Plasma Acceleration at EPAC

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A route to compact accelerators

Laser wakefield acceleration
- cm-scale gas target
- Intense laser driver
- Multi-GeV electrons

High-gradient (100 GeV/m) based on plasmas

Plasma accelerators can contribute to the next generation of colliders and light-sources
Laser-plasma accelerators go from 100 MeV to 8 GeV in a decade and half

2004-2019: A success story

2004 result: 10 TW laser, mm-scale plasma

2004 result:
- 10 TW laser
- mm-scale plasma
- ~100 MeV

2006 result:
- 40 TW laser
- cm-scale plasma
- 1.1 GeV
- <2.9%
- <1 mrad
- 10-30 pC

2014 result:
- 310 TW laser
- 9 cm-scale plasma

2019 result:
- 1 PW laser
- 20 cm-scale plasma

Contributors:
- Gonsalves et al., PRL 2019
Main challenges for laser-plasma accelerators

R & D is needed to produce consistent high quality LWFA beams for light-sources and high-energy physics applications.

The ESPP Accelerator roadmap highlights research priorities for plasma acceleration:

- **Beam quality**: high brightness, low emittance, high energy with low spread simultaneously
- **Beam stability**: Feedback and machine-learning optimization at PW laser level
- **Luminosity**: repetition rates beyond kHz with high wall-plug efficiency
- **Energy**: Staging multiple modules to reach 100s GeV energies for colliders (~30 years)

24 hour operation shown at DESY in 2020

Maier et al PRX 10, 031039 (2020)

2-stage acceleration shown at LBNL in 2016

Steinke et al Nature 530, 190 (2016)
Extreme Photonics Applications Centre

- £100M investment (UKRI & MOD)
- ~£6M p.a. expected operational cost
- Installation underway
- Operational in 2026
EPAC will be a driver for fundamental science and LPA applications

- State-of-the-art 10 Hz, 1 PW laser with two independent experimental areas
- Major upgrade to UK infrastructure for academic high-power laser community
- Focus on developing 10 Hz plasma accelerators for a range of applications in industry, medicine, defence, and security
- Improved capability for studies of fundamental science using laser-driven secondary sources
EPAC Facility Schematic

Top floor houses

- 1 PW@ 10Hz Laser areas and laser control room.
- Space for the addition of new laser systems: 2\textsuperscript{nd} and 3\textsuperscript{rd} synched beamlines
- Office space on 2\textsuperscript{nd} and 1\textsuperscript{st} floors

Ground Floor houses three double height radiologically shielded experimental areas

- Experimental area 1 (EA1) \(~38 \text{ m x 10 m,}\)
- Experimental area 2 (EA2) \(~18 \text{ m x 10 m}\)
- Future experimental area (EA3)
- Control rooms and auxiliary labs and future cleanroom space and development laser labs
EPAC Laser System

**EPAC specification**
1PW@10Hz

- Output Energy 30 J
- Pulse duration ≤ 30 fs
- Repetition rate 10 Hz, 1 Hz, Shot on Demand

- Pump for Ti:S is CLF developed 100J DiPOLE system.
- Additional space for future laser and experimental areas (eg. a 100Hz system under development)
Beam Transport

Laser Areas

EA1

2nd Floor

Ground Floor

EA2

Laser Areas

1st Floor
Shielded target areas on the ground floor

**EA1:**
Secondary source beamline
Fixed laser configuration LWFA
Flexible applications area
Electrons, x-rays, positrons, muons

**EA2:**
“Traditional” HPL target area
Large interaction chamber
Primarily high intensity solid interactions
HED, ions, neutrons

**EA3:**
Future development

Beam dumps
Control rooms & prep labs
Experimental Area 1 houses a PW-driven laser wakefield electron accelerator.

Timeline:
2023: Chambers and large equipment delivered
2024: Commissioning with internal laser
2025: Pulsed beam and LWFA commissioning
2026: Operational user facility

14 m OAP for 30 J
Focused to relativistic intensity ~ $6 \times 10^{18}$ Wcm$^{-2}$
Interaction chamber houses LWFA, diagnostics, and quadrupole magnets

Gas targets:
Jets, cells, capillaries
~cm to 10s cm

LASER & ELECTRONS

Beam and target camera

Quadrupole system for beam capture and focusing
EA1 – Application area

Secondary source parameters:
- 100 MeV – 10 GeV electrons
- 50 keV – 10 MeV tunable x-ray radiation
- Conversion to muon, positron, and γ-rays

Flexible 20m x 9m area
- Electron diagnostics
- X-ray detectors
- Sample stages
- Specialist rigs
EA1 internal view
EA1 beamline requirements

- Impact (positrons / muons / bremsstrahlung)
- Collisions (Inverse Compton Scattering & QED)
- X-ray Diffraction and Spectroscopy
- X-FEL
- Bimodal imaging (x-ray + neutron)

Equipment must be modular and portable to deliver a user program.
Start-to-end simulations

- Designing **beamlines** for various scenarios expected in EA1
- **Start-to-end** simulations – PIC for LWFA + magnet tracking codes
- Gaussian beams are **not** representative because of LWFA energy spread

**Difficulties:**
- Converting PIC output into useable input to tracking codes
- **High energy** – most LWFA beamline designs have been at 100s MeV level
- **Detail** – most published work does not fully analyse the system
- **Flexibility** – EPAC is driven by user demands, it needs to offer a choice of energy and sample position

The wide range of science demanded by EPAC means we need **multiple** beamline designs
Electron focusing for 1 GeV beam

The first set of 4 PMQs control the divergence but do not form a focus. Use the EM quad triplet to form focus at the required distance:

**Diagnostics** – spectrometer screen, transition radiation / emittance

**Sample irradiation** – high charge, broad band focussed metres from e-spec exit
Experimental priorities:
- High electron energies – 10 GeV possible
- XFEL – pushing to GeV / keV
- Industrial imaging PoC
- Sample irradiation (radiobiology, defence)
- Laser-electron collisions
Experimental Area 2 – Overview

Flexible configurations to enable a wide range of experiments

• Primary focus on high density laser-matter interactions for:
  • Optimization of secondary sources
  • Fundamental science
• Range of focal lengths to explore different regimes for ion acceleration
• Long focus can provide x-ray backlighter for HED and WDM plasma
• Future second beamline to combine multiple radiation sources
Experimental Area 2 will be a versatile area

**Timeline:**
- **2024:** Chambers and large equipment delivered
- **2025:** Area preparation
- **2026:** Commissioning experiments

**Focus Intensities:**
- **Short focus:** $\sim 4 \times 10^{21} \text{ Wcm}^{-2}$
- **Medium focus:** $\sim 4 \times 10^{20} \text{ Wcm}^{-2}$
- **Long focus:** $\sim 2 \times 10^{19} \text{ Wcm}^{-2}$
Experimental Area 2 – Internal view
Fundamental science using LWFA beams

Pioneering dual beam experiments with the Gemini laser

- Multi-GeV e- colliding with $10^{21}$ Wcm$^{-2}$ laser focus
- Measurable quantum-electrodynamic effects: radiation reaction, pair production, photon-photon scattering
- Non-linear Inverse Compton Scattering

Beamline arrangement for dual beam experiments
Configuration can easily be switched for laser-e-, laser-γ, and γ-γ collisions

EPAC will have much better stability & higher repetition-rate

Cole 2018, PRX 8, 011020; Poder 2018 PRX 8, 031004; Sarri 2014 PRL 113, 224801; Kettle 2021, NJP 23, 115006
LWFA driven Free-Electron-Laser

- 500 MeV
- Quad doublet 250 Tm^{-1} + EM + EM doublet
- 100 \mu m in the 3 undulators

Wang 2021, Nature 595, 516; Pousa 2022 PRL 129, 094801

LWFA and compact undulators can shrink size and cost but significant R&D is required
- 3 significant results in Nature recently (SIOM, INFN and HZDR)
- DESY have proposed conditioning scheme to reduce LWFA energy spread to 0.1%

EPAC aims to increase electron energies to GeV and x-ray range to keV
Preliminary calculations suggest FEL gain within 5 m
Proof-of-concept x-ray imaging using LWFA beams generated with Gemini

Gruse et al 2020, NIMA 983, 164369

Radiography and µCT at 20 keV, 30 µm resolution


EPAC will produce a range of x-ray energies suitable for dynamic imaging of composite, polymer, metallic, and dense objects

Radiography with MeV brems. ~400 µm resolution
Ultrafast XAS measurements with betatron

- Pump-probe with 10s fs temporal resolution – competitive with XFELs
- Studies of ultrafast transitions in HED plasmas
- Industrial product development – materials, batteries, photovoltaics

EPAC will increase the quality and acquisition rate of XAS data

Single-shot XANES and EXAFS of Cu edge

Kettle 2019, PRL 123, 254801; Kettle 2022 submitted
Stable LWFA operation over extended periods

DESY beamline proved LWFA can be stable
Fluctuations correlated to laser and target parameters and can be stabilised with feedback loops

Optimization using machine-learning techniques
Laser pulse shaping and varying gas target parameters optimises the specified property (e.g. electron energy, x-ray flux etc)

Bayesian optimisation of LWFA
Shalloo et al Nature Comm. 11, 6355 (2020); Jalas et al PRL 126, 104801 (2021)

Electron beam energy over 24 hours
Maier et al PRX 10, 031039 (2020)
High rep-rate targetry

To meet the increasing rep rate there is a change in focus from single component manufacture and machining to batch and high rep rate production. Collaborations and developments internally and externally are helping us to meet this challenge.

Tape targets with a 2µm position stability
Liquid sheets for plasma mirrors and targets
MEMS fabrication for mass-produced complex targetry
10Hz operation introduces novel issues for laser-plasma diagnostics
• Afterglow / radiation hardness of scintillators
• Resolution / sensitivity to fully benefit from micron source size
• Flexibility to deal with unknown source performance

EPAC will record many diagnostics at high repetition-rate
• Up to 5 GB/s; 1 – 2 PB annually
• Data held centrally and accessed through STFC cloud
• Data analysis packages under development with remote access
• A new regime for high-power lasers but have expertise within STFC
A large (international) collaboration is involved in building EPAC

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<thead>
<tr>
<th>CLF</th>
<th>Scientific Computing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>ASTeC</td>
</tr>
<tr>
<td>ISIS</td>
<td>SCAPA</td>
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<td>Technology</td>
<td>EPIC (India)</td>
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EuPRAXIA will drive plasma accelerators producing 10 GeV electron beams at 100 Hz:
• Sources with unprecedented properties for industrial and medical applications
• Laser driven XFEL

EuPRAXIA will be located at two sites:
• Beam-driven based at INFN, Frascati
• Laser-driven to be decided – EPAC is one of four shortlisted sites
• EPAC building could be extended for EuPRAXIA Experimental Areas

Preparatory phase (Nov 22 – Oct 26) is funded (3.5 M€)
• Choose second site (by 2024)
• Develop pre-TDR
• Project cost estimated 600 M€
Summary

Laser-driven accelerators are maturing

- LWFA has produced multi-GeV beams with reasonably low emittance, low energy spread, and high brightness but not simultaneously and continuously

- Producing high-quality beams from LWFA is central to proving their suitability for future large-scale facilities (eg. FELs, colliders…)

EPAC hopes to provide some milestones along the way, along with exploiting their applications