A Compact Post-acceleration Scheme for Laser Generated Protons

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Motivation and context

There are several conventional beamline facilities that are looking at laser-driven beamline projects.
Starting point: we consider "today" measured parameters and try to make beamlines out of it.

**TNSA 100 TW laser**

Laser:
- few J / ~1 ps (>10 TW)
- $I \lambda^2 > 10^{18}$ W cm$^{-2} \mu$m$^2$

Issue:
- Large energy spread
- Large beam divergence
- (Low energy)

**Surface contaminant (H$_2$O)**

Up to 67 MeV
- Emittance 100 times better than conventional accelerators
- Duration a few ps
Improvements using beam shaping with conventional accelerator devices

Combined accelerator

Injection studied using RF-cavity

Focalisation using Quadrupoles


M. Schollmeier et al., PRL 101, 055004 (2008)
Beam shaping with conventional accelerators becomes more fashionable

**Focusing with Solenoids**

F. Nürnberg et al., PAC 2009

V. Bagnoud et al., APB (2009)
8 T solenoid

Transport with 1 Hz

M. Nishiuchi et al Phys Rev STAB 13 071304 (2010), 5% spread, 10% efficiency

**Post-acc with modified DTL**

A. Almomani et al., Proceeding IPAC (2010)
General scheme for beam capture and post-acceleration

Looking for the best compromise in terms of
1) Highest (stable) energy
2) Highest dose
3) Lowest energy spread
4) Smallest beam divergence
5) Fully characterized source
6) Feasible
Focusing & energy selection: ultra-fast laser-triggered ion micro-lens

CPA\textsubscript{1} 
\begin{align*}
t &= 350 \text{ fs} \\
l &\approx 3 \times 10^{19} \text{ W.cm}^{-2} \\
\lambda &= 1 \text{ \textmu m}
\end{align*}

CPA\textsubscript{2} 
\begin{align*}
t &= 350 \text{ fs} \\
l &\approx 3 \times 10^{18} \text{ W.cm}^{-2} \\
\lambda &= 1 \text{ \textmu m}
\end{align*}

RCF and/or Magnetic Spectrometer

proton source foil

diverging proton beam

focused proton beam

Focusing fields are Debye sheath fields driven by the hot electrons

(A) initial stage

Debye sheath of hot electrons

(B) expansion stage

Zone of quasi-neutral expansion

CPA 2
The micro-lens offers (tunable) energy selection.

Cylinder
Best results in terms of energy spread, number of protons and beam divergence

w/o the micro-lens

with the micro-lens (0.2 MeV resolution)

simulation with the micro-lens (0.1 MeV resolution)

\( \Delta E/E \sim 3\% \)
Efficient reduction of the beam divergence (tunable)

Proton beam FWHM (mm)

Propagation distance (cm)

7.5 MeV with > 5 Å collimated
We use parameters measured in the micro-lens output for injection in the conventional section

- 6.9 to 7.1 MeV after the cylinder $\rightarrow 2 \times 10^9$ protons (320 pC)

- transverse source sizes (FWHM): $x=80\ \mu m$ with $\sigma_x=\sigma_y=20\ \mu m$

- residual divergence: $x'=y'=40\ \text{mrad}$ with $\sigma_x'=\sigma_y'=9\ \text{mrad}$

- un-normalized emittance $0.180\ \text{mm}\cdot\text{mrad}$

Simulations: Parmela / TStep
Drift Tube Lin(ear)ac(celerator) designed with EM Field solver for particle accelerators

We used typical state of the art capturing sections and accelerating structures DTLs (SNS)
48 cells, 0.17 MeV/cell, f=350 MHz

We use the drift-kick method (electric fields are designed with SUPERFISH, average = 3 MV/m)
Parmela results without space-charge

(a) Proton energy (MeV) vs. Propagation axis (cm)
(b) Unnormalized emittance (mm.mrad) vs. Propagation axis (cm)
(c) Normalized emittance (mm.mrad) vs. Propagation axis (cm)

Propagation axis (cm)

Transverse beam size (mm) vs. Propagation axis (cm)
Space charge effects

Average current for 350 MHz (all particles = 112 mA), SNS is 0.11 mA

SCDTL:  

- Short DTL tanks + side coupling cavities
- Side coupling cavities on axis with very small Permanent Magnet Quadrupole (PMQ) (3 cm long, 2 cm o.Ø, 6 mm i. Ø) for transverse focusing.
- Designed for medical applications
- S-band (3 GHz) very versatile to develop

L. Picardi et al., "Struttura SCDTL", Patent n. RM95-A000564
<table>
<thead>
<tr>
<th>Frequency</th>
<th>3 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of modules</td>
<td>2</td>
</tr>
<tr>
<td>Number of tanks/module</td>
<td>11</td>
</tr>
<tr>
<td>Number of cells/tank</td>
<td>4</td>
</tr>
<tr>
<td>Inter-tank distance</td>
<td>4.5 ( \beta \lambda ) in module #1, 4.5 ( \beta \lambda - 3.5 \beta \lambda ) in module #2</td>
</tr>
<tr>
<td>Bore radius</td>
<td>2 mm in module #1, 2.5 mm in the module #2</td>
</tr>
<tr>
<td>Total length</td>
<td>2.59 m</td>
</tr>
<tr>
<td>Average electric field, ( E_0 )</td>
<td>11.3 MV/m</td>
</tr>
<tr>
<td>Acc. electric field, ( E_0 T )</td>
<td>between 7 and 7.75 MV/m</td>
</tr>
<tr>
<td>Synchronous phase, ( \varphi_s )</td>
<td>-30°</td>
</tr>
<tr>
<td>Maximum PMQ gradient</td>
<td>220 T/m</td>
</tr>
<tr>
<td>RF power for the structure</td>
<td>&lt;1.5 MW</td>
</tr>
</tbody>
</table>
Lattice structure using Side Coupled DTLs

- **Solenoid**
  - Length: 70 mm
  - Diameter: 44 mm

- **Laser-generated proton source**
  - With µlens

- **Total length**: 2.59 m
  - Average electric field: 11.3 MV/m
  - Acc. electric field, $E_0T$: 7 - 7.75 MV/m
  - Max PMQ gradient: 220 T/m

- **Lattice structure using Side Coupled DTLs**

- **(PHELIX)**
  - Laser-generated proton source (with µlens)
  - Length: 17 mm

- **Solenoid**
  - Length: 70 mm
  - Diameter: 44 mm

- **(optimized)**
  - Length: 117 mm

- **SCDTL**
  - Length: 2590 mm

State of the art
PHELIX Solenoid (8.6 T)


C. Ronsivalle et al., Proceedings of IPAC'10, Kyoto, Japan
Output of SCDTL

Beam Envelope

Beam Energy

Shorter DTL
Beam dynamics with space charge yield high output current

Transmission (red points), output norm. emittance (blue points) versus the input current

Total output current (red) and useful output current (i.e. 0.6 MeV around maximum) (blue) versus the input current

Useful output current = 13 mA, ~36 % of total

TSTEP, 3 $10^5$ macroparticles
Spectrum becomes even more monoenergetic using the SCDTL

Normalized energy spectrum for 100 mA input current and two different lengths of the leading drift.

We have a laser-driven proton beamline!
Sensitivity study (typical for a beamline)

Study at the proton source

<table>
<thead>
<tr>
<th>Case</th>
<th>Input $\sigma_x$ ($\mu$m)</th>
<th>Input $\sigma_x'$ (mrad)</th>
<th>Input rms unnormalized emittance (mm-mrad)</th>
<th>Total output current (mA)</th>
<th>Useful output current (mA)</th>
<th>Output rms normalized emittance $(Exn*Eyn)^{0.5}$ (mm-mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>9</td>
<td>0.18</td>
<td>37</td>
<td>13</td>
<td>0.264</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>9</td>
<td>0.36</td>
<td>64</td>
<td>26</td>
<td>0.197</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>18</td>
<td>0.36</td>
<td>30</td>
<td>10</td>
<td>0.210</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>18</td>
<td>0.72</td>
<td>47</td>
<td>20</td>
<td>0.209</td>
</tr>
</tbody>
</table>
Sensitivity study (typical for a beamline)

Study with the lattice structure

- PMQ displacement in x,y (mm)
  - Transmission/Max. Transmission (%)
  - 50 runs, values uniformly distributed ±|Error amplitude|

- PMQ gradient (%)
  - Transmission/Max. Transmission (%)

- TANK field amplitude error (%)
  - Transmission/Max. Transmission (%)

Combined (95 % acceptance)
Conclusions

• It is possible to couple laser-generated protons to a high frequency LINAC in a compact acceleration hybrid scheme.

• A current between 13 and 26 mA can be captured and accelerated up to 15.5 MeV in ~3 m.

• A 10 Hz laser repetition rate corresponds to an average proton current of 43-86 pA that could be used to perform radiobiology experiments.

• Conventional accelerator community could provide necessary know-how and techniques to reach laser-driven beamlines
Thank you for your attention
Phase space in the structure

- Laser source
- SCDTL Input
- SCDTL Output

Δ Energy