Transverse emittance measurements at PITZ

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Joint DESY and University of Hamburg Accelerator Physics Seminar
Outline

- Emittance of the electron beam
- Motivation
  - SASE FEL
  - FLASH, XFEL and PITZ
- PITZ in details
  - hardware setup, operation parameters
- Emittance Measurement SYstem (EMSY)
  - optimization and error analysis
- Emittance measurement results at PITZ
  - optimized parameters
  - two different gun cavities
- Discussion
Emittance

**introduction**

\[
x' = \frac{p_x}{p_z}
\]

beam momentum \( \vec{P} \)

\[
\begin{pmatrix}
(x, y, z, x', y', p_z)
\end{pmatrix}
\]

\[
f(x, y, z, x', y', p_z)
\]

**emittance** is related to volume/area occupied by the electrons, the smaller - the better

→ central moments \( \langle \cdots \rangle \)
→ 2D projections \( f(x, x') \)
→ covariance matrix

\[
\Sigma_x = \begin{pmatrix}
\langle x^2 \rangle & \langle xx' \rangle \\
\langle xx' \rangle & \langle x'^2 \rangle
\end{pmatrix}
\]

\[
\Sigma'_x = R \cdot \Sigma_x \cdot R^T ;
\]

\[
R = D_1 \cdot Q_1 \cdot D_2 \cdot Q_2 \cdots D_n \cdot Q_n ...
\]
Emittance definition

\[
\Sigma_x = \begin{pmatrix}
\langle x^2 \rangle & \langle xx' \rangle \\
\langle xx' \rangle & \langle x'^2 \rangle
\end{pmatrix}
\]
\(\text{covariance matrix}\)

\[
\det|\Sigma_x| = \varepsilon_{rms}^2
\]
\[
\det|\Sigma_x| \cdot \beta \gamma = \varepsilon_{rms,n}^2
\]

RMS normalized emittance:

\[
\varepsilon_{x,rms} = \beta \gamma \cdot \sqrt{\langle x^2 \rangle \cdot \langle x'^2 \rangle - \langle xx' \rangle^2}
\]
European XFEL design parameters

- **Electron beam**
  - high peak current: \(~5 \text{ kA}\)
  - short bunch: \(20 \mu\text{m}\)
  - small emittance: \(1.4 \text{ mm.mrad}\)

- **Undulator**
  - strong field: \(1.5 \text{ T}\)
  - precise alignment: \(32 \mu\text{m}/260\text{m}\)
  - very long: \(100^{\text{s}}\text{ m}\)

- **SASE FEL**
  - short wavelength: \(0.1 \text{ nm}\)
  - high brilliance: \(10^{33} \text{ photons/s/mm}^2/\text{mrad}^2/0.1\%\)
  - ultra short pulse: \(< 100 \text{ fs}\)
\[ \varepsilon_n = 1 \text{ mm mrad} \]
\[ \varepsilon_n = 2 \text{ mm mrad} \]
\[ \varepsilon_n = 4 \text{ mm mrad} \]

\[ Q = 1 \text{ nC} \]

- XFEL goal: 0.9 mm mrad@injector $\Rightarrow$ 1.4 mm mrad@undulator
- if even smaller emittance $\Rightarrow$ new horizons: shorter wavelength, higher repetition rate
FLASH layout

- e⁻ source
- pre acceleration
- bunch compression

- further acceleration compression
- final acceleration
- collimation and undulation
PITZ

- Photo Injector Test-facility at DESY in Zeuthen
RF photo-injector

0. Photo cathode laser
1. Cs₂Te photo cathode
2. RF gun cavity
3. RF coupler
4, 5. Focusing solenoids
   Drift space
   Booster cavity
Extraction from $\text{Cs}_2\text{Te}$ cathode

- photo effect - quantum efficiency of $\text{Cs}_2\text{Te}$ cathode (Q.E.) etc.
- “Schottky effect” – lowering the potential barrier to the vacuum
- thermal emittance – remnant kinetic energy after the electron extraction
- mirror and space charge
Extraction

Photo-cathode laser

PTO, pulse-shaper, Nd:YLF pumped amplifier, frequency converter

- $\lambda = 262 \ nm$
- rise/fall time = 6 ps (2 ps upgrade)
- FWHM = 20 ps
- $\sigma_{xy}$ – tunable 0.1 to 3 mm diameter

FWHM=20.52ps; rt1=6.75ps; rt2=6.62ps; FTmod=6.10%

intensity, a.u.

-5 -4 -3 -2 -1 0 1 2 3 4

0 0.2 0.4 0.6 0.8 1

-25 -20 -15 -10 -5 0 5 10 15 20 25

t, ps
Acceleration

\[ E_{\text{acc}} = E(z) \cdot \sin(\omega t + \phi) \]
Emittance compensation
solenoid, linear space charge

**Envelope equation:**

\[ \sigma'' + \sigma' \frac{\gamma'}{\gamma} + \sigma \frac{\Omega^2 \gamma'^2}{\gamma^2} - \frac{I}{\sigma 2 I_A \gamma^3} - \frac{e_{n,\perp}^2}{\sigma_{\perp}^2 \gamma^2} = 0 \]
Emittance conservation
booster, invariant envelope

- when space charge and external focusing ratio equals beam rms
  - invariant envelope
  - emittance oscillation damped
  - beam size better contained

Envelope equation:

$$\sigma'^2 + \sigma' + \frac{\gamma'}{\gamma} + \sigma^2 \frac{\Omega^2}{\gamma^2} - \frac{I}{\sigma' 2I_A \gamma^3} - \frac{\varepsilon^2_{n,\perp}}{\sigma^3 \gamma^2} = 0$$

- $\sigma_x$ no booster
- $\sigma_x$ booster
- $\varepsilon_x$ no booster
- $\varepsilon_x$ booster
PITZ
diagnostic components

- Bunch charge
  - ICT and FC
- Transverse phase space
  - YAG and OTR screens
  - slit masks
- Momentum and momentum spread
  - two dispersive dipole magnets
- Longitudinal phase space
  - Cherenkov and OTR
  - streak camera
PITZ in details

EMSY1 4.3 m
EMSY2 6.6 m
EMSY3 9.9 m
PITZ parameters

- Cathode laser
  - 1 to 800 bunches per train @ 10 Hz rep. rate, 1 μs bunch spacing
  - Flat top micro pulse duration of 20 ps (FWHM) with 6 ps rise/fall
- Charge per bunch Q = 1 nC
  - Laser energy ~1 μJ @ 262 nm wavelength
- RF frequency 1.3 GHz
  - Max accelerating gradient 60 MV/m at the cathode
  - Pulse duration 900 μs with repetition 10 Hz
- Max. mean momentum P = 14.5 MeV/c (32 expected)
- Bunch length FWHM ~20 ps (I_p ~ 50 A)
- Transverse normalized emittance \( \varepsilon_n \)
  - Better than 0.9 mm.mrad !!!
Control parameters

0. Photo cathode laser
   - Transverse shape and size
   - Longitudinal distribution – fixed (limited tuning)

1. Cs$_2$Te photo cathode
2, 3. RF gun cavity, RF coupler
   - Amplitude and phase of the RF wave

4, 5. Focusing solenoids
   - Focusing strength of the main solenoid ($I_{main}$), the other compensates $I_{main}$

Drift space
   - fixed - numerically optimized

Booster cavity
   - Amplitude and phase of the RF wave
Emittance measurement methods – definition reminder

\[
\Sigma_x = \begin{pmatrix}
\langle x^2 \rangle & \langle xx' \rangle \\
\langle xx' \rangle & \langle x'^2 \rangle
\end{pmatrix}
\]

\(\text{covariance matrix}\)

\[
det|\Sigma_x| = \varepsilon_{\text{rms}}^2
\]

\[
det|\Sigma_x| \cdot \beta\gamma = \varepsilon_{\text{rms},n}^2
\]

**RMS normalized emittance:**

\[
\varepsilon_{x,\text{rms}} = \beta\gamma \cdot \sqrt{\langle x^2 \rangle \cdot \langle x'^2 \rangle - \langle xx' \rangle^2}
\]
Emittance measurement methods

- Multiple screen method

\[ \Sigma^n_x = R \cdot \Sigma^{n-1}_x \cdot R^T; \]

- Quadrupole scan technique

\[ \sigma_x^2(z) = \left[ \sigma_{x0}^2 - 2\alpha_{x0}\varepsilon_x L_d + \gamma_{x0}\varepsilon_x L_d^2 \right] + \frac{2\sigma_{x0}^2}{f} \left[ \frac{\alpha_{x0}}{\beta_{x0}} L_d - L_d \right] + \frac{2\sigma_{x0}^2}{f^2} L_d; \]

here: \( \alpha, \beta, \gamma \) – are the Twiss parameters; \( f \) – the quadrupole focusing strength
Emittance measurement methods

**single slit method**

Local uncorrelated divergence

\[ \langle x'^2 \rangle = \sqrt{\frac{\langle x_b^2 \rangle_i}{L_d^2}} \]

\[ \langle x'^2 \rangle = \frac{1}{n} \sum_{i=1}^{n} W_i \cdot \langle x'^2 \rangle_i \]

\( L_d = 2.334 \text{ m} \)

ASTRA simulation
Emittance measurement methods

single slit method

\[
\langle x'^2_i \rangle = \int x^2 \rho(x) \, dx
\]

local undivided divergence

\[ L_d = 2.334 \, m \]

\[ \sum \]
Slit method

general requirements

- Emittance dominated beamlets (slit opening)
  - Reliable signal from the beamlets
- The mask thickness must be enough to scatter the residual electrons
- Optimal drift length
  - enough distance for beamlet evolution (max. $L_d$)
    - resolution of the divergence
    - elimination of the influence from the initial beamlet size
  - minimizing the effect of space charge (min. $L_d$)
Emittance Measurement SYstem (EMSY)

- two orthogonal actuators
  - YAG or OTR screen
  - CCD camera
  - single slit mask
  - multi slit mask
  - separately movable
  - each slit acceptance adjustable

EMSY layout
Emittance Measurement: Systematic uncertainty

- beam size measurements
  - screen
    - saturation (YAG), screen geometry, multiple scattering etc.
  - optic lenses
  - CCD camera
- local divergence
  - beamlet size measurements
  - space charge contribution
  - noise from scattered electrons
- momentum measurements
  - dipole field errors
  - beam size associated
Electron beam size measurement

Simulation - ASTRA

Entries 50001
Mean x 8.124e-08
Mean y 1.58e-06
RMS x 0.0002833
RMS y 0.0002803

- 10°
φ = 0°

Mean x 8.124e-08
RMS x 0.0002833
RMS y 0.0002803

- 10°
φ = 0°

768x567 CCD chip
Screen area 20x20 mm
ASTRA –
- 750k particles, 1 nC
- gun only.
- Beam momentum ~ 5 MeV

○ 8 bit – 1/255
○ 12 bit – 1/4096
Emittance Measurement uncertainty
Space charge effect

- Envelope equations for non-symmetric beam
  - Used to calculate the beamlet evolution
  - Estimates the influence of the slit opening due to space charge on the beamlet size
- Uniform distribution used to solve the system

General parameters:
- $I = 50, \text{ A}$
- $\gamma = 10 .. 60$
- $\sigma_x = 0.2 .. 2, \text{ mm}$
- $\sigma'_x$ - scaled such that
- $\varepsilon_x = 1 \text{ mm.mrad}$
Emittance Measurement uncertainty

Space charge effect

- Envelope equations used

\[
\sigma_x'' = \frac{I}{I_a \cdot (\sigma_x + \sigma_y) \cdot \gamma^3} + \frac{\varepsilon_{nx}}{\sigma_x^3 \cdot \gamma^2} \\
\sigma_y'' = \frac{I}{I_a \cdot (\sigma_x + \sigma_y) \cdot \gamma^3} + \frac{\varepsilon_{ny}}{\sigma_y^3 \cdot \gamma^2}
\]

here:

- \( I \) - peak current [A], \( I_a \) - Alfven current (17.0 kA);
- \( \sigma_x \) - transverse size; \( \sigma'_x \) - transverse divergence;
- \( \varepsilon_x \) - normalized emittance; \( \gamma \) - Lorentz factor;

\( \langle xx' \rangle \) - for now it is assumed to be zero

- General parameters:
  - \( I \) = 50, A
  - \( \gamma \) = 10 .. 60
  - \( \sigma_x \) = 0.2 .. 2, mm
  - \( \sigma'_x \) - scaled such that
  - \( \varepsilon_x \) = 1 mm.mrad
Emittance uncertainty
nominal values at 30 MeV/c

- Asymmetric envelope equations solved for:
  - \( I = 50 \text{ A} \)
  - \( \gamma = 58.7 \text{ (30 MeV/c)} \)
  - \( \sigma_0 = 0.2 \text{ mm} \)
  - \( \sigma'_x = 0.0766 \text{ mrad} \)
  - \( \epsilon_x = 0.9 \text{ mm.mrad} \)

- Optical resolution of 50 lines/mm

- Uncertainty at \( L_d = 2 \text{ m} \)
  - 4.85 % (10 \( \mu \text{m} \) slit)
  - 155 \( \mu \text{m} \) beamlet rms size
Emittance uncertainty
nominal values at 15 MeV/c

- Asymmetric envelope equations solved for:
  - $I = 50$ A
  - $\gamma = 29.3$ (15 MeV/c)
  - $\sigma_0 = 0.2$ mm
  - $\sigma'_x = 0.153$ mrad
  - $\varepsilon_x = 0.9$ mm.mrad

- Optical resolution of 50 lines/mm

- Uncertainty at $L_d = 2$ m
  - 4.98 % (10 $\mu$m slit)
  - 318 $\mu$m beamlet rms size
Emittance uncertainty error map

Here:
- \( I = 50 \text{ A} \)
- \( \sigma_0 \) = variable, mm
- \( \sigma'_x \) - scaled to correspond
- \( \varepsilon_x \) = variable, mm.mrad

Uncertainty map
- \( L_d = 2 \text{ m} \)
- 10 \( \mu \text{m} \) slit opening
- 50 lines/mm

Emittance measurement uncertainty, \( L_d = 2.0 \text{ m}, \Delta I = 50 \text{ l/mm} \)
GEANT4 simulations

- Simplified G4 model
  - The signal to noise ratio
  - The energy deposited in the tungsten

- The plate thickness, the distance to the screen and used as variables
GEANT4 simulations
signal to noise ratio

\[ S2N = \frac{C_s}{C_n} \cdot \frac{A_n}{A_s} \]

Here:
- \( C_s \) – counts signal
- \( C_n \) – counts noise
- \( A_s \) – area of the signal
- \( A_n \) – area of the noise

**Slit parameters:**
- **Tungsten**
- **1 mm thickness**
- **10 \( \mu \)m slit opening**
The slit mask material is chosen to be Tungsten. The thickness of the slit mask must be 1 mm. The slit opening should be 10 μm. Distance \((L_d)\) between the screen and the mask is approximately 2 m. 12 bit camera resolution is required. Optical resolution better than 50 lines/mm.
Emittance measurements

Two different gun cavities of the same prototype

- gun 3.1 (October 2006)
  - max. gradient ~43 MV/m (FLASH spare gun)
  - optimization parameters:
    - $I_{\text{main}}$ around the focus at EMSY screen
    - booster phase (phase of the gun fixed $\phi_0+2$)
    - emittance measured at three locations downstream
  - only 8 bit cameras used

- gun 3.2 (August 2007)
  - max. gradient ~60 MV/m (1st test for XFEL gun)
  - optimization parameters:
    - $I_{\text{main}}$ scanned around the focus at EMSY screen
    - booster accelerating gradient (phases of gun $\phi_0$ and booster $\phi_0$ are fixed)
    - different initial beam sizes at the cathode
  - 12 bit cameras used for beamlet measurements
Emittance measurements
gun 3.1 (October 2006)

- Gun gradient ~43 MV/m (at the cathode)
- Final beam momentum ~ 13 MeV/c
- Laser rms spot size ~ 0.51 mm

φboo = 15 deg

φboo = 10 deg
Emittance measurements

**gun 3.1 (October 2006)**

### Measurement conditions:
- Mean momentum: ~ 4.95 @ gun
- ~ 13.0 @ booster
- Initial rms spot size: ~ 0.51 mm

### Best measurement taken:
- \( I_{\text{main}} = 282 \) [A]
- \( \varepsilon_x = 1.32 \pm 0.11 \) [mm mrad]
- \( \varepsilon_y = 1.43 \pm 0.17 \) [mm mrad]
Emittance measurements

**Comparison – gun 3.1 vs. gun 3.2**

- **Machine parameters:**
  - $XY_{ini} = 0.51$ mm (rms laser@cath)
  - Mean momentum MeV/c
    - Gun: 4.95
    - Booster: 12.85
    - $\phi_{booster} = \phi_0 + 5$ deg

- **Minimum emittance:**
  - Gun 3.1
    - $\varepsilon_{xy} = 1.37 \pm 0.14$ mm.mrad
    - $I_{main} = 282$ A (0.166 T)
  - Gun 3.2
    - $\varepsilon_{yy} = 1.54 \pm 0.15$ mm.mrad
    - $I_{main} = 290$ A (0.171 T)

- Beamlet observation CCD cameras different (8 & 12 bit)
Emittance measurements

**gun 3.2** (August 2007)

- EMSY1 only
- fixed phases @ max. momentum gain
- gun gradient \( \sim 60 \text{ MV/m} \) at cathode
- different laser diameter at cathode
  - Laser aperture \((XY_{\text{laser}})\) - 1.2, 1.5, 1.8 and 2.0 mm
  - rise/fall time \( \sim 6 \text{ ps} \)
  - FWHM \( \sim 20 \text{ ps} \)
- different booster gradients
  - final beam momentum of 9.5, 11, 13 and 14.5 MeV/c
Emittance measurements, gun 3.2 (August 2007)

- **9 MeV/c**: XY laser 1.5 mm
  - 20070726N, 10 μm, 9.77 MeV/c, 0.42 mm
- **11 MeV/c**: XY laser 1.2 mm
  - 20070727N, 10 μm, 11.05 MeV/c, 0.42 mm
- **13 MeV/c**: XY laser 1.5 mm
  - 20070726N, 10 μm, 13.00 MeV/c, 0.42 mm

- **9 MeV/c**: XY laser 1.8 mm
  - 20070729M, 10 μm, 9.51 MeV/c, 0.50 mm
- **11 MeV/c**: XY laser 1.8 mm
  - 20070728A, 10 μm, 10.97 MeV/c, 0.50 mm
- **13 MeV/c**: XY laser 1.8 mm
  - 20070729A, 10 μm, 13.04 MeV/c, 0.50 mm

- **9 MeV/c**: XY laser 2.0 mm
  - 20070726N, 10 μm, 9.44 MeV/c, 0.56 mm
- **11 MeV/c**: XY laser 2.0 mm
  - 20070729N, 10 μm, 10.90 MeV/c, 0.56 mm
- **13 MeV/c**: XY laser 2.0 mm
  - 20070729N, 10 μm, 13.06 MeV/c, 0.56 mm

Mean beam momentum:
- **9 MeV/c**: 1.5 mm
- **11 MeV/c**: 1.8 mm
- **13 MeV/c**: 2.0 mm
Results

gun 3.2 (August 2007)

xy_{laser} 1.2 mm

P_{mean} = 11, P_{mean} = 13, P_{mean} = 14.5, [MeV/c]
Results

best emittance

- Measurement conditions:
  - Laser
    - $XY_{ini}=0.36$ mm (rms)
    - rise/fall time 6 ps
    - FWHM = 20 ps
  - Maximum gradient $\sim 60$ MV/m
  - Gun and booster phases at max. momentum gain
    - $P_{\text{gun}}=6.44$ MeV/c
    - $P_{\text{boo}}=14.46$ MeV/c
  - Minimum emittance measured at $I_{\text{main}} = 374$ A (-0.220 T)

$\varepsilon_{xy} = 1.26 \pm 0.18$ mm.mrad

Emittance, [mm.mrad]

$I_{\text{main}}, [\text{A}]$
Results

best emittance – phase space

- measured phase space distribution
  - $X_\text{Yini}=0.36$ mm (rms)
  - $P_{\text{boo}}=14.46$ MeV/c
  - $I_{\text{main}} = 374$ A (-0.220 T)
Summary and outlook

- PITZ is capable of producing electron beams with small emittance
  - the smallest value achieved was $\varepsilon_{xy}=1.26\pm0.18$ mm.mrad (geom. avg.)
- Optimization of the emittance measurement system was done – slit mask, screen setup and readout system
  - wider momentum range
  - lower emittance
- Automatic measurement procedure implemented
  - faster measurements
  - more reliable results
- Main optimization parameters scanned
  - Solenoid strength
  - initial beam size
  - booster gradient
- To be improved:
  - differences between gun3.1 and gun3.2 have to be understood
- upgrade of the laser system is ongoing
  - 2 ps rise/fall times (XFEL milestone)
- in 2008 new booster cavity will be installed
  - improved stability
  - better field quality
  - more flexibility for studying the invariant envelope matching principle

Thank You for the attention!
Electron beam size measurement
optics contribution

- MTF formalism used
- Uncertainty as a function of beam size

\[ \frac{\sigma}{\sigma_0} = \left( \frac{\omega_0}{\omega} \right)^2 \]

\[ \sigma_0 = 30 \text{ mm}^{-1} \]

\[ \sigma_0 = 50 \text{ mm}^{-1} \]


TRANSVERSE BEAMSIZE MEASUREMENT SYSTEMS AT PITZ
R. Spesyvtsev, diploma thesis
Results

**gun 3.2** (August 2007)

Emittance obtained for different booster momentum gain

\[ \varepsilon_{x, n}, \varepsilon_{y, n}, \sqrt{\varepsilon_x \varepsilon_y} \]

- \( I_{\text{main}} = 374 \text{ A} \)
- \( X Y_{\text{laser}} = 1.2 \text{ mm} \)
Signal / Noise ↔ RMS ↔ Core emittance

x-x´-phase space distribution for the best emittance measurement, purely reconstructed from subsequent beamlet measurements:

100 % of data

\[ \varepsilon_n = 1.1 \text{ mm mrad} \]

\[ \varepsilon_n = 0.69 \text{ mm mrad} \]

Cut at 5% of max. amplitude (i.e. 6.5% of “charge”) [reasons: by purpose or because of noise, gain, sensitivity, bit depth, …]

Reminder: This \( \varepsilon_n \neq 1.25 \text{ mm mrad} \) because the separately measured beam size at the slit position is NOT taken into account here.

\( \Rightarrow \) projected emittance is reduced by 37 % !!

ASTRA: - 5% in particles \( \Rightarrow \) -38% in proj. emittance

For 95% RMS \( \Rightarrow \) \( \varepsilon_{x,y,n} \approx 0.8 \text{ mm mrad} \)