Present and future applications of laser-accelerated ions

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IZEST meeting, Strathclyde University, 13-15 Nov 2012

Laser Induced Beams of Radiation and their Applications
Basic Technology programme, 2007-2012

Collaboration

Also funded by Doctoral Training Centre in Applications of Next Generation Accelerators (2010-2017)
Outline

- Current properties of laser-ion beams
- Proposed applications/requirements
- Current, research applications:
  - Proton radiography
  - Radiobiology
- Future applications: cancer therapy
- Prospects for energy increase
  - Radiation Pressure Acceleration

Sheath acceleration: ion beam properties

- **Low emittance**: $\text{rms emittance} < 0.01 \pi \text{mm-mrad}$
- **Short duration source**: $\sim 1 \text{ ps (} \Delta E \Delta t < 10^{-6} \text{ eV-s) }$
- **High brightness**: $10^{17} - 10^{13} \text{ protons/ions in a single shot (> 3 MeV) }$
- **High current (if stripped of electrons): kA range**
  - **Divergent (~ 10s degrees)**
  - **Broad spectrum**
  - **Maximum energies**: ~ 70 MeV
  - **Scaling**: $E \sim (I\lambda^2)^{0.5} - I\lambda^2$

Ion beam from TARANIS facility, QUB

$E \sim 10^9 \text{ J on target in } 10 \mu \text{m spot}$

Intensity: ~$10^{19} \text{ W/cm}^2$, duration : 500 fs

Target: Al foil 10um thickness
Prospective applications of laser-driven ion acceleration

- Radiography (density measurements)
- Deflectometry (field measurements)
- Isochoric heating of matter
- Neutron production
- Material studies (Irradiation)
- Injection into conventional accelerators
  - Cancer therapy
  - Production of isotopes for PET
- Fusion Energy (Fast Ignition)
- Nuclear/particle physics applications

Applications already active with TNSA beams

- 150-250 MeV protons
- Carbon ions at 2-4 GeV
- Energies >GeV (high repetition)

General requirements of ion beam users

- Wide energy and fluence range
- Different ion species
- Homogeneous lateral beam distribution
- Stability in terms of energy and fluence distributions
- Variable beam spot size (from 2 mm up to 40 mm)
- Beam control (diagnostic and dosimetry) with < 5% errors
- Possibility of in-air irradiation

- Unique characteristics of laser-driven ion beams
  - Very short particle bunch duration: < 1 nsec, (> 5 nsec for conventional accelerator)
  - High dose-rate per bunch: \( -10^9 \text{ Gy/sec} \) (\( -10 \text{ Gy/sec} \) for conventional accelerators)
Research applications: proton radiography/deflectometry

Proton deflections provide a map of electric and magnetic fields in the interaction region.

Interaction: from fs to ns pulses, intensities from $10^{15}$ to $10^{19}$ Wcm$^{-2}$

2-D magnified projection of 3-D objects

Beam divergence

Projection Magnification

Laser pulses

Proton target

Mesh

Detector

Probed sample: solid or gas targets (optically overdense and underdense plasmas)

Interaction region

~ps temporal resolution

~µm spatial resolution

Multiframe capability

Proton radiography – ultrafast charge dynamics on laser-irradiated targets


10 ps

30 ps

50 ps

100 µm Al wire irradiated at $I \sim 3 \times 10^{19}$ W/cm$^2$
Investigation of B-field generation from short (ps), intense laser pulses


- Laser accelerated proton beams can provide ps temporal resolution
- Longitudinal probing: exclusion of transverse electric field-deflections.

Regime of interest to laser-driven ion acceleration ($t_L = 1$ ps, $I_L = 10^{19}$ W/cm², 10 μm Al foil)

- Appearance of two structures of proton accumulation.
- Inverted pattern in the reverse configuration.
- Clear dynamical evolution

Matching with particle tracer simulations allows reconstruction of B field profiles

Toroidal magnetic fields are able to reproduce the data in both experimental configurations
Relativistic interactions
electron currents in dense targets

- Ultralarge currents (above Alfven)
- Interplay with return current
- Weibel-type instabilities
- Self-collimation of electrons
- Relevance to ion acceleration/ fast ignition

Simulations and data for 50 TW interaction (VULCAN)

> PW backlighter would allow probing the interior of solids with limited scattering degradation
Relevance to Fast Ignition ICF

Charged particle therapy of cancer

Compared to conventional x-ray radiotherapy:

- **Ballistic advantages**
  - Ions permit precise targeting of the tumor, minimizing the dose deposition in healthy tissues

- **Biological advantages**
  - Large number of direct DNA damage. More effective in destroying radioresistant tumours (particularly with Carbon)
Hadrontherapy centres worldwide are limited in number

- 8 in the USA
- 6 in Japan
- 12 in Europe/Russia
- 3 in China, Korea, South Africa
- 1 in UK (Clatterbridge, limited to 60 MeV)

2 protontherapy trial centres currently being developed in the UK (active by 2017, UCLH London, Christie Hospital Manchester).

**Very high cost:** >£100 M for protons, >£250 M for proton+Carbon

**Significant fraction of costs:** transport/delivery systems (up to 50-70%)

*There is need for developing alternative approaches to hadrontherapy which may in future, help the treatment becoming more widespread / more efficient.*
Laser-driven ions: a source for future radiotherapy?

**Reduced cost/shielding/size:**
- possibility to avoid/reduce size of gantry
- laser transport rather than ion transport (vast reduction in radiation shielded space)

**Flexibility:**
- Possibility of controlling output energy and spectrum
- Possibility of varying accelerated species (H, C, but also intermediate species)

**Novel therapeutic/diagnostic options**
Mixed fields: x-ray + ions, multiple beams
In-situ diagnosis

**High dose rates effects**

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Radiobiology experiments

We carried out tests of biological effectiveness of laser-driven ions on V79 cells by using the TARANIS laser at QUB

**Main aims:**
- establish a protocol for proton irradiation compatible with a laser-plasma environment
- establish a procedure for on-shot dosimetry
- Demonstrate dose-dependent cell damage on single exposure, high dose irradiations
- test for any deviation from known results using conventional sources

**Previous:**
S. Yogo *et al*, APL, **98**, 053701 (2011)
S.D. Kraft *et al*, NJP, **12**, 085003 (2010)

Ongoing work at MPQ (Schreiber *et al*)

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Dose of ~1-10 Gy is delivered in several fractions
Each fraction has a short duration ~ 10 ns
But effective dose rate ~ Gy/s – Gy/min
**Setup for cell irradiation**

Dispersion: in 20mm from 3MeV to 10MeV

Energy Res.: ~ 2 MeV energy overlapping (500um slit)

Delivered dose @ 1-5MeV: ~ few Gy/shot

**Cell Irradiation Protocol for clonogenic assay**

1. **Chinese Hamster**
2. **Cell culture**
3. **Sample preparation**
4. **Colony formation**
5. **Post-irradiation processing**
6. **Cell Irradiation**

Shadows of the cell dots
**Single shot survival curve!**

Cell damage investigated at ultrahigh dose rates (> $10^9 \text{ Gy/s}$)

RBE$_{10}$ estimated at $\sim 1.4$

In line with “standard” results with V79 cells e.g. Folkard et al, (1996) – Same RBE with LET=17.8 Kev/µm

SF comparable with literature data at similar dose and energy but longer pulses

Higher dose/dose rates obtainable with **beam collimation**, or low dispersion magnetic systems

**Future tests**: DNA damage, higher LET ions, Effects of oxygen depletion

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**Ion energy increase**: several emerging mechanisms are being explored (besides TNSA optimization)

- **Radiation pressure acceleration**
  - Hole boring
    

- **Relativistic transparency/ Break out afterburner**

- **Shock acceleration**

  D. Haberberger et al, Nat Phys, 8.95 (2012)

- **Light Sail**

Radiation Pressure on thin foils - light sail

\[ F_R = (1 + R)A \frac{I_L}{c} \]
\[ v_i = \frac{(1 + R)\tau I_L}{m_i n_i d} \propto I \eta^{-1} \]
\[ \eta = m_i n_i d \]

\[ W \sim (I_L \tau/\eta)^2 \]

Issues at present intensities
• Competition with TNSA
• Hot electron heating cause foil disassembly (ultrathin foils are needed for moderate \( a_0 \))

Scaling decreases for relativistic ions:
0.3 scaling for \( v_i^{-} c \)

PIC investigations of Radiation Pressure Acceleration
(\textit{Light Sail} regime)

2D PIC ILLUMINATION code

Condition for stability of Light Sail identified (smooth transition between hole boring and light-sail phase, GeV protons at > 10^{22} W/cm^2)


Generally unstable at lower intensities, but:
2-species targets lead to stabilized acceleration of lighter species already at ~10^{20} W/cm^2.

**LIBRA campaigns at the CLF, RAL**

**VULCAN Petawatt**

Scans made by varying:
- Laser Intensity, polarisation
- Target density, thickness

**Pulse duration**
- \( \sim 750 \) fs

**Energy on target**
- up to \( 200 \) J

**Intensity up to**
- \( 3 \times 10^{20} \) W/cm\(^2\)

**Typical feature from ultrathin foils:**

*Co-moving ions of diff e/m*


100nm Cu; Linear Pol; \( I = 3 \times 10^{20} \) W/cm\(^2\)

Solid line: TP1 (laser axis)
Dotted line: TP2 (13° off axis)

*Hybrid regime* where RPA coexists with TNSA
No significant dependence on polarization
Scaling of carbon peak with Light sail parameter

Energy of peak scales ~ \((I \tau/\eta)^2\)

Conversion efficiency into peak ~ 1%

Scaling highly promising for achieving high Ion energies

Inset: PIC simulation scaled up from VULCAN data (2 X I, 1/2.5 target areal density)

\[ E_{\text{ion}} \propto (a_0^2 \tau_p/\chi)^2 \]

Increase Fluence, or, Decrease \(\chi\)

Red dots: 2D and 3D results from multispecies simulations of stable RPA taken from literature
Similar spectra and scaling in GEMINI results –
(Similar intensities but shorter pulses)

**GEMINI data:**
- **Laser parameters:** 50 fs, 6 J, 1-5 10^20 W/cm^2
- **Targets:** Carbon (amorphous), density: 2g/cc, thickness: 10-100 nm

**PIC syms**
- Only lightest species shows peaks – not bulk component
- Onset of target transparency for the thinnest targets?

Conclusions

**Present and future applications of laser-accelerated ions**

Some of present applications exploit unique and distinctive properties of laser-ion beams (short duration, low emittance, small source):
- Proton radiography/deflectometry
- Warm dense matter studies
- Real time material damage studies
- Ultra-high dose rate radiobiology

Applications currently covered by accelerators require a marked improvement of parameters for laser-drivers to be competitive:
- Compactness is a clear advantage, but improvements are required in terms of energy, flux..., but also high-average power, and more generally a beamline approach.

Future applications: Cancer therapy,
- Radiation Pressure Acceleration emerging from experiments, and promising for future delivery of pulses at high flux and high energies (medical energies and beyond)