Photo Injector Test facility at DESY, Zeuthen site

PITZ: Simulations versus Experiment

Mikhail Krasilnikov (DESY, Zeuthen site)
Darmstadt, 19.12.2013

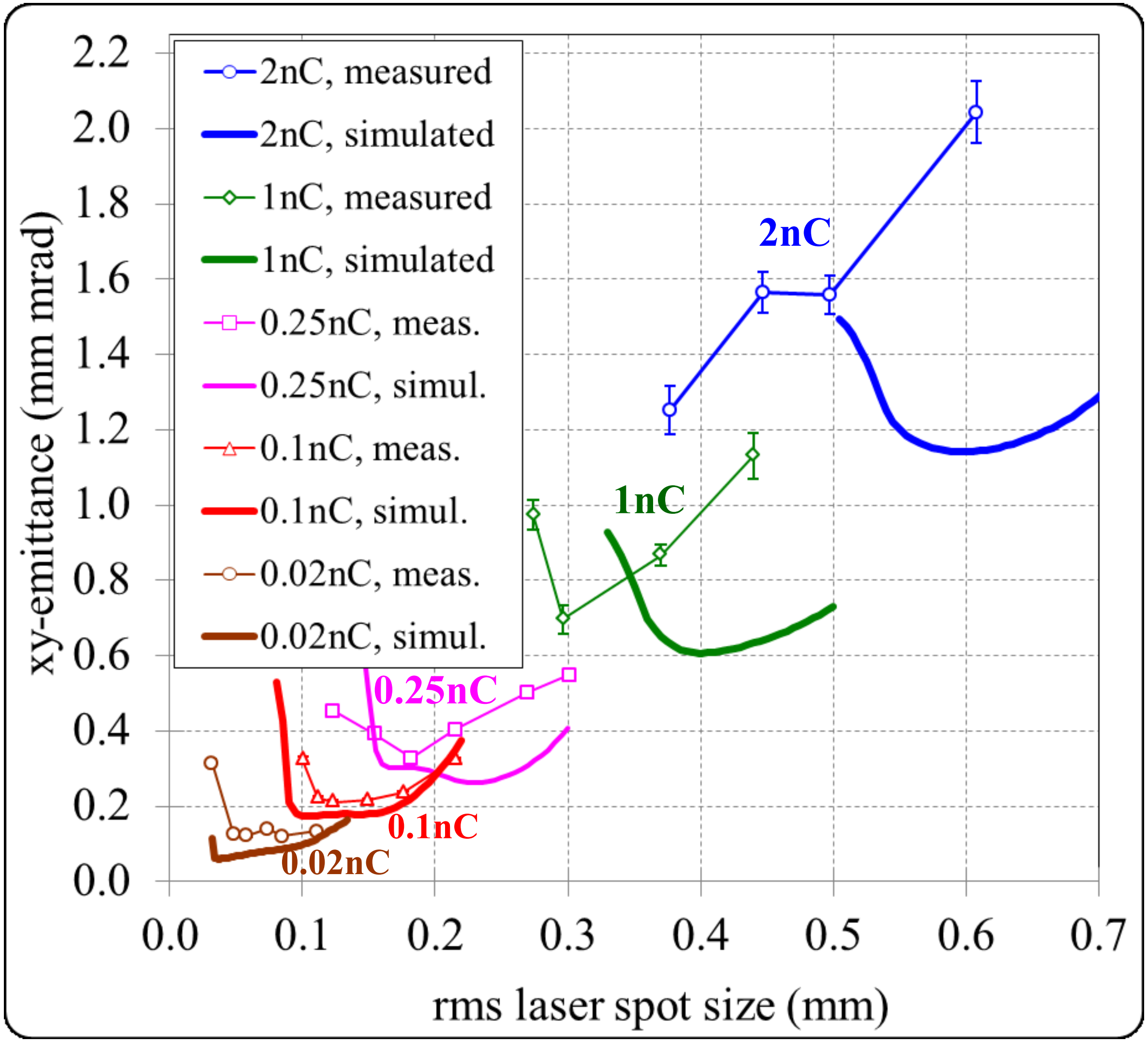
- Emittance and brightness vs. bunch charge
- Emission area homogeneity
- Emittance vs. main solenoid current
- “Fin structure” investigations – coaxial coupler kick?
- Photo emission studies – various cathode laser temporal profiles
- Recent problem: gun cavity resonance temperature drift

HELMHOLTZ | ASSOCIATION

DESY

Emittance versus Laser Spot Size for various Charges

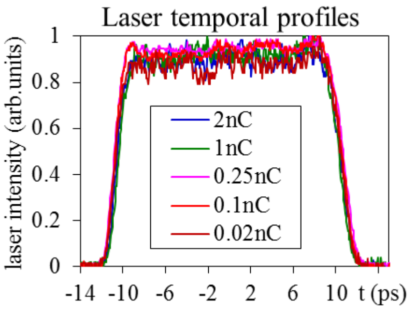
Measured (100%) rms normalized emittance vs. simulations



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

Charge, nC	Measured, mm mrad	Simulated, mm mrad
2	1.25±0.06	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

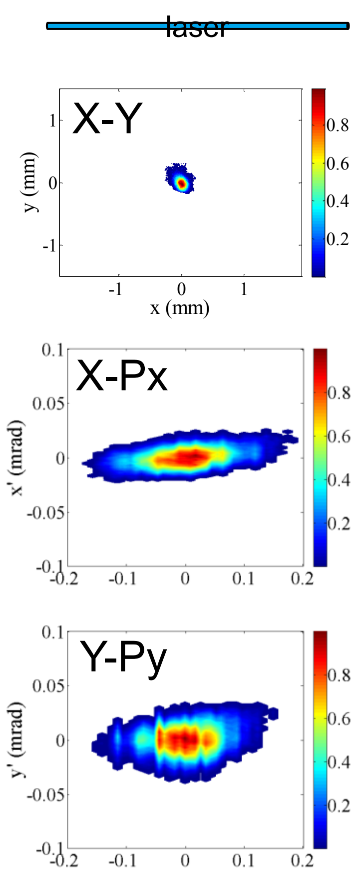


Emittance and Brightness versus Bunch Charge

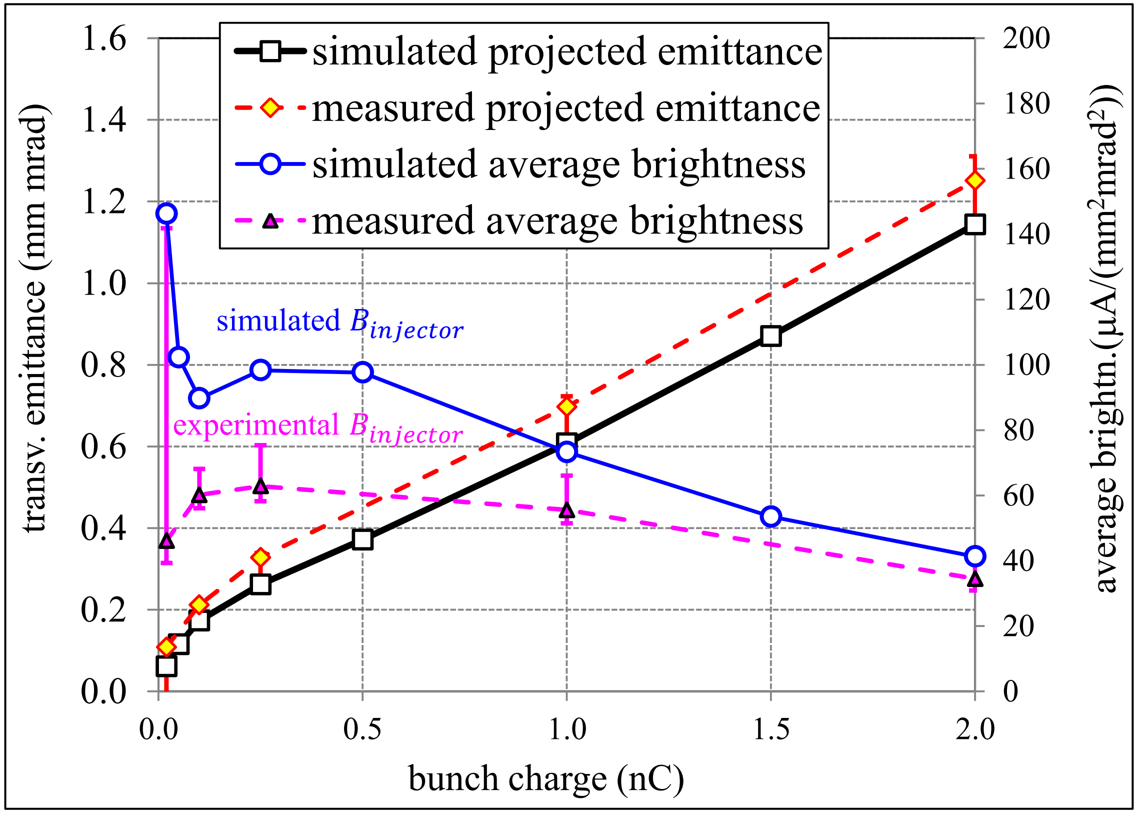
Cathode laser pulse duration was ***fixed at 21.5 ps (FWHM)*** *for all bunch charges!*

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

20pC measured

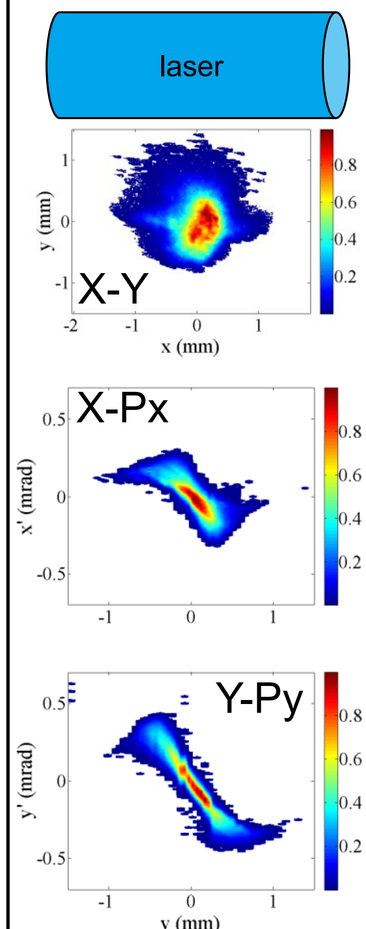


~linear SC



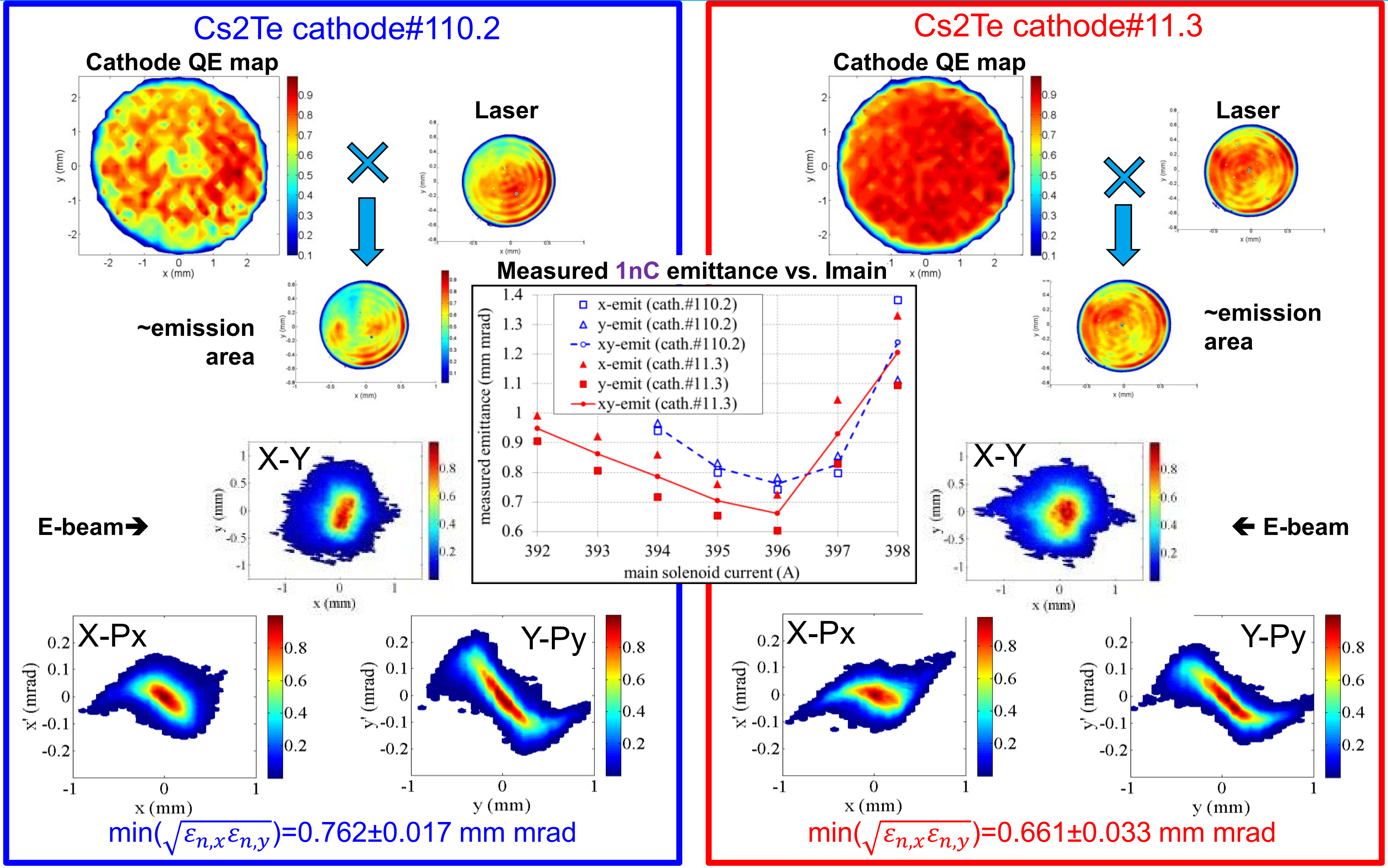
Bunch charge reduction at fixed cathode laser pulse duration → space charge (SC) modification

2nC measured

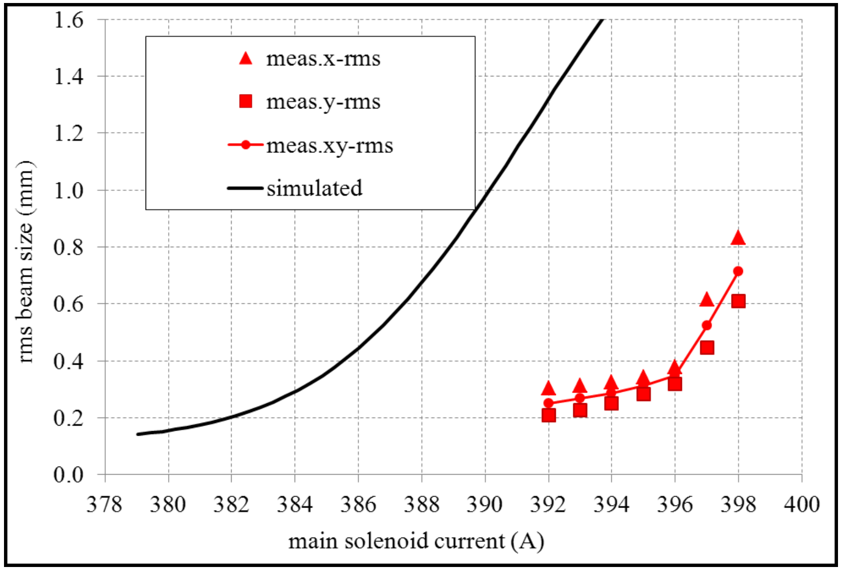


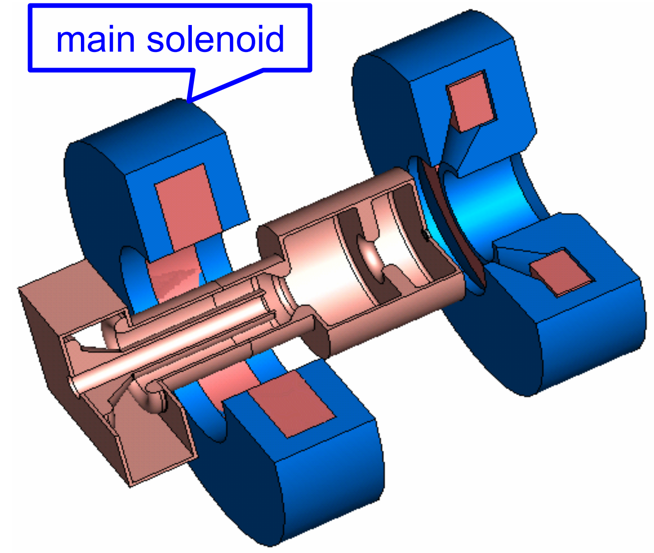
nonlinear SC

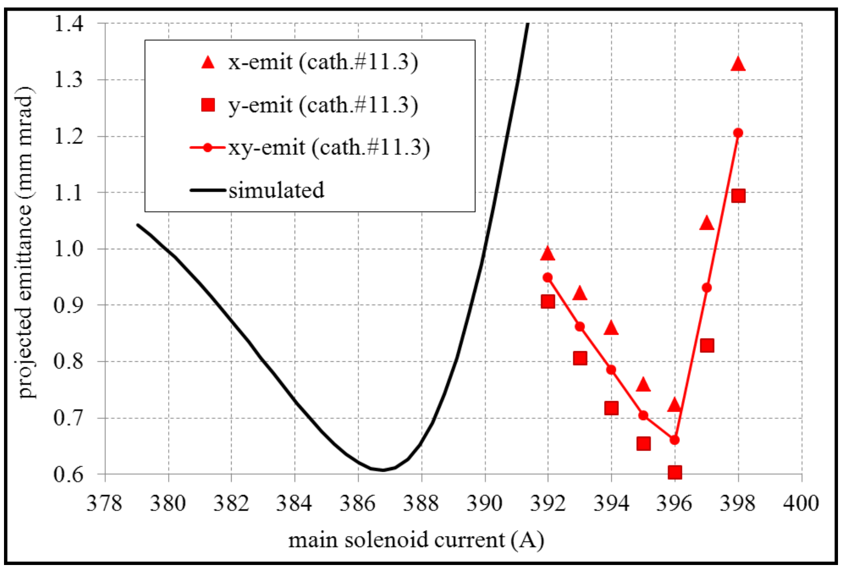
Emission Area Homogeneity



S←→M versus main solenoid current (1nC)





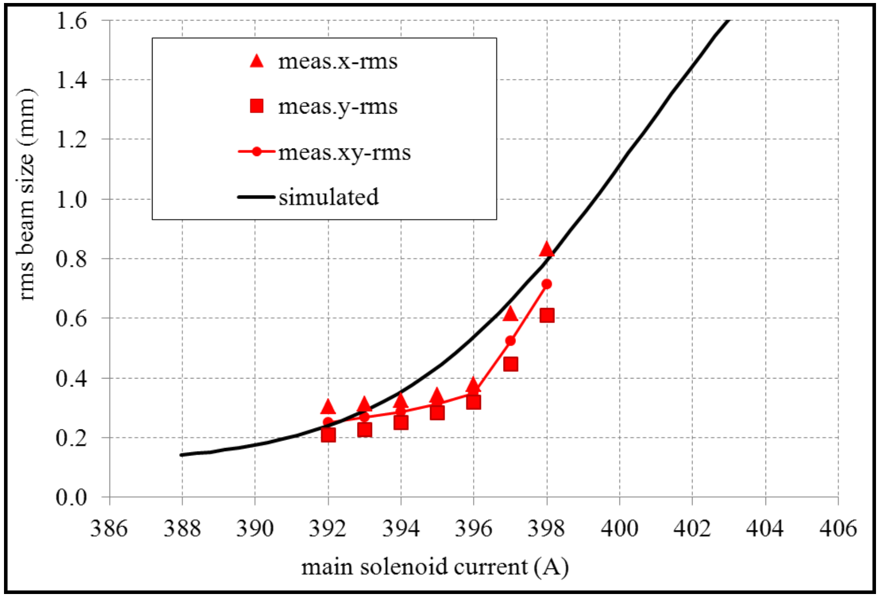


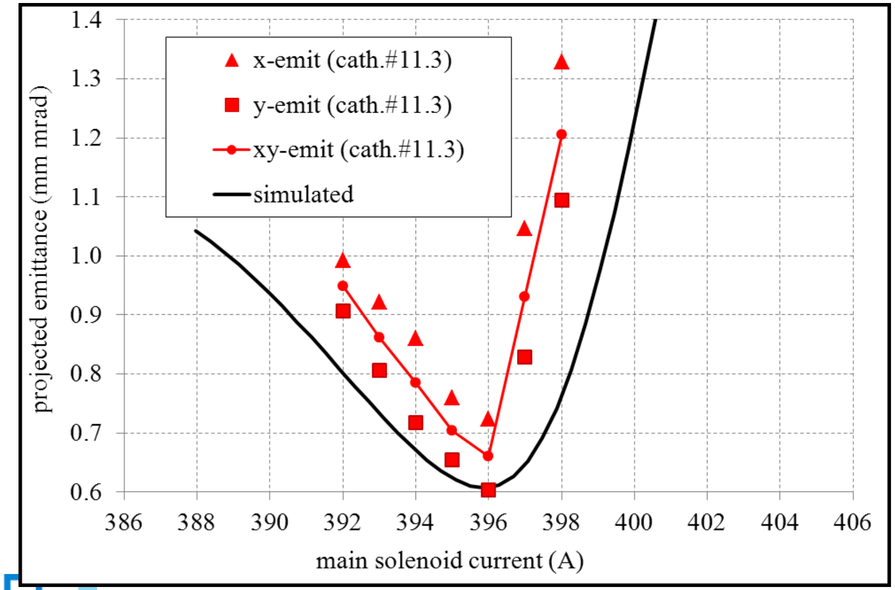
From magnetic measurements:

-Bmax[T]=0.0005893*Imain[A]-0.00001169

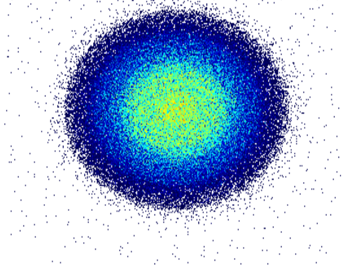
ΔI(M-S)~9A!

S←→M versus main solenoid current (1nC)

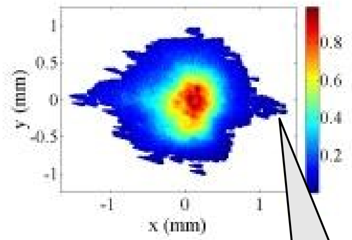




Simulated X-Y



Measured X-Y



?origin of these tails?

But:

→magnetizable girder

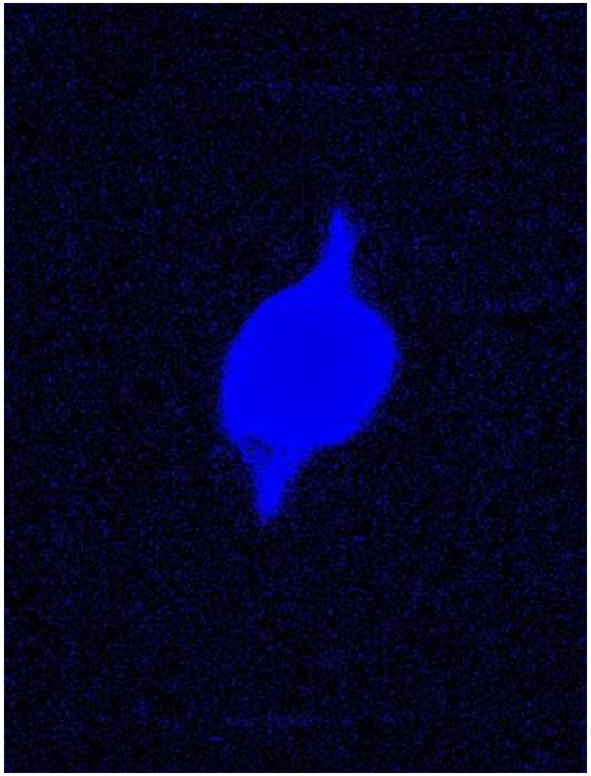
→weak Cu diamagnetism

Bmax→ Bmax*0.977

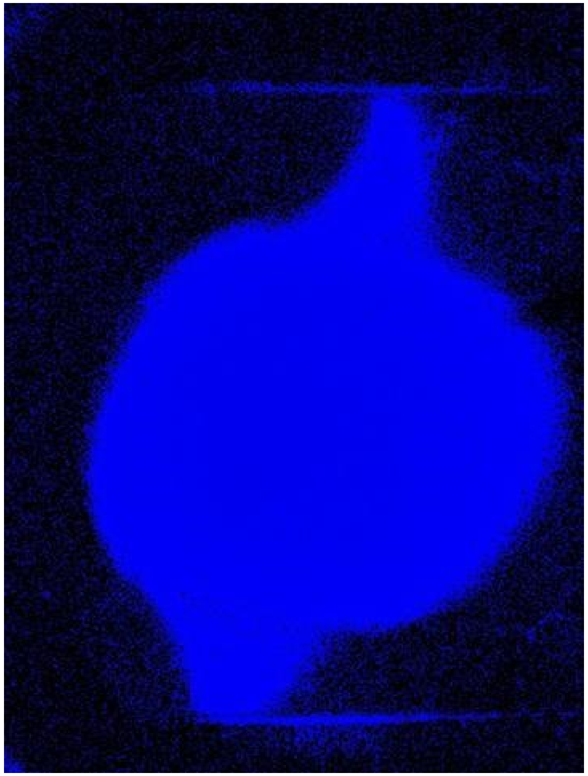
“Fin structure” investigations (Gun-4.3, not nominal setup)

Electron beam on HIGH1.Scr1 (EMSY, z=5.74m, Imain=363A)

booster on

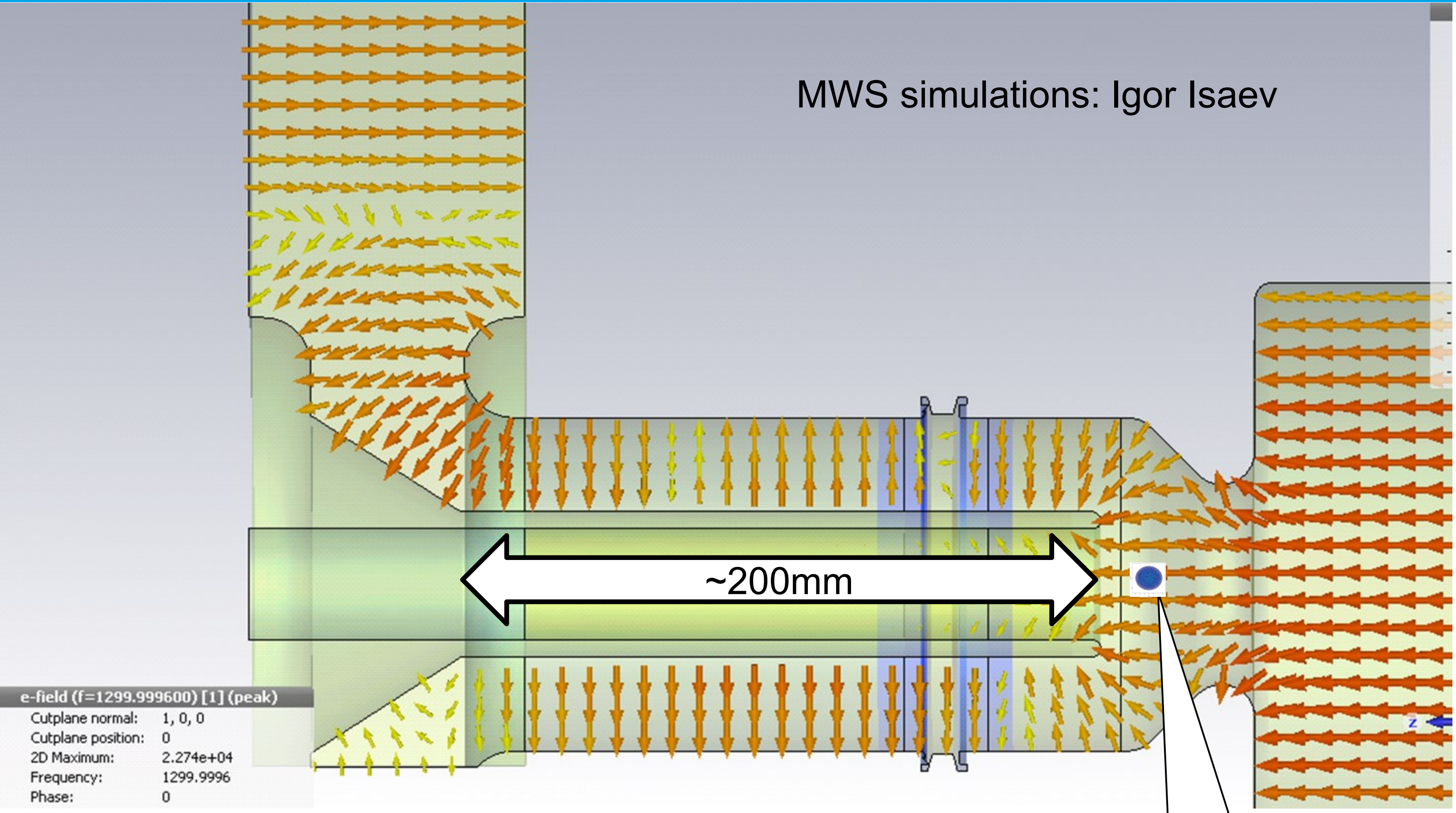


booster off



[Ref]→Report on Gun-4.3 conditioning at PITZ in 2013

RF field asymmetry?



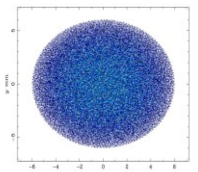
Coaxial Waveguide:
TE_{11} (H_{11}) mode,

$$f_c = \frac{k_c c}{2\pi} \approx \frac{c}{\pi(a+b)} = 1.331GHz$$

$$f_{c0} = \frac{k_c c}{2\pi} = 1.358GHz$$

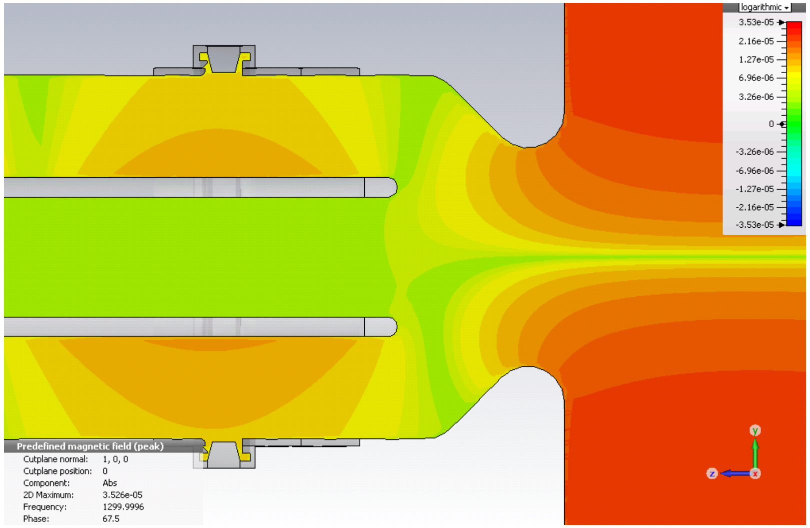
$$L_{att} = \frac{c}{2\pi\sqrt{{f_c}^2 - f^2}} = 121mm$$

Simulated e-beam

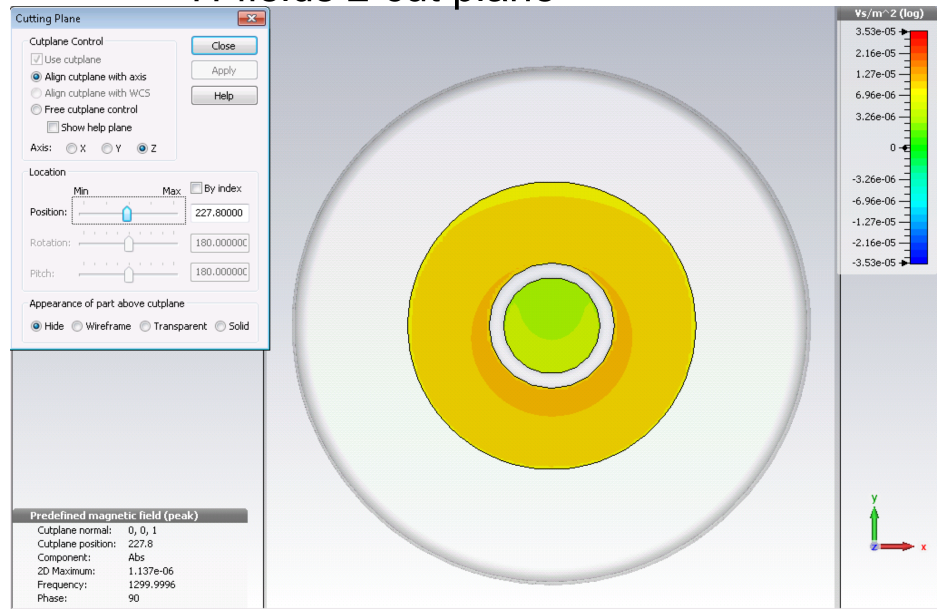


RF field asymmetry?

H-fields x-cut plane

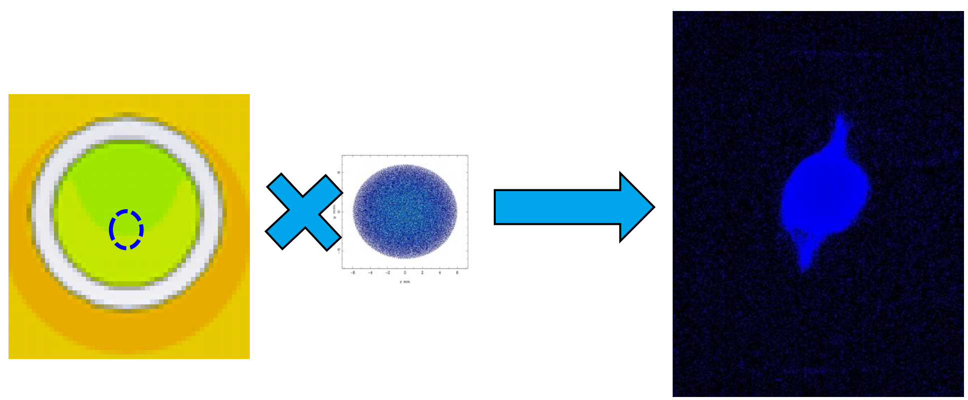


H-fields z-cut plane



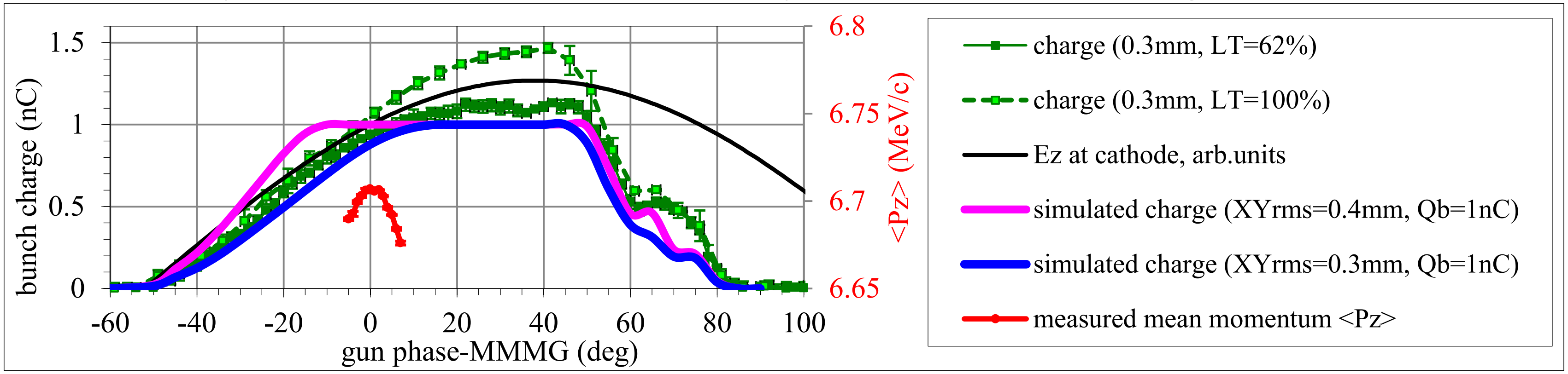
MWS simulations: Igor Isaev

More detailed modeling/simulations are required…



Photoemission studies at PITZ: motivation

> Discrepancy in simulated and experimentally produced bunch charge

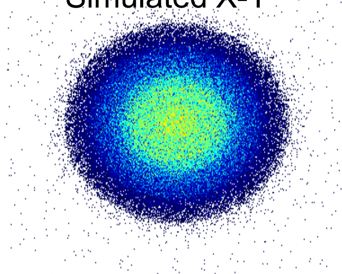


> Discrepancy in experimental and simulated optimum machine parameters:

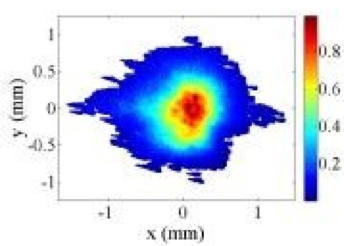
- Laser rms spot size: 0.3mm(exp) vs. 0.4mm(sim)
- Main solenoid current ΔI(M-S)~9A
- RF gun phase: +6deg(exp) vs. ~0deg(sim) → field enhancement?
- Experiment → close to the SC limit!

> Discrepancy in electron beam transverse profile (e.g. at EMSY1)

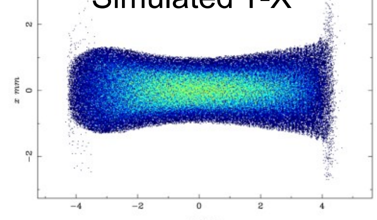
Simulated X-Y



Measured X-Y

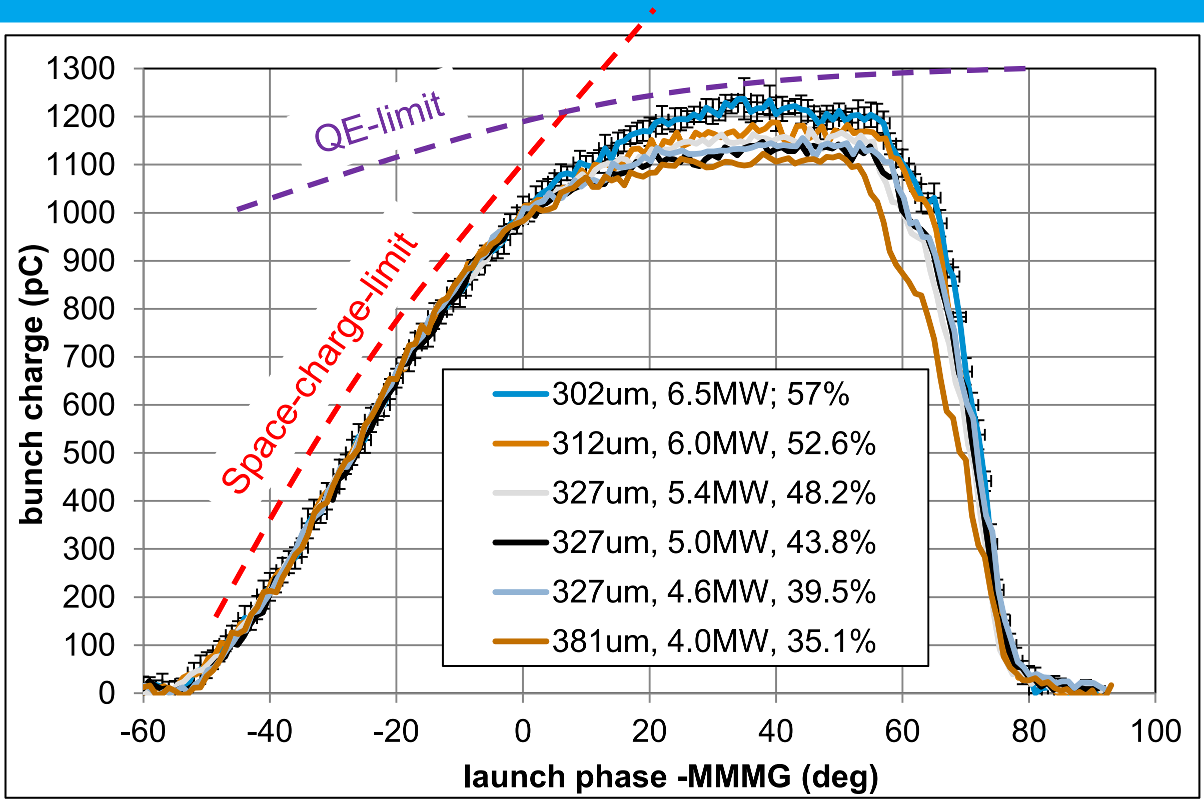


Simulated T-X



> Optimized photo injector → large fraction of the intrinsic cathode emittance in the overall emittance budget. (Slice) emittance formation ➔ in the cathode vicinity!

Emission studies: Ecath·LaserSpotSize=const



Parameters in legend: $(\sigma_{xy}^{laser},\ P_{rf,gun},\quad LT)$

$\sigma_{xy}^{laser} = \sqrt{\sigma_x \cdot \sigma_y}$ - rms spot size of the cathode laser

$P_{rf,gun}$ - peak rf power in the gun cavity

LT – laser transmission was always tuned to keep laser pulse energy constant

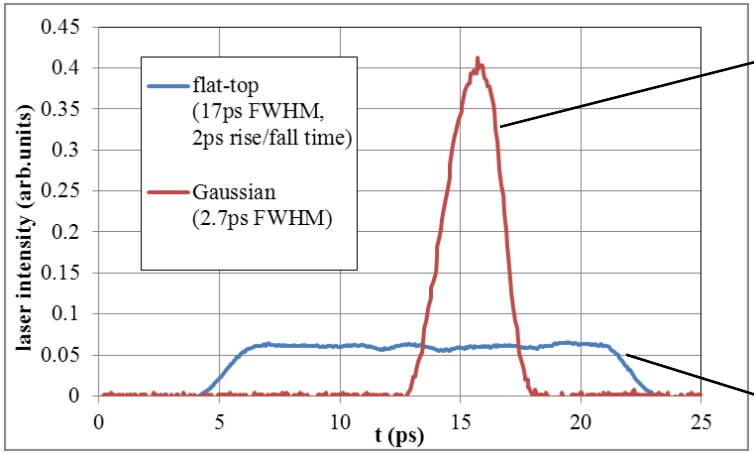
#	$P_{rf,gun}$, MW	σ_{xy}^{laser}, mm	LT, %	$\sqrt{P_{rf,gun} \cdot \sigma_{xy}^{laser}}$
1	6.49	0.302	57.0	0.769
2	5.99	0.312	52.6	0.764
3	5.45	0.327	48.2	0.763
4	5.00	0.341	43.8	0.762
5	4.55	0.361	39.5	0.770
6	3.99	0.382	35.1	0.762
Δ=	48%	-24%		STDEV=0.49%

Simultaneous variation of the rf field and the space charge density at the cathode by keeping the laser pulse energy and $E_{cath0} \cdot \sigma_{xy}^{laser}$ constant yields very similar extracted bunch charge for a rather wide range of the launch phase.

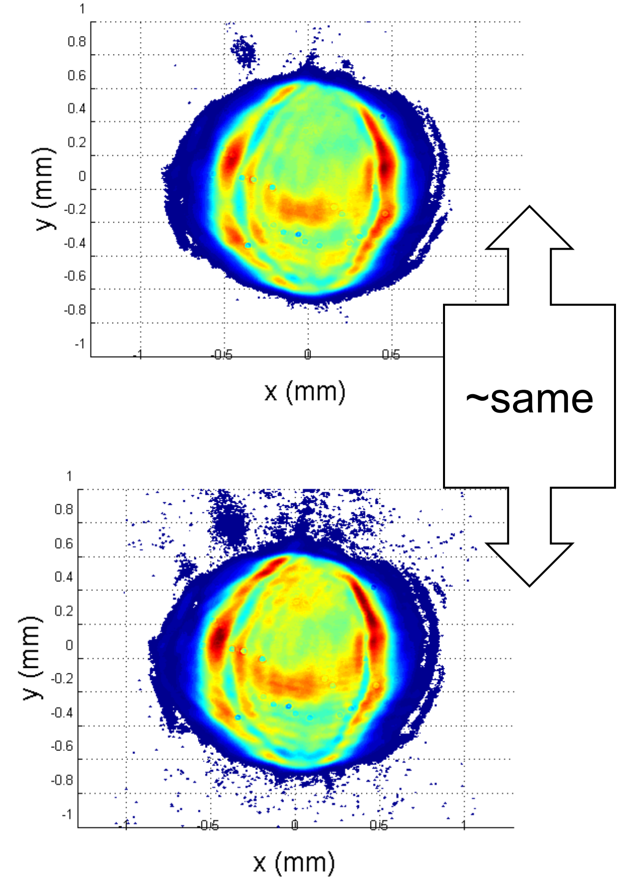
?From the parallel plate capacitor (PPC) model:
$Q_{QE-lim,PPCM} = \pi\varepsilon_0 R^2 E_0 \sin\varphi_0 = \pi\varepsilon_0 R^2 E_{cath}$

Emission G-FT program (February 2013): main idea

Laser temporal profile



Laser transverse distribution

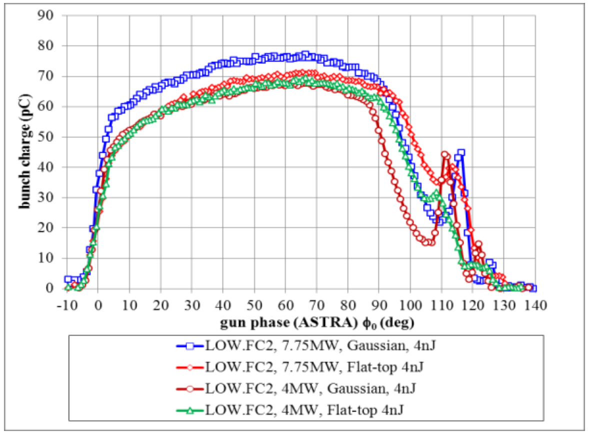


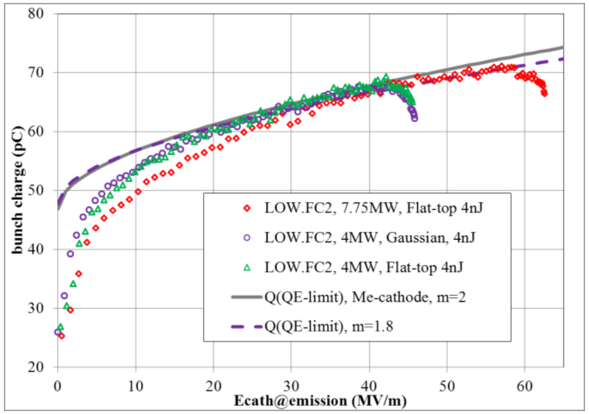
- x 2 gun gradients (7.75MW and 4MW)
- x laser pulse energies (e-meter in tunnel 4;20;37nJ), same for the Gaussian and F-T profiles
- long. momentum measurements
- laser pulse energy (LT) scans for the MMMG phase

	7.75MW	4MW
Flat-top (17ps)	case 1	case 3
Short Gaussian (2.7ps)	case 2	case 4

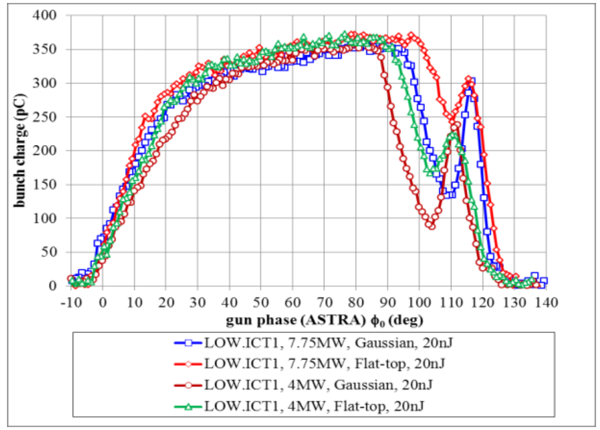
Emission studies: Field enhancement and QE-limited charge

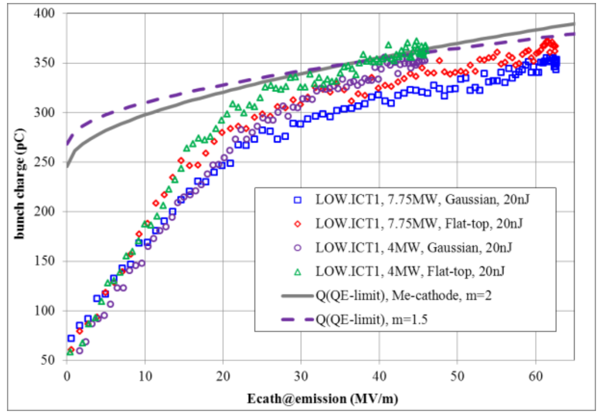
E_{laser}=4nJ



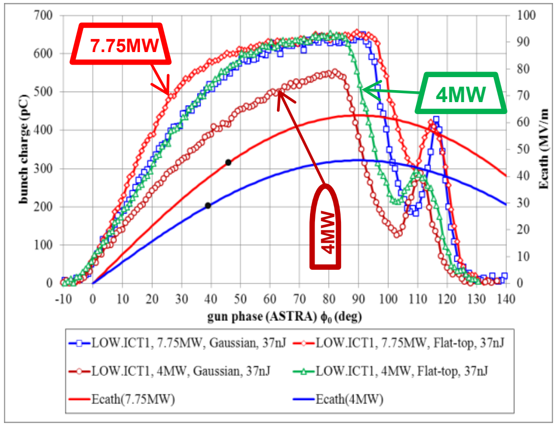


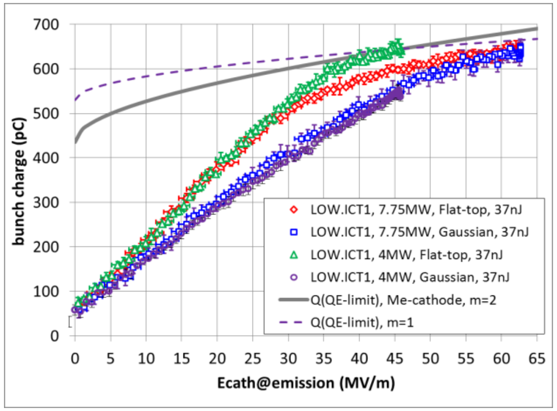
E_{laser}=20nJ





E_{laser}=37nJ





$$Q_{QE-lim} \propto Q_0\left(1-\sqrt{\frac{\phi_{eff}}{\hbar\omega}}\right)^m$$

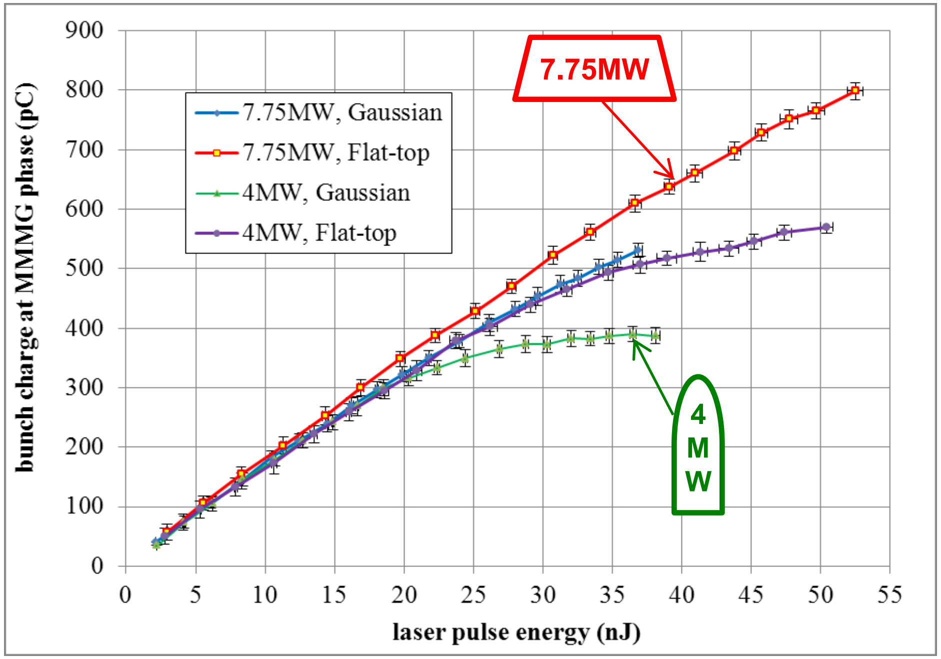
$$\phi_{eff} = 3.5eV - 0.0379\sqrt{E_{cath}(MV/m)};\ \hbar\omega = 4.81eV$$

E_{laser}		fitted Q_0 (m=2)	
(nJ)	/4nJ	(pC)	/Q0(4nJ)
4	1	2169	1.00
20	5	11384	5.25
37	9.25	20152	9.29

- m=2 ➔ better fit for low SCD@cathode
- Higher SCD ➔ m<2

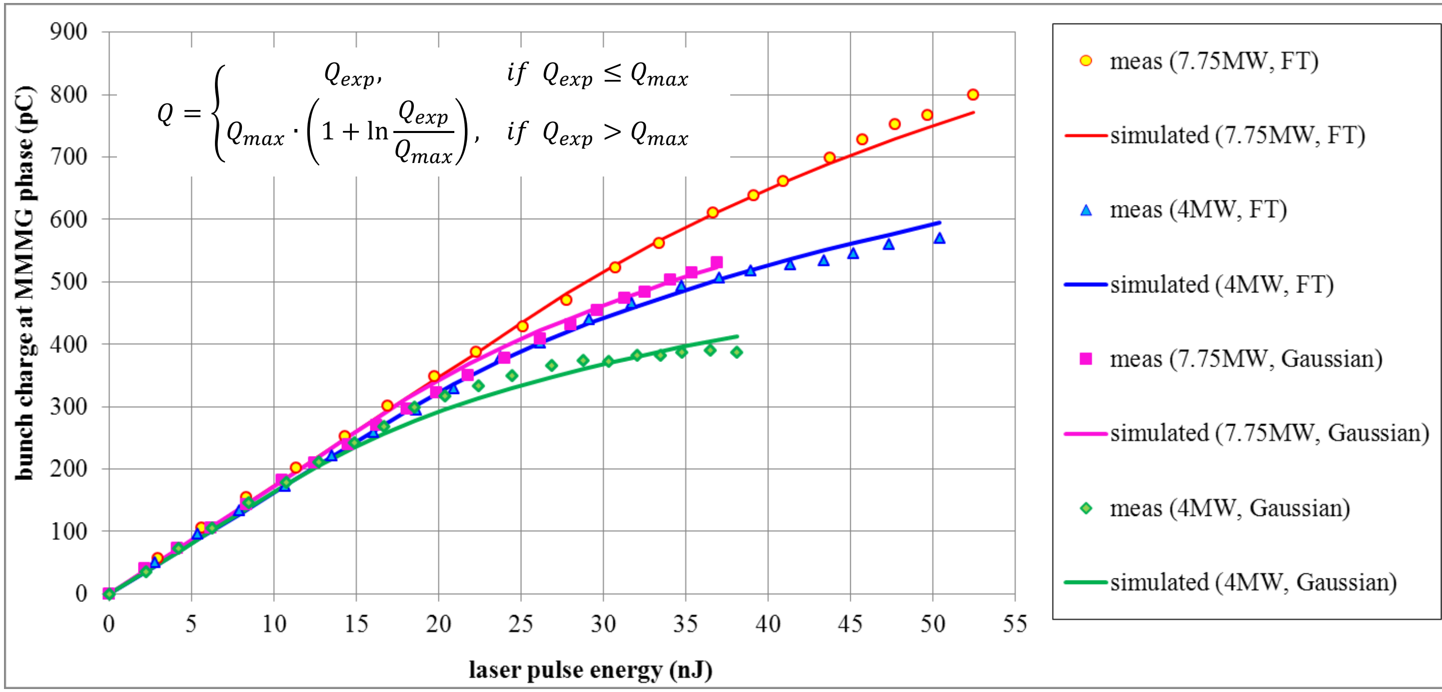
Laser pulse energy (laser transmission) scans

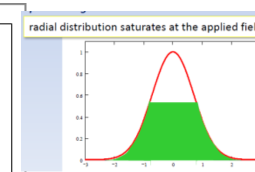
SPPhase = MMMG phase

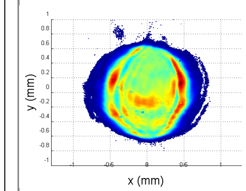


- The case of short Gaussian pulses and low gun gradient (4MW in the gun) ➔ the strongest saturation of the charge production due to a stronger space charge effect.
- The lowest space charge density case (– the flat-top and 7.75MW in the gun) ➔ the most linear charge production curve.
- It is interestingly enough the closeness of curves for the 4MW gun power and flat-top laser pulse to the dependence for 7MW and the short Gaussian pulse:
  - projected space charge density for these two cases is different (in a factor of ~6)
  - rf fields at the moment of emission is different (29MV/m for 4MW and 45MV/m for 7.75MW).

Laser transverse halo modeling-1: fitting measurements







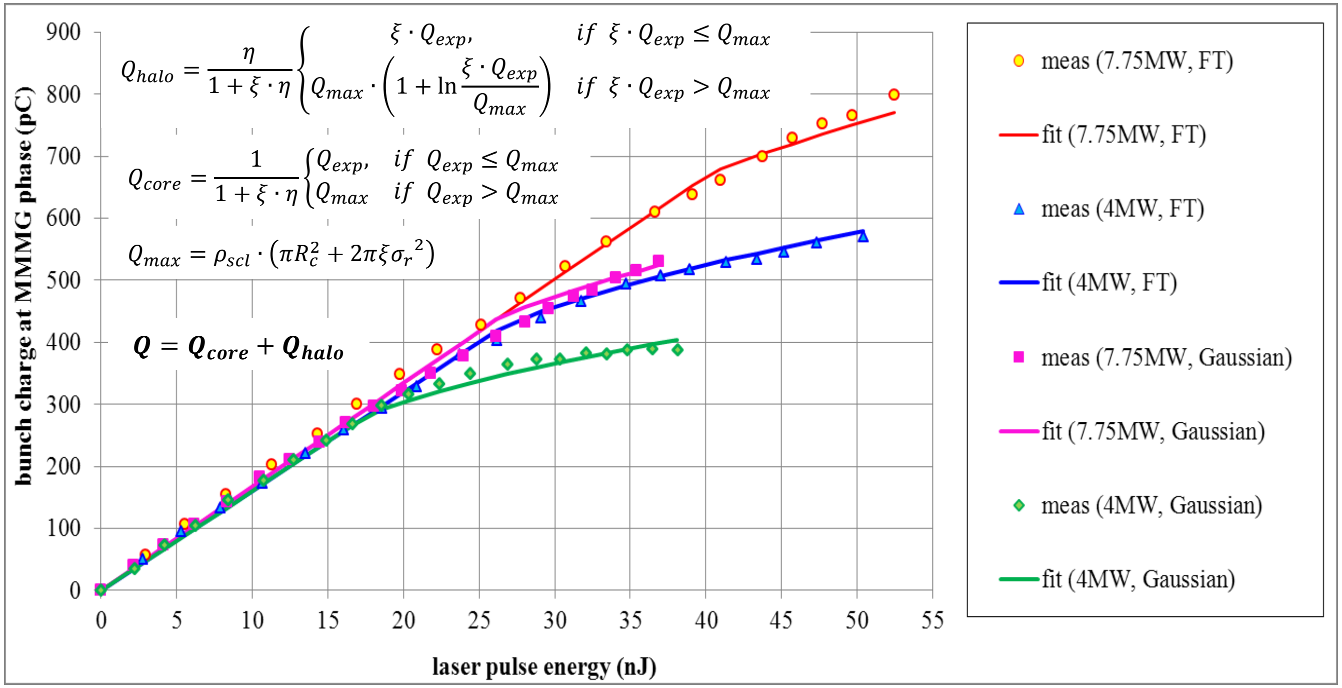
Simultaneous fit of 4 curves using: $Q_{max}(7.75MW) = Q_{max}(4.0MW) \cdot \frac{E_{cath2} \cdot \sin\varphi_{MMMG2}}{E_{cath1} \cdot \sin\varphi_{MMMG1}}$

Laser temporal profile	rf peak power	QE	Q_{max}	$\chi^2 = \sum \frac{(meas - fit)^2}{meas.error^2}$
Flat-top (17ps)	7.75MW	8.68%	457pC	12.9
Short Gaussian (2.7ps)			291pC	12.1
Flat-top (17ps)	4.0MW	8.12%	293pC	12.3
Short Gaussian (2.7ps)			187pC	21.8

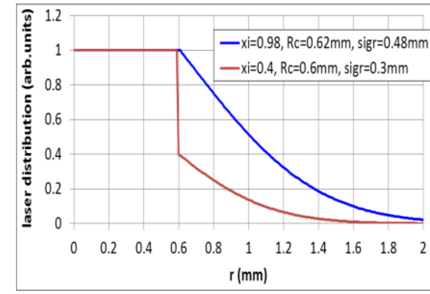
$$\frac{\rho_{scl}(flat-top)}{\rho_{scl}(Gaussian)} \approx 1.55$$

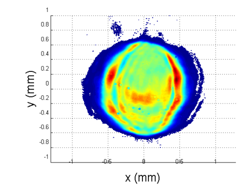
The overall χ^2 of the fit is 59.2, the reduced chi-squared statistic yields $\chi^2_{red} = \frac{\chi^2}{\nu} = 0.79$, where the number of degrees of freedom $\nu = N_{points} - N_{fit.par.} - 1 = 75$.

Laser transverse halo modeling-2: fitting measurements



radial flat-top core + Gaussian tails





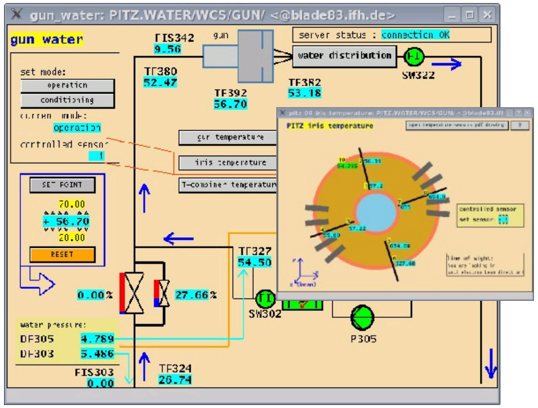
Simultaneous fit of 4 curves using: $Q_{max}(7.75MW) = Q_{max}(4.0MW)\cdot\frac{E_{cath2}\cdot\sin\varphi_{MMMG2}}{E_{cath1}\cdot\sin\varphi_{MMMG1}}$

Laser temporal profile	rf peak power	ξ	η	QE	Q_{max}	$\chi^2=\sum\frac{(meas-fit)^2}{meas.error^2}$
Flat-top (17ps)	7.75MW	0.98	1.17	8.36%	673pC	21.5
Short Gaussian (2.7ps)					445pC	16.7
Flat-top (17ps)	4.0MW			8.01%	432pC	5.2
Short Gaussian (2.7ps)					285pC	10.1

$$\frac{\rho_{scl}(flat-top)}{\rho_{scl}(Gaussian)}\approx 1.51$$

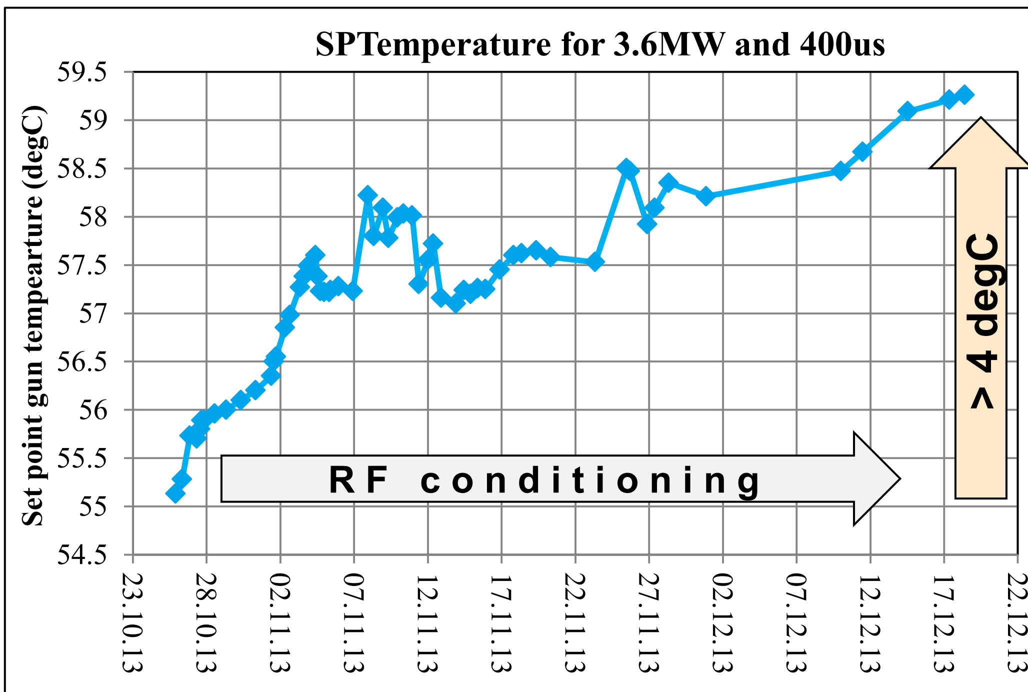
The overall χ^2 of the fit is 53.5, the reduced chi-squared statistic yields $\chi^2_{red}=\frac{\chi^2}{\nu}=0.73$, where the number of degrees of freedom $\nu = N_{points} - N_{fit.par.} - 1 = 73$.

Recent problem: gun cavity resonance temperature drift



The resonance temperature drift/variation of ~**4degC** over two months of conditioning seems to be real:

- The same temperature difference observed at various gun iris sensors
- There is a direct linear correlation of the gun iris temperature with temperature of input and output water channels
- Water flow is almost constant for the monitoring measurements
- Estimated heat transfer is constant within error bars
- Cathode re-insertion/exchange experiments show that these manipulations cannot explain the observed temperature drift



Measurement benchmark:
3.6MW in gun (reflection=4%), 400us,10Hz

NB: df/dT≅-22kHz/degC

? Inelastic deformation of the gun cavity?

?Can it be accurately simulated?

Conclusions

- PITZ → 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

- "Fin structure" investigations → asymmetry in RF fields in gun cavity due to the coaxial coupler kick has to be modelled and simulated in more details. Also – more dedicated measurements? **Any ideas are welcomed!**

- Photoemission studies at PITZ:
  - Key to understand the M-S discrepancies → **more precise modelling of the photoemission is needed** (intrinsic cathode emittance formation)
  - Important for further optimization (e.g. 3D ellipsoidal pulses)
  - Recent studies using short Gaussian and long flattop cathode laser pulses:
    - transient effect → depends on the laser temporal profile (parallel plate capacitor model)
    - field enhancement determined also by the peak field as well as by the space charge

- Long-term drift of the gun resonance temperature → **cavity deformations?**