FACET-II Start-to-End Simulations of Electron Beam

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Glen White
Overview

Start-to-end simulation of FACET-II e-beamline

- Injector simulation gun – L1 with GPT
- Linac and bunch compressor simulation with Lucretia, including upgraded layout for Sector 20 bunch compressor and final focus system

Simulations performed with different accelerator configurations*

*All sims with updated Sector 20 layout unless otherwise stated

- Single bunch, 2 nC, (TDR, W-Chicane)
  \( I_{pk} = 72 \text{ kA} \)

- Single bunch, high compression (using collimation & laser heater)
  \( I_{pk} = 50-302 \text{ kA} \)

- Single bunch, long bunch, good transverse quality (SFQED initial experiments)
  \( I_{pk} = 3 \text{ kA} \)

- 2 bunch (from cathode, 0.5 + 1.5 nC)
  \( I_{pk} = 30/60 \text{ kA} \) or \( 10/20 \text{ kA} \) with Laser Heater
# Electron Injector – Gun Parameters

![Diagram of the electron injector setup]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single Bunch</th>
<th>2 Bunch</th>
<th>Driver Pulse</th>
<th>Witness Pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gun rf Phase (deg off zero emission)</strong></td>
<td>10</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Laser spot Gaussian rms width pre-cut [mm]</strong></td>
<td>5.0</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cut radius on transverse laser spot [mm]</strong></td>
<td>2.68</td>
<td>2.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(initial dist. X2 rms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Laser pulse length (FWHM) [ps]</strong></td>
<td>7.0</td>
<td>7.0</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td><strong>L0-B phase w.r.t. ( \delta_{E,\text{min}} ) (deg)</strong></td>
<td>0</td>
<td>-9</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gun Solenoid Int. Field Strength [kG.m]</strong></td>
<td>0.38</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Beam Parameters @ L1

Parameter | FACET-II TDR | Double-Pulse Option
--- | --- | ---
| | Driver Pulse | Witness Pulse |
Bunch Charge [nC] | 2.0 | 1.6 | 0.5 |
Transverse Emittance (90%) [μm-rad] | 3.0 | 3.1 | 2.3 |
Peak Current [A] | 290 | 270 | 180 |
Bunch Length (rms) [μm] | 736 | 608 | 277 |
Bunch separation [mm] (peak-peak) | -- | | 2.18 |
Linac Bunch Compression – Single Bunch

RF Gun
L0
Injector

135 MeV
335 MeV
4.5 GeV
10.0 GeV

BC11
BC14
BC20

BC14 COLL
BC11 COLL
Existing W-chicane
OR new double-dogleg design

L1
L2
L3

Final Focus & Experimental Area

SLAC Linac Tunnel (Sectors 10 – 19)

\( \Phi = -20.5^\circ \)
\( \Phi = -39.4 - 40.0^\circ \)
\( \Phi = 0^\circ \)

Mean Energy = 0.335 GeV
\( \sigma_{dP} = 0.62 \% \)
\( \sigma_z = 856.9 \text{ um} \) l(pk) = 0.29 kA
\( \text{rms } dP/P = 0.65298 \% \)
\( \text{rms } Z = 735.642 \text{ um} \)

Mean Energy = 0.335 GeV
\( \sigma_{dP} = 0.63 \% \)
\( \sigma_z = 8566.9 \text{ um} \) l(pk) = 0.29 kA
\( \text{rms } dP/P = 0.65298 \% \)
\( \text{rms } Z = 735.642 \text{ um} \)

Mean Energy = 4.5 GeV
\( \sigma_{dP} = 2.11 \% \)
\( \sigma_z = 863.9 \text{ um} \) l(pk) = 0.44 kA
\( \text{rms } dP/P = 1.47258 \% \)
\( \text{rms } Z = 438.557 \text{ um} \)

Mean Energy = 10.0 GeV
\( \sigma_{dP} = 2.03 \% \)
\( \sigma_z = 863.7 \text{ um} \) l(pk) = 0.44 kA
\( \text{rms } dP/P = 1.47818 \% \)
\( \text{rms } Z = 90.216 \text{ um} \)

Mean Energy = 4.50 GeV
\( \sigma_{dP} = 2.03 \% \)
\( \sigma_z = 70.8 \text{ um} \) l(pk) = 3.56 kA
\( \text{rms } dP/P = 1.47818 \% \)
\( \text{rms } Z = 90.216 \text{ um} \)
• 1D CSR model only
• $\beta^*=50\text{cm}$
  • Chromatic effects challenging with large energy spread
Laser heater in electron injector: control Sector 20 bunch length (peak current) with minimal Linac re-tuning

- Also suppresses micro-bunching in Linac
- For $I_{pk} > 10$ kA, need 2D CSR model
Beam @ Sector 20 IP (PENT) – Single Bunch (+ LH,COLL)

- LH = 20 keV
- $\gamma \varepsilon_{x,y} = 33$, 2.8 $\mu$m-rad
- Non-trivial correlations in phase-space

$\beta^* = 10$ cm
Compression Profile Through BC20

Bunch parameters after named element from tracked macro particles

<table>
<thead>
<tr>
<th></th>
<th>BEGBC20</th>
<th>B1L</th>
<th>B2EL</th>
<th>B2ER</th>
<th>B1R</th>
<th>IP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma \varepsilon_x$ (µm-rad)</td>
<td>2.4</td>
<td>3.3</td>
<td>3.1</td>
<td>4.0</td>
<td>13.7</td>
<td>32.8</td>
</tr>
<tr>
<td>$I_{pk}$ (kA)</td>
<td>4.3</td>
<td>5.8</td>
<td>7.9</td>
<td>118.2</td>
<td>262.8</td>
<td>302.9</td>
</tr>
<tr>
<td>$\sigma_z$ (µm)</td>
<td>43.6</td>
<td>33.1</td>
<td>23.7</td>
<td>4.9</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Linac Bunch Compression – Single Bunch + L1X Linearizer (Low Energy Spread Configuration)

135 MeV

335 MeV

4.1 GeV

10.0 GeV

Mean Energy = 4.100 GeV

Mean Energy = 4.101 GeV

Mean Energy = 4.100 GeV

Mean Energy = 0.356 GeV

Mean Energy = 0.335 GeV

Mean Energy = 0.356 GeV

Mean Energy = 0.335 GeV

Mean Energy = 0.356 GeV

Mean Energy = 0.335 GeV

SLAC Linac Tunnel (Sectors 10 – 19)
Beam @ Sector 20 IP (PENT) – Single Bunch (+L1X & COLL) (Low Energy Spread Configuration)

- L1X Enables high \( I_{pk} (>100\text{ kA}) \) with low energy spread (<0.3%)
- \( \gamma \varepsilon_{x,y} = 37, 2.5 \text{ \mu m-rad} \)
**SFQED Configuration – Low Energy Spread, High Energy**

- $\beta_{x,y}^* = 10m$

Particle tracking:
- $\gamma \varepsilon_{x,y} = 4 \, \mu m\cdot\text{rad}$
- $\sigma_z = 250 \, \mu m$ full width
  - (79 $\mu m$ rms)
- $\sigma_{x,y} \sim 25 \, \mu m$ (core)
- $Q=2 \, \text{nC} \, (N_e=1.25\times10^{10})$

\[\sigma_y = 29.6 \, \mu m\]
\[\sigma_x = 24.4 \, \mu m\]
\[\text{rms } X = 56.0496 \, \mu m\]
\[\text{rms } Y = 52.4236 \, \mu m\]
\[Q = 1.99812 \, \text{nC}\]

\[dP = 0.0133 \%\]
\[I_{pk} = 6.00 \, \text{kA}\]
\[\text{Mean Energy} = 13,000 \, \text{GeV}\]
\[\text{rms } dP/P = 0.140375 \%\]
\[\text{rms } Z = 78.8032 \, \mu m\]
\[\text{Q} = 1.99812 \, \text{nC}\]
Linac Bunch Compression – 2 Bunch Configuration

SLAC Linac Tunnel (Sectors 10 – 19)

Distance (μm)

σ_z = 557.8 um I(pk) = 0.27 kA
rms dP/P = 1.36825 %
rms Z = 1186.9 um

σ_z = 35 MeV
I(pk) = 35 MeV
Mean Energy = 0.335 GeV

σ_z = 48.3 um I(pk) = 4.27 kA
rms dP/P = 1.99798 %
rms Z = 129.266 um

Mean Energy = 4.501 GeV

Mean Energy = 4.500 GeV

Mean Energy = 4.501 GeV

Mean Energy = 4.500 GeV
Beam @ Sector 20 IP (PENT) – 2 Bunch (Longitudinal)
IP Beam Parameters Controllable with Laser Heater and S20 Matching

\[ \Delta z = 150 \, \mu m \] (peak-peak)
Beam @ Sector 20 IP (PENT) – 2 Bunch (Transverse)

IP Beam Parameters Controllable with Laser Heater and S20 Matching

Drive Bunch

<- γε_{x,y} (90%) = 20.6, 37.1 μm-rad
γε_{x,y} (90%) = 20.6, 37.1 μm-rad ->

Witness Bunch

<- γε_{x,y} (90%) = 3.2, 2.6 μm-rad
γε_{x,y} (90%) = 5.9, 3.1 μm-rad ->
**IP Waist Locations for Drive and Witness Bunch**

 Witness Bunch

 Drive Bunch

 Q0FF

 \( \beta^Q, \alpha^Q \)

 “PENT”

 \( \beta^{IP}, \alpha^{IP} \)

 Drive Bunch Waist Location

 \( \beta^D, \alpha^D \)

 \( L^* = 2.7 \, \text{m} \)

 \( \Delta W \)

 \( \Delta W_{x,y} = 14.8, 34.1 \, \text{cm} \)

 \( \Delta W_{x,y} = 9.3, 12.3 \, \text{cm} \)

 S20 Matched for Mean Drive+Witness E

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**Table parameters extracted from tracked beam**

<table>
<thead>
<tr>
<th></th>
<th>( \alpha^Q ) [x,y]</th>
<th>( \beta^Q ) [x,y]</th>
<th>( \alpha^{IP} ) [x,y]</th>
<th>( \beta^{IP} ) [x,y]</th>
<th>( \alpha^D ) [x,y]</th>
<th>( \beta^D ) [x,y]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Witness</td>
<td>54, 56</td>
<td>148, 148 m</td>
<td>0.1, 0.7</td>
<td>5.0, 7.0 cm</td>
<td>-2.9, -6.4</td>
<td>46, 203 cm</td>
</tr>
<tr>
<td>Drive</td>
<td>32, 19</td>
<td>91, 59 m</td>
<td>1.7, 2.2</td>
<td>33, 33 cm</td>
<td>0.0, 0.0</td>
<td>8.9, 16 cm</td>
</tr>
<tr>
<td>Witness</td>
<td>44, 20</td>
<td>114, 51 m</td>
<td>-1.6, -1.0</td>
<td>20, 25 cm</td>
<td>0.5, 0.9</td>
<td>7.5, 23 cm</td>
</tr>
<tr>
<td>Drive</td>
<td>23, 17</td>
<td>64, 46 m</td>
<td>0.5, 0.0</td>
<td>15, 15 cm</td>
<td>0.0, 0.0</td>
<td>12, 16 cm</td>
</tr>
<tr>
<td>Configuration</td>
<td>$I_{pk}$ [kA]</td>
<td>$\sigma_z^*$ [μm]</td>
<td>$\sigma_x^*$ [μm]</td>
<td>$\sigma_y^*$ [μm]</td>
<td>$\gamma \varepsilon_x$ [μm-rad]</td>
<td>$\gamma \varepsilon_y$ [μm-rad]</td>
</tr>
<tr>
<td>-------------------------------</td>
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<td>-------------------</td>
<td>-------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>2 bunch (Witness, Drive)</td>
<td>28, 68</td>
<td>3.2, 2.2</td>
<td>3.0, 6.3</td>
<td>2.6, 9.1</td>
<td>3, 21</td>
<td>2.6, 12</td>
</tr>
<tr>
<td>2 bunch (W, D) + LH</td>
<td>15, 34</td>
<td>3.7, 3.4</td>
<td>4.1, 12.9</td>
<td>3.7, 8.2</td>
<td>4, 26</td>
<td>4.3, 12</td>
</tr>
<tr>
<td>Single Bunch, TDR</td>
<td>72</td>
<td>1.8</td>
<td>17.7</td>
<td>12.2</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Single Bunch + COLL + LH</td>
<td>302</td>
<td>0.4</td>
<td>14.3</td>
<td>5.0</td>
<td>33</td>
<td>3</td>
</tr>
<tr>
<td>Single Bunch + L1X + COLL + LH</td>
<td>161</td>
<td>0.6</td>
<td>4.6</td>
<td>4.4</td>
<td>37</td>
<td>3</td>
</tr>
<tr>
<td>Single Bunch, 13 GeV, + COLL (long bunch)</td>
<td>4.2</td>
<td>97</td>
<td>1.9</td>
<td>2.2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

$\gamma \varepsilon$ is normalized, “90% emittance”, $\sigma_{x,y,z}$ is Gaussian width of fit to core of distribution.

- Tracked particles at various locations stored on start-to-end tracking results web page: [http://www.slac.stanford.edu/~whitegr/F2_S2E](http://www.slac.stanford.edu/~whitegr/F2_S2E)
Bunch Compression in S20 FFS

- CSR in BC20 generates high-order \( z-r' \) correlations in bunch
- \( Z \)-motion in FFS depends on transverse momentum
  - i.e. \( dz = L/2 (px^2 + py^2) \) for each element
- In max compression configuration, enough to influence final peak current
  - Core \( \sigma_z \approx 500 \to 300 \) nm

Divergence angle vs. \( z \) at exit of BC20