Ion acceleration: some general points

- Several, fundamentally different mechanisms
- Large accelerating fields sustained by electron-ion separation in a plasma
- Very large fields ($10^{13}$ V/m) applied over very short distances ($\sim \mu$m)
- Mostly solids (high density targets)

Two classes of lasers are mainly used for ion acceleration

**High energy CPA systems**
- Nd: Glass technology
- 100s J energy, up to PW power
- Low repetition rate
- 100s fs duration
- $I_{\text{max}} \sim 10^{21} \text{ Wcm}^2$
- VULCAN, RAL (UK)
- Phelix, GSI (De)
- Trident, LANL (US)
- Texas PW, Austin (US)

**Ultrashort CPA systems**
- Ti:Sa technology
- 10s J energy, up to PW power
- 1-10 Hz repetition
- 10s fs duration
- $I_{\text{max}} \sim 10^{21} \text{ Wcm}^2$
- GEMINI, RAL (UK)
- Draco, HZDR (De)
- Pulser I, APRI (Kr)
- J-Karen, JAEA (J)
Laser-ion acceleration: why not use wakefield?

Standard laser wakefield methods cannot be used for accelerating ions

Issues:
1) $v_{\text{ion}} \ll v_{\text{wake}}$
2) $v_{\text{ion}}$ varies as ion is accelerated

Need of “slow wave”
Need of accelerating structure with variable phase

Some ideas:

Slow waves from Raman backscattering
Beat wave structure with variable phase velocity (frequency chirped pulses)
Breakdown of lectures

• Lecture 1: **Sheath acceleration processes**
  (Tue, 9 am, 40 min)

• Lecture 2: **Other mechanisms - new developments**
  (Thu, 3pm, 50 minutes)

• Lecture 3: **Applications**
  (Friday, 6.30 pm, 30 minutes)
Outline of Lecture 1

- **Historical introduction**
  - First observations

- **Target Normal Sheath Acceleration**
  - The basic process
  - State of the art and beam properties
Laser acceleration of ions from laser irradiated targets was studied from 1960s throughout the 90s.

Laser couples energy into electrons
Faster electrons drag ions

Ion acceleration was studied throughout the 90s


- Protons originate from contaminants
- Exponential spectrum with sharp cut-off
- Ions accelerated during plasma expansion
  (isothermal rarefaction model)
- Maximum energy of ions related to $T_{\text{hot}}$

VULCAN laser (CPA)

Target CH, Cu (15-25 µm thick)

Laser

Ion detector (CR39)

10 MeV

$E_{\text{max}} \sim I^{0.3}$
  (Beg's law)

$10^{19}$

$W/cm^2$

Laser intensity is key to efficient particle acceleration

**Chirped Pulse Amplification (CPA) Techniques**

- Short, high energy laser pulses
- \( v_{osc} \sim c \) (Relativistic interaction regimes)

Efficient and directional coupling of laser energy into energetic particles
Target Normal Sheath Acceleration (TNSA) from the rear of thin foils was studied from ~ 2000

Clark et al, PRL, 84, 670 (2000)
Maksimchuk et al, PRL, 84, 4108 (2000)
Snavely et al, PRL, 85, 2945 (2000)

Intensities rising above $10^{19}$ W/cm$^2$ – electron acceleration to MeV energies

Thin foils allow electrons to reach the rear of the target and establish a field there

Protons (from contaminants) have *beam* features contrary to lower energy, isotropic emission previously observed from the front.
LLNL data were obtained with Radiochromic film techniques

Counting activations

\( \text{Ti}^{48} (p,n) \text{V}^{48} \quad t_{1/2}=16\text{d}, \text{E}_{\text{thres}}=5\text{ MeV} \)

gives absolute #’s of protons in several spectral bands.

Spatial distribution of activation gives distribution of protons.

Radiochromic film layers:

Autoradiographs of activated d Ti discs:
Lawrence Livermore National laboratory experiments


- Sharp edge proton beam with cut off energy of 50MeV and slope of 6MeV
- Higher energy protons were more collimated than lower energy
- The proton beam was always normal to the back surface of the target
- No protons > 8 MeV were observed from the front of the target

Proton beams

Radiochromic Film (Rads)

PW beam
500J, 0.5ps
I ~ 4x10^{20}Wcm^{-2}
In 2000 there was controversy regarding the explanation of results ....

- Ponderomotive acceleration (up to a few MeV) followed by electrostatic acceleration due to electron escape 
  *(RAL-IC, CUOS Michigan)*

- Fast electrons are held in proximity of the target by space charge effects.
- E-field at discontinuity estimated as $E \sim T_{\text{hot}}/(eL_{\text{ion}})$ can also accelerate ions
  *(LLNL, supported by PIC simulations)*

- Acceleration by electric fields produced by the fast electrons travelling inside the target.
  *(RAL-IC)*
Several experiments have since shown that the dominant acceleration process for “thick” targets takes place at the target rear.

Creating a gradient artificially on the rear surface changes very significantly the proton beam energy.


Also:
Lecture 1 - TNSA

- **Historical introduction**
  - First observations

- **Target Normal Sheath Acceleration**
  - The basic process
  - State of the art and beam properties
The established mechanism: Sheath Acceleration (TNSA)
High density, high energy electrons lead to ultralarge field

\[ \rho = -e n_{\text{hot}} = -e n_0 \exp \left( -\frac{x}{\lambda_D} \right) \]

\[ \nabla \cdot E = \frac{dE}{dx} = \frac{\rho}{\varepsilon_0} \]

\[ E(0) = \int_0^\infty \frac{\rho}{\varepsilon_0} dx \]

Typical values:
- \( \lambda_D \sim 1 \, \mu \text{m} \)
- \( T_h \sim \text{MeV} \)

\[ E(0) = \frac{10^6 V}{10^{-6} m} \sim TV / m \]

S. Wilks et al, PoP, 8, 542 (2001)
Conventional particle accelerators use much smaller fields

Acceleration by much smaller Electric fields associated to alternating voltages (at RF or microwave frequencies)

\[ E_{\text{max}} \sim 50 \text{ MV/m} \]

(more than 10,000 smaller than with lasers)
TNSA ion beam properties

- Low emittance/ high laminarity
- Ultrashort duration (~ ps at the source)
- High brightness: $10^{11} - 10^{13}$ protons/ions in a single shot (> 3 MeV)
- High current (if stripped of electrons): kA range
- Divergent (~ 10s degrees)
- Broad spectrum

Very compact: E~1-10 TV/m
Acceleration lengths: ~ µm

Ion beam from TARANIS facility, QUB
E ~10 J on target in 10 µm spot
Intensity: ~$10^{19}$ W/cm², duration : 500 fs
Target: Al foil 10um thickness
Laser driven beams have excellent emission quality

**Highly laminar source** (virtual point source of ~µm size << real source)

**Ultralow emittance/virtual source:**

\[ \varepsilon_N < 0.1 \pi \text{ mm.mrad @ 15 MeV} \]

( < 0.004 mm-mrad;

Mesh with 12 µm pitch

CERN proton rf-linac:

\[ \varepsilon = 1.7 \pi \text{ mm-mrad} \]

*M.Borghesi et al, Phys Rev Lett., 92, 055003 (2004)*
PIC simulations predict an excellent longitudinal emittance

Rapid acceleration produces strong $\Delta E \cdot \Delta t$ correlation

$\Delta E \cdot \Delta t < 10^{-6}$ eV-s

Energy- or time-bunching may be possible with post-acceleration
Not only protons but heavier ions also accelerated

Spectra from VULCAN 100 TW: Pb target irradiated @ 5 $10^{19}$ W/cm$^2$

- Most of energy goes to protons
- Energy increases with charge

Varying the target, any ion can be accelerated (not straightforward with RF accelerators)
High efficiency conversion of laser energy to heavy ions is achieved by removing hydrogen contaminants from target.


Contaminant removal:
Ohmic heating
Laser heating
Laser ablation

20 J, 350 fs
1.054 μm

50 μm W + 1 μm CaF₂
(900°C)

20 J, 350 fs
1.054 μm

Laser-Ion Conv. Effic. (%)

Laser Pulse Energy (J)
TNSA energies – state of the art

A. Macchi, M. Borghesi, M. Passoni, Rev. Mod. Physics, 85, 751 (2013)

- Maximum published energies: ~85 MeV
- Conversion efficiency: ~ few %
- Acceleration more effective with higher energy, longer pulses, at equal intensities
- Effective on protons, less so on higher-Z species

- TNSA energies – state of the art

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“Record” spectra - long pulses (0.5-1 ps)

Large, high energy systems

RCF (and activation) measurements

I \sim \text{mid } 10^{20} \text{ W/cm}^2
Improved control of the laser parameters can lead to significant improvement

R.D. Snavely et al., PRL, 85, 2945 (2000)

F. Wagner et al., PRL, 116, 205002 (2016)

NOVA PW, LLNL
500J, 0.5ps
I \sim 4 \times 10^{20} \text{W/cm}^2
CH target, 100 \mu m thick

PHELIX, GSI
200J, 0.5 ps, I \sim 2 \times 10^{20} \text{W/cm}^2
CH$_2$ target, 0.9 \mu m

Better focusing, prepulse control….
Proton spectra from short pulse laser systems: ~ 20-50 fs

Near-linear scaling of proton energy with Laser energy/intensity (~ 9 MeV/J)

Some other high energy claims

Radiation pressure acceleration of protons to 93 MeV with circularly polarized petawatt laser pulses

Scattering noise interpreted as signal?

Need for community established protocols
Rigour in analysis