Low slice emittance preservation during bunch compression

S. Bettoni
M. Aiba, B. Beutner, M. Pedrozzi, E. Prat, S. Reiche, T. Schietinger

simona.bettoni@psi.ch
Outline

1. Introduction

2. Experimental studies
   a. Measurement procedure
   b. Characterization of the core emittance increase
   c. Systematic checks

3. Simulations
   a. Simulations scenarios
   b. Characterization of the core emittance blow-up

4. Discussion

5. Conclusions
Introduction: in other machines

1 < Compression factor ≤ 5

Compression factor ~ 4.5

Compression factor = 5.5
**SwissFEL: FEL in Switzerland**

<table>
<thead>
<tr>
<th>Building key figures</th>
<th>Overall length</th>
<th>Soil movements</th>
<th>Casted concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>740 m</td>
<td>95'000 m³</td>
<td>21'000 m³ or 50'000 t</td>
</tr>
</tbody>
</table>

### Soft X-ray

- **Wavelength**: 1 - 70 Å
- **Pulse duration**: 3 – 20 fs
- **Maximum e- beam energy**: 5.8 GeV
- **e- beam charge**: 10 – 200 pC
- **Repetition rate**: 100 Hz
- **Slice emittance (expected performances)**: 200 nm (10 pC); 300 nm (200 pC)
- **Slice energy spread**: 250-350 keV
- **Saturation length**: < 50 m

[2 May 2013](#)

### Hard X-ray

- **Wavelength**: 0.7 - 7 Å
- **Pulse duration**: 5 – 20 fs
- **Maximum e- beam energy**: 5.8 GeV
- **e- beam charge**: 10 – 200 pC
- **Repetition rate**: 100 Hz
- **Slice emittance (expected performances)**: 200 nm (10 pC); 300 nm (200 pC)
- **Slice energy spread**: 250-350 keV
- **Saturation length**: < 50 m

### Dates

- **Construction started in 2013**
- **Commissioning planned in Feb 2016**
- **Aramis user operation planned in Dec 2017**
- **Athos user operation planned in 2021**

---

*Pictures courtesy of I. Widmer*
**SwissFEL Injector Test Facility (SITF)**

**Missions**

- Benchmark the simulation expectations and prove the feasibility of SwissFEL
- Develop and test components/systems and optimization procedures in SwissFEL

**Commissioning phases**

**Phase 1:** Electron source and diagnostics (2010)

**Phase 2:** Phase 1 + (some) S-band accelerations (2010-2011)

**Phase 3:** Machine in full configuration: all RF structures operational and bunch compressor installed (2012-2013)

**Phase 4:** Undulator installed for several weeks (2014)

**Phase 4+:** PSI gun installed (Oct 2014)

---

**Max e-beam charge** | 200 pC
---|---
**Laser longitudinal shape** | Flat-top / Gaussian
**Laser longitudinal length** | 9.9 ps FWHM / 3.7 ps RMS
**Laser transverse shape** | Cut Gaussian
**Laser transverse RMS** | 0.18 mm
**Max e-beam energy** | 266 MeV
**Repetition rate** | 100 Hz
Slice emittance measurement

- $35 \text{ m} < \beta_x < 40 \text{ m}, \beta_y < 10 \text{ m}$ at the PM
- Phase advance in $y \sim 270^\circ$
- Phase advance in $x$ from 0 to $\sim 180^\circ$

$\varepsilon (\text{nm})$

Core emittance

Mismatch

$$M = \frac{1}{2} (\beta_0 - 2\alpha_0 \alpha + \gamma_0 \beta)$$

simona.bettoni@psi.ch
The bunch compression factor, CF, is given by:

\[ CF = \frac{1}{1 - hR_{56}} \]

h: relative longitudinal chirp

\( R_{56} \): derivative of the path length on energy
The bunch compression factor, CF, is given by:

\[ CF = \frac{1}{1 - hR_{56}} \]

h: relative longitudinal chirp

\( R_{56} \): derivative of the path length on energy

Core emittance increases versus CF
Core emittance increase does not depend on the beam energy
Core emittance increase is smaller for smaller BC bending angles

\[ CF = \frac{1}{1 - hR_{56}} \]
Measurements: optics dependence

At constant CF (<10) we varied the optics along the bunch compressor.

- High sensitivity of the core emittance increase on the optics along BC.
- Smaller emittance blow-up for $\alpha \sim \alpha_0 + 0.3$, corresponding to the optics with the small $\beta_x$ at the two last dipoles.
Systematic checks

Before proceeding we answered to these questions:

- Are the measurements resolution limited?
- The slice energy spread increases with the compression factor: are spurious dispersion and chromaticity along the single slice increasing the core emittance?
- Tilt in the (s,x) plane: ~10% emittance blow-up

Slice emittance does not depend on the TDC voltage (V>3 MV)

Uncompressed and decompressed bunch have similar slice emittances
Simulations scenarios

1. **Astra**
   - 3D space charge forces
   - No CSR

2. **Astra**
   - 3D space charge forces
   - 1D CSR

**Elegant**
- 1D space charge forces
- 1D CSR

**CSRTrack**
- 3D space charge forces
- 3D CSR

---

*User’s Manual for elegant*

Program Version 28.1.0
Advanced Photon Source
Michael Borland

July 24, 2015

---

*ASTRA*

Author: Klaus Floettmann
DESY

A Space Charge Tracking Algorithm
Version 3.0
October 2011
(Update April 2014)

---

simona.bettoni@psi.ch
1D versus 3D

- Not observed core emittance increase for the option 1
- Observed core emittance increase versus CF using 3D version of CSRTrack
- In the following vertical emittance equivalent to horizontal uncompressed and CF = 15

simona.bettoni@psi.ch
Dependence on BC angle

Simulated at constant CF the dependency of the slice emittance versus the BC bending angle.

Core emittance increase is smaller for a smaller BC bending angle.
Dependence on beam energy

Simulated at constant CF the dependency of the slice emittance versus the beam energy

Core emittance increase does not dramatically depend on the beam energy
Dependence on optics along BC

Varied the optics along BC at constant compression factor

**SIMULATIONS**

- Vertical
- $\alpha = \alpha_0 - 0.25$
- $\alpha = \alpha_0 + 0.10$
- $\alpha = \alpha_0 + 0.25$
- $\alpha = \alpha_0 + 0.40$
- $\alpha = \alpha_0 + 0.50$

**MEASUREMENTS**

Qualitative agreement

simona.bettoni@psi.ch
We measured less emittance blow-up starting from a larger slice emittance uncompressed bunch.

We simulated bunches at the entrance of the bunch compressor with different initial core emittances.

The larger the initial slice emittance, the smaller the relative core emittance blow-up is.
Discussion

- The simulations using the 1D model of CSRTTrack or Elegant do not show any core emittance increase with the bunch compression.

- Using the 3D model of CSRTTrack a core emittance increase is observed:
  - The dependency of the core emittance increase on the different beam setup qualitatively reproduces the behavior observed at SITF, and in particular:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Emittance growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression factor</td>
<td>Linear</td>
</tr>
<tr>
<td>Beam energy</td>
<td>Independent</td>
</tr>
<tr>
<td>Chicane bending angle</td>
<td>Smaller for smaller bending angle</td>
</tr>
<tr>
<td>Optics ($\beta_x$ at the end of BC)</td>
<td>Smaller for smaller $\beta_x$ at the last dipoles</td>
</tr>
</tbody>
</table>

- Measurements and simulations indicate CSR and 3D effects as the responsible for the observed core emittance increase.
By doing a full optimization we have achieved the following emittances for the 200 pC bunch charge:

<table>
<thead>
<tr>
<th>Slice emittance (nm)</th>
<th>Uncompressed</th>
<th>Compressed (CF = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>199±15*</td>
<td>199±27*</td>
</tr>
</tbody>
</table>

These values fulfill the SwissFEL requirements.
Conclusions

- Measured core emittance growth during compression at SITF, and it is:
  - Proportional versus the bunch compression factor (constant $R_{56}$)
  - Smaller for smaller chicane bending angle
  - Independent on the beam energy
  - Strongly dependent on the optics along the bunch compressor
  - Strongly dependent on the optics upstream the bunch compressor

- Using 3D model including CSR reproduced qualitatively all the measured dependencies

- Excluded some possible sources for the core emittance blow-up:
  - Resolution limit of the measurement
  - Slice energy spread via chromaticity or spurious dispersion
  - Horizontal tilt along the bunch

- CSR and 3D effects considered to be the main responsible for the observed phenomenon

- Measured ~200 nm slice emittance along a small fraction (flatness of the mismatch) and less than 300 nm for the majority of the bunch length

simona.bettoni@psi.ch
Acknowledgment

We would like to thank all the groups involved in the SwissFEL Test Facility and you for the attention.