# Core + Halo distributions for ASTRA

## A procedure to generate core + halo input distributions for ASTRA based on actual laser transverse distribution

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**Note: MatLAB scripts written by Mikhail Krasilnikov**

# 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.

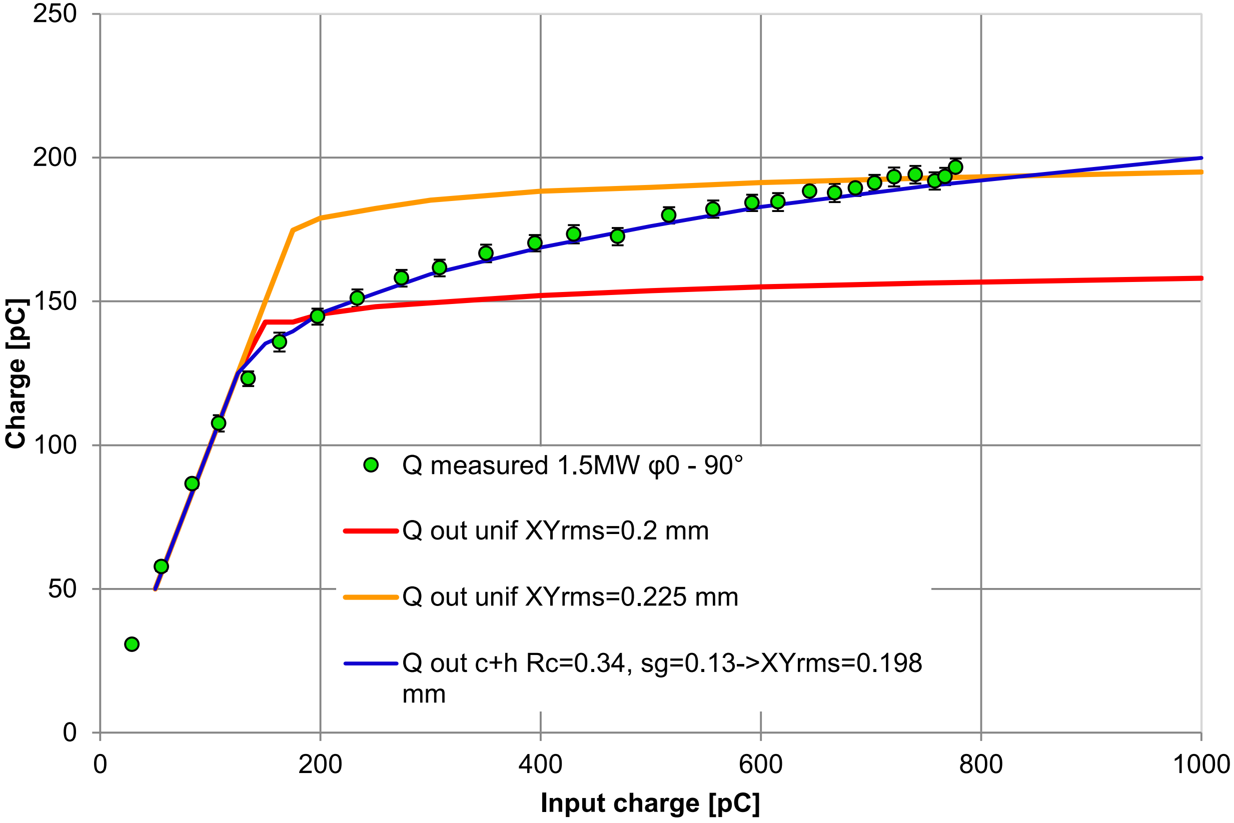
# Outline

1. Motivation: Using *core+halo* input distributions that match the laser transverse profile agree now with extracted charge measurements
2. Procedure overview
3. Characterization of laser transverse profile
4. Generation of particle input distribution based on laser transverse profile data
5. Procedure summary
6. Sensitivity of simulations and model to laser radial profile parameters
7. Laser radial halo dependence on laser settings and its effect on extracted charge
8. Conclusions

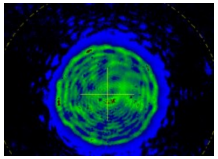
# When the core+halo initial distribution is utilized, ASTRA shows good agreement with extracted charge measurements

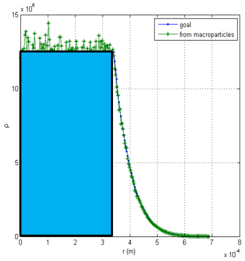
**If a uniform distribution is used instead, the charge saturates**

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

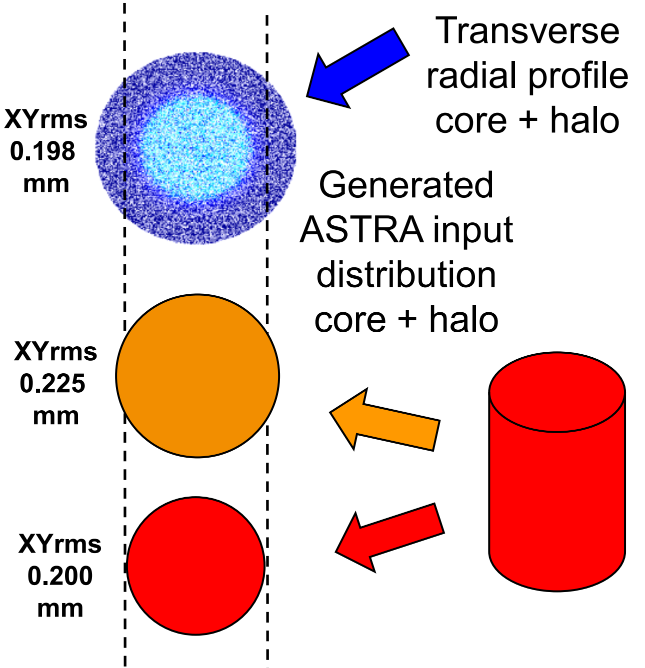


Laser radial distribution image





Transverse radial profile core + halo



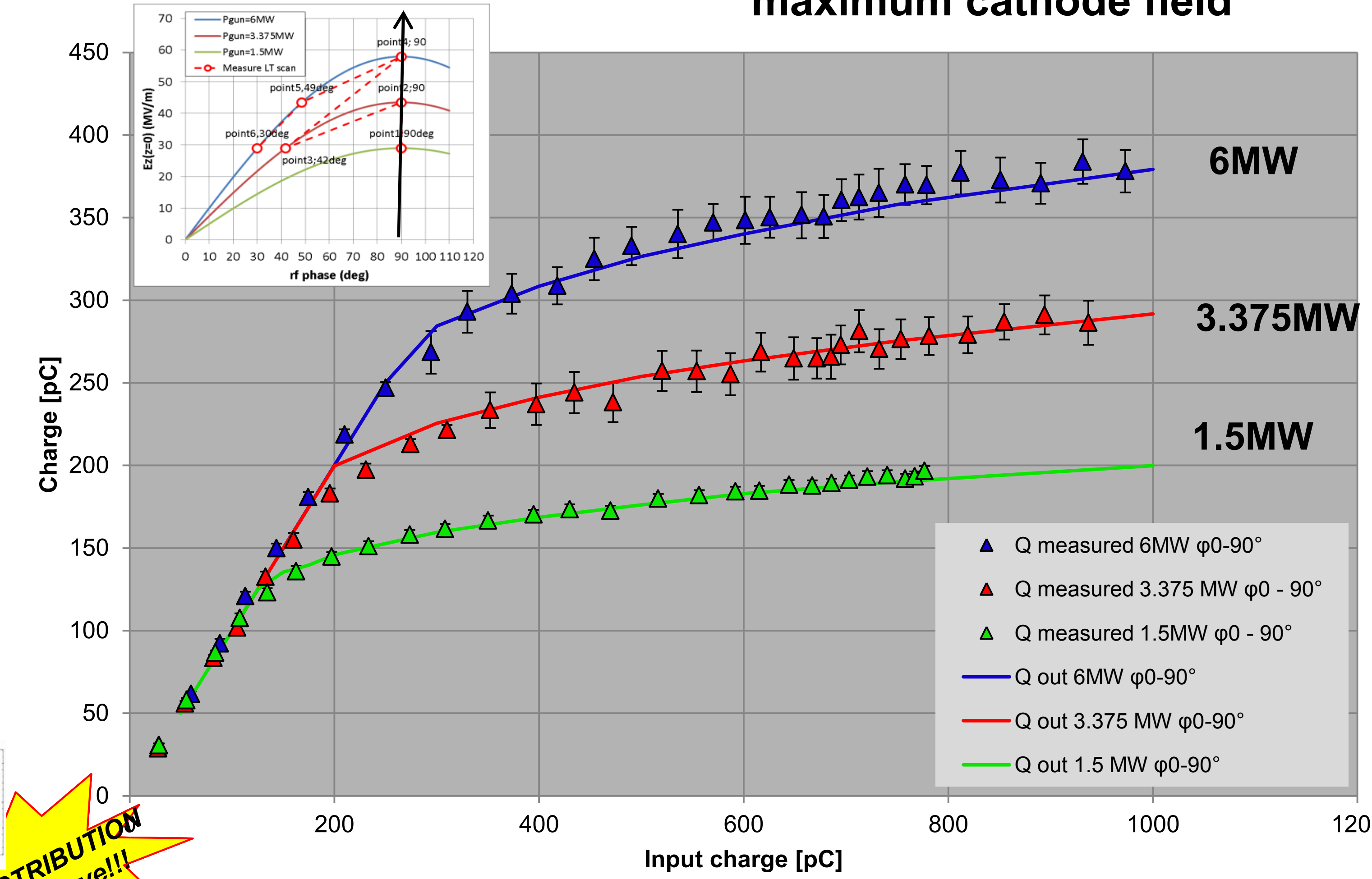
Generated ASTRA input distribution core + halo

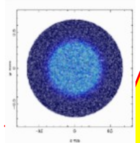
Nominal ASTRA input uniform distribution

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

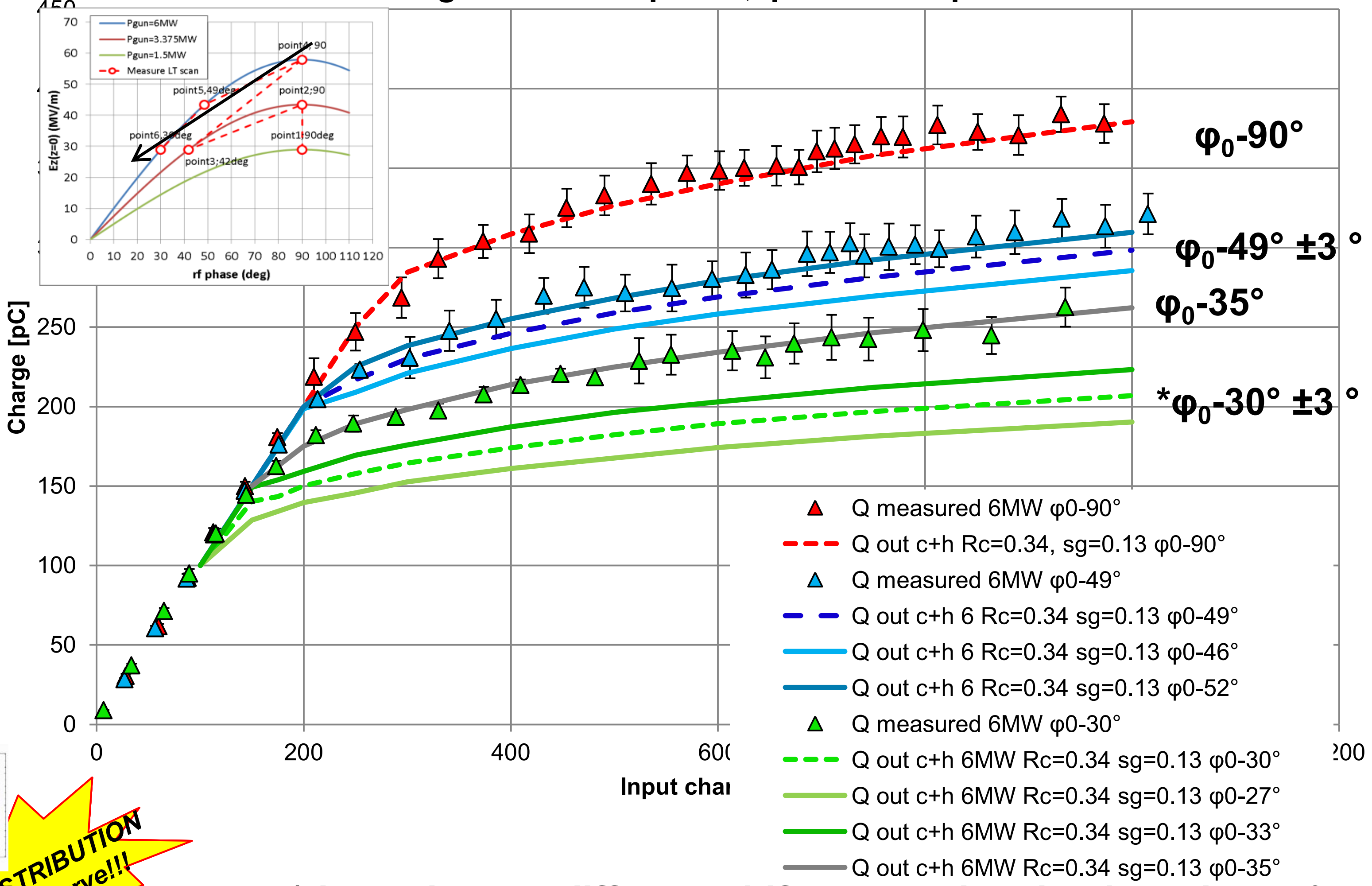


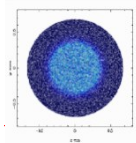


SAME DISTRIBUTION
For each curve!!!

# …for most cases….

## Extracted charge with core + halo for BSA 0.8 mm with 1.5 ps rms Gaussian temporal for Pgun=6MW at φ0-90°, φ0-49° and φ0-30°



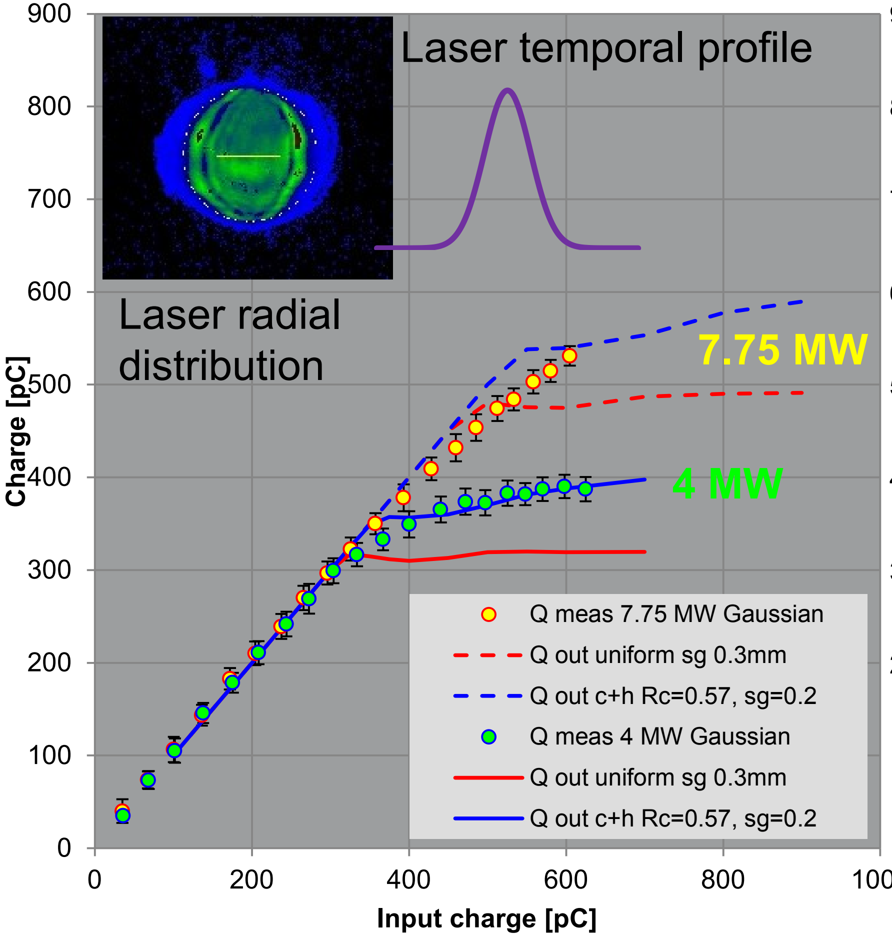


SAME DISTRIBUTION
For each curve!!!

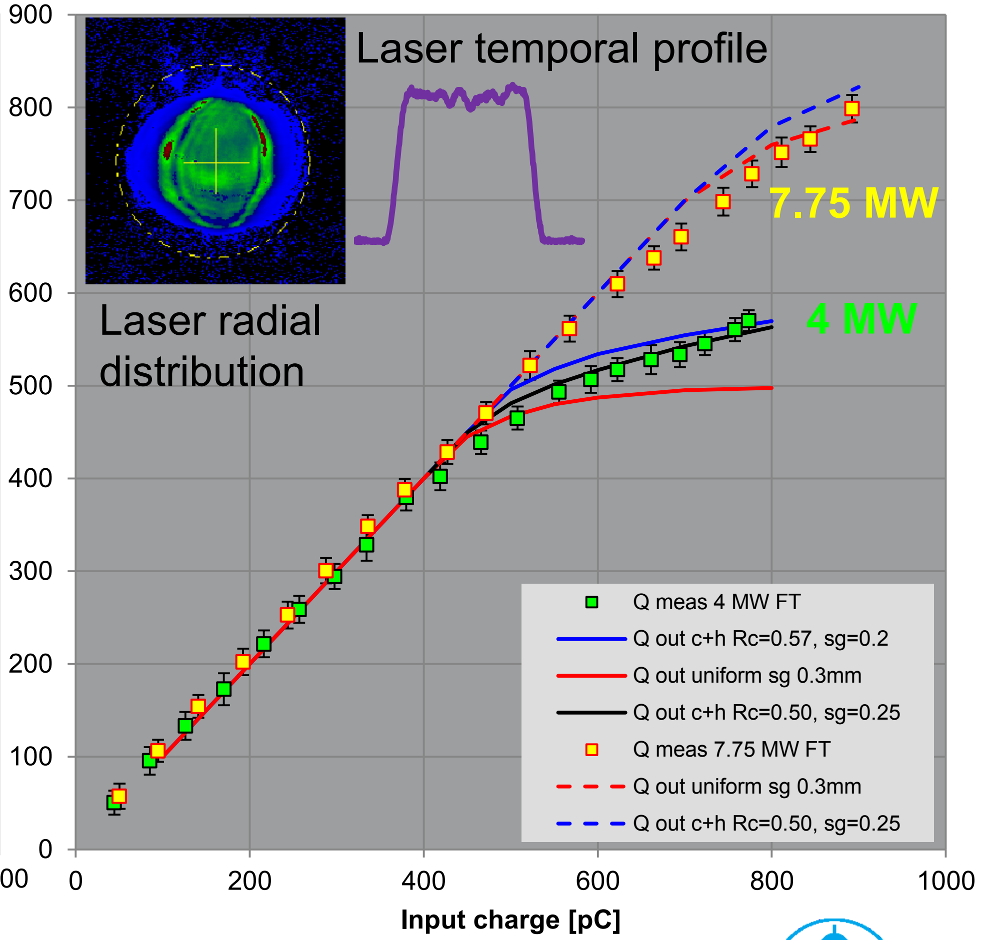
*data taken on different shift, uncertainty in phase is > 5 °

# …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 $\sigma_t$=1.06ps at MMMG**

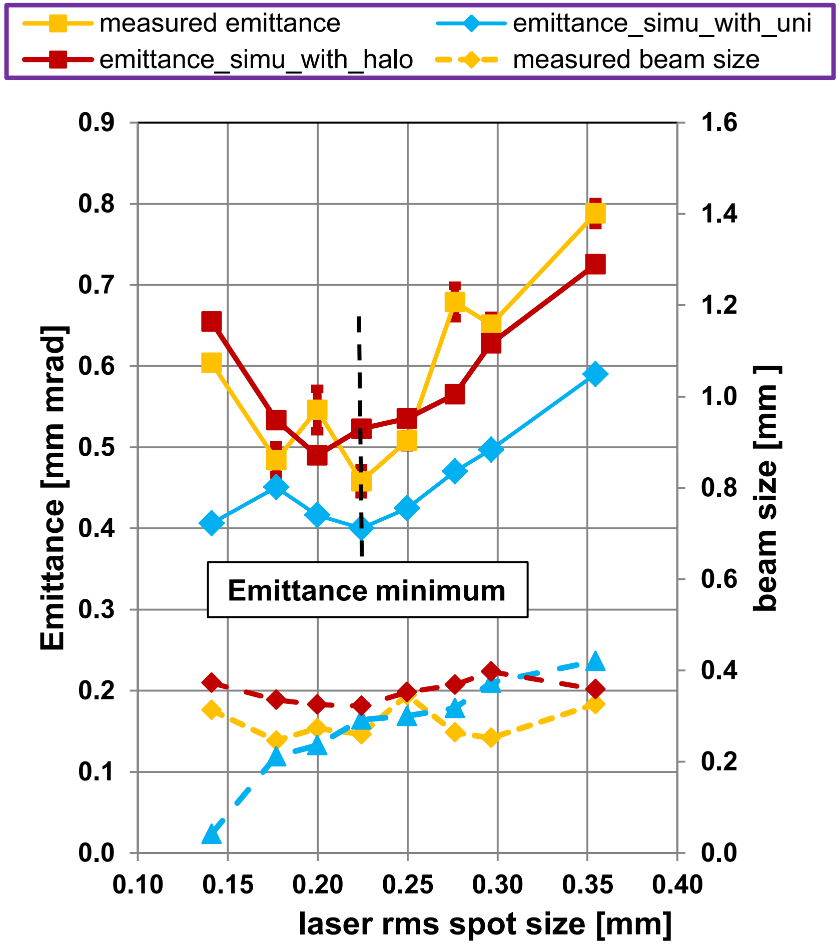


**Extracted charge vs laser pulse energy from 2013 for 1.2 mm beam diameter with FWHM=17 ps Flat Top at MMMG**

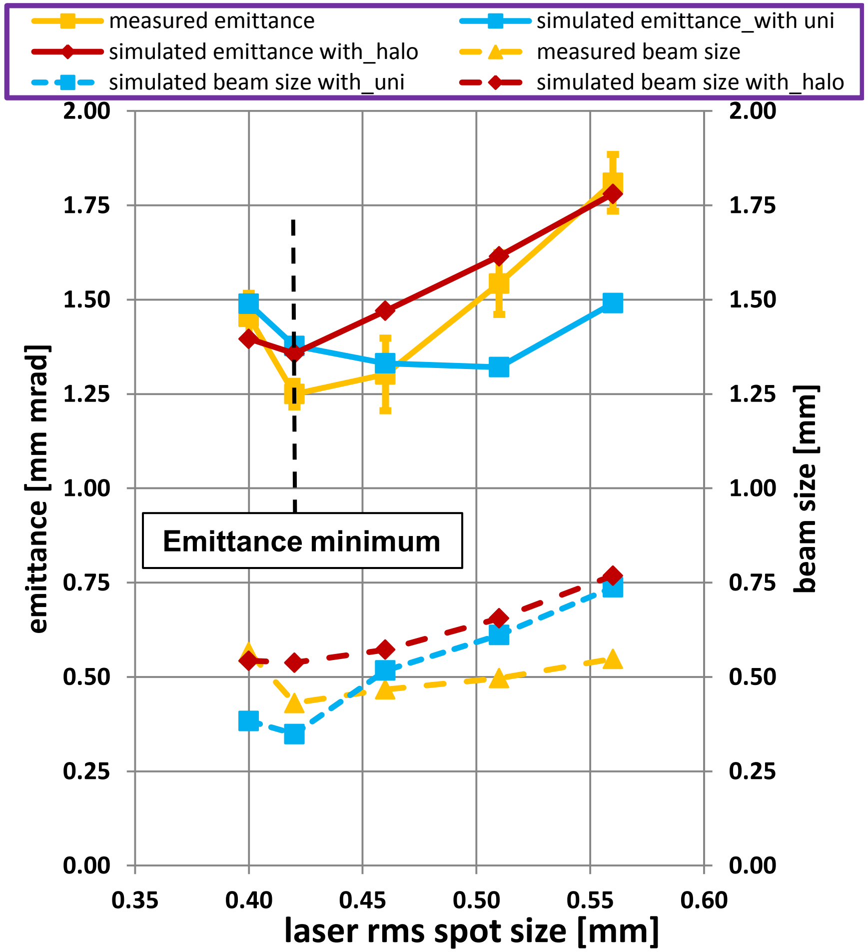


# Using core+halo input distributions in ASTRA renders closer agreement with emittance measurements than just using uniform core input distributions*

## 0.1 nC bunch charge



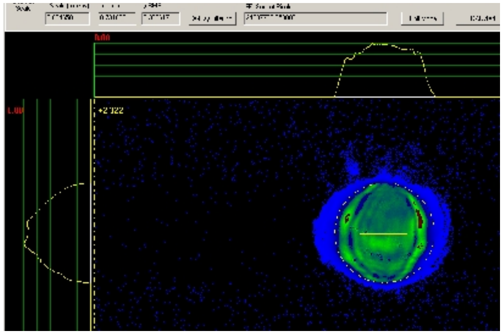
## 1 nC bunch charge



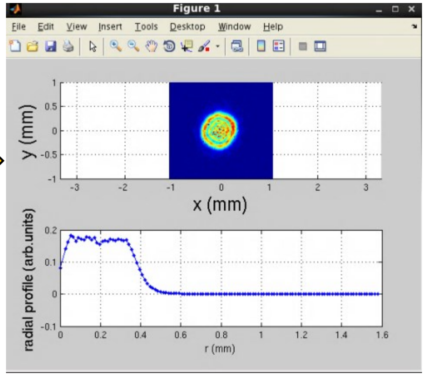
*ASTRA simulations by Q. Zhao (PITZ)

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

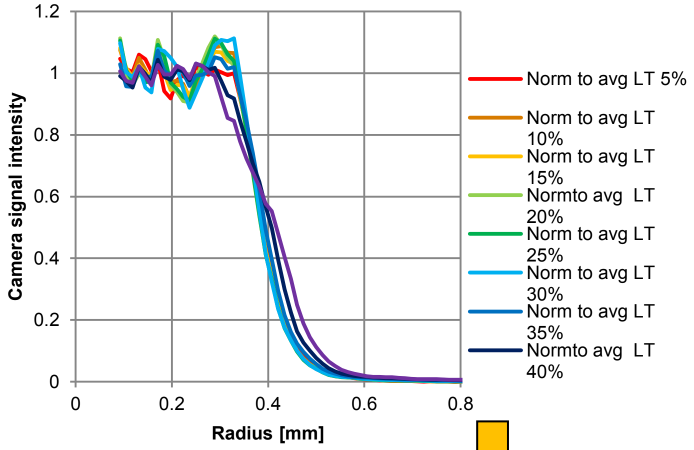
Laser distribution on virtual cathode imaging camera data capture



Virtual cathode data fitted in MatLab



Radial laser profile from MatLab data fit



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

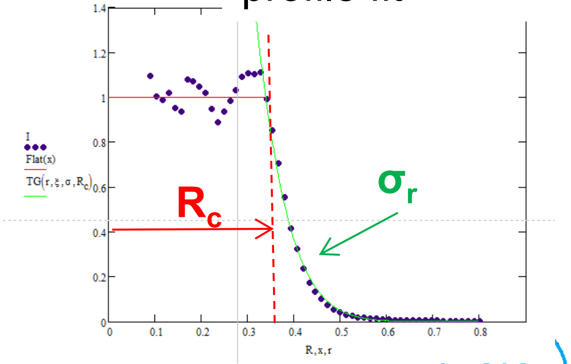
$\xi := 1$

$R_c := 0.34$

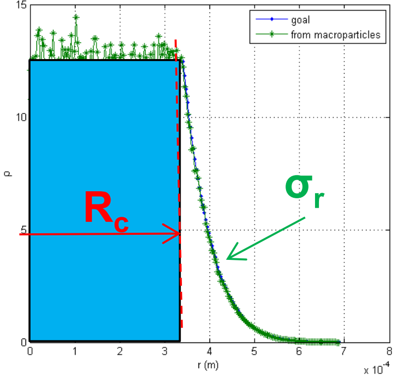
$\sigma := 0.15$

$r := 0.32, 0.321 .. 0.8$

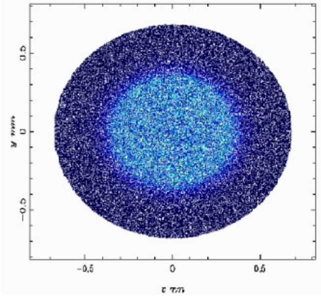
Curve fit to match radial laser profile fit



MatLab-generated input distribution for ASTRA with core + halo

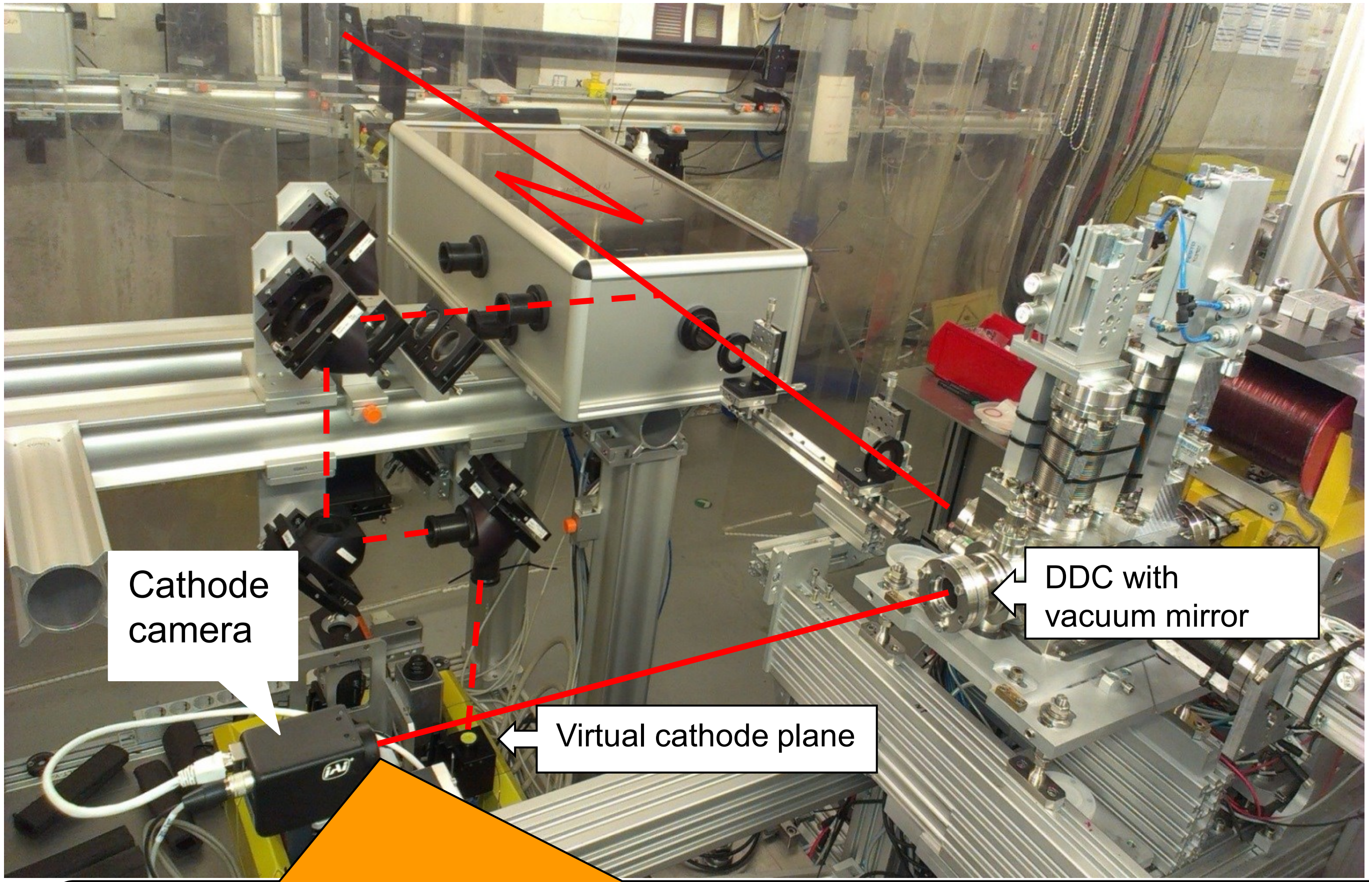


Input distribution shown by postpro with core + halo

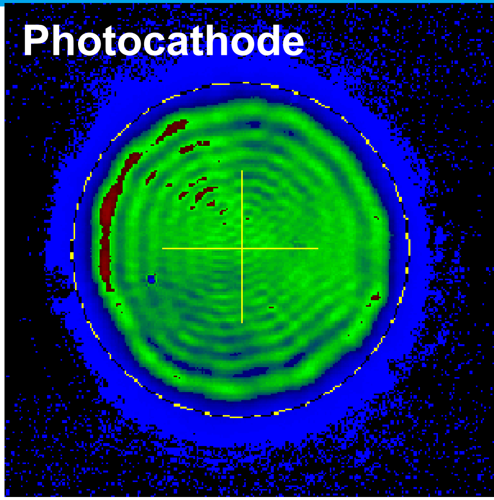


To ASTRA

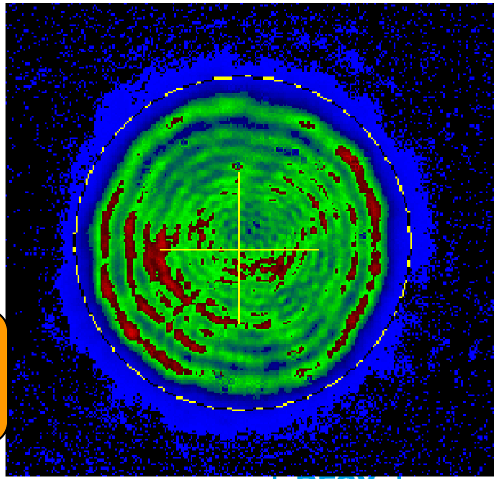
# To characterize the laser spot on the cathode: The laser beam shaping aperture (BSA) is imaged onto a CCD camera positioned at a plane equivalent to that of the actual cathode (Virtual Cathode 2, VC2) Data taken 12-March-2013*



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


Photocathode

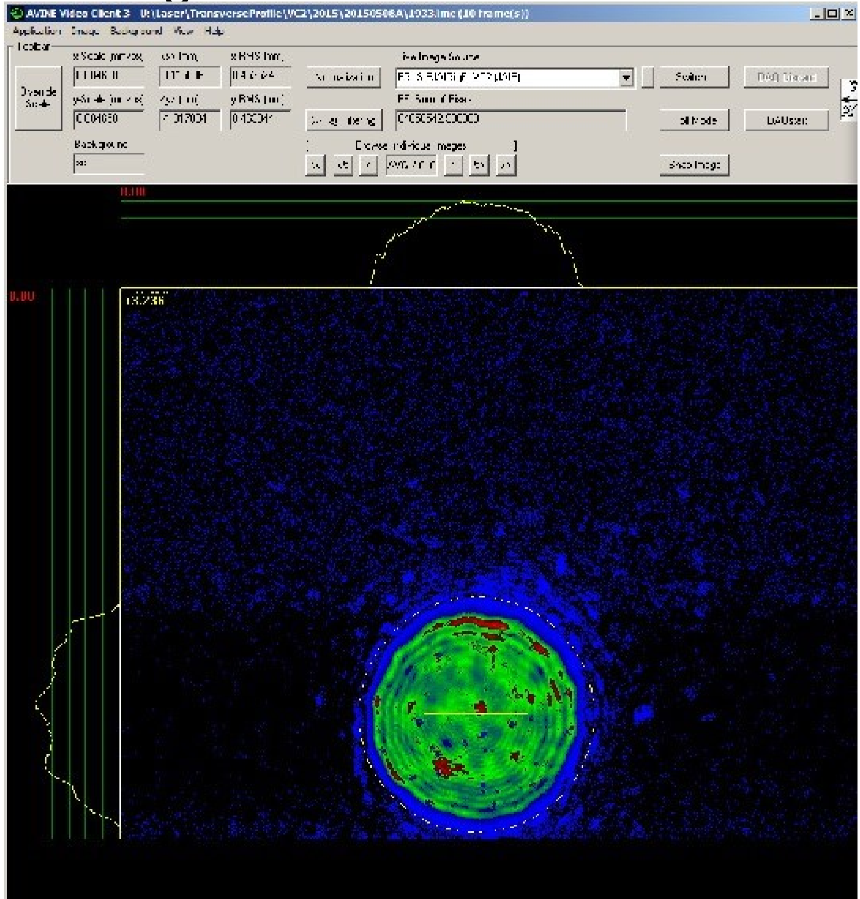
Virtual cathode plane



*M. Gross (PITZ)

# **Step 1**: Capturing VC2 image and data

1. Set BSA to desired value
2. Follow standard procedures to capture VC2 image and data, ensuring the image AND background data are saved in [\\doocs\measure\Laser\TransverseProfile\VC2**YYYY\SHIFT**](\\doocs\measure\Laser\TransverseProfile\VC2\YYYY\SHIFT)
3. Record VC2 image from Avine video client for reference, as shown below:



- Typically 2 x 20 frames (background + signal)

# Step 2: Reading the saved VC2 image & background data

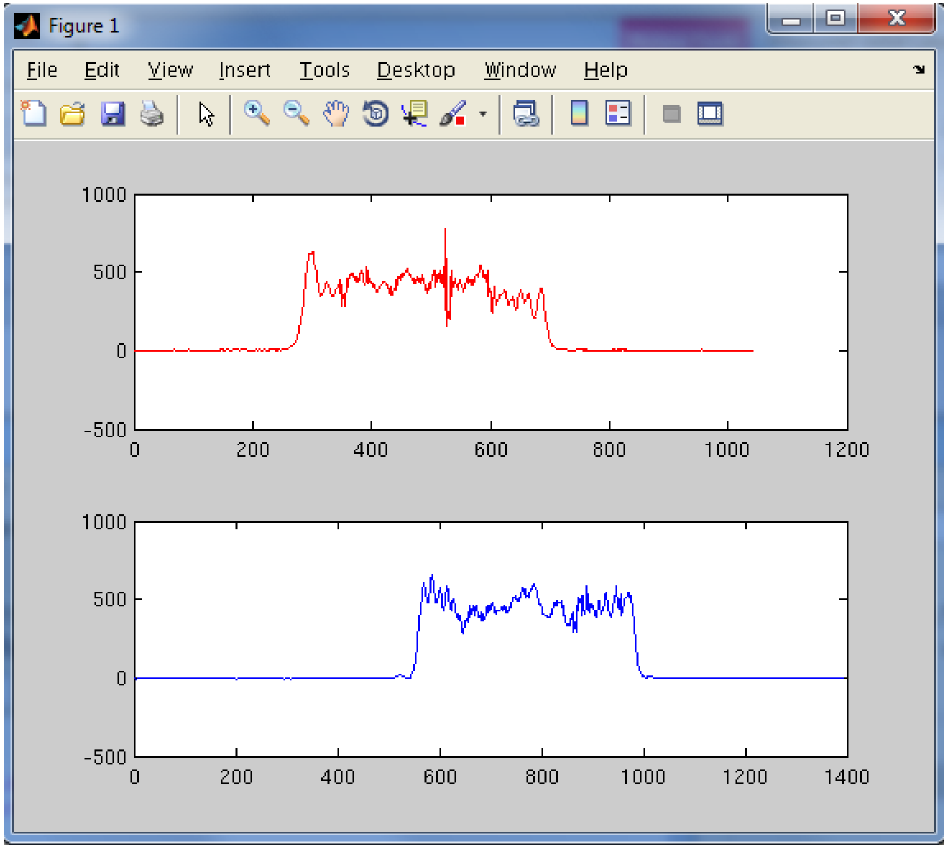
1. Open the MatLab script “*read_imc.m*” in LINUX environment. This script is saved in …..
2. Edit the script to set the **folder** from which the image and background **data file** will be loaded, as shown below:

```
clear all;
close all;
[imc_data, header_data] = avine_load_video_images_from_file('/doocs/measure/Laser/TransverseProfile/VC2/2015/20150514N/0027_LT16_BSA2.imc');
[bkc_data, header_data_bkc] = avine_load_video_images_from_file('/doocs/measure/Laser/TransverseProfile/VC2/2015/20150514N/0027_LT16_BSA2.bkc');
header_data_single = header_data(1);
camWidth = header_data_single{1}.width;
camHeight = header_data_single{1}.height;

scale = 0.00465; % mm/pixel

averageVector = zeros(camHeight,camWidth);
averageVectorBkc = zeros(camHeight,camWidth);
```

3. Run the script

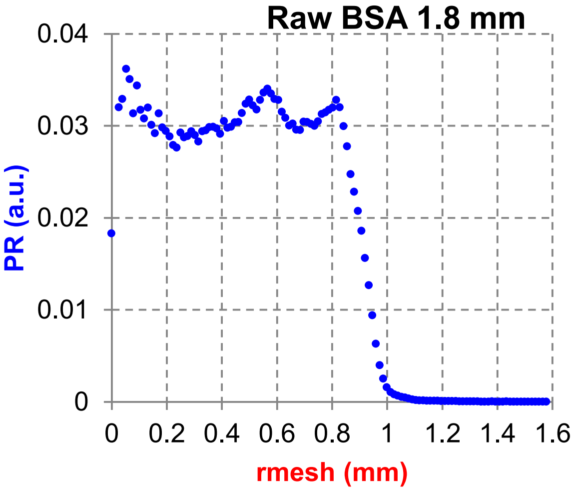
# Step 2 Continued

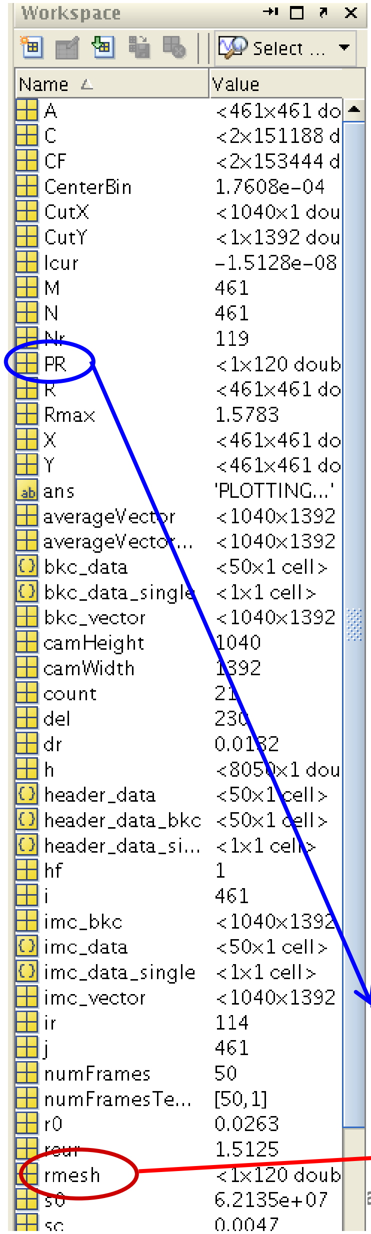
- The Script only reads the image data and subtracts the background.
- The only output is the display of the vertical and horizontal cuts, just to indicated it has finished reading the data.



# Step 3: Generating radial profile averaged over Φ

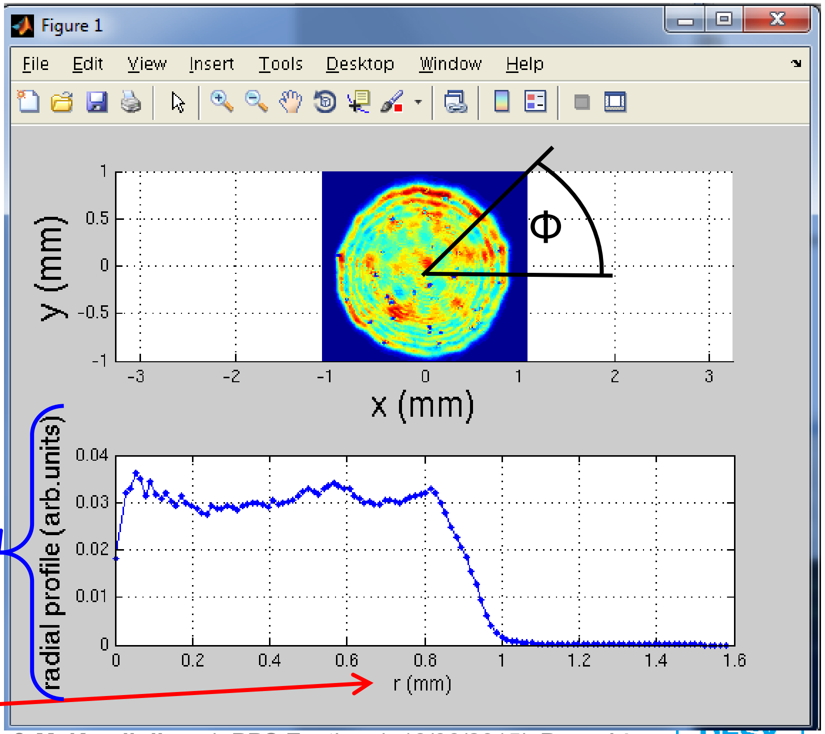
1. Open the MatLab script "*RadProfiler.m*" in LINUX environment. This script is saved in …..
2. Run the script
3. Make a radial profile in Excel or any other graphing tool with data stored in rmesh and PR





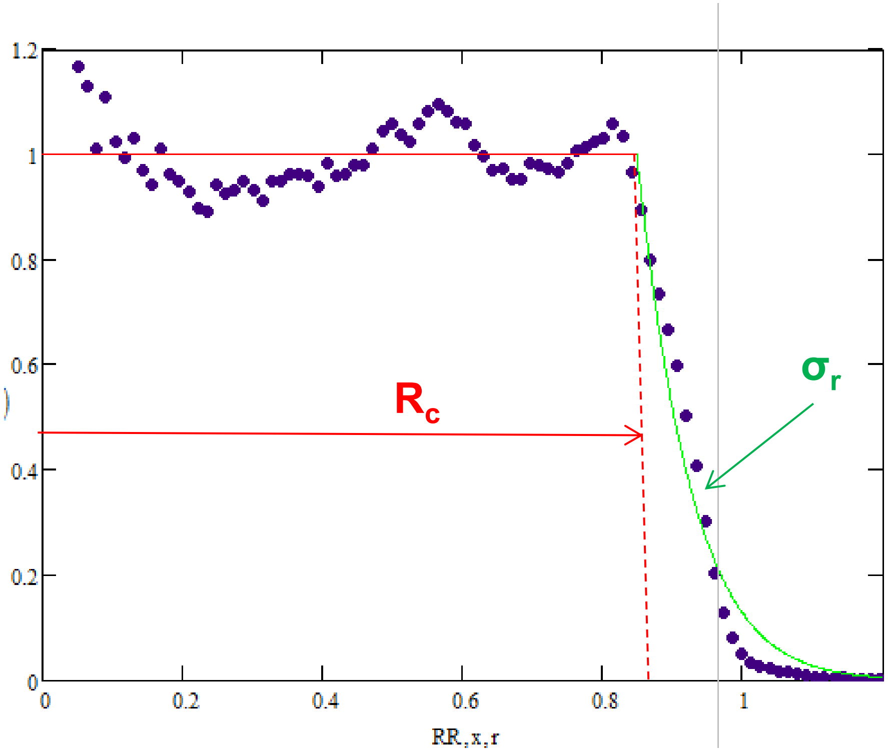
| Name | Value |
|---|---|
| A | <461x461 do |
| C | <2x151188 d |
| CF | <2x153444 d |
| CenterBin | 1.7608e-04 |
| CutX | <1040x1 dou |
| CutY | <1x1392 dou |
| Icur | -1.5128e-08 |
| M | 461 |
| N | 461 |
| Nr | 119 |
| PR | <1x120 doub |
| R | <461x461 do |
| Rmax | 1.5783 |
| X | <461x461 do |
| Y | <461x461 do |
| ans | 'PLOTTING...' |
| averageVector | <1040x1392 |
| averageVecto... | <1040x1392 |
| bkc_data | <50x1 cell> |
| bkc_data_single | <1x1 cell> |
| bkc_vector | <1040x1392 |
| camHeight | 1040 |
| camWidth | 1392 |
| count | 21 |
| del | 230 |
| dr | 0.0132 |
| h | <8050x1 dou |
| header_data | <50x1 cell> |
| header_data_bkc | <50x1 cell> |
| header_data_si... | <1x1 cell> |
| hf | 1 |
| i | 461 |
| imc_bkc | <1040x1392 |
| imc_data | <50x1 cell> |
| imc_data_single | <1x1 cell> |
| imc_vector | <1040x1392 |
| ir | 114 |
| j | 461 |
| numFrames | 50 |
| numFramesTe... | [50,1] |
| r0 | 0.0263 |
| rcur | 1.5125 |
| rmesh | <1x120 doub |
| s0 | 6.2135e+07 |
| sc | 0.0047 |

- The script takes the matrix data generated by *read_imc.m* and averages over Φ.
- It generates the graph and radial profile shown below
- The radial profile data is saved in the vectors rmesh and PR.



# Step 4: Finding core + halo parameters $R_c$ and $\sigma_r$ from radial profile

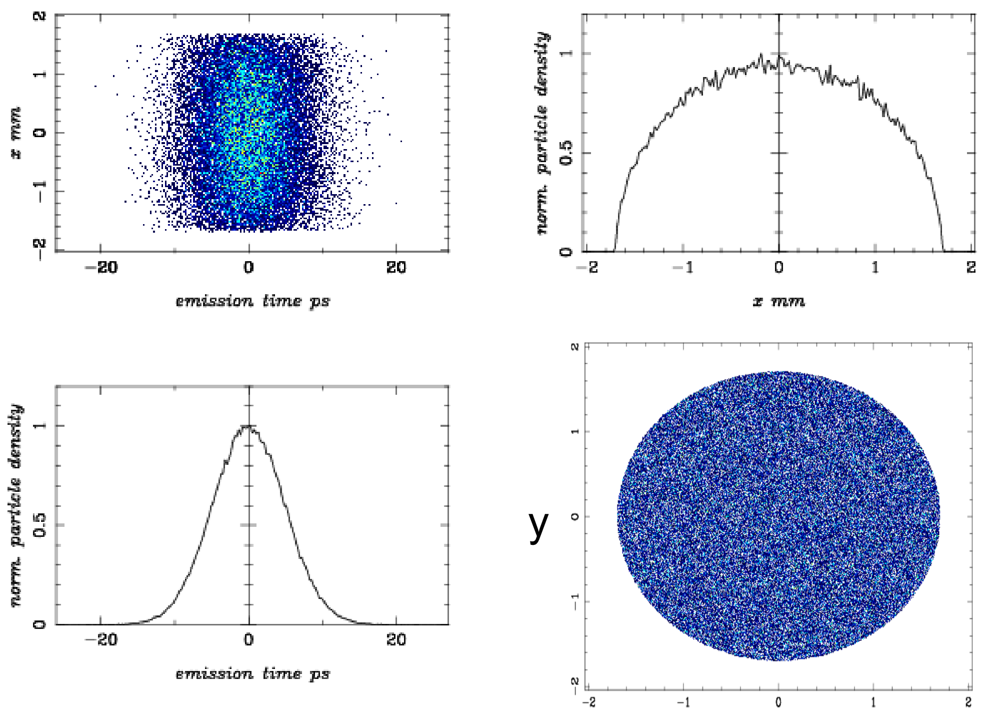
1. From the radial profile, find **$R_c$** and **$\sigma_r$** by fitting the following equation to the radial profile:
2. $$F(r) = exp\left[\frac{R^2 - r^2}{2\sigma^2}\right]$$

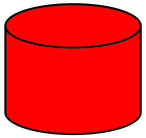


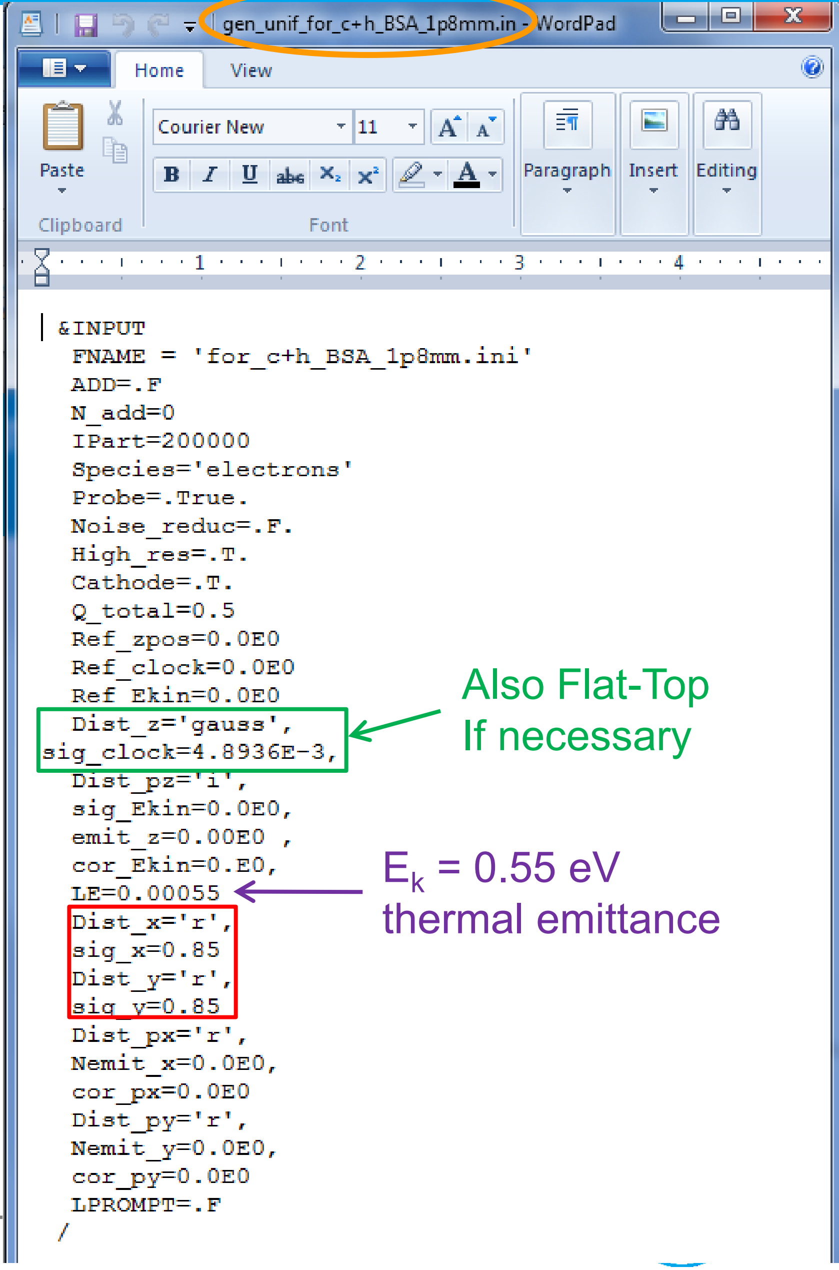
- This can be accomplished manually with MathCAD for example, or a MatLab script could be written for this purpose.
- For this particular case:
  - **$R_c$ = 0.85 mm**
  - **$\sigma_r$ = 0.26 mm**

# Step 5: Generating baseline uniform particle distribution needed for core + halo distribution

1. Edit a generic "*generator.in*" file to create a **uniform** distribution with:
   - Desired temporal profile, and
   - RMS beam size must be equal to Rc







```
&INPUT
  FNAME = 'for_c+h_BSA_1p8mm.ini'
  ADD=.F
  N_add=0
  IPart=200000
  Species='electrons'
  Probe=.True.
  Noise_reduc=.F.
  High_res=.T.
  Cathode=.T.
  Q_total=0.5
  Ref_zpos=0.0E0
  Ref_clock=0.0E0
  Ref_Ekin=0.0E0
  Dist_z='gauss',
sig_clock=4.8936E-3,
  Dist_pz='i',
  sig_Ekin=0.0E0,
  emit_z=0.00E0 ,
  cor_Ekin=0.E0,
  LE=0.00055
  Dist_x='r',
  sig_x=0.85
  Dist_y='r',
  sig_y=0.85
  Dist_px='r',
  Nemit_x=0.0E0,
  cor_px=0.0E0
  Dist_py='r',
  Nemit_y=0.0E0,
  cor_py=0.0E0
  LPROMPT=.F
/
```

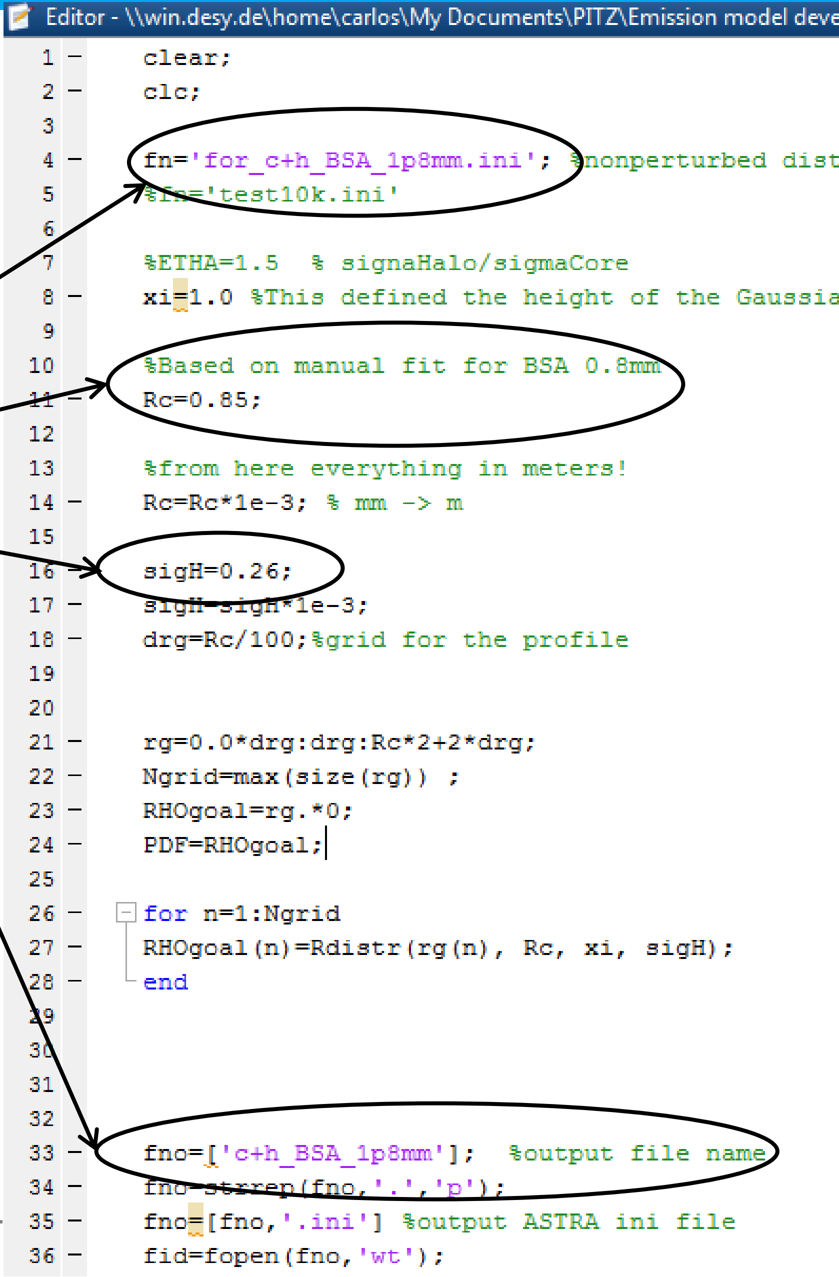
Also Flat-Top If necessary

$E_k$ = 0.55 eV thermal emittance

# Step 6: Generating core + halo distribution with $R_c$ and $\sigma_r$ based on uniform distribution

1. Open the MatLab script “*core_halo generator for ASTRA.m*”, saved in ….
2. Edit the script to:
   1. Load the uniform baseline distribution
   2. Set $R_c$
   3. Set $\sigma_r$
   4. Save the core + halo distribution

> NOTE: The script needs the macro named: *“Rdistr.m”*

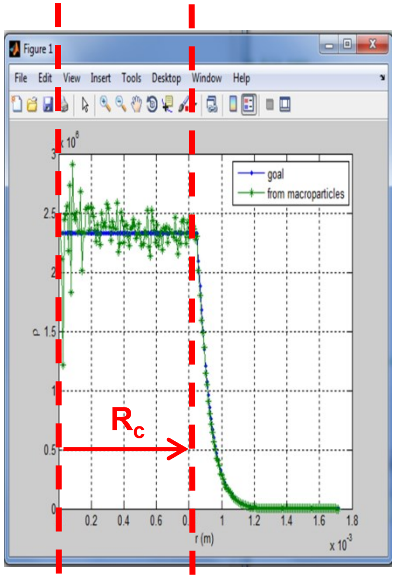


Editor - \\win.desy.de\home\carlos\My Documents\PITZ\Emission model deve

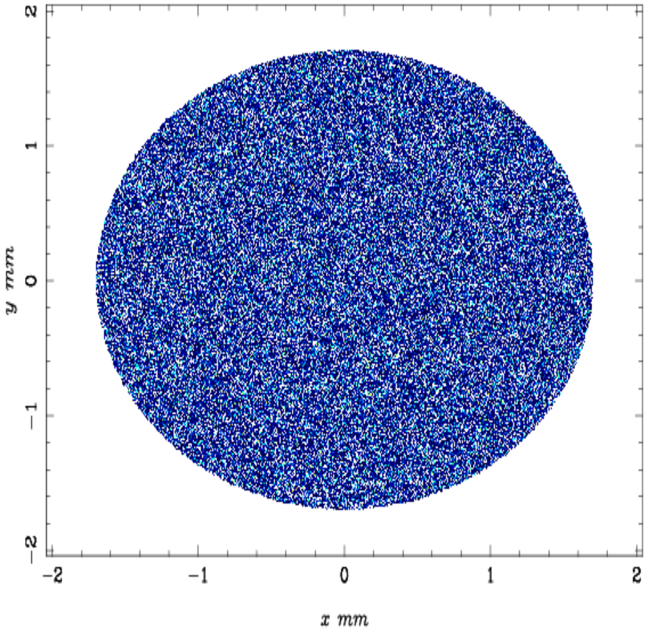
```
clear;
clc;

fn='for_c+h_BSA_1p8mm.ini'; %nonperturbed dist
%fn='test10k.ini'

%ETHA=1.5  % signaHalo/sigmaCore
xi=1.0 %This defined the height of the Gaussia

%Based on manual fit for BSA 0.8mm
Rc=0.85;

%from here everything in meters!
Rc=Rc*1e-3; % mm -> m

sigH=0.26;
sigH=sigH*1e-3;
drg=Rc/100;%grid for the profile


rg=0.0*drg:drg:Rc*2+2*drg;
Ngrid=max(size(rg)) ;
RHOgoal=rg.*0;
PDF=RHOgoal;

for n=1:Ngrid
RHOgoal(n)=Rdistr(rg(n), Rc, xi, sigH);
end




fno=['c+h_BSA_1p8mm'];  %output file name
fno=strrep(fno,'.','p');
fno=[fno,'.ini'] %output ASTRA ini file
fid=fopen(fno,'wt');
```

# Step 6: This is the last step in the procedure

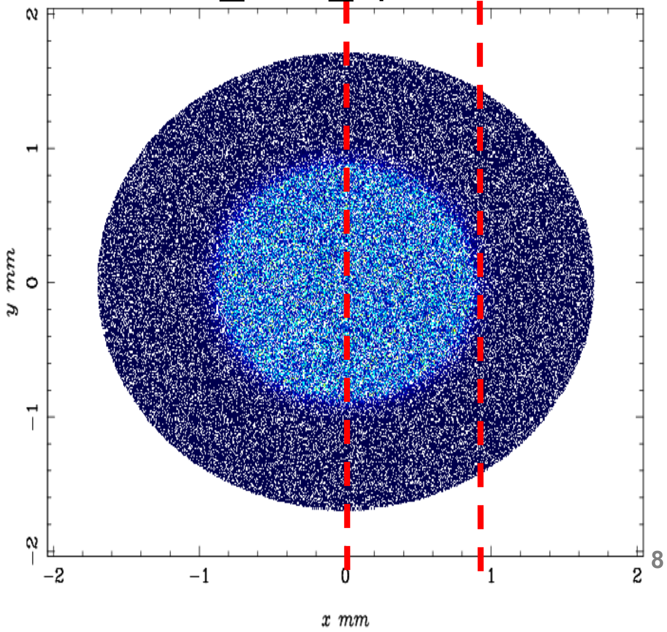
- The script takes the uniform baseline distribution and makes a new distribution composed of a flat-top core with radius $R_c$, and a decaying Gaussian-like halo shifted by $R_c$ and with $\sigma_r$ by modification of the macroparticle charge



for_c+h_BSA_1p8mm.ini



c+h_BSA_1p8mm.ini

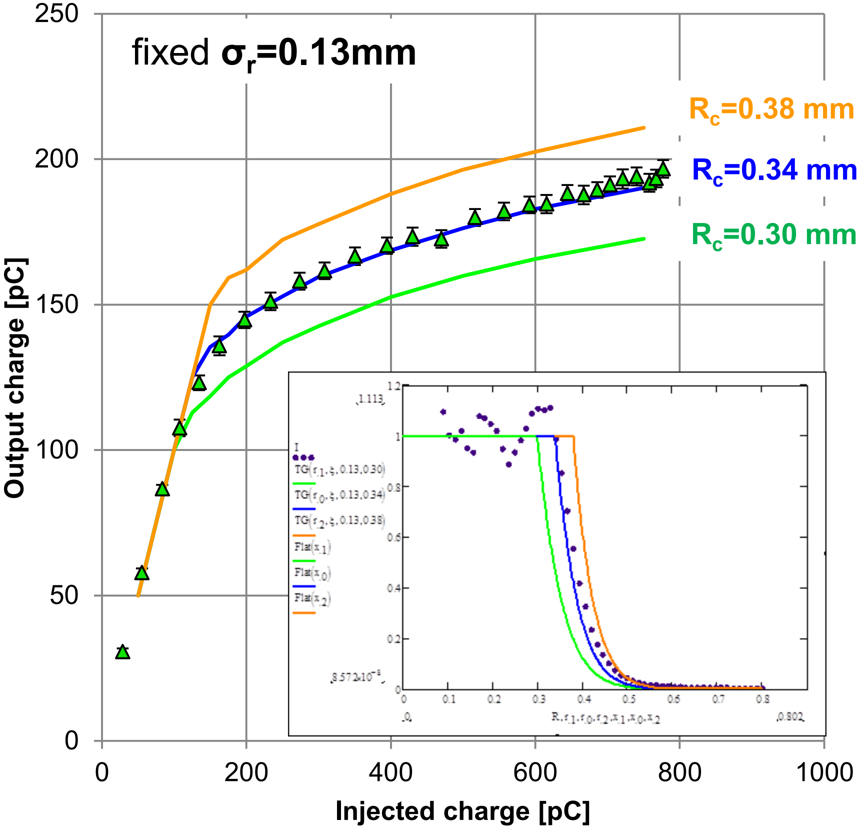


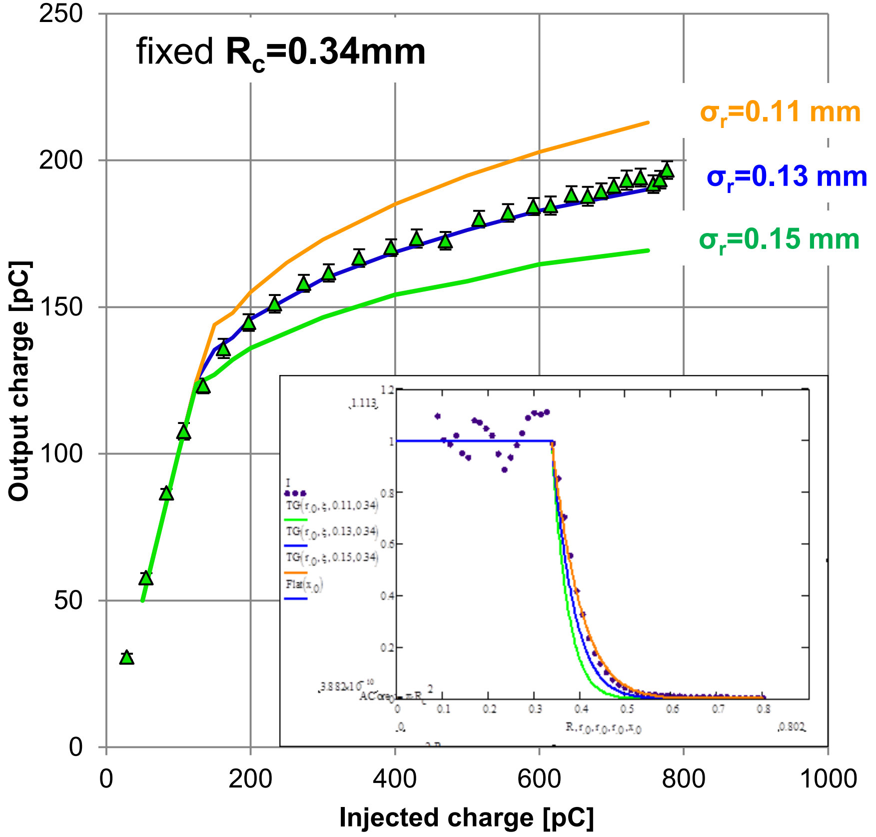
# Procedure summary

1. Capture VC2 image and data
2. Run MatLab script “read_imc.m” to read VC2 data
3. Run MatLab script “*RadProfiler.m*” to generate radial profile
4. Find core + halo parameters ($R_c$ , $\sigma_r$ ) from the radial profile
5. Generate baseline uniform particle distribution with XYrms= $R_c$
6. Run MatLab script “*core_halo generator for ASTRA.m*” with $R_c$ , $\sigma_r$ and baseline uniform distribution to generate core + halo input distribution to be used in ASTRA

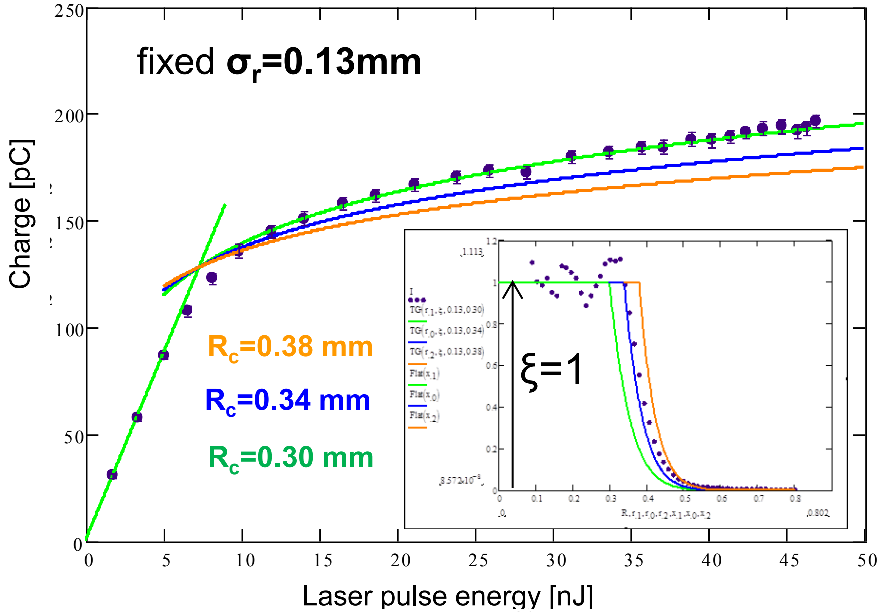
# The following graphs show the sensitivity of ASTRA simulations to the core + halo parameters $R_c$ and $\sigma_r$

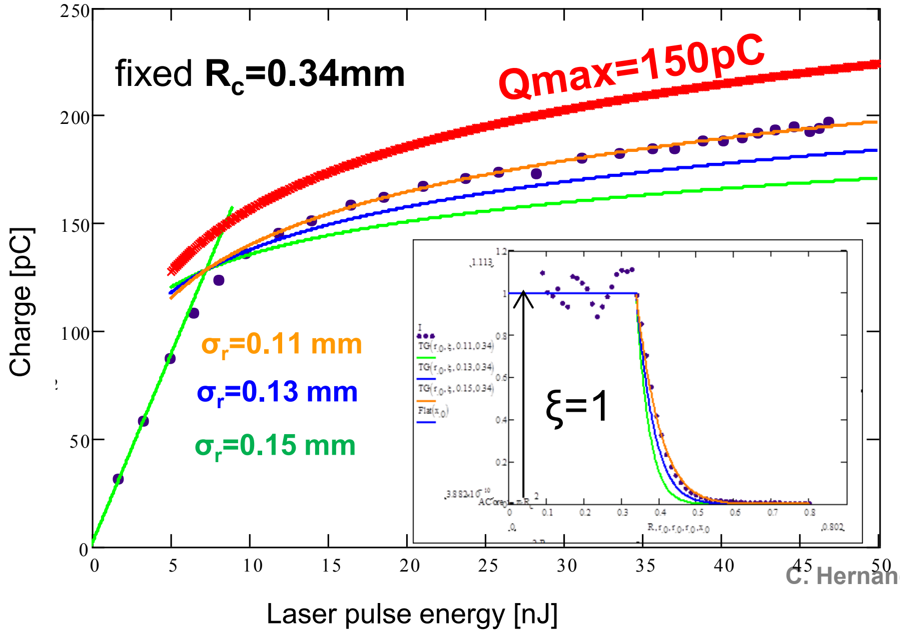
## Extracted charge vs laser pulse energy for temporal Gaussian $\sigma_t$=1.5 ps BSA=0.8mm Gun Power = 1.5MW and Gun Phase φ0 - 90°





# The following graphs shows the sensitivity of the semi-analytical model to the core + halo parameters $R_c$ and $\sigma_r$



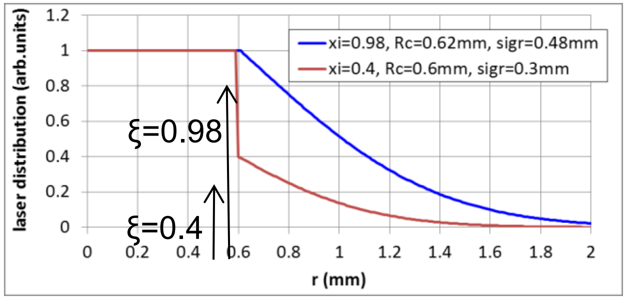


Model by Mikhail Krasilnikov (PITZ)

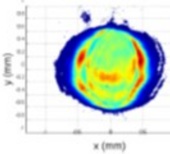
$$F_l(r) = \frac{E_l}{\pi R_c^2 + 2\pi\xi\sigma_r{}^2}\begin{cases} 1, & if\ \ r \le R_c \\ \xi e^{\frac{R_c^2 - r^2}{2\sigma_r^2}}, & if\ \ r > R_c \end{cases}$$

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

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



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



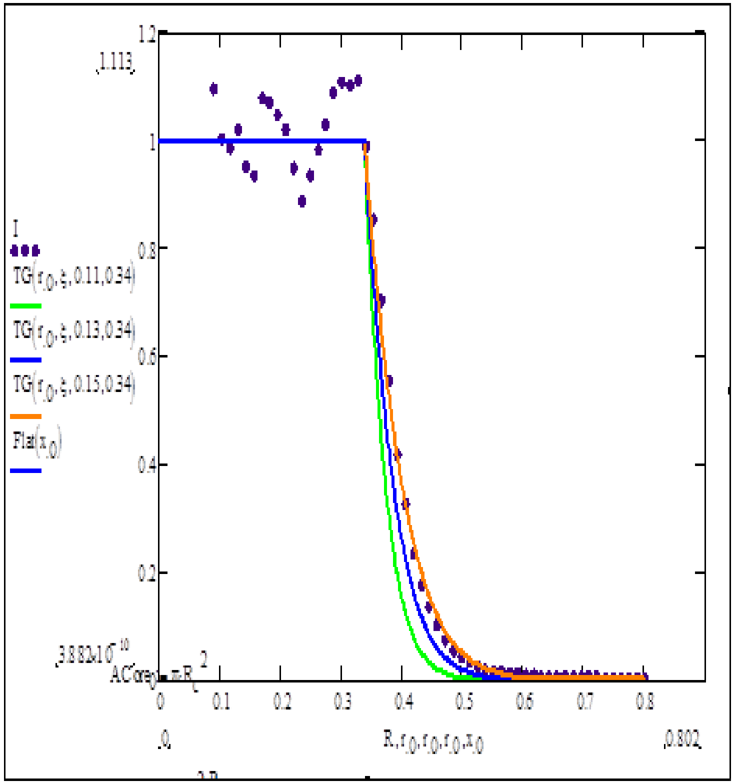
$$Q_{core} = \frac{1}{1 + \xi \cdot \eta}\begin{cases} Q_{exp}, & if\ \ Q_{exp} \le Q_{max} \\ Q_{max} & if\ \ Q_{exp} > Q_{max} \end{cases}$$

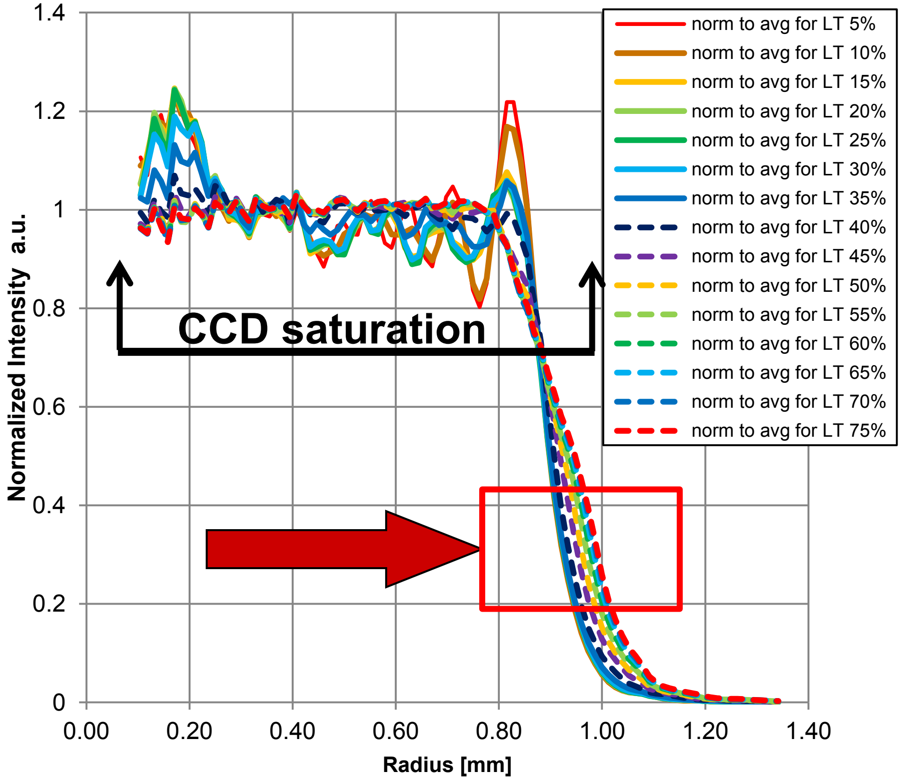
$$Q_{halo} = \frac{\eta}{1 + \xi \cdot \eta}\begin{cases} \xi \cdot Q_{exp}, & if\ \ \xi \cdot Q_{exp} \le Q_{max} \\ Q_{max} \cdot \left(1 + \ln \frac{\xi \cdot Q_{exp}}{Q_{max}}\right) & if\ \ \xi \cdot Q_{exp} > Q_{max} \end{cases}$$

Qmax is the only fit parameter (weight factor) in the semi-analytical model. Qmax=128pC except where indicated

# 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 $\sigma_r$ 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*



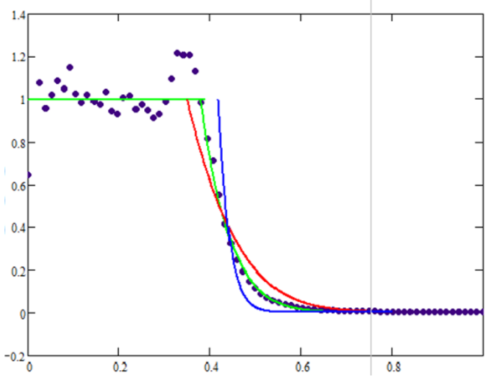


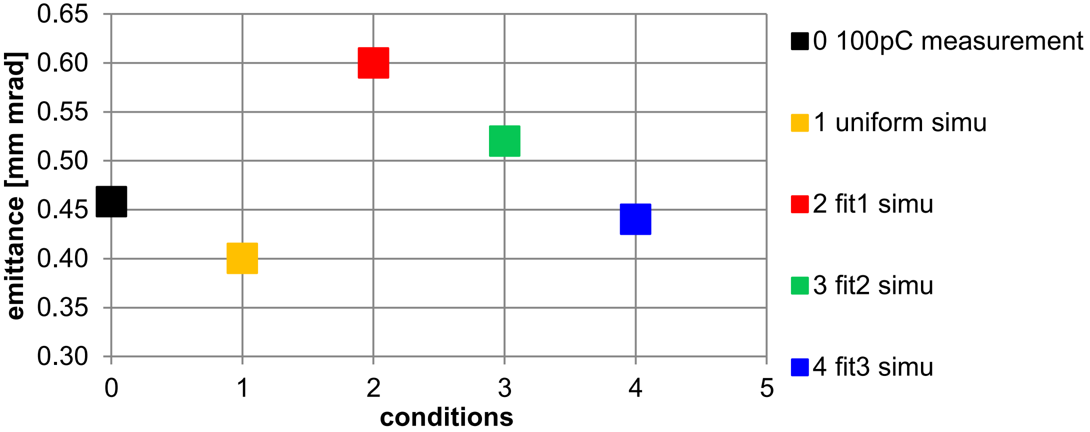
# Laser halo intensity distribution effect to emittance (Q. Zhao)

- 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.

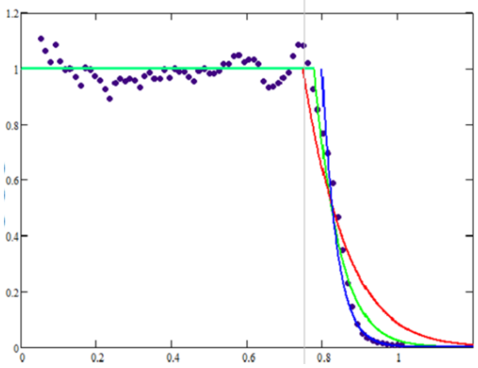
**conditions: 0-measurement, 1-uniform simu, 2-fit1 simu, 3-fit2 simu, 4-fit3 simu**

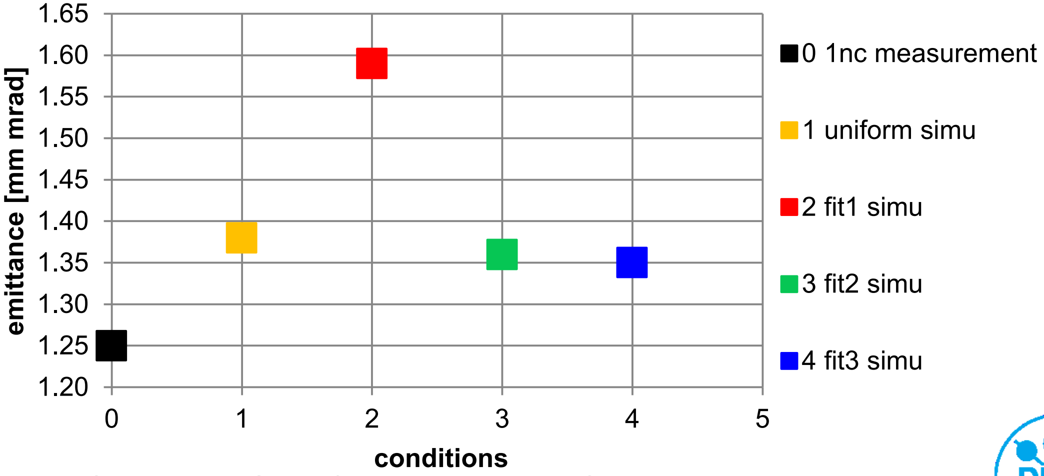
**100pC BSA= 0.9mm**



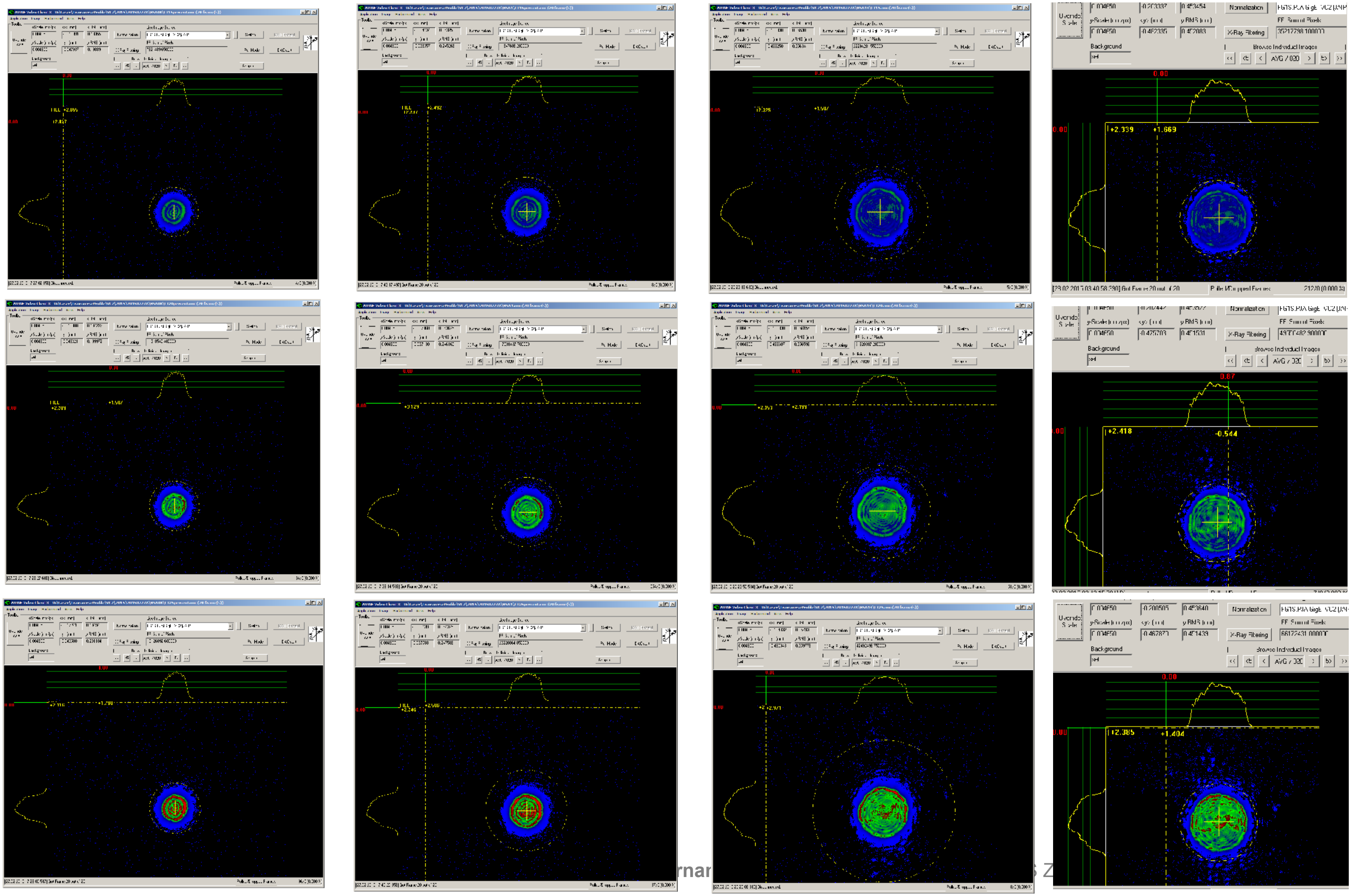


**1 nC BSA= 1.6mm**





# The imaged laser spot on the virtual cathode plane shows smaller halo / core *ratio* for larger beam diameters…



0.8 mm

1.0 mm

1.4 mm

1.8mm

Beam diameter

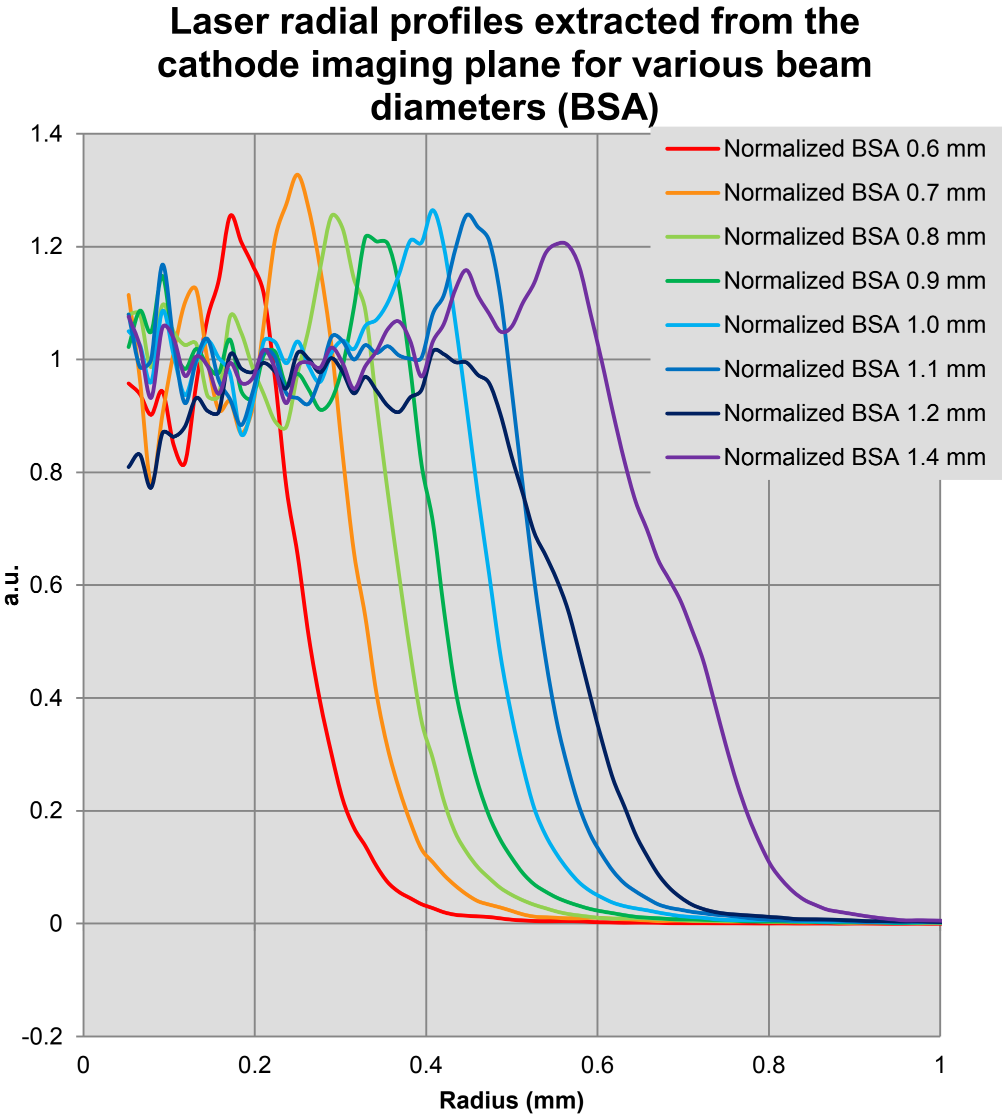
Relative Laser Intensity

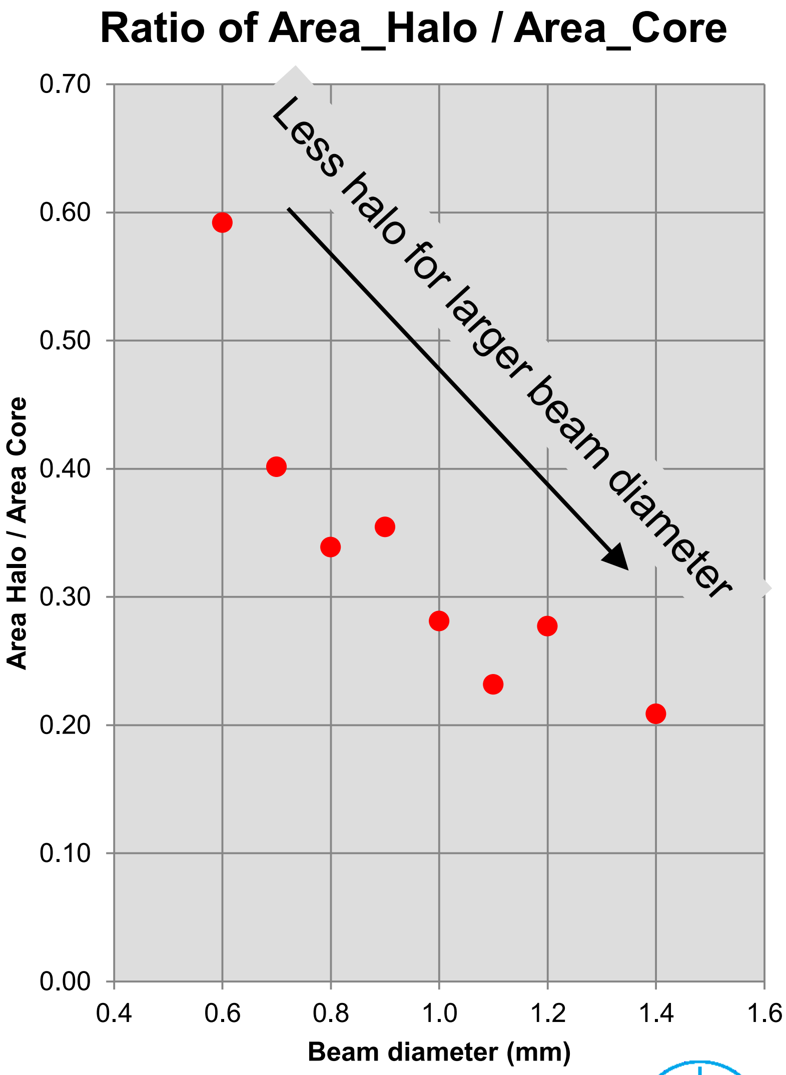
15%

20%

25%

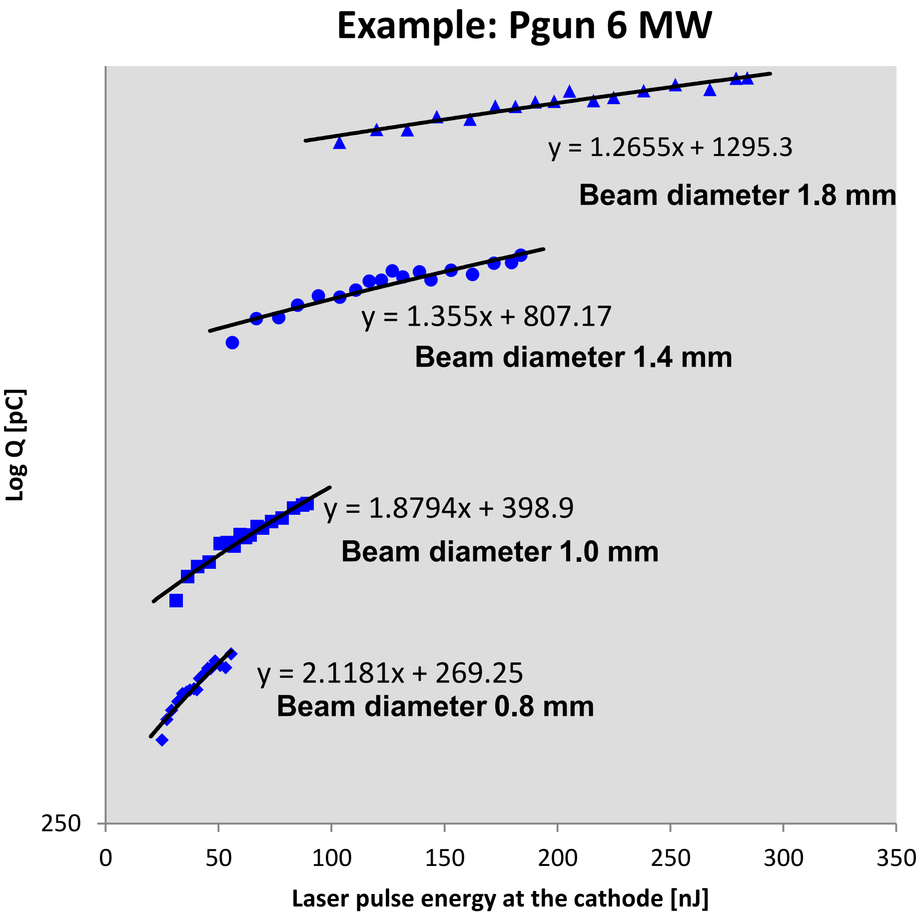
# …this means there is less Halo for larger BSA settings…



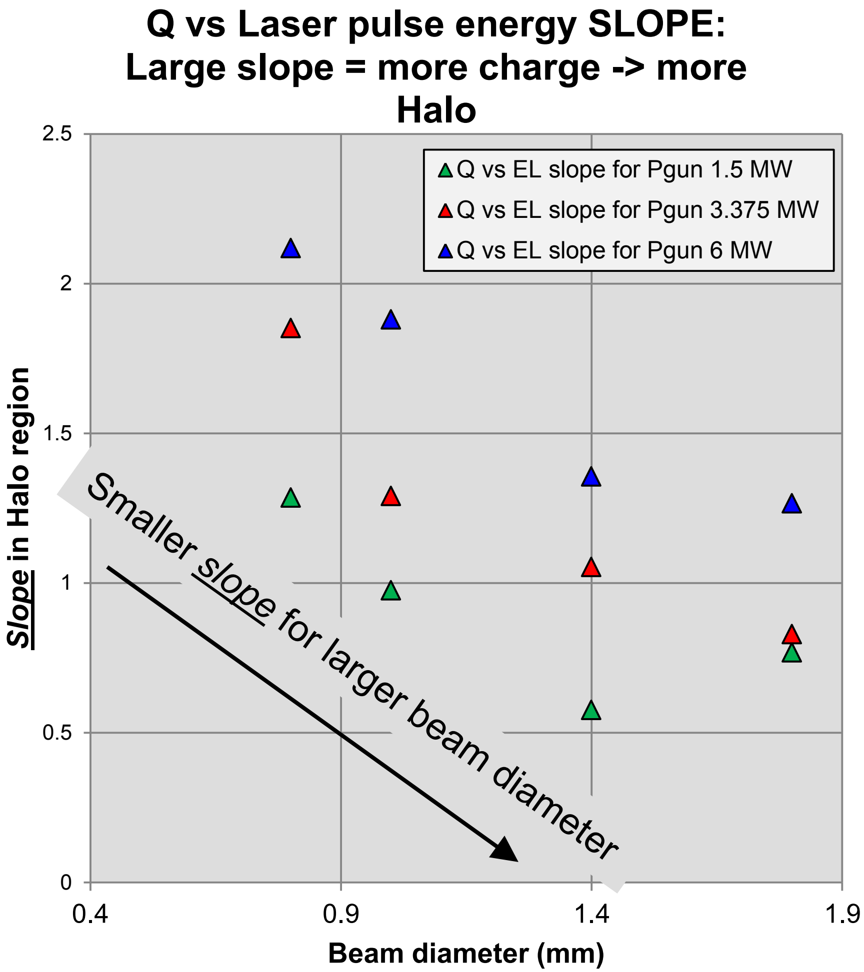


# …which is consistent with measurements showing that less charge is extracted from Halo for larger BSA settings

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



Example: Pgun 6 MW



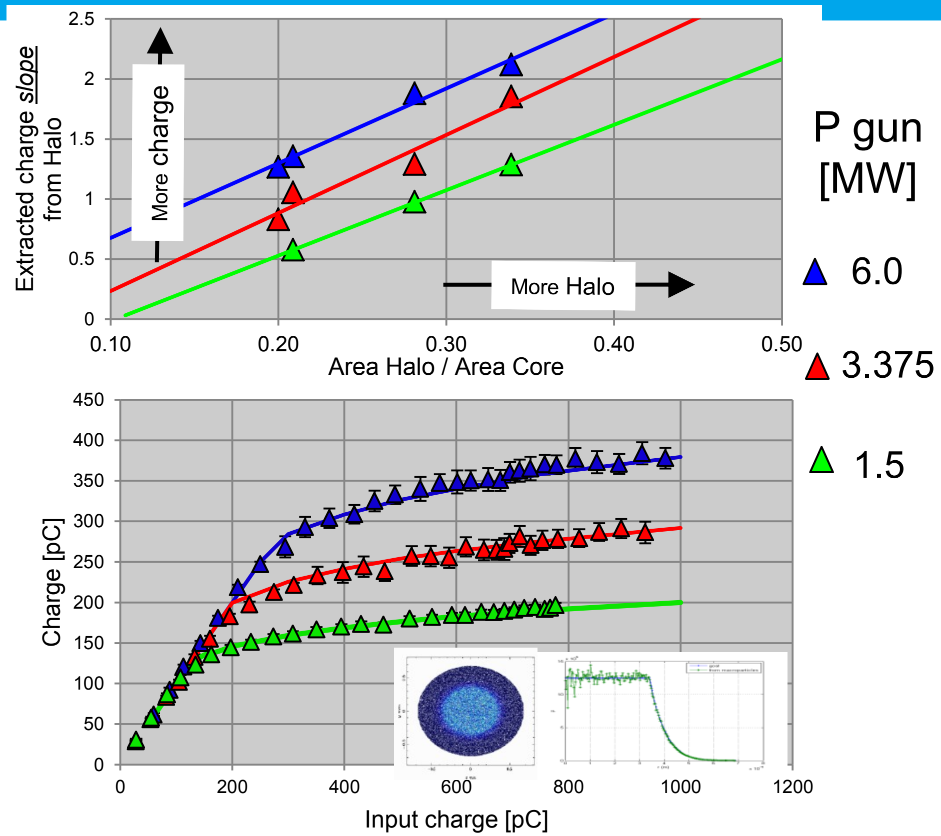
Q vs Laser pulse energy SLOPE: Large slope = more charge -> more Halo

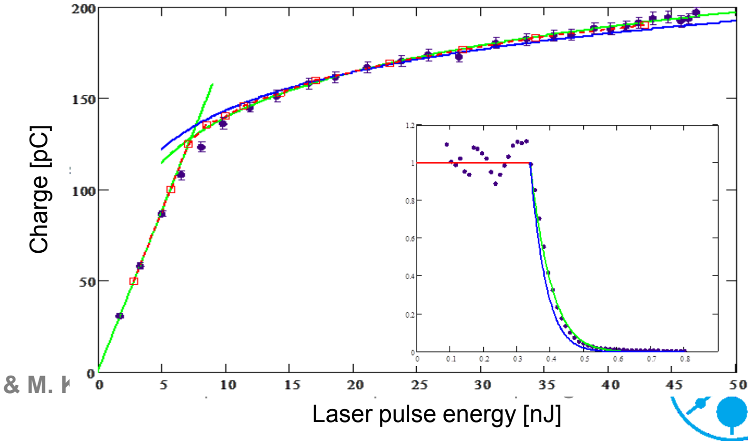
# Conclusions:

- 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 $\sigma_r$ 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



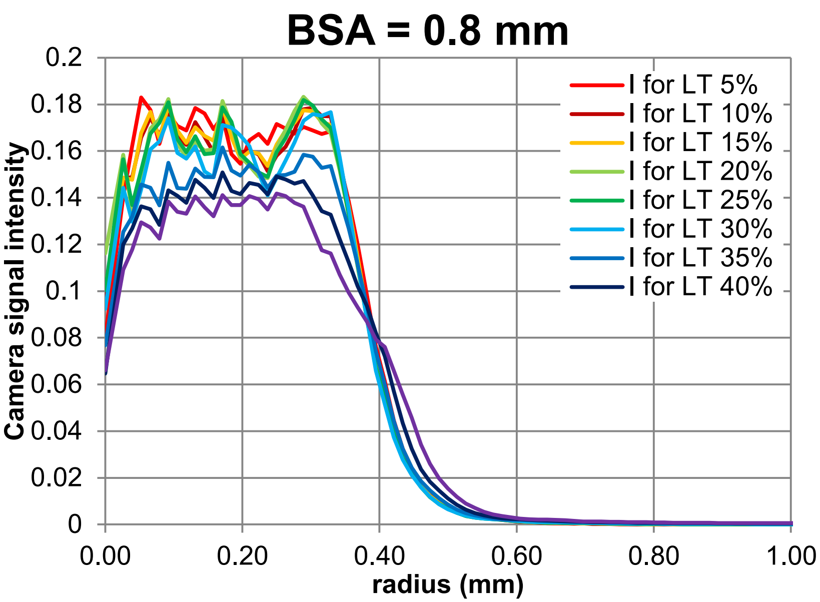


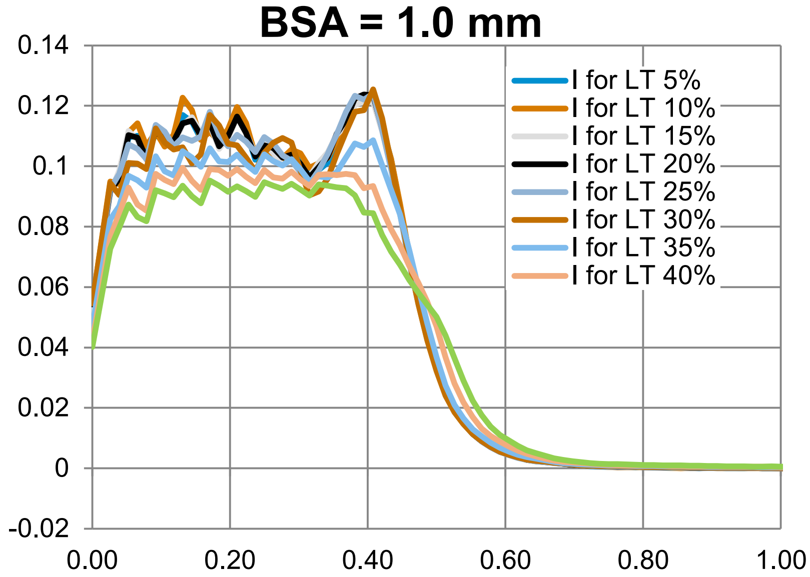
# BACKUP SLIDES

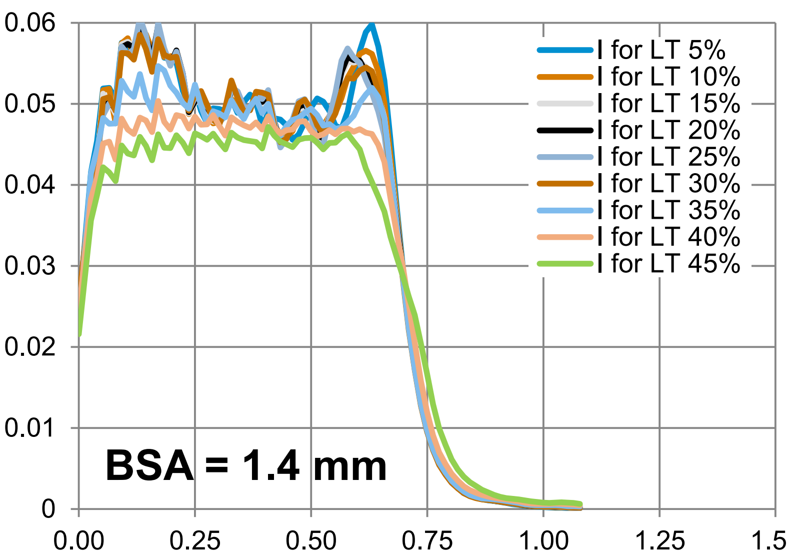
- BACKUP

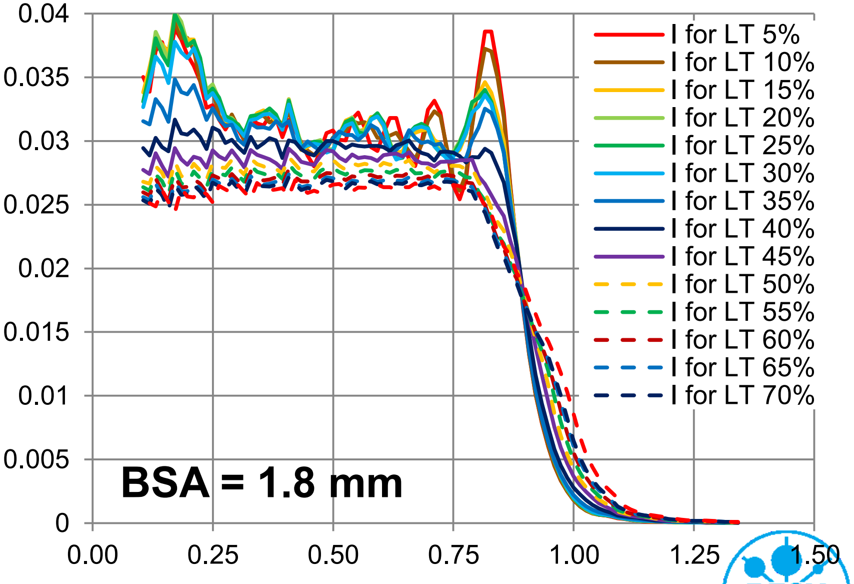
- SLIDES

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

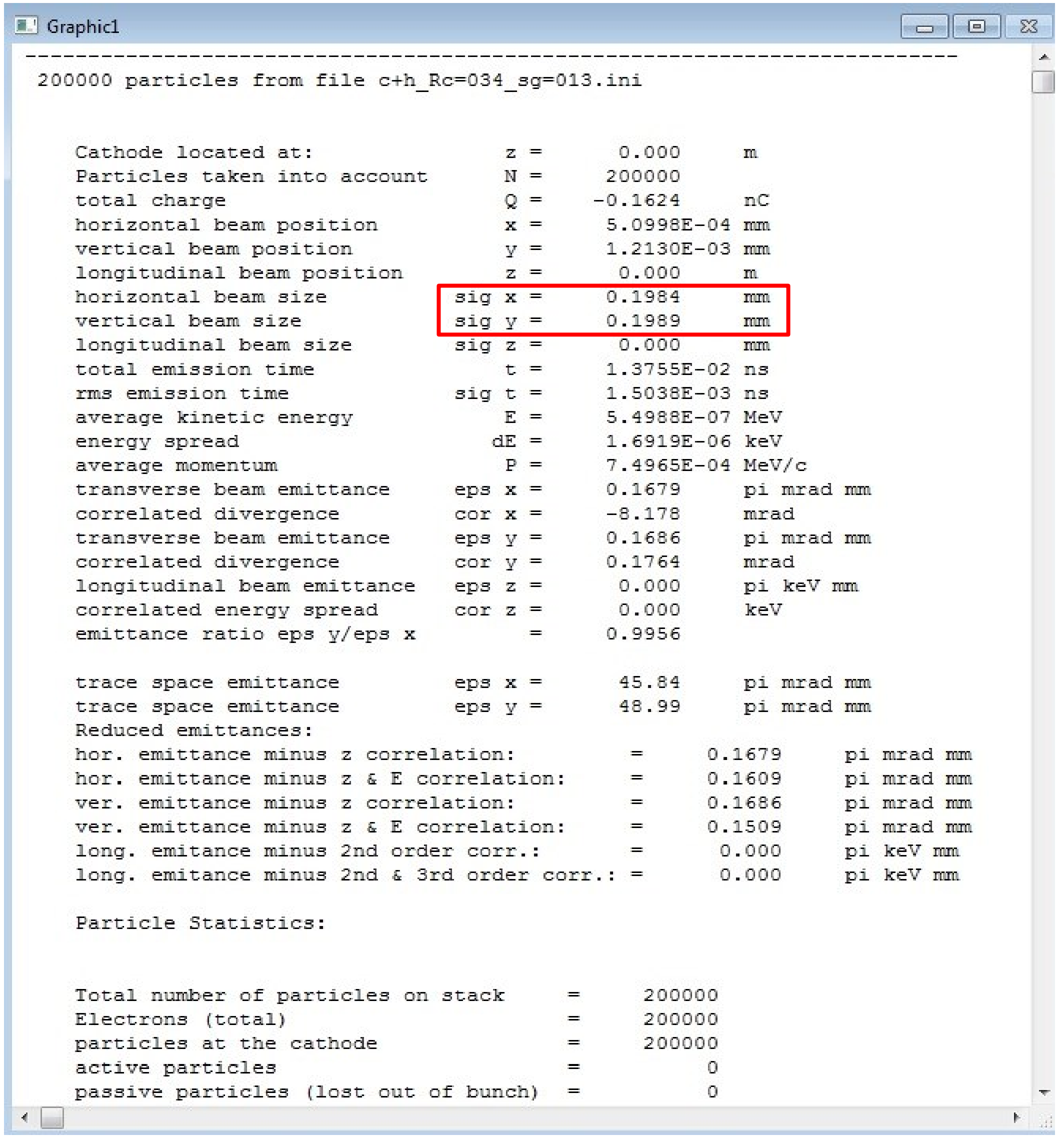

BSA = 0.8 mm


BSA = 1.0 mm


BSA = 1.4 mm


BSA = 1.8 mm

# The output from postpro shows that XYrms for core+halo distribution is very close to that for the uniform distribution



```
 --------------------------------------------------------------------------
 200000 particles from file c+h_Rc=034_sg=013.ini


    Cathode located at:                 z =      0.000     m
    Particles taken into account        N =     200000
    total charge                        Q =    -0.1624     nC
    horizontal beam position            x =     5.0998E-04 mm
    vertical beam position              y =     1.2130E-03 mm
    longitudinal beam position          z =      0.000     m
    horizontal beam size            sig x =     0.1984     mm
    vertical beam size              sig y =     0.1989     mm
    longitudinal beam size          sig z =      0.000     mm
    total emission time                 t =     1.3755E-02 ns
    rms emission time               sig t =     1.5038E-03 ns
    average kinetic energy              E =     5.4988E-07 MeV
    energy spread                      dE =     1.6919E-06 keV
    average momentum                    P =     7.4965E-04 MeV/c
    transverse beam emittance       eps x =     0.1679     pi mrad mm
    correlated divergence           cor x =     -8.178     mrad
    transverse beam emittance       eps y =     0.1686     pi mrad mm
    correlated divergence           cor y =     0.1764     mrad
    longitudinal beam emittance     eps z =      0.000     pi keV mm
    correlated energy spread        cor z =      0.000     keV
    emittance ratio eps y/eps x           =     0.9956

    trace space emittance           eps x =      45.84     pi mrad mm
    trace space emittance           eps y =      48.99     pi mrad mm
    Reduced emittances:
    hor. emittance minus z correlation:        =     0.1679     pi mrad mm
    hor. emittance minus z & E correlation:    =     0.1609     pi mrad mm
    ver. emittance minus z correlation:        =     0.1686     pi mrad mm
    ver. emittance minus z & E correlation:    =     0.1509     pi mrad mm
    long. emitance minus 2nd order corr.:      =      0.000     pi keV mm
    long. emitance minus 2nd & 3rd order corr.: =      0.000     pi keV mm

    Particle Statistics:


    Total number of particles on stack      =     200000
    Electrons (total)                       =     200000
    particles at the cathode                =     200000
    active particles                        =          0
    passive particles (lost out of bunch)   =          0
```

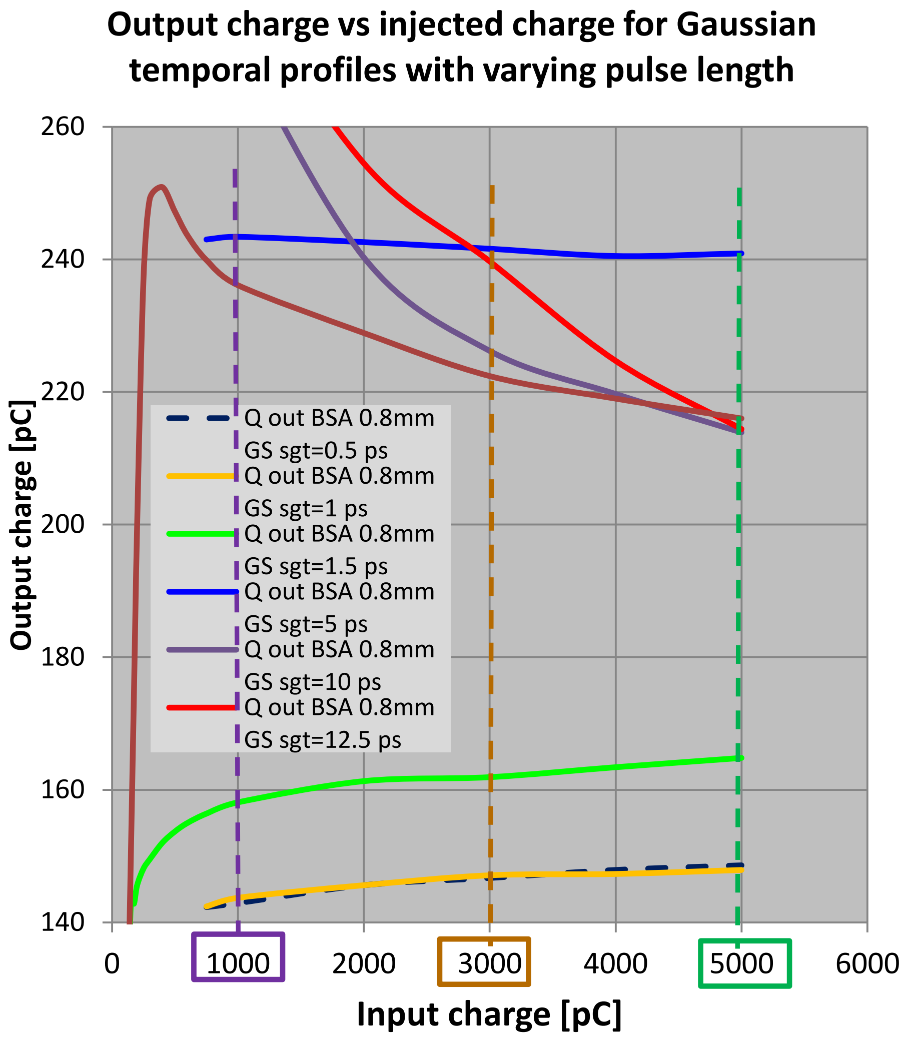
# Size (slide by M. Gross)

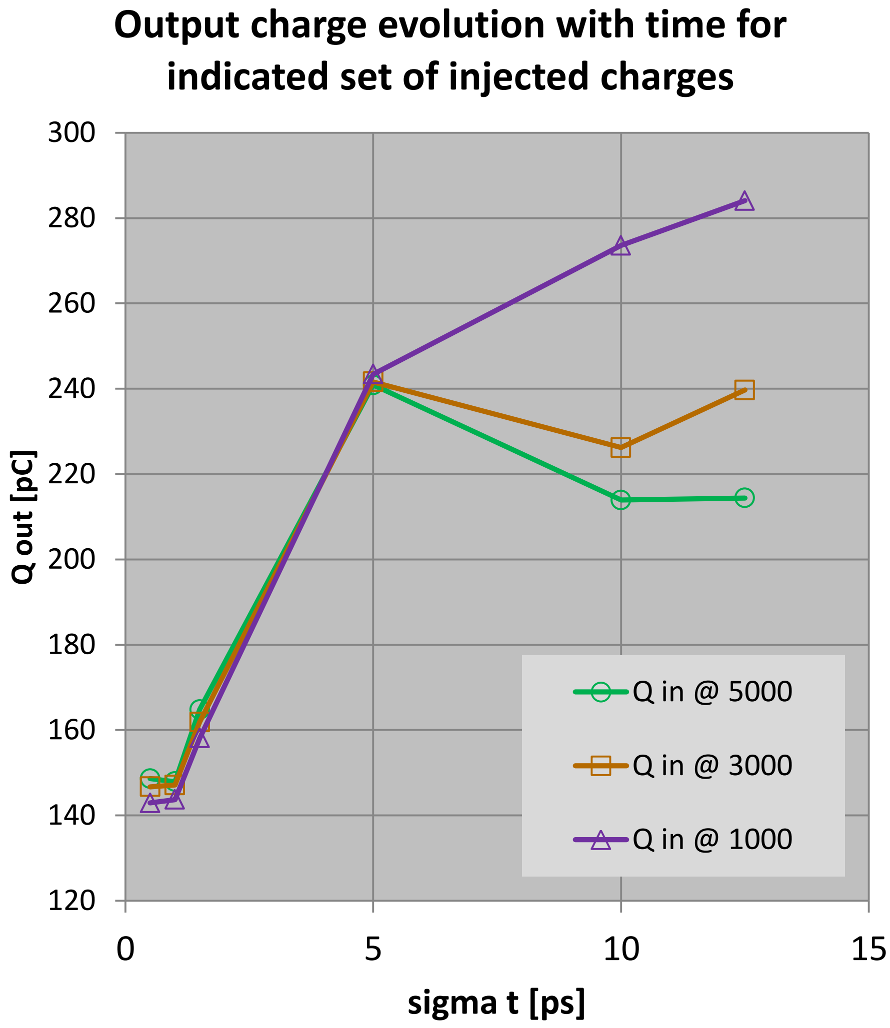
| BSA size [mm]* | Cathode camera | | | VC2 | | | Size ratios Cathode/VC2 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | xRMS | yRMS | xyRMS | xRMS | yRMS | xyRMS | x | y | xy | BSA/VC2 xyRMS |
| 0.08 | 0.066 | 0.065 | 0.065 | 0.064 | 0.063 | 0.063 | 1.03 | 1.03 | 1.03 | 1.26 |
| 0.16 | 0.056 | 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

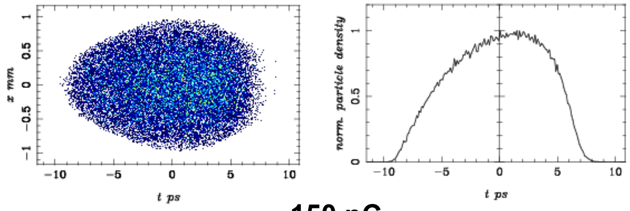
# The slope of the output charge depends on the initial bunch length


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

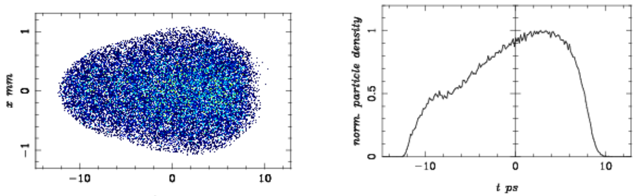

Output charge evolution with time for indicated set of injected charges

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

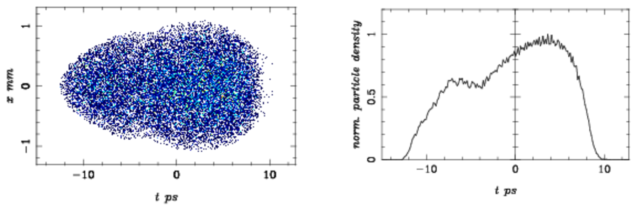
**100 pC**



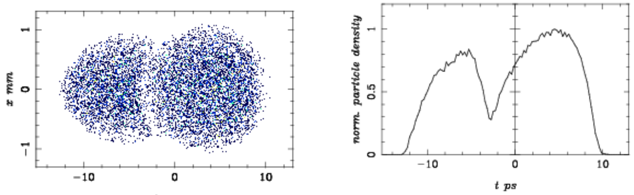
**150 pC**



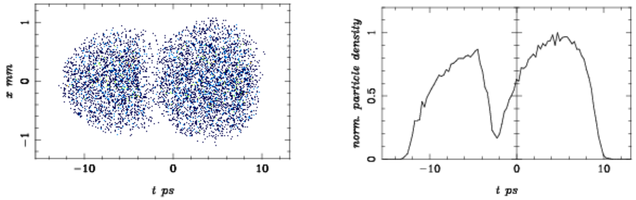
**200 pC**

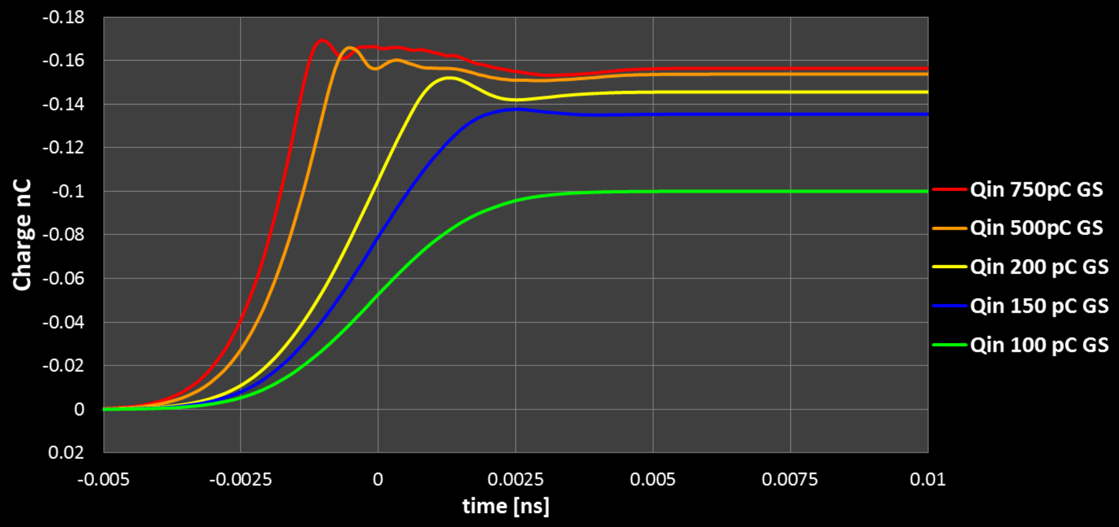


**500 pC**

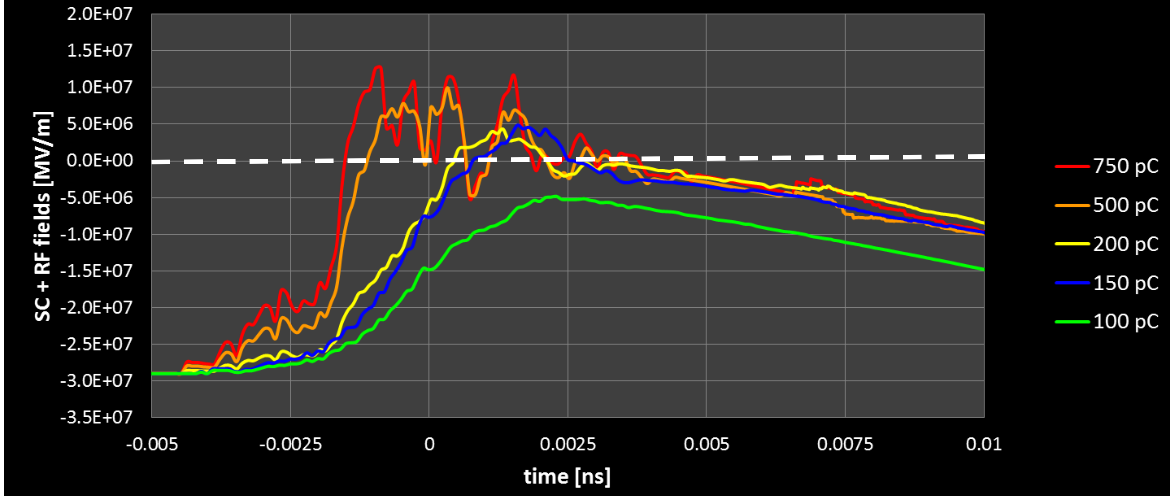


**750 pC**



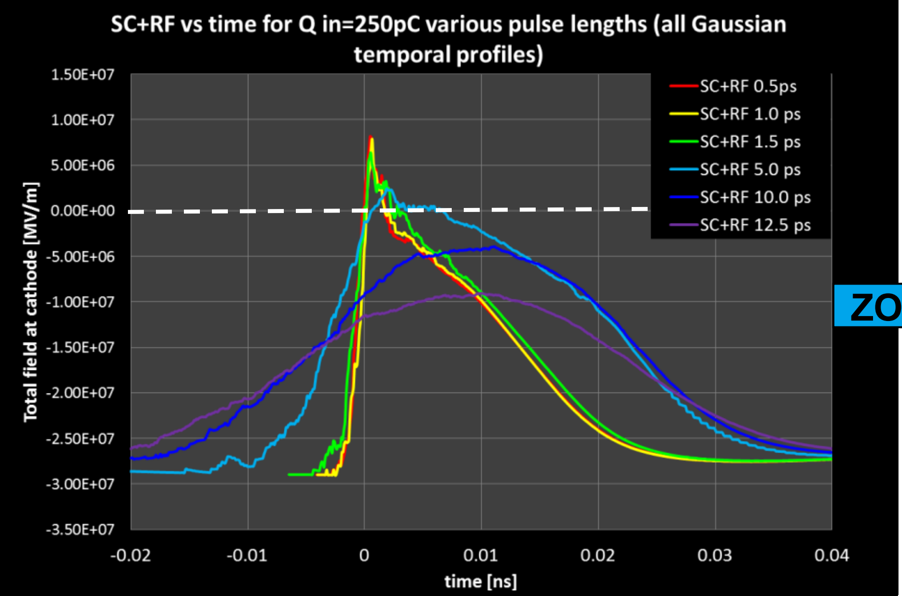


Output charge vs t for Gaussian temporal with sigt=1.5 ps for various injected charges

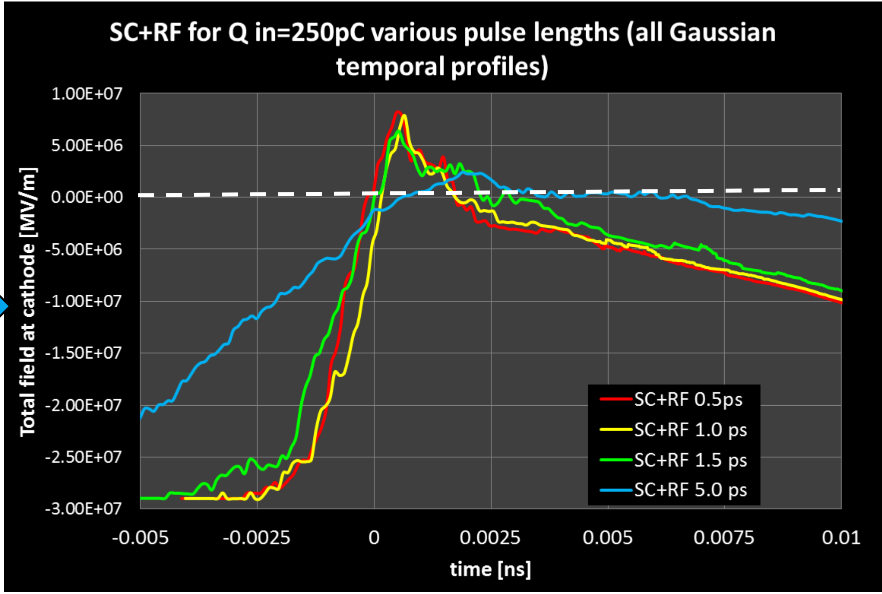


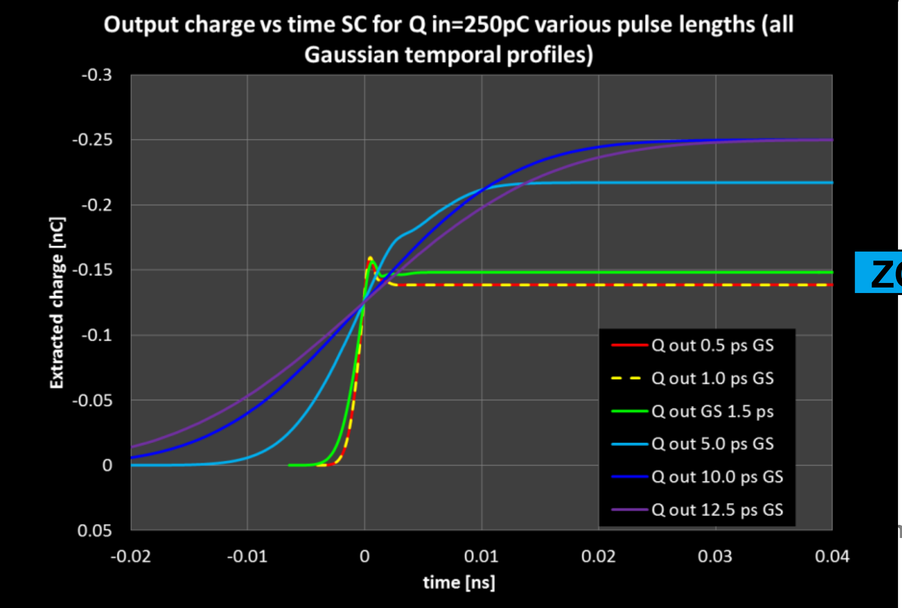
Cathode Total Electric field (SC+RF) vs time for Gaussian temporal sigt=1.5ps for various injected charges

**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.**

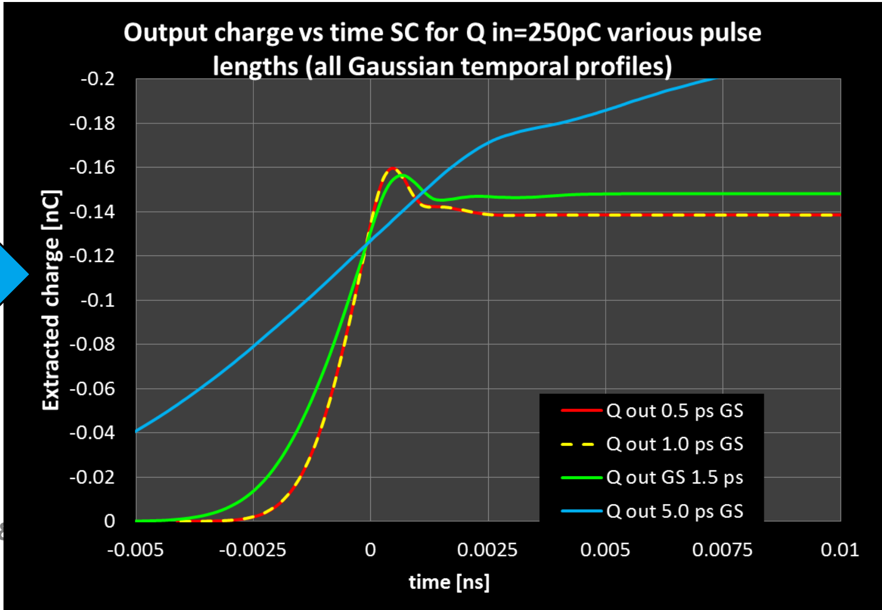

SC+RF vs time for Q in=250pC various pulse lengths (all Gaussian temporal profiles)

ZOOM IN


SC+RF for Q in=250pC various pulse lengths (all Gaussian temporal profiles)


Output charge vs time SC for Q in=250pC various pulse lengths (all Gaussian temporal profiles)

ZOOM IN


Output charge vs time SC for Q in=250pC various pulse lengths (all Gaussian temporal profiles)

# 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 $\Phi_0$-90 and BSA = 1.8 mm