Lasers in Particle Accelerators

Dr. Laura Corner

laura.corner@physics.ox.ac.uk

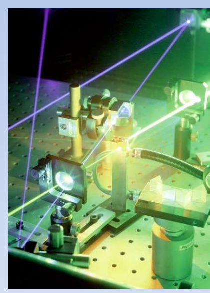
John Adams Institute for Accelerator Science, Oxford, UK

Outline

- What makes lasers special?
- Lasers in accelerators
- Diagnostics
- Sources of particles
- Drivers of accelerators

LASER

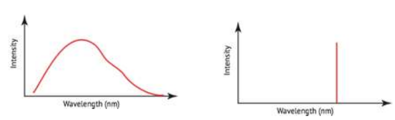
Light Amplification by Stimulated Emission of Radiation



Laser properties

- They produce highly directional beams.

- They have a narrow spectrum (bandwidth).



- They are spatially and temporally coherent.

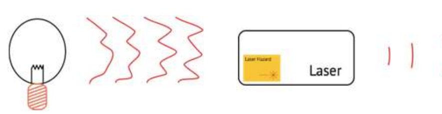


Diagram courtesy Prof. S. Hooker, Oxford

Making a laser

- All laser oscillators (as opposed to amplifiers) have 3 parts:
- Gain medium – gas, solid state, liquid – what provides the lasing transition.
- Pump – source of energy to create population inversion – usually another light source e.g. flashlamp or another laser, can be electrical discharge or current.
- Cavity – need to recirculate photons to stimulate emission on lasing transition – often mirrors around gain medium, can be medium itself.
- Lasing threshold – when gain (no. photons emitted in round trip) exceeds loss (number lost to absorption, through mirrors etc.).
- And that's it!

Laser types

Lasers come in many different styles:

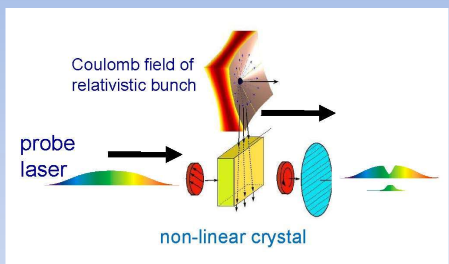
- Temporal structure - continuous wave (cw) or pulsed (down to femtoseconds).
- Wavelength - X-ray free electron lasers through visible to near infrared fibre and solid state systems, mid infrared quantum cascade lasers to 10.6μm CO_2 lasers.
- Low power (barcode scanners, laser pointers).
- High peak power (100s TW, PW systems available commercially).
- Need to consider what it is required for your application.
- Don't overspec – makes it very expensive!

Laser applications in accelerator physics

- Many applications of laser technology.
- Broadly 2 categories:
- Improving standard accelerators – diagnostics, timing, photocathodes.
- Driving new accelerators – laser driven plasma accelerators, dielectric laser acceleration, direct laser acceleration in vacuum.

Lasers for particle beam diagnostics

- Electro-optic methods for bunch length measurement.

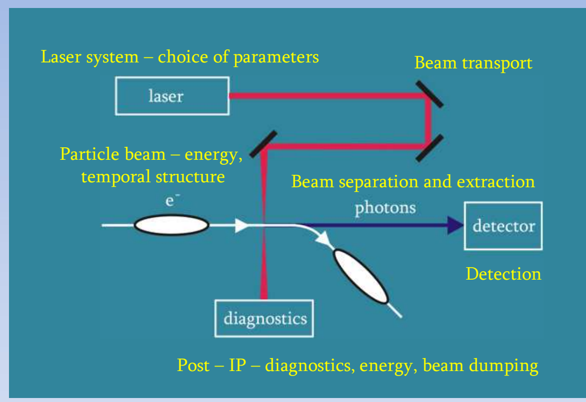


- Coulomb field of the particle bunch alters the optical properties of the nonlinear crystal.
- Changes polarisation state of laser propagating through crystal.
- Laser is chirped so spectral features directly relate to time.
- Particle bunch length measured single shot and non-destructively.

See for example:
- Pan et. al., MOPME077, IPAC 2013.

Lasers for particle beam diagnostics

- Laser based beam size measurement.



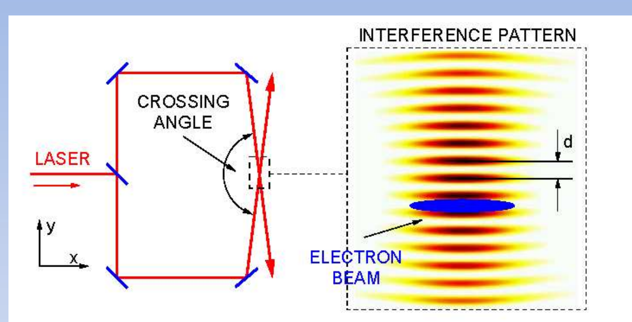
- Measure electron beams (Compton scattering) - SLC, ATF2.
- Also ion beams (photoneutralisation) - H^- laserwire at Linac 4, CERN.

See for example:

- Nevay et. al., Phys. Rev. ST Accel. Beams 17, 072802 (2014).
- Kruchinin et. al., MOPWI003, IPAC 2015.

Lasers for particle beam diagnostics

- Measuring really small beam sizes



- For < 1µm beams need something different – can't focus laser spot to much less than this.
- Cross 2 laser beams at large angle to make very narrow interference fringe pattern.
- Scan interference fringes across beam and look for modulation in Compton signal.
- This monitor is *really* hard to align and make work well. Requires very stable laser source.

See for example:

- White et. al., Phys. Rev. Letts. 112, 034802 (2014).
- Yan et. al., 261, TIPP 2014.

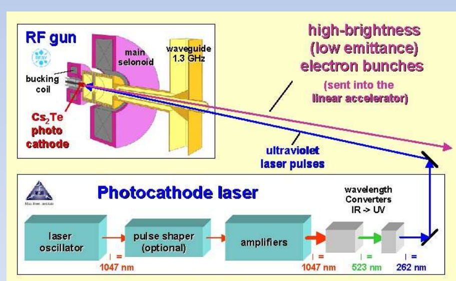
Timing and synchronisation in particle accelerators

- Modern large accelerators and free electron laser complexes need timing synchronisation for components such as beam, diagnostics, data acquisition at the fs level or even < fs.
- Fibre based distribution of signals derived from mode-locked pulsed lasers are now in use or planned at several facilities worldwide.
- As well as distributing a signal ‘clock’ need to be able to measure jitter and correct for it.
- Measurements of jitter between mode locked lasers using optical techniques has shown < 100 as jitter measurement.
- Using these techniques to measure and stabilise timing shown over 1.2km fibre for 16 days giving 0.6fs rms drift.

See for example:
- Peng et. al., Optics Letters 21, 19982 (2013)
- https://desy.cfel.de/ultrafast_optics_and__x_rays_division/research/timing_distribution_and_synchronization/

Lasers as particle sources - Photocathodes

- Can use laser pulses to produce electron bunches from photocathodes.
- Give bunches as short as the laser pulse without additional manipulation.
- Properties of the bunch can be controlled by the laser pulse shape in time and space.
- Laser must be stable and locked to rf for further acceleration.
- Light needed at energies > photocathode workfunction, generally uv.
- Laser needs second or third harmonic frequency conversion.
- Large area of laser research – need:
    - High pulse energy
    - Reliable running
    - Excellent pointing stability

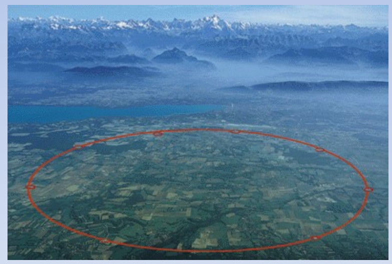


See for example:
- Penco et. al., Phys. Rev. Letts. 112 044801 (2014)
- Schreiber et. al., NIM A 445 (2000).

Lasers driving accelerators – plasma wakefield accelerators

- Conventional accelerators are widely used in science and medicine.
  - Acceleration gradient limited by electrical breakdown to < 100 MV/m.
  - This sets the size (& cost) of the machine.

Diamond



LHC

Plasma accelerators – how they work

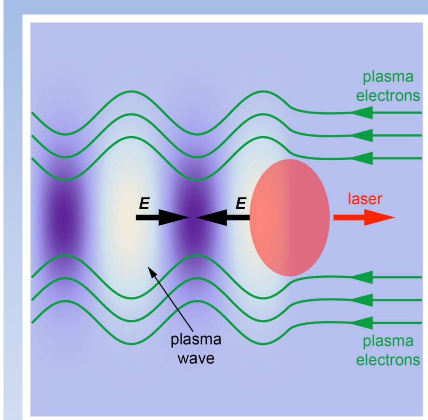


Diagram courtesy Prof. S. Hooker, Oxford

- Ponderomotive force of an intense laser pulse expels electrons from the region of the pulse to form a trailing plasma wakefield.
- The wakefield moves at speed of laser pulse (i.e. close to speed of light).
- Electric fields within wakefield can accelerate charged particles.
- Huge accelerating gradients – 1000 x conventional accelerators.
- 4 GeV in 9cm.
- 3.25 GeV in 14mm.
- Massive potential for reducing size and cost of particle accelerators.
- Shown positron acceleration, important for colliders.

See for example:

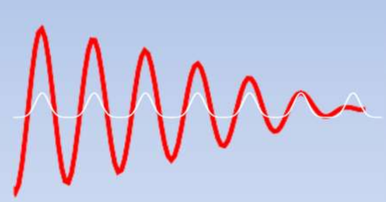
- Esarey et. al., Rev. Mod. Phys 81 1229 (2009)
- Kim et. al., Phys. Rev. Letts. 111 165002 (2013)

Laser plasma accelerators - What's the catch?

- Sounds great – why aren't all accelerators plasma based?
- Mainly driver problems – lasers required are 100s TW or PW, inefficient so heat up, only fire once an hour/every 20 mins.
- Even fastest PW laser in the world only fires at 1Hz – too slow for real applications.
- Also length of accelerator – only over ~ 10cm so far, need to show can put many stages together to get to really high energy.
- Quality of electron bunches not as good as conventional accelerators yet.
- These are all active areas of research.
- Not forgetting laser driven proton and ion acceleration too!

Resonantly pulse train laser wakefield acceleration

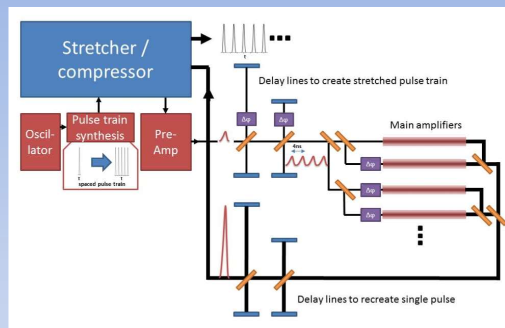
- Not original idea! Several theoretical papers have predicted efficient excitation of plasma oscillations with trains of low(er) energy pulses - like pushing a swing.



See:
Hooker et. al., Journal of Physics B 47 (2014)

- Energy per laser pulse reduced from joules to 10s mJ
  - Offers possibility of using different laser technologies.
  - Potential for much higher repetition rate.
  - Potential for much higher wall-plug efficiency.
- Lower peak intensity on optics.
  - Reduced damage, could be important at high repetition rate.
- Can be more efficient at exciting plasma wave than single pulse.

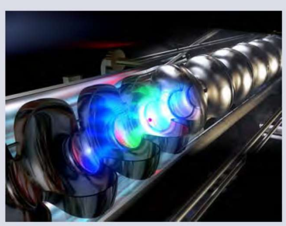
Fibre laser driven plasma acceleration



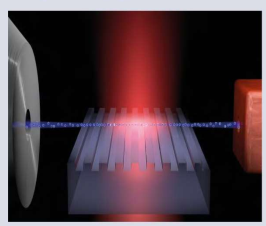
- Research teams developing fibre laser driver for pulse train driven acceleration.
- Fibres are more efficient, better spatial quality, smaller, operate at kHz repetition rates.
- Major improvement in plasma accelerators possible.
- Demonstrates how laser research can help drive accelerator research.

Dielectric laser accelerators

Particle accelerators: from RF to optical/photonic drive?



RF cavity (TESLA, DESY)



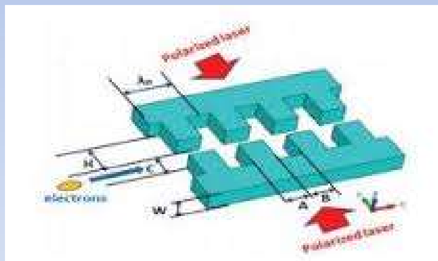
	Conventional linear accelerator (RF)	Laser-based dielectric accelerator (optical)
Based on	(Supercond.) RF cavities	Quartz grating structures
Peak field limited by	**Surface breakdown: 200 MV/m**	**Damage threshold: 30 GV/m**
Max. achievable gradients	**50 MeV/m**	**10 GeV/m**

P. Hommelhoff, ARD lunch sem., DESY, Jan. 2014

Slide courtesy Dr. P. Hommelhoff, Friedrich-Alexander-Universitat, Erlangen

Dielectric laser accelerators

- New area of accelerator research.
- Have shown acceleration of relativistic and non-relativistic electrons using laser and dielectric structures.
- Also beam manipulation e.g. deflection for use as beam position monitor.



https://www.liv.ac.uk/quasar/research/novel_accelerators/

See for example:
- Breuer et. al., Phys. Rev. ST Accel. Beams 17 021301 (2014)
- Peralta et. al., Nature 503 91 (2014)

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Direct laser acceleration in vacuum

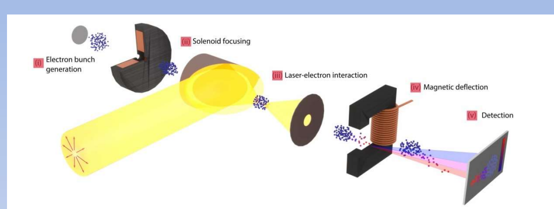
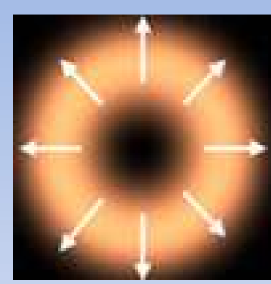


Figure 1| Conceptual schematic. A non-relativistic monoenergetic electron bunch is generated via a 40 kV DC gun (i) triggered by a small fraction of the optical beam. The electron bunch is then focused (ii) at the laser-electron IP using a solenoid. A subsequent off-axis parabola with a thru-hole allows for tight focusing of the optical beam to overlap with the electron bunch (iii). After the interaction, the electrons enter a dipole magnet deflector (iv) and are then mapped onto a CCD camera from the emission of a fluorescent screen placed after a micro-channel plate detector (v).



arXiv:1501.05101

- Light has a strong electric field – can we use this to accelerate electrons?
- How to get large on axis component? Focus radially polarised light beam.
- Vacuum acceleration – no medium to breakdown, not unstable.
- Carbajo et. al. Phys Rev. ST Accel. Beams 19, 021303 (2016) shown 3GeV/m – exciting result!

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Conclusion

- Lasers are a vital part of modern particle accelerators.
- Use as diagnostics, timing systems, sources of particles, drivers of new accelerators.
- Research and development of new laser sources will drive improvements in accelerators – smaller, cheaper, more efficient?