Investigations of the longitudinal phase space at a photo injector for the X-FEL
Contents

• Introduction
• PITZ
• Longitudinal phase space of a photoinjector
• Devices of longitudinal phase space measurement at PITZ
• Measurements and simulations of longitudinal phase space at PITZ
• Summary and outlook
Contents

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• Measurements and simulations of longitudinal phase space at PITZ
• Summery and outlook
Introduction

RF gun  Diagnostics  Accelerating Structures  Collimator  Undulators  Bypass  FEL Diagnostics
Laser  Bunch Compressor  Bunch Compressor  1000 MeV
5 MeV  127 MeV  450 MeV

260 m
gun: - beam of a few MeV
   -> space charge forces play a major role on emittance growth
   -> the initial electron bunch length: 20ps -> peak current: about 50 A

bunch compressor: - energy is high enough to neglect space charge forces
   - bunch compression increases peak current
   - optimum compression: only for a linear long. phase space
   -> 3rd harmonic
   -> knowledge of longitudinal phase space is of particular interest
Introduction

**RF gun**

- beam of a few MeV
  - space charge forces play a major role on emittance growth
  - the initial electron bunch length: 20ps -> peak current: about 50 A

**Bunch compressor:**
- energy is high enough to neglect space charge forces
- bunch compression increases peak current
- optimum compression: only for a linear long. phase space
  - 3\textsuperscript{rd} harmonic
- knowledge of longitudinal phase space is of particular interest

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**Electron Gun**

→ crucial element of a Free Electron Laser!
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PITZ
PITZ
PITZ

PITZ1 setup

PITZ2 setup
Setup of PITZ

GUN cavity

BOOSTER cavity

Version 17.12.2007
Setup of PITZ

Charge measurement:
- Faraday cup
- ICT
Setup of PITZ

beam size measurement:
- view screens combined with CCD Cameras
- wire scanners
- BPMs
Setup of PITZ

beam size measurement:
- view screens combined with CCD Cameras
- wire scanners
- BPMs

transverse emittance measurement:
- EMSYs: slit scan method
- tomography module
Setup of PITZ

- RF-deflector and tomography module
- dipole, slit and quadrupole
- quadrupole, aerogel and streak camera

slice emittance measurement:

GUN cavity

BOOSTER cavity
Setup of PITZ

**longitudinal phase space measurement:**
- Beam momentum distribution
- Longitudinal distribution
- Longitudinal phase space
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Longitudinal phase space of a photoinjector

- 1 nC
- 40 MeV/m
- 0.5m after the cathode
- laser:
  - long.: flat-top
    - FWHM: 20 ps
    - risetime: 7 ps
  - transv.: flat-top
    - Ø: 2 mm

Projections of longitudinal phase space:
- momentum distribution
- longitudinal distribution

Area of longitudinal phase space:
Emittance $\varepsilon_z$

$$\varepsilon_z = \sqrt{\langle (\Delta p_z)^2 \rangle \langle (\Delta z)^2 \rangle - \langle \Delta p_z \Delta z \rangle^2}$$
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• **Beam momentum distribution:** dipole magnet and a view screen
• **Bunch length:** - aerogel or OTR as radiators and a streak camera
  - RF deflector
• **Longitudinal phase space:** - dipole magnet, radiator and streak camera
  - RF deflector and dipole magnet
measurement of longitudinal distribution using streak camera

TV-camera -> tilted quartz -> aerogel -> 30 m optical transmission line to streak camera

- aerogel
- tilted quartz
- TV-camera
- OTR
- YAG

empty tube
measurement of longitudinal distribution using streak camera

Silica aerogel
n = 1.008 - 1.05
measurement of longitudinal distribution using streak camera

electron bunch is transformed into a light pulse with approximately the same temporal distribution by the Cherenkov effect

Silica aerogel
n = 1.008 – 1.05
Cherenkov radiator
measurement of longitudinal distribution using streak camera

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n = 1.008 – 1.05
Cherenkov radiator
- electron bunch is transformed into a light pulse with approximately the same temporal distribution by the Cherenkov effect
- light transport
- streak camera measurement

Silica aerogel
\[ n = 1.008 - 1.05 \]
Cherenkov radiator
measurement of longitudinal distribution using streak camera

- electron bunch is transformed into a light pulse with approximately the same temporal distribution by the Cherenkov effect
- light transport
- streak camera measurement
  - advantage compared to RF-deflector: measurement at several positions along the beamline
  - disadvantage compared to RF-deflector: poor resolution

Silica aerogel

\[ n = 1.008 - 1.05 \]

Cherenkov radiator
measurement of longitudinal distribution using streak camera
measurement of longitudinal distribution using streak camera

The amount of light produced by silica aerogel is several order of magnitude higher than the one of an OTR-screen.
The amount of light produced by silica aerogel is several order of magnitude higher than the one of an OTR-screen.
momentum measurement
\begin{align*}
\begin{pmatrix}
y \\
y' \\
x \\
x' \\
t \\
\Delta p/p \\
\end{pmatrix}
&= 
\begin{pmatrix}
R_{11} & R_{12} & 0 & 0 & 0 & R_{16} \\
R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\
0 & 0 & R_{33} & R_{34} & 0 & 0 \\
0 & 0 & R_{43} & R_{44} & 0 & 0 \\
R_{51} & R_{52} & 0 & 0 & 1 & R_{56} \\
0 & 0 & 0 & 0 & 0 & 1 \\
\end{pmatrix}
\begin{pmatrix}
y_0 \\
y'_0 \\
x_0 \\
x'_0 \\
t_0 \\
\Delta p_0/p_0 \\
\end{pmatrix}
\end{align*}
\[
p = \frac{e}{\alpha} \int B_{\text{dipole}}(l) \, dl
\]
\[
p_c = |e B_{\text{dipole}}(l)_{\text{eff}} / \alpha |
\]
\[
\Delta p = p_c \frac{\Delta y}{R_{16}}
\]
\[
R_{16} = \left( \frac{l}{\text{eff}} / \alpha + L_{\text{DA}} \tan \beta_{\text{out}} \right) (1 - \cos \alpha) + L_{\text{DA}} \sin \alpha \cdot L_{\text{DA}}
\]
momentum measurement

<table>
<thead>
<tr>
<th></th>
<th>Disp1.Scr1</th>
<th>Disp2.Scr1/2</th>
<th>Disp3.Scr1</th>
<th>spare dipole</th>
</tr>
</thead>
<tbody>
<tr>
<td>deflection angle $\alpha$</td>
<td>60°</td>
<td>180°</td>
<td>60°</td>
<td>60°</td>
</tr>
<tr>
<td>$\beta_{\text{in}}$</td>
<td>11° -&gt; 0°</td>
<td>0°</td>
<td>to be defined</td>
<td>31.7°</td>
</tr>
<tr>
<td>$\beta_{\text{out}}$</td>
<td>11° -&gt; 25°</td>
<td>0°</td>
<td>to be defined</td>
<td>2°</td>
</tr>
<tr>
<td>$r$ (mm)</td>
<td>~105 -&gt; 150</td>
<td>300</td>
<td>to be defined</td>
<td>~350</td>
</tr>
<tr>
<td>$L_{\text{DA}}$ (mm)</td>
<td>568.4 -&gt;~525</td>
<td>1411.5 / 1958.5</td>
<td>to be defined</td>
<td>507.6</td>
</tr>
<tr>
<td>$l_{\text{eff}}$ (mm)</td>
<td>141.2 -&gt;~160</td>
<td>941.65</td>
<td>to be defined</td>
<td>365.5</td>
</tr>
<tr>
<td>gap width (mm)</td>
<td>20 -&gt; 35</td>
<td>40</td>
<td>43</td>
<td>50</td>
</tr>
</tbody>
</table>
Measurement of longitudinal phase space

- Light pulse equivalent to temporal distribution of the electron bunch (produced by a radiator)
- Spatial distribution of the momenta in the bunch
- Measurement of longitudinal phase space

\[ p = \frac{e}{\alpha} \int B_{\text{dipole}}(l) \, dl \]

- Momentum measurement
- CCD-camera
- Light distribution equivalent to temporal and spatial distribution of the electron bunch behind the dipole (produced by a radiator)
- Measurement of longitudinal phase space
- Measurement of bunch length
- Light pulse equivalent to temporal distribution of the electron bunch (produced by a radiator)
- Measurement of optical transmission line transported to streak camera
spectrometer magnet HEDA1

deflecting angle: 180°
deflecting radius: 300 mm

\[ L_{\text{eff}} = \frac{1}{B_0} \int B_x \, dz \]

\[ L_{\text{eff}} = 941.6 \text{ mm} \]

geometrical length: \( L_{\text{geom}} = 942.5 \text{ mm} \)
spectrometer magnet HEDA1

\[ M_s = \begin{pmatrix} 1 & L_1 + L_2 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

\[ M_D = \begin{pmatrix} -1 & -L_1 - L_2 & 2\rho \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

deflecting angle: 180°
deflecting radius: 300 mm

\[ L_{\text{eff}} = \frac{1}{B_0} \int B_x \, dz \]

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spectrometer magnet HEDDA1

\[
M_s = \begin{pmatrix}
1 & L_1 + L_2 & 0 \\
0 & -1 & 0 \\
0 & 0 & 1 \\
\end{pmatrix}
\]

vertical distribution

\[
y = R_{11} y_0 + R_{12} y'_0 + R_{16} \Delta p_0 / p_0
\]

\[
\Rightarrow R_{16} dp_0 / p_0 \gg R_{11} y_0 + R_{12} y'_0
\]
spectrometer magnet HEDA1

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Vertical distribution

\[ y = R_{11} y_0 + R_{12} y'_0 + R_{16} \Delta p_0 / p_0 \]

\[ \Rightarrow R_{16} \frac{dp_0}{p_0} \gg R_{11} y_0 + R_{12} y'_0 \]
spectrometer magnet HEDAl1

\[
M_s = \begin{pmatrix}
1 & L_1 + L_2 & 0 \\
0 & -1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

vertical distribution

\[
y = R_{11} y_0 + R_{12} y'_0 + R_{16} \Delta p_0 / p_0
\]

\[
\Rightarrow R_{16} \frac{dp_0}{p_0} \gg R_{11} y_0 + R_{12} y'_0
\]

correction by deconvolution

\[
M_D = \begin{pmatrix}
-1 - L_1 & L_2 \\
0 & -1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

Intensity in relative units

without focussing

focus on \( S_2 \)
spectrometer magnet HEDA1

\[ M_s = \begin{pmatrix} 1 & L_1 + L_2 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

vertical distribution:
\[ y = R_{11} y_0 + R_{12} y'_0 + R_{16} \Delta p_0 / p_0 \]
\[ \Rightarrow R_{16} \Delta p_0 / p_0 \gg R_{11} y_0 + R_{12} y'_0 \]

temporal distribution:
\[ t = R_{51} y_0 + R_{52} y'_0 + t_0 + R_{56} \Delta p_0 / p_0 \]

correction by deconvolution
spectrometer magnet HEDA1

\[ M_S = \begin{pmatrix} 1 & L_1 + L_2 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

vertical distribution
\[ y = R_{11} y_0 + R_{12} y'_0 + R_{16} \Delta p_0 / p_0 \]
\[ \Rightarrow R_{16} \frac{d p_0}{p_0} \gg R_{11} y_0 + R_{12} y'_0 \]

temporal distribution:
\[ t = R_{51} y_0 + R_{52} y'_0 + t_0 + R_{56} \Delta p_0 / p_0 \]

correction by deconvolution
The spectrometer magnet configuration is shown with labels for L1, L2, S1, and S2. The equations for the vertical and temporal distributions are:

**Vertical distribution**: 
\[ y = R_{11} y_0 + R_{12} y'_0 + R_{16} \Delta p_0 / p_0 \]

**Temporal distribution**: 
\[ t = R_{51} y_0 + R_{52} y'_0 + t_0 + R_{56} \Delta p_0 / p_0 \]

These equations are used to focus on S2 and there is a mention of a correction by deconvolution.
spectrometer magnet HEDA1

vertical distribution
\[ y = R_{11} y_0 + R_{12} y'_0 + R_{16} \Delta p_0 / p_0 \]
\[ \Rightarrow R_{16} \Delta p_0 / p_0 \gg R_{11} y_0 + R_{12} y'_0 \]

temporal distribution:
\[ t = R_{51} y_0 + R_{52} y'_0 + t_0 + R_{56} \Delta p_0 / p_0 \]

correction by deconvolution
correction by shearing the image

\[
M_s = \begin{pmatrix}
1 & L_1 + L_2 & 0 \\
0 & -1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]
spectrometer magnet HEDA1

- **Q1**
- **Q2**
- **L1**
- **L2**
- **S1**
- **S2**
- **D**
- **Slit**
- **Booster**
- **Gun**

---

**Silica aerogel**

- $n = 1.05$
- Thickness: 2 mm

- $n = 1.05$
- Thickness: 5 mm
the optical system is the major limitation of resolution,

a system consisting of reflective optics is under development
Influence of the streak camera (C5680)

resolution is limited by:

- streak camera slit width and space charge
  - slit width of 100 μm: $\delta t = 1.75$ ps
  - correction: deconvolution (signal without RF-field)
- RF and laser jitter: 100 pulses: $\delta t = 0.99$ ps
- diff. momentum of photo electrons for diff. wavelength
  - with 10 nm: $\delta t = 0.16$ ps, without filter: $\delta t = 0.55$ ps
Influence of the streak camera (C5680)

Background of the streak camera with closed shutter

horizontal sensitivity

curvature-effect
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momentum measurement

- Gradient: ~40MV/m
- mean momenta are similar for different charge
- highest mean momentum: 4.8 MeV/c
  lunch phase: 35°
momentum measurement

- Gradient: $\sim$40MV/m
- Mean momenta are similar for different charge
- Highest mean momentum: 4.8 MeV/c
  
  Lunch phase: 35°
momentum gain
influence of charge momentum measurement

- Gradient: ~40MV/m
- mean momenta are similar for different charge
- highest mean momentum: 4.8 MeV/c
  lunch phase: 35°
- minimum momentum spread:
  30 pC: 5 keV/c at lunch phase: 35°
  1 nC: 13 keV/c at lunch phase: 30°
- for high phase the momentum distribution is cut by the screen
- at 1nC space charge effects increase momentum spread
- at 30 pC phase of maximum momentum gain is equal to phase of minimum momentum spread
  -> space charge forces small
longitudinal phase space simulations

- Energy gain in the gun
- Development of the momentum in the gun
- Long. laser profile
- Long. laser profile

Graphs show the changes in energy and momentum over time, with a focus on the laser profile.
longitudinal phase space simulations

40MV/m  
rise time = 7ps

60MV/m  
rise time = 7ps

60MV/m  
rise time = 2ps
longitudinal phase space simulations

Energy gain in the gun

Development of the momentum in the gun

40MV/m
rise time = 7ps

60MV/m
rise time = 7ps

60MV/m
rise time = 2ps

p (MeV/c) vs. z (mm)
longitudinal phase space simulations

- **40MV/m**
  - Rise time = 7ps

- **60MV/m**
  - Rise time = 7ps

- **60MV/m**
  - Rise time = 2ps

**Graphs:**

1. Left: Energy gain in the gun with different slopes corresponding to different field strengths.
2. Middle: Development of the momentum in the gun, showing a clear increase with distance for both field strengths.
3. Right: Further plots focusing on momentum changes with distance, highlighting differences in rise times.

**Axes:**

- **z (mm)**
- **p (MeV/c)**
longitudinal phase space simulations

40MV/m  
rise time = 7ps

60MV/m  
rise time = 7ps

60MV/m  
rise time = 2ps
longitudinal phase space simulations

40MV/m
rise time = 7ps

60MV/m
rise time = 7ps

60MV/m
rise time = 2ps
longitudinal phase space simulations

40MV/m
rise time = 7ps

60MV/m
rise time = 7ps

60MV/m
rise time = 2ps
longitudinal phase space simulations

40MV/m  
rise time = 7ps

60MV/m  
rise time = 7ps

60MV/m  
rise time = 2ps
longitudinal phase space simulations

40MV/m  
rise time = 7ps

60MV/m  
rise time = 7ps

60MV/m  
rise time = 2ps
longitudinal phase space simulations

40MV/m
rise time = 7ps

60MV/m
rise time = 7ps

60MV/m
rise time = 2ps
longitudinal phase space simulations

40MV/m
rise time = 7ps

60MV/m
rise time = 7ps

60MV/m
rise time = 2ps
longitudinal phase space simulations

- Energy gain in the gun:
  - 40MV/m, rise time = 7ps
  - 60MV/m, rise time = 7ps
  - 60MV/m, rise time = 2ps

- Development of the momentum in the gun:

longitudinal phase space simulations

40MV/m
rise time = 7ps

60MV/m
rise time = 7ps

60MV/m
rise time = 2ps
longitudinal phase space simulations

40MV/m
rise time = 7ps

60MV/m
rise time = 7ps

60MV/m
rise time = 2ps
longitudinal phase space simulations

- 40MV/m
  - rise time = 7ps
- 60MV/m
  - rise time = 7ps
  - rise time = 2ps
longitudinal phase space simulations

40MV/m
rise time = 7ps

60MV/m
rise time = 7ps

60MV/m
rise time = 2ps
longitudinal phase space simulations

- Beam density distribution for:
  - 1 nC
  - transv. laser diameter = 2mm
  - Flat-top laser
  - opt. gun phase

40MV/m rise time = 7ps

60MV/m rise time = 7ps

60MV/m rise time = 2ps
simulations for optimum phase, 1 nC, flat-top laser distribution at different positions (~40MV/m)
simulations for optimum phase, 30 pC, flat-top laser distribution at different positions (~40MV/m)

0.31 m
0.66 m
1.01 m
1.36 m
1.71 m
2.05 m
2.40 m
2.75 m
3.10 m
3.45 m
optimum phase, 30 pC, flat-top laser distribution

- for optimum phase accelerating field reaches its maximum during emission time this means electrons emitted in the middle of the bunch receive the highest acceleration due to the field
- due to space charge effects the particles in the beginning of the bunch become accelerated and the ones in the end decelerated
optimum phase, 1 nC, flat-top laser distribution

<table>
<thead>
<tr>
<th>measured</th>
<th>Astra</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWHM / ps</td>
<td>StSe: 25.2 +/- 1.3; DA: 28.5 +/- 3.3</td>
</tr>
<tr>
<td>long. emittance / $\pi$ keV mm</td>
<td>32.7 +/- 6.8</td>
</tr>
<tr>
<td>momentum / MeV</td>
<td>5.19 +/- 0.06</td>
</tr>
<tr>
<td>momentum spread / keV</td>
<td>46.0 +/- 5.1</td>
</tr>
<tr>
<td></td>
<td>25, 26, 6, 5, 19, 42, 2</td>
</tr>
</tbody>
</table>
momentum measurement after the booster cavity

(mean momentum)

(mean momentum (MeV/c))

(momentum spread)

(momentum spread (keV/c))
bunch length after the booster cavity

Bunch length and arrival time as a function of the booster phase

- Beam density distribution for:
  - 800 pC
  - transv. laser diameter = 1.5mm
  - Flat-top laser
  - opt. Gun phase

15.9 MeV/c
momentum measurement after the booster cavity

• Beam density distribution for:
  • 1 nC
  • transv. laser diameter = 2mm
  • Flat-top laser
  • opt. Gun phase

• Beam density distribution for:
  • 1 nC
  • transv. laser diameter = 1.5mm
  • Flat-top laser
  • opt. gun and booster phase
momentum measurement after the booster cavity

- Beam density distribution for:
  - 1 nC
  - transv. laser diameter = 1.5mm
  - Flat-top laser
  - opt. gun and booster phase

![Graph showing peak current vs laser diameter and current vs time]
The PITZ setup and its diagnostics was presented

A method to measure the longitudinal phase space and its projection used at PITZ was presented

Resolution of this method was analysed, the major limitation of the temporal resolution is the optical transmission, an replacement by reflective optics is ongoing

Examples of longitudinal phase space, bunch length and momentum measurement at PITZ and simulations were presented
Thanks for your attention