Plasma Wakefield Acceleration: The ASTeC Perspective

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ASTeC and the Cockcroft Institute

STFC & IoP PAB Workshop on Plasma Wakefield Acceleration
31st January 2014
Relevant Current Activities

ALICE – energy recovery linac and IR FEL

EMMA – non-scaling FFAG

VELA – RF photoinjector

Electron facilities, driven by STFC strategy, for academic and industrial users. Advanced technology demonstrations – SCRF, NCRF, single pass diagnostics, undulators, photocathode materials, THz bunch manipulation, ...
Relevant Current Activities

High strength, *tuneable*, Permanent Magnet quadrupoles (for CERN)

IEEE Trans ASC 24, 3, 4003205 (2014)
(Patent pending)

Laser generated THz used to manipulate electron bunch phase space on ALICE
Relevant Current Activities

Electro-optic diagnostics – Encoding electric field temporal profiles into optical probe intensity variations

Many demonstrations...

- Accelerator Bunch profile - FLASH, FELIX, SLAC, SLS, ALICE, FERMI, CERN, ... CLF, MPQ, Jena, Berkley, ...
- Laser Wakefield experiments - FLASH, FELIX, SLS, ...
- Emitted EM (CSR, CTR, FEL) -

Temporal Decoding @FLASH

CSR @FELIX

Mid-IRFEL lasing @FELIX

Laser Wakefield @ Max Planck Garching

Few facility implementations: remaining as experimental / demonstration systems

Relevant Current Activities

Beam optics design and phase space control & measurement

CLARA lattice from bunch compressor to dog-leg entrance

Simulation of CLARA bunch streaked by transverse deflecting cavity for slice measurements
Relevant Current Activities

Free electron laser design and modelling

Simulation results for the seeded harmonic cascade scheme in CLARA, showing peak power along the radiator compared to an equivalent SASE case (top), and the pulse properties at saturation (bottom).

Recent papers (with Strathclyde):
PRL 110, 104801 (2013)
PRL 110, 134802 (2013)
Nat. Photonics 4, 814 (2010)
Free Electron Lasers

- **FELs have made huge advances in the past few years**
  - First X-ray FEL in 2009 (LCLS) then SACLA in 2011
  - More X-ray facilities are under construction
  - Advanced soft X-ray facilities are also now operating routinely for users as well (FLASH & FERMI)

- **The potential for improvements is enormous**
  - Better temporal coherence
  - Better wavelength stability
  - Increased power
  - Better intensity stability
  - Much shorter pulses of light
  - Two-colour or Multi-colour output
  - ...
There Are Many Ideas!

- Many ideas to improve FEL output in these and other areas
- Most of these are **UNTESTED** and new ideas are emerging regularly
- Existing FELs have many users and high demand, so have little time for trying new things
- Only 3 FEL test facilities worldwide, and these mostly focus on temporal coherence (single wavelength) studies.
CLARA

• **We are proposing that the UK hosts a new dedicated flexible FEL Test Facility**
  - Capable of testing the most promising new schemes
  - A major upgrade of VELA (RF photoinjector user facility)

• **We have strategically decided to target ultra short pulse generation**
  - We are looking at the longer term capabilities of FELs, not short term incremental improvements
  - *Taking FELs into a new regime*
  - By demonstrating this goal we will have to tackle all the challenges currently faced by state of the art FELs (and a few more!)
To achieve our ultimate goal we will have to understand and overcome a large number of challenges – the same challenges that any advanced FEL must tackle.

The UK will therefore have the skills for any future FEL – no matter what the user requirements are.

CLARA must be an outstanding facility to reach this goal.
International Context

There are only **three** dedicated single pass FEL test facilities worldwide. We have assessed the capabilities and programmes of each of these facilities in turn and have confirmed that CLARA will offer unique capabilities and have a complementary programme to the other test facilities.

- **The NLCTA** at SLAC is a low energy (120 MeV) test accelerator deliberately focussing on near term R&D. The main goal of this facility is the development and optimization of EEHG for the improvement of temporal coherence and the generation of very high order harmonic generation.

- **The SDUV-FEL** in Shanghai first observed SASE lasing in 2009 and this has been followed by seeded FEL experiments, EEHG, and other techniques for generating high harmonics from a seed laser, such as HGHG. This is likely to morph into a user facility very soon.

- **The SPARC** test FEL at Frascati currently operates at 150 MeV with a planned upgrade to take it to 250 MeV. SASE lasing has been demonstrated and characterised, and direct High Harmonic Generation (HHG) seeding is being studied. SPARC has also carried out some short pulse experiments including energy chirped electron beams and undulator tapering and seeded superradiance. The facility capabilities are limited by the available space.
Goals, Opportunities and Benefits

• The proof of principle demonstrations of ultra-short photon pulse generation using schemes which are applicable to X-ray FELs and with extreme levels of synchronisation.
• The ability to test other novel schemes for increasing the intrinsic FEL output intensity stability, wavelength stability, or the longitudinal coherence using external seeding, self-seeding or other methods.
• The ability to generate higher harmonic radiation of a seed source using EEHG, HGHG, etc.
• The generation and characterisation of very bright (in 6D) electron bunches and the manipulation of the bunch properties with externally injected lasers.
• Enabling 5th Generation Light Source research: combining wakefield acceleration with electron bunch transport, characterisation, and matching to FEL.
• The development of advanced accelerator technologies, such as high repetition rate photoinjectors, novel undulators, RF structures, single bunch low charge diagnostics, and novel photocathode materials and preparation techniques.
• The enhancement of VELA, in terms of energy, beam power, and repetition rate.
• The development of vital skills within the UK accelerator community, including providing excellent opportunities for PhD students and post docs to work on a world class accelerator test facility.
• To use the electron beam for other potential applications, such as: ultrafast electron diffraction, plasma wakefield accelerator research, Compton scattering source of X-rays or gamma photons, dielectric wakefield acceleration, ...
Total length = 95m
Acceleration length = 17m
CLARA Parameters

Parameters have been generated to cover **4 different operating modes**.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Seeding</th>
<th>SASE</th>
<th>Ultra-short</th>
<th>Multibunch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Energy (MeV)</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Macropulse Rep Rate (Hz)</td>
<td>1–100</td>
<td>1–100</td>
<td>1–100</td>
<td>1–100</td>
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<tr>
<td>Bunches/macropulse</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>16</td>
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<tr>
<td>Bunch Charge (pC)</td>
<td>250</td>
<td>250</td>
<td>20–100</td>
<td>25</td>
</tr>
<tr>
<td>Peak Current (A)</td>
<td>125–400</td>
<td>400</td>
<td>~1000</td>
<td>25</td>
</tr>
<tr>
<td>Bunch length (fs)</td>
<td>850–250 (flat-top)</td>
<td>250 (rms)</td>
<td>&lt;25 (rms)</td>
<td>300 (rms)</td>
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<tr>
<td>Norm. Emittance (mm-mrad)</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
</tr>
<tr>
<td>rms Energy Spread (keV)</td>
<td>25</td>
<td>100</td>
<td>150</td>
<td>100</td>
</tr>
<tr>
<td>Radiator Period (mm)</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>

FEL output wavelengths from 400 nm to 100 nm
- Can make use of 800 nm laser for harmonic generation experiments
- Can use well established laser diagnostics for single shot pulse length measurements
- No need for long photon beamlines, can deflect by 90°
VELA

Initial Commissioning complete – first users September 2013
CLARA Status

- The CDR has been published (July 2013)
- The project has now been split into **two phases**
  - Phase 1 is happening now, procurement is progressing
    - Installation in 2015
  - **Phase 2 is not funded yet**
- SwissFEL (PSI) are providing the 3 linacs needed for Phase 2 together with a number of quadrupoles and solenoids (available Q4 2014) – **a very significant contribution!**

*Contributors: ASTeC, CI, DLS, INR Moscow, JAI, Oxford, Huddersfield, Lancaster, Liverpool, Manchester, RHUL, Strathclyde, SwissFEL*
VELA + CLARA Phase 1 (2015)

- **Will enable access to bright, short, up to ~50 MeV electron bunches for UK accelerator science and technology community**
- Will enable new high rep rate photoinjector to be characterised with beam whilst VELA/CLARA Phase 1 still operational (i.e. two guns)
- Potential for early exploitation of 20 TW laser
- Will enable higher energies for industry in the VELA user areas
- Will provide valuable experience with NC Linac & RF infrastructure before CLARA Phase 2
- Will save time when CLARA Phase 2 is funded

### Phase 1 parameters:

- **Max Energy**: ~50 MeV
- **Max Charge**: 250 pC
- **Norm. Emitt.**: <1 mm mrad
- **Min Bunch Length**: 50fs (rms), (10 MeV)
- **Max Peak Current**: 2kA
- **Bunches/RF pulse**: 1
- **Pulse Rep Rate**: 10 Hz (400Hz later)

0.8 J, 40 fs, Ti:Sa 20 TW
Exploitation of CLARA: Plasma Acceleration

Hybrid LWFA & PWFA

Rethink LWFA and PWFA: laser pulses are great for ionization, while electron bunches are better drivers.

Use the best of both worlds!

Use oscillating fields from laser pulse to ionize and to generate low-transverse momentum electrons.

ionization @~$10^{14}$ W/cm², produced electrons will receive very low transverse momentum (Lawson-Woodward)

Use unidirectional transverse fields from e-bunch to kick out electrons and to excite blowout.

ionization if $E_r > 5 \text{ GV/m}$

blowout if $n_b > n_e$
Exploitation of CLARA: Plasma Acceleration

What’s needed:
- LIT/HIT medium
- electron bunch driver to set up LIT blowout
- synchronized, low-intensity laser pulse to release HIT electrons within blowout
Exploitation of CLARA: Plasma Acceleration

CLARA: *both laser pulse and electron bunch*

CLARA has it both:

- intense laser pulse (Ti:Sa, 40 fs, 20 TW, S. Jamison)
- intense electron bunch

→ *predestined for hybrid PWFA schemes and applications*

CLARA has edge over existing and planned PWFA facilities:

- dedicated beamtime, not parasitic
- Excellent synchronization between laser pulse and electron bunch possible
- VELA/CLARA energy range ideal: not too low (can drive a plasma wave over extended distance), not too high (lower plasma wave phase velocity; allows for accurate driver and witness bunch diagnostics)
- Could start first experiments soon (laser-beam synchronization, electron beam diagnostics, gas jet/cell implementation, plasma lensing…)
- Could shape drive beam current profile to allow for higher transformer ratio/wake potential
Exploitation of CLARA: Plasma Acceleration

Summary

- there is absolutely a need for CLARA!
- various (hybrid) electron driven PWFA schemes can be tested
- underdense photocathode promises highest quality bunches (e.g., brightness >> LCLS)
- may lead to 5th gen. FEL light source
- University of Strathclyde/SCAPA to bring in
  a) laser & LWFA know-how (long-lasting collab. with S. Jamison et al.)
  b) plasma know-how (plasma sources, downramps etc.; collab. with G. Xia et al. has already begun)
  c) hybrid schemes
  d) underdense photocathode for highest beam quality
  e) FEL modelling of plasma-generated bunches (B. McNeil et al.)
- facility would have an absolute edge over other planned facilities, plus may arrive early
- collaboration w/ FACET/SLAC (E-210: Trojan Horse PWFA), UCLA (where LWFA & PWFA was invented), DESY/Uni Hamburg/CFEL...
  CLARA to have highest int’l visibility.

...
Exploitation of CLARA: Plasma Acceleration

Plasma Accelerator Research Station at CLARA

- Compared to electron driven plasma wakefield experiments at ATF@BNL, FACET@SLAC, FLASH II @DESY, INFN Frascati, beam energy at CLARA is intermediate, easy to handle and less radiation.

- Many interesting topics will be investigated:
  - Two bunch experiment (crafting two bunches via laser or mask collimator, one for driving plasma wakefield, the other for sampling the wakefield); for demonstrating energy doubling of CLARA beam.
  - Beam shaping study for high transformer ratio (beam density profile shaping by shaping the laser pulse), e.g. multi-bunches or hard-edge beam can be an ideal driver beam;
  - Self-modulation of a long electron bunch—provide inputs to CERN proton-driven PWFA experiment (AWAKE);
  - As the electron injector for a laser-driven wakefield acceleration (combined with LWFA research).

G. Xia, IoP CLARA Community Meeting, 2014
Exploitation of CLARA: Plasma Acceleration

VORPAL calculations from J. Smith, Tech-X using new Hartree HPC
A Stage 1 baseline specification that we envisage should be available from day one of the facility operation is:

- High brightness (more than $10^{11}$ photons/pulse) pulsed coherent light source coverage from THz to ~1 keV (with harmonics to ~5 keV)
- ~1 kHz repetition rate with even pulse spacing
- Photon source capable of smooth tuning across most of the spectral range
- Pulse durations down to ~20 fs
- Multi-colour capability for pump-probe experiments with synchronization jitter better than 10 fs. For example, Colour 1: THz- IR (pump)/ Colour 2: 100 eV-5 keV (probe)
- High degree of temporal coherence of fundamental and harmonics through seeding of the FEL

NLS CDR, 2010

Total length ~ 700 m
Acceleration length ~ 200 m
Energy = 2.25 GeV
Upgrade path to 1 MHz
LWFA-based FEL User Facility?

- The potential advantages of LWFA FEL are significant
- The LWFA experimental results continue to make progress
- There is still a long way to go before a NLS-like *user facility* could be credibly proposed

**LWFA-based FEL User Facility**

- **LWFA generated beam**, optimised for FEL, repeatable, stable, ...
- **Electron transport**, diagnostics, manipulation, matching to FEL, ...
- **Optimised FEL**, matched to LWFA beam characteristics
Scale of the Challenge: Plans at DESY

LAOLA: Related Projects and Schedule

2012 2013 2014 2015 2016 2017 2018

laser driven

- LUX: LWFA driven undulator & FEL
- REGAE: low energy injection

beam driven

- SINBAD: ARD distributed facility at DESY
- FLASHForward: high energy injection, Trojan horse
- PIZZ: self-modulation & high transformer ratio

Well funded programme targetting $x10$ in gain over spontaneous within 5 years

We require gain of $\sim 10^8$ for a user facility
Electron Transport

- The capture and transport of ultrashort, highly divergent bunches, with (relatively) large energy spread requires different approaches to manage the acceptance of magnetic transport systems.
- Preservation of the bunch quality in the presence of coherent synchrotron radiation and wakefields will be a major challenge with femtosecond bunches.
- The design difficulty is proportional to the beam energy spread, and inversely to the bunch length.
- **LWFA currently operate in a regime where both properties collude in exactly the wrong way!**

Sample tracking results of a 1% energy spread, 100 pC, 10 fs FWHM bunch with ELEGANT shows that quads, sexts, and octs are essential to ~preserve the bunch properties.  
J. Jones, ASTeC
LWFA Generated Beam & Electron Beam Transport: CLF Extension

Well aligned with needs of LWFA FEL, essential to have dedicated target and beamline

ASTeC science & technology capabilities can support wider-range science programmes

Plasma accelerator facility – CLF extension – an aspiration of the UK community

- Laser areas at 2nd floor including area for R&D on promising alternatives of next gen laser technology
- Dedicated experimental user areas for electron based work (gas target)
- Dedicated area for innovation and campus exploitation
- Dedicated experimental user area for ion / proton / neutron (solid target) work

Design and layout: CLF
LWFA-based FEL Challenges

- Energy spread is currently the most significant spoiler mechanism.
- The FEL interaction is severely affected with greatly reduced saturated powers and significantly longer saturation lengths.

- For NLS, $\rho \sim 2 \times 10^{-3}$
- For LCLS, $\rho \sim 5 \times 10^{-4}$

R. Bonifacio¹, L. De Salvo Souza and B.W.J. McNeil  *Optics Communications* 93 (1992) 179–185

B McNeil, Strathclyde
Mitigating Energy Spread*

Pre-conditioning the electron beam between the plasma accelerator and FEL entrance can improve the slice energy spread of the beam.

This can be done in e.g. a chicane which stretches out the energy chirped beam.

The reduction in energy spread is proportional to the stretch factor.

*Maier et al., PRX 2, 031019 (2012)
Diffraction*

The Rayleigh length $Z_R$ is that in which a beam diffracts to twice its transverse mode area. In an FEL amplifier, if the gain length of the FEL interaction is much greater than the Rayleigh length then diffraction will cause reduced coupling and longer saturation lengths.

$$Z_R = \frac{2\pi y_b^2}{\lambda_r} = \frac{2\pi \varepsilon_n \beta}{\lambda_r \gamma}$$

- Smaller emittance = larger diffraction

$$\rho \propto \left( \frac{I}{\gamma^2 \varepsilon_n \beta} \right)^{1/3}$$

- Smaller emittance = stronger FEL coupling

Too much diffraction can kill the FEL gain due to losses. The emittance can be too small!

*See: Saldin et al., NJP 12, 035010 (2010); Campbell et al., Phys. Plamas, 19, 093119 (2012) for further details

B McNeil, Strathclyde
FEL Modelling

• PUFFIN – A three dimensional, unaveraged free electron laser simulation code
• The *only* FEL simulation code that self-consistently models plasma-accelerator driven FEL interactions in all of their diversity:
  - Chirped beam
  - Ultra-short bunches
  - Multiple energy beams
  - …
• In demand internationally by other LWFA groups
• Installed on Hartree HPC

PHYSICS OF PLASMAS 19, 093119 (2012)

Puffin: A three dimensional, unaveraged free electron laser simulation code

L. T. Campbell\textsuperscript{1,2,a} and B. W. J. McNeil\textsuperscript{1,b}
\textsuperscript{1}University of Strathclyde (SUPA), Glasgow G4 0NG, United Kingdom
\textsuperscript{2}ASTeC, STFC Daresbury Laboratory and Cockcroft Institute, Warrington WA4 4AD, United Kingdom
Towards a LWFA-based FEL User Facility: A Coordinated Approach for the UK

Common goal defined by STFC

LWFA-based FEL User Facility

National co-ordinated programme, bringing together the accelerator, plasma, and FEL communities, focussed on a common goal

LWFA generated beam, optimised for FEL, repeatable, stable, ...

Electron transport, diagnostics, manipulation, matching to FEL, ...

Optimised FEL, matched to LWFA beam characteristics

Facilities

CLF, SCAPA

CLF, CLARA, SCAPA

CLARA, SCAPA

Expertise

CLF, IC, Strathclyde, JAI, QUB, ...

ASTeC, CI, JAI, ...

ASTeC, CI, DLS, JAI, Strathclyde, ...

Hartree, Vorpal, Osiris, ...

Hartree, ELEGANT, ASTRA, ...

Hartree, PUFFIN
Summary

• ASTeC has expertise in the design and simulation of electron accelerators and FELs
• We also have expertise across the relevant technologies
  • Undulators
  • RF Systems
  • Single shot diagnostics
  • Phase space manipulation with THz or RF
  • Photoinjectors
  • Permanent Magnet quadrupoles
• We are ready and want to contribute to a coordinated programme in the utilisation of LWFA towards a FEL user facility
• CLARA Phase 1 (2015) will enable beam driven work in the UK (amongst other things) and the 20 TW laser could also be exploited early
• CLARA Phase 2 (not yet funded) will expand these capabilities and also enable world leading experiments of RF driven FEL and, with further support, LWFA FEL
• The UK has three strong communities (plasma, accelerator and FEL) and much can be gained from bringing them together and giving them a common goal!