Transverse phase space studies with the new CDS booster cavity at PITZ.

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PhD Thesis
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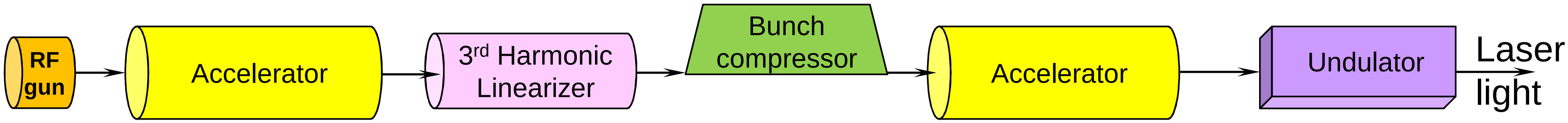
HELMHOLTZ ASSOCIATION

Outline

Motivation: High Brightness Photo Injector for SASE FEL

Linac based Free Electron Laser (e.g. FLASH, European XFEL)



- SASE FEL ➔ high phase space density of electron bunches already from the source

  Small transverse emittance and high current ➔ High brightness electron source $B = \frac{2I}{\varepsilon_{n,xy}^{2}}$

- 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)

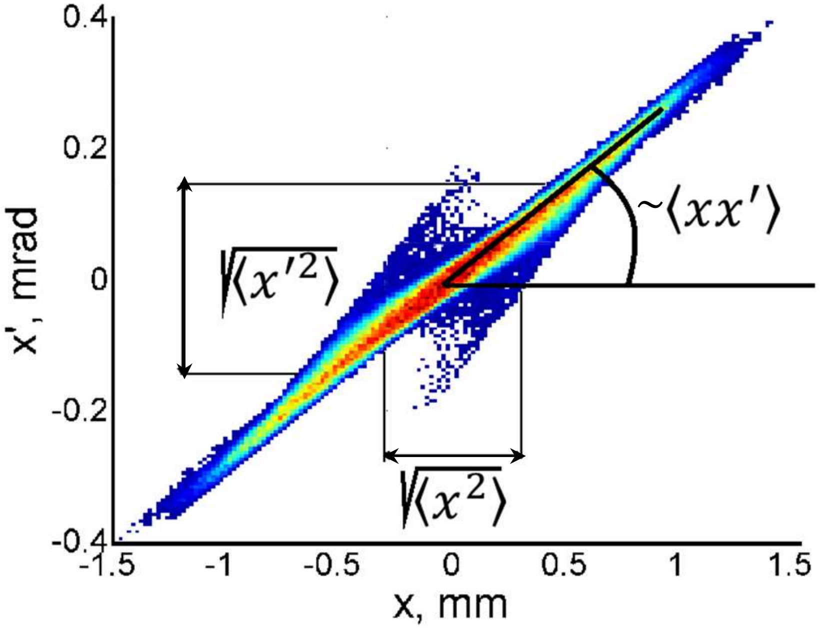
European XFEL: $\varepsilon_{n,xy}$ = 0.9 mm mrad @ 1nC at the end of injector

Phase space and emittance

- The phase space of the system is the space in which all possible states of the system are represented.
- Emittance is related to the volume/area occupied by the electron beam in phase space.
- 6D phase space can be split into 3x2D phase spaces: (x, x'); (y, y'); (z, p_z)
- Normalized transverse rms emittance for X plane:

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

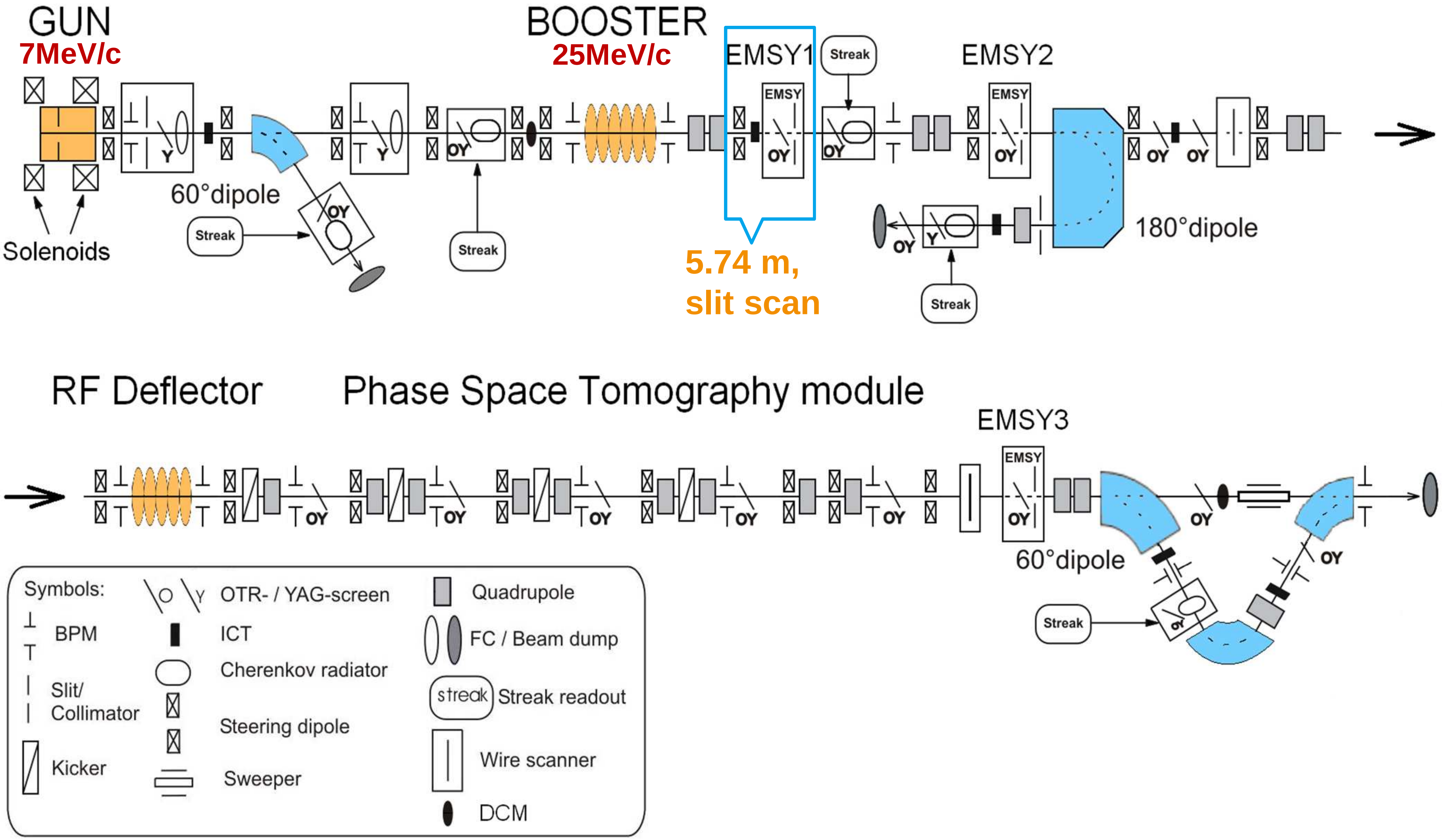
$$\beta = \frac{v}{c}, \gamma = \frac{1}{\sqrt{1-\beta^2}}$$



- Normalized transverse rms emittance for both planes:

$$\varepsilon_{n,xy} = \sqrt{\varepsilon_{n,x}\, \varepsilon_{n,y}}$$

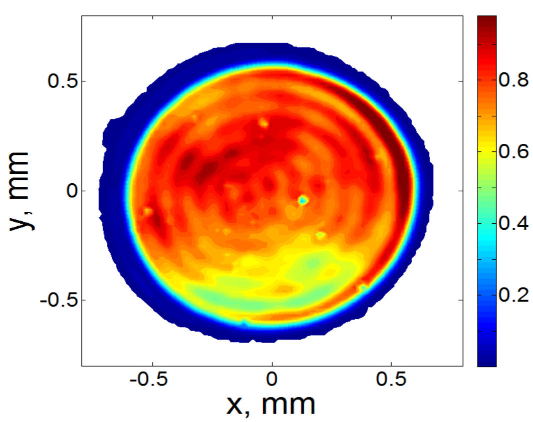
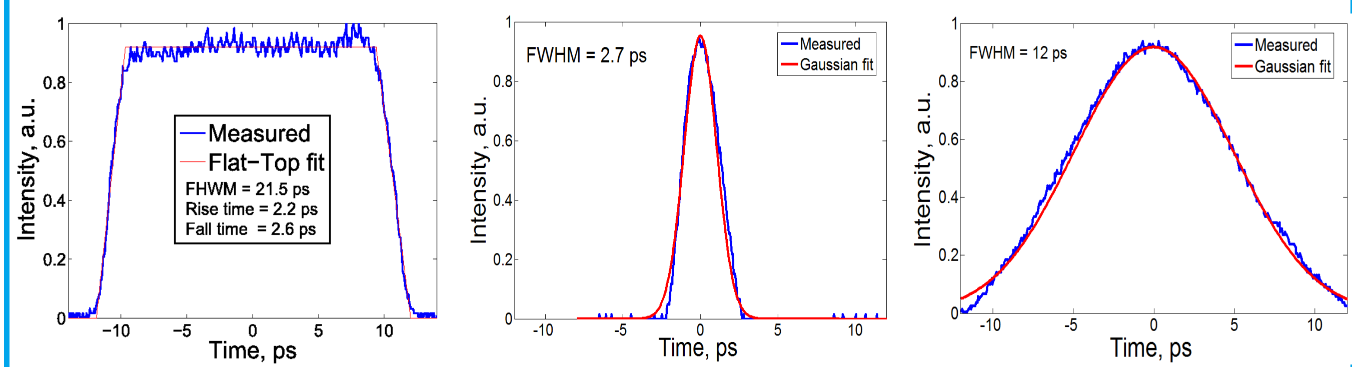
PITZ setup


GUN
7MeV/c
BOOSTER
25MeV/c
EMSY1
Streak
EMSY2
EMSY
OY
Y
60°dipole
Streak
Solenoids
180°dipole
5.74 m,
slit scan
RF Deflector
Phase Space Tomography module
EMSY3
60°dipole
Symbols:
OTR- / YAG-screen
Quadrupole
BPM
ICT
FC / Beam dump
Cherenkov radiator
Slit/
Collimator
streak
Streak readout
Steering dipole
Kicker
Wire scanner
Sweeper
DCM

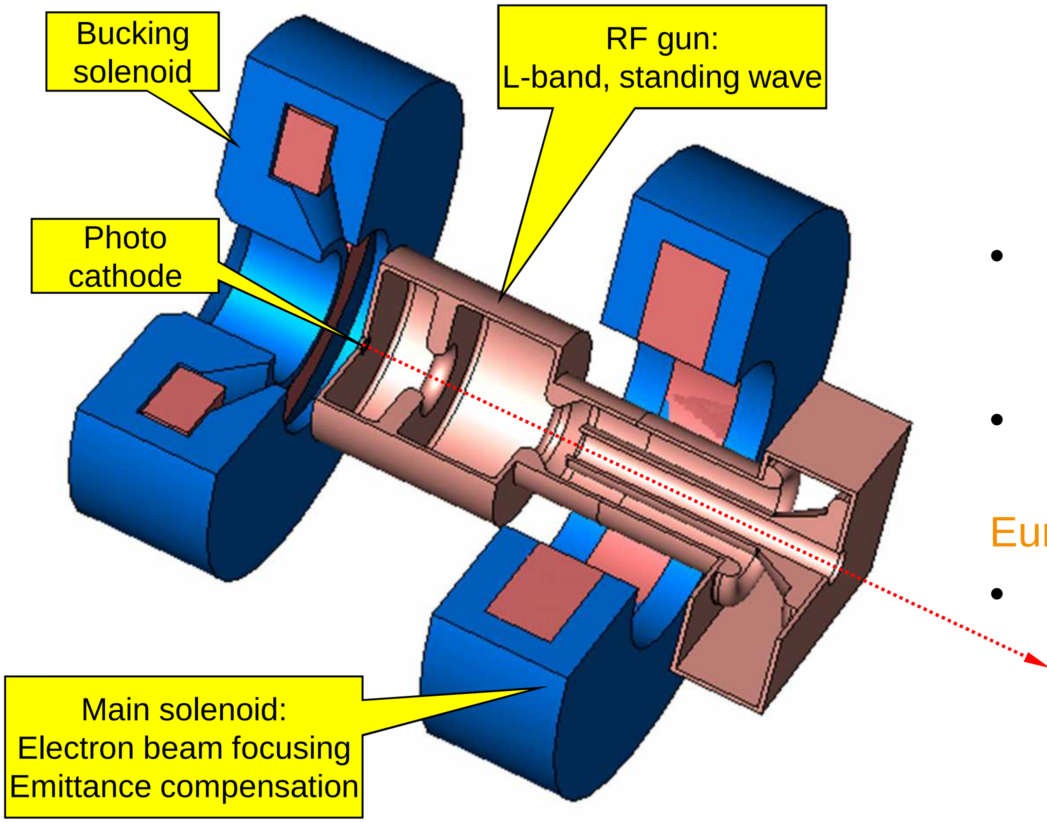
Photocathode UV laser system

Flexible photocathode laser system was developed by Max Born Institute, Berlin

Wavelength **λ = 258 nm**

Transverse distribution at the photo cathode	Various longitudinal distributions at the photo cathode
	

RF gun



- **Capable of high average power → long electron bunch trains (up to 800 us)**
- **Low normalized transverse emittance:**

European XFEL requires $\varepsilon_n < 0.9\ mm\ mrad$

- **Beam momentum up to 7 MeV/c**

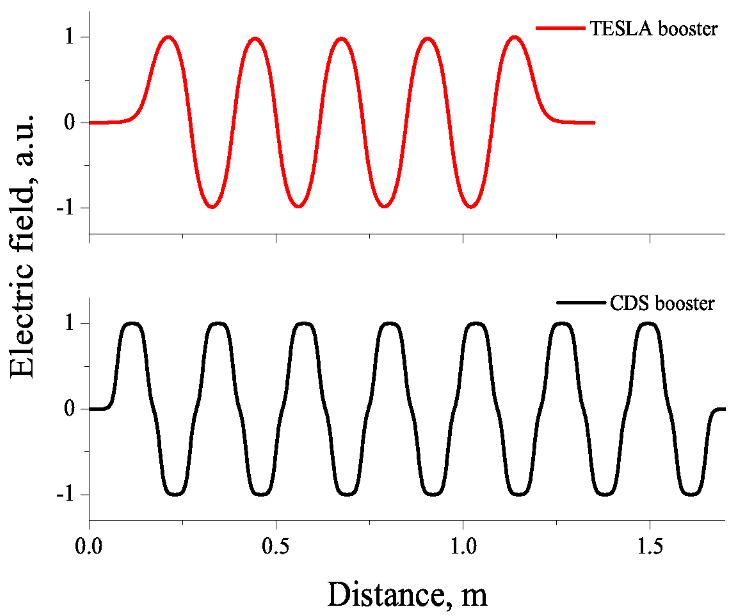
CDS and TESLA boosters

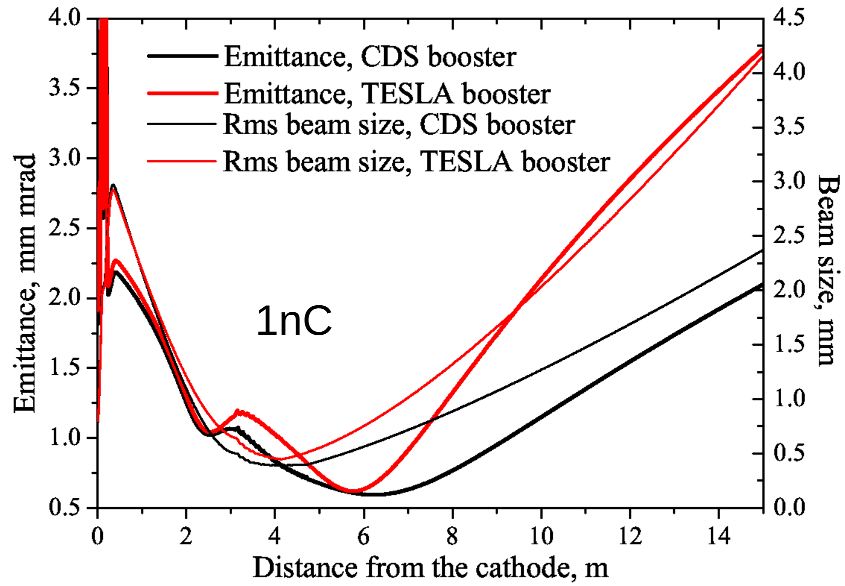
TESLA booster:

- Similar to superconducting modules used at FLASH and European XFEL, but normal conducting.
- Limited cooling capability: only 50 µs RF pulse length can be used.
- Hard to control, hard to operate
- Low gradient (<$p_{z,max}$> ≈ 15 MeV/c) – bad emittance conservation.

CDS booster:

- Normal conducting with well defined fields
- Increased cooling capability: up to 900 µs RF pulse lengths can be used.
- Easy in control and operation
- Higher gradient (<$p_{z,max}$> ≈ 25 MeV/c) – good emittance conservation.





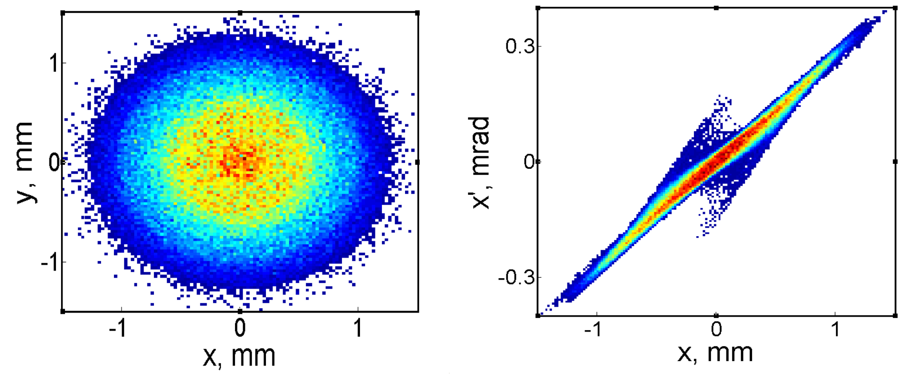
Emittance simulations, starting point

- A Space Charge TRacking Algorithm (ASTRA) ➔ Tracking of particles through external fields (electromagnetic RF, solenoid, dipole and quadrupole fields) + space-charge

- Flat-top laser with 21.5 ps length at FWHM and 2 ps rise/fall times as in experiment
- Gun on-axis peak field of 60.5 MV/m
- Experimentally measured RF and solenoid fields + beamline aperture as input for simulations
- Emittance optimization at the position of EMSY1, 5.74 m downstream the cathode

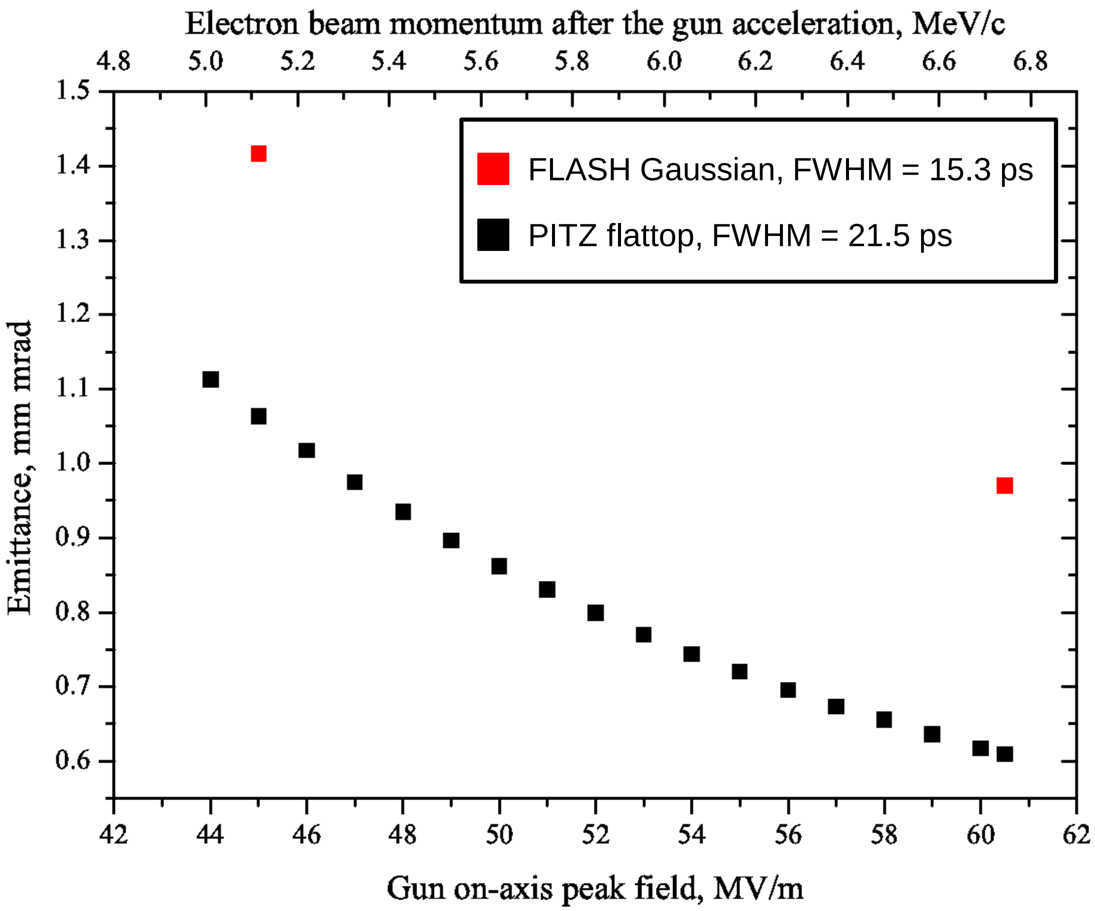
- Emittance optimization varying different machine parameters, 1nC charge:
  - Laser spot size on the cathode
  - Main solenoid current
  - Gun launching phase
  - Booster accelerating gradient

$\boldsymbol{\varepsilon_{n,x} = \varepsilon_{n,y} = 0.61\ mm\ mrad}$ **@ 1nC**



Simulations. 1nC charge.

Emittance dependence on gun on-axis peak field.



- FLASH operates at about 45 MV/m gun field, Gaussian longitudinal laser shape
- European XFEL will operate at about 60 MV/m gun field, longitudinally flat-top laser

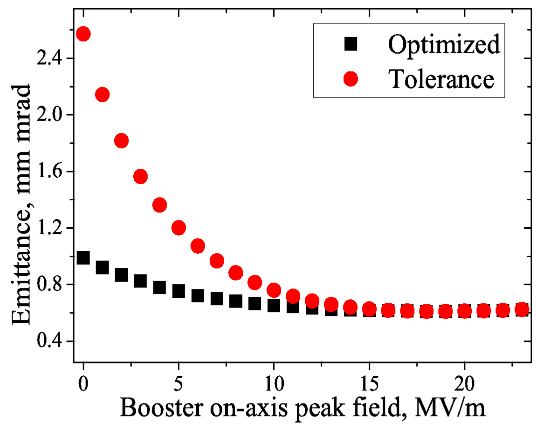
Upgrade of the FLASH photocathode laser system to PITZ type and increase of gun on-axis peak field to 60 MV/m ➔ Emittance reduction by a factor of 2.33.

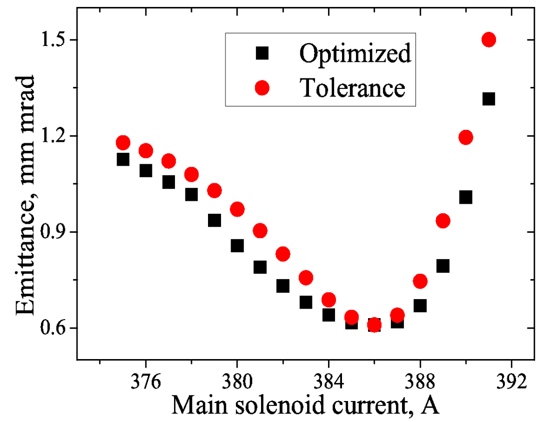
Simulations. E_gun = 60.5 MV/m. 1 nC charge.

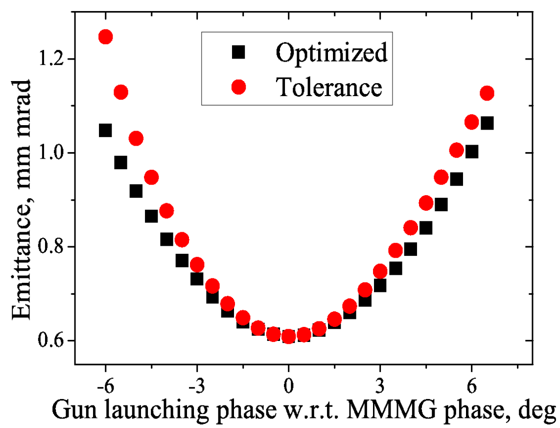
■ Optimized, varied parameters:
- Main solenoid current
- Gun launching phase
- Booster on-axis peak field
- Laser spot size on the cathode

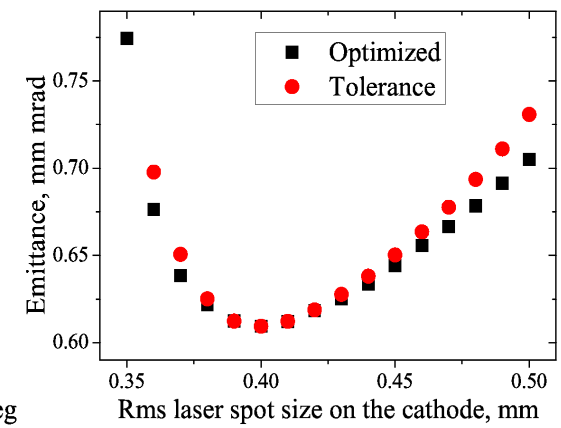
■ Tolerance: 3 out of 4 are fixed to optimum values which deliver emittance of 0.61 mm mrad.

Most sensitive parameters:
- Main solenoid current
- Gun launching phase

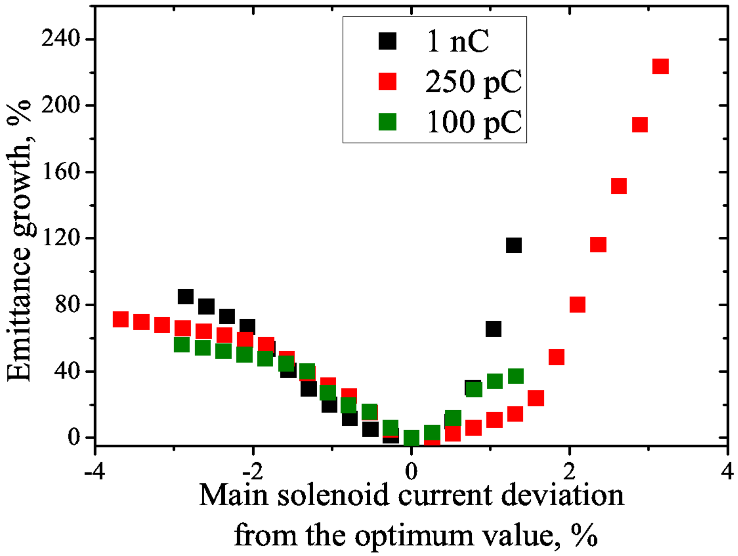


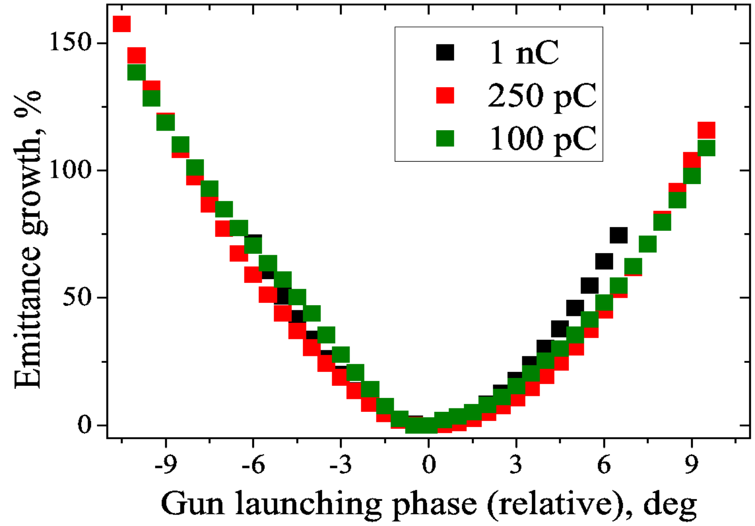


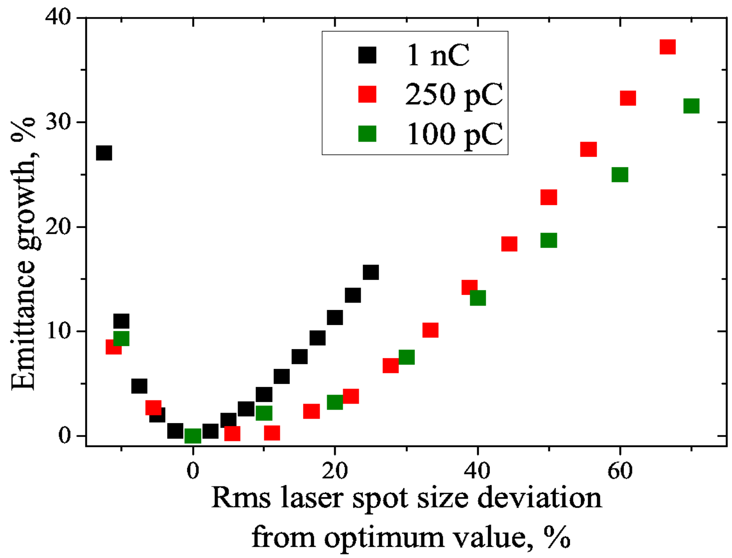




Simulated emittance growth for different electron beam charges



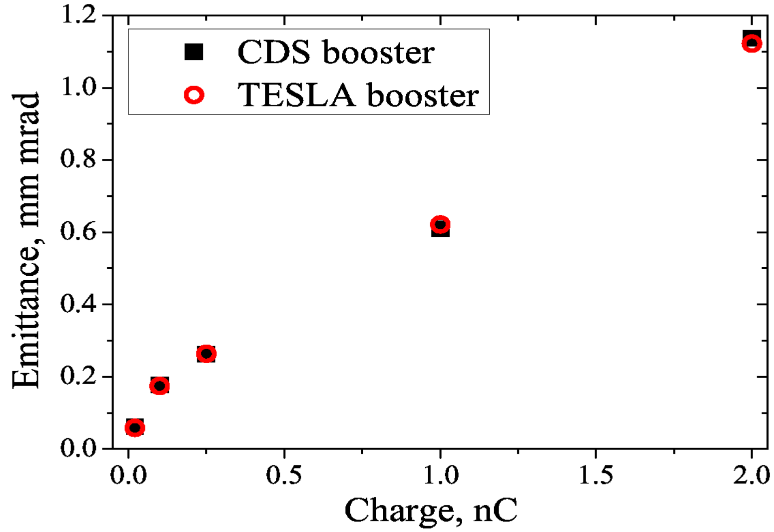




Similar emittance growth with the deviation of the certain parameter from its optimum value for all tested electron beam charges.

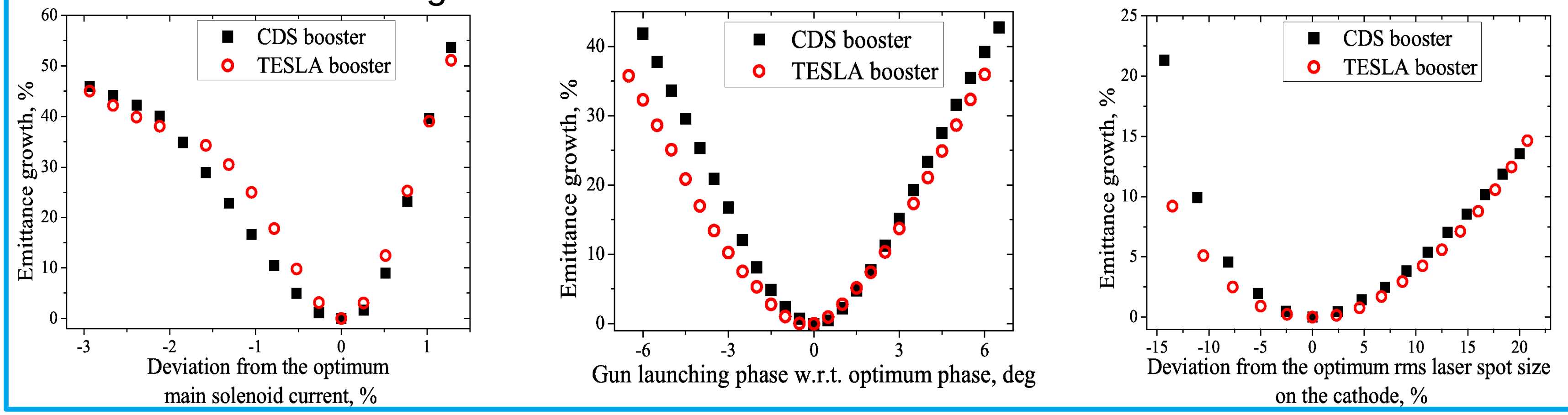
2nC and 20 pC are simulated as well and have similar dependencies.

Simulations. Optimized emittance for different charges. TESLA vs. CDS

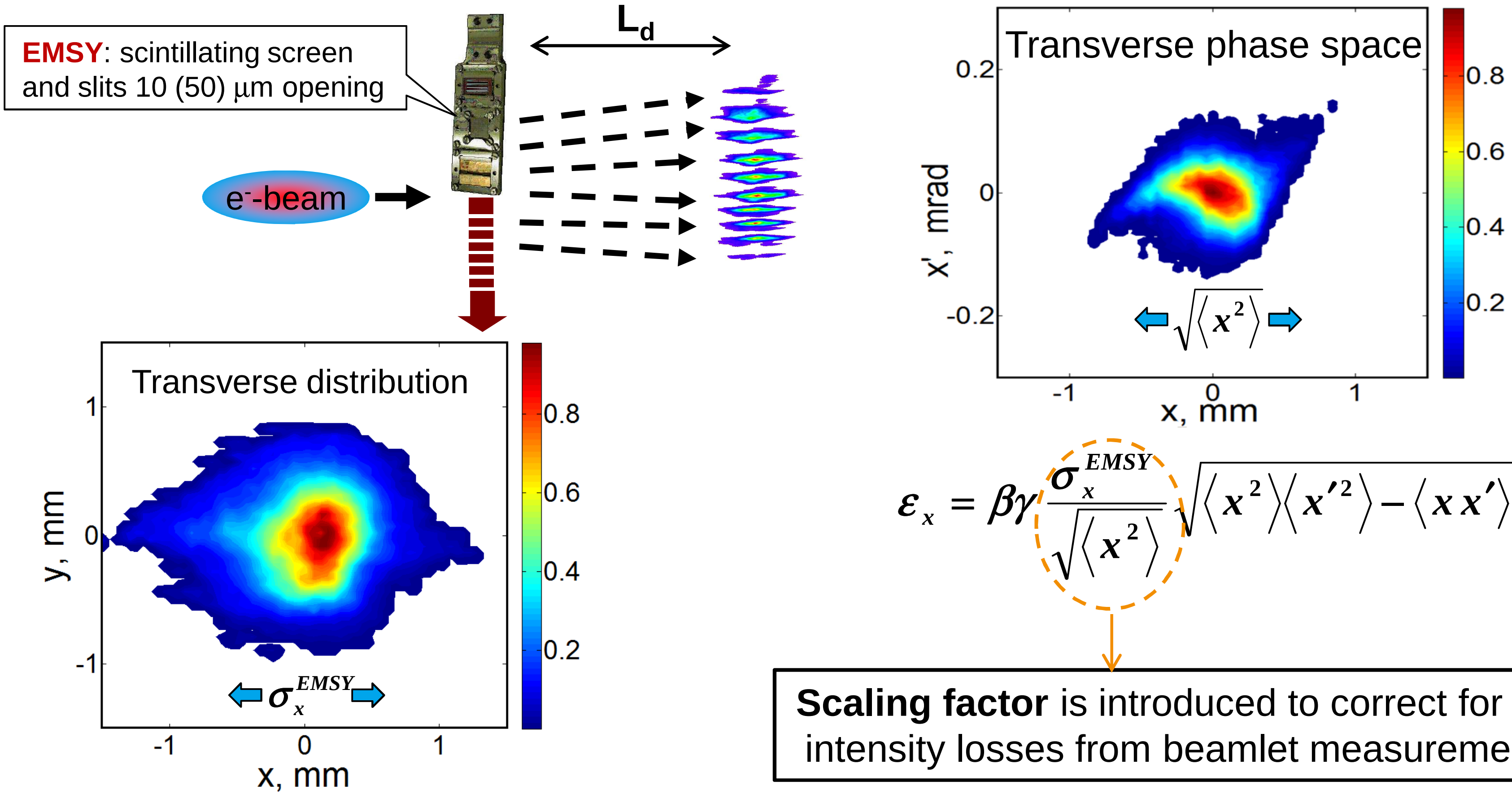


	Resulting parameters for CDS booster			
Q, nC	σ_{xy}, mm	I_{main}, A	Φ_{gun}, deg	ε_n, mm mrad
2	0.59	387	-1	1.138
1	0.4	386	0	0.61
0.25	0.23	385	1.5	0.262
0.1	0.1	385	2	0.174
0.02	0.035	380	1.5	0.061

Emittance growth with the deviation from the optimum machine parameter for electron beam with 1nC charge



Emittance measurements method and procedure



$$\varepsilon_x = \beta\gamma \frac{\sigma_x^{EMSY}}{\sqrt{\langle x^2 \rangle}} \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$

Scaling factor is introduced to correct for low intensity losses from beamlet measurements

For the certain laser spot size, gun phase and electron beam charge solenoid scan is performed. Several statistical measurements are done for the main solenoid current delivering the minimum emittance value defined from the solenoid scan.

Systematic errors

Systematic errors sources:

• Finite slit opening size and space-charge in beamlets: beamlet tracking – about 4% overestimation.	10 µm slit opening 3D space-charge forces
• Camera properties: imaging of the simulated distributions according to the CCD camera properties – about 2% for Q ≥ 100pC, 146% for Q = 20 pC.	Pixel size: 9.3 µm Bit depth: 12 (0-4095) Magnification lens A250 
• Deviation of machine parameters from optimum values: reasonable deviations are considered for each machine parameter, highest possible emittance difference is taken into account – about 10% for all charges.	Main solenoid current: 1 A Gun launching phase: 1 deg Booster momentum gain: 100 keV/c Laser beam size on the cathode: 10 µm

Charge, nC	Camera	Machine parameters
2	<1%	8%
1	3%	12%
0.25	<1%	13%
0.1	1.2%	8%
0.02	146%	10%

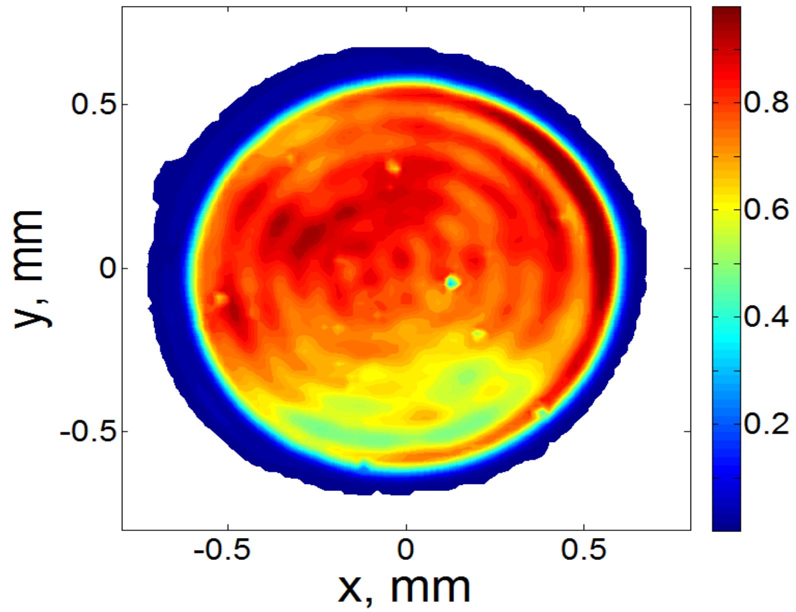
Total emittance overestimation: about 13 % for all charges except 20 pC. For 20 pC charge emittance overestimation by more than factor of 2 is expected.

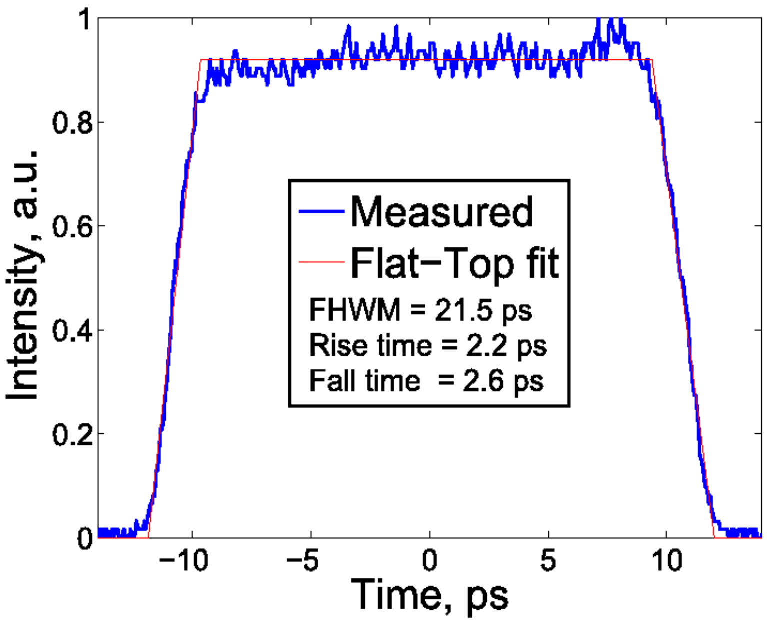
Measurements. Best emittance for 1nC beam charge. Laser parameters

UV Laser parameters:

Rms spot size of σ_{xy} = 0.3 mm

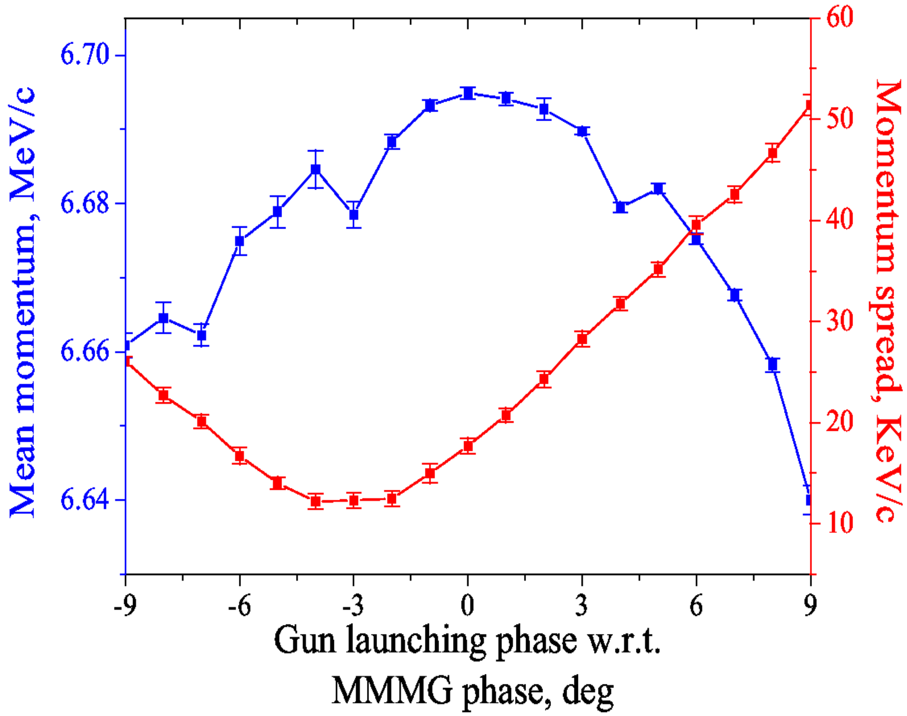
Length at FWHM = 21.5 ps

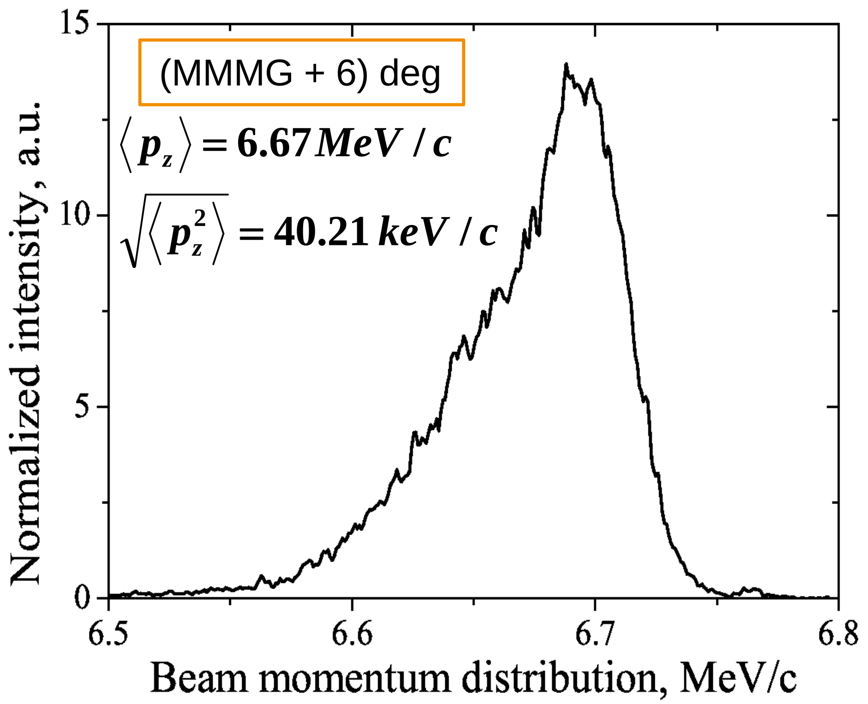




Measurements. Best emittance for 1nC beam charge. Momentum and phase determination

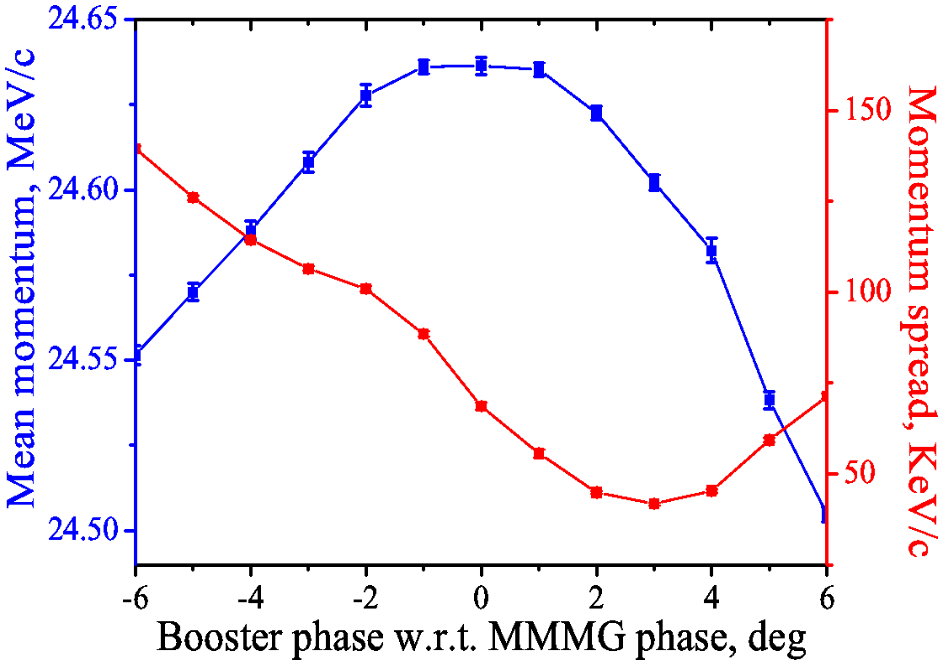
Momentum scan after gun acceleration: determine phase of maximum mean momentum gain. Best emittance was measured at (MMMG+6) deg phase.

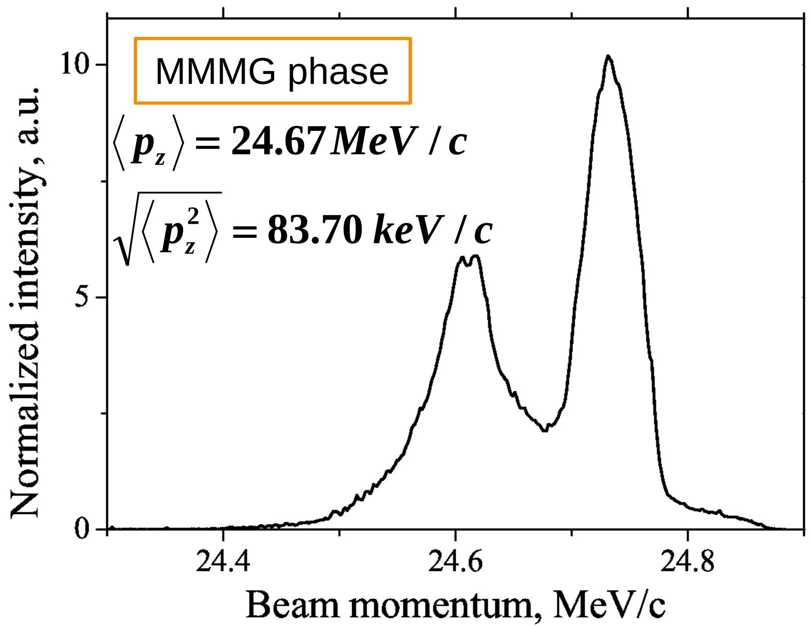




Measurements. Best emittance for 1nC beam charge. Momentum and phase determination

Momentum scan after booster acceleration: determine phase of maximum mean momentum gain. Best emittance was measured at MMMG phase.

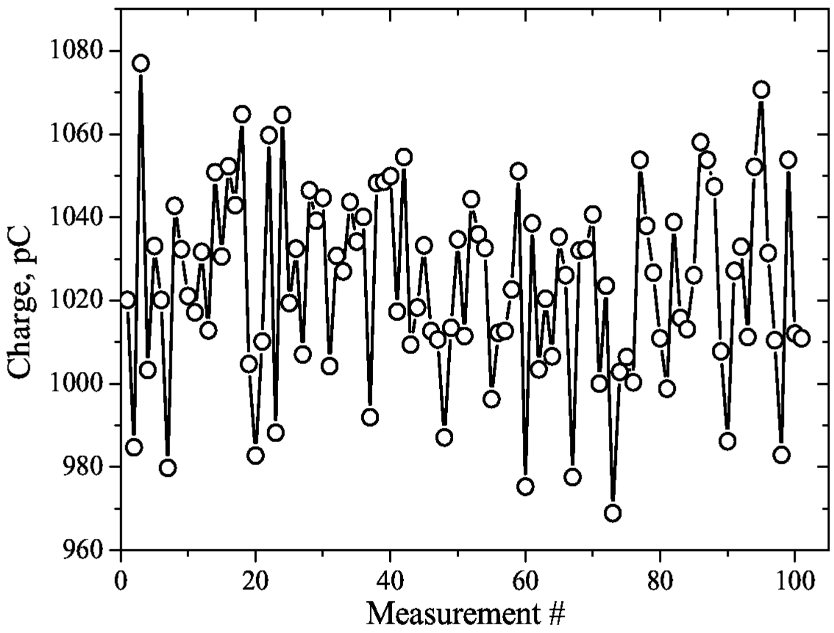


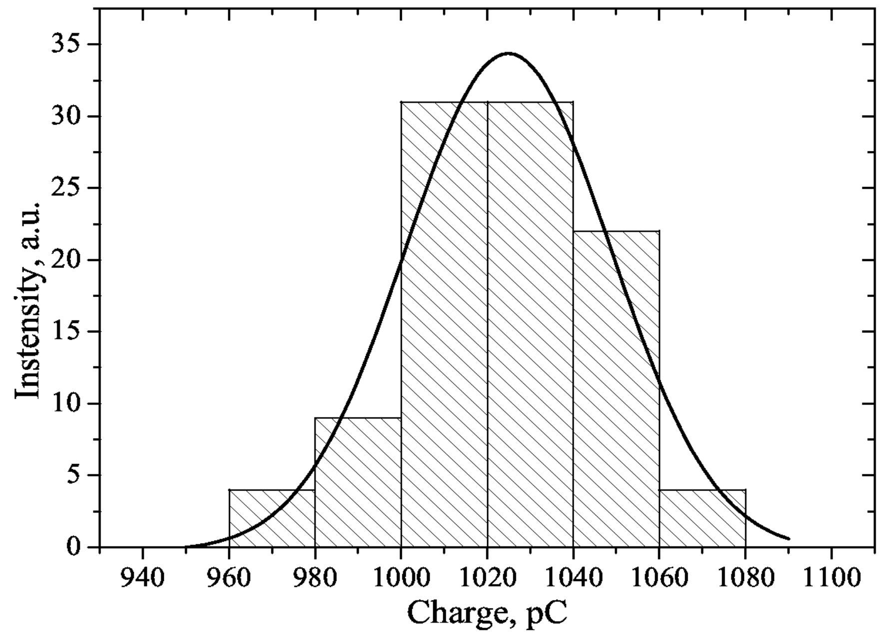


Measurements. Best emittance for 1nC beam charge. Charge measurement

Charge measurement was performed with the help of integrated current transformer installed directly downstream the CDS booster. Measurement yields charge of:

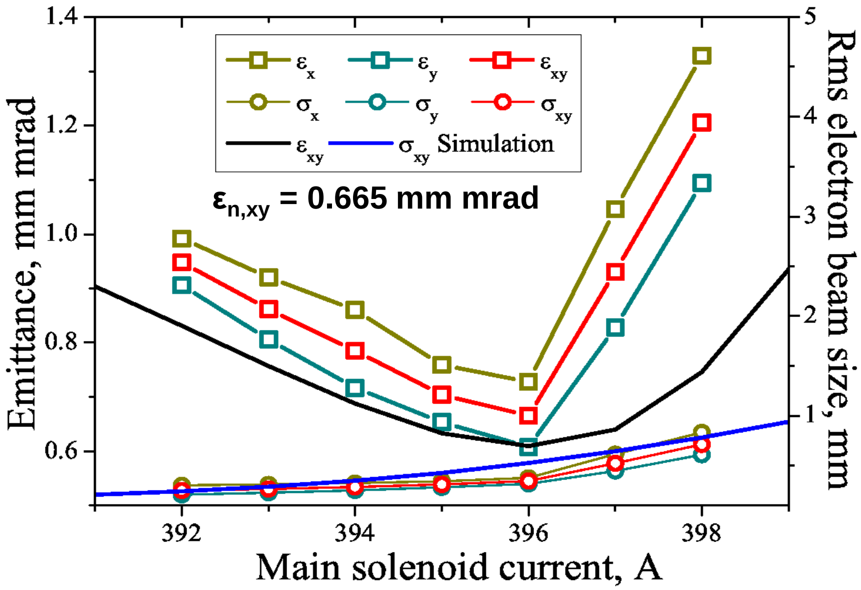
$$Q = 1.02 \pm 0.02\ nC$$



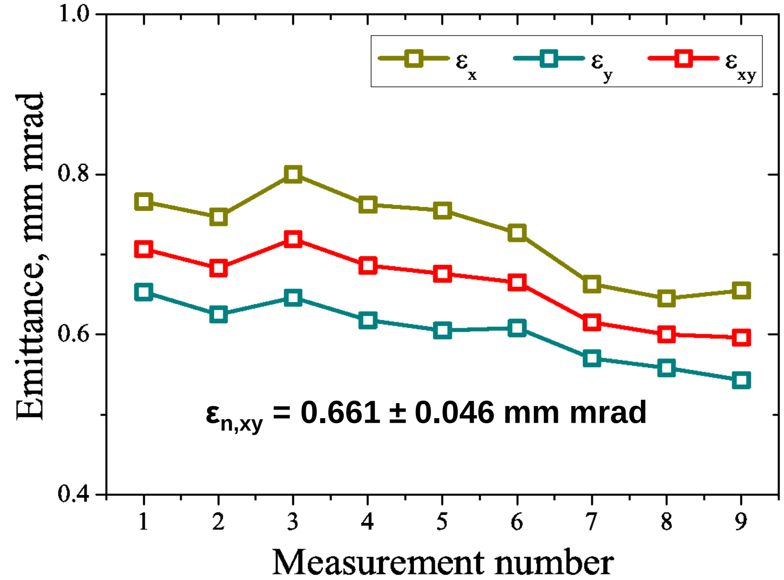


Measurements. Best emittance for 1nC beam charge. Solenoid scan, statistics and trace spaces

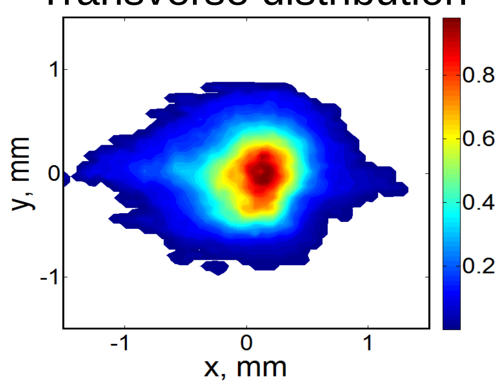
Solenoid scan, +10 A



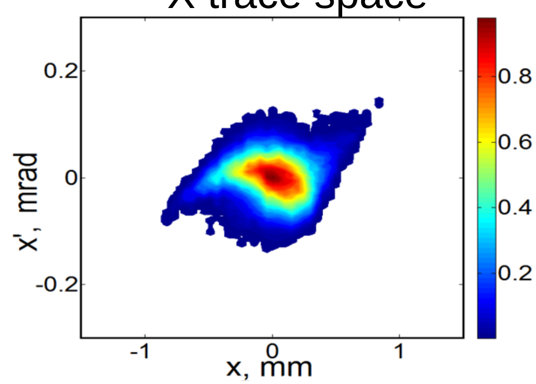
Statistics for I_{main} = 396 A



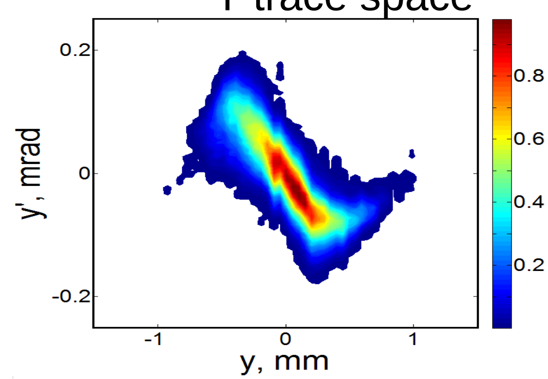
Transverse distribution



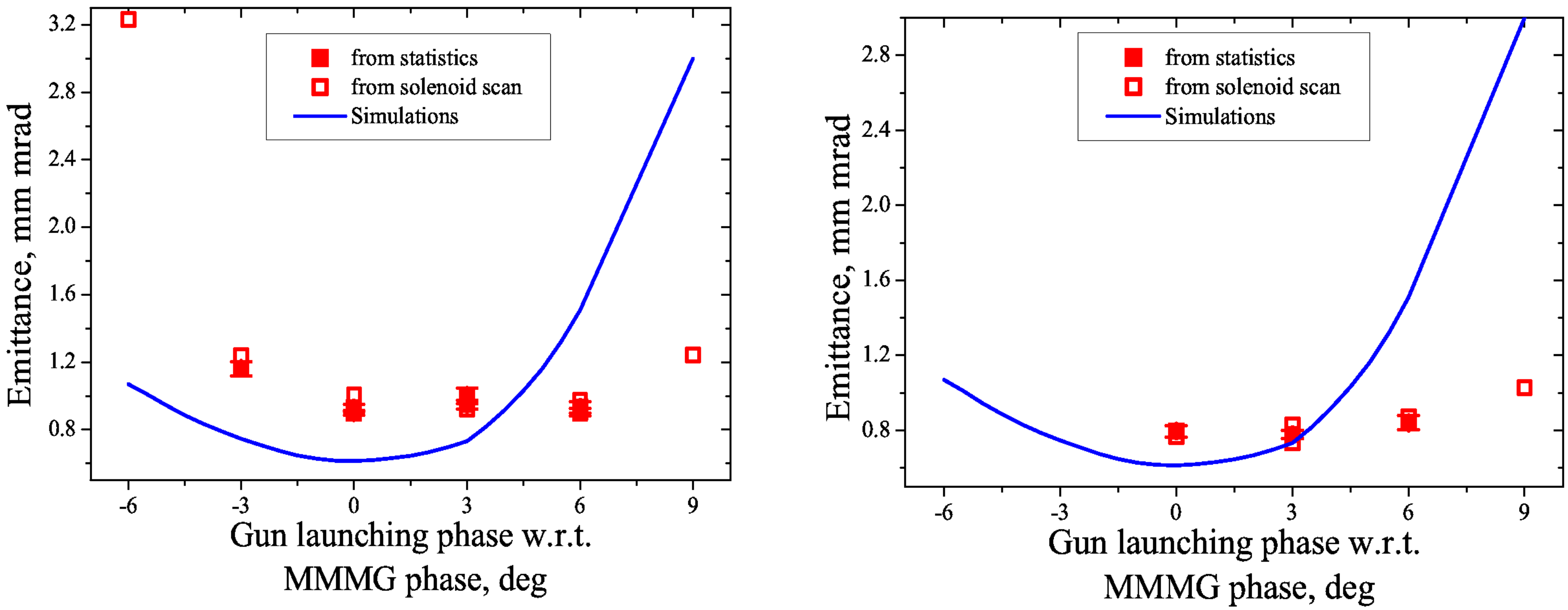
X trace space



Y trace space

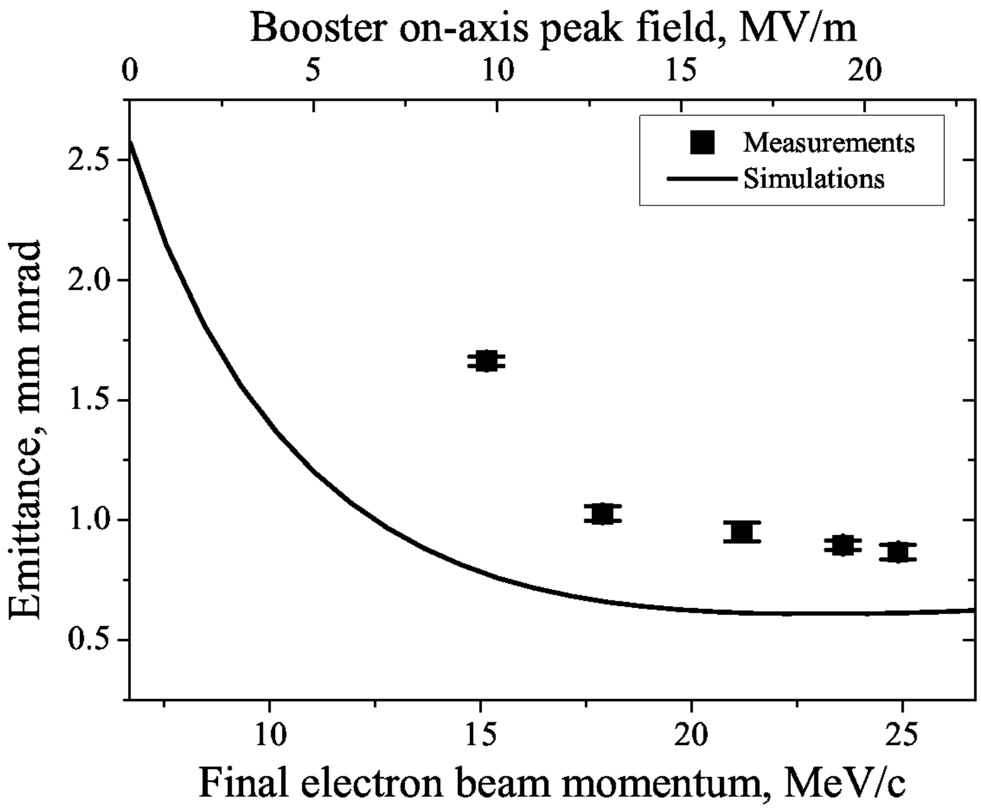


Measurements. Emittance dependence on the gun launching phase for 1nC charge



- Statistical error bars are hidden within the marker size on both plots.
- Extraction of 1nC charge is not possible for the rms laser spot size on the cathode of 0.3 mm in simulations ➔ use 0.4 mm as delivering minimum emittance as well as 0.3 delivers minimum emittance during measurements.

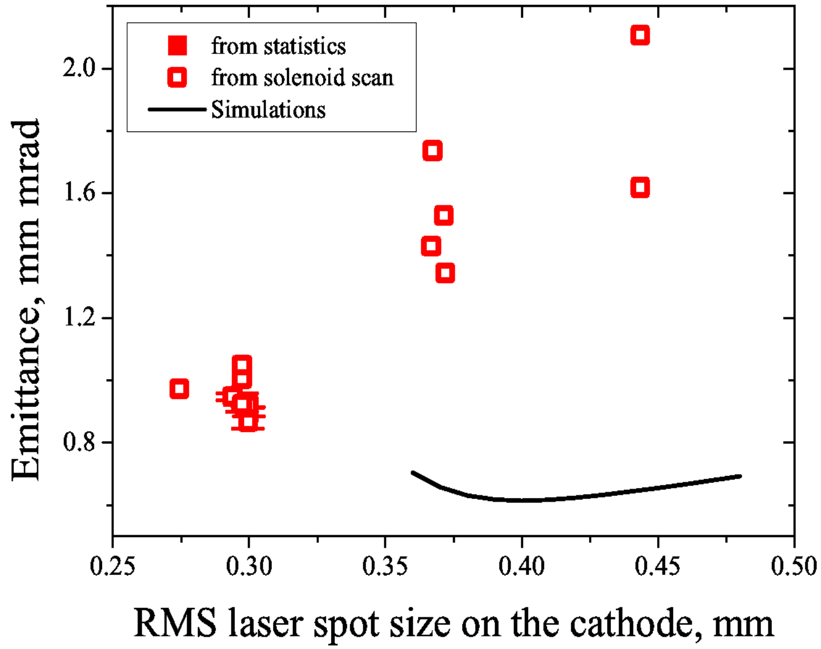
Measurements. Emittance dependence on the booster accelerating gradient for 1nC charge



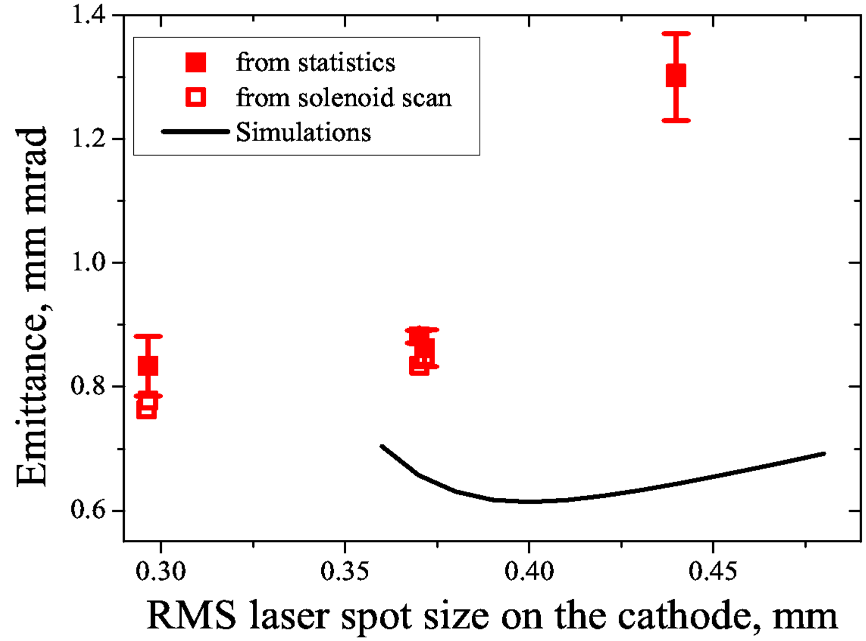
- Measurements were performed at the beginning of the a period – not optimized machine parameters.
- Good qualitative agreement with the simulation data.
- Plateau part nearly reached – power limited by available CDS booster RF system.

Measurements. Emittance dependence on the laser spot size on the cathode for 1nC charge

Measurement before upgrade of the UV laser system.

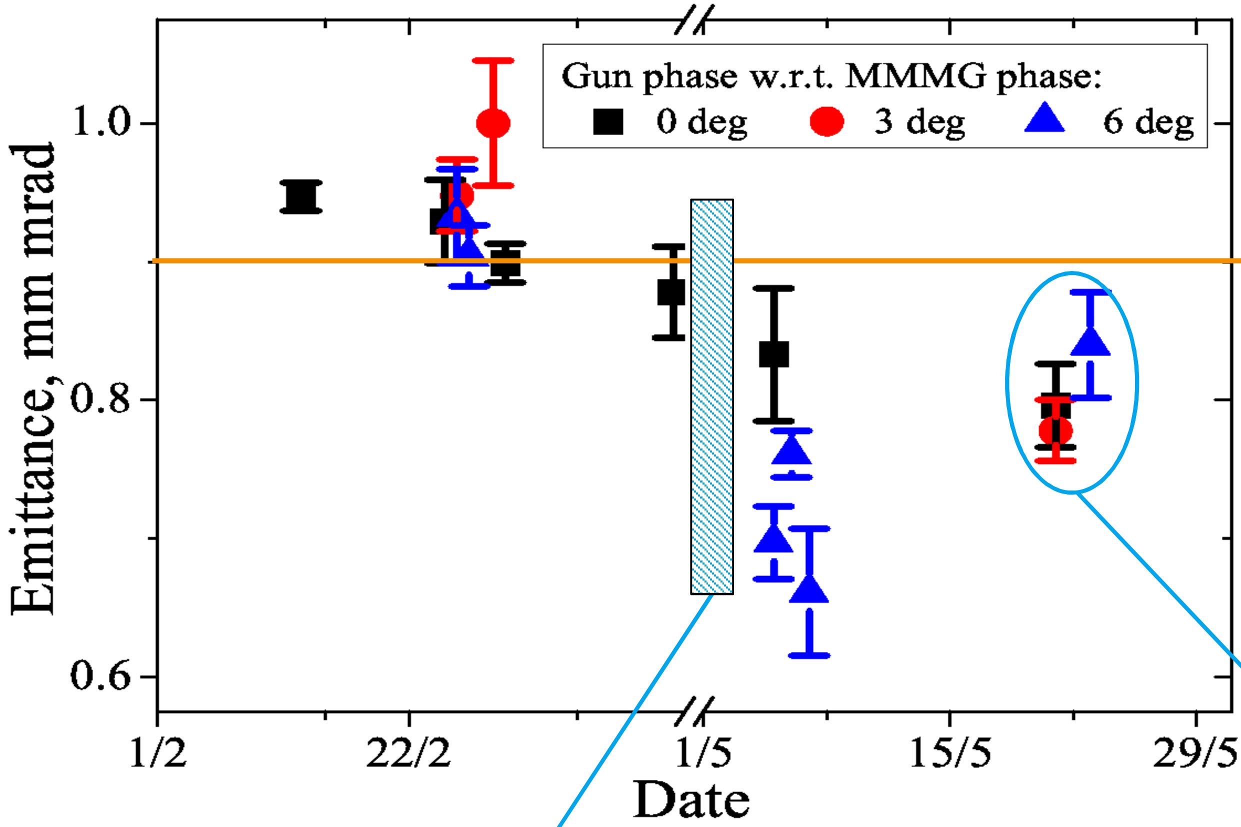


Measurement after upgrade of the UV laser system.



Problem: not possible to extract 1nC in simulation for the rms laser spot size on the cathode of less than 0.36 mm. Schottky-like effect? Not yet understood.

Measurements. Emittance evolution during the run period for 1nC charge



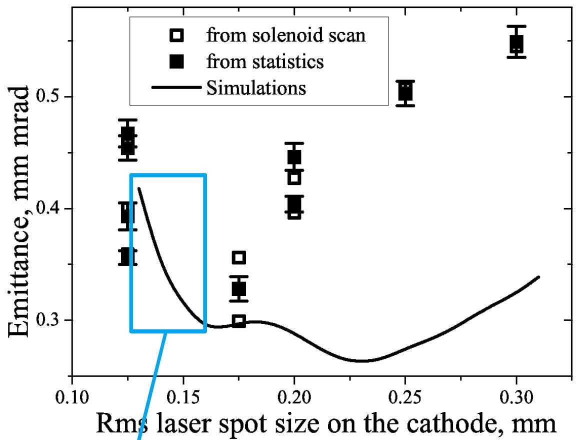
European XFEL requirement

$\varepsilon_{n,xy}$ < 0.9 mm mrad was measured regularly

Upgrade of UV laser system

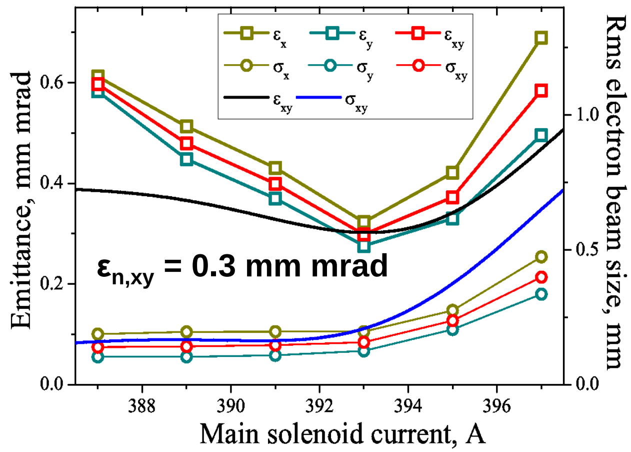
Problems with laser system – increased emittance

Emittance measurements. 250 pC beam charge

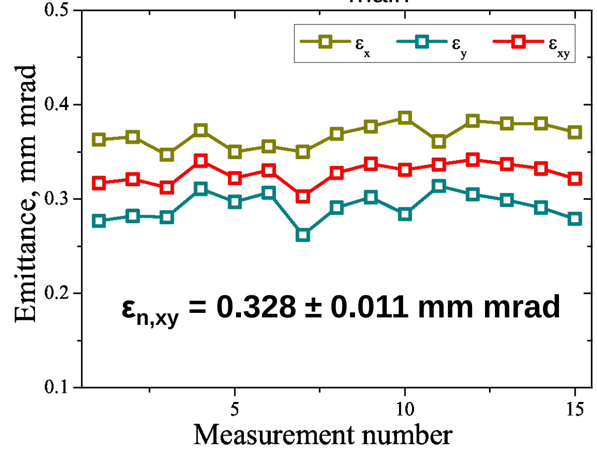


Lost particles

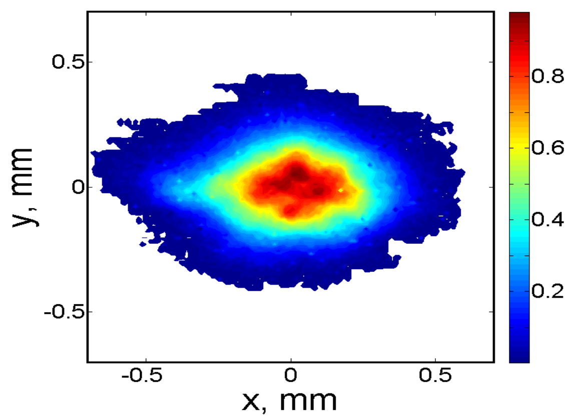
Solenoid scan, +8 A



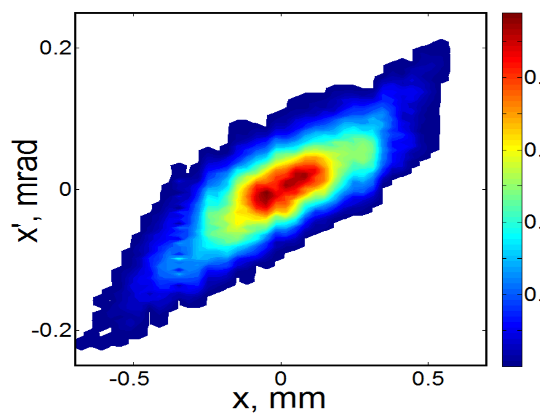
Statistics for I_{main} = 393 A



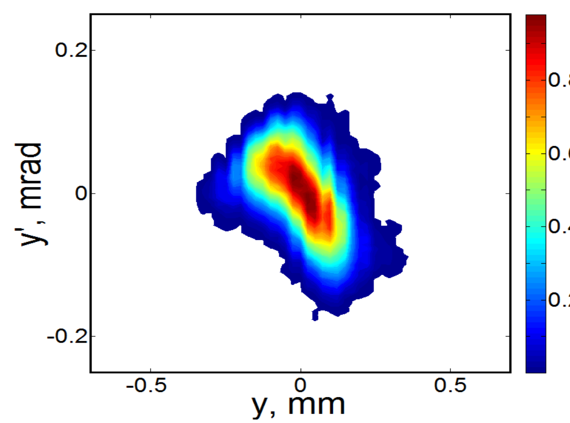
Transverse distribution



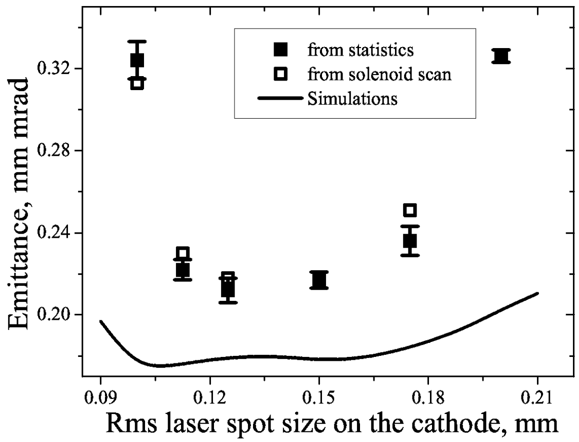
X trace space



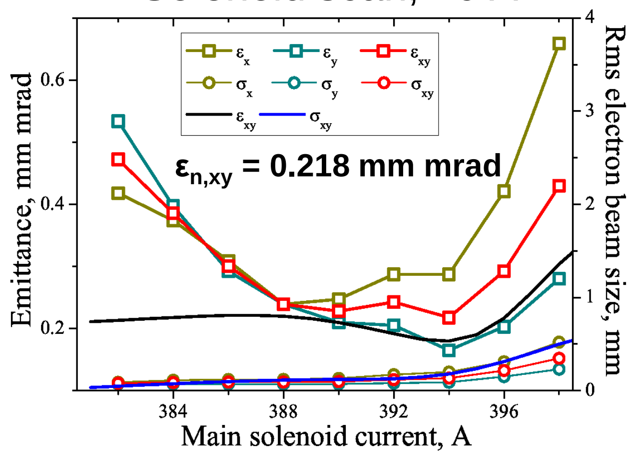
Y trace space



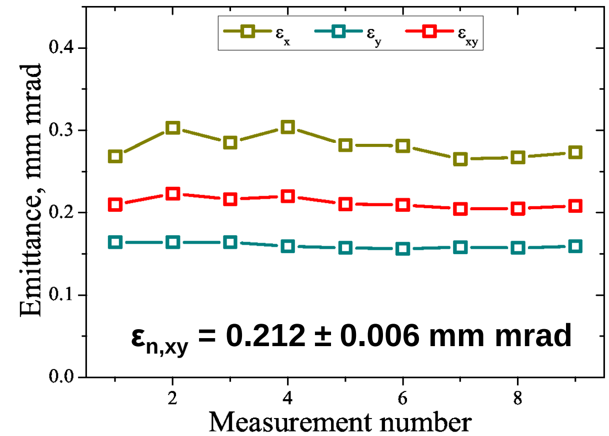
Emittance measurements. 100 pC beam charge



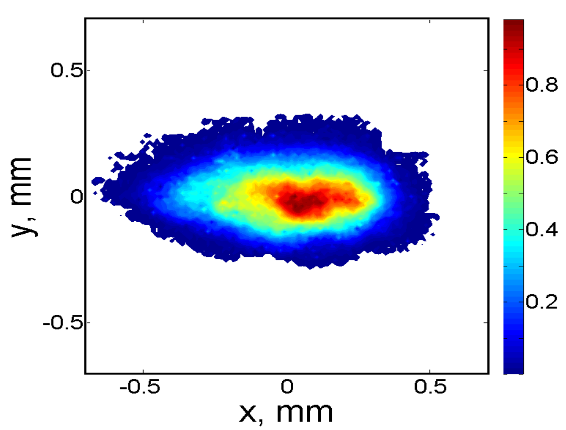
Solenoid scan, +9 A



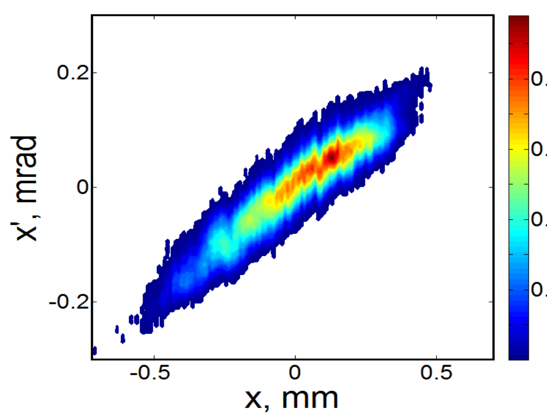
Statistics for I_{main} = 394 A



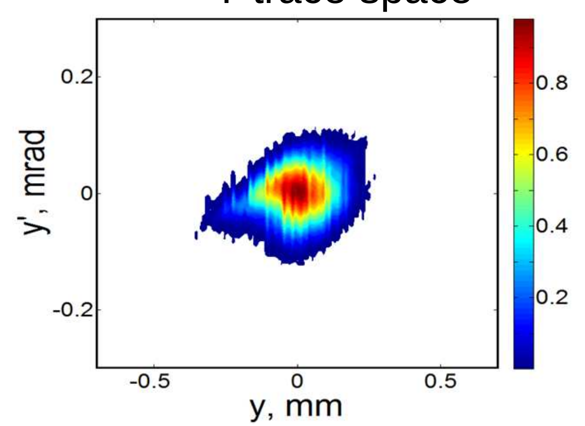
Transverse distribution



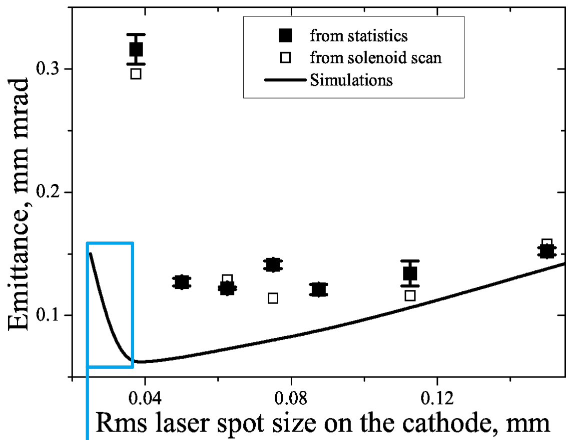
X trace space



Y trace space

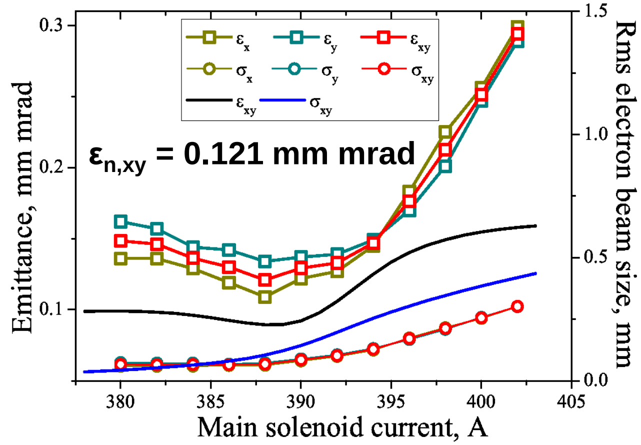


Emittance measurements. 20 pC beam charge

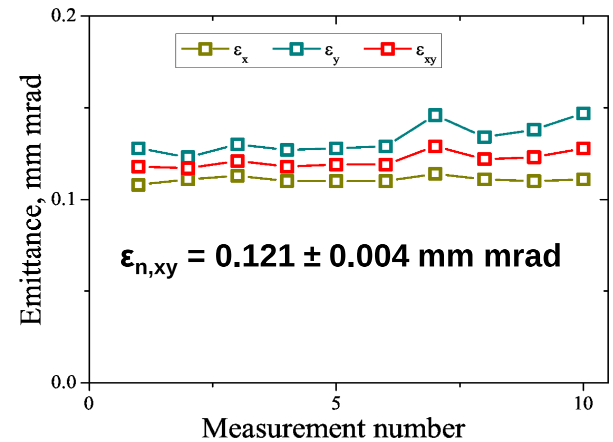


Particles lost

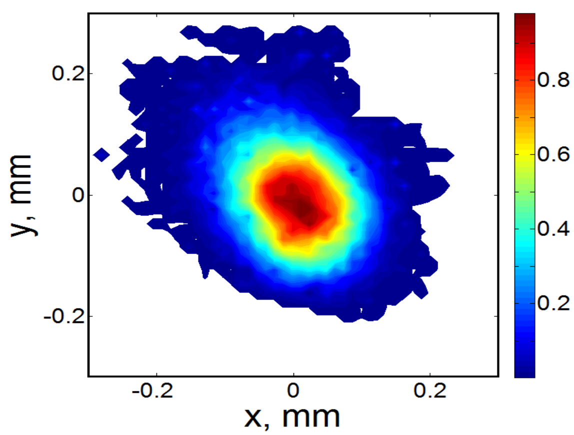
Solenoid scan, +8 A



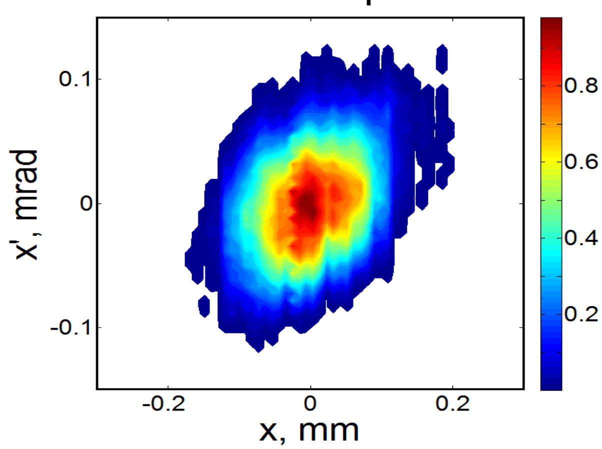
Statistics for I_{main} = 388 A



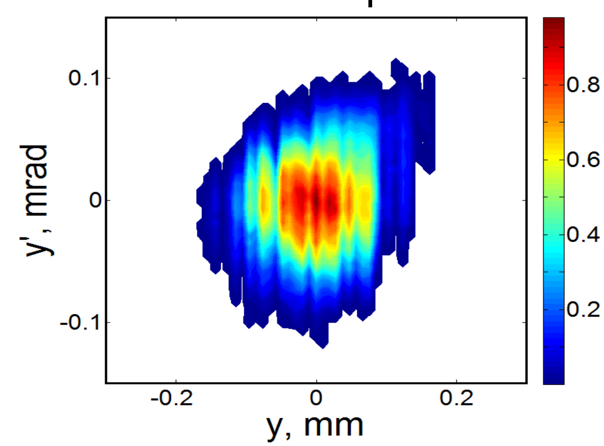
Transverse distribution



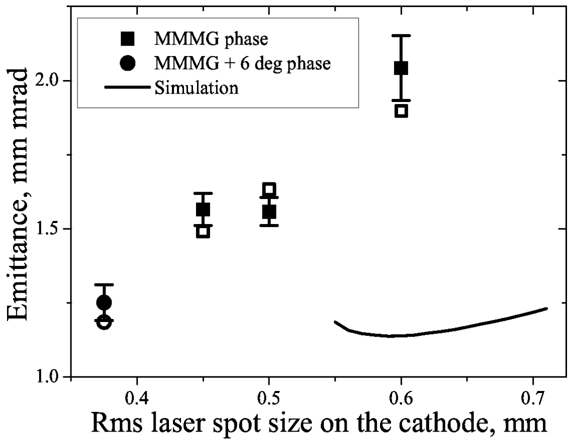
X trace space



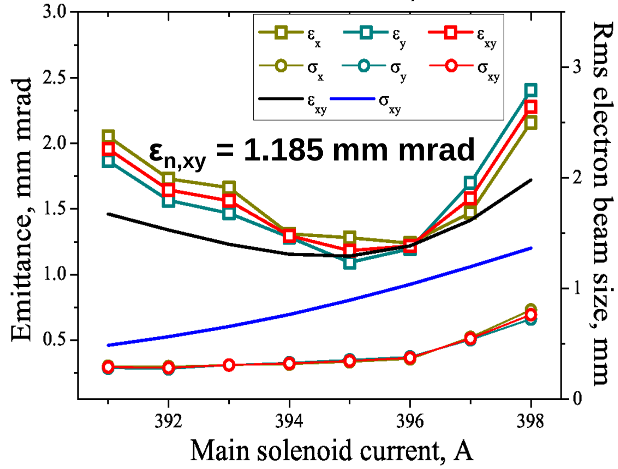
Y trace space



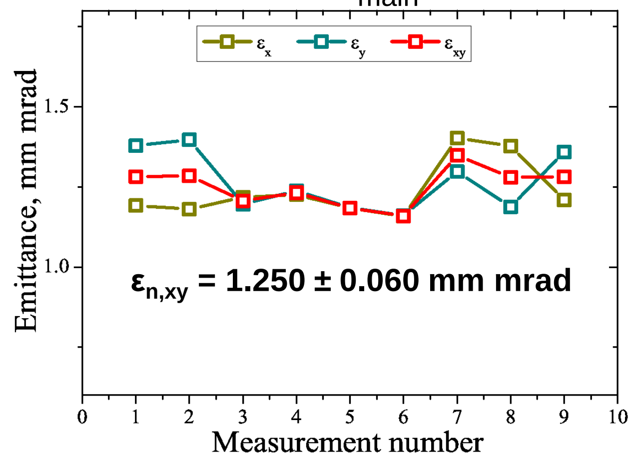
Emittance measurements. 2 nC beam charge



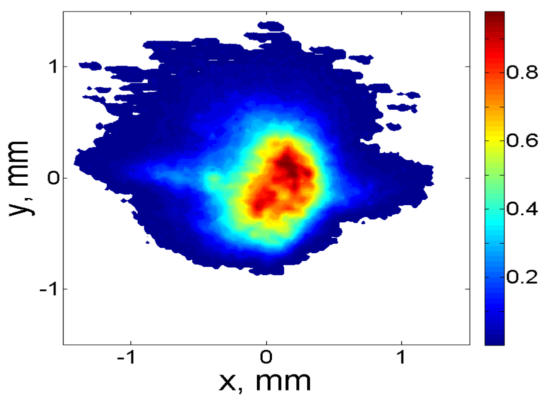
Solenoid scan, +8 A



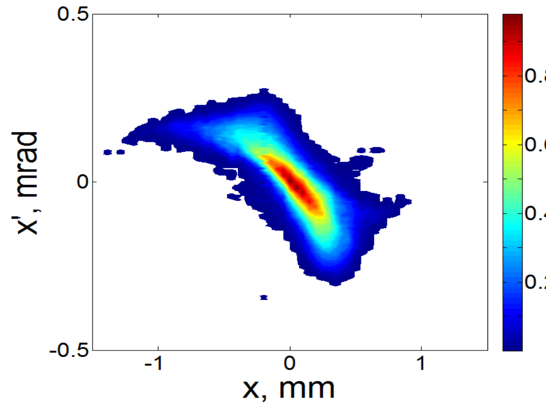
Statistics for I_{main} = 395 A



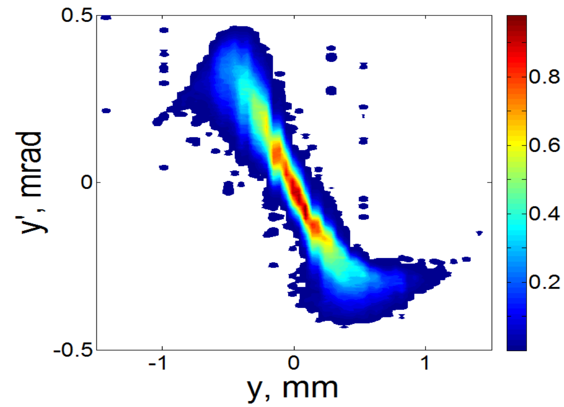
Transverse distribution



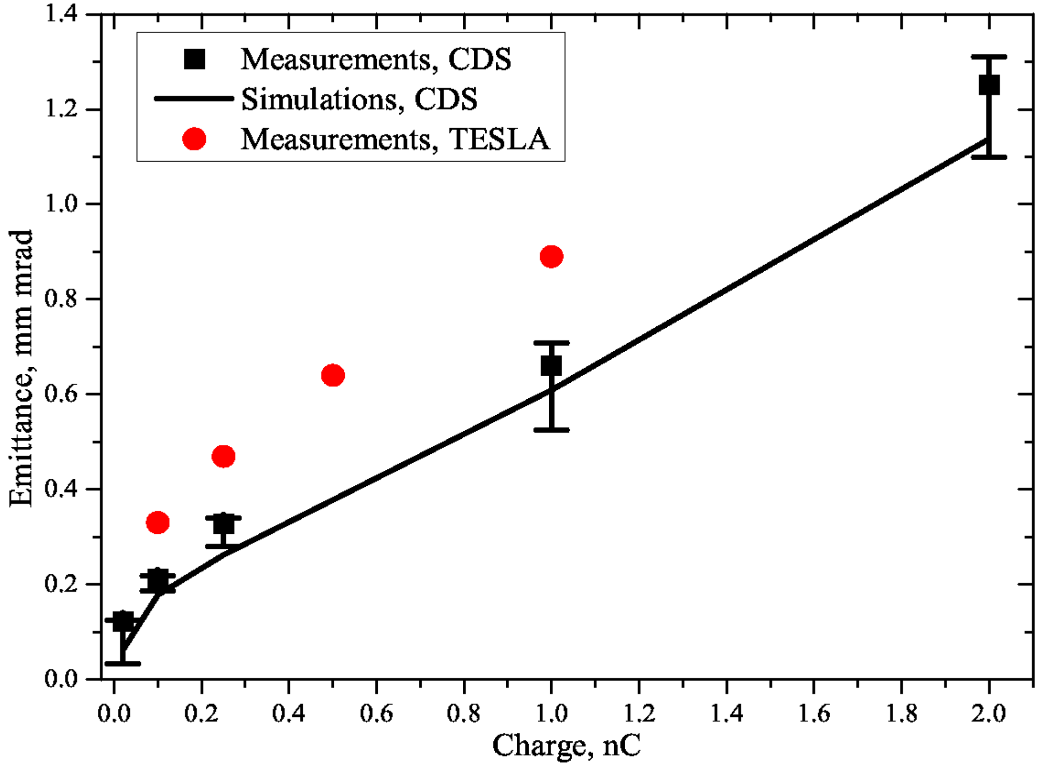
X trace space



Y trace space



Measured emittance dependence on charge for different booster types and comparison to the simulations



- Simulations for TESLA and CDS booster gave about the same results.
- Reduction of the emittance measured with CDS as compared to TESLA booster:
  - Improvement of gun LLRF system – gun phase stability
  - Improvement of UV laser system
  - Other improvements

Measured emittance dependence on charge for different booster types and comparison to the simulations

	Simulations				
Q, nC	σ_L, mm	I_{main}, A	Φ_{gun}, deg	ε_n, mm mrad	$\Delta\varepsilon_n$, mm mrad
2	0.59	387	-1	1.138	
1	0.4	386	0	0.61	
0.25	0.23	385	1.5	0.262	
0.1	0.1	385	2	0.174	
0.02	0.035	380	1.5	0.061	
	Measurements				
2	0.375	395	6	1.251	±0.060 - 0.093
1	0.3	396	6	0.661	±0.046 - 0.09
0.25	0.175	393	0	0.328	±0.011 - 0.037
0.1	0.113	394	0	0.212	±0.006 - 0.019
0.02	0.088	388	0	0.121	±0.004 - 0.083

Statistical

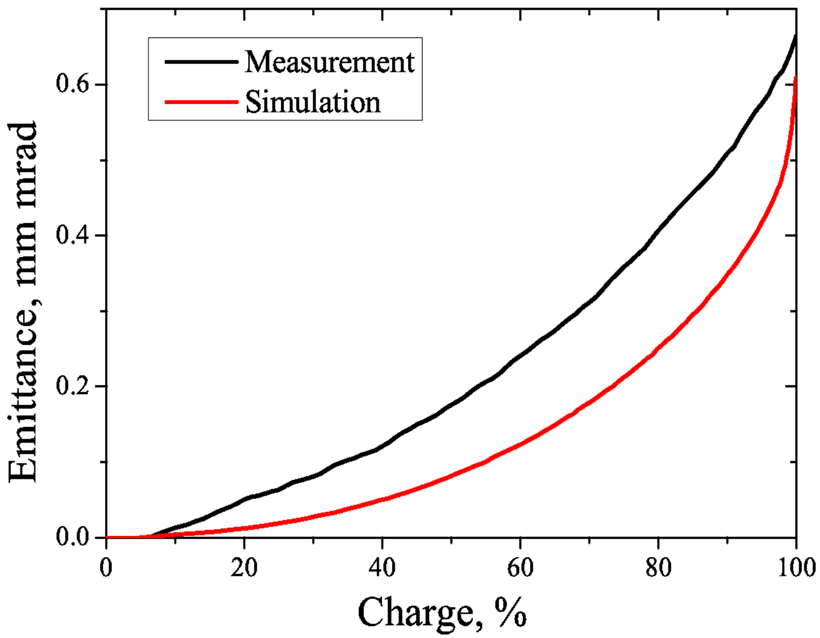
Systematic

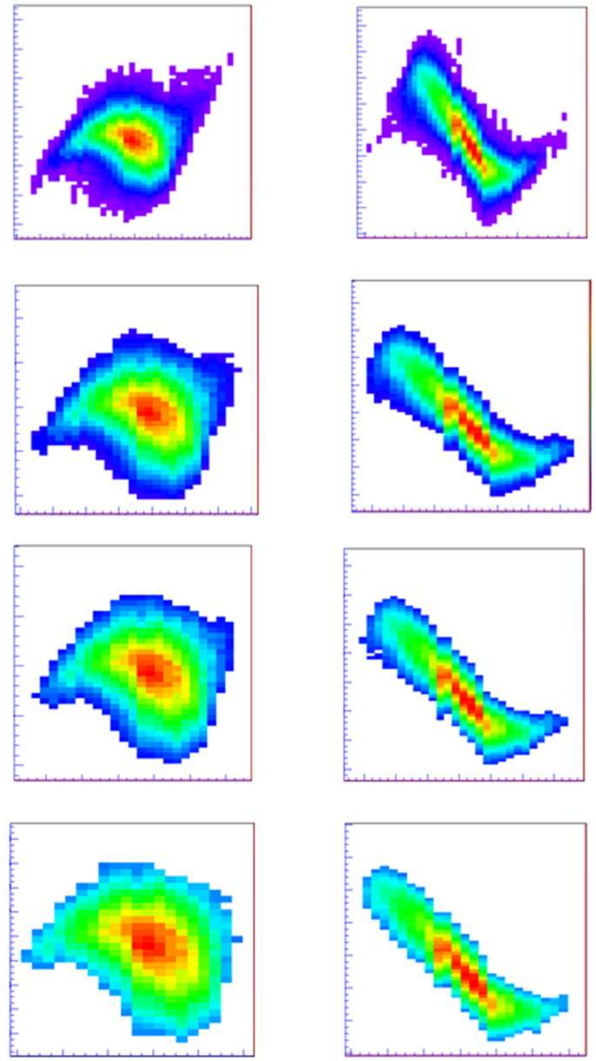
- Systematic offset (8-10 A) in main solenoid current: field profiles measurements and smoothing, magnetizable components in the beamline.
- Laser spot size and gun phase: enhanced electron emission in the presence of the electric field is not taken into account during the simulations

Core emittance for 1nC charge

FEL lasing: particle from outermost phase space region do not contribute

Calculate emittance from the fraction of the phase space inside the equidensity contour: core emittance.





$\varepsilon_{n,xy}(100\ \%) =$ 0.664 mm mrad

$\varepsilon_{n,xy}(95\ \%) =$ 0.591 mm mrad

$\varepsilon_{n,xy}(90\ \%) =$ 0.529 mm mrad

$\varepsilon_{n,xy}(80\ \%) =$ 0.427 mm mrad

Conclusions

- Emittance measured and simulated with the electron gun used at FLASH and European XFEL – requirements satisfied. Upgrade of RF gun system and photocathode laser system at FLASH can reduce emittance significantly.

- Methodical emittance studies in simulations: wide multiparameter scans were performed for different electron beam charges.

- Systematic errors investigated: for low charge measurements upgrade of the optical system is necessary. For other charges total systematic error of about 13% can be expected.

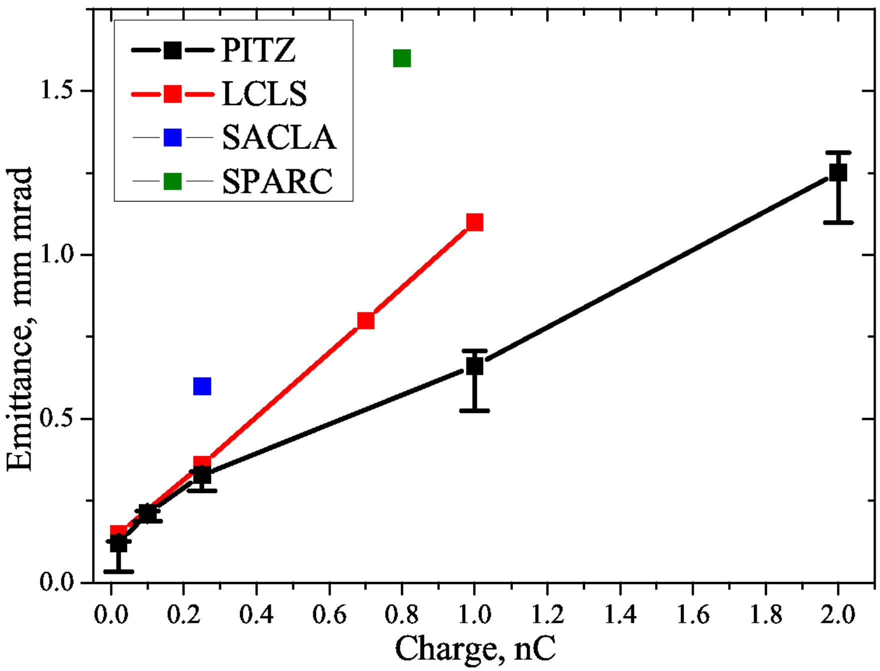
- Comparison between TESLA and CDS boosters: similar emittance for all charges, better emittance conservation for CDS. Same emittance can be expected at European XFEL.

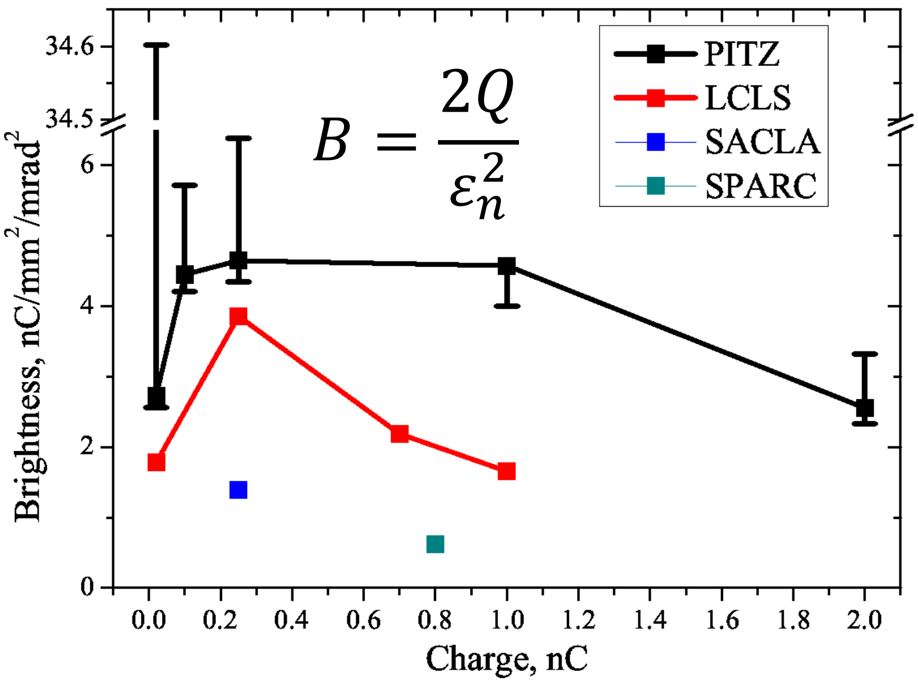
- Emittance measurements for 1nC charge yield to emittance of about 0.7 mm mrad - European XFEL requirements are satisfied.

Conclusions

- Emittance values measured for different electron beam charges are significantly lower than at other FEL facilities.

Emittance at the end of injector for different facilities





Outlook

- Transverse deflecting cavity - time resolved emittance measurements with high resolution in the nearest future.

- Emittance measurements along the beamline and comparison to simulation data can give better understanding the electron beam dynamics.

- Difference of the optimum machine parameters at which minimum emittance values were found during the simulations and experiments - further investigations of photoemission are necessary.

- Emittance measurements for flat-top laser with the length of less than 20 ps are necessary for low charges.

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Thank you for attention!