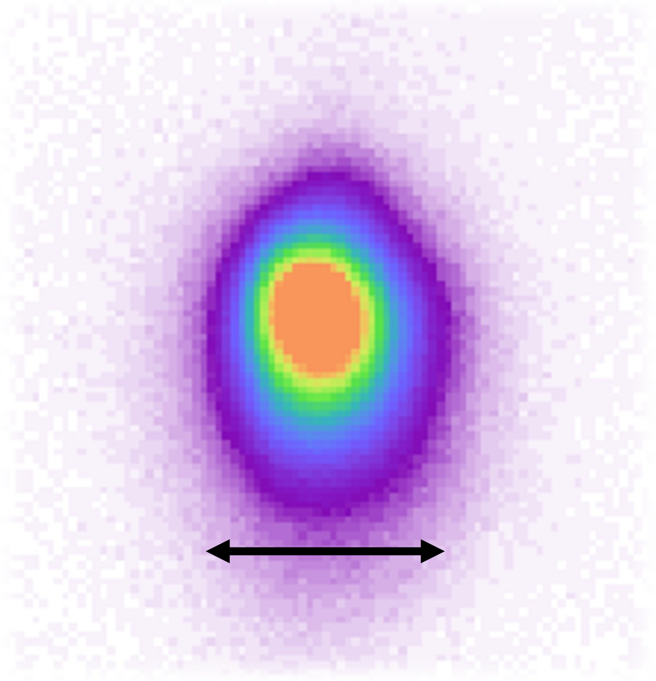
EuXFEL Operator Training
Injector beam optics measurements

Matthias Scholz
March 18, 2025

First things first

- The width of the beam (in horizontal or vertical plane) at a certain position in the beamline depends on two things: The so-called beta function at the position and the emittance.



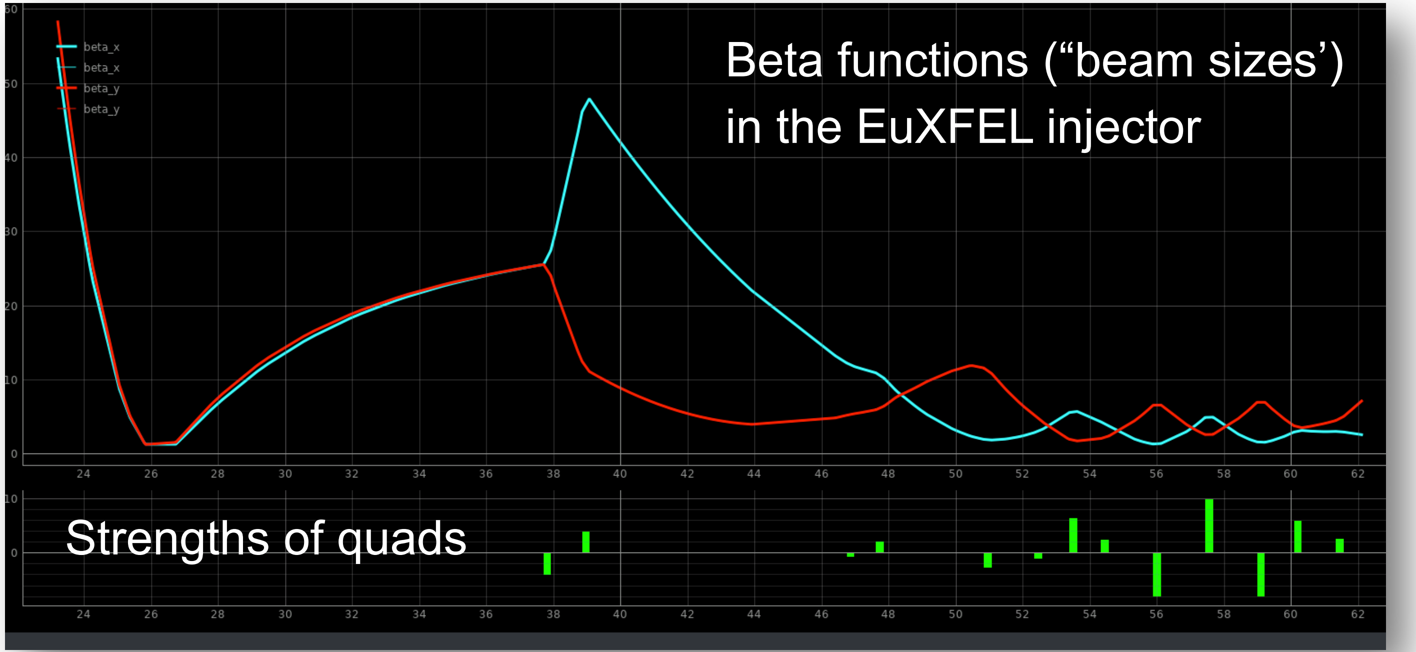
$$\sqrt{\epsilon_x \beta_x}$$

A screenshot from the camera OTRC.59.I1in the XFEL injector

First things first

- Matching means, that the actual electron beam parameters fit to the design optics of the lattice (given by the position and strength of magnets). In other words, the beam's size at different positions in the accelerator is as designed.
- The lattice is designed such that the electron beam's quality in the undulator beamlines is as good as possible for lasing.

Position of the cathode

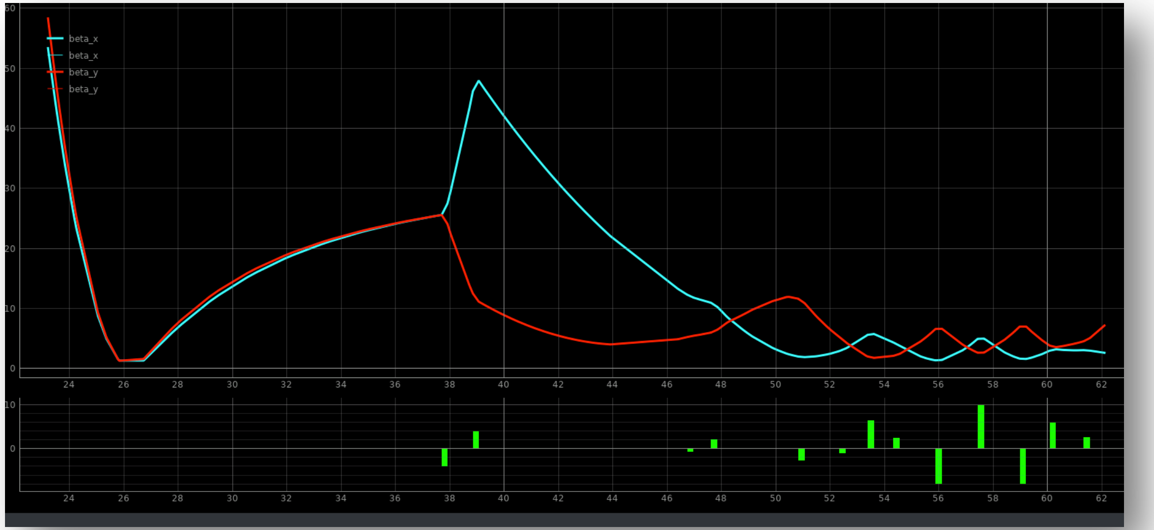


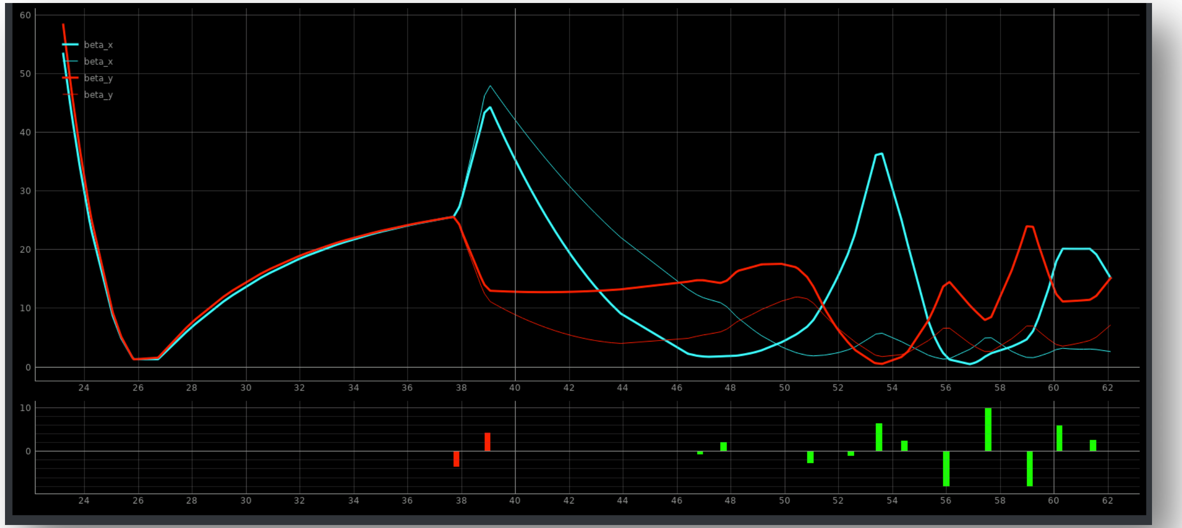
I1 matching section

First things first

- Matched and mismatched beams in I1

The beam sizes are different from what we need for successful operation

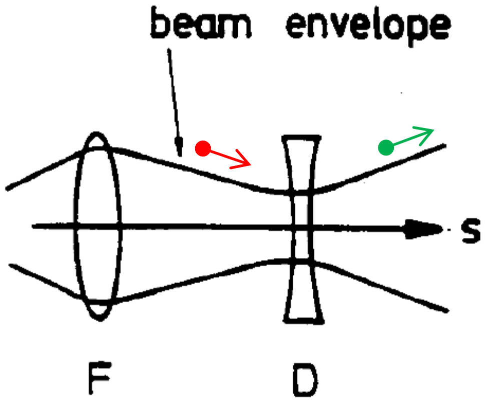


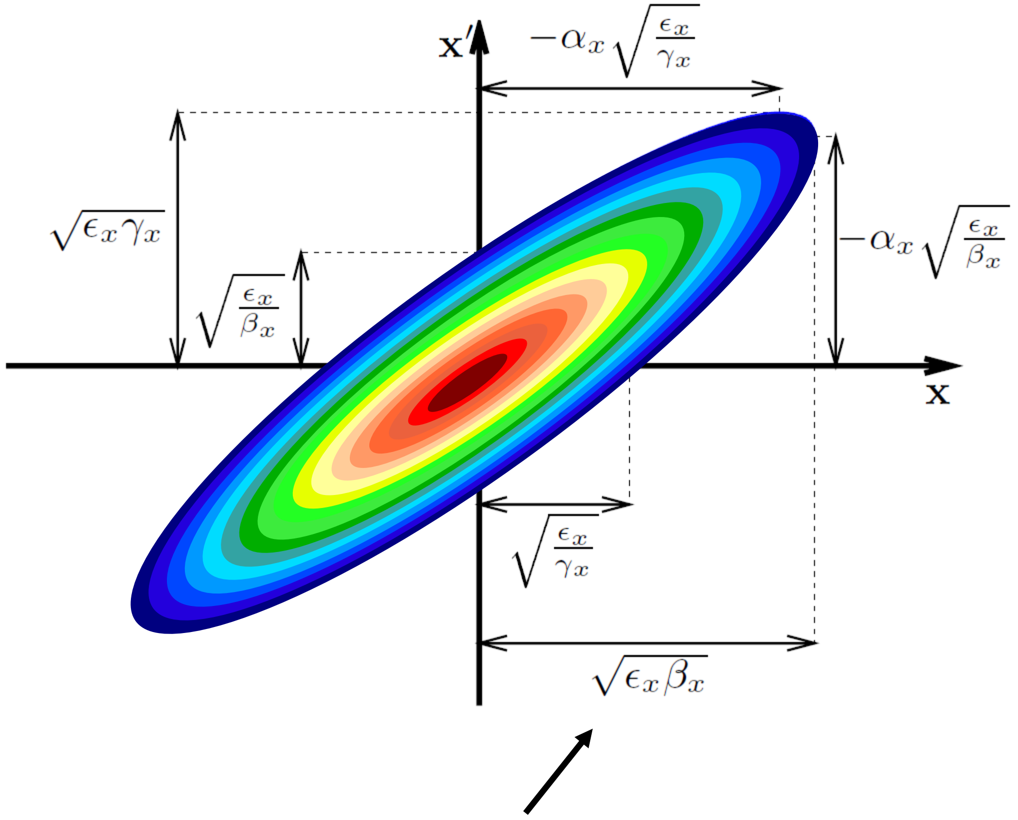


Changed the strengths of two quads in A1 and AH1

Emittance and Twiss-parameters

- The beam orientation is described with the Twiss-parameters (α, β, γ).
- The "slope" of the ellipses are a signature of convergent or divergent beams.
- A beam which does not have the same orientations (with respect to design optics) is called "mismatched" even if the emittance is the same.





This, can actually be measured (transverse beam sizes) e.g. with a screen or wire!

Emittance

- Area covered by particles in phase space is called emittance
- We can assume an elliptical distribution
- Emittance is conserved in linear optics (Liouville's theorem)
  => beam behaves like an incompressible liquid
  => focusing the beam will increase its divergence
- Small beams with little divergence as required for SASE lead to small emittance requirements.

Emittance and Twiss-parameters

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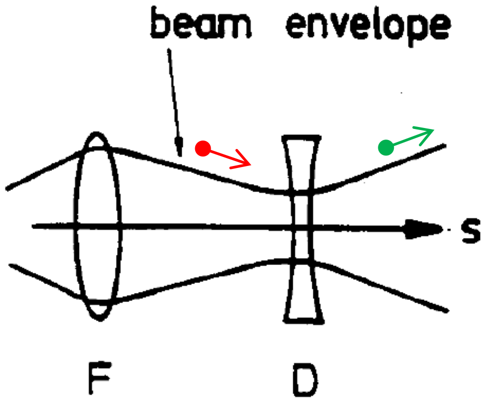
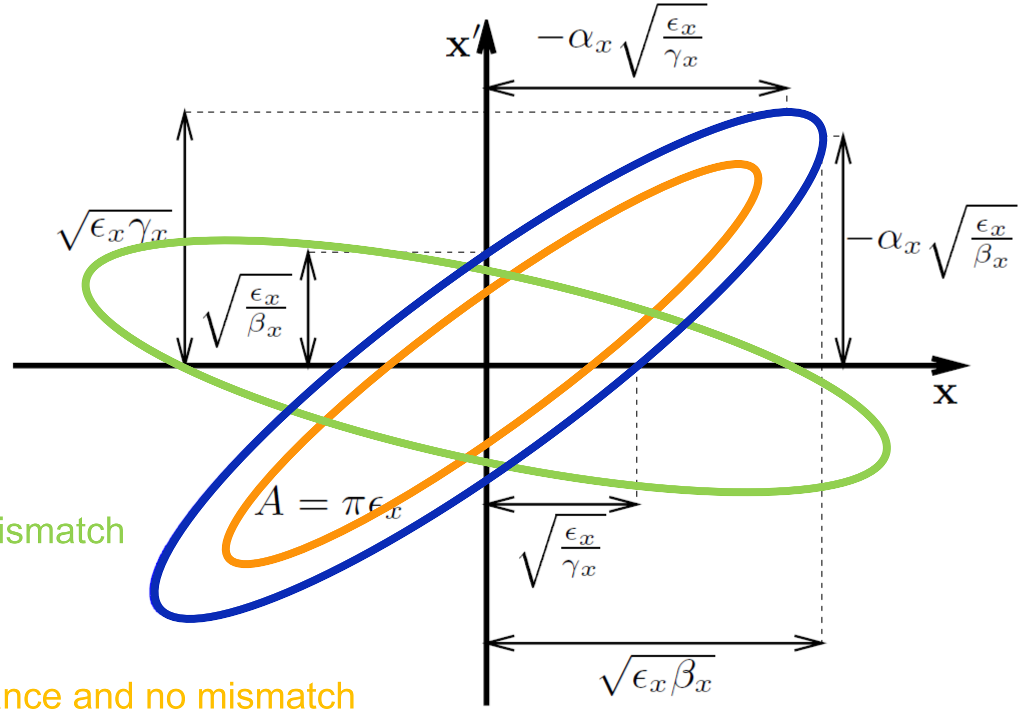
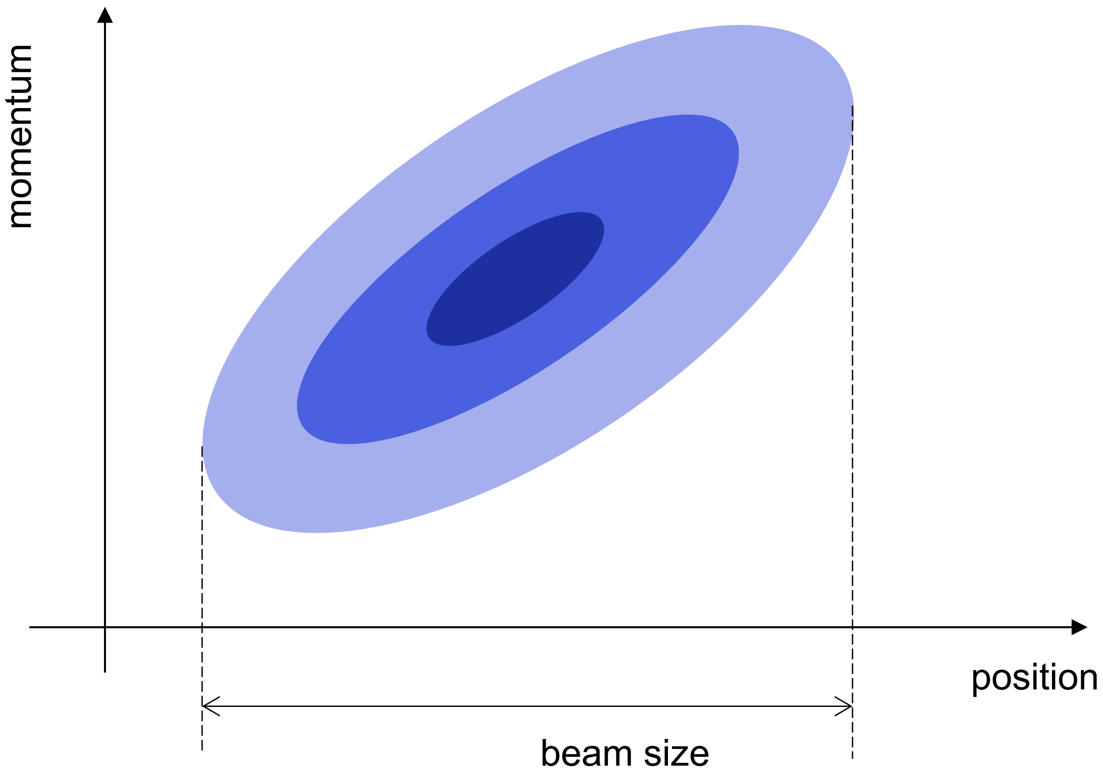




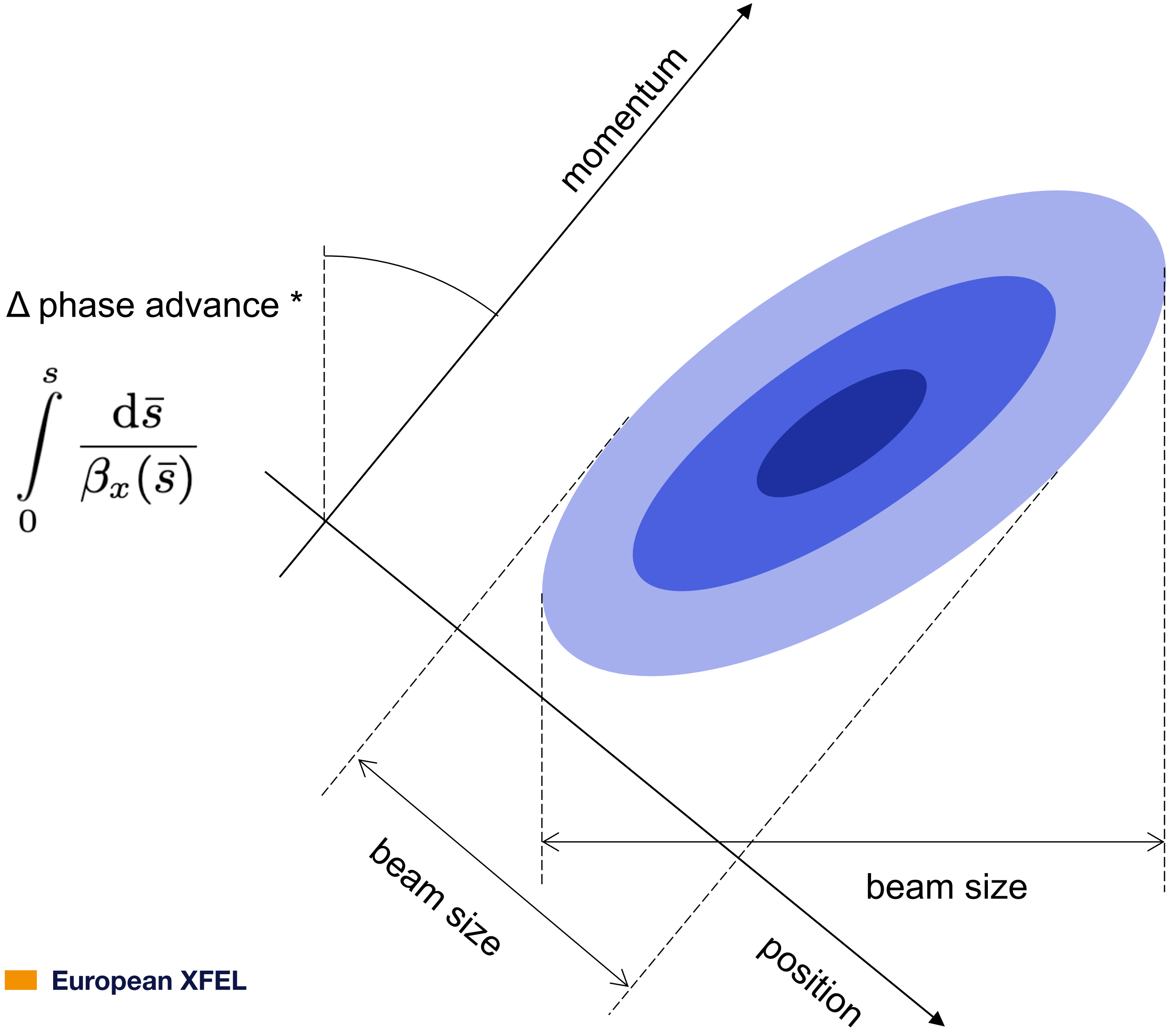
same emittance with mismatch

smaller emittance and no mismatch

Emittance and beam size measurements



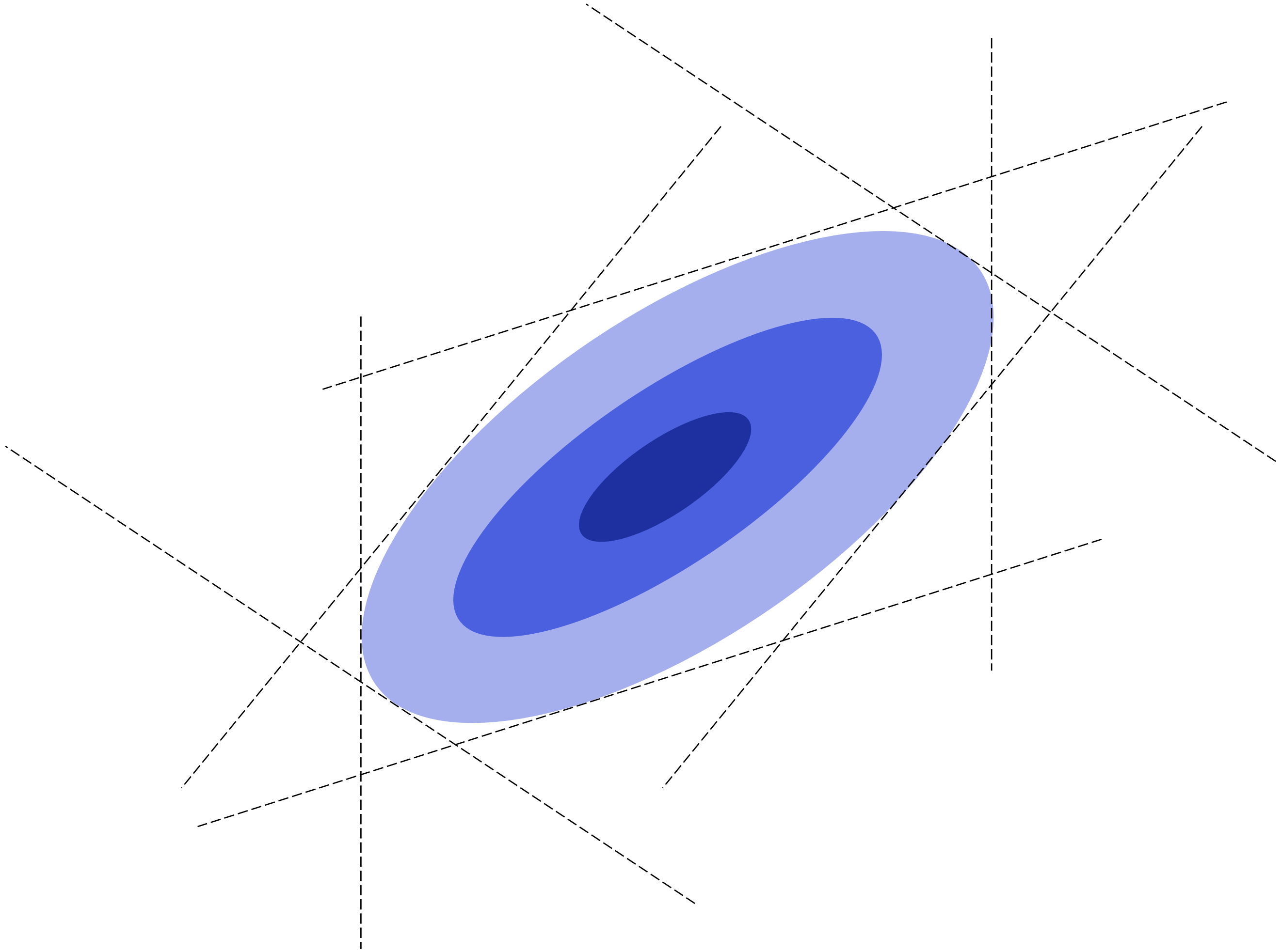
Emittance and beam size measurements



$$\psi_x(s) = \int_0^s \frac{\mathrm{d}\bar{s}}{\beta_x(\bar{s})}$$

* This is only true in the so called normalized phase space, but for simplicity's sake, let's keep it that way.

Emittance and beam size measurements



How to determine emittance and Twiss parameters

The definition of the emittance and the Twiss parameters at position 0 using the second beam moments.

$$\varepsilon_x = \sqrt{\langle x_0^2 \rangle \langle {x'_0}^2 \rangle - \langle x_0 x'_0 \rangle^2}$$

and

$$\begin{pmatrix} \beta_{x0} \\ \alpha_{x0} \\ \gamma_{x0} \end{pmatrix} = \begin{pmatrix} \langle x_0^2 \rangle / \varepsilon_x \\ -\langle x_0 x'_0 \rangle / \varepsilon_x \\ \langle {x'_0}^2 \rangle / \varepsilon_x \end{pmatrix}$$

We can only measure <X^2>, the squared rms beam size σ^2.

-> not enough…

However, we know how <X^2> is transformed from 0 to i using the transfer matrix elements R_{kl}

$$\langle x_i^2 \rangle = {R_{11}^{(i)}}^2 \langle x_0^2 \rangle + {R_{12}^{(i)}}^2 \langle {x'_0}^2 \rangle + 2 R_{11}^{(i)} R_{12}^{(i)} \langle x_0 x'_0 \rangle$$

$$+ 2 R_{11}^{(i)} R_{16}^{(i)} \langle x_0 \delta_0 \rangle + 2 R_{12}^{(i)} R_{16}^{(i)} \langle x'_0 \delta_0 \rangle + {R_{16}^{(i)}}^2 \langle \delta_0^2 \rangle$$

We do the measurements in section with no bending magnets and assume that the transfer matrix elements R_{16} and R_{26} are zero.

How to determine emittance and Twiss parameters

The definition of the emittance and the Twiss parameters at position 0 using the second beam moments.

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

and

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

We can only measure <X²>, the squared rms beam size $\boldsymbol{\sigma}^2$.

-> not enough…

However, we know how <X²> is transformed from 0 to $\boldsymbol{i}$ using the transfer matrix elements R_{kl}

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

can be measured

three unknowns

Transfer matrix elements -> well known

Calculation of beam moments

Lets make 3 measurements with different transfer matrices!

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

can be measured

Transfer matrix elements -> well known

three unknowns and 3 equations

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

Done. All 3 required beam moments can be calculated.

Fit of beam moments

- Calculating the beam moments with 3 measurements does not result in any error estimations!
- -> Preferably more than 3 measurements should be made.
- The beam moments can be determined by a least square fit:

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

minimize

known (orange and blue circles)

fit parameters (green circles)

Measurements of the Transverse Emittance at the VUV-FEL

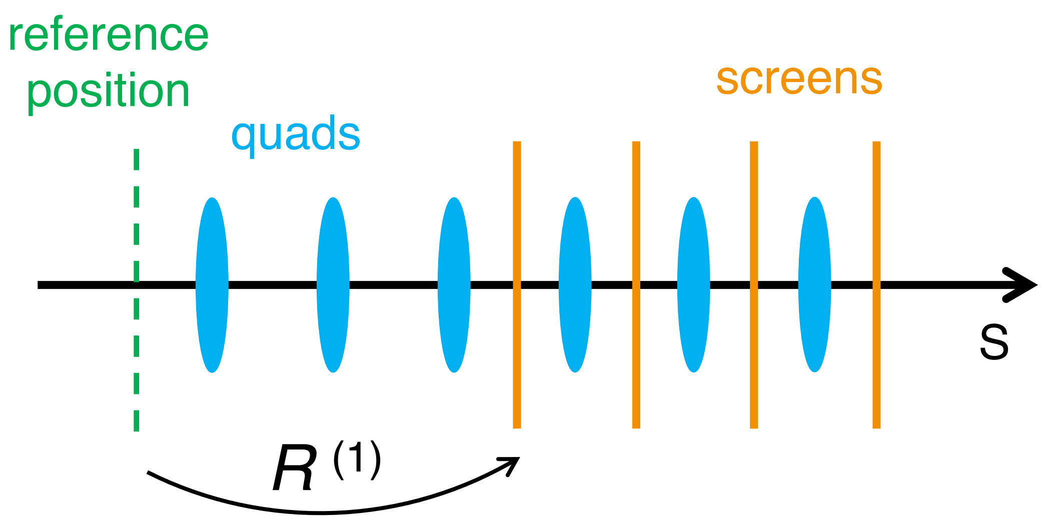
Diploma Thesis
by
Florian Löhl

submitted to the
Department of Physics of the University of Hamburg

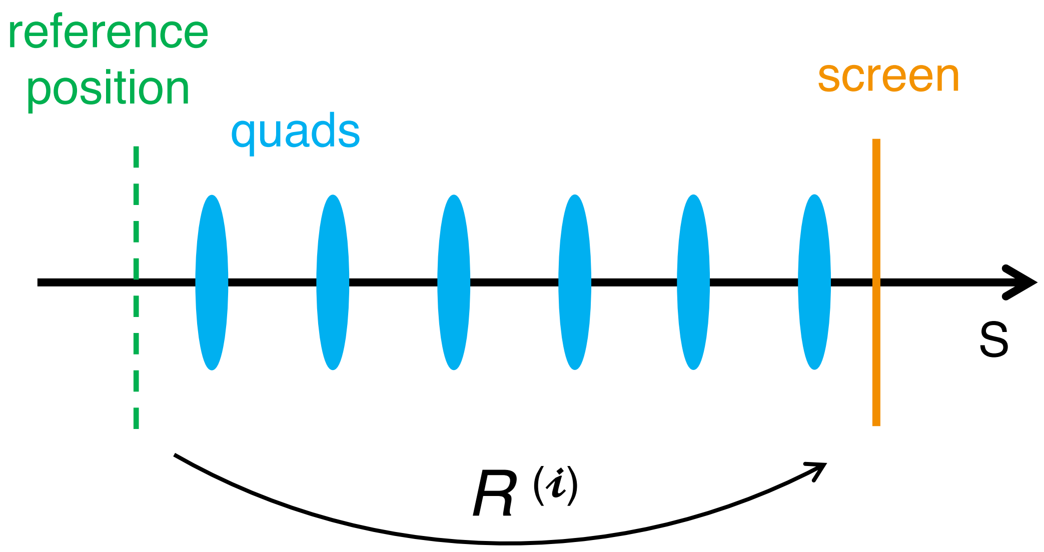
Measurement methods

How to make at least 3 different measurements with different transfer matrices between a reference position and the measurement position.

4 screen method

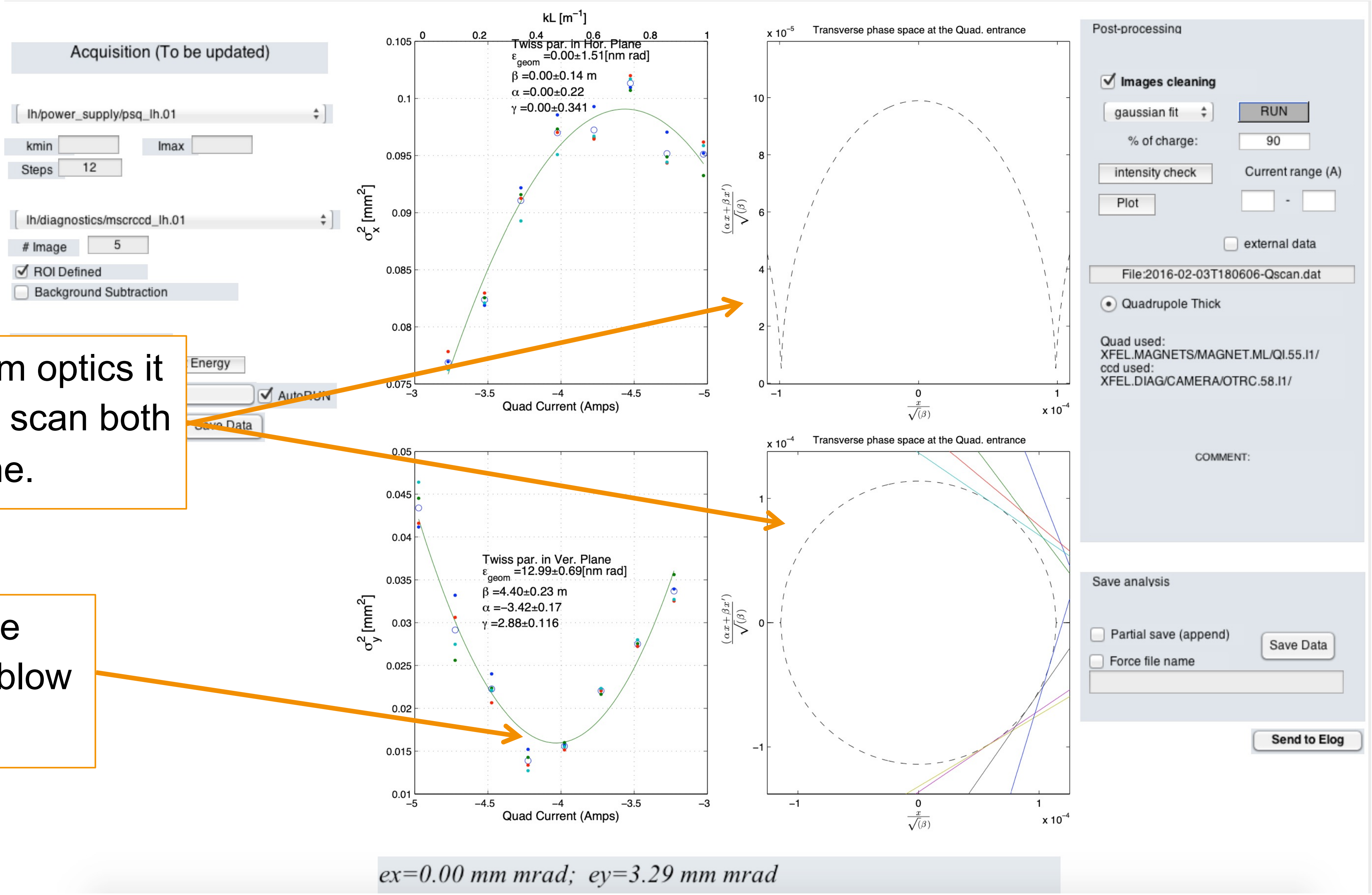


quad scan



Different transfer matrix due to $i = 1,\ldots,N$ quad settings

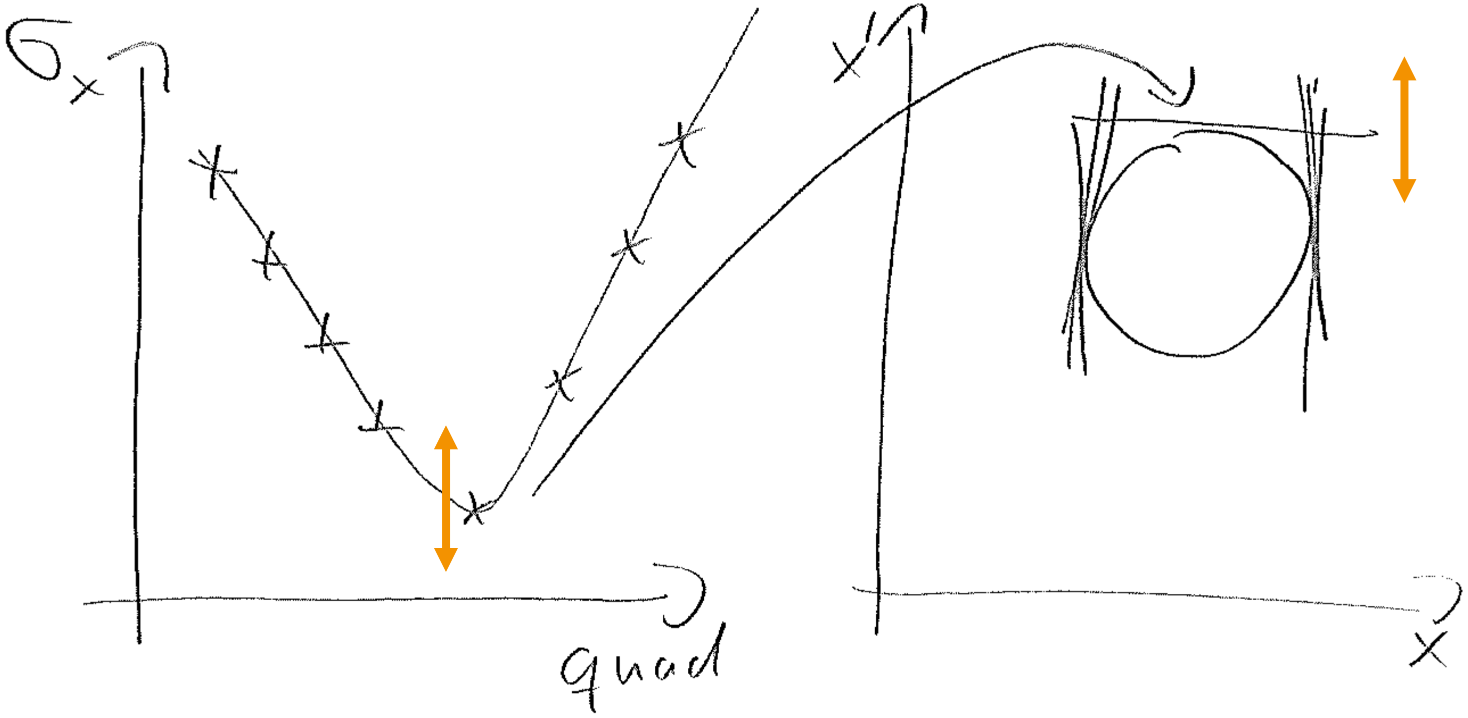
Single quad scan



Depending on the beam optics it is often not possible to scan both planes at the same time.

A very small beam size in the injector can lead to a beam blow up due to space charge.

Single quad scan and scan step sizes



- If equally large steps are selected for the magnetic strength, this can potentially lead to doubtful measurement results.
- The measurement result of the emittance in the example on the right hand side is absolutely dominated the one measurement taken in the beam waist.

Many thanks to Bolko for the nice and explanatory drawing ☺

Multi quad scans

- Using more than one quadrupole has the advantage that:
  - The beam size at the screen can be kept constant for all measurement steps. No small beams are necessary that might be blown up by space charge.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17,** 052801 (2014)

Four-dimensional transverse beam matrix measurement using the multiple-quadrupole scan technique

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(Received 10 July 2013; published 19 May 2014)

Accurate measurements of the transverse beam properties are essential to understand and optimize particle beams. We present an optimized method that uses three quadrupole magnets and one profile monitor to measure the full 4D transverse matrix of the beam. The method has been applied to the SwissFEL Injector Test Facility (SITF) at the Paul Scherrer Institute (Villigen). The SITF is the principal test bed and demonstration plant for the SwissFEL project, which aims at realizing a hard-x-ray free-electron laser in 2017. Simulations, measurements, and results of cross-plane coupling correction are presented.

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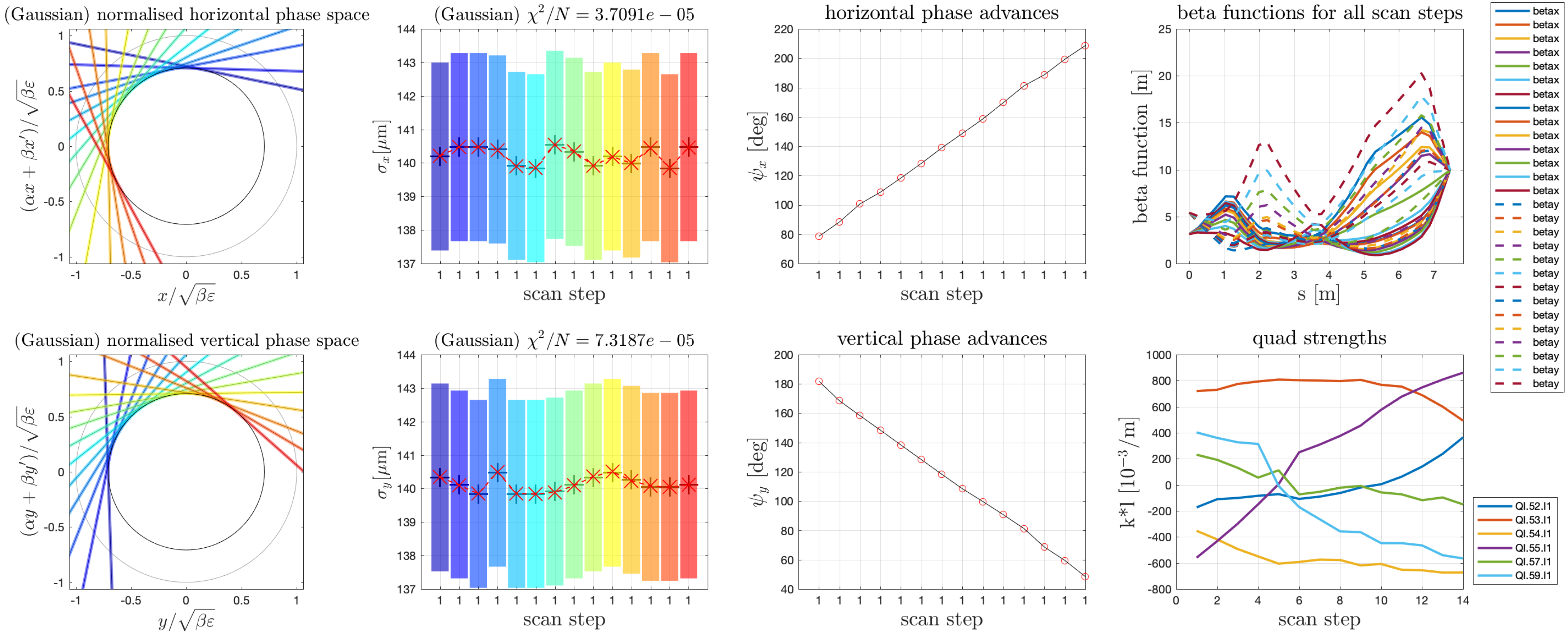
I. INTRODUCTION

Precise knowledge of the transverse beam parameters is essential in all types of charged particle accelerators. In this study we focus on the transverse properties of the electron

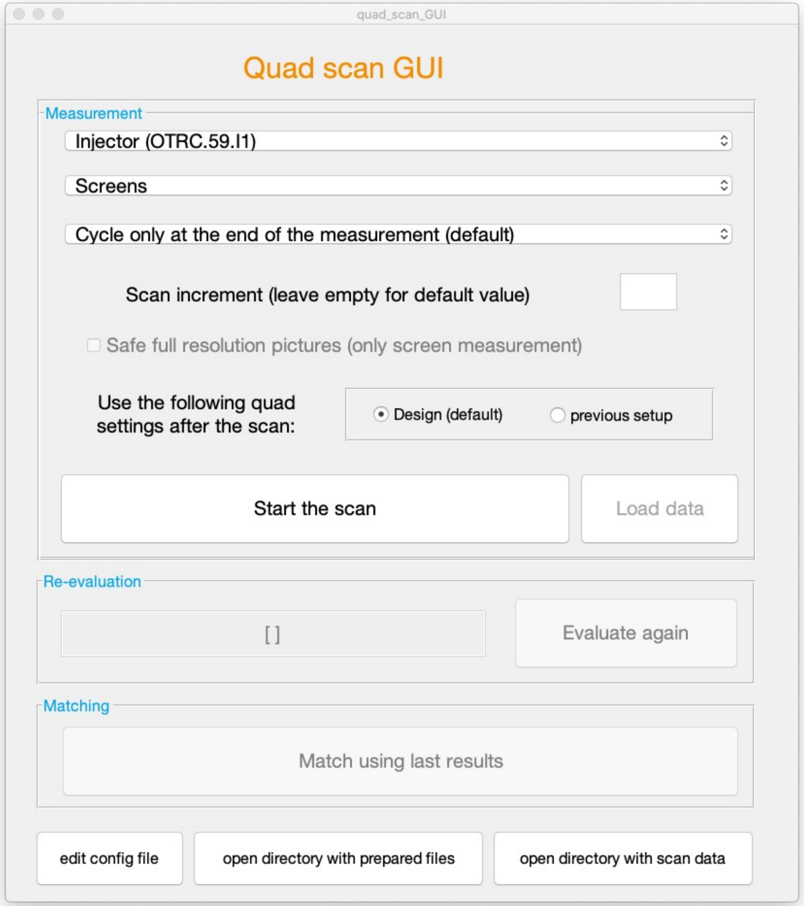
beam parameters (beam sizes and coupling correlation) are measured at a single position and quadrupole strengths are changed to generate the required optics for the 4D measurement. Four-dimensional measurements by means

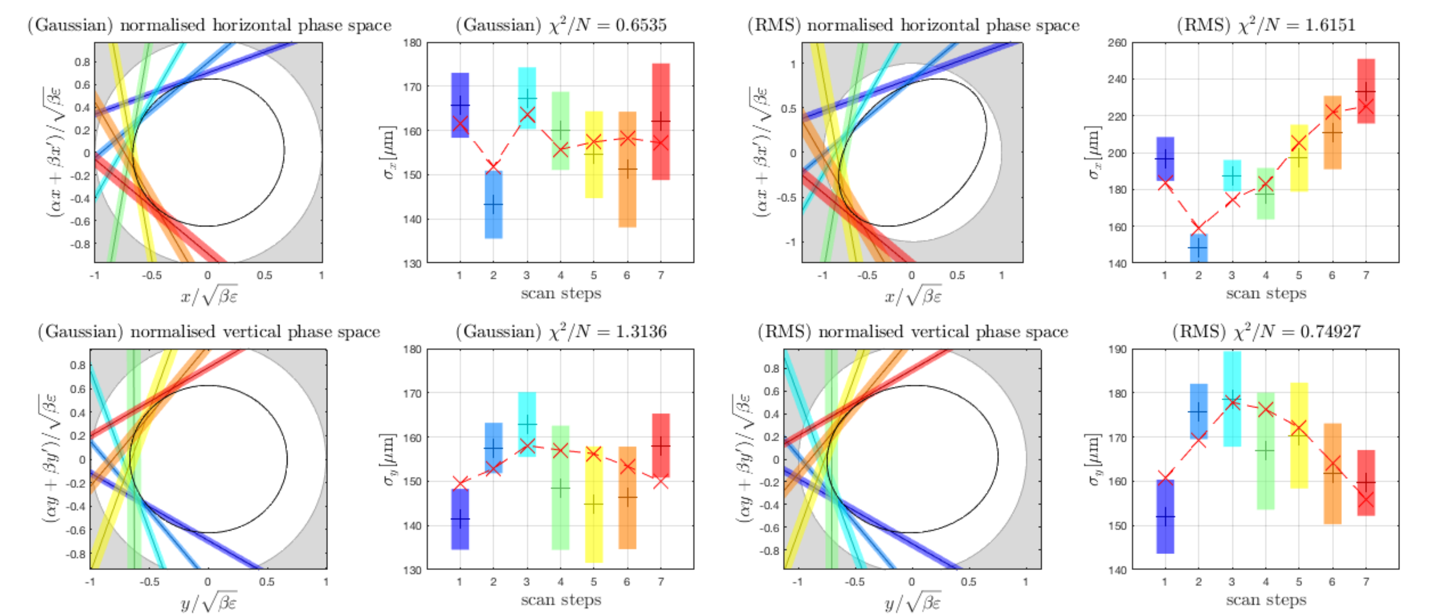
- Both transverse planes can be scanned over a wide range in the same measurement (advantage over most single quad scans).
- Many measurement steps are possible thus measurement errors in single measurements can be found and neglected (advantage over multi-screen method).

Prepared quad scan for the EuXFEL injector



Optics matching in the injector using screen stations and multi knob quad scans





ε_x	BMAG $_x$	α_x	$\alpha_{x,design}$	β_x	$\beta_{x,design}$
4.3273e-07	1.0427	0.1518	0.1770	1.9437	1.8880

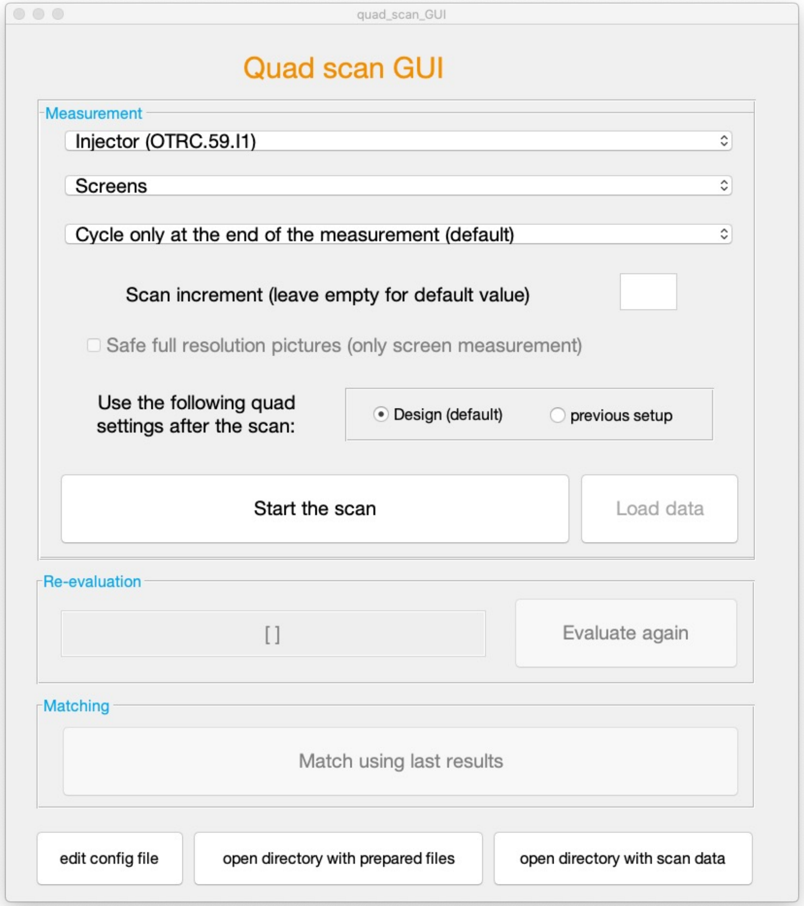
ε_y	BMAG $_y$	α_y	$\alpha_{y,design}$	β_y	$\beta_{y,design}$
4.1945e-07	1.0683	1.3346	1.2450	19.3076	18.0760

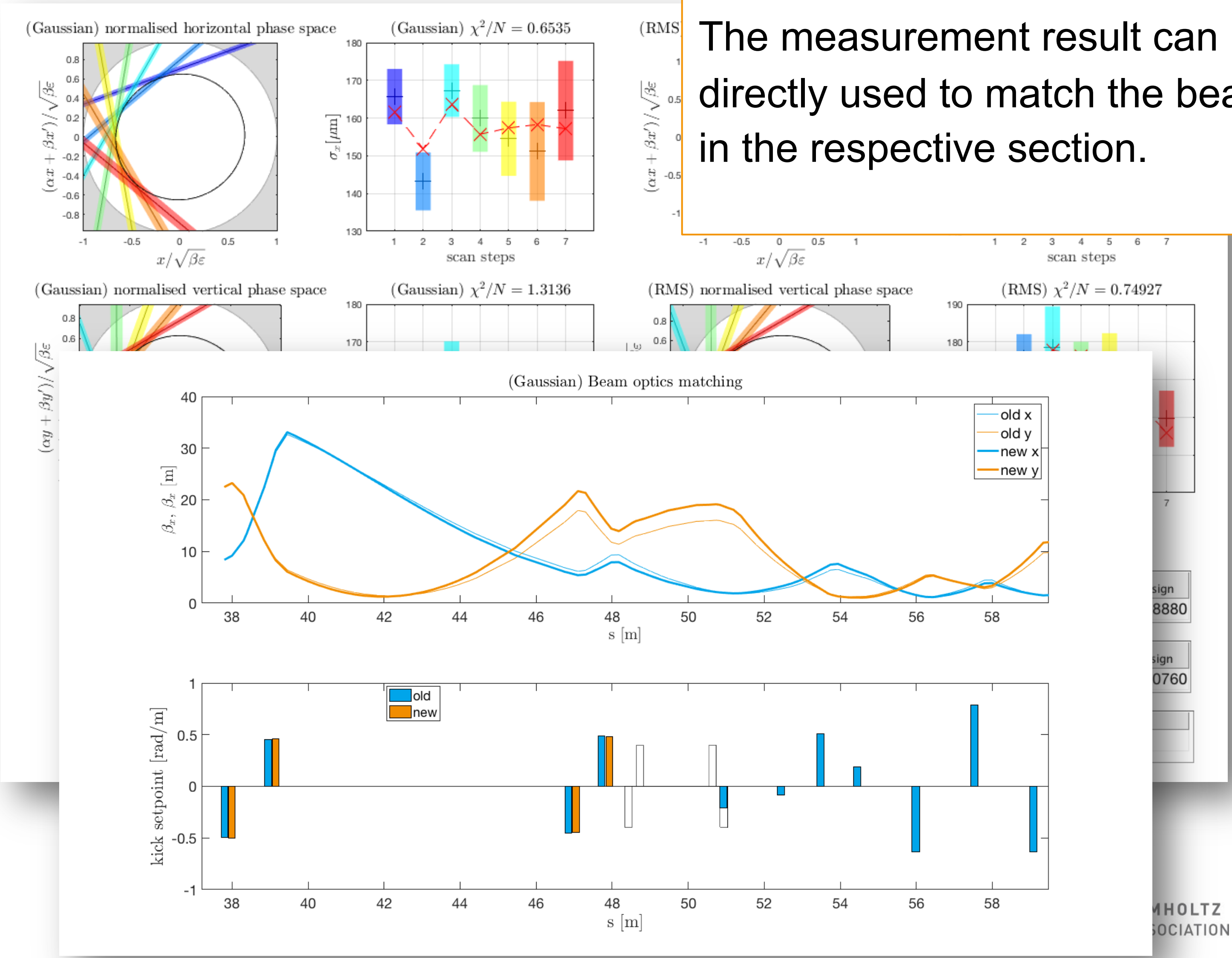
ε_x	BMAG $_x$	α_x	$\alpha_{x,design}$	β_x	$\beta_{x,design}$
6.4468e-07	1.4183	-0.1684	0.1770	2.0079	1.8880

ε_y	BMAG $_y$	α_y	$\alpha_{y,design}$	β_y	$\beta_{y,design}$
4.8571e-07	1.1654	1.4149	1.2450	21.0053	18.0760

I_SOLA [A]	I_SOLB [A]	Gun gradfient [MV]	Gun phase [deg]	bunch charge [nC]	Beam energy [GeV]	Reference point	Screen
25	350	56.9000	-38.4000	0.2500	130	QI.50.I1.U	OTRC.59.I1

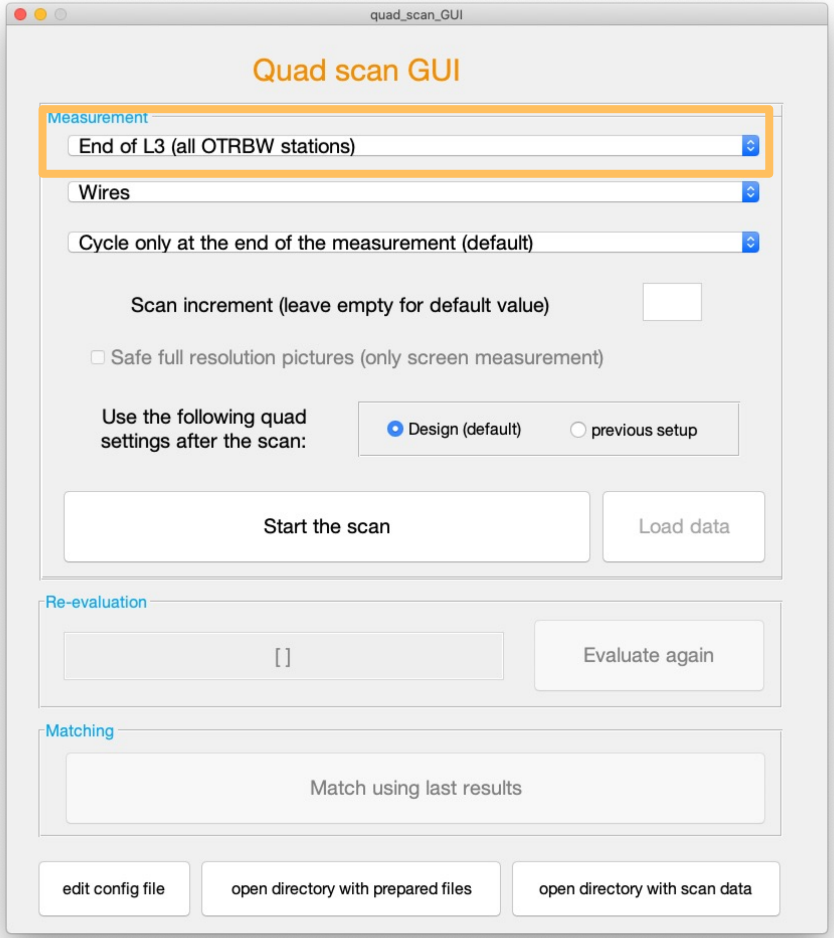
Optics matching in the injector using screen stations

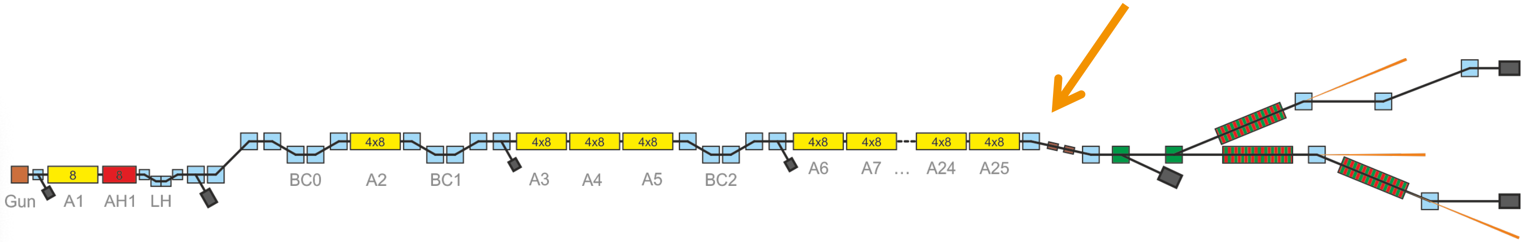




The measurement result can be directly used to match the beam in the respective section.

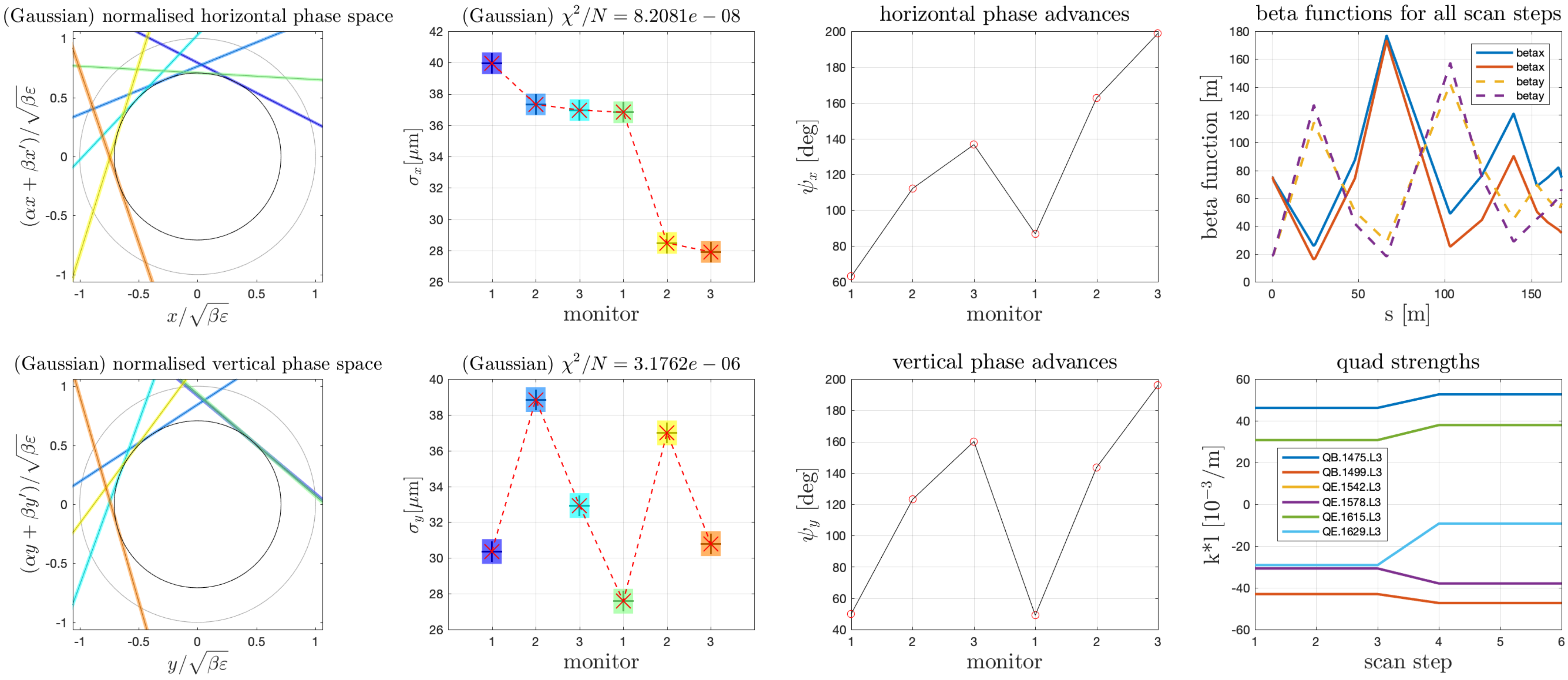
Beam optics measurements downstream L3





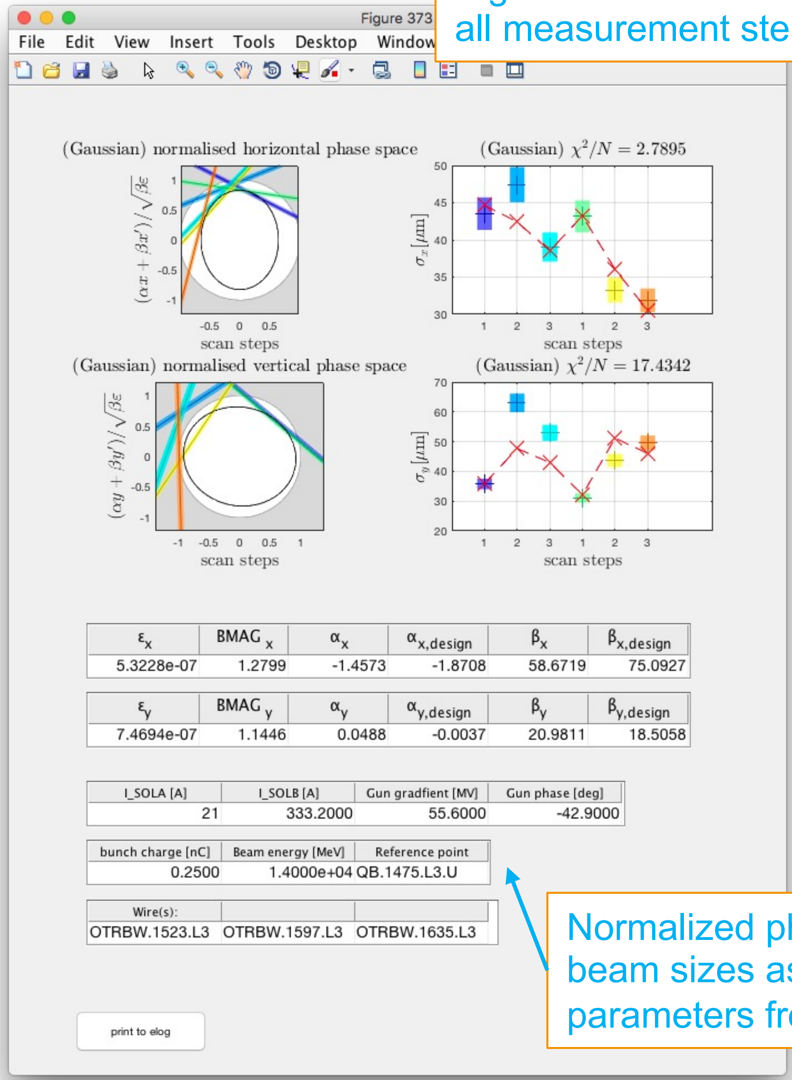
- Final beam optics measurements and corrections at the end of the main linac.
- This measurement can be carried out using either screens or wire scanners.
- It ensures, inter alia, an effective collimation in the following section.

Prepared quad scan for L3



Measurement results for quad scans with wires

Signals from all wires and for all measurement steps



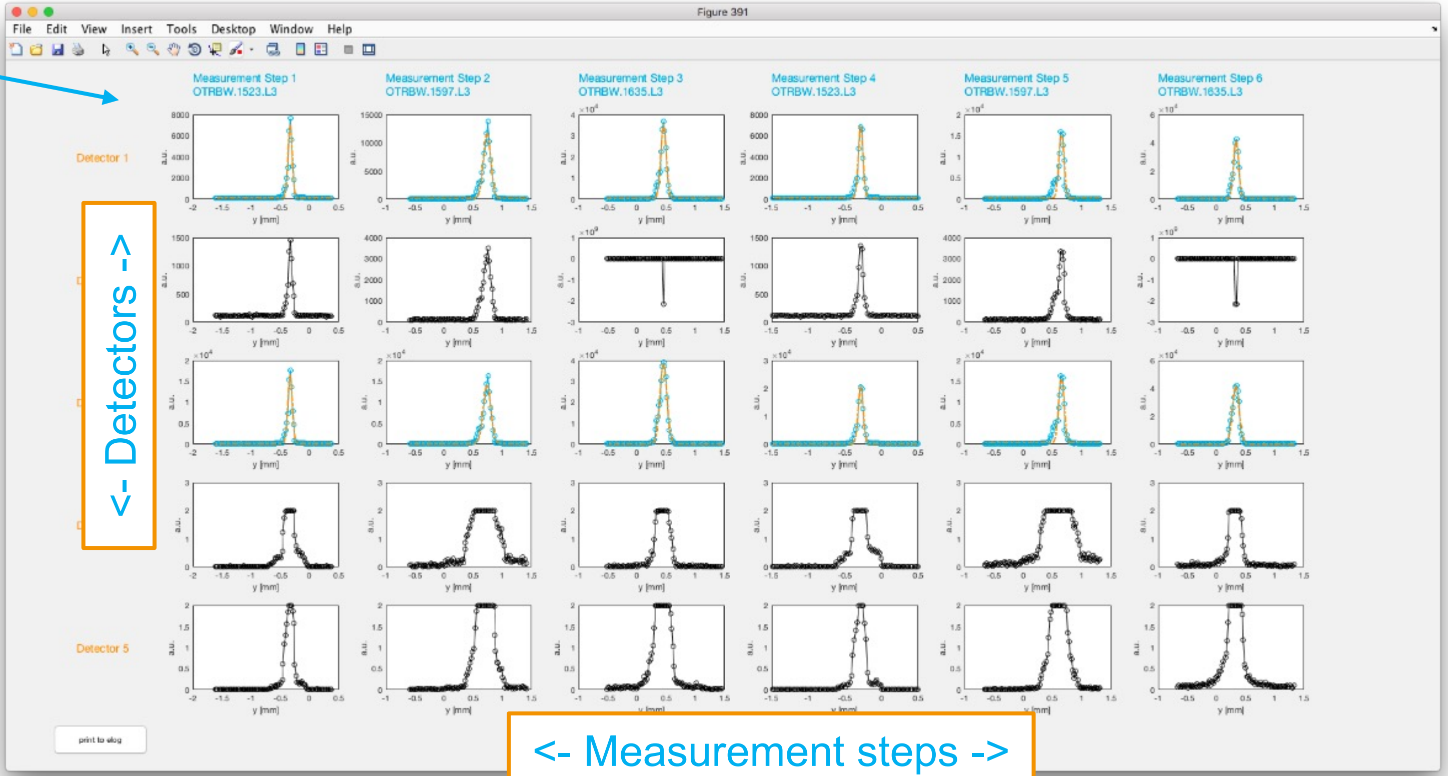
ε_x	BMAG $_x$	α_x	$\alpha_{x,design}$	β_x	$\beta_{x,design}$
5.3228e-07	1.2799	-1.4573	-1.8708	58.6719	75.0927

ε_y	BMAG $_y$	α_y	$\alpha_{y,design}$	β_y	$\beta_{y,design}$
7.4694e-07	1.1446	0.0488	-0.0037	20.9811	18.5058

I_SOLA [A]	I_SOLB [A]	Gun gradfient [MV]	Gun phase [deg]
21	333.2000	55.6000	-42.9000

bunch charge [nC]	Beam energy [MeV]	Reference point
0.2500	1.4000e+04	QB.1475.L3.U

Wire(s):		
OTRBW.1523.L3	OTRBW.1597.L3	OTRBW.1635.L3



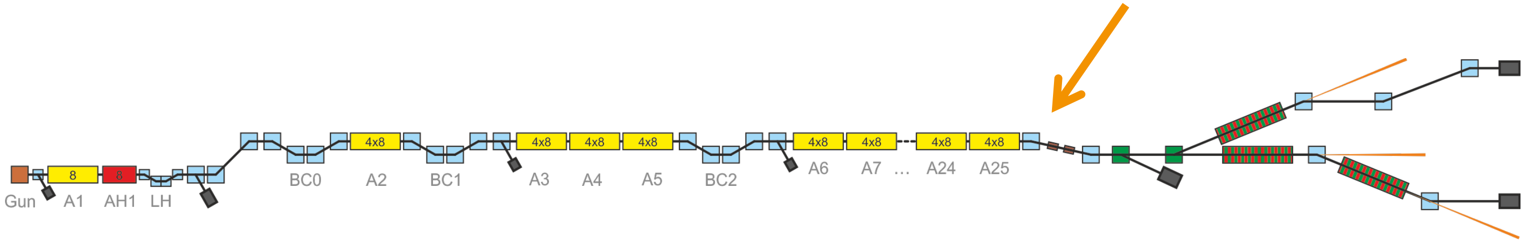
<- Detectors ->

<- Measurement steps ->

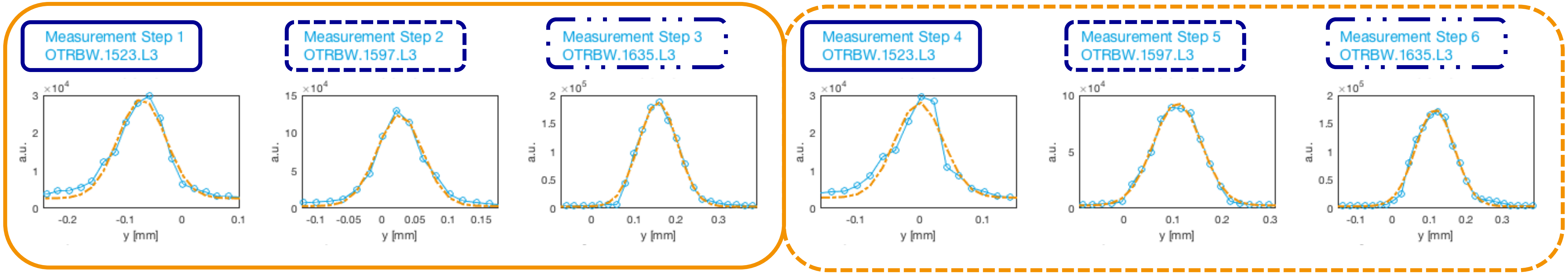
Normalized phase spaces and beam sizes as well crucial scan parameters from the measurement.

- Blue intensity traces indicate that the data from the respective detector is used for the evaluation.
- Thus, saturated signals should be presented in black, which means they are not considered in the evaluation.
- The upper plot is shown twice, one plot for each plane.

Beam optics measurements downstream L3



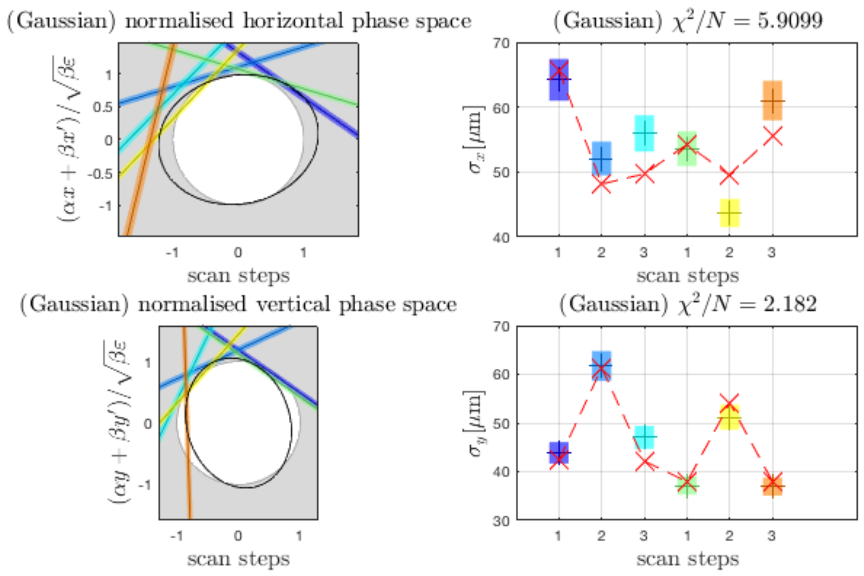
Electron beam profiles



A quadrupole scan using :

- Two different beam optics
- Three different wire scanners (or screen stations)

Optics matching in L3



ε_x	BMAG $_x$	α_x	$\alpha_{x,design}$	β_x	$\beta_{x,design}$
1.2071e-06	1.2549	-2.7815	-2.1766	101.1636	81.8567

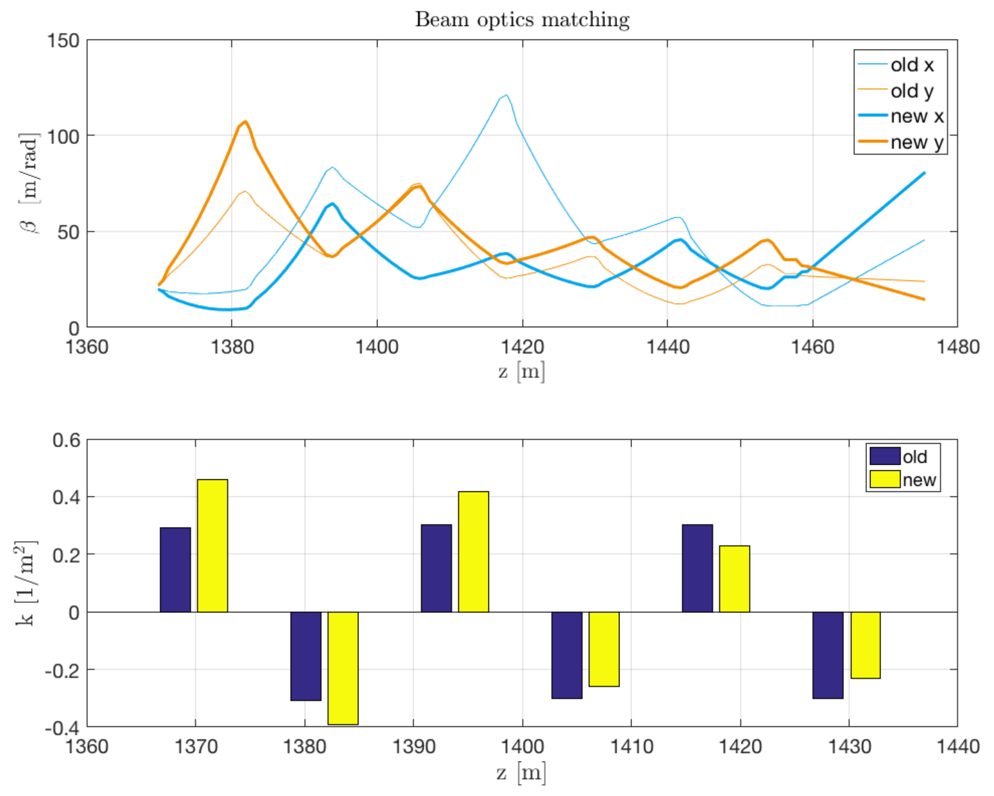
ε_y	BMAG $_y$	α_y	$\alpha_{y,design}$	β_y	$\beta_{y,design}$
8.9710e-07	1.2806	0.1023	-0.0437	11.9247	14.4968

I_SOLA [A]	I_SOLB [A]	Gun gradfient [MV]	Gun phase [deg]
25.4000	349	56.9000	-39

bunch charge [nC]	Beam energy [MeV]	Reference point
0.2500	1.4001e+04	QB.1475.L3.U

Wire(s):		
OTRBW.1523.L3	OTRBW.1597.L3	OTRBW.1635.L3

- The beam optics measurement presentation is the same as for the screen measurements.
- The measurement result can used to match the beam in L3.



Tools Advertising

Multi quad scan GUI

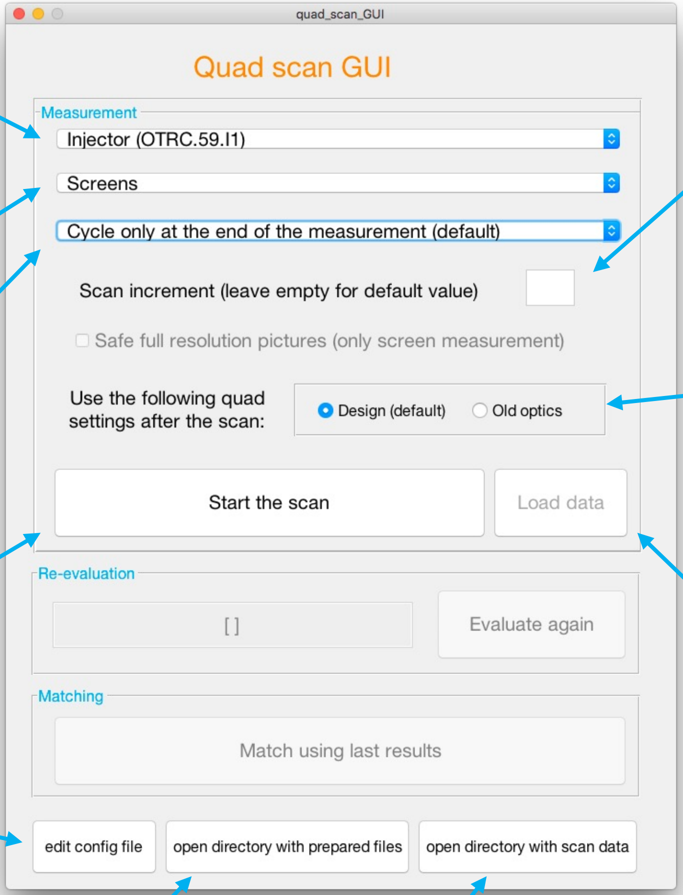
Select a beamline section

Select the measurement device: Screens or wires? The default device is automatically set for each beamline section.

Select the preferred cycling procedure.

Start the scan

It is necessary to change matching quads, wire scan detectors or something else? Press ‘edit config file’.



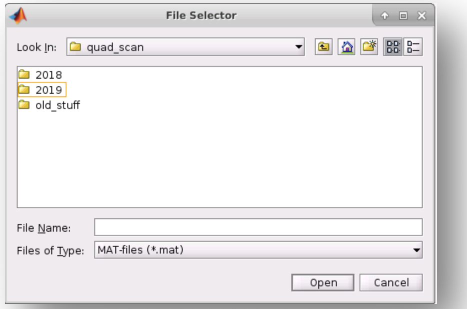
Access to the prepared quad scan files.

Access to all quad scan measurement data.

Increment: only every nth step of the measurement will be taken.

Chose beam optics after measurement: either design values or beam optics used before the measurement.

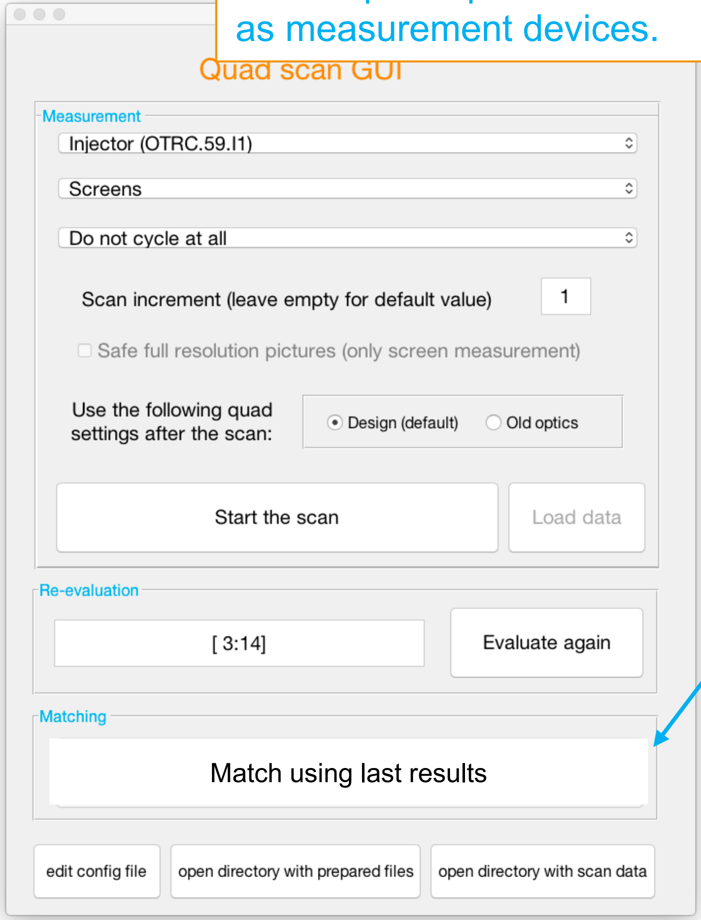
New button: load and plot old measurements. Opens a file selector GUI.

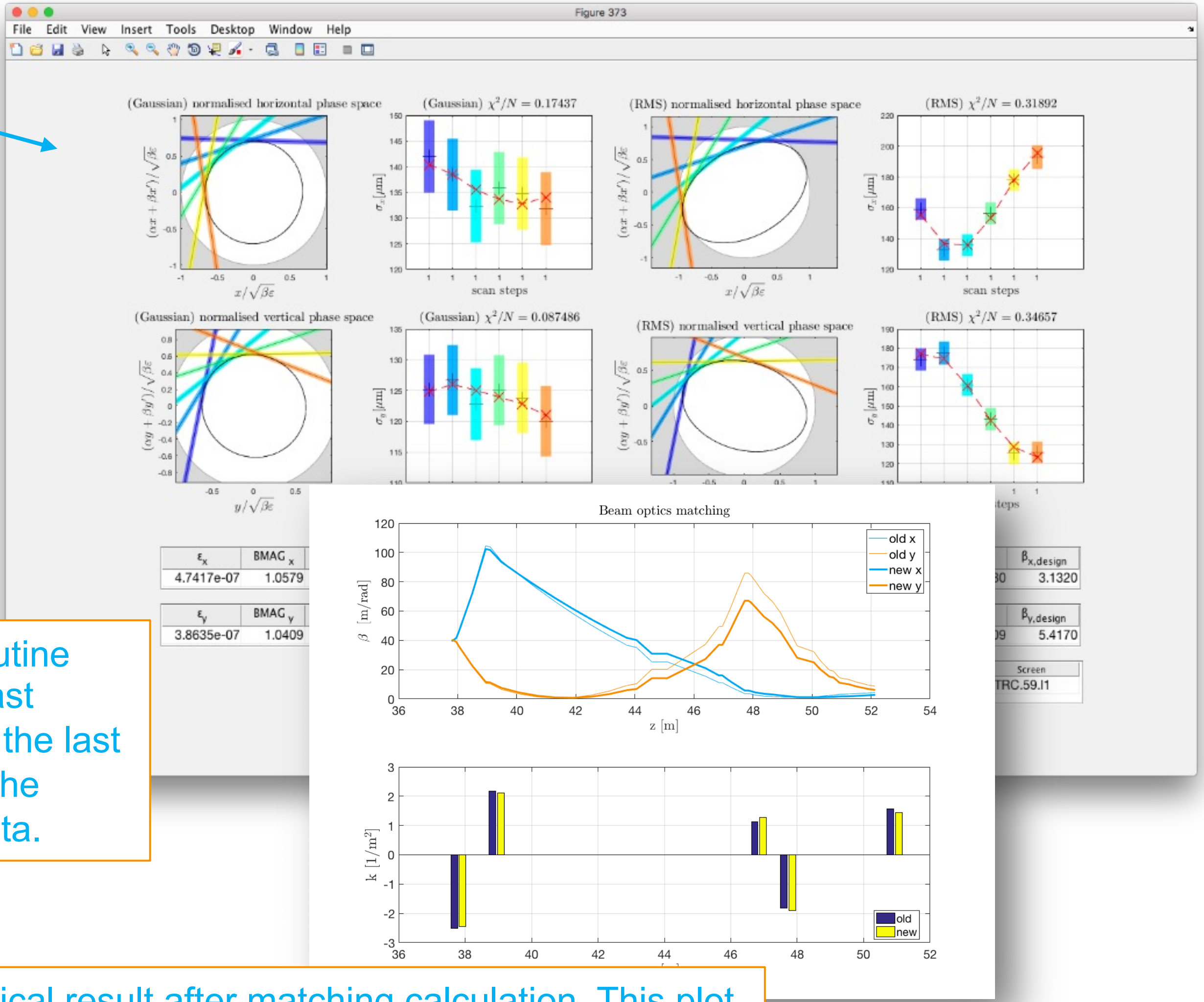


Measurement results for quad scans with screens

Tools Advertising

Well know measurement presentation after a quadrupole scan using screen as measurement devices.





The matching routine uses either the last measurement or the last re-evaluation of the measurement data.

Typical result after matching calculation. This plot is only shown if the algorithm found a solution.

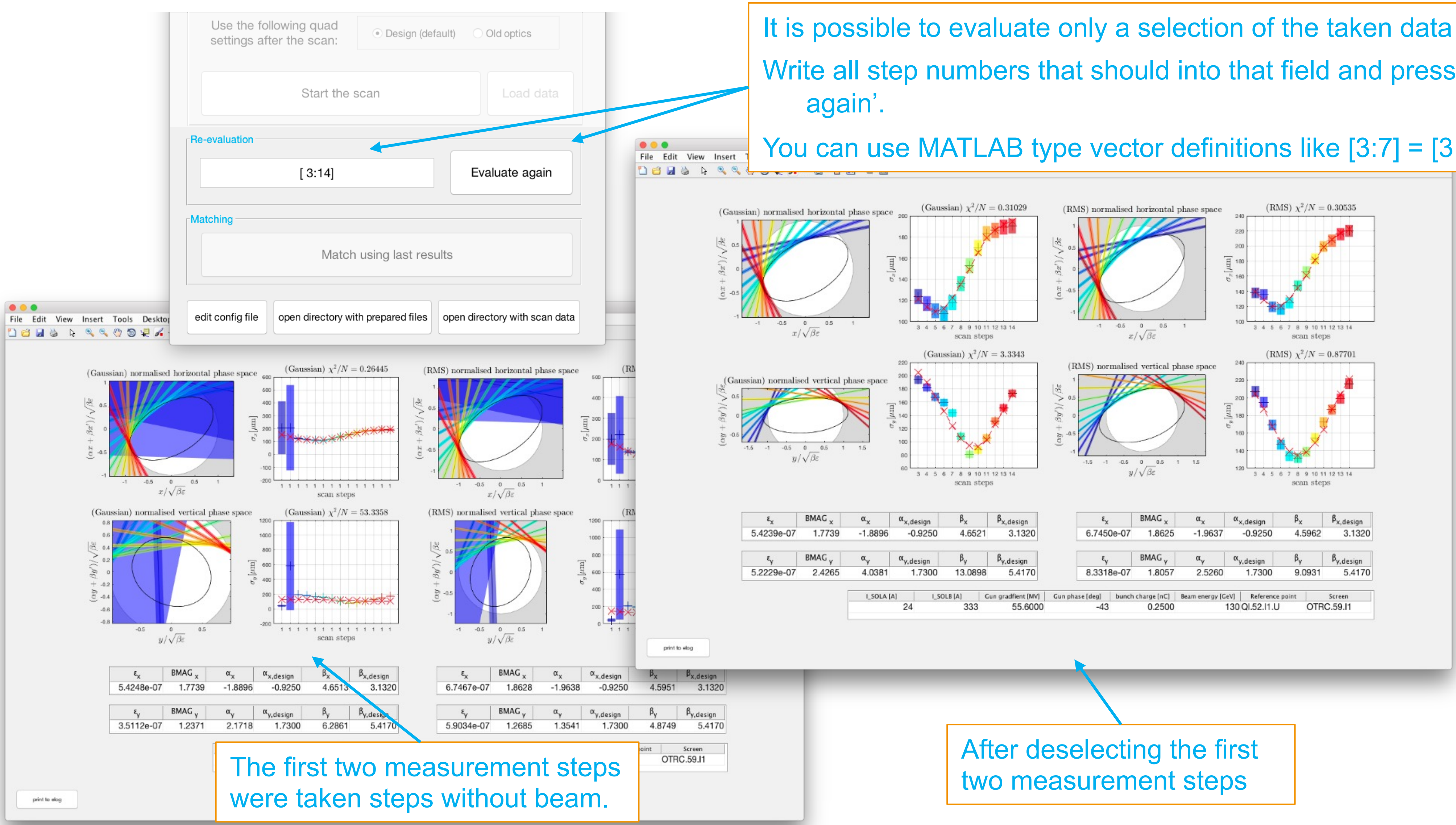
Tools Advertising

Deselecting single measurements

It is possible to evaluate only a selection of the taken data steps.

Write all step numbers that should into that field and press 'Evaluate again'.

You can use MATLAB type vector definitions like [3:7] = [3 4 5 6 7].



The first two measurement steps were taken steps without beam.

After deselecting the first two measurement steps

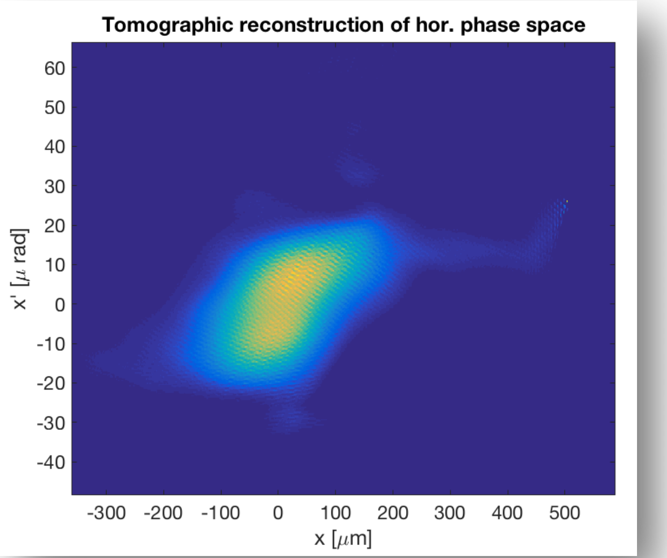
Be careful with the deselection of measurement steps and with the following evaluation of the data!

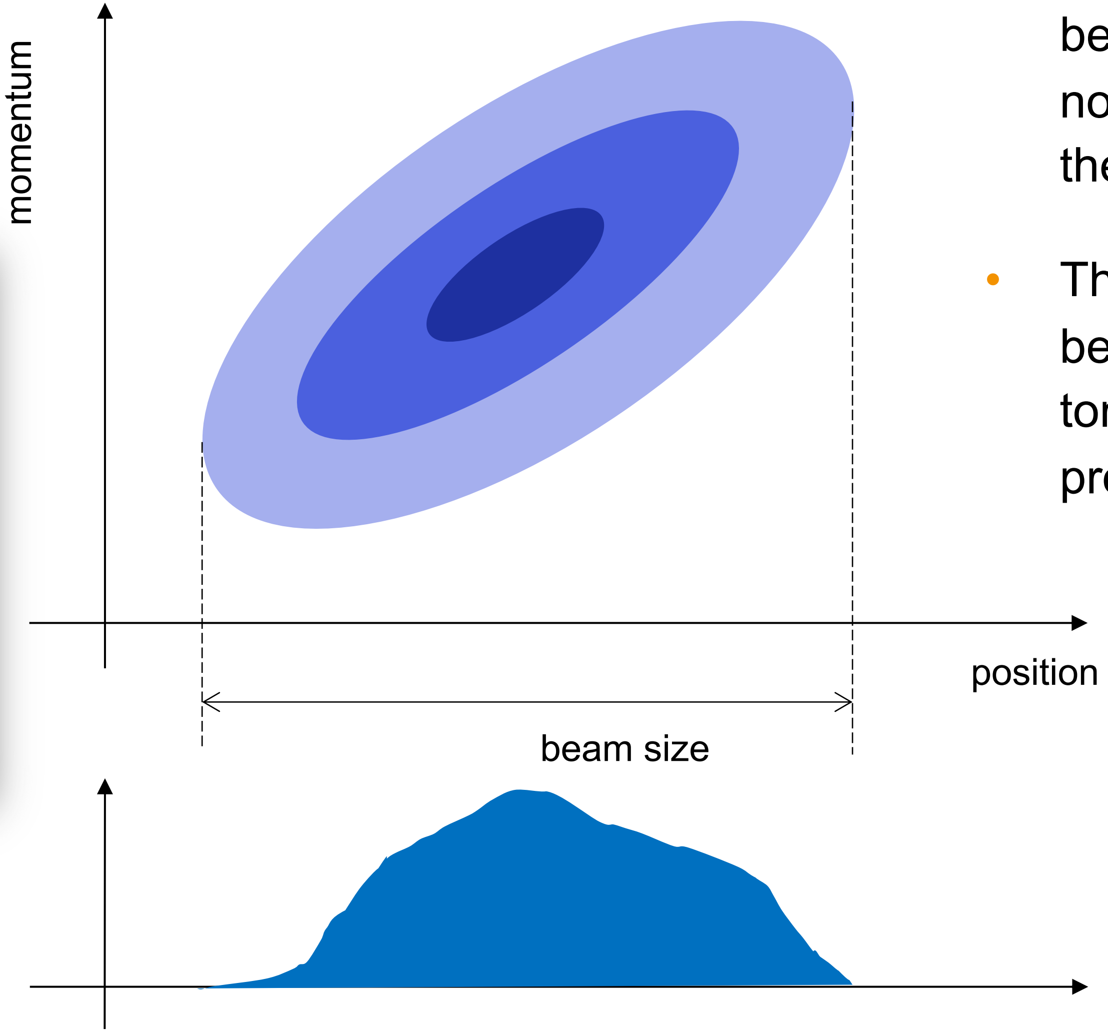
This functionality must only be used to deselect measurements steps that went clearly wrong (e.g. no beam).

It must not be used to deselect 'unwanted' measurement steps to improve e.g. emittance size or beam optics matching!

Tomographic reconstruction of transverse phase spaces

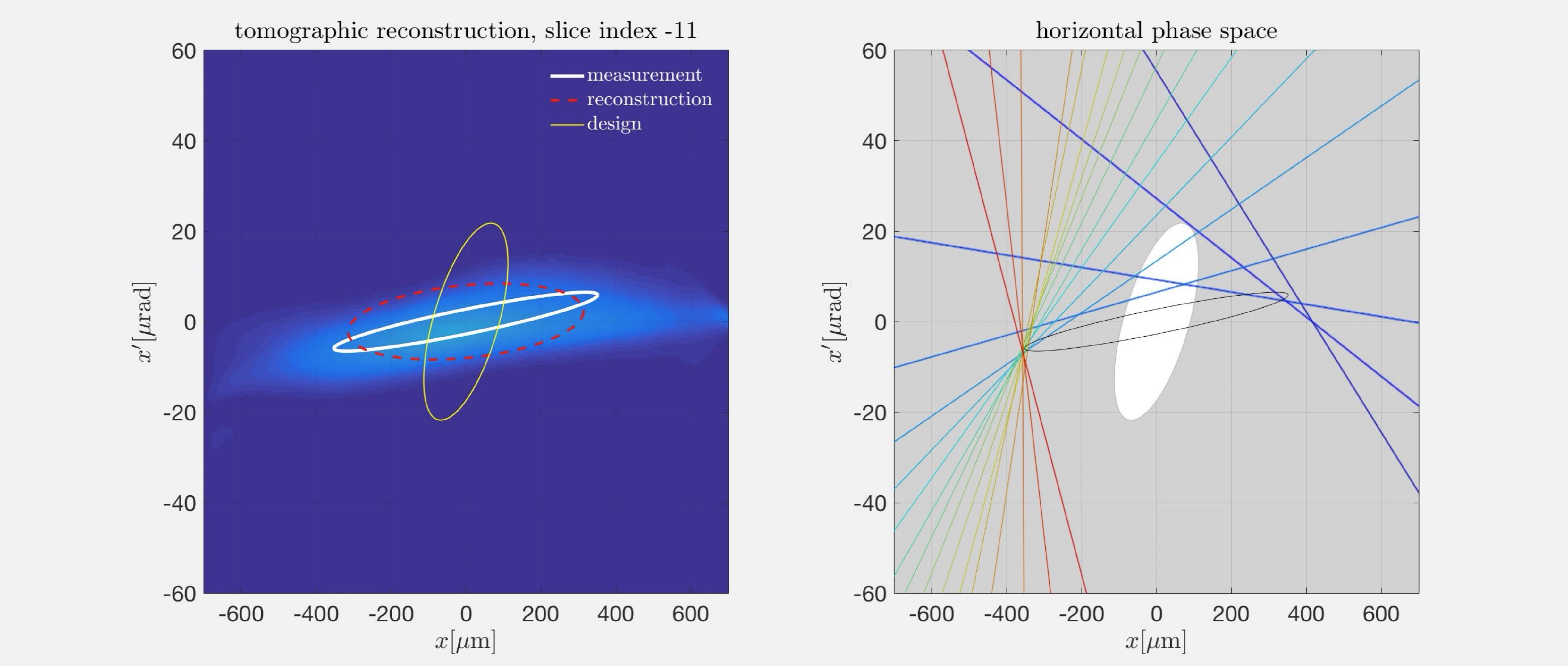
Tomographic reconstruction of the horizontal phase space for the center slice.



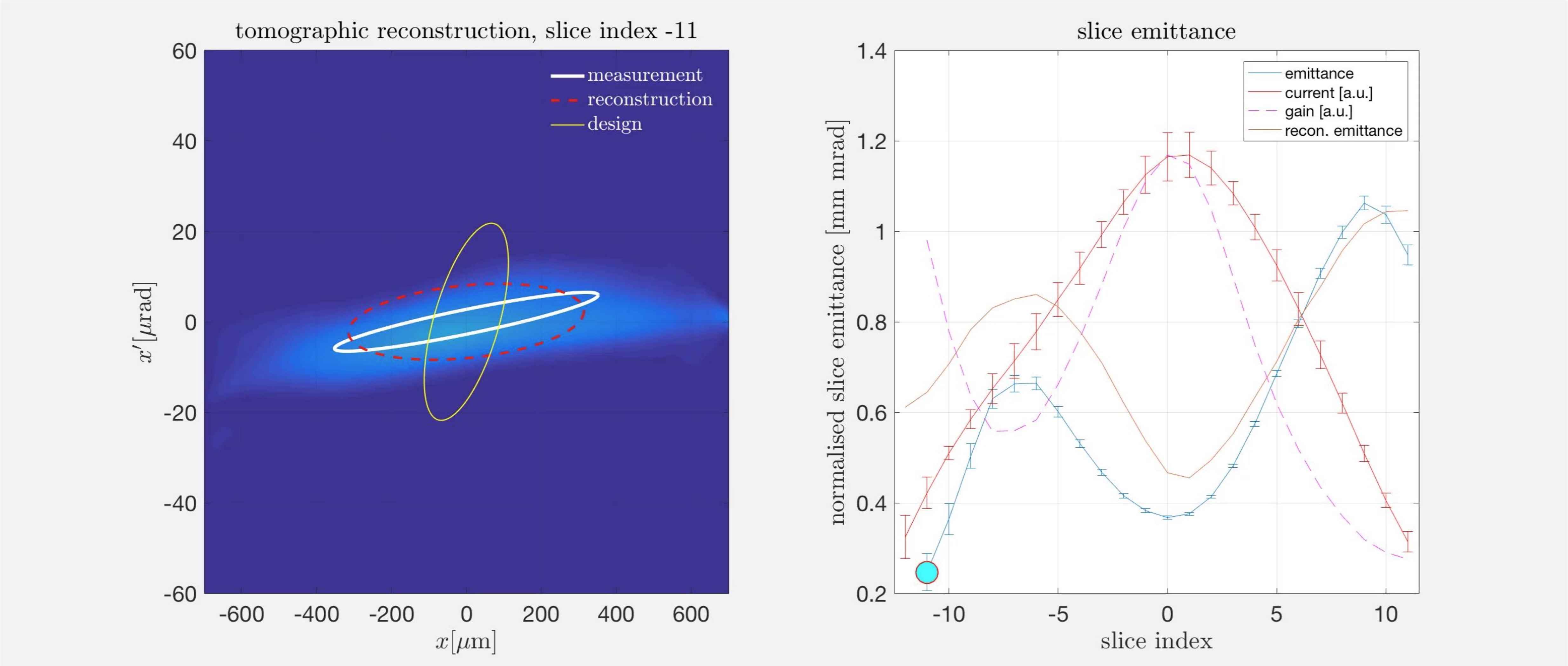


- Even more information about the beam can be obtained by using not only the beam sizes but also the profiles.
- The transverse phase spaces can be reconstructed using a tomographic algorithm and the profiles from different 'angles'.

Tomographic reconstruction of the hor. phase space using a quad scan

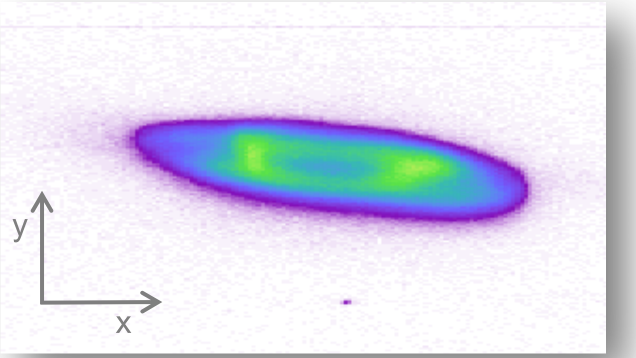


Tomographic reconstruction of the hor. phase space using a quad scan

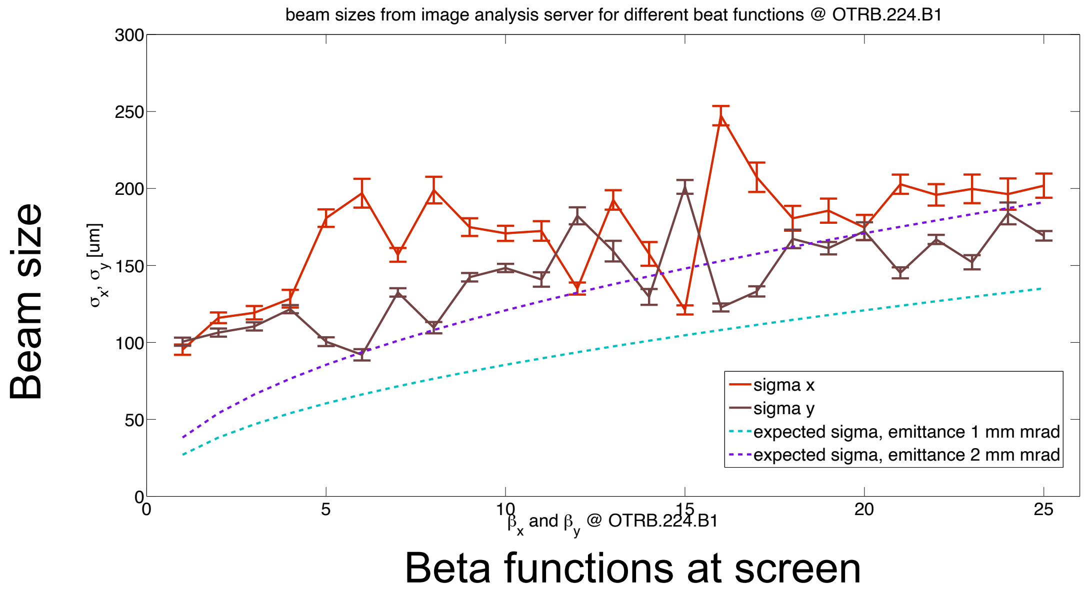


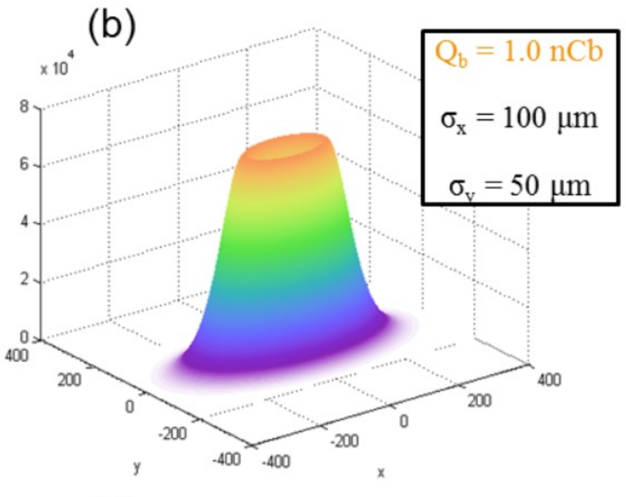
EuXFEL Lyso screens

- It turned out that measured emittances sizes depended on the beam size on the screens.
- In addition, the beam spots one the screens were not gaussian shaped but looked like smoke rings.

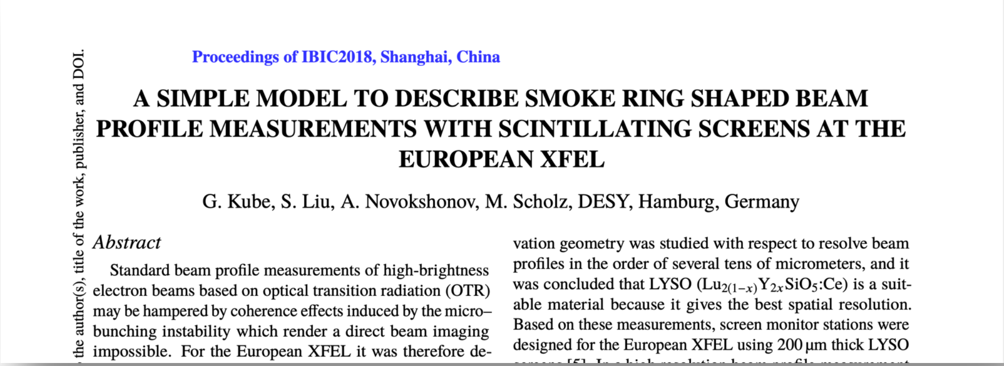


- It was not clear if the beam looks like that or if the LYSO screens can not display the bunches correctly.
- No others screens were available in the machine.





- It turned out that it was a quenching effect of the scintillators.
- That effect could be reproduced in simulations.
- Most of the screen have been or will be replaced with YAP or GGAG.


Proceedings of IBIC2018, Shanghai, China

A SIMPLE MODEL TO DESCRIBE SMOKE RING SHAPED BEAM PROFILE MEASUREMENTS WITH SCINTILLATING SCREENS AT THE EUROPEAN XFEL

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Abstract

Standard beam profile measurements of high-brightness electron beams based on optical transition radiation (OTR) may be hampered by coherence effects induced by the micro–bunching instability which render a direct beam imaging impossible. For the European XFEL it was therefore de- vation geometry was studied with respect to resolve beam profiles in the order of several tens of micrometers, and it was concluded that LYSO ($Lu_{2(1-x)}Y_{2x}SiO_5$:Ce) is a suitable material because it gives the best spatial resolution. Based on these measurements, screen monitor stations were designed for the European XFEL using 200 µm thick LYSO

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