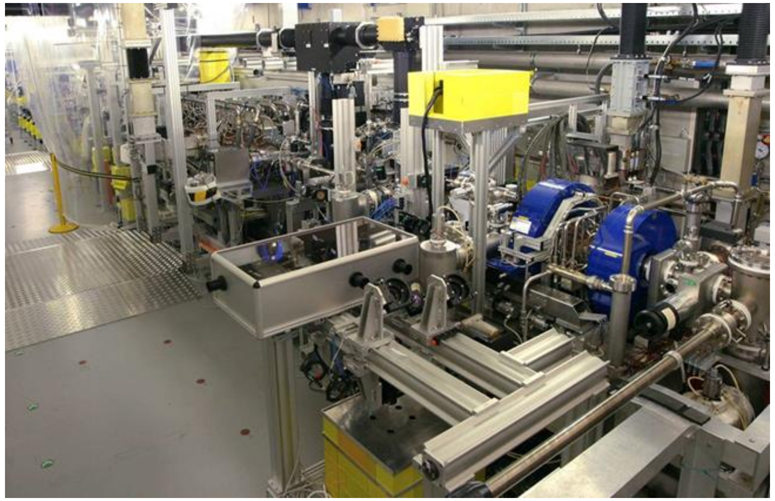
Transverse emittance measurements at PITZ

Transverse emittance measurements of space charge dominated beams at the Photo Injector Test facility at DESY, Zeuthen site (PITZ)



Mikhail Krasilnikov
Topical Workshop on “Emittance Measurements for Light Sources and FELs”,
ALBA Synchrotron January 29 - 30, 2018

Outline:
- PITZ facility
- Beam dynamics simulations
- Procedures to measure transverse emittance
- Emittance measurements of space charge dominated beams
- Emittance measurements at PITZ

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY

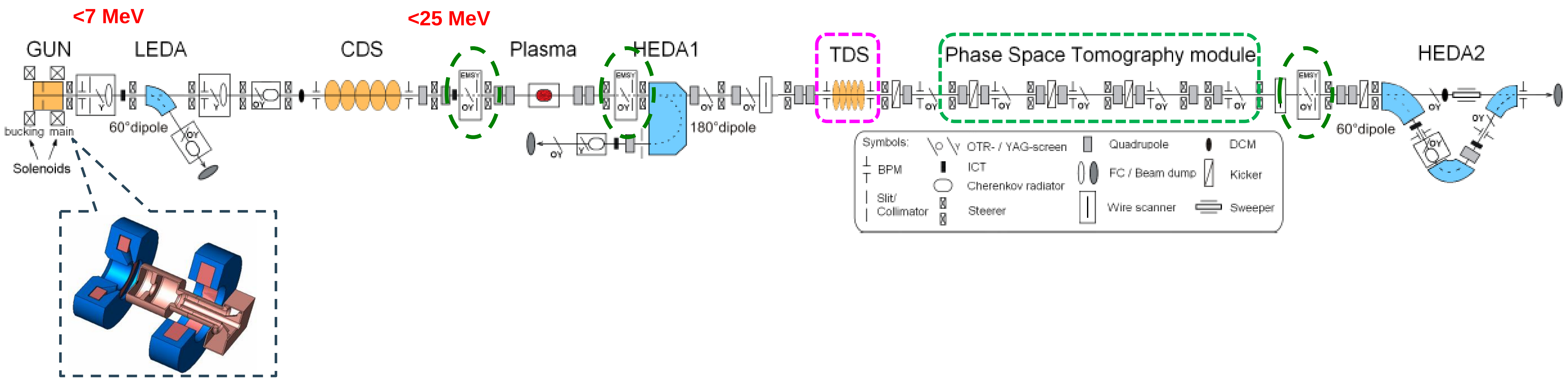
PITZ facility

Photo Injector test facility for high brightness electron source optimization

Photo Injector Test facility at DESY, Zeuthen site (PITZ)

PITZ focuses on the development, test and optimization of high brightness e-sources for SC linac driven FELs:

- test-bed for FEL injectors: FLASH, the **European XFEL** (conditioning and characterization of gun cavities and photo injector subsystems, e.g. photocathode laser)
- **high brightness → small ε_{tr} (projected and slice)**
- further studies → e.g. cathodes: dark current, photoemission, QE, thermal emittance, …

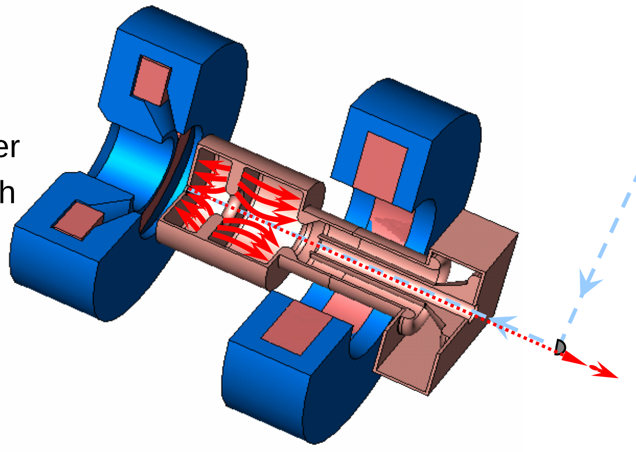


PITZ "engine": RF-Gun and Photocathode (PC) Laser

Highlights of the facility

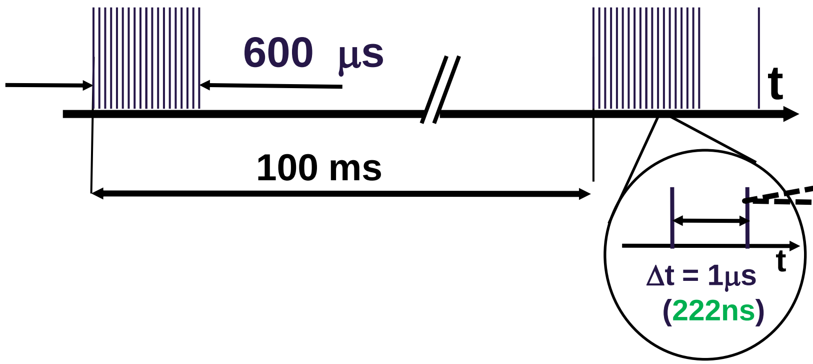
RF gun

- L-band (1.3 GHz) 1.6-cell copper cavity
- Ecath>~60MV/m → 7MeV/c e-beams
- 650us x 10Hz → up to 45 kW av. RF power
- Cs_2Te PC (QE~5-10%) → up to 5nC/bunch
- LLRF control for amp&phase stability
- Solenoid for emittance compensation



Pulse Train Time Structure:

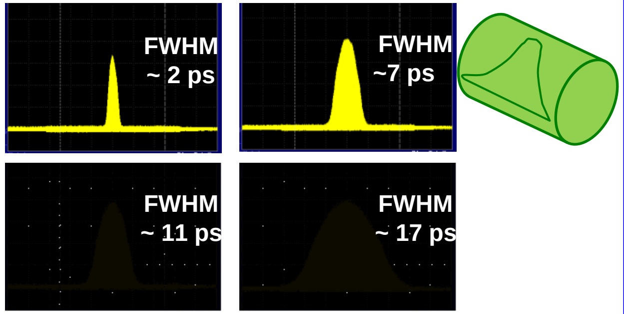
PITZ and **EXFEL** trains with up to 600 (2700) laser pulses



Photocathode laser(s) (UV)

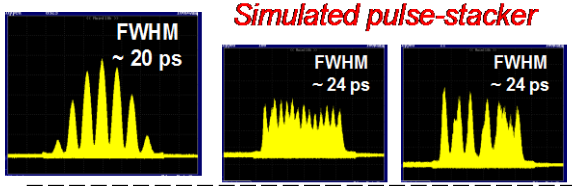
Default PC laser system (Max-Born-Institute, Berlin)

Gaussian:

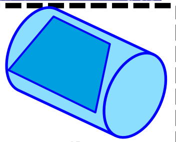


Multicrystal birefringent pulse shaper containing 13 crystals

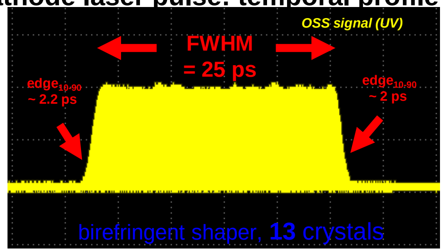
Simulated pulse-stacker



Flattop



Cathode laser pulse: temporal profile



Institute of Applied Physics of the Russian Academy of Sciences

New PC laser ELLA

3D (ellipsoidal) pulse shaper:

- SLM based
- Upgrade with VBG

Oscillator upgrade – Pharos-20W-1MHz frontend

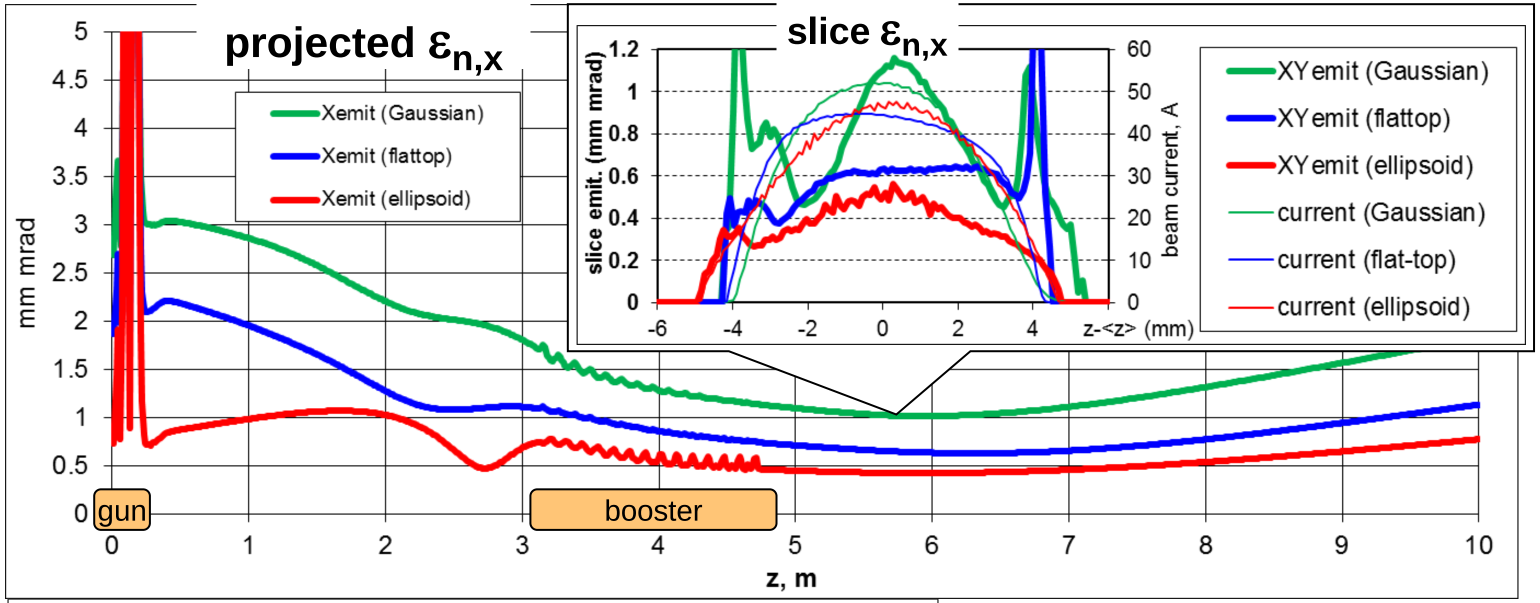
Pulse length 0.25-10ps+

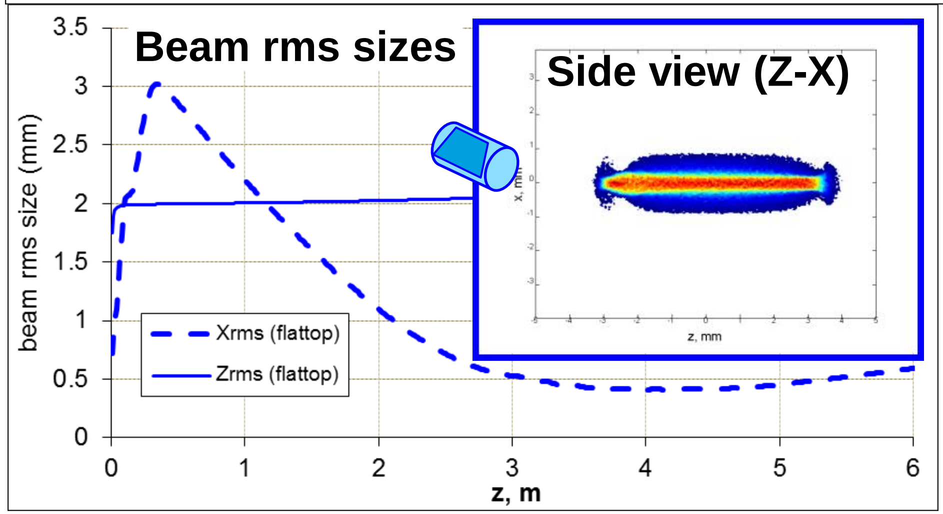
Beam Dynamics Simulations

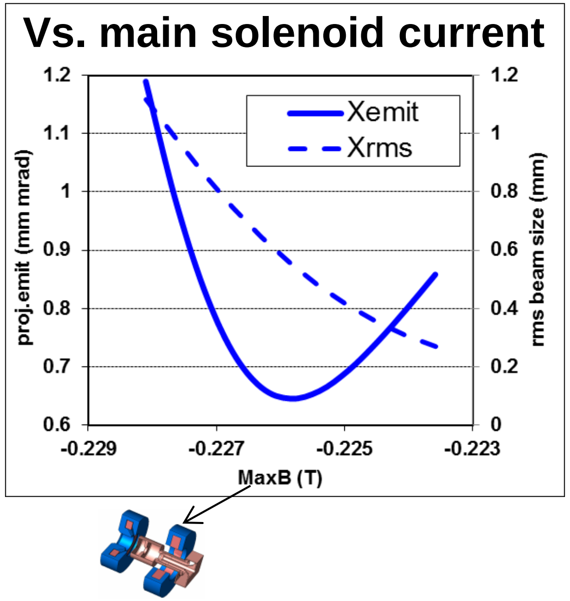
ASTRA simulations for PITZ setup with 3 shapes of the photocathode laser pulse

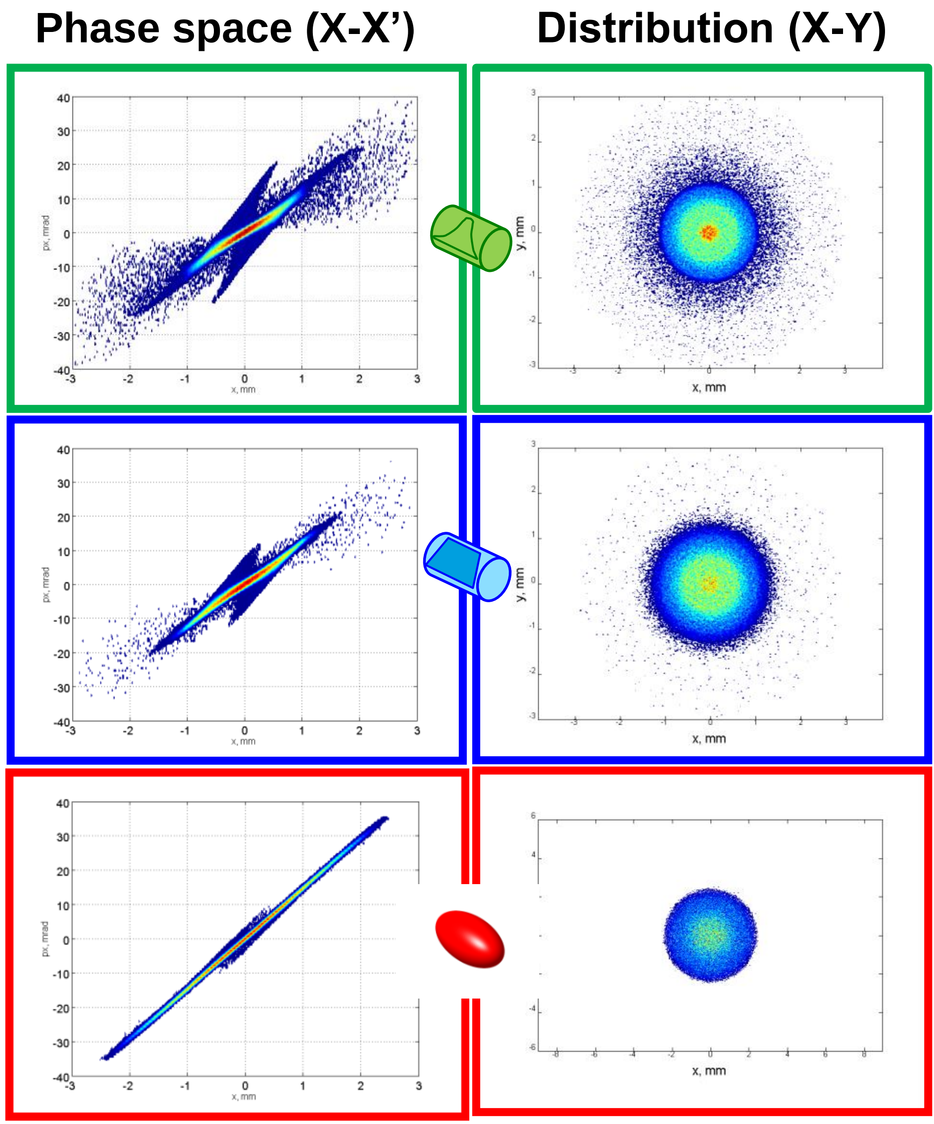
Beam Dynamics Simulations (ASTRA)

PITZ setup, 1nC bunch charge optimization for 3 photocathode laser pulse shapes







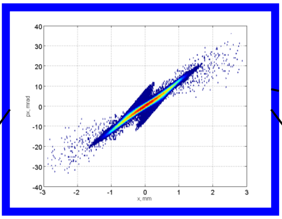


Procedures to measure transverse emittance in photo injectors

Optimization of transverse phase space in photo injectors

Transverse Phase Space Measurements

Emittance measurements in Photo Injectors



CSR (undulator) based?

Space charge dominated

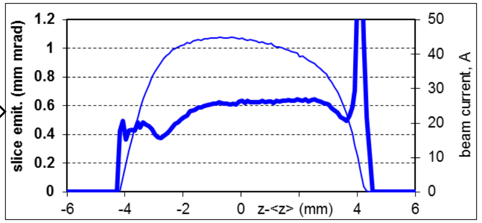
Emittance dominated

Slit mask techniques:
- based on conversion of a **space charge dominated** beam **into emittance dominated** beamlets

- Multi screen:
  - Based on linear beam matrix approach
  - 3 beam size measurements (at 3 positions) are needed for the known elements of the transport matrix (phase advance)
- Quad(s) scan
  - Beam size measurements as a function of varied transport matrix
- Tomography
  - Related to Radon theorem: N-dim object reconstruction from M projections in (N-1) dim space

× Time resolved

Slice emittance measurements



Emittance measurements of space charge dominated beams

Slit techniques to reconstruct transverse phase space

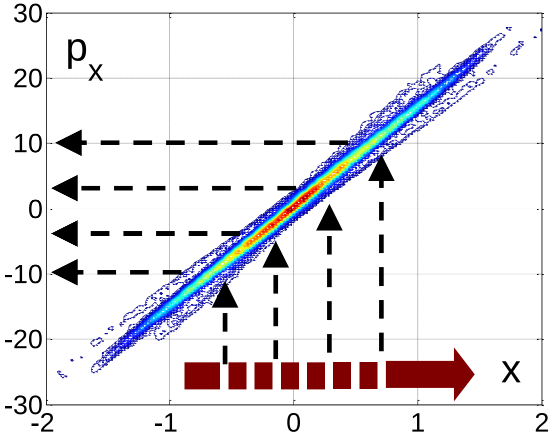
Slit technique - general

Space charge dominated beam → emittance (divergence) dominated beamlet

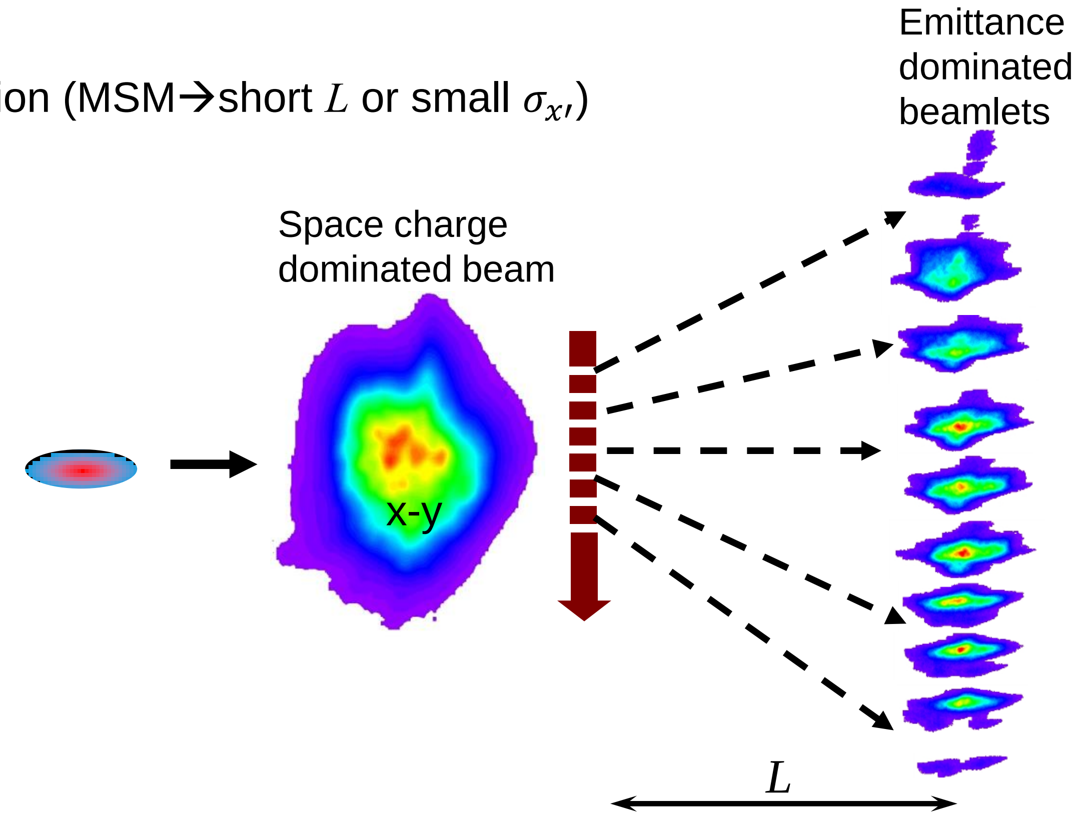
Multi slit mask (MSM) = single shot measurement, but:

- Overlapping of beamlets when optimized for high resolution (MSM→short L or small $\sigma_{x'}$)
- Small beam size →low sampling of the phase space

➔ Scanning with a single slit



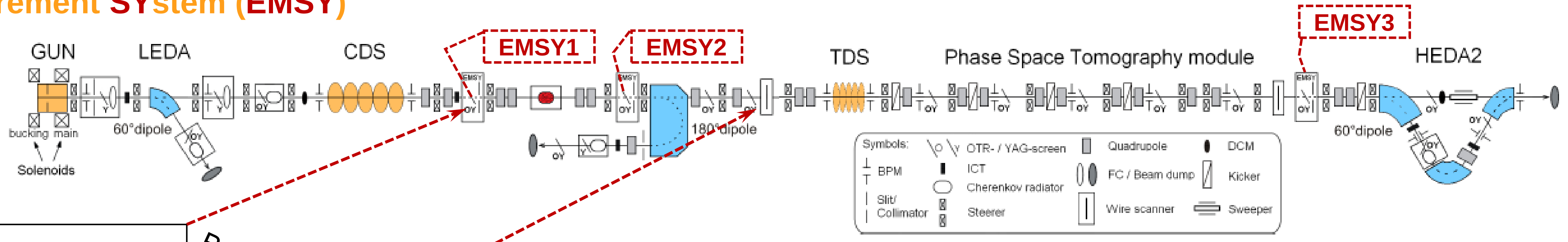
Transverse phase space reconstruction



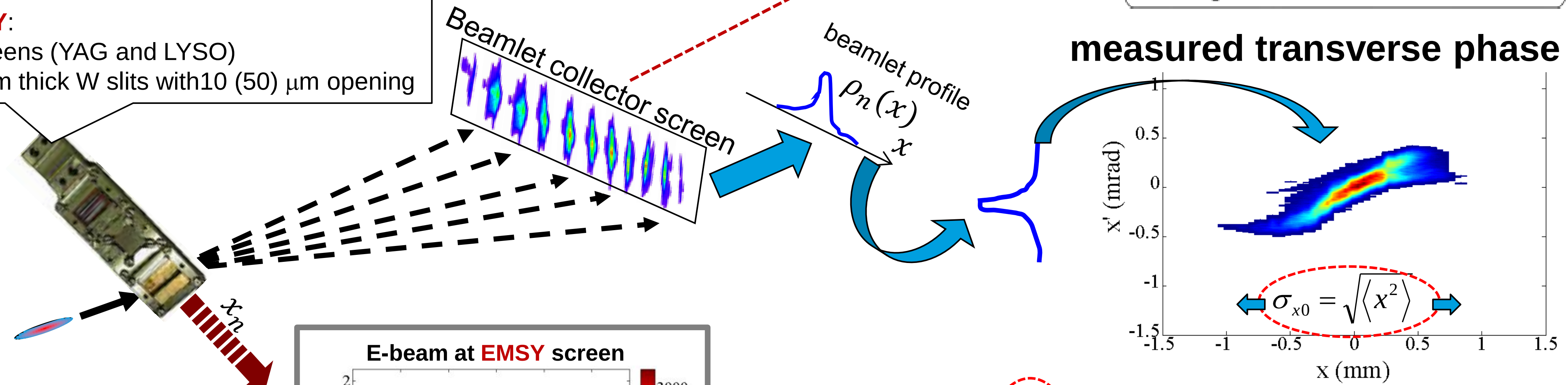
$$\varepsilon_{nx} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

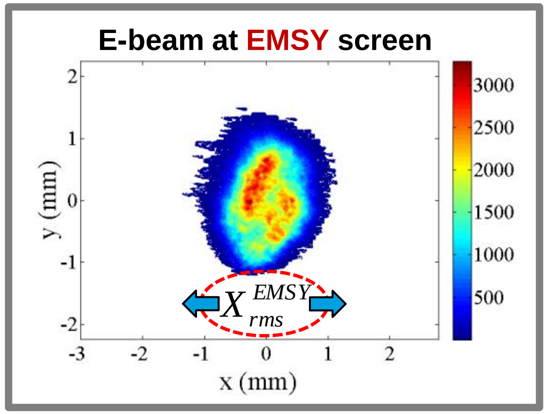
Slit Scan Technique for Emittance Measurements at PITZ

Emittance Measurement SYstem (EMSY)



EMSY:
- screens (YAG and LYSO)
- 1mm thick W slits with10 (50) µm opening





$$\varepsilon_{n,x} = \beta\gamma \cdot \frac{X_{rms}^{EMSY}}{\sqrt{\langle x^2 \rangle}} \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

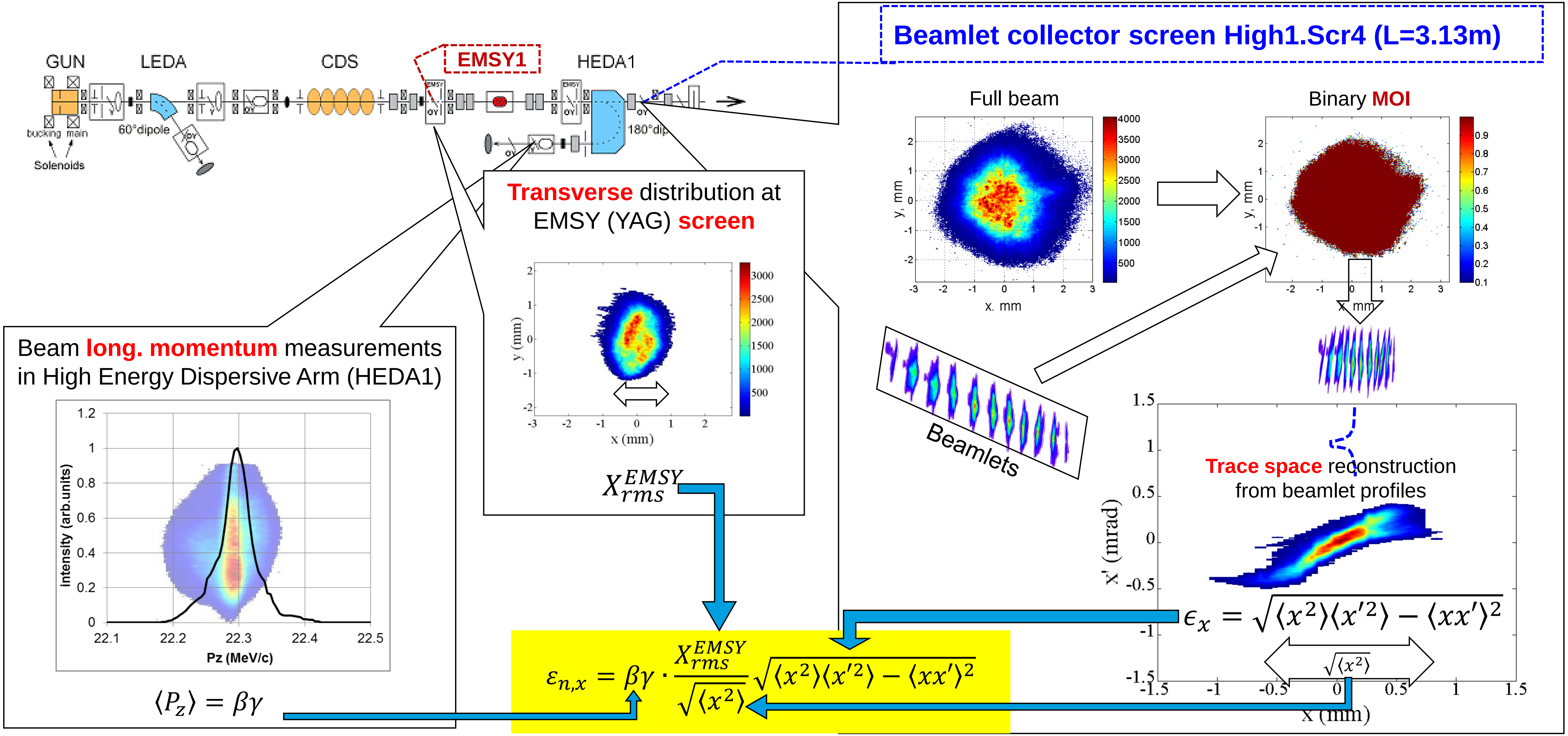
"100%" rms emittance

As conservative as possible!

Correction factor (~1.2 ...1.5) introduced to correct for low intensity losses from beamlet measurements

Emittance using slit-scan at PITZ

Relevant measurements to obtain rms normalized emittance



$$X_{rms}^{EMSY}$$

$$\langle P_z \rangle = \beta\gamma$$

$$\epsilon_x = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

$$\sqrt{\langle x^2\rangle}$$

$$\varepsilon_{n,x} = \beta\gamma \cdot \frac{X_{rms}^{EMSY}}{\sqrt{\langle x^2\rangle}} \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

Image processing and beam size analysis

Background subtraction, noise filtering

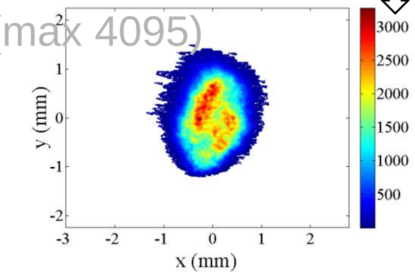
Beam / beamlets transverse distribution measurements:

- Screen (**YAG**, LYSO, OTR) → 90° YAG with mirror behind
- Optical system for light transport → iris, zoom options (f160, f250)
- CCD camera → read out
- Image processing

Beam image **quality** management → **3000-criteria**:

MaxPixelValue=Φ(NoP, CameraGain)≥3000 (max 4095)

1) 1 pulse (*NoP=1*), *CameraGain*→~22
2) If not → increase *NoP*
3) *Min(NoP)* - priority



EMSY (&MOI) data **taking**:

0) e.g. 10 frames **Signal** + 10 frames **Background** (laser shutter closed)

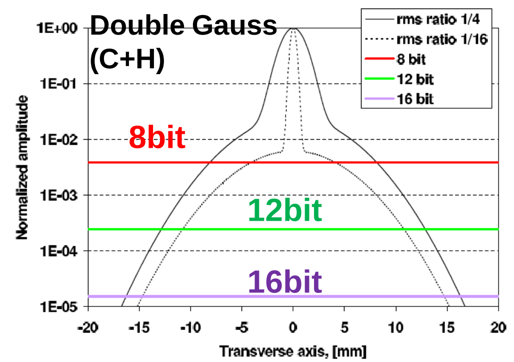
EMSY (&MOI), beamlets **image processing**:

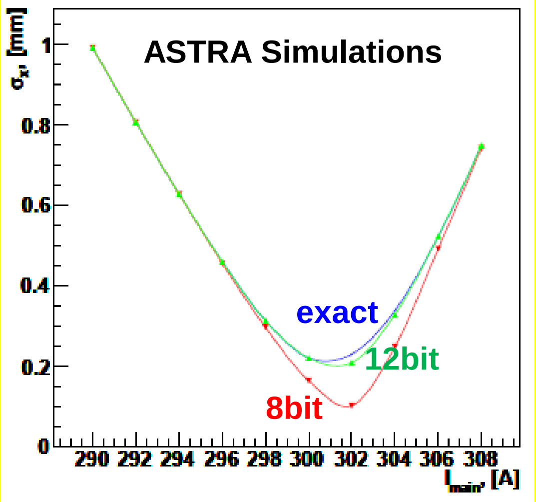
1) <Signal>, <Background>
2) Noise-sigma-cut filter → mask **M**:
   - <Signal>-<Background> $\leq \text{cut} \cdot \sigma_{bkg}$ → **M=0**, otherwise **M=1**
3) "Neighbors filters" (×N~3):
   - Removing pixel **product** filter $\prod$
   - Restoring pixel **sum** filter $\sum$

No Gaussian fit!

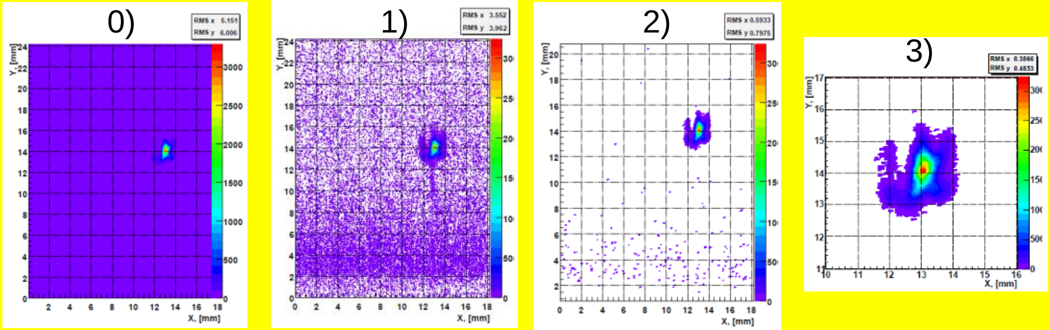
Read out: CCD camera **Prosilica GC-1350**

- Gain: 0 to 25 dB
- Black level control: Auto (not controllable)
- Minimum shutter: 10 us
- Chip size: 1360x1024
- Pixel size: 4.65
- **12bit**





L.Staykov "Characterization of the transverse phase space at the photo-injector test facility in DESY, Zeuthen site", PhD Thesis, Hamburg 2008



Slit station design considerations

Local beam divergence measurements (e.g., 1nC, 25MeV, 0.5 mm, 0.6 mm mrad)

- Slit **material** and **thickness** s → 1 mm W(X_0=0.35 cm)
  - Stop/scatter (~20-25MeV) electrons
  - Good heat conductivity (pulse trains)

$$\theta_{rms} = \frac{19.2MeV}{E}\sqrt{\frac{s}{X_0}}\left[1 + 0.2\ln\left(\frac{s}{X_0}\right)\right] \qquad \theta_{rms} \gg \frac{D}{L}$$

- Slit **opening** d → 10 (50) um
  - Good enough signal
  - Small space charge effect

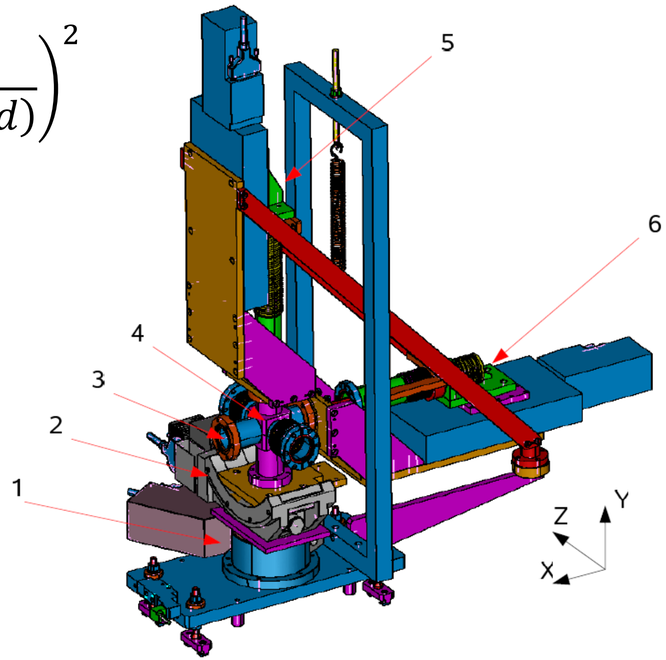
$$\sigma_{beamlet}^{meas} = \sqrt{L^2 \cdot \sigma'^2 + \left(\frac{d}{12}\right)^2}$$

L.Staykov "Characterization of the transverse phase space at the photo-injector test facility in DESY, Zeuthen site", PhD Thesis, Hamburg 2008

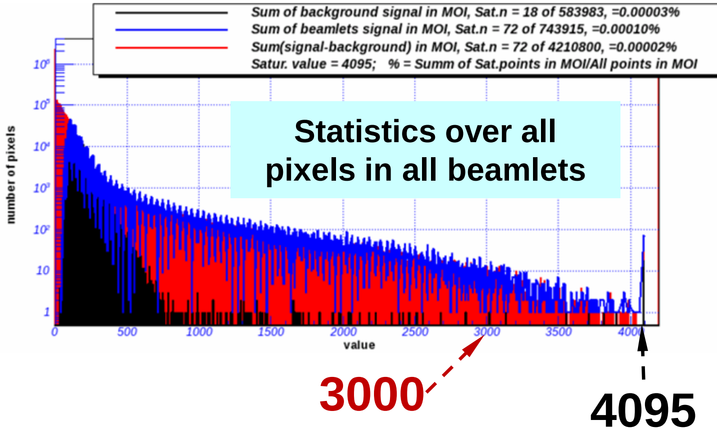
- **Drift length** L choice → $L \gg 0.12m(d = 10\mu m)$ → PITZ: 2.6-3.1m
  - ^Resolution ($L \gg \frac{d}{(\sigma_x'^2\sqrt{12})}$)
  - ↓S2N
  - ↓Space charge

$$\frac{S}{N} \geq \frac{1}{2}\left(\frac{\theta_{rms} \cdot L}{\sigma \cdot (1 + \sigma' \cdot L/d)}\right)^2$$

- Slit mask **positioning**
  - Linear stages Newport MM100-PP1 → step Δ~10um
- Slit mask **alignment** (angular acceptance):
  - Rotational stage Newport RV120-PP
  - Goniometric stage Newport BGM120-PE
    - → step: 10urad (range: ~3mrad)

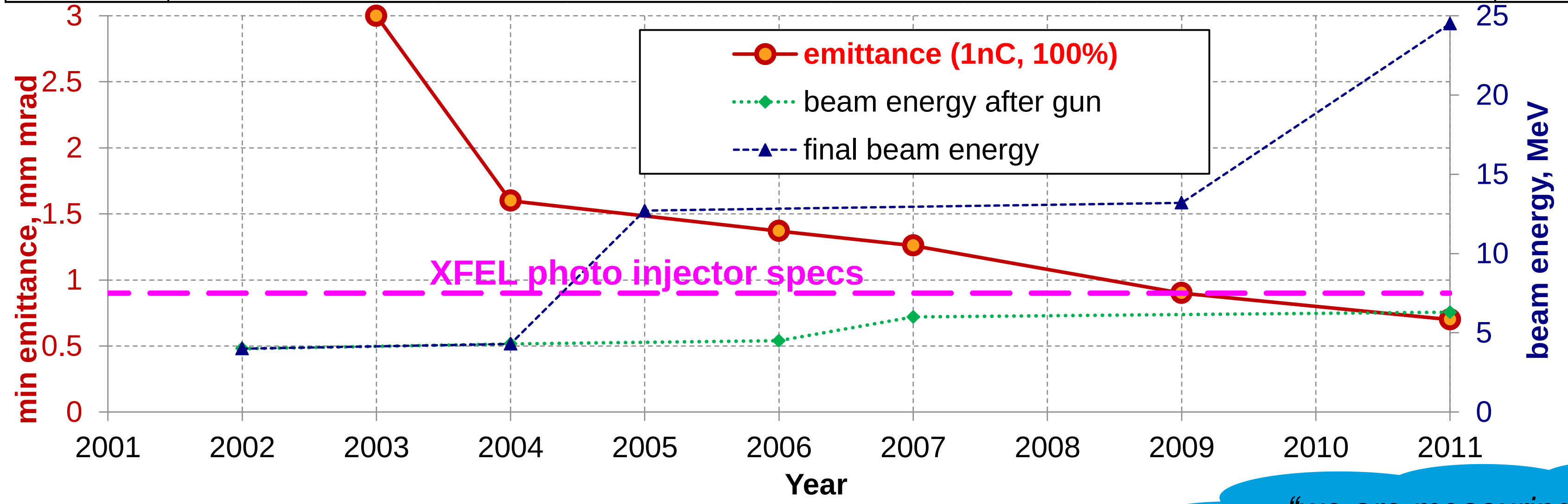


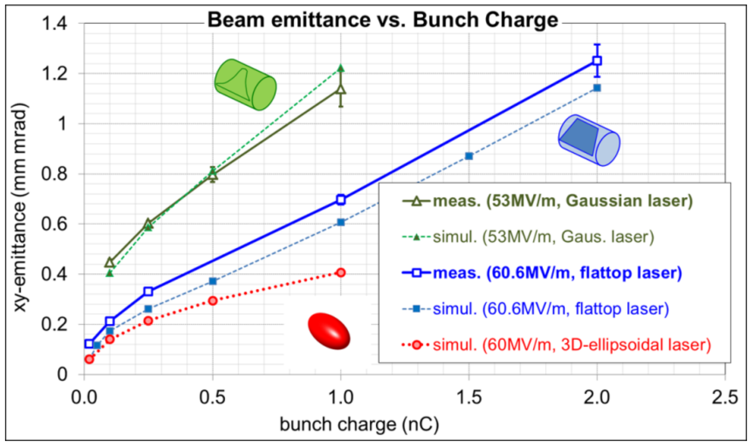
Beamlets quality management
→ extended **3000-criteria**:



PITZ evolution 2000-2017

	Year-->	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
gun	cavity	gun-2	FLASH	gun-1		gun-3.1 FLASH	g-3.2	gun-4.2	FLASH	gun-4.1		FLASH g-3.1	FLASH 4.3 XFEL	XFEL* 4.4	gun-4.2	gun-4.6	XFEL g-4.5
	Ez,MV/m	35	37	42-->60		43			60								
	Ebeam	~4MeV		4.3MeV-->6MeV		4.5MeV			~6.5MeV								
boo	cavity		no		TESLA at 2.5m			TESLA at 3.1m			CDS at 3m					CDS at 2.6m	
	Ebeam						~13MeV			~25MeV					22MeV*		
laser	temp ps	10	6/24\6	→	→	6/24\6		2/22\2	→	→	→	→	→	2/22\2	11*		
emit	EMSY1		z=1.618m		z=4.3m				z=5.74m						z=5.277m		
	L		1.01m		2.334m				2.64m						3.133m		
	method	center BL	3xBLs		e-meter		11xBLs				continuous synchronized (detailed) scan					+slice with TDS	
	min $\mathcal{E}_{n,xy}$ mm mrad (charge)		3 (1nC)	1.5-1.7 (1nC)		1.37 (1nC)	1.26 (1nC)		0.9 (1nC)		0.7 (1nC)				0.8 (0.5nC)		
PITZ goals						small emittance (nominal EXFEL)						+reliability at full performance / +THz		+plasma	+emittance (EXFEL startup)		





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

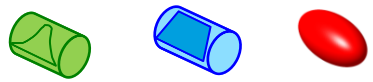
Emittance measurements at PITZ

Multi parametric experimental emittance optimization at the PITZ photo injector

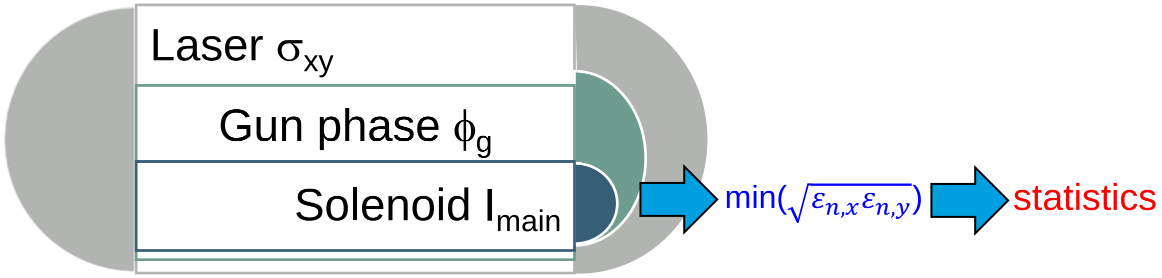
How to achieve small emittance

PITZ experience

- High gradient at the cathode ~60MV/m (1.3GHz)
- Cathode laser pulse shaping



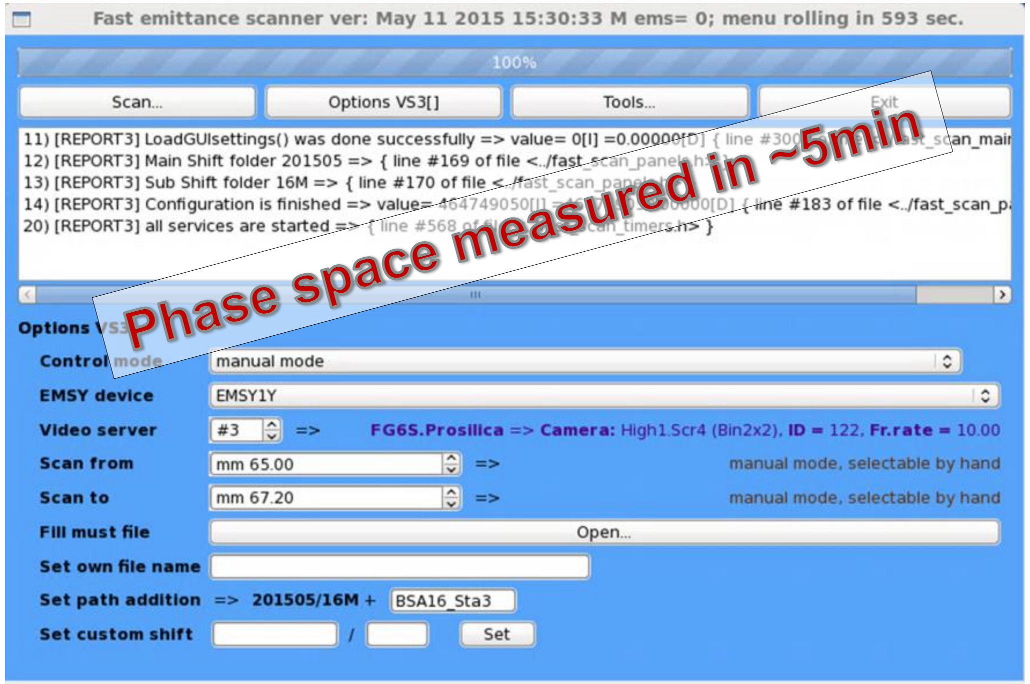
- Gun and booster amplitude and phase stability
- Beam based alignment, trajectory optimization, elimination/compensation of imperfections
- Emittance compensation and conservation → multi parametric machine tuning (solenoid, laser spot size, gun phase, booster, alignment and beam trajectory,…)



Slit scan technique at PITZ

How it works now

- Setup the machine
  - laser temporal and transverse
  - laser BBA at the cathode
  - gun phase
  - bunch charge
  - booster phase and gradient – beam energy (**longitudinal momentum**)
- Adjust slit angles
  - Angle scans for the center beamlet → max SoP
- For every main solenoid current (bucking in compensation)
  - Beam transverse distribution (rms size) at **EMSY** → 12-bit camera!; frames=10xSignal+10xBkg (laser shutter closed) with adjusted camera gain G and NoP
  - Beam transverse distribution at beamlet collection screen for **MOI** → 12-bit camera! frames=10xSignal+10xBkg (laser shutter closed) with adjusted camera gain G and NoP
  - **Slit scan** (typical speed 0.1-0.5mm/sec) with simultaneous **beamlet** image taking. Synchronization of the slit position and the frame acquisition (10Hz!) with adjusted camera gain G and NoP
  - **Slit scan** with closed laser shutter for the average **bkg** calculation
- Transverse phase space reconstruction and emittance calculations
  - Phase space linear shift to take the slit position into account
  - Scale procedure
- Error analysis (systematic and statistics – e.g. 3x3)



Systematic error $\left(\frac{meas*}{simul}-1\right)$ **estimations**

Due to finite pixel size

Q, nC	X_{rms}^{EMSY}	ε_x
2	<1%	<1%
1	<1%	~3%
0.25	<1%	>-1%
0.1	<1%	~1.2%
0.02	<1%	146%

Uncertainty w.r.t. optim. par.

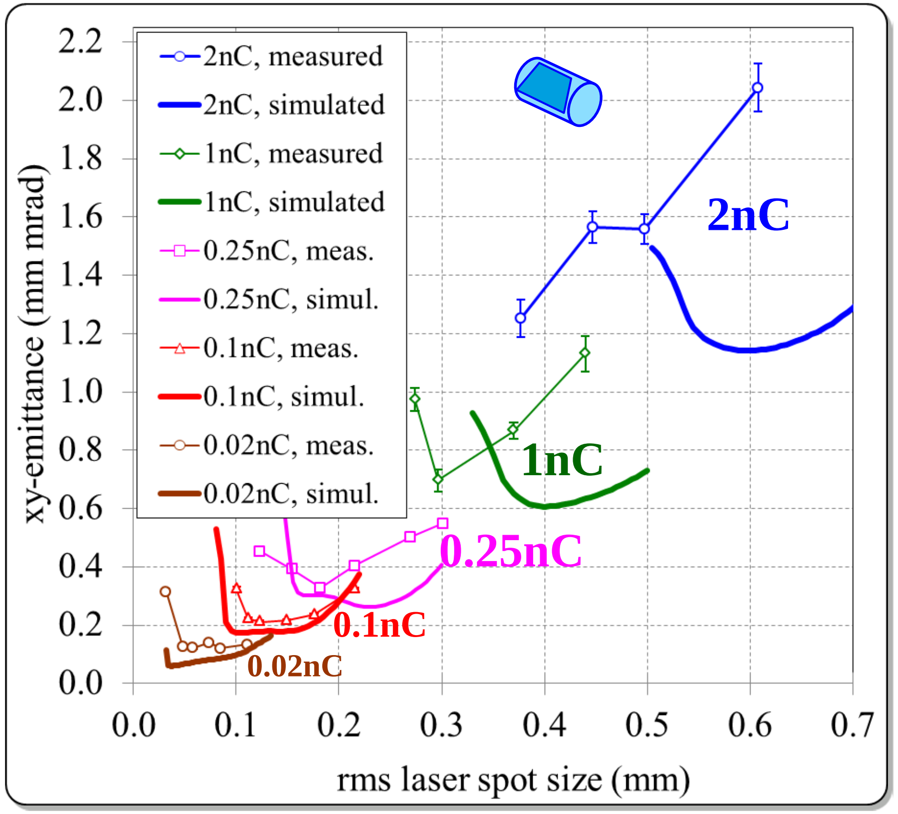
Q, nC	ε_x
2	8%
1	12%
0.25	13%
0.1	8%
0.02	10%

G. Vashchenko "Transverse phase space studies with the new CDS booster cavity at PITZ", PhD Thesis, Hamburg 2013

Additionally: screen/camera inhomogeneity/noise, calibration, effects of image filters, jitters

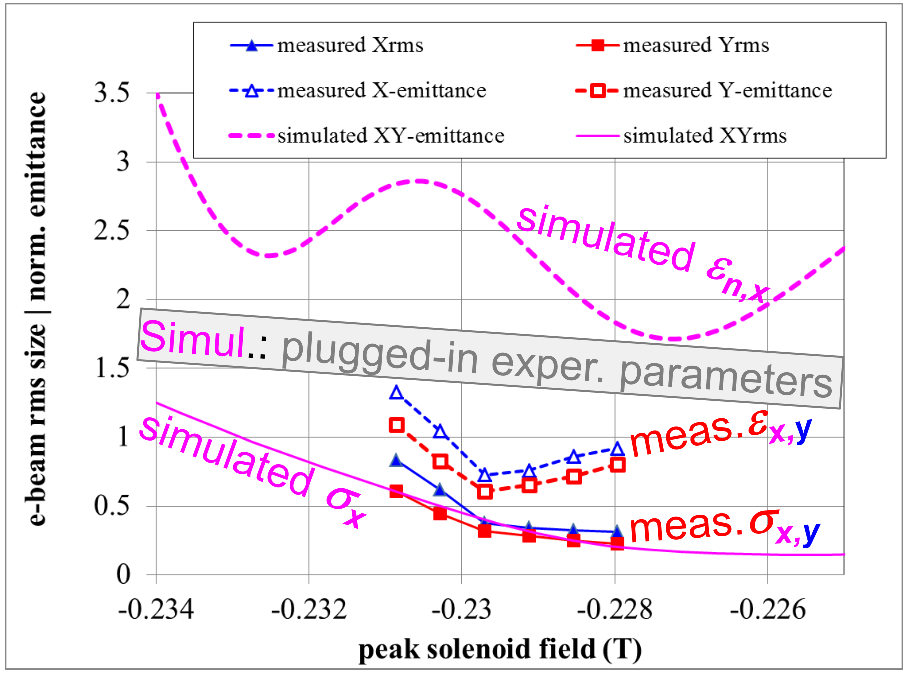
Emittance versus Laser Spot Size for various Charges

Measured (100%) rms normalized emittance vs. simulations

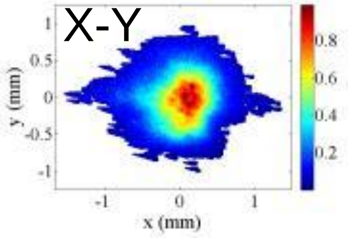


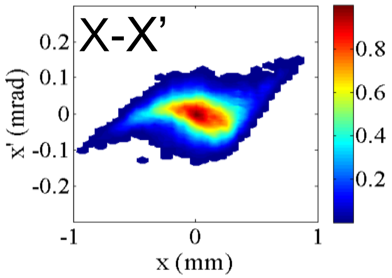
Minimum emittance ($\sqrt{\varepsilon_{n,x}\varepsilon_{n,y}}$)

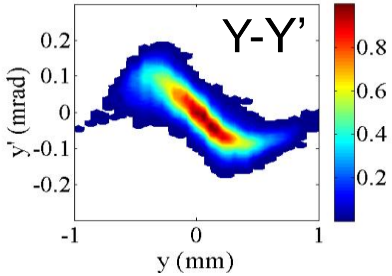
Charge, nC	Measured, mm mrad	Simulated, mm mrad
2	1.25±0.06stat+0.01syst	1.14
1	0.70±0.02stat+0.02syst	0.61
0.25	0.33±0.01stat-0.003syst	0.26
0.1	0.21±0.01stat+0.0003syst	0.17
0.02	0.121±0.001stat+0.18syst*	0.06



Measured 1nC electron beam



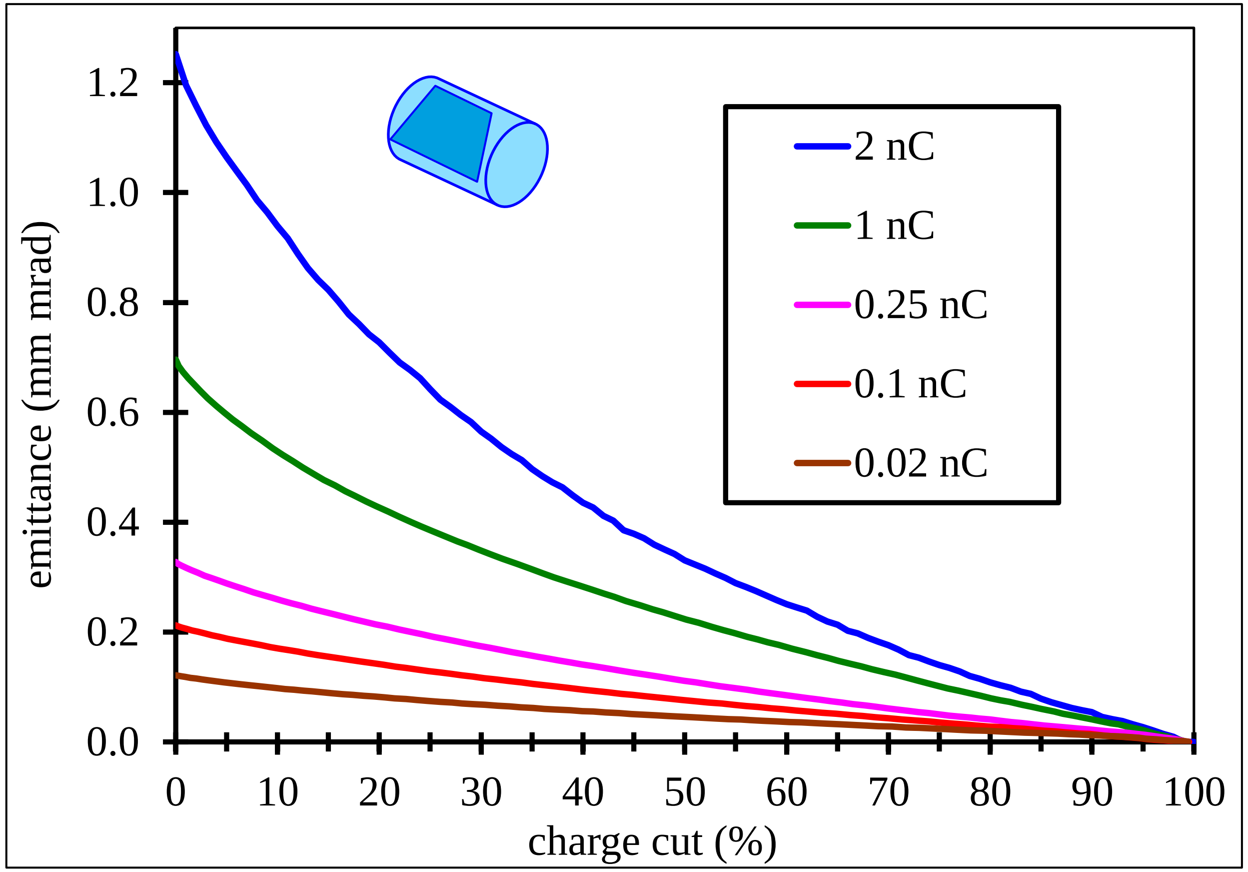




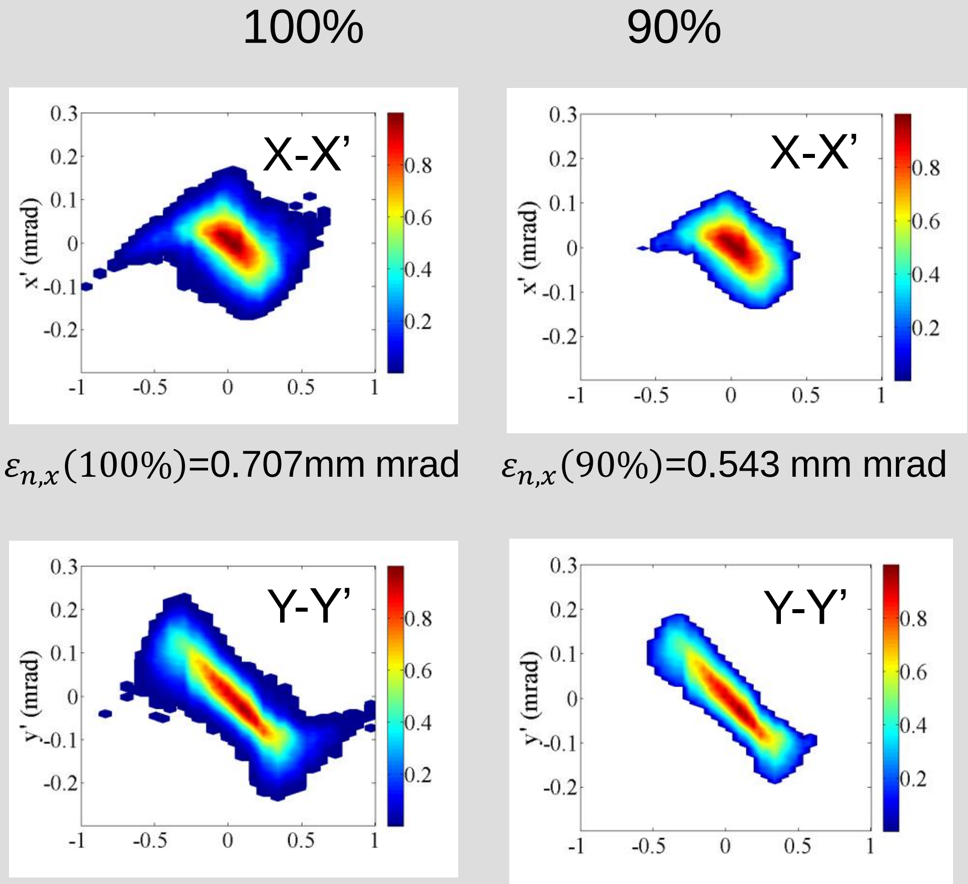
- Optimum machine parameters (laser spot size, gun phase): experiment ≠ simulations
- Difference in the optimum laser spot size is bigger for higher charges (~good agreement for 100pC)
- Simulations of the emission is under improvements

Core Emittance

Intensity (charge) cut of phase space



Measured Transverse Phase Space (1nC)



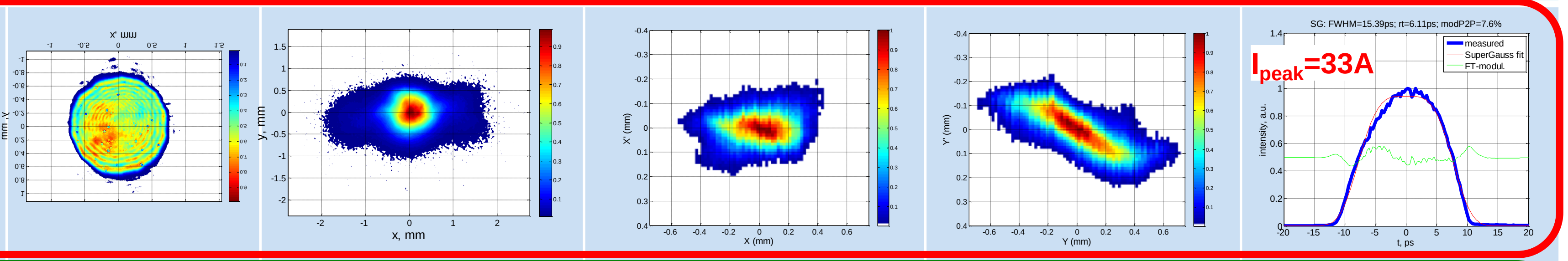
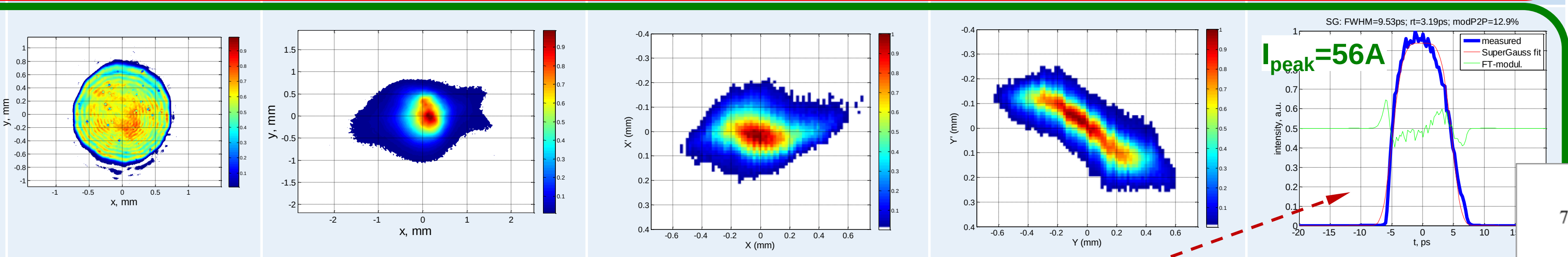
$\varepsilon_{n,x}(100\%)$=0.707mm mrad $\varepsilon_{n,x}(90\%)$=0.543 mm mrad

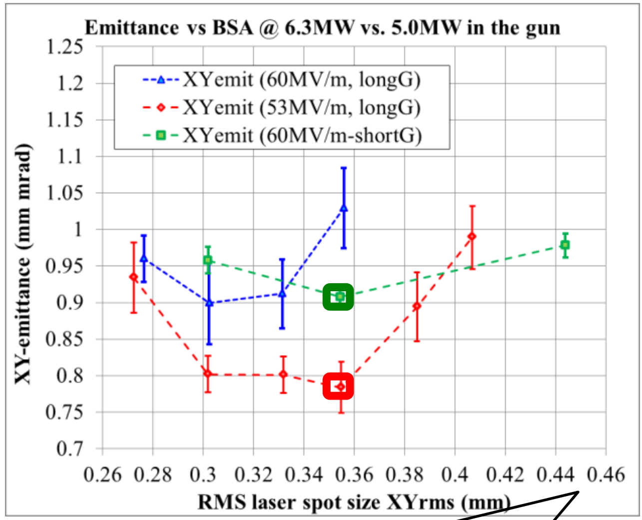
$\varepsilon_{n,y}(100\%)$=0.685 mm mrad $\varepsilon_{n,y}(90\%)$=0.515 mm mrad

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

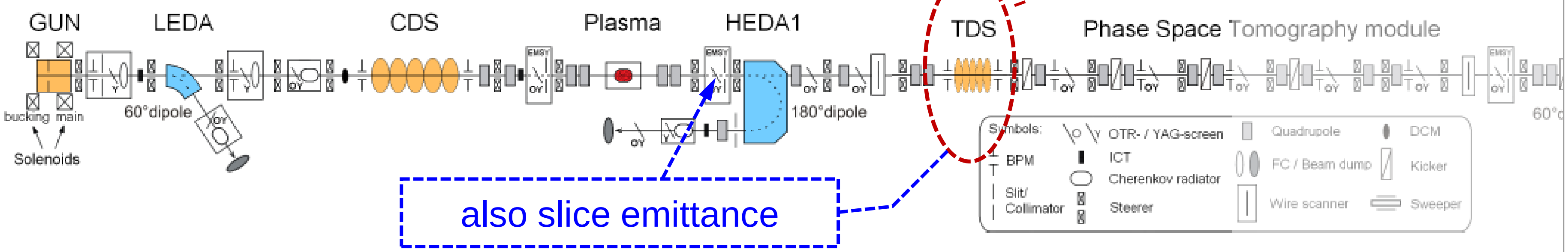
Measured Emittance and Brightness (2015)

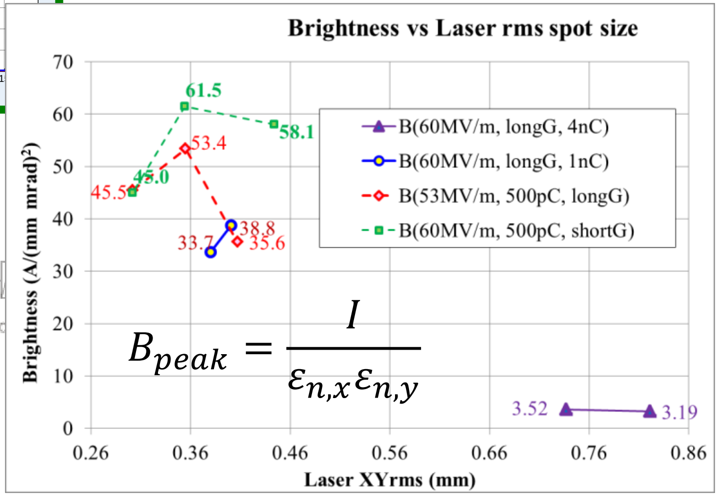
Gaussian photocathode laser pulses

Cathode laser temporal	VC2 (laser)	E-beam at EMSY1	X-X’	Y-Y’	E-beam temporal profile (TDS)
Long Gaussian ~11.5ps FWHM 53MV/m					
Short Gaussian ~2-2.5ps FWHM 60MV/m					



Various photo cathode pulse length, various gun gradients





$$B_{peak} = \frac{I}{\varepsilon_{n,x}\varepsilon_{n,y}}$$

Conclusions and Outlook

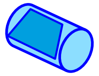
Transverse emittance measurements of space charge dominated beams at PITZ

- Slit Scan Technique (**SST**) is a standard method used to measured the transverse phase space of space charge dominated electron beams at PITZ
- Main paradigm → to be **conservative** - to measure as much as possible beam signal, trying to avoid unnecessary assumptions/simplifications
- SST at PITZ has been improved significantly since start of its usage:
  - automated quasi-continuous synchronized slit scan → ~100 positions of 10um tungsten slit
  - scale factor applies to correct for low intensity losses from beamlet measurements
  - 3000-criteria for the image quality management
- PITZ experience on high brightness photo injector optimization:
  - multiparametric emittance minimization (Imain, laser ⊥−∥ , gun E_0 and φ_0, beam trajectory etc.)
  - major problem: measurements ≠ simulations
  - emittance optimized for **0.02-2nC** bunches for various laser pulse shapes → e.g. 0.7 mm mrad @ 1nC
- **Outlook**:
  - **slice** emittance using TDS → SST and Quads scan ongoing
  - Also general trend towards lower bunch charges
  - further automatization (e.g “autogain” for quality measurements, automatic scan range, etc.)
  - **4D** phase space reconstruction (“Virtual Pepper Pot”)
  - image processing need more advanced filters

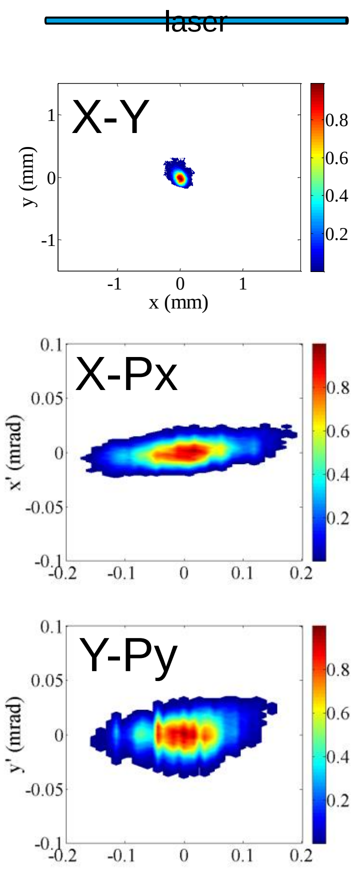
Backup slides

Emittance and Brightness versus Bunch Charge (2011)

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

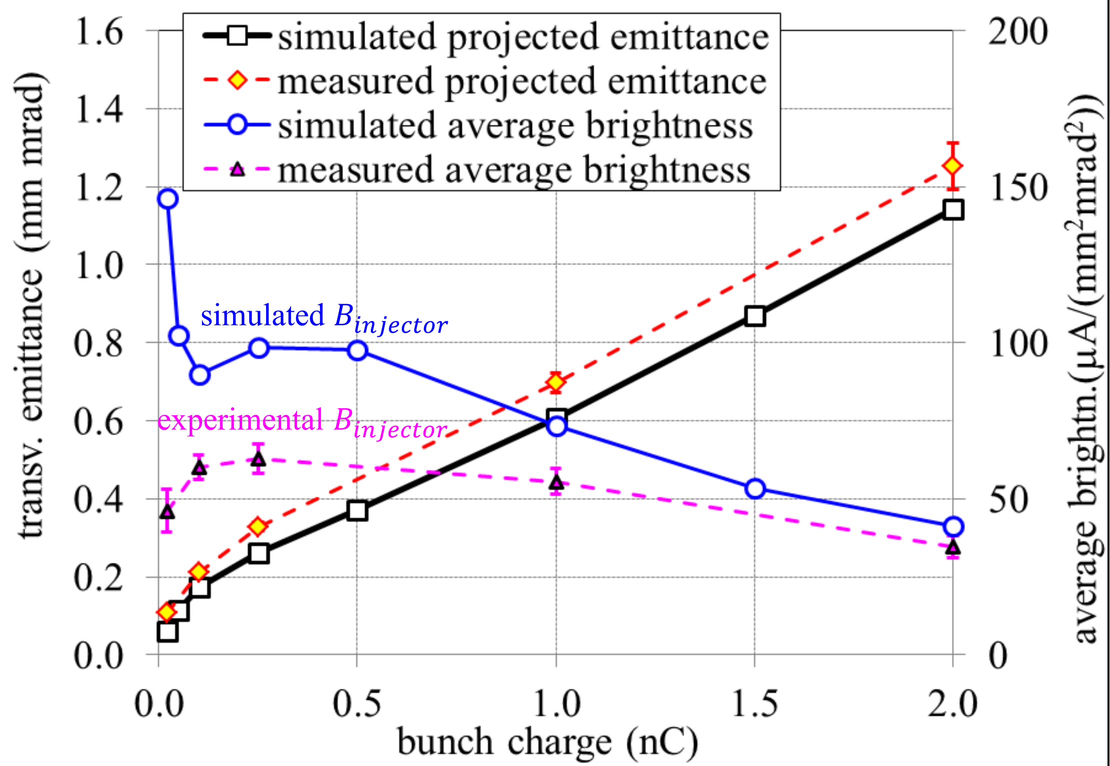


20pC measured



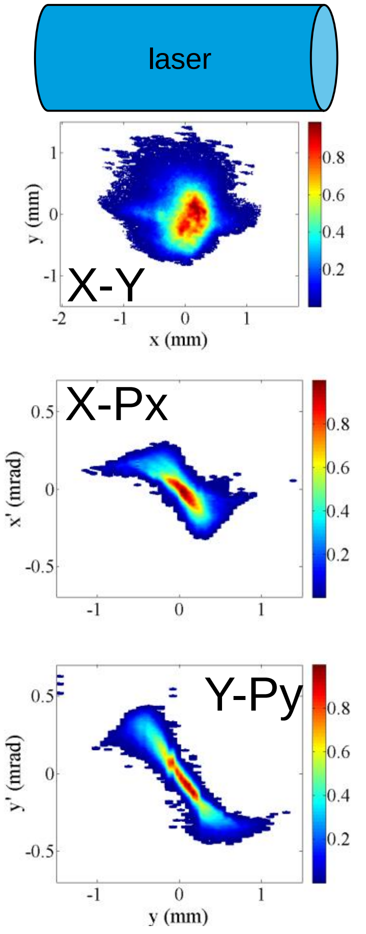
~linear SC

$$B_{injector} = \frac{I_{injector}}{\varepsilon_x \varepsilon_y} = \frac{Q \cdot NoP \cdot RR}{\varepsilon_x \varepsilon_y}$$



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

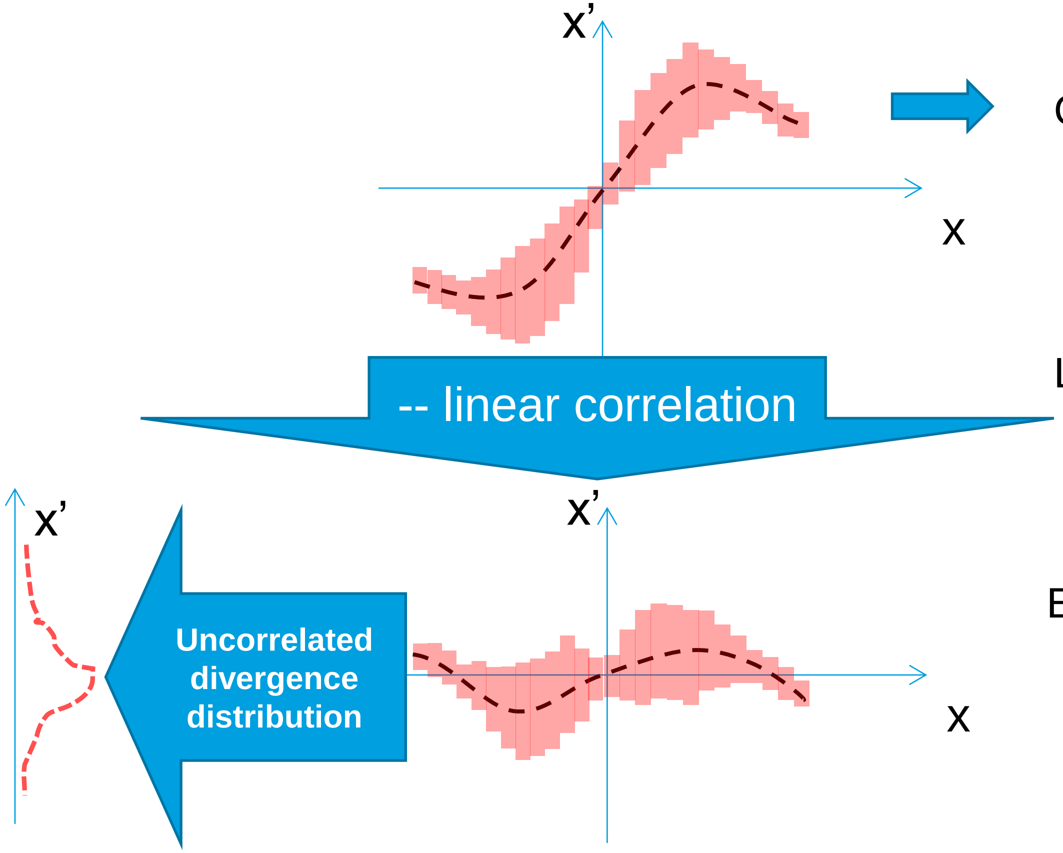
2nC measured



nonlinear SC

Correction factor

From uncorrelated emittance to the scaled normalized emittance



Geom. (trace space) emittance $\epsilon_x = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$

Linear correlation $\tilde{x}' = x' - c\cdot x \leftrightarrow \langle x\tilde{x}'\rangle = 0$ $\qquad c = \dfrac{\langle xx'\rangle}{\langle x^2\rangle}$

Emittance is invariant:

$$\epsilon_x = \tilde{\epsilon}_x = \sqrt{\langle x^2\rangle\langle\widetilde{x}'^2\rangle - \langle x\tilde{x}'\rangle^2} = \sqrt{\langle x^2\rangle}\sqrt{\langle\widetilde{x}'^2\rangle}$$

Normalized emittance (to be measured):

$$\varepsilon_{n,x} = \beta\gamma\cdot X_{rms}^{EMSY}\cdot\tilde{X}'_{rms}$$

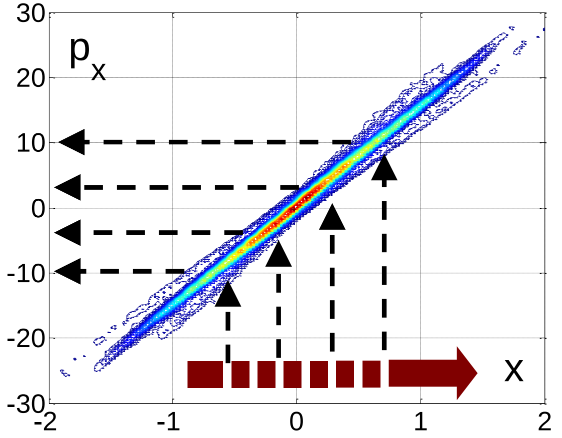
Uncorrelated RMS divergence:

$$\tilde{X}'_{rms} = \sqrt{\langle\widetilde{x}'^2\rangle} = \frac{\epsilon_x}{\sqrt{\langle x^2\rangle}}$$

$$\varepsilon_{n,x} = \beta\gamma\cdot\frac{X_{rms}^{EMSY}}{\sqrt{\langle x^2\rangle}}\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

Slit scan technique at PITZ: evolution

Slit scan step (spacing) choice



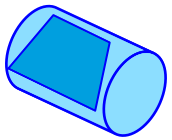
- 2002-2003 rough divergence estimation using **center** beamlet, **8 bit** cameras
- 2003-2005 sheared emittance estimation using **3 slit positions** $(0; \pm 0.7 \cdot X_{rms}^{EMSY})$, 8-bit cameras
- 2005-2008 – standard **“manual”** slit **scan** (~200um step) → phase space reconstruction, **12-bit** cameras
- 2009-now – automated quasi-**continuous synchronized** slit scan with adjustable scan speed → phase space “on-line”, 12-bit cameras, zoom option, scale procedure

The emittance measurement procedure at PITZ:
- under permanent improvement in terms of resolution and sensitivity
- as conservative as possible **(100% rms emittance)!**

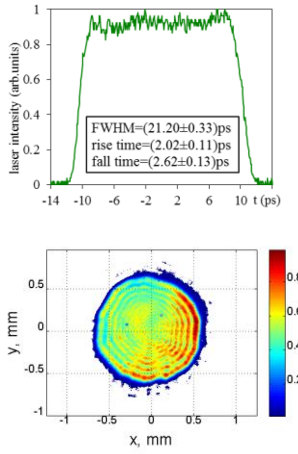
*!NB: measured emittance values are permanently **reducing** as a result of machine upgrades and extensive optimization of beam parameters*

ASTRA simulations for 2011 case using Core+Halo

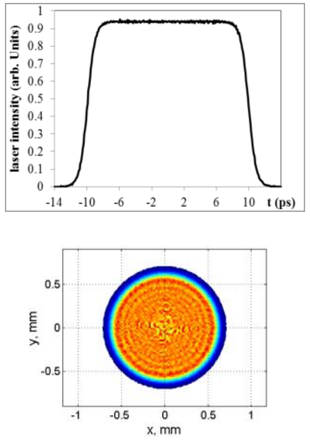
- BUT for flattop photocathode laser pulses

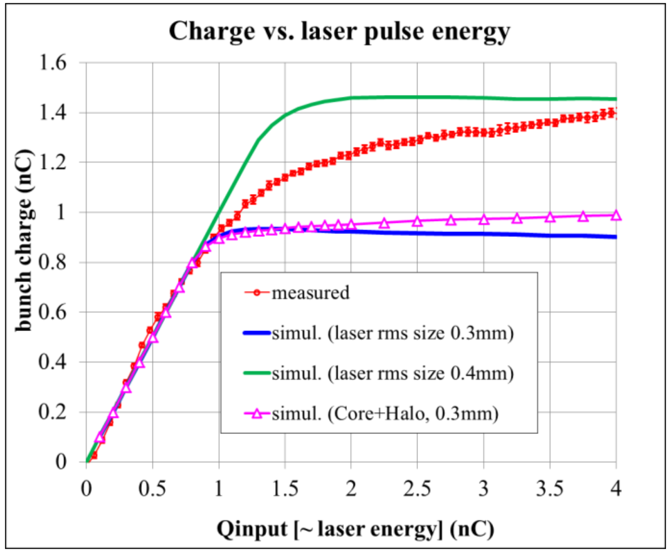


measured

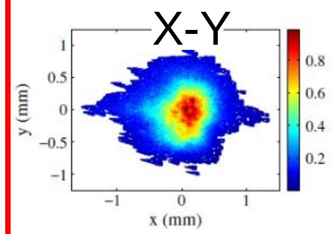


Used in simulations





measured

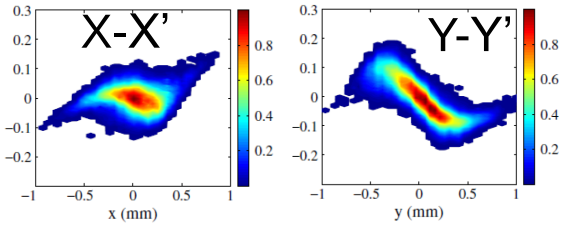


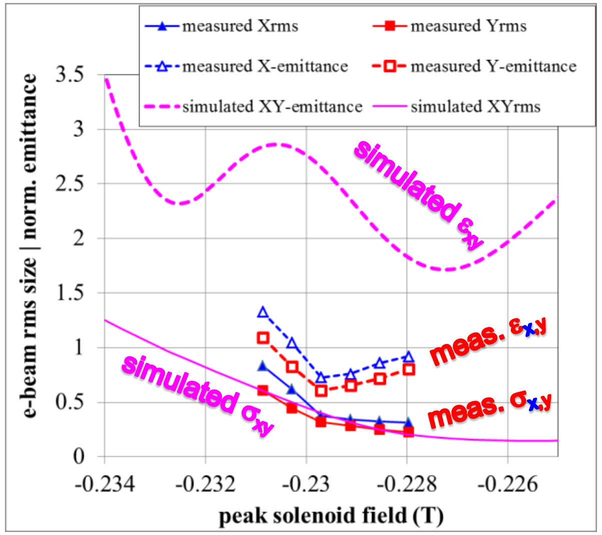
ϕ_{gun}=MMMG+6°

Q=1nC*

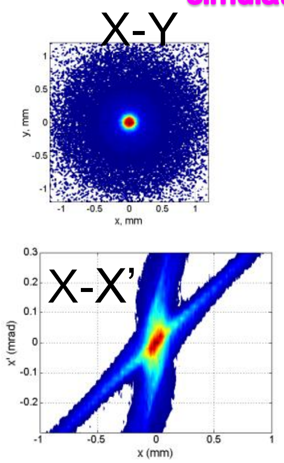
ε_x=0.72 mm mrad

ε_x=0.60 mm mrad





simulated



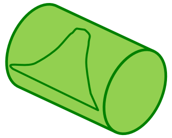
Parameters "plugged" from measurements:

ϕ_{gun}=MMMG+6°

Q=0.97nC

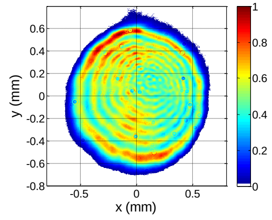
ε_x=2.5 mm mrad

ASTRA simulations for Gaussian pulses using Core+Halo

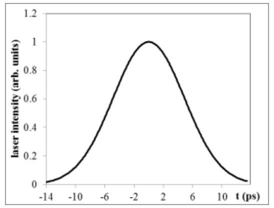


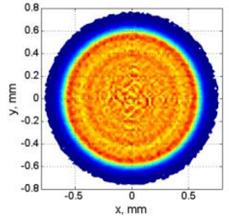
measured

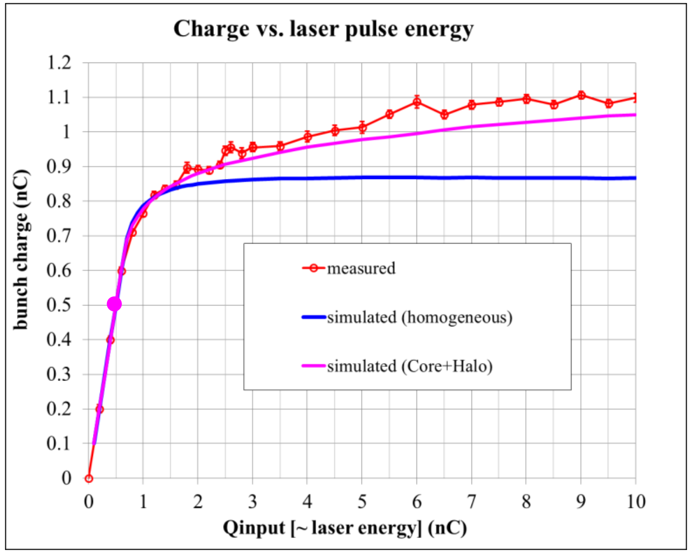
?



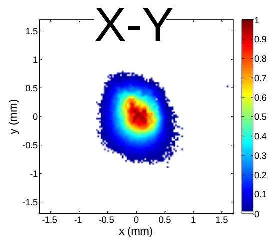
Used in simulations







measured

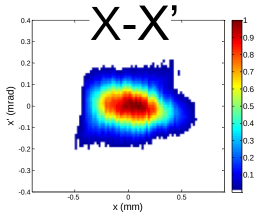


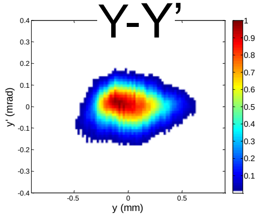
ϕ_{gun}=MMMG

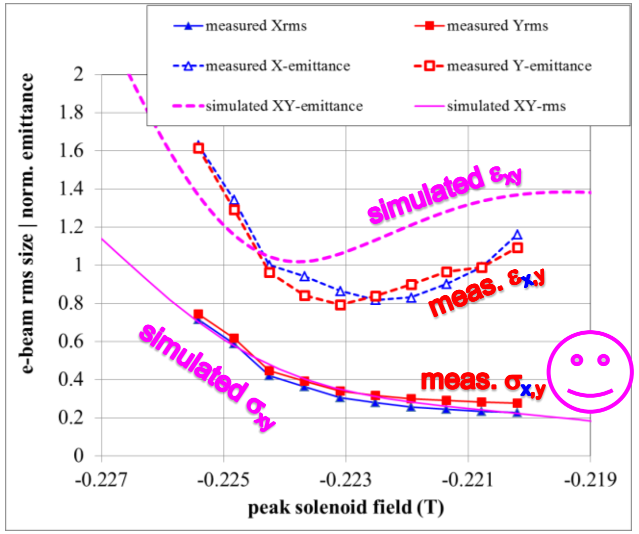
Q=0.5nC

ε_x=0.82 mm mrad

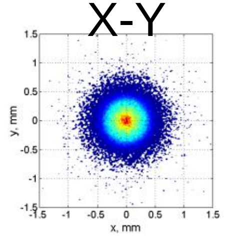
ε_x=0.84 mm mrad







simulated

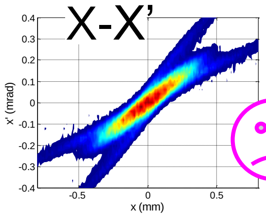


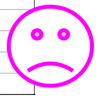
Parameters "plugged" from measurements:

ϕ_{gun}=MMMG

Q=0.5nC

ε_x=1.05 mm mrad

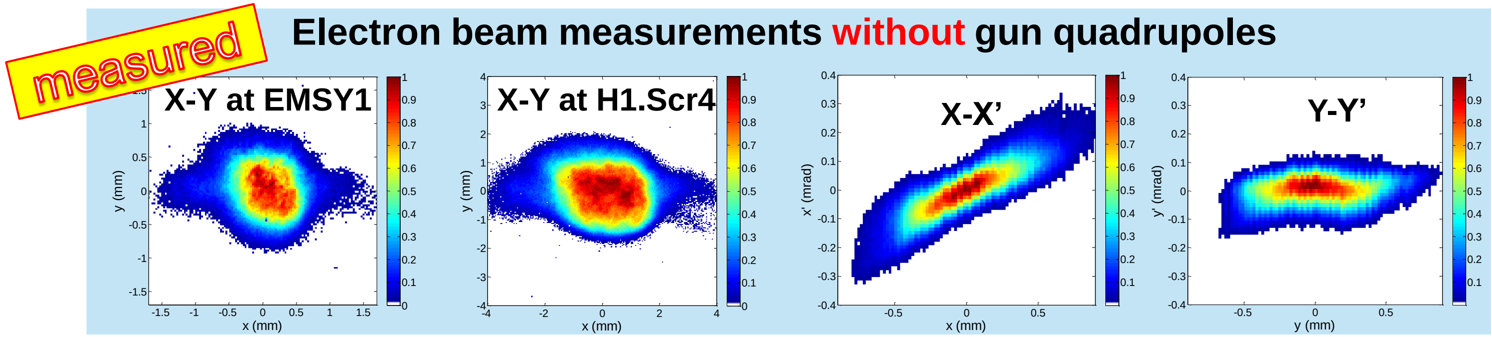


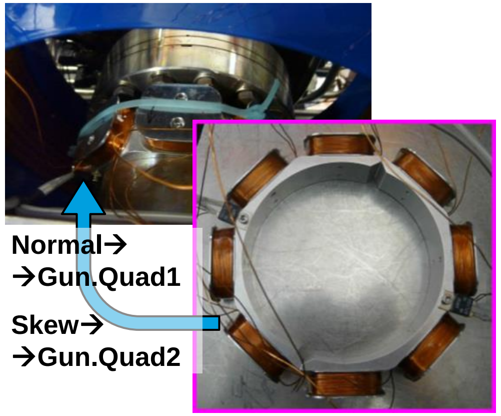


Electron beam X-Y asymmetry compensation with gun quads

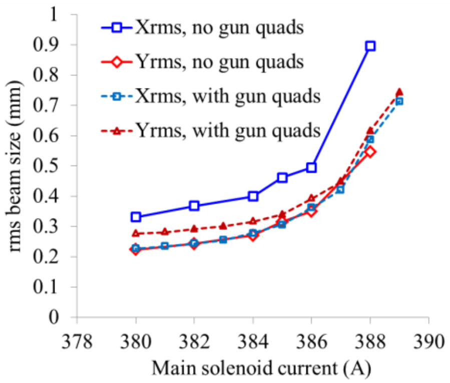
(0.5nC, Gaussian photocathode laser pulse)

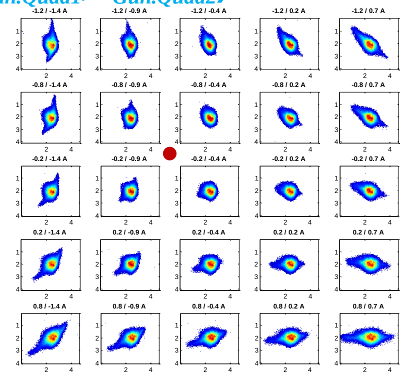
Electron beam measurements **without** gun quadrupoles

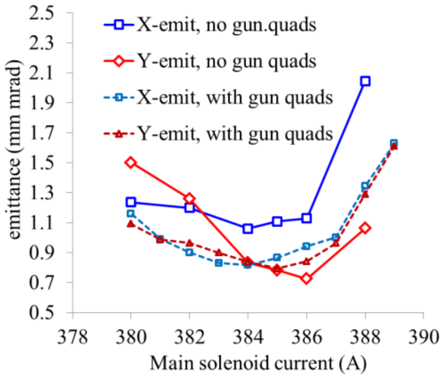




($I_{Gun.Quad1}$; $I_{Gun.Quad2}$) scan at EMSY1







	No gun quads	With gun quads
I_{main}(A)	386	384
$I_{gun.quad1}$ (A)	0	-0.5
$I_{gun.quad2}$ (A)	0	-0.6
σ_x@EMSY1 (mm)	0.50	0.28
σ_y @EMSY1 (mm)	0.35	0.32
$\varepsilon_{x,n}$ (mm mrad)	**1.13**	**0.82**
$\varepsilon_{y,n}$ (mm mrad)	**0.73**	**0.84**
$\sqrt{\varepsilon_{x,n}\varepsilon_{y,n}}$ (mm mrad)	**0.91**	**0.83**
β_x (m)	6.53	3.18
β_y (m)	6.49	3.24
γ_x (mrad)	0.56	0.32
γ_y (mrad)	0.16	0.31

Electron beam measurements **with** gun quadrupoles

($I_{Gun.Quad1}$=-0.6A; $I_{Gun.Quad2}$=-0.5A)