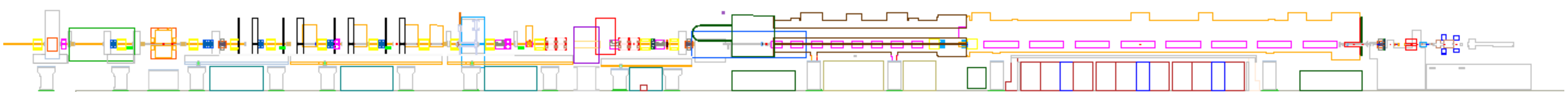
European XFEL Injector Commissioning Results

Bolko Beutner
on behalf of the European XFEL Team
DESY Hamburg

Santa Fe, NM, USA
August 23, 2017

European XFEL Injector



Emittance measurements and optimizations (projected and slice)

Long bunch train operation

Tomographic reconstruction of horizontal phase space

Gun Operation

European XFEL

- Superconducting Linac with 17.5 GeV design energy
- Long bunch trains (2700 bunches per train at 10 Hz)
  - 600 µs RF pulses at 4.5 MHz
  - Up to 473 kW beam power (300 kW per beam dump)
  - Flexible bunch patterns for experiments
- More then 10 years experience form FLASH and TTF
- Gun R&D and conditioning at PITZ in DESY Zeuthen

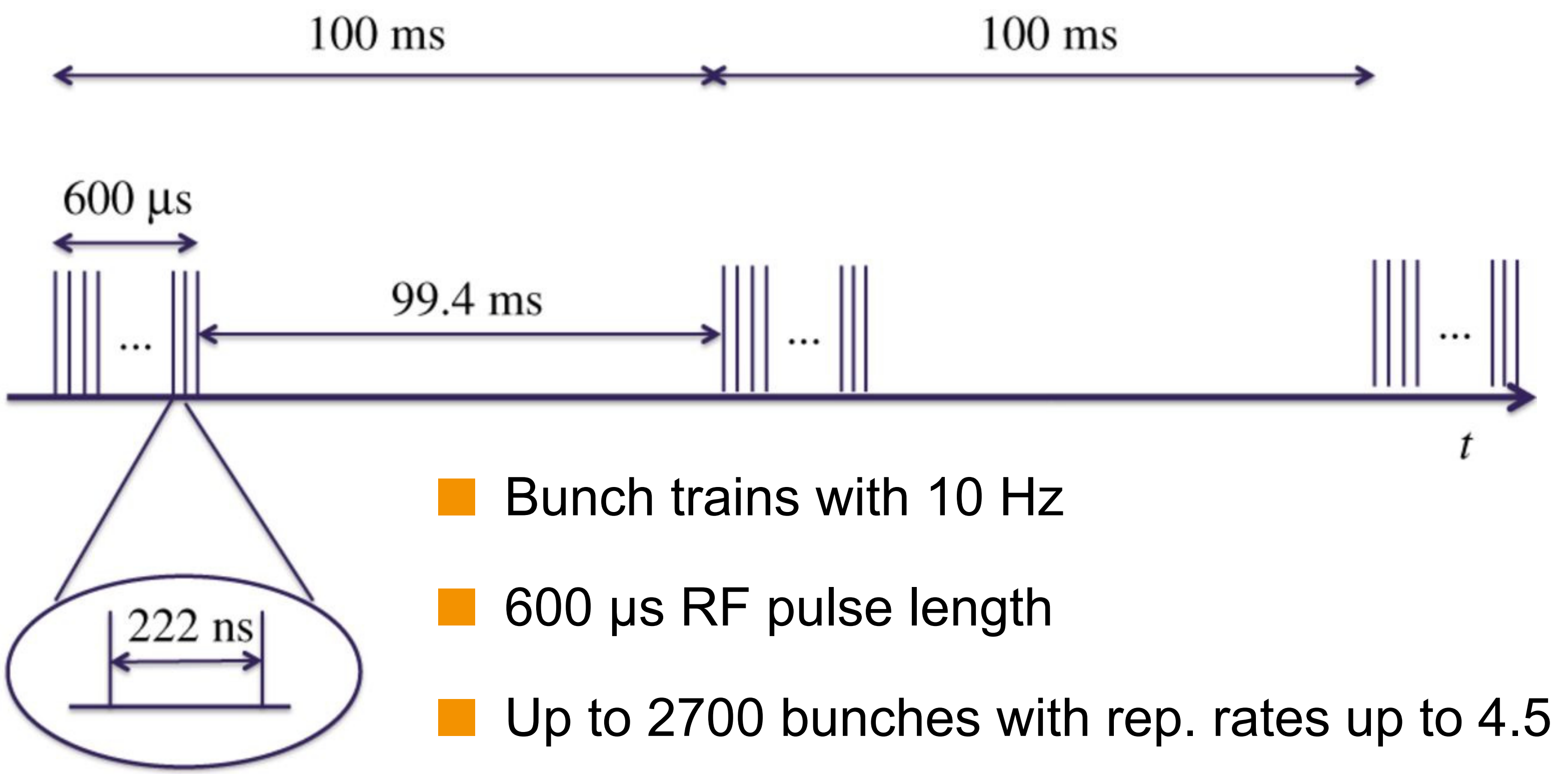
Participating countries

MOC03 Commissioning and First Lasing of the European XFEL

European XFEL

DESY

Time Structure



- Bunch trains with 10 Hz
- 600 µs RF pulse length
- Up to 2700 bunches with rep. rates up to 4.5 MHz
- Individual distribution on different user stations

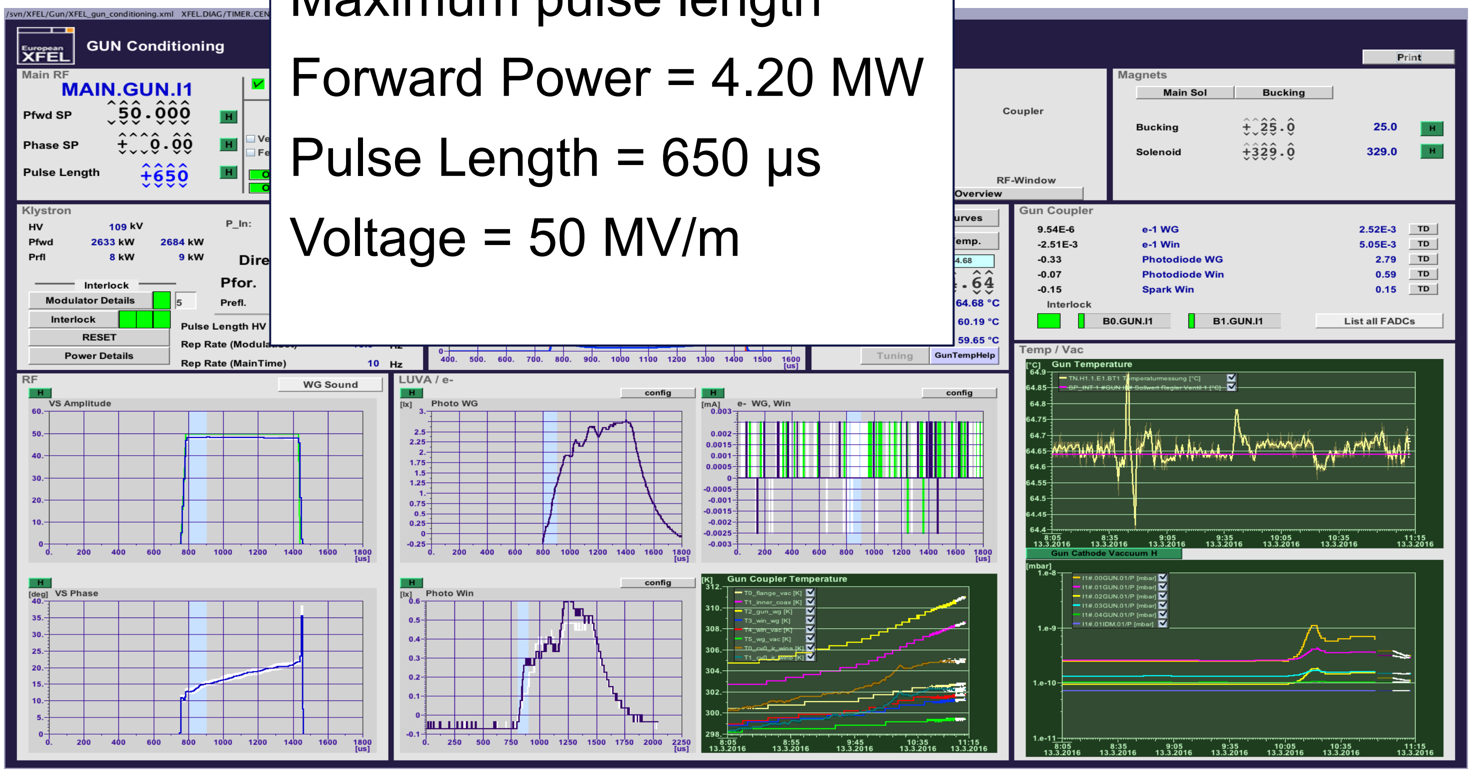
Maximum Pulse Length and Maximum Gradient in the Gun

Maximum pulse length

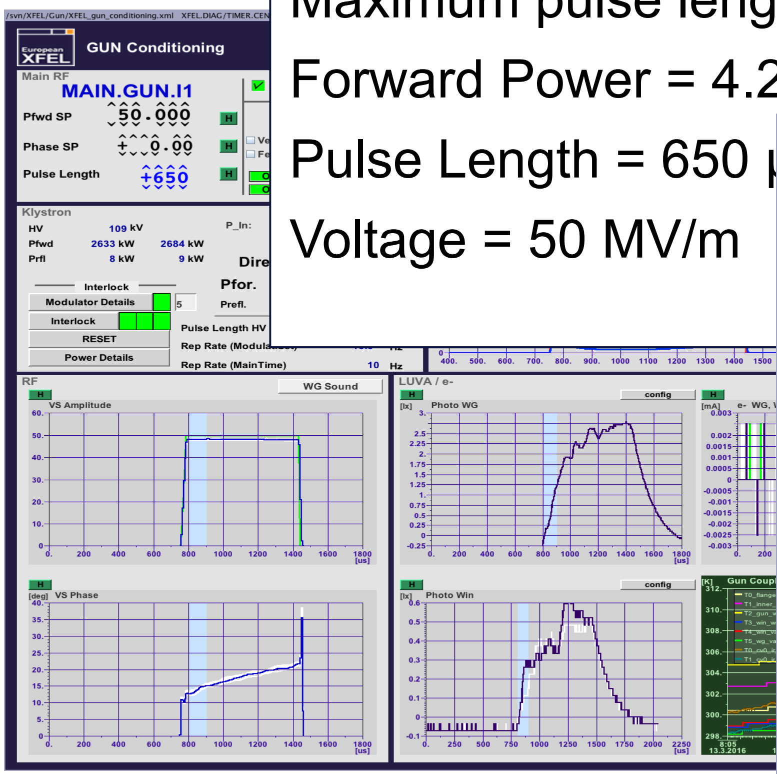
Forward Power = 4.20 MW

Pulse Length = 650 μs

Voltage = 50 MV/m



Maximum Pulse Length and Maximum Gradient in the Gun



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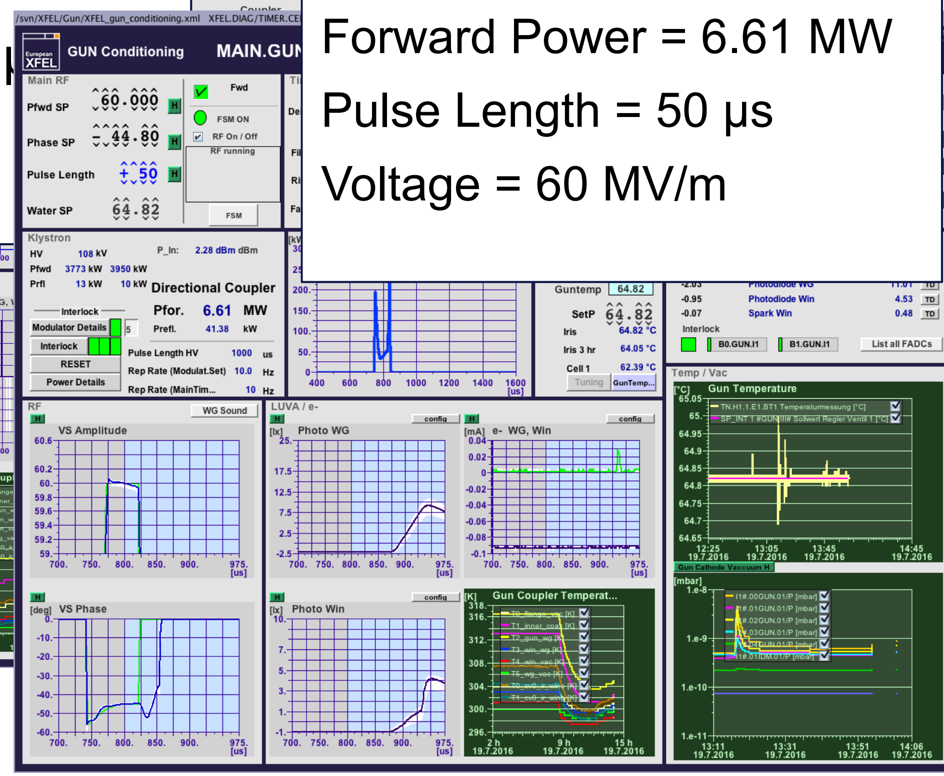


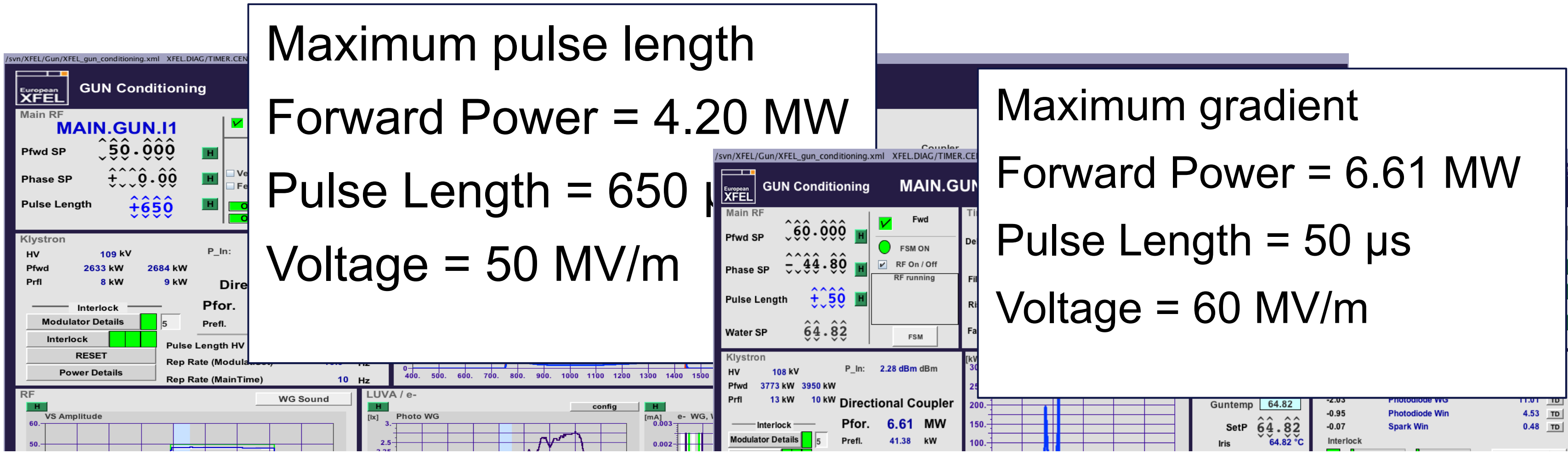
Maximum gradient

Forward Power = 6.61 MW

Pulse Length = 50 µs

Voltage = 60 MV/m

Maximum Pulse Length and Maximum Gradient in the Gun



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Forward Power = 4.20 MW

Pulse Length = 650 µ

Voltage = 50 MV/m

Maximum gradient

Forward Power = 6.61 MW

Pulse Length = 50 µs

Voltage = 60 MV/m

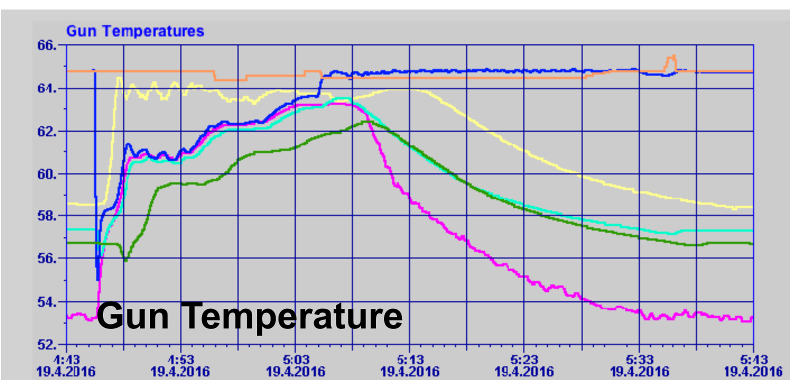
- At XFEL gun gradient and pulse length is not simultaneously set to maximum to avoid stress on the RF window
- Gun pulse length limited to about 100us in 2017 to ensure SASE studies and first user experiments at XFEL (single RF window configuration)
- Using a two RF windows configuration long pulses at high gradient are possible (PITZ)

Gun Start-up

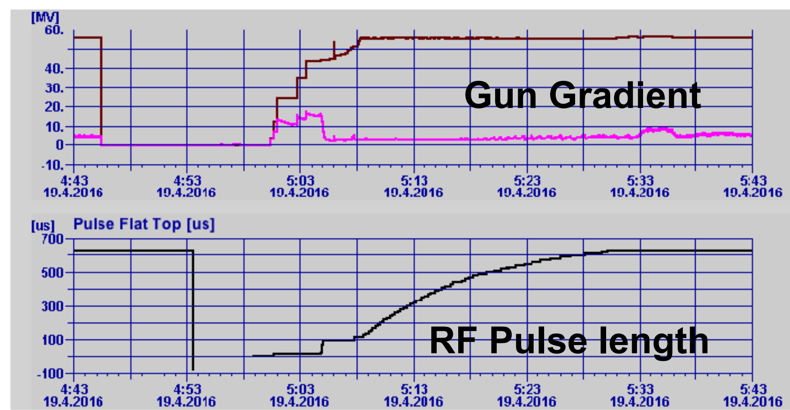
- Up to 50 kW heat load on the Gun cavity from the RF
- Water regulation is slower than the RF power changes
  - 0.05 deg C temperature stability requirement to stay on resonance

→ Frequency mismatch (detuning) during start-up

- slow ramp to give the water time to adjust



~1 hour



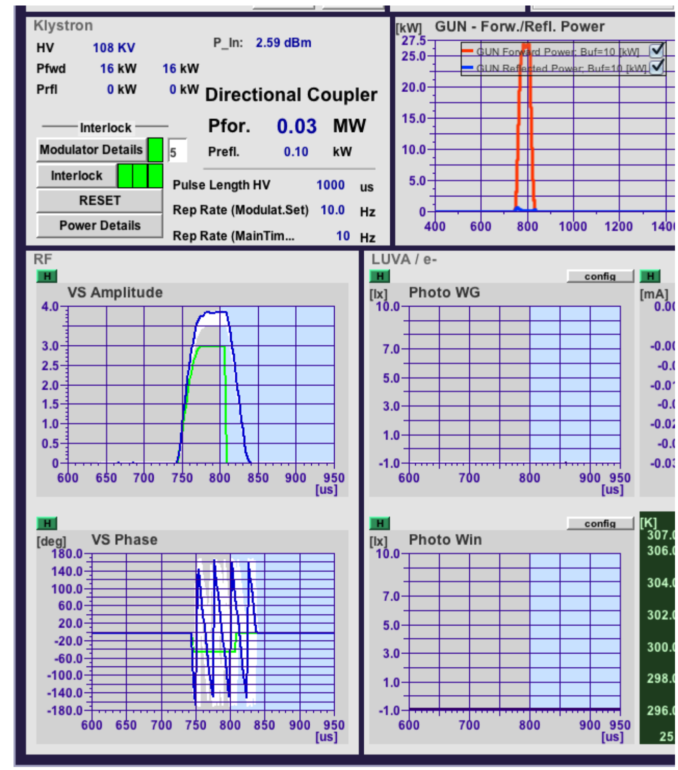
~1 hour

European XFEL

DESY

Fast Gun Start-up

- Detuning is compensated by phase slope on LLRF baseband
- During the ramp phase slope is constantly adjusted to keep reflected power low
- Automised with a Finite State Machine Controls server
- Automatic small adjustments of the RF pulse length to use RF as fast “heater” to keep reflected power low during standard operation



Y. Renier, et. al, Fast Automatic Ramping of High Average Power Guns, IPAC2017, DK

Fast Gun Start-up

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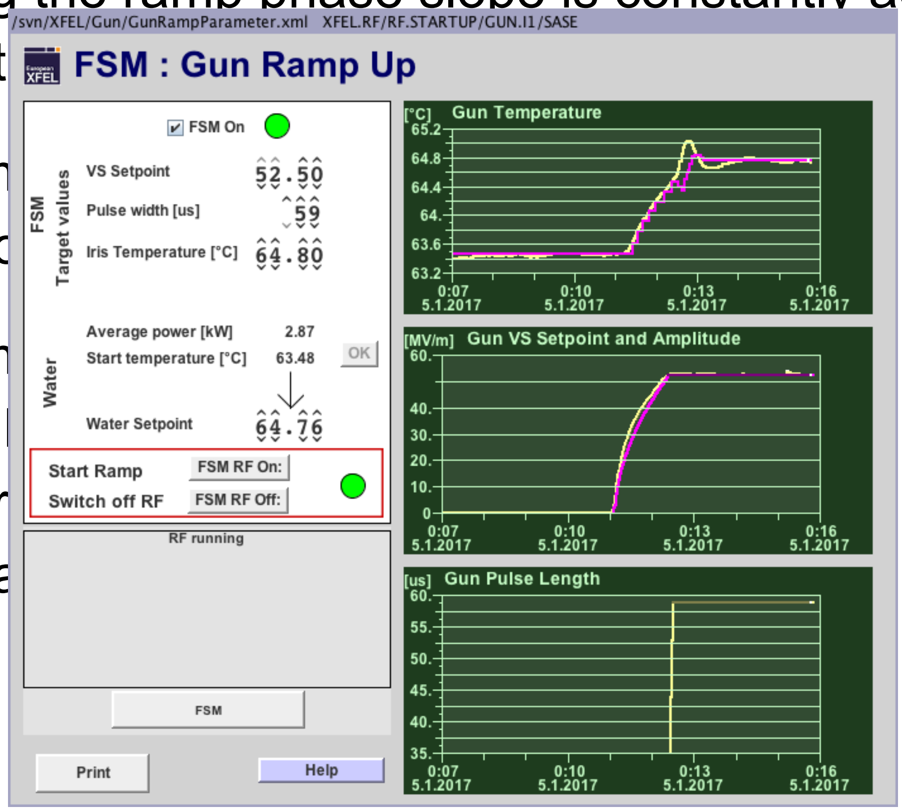

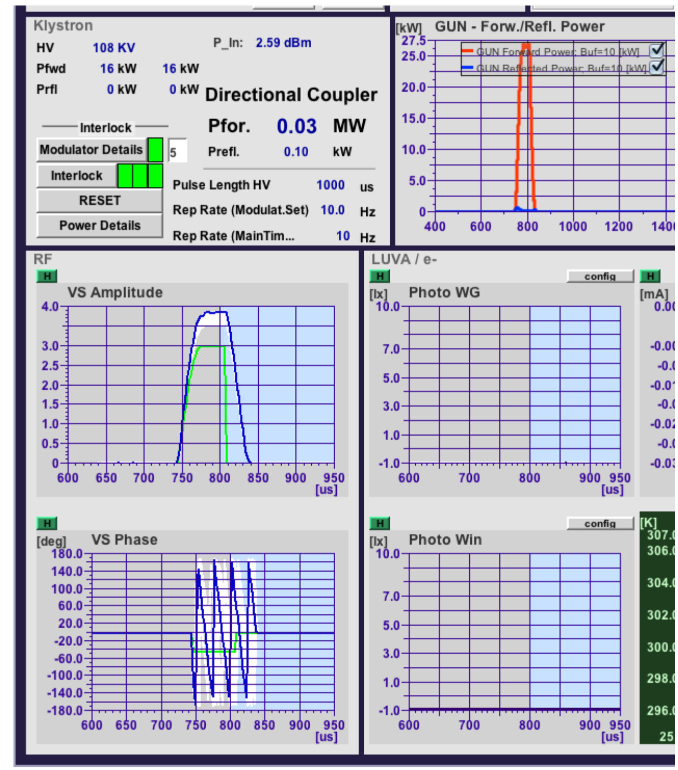

Y. Renier, et. al, Fast Automatic Ramping of High Average Power Guns, IPAC2017, DK

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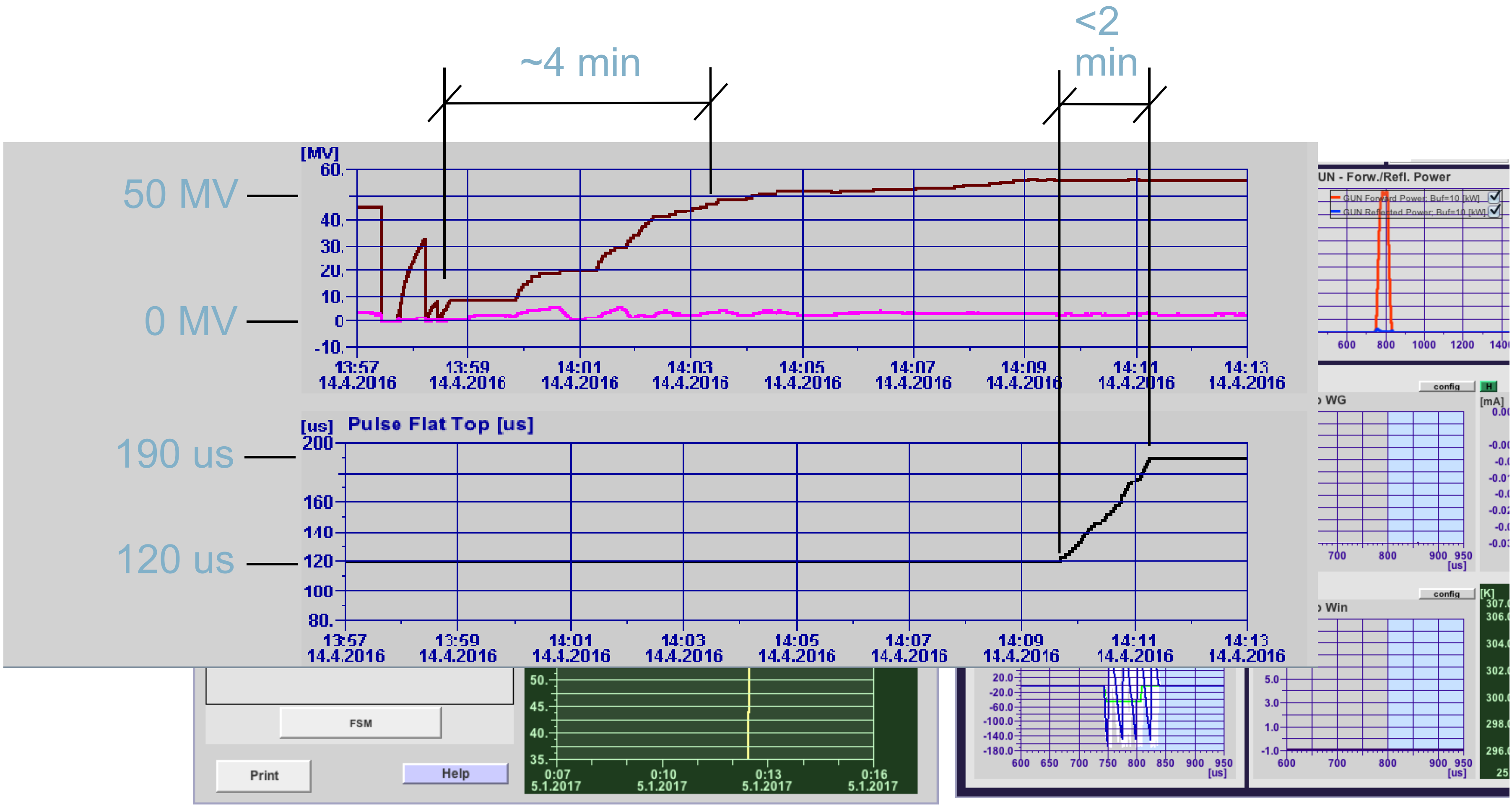


Y. Renier, et. al, Fast Automatic Ramping of High Average Power Guns, IPAC2017, DK

Photo Cathode Laser

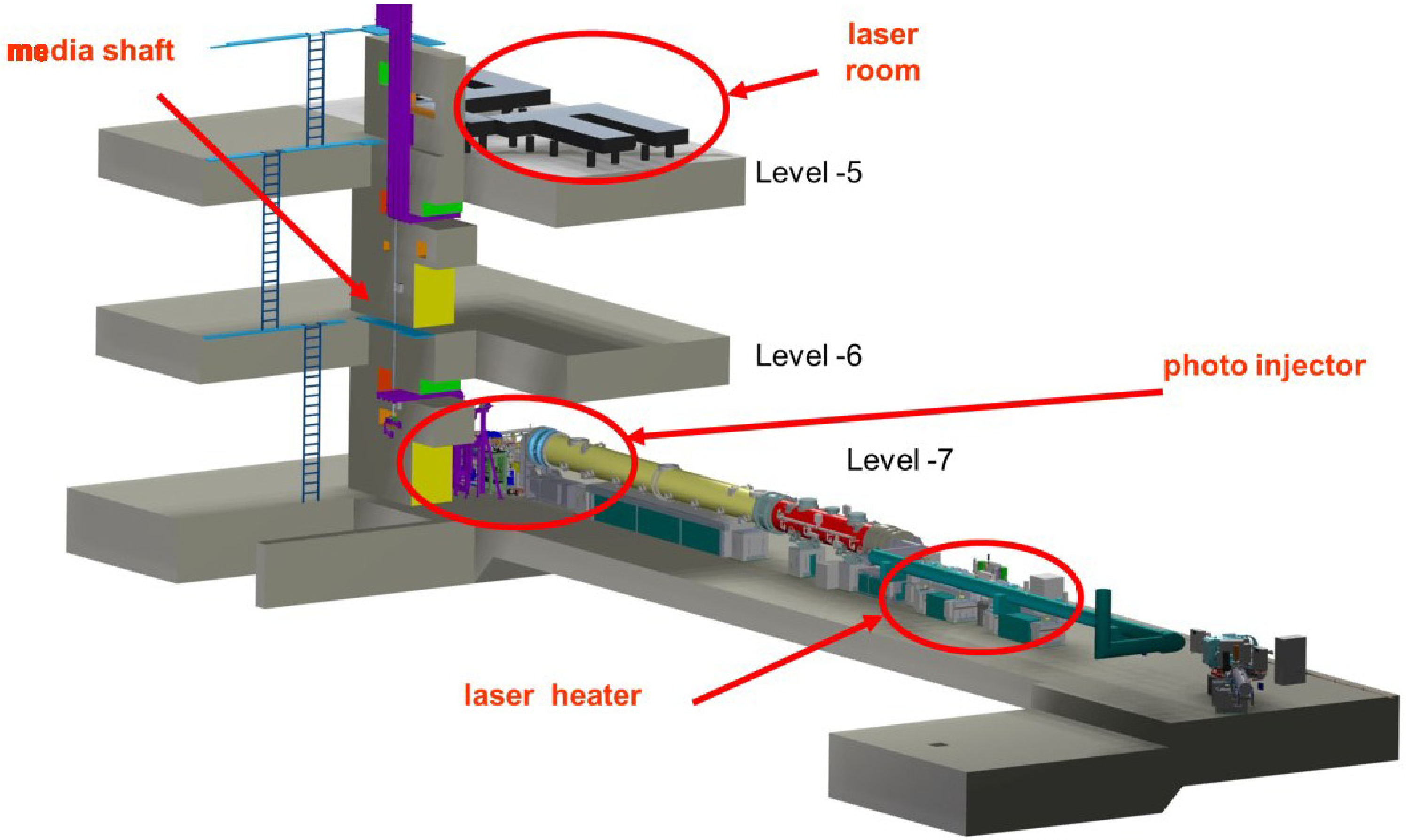
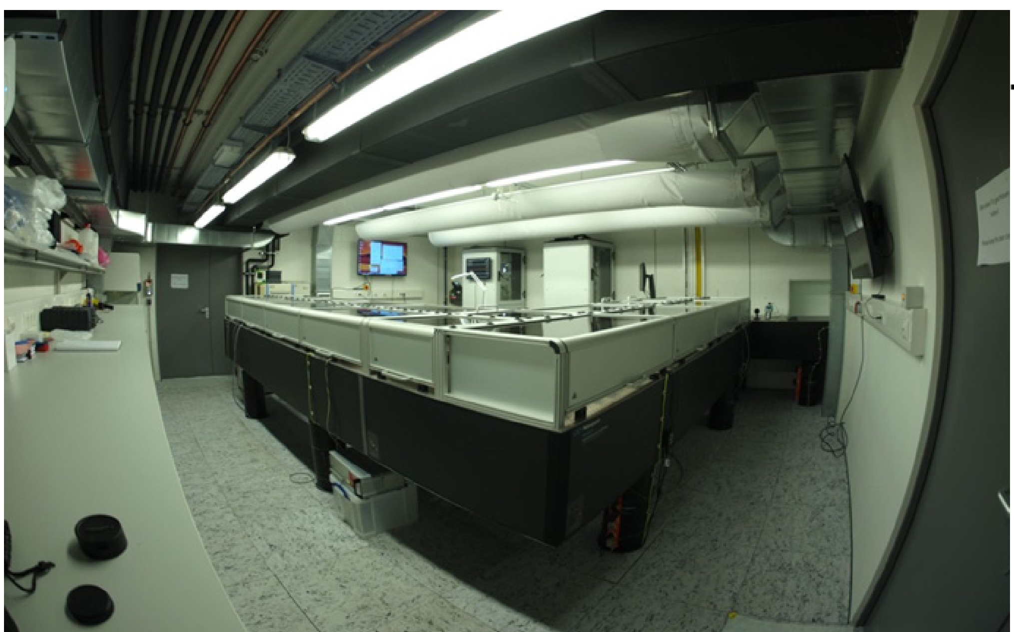
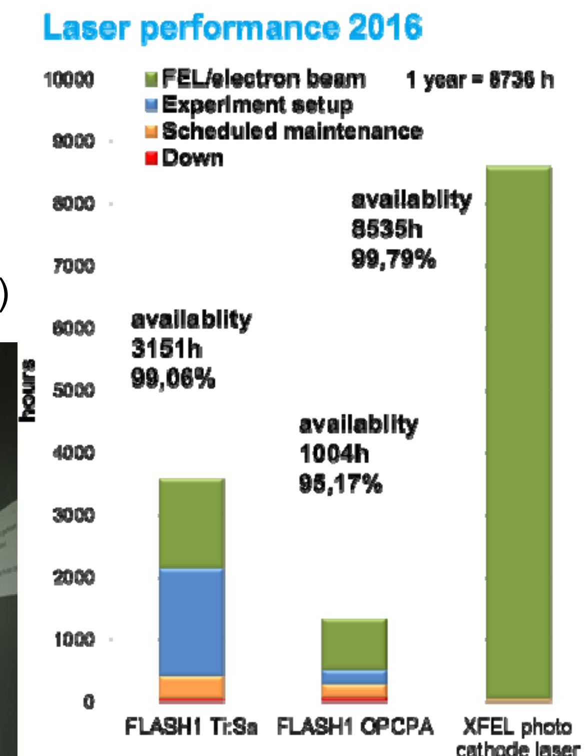


Photo Cathode Laser

- **10 Hz pulse train laser up to 2700 pulses**
- Yb:YAG laser
- 257 nm ≤ 4 μJ
- 1030 nm > 50 μJ
- Profile:
  - Transverse: truncated Gaussian (“Flattop”)
    (variable / e.g. 1.2 mm at 500 pC)
  - Longitudinal: Gaussian or Pulse Stacker
    (most data in this talk are for the Gaussian with 24 ps FWHM)





Injector operation with 2000 bunches, 0.5 nC

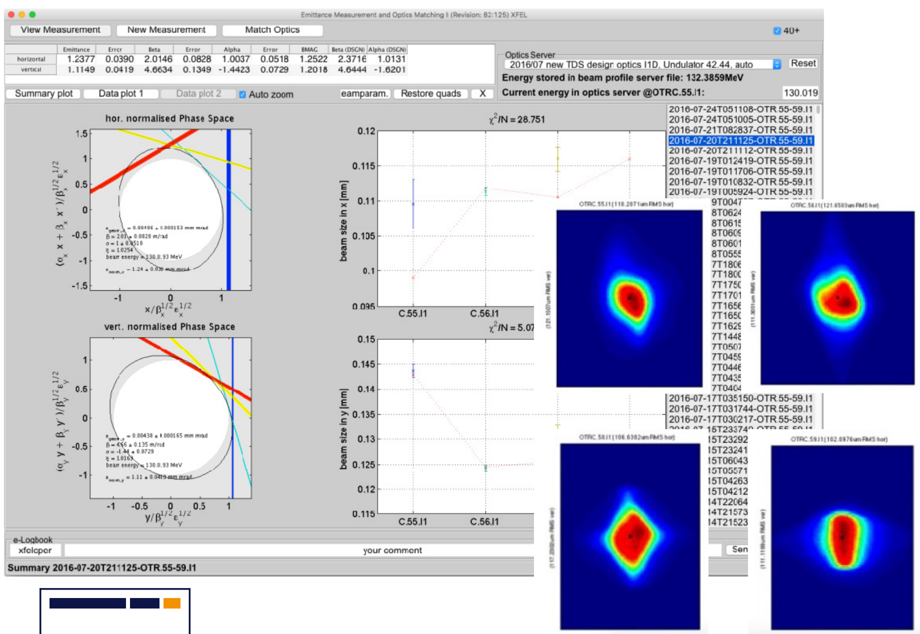
Comparison of TDR and Achieved Parameters

Quantity	TDR	Achieved
Macro pulse repetition rate	10 Hz	10 Hz
RF pulse length (flat top)	650 µs	670 µs
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

On-Axis Projected Emittance Measurements

- Four screens are moved into the beam trajectory and the beam sizes are measured on each screen
  - Screens are moved in and out (blocking beam operation)
  - few minutes per measurement
  - Limited to one bunch operation



Best results at a gun gradient of 53 MV/m

Charge	Horizontal	Vertical
50 pC	0.56±0.01 μm rad	0.64±0.01 μm rad
100 pC	0.77±0.02 μm rad	0.83±0.03 μm rad
500 pC	1.28±0.02 μm rad	1.23±0.03 μm rad
1000 pC	2.95±0.02 μm rad	2.81±0.03 μm rad

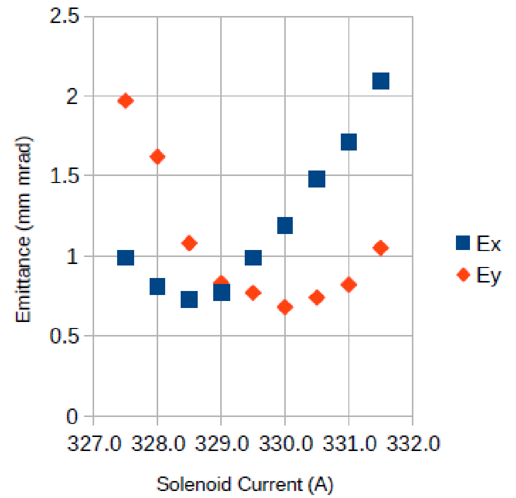
Most of the time was spend to optimize emittances of the 500 pC case.

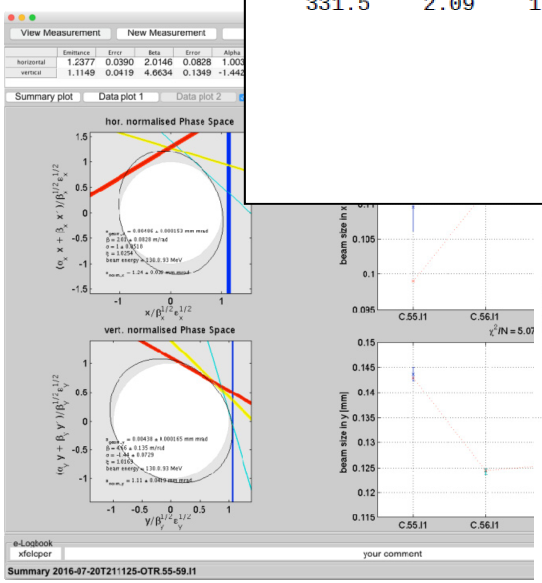
On-Axis Projected Emittance Measurements

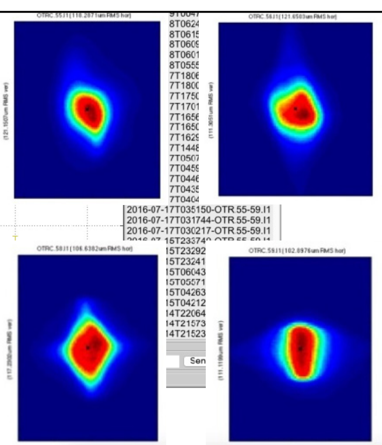
- Fo… he beam siz…
  - S… tion)
  - fe…
  - L…

100 pC, 0.5 mm iris, gun -45 deg f.z.c.

Solenoid current (A)	Ex (mm mrad)	Ey (mm mrad)	BMAGx	BMAGy	sqrt(Ex Ey) (mm mrad)
331.0	1.71	0.82	1.36	1.22	1.18
330.5	1.48	0.74	1.13	1.33	1.05
330.0	1.19	0.68	1.18	1.67	0.90
329.5	0.99	0.77	1.4	1.95	0.87
329.0	0.77	0.83	1.58	1.43	0.80
328.5	0.73	1.08	1.74	1.97	0.89
328.0	0.81	1.62	1.14	1.4	1.15
327.5	0.99	1.97	1.22	1.73	1.40
331.5	2.09	1.05	1.47	1.57	1.48







…radient of 53 MV/m

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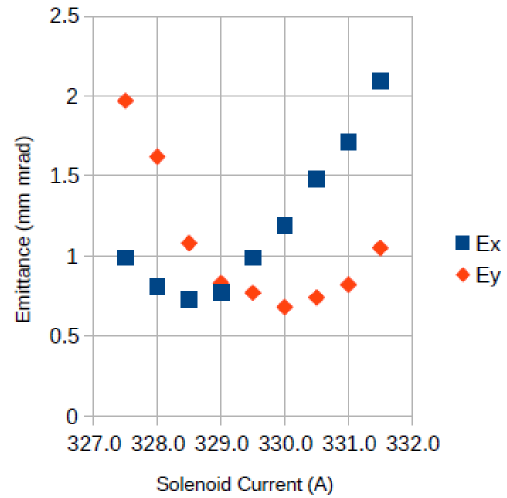

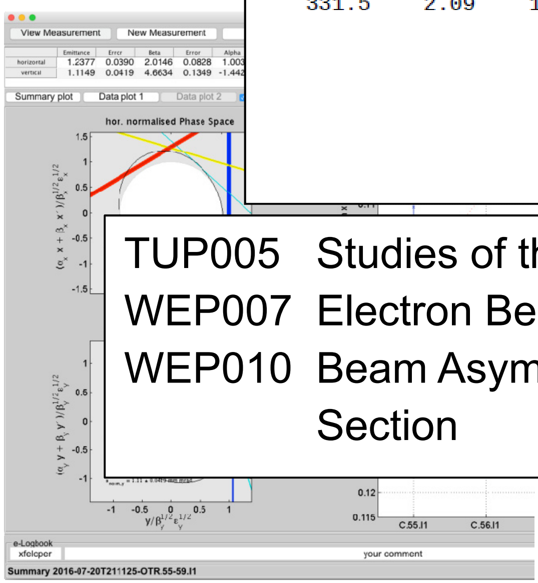

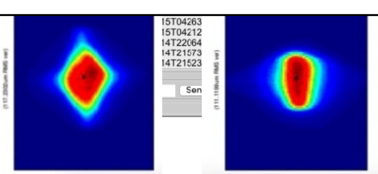

[...]radient of 53 MV/m

	Vertical
	[...]um rad
	[...]um rad
	[...]um rad
	[...]um rad

TUP005 Studies of the Transverse Beam Coupling in the European XFEL Injector
WEP007 Electron Beam Asymmetry Compensation with Gun Quadrupoles at PITZ
WEP010 Beam Asymmetry Studies with Quadrupole Field Errors in the PITZ Gun Section

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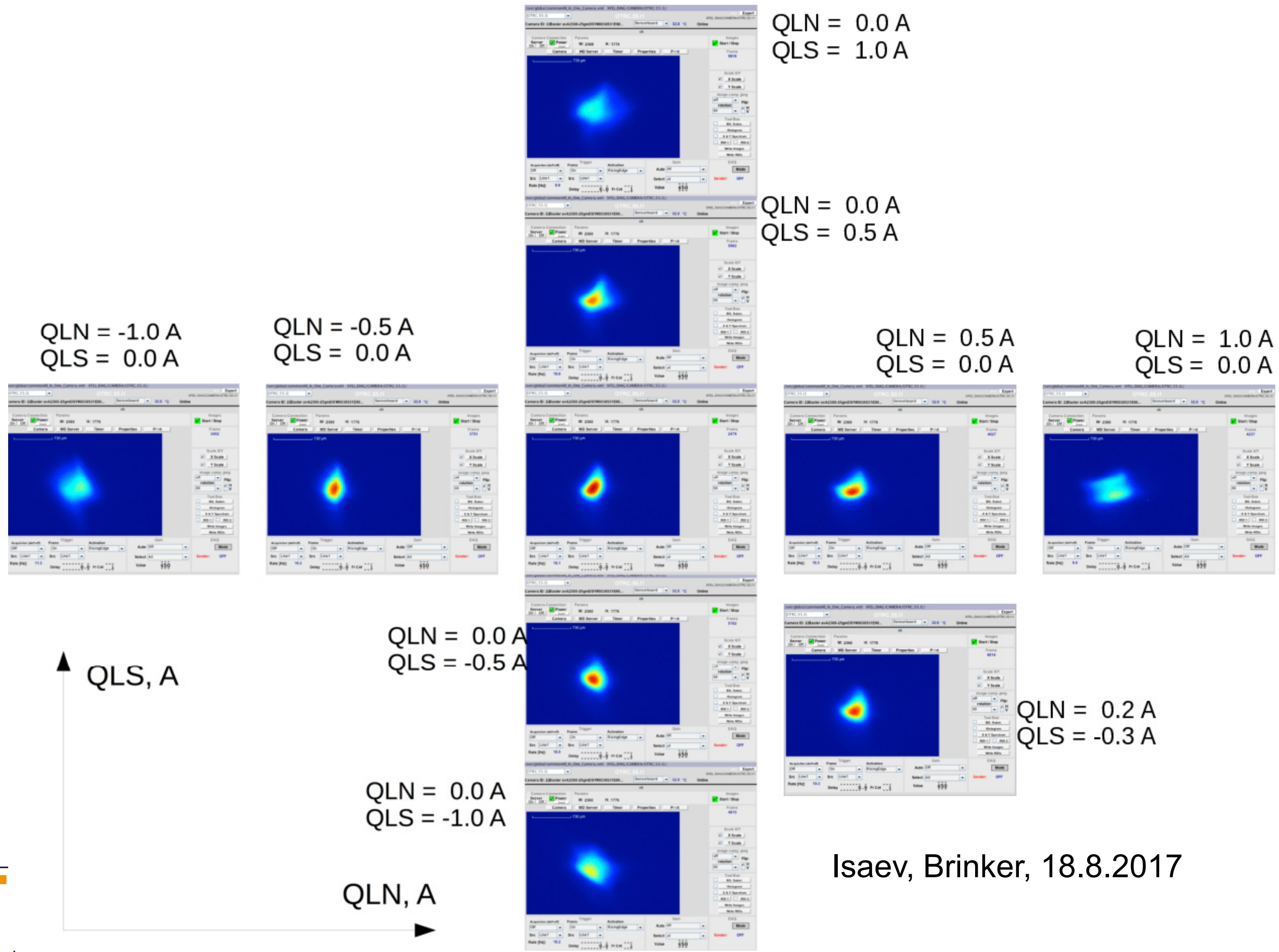
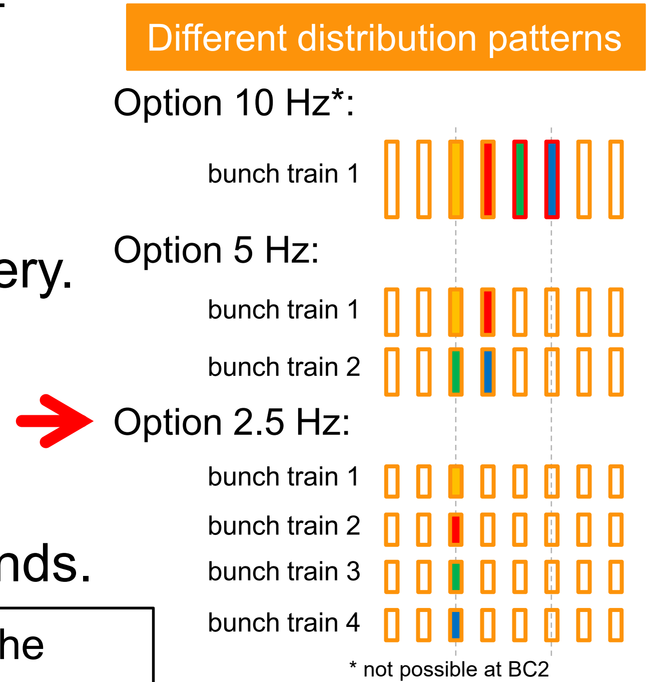
First Gun Corrector Quadrupole Studies in Hamburg

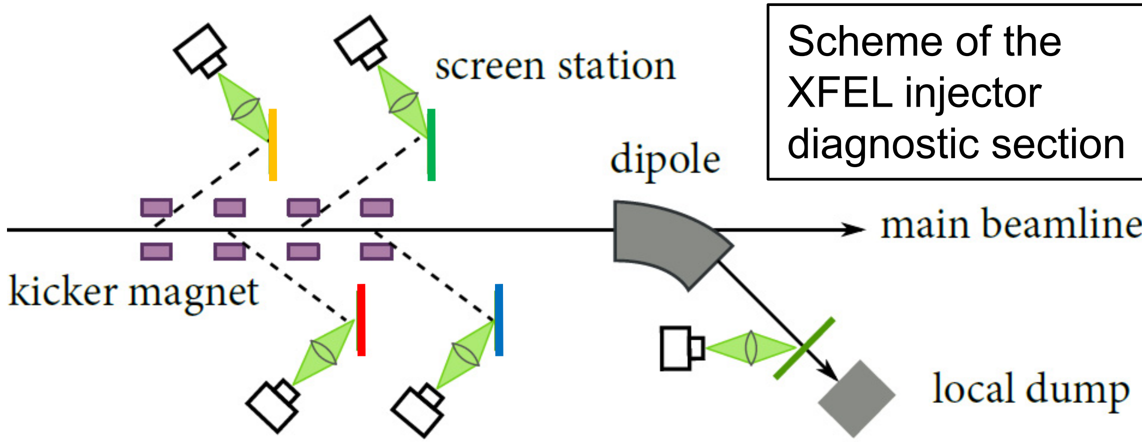


Isaev, Brinker, 18.8.2017

Four-Screen Method with Off-Axis Screens

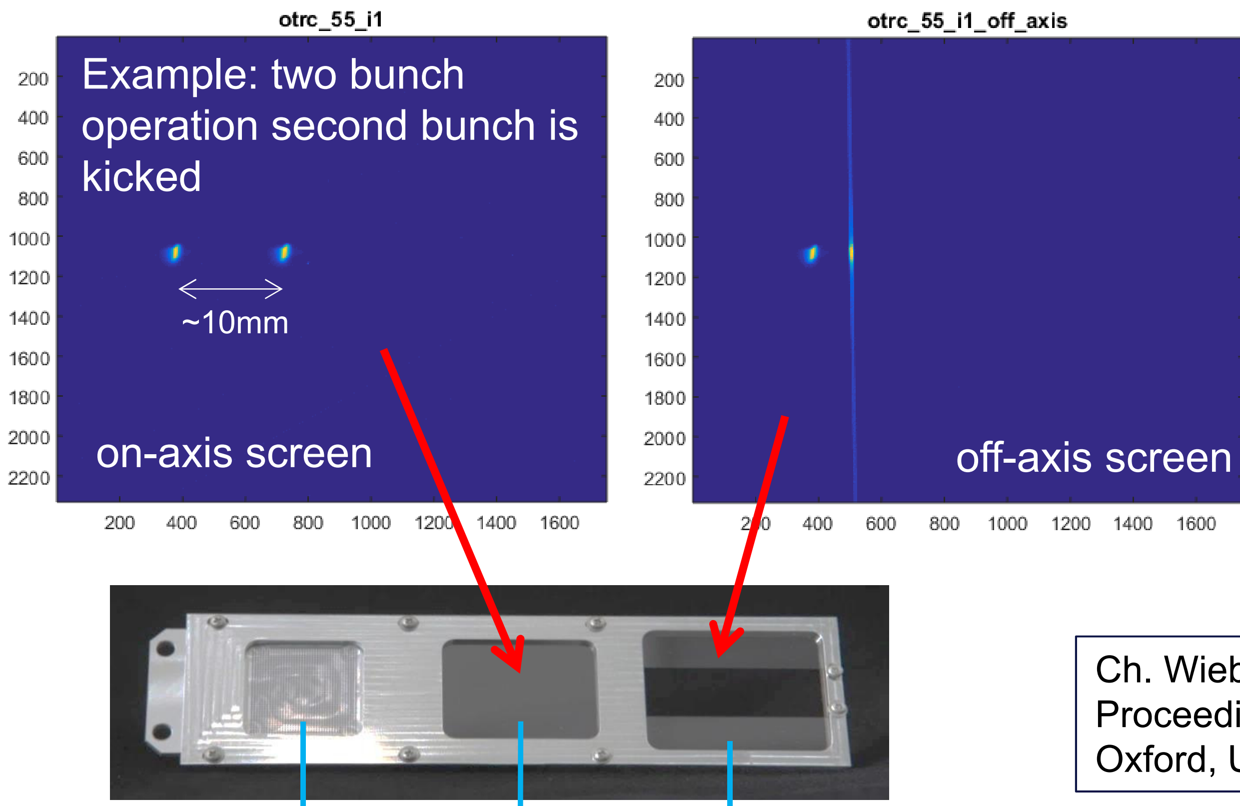
- Fast kickers allow to kick single bunches out of the trains to the screens while those are in off-set position.
- “Semi-parasitic” diagnostics during beam delivery.
- It is not necessary to move the screens in and out.
- These measurements take only about 10 seconds.





Scheme of the XFEL injector diagnostic section

Off-Axis Screen Configuration



Ch. Wiebers et al.
Proceedings of IBIC2013, Oxford, UK

2 half 200µm thick LYSO screens (off-axis)

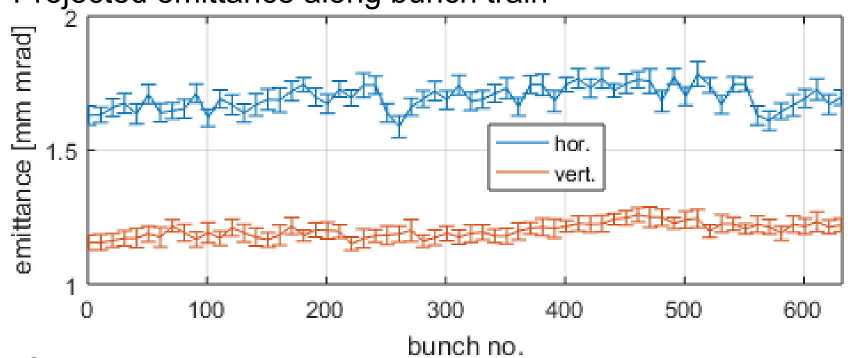
200µm thick LYSO screen (on-axis)

dot grid target(spot Ø .50mm)

Emittance measurements along bunch trains

- Kicker timing can be set to investigate any bunch of the train
- Phase space measurement along the bunch train and thus intra-train beam dynamics studies are possible

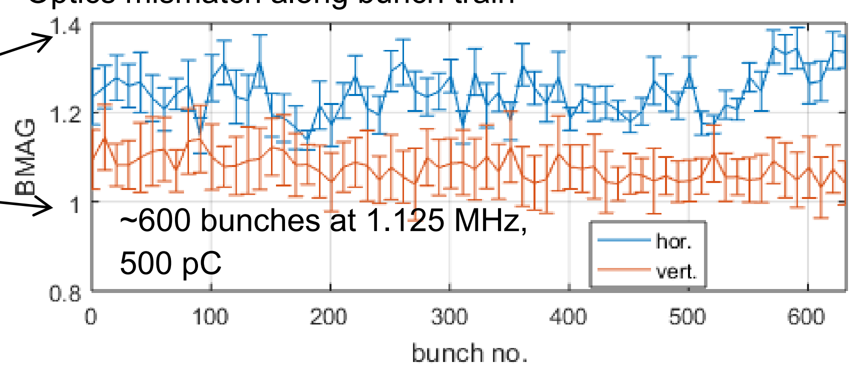
Projected emittance along bunch train



Optics mismatch along bunch train

Up to a factor 1.4 with respect to design beta functions

Matched to design optics



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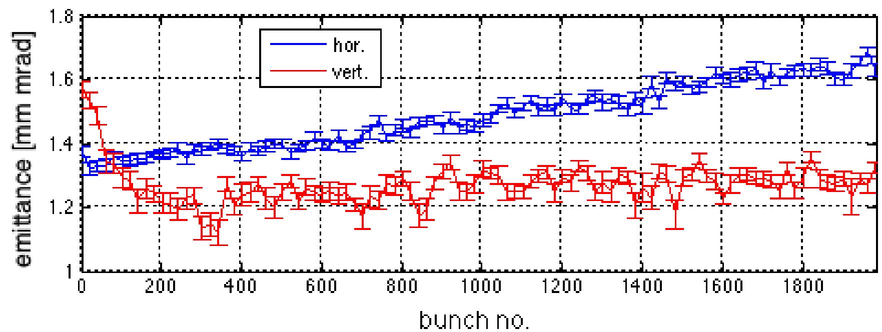

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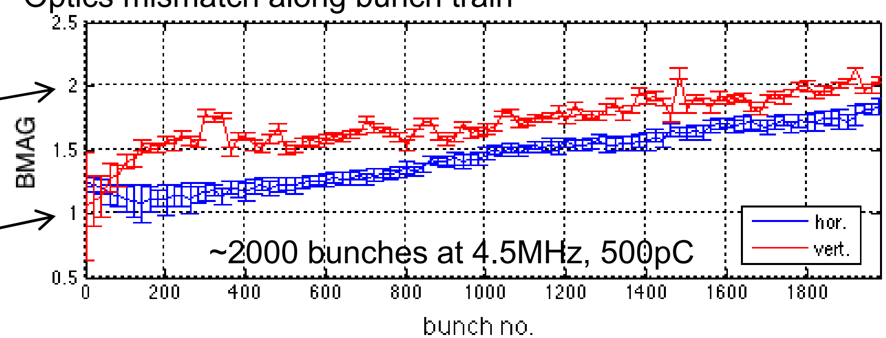

Up to a factor 2 with respect to design beta functions

Matched to design optics

Emittance measurements along bunch trains

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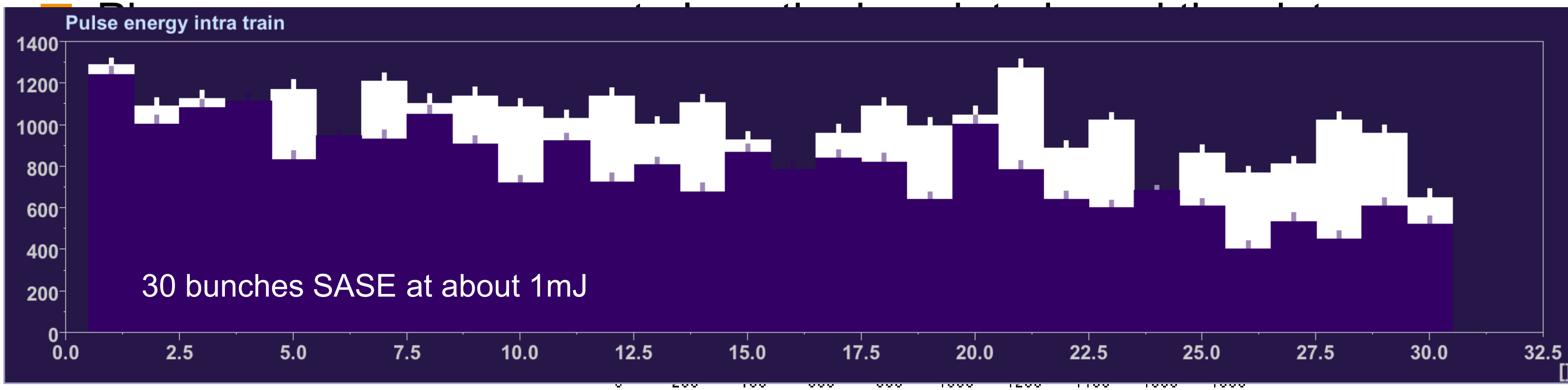

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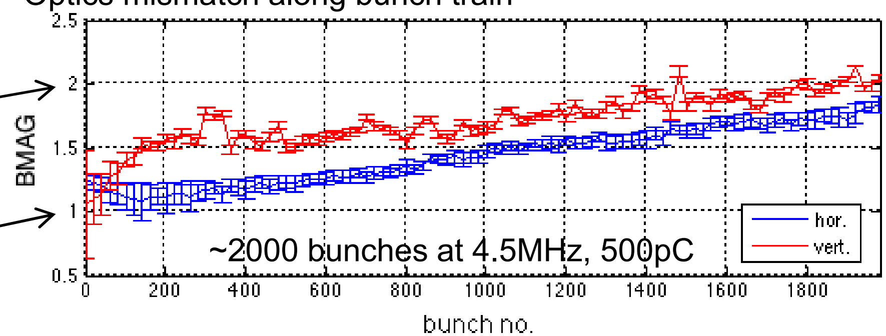
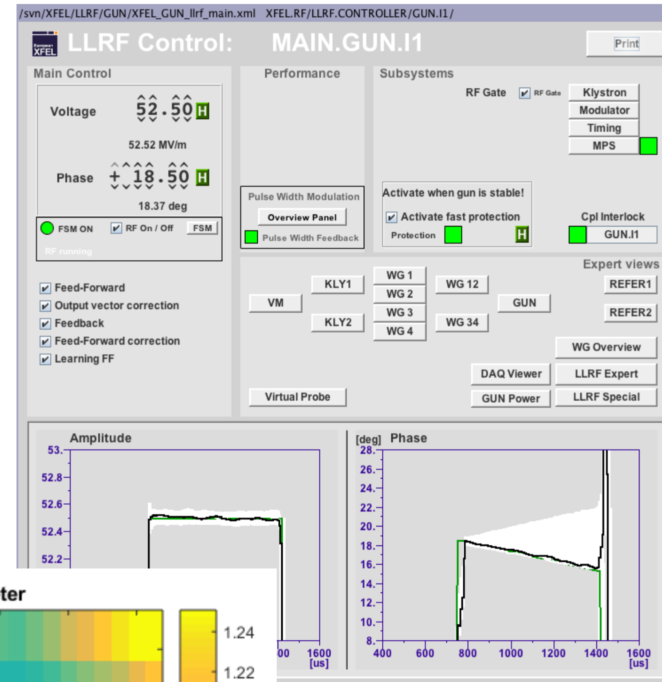
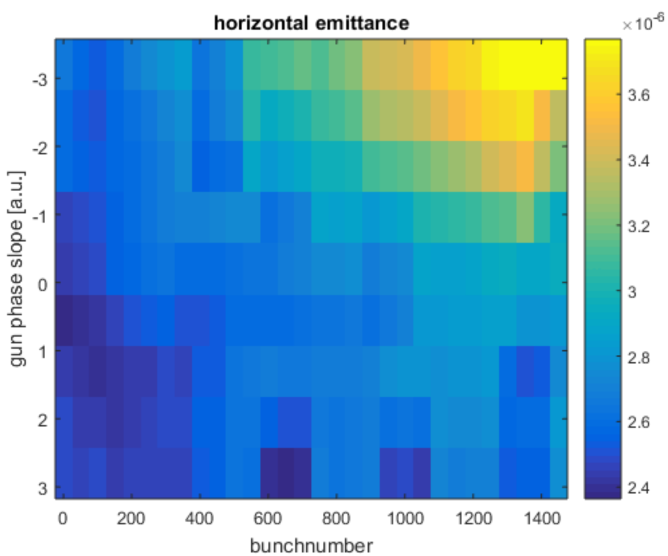
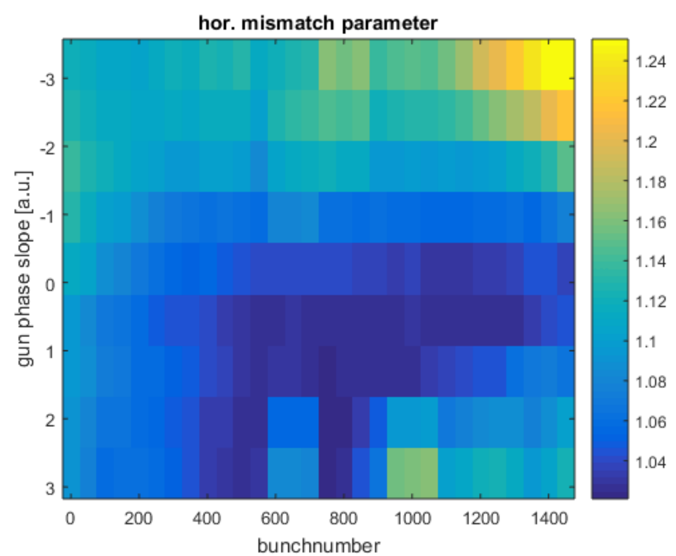


SASE Variations along the Bunch Train

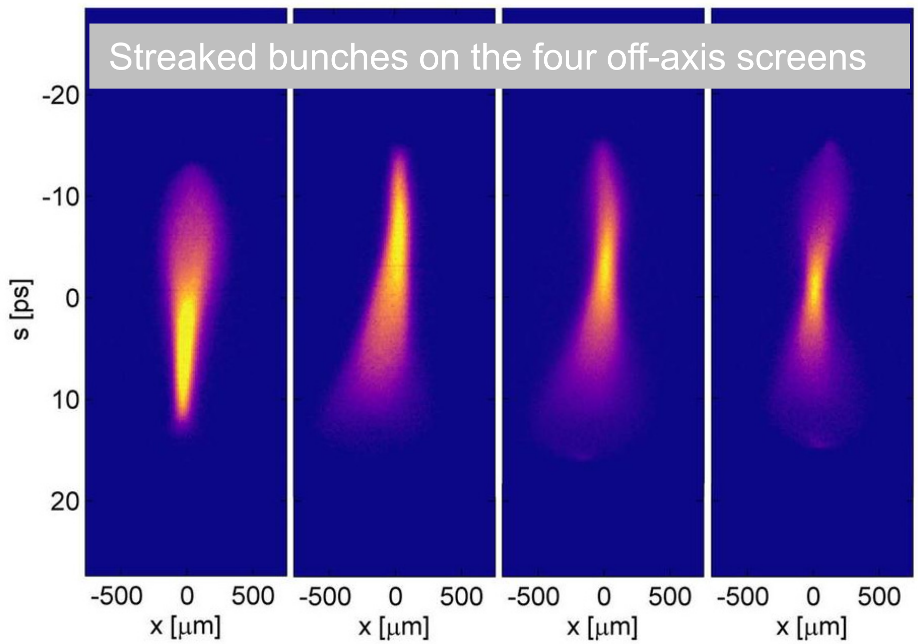
- Intra-train variations probably caused by Laser or Gun RF
- Beam parameters along the train can be modified by applying an phase- or gradient slope on the gun LLRF



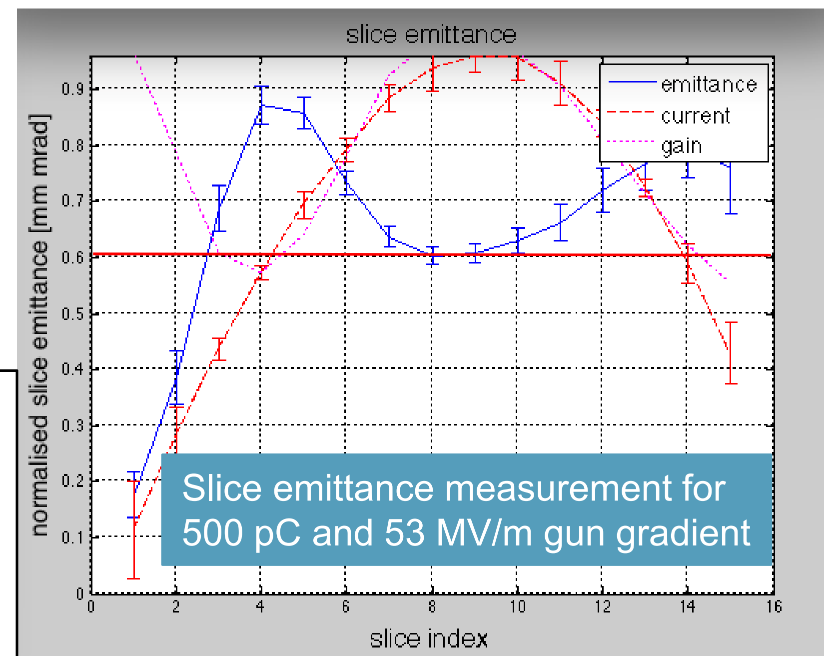




Slice Emittance Measurements

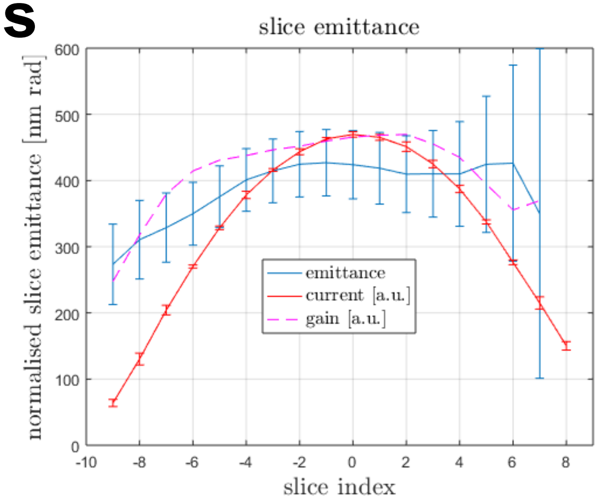


We are able to match single slices of the bunch. One matching iteration takes about 2 minutes including the magnet cycling.



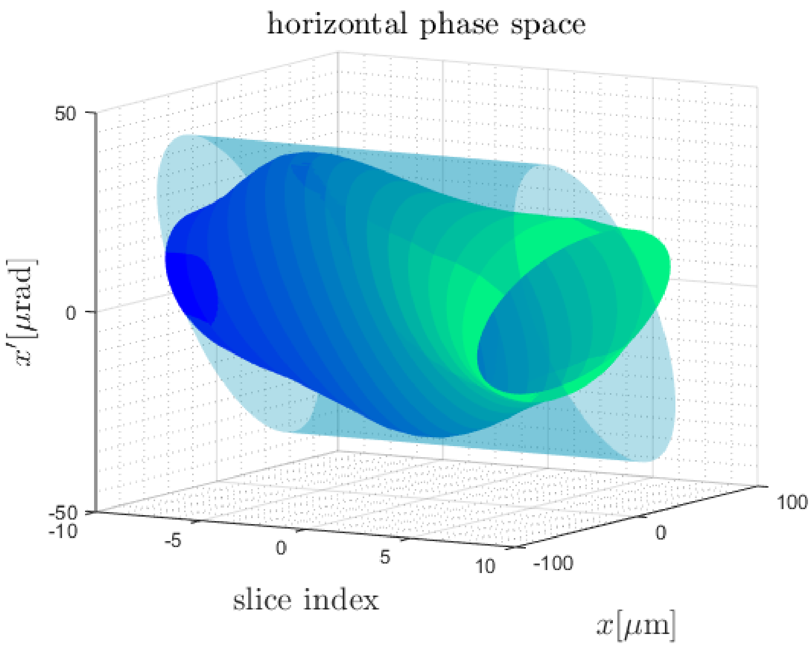
The smallest slice emittances achieved so far (four-screen method):
0.6 μm rad with 53 MV/m gun gradient (500 pC)
0.5 μm rad with 60 MV/m gun gradient (500 pC)
0.4 μm rad with 60 MV/m gun gradient (400 pC)

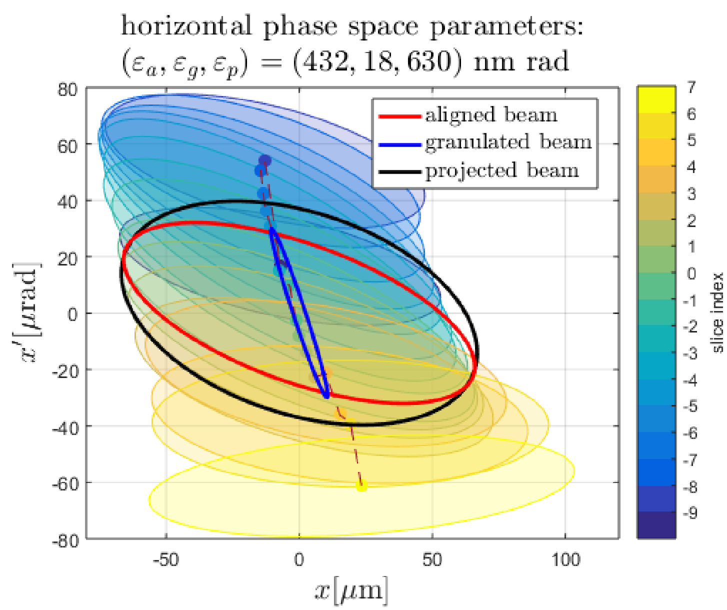
Slice Emittance Phase Space Analysis



- Data from Slice emittance can be used to study projected phase space

Example: 200 pC at 60 MV/m gun voltage

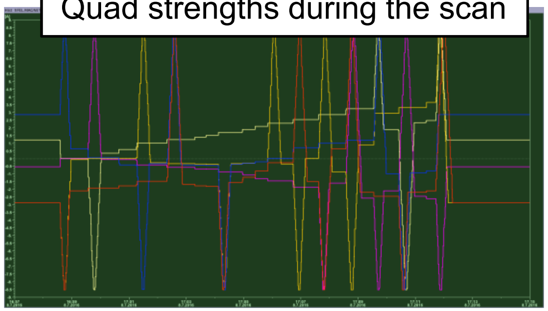




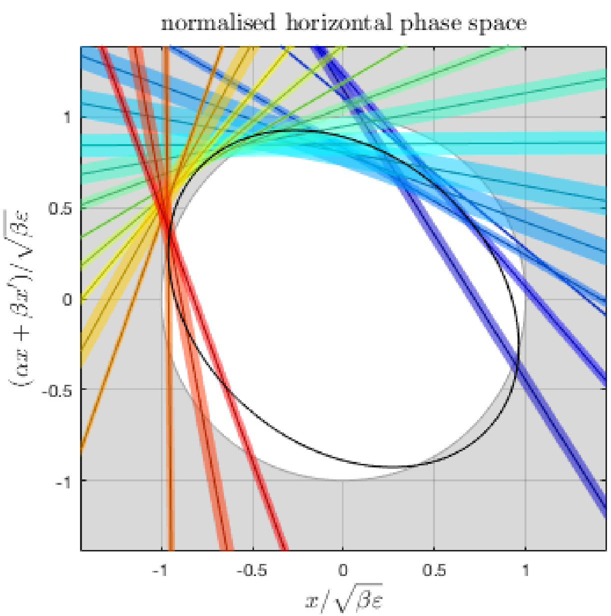
V. Balandin, private communication
C. Mitchell, “A General Slice Moment Decomposition of RMS Beam Emittance“, arXiv:1509.04765v1[physics.acc-ph], 2015.

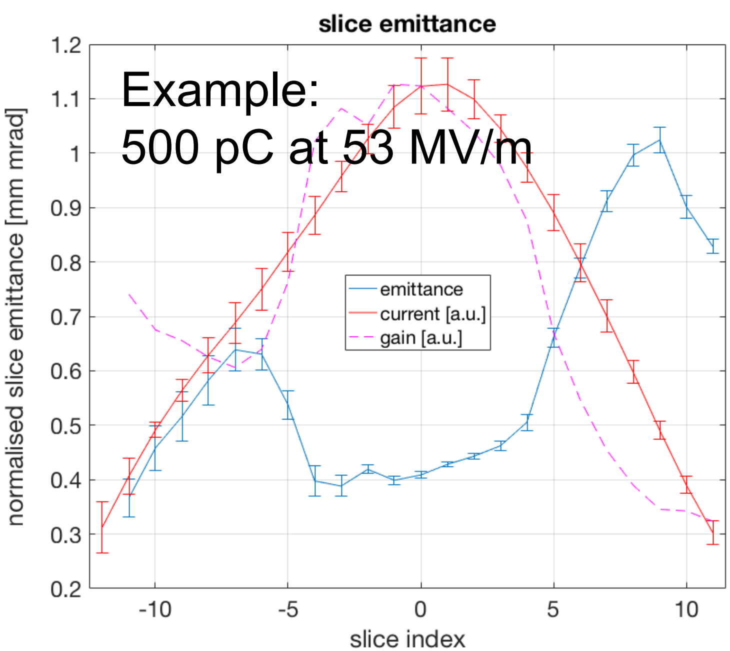
Emittance Calculations using Multi Knob Quadrupole Scans

- Multiple-quads scans are used for “high-resolution” measurements of slice and projected emittance
  - optimised spot sizes on the screen
  - Arbitrary number of data points
  - Longitudinal resolution is improved compared to multi-screen



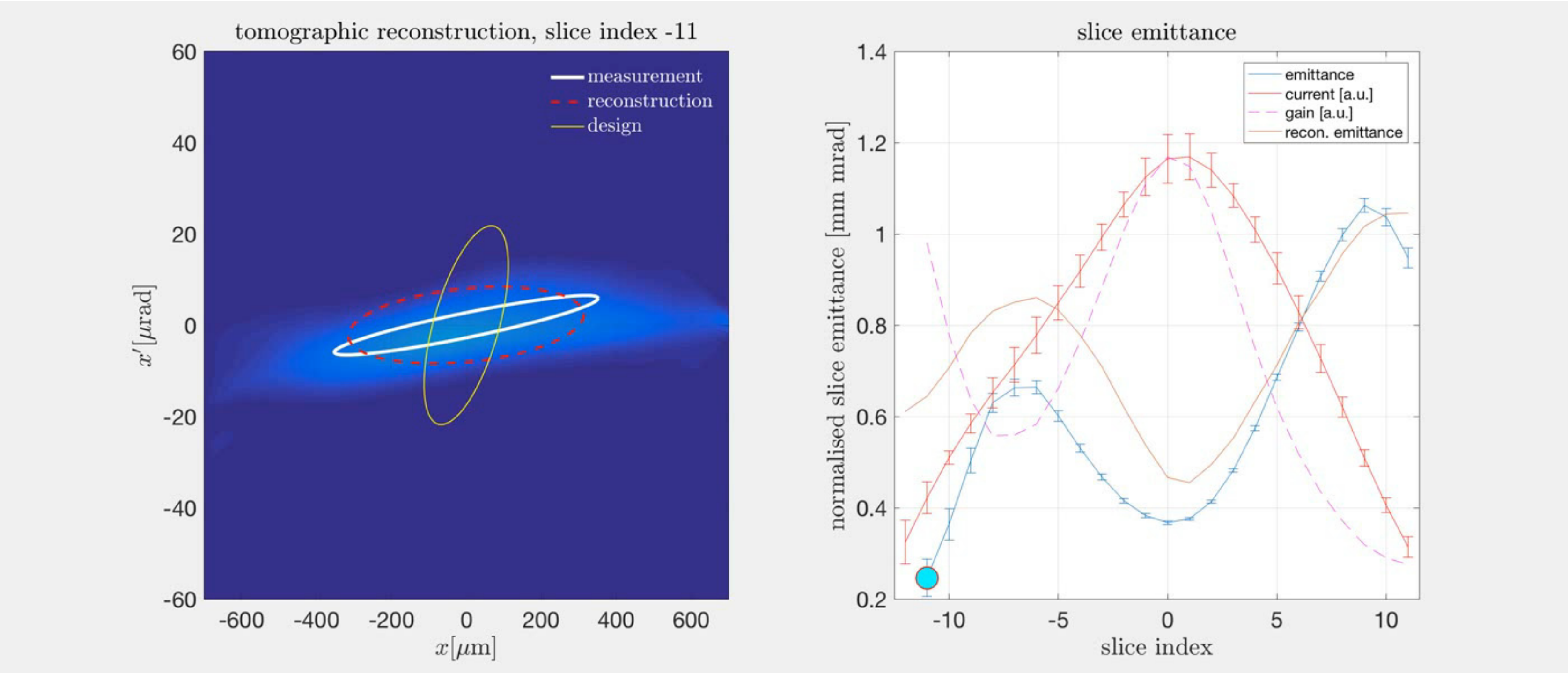
Quad strengths during the scan





Phase Space Tomography – Slice resolved

- Tomographic phase-space reconstruction allows for detailed studies on beam dynamics (MENT algorithm to be usable with limited number of data)
- Enables detailed beam dynamics studies



M. Scholz, B. Beutner, Electron Beam Phase Space Tomography at the European XFEL Injector, IPAC 17

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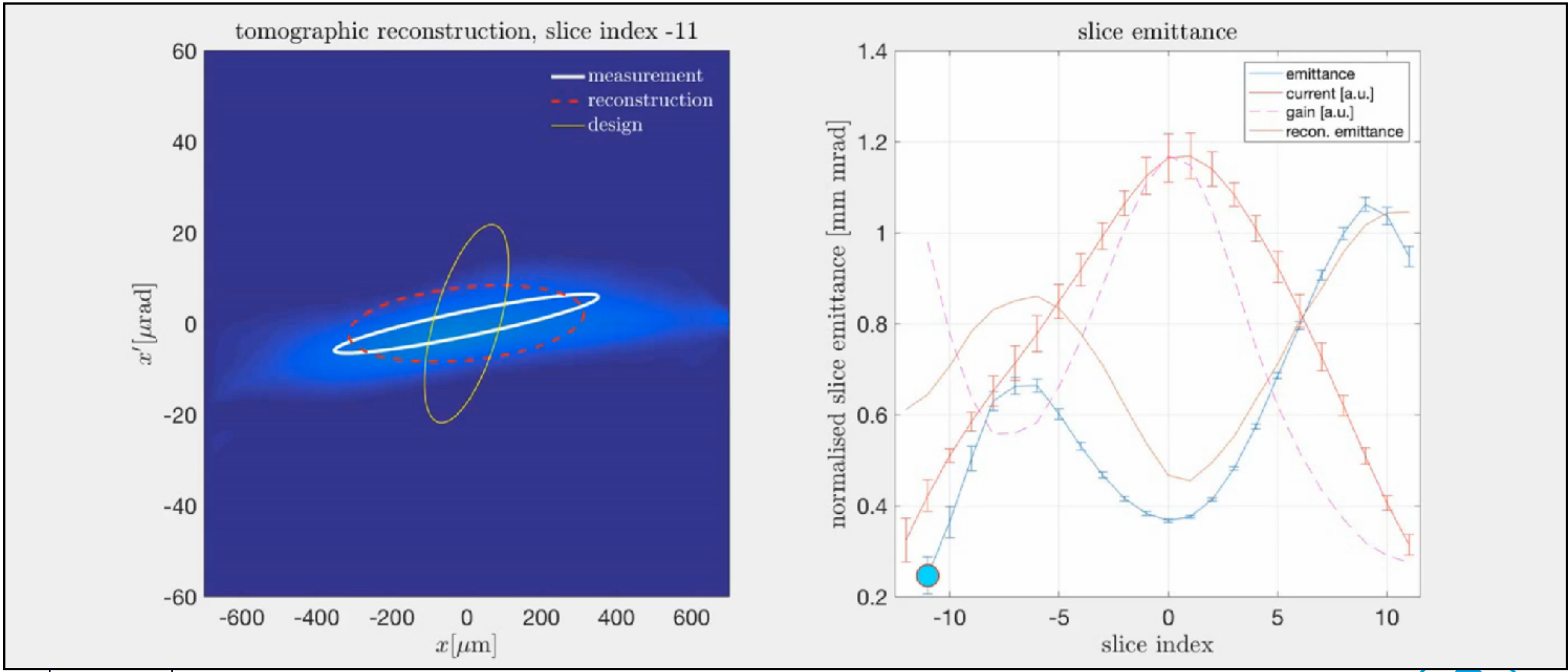
Click into graphic to start movie

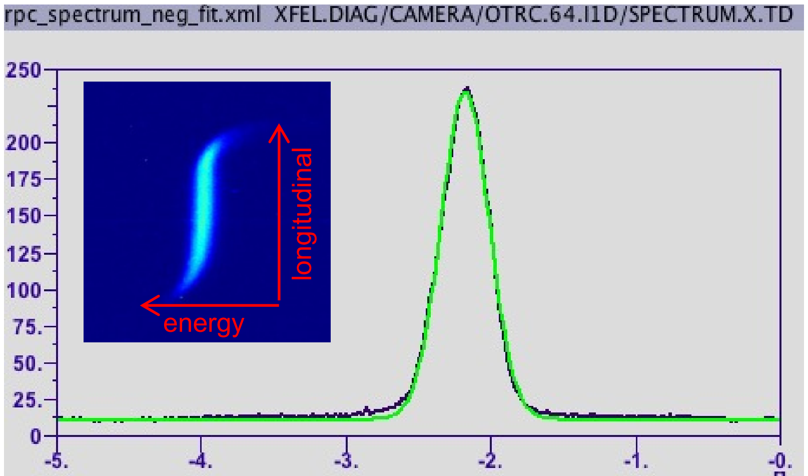


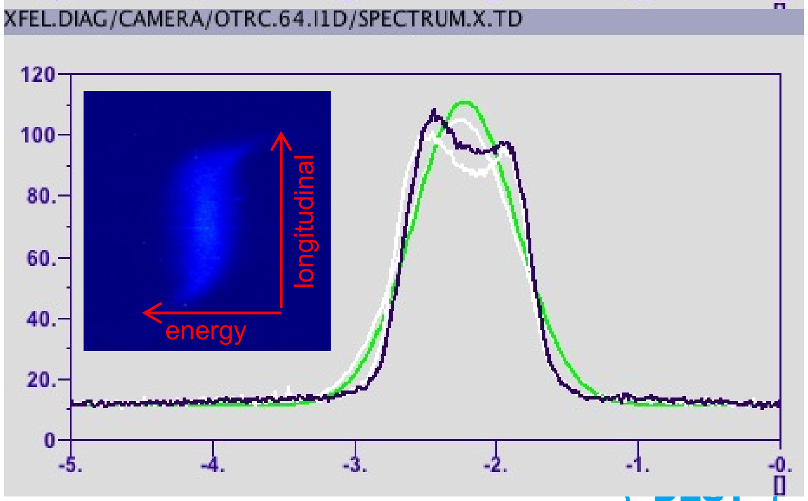
M. Scholz, B. Beutner, Electron Beam Phase Space Tomography at the European XFEL Injector, IPAC 17

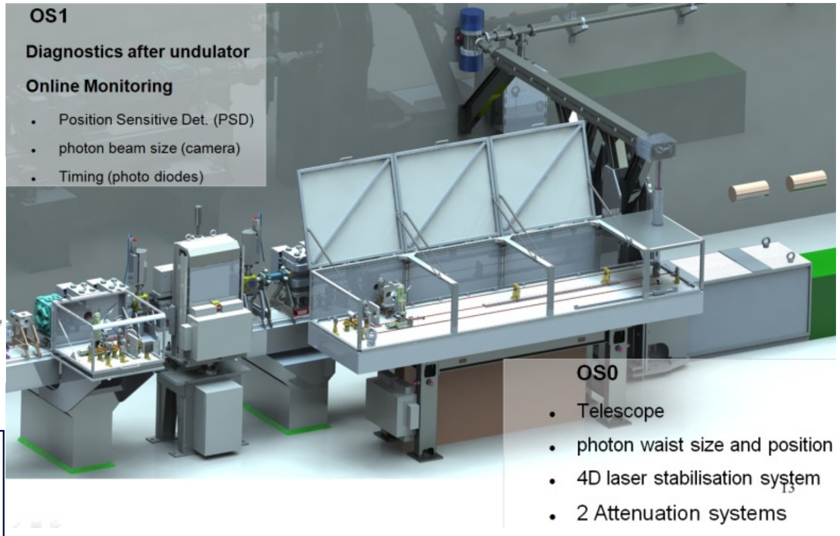
Laser Heater

WEP018 Electron Beam Heating with the European XFEL Laser Heater

- Parameters:
  - Pulse Energy: up to about 200 µJ
  - Undulator Period: 7.4 cm
  - Laser Wavelength: 1030 nm
- Heating with 35 µJ Laser energy:
  ~11 keV -> ~35 keV







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Laser Hea

- Parametei
  - Pulse Er
  - Undulatc
  - Laser W
- Heating w
  ~11 keV ->

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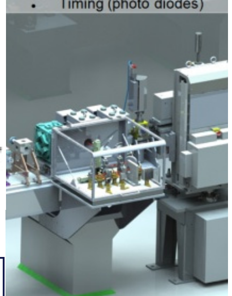
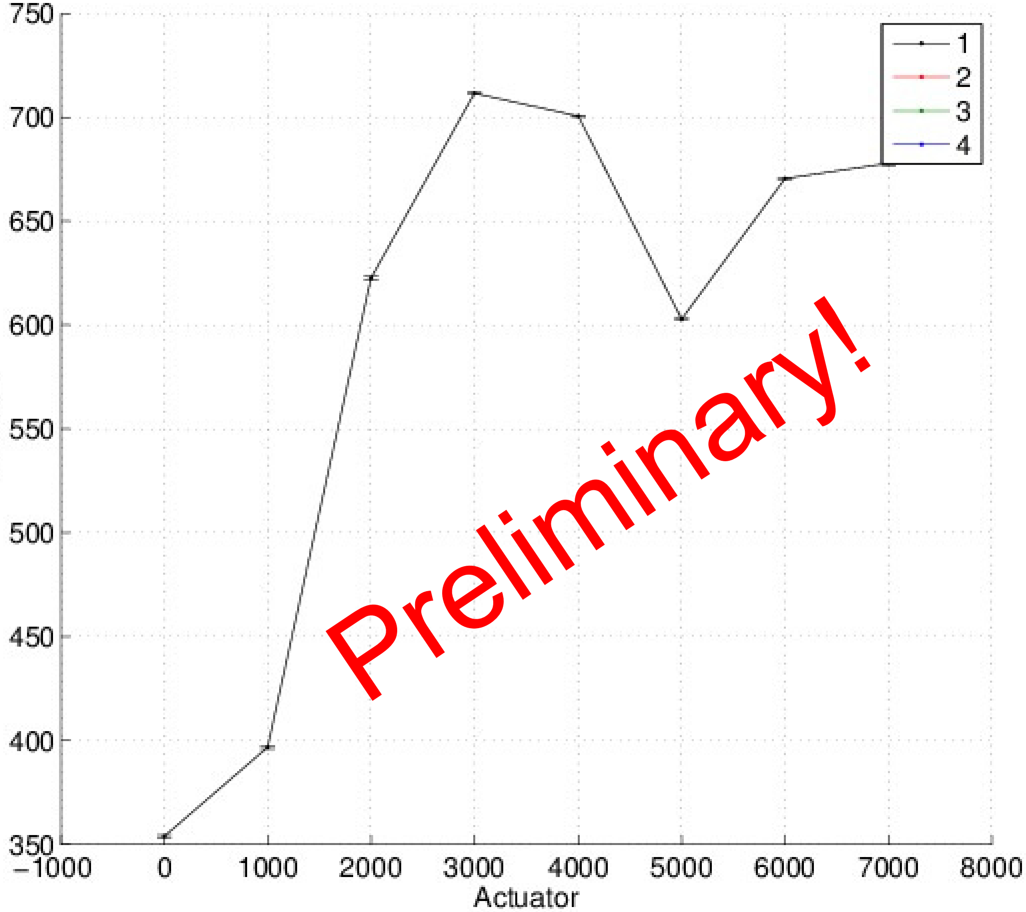
OS1

Diagnostics after undula

Online Monitoring

- Position Sensitive Det. (P
- photon beam size (camer
- Timing (photo diodes)





scan laser intensity, E=130MeV, 0.5nC, gap = 42.4mm

File: /home/xfeloper/data/scantool/2017–08–07T185620.mat

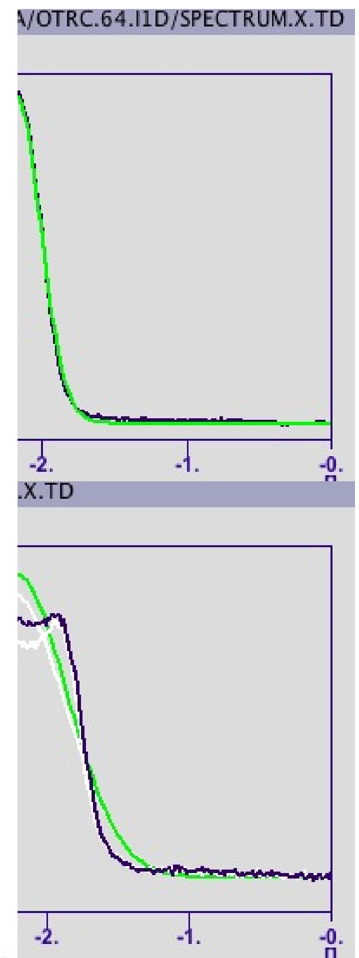
Duration: 2017–08–07 18:56:52 – 19:01:19

Samples/point: 30

Scan from: Scan Tool version 2017–02–08

Actuator: XFEL.UTIL/LASERHEATER.MOTOR/LAMBDA2.LHOS0/POS.SET

Sensor 1: XFEL.FEL/XGM.PHOTONFLUX/XGM.2643.T9/PHOTONFLUX.UJ.DISPLAY



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Thank You for Your Attention!

and special thanks to all colleagues contributing to the European XFEL