

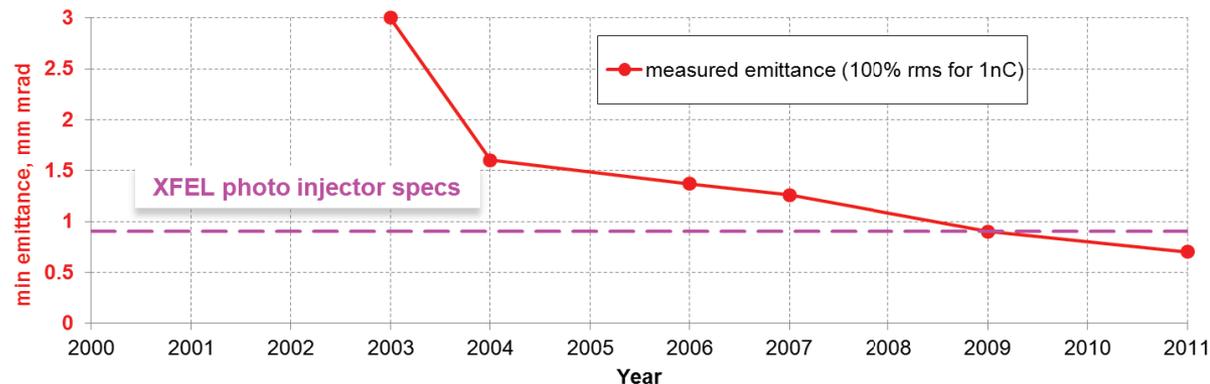
Photo Injector Test facility at DESY, Zeuthen site

PITZ EXPERIENCE ON THE EXPERIMENTAL OPTIMIZATION OF THE RF PHOTO INJECTOR FOR THE EUROPEAN XFEL

Mikhail Krasilnikov (DESY) for the PITZ Team

FEL 2013 conference, New York, USA, 27.08.2013

Year-->		2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
gun	cavity	gun-2		gun-1		gun-3.1	gun-3.2	gun-4.2		gun-4.1	
	E_z	35MV/m	37MV/m	42MV/m-->57MV/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	→		
	EMSY1 at	z=1.618m			z=4.3m		z=5.74m				
emittance	Ldrift	1.01m			2.334m		2.64m				
	methodics	center BL	3xBLS		e-meter	11xBLS			detailed scan		
	min ϵ_{xy} (1nC)		3	1.5-1.7		1.37	1.26	0.9		0.7	
	mm mrad										



Motivation: High Brightness Photo Injector for SASE FEL

Linac based Free Electron Laser



- > SASE FEL → high phase space density of electron bunches already from the source
High brightness electron source = small transverse emittance
- > 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 (FLASH and the European XFEL)

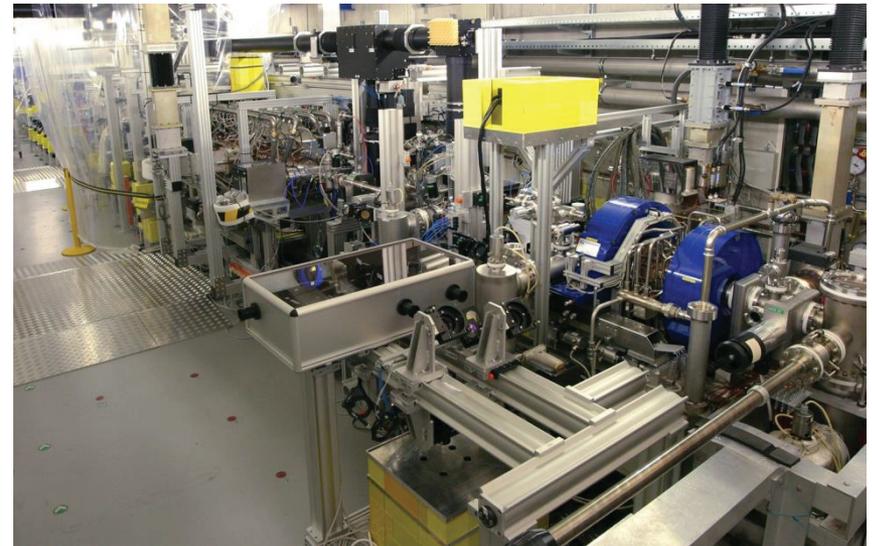


Photo Injector Test Facility at DESY in Zeuthen (PITZ)

> RF gun

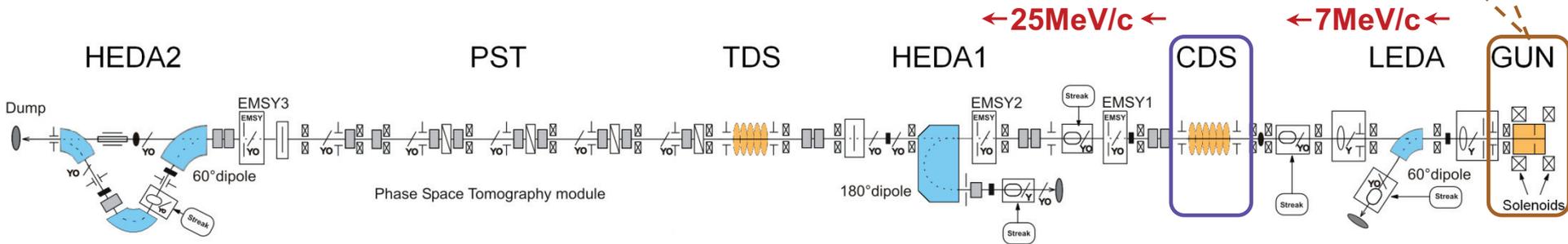
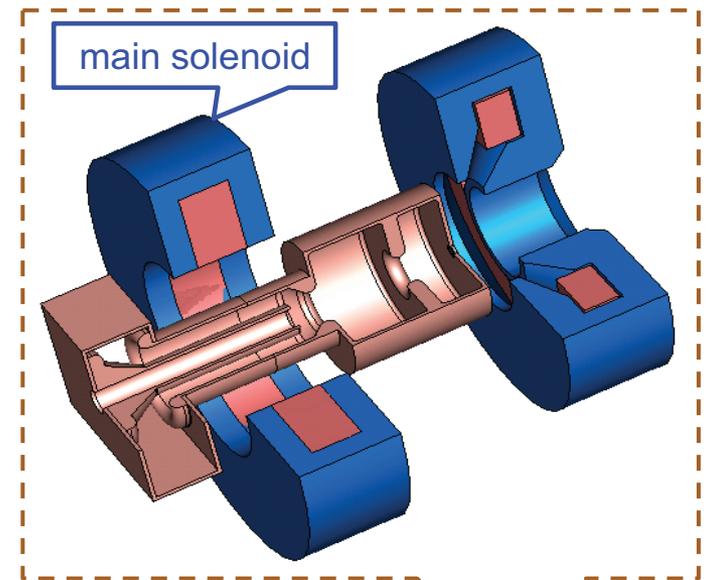
- L-band 1.6-cell copper cavity
- Dry ice cleaning → low dark current (<100uA@6MW)
- Cs₂Te photocathode (QE~5-10%)
- LLRF control for amplitude and phase stability
- Solenoid for emittance compensation

> Photocathode laser

- Pulse train structure
- Micropulse temporal shaping

> CDS booster

- L-band, 14-cell copper Cut-Disc-Structure
- Matching → emittance conservation

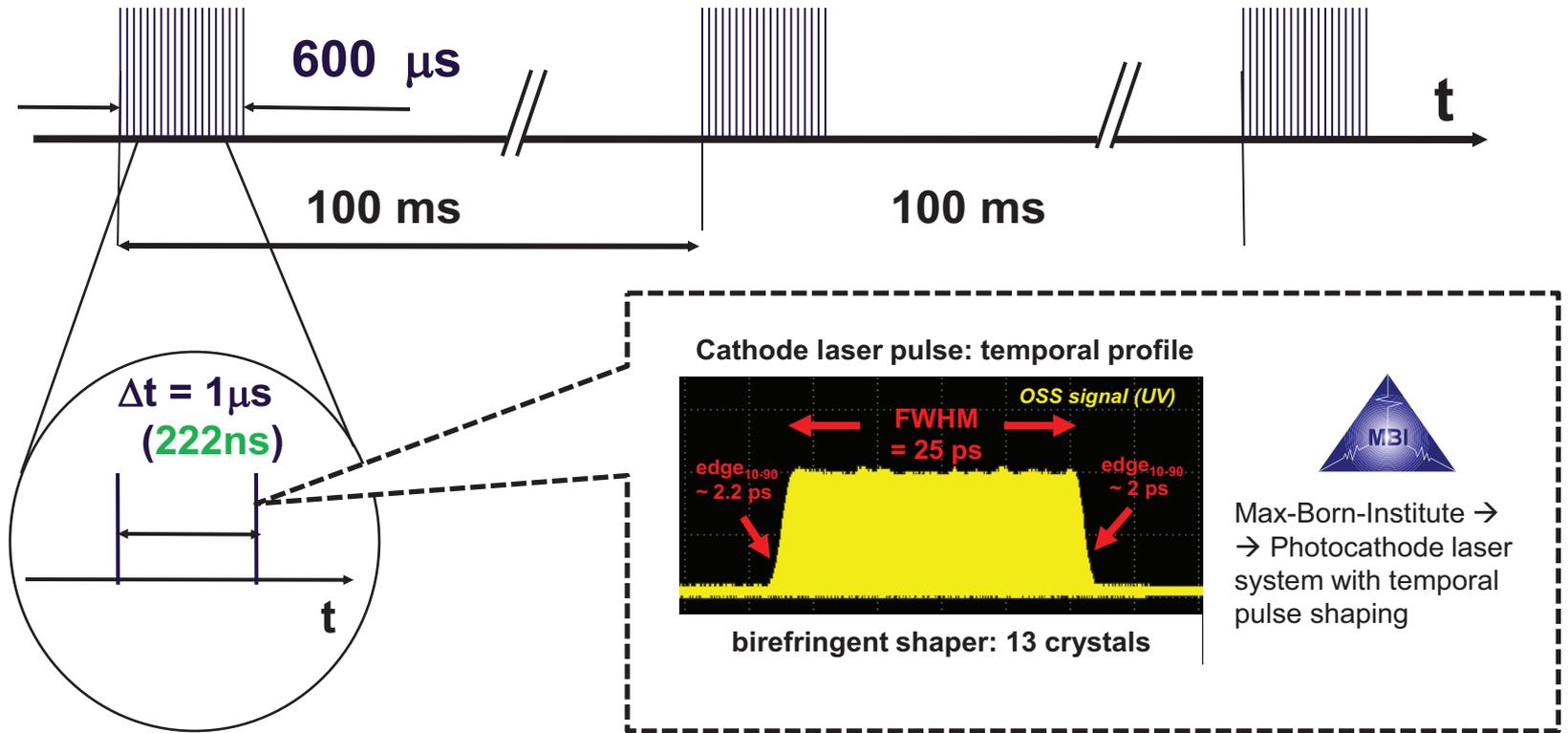


XFEL Photo Injector Performance Requirements → PITZ

subsystem	parameter	value	remarks
RF gun cavity	frequency	1.3 GHz	L-band 10MW MBK
	E-field at cathode	60 MV/m	dark current issue
	RF pulse duration	650 us	max
	Repetition rate	10 Hz	max
Cathode laser	Temporal → flat top → FWHM	~20 ps	challenge  ~20ps 
	Temporal → flat top → rise/fall 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	0.02-1nC (Post-TDR)
	Projected emittance at injector	0.9 mm mrad	→ for 1 nC
	Bunch peak current	5 kA	after bunch compression (not at PITZ)
	Emittance (slice) at undulator	1.4 mm mrad	0.4-1.0 mm mrad (Post-TDR)

Pulse Train Time Structure: PITZ and European XFEL

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

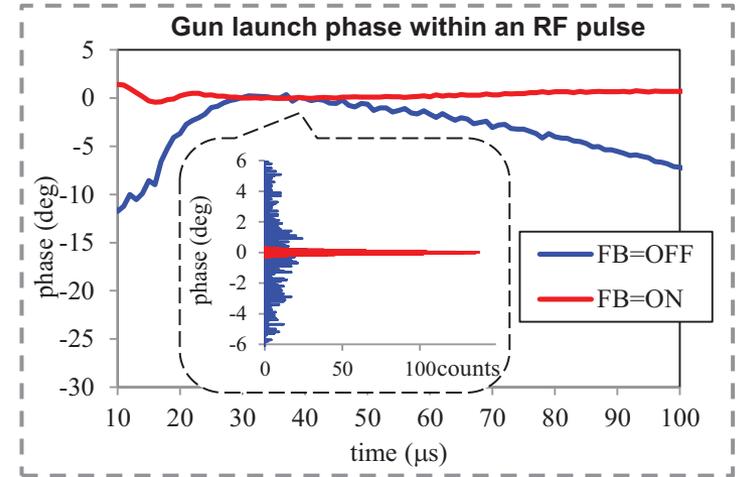


27000 electron bunches per second

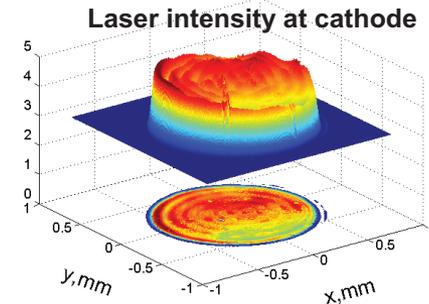
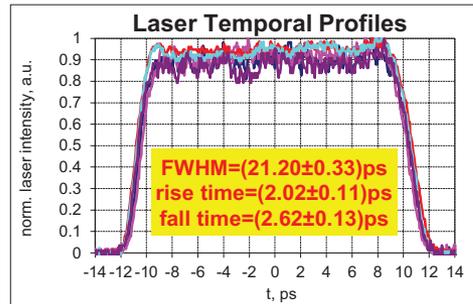
How to achieve small emittance

- High **gradient** at the cathode $\sim 60\text{MV/m}$ (1.3GHz)
- Gun launch **phase** stability

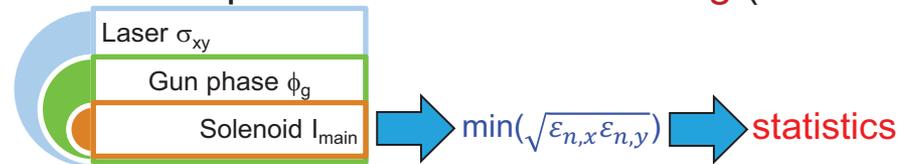
10-MW in-vacuum directional coupler



- Cathode laser pulse **shaping**



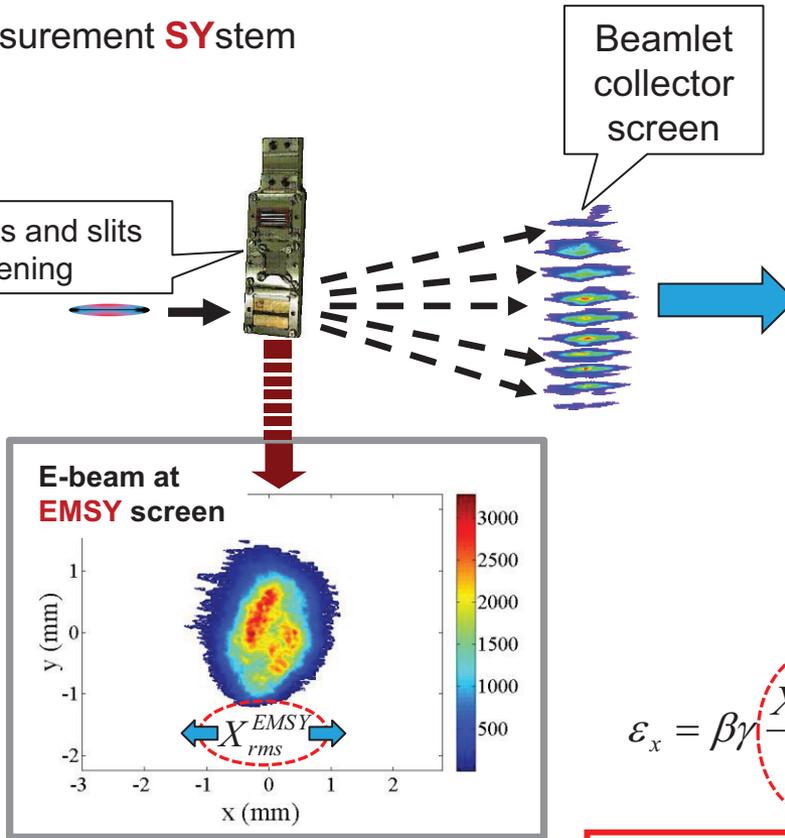
- Beam based **alignment**, trajectory optimization
- Emittance compensation and conservation \rightarrow multi parametric machine **tuning** (solenoid, laser spot size, gun phase, booster,...)



Slit Scan Technique for Emittance Measurements at PITZ

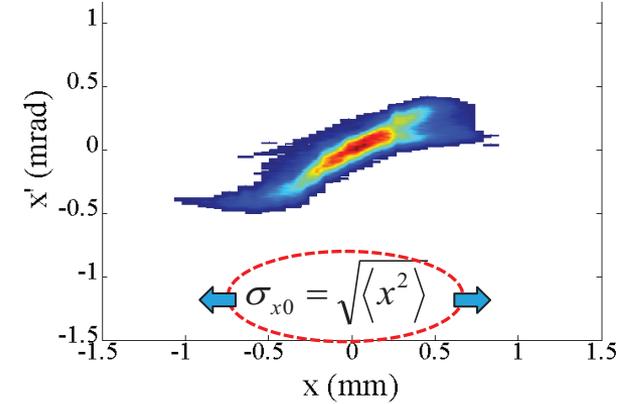
Emittance Measurement **S**ystem

EMSY: screens and slits
10 (50) μm opening



Beamlet collector screen

measured transverse phase space



As conservative as possible!

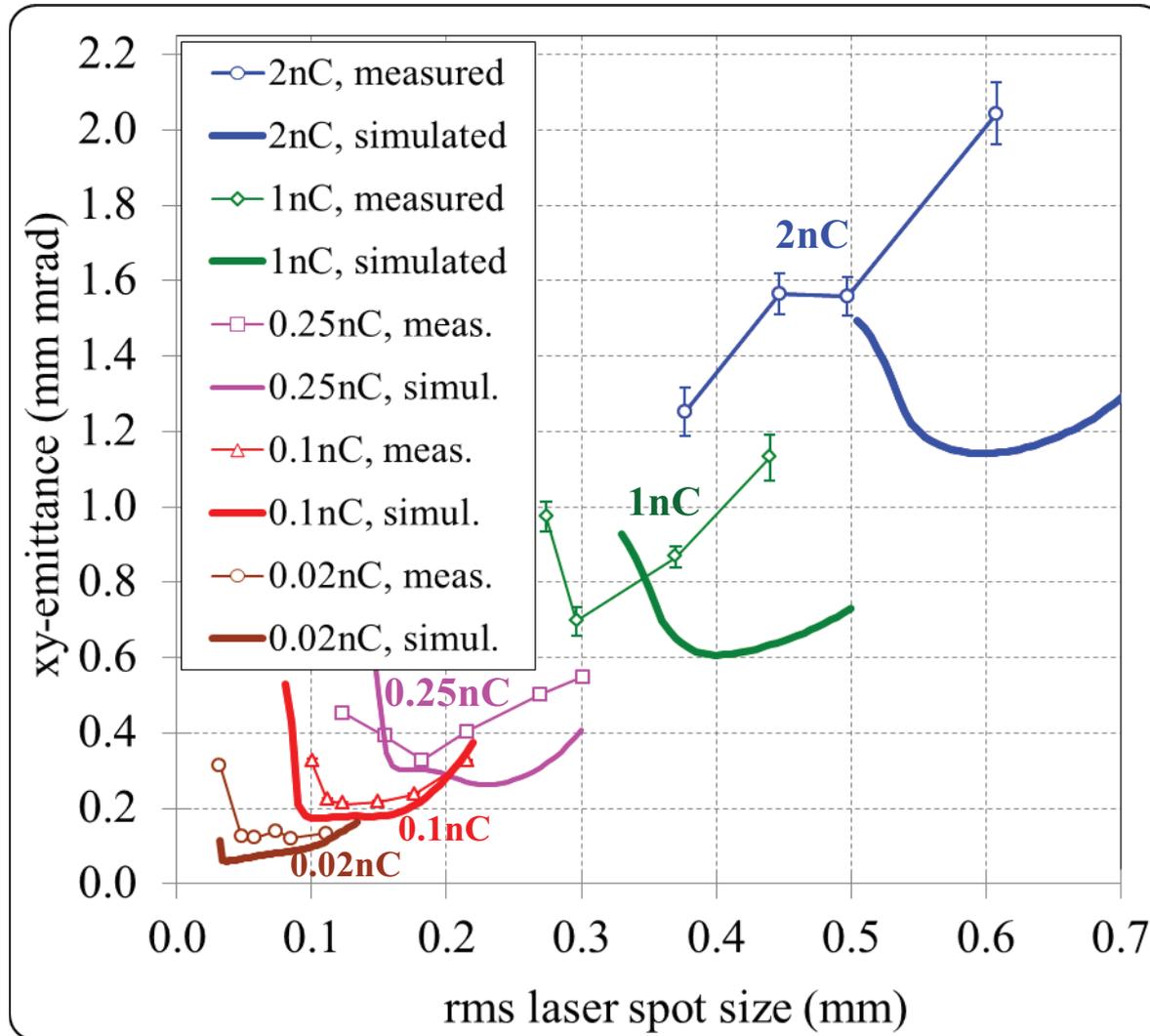
$$\epsilon_x = \beta\gamma \frac{X_{rms}^{EMSY}}{\sigma_{x0}} \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2} \rightarrow \text{"100%" rms emittance}$$

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

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

Emittance versus Laser Spot Size for various Charges

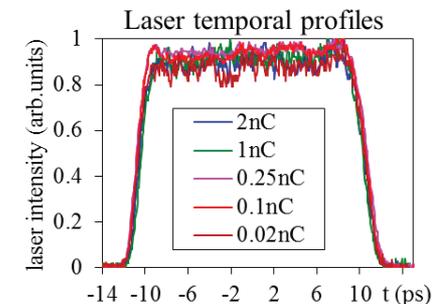
Measured (100%) rms normalized emittance vs. simulations



Minimum emittance ($\sqrt{\epsilon_{n,x}\epsilon_{n,y}}$)

Charge, nC	Measured, mm mrad	Simulated, mm mrad
2	1.25±0.06	1.14
1	0.70±0.02	0.61
0.25	0.33±0.01	0.26
0.1	0.21±0.01	0.17
0.02	0.121±0.001	0.06

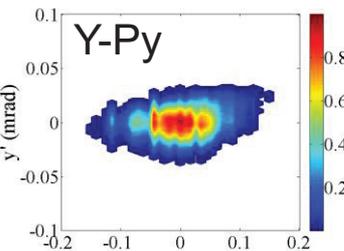
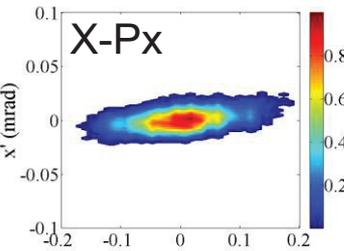
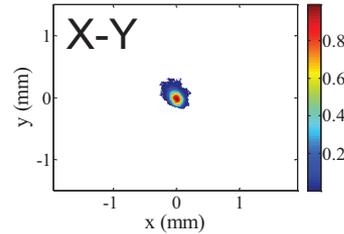
- Optimum machine parameters (laser spot size, gun phase):
experiment ≠ simulations
- Difference in the **optimum laser spot size** is bigger for higher charges (~good agreement for 100pC)
- Simulations of the **emission** needs to be improved



Emittance and Brightness versus Bunch Charge

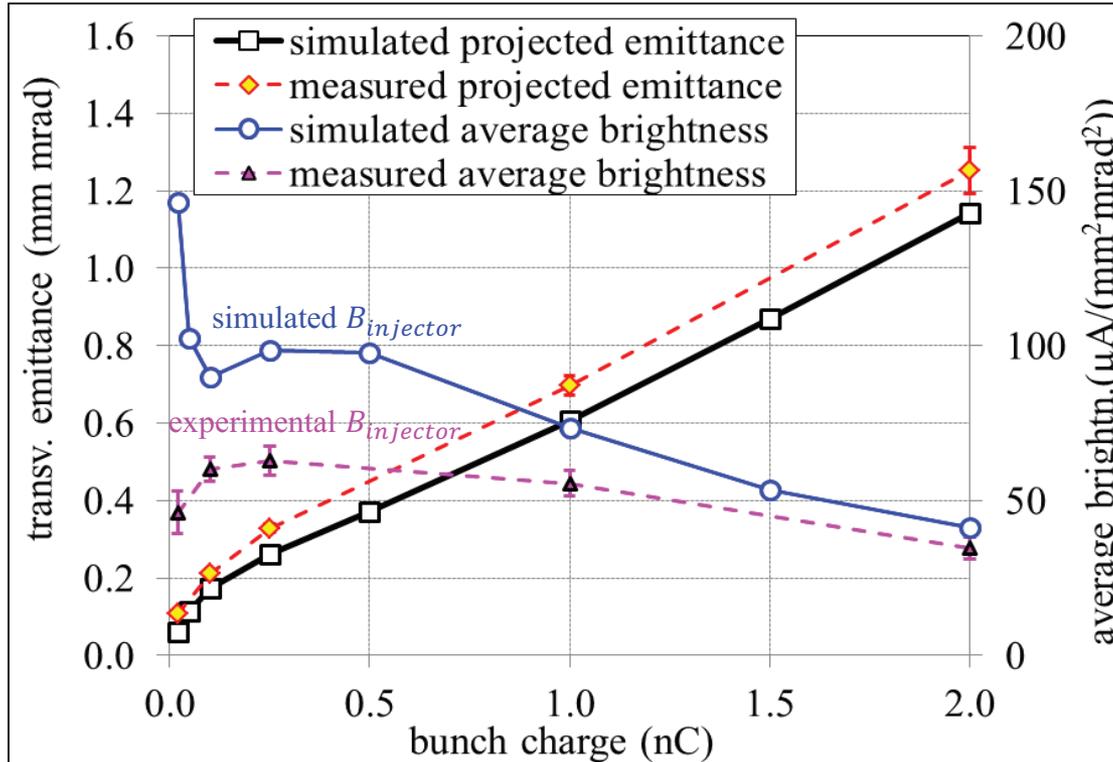
Cathode laser pulse duration was **fixed at 21.5 ps (FWHM)** for all bunch charges!

20pC measured



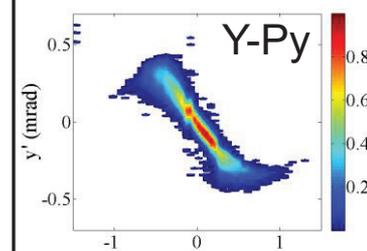
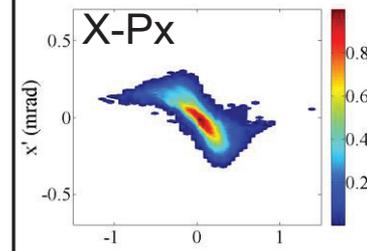
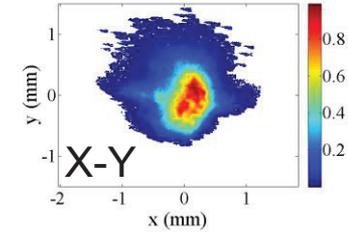
~linear SC

$$B_{injector} = \frac{I_{injector}}{\epsilon_x \epsilon_y} = \frac{Q \cdot NoP \cdot RR}{\epsilon_x \epsilon_y}$$



Bunch charge reduction at fixed cathode laser pulse duration \rightarrow space charge (SC) modification

2nC measured



nonlinear SC

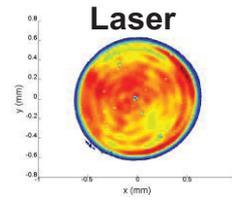
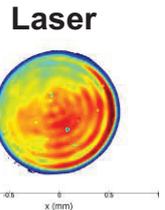
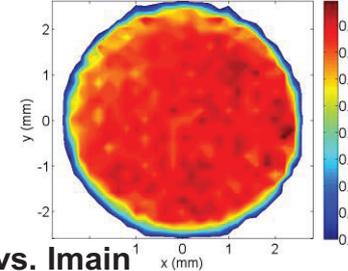
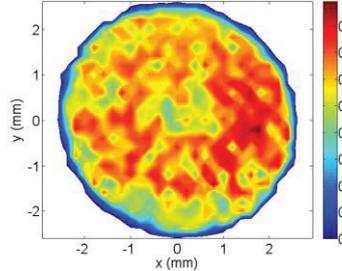
Emission Area Homogeneity

Cs2Te cathode#110.2

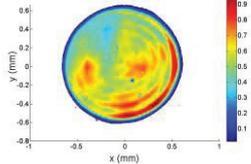
Cs2Te cathode#11.3

Cathode QE map

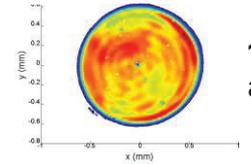
Cathode QE map



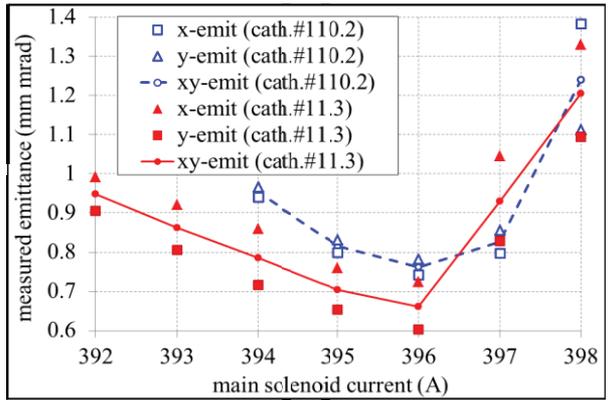
~emission area



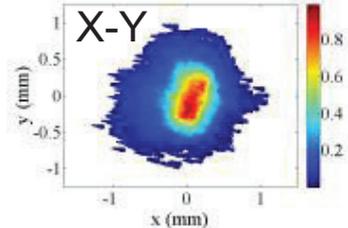
~emission area



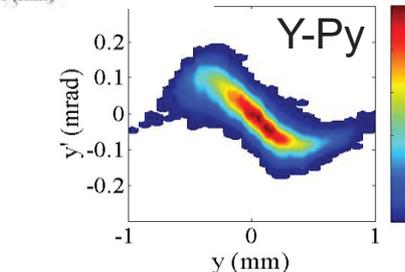
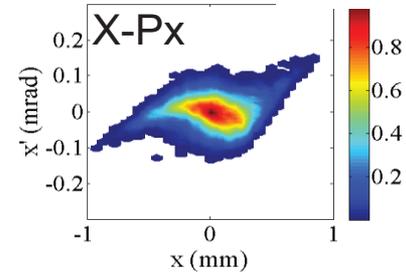
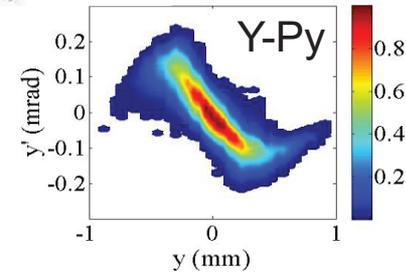
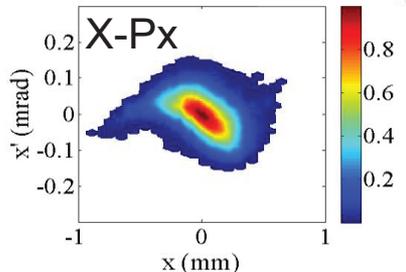
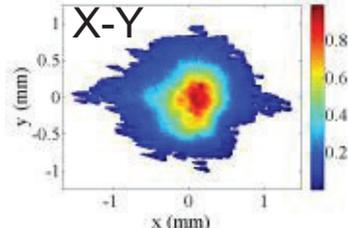
Measured 1nC emittance vs. I_{main}



E-beam →



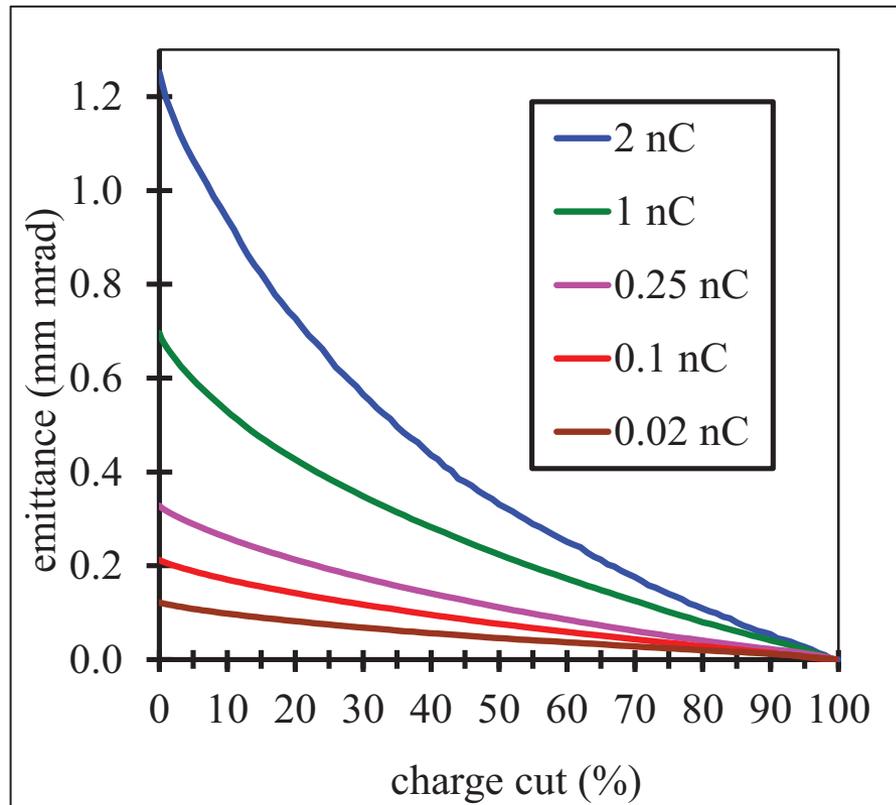
← E-beam



$$\min(\sqrt{\epsilon_{n,x}\epsilon_{n,y}}) = 0.762 \pm 0.017 \text{ mm mrad}$$

$$\min(\sqrt{\epsilon_{n,x}\epsilon_{n,y}}) = 0.661 \pm 0.033 \text{ mm mrad}$$

Core Emittance

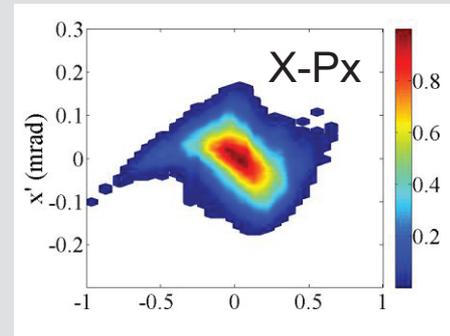


Raw phase space (100%) → intensity cut → charge cut → core emittance

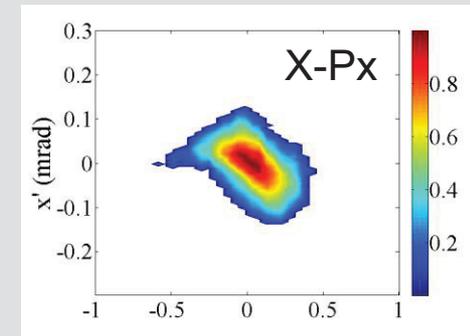
Measured Transverse Phase Space (1nC)

100%

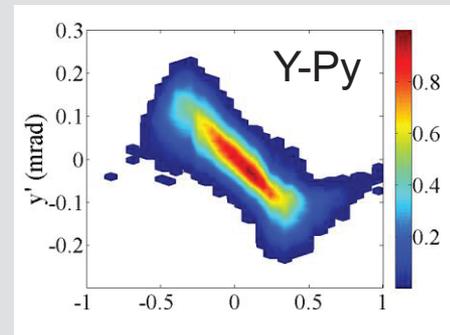
90%



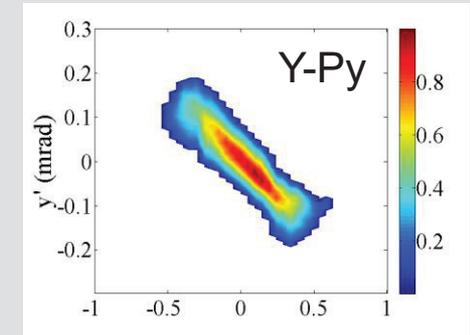
$$\epsilon_{n,x}(100\%) = 0.707 \text{ mm mrad}$$



$$\epsilon_{n,x}(90\%) = 0.543 \text{ mm mrad}$$



$$\epsilon_{n,y}(100\%) = 0.685 \text{ mm mrad}$$



$$\epsilon_{n,y}(90\%) = 0.515 \text{ mm mrad}$$

Conclusions and Outlook

> The Photo Injector Test facility at DESY in Zeuthen (PITZ) develops **high brightness** electron sources for SASE FELs:

- specs for the European XFEL have been demonstrated and surpassed (emittance <0.9 mm mrad at 1nC)
- XFEL gun conditioned at PITZ (**TUPSO30**) → Hamburg in July 2013
- beam emittance has also been optimized for a wide range of bunch charge (20pC...2nC)
- optimized measured emittance:

Q	$\min(\sqrt{\varepsilon_{n,x}\varepsilon_{n,y}}), 100\%$ mm mrad	$\min(\sqrt{\varepsilon_{n,x}\varepsilon_{n,y}}), 90\%$ mm mrad
20 pC	0.12	0.10
100 pC	0.21	0.17
250 pC	0.33	0.26
1 nC	0.70	0.53
2 nC	1.25	0.94

> PITZ serves also as a benchmark for **theoretical understanding** of the photo injector physics (beam dynamics simulations vs. measurements)

- rather good agreement on emittance minima between measurements and simulations
- optimum machine parameters: **simulations ≠ experiment**
- simulations of the **emission** needs to be improved

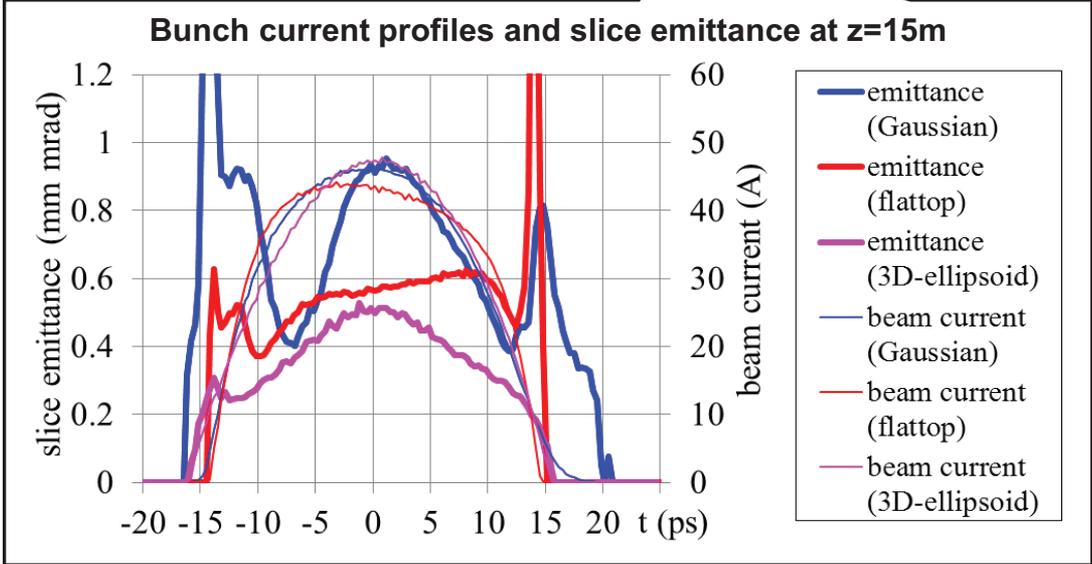
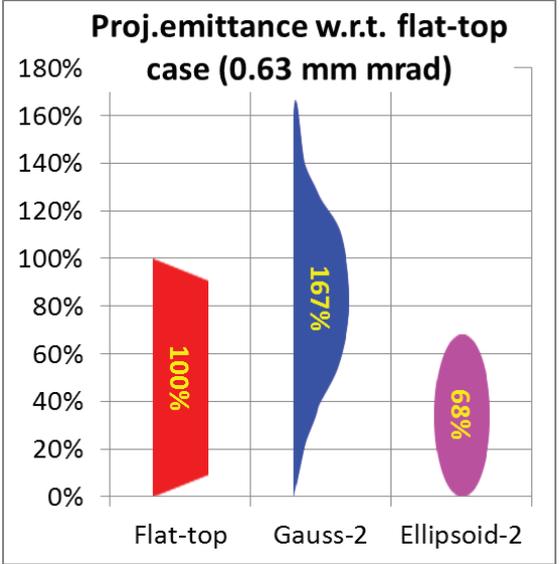
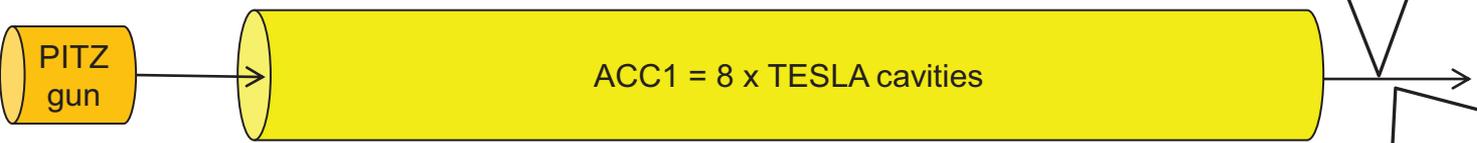
> Outlook:

- **slice** diagnostics (RF deflector) → transverse emittance and longitudinal phase space
- next step in optimization → **3D ellipsoidal** cathode laser pulses → BMBF and HGF projects (collaboration DESY-IAP-JINR)

Outlook: Beam Dynamics Simulations: XFEL Photo Injector (1nC)


 → Various shapes of the photocathode laser pulse
 (Gaussian and Flattop temporal profiles vs. 3D-ellipsoid)

$z=15\text{m}$
 $E_{beam} \sim 150\text{MeV}$
 $\sigma_t \sim 7\text{ps}$



- 3D ellipsoidal cathode laser pulses → Major improvements on beam emittance
- Developments of the new laser system are on-going → more details → TUPS036, TUPS039

Acknowledgements

PITZ Team

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INR, Moscow: V. Paramonov

HZB, Berlin: D. Richter

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Thank you for your attention!