Slice Emittance Measurements at the SwissFEL Injector Test Facility

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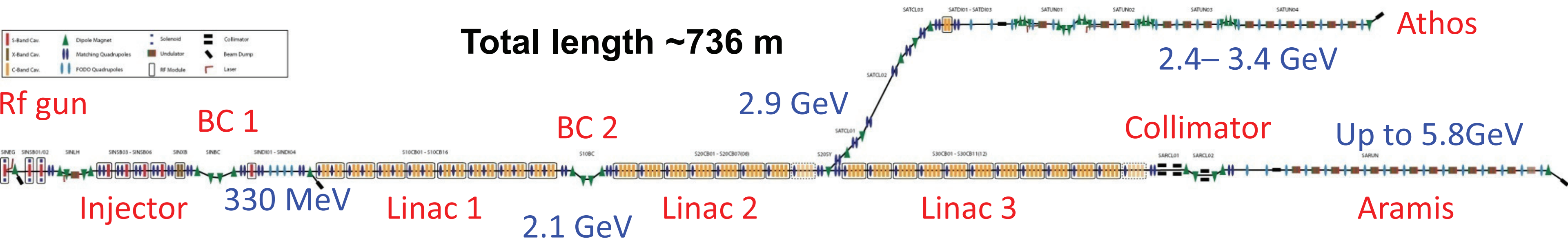
SwissFEL: a hard and soft X-ray FEL in Switzerland

+ SwissFEL



Electron source
RF gun with Ti-Sapp. laser driven Cu 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

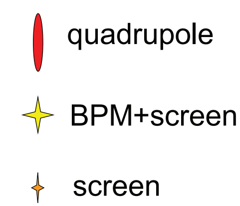
Construction started in 2013
Commissioning planned to start in 2015
User operation for Aramis planned in 2017
Athos planned for 2019

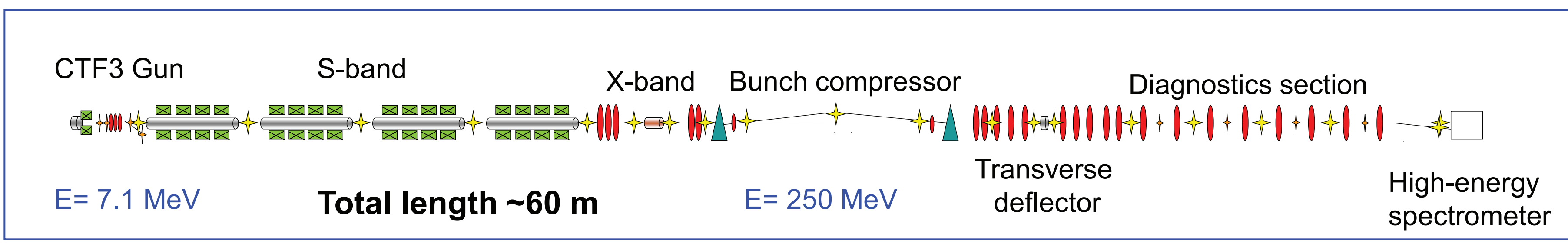
Missions

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





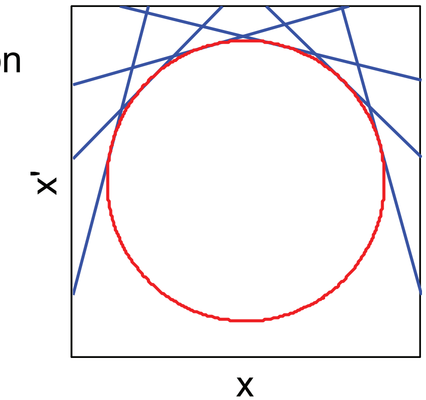
- **Phase 4: Installation of new PSI gun + undulator experiment (11/2013)**

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



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

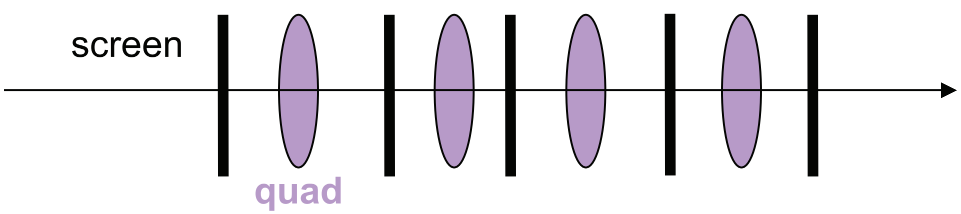
$$\beta_x = \langle x^2 \rangle / \varepsilon_x$$

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

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

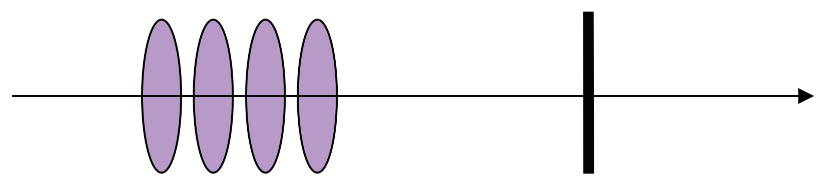
- There are two general strategies to scan the phase advance

I. Multiple position with fixed optics: *FODO*



Parasitic measurements
More equipment
Dedicated long lattices
Not flexible

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



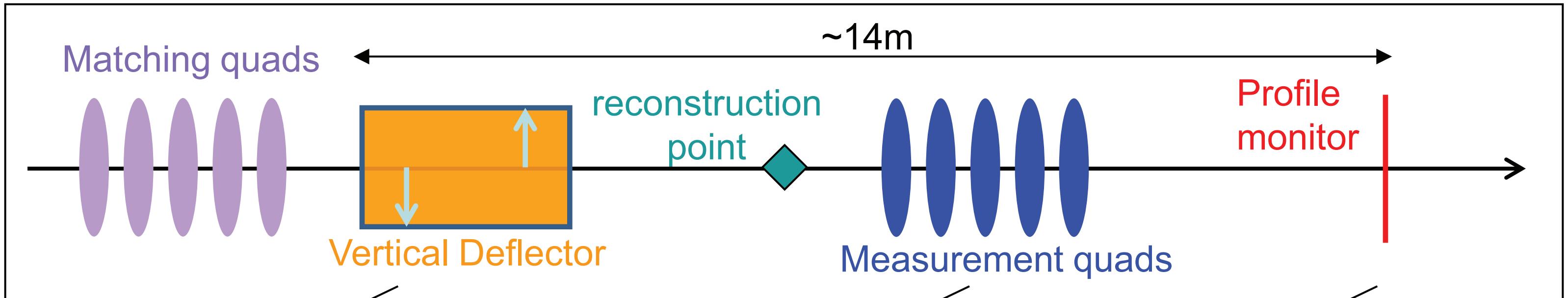
No parasitic measurements
Less equipment
More compact
Very flexible

Chosen option for projected and slice emittance meas.

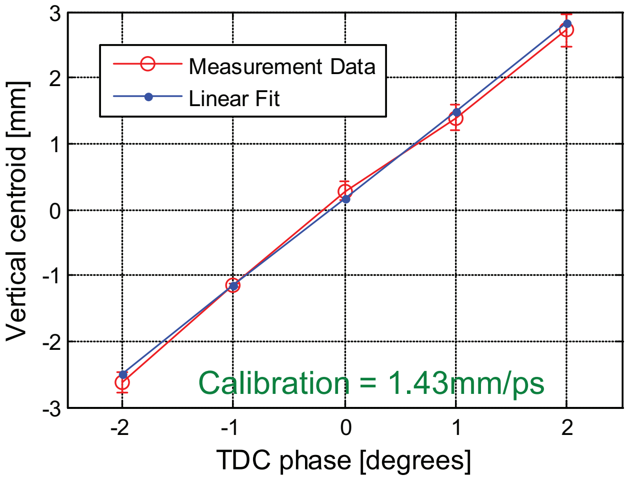
Slice emittance measurements at SITF

+ SwissFEL

For FELs it is necessary to know the beam parameters corresponding to a small part of the whole electron bunch, the so-called **slice parameters**. We measure the **horizontal** slice emittance.



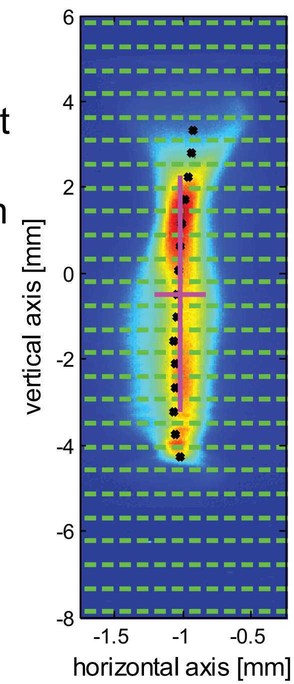
Deflector calibration. The phase of the deflector is changed to obtain calibration between transverse and time coordinates



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

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

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.

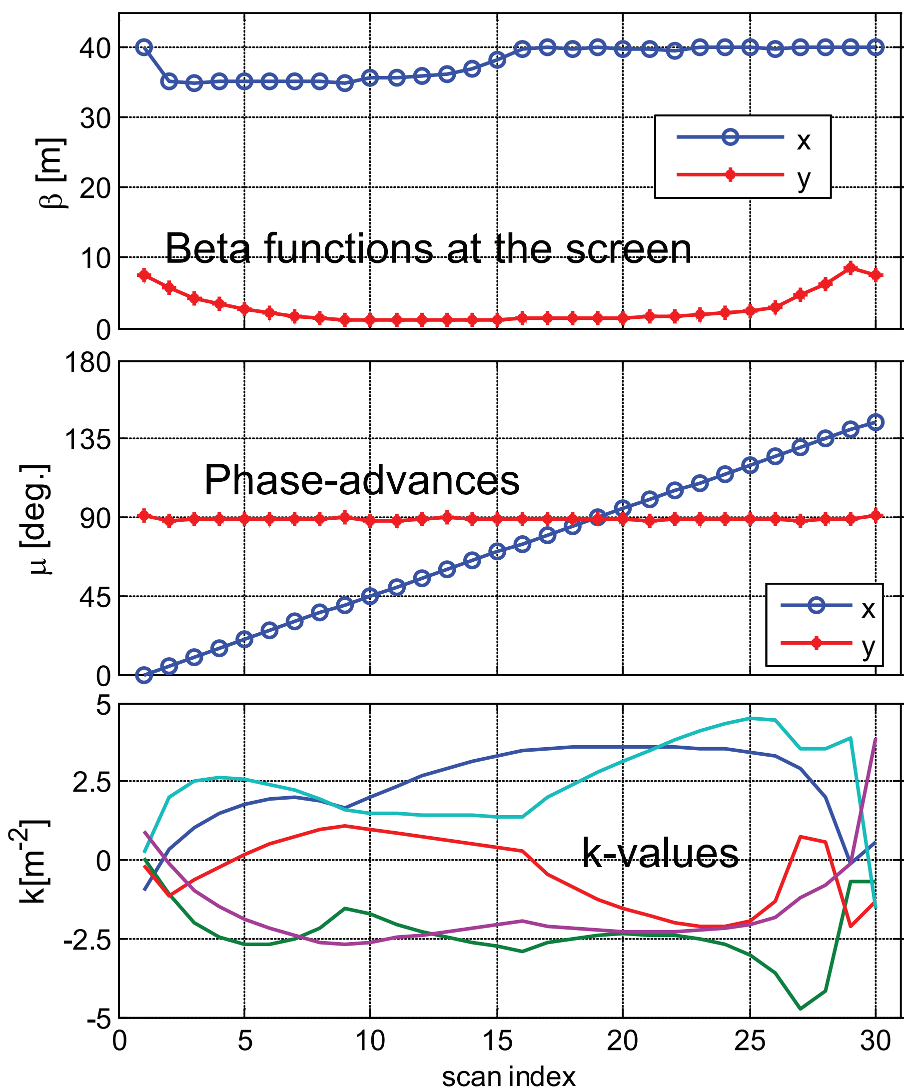


Optics for slice emittance measurements

Longitudinal resolution $\frac{\sqrt{\varepsilon_y/(\beta\gamma)}\cdot E}{\sqrt{\beta_{y_{TD}}}\cdot\sin(\Delta\mu_y)\cdot k\cdot V_{TD}}$

β_{yTD} : β-function at the deflector = 40m
$\Delta\mu_y$: vertical phase-advance between deflector and screen
k: deflector wavenumber ~= 60
V_{TD}: deflector voltage, V_{MAX} = 5MV
E: beam energy; ε_y= vertical emittance

resolution ~4 μm (for V=5MV, ε_y=0.5μm, E=250MeV)



5 quadrupoles between the deflector and the screen are used to:

- Scan phase-advance in x
- Keep β_x under control: $35\leq\beta_x\leq40$
- Keep β_y small to control streaked size: $\beta_y<10$
- Keep optimum long. resolution: $\sin(\Delta\mu_y)$ ~ 1

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

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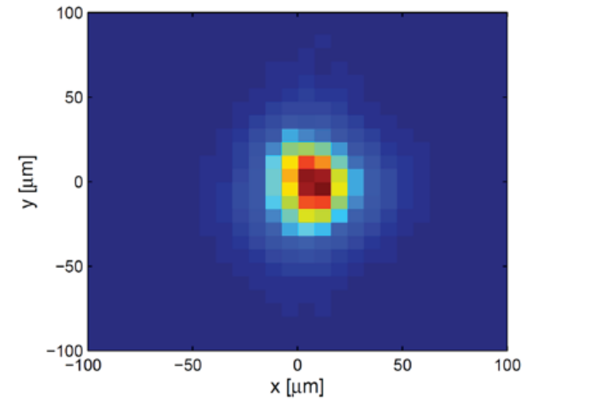
Resolution, errors and matching

+ SwissFEL

- Long. resolution = **4 μm** (for V=5MV, ε_y=0.5μm, E=250MeV)

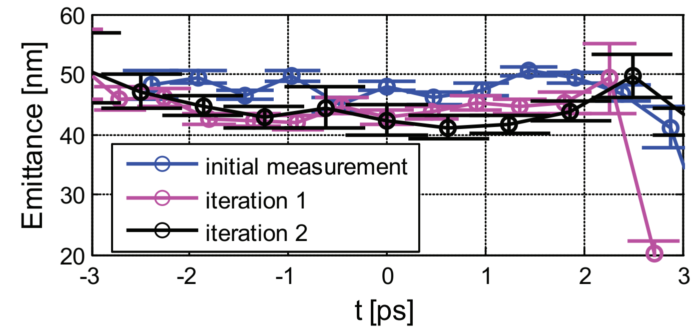
- SwissFEL profile monitor (YAG + OTR) is used for emittance measurements.
  - Beam size resolution is ~15 μm, equivalent to an emittance resolution of **~3 nm** (E=250MeV, β=35m)
  - Signal to noise ratio is good enough to measure slice emittance down to **~1pC** level

Beam image close to screen resolution limit



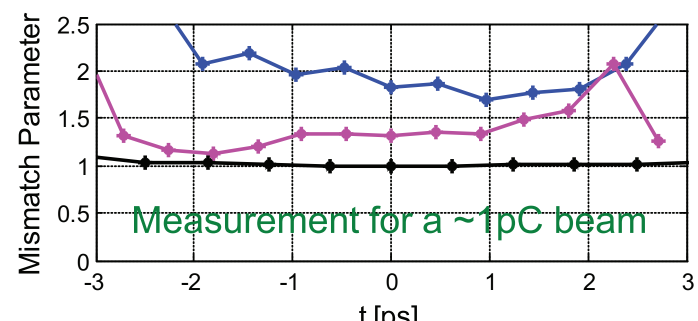
Errors

- 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 2.7% (if $\Delta\mu_x$=10°).
- 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



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

Emittance optimization

+ SwissFEL

- Strategy: optimize projected emittance in both planes, then measure slice emittance (in x)
- So far mainly optimization for uncompressed bunches for 10 pC and 200 pC
- Studies for compressed bunches are ongoing.
- 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
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 emittance optimization. Cross-plane coupling correction

- Coupling measurement by 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)

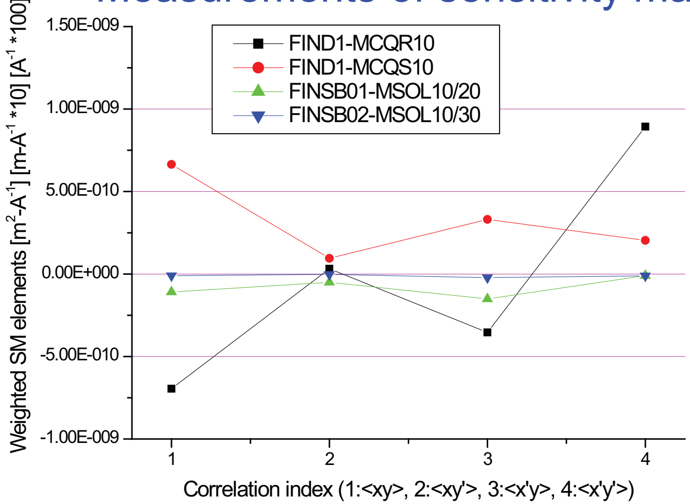
$\vec{P}$: *Beam parameters to be corrected*

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

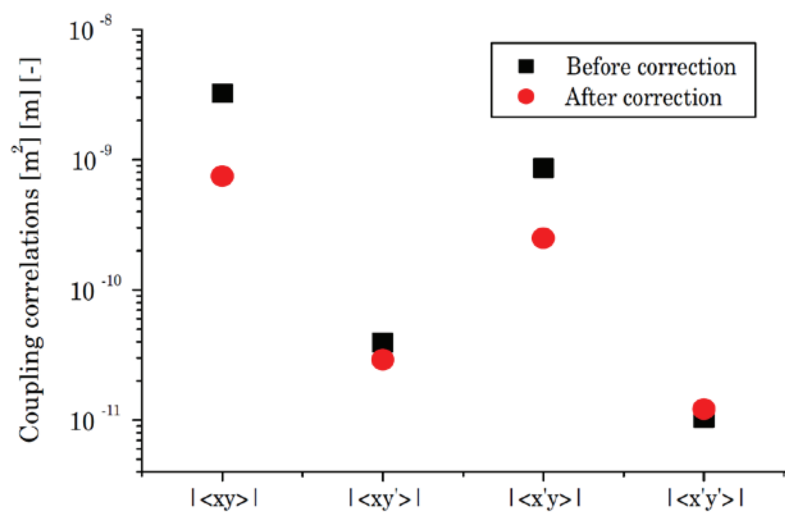
S : *Sensitivity matrix*

$\vec{C}$: *Corrections*

Measurements of sensitivity matrix



Correction results



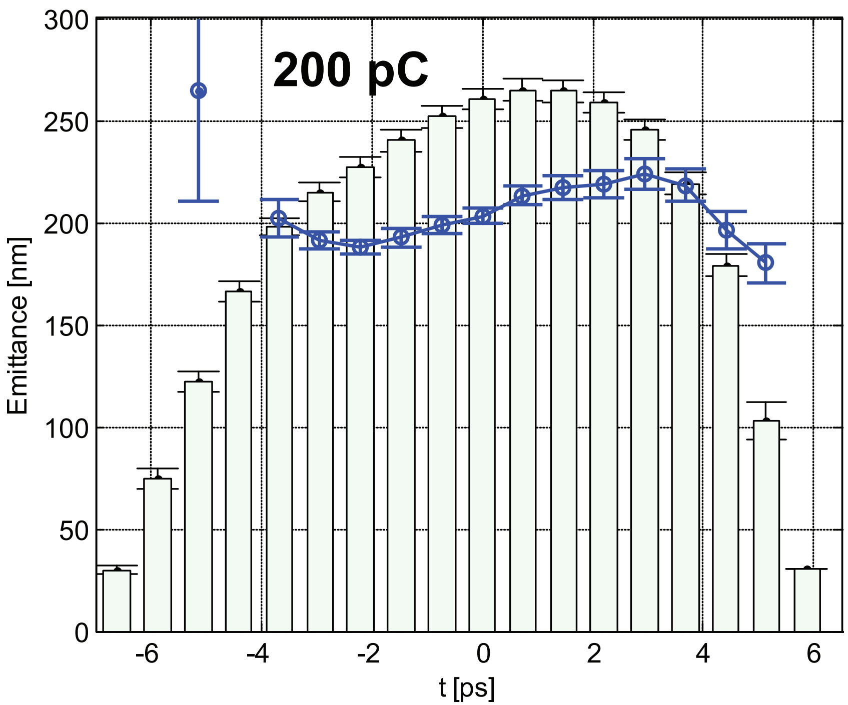
Coupling contributions largely suppressed

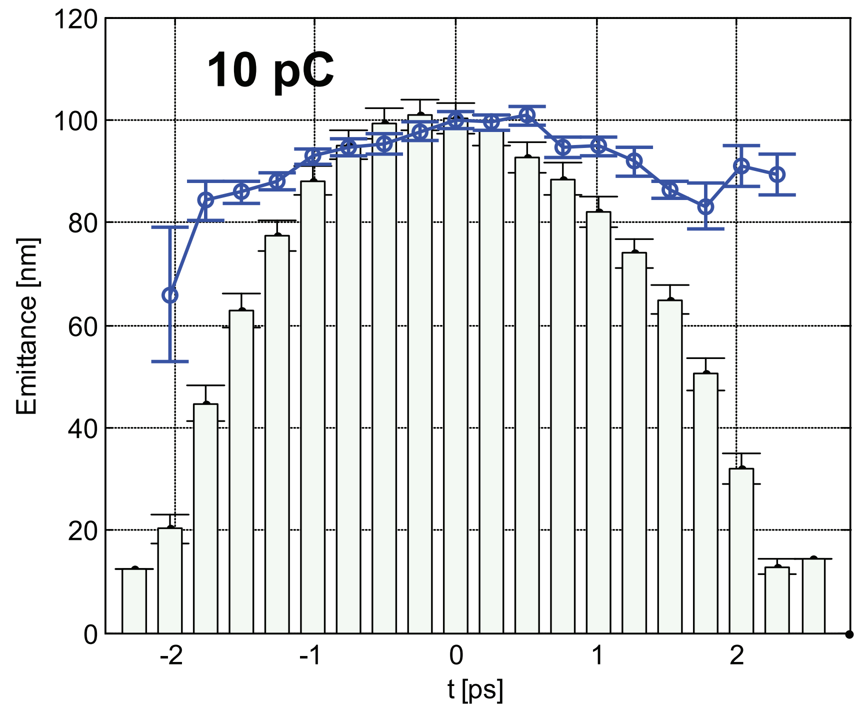
Optimum Emittances

- By doing a full optimization we have achieved the following emittances (uncompressed beam)

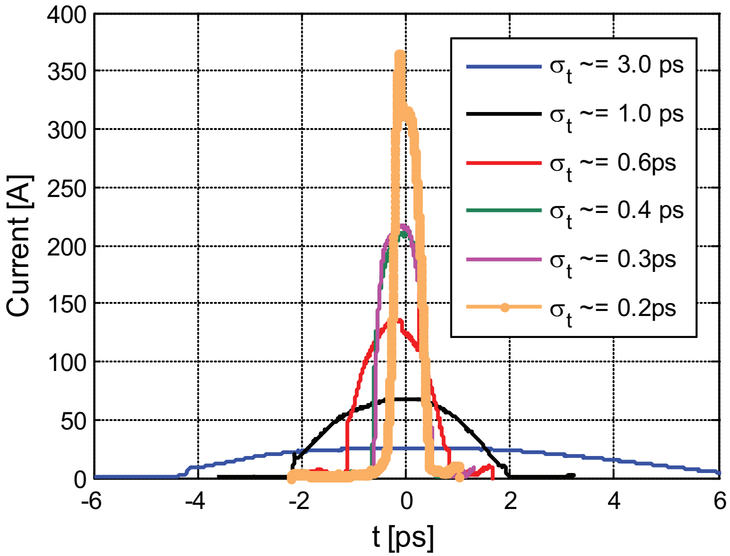
	200 pC	10 pC
Projected emittance	~0.30 µm	~0.15 µm
Slice emittance	~0.20 µm	~0.10 µm

- These emittance values fulfill the SwissFEL requirements for uncompressed beams
- Emittance values are stable in short-term and optimum settings are reproducible





First results with compression

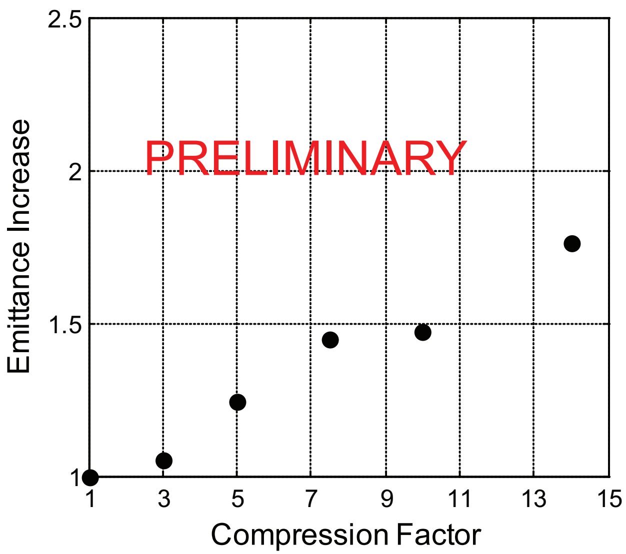


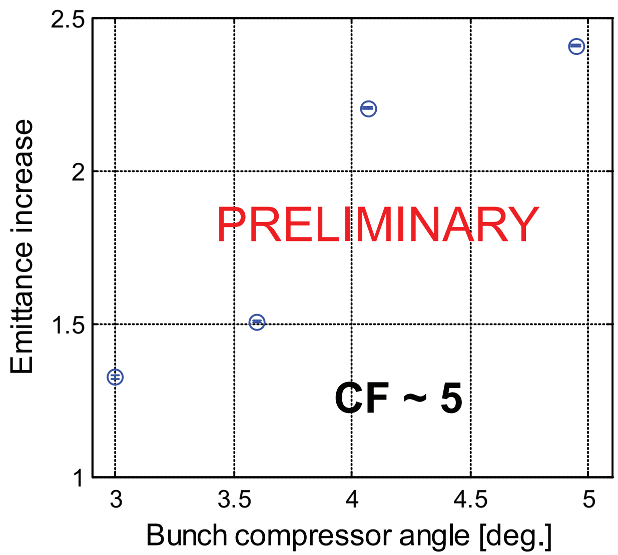
First results show a slice emittance increase when we compress the 200 pC beam for CF> 5

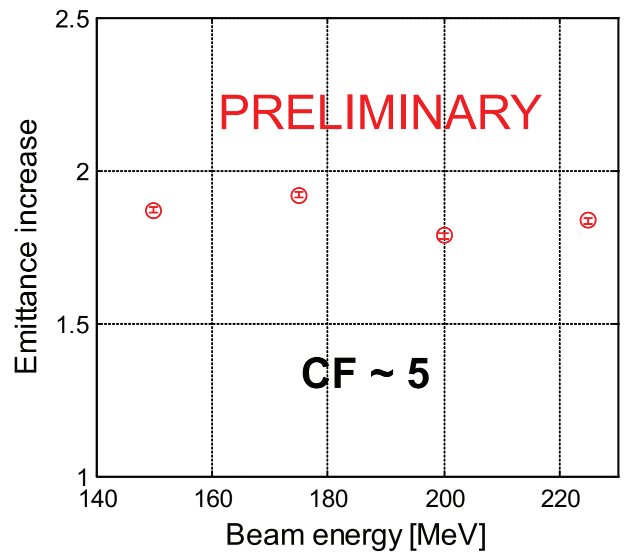
The measured emittance increase seems to:

- Do not be due to energy chirp
- Depend on the compression factor
- Depend on the bunch compressor angle
- Do not depend on the beam energy

The emittance increase might be due to CSR (not predicted by simulations) or any other contribution from the bunch compressor. Investigations are ongoing…







Summary and next steps

Summary

➢ Method to measure slice emittance developed and tested at the SwissFEL Injector Test Facility

- Longitudinal resolution is ~4 μm
- Emittance resolution is ~3 nm
- Successful optics matching

➢ Excellent results achieved for uncompressed bunches:

- ~200 nm for 200 pC
- ~100 nm for 10 pC
- These values fulfill the SwissFEL requirements

Next steps

➢ Continue emittance optimization for compressed bunches

Acknowledgments

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

Thanks for your attention!