Measurements and modeling of space charge assisted photoemission at PITZ

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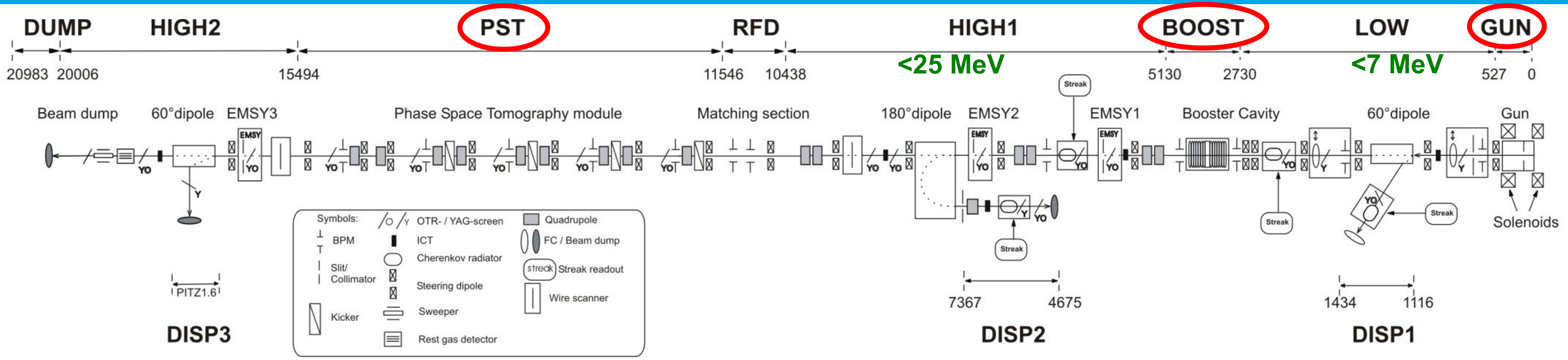
Experimental optimization of the PITZ photo injector for a nC bunch charge level resulted in machine parameters corresponding to a space charge assisted photo emission from the Cs_2Te cathode. Several additional dedicated emission studies have been performed in order to study the charge production as a function of photo injector parameters like rf peak power in the gun, laser spot size at the cathode and laser pulse energy. Results of these studies will be discussed.

Photo Injector Test facility at DESY, Zeuthen site



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:

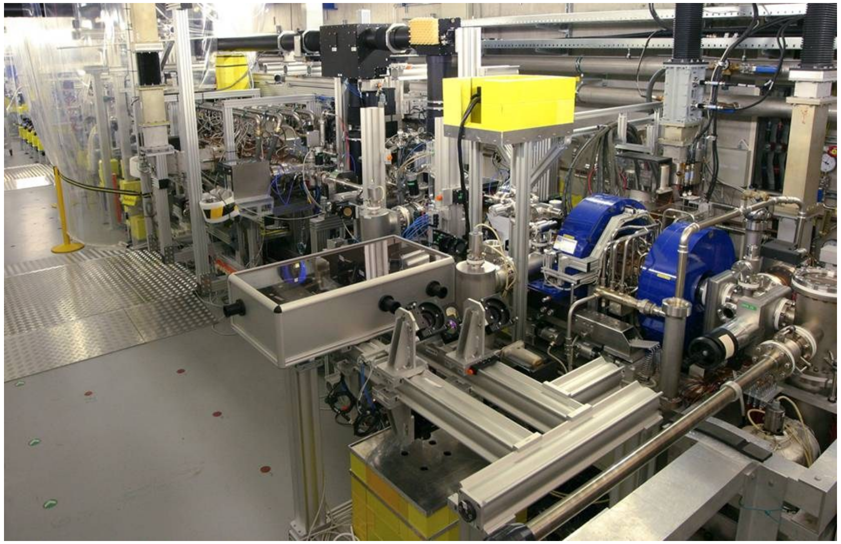
⇒ test-bed for FEL injectors: FLASH, the European XFEL

⇒ **small ε_{tr}**

⇒ stable production of short bunches with small σ_E

⇒ further studies → e.g. cathodes: dark current, photoemission, QE, thermal emittance, …

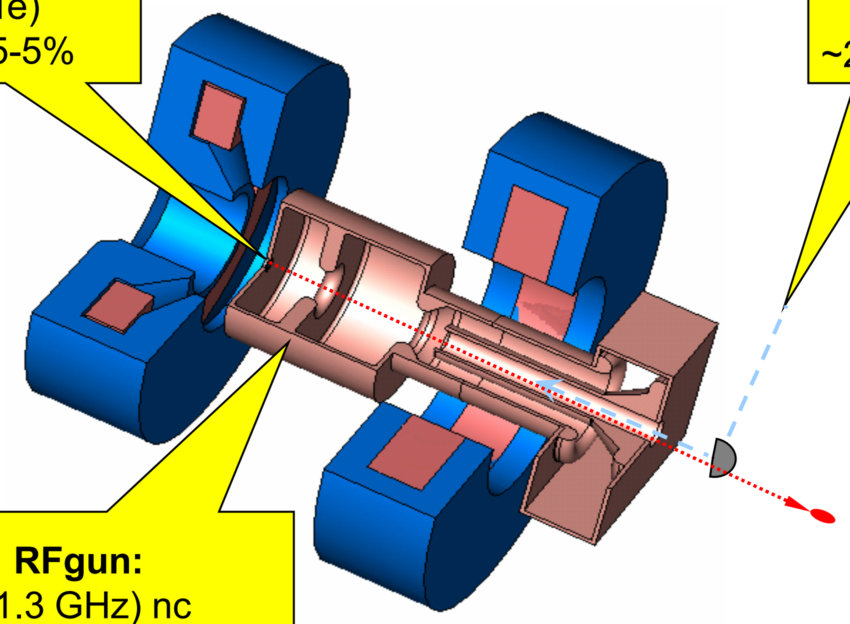
+ detailed comparison with simulations = benchmarking for the PI physics



PITZ RF gun and photo cathode laser

Photo cathode
(Cs_2Te)
QE~0.5-5%

Cathode laser
257nm
~20ps (FWHM)

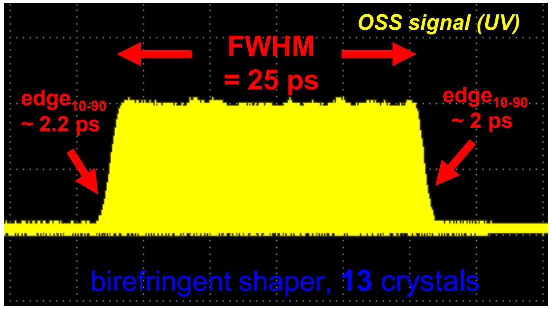


RFgun:
L-band (1.3 GHz) nc
(copper) **standing wave**
1½-cell cavity

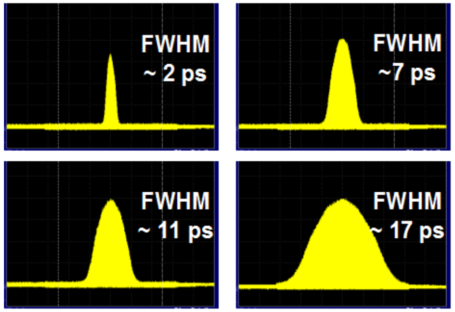
Peak rf power: up to 7MW
Ez@cathode: > 60MV/m

Temporal pulse shaper

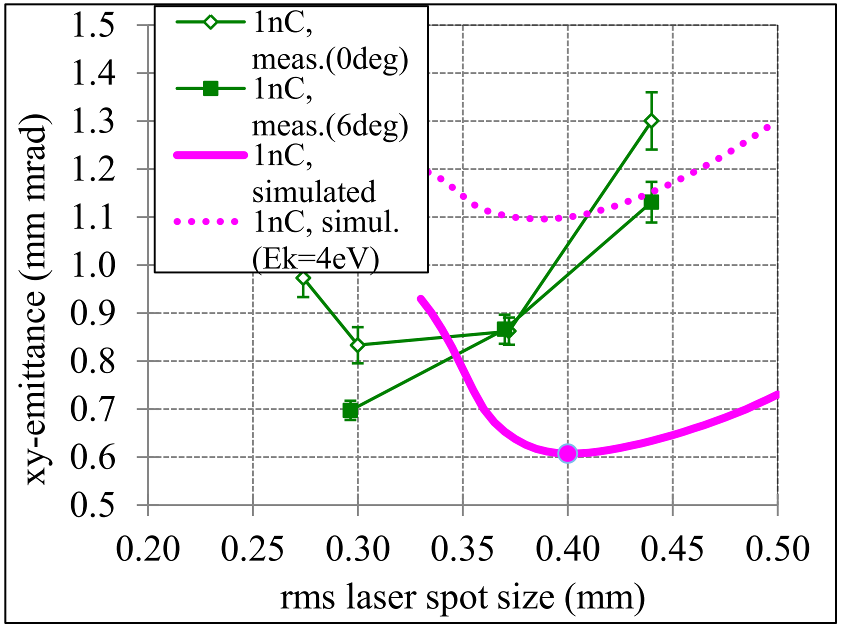
Flattop

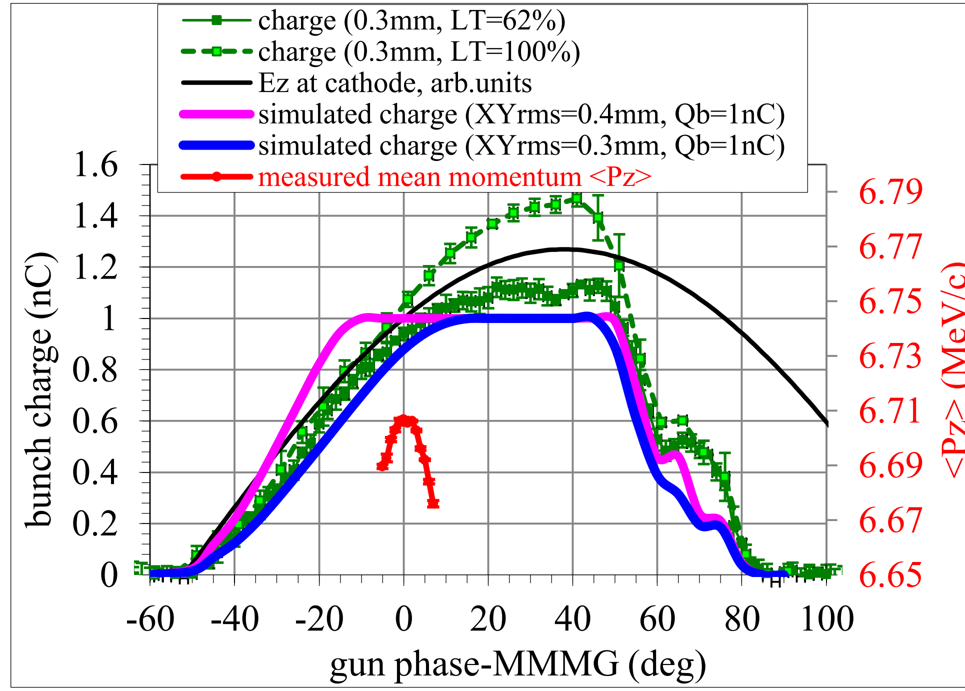


Gaussian:

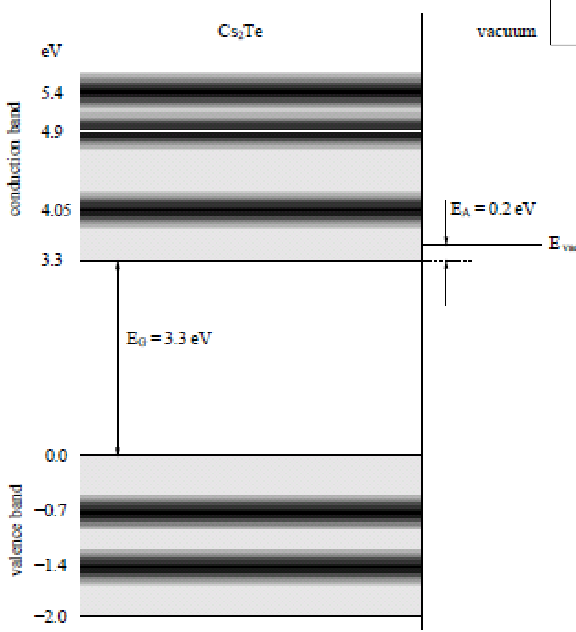


Emission studies: motivation





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

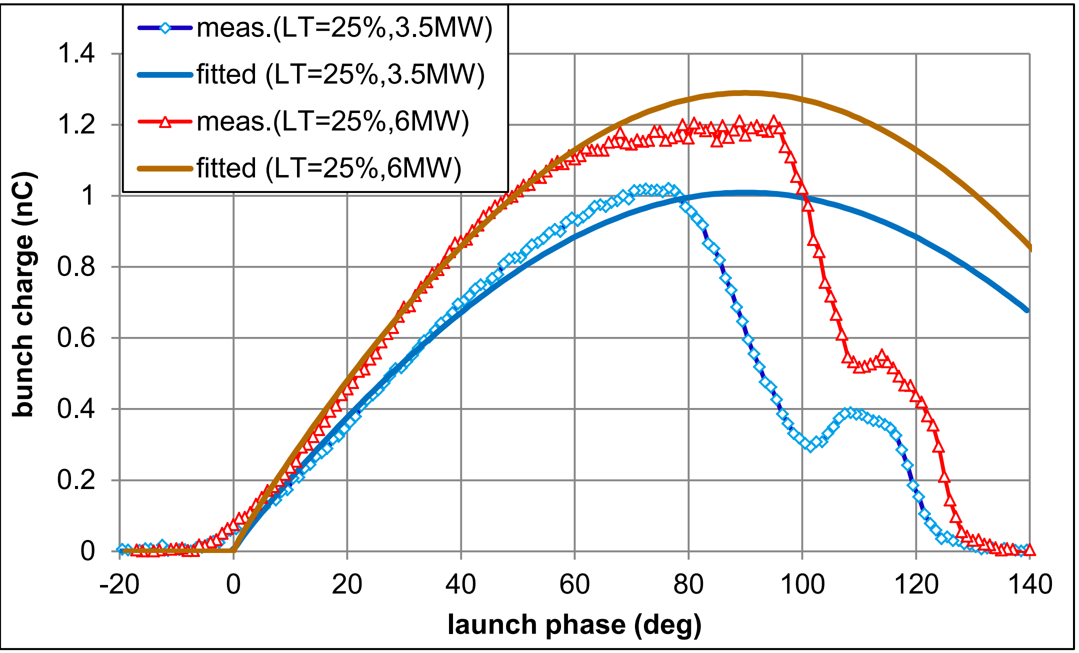
PITZ Photo Injector Test Facility Zeuthen

DESY

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*

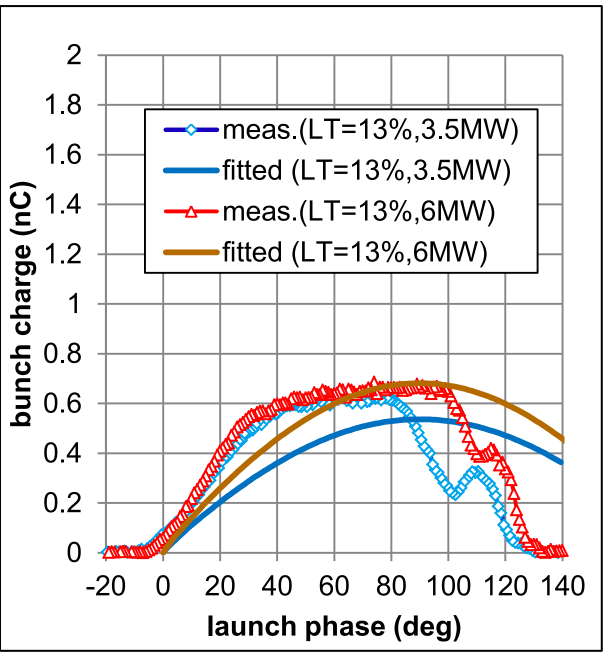
Main solenoid: 400A
Charge measured by LOW.ICT1 → z=0.9m

Emission studies: modeling → RF field

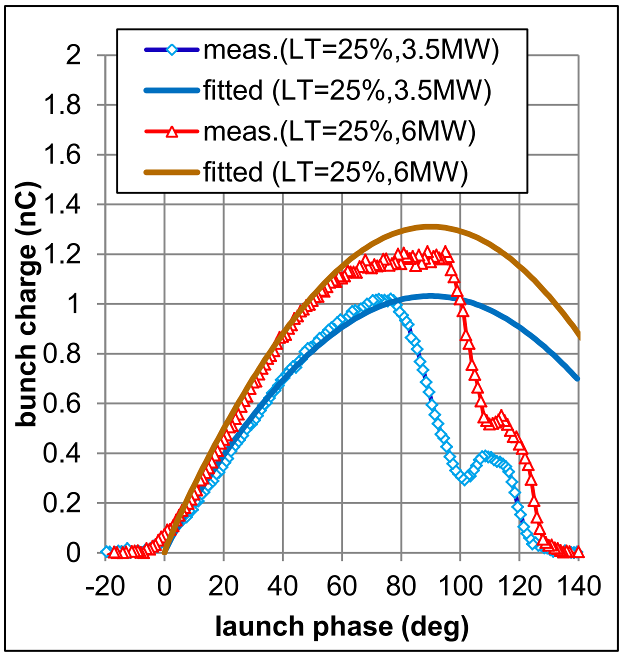
Simultaneous fitting (LT=13% and 25%):
Phase range: 10→70deg
$E = E_{cath} \cdot sin\varphi_0$
η=8.44E-8
b=205.9
m=1.805

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

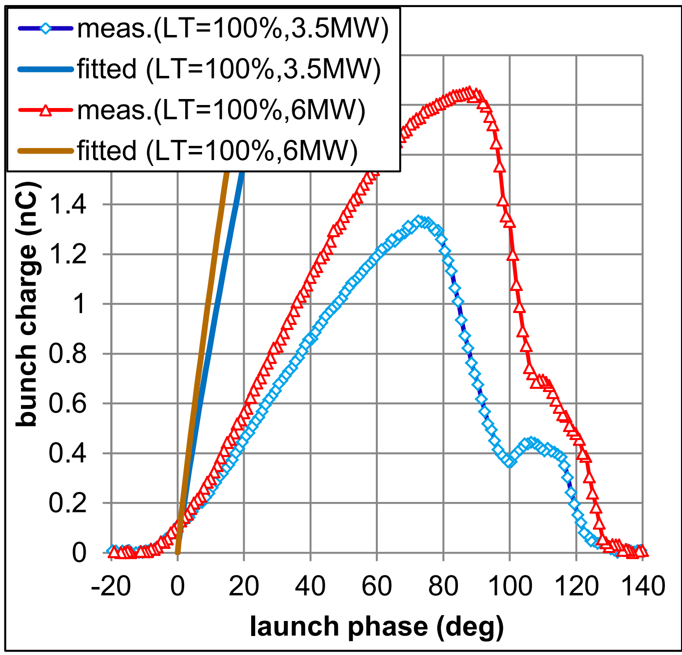
LT=13%



LT=25%



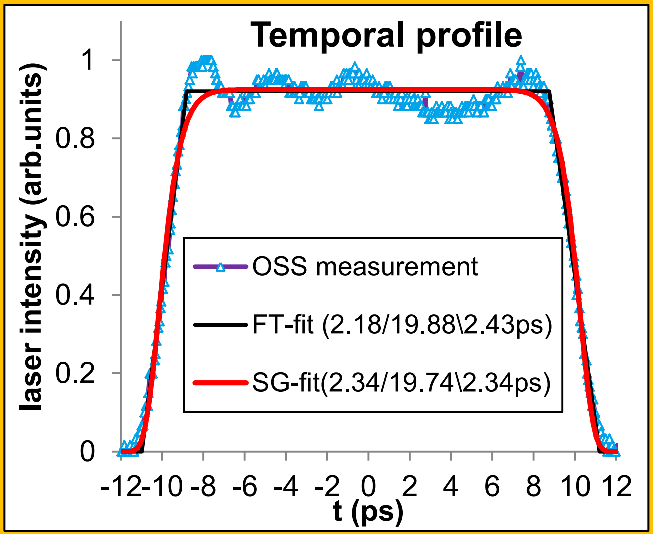
LT=100%

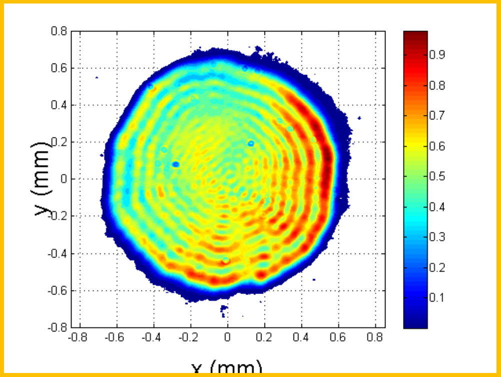


- **Simultaneous fitting → assumptions are not correct?**
- **Almost no RF impact for low SC density**
- **RF field impact increases with SC density increase**

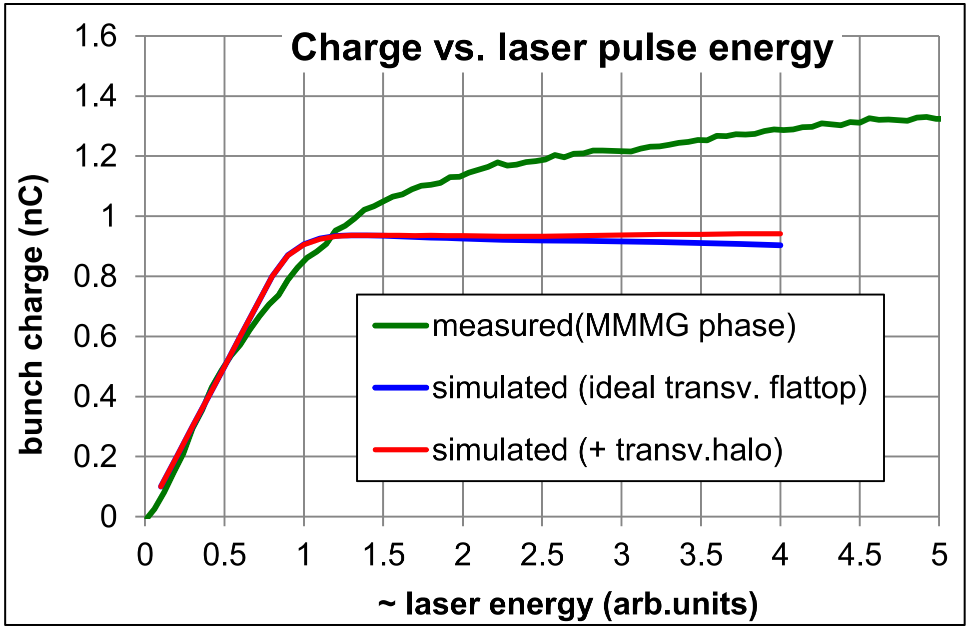
Emission studies: LT scans and ASTRA simulations

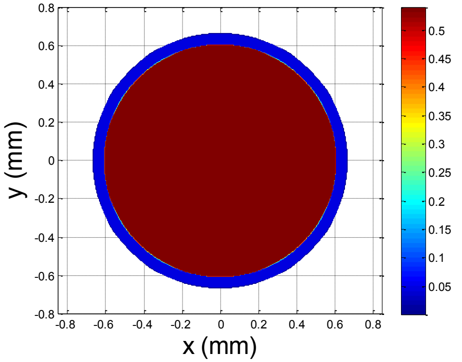
Measured cathode laser shapes





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

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

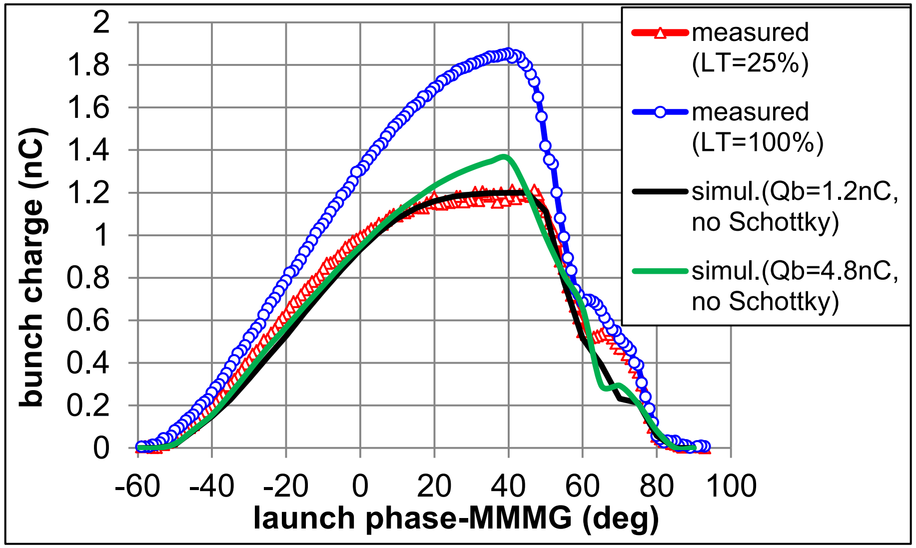
$LT = \xi \cdot LT0$

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

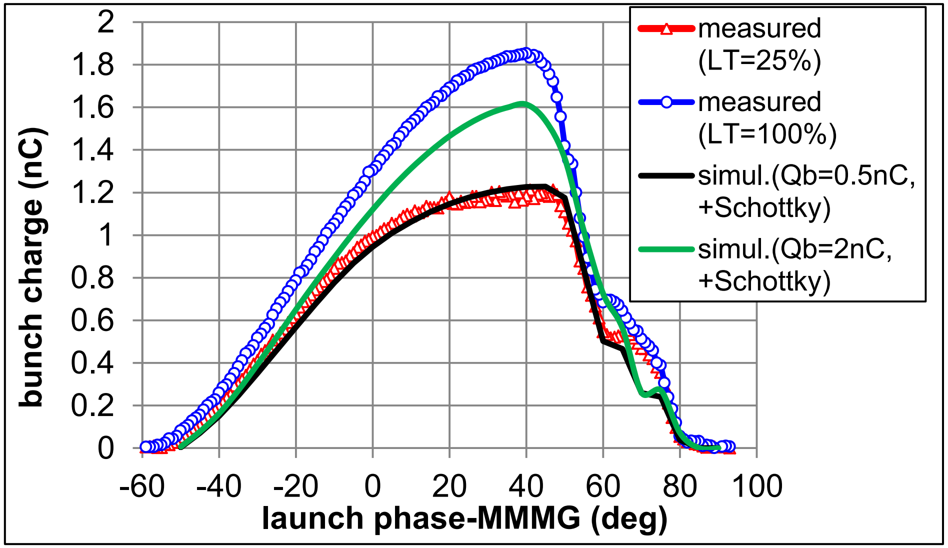
$S_{Schottky} = \xi \cdot S_{Schottky0}$

Schottky constants should be scaled with laser pulse energy

No Schottky effect applied



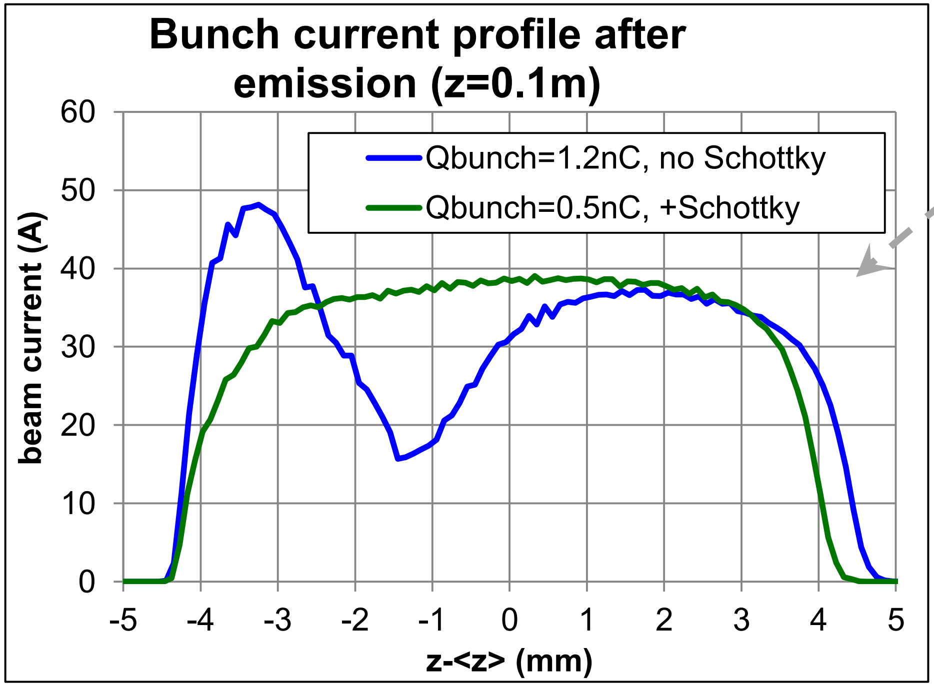
Schottky parameter fitting

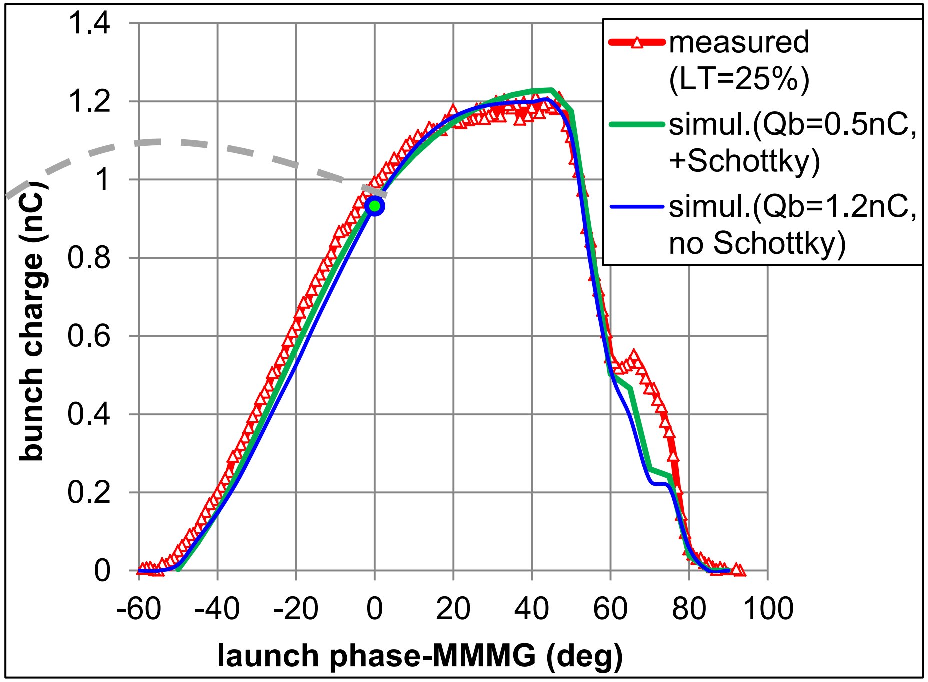


$$\xi = \frac{100\%}{25\%} = 4$$

Qbunch= 0.5nC
L_Schottky= 0.0059983
S_Schottky= 0.109529

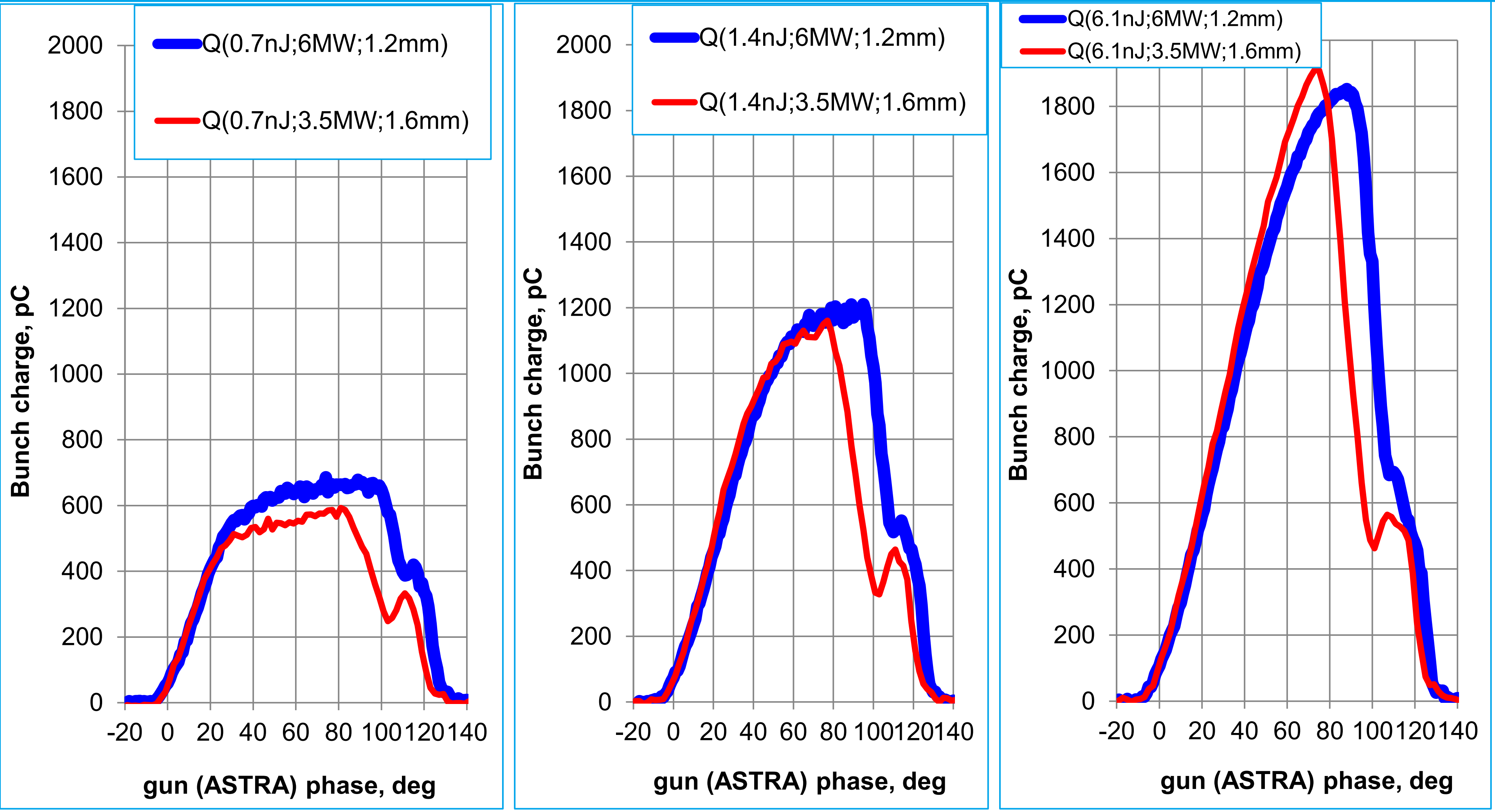
ASTRA simulations: Schottky effect impact





Applied Schottky effect ➔ more smooth charge extraction

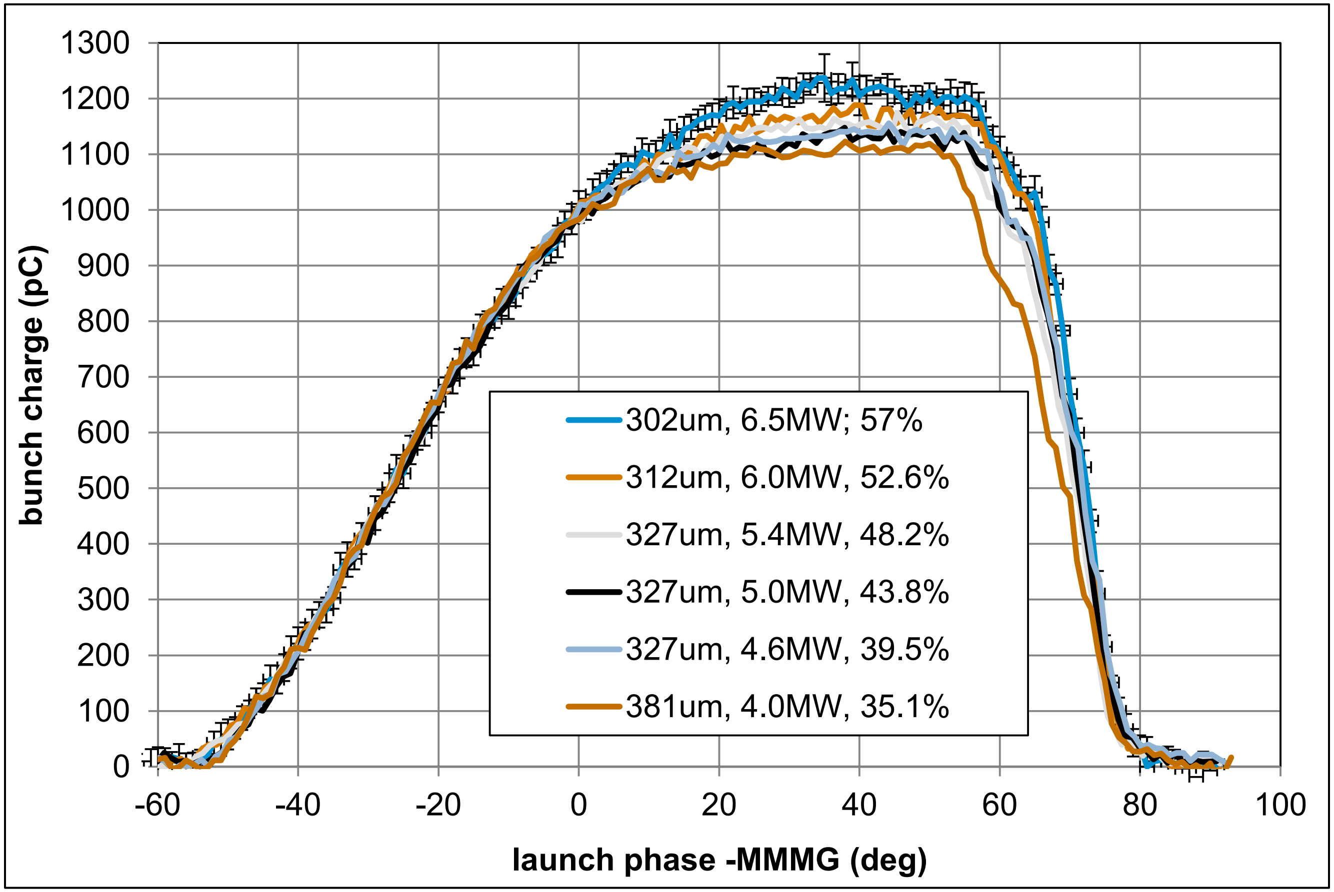
Further emission studies:
+ laser spot size and pulse energy variation



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

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

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

> 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:

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

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