Lattice Design and Start-to-end Simulations for the ARES Linac

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September 27, 2017
Outline

- Overview
- The ARES linac and its working points
- Benefit of energy upgradation
The ARES linac - applications

<table>
<thead>
<tr>
<th>Q (pC)</th>
<th>0.5 ~ 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε (μm)</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>σ_t (fs)</td>
<td>0.5 ~ 30</td>
</tr>
<tr>
<td>σ_BTJ (fs)</td>
<td>&lt; 10</td>
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</tbody>
</table>

| Beam dynamics studies, e.g. bunch compression schemes comparison |
| R&D on advanced beam diagnostics, e.g. 3D charge distribution reconstruction for ultra-short bunches |
| LWFA | FEL |
| Other advanced accelerating structures, e.g. DLA |
| Other applications |

Monday - WG3 parallel - U. Dorda, Status and Objectives of the Dedicated Accelerator R&D Facility "SINBAD" at DESY
Monday – WG5 parallel – D. Marx, New Measurement Techniques Using a Novel X-band Transverse Deflecting Structure with Variable Polarization
Monday – Poster – A. Pousa, Limitation On Slice Energy Spread in a Plasma Accelerator
Monday – Poster – E. Svyten, Beam Quality Preservation in a Laser-Plasma Accelerator with External Injection in the Context of EuPRAXIA
Monday – Poster – F. Mayet, Simulations and Plans for Possible DLA experiments at SINBAD
Monday – Poster – W. Kuropka, Full PIC Simulation of First ACHIP Experiment @ SINBAD

100-MeV ARES linac

Energy upgradation in the future.

B. Marchetti, TUPAB040, IPAC17

Energy upgradation in the future.
The ARES linac - Layout

$\mathbf{M} = \begin{bmatrix} 0 & 2f \\ -1/(2f) & 1 \end{bmatrix}$

$R_{56} = 10\ mm$

$E = 100\ MeV$
(for compressed or chirped bunch)

Gun diagnostic table
Gun and solenoids
Traveling-wave structures with surrounding solenoids
Temporary experimental area
Space for future possible energy upgrade
Beam dynamics simulations

- Linac
  - ASTRA

- Timing / position / pointing stabilities
  - ASTRA + ELEGANT

- Matching / bunch compression / final focus
  - IMPACT-T (cross-checked by CSRTrack)

- Collimation
  - Shower

- Dogleg
  - ELEGANT
The ARES linac – generation of sub-fs bunches

<table>
<thead>
<tr>
<th>Initial bunch charge (pC)</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
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<tbody>
<tr>
<td>Final bunch charge (pC)</td>
<td>0.4</td>
<td>0.7</td>
<td>1.6</td>
<td>2.7</td>
<td>4.8</td>
</tr>
<tr>
<td>Initial bunch length (ps)</td>
<td>2.0</td>
<td>2.1</td>
<td>2.2</td>
<td>2.5</td>
<td>2.8</td>
</tr>
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Beam parameters at the chicane exit

The ARES linac – Ideal slit vs. real slit

Simulated by Shower (EGS4)

Copper slit

Slow down the unwanted electrons!

2 cm copper

After compression

5 cm aperture
The ARES linac – working points

Beam parameters at the plasma entrance
MC: pure magnetic compression, VB: pure velocity bunching, HB: hybrid compression

<table>
<thead>
<tr>
<th></th>
<th>WP1</th>
<th>WP2</th>
<th>WP3</th>
<th>WP4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q (pC)</td>
<td>0.8</td>
<td>5.7</td>
<td>30</td>
<td>17.3</td>
</tr>
<tr>
<td>$\sigma_t$ (fs)</td>
<td>0.5</td>
<td>2.0</td>
<td>29.6</td>
<td>12.2</td>
</tr>
<tr>
<td>I (kA)</td>
<td>0.6</td>
<td>1.1</td>
<td>1.6</td>
<td>1.5</td>
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<tr>
<td>$\varepsilon_{x, \text{slice}}$ / $\varepsilon_{y, \text{slice}}$ ($\mu$m)</td>
<td>0.11 / 0.11</td>
<td>0.38 / 0.33</td>
<td>0.64 / 0.64</td>
<td>0.28 / 0.38</td>
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<tr>
<td>$\beta_x$ / $\beta_y$ (mm)</td>
<td>1.8 / 3.1</td>
<td>5.2 / 1.5</td>
<td>\</td>
<td>4.5 / 0.9</td>
</tr>
<tr>
<td>Compression method</td>
<td>MC</td>
<td>MC</td>
<td>VB</td>
<td>HB</td>
</tr>
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Challenges at ARES:
1. Matching section between chicane and plasma is not feasible due to space-charge effects
2. The Twiss parameters at the chicane exit have a small range
The ARES linac – LPSs at the plasma entrance

WP1: $\sigma_t = 0.52 \text{ fs}, \sigma_\delta = 0.0017, Q = 0.79 \text{ pC}$

WP2: $\sigma_t = 2.0 \text{ fs}, \sigma_\delta = 0.0043, Q = 5.7 \text{ pC}$

WP3: $\sigma_t = 30.0 \text{ fs}, \sigma_\delta = 0.005, Q = 30.0 \text{ pC}$

WP4: $\sigma_t = 12.0 \text{ fs}, \sigma_\delta = 0.0027, Q = 17.0 \text{ pC}$
The ARES linac – timing stability

The reference is the Master oscillator

\[ \sigma_t = \sqrt{\sigma_{B2RF}^2 + \sigma_{L2RF}^2 + \sigma_A^2} \]

\[ \approx \sqrt{\frac{R_{56}^2}{c^2} \left[ \left( \frac{E_0}{E} \right)^2 \sigma_{E0}^2 + \frac{1}{N} \left( \frac{E - E_0}{E} \right)^2 \sigma_{\delta V}^2 + \frac{h^2}{N k_{rf}^2} \sigma_{\phi}^2 + \sigma_{\delta B}^2 \right] + (1 + hR_{56})^2 \sigma_{t_0}^2 + \sigma_{L2RF}^2 + \sigma_A^2} \]

10 fs bunch arrival-time jitter \(~0.01\) deg

The reference is the drive laser

The phase jitter changes to \( \tilde{\sigma}_\phi = \sqrt{\sigma_{\phi}^2 + c^2 k_{RF}^2 (\sigma_{L2RF}^2 + \sigma_A^2)} \)

\[ hR_{56} \approx -1 \]

\[ \sigma_t = \sigma_{TOF}. \]
Chromatic aberration during matching (in)

Matching condition for a hard edge plasma

\[ \beta_x = \beta_y \approx \frac{1}{\sqrt{K_r}}, \alpha_x = \alpha_y \approx 0 \]

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<tr>
<th>With ANGUS laser</th>
<th>Linear regime</th>
<th>Blow-out regime</th>
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<tbody>
<tr>
<td>Plasma density (cm(^{-3}))</td>
<td>10(^{16})</td>
<td>10(^{17})</td>
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<tr>
<td>Matched beta function (mm)</td>
<td>0.80</td>
<td>0.47</td>
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</table>

Final beta function:

\[ \beta_{xf} = \frac{f^2}{\beta_{xi}} + \sigma_\delta^2 \beta_{xi} \]

Emittance growth:

\[ \frac{\Delta \epsilon_x}{\epsilon_x} \approx \frac{\sigma_\delta^2 \beta_{xi}^2}{2f^2} \]

Final focus triplet: 2-cm-long, 250 T/m, 500 T/m, 500 T/m PMQ

Incoming beta function ranges from 6 ~ 22 m

Goal: 1 mm beta function

Absolute momentum spread

J. Zhu, et al., THPVA007, Proceedings of IPAC2017
The ARES linac – LWFA driven FEL

FEL parameters are calculated using Ming Xie’s formula

\[ \gamma = 430 \] was chosen in light of the planned BELLA experiment


Assume the relative energy spread can be preserved!

**WP2** (slightly decompressed)

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<td><strong>I_{beam}</strong> (kA)</td>
<td><strong>\sigma_t</strong> (fs)</td>
<td><strong>\varepsilon_{x, slice}</strong> (\mu m)</td>
<td><strong>\bar{\beta}_x</strong> (m)</td>
<td><strong>\sigma_{\delta, slice}</strong> (%)</td>
<td><strong>\gamma</strong></td>
<td><strong>\lambda_u</strong> (cm)</td>
<td><strong>K_0</strong></td>
<td><strong>\lambda_r</strong> (nm)</td>
<td><strong>\rho_P</strong></td>
<td><strong>L_G</strong> (m)</td>
<td><strong>L_c</strong> (\mu m)</td>
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<tr>
<td>5.7</td>
<td>0.41</td>
<td>3.3</td>
<td>0.38</td>
<td>0.7</td>
<td>0.18</td>
<td>430</td>
<td>1.5</td>
<td>1.00</td>
<td>60.8</td>
<td>0.0053</td>
<td>0.262</td>
<td>1.06</td>
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<tr>
<td>2.7</td>
<td>0.18</td>
<td>1663</td>
<td>1.5</td>
<td>1.00</td>
<td>4.1</td>
<td>0.0014</td>
<td>4.87</td>
<td>1.32</td>
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**WP4**

* A. Maier, *Matter and Technologies Kickoff Meeting, DESY Hamburg (2015)*

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<td><strong>\sigma_{\delta, slice}</strong> (%)</td>
<td><strong>\gamma</strong></td>
<td><strong>\lambda_u</strong> (cm)</td>
<td><strong>K_0</strong></td>
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<td><strong>\rho_P</strong></td>
<td><strong>L_G</strong> (m)</td>
<td><strong>L_c</strong> (\mu m)</td>
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<td>0.7</td>
<td>0.16</td>
<td>430</td>
<td>1.5</td>
<td>1.00</td>
<td>60.8</td>
<td>0.0090</td>
<td>0.114</td>
<td>0.46</td>
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<tr>
<td>2.7</td>
<td>0.16</td>
<td>1663</td>
<td>1.5</td>
<td>1.00</td>
<td>4.1</td>
<td>0.0023</td>
<td>0.718</td>
<td>0.20</td>
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Dogleg beamline with tunable $R_{56}$

Geometrical constraints inside the SINBAD tunnel
Horizontal displacement: 5.8 m, Length: ~10 m, Bending angle: 20 deg

3 DOFs: $R_{56}$, $\eta$ and $\eta'$

Isochronous (2.7 fs -> 2.2 fs)

Bunch compressor (180 fs -> 19 fs)
Energy upgradation

We like the EuPRAXIA’s working point: **3 kA, 30 pC**!

Higher energies were achieved by scaling the beam parameters after the linac.
Summary

- The start-to-end simulations have shown different working points (0.8 ~ 30 pC, 0.5 ~ 30 fs rms) at the ARES linac, aiming typically for LWFA and LWFA-driven FEL.

- The peak current is limited to around 1.5 kA due to the space-charge effects. The space-charge effects also make the matching (in) very challenging. Energy upgradation is highly desirable.

Thank you!