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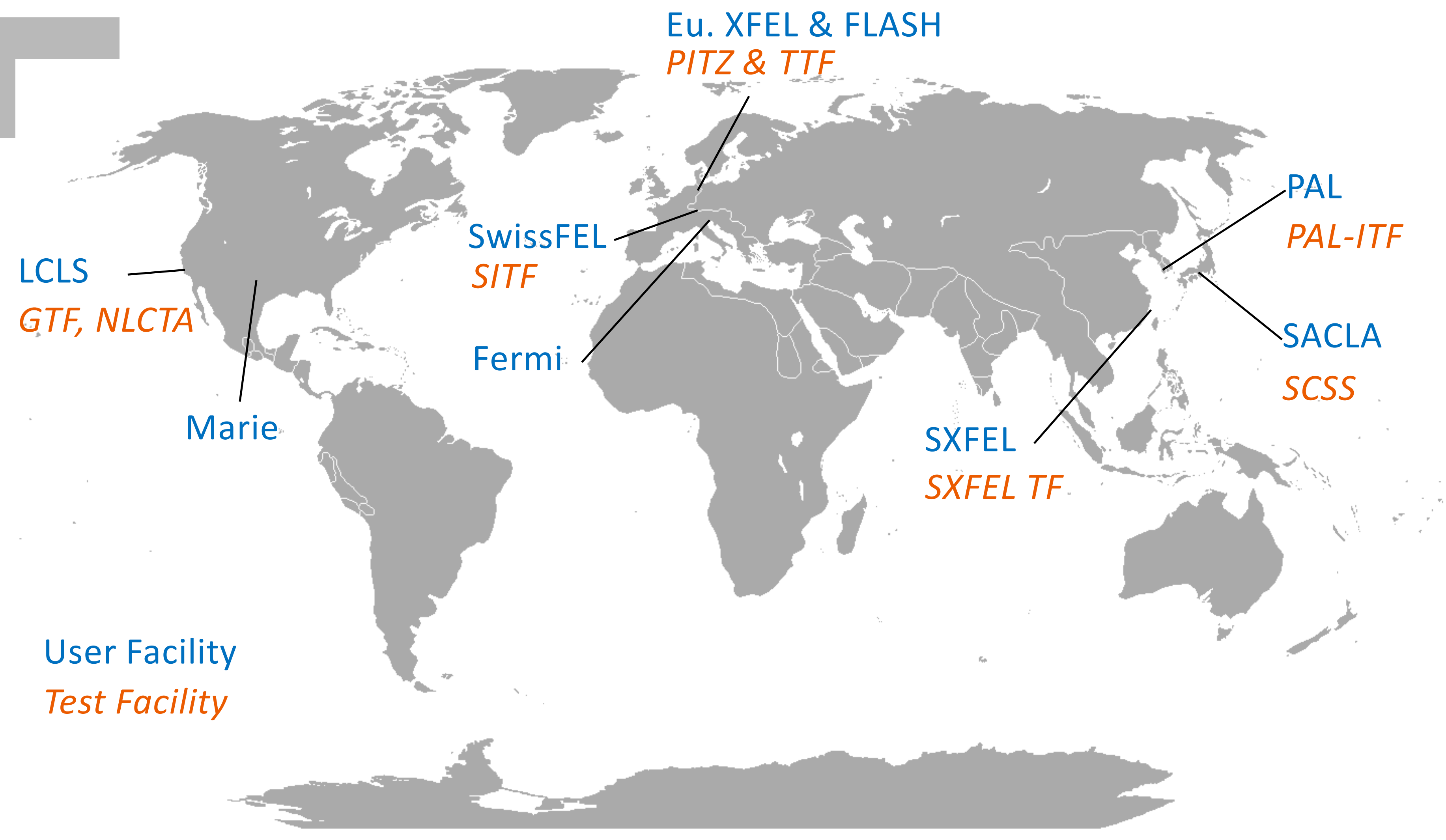
Sven Reiche:: SwissFEL Beam Dynamics :: Paul Scherrer Institut

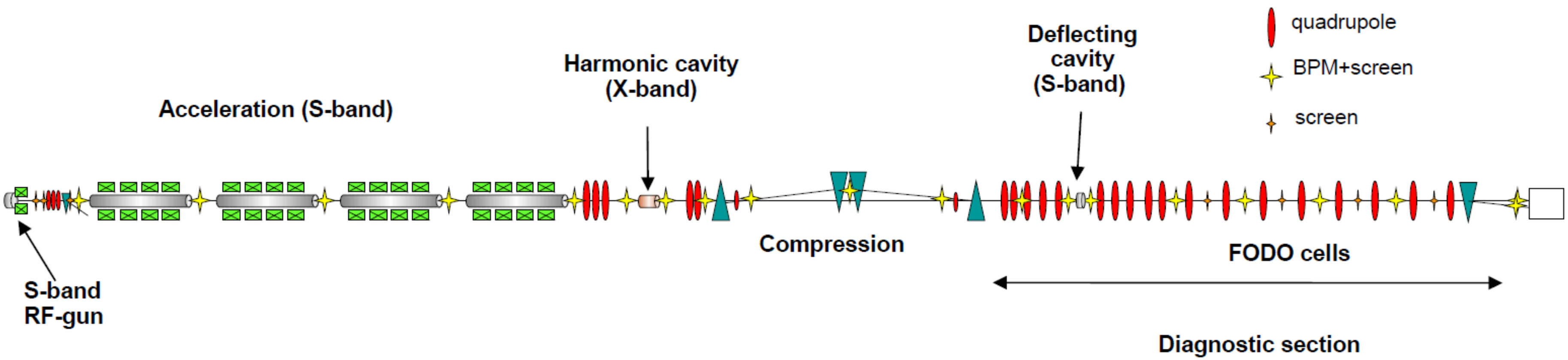
Studies at the SwissFEL Injector Test Facility

Insert the occasioCALIFES Workshop, Oct 2016

X-ray FEL Facilities and Their Test Facilities



SwissFEL Injector Test Facility



- Goals
  - Demonstrate beam quality needed for SwissFEL
  - Demonstrate preserved beam qualities after compression
  - Demonstrate performance of new diagnostics
  - Test in-vacuum undulator U15 and demonstrate FEL amplification

- Operation 2010-2014

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Summary of beam physics studies at SITF

Beam and lattice characterization procedures

- Transverse beam characterization
  - Symmetric single-quad scan *[E. Prat, NIMA 743, 103 (2014)]*
  - 4D measurements *[E. Prat and M. Aiba, PRSTAB 17, 052801 (2014)]*
  - Beam-size free optics measurements *[M. Aiba et al, NIMA 753, 24 (2014)]*
  - SwissFEL profile monitor *[R. Ischebeck et al, PRSTAB 18, 082802 (2015)]*
- Longitudinal beam characterization and time-resolved measurements
  - Measurement of bunch length (TD) and beam slice parameters with transverse deflector and dispersion method *[E. Prat and M. Aiba, PRSTAB 17, 032801 (2014)]*

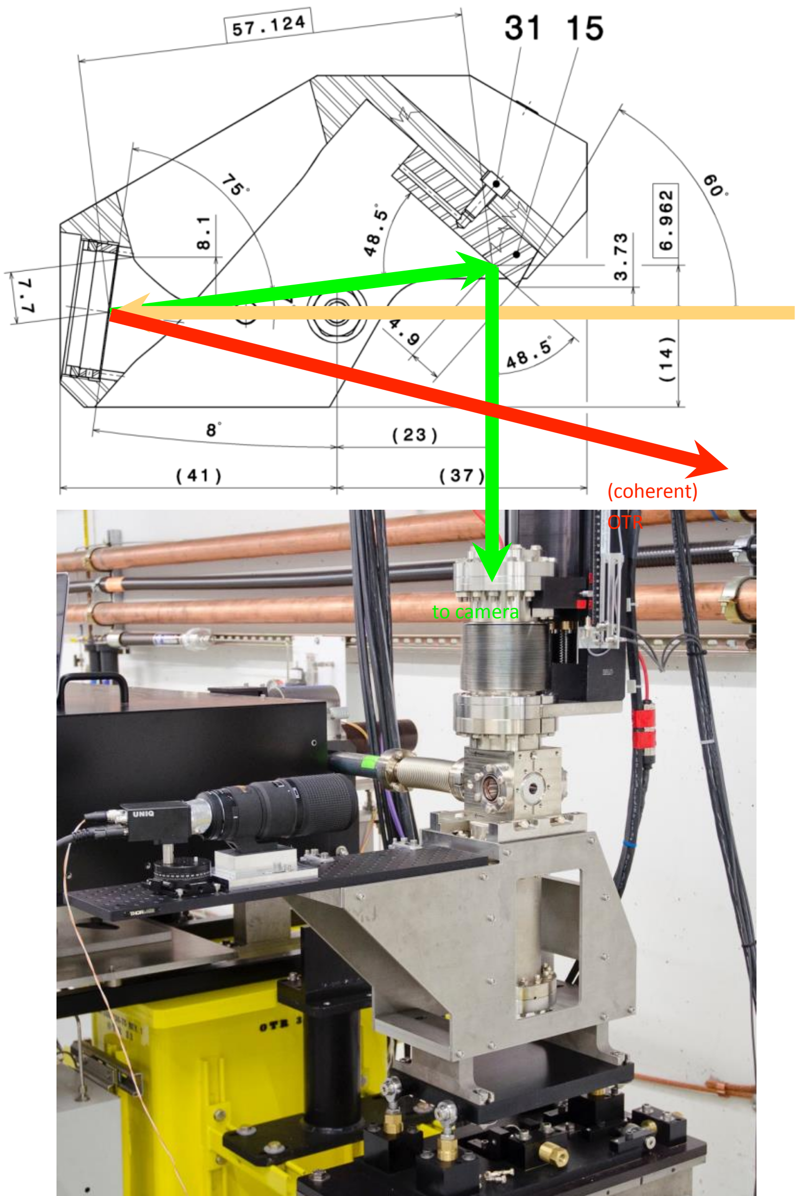
Beam physics results

- Cathode (thermal/intrinsic) emittance measurements:
  - Wavelength dependence *[M. C. Divall et al, PRSTAB 18, 033401 (2015)]*
  - Gradient dependence *[E. Prat et al, PRSTAB 18, 063401 (2015)]*
  - Copper vs cesium telluride *[E. Prat et al, PRSTAB, 043401 (2015)]*
- Optimization of uncompressed beam:
  - Measurements *[E. Prat et al, PRSTAB 17, 104401 (2014)]*
  - Automatic optimization *[S. Bettoni et al, PRSTAB 18, 123404 (2015)]*
- Emittance preservation at compression *[S. Bettoni et al, PRAB 19, 034402 (2016)]*
- Further measurements:
  - Passive “streaker” *[S. Bettoni et al, PRAB 19, 021304 (2016)]*
  - Beam tilts meas. and correction *[M. Guetg et al, PRSTAB 18, 030701 (2015)]*
  - Comparison FODO vs quad-scan measurements *[M. Yan et al, FEL14, 941 (2015)]*

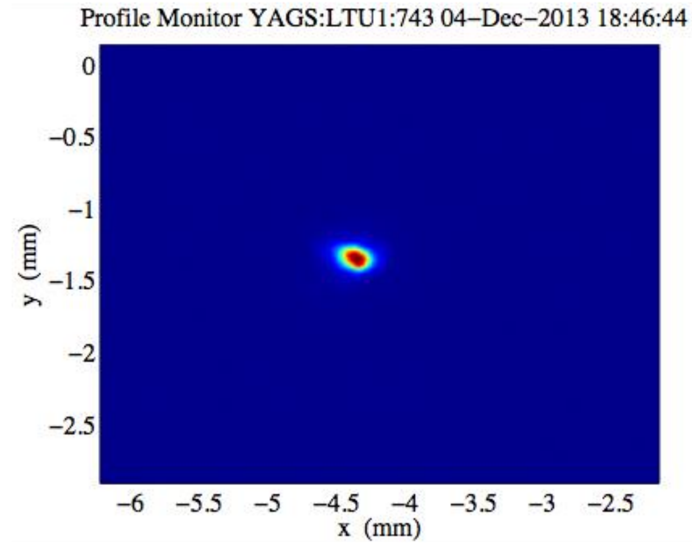
Measurements at LCLS (December 2013)

- Measurements at LCLS show <u>no sign</u> of coherent OTR on the camera

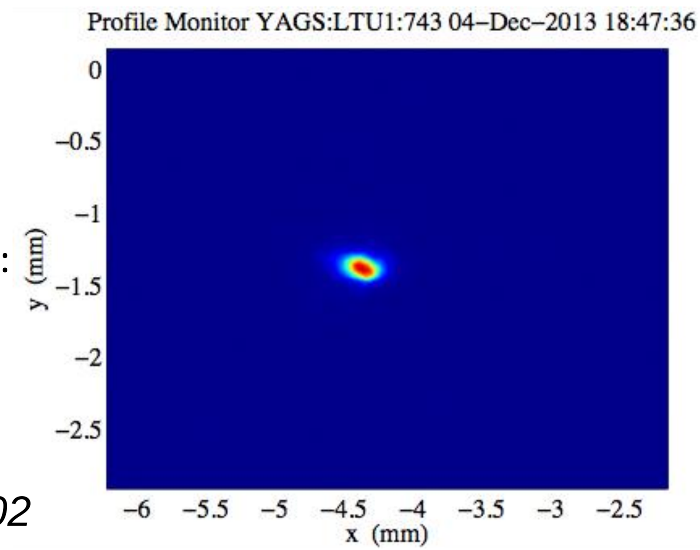
Installation in the LCLS Linac-to-Undulator line



Laser heater ON:



Laser heater OFF:



[R. Ischebeck et al, PRSTAB 18, 082802 (2015)]

Emittance resolution, errors and matching

- SwissFEL profile monitor (YAG)
  - Beam size resolution is ~15 μm, equivalent to an emittance resolution of 1-3 nm (E=250MeV)
  - Signal to noise ratio is good enough to measure slice emittance for bunch charges of less than 1pC

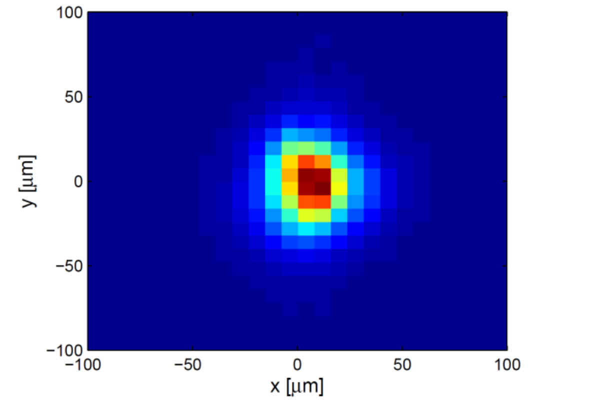
Errors

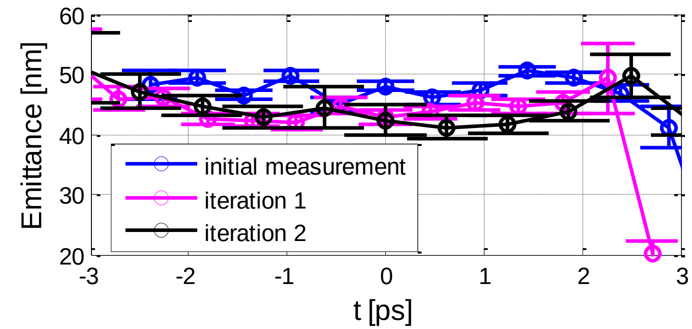
- Statistical errors from beam size variations (what is shown in the error bars of the measurements). For 5% of beam size measurement error this is below 3% (if $\Delta\mu_x$=10deg).
- Systematic errors expected to be below 5%:
  - Screen calibration (~1%→~2%) and resolution
  - Energy and quadrupole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

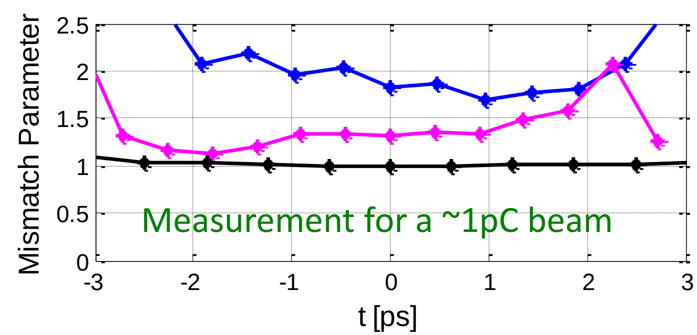
Matching

- 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







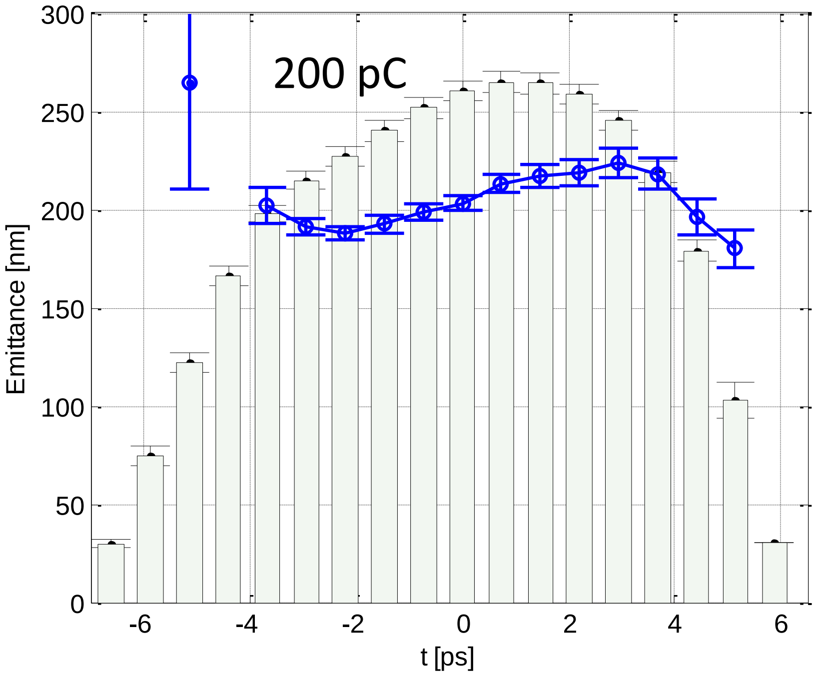
$$M = \frac{1}{2}(\beta\gamma_D - 2\alpha\alpha_D + \gamma\beta_D)$$

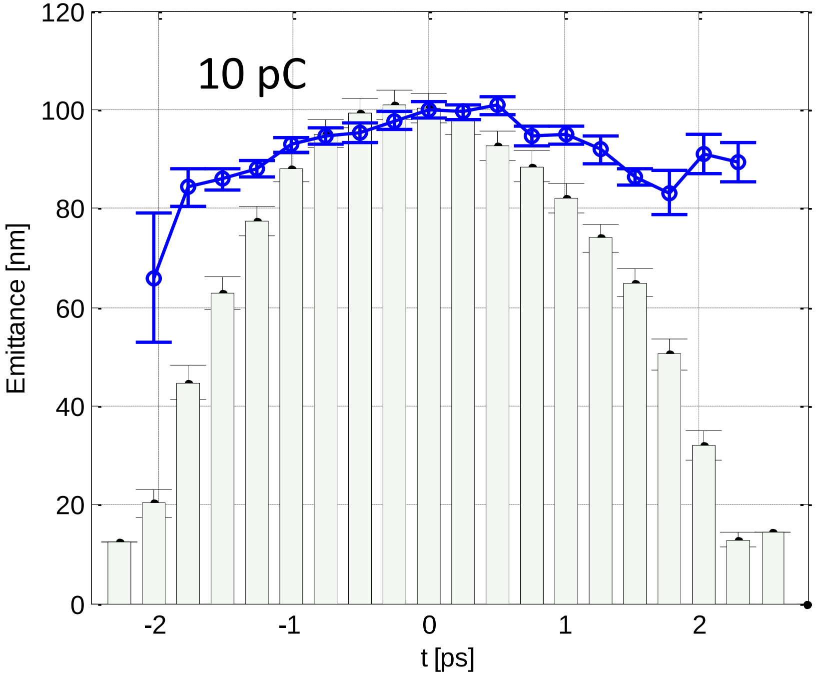
Optimum emittances

- We have achieved the following emittances *[E. Prat et al, PRSTAB 17, 104401 (2014)]*

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

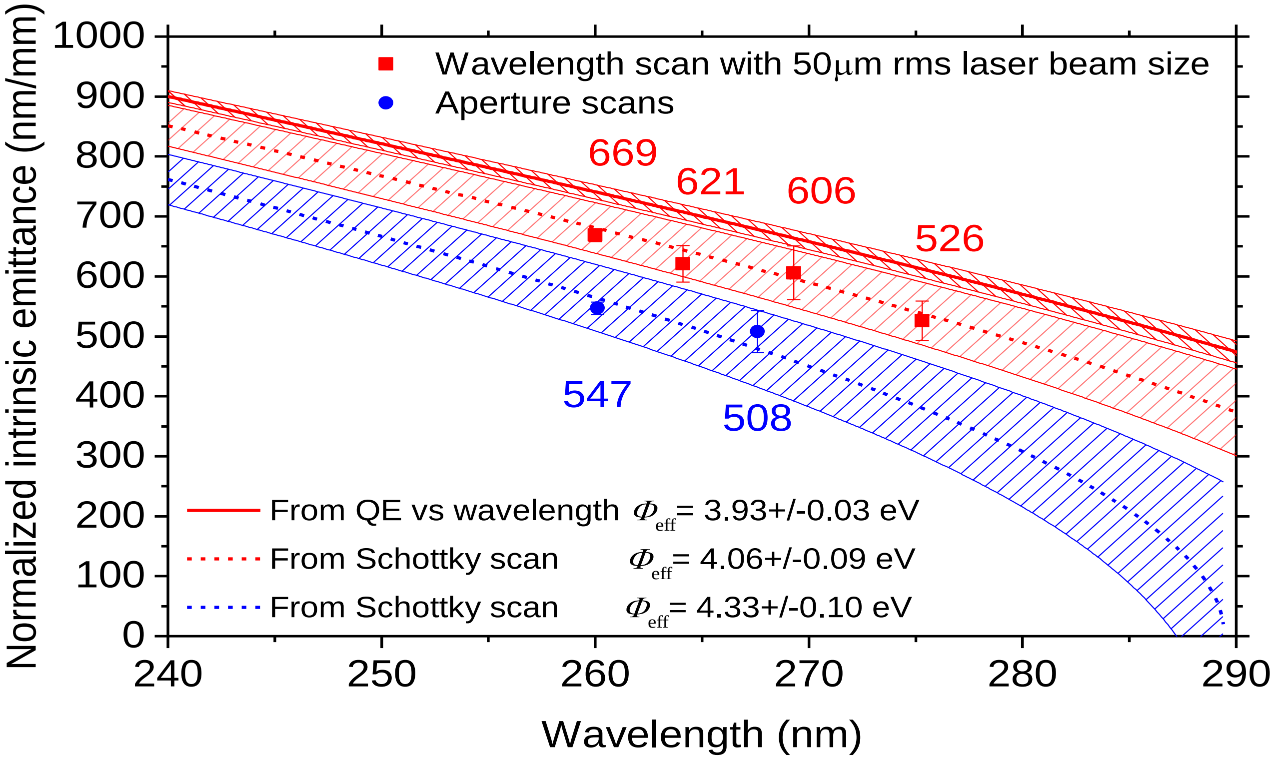
- These emittance values fulfill the SwissFEL requirements
- Emittance values are stable in short-term and optimum settings are reproducible
- Emittance is preserved for compressed bunches after careful adjustment of the optics





Wavelength dependence: summary

[M. C. Divall et al, PRSTAB 18, 033401 (2015)]



- 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

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 (yellow)
Cathode field dependence (pink)
Cs_2Te measurements (green)

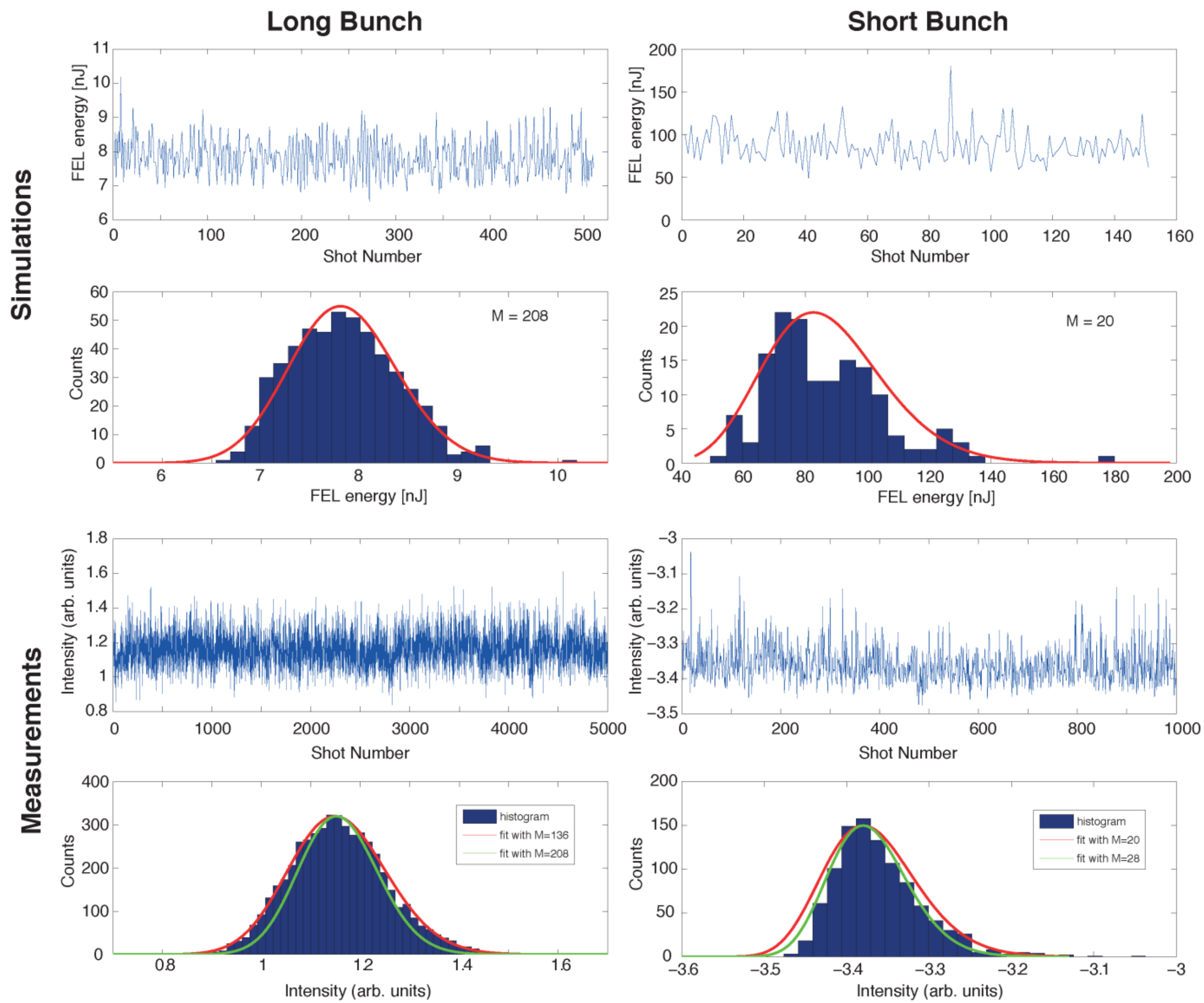
(*) Normalized to 262 nm and 50 MV/m

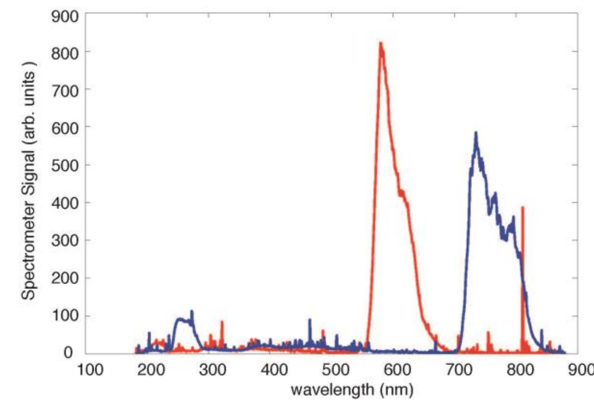
Measurements at other labs

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)]

First FEL in Switzerland





- Test of U15 undulator
- Very little diagnostics (YAG screen, spectrometer)
- Good agreement with numerical model though no further insight into beam parameters.

Lessons learnt from SITF

- "The injector is moved as it is to SwissFEL" has become obsolete:
  - Emittance optimization requires a longer drift between gun and first RF structures
  - Laser heater was not implemented yet
  - Active correction with quads, skew quads and sextupoles in chicane added
  - Dedicated FODO lattice for diagnostics is impractical (required length, resolution problems on screen, multiple screens, space charge effects increased)
  - Increase of nominal beam energy of first compression stage and longer bunch compressor
  - Cu-cathode and pulse stacking is major cause of microbunching.
  - Tunability in gun laser wavelength for smaller thermal emittances is not worth the effort with respect to increased operation cost and stability.
  - Design of large good field region for chicane magnets causes huge stray field
  - In efficient matching before compressor (high k_1 values and beam chirp)

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Things, which could have been studied…

- New Gun Design (C-Band gun)
- Laser Seeding at 50 nm (HHG vs HGHG vs EEHG)
- Non-linear compression
- Advanced phase-space manipulation with wakes
- Measurement of intrinsic energy spread, Coulomb scattering in the gun.
- More longitudinal diagnostics (invasive and non-invasive)
- Beam based THz generation (moved to FLUTE/KIT)
- Microbunch gain curve

Some will be measured at SwissFEL, though in the future it is foreseen to rebuilt SITF in a reduced form, mostly for Gun and RF testing.

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Acknowledgement

- Thanks to the SITF Team: *M. Pedrozzi, M. Aiba, E. Prat, S. Bettoni, T. Schietinger, R. Ischebeck, B. Keil, M. Duval, A. Triserio, C. Viccario and many more…*