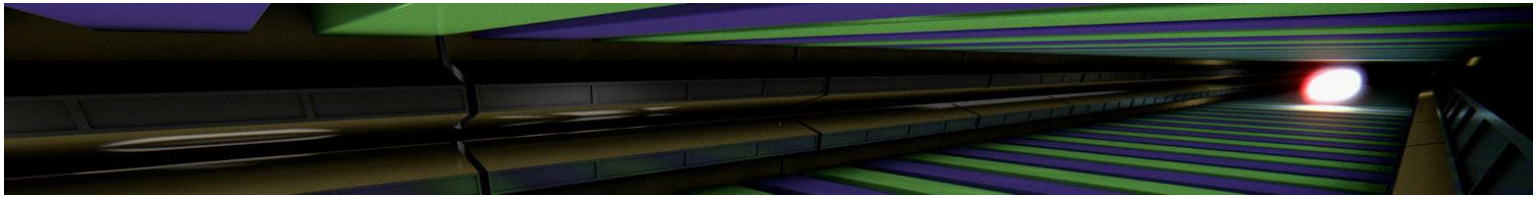


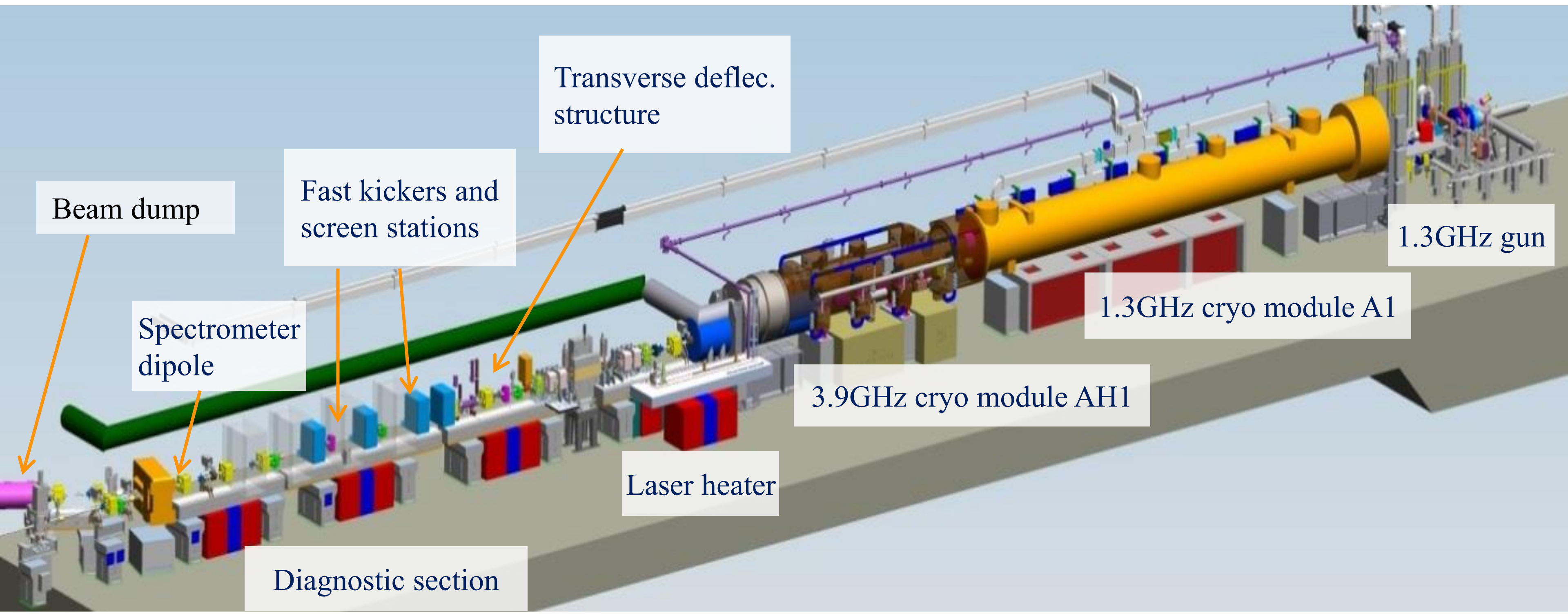
Commissioning of the European XFEL Injector

Frank Brinker, DESY

for the commissioning team

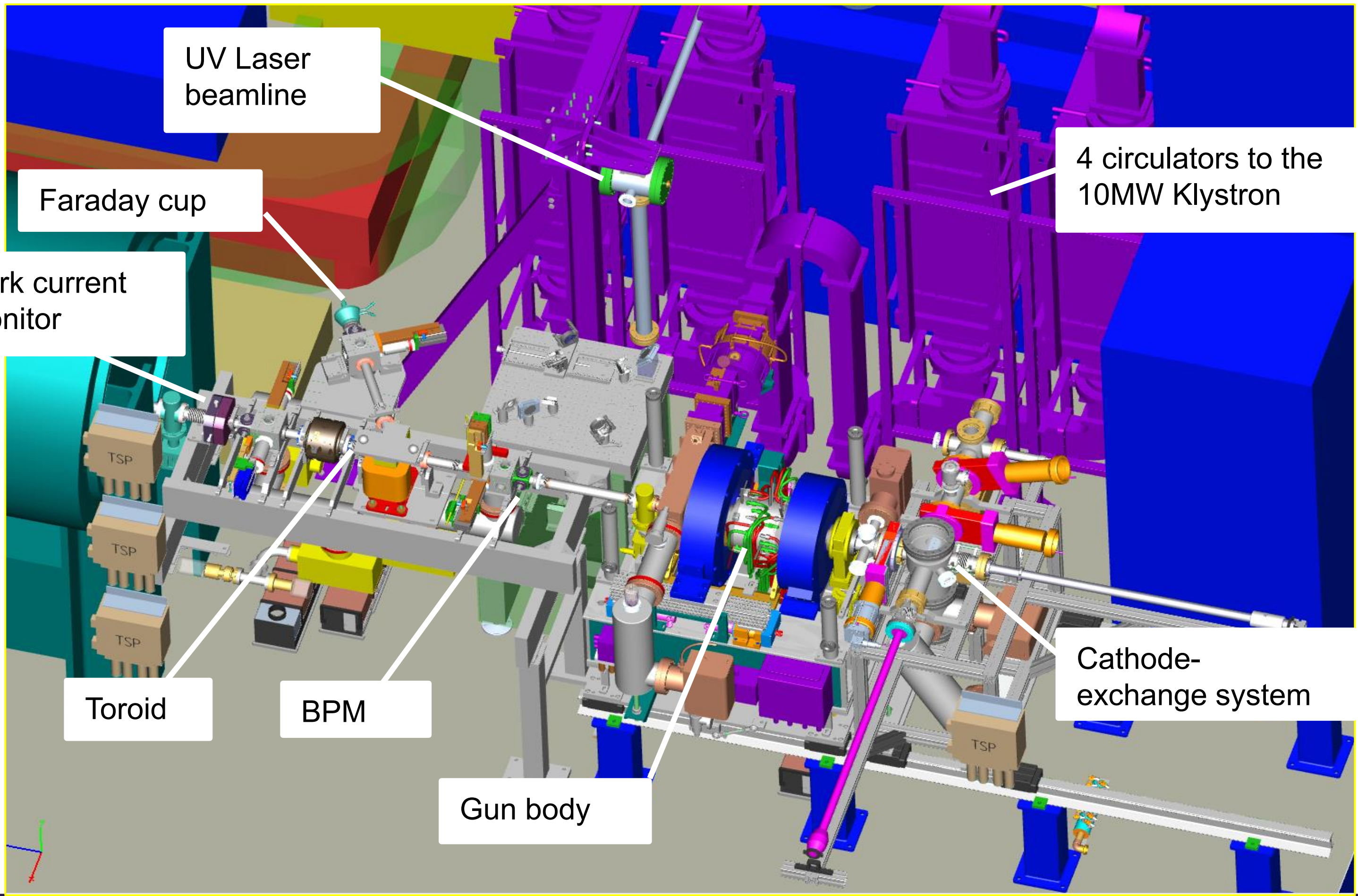
The European XFEL Facility

View into the injector tunnel



Stepwise commissioning during installation

In order to gain valuable experiences with the different systems at an early stage the commissioning started already end of 2013 with the gun.

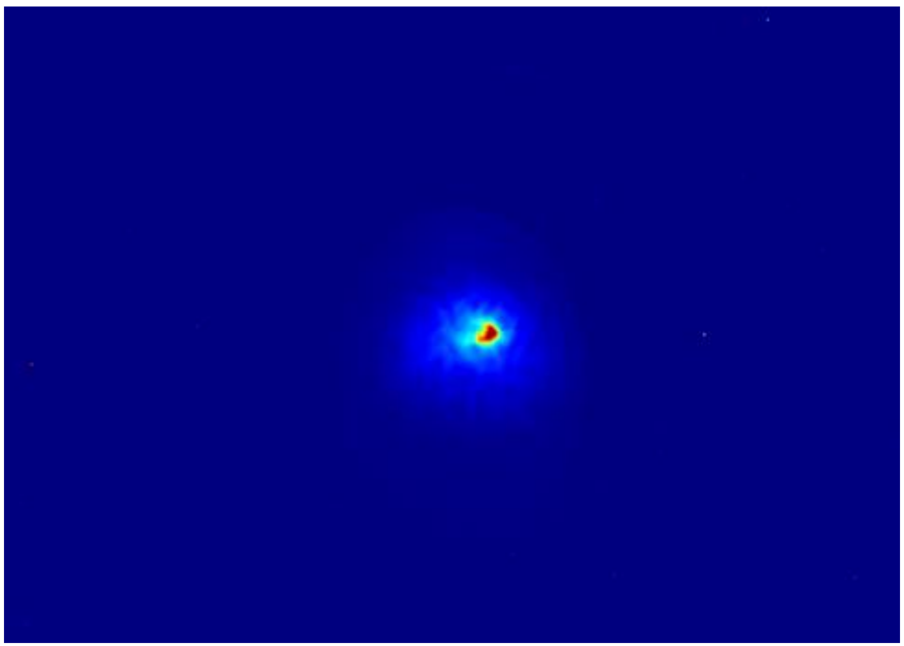


European XFEL

First photo electrons

After RF operation of the gun in Dec 2013 and Sept. 2014 the UV-laser installation was finished beginning 2015 :

February 10th 2015 First photo electrons from the XFEL Gun!:



Screen picture of the first photo electrons at XFEL – 3mm Aperture, 20 Bunche, 10 Hz, ca. 2nC

1.3 GHz, 1.5 cells

$Q_0 \cong 20000$

Gradient on cathode: 50 – 60 MV/m

650 μs pulse length , 10 Hz rep. rate

Max. average RF Power: 42 kW

Emittance (1nC) : < 0.9 mm mrad

Cs_2Te Cathode

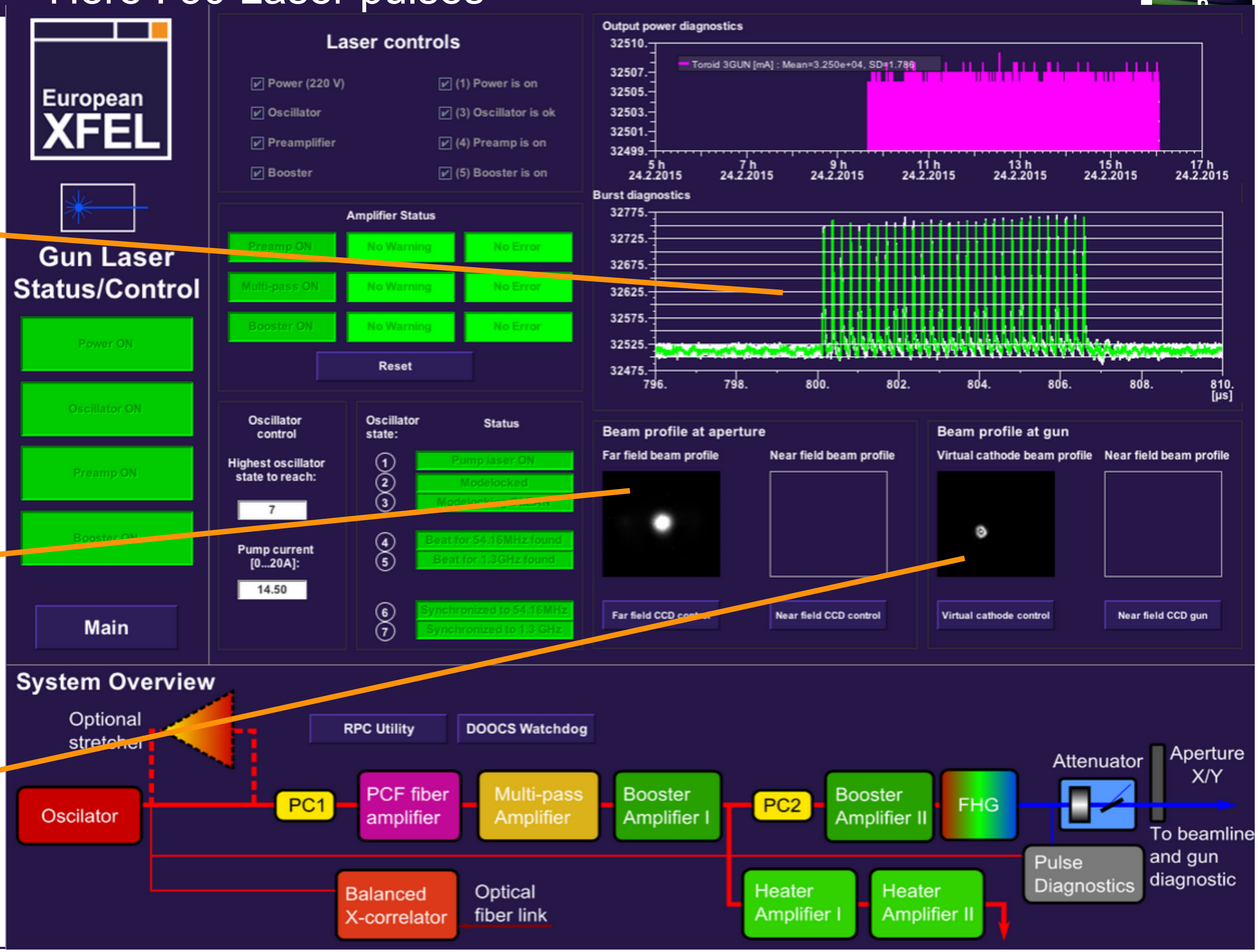
Operations panel of the laser system (MBI, Berlin)

Here : 30 Laser pulses

Pulse energy

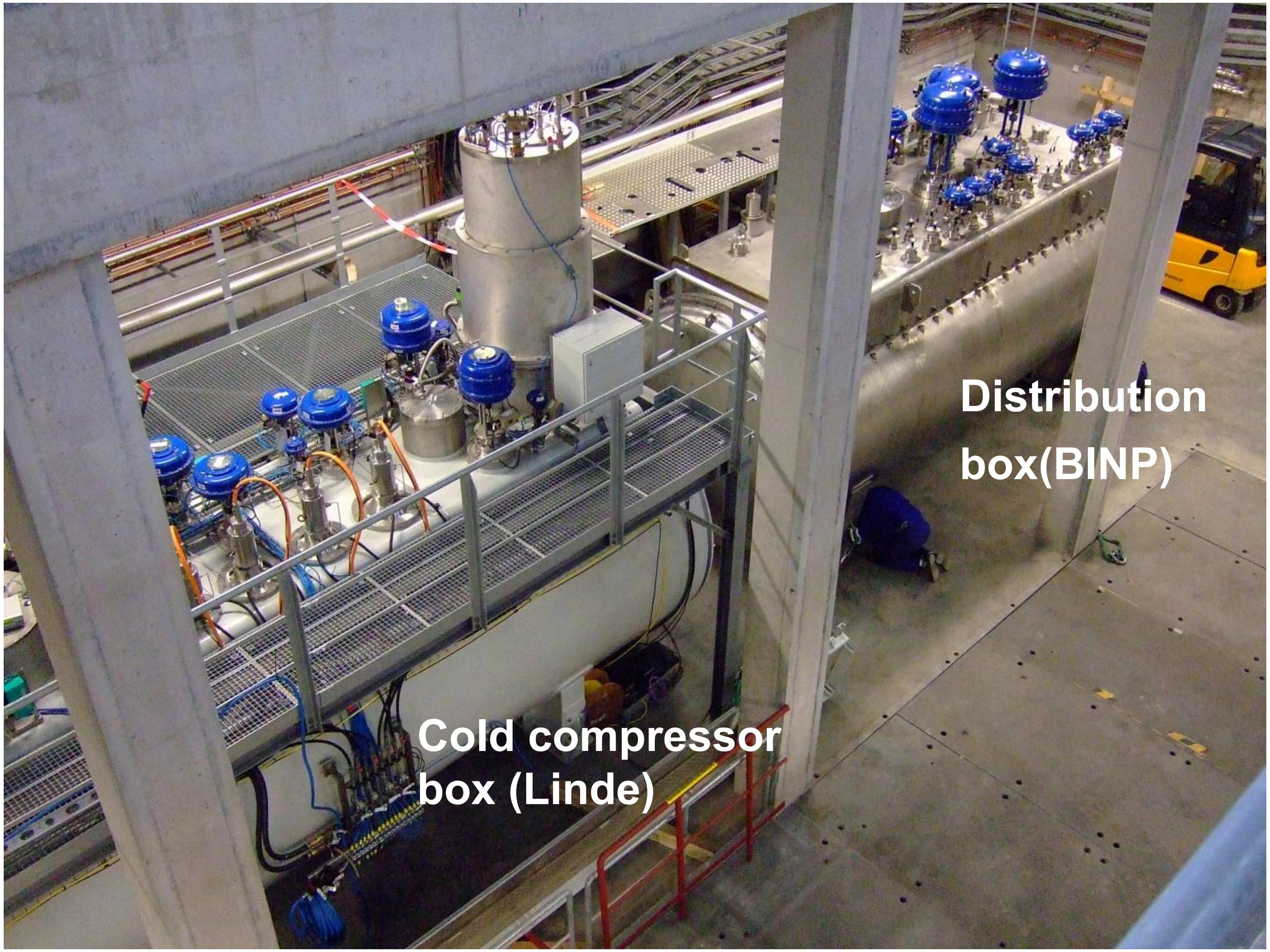
Laser profile before the aperture

and on the virtual cathode

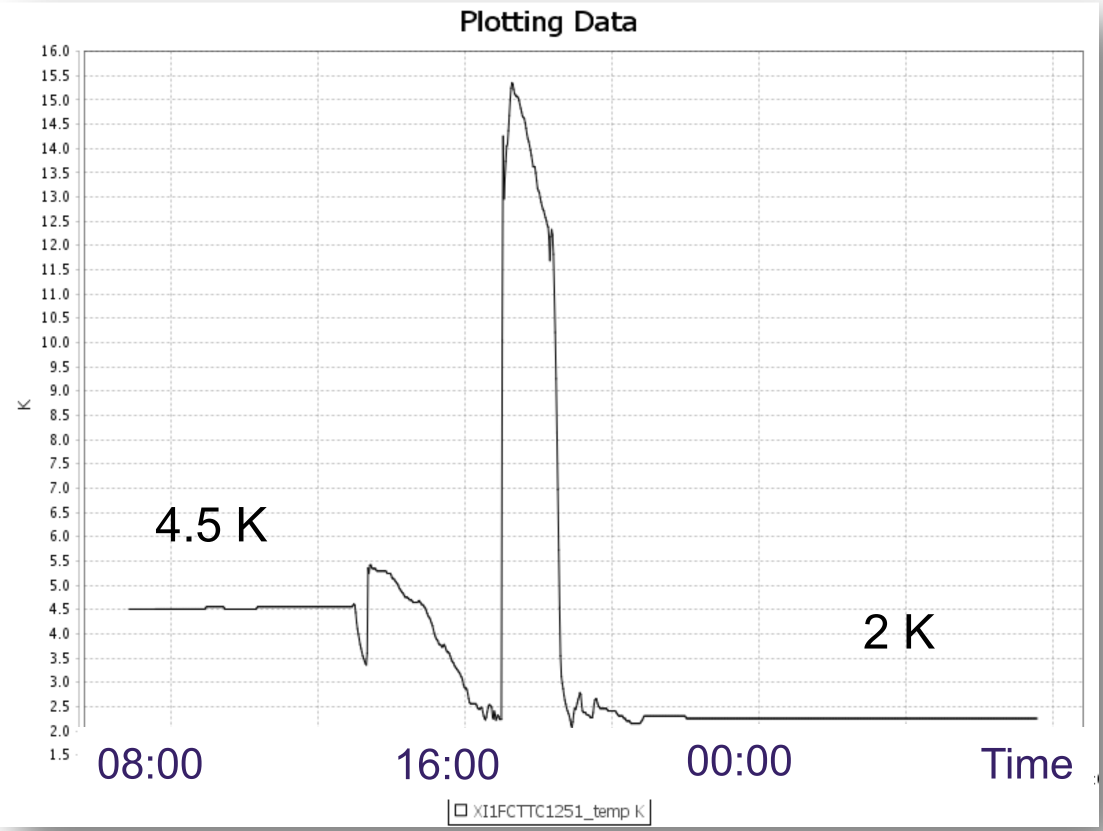


November 2015 : complete Installation is finished with the 3rd harmonic module (INFN)

Installation of the XFEL cryo plant finished:



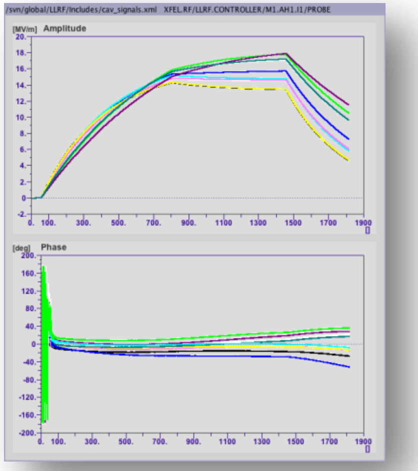
After technical commissioning of the modules : Injector cooldown

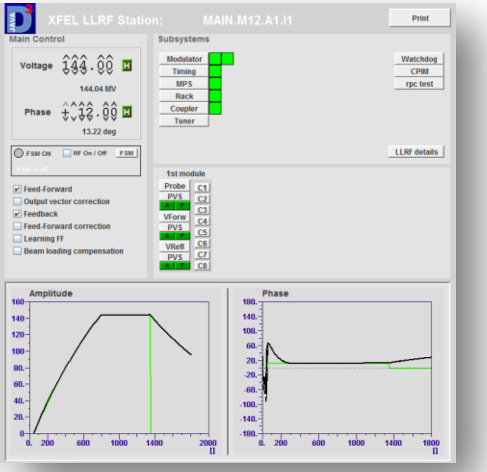


- December 9
  - Starting cooldown of the the injector for the first time.
  - First cooldown of AH1 module at all !
- December 14
  - Injector is at 2K
- December 15
  - Stable 2 K in the injector with cold compressors.

Accelerating 1.3 GHz module A1

- Cavities were tuned to resonance between December 16. - 18.
- December 18.
  - Rough calibration of all cavity signals
  - All loaded Q were adjusted to 4.6e6 using the automatic Ql adjustment tool.
  - All feedback loops were closed and module was running with nominal amplitude.

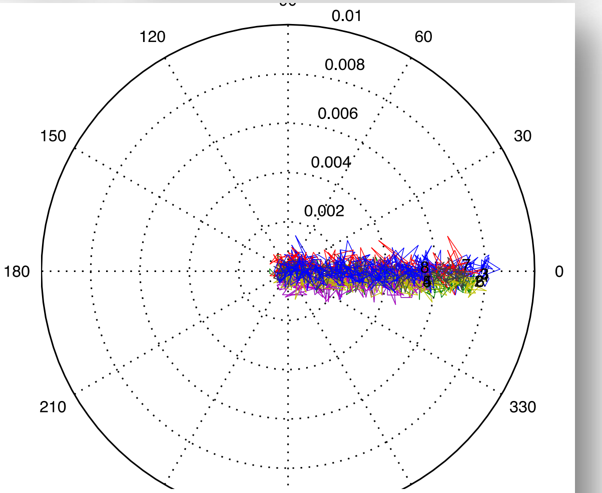




/svn/XFEL/LLRF/SC_modules/Injector/XLLRF_inj_diag_cav.xml XFEL.RF/LLRF.DIAGNOSTICS/A1.I1/

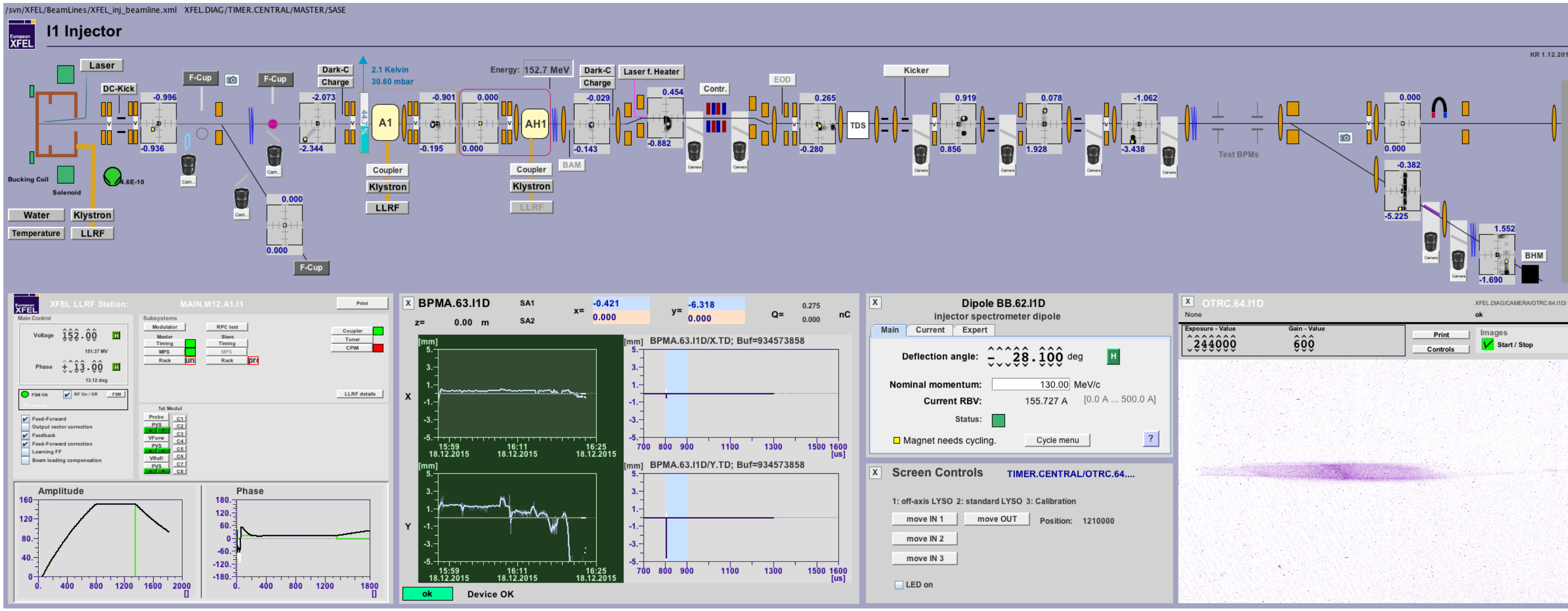
Diagnostic server readouts f... MAIN.M12.A1.I1

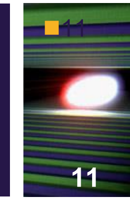
	C1	C2	C3	C4	C5	C6	C7	C8	
dA/A pulse2p	0.0040	0.0053	0.0127	0.0017	0.0029	0.0060	0.0104	0.0126	%
dP pulse2p	0.2359	0.2024	0.1343	0.1609	0.1214	0.1344	0.0958	0.1849	deg
loaded Q	4.49E6	4.57E6	4.59E6	4.57E6	4.62E6	4.52E6	4.62E6	4.60E6	
Detuning	-100	-145	17	-97	-259	-91	-167	-179	Hz



Cavity phasing of A1 was achieved January 9, 2016.

18.12.2015 - First Beam into the Injector Dump





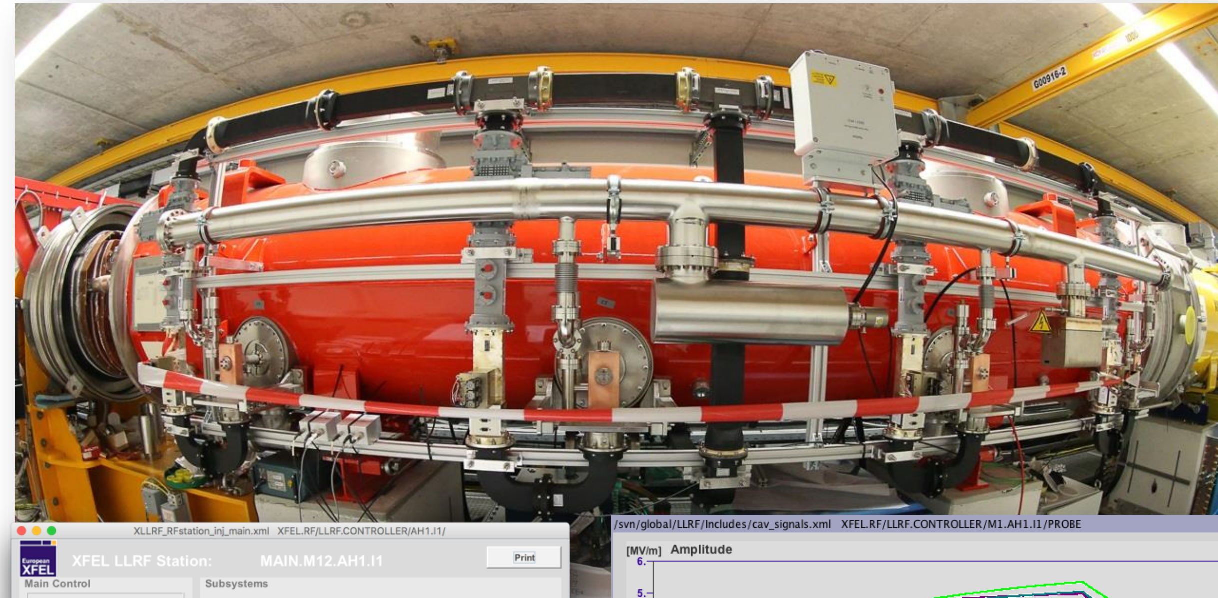
≈ 1% of accelerator length

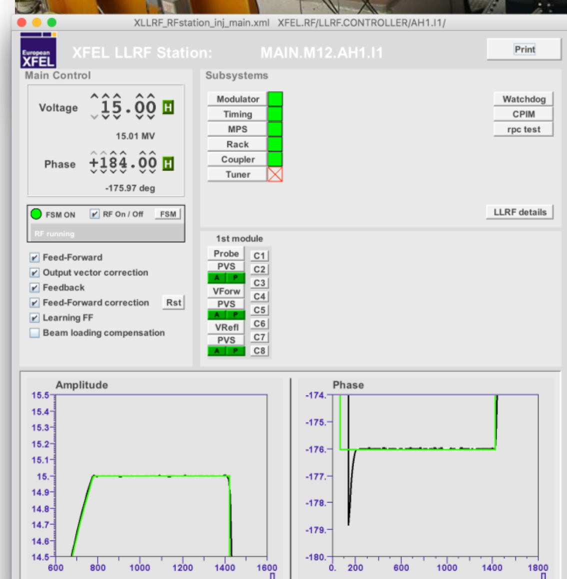
≈ 1% of final energy

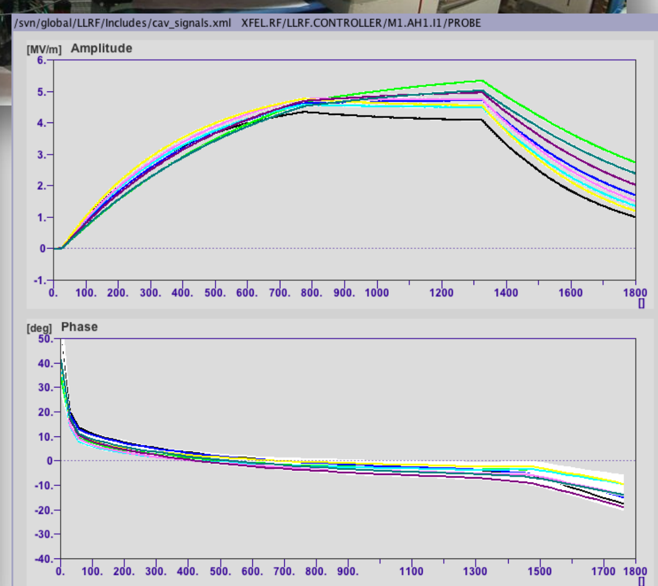
≈ 1% of electrons/second

but all accelerator sub-systems needed and functional

Third harmonic module AH1 (INFN, Milano)







- **18 December 2015:** First *rough* calibration
  - Nominal pulse structure Fill Time: 750 us
  - Flat Top: 650 us
  - Gradient well above nominal 30 MV of VS voltage
  - First quench > 45 MV
- **10 February 2016 :**
  - QL aligned well within the 10% requirement
  - Phases within 15°
- **16 February 2016 :** Back on beam
  - Moved to -180° (wrt on-crest), calibration with beam energy

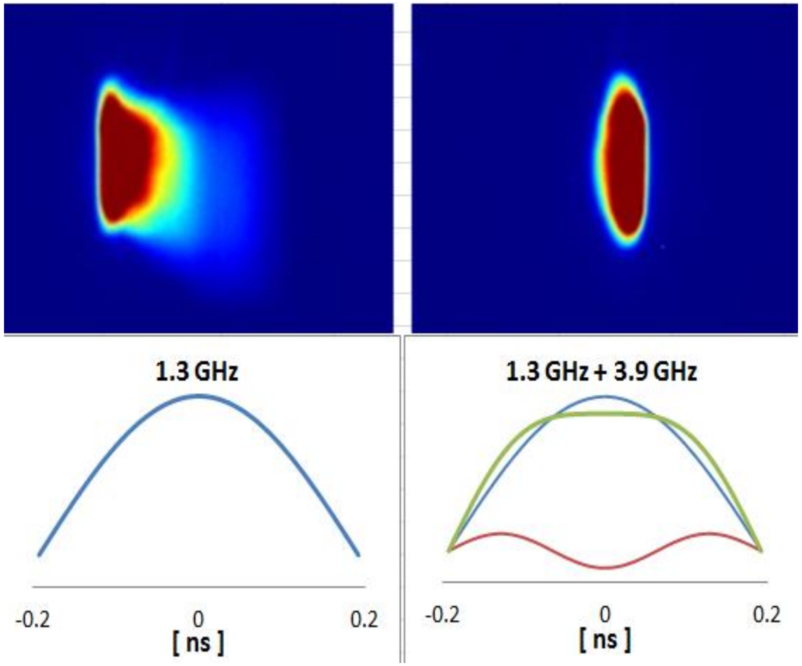
For details on SC modules see D.Reschke's talk on Thursday THYB01 on

'Performance of Superconducting Cavities for the European XFEL',

Reduced energy spread

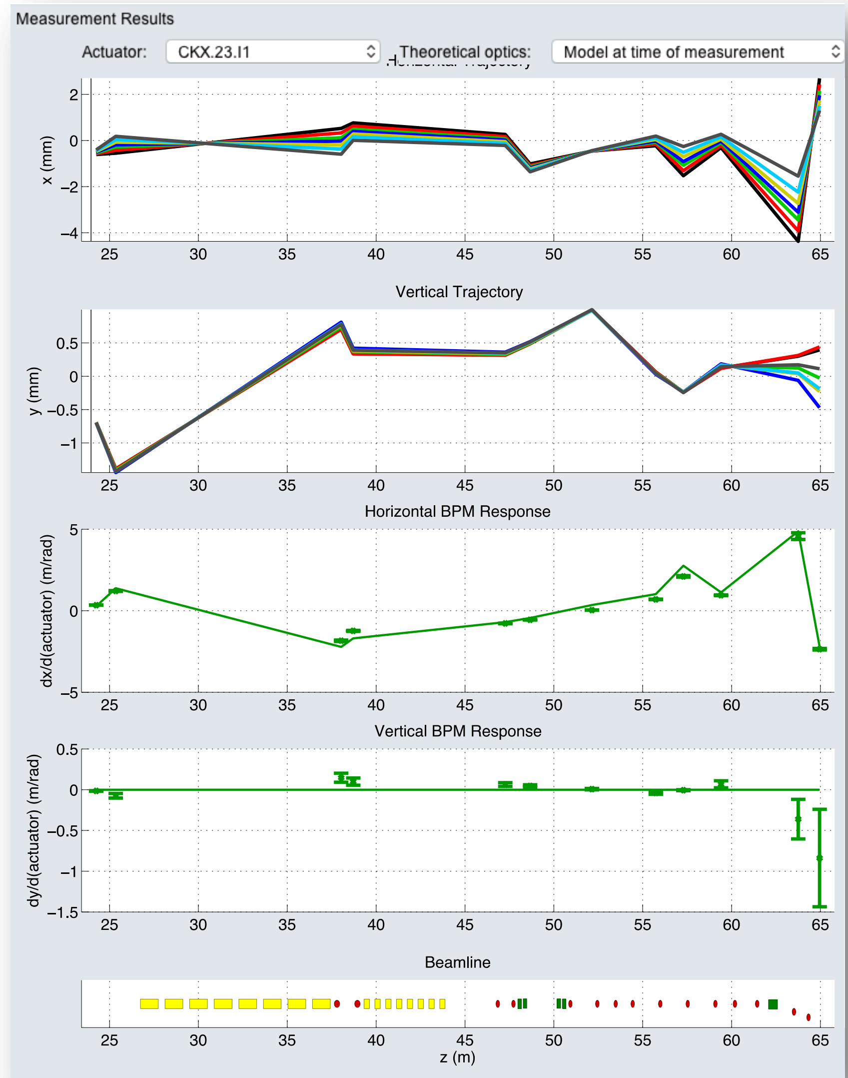
Beam in the dump line with large dispersion

3rd harmonic off   3rd harmonic at -16 MV



Optics checks: Trajectory responses and magnet model

- Trajectory response measurements show good matching with theoretical predictions.
  - The optics model used in the optics server is correct.
  - The magnetic fields of the quadrupole magnets are well known.

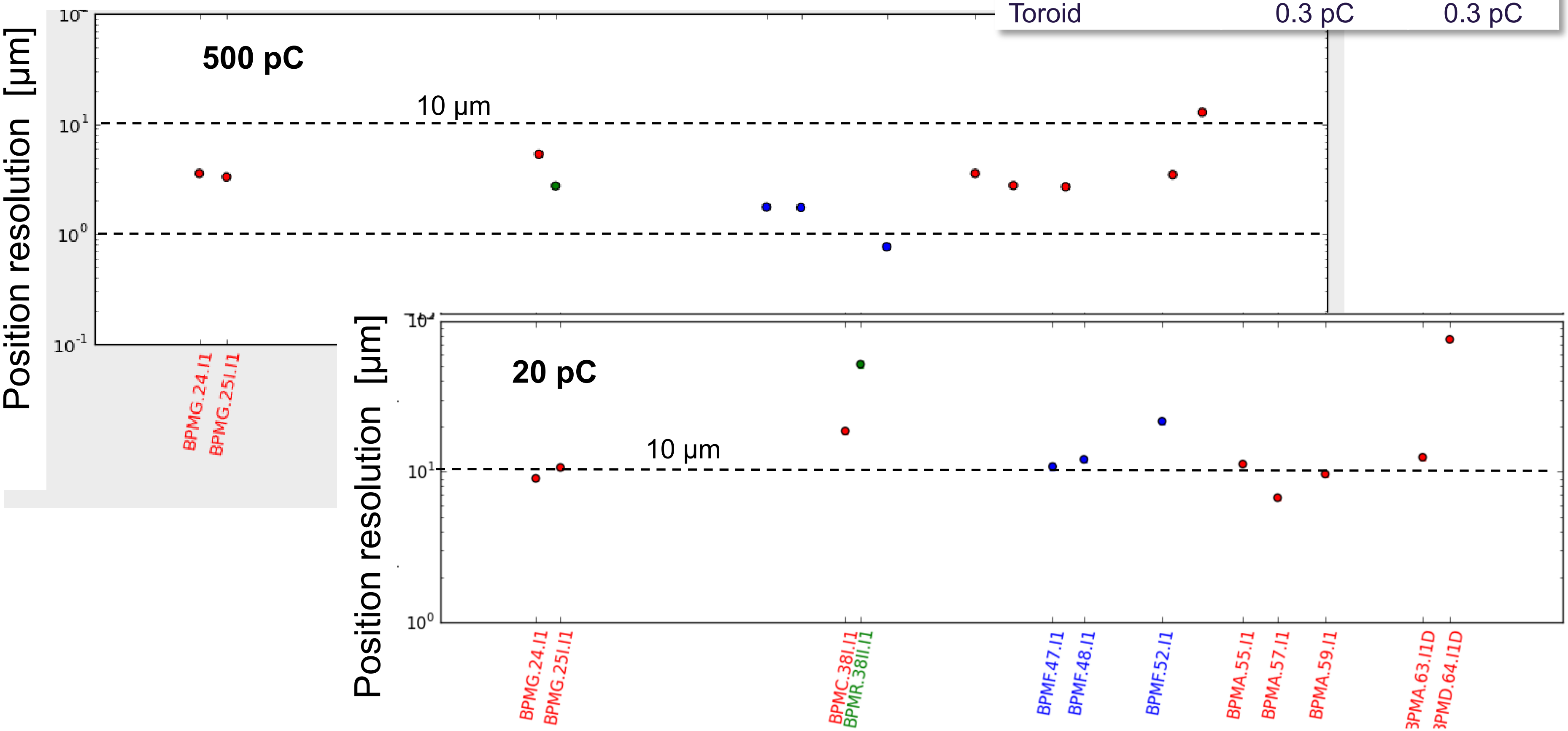


Beam Position Monitor Performance (PSI, CEA/IRFU)

- Newly developed BPM system (DESY/PSI/CEA)
- Performs smoothly and beyond specs
- Single shot resolution :
  - 1-5 µm at 500 pC
  - 10 – 50 µm at 20 pC

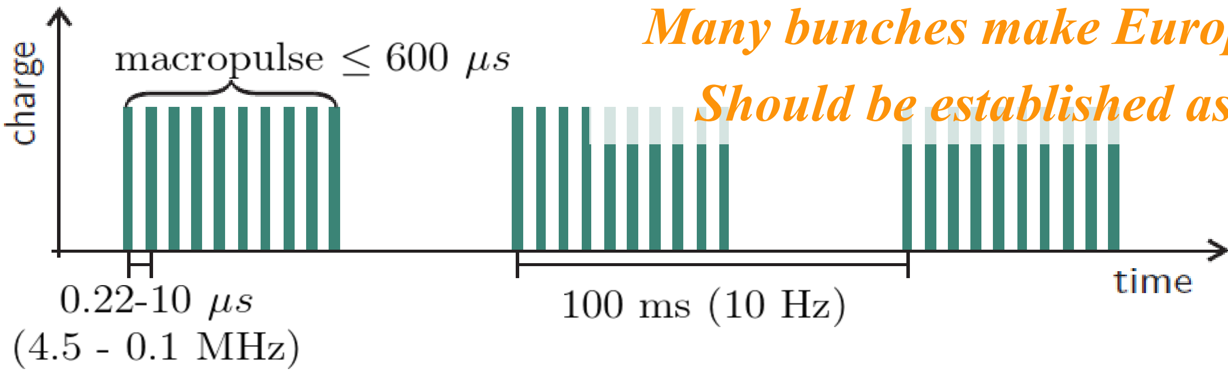
Resolution of the diagnostics

	at 20 pC	at 500 pC
button BPM	10 µm	5 µm
cavity BPM	10 µm	<2 µm
re-entrant BPM	50 µm	5 µm
Toroid	0.3 pC	0.3 pC



European XFEL

Long Bunch Trains



Many bunches make European XFEL unique

Should be established as soon as possible

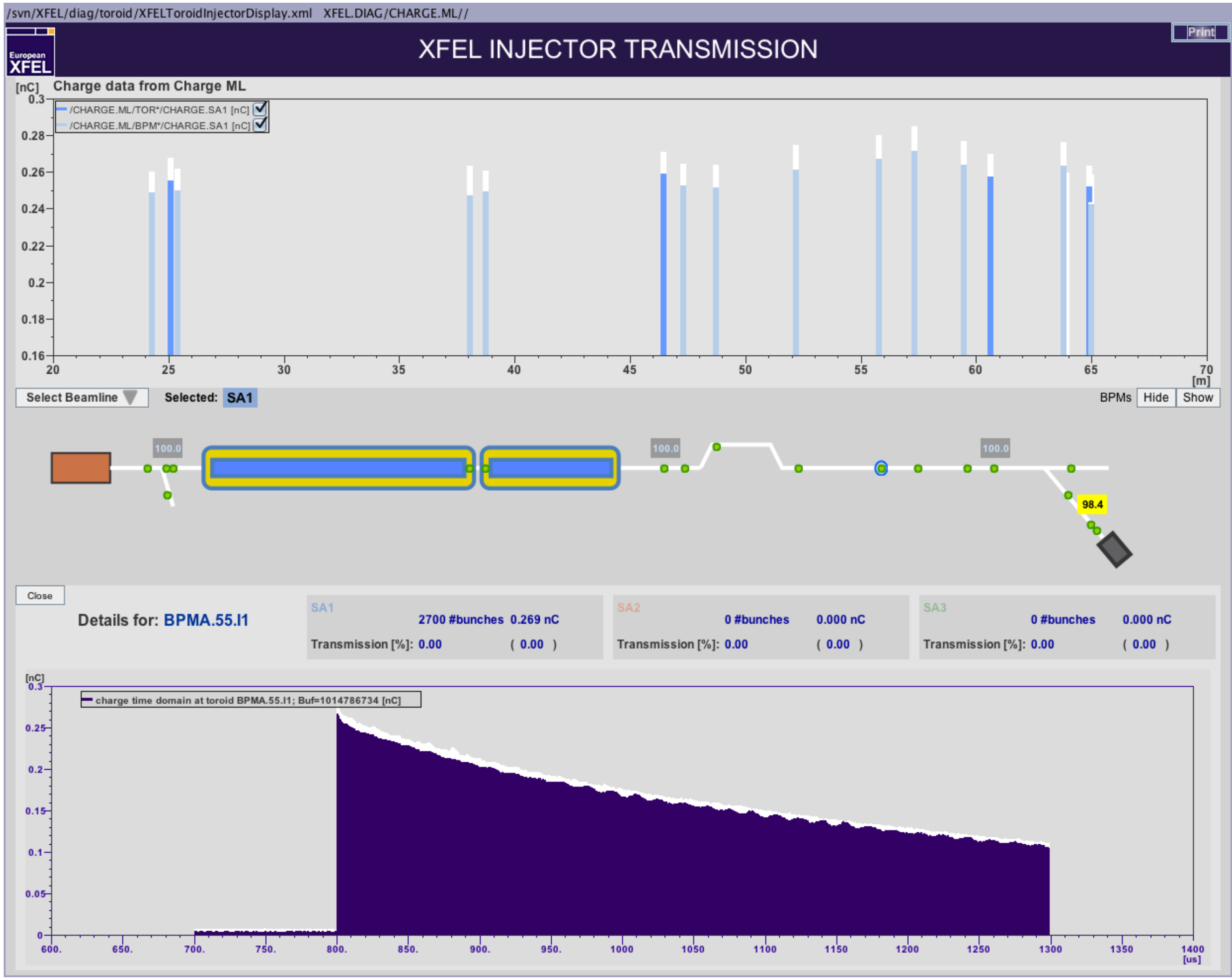
- 1 to 2700 bunches per train at a 10Hz repetition rate
- 2 W to 3.5 kW beam power at 130MeV and 1nC (10-472kW at 17.5GeV)
- Expected dark current of up to about 30 W at 130MeV and 600 µs
- ➢ Commissioning of Machine protection has first priority!

The machine protection system MPS sets the bunch numbers depending on:

- Status of magnets, screens, valves
- Status of cryogenics and modules
- Losses along the machine (measured with scintillators)

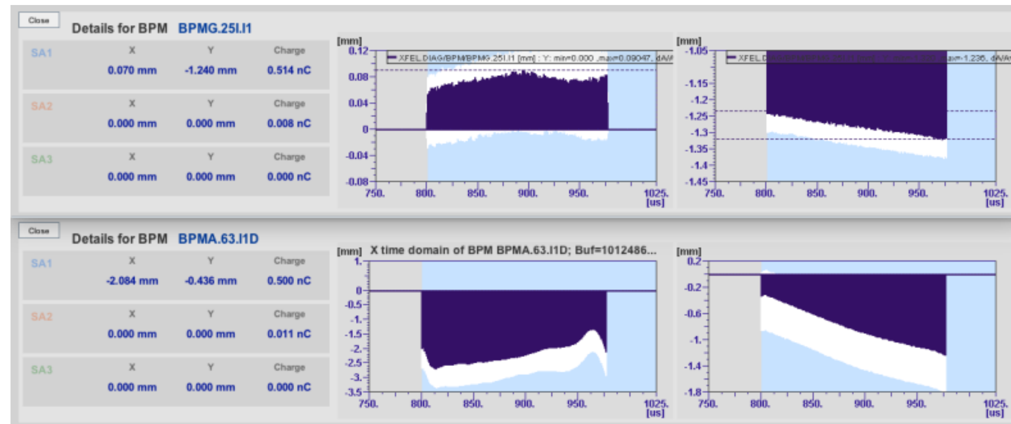
Long Bunch Train Operation

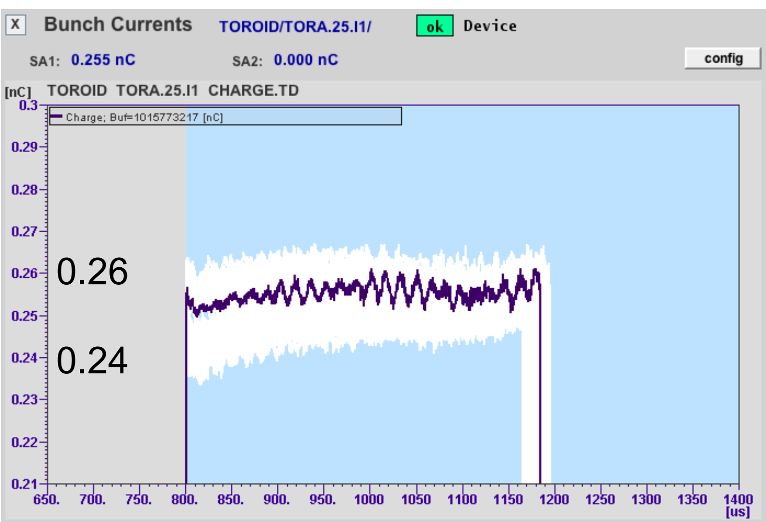
- March 19th : Operation of full bunch train at 250 pC !
- Low losses
- Low activation



Long bunch train: Issues

- Fine tuning of low-level RF Feedback and Feedforward systems to control RF flat top with beam loading
- Adjustment of laser parameters to avoid charge and trajectory variations





Variation of orbit after gun and in dispersive section

Charge stability much better after laser adjustment

See also the talk from K.P.Przygoda on Thursday THOAA03 on "MTCA based cavity regulation"

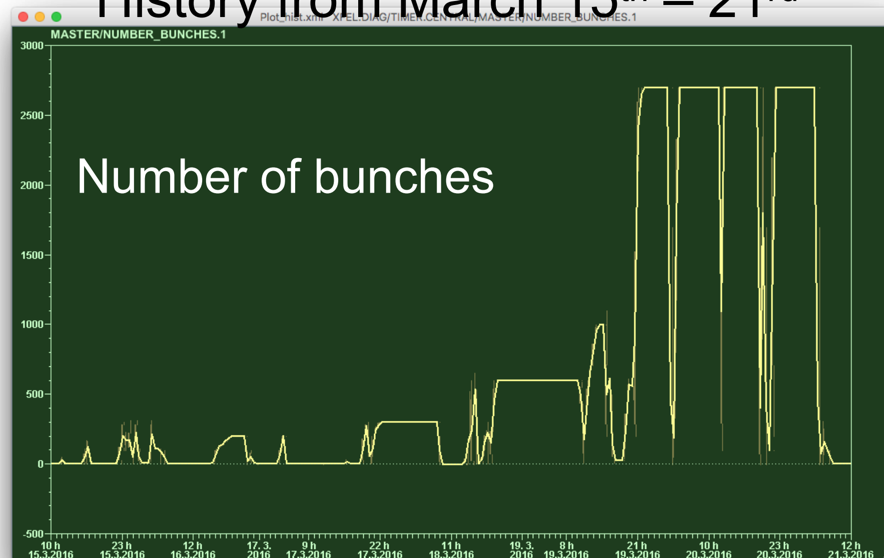
Injector operation with 2000 bunches, 0.5 nC

- Transmission through the injector beamline.
- Charge distribution over the pulse train – corrected with the injector laser power

European XFEL

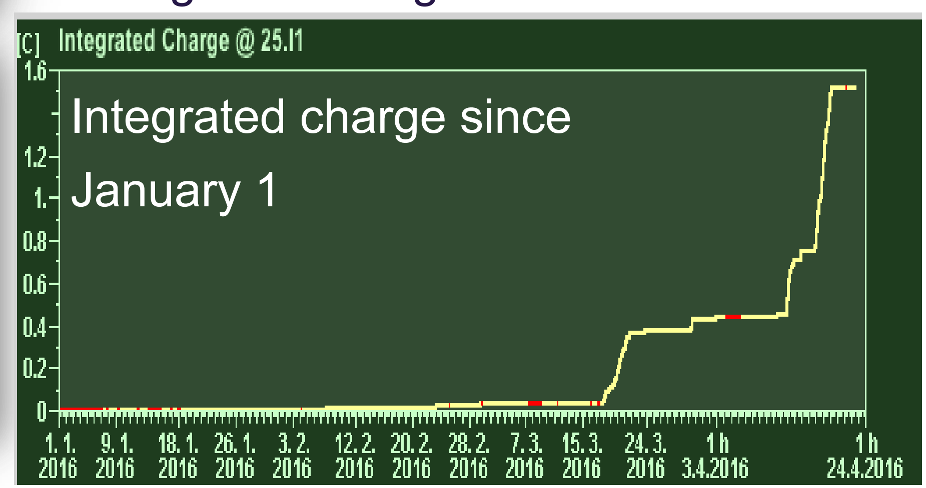
Injector operation with 2700 bunches

History from March 15^{th} – 21^{rd}



- The operation of the injector with 2700 bunches did not increase the losses.
  - The losses are dark current dominated.

Integrated charge so far is ~1.5 C.



DESY HELMHOLTZ ASSOCIATION

Automatic optics matching and emittance measurement

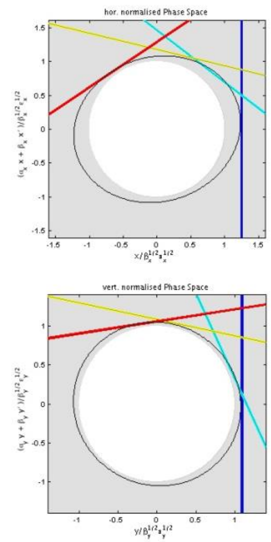
- Projected emittances of ~1.2 mm mrad could be achieved with a 500 pC bunch charge.

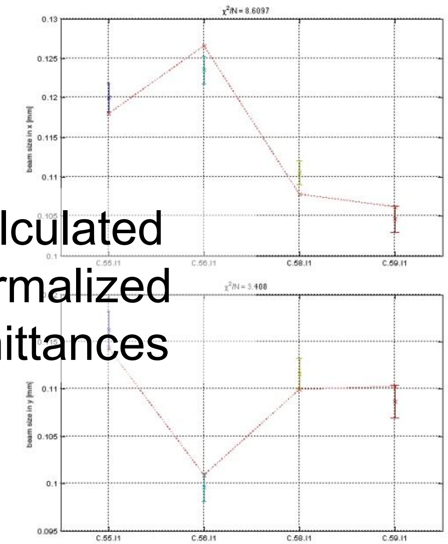
e.g.

Plane	Emittance	BMAG
horizontal	1.3 mm mrad	1.16
vertical	1.1 mm mrad	1.04

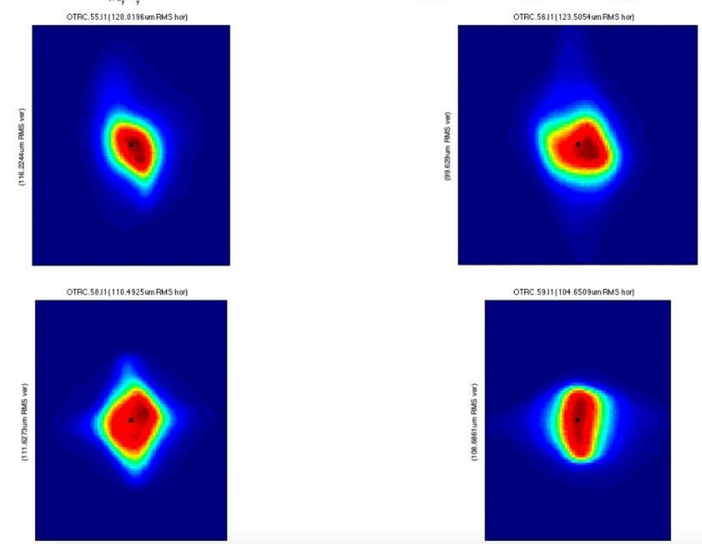
The BMAG parameter is a measure for the beta function error

- A link to the optics server allows the automatic matching of the optic with a chosen set of quads
- The deformations of the bunch shapes indicate distortions which need further investigations.



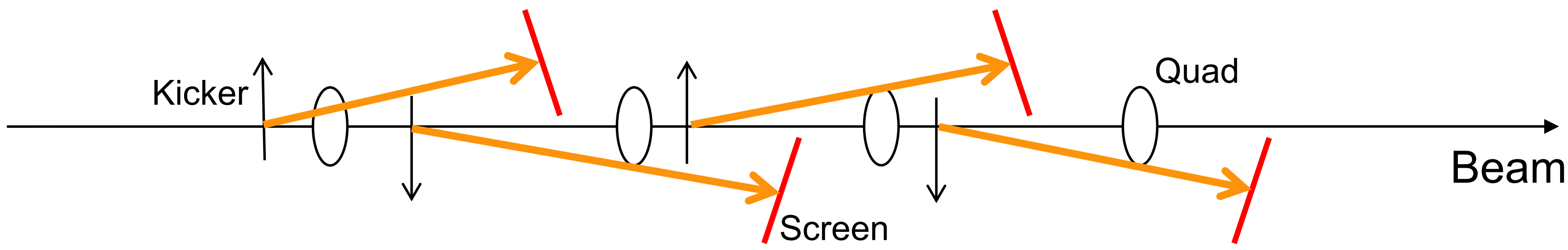


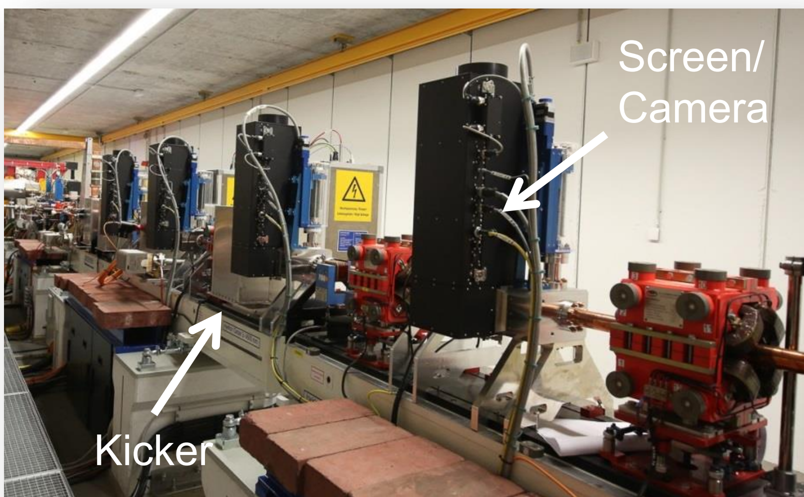
Calculated normalized emittances



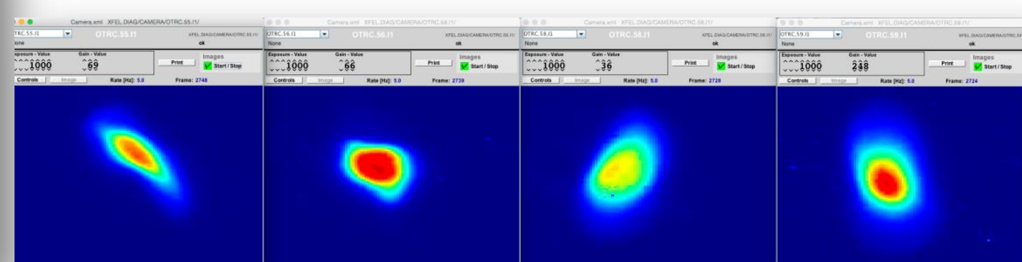
Emittance measurement with kickers and off-axis screens in the diagnostic section

- Off-axis screens and fast kickers in the diagnostic section allow to measure emittances of single bunches during operation with long bunch trains.

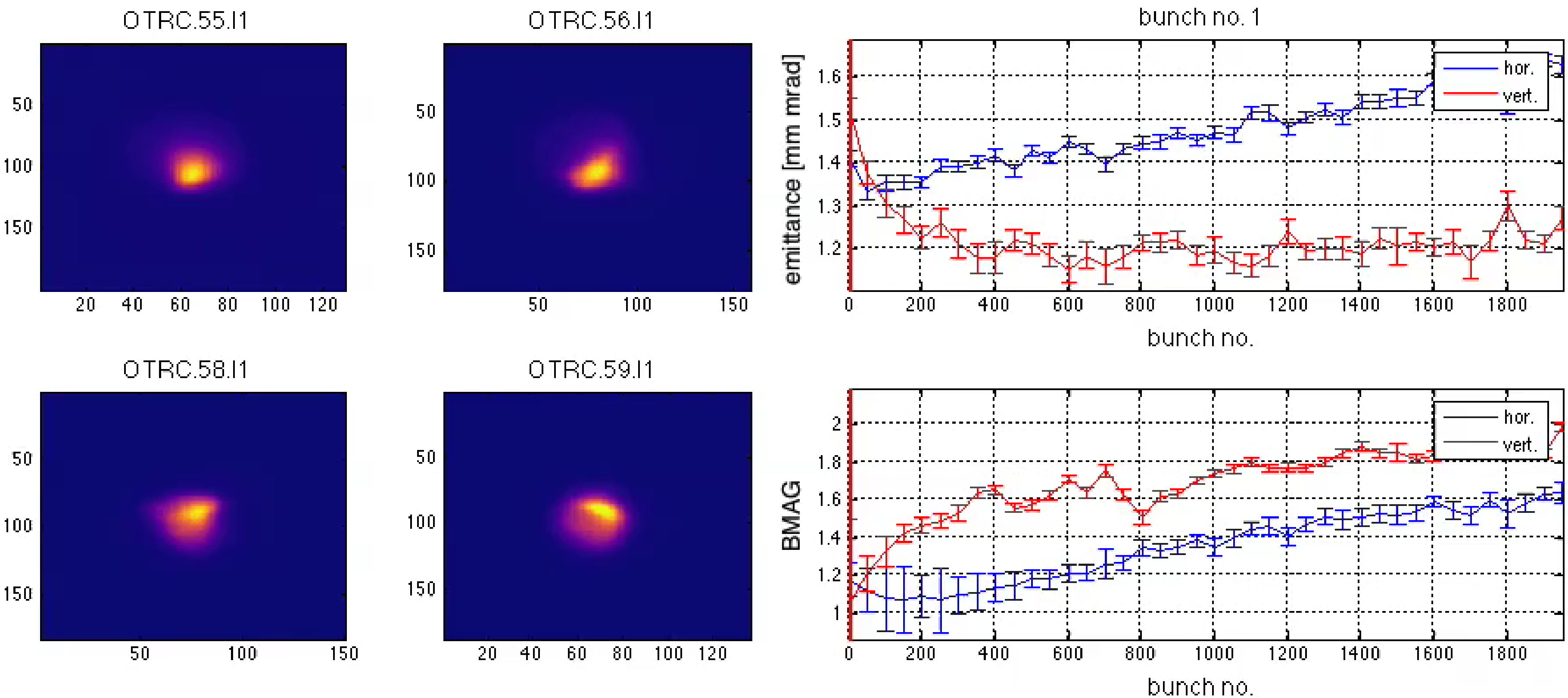




- These measurements are fast and allow also to measure the emittance and mismatch evolution over the bunch train.



Emittance measurements with off-axis screens



- Evolution of the projected emittance, the mismatch and the beam shape over the bunch train.

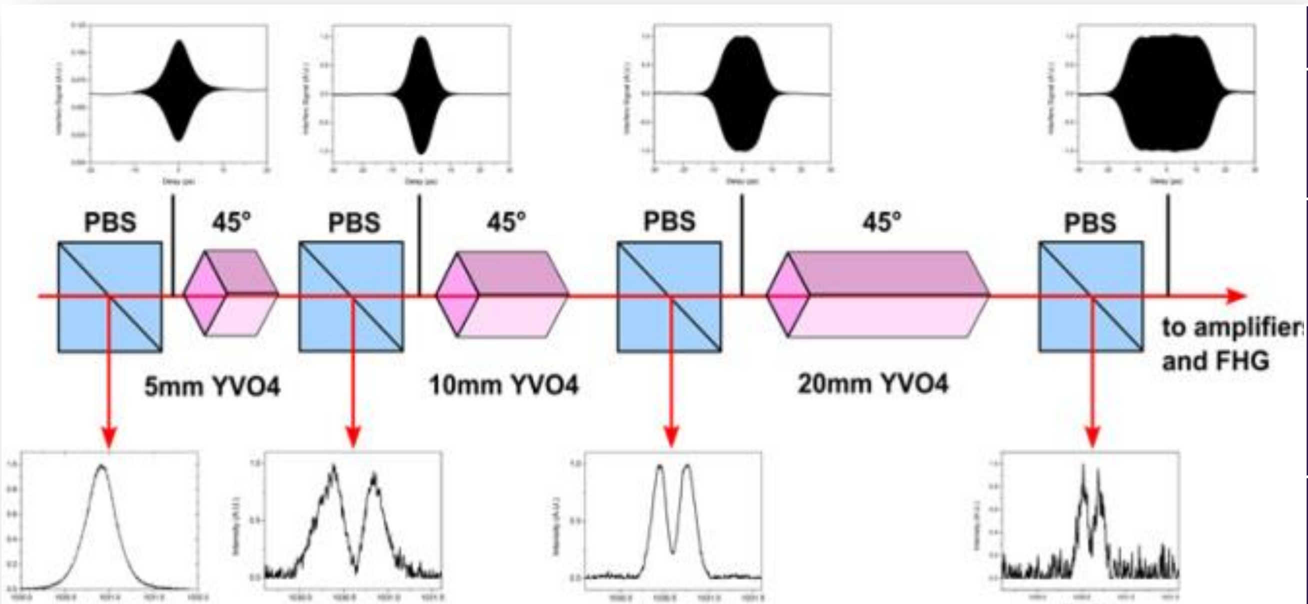
Courtesy of B. Beutner

Further automated procedures in operation and developement

- Phase scans of Gun and modules
- Charge feedback
- Generic scan tool (QE-Map, dipole scans, gun alignment, …)
- Orbit stabilization
- Dispersion correction

Injector laser stacker (Lyot type)

- Investigate influence and operation of flat top laser pulses.



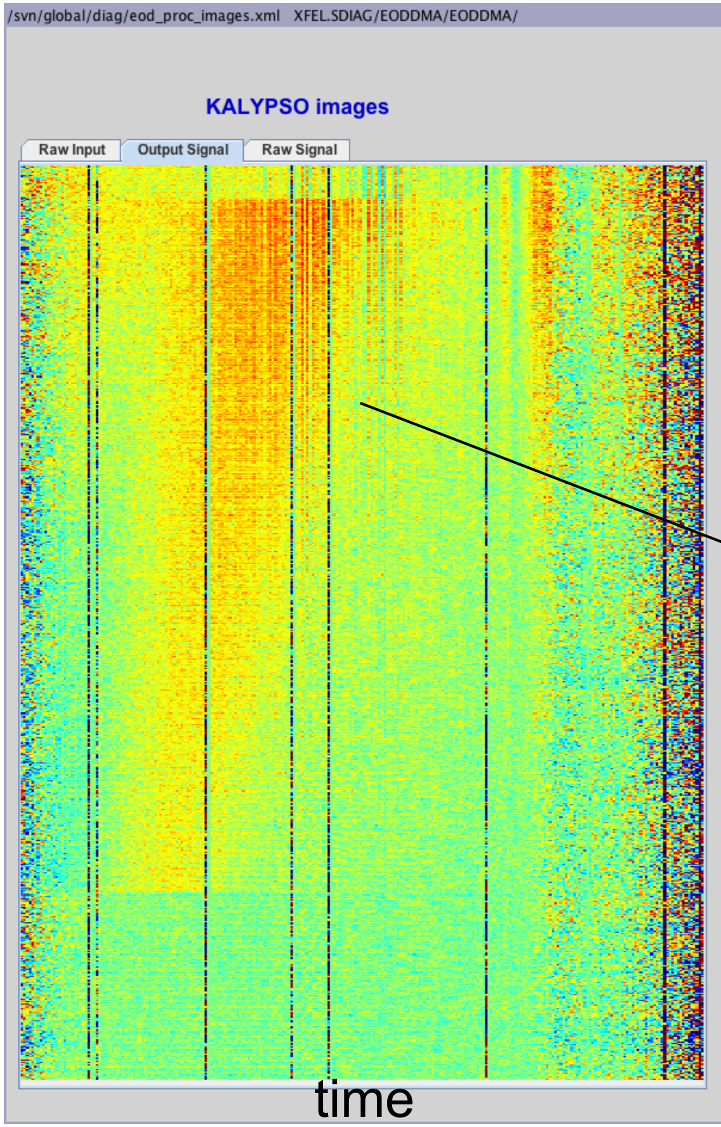
Gain material	Yb:YAG
Intra burst repetition rate	4.5 MHz, 3 MHz, 1MHz, 100 kHz
Pulse width (FWHM)	Phase 1 (MBI): Short pulse: < 3 ps Long pulse: ~12 ps Phase 2 (DESY): Shaped 26 ps with 2 ps rising edges
Energy per pulse in burst	> 0.7 µJ pP @ 3 ps > 3 µJ pP @ 10 ps

Courtesy of L.Winkelmann, I Hartl

- The laser pulse stacker can be used since April15.
- Max. Pulse length is 26 ps (FWHM) at the moment.
- The reduced space charge effects should lead to a smaller emittance as shown at the test facility PITZ.
- This effect could not be seen yet. We need more time for further studies.

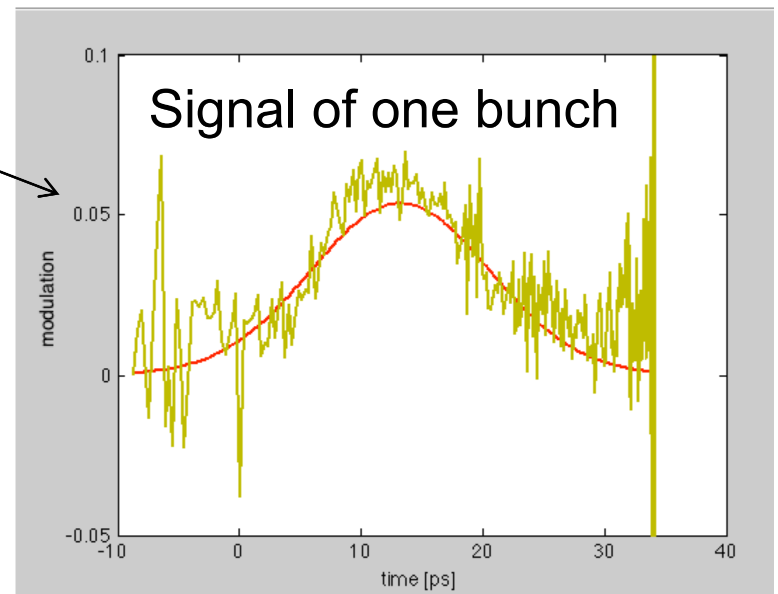
Preliminary results : Bunch length measurements with EOD

Bunch number



A laser passes through a crystal which is placed near to the beam. The electrical bunch field influence the outcoming laser pulse.

Better suited for measurements after the first bunch compressors – in the injector the bunches are too long for a clear signal.

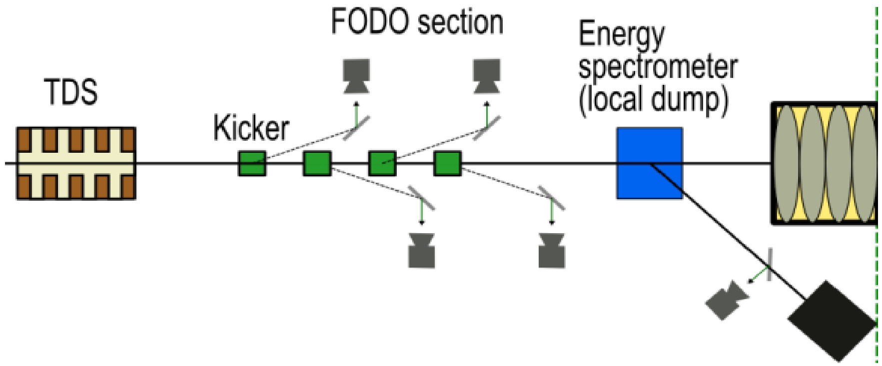


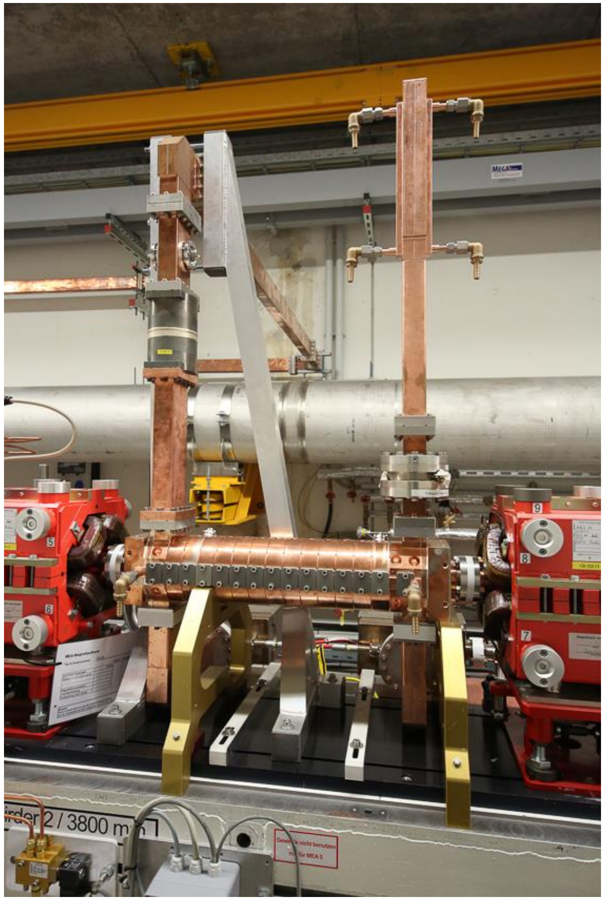
courtesy of C.Gerth, P.Peier, B.Steffen

Next Steps: TDS System (INR, Moscow)

- 3.0 GHz, 3 MW, < 3 μs pulse length
- RF-station is operational
- Structure will be connected these days
- Technical commissioning planned for this month

- Beam commissioning:
  - Establish procedures for automated measurement of slice parameters within bunch train

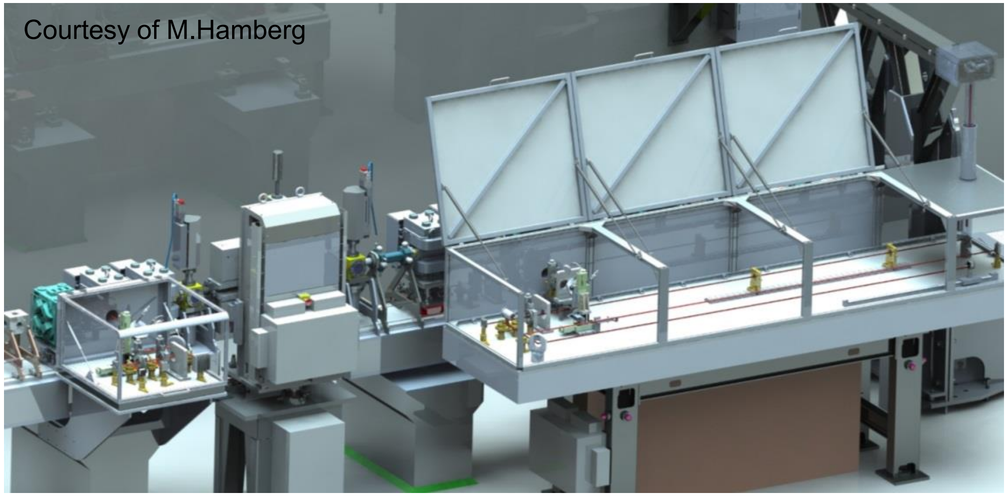


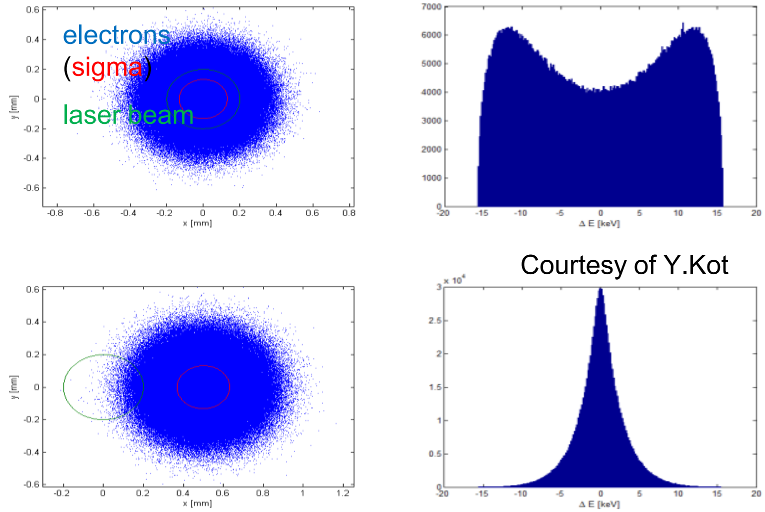


Next Steps:
Laser Heater (Univ. Uppsala)

To avoid micro bunch instabilities a moderate increase of the energy spread is foreseen by means of a laser heater.

A part of the IR laser which drives the Gun laser is coupled out and will be brought to overlap with the electrons in a wiggler magnet

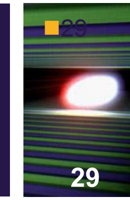




- The IR laser is successfully aligned through the laser beamline (~40m) and wiggler vacuum chamber.
- Next steps:
  - Find transverse and longitudinal overlap
  - Investigate laser-beam interaction, find optimal working points

European XFEL

Conclusion & Outlook



Injector commissioning goals:

Quantity	Value	Achieved
Macro pulse repetition rate	10 Hz	10 Hz
RF pulse length (flat top)	600 μs	>600 μs
Bunch repetition frequency within pulse	4.5 MHz	4.5 MHz
Bunch charge	20 pC – 1 nC	20 pC – 1 nC
Slice emittance	0.4 - 1.0 mm mrad	TDS by May

- Full injector commissioning started Dec. 2015 and will continue until end of July '16
- Sub-systems operate reliably, often beyond specs
- Minimum goal for emittance reached, sufficient for first lasing at XFEL
- Extensive emittance studies needed to investigate the full potential
- TDS and Laser Heater to be commissioned in May
- "Frequency ramping" of the gun in preparation

DESY HELMHOLTZ ASSOCIATION

Acknowledgements

The started operation of the injector is the result of the tremendous effort of all partners of this project from design, fabrication and testing of the components to installation and commissioning over the last years.

Many thanks to all the colleagues who contributed to this success.

Thank you for your attention!