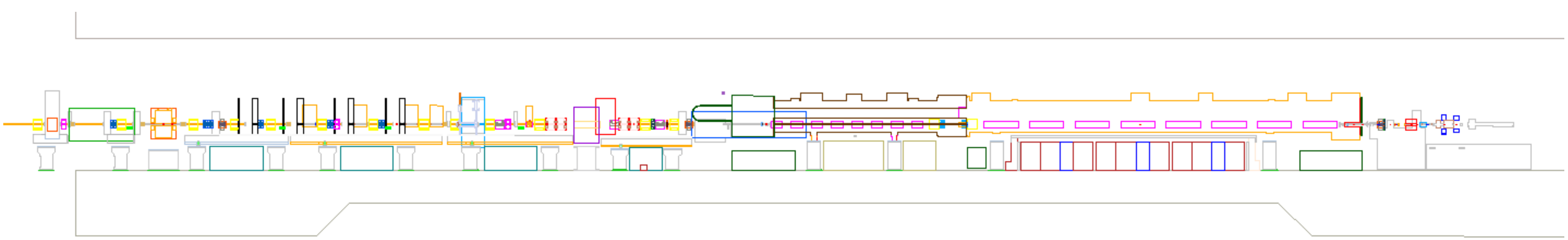
Injector Commissioning

Matthias Scholz and Bolko Beutner
for the commissioning team

European XFEL Injector



Long bunch train operation

Tomographic reconstruction of horizontal phase space

Beam direction

Emittance measurements and optimizations (projected and slice)

Emittance measurements along bunch trains (projected and slice)

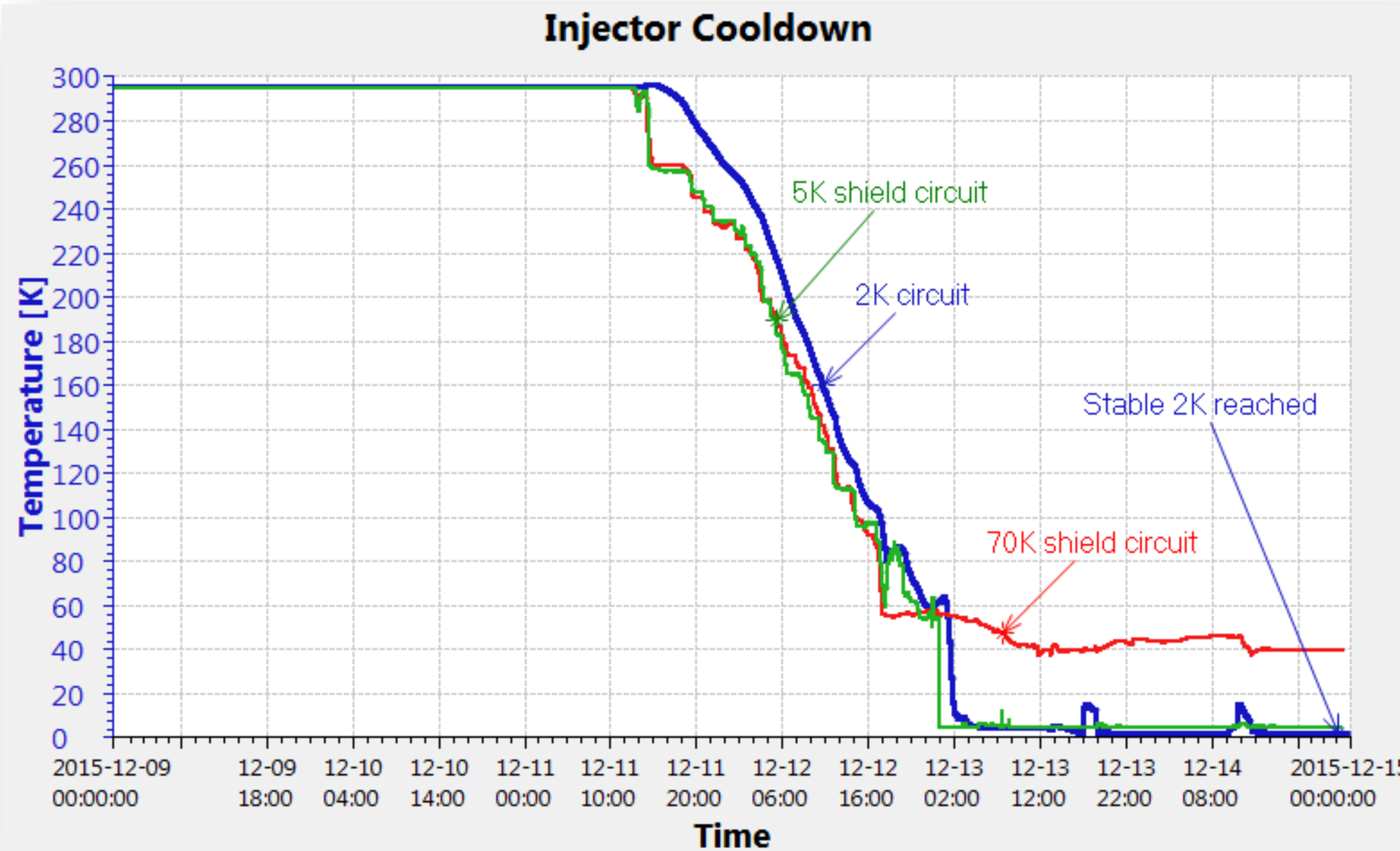
Comparison of TDR and achieved parameters

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 proj. 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).

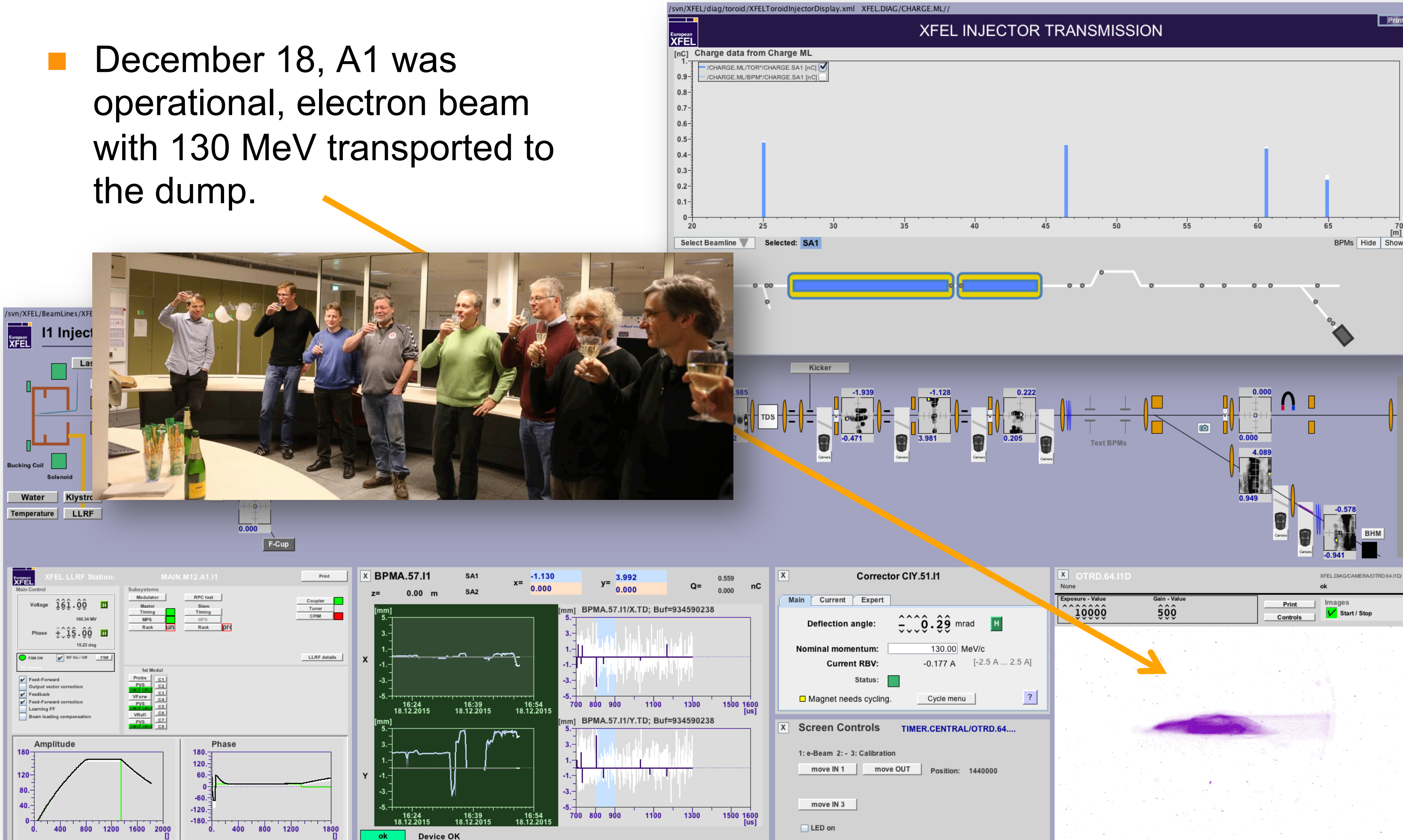
XFEL injector cooldown



Injector cooldown December 11-15

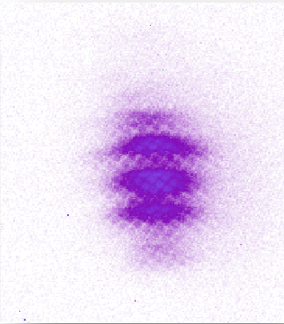
Electron beam in the injector dump

- December 18, A1 was operational, electron beam with 130 MeV transported to the dump.

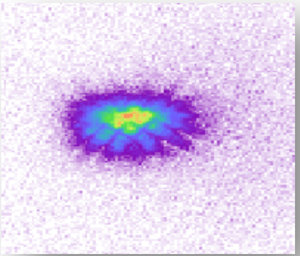


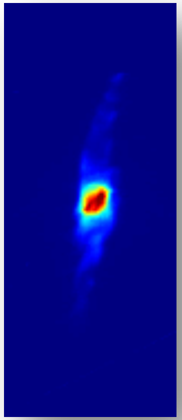
Injector laser

Initial difficulties with the alignment of the injector laser could be fixed mid February 2016.

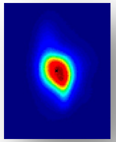


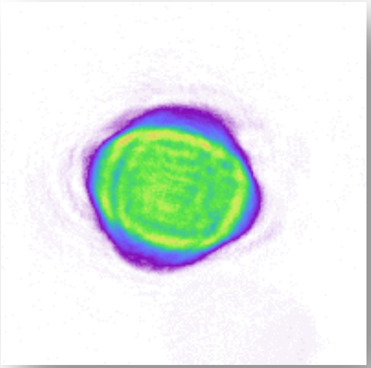
SCRN.24.I1



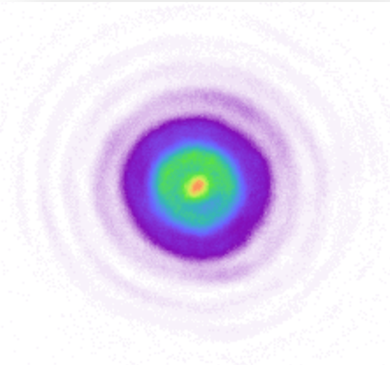


OTRC.55.I1





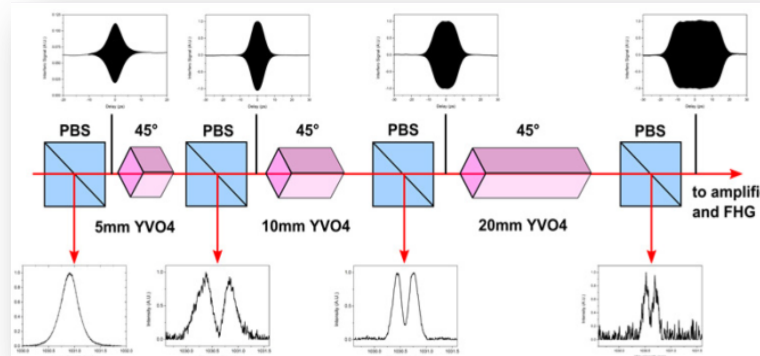
Far field camera

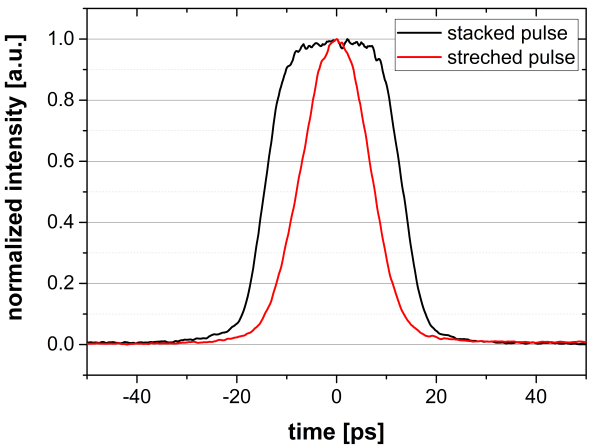


Near field camera

Injector laser stacker

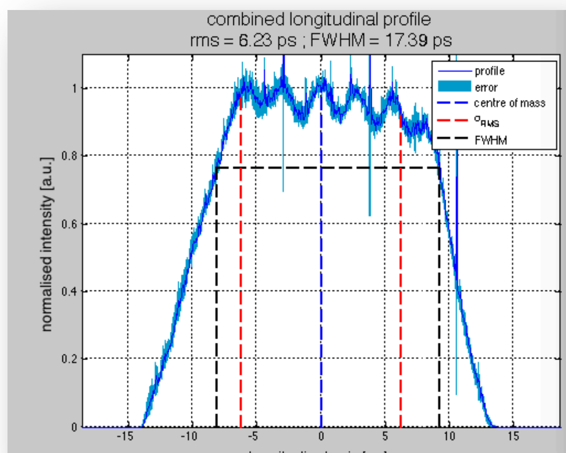
- It is possible to stack the injector laser pulse.
  - The longitudinal laser profile is changed from Gaussian to flat top.
  - Reduced space charge effects should lead to smaller projected emittances.





Streak camera scan of the laser pulse with and without stacker.

Longitudinal profile of the electron bunch while the stacker was in use

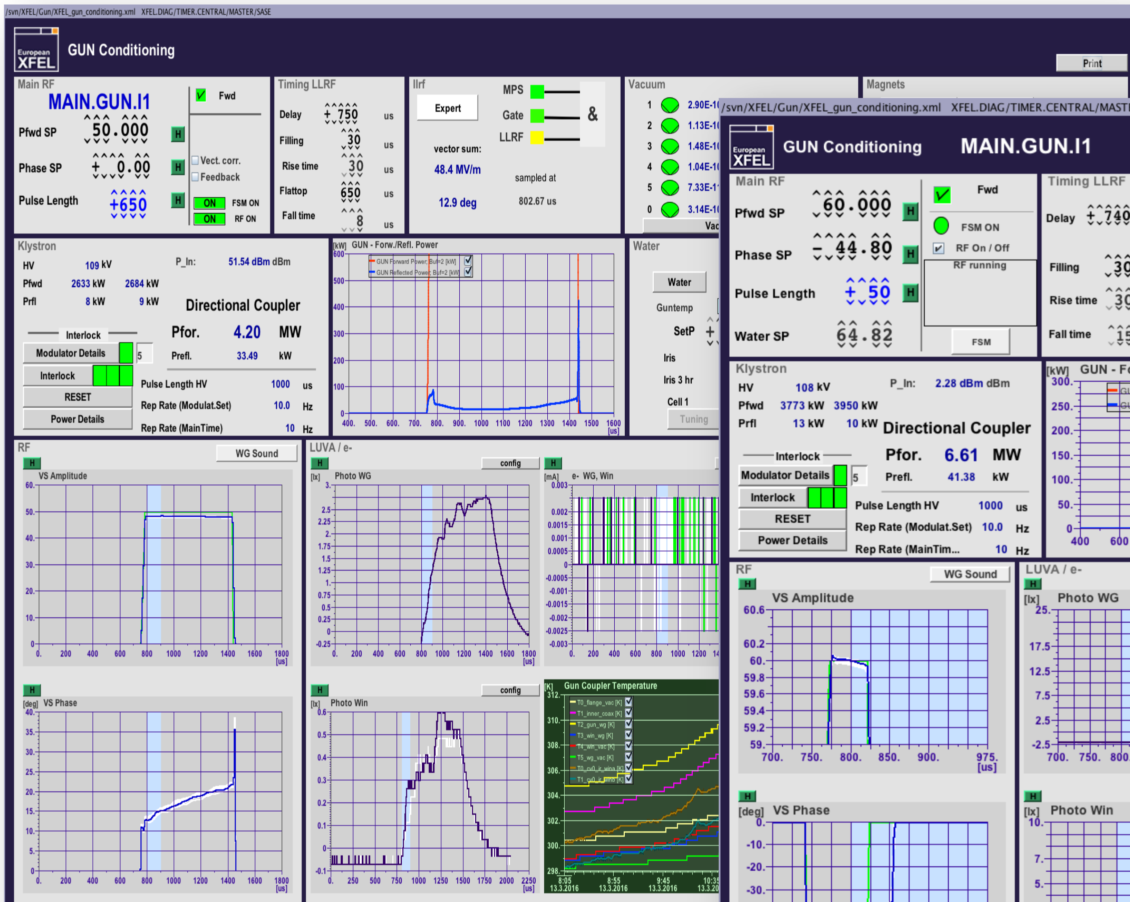


More information about longitudinal profile measurements of electron bunches will follow.

Only three out of four stages of the laser stacker could be used during the first deployment. This leads to a visible modulation of the electron bunch.

Maximum pulse length and maximum gradient

The gun pulse length reached 650 us March 13

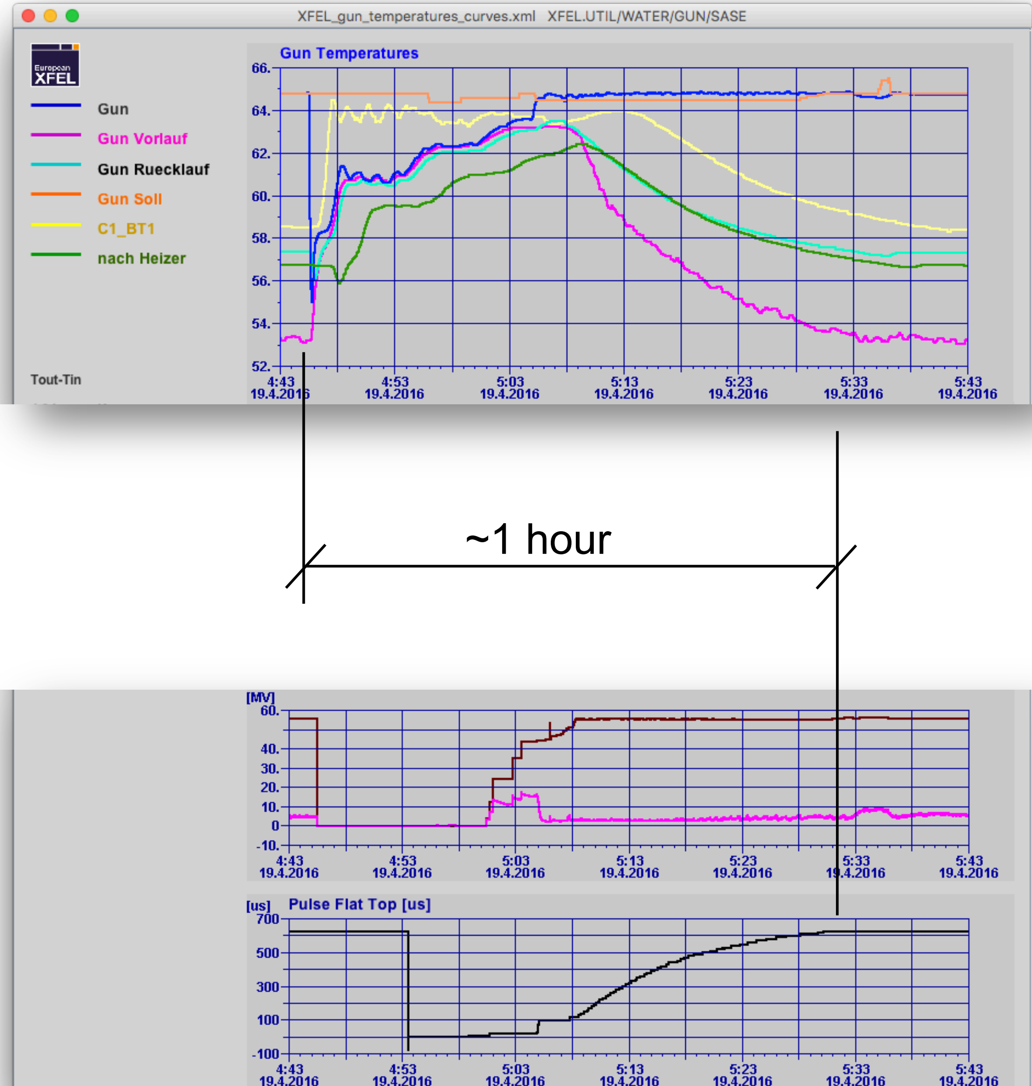


Maximum gradient reached first time July 18

Matthias Scholz, Bolko Beutner

Restarting the electron gun by hand

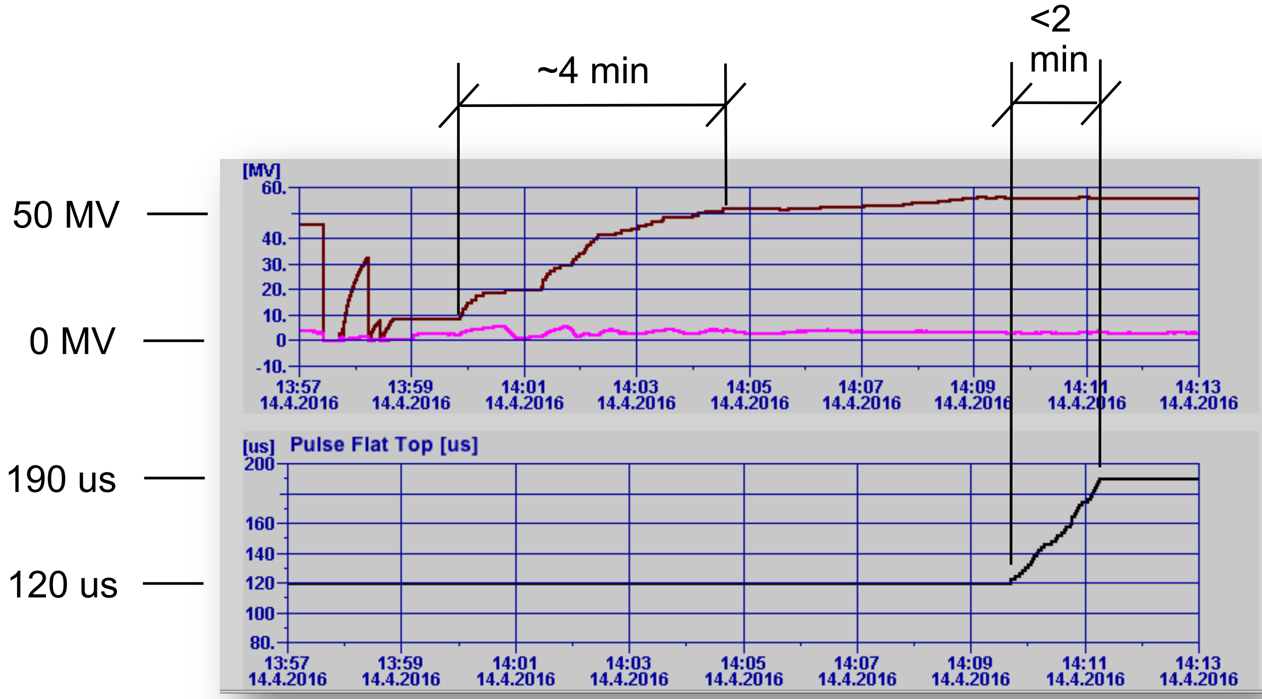
- Restarting the gun by hand takes typically 1 hour.
- Typically the gun gradient is increased with a small RF pulse length (~20 us).
- Then the pulse length is increased to the required length (650 us).
- It is important to watch the gun temperature in order to stay on resonance. This keeps the reflected power low.



Fast restart of the electron gun using the FSM

- There is the possibility to restart the gun much faster
  - LLRF parameters can be adjusted such that the resonance conditions are always fulfilled while ramping up the gradient and the pulse length.
  - The water temperature regulation is disabled during the fast restart in order to avoid an overshooting gun temperature at the end of the ramp.
  - Tests showed that the gun can be ramped up within minutes to gradients of 55 MV/m and pulse length of ~160 us. Experts are optimistic that this method can also be used for the maximum pulse length. Further test will be carried out soon.

Fast restart of the electron gun using the FSM



- Fast restart of the gun using the FSM takes only minutes.
- Promising tests were carried out in Zeuthen after the shutdown of the XFEL injector.
- It is now possible to ramp up the gun to full power and pulse length in minutes.

How to measure electron beam emittances

- Definition of emittance with beam moments

$$\varepsilon_x = \sqrt{\langle x_0^2\rangle\langle x_0'^2\rangle - \langle x_0 x_0'\rangle^2}$$

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- Beam size at point i is measured

$$\sigma_{x,i}^2 = \langle x_i^2 \rangle = {R_{11}^i}^2 \langle x_0^2 \rangle + {R_{12}^i}^2 \langle x_0'^2 \rangle + 2 R_{11}^i R_{12}^i \langle x_0 x_0' \rangle$$

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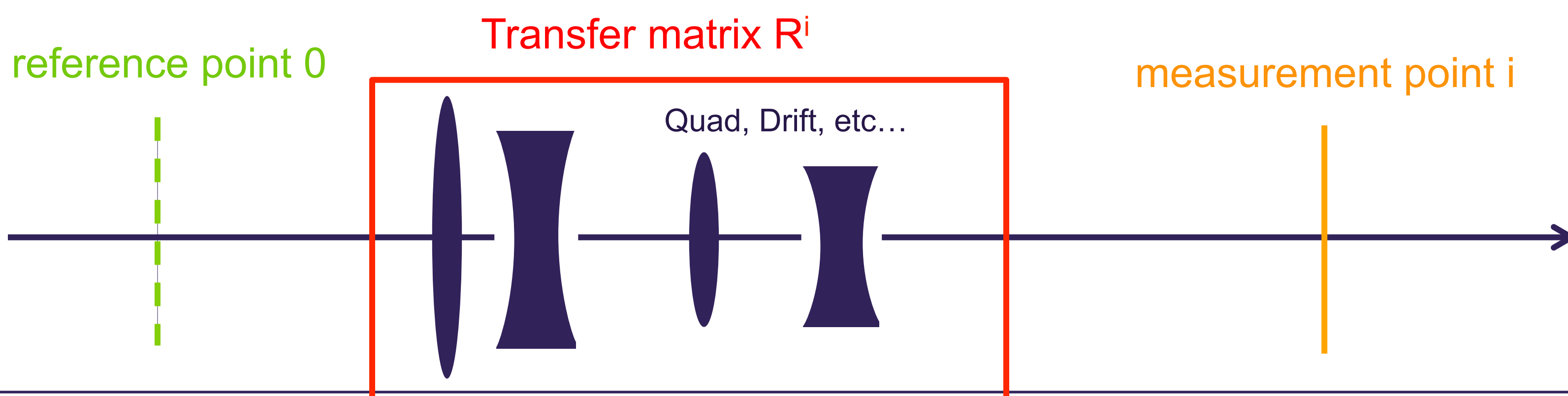
- Transfer matrix (beam optics)

$$R^{\mathrm{i}} = R^{\mathrm{i}}{}_{\mathrm{quad}}\, R^{\mathrm{i}}{}_{\mathrm{drift}}\, R^{\mathrm{i}}{}_{\mathrm{quad}} \cdots$$



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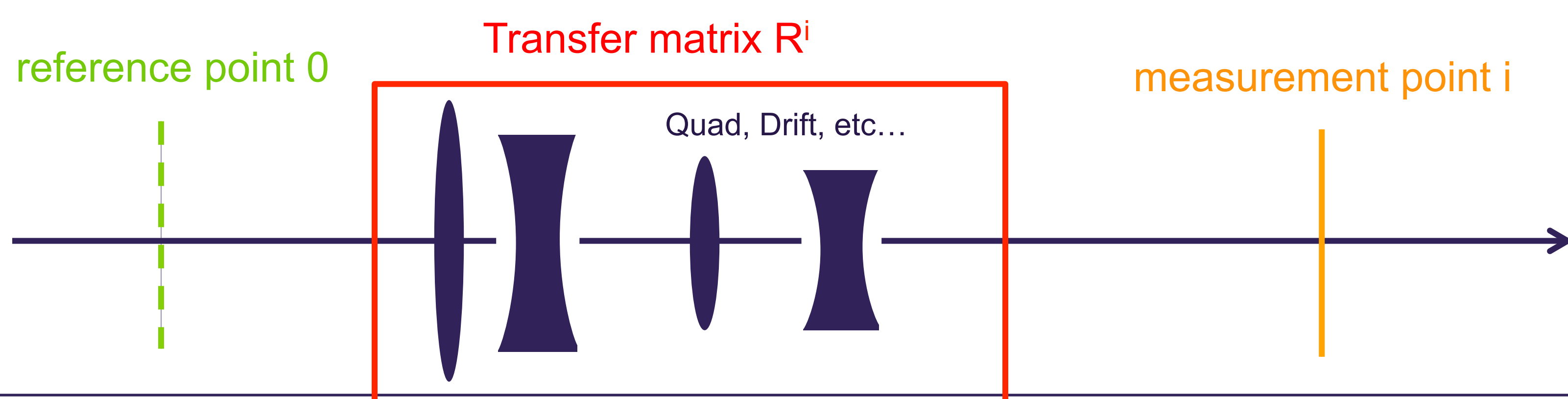
- Transfer matrix (beam optics)

$$R^{\mathrm{i}} = R^{\mathrm{i}}_{\mathrm{quad}}\, R^{\mathrm{i}}_{\mathrm{drift}}\, R^{\mathrm{i}}_{\mathrm{quad}} \cdots$$

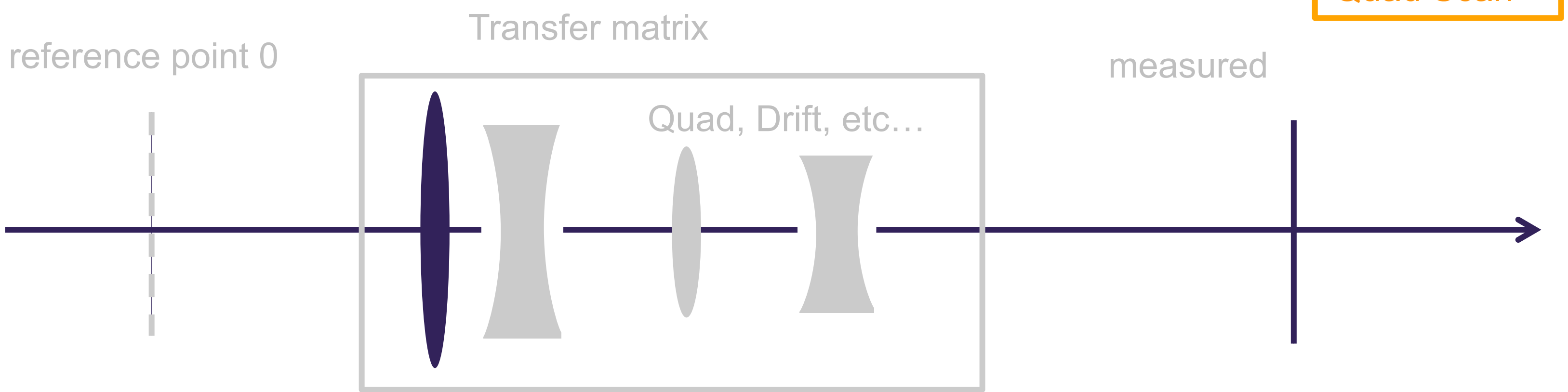
- At least 3 measurements with different R^i gives you the beam moments

$$\sigma_{x,1}^2 = \langle x_1^2\rangle = {R_{11}^1}^2 \langle x_0^2\rangle + {R_{12}^1}^2 \langle x_0'^2\rangle + 2R_{11}^1 R_{12}^1 \langle x_0 x_0'\rangle$$
$$\sigma_{x,2}^2 = \langle x_2^2\rangle = {R_{11}^2}^2 \langle x_0^2\rangle + {R_{12}^2}^2 \langle x_0'^2\rangle + 2R_{11}^2 R_{12}^2 \langle x_0 x_0'\rangle$$
$$\sigma_{x,3}^2 = \langle x_3^2\rangle = {R_{11}^3}^2 \langle x_0^2\rangle + {R_{12}^3}^2 \langle x_0'^2\rangle + 2R_{11}^3 R_{12}^3 \langle x_0 x_0'\rangle$$



Quad scan and multi screen method

Quad Scan



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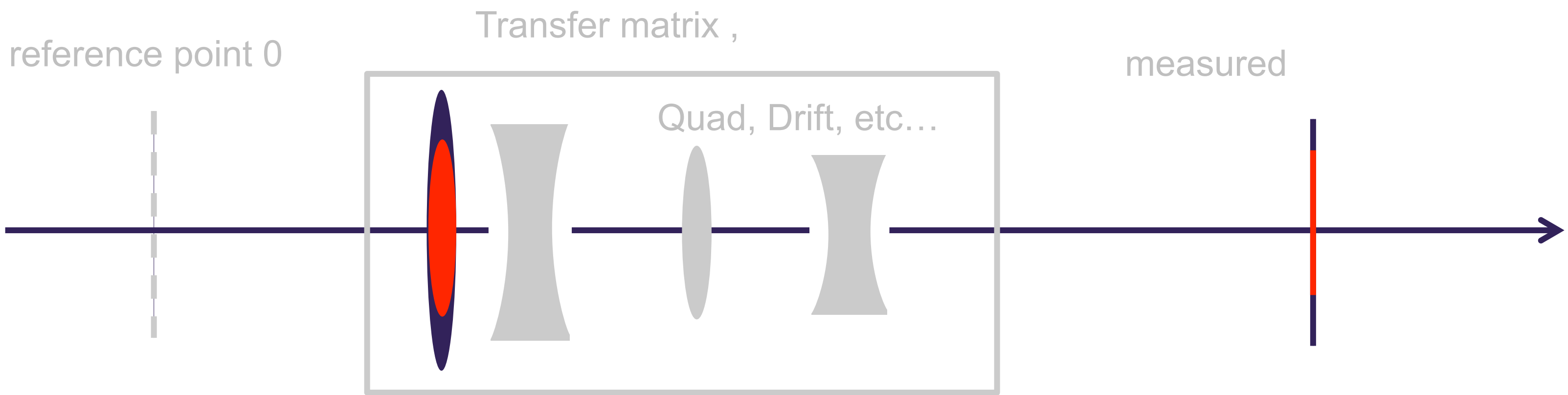

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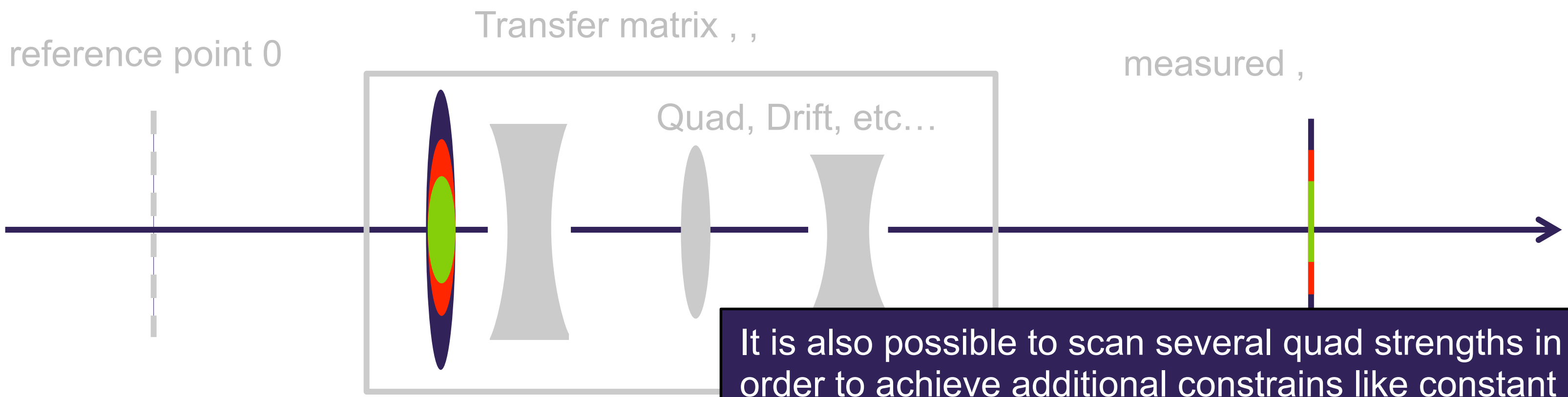
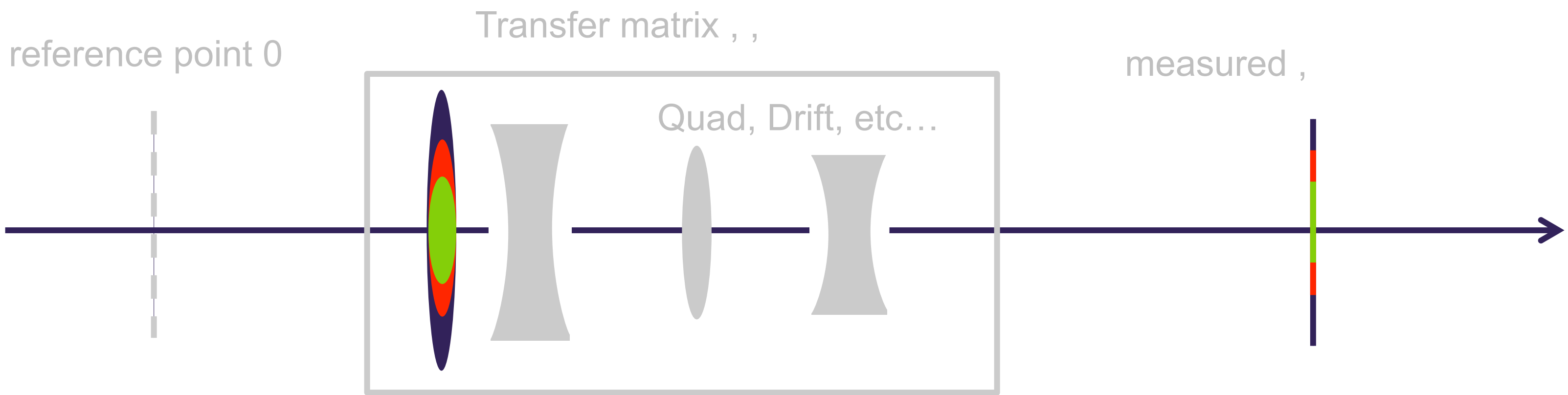


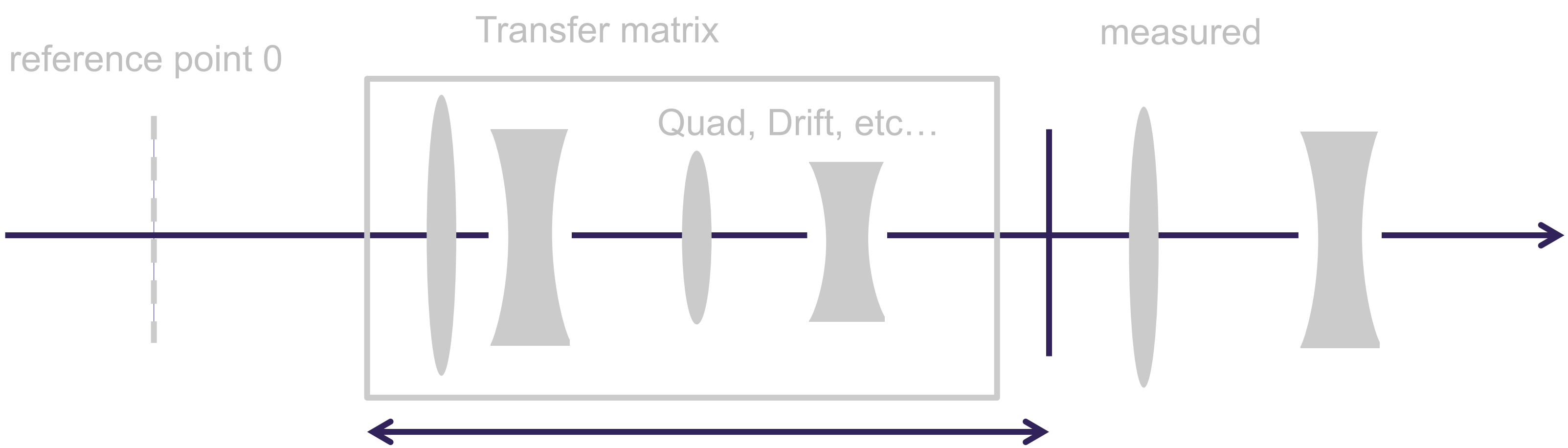
It is also possible to scan several quad strengths in order to achieve additional constrains like constant beam size on the screen.

Quad scan and multi screen method

Quad scan



Multi Screen



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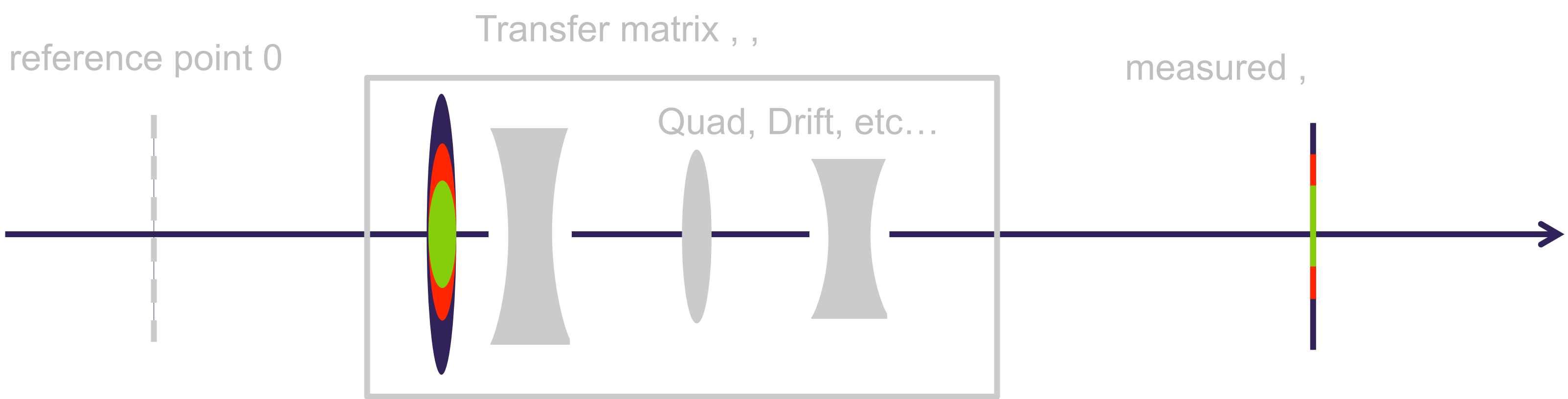
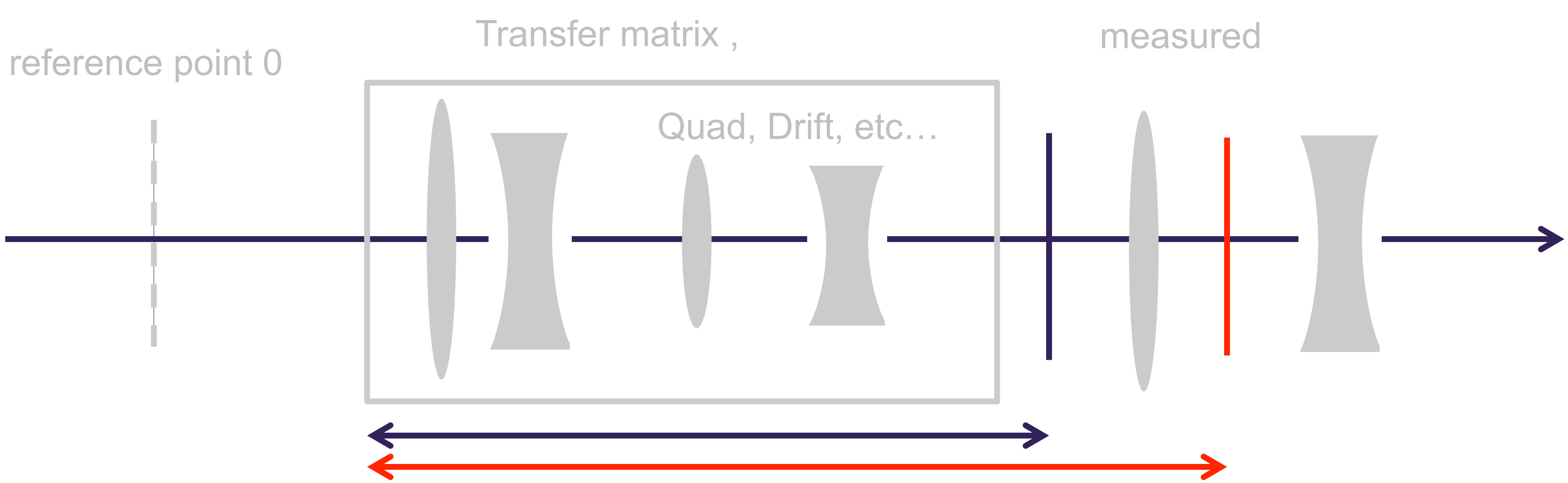
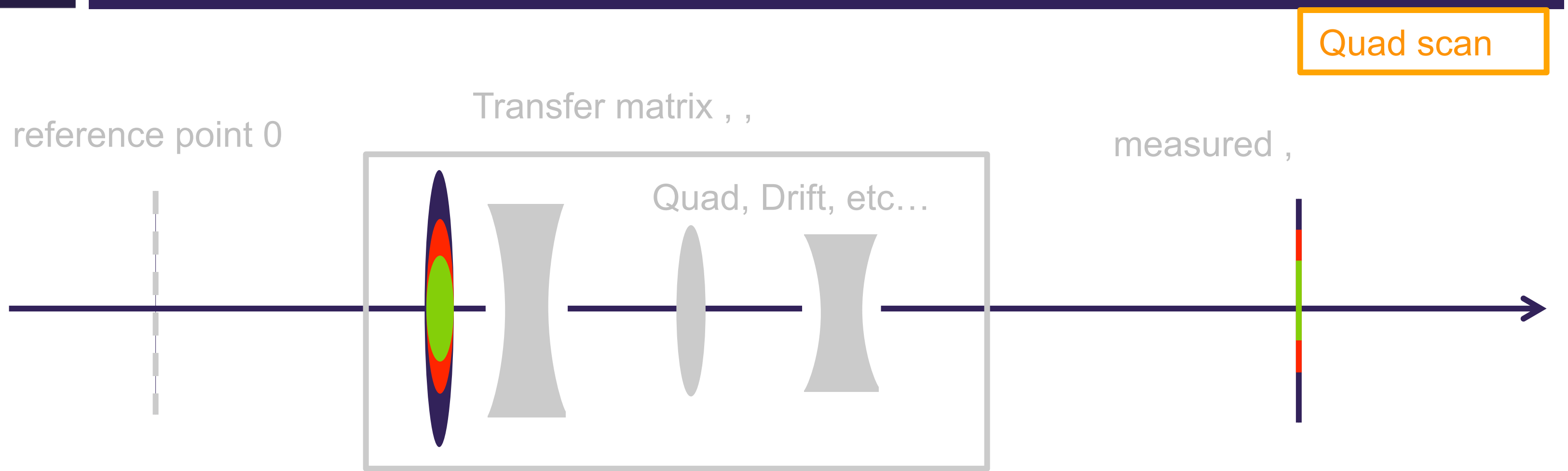
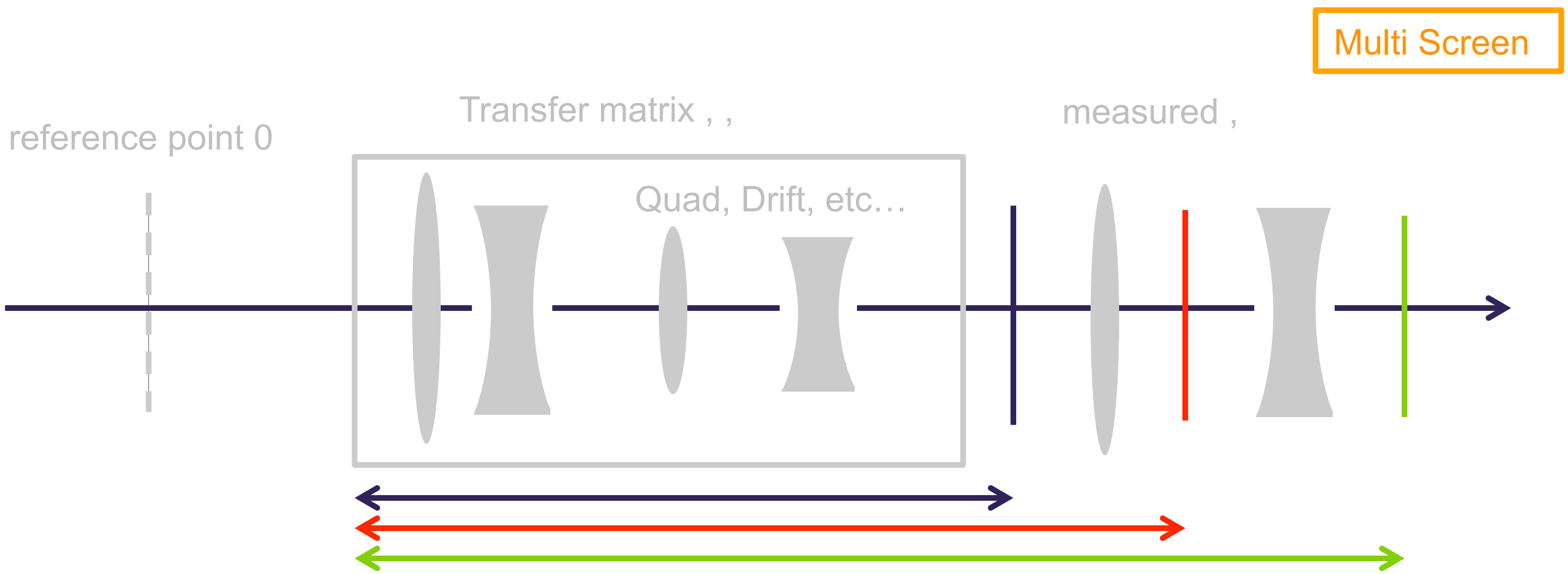


Multi Screen



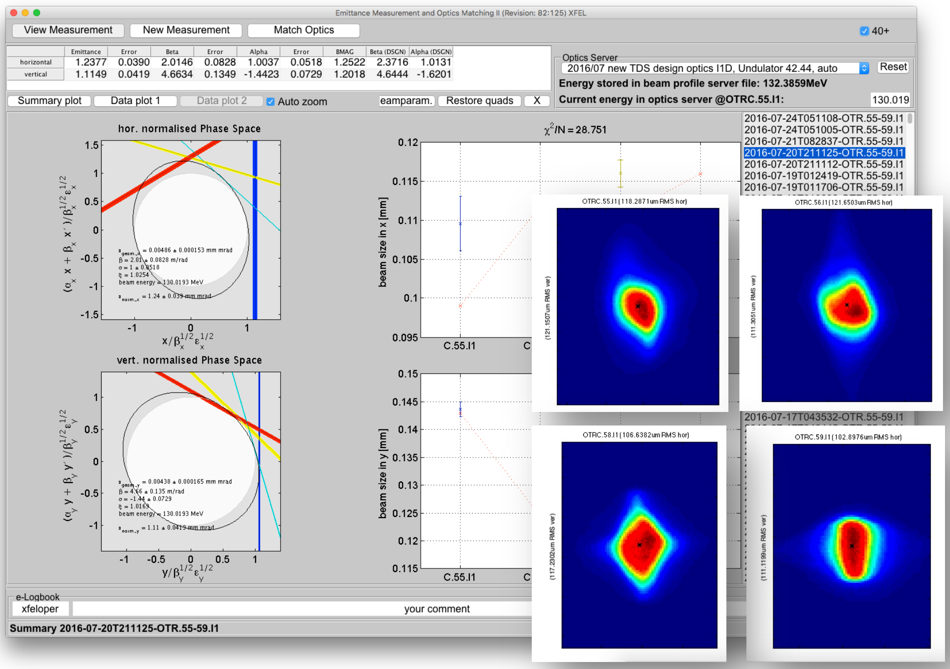
Quad scan and multi screen method





XFEL injector and 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 µm rad	0.64 µm rad
100 pC	0.77 µm rad	0.83 µm rad
500 pC	1.28 µm rad	1.23 µm rad
1000 pC	2.95 µm rad	2.81 µm rad

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.

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  - W
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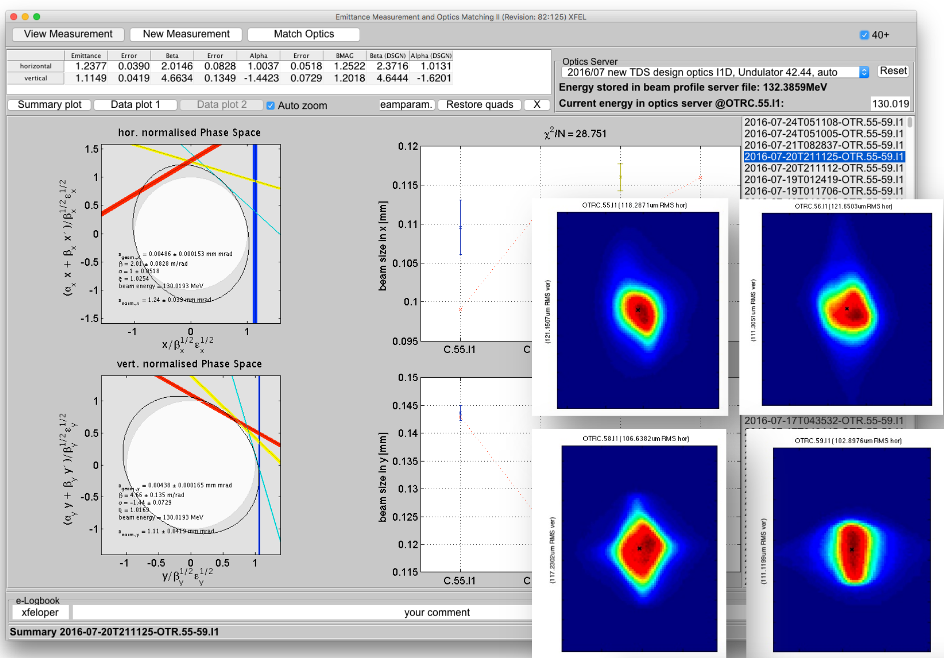
Cons: One measurement takes several minutes to move the screen in and out…



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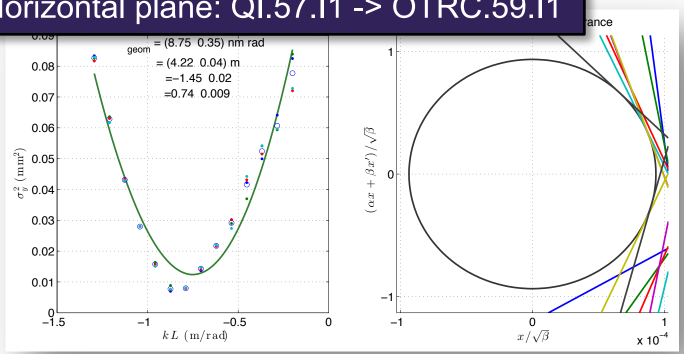
XFEL injector and quadrupole scans

- There are two possibilities for quad scans with one quadrupole in the injector.
  - Applying a special beam optics that is suitable to scan both planes with one quad and one screen at the same time.
  - Using two different quads and screens for horizontal and vertical plane with the default injector beam optics.

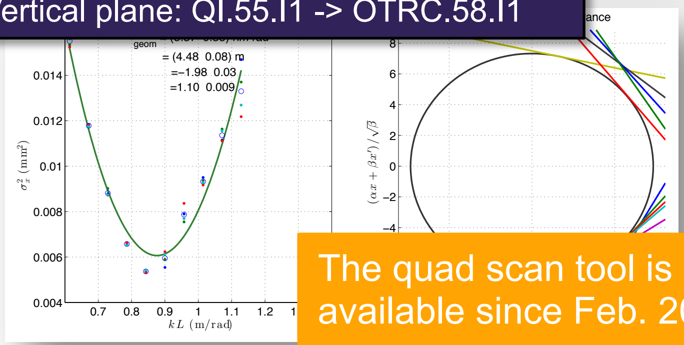
Comparing results achieved with a quad scan and a four screen method. The bunch charge was 500 pC.

	Horizontal	Vertical
Quad scan	2.30 µm rad	1.41 µm rad
4 screens	2.51 µm rad	1.63 µm rad

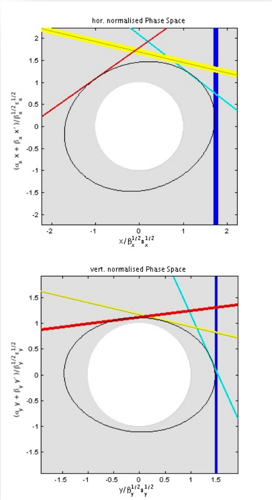
Horizontal plane: QI.57.I1 -> OTRC.59.I1

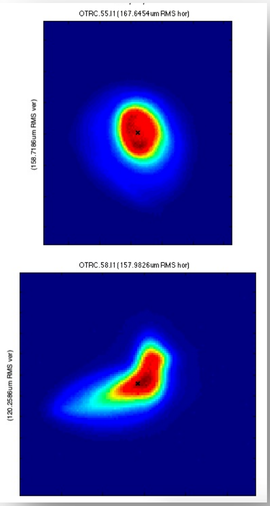


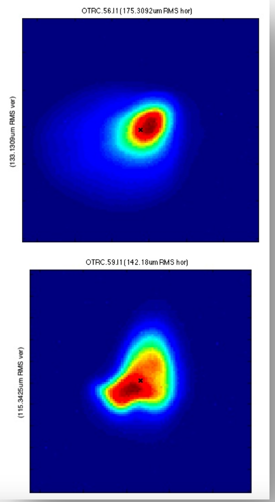
Vertical plane: QI.55.I1 -> OTRC.58.I1



The quad scan tool is available since Feb. 2016.



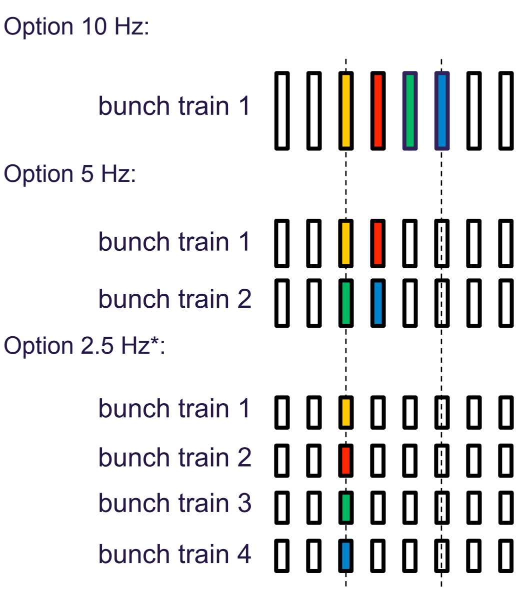




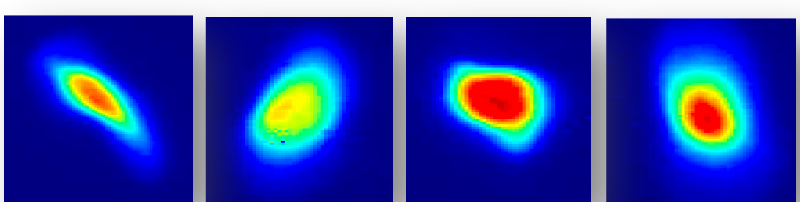
Four screen method with off-axis screens

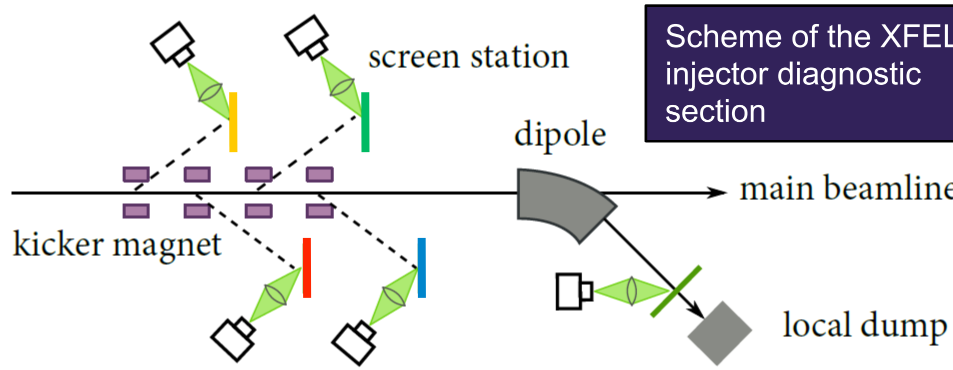
- The XFEL can deliver up to 2700 bunches with a bunch to bunch repetition rate of 4.5 MHz .
- Fast kickers allow to kick single bunches out of the trains to the screens while those are in off-set position.
- That allows us to measure the emittances and beam optics parameters on-line while all other 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

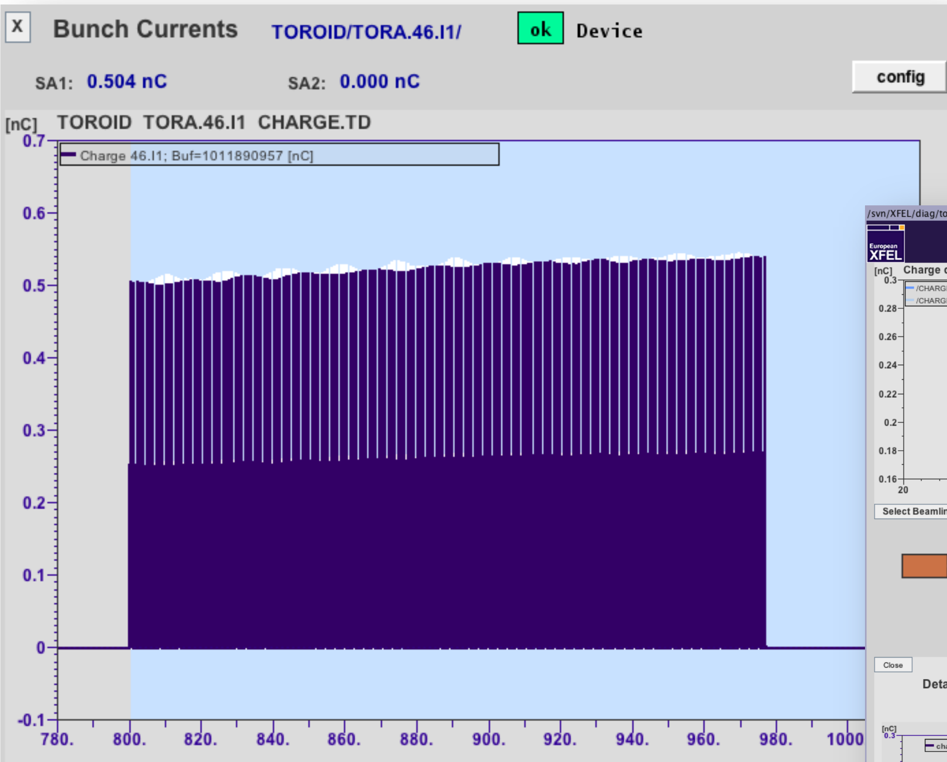




Scheme of the XFEL injector diagnostic section

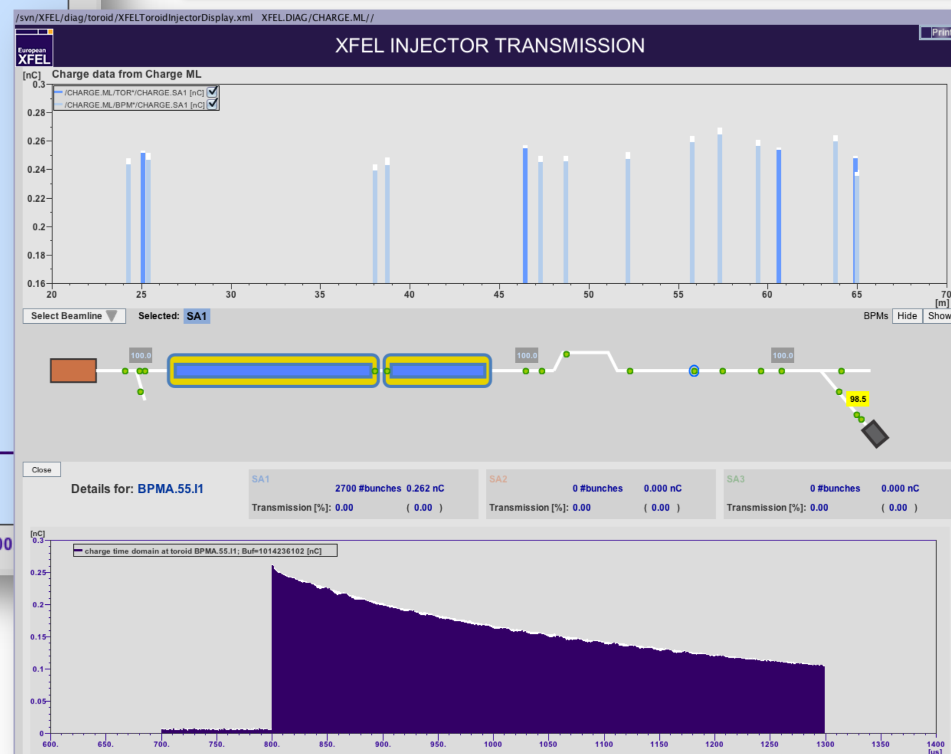
Multi bunch operation

- Multi bunch operation (> 30 bunches) started March 16, 2016

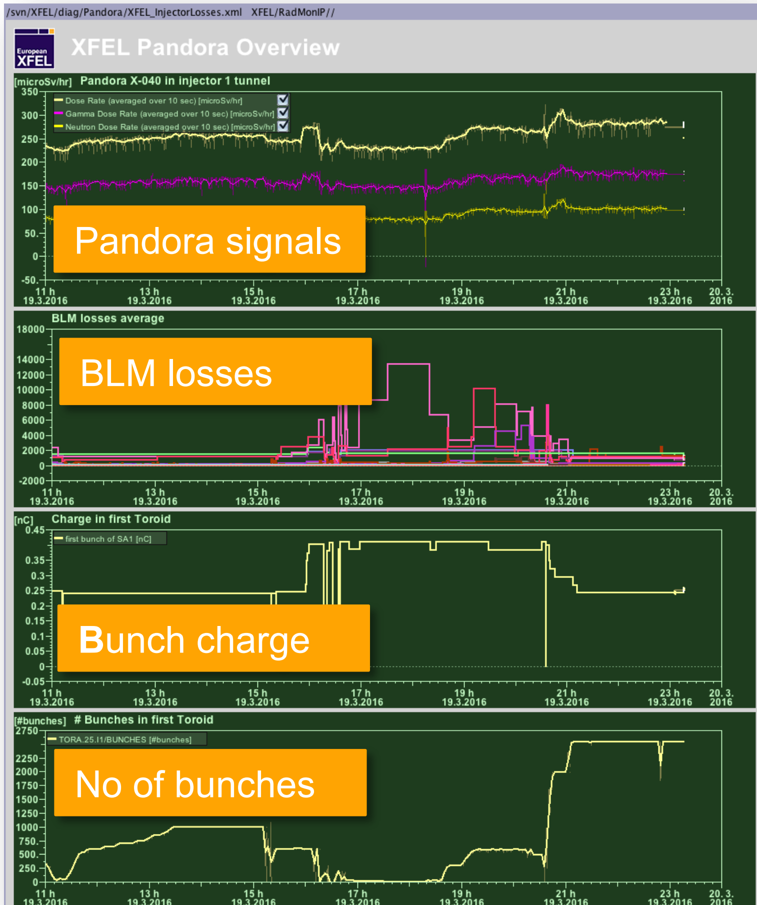


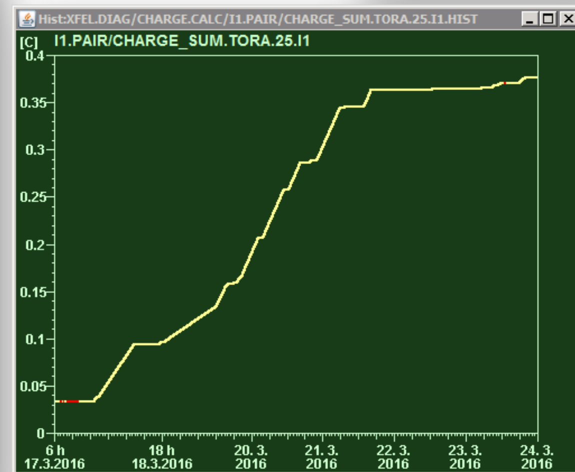
March 16, 200 bunches, 1.125 MHz repetition rate, 500 pC bunch charge

March 19, 2700 bunches, 4.5 MHz repetition rate, 150-300 pC bunch charge



After the first run with 2700 bunches





Extracted charge March 17-22

Messprotokoll zum Ausmessen von Stellen mit erhˆ hter Radioaktivit%t bei XFEL-Inj. 1

Datum:	22.03.2016
Zeit:	08:20
Beschleuniger:	XFEL - Inj. 1
gemessen von:	P. Hartz / Gerdt
Messger%t:	6150AD2
Bemerkung:	

		Dosisleistung in 30cm [µSv/h]	Dosisleistung Oberfl%che [µSv/h]	Bemerkung
		0,2	0,2	
		0,2	0,2	
		0,2	0,3	45m
		0,2	0,2	
		0,2	0,3	rechts
		0,2	1,0	Bello
		0,2	0,4	rechts
		0,2	1,0	rechts
59m	Quadropol QI.59.I1	0,2	3,2	rechts
60m	Quadropol QI.60.I1	0,2	4,2	rechts
60m	Toroid 60.I1	0,2	1,5	rechts
62m	Dipol BP.62.I1	5,0	240,0	rechts
63m	GP IP-HV-1060	2,0	100,0	rechts
64m	Quadropol QI.64.I1	2,0	25,0	rechts
65m	Dump Flansch	0,4	13,0	
Wand	Dump Bohrung	-	1540,0	rechts unten

Pandora readings did not change dramatically after switching to 2700 bunches

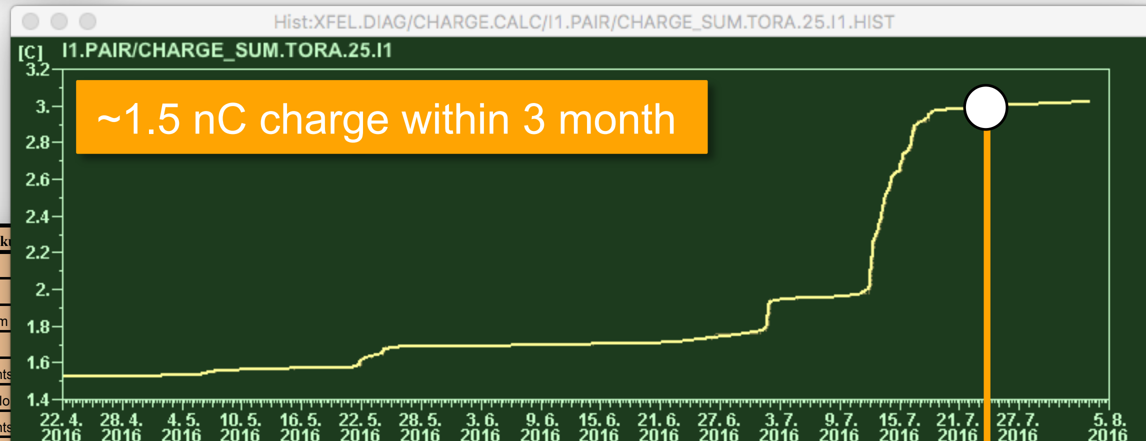
Beam line activation measurement March 22, 2016

After the most intense run

Messprotokoll zum Ausmessen von Stellen mit erhˆ hter Radioaktivit%t bei XFEL-Inj. 1

Datum:	25.07.2016
Zeit:	08:50
Beschleuniger:	XFEL - Inj. 1
gemessen von:	Hartz
Messger%t:	6150AD2
Bemerkung:	

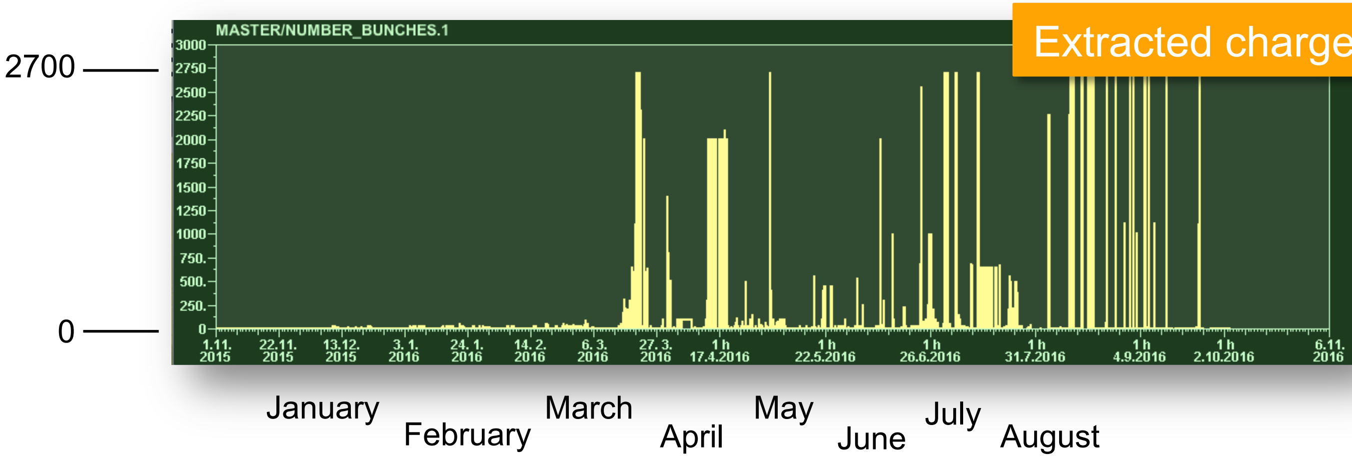
Messort	Bezeichnung	Dosisleistung in 30cm [µSv/h]	Dosisleistung Oberfl%che [µSv/h]	Bemerku
25m	Toroid 25.I 1	0,2	0,2	
26-38m	Modul A1.I1	0,2	0,2	
38-45m	Modul Att1.I1	0,2	0,2	45m
46m	Toroid 46.I1	0,2	0,2	
48m	Dipol BL48.I1	0,2	6,5	rechts
48m	Target-OTRL.48.I1	0,3	0,5	Bello
55m	CIY.55.I1	0,2	0,3	rechts
56m	Target-OTRC.56.I1	0,2	0,5	rechts
59m	Quadropol QI.59.I1	0,3	2,0	rechts
60m	Quadropol QI.60.I1	0,3	2,7	rechts
60m	Toroid 60.I1	0,5	4,0	rechts
62m	Dipol BP.62.I1	2,0	23,0	rechts
63m	GP IP-HV-1060	4,0	26,0	rechts
64m	Quadropol QI.64.I1	0,5	9,0	rechts
65m	Dump Flansch	4,0	10,0	
Wand	Dump Bohrung	-	526,0	rechts unten ca. 1,60m Tief



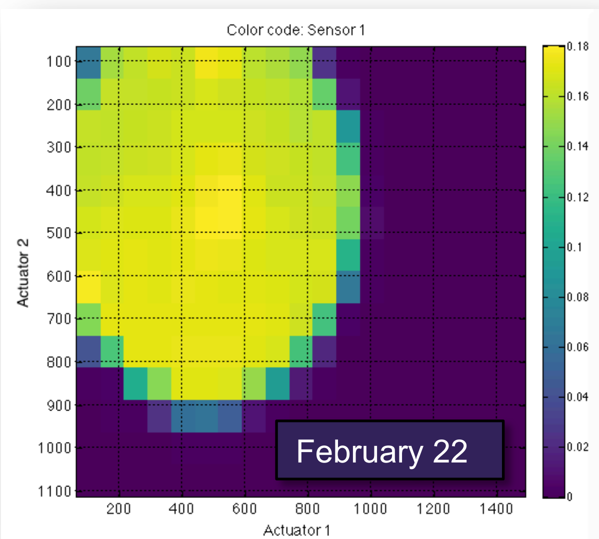
We improved the beam transport to the injector dump and reduced the activation of the beamline.

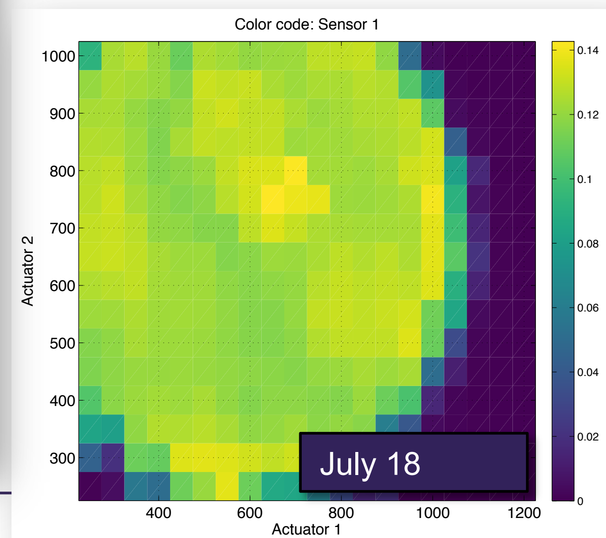
Long bunch train operation and photo cathode QE

Extracted charge in total: ~3 nC



Comparison of the first and last QE map

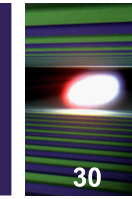




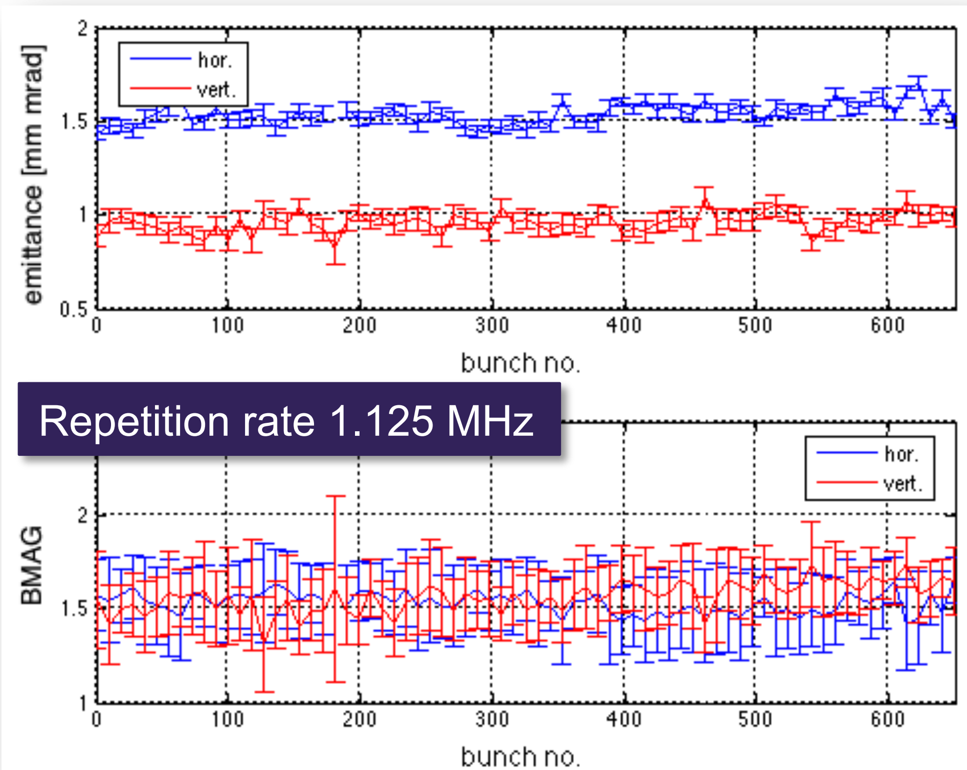
- Extracted charge at different positions of the gun cathode taken February 22 and July 18. The impact of the injector laser on the cathode is visible.
- This is known from FLASH. There the QE of a new cathode drops by ~20% at the used position but stays constant after that.

European XFEL

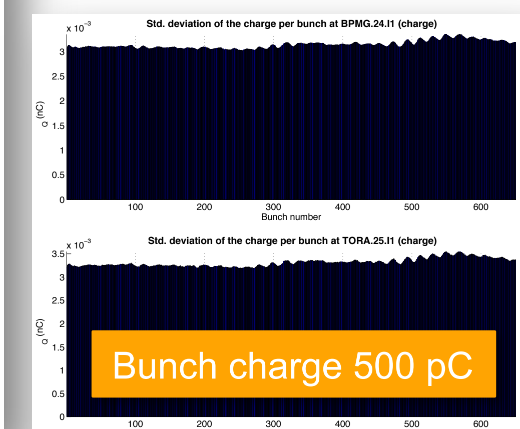
Emittance measurements along bunch trains



- 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.

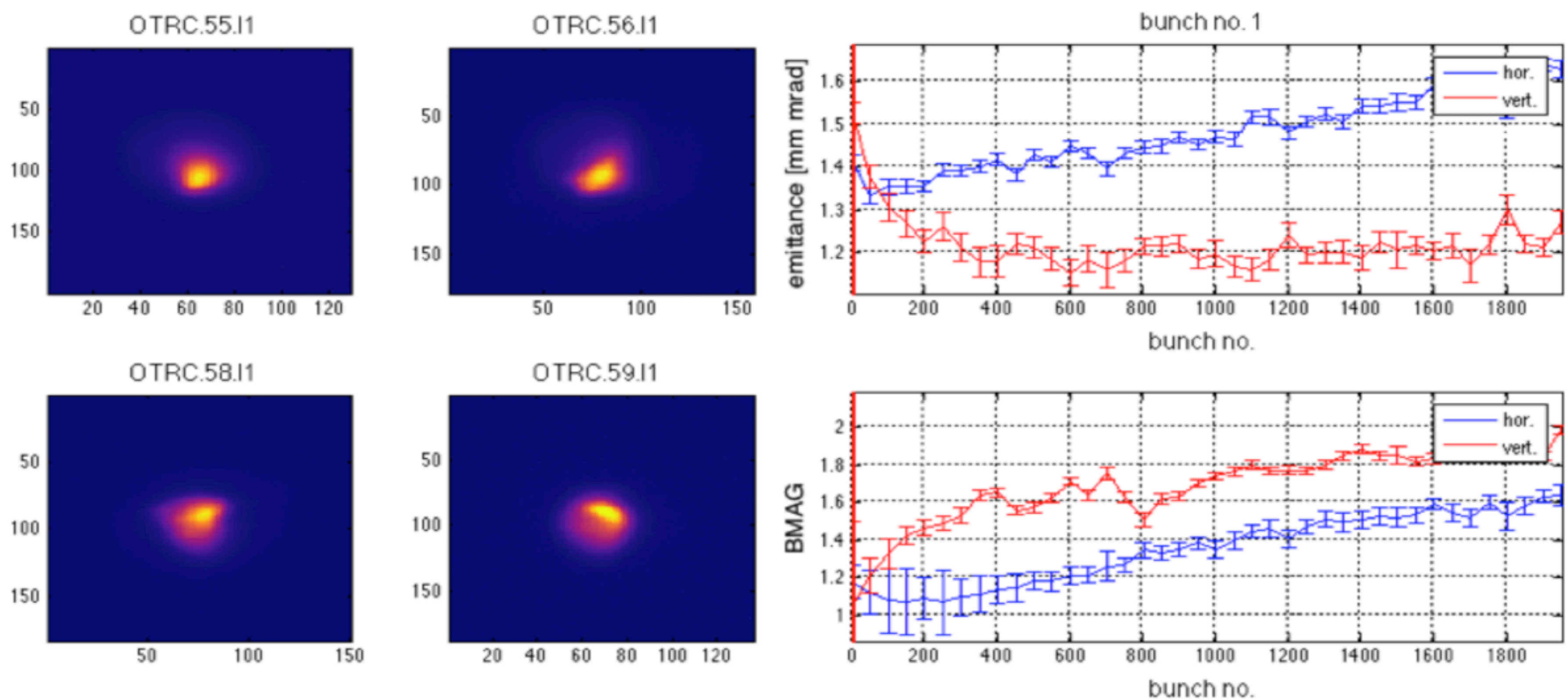


An example for projected emittance measurements along the bunch train. Both emittances as well as the mismatch are almost constant over the train.



HELMHOLTZ ASSOCIATION

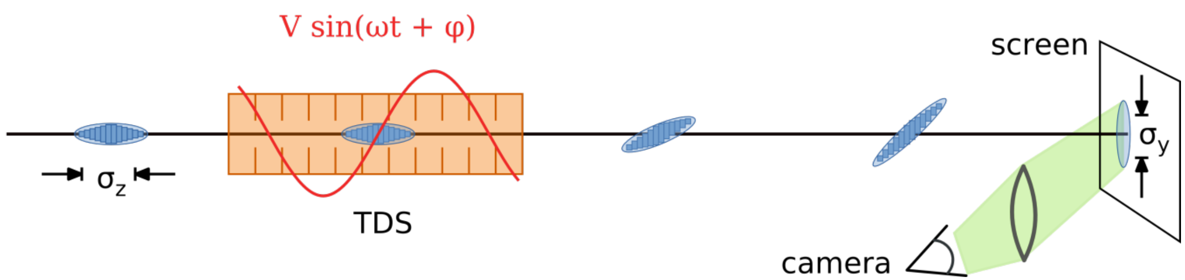
Emittance measurements along bunch trains

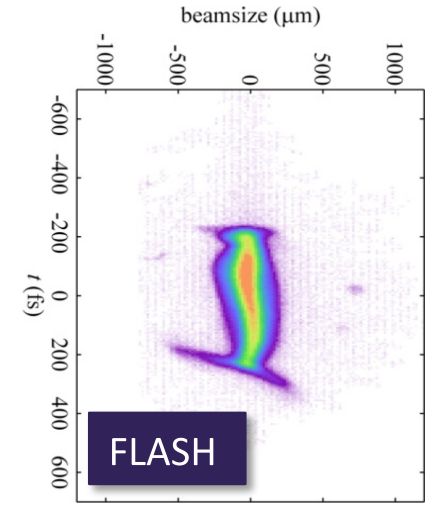


- Evolution of the projected emittance, the mismatch and the beam shape over the bunch train. The bunch charge was 500 pC.
- This measurement was taken while the injector laser stacker was in use. The unstable emittances and mismatches are eventually due to alignment issues with the stacker.

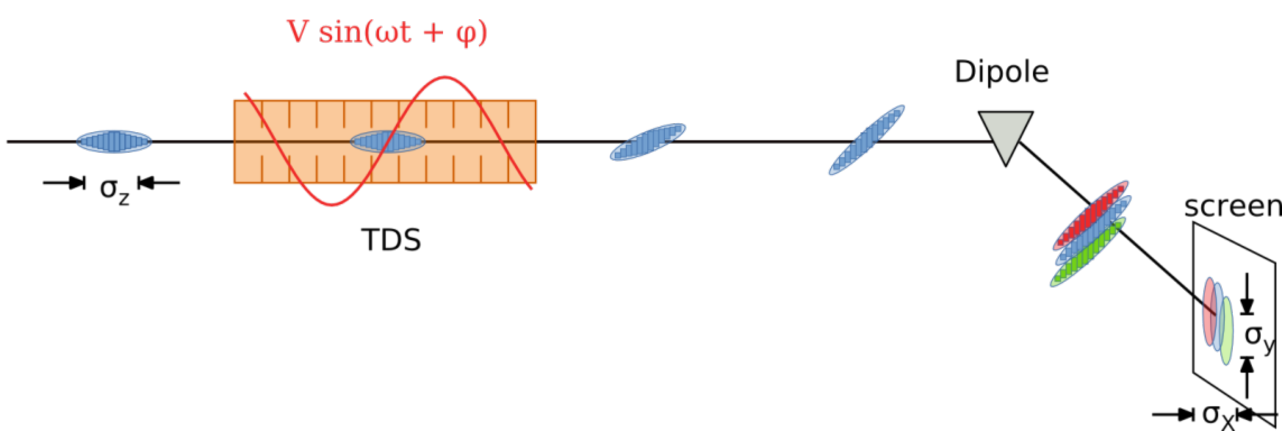
TDS

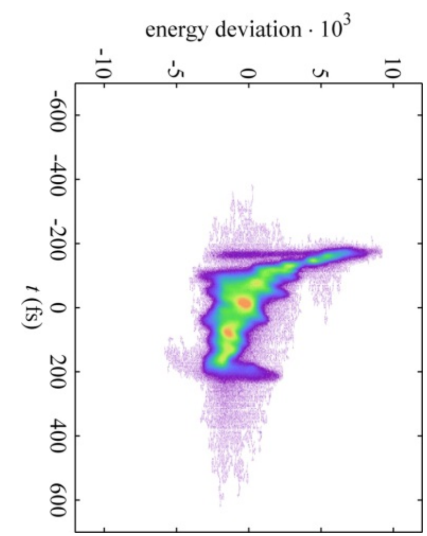
Transversely Deflecting Structure (TDS) + screen





TDS + dipole (dispersive section) + screen

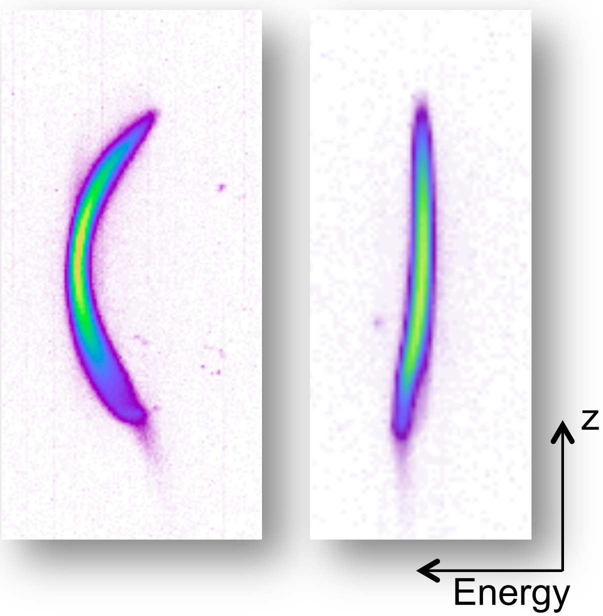




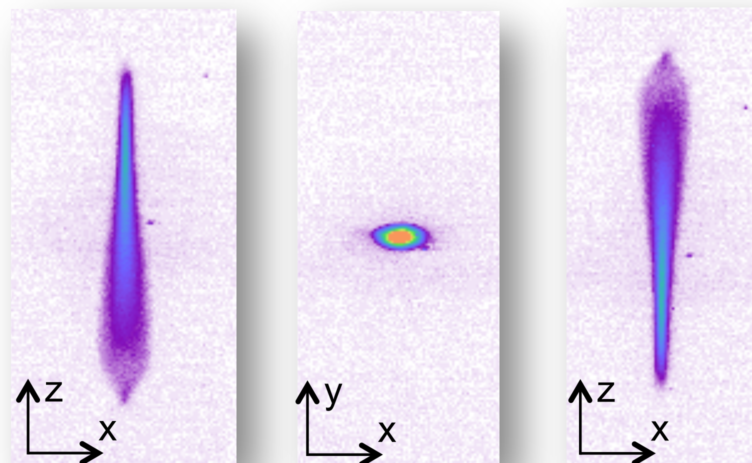
TDS

- TDS operation started May 24.

Linearization of the longitudinal phase space using the third harmonic acceleration module AH1. Picture were taken in the dump beamline (dispersion).



The first pictures of streaked bunches in the XFEL injector using the two zero crossings. The pictures were taken in the diagnostic section.

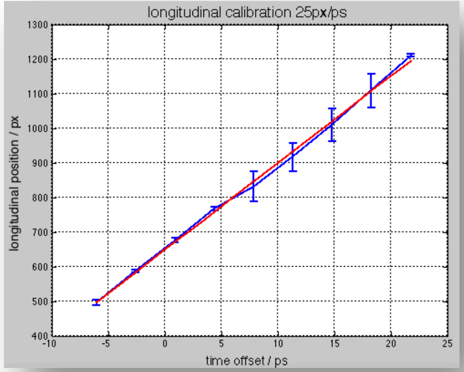


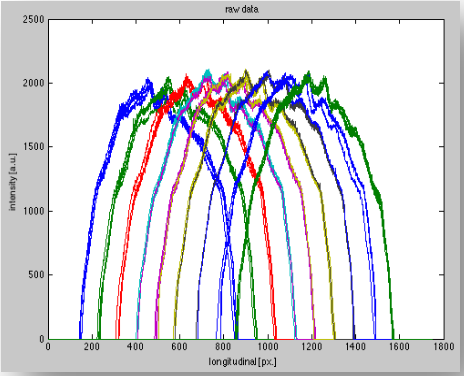
With the TDS available we were able to measure electron bunch lengths as well as slice emittances.

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.

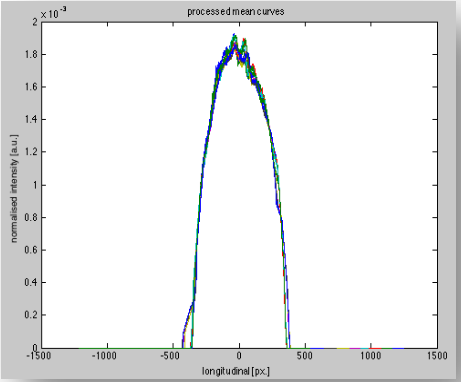
Calibration curve

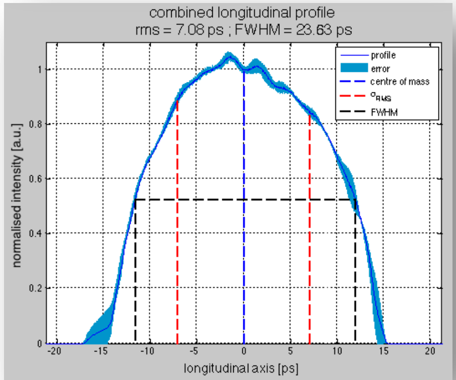




Profiles of the single measurements

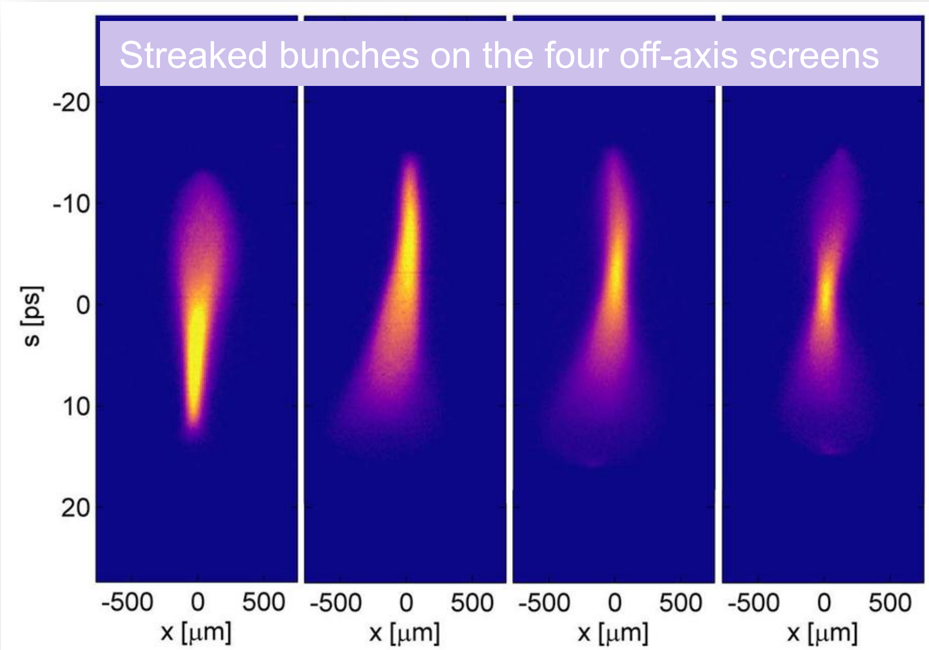
Combined profiles





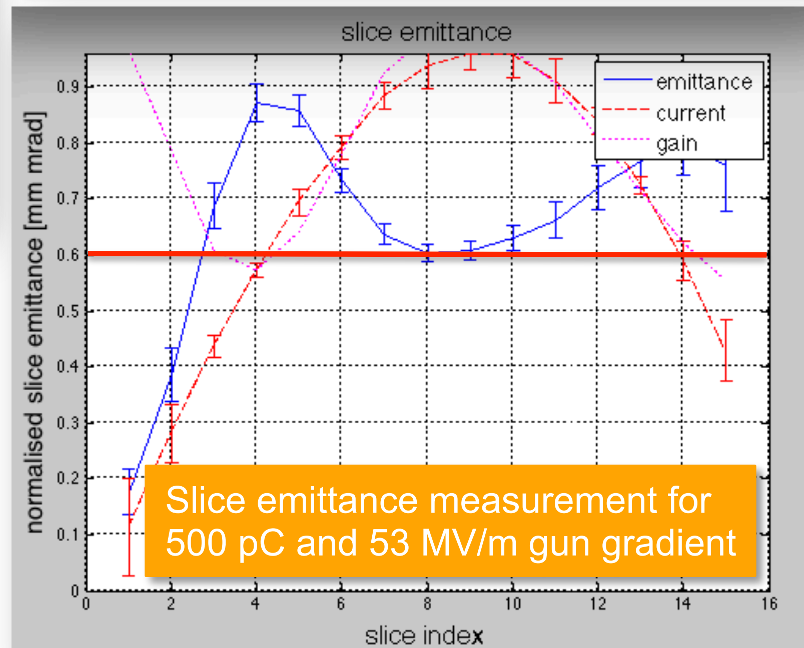
Final evaluation

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 the magnet cycling.



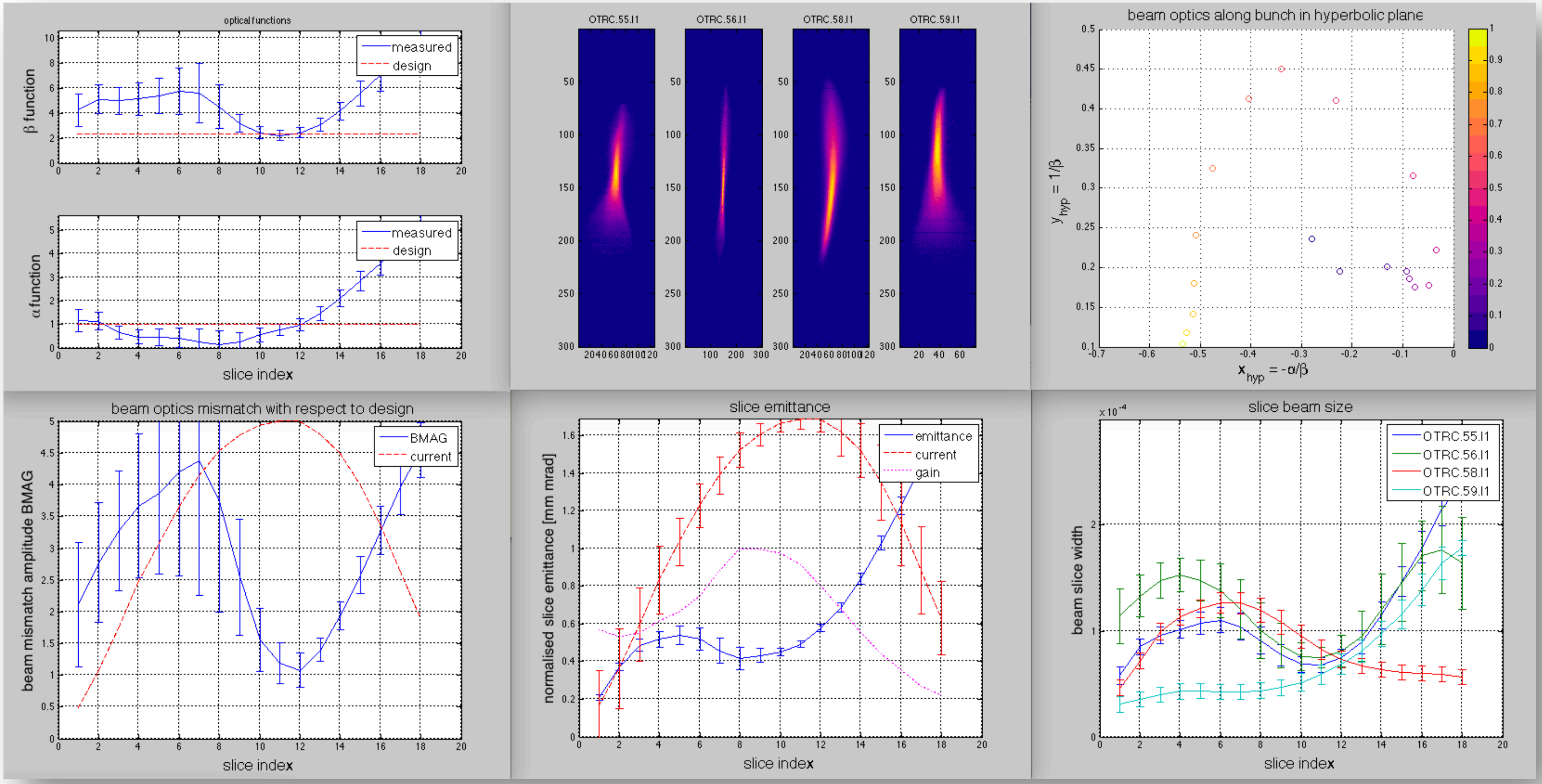
Slice emittance measurement for 500 pC and 53 MV/m gun gradient

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

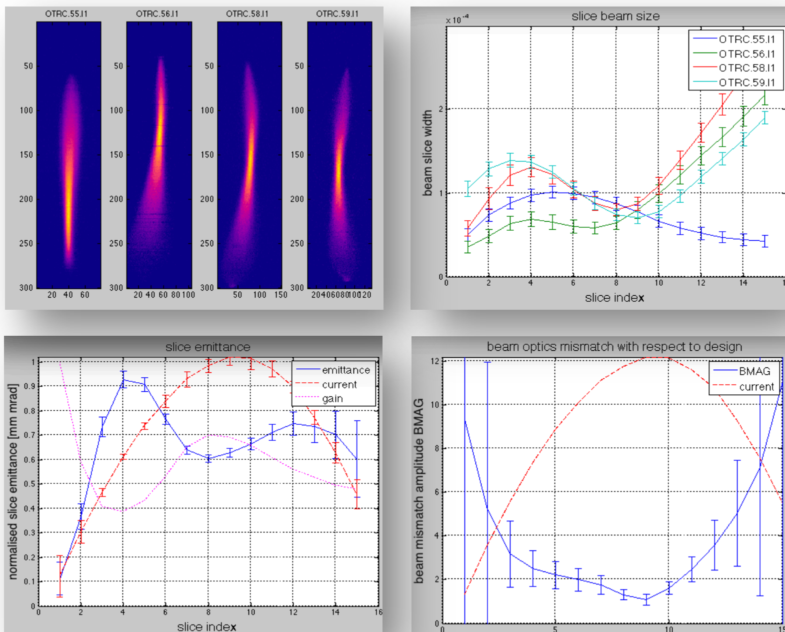
Slice emittance measurements with 60 MV/m gun gradient

The smallest slice emittance of about 0.4 mm mrad for a 400 pC bunch was achieved with 60 MV/m gun gradient on July 25 (The night shift before the shutdown).

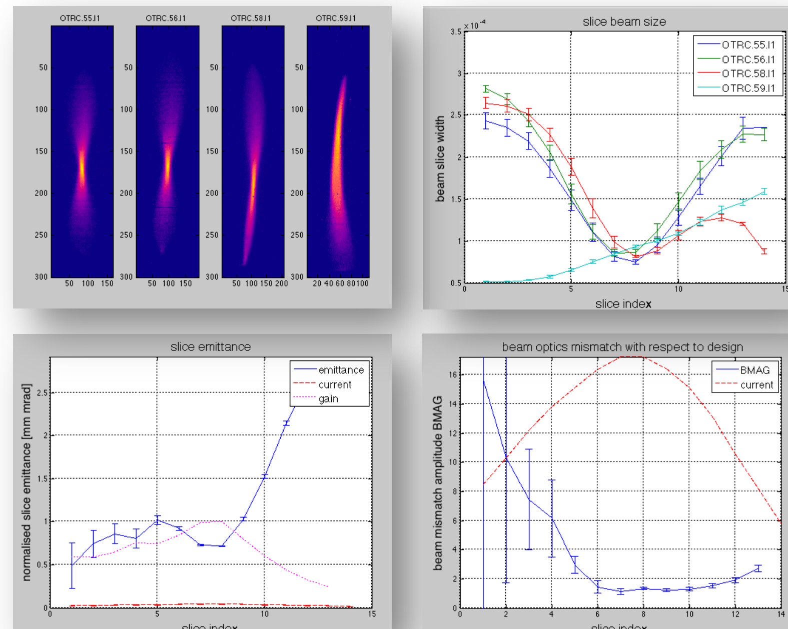


Slice emittance studies with different gun phases and solenoid currents

- It is possible to run the injector with different gun phases and solenoid currents while the beam is always matched perfectly.
- The following pictures show two different working points and their impact on the slice emittances respectively on the shape of the bunches.



Gun phase 43 degree, solenoid current 321 A.
This setup is close to what we worked out during the optimization of the projected emittances.



Gun phase 35 degree, solenoid current 314 A.
This setup is closer to the gun phase and solenoid current typically used at FLASH.

Slice emittance studies with different gun phases and solenoid currents

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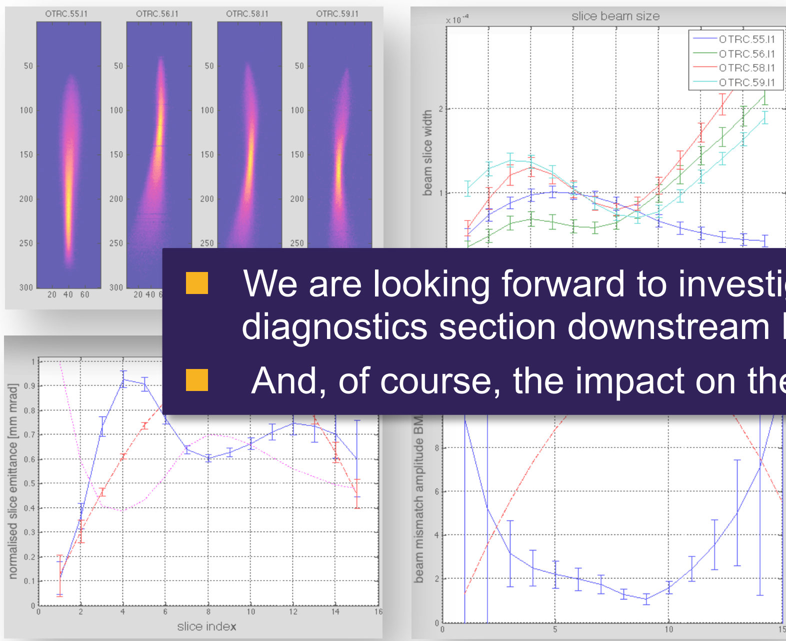
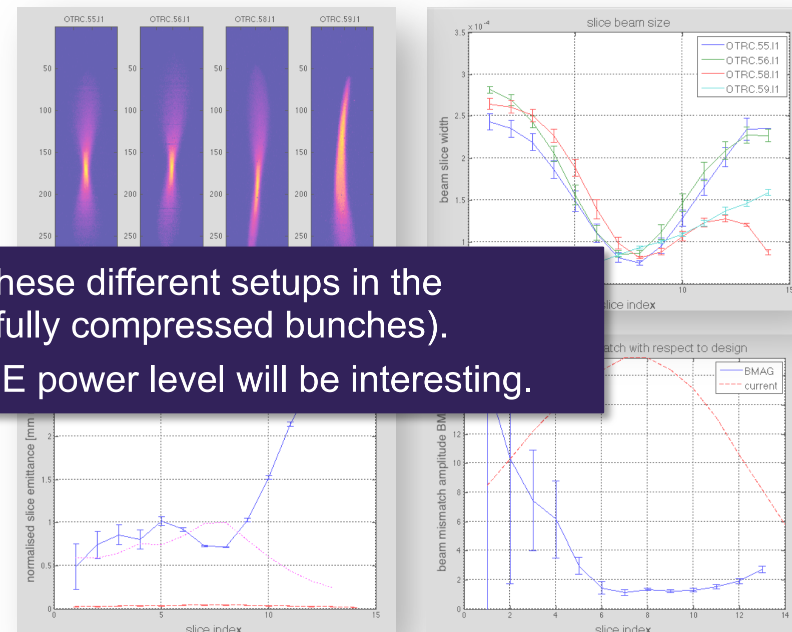




- We are looking forward to investigate these different setups in the diagnostics section downstream BC2 (fully compressed bunches).
- And, of course, the impact on the SASE power level will be interesting.

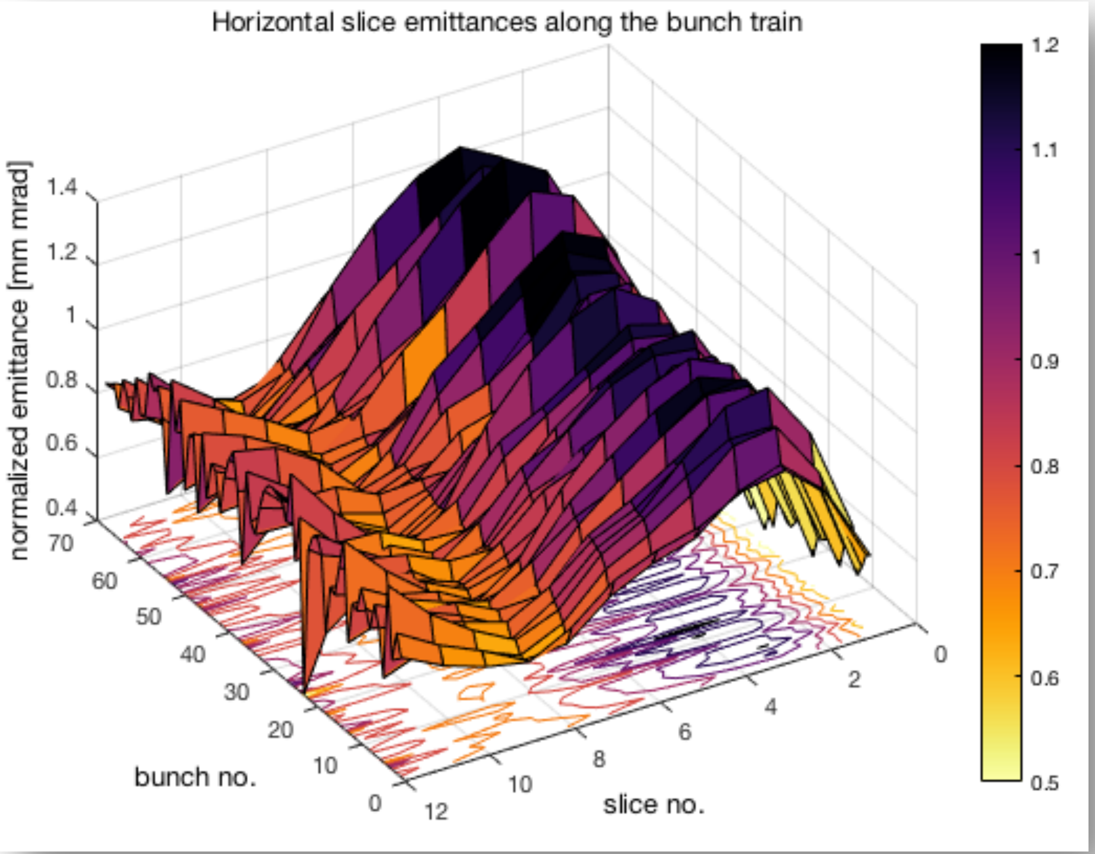
Gun phase 43 degree, solenoid current 321 A.
This setup is close to what we worked out during the optimization of the projected emittances.

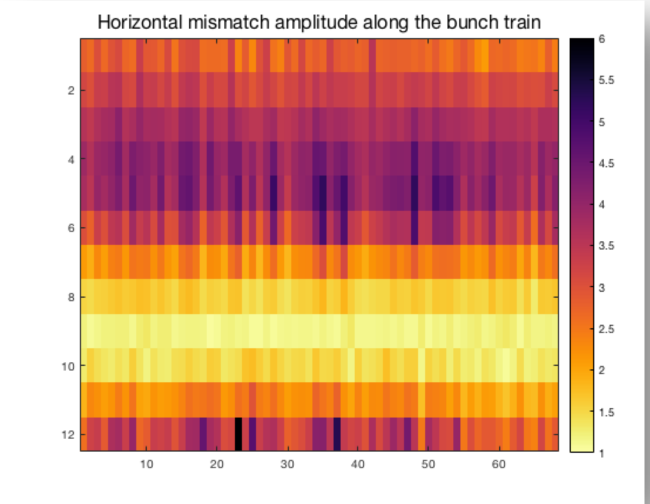
Gun phase 35 degree, solenoid current 314 A.
This setup is closer to the gun phase and solenoid current typically used at FLASH.

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





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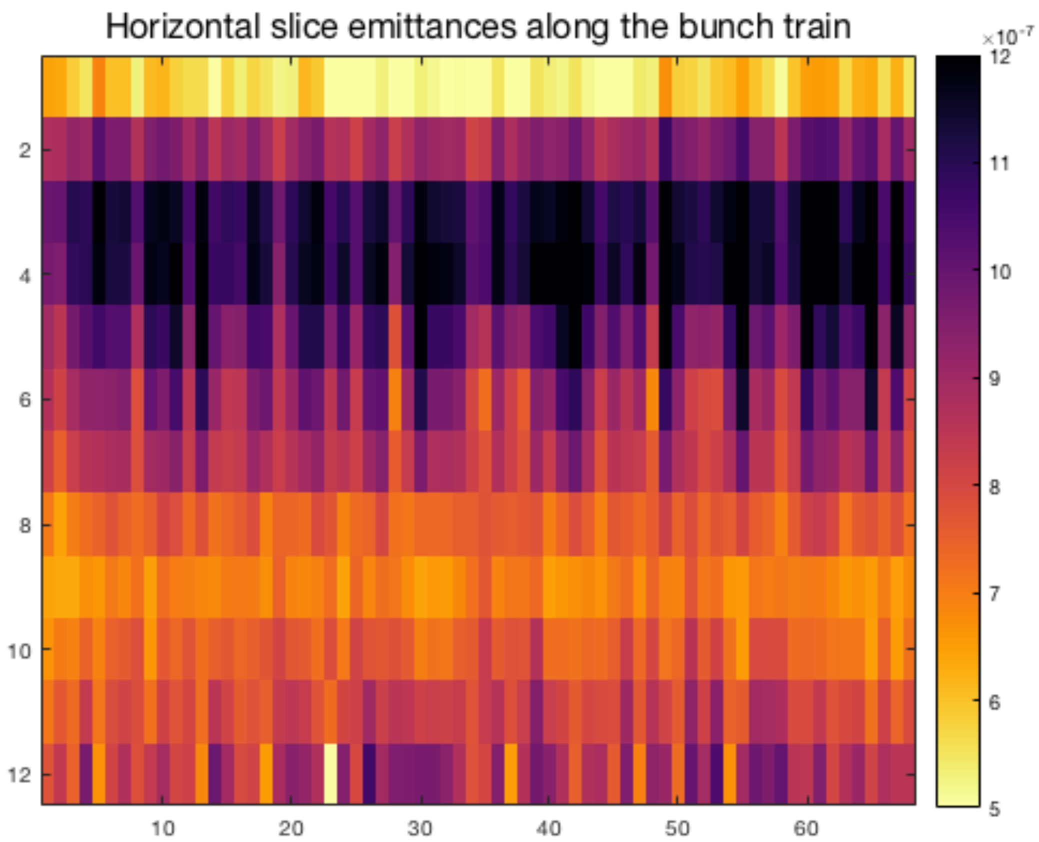
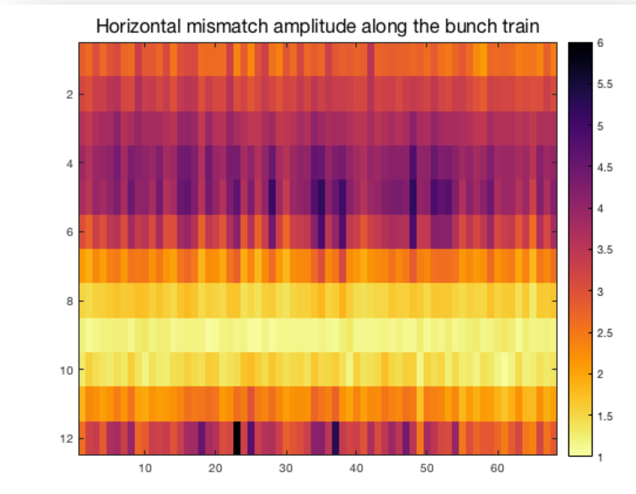
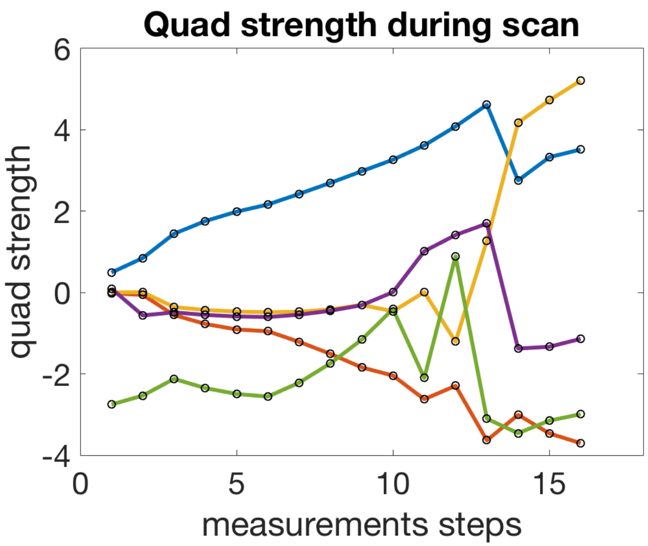




Multi knob quadrupole scan data

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

K-values of 5 quadrupole magnets

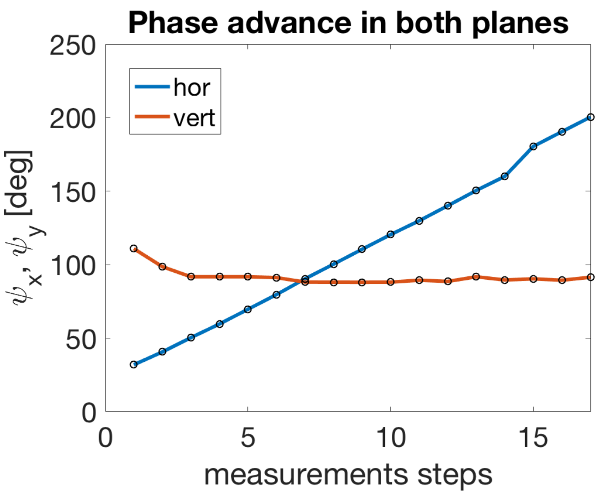


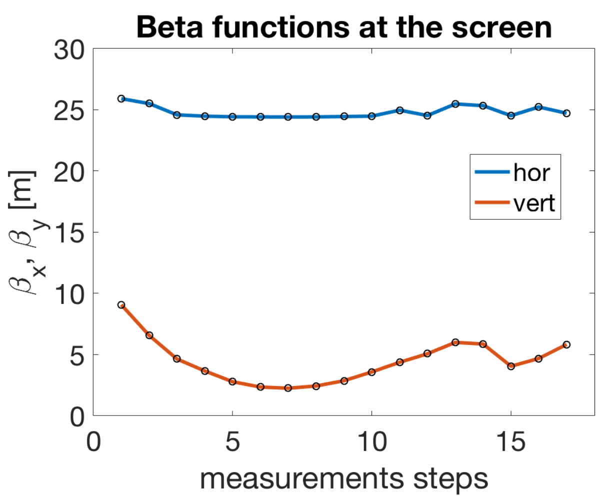
18 steps of the quad scan

- The vertical phase advance between the TDS and screen is constant.
- The phase advance in horizontal plane changes in 18 steps of 10 degree.

Both beta-functions are almost constant for all measurement steps.

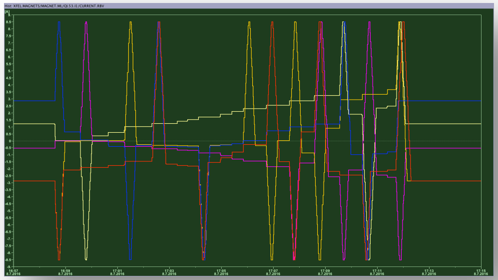
- A small beam in the horizontal plane improves the measurement resolution
- A larger beta function in vertical plane lead to a more effective streak.





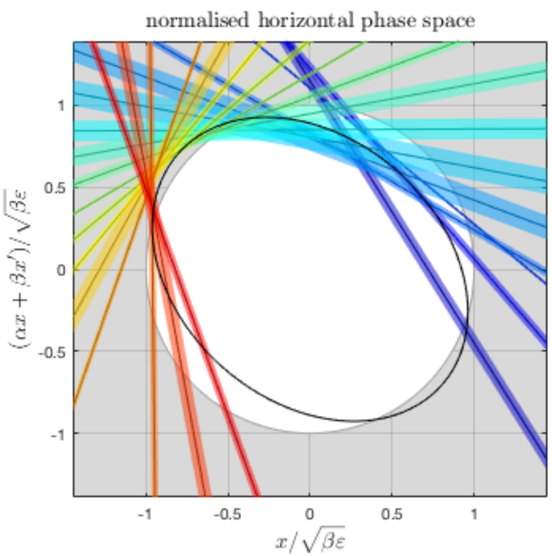
Emittance calculations and tomography using multi knob quadrupole scan data

Results of the quadrupole scan with 5 magnets

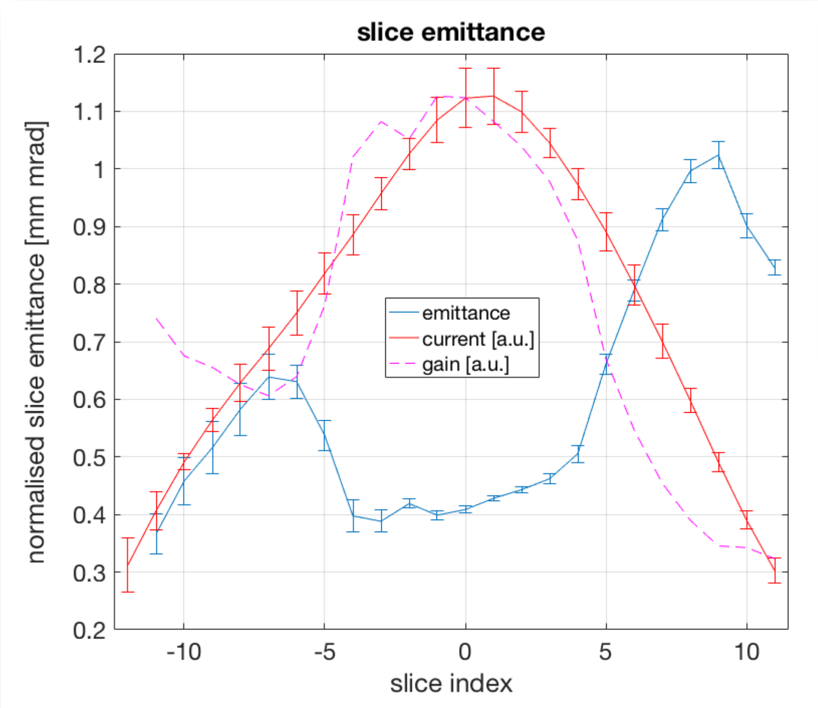


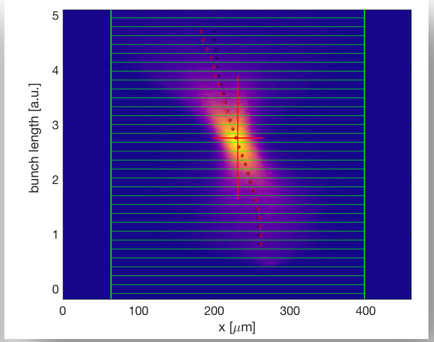
Quad strengths during the scan

- 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.

Emittance calculations and tomography using multi knob quadrupole scan data

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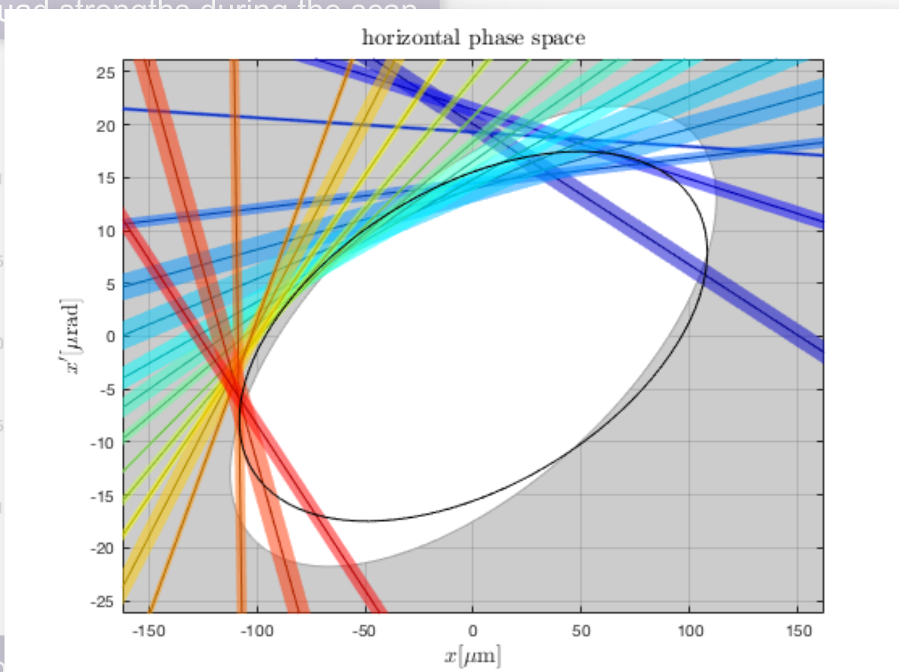
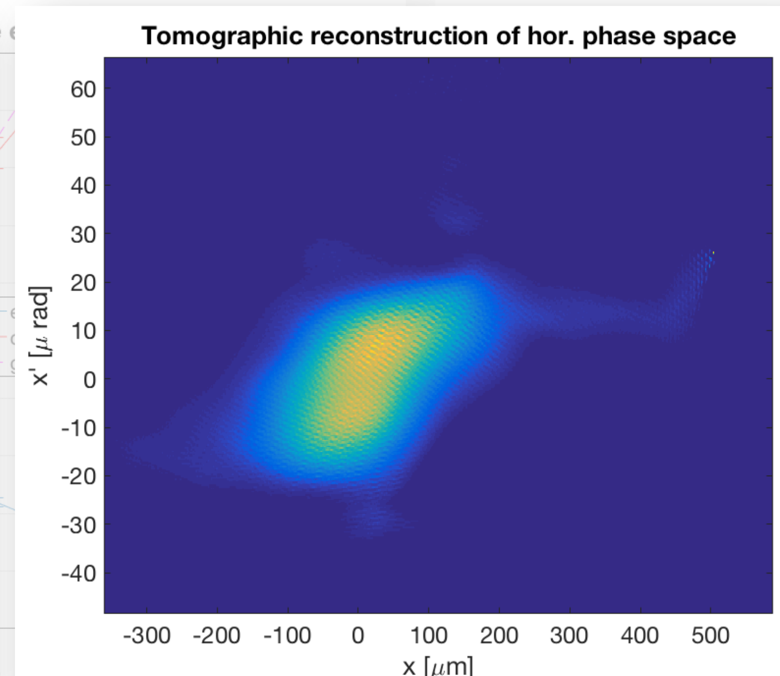
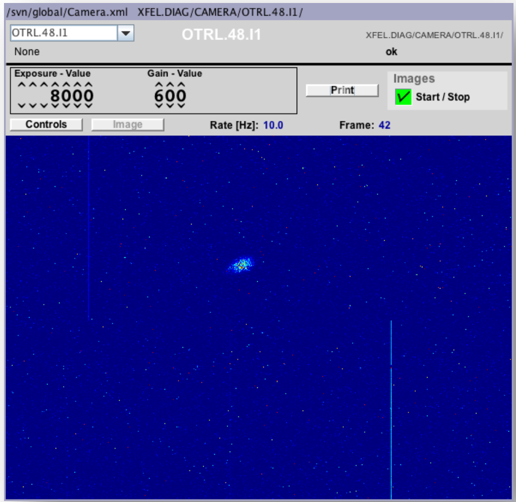
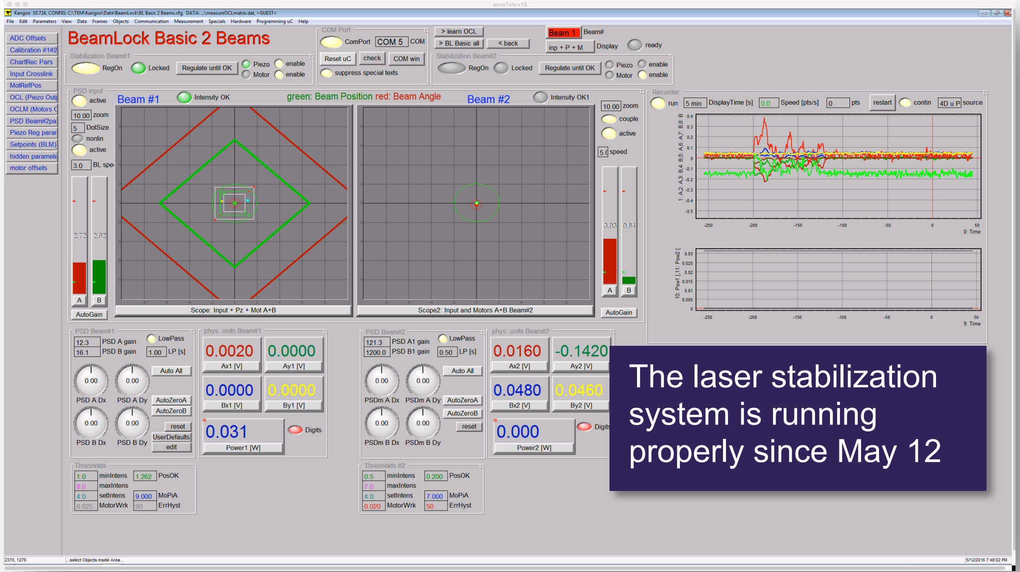




Laser heater commissioning



First time that the infrared laser was detected on one of the LH screens (OTRL.48.I1): April 21



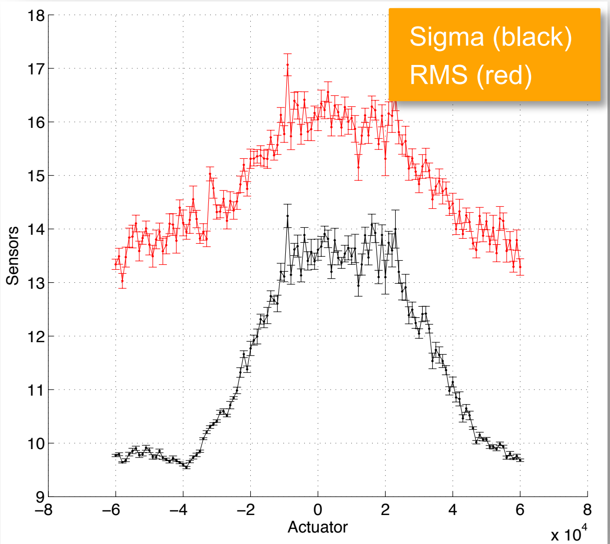
The laser stabilization system is running properly since May 12

	d(DeltaX)	d(DeltaY)	d(alpha)	d(beta)
d(x_48)	-6.453017372362659660e-05	-1.144028251288580044e-05	1.270074507402253111e-05	-1.527340044337490137e-03
d(y_48)	-8.360182533703755920e-07	-9.395186891863471237e-05	1.742450383604300873e-03	1.625620930141716210e-05
d(x_50)	9.031589576653397853e-05	-8.010383048699555106e-06	9.631239744657571380e-05	2.591603048257797113e-03
d(y_50)	-5.854208512050469781e-06	9.269672489468871698e-05	-2.592967224354790230e-03	4.491042147777443651e-05

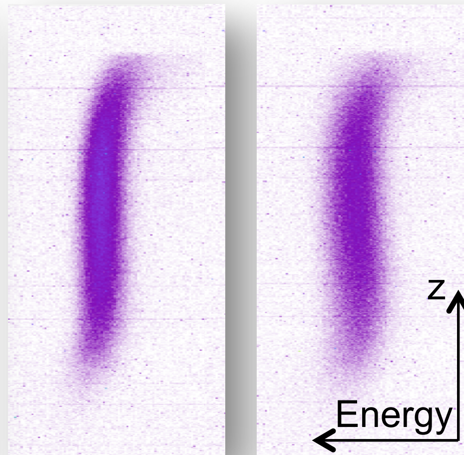
A response matrix of the laser alignment system in the tunnel was measured in order atomize the overlapping of infrared laser and electron beam.

May 20.

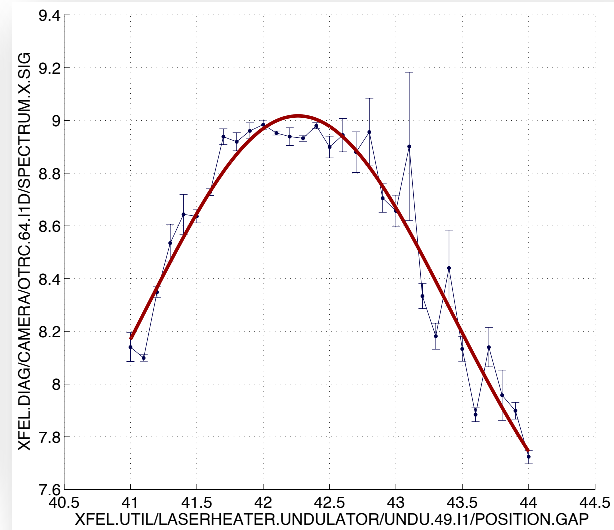
Laser heater commissioning



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



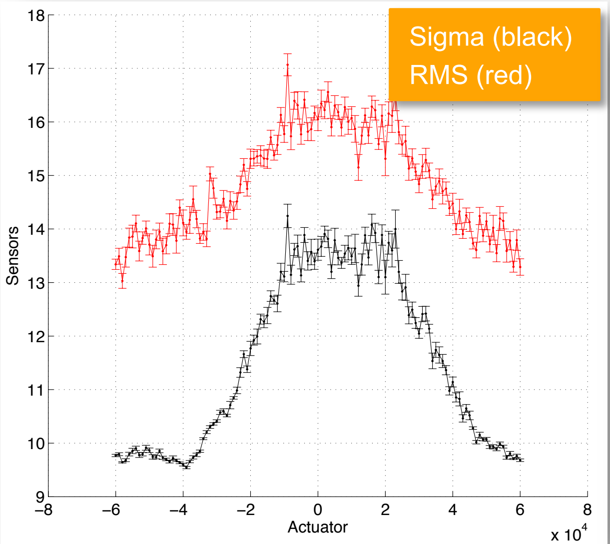
Two streaked bunches in the dispersive arm. On the left hand side without LH and on the right hand side with an increased energy spread due to laser heating.



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.

Laser heater commissioning



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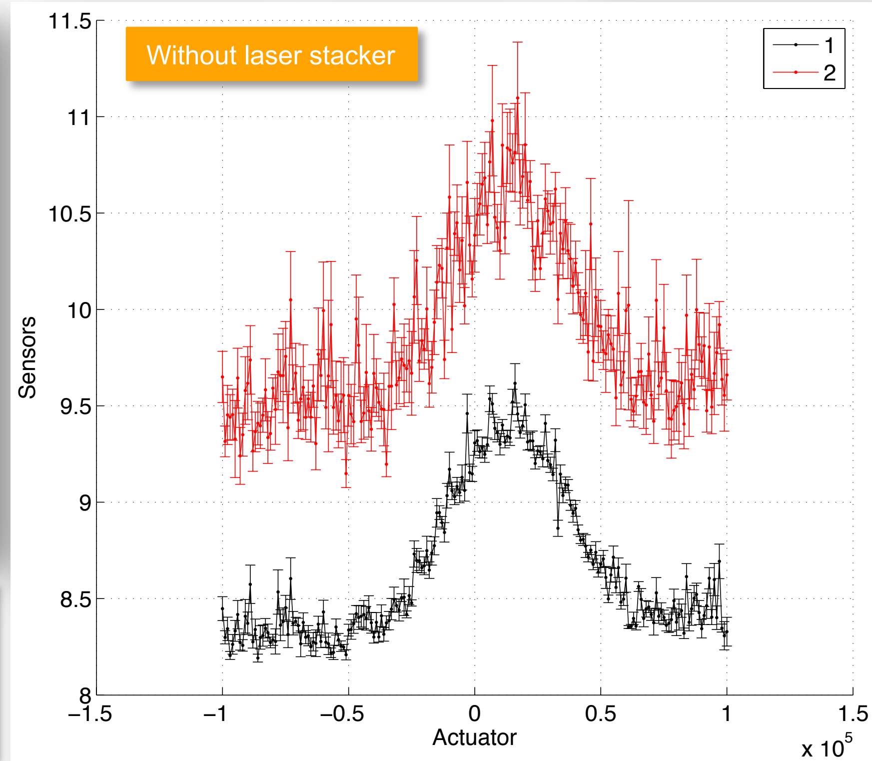

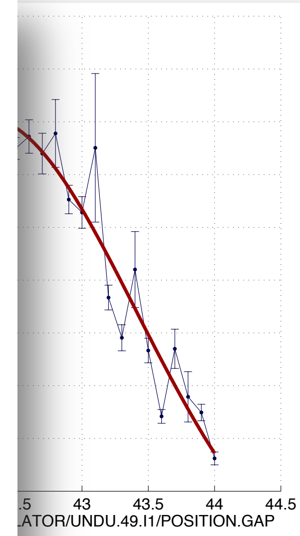

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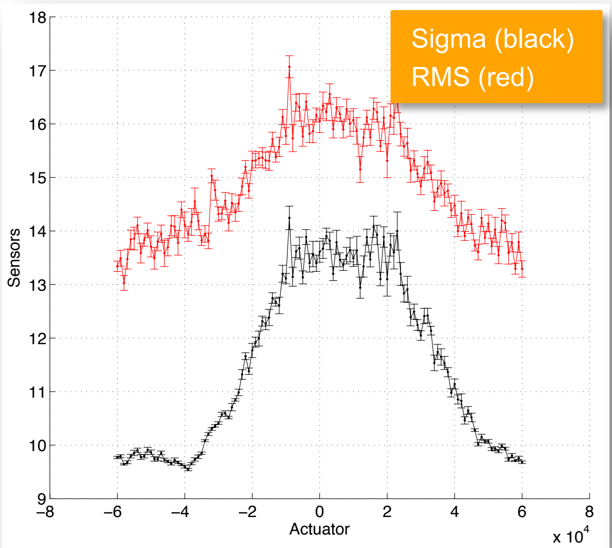

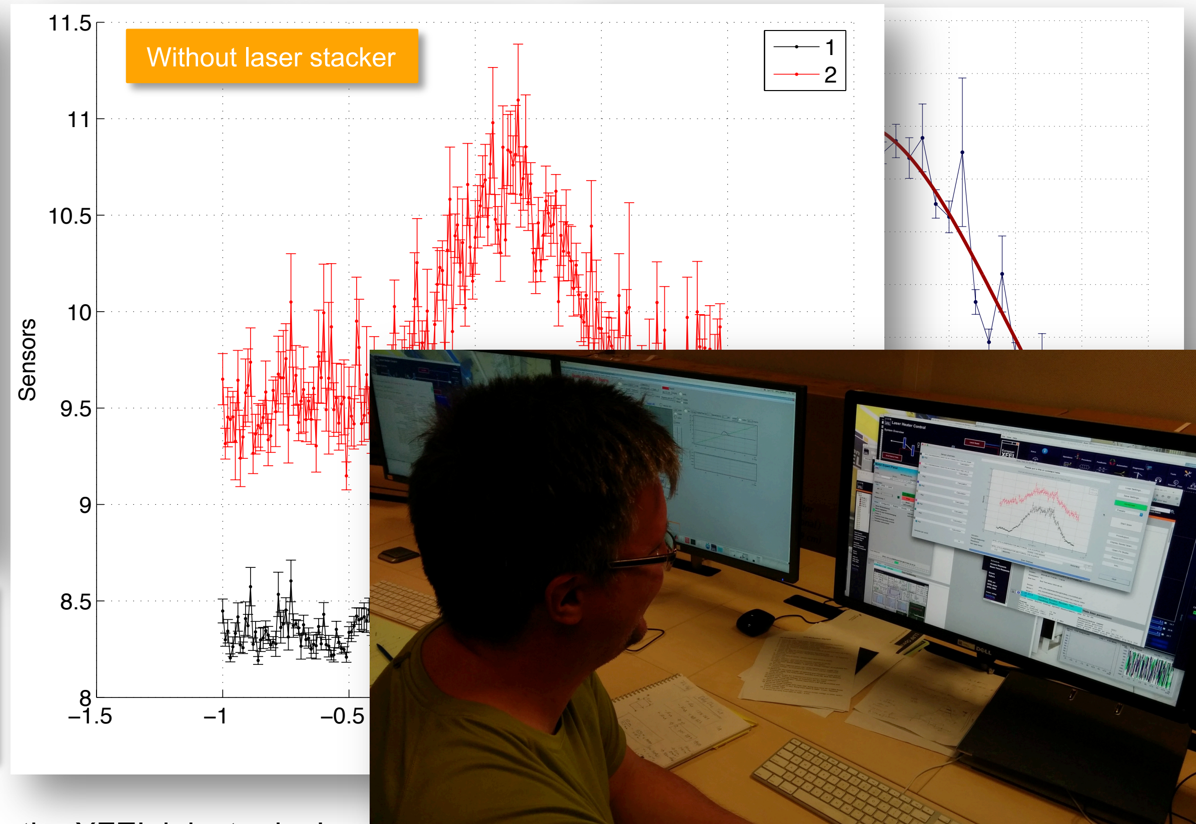

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Thank you for your attention!

All of those 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!