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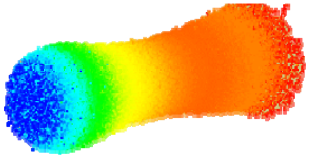
Electron Emission Studies Using Enhanced QE Models

DESY-TEMF Collaboration Meeting
S2/17 • R 114 • TEMF • Darmstadt
24.06.2016



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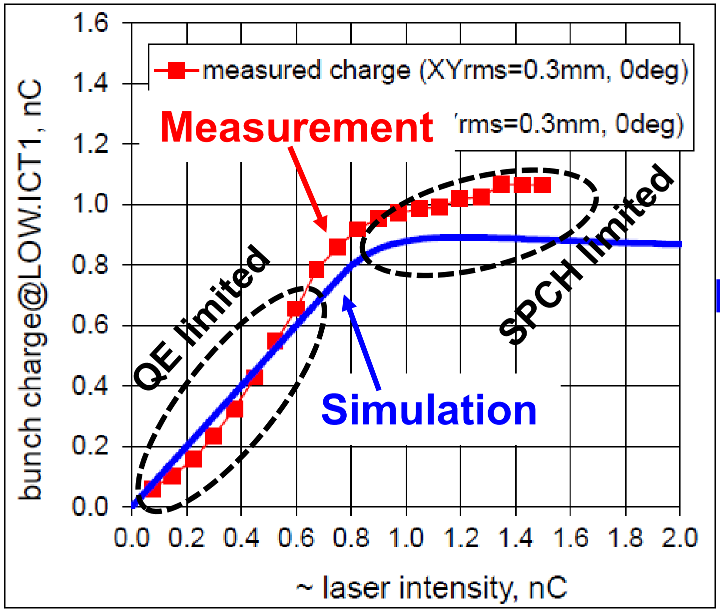
- Motivation
- Beam dynamics codes
- Photocathode QE model(s)
- Dynamic charge production in QE limited regime
- Effects in space-charge dominated regime
- Summary and Outlook

Motivation

1. **To understand measurement vs. simulation discrepancies for PITZ***
   - Discrepancies in total bunch charge
2. **To improve beam dynamics codes for emission studies**
   - Conventional PIC/PP models: direct charge production not possible
   - Cathode phenomenon due to fields and driving laser pulses not modeled



Charge vs. Laser Intensity

Introducing modified QE models (interfaces) to beam dynamics simulations

***M. Krasilnikov, Motivation of emission studies at PITZ, DESY, 06.2015**

Beam dynamics codes

❖ 3D Lienard-Wiechert (LW) PP code [1] → Implementation of QE models

- Exact LW field solution for relativistic charged particles
- No geometry (except for cathode)
- Numerically expensive (full particle history stored)

❖ Uniform Motion Average Frame (UMAF) PP code & ASTRA PIC code [2]

- Average rest beam frame (ASTRA / PARMELA type)
- No retardation or acceleration
- Numerically more efficient

❖ 3D CST Particle Studio (CST PS) PIC solver [3]

- Full-wave codes, full geometry
- Less efficient in 3D: not applicable for long accelerator structures

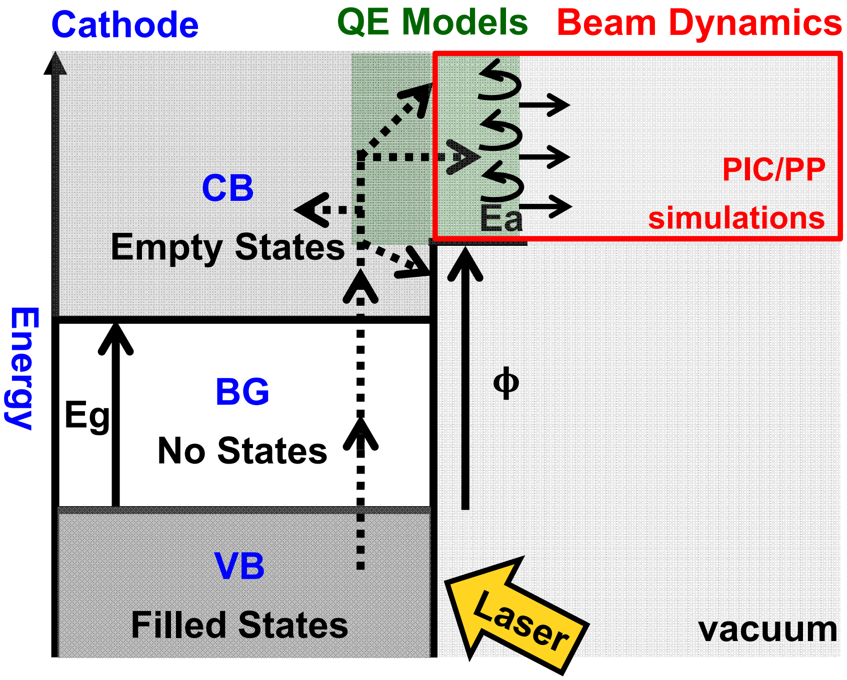
Demonstration of results

[1] E. Gjonaj, DESY/TEMF collaboration meeting, Hamburg, 2011.

[2] K. Floettmann, ASTRA particle tracking code [http://www.desy.de/~mpyflo/].

[3] Computer Simulation Technology, www.cst.de.

Dynamic beam generation



Band structure sketch and QE interface between cathode and vacuum

- Cathode performance → Quantum Efficiency (QE)
- QE → work function $\boldsymbol{\phi}$ (energy)
- Modifications of $\boldsymbol{\phi}$
  → surface barrier reduction $\boldsymbol{\Delta\phi_{sch}}$ → field effect
  → plasma work function $\boldsymbol{\Delta\phi_{p}}$ → laser effect
- Cathode field, $\boldsymbol{E_{cath}(r,t)}$
  → **time and space dependent**
  → 3D full relativistic RF + space-charge fields
- Driving laser pulse, $\boldsymbol{I(r,t)}$
  → **time and space dependent**
  → beam halo and electron-hole plasma
- **Dynamic beam generation**

Theoretical QE forms ⇨

(Semi-) Analytical QE models

- **Based on Spicer's 3-step theory[4]**
  1. Photoexcitation
  2. Transport to surface
  3. Escape to vacuum

  → **simple formulas for QE**

- **QE models**
  - **For metals:** Fowler-Du Bridge model[5]
  - **For semiconductors:** Spicer's and Jensen's[4,6]

- **Spicer's semiconductor model**

Given laser intensity $I(l, h\nu)$, l: penetration depth,

Photoemission current

$$\boxed{i(h\nu)d(h\nu) = \int_0^l \alpha(h\nu)\, I(l, h\nu) P(l, h\nu)\, dl\, d(h\nu)}$$

Absorption coefficient, $\alpha(h\nu)$ **Escape probability, $P(l, h\nu)$**

$$\boxed{QE_{spicer} = \frac{B}{1 + g(h\nu - \phi)^{-m}}}$$

B → emission probability, form factor
g → absorption factor
Exponent index, m = 1.5 (experimental)
Material work function, ϕ = Eg + Ea

(Semi-) Analytical QE models

- **Kevin L. Jensen's semiconductor model** [6]

$$QE = \underbrace{\frac{1}{2}(1-R_w)}_{\textbf{absorption}}\left\{\frac{8}{y^4}\int_1^y x^3 \underbrace{\left(\int_{\frac{1}{x}}^1 s f_\lambda(s, E_a x^2)\,ds\right)}_{\textbf{weighted scattering fraction}} dx\right\} \underbrace{\sqrt{1+\frac{\Delta E}{E_a}}}_{\textbf{escape probability}}$$

For small ΔE (near threshold), a simplified form:

$$\boxed{QE_{Jensen} = \frac{1-R_w}{2}\left[\frac{1}{(p_0+1)\left(1+\frac{E_a}{\Delta E}\right)^2}\right]\sqrt{1+\frac{\Delta E}{E_a}}}$$

$\Delta E = h\nu - (E_g + E_a)$

E_g: band gap, E_a: electron affinity

R_w: reflection factor

p_0: form factor, ratio of penetration depth to distance between two events

For Cs_2Te photocathodes

$E_g = 3.3\ \mathrm{eV}$

$E_a = 0.2\ \mathrm{eV}$

$h\nu = 4.81\ \mathrm{eV}$ at 257 nm

Model implementation

$$QE = \frac{B}{1 + g(h\nu - \phi)^{-1.5}}$$ (Spicer's)

$$QE = \frac{1}{2}(1 - R_w)\left[\frac{1}{(p_0 + 1)\left(1 + \frac{E_a}{\Delta E}\right)^2}\right]\sqrt{1 + \frac{\Delta E}{E_a}}$$ (Jensen's)

$$QE = \eta(h\nu - \phi)^2$$ (Fowler-Dubridge model)

QE forms:

1> Power law different

2> Interpretation of modeling theory different

Performances in charge production

→ see simulation results

QE modifications

- Modified cathode work function

$$\phi = E_g + E_a - \Delta\phi_{sch} + \Delta\phi_p$$

$$\Delta E = h\nu - \phi$$

- Surface potential reduction (Schottky)

$$\Delta\phi_{sch}(r,t) = \sqrt{\frac{e^3}{4\pi\varepsilon_0}E_{cath}(r,t)}$$

- Relativistic full cathode field on-the-fly

$$E_{cath}(r,t) = E_{rf}(r,t) + E_{spch}(r,t)$$

- Plasma work function (experimental)

$$\Delta\phi_p = \alpha * [I(r,t)]^{1/2}$$

I → laser intensity, α → material property constant [7]

- Edge-halo in transverse laser profile [8]

$$W_l(r, R_c, \sigma) \sim \exp\left(\frac{R_c^2 - r^2}{2 * \sigma^2}\right)$$

- Linear modification of initial energy (E_{p1}=4.05eV for Cs2Te)

$$E_{kin} = E_{p1} - \phi$$

Model implementation

- **Total bunch charge produced at the cathode**

$$\Delta E = h\nu - \left(E_g + E_a - \sqrt{\frac{e^3}{4\pi\varepsilon_0}\left[E_{rf}(r,t) + E_{spch}(r,t)\right]} + \alpha\big(I(r,t)\big)^{1/2} \right)$$

$$QE(r,t) = \frac{1}{A\left(1+\frac{E_a}{\Delta E}\right)^2}\sqrt{1+\frac{\Delta E}{E_a}}$$

QE varies with time and space

Cathode characterization needed

$$Q(r,t) = \int_0^t \iint_S e\,\frac{P_{laser}(r,\tau)W_l(r,R_c,\sigma)}{h\nu}\,QE(r,\tau)\,d^2r\,d\tau$$

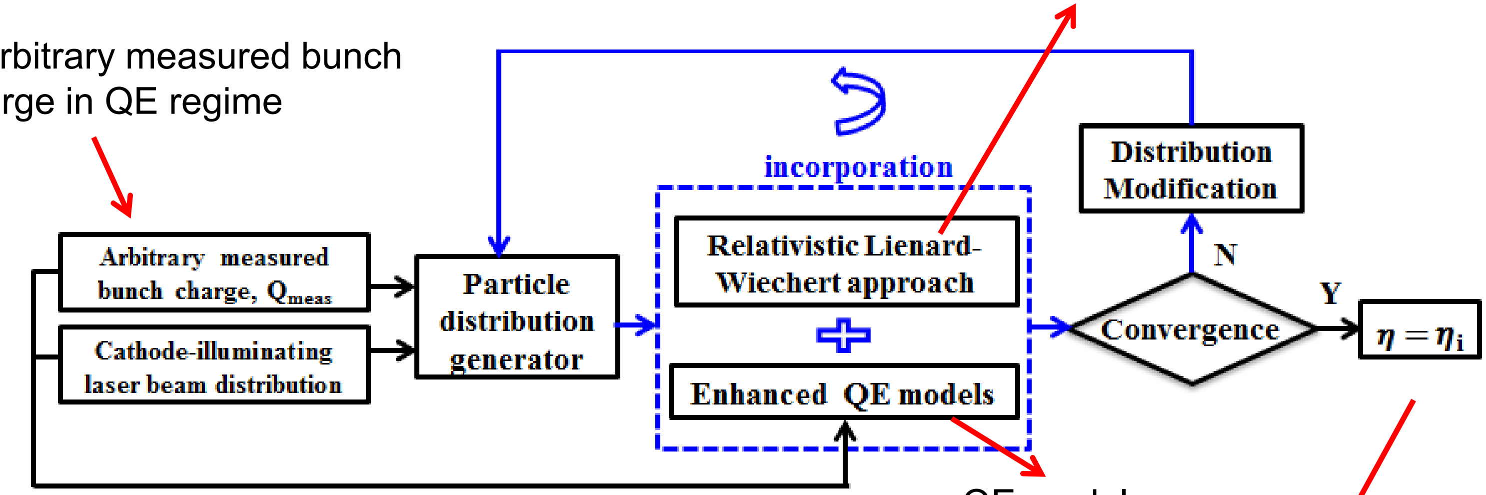
Beam generation using full dynamic fields

Model implementation

- **Cathode form factor determination**

Using an arbitrary measured bunch charge in QE regime

Beam dynamics codes



Arbitrary measured bunch charge, Q_{meas}

Cathode-illuminating laser beam distribution

Particle distribution generator

incorporation

Relativistic Lienard-Wiechert approach

+

Enhanced QE models

Convergence

N

Distribution Modification

Y

$\eta = \eta_i$

QE models

Used as an input parameter for simulations involving different beam and gun parameters

Consistent form factors found

Model implementation

- cathode characterization for the PITZ gun[9,10]

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No.	Laser Profile	RF Power	E_{laser}	Form factor
1	GS	1.5 MW	8.22 nJ	**0.0477**
2			16.32 nJ	**0.0456**
3			24.79 nJ	**0.0448**
4			32.23 nJ	**0.0432**
1	GS	1.5 MW	34.96 nJ	**0.002710**
2			63.35 nJ	**0.002608**
3			113.34 nJ	**0.002548**
4			163.08 nJ	**0.002451**
5			205.81 nJ	**0.002332**
6			252.65 nJ	**0.002371**
1	GS	1.5 MW	8.22 nJ	**9.0704**
2			16.32 nJ	**9.3736**
3			24.79 nJ	**9.5080**
4			32.23 nJ	**9.8863**

Cathode 1 (QE≈8.5%)

$\bar{\eta} \approx 0.0453$

relative error < 6%

Cathode 2 (QE≈0.6%)

$\bar{\eta} \approx 0.002503$

Fowler-Dubridge model

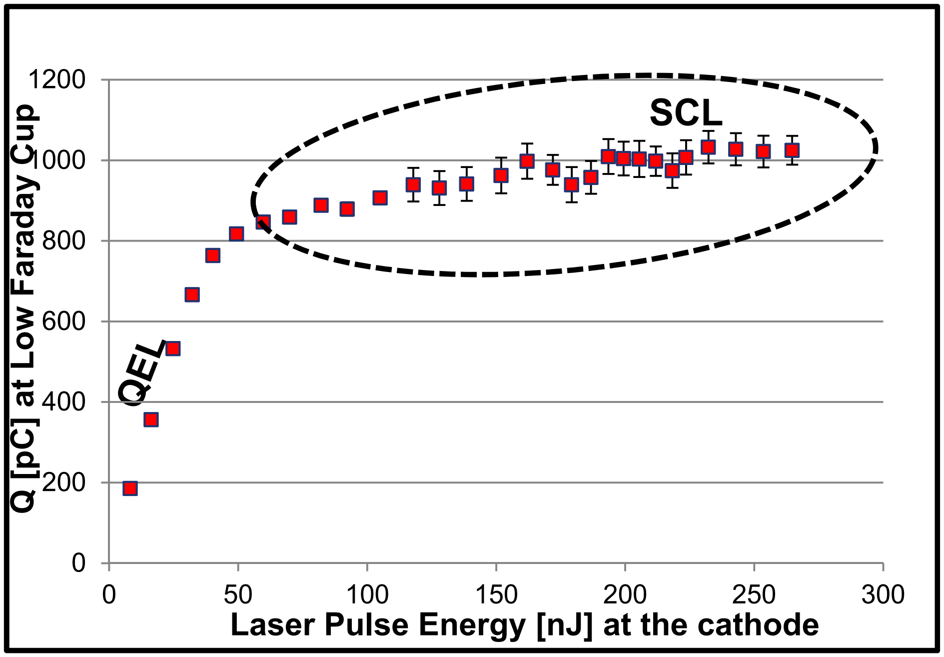
Cathode 1 (QE≈8.5%)

$p_0 \approx 9.4596$ →

Jensen's model

1. **Cathode form factors consistent for same cathode (models applicable)**
2. **Characterizations different for different QE models**

Simulations in SPCH dominated regime



1. **Comparisons with measurements**
   - For a fresh cathode (QE=~8.5%) and a worn cathode (QE=~0.6%)
   - Experimental conditions: Prf=1.5MW, BSA=1.8mm, temporal profile: short Gaussian 1.5ps rms

2. **Comparisons between enhanced QE models**
   - Fowler-Du Bridge model (metals)
   - Spicer’s model (semi)
   - Jensen’s model (semi)

3. **Comparisons between numerical approaches**
   - UMAF PP
   - LW PP
   - CST PS PIC
   - ASTRA PIC

Simulations in SPCH dominated regime

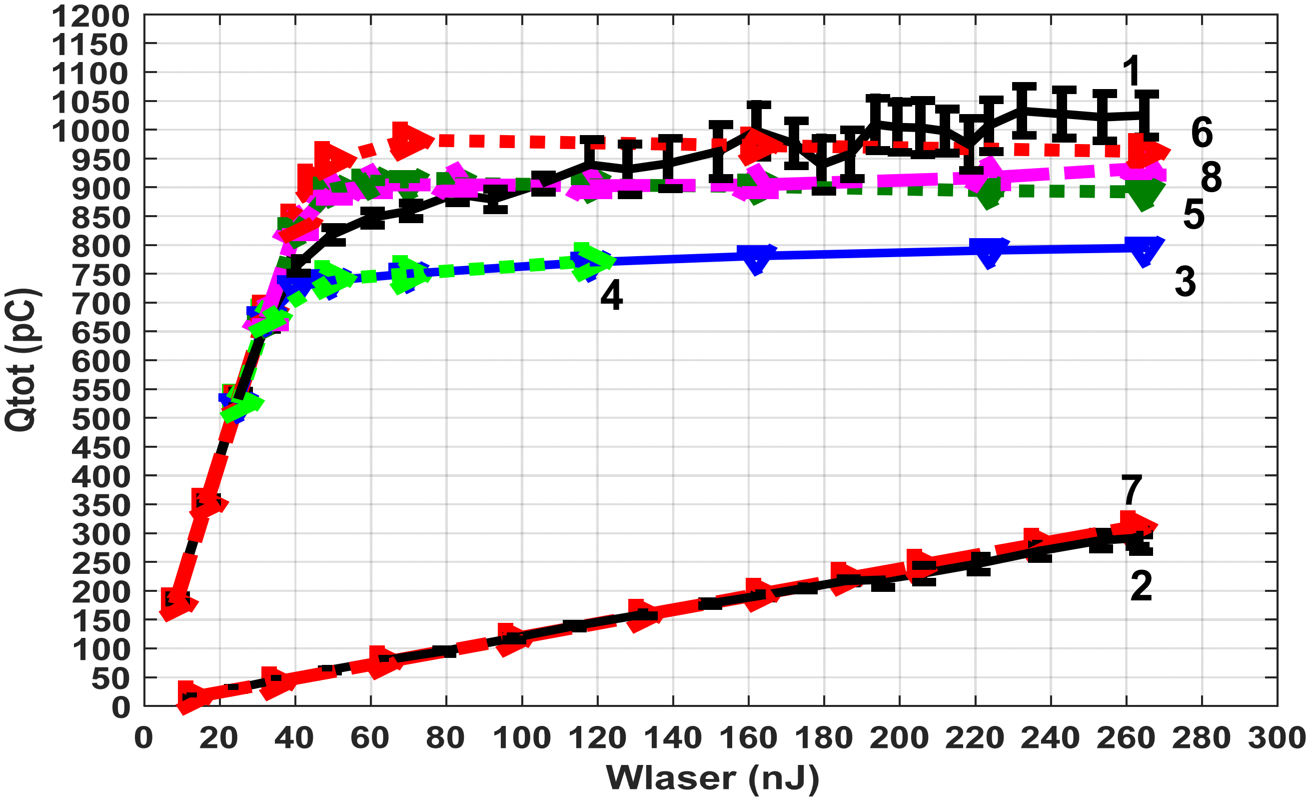
- comparisons between numerical approaches

- Using radial uniform distributions
- With or without Fowler-Dubridge model

4 vs. 5
→ both UMAF
→ using QE model better, 5

5 vs. 6
→ both using same QE
→ full EM better, 6

6 vs. 8
→ both full EM
→ using QE model better, 6



1	▬ ▬ ▬	Measurements, "fresh" cathode, top curve	5	▬ ▬ ▬	UMAF PP simulations with F-DB model
2	▬ ▬ ▬	Measurements, "worn" cathode, bottom curve	6	▬ ▬ ▬	LW simulations with F-DB model, fresh cathode
3	▬ ▬ ▬	ASTRA simulations	7	▬ ▬ ▬	LW simulations with F-DB model, worn cathode
4	▬ ▬ ▬	UMAF PP simulations	8	▬ ▬ ▬	CST PS PIC simulations

Simulations in SPCH dominated regime
- comparisons between enhanced QE models

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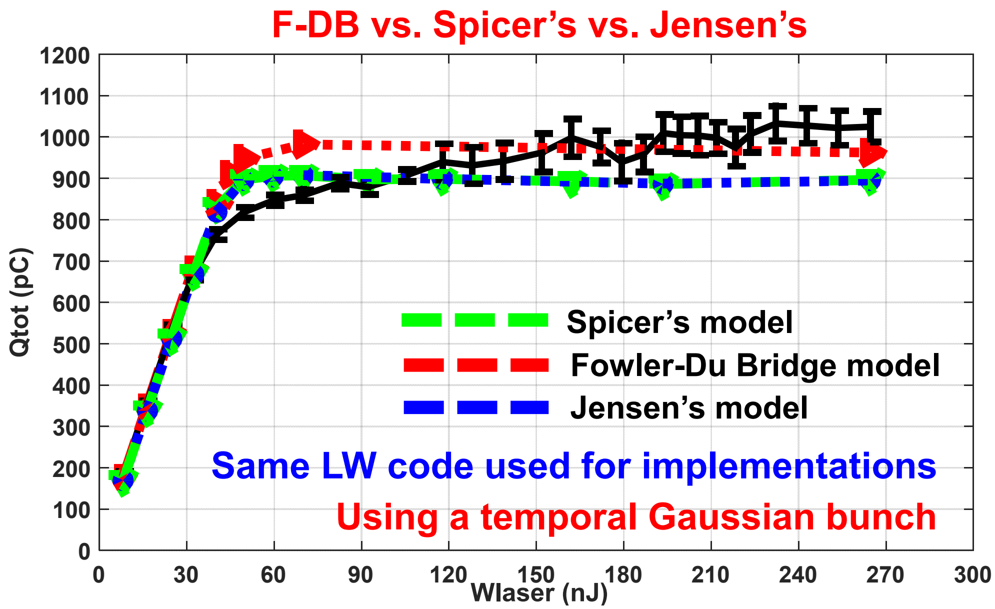
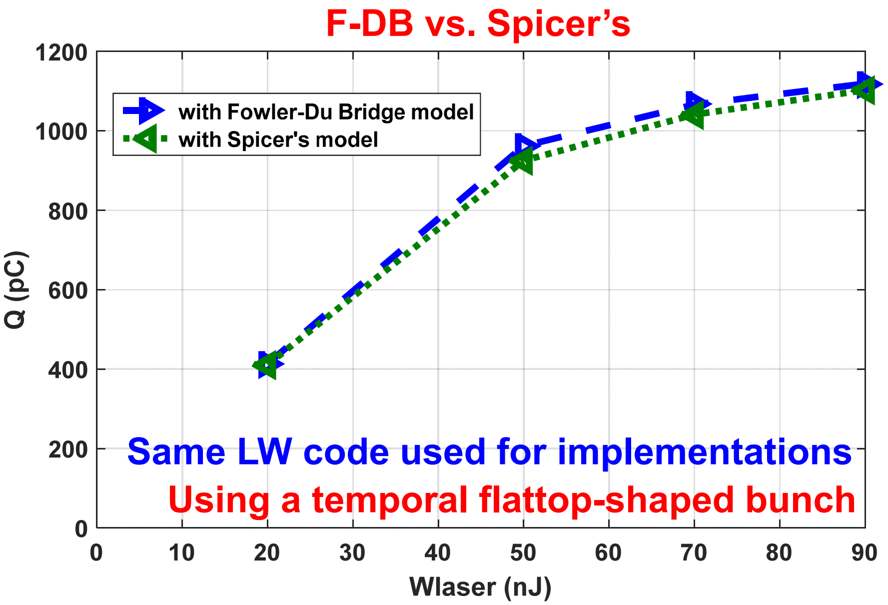

F-DB vs. Spicer's vs. Jensen's

Same LW code used for implementations

Using a temporal Gaussian bunch


F-DB vs. Spicer's

Same LW code used for implementations

Using a temporal flattop-shaped bunch

Spicer's vs. Jensen's

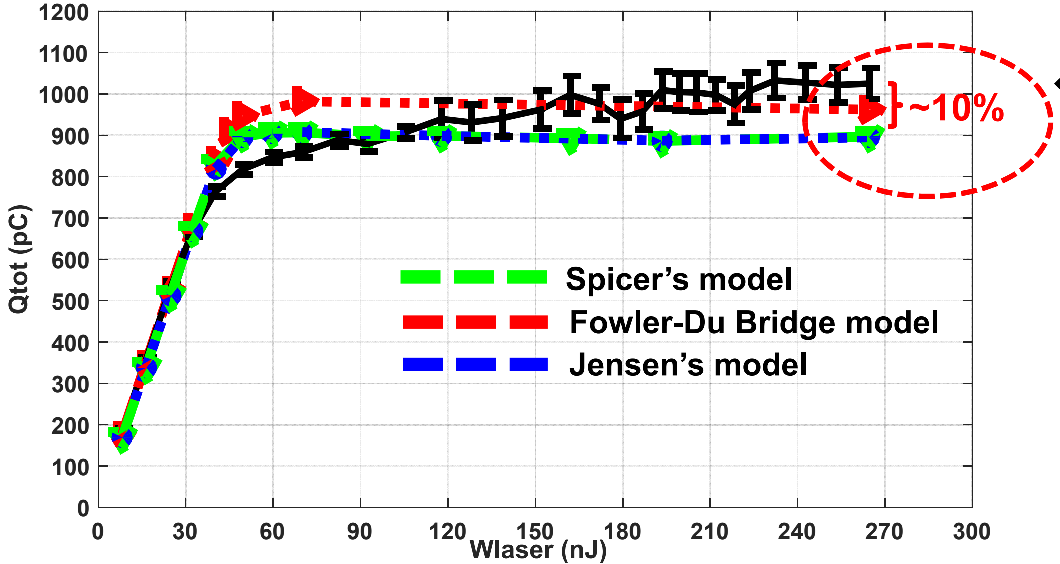
→ both for semiconductors and threshold emission
→ using same code for implementation
→ good agreements, blue and green (left figure)

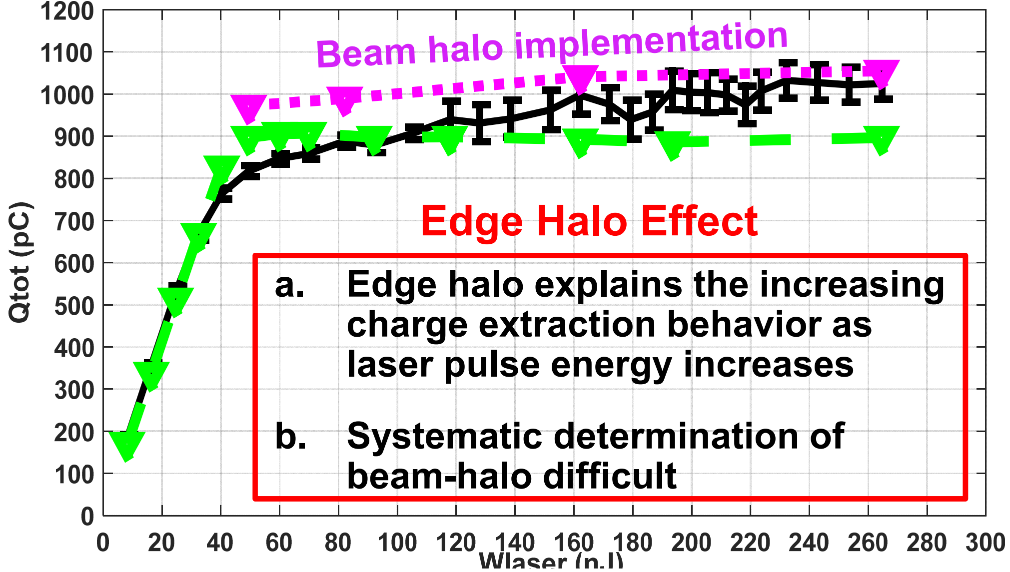
F-DB vs. Spicer's

→ Cathode characterizations different
→ Using different form factors, measurements reproduced in QE regime
→ In SPCH regime
  → F-DB gives slightly higher charges for GS bunches
  → Performances similar for FT bunches (right figure)

Effects in SPCH dominated regime

-"edge halo effect"





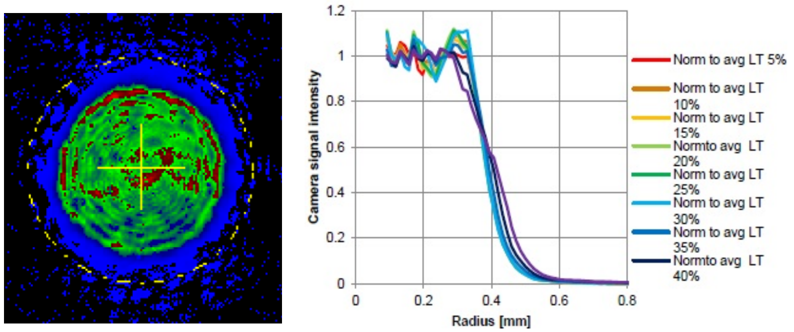
Edge Halo Effect

a. Edge halo explains the increasing charge extraction behavior as laser pulse energy increases

b. Systematic determination of beam-halo difficult

- ❖ Slight increasing behavior in SPCH regime → induced edge halo in the transverse laser distribution

Laser spot on virtual cathode



- ❖ Beam-halo model of PITZ[8] used for implementation (Rc~0.9 mm, S_g~0.25) with LW approach and Spicer's model

Effects in SPCH dominated regime

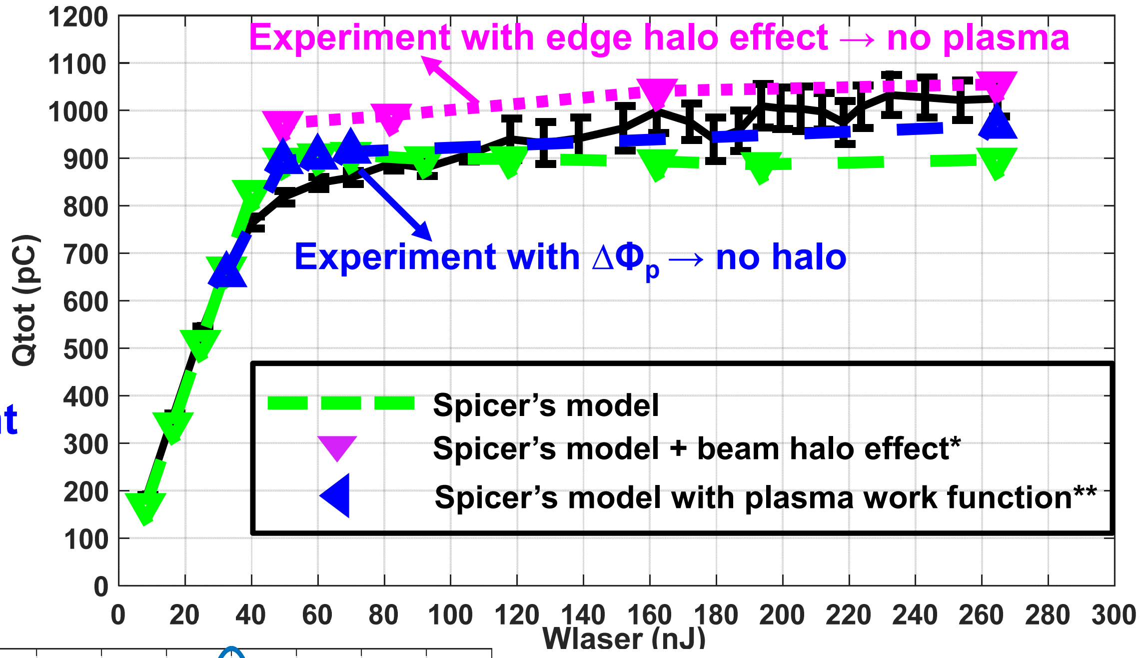
-"plasma work function"

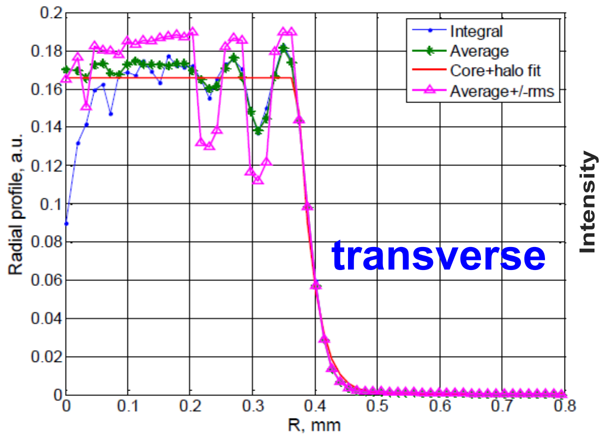
- **Laser-induced plasma work function****
  a. Work function increased by high laser intensity induced plasma

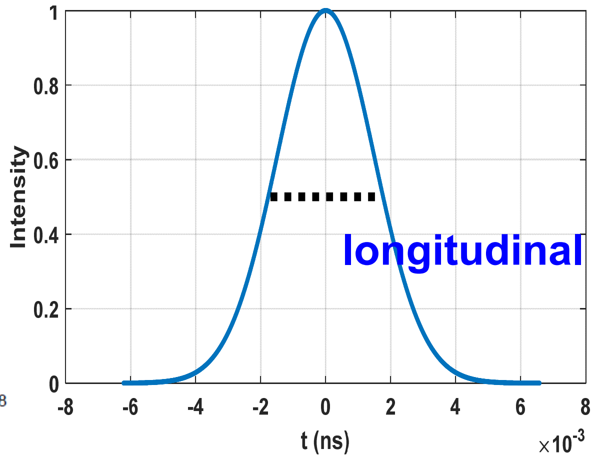
  b. $\Delta\phi_p \sim \alpha * [\, I(r,t)\,]^{1/2}$

  ⟶ **time and space dependent**

  I → laser intensity, α → material property constant







⟶ **Combined effect?**

*M. Krasilnikov, Emission (re-) measurements at PITZ, 2015

**Max Zolotorev, SLAC-PUB-5896, 09.1992

Summary and Outlook

1. **Incorporation of QE models with beam dynamics codes for emission modeling**

2. **Current status**
    - Simulation tool for emission studies
        - Multiple particle field computation approaches developed
        - Various emission models implemented
        - Relevant field and laser effects modeled
    - Emission studies performed for PITZ using proposed method
        - QE models enhances emission
        - Full EM implementation enhances emission

3. **Remaining problem**
    - Discrepancy in the transition area (Q w.r.t. laser energy)

4. **Outlook and Discussion**
    - Edge-halo effect combined with plasma work function (?)
    - More comparisons with measurements for validation

Thank you for your attention!

References

1. E. Gjonaj, DESY/TEMF collaboration meeting, Hamburg, 2011.
2. Computer Simulation Technology, www.cst.de.
3. K. Floettmann, ASTRA particle tracking code www.desy.de.
4. W.E. Spicer, Phys. Rev. 112, 114 (1958).
5. L.A. DuBridge, Phys. Rev. 43, 0727 (1933).
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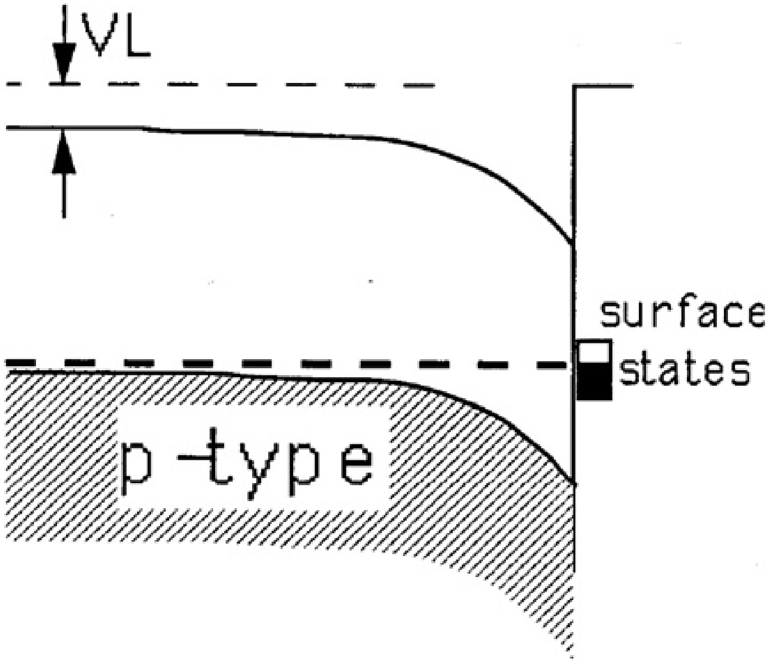
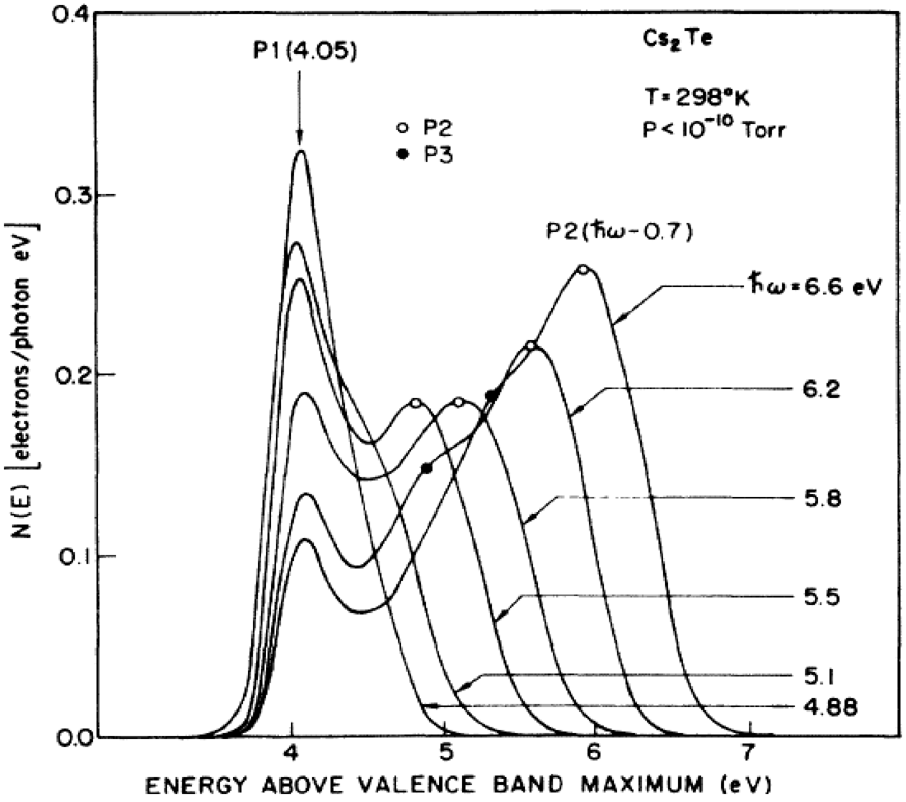
Backups



Band bending of p-type semiconductor



Final energy states of Cs_2Te