Selected Beam Studies at PITZ in 2017

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TEMF-DESY Collaboration Meeting
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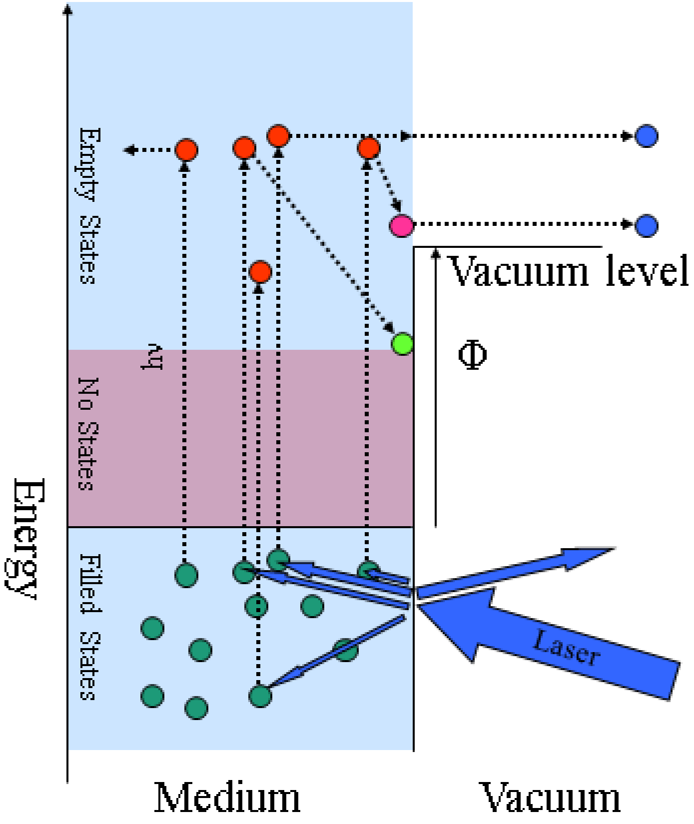
Contents

- Photoemission modeling in the gun
- Updates on beam asymmetry studies
- Summary

Review of Three-Step Photoemission (PE) model



1. **Optical excitation of electrons**
   - Reflection
   - Transmission
   - Energy distribution DOS
2. **Migration of electrons to solid surface**
   - e^--phonon scattering (momentum change)
   - e^--defect scattering (momentum change)
   - e^--e^- scattering (energy change, metal)
   - Random Walk (Monte Carlo)
3. **Escape to vacuum**
   - Overcome work function
     - ✓ Eg(band gap) + Ea(electron affinity) for semiconductor
     - ✓ Eg variation, Ea variation
     - ✓ Surface potential reduction due to field effect

For thorough descriptions, see:

W. E. Spicer, Phys. Rev., 112 114 (1958)
M. Cardona and L.Ley: Photoemission in Solids 1, (Springer-Verlag, 1978)
W. E. Spicer & A. Herrera-Gomez, SLAC-PUB-6306 (1993)
D. H. Dowell et al., Appl. Phys. Lett., 63, 2035 (1993)

J. Smedley, P3 workshop 2016
K. L. Jensen, P3 workshop 2016
L. Cultrera, EWPAA 2017
J. Smedley, EWPAA 2017

Motivation of further PE modeling at PITZ

- Explain PE associated measurement-simulation discrepancies in the gun
  - **Charge** production
  - Slice **energy spread**
  - Bunch **length**
  - Beam **asymmetries**, etc.
- Assist semiconductor photocathode R&D

Background:

+ *Photocathode R&D usually focuses on **"single electron" emission mechanism***
+ *Operation condition of PITZ for optimized emittance **@ transition regime between QE and space charge limited emission regimes***
+ *Classical **electrodynamics** seems **not sufficient** explaining transient PE process*
+ ***Intrinsic emittance modeling** not yet thorough*

Our Challenge: Improved modeling of photoemission process

→ At the semiconductor-vacuum interface in the gun how to model quantum mechanics with the presence of strong electromagnetic fields (RF + SPCH = collective effects)

Space charge dominated PE modeling

1. Driving (UV) laser

- Realistic transverse (Virtual-Cathode-based Core+Halo model*) distributions
- Realistic temporal distributions

→ **initializing transient emission process**

2. Photocathode

- QE map and QE characterization

→ **intrinsic emission homogeneity**

3. EM fields in close cathode vicinity

- RF, image charge & space charge

→ **time and space dependent cathode work function modulation**

4. Quantum mechanics with the presence of strong EM fields at Semiconductor-Vacuum interface

- Surface states
- Band bending

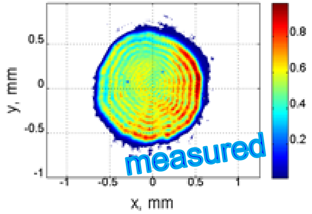
→ **time and space dependent electron affinity variation**

→ **kinetic energy variation**

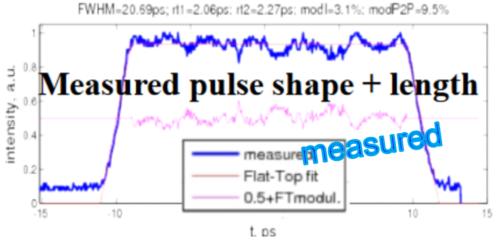
5. Others

- Temperature
- Surface charge limit**
- Secondary emission, etc.

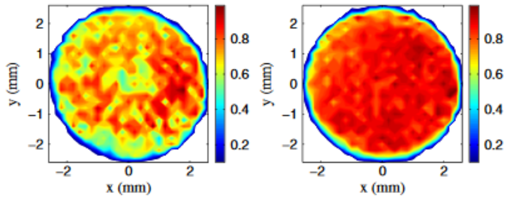
Cathode UV laser spot



Laser temporal profile



QE homogeneity



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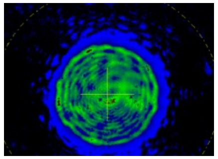
* C. Hernandez-Garcia et al., *NIM A 871 (2017) 97–104*

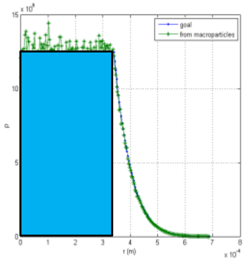
**M. Zolotorev, *SLAC-PUB-5896 ,1992*

Status: Core + Halo Model applied to ASTRA simulations

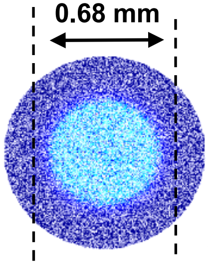
If a uniform distribution is used instead, the charge saturates

Laser radial distribution image



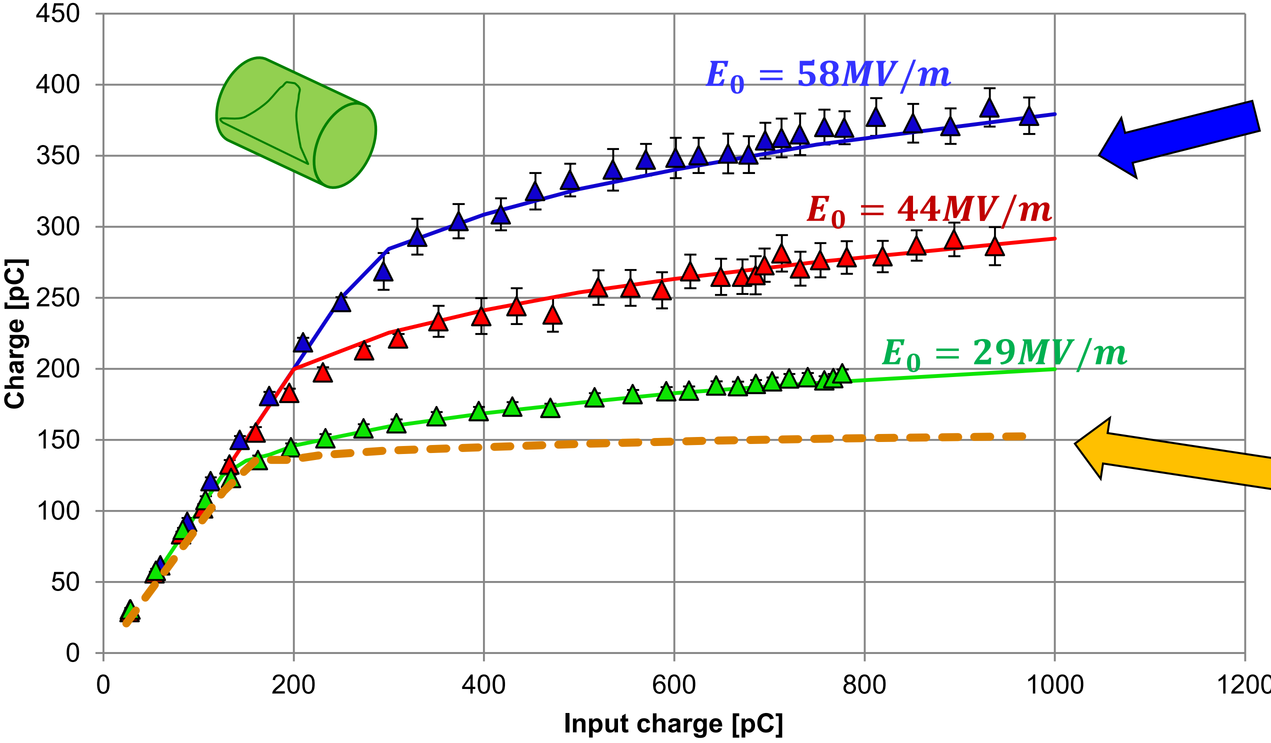


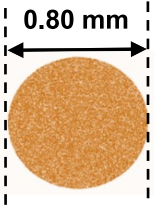
Transverse radial profile core + halo



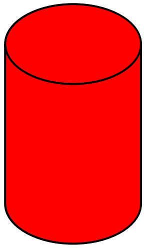
Generated ASTRA input distribution core + halo

Extracted charge with core + halo for 0.8 mm beam diameter with 1.5 ps rms Gaussian temporal at maximum cathode field (ϕ_0=90°)





Nominal ASTRA input uniform distribution

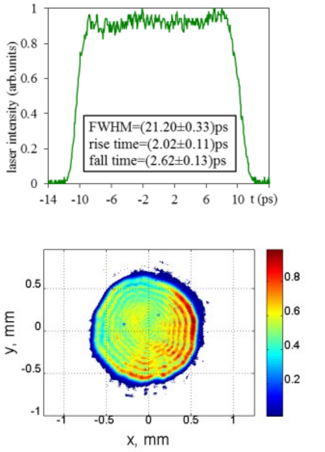


Nominal transverse uniform radial profile

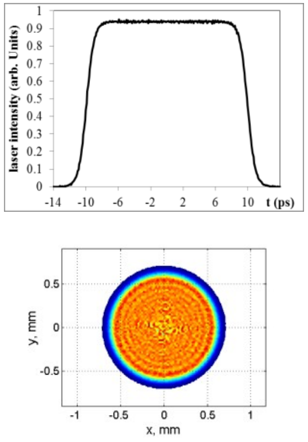
Status: ASTRA simulations for 2011 case using Core+Halo

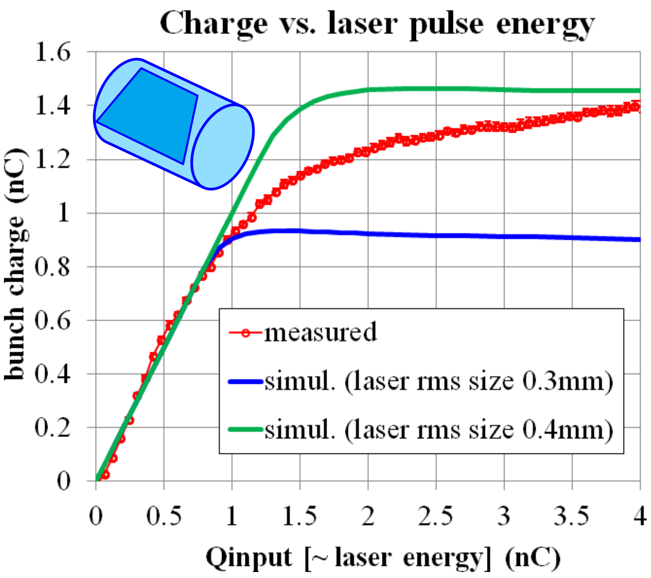
- BUT for flattop photocathode laser pulses

measured

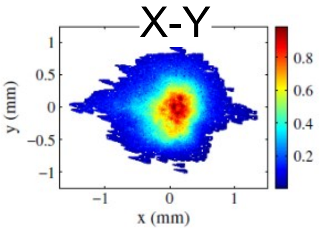


Used in simulations





measured

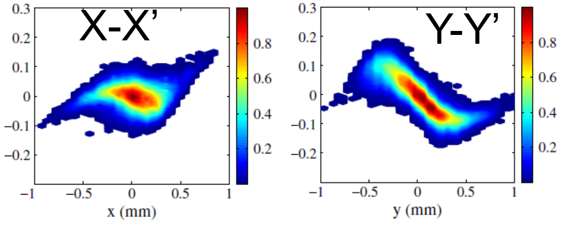


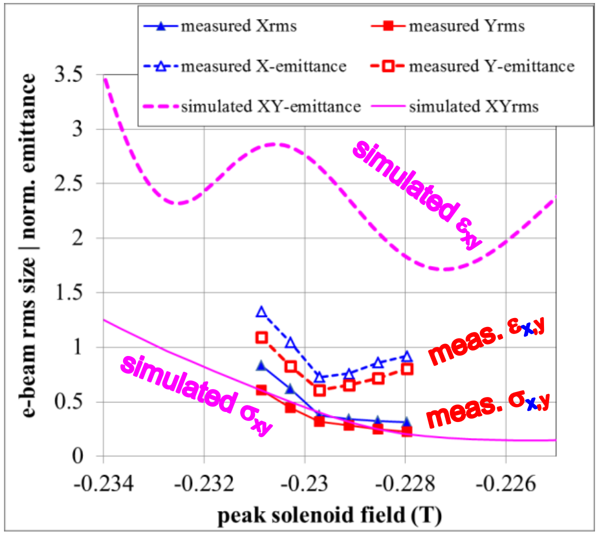
ϕ_{gun}=MMMG+6°

Q=1nC*

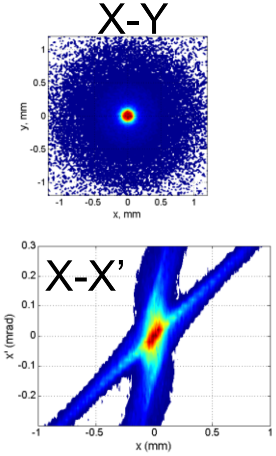
ε_x=0.72 mm mrad

ε_x=0.60 mm mrad





simulated



Parameters "plugged" from measurements:

ϕ_{gun}=MMMG+6°

Q=0.97nC

ε_x=2.5 mm mrad

Status: PE modeling using a 3D full EM Lienard-Wiechert (LW) approach*

*E. Gjonaj, TEMF, TU Darmstadt

LW Approach with 3D emission process

- **LW solution for the electromagnetic field of a charged particle** in arbitrary motion
- **Full particle trajectory** stored and used for field computation
- Field-induced work function modification:

$$\Delta\Phi_f(r_\perp,t) = \sqrt{\frac{q^3}{4\pi\varepsilon_0}\left[E_{rf}(r_\perp,t) + E_{sc}(r_\perp,t)\right]}$$

- Charge production per simulation time step:

$$dQ(\mathbf{r}_\perp,t) = \Delta t \iint_S q\frac{P_l(\mathbf{r}_\perp,t)}{h\nu} QE(\mathbf{r}_\perp,t)dS$$

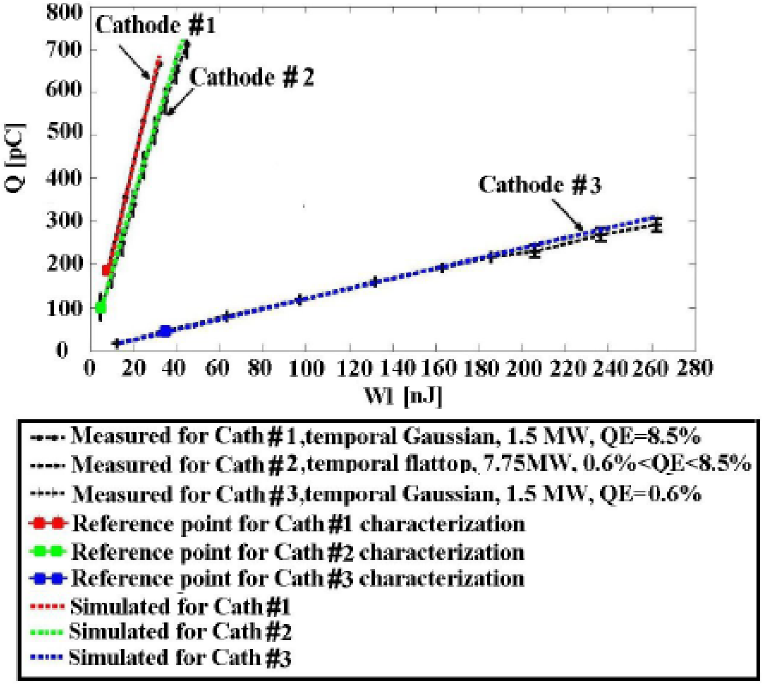
$$QE = \frac{(1-R_w)\sqrt{1+\frac{hv-\Phi_w}{E_a}}}{2(p_0+1)(1+\frac{E_a}{hv-\Phi_w})^2}$$

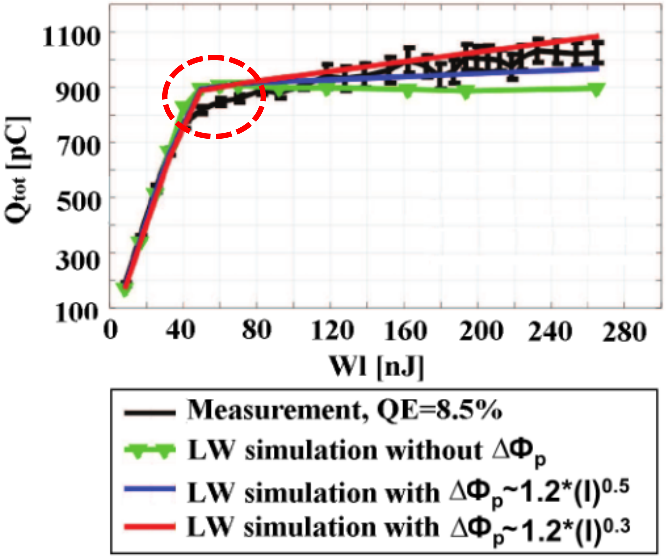
K. Jensen, 2007

Status

- **Dynamic generation** of emitted **particle distribution** at cathode according to **time-dependent emission models,** taking into account **full electromagnetic fields** (RF + space-charge) during emission
- Charge production in **QE limited regime** agrees with measurements
- In **space charge dominated regime,** remaining deviations w.r.t. simulations probably due to:

  ✓ Ideal beam distributions initially plugged in the simulations or/and time dependent work function variation resulting from quantum mechanics





Further PE modeling: band bending → space charge layer

Surface states

- Due to lattice translational symmetry broken @cathode surface
- Surface band lying **within bandgap** of the bulk (fewer bonds)
- Possessing **charging character**

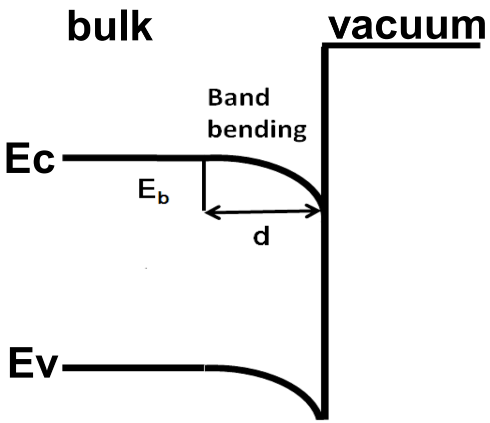
Surface states → band bending

- Charge carriers falling into surface states → **"surface charged“**
- Matching fermi level at bulk and surface → band bent
- Band bending → **space charge layer formed** (from surface into the bulk)

Characteristics

- Band bends **quadratically**
- **Local curvature proportional to local space charge density**
- Bending amount and width depending also on **material properties**

$$E_{bb} \propto \frac{\rho_{sc}(r,t)d^2}{\varepsilon}$$



Further modeling approach needed

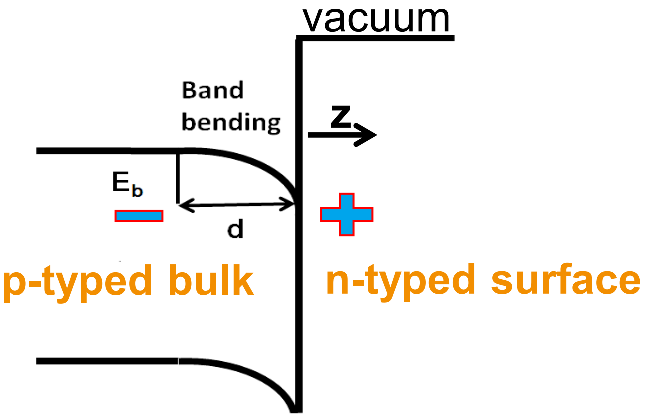
PE modeling: interpretation of surface space charge layer

- **For Cs_2Te**
  - **Donor-like surface, acceptor-like bulk**
  - Band bends **downwards** at surface
- **Electrons may be extracted from**
  - Valence band (VB)
  - Surface band (SB)

→ ratio of VB and SB (emitted) electrons changes E_{kin} and ε_{th}

- **Surface space charge layer may affect electron affinity**

→ time and space dependent $E_a \propto \rho_{sc}(r,t)$



UV@257nm → $E_{ph} \approx 4.82$ eV

✓ **Intrinsic cathode work function $\Phi_w = E_g + E_a$**

✓ **Work function due to presence of strong space charge densities @cathode surface**

$$\Phi_w \rightarrow \Phi'_{w\_SB} = E_g \boxed{- E_{SB}} + E_a \boxed{- E_{bb}\left[\rho_{sc}(r_\perp,t)\right]} \boxed{- \Delta\Phi_f(r_\perp,t)}$$

$$\Phi_w \rightarrow \Phi'_{w\_VB} = E_g \boxed{\phantom{- E_{SB}}} + E_a \boxed{- E_{bb}\left[\rho_{sc}(r_\perp,t)\right]} \boxed{- \Delta\Phi_f(r_\perp,t)}$$

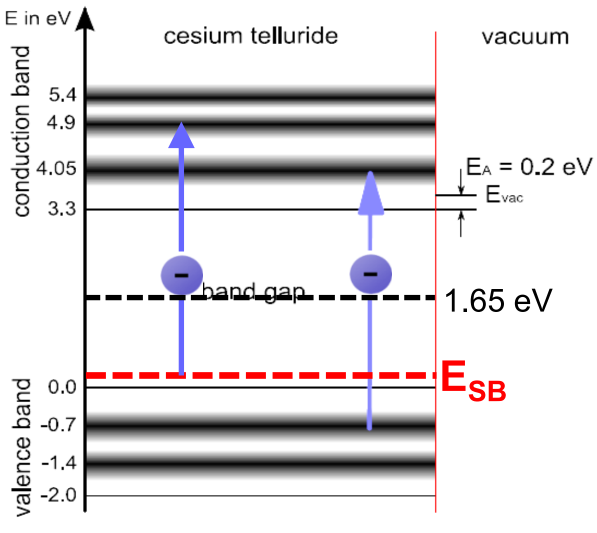
Surface band Band bending Field effect

$$\Delta\Phi_f(r_\perp,t) = \sqrt{\frac{q^3}{4\pi\varepsilon_0}\left[E_{rf}(r_\perp,t) + E_{sc}(r_\perp,t)\right]}$$

$$QE = \frac{(1-R_w)\sqrt{1+\frac{hv-\Phi_w}{E_a}}}{2(p_0+1)(1+\frac{E_a}{hv-\Phi_w})^2}$$

QE: K. Jensen

✓ **Kinetic energy E_{kin} varied accordingly**



✓ **Intrinsic emittance**

If $\varphi \leq \varphi_{max} = \arccos\sqrt{E_a/E_{kin}}$

$$\epsilon_{n,rms} = \frac{r}{2}\sqrt{\frac{2E_{kin}}{m_0c^2}\frac{1}{\sqrt{3}}}\sqrt{\frac{2+\cos^3\varphi_{max} - 3\cos\varphi_{max}}{2(1-\cos\varphi_{max})}}$$

→ optimization w.r.t. space charge

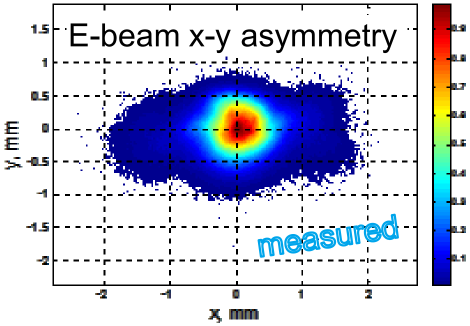
Updates on beam asymmetry studies

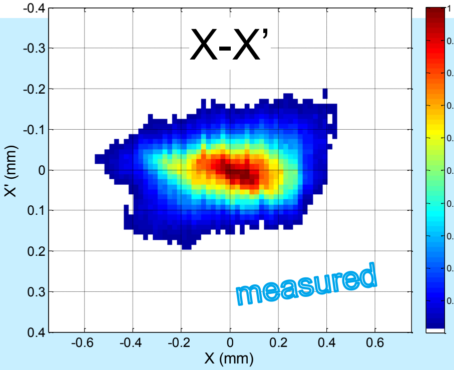
(RF coupler kick simulations &
Gun quadrupole for compensating beam asymmetries)

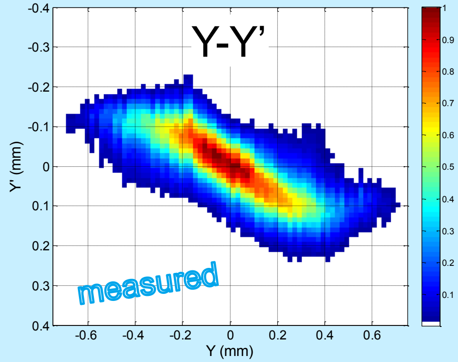
+ Igor Isaev

Motivation of beam asymmetry studies

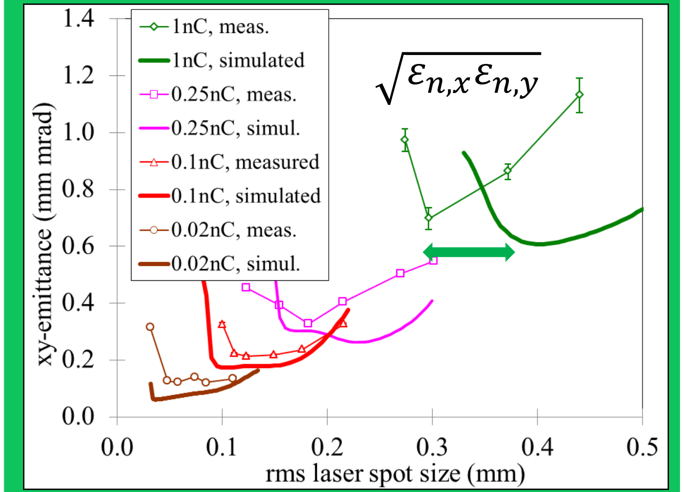
Asymmetry → kick?



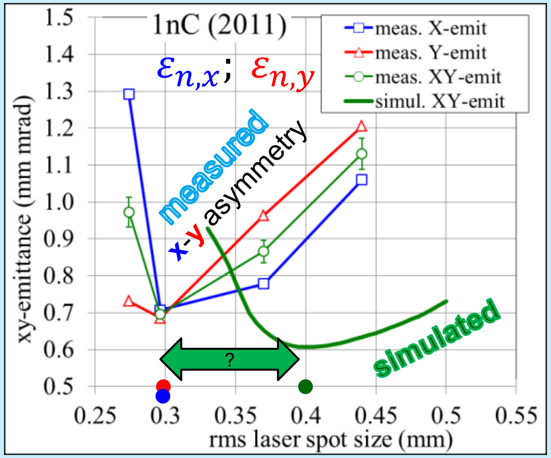




Space charge



M. Krasilnikov et al., PRSTAB 15, 100701, 2012.



Possible sources of the beam asymmetry:

- ~~**Vacuum mirror**~~
- ~~**Stray magnetic fields**~~
- ~~**Related to the laser polarization**~~
- ~~**Particular cathode**~~
- **…**
- **RF coupler field asymmetry**
- **Solenoid imperfections (anomalous quadrupole fields)**

Ongoing activities

→ coupler kick simulations

→ solenoid field simulations

→ simulations with rotational quads model for fitting measurements

→ gun quadrupole designs and simulations

→ gun quads compensation

Updates on coupler RF kick studies (no solenoids)

Kick characterization

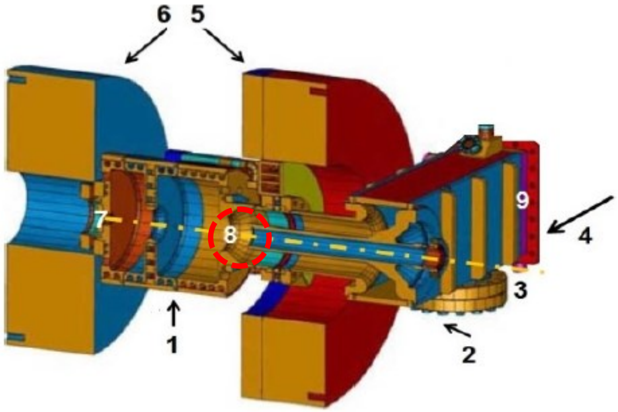
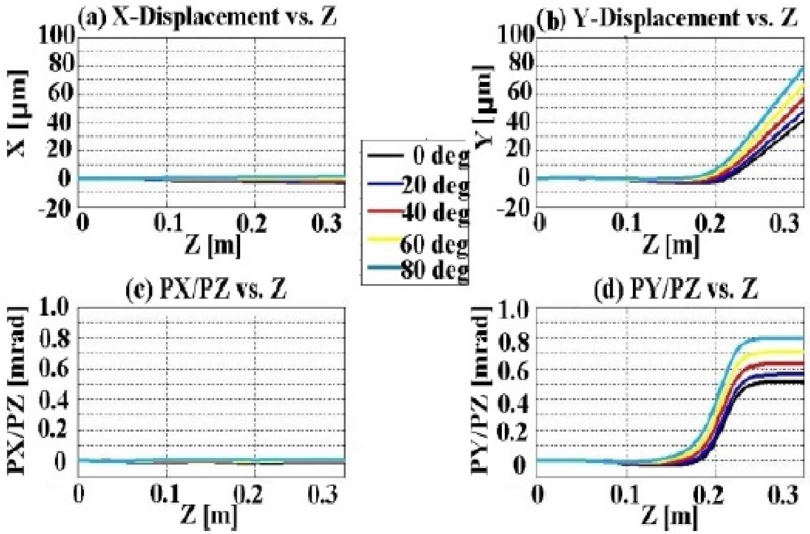


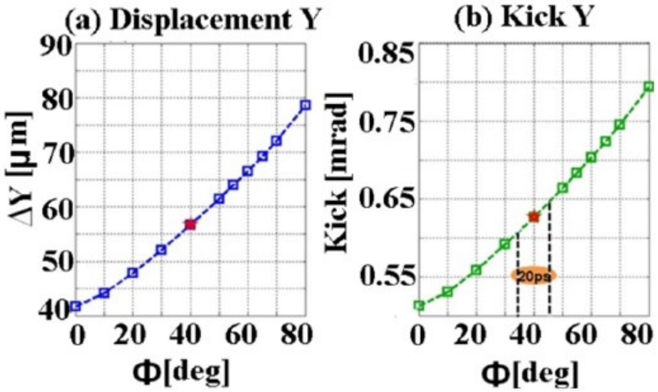
Figure 1: Sketch of the PITZ gun with coaxial RF coupler: 1-gun cavity, 2-door-knob transition, 3-cavity axis, 4-RF feeding direction, 5-main solenoid, 6-bucking solenoid, 7-cathode, 8-end of coaxial line and 9-reference position of WG port for simulations. Note that this sketch is rotated by 90 degrees compared to the computational model used in the follow-up simulations.

Beam centroid tracking using field map



- Field calculation done under optimum operation condition of the gun (mini.S11 by adjusting inner conductor length)
- 3D field map used for later particle tracking simulations
- RF dynamics → no solenoids, no space charge *Y. Chen et al.,FEL2017 proceedings, WEP005*

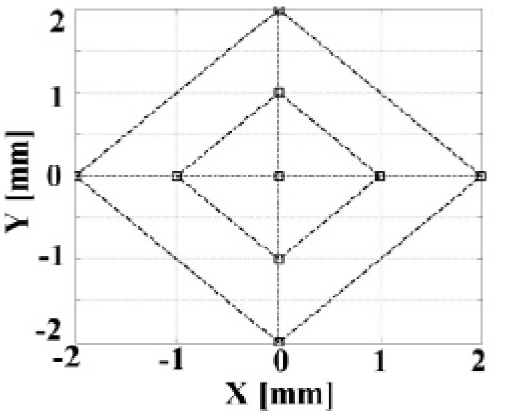
Vertical displacement at z = 0.3 m and kick strength as a function of the gun phase



Updates on coupler RF kick studies (no solenoids)

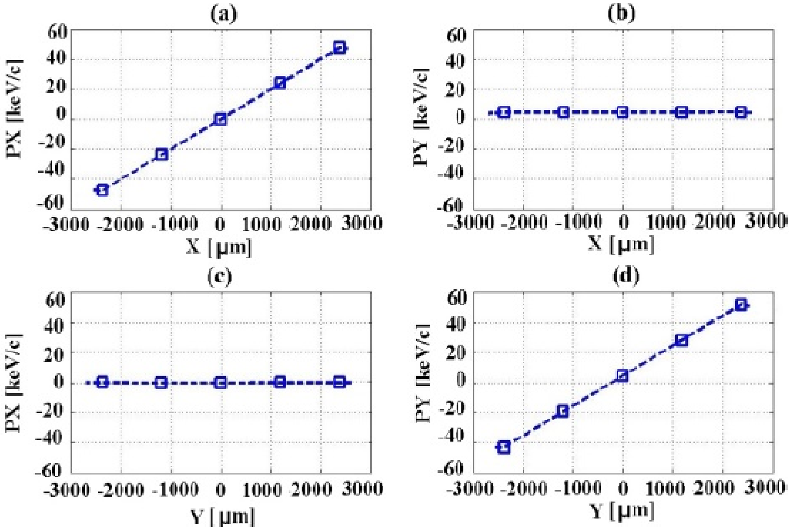
> Kick quantification

Beam centroid positions on cathode plane



- Using field map tracking a set of particles on the cathode plane though kick region till door-knob transition region

Particle tracking simulation results for multipole expansion based quantification of the integral kick



- Fitting multipole expansion form of the integral kick using simulation results

Multipole expansion of the integral kick

$$P_X = P_{0x} + (K_{RF} + K_N)X + K_S Y$$

$$P_Y = P_{0y} + (K_{RF} - K_N)Y + K_S X$$

X, Y: particle offsets from the axis at the location of the integral kick
P_X, P_Y: particle transverse momenta in the horizontal and vertical direction
P_{ox}, P_{oy}: horizontal and vertical dipole kicks
K_{RF}: RF focusing strength of cylindrical symmetric mode
K_N and K_s: normal and skew quadrupole kick strength

✓ **Vertical dipole kick~4.576 keV/c, time dependent**

✓ **Quadrupole kick strength estimation**

- Normal quadrupole component ~1.0e-5 keV/c/μm
- Skew quadrupole component~5.0e-6 keV/c/μm

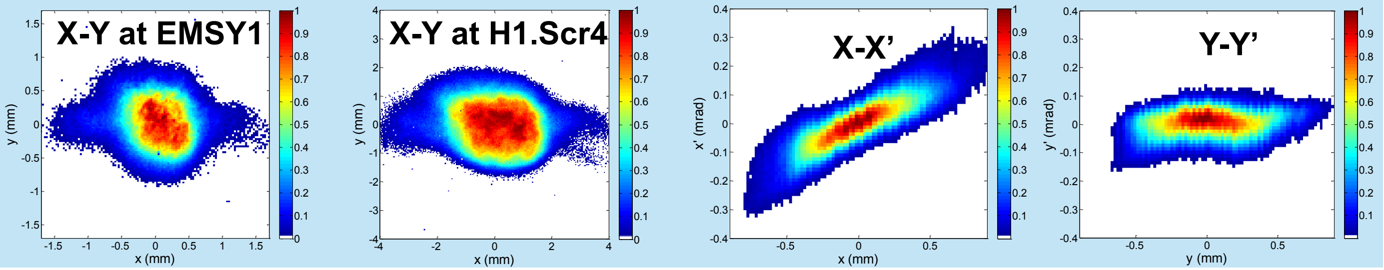
✓ **(20-ps) Bunch tail sees higher kick strength than the head by 0.05 mrad @ 6.5MW**

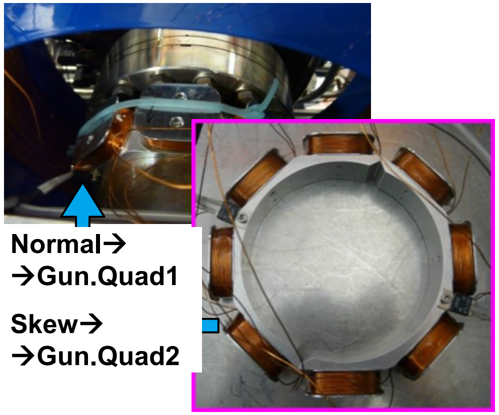
Electron beam X-Y asymmetry compensation with gun quads

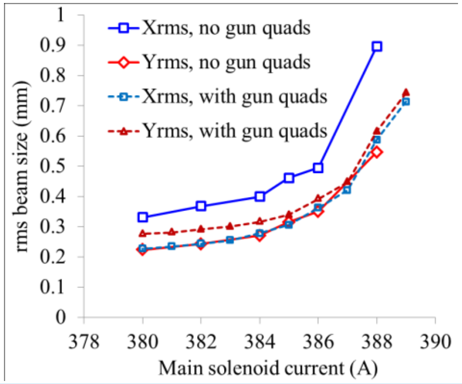
measured

(0.5nC, Gaussian photocathode laser pulse)

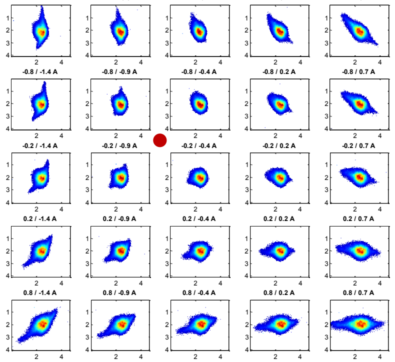
Electron beam measurements without gun quadrupoles

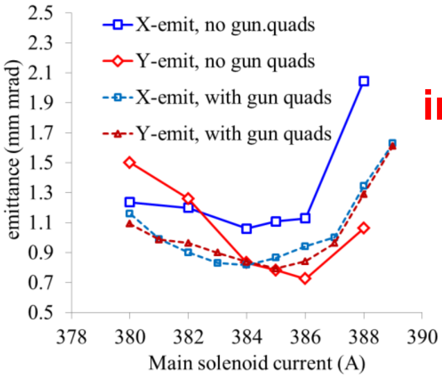






$(I_{Gun.Quad1}; I_{Gun.Quad2})$ scan at EMSY1



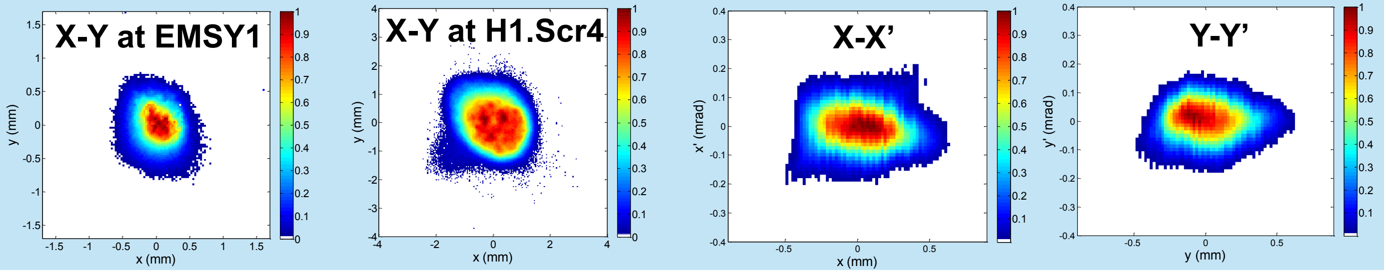


Gun quads copy installed at EXFEL and prepared for FLASH

	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**

Electron beam measurements with gun quadrupoles

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



M. Krasilnikov et al.,FEL2017 proceedings, WEP007

Summary

- Further **photoemission modeling** towards **quantum mechanics** with the presence of **strong space charge densities** at cathode surface
  - current status
  - further modeling approaches

- Coax **coupler RF kick** characterized and quantified under **optimized operation** conditions of the gun
  - **Time dependent vertical dipole kick**, ~0.65 mrad (MMMG phase, 6.5MW)
  - Small quadrupole kick estimated

- **Beam asymmetry compensation** with gun quadrupoles optimization
  - Promising results → "**round beam, round emittance**"

Thank you very much!

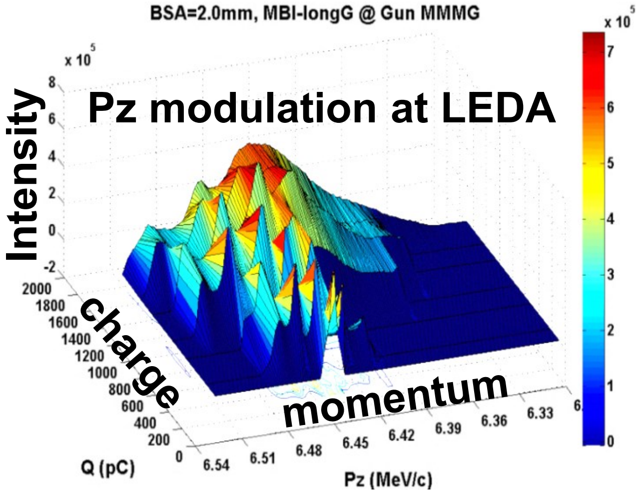
Backup: Updates on "Pz modulation" studies

See: M. Krasilnikov, DESY-TEMF-Meeting, 01.2017

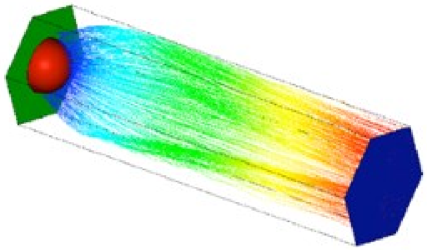
> (?)Cathode laser temporal profile

- Long Gaussian (11-11.5ps FWHM, Lyot filter in) →Pz modulation observed
- Short Gaussian (~2ps FWHM, Lyot filter out) → not yet observed

→ Lyot filter, the source of modulation?



> (?)Emission mechanism

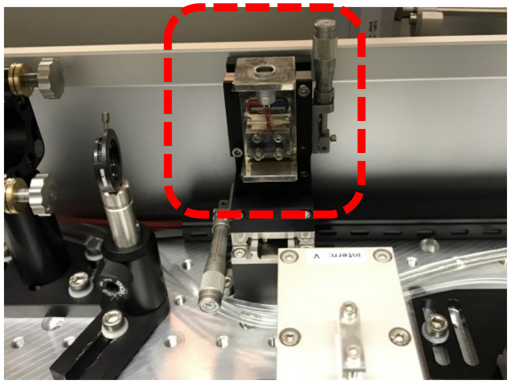


Emitted charge → fields on surface that affects subsequent emissions

→ "oscillations induced by a sudden influx of charge can persist".

Demonstration for Cu and Cs_3Sb using MICHELLE

- *J.J. Petillo et al., IEE trans. Electron Devices 52, 742 (2005)*
- *K.L. Jensen et al., J.Vac.Sci. Technol. 26 (2), 831 (2008)*



Lyot filter in the regenerative amplifier