Development of laser-driven ion sources and application to radiobiology

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Project aims to develop target, detector and interaction technology required for high repetition, high energy operation of laser-driven particle and radiation sources.
LIBRA team and collaborators

- Strathclyde University, Glasgow (UK): P. McKenna, D. C. Carroll, O. Tresca, X. Yuan
- University of Surrey: K. Kirkby, C. J. Jeynes, M. Merchant
- Birmingham University: S. Green, F. Fiorini, D. Kirby
- Heinrich Heine Universitaat Duesseldorf (D): M. Cherchez, J. Osterholtz, O. Willi
- University of Pisa (I): A. Macchi
- Forschungzentrum Julich (D): P. Gibbon, A. Karmakar
Outline

*Ion acceleration – mechanisms (TNSA, RPA)*

**Recent and current LIBRA activities:**

*Laser-driven ion acceleration*
  *Ultrathin foil experiments*
  *Radiation pressure effects* (modelling & experiments)

*Live cell irradiation: dosimetry and biological effects*
Present mechanism: Target Normal Sheath Acceleration

- Relies on production of high energy (MeV) electrons (e.g. via JXB, oscillating component of ponderomotive force) which propagate through the foil

- Acceleration under effect of the electron pressure and decoupled from laser interaction

- Well tested and robust mechanism

- Effective at realistic intensities

- Broad spectrum, diverging beams

- Conversion efficiency ~ %

\[ I^{0.5} < \text{Scaling} < I \]

- Interest in thin foils - larger accelerating fields

S.P. Hatchett et al, Phys Plasmas, 7, 2076 (2000)


\[ \text{Emax: } \sim 70 \text{ (100?) MeV for } \sim 100 \text{s fs/ps pulses} \]

\[ \sim 20 \text{ MeV for 10s fs pulses} \]
Radiation pressure in laser matter interaction

**Radiation pressure** upon light reflection from a mirror surface:

\[ p_R = \frac{2I_L}{c} \]

\[ P_L = 60 \text{ Gbar} \]
\[ @ 10^{20} \text{Wcm}^{-2} \]

In a plasma the effect is felt by the electrons via the **ponderomotive force**

\[ f_p = -\frac{m}{4} \frac{\partial}{\partial x} v_{os}(x) (1 - \cos 2\omega_0 t) \]

Non-oscillating term

Oscillating term

**Steady pressure**, transferred to ions via space-charge

**JXB heating, hot electrons**

Ions are pushed into overdense plasma

\[ \frac{u}{c} = \left( \frac{n_{cr}}{2n_{pe}} \frac{Zm}{M} \frac{I\lambda^2_{\mu}}{1.37 \times 10^{18}} \right)^{1/2} \]

**Hole boring**

Liquid hydrogen target

6 \(10^{22}\) W/cm\(^2\)

A. Robinson

PPCF 2009
RPA on thin foils - light sail

• Cyclical re-acceleration of ions
• Narrow-band spectrum (whole-foil acceleration)
• Fast scaling with intensity

$F_R = (1 + R) A \frac{I_L}{c}$

$\Rightarrow v_i = \frac{(1 + R) \tau I_L}{m_i n_i d} \propto I \tau \eta^{-1}$

$\eta = m_i n_i d$  Areal density

$W \sim a_0^2 \frac{\tau}{\eta^2}$

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

Use of circular polarization:
No JxB acceleration
No TNSA
No target heating
Quasi-static pressure drive

APL Robinson et al, NJP, 10, 013021 (2009)
Current trends in Laser-driven Ion Acceleration

**Goals of current research:**
- Increase **energy**
- Increase **efficiency** of laser energy conversion into ions
- Improve/control **spectrum** (mono-energetic ions)
- Beam quality, repetition rate, collimation, purity

**Radiography/deflectometry**

**Isochoric heating of matter**

**Fusion Energy (Fast Ignition)**

**Injection into conventional accelerators**

**Cancer therapy**

**Production of isotopes for PET**

Industrial applications (implantation, lithography)

Nuclear/particle physics applications

- Optimize existing mechanisms
- Investigate new ones:
  - Radiation pressure acceleration
  - BOA

150-250 MeV protons
2-4 GeV carbon ions
Laser facilities employed by LIBRA consortium

1) **GEMINI laser**
- Pulse duration \( \sim 50 \) fs
- Energy on target up to 12 J (~250 TW)
- \( \lambda = 0.8 \mu m \)
- Intensity up to \( 0.5 - 1.0 \times 10^{21} \) W/cm\(^2\) (f/2 focusing)
- Contrast \( \sim 10^{7} \cdot 10^{8} \)

2) **VULCAN Petawatt**
- Pulse duration \( \sim 500 \) fs
- Energy on target up to 400 J
- \( \lambda = 1.053 \mu m \)
- Intensity up to \( 0.5 - 1.0 \times 10^{21} \) W/cm\(^2\)
- Contrast \( \sim 10^{7} \cdot 10^{8} \)

Plasma mirror losses limit intensity to \( \sim 5 \cdot 8 \times 10^{20} \) W/cm\(^2\).
•**GEMINI** - Proton acceleration at $35^\circ$ laser incidence from ultrathin foils


**Target: Al**

**Intensity on the target**

$>5 \times 10^{20} \text{ W/cm}^2$

**Flux along RSTN**

Conversion efficiency $\sim 6.5\%$

Integrated over the measured $2$–$12$ MeV energy range for the protons

Solid line based on Andreev, *PRL*, 2008
Proton acceleration at normal incidence

✓ Highest proton energy ~ 20 MeV
✓ Highest $C^{6+}$ energy ~ 240 MeV (with 25nm Carbon)

Linear polarisation

Conversion efficiency

Integrated over the measured 2–20 MeV energy range assuming 8° solid angle gives ~ 11%

M.Passoni et al., New J Phys, 12, 045012 (2010)
Radiation pressure acceleration in the light sail mode: GeV energies at $10^{22}$ W/cm$^2$


Unstable case


RT instability

F. Pegoraro, S.V. Bulanov
PRL (2007)
In multi-species targets the acceleration of the lighter species is inherently more stable

- Nanofoil target: electron density $n_{e0} = 200 n_c$, thickness $l_0 = 8 \text{nm} < l_s$
  
  C$_6^+$ and H$^+ : n_{iC0} = 32.65 n_c$, $n_{ip0} = 4.1 n_c$ with $n_{iC0}:n_{ip0} = 8:1$

  $$l_0 \sim 5 \times 10^{19} \text{W/cm}^2,$$ 40 laser cycles, $\lambda = 1 \mu\text{m}$

The C$_6^+$ layer has insufficient charge-balancing electrons - **Coulomb explosion**

The proton layer moves ahead of the C$_6^+$ layer.

Debunching of the electron layer - complete separation of the C$_6^+$ and proton layers. Strong electron leakage

Proton layer is surrounded by an excess number of electrons---**Stable RPA!!**
In CH target protons “borrow” the electrons from C$^{6+}$ layer to achieve stable RPA

$10^2 \lambda^2 \sim 5 \times 10^{19}$ W/cm$^2$

A quasi-monoenergetic proton beam is obtained with density about $0.25n_c$, peak energy 18MeV.

$100$ Mev protons with $I_0 \lambda^2$ a few times $10^{20}$ W/cm$^2$

Features of multispecies acceleration are consistent with other observations:


A. Macchi et al, PRL, 103, 085003 (2009)
A. P. L. Robinson et al., NJP. 10, 013021 (2008)
At “reasonable” intensities is Circular Polarization an essential requirement for stable light sail?

\[
\frac{v_b}{c} = \frac{\sqrt{n_c m_e / n_i m_i a}}{1 + \sqrt{n_c m_e / n_i m_i a}},
\]

Can hole boring reach the rear during the pulse and “interfere” with TNSA?

**Conditions:**

\[\ell_0 < v_B \tau / 2\]

Target thin enough (or pulse long enough)

\[
\frac{1}{\pi n_0} < l_0 / \lambda < \frac{1}{2\pi} \sqrt{\frac{n_c}{n_0}} a \exp\left[\sqrt{\frac{Z n_c}{n_0}} \frac{a}{\gamma n_c} \left(\frac{n_0}{\gamma n_c}\right)^{1/4} + \frac{1 - \ln 2}{2}\right]
\]

\[\varepsilon \approx 2\pi \frac{Z m_e a_0^2 \tau_L}{A m_p \zeta}\]
Concept tested by 2D PIC simulations

B. Qiao et al, submitted (2011)

80 nm C6+ foil irradiated at $3 \times 10^{21} \text{ W/cm}^2$, $n_e=600 \, n_c$

LINEAR POLARIZATION
“Hybrid” LS is possible with thin enough targets or long enough pulses

B. Qiao et al, submitted (2011)

Limits on foil thickness for 66 fs pulses

Even better with two species
At present intensities ($10^{20}$-$10^{21}$ W/cm$^2$) what could be experimental signatures of RPA?

- Narrow band spectral features
- Fast scaling of energy
- Characteristic features of multi species targets (say C- H): **peak of H beyond Carbon max energies**
- Some degree of polarization dependence (CP vs LP) (or not so clear?)
- Dependence on target areal density
- Collimated emission from the target

Directional jetting from rear of thin foils irradiated at $\sim 10^{20}$ W/cm$^2$.


Spectral modifications of C spectrum with CP from 5 nm DLC foils @ $5 \times 10^{19}$ W/cm$^2$
Spectral peaks seen on VULCAN Petawatt experiment and thin metallic targets

50nm Cu  Circular Pol  
$I = 1 \times 10^{20}$ W/cm$^2$

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

700 fs, 400 J, $I > 10^{20}$ W/cm$^2$

Solid line: TP1 spectrum (laser axis)  
Dotted line: TP2 spectrum (13º)

Targets thicker than 0.5 µm show standard continuous, decreasing spectra  
Peaks observed regardless of laser polarization - Hybrid scheme where TNSA and RPA cohesist  
(B. Qiao et al, submitted to PRL, 2011)
General spectral features are captured well by PIC simulations

![Spectral Features](image)

- **Experimental data**
- **2D PIC simulations (ILLUMINATION code @QUB)**

**Hybrid regime where RPA coexists with TNSA**

- $e/m = 0.42$ (Cu$^{27+}$?)
- $e/m = 1$
- $e/m = 0.5$
Scaling of carbon peak with Light sail parameter

Energy of peak scales $\sim \left(\frac{a_0^2 dt}{\eta}\right)^2$

$dt$ is the time the target is driven in light sail mode, i.e. laser pulse duration minus the time taken for the hole boring phase to go through the target.

Henig, PRL (2009)
Scaling highly promising for achieving high proton energies

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

**TARANIS @ QUB:**
- Ti:Sapphire-Nd:glass
- Wavelength: 1053nm
- Pulse duration of ~500fs
- Beam energy up to 15J
- Beam profile: Flat top relay imaged
- Repetition rate: One shot every 12 min

**TARANIS proton spectrum**

**T. Dzelzainis et al, LPB, 28, 451 (2010)**

**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
Dispersion: in 20mm from 3MeV to 10MeV

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

Delivered dose @ 1-5MeV: ~ few Gy/shot
Cell preparation and treatment (V79 – chinese hamster lung cells)

- Cells were placed at six spots (disks)
- The diameter of each disk is 2 mm.
- Four cell disks were irradiated.
- Two cell disks were used as control point which were not irradiated by protons
- Post–plating, cells were maintained at 37° C in an atmosphere of 5% CO2 in the incubator.

Surviving Fraction = Colonies Counted/ (Cells seeded * (PE/100))
In-situ dosimetry allows on-shot beam characterization


Set-up allows simultaneous irradiation of 4 samples with doses of up to 5 Gy in ~ ns proton pulses

Energy spread on cells due to selection slit

- Extreme dose-rates are achieved (up to ~5 $10^9$ Gy/s)
- Single exposure (non fractionated dose delivery)

Cell dots

Only data from B and C has been used

FLUKA simulation/ RCF analysis
Single shot clonogenic survival curve!

\[ \text{SF}_{\text{XRay}} = \exp(-0.0336 x^2 - 0.311 x) \]
\[ \text{SF}_{\text{Proton}} = \exp(-0.0339 x^2 - 0.106 x) \]

Dose rate > 10^9 Gy/s

In line with “standard” results with V79 cells
Same RBE with LET=17.8 Kev/µm

RBE = 1.4 ± 0.2
Consistent with other V79 proton data?
Summary and perspectives

Activities of LIBRA consortium

- Ion acceleration:
  - New regimes of acceleration using thin foils
  - Increased peak energies of C6+ and H+ with short pulses
  - Emerging RPA features
  - Scaling highly promising for intensity/power regimes planned in future facilities

- Radiobiology
  - Developed set-up for ultra-high dose rate irradiation on single exposure
  - Demonstrated dose-dependent cell damage
  - No clear difference due to dose-rate identified in this range (good for therapy)
  - Scope for interesting radiobiology by reducing further the burst duration?