Transverse emittance measurements at PITZ

Transverse emittance measurements of space charge dominated beams at the Photo Injector Test facility at DESY, Zeuthen site (PITZ)

Mikhail Krasilnikov
Topical Workshop on “Emittance Measurements for Light Sources and FELs”, ALBA Synchrotron January 29 - 30, 2018

Outline:
• PITZ facility
• Beam dynamics simulations
• Procedures to measure transverse emittance
• Emittance measurements of space charge dominated beams
• Emittance measurements at PITZ
PITZ facility

Photo Injector test facility for high brightness electron source optimization
Photo Injector Test facility at DESY, Zeuthen site (PITZ)

PITZ focuses on the development, test and optimization of high brightness e-sources for SC linac driven FELs:

- test-bed for FEL injectors: FLASH, the European XFEL (conditioning and characterization of gun cavities and photo injector subsystems, e.g. photocathode laser)
- high brightness $\rightarrow$ small $\varepsilon_{tr}$ (projected and slice)
- further studies $\rightarrow$ e.g. cathodes: dark current, photoemission, QE, thermal emittance, …
PITZ “engine”: RF-Gun and Photocathode (PC) Laser

Highlights of the facility

RF gun
- L-band (1.3 GHz) 1.6-cell copper cavity
- Eca = 60 MV/m → 7 MeV/c e-beams
- 650 μs × 10 Hz → up to 45 kW av. RF power
- Cs₂Te PC (QE~5-10%) → up to 5 nC/bunch
- LLRF control for amp&phase stability
- Solenoid for emittance compensation

Pulse Train Time Structure:
PITZ and EXFEL trains with up to 600 (2700) laser pulses

 Default PC laser system (Max-Born-Institute, Berlin)
Gaussian:

Multicrystal birefringent pulse shaper containing 13 crystals

Simulated pulse-stacker

Flattop

Cathode laser pulse: temporal profile

 Institut of Applied Physics of the Russian Academy of Sciences

New PC laser ELLA

3D (ellipsoidal) pulse shaper:
- SLM based
- Upgrade with VBG

Oscillator upgrade – Pharos-20W-1MHz frontend
Pulse length 0.25-10 ps
Beam Dynamics Simulations

ASTRA simulations for PITZ setup with 3 shapes of the photocathode laser pulse
Beam Dynamics Simulations (ASTRA)

PITZ setup, 1nC bunch charge optimization for 3 photocathode laser pulse shapes

Phase space (X-X')

Distribution (X-Y)

Beam rms sizes

Side view (Z-X)

Vs. main solenoid current

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Procedures to measure transverse emittance in photo injectors

Optimization of transverse phase space in photo injectors
Transverse Phase Space Measurements

Emittance measurements in Photo Injectors

- Space charge dominated
  - Slit mask techniques:
    - based on conversion of a **space charge dominated** beam into **emittance dominated** beamlets

- Emittance dominated
  - Multi screen:
    - Based on linear beam matrix approach
    - 3 beam size measurements (at 3 positions) are needed for the known elements of the transport matrix (phase advance)
  - Quad(s) scan
    - Beam size measurements as a function of varied transport matrix
  - Tomography
    - Related to Radon theorem: N-dim object reconstruction from M projections in (N-1) dim space

- Time resolved
  - Slice emittance measurements
Emittance measurements of space charge dominated beams

Slit techniques to reconstruct transverse phase space
Slit technique - general

Space charge dominated beam → emittance (divergence) dominated beamlet

Multi slit mask (MSM) = single shot measurement, but:
• Overlapping of beamlets when optimized for high resolution (MSM→short L or small $\sigma_{x'y'}$)
• Small beam size → low sampling of the phase space

→ Scanning with a single slit

Transverse phase space reconstruction

$$\varepsilon_{nx} = \beta \gamma \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$
Slit Scan Technique for Emittance Measurements at PITZ

Emittance Measurement SYstem (EMSY)

**EMSY:**
- screens (YAG and LYSO)
- 1mm thick W slits with 10 (50) µm opening

**Beamlet collector screen**

**Beamlet profile**

**measured transverse phase space**

**E-beam at EMSY screen**

\[ \varepsilon_{n,x} = \beta \gamma \frac{x_{\text{rms}}^{\text{EMSY}}}{\sqrt{\langle x^2 \rangle}} \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \]

"100%" rms emittance

As conservative as possible!

Correction factor (~1.2 ... 1.5) introduced to correct for low intensity losses from beamlet measurements
Emittance using slit-scan at PITZ

Relevant measurements to obtain rms normalized emittance

Beamlet collector screen High1.Scr4 (L=3.13m)

Transverse distribution at EMSY (YAG) screen

Beam long, momentum measurements in High Energy Dispersive Arm (HEDA1)

\[ \langle P_z \rangle = \beta \gamma \]

\[ \epsilon_{n,x} = \beta \gamma \cdot \frac{X_{\text{RMS}}^{\text{EMSY}}}{\sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}} \]

Trace space reconstruction from beamlet profiles

\[ \epsilon_x = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \]
Image processing and beam size analysis

Background subtraction, noise filtering

Beam / beamlets transverse distribution measurements:
- Screen (YAG, LYSO, OTR) → 90° YAG with mirror behind
- Optical system for light transport → iris, zoom options (f160, f250)
- CCD camera → read out
- Image processing

Beam image quality management → 3000-criteria:
\[ \text{MaxPixelValue} = \Phi(\text{NoP}, \text{CameraGain}) \geq 3000 \ (\text{max} \ 4095) \]
1) 1 pulse (NoP=1), CameraGain→~22
2) If not → increase NoP
3) Min(NoP) - priority

EMSY (&MOI) data taking:
0) e.g. 10 frames Signal + 10 frames Background (laser shutter closed)

EMSY (&MOI), beamlets image processing:
1) \(<\text{Signal}>, <\text{Background}>\)
2) Noise-sigma-cut filter → mask \(M\):
   - \(<\text{Signal}> - <\text{Background}> \leq \text{cut} \cdot \sigma_{bg} \rightarrow M=0\), otherwise \(M=1\)
3) “Neighbors filters” (×N~3):
   - Removing pixel product filter \(\prod\)
   - Restoring pixel sum filter \(\sum\)

Read out: CCD camera Prosilica GC-1350
- Gain: 0 to 25 dB
- Black level control: Auto (not controllable)
- Minimum shutter: 10 us
- Chip size: 1360x1024
- Pixel size: 4.65
- 12bit


No Gaussian fit!
Slit station design considerations

Local beam divergence measurements (e.g., 1nC, 25MeV, 0.5 mm, 0.6 mm mrad)

• Slit material and thickness $s \rightarrow 1 \text{ mm } W(X_0=0.35 \text{ cm})$
  - Stop/scatter (≈20-25MeV) electrons
  - Good heat conductivity (pulse trains)

• Slit opening $d \rightarrow 10 \text{ (50) um}$
  - Good enough signal
  - Small space charge effect

• Drift length $L$ choice $\rightarrow L \gg 0.12m(d = 10 \mu m) \rightarrow$ PITZ: 2.6-3.1m
  - Resolution ($L \gg \frac{d}{(\sigma^2 \sqrt{12})}$)
  - ↓S2N
  - ↓Space charge

• Slit mask positioning
  - Linear stages Newport MM100-PP1 $\rightarrow$ step $\Delta \sim 10 \mu m$

• Slit mask alignment (angular acceptance):
  - Rotational stage Newport RV120-PP
  - Goniometric stage Newport BGM120-PE $\rightarrow$ step: 10urad (range: ~3mrad)

\[
\theta_{\text{rms}} = \frac{19.2 \text{MeV}}{E} \sqrt{\frac{S}{X_0}} \left[ 1 + 0.2 \ln \left( \frac{S}{X_0} \right) \right]
\]

\[
\theta_{\text{rms}} \gg \frac{D}{L}
\]

\[
\sigma_{\text{beamlet}}^{\text{meas}} = \sqrt{L^2 \cdot \sigma^2 + \left(\frac{d}{12}\right)^2}
\]

Statistics over all pixels in all beamlets

Beamlets quality management $\rightarrow$ extended 3000-criteria:

## PITZ evolution 2000-2017

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</tr>
</thead>
<tbody>
<tr>
<td>cavity</td>
<td>gun-2</td>
<td>gun-1</td>
<td>gun-3.1</td>
<td>g-3.2</td>
<td>gun-4.2</td>
<td>gun-4.1</td>
<td>g-3.3</td>
<td>4.3</td>
<td>4.4</td>
<td>gun-4.2</td>
<td>gun-4.6</td>
<td>g-4.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_z$/MV/m</td>
<td>35</td>
<td>37</td>
<td>42→60</td>
<td>43</td>
<td>60</td>
<td></td>
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</tr>
<tr>
<td>beam</td>
<td>~4MeV</td>
<td>4.3MeV~8MeV</td>
<td>4.5MeV</td>
<td>~6.5MeV</td>
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<tr>
<td>echo</td>
<td>no</td>
<td>TESLA at 2.5m</td>
<td>TESLA at 3.1m</td>
<td>CDS at 3m</td>
<td>CDS at 2.6m</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>echo temp</td>
<td>10</td>
<td>6/24/6</td>
<td>6/24/6</td>
<td>2/22</td>
<td>2</td>
<td>~13MeV</td>
<td>~25MeV</td>
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<tr>
<td>EMSY1</td>
<td>z=1.618m</td>
<td>z=4.3m</td>
<td>z=5.74m</td>
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<td></td>
</tr>
<tr>
<td>L</td>
<td>1.01m</td>
<td>2.334m</td>
<td>2.64m</td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>method</td>
<td>center BL</td>
<td>3xBLS</td>
<td>e-meter</td>
<td>11xBLS</td>
<td>continuous synchronized (detailed) scan</td>
<td>+slice with TDS</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>min $\varepsilon_{xy}$ (mm mrad) (charge)</td>
<td>3 (1nC)</td>
<td>1.5-1.7 (1nC)</td>
<td>1.37 (1nC)</td>
<td>1.26 (1nC)</td>
<td>0.9 (1nC)</td>
<td>0.7 (1nC)</td>
<td>0.8 (0.5nC)</td>
<td></td>
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</tbody>
</table>

### PITZ goals
- small emittance (nominal EXFEL)
- reliability at full performance
- emittance (EXFEL startup)
- THz
- plasma

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**XFEL photo injector specs**
- emittance (1nC, 100%)
- beam energy after gun
- final beam energy

**Beam emittance vs. Bunch Charge**
- min-emittance (mm mrad)
- beam energy (MeV)

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"we are measuring more and more of less and less…"
Emittance measurements at PITZ

Multi parametric experimental emittance optimization at the PITZ photo injector
How to achieve small emittance

PITZ experience

- High gradient at the cathode ~60MV/m (1.3GHz)
- Cathode laser pulse shaping
- Gun and booster amplitude and phase stability
- Beam based alignment, trajectory optimization, elimination/compensation of imperfections
- Emittance compensation and conservation $\rightarrow$ multi parametric machine tuning (solenoid, laser spot size, gun phase, booster, alignment and beam trajectory, …)
Slit scan technique at PITZ

How it works now

- Setup the machine
  - laser temporal and transverse
  - laser BBA at the cathode
  - gun phase
  - bunch charge
  - booster phase and gradient – beam energy (longitudinal momentum)
- Adjust slit angles
  - Angle scans for the center beamlet → max SoP
- For every main solenoid current (bucking in compensation)
  - Beam transverse distribution (rms size) at EMSY → 12-bit camera;
    frames=10xSignal+10xBkg (laser shutter closed) with adjusted camera gain G and NoP
  - Beam transverse distribution at beamlet collection screen for MOI → 12-bit camera;
    frames=10xSignal+10xBkg (laser shutter closed) with adjusted camera gain G and NoP
- Slit scan (typical speed 0.1–0.5mm/sec) with simultaneous beamlet image taking.
  Synchronization of the slit position and the frame acquisition (10Hz)
  with adjusted camera gain G and NoP
- Slit scan with closed laser shutter for the average bkg calculation
- Transverse phase space reconstruction and emittance calculations
  - Phase space linear shift to take the slit position into account
  - Scale procedure
- Error analysis (systematic and statistics – e.g. 3x3)

Systematic error \( \frac{\text{meas} - \text{simul}}{\text{simul}} \) estimations

Due to finite pixel size

<table>
<thead>
<tr>
<th>Q, nC</th>
<th>( \chi_{\text{EMSY}} )</th>
<th>( \epsilon_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>1</td>
<td>&lt;1%</td>
<td>~3%</td>
</tr>
<tr>
<td>0.25</td>
<td>&lt;1%</td>
<td>&gt;1%</td>
</tr>
<tr>
<td>0.1</td>
<td>&lt;1%</td>
<td>~1.2%</td>
</tr>
<tr>
<td>0.02</td>
<td>&lt;1%</td>
<td>146%</td>
</tr>
</tbody>
</table>

Uncertainty w.r.t. optim. par.

<table>
<thead>
<tr>
<th>Q, nC</th>
<th>( \epsilon_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8%</td>
</tr>
<tr>
<td>1</td>
<td>12%</td>
</tr>
<tr>
<td>0.25</td>
<td>13%</td>
</tr>
<tr>
<td>0.1</td>
<td>8%</td>
</tr>
<tr>
<td>0.02</td>
<td>10%</td>
</tr>
</tbody>
</table>


Additionally: screen/camera inhomogeneity/noise, calibration, effects of image filters, jitters
Emittance versus Laser Spot Size for various Charges

Measured (100%) rms normalized emittance vs. simulations

Minimum emittance ($\sqrt{\varepsilon_{n,x}\varepsilon_{n,y}}$)

<table>
<thead>
<tr>
<th>Charge, nC</th>
<th>Measured, mm mrad</th>
<th>Simulated, mm mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.25±0.06stat+0.01syst</td>
<td>1.14</td>
</tr>
<tr>
<td>1</td>
<td>0.70±0.02stat+0.02syst</td>
<td>0.61</td>
</tr>
<tr>
<td>0.25</td>
<td>0.33±0.01stat-0.003syst</td>
<td>0.26</td>
</tr>
<tr>
<td>0.1</td>
<td>0.21±0.01stat+0.0003syst</td>
<td>0.17</td>
</tr>
<tr>
<td>0.02</td>
<td>0.121±0.001stat+0.18syst*</td>
<td>0.06</td>
</tr>
</tbody>
</table>

• Optimum machine parameters (laser spot size, gun phase): experiment ≠ simulations
• Difference in the optimum laser spot size is bigger for higher charges (~good agreement for 100pC)
• Simulations of the emission is under improvements

Measured 1nC electron beam

X-Y

X-X’

Y-Y’
Core Emittance
Intensity (charge) cut of phase space

Raw phase space (100%) → intensity cut → charge cut → core emittance

Measured Transverse Phase Space (1nC)

<table>
<thead>
<tr>
<th>100%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε_{n,x} (100%) = 0.707 mm mrad</td>
<td>ε_{n,y} (90%) = 0.543 mm mrad</td>
</tr>
<tr>
<td>ε_{n,y} (100%) = 0.685 mm mrad</td>
<td>ε_{n,y} (90%) = 0.515 mm mrad</td>
</tr>
</tbody>
</table>
# Measured Emittance and Brightness (2015)

## Gaussian photocathode laser pulses

<table>
<thead>
<tr>
<th>Cathode laser temporal</th>
<th>VC2 (laser)</th>
<th>E-beam at EMSY1</th>
<th>X-X'</th>
<th>Y-Y'</th>
<th>E-beam temporal profile (TDS)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Long</strong></td>
<td><img src="image" alt="VC2" /></td>
<td><img src="image" alt="E-beam at EMSY1" /></td>
<td>![X-X']</td>
<td>![Y-Y']</td>
<td><img src="image" alt="E-beam temporal profile" /></td>
</tr>
<tr>
<td>Gaussian ~11.5ps FWHM 53MV/m</td>
<td><img src="image" alt="Long Gaussian" /></td>
<td><img src="image" alt="Long Gaussian" /></td>
<td><img src="image" alt="Long Gaussian" /></td>
<td><img src="image" alt="Long Gaussian" /></td>
<td><img src="image" alt="Long Gaussian" /></td>
</tr>
<tr>
<td><strong>Short</strong></td>
<td><img src="image" alt="Short Gaussian" /></td>
<td><img src="image" alt="Short Gaussian" /></td>
<td><img src="image" alt="Short Gaussian" /></td>
<td><img src="image" alt="Short Gaussian" /></td>
<td><img src="image" alt="Short Gaussian" /></td>
</tr>
<tr>
<td>Gaussian ~2.5ps FWHM 60MV/m</td>
<td><img src="image" alt="Short Gaussian" /></td>
<td><img src="image" alt="Short Gaussian" /></td>
<td><img src="image" alt="Short Gaussian" /></td>
<td><img src="image" alt="Short Gaussian" /></td>
<td><img src="image" alt="Short Gaussian" /></td>
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</tbody>
</table>

*Note: The images show the emittance profiles for both long and short Gaussian pulse durations. The long pulse has an emittance of 33A, and the short pulse has an emittance of 56A.*

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**Brightness vs Laser rms spot size**

\[
B_{\text{peak}} = \frac{I}{\varepsilon_n x \varepsilon_n y}
\]

*where \( I \) is the current, and \( \varepsilon_n x \varepsilon_n y \) is the normalized emittance.*

---

**Emittance vs BSA @ 6.3MW vs. 5.0MW in the gun**

- **XYemit (60MV/m, longG)**
- **XYemit (53MV/m, longG)**
- **XYemit (60MV/m-shortG)**

*The graph compares the emittance for different pulse durations and intensities.*

---

**Various photo cathode pulse length, various gun gradients**

- **B(60MV/m, longG, 6c)**
- **B(60MV/m, longG, 1c)**
- **B(53MV/m, 500pC, longG)**
- **B(60MV/m, 500pC, shortG)**

*The chart illustrates the brightness for various cathode pulse lengths and gun gradients.*

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**Phase Space Tomography module**

- **GUN**
- **LEDA**
- **CDS**
- **Plasma**
- **HEDA1**
- **TDS**
- **Phase Space Tomography module**

*The module is used for measuring the phase space distribution of the beams.*

---

**Also slice emittance**

*This indicates the ability to slice the emittance for analysis.*
Conclusions and Outlook

Transverse emittance measurements of space charge dominated beams at PITZ

- Slit Scan Technique (SST) is a standard method used to measured the transverse phase space of space charge dominated electron beams at PITZ.

- Main paradigm → to be conservative - to measure as much as possible beam signal, trying to avoid unnecessary assumptions/simplifications.

- SST at PITZ has been improved significantly since start of its usage:
  - automated quasi-continuous synchronized slit scan → ~100 positions of 10um tungsten slit
  - scale factor applies to correct for low intensity losses from beamlet measurements
  - 3000-criteria for the image quality management

- PITZ experience on high brightness photo injector optimization:
  - multiparametric emittance minimization (Imain, laser \( \perp - \parallel \), gun \( E_0 \) and \( \varphi_0 \), beam trajectory etc.)
  - major problem: measurements ≠ simulations
  - emittance optimized for \( \text{0.02-2nC} \) bunches for various laser pulse shapes → e.g. 0.7 mm mrad @ 1nC

- **Outlook:**
  - slice emittance using TDS → SST and Quads scan ongoing
  - also general trend towards lower bunch charges (pC and fC)
  - further automatization (e.g. “autogain” for quality measurements, automatic scan range, etc.)
  - 4D phase space reconstruction (“Virtual Pepper Pot”)
  - image processing need more advanced filters
Backup slides
Emittance and Brightness versus Bunch Charge (2011)

Cathode laser pulse duration was fixed at 21.5 ps (FWHM) for all bunch charges!

Bunch charge reduction at fixed cathode laser pulse duration \( \Rightarrow \) space charge (SC) modification

\[ B_{\text{injector}} = \frac{I_{\text{injector}}}{E_x E_y} \frac{Q \cdot NoP \cdot RR}{E_x E_y} \]

\( \sim \) linear SC

\( \sim \) nonlinear SC
Correction factor

From uncorrelated emittance to the scaled normalized emittance

Geom. (trace space) emittance $\epsilon_x = \sqrt{\langle x^2 \rangle \langle x''^2 \rangle - \langle xx' \rangle^2}$

Linear correlation $\tilde{x}' = x' - c \cdot x \leftrightarrow \langle xx' \rangle = 0$

$c = \frac{\langle xx' \rangle}{\langle x^2 \rangle}$

Emittance is invariant:

$\epsilon_x = \tilde{\epsilon}_x = \sqrt{\langle x^2 \rangle \langle \tilde{x}''^2 \rangle - \langle x \tilde{x}' \rangle^2} = \sqrt{\langle x^2 \rangle \langle \tilde{x}''^2 \rangle}$

Normalized emittance (to be measured):

$\epsilon_{n,x} = \beta \gamma \cdot \tilde{x}_{rms} \cdot \tilde{x}'_{rms}$

$\epsilon_{n,x} = \beta \gamma \cdot \frac{\tilde{x}_{rms}^{EMS Y} \sqrt{\langle x^2 \rangle} \sqrt{\langle x^2 \rangle \langle x''^2 \rangle - \langle xx' \rangle^2}}{\sqrt{\langle x^2 \rangle}}$
Slit scan technique at PITZ: evolution

Slit scan step (spacing) choice

- 2002-2003 rough divergence estimation using **center** beamlet, **8 bit** cameras
- 2003-2005 sheared emittance estimation using **3 slit positions** $\pm 0.7 \cdot X_{rms}^{EMS}$, 8-bit cameras
- 2005-2008 – standard “**manual**” slit **scan** (~200um step) $\rightarrow$ phase space reconstruction, **12-bit** cameras
- 2009-now – automated quasi-**continuous synchronized** slit scan with adjustable scan speed $\rightarrow$ phase space “on-line”, 12-bit cameras, zoom option, scale procedure

The emittance measurement procedure at PITZ:
- under permanent improvement in terms of resolution and sensitivity
- as conservative as possible (**100% rms emittance**)!

**INB:** measured emittance values are permanently **reducing** as a result of machine upgrades and extensive optimization of beam parameters
ASTRA simulations for 2011 case using Core+Halo

- BUT for flattop photocathode laser pulses

\[ \phi_{\text{gun}} = \text{MMMG+6°} \]
\[ Q = 1 \text{nC}^* \]
\[ \varepsilon_x = 0.72 \text{ mm mrad} \]
\[ \varepsilon_y = 0.60 \text{ mm mrad} \]

Parameters "plugged" from measurements:
\[ \phi_{\text{gun}} = \text{MMMG+6°} \]
\[ Q = 0.97 \text{nC} \]
\[ \varepsilon_x = 2.5 \text{ mm mrad} \]
ASTRA simulations for Gaussian pulses using Core+Halo

X-Y: \( \phi_{\text{run}}=\text{MMM} \)

Q=0.5 nC

\( \varepsilon_x=0.82 \) mm mrad

\( \varepsilon_y=0.84 \) mm mrad

X-X':

Y-Y'

Parameters "plugged" from measurements:

\( \phi_{\text{run}}=\text{MMM} \)

Q=0.5 nC

\( \varepsilon_x=1.05 \) mm mrad

Charge vs. laser pulse energy

- measured
- simulated (homogeneous)
- simulated (Core+Halo)
Electron beam X-Y asymmetry compensation with gun quads

(0.5nC, Gaussian photocathode laser pulse)

*Electron beam measurements without gun quadrupoles*

*Electron beam measurements with gun quadrupoles*

<table>
<thead>
<tr>
<th></th>
<th>No gun quads</th>
<th>With gun quads</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{\text{main}}$ (A)</td>
<td>386</td>
<td>384</td>
</tr>
<tr>
<td>$I_{\text{gun}_\text{quad1}}$ (A)</td>
<td>0</td>
<td>-0.5</td>
</tr>
<tr>
<td>$I_{\text{gun}_\text{quad2}}$ (A)</td>
<td>0</td>
<td>-0.6</td>
</tr>
<tr>
<td>$\sigma_x$ @EMS1 (mm)</td>
<td>0.50</td>
<td>0.28</td>
</tr>
<tr>
<td>$\sigma_y$ @EMS1 (mm)</td>
<td>0.35</td>
<td>0.32</td>
</tr>
<tr>
<td>$\varepsilon_{x,R}$ (mm mrad)</td>
<td>1.13</td>
<td>0.82</td>
</tr>
<tr>
<td>$\varepsilon_{y,R}$ (mm mrad)</td>
<td>0.73</td>
<td>0.84</td>
</tr>
<tr>
<td>$\sqrt{\varepsilon_{x,R}^2 \varepsilon_{y,R}^2}$ (mm mrad)</td>
<td>0.91</td>
<td>0.83</td>
</tr>
<tr>
<td>$\beta_x$ (m)</td>
<td>6.53</td>
<td>3.18</td>
</tr>
<tr>
<td>$\beta_y$ (m)</td>
<td>6.49</td>
<td>3.24</td>
</tr>
<tr>
<td>$\gamma_x$ (mrad)</td>
<td>0.56</td>
<td>0.32</td>
</tr>
<tr>
<td>$\gamma_y$ (mrad)</td>
<td>0.16</td>
<td>0.31</td>
</tr>
</tbody>
</table>