Simulations and Performance

Alban Mosnier (CEA)

EAAC 2017, Sept. 19th

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 653782.
Among the various applications considered in EuPRAFlAXIA, the hardest e-beam requirements likely come from FEL.

Electron beam requirements

- Among the various applications considered in EuPRAFlAXIA, the hardest e-beam requirements likely come from FEL.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Baseline value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle type</td>
<td>e</td>
<td>Electrons</td>
</tr>
<tr>
<td>Energy</td>
<td>E</td>
<td>5 GeV</td>
</tr>
<tr>
<td>Charge</td>
<td>Q</td>
<td>30 pC</td>
</tr>
<tr>
<td>Bunch length (FWHM)</td>
<td>( \tau )</td>
<td>10 fs</td>
</tr>
<tr>
<td>Peak current</td>
<td>I</td>
<td>3 kA</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>f</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>N</td>
<td>1</td>
</tr>
<tr>
<td>Total energy spread (RMS)</td>
<td>( \sigma_E/E )</td>
<td>1%</td>
</tr>
<tr>
<td>Slice energy spread (RMS)</td>
<td>( \sigma_{E,s}/E )</td>
<td>0.1%</td>
</tr>
<tr>
<td>Trans. Norm. emittance</td>
<td>( \varepsilon_{N,x}, \varepsilon_{N,y} )</td>
<td>1 mm mrad</td>
</tr>
<tr>
<td>Alpha function</td>
<td>( \alpha_x, \alpha_y )</td>
<td>0</td>
</tr>
<tr>
<td>Beta function</td>
<td>( \beta_x, \beta_y )</td>
<td>5 m</td>
</tr>
</tbody>
</table>

Critical parameters

- \( \frac{\sigma_{\gamma}}{\gamma} \ll \rho \)
- \( \frac{\varepsilon_n}{\gamma} \approx \frac{\lambda}{2\pi} \)

- **Target values for the 5 GeV electron beam parameters at the entrance of the undulators (IPAC EuPRAFlAXIA paper)**
- **Table also valid for the 1 GeV e-beam, though 1.5 kA peak current with smaller \( \varepsilon \) & \( \sigma_E \) is also considered**
- **High peak current**
- **Very low emittance**
- **Very small energy spread**
Electron acceleration in plasma cannot be fully predicted by analytic theory owing to nonlinear effects of laser pulse evolution, wakefield evolution and motion of the accelerated beam.

Particle-In-Cell (PIC) codes widely used tool for the investigation of both laser- and beam-driven plasma acceleration.

Including sophisticated techniques, as: Moving window (mandatory for long propagation lengths) Parallelization (mandatory for 2D-3D simulations) Flexible and quick output analysis, Ionisation (Field Ionisation / Collision Ionisation) etc.

With all variants to speed up simulations: Lorentz boosted frame, azimuthal Fourier decomposition, hybrid kinetic-fluid codes, etc.

And dispersion-free algorithms to mitigate numerical Cherenkov instability: FDTD (finite-difference time domain, as Yee scheme) vs PSATD (pseudo-spectral analytical time domain) algorithms.
Simulation codes

Simulation codes used in EuPRAXIA-WP2 for laser-driven plasma acceleration, as well in WP9 and WP14 for beam-driven plasma acceleration

<table>
<thead>
<tr>
<th>PIC code used</th>
<th>Users</th>
<th>additional features</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSIRIS</td>
<td>IST, DESY</td>
<td>Boosted frame technique, quasi-3D cylindrical field harmonics, PGC* algorithm in 3D (laser envelope)</td>
</tr>
<tr>
<td>WARP</td>
<td>CNRS/LPGP, CEA</td>
<td>Boosted frame technique, quasi-3D cylindrical field harmonics, adaptive mesh refinement</td>
</tr>
<tr>
<td>CALDER-Circ</td>
<td>LOA</td>
<td>Quasi-3D Cylindrical field harmonics</td>
</tr>
<tr>
<td>SMILEI</td>
<td>CNRS/LLR</td>
<td>Dynamic load balancing</td>
</tr>
<tr>
<td>ALaDyn Architect</td>
<td>INFN_SparcLab (PISA_ILIL)</td>
<td>full PIC code, bunch &amp; bg treated with macroparticles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>hybrid code, bunch as PIC and bg as fluid (no QSA)</td>
</tr>
<tr>
<td>HiPACE</td>
<td>DESY</td>
<td>Full 3D PIC code, Quasi-static approximation (PWFA)</td>
</tr>
<tr>
<td>PIConGPU</td>
<td>DESY</td>
<td>designed to run on Graphical Processing Units (GPUs)</td>
</tr>
</tbody>
</table>

* Ponderomotive Guiding Center
## Stability study with PIC codes

### Typical table of errors:
- misalignment, fluctuation of plasma density, injected e-beam and laser pulse

<table>
<thead>
<tr>
<th></th>
<th>Min. Value (ex. jitter)</th>
<th>Max. Value (ex. slow drifts)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>plasma</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>density</td>
<td>1%</td>
<td>10%</td>
</tr>
<tr>
<td><strong>alignment error (plasma axis wrt e-beam and laser)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>position [µm]</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>angle [µrad]</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td><strong>e-beam and driver synchronization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time shift [fs]</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td><strong>plasma lens</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic field</td>
<td>1%</td>
<td>10%</td>
</tr>
<tr>
<td><strong>Injected e-beam</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>charge</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>energy</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>emittance</td>
<td>10%</td>
<td>50%</td>
</tr>
<tr>
<td>bunch length</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td><strong>Laser (global fluctuations)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>5%</td>
<td>20%</td>
</tr>
<tr>
<td>beam spot radius</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>intensity</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>focal plane position [mm]</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>Pointing stability</td>
<td>1 µrad</td>
<td>1 µrad</td>
</tr>
</tbody>
</table>

### + Laser pulse imperfections
- *most published simulations use perfect Gaussian profiles*

**Transverse profile**

- Super-Gaussian \( I(\rho) = I_0 \exp \left[ -\left( \rho / w \right)^\alpha \right] \)
  - \( \alpha = 2 \) Gaussian profile
  - \( \alpha = 4 - 10 \) "top-hat" profile

with angular asymmetries

\[
A_L(\rho, \theta) = \sum A_m(\rho, \theta) \exp[-im\theta]
\]

**Time profile of the laser pulse**

\[
A_L(z, \rho, \theta, t) = A^0_L(z, \rho, \theta) \exp[-(\tau / \tau_L)^2 - i(\omega \tau + \varphi_L)]
\]

\( \varphi_L \) relative phase between high-frequency laserfield and envelope

**Spatio-temporal correlation**

\[
\delta \varphi_L(\omega, \rho) = \varphi_L(\omega_0, \rho) - \delta \varphi_L
\]

\( \delta \varphi_L \) phase variation of spatial-temporal correlation
can be inferred from new experimental technics enabling the measurement of such correlations

Transverse intensity profile of laser pulse

- LBNL experiment capillary discharge waveguide
  - the fluence profile evolution of the laser pulse through the waveguide depends strongly on the initial profile Gaussian or top-hat (large diffraction in the middle)

W.P. Leemans et al PRL 113, 245002 (2014)

Transverse intensity distribution and wavefront distortion

Gaussian

Exp. Spot and phase

Initial laser spot potential vector evolution


Energy spectrum of e-
• **Config 1:** LPA with internal injection

  ![Diagram](diagram1.png)

• **Config 2:** LPA with external injection from RF injector

  ![Diagram](diagram2.png)

• **Config 3:** LPA with external injection from Laser Plasma injector

  ![Diagram](diagram3.png)

• **Config 4:** BPA with external injection from RF injector

  ![Diagram](diagram4.png)
Problematics

- **High-energy LP injector**
  - Can we inject (self-injection) and accelerate a beam with good quality (meeting user requirements) to 1, 2, ...5 GeV in a single stage?

- **Low-energy LP injector**
  - What is the most promising method to achieve a 150 MeV beam with good quality to be further accelerated (meeting the FEL requirements)?

- **RF injector**
  - Inject the beam with expected parameters from RF photo-injector high energy / low charge?

- **Plasma accelerating section**
  - What are the most promising options?
    Non-linear with self-guiding / linear regime with plasma channel
• **Problematic 1**

  Can we inject (self-injection) and accelerate a beam with sufficient good quality (meeting user requirement) to 1, 2, ...5 GeV in a single stage?
High-energy LP Injector

- Based on **self-injection method**
  1. relativistic self-focusing of the pulse to create the ponderomotive blowout
  2. transient bubble expansion sufficient to trigger self-injection of background electrons
  3. rapid termination of self-injection and formation of a quasi mono-energetic bunch
  4. acceleration to GeV energy over ~1 cm distance, without low-energy background

- **1 GeV LPI with 0.6 PW laser power** [F. Massimo, A. Beck]

<table>
<thead>
<tr>
<th>Laser</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>600 TW (15 J)</td>
</tr>
<tr>
<td>Waist $w_0$</td>
<td>30 μm</td>
</tr>
<tr>
<td>$a_0$</td>
<td>4.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plasma</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $n_0$</td>
<td>$8.6 \times 10^{17}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extracted beam</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>@0.7cm</td>
<td>@1.3cm</td>
</tr>
<tr>
<td>Energy</td>
<td>1.1 GeV</td>
</tr>
<tr>
<td>Charge</td>
<td>610 pC</td>
</tr>
<tr>
<td>E spread rms</td>
<td>6.6 %</td>
</tr>
<tr>
<td>$\epsilon_{N_{xy}}$ (mm.mrad)</td>
<td>1.5, 1.5</td>
</tr>
</tbody>
</table>

Parameters from A. Beck, NIM A 740 (2014)
Simulations Calder-Circ with anti-Cherenkov stencil

Suitable for FEL amplification?
• **Problematic 2:**
  What is the most promising method to achieve a 150 MeV beam with good quality to be further accelerated in a LP section (meeting the FEL requirements)?

- Soft density down-ramp
- Shock injection
- Ionization injection
- Other methods
Low-energy LP Injector

- Based on **down-ramp method** → slows down the plasma wave

\[
\begin{align*}
  n_{ph} &= 1.5 \times 10^{19} \text{ cm}^{-3} \\
  n_{p0} &= 1.0 \times 10^{19} \text{ cm}^{-3}
\end{align*}
\]

\[33.5 \mu m \quad 875 \mu m\]

\[236 \text{ MeV} \quad 80 \text{pC} \quad [\text{IST, U. Sinha, J. Vieira}]\]

**Laser**
- Power: 8.4 TW
- Waist \(w_0\): 7 \(\mu m\) ~ 1.4 x matched spotsize
- \(a_0\): 2.83

**Plasma**
- Density \(n_{p0}\): 1 \(x 10^{19} \text{ cm}^{-3}\)
- **Extracted beam @sweet spot**
  - Energy: 236 MeV
  - Charge: 81.5 pC
  - E spread FWHM: 9.3 %

\[a_0 = 2.83, \quad w_0 = 5 \mu m, \quad \tau = 25 \text{ fs}\]

- Field almost flat with unmatched laser spot

**OSIRIS Simulations with PGC approximation**

- Laser spot size scan: \(5 \rightarrow 10 \mu m\)
- Density scan: constant density slope

**Sweet spot**

\[43.3 \text{ pC} \quad 121.5 \text{ MeV} \quad 22.5\%\]
• Based on **shock injection**
  
  - Changing length & height of the downramp
  - Scan parameters (for $a_0 = 2.5$)
    
    $$L_{\text{downramp}} = 10 - 50 \ \mu m , \ K = 1.2, 1.3, 1.5$$
  
  ➢ 150 MeV 30 pC [LOA, F. Massimo]
Low-energy LP Injector

- Based on **shock injection**
  - Changing length & height of the downramp
  - Scan parameters (for $a_0 = 2.5$)
    \[ L_{\text{downramp}} = 10 - 50 \, \mu m, \quad K = 1.2, 1.3, 1.5 \]

- 150 MeV 30 pC [LOA, F. Massimo]

### Laser
- Power: 30 TW
- Waist $w_0$: 12 µm
- $a_0$: 2.5

### Plasma
- Density $n_0$: $3 \times 10^{18}$ cm$^{-3}$

### Extracted beam $@K=1.3$ $L_{\text{dr}}=30 \, \mu m$
- Energy: 150 MeV
- Charge: 30 pC
- E spread rms: 7%
- $\varepsilon_{N,x,y}$ (mm.mrad): 0.8, 1.0
Low-energy LP Injector

- Based on shock injection
  - Changing also the laser energy
  - Scan parameters $a_0 = 2.16, 2.5, 2.79$
    $L_{\text{downramp}} = 10 - 50 \mu m, K = 1.3, 1.5, 1.7$

$150 \text{ MeV} 30 \text{ pC} \text{ [LOA, F. Massimo]}$

<table>
<thead>
<tr>
<th>Laser</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>$30 \text{ TW}$</td>
</tr>
<tr>
<td>Waist $w_0$</td>
<td>$12 \mu m$</td>
</tr>
<tr>
<td>$a_0$</td>
<td>$2.5$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plasma</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $n_0$</td>
<td>$3 \times 10^{18} \text{ cm}^{-3}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extracted beam @$K=1.3$ $L_{\text{downramp}}=30 \mu m$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>$150 \text{ MeV}$</td>
</tr>
<tr>
<td>Charge</td>
<td>$30 \text{ pC}$</td>
</tr>
<tr>
<td>E spread rms</td>
<td>$7 %$</td>
</tr>
<tr>
<td>$\varepsilon_{N,x,y} \text{ (mm.mrad)}$</td>
<td>$0.8, 1.0$</td>
</tr>
</tbody>
</table>

Emittance and Energy spread increase with $a_0$. 

A. Mosnier  
EAAC 2017, Sept. 28$^{\text{th}}$ - Simulations and Performance  
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Low-energy LP Injector

• Based on ionization injection
  – Ionization of inner shells of high Z atom (ex. N) at $I_{\text{peak}}$ of laser pulse
  – Features: simple target configuration, moderate laser intensity, higher injected charge, emittance lower than self-injection scheme

➢ LPGP parametric study [P. Lee et al]

<table>
<thead>
<tr>
<th>Laser</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>100 TW</td>
</tr>
<tr>
<td>Waist $w_0$</td>
<td>16 μm</td>
</tr>
<tr>
<td>Initial $a_0$</td>
<td>1.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plasma</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $n_0$ max</td>
<td>$4 \times 10^{18}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>

Extracted beam (descending gradient)

| Energy       | 82.6 MeV          |
| Charge       | 50 pC             |
| E spread FWHM| 11 %              |
| $\varepsilon_{x,y}$ | 0.33, 2.1 mm.mrad |

Changing density profile with cst N$_2$ fraction (1%)

Density profile

<table>
<thead>
<tr>
<th>Profile</th>
<th>$E_{\text{peak}}$ (MeV)</th>
<th>$\Delta E/E$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELISA</td>
<td>65.7</td>
<td>13.1</td>
</tr>
<tr>
<td>Descending gradient</td>
<td>82.6</td>
<td>11.0</td>
</tr>
<tr>
<td>Plateau</td>
<td>90.8</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Bunch charge ~ 40-50 pC
Larger emittance in the laser polarisation plane $\varepsilon_{x,y} = 0.33, 2.1$ μm
Low-energy LP Injector

• Based on ionization injection
  – Ionization of inner shells of high Z atom (ex. N) at \( I_{\text{peak}} \) of laser pulse
  – Features: simple target configuration, moderate laser intensity, higher injected charge, emittance lower than self-injection scheme

  ➢ LPGP parametric study [P. Lee et al]

### Laser
- Power: 100 TW
- Waist \( w_0 \): 16 \( \mu \text{m} \)
- Initial \( a_0 \): 1.6

### Plasma
- Density \( n_0 \) max: \( 4 \times 10^{18} \) cm\(^{-3} \)

### Extracted beam
- \( L_{\text{cell}} \) 1 mm, 0.35% \( \text{N}_2 \)
- Energy: 142 MeV
- Charge: 27 pC
- E spread rms: 3.8 %
- \( \varepsilon_{N x,y} \): 0.8, 1.8 mm.mrad

#### 0.35% \( \text{N}_2 \) and longer cell (1→1.3 mm)
- Energy: 196 MeV
- Charge: 27 pC
- E spread rms: 3.2 %
- \( \varepsilon_{N x,y} \): 1.3, 2.3 mm.mrad

Patrick Lee - WG6 Tuesday afternoon
Multi-pulse ionization injection

- Combination of multi-pulse resonant wakefield and ionization injection
  - A resonant multi-pulse drives a large-amplitude plasma wave
  - The wave traps electrons extracted by further ionization

INO-CNR study [P. Tomassini et al]

<table>
<thead>
<tr>
<th>Drive Laser (x 8 pulses)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>0.64</td>
</tr>
<tr>
<td>Waist $w_0$</td>
<td>45 μm</td>
</tr>
<tr>
<td>Pulse length</td>
<td>30 fs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ionization Laser (2nd harmonic)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>0.41</td>
</tr>
<tr>
<td>Waist $w_0$</td>
<td>3.5 μm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plasma</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $n_0$</td>
<td>$5 \times 10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Length</td>
<td>6.5 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extracted beam</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>265 MeV</td>
</tr>
<tr>
<td>Charge</td>
<td>3.8 pC</td>
</tr>
<tr>
<td>E spread rms</td>
<td>0.65 %</td>
</tr>
<tr>
<td>$\varepsilon_{N_{x,y}}$ (mm.mrad)</td>
<td>0.08, 0.02</td>
</tr>
</tbody>
</table>

Main Features:
- Ultra-low emittance
- Low energy spread
- Energy can be extended (laser guiding)
**LP accelerating section**

- **Beam injected from RF photo-injector (RFI)**
  - Inject the beam with expected parameters from RF photo-injector **but at low charge**?
    - $E_b \sim 100$ MeV, $\sigma_z \leq 1$ fs, $\varepsilon_n < 1$ $\mu$m
    - but $Q_b \sim 1$ pC
  - Inject the beam with expected parameters from RF photo-injector **but at high energy**?
    - $Q_b \sim$ few 10's pC, $\sigma_z \sim 10$-30 fs, $\varepsilon_n < 1$ $\mu$m
    - but $E_b \sim$ few 100's MeV

- **Beam injected from optical injector (LPI)**
  - Short bunch but higher energy spread
• External injection **low charge, sub-fs @SINBAD**
  ➢ Moderate laser power, [M. Weikum et al, Desy]

### Injector exit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>~ 100 MeV</td>
</tr>
<tr>
<td>Charge</td>
<td>0.7 pC</td>
</tr>
<tr>
<td>Bunch length rms</td>
<td>0.77 fs</td>
</tr>
<tr>
<td>Emittance Norm</td>
<td>≤ 0.2 μm</td>
</tr>
</tbody>
</table>

### Laser parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>~200 TW</td>
</tr>
<tr>
<td>Waist w₀</td>
<td>42.5 μm</td>
</tr>
<tr>
<td>a₀</td>
<td>1.8</td>
</tr>
<tr>
<td>Pulse length FWHM</td>
<td>25 fs</td>
</tr>
</tbody>
</table>

### Plasma

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>density n₀</td>
<td>10^{17} cm⁻³</td>
</tr>
<tr>
<td>Length (plateau)</td>
<td>1.25 cm</td>
</tr>
</tbody>
</table>

### ARES Linac

Though not a working point in EuPRAXIA

without guiding → 224 MeV

➢ **Ultrashort bunch** ⇒ small energy spread but limited by the uncorrelated spread due to transverse gradient of the wakefields

➢ Careful matching required with ~ 1 cm long density upramp

➢ longer plasma (>10cm) to achieve 1 GeV level with laser guiding but increase of emittance and Espread due to numerical dephasing

**2D OSIRIS simulation (Lehe Solver with anti-Cherenkov stencil)**
• External injection low charge, sub-fs @SINBAD
  ➢ High laser power 100 J [E. Svystun, Desy]

**LPAS fed by RFI**

**Injector exit**
- Energy: 83.5 MeV
- Charge: 0.74 pC
- Bunch length rms: 0.87 fs
- Emittance Norm: 0.14 μm

**Laser parameter (100 J)**
- Power: 953.5 TW
- Waist $w_0$: 64 μm
- $a_0$: 3.1
- Pulse length FWHM: 100 fs

**Plasma**
- density $n_0$: $10^{17}$ cm$^{-3}$
- Length (plateau): 25 mm (1 GeV) 65 mm (2 GeV)

Injection phase and ramp optimisation
⇒ small energy spread & emittance growth

$\Delta E/E < 0.1\%$
• 1 GeV from high-energy RF injector

results of EuPRAXIA@SPARC_LAB studies

S-Band photo-injector \(~100\) MeV + X-band \(~500\) MeV
to generate high-quality beams: 1 bunch for LPA scheme
or 1 witness bunch + 1 driving bunch for BPA scheme
Laser driven PA fed by RFI

Plasma density: $10^{17}$ cm$^{-3}$
Plasma plateau length: 6 cm
Exponential ramp characteristic length $\lambda_\beta/2 = 2.5$ mm
Laser: 6.13 J, 112 fs, $a_0=1.15$
Effective Eacc: 9 GV/m

---


Andrea Rossi - WG1 Tuesday afternoon
Simulations with Architect

**A. Marocchino – WG6 Tuesday afternoon**

**Beam driven PA fed by RFI**

- **Plasma density**: $10^{16}$ cm$^{-3}$
- **Plasma plateau length**: 27 cm
- **Ramp length (ideal)**: 5 mm
- **Driver bunch**: $Q_b = 200$ pC, $\sigma_z = 50$ μm, $\sigma_E = 0.1\%$, $\varepsilon_x,\varepsilon_y = 3$ μm
- **Effective Eacc**: 1.85 GV/m

---

**Witness bunch evolution**

**Table**

<table>
<thead>
<tr>
<th>Witness</th>
<th>Entrance</th>
<th>Exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ [GeV]</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_E$ [%]</td>
<td>0.06</td>
<td>0.73</td>
</tr>
<tr>
<td>$Q$ [pC]</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>$\sigma_{z \text{ rms}}$ [μm]</td>
<td>3.5</td>
<td>3.3</td>
</tr>
<tr>
<td>$\varepsilon_x$ [μrad]</td>
<td>0.4</td>
<td>0.48</td>
</tr>
<tr>
<td>$\varepsilon_y$ [μrad]</td>
<td>0.4</td>
<td>0.81</td>
</tr>
<tr>
<td>$\sigma_x$ [μm]</td>
<td>0.73</td>
<td>1.2</td>
</tr>
<tr>
<td>$\sigma_y$ [μm]</td>
<td>1.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>
**FEL Genesis simulation**

**Undulator $\lambda_u=1.5$ cm**

### Laser-driven plasma acc.

- **Radiation growth along undulator**
  - Without ramps
  - With ramps
  - With tapering

### Beam-driven plasma acc.

- **Radiation growth along undulator**
  - Without ramps
  - With ramps
  - With tapering

#### Number of photons

- **At 12 m**
  - Without ramps: $2.5 \times 10^{11}$
  - With ramps: $3 \times 10^{11}$
  - With tapering: $1.6 \times 10^{11}$

- **At 30 m**
  - Without ramps: $6.4 \times 10^{11}$
  - With ramps: $5.2 \times 10^{11}$
  - With tapering: $3.6 \times 10^{11}$

#### Spectral density @ 15 m

- **Quasi-single structure**
- **Quasi-single spike structure**

- **Power density @ 15 m**
  - Without ramps
  - With ramps
  - With tapering

- **Spectral density @ 15 m**
  - Without ramps
  - With ramps
  - With tapering

**Vittoria Petrillo**

---

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LPAS fed by LPI

- Quasi-linear regime with plasma channel
  - Main parameters inferred from analytical expressions (checked by WARP 3D simulations + boosted frame)
  - Energy gain

\[
\Delta \gamma_b = \frac{2}{\pi} k_p L_{dp} \frac{E_{z,\text{max}}}{E_0} \left[ \left( 1 + \frac{L_{\text{acc}}}{L_{pd}} \right) \sin \left( \frac{\pi L_{\text{acc}}}{2 L_{dp}} \right) + \frac{2 L_{dp}}{\pi L_{pd}} \left( \cos \left( \frac{\pi L_{\text{acc}}}{2 L_{dp}} \right) - 1 \right) \right] = f(k_p, a_0, w_0)
\]

- For a given energy gain, laser strength and norm. spot size, there is a plasma density value which minimizes the plasma channel length

\[
n(r) = n_0 \left( 1 + \frac{\Delta n}{n_0} \frac{r^2}{r_0^2} \right)
\]

- Matched beam to preserve the emittance

**Laser**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>strength $a_0$</td>
<td>$\sqrt{2}$</td>
</tr>
<tr>
<td>spot size $w_0$</td>
<td>45 $\mu$m</td>
</tr>
<tr>
<td>rms pulse length $\sigma_t$</td>
<td>64.5 fs</td>
</tr>
<tr>
<td>peak power</td>
<td>136 TW</td>
</tr>
<tr>
<td>energy</td>
<td>15.5 J</td>
</tr>
</tbody>
</table>

**Plasma**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $n_0$</td>
<td>$1.5 \times 10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>channel depth $\Delta n/\Delta n_c$</td>
<td>$\sim 0.5$</td>
</tr>
<tr>
<td>acc. length $L_{\text{acc}}$</td>
<td>$\sim 30$ cm</td>
</tr>
</tbody>
</table>

**Injected beam**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>150 MeV</td>
</tr>
<tr>
<td>$\varepsilon_{N,x,y}$</td>
<td>1 mm.mrad</td>
</tr>
<tr>
<td>charge</td>
<td>Low (1 pC)</td>
</tr>
<tr>
<td>Bunch size $\sigma_{x,y}$</td>
<td>1.3 $\mu$m</td>
</tr>
</tbody>
</table>

For a given energy gain, laser strength and norm. spot size, there is a plasma density value which minimizes the plasma channel length.
• Quasi-linear regime with plasma channel
  – **Correlated energy spread**: induced by wakefield curvature + beam-loading
    • beam loading compensation → bunchlength optimisation (further reduced by bunch shaping)
  – **Slice energy spread**: induced by radial dependance of
    • accelerating field [negligible when driver (beam or laser) >> bunch size]
    • longitudinal field excited by the accelerated bunch [cannot be neglected]

---

**Laser**
- Strength $a_0 = \sqrt{2}$
- Spot size $w_0 = 45 \, \mu m$
- RMS pulse length $\sigma_t = 64.5 \, fs$
- Peak power $= 136 \, TW$
- Energy $= 15.5 \, J$

**Plasma**
- Density $n_0 = 1.5 \times 10^{17} \, cm^{-3}$
- Channel depth $\Delta n/\Delta n_c \approx 0.5$
- Acc. length $L_{acc} \approx 30 \, cm$

**Injected beam**
- Energy $= 150 \, MeV$
- Energy spread $= 3 \, %$
- $\varepsilon_{N,x,y} = 1 \, mm.mrad$
- Charge $= 30 \, pC$
- Bunch size $\sigma_{x,y} = 1.3 \, \mu m$

---

$n_b \sim 10^{19} \, cm^{-3} \gg n_0$

**Correlated $E_{\text{spread}}$ optimization**

**Slice $E_{\text{spread}}$ minimization**
- Bunch size $\downarrow$
- Plasma density $\downarrow$

Ex. $10^{17} \rightarrow 10^{16} \, cm^{-3}$ needs $\sim 1m$ plasma length to reach 5 GeV beam

$\varepsilon_{n,x} = 0.5 \, \mu m$

$\varepsilon_{n,x} = 1.0 \, \mu m$
Conclusions

• Numerous simulations carried out within the EuPRAxIA framework

• Parametric studies of Laser Plasma Injector
  – high energy (self-injection), low energy (down-ramp, shock injection, ionization, multi-pulse)

• Plasma accelerator section
  – Beam injected from RF injector (high energy) and LP injector (low energy)

• Next steps
  – End-to-end simulations (started at SparcLab)
  – Error study (Introduce various fluctuations: laser imperfections, plasma density, alignment, ...)

A. Mosnier
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Big thanks to all members of the EuPRAXIA WP2
For the great job made during these ~ 18 months, and
For providing me all material shown in this presentation

Special thanks also to Phi Nghiem who accepted to replace me from now as coordinator of WP2 with Luis and Jorge from IST
END