Plasma Acceleration in John Adams Institute and beyond

Andrei A. Seryi
John Adams Institute for Accelerator Science

STFC & Particle Accelerators and Beams group workshop on Plasma Wakefield Acceleration

31 January 2014
Plasma acceleration in JAI and beyond

- Plasma acceleration – new perspectives
  - Evolution of accelerator communities
  - UK community contributions
  - UK community aspiration
  - JAI contribution
    - Three main directions
    - Novel promising ideas in laser-plasma
    - Collaborations and training
  - UK & overall European plans
- Summary
Accelerators
Plasma
Lasers

Compact light sources
HEP discovery machines
Impact on society within ~5 years
HEP applications in ~20 yrs or more
Plasma acceleration in JAI and beyond

- Plasma acceleration – new perspectives
  - Evolution of accelerator communities
    - UK community contributions
    - UK community aspiration
    - JAI contribution
      - Three main directions
      - Novel promising ideas in laser-plasma
      - Collaborations and training
    - UK & overall European plans
- Summary
The merge characterized by leading labs creating flagship facilities and experiments aimed at plasma acc.
Plasma acceleration – new perspectives

Evolution of accelerator communities

UK community contributions

UK community aspiration

JAI contribution
- Three main directions
- Novel promising ideas in laser-plasma
- Collaborations and training

UK & overall European plans

Summary
• 2004: First quasi-monoenergetic beams generated (IC & Oxford & Strathclyde, LBNL, LOA)

• 2006 First GeV beams generated (Oxford & LBNL)

• 2008 Generation of visible radiation in undulator (Strathclyde & Jena)

• 2009 Measurement of $E_z L \sim 1$ GeV in weakly nonlinear regime (LPGP, Strathclyde, Lund, JIHT)

• 2009: Generation of extreme UV radiation in undulator (MPQ & Oxford)

• 2011: Biological imaging with betatron radiation (IC, Michigan & MPQ)

• Aug 2013: Acceleration to 4.2 GeV (15J, 40fs) BELLA, LBNL
Achievements of UK community in plasma acceleration in large extend depend on access to national laser facility

Laser facilities at CLF are oversubscribed many times

The need to enhance national capabilities in this area is critical
• Plasma acceleration – new perspectives

• Evolution of accelerator communities

• UK community contributions

• UK community aspiration

• JAI contribution
  – Three main directions
  – Novel promising ideas in laser-plasma
  – Collaborations and training

• UK & overall European plans

• Summary
The next two slides is the result of several pre-meetings, Webex and email consultations within the community

- Discussed with ASTeC, CI, CLF, JAI, Imperial, Oxford, Strathclyde Univ., Queen’s Univ., …

The endorsement for this message is strongly emerging

Today’s speakers will comment on various aspects of the message

We hope this strong message from the community will be heard
Plasma accelerator facility – CLF extension –
an aspiration of the UK community

• The vibrant UK plasma accelerator community is strongly endorsing creation of dedicated plasma acceleration facility at extension of CLF

• This facility will:
  – Enable the strategic development of plasma based accelerators
  – Build up on UK strength, and many pioneering results by UK scientists
  – Put UK on a competitive track with world development
  – Allow our focus on creation of user-aimed high beam/light quality experimental area
  – Allow developing novel technologies for lasers and laser plasma acceleration
  – Engage community of Diamond users bringing our R&D closer to science needs
  – Be compatible and complementary with application-aimed SCAPA facility and beam-driven plasma acceleration at anticipated CLARA and university-scale labs like ASL
  – Enhance connection of academic community opening opportunities for strategic support for next generation accelerator training
  – Fit into emerging European plans on creation of many user aimed plasma acceleration facilities

• The community hopes that STFC (& EPSRC) will be able to make this plan a reality

Community consultations have shown that this message is strongly supported by the community
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

Community consultations have shown that this message is strongly supported by the community
Plasma acceleration in JAI and beyond

- Plasma acceleration – new perspectives
- Evolution of accelerator communities
- UK community contributions
- UK community aspiration

- JAI contribution
  - Three main directions
  - Novel promising ideas in laser-plasma
  - Collaborations and training

- UK & overall European plans

- Summary
Far-Infrared Coherent Radiation
- CSR, CDR for beam diagnostics
- Soft-X ray and microwave source based on Thomson scattering of CDR

Nano-resolution BPM
- C, S-band (~100nm resol.)
- Special ~nm resolution

Coherent Smith-Purcell radiation
- Longitudinal diagnostics – extending to fs range

Laser – wire

Ultra-fast nanosecond feedback
directions: Enabling Acc. Techniques

- 3rd Gen Light Sources
- Future 4th Gen Light Source design
- ISIS & ESS neutron sources
- Neutrino Factory / $\mu$-cooling
- Accelerators for cancer therapy
- Ion sources
- LHC upgrade
- Linear Colliders
- FCC

[Diagram of accelerator and related components]
Compact X-ray light sources based on laser-plasma acceleration

Aim to develop practical applications

Project developed in collaboration with science centres in UK and worldwide

1 GeV acceleration in just 3 cm of plasma

Rapid progress in beam energy achieved with laser-plasma acceleration shows that the synergy of accelerators, laser and plasma is revolutionizing the field of accelerator science
Transition radiation as a longitudinal bunch diagnostic

• Have developed coherent optical transition radiation (COTR) as diagnostic of longitudinal bunch profile.
• Work done in collaboration with Stefan Karsch at MPQ, Garching
• Have used this approach to measure durations of ~ 500 MeV electron bunches from laser wakefield accelerator
• Measured bunch duration < 5fs

S. Bajlekov et al, PRSTAB 16, 040701, 2013

S. Hooker, et al
Transition radiation as a transverse bunch diagnostic

- Have also developed coherent optical transition radiation (COTR) as diagnostic of transverse bunch profile.
- Work done in collaboration with Stefan Karsch at MPQ, Garching
- Measured near-field of COTR from thin screen simultaneously with fluorescence from YAG screen
- Used new algorithm for deducing bunch shape from ring-like COTR pattern.

S. Hooker, et al
• In experiments with Gemini laser demonstrated acceleration to 900 MeV using ~3.6J, 55 fs laser pulses

A. Walker et al, Submitted

Capillary discharge waveguide

Laser focal spot improved by use of soft aperture

Measured variation of max. electron energy as function of plasma density in reasonable agreement with simple models

First observation of laser pulse compression in plasma channel. First simultaneous observation of pulse compression and electron acceleration

S. Hooker, et al.

36 consecutive laser shots showing consistent beam generation. Fluctuations in bunch energy shown to arise from laser parameter fluctuations
Plasma Acc in Imperial

Just a few examples
Detailed description of the IC program in the talk by Z. Najmudin

Towards light sources - small source size ideal for phase contrast imaging

Multi-pulse LWFA (MP-LWFA)

Almost all LWFA experiments today use a single driving pulse:
- Pulse energy \( \sim \) few joules
- Pulse duration \( \sim \) 50 fs
- Rep. rate typically \( < 10 \text{ Hz} \)
- Wall-plug efficiency \( < 0.1\% \)

But many potential applications (e.g. light sources) require:
- Rep. rate \( \geq 1 \text{ kHz} \)
  - ARPES
  - XAS & XPS
  - Tomography etc.
- Wall-plug efficiency \( \gg 1\% \)
  - Vital for particle colliders

Multi-Pulse Laser Wakefield Acceleration: A New Route to Efficient, High-Repetition-Rate Plasma Accelerators and High Flux Radiation Sources, S. M. Hooker, R. Bartolini, S. P. D. Mangles, A. Tunnermann, L. Corner, J. Limpert, A. Seryi, and R. Walczak
http://arxiv.org/abs/1401.7874v1
Multi-pulse LWFA (MP-LWFA)

- Use a train of pulses separated by plasma period to resonantly excite wakefield
- Energy stored efficiently in plasma wave
- Can tune pulse separation to avoid saturation (unlike beat-wave scheme)
- This is not an original idea!
  - K. Nakajima PRA 45 1149 (1992)
  - Dalla & Lontano PRE 49 R1819 (1994)
  - Umstadter et al. PRL 72 1224 (1994)
MP-LWFA: Advantages

- Energy per laser pulse reduced from joules to tens of mJ
  - Offers possibility of using different laser technologies
- Lower peak power on optics
  - Reduced damage, could be important at high rep. rate
- Avoids relativistic self-focusing etc. since \( P < P_c \) for each pulse
- Can be more efficient than single pulse

JAI team, in collaboration with Jena (Germany)
Fibre lasers can deliver kW mean powers at wall-plug efficiencies > 20%

Fibre lasers can generate short pulses with very high efficiency

- Pulses in 2 mJ, < 500fs range generated at > 1 kHz


- Efficiency > 20%

Multi-Pulse Laser Wakefield Acceleration: A New Route to Efficient, High-Repetition-Rate Plasma Accelerators and High Flux Radiation Sources, S. M. Hooker, R. Bartolini, S. P. D. Mangles, A. Tunnermann, L. Corner, J. Limpert, A. Seryi, and R. Walczak

http://arxiv.org/abs/1401.7874v1

JAI team, in collaboration with Jena (Germany)
1D and 3D fluid simulations show:

- Single pulse $E_{\text{acc}} = 0.160 \text{ GV/m}$
- Gradient increases linearly up to ~60 pulses
- Max $E_{\text{acc}} = 9.6 \text{ GV/m} (~70$ pulses)
- $\Delta W = 2.5 \text{ GeV in } L_d = 265 \text{ mm}$
- $E_{\text{acc}}$ rolls over due to loss of resonance (relativistic mass increase)...
- ... but this can be overcome by re-tuning pulse train

Laser-plasma parameters:
- $E = 10 \text{ mJ/pulse}$
- $\tau = 100 \text{ fs}$
- $w_0 = 20 \mu\text{m}$
- $a_0 = 0.1$
- $n_e = 1.7 \times 10^{17} \text{ cm}^{-3}$

Simulations by Naren Ratan

JAI team, in collaboration with Jena (Germany)
PIC simulations for hydrogen plasma

Wakefield at $t = 43 \ T_{pe}$

Wakefield at $t = 65 \ T_{pe}$

Laser-plasma parameters
- $E = 10 \text{ mJ} / \text{pulse}$
- $\tau = 50 \text{ fs}$
- $w_0 = 20 \ \mu\text{m}$
- $a_0 = 0.14$
- $n_e = 7.0 \times 10^{17} \text{ cm}^{-3}$

Estimates of onset of ion motion agree very well with PIC simulations:
- for H-plasma: $T_{pi} \approx 40$ periods
- for Xe-plasma ($Z_i \approx 3$): $T_{pi} \approx 280$ periods
- Should be able to drive wake for $\sim 100$ periods

Simulations by Stuart Mangles

JAI team, in collaboration with Jena (Germany)
Aim to develop MP-LWPA technology & create 100MeV demo at ASL in OX DWB

Applied to ERC Synergy (JAI+Jena) in 2013, got to ~very top, but not through

Funds from ERC would allow leveraging Univ of Oxford funds for construction

Aiming to submit an amended application to HZ2020 to FET-Open call

Technology developed at MP-LWFA/ASL project can be one of alternatives for high quality/high rep rate beamline for UK national facility at CLF extension
JAI collaborations and training

• JAI collaborating with many centres in UK & worldwide and in particular
  – Is (will be) collaborating with plasma accelerator centres in UK
    • CLF and the discussed new facility at CLF extension
    • Plasma acceleration developments by ASTeC
    • Plasma acceleration development at SCAPA

• JAI is contributing to training of next generation of scientists and in particular
  – Contributing to training of plasma acceleration experts
  – Developing innovative synergetic courses on plasmas-lasers-accelerators
  – Will be prepared to contribute to meeting the increased demand for experts versatile in all of the three fields:
    • Physics of plasmas, lasers and accelerators
Plasma acceleration in JAI and beyond

- Plasma acceleration – new perspectives
- Evolution of accelerator communities
- UK community contributions
- UK community aspiration
- JAI contribution
  - Three main directions
  - Novel promising ideas in laser-plasma
  - Collaborations and training
- UK & overall European plans
- Summary
UK plans and overall European plans

- UK plans (as seen from today’s talks) are wide and include
  - CLF and CLF Extension, work at SCAPA, at CLARA, etc
- Overall European coordination
  - Increasing coordinating efforts by EuroNNAC
  - EuroNNAC aiming at facilitating coordination of plasma accelerator community submissions to HZ2020 FETOpen calls
  - EuroNNAC aiming to coordinate all-European design study for a "European Plasma Accelerator with High Beam Quality and Pilot Applications“ – will likely aim at creation of several facilities
    - This would be open to all interested labs/univ. & also non-European partners
    - Goal is to work out the design for such a facility, the best location(s) in Europe, distribution of work and resources among partners
      - The likely criteria for location will include proximity of existing 3rd/4th gen light source, with immediate access to the community of users
    - This is a required step to get to ESFRI roadmap which is a prerequisite for large EU funding
      - The UK community aspiration – facility at CLF extension – is compatible with these all-European plans
Plasma acceleration in JAI and beyond

- Plasma acceleration – new perspectives
- Evolution of accelerator communities
- UK community contributions
- UK community aspiration
- JAI contribution
  - Three main directions
  - Novel promising ideas in laser-plasma
  - Collaborations and training
- UK & overall European plans
- Summary
Summary

• Plasma acceleration give new perspectives to our field
• The communities are evolving
  – traditional accelerator community and plasma accelerator communities merging forces, creating new quality
• UK community - many pioneering contributions to plasma acc
  – Dedicated support of this prolific field is needed
• UK community - aspiration for a dedicated facility at CLF extension

• JAI:
  – has made significant contributions to the plasma accelerator field
  – recently suggested (JAI+Jena) novel idea for kHz efficient plasma acc based light source – MP-LWFA
  – This novel technology can be potentially used for high rep rate/high beam quality user’s beamline at CLF extension facility
  – Is contributing to training of nxt gen scientists who can advance our field
• UK plans for CLF extension fit very well to the overall European plans
• We hope that aspirations of the community can turn into reality