Simulations at PITZ, status 2012

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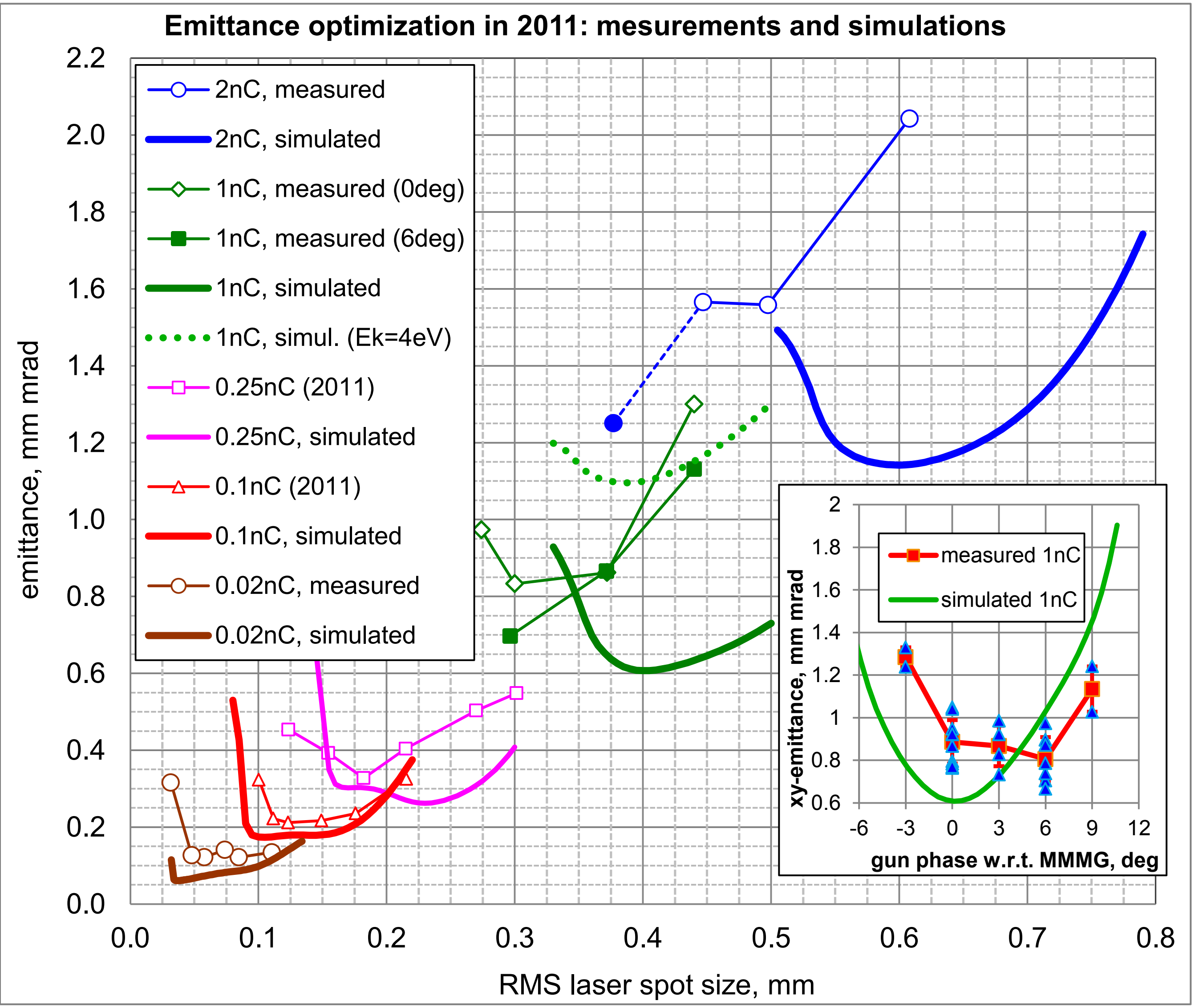
Emittance vs. Laser Spot size for various charges

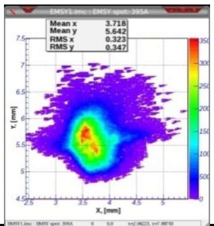
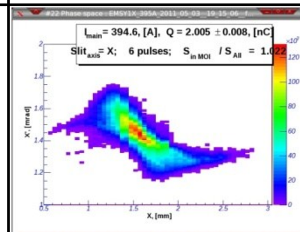
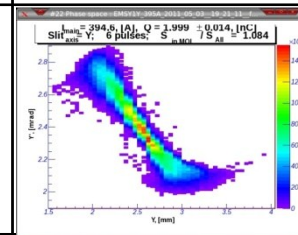
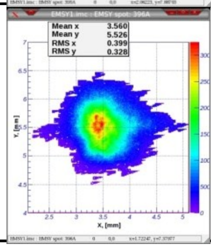
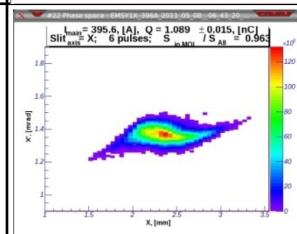
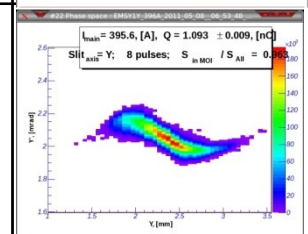
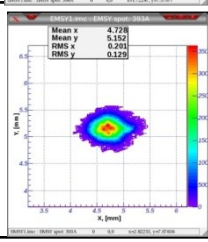
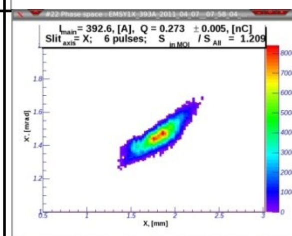
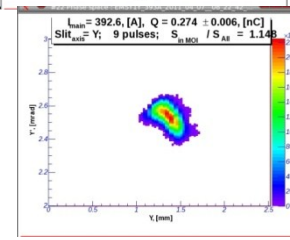
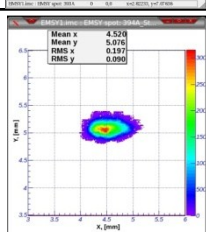
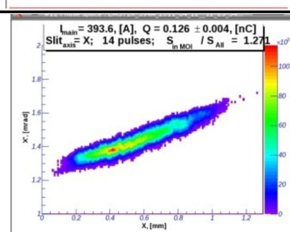
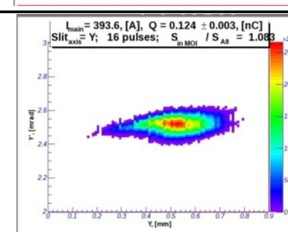
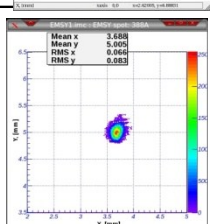
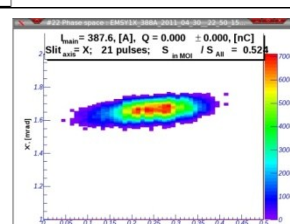
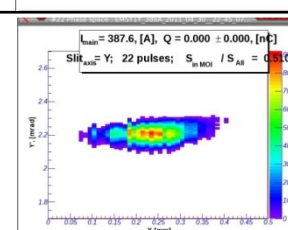


Minimum emittance

Charge, nC	Meas., mm mrad	Simul., mm mrad
2	1.25	1.14
1	0.70	0.61
0.25	0.33	0.26
0.1	0.21	0.17
0.02	0.12	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)
- A radial homogeneous laser pulse distribution is used in simulations whereas the experimental transverse distribution is not perfect
- Artificial increase of the thermal kinetic energy at the cathode (from 0.55eV to 4eV) did not improve the understanding

Measured Phase Spaces for various bunch charges

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

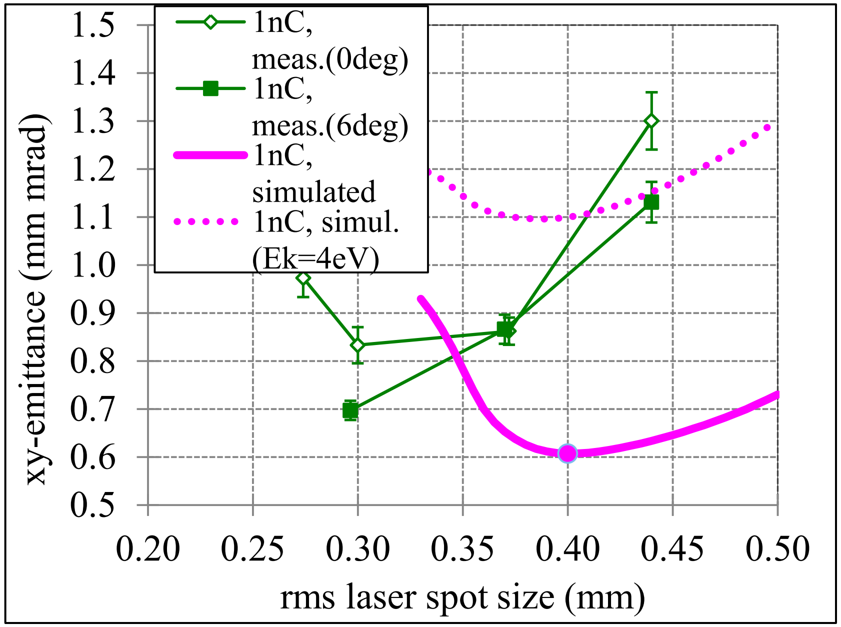
zoomed

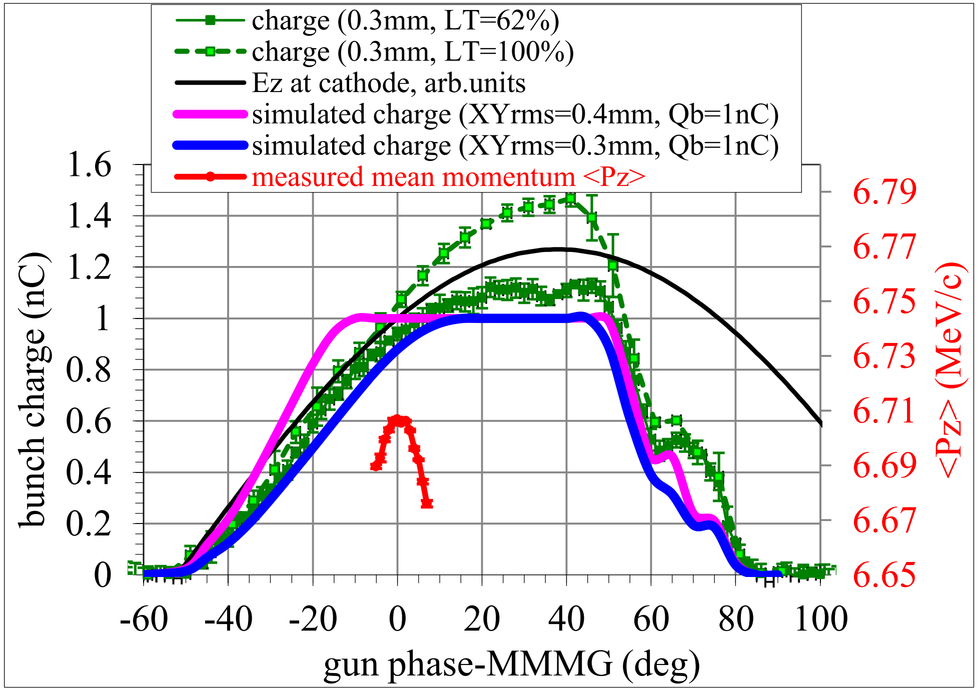
Problems

- Photo emission → charge production
- E-beam asymmetry investigations:
  - Cathode laser transverse distribution
  - Solenoid imperfections
  - RF gun coaxial power coupler → kick ? (new)
- 3D ellipsoidal distribution (new):

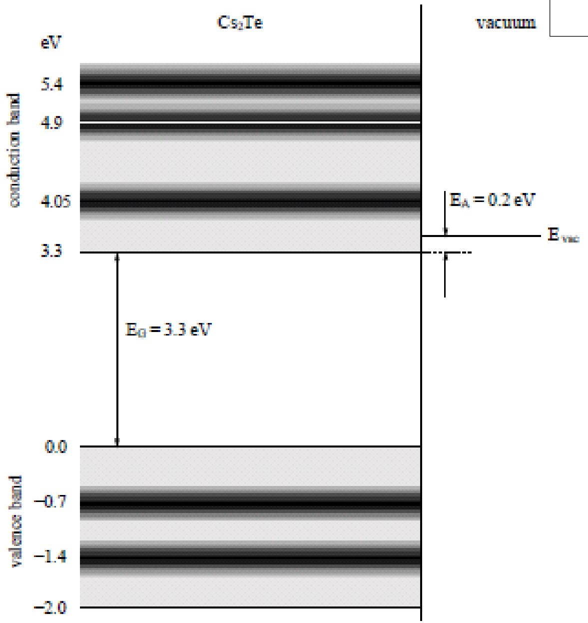
  Impact of laser pulse shape imperfections

Emission studies: motivation





R. A. Powel et. al. Photoemission Studies of Cesium Telluride. Phys. Rev. B, 8: 3987–3995, 1973.



Cs_2Te:

E_G=3.3eV

$E_A=E_{vac}-E_G$=0.2eV

$E_T=E_G+E_A$=3.5eV

$E_k=E_{ph}$-ET=4.05eV-E_T=0.55eV

?Field enhancement?

Emission studies: modeling

D.Dowell, J.Schmerge "Quantum efficiency and thermal emittance of metal photocathodes", PRST-AB 12, 074201 (2009)

$$QE \approx \frac{1-R(\omega)}{1+\frac{\lambda_{opt}(\omega)}{\bar{\lambda}_{e-e}(\omega)}} \cdot \frac{\left(\hbar\omega-\phi_{eff}\right)^2}{8\phi_{eff}(E_F+\phi_W)}$$

, where the effective work function (Schottky term): $\phi_{eff} = \phi_W - e\sqrt{\frac{e\beta E}{4\pi\varepsilon_0}}$

The emitted charge:

$$Q = \frac{1-R(\omega)}{1+\frac{\lambda_{opt}(\omega)}{\bar{\lambda}_{e-e}(\omega)}} \cdot \frac{N_\gamma}{8\phi_{eff}(E_F+\phi_W)}\left(\hbar\omega-\phi_W+e\sqrt{\frac{e\beta E}{4\pi\varepsilon_0}}\right)^2$$

D.Dowell, PAC 2011 Tutorial → Derivation of Schottky scan function: emitted charge vs. launch phase→ 2-parameter fit

$$Q \propto \eta \cdot LT \cdot \left(1+b\sqrt{E}\right)^m$$

LT = laser transmission (%)

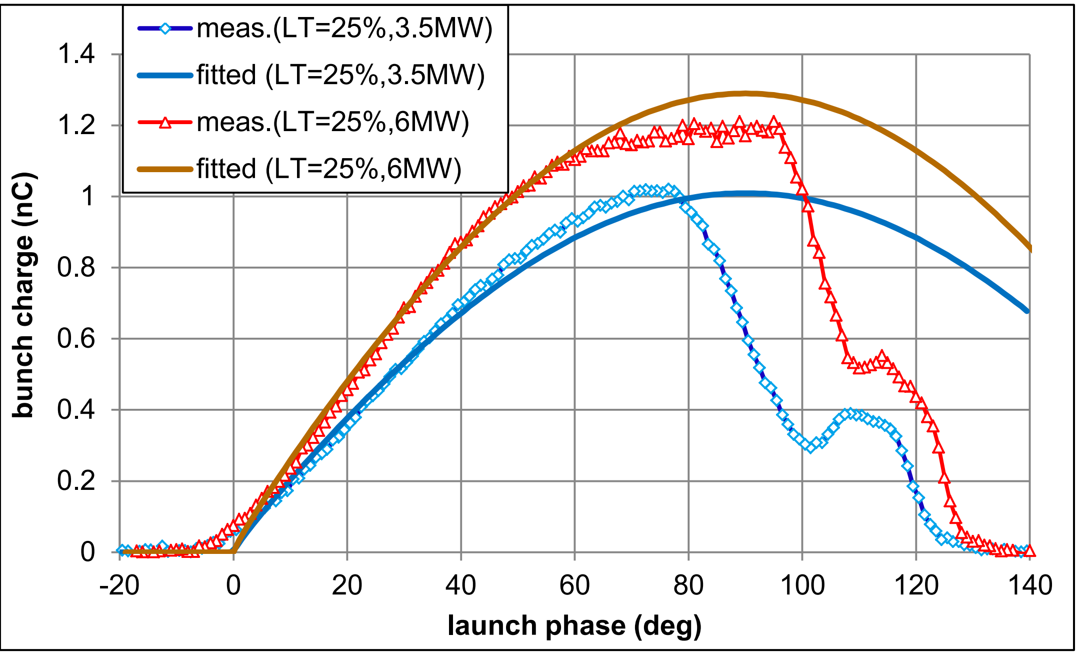
E – field at the cathode (MV/m)

η, b, m – fitting parameters

Emission studies: modeling → RF field influence (LT=25%)

$$Q \propto \eta \cdot LT \cdot \left(1 + b\sqrt{E}\right)^m$$

LT = laser transmission (%)
E – field at the cathode (MV/m)
η, b, m – fitting parameters



$LT = LT0$ = 25% (1nC at MMMG phase for 6MW)

RF power (MW)	Ecath (MV/m)	max <Pz> (MeV/c)
6.02	62.0	6.83
3.54	47.6	5.43

Fitting:
Phase range: 10→70deg
$E = E_{cath} \cdot sin\varphi_0$
η=1.2148E-5
b=10.9222
m=1.8705 (1.8977-2.1081)→2
+convolution with laser temporal profile

Measurements:
Laser:
- *Temporal → flattop 2/20\2ps*
- *Transverse → 0.3 mm rms*

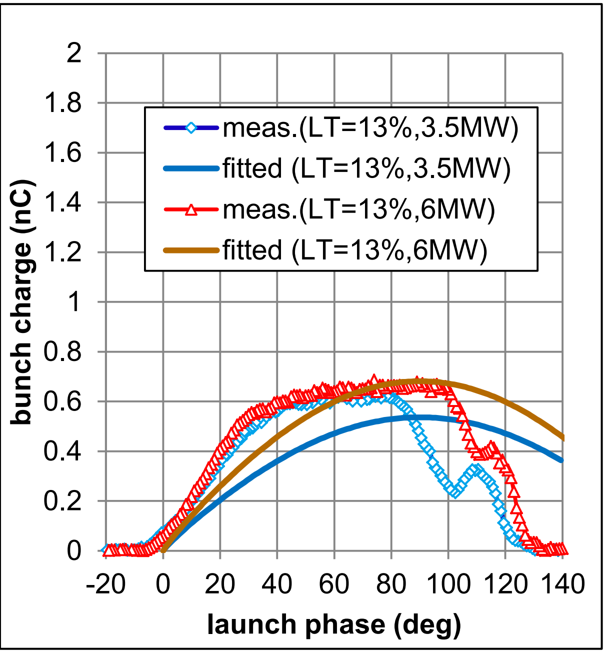
Main solenoid: 400A
Charge measured by LOW.ICT1 → z=0.9m

Emission studies: modeling → RF field

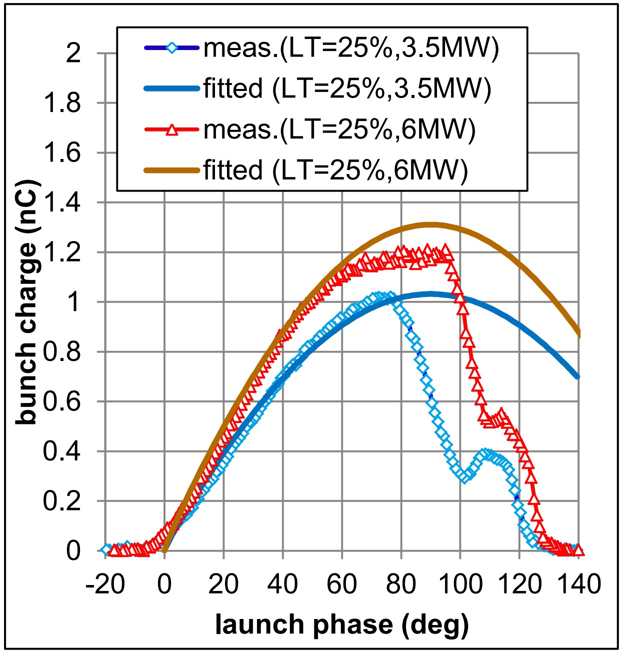
Simultaneous fitting (LT=13% and 25%):
Phase range: 10→70deg
$E = E_{cath} \cdot sin\varphi_0$
η=8.44E-8
b=205.9
m=1.805

$$Q \propto \eta \cdot LT \cdot \left(1 + b\sqrt{E}\right)^m$$

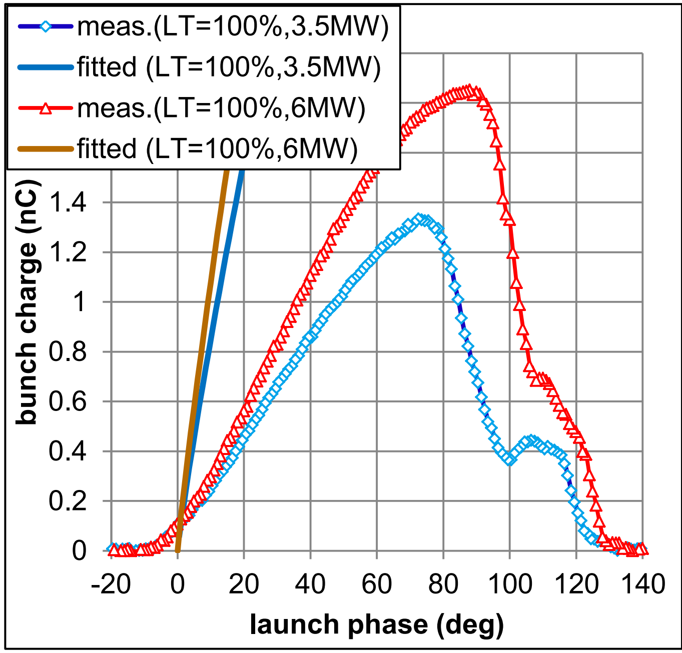
LT=13%



LT=25%



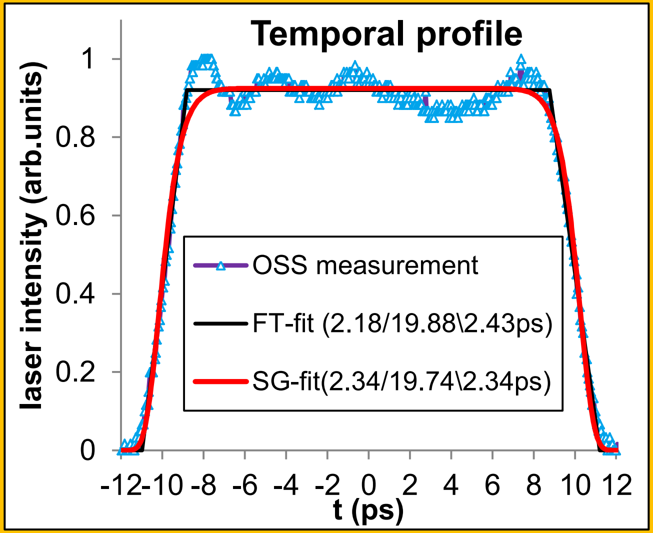
LT=100%

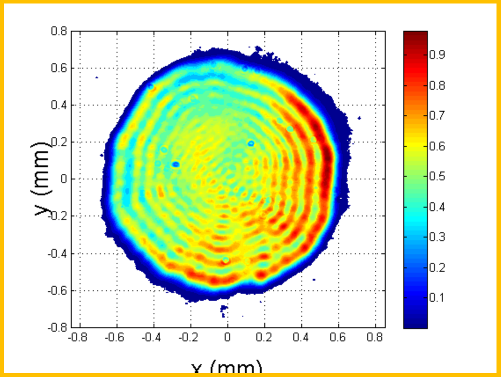


- **Simultaneous fitting → assumptions are not correct?**
- **Almost no RF impact for low SC density**
- **RF field impact increases with SC density increase**

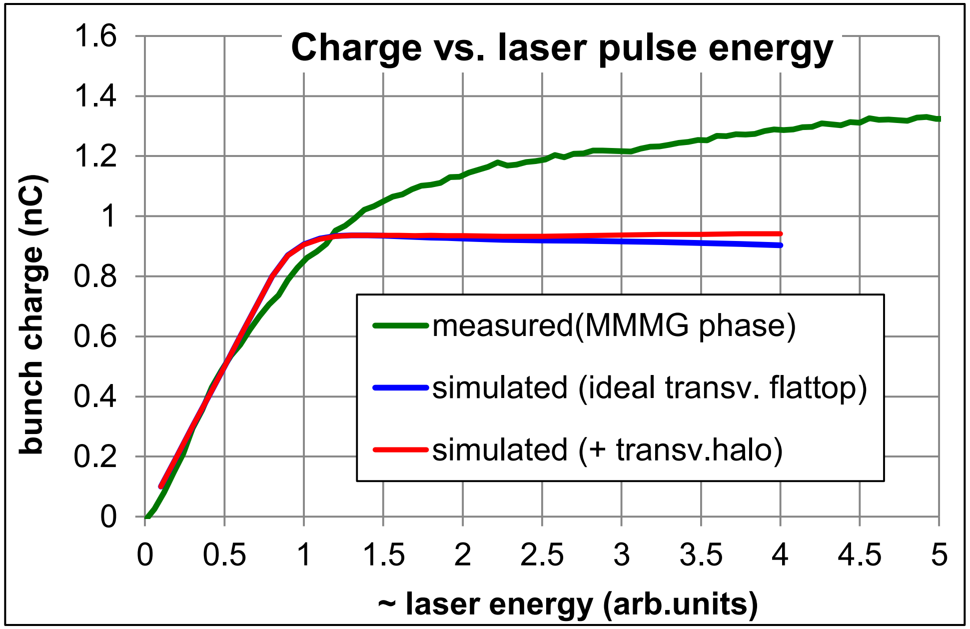
Emission studies: LT scans and ASTRA simulations

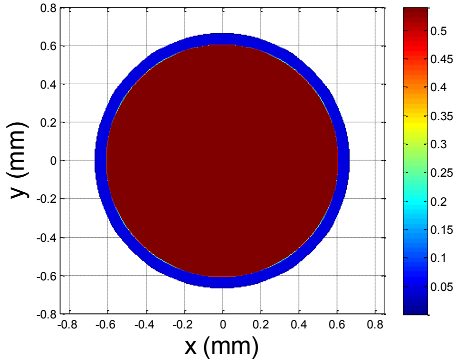
Measured cathode laser shapes





Transverse halo modeling in ASTRA





Rather small effect!

ASTRA simulations: Schottky effect implementation

ASTRA: charge of a particle at the time of its emission:

$$Q = Q_0 + S_{Schottky} \cdot \sqrt{E} + L_{Schottky} \cdot E$$

$$Q \propto \eta \cdot LT \cdot \left(1 + b\sqrt{E}\right)^2$$

ASTRA input:

$[Q_{bunch}, S_{Schottky}]$ → 2-parameter fitting

$$L_{Schottky} = \frac{S_{Schottky}{}^2}{Q_{bunch}}$$

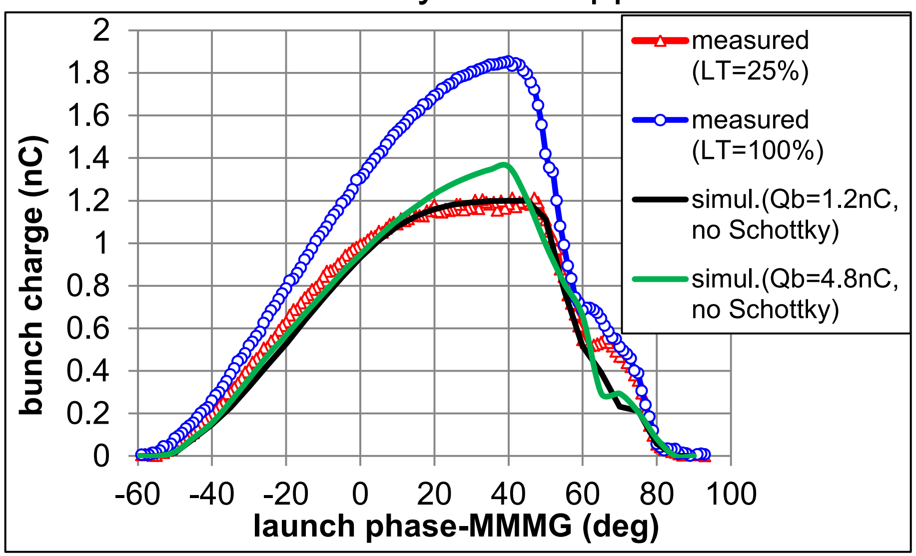
$LT = \xi \cdot LT0$

$Q_{bunch} = \xi \cdot Q_{bunch0}$

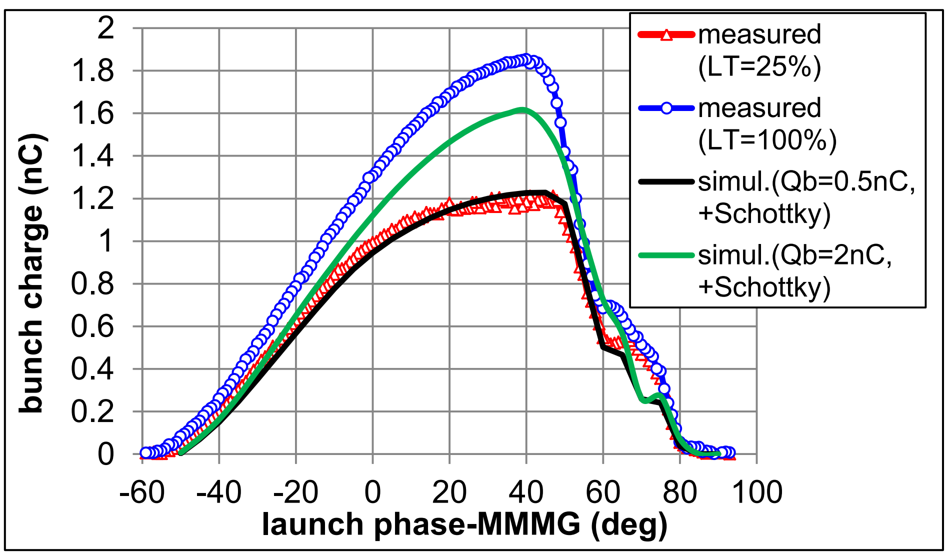
$S_{Schottky} = \xi \cdot S_{Schottky0}$

Schottky constants should be scaled with laser pulse energy

No Schottky effect applied



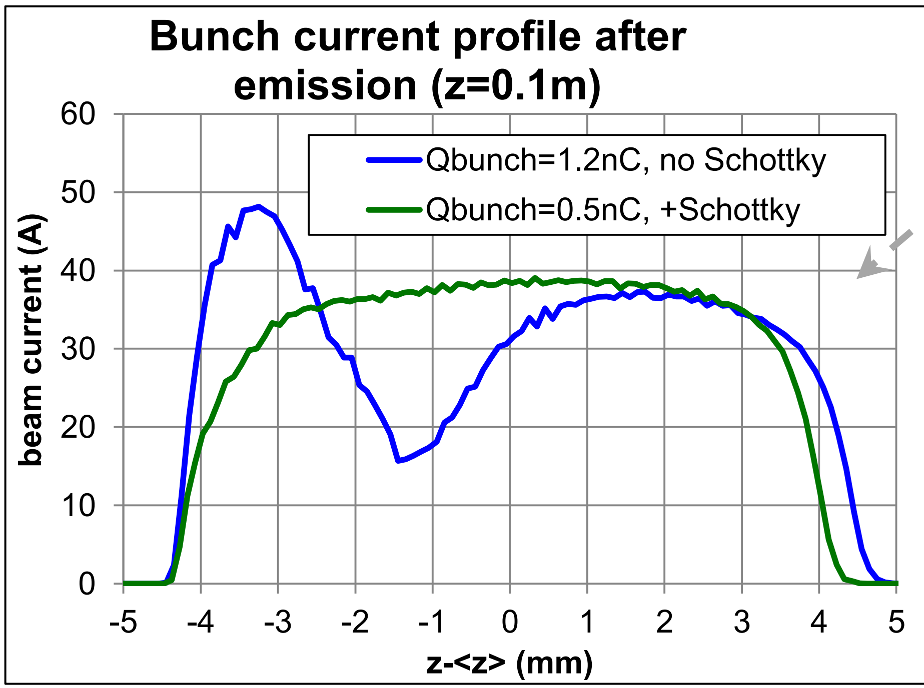
Schottky parameter fitting

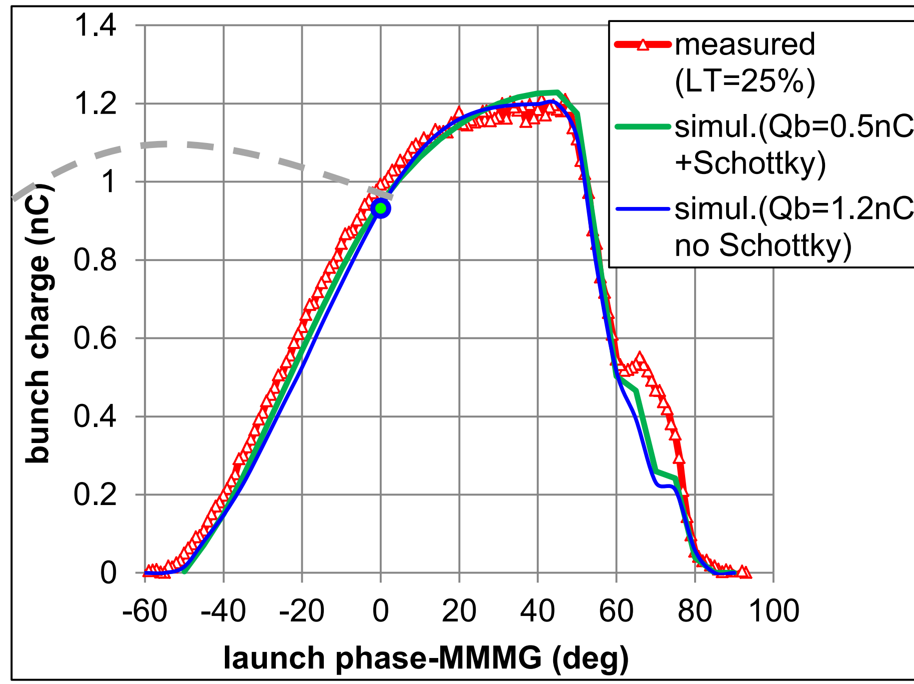


$$\xi = \frac{100\%}{25\%} = 4$$

Qbunch= 0.5nC
L_Schottky= 0.0059983
S_Schottky= 0.109529

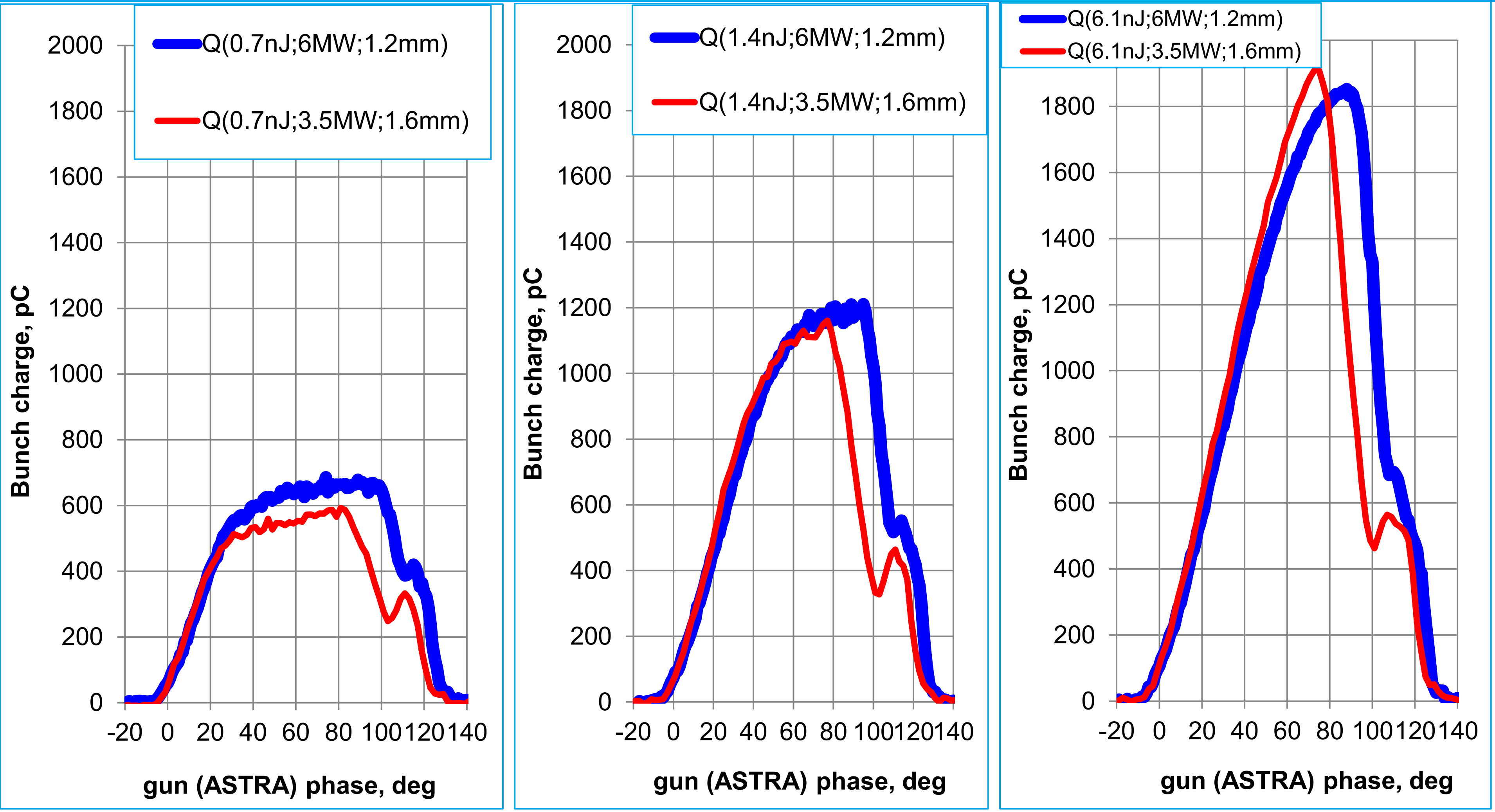
ASTRA simulations: Schottky effect impact





Applied Schottky effect ➔ more smooth charge extraction

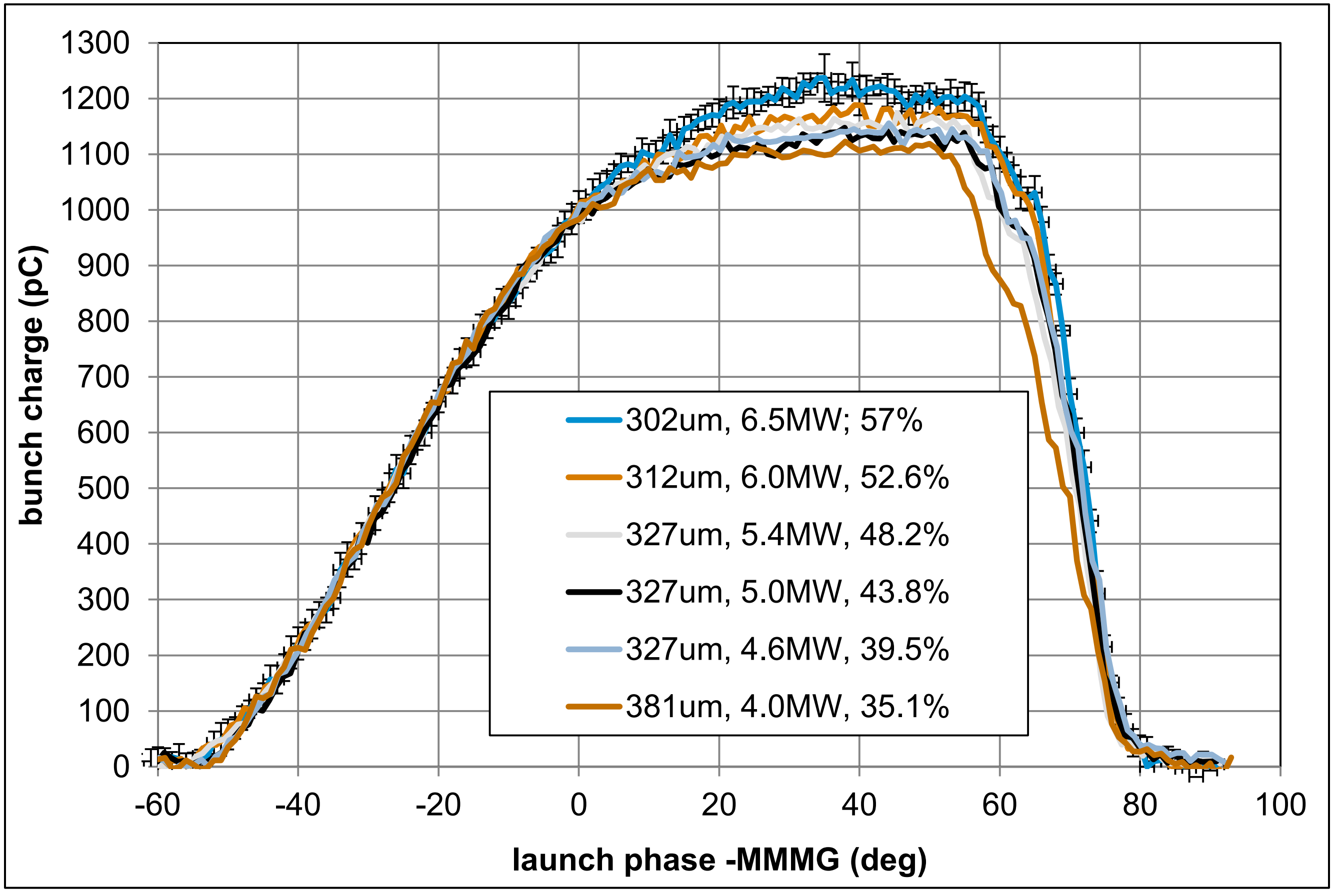
Further emission studies:
+ laser spot size and pulse energy variation



$$\sqrt{P_{rf}} \cdot LaserSpotDiameter = \sqrt{6} \cdot 1.2 = \sqrt{3.5} \cdot 1.6 = 3 = inv?$$

$$E_{cath} \cdot \sqrt{\sigma_x^l \cdot \sigma_y^l} = inv?$$

Further emission studies: Ecath·LaserSpotSize=const



Parameters in legend: (σ_{xy}^{laser}, $P_{rf,gun}$, *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.

Conclusions (photo emission studies)

> Studies of the space charge assisted photoemission at PITZ:

- L-band, Cs_2Te, E_{cath0}>60MV/m
- Basic measurement = launch phase scan for a bunch charge
- Experimental optimum (w.r.t. beam emittance) conditions → space charge assisted emission
- Simulated conditions ≠ experimental
- Schottky-like effect is stronger pronounced for higher space charge densities
- Simple (simultaneous) fitting of the macroscopic Schottky model does not work
- ASTRA simulations of the phase scans:
  - Cathode laser halo implementation → rather small effect
  - Simultaneous simulations of different machine conditions are hard and still delivering generally smaller charges than experimentally obtained
  - Applied Schottky-like effect resulted in a more smooth charge extraction
- Further experimental photoemission studies:

$$E_{cath0} \cdot \sigma_{xy}^{laser} \quad \sim \text{inv?}$$

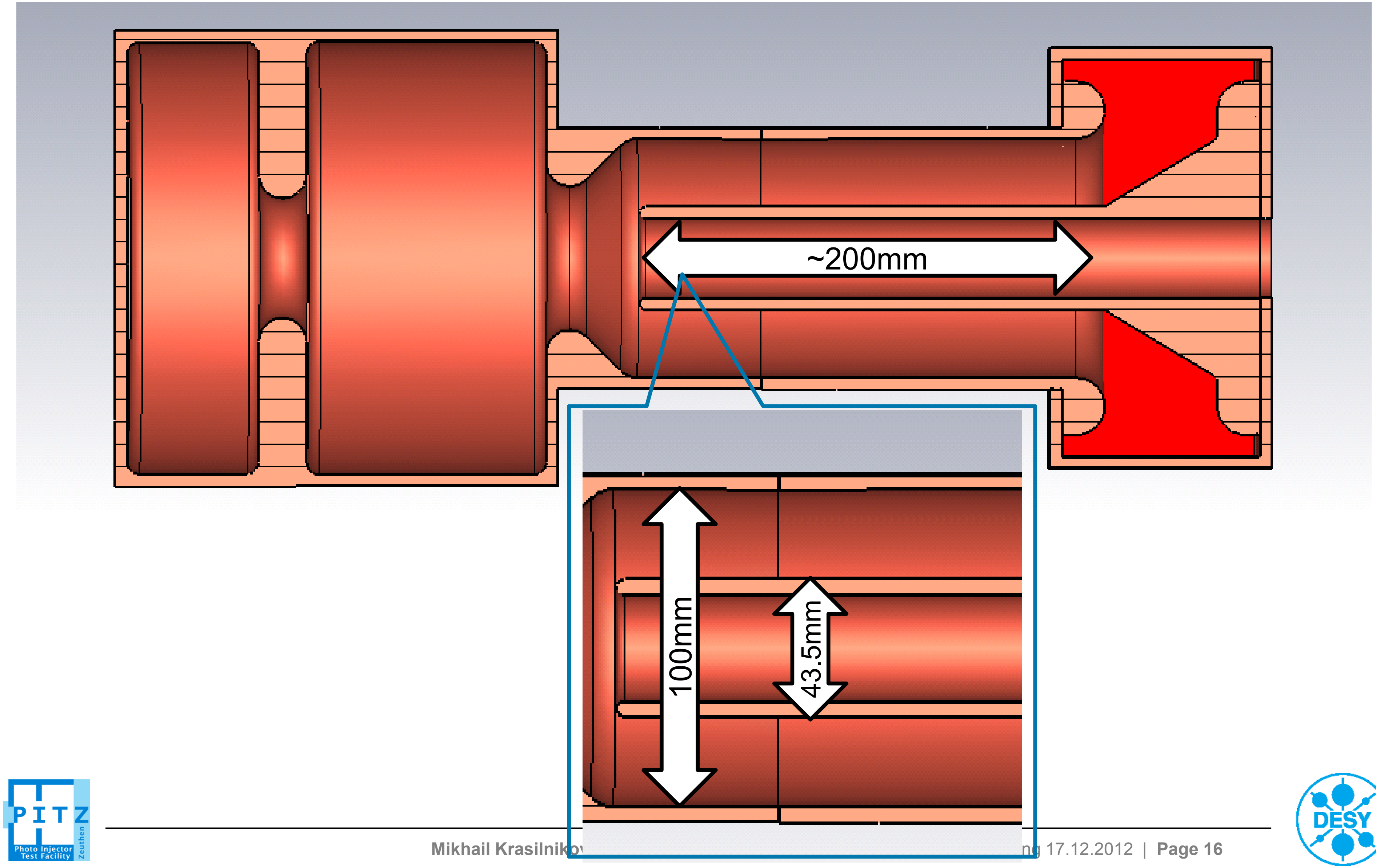
- Several other measurements have been taken (e.g. Gaussian vs. flattop laser pulses) have been done, treatment is ongoing

Problems

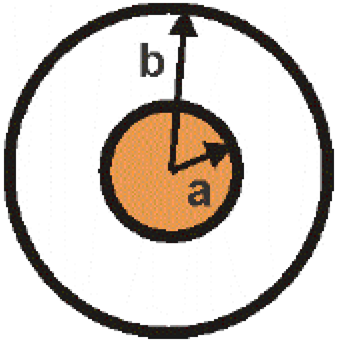
- Photo emission → charge production
- E-beam asymmetry investigations:
  - Cathode laser transverse distribution --> VC images available
  - Solenoid imperfections → ??
  - RF gun coaxial power coupler → kick ? (new)
- 3D ellipsoidal distribution (new):

  Impact of laser pulse shape imperfections

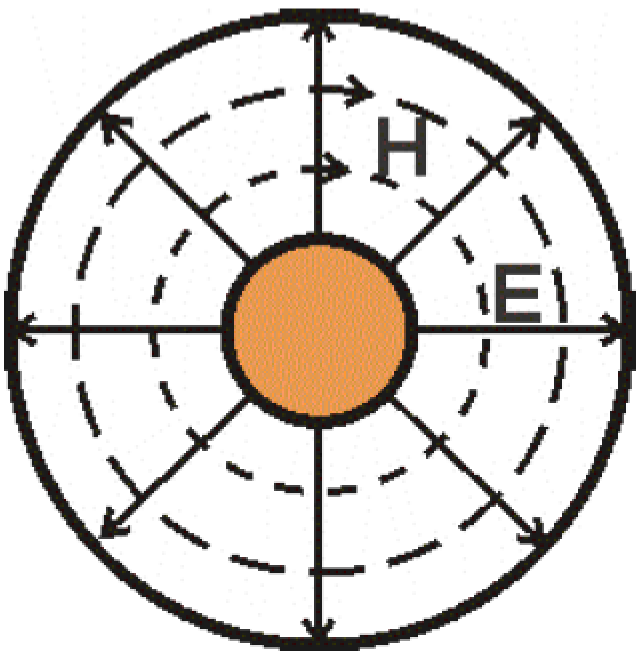
PITZ RF-Gun Cavity Geometry



Coaxial Waveguide: TEM Mode



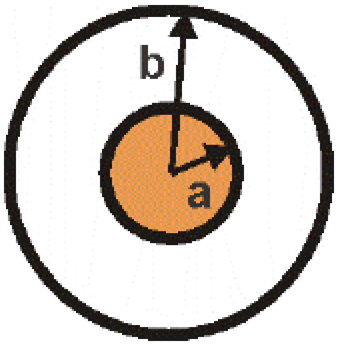
$$V(\rho) = \frac{V_0 \ln \frac{b}{\rho}}{\ln \frac{b}{a}}$$



$$\mathbf{E} = \frac{V_0}{\ln \frac{b}{a}} \frac{\mathbf{a}_\rho}{\rho} e^{-jkz}$$

$$a = 21.75mm$$
$$b = 50mm$$

Coaxial Waveguide: Higher Order Modes



TE Modes

$$\begin{cases} \nabla_t^2 h_z + k_c^2 h_z = 0 \\ \left.\dfrac{\partial h_z}{\partial \rho}\right|_{\rho=a,b} = 0 \end{cases}$$

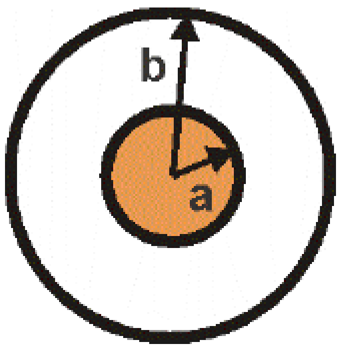
$$\text{Let } h_z(\rho,\phi) = \overbrace{[A\sin(m\phi) + B\cos(m\phi)]}^{\text{Polarization degenerate}}[CJ_m(k_c\rho) + DY_m(k_c\rho)]$$

Boundary Conditions

$$\Rightarrow \begin{cases} CJ_m'(k_c a) + DY_m'(k_c a) = 0 \\ CJ_m'(k_c b) + DY_m'(k_c b) = 0 \end{cases}$$

$$\Rightarrow J_m'(k_c a)Y_m'(k_c b) - J_m'(k_c b)Y_m'(k_c a) = 0$$

Coaxial Waveguide: TE_{11} (H_{11}) Mode

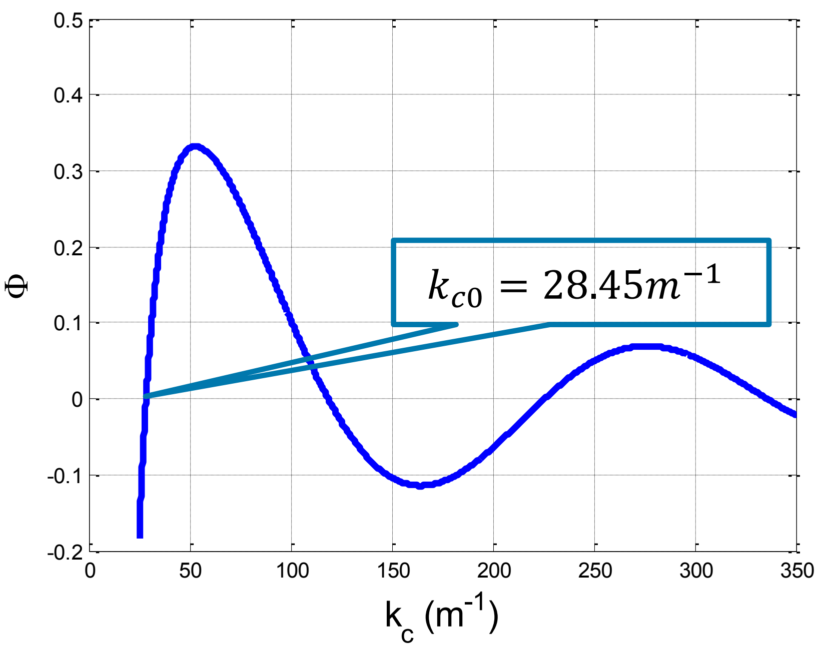


The first (lowest) high order mode is H_{11} (TE_{11}) with $k_c \approx \frac{2}{a+b} = 27.9m^{-1}$

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

$$h_z = [CJ_1(k_c\rho) + DY_1(k_c\rho)] \cdot \cos(\phi)$$

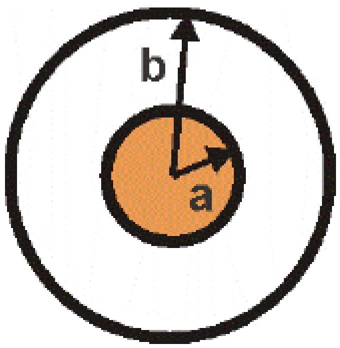
$$\Phi(k_c) = J_1'(k_c a) \cdot Y_1'(k_c b) - J_1'(k_c b) \cdot Y_1'(k_c a) = 0$$



$$J_1'(x) = J_0(x) - \frac{J_1(x)}{x}; \quad Y_1'(x) = Y_0(x) - \frac{Y_1(x)}{x}$$

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

Coaxial Waveguide: TE_{11} (H_{11}) Mode



$$f_{c0} = \frac{k_c c}{2\pi} = 1.358GHz > 1.3GHz$$

$$k_{c0} = 28.45m^{-1}$$

The waveguide propagation constant $(E \sim e^{-\gamma z})$ in terms of the waveguide cutoff frequency f_c:

$$\gamma = \frac{2\pi i}{c}\sqrt{f^2 - f_c^{\,2}}$$

The nominal frequency (1.3GHz) corresponds to the evanescent TE_{11} mode with attenuation coefficient $(E \sim e^{-\alpha z})$:

$$\alpha = \frac{2\pi}{c}\sqrt{f_c^{\,2} - f^2}$$

The corresponding attenuation length:

$$L_{att} = \frac{c}{2\pi\sqrt{f_c^{\,2} - f^2}} = 0.121m$$

Problems

- Photo emission → charge production
- E-beam asymmetry investigations:
  - Cathode laser transverse distribution
  - Solenoid imperfections
  - RF gun coaxial power coupler → kick ? (new)

- 3D ellipsoidal distribution (new):

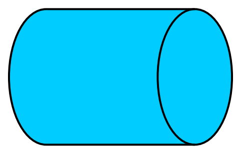
  Impact of laser pulse shape imperfections

Laser pulse shaping studies for further improvement of the electron beam quality in a photo injector

$$\varepsilon = \sqrt{\varepsilon_{cath}^2 + \varepsilon_{RF}^2 + \varepsilon_{SpCh}^2}$$

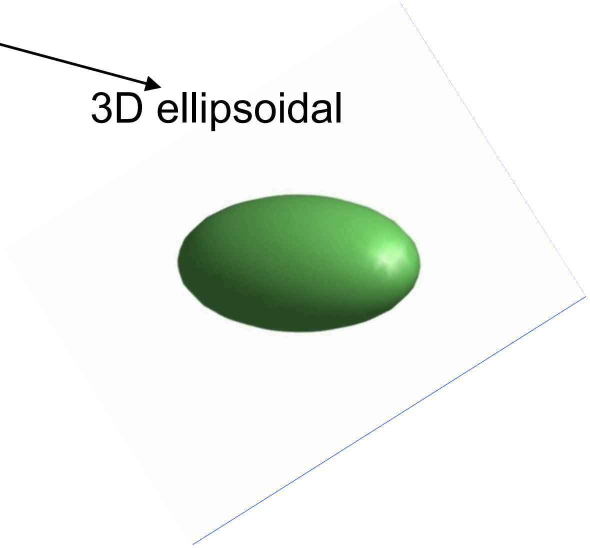
$$\text{cathode laser shape: } \varepsilon_{SpCh} \rightarrow \min$$

cylindrical

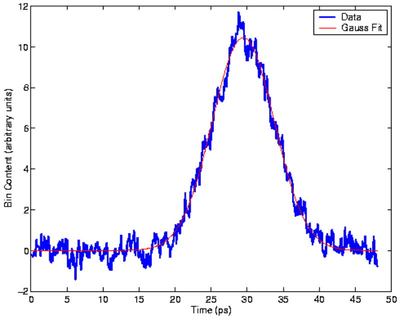


temporally

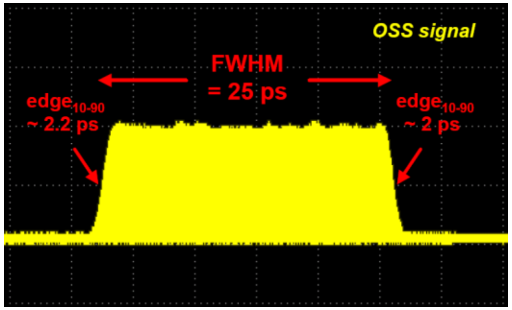
3D ellipsoidal



Gaussian
(e.g. FLASH)
Trms=4.4ps



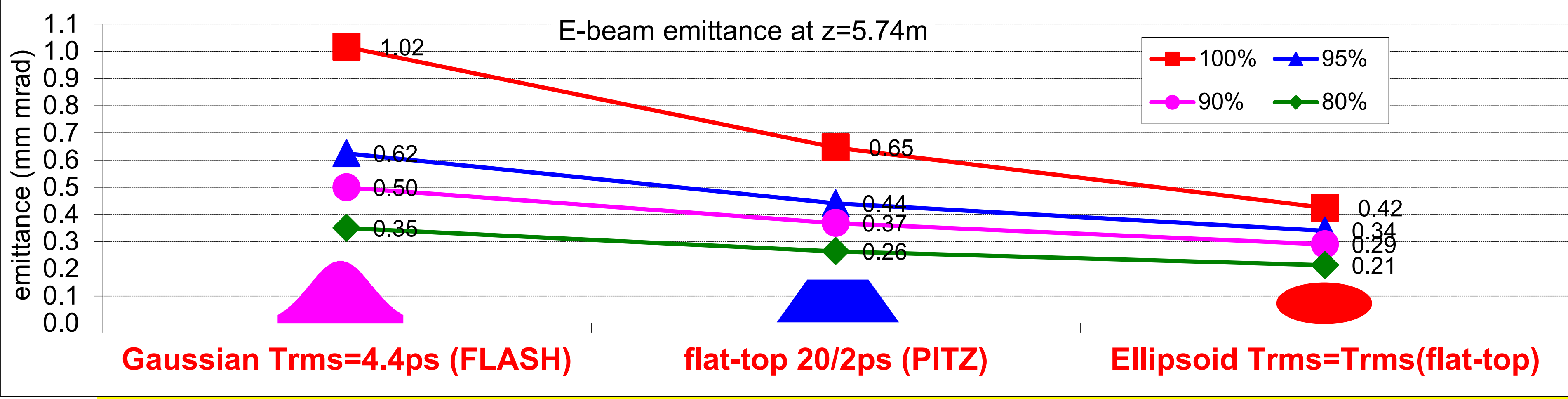
Flat-top
(e.g PITZ)
FWHM~20ps, rt~2ps

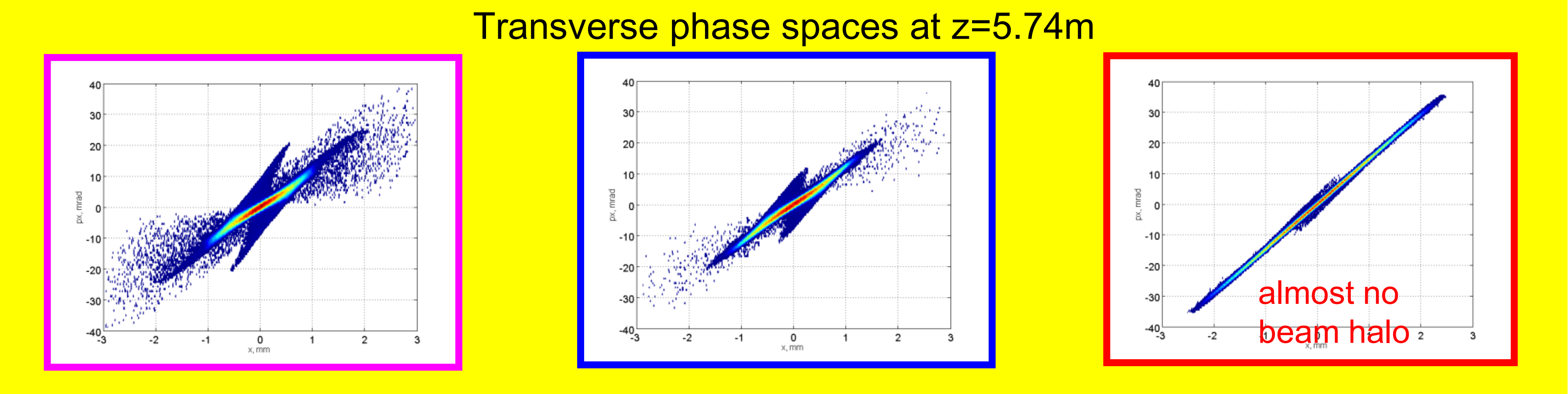


Beam dynamics (ASTRA) simulations for PITZ-1.8 setup

New option for the photo cathode laser → 3D ellipsoid

BD simulations for 1 nC bunch charge



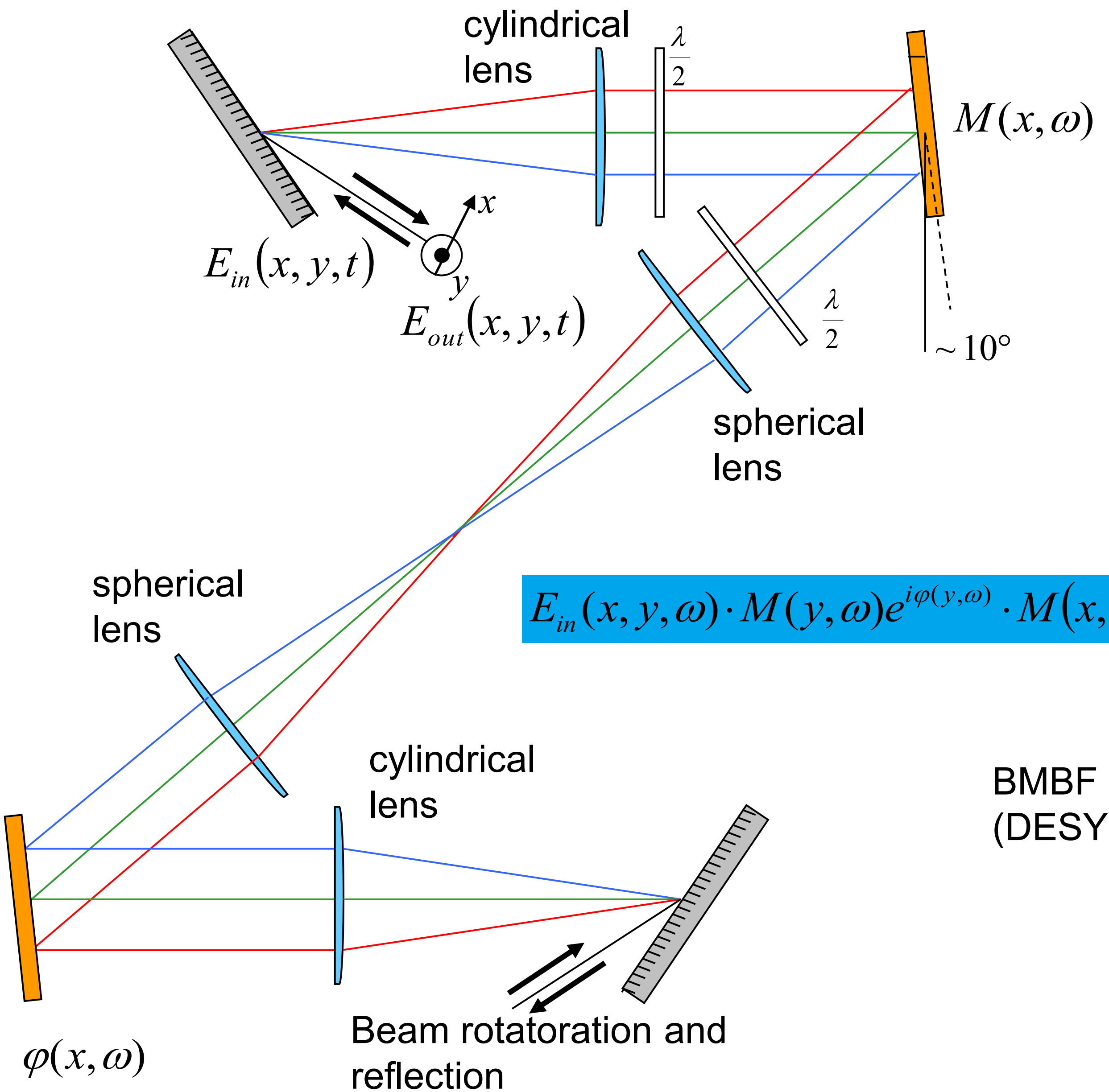


Advantages of 3D ellipsoidal cathode laser pulses:

- 30-50% lower average slice emittance → higher **brilliance**
- long. phase space +3rd harm. → better **compression**
- ~no beam halo → better signal/noise, reduced **rad. damage**
- less sensitive to machine settings → higher **stability**

The BMBF-project (05K10CHE) "Development and experimental test of a laser system for producing quasi 3D ellipsoidal laser pulses" for the period of 3 years (2011-2013) has been started in the framework of the German-Russian collaboration "Development and Use of Accelerator-Based Photon Sources" (DESY-JINR-IAP)

Pulse Shaping using 2D SLM

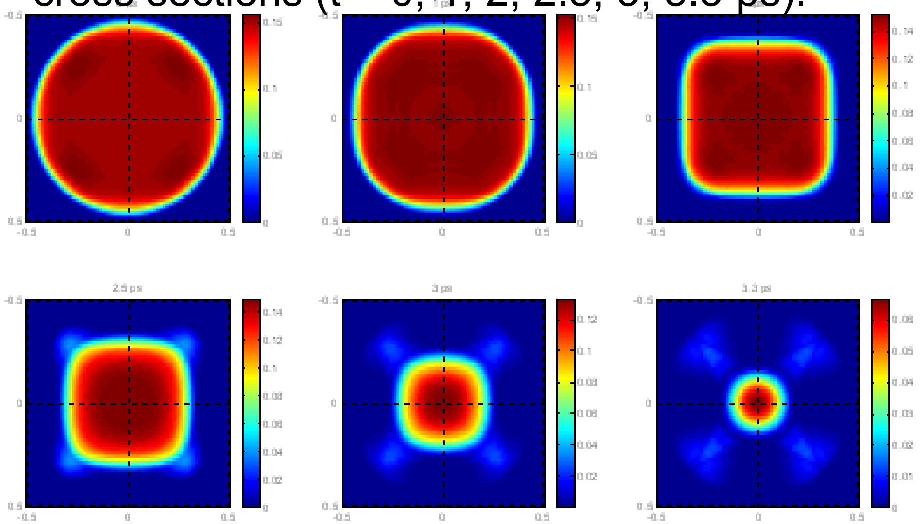


$$E_{in}(x,y,\omega)\cdot M(y,\omega)e^{i\varphi(y,\omega)}\cdot M(x,\omega)e^{i\varphi(x,\omega)} = E_{out}(x,y,\omega)$$

BMBF project 05K10CHE
(DESY - IAP RAS N.Novgorod)

Practical realization of the BMBF-Project 05K10CHE

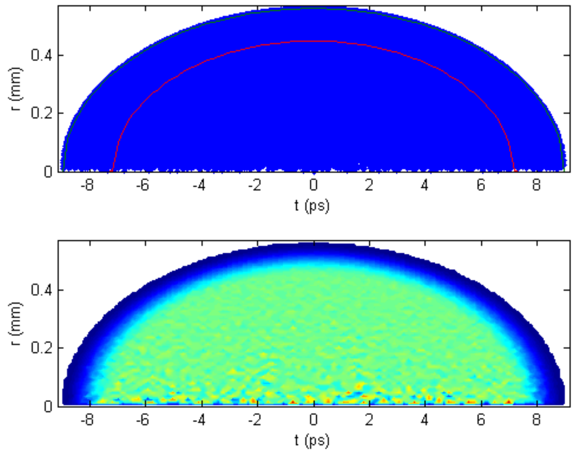
3-D ellipsoid laser transverse distribution at different time cross sections (t = 0; 1; 2; 2.5; 3; 3.3 ps).



3-D ellipsoid laser pulse shape imperfections have to be studied for tolerances:

1. Sharpness of edges
2. Rotational symmetry distortions
3. Shape stability

1. Sharpness of 3D ellipsoid edges



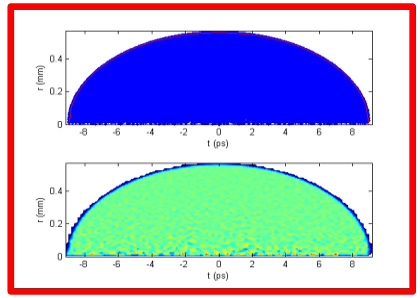
1. Sharpness of 3D ellipsoid edges

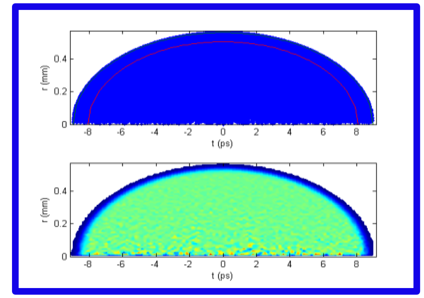
δ - border sharpness parameter

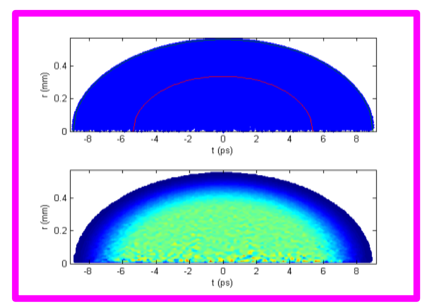
$$\theta = \sqrt{\left(\frac{r}{R}\right)^2 + \left(\frac{t}{T}\right)^2}$$

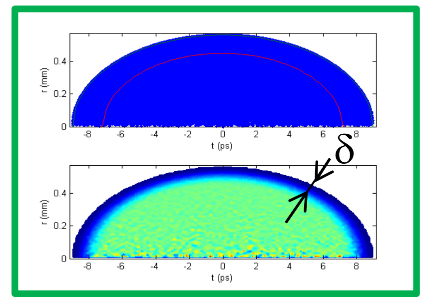
Modification of the initially homogeneous laser intensity distribution:

$$\rho = \rho_0 \begin{cases} 1, & if\ \theta < 1-\delta \\ \dfrac{1-\sin\left[\pi\cdot\left(\dfrac{\theta-1}{\delta}+\dfrac{1}{2}\right)\right]}{2}, & if\ 1-\delta \le \theta \le 1 \end{cases}$$









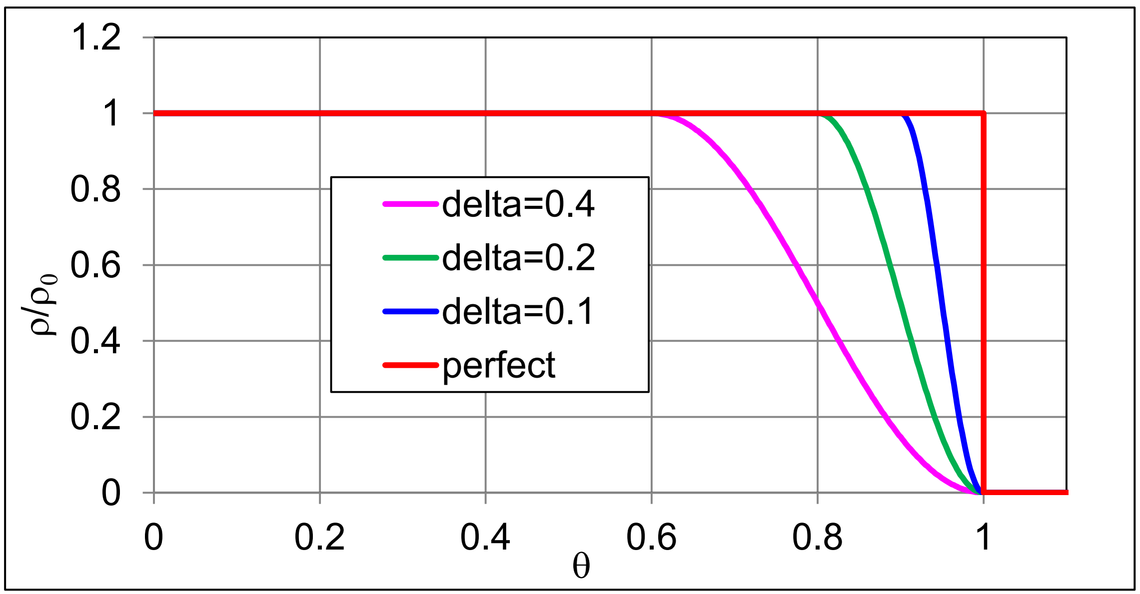


Fig.7. Intensity modification with the border sharpness.

Phase spaces at different border widths (setup2)

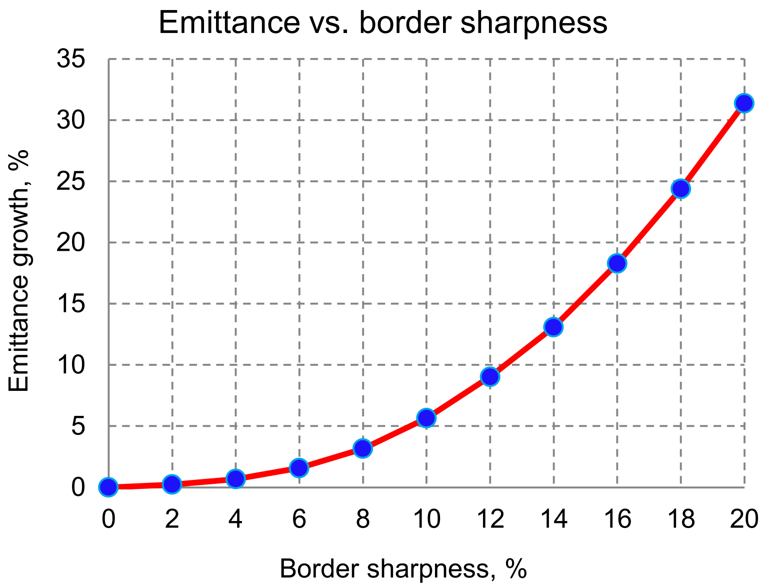
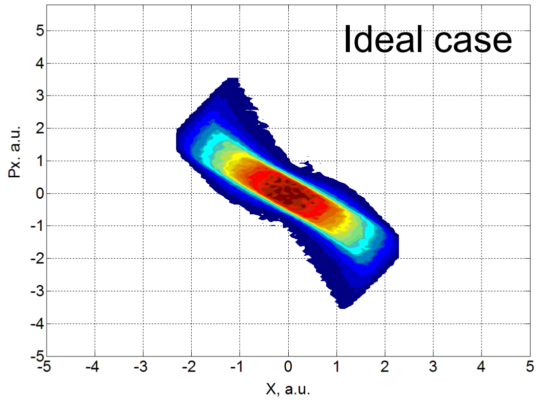
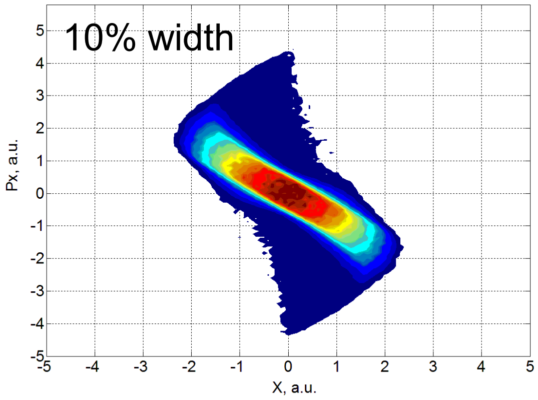
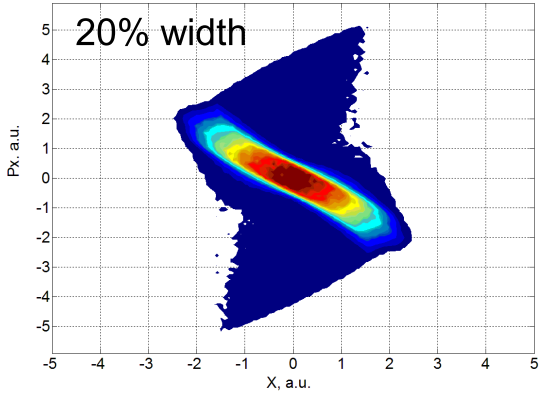


Fig.8. Emittance growth with border width.







> Critical emittance growth (30%) for 20% border width

Summary (3D ellipsoidal laser pulses)

> 3D ellipsoid imperfections:

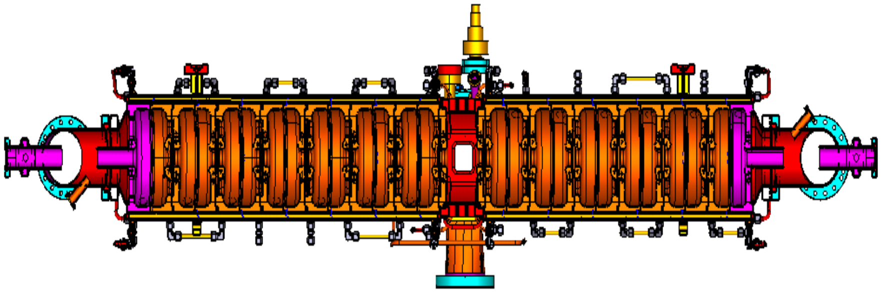
- → Border sharpness influence on beam emittance has been simulated. 30% emittance growth (critical) at 20% border width

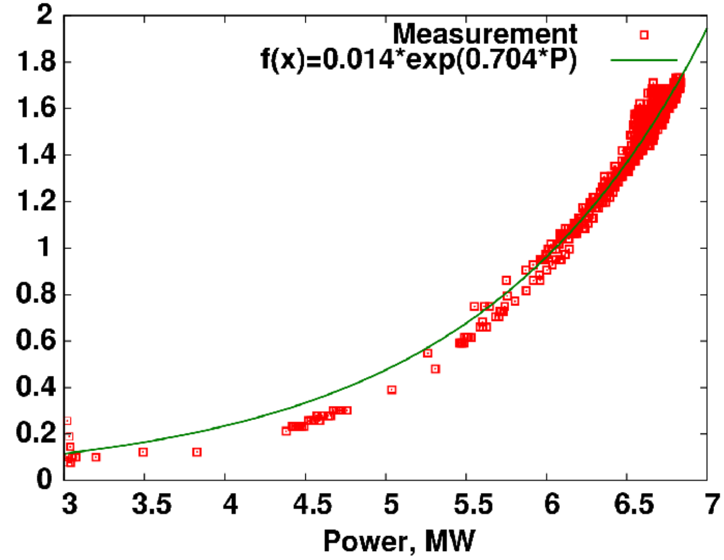
> Still to be done:

- Nonhomogeneous sharpness (t-r)
- Rotational asymmetry (“squared” shape)
- Shape modulations
- S2e simulations (bunch compression studies)
- …

The End

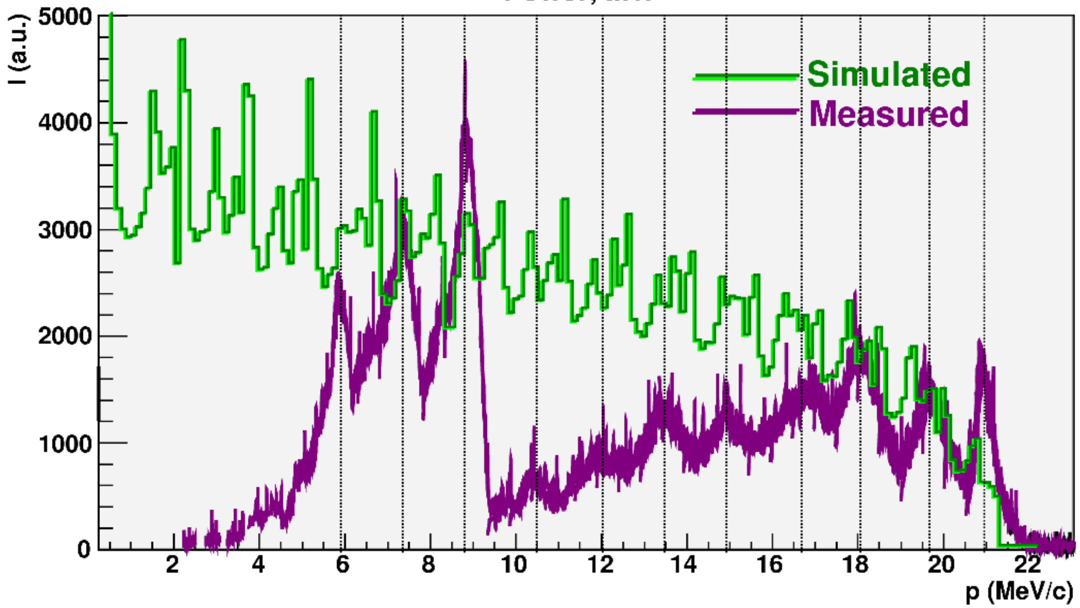
CDS Booster dark current problem





Measurement was done using Dark Current Monitor (DCM)

Measurement was done downstream in High Energy dispersive arm



- **Well pronounced bumps**
- **Three cells have the most contribution**
- **Three bumps are missing in low energy part of the spectrum**

Simulation request for PITZ

Observation / problem / idea	? to be simulated
Core emittance	"Phase space collimator (beam scraper)" ?influence of image charges + wakes
Measured e-beam shape (asymmetry, tails), transverse phase space (emittance) depend on trajectory	•Magnetic components (active, passive), e.g. solenoid imperfections? •Wake field (like) effects (VM, DDC,…)
Charge production, influence of real laser transverse and temporal profiles (imperfections)	Beam dynamics simulations, especially in the cathode vicinity (emission), slice emittance formation
E-beam matching into the tomography section	Using V-code with space charge to find quad strength
Particle driven plasma wake field acceleration	Self modulation of the driver, etc
…	