The

ALPHA-X

Laser Wakefield Accelerator (LWFA): towards a compact light source

Mark Wiggins

Contents

University of Strathclyde Glasgow

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	U. St. Andrews	U. Dundee	U. Abertay Dundee	Cockcroft Institute
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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

Group Leader: Prof. Dino Jaroszynski

Experiments: Riju Issac, Gregor Welsh, Enrico Brunetti, Gregory Vieux

PhDs: Richard Shanks, Maria Pia Anania, Silvia Cipiccia, Salima Abuazoum, Grace Manahan, Constantin Aniculaesei, Anna Subiel, David Grant

Theory: Bernhard Ersfeld, Ranaul Islam, Gaurav Raj, Adam Noble

PhDs: John Farmer, Sijia Chen, Ronan Burgess, Yevgen Kravets

Technicians: David Clark, Tom McCanny

Visiting Professor: Rodolfo Bonifacio

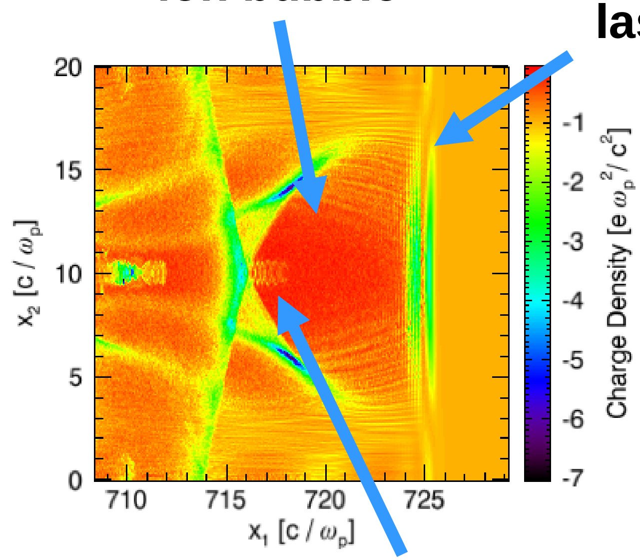
Scottish Universities Physics Alliance

The LWFA

- Tajima & Dawson PRL **43**, 267 (1979).
- Intense femtosecond laser propagating in underdense plasma.
- Relativistically self-guided channel.
- Ponderomotive force leads to charge separation and plasma density wake.
- Electrons trapped at back of bubble and accelerated in the very large electrostatic fields.

ion bubble

laser



self-injected electron bunch undergoing betatron oscillations

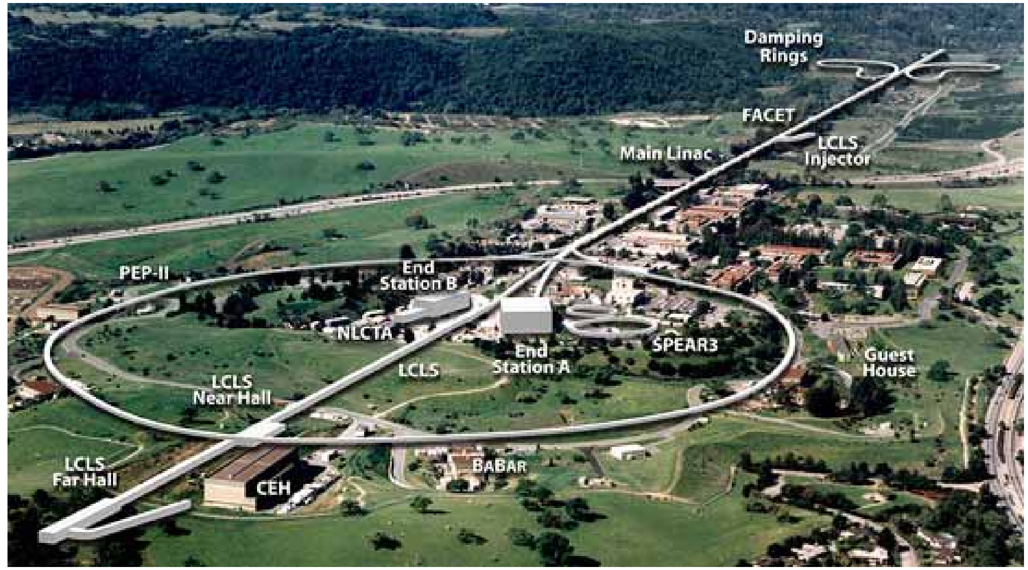
- Electron velocity (~*c*) > laser group velocity and electrons catch up on laser.
- Energy at dephasing length:

$$\gamma_{\max} \approx \frac{2 a_0 \gamma_g^2}{3}, \quad \gamma_g = \frac{\omega_0}{\omega_p}$$

Motivation

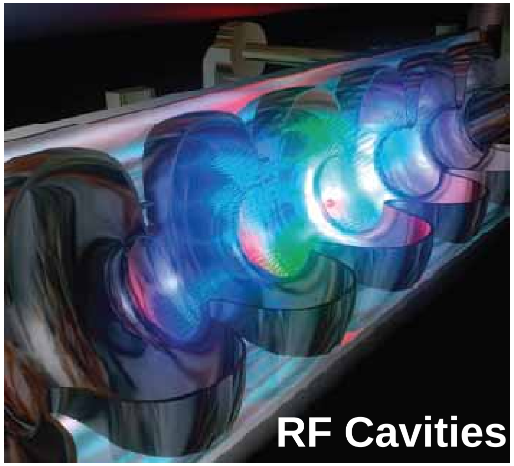
SLAC NATIONAL ACCELERATOR LABORATORY

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

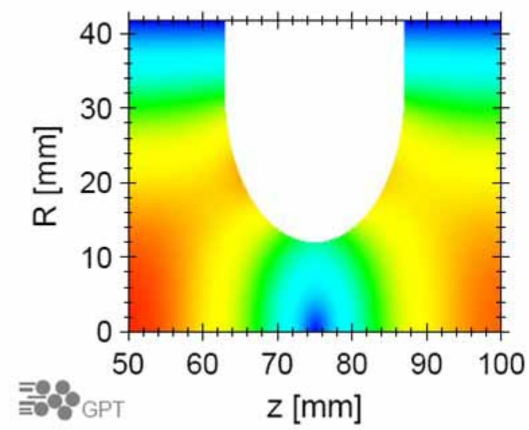


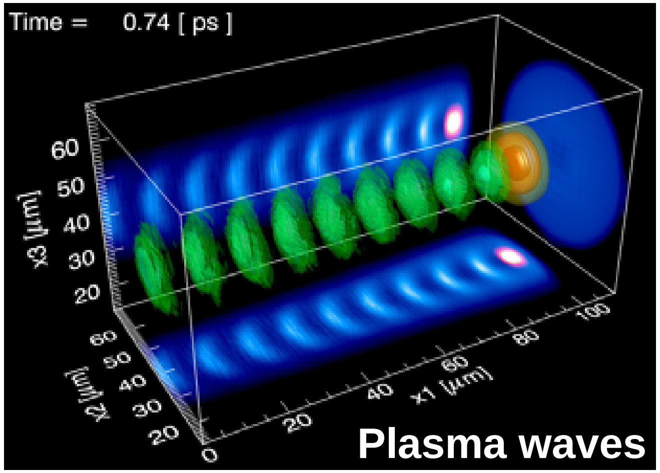
- Conventional synchrotrons and FELs are <u>very</u> large
- A LWFA-driven light source is ultra-compact
- Accelerating gradient ~100 GeV/m
- Great uses: short pulses, small source sizes
- Wider accessibility

Conventional v Plasma Accelerators



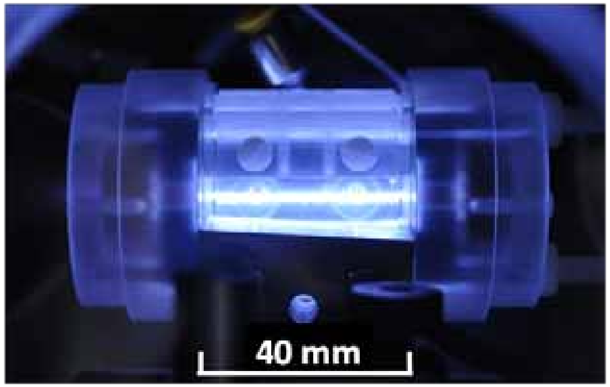
- Max. E field ~100 MV/m
- Limited by breakdown





- 1000 times smaller & cheaper
- 1 GeV in 33 mm capillary (LBNL 2006)

Strathclyde Capillary



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Our goal

LWFAs to date

- High charge density: 10's of pC in inferred ~ 10 fs (peak current *I* ~ kA)
- Low emittance: inferred ε_N ~ few π mm mrad (no direct measurements)
- Significant relative energy spread σ_γ/γ ~ 1 – 2% at best
- X-ray FEL needs σ_γ/γ ~0.1%

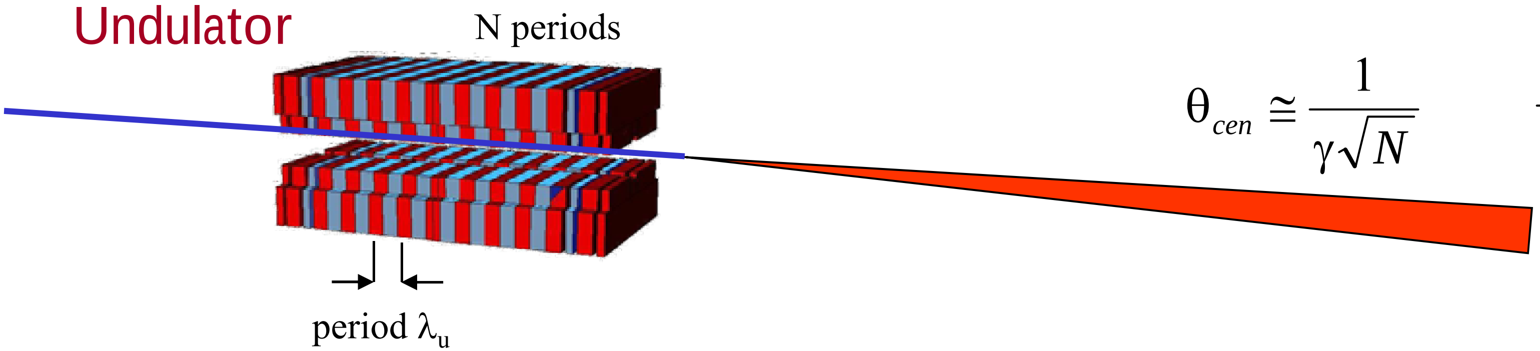
- We are looking to produce high quality electron beams (high *I*, low ε_N , low σ_γ/γ)
- And to apply them in useful ways:
- Medical imaging
- Ultrafast probing
- Detector development for nuclear physics
- Strathclyde/Glasgow/Institute for Cancer Research project (e^- beam therapy)

- Future plans at the end...

Synchrotron / undulator radiation

- Relativistic electrons in a magnetic field follow a curved trajectory and i.e. they are accelerated.
- Radiation emitted into a narrow cone (lab frame of reference).
- Single magnet: synchrotron, Magnet array: undulator or wiggler.

Undulator



$$\theta_{cen} \cong \frac{1}{\gamma\sqrt{N}} \qquad \frac{\Delta\lambda}{\lambda} = \frac{1}{N}$$

- Undulator Equation

$$\lambda = \frac{\lambda_u}{2h\gamma^2}\left(1 + \frac{K^2}{2} + \theta^2\gamma^2\right)$$

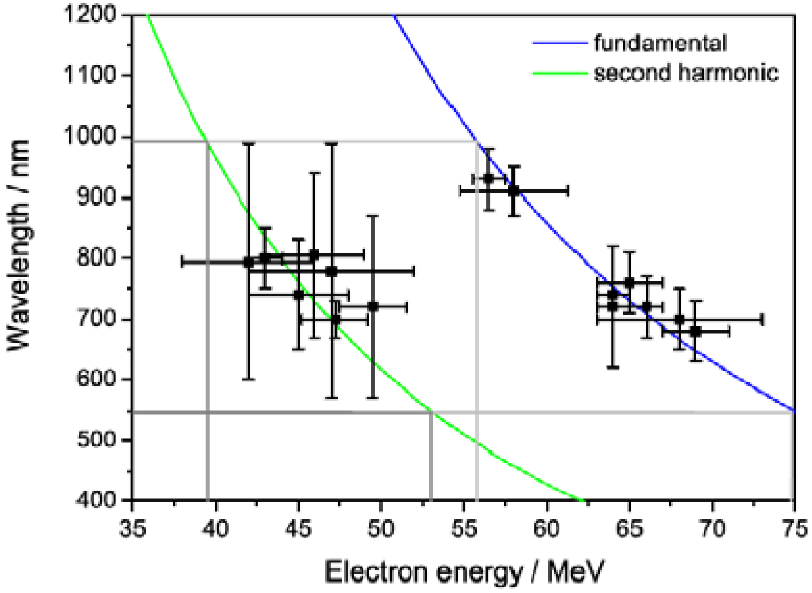
where h is the harmonic order and $K = \lambda_u eB/2\pi m_0 c < 1$

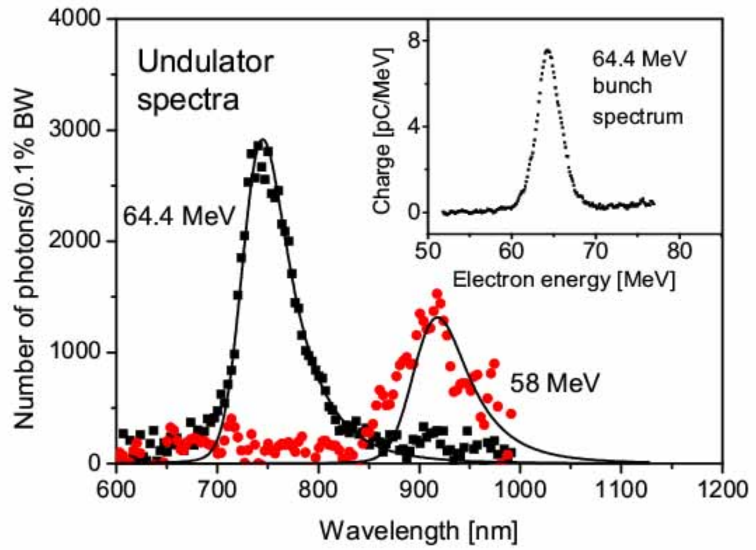
LWFA undulator radiation

- Jena / Strathclyde / Stellenbosch experiment
- 55-70 MeV electrons
- VIS/IR synchrotron radiation

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

Gallacher et al.,
Phys. Plasmas **16**, 093102 (2009)

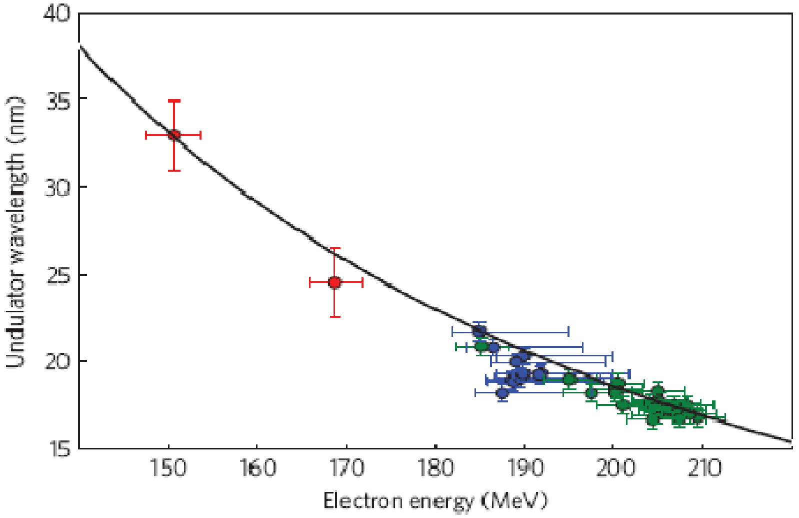




LWFA undulator radiation

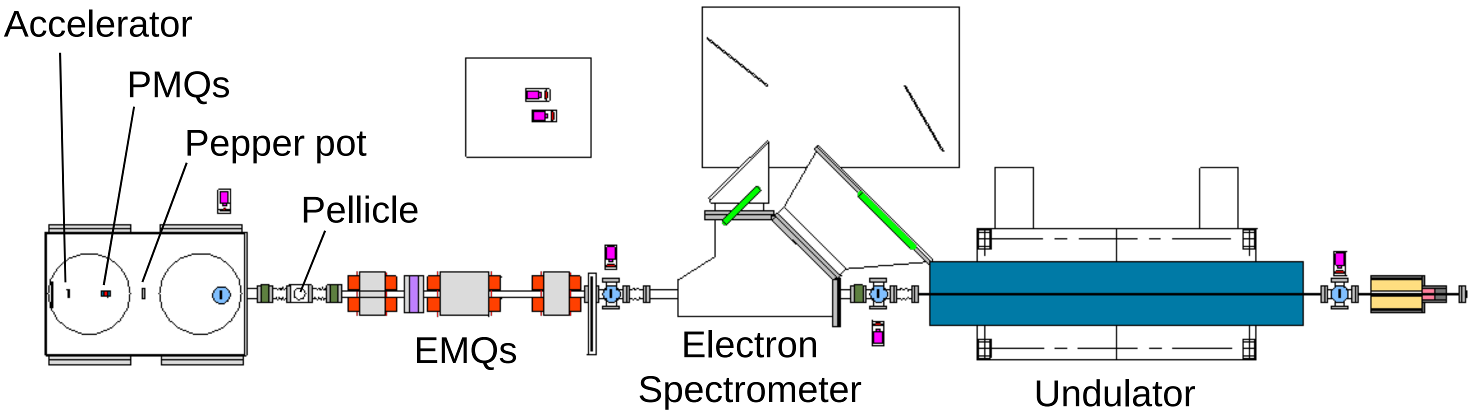
- MPQ/ FZD / Oxford experiment
- 150-210 MeV electrons
- XUV synchrotron radiation

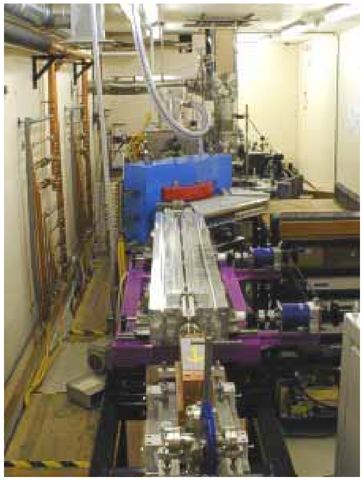
Fuchs et al.,
Nature Phys. **5,** 826 (2009)



- Next step: Free-electron laser for $10^6 - 10^8$ increase in photon output
- High FEL gain criteria: $\varepsilon_n < \lambda\gamma/4\pi$ and $\sigma_\gamma/\gamma < \rho$
- Need the beam quality and good transport...

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

Electron Spectrometer

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

Dual function device

High resolution chamber

Resolution – design ~ 0.1%

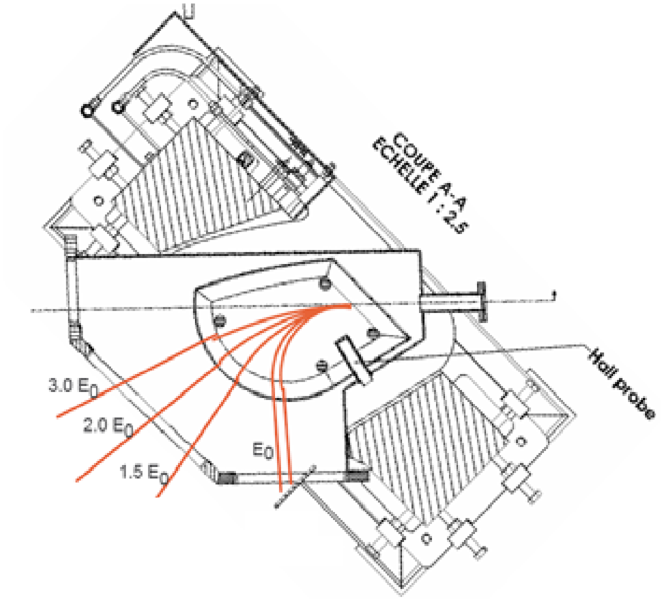
Electron energy up to 105 MeV (B_{max} = 1.65 T)

High energy chamber

Uses upstream quadrupoles to aid focusing

Energy resolution ~0.2 – 10% (energy dependent)

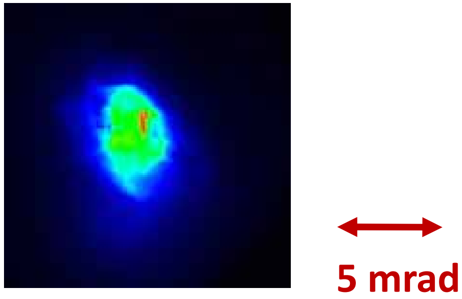
Electron energy up to ~ 660 MeV (B_{max} = 1.65 T)

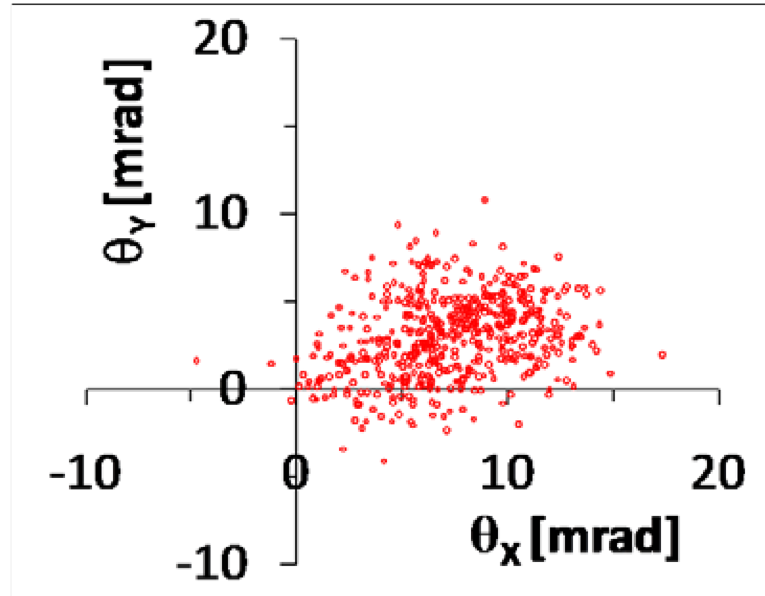


Ce:YAG crystal
300 × 10 × 1 mm

14-bit PGR Grasshopper camera not shown

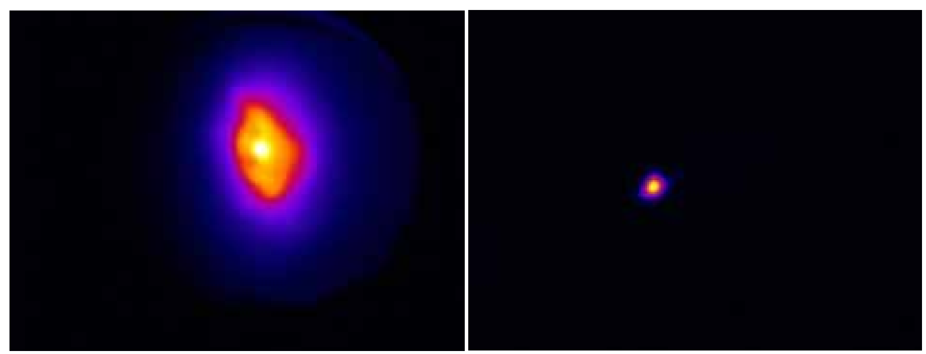
Experimental Results – beam pointing





- 500 consecutive shots
- narrow divergence (~2 mrad) beam
- wide divergence halo
- θ_X = (7 ± 3) mrad, θ_Y = (3 ± 2) mrad

- 8 mrad acceptance angle for EMQs
- 25% pointing reduction with PMQs installed

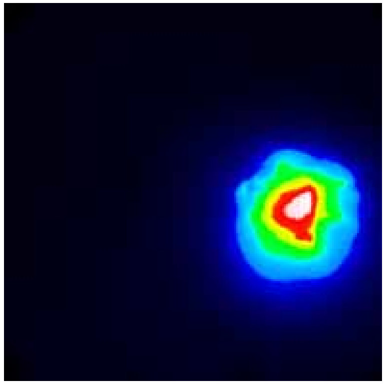


no PMQs　　PMQs in

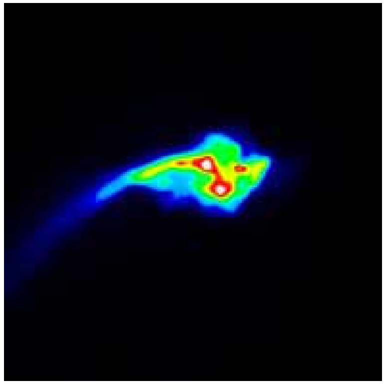
Experimental Results – PMQs

- 1.5 T magnets (similar to the MPQ design)
- Triplet settings for collimation of the “main peak” monoenergetic electron bunch

- Swirls due to low energy halo electrons

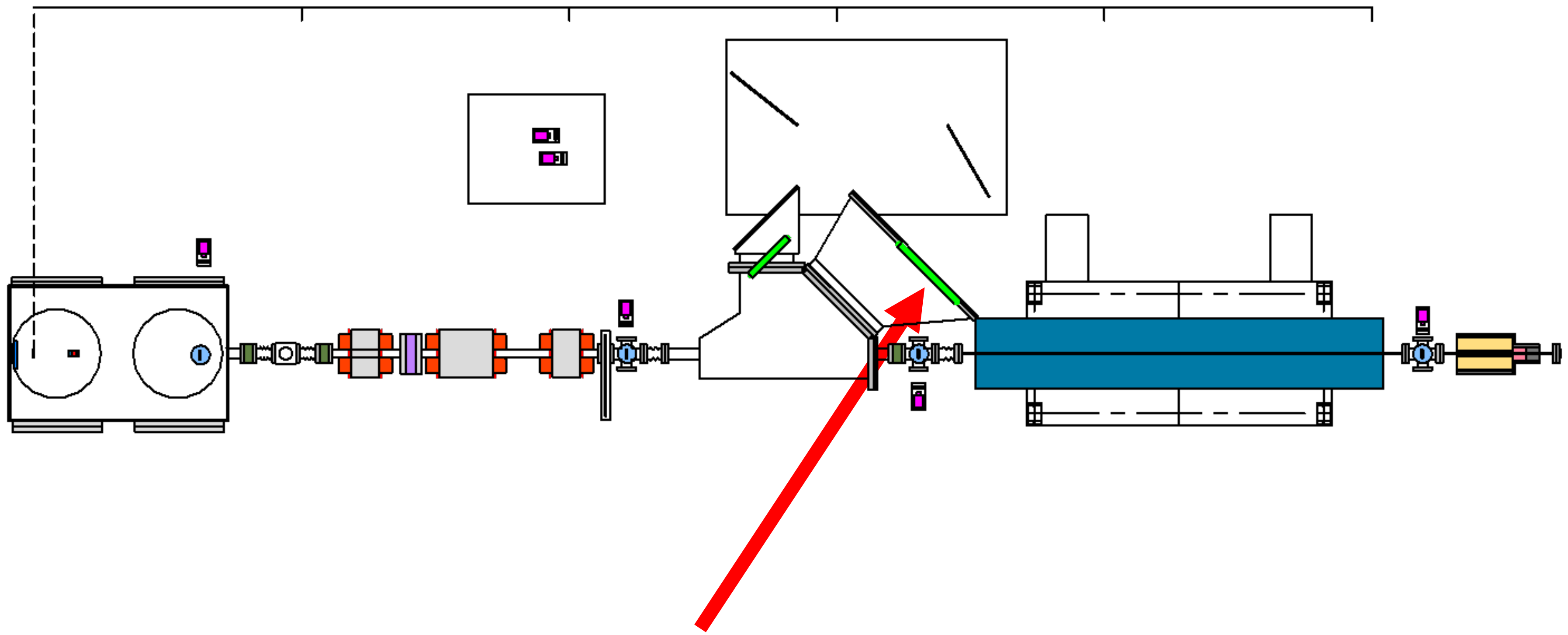


no PMQs

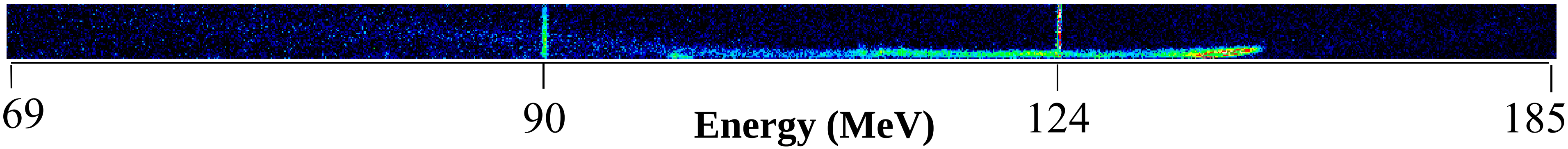


PMQs in

Experimental Results – energy stability



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



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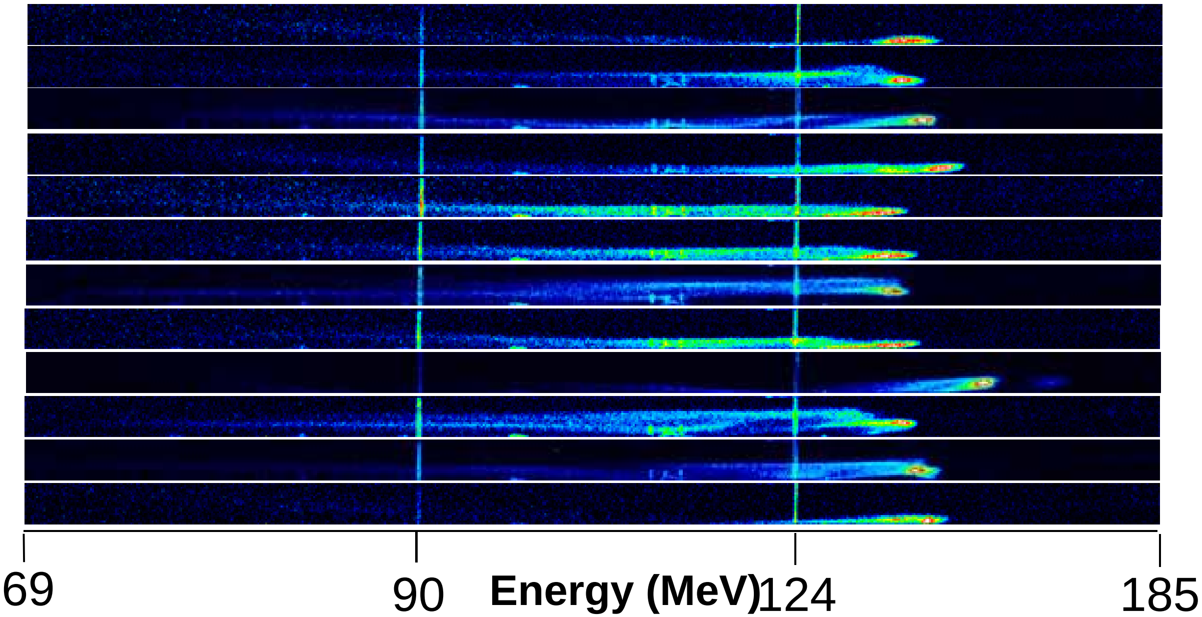
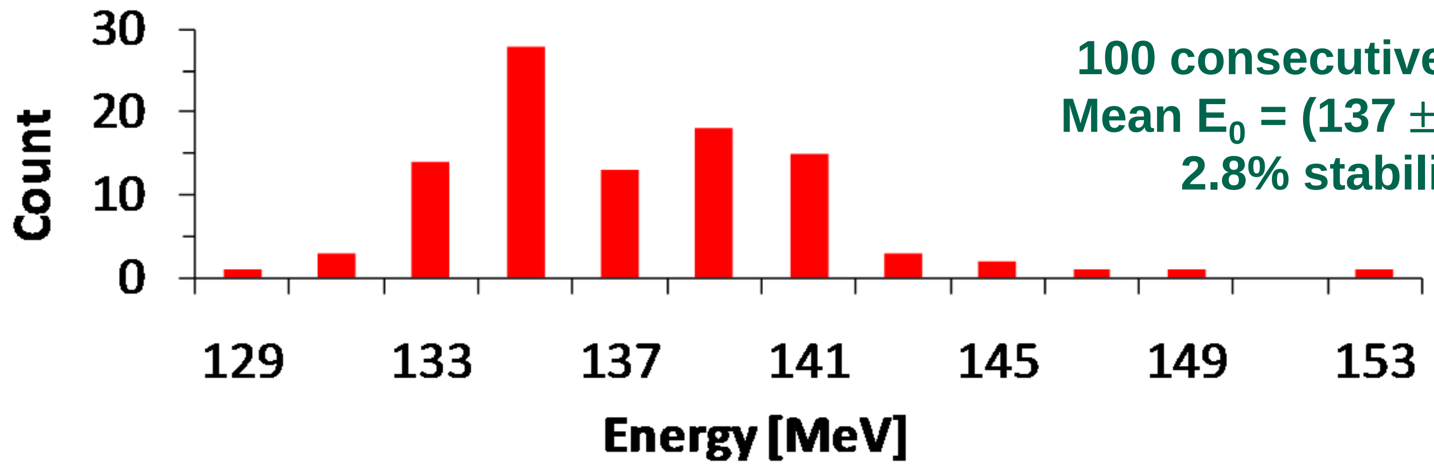
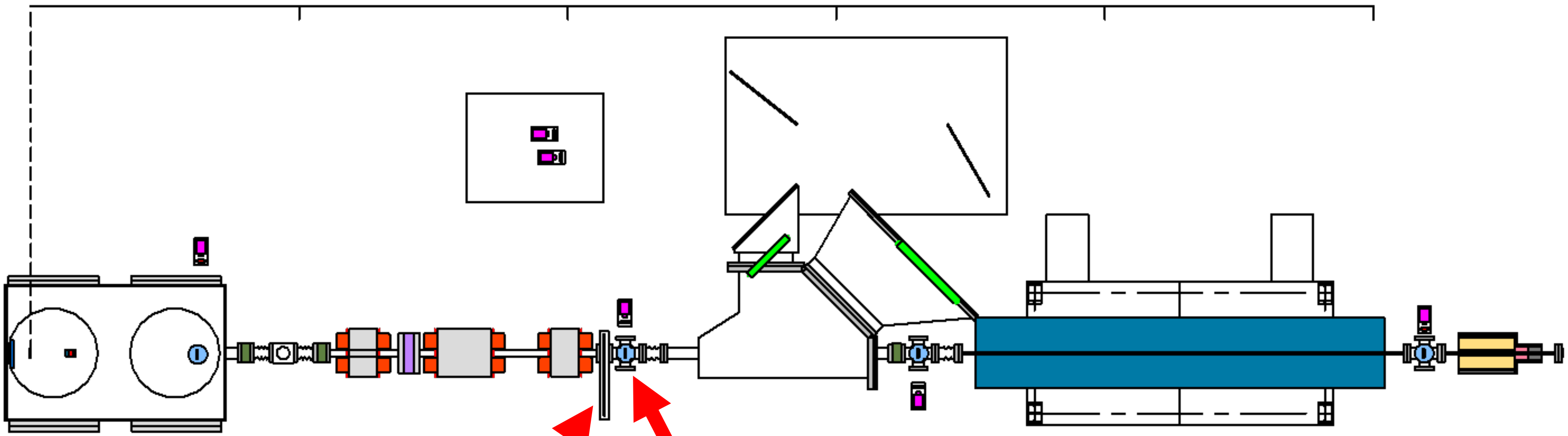
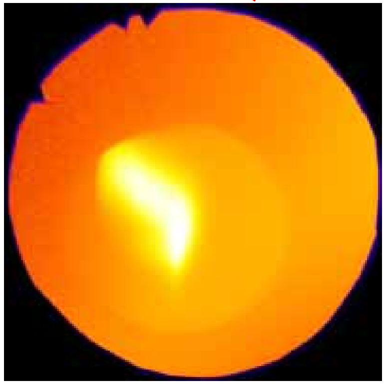




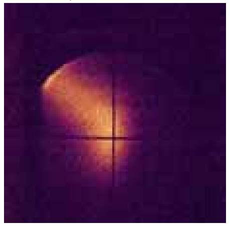
100 consecutive shots
Mean E_0 = (137 ± 4) MeV
2.8% stability

Experimental Results – charge

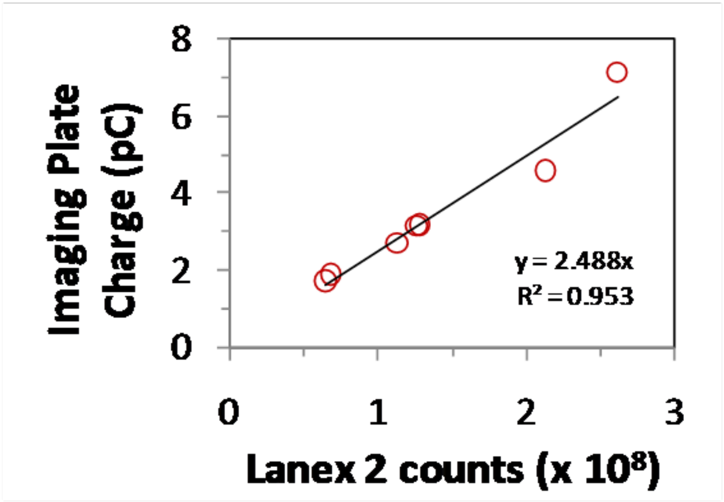




Imaging Plate

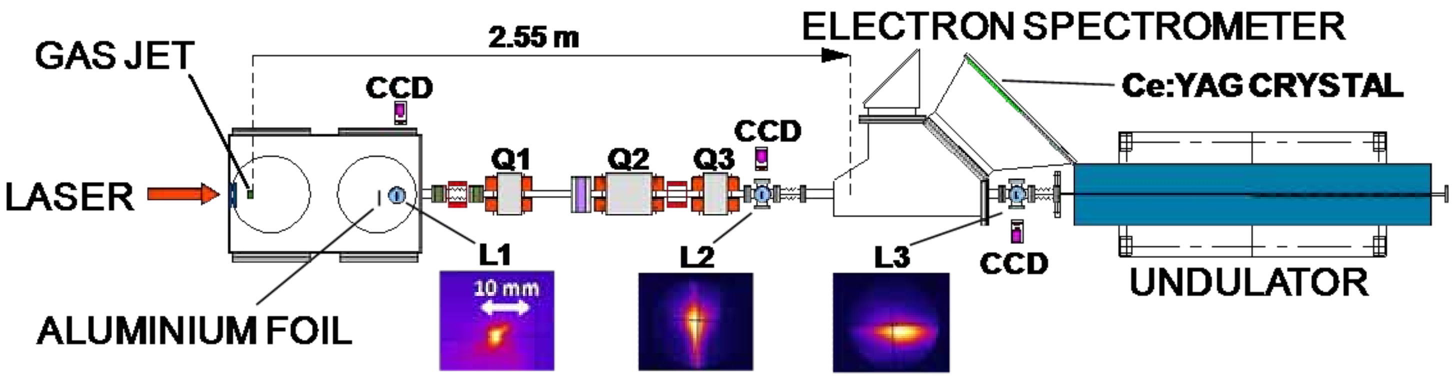


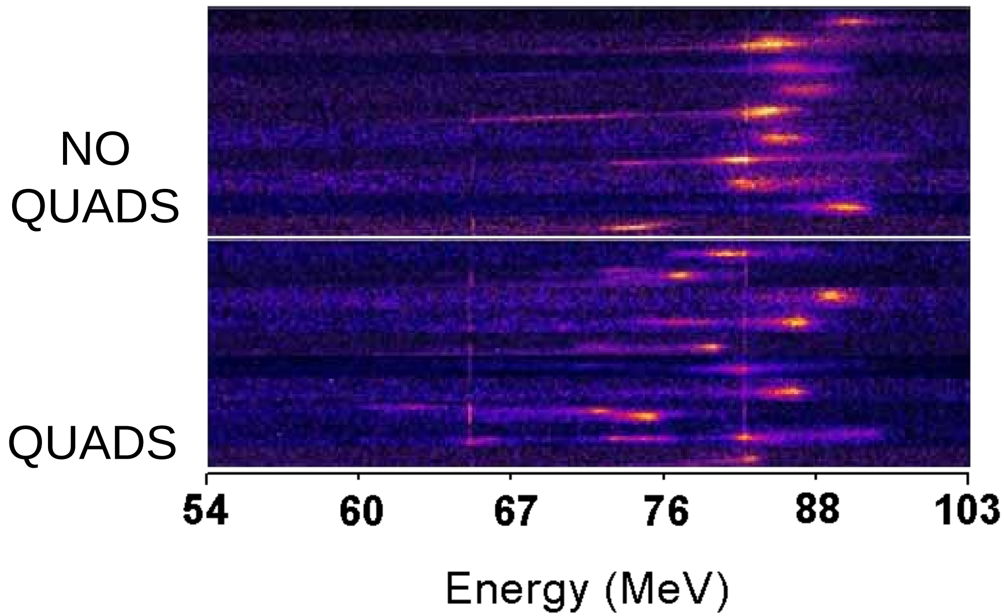
LANEX 2

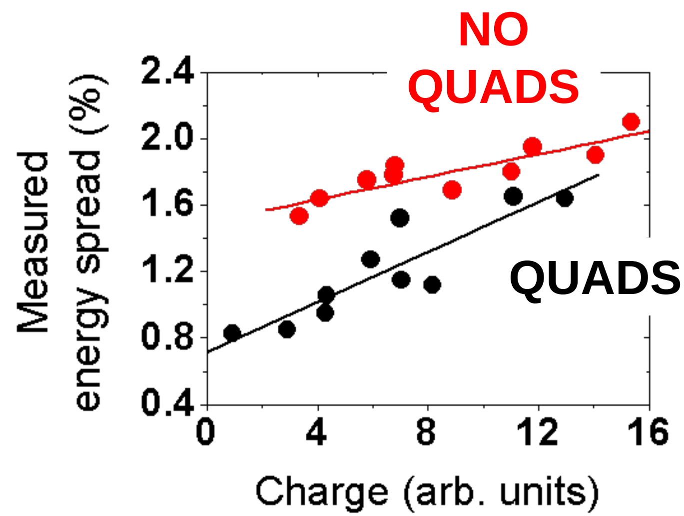


All screens now calibrated

Experimental Results – energy spectra I

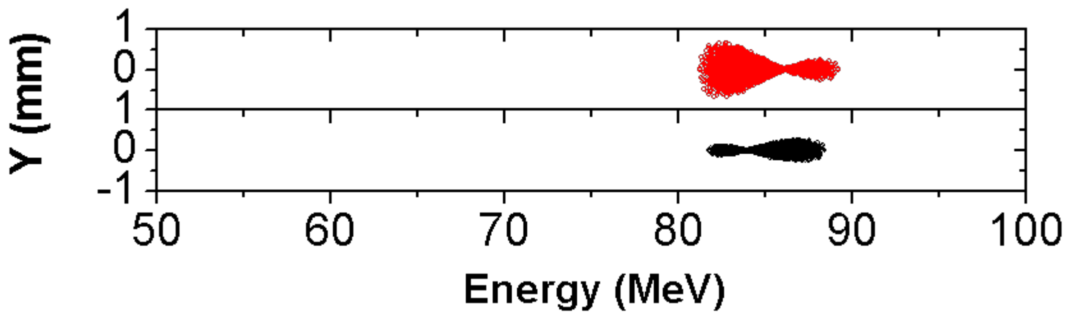




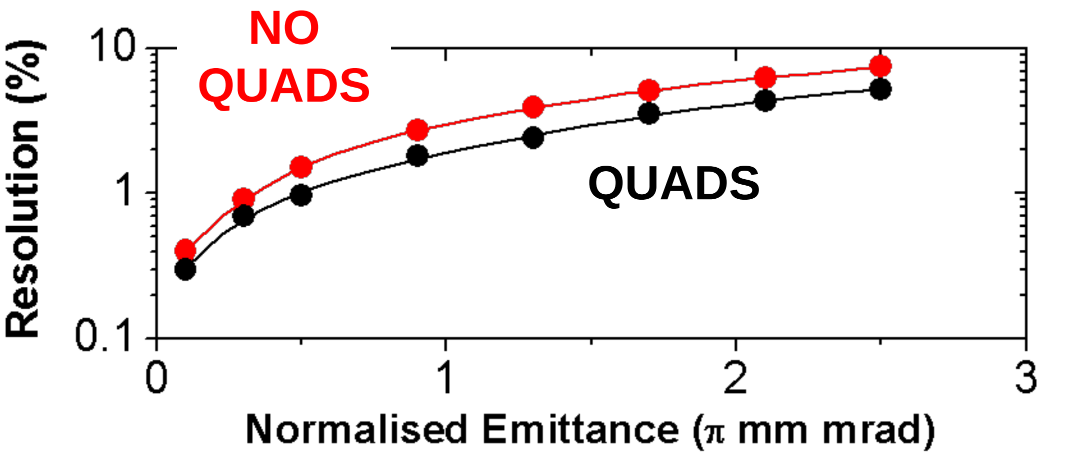


Simulations of electron spectrometer response

- 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 $\varepsilon_N = 0.5\pi$ mm mrad
zero energy spread

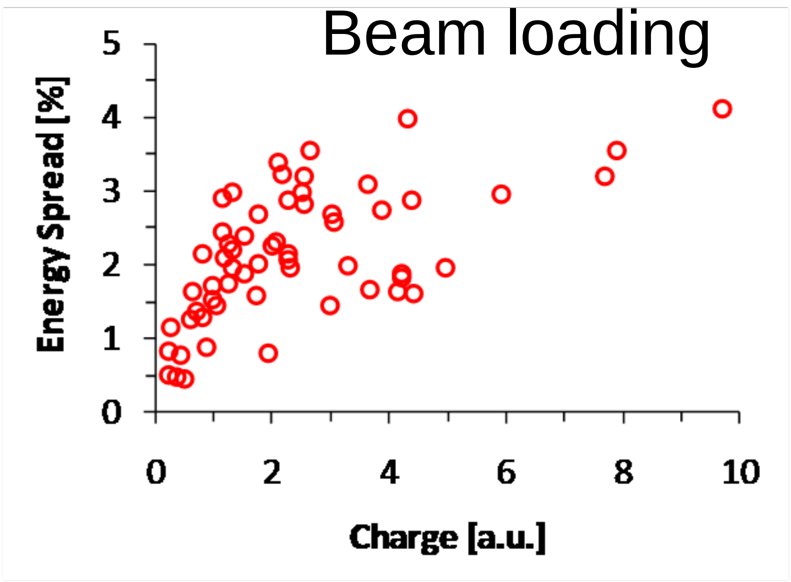


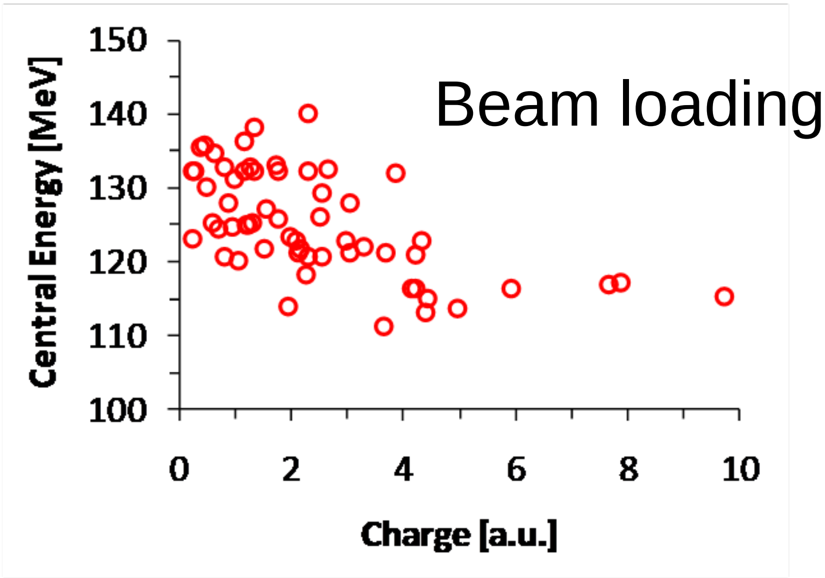
electron beam energy = 83 MeV
r.m.s. source size = 2 μm
spectrometer field = 0.59 T
zero energy spread

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

Experimental Results – energy spectra II

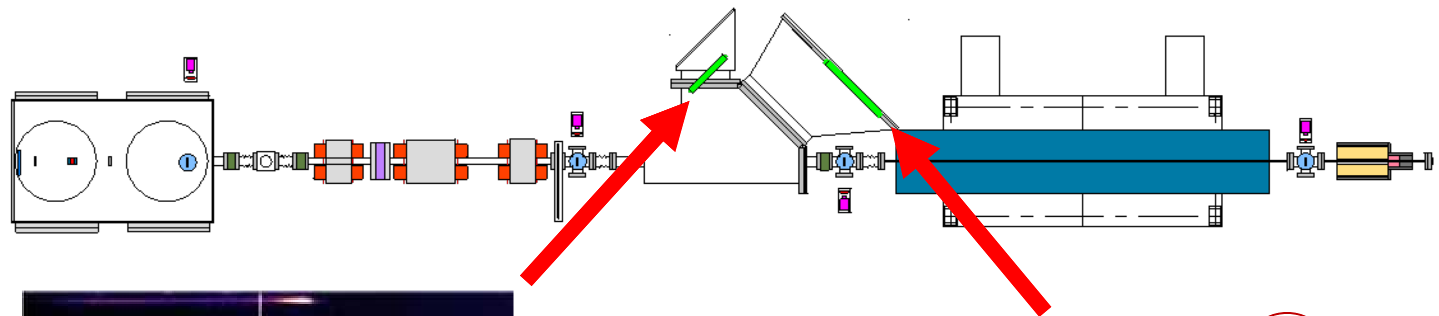
- Scaling of central energy and energy spread with charge

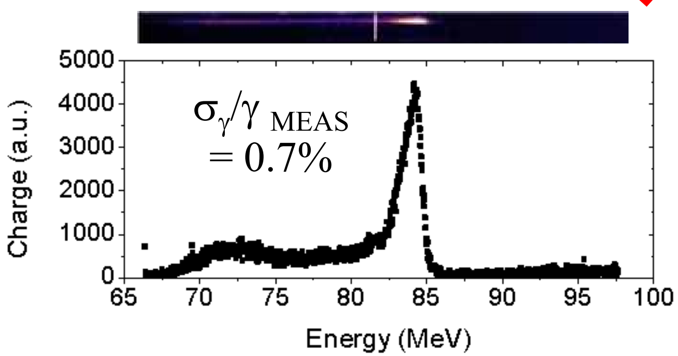


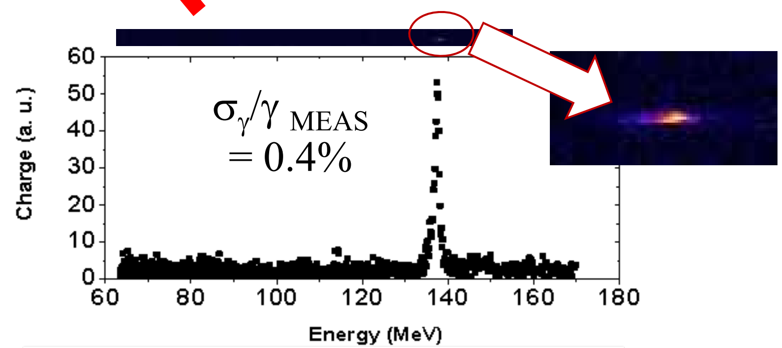


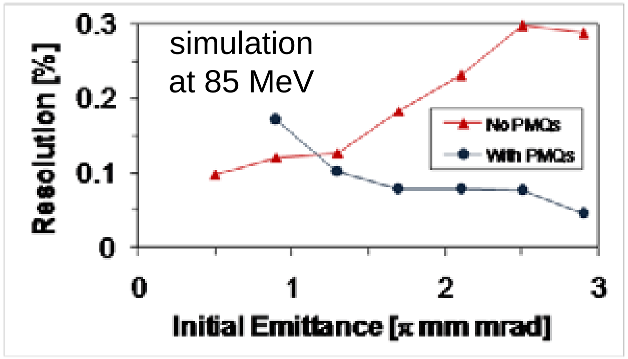
- Wiggins et al., PPCF **52**, 124032 (2010).

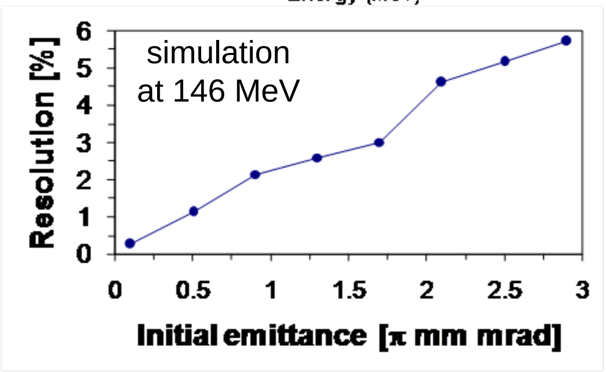
Experimental Results – energy spectra III



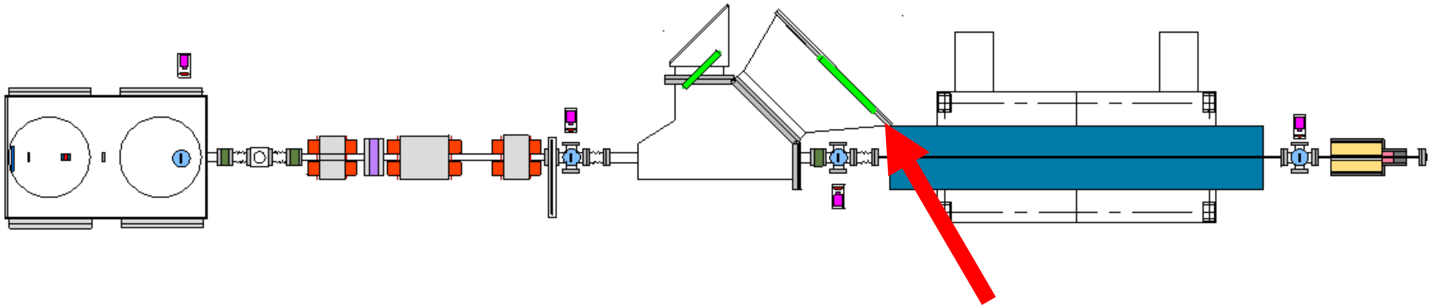


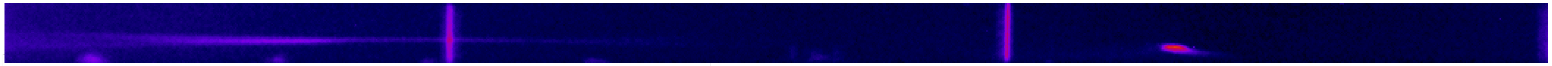


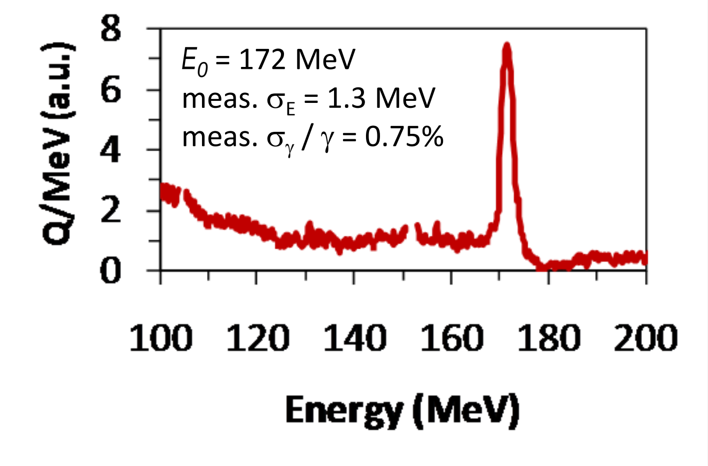


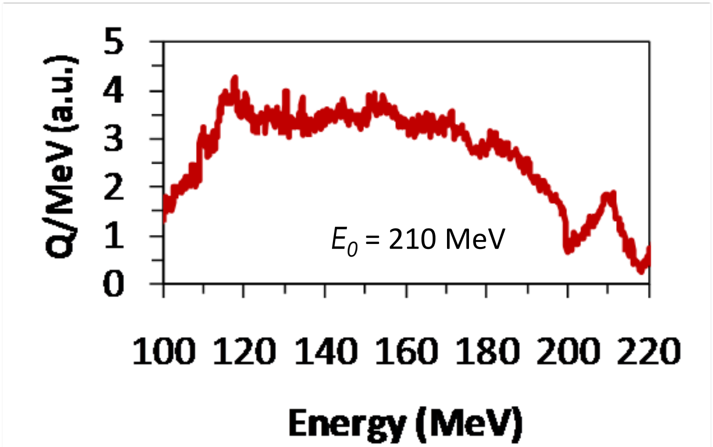


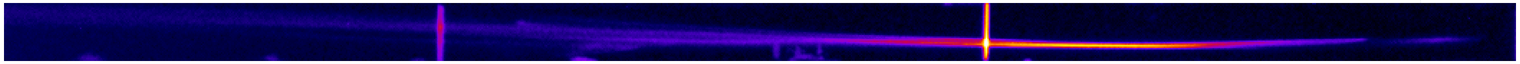
Experimental Results – energy spectra III







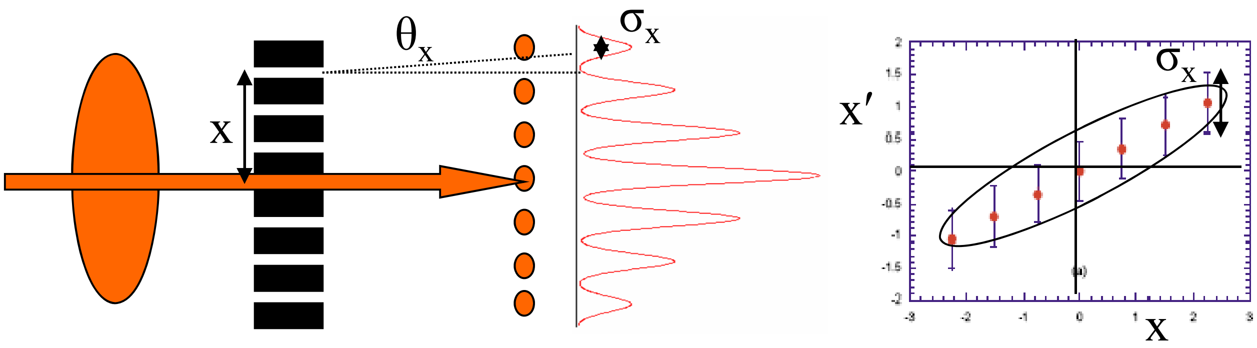




- 2mm gas jet: accelerating gradient ≈1 GeV/cm
- A hint of a fixed absolute energy spread ~ 0.6-0.8 MeV

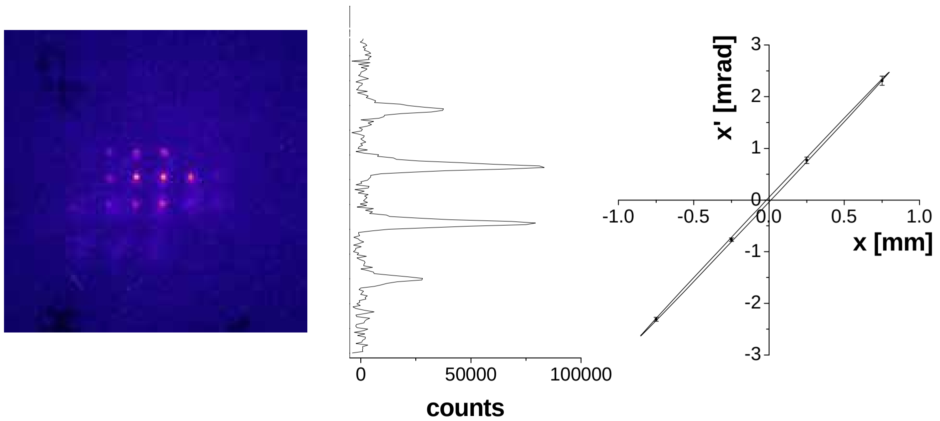
Experimental Results – transverse emittance

- 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)

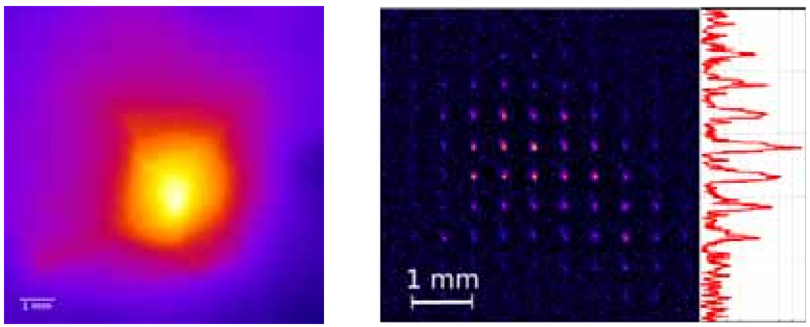
- First generation mask with hole $\phi \sim 55\ \mu m$



- divergence 4 mrad
- hole size correction
- limited by detection system
- $\varepsilon_N < (5.5 \pm 1)\pi$ mm mrad

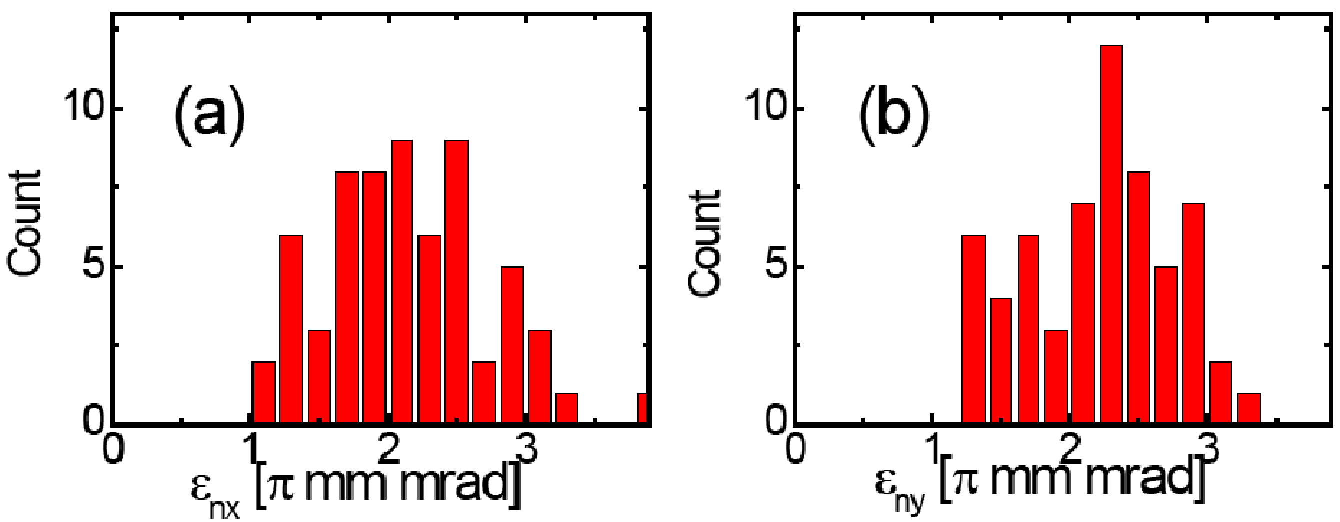
Experimental Results – transverse emittance

- Second generation mask with hole $\phi \sim 25\ \mu m$ and improved detection system

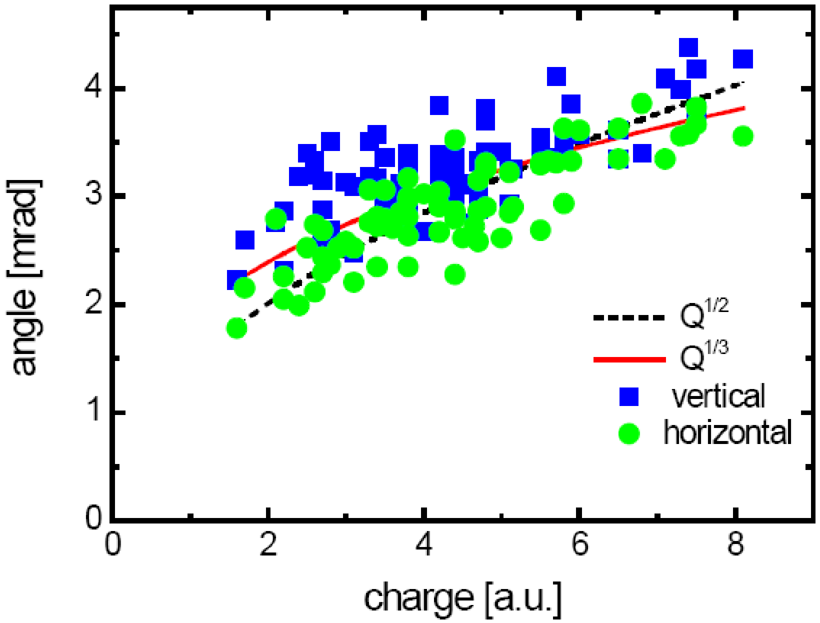


False colour image of an electron beam with and without the pepper-pot mask.

- divergence 2-4 mrad for this run with 125 MeV electrons
- average $\varepsilon_N = (2.0 \pm 0.6)\pi$ mm mrad
- best $\varepsilon_N = (1.0 \pm 0.1)\pi$ mm mrad
- Elliptical beam: $\varepsilon_{N,X} > \varepsilon_{N,Y}$
- Resolution limited



Experimental Results – transverse emittance



- 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.

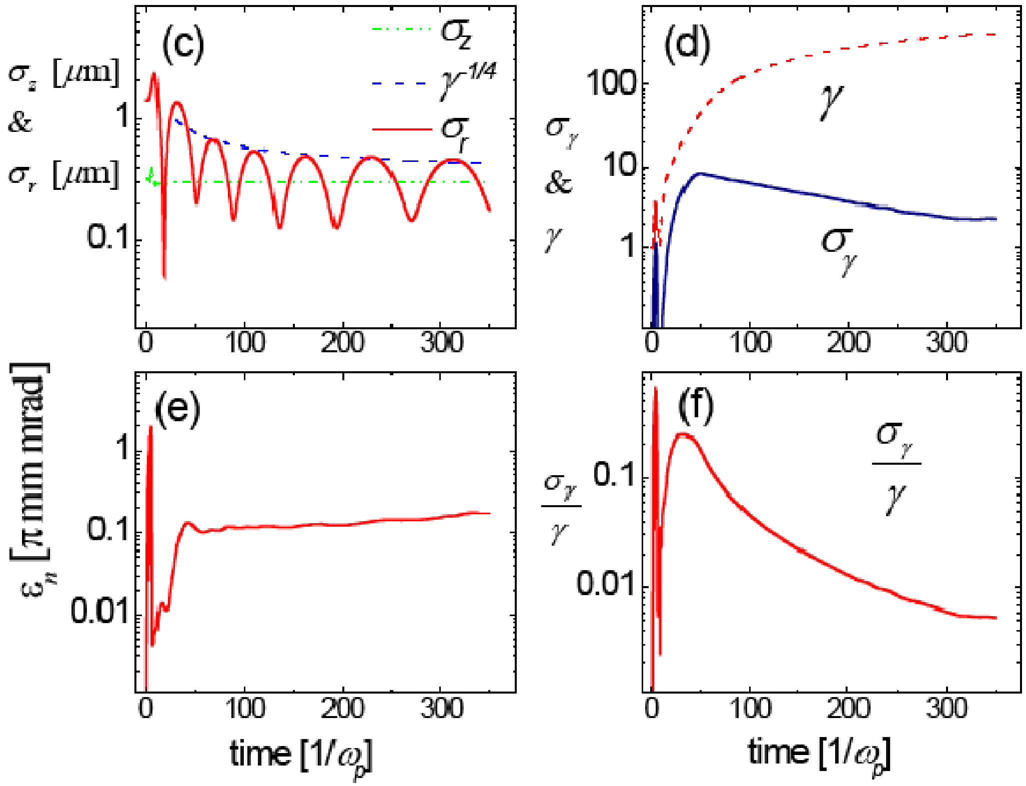
State of play

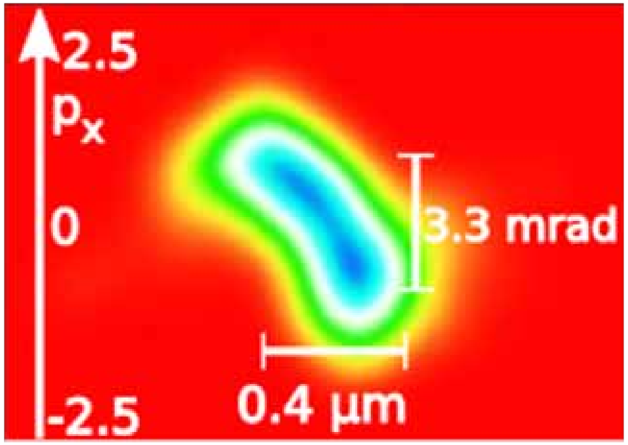
- Measured low $\sigma_\gamma/\gamma < 1\%$ ($\rightarrow$ 0% with spectrometer response)
- Measured $\varepsilon_N = 1\pi$ mm mrad (detector-limited, inferred ~0.5 π mm mrad)
- Measured $\sigma_\tau = 2$ fs
- Measured charge Q = 1-5 pC

- Why do we get these high quality beams?

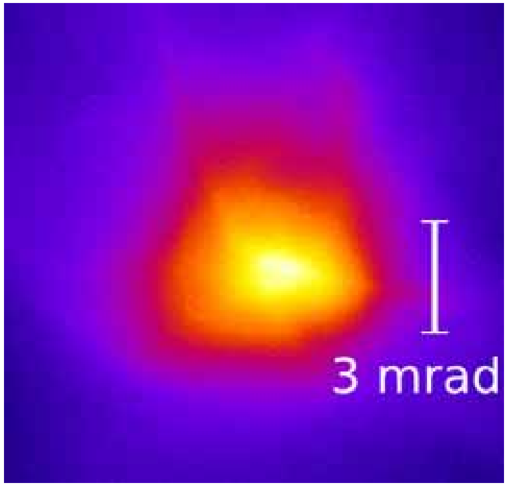
- Operating in a near-threshold, low charge regime.
- Use PIC simulations and reduced models to understand our accelerator.
- Injection of electrons from a small volume of phase-space.
- Reduced model in progress.

PIC simulations of our LWFA





Phase-space distribution



Measured beam profile

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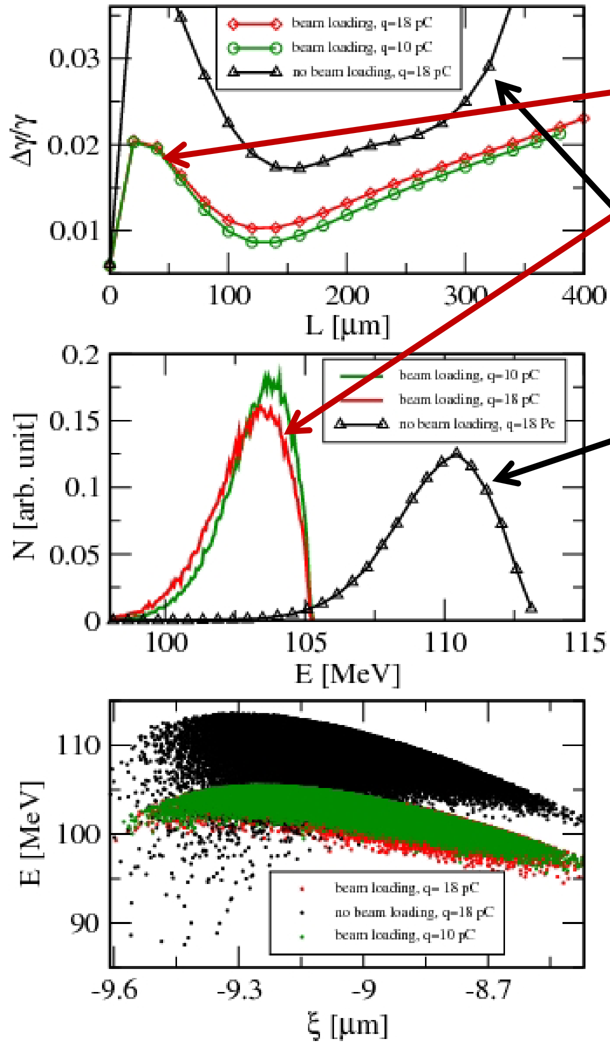
Beam loading simulations

- 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

- $\lambda_p = 7\ \mu m$
- $l_{bunch} = 1\ \mu m$

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

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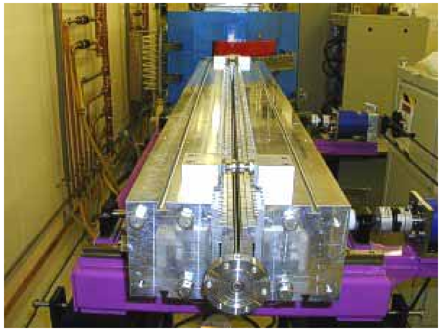
Viability of LWFA-driven FEL

- High FEL gain criteria: $\varepsilon_n < \lambda\gamma/4\pi$ & $\sigma_\gamma/\gamma < \rho$
- Experimental $\varepsilon_n \leq 1\pi$ mm mrad & $\sigma_\gamma/\gamma \leq 0.007$
- For fixed σ_γ = 0.6 MeV, σ_γ/γ reduces at short λ

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

Electron energy (MeV)	Radiation λ (nm)	Emittance criterion (π mm mrad)	Gain parameter ρ	Relative energy spread
90	261	3	0.011	0.007
150	94	2	0.006	0.004
500	8	0.6	0.002	0.001(?)

ALPHA-X Undulator

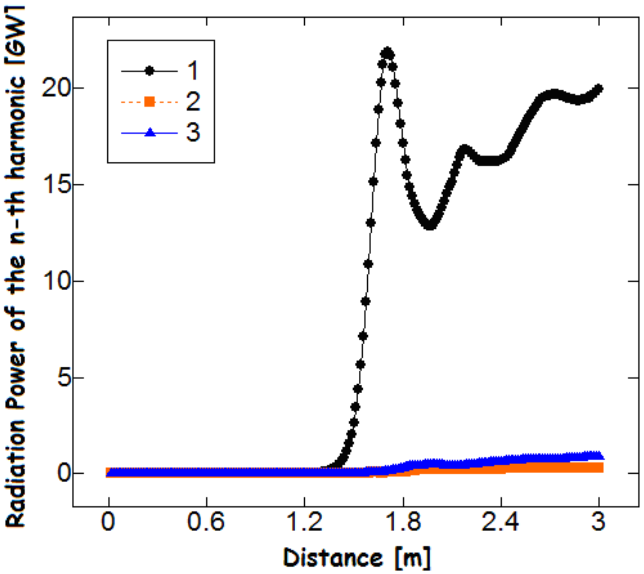


λ_u = 15 mm, N = 200, a_u = 0.38

- Actually, need to consider the slice parameters:
- slice ε_n & σ_γ/γ in a co-operation length

$$l_c = l_g\left(\frac{\lambda}{\lambda_u}\right), \quad l_g = \frac{(1+\Lambda)\lambda_u}{4\pi\sqrt{3}\,\rho}$$

FEL Simulation



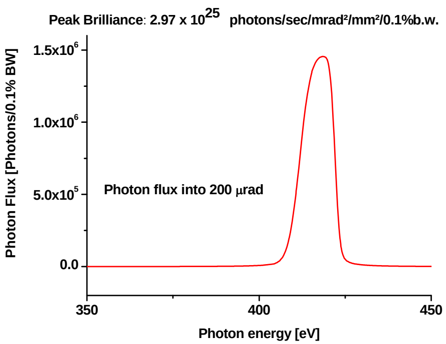
SIMPLEX CODE SIMULATION RESULTS

(100 MeV electrons)

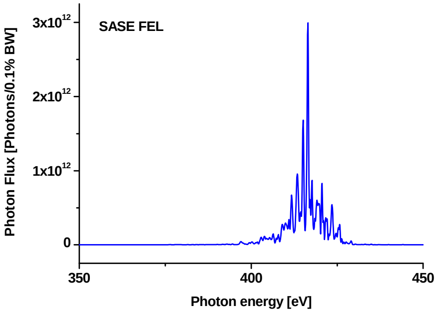
Saturation power(1st harmonic): 20 GW

@ saturation distance: 1.8 m

synchrotron radiation



matched beam SASE FEL



Synchrotron:

Peak Brilliance B = 3 x 10^{25} photons/sec/mrad^2/mm^2/0.1% BW

Average brilliance *B* = 2.5 x 10^{11} for PRF 10 Hz

With laser improvements: PRF 1 kHz $\rightarrow$ average brilliance *B* >10^{13}

FEL: *B* >10^6 times higher

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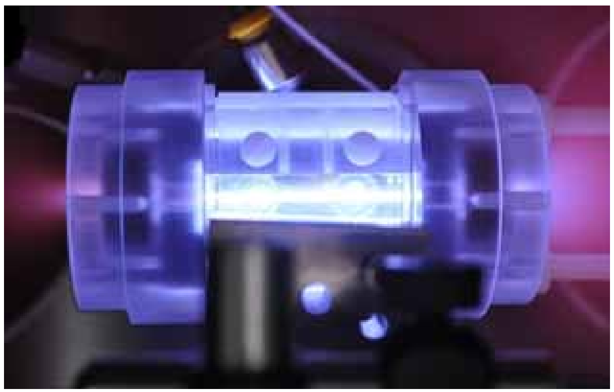
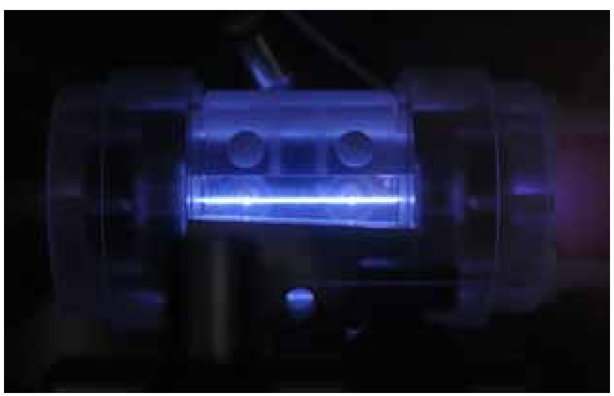
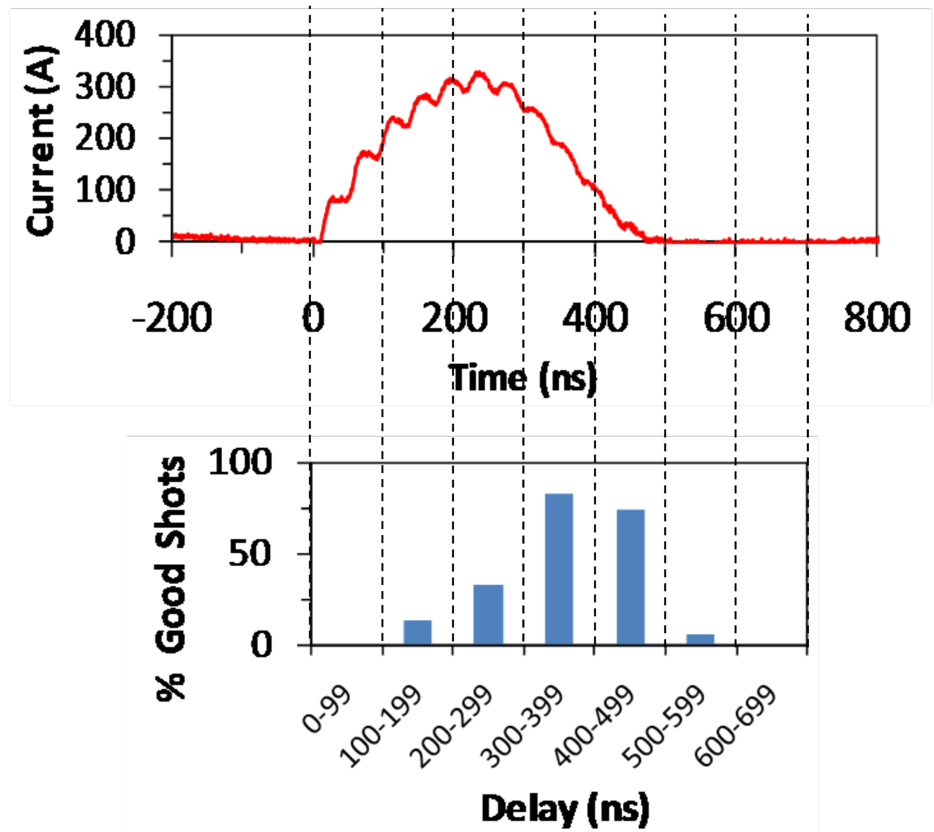
Strathclyde capillary beams

- RAL Astra Gemini experiment (X-ray betatron radiation)
- 40 mm, 280 μm capillary
- Stable electron beam generation with large plasma discharge time window.







ALPHA - X Summary

- High quality 70 – 180 MeV electron beams produced on the ALPHA-X beam line.
- energy spread, emittance, bunch length and charge are inter-connected.
- low charge for good quality with kA peak current.
- FEL gain should be observable in VUV – XUV spectral range.

Progress is advancing nicely towards a working
compact soft X-ray FEL driven by a LWFA electron beam

$\rightarrow$ long gas jet, gas cell or capillary accelerator

Thank you

ALPHA-X

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

Funded by

EPSRC
Engineering and Physical Sciences Research Council

Laserlab Europe

eli extreme light infrastructure