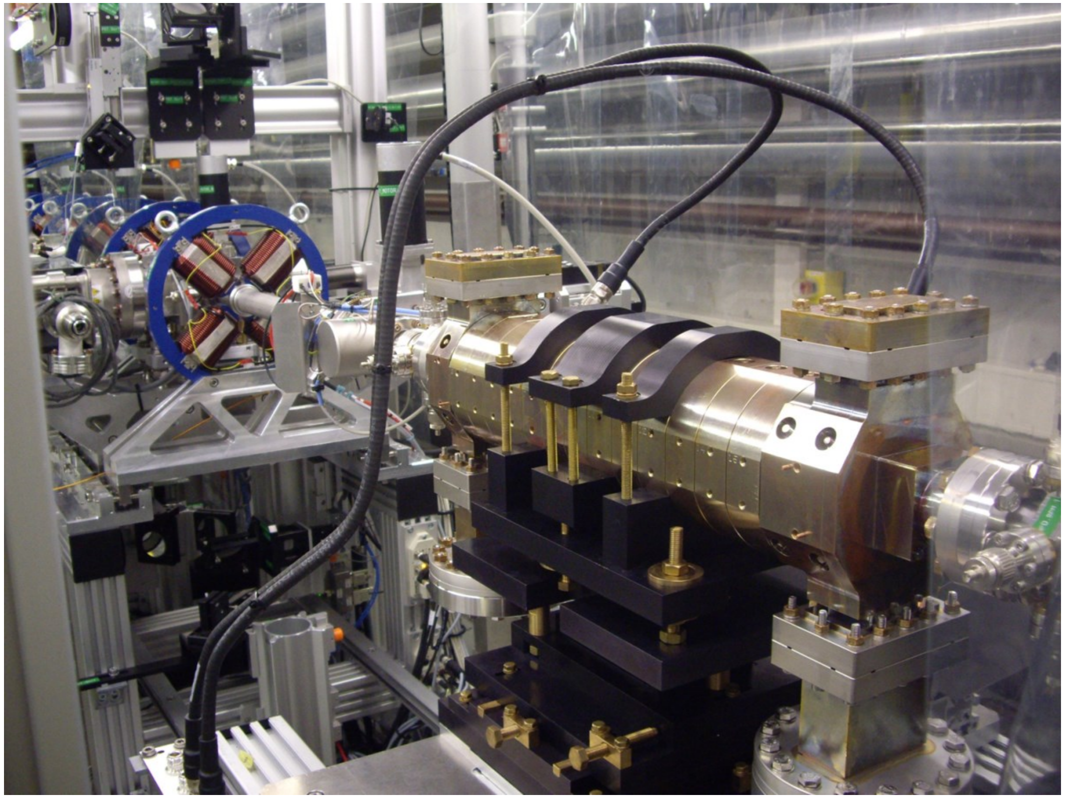
First Slice Emittance Measurements using the PITZ TDS

- Introduction
- Measurement Procedure
  - acquisition, analysis, tools
- First Results and simulations
- Outlook



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04.02.2016, PITZ Physics Seminar

HELMHOLTZ | GEMEINSCHAFT

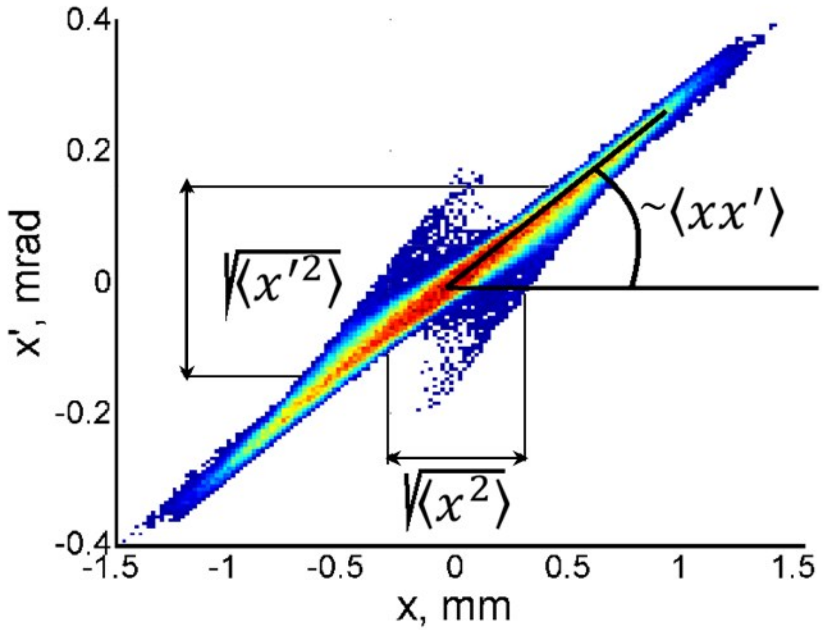
DESY

Introduction: Emittance

- Emittance = phase or trace space area occupied by electrons
- „Normalized transverse rms emittance“ defined by statistical moments of the electron distribution:

$$\varepsilon_{n,x} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

- „Projected emittance“: <x²>,<x‘²>,<xx‘> are integrals over the whole e-bunch
- „**Slice emittance**“: Emittance as function of the longitudinal position in the bunch; <x…> evaluated for discrete z-intervals.



For XFELs, slice emittance is more important than projected emittance, because low charge / high emittance tails do not contribute to lasing!

Quadrupole Scan Technique

> Idea:

- Backtracking the measured beam size <x²> through a known beam transport matrix.
- Measure <x²> for different matrices but the same starting distribution x_0, x_0', then fit a parabola.

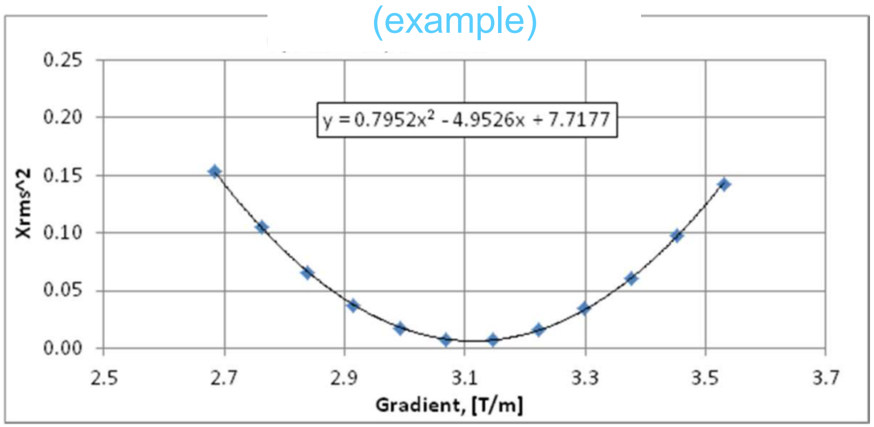
> General approach (linear matrix optics): $x = R_{11}x_0 + R_{12}x_0'$

$$\rightarrow \langle x^2 \rangle = R_{11}^2 \langle x_0^2 \rangle + 2R_{11}R_{12}\langle x_0 x_0' \rangle + R_{12}^2 \langle x_0'^2 \rangle$$

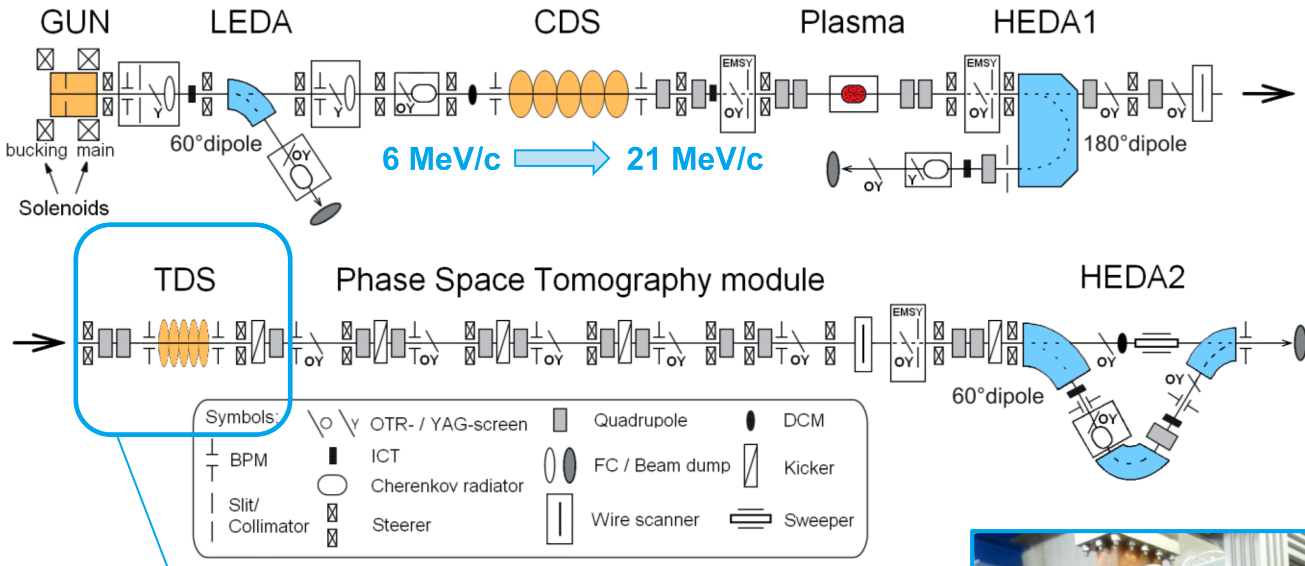
- With at least 3 measurements, the unknown moments of the starting distribution can be obtained by a parabola surface fit (e.g. „poly22“ fittype in Matlab)
- Emittance at the *starting position* follows from standard formula on p.2

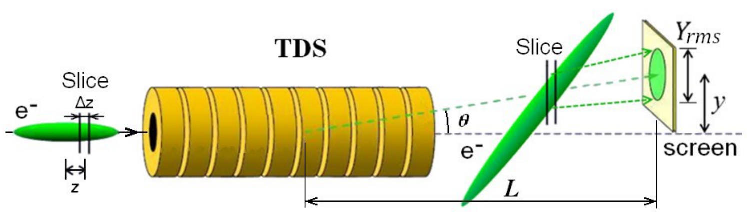
> Special case of just one quad followed by a fixed drift space:

$$\langle x^2 \rangle = \langle x_0^2 \rangle (1 - l \cdot l_{eff} \cdot k)^2 + \\ +2\langle x_0 x_0' \rangle (1 - l \cdot l_{eff} \cdot k)(l + l_{eff}) + \langle x_0'^2 \rangle (l + l_{eff})^2$$



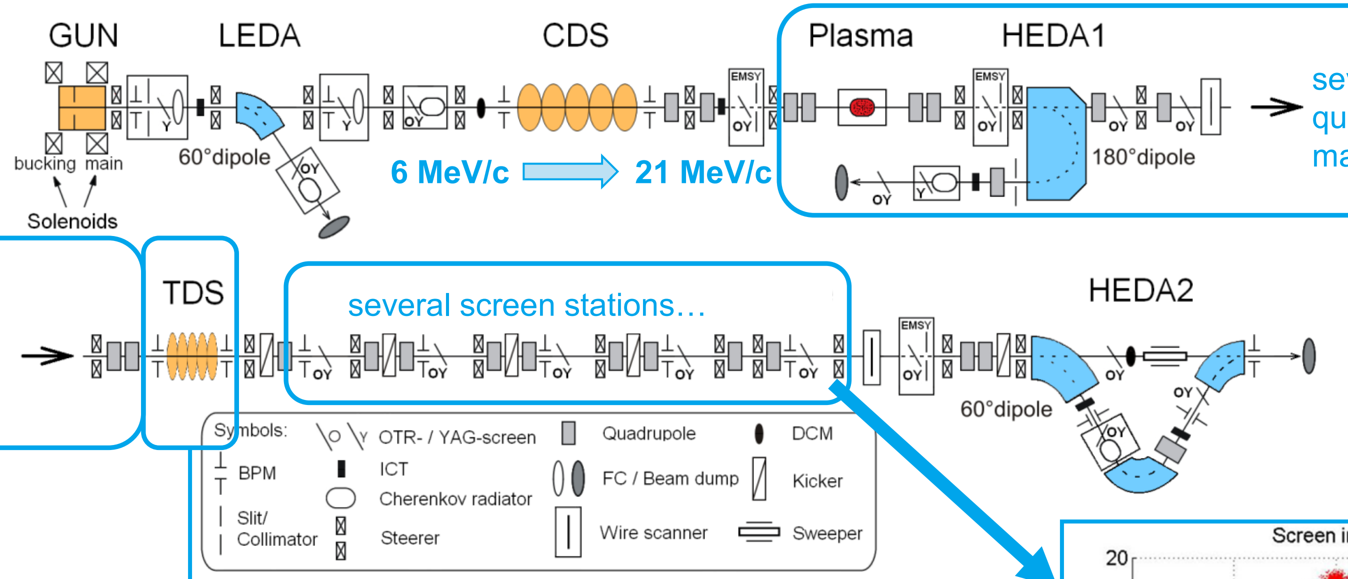
PITZ Setup



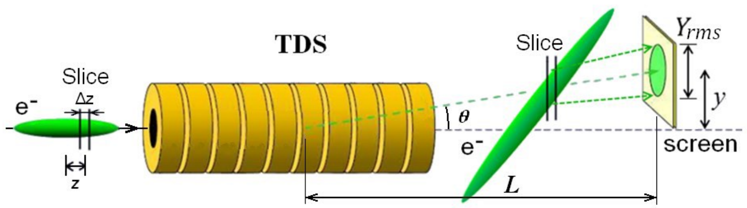


deflecting cavity: bunch length mapped to vertical axis

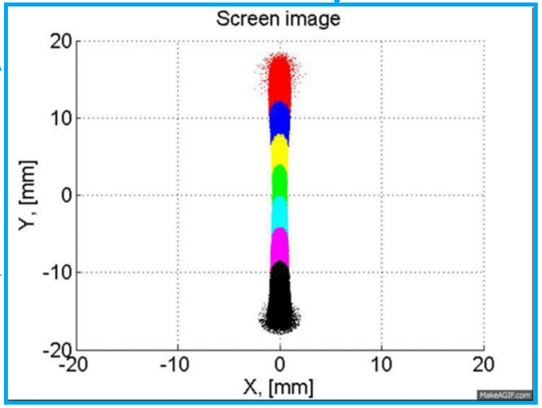
Slice Emittance Measurement



several quadrupole magnets…



deflecting cavity: bunch length mapped to vertical axis



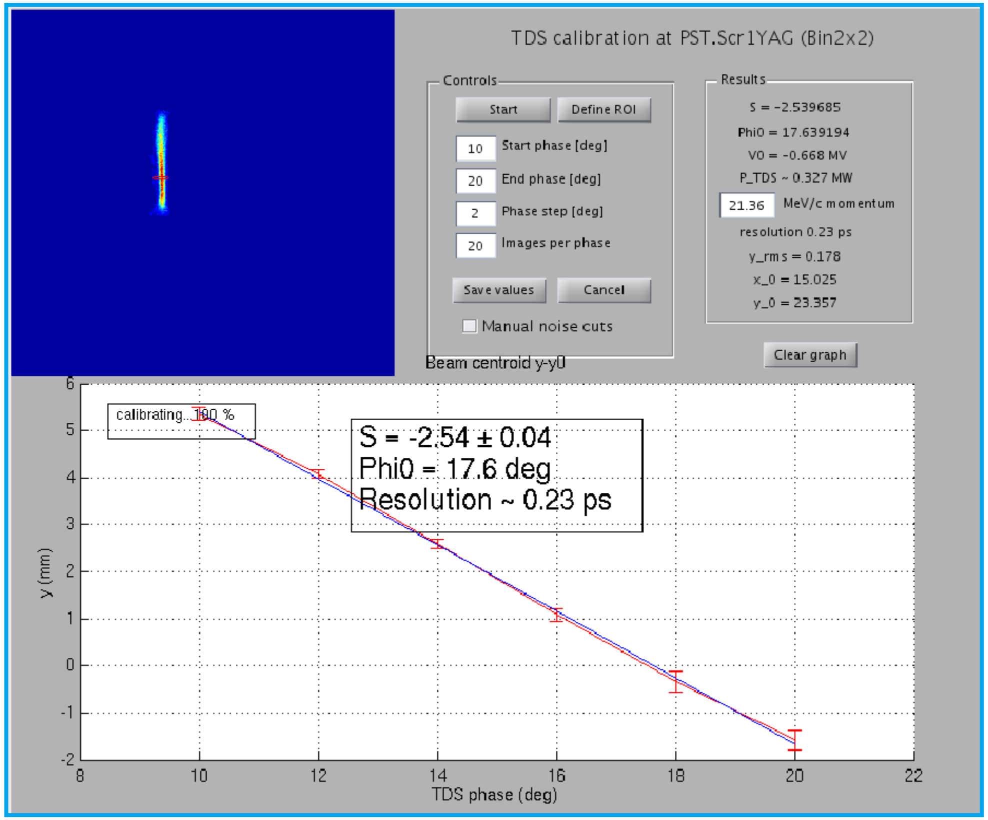
applying quad-scan technique to TDS-separated longitudinal slices of the bunch =

horizontal slice emittance measurement!

Measurement Procedure

1. Image acquisition for various quad settings (**TDS_main.m**)
2. Extracting all <x^2> data (**SLEM.m**)
3. Fitting, plotting, exporting and comparison with ASTRA distributions (**SLEM2.m**)

1. Image acquisition

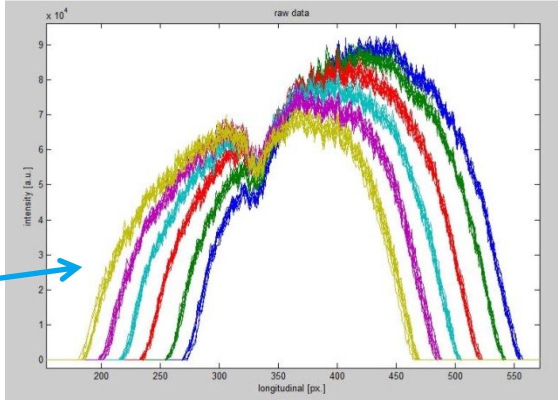


- Just use the same tool as for bunch length measurements! (**TDS_main.m**)
- All acquired images (~50-200) are automatically saved in one *.mat file, together with calibration, bunch length, etc.
- Quad settings are currently not saved, will be added soon…

1. Image acquisition

Planned updates (until May/June…)

- Automatically save machine parameters like quad settings
- SuperGauss fit for FWHM analysis
- Streamline GUI
- Save ROI-sized images only (not full size)
- Add streak direction indicator („time arrow“, but this must be once set by operator)
- Screen sensitivity maps for normalization
  - Similar to QE map acquisition, but much faster (10 images per second and steerers don‘t need few seconds for each step)
  - Current profiles already have *some* of this information, but very rough and not 2-dimensional…



2a. Writing a definition file

- **SLEM.m** needs to know which files to analyze and which quad settings belongs to which file

KW34_100pC.txt - Editor

Datei Bearbeiten Format Ansicht ?

```
%SLEM Measurements (100 pC, BSA08, Imain356) in
%\doocs\measure\LongPhSp\2015\TDScalib\TDSscan2015\20150823M\
%p[MeV/c]           I_Q9[A]           I_Q10[A]          *.matfile

21.6     4.76     -5.2     calib_0922.mat
21.6     4.76     -5.3     calib_0939.mat
21.6     4.76     -5.4     calib_0945.mat
21.6     4.76     -5.5     calib_0952.mat
21.6     4.76     -5.6     calib_1000.mat
21.6     4.76     -5.7     calib_1009.mat
21.6     4.76     -5.8     calib_1030.mat
21.6     4.76     -5.9     calib_1035.mat
21.6     4.76     -6.0     calib_1040.mat
21.6     4.76     -6.1     calib_1044.mat
21.6     4.76     -6.2     calib_1050.mat
21.6     4.76     -6.3     calib_1054.mat
```

- **Outlook: enhanced table including all quads, screen and solenoid…**

slem_def.txt - Editor

Datei Bearbeiten Format Ansicht ?

```
%%% SLEM Measurements template
%%% first some constants, starting with one "%"
%%% then table with 14 columns: matfile screen# I_main[A] I_high.Q10[A] I_Q9....Q1[A]

%pathname = Q:\group\pitz\doocs\measure\LongPhSp\2015\TDScalib\TDSscan2015\20150823M\
%momentum = 21.6          % MeV/c

%charge = 100             % pC, just for reference
%BSA = 0.8                % mm, just for reference
%VC2path = Q:\group\pitz\doocs\measure\Laser\TransverseProfile\VC2\2015\20150822N\
%VC2file = BSA0.8_6H49.imc        % just for reference

calib_0922.mat  1 350   -5.2    4.76    0 0 0 0 0 0 0 0 0
calib_0939.mat  1 350   -5.4    4.76    0 0 0 0 0 0 0 0 0
calib_0945.mat  1 350   -5.5    4.76    0 0 0 0 0 0 0 0 0
calib_0952.mat  1 350   -5.6    4.76    0 0 0 0 0 0 0 0 0
calib_1000.mat  1 350   -5.7    4.76    0 0 0 0 0 0 0 0 0
calib_1009.mat  1 350   -5.8    4.76    0 0 0 0 0 0 0 0 0
calib_1030.mat  1 350   -5.9    4.76    0 0 0 0 0 0 0 0 0
calib_1035.mat  1 350   -6.0    4.76    0 0 0 0 0 0 0 0 0
calib_1040.mat  1 350   -6.1    4.76    0 0 0 0 0 0 0 0 0
calib_1044.mat  1 350   -6.2    4.76    0 0 0 0 0 0 0 0 0
calib_1050.mat  1 350   -6.3    4.76    0 0 0 0 0 0 0 0 0
calib_1054.mat  1 350   -6.4    4.76    0 0 0 0 0 0 0 0 0
```

2. SLEM.m

> Purpose of **SLEM.m:**

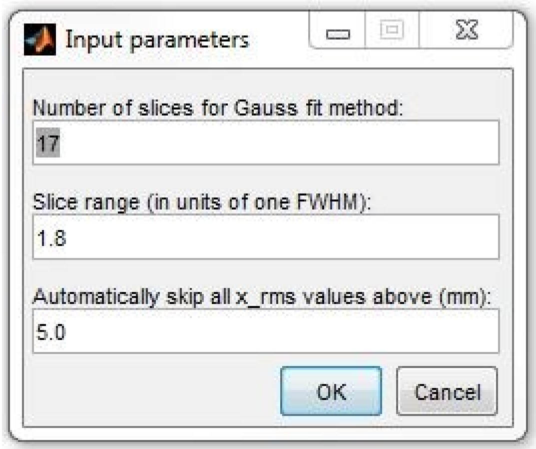
- Extracting all <x²> slice data from all images
- Input up to ~1 GB, output just a few MB
- Takes about 15 minutes for 150 MB of images
- Two different methods to determine <x²>: Gauss fit and rms
- Automatic and interactive masking of slices and frames
- Variable slice width for rms-method:

For each vertical line y, calculate and save variance V_y, center of mass E_y and sum of pixels P_y (line charge). The slice variance <x²> can then be calculated for slice range Y=[y1:y2] by

$$\langle x^2 \rangle = \frac{\sum_Y P_y \left(V_y + E_y^2 \right)}{\sum_Y P_y} - \left(\frac{\sum_Y P_y E_y}{\sum_Y P_y} \right)^2$$

2. SLEM.m

(a)



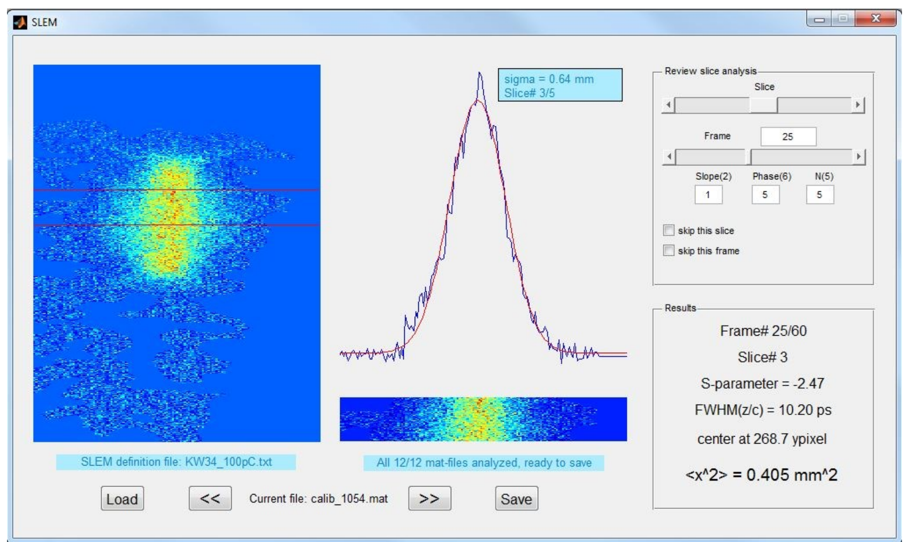
(b)

Analyzing, please wait ~5 min

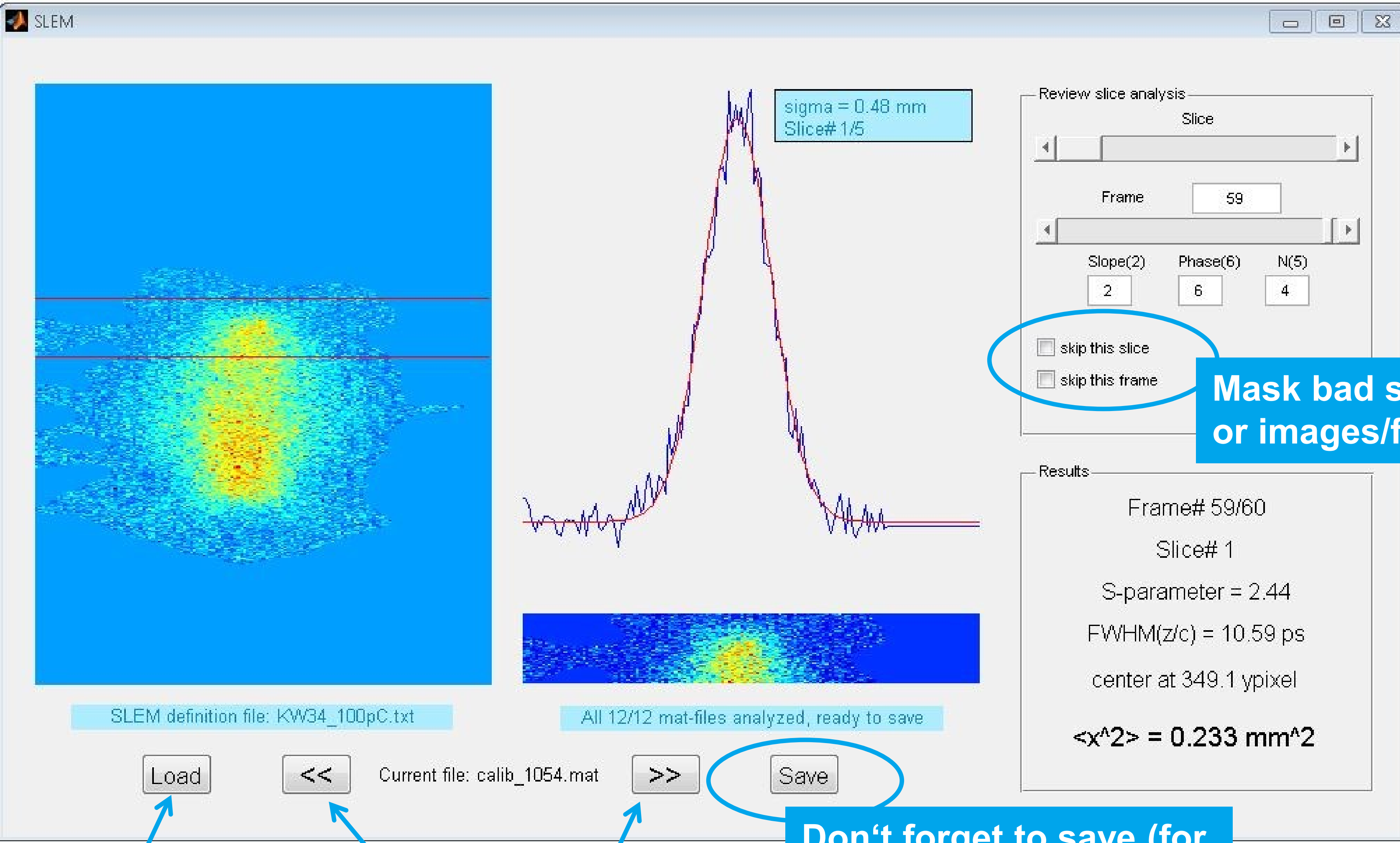
- Automatic evaluation of all images
- Takes ~15 min for 12240 Gauss fits (60 frames x12 files x17 slices)

(c)

- Manual review of the slice analysis
- Option to mask individual frames or slices



2. SLEM.m



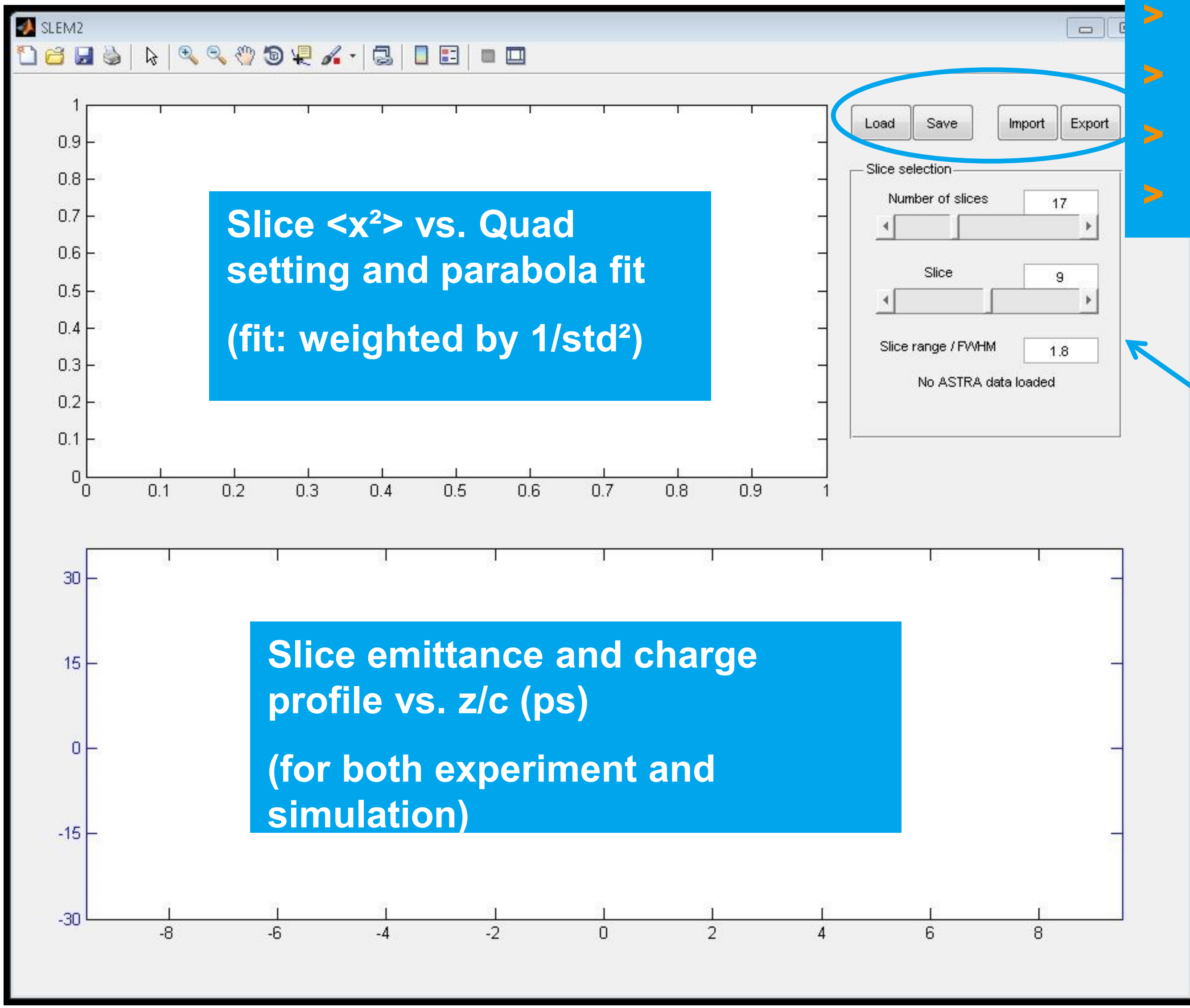
Mask bad slices or images/frames

Don‘t forget to save (for later use in SLEM2.m…)

New analysis

Cycle through TDS measurements

3. SLEM2.m



Slice <x²> vs. Quad setting and parabola fit

(fit: weighted by 1/std²)

Slice emittance and charge profile vs. z/c (ps)

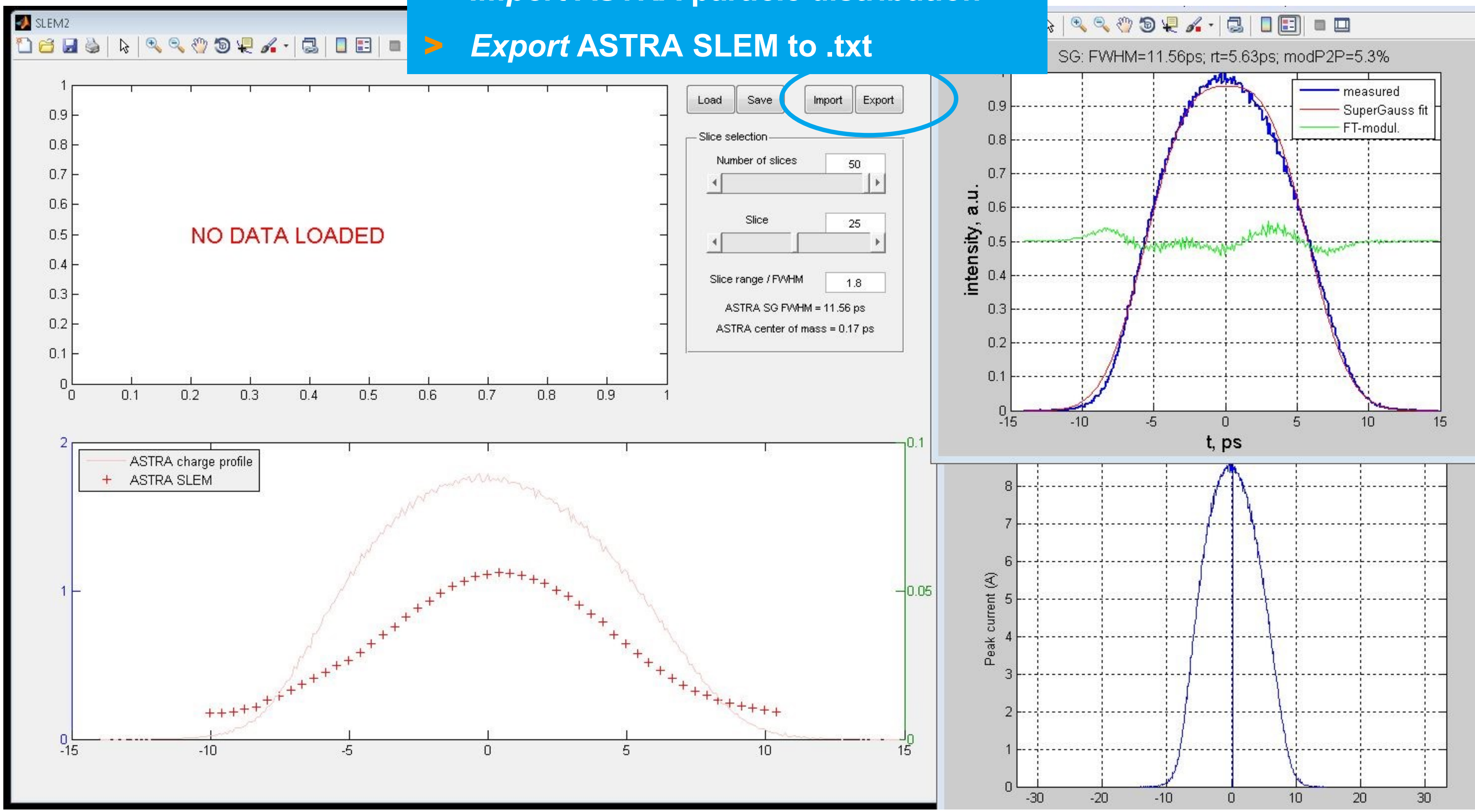
(for both experiment and simulation)

- *Load* SLEM.m output
- *Save* results to .txt
- *Import* ASTRA data
- *Export* ASTRA result (txt)

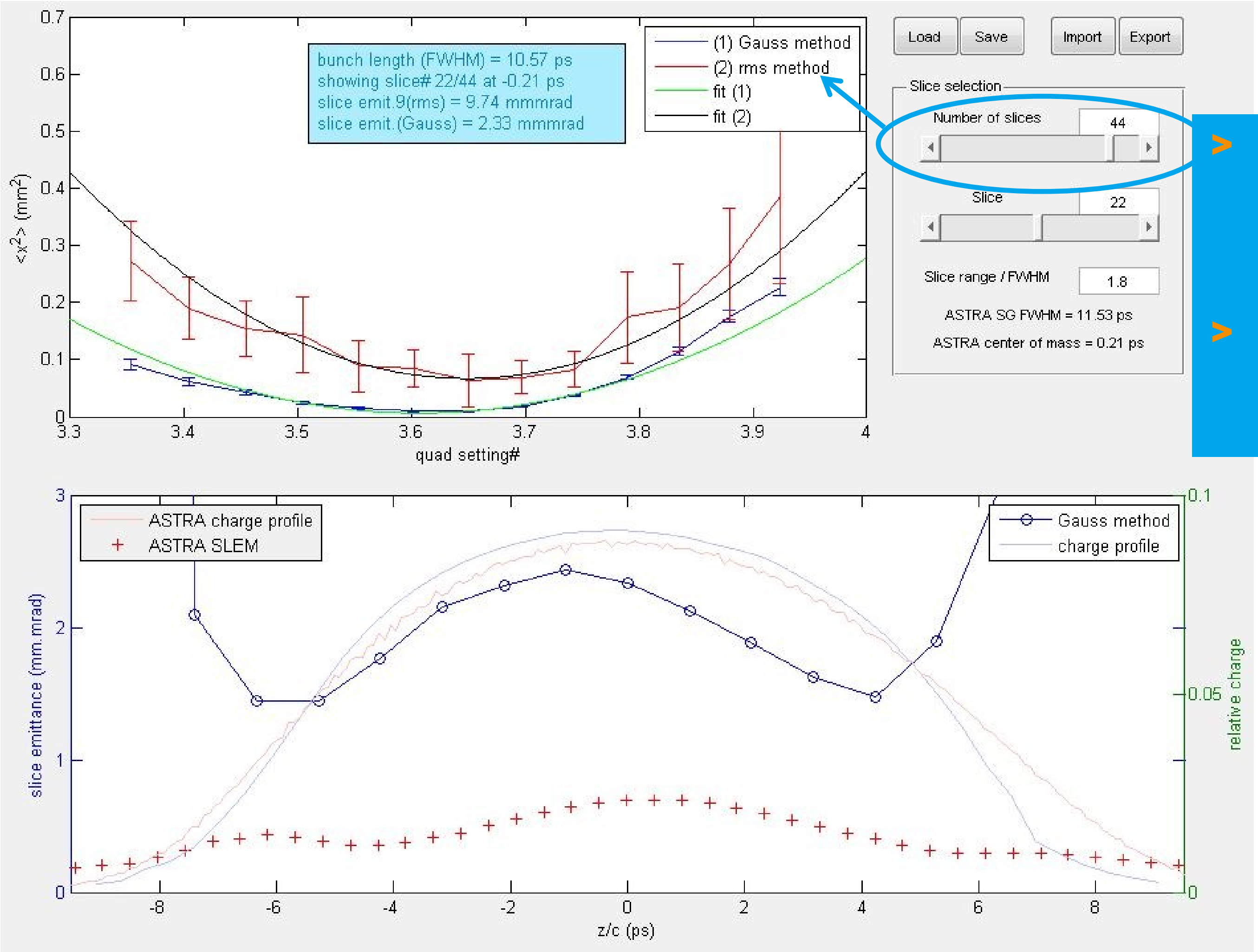
- Change slice width
- Change slice range
- Select the slice to display in graph on the left

ASTRA with SLEM2.m

- > *Import* **ASTRA particle distribution**
- > *Export* **ASTRA SLEM to .txt**



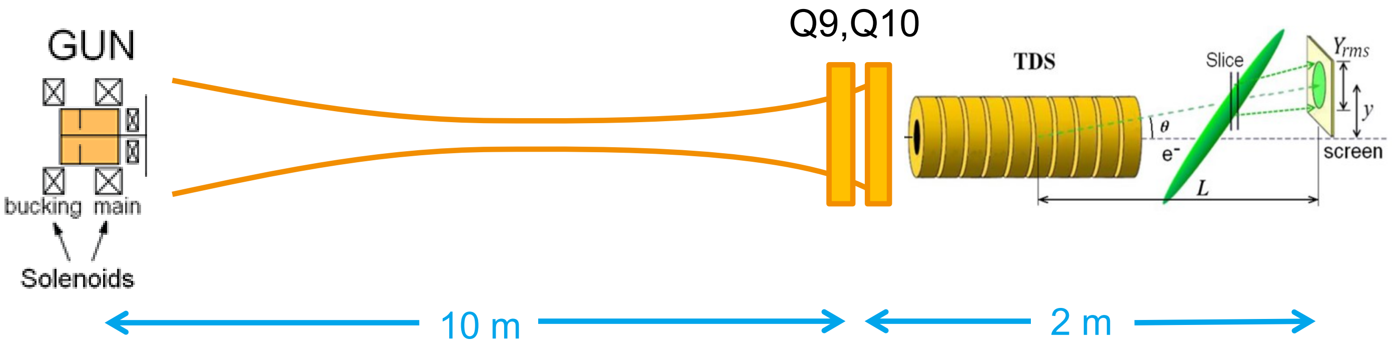
SLEM2.m



- Number of slices („y-binning“) can be changed for the rms method and for ASTRA data
- Gauss-method slice width and range is fixed (by SLEM.m)

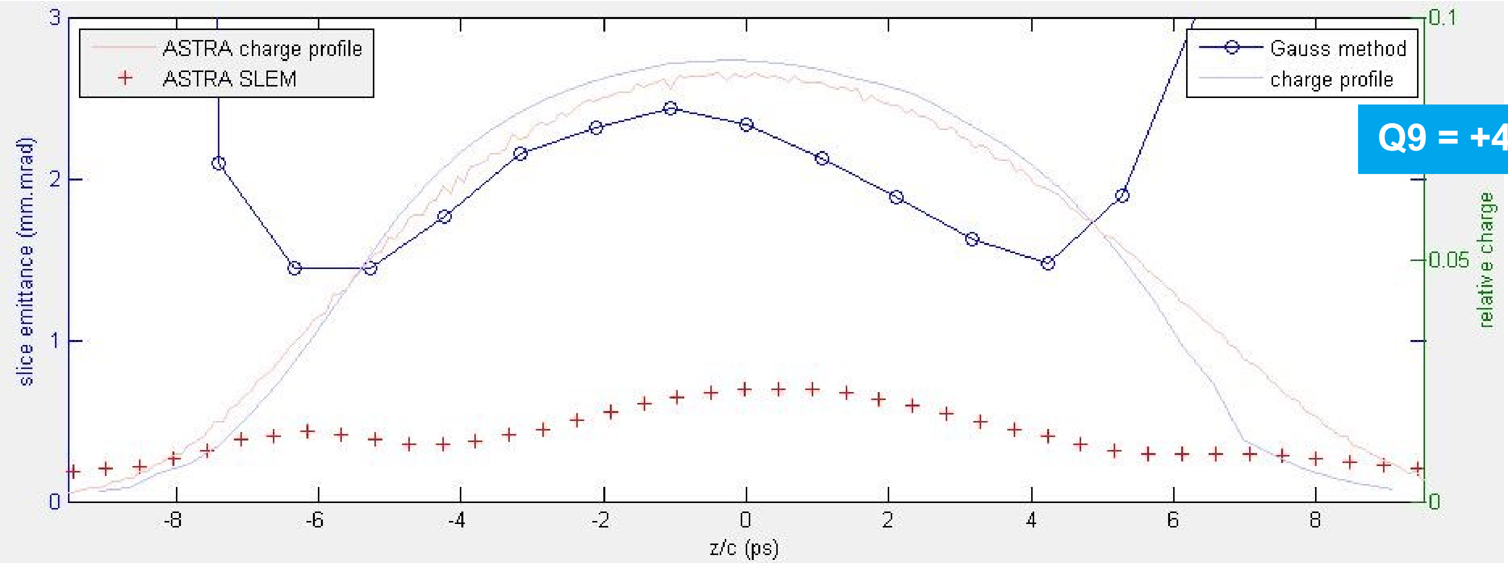
First SLEM measurement in KW34/2015: Setup

- 100 pC, 0.8 mm laser spot size
- E-XFEL startup conditions
  - (53 MV/m)
  - long Gaussian laser pulses
- Simple optics, similar to emittance measurements
  - Solenoid focus at ~6 m from cathode.
  - Quads just before TDS (11 m) focus onto screen at 12 m.

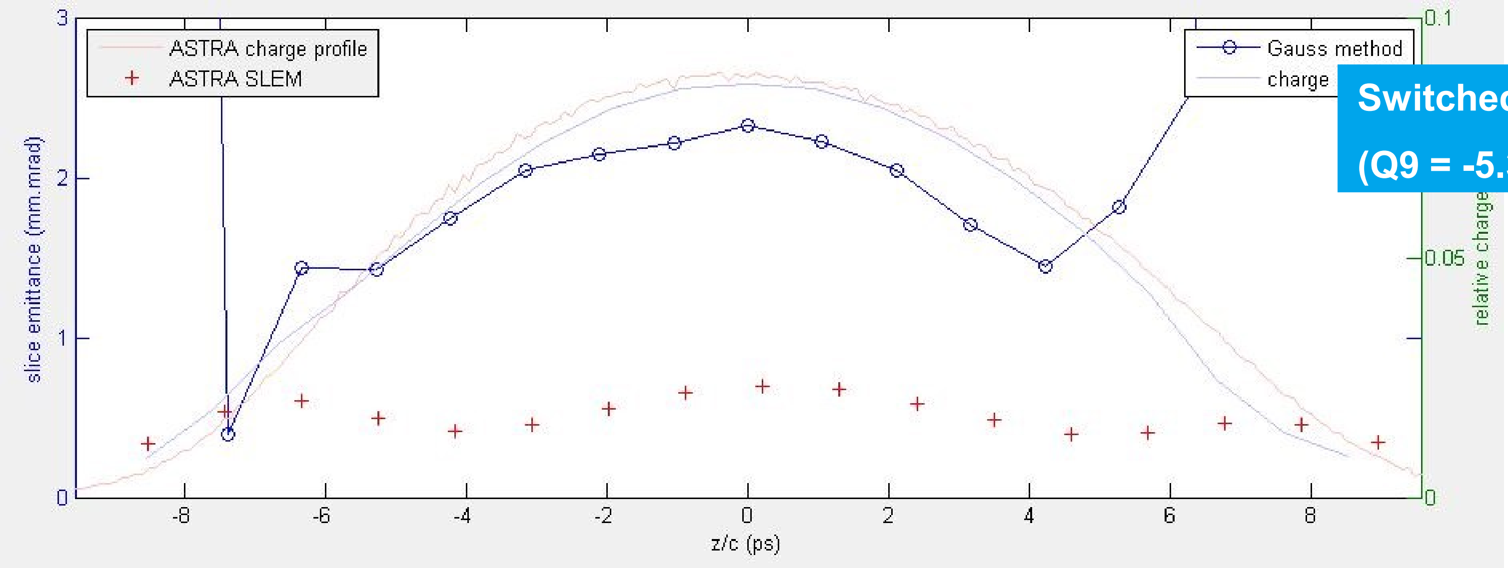


- Bunch length ~11 ps
- Resolution ~0.5 - 1.0 ps FWHM, depending on quad settings
- Reasonable number of longitudinal slices ~10 - 20

First SLEM measurement: results



Q9 = +4.76 A

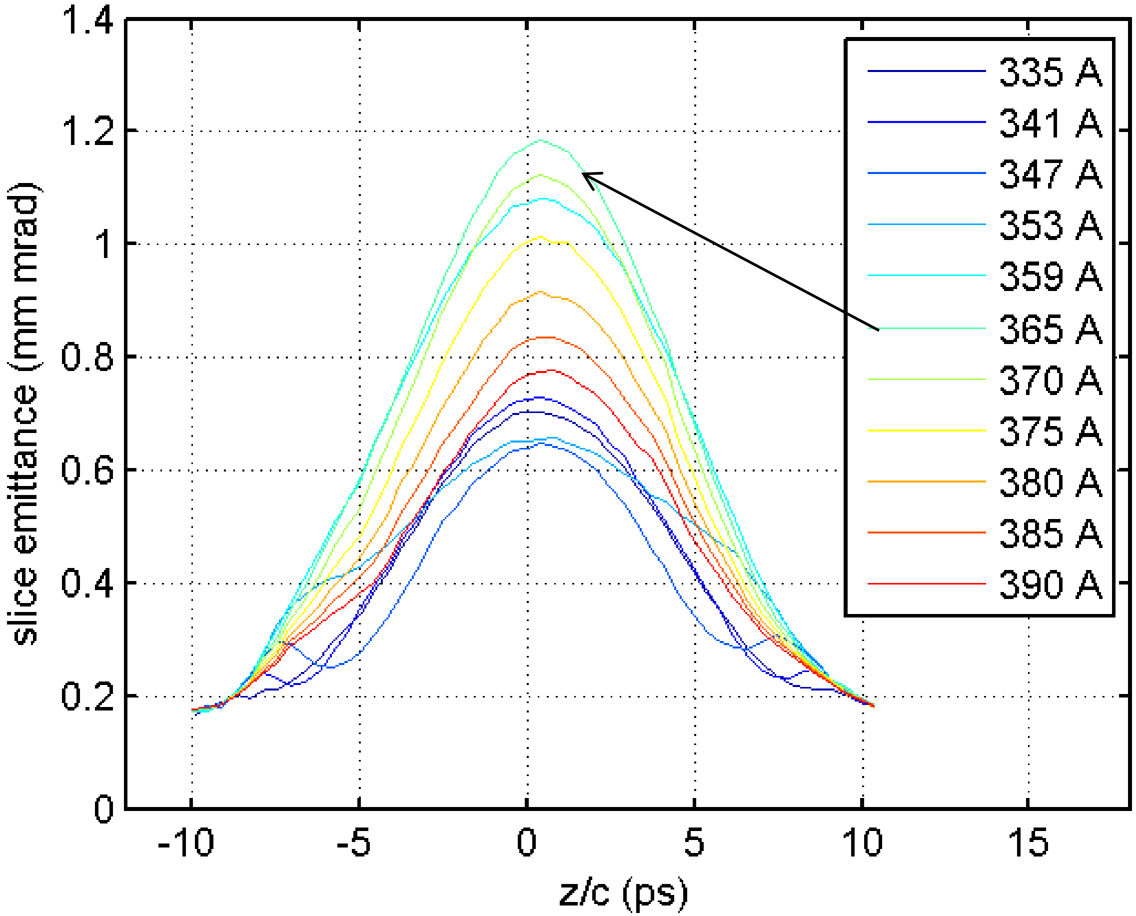


Switched quads

(Q9 = -5.3 A)

ASTRA: SLEM vs. Solenoid current

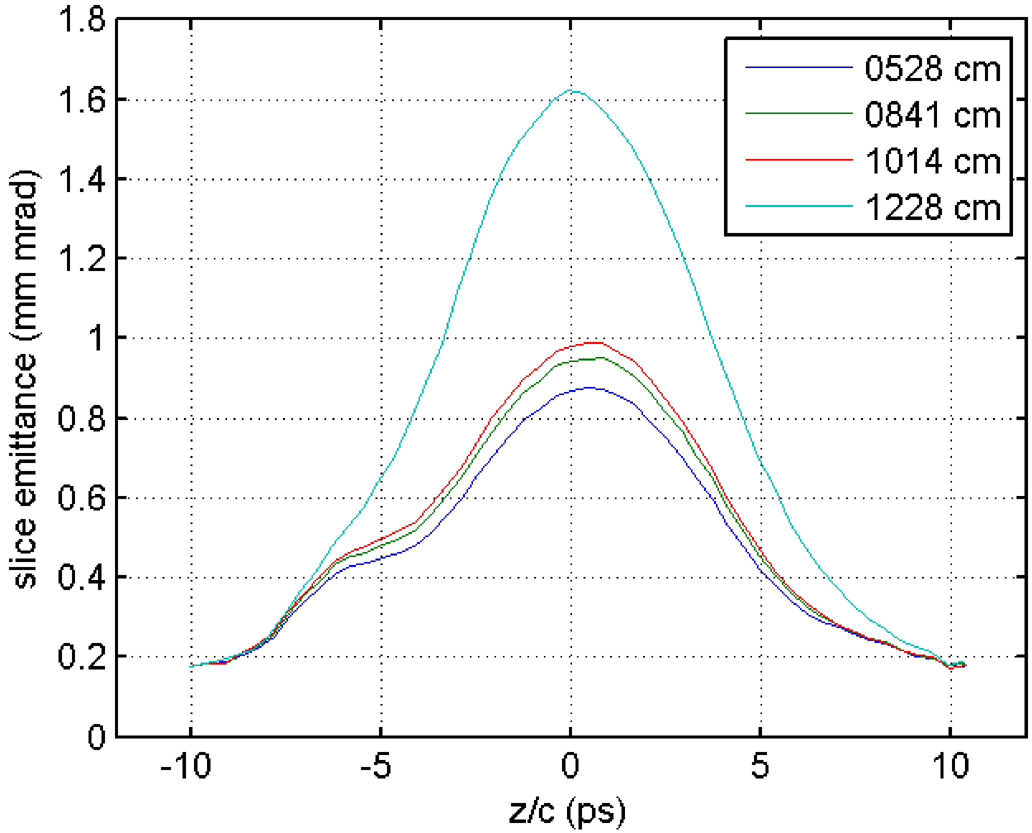
100 pC, 53 MV/m, 9 ps Gauss, Core + Halo, Q9=-5 A,
Bunch length ~10.5 ps, evaluated 7 cm before Q10



- Central SLEM varies by almost factor 2 (0.6-1.2 mmmrad)
- Maximum at 365 A
- Minimum at 353 A
- Large jump from 359 to 353 A

ASTRA: SLEM vs. Screen position

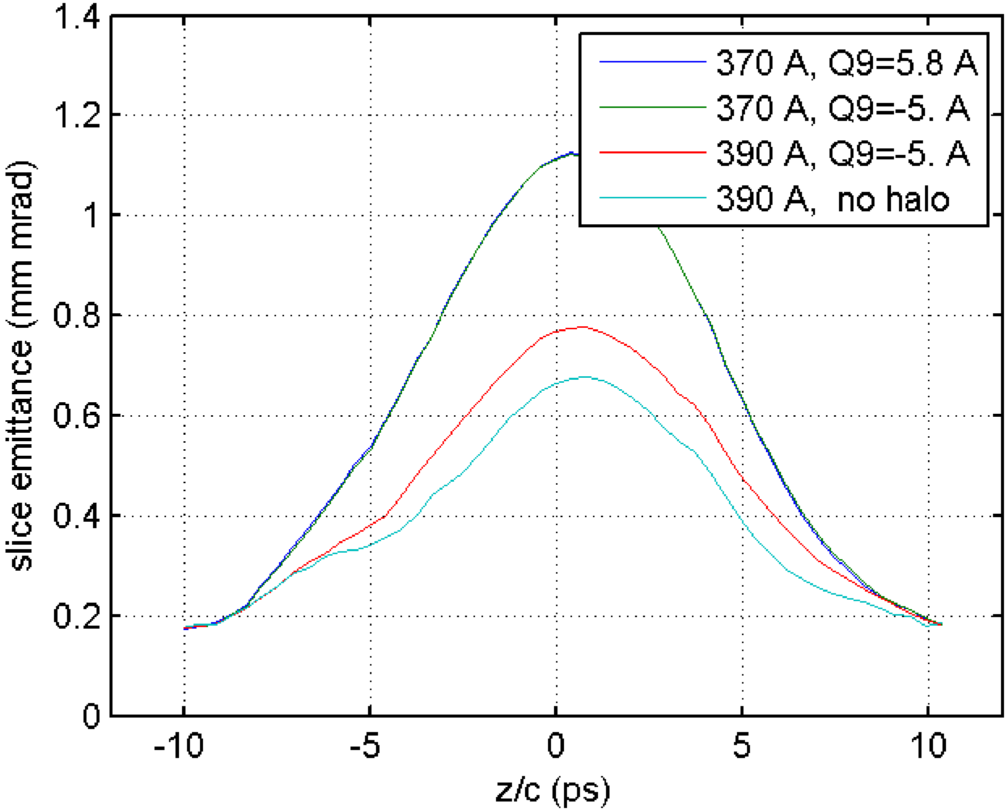
100 pC, 53 MV/m, 9 ps Gauss, Core + Halo, Q9=+5.8 A,
Bunch length ~10.5 ps, evaluated 7 cm before Q10
I_main = 365 A
Additional screens: High1.scr1&4, PST.scr1



- Small increase (~15%) from booster to Q10
- Large jump (60%) on the last 2 meters to PST.Scr1 due to strong quad focusing

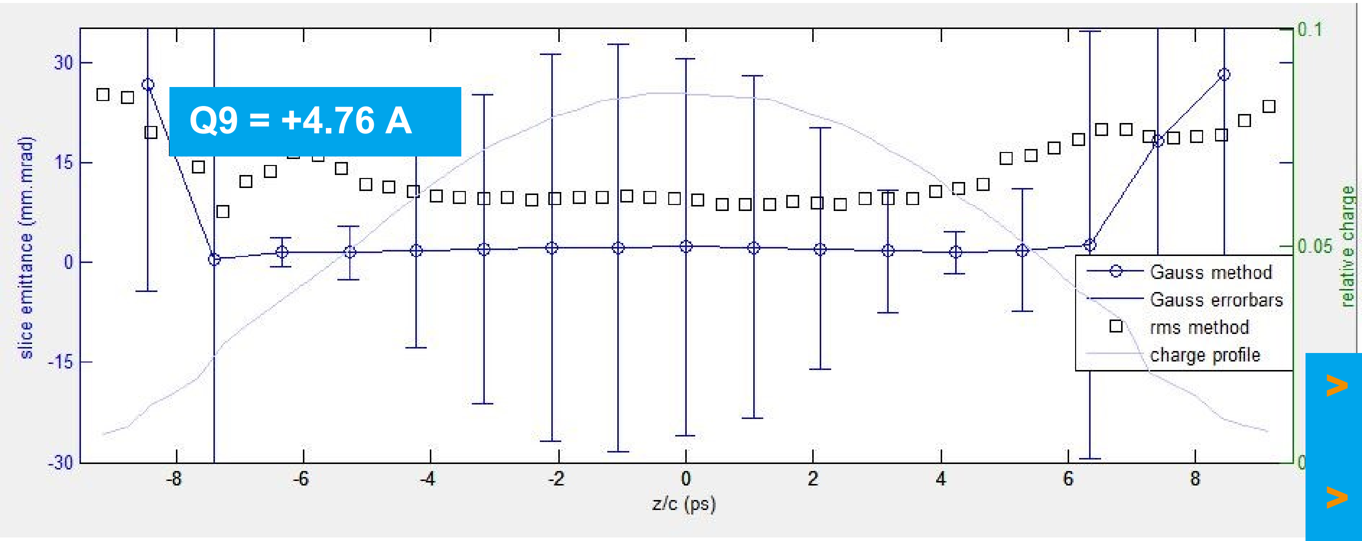
ASTRA: SLEM vs. Q9 and transverse laser profile

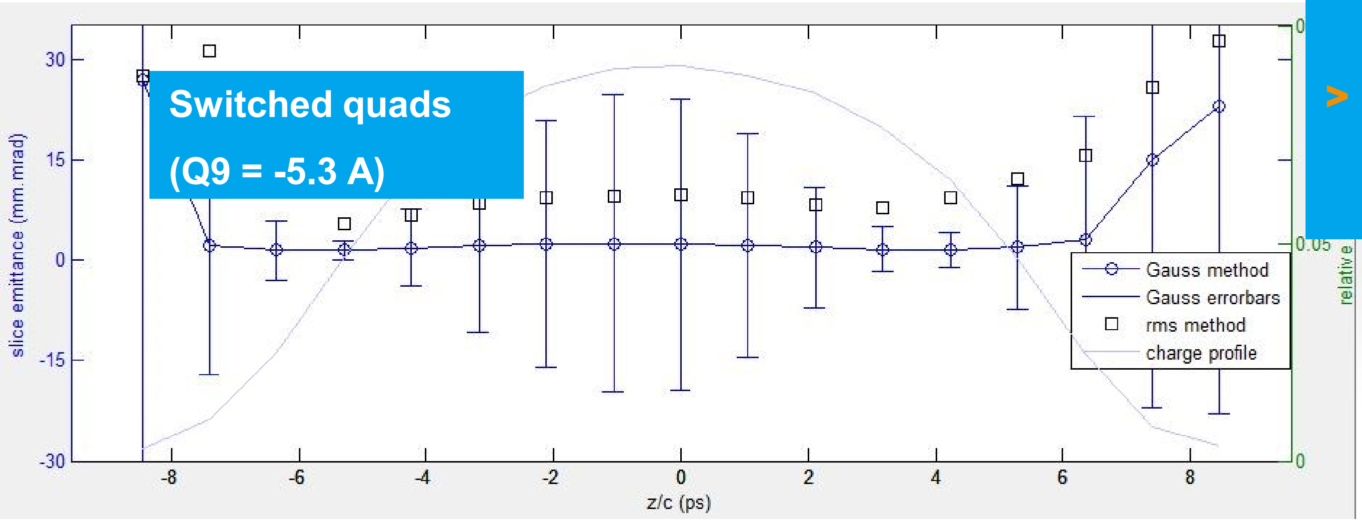
100 pC, 53 MV/m, 9 ps Gauss,
Bunch length ~10.5 ps, evaluated 7 cm before Q10



- Q9 setting hardly matters
- Core + Halo profile increases SLEM by ~15%

First SLEM measurement: adding errorbars

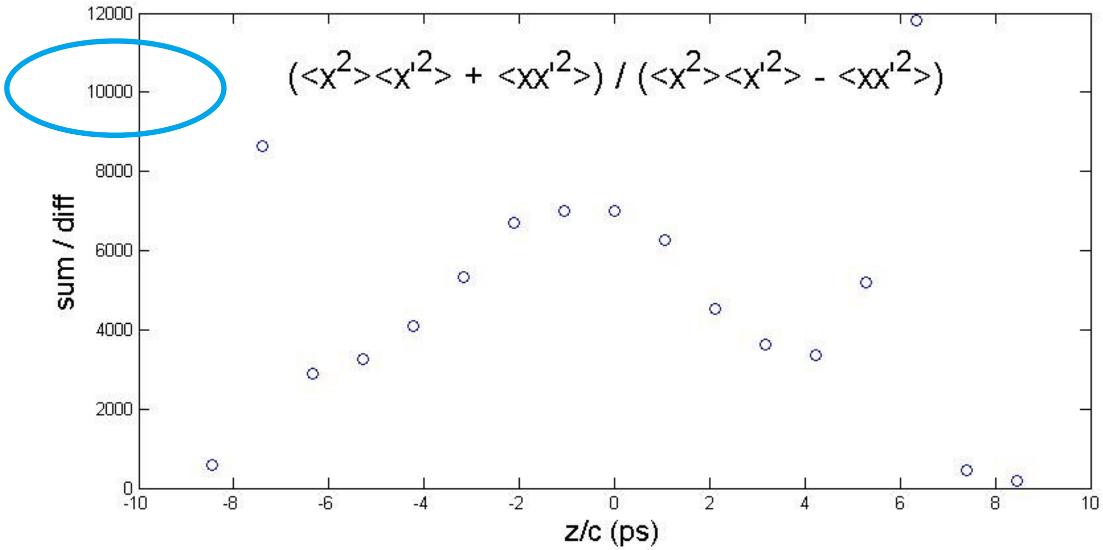




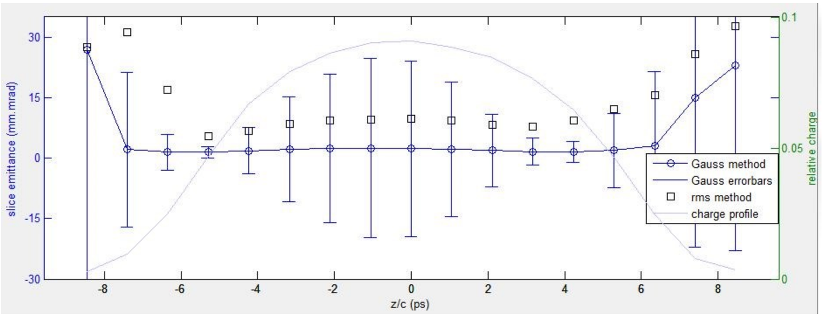
- Obtained by standard error propagation law
- From the 95% confidence bounds of the three fit paramters (divided by 4)
- Probable issue: errors of the fit paramters are not independent!

First SLEM measurement: adding errorbars

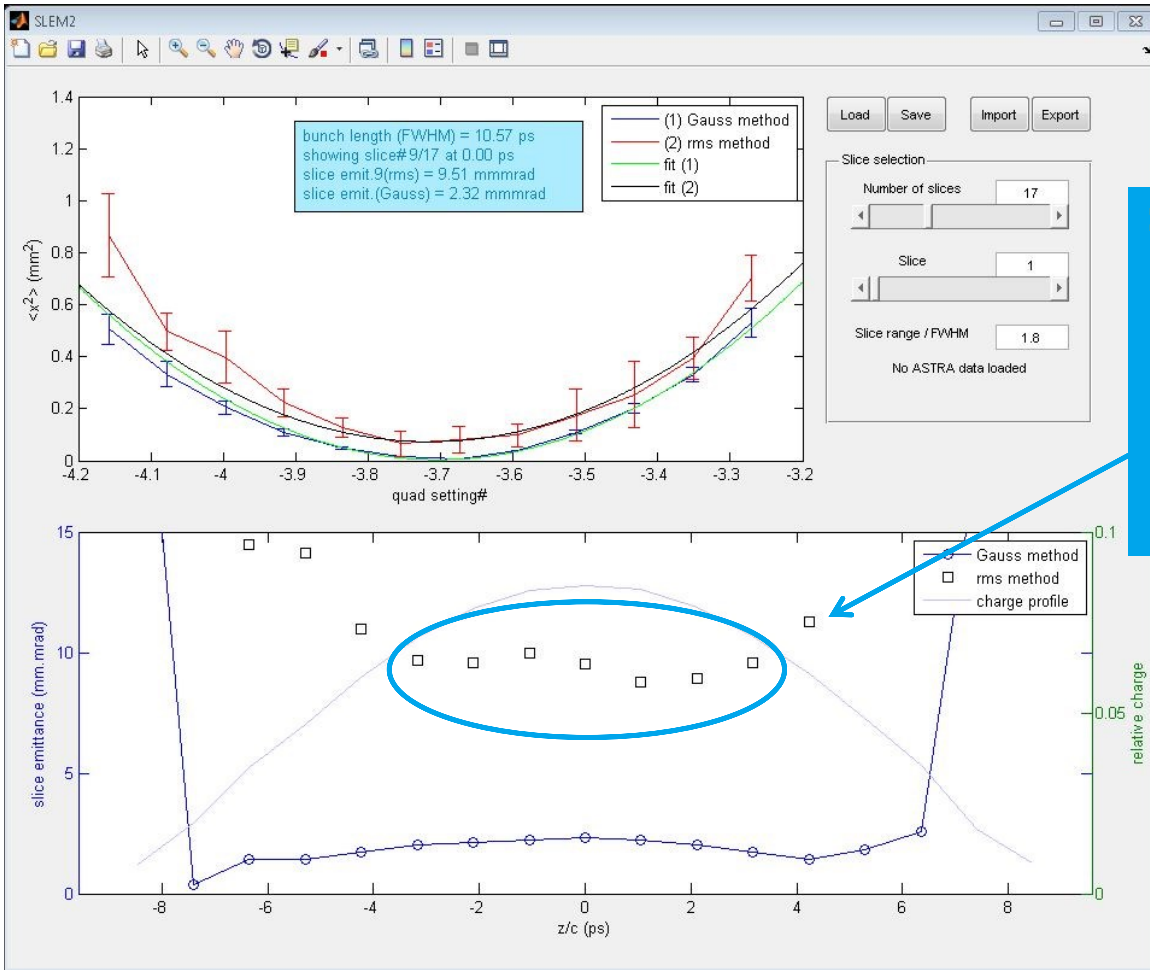
Source of the huge errobars?



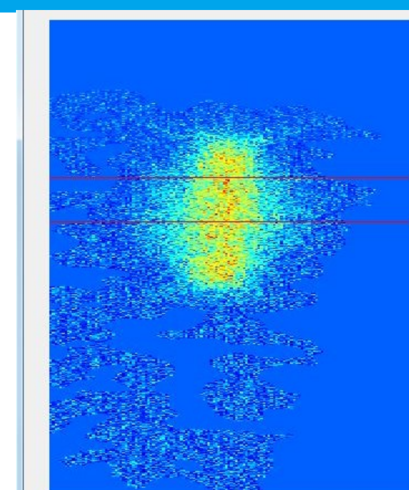
- Almost perfect xx' correlation!
- Natural behaviour of a parallel beam that just passed a quadrupole
- …so we probably just need to choose a different reconstruction point (i.e. before Q9)



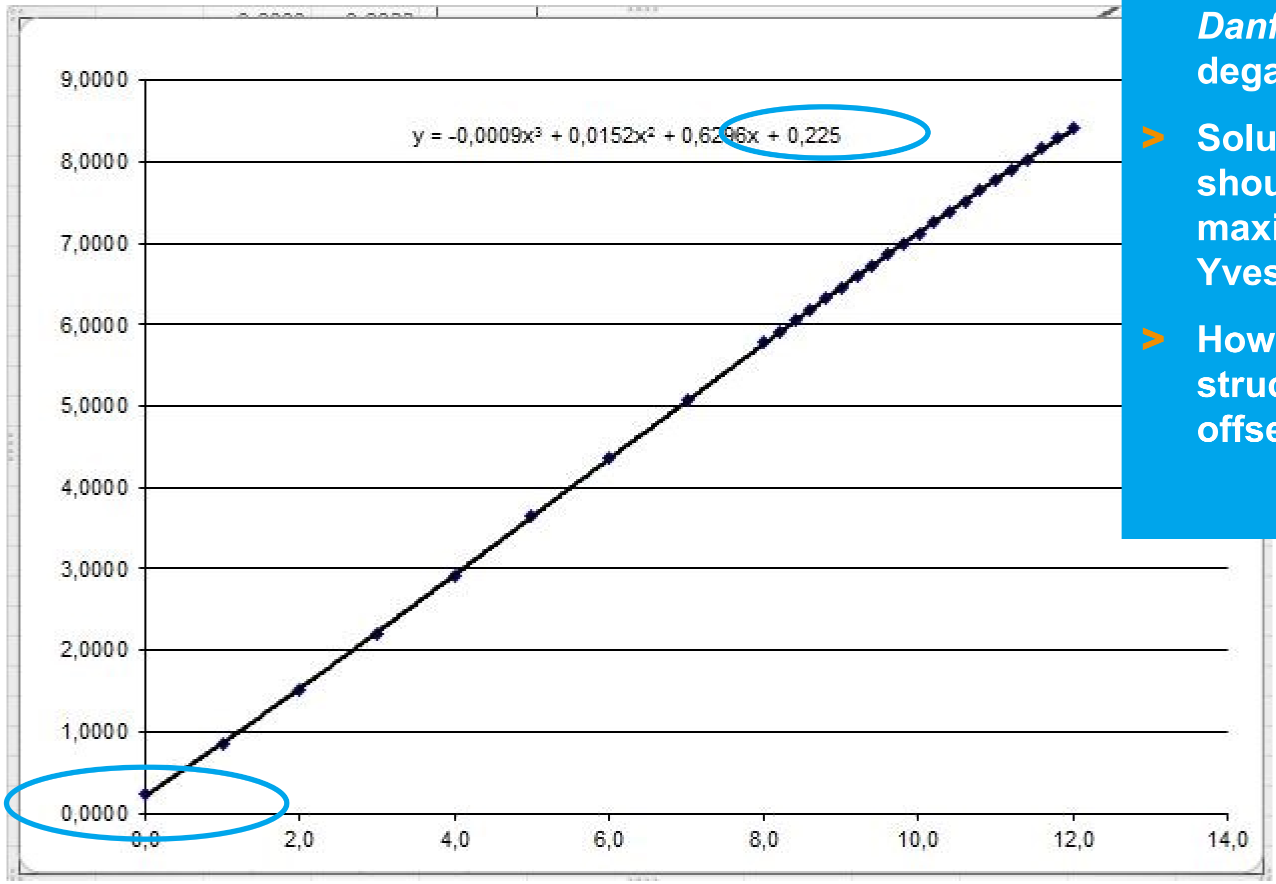
First SLEM measurement: rms method



- Much worse results, caused by…
  - Noise, bad masks of interest
  - Not (yet) proper background handling (negative pixel values…)
  - Manual slice/frame review and masking for all 12000 slices not done (yet?)…



Quadrupole calibration



- Calibration curves from *Danfysik* were NOT done with degaussed magnets!
- Solution: during shifts we should always start from maximum current (or use Yves' tool)
- However, for SLEM reconstruction at least the constant offset doesn't matter much

Summary of SLEM in KW34/2015

- Qualitatively, the first rough slice emittance measurements show similar trend and order of magnitude than ASTRA simulations.
- But actual numbers are 2-3 times too large, not explainable by generous variations of solenoid current.
- „Rms method“ needs more work.
- Different reconstruction point should be chosen.
- Outlook: choose *arbitrary* quad or screen from a list for reconstruction in SLEM2.m (work in progress…)

Outlook: Simulation of Measurements (=>Chaipattana)

- Do a full simulation of the measurement, i.e. ASTRA tracking of the e-bunch through the quadrupoles and the TDS field until the screen, then apply the same analysis as for the experimental images on PST.scr1.
- Start with the simulations presented here (for various solenoid currents) and just add the TDS field! (from D. Malyutin's simulations)
- Then we have three SLEM curves to compare: Experiment, Simulation and Simulation of experiment.
- After that, perform simulations and simulations of measurements for
  - Various bunch charges (at least for 1 nC, 500 pC, 100 pC)
  - Various quad settings
  - Various observation screens

(*) in terms of temporal resolution and accuracy

- The goal is to define reasonable parameter ranges for the actual measurements, especially the best(*) transport matrix (quad settings, screen selection)…
- …and to estimate the systematic measurement errors from space charge, dispersion and TDS field!

Thank you for your attention!