PAUL SCHERRER INSTITUT

Eduard Prat :: FEL Beam Dynamics :: Paul Scherrer Institute

Emittance Measurements at SwissFEL

June 16 2021

Contents

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

Contents

PAUL SCHERRER INSTITUT PSI

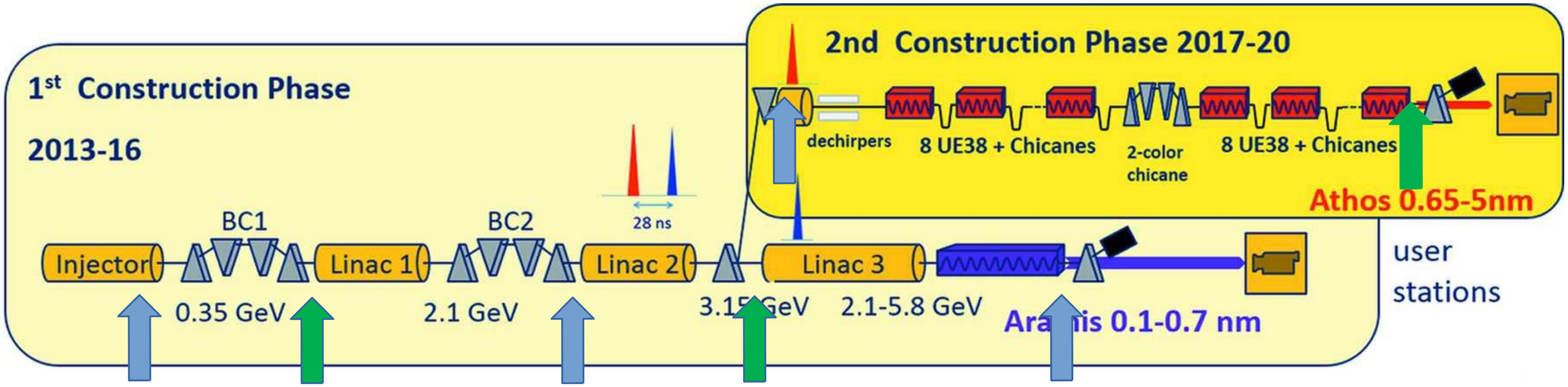
SwissFEL

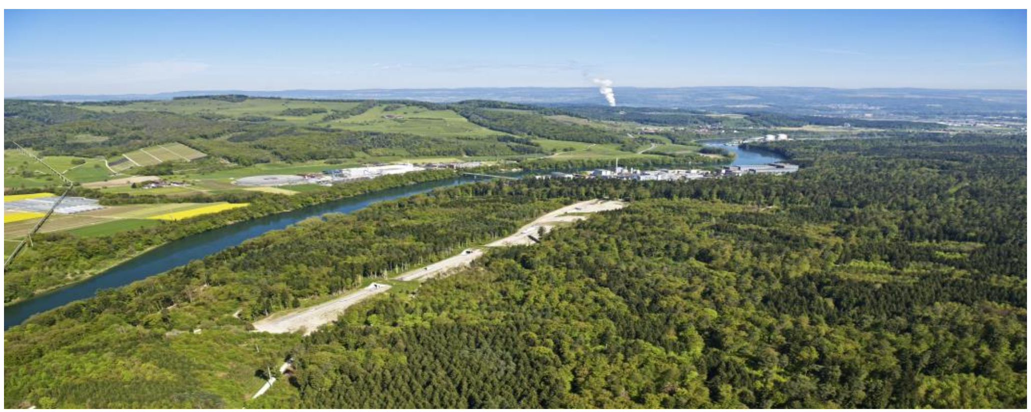
Athos:

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

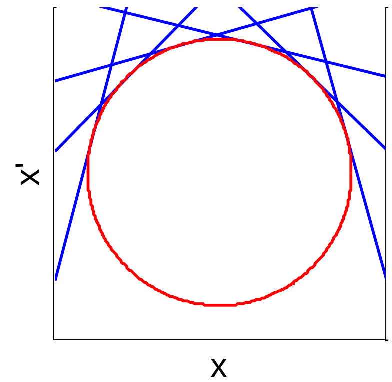
(blue arrow) Projected

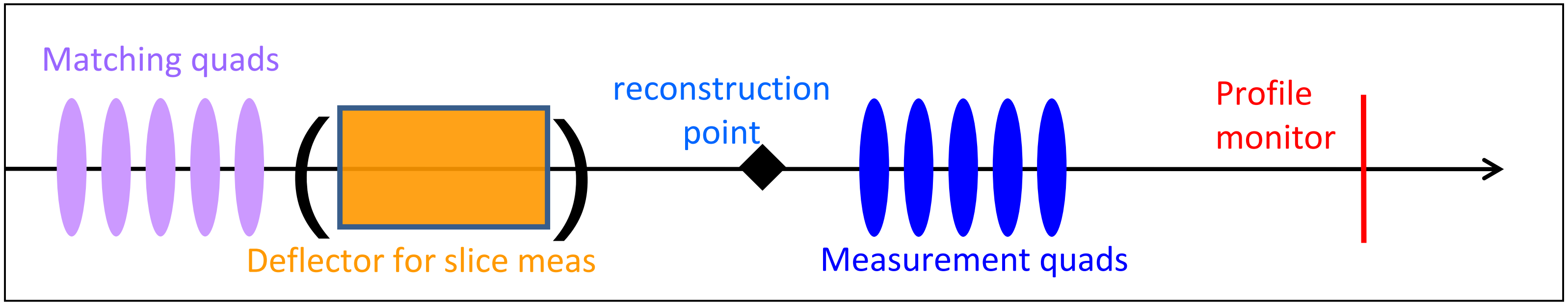
(green arrow) Projected and slice

Contents

(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

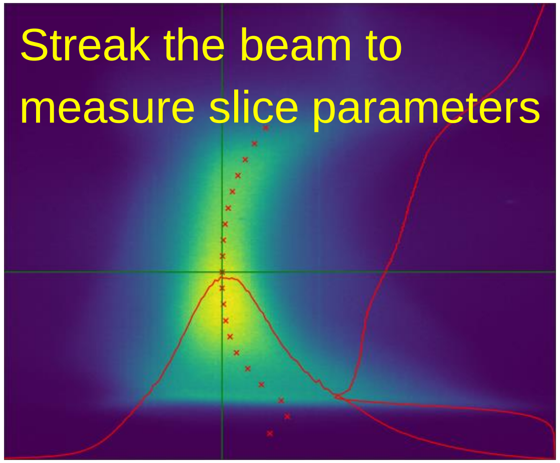




Beam size monitors:

- 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

measured   true   resolution

- General: $$\sigma_M^2 = \sigma^2 + \sigma_R^2 = \frac{\epsilon_n \beta_s}{\gamma} + \sigma_R^2$$

- If beam size at the screen is constant during the measurement:

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

3 ways to decrease this term

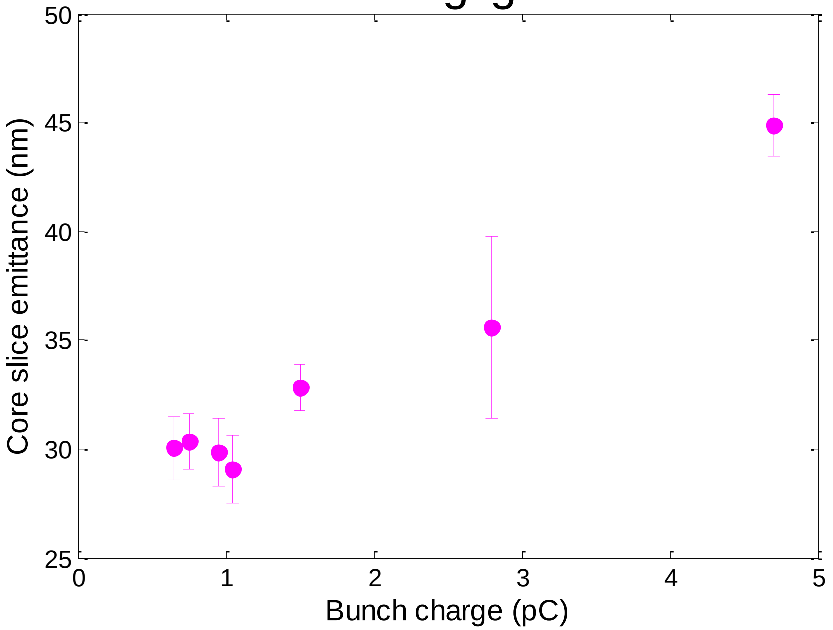
1) Increase β_s . Limited by lattice and phase advance (70 m in slice emittance at linac 3)

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

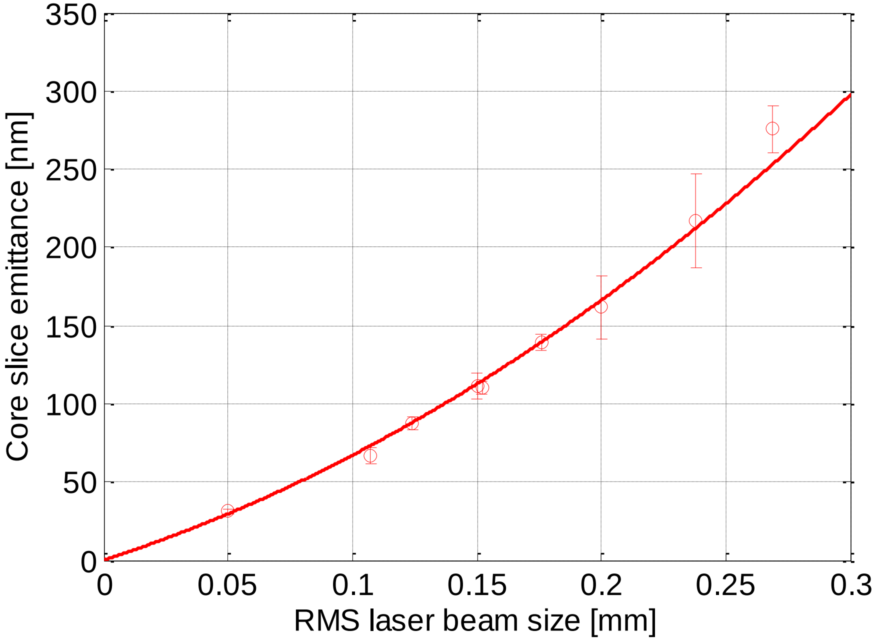
3) Improve resolution σ_R Wire scanners have better resolution than screens (only usable for projected)

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

Contents

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$\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*

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

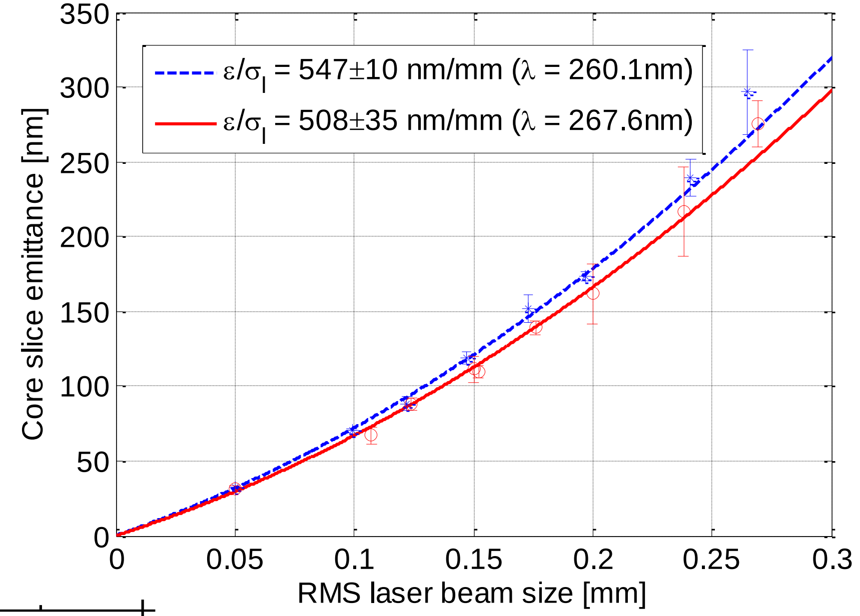
Wavelength dependence

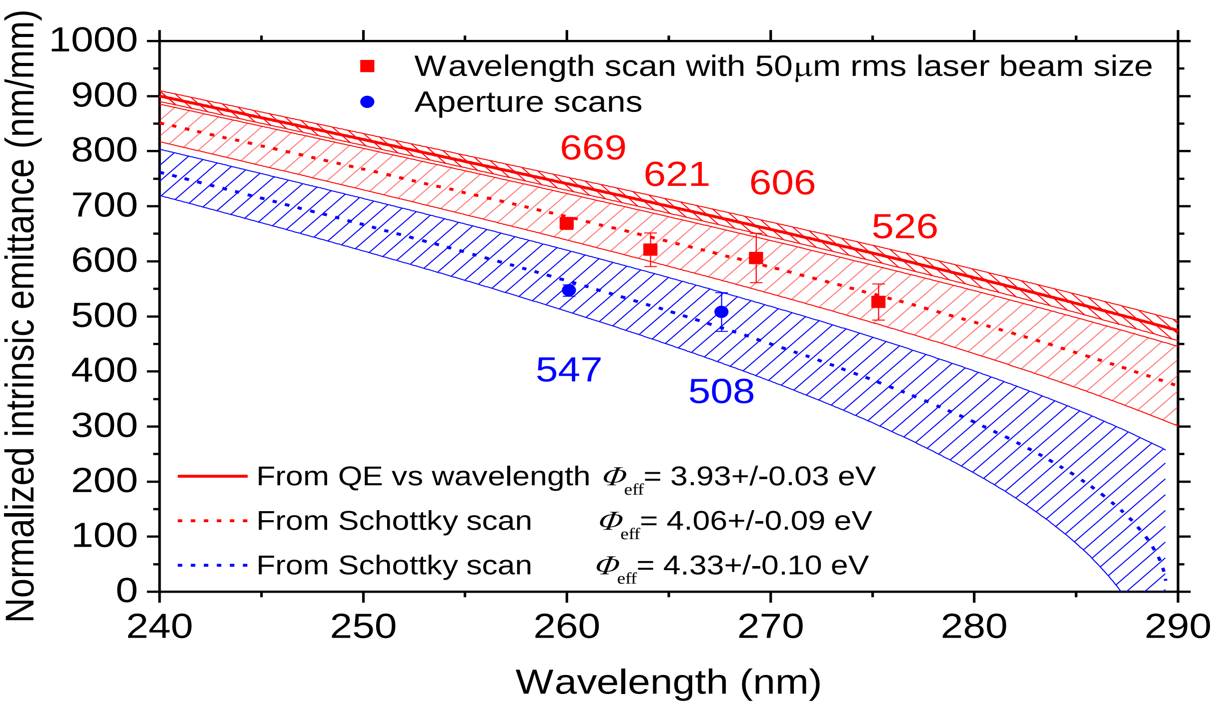
Set 1: (260.1 nm and 267.6 nm)

•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%)





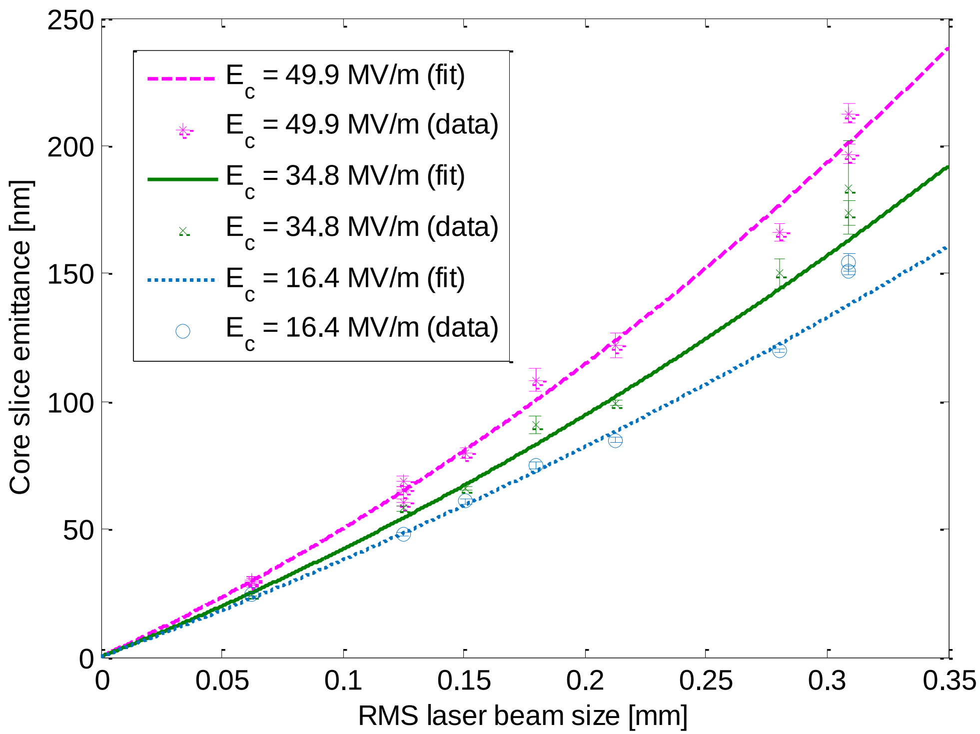
- Wavelength dependence as expected by theory

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

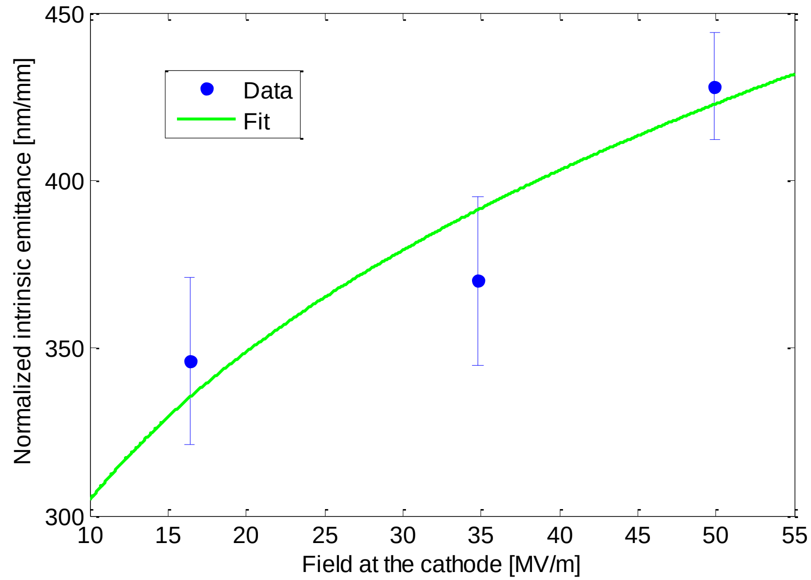
- Same cathode show different work function after one month of operation

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



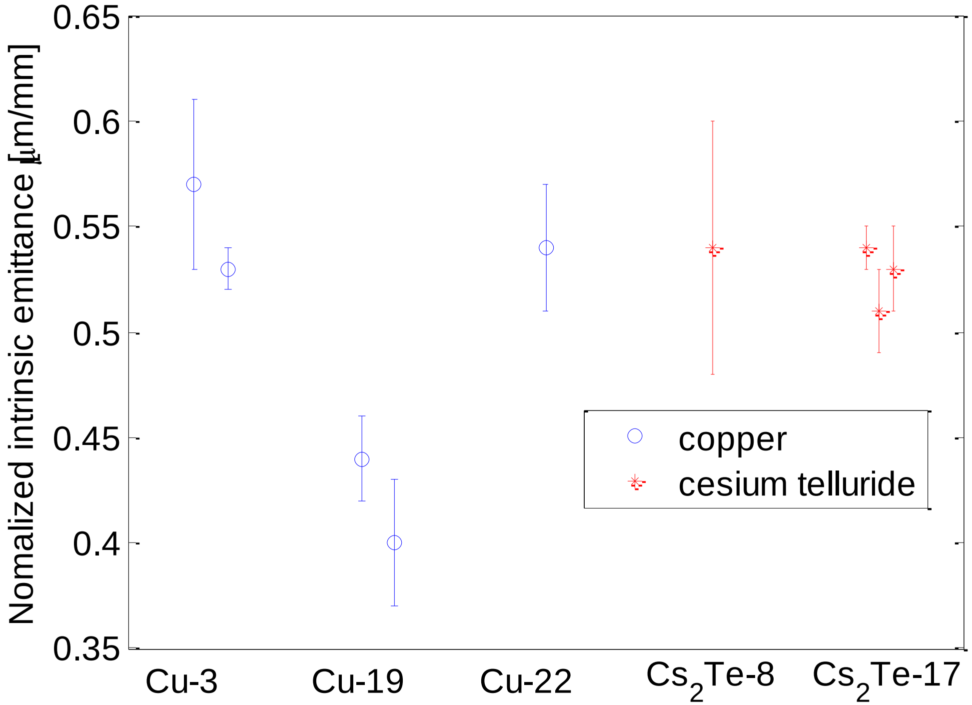
- Quadratic component decreases as a function of the gradient □ higher order effects are due to rf



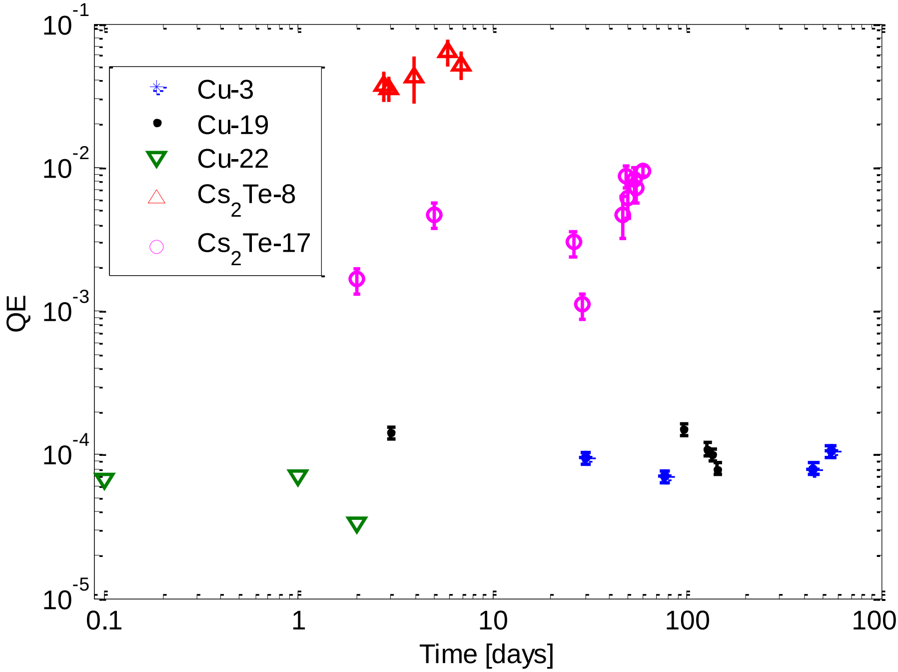
- Best fit with Φ_w= 4.70±0.07 eV and β = 0.79±0.52. Good agreement with expectations
- Thermal emittance is reduced by 20% but overall emittance can be worse due to lower beam energy. Moreover QE is suppose to be much worse (60% smaller)

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**

PAUL SCHERRER INSTITUT PSI

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)]

Contents

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

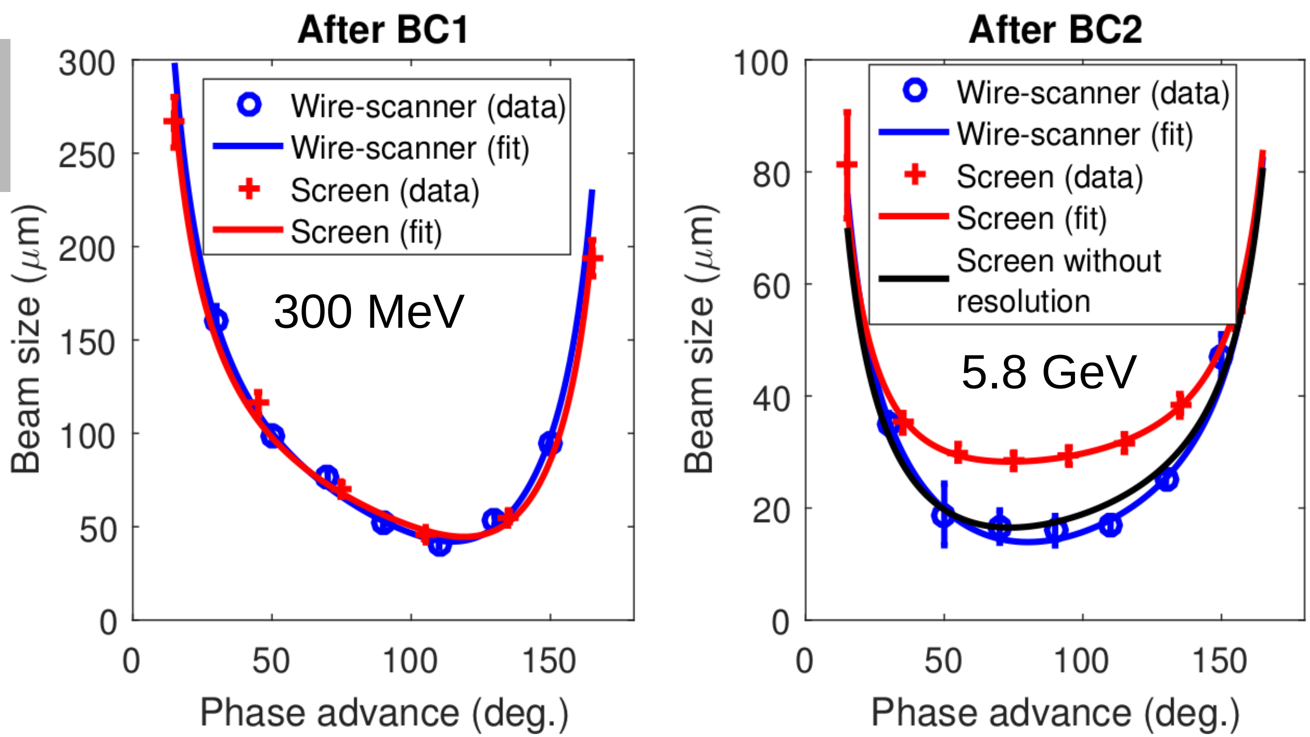
- Transverse coupling
- Coherent Synchrotron Radiation
- Leaked dispersion
- Transverse wakefields

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

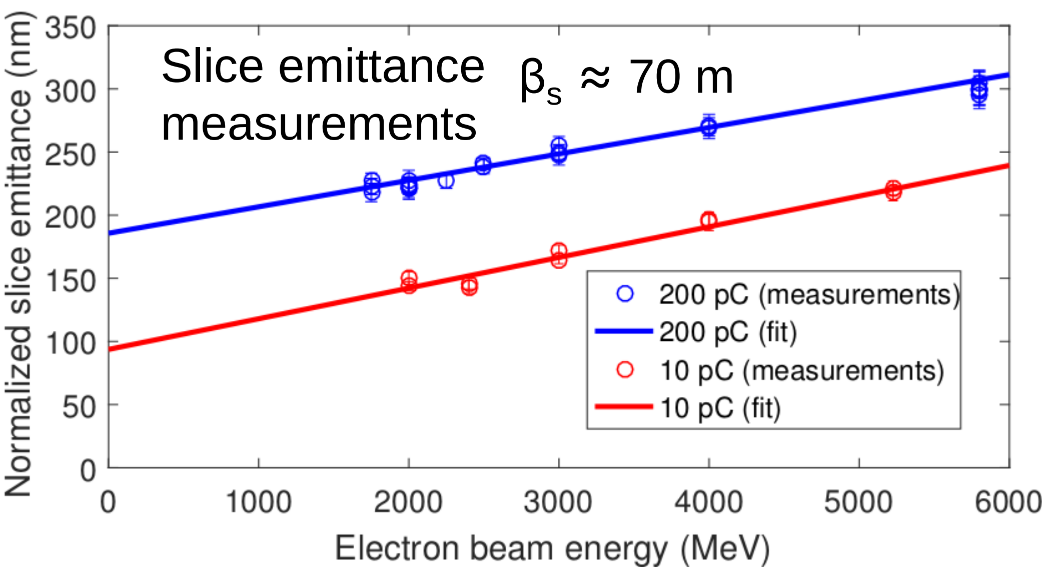
+90% measured ε from YAG screen!

- 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?*

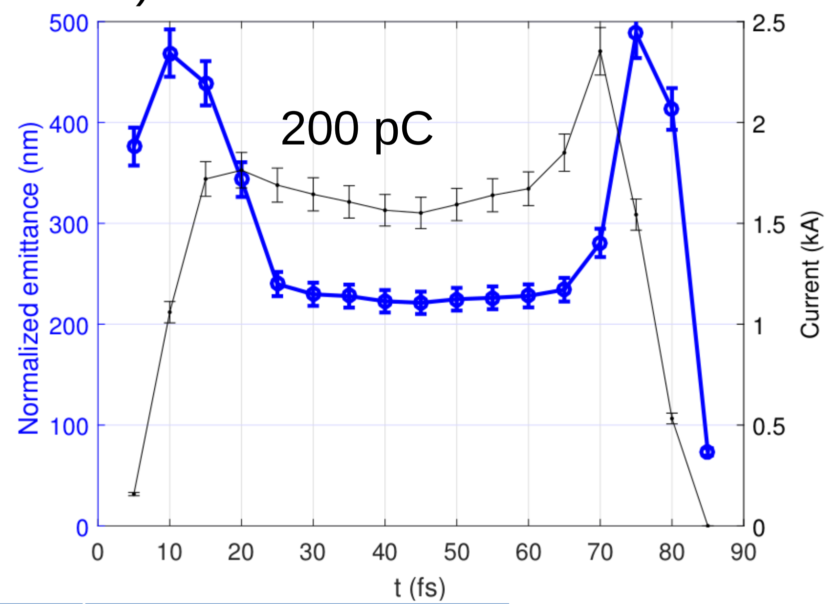
Overcoming screen resolution for slice measurement

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

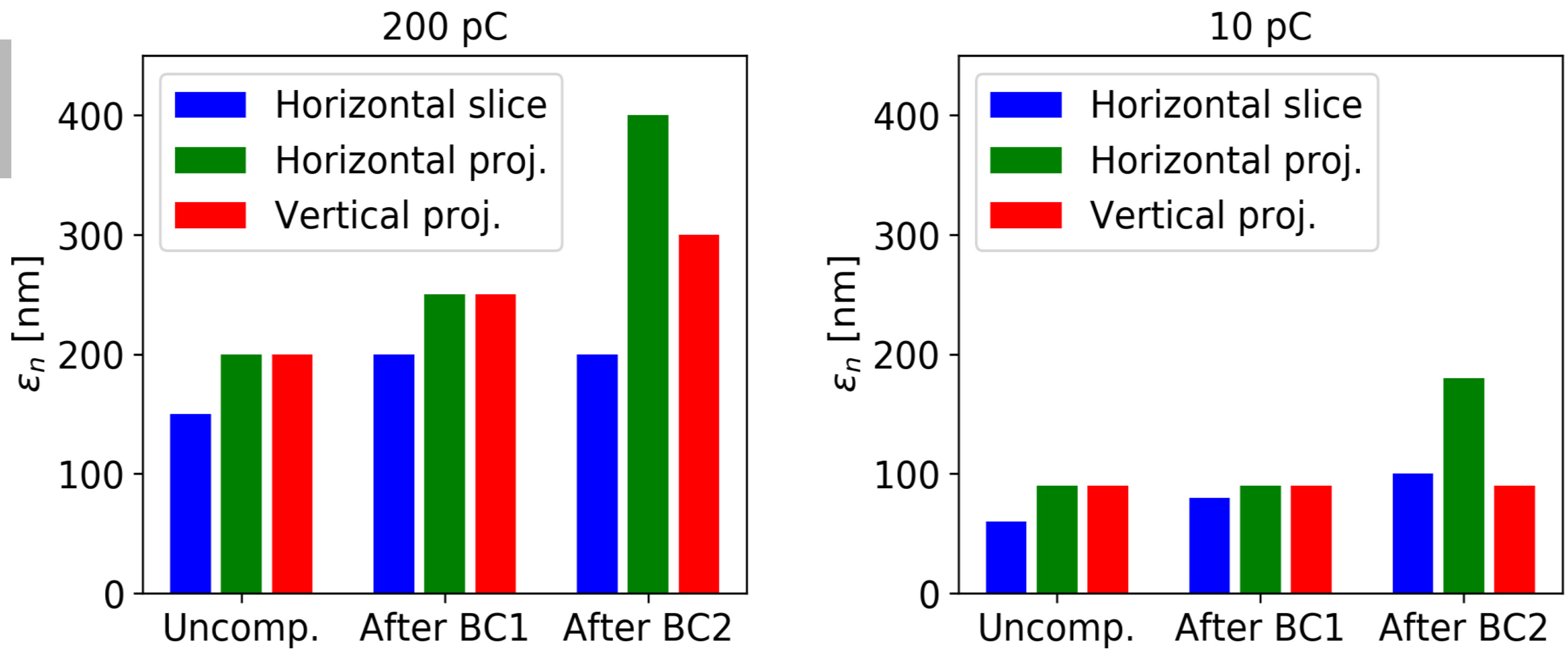


After BC2 (screen)



	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

Contents

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

Conclusion

- 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.