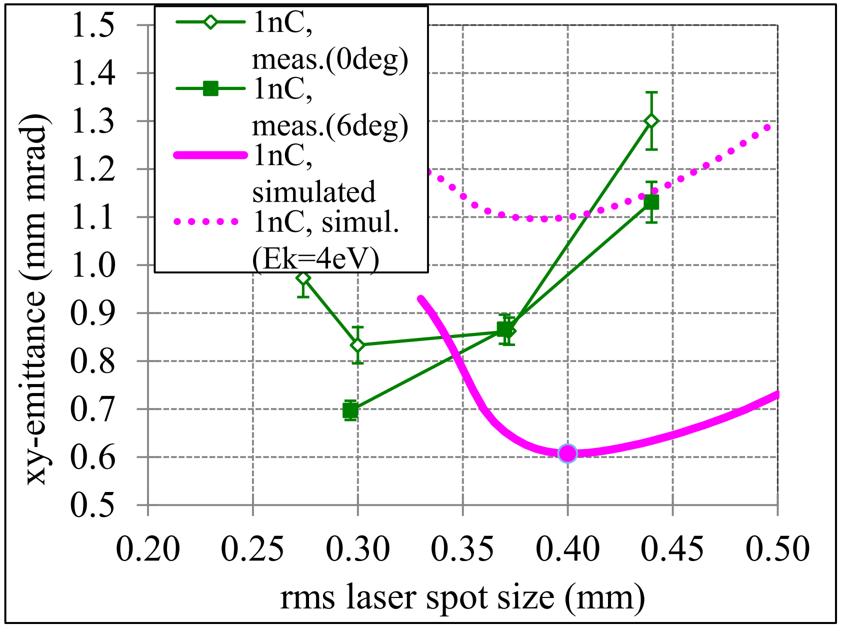
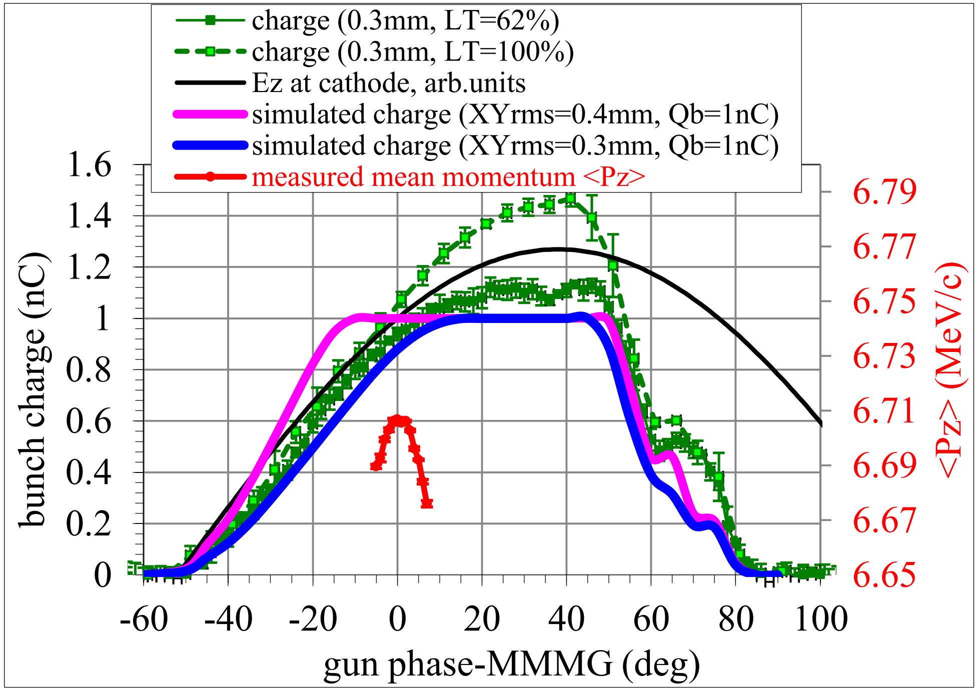
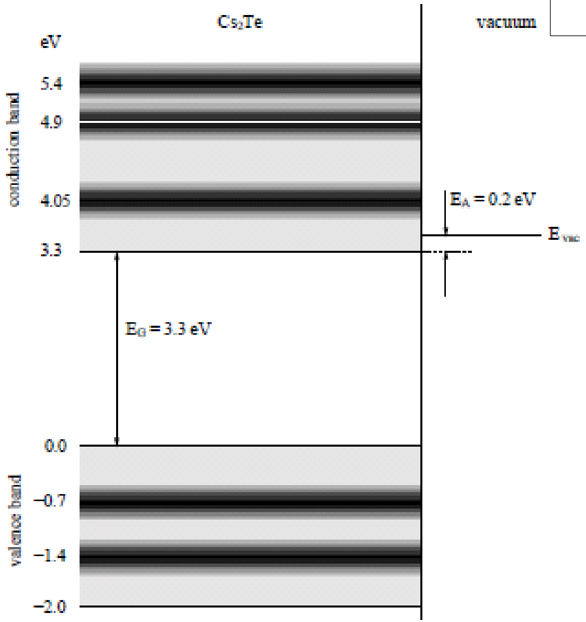
Photoemission studies at PITZ in February 2013

M.Krasilnikov

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

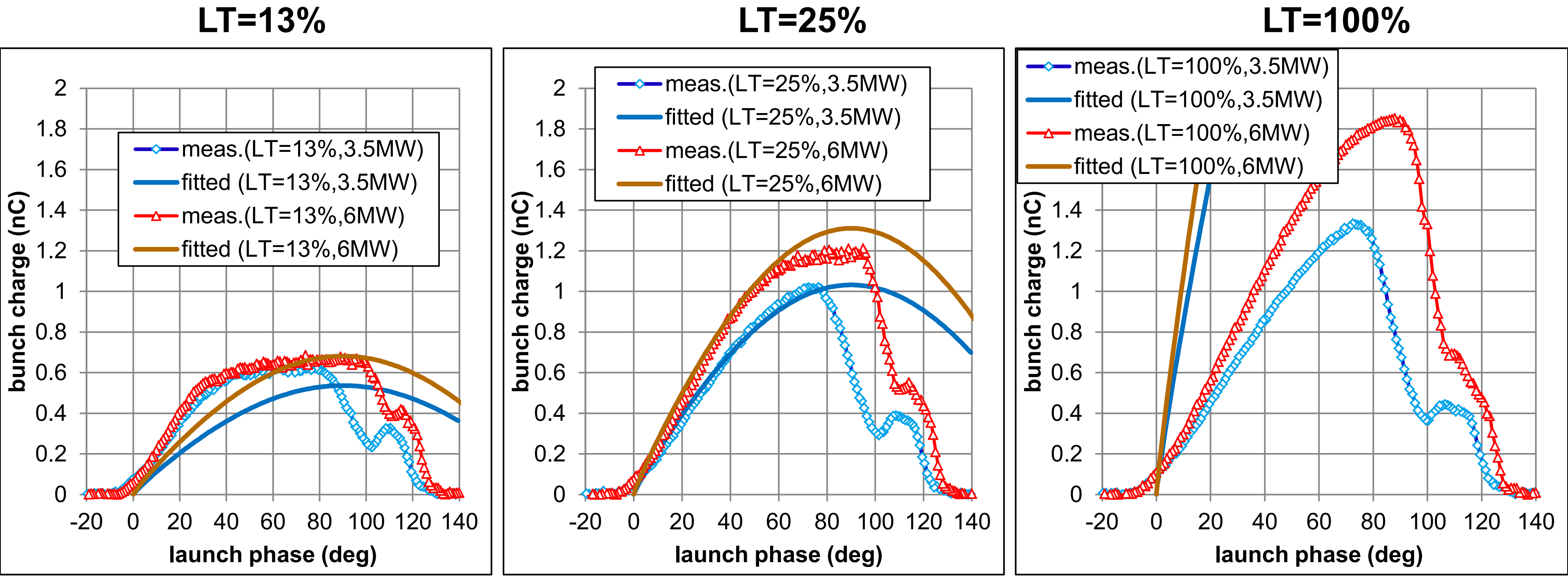
$$Q \propto \eta \cdot LT \cdot \left(1+b\sqrt{E}\right)^m$$

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

Emission studies: modeling → RF field

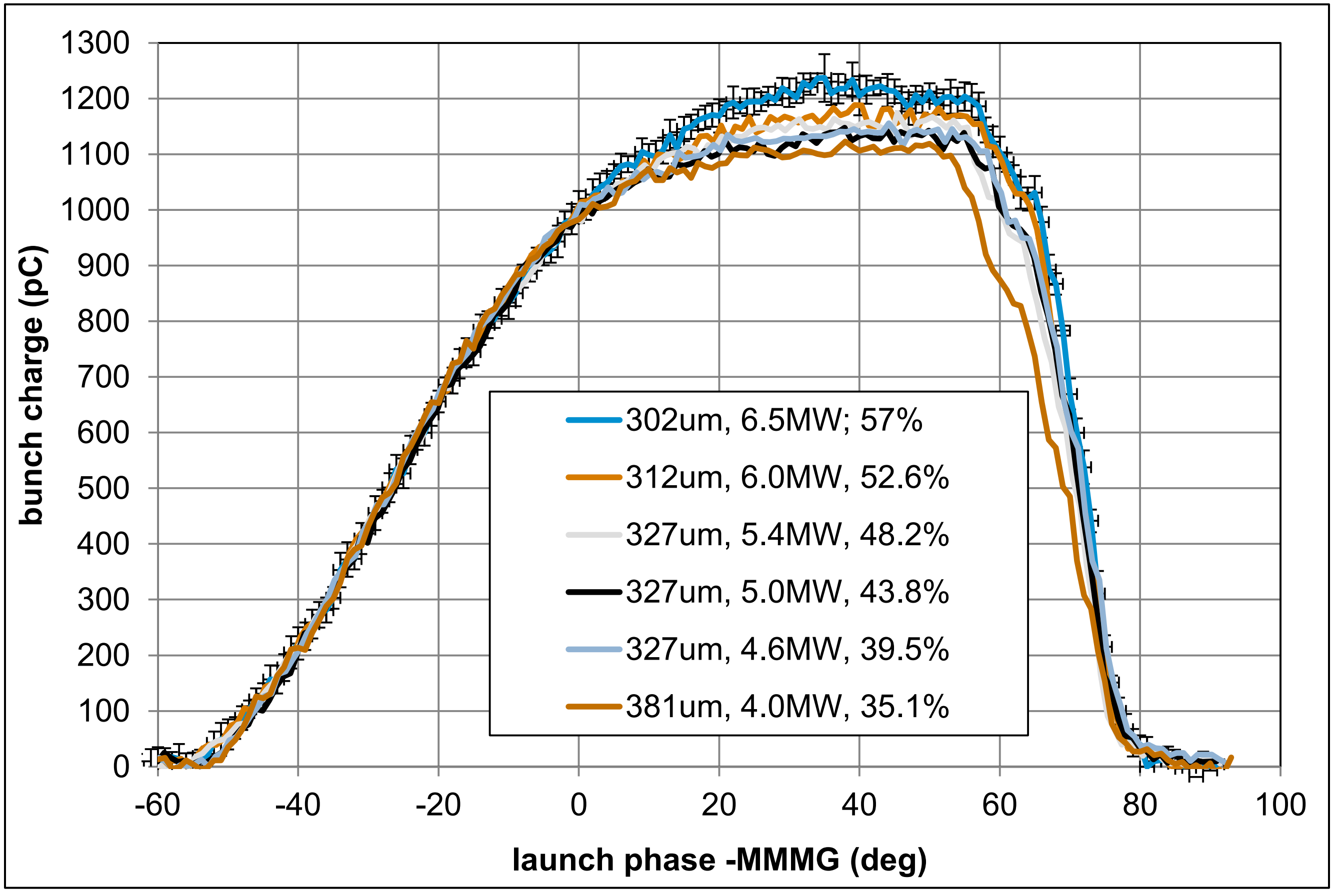
Simultaneous fitting (LT=13% and 25%):
Phase range: 10→70deg
$E = E_{cath} \cdot sin\varphi_0$
η=8.44E-8
b=205.9
m=1.805

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



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

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

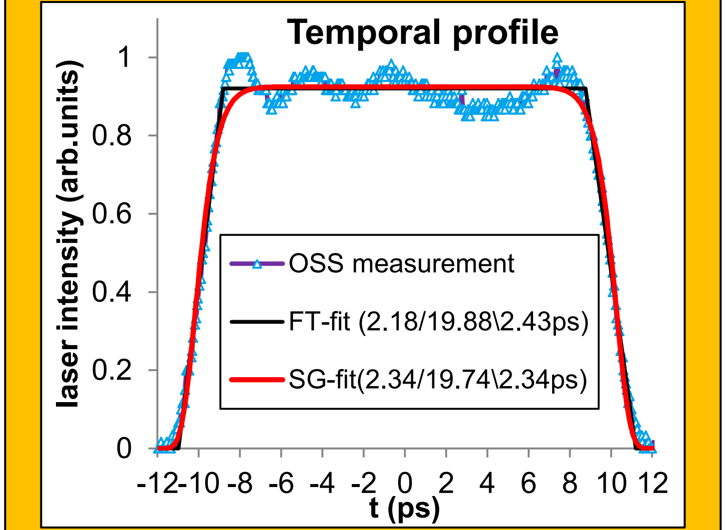
LT – laser transmission was always tuned to keep laser pulse energy constant

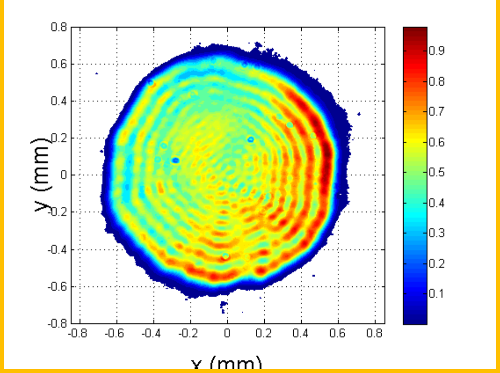
#	$P_{rf,gun}$, MW	σ_{xy}^{laser}, mm	LT, %	$\sqrt{P_{rf,gun}} \cdot \sigma_{xy}^{laser}$
1	**6.49**	**0.302**	57.0	**0.769**
2	**5.99**	**0.312**	52.6	**0.764**
3	**5.45**	**0.327**	48.2	**0.763**
4	**5.00**	**0.341**	43.8	**0.762**
5	**4.55**	**0.361**	39.5	**0.770**
6	**3.99**	**0.382**	35.1	**0.762**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

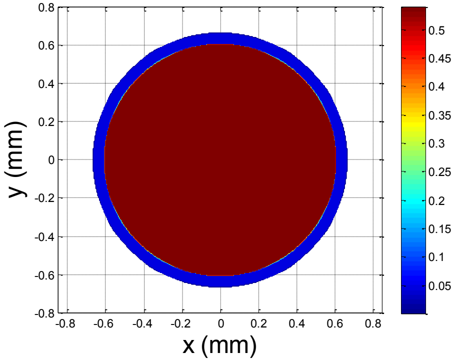
Emission studies: LT scans and ASTRA simulations

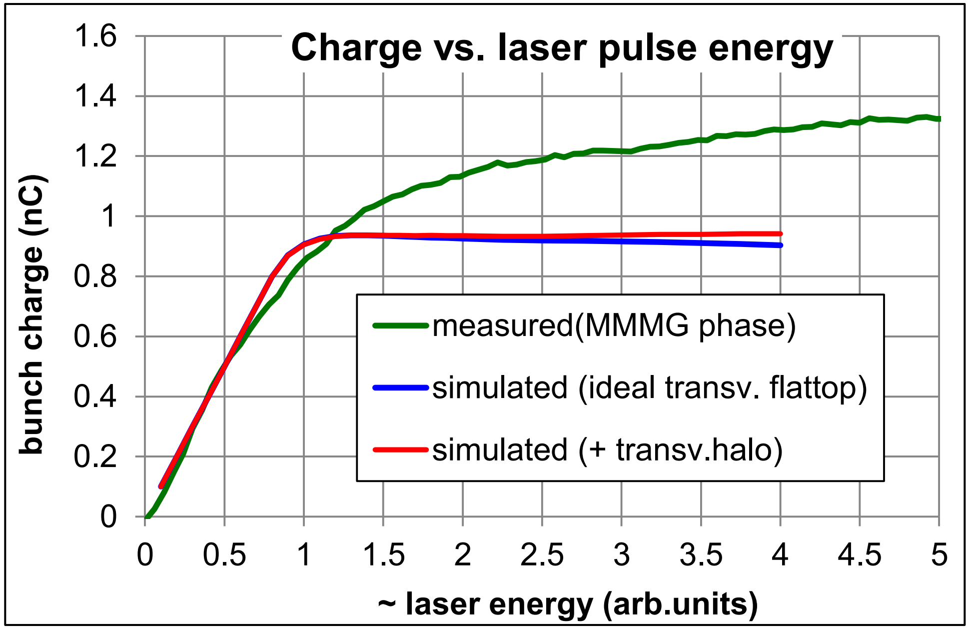
Measured cathode laser shapes





Transverse halo modeling in ASTRA





Rather small effect!

PITZ RF gun and photo cathode laser

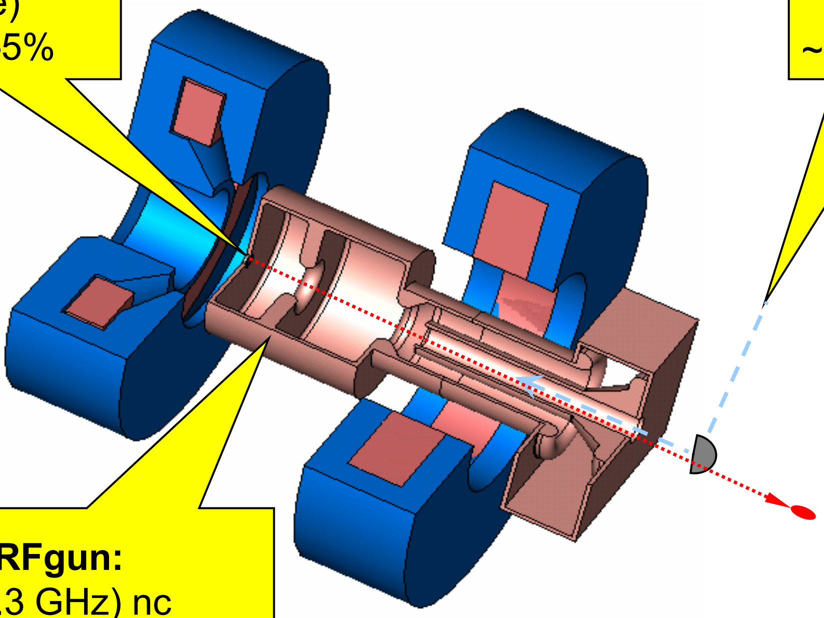


Photo cathode
(Cs_2Te)
QE~0.5-5%

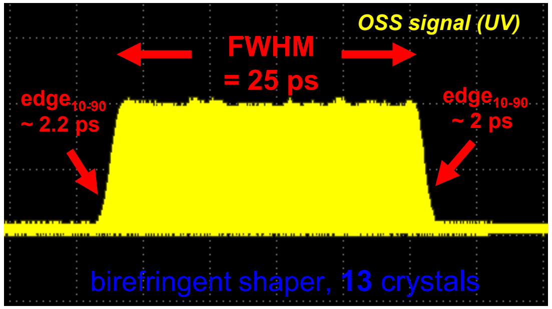
Cathode laser
257nm
~20ps (FWHM)

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

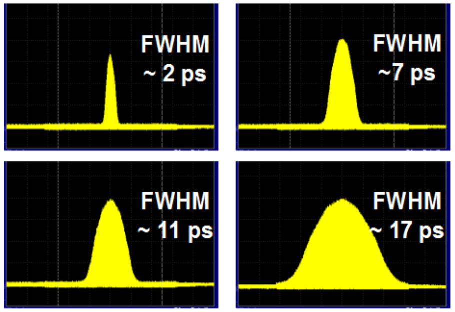
Peak rf power: up to 7MW
Ez@cathode: > 60MV/m

Temporal pulse shaper

Flattop

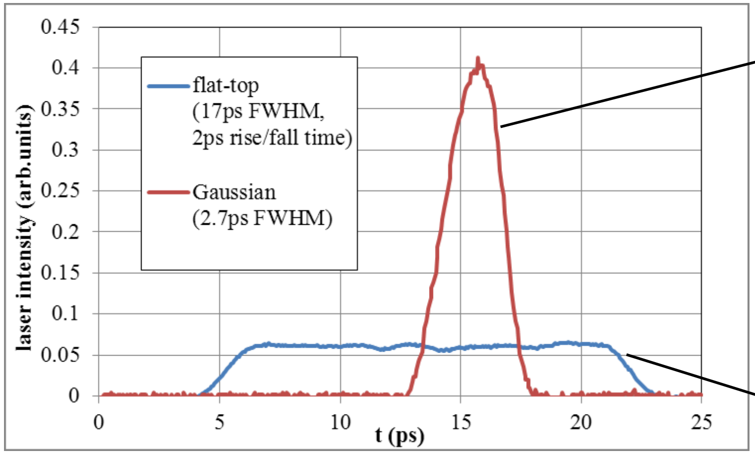


Gaussian:

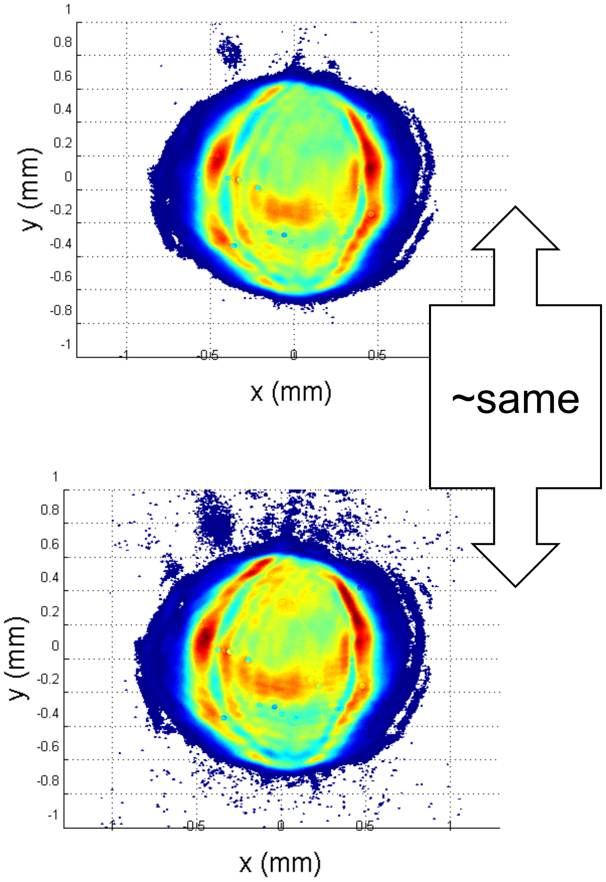


Emission G-FT program: main idea

Laser temporal profile

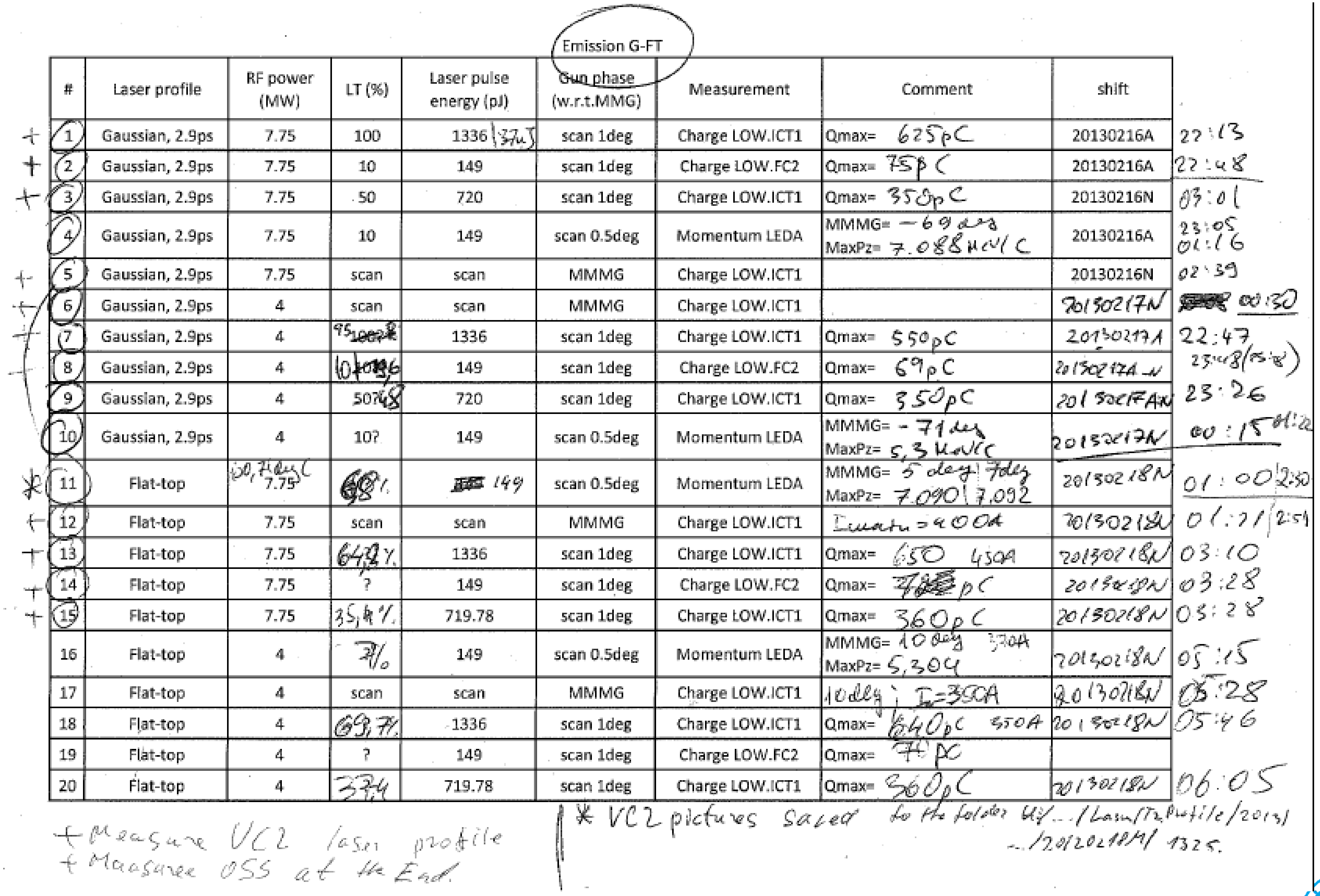


Laser transverse distribution



- 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

New measurements – Emission G-FT program
February 2013



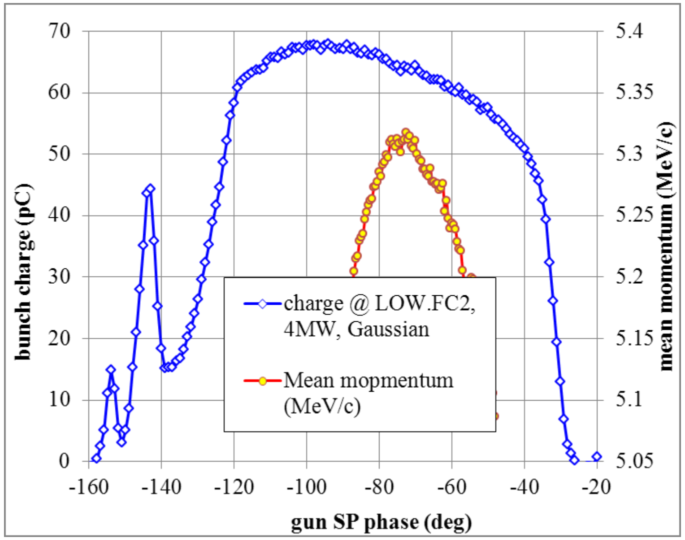
	#	Laser profile	RF power (MW)	LT (%)	Laser pulse energy (pJ)	Emission G-FT Gun phase (w.r.t.MMG)	Measurement	Comment	shift	
+	1	Gaussian, 2.9ps	7.75	100	1336 (37uJ)	scan 1deg	Charge LOW.ICT1	Qmax= 625pC	20130216A	22:13
+	2	Gaussian, 2.9ps	7.75	10	149	scan 1deg	Charge LOW.FC2	Qmax= 75pC	20130216A	22:48
+	3	Gaussian, 2.9ps	7.75	50	720	scan 1deg	Charge LOW.ICT1	Qmax= 350pC	20130216N	03:01
	4	Gaussian, 2.9ps	7.75	10	149	scan 0.5deg	Momentum LEDA	MMMG= −69 deg MaxPz= 7.088 MeV/c	20130216A	23:05 01:16
+	5	Gaussian, 2.9ps	7.75	scan	scan	MMMG	Charge LOW.ICT1		20130216N	02:39
+	6	Gaussian, 2.9ps	4	scan	scan	MMMG	Charge LOW.ICT1		20130217N	00:30
+	7	Gaussian, 2.9ps	4	95 ~~100%~~	1336	scan 1deg	Charge LOW.ICT1	Qmax= 550pC	20130217A	22:47
+	8	Gaussian, 2.9ps	4	10 ~~10%~~	149	scan 1deg	Charge LOW.FC2	Qmax= 69pC	20130217A_N	23:48(05:8)
	9	Gaussian, 2.9ps	4	50% 48	720	scan 1deg	Charge LOW.ICT1	Qmax= 350pC	20130217AN	23:26
	10	Gaussian, 2.9ps	4	10?	149	scan 0.5deg	Momentum LEDA	MMMG= −71 deg MaxPz= 5,3 MeV/c	20130217N	00:15 01:22
*	11	Flat-top	100,7deg C 7.75	68%	~~1336~~ 149	scan 0.5deg	Momentum LEDA	MMMG= 5 deg | 7deg MaxPz= 7.090 | 7.092	20130218N	01:00 | 2:50
+	12	Flat-top	7.75	scan	scan	MMMG	Charge LOW.ICT1	Imain=400A	20130218N	01:21 | 2:51
+	13	Flat-top	7.75	64,2%	1336	scan 1deg	Charge LOW.ICT1	Qmax= 650 450A	20130218N	03:10
+	14	Flat-top	7.75	?	149	scan 1deg	Charge LOW.FC2	Qmax= [illegible] pC	20130218N	03:28
+	15	Flat-top	7.75	35,4%	719.78	scan 1deg	Charge LOW.ICT1	Qmax= 360pC	20130218N	05:28
	16	Flat-top	4	3%	149	scan 0.5deg	Momentum LEDA	MMMG= 10 deg 370A MaxPz= 5,304	20130218N	05:15
	17	Flat-top	4	scan	scan	MMMG	Charge LOW.ICT1	10deg ; I=350A	20130218N	05:28
	18	Flat-top	4	69,7%	1336	scan 1deg	Charge LOW.ICT1	Qmax= 640pC 350A	20130218N	05:46
	19	Flat-top	4	?	149	scan 1deg	Charge LOW.FC2	Qmax= 74 pC		
	20	Flat-top	4	37,4	719.78	scan 1deg	Charge LOW.ICT1	Qmax= 360pC	20130218N	06:05

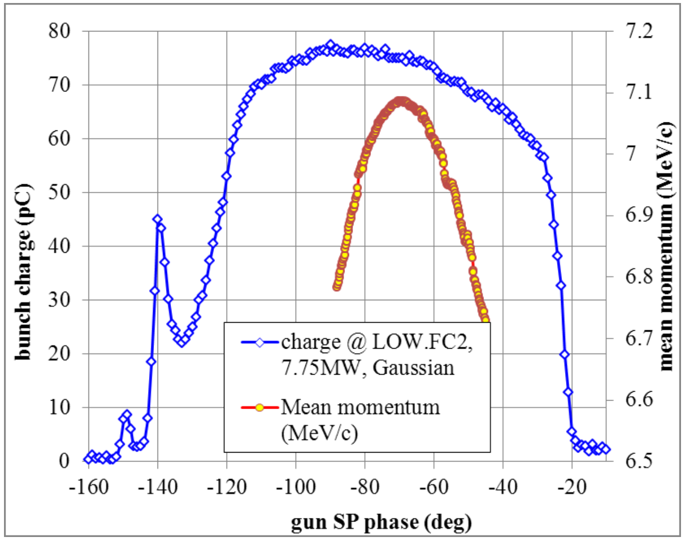
+ Measure VC2 laser profile
+ Measure OSS at the End.

* VC2 pictures saved to the folder U:/.../Laser/TrProfile/2013/
.../20130218M/ 1325.

MMMG phase determination = low Q Schottky + LEDA scans

- Short Gaussian temporal profile
- Gun FB is on (tuned, reflection <3%)





$$\varphi_0 = \Phi_0 - \text{gun SP phase}$$

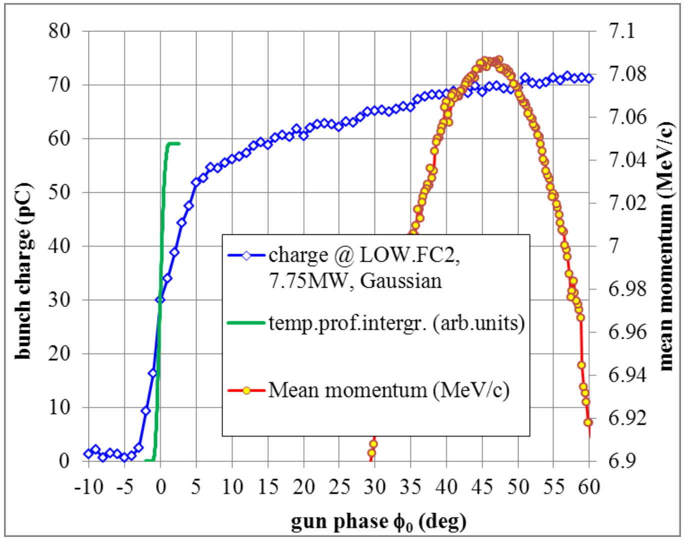
$$\Phi_0(4.0\text{MW}) = -32\text{deg}$$

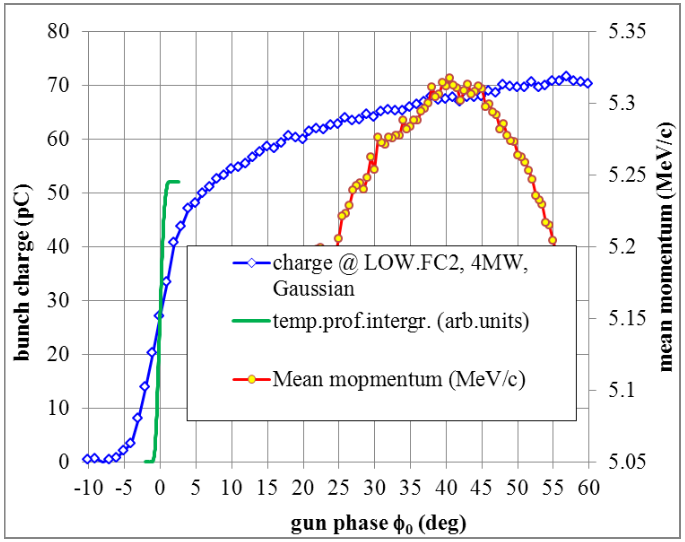
$$\Phi_0(7.75\text{MW}) = -23\text{deg}$$

Zero-crossing phase determination

- Compared with the measured integrated temporal laser profile (time converted into rf phase units)
- Zero phase ➔ middle of the rising edge

$$\varphi_0 = \Phi_0 - \text{gun SP phase}$$





$$\Phi_0(7.75\text{MW}) = -23\text{deg}$$

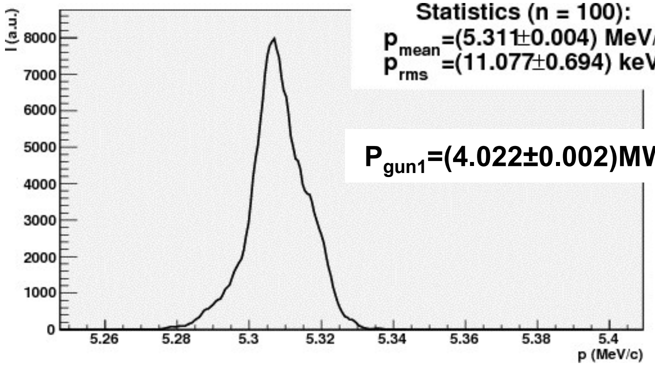
$$\Phi_0(4.0\text{MW}) = -32\text{deg}$$

$$\Phi_{MMMG}(7.75\text{MW}, \text{gun SP phase} = -69\text{deg}) = 46\text{deg}$$

$$\Phi_{MMMG}(4.0\text{MW}, \text{gun SP phase} = -71\text{deg}) = 39\text{deg}$$

- The discrepancy in the slope → rf phase jitter or/and by the laser timing jitter to the master oscillator?
- Estimations on the **rms phase jitter** :
  - ~2.5deg (5.2ps) ➔ for the short Gaussian laser pulses
  - ~1.8deg (2.9ps) ➔ for the flat-top cathode laser pulses.

MMMG phase measurements vs. simulations

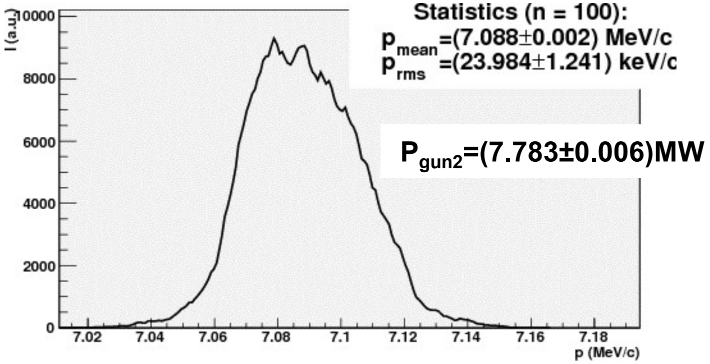


Statistics (n = 100):
p_{mean}=(5.311±0.004) MeV/c
p_{rms}=(11.077±0.694) keV/c

P_{gun1}=(4.022±0.002)MW

$$\Phi_{MMMG}(4.0\text{MW, gun SP phase} = -71\text{deg}) = \mathbf{39deg}$$

$$\sqrt{\frac{P_{gun2}}{P_{gun1}}} = 1.39$$



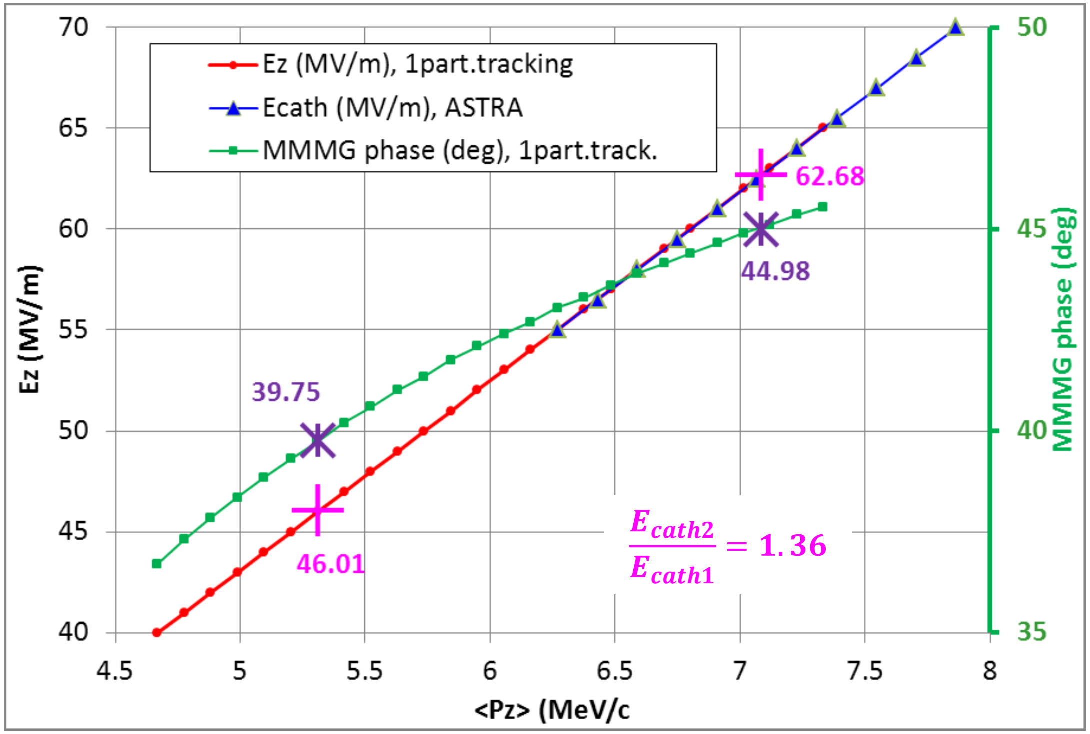
Statistics (n = 100):
p_{mean}=(7.088±0.002) MeV/c
p_{rms}=(23.984±1.241) keV/c

P_{gun2}=(7.783±0.006)MW

$$\Phi_{MMMG}(7.75\text{MW, gun SP phase} = -69\text{deg}) = \mathbf{46deg}$$

Simulated:
Max<Pz>=5.311MeV/c:

- E_{cath1}=46.01MV/m
- Phase=39.75deg



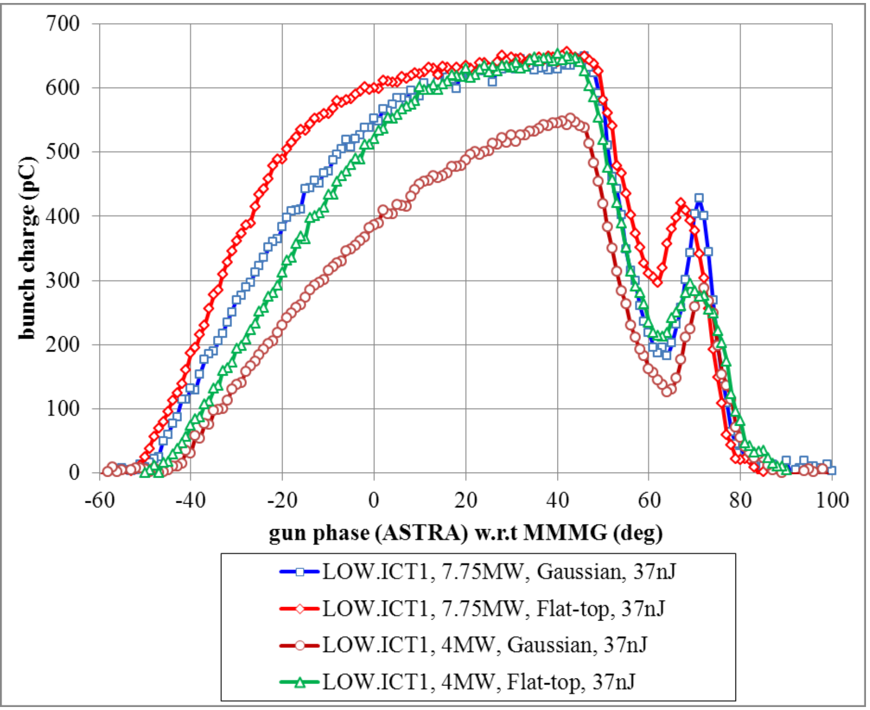
$$\frac{E_{cath2}}{E_{cath1}} = 1.36$$

Simulated:
Max<Pz>=7.088MeV/c:

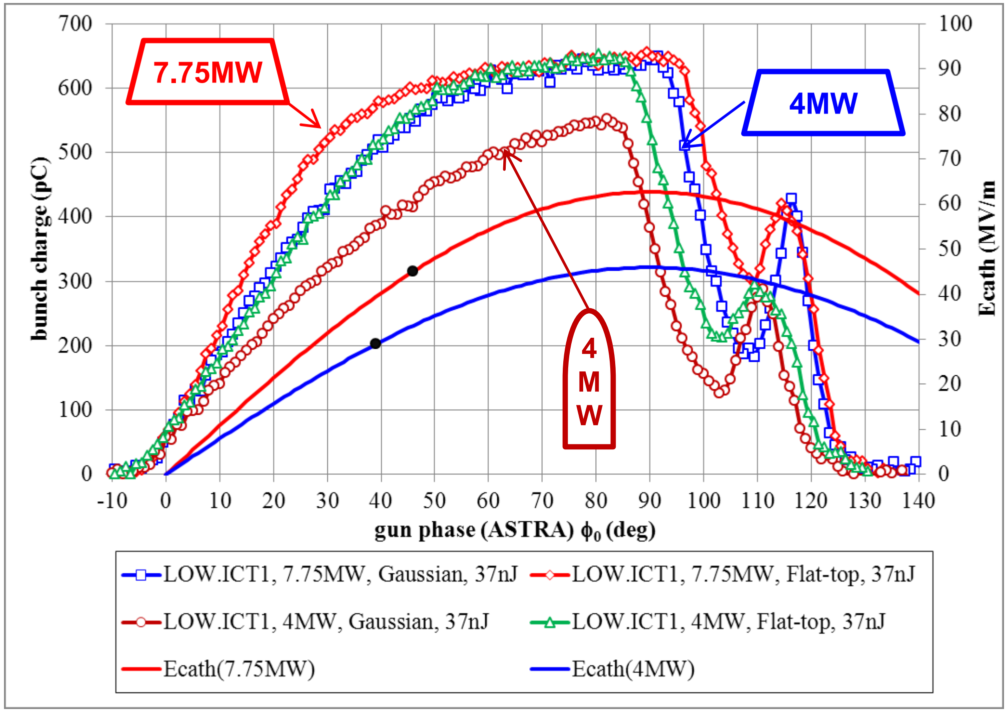
- E_{cath2}=62.68MV/m
- Phase=44.98deg

Schottky scans for the maximum laser pulse energy

Phase → w.r.t. MMMG phase



Phase → w.r.t. zero phase



From the parallel plate capacitor model:

$$Q_{QE-lim,PPCM} = \pi\varepsilon_0 R^2 E_0 \sin\varphi_0 = \pi\varepsilon_0 R^2 E_{cath}$$

E.g. for

$$E_{cath} = 50\frac{MV}{m}; R = 0.6mm;$$

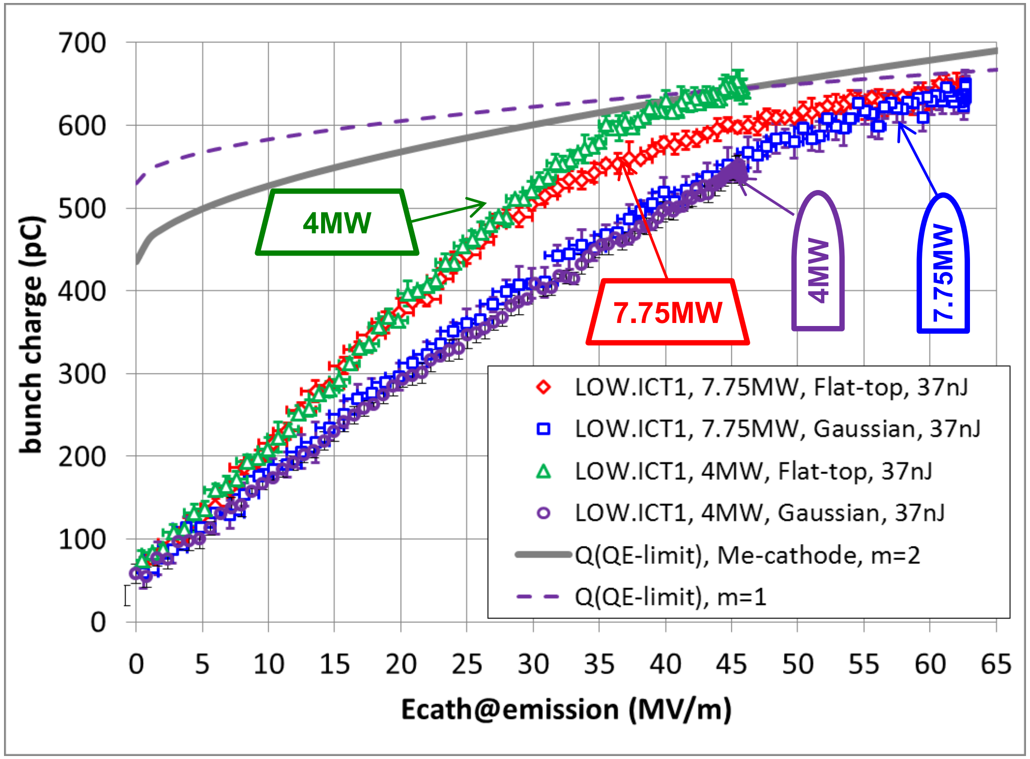
$Q_{QE-lim,PPCM} \cong 500pC$ << observed!!!

$$Q_{QE-lim} \propto \mathrm{Q}_0\left(1-\sqrt{\frac{\phi_{eff}}{\hbar\omega}}\right)^m$$

$$\hbar\omega = 4.81eV$$

$$\phi_{eff} = E_G + E_A - 0.0379\sqrt{E_{cath}(MV/m)}$$

Field enhancement fits (37nJ case)



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

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

$$\hbar\omega = 4.81eV$$

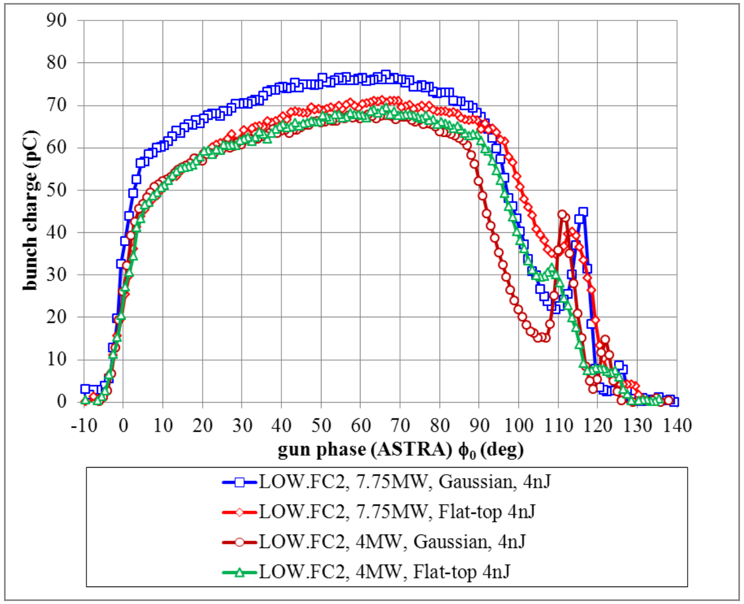
$$Q_{m=2}(50MV/m) = 655pC$$
$$Q_{m=1}(50MV/m) = 650pC$$

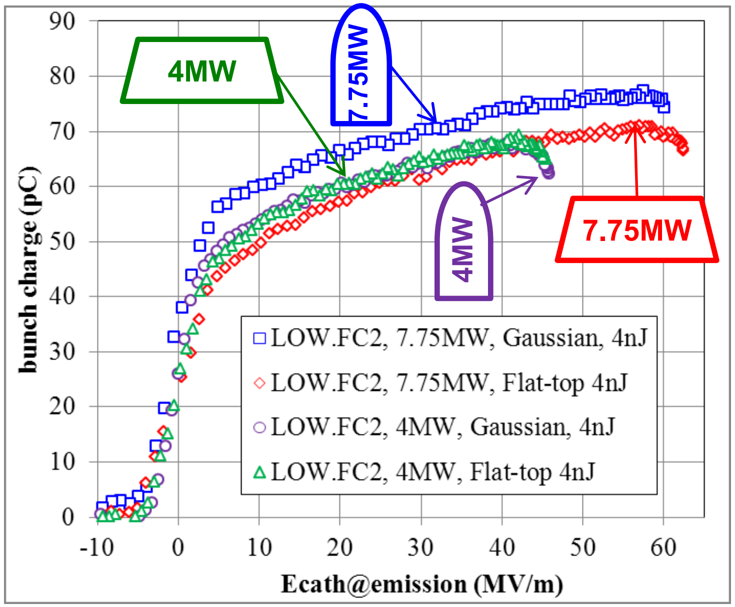
- The difference in increasing parts of the measured curves → space charge effects?
- Common upper part ➔ QE-limit, which is not dependent on space charge density at the cathode, because the high electric rf field at the cathode compensates the space charge effect.
- The difference in dependencies for 7.75MW and 4MW (both flat-top profiles) can be explained by difference in the emission dynamics. The laser pulse duration is ~8deg of rf and for 4MW case the electric field of ~45MV/m corresponds to the peak field (φ_0~90deg), whereas for 7.75MW it corresponds to the phase $\varphi_0 \sim 45deg$. → surface states?
- The fits based on the experimental data shows that for the field range >40MV/m better approximation is obtained for $m \leq 2$?

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

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

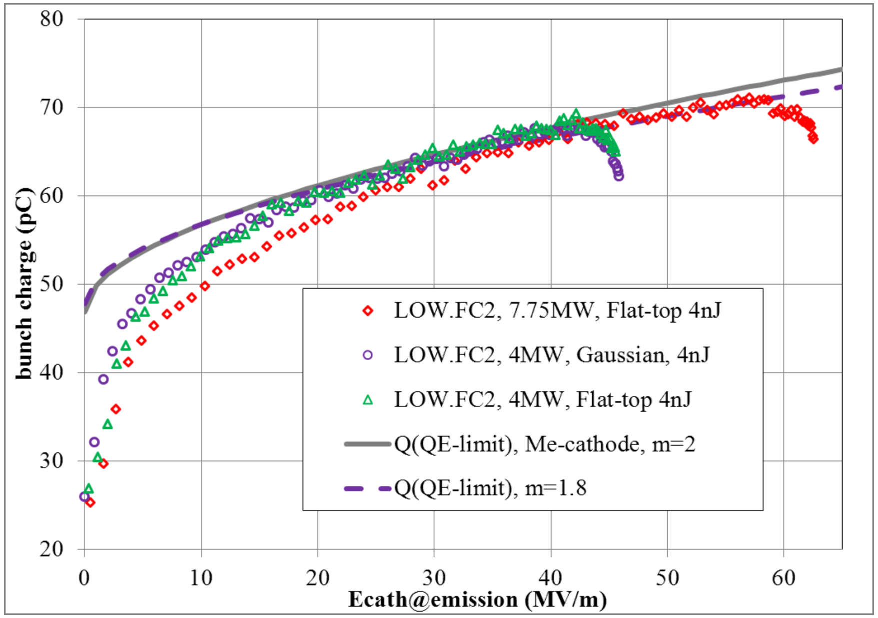
Field enhancement fits (4nJ case)





!NB:
LT(Gaus,7.75MW)=10%
LT(Gaus,4.0MW)=9.6%
An LT scan (0→100%) in-between…

~~7.75MW~~



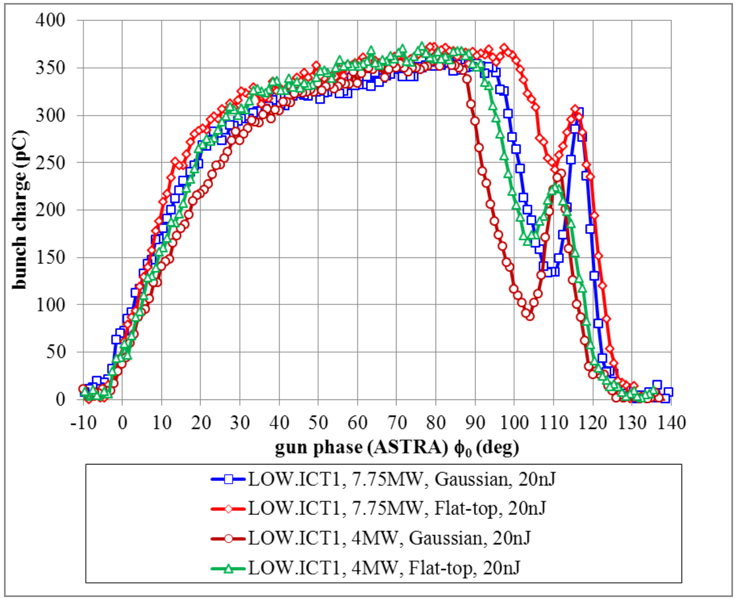
$$Q_{QE-lim} \propto Q_0\left(1-\sqrt{\frac{\phi_{eff}}{\hbar\omega}}\right)^m$$

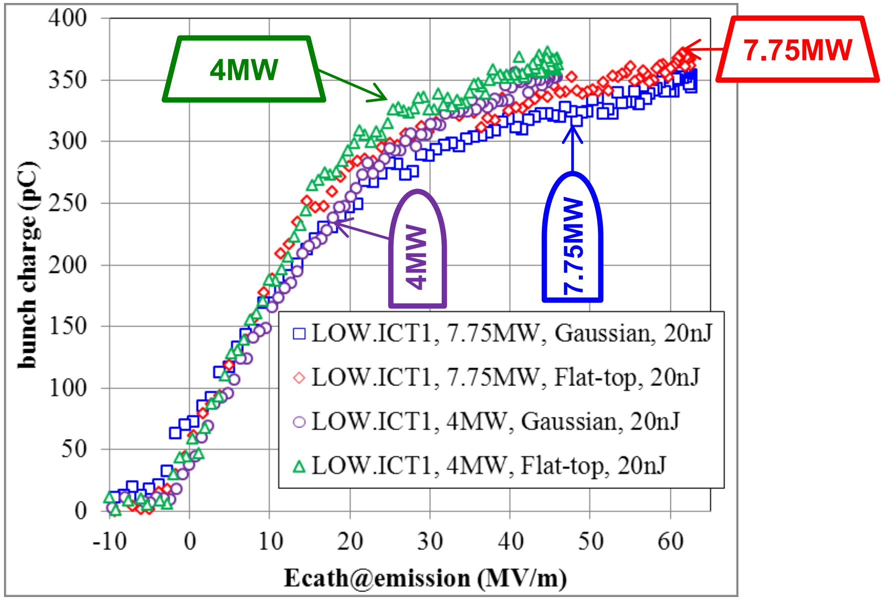
$$\phi_{eff} = 3.5eV - 0.0379\sqrt{E_{cath}(MV/m)}$$

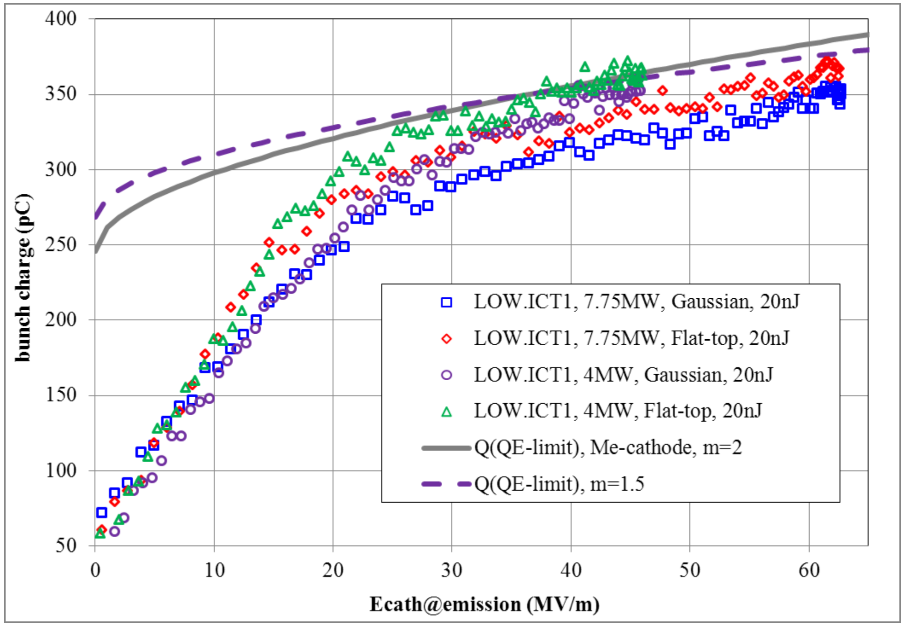
$$\hbar\omega = 4.81eV$$

$$Q_{m=2}(50MV/m) = 70.5pC$$
$$Q_{m=1.8}(50MV/m) = 69pC$$

Field enhancement fits (20nJ case)







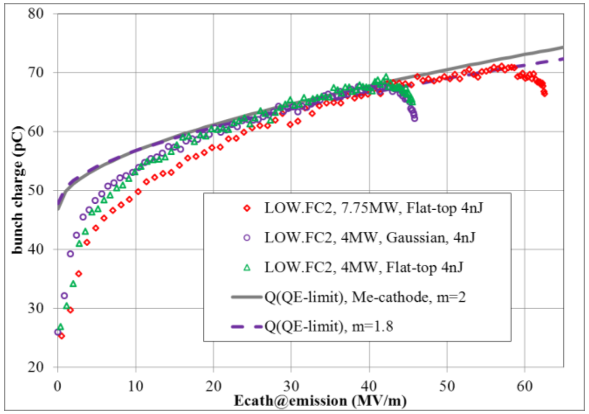
$$Q_{QE-lim} \propto Q_0\left(1-\sqrt{\frac{\phi_{eff}}{\hbar\omega}}\right)^m$$

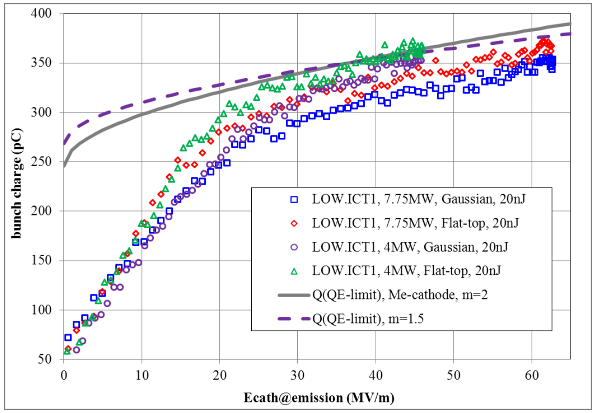
$$\phi_{eff} = 3.5eV - 0.0379\sqrt{E_{cath}(MV/m)}$$

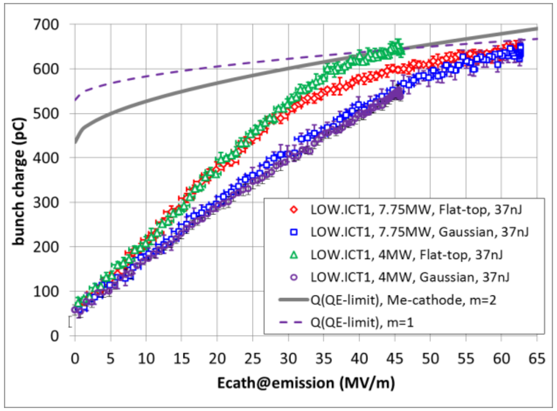
$$\hbar\omega = 4.81eV$$

$$Q_{m=2}(50MV/m) = 370pC$$
$$Q_{m=1.5}(50MV/m) = 365pC$$

Field enhancement fits: discussion







$$Q_{QE-lim} \propto Q_0\left(1-\sqrt{\frac{\phi_{eff}}{\hbar\omega}}\right)^{m=2}$$

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

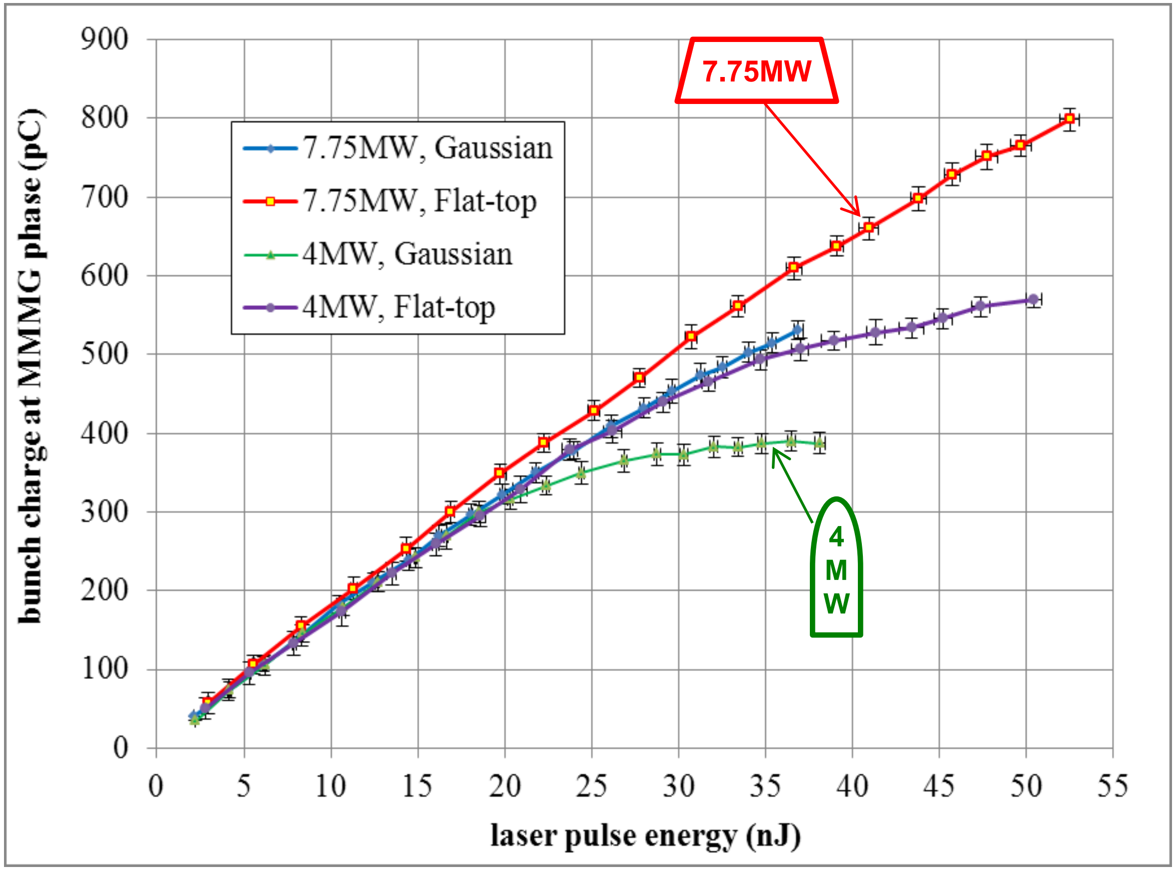
$$\hbar\omega = 4.81eV$$

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

OK

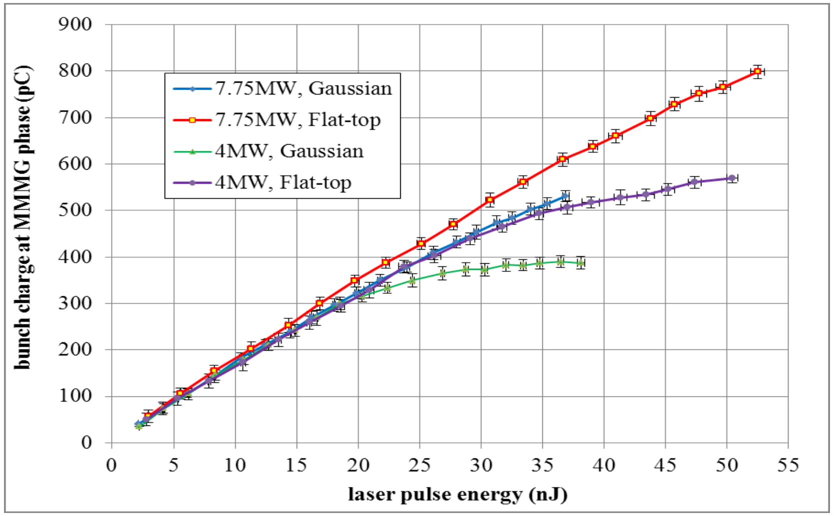
Laser pulse energy (laser transmission) scans

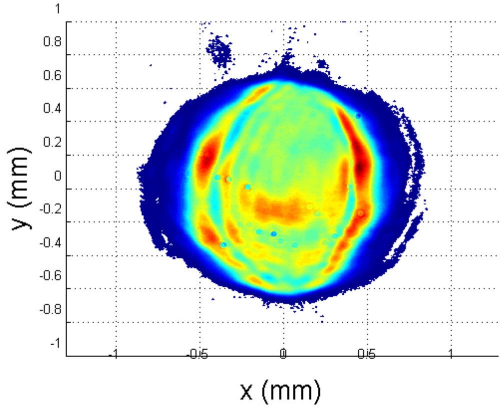
SPPhase = MMMG phase

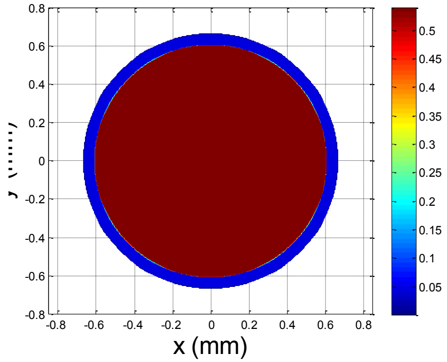


- The case of short Gaussian pulses and low gun gradient (4MW in the gun) ➔ the strongest saturation of the charge production due to a stronger space charge effect.
- The lowest space charge density case (– the flat-top and 7.75MW in the gun) ➔ the most linear charge production curve.
- It is interestingly 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 pulse energy scans: measurements vs. simulations

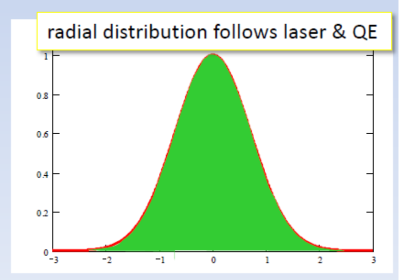




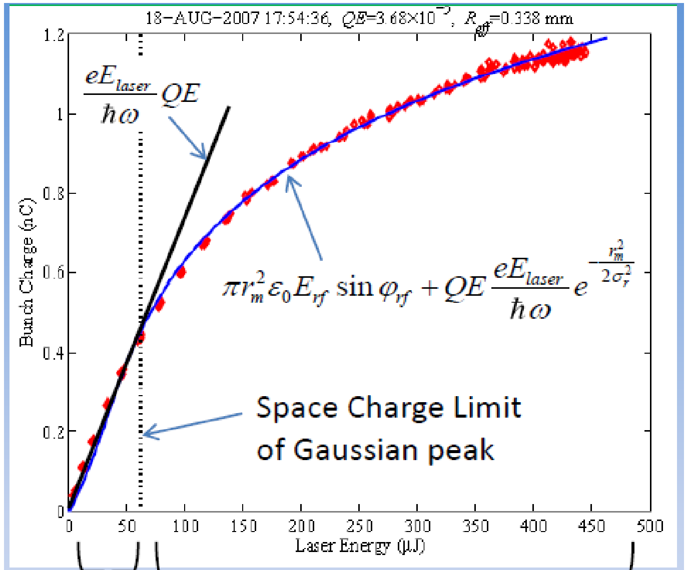


A simple model to estimate this effect was suggested in:

- [J. Rosenzweig et al., “Initial measurements of the UCLA rf photoinjector”, NIM A 341 (1994) 379-385].
- [David. H.Dowell, “Tutorial on (generating) high brightness beams”, PAC11 Tutorial, April 1, 2011]


radial distribution follows laser & QE

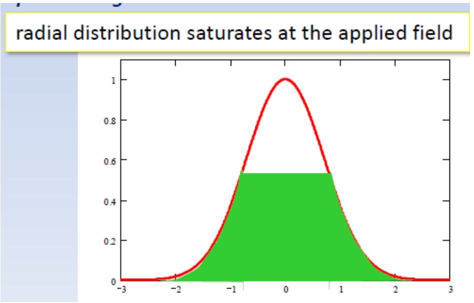
QE Limited Emission


18-AUG-2007 17:54:36, $QE=3.68\times10^{-}$, R_{eff}=0.338 mm

$$\frac{eE_{laser}}{\hbar\omega}QE$$

$$\pi r_m^2\varepsilon_0 E_{rf}\sin\varphi_{rf}+QE\frac{eE_{laser}}{\hbar\omega}e^{-\frac{r_m^2}{2\sigma_r^2}}$$

Space Charge Limit of Gaussian peak


radial distribution saturates at the applied field

Space Charge Limited Emission

MK: PPC model used!

Laser transverse halo modeling-1: Gaussian radial profile

Assuming emission limitation while the space charge density exceeds some threshold value ρ_{scl} for a Gaussian radial distribution of the cathode laser intensity:

$$F(r) = \frac{E_l}{2\pi\sigma_r} e^{-\frac{r^2}{\sigma_r{}^2}}$$

where $E_l = \int_0^\infty F(r) 2\pi r dr$ is the laser pulse energy

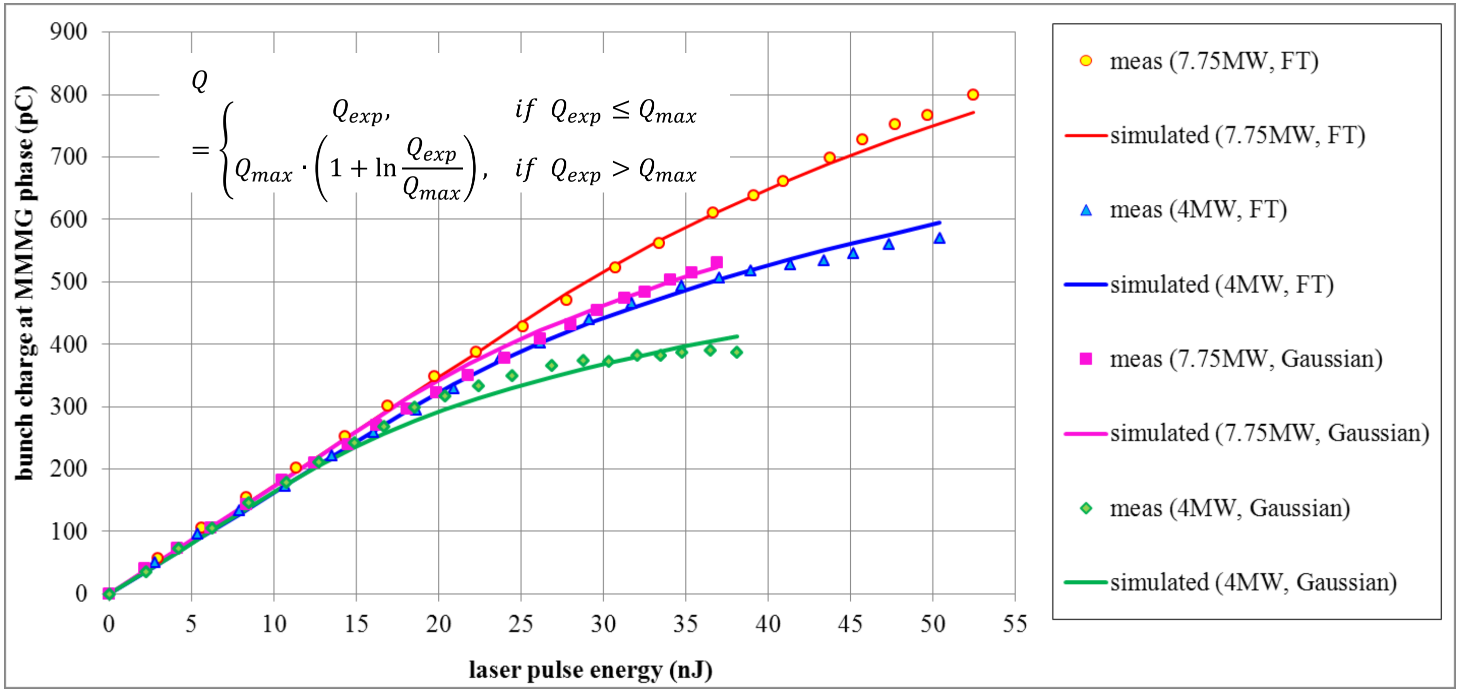
Using the expression for the quantum efficiency for the Cs_2Te cathode $QE[\%] \cong 0.5 \frac{Q_{exp}[pC]}{E_l[nJ]}$, where Q_{exp} is theoretically expected charge which would be emitted without presence of space charge (cathode image) forces.

By taking into account the space charge density limit ρ_{scl} and denoting $Q_{max} = 2\pi\sigma_r{}^2\rho_{scl}$ produced charge can be calculated as

$$Q = \begin{cases} Q_{exp}, & if\ \ Q_{exp} \leq Q_{max} \\ Q_{max} \cdot \left(1 + \ln \frac{Q_{exp}}{Q_{max}}\right), & if\ \ Q_{exp} > Q_{max} \end{cases}$$

Another assumption → the dependence $\rho_{scl} \propto E_0 sin\varphi_0$

Laser transverse halo modeling-1: fitting measurements



$$Q = \begin{cases} Q_{exp}, & if\ \ Q_{exp} \le Q_{max} \\ Q_{max} \cdot \left(1 + \ln \dfrac{Q_{exp}}{Q_{max}}\right), & if\ \ Q_{exp} > Q_{max} \end{cases}$$

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

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

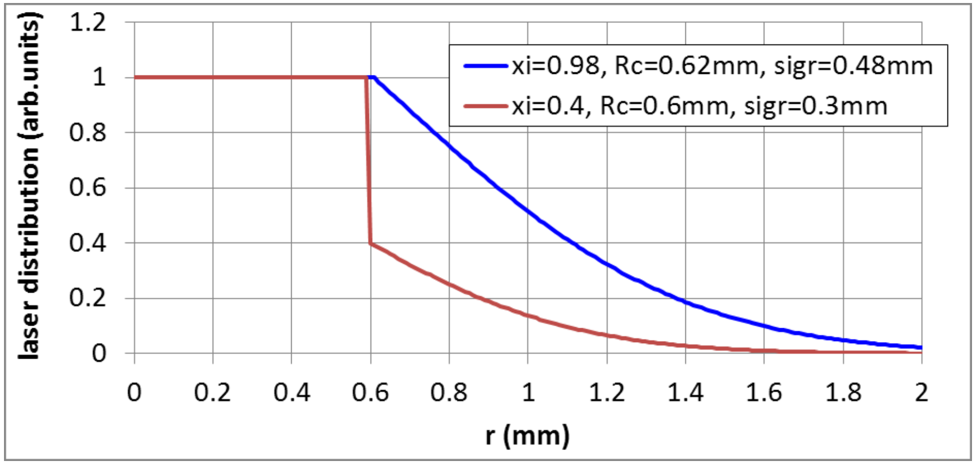
$$\boldsymbol{\frac{\rho_{scl}(flat-top)}{\rho_{scl}(Gaussian)} \approx 1.55}$$

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: radial flat-top + Gaussian tails

$$F_l(r) = \frac{E_l}{\pi R_c^2 + 2\pi\xi{\sigma_r}^2}\begin{cases} 1, & if\ \ r \le R_c \\ \xi e^{\frac{R_c^2 - r^2}{2\sigma_r^2}}, & if\ r > R_c \end{cases}$$

$$\rho_Q(r) = \frac{2QE \cdot E_l}{\pi R_c^2 + 2\pi\xi{\sigma_r}^2}\begin{cases} 1, & if\ \ r \le R_c \\ \xi e^{\frac{R_c^2 - r^2}{2\sigma_r^2}}, & if\ r > R_c \end{cases}$$



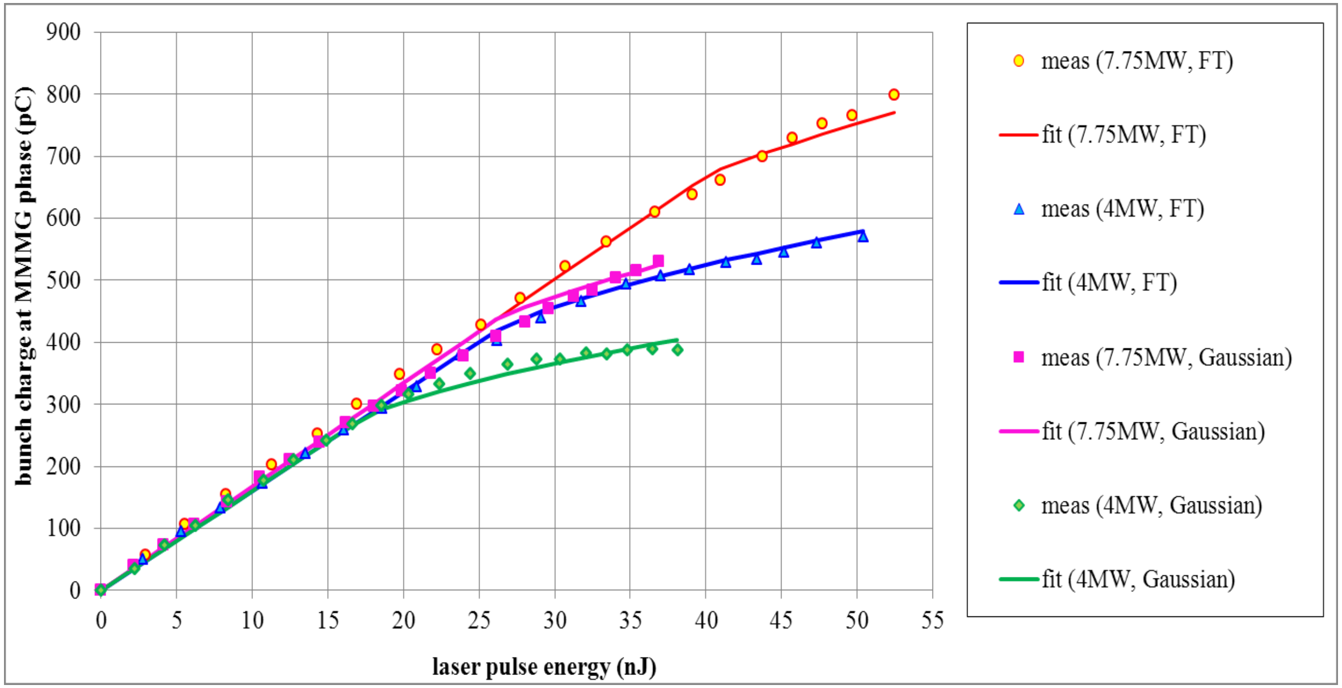
$$\boldsymbol{Q = Q_{core} + Q_{halo}}$$

$$Q_{core} = \frac{1}{1 + \xi \cdot \eta}\begin{cases} Q_{exp}, & if\ \ Q_{exp} \le Q_{max} \\ Q_{max} & if\ \ Q_{exp} > Q_{max} \end{cases}$$

$$Q_{halo} = \frac{\eta}{1 + \xi \cdot \eta}\begin{cases} \xi \cdot Q_{exp}, & if\ \ \xi \cdot Q_{exp} \le Q_{max} \\ Q_{max} \cdot \left(1 + \ln\frac{\xi \cdot Q_{exp}}{Q_{max}}\right) & if\ \ \xi \cdot Q_{exp} > Q_{max} \end{cases}$$

$$Q_{max} = \rho_{scl} \cdot \left(\pi R_c^2 + 2\pi\xi{\sigma_r}^2\right)$$

Laser transverse halo modeling-2: 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	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 $\nu = N_{points} - N_{fit.par.} - 1 = 73$.

Conclusions

- From previous photoemission studies:
  - 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
  - Possible emission invariant $E_o \sin\varphi_0 \cdot R_{laser} = inv?$
- Recent (Feb.2013) results:
  - 2 temporal profiles (laser pulse length ~ factor 6), the same transverse spot size, 3 laser pulse energies (tuned for both temporal profiles), 2 peak rf power levels (~ factor 2)
  - Field enhancement fit for the QE-limited emission $Q_{QE-lim} \propto Q_0\left(1-\sqrt{\phi_{eff}/\hbar\omega}\right)^m$:
    - Rather good agreement in Q_0 values for m=2 (Me-cathode model)
    - Charge dependence on electric field → strong dependence on SC density:
      - Low SC density → m~2
      - High SC density → m~1
  - Laser pulse energy scans for the MMMG phase:
    - Gaussian transverse tails fit → rather poor
    - F-T core + Gaussian tails → better, but still
    - SC limit ratio ~1.5 (despite laser pulse length ratio is ~6)
    - F-T(4MW) ~ Gaussian(7.75MW)
  - Emission:
    - transient effect → depends on the laser temporal profile (~~parallel plate capacitor model~~)
    - field enhancement determined also by the peak field