Beam manipulation with velocity bunching for PWFA applications

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on behalf of the SPARC_LAB collaboration
SPARC_LAB test-facility

High brightness photo-injector

Low-current operation
- 30-170 MeV beam energy
- 1-10 ps bunch duration

Thomson source

FEL

High-current operation (VB)
- 80-120 MeV beam energy
- 20 fs - 1 ps bunch duration

THz radiation source

FEL (single spike + seeding)

Multi-bunch trains

LWFA (external injection)

Narrowband THz

FEL (2 colors)

PWFA (w/ resonant scheme)

FLAME: a 300 TW Ti:Sa laser

Final amplification stage from ~600 mJ to 6J

- Energy: 7 J
- Duration: 23 fs
- Wavelength: 800 nm
- Bandwidth: 60/80 nm
- Spot @ focus: 10 μm
- Peak Power: 300 TW
- Contrast Ratio: 10$^{10}$

FLAME @ SPARC_LAB
- LWFA (external injection)
- Thomson scattering
Radiation source activities

**FLAME laser**
- $E_L = 5 \text{ J (800 nm)}$
- $\Delta t_{L,B} = 3-12 \text{ ps}$
- $Q_B = 0.2-1 \text{ nC}$
- $E_B = 28-150 \text{ MeV}$
- $E_X = 20-550 \text{ keV}$

**Free Electron Laser (SASE + seeded)**
- $\lambda_u = 2.8 \text{ cm}$
- $N_u = 77$
- Gap = 0.8-20 cm
- $K = 0.38-2.1$
- $Br = 1.31 \text{ T}$

**Thomson X-rays source**

**THz station – user experiments**
- $E_{THz} = 40 \mu\text{J}$
- $P_{peak} = 100 \text{ MW}$
- $\Delta t_{THz} < 100 \text{ fs}$
Plasma-based acceleration activities

- Several plasma-based schemes will be tested
  - **PWFA** resonant scheme → 1-2 GV/m expected
    - $n_e \sim 10^{16}$ cm$^{-3}$, 1 mm diameter capillary, Hydrogen
  - **LWFA**, external injection → 5-10 GV/m expected
    - $n_e \sim 10^{17}$ cm$^{-3}$, 100 μm diameter capillary, Hydrogen

- **Goal:** high quality accelerated beams
  - Maintain the high brightness of injected beams

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**Resonant PWFA**

- **Accelarating ($E_z$)**
- **Decelerating ($E_z$)**
- **Focusing ($E_r$)**
- **Defocusing ($E_r$)**
- Witness

**LWFA (external injection)**

- **bunch externally injected**

F. Massimo and A. Marocchino - Architect
Ultra-short electron beams

- Current demands require high current beams
  - **PWFA-LWFA**: high wakefield amplitude (i.e. high driver density), low energy spread (i.e. short witness).
  - **Advanced radiation sources**: high peak currents (FEL), short beams (broadband THz radiation).

- Velocity bunching @ SPARC_LAB
  - **RF structure embedded in solenoid fields for emittance compensation**

Laser-comb with velocity bunching

- **Laser-comb**: multiple bunches train produced directly at the cathode
  - Pulses delayed by birefringent crystals, delay lines to take full control of distances
  - Easy setup, half-wave plates for (un)balancing (charge ramps…)


- Velocity bunching for bunch compression
  - Distance and duration tuning by moving S1 phase
  - Different approach with respect to other multi-bunches schemes, e.g. @ FACET.


Laser-comb: optical setup

Tuning knobs

Measurement tools

5 bunches (charge ramp)

- THz flag
- Quadrupoles
- RF Deflector
- Dipole

- Energy measurement
- Longitudinal Phase-Space
- Multiple-bunches QSCAN (energy separation)

CTR/CDR emission in THz range
Longitudinal diagnostics

Cianchi, A. et al. Six-dimensional measurements of trains of high brightness electron bunches. PRSTAB 18 082804.
Single-shot and non-destructive tool

- Multi-bunches trains have been measured with Electro-Optical Sampling
  - Single-shot, non-intercepting
  - 80 fs (rms) temporal resolution
- Goal: monitor beam injection in plasma

PWFA and LWFA requirements
**LWFA by external injection (I)**

- **Average accelerating field:** 7 GV/m \( (n_0 = 10^{17} \text{ cm}^{-3}) \)
- **Optimized matching**
  - *Simulations show emittance growth limited to 10%*
  - *Input ramp: relaxed beam transverse matching*
- **Energy spread ~ 0.9%, strongly reduced at exit**
  - *Exit ramp: acts as a dechirper (\( \lambda_p \) increases)*

High quality ultra-short beams with VB

Single-spike FEL means high quality ultra-short beam!

Collected FEL light, 100 fs (rms), 40 μJ

Bunch parameters

<table>
<thead>
<tr>
<th>Charge (pC)</th>
<th>Energy (MeV)</th>
<th>Energy Spread (%)</th>
<th>Duration (fs)</th>
<th>Emittance (μm)</th>
<th>Peak current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>114</td>
<td>0.1</td>
<td>26</td>
<td>1.2</td>
<td>400</td>
</tr>
</tbody>
</table>
Laser vs $e^-$ beam time-jitter reduction

**Photo-cathode laser**

- bunch mainly linked to PC laser

**VB compression**

- bunch mainly linked to RF (VB)
- → increase of laser - $e^-$ jitter

**Magnetic compression (dogleg)**

- 50 pC, 90 fs bunch
- laser-$e^-$ time-jitter linkage recovered by dogleg

Hybrid compression: bunch shortening by VB, relative ATJ reduction by **magnetic compression**

- 19 fs jitter!

EOS - time of arrival measurement

EOS - time of arrival measurement

Pompili, R. et al. submitted to PRSTAB.
PWFA – Quasi-nonlinear regime

- Condition for blowout: \[ \frac{n_b}{n_p} > 1 \]
  - Bubble formation w/o wave-breaking, \( \lambda_p \) is constant \( \rightarrow \) resonant scheme in blowout
  - Linear focusing force \( \rightarrow \) emittance preserved

- A measure of nonlinearity is the normalized charge
  \[ \tilde{Q} = \frac{N_b k_p^3}{n_p} = 4 \pi k_p r_e N_b \rightarrow \begin{cases} \ll 1 & \text{linear regime} \\ > 1 & \text{blowout regime} \end{cases} \]

- Using low emittance, high brightness beams we have
  \[ \tilde{Q} < 1 \quad \frac{n_b}{n_p} > 1 \]

- These conditions define the quasi-nonlinear (QNL) regime
  \( n_p = 10^{16} \, \text{cm}^{-3}, \; Q_p = 200 \, \text{pC}, \; \sigma_t = 180 \, \text{fs}, \; \sigma_x = 5.5 \, \text{um} \rightarrow n_b \sim 5n_p \) and \( \tilde{Q} = N_b k_p^3 / n_p \approx 0.8 \)

**Acceleration in plasma**

- **Hybrid kinetic-fluid simulation by Architect**
  - **PIC (bunch), fluid (plasma), 3-5 hours for 3 cm**
  - Cross-checked with full PIC codes (ALaDyn)

<table>
<thead>
<tr>
<th></th>
<th>Q (pC)</th>
<th>σt (fs)</th>
<th>σx (μm)</th>
<th>E (MeV)</th>
<th>ε (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td>200</td>
<td>180</td>
<td>5.5</td>
<td>116</td>
<td>4.5</td>
</tr>
<tr>
<td>Witness</td>
<td>20</td>
<td>35</td>
<td>3</td>
<td>116</td>
<td>2.4</td>
</tr>
</tbody>
</table>

→ A. Marocchino, → F. Massimo
WG6, Wed16

\[ n_p = 10^{16} \text{ cm}^{-3} \]
\[ E_z \sim 1.1 \text{ GV/m} \]
Toward the PWFA
VB dynamics: 1 driver + witness

**Experimental results!**

**Laser profile on photo-cathode**

**Driver + witness (20 pC)**

**Witness position adjusted online**

**LPS at linac exit**

- 120-180 fs (D)
- 80-130 fs (W)
- 200 pC
- 140 fs
- 400 pC
- 100 fs

**Current profile**
VB dynamics: N driver + witness

50 pC drivers + 20 pC witness

resonant scheme @ \( n_p = 10^{16} \text{ cm}^{-3} \) → bunch distance = \( \lambda_p \approx 1.1 \text{ ps} \)

Experimental results!

Laser profile on photo-cathode

Longitudinal Phase Space

Current profile

Laser profile on photo-cathode

Longitudinal Phase Space

Current profile
Witness – tuning and characterization

Single bunch emittance scan

![Graph showing emittance versus current with markers for Total projected $\varepsilon_{nx}$, Witness $\varepsilon_{nx}$, Driver 1 $\varepsilon_{nx}$, and Driver 2 $\varepsilon_{nx}$]

-1.67 ps

Reference

+1.67 ps

Witness position tuning with laser delay line!
Ramped comb beams

Longitudinal Phase Space

\[ Q_{\text{tot}} = 250 \, \text{pC} \]

Witness

Time Distance: 0.91 ps, Energy Distance: 0.02 MeV
Time Distance: 0.79 ps, Energy Distance: 0.02 MeV
Time Distance: 1.30 ps, Energy Distance: 0.02 MeV
Time Distance: 1.60 ps, Energy Distance: 0.11 MeV

Charge

Q: 6.2%, dE: 0.06 MeV, dt: 0.37 ps
Q: 16.3%, dE: 0.09 MeV, dt: 0.56 ps
Q: 27.9%, dE: 0.10 MeV, dt: 0.48 ps
Q: 39.0%, dE: 0.19 MeV, dt: 0.40 ps
Q: 10.6%, dE: 0.08 MeV, dt: 0.27 ps
**Recipe for PWFA beams**

- Generation of the required train bunches
  - $\sigma_t=100$ fs (rms) laser @ cathode (blowout [1,2])
  - Laser pulse distance at cathode: 2.4 ps
  - Driver-Witness distance at linac exit: 550 fs

<table>
<thead>
<tr>
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<th>Driver</th>
<th>Witness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge (pC)</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>107.6</td>
<td>107.4</td>
</tr>
<tr>
<td>Final focus (µm)</td>
<td>5.5</td>
<td>3</td>
</tr>
<tr>
<td>Duration (fs)</td>
<td>190</td>
<td>40</td>
</tr>
<tr>
<td>Emittance (µm)</td>
<td>3.9</td>
<td>2.7</td>
</tr>
</tbody>
</table>

[Bunch crossing](#)  
[Bunch 1](#)  
[Bunch 2](#)  
[Distance](#)  

**Hollow driver beams**

- Witness degradation during bunch crossing
  - *Driver as nonlinear lens* → emittance growth
  - *Driver field opposed to RF* → lower compression
- Use of hollow driver beam
  - ✓ No beam-beam effects → unperturbed witness
  - ✗ Higher driver emittance (larger spot on cathode)

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**Witness evolution**

- **Bunch crossing**
  - Duration (s)
  - 4 × 10^{-13}
  - 3
  - 2
  - 1
  - 0
  - 0
  - 2
  - 4
  - 6
  - 8
  - 10
  - 12

- **Emittance (m rad)**
  - 4 × 10^{-7}
  - 3
  - 2
  - 1
  - 0

- **0.3 μm**

- **22 fs**

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**Graphical representation**

- Color-coded distribution with small spot size and compact bunch crossing.
Hollow driver – comb beams

Large hole in order to avoid space-charge filling it!

<table>
<thead>
<tr>
<th>Driver</th>
<th>( \Delta t ) (fs)</th>
<th>( \varepsilon_n ) (( \mu )m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver 1</td>
<td>164</td>
<td>4.8</td>
</tr>
<tr>
<td>Driver 2</td>
<td>81</td>
<td>6.1</td>
</tr>
<tr>
<td>Driver 3</td>
<td>43</td>
<td>5.7</td>
</tr>
<tr>
<td>Driver 4</td>
<td>40</td>
<td>5.3</td>
</tr>
<tr>
<td>Witness</td>
<td>26</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Further optimization is possible...

20 pC witness

0 2 4 6 8 10 12
Duration (s)

0 0.5 1 1.5 2 2.5 3 3.5
Emittance (m rad)

R. Pompili
Conclusions

- **Velocity bunching with emittance compensation @ SPARC_LAB**
  - *Results show that VB scheme is able to produce beams meeting PWFA and LWFA (by external injection) requirements*

- **Together with laser-comb technique it allows resonant PWFA schemes, too**
  - *Full control of bunch durations, distances and charges demonstrated @ SPARC_LAB*
  - *Current measurement tools allow a complete characterization of all bunches*

- **PWFA in quasi-nonlinear regime shows promising results**
  - *High accelerating gradients, emittance preservation, extension to resonant schemes*

- **Hollow driver beams avoid witness bunch degradation during VB**
  - *Ultra-short bunches with ultra-low emittance can be produced*
  - *Goal: preserve high brightness beams during plasma acceleration process*
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