FEL Bandwidth Calculation for EXFEL SASE1 and Work Progress for FLASH2 Seeded FEL simulation

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S2E Meeting

DESY
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FEL Bandwidth Calculation for EXFEL SASE1

The energy chirp related FEL bandwidth calculation for different beam energy and different bunch charge cases.

E = 17.5 GeV, 14.0 GeV, 12.0 GeV, 8.5 GeV
Q = 1.0 nC, 0.5 nC, 0.25 nC, 0.1 nC, 0.02 nC

λ = 0.1 nm
Beam dynamics simulation

FEL Bandwidth Calculation for EXFEL SASE1

L1: ACC2
L2: ACC3+ ACC4+ ACC5
L3: ACC6+ ...+ ACC26

200000 particles

ASTRA (tracking with space charge effects, cylindrical symmetric algorithm)

CSRtrack (tracking with CSR effects)

TM - transverse matching to the design optics
FEL Bandwidth Calculation for EXFEL SASE1

Longitudinal phase space before SASE1 undulator:

\[
\begin{align*}
\text{E=17.5GeV, Q=1.0nC} & \quad \text{E=17.5GeV, Q=0.5nC} & \quad \text{E=17.5GeV, Q=0.25nC} & \quad \text{E=17.5GeV, Q=0.1nC} & \quad \text{E=17.5GeV, Q=0.02nC} \\
\text{E=14.0GeV, Q=1.0nC} & \quad \text{E=14.0GeV, Q=0.5nC} & \quad \text{E=14.0GeV, Q=0.25nC} & \quad \text{E=14.0GeV, Q=0.1nC} & \quad \text{E=14.0GeV, Q=0.02nC} \\
\text{E=12.0GeV, Q=1.0nC} & \quad \text{E=12.0GeV, Q=0.5nC} & \quad \text{E=12.0GeV, Q=0.25nC} & \quad \text{E=12.0GeV, Q=0.1nC} & \quad \text{E=12.0GeV, Q=0.02nC} \\
\text{E=8.5GeV, Q=1.0nC} & \quad \text{E=8.5GeV, Q=0.5nC} & \quad \text{E=8.5GeV, Q=0.25nC} & \quad \text{E=8.5GeV, Q=0.1nC} & \quad \text{E=8.5GeV, Q=0.02nC}
\end{align*}
\]
Peak-to-peak energy chirp in the lasing fraction of the bunch (FWHM)

<table>
<thead>
<tr>
<th></th>
<th>17.5 GeV</th>
<th>14 GeV</th>
<th>12 GeV</th>
<th>8.5 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 nC</td>
<td>7.05 MeV</td>
<td>7.05 MeV</td>
<td>7.00 MeV</td>
<td>6.75 MeV</td>
</tr>
<tr>
<td>0.25 nC</td>
<td>8.23 MeV</td>
<td>8.02 MeV</td>
<td>7.82 MeV</td>
<td>7.61 MeV</td>
</tr>
<tr>
<td>0.10 nC</td>
<td>11.19 MeV</td>
<td>12.01 MeV</td>
<td>12.52 MeV</td>
<td>14.05 MeV</td>
</tr>
<tr>
<td>0.02 nC</td>
<td>37.4 MeV</td>
<td>41.85 MeV</td>
<td>45.73 MeV</td>
<td>53.65 MeV</td>
</tr>
</tbody>
</table>
FEL Bandwidth Calculation for EXFEL SASE1
## FEL Bandwidth Calculation for EXFEL SASE1

### $\lambda = 0.1 \text{ nm}$

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>Natural bandwidth</th>
<th>Spectrum increase</th>
<th>Simulation results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 nC</td>
<td>0.11%</td>
<td>0.113%</td>
<td>0.225%</td>
</tr>
<tr>
<td></td>
<td>0.1%</td>
<td>0.14%</td>
<td>0.22%</td>
</tr>
<tr>
<td></td>
<td>0.09%</td>
<td>0.165%</td>
<td>0.22%</td>
</tr>
<tr>
<td></td>
<td>0.068%</td>
<td>0.238%</td>
<td>0.22%</td>
</tr>
<tr>
<td>0.5 nC</td>
<td>0.133%</td>
<td>0.124%</td>
<td>0.229%</td>
</tr>
<tr>
<td></td>
<td>0.124%</td>
<td>0.101%</td>
<td>0.25%</td>
</tr>
<tr>
<td></td>
<td>0.103%</td>
<td>0.117%</td>
<td>0.237%</td>
</tr>
<tr>
<td></td>
<td>0.078%</td>
<td>0.159%</td>
<td>0.235%</td>
</tr>
<tr>
<td>0.25 nC</td>
<td>0.14%</td>
<td>0.134%</td>
<td>0.256%</td>
</tr>
<tr>
<td></td>
<td>0.134%</td>
<td>0.114%</td>
<td>0.25%</td>
</tr>
<tr>
<td></td>
<td>0.110%</td>
<td>0.13%</td>
<td>0.248%</td>
</tr>
<tr>
<td></td>
<td>0.083%</td>
<td>0.179%</td>
<td>0.264%</td>
</tr>
<tr>
<td>0.10 nC</td>
<td>0.16%</td>
<td>0.155%</td>
<td>0.292%</td>
</tr>
<tr>
<td></td>
<td>0.155%</td>
<td>0.165%</td>
<td>0.36%</td>
</tr>
<tr>
<td></td>
<td>0.120%</td>
<td>0.209%</td>
<td>0.33%</td>
</tr>
<tr>
<td></td>
<td>0.090%</td>
<td>0.331%</td>
<td>0.464%</td>
</tr>
<tr>
<td>0.02 nC</td>
<td>0.167%</td>
<td>0.160%</td>
<td>0.640%</td>
</tr>
<tr>
<td></td>
<td>0.160%</td>
<td>0.152%</td>
<td>0.65%</td>
</tr>
<tr>
<td></td>
<td>0.152%</td>
<td>0.122%</td>
<td>0.56%</td>
</tr>
<tr>
<td></td>
<td>0.122%</td>
<td>0.58%</td>
<td>0.58%</td>
</tr>
</tbody>
</table>

1) **Natural bandwidth:** $\left| \frac{\Delta \lambda}{\lambda_0} \right|_{\text{FWHM}} \sim 2\rho$ \hspace{2cm} ($\rho$: FEL parameter)

2) **Spectrum increase** according to: $2 \left| \frac{\Delta E}{E_0} \right|_{\text{FWHM}}$

3) **Simulation results:** FWHM values of the spectrum from Genesis (5 random seeds for shot noise)
Seeded FEL Simulation for FLASH2

Previous work

Peak power $P_{\text{laser}} = 125$ MW
Rayleigh length $z_R = 4.2$ m
Pulse duration of $\tau = 30$ fs (FWHM)
Wavelength $\lambda = 235$ nm

Q = 0.5 nC
Seeded FEL Simulation for FLASH2

New model of the seeding laser

- Pulse energy = 6.0 μJ
- Rayleigh length $z_R = 4.2$ m
- Pulse duration of $\tau = 100$ fs (FWHM)
- Wavelength $\lambda = 266$ nm

Total length $\sim 90$ μm

$Q = 1.0$ nC

$\varepsilon_x^{proj} = 2.19 \mu m \cdot rad, \varepsilon_y^{proj} = 2.18 \mu m \cdot rad$
Seeded FEL Simulation for FLASH2

<table>
<thead>
<tr>
<th>Modulator 1</th>
<th>Radiator 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_u = 6.7 \text{ cm}$</td>
<td>$\lambda_u = 3.14 \text{ cm}$</td>
</tr>
<tr>
<td>$N = 30$</td>
<td>$N = 152$</td>
</tr>
<tr>
<td>$L_u \sim 2 \text{ m}$</td>
<td>$L_u \sim 4.773 \text{ m}$</td>
</tr>
</tbody>
</table>

$\lambda/7 (n=?)$

$\lambda/7 = 266 \text{ nm}$

$\lambda/7 = 38 \text{ nm}$

$76 \times \lambda_u + Q + 76 \times \lambda_u$

Schematic layout of the seeding undulator section

<table>
<thead>
<tr>
<th>Extraction arc section</th>
<th>Modulator-1</th>
<th>Radiator-1</th>
<th>Modulator-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.01 m</td>
<td>19.41 m</td>
<td>2.39 m</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam optics matching</th>
<th>Beta function [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_x$</td>
<td>$\beta_y$</td>
</tr>
</tbody>
</table>

$z [\text{ m}]$

$0 3 6 9 12 15 18 21$

$0 10 20 30 40 50$

$\text{Beta function [m]}$
Seeded FEL Simulation for FLASH2

Energy modulation at the exit of the modulator

\[ I = \frac{c q k E_{mod}}{\sqrt{2 \pi} \sigma_E} \]

\[ E_{mod} \sim 0.8 \text{ MeV} \]
Seeded FEL Simulation for FLASH2

Estimations in the dispersive chicane:

(1) $r_{56}$ for the complete compression (referring to the middle of the modulated part of the bunch): $r_{56} = E/(kE_{mod}) = 53 \ \mu m \rightarrow R \sim 14.5 \ m$

(2) rms length of the sub-bunches after complete compression: $\sigma = \frac{r_{56}E}{E} \approx 8 \ nm$

(3) Charge in one wavelength: $q_{\lambda} = I \frac{\lambda}{c} \approx 0.887 \ pC$

(4) Charge which can be compressed: $q = q_{\lambda}/2$

(5) Scaling of steady state csr of gaussian bunch: $E_c = \frac{1}{\sqrt[3]{3(2\pi)^2R^3\sigma^3}} \frac{q}{\varepsilon} \sim 23.4 \ MV/m$

CSRtrack simulation:

(1) required resolution $\sim 4 \ nm \ll \sigma$

(2) required step width $\sim 0.2 \ mm \ll R \sigma/\sigma_x = 1 \ mm$

(3) Particle number $\sim 15 \ M$

CSRTrack simulation is in process …
Plans

(1) Harmonic optimization for the radiator.
(2) Continue to do the cascaded HGHG simulation.