCASTER UNIVERSITY

Partners – L. Silva & T. Mendonca (IST), B. Cros (UPS - LPGP), W. Leemans (LBNL), B. van der Geer & M. de Loos (Pulsar Phys), G. Shvets (UTA), J. Zhang (CAS)

And numerous collaborators

ALPHA-X Project

University of Strathclyde Glasgow

Group Leader: Prof. Dino Jaroszynski

Experiments: Riju Issac, Gregor Welsh, Enrico Brunetti, Gregory Vieux
PhDs: Richard Shanks, Maria Pia Anania, Silvia Cipiccia, Xue Yang, Salima Abuazoum, Grace Manahan, Constantin Aniculaesei, Anna Subiel, David Grant

Theory: Bernhard Ersfeld, Ranaul Islam, Gaurav Raj, Adam Noble
PhDs: John Farmer, Sijia Chen, Yevgen Kravets

Technicians: David Clark, Tom McCanny

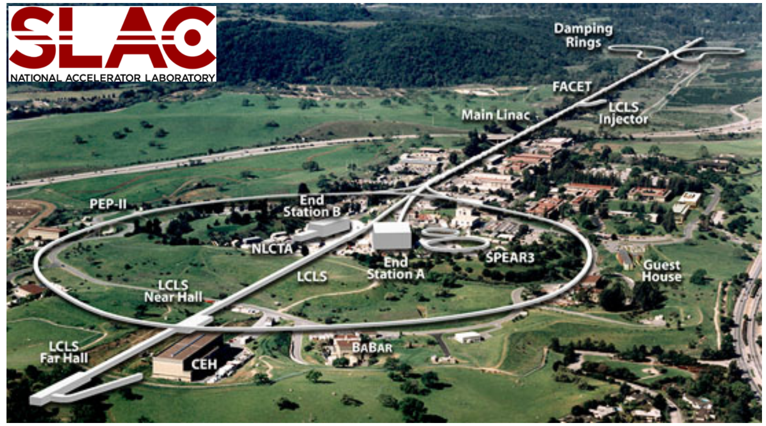
Visiting Professor: Rodolfo Bonifacio

SUPA®

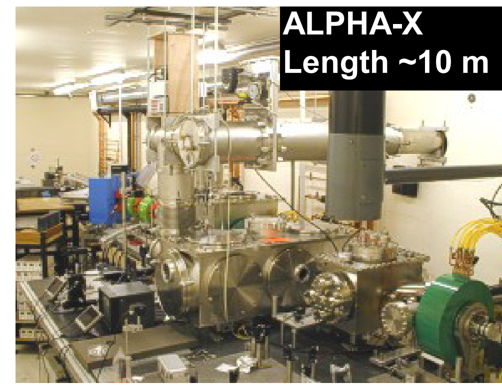
Scottish Universities Physics Alliance

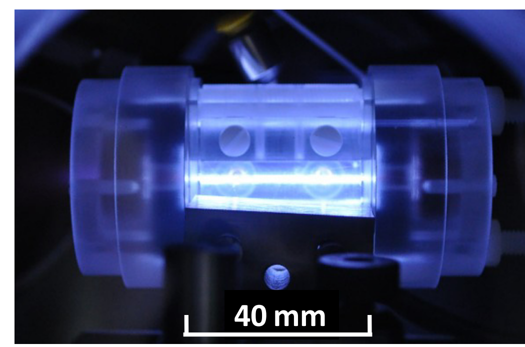
Motivation

User Facilities:
SSRL synchrotron
LCLS X-ray FEL
RF Linac:
3.2 km long
50 GeV electrons
16 MeV/m gradient



- Conventional synchrotrons and FELs are very large
- A LWFA-driven light source is ultra-compact
- Accelerating gradient ~100 GeV/m
- Great uses: short pulses, small source sizes
- Wider accessibility



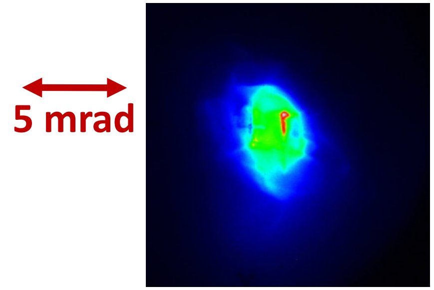


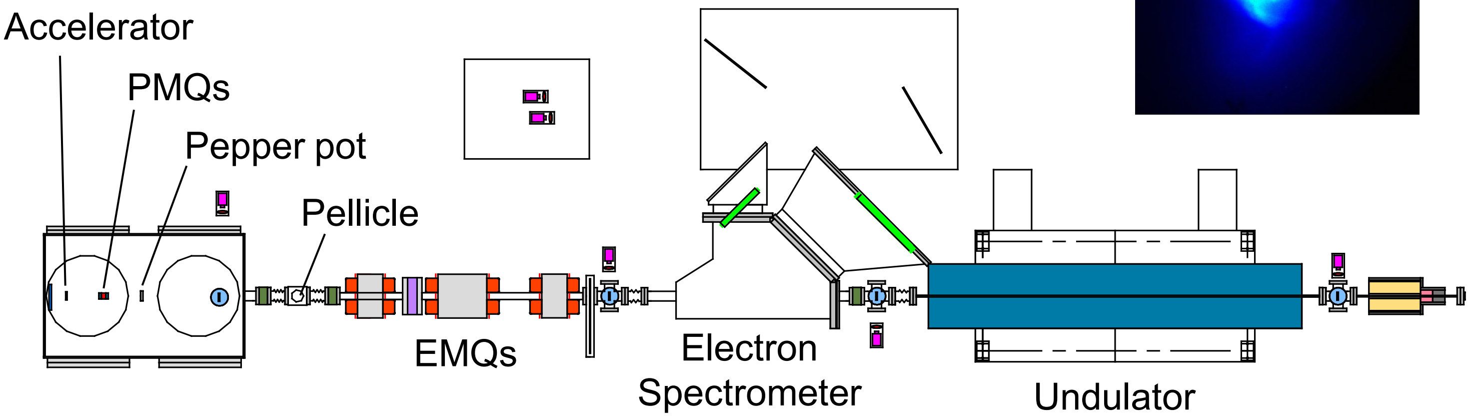
Our goal

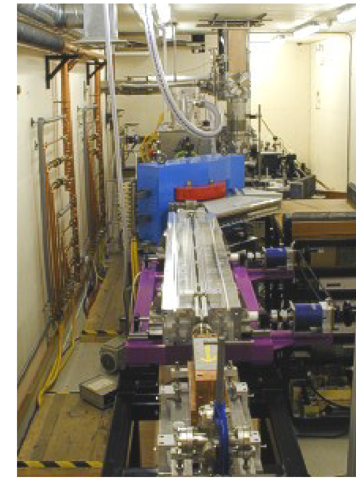
- We aim to produce high quality electron beams
  (high peak current, low ε_N , low σ_γ/γ)
  and bright radiation sources → X-ray, gamma ray
- X-ray FEL needs σ_γ/γ <0.1%

- And to apply them in useful ways:
- Medical imaging
- Ultrafast probing
- Detector development for nuclear physics
- Medical applications
  → Scottish Centre for the Application of Plasma-based Accelerators (SCAPA)

ALPHA-X Beam Line

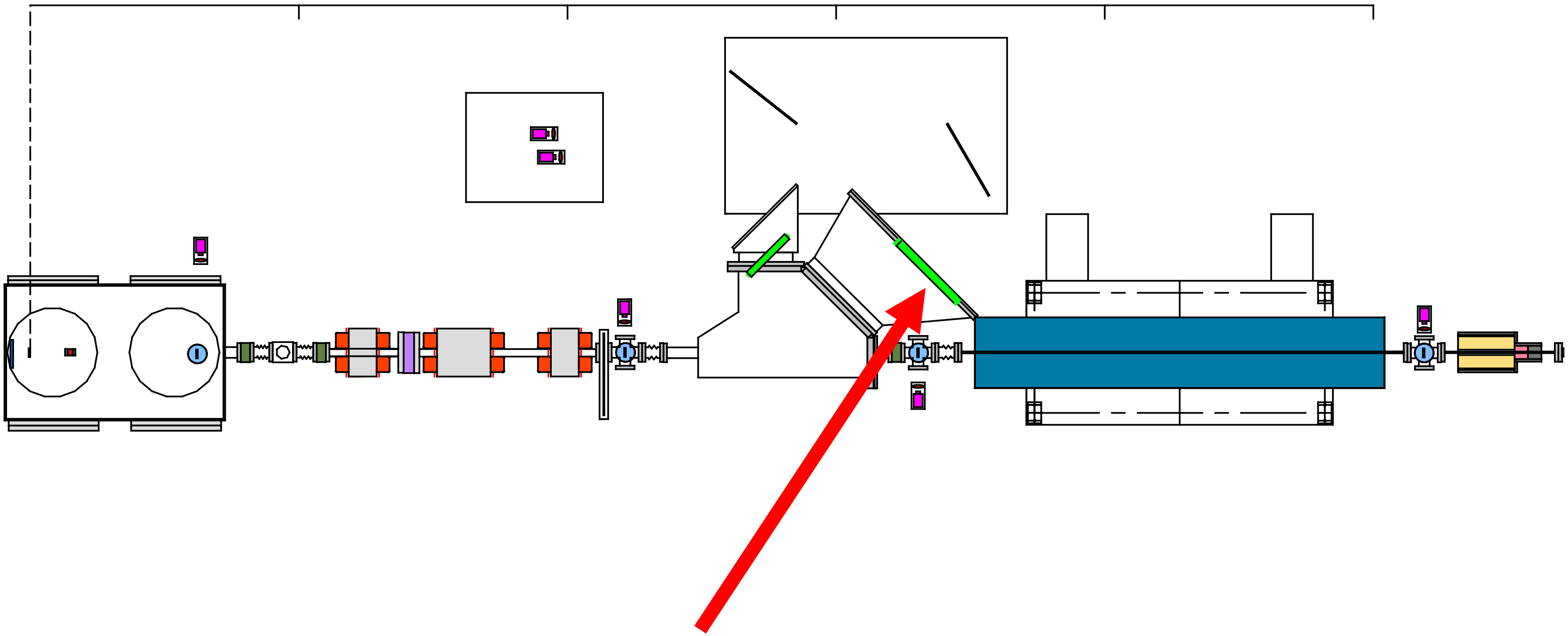




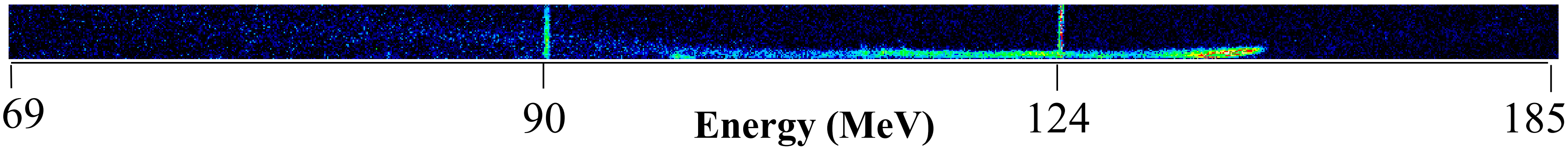


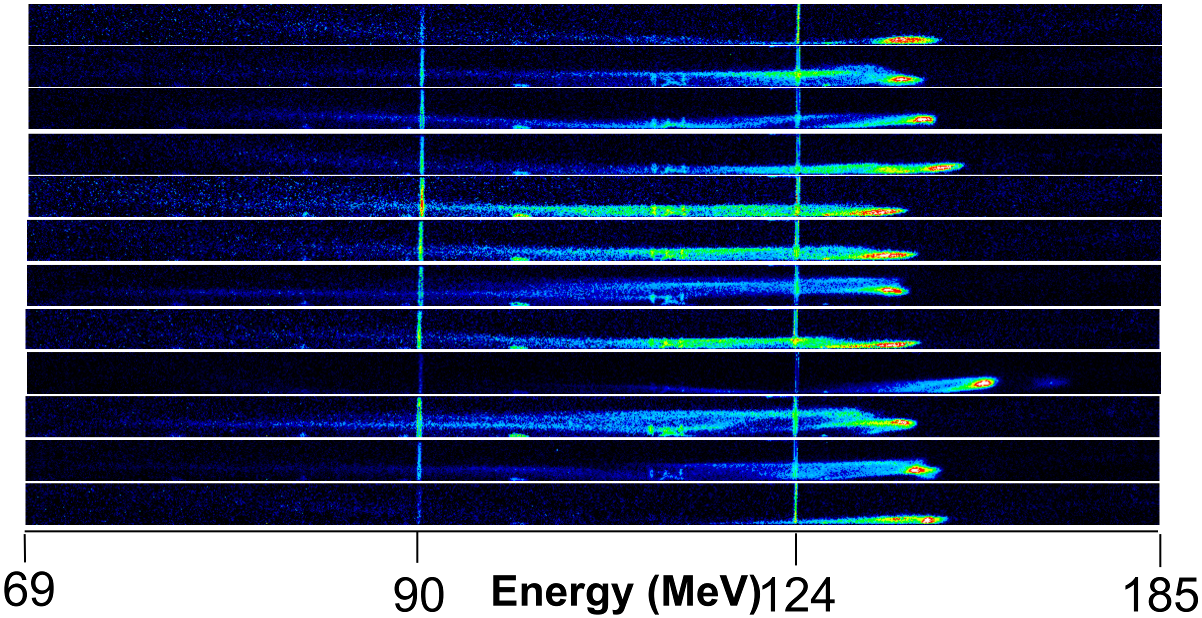
- Laser: λ_0 = 800 nm, E = 900 mJ, τ = 35 fs, P = 26 TW, $I = 2 \times 10^{18}$ Wcm^{-2}, initial a_0 = 1.0
- Gas Jet: helium, 2 mm nozzle, $n_e \approx 1 - 5 \times 10^{19}$ cm^{-3}
- Quadrupole magnets: permanent (PMQs) & electromagnetic (EMQs)
- Beam profile monitors: pop-in Lanex screens / Ce:YAG crystals
- Diagnostics: pop-in emittance mask & pop-in aluminium pellicle for transition radiation
- Imaging electron spectrometer: Ce:YAG crystals, <660 MeV with ~0.1-5% resolution

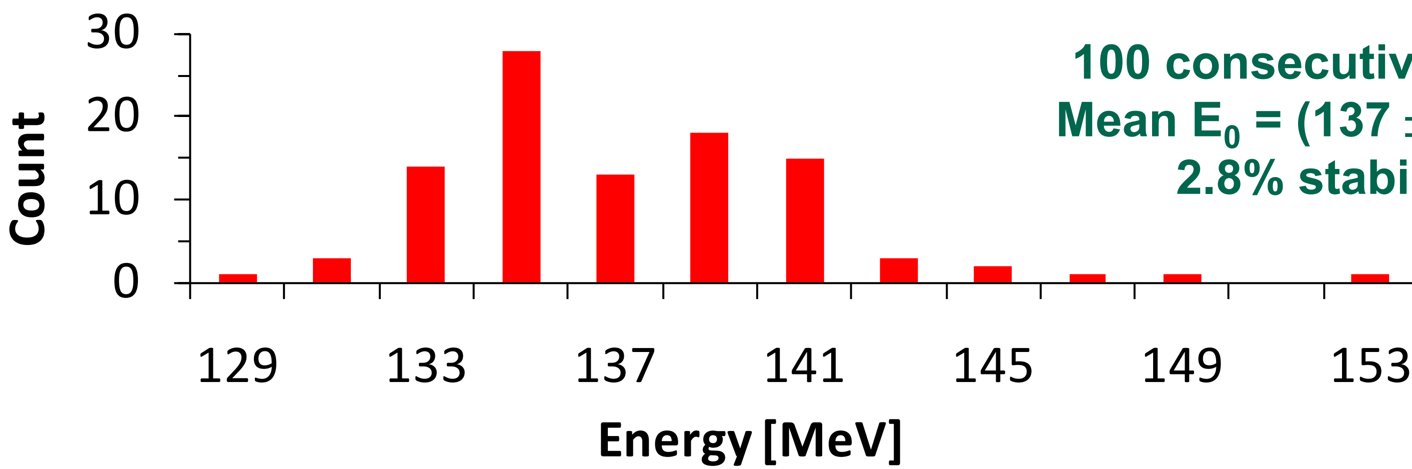
Experimental Results – energy stability



Electron Spectrometer: 200 consecutive shots (spectrum on 196 shots)

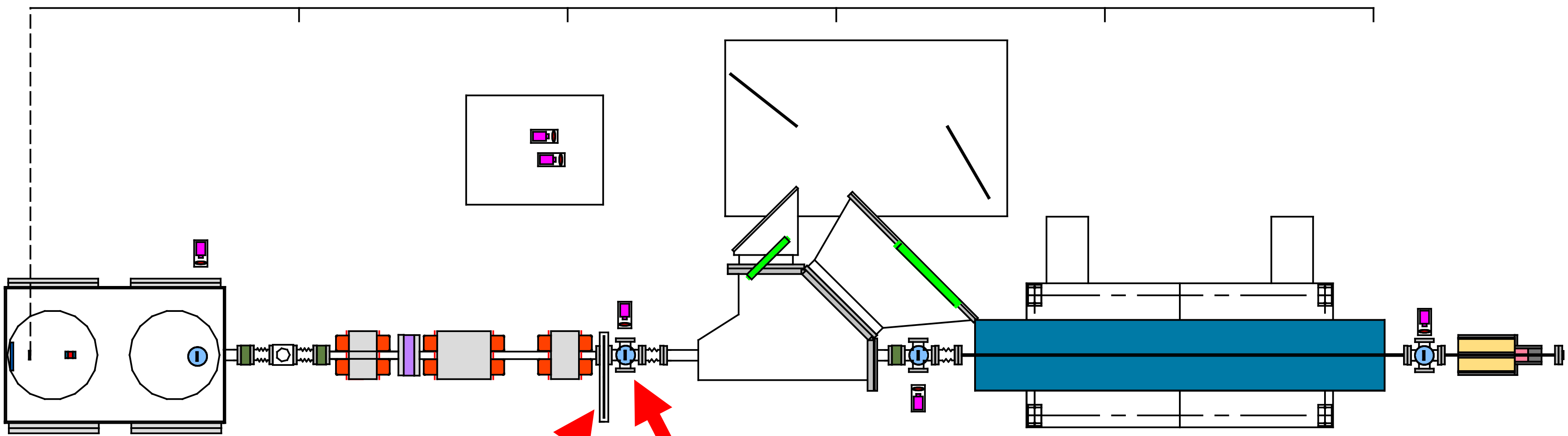


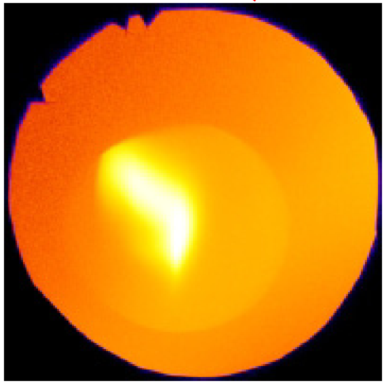




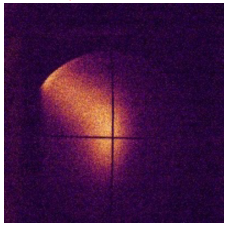
100 consecutive shots
Mean E_0 = (137 ± 4) MeV
2.8% stability

Experimental Results – charge

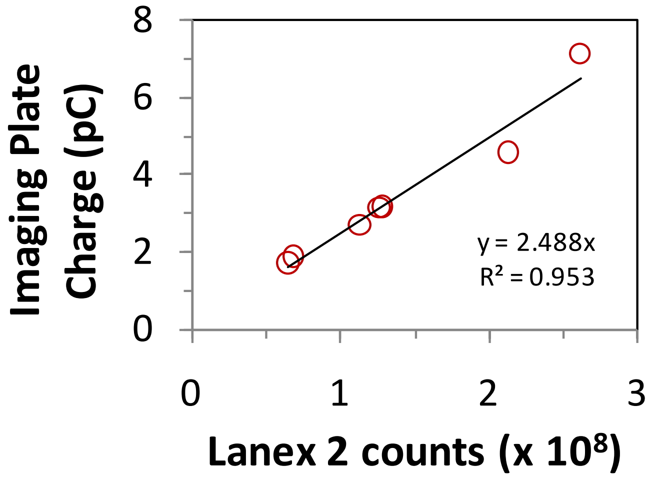




Imaging Plate

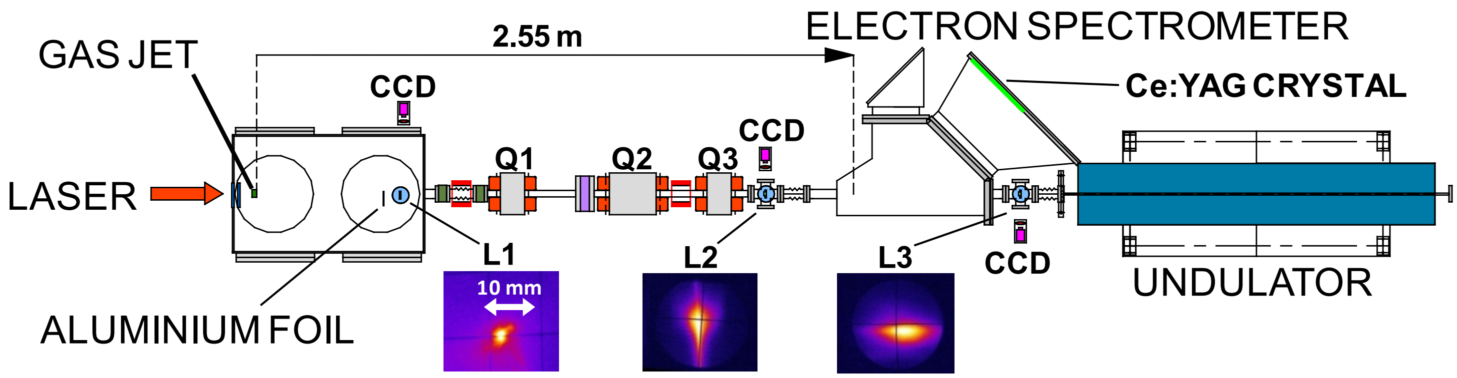


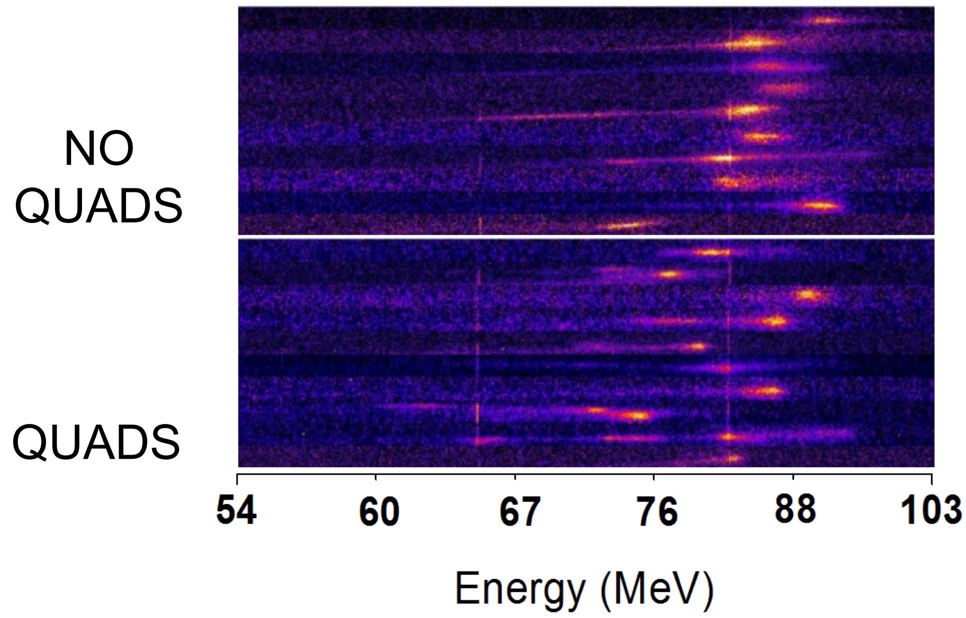
LANEX 2

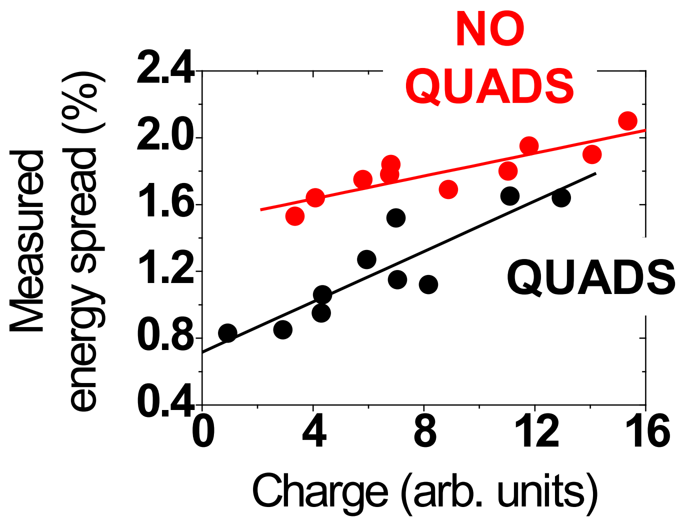


All screens now calibrated

Experimental Results – energy spectra I

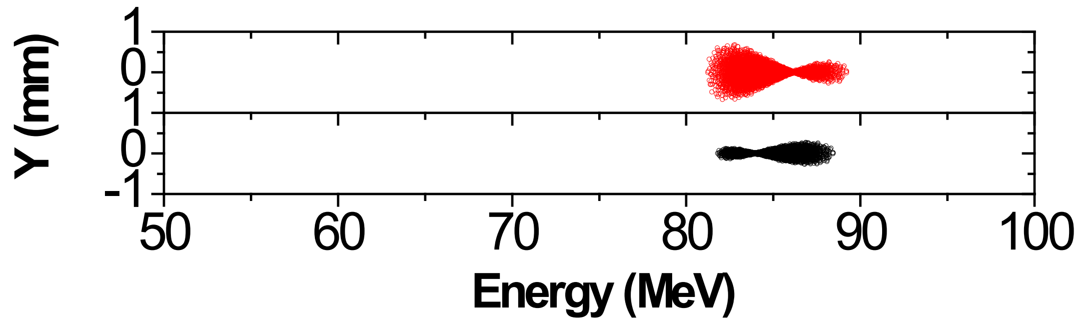




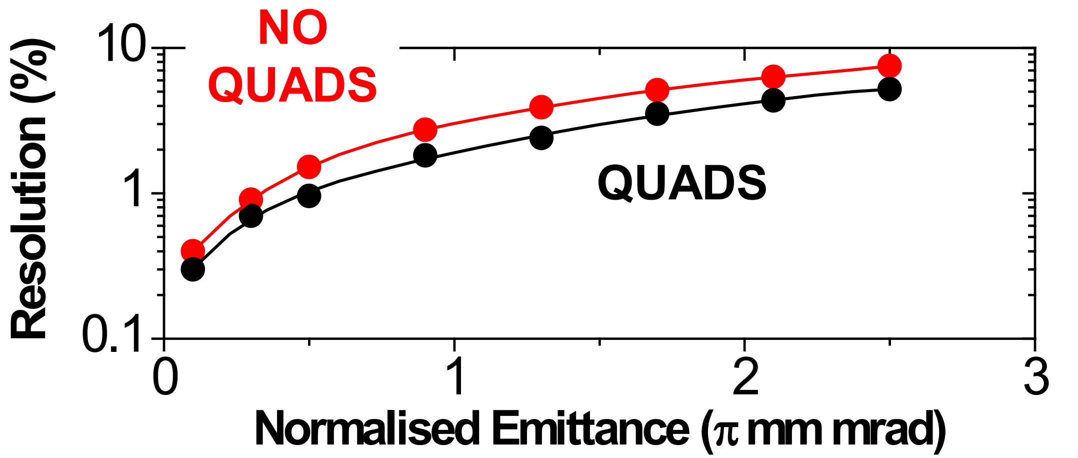


Simulations of electron spectrometer response

- General Particle Tracer (GPT) code
- Analytical B field (fringe field responsible for the butterfly profile at 0% spread)



electron beam energy = 83 MeV
r.m.s. source size = 2 μm
spectrometer field = 0.59 T
emittance ε_N = 0.5π mm mrad
zero energy spread



electron beam energy = 83 MeV
r.m.s. source size = 2 μm
spectrometer field = 0.59 T
zero energy spread

i.e. to measure small spreads, emittance must be small!

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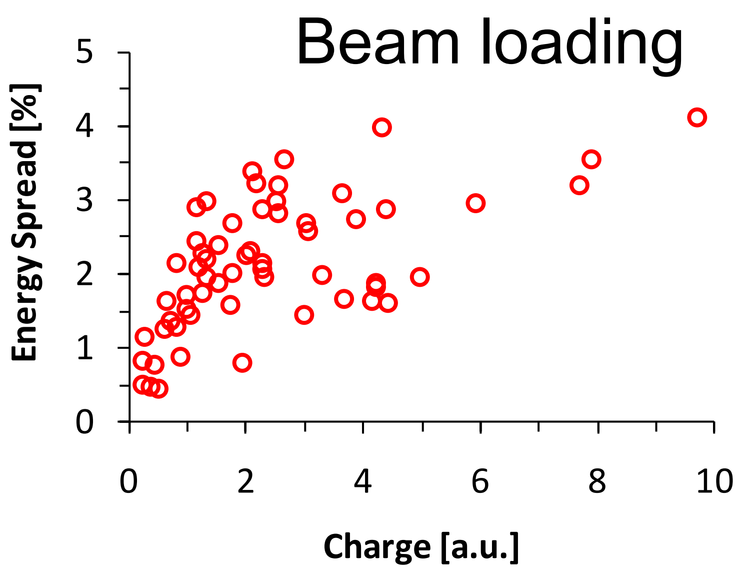
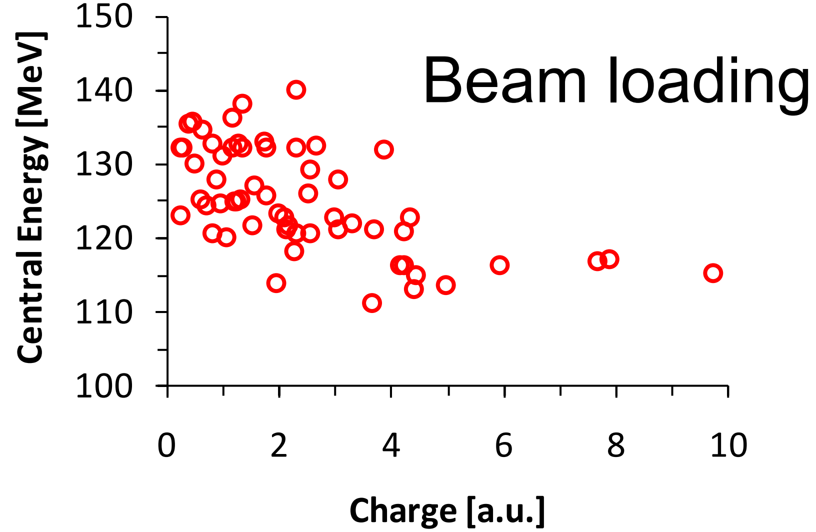
Experimental Results – energy spectra II

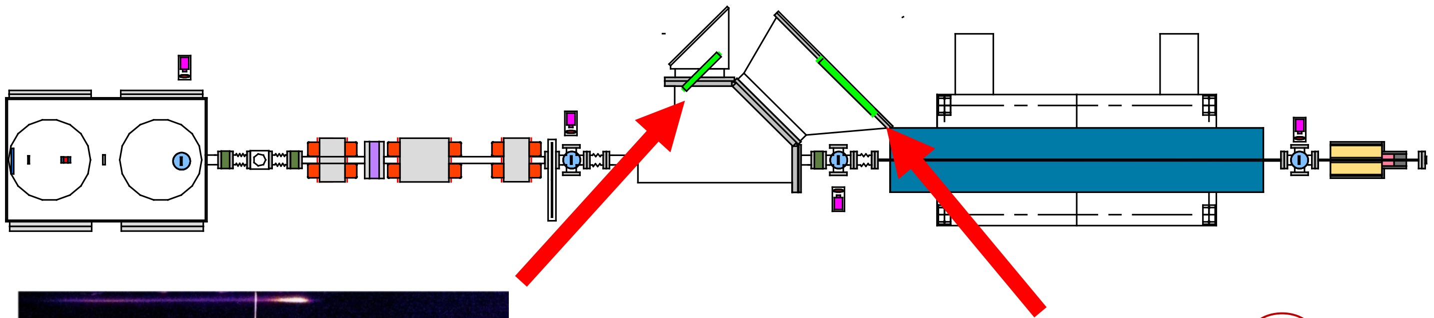
- Scaling of central energy and energy spread with charge

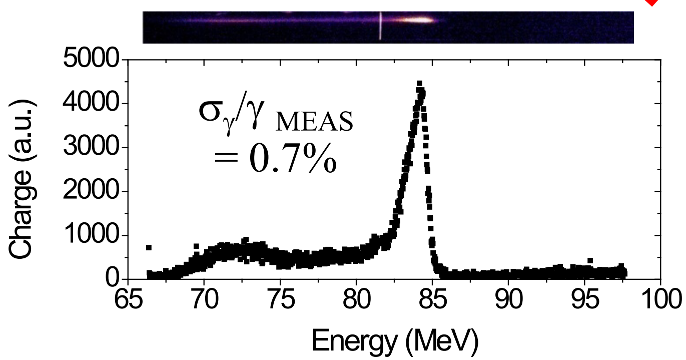


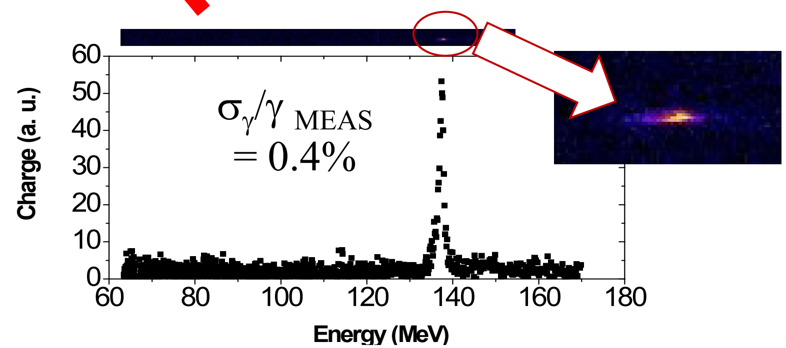


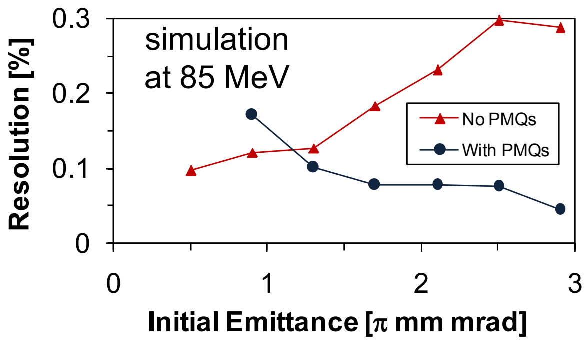
- Wiggins et al., PPCF **52**, 124032 (2010).

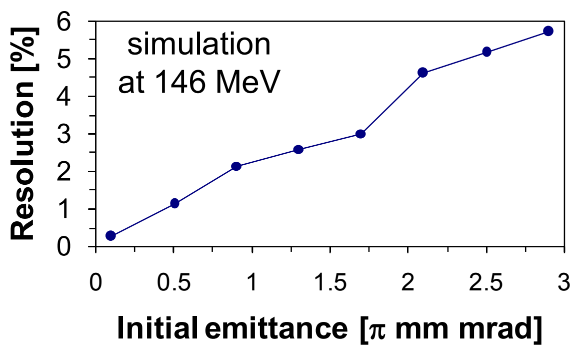
Experimental Results – energy spectra III



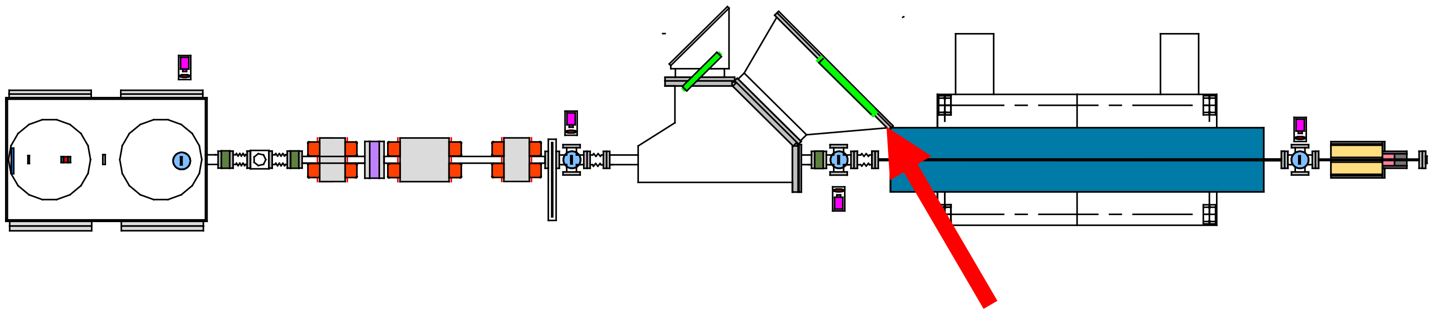


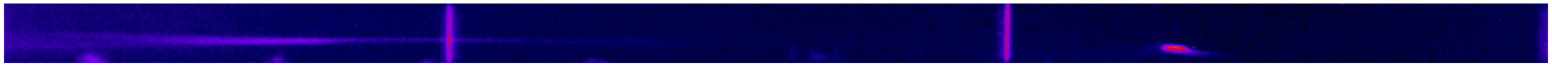


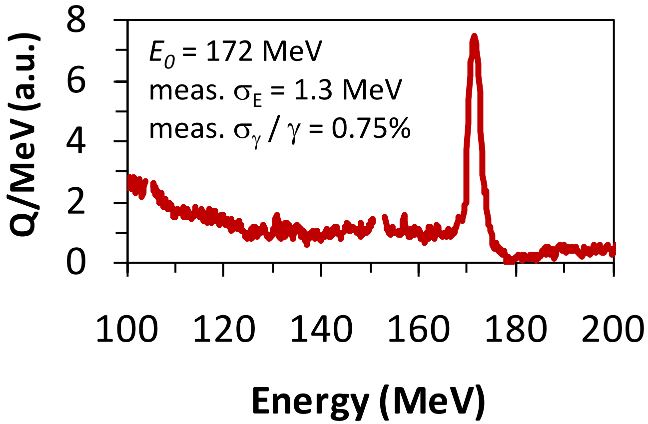


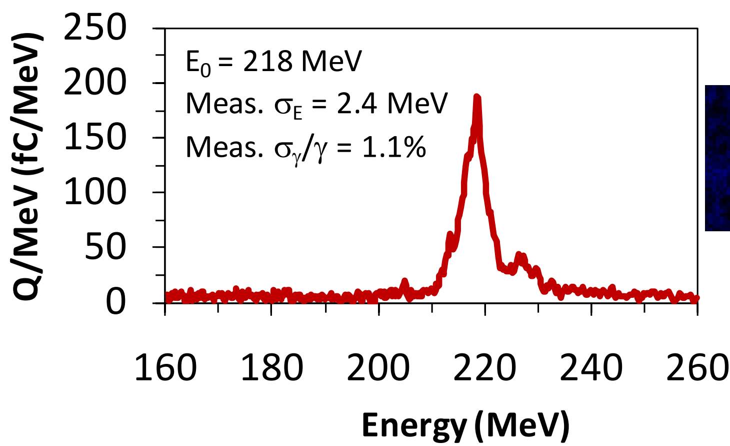


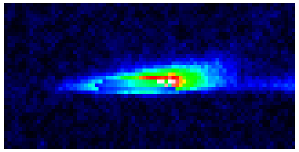
Experimental Results – energy spectra III







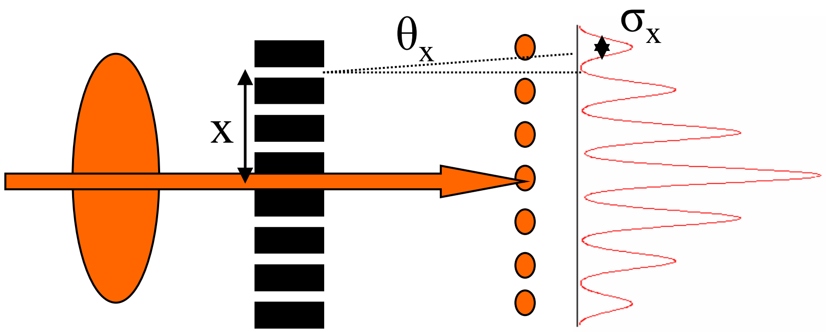


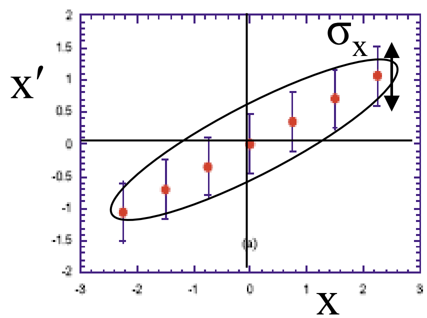


- Scaling with plasma density $E \propto n^{2/3}$
- 2 mm gas jet: accelerating gradient >1 GeV/cm at lower $n \sim 0.8 \times 10^{19}$ cm^{-3}
- Evidence of fixed absolute energy spread ~ 600-800 KeV

Experimental Results – emittance I

- Pepper pot mask technique





$\langle x \rangle \propto I^{*}x$ - averaged

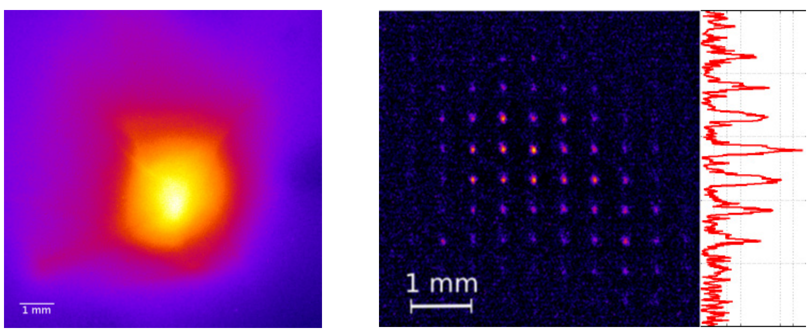
$\langle x' \rangle \propto I^{*}(\theta_x + \sigma_x)$ – averaged

Emittance (rms):

$\varepsilon_{x,\,rms} = [\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2]^{1/2}$

Direct Calculation:

(Zhang FERMILAB-TM-1988)



False colour image of an electron beam with and without the pepper-pot mask.

- divergence 2-4 mrad for this run with 125 MeV electrons
- average $\varepsilon_N = (2.0 \pm 0.6)\pi$ mm mrad
- best $\varepsilon_N = (1.1 \pm 0.1)\pi$ mm mrad
- Elliptical beam: $\varepsilon_{N,X} > \varepsilon_{N,Y}$
- Resolution limited

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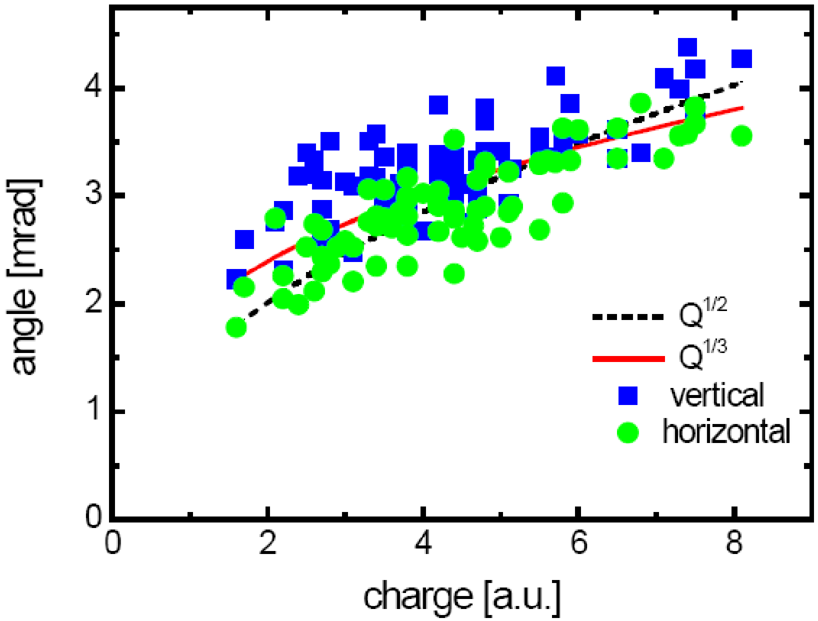
Experimental Results – emittance II

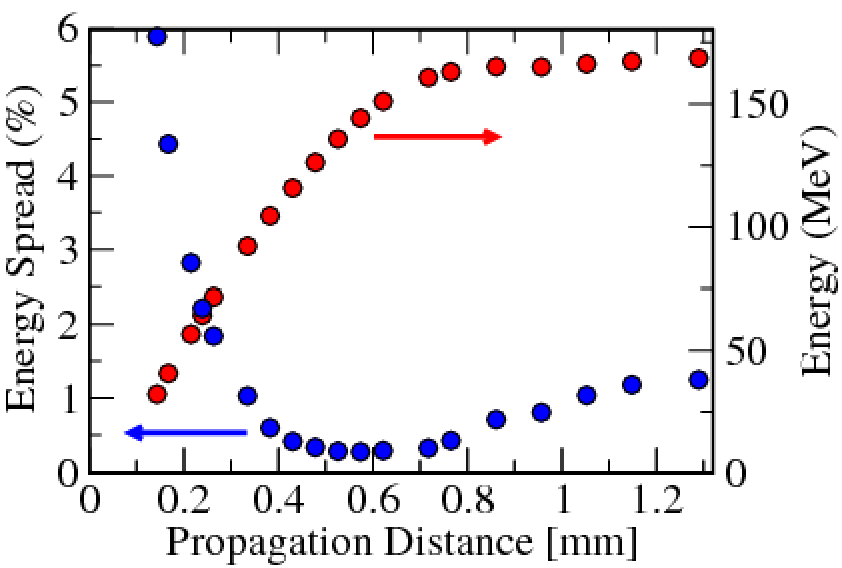


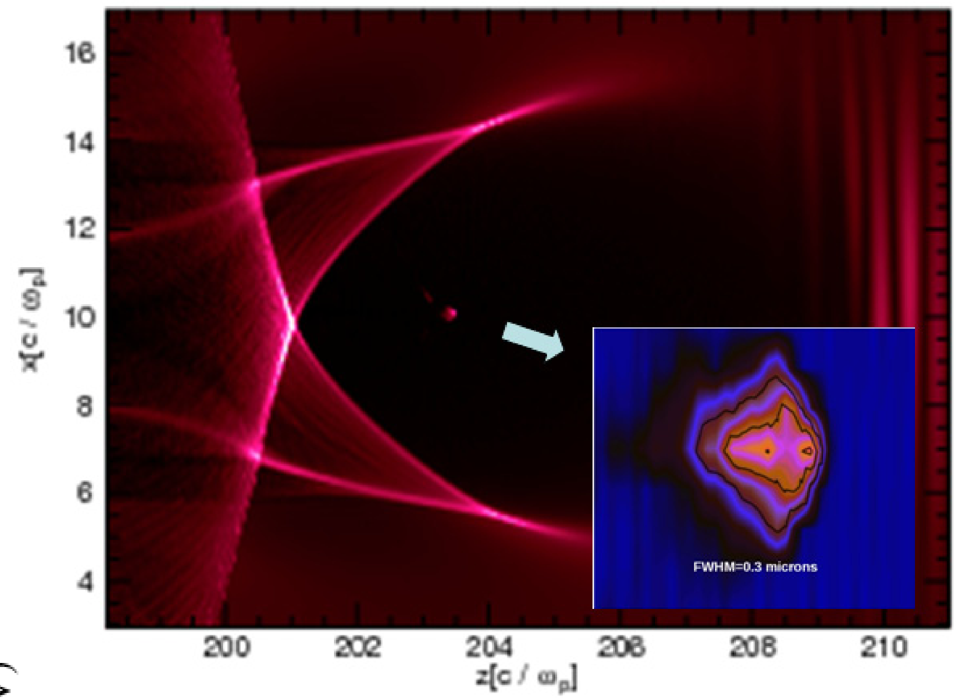
- Measured emittance consistent with ~1 fs bunch
- $\theta \propto Q^{1/2}$ scaling: implies constant σ_z
- $\theta \propto Q^{1/3}$ scaling: very slow increase of σ_z with Q

- Brunetti et al., Phys. Rev. Lett. **105**, 215007 (2010).
- Experiments with third generation mask in progress (up to 300 MeV).

PIC simulations of our LWFA

- 2D OSIRIS PIC code (IST)
- Higher initial a_0 needed to represent self-focused beam and to obtain self-injection.
- Minimal bunch degradation around dephasing length.



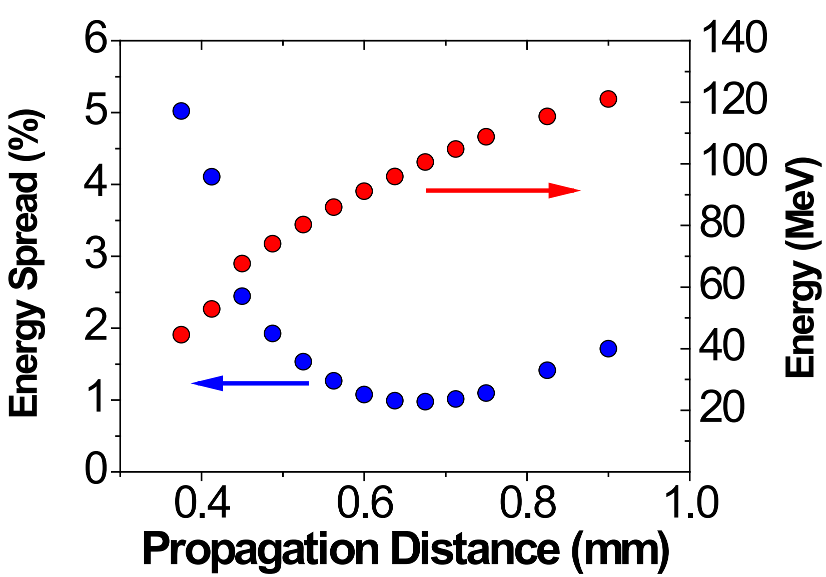


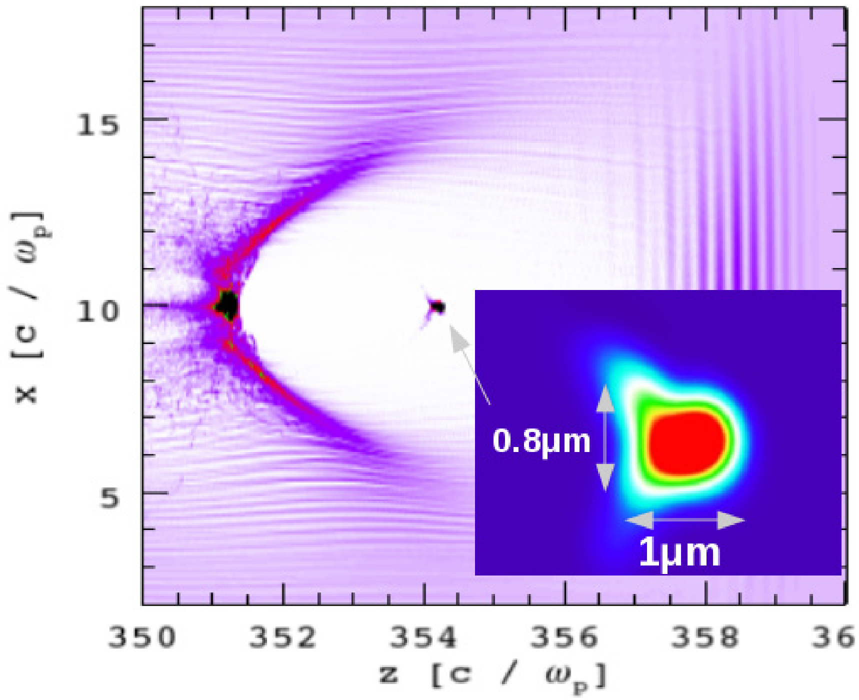
plasma density = 1.5×10^{19} cm^{-3}
laser a_0 = 3

<u>output electron bunch</u>
charge ~ 1 pC
energy spread < 1%
source size ~ 0.3 μm FWHM
emittance ~ 0.1 – 0.2π mm mrad
bunch length ~ 0.35 μm FWHM

PIC simulations of our LWFA

- 3D OSIRIS PIC code (IST)
- Demonstrates narrow energy spread production (a_0 = 1.8 → 0.7%, 4 pC).
- Experiment and simulation still to reconcile fully (sensitive to entrance density ramp, ...)



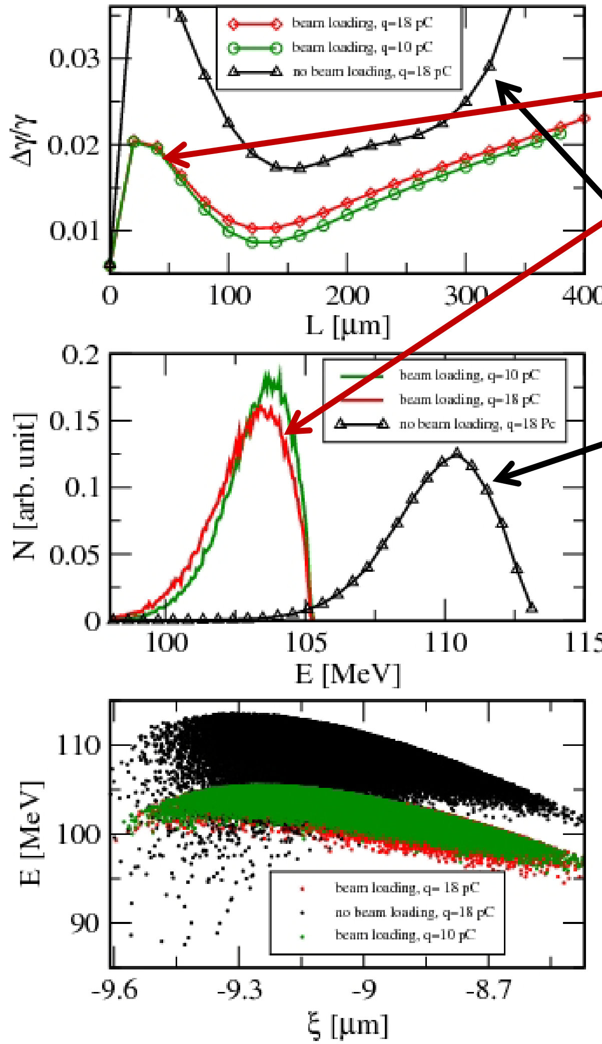


plasma density = 0.8×10^{19} cm^{-3}
laser a_0 = 2

<u>output electron bunch</u>
charge = 6 pC
energy spread ~1%
source size ~ 0.8 μm FWHM
bunch length ~ 1 μm FWHM

Beam loading simulations

- 2-D reduced model
- No self-injection (external 6 MeV beam is input)
- Optimal charge for flattening potential along beam and obtaining minimum spread



With beam loading

No beam loading

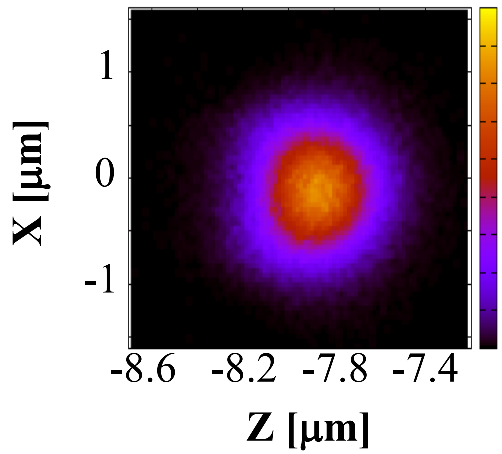
With beam loading and 10 pC change

- λ_p = 7 μm
- l_{bunch} = 1 μm

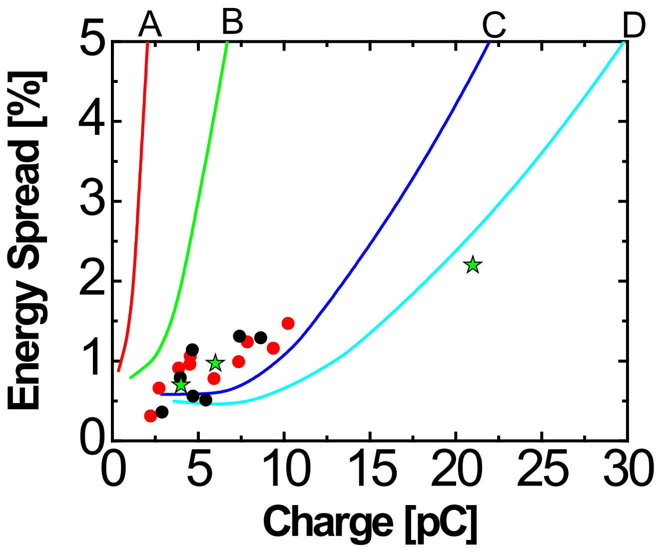
- Beam loading reduces the variation in accelerating potential along the bunch

Beam loading simulations

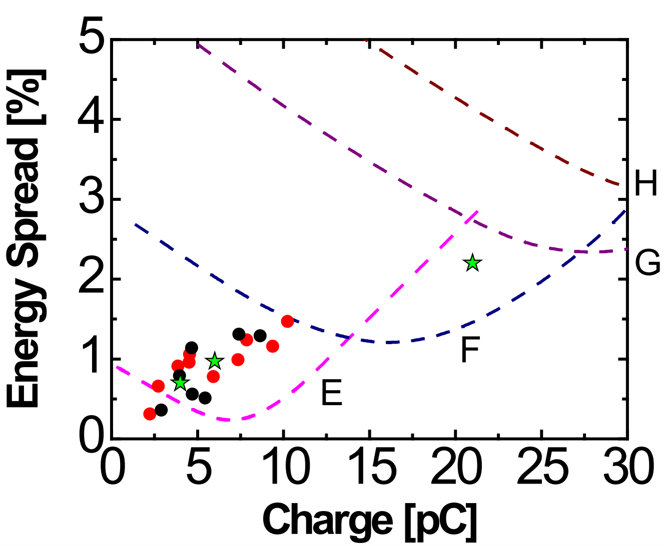
<u>Reduced model</u>
Plasma density = 1.2×10^{19} cm^{-3}
laser a_0 = 2.0
spot size = 10 μm
beam volume ~1 μm^3



Different peak currents
(A: 0.5 kA, B: 1.4 kA, C: 2.3 kA, D: 4.5 kA).
Charge variation via bunch length variation



Different initial σ bunch lengths
(H: 0.7 μm, G: 0.6 μm, F: 0.3 μm, E: 0.1 μm).
Charge variation via peak current variation



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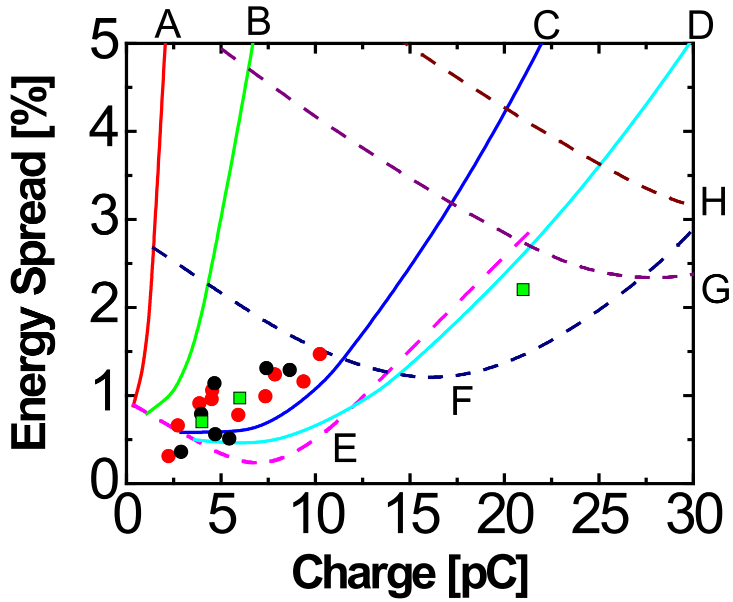
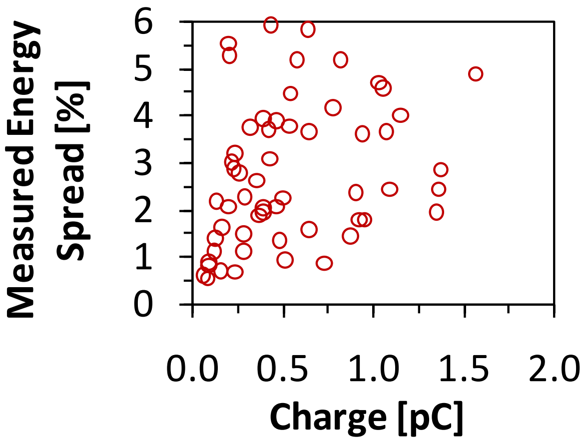
Beam loading simulations



Implies a short bunch duration σ ~1 fs
c.f. transition radiation measurements

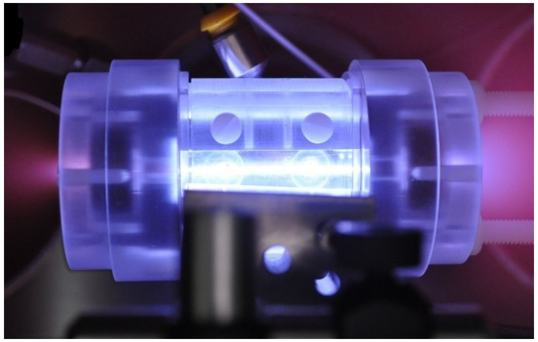
•Implies increasing bunch length for increasing charge
c.f. divergence measurements

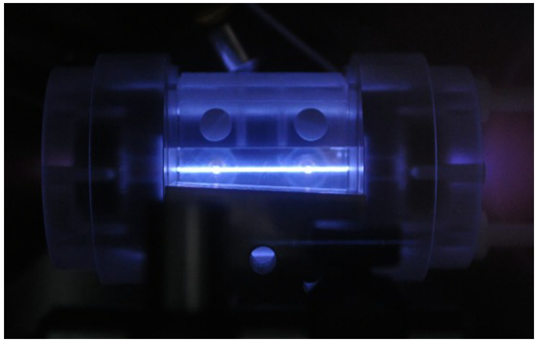


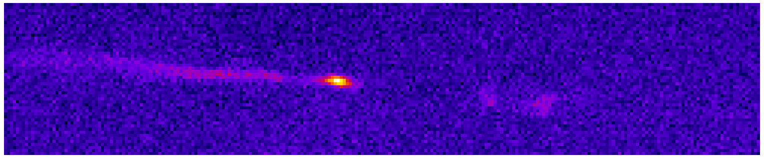
- Never observe increased energy spread at low charge!
- Demonstrates validity of reduced model.

Strathclyde capillary beams

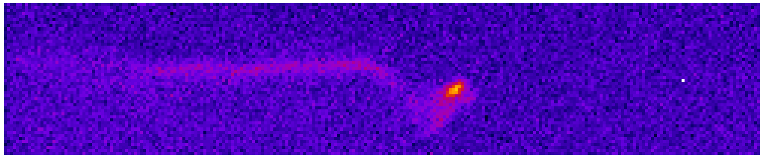
- RAL Astra Gemini experiment (X-ray and gamma-ray betatron radiation)
- 40 mm, 280 μm capillary
- Stable electron beam generation with large plasma discharge time window.
- Simple bending magnet for electron spectrum diagnostic (no focusing fields).



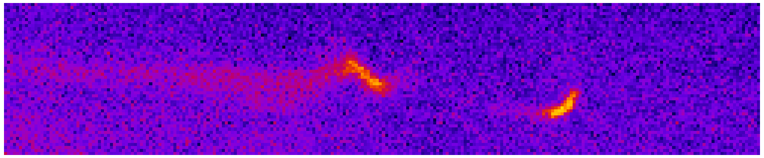




E_0 = 340 MeV, σ_γ/γ $_{MEAS}$ ~ 2.5%



E_0 = 510 MeV, σ_γ/γ $_{MEAS}$ ~ 3%



E_0 = 770 MeV, σ_γ/γ $_{MEAS}$ ~ 4%

Lanex Screen images

ALPHA-X Summary

- High quality 70 – 220 MeV electron beams produced on the ALPHA-X beam line.
- 2 mm gas jet accelerator (tunable)
- Narrow energy spread (measured < 1%)
- Low normalised transverse emittance (measured 1.1 π mm mrad)

- Energy spread, emittance, bunch length and charge are inter-connected.
- Low charge for good quality with kA peak current.

- Capillary Discharge Waveguides $\rightarrow$ 100s of MeV electron beams
- LWFA-driven FEL under development

Thank you

ALPHA-X

http://phys.strath.ac.uk/alpha-x

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EPSRC

Engineering and Physical Sciences
Research Council

Science & Technology
Facilities Council

Laserlab
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