PAUL SCHERRER INSTITUT

SwissFEL Beam Dynamics :: Paul Scherrer Institute
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Emittance Measurements and Minimization at SwissFEL

FEL Conference 2019, Hamburg

Towards compact and cost-efficient FELs

Normalized emittance $\epsilon_n = \gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$

Can be calculated for the whole electron bunch (*projected*) or a subset (*slice*). Most important for FELs is the *slice emittance*. Both should be minimized!

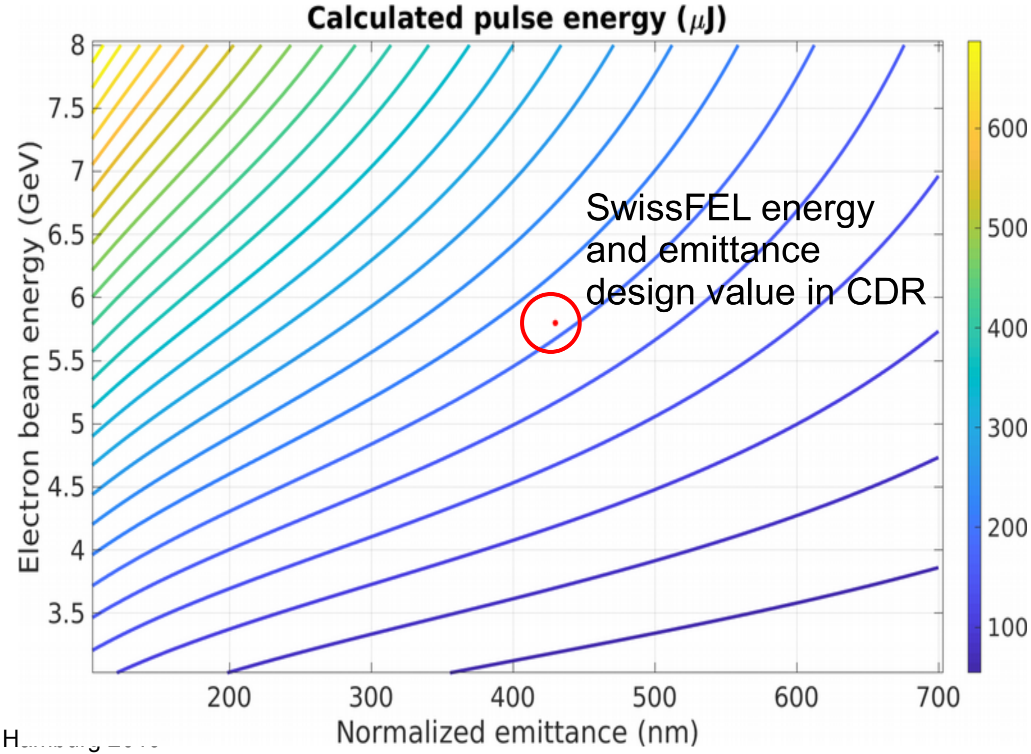
From FEL theory, a condition for transverse coherence:

$$\epsilon_n/\gamma \approx \lambda/4\pi$$

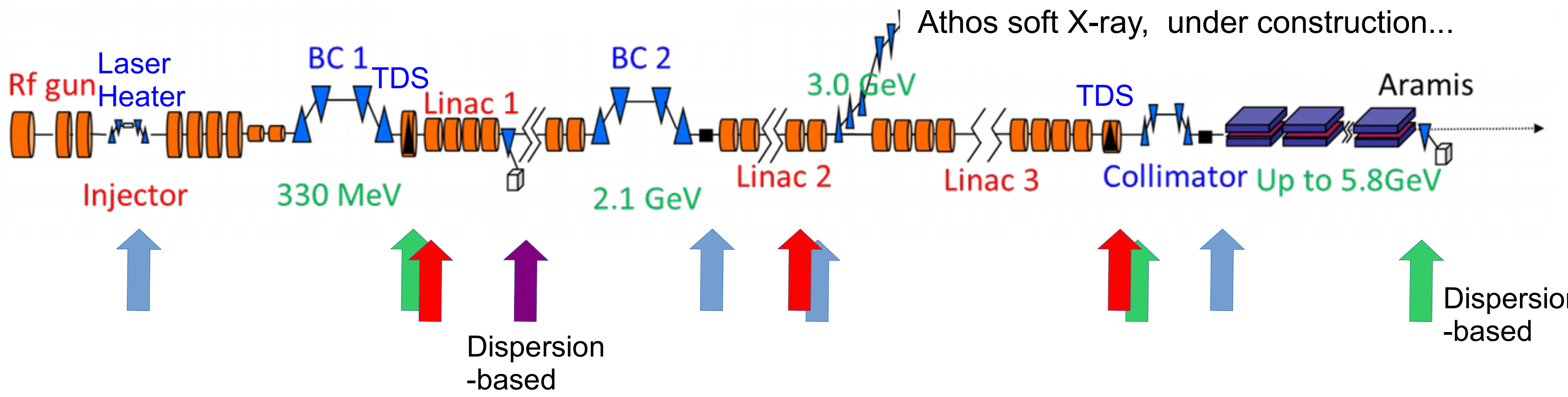
Emittance is fundamental for FELs. If lower:

- Same performance can be reached with lower beam energy
- Better performance at a given beam energy

Ming Xie model for FEL pulse energy
(λ = 0.1 nm, standard SwissFEL parameters but λ_U variable)



The SwissFEL facility



“Aggressive design” (H. Tanaka on Monday)

Emittance measurements locations

Wavelength	1 Å - 70 Å
e^- Energy	5.8 GeV
e^- Bunch charge	10 – 200 pC
Total length	736 m

- Projected with screen
- Projected and horizontal slice with screen
- Projected with wire scanner
- Projected and vertical slice with screen

Much consideration for emittance measurements during design phase of SwissFEL

C. Milne *et al.*, *SwissFEL: the Swiss X-ray Free Electron Laser*, App. Sci., 2017, 7, 720

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

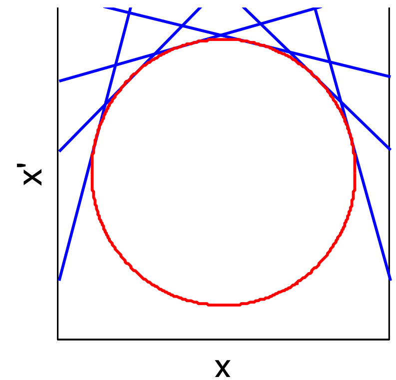
Mitigated with

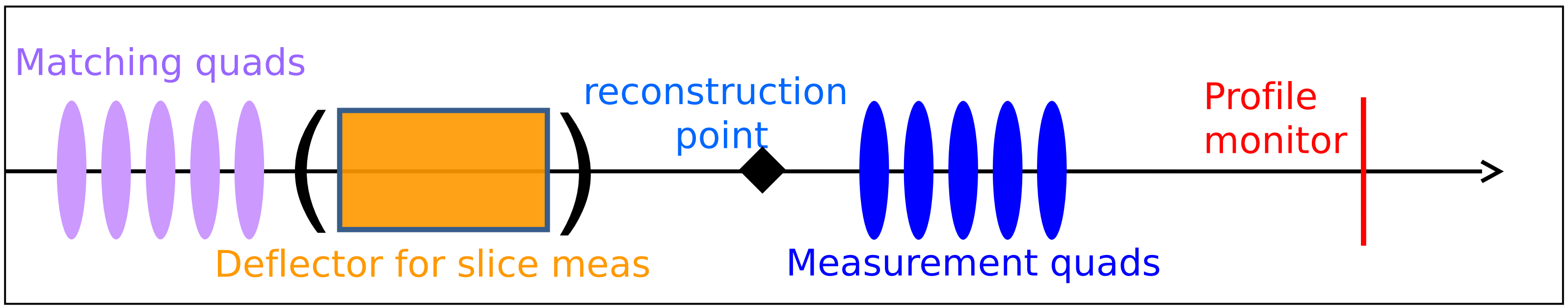
- Coupling correction
- Compression setup
- Optics in the bunch compressors
- Orbit alignment
- Beam tilt correction

We optimize the emittance for every machine setup

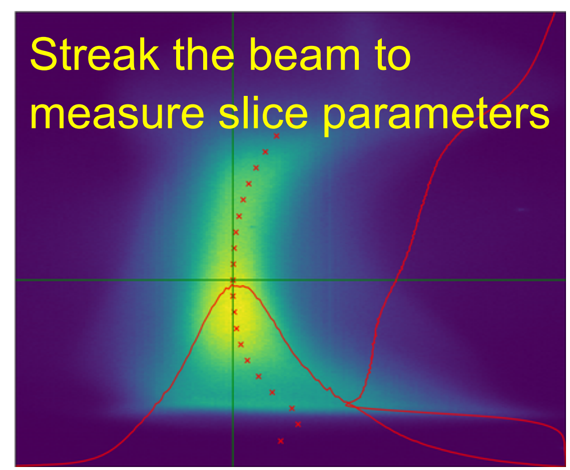
(Slice) Emittance measurements

- 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



Emittance measurement errors

Statistical errors
- Machine jitter → take several images per phase advance step

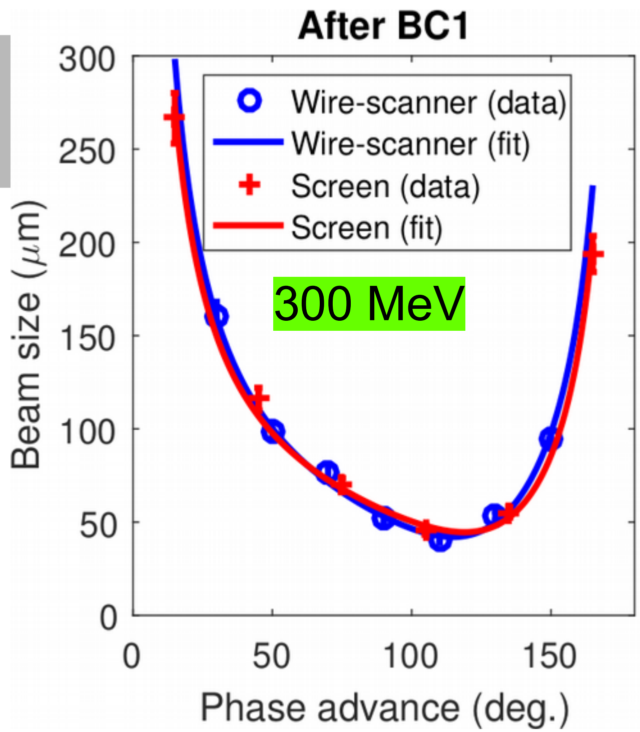
Systematic errors
- *Profile monitor resolution (see below)*
- Screen profile monitor calibration, expected <5% error in emittance
- Other errors (energy, quadrupole, Gaussian fit etc) expected <5% error

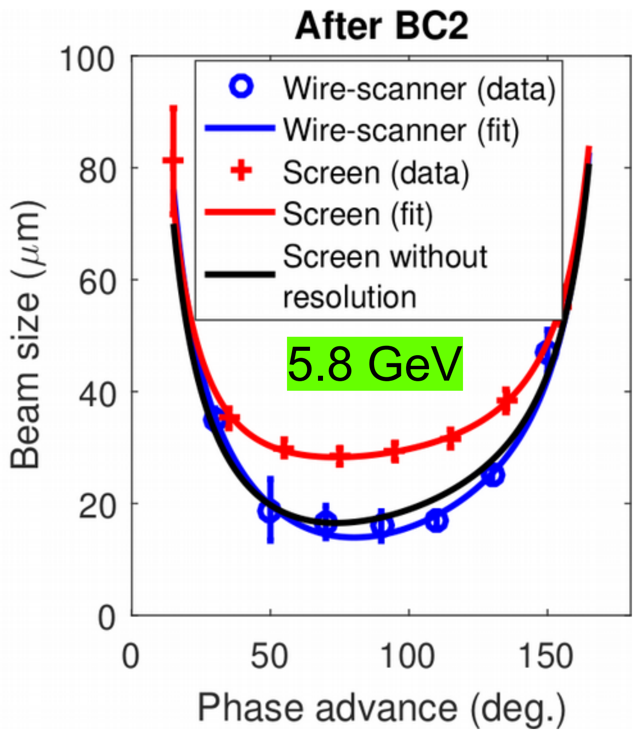
Concerning profile monitor resolution

- General: $$\underbrace{\sigma_M^2}_{\text{measured}} = \underbrace{\sigma^2}_{\text{true}} + \underbrace{\sigma_R^2}_{\text{resolution}} = \frac{\epsilon_n \beta_s}{\gamma} + \sigma_R^2$$
- If beam size (β_s) 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 in β_s is limited by lattice and phase advance (70 m in our case)
2) Decrease of beam energy (γ) is not ideal (and also limited by effects such as space charge)
3) Improve resolution σ_R. Wire scanners have better resolution than screens. (only for projected)

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!

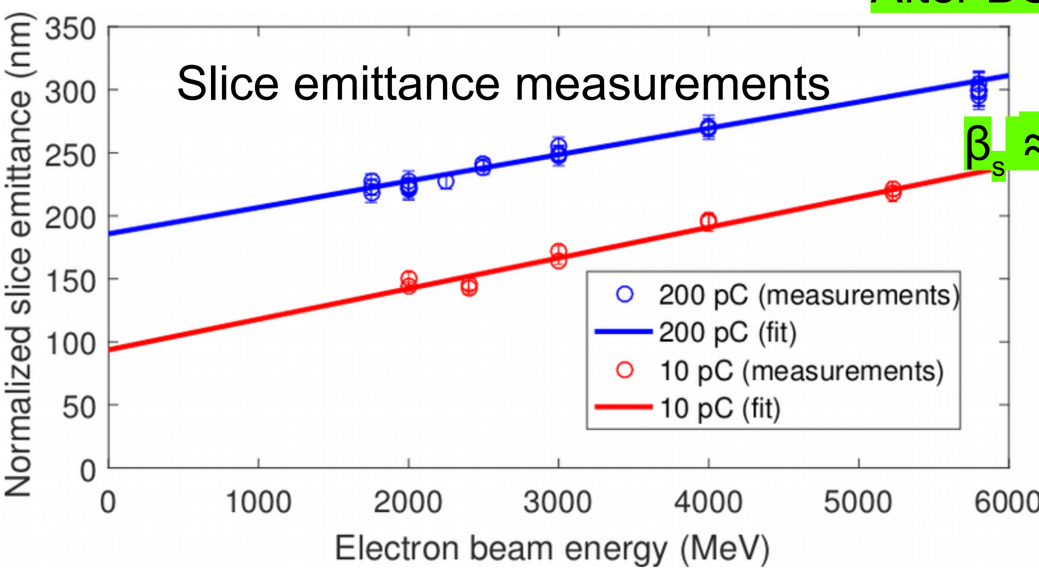
- Perfect agreement at 300 MeV for projected emittance measurements at low energy
- Screens overestimate beam sizes and emittance at high energies
- Wire scanners required for high energies
- *What about slice emittance measurement at high energy?*

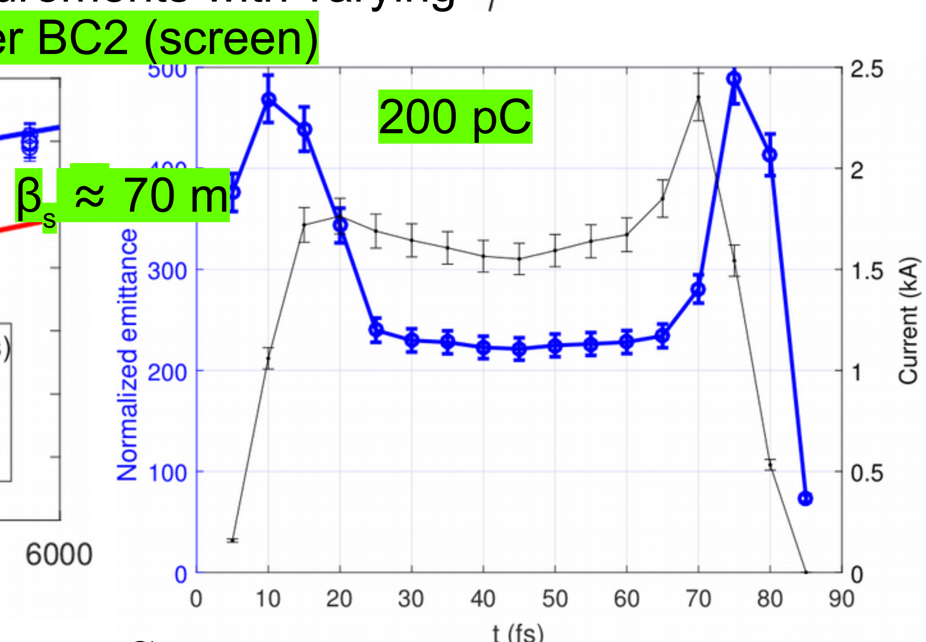
Overcoming screen resolution for slice measurement

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

Linear equation in γ

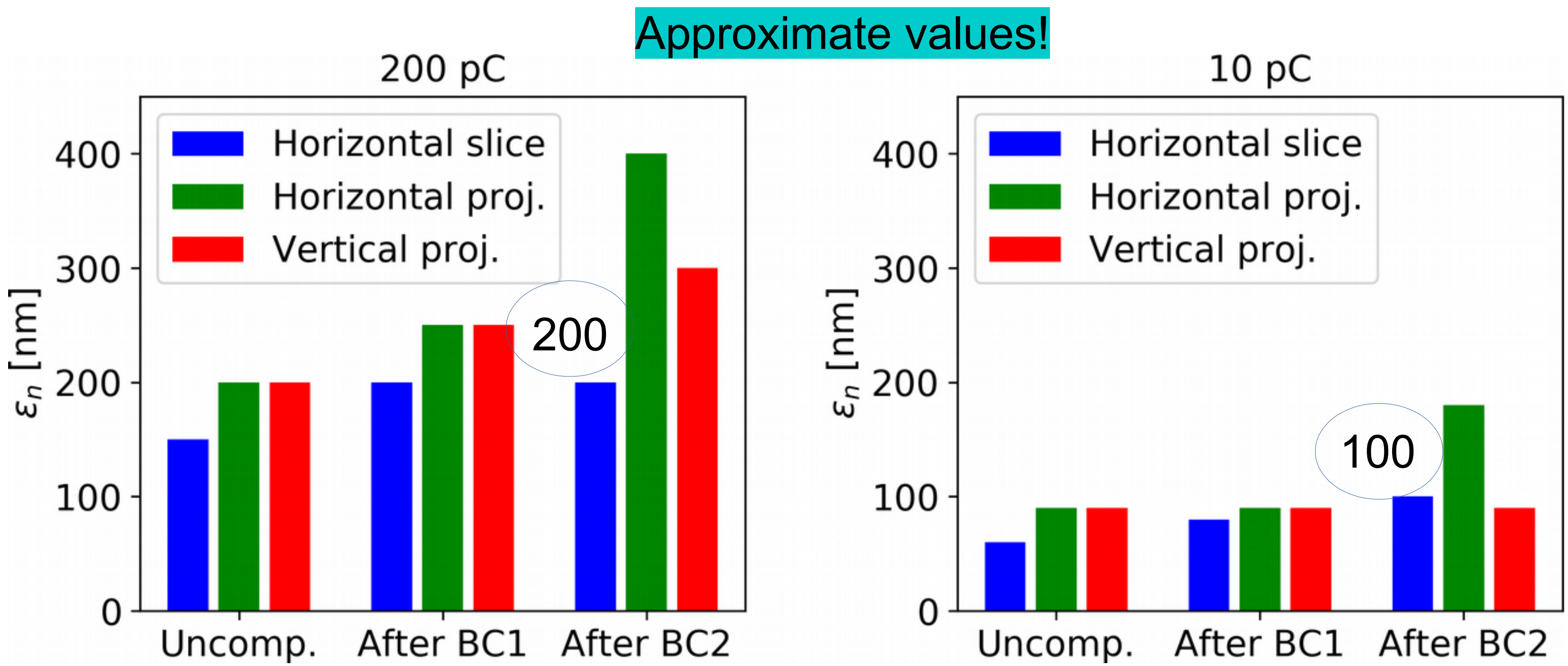
Assuming normalized slice emittance is independent of γ we can estimate true emittance and screen resolution by measurements with varying γ





	200 pC	10 pC
ϵ_n [nm]	186 ± 3	94 ± 5
σ_R [μm]	27 ± 7	29 ± 8

Summary of measured emittances



- Short-term reproducibility of measured emittance is excellent (about 2%)
- After machine start-up and re-optimiziation, ε after BC2 varies by about 10-20%

Thank you for your attention

Conclusions

- Lowest emittance for an X-ray FEL measured (to our knowledge)
  → Low ε source, optimization techniques and high-resolution diagnostics
- A method to overcome the screen resolution was demonstrated
- Low emittance allows us to generate pulses with up to 500 μJ energy, much higher than specified in the SwissFEL CDR
- Low emittance is paving the way for more compact 1 Å FELs with ≈4 GeV beam energy (provided undulator technology allows)