A European Perspective on Plasma Acceleration

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Coordinator European Network for Novel Accelerators (EuroNNAc)
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Workshop on Plasma Acceleration
STFC, London 31.1.2014
Outline

> Why plasma acceleration and novel accelerators?

> The European environment
  - European Network for Novel Accelerators
  - Status and plans in continental Europe

> What is missing on the grand scheme?

> Comments on UK work:
  - Strengths and weaknesses
  - My input

> Conclusion
Lepton collider options beyond LHC
ILC (phase 1 to full, up to 1 TeV c.m.)

CLIC (similar footprint for up to 3 TeV c.m.)

TDR’s published

Lepton collider options beyond LHC

SPS

LEP/LHC

S. S. S.
Lepton collider options beyond LHC

- ILC (phase 1 to full, up to 1 TeV c.m.)
- CLIC (similar footprint for up to 3 TeV c.m.)
- SPS
- LEP/LHC
- LHeC (e-p, ERL)

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Lepton collider options beyond LHC

- ILC (phase 1 to full, up to 1 TeV c.m.)
- CLIC (similar footprint for up to 3 TeV c.m.)
- FCC (Future Circular Collider)
  - 100 km, e+e-, pp
  - Technical design to be done

SPS (injector to TLEP?)
LEP/LHC (injector to TLEP?)
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μ⁺μ⁻ collider

Plasma Linear Collider
R&D on feasibility ongoing

New compact accelerators

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Lepton collider options beyond LHC

New compact accelerators

- $\mu^+\mu^-$ collider
- Plasma Linear Collider
  R&D on feasibility ongoing

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- FCC
  Future Circular Collider
  100 km, e+e-, pp
  Technical design to be done
The Advent of Compact Plasma Accelerators

New compact accelerators

Cost of large-scale accelerators becomes prohibitive.

Either factor 2-3 cost reduction in conventional technology. Really possible?

Only way ahead: change in technology → plasma or other novel accelerators.

Plasma acceleration works: it produces beam at the GeV level on a very compact scale.

Possibilities for compact, applied accelerators at the GeV scale with high societal impact:

- Medical imaging, medical treatment, compact light sources for research on materials, biological processes, ultrafast chemistry, engineering, …

We see that this drives development!
LETTERS

GeV electron beams from a centimetre-scale accelerator

W. P. LEEMANS*1, B. NAGLER1, A. J. GONSALVES2, Cs. TÓTH1, K. NAKAMURA1,3, C. G. R. GEDDES1, E. ESAREY*1, C. B. SCHROEDER1 AND S. M. HOOKER2

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A breakthrough result

UK community involved!

Present status:
Beam not used.
Method pushed to 4.2 GeV e- beam.
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- **The European environment**
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- Conclusion
EU Funded Network on Novel Acceleration

EuroNNAc
European Network for Novel Accelerators

- University of Oxford
- University of Strathclyde
- Manchester University
- Lancaster University
- Cockcroft Institute
- STFC Daresbury Laboratory
- John Adams Institute
- ASTeC
- STFC Central Laser Facility
- Liverpool University
- University College London
- Imperial College
- Instituto Superior Tecnico de Lisboa
- EINDHOVEN University of Technology
- University Düsseldorf
- LMU University Munich
- DESY
- GSI
- Max-Planck-Institute for Quantum Optics
- Max-Planck-Institute for Physics
- Helmholtz Institute Jena
- Helmholtz-Zentrum Dresden-Rossendorf
- University Hamburg
- Lund University
- Budker INP
- Institute of Applied Physics RAS
- KEK
- Fermilab
- SLAC
- UCLA
- LBNL
- BNL
- ICFA
- ICUIL
- INFN-LNF
- Pisa University and INFN
- Consiglio Nazionale Delle Ricerche, INO
- University of Rome LA SAPIENZA
- Inst. of Physics, Chinese Academy of Sciences
- Tsinghua University, Beijing
- Shanghai Jiao Tong University

Extreme Light Infrastructures (ELI)

European Organization for Nuclear Research (CERN)

PSI
Our Mission on One Slide…

- **Identify synergies**
- **Build bridges**
- **Define roadmap**
- **European facility**
- **Plasma Science**
- **Laser Science**
- **Ultra-fast Science**
- **Accelerator Science**

_EuroNNAACc_ European Network for Novel Accelerators
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The big French project.

Laser: APOLLON, 150J / 15fs, 1 shot/min, 5-10 PW, $10^{23}$ W/cm² plus satellite lasers.

450 m² experimental area for plasma acceleration of e⁻. Possibility to extend into 200m long acc. tunnel.
X-5 Project at LOA, France

- Salle Jaune Laser: 70 TW, repetition rate 10 Hz, pulse duration of 30 fs

- Goals:
  - Exploration of new laser plasma accelerator blueprints for the production of electron beams and very strong peak point currents.
  - These electron beams will be used in a variety of domains, including life science and materials science.
  - They will also be used to study the blueprint of compact free electron lasers (FEL) for the production of intense X and XUV beams.

Victor Malka
Researcher at CNRS and Lecturer
An excellence grant for LOA.

Victor Malka, a CNRS researcher and lecturer in the physics department at X, works at ENSTA, in a team that he set up in 2001 to study laser-plasma particle acceleration. In July 2008, he was awarded a grant by the European Research Council of 2.2 million euros. The grant was awarded in two categories: junior and senior. It was in the second category that he was rewarded for his many scientific works and for his ability to create new fields of research.
COXINEL Project at SOLEIL, France

> COXINEL: COherent Xray source INferred from Electrons accelerated by Laser.

> Leader: Marie-Emmanuelle Couprie, SOLEIL

> Goals:

  - COXINEL aims to demonstrate that, by using laser acceleration, it is possible to obtain the free-electron laser (FEL) amplification needed to develop more compact light sources.
  - FEL are the first tunable X-ray lasers and the most intense light sources in the X-ray energy domain.
  - COXINEL benefits from a very favorable environment at SOLEIL and more widely on the Paris-Saclay campus, particularly in terms of engineering, to turn the ideas and theories that physicists have devised into reality.

> Closely connected to project X-5 in LOA.
**Figure 1 |** Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of -1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of -10 kHz (7).

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**The future is fibre accelerators**

_Gerard Mourou, Bill Brocklesby, Toshiki Tajima and Jens Limpert_

Could massive arrays of thousands of fibre lasers be the driving force behind next-generation particle accelerators? The International Coherent Amplification Network project believes so and is currently performing a feasibility study.
SPARC LAB, Frascati, Italy

- Electron beam: 150 MeV, multi-bunch, bunch length below 300 fs, 200 pC, 1 μm norm. emittance

- FLAME laser: Ti:Sa, chirped pulse amplification (CPA), 200 TW, 25 fs long, 10 Hz repetition rate, wavelength 800 nm

- SPARC LAB is a multi-purpose user facility. Includes experiments on laser- and beam-driven plasma wakefield acceleration experiments. See example of laser-generated electrons.

- Comb project is resonant beam plasma wakefields.
LUND Laser Center, Sweden

- Well established lab, since 1992.
- Laser: 60 TW + 5 TW + 3 TW (three separate compressors). Emphasis on:
  - Stability (pulse-to-pulse)
  - Reliability (day-to-day)
  - Contrast (ex. plasma mirrors)
  - Beam pointing (active control)
  - Wavefront (adaptive optics)
- Limited by manpower.

Electrons

Protons

X-rays

C.G. Wahlstroem
Laser: 10-15 fs duration, up to 10 PW. End stage: a few kJ in 15 fs (~200 PW) with low repetition rate (minute based).

Might be the big player in some years.

New techniques for medical image-display and diagnostics, radiotherapy, tools for new materials developing and testing, latest in X-ray optics, etc.

Laser-accelerated, versatile electron and proton/ion source emitting in an unprecedented energy range (1 GeV to 100 GeV). Provide a major contribution for the development of future high-quality and low-cost proton sources for cancer therapy.
AWAKE experiment, CERN

- International collaboration with approved experiment at CERN beam.

- Driver: 450 GeV proton bunch, 1e11, 3.5\(\mu\)m emittance, bunch length \(\gg\) plasma wavelength

- Modulation experiment:
  - The first parts of the proton bunch induce a plasma wakefield that starts self-modulating the parts of the bunches.
  - Microbunching starts happening:
    1) Protons at focusing regions survive.
    2) Protons at defocusing regions get lost.
  - Surviving microbunches induce wakefields.
  - Accelerate injected electrons from several 10 MeV to GeV.
CALA Project, Munich, Germany

- Builds on expertise at MPQ and LMU.
- Successful in laser-driven generation of electron beams. See example with MPQ lasers.
- Ongoing: 63 M€ investment. Financed by State Bavaria and Germany.
- CALA completion: 2015…
Largest science organization in Germany. Funded 90% by German federal government, 10% by local states.

Helmholtz ARD program: accelerator research as an independent research field in the Helmholtz program. Plus 13 German partner universities.

Coordination: Reinhard Brinkmann
Deputy: Andreas Jankowiak
Helmholtz Distributed ARD Test Facility

Theme 1: **Collaboration**
Networking of existing research infrastructure.

Theme 2: **Synergy**
Extension of facilities for common usage.

Theme 3: **Leadership**
Establishment of a few flagship projects for internationally leading research with the aim of ultra-compact accelerators and radiation sources (plasma acceleration major player).

In the process of preparing a funding proposal to Helmholtz (strategic funds).

The preparation team:
R. Assmann (DESY), V. Bagnoud (GSI), M. Büscher (HZJ), A. Jankowiak (HZB), M. Kaluza (HIJ), A.-S. Müller (KIT), U. Schramm (HZDR)
**Short Innovative Bunches & Accelerators at DESY**

**Compact Atto-Second Light Source**
50 as, ICS
ERC Synergy Grant 14 M€, DESY, Uni HH, Arizona

**UltrasHORT electron pulse**
< 1 fs with conventional technology
ARD, DESY, Uni HH, KIT

**Developability to use plasma acceleration, scalability**
> 1 GeV/m, useable beam quality, FEL?
LAOLA, ARD, DESY, Uni HH

**Room for further phases and users**
Third party funding, interest from ELI, ...

**Footprint:** 90 m x 50 m
Plasma Acceleration at Hamburg: LAOLA

> Laser: Ti:Sa 200 TW, 25 fs pulse length, 5 Hz repetition rate
  - Initially: Laser-driven wakefields in REGAE. LUX exp. towards FEL.
  - Later: Move to SINBAD facility.

> Beams:
  - **REGAE**: 5 MeV, fC, 7 fs bunch length, 50 Hz
  - **FLASH**: 1.25 GeV, 20 – 500 pC, 20 - 200 fs bunch length, 10 Hz.

> Future **SINBAD**: 100 MeV, 0.01 – 3 pC, down to 10 fs bunch length, 10 – 1000 Hz
Plasma Acceleration at Hamburg: LAOLA

<table>
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<tr>
<th>Year</th>
<th>LUX: LWFA driven undulator &amp; FEL</th>
<th>REGAE: low energy injection</th>
<th>SINBAD: ARD distributed facility at DESY</th>
<th>FLASHForward: high energy injection, Trojan horse</th>
<th>PITZ: self-modulation &amp; high transformer ratio</th>
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Laser and equipment moves

preparation  installation  operation
The long beam drivers for plasmas will be available in AWAKE/CERN (high power proton) and PITZ/Germany (electrons). Modulation experiments.

The most powerful laser drivers for plasmas will have reached 5 – 10 PW in CILEX/France, ELI/Czech and Munich/Germany. “Table-top” accelerators and radiation sources, towards the 10-100 GeV with captured plasma electrons.

The Intermediate laser drivers with industrial quality and 100 – 200 TW will be available at LOA/France, Dresden/Germany, Lund/Sweden, Frascati/Italy and DESY/Germany. High quality “table-top” accelerators and radiation sources, GeV class beam with captured plasma electrons, ion beams, medical applications.

The short, efficient and shapeable beam drivers for plasmas will be available in SPARC/Italy and FLASH/DESY. Booster applications for existing accelerators/FEL’s. Very low emittance beam generation (Trojan horse, …).

Ultra-short, relativistic electron bunches for injection into a laser-driven plasma will be available at SPARC/Italy and DESY/Germany. Probing of plasma wakefield, reduced complexity plasma accelerator, possibility of staging.
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➤ Comments on UK work:
  ▪ Strengths and weaknesses
  ▪ My input
➤ Conclusion
What is Missing on the Grand Scale?

Look at most popular direction: Plasma acceleration (internal injection)

Highly complex process inside plasma:

(1) e- beam trapping. (2) e- beam bunching (long & transv). (3) e- beam accel. from thermal to relativistic energies, rapidly varying $\beta$. (4) Simultaneous transverse focusing and guiding. (5a) Undulating in plasma wakefield $\rightarrow$ light source. (5b) Extraction of e- beam with large energy spread.
What is Missing on the Grand Scale?

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Highly complex process inside plasma:

1. e- beam trapping.
2. e- beam bunching (long & transv).
3. e- beam accel. from thermal to relativistic energies, rapidly varying $\beta$.
4. simultaneous transverse focusing and guiding.
5a. Undulating in plasma wakefield $\rightarrow$ light source.
5b. Extraction of e- beam with large energy spread.

Too complex for accelerator applications?
**Beam Physics Limit: Ruth and Pis in 1986**

Driver (γ or e-) $\rightarrow$ Accelerated bunch

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**Fig. 1.**

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PLASMA ACCELERATORS*

RONALD D. RUTH AND PISIN CHEN†

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SLAC – PUB – 3906
March 1986
(A)
Useful phase: ¼ of plasma wavelength
Must stick into window
Head acc. bunch always gains less energy
Tail acc. bunch always gains more energy
**Always get large correlated energy spread**
Compensate with space charge \(\rightarrow\) complicated!
What is Missing on the Grand Scale?

> **Reduce complexity:**

No new records, break process into pieces, *simplicity* as driver, optimize one by one, correction methods

Example: external injection

> **Beam physics:**

Transport lines for generated beam to characterize in detail, develop correction methods (example: dechirping by wakefields?!)
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A full assessment would require, of course, a review with presentations and documents. So take these comments as my personal impressions, probably being ignorant of some facts.

**Strengths:**

- The **scientists** involved. Well-respected, high reputation in the field, high level work in UK, collaboration in leading experiments in world (BELLA, AWAKE, FlashForward, …).
- The excellence of **universities** and the many good, young **students**.
- Experiments at **CLF** laser facility, **SCAPA**: develop key technology, acceleration results.
- Technology of the **plasma channel**. World-leading research in the UK.
- Software and **simulation** of plasma acceleration.
- User **community light sources** and presence of **conventional accelerator specialists**.

**Weaknesses:**

- Unclear UK wide strategy.
- Lack of dedicated facilities with plans/funds for upgraded technology.
Final Comments I

> The field of **plasma accelerators is developing rapidly with major investments being realized around Europe**. Significant support from states but also EU science funding.

> The UK is a well respected player with long tradition in this field, excellent reputation and measurable outcome. The **UK has an excellent base for remaining one of the leaders**.

> Applications of initial plasma accelerators fit into the direction of UK science work, as far as I can judge.

> On the **collaboration** side, the UK is well set up, probably limited by resources.

  - There is a long tradition of DESY-UK collaboration and this is still continuing. Further collaboration is of course very welcome from our side.

> From my perspective, it is justified and advisable that additional strategic UK funding is made available for novel accelerator R&D.
Final Comments II

> **Synergy – innovation – application:**

- The presence of photon science users (e.g. materials, biology), conventional accelerator specialists, laser physicists and novel accelerator specialists at one place opens unique synergy and believable potential to develop novel accelerators with relevant applications. Recognized by funding agencies, e.g. ERC grants to Paris (4 M€) and Hamburg (14 M€).

> **Laser technology:**

- Laser parameters are still improving rapidly. The laser frontier will yield new records. If not needed for other reasons, difficult to keep up with ongoing projects (CILEX, CALA, ELI). Profit from European user facilities, e.g. ELI.

> My hope: UK as a strong competitor in this field with a strong home basis and continuing collaborations with world-wide efforts.

> Also, **involvement in new EU applications**, as discussed in EuroNNAc:

- EU design study (4 M€) for a “**European Plasma Accelerator with Useable Beam Quality and Pilot Applications**”. First step to get on the ESFRI roadmap.
- ITN network (C. Welsch). Two additional FET applications?
Thank you for your attention…