Photoemission studies at PITZ:

Analysis on extracted charge vs laser pulse energy from Cs_2Te photocathodes under high RF field strengths

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HELMHOLTZ ASSOCIATION

DESY

Overview: Behavior of extracted charge vs laser pulse energy

> Observations:

- The charge extraction is linear for low laser pulse energies (this is how we measure the quantum efficiency, “single particle” regime).
- But for higher laser pulse energies (saturation regime) the charge extraction dependence on laser energy is much weaker (“collective effects” space charge regime).
- We have consistently observed that the extracted charge for high laser pulse energy is larger than that predicted by simulations for a variety of gun settings and laser parameters.
- The extracted charge in the saturation regime depends on specific laser beam parameters and gun operating settings.

> Hypothesis:

- Although the extracted charge saturates in the core of the uniform laser transverse distribution, radial laser halo contributes to additional extracted charge.

> Experiment:

- To test our hypothesis, we have generated initial (input) distributions fitted to first order to the measured laser transverse profiles, which in fact have a radial profile comprised of a flat-top core with Gaussian-like decaying halo.

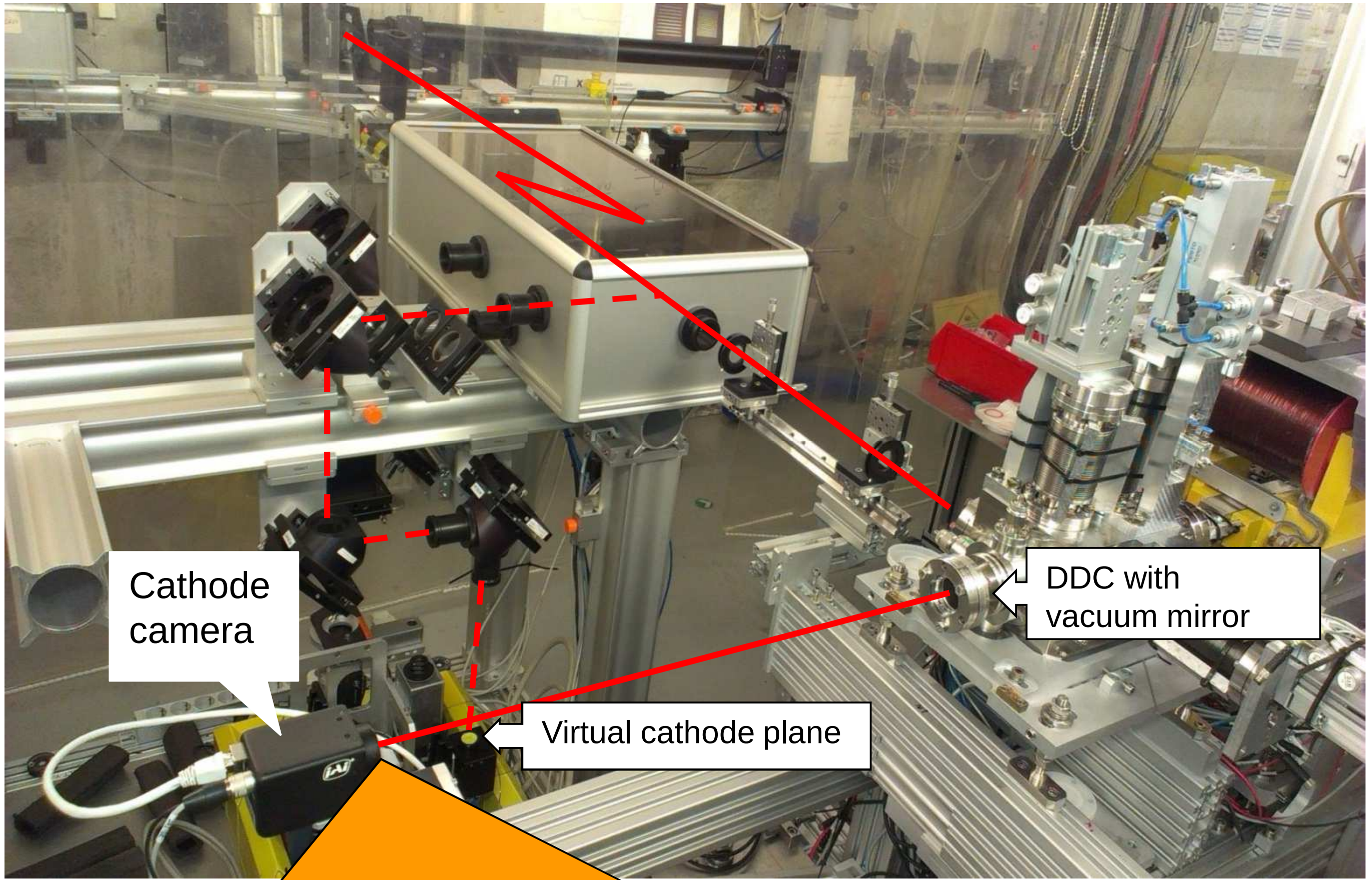
> Results:

- Using these distributions, we obtain now agreement to first order between ASTRA simulations and measured extracted charge vs laser pulse energy.
- Our observations seem to indicate that halo is contributing to excess extracted charge compared to a uniform core transverse laser distribution.

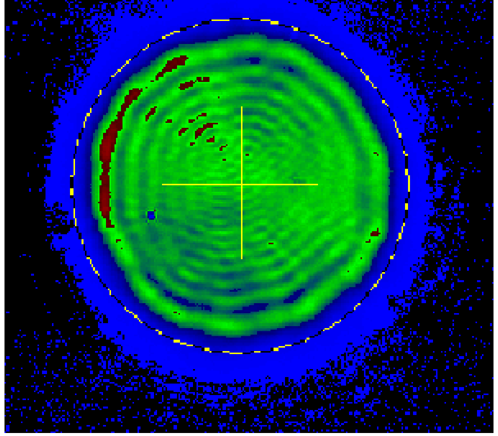
Outline

1. Characterization of laser transverse profile
2. Generation of particle input distribution based on laser transverse profile data
3. Comparison of measurements with simulations and with semi-analytical model using generated input distribution
4. Sensitivity of simulations and model to laser radial profile parameters
5. Effect of generated core+halo distributions on emittance simulations
6. Laser radial halo dependence on laser settings and its effect on extracted charge
7. Conclusions

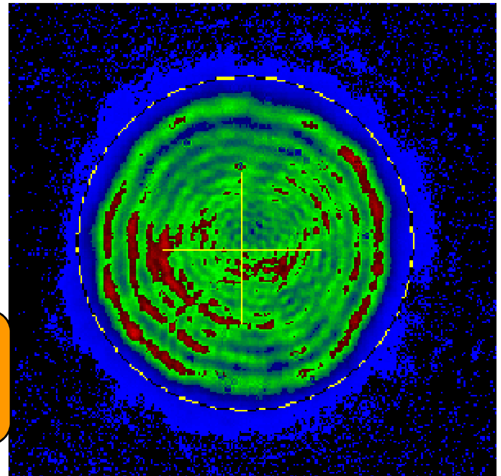
To characterize the laser spot on the cathode: The laser beam shaping aperture (BSA) is imaged onto a CCD camera positioned at a plane equivalent to that of the actual cathode (12-March-2013)*



Photocathode



Virtual cathode plane

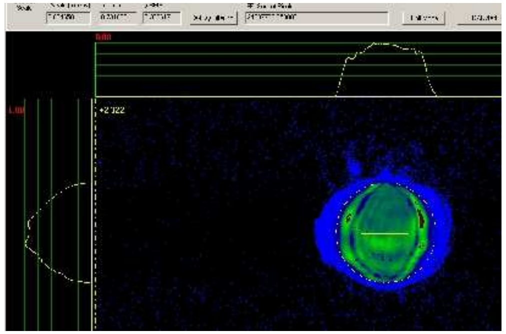


The Cathode camera CCD is placed at the exact location of the Cs2Te photocathode at the back plane of the gun cavity

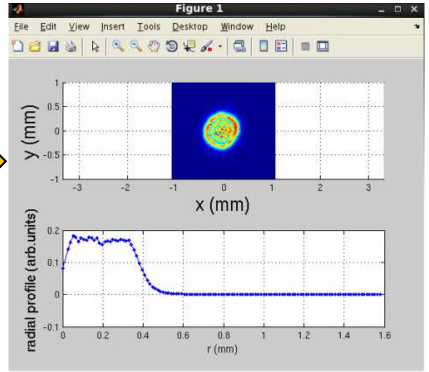
*M. Gross (PITZ)

The procedure consists on generating particle input distributions derived from the radial curve fit to the measured laser transverse profile:

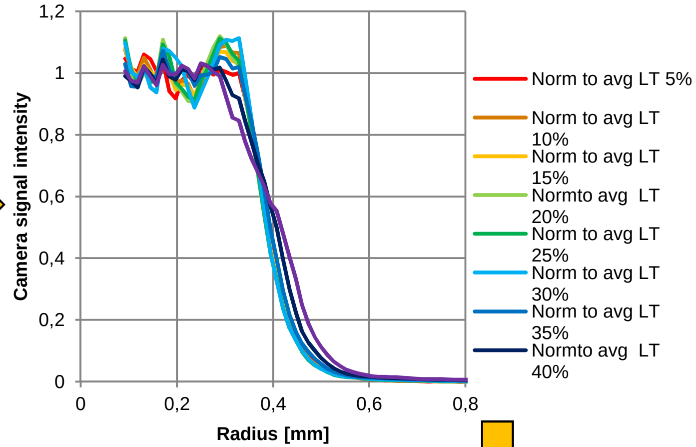
Laser distribution on virtual cathode imaging camera data capture



Virtual cathode data fitted in MatLab



Radial laser profile from MatLab data fit



$$TG(r,\xi,\sigma,R_c) := \xi\cdot\exp\left(\frac{R_c^2 - r^2}{2\cdot\sigma^2}\right)$$

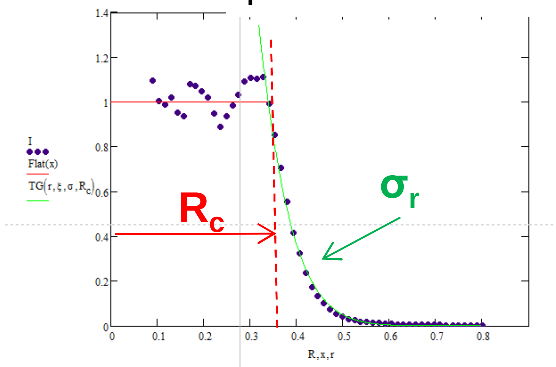
$\xi := 1$

$R_c := 0.34$

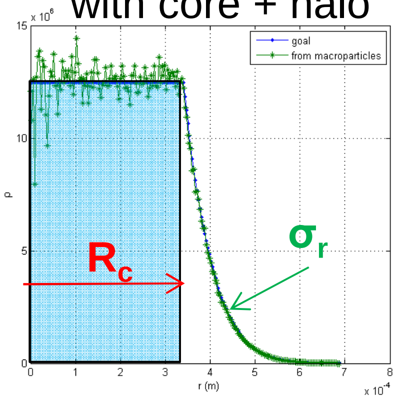
$\sigma := 0.15$

$r := 0.32, 0.321 .. 0.8$

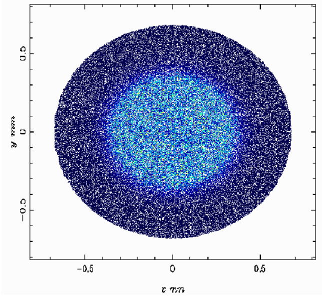
Curve fit to match radial laser profile fit



MatLab-generated input distribution for ASTRA with core + halo



Input distribution shown by postpro with core + halo



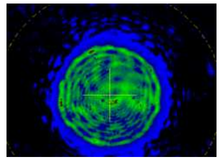
To ASTRA

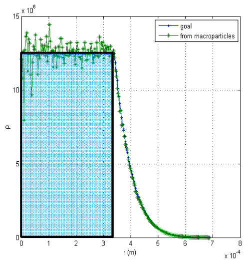
DESY

When the core+halo initial distribution is utilized, ASTRA shows good agreement with extracted charge measurements

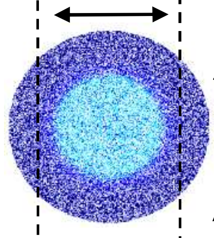
If a uniform distribution is used instead, the charge saturates

Laser radial distribution image



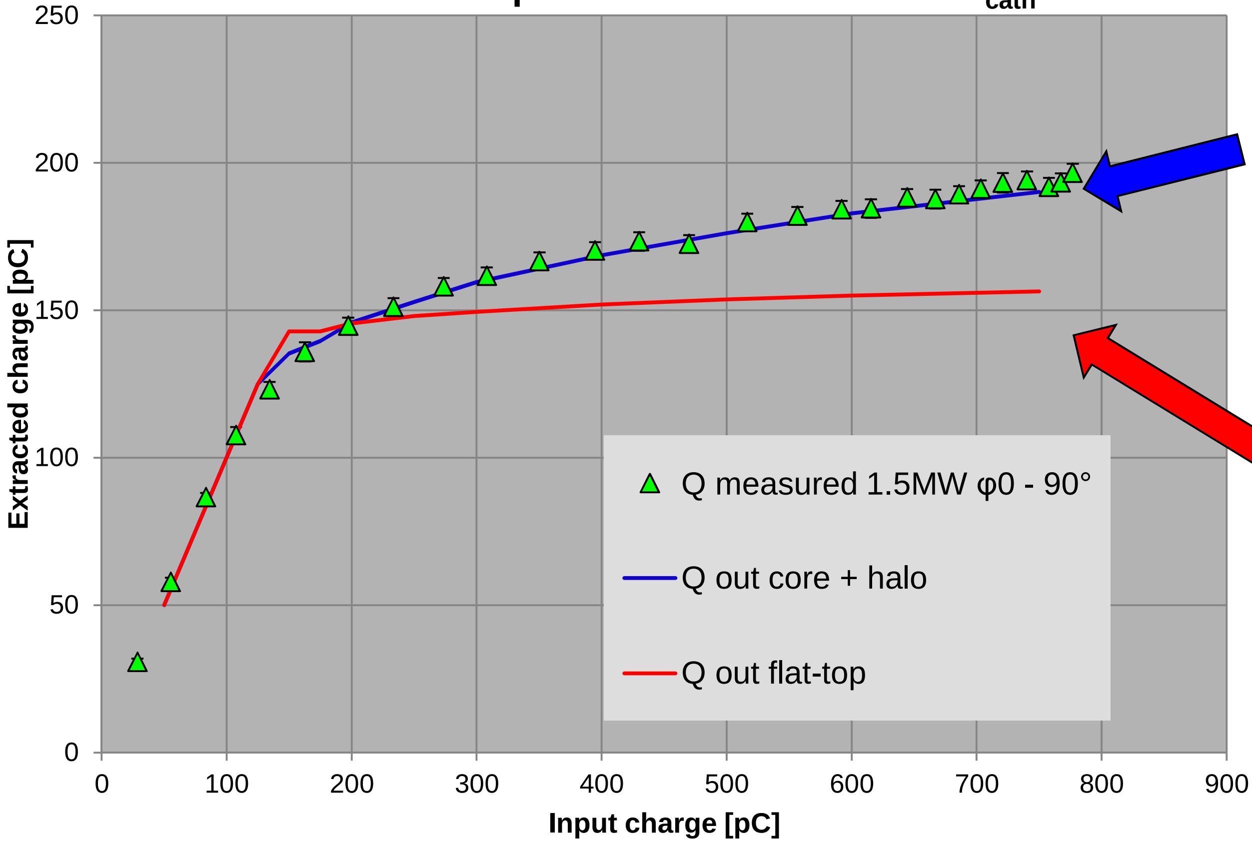


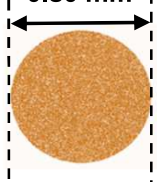
Transverse radial profile core + halo



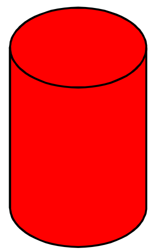
Generated ASTRA input distribution core + halo

Extracted charge vs laser pulse energy for temporal Gaussian σ_t=1.5 ps BSA=0.8mm Gun Power = 1.5MW and Gun Phase φ0 - 90° set for maximum E_{cath}





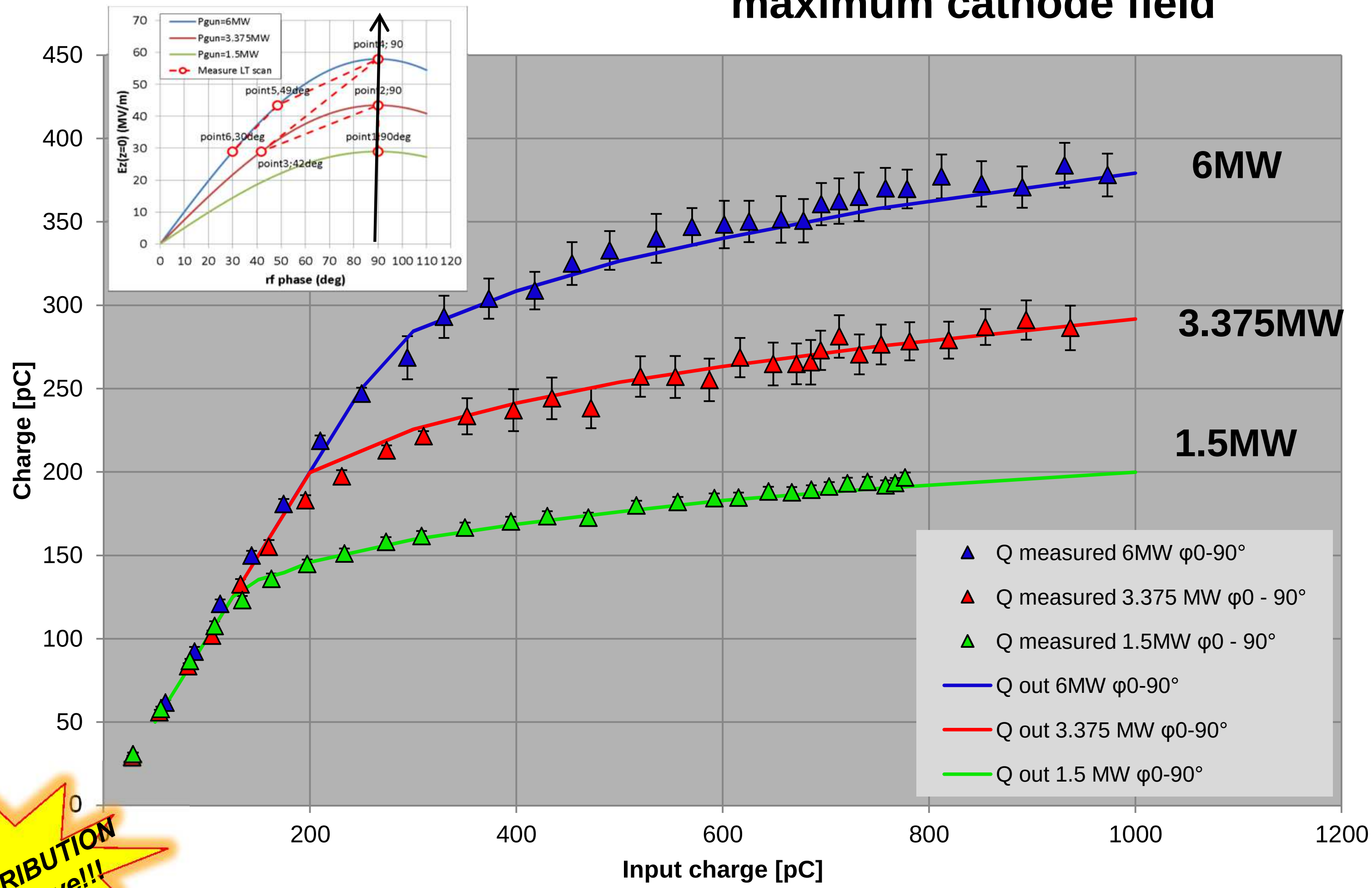
Nominal ASTRA input uniform distribution

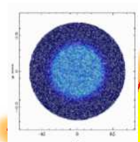


Nominal transverse uniform radial profile

Once a fit is found, the core + halo input distribution fits the experimental data…

Extracted charge with core + halo for 0.8 mm beam diameter with 1.5 ps rms Gaussian temporal at maximum cathode field

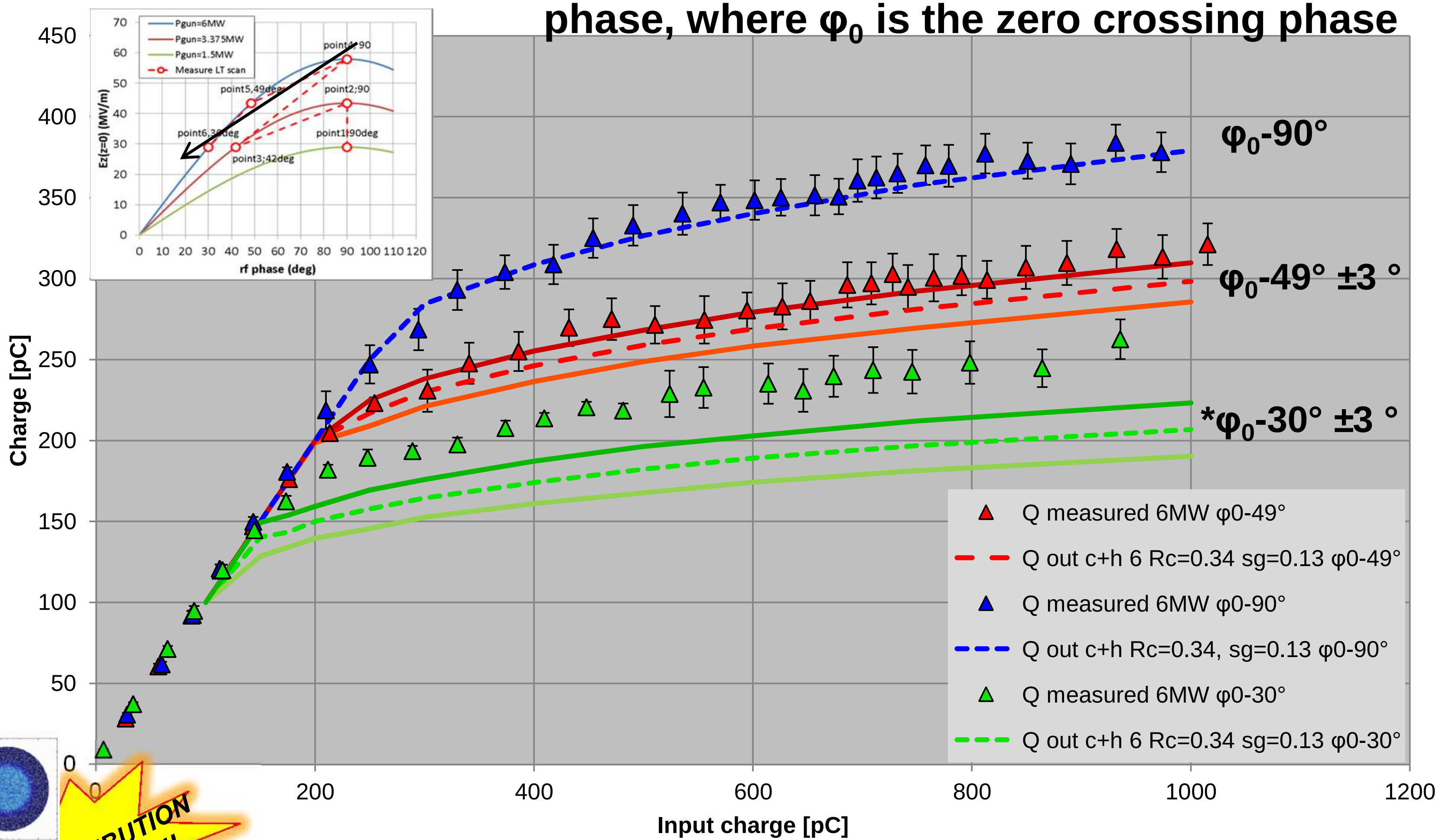


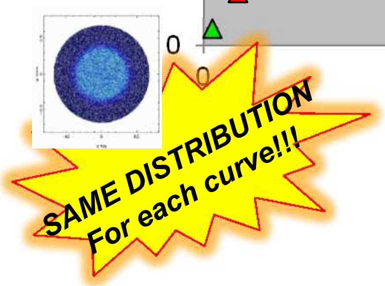


SAME DISTRIBUTION
For each curve!!!

…for most cases….

Extracted charge with core + halo for 0.8 mm beam diameter with 1.5 ps rms Gaussian temporal at Pgun=6MW for each phase, where φ_0 is the zero crossing phase

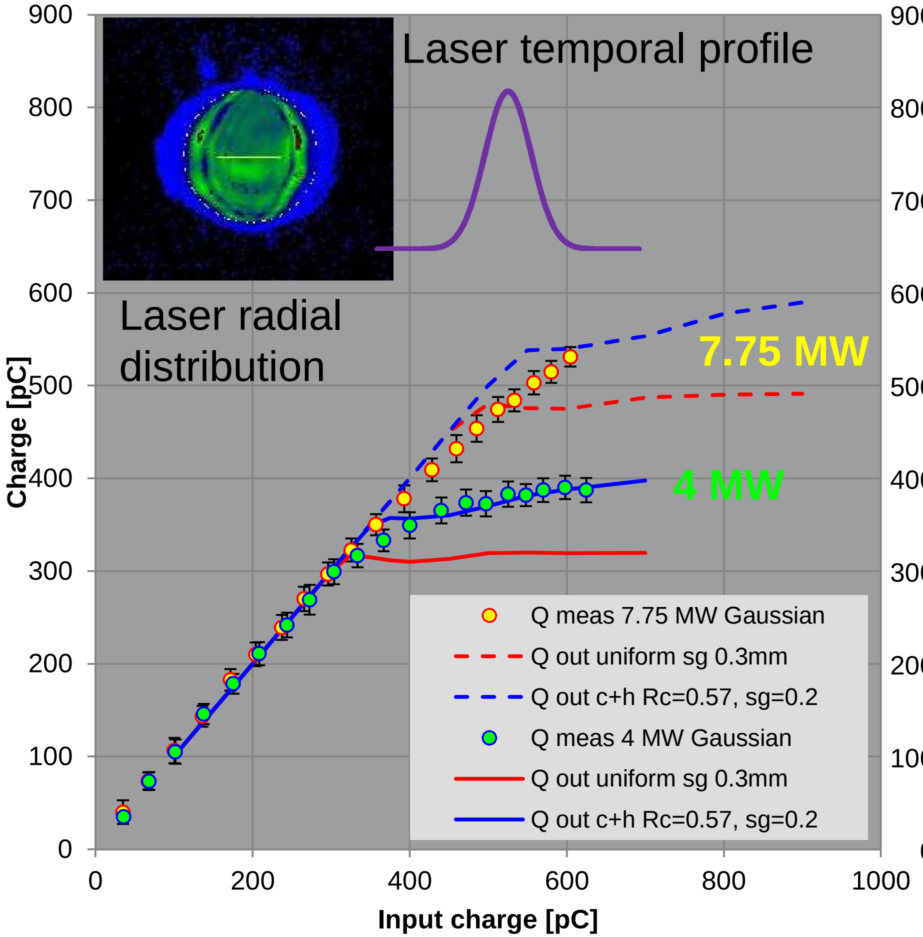




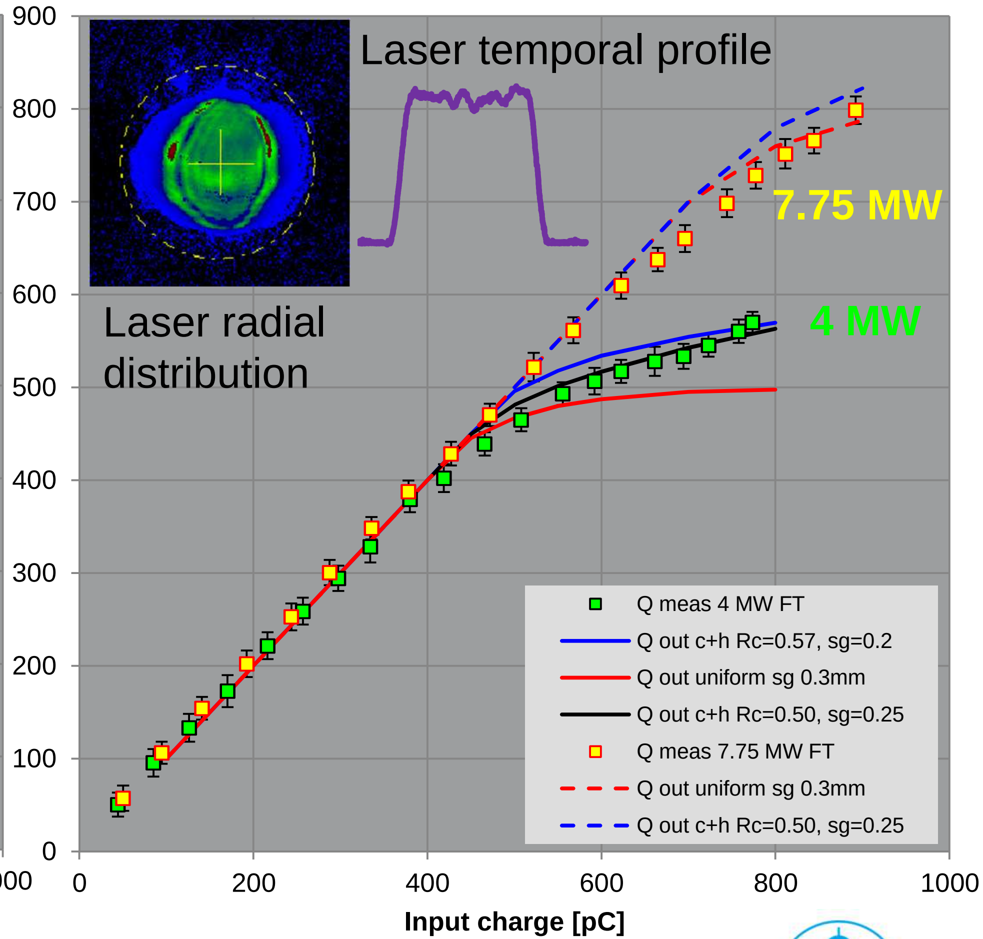
***data taken on different shift, uncertainty in phase is > 5 °**

…and to first order for different Gun power, phase, temporal profile and radial size from measurements taken in 2013.

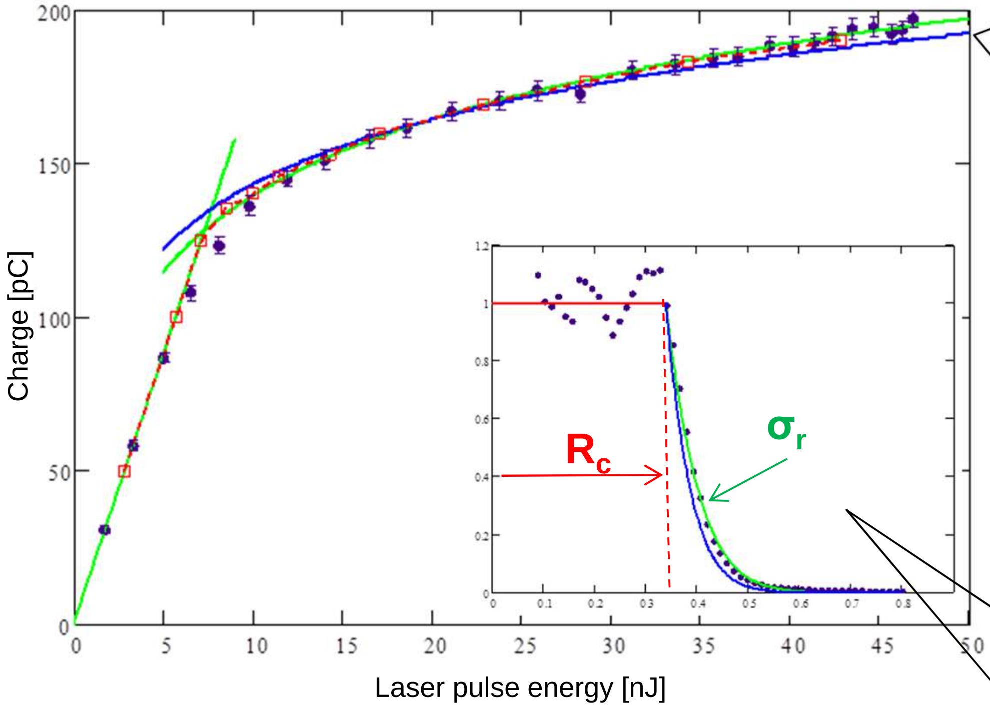
Extracted charge vs laser pulse energy from 2013 for 1.2 mm beam diameter with Gaussian σ_t=1.06ps at MMMG



Extracted charge vs laser pulse energy from 2013 for 1.2 mm beam diameter with FWHM=17 ps Flat Top at MMMG



Using M. Krasilnikov's model with the core radius R_c and halo Gaussian σ_r found from the laser radial profile, and fitting only Qmax, one gets fairly good agreement with ASTRA and with experimental measurements in the saturated region



● Measured charge, Pgun=1.5 MW, BSA=0.8mm

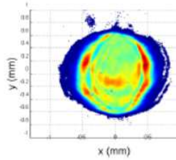
Core + Halo model R_c=0.34 mm, σ_r=0.13 mm

Core + Halo model R_c=0.34 mm, σ_r=0.15 mm

ASTRA Core + Halo R_c=0.34 mm, σ_r=0.13 mm

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

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



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

Qmax is the only fit parameter for the model while R_c and σ_r are those found from the laser profile data. QE is inferred from the unsaturated (linear) curve $Q_{exp}=2\cdot QE\cdot E_{laser}$

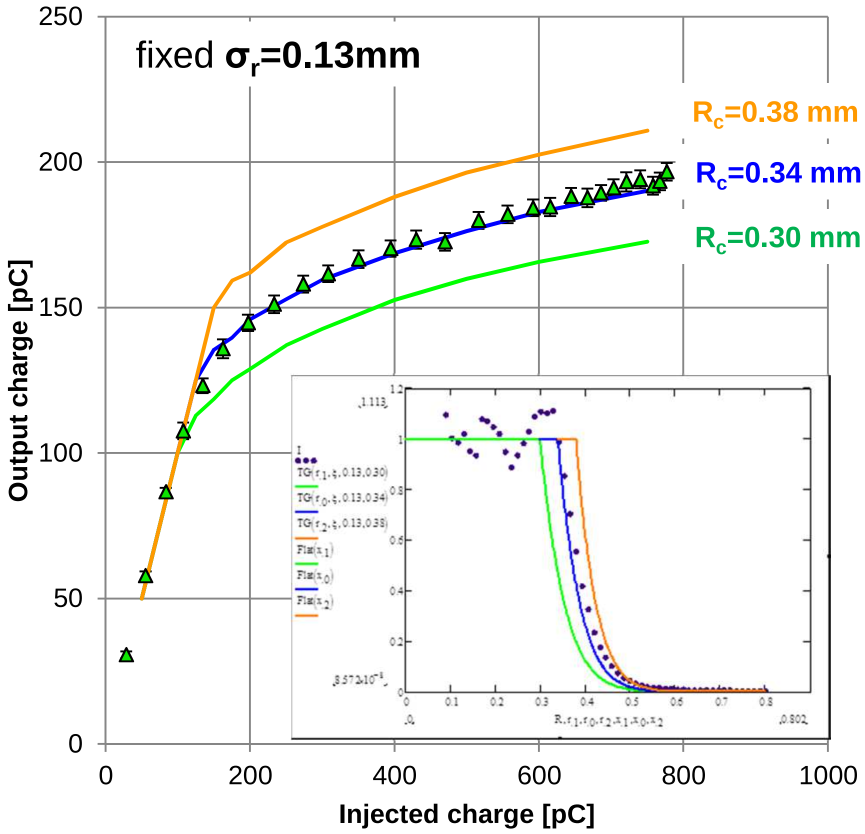
$$F_l(r) = \frac{E_l}{\pi R_c^2 + 2\pi\xi{\sigma_r}^2}\begin{cases} 1, & if\ \ r \le R_c \\ \xi e^{\frac{R_c^2-r^2}{2\sigma_r^2}}, & if\ r > R_c \end{cases}$$

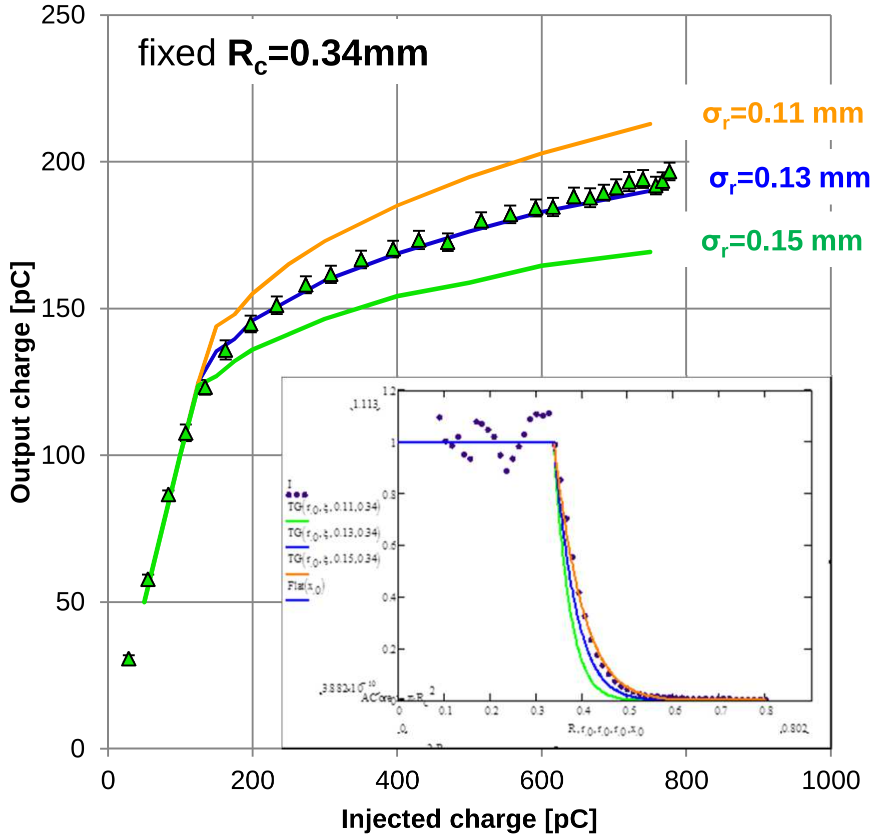
$$\rho_Q(r) = \frac{2QE\cdot E_l}{\pi R_c^2 + 2\pi\xi{\sigma_r}^2}\begin{cases} 1, & if\ \ r \le R_c \\ \xi e^{\frac{R_c^2-r^2}{2\sigma_r^2}}, & if\ r > R_c \end{cases}$$

$$\eta = \frac{2\sigma^2}{R^2}$$

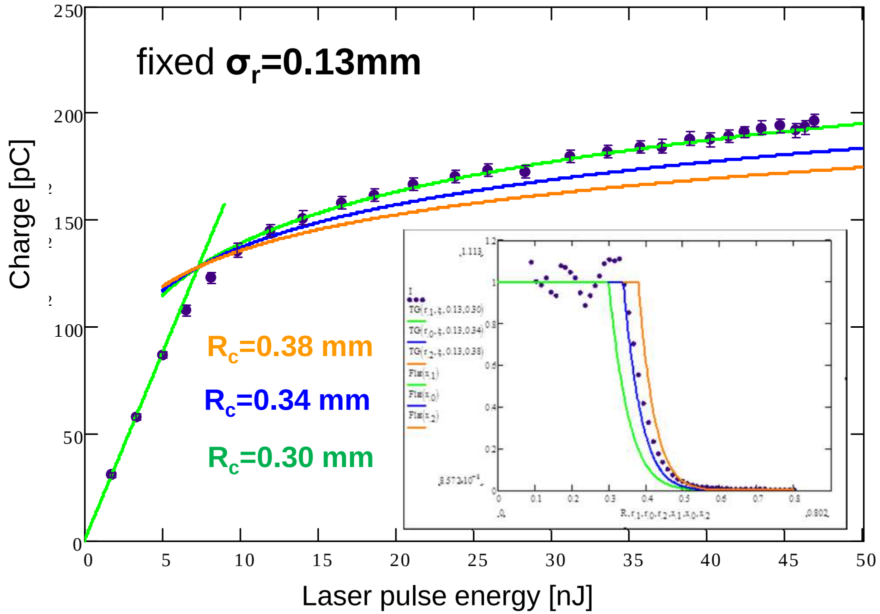
The following graphs show the sensitivity of ASTRA simulations to the core + halo parameters R_c and σ_r

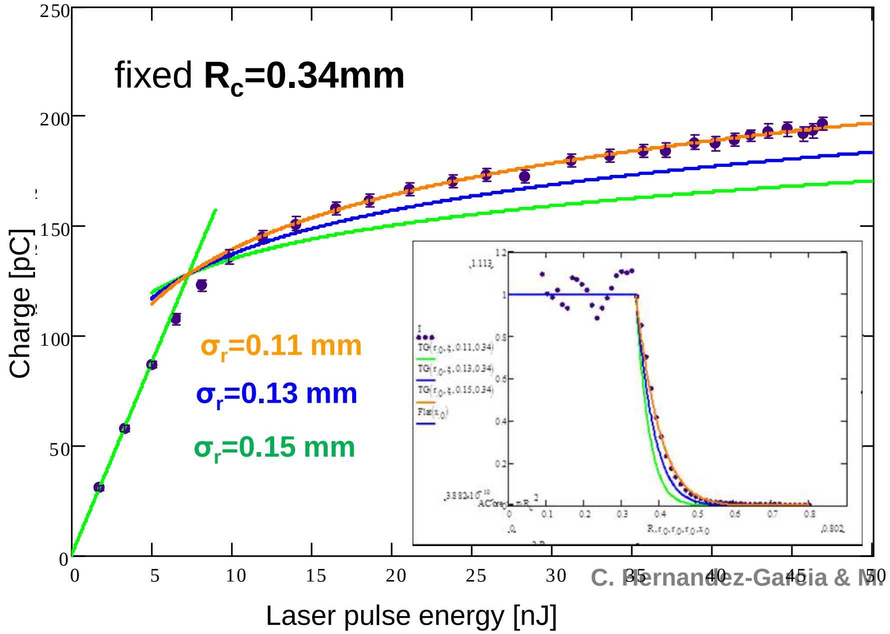
Extracted charge vs laser pulse energy for temporal Gaussian σ_t=1.5 ps
BSA=0.8mm Gun Power = 1.5MW and Gun Phase φ0 - 90°





The following graphs shows the sensitivity of the semi-analytical model to the core + halo parameters R_c and σ_r





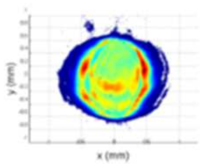
$$F_l(r) = \frac{E_l}{\pi R_c^2 + 2\pi\xi\sigma_r{}^2}\begin{cases} 1, & if\ r \le R_c \\ \xi e^{\frac{R_c^2 - r^2}{2\sigma_r^2}}, & if\ r > R_c \end{cases}$$

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

$$\eta = \frac{2\sigma^2}{R^2}$$

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

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

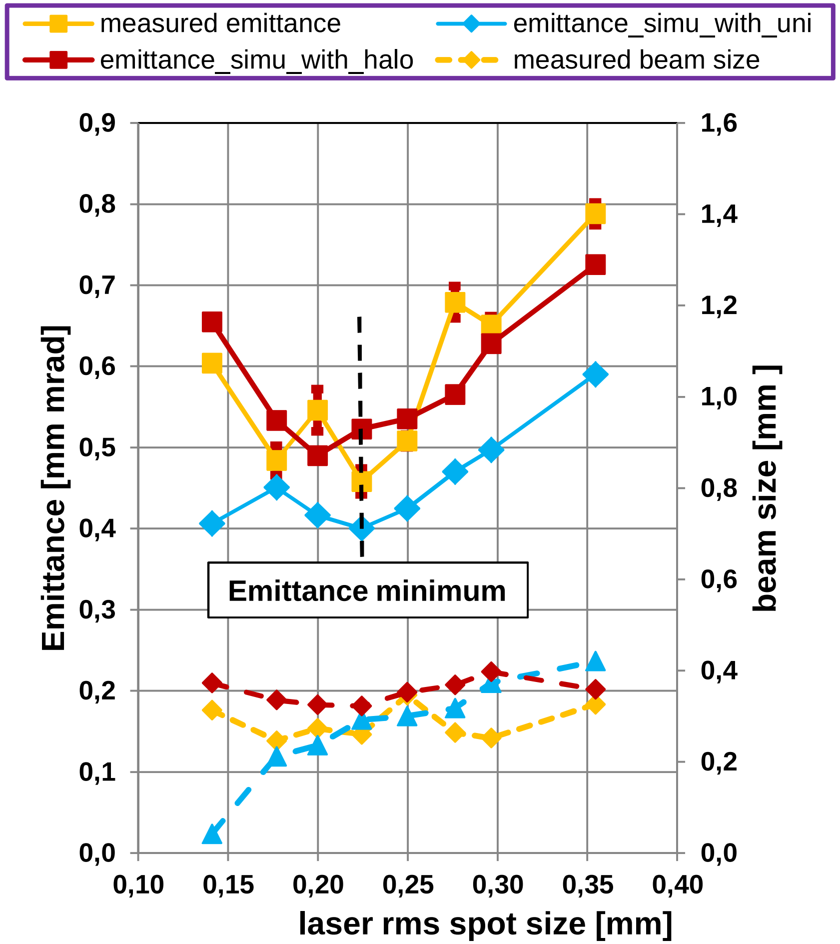


$$Q_{halo} = \frac{\eta}{1 + \xi \cdot \eta}\begin{cases} \xi \cdot Q_{exp}, & if\ \xi \cdot Q_{exp} \le Q_{max} \\ Q_{max} \cdot \left(1 + \ln \frac{\xi \cdot Q_{exp}}{Q_{max}}\right) & if\ \xi \cdot Q_{exp} > Q_{max} \end{cases}$$

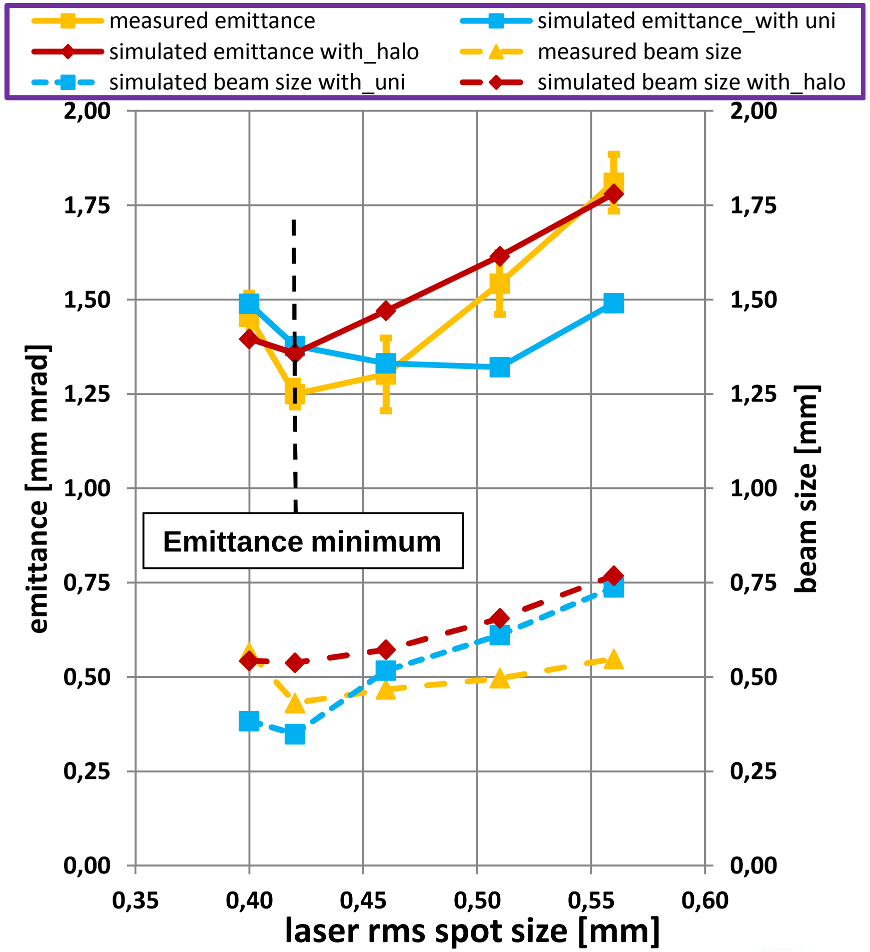
Qmax has been kept fixed for all shown cases

Using core+halo input distributions in ASTRA renders closer agreement with emittance measurements than just using uniform core input distributions*

0.1 nC bunch charge



1 nC bunch charge



*ASTRA simulations by Q. Zhao (PITZ)

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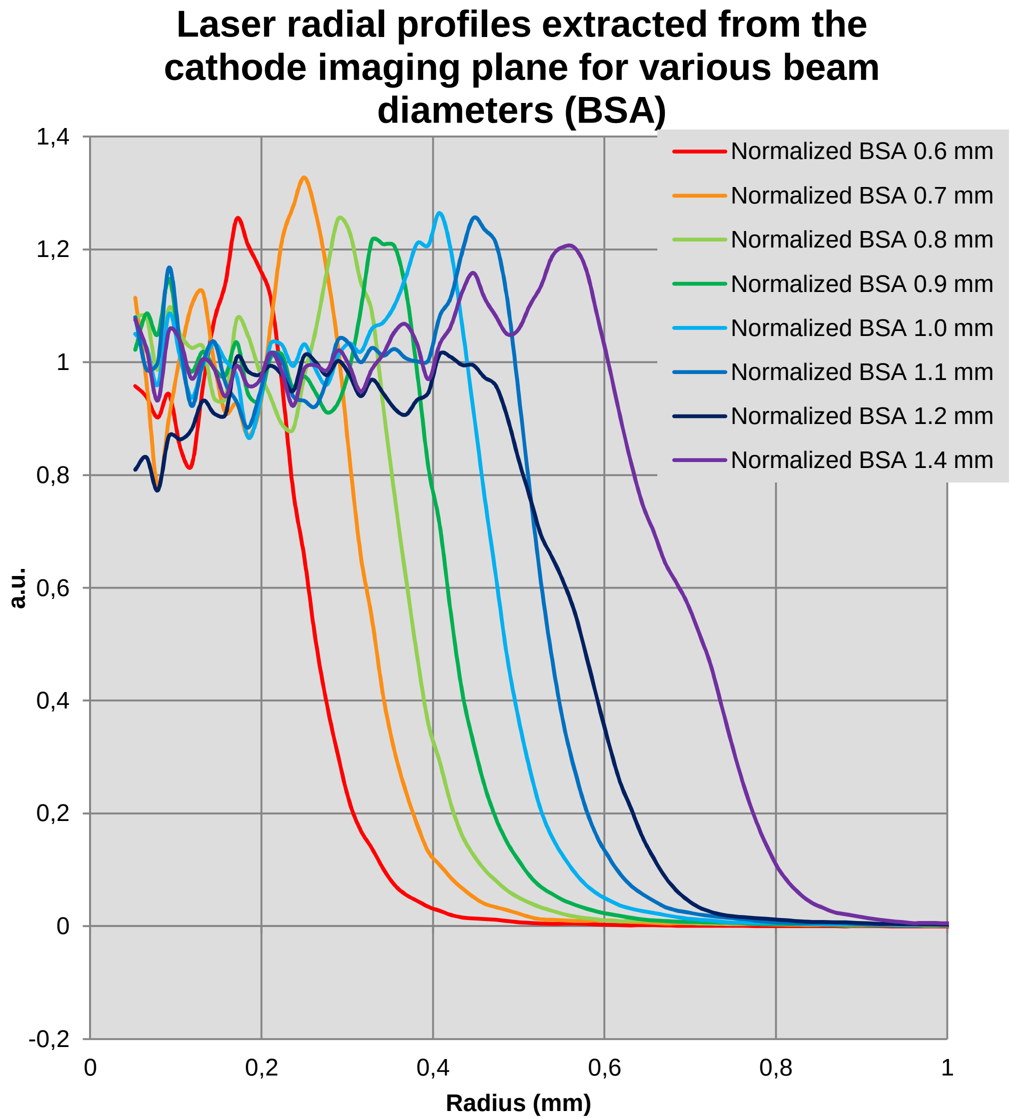
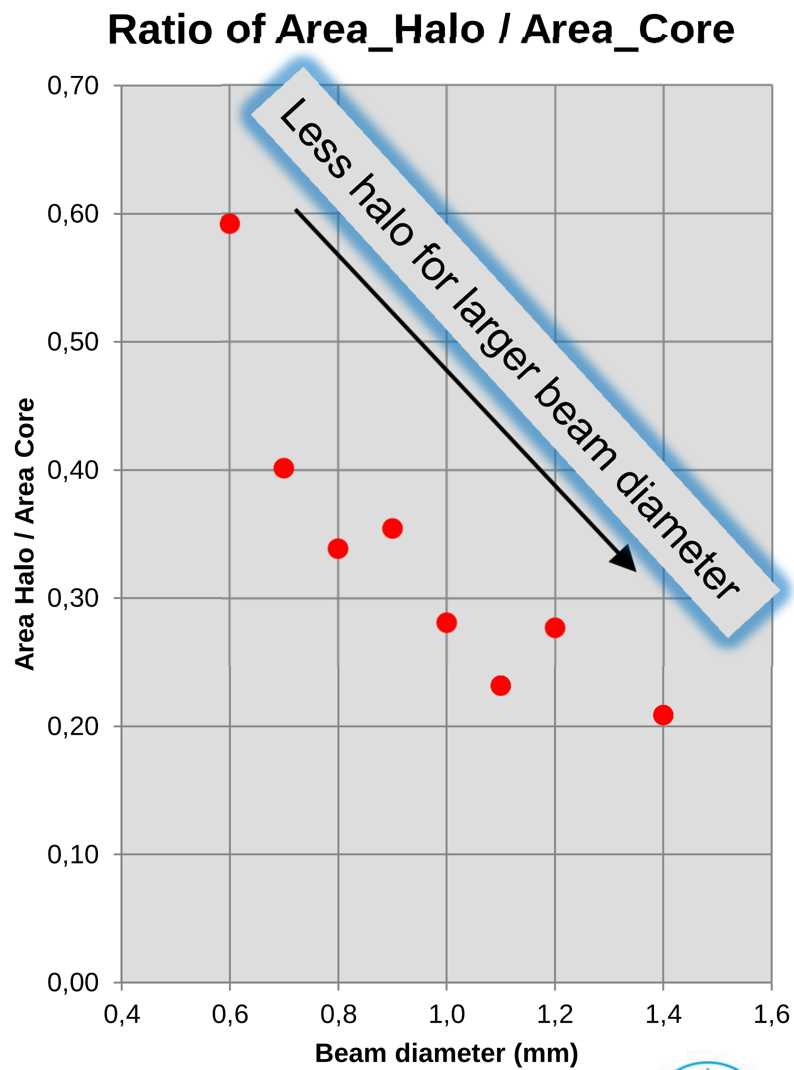
Our hypothesis about Halo decreasing as the beam diameter increases is confirmed by measured laser radial profiles…

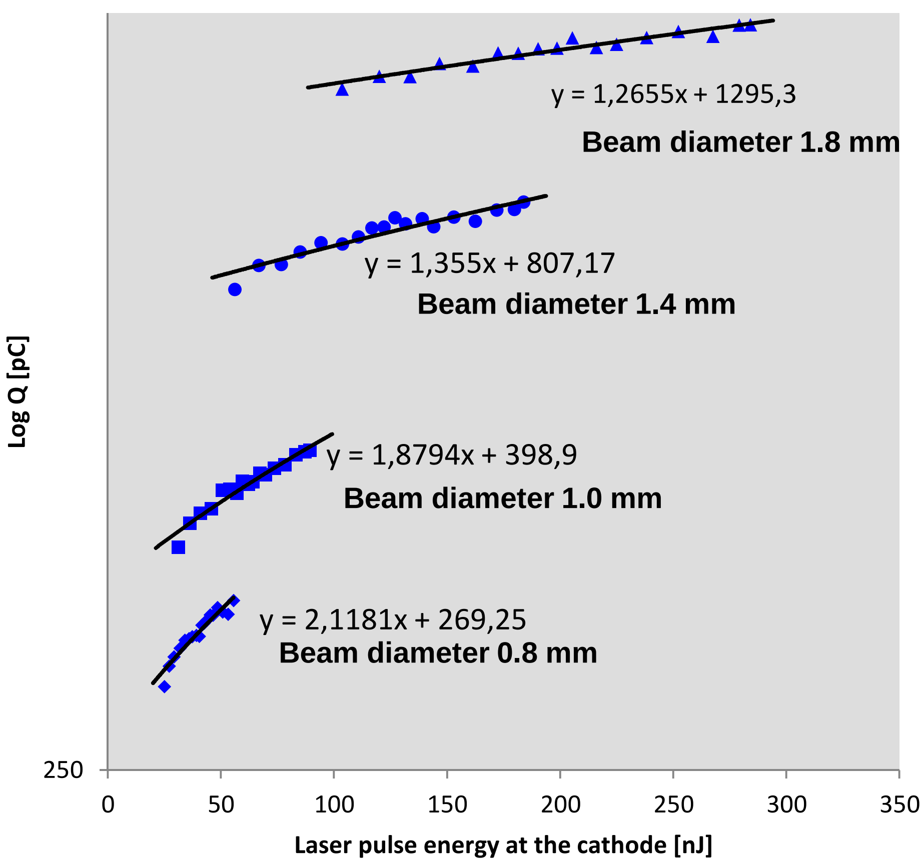




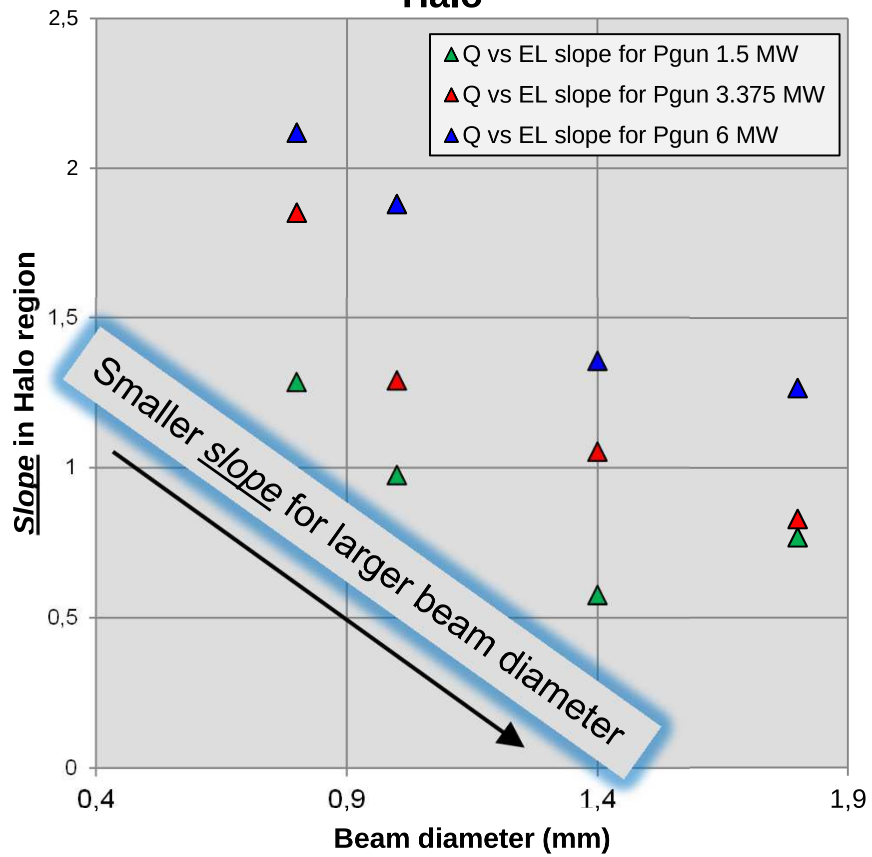
…and also by the electron beam data, where less charge is extracted from Halo for larger beam diameter

- The *slope* indicates that charge continues to be extracted from the saturated regions even though charge from core has saturated

Example: Pgun 6 MW

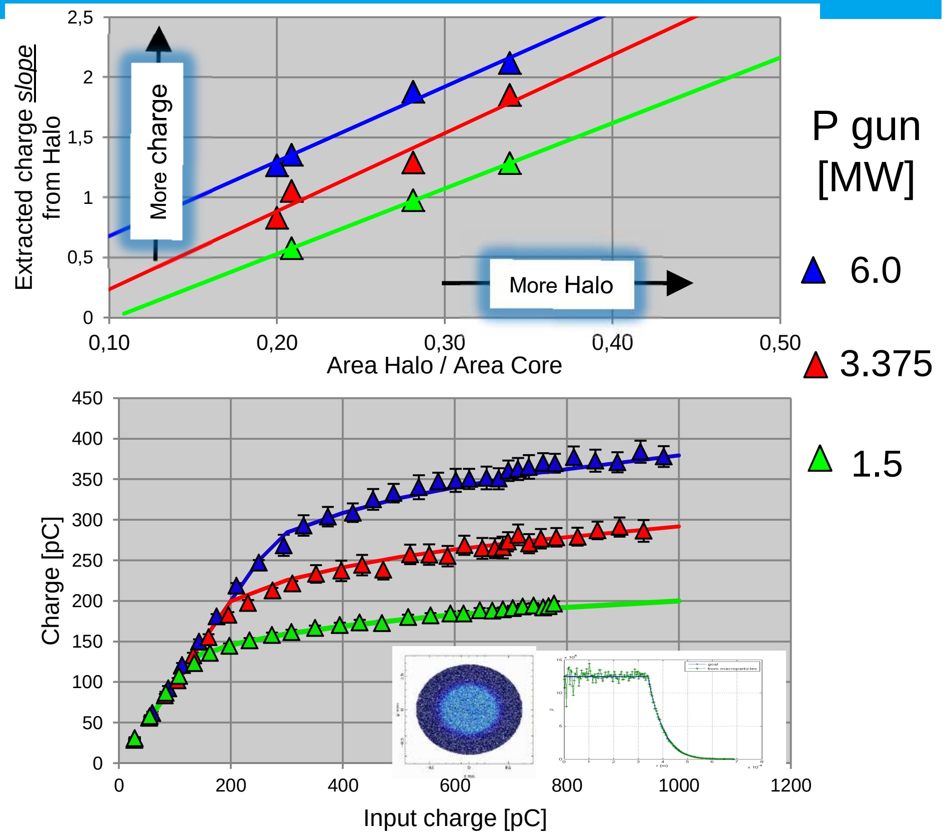


Q vs Laser pulse energy SLOPE: Large slope = more charge -> more Halo

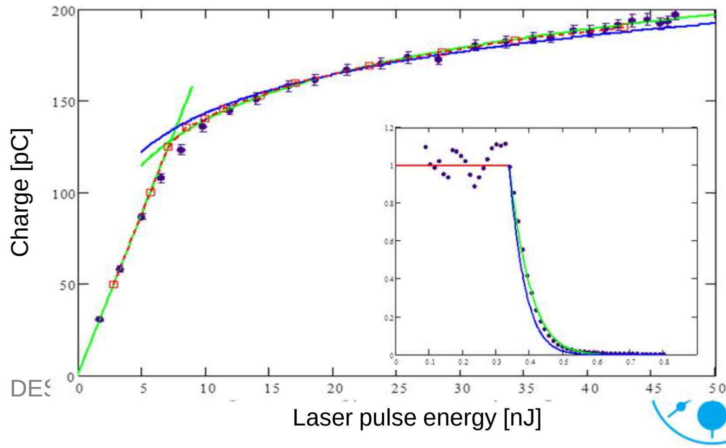


Conclusions:

- The relationship between the **amount** of **halo** in the measured **laser** radial distribution seems to be **proportional** to the **amount** of **extracted charge** in the saturated emission region.



- The **measured** charge vs laser pulse energy can be reproduced by **ASTRA** simulations when **core + halo** radial profiles are utilized as input distributions based on fits to actual laser radial profiles.



- Using M. Krasilnikov's **model** with the **core** radius and **halo** Gaussian σ_r found from the laser radial profile, and fitting only Qmax, one gets fairly good agreement with **ASTRA** and with experimental **measurements** in the saturated region

BACKUP SLIDES

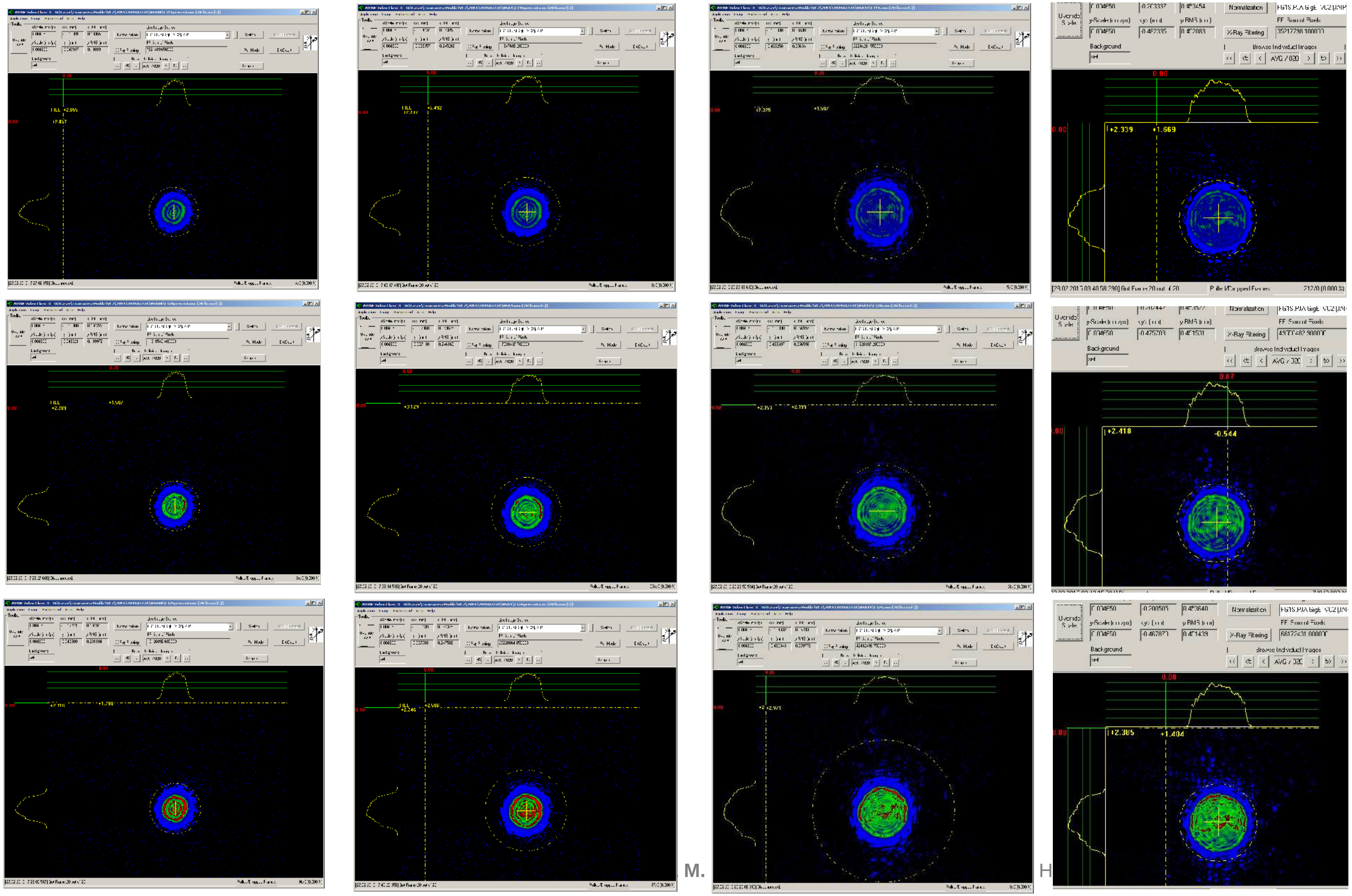
> BACKUP

> SLIDES

The imaged laser spot on the virtual cathode plane shows larger halo (blue) / core for smaller beam diameters

Beam diameter: 0.8 mm | 1.0 mm | 1.4 mm | 1.8mm

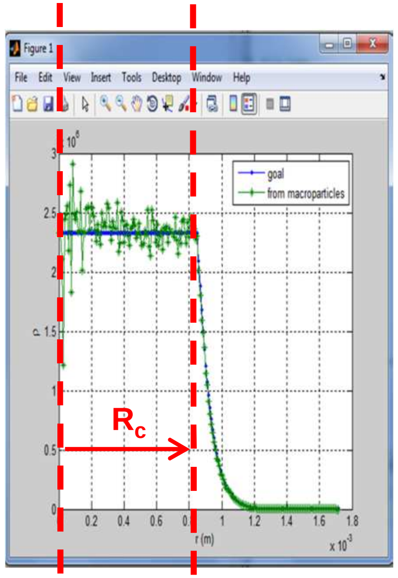
Relative Laser Intensity: 15% | 20% | 25%



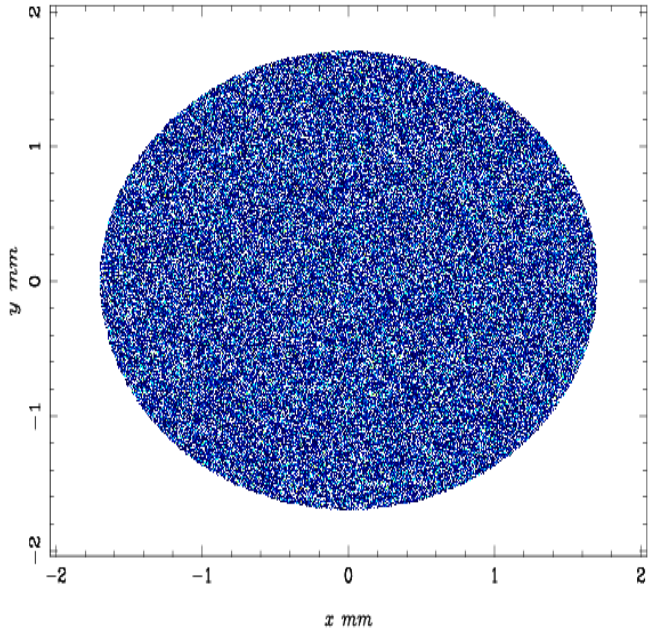
M. H

Step 6: This is the last step in the procedure

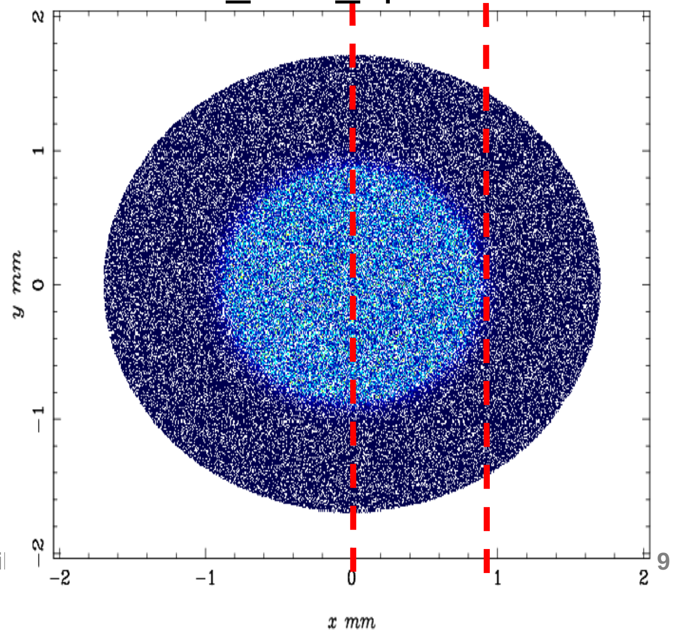
- The script takes the uniform baseline distribution and makes a new distribution composed of a flat-top core with radius R_c, and a decaying Gaussian-like halo shifted by R_c and with σ_r by modification of the macroparticle charge



for_c+h_BSA_1p8mm.ini

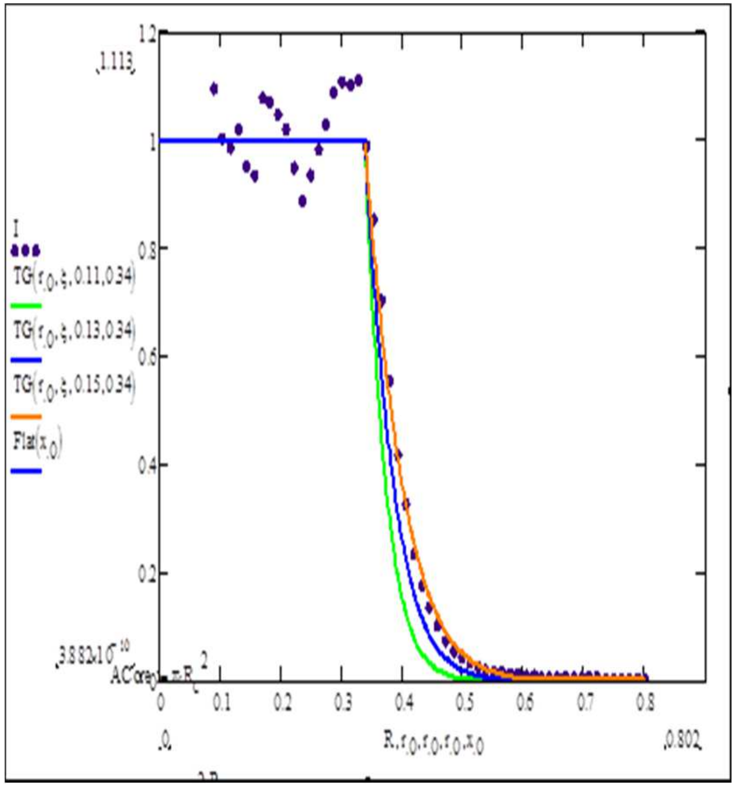


c+h_BSA_1p8mm.ini

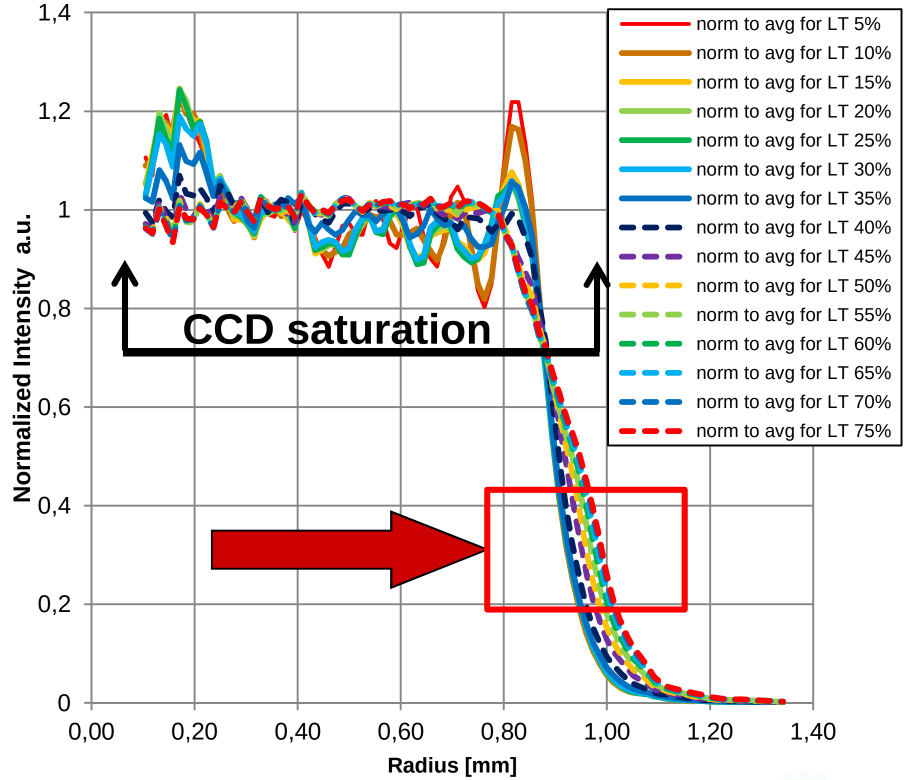


CAUTION!!! Note that halo changes also with increased Laser Transmission (LT).

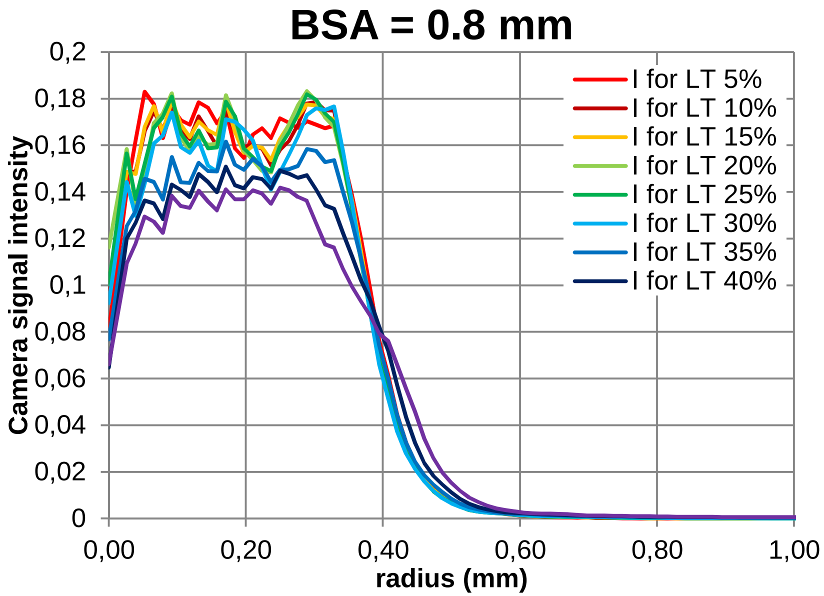
- This means that if the VC2 image is captured with *low LT*, R_c and σ_r are found fitting *that* laser radial profile

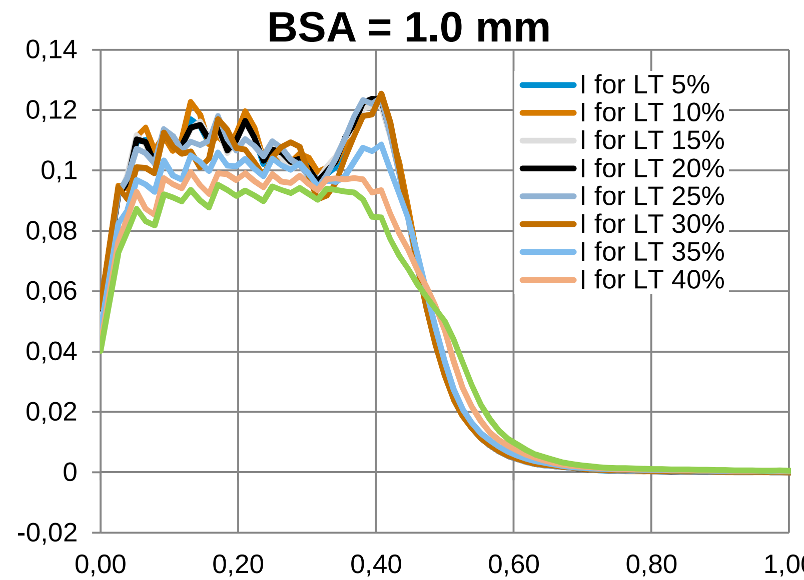


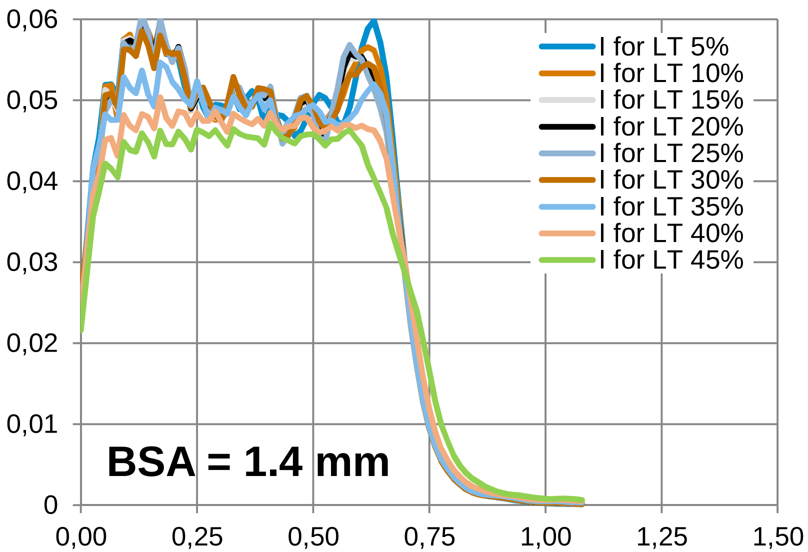
- HOWEVER often the emittance is measured with *higher* LT values, which are not VC2 captured, but that certainly *changes the halo profile*

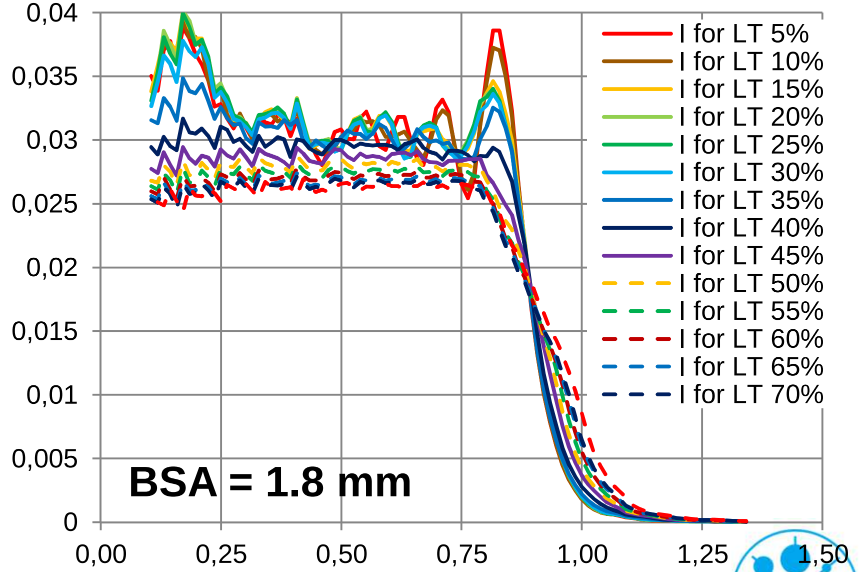


Laser radial profiles extracted from measured transverse distributions (integrated over ϕ) for various beam diameters









Size (M. Gross)

BSA size [mm]*	Cathode camera			VC2			Size ratios Cathode/VC2			
	xRMS	yRMS	xyRMS	xRMS	yRMS	xyRMS	x	y	xy	BSA/VC2 xyRMS
0.08	0.066	0.065	0.065	0.064	0.063	0.063	1.03	1.03	1.03	1.26
0.16	0.056	0.068	0.062	0.055	0.062	0.058	1.02	1.10	1.06	2.74
0.22	0.072	0.085	0.078	0.067	0.078	0.072	1.07	1.09	1.08	3.04
0.33	0.095	0.107	0.101	0.091	0.106	0.098	1.04	1.01	1.03	3.36
0.75	0.202	0.21	0.206	0.203	0.205	0.204	1.00	1.02	1.01	3.68
1.13	0.3	0.301	0.300	0.306	0.294	0.300	0.98	1.02	1.00	3.77
1.52	0.413	0.402	0.407	0.409	0.4	0.404	1.01	1.01	1.01	3.76
1.98	0.511	0.499	0.505	0.504	0.493	0.498	1.01	1.01	1.01	3.97
2.37	0.624	0.604	0.614	0.618	0.588	0.603	1.01	1.03	1.02	3.93
3.5	0.843	0.817	0.830	0.836	0.791	0.813	1.01	1.03	1.02	4.30
						Average:	1.02	1.04	1.03	

> Laser beam a little bit bigger on photocathode (1 to 3%)

> *BSA (calibration?) – Ratio BSA size to xyRMS about 4 for flat tops, reduced for smaller sizes

- No flat top for small BSA

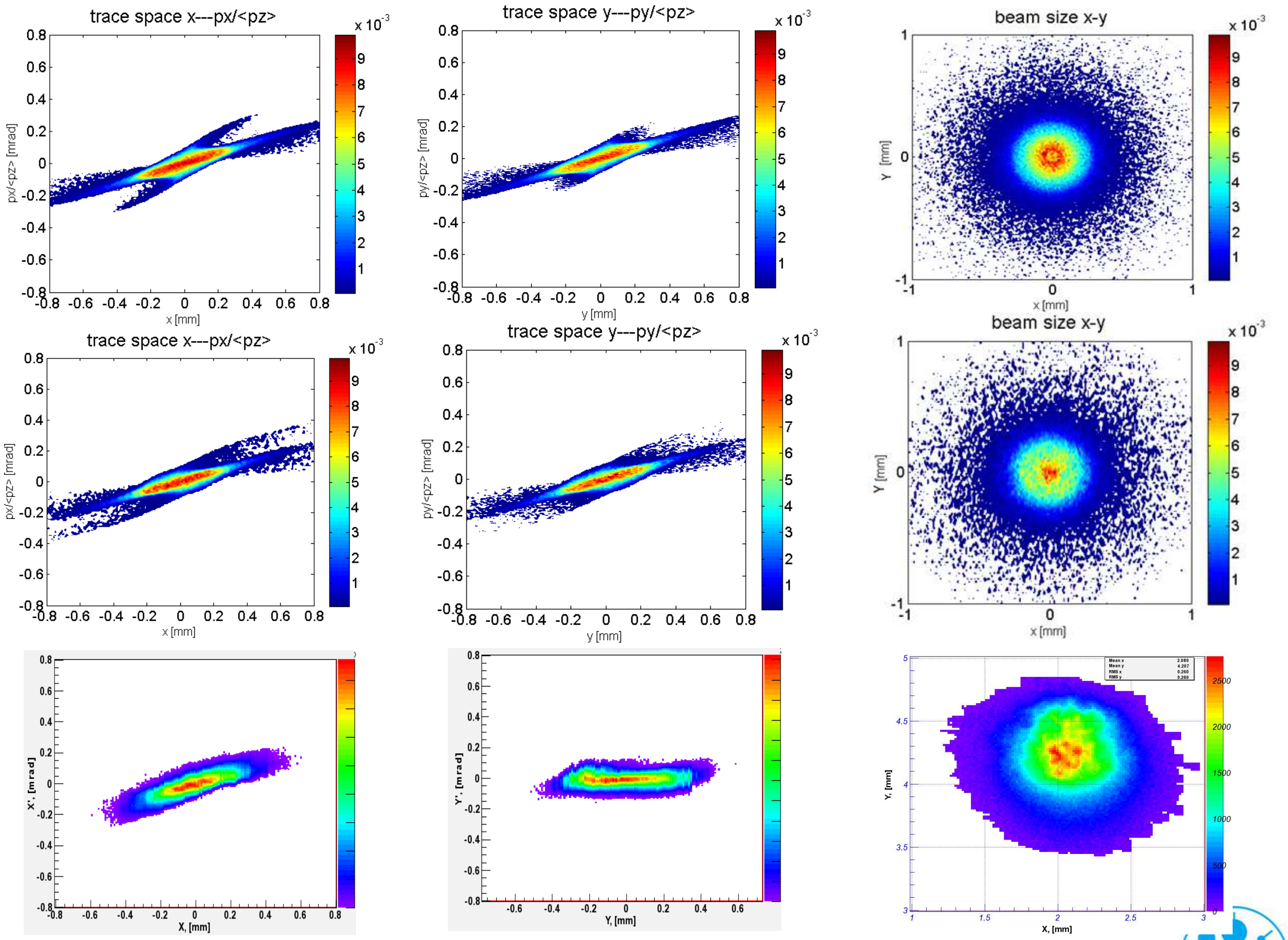
Phase space BSA = 0.9 mm, 100 pC, at EMSY1 (Q. Zhao)

X Phase space | Y Phase space | X-Y Beam size

Uniform

Core+ halo

Experiment



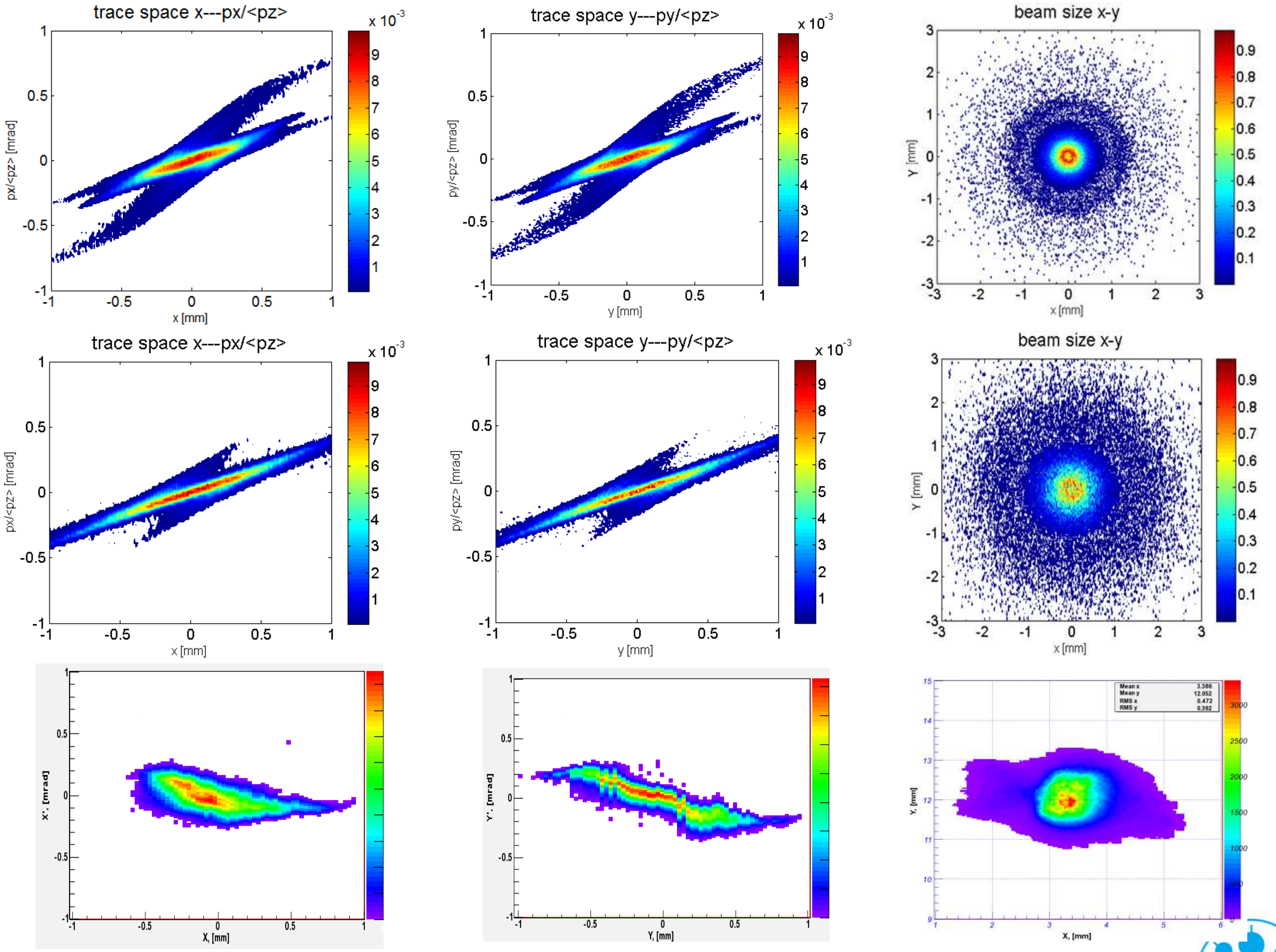
Phase space BSA = 1.6 mm, 1 nC, at EMSY1 (Q. Zhao)

X Phase space | Y Phase space | X-Y Beam size

Uniform

Core+halo

Experiment



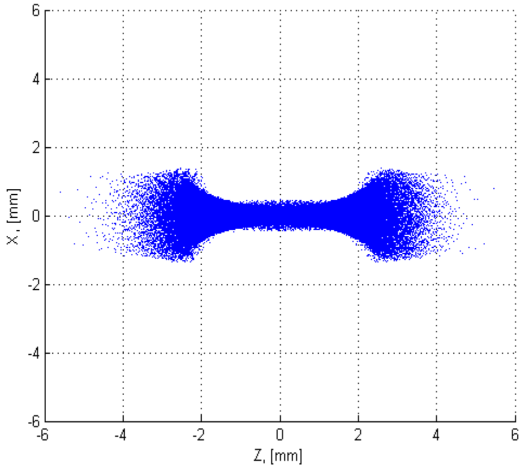
Particle distribution x-z, Z at EMSY1 (Q. Zhao)

BSA0.9mm 100 pC

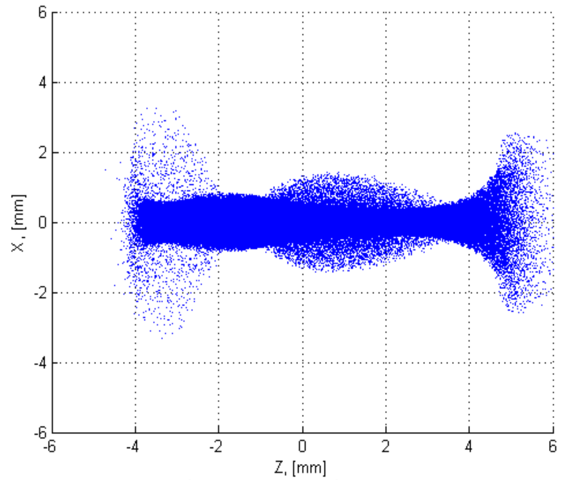
BSA1.6mm 1 nC

Uniform

A= xrms/zrms=0.265/1.387=0.191

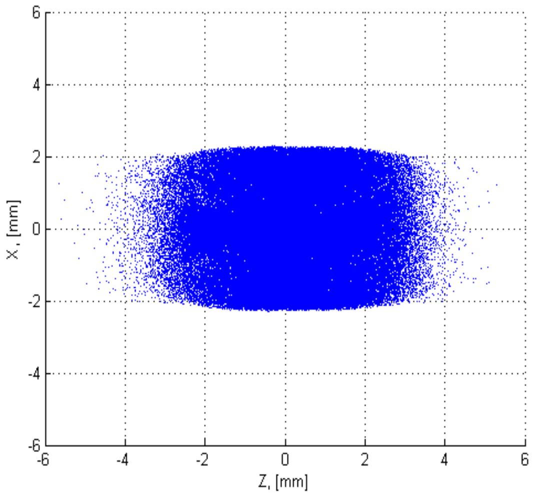


A= xrms/zrms=0.349/2.221=0.157

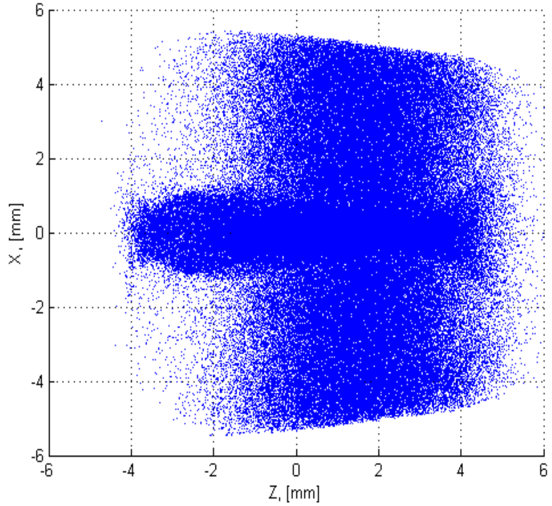


Core+halo

A= xrms/zrms=0.310/1.385=0.224



A= xrms/zrms=0.537/2.201=0.244

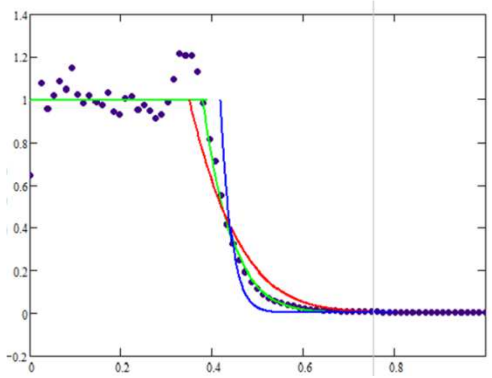


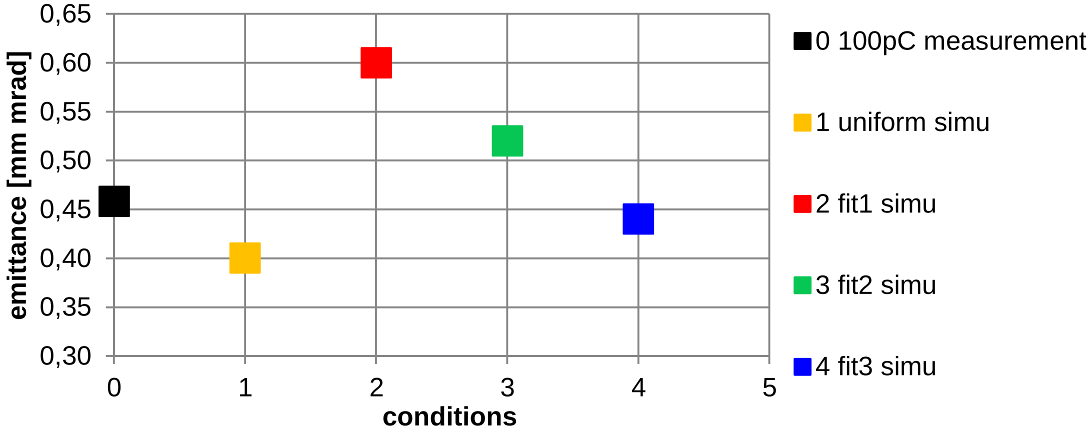
Laser halo intensity distribution effect to emittance (Q. Zhao)

- The laser on VC2(virtual cathode) data recorded with low Laser transmission (LT)~18%, but for high bunch Charge, the LT will be much higher. So from above simulation, the halo fit from data On VC2 is not considered the halo intensity distribution.

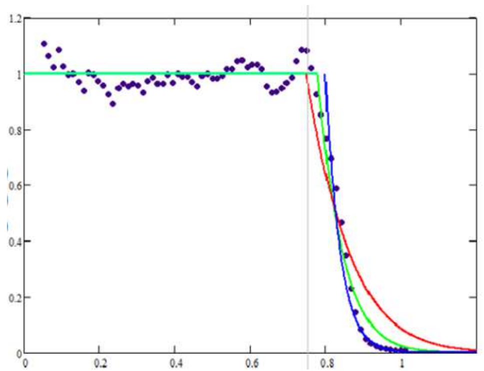
conditions: 0-measurement, 1-uniform simu, 2-fit1 simu, 3-fit2 simu, 4-fit3 simu

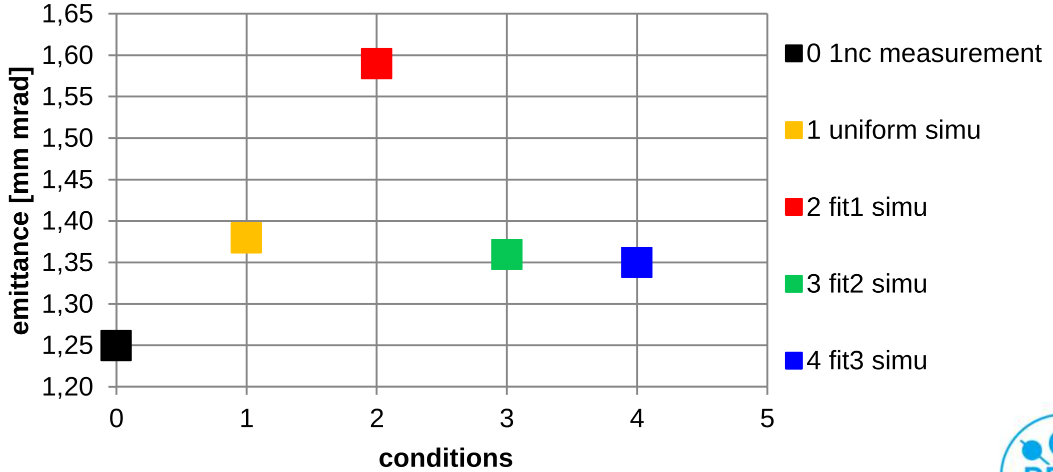
100pC BSA= 0.9mm





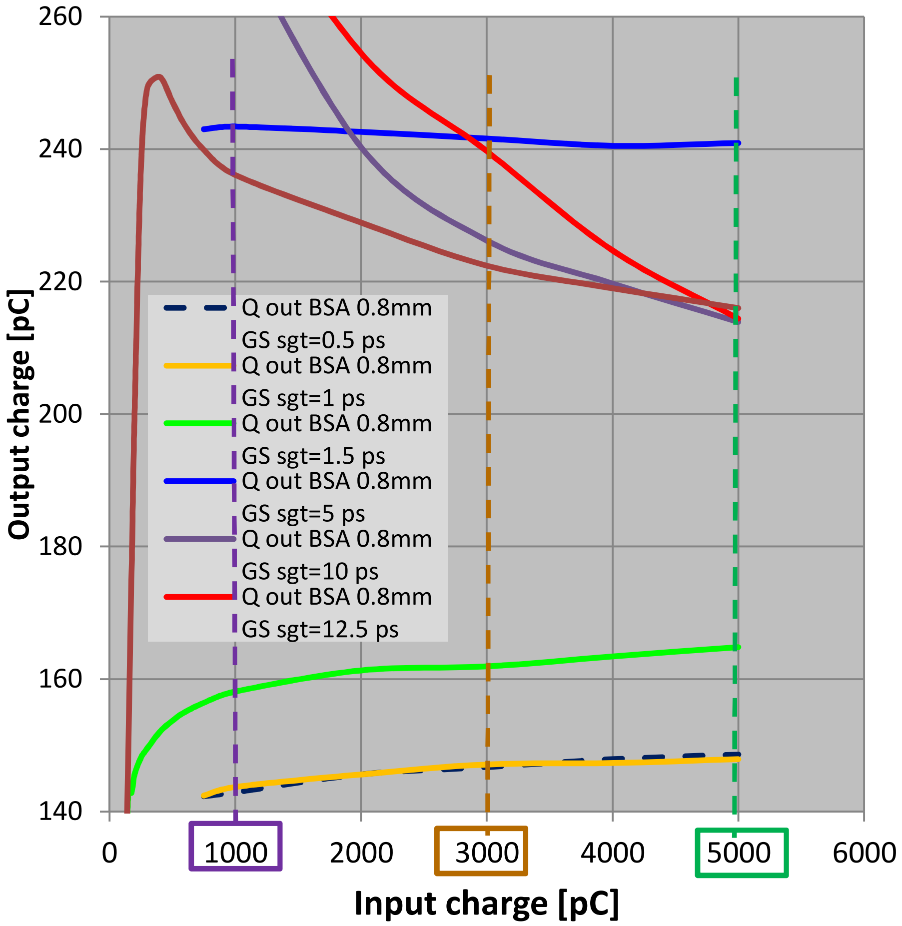
1 nC BSA= 1.6mm



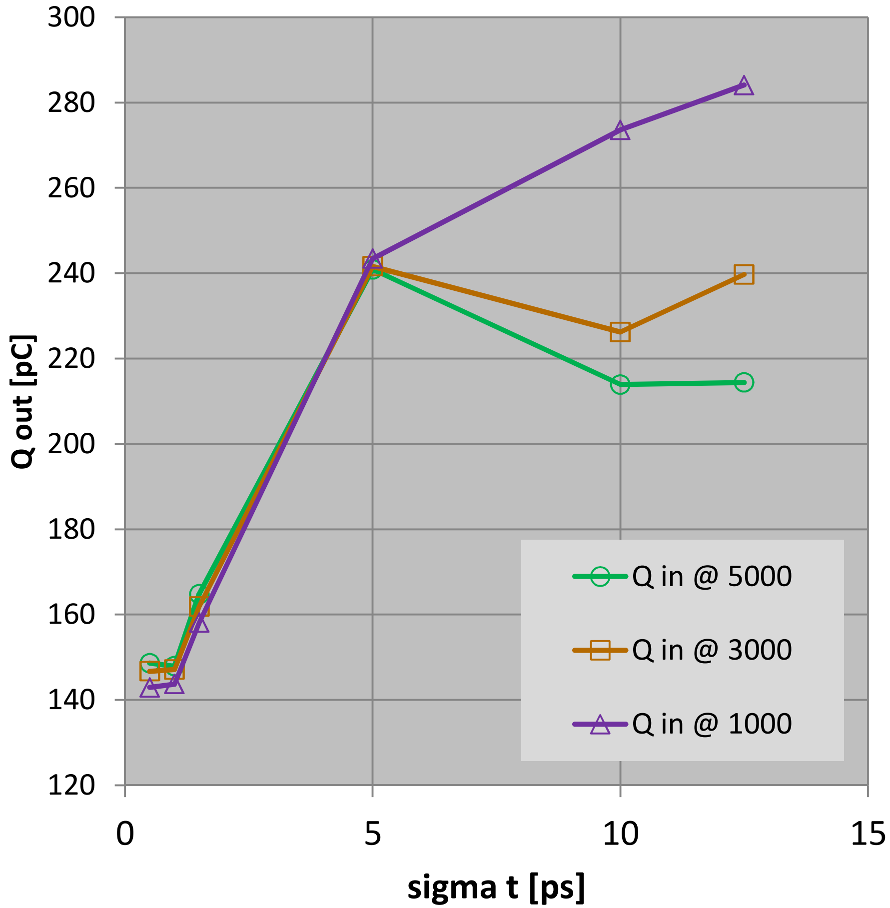


The slope of the output charge depends on the initial bunch length

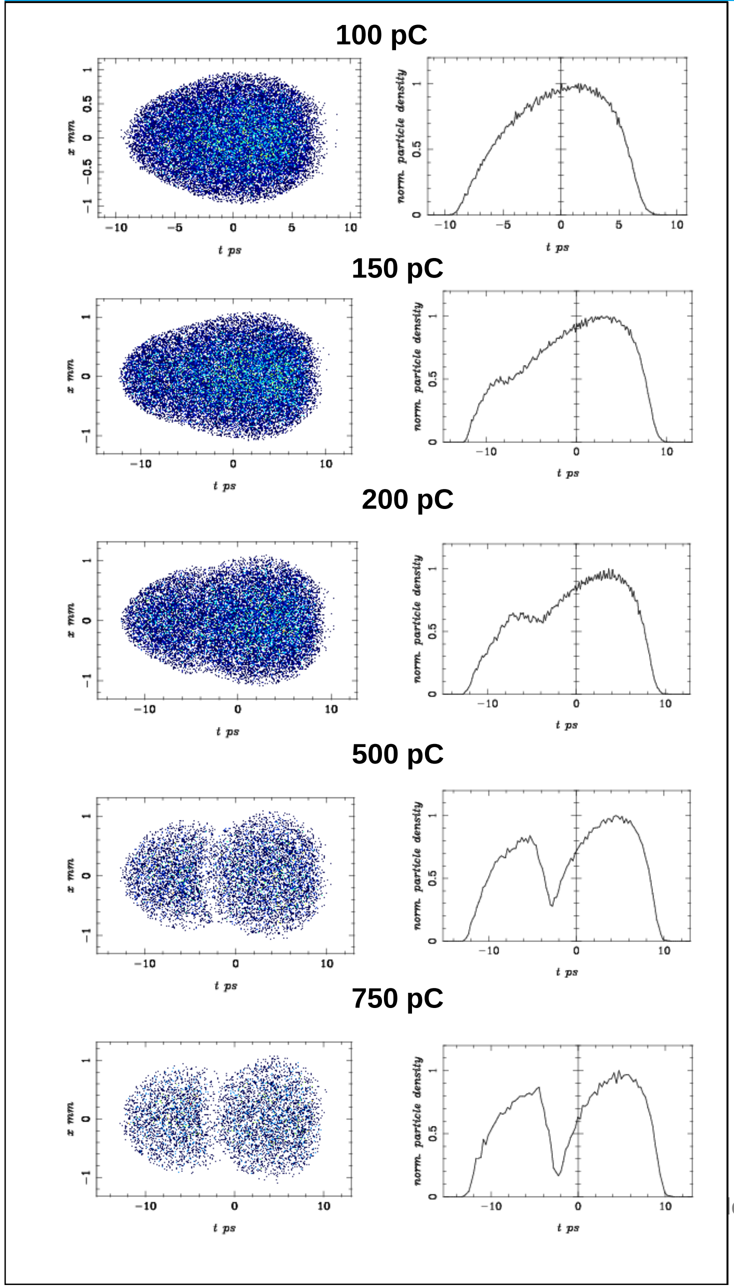
Output charge vs injected charge for Gaussian temporal profiles with varying pulse length

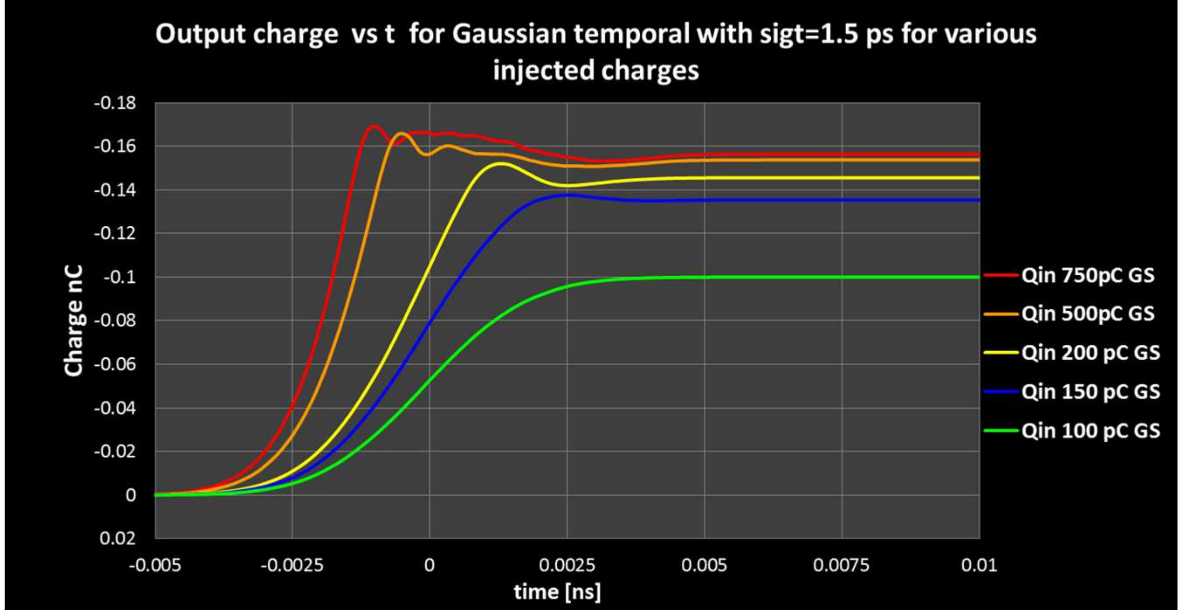


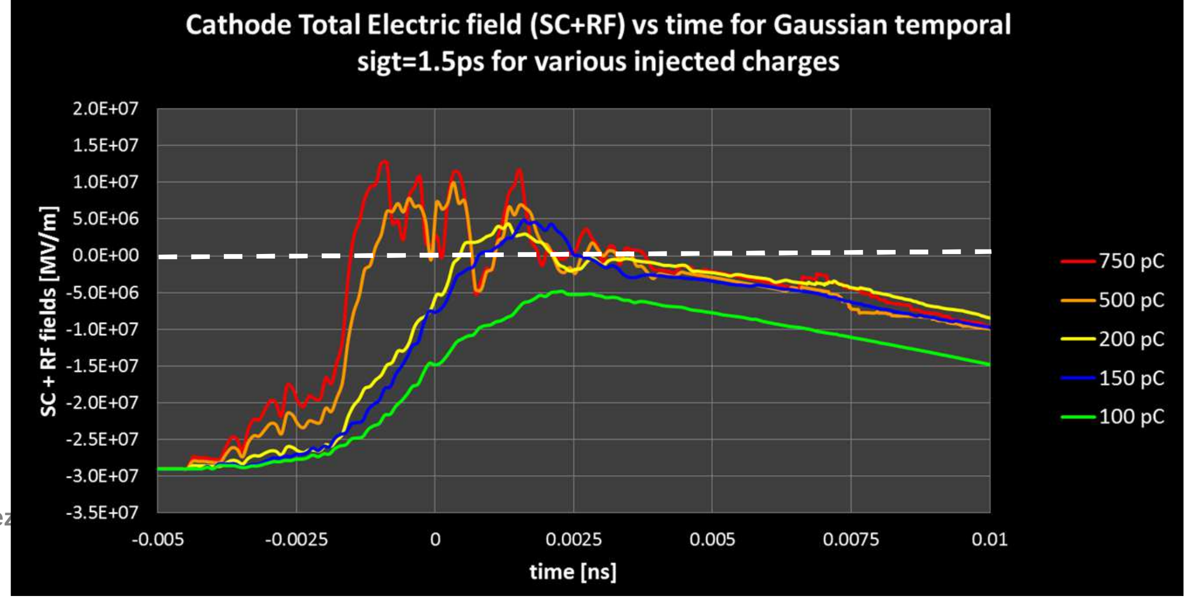
Output charge evolution with time for indicated set of injected charges



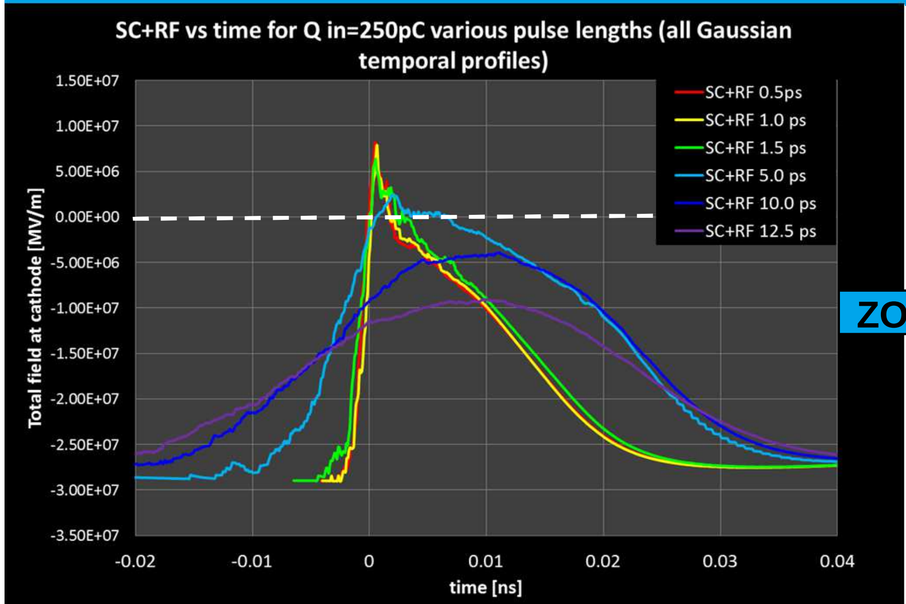
More charge can be extracted as the injected current is increased due to the formation of the virtual cathode



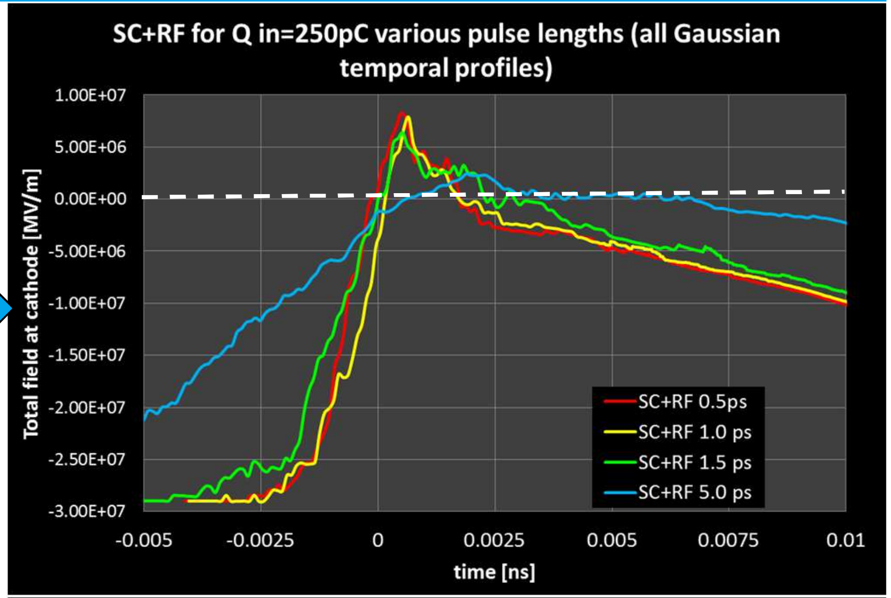


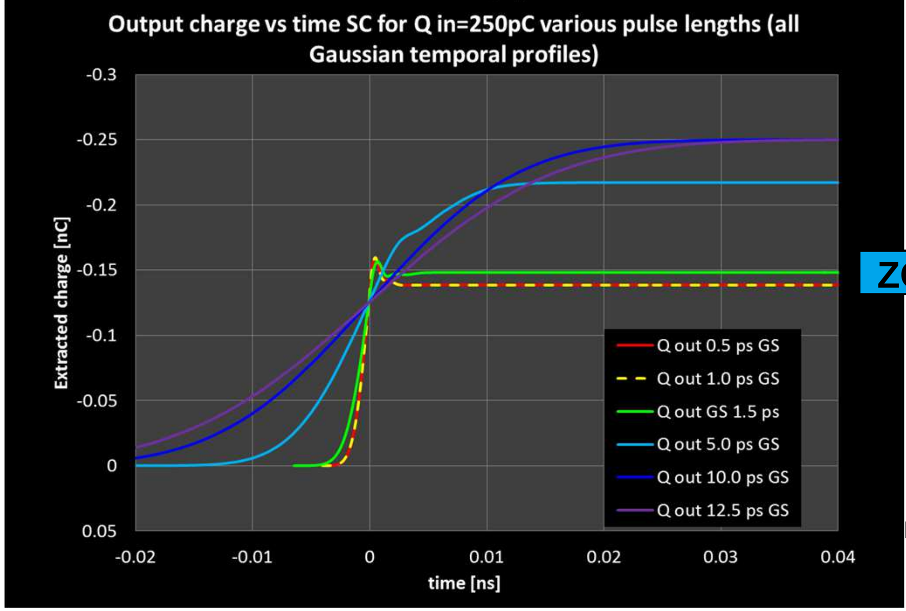


The formation of the virtual cathode is characterized by oscillations in the space charge field at the surface. As the particles at the head of the bunch move away from the surface, the charge density drops increasing the field at the cathode which in turn allows for more charge to be extracted. The process repeats in an oscillatory fashion.



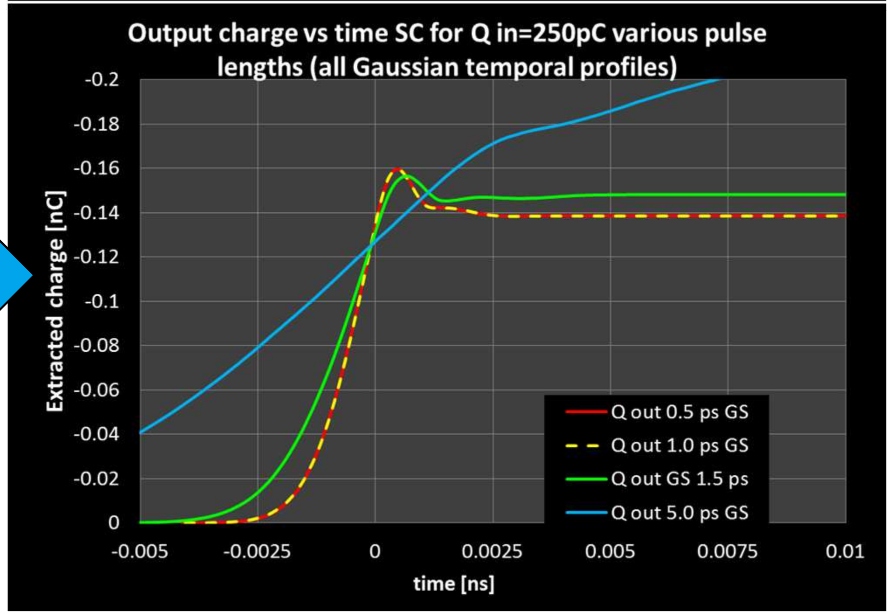
ZOOM IN



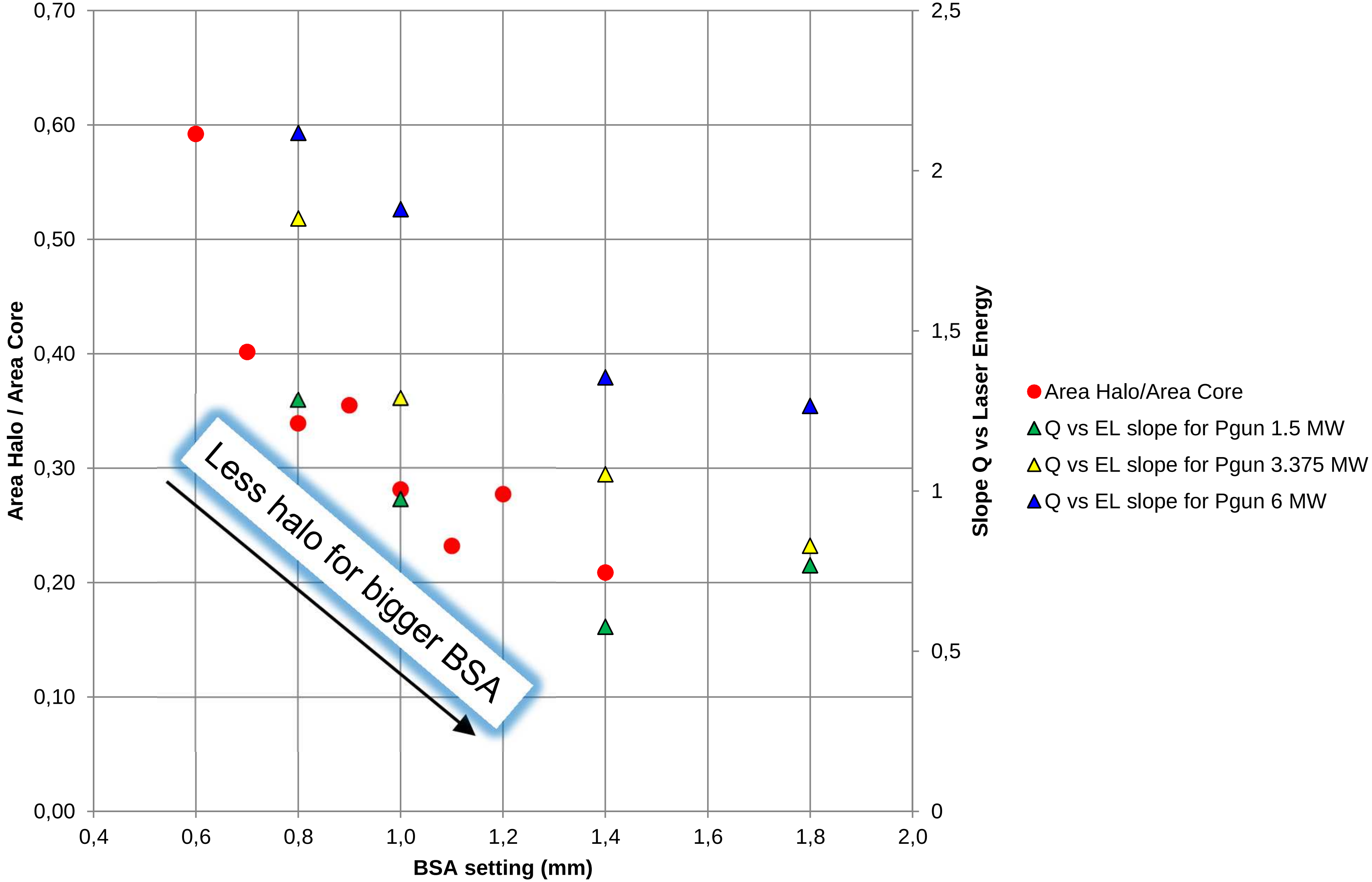


ZOOM IN

Krasilnikov

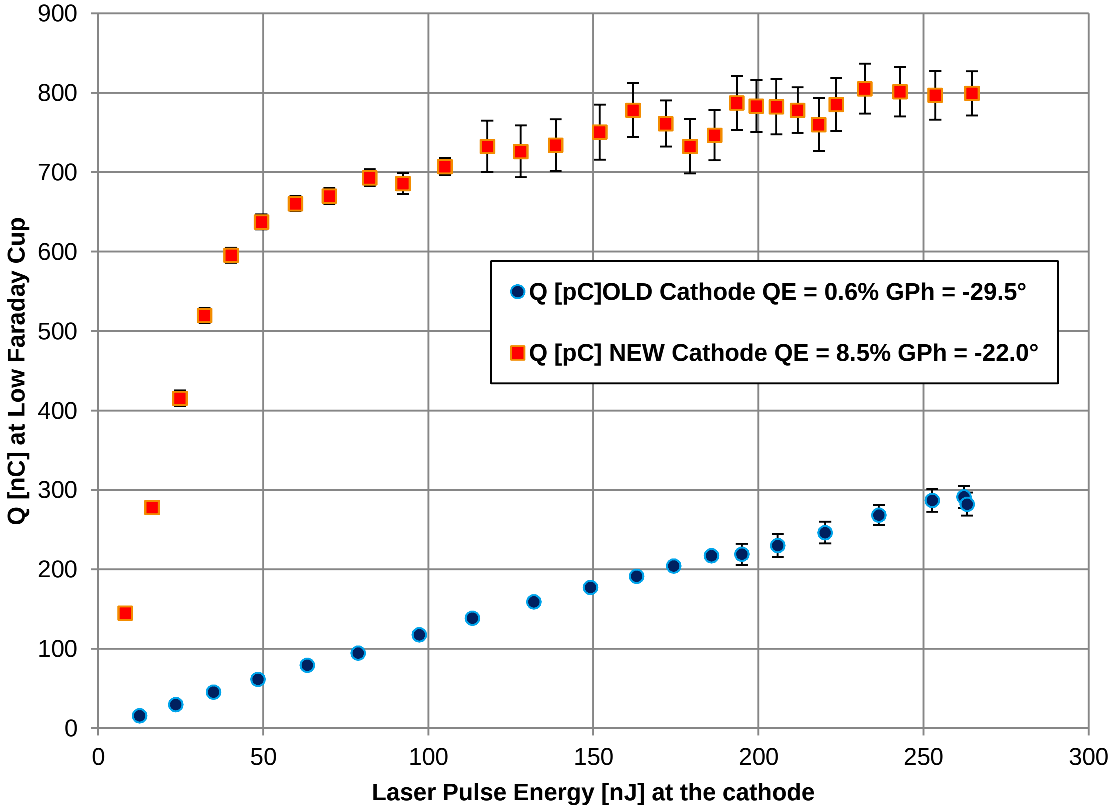


CONCLUSION: Behavior of Halo as a function of BSA is consistent for both, laser radial profile measurements and beam extracted charge



In addition, QE scans for old and new cathodes are drastically different.

- How to reproduce these measurements in simulations if machine parameters are the same for both?
- Pgun = 1.5 MW at Φ_0-90 and BSA = 1.8 mm



Measurements taken on Feb-Mar 2015 consists of 4 BSA settings, each with 9 different Gun power and phase settings = 36 QE scans

		BSA 1.8 mm	BSA 1.4 mm	BSA 1.0 mm	BSA 0.8 mm
	VC2 data taken on:	SHIFT:20150227N Comments:2015028M	SHIFT:20150227A Comments:____	SHIFT:20150227A Comments:____	SHIFT:20150227A Comments:____
P Gun (MW)	Gun SP Phase				
		Charge vs Laser Energy taken on:	Charge vs Laser Energy taken on:	Charge vs Laser Energy taken on:	Charge vs Laser Energy taken on:
1.5	ϕ_0-90°	SHIFT:20150227N Comments:10db scope att in	SHIFT:20150227A Comments:____	SHIFT:20150227A Comments:____	SHIFT:20150227N Comments:___
1.5	MMMG	SHIFT:20150227N Comments:10db scope att in	SHIFT:20150227A Comments:____	SHIFT:20150227A Comments:____	SHIFT:20150227N Comments:#1???
3.375	ϕ_0-90°	SHIFT:20150228M Comments:10db scope att in	SHIFT:20150301M Comments:10db scope att in	SHIFT:20150301A Comments:____	SHIFT:20150302M Comments:____
3.375	ϕ_0-42°	SHIFT:20150228M Comments:10db scope att in	SHIFT:20150301M Comments: Remeasured	SHIFT:20150301A Comments:____	SHIFT:20150302M Comments:_same as MMMG phase
3.375	MMMG	SHIFT:20150228M Comments:10db scope att in	SHIFT:20150301M Comments: Remeasured	SHIFT:20150301A Comments:____	SHIFT:20150302M Comments:____
6	ϕ_0-90°	SHIFT:20150228A Comments:10db scope att in	SHIFT:20150228A Comments:10db scope att in	SHIFT:20150301A Comments:____	SHIFT:20150301N Comments:____
6	ϕ_0-49°	SHIFT:20150228A Comments:10db scope att in	SHIFT:20150228A Comments:10db scope att in	SHIFT:20150301A Comments:____	SHIFT:20150301N Comments:____
6	ϕ_0-30°	SHIFT:20150228A Comments:10db scope att in	SHIFT:20150228A+N Comments:10db scope att in	SHIFT:20150301A+N Comments:____	SHIFT:____ Comments:_same as MMMG phase
6	MMMG	SHIFT:20150228A Comments:10db scope att in	SHIFT:20150228A+N Comments:10db scope att in, FC + ICT	SHIFT:20150301A+N Comments:_Data not taken	SHIFT:20150301N Comments:____

In addition, Virtual Cathode measurements were taken for each BSA as a function of LT.

Data for the old cathode (QE = 0.6%) is also available for the set of parameters indicated by this color

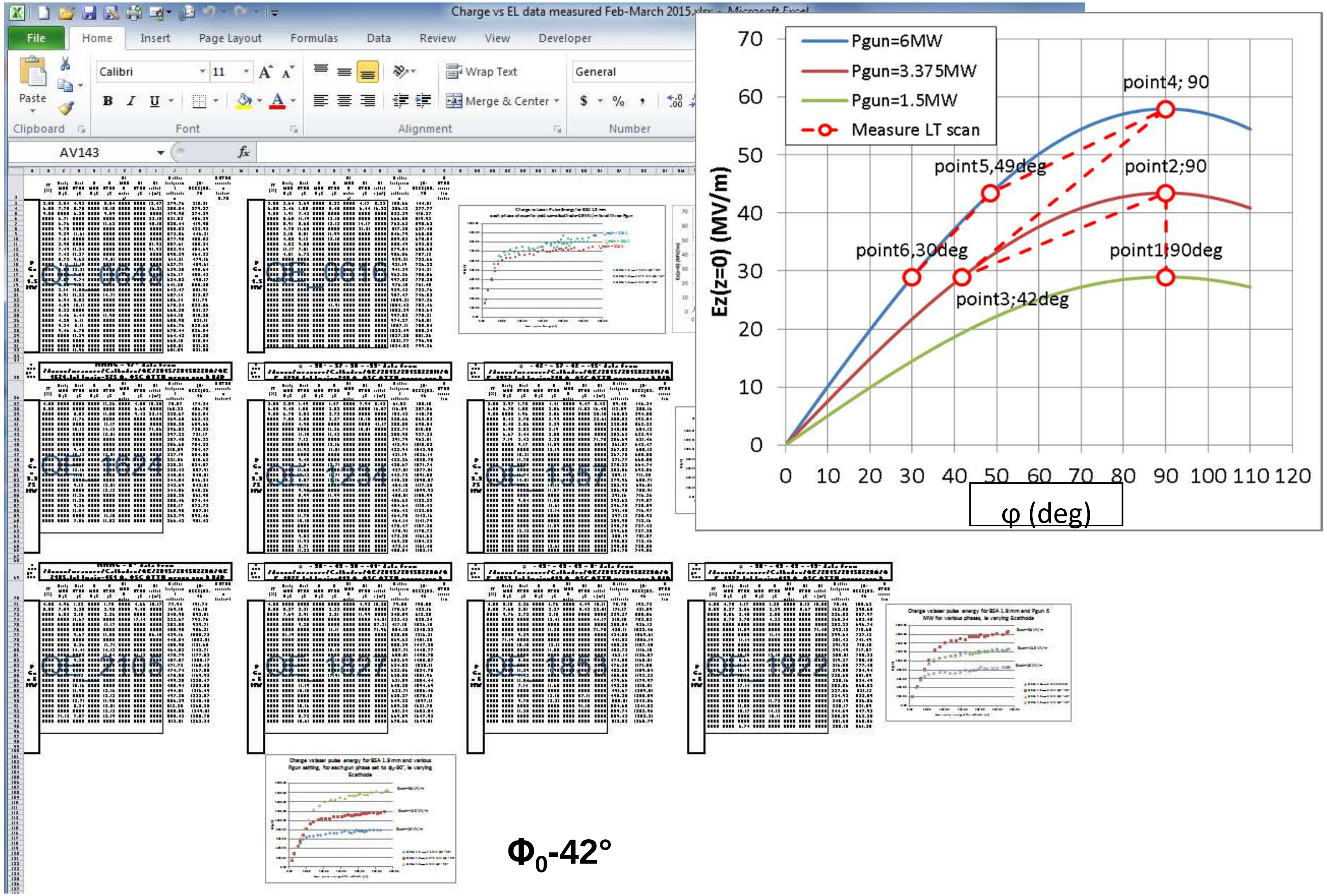
For each BSA, a total of 9 QE scans were taken at the indicated gun settings corresponding to different Ecath

P gun

1.5 MW

3.375 MW

6 MW



Φ_0-42°

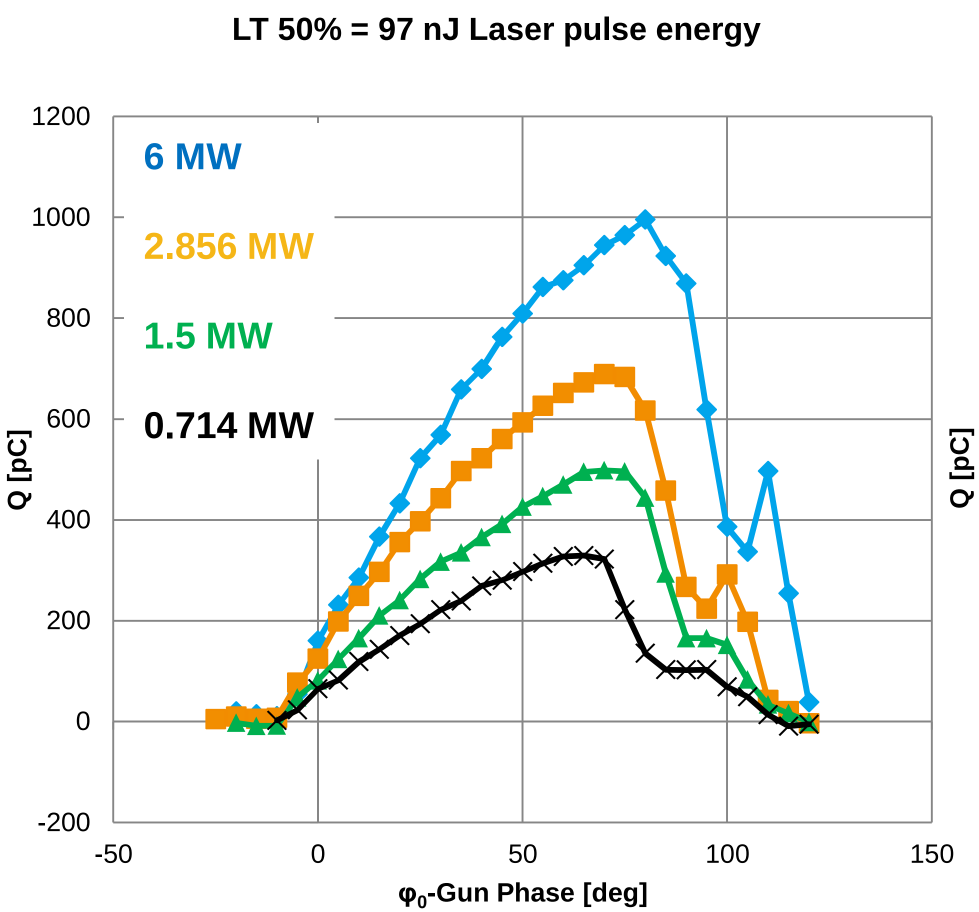
Gun SPPhase → **MMMG** **Φ_0-90°** **Φ_0-49°** **Φ_0-30°**

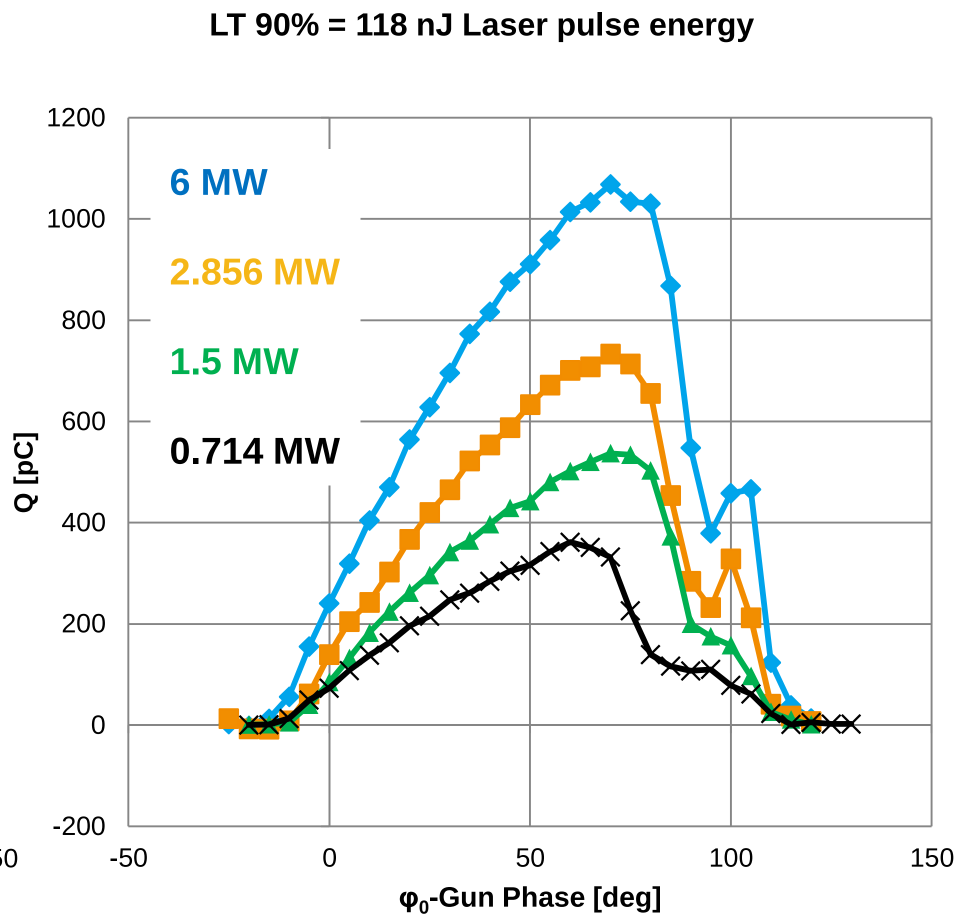
Each QE scan was captured and recorded in Excel with the information shown below

Q BSA 1.8 mm 1.5MW ϕ0 - 90°	ϕ₀ - 90° = 68 - 90 = -22° data from /doocs/measure/Cathodes/QE/2015/20150227N/QE_0616.txt Imain=130 A, OSC ATTN wrong pos & 10dB selection in script-> corr factor =0.78

	LT (%)	Backg MEAN pC	Back STDV pC	Q MEAN pC	Q STDV pC	EL MEAN meter pJ	EL STDV pC	EL cathode [nJ]	Q after background subtraction	(Q-BCKG)X0.78
P Gun 1.5 MW	3.00	2.64	3.69	188.30	5.33	385.06	4.17	8.22	185.66	144.81
	6.00	3.46	1.50	359.58	5.40	764.33	6.44	16.32	356.12	277.77
	9.00	1.91	7.43	534.30	12.70	1161.14	10.47	24.79	532.39	415.27
	12.00	8.60	11.19	675.18	12.15	1509.82	10.40	32.23	666.58	519.93
	15.00	5.91	8.65	769.55	12.13	1884.71	14.17	40.24	763.63	595.63
	18.00	4.75	11.65	822.04	12.37	2316.20	21.31	49.45	817.28	637.48
	21.00	2.10	8.01	848.89	11.99	2798.70	23.30	59.75	846.79	660.50
	24.00	4.08	9.13	863.11	13.10	3279.80	26.51	70.02	859.03	670.04
	27.00	4.53	9.80	893.02	13.85	3851.70	22.43	82.23	888.49	693.02
	30.00	11.17	7.01	890.20	16.79	4324.20	29.82	92.32	879.04	685.65
	33.00	4.51	6.72	911.07	13.83	4921.10	35.36	105.06	906.56	707.12
	36.00	159.76	54.62	1099.07	41.65	5521.20	36.08	117.87	939.31	732.66
	39.00	176.90	34.73	1108.09	42.00	5994.40	48.67	127.97	931.19	726.33
	42.00	182.62	33.67	1123.91	41.76	6490.90	42.29	138.57	941.29	734.21
	45.00	171.58	21.54	1133.84	44.40	7116.10	46.45	151.92	962.26	750.56
	48.00	142.07	39.66	1139.89	43.53	7588.60	56.01	162.01	997.82	778.30
	51.00	159.63	45.41	1135.79	37.17	8054.60	51.24	171.95	976.15	761.40
	54.00	192.60	23.88	1132.03	43.83	8396.60	55.44	179.26	939.43	732.76
	57.00	181.96	33.29	1139.43	40.63	8745.80	55.16	186.71	957.47	746.83
	60.00	152.50	22.02	1161.81	43.45	9062.70	61.44	193.48	1009.31	787.26
	63.00	157.17	62.16	1161.60	41.91	9338.90	57.80	199.37	1004.43	783.46
	66.00	157.14	37.52	1160.53	44.72	9623.00	56.31	205.44	1003.39	782.64
	69.00	172.30	28.78	1170.13	36.47	9923.80	58.69	211.86	997.83	778.31
	72.00	176.22	23.53	1150.59	42.87	10224.60	56.84	218.28	974.37	760.01
	75.00	151.13	37.88	1158.24	42.65	10472.10	66.90	223.56	1007.11	785.54
	78.00	149.40	35.31	1181.89	40.35	10878.70	50.18	232.25	1032.49	805.34
	81.00	149.18	29.46	1176.56	40.00	11375.80	61.45	242.86	1027.38	801.36
	84.00	158.59	37.45	1180.36	39.39	11877.20	64.04	253.56	1021.77	796.98
	87.00	154.34	34.13	1179.17	35.59	12398.20	76.98	264.68	1024.83	799.36

Phase scans taken for Darmstadt, BSA 1.4 mm





The laser pulse energy is only 20% higher even though LT is two times higher

As expected, the phase scans for the old (QE 0.6%) and new cathode (QE 8%) are drastically different.

- How to reproduce these measurements in simulations if machine parameters are the same for both?
- The input charge is Qbunch = 2xQExE$_{L.}$ The product of QExE$_L$ could be adjusted to match the low QE cathode, but the codes do not include input parameters for QE and laser energy, they use total input charge.