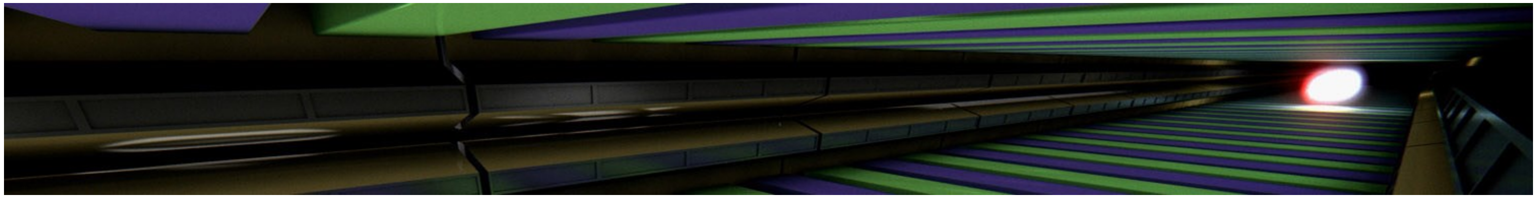
European XFEL



Emittance Measurements at the European XFEL

Bolko Beutner

DESY Zeuthen, 11.10.16

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Outline of the Talk

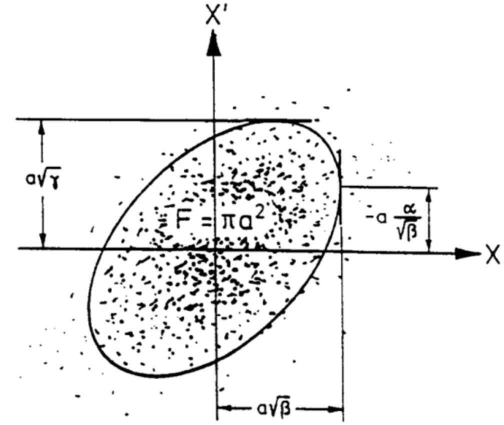
- Optics based Measurement Techniques
- Optics Matching
- XFEL Diagnostic Sections
- Slice Emittance
- Image Analysis
- Measurement Infrastructure and Procedures
- Phase Space Tomography

Literature and source of some robbed images on these slides:

- F. Loehl, “Measurements of the Transverse Emittance at the VUV-FEL”, DESY-THESIS 2005-014, TESLA-FEL 2005-03
- M. Minty and F. Zimmermann, “Measurements and control of charged particle beams”, Springer, Berlin, Heidelberg, New York, 2003.
- J. Rossbach and P. Schmueser, “Basic Course on Accelerator Optics”
- M. Yan, “Online diagnostics of time-resolved electron beam properties with femtosecond resolution for X-ray FELs”, DESY-THESIS-2016-017.

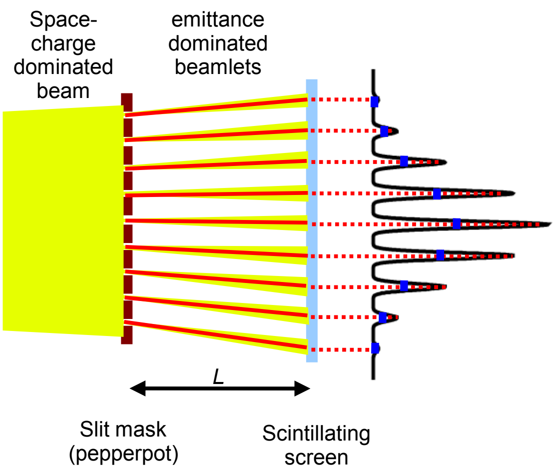
Introduction

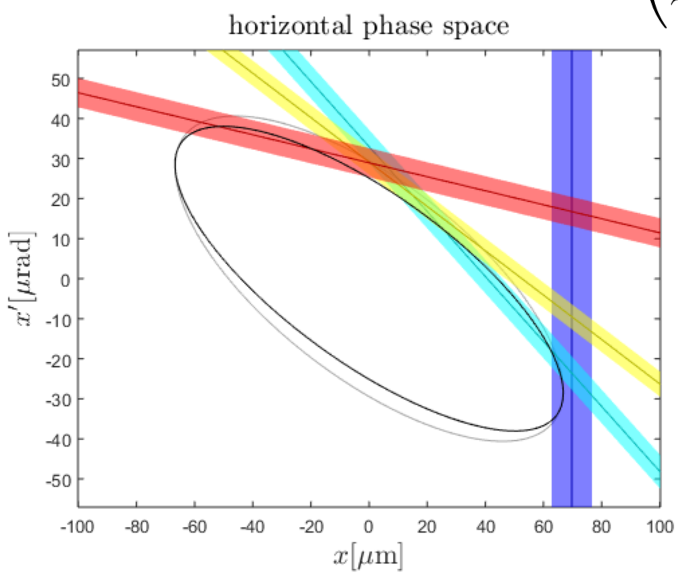
- Emittance and beam optics are important for machine operation and FEL performance
- At high energies optics based methods are preferred over slit based techniques
- Slice resolved measurement with a transverse deflecting structure

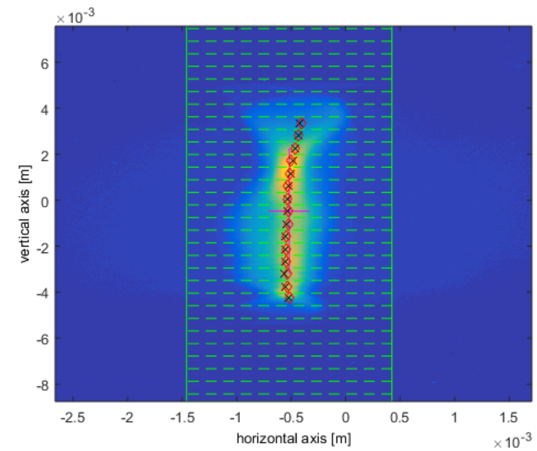


$$\varepsilon_x = \sqrt{\langle x_0^2 \rangle \langle x_0'^2 \rangle - \langle x_0 x_0' \rangle^2}$$

$$\begin{pmatrix} \beta_{x0} \\ \alpha_{x0} \\ \gamma_{x0} \end{pmatrix} = \begin{pmatrix} \langle x_0^2 \rangle / \varepsilon_x \\ -\langle x_0 x_0' \rangle / \varepsilon_x \\ \langle x_0'^2 \rangle / \varepsilon_x \end{pmatrix}$$

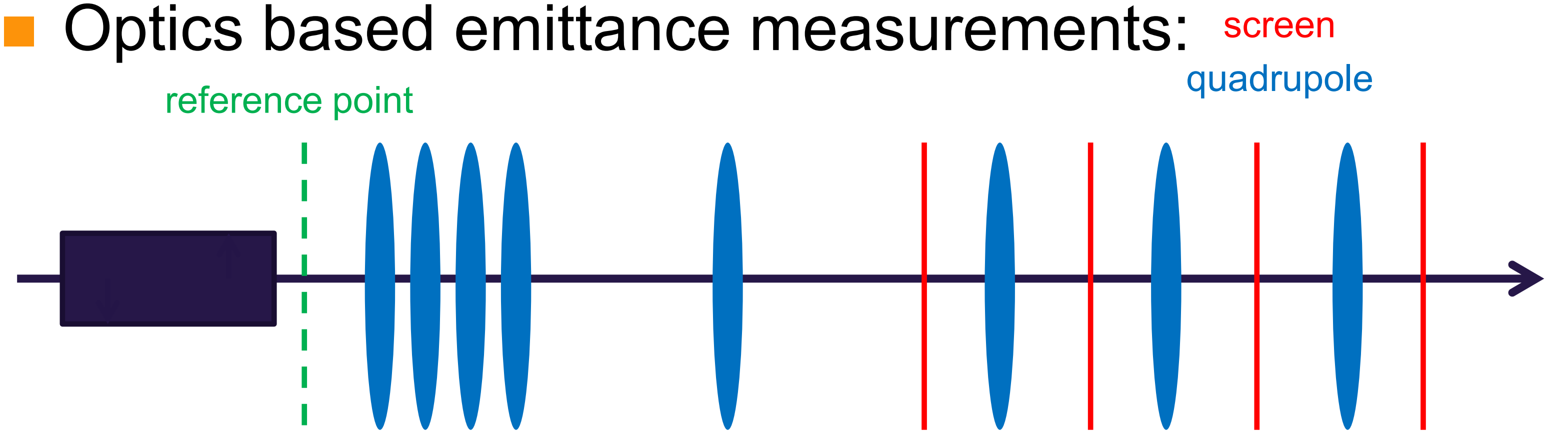






Optics Based Emittance Measurements

- Optics based emittance measurements:



- Beam moments are determined at a reference point using either:
  - → one screen while varying the quadrupole settings
  - → at multiple positions along a constant lattice
- Slice resolved measurements in combination with a transverse deflecting structure (TDS)

Fit of Beam Moments

Beam size at *point* i as a function of initial beam moments:

$$\sigma_{x,i}^2 = \langle x_i^2 \rangle = {R_{11}^i}^2 \langle x_0^2 \rangle + {R_{12}^i}^2 \langle x_0'^2 \rangle + 2R_{11}^i R_{12}^i \langle x_0 x_0' \rangle$$

From the beam moments emittance (and twiss parameters) are determined:

$$\varepsilon_x = \sqrt{\langle x_0^2 \rangle \langle {x_0'}^2 \rangle - \langle x_0 x_0' \rangle^2} \qquad \begin{pmatrix} \beta_{x0} \\ \alpha_{x0} \\ \gamma_{x0} \end{pmatrix} = \begin{pmatrix} \langle x_0^2 \rangle / \varepsilon_x \\ -\langle x_0 x_0' \rangle / \varepsilon_x \\ \langle {x_0'}^2 \rangle / \varepsilon_x \end{pmatrix}$$

In an ideal measurement three data points are sufficient:

$$\begin{aligned} \sigma_{x,1}^2 &= \langle x_1^2 \rangle = {R_{11}^1}^2 \langle x_0^2 \rangle + {R_{12}^1}^2 \langle x_0'^2 \rangle + 2R_{11}^1 R_{12}^1 \langle x_0 x_0' \rangle \\ \sigma_{x,2}^2 &= \langle x_2^2 \rangle = {R_{11}^2}^2 \langle x_0^2 \rangle + {R_{12}^2}^2 \langle x_0'^2 \rangle + 2R_{11}^2 R_{12}^2 \langle x_0 x_0' \rangle \\ \sigma_{x,3}^2 &= \langle x_3^2 \rangle = {R_{11}^3}^2 \langle x_0^2 \rangle + {R_{12}^3}^2 \langle x_0'^2 \rangle + 2R_{11}^3 R_{12}^3 \langle x_0 x_0' \rangle \end{aligned}$$

$$\begin{pmatrix} \langle x_0^2 \rangle \\ \langle x_0 x_0' \rangle \\ \langle {x_0'}^2 \rangle \end{pmatrix} = \begin{pmatrix} R_{11}^{(1)2} & 2R_{11}^{(1)} R_{12}^{(1)} & R_{12}^{(1)2} \\ R_{11}^{(2)2} & 2R_{11}^{(2)} R_{12}^{(2)} & R_{12}^{(1)2} \\ R_{11}^{(3)2} & 2R_{11}^{(3)} R_{12}^{(3)} & R_{12}^{(1)2} \end{pmatrix}^{-1} \begin{pmatrix} \sigma_{x,1}^2 \\ \sigma_{x,2}^2 \\ \sigma_{x,3}^2 \end{pmatrix}$$

In a real measurement more then three data points are taken and the beam moments are determined by a least square fit:

$$\chi^2 = \sum_i \left[\frac{\langle x_i^2 \rangle - \left({R_{11}^i}^2 \langle x_0^2 \rangle + {R_{12}^i}^2 \langle x_0'^2 \rangle + 2R_{11}^i R_{12}^i \langle x_0 x_0' \rangle \right)}{\sigma_{\langle x_i^2 \rangle}} \right]^2$$

unknowns to be determined by the measurement

determined by diagnostics (screens / Image Analysis Server)

provided by beam dynamics (Optics Server)

Fit of Beam Moments II

- Penalty function is the quadratic sum of beam size deviation from the transported assumed moment normalised with beam size error

$$\chi^2 = \sum_{i=1}^{n} \left[\frac{\langle x^2_{(i)} \rangle - f_i(\langle x_0^2 \rangle, \langle x_0 x_0' \rangle, \langle {x_0'}^2 \rangle)}{\sigma_{\langle x^2_{(i)} \rangle}} \right]^2$$

$$f_i(\langle x_0^2 \rangle, \langle x_0 x_0' \rangle, \langle {x_0'}^2 \rangle) = {R_{11}^{(i)}}^2 \langle x_0^2 \rangle + 2 R_{11}^{(i)} R_{12}^{(i)} \langle x_0 x_0' \rangle + {R_{22}^{(i)}}^2 \langle {x_0'}^2 \rangle$$

- With

$$\boldsymbol{a} = \begin{pmatrix} \langle x_0^2 \rangle \\ \langle x_0 x_0' \rangle \\ \langle {x_0'}^2 \rangle \end{pmatrix} \quad \text{and} \quad \boldsymbol{b} = \begin{pmatrix} \frac{\langle x^2_{(1)} \rangle}{\sigma_{\langle x^2_{(1)} \rangle}} \\ \frac{\langle x^2_{(2)} \rangle}{\sigma_{\langle x^2_{(2)} \rangle}} \\ \vdots \\ \frac{\langle x^2_{(n)} \rangle}{\sigma_{\langle x^2_{(n)} \rangle}} \end{pmatrix} \qquad \boldsymbol{B} = \begin{pmatrix} \frac{{R_{11}^{(1)}}^2}{\sigma_{\langle x^2_{(1)} \rangle}} & \frac{2 R_{11}^{(1)} R_{12}^{(1)}}{\sigma_{\langle x^2_{(1)} \rangle}} & \frac{{R_{12}^{(1)}}^2}{\sigma_{\langle x^2_{(1)} \rangle}} \\ \frac{{R_{11}^{(2)}}^2}{\sigma_{\langle x^2_{(2)} \rangle}} & \frac{2 R_{11}^{(2)} R_{12}^{(2)}}{\sigma_{\langle x^2_{(2)} \rangle}} & \frac{{R_{12}^{(2)}}^2}{\sigma_{\langle x^2_{(2)} \rangle}} \\ \vdots & \vdots & \vdots \\ \frac{{R_{11}^{(n)}}^2}{\sigma_{\langle x^2_{(n)} \rangle}} & \frac{2 R_{11}^{(n)} R_{12}^{(n)}}{\sigma_{\langle x^2_{(n)} \rangle}} & \frac{{R_{12}^{(n)}}^2}{\sigma_{\langle x^2_{(n)} \rangle}} \end{pmatrix}$$

the penalty function can be written in compact form

$$\chi^2 = \sum_{i=1}^{n} \left[b_i - \sum_{j=1}^{3} B_{ij} a_j \right]^2$$

Fit of Beam Moments III

- Analytic minimisation with standard techniques:

$$\chi^2 = \sum_{i=1}^{n} \left[b_i - \sum_{j=1}^{3} B_{ij} a_j \right]^2$$

$$\begin{pmatrix} \partial\chi^2/\partial a_1 \\ \partial\chi^2/\partial a_2 \\ \partial\chi^2/\partial a_3 \end{pmatrix} = 2 \begin{pmatrix} \sum_{i=1}^{n} \sum_{j=1}^{3} B_{ij} B_{i1} a_j \\ \sum_{i=1}^{n} \sum_{j=1}^{3} B_{ij} B_{i2} a_j \\ \sum_{i=1}^{n} \sum_{j=1}^{3} B_{ij} B_{i3} a_j \end{pmatrix} - 2 \begin{pmatrix} \sum_{i=1}^{n} b_i B_{i1} \\ \sum_{i=1}^{n} b_i B_{i2} \\ \sum_{i=1}^{n} b_i B_{i3} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

- This can be rewritten as:

$$\boldsymbol{B}^T \boldsymbol{b} = \left(\boldsymbol{B}^T \boldsymbol{B} \right) \boldsymbol{a}$$

  and eventually:

$$\boldsymbol{a} = \left(\boldsymbol{B}^T \boldsymbol{B} \right)^{-1} \boldsymbol{B}^T \boldsymbol{b}$$

- The least-square fit is represented by an matrix inversion
- This form is numerically often more efficiently to implement than the original fit

Measurement Errors

- Errors on beam moments are determined from the beam-size measurement error using standard error propagation

$$\sigma_g^2 = \sum_{i=1}^{n} \left(\frac{\partial g}{\partial x_i}\right)^2 \sigma_{x_i}^2 + \sum_{i=1}^{n} \sum_{j=1, j\neq i}^{n} \frac{\partial g}{\partial x_i} \frac{\partial g}{\partial x_j} \mathrm{cov}(i,j)$$

$$\boldsymbol{f} = \begin{pmatrix} \beta_{x0} \\ \alpha_{x0} \\ \epsilon_{x0} \end{pmatrix} = \begin{pmatrix} a_1/\sqrt{a_1 a_3 - a_2^2} \\ -a_2\sqrt{a_1 a_3 - a_2^2} \\ \sqrt{a_1 a_3 - a_2^2} \end{pmatrix}$$

$$\sigma_{a_k}^2 = \sum_{i=1}^{n} \left(\frac{\partial a_k}{\partial \langle x_{(i)}^2 \rangle}\right)^2 \sigma_{\langle x_{(i)}^2 \rangle}^2$$

- An equivalent notation is possible which is typically easier to implement

$$a_k = \sum_{j=1}^{3} C_{kj} \left[\boldsymbol{B}^T \boldsymbol{b}\right]_j \qquad \boldsymbol{C} = \left(\boldsymbol{B}^T \boldsymbol{B}\right)^{-1}$$

$$\sigma_f^2 = (\nabla_a \boldsymbol{f})^T \boldsymbol{C} (\nabla_a \boldsymbol{f}) = \begin{pmatrix} \sigma_{\beta_{x0}}^2 & \cdots & \cdots \\ \cdots & \sigma_{\alpha_{x0}}^2 & \cdots \\ \cdots & \cdots & \sigma_{\epsilon_{x0,rms}}^2 \end{pmatrix}$$

```
% calculate errors
gf(1,1,:,:) = (xsq.*xpsq-2*xxp.^2)./(2*(xsq.*xpsq-xxp.^2).^(3/2));
gf(1,2,:,:) = -xxp.*xpsq./(2*(xsq.*xpsq-xxp.^2).^(3/2));
gf(1,3,:,:) = xpsq./(2*(xsq.*xpsq-xxp.^2).^(1/2));
gf(2,1,:,:) = xsq.*xxp./(xsq.*xpsq-xxp.^2).^(3/2);
gf(2,2,:,:) = xsq.*xpsq./(xsq.*xpsq-xxp.^2).^(3/2);
gf(2,3,:,:) = -xxp./(xsq.*xpsq-xxp.^2).^(1/2);
gf(3,1,:,:) = -xsq.^2./(2*(xsq.*xpsq-xxp.^2).^(3/2));
gf(3,2,:,:) = -xxp.*xsq./(2*(xsq.*xpsq-xxp.^2).^(3/2));
gf(3,3,:,:) = xsq./(2*(xsq.*xpsq-xxp.^2).^(1/2));
```

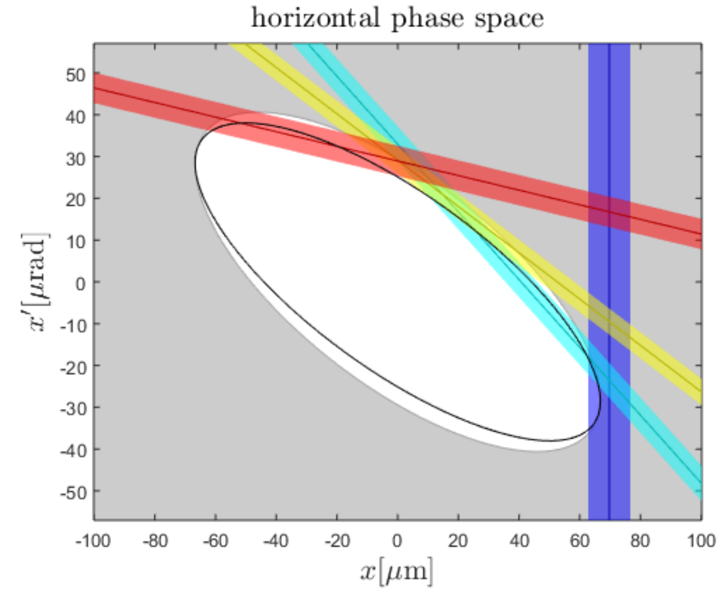
Measurement Errors II

- Beam size used for the fit is the mean of all spots (typically 20)
- Error is estimated as the square root of the variance which is not additionally normalised with $\frac{1}{\sqrt{(N)}}$
- Important purpose of the error is to provide individual weights of each screen for the least square fit
- Estimates by using subsamples and assuming no error gives comparable results if the beam size errors are of comparable size
- Monte-Carlo simulation estimate of errors from sample assuming perfect match and 5% beam size error:

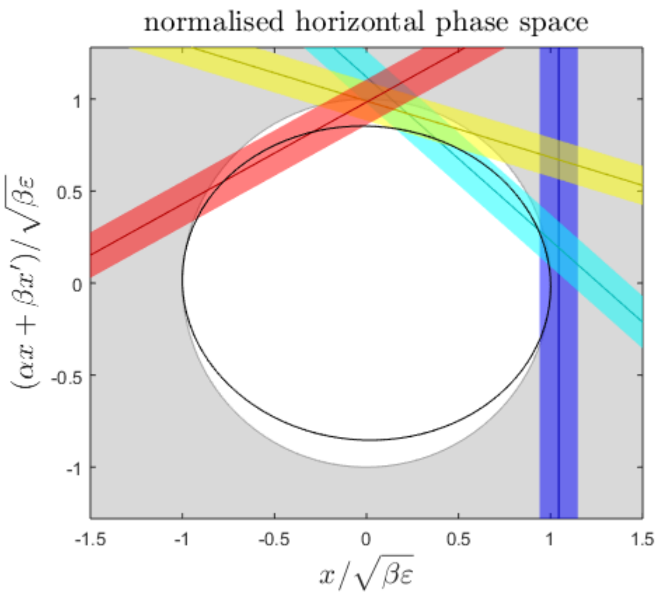
	error propagation	1k random samples	correct
emittance [mm mrad]	0.902	0.895	0.9
error [mm mrad]	0.054	0.052	-

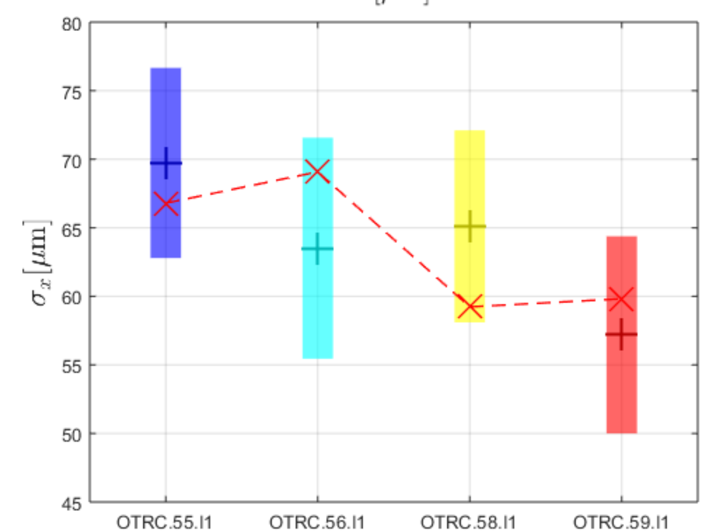
Visualizations of Fit Results

- Different visualizations of the fit are useful to judge measurement quality
- The design (white) and measured (black) ellipse should agree
- Measured ellipse (black) should touch all beam size measurement lines (colors)
- In normalised phase space the ellipse should be a circle (transfer matrices are rotations)



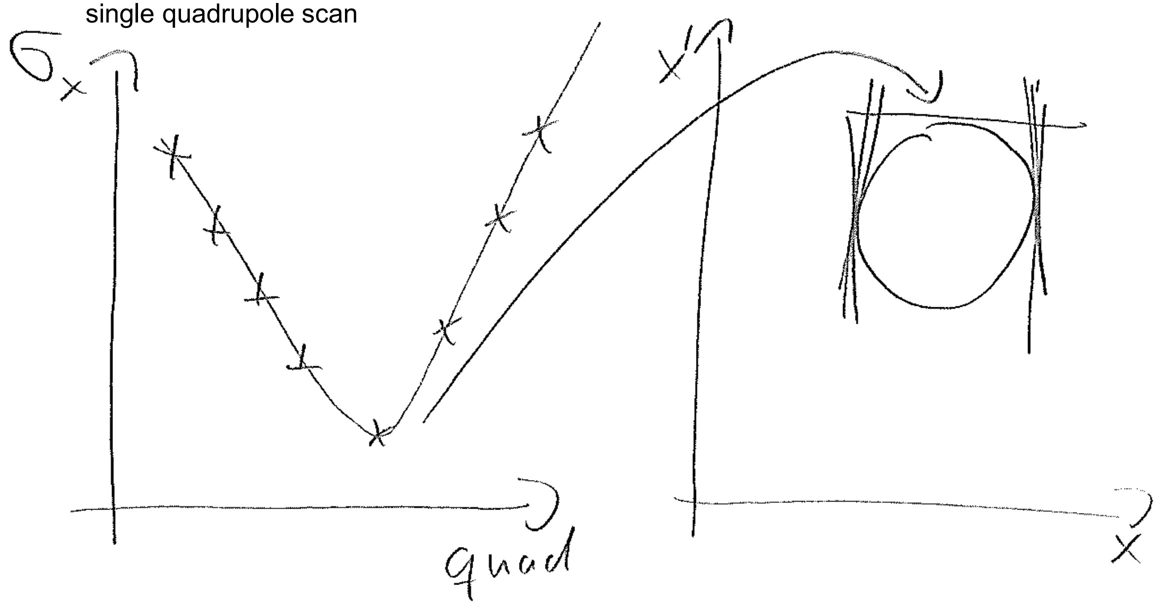
$$u$$
$$\Downarrow$$
$$\left(\frac{u}{\sqrt{\beta_u \varepsilon_u}}, \frac{\alpha_u u + \beta_u u'}{\sqrt{\beta_u \varepsilon_u}}\right)$$
$$\text{with } u = x, y$$





Impact of Optics Mismatch

Example:
single quadrupole scan



- A mismatched beam (with respect to design optics) is not only undesirable because of the resulting unknown beam transport
  – a mismatched beam makes the measurement itself unreliable!
  - Equal weights of beam sizes in fit for matched beam (in periodic lattice) leads to compensation of statistical beam size errors
  - Transfer matrices need to be sufficiently different to have a “well defined” solution – sufficiently large phase advance range (about 120deg)

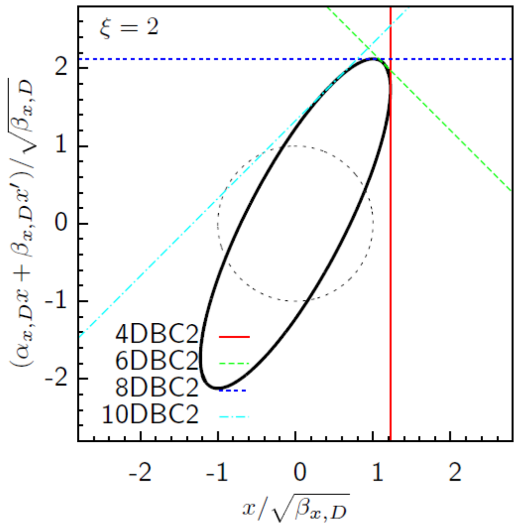
Systematic Measurement Errors due to Optics Mismatch

- Beam Mismatch:

$$\xi = \frac{1}{2}\left(\gamma\beta_0 - 2\alpha\alpha_0 + \beta\gamma_0\right)$$

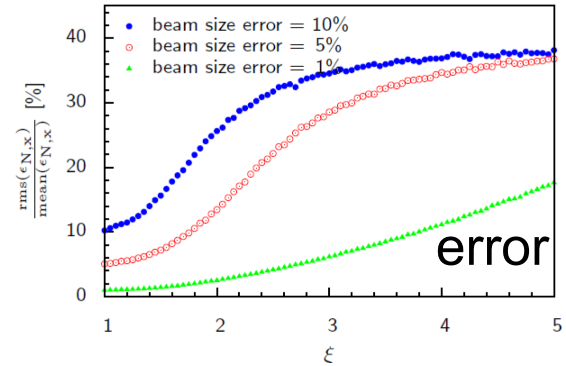
$$\mathrm{BMAG} = \xi + \sqrt{\xi^2 - 1}$$

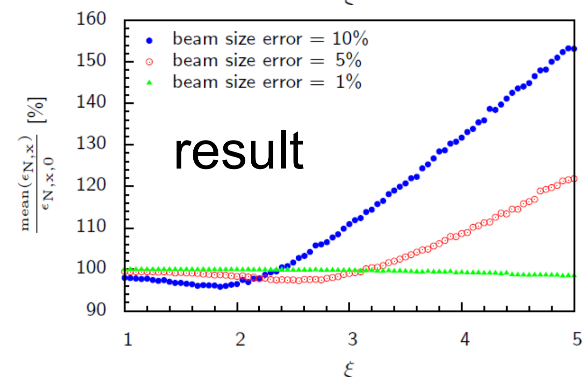
$$\frac{\beta_0}{\mathrm{BMAG}} < \beta < \mathrm{BMAG} \cdot \beta_0$$

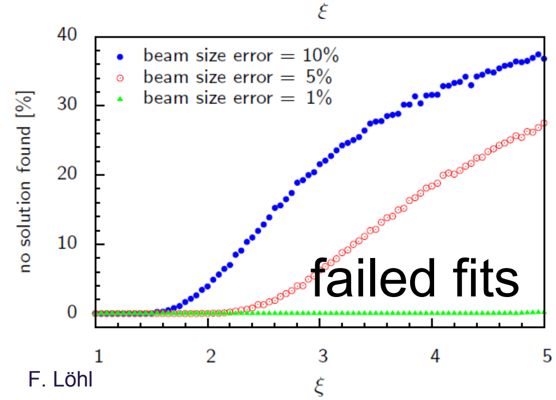


$$\alpha_x = \alpha_{x,D} - \sqrt{2\xi - 2}$$

- Monte Carlo Studies:
  Example FLASH:
  20k random beam size error ensembles







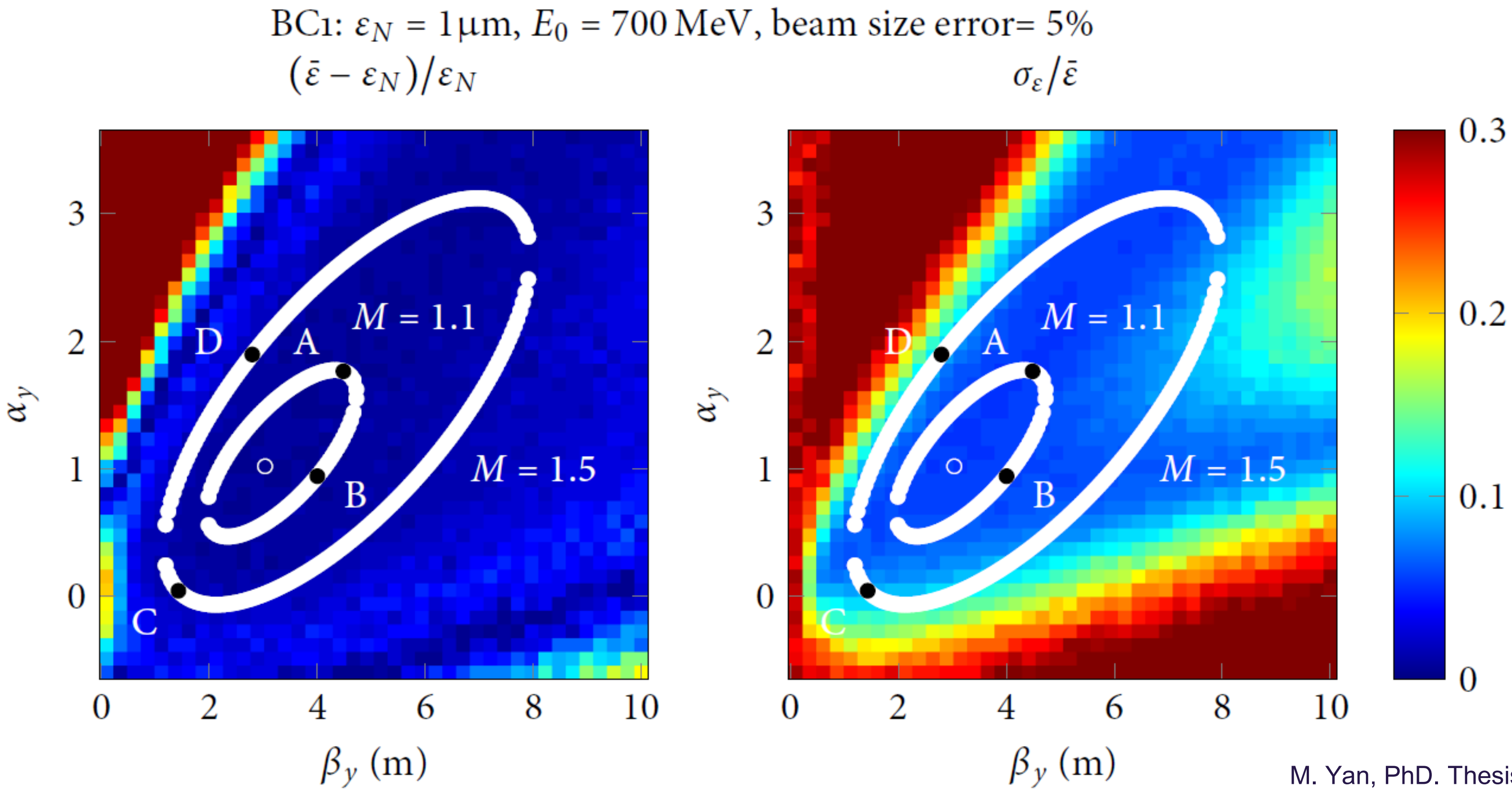
F. Löhl

- Sensitivity on beam size error increase with “beam mismatch” or non optimal phase advance range

  - Beam should be matched to BMAG < 1.1
  - Do not trust measurements with mismatch higher than BMAG = 2

Mismatch map

- Full "mismatch map" gives a detailed insight into acceptable beam mismatch
- Emittance error as big as beam size error for matched beam (~4.5% in this example for 5% beam size error)

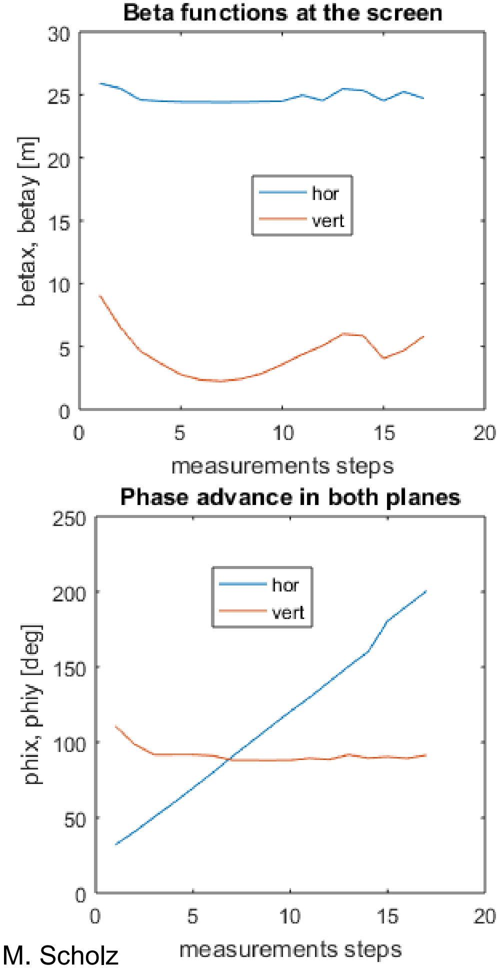


M. Yan, PhD. Thesis 2015

Measurement Methods

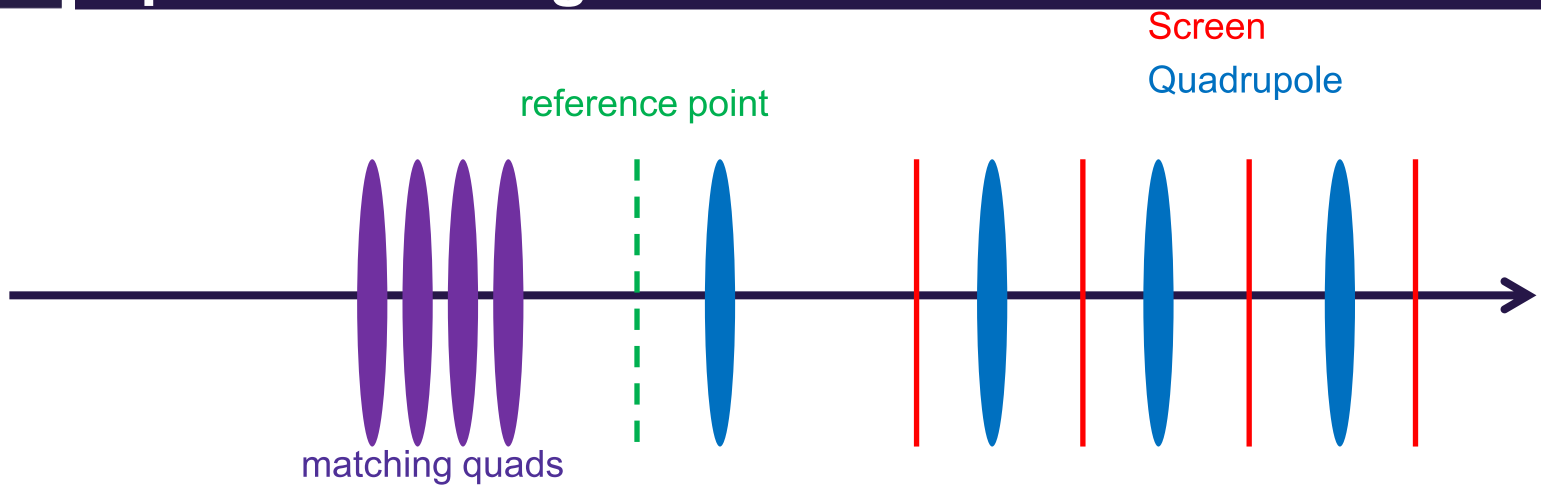
- Quad Scan
  - Single quad (signal to noise, uneven phase advance, can be improved but needs special initial conditions)
  - Multi-knob (needs defined initial optics)
- Multi-Position
  - FODO (optics matching, cancel energy error to first order for the normalised emittance)
  - “irregular” (anywhere in your lattice – typically not ideal boundary conditions)
- Additional boundary conditions from beam size requirements on the screen to optimise resolution
- Matching required to guarantee good phase advance coverage and “uniform” phase space sampling

Example:
Multi-knob scan



M. Scholz

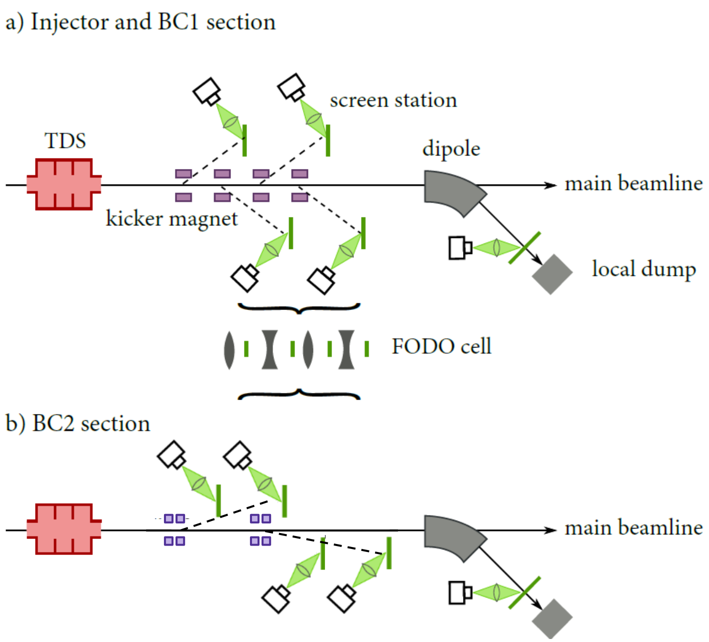
Optics Matching

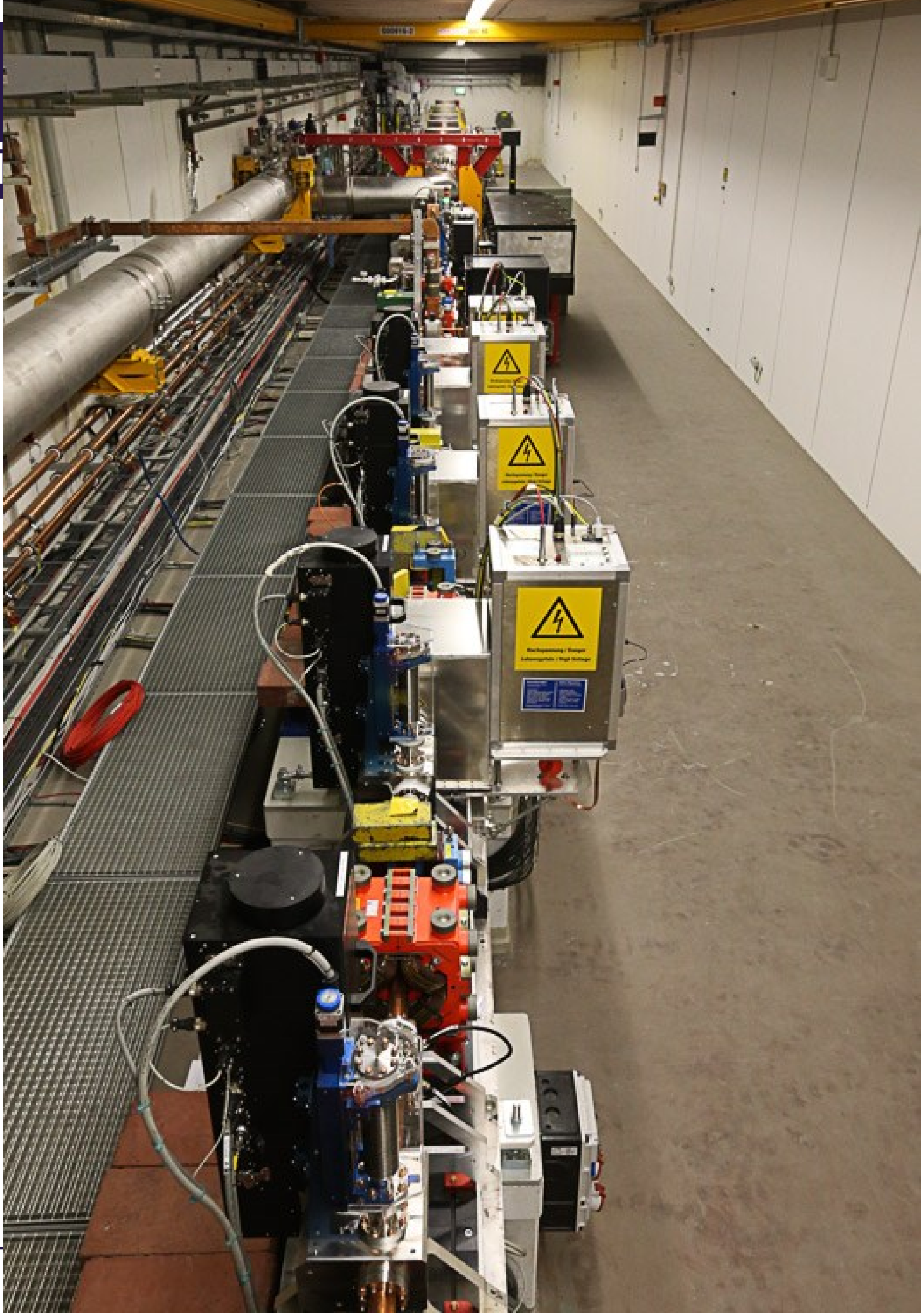


- A mismatched beam at a reference point can be “matched” by tuning upstream quads
- Results from a optics measurement are used by a matching tool to calculate a matching quad setup
- Another measurement is required to confirm improved BMAG
- Iterate until desired mismatch is reached

XFEL Diagnostic Secti

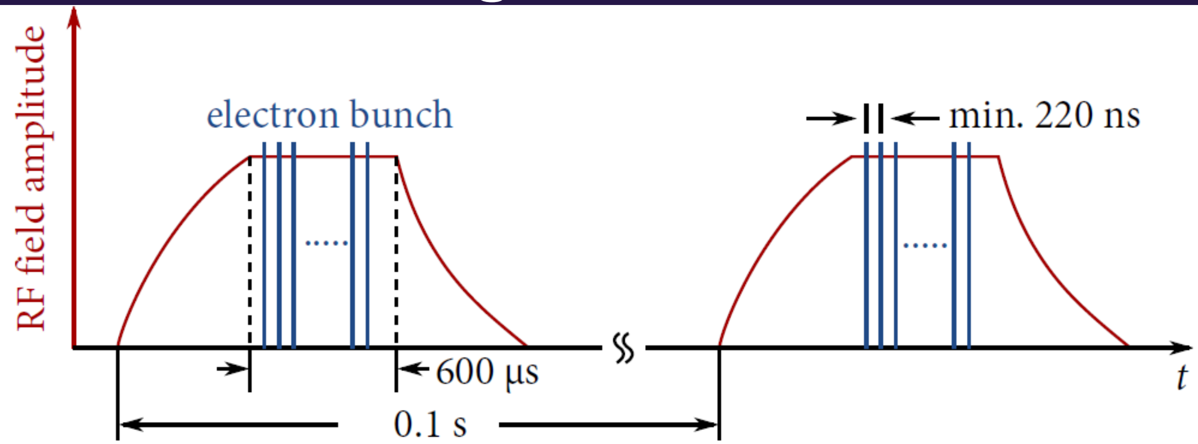
- Diagnostics sections in Injector and downstream of BC1 and BC2
- Transverse deflecting structures (TDS) in each section (BC1 delayed)
- Kickers for "semi-parasitic" operation



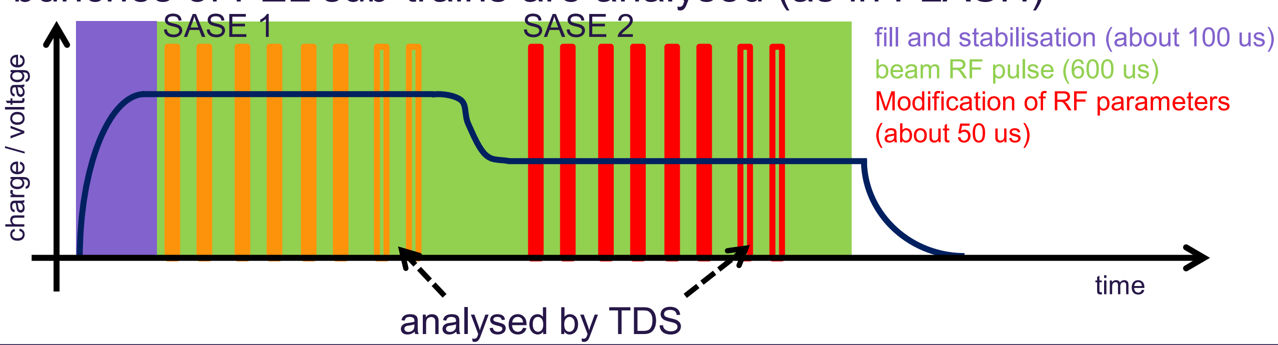


European XFEL

"Semi-Parasitic" Diagnostics



- Semi-parasitic operation of TDS in parallel to FEL operation using electron beam kickers
- Up to 4 bunches can be streaked at 1MHz (3.5 us flat-top duration)
- At BC1 and BC2 more than one bunch is affected by the TDS
  => implications for machine protection (MPS)
- Trailing bunches of FEL sub-trains are analysed (as in FLASH)



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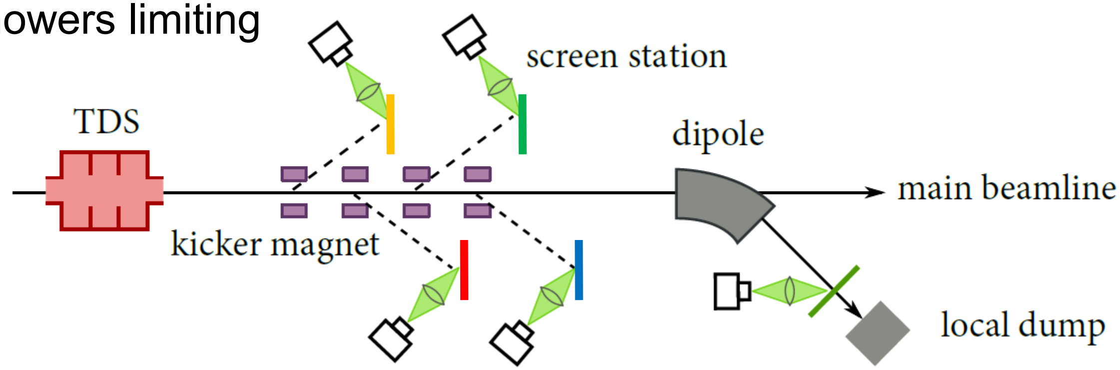
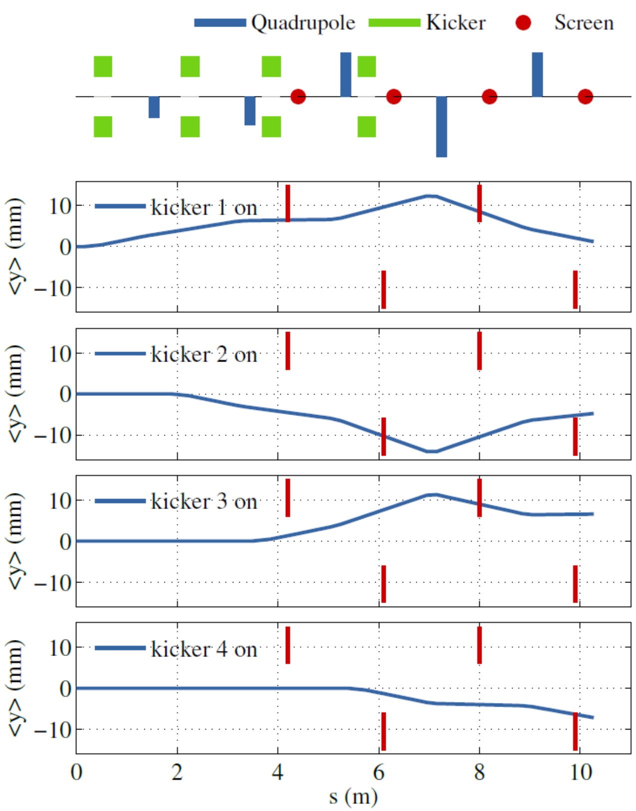
Kicker Operation

- Four bunches (at 1 MHz) can be streaked with the TDS systems
- Beam trajectories for kicked bunches on the first two screens intersect with the last two screens in addition to radiation showers limiting image quality



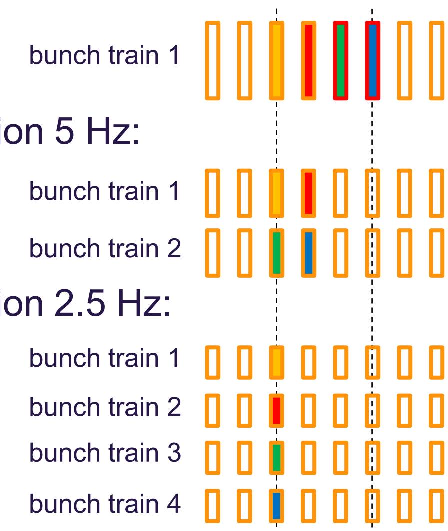
Example: XFEL BC1



Option 10 Hz*:

Option 5 Hz:

Option 2.5 Hz:

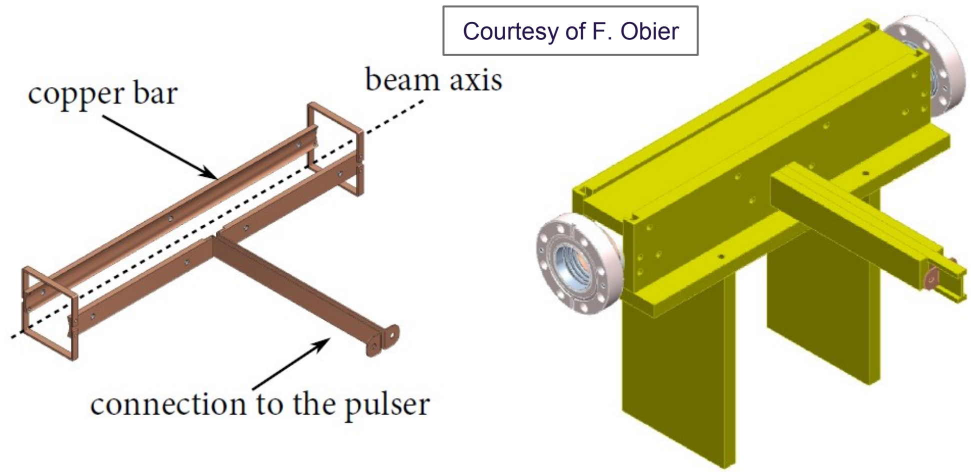


* not possible at BC2

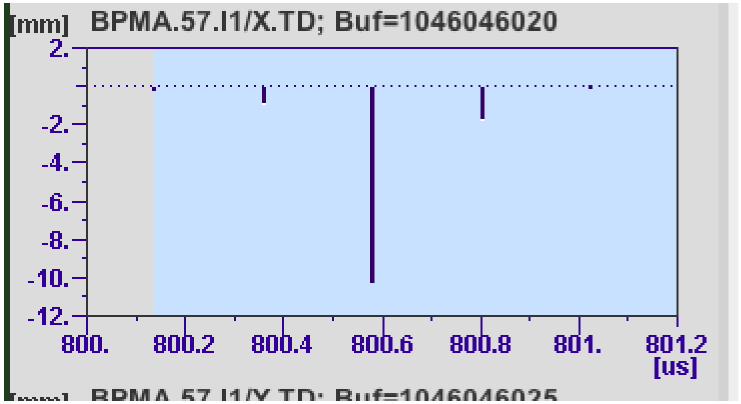
To avoid overlapping beam spots the number of bunches streaked per shot (10 Hz) can be reduced to 2 or even one.

An advantage of the 2.5 Hz option would be that always the same bunch along the train is streaked and analysed.
=> scans along the train / intra-train stability studies

Fast Kicker Magnets

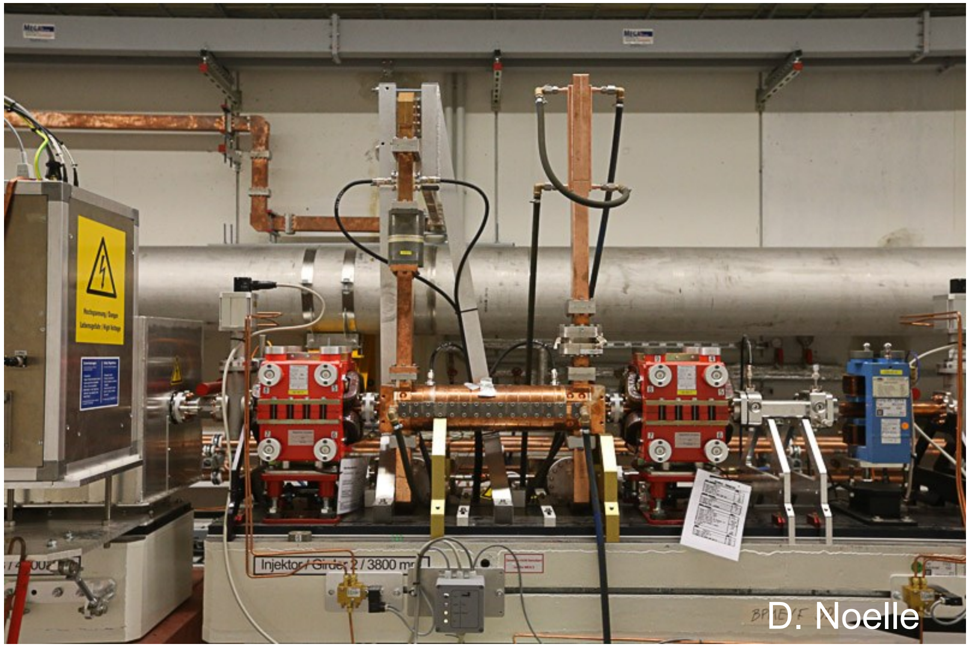


Distortion of adjacent bunches at 4.5MHz:

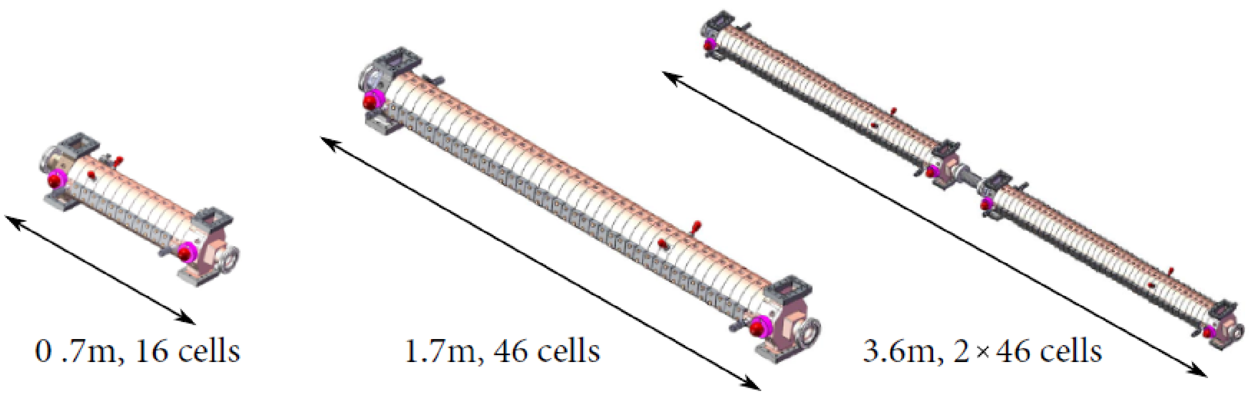


- Maximum length of 350 mm defined by bunch repetition rate of 4.5 MHz (380 ns half sine wave)
  => 2 kickers in series required in BC2 to achieve sufficient kick strength (two pairs installed)
  => online slice emittance measurements not possible
- 4 TDS kickers in the XFEL injector are in operation – others are installed

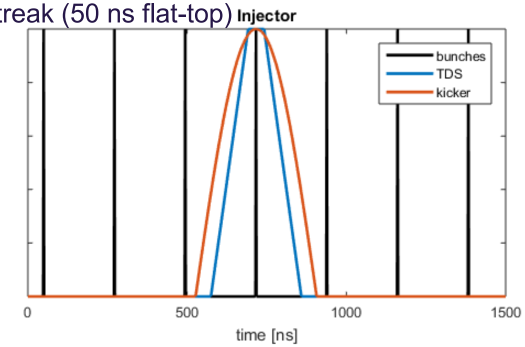
TDS Systems

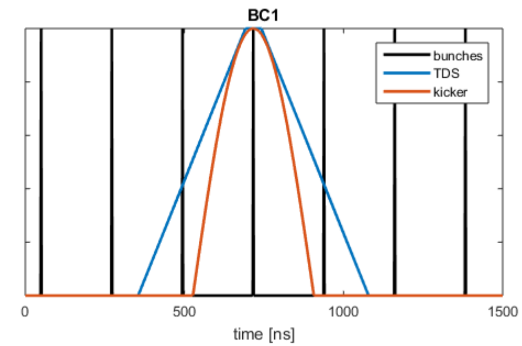


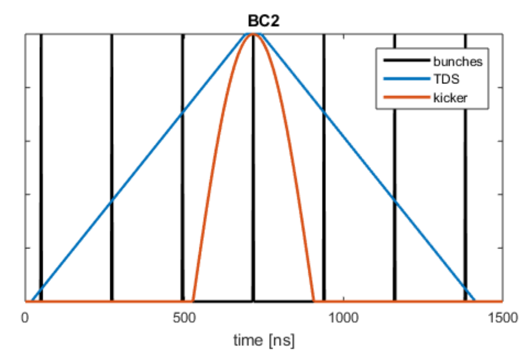
a) Injector section b) BC1 section c) BC2 section



Example: 4.5 MHz mode, single-bunch streak (50 ns flat-top)

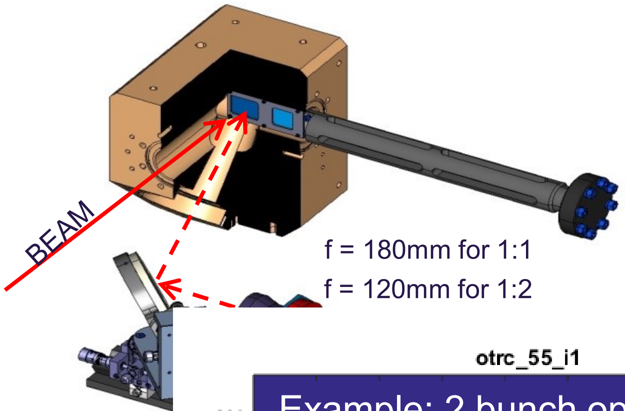


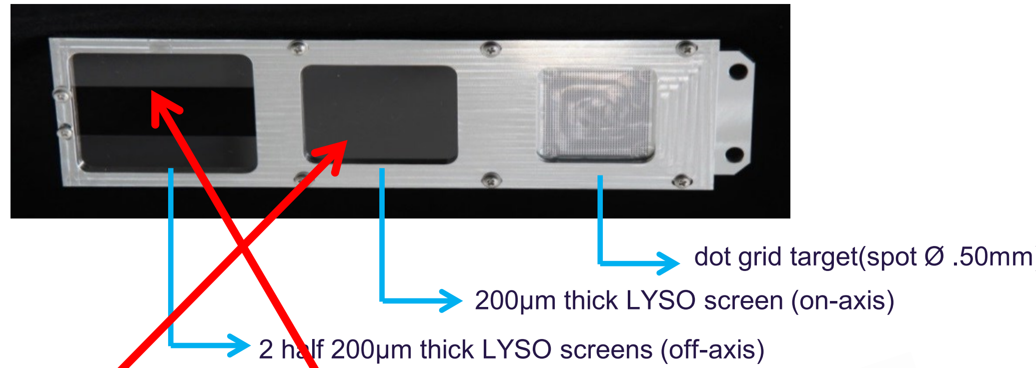


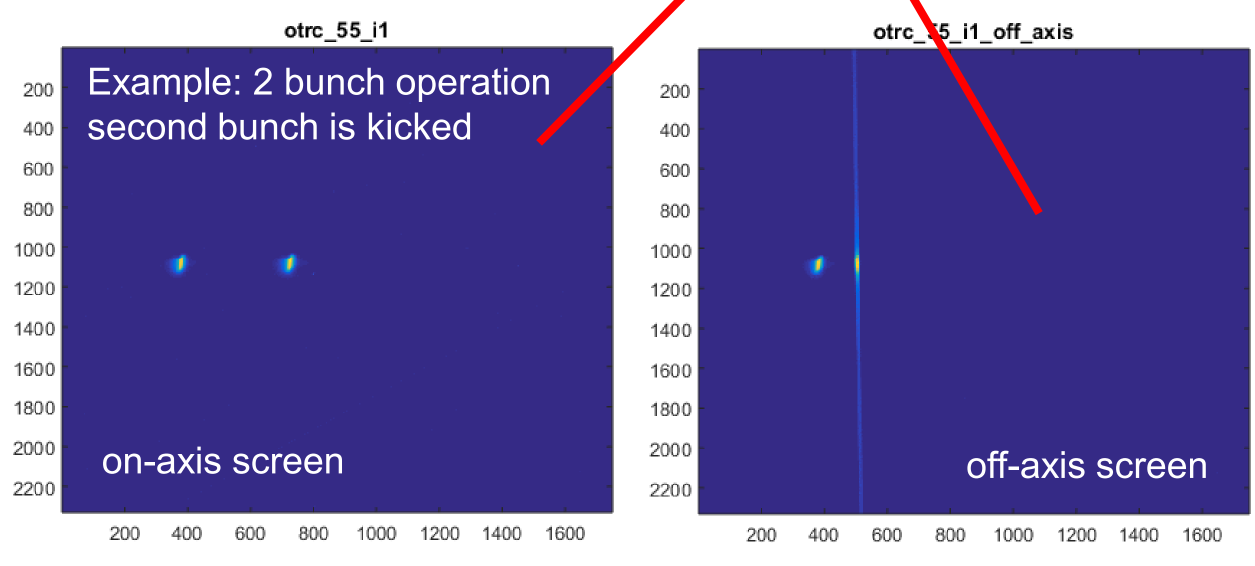


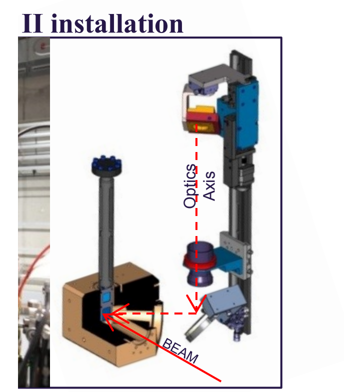
Screen Station for European XFEL

- monitor setup

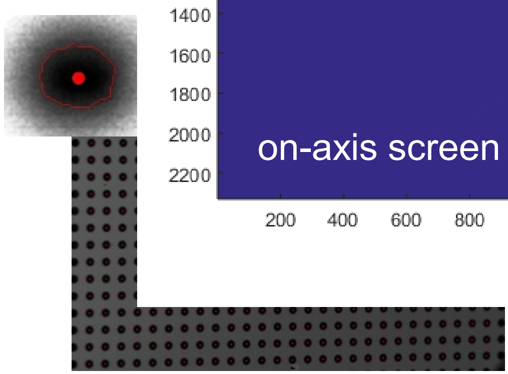


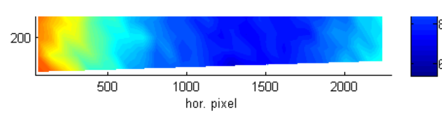






- optical l





on geometry

lution

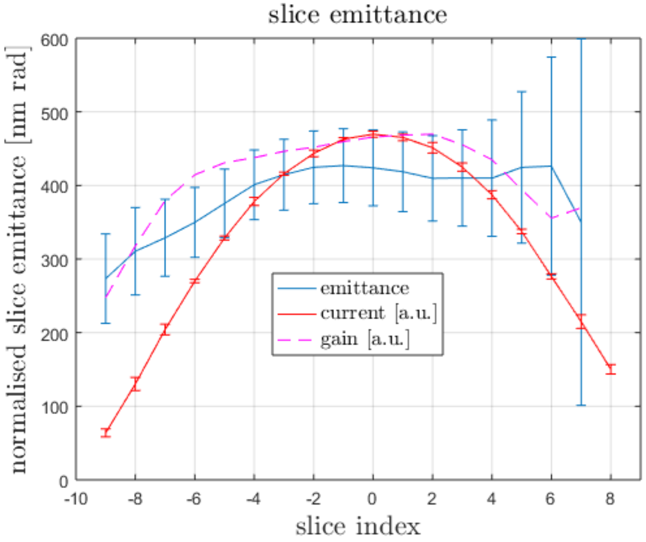
unction)

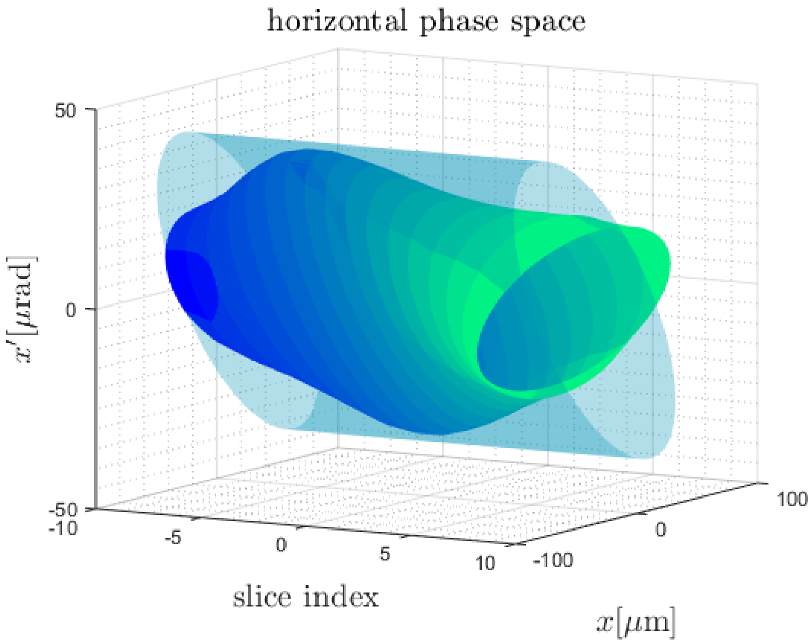
Slide thanks to G. Kube

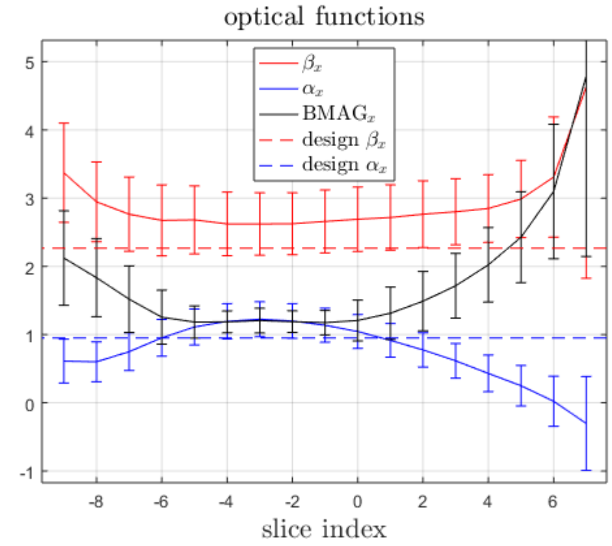
Ch. Wiebers et al. Proceedings of IBIC2013, Oxford, UK

Slice Emittance

- FEL Process acts in a “slice” much shorter then the bunch length
- Projected emittance would underestimate the phase space density of each slice
- Longitudinal resolved measurements using a transverse deflecting structure (TDS)







Slice vs. Projected Emittance

- Aligned Beam – assuming all slice centroids are aligned:

$$m_p(\beta_1, \beta_2) = \frac{\beta_1 \gamma_2 - 2\alpha_1 \alpha_2 + \gamma_1 \beta_2}{2}$$

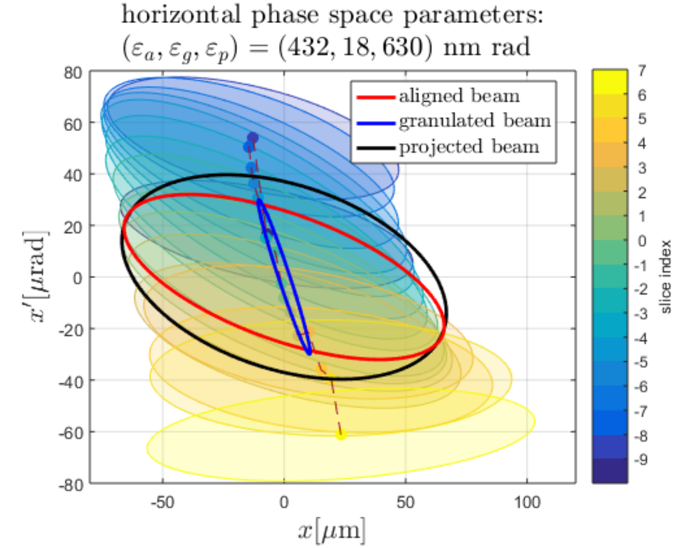
$$w_1 + w_2 + \ldots + w_n = 1$$

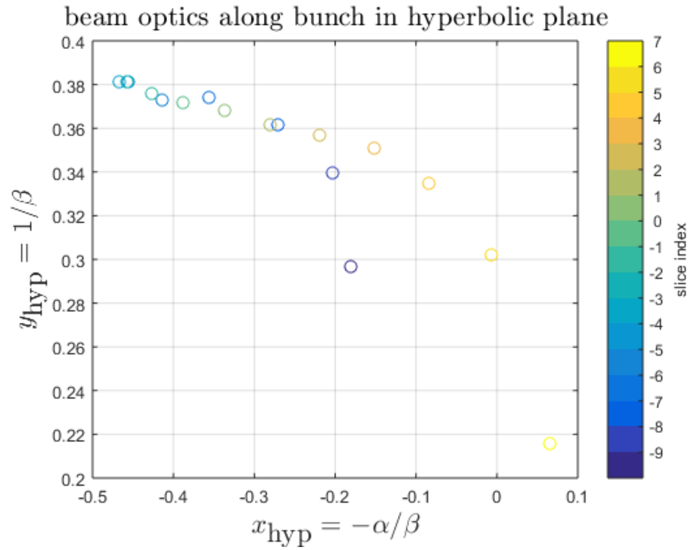
$$\epsilon_a^2 = \sum_{m,l=1}^{n} m_p(\beta_m, \beta_l)\,(w_m \epsilon_m)\,(w_l \epsilon_l)$$

$$\beta_a = \frac{1}{\epsilon_a} \sum_{m=1}^{n} w_m \epsilon_m \beta_m$$

$$\alpha_a = \frac{1}{\epsilon_a} \sum_{m=1}^{n} w_m \epsilon_m \alpha_m$$

$$\gamma_a = \frac{1}{\epsilon_a} \sum_{m=1}^{n} w_m \epsilon_m \gamma_m$$





V. Balandin

Slice vs. Projected Emittance

- Granulated Beam – emittance obtained from the slice centroids ("train emittance"):

$$\left\langle (\bar{x} - \langle \bar{x} \rangle_w)^2 \right\rangle_w = \sum_{m=1}^{n} w_m \bar{x}_m^2 - \left(\sum_{m=1}^{n} w_m \bar{x}_m \right)^2$$

$$\langle (\bar{x} - \langle \bar{x} \rangle_w)(\bar{p} - \langle \bar{p} \rangle_w) \rangle_w = \sum_{m=1}^{n} w_m \bar{x}_m \bar{p}_m - \left(\sum_{m=1}^{n} w_m \bar{x}_m \right) \left(\sum_{m=1}^{n} w_m \bar{p}_m \right)$$

$$\left\langle (\bar{p} - \langle \bar{p} \rangle_w)^2 \right\rangle_w = \sum_{m=1}^{n} w_m \bar{p}_m^2 - \left(\sum_{m=1}^{n} w_m \bar{p}_m \right)^2$$

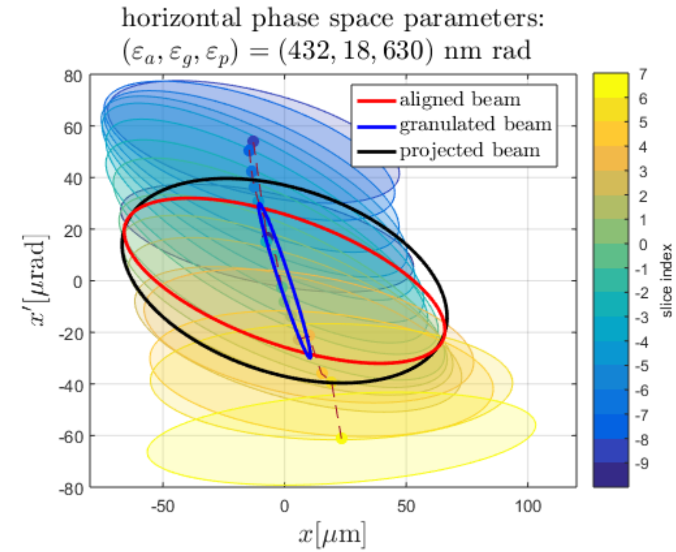
- p_m is obtained by fit: might be distorted by dispersion, wakes, …

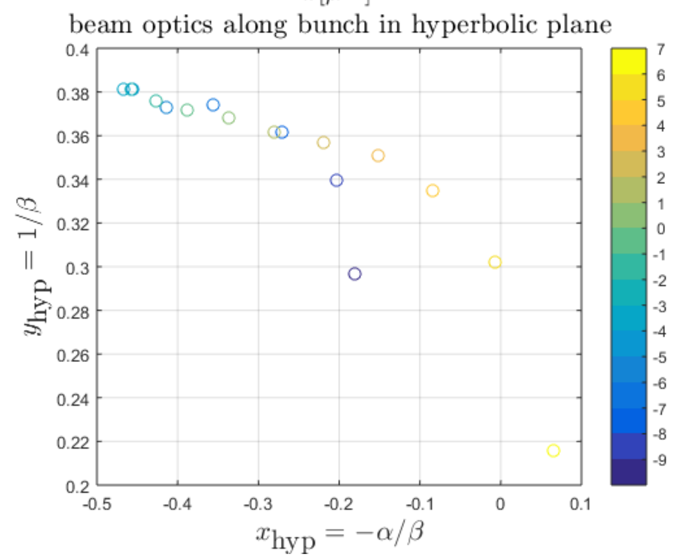
$$\chi^2 = \sum \left[x^{(i)} - \frac{\left(R_{11}^{(i)} \bar{x}_m + R_{12}^{(i)} \bar{p}_m \right)}{\sigma_x^{(i)}} \right]^2$$

$$\epsilon_g^2 = \left\langle (\bar{x} - \langle \bar{x} \rangle_w)^2 \right\rangle_w \cdot \left\langle (\bar{p} - \langle \bar{p} \rangle_w)^2 \right\rangle_w - \langle (\bar{x} - \langle \bar{x} \rangle_w)(\bar{p} - \langle \bar{p} \rangle_w) \rangle_w^2$$

$$\beta_g = \frac{\left\langle (\bar{x} - \langle \bar{x} \rangle_w)^2 \right\rangle_w}{\epsilon_g} \qquad \alpha_g = -\frac{\langle (\bar{x} - \langle \bar{x} \rangle_w)(\bar{p} - \langle \bar{p} \rangle_w) \rangle_w}{\epsilon_g}$$

$$\gamma_g = \frac{\left\langle (\bar{p} - \langle \bar{p} \rangle_w)^2 \right\rangle_w}{\epsilon_g}$$





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Slice vs. Projected Emittance

- Projected Beam:

$$\epsilon^2 = \epsilon_a^2 + \epsilon_g^2 + \epsilon_a \Big[\gamma_a \left\langle (\bar{x} - \langle \bar{x} \rangle_w)^2 \right\rangle_w$$

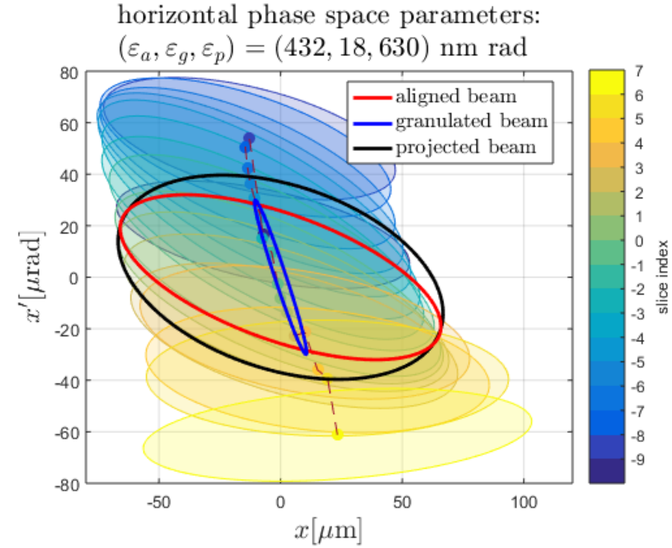
$$+ 2\alpha_a \left\langle (\bar{x} - \langle \bar{x} \rangle_w)(\bar{p} - \langle \bar{p} \rangle_w) \right\rangle_w$$

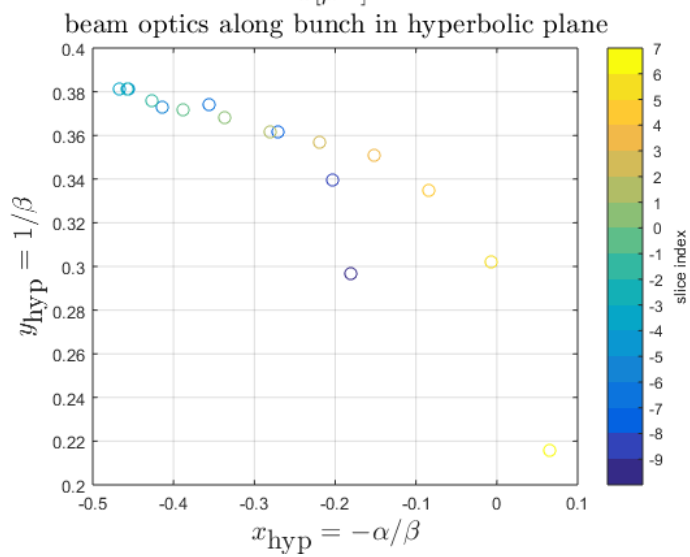
$$+ \beta_a \left\langle (\bar{p} - \langle \bar{p} \rangle_w)^2 \right\rangle_w \Big]$$

$$\beta = \frac{\epsilon_a \beta_a + \left\langle (\bar{x} - \langle \bar{x} \rangle_w)^2 \right\rangle_w}{\epsilon}$$

$$\alpha = \frac{\epsilon_a \alpha_a - \left\langle (\bar{x} - \langle \bar{x} \rangle_w)(\bar{p} - \langle \bar{p} \rangle_w) \right\rangle_w}{\epsilon}$$

$$\gamma = \frac{\epsilon_a \gamma_a + \left\langle (\bar{p} - \langle \bar{p} \rangle_w)^2 \right\rangle_w}{\epsilon}$$





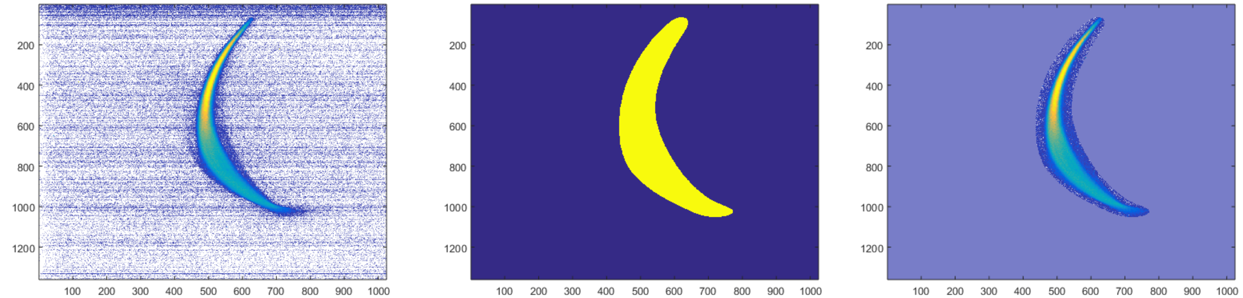
V. Balandin

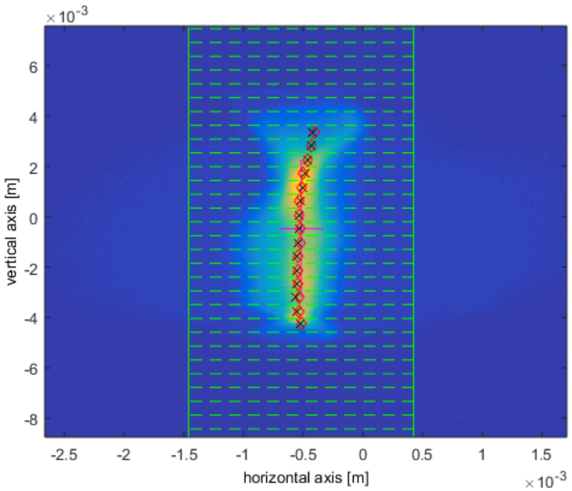
European XFEL

Image Analysis Overview

- Image analysis code developed at DESY (Roehrs, Behrens, Yan, BB)
- Experience from FLASH, SFITF, LCLS, ...
- Fine tuning of hardware specific parameters

- automised mask-of-interest to enable efficient RMS spot size analysis (“Noisecut”)





- Slicing of beam images for slice resolved analysis

- Shearing of beamlets to mitigate effects from beam tilts or dispersion on chirped beams

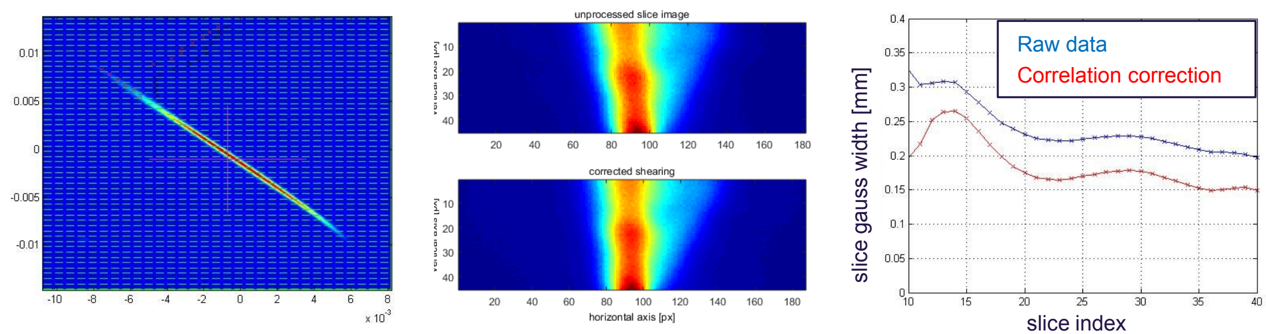


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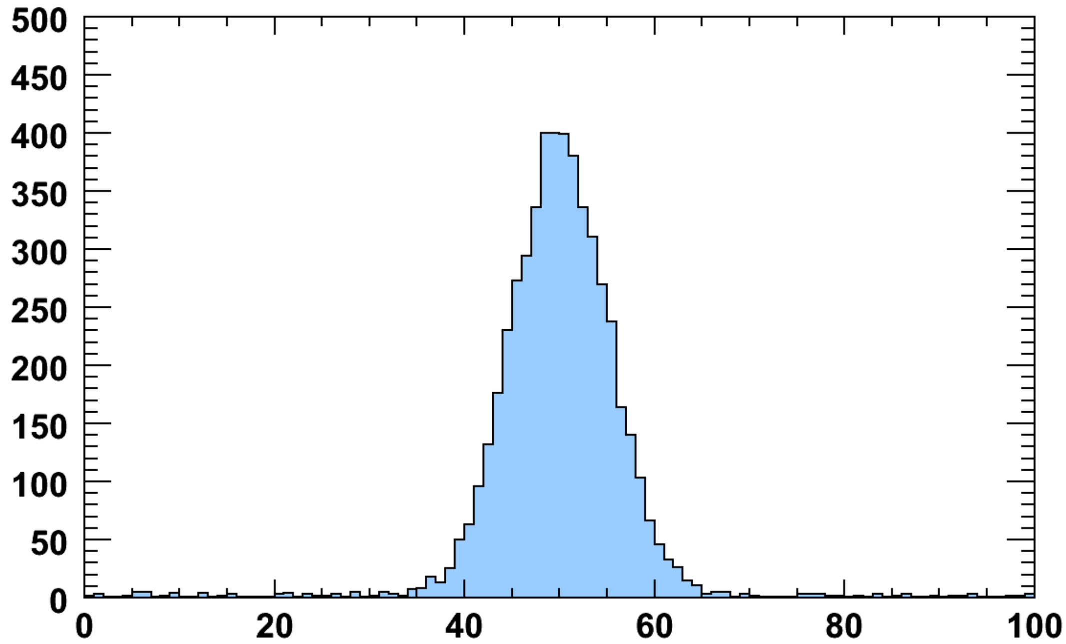
Image Analysis

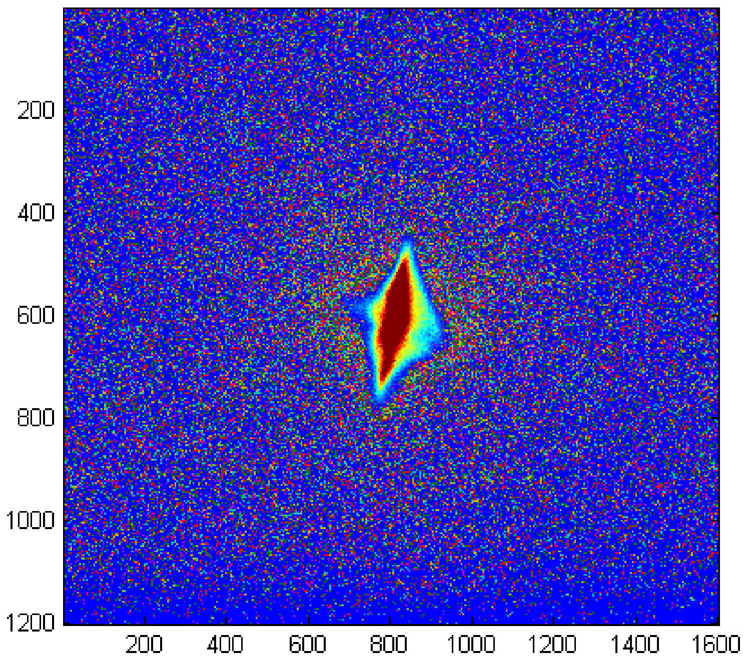
- Beam Size Determination
  - Gaussian is robust but only applicable if the beam spot is Gaussian or at least symmetric
  - RMS is well defined only if no noise is present since the contribution of each bin goes with the square of the distance to the centre-of-mass

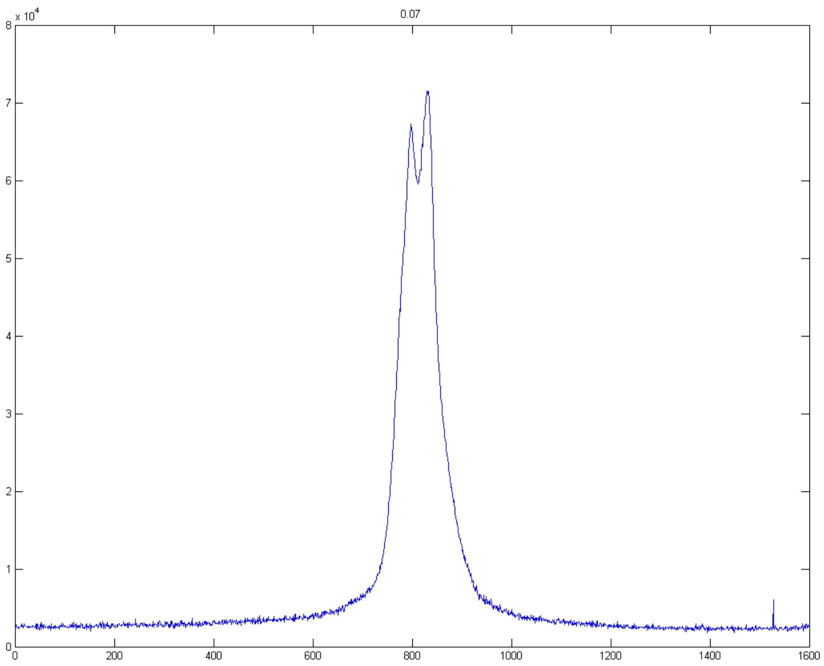
=> Masking of noise is required if RMS is used



“Noisecut”

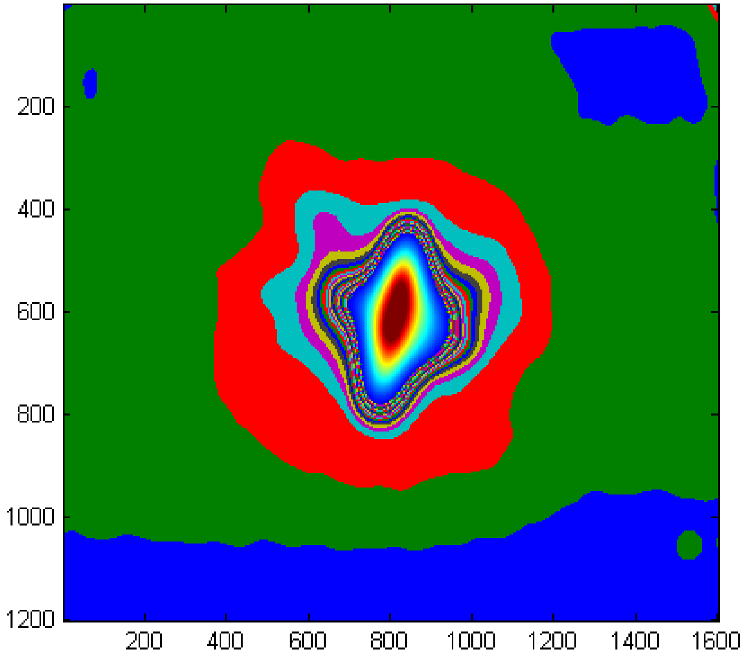
- Initial Image with noise to dominate RMS calculation

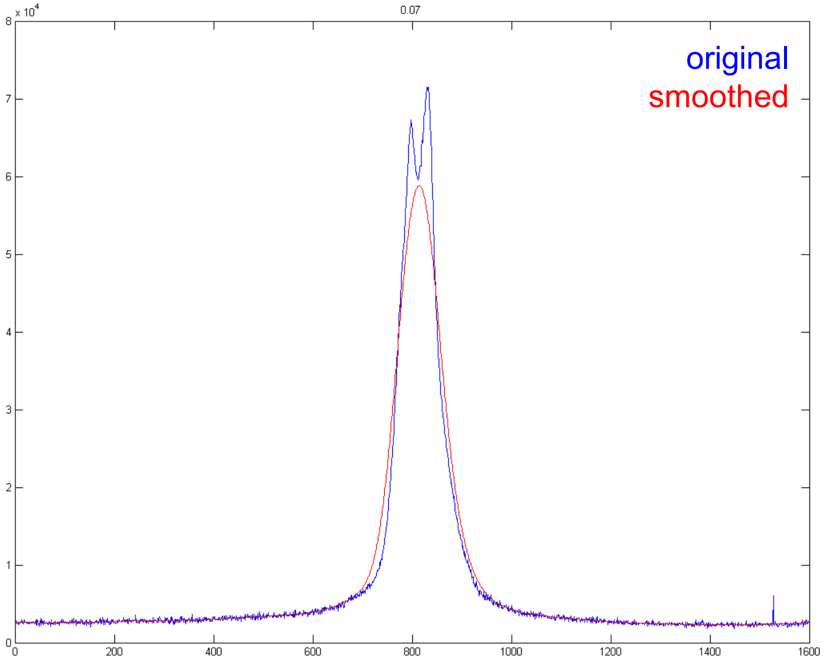




“Noisecut”

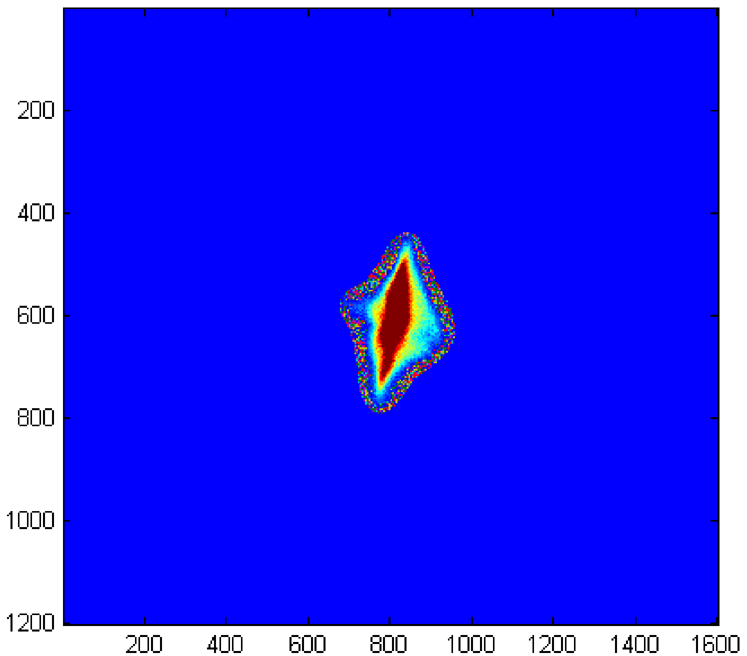
- Initial Image with noise to dominate RMS calculation
- Intermediate smoothing of image (e.g. Gaussian filter)

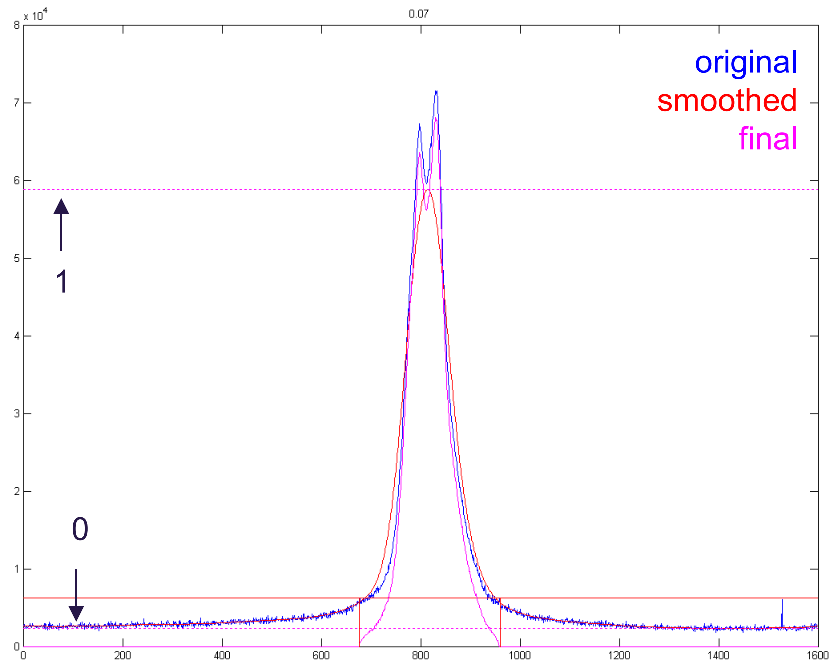




"Noisecut"

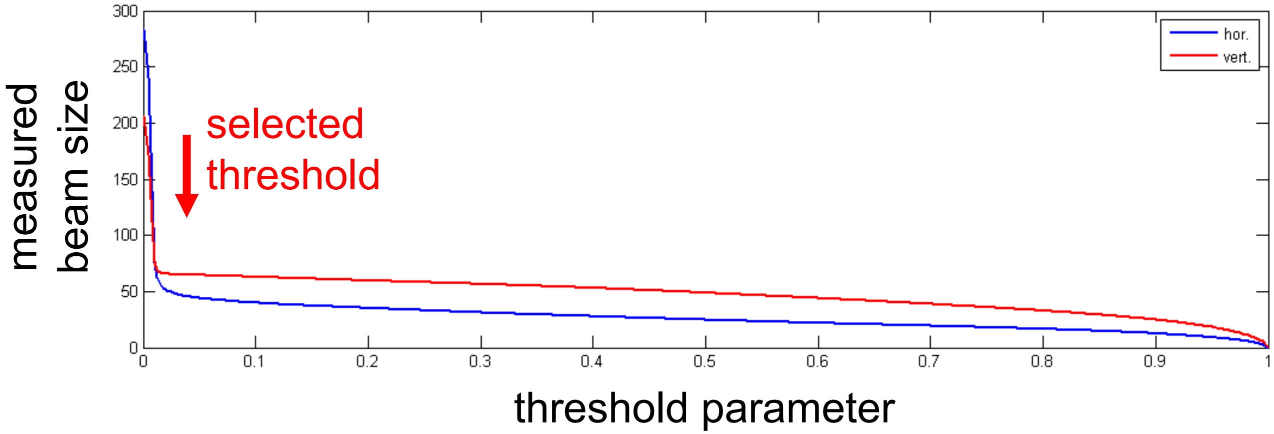
- Initial Image with noise to dominate RMS calculation
- Intermediate smoothing of image (e.g. Gaussian filter)
- Determination of mask by application of threshold to smoothed image



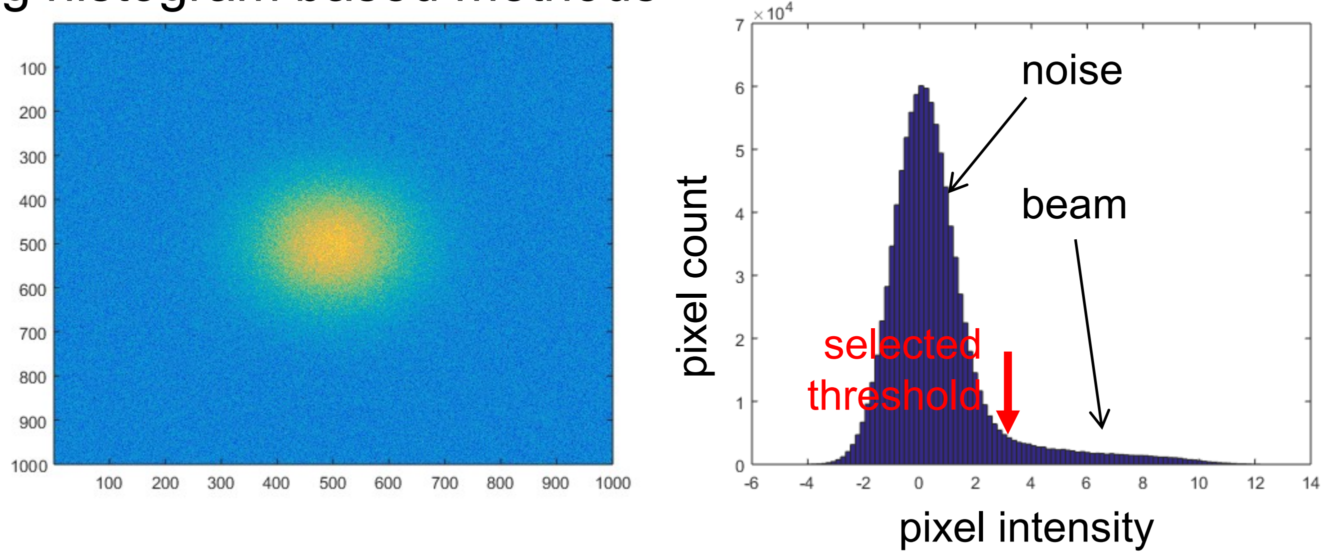


"Noisecut" Threshold Determination

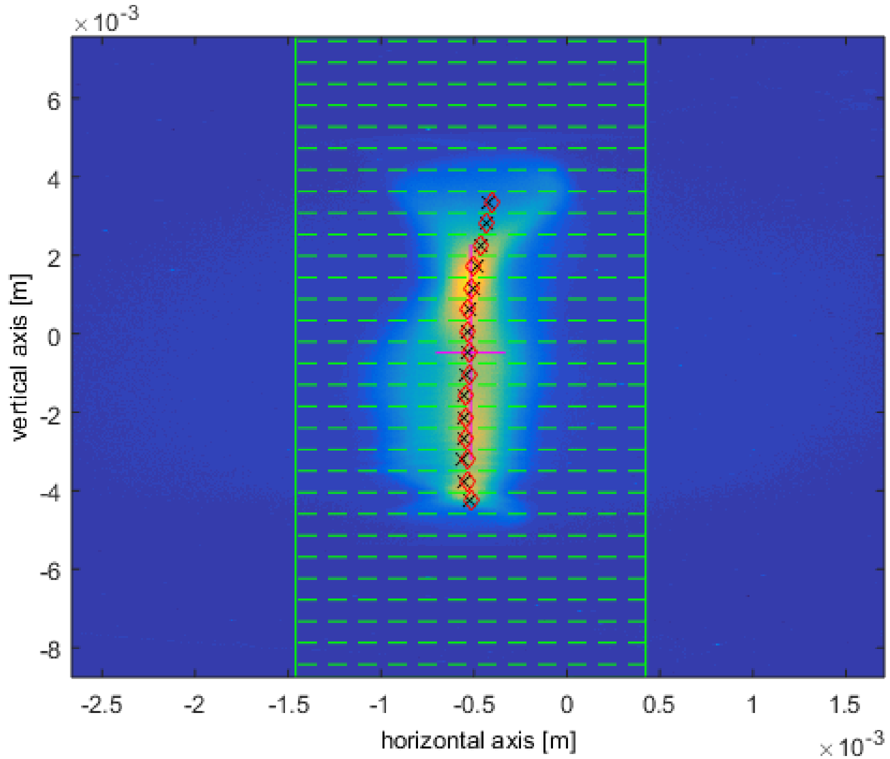
- Threshold determination either by a scan



or using histogram based methods



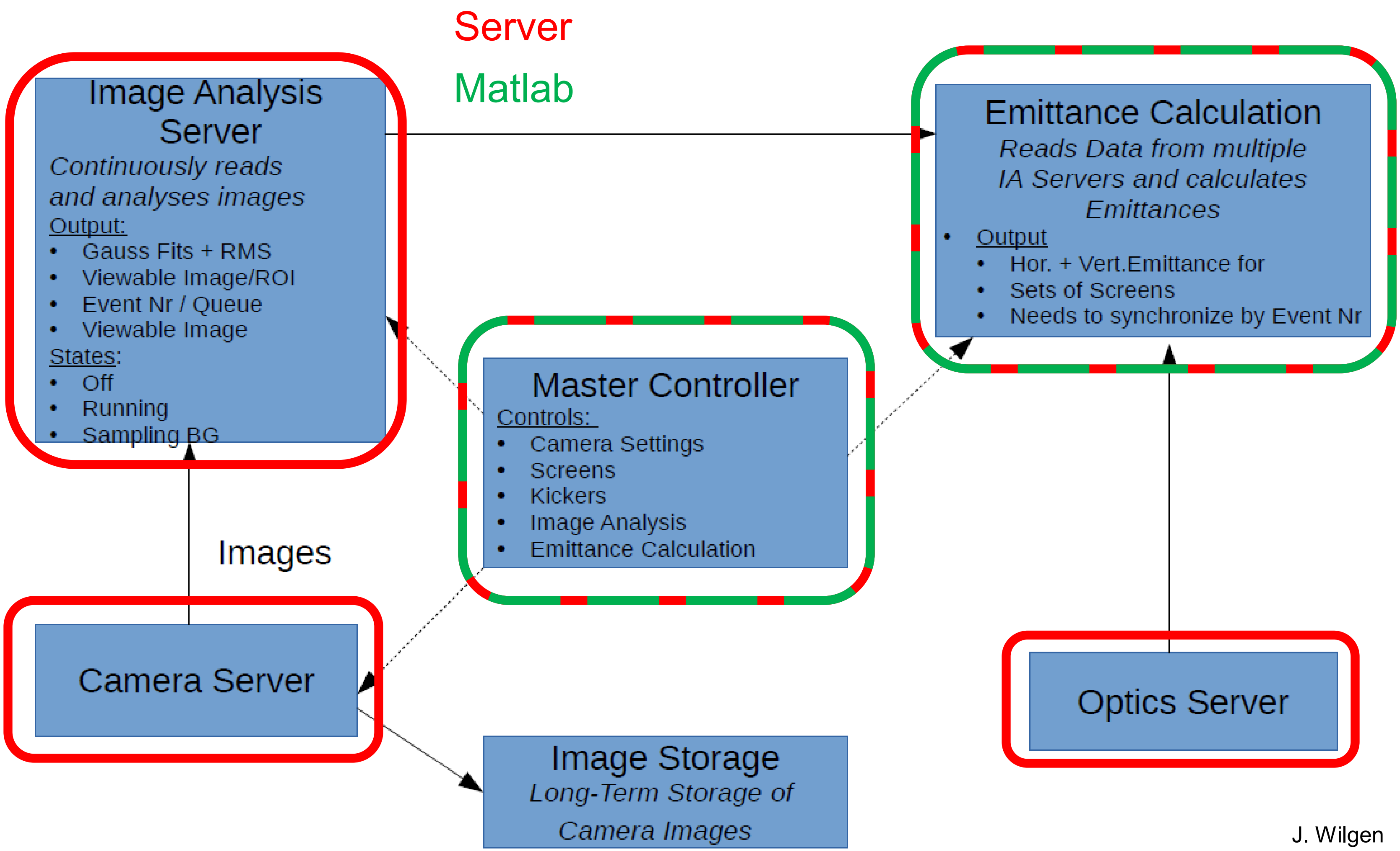
Sliced Image Analysis



- Restrict analysis to region-of-interest (ROI)
- Find reference point (has to match on all images regardless of position jitter) – typically centre-of-mass
- Apply a matching slice width (either calibrated time interval or relative to individual longitudinal sigma)

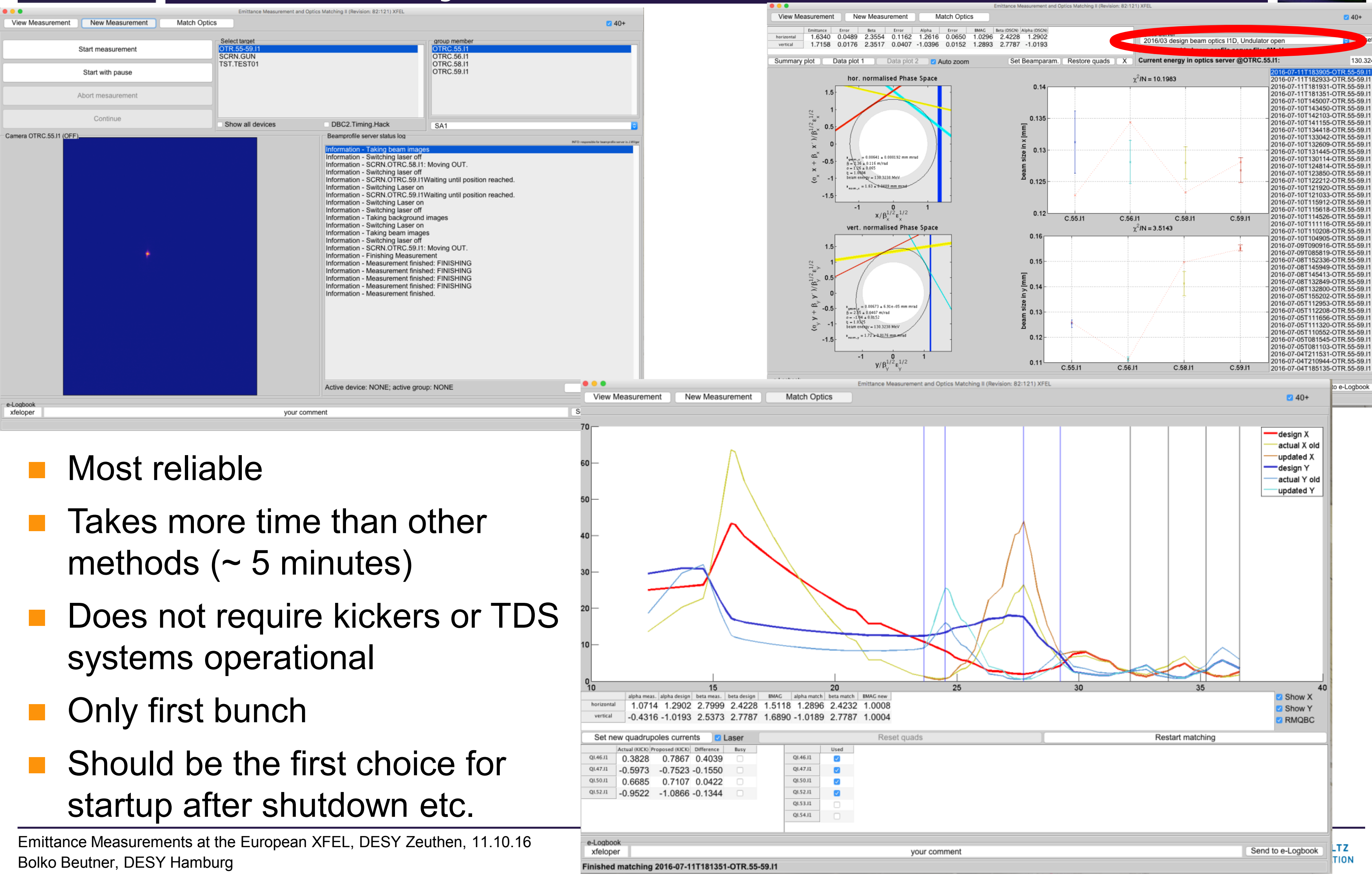
Measurement Infrastructure

Services Needed for Off-Axis Emittance Measurement



J. Wilgen

On-Axis Projected Measurements



- Most reliable
- Takes more time than other methods (~ 5 minutes)
- Does not require kickers or TDS systems operational
- Only first bunch
- Should be the first choice for startup after shutdown etc.

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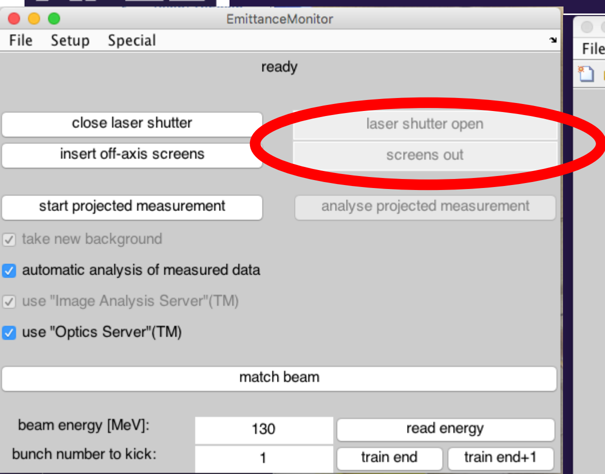
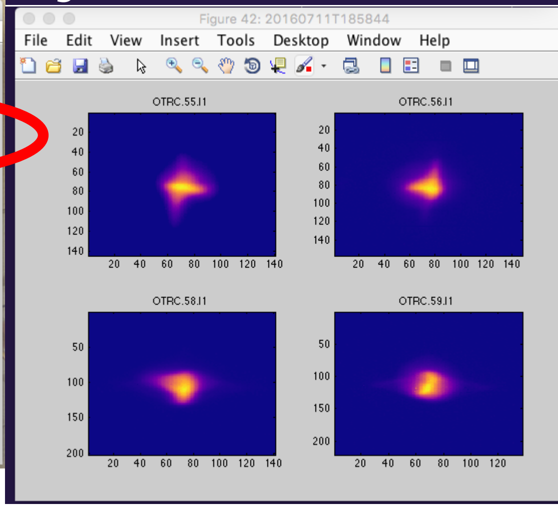
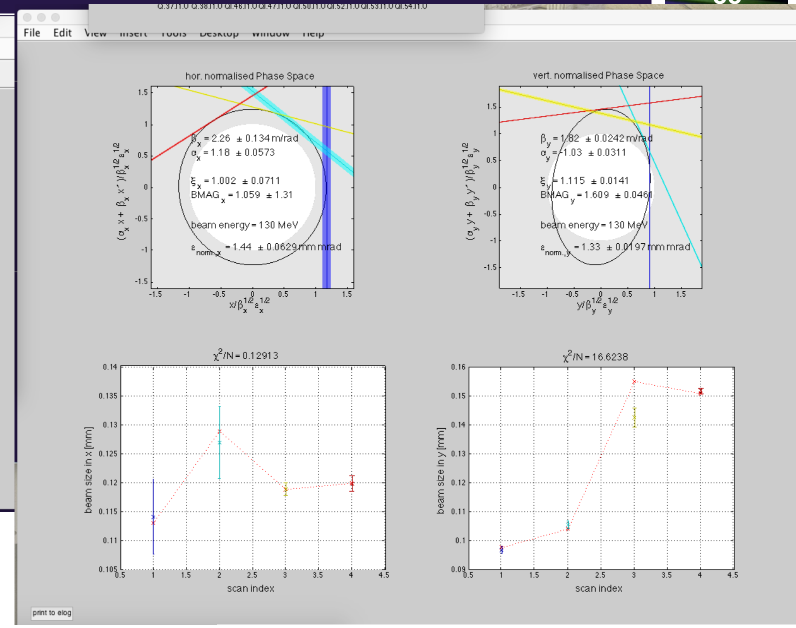
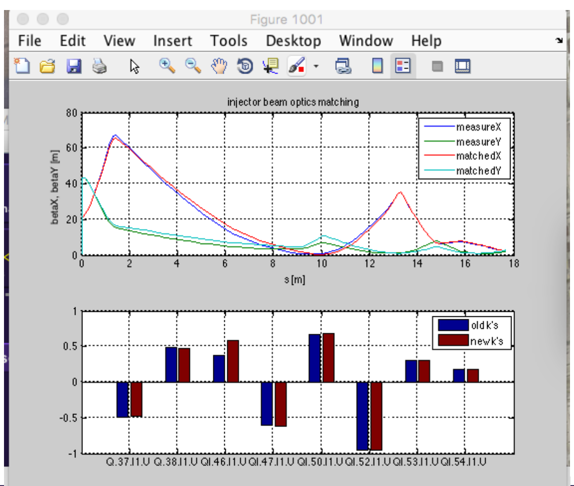
Off-Axis Projected Measurements

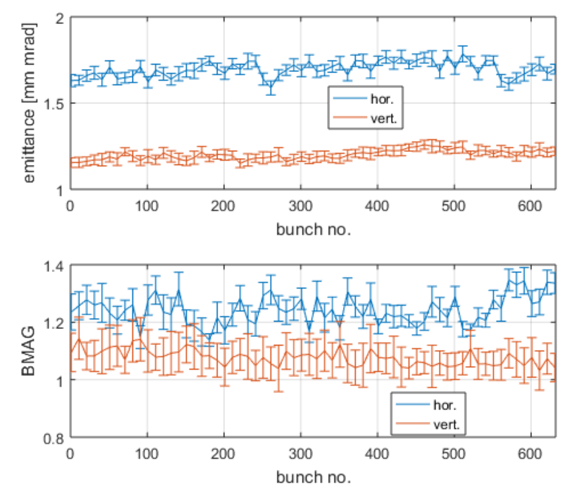






- Use of kickers allows for much faster measurements (about 20s)
- Orbit and optics mismatch needs to be good
- Allows for measurements of other than the first bunch
- Make sure that the energy chirp is removed
- Main tool for tuning of projected emittance





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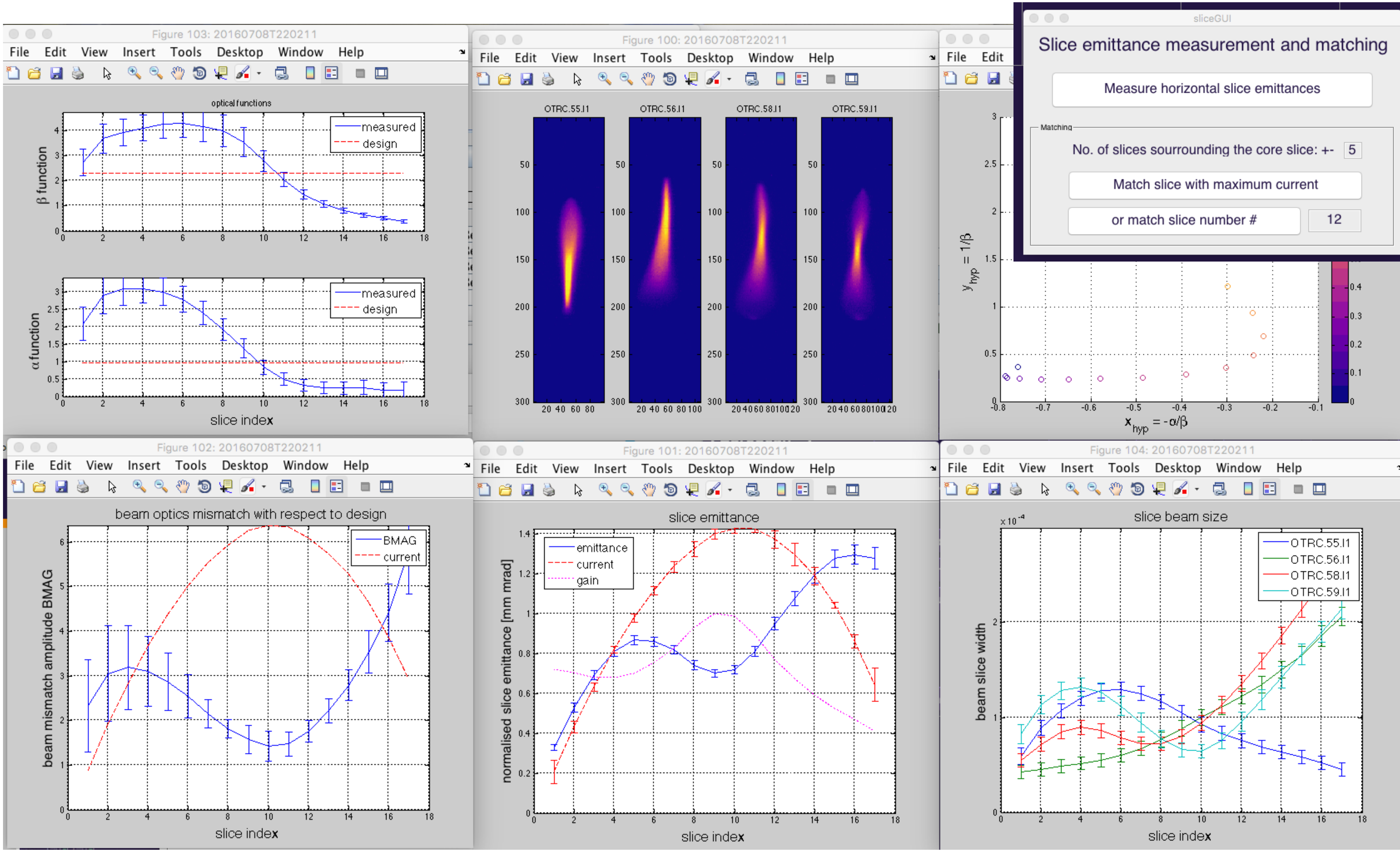
Slice Emittance Measurements



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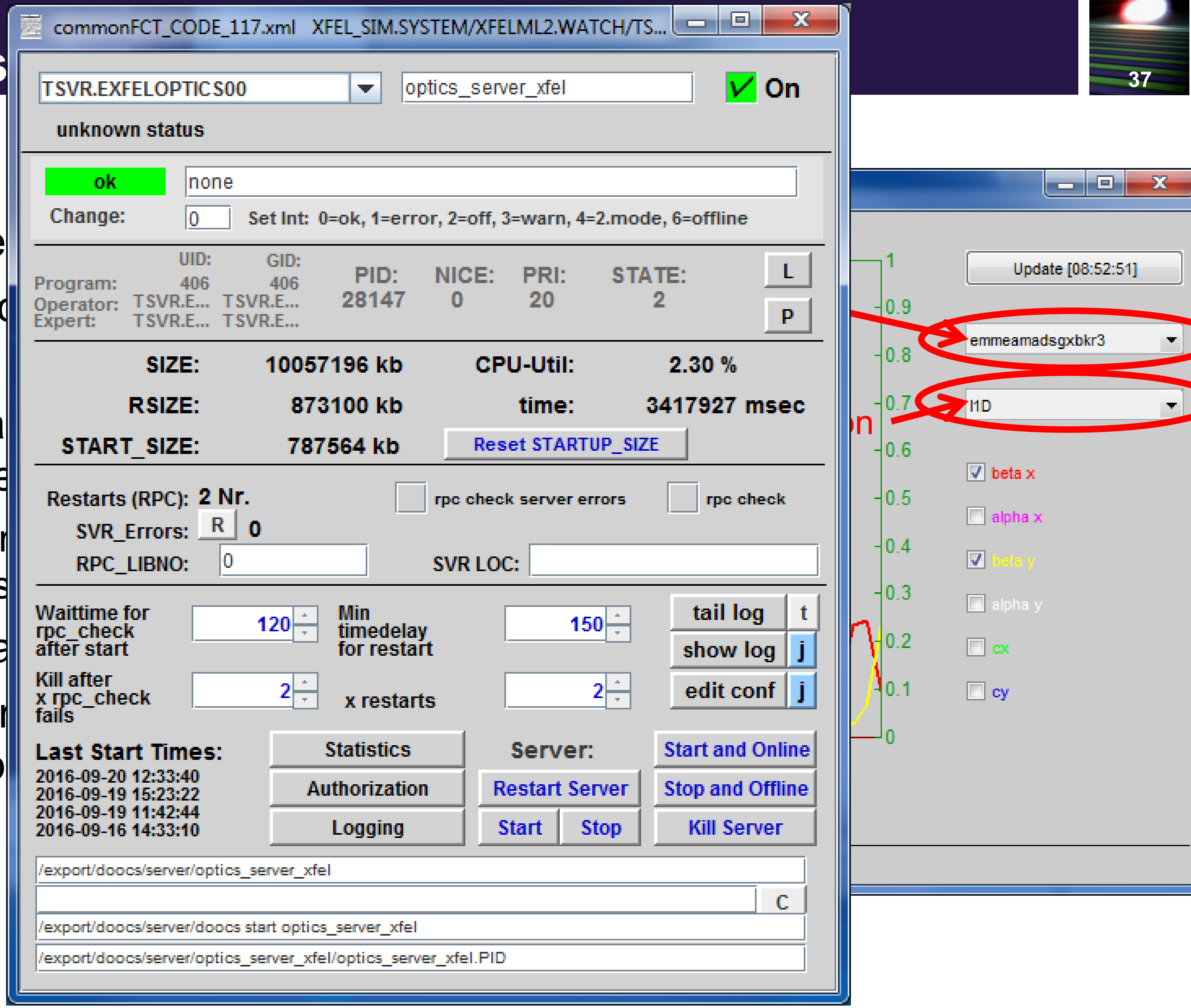
Optics

- Tine Server
- Elegant backe
- Matlab Interfac Xoptics
- Different Priva Machine Mode
  - Can be gener from control s
- Matching capa
- GUI to monitor different setup



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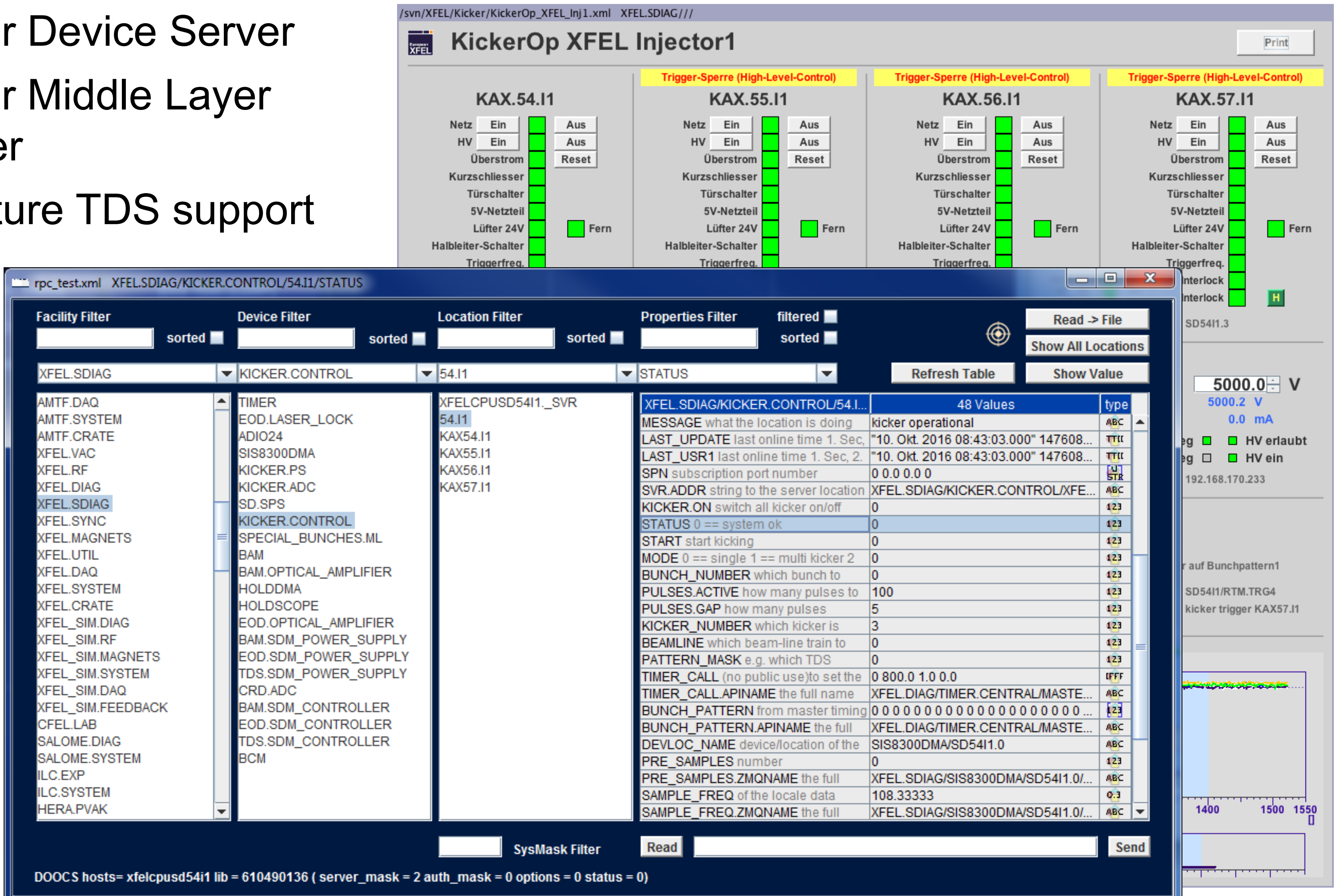
Kicker Control

- Kicker Device Server
- Kicker Middle Layer Server
  - Future TDS support



Beam Profile Server

- Used by the on-axis emittance measurement tool
- Abstract layer to unify screen and wire profile measurements
- Automatic screen and wire mover control
- Images and results are stored on a web server to be analysed by various tools

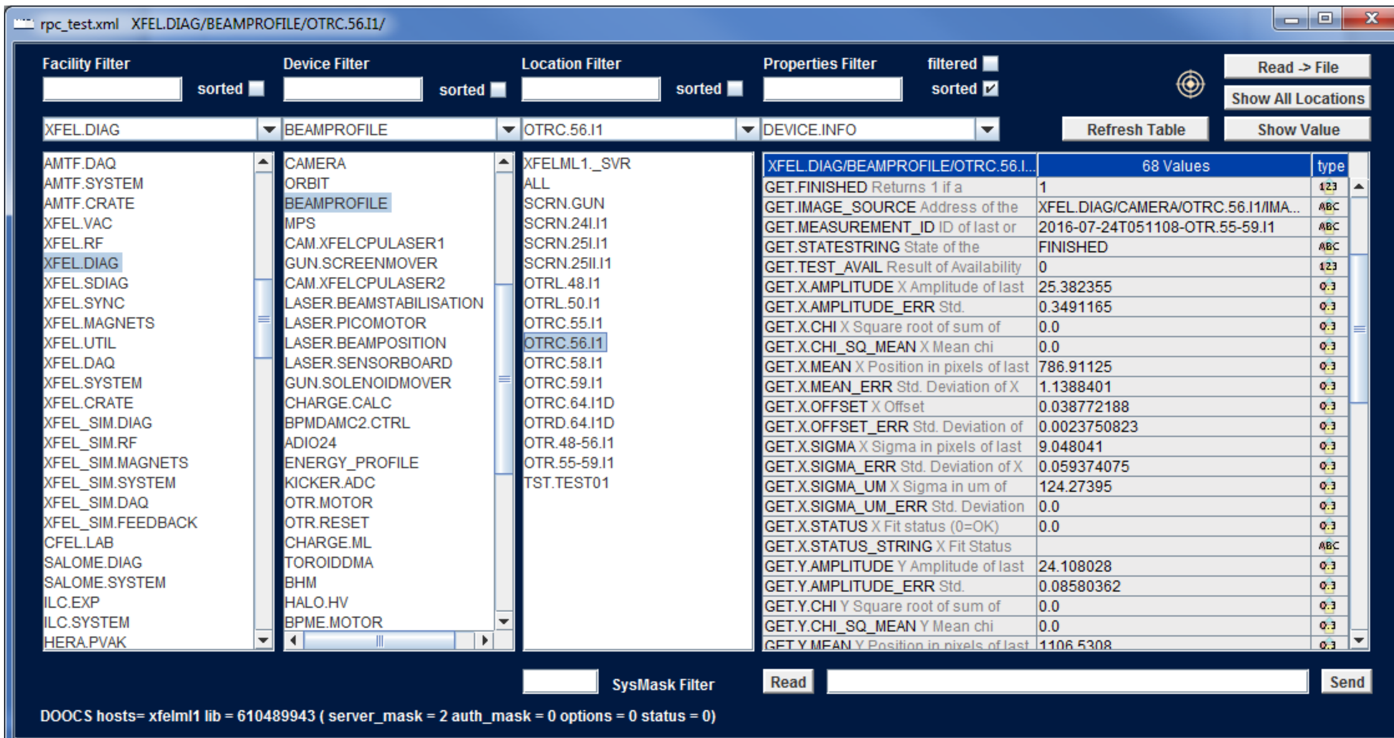


Image Analysis Server

- Running on Camera Server Hardware
  - Efficient ZMQ data exchange with camera server
- Rescaling of image size (more on next slide)
- “Noisecut” on the projected profiles for RMS analysis
- Only results no images are transported to the user client
- Slice analysis with 10Hz to be used for online slice measurements

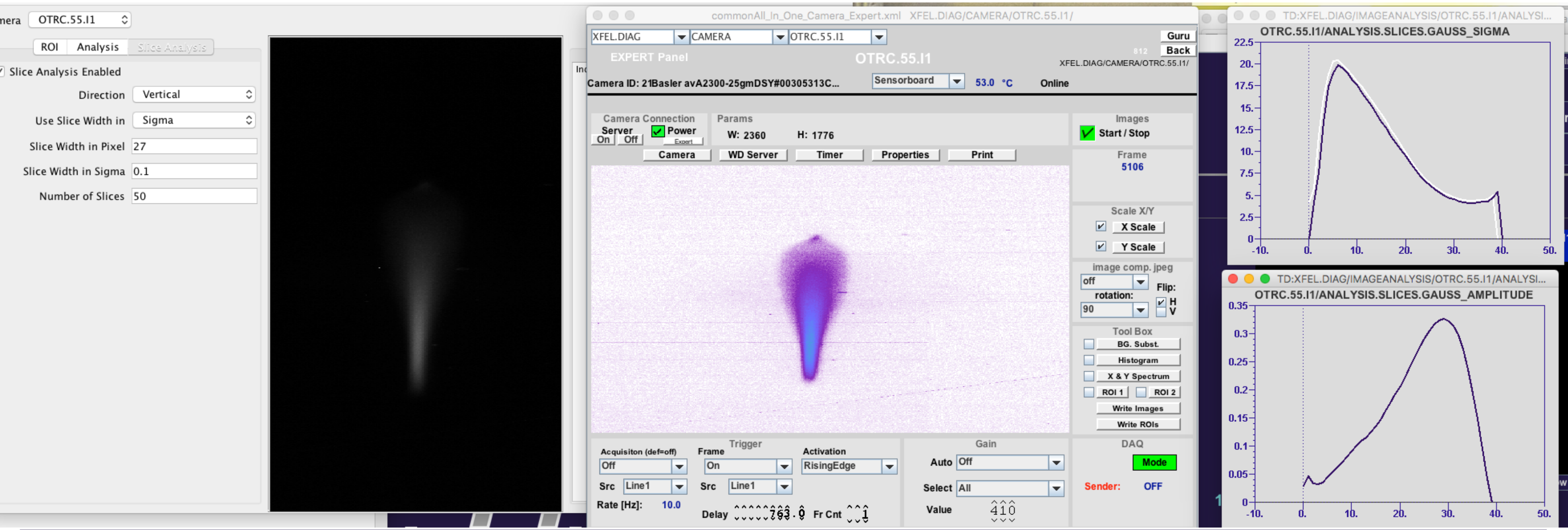


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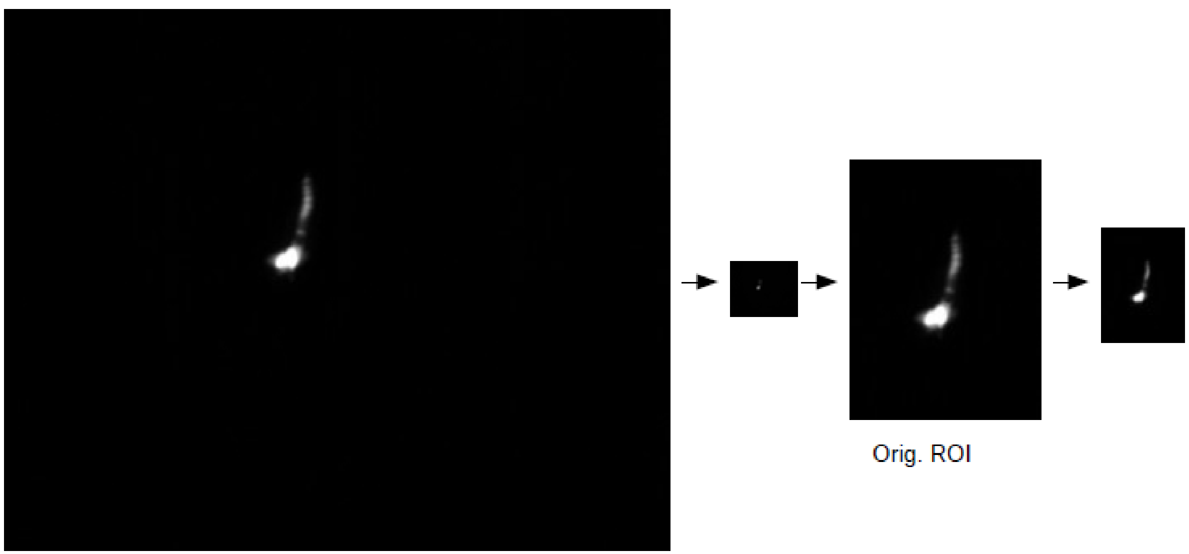
Image Analysis Server II

- Fast processing optimisation
  - ROI is selected based on a Gaussian fit on a downscaled image (typically factor 10 in each dimension – 100x smaller image)
  - ROI is then selected and scaled to a maximum size (typically 300px)
  - Analysis in Scaled ROI
- Faster analysis without sacrificing accuracy

Comparison

NAME	NORMAL	ROI	ROI Scaled
Scale Factor	1	1	2.64219
Width	2330	797	258
Height	1750	772	297
TCreate		74.616	1.859
TConv	19.889	3.687	0.215
Tproj	52.194	6.924	0.282
TGauss	5.758	3.219	1.037
Trms1	0.139	0.057	0.025
Trms2	0.26	0.126	0.072
Xrms1	44.3246	39.2784	38.8938
Xrms2	42.1834	39.3634	38.4111
Yrms1	83.8946	81.2801	81.345
Yrms2	83.1235	81.325	81.4492
Xsigma	43.3999	43.3153	43.3627
YSigma	23.5893	22.7966	22.8107

Analysis of whole image	ca. 80ms
Analysis of ROI (ROI)	ca. 100ms
Analyse of ROI with Scaling	ca. 3.5ms



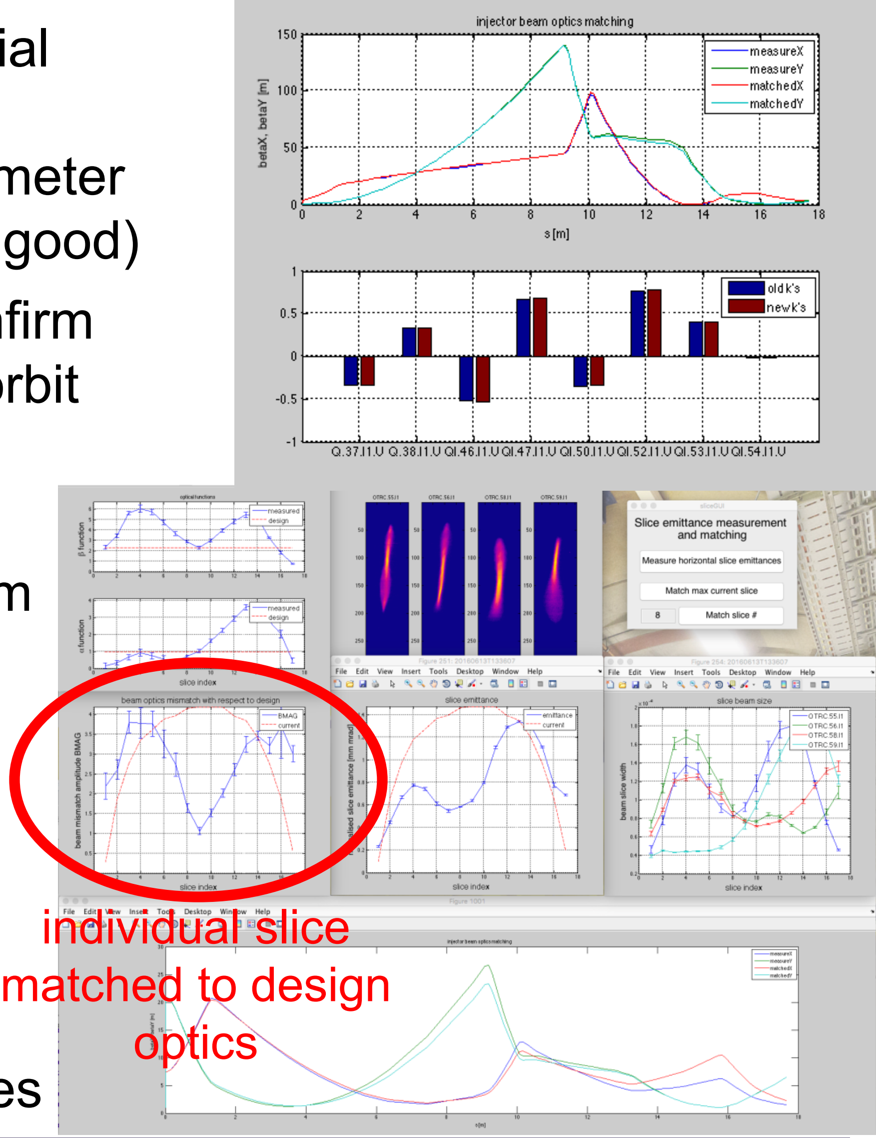
Orig. ROI

Orig. Image 2330x1750 Scaled Image Scaled ROI

J. Wilgen

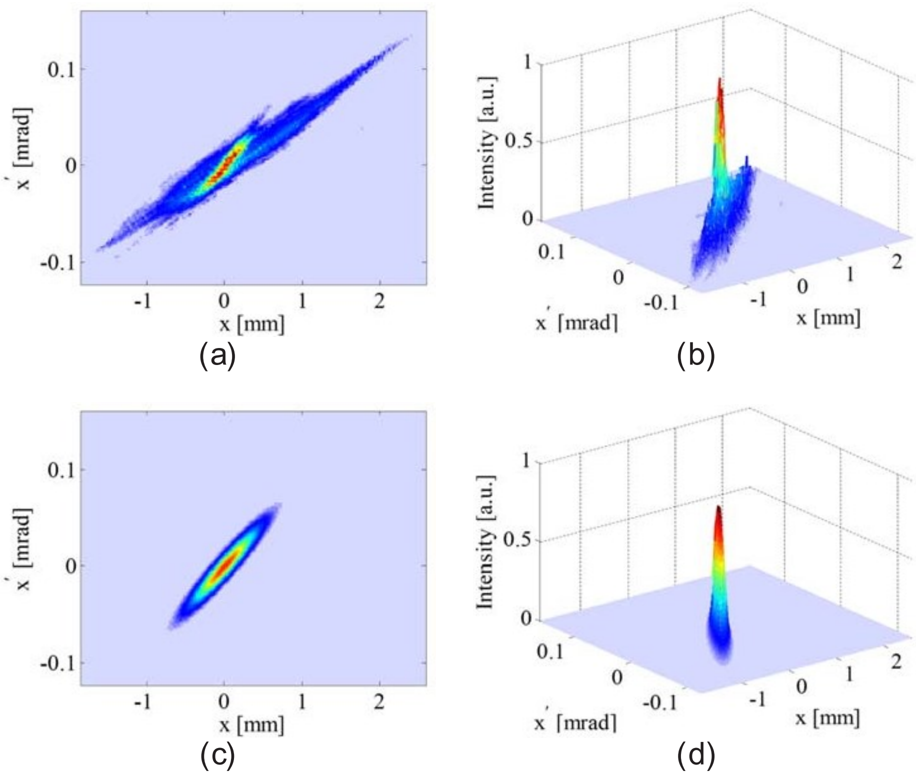
Emittance Measurement Procedure

- Start with on-axis measurements for initial beam matching (about 20 minutes)
  (only after long downtime or major parameter change – otherwise sequencer files are good)
- Off-axis projected measurements to confirm match, kicker status and strength, and orbit
  (typically stable and reproducible)
  (normally less then 5 min.)
- Adjustments and parameter scan if beam quality is not sufficient
  (variable depending on shift goal)
- TDS setup
  (not standardised yet since the TSD system is work in progress)
- Slice emittance studies
- Matching to individual bunches and slices

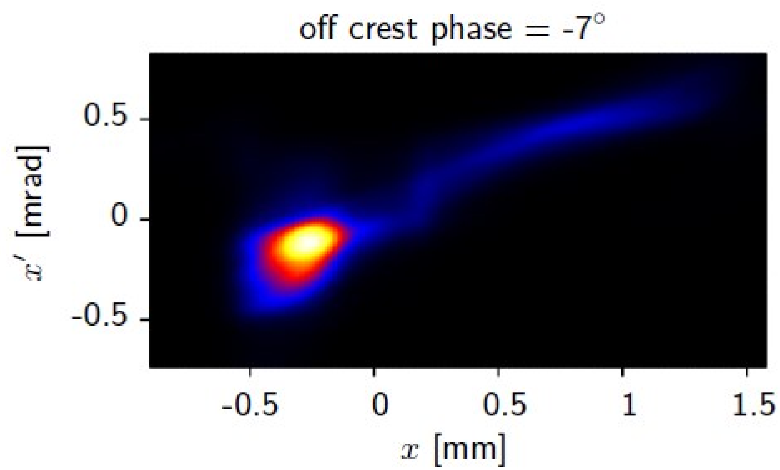


Motivation for Tomographic Reconstruction of the Transverse Phase Space

M. Röhrs, DESY-THESIS-2008-012



- Advanced studies of phase space dynamics are possible with tomographic reconstruction.
- Example FLASH (without 3rd harmonic module):
  - Plots a) and b) on the left hand side show the reconstructed horizontal phase space distribution. The measured slice emittances of this distribution could not explain the achieved SASE pulse energy.
  - After reconstructing the phase space one was able to identify a subset of particles mainly contributing to the SASE process (Plots c) and d)). The smaller emittance of these particles was in line with the SASE pulse energy measurements.

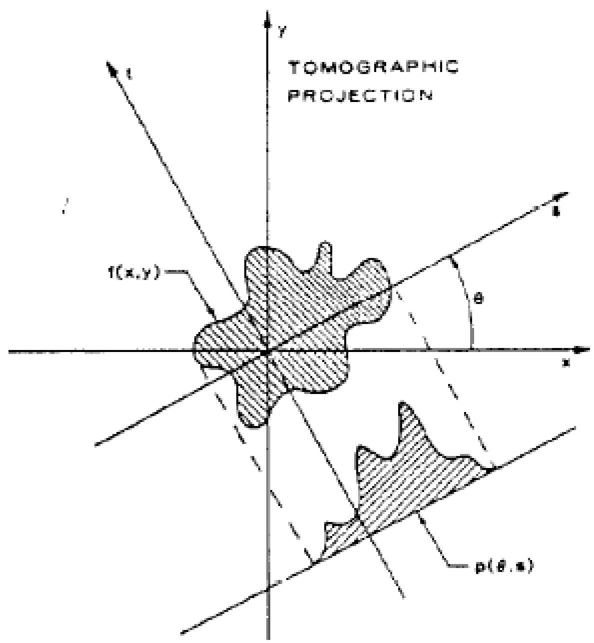


F. Löhl, DESY-THESIS 2005-014

- CSR effects led to the development of a “tail” in the horizontal phase space. This dynamics could be imaged with tomographic methods.

Phase Space Tomography

- Recovery of density functions based on projections
- For an arbitrary density function (e.g. complicated internal structure) a high number of projections is required
- Distributions with little internal structure (e.g. electron beam phase spaces) results can be improved by the maximum entropy algorithm (MENT)



SITZUNG VOM 30. APRIL 1917.

Über die Bestimmung von Funktionen durch ihre Integralwerte längs gewisser Mannigfaltigkeiten.

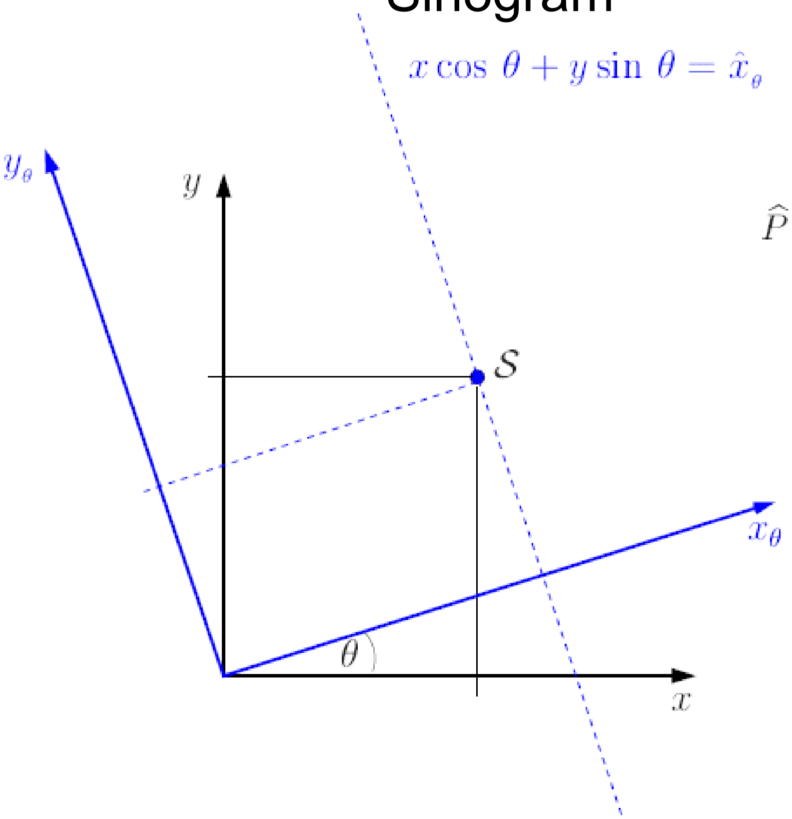
Von

Johann Radon.

Integriert man eine geeigneten Regularitätsbedingungen unterworfene Funktion zweier Veränderlichen x, y — eine *Punktfunktion* $f(P)$ in der Ebene — längs einer beliebigen Geraden g, so erhält man in den Integralwerten $F(g)$ eine *Geradenfunktion*. Das in Abschnitt A vorliegender Abhandlung gelöste Problem ist die Umkehrung dieser linearen Funktionaltransformation, d. h. es werden folgende Fragen beantwortet: kann jede, geeigneten Regularitätsbedingungen genügende Geradenfunktion auf diese Weise entstanden gedacht werden? Wenn ja, ist dann f durch F eindeutig bestimmt und wie kann es ermittelt werden?

Tomography – Radon Transform

Radon Transform:
"Sinogram"



$$P(\theta, x_\theta) = \int_{x\cos\theta + y\sin\theta = x_\theta} \rho_{\text{ini}}(x, y)\; dy_\theta$$

$$= \int_{-\infty}^{\infty} \rho_{\text{ini}}(x_\theta \cos\theta - y_\theta \sin\theta\,,\; x_\theta \sin\theta + y_\theta \cos\theta)\, dy_\theta$$

can be replaced by beam transport matrix

$$\widehat{P}(\theta, \omega) = \int_{-\infty}^{\infty} P(\theta, x_\theta)\; e^{(-2\pi i\,\omega\, x_\theta)} dx_\theta$$

$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho(x_\theta \cos\theta - y_\theta \sin\theta\,,\; x_\theta \sin\theta + y_\theta \cos\theta)\; e^{(-2\pi i\,\omega\, x_\theta)}\; dx_\theta\, dy_\theta$$

$$= \mathcal{F}(\omega\cos\theta,\; \omega\sin\theta)$$

Inverse Radon Transform:

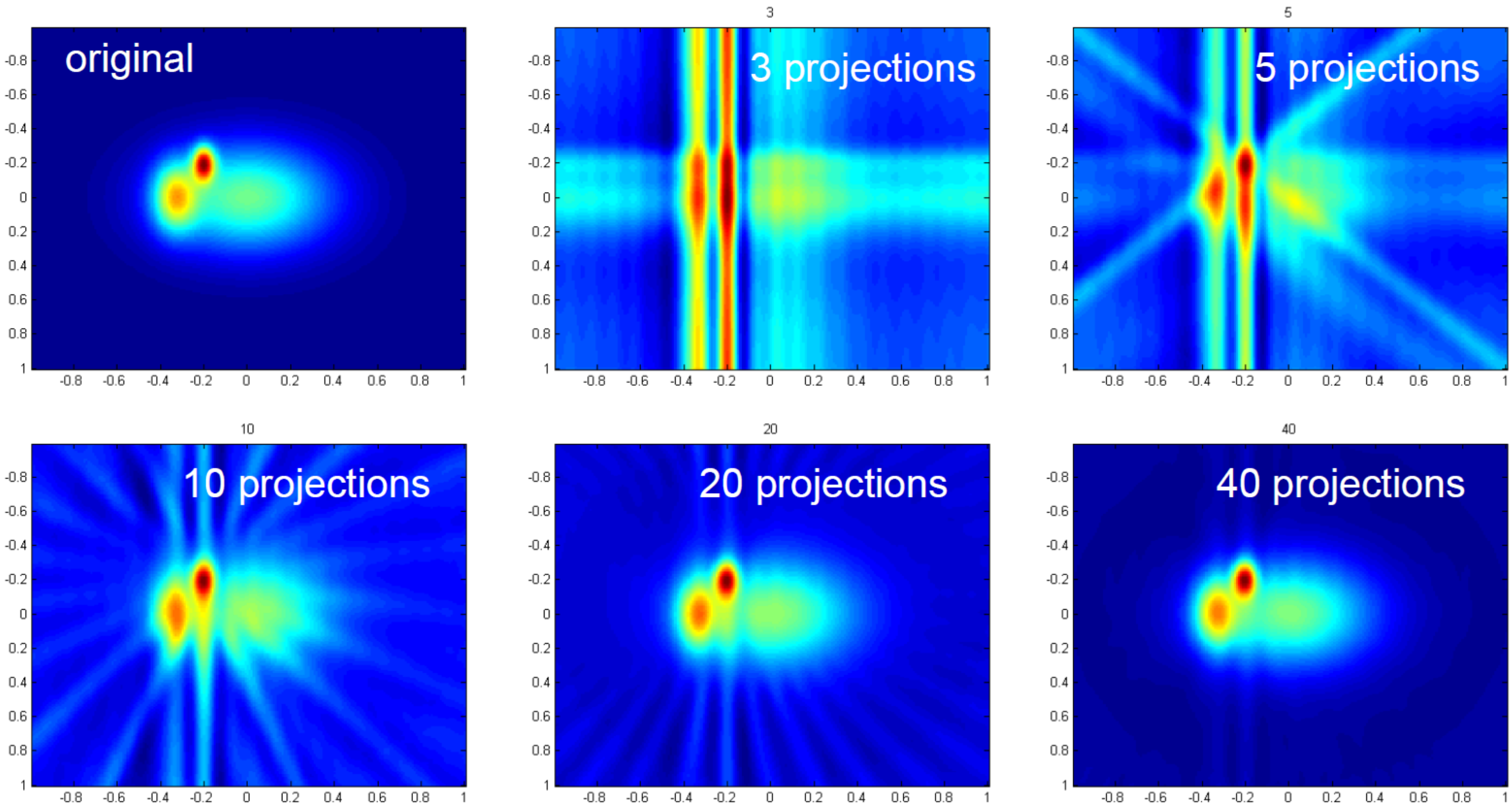
$$\rho(x, y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathcal{F}(u, v)\; e^{(+2\pi i\,(x\cdot u + y\cdot v))}\; du\, dv$$

$$= \int_{0}^{\pi}\int_{-\infty}^{\infty} \mathcal{F}(\omega\cos\theta, \omega\sin\theta)\; e^{(+2\pi i\,(x\omega\cos\theta + y\omega\sin\theta))} \begin{vmatrix} \frac{\partial u}{\partial\theta} & \frac{\partial v}{\partial\theta} \\ \frac{\partial u}{\partial\omega} & \frac{\partial v}{\partial\omega} \end{vmatrix}\, d\omega\, d\theta$$

$$= \int_{0}^{\pi}\int_{-\infty}^{\infty} \widehat{P}(\theta, \omega)\; e^{(+2\pi i\,(x\omega\cos\theta + y\omega\sin\theta))}\; \omega\; d\omega\, d\theta$$

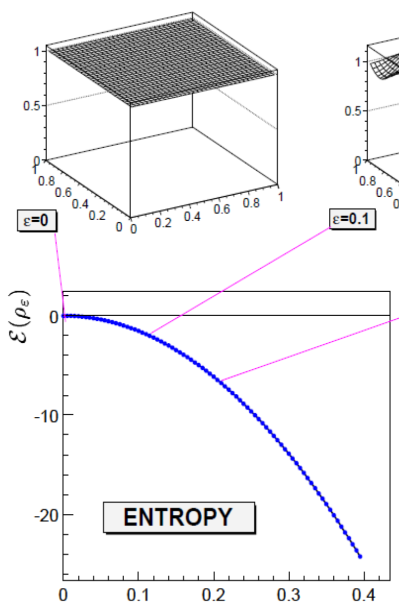
Integral 0 to 180 deg can only be approximated by finite number of projections

Reconstruction – Filtered Back-Projection



Maximum Entropy Algorithm

- Maximum entropy condition enforces minimum structure without additional boundary conditions
- Each polygon defined by the projections and the transfer matrices is assigned a constant value in an iterative procedure using a Gauss-Seidel algorithm



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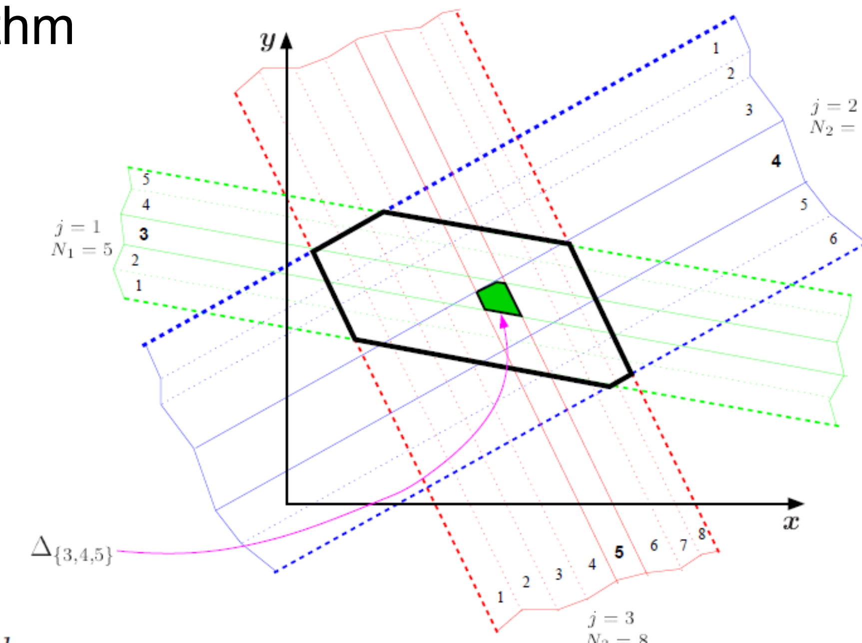
Entropy:

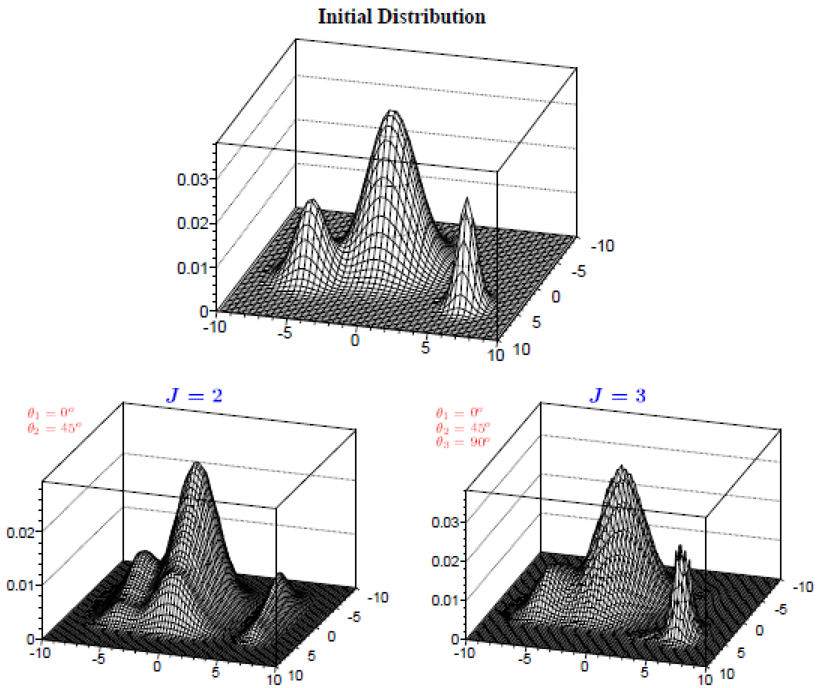
$$H = \int_D -f(x,y) \cdot ln(f(x,y))\, dx\, dy$$

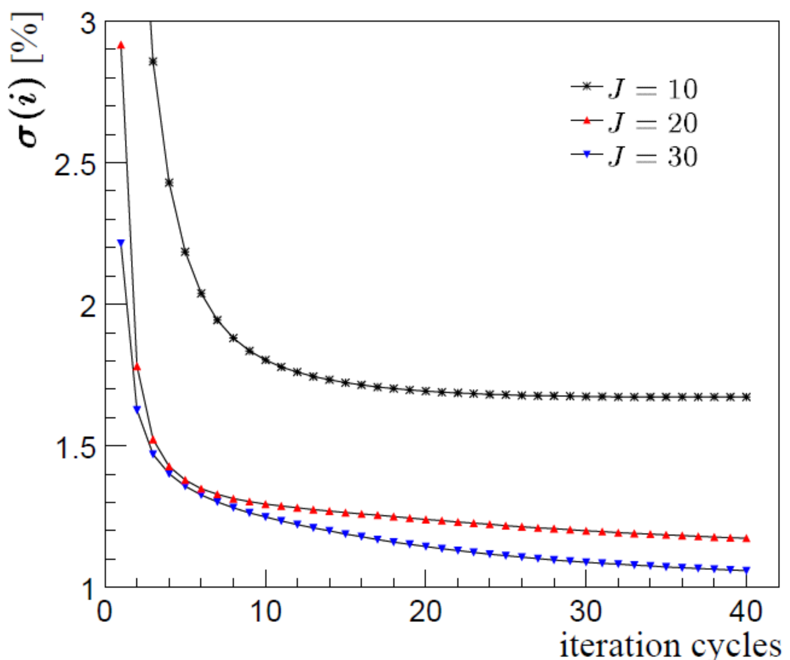


G. N. Minerbo, *MENT: A Maximum Entropy Algorithm for reconstructing a source from projection data*, Comp. Graphics Image Proc. **48** (1979).

Example – MENT on Gaussian Distributions

- MENT gives reasonable agreement for much less projections then “filtered back-projection”
- Few iterations required (typically 5 for XFEL studies)





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Thank You for Your Attention!