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Emittance Measurements at SwissFEL

June 16 2021

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- SwissFEL
- Emittance measurement procedures
- Thermal emittance measurements at the SwissFEL Injector Test Facility
- Emittance optimization and results at SwissFEL
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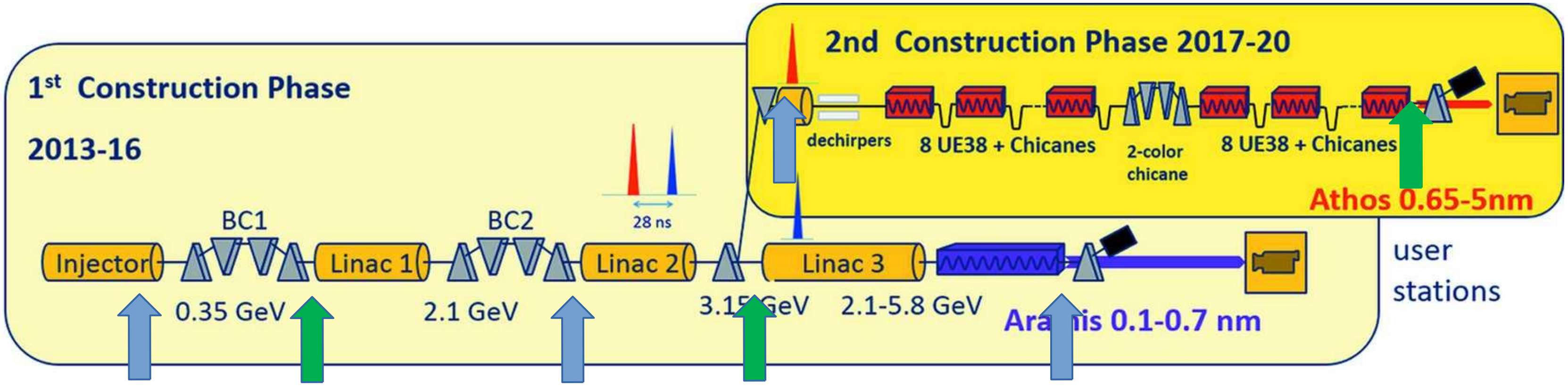
SwissFEL

Athos:

Soft X-ray FEL, λ=0.65–5.0 nm

Variable polarization, Apple-X undulators

First users 2021



Aramis:

Hard X-ray FEL, λ=0.1–0.7 nm

Linear polarization, in-vacuum undulators

First users 2018

Main parameters:

Photon wavelength: 0.1–5 nm

Photon energy : 0.2–12 keV

Pulse duration : 1–20 fs

Electron energy : up to 5.8 GeV

Electron bunch charge: 10–200 pC

Repetition rate: 100 Hz (2-bunches)

SwissFEL Injector Test facility

Injector including BC1

250 MeV energy

Operation: 2010-2014

Emittance measurements locations

➡ Projected

➡ Projected and slice

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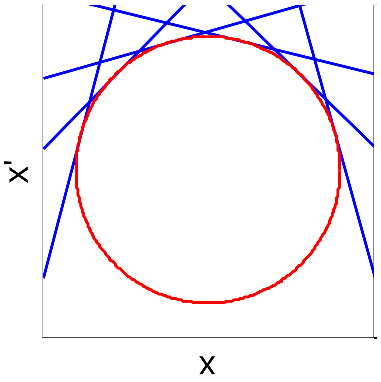
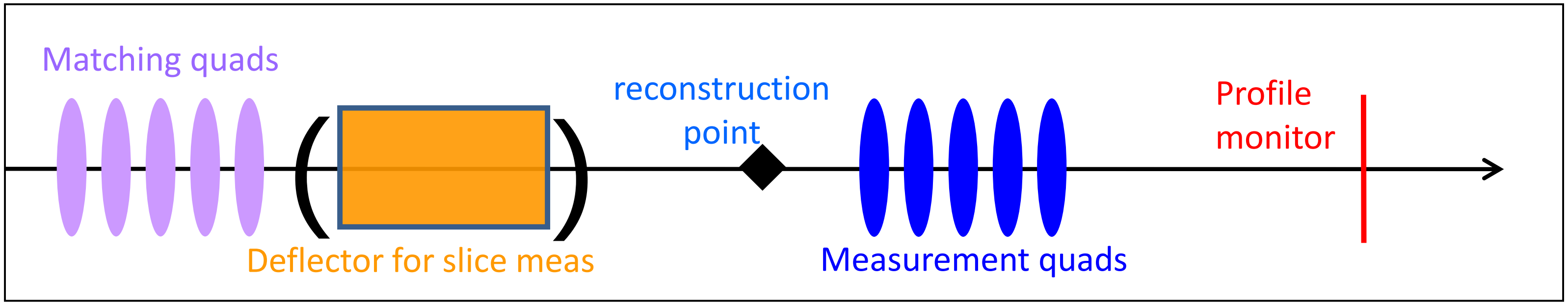
(Slice) Emittance measurements

- Measure beam sizes for different phase advances (close to 180°)
- Phase advance is scanned using quadrupole magnets
- Solution for Twiss parameters is used for matching




Matching quads

Deflector for slice meas

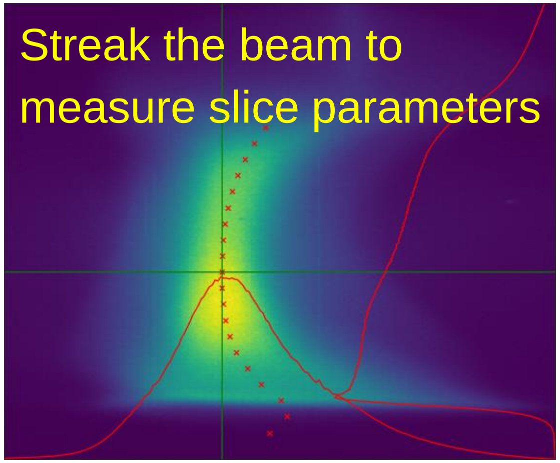
reconstruction point

Measurement quads

Profile monitor

Beam size monitors:

- Scintillating YAG screen (slice and projected, single-shot, ≈10 μm res)
- Wire scanners (projected only, multi-shot, higher resolution, ≈1 μm res)
- We determine the beam size with Gaussian fit σ


- Streak the beam to measure slice parameters

Emittance measurement errors

Statistical errors

- Machine jitter → take several images per phase advance step

Systematic errors

- *Profile monitor resolution (see below)*
- Screen profile monitor calibration, expected <5% error in emittance
- Other errors (energy, quadrupole, Gaussian fit etc) expected <5% error

Concerning profile monitor resolution

- General: $$\overset{\text{measured}}{\sigma_M^2} = \overset{\text{true}}{\sigma^2} + \overset{\text{resolution}}{\sigma_R^2} = \frac{\epsilon_n \beta_s}{\gamma} + \sigma_R^2$$
- If beam size at the screen is constant during the measurement:

$$\epsilon_{n,M} = \frac{\gamma \sigma_M^2}{\beta_s} = \epsilon_n + \boxed{\frac{\gamma}{\beta_s}\sigma_R^2}$$

3 ways to decrease this term

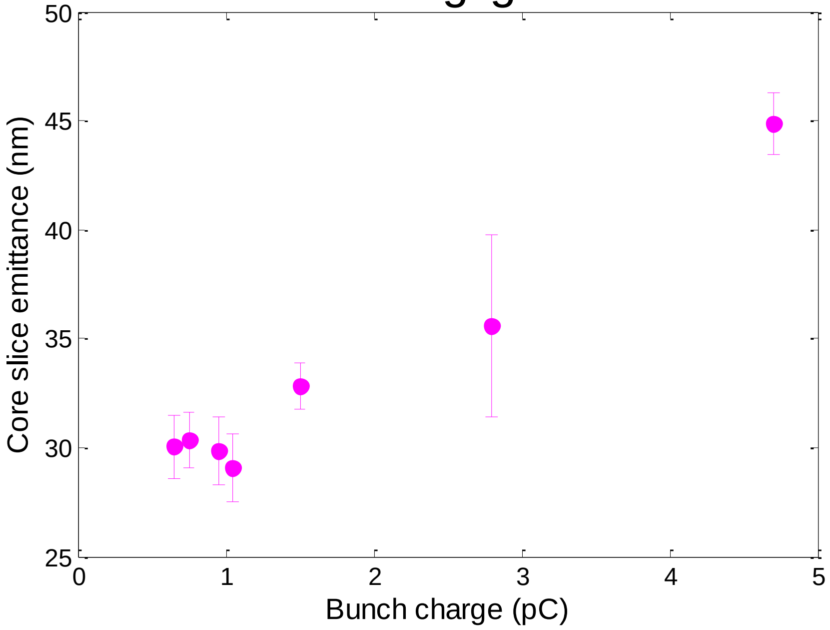
1) Increase β_s . Limited by lattice and phase advance (70 m in slice emittance at linac 3)

2) Decrease beam energy (γ) (limited by effects such as space charge)

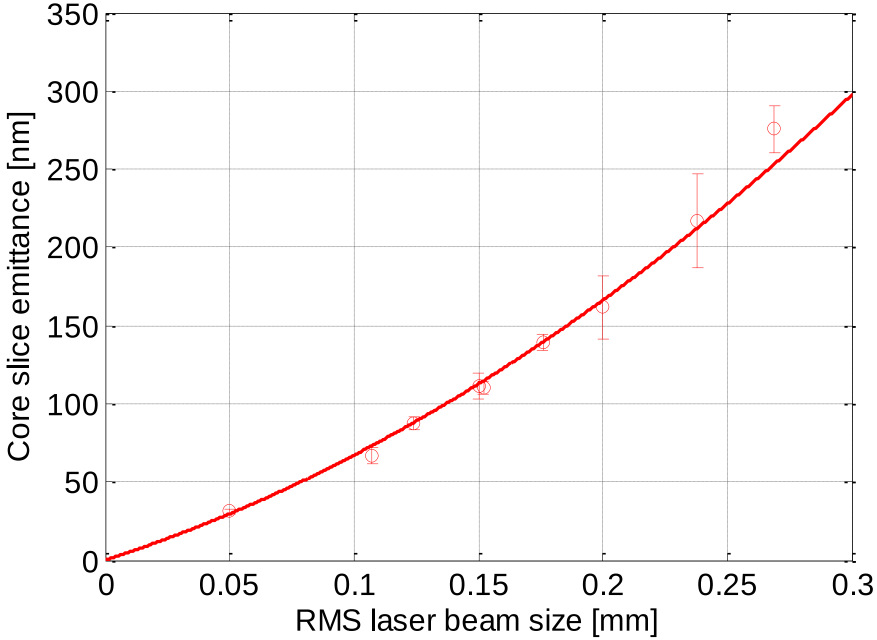
3) Improve resolution σ_R Wire scanners have better resolution than screens (only usable for projected)

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 (more pronounced in old SwissFEL gun).
- Normalized thermal emittance as first order term of second-order fit to the data

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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

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

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±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*

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 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

- 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

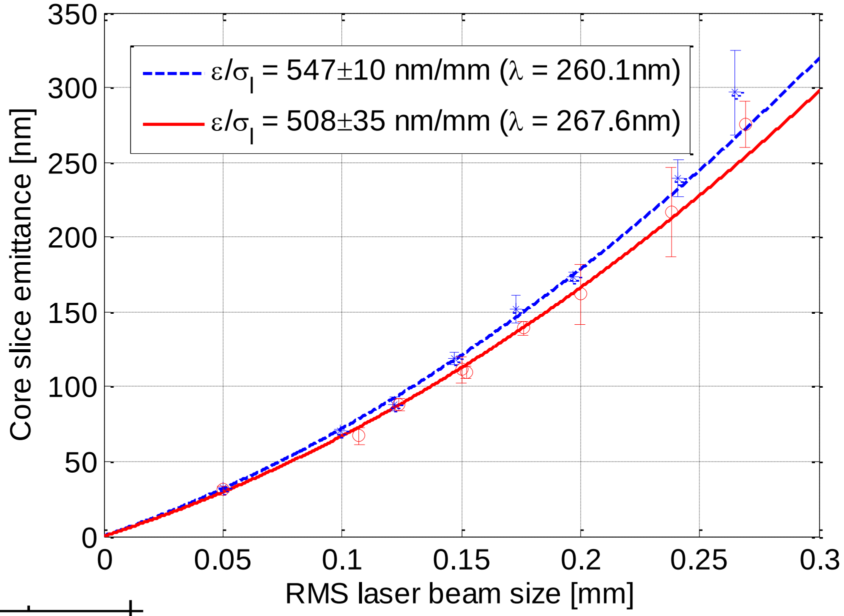
Wavelength dependence

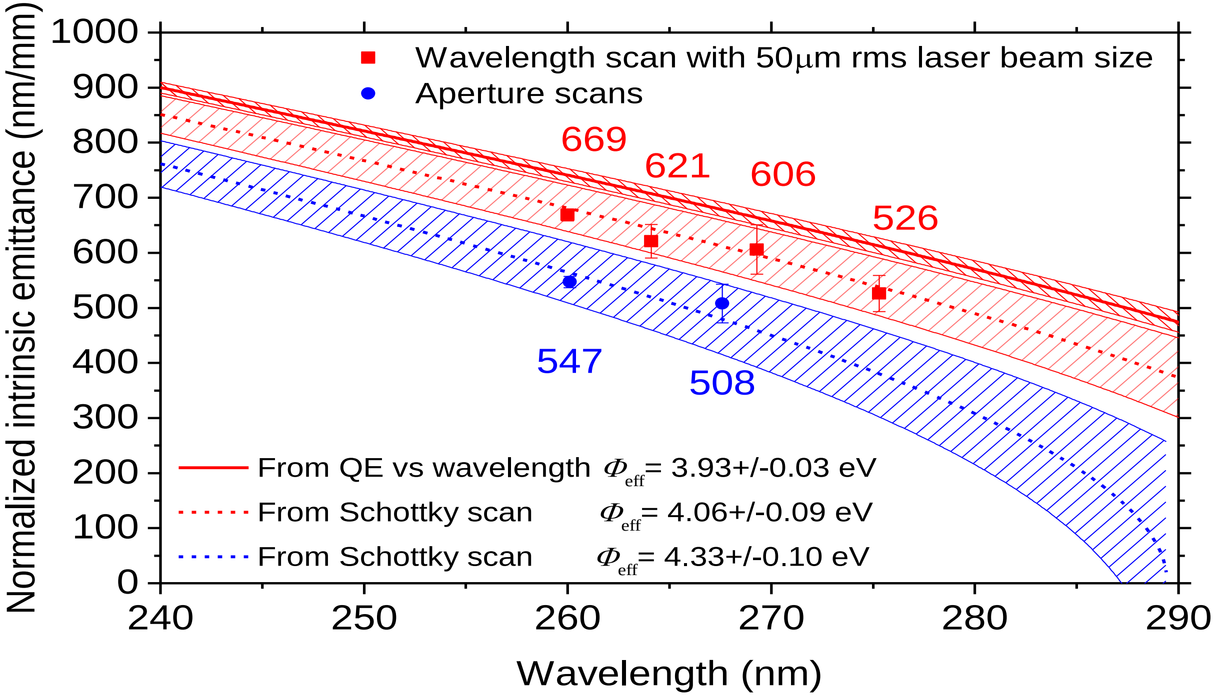
Set 1: (260.1 nm and 267.6 nm)

- Direct emittance measurement (aperture 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%)





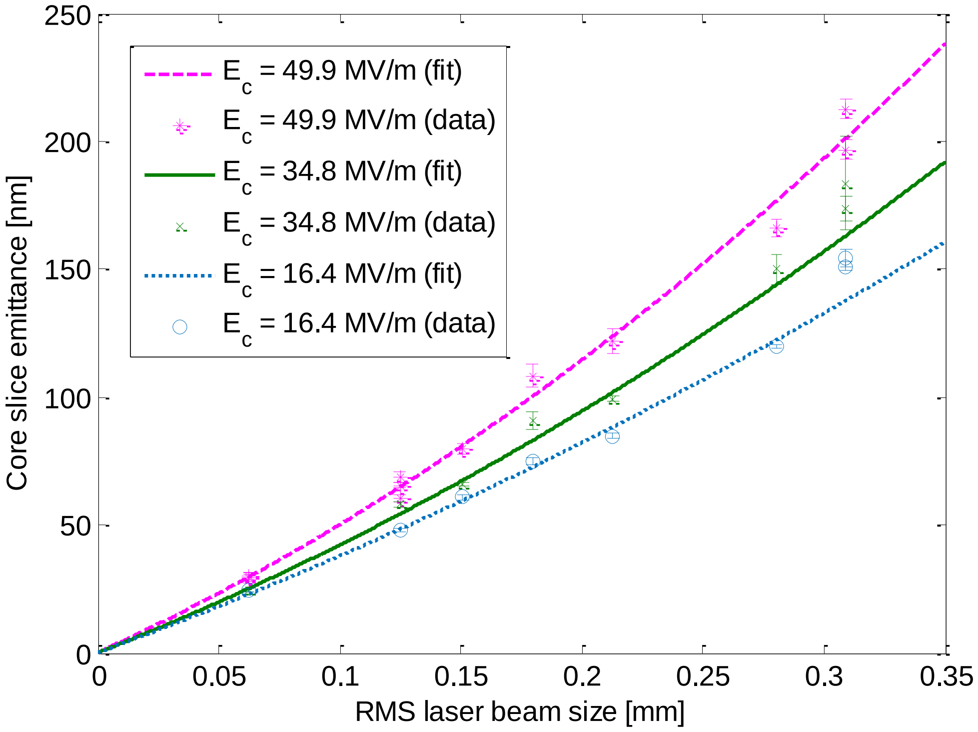
- ➢ Wavelength dependence as expected by theory

$$\varepsilon_{th} / \sigma_l \propto \sqrt{\phi_l}$$

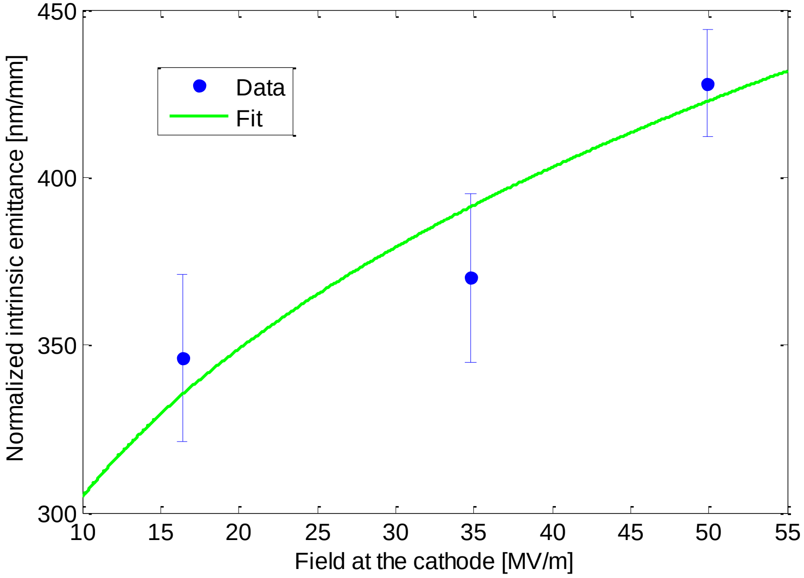
- ➢ Same cathode show different work function after one month of operation

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



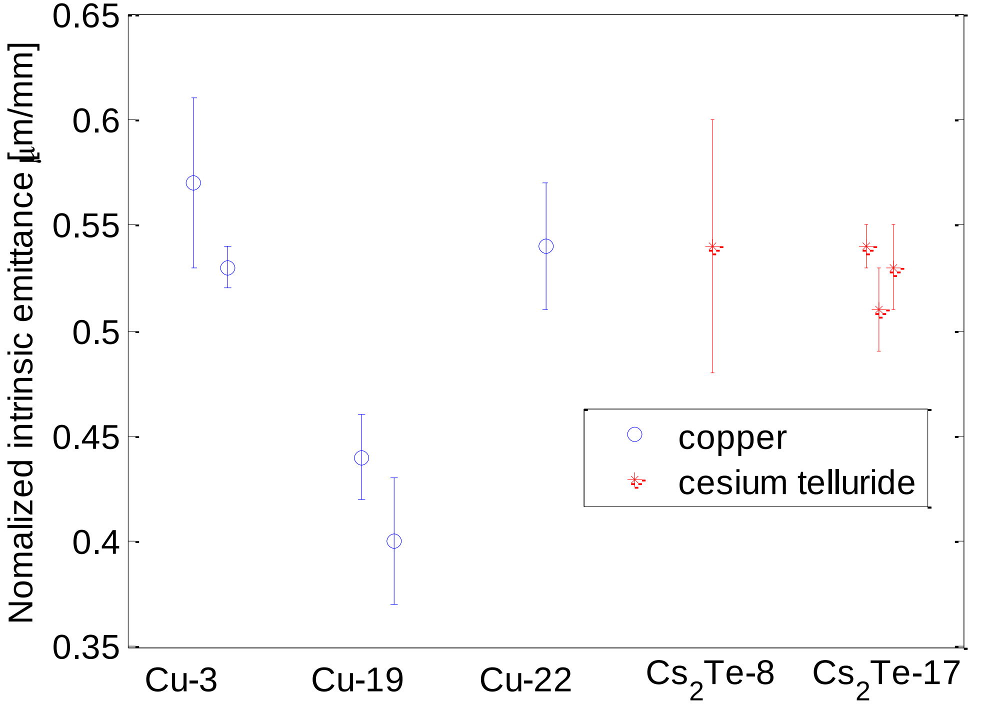
- Quadratic component decreases as a function of the gradient → higher order effects are due to rf



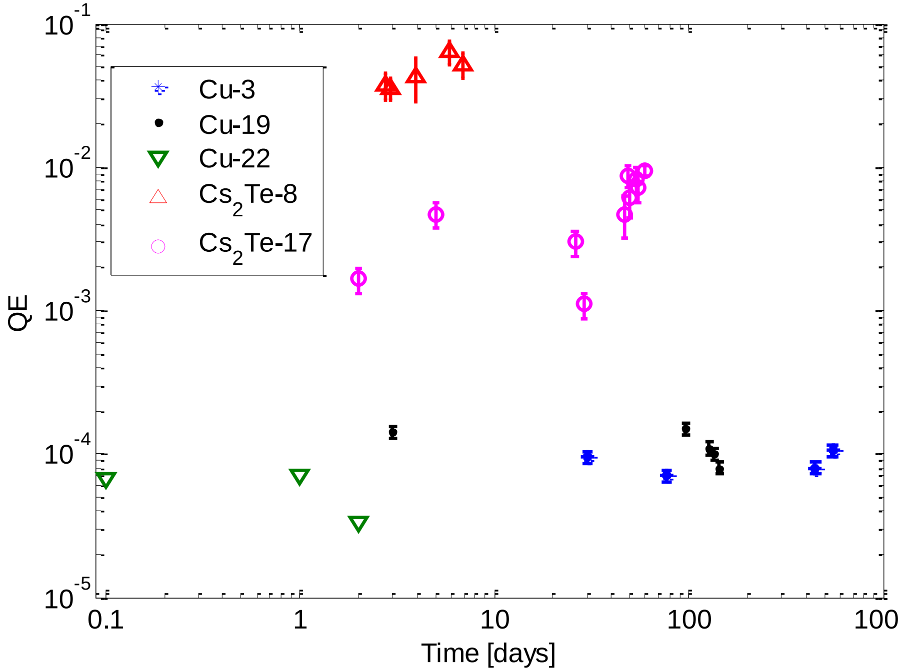
- Best fit with Φ_w= 4.70±0.07 eV and β = 0.79±0.52. Good agreement with expectations
- Thermal emittance is reduced by 20% but overall emittance can be worse due to lower beam energy. Moreover QE is suppose to be much worse (60% smaller)

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 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

Source emittance contributions:

- Emittance from cathode / laser
- Space-charge forces
- RF fields at the gun

Optimized with

- Laser transverse size
- Gun RF gradient (maximum)
- Gun solenoid field
- In design phase: distance between gun and booster

Emittance growth sources

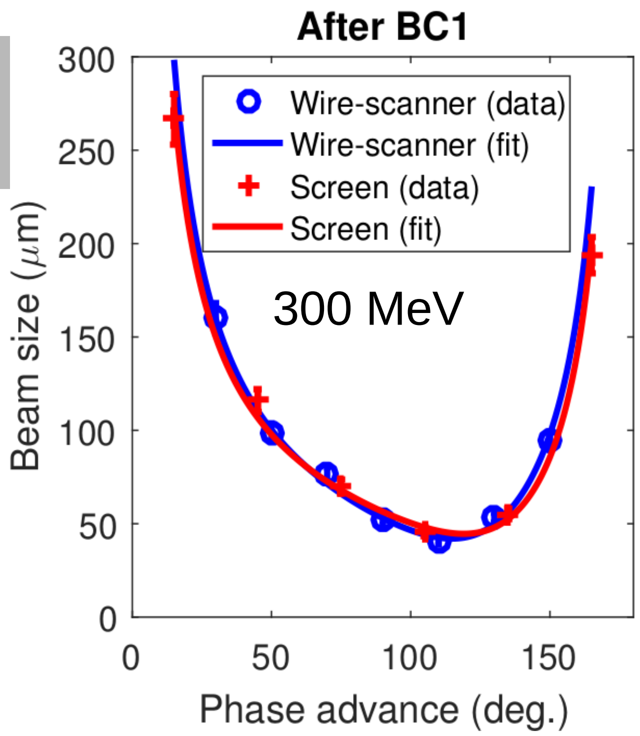
- Transverse coupling
- Coherent Synchrotron Radiation
- Leaked dispersion
- Transverse wakefields

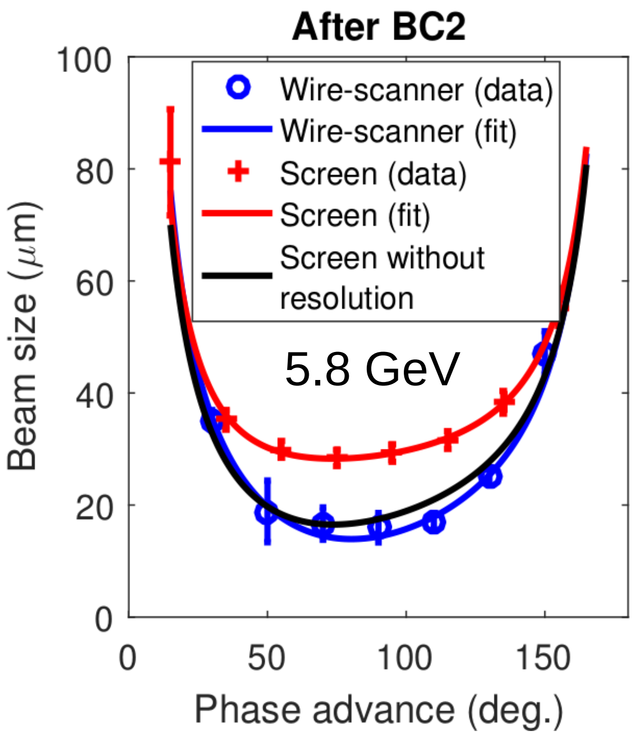
Mitigated with

- Coupling correction
- Compression setup
- Optics in the bunch compressors
- Orbit alignment
- Beam tilt correction

We optimize the emittance for every machine setup

Wire scanners compared to screens





ϵ_n [nm]	WS	screen
BC1	80 ± 4	85 ± 3
BC2	178 ± 17	339 ± 19

Assuming WS beam size is correct after BC2, estimated σ_R: 23±4 µm

+90% measured ε from YAG screen!

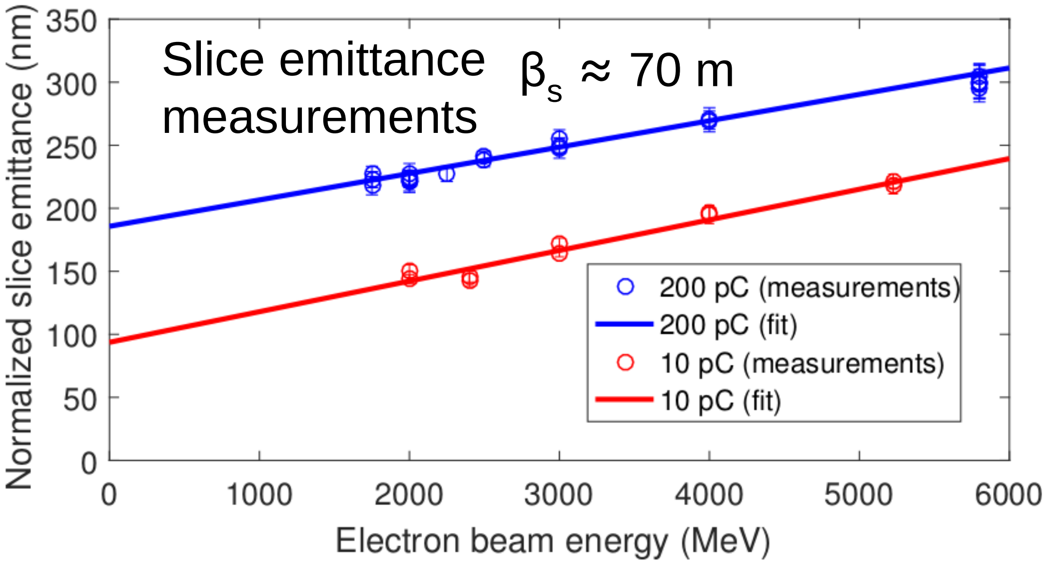
- Perfect agreement at 300 MeV for projected emittance measurements at low energy
- Screens overestimate beam sizes and emittance at high energies
- Wire scanners required for high energies
- *What about slice emittance measurement at high energy?*

Overcoming screen resolution for slice measurement

$$\epsilon_{n,M} = \epsilon_n + \frac{\gamma}{\beta_s}\sigma_R^2$$

Linear equation in γ

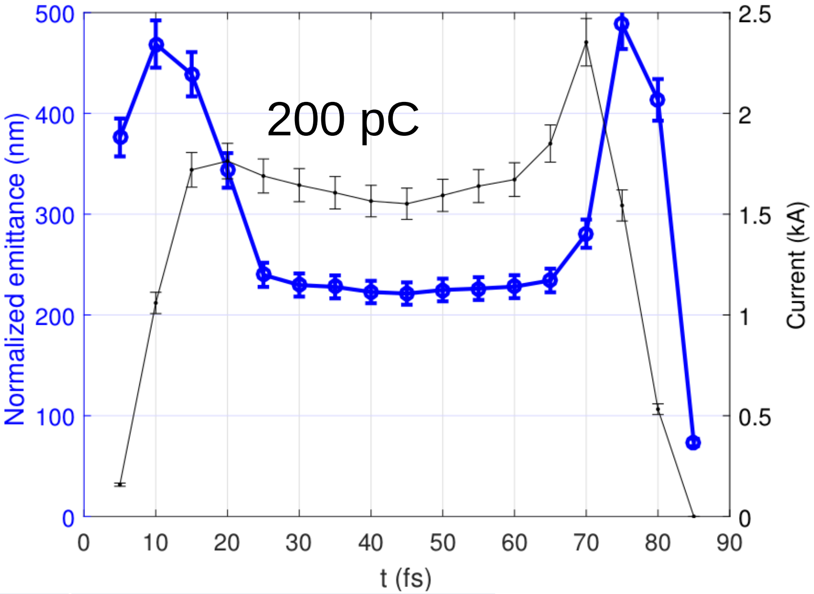
Assuming normalized slice emittance is independent of the beam energy, we can estimate true emittance and screen resolution by measurements for different energies



Slice emittance measurements

$\beta_s \approx 70$ m

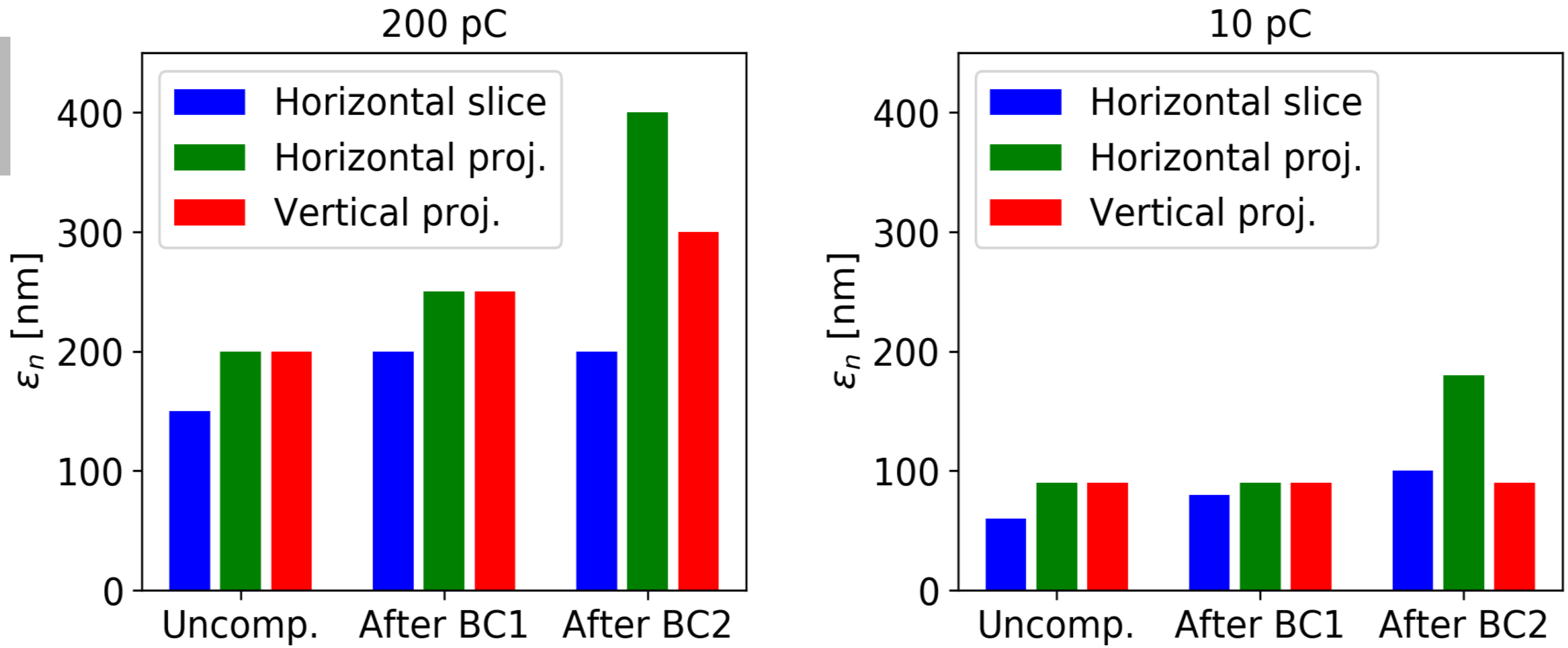
After BC2 (screen)



200 pC

	200 pC	10 pC
Norm. emit. (nm)	186 ± 3	94 ±5
Resolution (um)	27 ± 7	29 ± 8

Summary of measured emittances



σ_t ~3 ps ~450 fs ~35 fs

σ_t ~1.4 ps ~20 fs ~3 fs

- Short-term reproducibility of measured emittance is excellent (about 2%)
- After machine start-up and re-optimization, ε after BC2 varies by about 10-20%
- Quite low emittance values setting new standards for linacs

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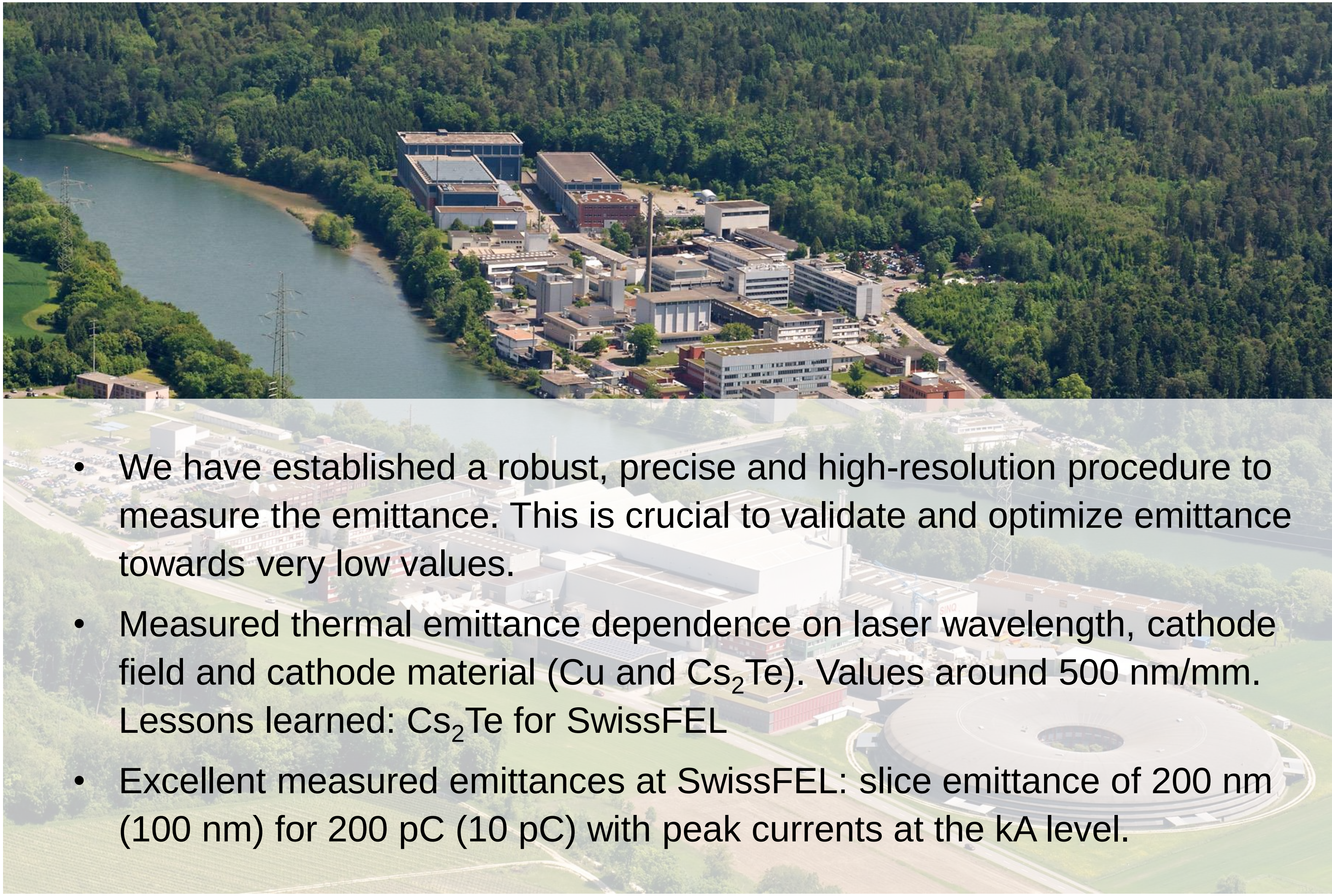

- We have established a robust, precise and high-resolution procedure to measure the emittance. This is crucial to validate and optimize emittance towards very low values.
- Measured thermal emittance dependence on laser wavelength, cathode field and cathode material (Cu and Cs_2Te). Values around 500 nm/mm. Lessons learned: Cs_2Te for SwissFEL
- Excellent measured emittances at SwissFEL: slice emittance of 200 nm (100 nm) for 200 pC (10 pC) with peak currents at the kA level.