1 Geometry

2 CSRtrack calculation for ideal gaussian bunch
   2.1 Collimator
   2.2 TD1
   2.3 TD20

3 Attempts to avoid/reduce longitudinal effects
   3.1 Shielding
   3.2 Magnet lengths and splitted arcs
   3.3 In principle

4 Realistic model for longitudinal phase space + collimator
   impedance model (from database)
   4.1 1D simulation
   4.2 Collimator {impedance model, CSRtrack with distributed imp.}
   4.3 TD1 and TD20

5 Summary / Conclusion
1 Geometry

Collimation section: $L = 180$ m

TD1: $L = 85.56$ m $\phi = 2.25$ deg

TD20: $L = 147.62$ m $\phi = 6.68$ deg

[Diagrams showing longitudinal lattice coordinate, angle, and cartesian coordinates]
5 Summary / Conclusion

2 CSRtrack calculation for ideal gaussian bunch ($\varepsilon = 1\,\mu\text{m}$)

- Collimator: emittance growth <1 %, energy spread 2.6 MeV
- TD1: emittance growth 40 %, energy spread 2.0 MeV
- TD20: emittance growth 41 %, energy spread 3.5 MeV, compression effects

3 Attempts to avoid/reduce longitudinal effects

- None of the shielding effects can be used.
- There is a weak influence of magnet length on the rms energy spread.

4 Realistic model for longitudinal phase space + collimator impedance model

- After BC2, energy spread: 2.9 MeV
- After the collimator, energy spread: 15.2 MeV, emittance growth $\approx$ 8 %

**Significant (non-CSR collimator impedance) $\rightarrow$ 12 MeV rms spread**

- After collimator + TD1: energy spread 15.2 MeV, emittance growth 27 % **
- After collimator + TD20: over-compression due to uncompensated r56

**It is difficult to avoid CSR induced energy spread**

- Emittance growth due to centroid shift can be controlled / compensated.
2 CSRtrack calculation for ideal gaussian bunch

Gaussian fit of the bunch shape from S2E simulations
(Igor Zagorodnov)

Bunch shape from S2E simulations by Martin Dohls

$q = 0.56 \text{nC}$
$\sigma = 12.5 \text{µm}$

simulation with gaussian bunch
$I_{\text{peak}} = 5 \text{kA}$, $q = 0.5 \text{nC}$ ($\rightarrow \sigma = 12.5 \text{µm}$)
normalized transv. emittance $= 1 \text{µm}$
2.1 Collimator

\[ \beta_y/m, \beta_x/m \]

phase advance to end-point

\[ \psi_x - \psi_{x,\text{end}}/2\pi, \psi_y - \psi_{y,\text{end}}/2\pi \]

L = 180 m, mode A

\[ m/R_c \]

\[ T_{5,6}^{(\text{end-S})}/m, T_{1,6}^{(\text{end-S})}/m, T_{2,6}^{(\text{end-S})} \]

\[ T_{1,6}^{(\text{S-0})}/m, T_{2,6}^{(\text{S-0})}/m \]

without self effects
self effects, 1d CSR model
centroid properties of a gaussian bunch 1nC, Ipeak=5kA
no chirp

XFEL collimation section, mode A

energy deviation (eV)

longitud. lattice coordinate (m)

energy deviation (eV)

longitud. bunch coordinate (m)

longitudinal field (V/m)

horizontal offset (m)
XFEL collimation section, mode A

self effects, 1d CSR model
centroid properties of a gaussian bunch 1nC, Ipeak=5kA
no chirp

normalized horizontal emittance (m)

longitud. lattice coordinate (m)

rms energy spread (eV)
2.2 TD1

Without self effects

$L = 85.56 \, m \, \phi = 2.25 \, \text{deg}$

Phase advance to end-point

$\psi_x - \psi_{x,\text{end}} \quad 2\pi$

$\psi_y - \psi_{y,\text{end}} \quad 2\pi$

Curvature

$\frac{m}{R_c}$

$\frac{T_{(\text{end} \rightarrow S)}}{m}$

$50 \cdot T_{(\text{end} \rightarrow S)}$

$\frac{T_{(S \rightarrow 0)}}{m}$

$\frac{T_{(S \rightarrow 0)}}{m}$

$\frac{T_{1,6}}{m}$

$\frac{T_{2,6}}{m}$

$L = 85.56 \, m \, \phi = 2.25 \, \text{deg}$
TD1; L = 85.56 m \( \phi = 2.25 \text{ deg} \)

self effects, 1d CSR model
centroid properties of a gaussian bunch 1nC, Ipeak=5kA
no chirp

energy deviation (eV)

longitud. lattice coordinate (m)

longitud. bunch coordinate (m)

horizontal offset (m)

longitudinal field (V/m)
TD1; $L = 85.56$ m $\phi = 2.25$ deg

self effects, 1d CSR model
centroid properties of a gaussian bunch 1nC, $I_{\text{peak}}=5kA$
no chirp

1.99E6
1.395

normalized horizontal emittance (m)

longitud. lattice coordinate (m)

1.99E6
1.1E0

rms energy spread (eV)
2.3 TD20

without self effects

$L = 147.62 \, m \, \varphi = 6.68 \, \text{deg}$
TD20; L = 147.62 m φ = 6.68 deg

self effects, 1d CSR model
centroid properties of a gaussian bunch 1nC, Ipeak=5kA
no chirp
self effects, 1d CSR model
centroid properties of a gaussian bunch 1nC, \( I_{\text{peak}} = 5\, \text{kA} \)
no initial chirp

TD20; \( L = 147.62 \, \text{m} \)
\( \Phi = 6.68 \, \text{deg} \)
TD20; L = 147.62 m \( \varphi = 6.68 \) deg

self effects, 1d CSR model
centroid properties of a gaussian bunch 1nC, \( I_{\text{peak}} = 5kA \)
no chirp

<table>
<thead>
<tr>
<th>normalized horizontal emittance (m)</th>
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<table>
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<th>rms energy spread (eV)</th>
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3 Attempts to avoid/reduce longitudinal effects
3.1 Shielding

self effects, 1d CSR model
centroid properties of a gaussian bunch 1nC, Ipeak=5kA
no chirp

$h = \infty$

$h = 4 \text{ cm}$

$h = 2 \text{ cm}$
3.2 Magnet lengths and splitted arcs

self effects, 1d CSR model
centroid properties of a gaussian bunch 1nC, Ipeak=5kA
no chirp

- curvature
- avoid gaps
- avoid gaps, short & strong magnets

longitudinal field (V/m)
magnet lengths and splitted arcs

self effects, 1d CSR model
centroid properties of a gaussian bunch 1nC, Ipeak=5kA
no chirp
3.3 In principle

shielding by horizontal planes

circular motion: shielding parameter $x \ll 3$

\[
R_{\text{bend}} \approx 100 \text{ m} \\
\sigma \approx 12.5 \text{ } \mu\text{m}
\]

\[
h \ll 3^{\frac{3}{2}}R_{\text{bend}}\sigma^2 \approx 7.5 \text{ mm}
\]

\[
\text{but } 2R_{\text{pipe}} \approx 40 \text{ mm}
\]

transients: shielding by dispersion in waveguide

\[
\frac{L}{v_{\text{ph}}(\omega_{\text{rms}})} - \frac{L}{c} \gg \frac{\sigma}{c}
\]

\[
L \gg \frac{2}{\sigma} \left( \frac{c}{\omega_{\text{cutoff}}} \right)^2
\]

\[
L \gg \frac{2}{\pi^2} \frac{h^2}{\sigma}
\]

\[
h \approx 40 \text{ mm } \rightarrow L \gg 26 \text{ m}
\]

remark: kicker $R = 1 \text{ cm}$
shielding by horizontal obstacles

circular motion

\[ w \approx \frac{3}{2} \sqrt[3]{R_{\text{bend}} \sigma^2} \]

\[ L_o = \frac{3}{2} \sqrt{24 R_{\text{bend}}^2} \sigma \]

transient (exit, case ‘long magnet”, \( \beta=1 \))

\[ w \approx 1.7 \frac{3}{2} \sqrt[3]{R_{\text{bend}} \sigma^2} \]
steady state and transient longitudinal CSR field

steady state in arc \[ |E| \propto E_c = \frac{1}{\pi} \frac{Z_0 \hat{I}}{L_o} \]

asymptotic after arc \[ E \approx -\frac{1}{2\pi} \frac{Z_0 I(s)}{(0.5L_o + \Delta S)} \]
rough estimation for energy loss or energy spread

steady state in arc \[ |E| \propto E_c = \frac{1}{\pi} \frac{Z_0 \hat{I}}{L_o} \]

asymptotic after arc \[ E \approx -\frac{1}{2\pi} \frac{Z_0 I(s)}{\left(0.5L_o + \Delta S\right)} \]

\[ E = \frac{L_{\text{bend}} + \Delta S}{\int_0^{L_{\text{bend}} + \Delta S} E \, dS \propto E_c \left( L_{\text{bend}} + 0.5L_0 \ln\left(1 + 2\Delta S/L_o\right) \right) \] \text{ with } \[ L_o = \sqrt[3]{\frac{24R^2_{\text{bend}}}{\sigma}} \]

\[ \phi_{\text{bend}} = \frac{L_{\text{bend}}}{R_{\text{bend}}} \]

\[ \Delta S = \min \left\{ \sigma/(1 - \beta), \right. \]

shielding length, next element \[ } \]

\[ E \propto \frac{Z_0 \hat{I}}{2\pi} \left( \phi_{\text{bend}}^3 \sqrt[3]{\frac{R_{\text{bend}}}{3\sigma}} + \ln\left(1 + \frac{\Delta S}{\sqrt[3]{3R^2_{\text{bend}}\sigma}}\right) \right) \]
example: (CSRtrack – projected)
rms energy spread for bend + drift
($I_{\text{peak}} = 5 \, \text{kA, } \sigma = 12.5 \, \mu\text{m}$)

$E_{\text{rms}}/\text{MeV}$

$L_{\text{bend/m}} = 0.1, 0.3, 0.5, 1.0, 3.0, 5.0$

$\varphi = 1 \, \text{deg}$

$\varphi = 0.3 \, \text{deg}$

$\varphi = 3 \, \text{deg}$
example: (CSRtrack – projected)
L = 100 m $\varphi = 3.00$ deg
long weak magnet $\rightarrow$ many short strong magnets
example: (CSRtrack – projected)
dogleg with 2 magnets

\[ \phi = 1.5 \text{ deg} \]

\[ L_{\text{bend}} = 80 \text{ m} \]

\[ E_{\text{rms/MeV}} = 1.854, 1.631, 1.323, \boxed{1.233}, 1.305 \]
4 Realistic model for longitudinal phase space
+ collimator impedance model (from database)

4.1 1D simulation

(interval transverse phase space $\varepsilon_\gamma = 1\mu m$), working point "0"

- BC0
  - 130MeV
  - L0→1
  - 50 A
  - cavity wake
  - 1D-CSR

- BC1
  - 500MeV
  - L1→2
  - 850 A
  - cavity wake
  - 1D-CSR
L1→2
BC2 2GeV
main LINAC 17.5 GeV

850 A 5 kA

cavity wake 1D-CSR cavity wake 1D-CSR
space charge space charge in collimator
main LINAC

old design “2BC”

after BC2

cavity wakes + SC

new design “3BC” (V0)

reduced remaining chirp

cavity wakes + SC

100 modules

84 modules
4.2 Collimator

L = 180 m

5 kA

rms = 2.9 MeV

1D-CSR in collimator

1D-CSR + other impedances
collimator – impedance budget (Olga Zagorodnova)

**Impedance budget**

<table>
<thead>
<tr>
<th>Section</th>
<th>El type</th>
<th>Num</th>
<th>Loss (kV/m)</th>
<th>% Spread (kV/m)</th>
<th>% Peak (kV/m)</th>
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<td>CL</td>
<td>PUMCL</td>
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<td>7.66E-02</td>
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<td>1.32E+00</td>
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<td>8.09E+00</td>
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<tr>
<td></td>
<td>BPMCL</td>
<td>12</td>
<td>7.10E+03</td>
<td>31</td>
<td>1.11E+04</td>
</tr>
</tbody>
</table>

rms energy spread ≈ 11.2 MeV

pessimistic estimation
BPMCL = 12 cavity BPMs
KICK = 4 kickers (4x10m, r=1cm, κ=2E6 S/m)
CSRtrack calculation with distributed collimator impedance

XFEL collimation section, mode A
ideal gaussian bunch
“realistic model” (transversely ideal)

remark: kicker after collimator dog leg is “distributed”

normalized horizontal emittance (m)

longitud. lattice coordinate (m)

1.091 1.082
1.008

rms energy spread (eV)

CSR + distributed impedance
only CSR

before collimator 0.0 MeV
before collimator 2.0 MeV
after collimator 12.0 MeV
after collimator 15.2 MeV
only collimator 12 MeV
CSRtrack calculation with distributed collimator impedance

XFEL collimation section, mode A realistic bunch

\[ z = 132 \quad 142 \quad 152 \quad 162 \quad 172 \quad 200 \]

\[ x/\mu m \quad s/\mu m \quad x/\mu rad \quad \Delta E/\text{MeV} \]
1D-CSR, no other impedances

4.3 TD1 and TD20

- Collimator
- Collimator & TD1
- Collimator & TD20

**ε** = 1.008 µm *
* only colli.

**ε** = 1.27 µm **
** only TD1

**ε** = 1.27 µm **
** only TD1

Further compression

\[ \text{rms} = 16.6 \text{ MeV} \]

\[ \text{rms} = 15.2 \text{ MeV} \]

\[ \text{rms} = 22 \text{ MeV} \]
2 CSRtrack calculation for ideal gaussian bunch ($\varepsilon = 1 \mu m$)

- Collimator: emittance growth <1 %, energy spread 2.6 MeV
- TD1: emittance growth 40 %, energy spread 2.0 MeV
- TD20: emittance growth 41 %, energy spread 3.5 MeV, compression effects

3 Attempts to avoid/reduce longitudinal effects

- No shielding effects can be used
- Weak influence of magnet length on rms energy spread

4 Realistic model for longitudinal phase space + collimator impedance model

- After BC2: energy spread 2.9 MeV
- After collimator: energy spread 15.2 MeV, emittance growth $\approx 8 \%$
  - Significant (non-CSR collimator impedance) $\rightarrow$ 12 MeV rms spread
- After colli+TD1: energy spread 15.2 MeV, emittance growth 27 % **
- After colli+TD20: over-compression due to uncompensated r56

It is difficult to avoid CSR induced energy spread

Emittance growth due to centroid shift can be controlled / compensated