Beam Simulations for FLUTE, a Linac Based Compact THz Source

Marcel Schuh for the FLUTE team
ICAP 2012, Rostock-Warnemünde, Germany, MOACC1
Outline

- Motivation
- Linac and bunch compression design
- Simulations
  - Tools
  - Optimization
  - Error studies
- Outlook
Motivation
From the users point of view

- Single cycle (broadband) THz pulses and very high peak electric fields of the order of $3 \times 10^8$ V/m
Motivation
From the accelerator science point of view

- Study for a future compact, broadband accelerator based THz source
- Serve as a test bench for new beam diagnostic methods and tools
- Compare different coherent radiation generation schemes in simulation and experiment:
  - Coherent Synchrotron Radiation (CSR)
  - Coherent Transition Radiation (CTR)
  - Coherent Edge Radiation (CER)
- Systematic bunch compression studies:
  - Different compression schemes
  - Large charge range up to several nC per bunch → Study space charge and CSR induced effects and instabilities
- Test facility for accelerator studies within the Helmholtz “ARD“ initiative
### General Linac Layout

**RF Photo Gun**

- **Solenoid**

**Traveling Wave Linac**

**Bunch Compressor**

**Matching Cell**

### Laser

<table>
<thead>
<tr>
<th>Laser</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Wavelength</td>
<td>nm</td>
<td>266</td>
</tr>
<tr>
<td>Energy on cathode</td>
<td>mJ</td>
<td>0.6</td>
</tr>
<tr>
<td>Laser pulse length</td>
<td>ps</td>
<td>≤4</td>
</tr>
<tr>
<td>Laser spot size</td>
<td>mm</td>
<td>2.25</td>
</tr>
</tbody>
</table>

### Gun

<table>
<thead>
<tr>
<th>Gun</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>GHz</td>
<td>2.998</td>
</tr>
<tr>
<td>Cells</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Peak E-Field</td>
<td>MV/m</td>
<td>~100</td>
</tr>
<tr>
<td>Peak power</td>
<td>MW</td>
<td>~20</td>
</tr>
<tr>
<td>Output energy</td>
<td>MeV</td>
<td>7</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>nC</td>
<td>≤3</td>
</tr>
</tbody>
</table>

### Linac

<table>
<thead>
<tr>
<th>Linac</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>GHz</td>
<td>2.998</td>
</tr>
<tr>
<td>Length</td>
<td>m</td>
<td>5.2</td>
</tr>
<tr>
<td>Acc. Gradient</td>
<td>MV/m</td>
<td>~10</td>
</tr>
<tr>
<td>Peak power</td>
<td>MW</td>
<td>~20</td>
</tr>
<tr>
<td>Output energy</td>
<td>MeV</td>
<td>~41</td>
</tr>
<tr>
<td>Max. Rep. Rate</td>
<td>Hz</td>
<td>10-100</td>
</tr>
</tbody>
</table>

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Bunch compressor

- Goal: compress a negative chirped beam

- Phase one design
  - 4 bending magnets
  - Same length and strength
  - Mirror symmetry

- Beam dynamics effects
  - CSR
  - Space charge

- Present Layout
  - $L_{d1} = 0.5 \text{ m}$
  - $L_{d2} = 1.0 \text{ m}$
  - $L_b = 0.3 \text{ m}$
  - $\rho(p) = 1.8 \text{ to } 2.2 \text{ m (charge dependent)}$
  - $R_{56} = 29 \text{ to } 36 \text{ mm}$

$$R_{56}(p) = 2 \frac{L_b^2}{\rho(p)^2} \left( \frac{2}{3} L_b + L_{d1} \right)$$
Beam dynamics simulation tool chain

- **Gun**
  - ASTRA
    - Generated input distribution: $5 \cdot 10^3 - 10^6$ macro particle
    - Space charge effects - cylindrical symmetry

- **Linac**
  - ASTRA
    - Space charge effects - cylindrical symmetry
  - ELEGANT
    - Wakes (planed)

- **Bunch Compressor**
  - ASTRA
    - Space charge effects - 3D
  - CSRtrack
    - CSR effects
    - Space charge effects
  - ELEGANT
    - CSR effects (in preparation)
Longitudinal phase space evolution for 100 pC
Longitudinal phase space evolution for 3 nC
Parameter scans and optimization

- **Global goal:** Minimize the bunch length

- **Parameters to optimize as function of the bunch charge:**
  - Laser
    - Pulse length and profile
    - Spot size and transverse distribution
  - RF
    - Gun RF phase
    - Linac RF phase
  - Bunch compressor
    - Magnet length
    - Drift space
    - Bending radius
  - Focusing elements
    - Solenoid strength
    - Matching cell
  - Element position

- **Method used up to now:** Parameter scans
Laser spot size optimization

- A Gaussian distribution is taken for the laser in the transverse plane as well as temporal.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>nC</td>
<td>3</td>
</tr>
<tr>
<td>Laser pulse length</td>
<td>ps</td>
<td>4</td>
</tr>
<tr>
<td>Laser spot size</td>
<td>mm</td>
<td>2.25</td>
</tr>
<tr>
<td>Solenoid</td>
<td>T</td>
<td>0.05</td>
</tr>
</tbody>
</table>
ASTRA vs. CSRtrack

- Optimize bunch compressor bending radius $\rho$ for different bunch charges independently in ASTRA and CSRtrack
  - Magnet length and drift space between magnets is 50 cm in this study
  - ASTRA: 3D space charge with 1 Million macro particles
  - CSRtrack: 3D space charge and CSR with 50000 macro particles

<table>
<thead>
<tr>
<th>Charge</th>
<th>Laser pulse</th>
<th>ASTRA bunch length</th>
<th>CSRtrack bunch length</th>
<th>ASTRA $\rho$</th>
<th>CSRtrack $\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pC</td>
<td>ps</td>
<td>fs</td>
<td>fs</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>14.33</td>
<td>14.78</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>100</td>
<td>4</td>
<td>173.33</td>
<td>171.16</td>
<td>3.85</td>
<td>3.9</td>
</tr>
<tr>
<td>3000</td>
<td>4</td>
<td>250.00</td>
<td>429.6</td>
<td>3.45</td>
<td>3.4</td>
</tr>
</tbody>
</table>
## Optimization

- Parameters optimized using parameter scans
  - Laser spot size and pulse length
  - Bending radius

<table>
<thead>
<tr>
<th>Charge</th>
<th>Laser pulse</th>
<th>Laser spot size</th>
<th>Bending radius</th>
<th>$R_{56}$</th>
<th>Bunch length</th>
</tr>
</thead>
<tbody>
<tr>
<td>pC</td>
<td>ps</td>
<td>mm</td>
<td>m</td>
<td>mm</td>
<td>fs</td>
</tr>
<tr>
<td>3000</td>
<td>4</td>
<td>2.25</td>
<td>1.9</td>
<td>36.1</td>
<td>183</td>
</tr>
<tr>
<td>1000</td>
<td>3</td>
<td>1.5</td>
<td>1.95</td>
<td>34.2</td>
<td>112</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>0.5</td>
<td>2.1</td>
<td>29.4</td>
<td>52</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0.05</td>
<td>2.15</td>
<td>28</td>
<td>15</td>
</tr>
</tbody>
</table>
Simulated longitudinal bunch shape after chicane

- Derive analytically CSR, CER and CTR spectrum from these distributions

*M. Schwarz, IPAC12, MOPPP003*
Coherent synchrotron radiation spectrum

\[
\frac{dl}{df} / \text{J/Hz}
\]

\[
f / \text{THz}
\]

- 3 nC
- 100 pC
Error studies

- Magnet errors
  - Power supply
  - Field
  - Alignment

- RF and timing errors
  - Amplitude
  - Phase
  - Synchronization
    - RF to laser
    - Beam to experiment / diagnostic

- Laser shot to shot errors
  - Intensity
  - Spot position
  - Time jitter

- Element alignment errors
Bend power supply error study

- The compression depends on the bending field
- The bending radius is direct proportional to the magnet current
- Current stability better than $5 \cdot 10^{-3}$ is needed
Synchronisation RF with laser

- Vary phase between RF and laser

![Graph showing bunch length vs. phase error](image-url)
RF linac phase scan

- Constant phase in gun (reference working point)
- Scan phase in linac relative to working point
RF error studies

- Vary phase and amplitude together in gun and linac
- Bunch charge: 3 nC
Outlook

- Finish start to end error studies to define tolerances for the power supplies, LLRF system and alignment

- Additional studies with ELEGANT and optimization with Multiobjective genetic algorithms (MOGA)
  - See also talk of M. Streichert TUABC2

- Finalize the linac layout including all devices (pumps, diagnostics, etc.)
Thank you for your attention!

Acknowledgment: