Commissioning results from European XFEL injector

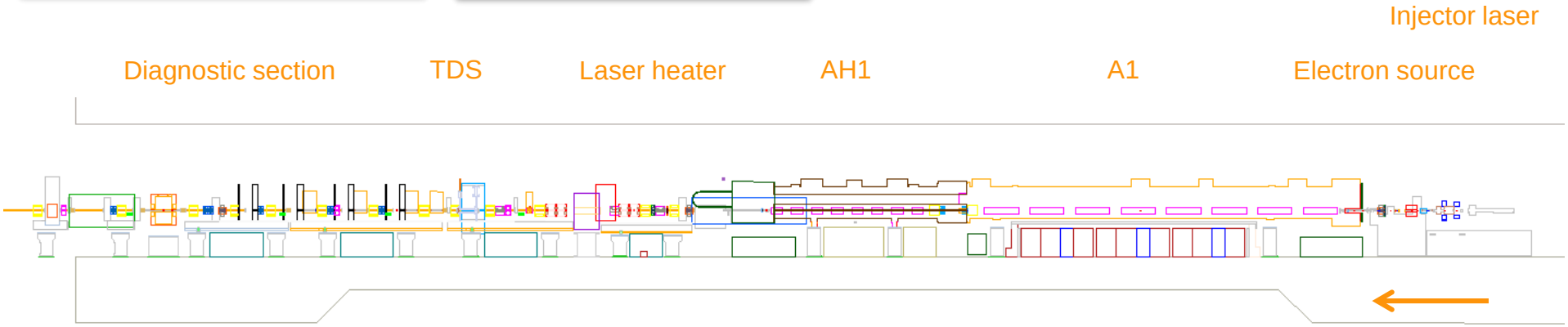
Matthias Scholz

for the commissioning team

European XFEL Injector

Design energy is 130 MeV

Up to 27000 bunches/s



Comparison of TDR and achieved parameters

Quantity	TDR	Achieved
Macro pulse repetition rate	10 Hz	10 Hz
RF pulse length (flat top)	650 us	670 us
Bunch repetition frequency within pulse	4.5 MHz	4.5 MHz
Bunch charge	20 pC - 1 nC	20 pC – 1 nC
Slice emittance (about 50 MV/m gradient, 500 pC)	0.6 mm mrad	0.6 mm mrad*
Achieved projected emittance for 500 pC bunches and ~53 MV/m gun gradient		1.2 mm mrad

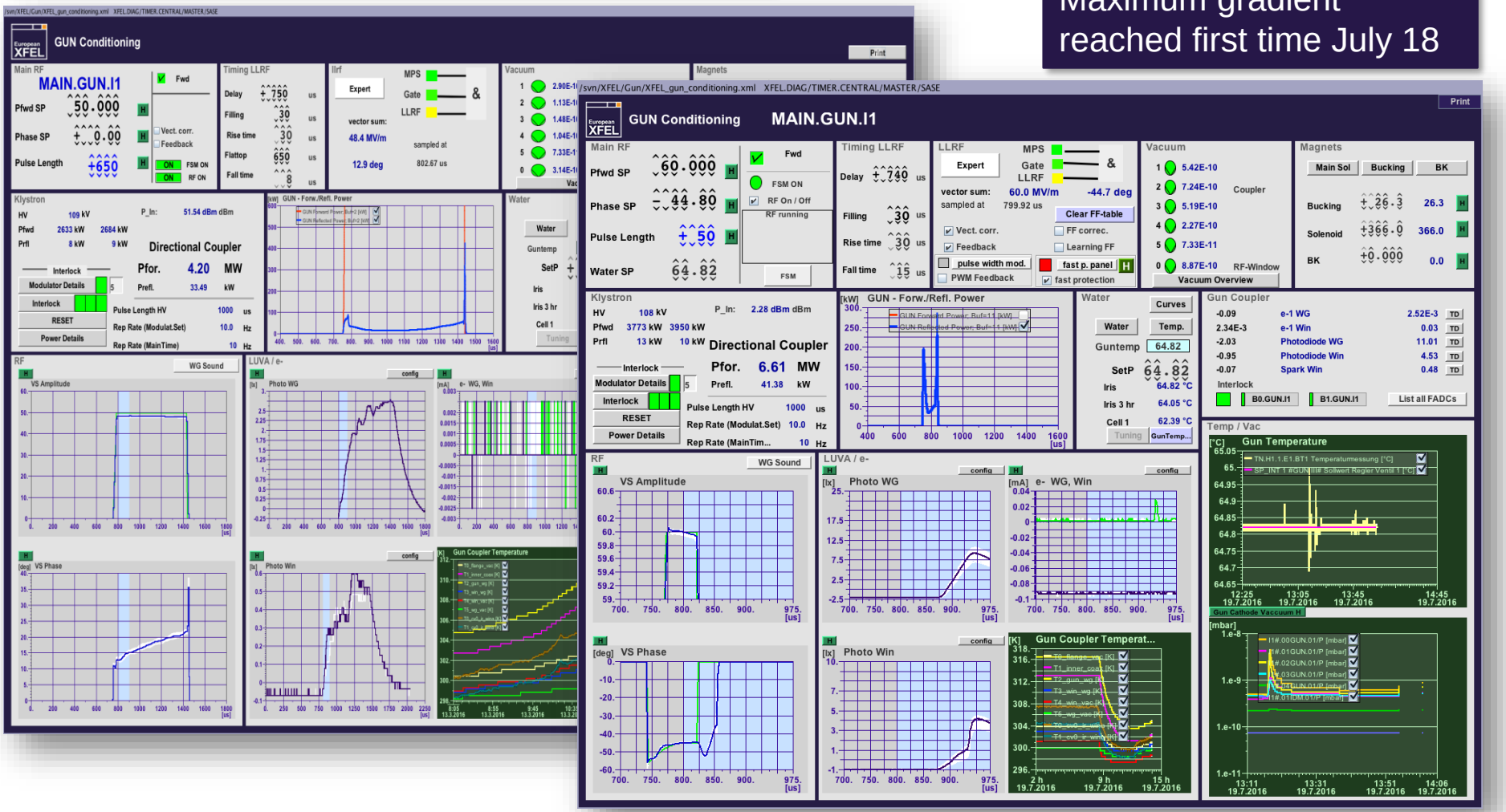
- TDR parameters could be reached

*This value was measured using the four-screen-method. The best results achieved, 0.4 mm mrad for the same bunch charge and gun gradient, was measured with a multi knop quadrupole scan (to be presented later).

Maximum pulse length and maximum gradient

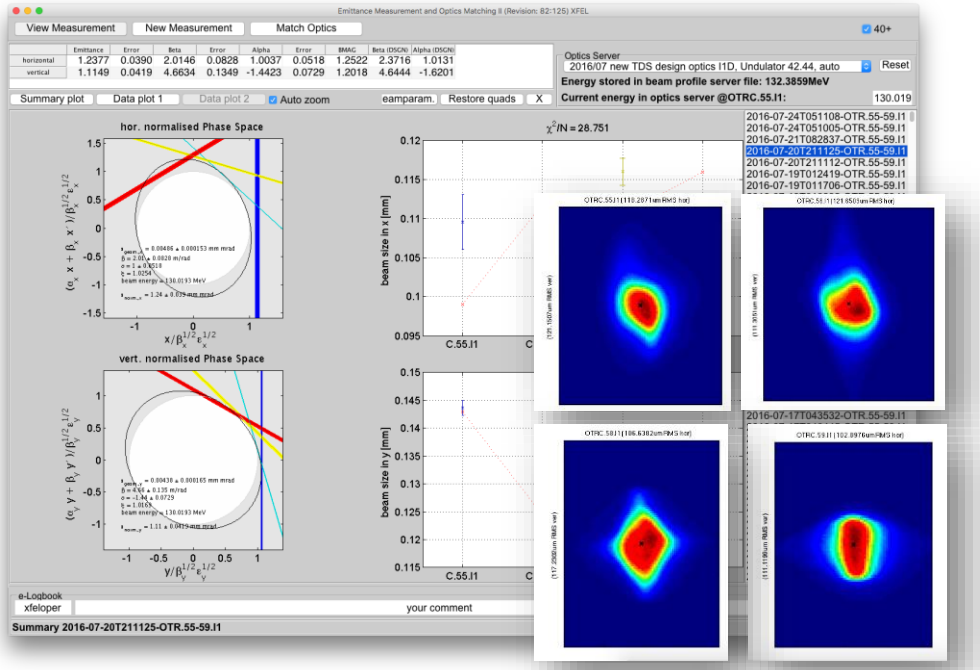
The gun pulse length reached 650 us March 13

Maximum gradient reached first time July 18



XFEL injector emittance measurements, the four screen method

- Four screens are moved into the beam trajectory and the beam sizes are measured on each screen.
  - Well know procedure, has been used at FLASH for years.
  - It is the most stable measurement for emittances available in the XFEL injector.
  - We have a highly developed Matlab tool for measurements and matching that is well known by the operators.



Best results from projected emittance measurements for different bunch charges. These numbers were measured with a gun gradient of 53 MV/m.

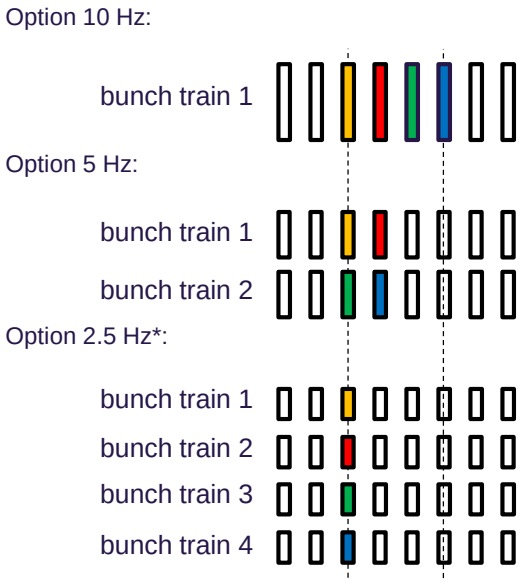
Charge	Horizontal	Vertical
50 pC	0.56 mm mrad	0.64 mm mrad
100 pC	0.77 mm mrad	0.83 mm mrad
500 pC	1.28 mm mrad	1.23 mm mrad
1000 pC	2.95 mm mrad	2.81 mm mrad

Most of the time was spend to optimize emittances of the 500 pC case. Thus it is possible that the other results can be improved further in the future.

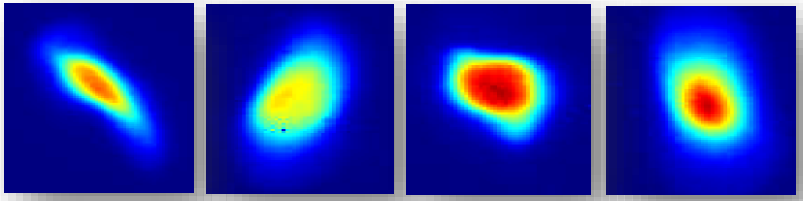
Four screen method with off-axis screens

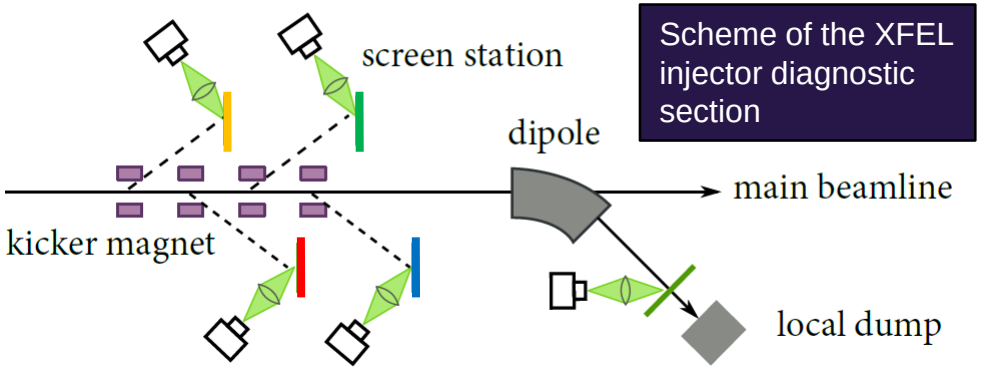
- The XFEL can deliver up to 2700 bunches with a bunch to bunch repetition rate of 4.5 MHz .
- Fast kickers allow to kick single bunches out of the trains to the screens while those are in off-set position.
- That allows us to measure the emittances and beam optics parameters on-line while all other bunches are delivered to the undulators.
- In addition, it is not necessary to move the screens in and out. Thus, these measurements take only ~20 seconds.
- There are Matlab tools available, which were used frequently by the operators during the last injector run.

Different distribution patterns



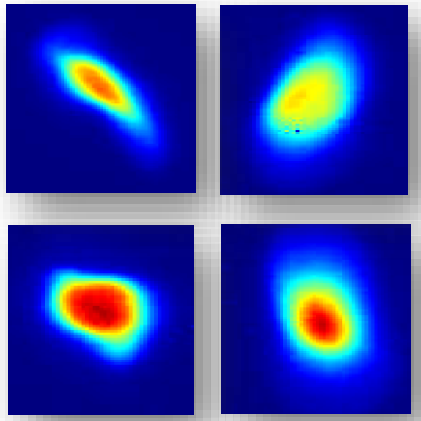
First time beam on all four off-axis screens: March 3, 2016





Scheme of the XFEL injector diagnostic section

Four screen method with off-axis screens



Different distribution patterns

Option 10 Hz:

bunch train 1

Option 5 Hz:

bunch train 1

bunch train 2

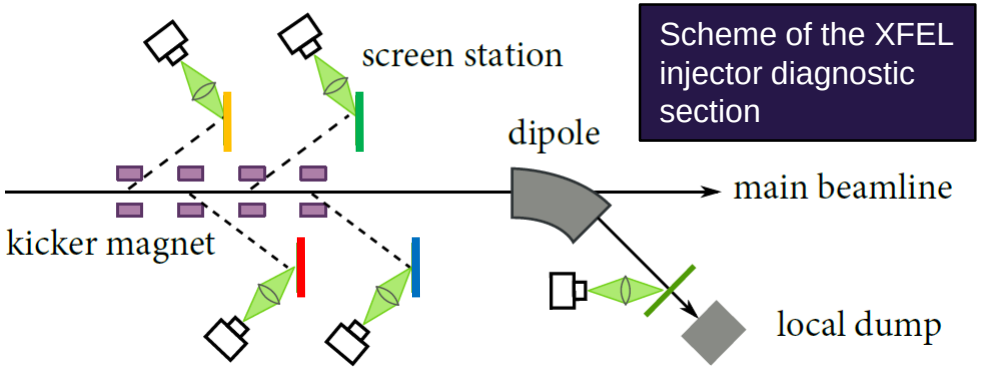
Option 2.5 Hz*:

bunch train 1

bunch train 2

bunch train 3

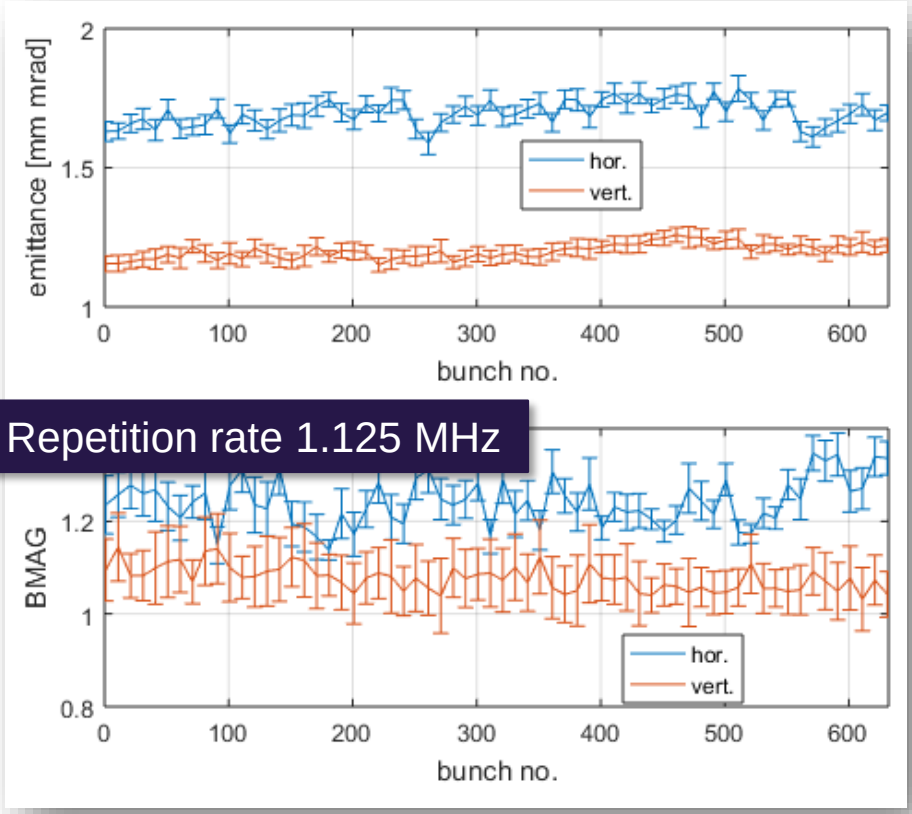
bunch train 4



Scheme of the XFEL injector diagnostic section

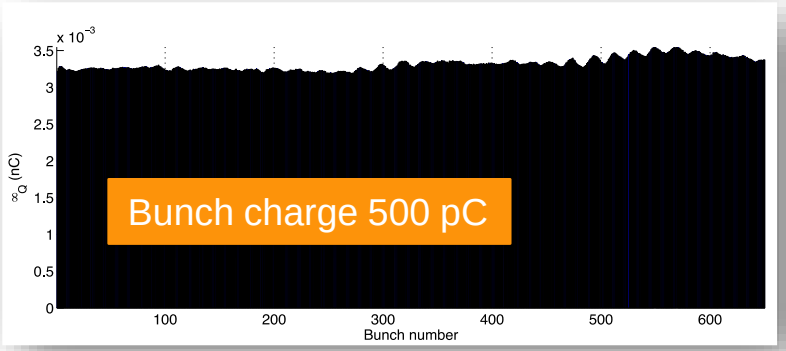
Emittance measurements along bunch trains

- Each of the bunches within a bunch train can be kicked to the off-axis screens.
- This allows us to study the beam emittances and matching parameters along the bunch train and to match any of these bunches.
- First emittances measurement along the bunch train: April 12.



Repetition rate 1.125 MHz

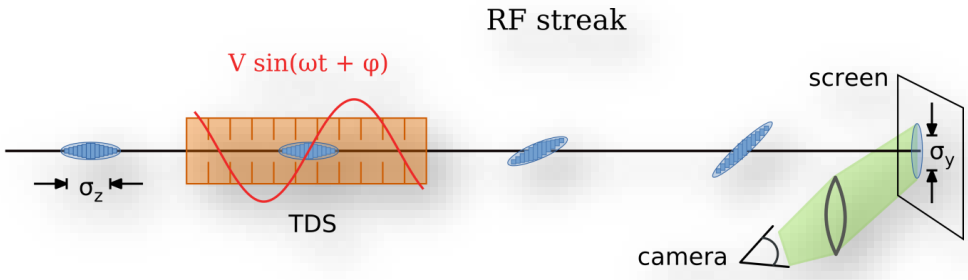
An example for projected emittance measurements along the bunch train. Both emittances as well as the mismatch are almost constant over the train.

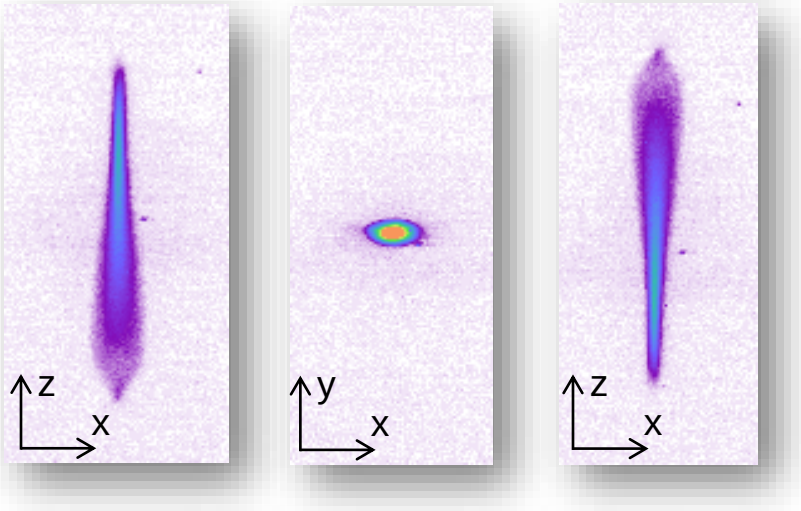


Bunch charge 500 pC

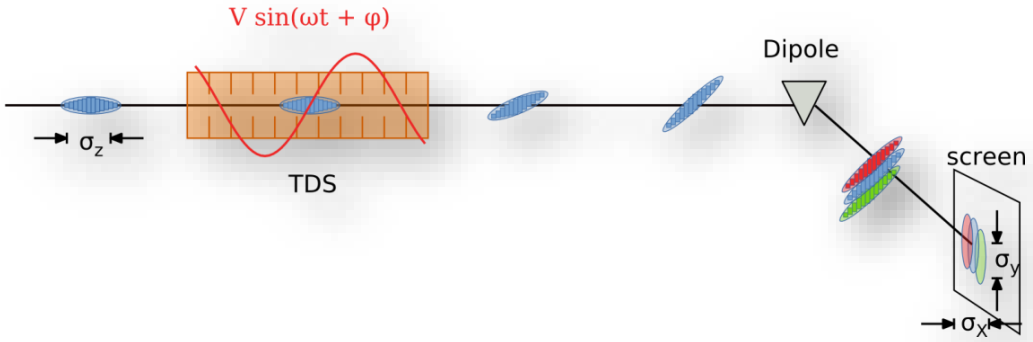
Transversely deflecting structure

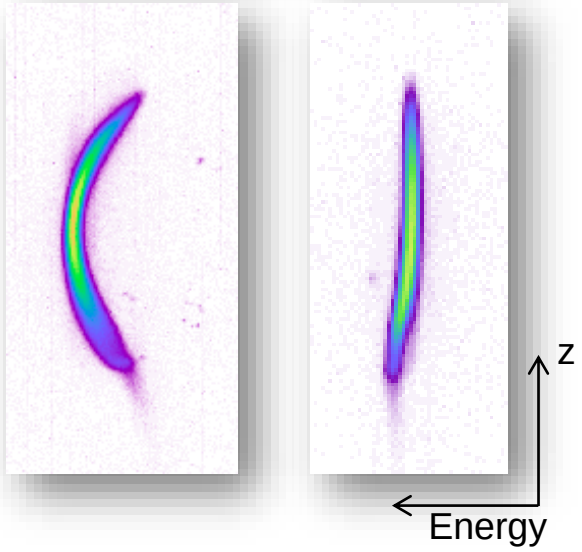
Transversely Deflecting Structure (TDS) + screen





TDS + dipole (dispersive section) + screen

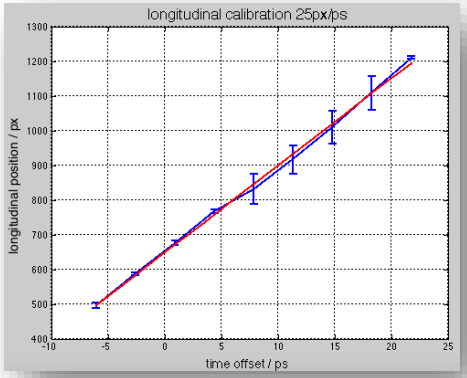


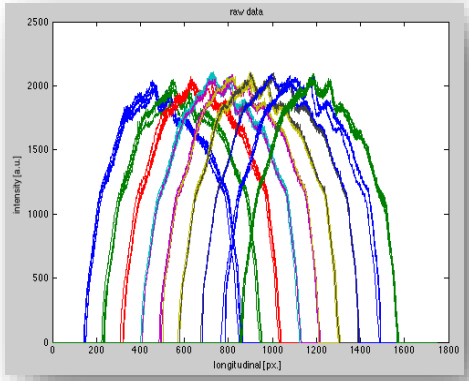


Bunch length measurements

- There is a tool available for investigations of the longitudinal bunch profile.
- It takes several camera pictures of a streaked bunch with slightly different TDS phases. That allows to recalculate the calibration curve for each measurement.

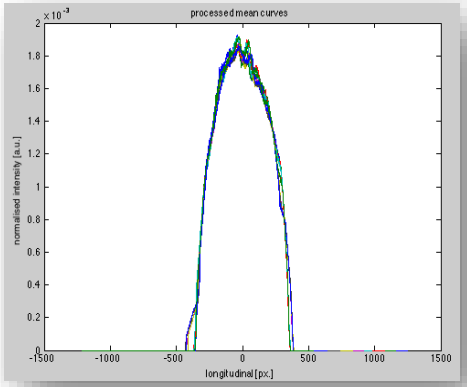
Calibration curve

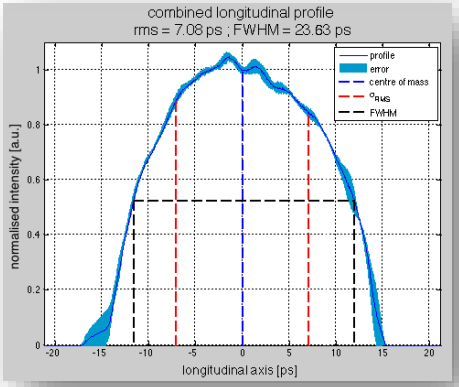




Profiles of the single measurements

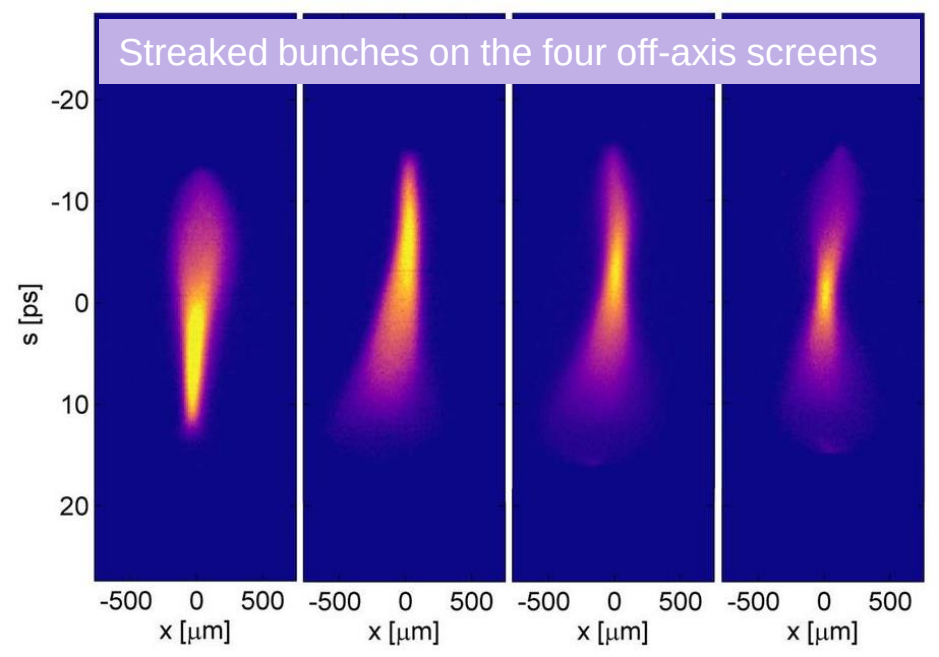
Combined profiles





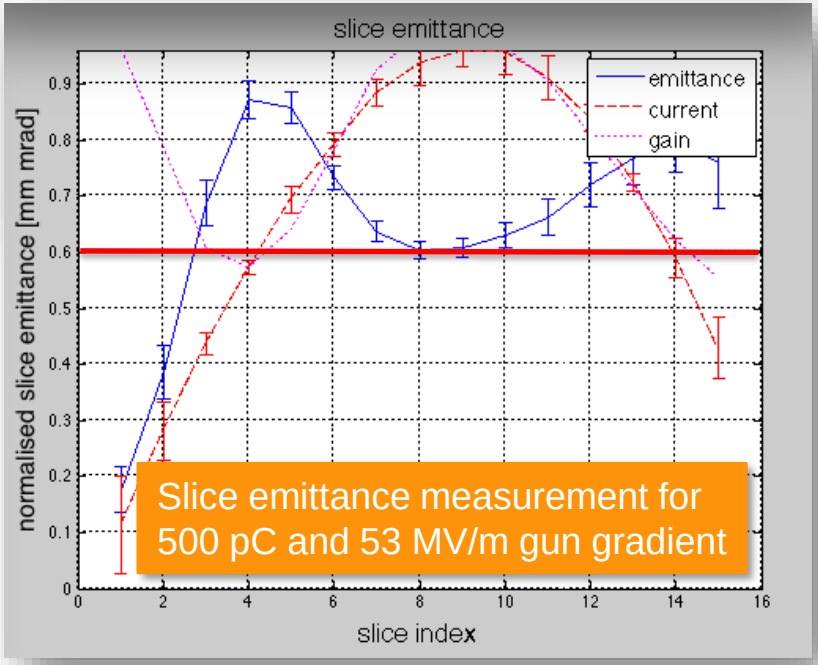
Final evaluation

Slice emittance measurements with four screens



Slice emittances can be measured and evaluated within 20 seconds using fast kickers and off-axis screens.

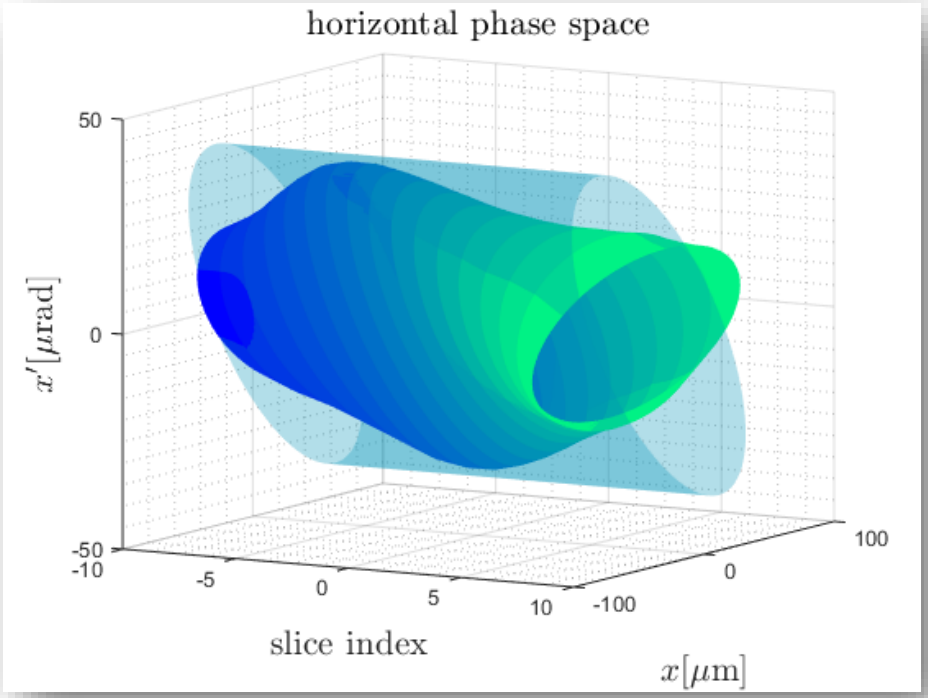
We are able to match single slices of the bunch. One matching iteration takes about 2 minutes including magnet cycling.

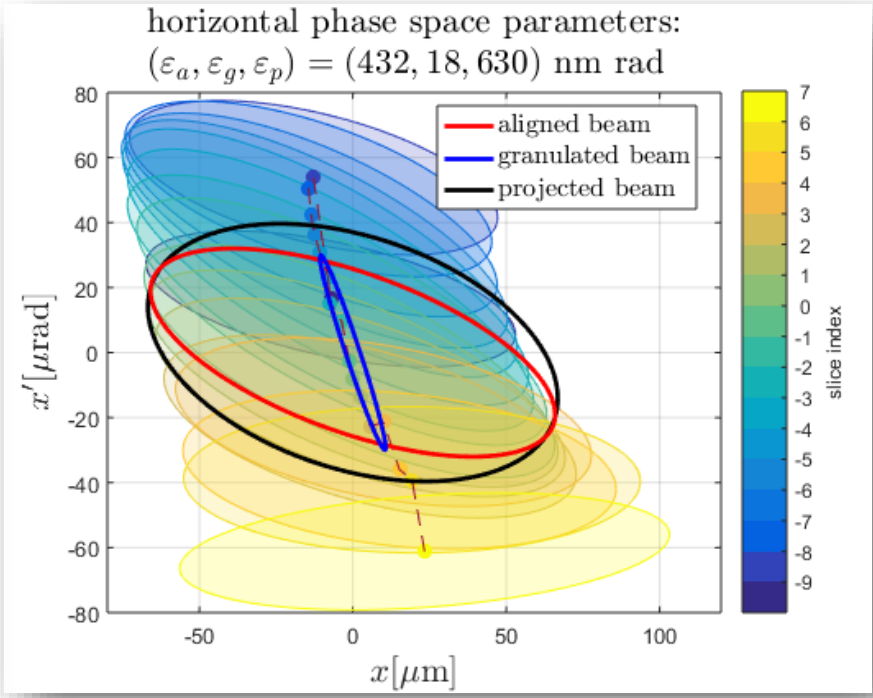


The smallest slice emittances achieved so far using the four screen method (and 500 pC bunches) were:

- 0.6 μm rad with 53 MV/m gun gradient
- 0.5 μm rad with 60 MV/m gun gradient

Further evaluation of slice emittance measurements





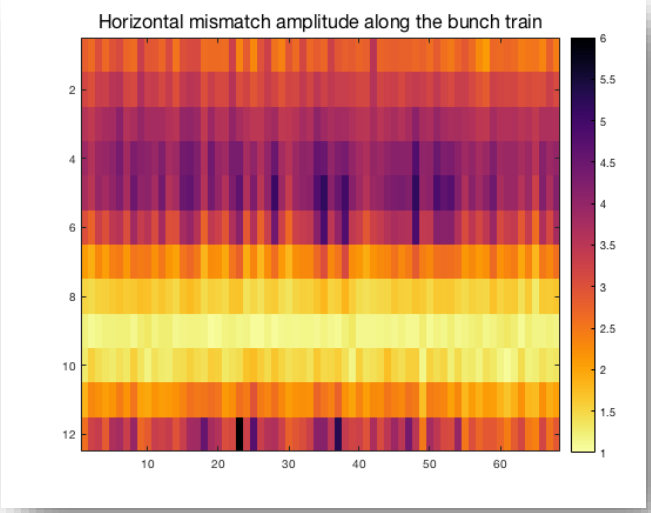
- Dark blue to green: Phase space ellipses for all bunch slices.
- Light blue: Phase space ellipse with design Twiss parameters and normalized emittance of 0.5 mm mrad.

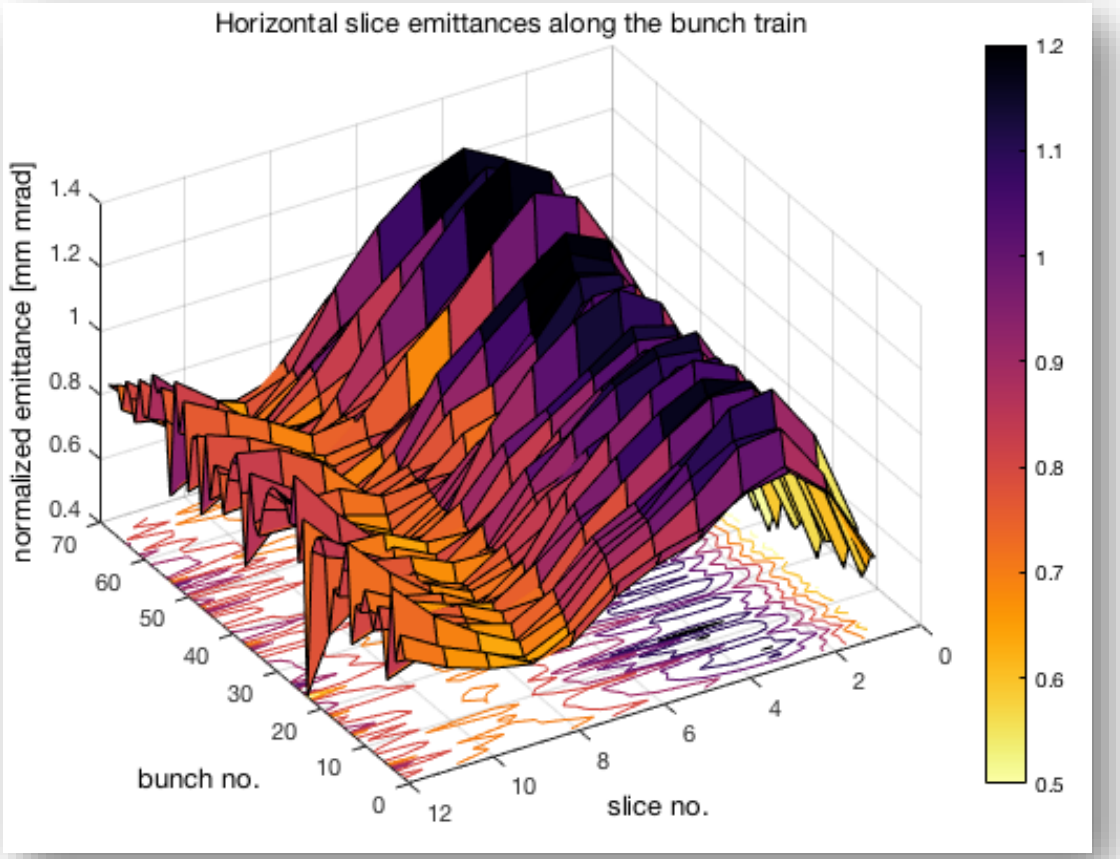
- Granulated beam: Phase space ellipse representing the positions of the bunch's slice center positions.
- Aligned beam: Projected emittance with aligned slice center positions.

Slice emittance measurements along bunch trains

- With the TDS, the fast kickers and the off-axis screens, it is also possible to measure slice emittances along the bunch trains.
- As expected, the core slice emittances are smaller and even more stable along the train compared to the projected emittances.

Slice emittances along the bunch train were measured for the first time July 9

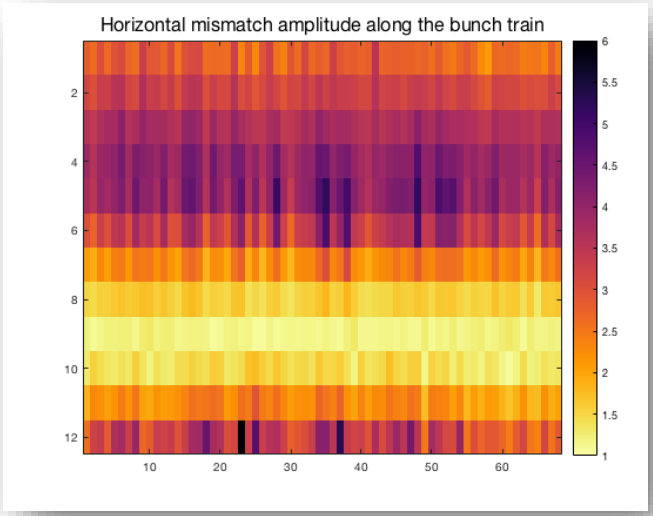


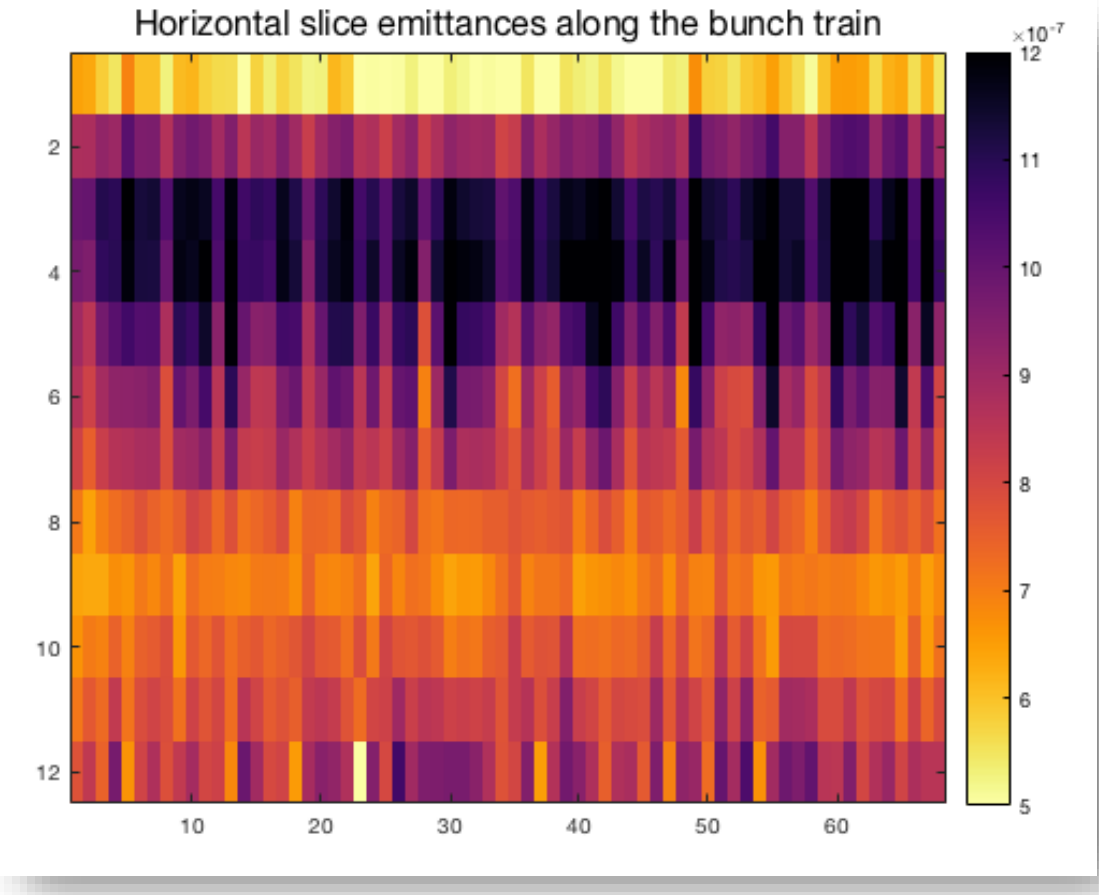


Slice emittance measurements along bunch trains

- With the TDS, the fast kickers and the off-axis screens, it is also possible to measure slice emittances along the bunch trains.
- As expected, the core slice emittances are smaller and even more stable along the train compared to the projected emittances.

Slice emittances along the bunch train were measured for the first time July 9

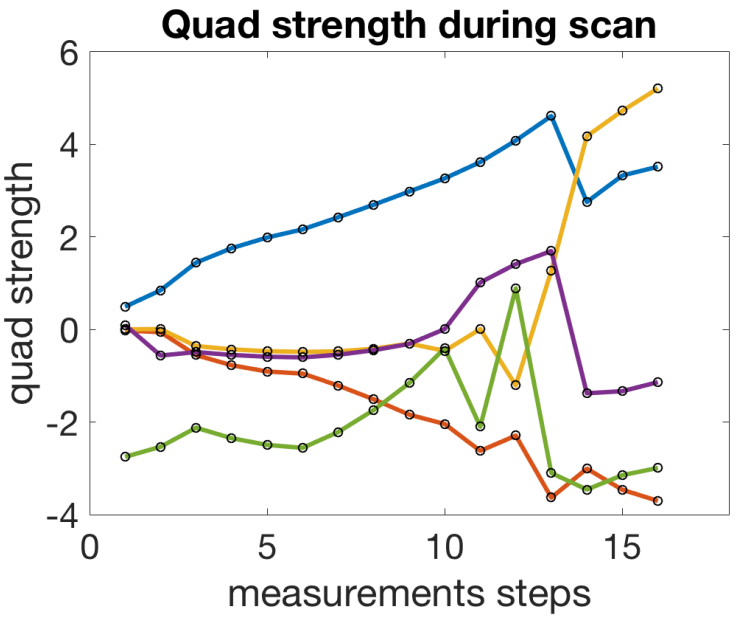




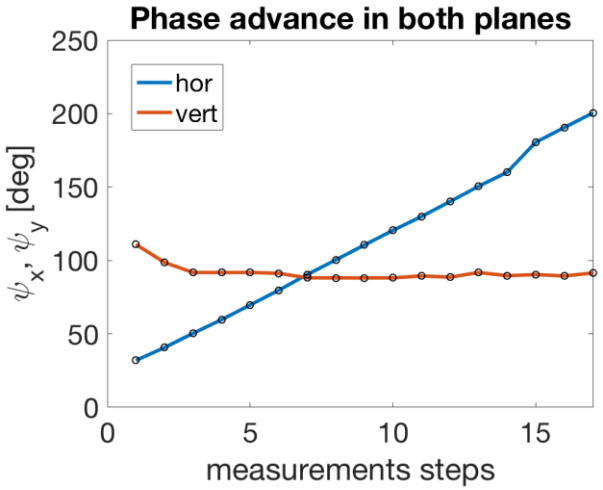
Multi knob quadrupole scan data

Scans with 5 quadrupole magnets were developed to measure slice emittances with only one screen.

K-values of 5 quadrupole magnets

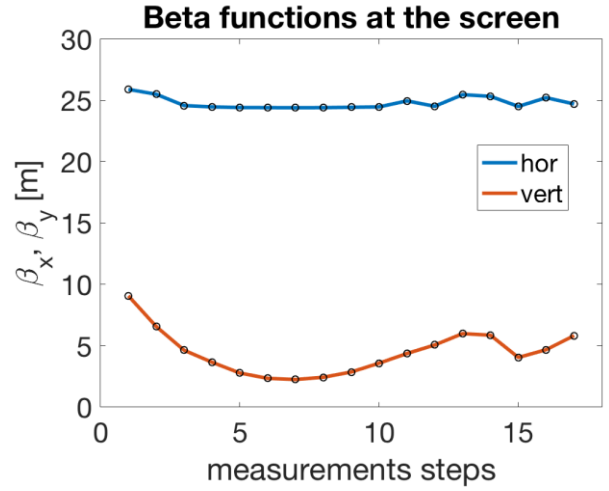


17 scan steps



Horizontal phase advance changes by 10 degree per step

Constant phase advance in vertical plane between TDS and screen

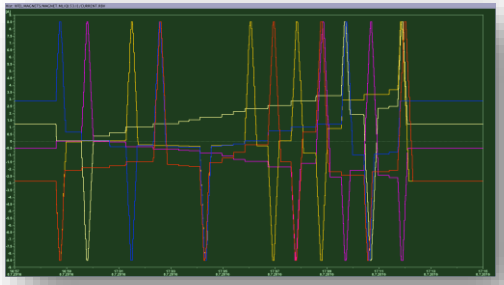


Larger beta function in vertical plane lead to a more effective streak.

A small beam in the horizontal plane improves the measure-ment resolution

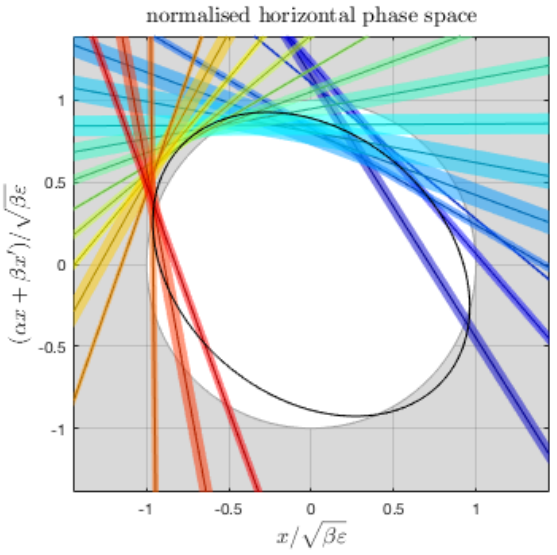
Emittance calculations and tomography using multi knob quadrupole scan data

- Results of the quadrupole scan with 5 magnets

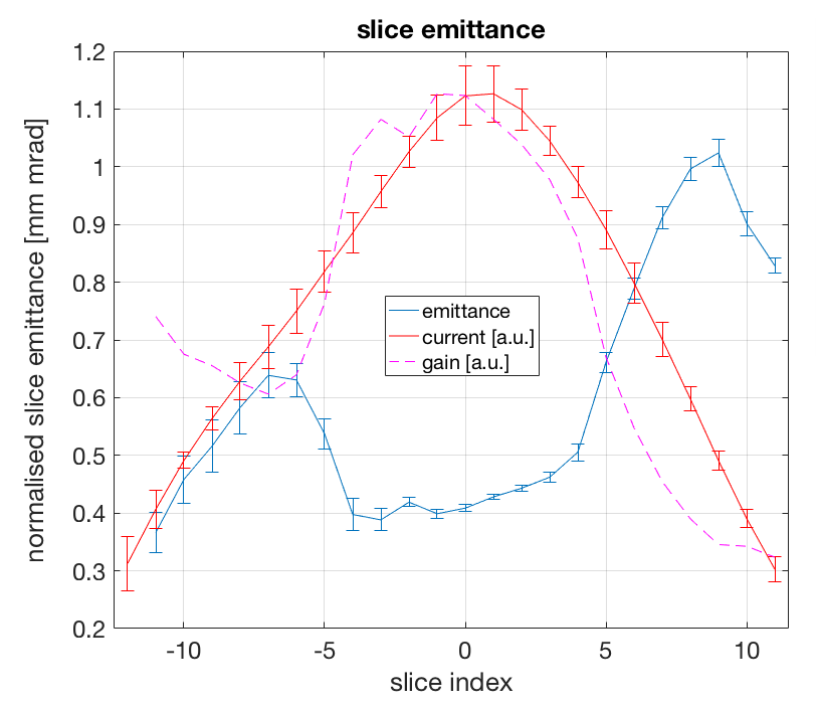


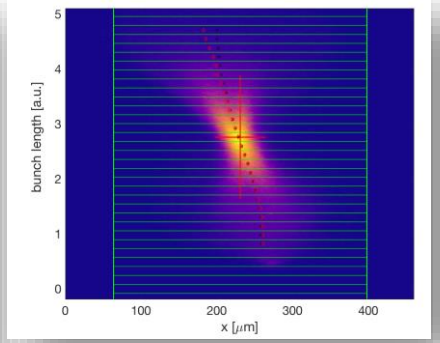
Quad strengths during the scan

- Quad scan using a 500 pC bunch and a gun gradient of 53 MV/m.
- The calculated core emittance is around 0.4 µm rad and thus smaller than the core emittances measured with the four screen method.
- The main difference between the two measurements is that the quad scan does not require the fast kickers. This will be investigated further.



Normalized horizontal phase space

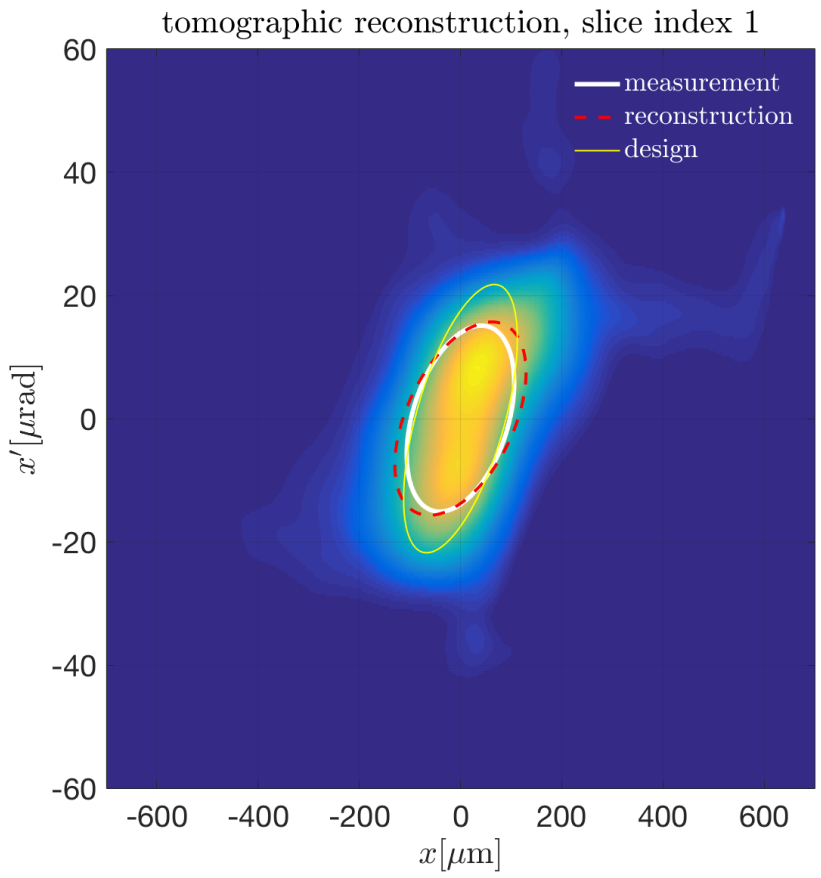


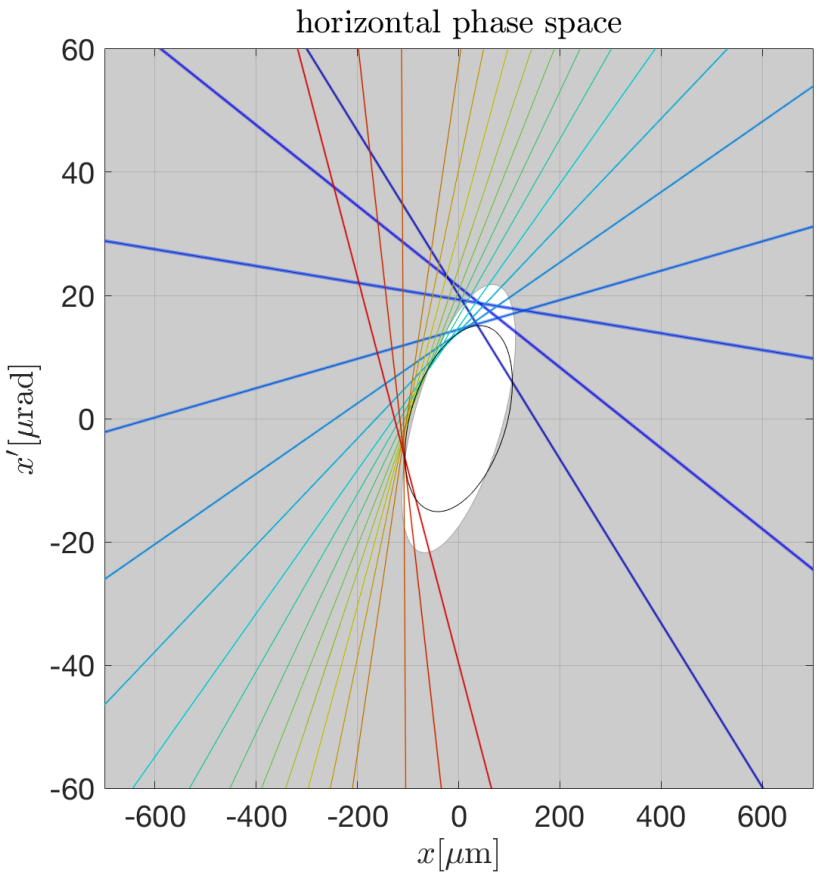


Camera picture of a streaked bunch. The green lines show the single slices.

Tomography using multi knob quadrupole scan data

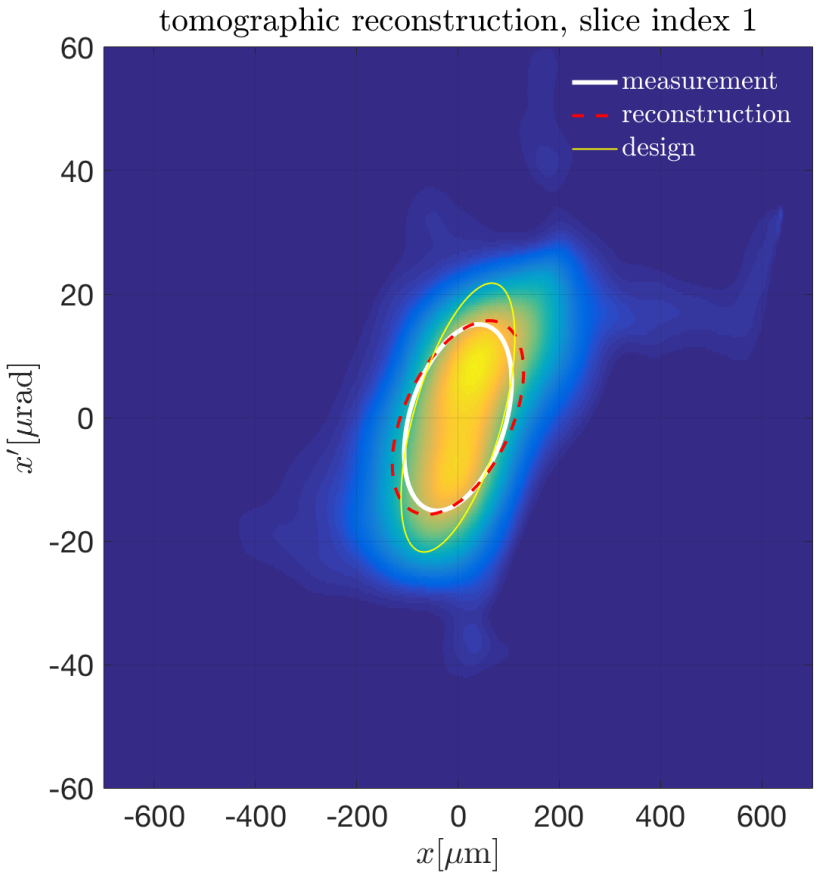
Reconstructed phase space and normalized slice emittance

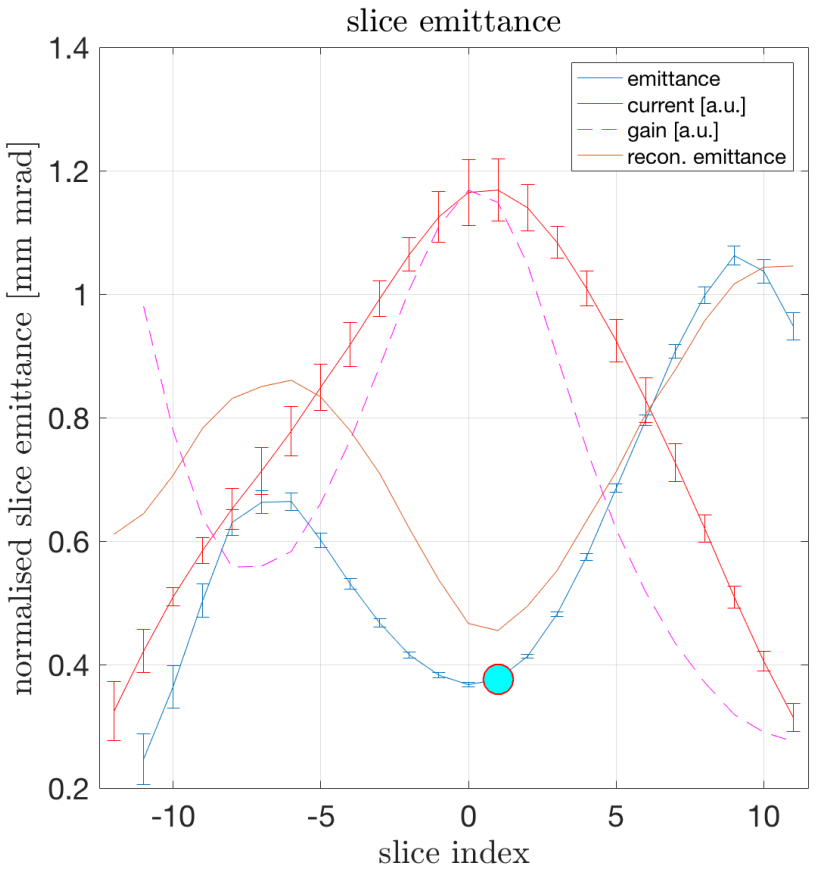




Tomography using multi knob quadrupole scan data

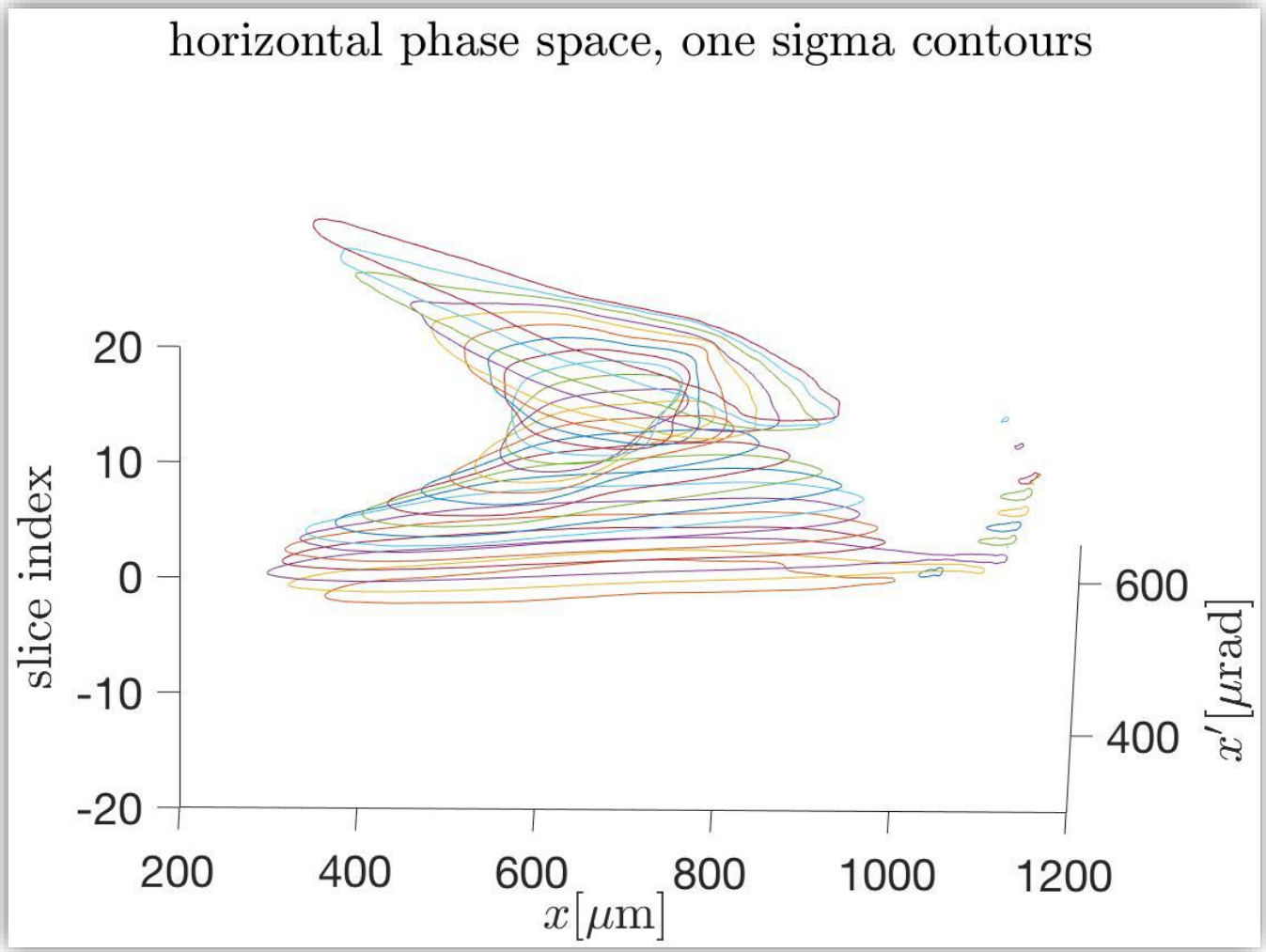
Reconstructed phase space and phase ellipses from emittance measurement



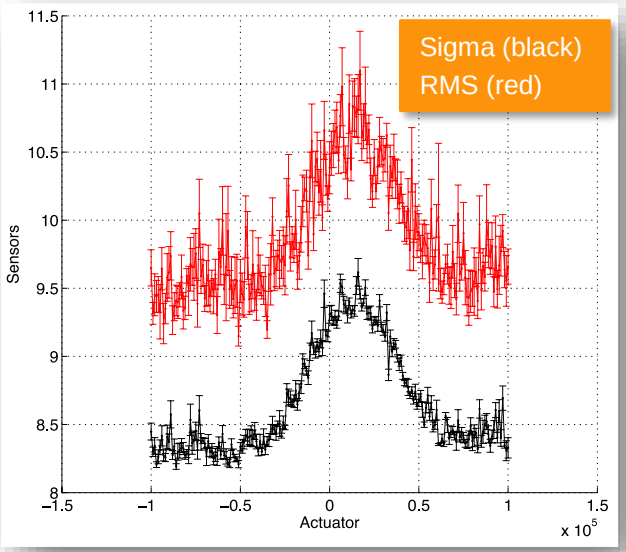


Tomography using multi knob quadrupole scan data

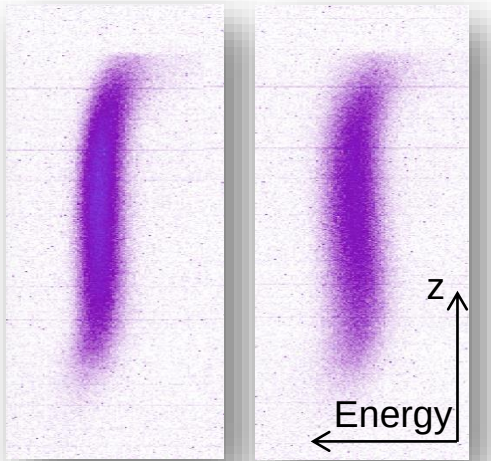
One sigma contours in horizontal phase space of all bunch slices



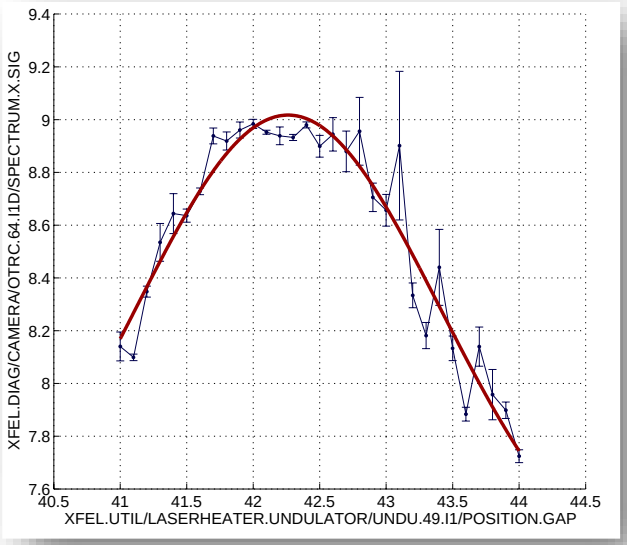
Laser heater commissioning



First proper measurement showing the growing beam size in the dispersive section due to laser heating (increasing energy spread). June 21



Two streaked bunches in the dispersive arm. On the left hand side without LH and on the right hand side with an increased energy spread due to laser heating.



A scan of the laser heater undulator gap for different beam energies (the plot shows the results for 130 MeV) did confirm the expected correlation.

- First operation of the laser heater in the XFEL injector in June 21.
- The horizontal beam size was measured in the dispersive section (dump beamline) while scanning the arrival time of the laser respectively the laser heater undulator gap.
- An increase of the horizontal beam width could be measured for the expected undulator gap.
- The laser amplifier was not yet installed during these tests. Thus, we expect a stronger effect during following measurements.

Thank you for your attention!

All of the shown successes and measurements could not have been achieved without the work of many colleagues. Thanks a lot to all members of the commissioning and of the project team!