Thermal Emittance Measurements at the SwissFEL Injector Test Facility

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Conclusion

- Method to measure slice emittance developed and tested at the SwissFEL Injector Test Facility:
  - Errors estimated to be smaller than 5%
  - Longitudinal resolution of ~4 µm (with TD) / Emittance resolution of 2-3 nm
  - Normalized emittance measured down to 25 nm for a beam charge of 30 fC
  - Normalized thermal emittance measured down to ~350 nm/mm
- Thermal emittance measurements agree well with theoretical expectations
  - Effective work functions,
  - Wavelength and cathode field dependence
- Effective work function can be reconstructed from Schottky and wavelength scans
- Measured Cu and Cs_2Te under the same conditions. Cs_2Te seems a viable option for SwissFEL:
  - Slice and thermal emittance ~25% higher than for Cu
  - QE of few per cent ~2 orders of magnitude higher than for Cu

Introduction (I)

+ SwissFEL

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

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

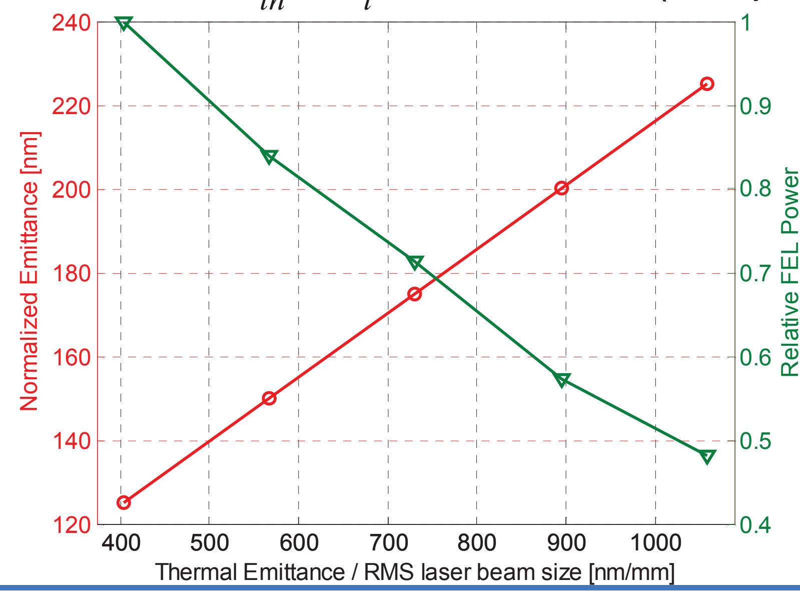
$$\varepsilon_{th} = \sigma_l \sqrt{\frac{\phi_l - \phi_{eff}}{3 m_0 c^2}}$$

σ_l rms laser beam size,

ϕ_l laser photon energy,

ϕ_{eff} effective work function

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



Introduction (II)

+ SwissFEL

$$\varepsilon_{th} = \sigma_l \sqrt{\frac{\phi_l - \phi_{eff}}{3m_0c^2}}$$

Effective work function $$\phi_{eff} = \phi_w - \phi_s = \phi_w - \sqrt{\frac{e^3}{4\pi\varepsilon_0}\beta E_c(\varphi)}$$

ϕ_w material work function ϕ_s Schottky effect

β Enhancement factor (surface properties)

$E_c(\varphi)$ Field on the cathode at injection phase φ

Expected effective work functions: ~4.0 eV for copper, ~3.6 eV for cesium telluride

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

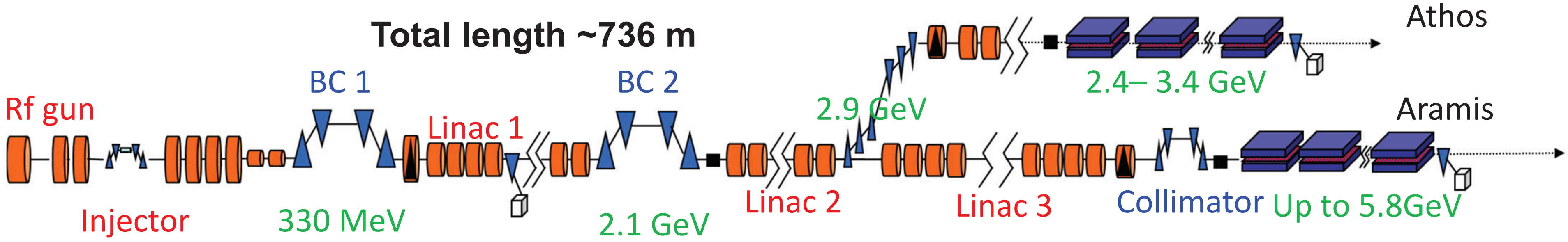
The effective work function can be determined by measuring the **QE as a function of the phase (Schottky scan)** OR the **QE as a function of the laser energy (wavelength scan)**

Refs:

D. H. Dowell and J. Schmerge, Phys. Rev. ST Accel. Beams 12, 074201 (2009).
K. Flöttmann, TESLA FEL Report No. 1997-01, 1997.
Z. M. Yusof, M. E. Conde, and W. Gai, Phys. Rev. Lett. 93, 114801 (2004).
H. J. Qian et al, Phys. Rev. ST Accel. Beams 15, 040102 (2012).

SwissFEL: a hard and soft X-ray FEL in Switzerland

+ SwissFEL



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: end 2015 – mid 2017
User operation for Aramis planned in 2017
Athos planned for 2019

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

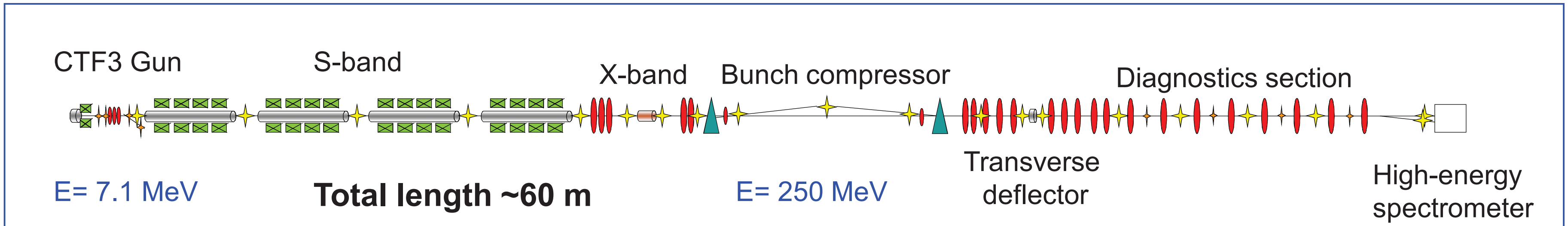
Commissioning phases

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

quadrupole

BPM+screen

screen



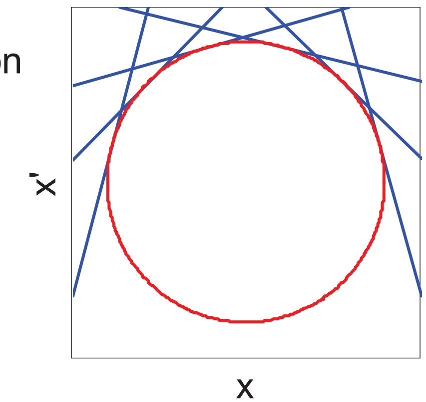
- **Phase 4: Undulator experiment (first FEL in Switzerland, see MOP053) + installation of new PSI gun, see THP049 (2014)**

Optics-based emittance measurements

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

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

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



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

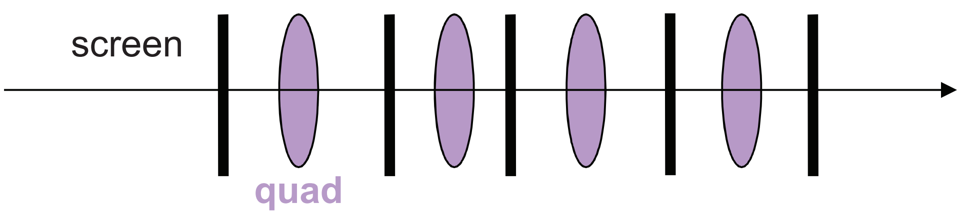
$$\beta_x = \langle x^2 \rangle / \varepsilon_x$$

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

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

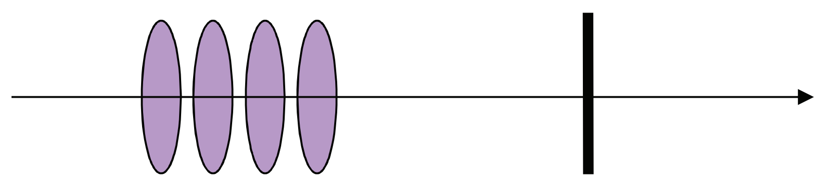
- There are two general strategies to scan the phase advance

I. Multiple position with fixed optics: *FODO*



Parasitic measurements
More equipment
Dedicated long lattices
Not flexible

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



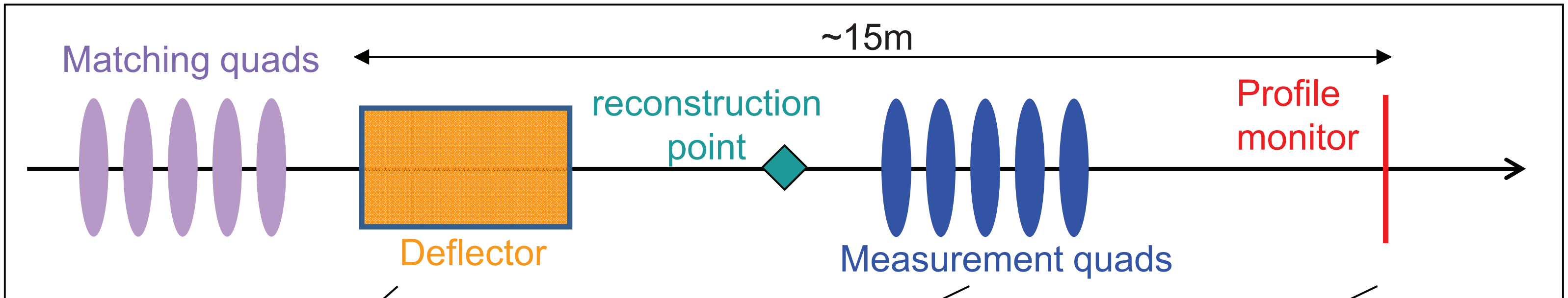
No parasitic measurements
Less equipment
More compact
Very flexible

Chosen option for emittance meas.

Slice emittance measurements at SITF

+ SwissFEL

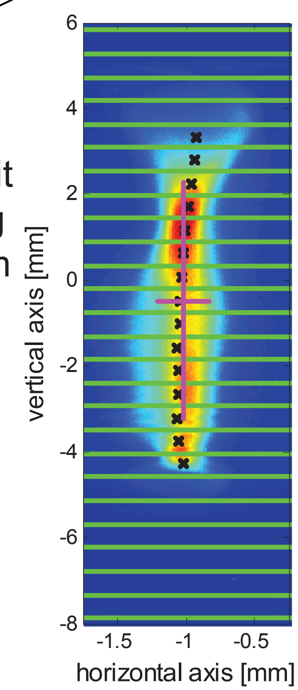
The beam is **deflected** in one direction as a function of time and the slice parameters in the other direction are reconstructed using 2D profile monitors.



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

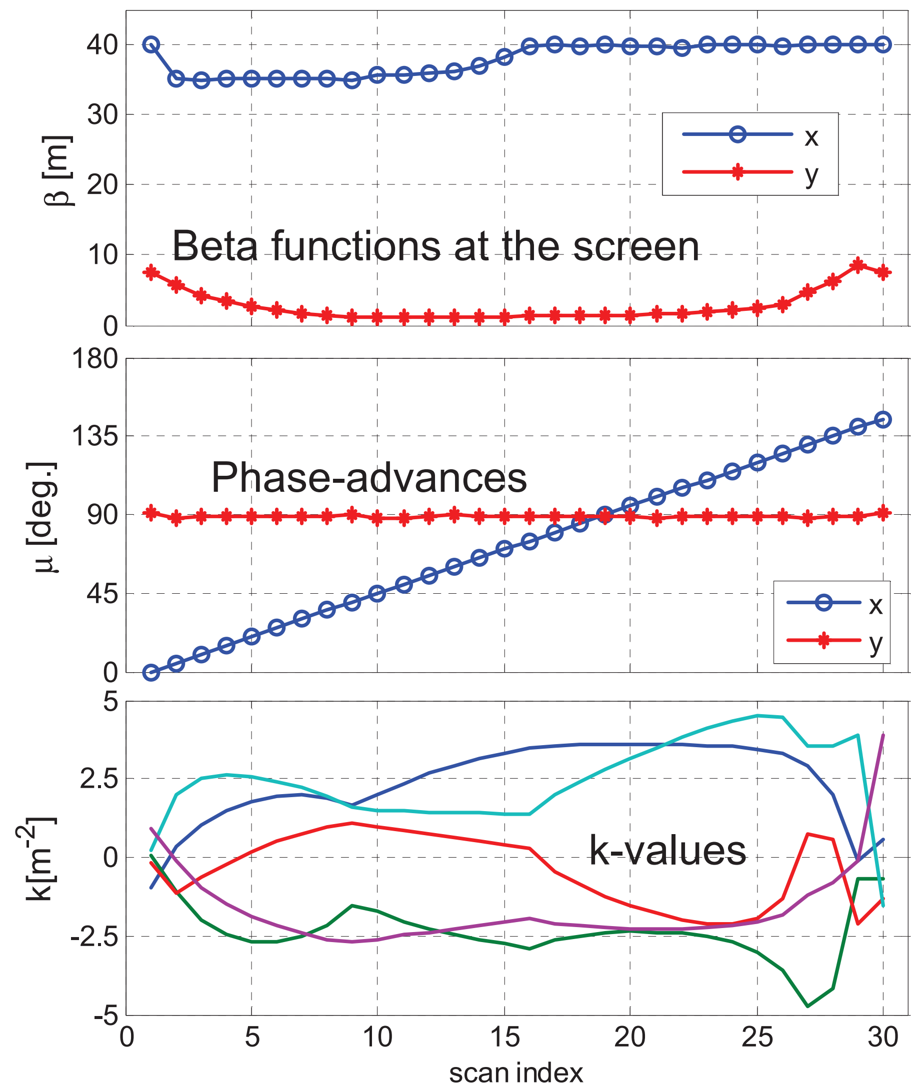
5 quadrupoles are used to:
- Scan phase-advance in the meas. plane
- Optimize longitudinal resolution
- Keep beta-functions at the PM under control

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

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 **2-3 nm** (E=250MeV)
  - Signal to noise ratio is good enough to measure slice emittance for bunch charges of less than **1pC**

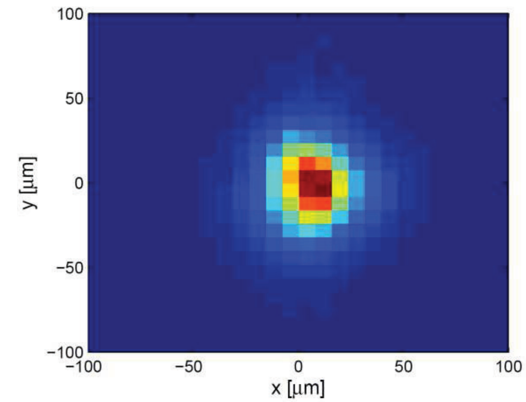
Errors

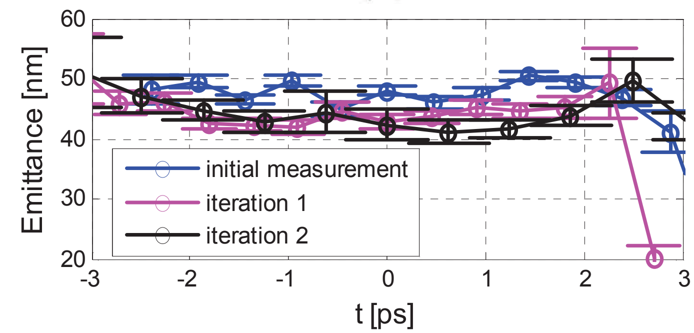
- Statistical errors from beam size variations (what is shown in the error bars of the measurements). For 5% of beam size measurement error this is below 3% (if $\Delta\mu_x$=10deg).
- Systematic errors expected to be below 5%:
  - Screen calibration (~1%→~2%) and resolution
  - Energy and quadrupole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

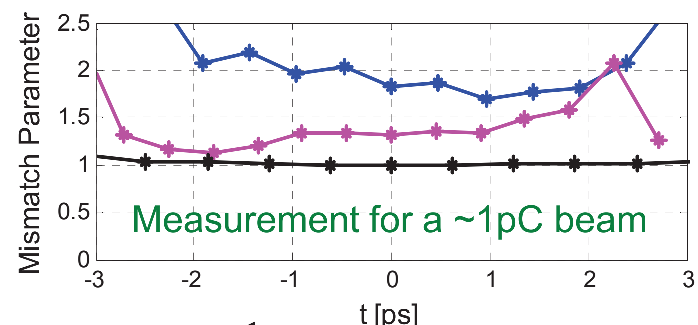
Matching

- 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

Beam image close to screen resolution limit

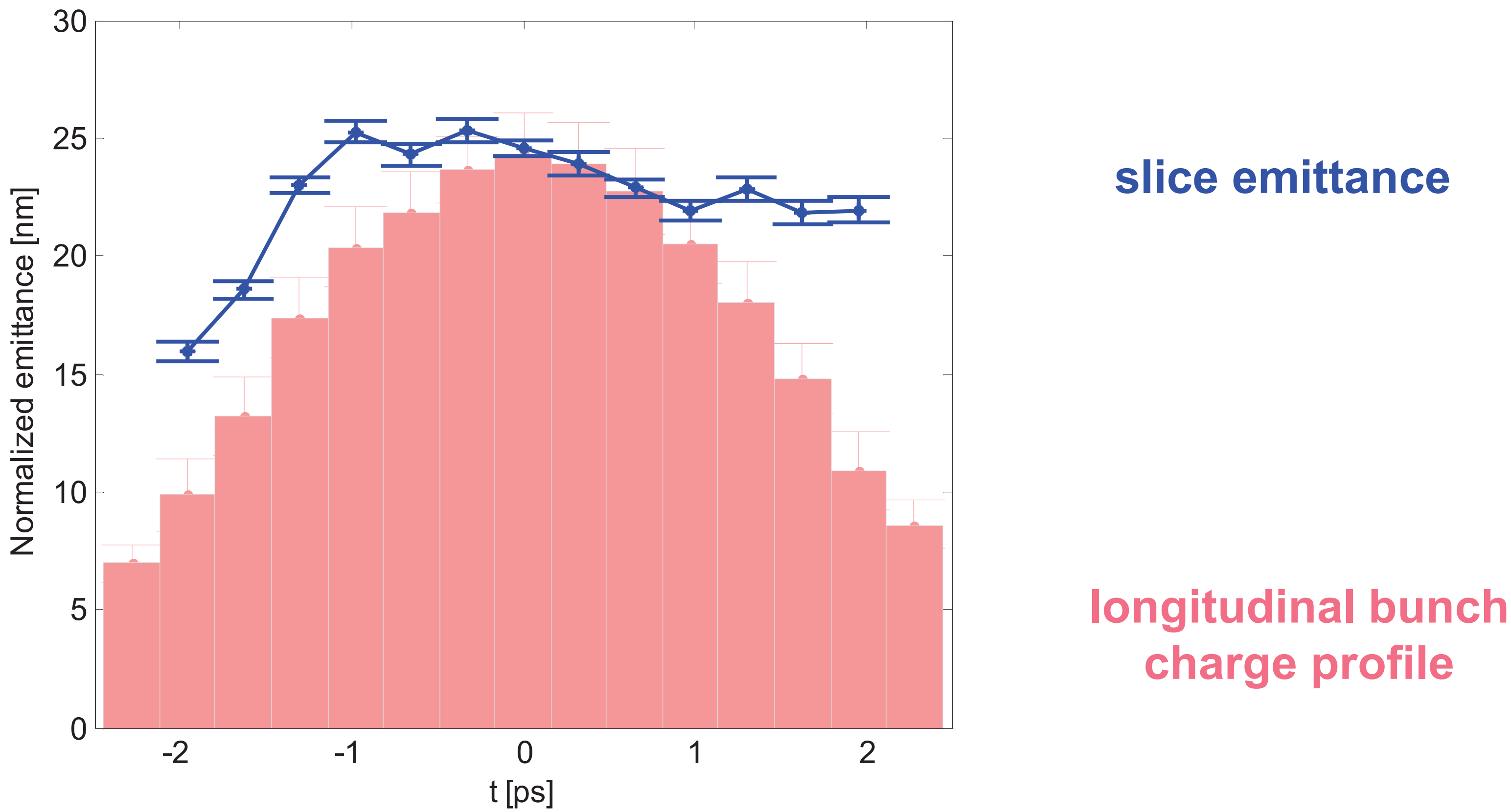






$$M = \frac{1}{2}(\beta\gamma_D - 2\alpha\alpha_D + \gamma\beta_D)$$

Smallest measured emittance



- Measurement done for a total bunch charge of about **30 fC**
- Measurement done with low gradient (E=3.7 MeV) and smallest laser aperture (rms laser beam size around 50 μm)
- Core slice emittance **< 25 nm**

Overview of the 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 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 (wavelength dependence measurements)
- ND:YLF laser (all the rest)

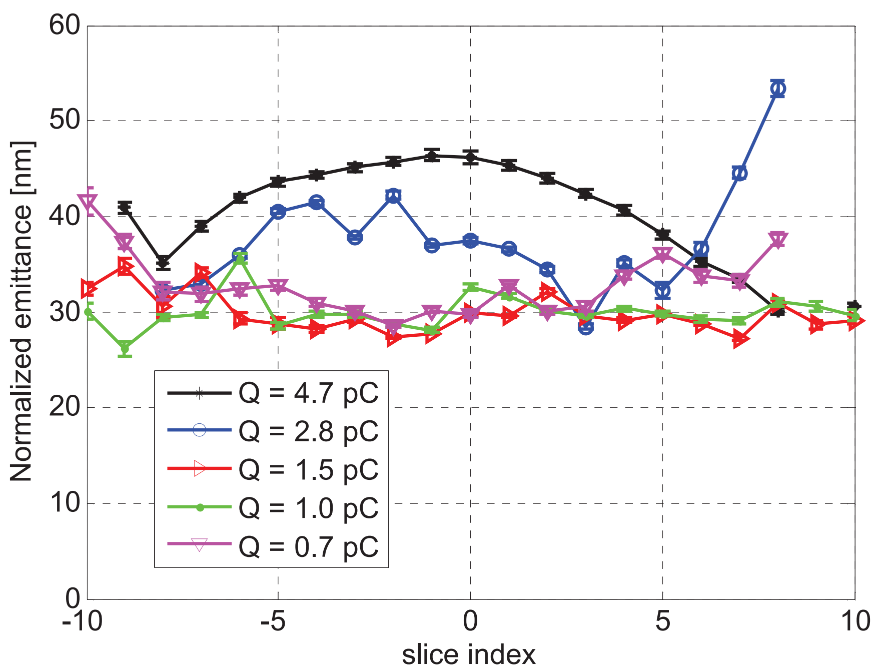
Used cathodes (see **THP046**)

- Copper: cath_3 (laser dependence), cath_19 (field at the cathode dependence)
- Cesium telluride: cath_13 and cath_8

From the slice emittance to the thermal emittance

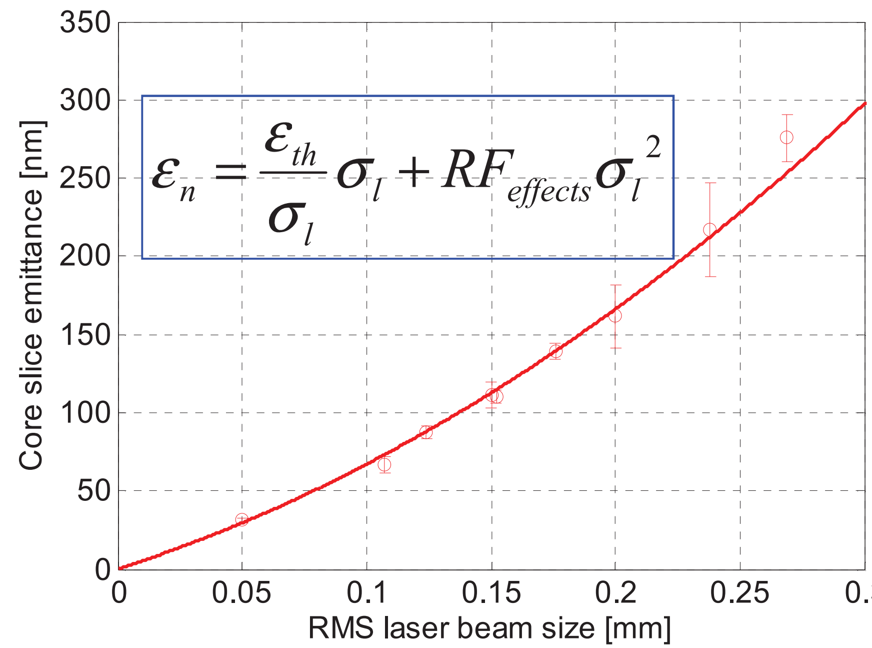
+ SwissFEL

1) Be sure that space-charge effects are negligible



- 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!

2) Take into account the high-order rf effects



$$\varepsilon_n = \frac{\varepsilon_{th}}{\sigma_l}\sigma_l + RF_{effects}\sigma_l^2$$

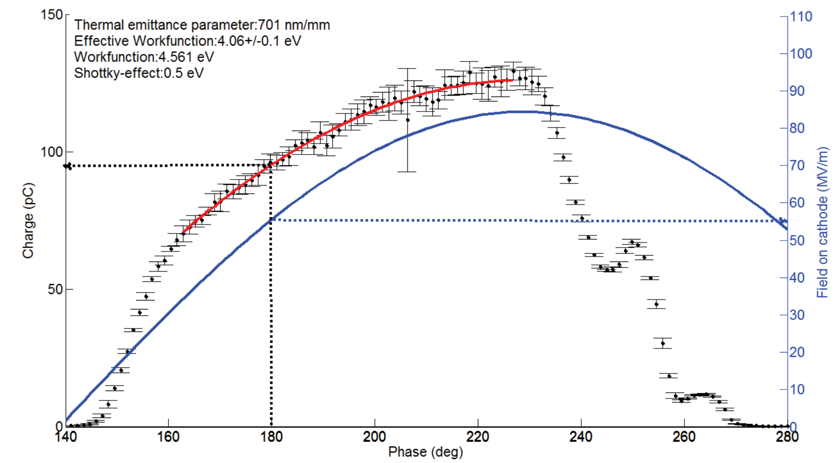
•The high-order effects depend on the rf field (see next slides)
•Linear behavior with new SwissFEL gun

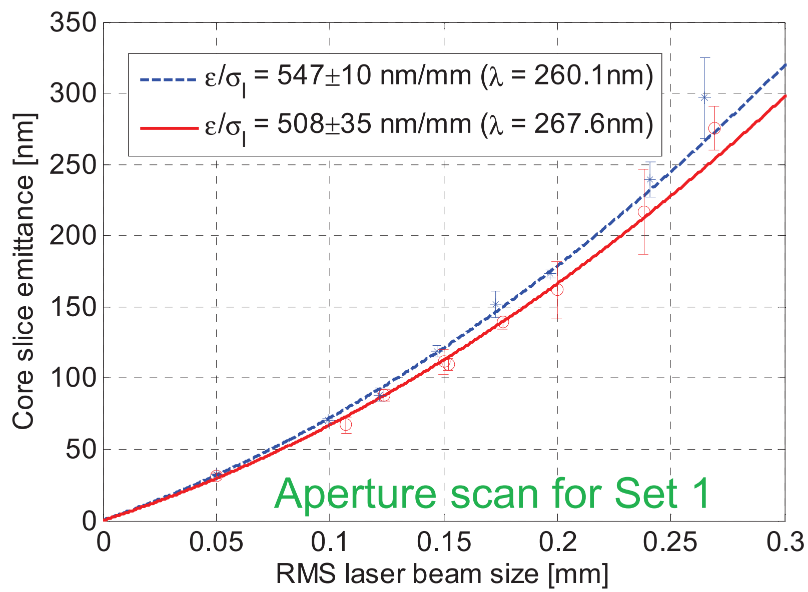
Wavelength dependence

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

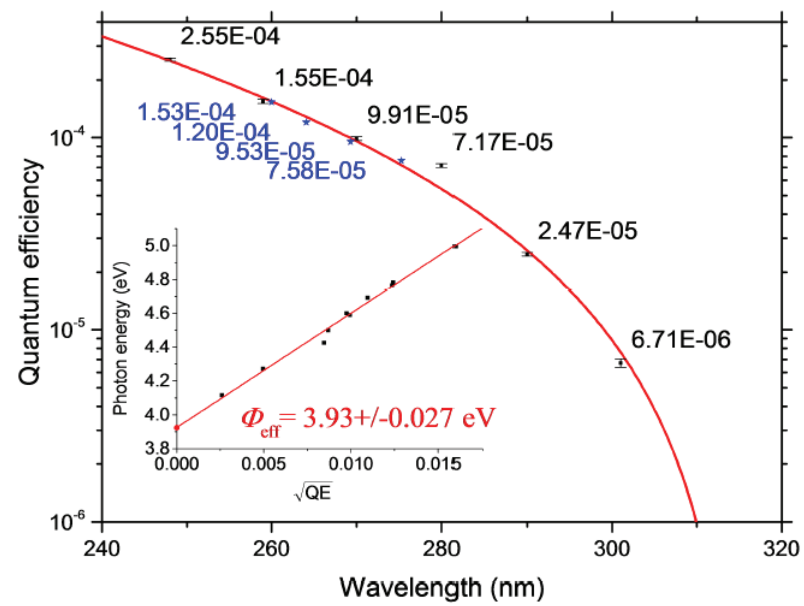
Set 2 (1 month later than set 1):
- Slice emittance at smallest aperture for 4 wavelengths between 260.1 nm and 275 nm (overestimates thermal emittance by 10-20%)
- Schottky scan
- Wavelength scan (250-300 nm)

Schottky-scan example



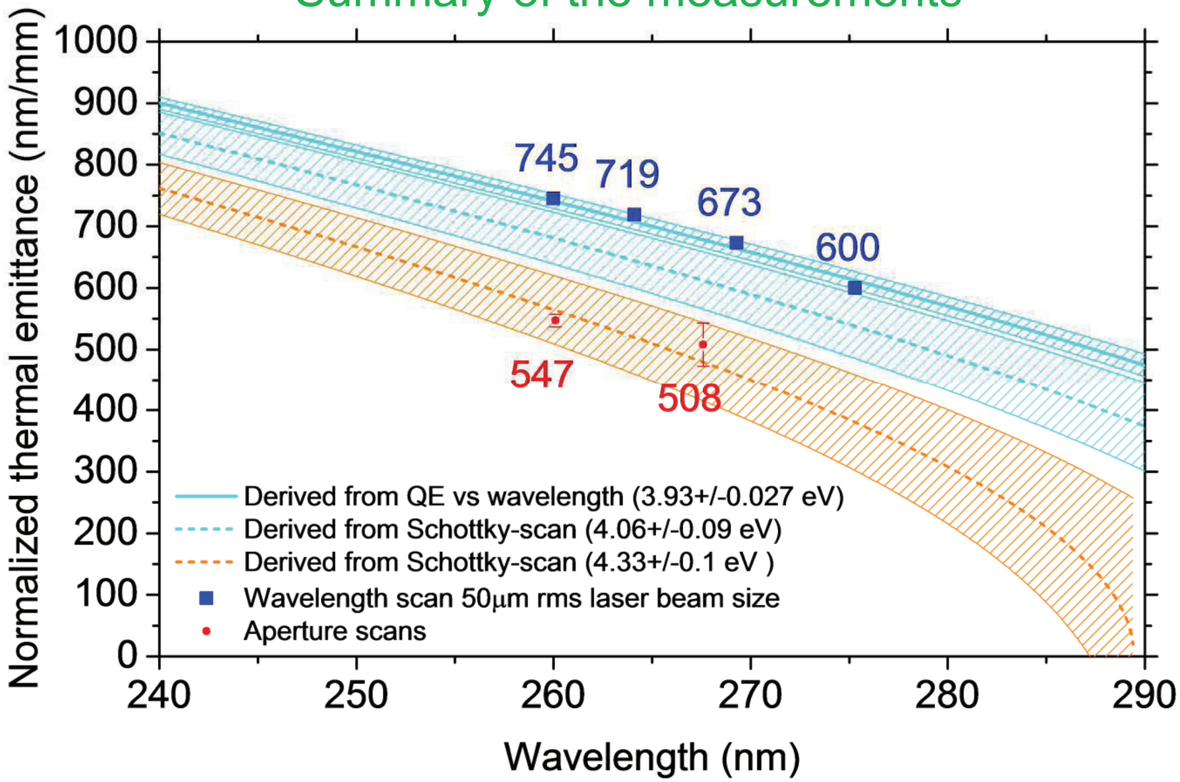


Wavelength scan for Set 2



Wavelength dependence

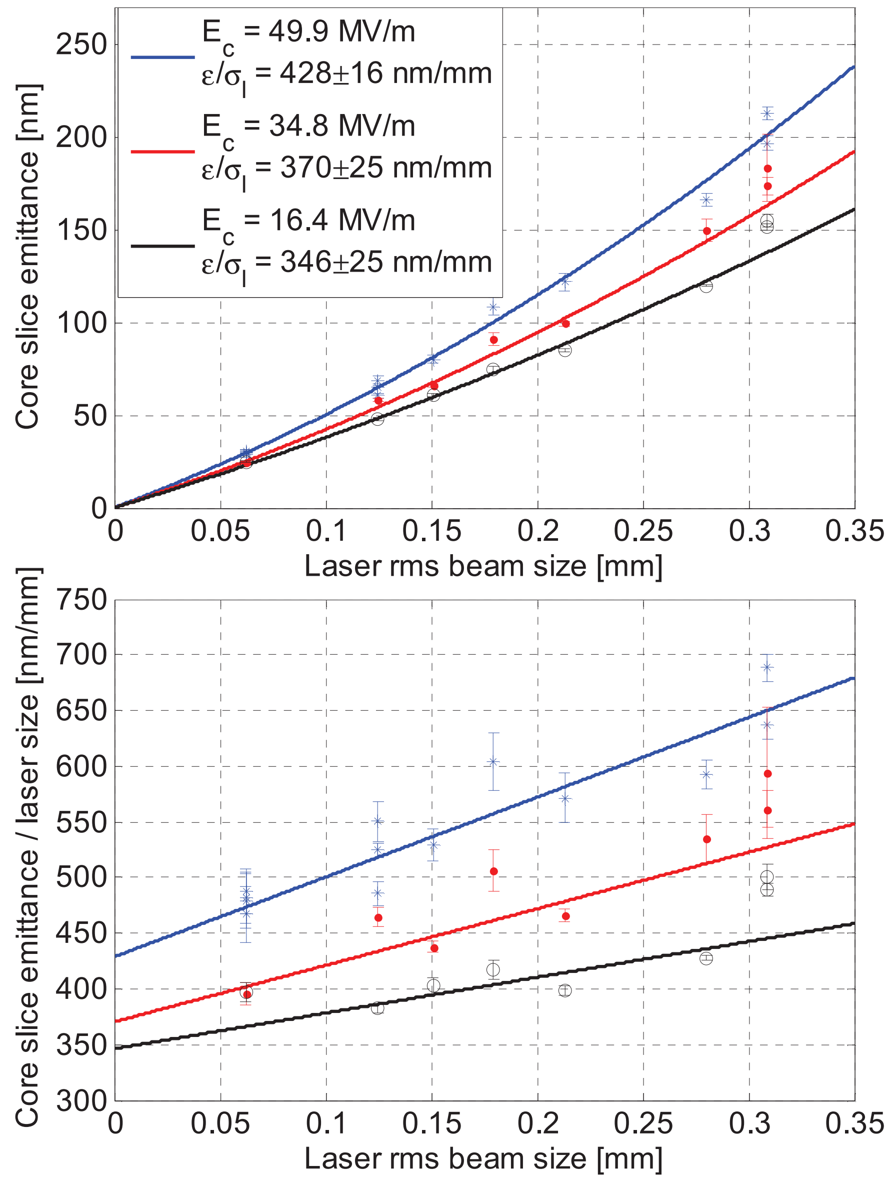
Summary of the measurements



- 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
- Same cathode show different work function after one month of operation

Field at the cathode dependence

Field at the cathode [MV/m]	Normalized thermal emittance [nm/mm]	Quadratic component [nm/mm2]
49.9	428±16	716±84
34.8	370±25	508±137
16.4	346±25	321±105



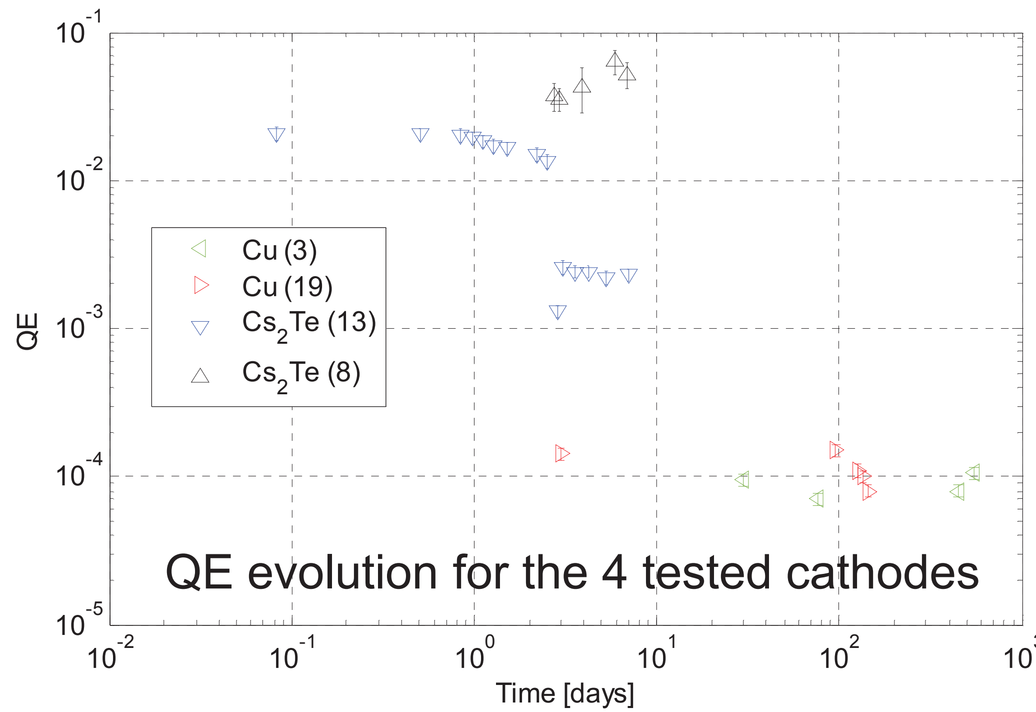
- Quadratic component decreased as a function of the gradient → higher order effects are due to rf
- Normalized thermal emittance changed as a function of the gradient as expected by theory $\varepsilon_{th} / \sigma_l \propto E_c(\varphi)^{1/4}$

Material dependence: Cu vs Cs_2Te

Cathode material	Cathode label	Normalized thermal emittance [nm/mm]	Slice emittance at 200 pC [nm]	QE
Cu	19	430±20 (*)	~200	$\sim 10^{-4}$
Cs_2Te	13	713±88	~250	10^{-2} - 10^{-3}
Cs_2Te	8	549±29 (*)	-	$>10^{-2}$

(*) Measurements done with the same machine conditions

- Two Cs_2Te cathodes tested for a week
- Cs_2Te seems a viable alternative to Cu for SwissFEL
  - Emittance is only ~25% worse
  - QE is ~2 orders of magnitude higher
- Need to improve QE homogeneity
- More tests needed



Summary

Label	Material	Meas. day	Norm. thermal emittance [nm/mm]	Laser wavelength [nm]	Field on the cathode [MV/m]
3	Cu	31-10-2012	547±10	260.1	49.9
3	Cu	30-10-2012	508±35	267.6	49.9
19	Cu	25-09-2013	428±16	262.0	49.9
19	Cu	25-09-2013	370±25	262.0	34.8
19	Cu	27-09-2013	346±25	262.0	16.4
19	Cu	04-04-2014	430±20	262.0	49.9
13	Cs_2Te	28-10-2013	713±88	262.0	49.9
8	Cs_2Te	04-04-2014	549±29	262.0	49.9

Wavelength dependence (yellow)
Field at the cathode dependence (pink)
Cathode material dependence (green)

Measurements at other labs (Cu): **~900 nm/mm**

H. J. Qian et al, Phys. Rev. ST Accel. Beams 15, 040102 (2012)
Y. Ding et al, Phys. Rev. Lett. 102, 254801 (2009)

Conclusion

- Method to measure slice emittance developed and tested at the SwissFEL Injector Test Facility:
  - Errors estimated to be smaller than 5%
  - Longitudinal resolution of ~4 µm (with TDC) / Emittance resolution of 2-3 nm
  - Normalized emittance measured down to 25 nm for a beam charge of 30 fC
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- Thermal emittance measurements agree well with theoretical expectations
  - Effective work functions,
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- Effective work function can be reconstructed from Schottky and wavelength scans

- Measured Cu and Cs_2Te under the same conditions. Cs_2Te seems a viable option for SwissFEL:
  - Slice and thermal emittance ~25% higher than for Cu
  - QE of few per cent ~2 orders of magnitude higher than for Cu

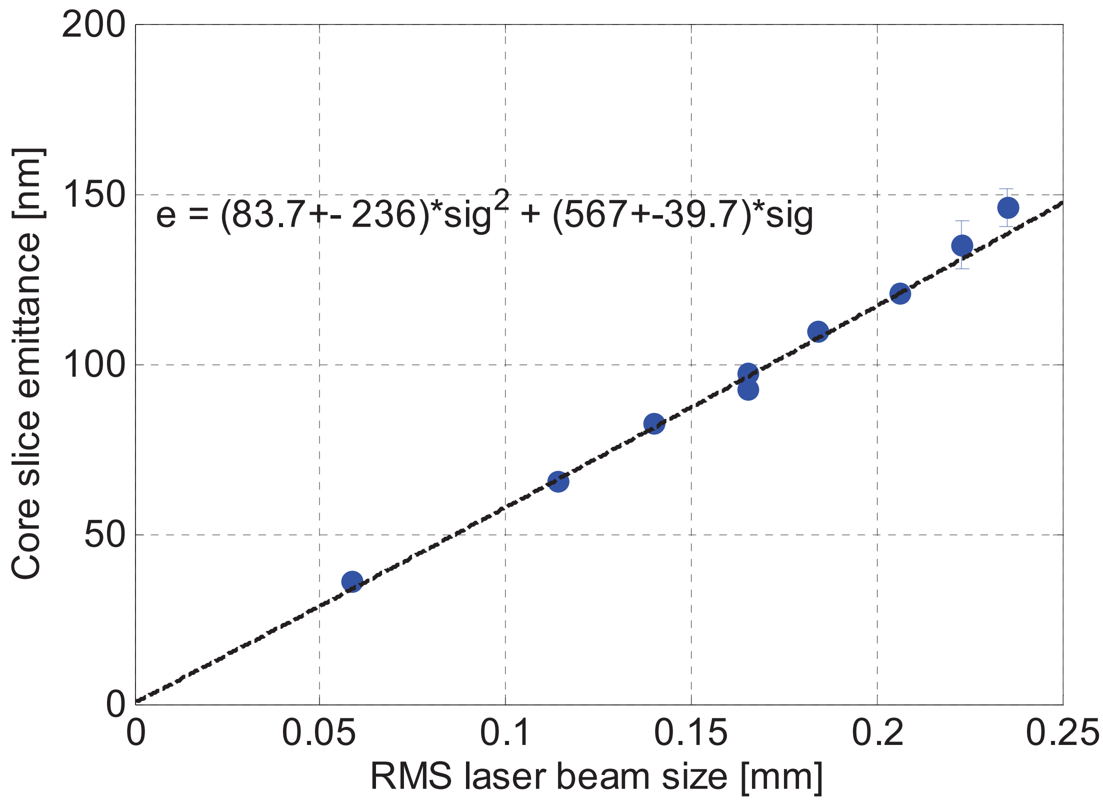
Acknowledgments

We would like to thank
All technical groups involved in the SwissFEL Test Facility

Special thanks go to Rasmus Ischebeck to develop and implement the SwissFEL profile monitor used in our measurements

Thanks for your attention!

Backup 1: thermal emittance with new SwissFEL gun (Copper)



- ➢ Second order effects are negligible
- ➢ Normalized thermal emittance comparable to old cathodes and old gun