Emittance Optimization at PITZ for FLASH and for the European XFEL

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Content:

- Photo Injector Test facility at DESY in Zeuthen (PITZ)
  - motivation, specs and PITZ-1.8 setup
  - main components (gun, booster, cathode laser)
- Emittance experimental optimization at PITZ
  - 13.01.2012 → 10 years of photo electrons at PITZ
  - measurement procedure
  - emittance 2009-2011 improvements
  - emittance for bunch charge from 20pC to 2nC
- Summary and outlook

HELMHOLTZ ASSOCIATION

PITZ Photo Injector Test Facility Zeuthen

DESY

Photo Injector Test facility at DESY in Zeuthen

The Photo Injector Test facility at DESY in Zeuthen (PITZ) focuses on the development, test and optimization of high brightness electron sources for superconducting linac driven FELs:

⇒ test-bed for FEL injectors: FLASH, the European XFEL

⇒ **small transverse emittance (<1 mm mrad @ 1 nC)**

⇒ stable production of short bunches with small energy spread

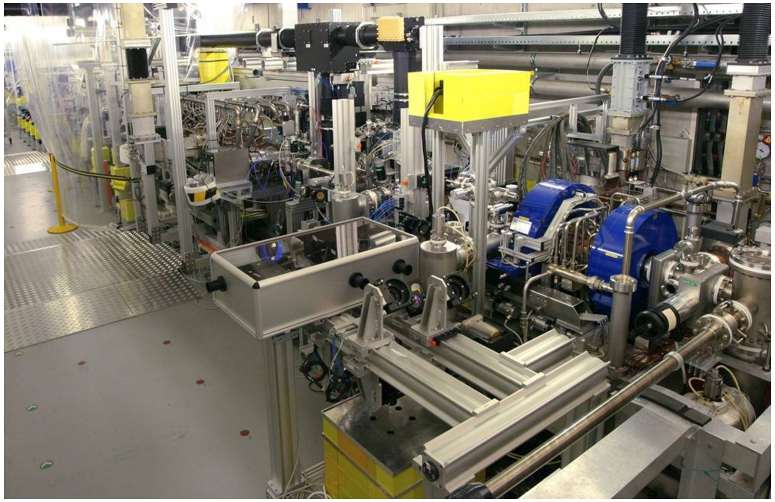
⇒ further studies: dark current, QE, thermal emittance, …

+ detailed comparison with simulations = benchmarking for the PI physics

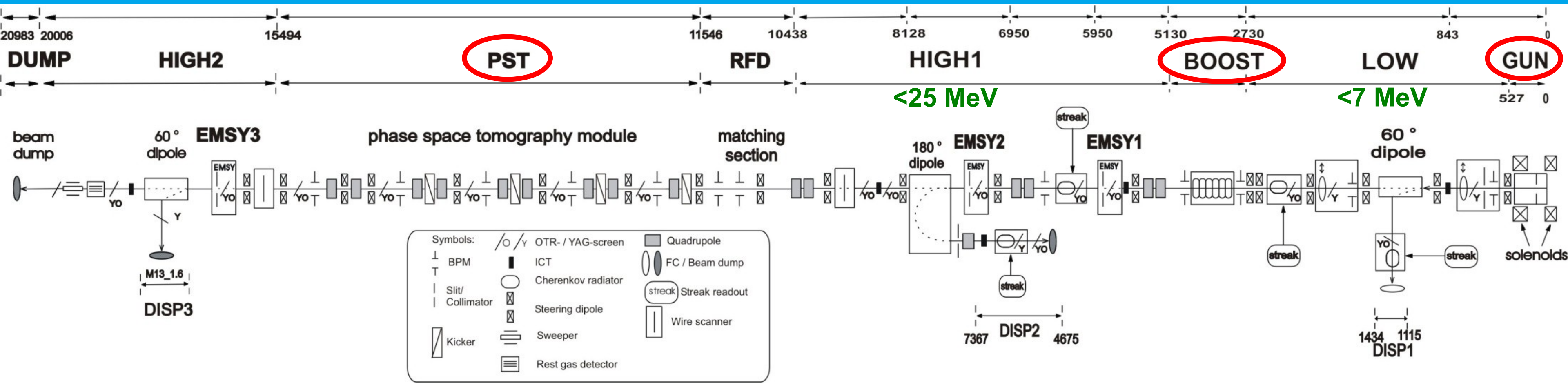
extensive R&D on photo injectors in parallel to FLASH operation

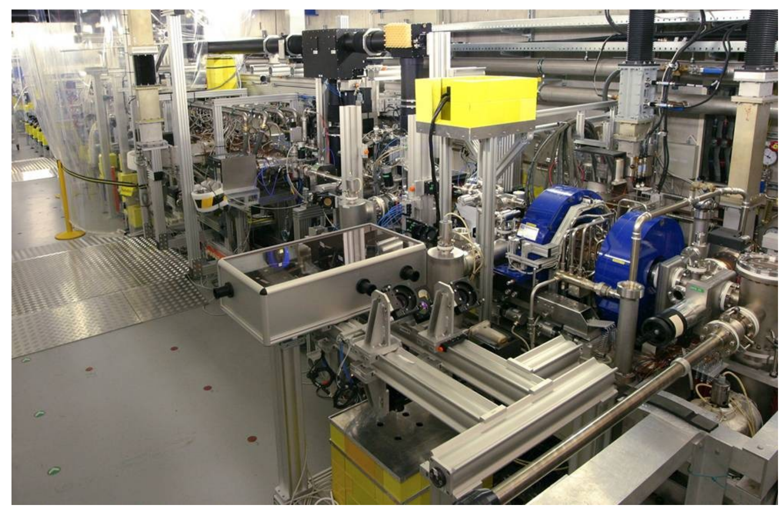
test and optimize rf guns for subsequent operation at the FLASH and XFEL

test new developments (laser, cathodes, beam diagnostics)



PITZ-1.8 setup



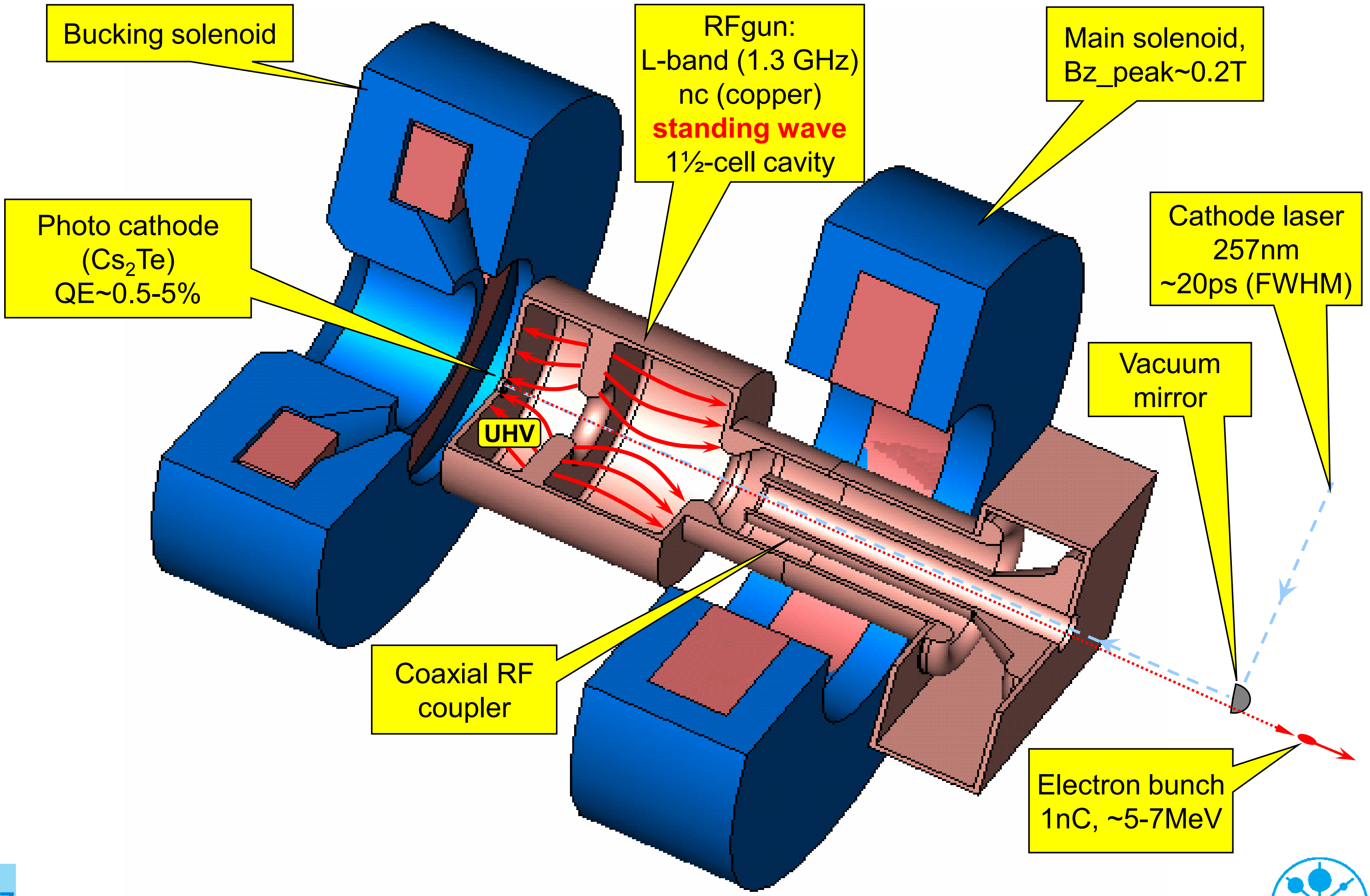


XFEL Photo Injector Key Parameters to be tested at PITZ

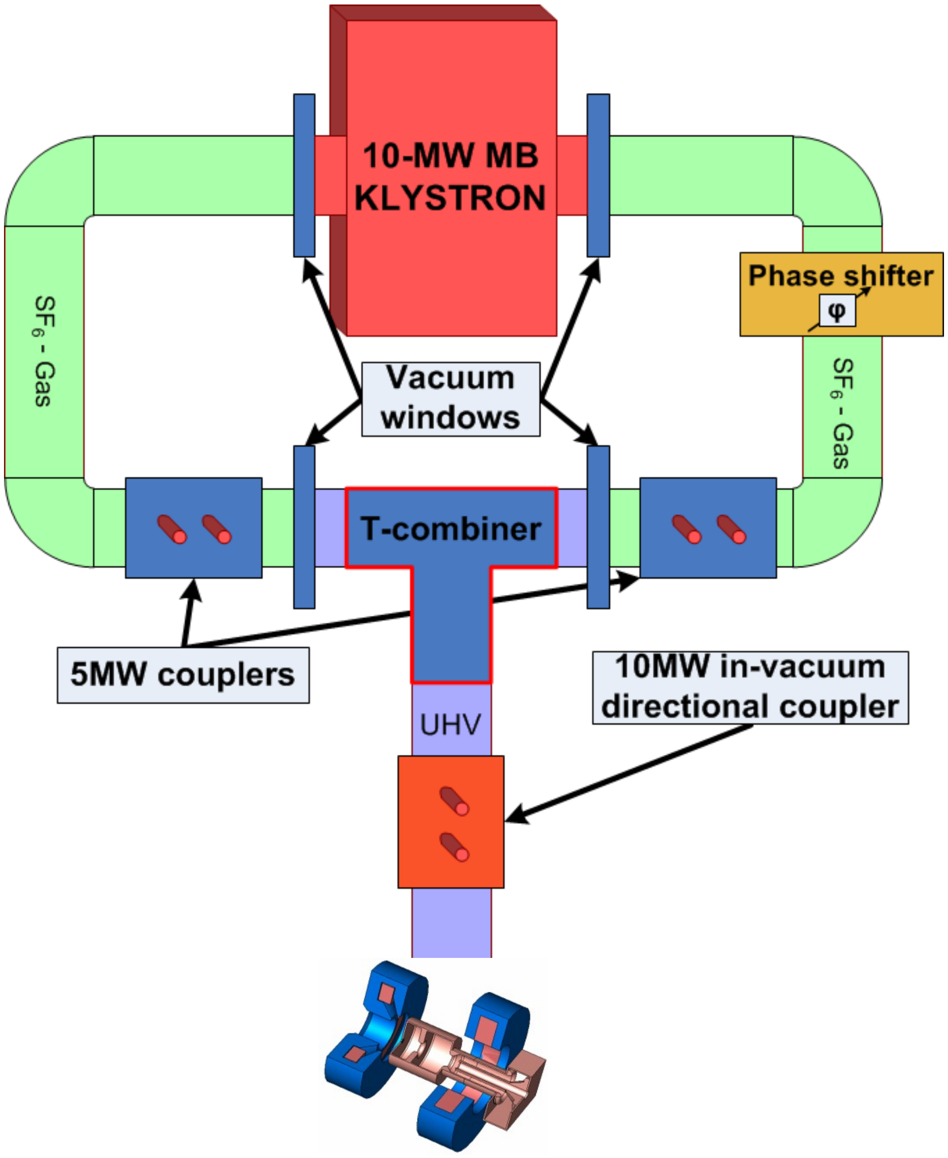
subsystem	parameter	*value*	remarks
RF gun cavity	frequency	*1.3 GHz*	
	E-field at cathode	***60 MV/m***	dark current issue
	RF pulse duration	*700 us*	max
	Repetition rate	*10 Hz*	max
Cathode laser	Temporal –> flat top –> FWHM	***20 ps***	**challenge** 20ps
	Temporal –> flat top –> rise/fal time	***2 ps***	
	Transverse – rad.homogen.XYrms	*0.3-0.4 mm*	fine tuning -> **thermal emittance**
	Pulse train length	*600 us*	max
	Bunch spacing	*222 ns (4.5MHz)*	1us (1MHz) at PITZ now
	Repetition rate	*10 Hz*	max
Electron beam	Bunch charge	*1 nC*	other charges under consideration
	Projected emittance at injector	***0.9 mm mrad***	
	Bunch peak current	*5 kA*	after bunch compression (not at PITZ)
	Emittance (slice) at undulator	***1.4 mm mrad***	

Main efforts at PITZ towards XFEL photoinjector

PITZ RF-Gun


Bucking solenoid
RFgun:
L-band (1.3 GHz)
nc (copper)
standing wave
1½-cell cavity
Main solenoid,
Bz_peak~0.2T
Photo cathode
(Cs_2Te)
QE~0.5-5%
Cathode laser
257nm
~20ps (FWHM)
Vacuum
mirror
UHV
Coaxial RF
coupler
Electron bunch
1nC, ~5-7MeV

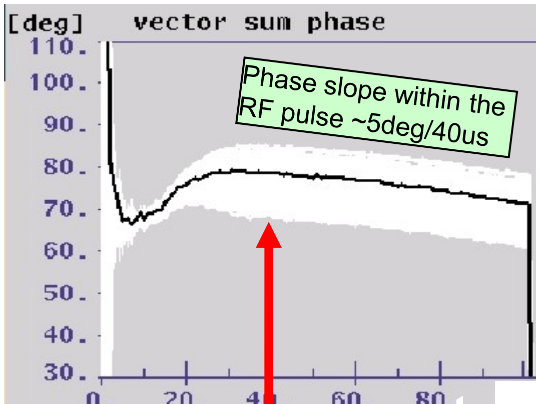
RF Gun Feed System

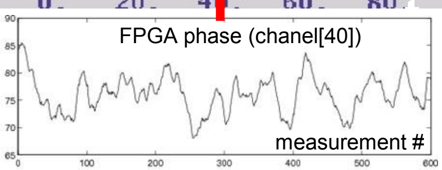


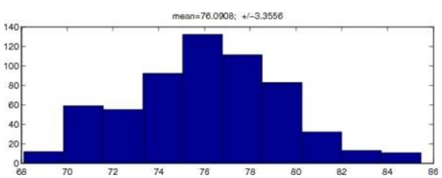
Improvement of the RF gun phase stability

2009 (no FB)

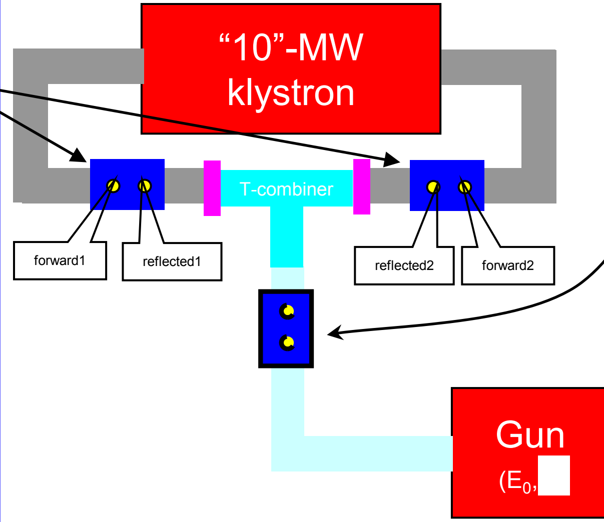
FPGA phase, reconstructed from virtual ADC probes based on 2x5MW directional couplers



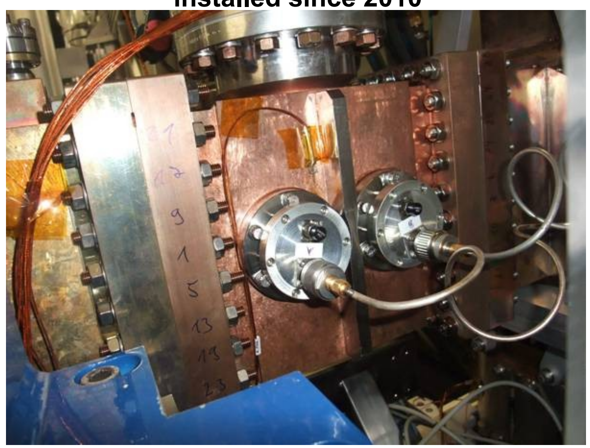




Phase fluctuations:
- **10..15 deg (p-p)**
- 2..4 deg (rms)



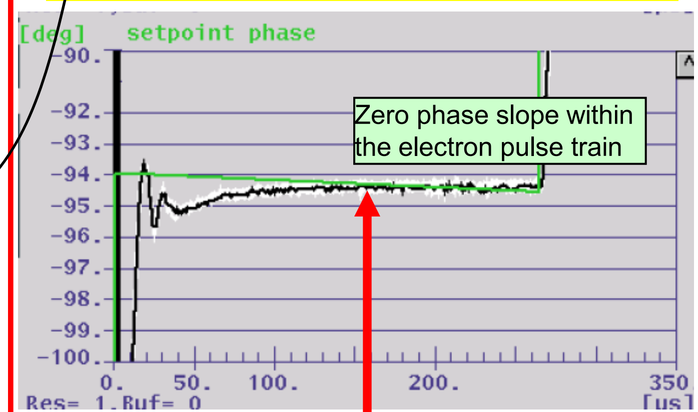
10-MW in-vacuum directional coupler installed since 2010

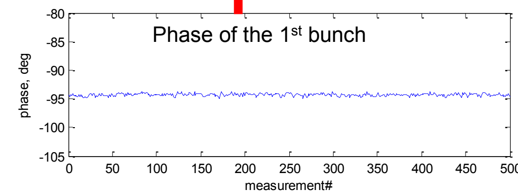


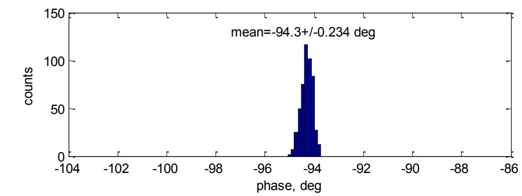
Manufacturer: Mega Industries, USA

2011 (FB is ON!)

FPGA phase, measured by 10MW in-vacuum directional coupler



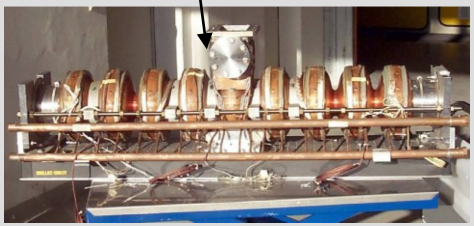




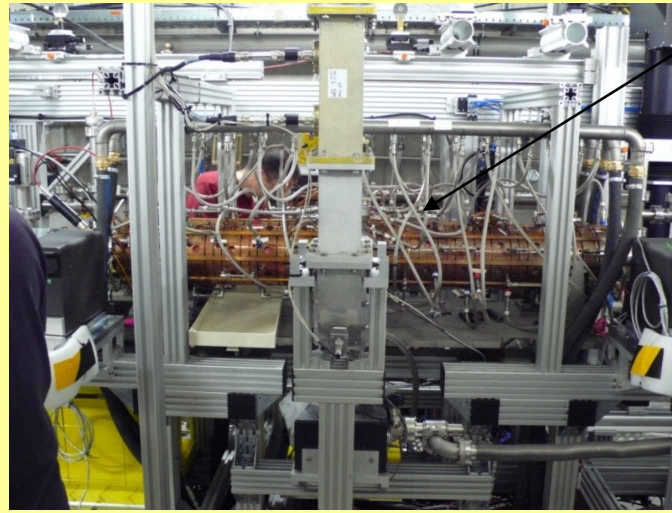
Phase fluctuations:
- **1..1.5 deg (p-p)**
- 0.2..0.3 deg (rms)

Booster upgrade at PITZ: TESLA→CDS

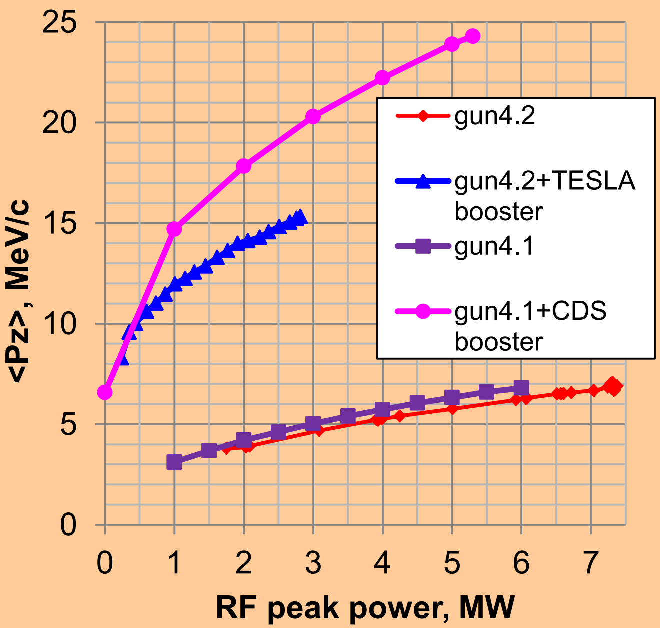
Old **TESLA**-booster was in 2010 replaced with a specially designed for PITZ **CDS**-booster



•restricted peak gradient (final beam momentun ~13MeV/c)
•short RF pulses only (50-100us)



CDS = Cut-Disc-Structure
•improved water cooling system
•higher peak gradients (final beam momentum ~25MeV/c
•long RF pulses (up to 700us)
•longer acceleration (L~1.4m)
•precise phase and amplitude control (RF probes)
•Symmetrical couplers



Booster schematic cavity layout.
1 - regular cells,
2 - rf coupler, 3 - rf flanges,
5, 5a - photo multipliers,
6, 6a- vacuum gauges,
7 - pumping ports,
8 - ion pumps,
9 - internal cooling circuit,
10 - outer cooling circuit,
11 - support and adjustment.

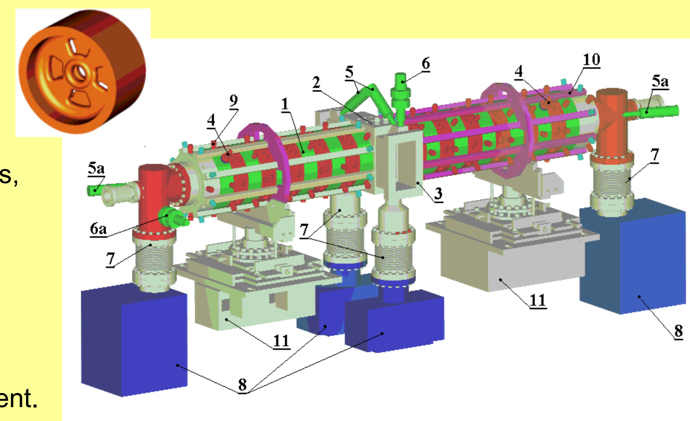
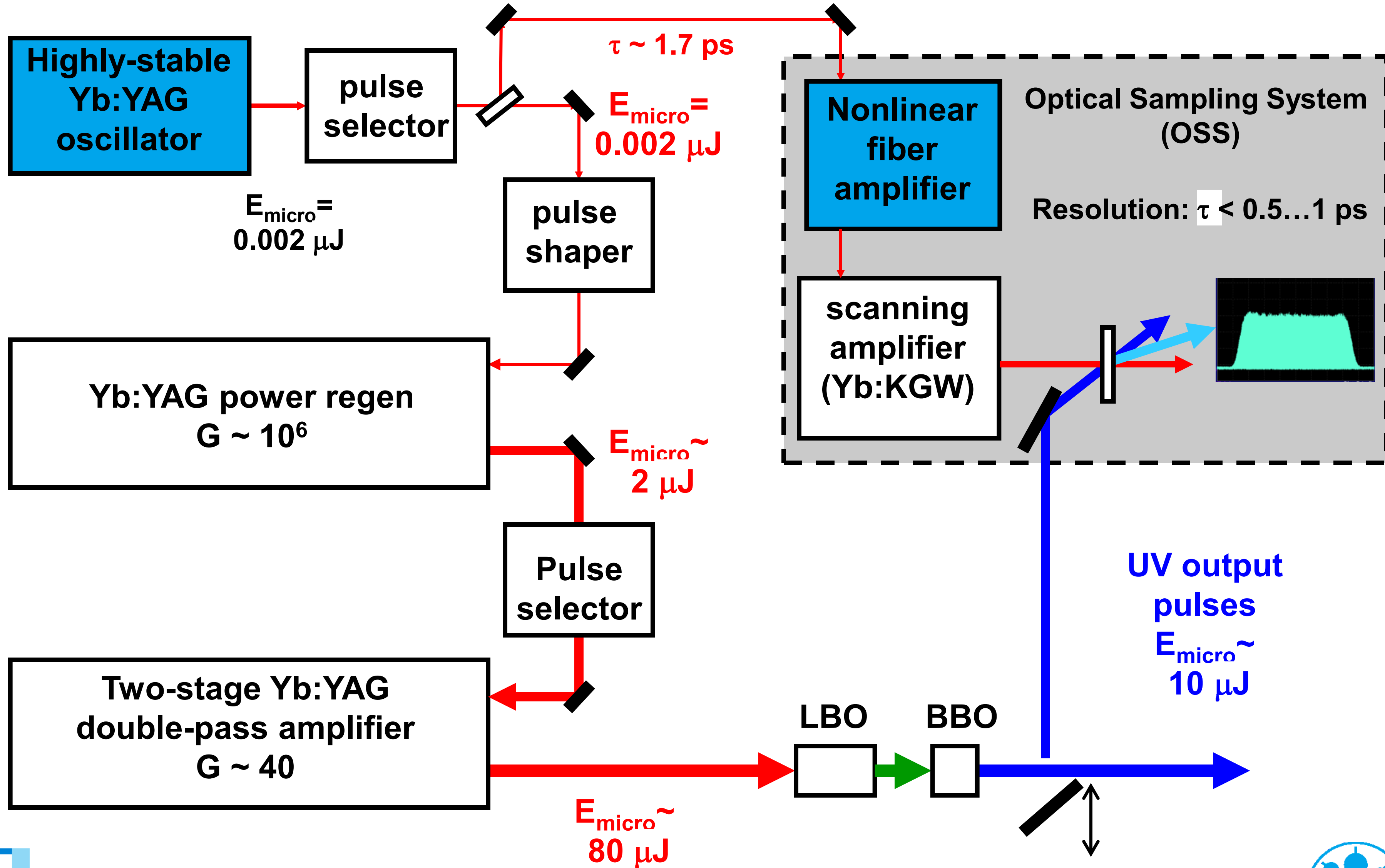
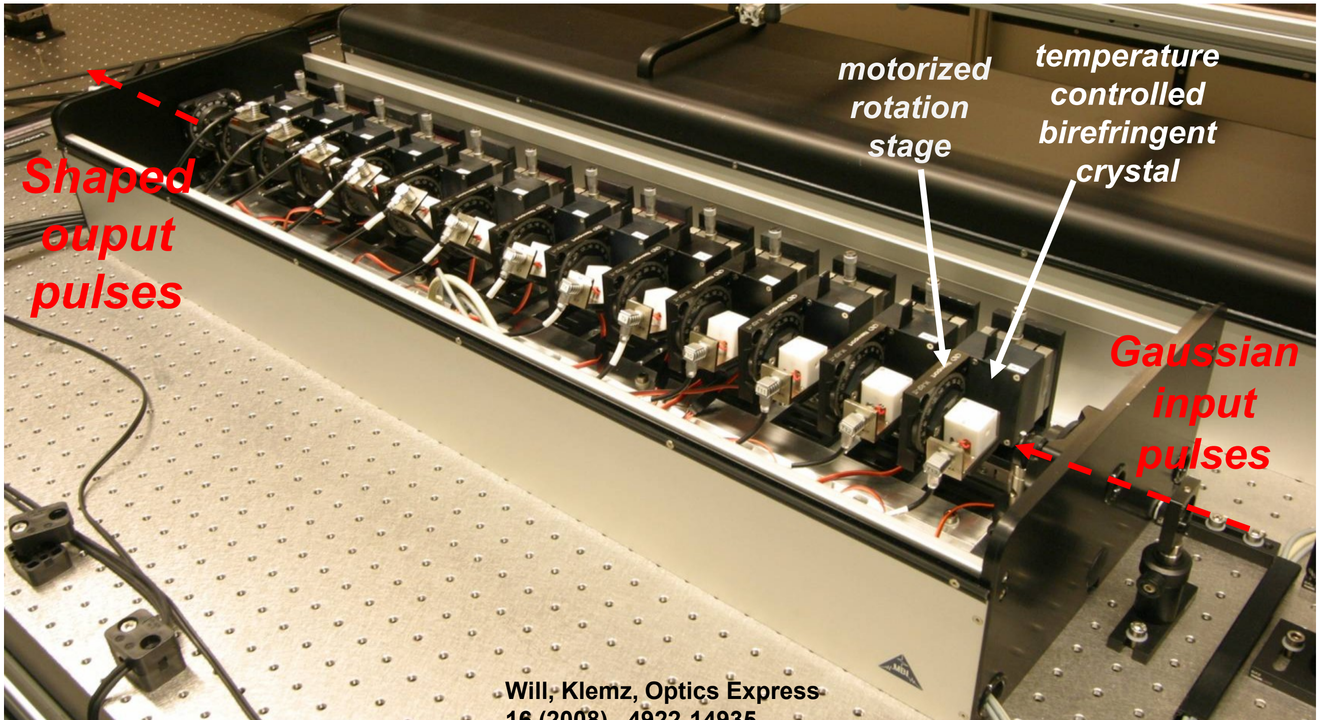


Photo cathode laser (Max-Born-Institute, Berlin)

Yb:YAG laser at PITZ with integrated optical sampling system

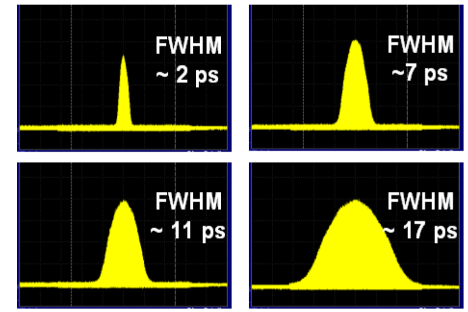


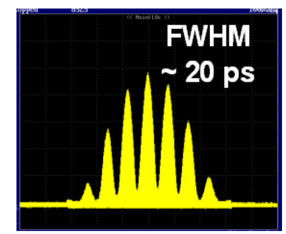
Multicrystal birefringent pulse shaper containing 13 crystals



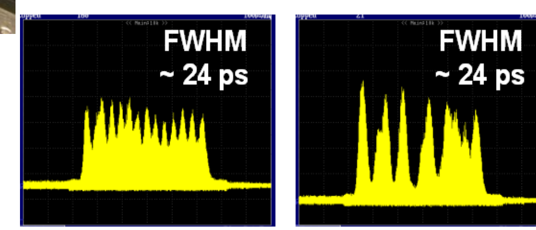
Will, Klemz, Optics Express
16 (2008) , 4922-14935

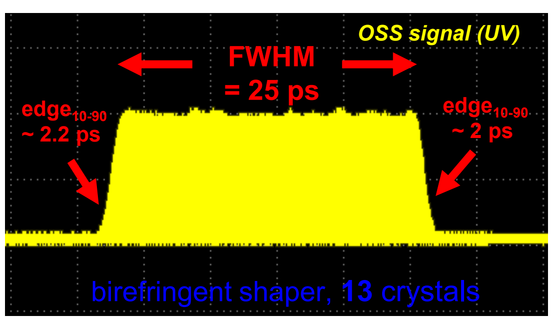
Gaussian:





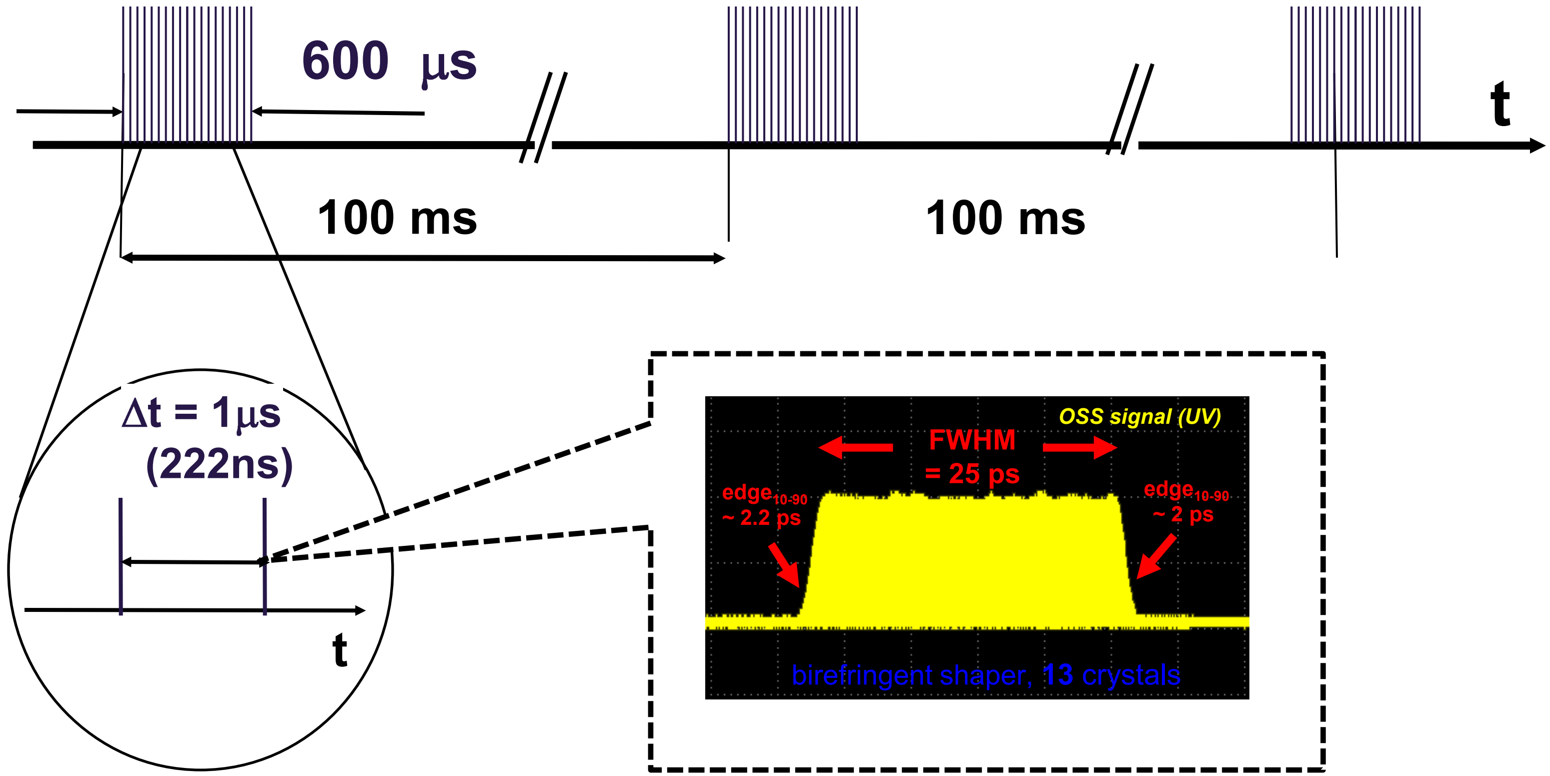
Simulated pulse-stacker





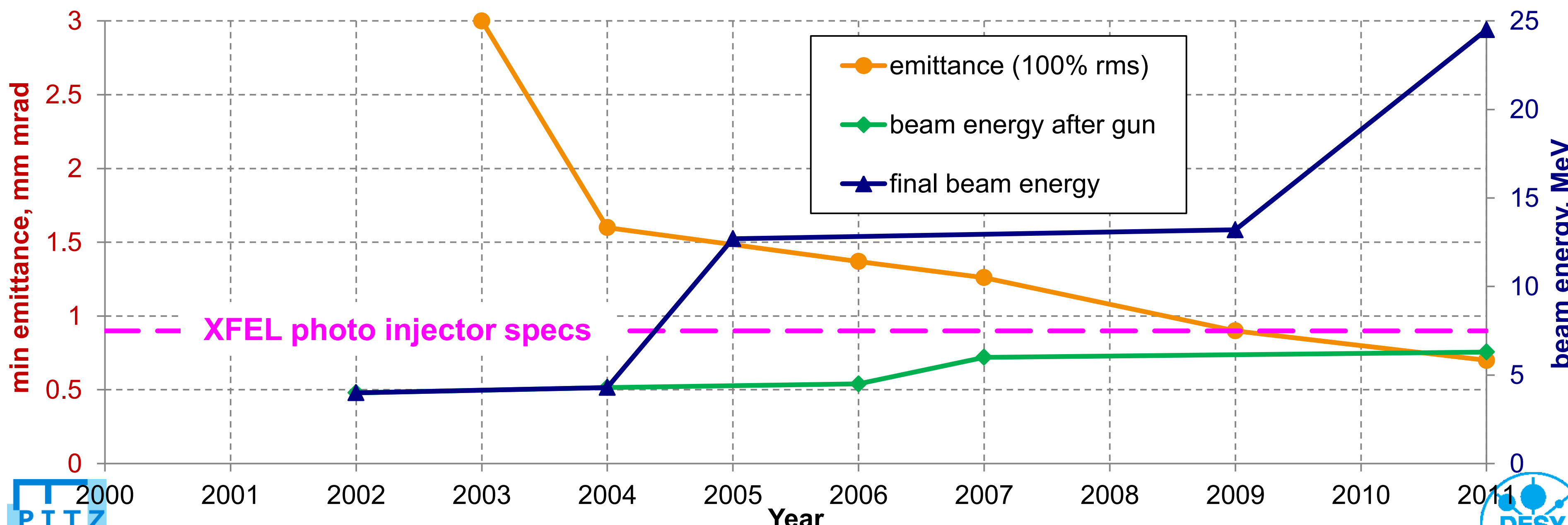
Time structure: PITZ (European XFEL)

Trains with up to 600 (2700) laser pulses → electron bunches of 1nC each



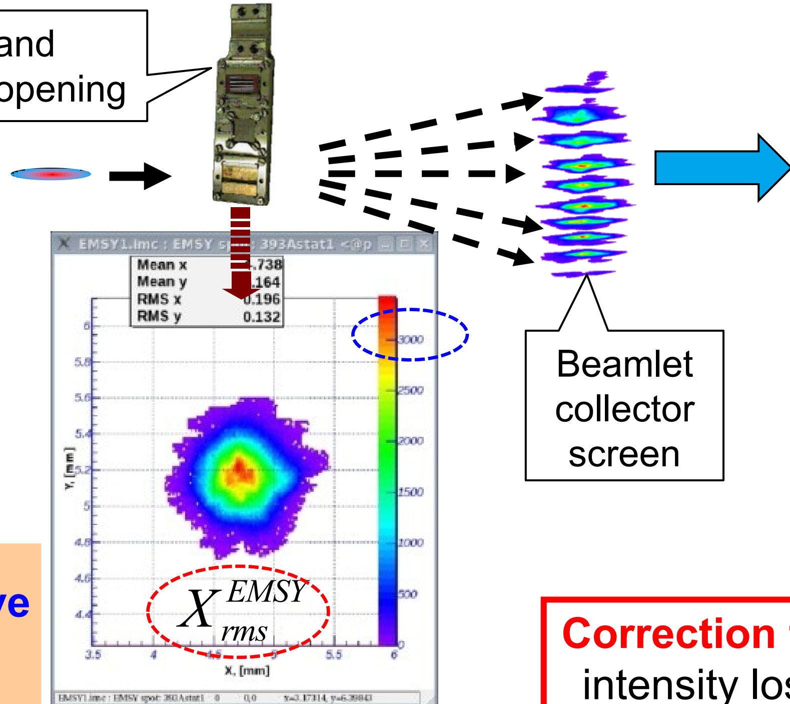
PITZ evolution 2000-2011

		2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
	Year-->	2002	2003 FLASH	2004	2005	2006 FLASH	2007	2008	2009 FLASH	2010	2011
gun	cavity	**gun-2**		**gun-1**		**gun-3.1**	**gun-3.2**	**gun-4.2**		**gun-4.1**	
	Ez	35MV/m	37MV/m	42MV/m-->60MV/m		43MV/m	60MV/m				
	beam energy	~4MeV		4.3MeV-->6MeV		4.5MeV	~6MeV				
booster	cavity	no			TESLA at 2.5m		TESLA at 3.1m			CDS at 3m	
	beam energy				~13MeV					~25MeV	
laser	temporal	10ps	6/24\6ps →				6/24\6ps	2/22\2ps →			
emittance	EMSY1 at	z=1.618m			z=4.3m		z=5.74m				
	Ldrift	1.01m			2.334m		2.64m				
	methodics	center BL	3xBLs		e-meter	11xBLs			detailed scan		
	min ε_{xy} (1nC) mm mrad		**3**	**1.5-1.7**		**1.37**	**1.26**		**0.9**		**0.7**

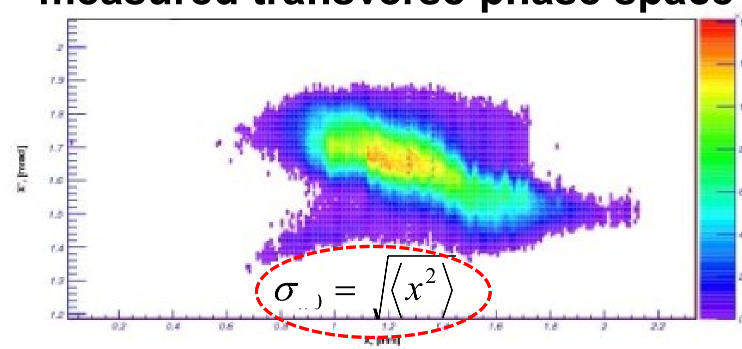


Slit scan technique at PITZ: how it works now

EMSY: screens and slits 10 (50) μm opening



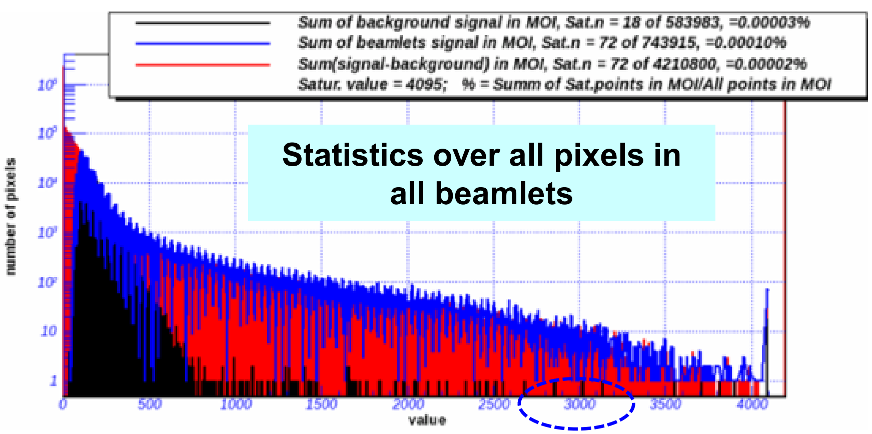
measured transverse phase space



$$\varepsilon = \beta\gamma \frac{X^{EMSY}_{rms}}{\sigma} \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

As conservative as possible !

Correction factor introduced to correct for low intensity losses from beamlet measurements



12-bit camera is important!

Quality criteria: max bit ≥3000 (at least from 4095=2^{12}-1 max)

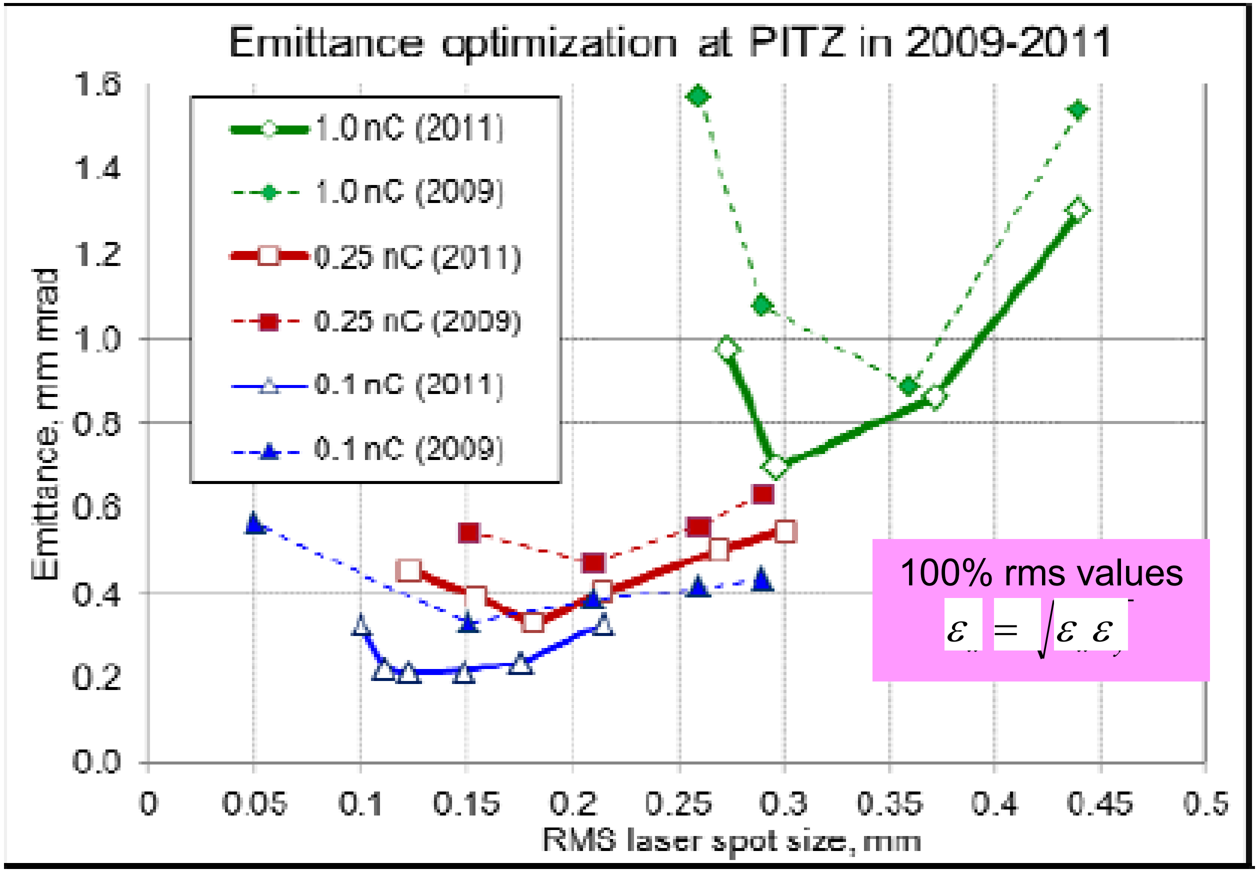
The emittance measurement procedure at PITZ:

- under permanent improvement in terms of resolution and sensitivity
- as conservative as possible **(100% rms emittance)!**

*!NB: measured emittance numbers are permanently **reducing** as a result of machine upgrades and extensive optimization*

"we are measuring more and more of less and less…"

Emittance Improvement 2009 → 2011



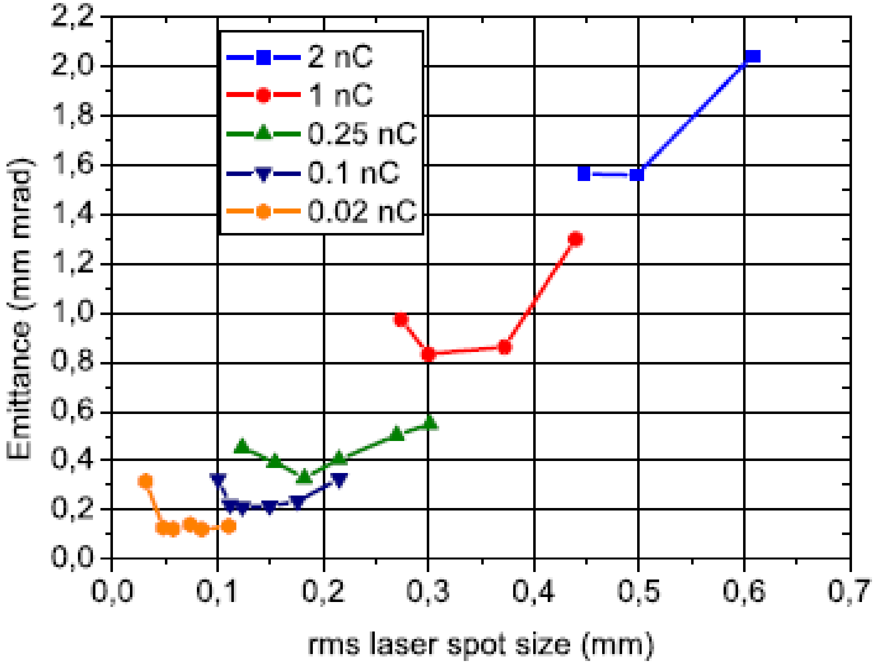
Q nC	ε(2011) mm mrad	δε(2011→2009) %
1.0	0.70	-20%
0.25	0.33	-30%
0.1	0.21	-35%

Improvements:

- Gun phase stability (10MW coupler+FB)
- Laser stability + beam transport
- Magnetizable components removing

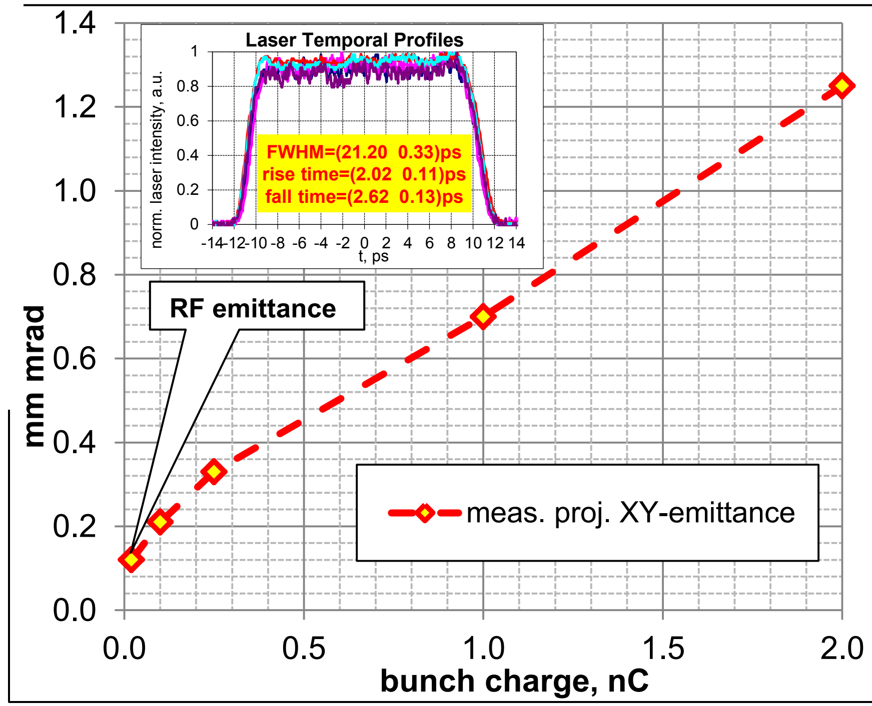
Better emittance improvement for lower bunch charges → due to the long pulse train operation (→ "3000-creteria" = f[gain,NoP])

Emittance vs. Laser Spot size for various charges



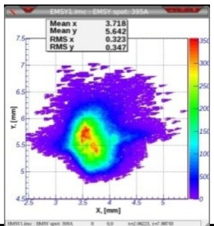
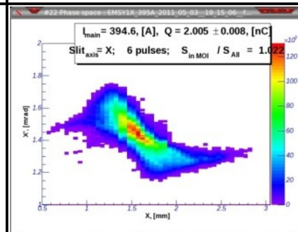
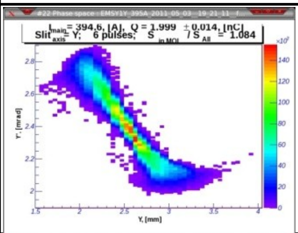
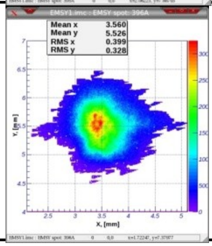
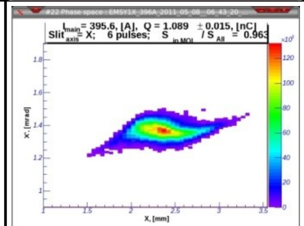
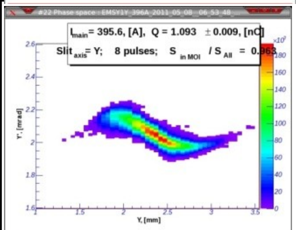
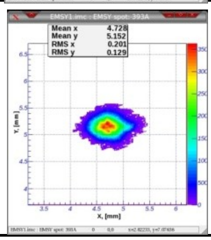
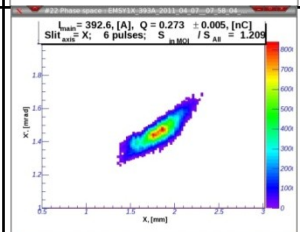
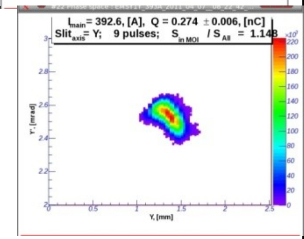
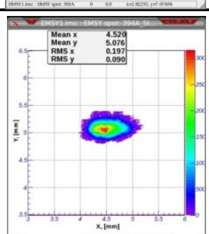
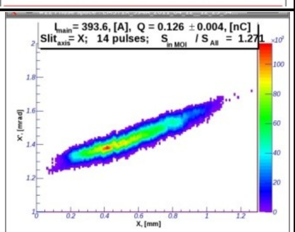
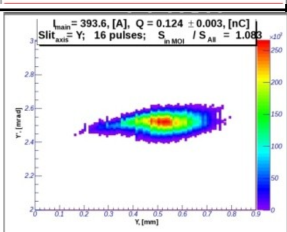
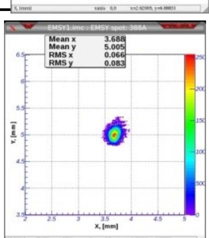
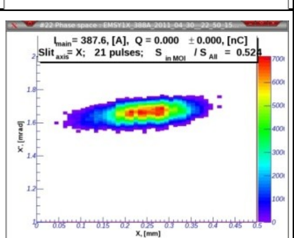
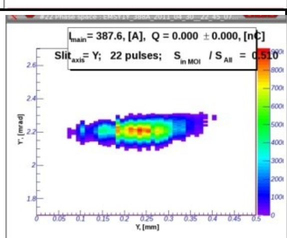
Minimum emittance measured in 2011 at PITZ

Charge, nC	100% rms xy-emittance,mm mrad
2	1.25±0.080
1	0.70±0.026
0.25	0.33±0.003
0.1	0.21±0.001
0.02	0.12±0.0005



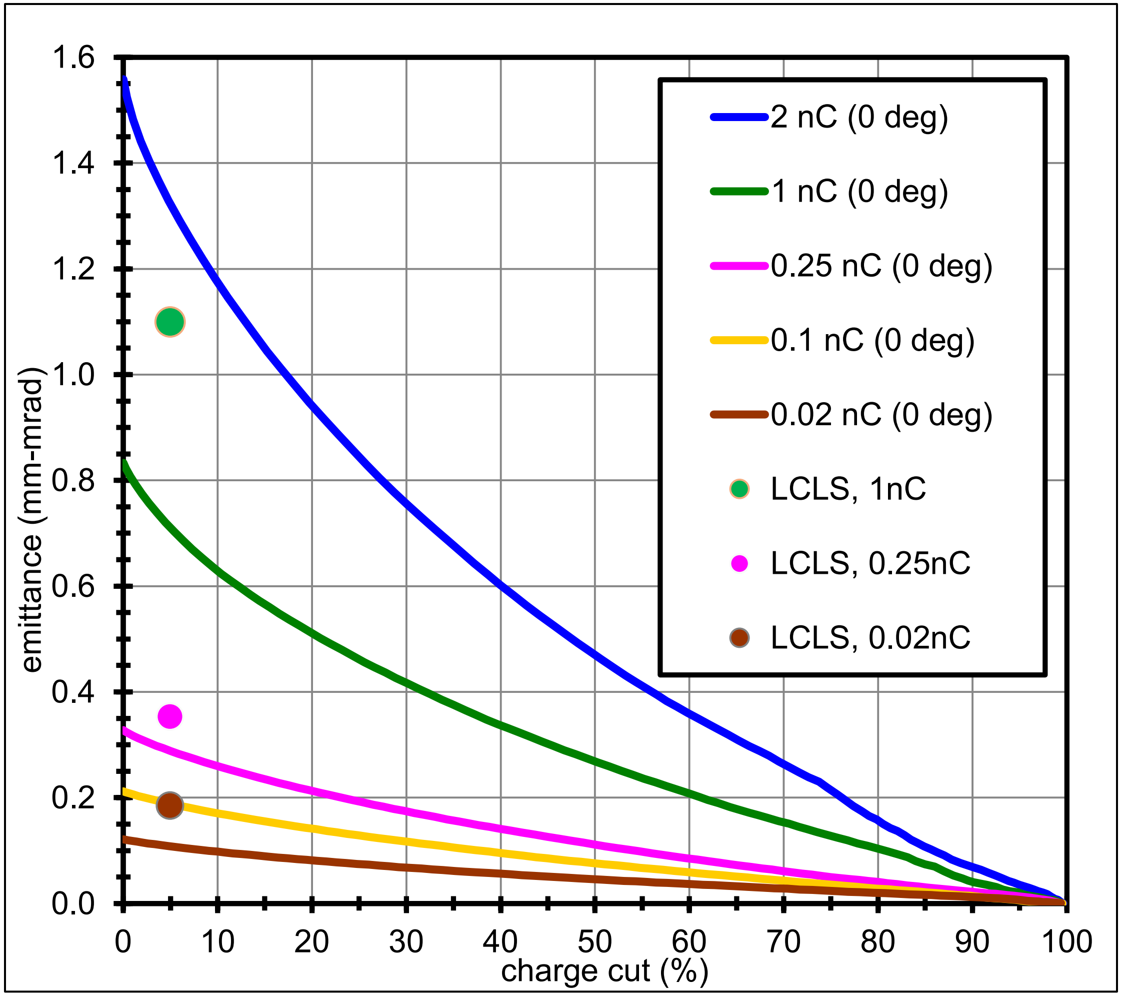
Measurements vs. simulations: rather good agreement in emittance values, but optimum machine parameters…

Measured Phase Space for various bunch charges

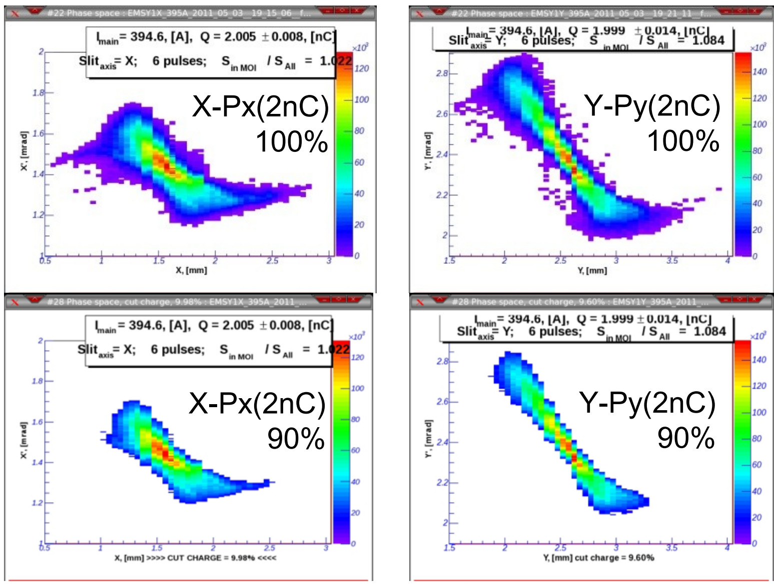
Qbunch / Las.XYrms	Beam at EMSY1: XY-Image	Beam at EMSY1: σ_x / σ_y	Horizontal phase space	Horizontal phase space: ε_x	Vertical phase space	Vertical phase space: ε_y	ϕ_{gun}
2 nC / 0.38 mm		0.323mm 0.347mm		1.209 mm mrad		1.296 mm mrad	+6deg
1 nC / 0.30 mm		0.399mm 0.328mm		0.766 mm mrad		0.653 mm mrad	+6deg
0.25 nC / 0.18 mm		0.201mm 0.129mm		0.350 mm mrad		0.291 mm mrad	0deg
0.1 nC / 0.12 mm		0.197mm 0.090mm		0.282 mm mrad		0.157 mm mrad	0deg
0.02 nC / 0.08 mm		0.066mm 0.083mm		0.111 mm mrad		0.129 mm mrad	0deg

zoomed

Core Emittance for various bunch charges



Charge, nC	PITZ, 100%, mm mrad	LCLS, 95% mm mrad
2	1.25	
1	0.70	1.10
0.7		0.80
0.25	0.33	0.35
0.1	0.21	
0.02	0.12	0.19



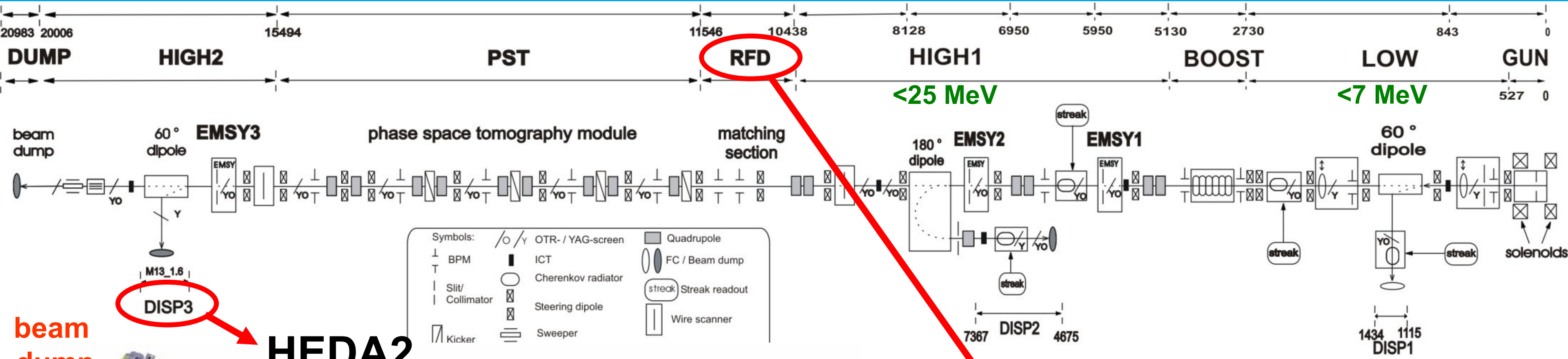
LCLS data:

- P. Emma, "Beam Brightness Measurements in the LCLS Injector“
- J. Frisch, "Operation and Upgrades of the LCLS", LINAC2010

Emittance Optimization at PITZ-1.8: Summary

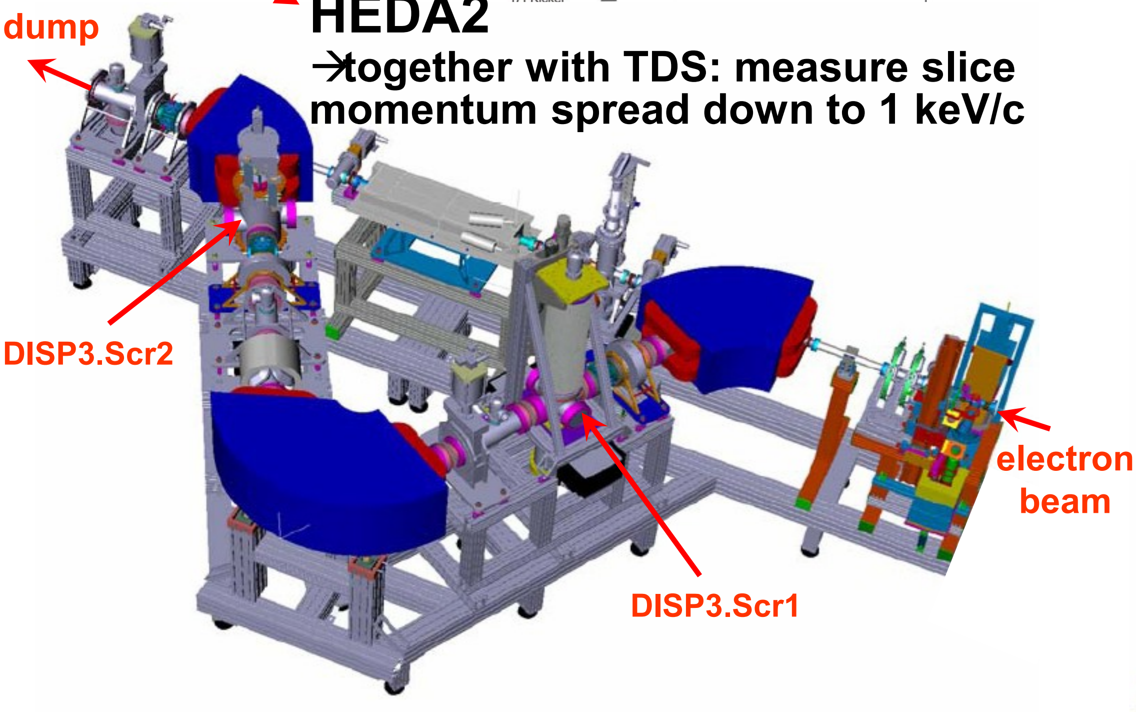
- PITZ has set a new benchmark for high brightness electron sources:
  - specs for the European XFEL have been demonstrated and surpassed (emittance <0.9 mm mrad at 1nC)
  - beam emittance has also been optimized for a wide range of bunch charge (20pC…2nC)
- Emittance measurement procedure
  - nominal method → single slit scan for detailed phase space reconstruction
  - as conservative as possible → 100% rms emittance
  - continuous improvement of the procedure
- Emittance measurements at PITZ:
  - 2009-2011 upgrade (gun phase stability) resulted in ~ 30% emittance value reduction
  - Optimized measured emittance (100% rms ε_{xy}):
    ε(20pC)=0.12mm mrad; ε(100pC)=0.21mm mrad; ε(250pC)=0.182mm mrad; ε(1nC)=0.70mm mrad; ε(2nC)=1.25 mm mrad
  - For chosen measurement conditions: emittance ~ linearly on the bunch charge
- PITZ serves also as a benchmark for theoretical understanding of the photo injector physics (beam dynamics simulations vs. measurements)
  - Rather good agreement on emittance values between measurements and simulations
  - Optimum machine parameters: simulations ≠ experiment (talk on Thursday)
- Outlook:
  - New klystron for the gun
  - New diagnostics for slice emittance and slice energy spread
  - XFEL gun conditioning and characterization

Outlook: PITZ upgrade ongoing this year



HEDA2

→together with TDS: measure slice momentum spread down to 1 keV/c



Transverse Deflecting Structure (TDS)

→time resolved measurements