Summary from Beam Dynamics Meetings

T. Limberg for the (XFEL) Beam Dynamics Group

Baboi, Nicoleta-Ionela; Balandin, Vladimir; Beutner, Bolko; Brinkmann, Reinhard; Castro-Garcia, Pedro; Decking, Winfried; Dohlus, Martin; Faatz, Bart; Floettmann, Klaus; Geloni, Gianluca Aldo; Gerth, Christopher; Golubeva, Nina; Huening, Markus; Kim, Yujong; Koerfer, Markus; Limberg, Torsten; Noelle, Dirk; Roehrs, Michael; Rossbach, Joerg; Saldin, Evgueni; Schlarb, Holger; Schneidmiller, Evgeny; Seidel, Mike; Vogel, Elmar; Walker, Nicholas John; Yurkov, Mikhail; Zagorodnov, Igor
• Lattice Work and List of Components (W. Decking)

• Bunch compression stability dependence on rf parameters (Dohlus, Limberg), amplitude and phase stability for I/Q detection (H. Schlarb)

• Wake fields and their impact on SASE (Igor Zagarodnov, Martin Dohlus)

• VUV-FEL or TTF-II activities (Vladimir Balandin, M. Dohlus)
Lattice Work (W. Decking)
web page by Bartosz Poljancewicz

Injector lattice with dogleg done

Lattice complete for whole machine
Figure 3: Injector layout of the XFEL
Figure 2: Layout of the XFEL
<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SECTION</td>
<td>NAME</td>
<td>TYPE</td>
<td>LENGTH</td>
<td>STRENGTH</td>
<td>S</td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>START</td>
<td>-</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00000</td>
<td>-2.88E+00</td>
<td>-5.12E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>3</td>
<td>INJ1</td>
<td>GUN</td>
<td>(All)</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00000</td>
<td>-2.88E+00</td>
<td>-5.12E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>4</td>
<td>INJ</td>
<td>-</td>
<td>(Top 10...)</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>1.50000</td>
<td>-2.88E+00</td>
<td>-4.97E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>5</td>
<td>ACC</td>
<td>START</td>
<td>-</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>2.75930</td>
<td>-2.88E+00</td>
<td>-4.85E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>6</td>
<td>ACC00</td>
<td>CELL1</td>
<td>-</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>4.14290</td>
<td>-2.88E+00</td>
<td>-4.71E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>7</td>
<td>ACC00</td>
<td>CELL1</td>
<td>DUMP</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>5.52650</td>
<td>-2.88E+00</td>
<td>-4.57E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>8</td>
<td>ACC00</td>
<td>CELL1</td>
<td>ECOL</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>6.91010</td>
<td>-2.88E+00</td>
<td>-4.43E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>9</td>
<td>ACC00</td>
<td>CELL1</td>
<td>HKIC</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>8.29370</td>
<td>-2.88E+00</td>
<td>-4.30E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>10</td>
<td>ACC00</td>
<td>CELL2</td>
<td>MARK</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>9.67730</td>
<td>-2.88E+00</td>
<td>-4.16E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>11</td>
<td>ACC00</td>
<td>CELL2</td>
<td>MONI</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>11.06090</td>
<td>-2.88E+00</td>
<td>-4.02E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>12</td>
<td>ACC00</td>
<td>CELL2</td>
<td>OCTU</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>12.44450</td>
<td>-2.88E+00</td>
<td>-3.88E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>13</td>
<td>ACC00</td>
<td>CELL2</td>
<td>QUAD</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>13.82830</td>
<td>-2.88E+00</td>
<td>-3.74E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>14</td>
<td>ACC00</td>
<td>Q.1</td>
<td>-</td>
<td>1.50E-01</td>
<td>-3.79E-01</td>
<td>12.94880</td>
<td>-2.88E+00</td>
<td>-3.65E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>15</td>
<td>ACC00</td>
<td>Q.2</td>
<td>QUAD</td>
<td>1.50E-01</td>
<td>2.32E-01</td>
<td>13.30980</td>
<td>-2.88E+00</td>
<td>-3.52E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>16</td>
<td>ACC00</td>
<td>BPM</td>
<td>-</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00000</td>
<td>-2.88E+00</td>
<td>-3.45E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>17</td>
<td>ACC00</td>
<td>BPM</td>
<td>QUAD</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00000</td>
<td>-2.88E+00</td>
<td>-3.42E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>18</td>
<td>ACC</td>
<td>END</td>
<td>MARK</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>13.59120</td>
<td>0.00E+00</td>
<td>13.59120</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>19</td>
<td>INJ</td>
<td>KVA</td>
<td>VKIC</td>
<td>1.00E+01</td>
<td>0.00E+00</td>
<td>0.00000</td>
<td>-2.88E+00</td>
<td>-3.52E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>20</td>
<td>INJ</td>
<td>KHA</td>
<td>HKIC</td>
<td>1.00E+01</td>
<td>0.00E+00</td>
<td>0.00000</td>
<td>-2.88E+00</td>
<td>-3.50E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>21</td>
<td>INJ</td>
<td>BPM</td>
<td>MONI</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00000</td>
<td>-2.88E+00</td>
<td>-3.49E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>22</td>
<td>INJ</td>
<td>Q1.3</td>
<td>QUAD</td>
<td>2.50E-01</td>
<td>9.15E-01</td>
<td>16.74120</td>
<td>-2.88E+00</td>
<td>-3.42E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>23</td>
<td>INJ</td>
<td>Q1.4</td>
<td>QUAD</td>
<td>2.50E-01</td>
<td>-8.61E-01</td>
<td>17.09120</td>
<td>-2.88E+00</td>
<td>-3.42E+01</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>24</td>
<td>INJ</td>
<td>Q1.5</td>
<td>QUAD</td>
<td>2.50E-01</td>
<td>-2.79E-01</td>
<td>20.34120</td>
<td>-2.88E+00</td>
<td>-3.09E+01</td>
<td>0.00E+00</td>
</tr>
</tbody>
</table>
BUNCH COMPRESSION STABILITY DEPENDENCE ON RF PARAMETERS:
Layout of the European XFEL Bunch Compression System

$\sigma_s = 2 \text{ mm}$  
$I_{\text{peak}}: 50 \text{ A}$

$\sigma_s = 0.1 \text{ mm}$  
$I_{\text{peak}}: 1 \text{ kA}$

$\sigma_s = 0.02 \text{ mm}$  
$I_{\text{peak}}: 5 \text{ kA}$

3rd Harmonic RF
Booster Linac with 3x4 Modules
Undulator

$\sigma_s$ peak $= 2 \text{ mm}$  
$I: 50 \text{ A}$

$\sigma_s$ peak $= 0.1 \text{ mm}$  
$I_{\text{peak}}: 1 \text{ kA}$

$\sigma_s$ peak $= 0.02 \text{ mm}$  
$I_{\text{peak}}: 5 \text{ kA}$

Chicane Lay Out

- Module
- Bending Magnet
- Vertical Deflection Cavity Section
- Wire Scanner Section
- Bunch Length Measurement (with Optical Replica Method)

500 MeV
up to 2.5 GeV (at 20 MeV/m in booster)
20 GeV
### Sensitivity Table for European XFEL

- **Criterion:** $I_{\text{peak}}$ changes from 5 kA to 5.5 kA (SASE statistical fluctuation: 5-10%)

Can we relax this tolerance?

<table>
<thead>
<tr>
<th>Beam Parameter</th>
<th>Change (Unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac Phase</td>
<td>0.013 degrees</td>
</tr>
<tr>
<td>3rd harmonic Phase</td>
<td>-0.04 degrees</td>
</tr>
<tr>
<td>3rd harmonic Amplitude</td>
<td>0.06 (~0.05%) MV</td>
</tr>
<tr>
<td>Magnet Strength 1st Chicane</td>
<td>-0.0005 relative change</td>
</tr>
<tr>
<td>Magnet Strength 2nd Chicane</td>
<td>-0.01 &quot;</td>
</tr>
</tbody>
</table>

**Beam Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Change (Unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge ($I_{\text{peak}}$ = constant)</td>
<td>0.05 relative change</td>
</tr>
<tr>
<td>$I_{\text{peak}}$ (Charge = constant)</td>
<td>-0.02 &quot;</td>
</tr>
<tr>
<td>Charge (Length = constant)</td>
<td>-0.05 &quot;</td>
</tr>
</tbody>
</table>
$V_1, V_n, \phi_1, \phi_n$ are the voltages and phases for the fundamental mode rf and the nth harmonic of the first compression stage ($n=3$ for European XFEL, $n=4$ for LCLS)

$V_1$ and $V_n$ are later on replaced by normalized amplitudes $a_1$ and $a_n$. 
Error sensitivity of compression factor $C$ with respect to phase (or amplitude) offset $x$:

$$\frac{1}{C_0} \frac{\partial C}{\partial x} = A \frac{\partial p}{\partial x} + B \frac{\partial p'}{\partial x}$$

$$p = p(s_a, x)$$

$$\partial p'/\partial x = \partial^2 p/\partial x \partial s_a$$

$$A = -2(C_0 - 1)t_{566}/r_{56}$$

$$B = -C_0 r_{56}$$

Example: For phase jitter of the fundamental mode rf (first stage) \( \left( \varphi_1 = \varphi_{1\text{design}} + x \right) \)

$$p(s_a, x) = a_1 \cos(k s_a + \varphi_1 + x) + a_n \cos(nk s_a + \varphi_n)$$

And the bunch compression factor sensitivity is

$$\frac{1}{C_0} \frac{\partial C}{\partial x} = -a_1 \left( A \sin \varphi + Bk_i \cos \varphi_i \right)$$

Footnote: 2-stage system in the case of E-XFEL very similar to 1st stage:

$$\frac{\partial C^{(1+2)}}{C_0^{(1+2)}} = \frac{C_0^{(1+2)}}{C_0^{(1+2)}} \left\{ \frac{\partial C^{(1)}}{C_0^{(1)} \partial x} - C_0^{(1+2)}/r_{56} a \frac{\partial p^{(1)}}{\partial x} \right\}$$

small for the E-XFEL
Impossible with a single frequency system, but for the combination of fundamental mode and higher harmonic rf systems a working point can be found...

\[
1 + p(s_1) = \begin{cases} 
0 & \Delta \varphi_1 = \frac{\Delta}{2}\Delta \\
-\Delta & \Delta \varphi_3 = \frac{-\Delta}{2}\Delta
\end{cases}
\]

...where for increased beam energy due to phase jitter, chirp increases in strength:

→ effectively reduced R56 of magnet chicane is compensated by the stronger chirp
Amplitude (normalized) and phase of the fundamental mode rf \((a_1, \varphi_1)\) and of the higher harmonic rf \((a_n, \varphi_n)\) are combined to set up four ‘knobs’:

\[
\begin{bmatrix}
1 & 0 & 1 & 0 \\
0 & -k & 0 & -(nk) \\
-k^2 & 0 & -(nk)^2 & 0 \\
0 & k^3 & 0 & (nk)^3
\end{bmatrix}
\begin{bmatrix}
a_1 \cos \varphi_1 \\
a_1 \sin \varphi_1 \\
a_n \cos \varphi_n \\
a_n \sin \varphi_n
\end{bmatrix}
= \begin{bmatrix}
1 \\
p_0^{(1)} \\
p_0^{(1)} \\
p_0^{(1)}
\end{bmatrix}
\]

Beam energy (normalized)

Chirp

2\textsuperscript{nd} and 3\textsuperscript{rd} derivatives of particle momentum deviations

Impact on final longitudinal bunch shape weaker, can be used as a relatively free parameter to reduce rf phase tolerances
Rf Phase Jitter Sensitivity Optimization Scenarios

Scanned $p''''$ for different scenarios:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0^{(1)}/$MeV</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>$C^{(1)}$</td>
<td>20</td>
<td>14</td>
<td>20</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>$r_{56}^{(1)}/$mm</td>
<td>84.4</td>
<td>101.4</td>
<td>82.3</td>
<td>109.3</td>
<td>89.1</td>
<td>68.4</td>
</tr>
<tr>
<td>$\phi_1^{(2)}/$deg</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>$r_{56}^{(2)}/$mm</td>
<td>19.2</td>
<td>19.0</td>
<td>29</td>
<td>29.3</td>
<td>29.3</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Used 1D tracking code which includes:

- wakefields
- non-linearities of rf and magnet chicanes
- longitudinal space charge

Let’s pick this one
The phase and amplitude offsets which are plotted on the vertical scale cause a change of the final peak current of 10%.

3rd harmonic rf voltage plotted on the horizontal axis; it scales with $\rho''$. 
RF Phase Jitter Sensitivity Optimization Numerical Results:
Fundamental Mode RF Voltage and Amplitude Sensitivities for both Systems
Final Longitudinal Beam Profiles for Different rf Settings
(case 5)

Peak Current

$I/kA$

$V_{3}^{(1)}/MV$

Longitudinal bunch position
• The phase jitter sensitivity of the European XFEL bunch compression system can be reduced by more than an order of magnitude if the amplitudes and phases of the fundamental mode rf and the higher harmonic rf system are correctly chosen to provide phase jitter compensation.

• The 3rd harmonic system has to be operated with an amplitude of 200-250 MV, more than twice the minimum value necessary to compensate the non-linearities of the fundamental mode rf and the magnet chicanes. At that working point, phase jitter tolerances are of the order of a degree for both rf systems, compared to a few hundredth of a degree in the previous design. Amplitude jitter tolerances are $1.5 \cdot 10^{-4}$ for the 3rd harmonic rf and $3 \cdot 10^{-4}$ for the fundamental mode rf.
Phase and Amplitude error:

\[ d\phi = \phi - \phi \]
\[ dA = A - A \]

Is determined by the resolution for I and Q measurements.

But resolution equals \( \sigma_I = \sigma_Q \)

\[ \Rightarrow d\phi = dA/A \quad \text{or} \]
\[ \Rightarrow 1^\circ \propto 1.75\% \]

- To improve the amplitude stability additional detectors are required
- Slow phase drifts in cables and electronics reduce the accuracy
- Good phases reference (LO), e.g. new synchronization eliminates reference drifts
• jitter assumptions: \( \frac{dV_1}{V_1} = \frac{dV_2}{V_2} = 1.7 \times 10^{-4} \) (0.01° L-Band)
  \( \frac{dV_3}{V_3} = 2.2 \times 10^{-4} \) (0.015° at 3.9GHz [not full benefit or higher f])
• variation of \( E''' \) allows to operated with distributed tolerance (minimum)
• but relaxed phase sensitivity cause critical amplitude tolerance (1)

![Graph showing RF tolerance for XFEL variation of compression after BC2](image_url)
• most critical is amplitude jitter of 1.3GHz $V_1$
• phase jitter dominates for larger $|E''''|$ (correlated jitter with $\phi_1 = +3\phi_3$)
• operation point (1): arrival time jitter increased by 40%, $\phi_1$ critical

Desired: Sub-sigma e.g.
$dt < \sigma_t$
• variation of E”’” allows to select minimum
  - of compression jitter and
  - of arrival time jitter

• for I/Q detection 1° = 1.7% => both minima close to one another

• currently operation point (1) does not provide advantages

• preferable to develop additional RF amplitude detectors to reduce
  arrival time jitter and to achieve higher flexibility in the operation
  point of E”’”.

• beam based monitors of the energy, the compression and the arrival
  timing for FBs are most critical and will dominantly influence
  the final choice of the machine operation settings.
• only measurements shot-to-shot (no detectors available for intra-pulse trains)
• amplitude stability ACC1 (8 cav.) best result $\sigma_A/A = 0.028\%$, typical =0.05%
• phase stability with pyro-detector $\sigma_\phi = 0.067^\circ$ (but laser and gun phase included)

- ACC1 operation at feedback gain of 60 (2005−06−02T135158)
  - energy jitter = 0.028%
  - $\sigma_A/A = 0.028\%$, typical =0.05%
  - $\sigma_\phi = 0.067^\circ$ (but laser and gun phase included)

• TTF1:  5 times better within the macro-pulse compared to shot-to-shot
• upgrade of LLRF: DSP -> FPGA, down-converters from 250kHz -> 81MHz
  => high resolution, lower latency and no ripple -> high gain 100-200 possible
  $\sigma_A/A = 5e-5$ within pulse possible => intrinsic 3 mdeg phase
$w = 1 \text{mm} - \text{width of the slot}$
$L = 5 \text{m} - \text{length of the slot}$

Other wakes are small (<25%) compared to Undulator Chamber (~250 m)
Effect of the slot is small.

- Accuracy estimation of the numerical results.
- Wake scaling for geometry parameters.

Used tools:
- ECHO (time-domain),
- CST Microwave Studio (modeling, meshing),
- Matlab (pre- and postprocessing).
Longitudinal wake for the case of the elliptical pipe (3.8mm)

<table>
<thead>
<tr>
<th></th>
<th>pro section (6.1 m)</th>
<th>Loss, V/pC</th>
<th>Spread, V/pC</th>
<th>Peak, V/pC</th>
</tr>
</thead>
<tbody>
<tr>
<td>absorber</td>
<td>1</td>
<td>42</td>
<td>16</td>
<td>-58</td>
</tr>
<tr>
<td>pumping slot</td>
<td>1</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>&gt;-0.3</td>
</tr>
<tr>
<td>pump</td>
<td>1</td>
<td>9</td>
<td>4</td>
<td>-13</td>
</tr>
<tr>
<td>BPM</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bellow</td>
<td>1</td>
<td>13</td>
<td>5</td>
<td>-18</td>
</tr>
<tr>
<td>flange gap</td>
<td>1</td>
<td>6</td>
<td>2.4</td>
<td>-8.5</td>
</tr>
<tr>
<td>Total geom.</td>
<td></td>
<td>70</td>
<td>&lt;28</td>
<td>-98</td>
</tr>
<tr>
<td>resistive (Cu)</td>
<td>6.1m</td>
<td>220</td>
<td>279</td>
<td>-542</td>
</tr>
<tr>
<td>resistive (Al)</td>
<td>6.1m</td>
<td>303</td>
<td>325</td>
<td>-660</td>
</tr>
</tbody>
</table>
Effect of wake fields (round pipe) on SASE

\[ W_\parallel \left[ \frac{kV}{nC \cdot m} \right] \]

\[ W_\parallel \left[ \frac{V}{nC \cdot m} \right] \]

ELOSS = -51 keV/m

<table>
<thead>
<tr>
<th></th>
<th>Loss, kV/nC/m</th>
<th>Spread, kV/nC/m</th>
<th>Peak, kV/nC/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>geometrical</td>
<td>20</td>
<td>12</td>
<td>-32</td>
</tr>
<tr>
<td>resistive</td>
<td>31</td>
<td>39</td>
<td>-75</td>
</tr>
<tr>
<td>total</td>
<td><strong>51</strong></td>
<td><strong>49</strong></td>
<td><strong>-105</strong></td>
</tr>
</tbody>
</table>
GENESIS Calculation of SASE Power with and without Undulator Tapering

\[ \frac{\langle P_{\text{sat}} \rangle}{\langle P_{\text{wake}} \rangle} = 2.1 \]

\[ \frac{\langle P_{\text{sat}} \rangle}{\langle P_{\text{wake+taper}} \rangle} = 1.5 \]
Tapering (steady state)

with ELOSS = - 51 keV/m

\[ \frac{\Delta a_w}{a_w} \approx \frac{\Delta \gamma}{\gamma} = \frac{\Delta E}{E} = \frac{51[keV/m] \cdot 250[m]}{20[GeV]} = 6.375 e^{-4} \]

\[ \frac{\Delta a_w}{a_w} = 8.0 e^{-4} = 1.5 \rho_1 \quad \text{Taper} \sim 64 \text{ keV/m} \]
1. For smooth Gaussian bunch the wake field reduces the power by factor 2.1

2. The tapering allows to reduce the degradation to a factor of 1.5

3. The numerical simulations are required to find an optimal tapering.

4. The wake effect for the expected bunch shape should be analyzed.
Wake Field Calculations for Different Bunch Shapes and Undulator Pipe Materials (M.D.)

- **Shape 0**
- **Shape 3**
No big difference between Al and Cu

300nm roughness; shape 3

$R_{\text{pipe}} = 3.8 \text{ mm}$

\begin{figure}
\centering
\includegraphics{graph.png}
\end{figure}

$W \over V/\mu\text{Cm}$

\begin{align*}
\text{av.} / \ (V/\mu\text{Cm}) &= -32, -26 \\
\text{rms.} / \ (V/\mu\text{Cm}) &= 71, 71
\end{align*}
One has to put a guess in some point.
CSR Calculation for TTF2

\[ \sigma_z = 1.821 \text{ mm} \quad 795 \mu\text{m} \quad 728 \mu\text{m} (\text{FWHM} \sim 188 \text{ fs}) \]

\[ E = 127 \text{ MeV} \quad E = 380 \text{ MeV} \]

\[ E - E_{\text{ref}} \quad \text{MeV} \]

\[ z \quad \text{mm} \]

\[ I \quad \text{A} \]

\[ z \quad \text{mm} \]

\[ x \quad \text{m} \]

\[ z \quad \text{m} \]