Laser accelerated ions and their potential for therapy accelerators

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1. Introduction to p driver parameters
2. Proton therapy accelerators
3. Beam quality source-collimation-accelerator
   - PHELIX-GSI experiment
   - scaling laws
4. Impact on accelerator scenarios
5. preliminary conclusions

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            M. Roth (TU Darmstadt), M. Droba (U Frankfurt)
1. Introduction to p driver parameters

What are lasers competing with?

SNS Accelerator Complex

Front-End:
Produce a 1-msec long, chopped, H- beam

Accumulator Ring:
Compress 1 msec long pulse to 700 nsec

2.5 MeV LINAC

1000 MeV

Current

945 ns

Chopper system makes gaps

Liquid Hg Target

I. Hofmann  HIAT09
**Injector Chain: New Proton Linac for FAIR at GSI**

**Crossed-bar H-Structure**

- Beam Energy: 70 MeV
- Beam Current: 70 mA
- Protons / Pulse: $7 \cdot 10^{12}$
- Pulse Length: 36 µs
- Repetition Rate: 4 Hz
- Rf Frequency: 352 MHz

(Uinv. Frankfurt U. Ratzinger)
Heidelberg Ion Therapy Facility
(HIT - accelerator built by GSI, fully operational end of 2009)
Summary on Proton Drivers

What can conventional proton accelerators achieve? (some examples)

<table>
<thead>
<tr>
<th>Facility</th>
<th>MeV</th>
<th>p/sec</th>
<th>p/ spill or micropulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNS Oakridge (Spallation Neutron Source)</td>
<td>1000</td>
<td>$6 \times 10^{15}$</td>
<td>$2 \times 10^9/10$ns</td>
</tr>
<tr>
<td>FAIR p driver linac (→ antiproton facility)</td>
<td>70</td>
<td>$\sim 10^{13}$</td>
<td>$2 \times 10^9/10$ns</td>
</tr>
<tr>
<td>Proton therapy (typical)</td>
<td>$\sim 250$</td>
<td>$\sim 10^{10}$</td>
<td>$5 \times 10^{10}/10$s spill</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\sim 5 \times 10^7/\text{voxel (100 Hz)}$</td>
</tr>
</tbody>
</table>

→ Laser p/ion acceleration may be competitive in the area of therapy

<table>
<thead>
<tr>
<th>Facility</th>
<th>Beam power (in photons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNS</td>
<td>1 MW</td>
</tr>
<tr>
<td>FAIR</td>
<td>100 W</td>
</tr>
<tr>
<td>HIT</td>
<td>0.2 W</td>
</tr>
<tr>
<td>5 Hz PW laser system</td>
<td>150 W</td>
</tr>
</tbody>
</table>

⇒ efficiency of "photons into usable protons/ions" crucial !!
(Example: in GSI-PHELIX experiment $\sim 3 \times 10^{-5}$)
2. Proton/Ion Therapy Accelerators

two (theoretical) options:
laser + post accelerator - laser to full energy

A. Laser acceleration replacing "injector linac" + conventional post-accelerator (linac/circular)

B. Full laser acceleration \( \rightarrow \) p directly to 250 MeV or C to 350 MeV \( \rightarrow \) transferred to patient
Summary on issues in proton therapy following Linz & Alonso PRSTAB10, 094801 (2007):

<table>
<thead>
<tr>
<th>Conventional (Cyclotron, Linac+Synchrotron)</th>
<th>Laser Accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Beam Energy 200 – 250 MeV</td>
<td>in theory possible</td>
</tr>
<tr>
<td>2. Energy variability &quot;+&quot; in synchrotron</td>
<td>? demanding</td>
</tr>
<tr>
<td>3. ΔE/E ~ 0.1%</td>
<td>? demanding</td>
</tr>
<tr>
<td>4. Intensity 10^{10} /sec</td>
<td>10^9/10^8 at 10/100 Hz</td>
</tr>
<tr>
<td>5. Precision for scanning &quot;+&quot; in synchrotrons</td>
<td>? large Δp/p</td>
</tr>
</tbody>
</table>

Linz & Alonso didn't quantify their highly critical arguments against laser acceleration!
3. Beam quality source-collimation-accelerator

1. The production phase space is extremely small – consequence of small \( \mu \)m size focal spot and <ps time duration – often "sold" as attractive feature of laser acceleration

2. Can we take advantage of the extremely small production phase space?

3. No, it won't survive collection and following transport!

*Single particle* effects degrading quality:
- chromatic aberration (second order effect): \( \delta x \sim x' \delta p/p \)

yet unexplored and open issues:

*Collective effects*:
- proton + neutralizing electron space charge at source - under study
  (separation of p and e\(^-\) by solenoid B field)
- proton beam space charge further downstream - appears controllable
  ("geometric" aberration by nonuniform space charge)
In 2008 demonstrated first time:
• 170 TW power
• 700 fs pulse length (120 J)
• novel copper focusing parabola
• spot size 12 X 17 µm (FWHM)
• Intensity: ~ 4 x 10^{19} W/cm²

EXPERIMENT: Laser Ion Acceleration (TUD - GSI)

Goal:
Collimate an intense, laser generated proton beam using a pulsed solenoid magnet → transfer to conventional accelerator optics

(Simulation CST-Studio, I. Albers, TUD)
Results of the first PHELIX experiment on laser proton acceleration

- Excellent laser beam quality
- Ion energy comparable with other systems
- Ion number as calculated
- All on the very first shot!! (further optimization pending)

Setup to test proton production

\[ N_0 = 1.52 \times 10^{13} \]

8x10^{10} protons in \( \Delta E/E = +/- 0.04 \)
Chromatic effect blows up integrated emittance from bunch head to tail – common collimation problem
solenoid focusing: $\Delta f/f \sim 2 \Delta p/p$

10 MeV protons produced at 20° opening cone
- modeled $\Delta E/E = +/-0.04$ by beams of 9.6 ... 10.4 MeV to describe chromatic effective emittance $\sim x´_{ini} \Delta p/p$
- much enlarged "effective spot"
- initial emittance < 1 mm mrad replaced by "effective emittance" 240 mm mrad

Effective spot with enlargement to: 12mm x 20mrad=240 mm mrad
need to reduce initial cone angle
Detailed tracking simulation with DYNAMION* code (quadrupole channel)

- reduced cone angle from 22° to 2.5°
- confirms chromatic effect
- shows also nonparaxial effect

* S. Yaramishev et. al.
DYNAMION: comparison for quadrupole and solenoid collimators / cone angle of 2.5°

- The real solenoid field requires a large field of 16 T.
- Symmetric focusing avoids large excursions as in quadrupoles.
- Larger distance source-solenoid reduces field, but increases chromatic effect approaching quadrupole.

**Solenoid**
- Requires large field of 16 T.
- Symmetric focusing avoids large excursions as in quadrupoles.
- Larger distance source-solenoid reduces field, but increases chromatic effect → approaching quadrupole.
Combined chromatic and space charge effects

production cone angle $5^0$ (86 mrad) $\Delta E/E = +/-0.04$
extrapolate to $10^0$ at 30 mA $\Rightarrow \varepsilon \sim 40 \pi \text{ mm mrad with } 2 \times 10^9 \text{ p (reference bunch)}$
Applied to synchrotron injection at 10 MeV

20 m debuncher drift (with focusing)
pulse length ps → 30 ns

RF bunch rotation
400 kV 10 MHz
ΔE/E 0.04 → 0.004

repeat 25 times
bunch into bucket
of 10 MHz (~70 kV)

reference p bunch:
2×10^9 p  ΔE/E=+/− 0.04 from cone +/− 10° →
ε~40 π mm mrad  δp/p~0.004
→ match well with space charge limit in ring !!

next at GSI (2009/10):
we plan experiment with single bunch and 2 m drift + 108 MHz bunch rotator
→ diagnose 3D phase space + efficiency to verify our modeling
### Parameters: laser injector – full laser scenario

<table>
<thead>
<tr>
<th>Ion</th>
<th>(N_{\text{bunch}})</th>
<th>(N_{\text{ring}})</th>
<th>(\Delta Q_{\text{inc}}) (space charge)</th>
<th>(h)</th>
<th>(\varepsilon_{\text{final}}) (\pi) mm mrad (estimated)</th>
<th>(\delta p/p_{\text{final}}) (estimated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p)</td>
<td>(2 \times 10^9)</td>
<td>(5 \times 10^{10})</td>
<td>0.1 (1 s!!!)</td>
<td>25</td>
<td>(~10) assume 10° cone</td>
<td>(~0.001)</td>
</tr>
<tr>
<td>(C^{6+})</td>
<td>(6 \times 10^8)</td>
<td>(1.5 \times 10^{10}) every 10 s</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\text{full laser:})</td>
<td>(N_{\text{batch}})</td>
<td>(N_{\text{fraction}})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(p)</td>
<td>(5 \times 10^7)</td>
<td>(5 \times 10^{10}) for 3D scanning in 10 s</td>
<td>(&lt;10) ? assume 2.5° cone</td>
<td></td>
<td>(&lt;0.001) linac bunch rotator: (~2-5) m length</td>
<td></td>
</tr>
</tbody>
</table>

### Laser:

- \(~10\) Hz
- \(~10\) Hz
- \(~10\) Hz
- \(~10\) Hz
- \(~10\) Hz
- \(~10\) Hz
- \(5\) Hz / \(30\) fJ
- \(~10\) Hz
- \(100\) Hz
- \(>\) PW
Conclusions

• As of today laser acceleration has a theoretical potential to compete with conventional drivers for therapy
• extremely high initial beam quality lost after collector → small "usable" fraction of total particle yield (PHELIX: "use" 3x10^{-3} of proton and 3x10^{-5} of photon yield)
• "laser injector" into synchrotron
  - should be ok (based on PHELIX data)
  - 10 Hz Petawatt laser in reach
  - hard to compete with linac technology !!
• "full energy laser" scenario lacks data
  - small cones (~2-3^0), smaller production ∆E/E (100%→10-20%)
  - >100 Hz laser systems, nm foils (problems?)
  - reproducibility, precision unknown
• New accelerator technologies take time!!