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

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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)

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)
Alpha-X Project

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Technicians: David Clark, Tom McCanny

Visiting Professor: Rodolfo Bonifacio

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 $\varepsilon_N$, low $\sigma_\gamma/\gamma$)
  and bright radiation sources $\rightarrow$ X-ray, gamma ray
• X-ray FEL needs $\sigma_\gamma/\gamma < 0.1\%$

• And to apply them in useful ways:
  • Medical imaging
  • Ultrafast probing
  • Detector development for nuclear physics
  • Medical applications
    $\rightarrow$ Scottish Centre for the Application of Plasma-based Accelerators (SCAPA)
ALPHA-X Beam Line

- Laser: $\lambda_0 = 800 \text{ nm}, E = 900 \text{ mJ}, \tau = 35 \text{ fs}, P = 26 \text{ TW}, I = 2 \times 10^{18} \text{ Wcm}^{-2}$, initial $a_0 = 1.0$

- Gas Jet: helium, 2 mm nozzle, $n_e \approx 1 - 5 \times 10^{19} \text{ cm}^{-3}$

- 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)

Energy (MeV)

69  90  124  185
100 consecutive shots
Mean $E_0 = (137 \pm 4)$ MeV
2.8% stability
Experimental Results – charge

Imaging Plate

LANEX 2

Imaging Plate Charge (pC)

Lanex 2 counts (x 10^8)

y = 2.488x
R² = 0.953

All screens now calibrated
Experimental Results - energy spectra I

LASER
GAS JET
ALUMINIUM FOIL
CCD
Q1 Q2 Q3
L1 L2 L3
CE:YAG CRYSTAL
ELECTRON SPECTROMETER
UNDULATOR

Measured energy spread (%)

Charge (arb. units)

Energy (MeV)

NO QUADS
QUADS

0 0.4 0.8 1.2 1.6 2.0 2.4
0 4 8 12 16

NO QUADS
QUADS
Simulations of electron spectrometer response

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

\[ \text{electron beam energy} = 83 \text{ MeV} \]
\[ \text{r.m.s. source size} = 2 \ \mu m \]
\[ \text{spectrometer field} = 0.59 \ T \]
\[ \text{emittance} \ \varepsilon_N = 0.5\pi \text{ mm mrad} \]
\[ \text{zero energy spread} \]

\[ \text{i.e. to measure small spreads, emittance must be small!} \]
Experimental Results - energy spectra II

- Scaling of central energy and energy spread with charge

![Graph showing the scaling of central energy and energy spread with charge.]

- Wiggins et al., PPCF 52, 124032 (2010).
Experimental Results – energy spectra III

\[ \frac{\sigma}{\gamma} \text{ MEAS} = 0.7\% \]

\[ \frac{\sigma}{\gamma} \text{ MEAS} = 0.4\% \]

Simulation at 85 MeV

Resolution [%]

Initial Emittance [\(\pi\) mm mrad]

Simulation at 146 MeV

Resolution [%]

Initial emittance [\(\pi\) mm mrad]
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 $\sim 600$-800 KeV
Experimental Results - emittance I

- Pepper pot mask technique

\[ \langle x \rangle \propto I^*x \quad - \text{averaged} \]
\[ \langle x' \rangle \propto I^*(\theta_x + \sigma_x) \quad - \text{averaged} \]

Emittance (rms):
\[ \varepsilon_{x, \text{rms}} = [\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2]^{1/2} \]

Direct Calculation:
(Zhang FERMILAB-TM-1988)

- 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

False colour image of an electron beam with and without the pepper-pot mask.
Experimental Results – emittance II

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

- 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 = $1.5 \times 10^{19}$ cm$^{-3}$
laser $a_0 = 3$

output electron bunch
charge ~ 1 pC
energy spread < 1%
source size ~ 0.3 µm FWHM
emittance ~ $0.1 - 0.2 \pi$ mm mrad
bunch length ~ 0.35 µm FWHM
PIC simulations of our LWFA

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

- plasma density $= 0.8 \times 10^{19}$ cm$^{-3}$
- laser $a_0 = 2$
- output electron bunch charge $= 6$ pC
- energy spread $\sim 1\%$
- source size $\sim 0.8 \mu$m FWHM
- bunch length $\sim 1 \mu$m 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

\[ \lambda_p = 7 \, \mu m \]
\[ l_{bunch} = 1 \, \mu m \]

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

**Reduced model**
- Plasma density = $1.2 \times 10^{19}$ cm$^{-3}$
- Laser $a_0 = 2.0$
- Spot size = 10 μm
- Beam volume $\sim 1 \, \mu$m$^3$

**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
Beam loading simulations

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

Implies a short bunch duration $\sigma \sim 1$ fs

$c.f$. transition radiation measurements

- Implies increasing bunch length for increasing charge
  $c.f$. divergence measurements
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).

\[ E_0 = 340 \text{ MeV}, \sigma_{\gamma/\gamma}^{\text{MEAS}} \sim 2.5\% \]

\[ E_0 = 510 \text{ MeV}, \sigma_{\gamma/\gamma}^{\text{MEAS}} \sim 3\% \]

\[ E_0 = 770 \text{ MeV}, \sigma_{\gamma/\gamma}^{\text{MEAS}} \sim 4\% \]
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 $1.1 \, \pi \, \text{mm mrad}$)
• Energy spread, emittance, bunch length and charge are inter-connected.
• Low charge for good quality with kA peak current.
• Capillary Discharge Waveguides → 100s of MeV electron beams
• LWFA-driven FEL under development
Thank you

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