Prospects for Plasma Wakefield Acceleration at the MAX IV Laboratory

Olle Lundh
Department of Physics, Lund University, Sweden

EAAC — European Advanced Accelerator Conference
Isola d’Elba, Italy, 24-30 September 2017
Acknowledgements

Lund University
Jonas Björklund Svensson
Henrik Ekerfelt

MAX IV Laboratory
Francesca Curbis
Sara Thorin
Sverker Werin

CEA
Xavier Davoine
Particle acceleration in a plasma

LWFA
Wakefield driven by laser pulse
+ Lasers are compact and available
+ Internal injection schemes well developed
- External injection (synchronisation) difficult
- Dephasing limits energy in one stage

PWFA
Wakefield driven by particle beam
+ No dephasing, energy gain limited by depletion
+ External injection (synchronisation) “easier”
- Needs large particle accelerator
Outline

• What is MAX IV Laboratory and its 3 GeV linac?

• Can it be used for acceleration of double-bunches?

• Can it be used for PWFA with external injection?
MAX IV Laboratory

Accelerators
✦ 1.5 GeV ring - circumference 96 m
✦ 3 GeV ring - circumference 528 m
✦ 3 GeV linac - length 300 m

Beamlines
✦ 14 (soon 17) BLs funded
✦ 5 BLs open to users
✦ 25 BLs in 2026
✦ Short Pulse Facility
2011: Brunnshög outside Lund
2011-2015: Building construction
2013-2015: Linac installation and commissioning
2015: Buildings completed
Feb 7 2015: 3 GeV achieved in the linac
Midsummer 2016: Inauguration
Planned: Science Village, between MAX IV and ESS
MAX IV Linear Accelerator

Operation modes

- Top-up injection for storage rings (~every 5-10 min)
- Driver for Short Pulse Facility (SPF, 100 Hz)

Contact: Sara Thorin
Simulation - full compression

**Gun – 1st linac:** ASTRA
**Linac + compressors:** ELEGANT

- **Charge:** 100 pC
- **Δt fwhm:** 10 fs
- **Peak current:** 14 kA
- **Compression factor:** 500
- **Slice $\varepsilon N$:** 1.5 mm mrad
- **Proj $\varepsilon N$:** 2.4 mm mrad
- **Emittance increase (slice):** 375%
- **Slice $\Delta E/E$:** 0.25%
Simulation - small emittance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>100 pC</td>
</tr>
<tr>
<td>Δt fwhm</td>
<td>100 fs</td>
</tr>
<tr>
<td>Peak current</td>
<td>1.5 kA</td>
</tr>
<tr>
<td>Compression factor</td>
<td>50</td>
</tr>
<tr>
<td>Slice εN</td>
<td>0.42 mm mrad</td>
</tr>
<tr>
<td>Proj εN</td>
<td>0.55 mm mrad</td>
</tr>
<tr>
<td>Emittance increase</td>
<td>5 %</td>
</tr>
<tr>
<td>Slice ΔE/E</td>
<td>0.035 %</td>
</tr>
</tbody>
</table>

Gun – 1st linac: ASTRA
Linac + compressors: ELEGANT

ELEGANT simulation: Sara Thorin
FemtoMAX

Ultrafast X-ray beam line for studies of the structure and dynamics of materials

2-20 keV, $10^7$ photons @ 6 keV

Ultrafast laser (10 mJ@800 nm)

Crystal monochromator, focusing mirror, Be-lenses, robot detector holder...

First users 2017, full operation 2018

Contact: Prof. Jörgen Larsson
Bunch compressors - double achromats

Zero dispersion - transfer section is easily extended for distribution to experiments
Conceptual Design Study

- Two year study of feasibility and detail planning for a soft x-ray laser beamline
- Will start 2018

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1-5 nm</td>
</tr>
<tr>
<td>Photon energy</td>
<td>0.25-1 keV</td>
</tr>
<tr>
<td>Pulse length</td>
<td>10-100 fs</td>
</tr>
<tr>
<td>Rep rate</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Power (peak)</td>
<td>~1 GW</td>
</tr>
<tr>
<td>Ph/pulse</td>
<td>$10^{11-12}$</td>
</tr>
</tbody>
</table>

Contact: Pedro Fernandes Tavernes (MAX IV)
Short Pulse Facility - PlasMAX proposal

PROPOSAL

PWFA beam line

Laser hutch

Control hutch

Plasma

PlasMAX

FemtoMAX
Two laser pulses to gun, $\Delta T = 5\text{ps}$

BC1 @ 250 MeV

Linac 1250 MeV

Linac 1500 MeV

Extraction 1.5 GeV

Extraction 3 GeV

BC2 @ 3 GeV

Plasma cell

ELEGANT simulation
Two laser pulses to gun, $\Delta T = 5\text{ps}$

BC1 @ 250 MeV

Linac 1250 MeV

Linac 1500 MeV

BC2 @ 3 GeV

Extraction 1.5 GeV

Extraction 3 GeV

Plasma cell

Linac 250 MeV

ELEGANT simulation
Two laser pulses to gun, $\Delta T = 5\text{ps}$

**BC1 @ 250 MeV**

**Linac 1250 MeV**

**Linac 1500 MeV**

**BC2 @ 3 GeV**

**Extraction 1.5 GeV**

**Extraction 3 GeV**

**Plasma cell**

---

**ELEGANT simulation**
Two laser pulses to gun, $\Delta T = 5$ ps

BC1 @ 250 MeV

Linac 1250 MeV

Linac 1500 MeV

BC2 @ 3 GeV

Extraction 1.5 GeV

Extraction 3 GeV

Plasma cell

Linac 250 MeV

ELEGANT simulation
Preliminary focusing system

BC2: 2nd achromat

Final focus

$\beta^* \approx 30 \text{ cm at focus}$
Preliminary focusing system

Final focus

$\beta^* \approx 30 \text{ cm at focus}$
Adjustable beams

Beam A | Drive | Witness
------|-------|-------
Delay | 310   | fs    |
Duration | 50   | 62   | fs    |
Peak current | 2.2  | 1.4  | kA    |
Peak density | 4.0  | 2.1  | $10^{17}$ cm$^{-3}$ |
Charge (pC) | 150  | 100  | pC    |
Emittance hor. | 0.47 | 0.40 | mm mrad |
Emittance, vert. | 0.35 | 0.38 | mm mrad |
Width, hor. | 15   | 11   | µm    |
Width, vert. | 8.5  | 9.8  | µm    |
Energy spread | 0.8  | 0.8  | %      |

Beam B | Drive | Witness
------|-------|-------
Delay | 195   | fs    |
Duration | 31   | 55   | fs    |
Peak current | 3.3  | 1.5  | kA    |
Peak density | 6.0  | 2.6  | $10^{17}$ cm$^{-3}$ |
Charge (pC) | 150  | 100  | pC    |
Emittance hor. | 0.51 | 0.40 | mm mrad |
Emittance, vert. | 0.34 | 0.37 | mm mrad |
Width, hor. | 15   | 9.3  | µm    |
Width, vert. | 8.6  | 9.4  | µm    |
Energy spread | 0.9  | 0.9  | %      |
### Plasma parameters

- $L_{\text{ramp}} = 500$ μm
- $L_{\text{plateau}} = 500$ mm
- $n_e = 1.1 \times 10^{17}$ cm$^{-3}$

### Bunch parameters

- 3.3 kA
- 31 fs (FWHM)
- 10 μm (FWHM)
- 150 pC
- $n_b = 6 \times 10^{17}$ cm$^{-3}$

---

Simulation using CALDER-CIRC

Plasma density chosen so both bunches are in the bubble

**Driver bunch**
- 3.3 kA
- 31 fs (FWHM)
- 10 µm (FWHM)
- 150 pC
- \(n_b = 6 \times 10^{17} \text{ cm}^{-3}\)

**Driver bunch**
- 1.5 kA
- 55 fs (FWHM)
- 10 µm (FWHM)
- 100 pC
- \(n_b = 2.6 \times 10^{17} \text{ cm}^{-3}\)

Plasma parameters
- \(L_{\text{ramp}} = 0.5 \text{ mm}\)
- \(n_e = 1.1 \times 10^{17} \text{ cm}^{-3}\)

Simulation using CALDER-CIRC
177 mm
Depletion of the driver after 35 cm
Witness energy = 5.1 GeV (2.1 GeV gain)
Effective accelerating gradient 6 GV/m
Energy spread 1.5%
Energy gain and spread

Energy spread grows during acceleration to ~3%
Momentum compression during driver depletion
\( \Delta E/E = 1.5\% \) at 5.1 GeV
Efficient energy transfer

~60% of the energy lost by driver is gained by witness
Prospects for PWFA at MAX IV

Conclusions
Yes, the MAX IV Linac is *excellent* for PWFA
Witness energy gain of 6 GeV/m
There is space (~25 m) in the switchyard
Synergies with existing and planned BLs at the SPF

What’s next?
Produce and measure kA-double-bunches
Endorsement by the MAX IV laboratory (enter strategic plan)
• Make a strong science case
• Identify a large user pool