Electron bunch diagnostic at PITZ

Techniques and their limitations

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Phase space characterization at PITZ

> **Transverse projected emittance:**
  - slit scan method (main method at PITZ)
  - quad(s) scan
  - transverse phase space tomography

> **Transverse slice emittance:**
  - booster off-crest + spectrometer
  - upcoming: RF deflector

> **Longitudinal emittance:**
  - bunch length measurements
  - momentum spread measurements
  - longitudinal phase space reconstruction
Electron beam characterization with PITZ2

Scheme of the PITZ2 setup:

- **bunch charge**: Faraday Cups, ICTs
- **beam size**: YAG screens
- **momentum and momentum spread**: spectrometer
- **bunch length / longitudinal phase space**: aerogel / quartz + streak camera, later also RF deflector (TDS)
- **emittance** (thermal, projected, slice) with EMSYs, quads, tomographic section (PST)
- ...
Properties of the photo cathode laser

> **Transverse profile:** ~ flat top

<table>
<thead>
<tr>
<th>BSA=1.2mm (1nC)</th>
<th>BSA=0.5mm (0.1nC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_x=0.30$ mm</td>
<td>$\sigma_x=0.13$ mm</td>
</tr>
<tr>
<td>$\sigma_y=0.29$ mm</td>
<td>$\sigma_y=0.12$ mm</td>
</tr>
</tbody>
</table>

> **Longitudinal distribution:**
20…25 ps flat-top, 2-3 ps rise / fall times

... or Gaussian shape (few ps)

**Pulse train structure:**
10 Hz, 800µs, 1 MHz
Transverse emittance measurements: principle

➢ Method:
   ▪ slit scan technique (space charge dominated beam)
   ▪ using the Emittance Measurement System consisting of horizontal / vertical actuators with YAG / OTR screens and slits (50 µm / 10 µm)
   ▪ as conservative as possible: 100% rms emittance

➢ Procedure:
   ▪ beam size $\sqrt{\sigma_x^2}$ is measured @ slit position using screen
   ▪ beam local divergence $\sqrt{\sigma_x^2}$ is estimated from beamlet sizes @ observation screen (12 bit camera)

scaled emittance $\varepsilon_{scaled}^n = \frac{\sigma_x}{\sqrt{\langle x^2 \rangle}} \beta \gamma \sqrt{\langle x^2 \rangle \cdot \langle x'^2 \rangle - \langle xx' \rangle^2}$

scale factor ($>1$) corrects for underestimation of the beamlet size due to low intensity losses
### Transverse emittance measurements: examples

<table>
<thead>
<tr>
<th>Qbunch</th>
<th>Beam at EMSY1</th>
<th>Horizontal phase space</th>
<th>Vertical phase space</th>
<th>( \phi_{\text{gun}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XY-Image</td>
<td>( \sigma_x/\sigma_y )</td>
<td>( \varepsilon_x )</td>
<td>( \varepsilon_y )</td>
</tr>
<tr>
<td>Las.XYrms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 nC</td>
<td><img src="image1.png" alt="Image" /></td>
<td>0.323mm (0.347\text{mm} )</td>
<td>1.209 (\text{mm mrad})</td>
<td>1.296 (\text{mm mrad})</td>
</tr>
<tr>
<td>0.38 mm</td>
<td><img src="image2.png" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 nC</td>
<td><img src="image3.png" alt="Image" /></td>
<td>0.399mm (0.328\text{mm} )</td>
<td>0.766 (\text{mm mrad})</td>
<td>0.653 (\text{mm mrad})</td>
</tr>
<tr>
<td>0.30 mm</td>
<td><img src="image4.png" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25 nC</td>
<td><img src="image5.png" alt="Image" /></td>
<td>0.201mm (0.129\text{mm} )</td>
<td>0.350 (\text{mm mrad})</td>
<td>0.291 (\text{mm mrad})</td>
</tr>
<tr>
<td>0.18 mm</td>
<td><img src="image6.png" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1 nC</td>
<td><img src="image7.png" alt="Image" /></td>
<td>0.197mm (0.090\text{mm} )</td>
<td>0.282 (\text{mm mrad})</td>
<td>0.157 (\text{mm mrad})</td>
</tr>
<tr>
<td>0.12 mm</td>
<td><img src="image8.png" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.02 nC</td>
<td><img src="image9.png" alt="Image" /></td>
<td>0.066mm (0.083\text{mm} )</td>
<td>0.111 (\text{mm mrad})</td>
<td>0.129 (\text{mm mrad})</td>
</tr>
<tr>
<td>0.08 mm</td>
<td><img src="image10.png" alt="Image" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Zoomed
Transverse emittance measurements: results

Results:
- Beam emittance has been optimized for a wide range of bunch charges (20pC; 100pC; 250pC; 1nC; 2nC)
- emittance ~ linearly on the bunch charge
- rather good agreement between measured and simulated emittance values

Limitations:
- not a single-shot method
- for low charges: many bunches integrated
- visibility of tails is problematic, especially for low charges
Transverse slice emittance measurements

> Method:
- introduce bunch energy chirp by off-crest operation of the booster cavity
- quad scan in dispersive section

> Results:
- horizontal slice emittance can be measured with a resolution of 1.5 ps (50° off-crest)
- for charges down to 110 pC

> Limitation:
- charge limit set by interplay between resolution (defined by booster phases) and signal detection at far off-crest phases
Phase space tomography: setup

> Method:
  - use a sequence of quadrupole magnets and view screens to simultaneously measure the x-x’ and y-y’ planes of the electron beam phase space (single shot method)
  - also for small charges (with certain limitations)
  - independent and additional emittance measurement device

> Realization:
  - matching section followed by three identical FODO cells (phase advance 45°) separated by four screens
Phase space tomography: procedure

- Procedure:
  - phase space rotation in FODO lattice (complete 180° rotation)
  - get beam profile at equidistant phase advances / rotation angles, create projections
  - calculate transfer matrices / description of phase space transformations
  - reconstruction with MENT algorithm
Phase space tomography: results

Results:

- reconstructed emittances comparable to results from EMSY2 and EMSY3 measurements (stations before and after tomographic sections)

- Implementation of space charge in the reconstructions results in smaller emittance
Phase space tomography: limitations

- Limitations:
  - a positioning accuracy of 100 µm/ 10 mrad is required to keep the systematic uncertainty of the measured emittance below 10 %
  - matching of space charge dominated beam is already a simulation challenge; errors in emittance can easily go up to ~30%
  - at PITZ unpredictable emittance increase due to matching with the current lattice (which is not dense enough to get useful information for trajectory optimization)
  - resolution limit of system YAG screen/ magnification lens/ camera is currently 120 µm (minimum RMS beam size)
    → results in emittance limit (small beam size = small emittance since beta=1)
    → indirect lower charge limit (~100pC)
Longitudinal phase space measurements (1)

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

- area of longitudinal phase space: longitudinal emittance
  \[ \varepsilon_z = \sqrt{\langle (\Delta p_z)^2 \rangle \langle (\Delta z)^2 \rangle - \langle \Delta p_z \Delta z \rangle^2} \]

- Method: radiator + streak camera
  - electrons emit Cherenkov photons in a radiator
  - Cherenkov light is analyzed by a streak camera

Simulation (5 MeV)

Light production of silica aerogel compared to OTR

Time resolution of silica aerogel
Longitudinal phase space measurements (1)

Results:

- longitudinal phase space measurements in the low energy dispersive section (~5 MeV)

<table>
<thead>
<tr>
<th>measured</th>
<th>Astra</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWHM / ps</td>
<td>SS: 25.2 +/- 1.3; DA: 28.5 +/- 3.3</td>
</tr>
<tr>
<td>long. emittance / p 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>
</tbody>
</table>
Longitudinal phase space measurements (1)

> Limitations:

- long optical transmission line from the radiator to the streak camera (~35m) limits the resolution of the system
- a system consisting of reflective optics can improve the resolution (but was never realized)
- complicated and time consuming alignment procedure of the optical transmission line
- transmission reduces with time due to radiation damages of lenses by high radiation level of the booster cavity
**Method**: imaging of longitudinal phase space with RF deflector

- time scale from transverse deflecting system (TDS)
- energy scale from spectrometer

**Measurement principle:**

**Simulation results:**
> Limitations:

- TDS temporal resolution for different beam size in the TDS

\[
\sigma_t = \frac{\varepsilon_y}{\sigma_y \cdot \sin(\Delta\psi_y)} \cdot \frac{p_0 c}{eV_0 k} \cdot \frac{1}{c}
\]

- TDS induced momentum spread for different beam size in the TDS

\[
\sigma_\delta = \frac{eV_0 k}{p_0 c} \cdot \sigma_y
\]

- Interplay between time resolution and momentum resolution:
  \(~100\text{fs} @ 20\text{ keV/c}\)

- Resolution limit for low charges to be studied

We are looking forward to the commissioning of the TDS at PITZ ☺
Method: longitudinal phase space tomography

- phase space rotation using booster cavity
- reconstruction using tomographic techniques

Longitudinal phase space and momentum distributions (simulation):
Results:

- tomographic reconstruction of the longitudinal phase space upstream the booster

Limitations:

- for small charges: momentum distribution is noisy, even if momentum resolution is better (limit of spectrometers)
- high charge limit defined by space charge
Acknowledgements

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- Transverse emittance evaluation
  M.Krasilnikov, G.Vashchenko (PhD 2012)

- Transverse slice emittance evaluation
  Y.Ivanisenko (PhD 2012)

- Phase space tomography
  G. Asova (PhD 2012), G.Kourkafas (PhD in progress)

- Longitudinal phase space characterization
  J.Roensch (PhD 2009), D.Malyutin (PhD in progress)