Eduard Prat:: Paul Scherrer Institut

Emittance measurements and minimization at the SwissFEL Injector Test Facility

DESY Zeuthen, May 20, 2016

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Introduction

- Transversely coherent FEL radiation is generated when $\frac{\varepsilon_n}{\gamma} = \frac{\lambda}{4\pi}$

ε_n : normalized emittance, γ: Lorentz factor, λ : FEL wavelength

- If the normalized emittance is reduced:
  - The final beam energy can be decreased: more compact and cheaper accelerator ☺
  - Higher radiation power and shorter undulator line for a given beam energy ☺

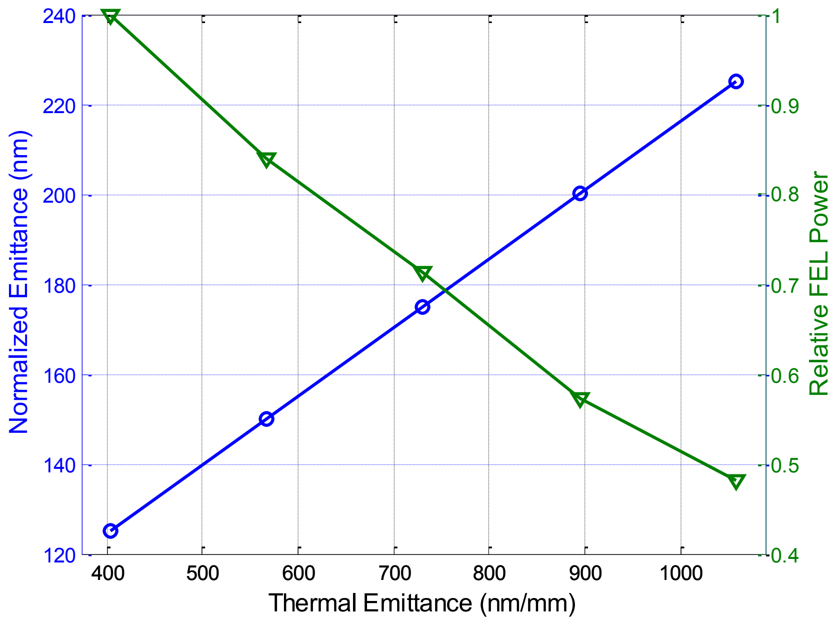
- The thermal emittance is a significant contributor of the final beam emittance (~70% for the SwissFEL case)

It can be expressed as (neglecting tilted surface effects):

$$\varepsilon_{th} = \sigma_l \sqrt{\frac{2E_k}{3m_e c^2}}$$

σ_l: rms laser beam size

Relative FEL power vs normalized thermal emittance $\varepsilon_{th}/\sigma_l$ for SwissFEL (200 pC)



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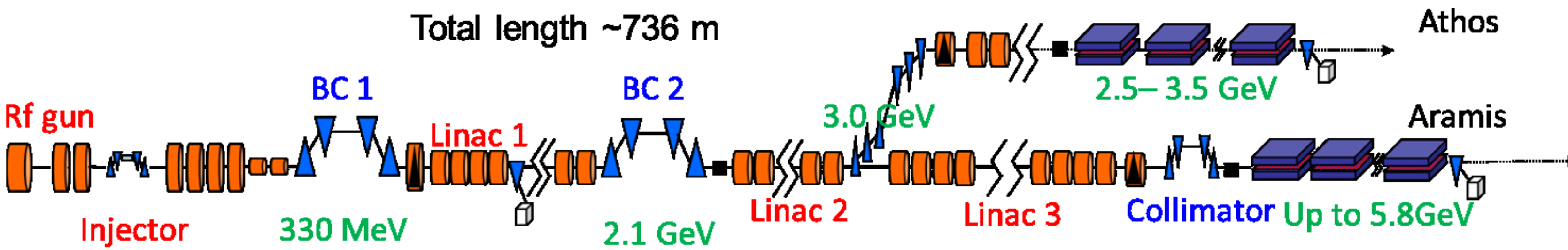
SwissFEL: an X-ray FEL in Switzerland



Electron source

RF gun with CaF_2 laser driven with Cu (or Cs_2Te) photocathode

RF structures

- Normal conducting
- Gun and Injector: S-band
- Linac: C-band
- X-band for phase-space linearization

Undulator beamlines

1. **Aramis**: hard X-ray FEL for SASE (1-7 Å) and self-seeding. In-vacuum , planar undulators with variable gap, period = 15mm
2. **Athos**: soft X-ray FEL for SASE (7-70 Å) and self-seeding. Undulators with variable gap and full polarization control, period = 40mm

Wavelength	1 Å - 70 Å
Pulse duration	3 – 20 fs
e^- Energy	5.8 GeV
e^- Bunch charge	10 – 200 pC
Repetition rate	100 Hz
Slice emittance (design)	0.18 µm (10 pC) 0.43 µm (200 pC)
Slice energy spread	250 – 350 keV
Saturation length	<50 m

Construction started in 2013
Commissioning: from June 2016
First light planned for 2017, first users from 2018
Athos: first light expected for 2020

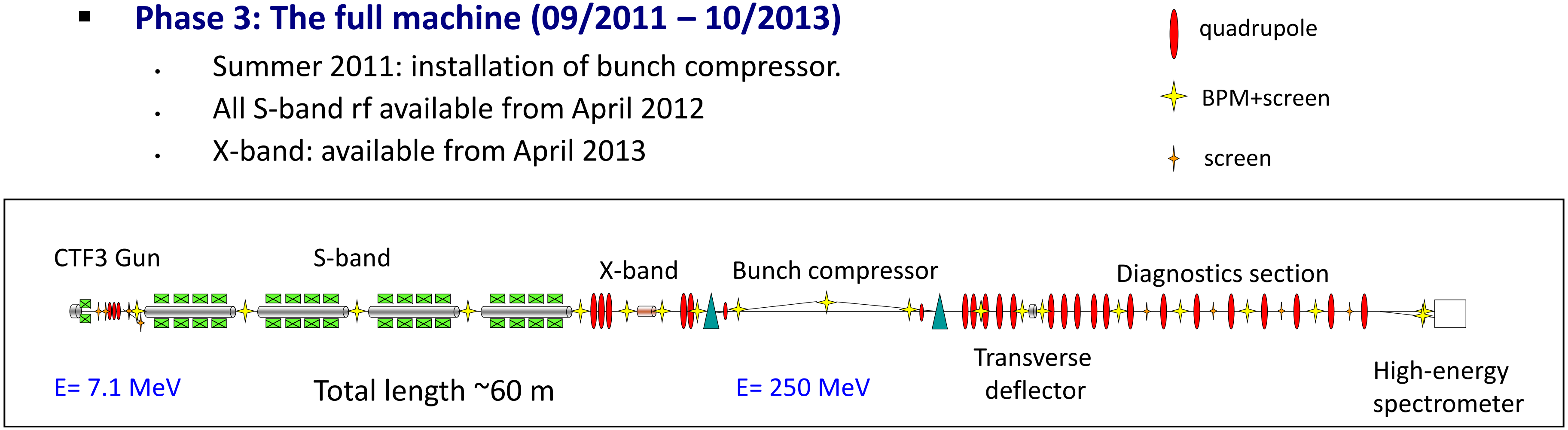
The SwissFEL Injector Test Facility (SITF)

Missions

1) Benchmark the performance predicted by simulations and prove the feasibility of SwissFEL
2) Develop and test components/systems and optimization procedures for SwissFEL

Commissioning phases

- **Phase 1: Electron source and diagnostics (03/2010 – 07/2010)**
- **Phase 2: Phase 1 + (some) S-band acceleration (08/2010 – 05/2011)**
- **Phase 3: The full machine (09/2011 – 10/2013)**
  - Summer 2011: installation of bunch compressor.
  - All S-band rf available from April 2012
  - X-band: available from April 2013



- **Phase 4: Undulator experiment + installation of new PSI gun (01/2014 – 10/2014)**
  First FEL light in Switzerland! *[S. Reiche, FEL14, p. 144 (2015)]*

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Summary of beam physics studies at SITF

Beam and lattice characterization procedures

- Transverse beam characterization
  - Symmetric single-quad scan *[E. Prat, NIMA 743, 103 (2014)]*
  - 4D measurements *[E. Prat and M. Aiba, PRSTAB 17, 052801 (2014)]*
  - Beam-size free optics measurements *[M. Aiba et al, NIMA 753, 24 (2014)]*
  - **SwissFEL profile monitor** *[R. Ischebeck et al, PRSTAB 18, 082802 (2015)]*
- Longitudinal beam characterization and time-resolved measurements
  - Measurement of bunch length (TD) and **beam slice parameters with transverse deflector** and dispersion method *[E. Prat and M. Aiba, PRSTAB 17, 032801 (2014)]*

Beam physics results

- **Cathode (thermal/intrinsic) emittance measurements:**
  - **Wavelength dependence** *[M. C. Divall et al, PRSTAB 18, 033401 (2015)]*
  - **Gradient dependence** *[E. Prat et al, PRSTAB 18, 063401 (2015)]*
  - **Copper vs cesium telluride** *[E. Prat et al, PRSTAB, 043401 (2015)]*
- **Optimization of uncompressed beam:**
  - **Measurements** *[E. Prat et al, PRSTAB 17, 104401 (2014)]*
  - Automatic optimization *[S. Bettoni et al, PRSTAB 18, 123404 (2015)]*
- Emittance preservation at compression *[S. Bettoni et al, PRAB 19, 034402 (2016)]*
- Further measurements:
  - Passive “streaker” *[S. Bettoni et al, PRAB 19, 021304 (2016)]*
  - Beam tilts meas. and correction *[M. Guetg et al, PRSTAB 18, 030701 (2015)]*
  - Comparison FODO vs quad-scan measurements *[M. Yan et al, FEL14, 941 (2015)]*

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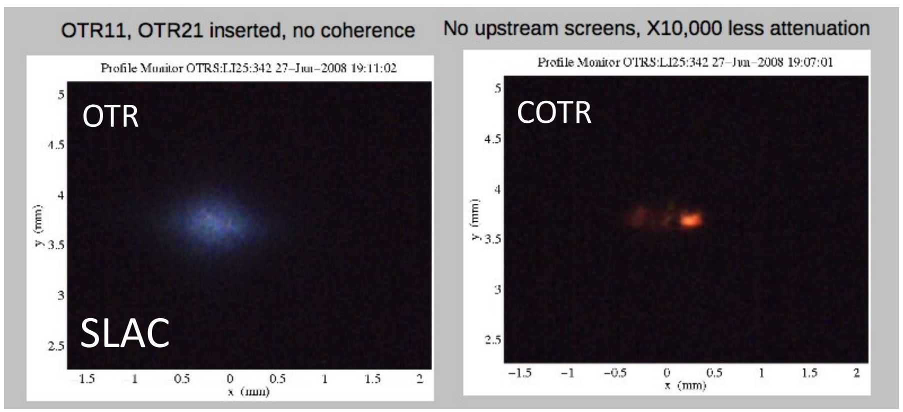
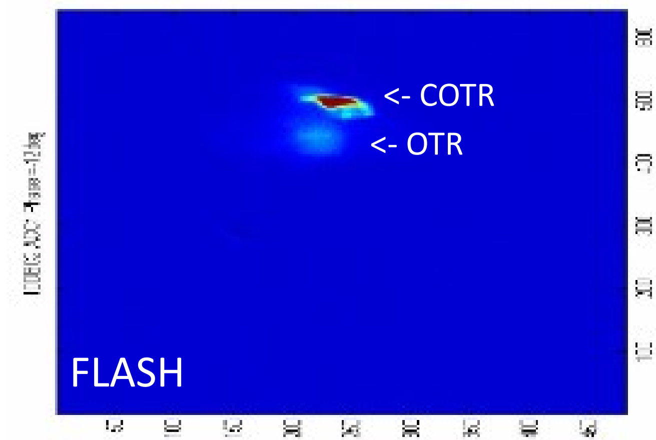
Problem: coherent optical transition radiation

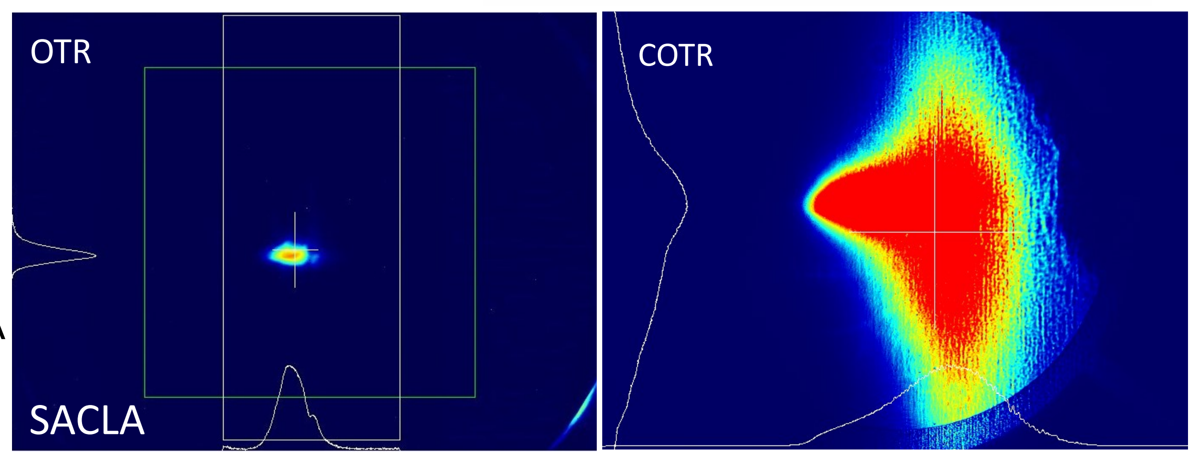
- Traditionally, we use optical transition radiation monitors to measure beam profile
- Highly compressed beams emit coherent radiation that disturbs the measurement
- First observed at LCLS, meanwhile also at FLASH and SACLA





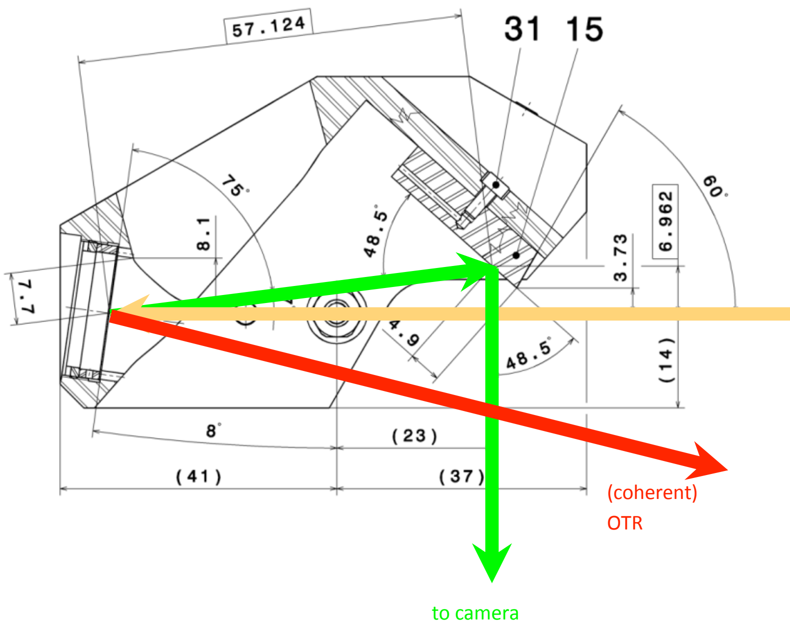
Joe Frisch, SLAC

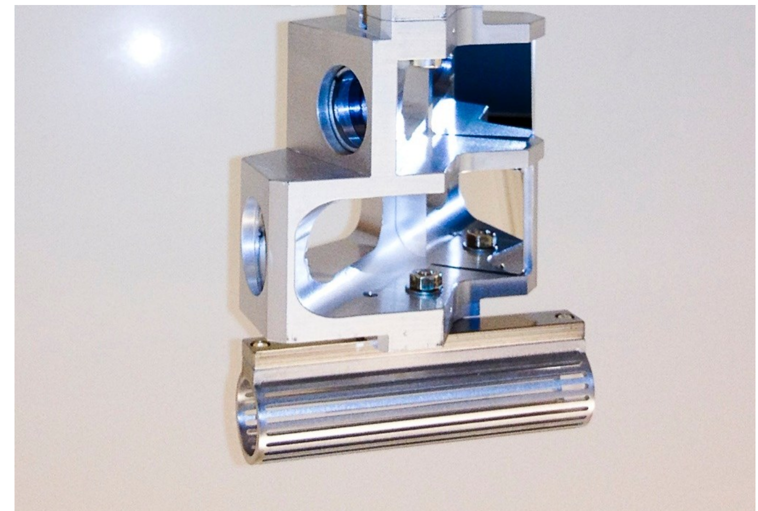
Yuji Otake, SACLA



Solution: use scintillator, direct COTR away

- Transverse profile imager developed at PSI directs COTR away from the camera

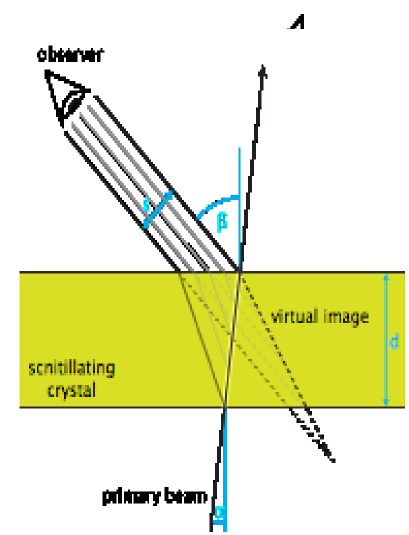




- At the same time, it achieves a good spatial resolution:

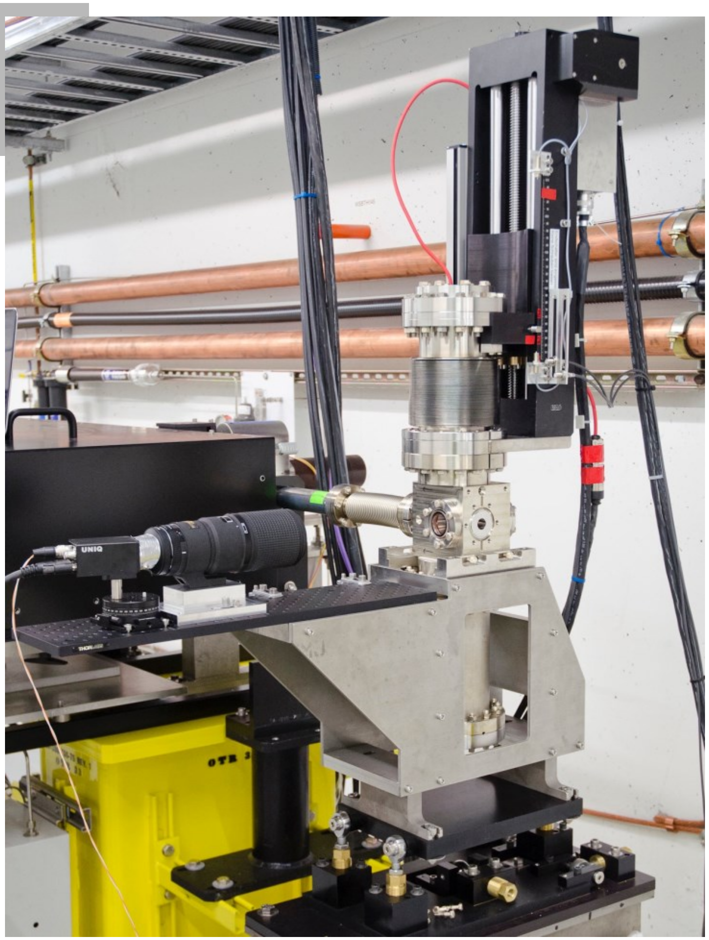
  The YAG / LuAG scintillators are observed at such an angle that Snell's law of refraction is observed. Therefore, we can image beams that are smaller than the thickness of the scintillator.

  At SITF: thickness is 100 μm, beam sizes down to 15 μm have been measured



Measurements at LCLS (December 2013)

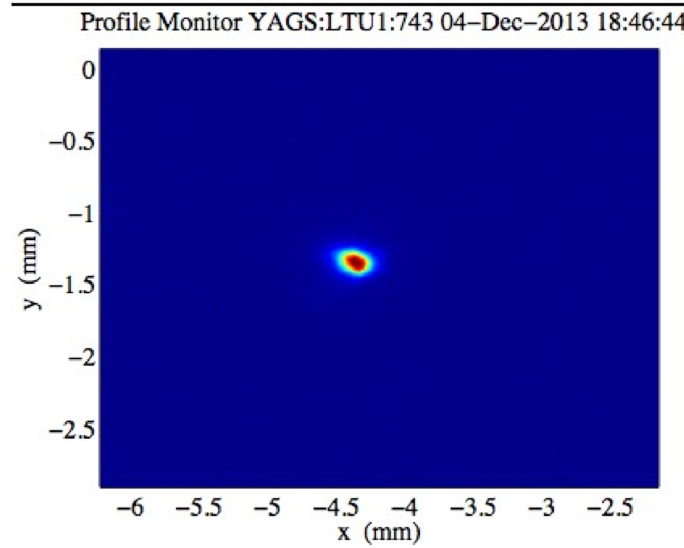
- Measurements at LCLS show <u>no sign</u> of coherent OTR on the camera



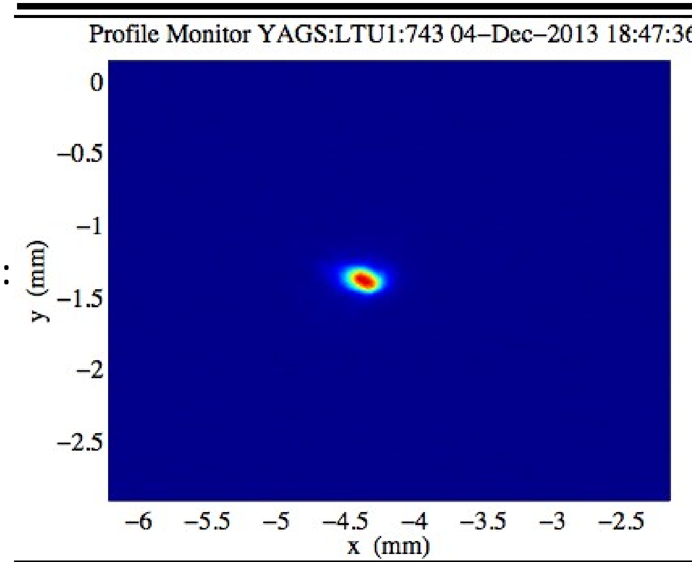
Installation in the LCLS

Linac-to-Undulator line

Laser heater ON:



Laser heater OFF:



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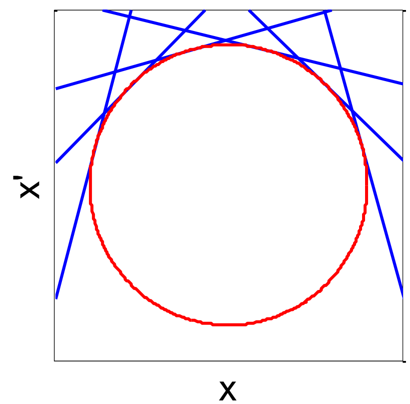
Optics-based emittance measurements

- The initial beam moments at s_0 are obtained by measuring the beam sizes at s for different optics transformations

$$\left\langle x^2 \right\rangle_s = R_{11}^2 \cdot \left\langle x^2 \right\rangle_{s_0} + R_{12}^2 \cdot \left\langle x'^2 \right\rangle_{s_0} + 2R_{11}R_{12} \cdot \left\langle xx' \right\rangle_{s_0}$$

- At least 3 transformations are needed, but more measurements improve the robustness of the reconstruction



$$\varepsilon_x = \sqrt{\left\langle x^2 \right\rangle \cdot \left\langle x'^2 \right\rangle - \left\langle xx' \right\rangle^2}$$

$$\beta_x = \left\langle x^2 \right\rangle / \varepsilon_x$$

$$\gamma_x = \left\langle x'^2 \right\rangle / \varepsilon_x$$

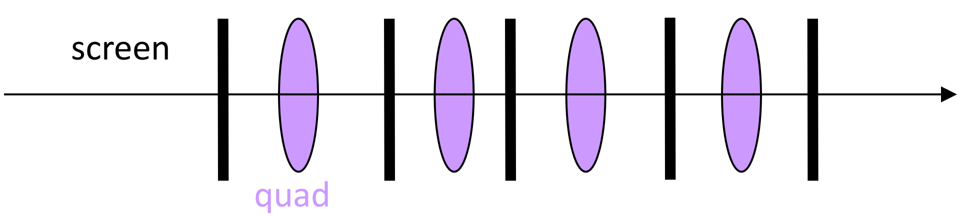
$$\alpha_x = -\left\langle xx' \right\rangle / \varepsilon_x$$

- The best reconstruction is when the phase-advance is covered regularly between 0 and π

- From the beam moments the emittance and the Twiss parameters are obtained

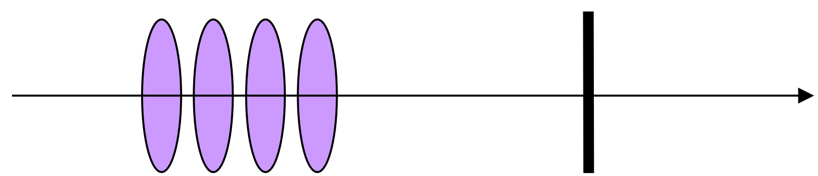
- There are two general strategies to scan the phase advance

I. Multiple position with fixed optics: *FODO*



Parasitic measurements
More equipment
Dedicated long lattices
Not flexible
Generally worse resolution

II. Fixed position with multiple optics: *Quadrupole scan*



No parasitic measurements
Less equipment
More compact
Very flexible
Generally better resolution

Chosen option for emittance meas.

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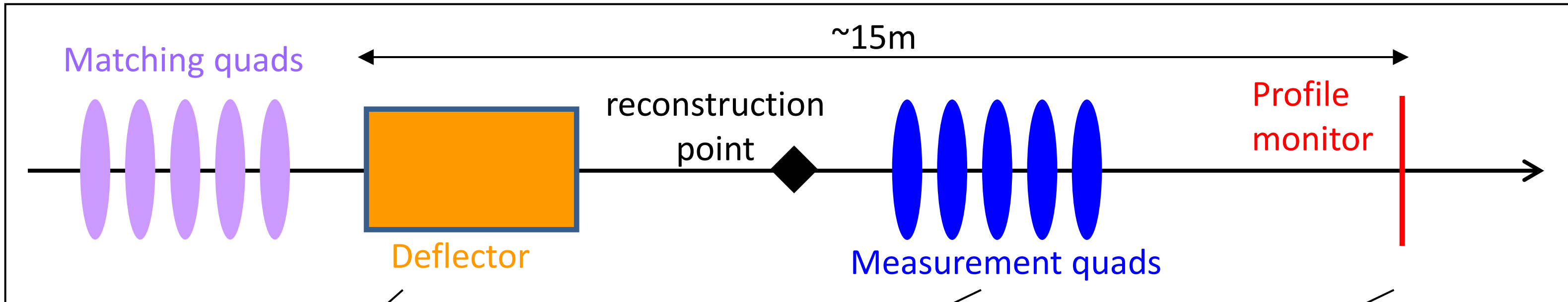
Slice emittance measurements at SITF

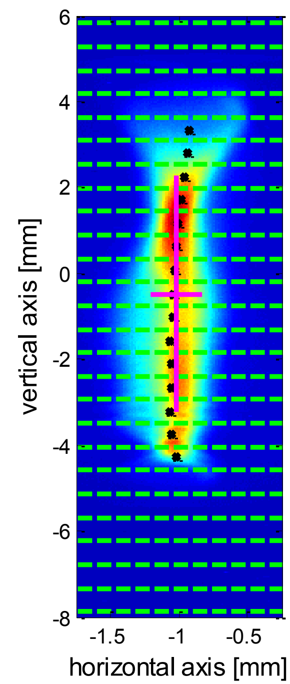
The beam is deflected in one direction as a function of time and the slice parameters in the other direction are reconstructed using 2D profile monitors.



Deflection.
The streaking can be done:
1. Using an RF Transverse Deflector (TD) (y)
2. Introducing dispersion to an energy chirped beam (x and y)

Optics. The optics are scanned using 5 quads between the transverse deflector and the observation point

Image analysis. The beam is split into slices, using the centroid from Gauss fit as a reference. Per each slice the beam size from Gauss fit is obtained.



Emittance/mismatch determination. From the beam sizes per each optics the emittance and optics are obtained per each slice

Optics for slice emittance measurements

5 quadrupoles are used to:

- Scan phase-advance in the meas. plane
- Optimize longitudinal resolution
- Keep β-functions at the PM under control

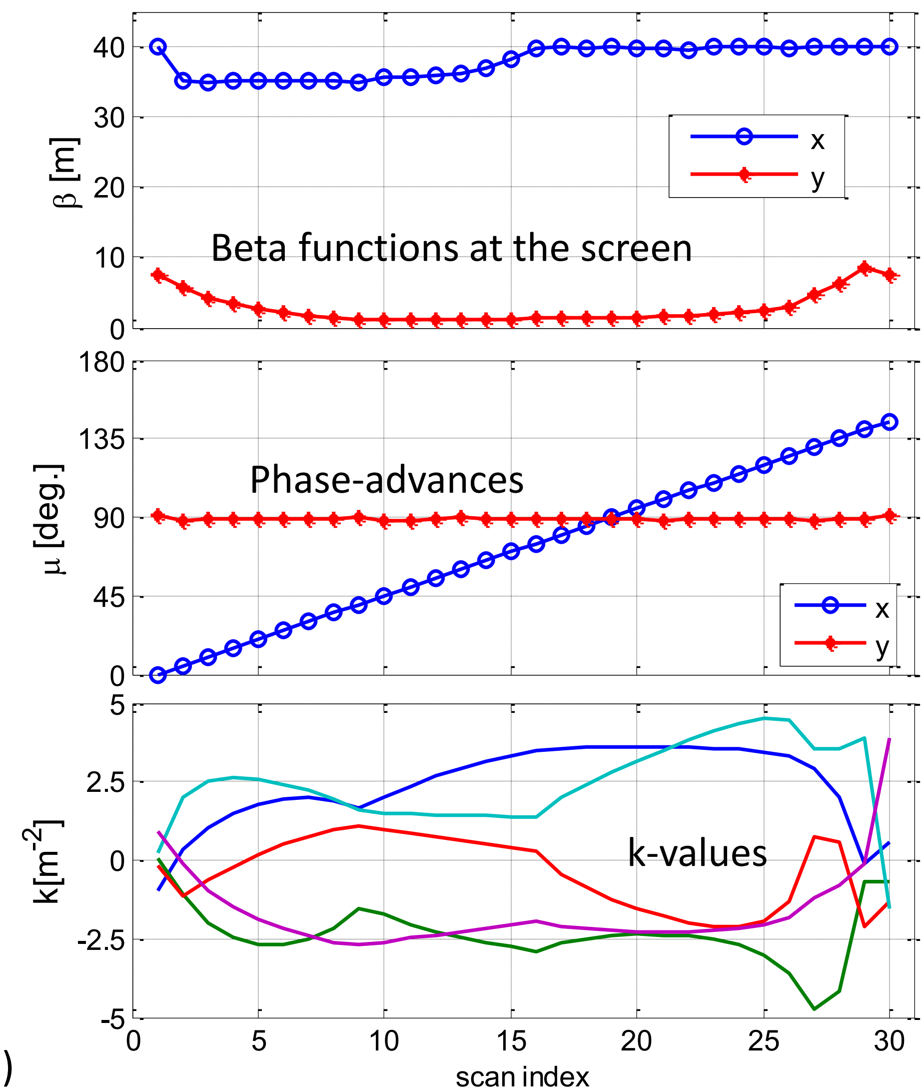
K-values are obtained doing an optimization with the code *elegant*

$$\text{Longitudinal resolution} \propto \frac{\sqrt{\varepsilon_y}}{\sum_i \sqrt{\beta_{y_{TD_i}}} \cdot \sin(\Delta\mu_{y_{TD_i \to PM}})}$$

β_{yTDi} : β-function at the deflector *i* in the streaking direction
$\Delta\mu_{yTDi \to PM}$: vertical phase-advance in the streaking direction between deflector *i* and profile monitor
ε_y= emittance in the streaking direction

Long. resolution (assuming , ε_y=0.5μm, E=250MeV)
TD: ~**4 μm** (V=5MV)
Dispersion method (dE/E=1%):
x meas: 5 slices per bunch length (quad. kick = 5mrad)
y meas: 6 slices per bunch length (max. corr. strength)

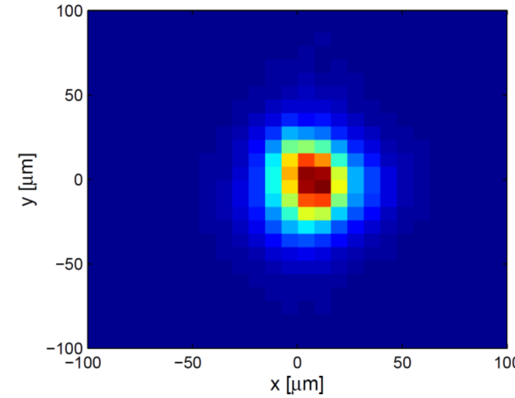
Optics example for TD measurements

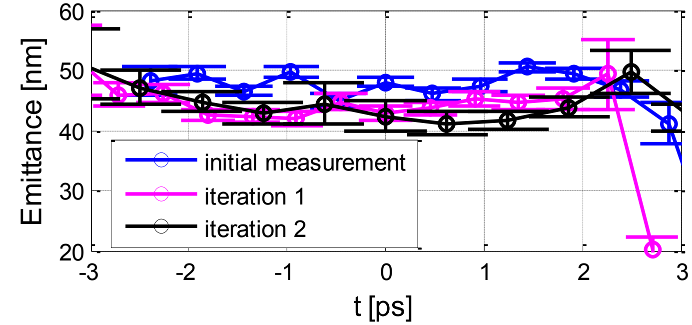


Emittance resolution, errors and matching

- SwissFEL profile monitor (YAG)
  - Beam size resolution is ~15 μm, equivalent to an emittance resolution of 1-3 nm (E=250MeV)
  - Signal to noise ratio is good enough to measure slice emittance for bunch charges of less than 1pC

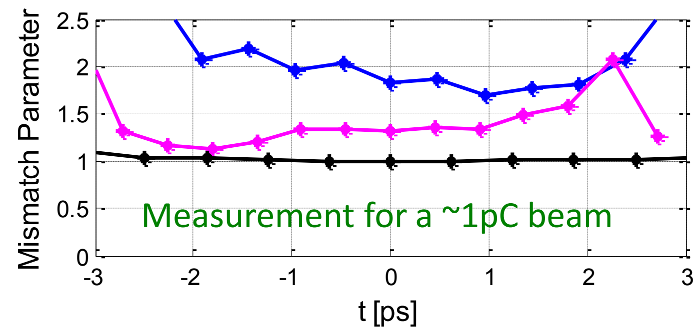
Beam image close to screen resolution limit





Errors

- Statistical errors from beam size variations (what is shown in the error bars of the measurements). For 5% of beam size measurement error this is below 3% (if $\Delta\mu_x$=10deg).
- Systematic errors expected to be below 5%:
  - Screen calibration (~1%→~2%) and resolution
  - Energy and quadrupole field errors (<1%)
  - Optics mismatch
  - Others (e.g. errors associated to Gauss fit)



Matching

- Beam core is always matched to exclude errors due to optics mismatch
- Matching of the core works normally in 1-2 iterations
- Successful matching gives us confidence in the obtained emittance values

$$M = \frac{1}{2}(\beta\gamma_D - 2\alpha\alpha_D + \gamma\beta_D)$$

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Thermal emittance

$$\varepsilon_{th} = \sigma_l \sqrt{\frac{2E_k}{3m_e c^2}}$$

E_K: average kinetic energy of the electrons at the cathode surface

metals: $$2E_k = \phi_l - \phi_w + \phi_{Sch}$$

semiconductors: $$2E_k = \phi_l - E_g - E_a + \phi_{Sch}$$

Schottky effect: $$\phi_{Sch} = \sqrt{\frac{e^3}{4\pi\varepsilon_0}\beta E_c}$$

Φ_l: laser photon energy, Φ_w: material work function
E_g: gap energy, E_a: electron affinity, E_{g+} $E_{g:}$ threshold energy
β: local field enhancement factor (surface properties), E_c: field at the cathode

Wide range of values in literature: Φ_w= 4.66$\pm$0.51 eV, E_{g+} E_g = 3.5 – 4.6 eV, β=1-5 and higher

→ *Thermal emittance can not be estimated accurately and needs to be measured*

When E_c varies in a small range for a metal photocathode $$QE \propto \left(\phi_l - \phi_{eff}\right)^2$$

The effective work function (Φ_l-Φ_w)c an be determined by measuring the QE as a function of the phase (Schottky scan) OR the QE as a function of the laser energy (wavelength scan)

Overview of thermal emittance measurements

Thermal emittance measurements as a function of

- Laser wavelength
- Field at the cathode
- Cathode material: copper and cesium telluride

Procedures

- Emittance: The thermal emittance is defined as the core slice emittance when space-charge and rf effects are negligible
  The normalized thermal emittance $\varepsilon_{th}/\sigma_{l}$ is reconstructed by measuring the emittance as a function of the rms laser beam size
- The effective work function for copper can be alternatively reconstructed from:
  - Wavelength scan (QE vs laser wavelength)
  - Schottky scan (QE vs rf phase)
- The QE is measured by recording the charge at a calibrated BPM (2.6 m downstream of the gun) as a function of the laser intensity.

Used lasers

- Ti:Sapphire laser + OPA (variable wavelength)
- ND:YLF laser (wavelength fixed to 262 nm)

Used cathodes

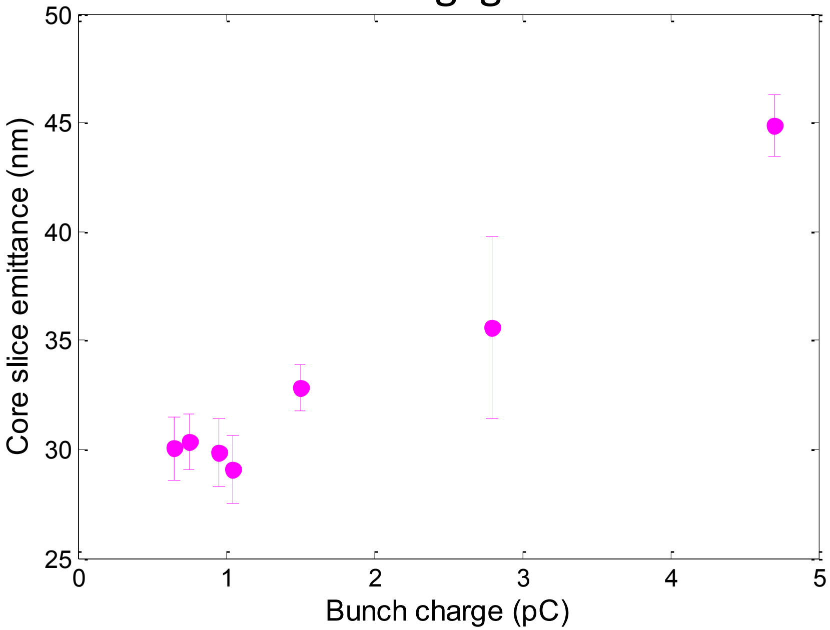
- Copper: Cu-3 (laser dependence), Cu-19 (field at the cathode dependence), Cu-22
- Cesium telluride: Cs_2Te-8, Cs_2Te-17

Used guns

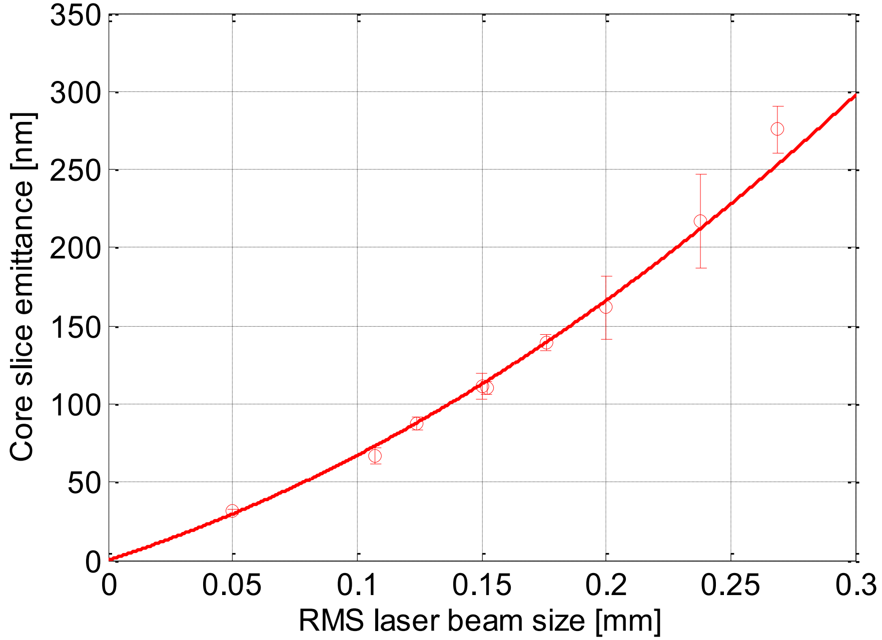
- CTF3 gun: cathode field is 50 MV/m
- PSI gun: cathode field if 76 MV/m

From slice emittance to thermal emittance

1) Be sure that space-charge effects are negligible



2) Take into account the high-order rf effects



- We find the space-charge limit by decreasing the charge until the emittance is constant. Then the charge-density is kept constant for all the laser sizes
- Need to have high-sensitivity profile monitor!

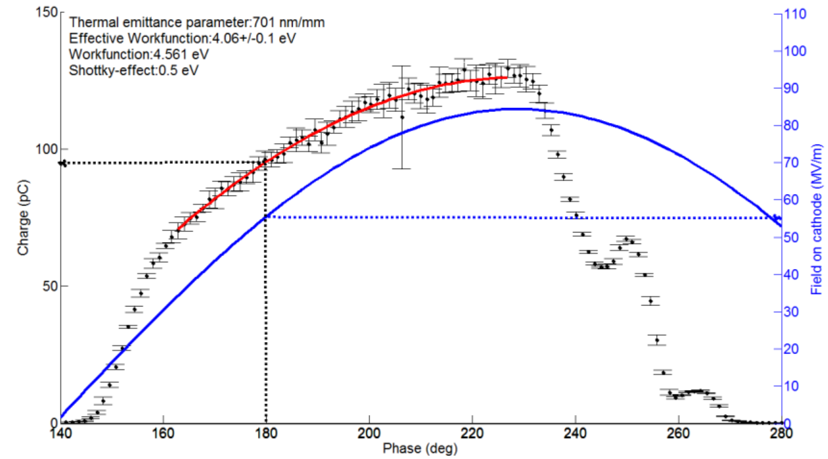
- The high-order effects depend on the rf field (see next slides)
- More linear behavior with new SwissFEL gun

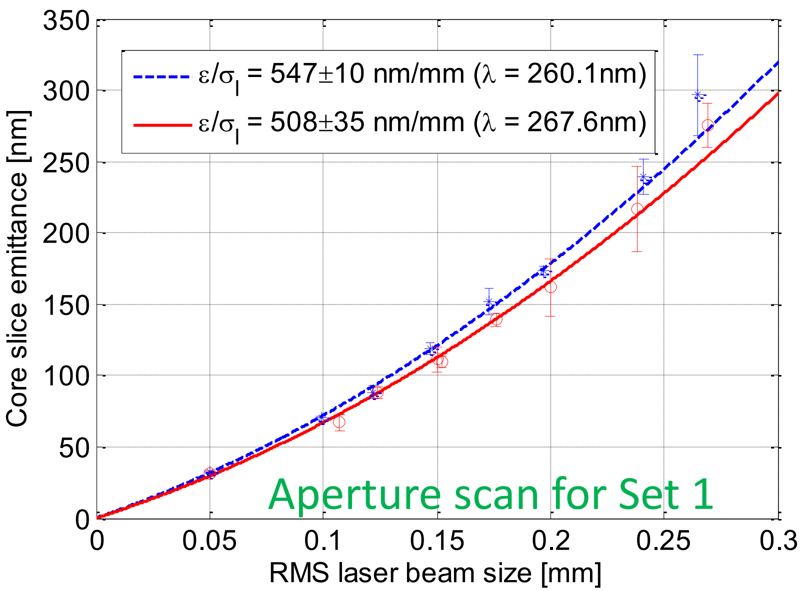
Wavelength dependence

Set 1: (260.1 nm and 267.6 nm)
- Direct emittance measurement (aperture scan)
- Schottky scan

Set 2 (1 month later than set 1):
- Slice emittance at smallest aperture for 4 wavelengths between 260.1 nm and 275 nm (overestimates thermal emittance by 10-20%)
- Schottky scan
- Wavelength scan (250-300 nm)

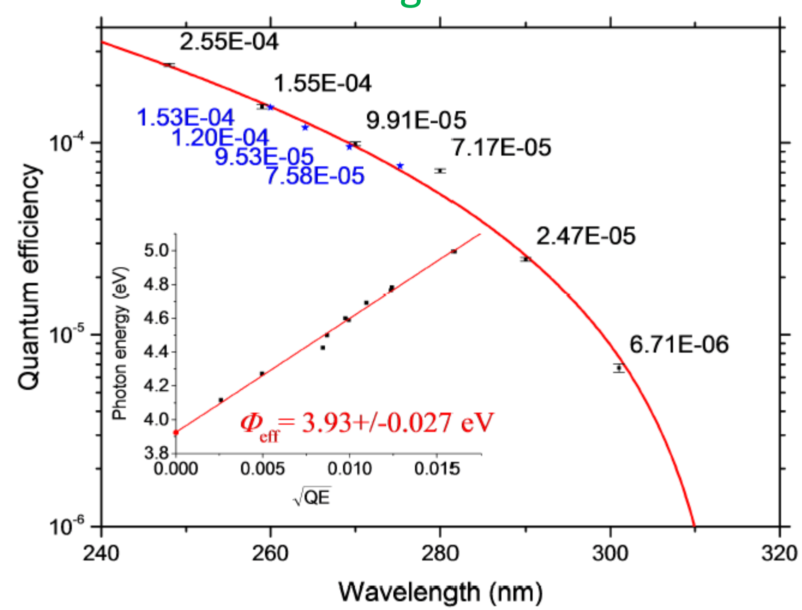
Schottky-scan example





Aperture scan for Set 1

Wavelength scan for Set 2



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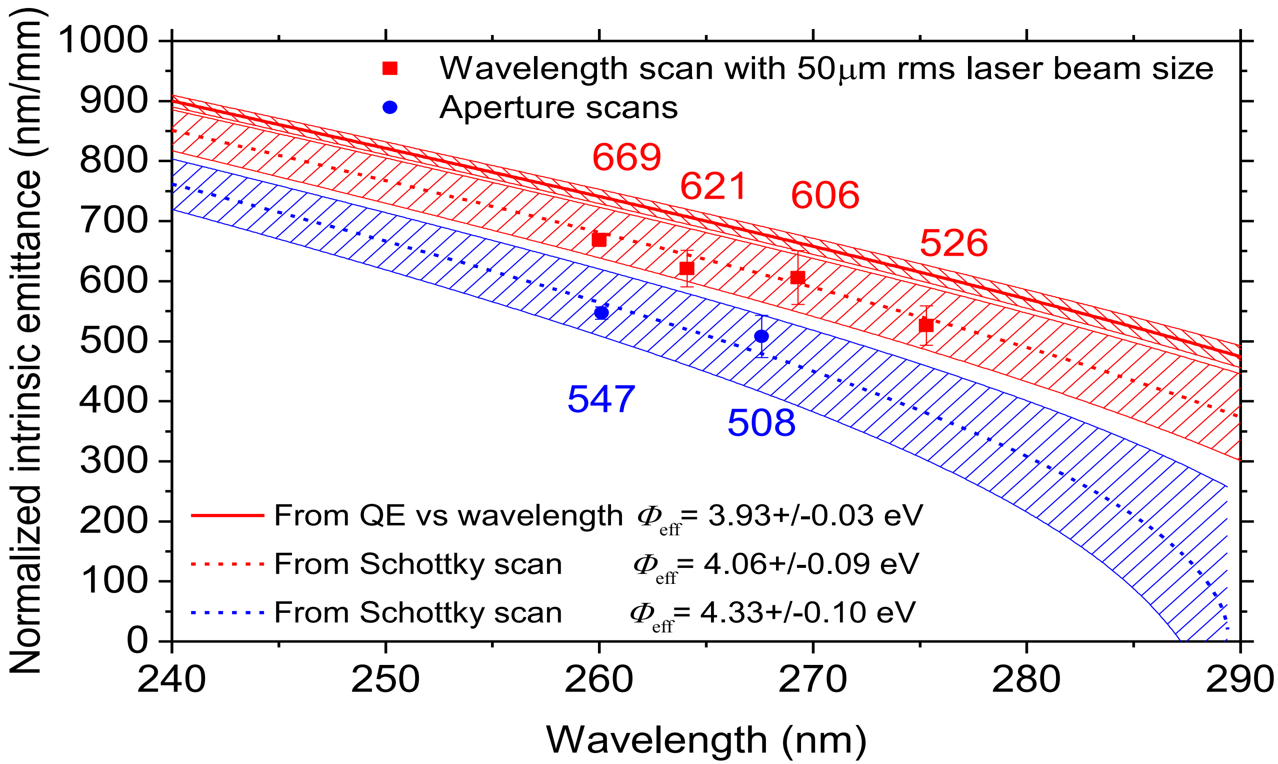
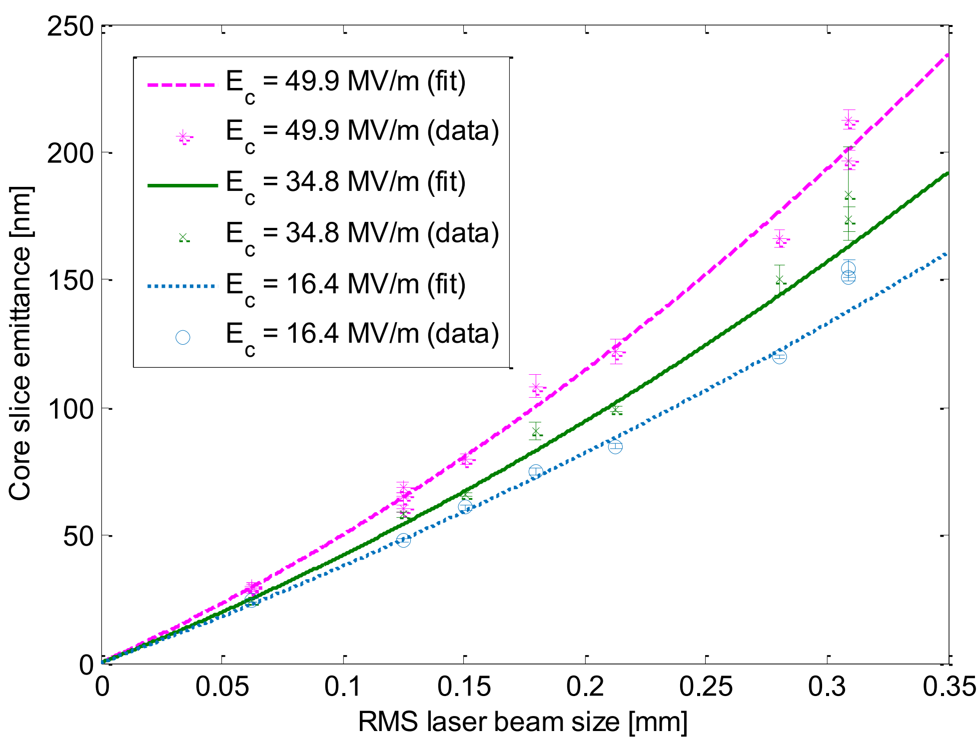
Wavelength dependence: summary



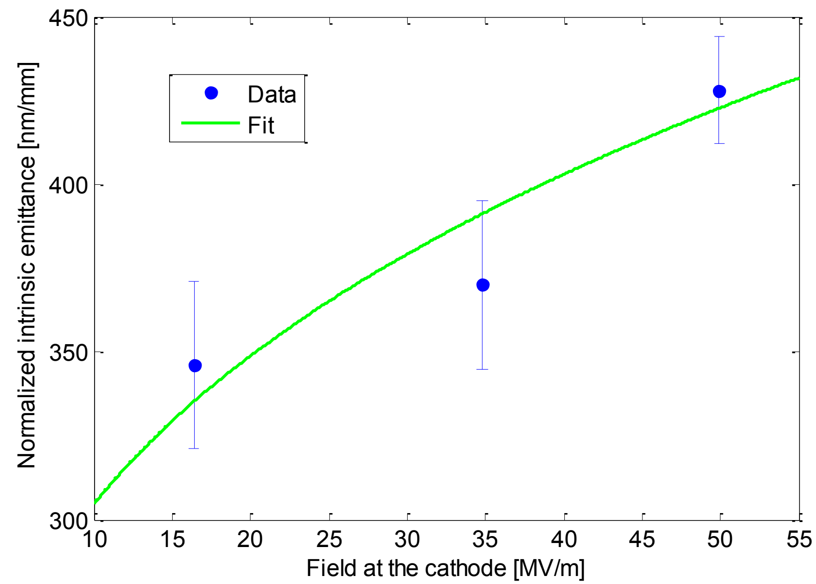
- Measurements agree well with expected work functions
- Wavelength dependence as expected by theory $\varepsilon_{th} / \sigma_l \propto \sqrt{\phi_l}$
- Wavelength-scans and Schottky-scans can be used to reconstruct the normalized thermal emittances (but larger errors)
- Same cathode show different work function after one month of operation

Field at the cathode dependence

Field at the cathode (MV/m)	$\varepsilon_{th}/\sigma_l$ (nm/mm)	Quadratic component (nm/mm^2)
49.9	428±16	724±84
34.8	370±25	505±137
16.4	346±25	321±105



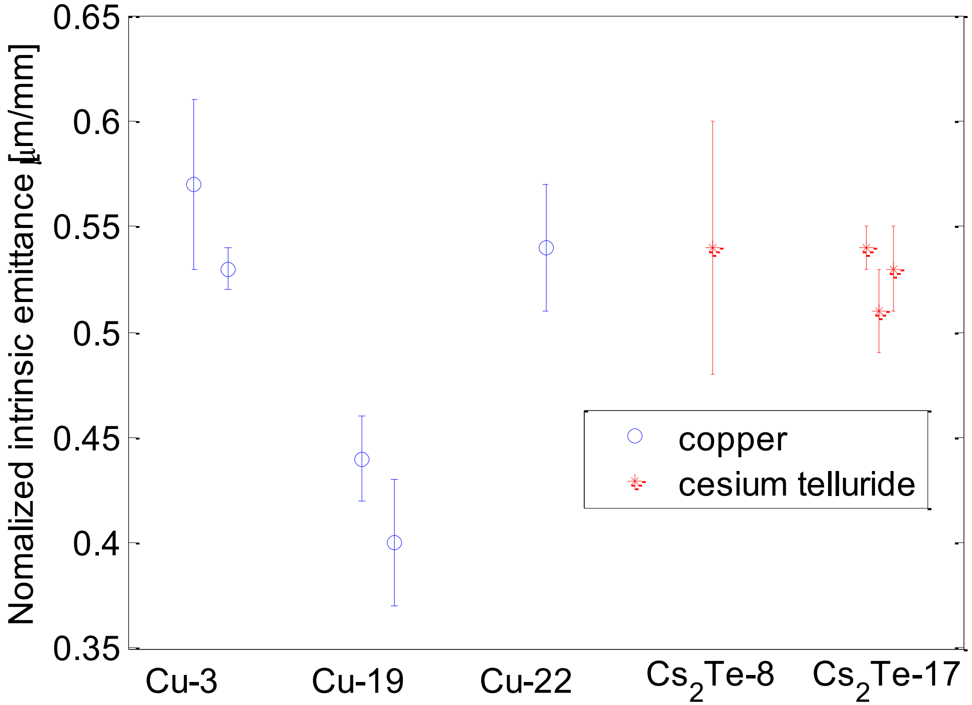
- Quadratic component decreases as a function of the gradient → higher order effects are due to rf



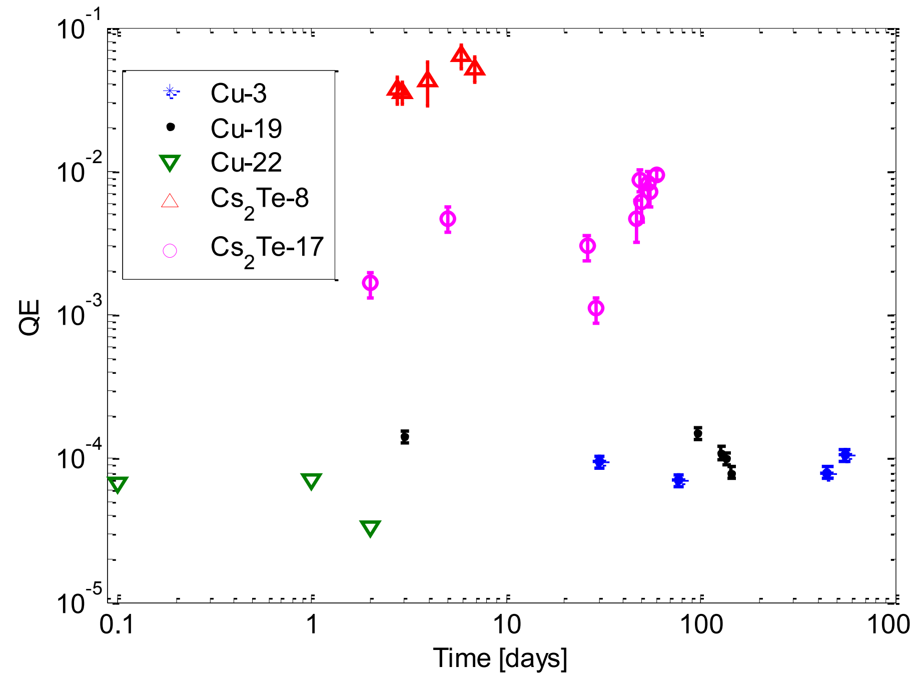
- Best fit with Φ_w= 4.70±0.07 eV and β = 0.79±0.52. Good agreement with expectations
- Thermal emittance is reduced by 20% but overall emittance can be worse due to lower beam energy. Moreover QE is suppose to be much worse (60% smaller)

Material dependence: Cu vs Cs_2Te

Thermal emittance measurements
(normalized for λ = 262 nm and 50 MV/m)



QE measurements



- The QE of Cs_2Te is about 2 orders of magnitude larger than for Cu
- The thermal emittance is equivalent

Conclusion: **Cs_2Te will be used for SwissFEL**

Summary of thermal emittance measurements

Material	Meas. day	$\varepsilon_{th}/\sigma_l$ (µm/mm)	Laser wave. (nm)	Cathode field (MV/m)	$\varepsilon_{th}/\sigma_l$ (norm. *) (µm/mm)
Cu-3	31-10-2012	0.55±0.01	260.1	49.9	0.53±0.01
Cu-3	30-10-2012	0.51±0.04	267.6	49.9	0.57±0.04
Cu-19	25-09-2013	0.44±0.02	262.0	49.9	0.44±0.02
Cu-19	25-09-2013	0.37±0.03	262.0	34.8	0.40±0.03
Cu-19	27-09-2013	0.35±0.03	262.0	16.4	0.43±0.03
Cu-19	04-04-2014	0.40±0.03	262.0	49.9	0.40±0.03
Cu-22	13-04-2014	0.58±0.03	262.0	76	0.54±0.03
Cs_2Te-8	04-04-2014	0.54±0.06	262.0	49.9	0.54±0.06
Cs_2Te-17	08-04-2014	0.54±0.01	266.6	76.0	0.54±0.01
Cs_2Te-17	08-04-2014	0.50±0.02	266.6	76.0	0.51±0.02
Cs_2Te-17	08-04-2014	0.52±0.02	266.6	76.0	0.53±0.02

Wavelength dependence
Cathode field dependence
Cs_2Te measurements

(*) Normalized to 262 nm and 50 MV/m

Measurements at other labs

Cu: **~0.9 µm/mm** *[H. J. Qian et al, PRSTAB 15, 040102 (2012)], [Y. Ding et al, PRL. 102, 254801 (2009)]*

Cs_2Te: **> 1 µm/mm** *[F. Stephan et al., PRSTAB 13, 020704 (2010)]*

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Emittance optimization for uncompressed beams

- Strategy: optimize projected emittance in both planes, then measure slice emittance
- Optimization mainly for 200 pC
- Main used knobs:

Knob	Physics effect	Comments
Laser longitudinal profile	Invariant envelope matching	Tuned to flat top
Laser transverse profile	Emittance and x/y asymmetry	Tuned as homogeneous and symmetric as possible
Laser alignment	Orbit, dispersion	Standard beam based alignment
Laser radius (aperture)	Invariant envelope matching	Iris set to simulated optimum / scanned
Gun solenoid field	Invariant envelope matching	Scanned empirically
Gun solenoid alignment	Orbit (wakes), dispersion	Standard beam based alignment
Corrector quads in solenoid	x/y coupling	Systematically optimized
Gun gradient	Invariant envelope matching	Set to design in spectrometer (7.1 MeV)
Gun phase	Optimize energy spread	Minimize beam size in spectrometer
FINSB01 gradient	Emittance matching	Set to design
FINSB solenoids	x/y coupling	Systematically optimized
Orbit through FINSB1-4	Projected emittance (wakes)	Beam based alignment
Orbit after S-band	Dispersion	Beam based alignment

Example of optimization: coupling correction

- Coupling measurement with multi-quadrupole scan
- General correction approach: $\vec{P} = S\vec{C} \rightarrow \vec{C} = S^{-1}\vec{P}$
- Knobs
  - Quad correctors in gun solenoid (normal/skew)
  - S-band solenoid pairs (increase one of them and decrease the other):
  - FINSB01-MSOL10 + FINSB01-MSOL20 / FINSB02-MSOL10 + FINSB02-MSOL30
  - (4 skew Q correctors available in addition at SwissFEL)

$\vec{P}$: *Beam parameters to be corrected*

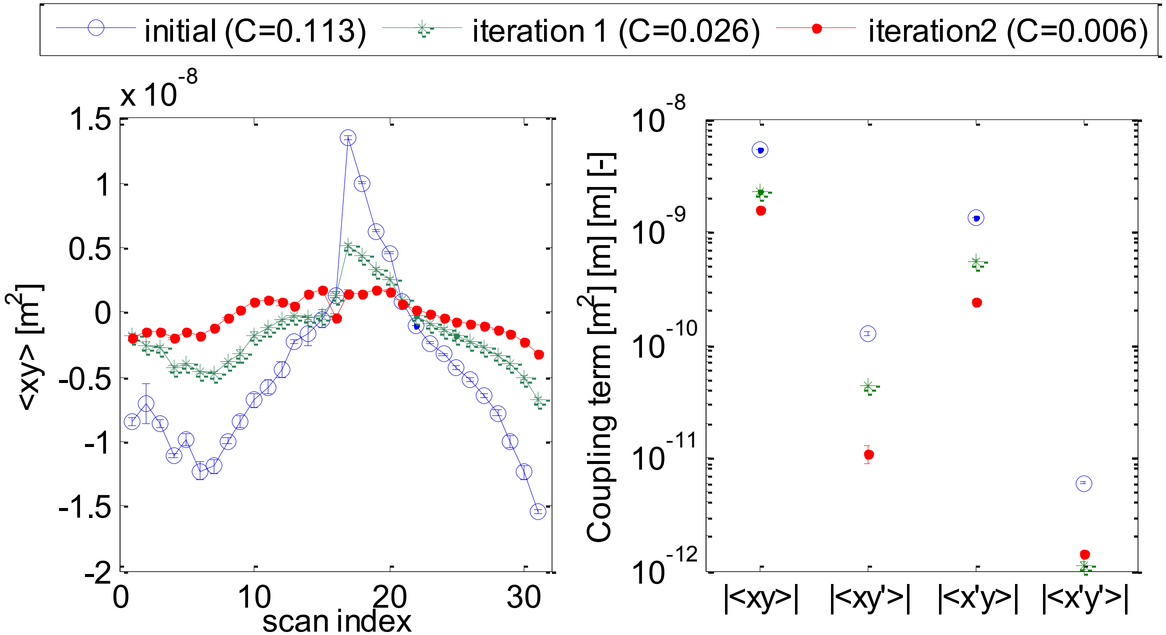
$<xy>, <xy'>, <x'y>, <x'y'>$

S : *Sensitivity matrix*

$\vec{C}$: *Corrections*

Correction results

Coupling contribution to the emittance *C* reduced from 11.3% to 0.6% in 2 iterations

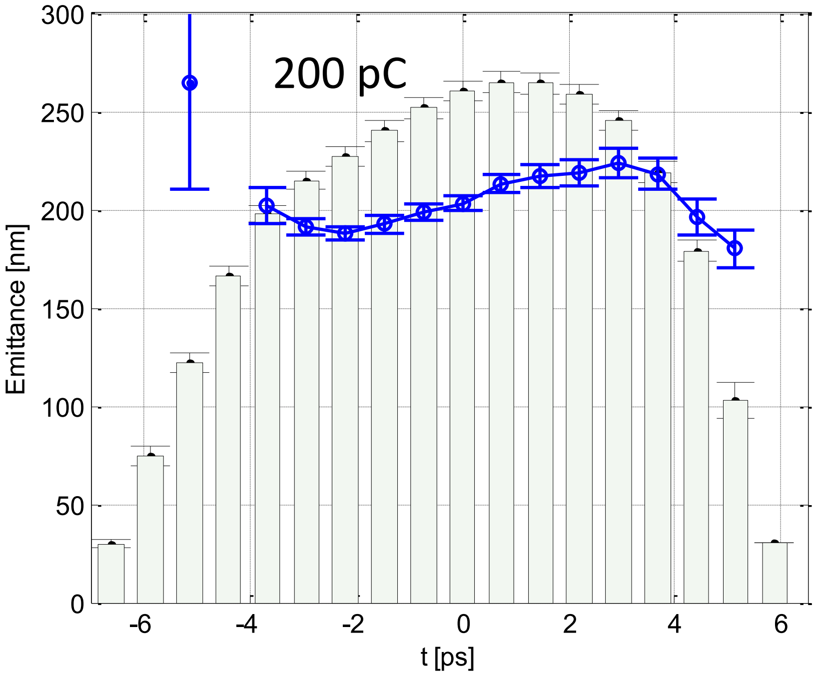


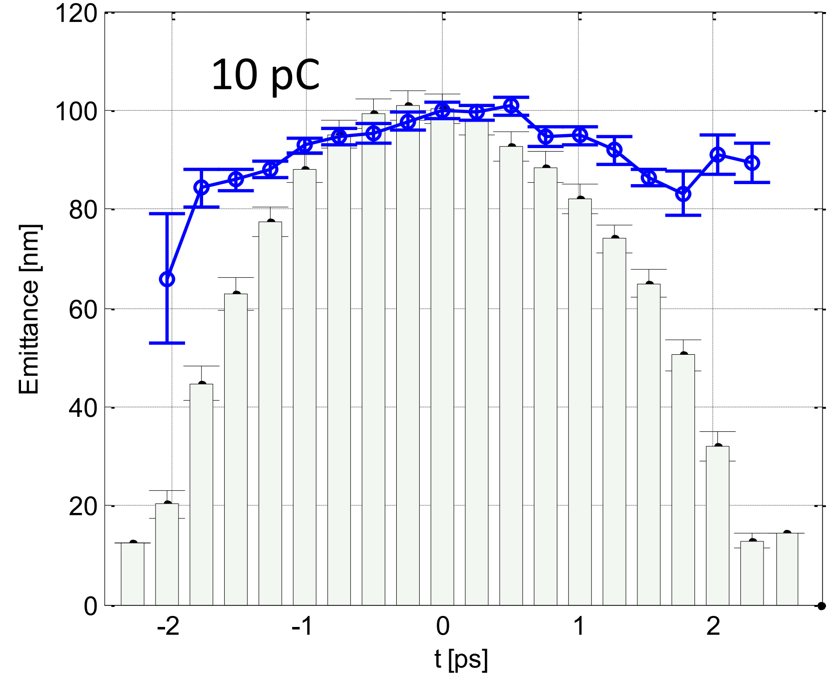
Optimum emittances

- We have achieved the following emittances

	200 pC	10 pC	25 pC
Projected emittance	~0.30 µm	~0.15 µm	~0.15 µm
Slice emittance	~0.20 µm	~0.10 µm	~0.10 µm

- These emittance values fulfill the SwissFEL requirements
- Emittance values are stable in short-term and optimum settings are reproducible
- Emittance is preserved for compressed bunches after careful adjustment of the optics





Conclusions

- We have established a precise method of high resolution to measure the emittance: errors are below the 5% level, longitudinal resolution is about 10 fs. This is crucial to measure thermal emittance and to optimize injector emittance towards very low values.
- Measured thermal emittance dependence on laser wavelength, cathode field and cathode material (Cu and Cs_2Te). Values around 500 nm/mm. Lessons learned: use Cs_2Te for SwissFEL
- Excellent measured emittances that fulfill the SwissFEL requirements: slice emittance of 200 nm for 200 pC (and 100 nm for 25 pC)