TOWARDS A COMPACT XUV FREE-ELECTRON LASER: CHARACTERISING THE IMPROVING BEAM QUALITY OF ELECTRON BEAMS GENERATED IN A LASER WAKEFIELD ACCELERATOR

Mark Wiggins

SUPA

University of Strathclyde Glasgow

Acknowledgements

Director: Prof. Dino Jaroszynski

Experiments: Maria Pia Anania, Enrico Brunetti, Silvia Cipiccia, Riju Issac, Richard Shanks, Gregory Vieux, Gregor Welsh, Xue Yang

Theory: Sijia Chen, Bernhard Ersfeld, John Farmer, Ranaul Islam, Gaurav Raj

Technicians: David Clark, Tom McCanny

- Electron spectrometer and beam line collaborators

Allan Gillespie (University of Dundee)

Allan MacLeod (University of Abertay Dundee)

Bas van der Geer & Marieke de Loos (Pulsar Physics, Eindhoven)

Content

- Motivation: quality beams for an X-ray radiation source
- The ALPHA-X beam line: experimental setup
- Experimental results:

    beam divergence & pointing

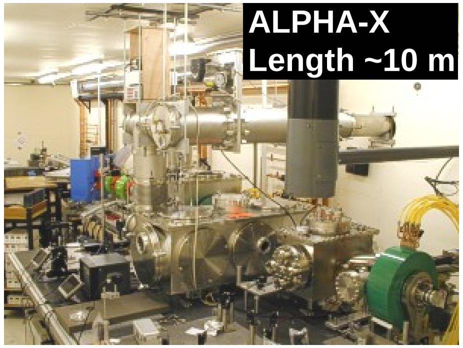
    emittance

    energy spectrum

- Narrow spread simulation
- Outlook for free-electron laser (FEL) driven by LWFA beam
- Conclusions

Motivation

- Conventional synchrotrons and FELs are *very* large
- A LWFA-driven light source is ultra-compact
- Short pulse duration (~10 fs)
- Small source size (few μm)
- Very high peak brilliance

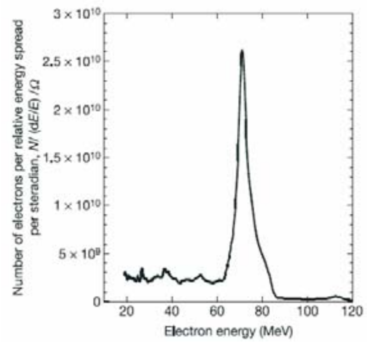


- RF accelerators produce electron beams with emittance ε_N ~1π mm mrad and energy spread ~ 0.1%.
- Unprecedented peak brilliance expected in the X-ray FELs.
- Beam quality & stability are the challenges for LWFA-driven FELs.

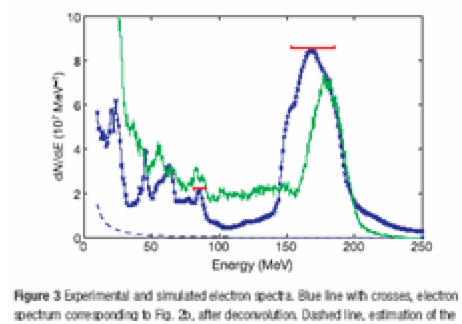
LWFAs to date

- High charge density: 10’s of pC in ~10 fs (kA peak current)
- Low emittance: ε_N ~few π mm mrad (no direct measurements)
- Significant relative energy spread σ_γ/γ ~ 2 – 10%

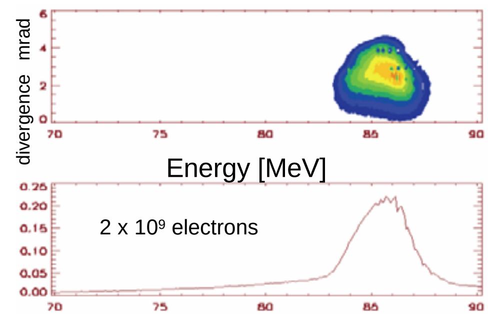
“Dream beam” papers Nature **431**, 535-544 (2004)



Mangles et al.

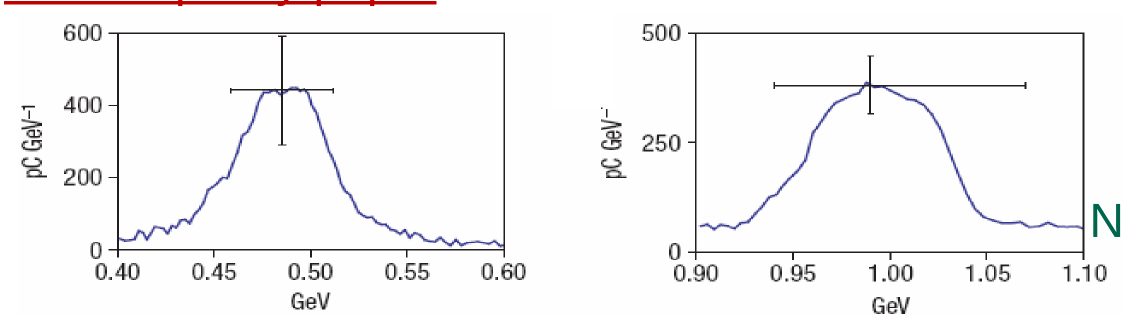


Faure et al.



Geddes et al.

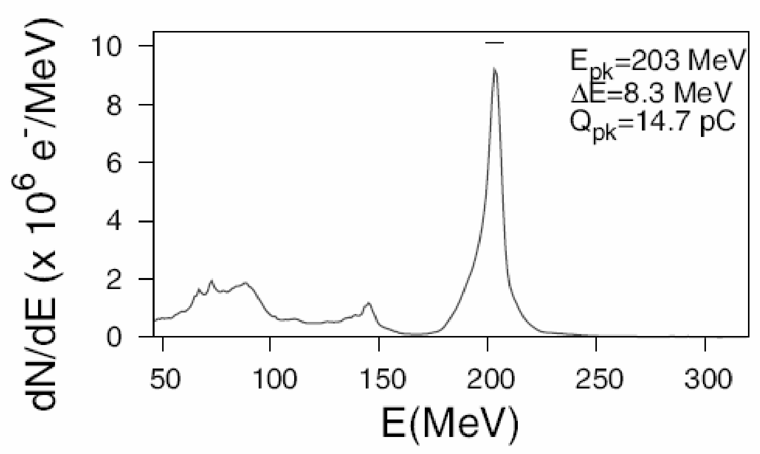
GeV Capillary paper



Leemans et al.,
Nature Phys. **2**, 696 (2006)

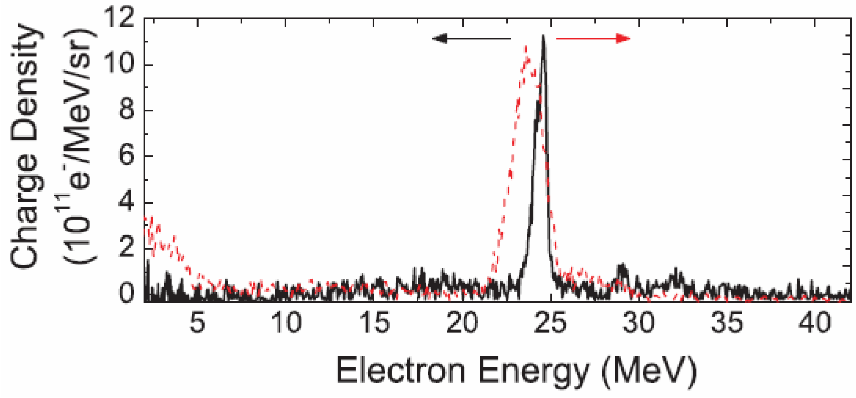
Recent LWFA beams

- Close to $\sigma_\gamma/\gamma \sim 1\%$



- LOA "Salle Jaune" two-beam expt
- Helium gas jet

Malka et al. ,
Phys. Plasmas **16**, 056703 (2009).



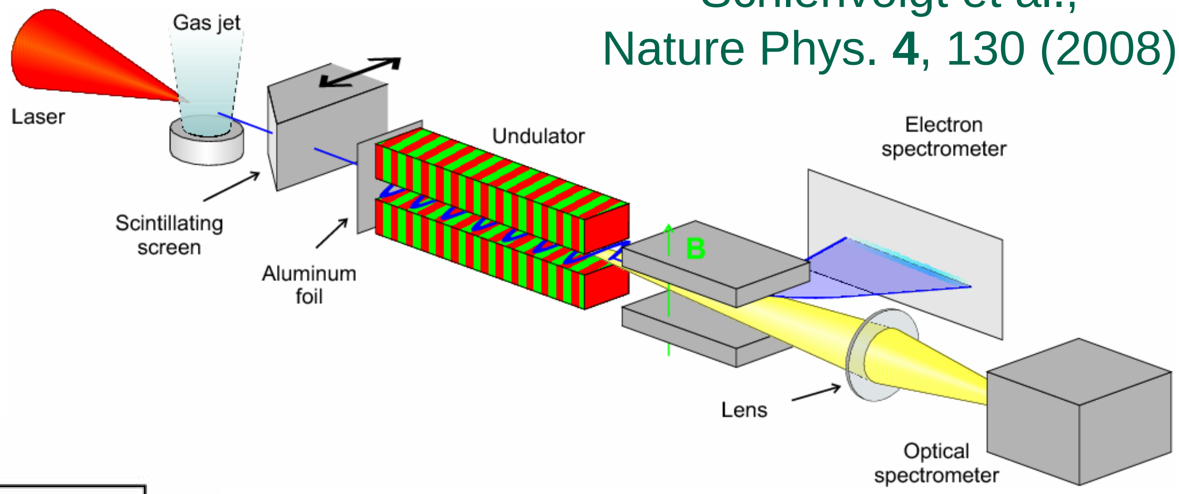
- 8 fs, 40 mJ laser pulse
- Helium gas jet

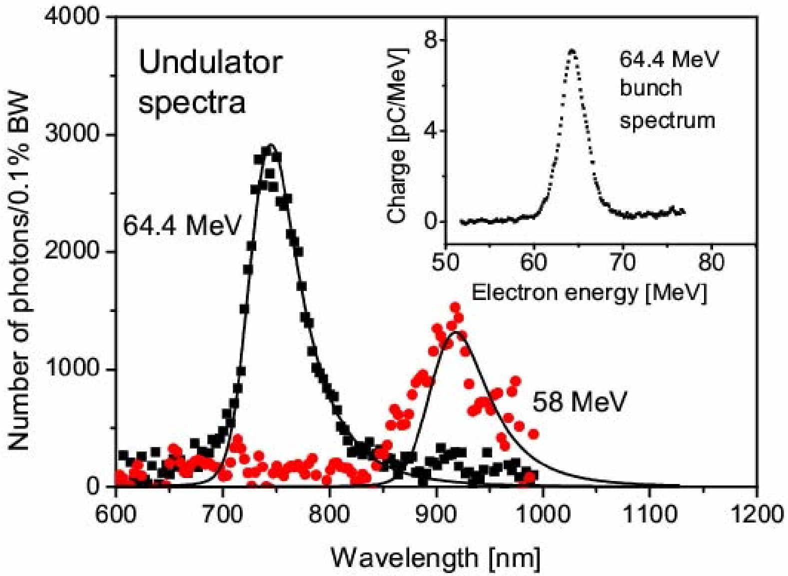
Schmid et al.,
Phys. Rev. Lett. **102**, 124801 (2009).

Undulator radiation demonstration

- Strathclyde, Jena, Stellenbosch collaboration
- 55 – 70 MeV electrons
- VIS/IR synchrotron radiation

Schlenvoigt et al., Nature Phys. **4**, 130 (2008)

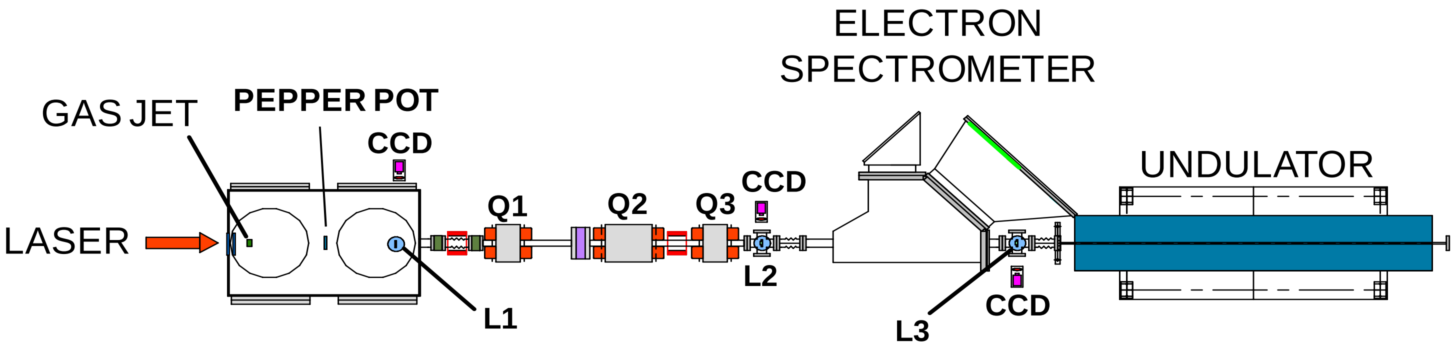


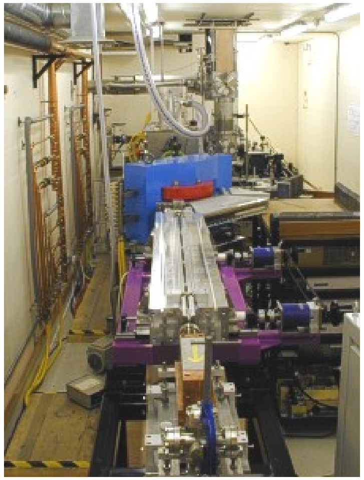


- Measured σ_γ/γ ~ 2.2 – 6.2%
- Analysis of undulator spectrum and modelling of spectrometer places actual σ_γ/γ closer to 1%
- Paper to be submitted

ALPHA-X Beam Line

Advanced Laser Plasma High-energy Accelerators towards X-rays





- Laser: λ_0 = 800 nm, E = 900 mJ, τ = 35 fs, $I = 2 \times 10^{18}$ Wcm^{-2}, a_0 = 1.0
- Gas Jet: hydrogen, 2 mm nozzle, $n_e \approx 1 - 5 \times 10^{19}$ cm^{-3}
- Beam profile monitors: Lanex screens L1, L2, L3 imaged by 12-bit PGR Flea cameras
- Quadrupole magnets: Q1 (Y-focus, X-defocus), Q2 & Q3 (Y-defocus, X-focus)

Electron Spectrometer

- Designed by Allan Gillespie / Allan MacLeod
- Built by Sigmaphi (France)

Dual function device

Low energy chamber

High resolution – design ~ 0.1% (FWHM)

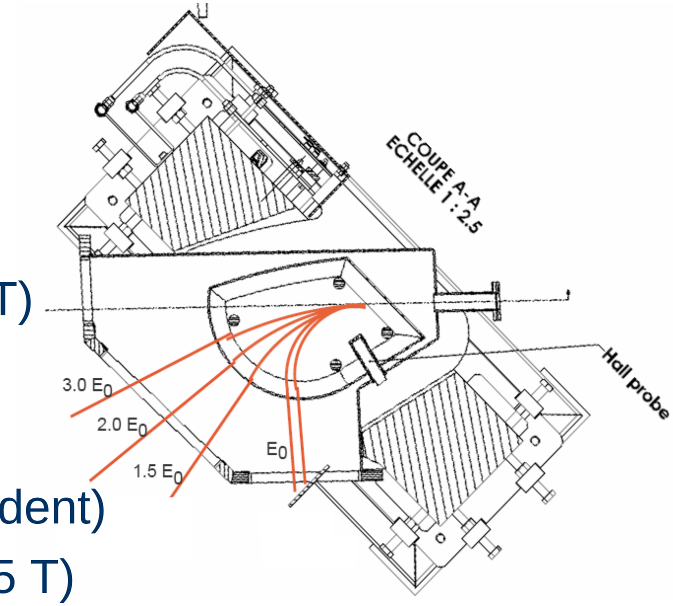
Electron energy up to 105 MeV (B_{max} = 1.65 T)

High energy chamber

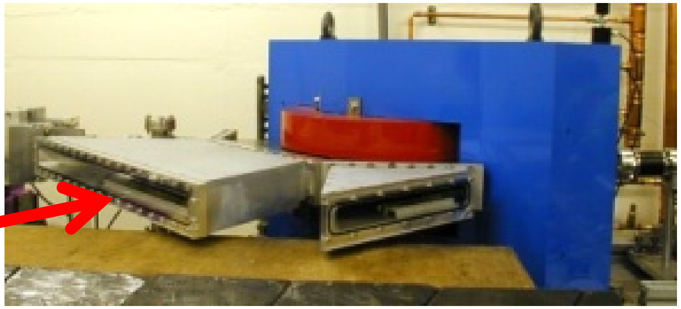
Uses upstream quadrupoles to aid focusing

Energy resolution ~0.2 – 10% (energy dependent)

Electron energy up to ~ 660 MeV (B_{max} = 1.65 T)



Ce:YAG crystal
300 × 10 × 1 mm

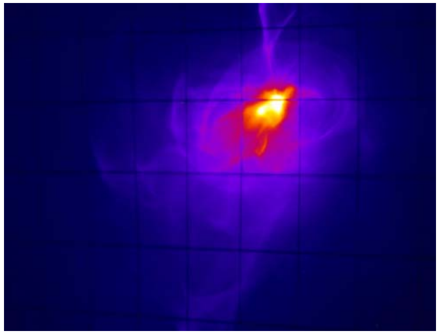


12-bit PGR Flea camera not shown

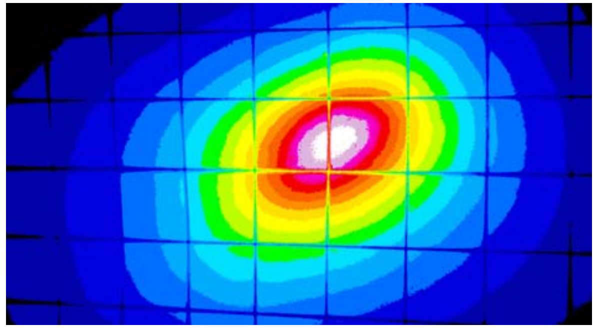
University of Strathclyde Glasgow

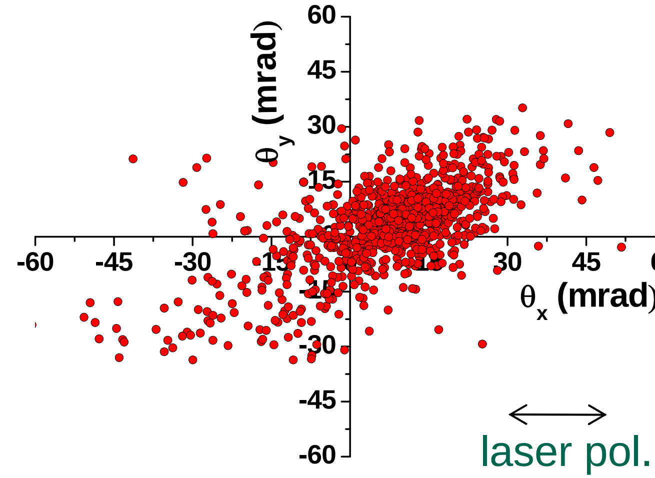
Experimental Results – beam divergence/pointing

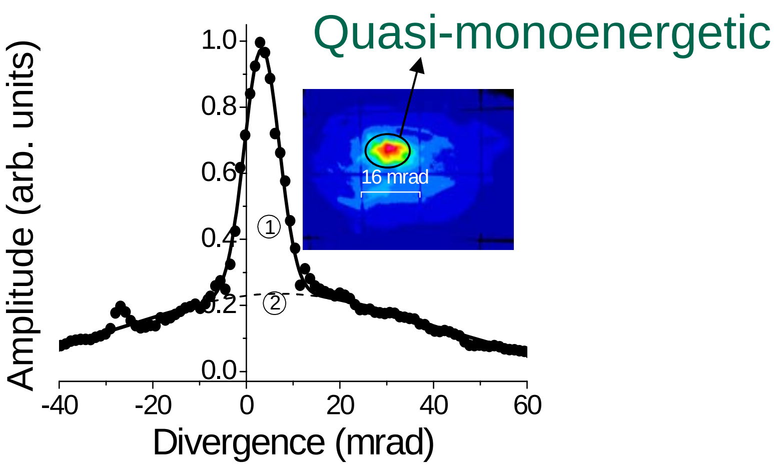
L1 profile (z = 0.6 m)



Average over 1000 shots



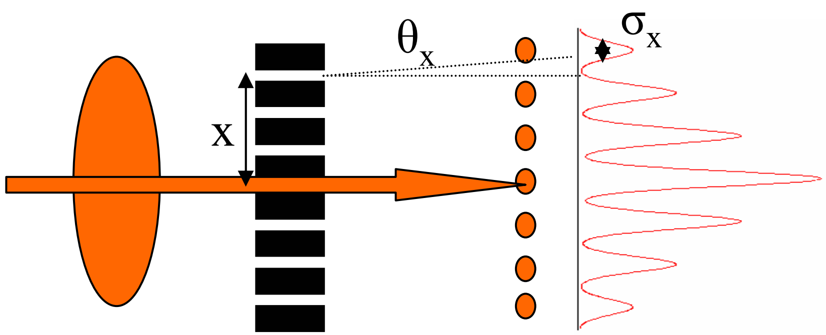


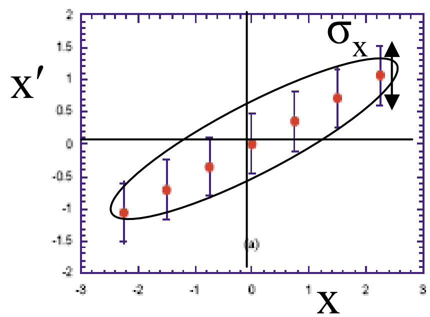


- Fit two Gaussian profiles
- Low divergence (~3 mrad) centre: 10% charge
- High divergence (~30 mrad) halo: 90% charge

- Elliptical beam at 40° to laser polarisation
  (λ_p = 5μm < $c\tau_{laser}$)
- c.f. Mangles et al., PRL **96**, 215001 (2006)
- Mean pointing angle = 8 mrad
- Lower plasma density (λ_p = 10μm ≈ $c\tau_{laser}$)
  → less elliptical and less offset
- Theoretical model on-going
- Control pointing using quadrupole lenses

Experimental Results – emittance





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

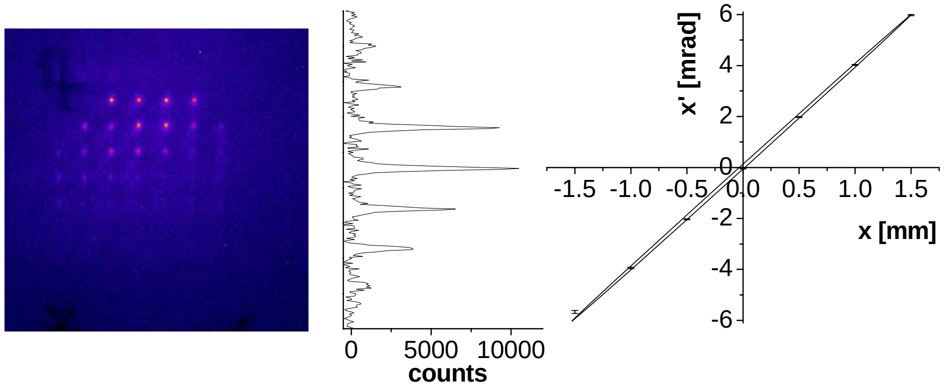
$\langle x' \rangle \propto I^*(\theta_x + \sigma_x)$ – averaged

Emittance (rms):

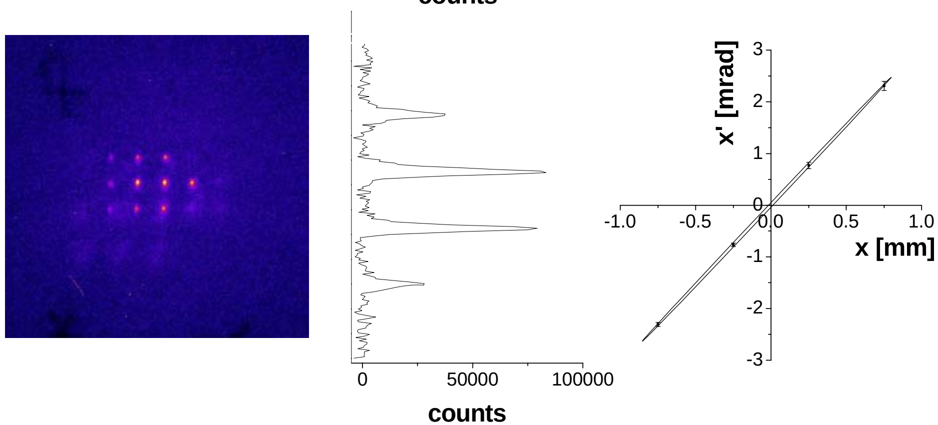
$\varepsilon_{x,\,rms} = [\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2]^{1/2}$

Direct Calculation:

(Zhang FERMILAB-TM-1988)



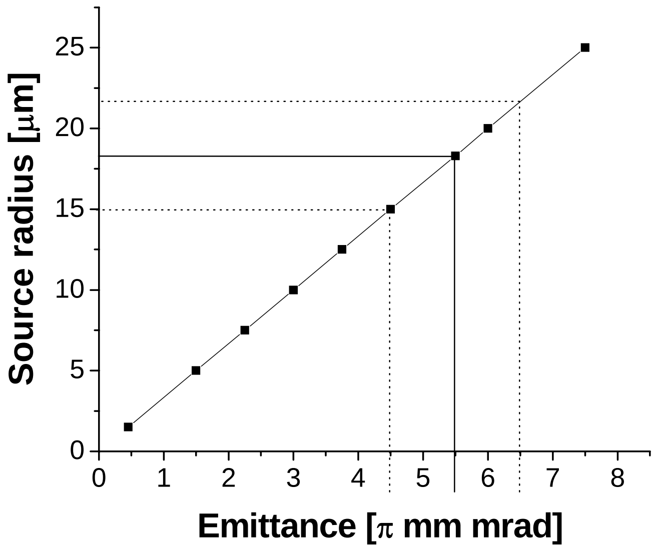
- divergence 6 mrad
- hole size correction
- limited by detection system
- $\varepsilon_{N,x} < (7.8 \pm 1)\ \pi$ mm mrad



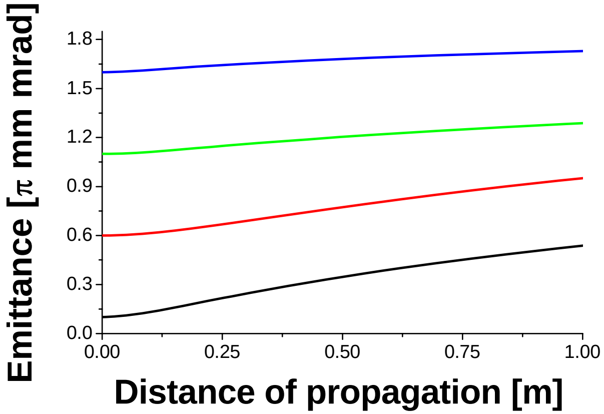
- divergence 4 mrad
- $\varepsilon_{N,x} < (5.5 \pm 1)\ \pi$ mm mrad

University of Strathclyde Glasgow

Emittance



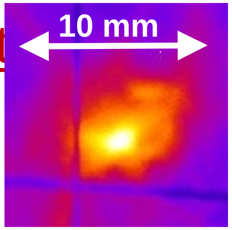
- General Particle Tracer (GPT) simulations:
  includes space charge effects
- Charge 100 pC, duration 10 fs, energy spread 1%
- Upper limit source size: 18 μm
- Predicted source size 2 – 3 μm → ε_n ~ 0.5 π mm mrad



- GPT simulations
- Emittance growth

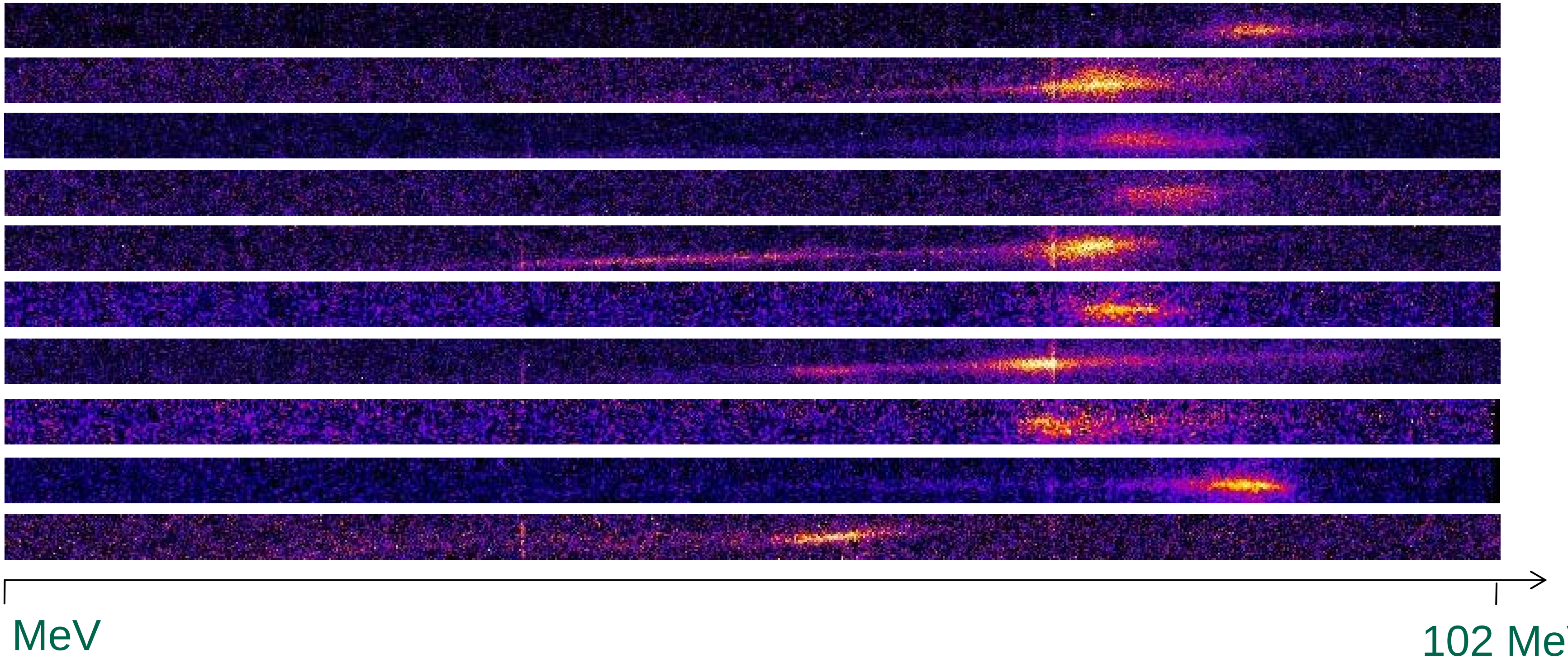
Experimental Results – energy spectra I

- Operating mode: <u>no additional focusing with quadrupole magnet</u>
- Propagation of few mrad divergence beam into spectrometer
- Y and X focusing by spectrometer field only

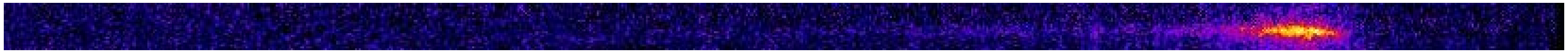


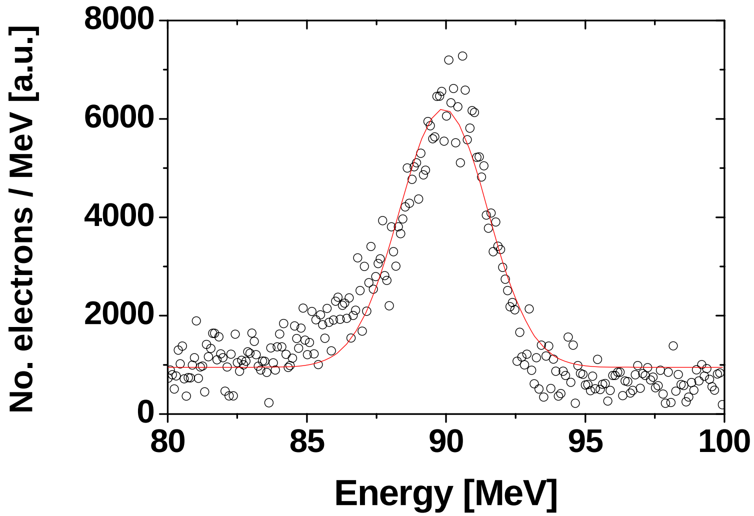
L1 profile

False colour Ce:YAG screen images



Measured spectra – no quads

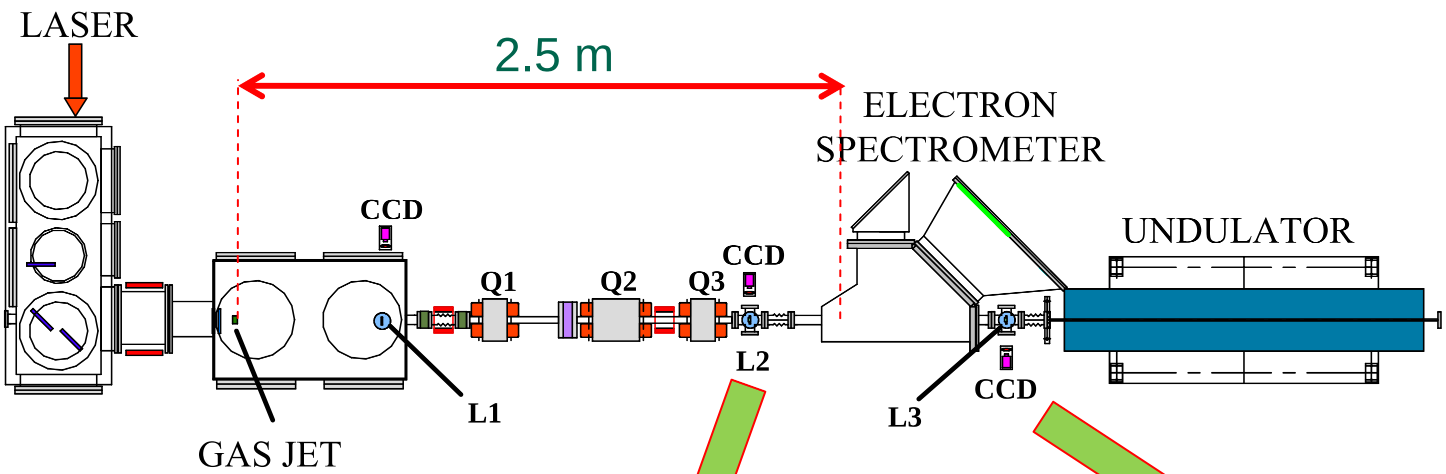




- 10 shots with the lowest spread
- Mean E = 84 ± 5 MeV (highest 90.4 MeV)
- Mean σ_γ/γ = 1.7 ± 0.3% (lowest 1.2%)

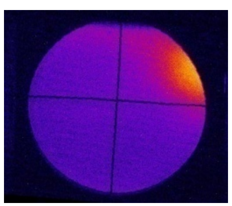
- Nice but can be improved with better beam transport
- Spectrometer designed for ideal parallel beam
- Spectrum broadened for a divergent beam (small effect in this case)

Beam transport

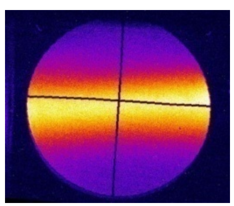


L3 profile:
screen ϕ = 18 mm
at z = 3.3 m

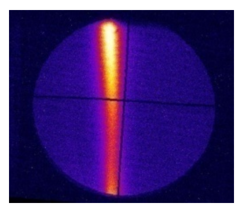
L2 profiles: screen ϕ = 18 mm at z = 2.2 m



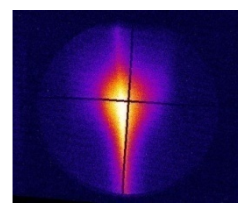
No quads
Electron beam
pointing $\geq$ 8
mrad



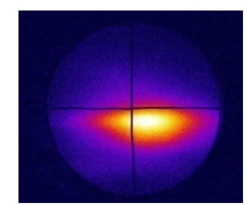
Q1 ON
Y focusing



Q2 ON
X focusing



Q1 & Q3 ON
Y & X
focusing

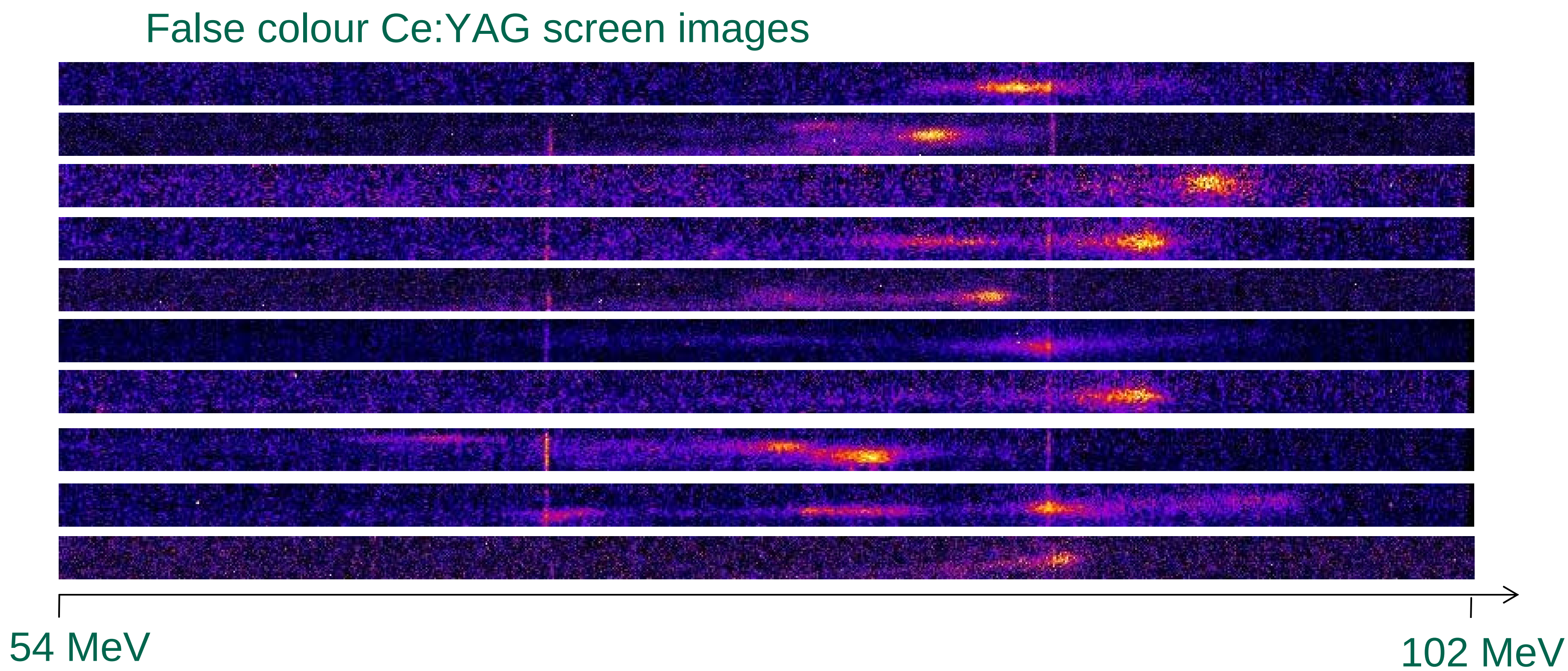


Q1 & Q2 ON
Y & X focusing
2σ beam width 5.4 $\times$
1.9mm

- Quads also control beam pointing

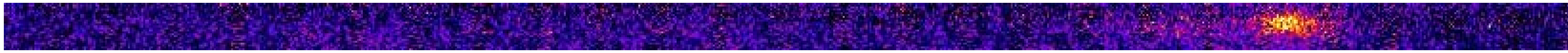
Experimental Results – energy spectra II

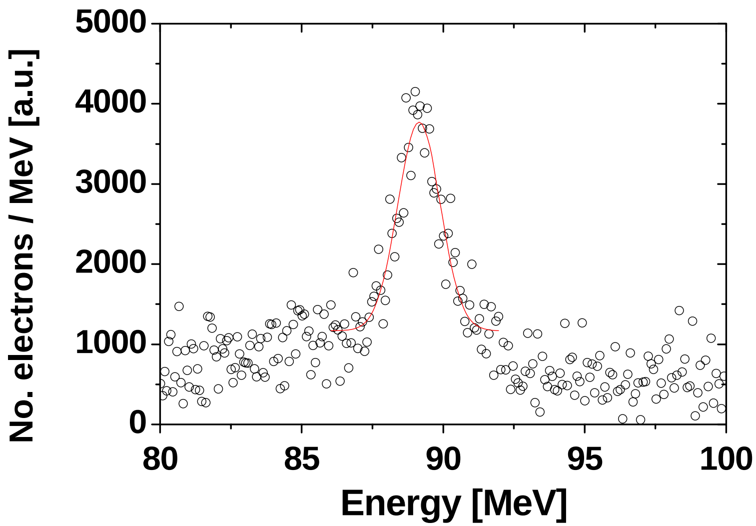
- Operating mode: <u>additional focusing with quadrupole magnets</u>
- However, elliptical beam profiles indicate transport not quite optimised



University of Strathclyde Glasgow

Measured spectra – quads on

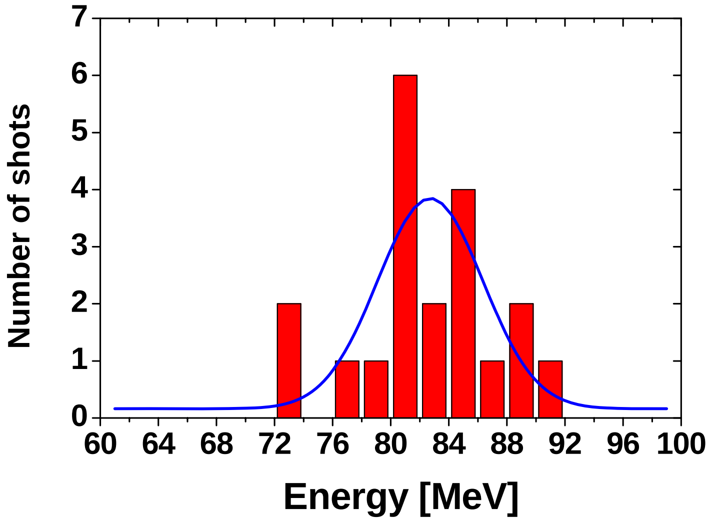


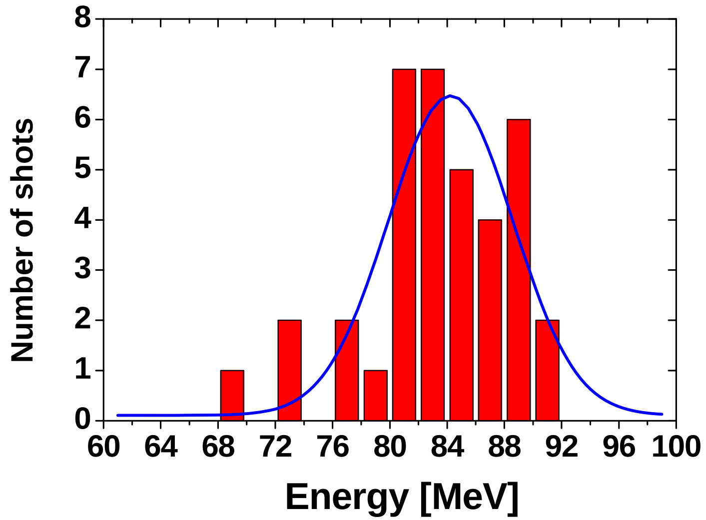


- 10 shots with the lowest spread
- Mean E = 82 $\pm$ 4 MeV (highest 89.2 MeV)
- Mean σ_γ/γ = 1.1 $\pm$ 0.4% (lowest 0.8%)

- Smaller measured relative energy spread
- Close to spectrometer resolution (still to be confirmed)
- Deconvolution yields a lower spread

Energy stability





- Best 20 shots
  - mean E = 82.8 MeV
  - σ_{rms} = 4.6 MeV
- Gaussian fit
  - centre E = 82.7 MeV
  - σ_{rms} = 3.6 MeV

- Best 37 shots
  - mean E = 83.4 MeV
  - σ_{rms} = 5.1 MeV
- Gaussian fit
  - centre E = 84.2 MeV
  - σ_{rms} = 4.4 MeV

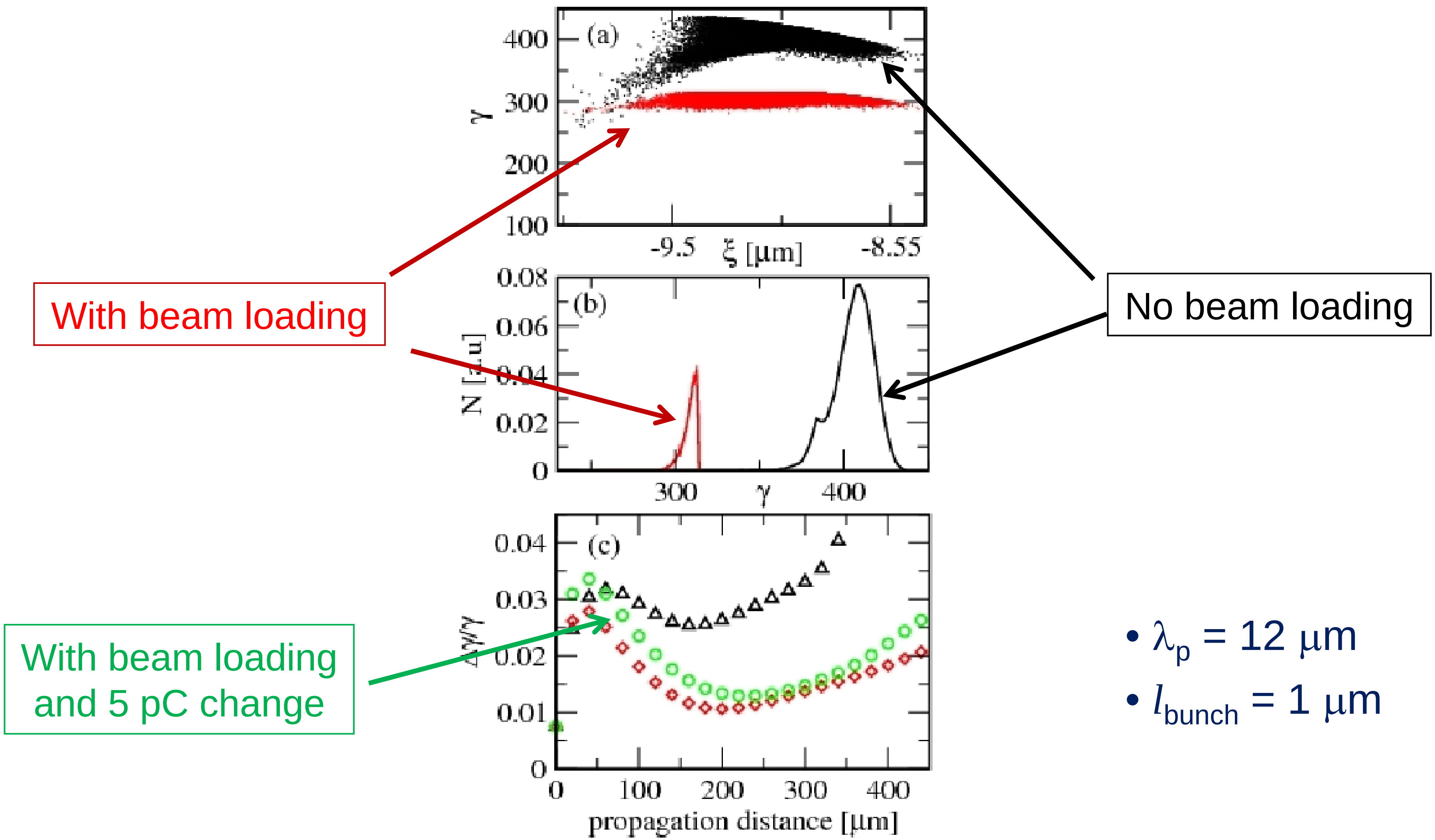
- ±6% shot-to-shot energy stability when good electron bunches are produced

Beam loading simulation

- Self-consistent reduced model to study effect of wakefield modification by the laser pulse (beam loading)
- Laser pulse modification due to varying local refractive index
- Electron bunch injected at optimal position into the wake

- Laser $a_0 = 2$
- Plasma $n_e = 1.3 \times 10^{19}$ cm^{-3}
- Electron bunch 2.5 pC in 1 μm^3 volume

Beam loading simulation



- λ_p = 12 μm
- l_{bunch} = 1 μm

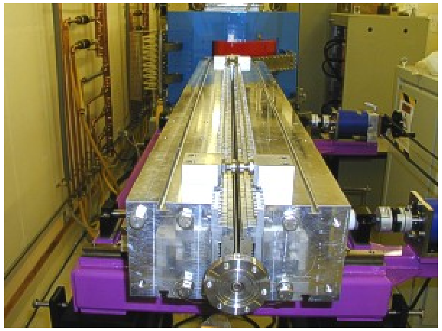
- Beam loading reduces the variation in accelerating potential along the bunch

FEL viability

- High FEL gain criteria: $\varepsilon_n < \lambda\gamma/4\pi$ and $\sigma_\gamma/\gamma < \rho$

$$\rho = \frac{1}{2\gamma}\left[\frac{I_p}{I_A}\left(\frac{\lambda_u a_u}{2\pi\sigma_x}\right)^2\right]^{1/3}$$

- ALPHA-X undulator
  - 90 MeV: λ = 260 nm
  - 500 MeV: λ = 8 nm



λ_u = 15 mm, N = 200, a_u = 0.38

- Emittance (inferred from divergence and measured directly) ~few $\times 10^{-6}$ m rad
  - 90 MeV: need $\varepsilon_n < 3\ \pi$ mm mrad
  - 500 MeV: need $\varepsilon_n < 0.6\ \pi$ mm mrad

- Relative energy spread ≤ 0.008
  - 90 MeV: $\rho \sim 0.011$ and 47 ideal gain lengths
  - 500 MeV: $\rho \sim 0.002$ and 8 ideal gain lengths

- Peak brilliance $>10^{30}$ photons / (s mm^2 mrad^2 0.1% BW)

Summary

- High quality electron beams produced on the ALPHA-X beam line.
- 90 MeV electron beams driven by a_0 = 1.0 laser pulse in gas jet.
- study of beam divergence, pointing & shape.
- relative energy spread = 0.8% (upper limit).
- measured emittance $\varepsilon_N = 5.5\pi$ mm mrad (upper limit).
- understood in terms of beam loading phenomenon smoothing the potential along the electron bunch length.
- FEL gain: should be observable in DUV – XUV spectral range.
- compact soft X-ray FEL driven by a LWFA electron beam is a step closer.

University of Strathclyde Glasgow

Immediate tasks

- Confirm bunch charge → imaging plates
- Electron spectrometer simulations with GPT code → instrument resolution
- Spectral measurements using high resolution chamber
- Improved emittance measurements
- Improve beam transport → Anania talk (TU2PBC04)

Also

Benchmark value for X-ray FEL

- Theoretical modelling for energy spread approaching 0.1%

  → beam loading optimisation
- Two beam case: Davoine et al., Phys. Rev. Lett. **102**, 065001 (2009).
- Our one beam case: shows good potential without added complication.

Thank you

ALPHA-X

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

Funded by

EPSRC
Engineering and Physical Sciences Research Council

euro LEAP

Laserlab Europe

eli extreme light infrastructure