Ultra-high-Gradient Compact Accelerator Development

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Beyond RF- technology: towards GV - TV/m

Options:
- electron-driven plasma waves (SLAC ‘afterburner’)
- laser-driven plasma waves
- laser in vacuum
- pulsed-DC
Laser-driven plasma waves: principle

**Longitudinal wake-field:**
- blue – accelerating,
- red – decelerating.

**Transverse wake-field:**
- blue – focusing,
- red – defocusing.

\[ \lambda_{\text{plasma}} = 10 \mu m - 1 \text{ mm} ; \quad \text{gradient } 1 \text{ GV/m} - 1 \text{ TV/m}, \text{ limited by wave breaking} \]
Laser-driven plasma waves: Options

- nozzles
- multi-TW laser
- gas jet
- electrons
- drive laser
- injector
- acceleration structure

'hot-beam' source

'controlled' acceleration
in $10^{-4} \text{ mm}^3$, a 5-step process occurs:

1- laser ionizes gas for 100% in few fs
2- self-focussing *
3- creation of wakefield wave
4- electron trapping by wave breaking *
5- acceleration in wakefield

*= instability

electron beam:
- charge per pulse several nC
- short pulse (~ 100 fs)
- norm. emittance few µm

but
- MeV-'temperature' beam
- shot-to-shot intensity variations of factor 3-10

Hot-beam Source

gas jet (~ 1 atm.)
Hot-beam Source: Experiments

**self-modulated regime:**
\[ \tau_{\text{laser}} \geq \omega_{\text{plasma}} \]

**forced wakefield regime:**
\[ \tau_{\text{laser}} \leq \omega_{\text{plasma}} \]

*Najmudin et al., Phys. Plasmas 10, 2071 (2003)*
Hot-beam Source: possible applications

- pulsed radiolysis / electron-photon pump probe

- X- and $\gamma$-ray source

- use energy slice for injection into 2$\text{nd}$ stage wakefield accelerator

- proton beams $\leq 10$ MeV (from foil) for radio-isotope production
Beat-wave Acceleration

$\omega_1 & \omega_2$ ($\omega_1 - \omega_2 = \omega_{\text{plasma}}$)

plasma with beat wave

electrons

injection: 12 MeV, 10 ps

$\lambda_{\text{plasma}} = 300 \ \mu$m

gradient=1.3 GV/m

Controlled Wakefield Acceleration: Lay-out & Issues

TW drive laser

laser for internal injection

injector
\( \geq 10 \text{ MeV} \)

plasma waveguide

accelerated electrons

issue:
\( \tau_{\text{bunch}} = 1 \text{ - } 100 \text{ fs} \)
\( \varepsilon_n \sim 1 \mu \text{m} \)

issue:
synchronization \( \ll \tau_{\text{bunch}} \)

issue:
- \( n_e = 10^{17} \text{ – } 10^{20} \text{ cm}^{-3} \)
- hollow, parabolic radial \( n_e \)-profile
- length several cm
- 100% ionization
- radius 20-50 \( \mu \text{m} \)
Alternative for injection / compression / acceleration

1: accelerating field
2: wake-field potential
3: laser pulse
4: initial electron bunch
5: trapped e-bunch

Khachatryan, Van Goor, Boller, Proceedings PAC'03, 1900 (2003).

EPAC 04, Luzern, July 5-9, 2004
## Issue 1: Plasma Waveguiding of TW Laser Pulses

<table>
<thead>
<tr>
<th>Option</th>
<th>Process</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>● self-focussing</td>
<td>local change of refract. index due to relat. mass correction of oscillating electrons</td>
<td>instability</td>
</tr>
<tr>
<td>● gas-filled capillary</td>
<td>internal reflection; laser ionizes gas</td>
<td>single shot</td>
</tr>
<tr>
<td>● pulsed discharge in capillary</td>
<td>plasma cooling at capillary wall; radially expanding shock wave creates hollow density profile</td>
<td>simple, durable, &gt; 90% transmission</td>
</tr>
<tr>
<td>● laser ionization</td>
<td>ionization and heating creates shockwave and hollow profile</td>
<td>optically complex; works down to radii of 5 µm</td>
</tr>
</tbody>
</table>
Capillary discharge plasma channel

Butler, Spence, Hooker, PRL 89,185003 (2002)

1.0 = $10^{17}$ W/cm²

Status:  
- simple and cheap  
- good transmission of TW pulses  
- further work needed for pressures $\leq 10^{18}$ cm⁻³ ($\lambda_{\text{plasma}} \geq 300$ µm)
Laser-produced plasma channels

Issue 2: Synchronisation of RF and laser

- State-of-the-art for case of RF master / laser slave: ~ 1 ps

- Recent progress at TU- Eindhoven by choosing laser master / RF slave: 80 fs (Kiewiet et al., NIM-A, A484, 619, 2002)

- Easy route towards 10 fs: - klystron power stability 0.1% → 0.05%
  - RF cavity 2.6 cell → 2.5 cell
## Issue 3: Injection

Options for 10-100 fs bunches with reasonable charge ($I_{\text{peak}} = 100 \text{ A} - 1 \text{ kA}$)

<table>
<thead>
<tr>
<th></th>
<th>achieved</th>
<th>promised</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>external:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- RF photogun &amp; metal cathode</td>
<td>1 ps, 100 pC</td>
<td>100 fs, 10 pC</td>
</tr>
<tr>
<td>- pulsed-DC photogun &amp; metal cathode</td>
<td>(1.3 GV / m)</td>
<td>100 fs, 100 pC</td>
</tr>
<tr>
<td>- idem, with novel approach to ultra-high brightness</td>
<td>--</td>
<td>10 fs, 50 pC</td>
</tr>
<tr>
<td><strong>internal:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- optical injecton</td>
<td>--</td>
<td>1 fs, 1 pC</td>
</tr>
</tbody>
</table>

EPAC 04, Luzern, July 5-9, 2004
RF photogun

Fred Kiewiet et al., thesis TU-Eindhoven and submitted to Phys. Rev. ST

bunch: - 8 MeV
- 100 pC, 1 ps or 10 pC, 100 fs
- $\varepsilon_n \cong 1 \mu m$
Pulsed-DC photogun: $\geq 1$ GV / m on cathode

Dmitry Vyuga and Seth Brussaard, TU-Eindhoven

Voltage doubling $\rightarrow$ 4 MV across 3-mm gap, i.e. 1.3 GV/m

Controlled field emission of 4 MeV electrons

EPAC 04, Luzern, July 5-9, 2004
Integrated Experiment with *present* components

now:

*injected bunch*
10 pC, 100fs (30 µm)

0.25 $\lambda_{\text{plasma}}$
50 µm

accelerated bunch
50 ± 20 MeV

later:

100 pC, 50 fs (15 µm)

250 µm

200 ± 5 MeV
Phase-space control of short bunches with high space charge

Standard approach:

- keep space charge low near cathode
- use ps-laser on (high-efficiency) ps-response cathode
- compress to sub-ps at high energy

Novel, counter-intuitive approach for compact injector:

- use fs-laser on (low-efficiency) fs-response cathode
- keep bunch in ‘pancake’ regime up to $\gamma$ as high as possible
- this reduces emittance dilution due to Coulomb explosion
Pancakes evolving into bunches with purely linear self-fields

*Luiten, Van der Geer and Van der Wiel, PRL 2004 (accepted)*

**Graphs:**
- Graph showing the evolution of a laser beam with labels indicating linear self-fields.
- Graphs comparing different distributions: Flat-top, Ellipse, and Gauss.
- Graphs illustrating the RMS emittance for different distributions.

**Graph Details:**
- **Flat-top** distribution,
- **Ellipse** distribution,
- **Gauss** distribution,
- Longitudinal position [mm] vs. RMS emittance [µm],
- Time: $t = 50$ ps, Energy: $E = 1$ MeV.
Conclusion & Outlook: 1

• ‘Hot-beam’ source:
  - works; provides energies up to few 100 MeV
  - may find niche applications
  - progress towards mono-energetic beams
    requires all-optical injection of ∼ 1 fs bunches
Conclusion & Outlook : 2

- **Controlled acceleration:**
  - components available for first demo of ‘regular’ acceleration and of novel injection / compression / acceleration scheme
  - integrated experiments being prepared by national consortia in both The Netherlands \(^1\) and the UK \(^2\)
  - full demo requires further development
    - on injector: demo of laser radial profile shaping and / or of pulsed-DC photogun
    - on plasma channel: operation at lower pressure / longer plasma waves

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1) TU-Eindhoven, FOM-Institute for Plasma Physics, University Twente
2) Univ Strathclyde, RAL, Imperial College, Oxford Univ, Daresbury Lab, St. Andrew’s Univ, Univ Abertay