Heating of a beam dechirper for the XFEL

Frederik Quetscher, Erion Gjonaj
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- Dechirper Description
- Simulation Procedure
- Constant Beam Current Simulations
- Bunch Train Simulations Simulations
- Summary & Conclusion
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Dechirper Description

- Chamber geometry

Courtesy: A. Fisher, SLAC
Dechirper Description

- Dechirper geometry

![Dechirper Diagram]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth, $h$</td>
<td>0.5</td>
<td>mm</td>
</tr>
<tr>
<td>Gap, $t$</td>
<td>0.25</td>
<td>mm</td>
</tr>
<tr>
<td>Period, $p$</td>
<td>0.5</td>
<td>mm</td>
</tr>
<tr>
<td>Half aperture, $a$</td>
<td>0.7</td>
<td>mm</td>
</tr>
<tr>
<td>Half width, $w$</td>
<td>6</td>
<td>mm</td>
</tr>
<tr>
<td>Length, $L$</td>
<td>2</td>
<td>m</td>
</tr>
</tbody>
</table>

K. Bane, G. Stupakov, E. Gjonaj, Joule heating in a flat dechirper
Power loss estimates

\[ P = Q^2 k_{\text{loss}} f_{\text{rep}} \]

### SLAC
- \( Q = 300 \text{pC}, \ f_{\text{rep}} = 100 \text{kHz} \)
- \( l_z = 60 \mu\text{m} \)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>( P_{\text{heat,ana}} ) [W/m]</th>
<th>( P_{\text{heat,num}} ) [W/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two plates, ( a = 0.7 \text{ mm} )</td>
<td>5</td>
<td>21</td>
</tr>
<tr>
<td>Single plate, ( b = 0.25 \text{ mm} )</td>
<td>14</td>
<td>24</td>
</tr>
</tbody>
</table>

### The EXFEL
- \( Q = 500 \text{pC}, \ f_{\text{rep}} = 27 \text{kHz} \)
- \( \sigma_z = 25 \mu\text{m} \)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>( P_{\text{heat,ana}} ) [W/m]</th>
<th>( P_{\text{heat,num}} ) [W/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two plates, ( a = 0.7 \text{ mm} )</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>Single plate, ( b = 0.25 \text{ mm} )</td>
<td>10</td>
<td>18</td>
</tr>
</tbody>
</table>

Courtesy: I. Zagorodnov, DESY
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Simulation Procedure

- Simulation geometry

Material:
Pure aluminum

![Simulation Geometry Diagram](image)

- Material: Pure aluminum

- Dimensions:
  - 80 mm
  - 30 mm
  - 89 mm
  - B (6 mm)
Simulation Procedure

Configuration 1: Losses on top surface only

Configuration 2: Losses on side surface only

Configuration 3: Losses on bottom surface only

Configuration 4: Losses on all surfaces
Simulation Procedure

<table>
<thead>
<tr>
<th>Constant beam current</th>
<th>Train of bunches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source location</td>
<td>Only top (highest temperature)</td>
</tr>
<tr>
<td>(top, sides, bottom, all)</td>
<td>Source width (0.6…12 mm)</td>
</tr>
<tr>
<td>Source width (0.6…12 mm)</td>
<td>Only isothermal</td>
</tr>
<tr>
<td>Boundary conditions</td>
<td>Only isothermal</td>
</tr>
<tr>
<td>(isothermal, radiation)</td>
<td>Source width (0.6…12 mm)</td>
</tr>
<tr>
<td>Emissivity (0.05…1)</td>
<td>-</td>
</tr>
<tr>
<td>Power (5…25 W/m)</td>
<td>-</td>
</tr>
</tbody>
</table>

- No beam structure
- Constant loss power
- 10 trains / second (each train contains 2700 bunches with rate 4.5 MHz)
- Pulsed loss power
Simulation Procedure

▪ Transient heat distribution in metal
  - Heat conduction equation:

\[
\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = \dot{q}_V
\]

▪ Heat radiation at outer chamber-surface
  - Stefan–Boltzmann law:

\[
\dot{q}_A = \varepsilon \sigma (T^4 - T_0^4)
\]
  • Only radiation to ambient considered (no surface-to-surface radiation)
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Constant Beam Current Simulations

- Temperature distribution
  - Loss power: 15 W/m
  - Source width: 6 mm
  - Ambient temperature: 20 °C
  - Isothermal outer boundary
  - Very small temperature increase (~0.7 °C)
Constant Beam Current Simulations

- Influence of source width

![Graph showing temperature variation with source width](image)

- P=15 W/m, boundary=isothermal
Constant Beam Current Simulations

- Influence of boundary condition

P=15 W/m  boundary=radiation  source=top  emissivity=0.1
Constant Beam Current Simulations

- Influence of (outer) surface emissivity

![Graph showing temperature in °C vs emissivity]

- $P=15$ W/m
- boundary=radiation
- source=top
- width=0.6 mm
Constant Beam Current Simulations

- Variation with power

![Graph showing temperature variation with power]

- boundary=radiation     source=top     width=0.6 mm     emissivity=0.1

estimated SLAC parameters
estimated EXFEL parameters
Constant Beam Current Simulations

- **Isothermal boundary**
  - Very small temperature increase (< 1°C) for all considered parameters
  - Small influence of spatial loss distribution (source location and width)

- **Radiation boundary**
  - Temperature increases up to 25-90 °C (ambient temperature 20 °C)
  - For aluminum with $\varepsilon = 0.1$ (nominal case), $T = 57.7$ °C
  - Strong dependence on emissivity of the outer pipe surface
  - Temperature scales about linear with power
  - Small influence of spatial loss distribution (source location and width)
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Bunch Train Simulations

- Rectangular signal
- Period time:
  - 10 trains per second
  - $T_p = 0.1 \text{s}$
- Hold time
  - 2700 bunches at 4.5 MHz
  - $T_h = \frac{2700}{4.5 \text{ MHz}} = 0.6 \text{ ms}$
- Amplitude
  - $P_{mean} = 15 \text{ W/m}$
  - $\hat{P} = 2500 \text{ W/m}$
Bunch Train Simulations

- Transient heating for single pulse

- source=top
- width=0.6 mm
- P=15 W/m
- t=0…1.2 ms
- peak temperature=23.39 °C
Bunch Train Simulations

- Transient heating for single pulse

<table>
<thead>
<tr>
<th>Temperature in °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
</tr>
<tr>
<td>22.5</td>
</tr>
<tr>
<td>22</td>
</tr>
<tr>
<td>21.5</td>
</tr>
<tr>
<td>21</td>
</tr>
<tr>
<td>20.5</td>
</tr>
<tr>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time in ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>70</td>
</tr>
<tr>
<td>80</td>
</tr>
<tr>
<td>90</td>
</tr>
<tr>
<td>100</td>
</tr>
</tbody>
</table>

P=15 W/m  source=top  width=0.6 mm
Bunch Train Simulations

- Estimation for multiple pulses
  - Short hold time
    - Very small time step (<0.1 ms)
  - Long heating time for whole system (~1000 s)
    - Extremely long simulation
- Estimation of peak temperature
  - Constant current and pulsed beam have same steady state
  - In the steady state, single pulse only causes local temp. increase
  - Single pulse does not affect radiation at outer surface
  - Superposition of steady state temperature with temperature increase caused by single pulse
Bunch Train Simulations

- Peak temperature estimation for isothermal boundary

![Graph showing temperature vs. width with different lines for steady state, peak, and single pulse. Parameters: $P=15 \text{ W/m}$, boundary=isothermal, source=top.](image-url)
Bunch Train Simulations

- Peak temperature estimation for radiation boundary

\[ P = 15 \text{ W/m} \quad \text{boundary=radiation} \quad \text{source=top} \quad \text{emissivity}=0.1 \]
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Summary & Conclusion

- Single pulse loss causes very slight temperature increase (<4 °C)
- Temperature peaks decay fully between consecutive pulses
- Extremely small effect of single pulses on the radiating boundary
- Estimation of the full bunch train peak temperatures by superposition:
  - No cooling, $\varepsilon=0.1$, 15 W/m: 61.2 °C
  - No cooling, dark paint, 15 W/m: <35 °C
  - Cooling outer pipe to ambient temperature: 24.2 °C