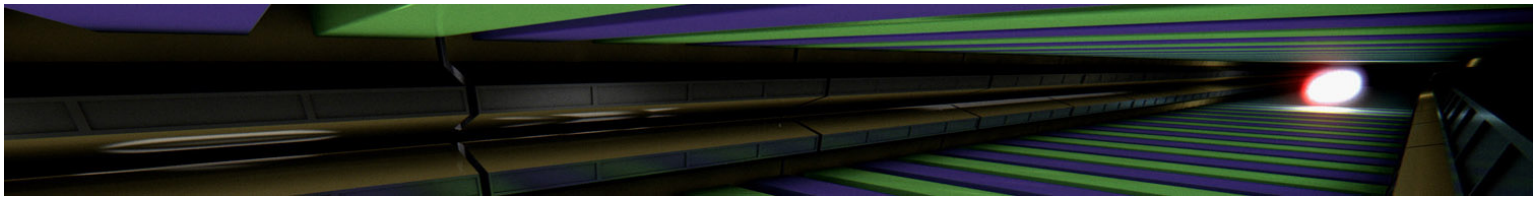


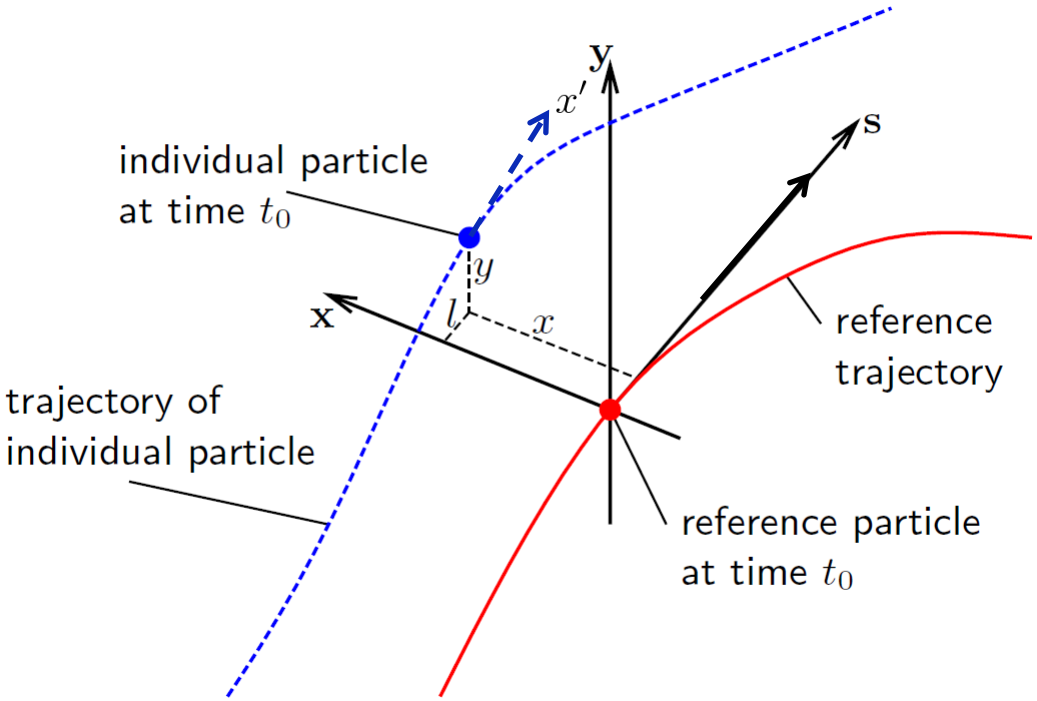
Beam Optics and Emittance

Bolko Beutner

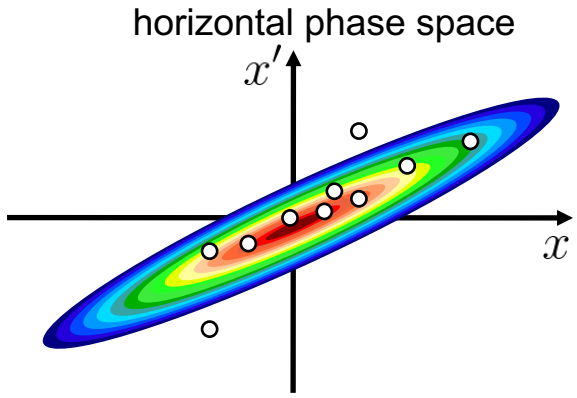
21.01.2020

Introduction

Beam Dynamics Coordinates



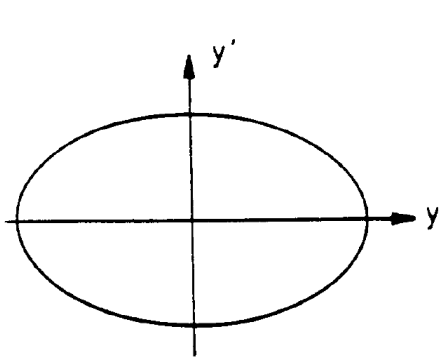
$$\boldsymbol{X}(s) = \begin{pmatrix} x \\ x\prime \\ y \\ y\prime \\ l \\ \delta \end{pmatrix}$$



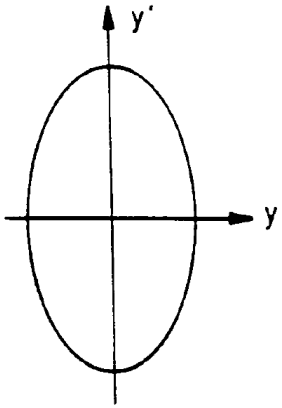
- Co-moving coordinate system with respect to design trajectory (right-handed-system at XFEL)
- Phase space is generated between distance and angle to the design orbit in each plane

Emittance

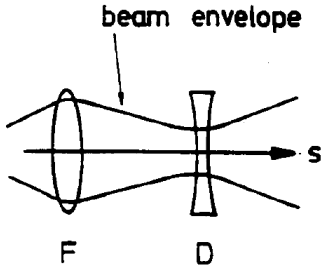
- Area covered by particles in phase space is called emittance
- We can assume an elliptical distribution
- Emittance is conserved in linear optics (Liouville's theorem)
  => beam behaves like an incompressible liquid
  => focusing the beam will increase its divergence
- Small beams with little divergence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



center of F quad

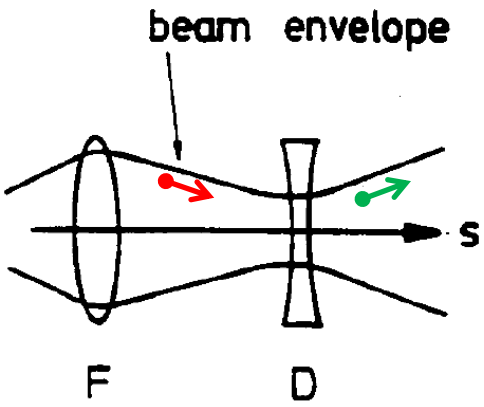


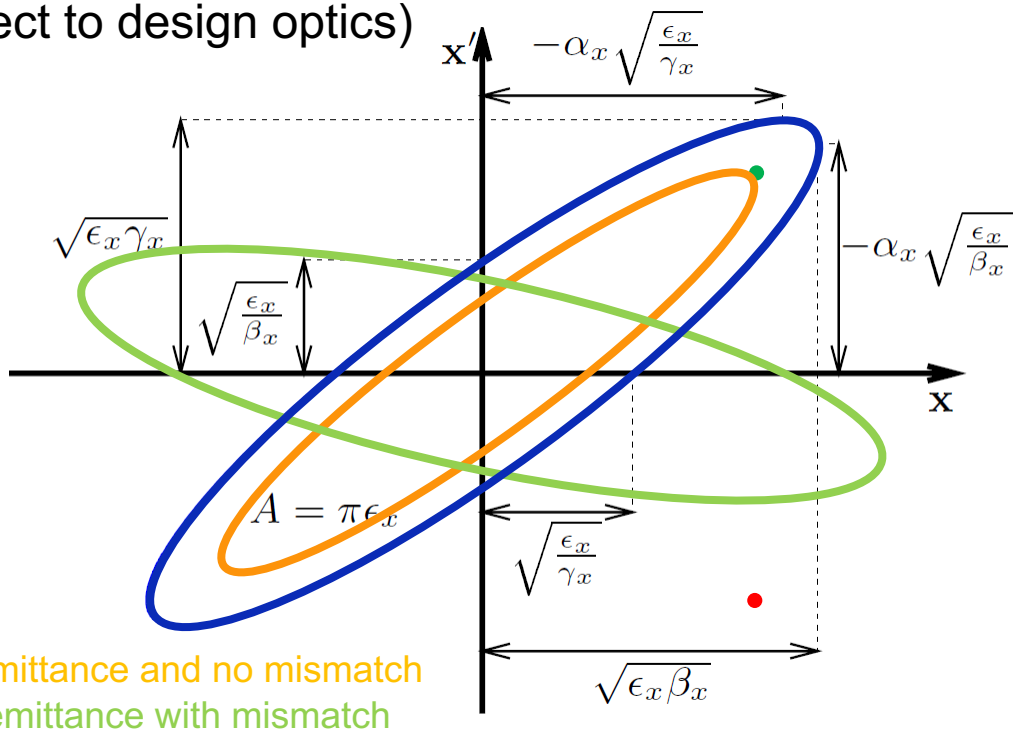
center of D quad



Beam Optics

- While the area is conserved the orientation of the phase space ellipse is not
- Beam orientation is measured with the “twiss” parameters (α, β, γ)
- “slope” of such ellipses are a signature of convergent or divergent beams
- A beam which does not have the same orientations is called “mismatched” (with respect to design optics) even if the emittance is the same

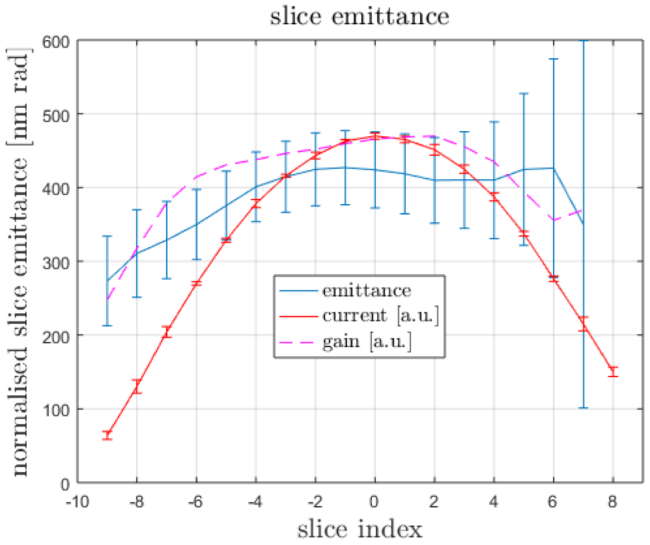


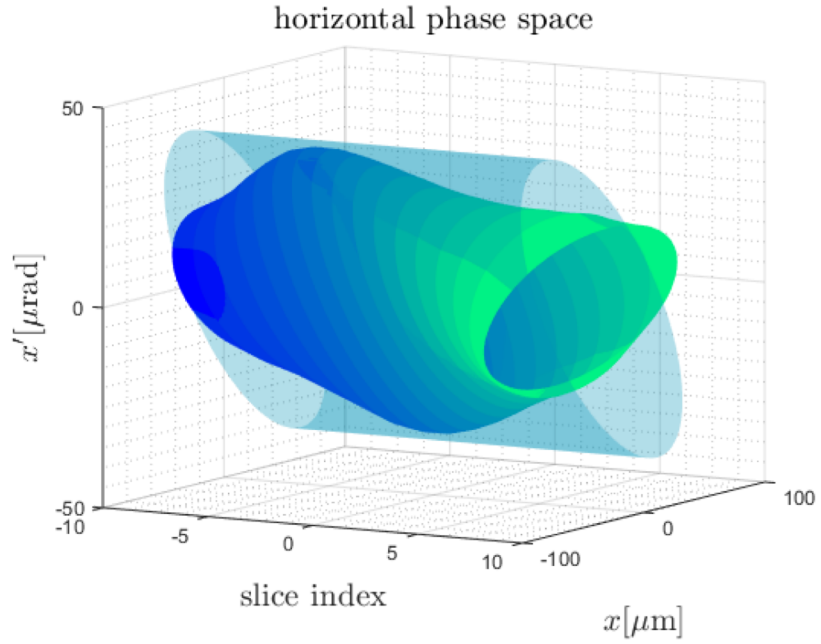


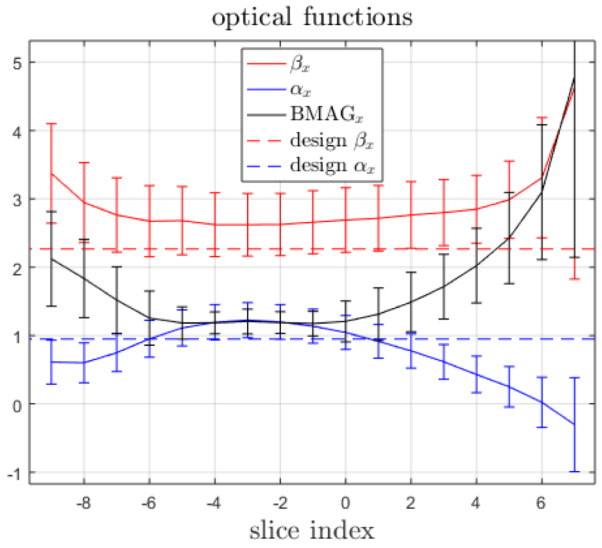
smaller emittance and no mismatch
same emittance with mismatch

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)

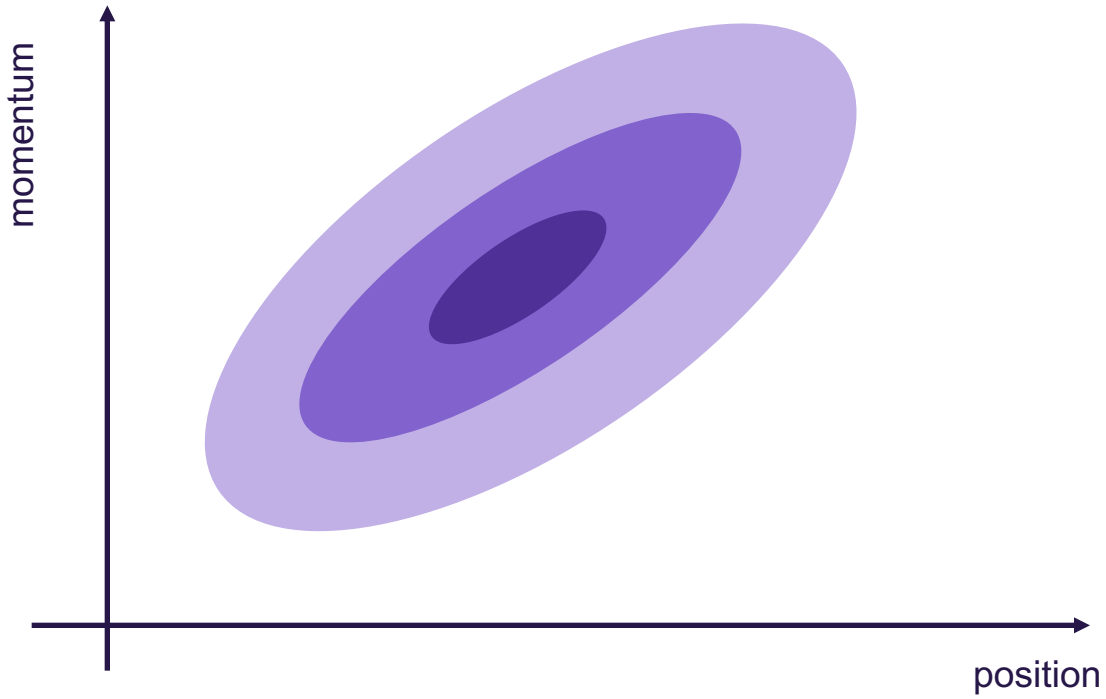




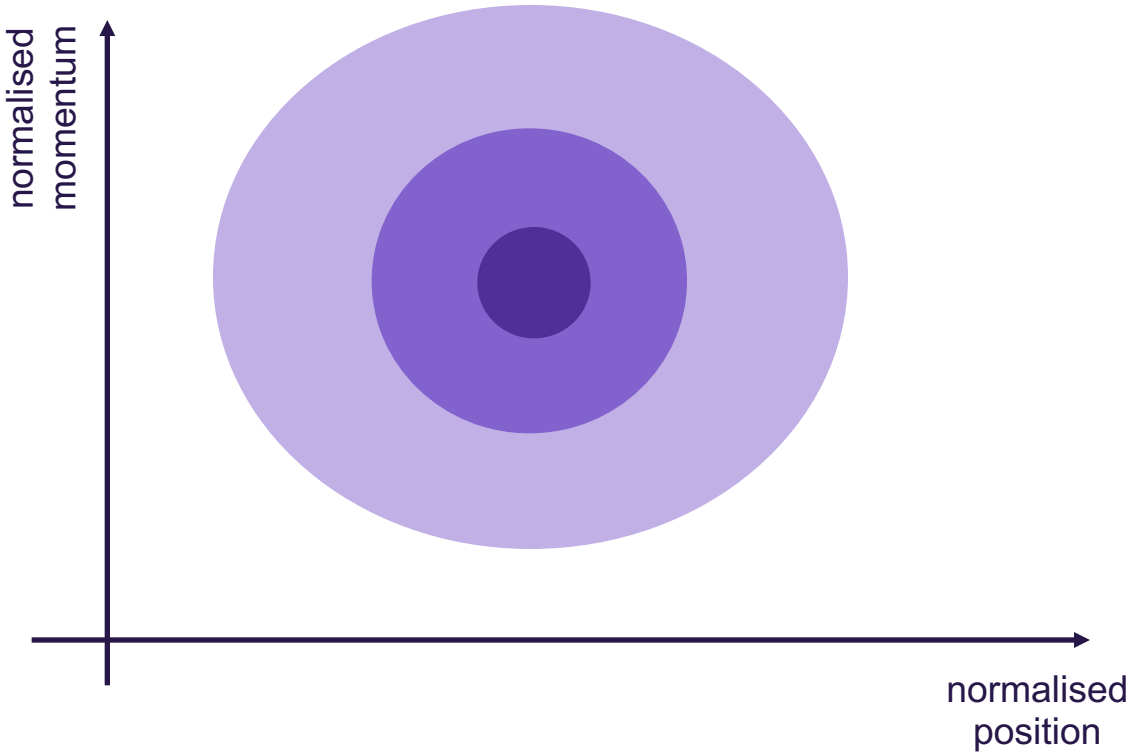


Measurements

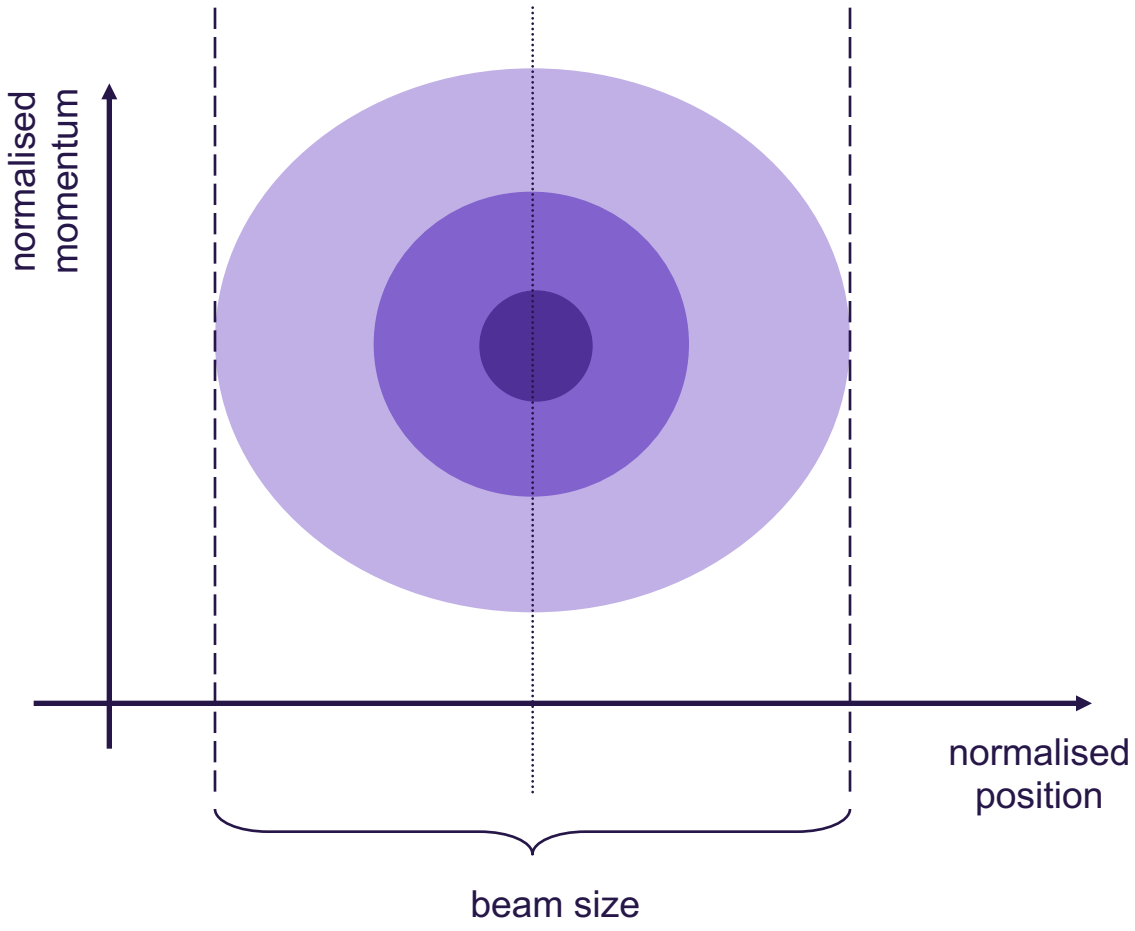
Principle of Optics Measurements



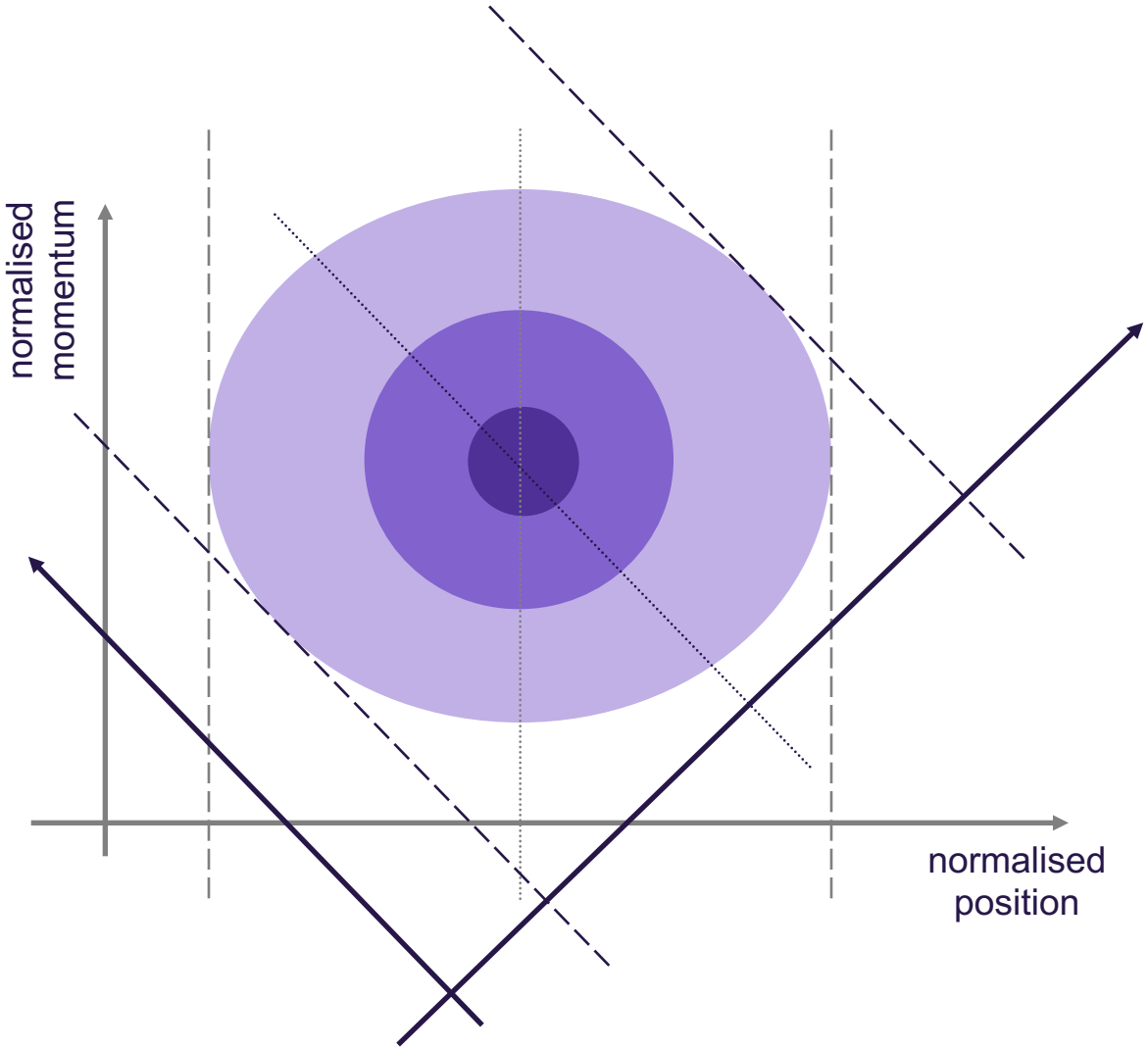
Principle of Optics Measurements



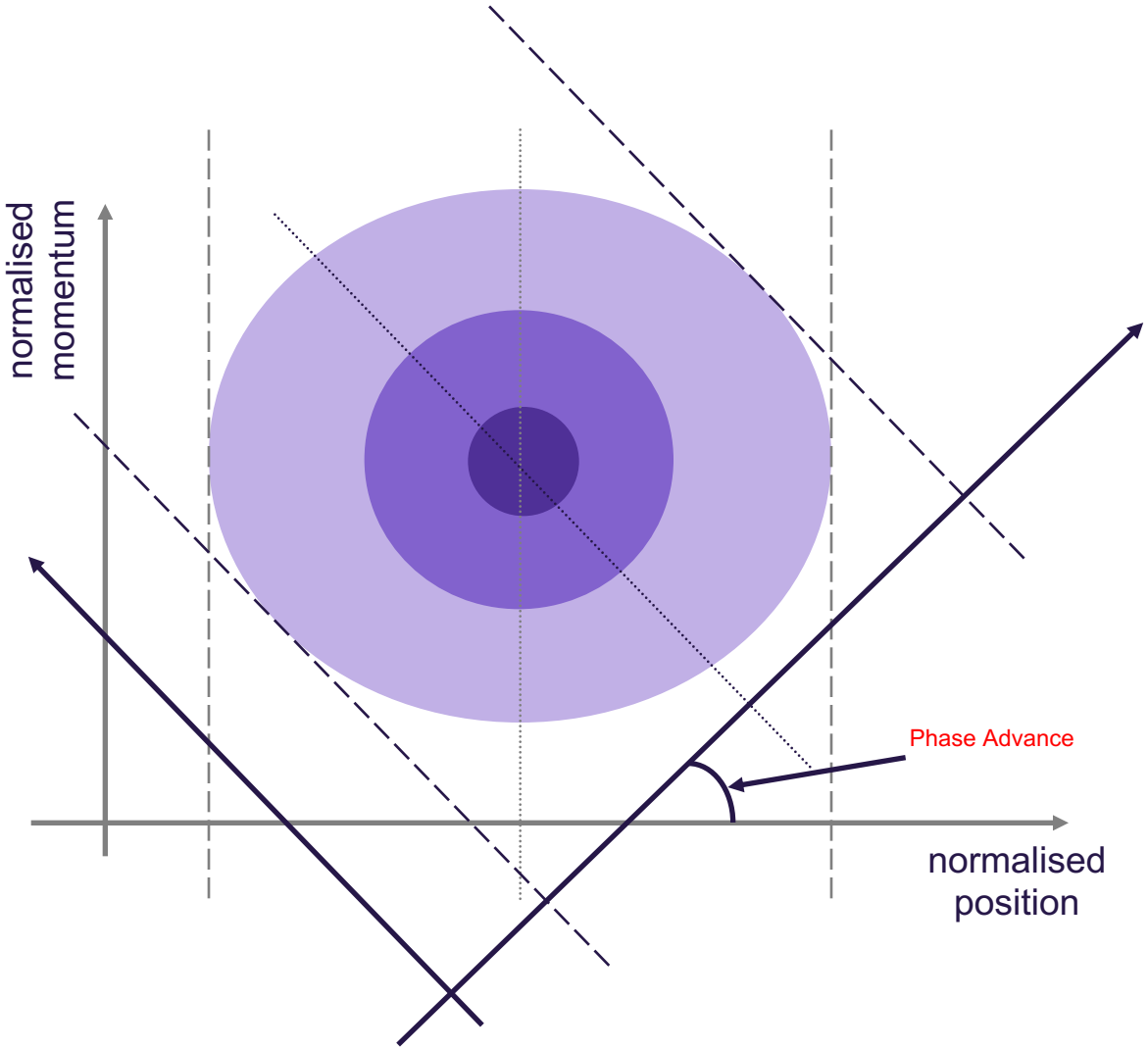
Principle of Optics Measurements



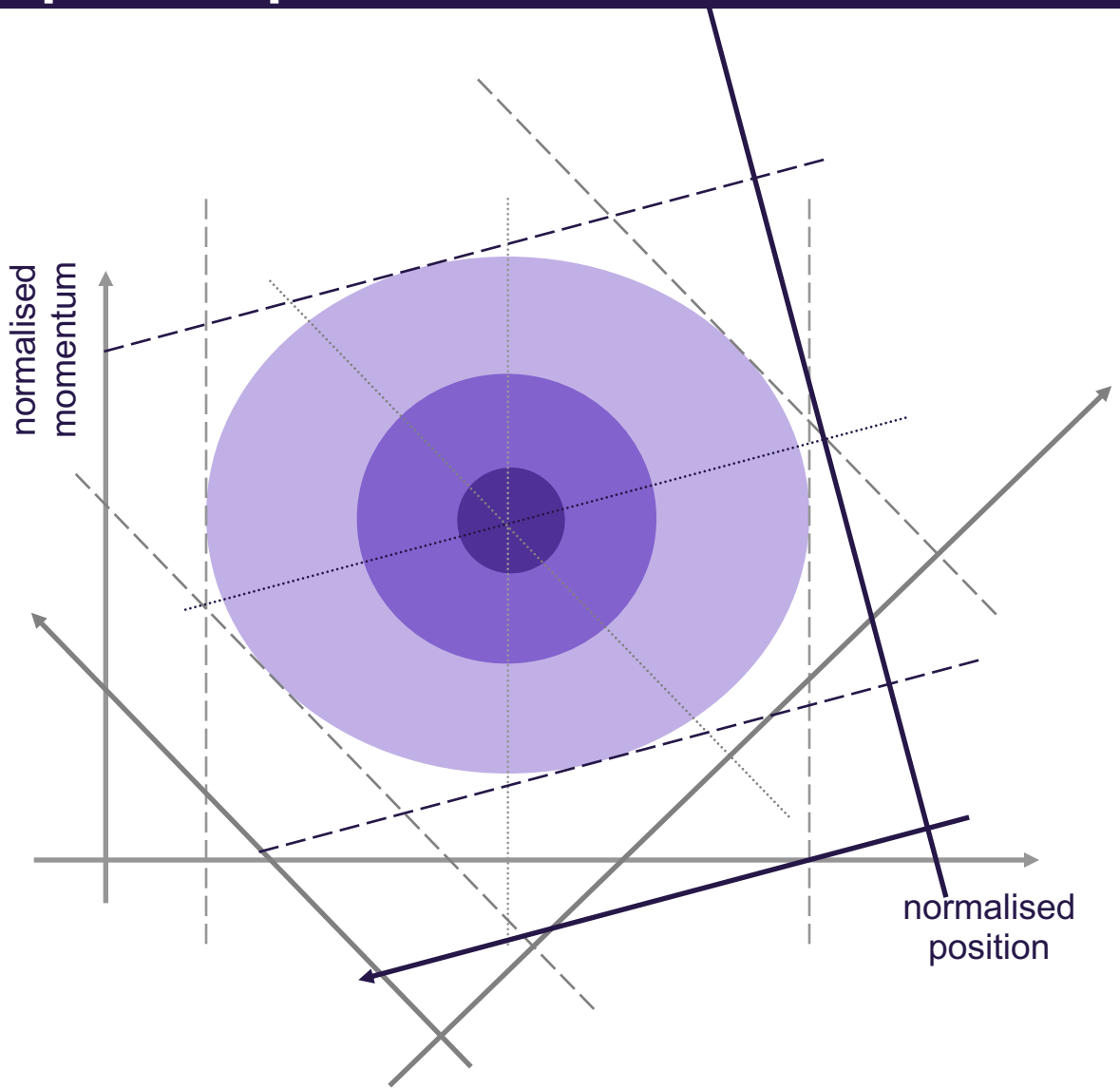
Principle of Optics Measurements



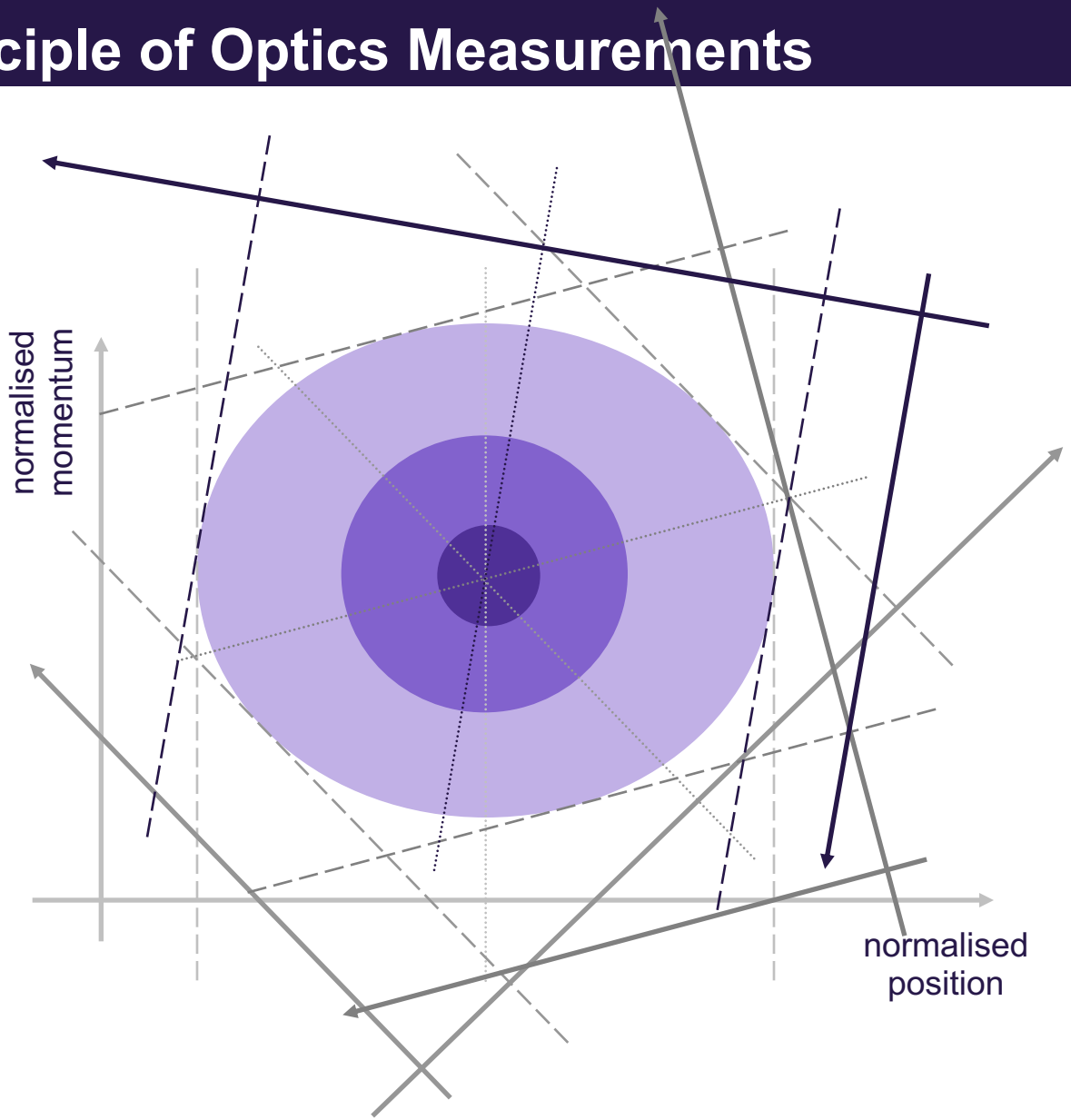
Principle of Optics Measurements



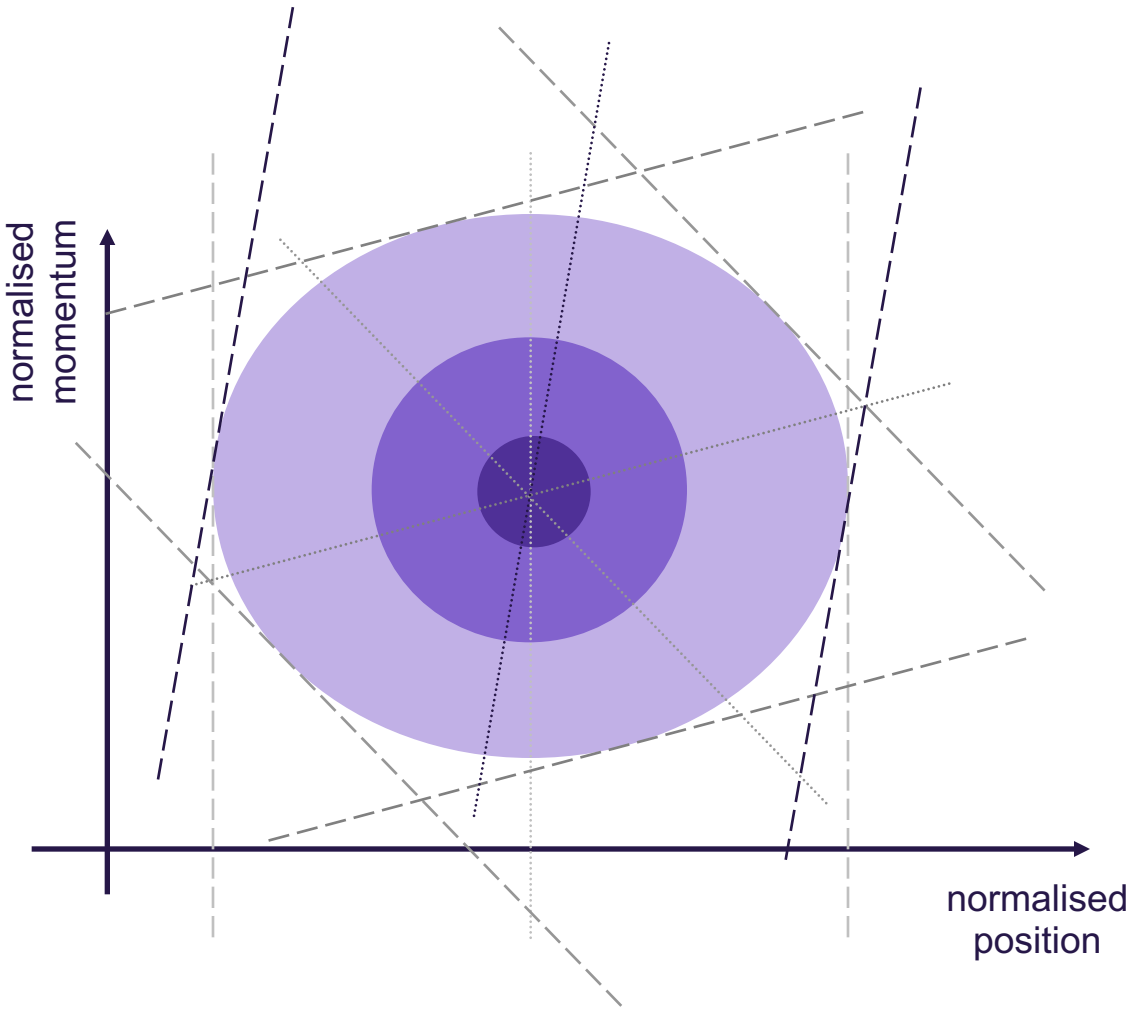
Principle of Optics Measurements



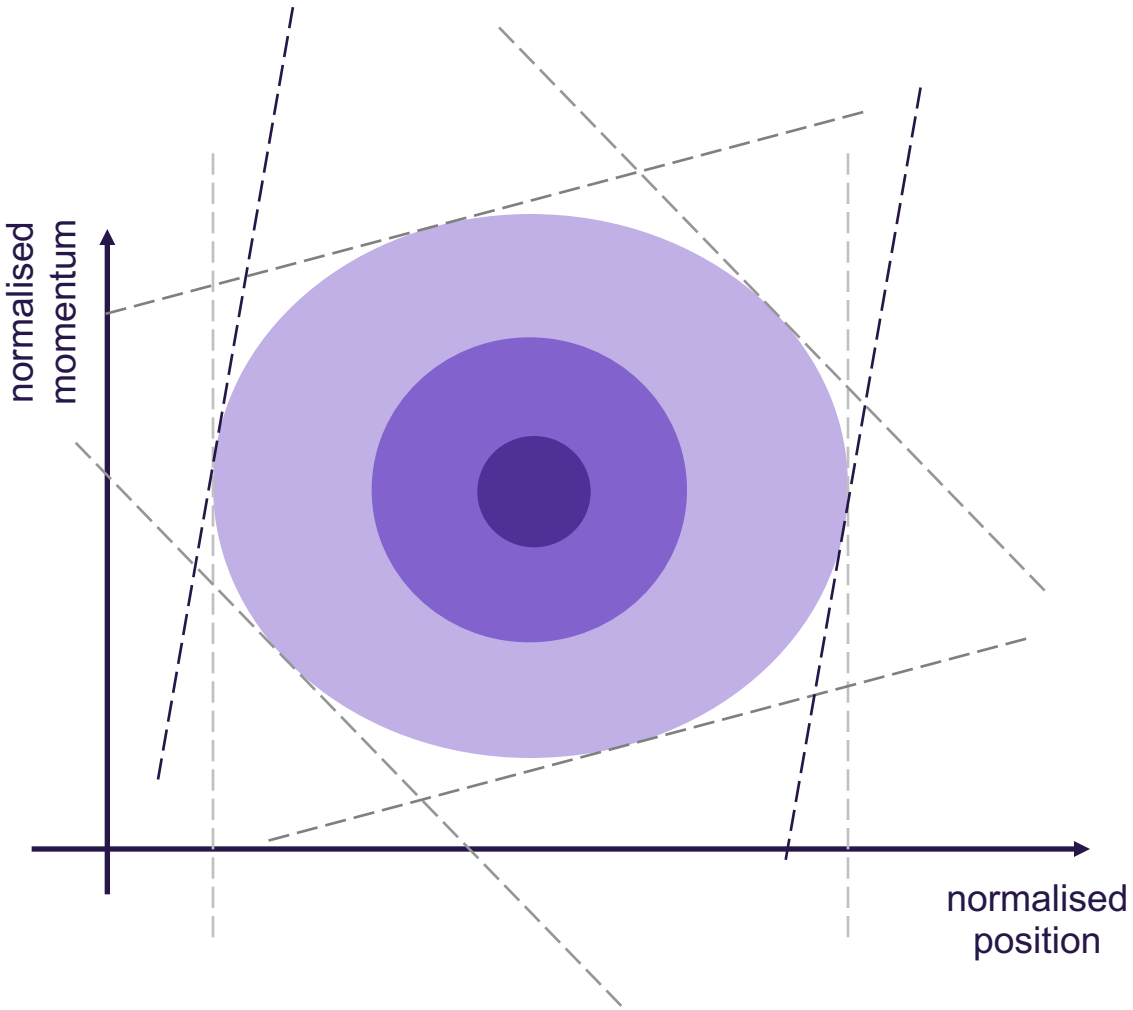
Principle of Optics Measurements



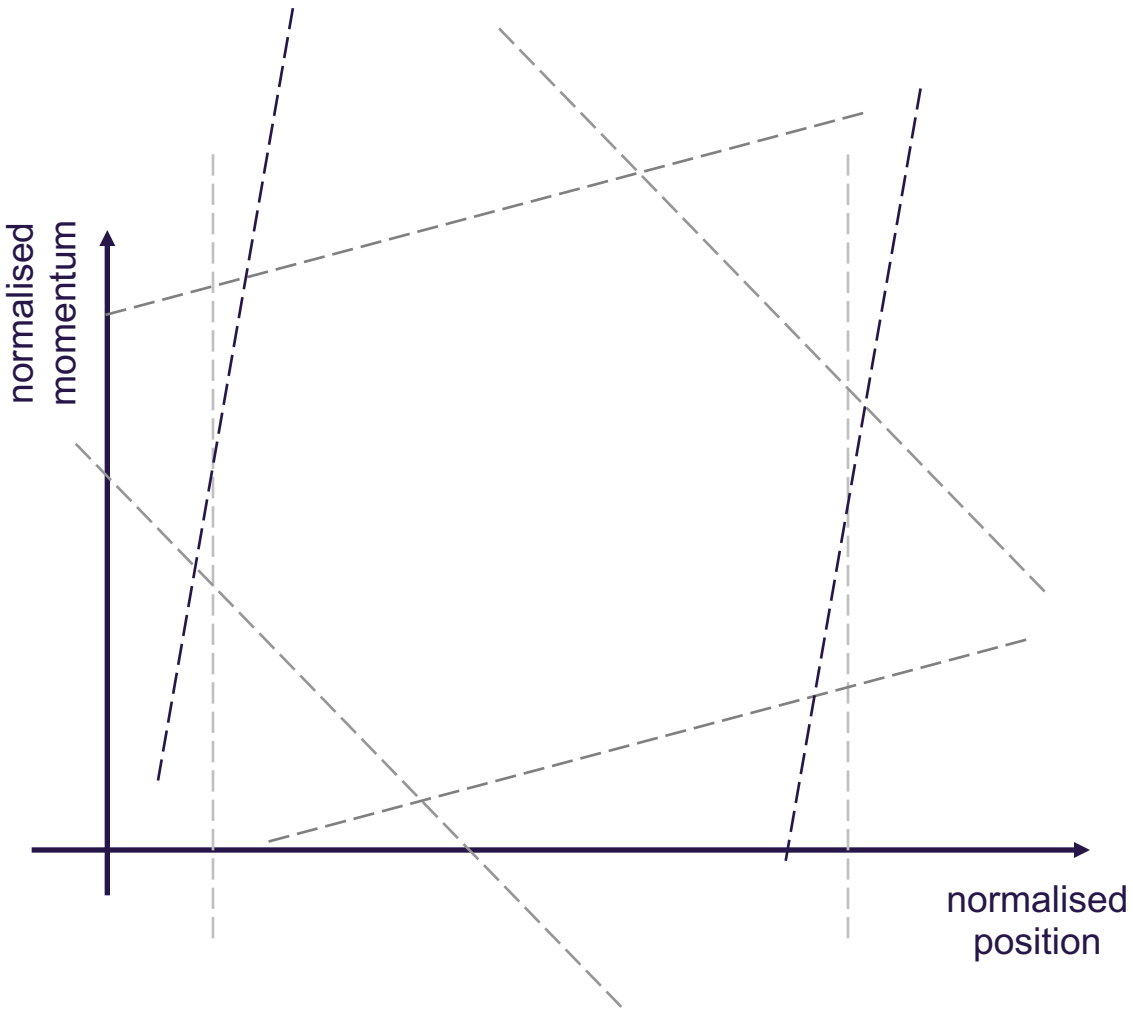
Principle of Optics Measurements



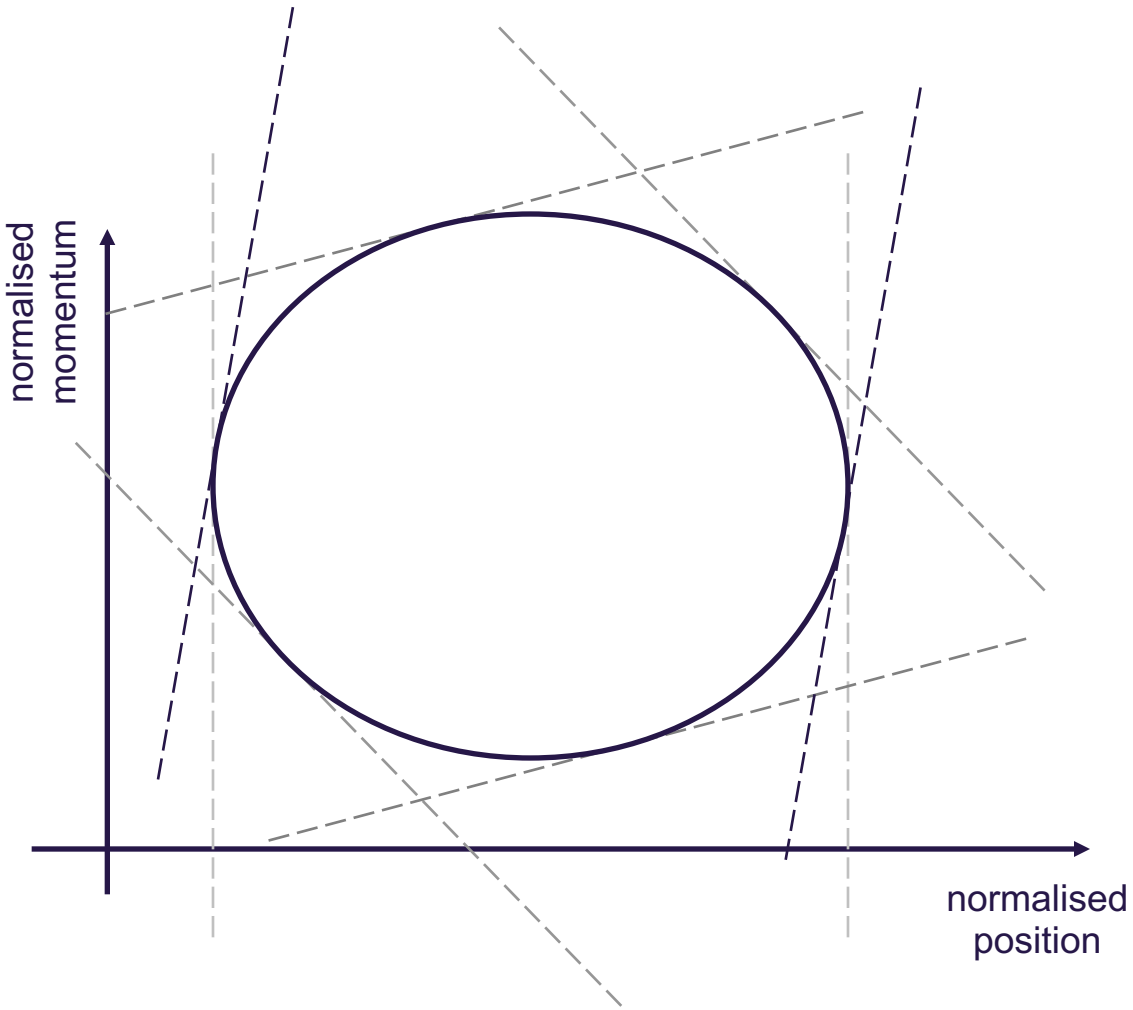
Principle of Optics Measurements



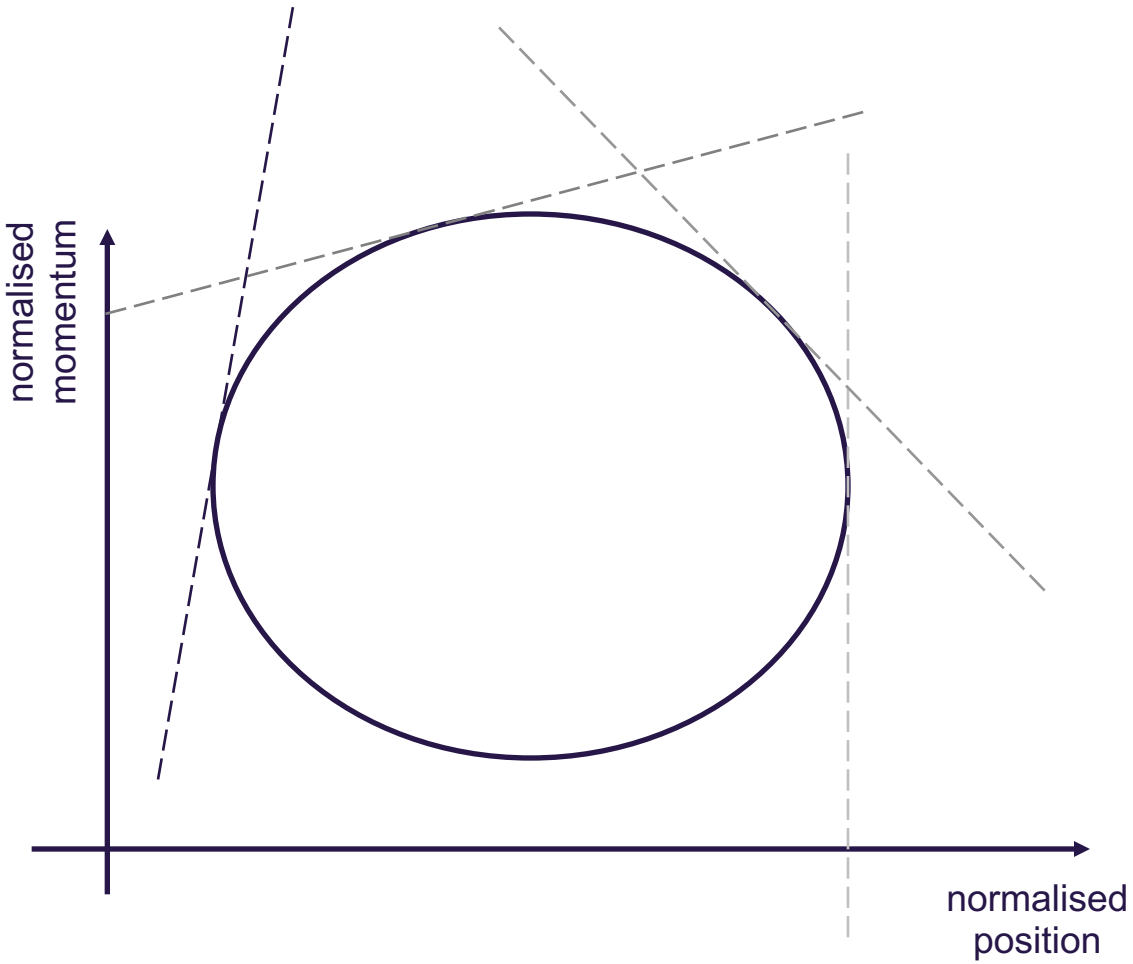
Principle of Optics Measurements



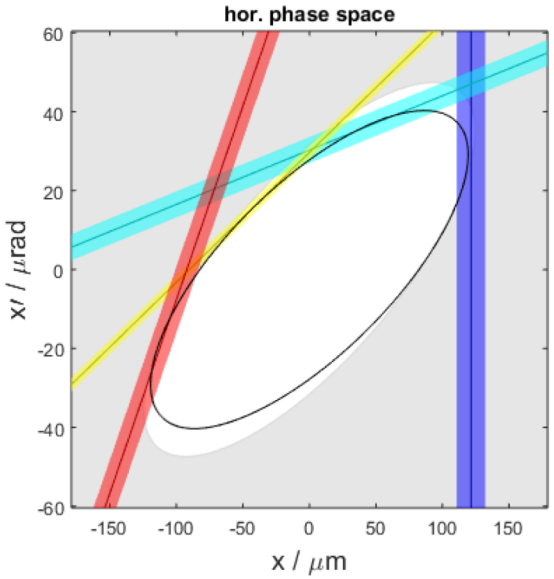
Principle of Optics Measurements



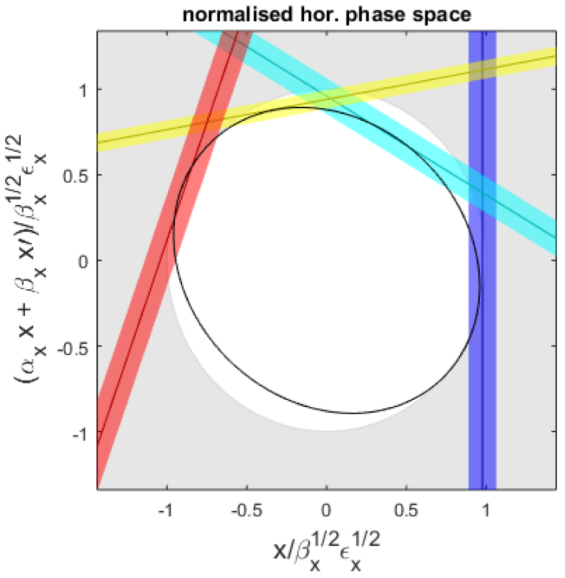
Principle of Optics Measurements

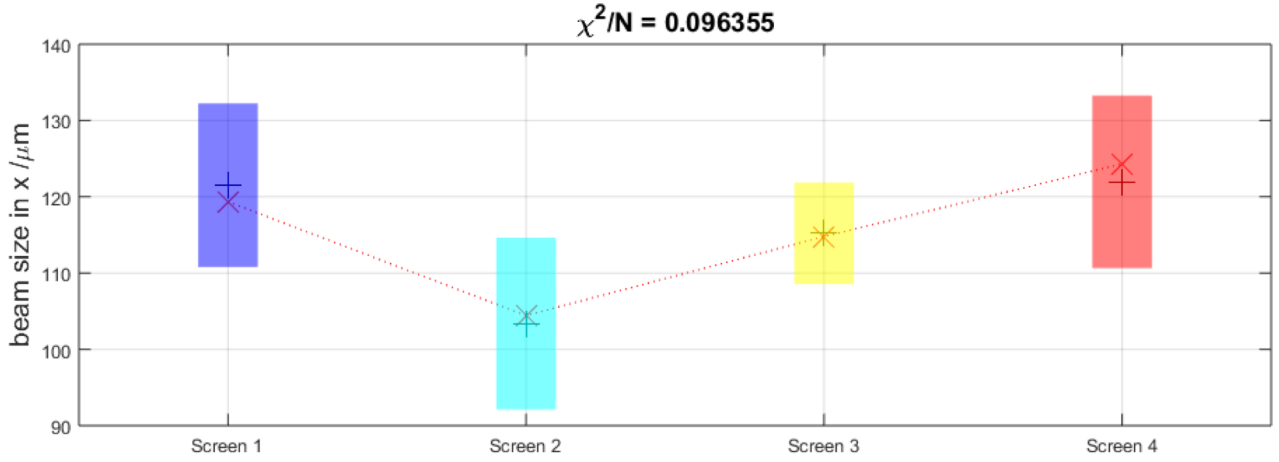


Measurement Fit Summary



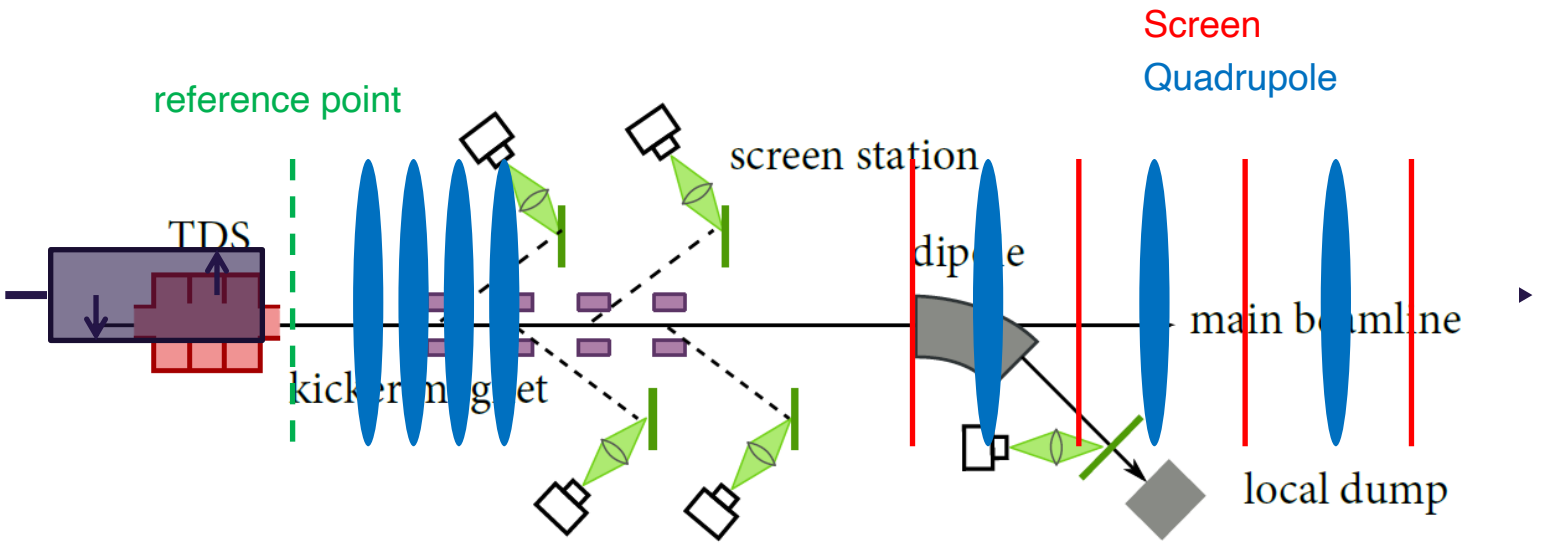
- Different visualizations of the fit are displayed to judge measurement quality
- The design (white) and measured (black) ellipse should agree
- Measured ellipse (black) should touch all beam size measurement lines (colors)
- In normalised phase space the ellipse should be a circle





Optics-/Emittance Measurements

- Optics and Emittance is determined from beam size measurements:

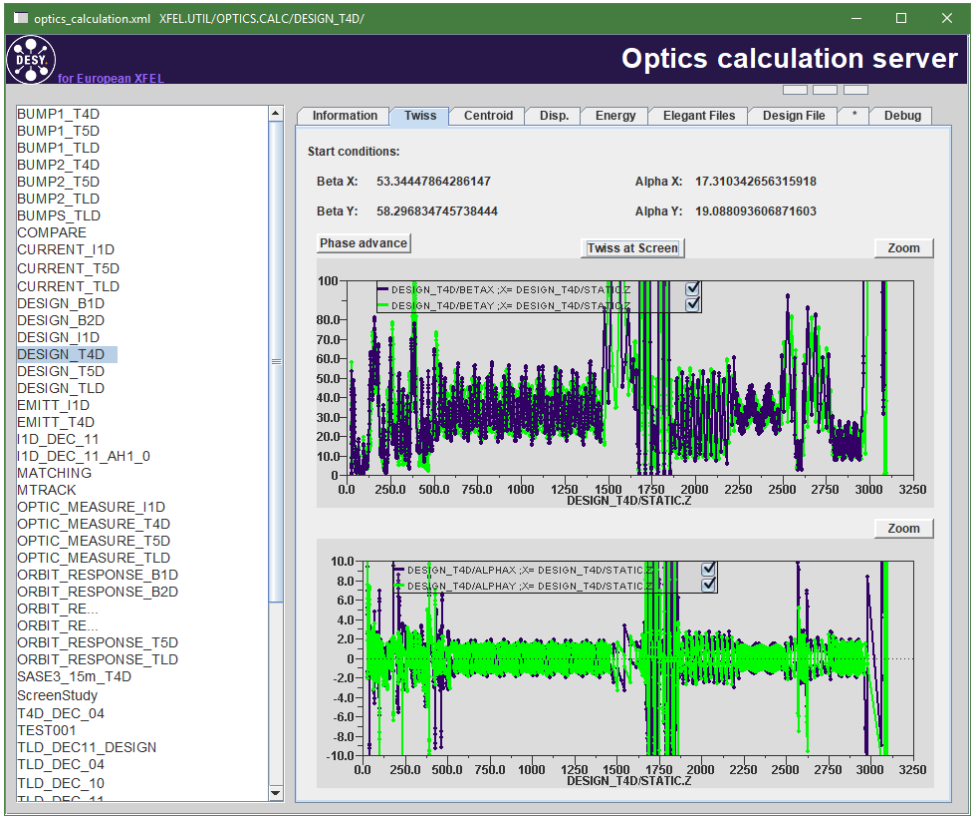


- Beam moments are determined at a reference point using either:
  - one screen while varying the quadrupole settings
  - at multiple positions along a constant lattice (FODO)
- Slice resolved measurements in combination with a transverse deflecting RF-structure (TDS)

Matching

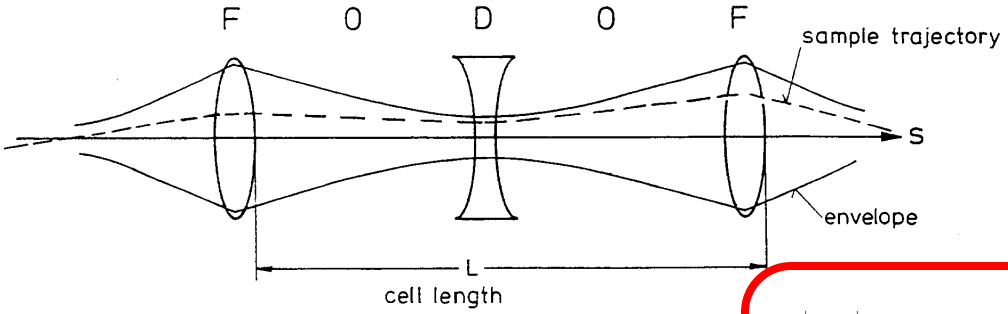
Design Optics

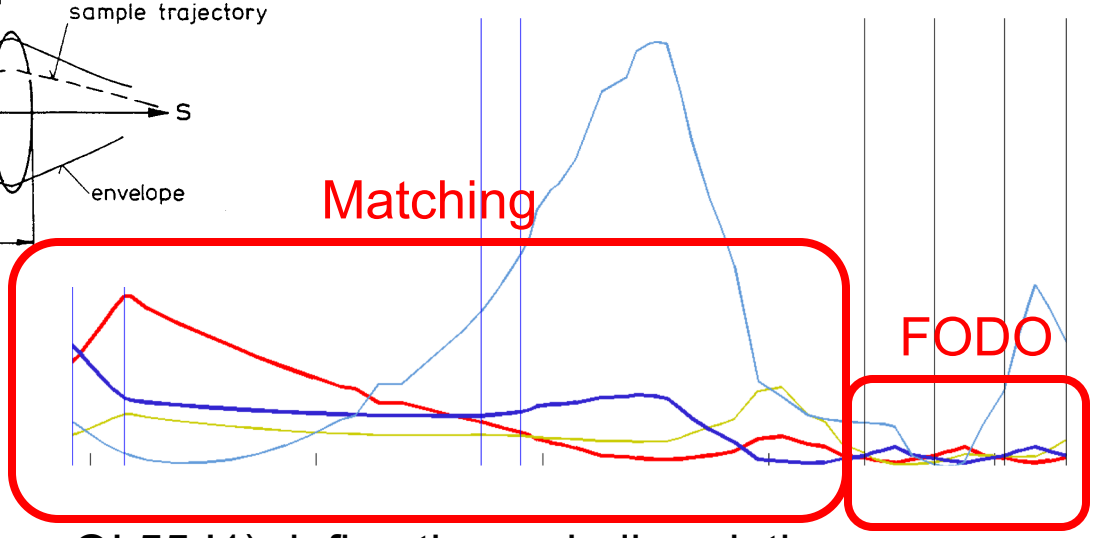
- Optics is designed for optimal beam transport, efficient collimation, FEL output power, …
- Optics initial condition (after A1) determine the beam optics in the whole machine (different in storage rings)
- Deviations in the initial conditions or lattice inaccuracies have to be adjusted by matching quadrupoles



Design Optics

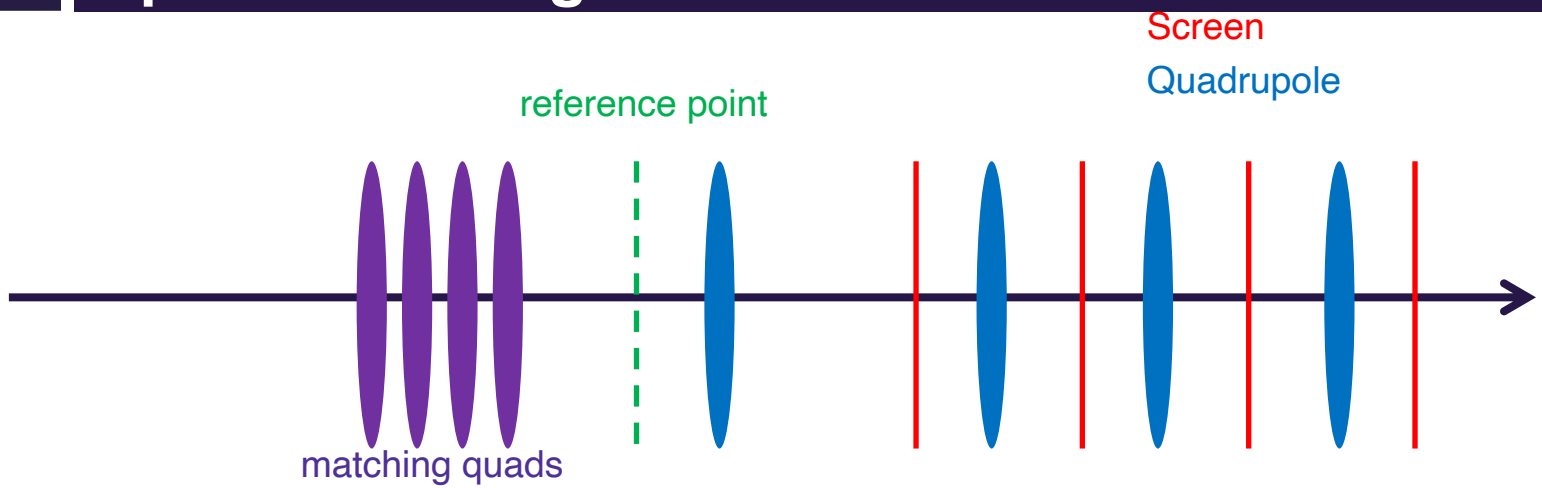
- Design optics in the Diagnostic Sections are defined by the periodic FODO lattice
  - Unique periodic solution





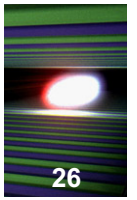
- Example: XFEL Injector
  - Quads QI.55.I1, QI.57.I1, and QI.59.I1 (same strength as QI.55.I1) define the periodic solution
  - Upstream quads match the beam from gun section to the periodic solution
  - Downstream quads are set assuming the periodic solution as a start e.g. transport to the I1D dump.

Optics Matching



- A mismatched beam at a reference point can be “matched” by tuning upstream quads
- Results from a optics measurement are used from a matching tool to calculate a quad setup
- Another measurement is required to confirm improved BMAG
- Iterate until desired mismatch is reached (better than 1.1)

Matching or NOT Matching?



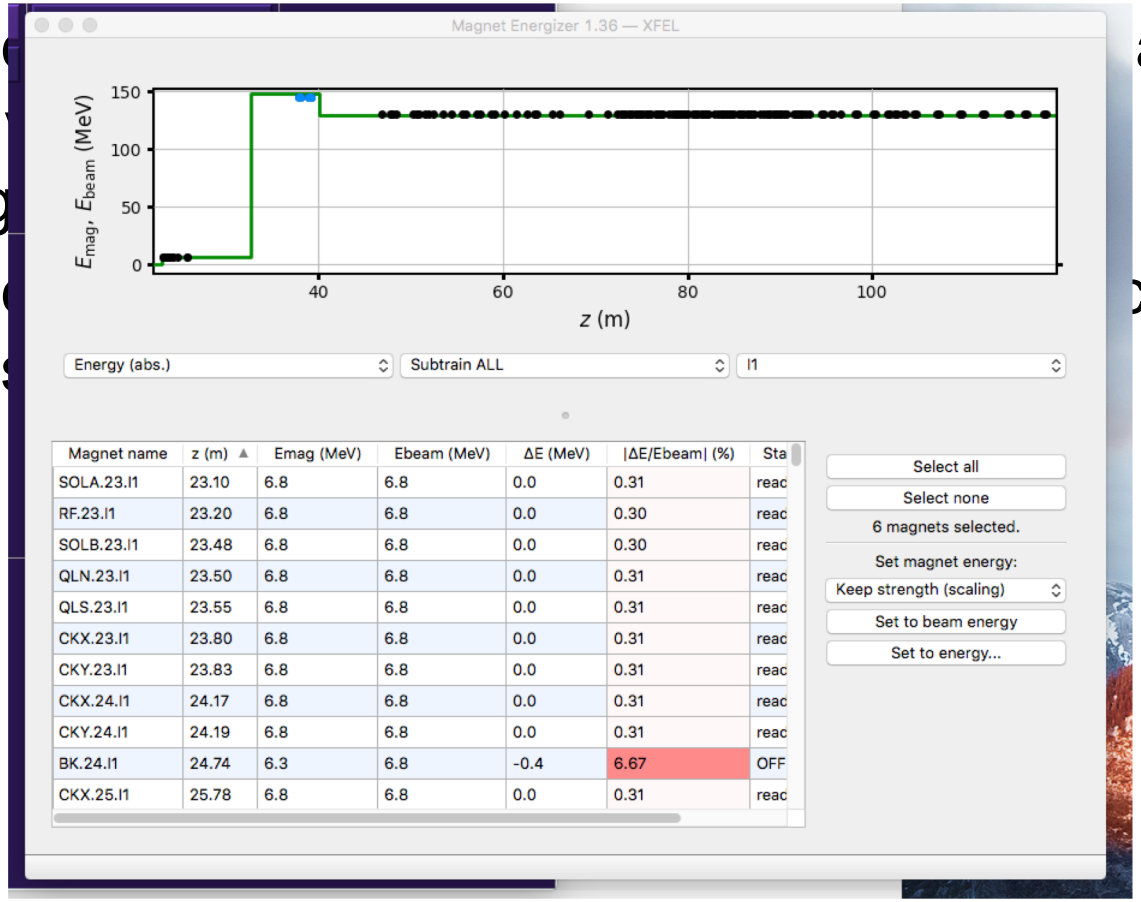
In standard operation we typically load a file from a previous SASE run. Therefore we can assume the configuration of the matching quads is correct if the gun is set correctly (otherwise SASE performance would be poor).

- Set machine (injector) on-crest (zero chirp and zero curvature) and energize the quads correctly
- If a file is loaded try to match without changing the quads – assuming the quads are set correctly before
  - vary gun phase
  - vary main solenoid
- Try matching with quads if gun phase and solenoid do not improve matching

Energizing of injector cold quads

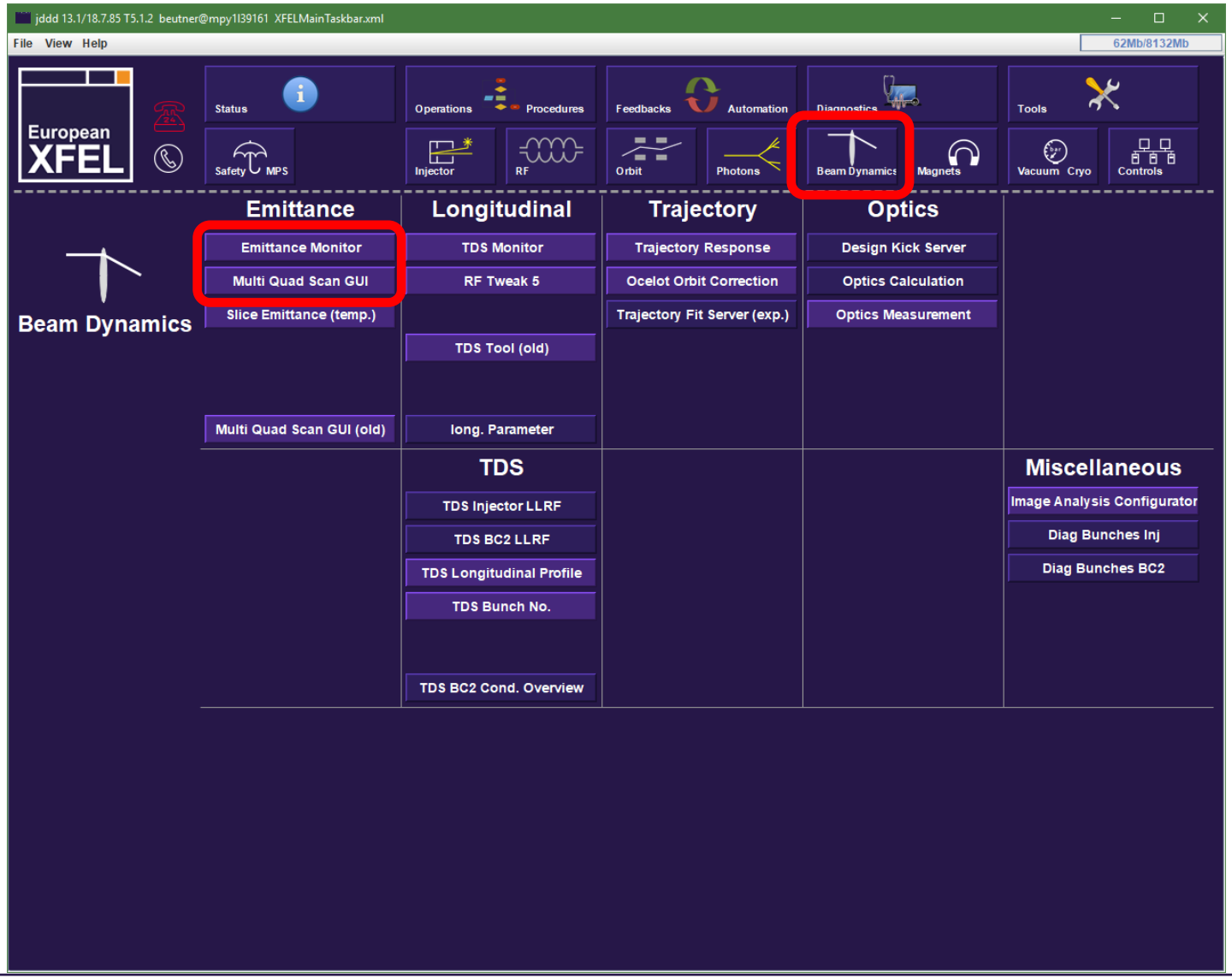
If matching with the quads is done on-crest the magnets between A1 and AH1 need to be:

- energize… and third deri… matching…
- energize… crest compress…



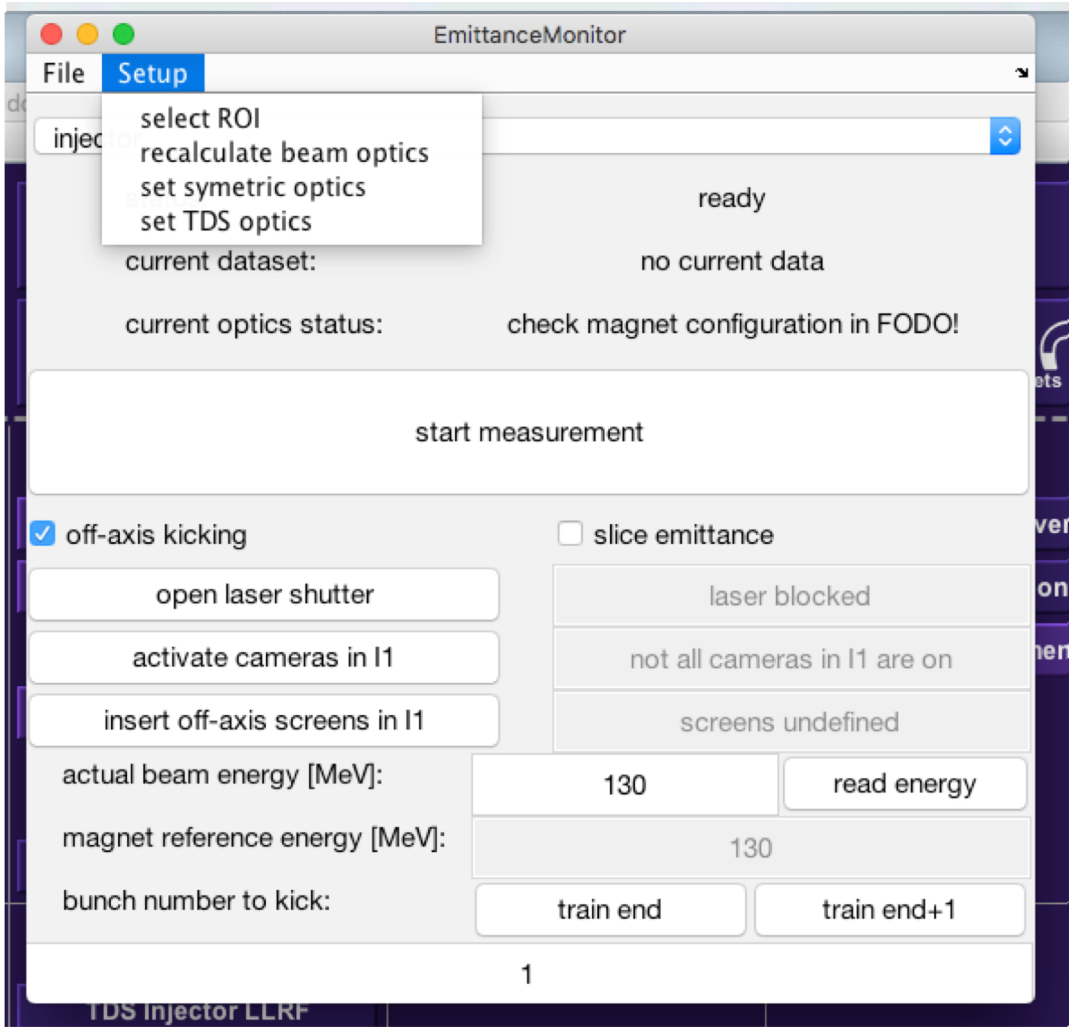
Tools at XFEL

XFEL Tools


jddd 13.1/18.7.85 T5.1.2 beutner@mpy1l39161 XFELMainTaskbar.xml
File View Help
62Mb/8132Mb
European XFEL
Status
Operations
Procedures
Feedbacks
Automation
Diagnostics
Tools
Safety
MPS
Injector
RF
Orbit
Photons
Beam Dynamics
Magnets
Vacuum
Cryo
Controls
Beam Dynamics
Emittance
Emittance Monitor
Multi Quad Scan GUI
Slice Emittance (temp.)
Multi Quad Scan GUI (old)
Longitudinal
TDS Monitor
RF Tweak 5
TDS Tool (old)
long. Parameter
Trajectory
Trajectory Response
Ocelot Orbit Correction
Trajectory Fit Server (exp.)
Optics
Design Kick Server
Optics Calculation
Optics Measurement
TDS
TDS Injector LLRF
TDS BC2 LLRF
TDS Longitudinal Profile
TDS Bunch No.
TDS BC2 Cond. Overview
Miscellaneous
Image Analysis Configurator
Diag Bunches Inj
Diag Bunches BC2

Emittance Monitor Tool

- Unified Emittance and Optics Tool:
  - Projected Emittance
  - Slice Emittance (not in B1)
  - on-axis measurements
  - off-axis (presently only in I1)
  - Optics Matching
  - Can load old measurement data
  - If kickers for off-axis screens are used a bunch number can be selected



DOOCS Wiki: SCM | XFEL e-Logbook

ttfinfo.desy.de/XFELelog/index.jsp

European XFEL

Status: operation up to B1D with 130 MeV, emittance studies

News: Beam in TLD Dump

13.03.17 13:34

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Figure 1945

File Ed

03.11.2019 10:49 emittance monitor tool **matching toward QI.52.I1_START**

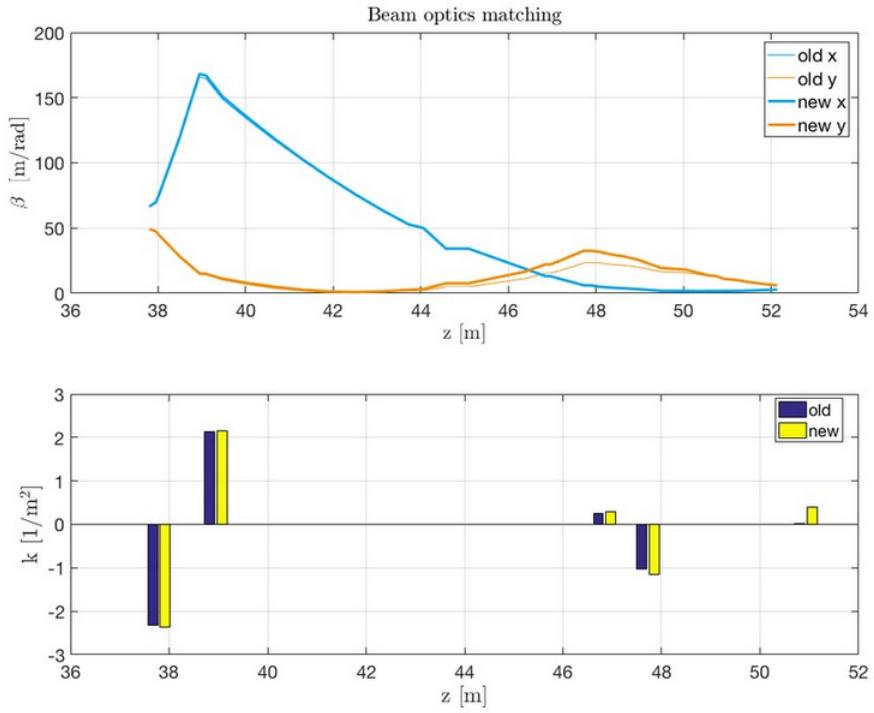
optics matching for QI.52.I1_START

twiss parameters:

	measured	target
beta x	3.342	3.132
beta x	-1.0546	-0.925
beta x	5.4576	5.417
beta x	1.7081	1.73

matching configuration:

matching quadrupole	old k [1/m^2]	new k [1/m^2]	Delta [1/m^2]	relative [%]	sign change
Q.37.I1	-2.3227	-2.3724	-0.049703	-2.1399	-
Q.38.I1	2.1256	2.148	0.02236	1.0519	-
QI.46.I1	0.26118	0.29009	0.02891	11.0692	-
QI.47.I1	-1.0309	-1.154	-0.12316	-11.9474	-
QI.50.I1	0.022027	0.39045	0.36842	1672.5703	-



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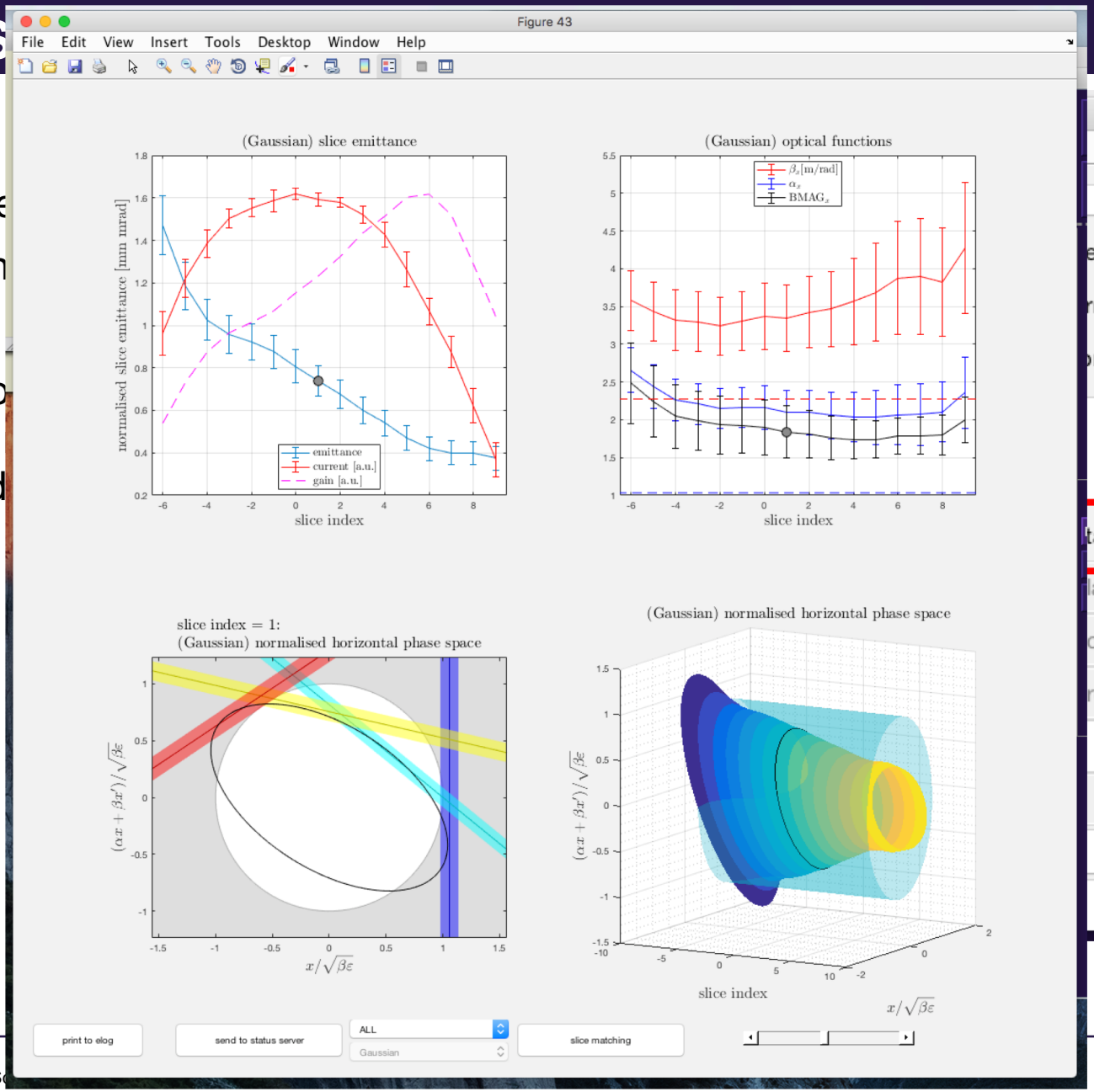


Multi Quad Scan GUI

Select a beamline section

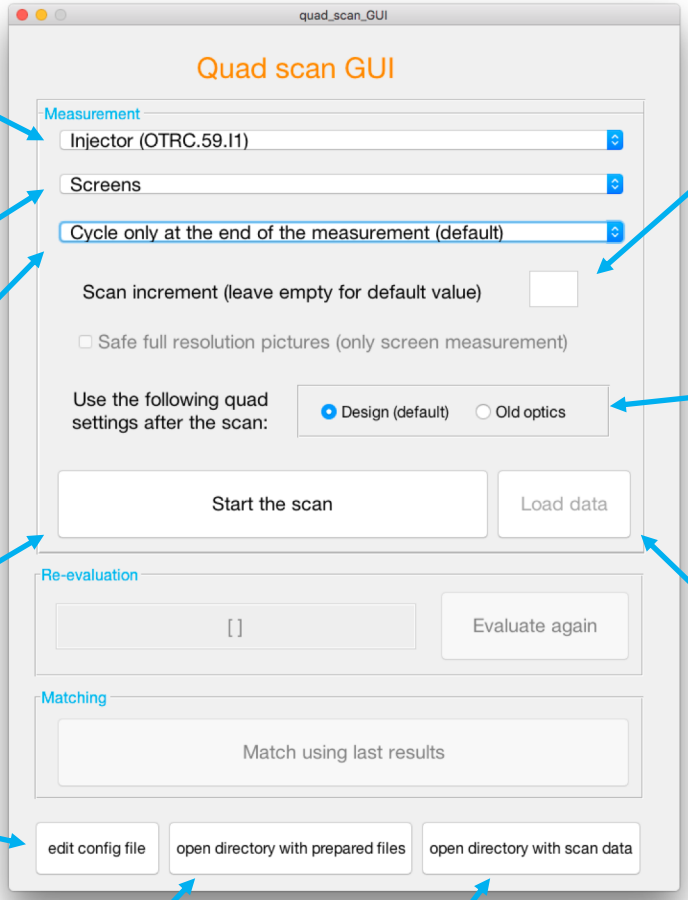
Select the measurement device: Screens or wires? The default device is automatically set for each beamline section.

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.

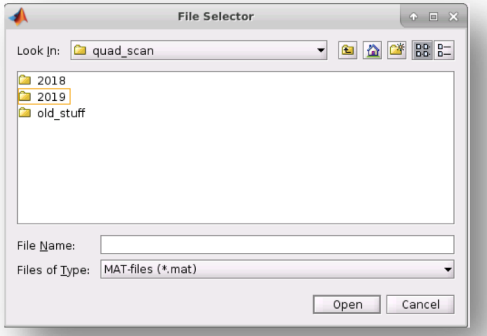


Access to all quad scan measurement data.

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

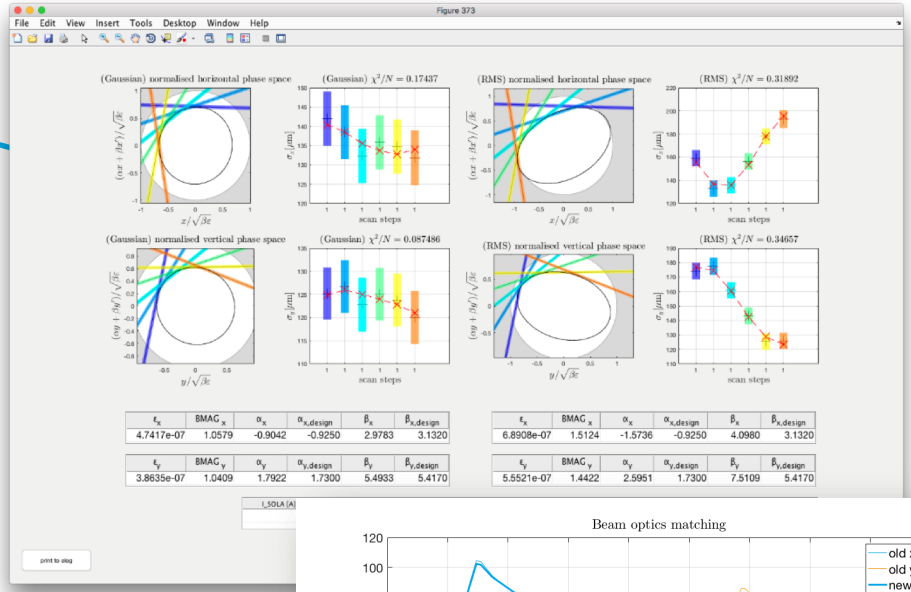
Chose beam optics after measurement: either design values or beam optics used before the measurement.

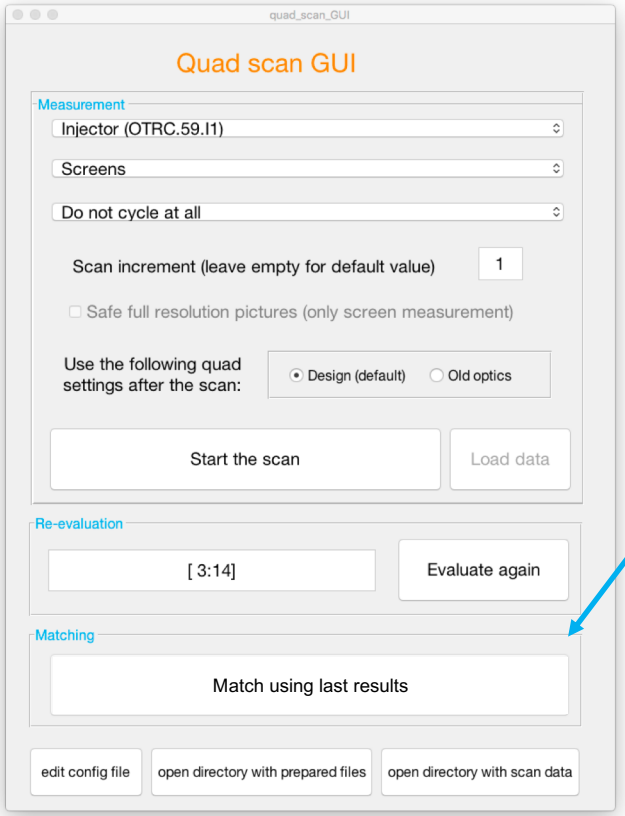
New button: load and plot old measurements. Opens a file selector GUI.



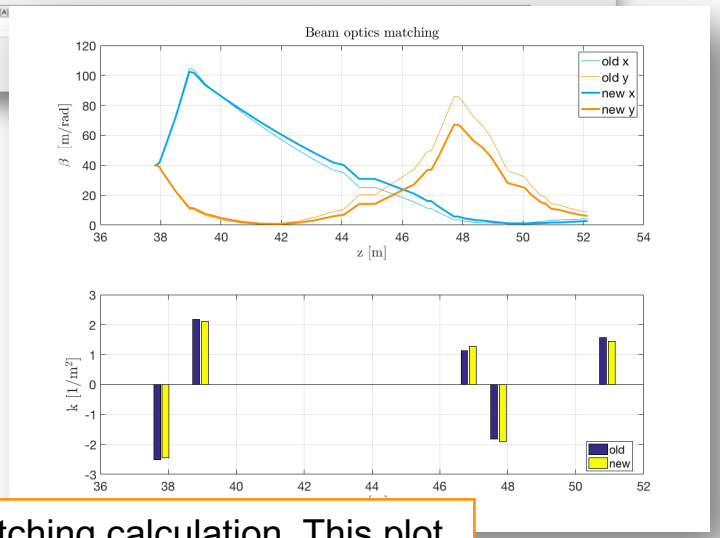
Measurement results for quad scans with screens

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





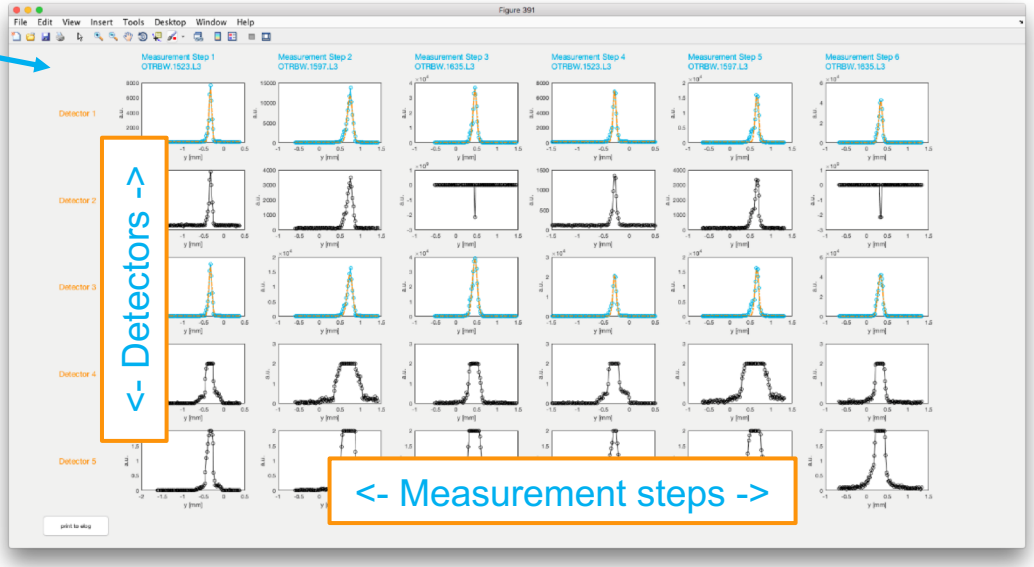
The matching routine uses either the last measurement or the last re-evaluation of the measurement data.

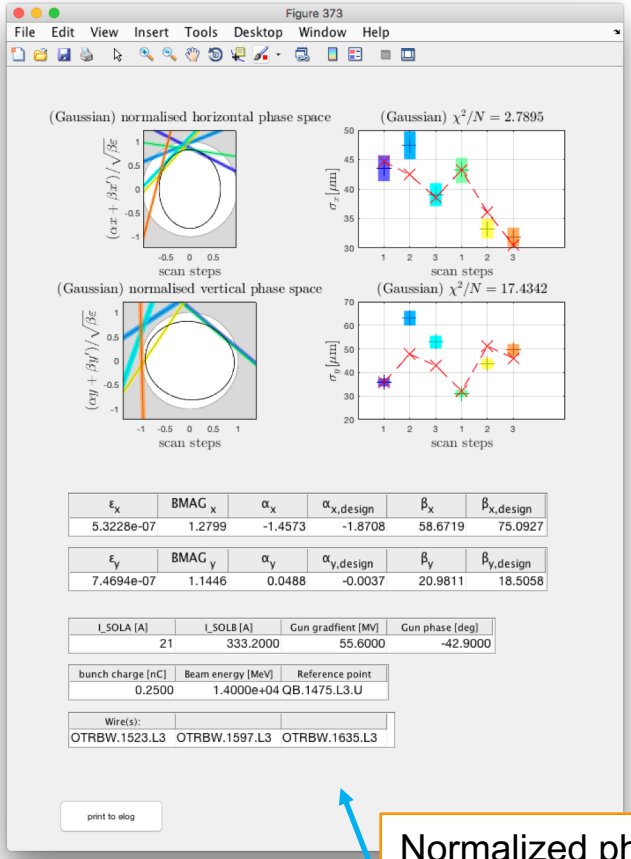


Typical result after matching calculation. This plot is only shown if the algorithm found a solution.

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 gradient [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

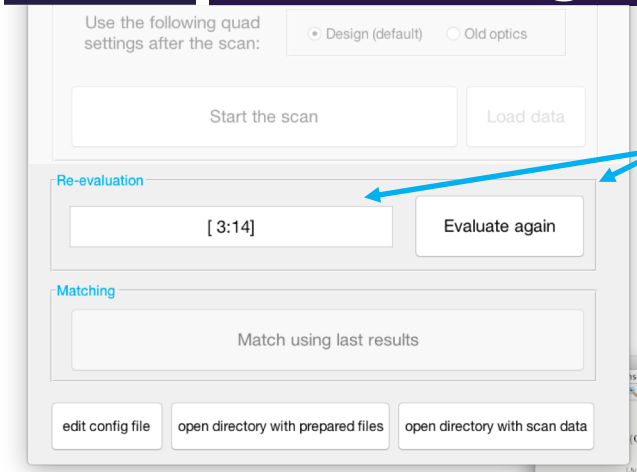
Wire(s):		
OTRBW.1523.L3	OTRBW.1597.L3	OTRBW.1635.L3

- 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.

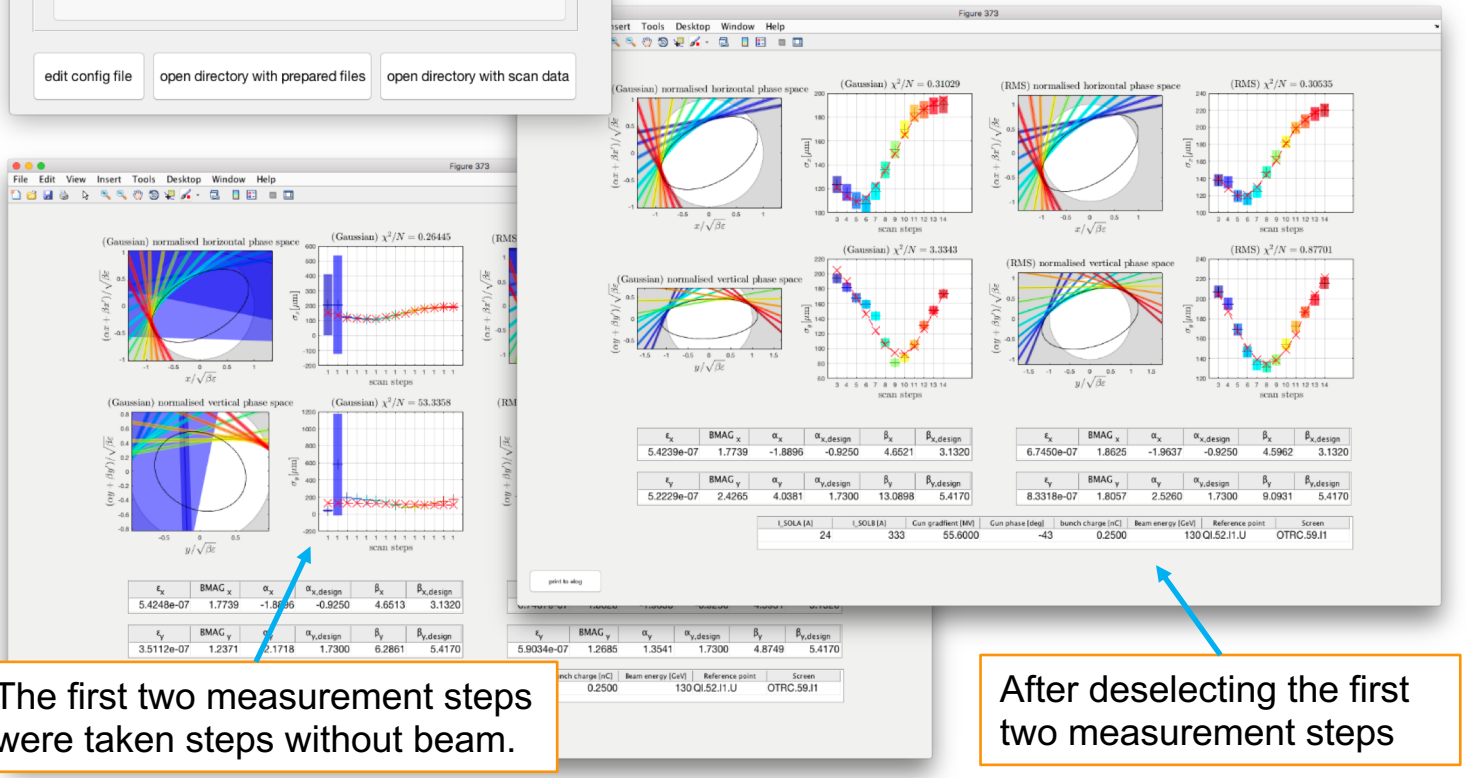
Normalized phase spaces and beam sizes as well crucial scan parameters from the measurement.

European XFEL

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.

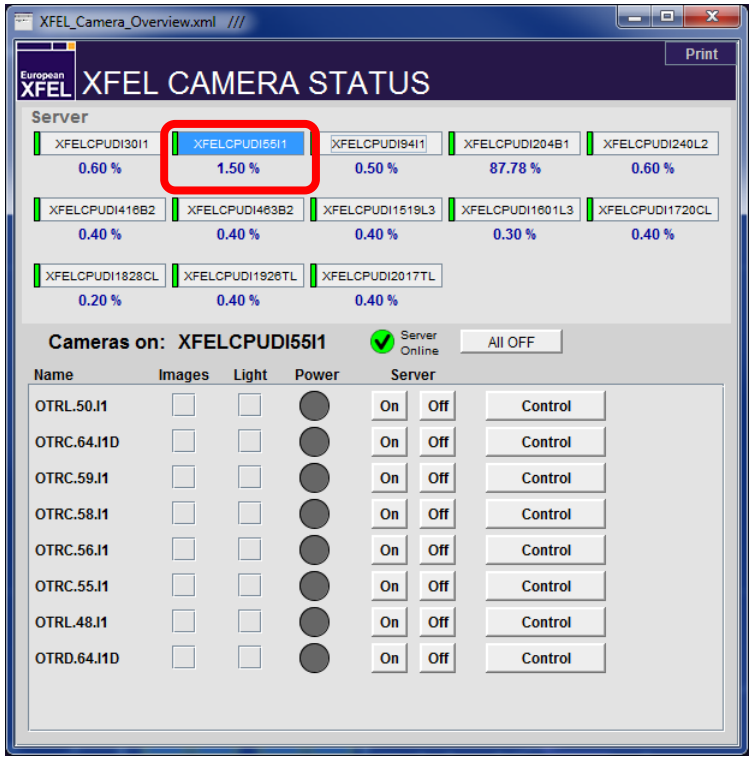
After deselecting the first two measurement steps

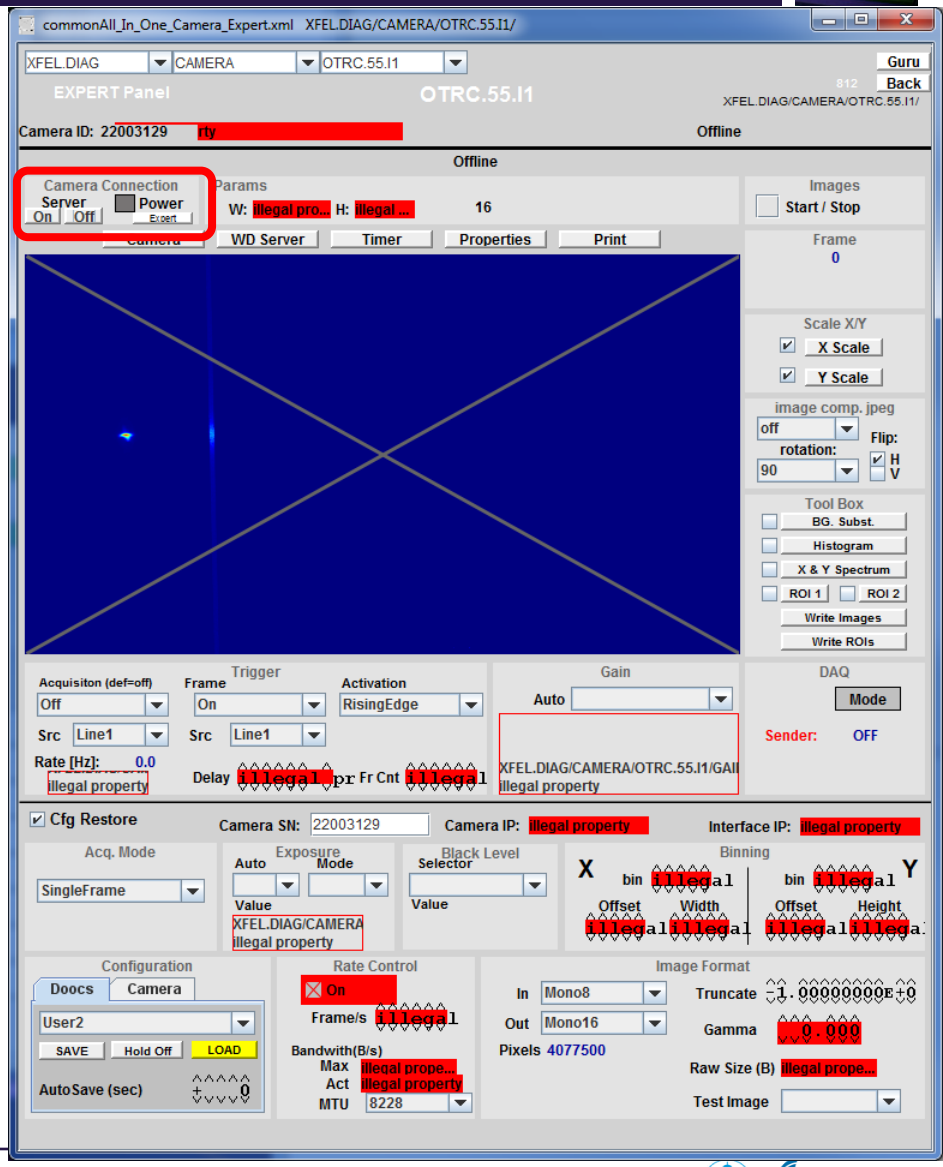
Be careful with the deselection of measurement steps and with the following evaluation of the data!

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!

Camera Server Issues

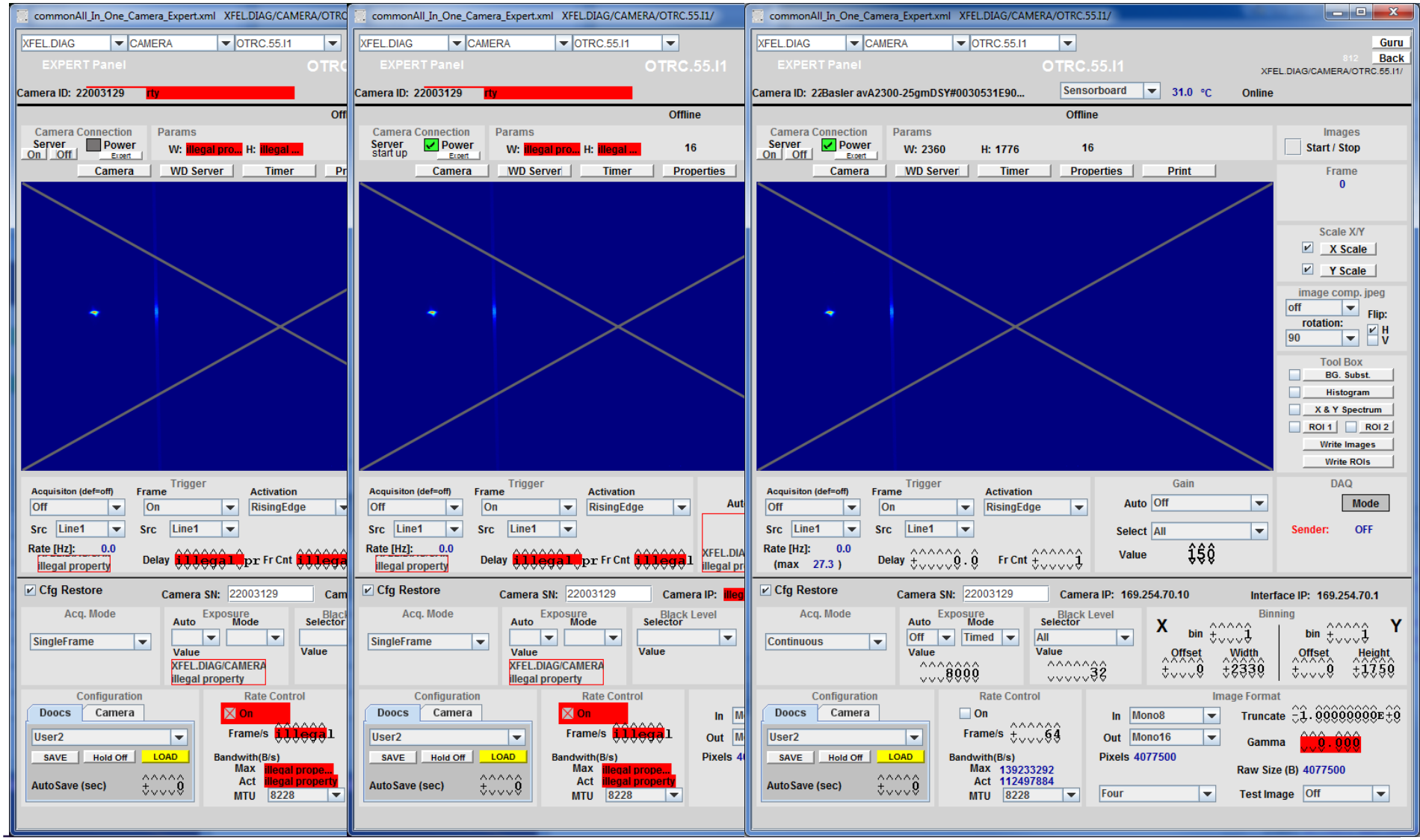




- Check CPU load
- Only the 4 cameras in the section should be powered
- Deactivate image acquisition

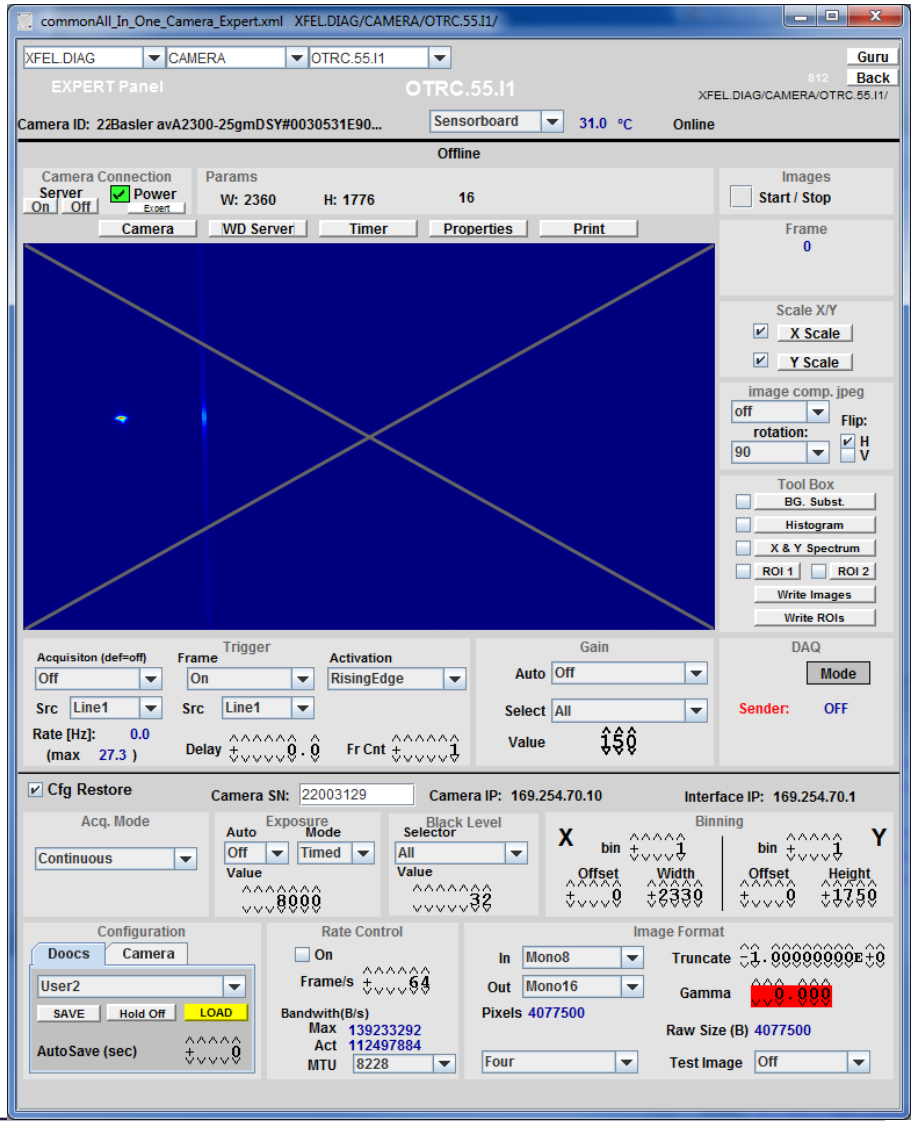
European XFEL

Camera (Server) Startup



Camera Default Values

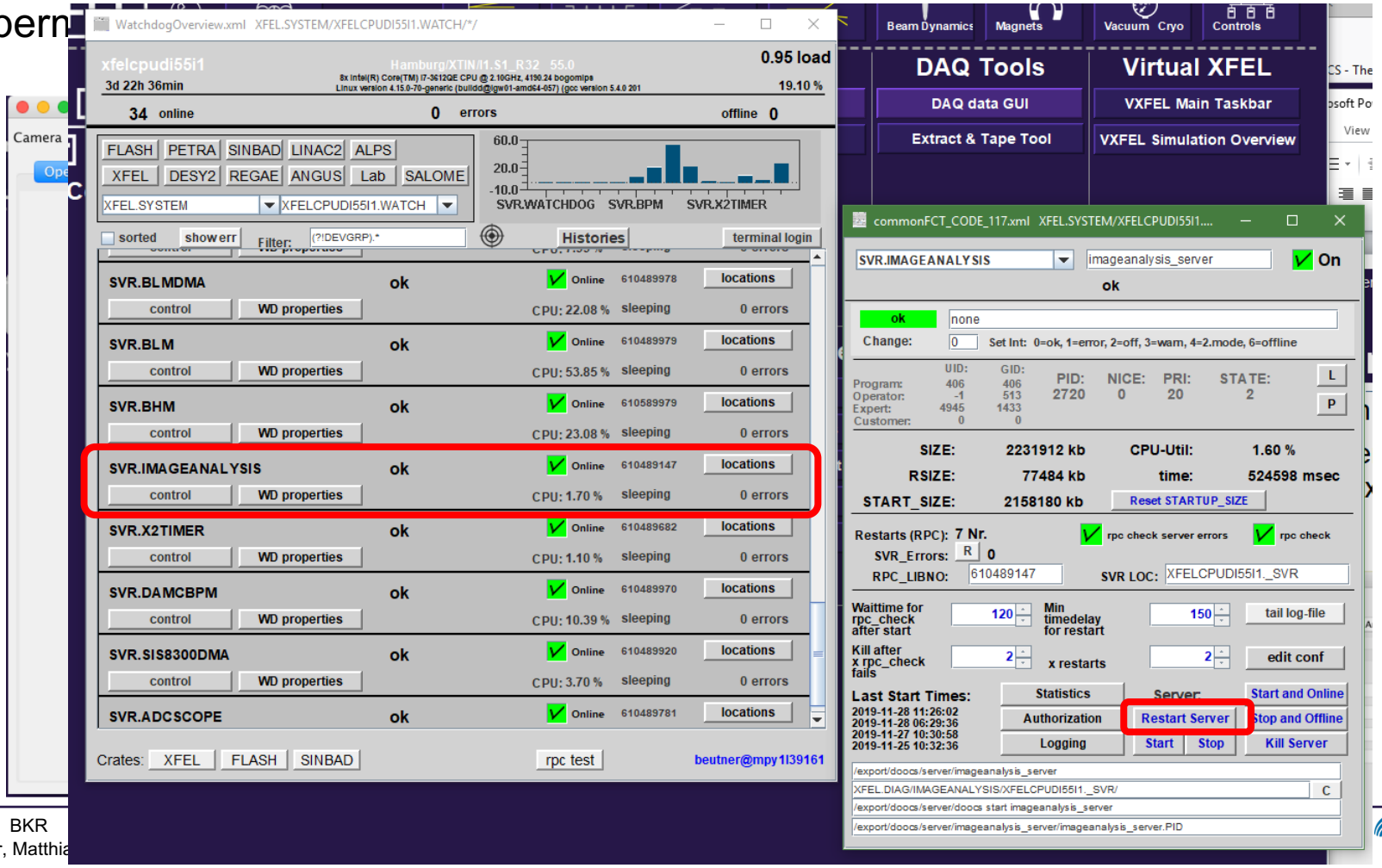
- Default Values of cameras are set if Emittance Monitor is used to activate them
- Proper settings:
  - IN: Mono12Packed
  - OUT: Mono16
  - Truncate: -1
  - Exposure: maximum 1000
  - Acquisition: off
  - Frame: on
  - “Tool Box” checkboxes: off



European XFEL

Image Analysis Server Expert Tool

- Check if you can see images updating in “Continuous” mode
- In case of problems => restart image analysis server via the Doocs watchdog (call expert RC, BB, J. Wilgen, or any controls person with perm



Camera Lifetime

- Cameras die fast!
  - On average each camera was exchanged once during the injector run
  - Deactivate cameras every time you don’t need them for a foreseeable time
  - Emittance Monitor Tools gives a list off all activated emittance cameras at shutdown and offers to close them
  - Do it….


Quit
Yes
No
Cancel

Thank You for Your Attention…

Literature:

- M. Minty and F. Zimmermann, “Measurements and control of charged particle beams”, Springer, Berlin, Heidelberg, New York, 2003.
- F. Loehl, “Measurements of the Transverse Emittance at the VUV-FEL”, DESY-THESIS 2005-014, TESLA-FEL 2005-03
- J. Rossbach and P. Schmueser, “Basic Course on Accelerator Optics”

Measurement Theory

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

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

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

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

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

In an ideal measurement three data points are sufficient:

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

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

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

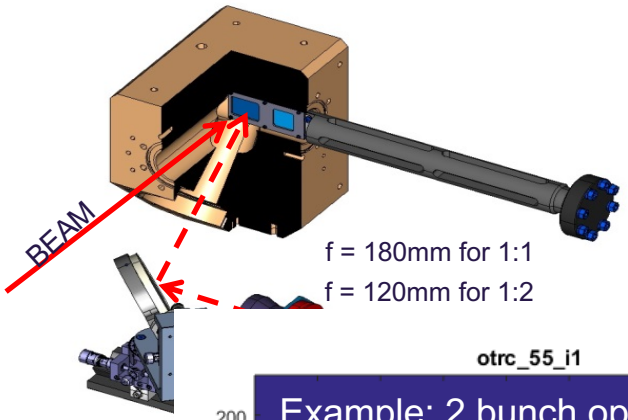
unknowns to be determined by the measurement

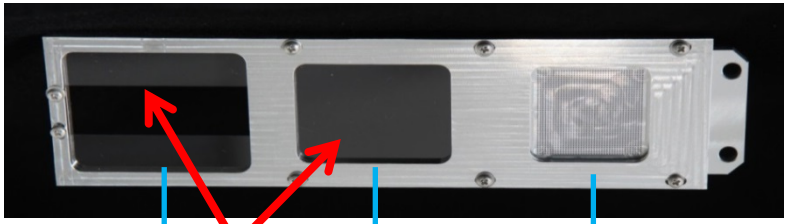
determined by diagnostics (screens / Image Analysis Server/ wire-scanner)

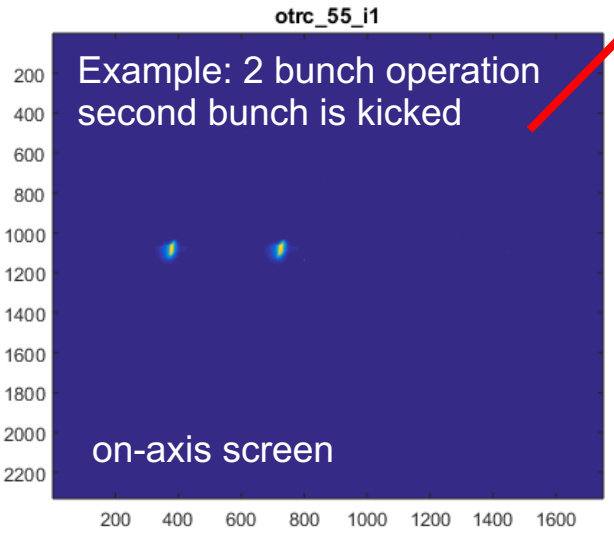
provided by beam dynamics (Optics Server)

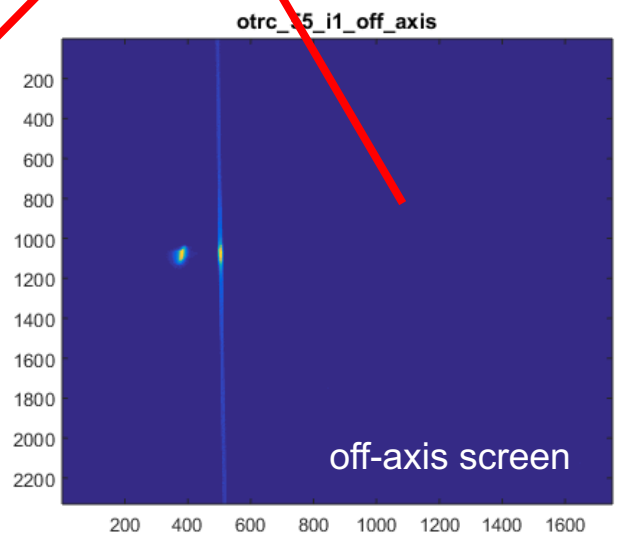
Screen Station for European XFEL

- monitor setup

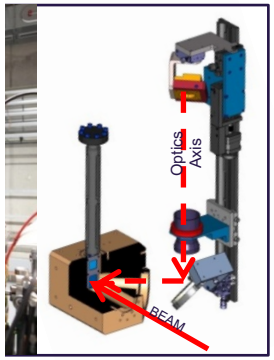




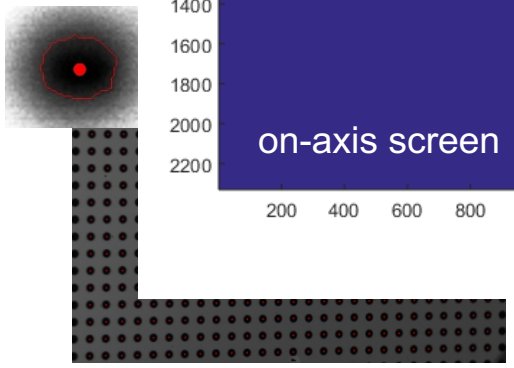


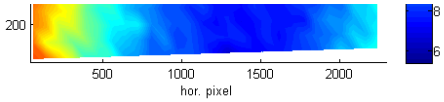


II installation



- optical





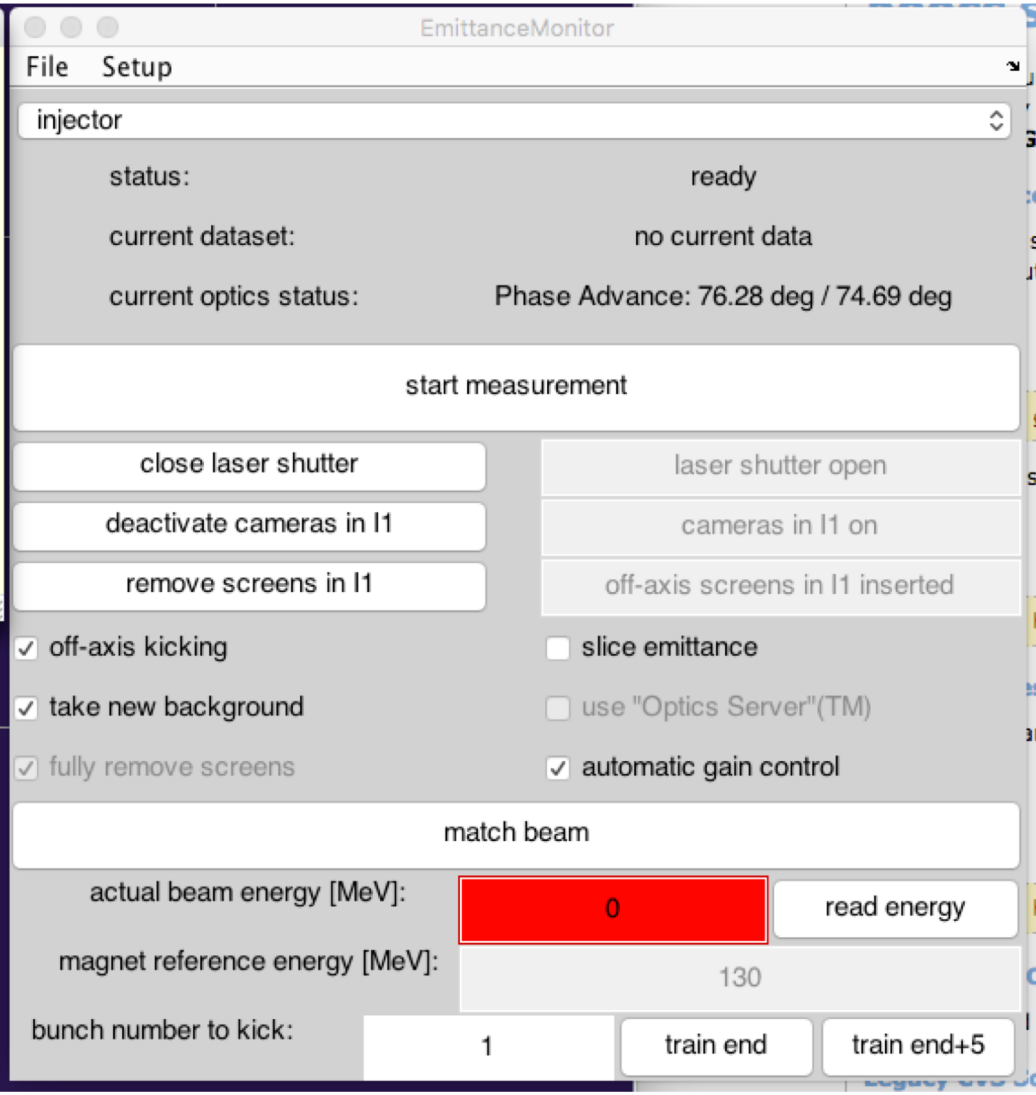
on geometry

lution
unction)

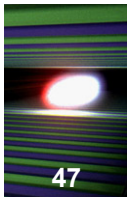
Slide thanks to G. Kube

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

Tool at Start-up



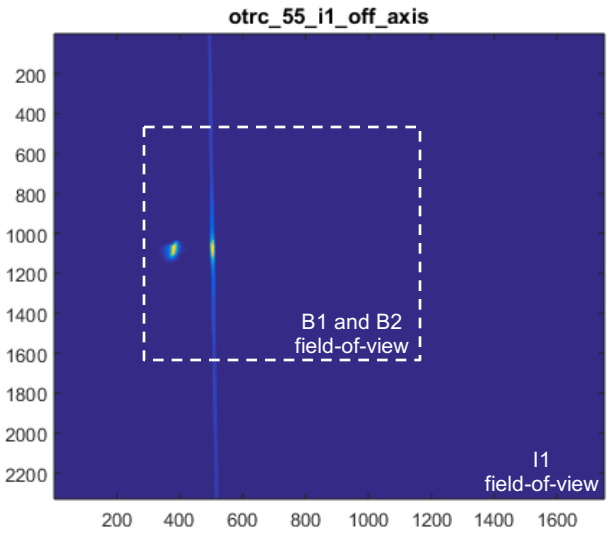
Problems



- Screens Inserted correctly / Cameras activated / …
  - Use buttons on the tool
- Is the Orbit good?
  - Check if beam is on screen?
  - In case of off-axis measurement try on-axis
  - or start kickers manually
- Are the magnets properly set?
  - Strength and magnet energy
    => check phase advance
    - » projected emittance: (76/76) deg
    - » slice emittance: (76/45) deg
- Are the cameras working properly?
- Is the Image Analysis Server in operation?
  - ROI configuration?

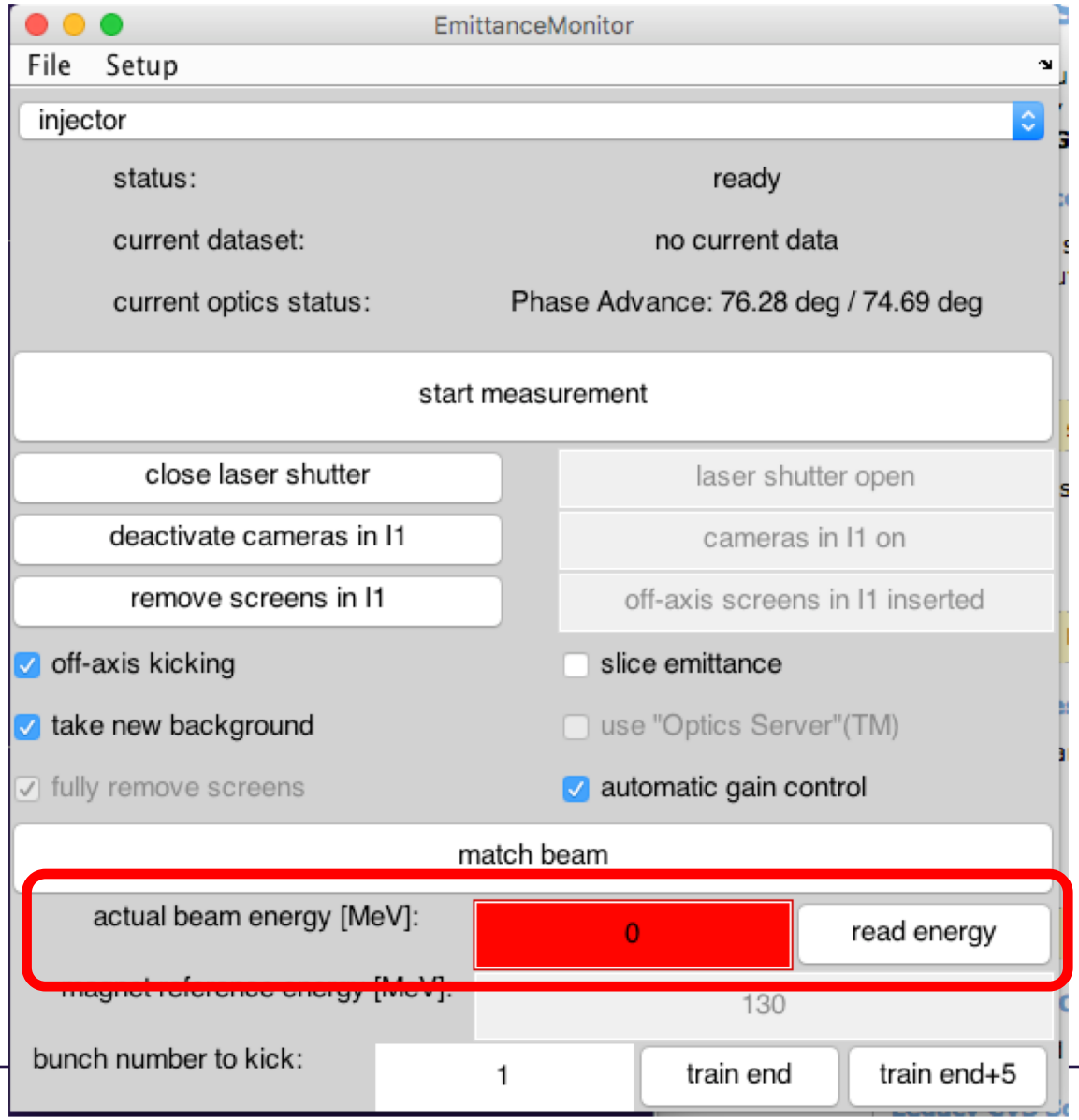
Orbit Problems

- Area of off-axis screens is smaller
  - Make sure the kicked beam hits them

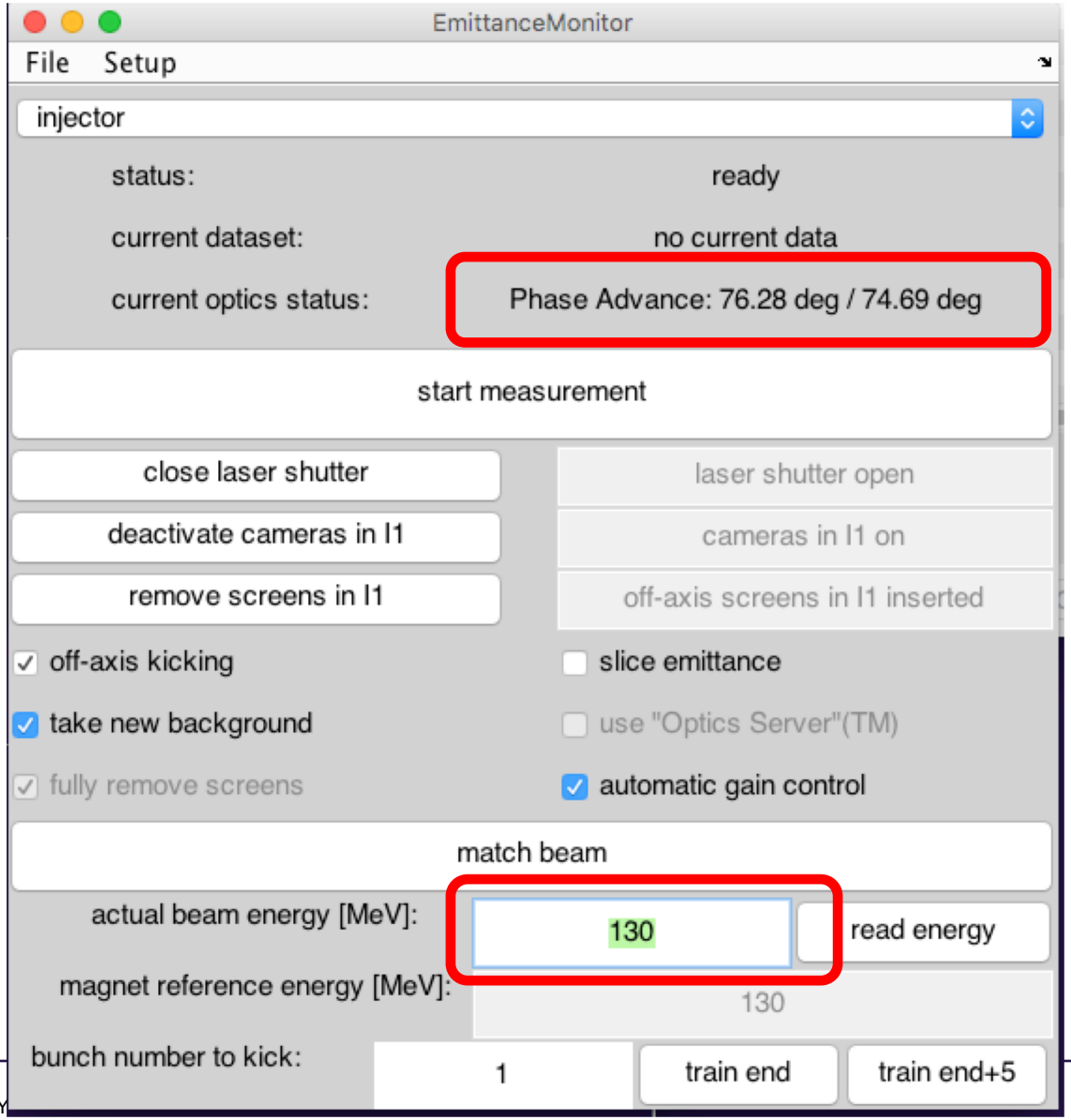


- Screens in B1 and B2 are of the same size but the imaging on the chip is 1:1 (factor 2 in each plane compared to I1)
  - Field-of-view is 2.54 cm in diagonal
  - If beam is not visible insert screen in question and move beam with orbit correctors

Energy Setup

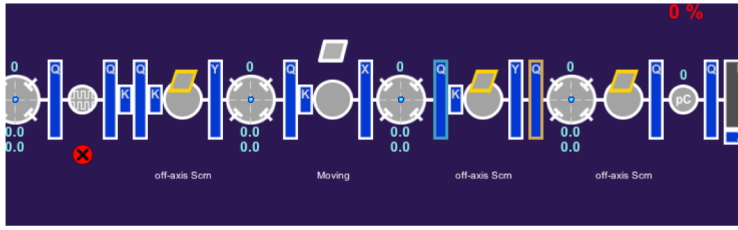


Manual Setting of energy

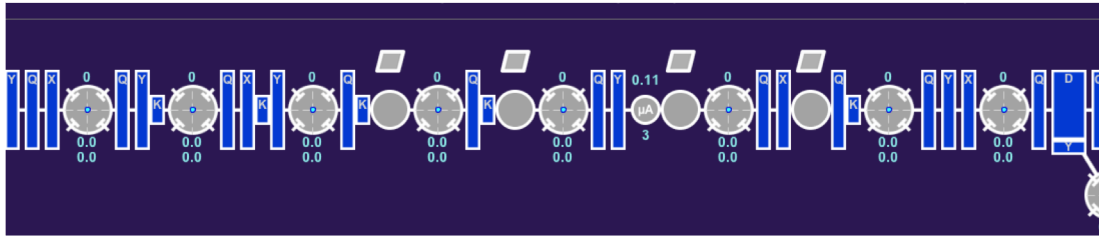


FODO Configurations

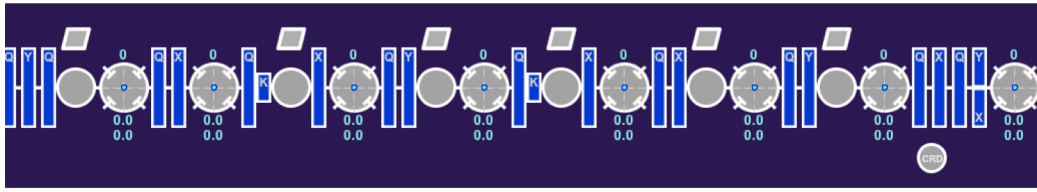
- I1 from 55 to 59m (horizontal kick)
  - Projected: (76/76) deg
    - → Gen. kick = (-0.8382, +0.8382, -0.8382) rad/m
  - Slice: (76/45) deg
    - → Gen. kick = (-0.6271, +0.7792, -0.6271) rad/m



- B1 from 219 to 226m (vert. kick)
  - Projected: (76/76) deg
    - → Gen. kick = (+0.6769, -0. 6769, +0. 6769) rad/m

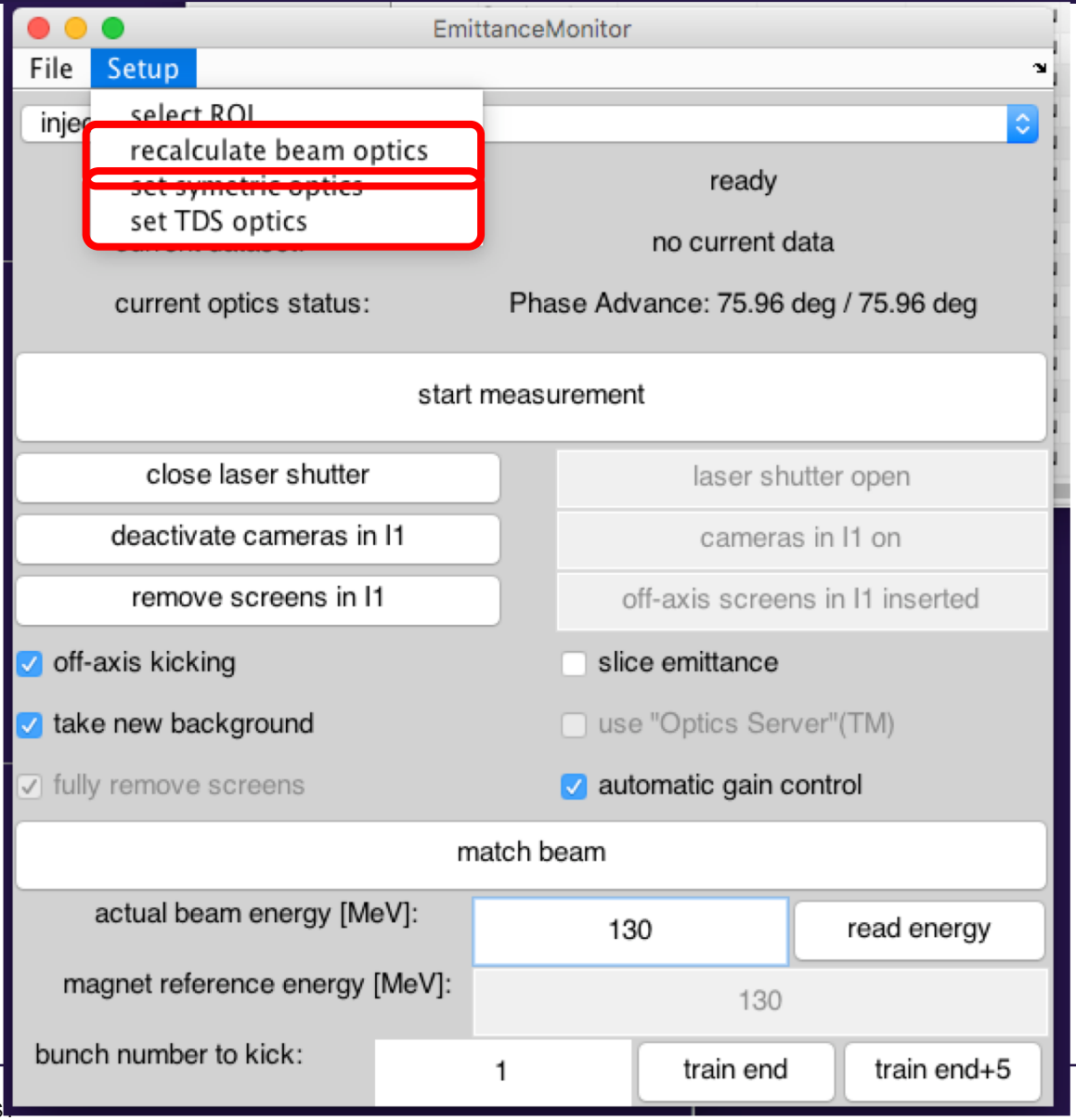


- B2 from 444 to 459m (vert. kick)
  - Projected: (76/76) deg
    - → Gen. kick = (+0.3310, -0.3310, +0.3310) rad/m

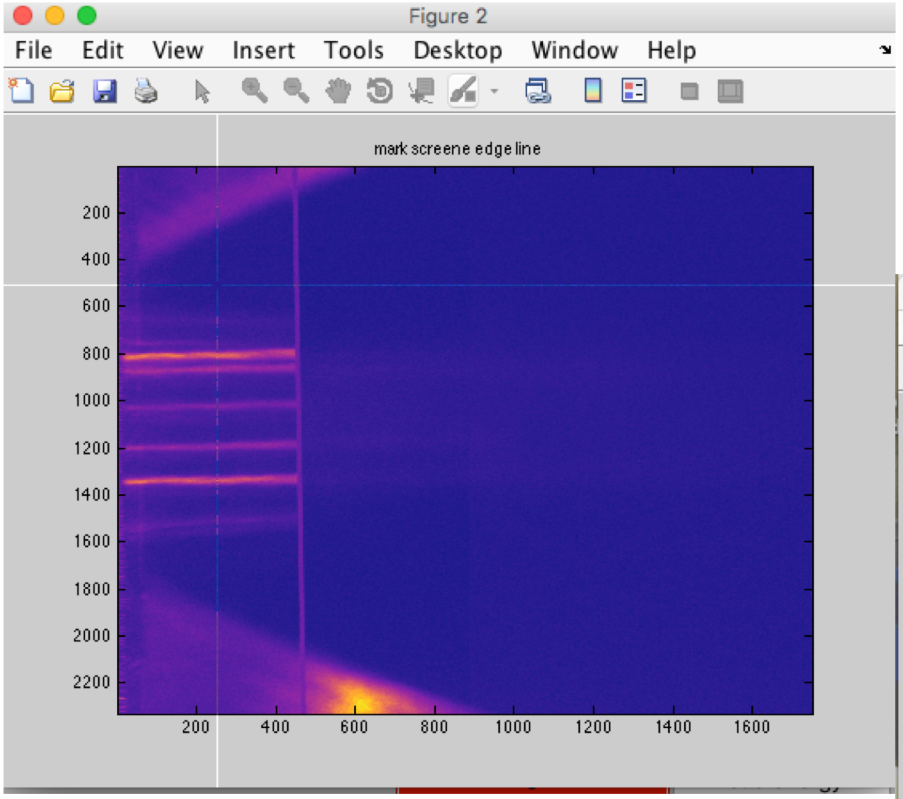


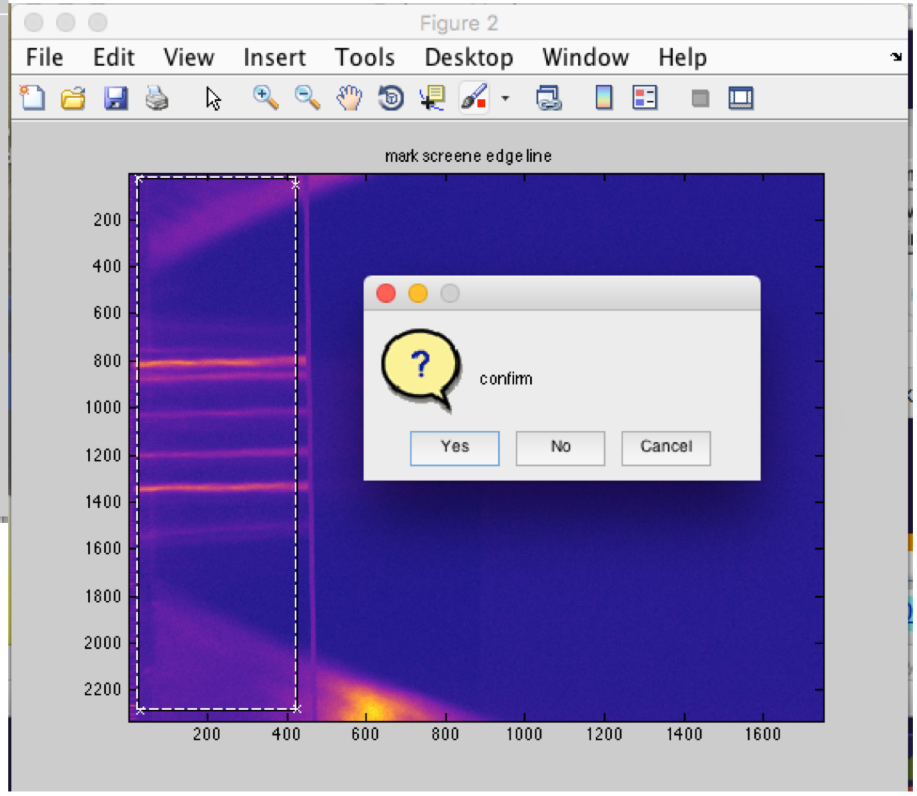
- If phase advance values are not correct check magnets and energy – and recalculate optics model in tool!

Optics Options

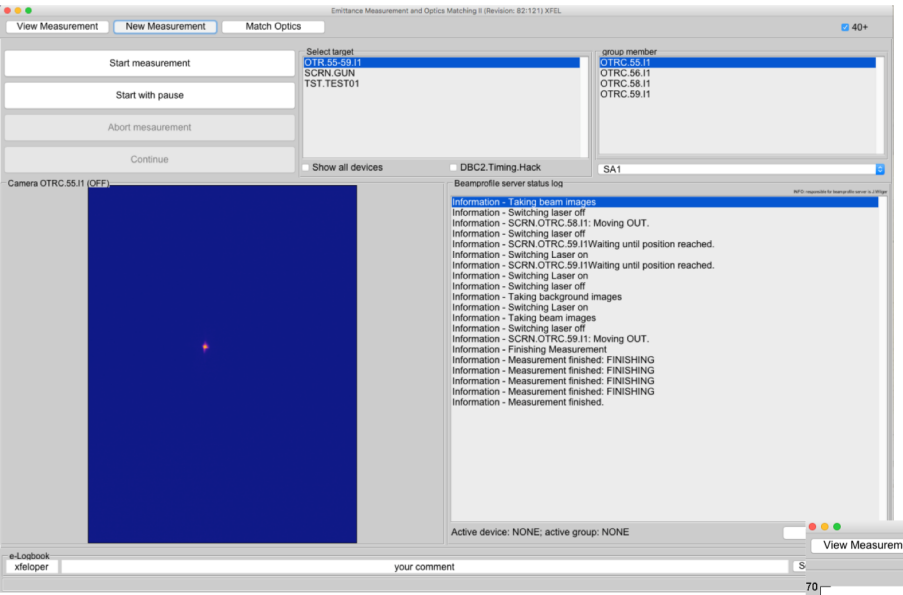


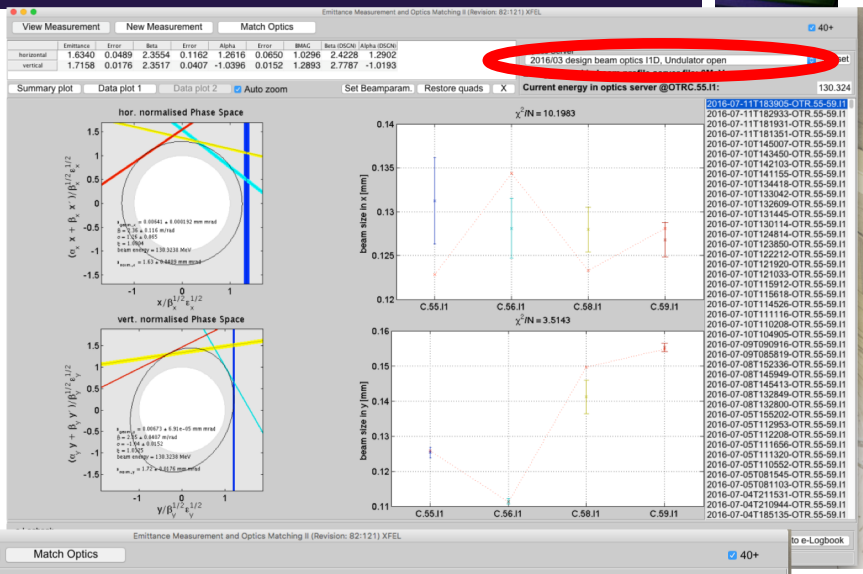
ROI Configuration Tool

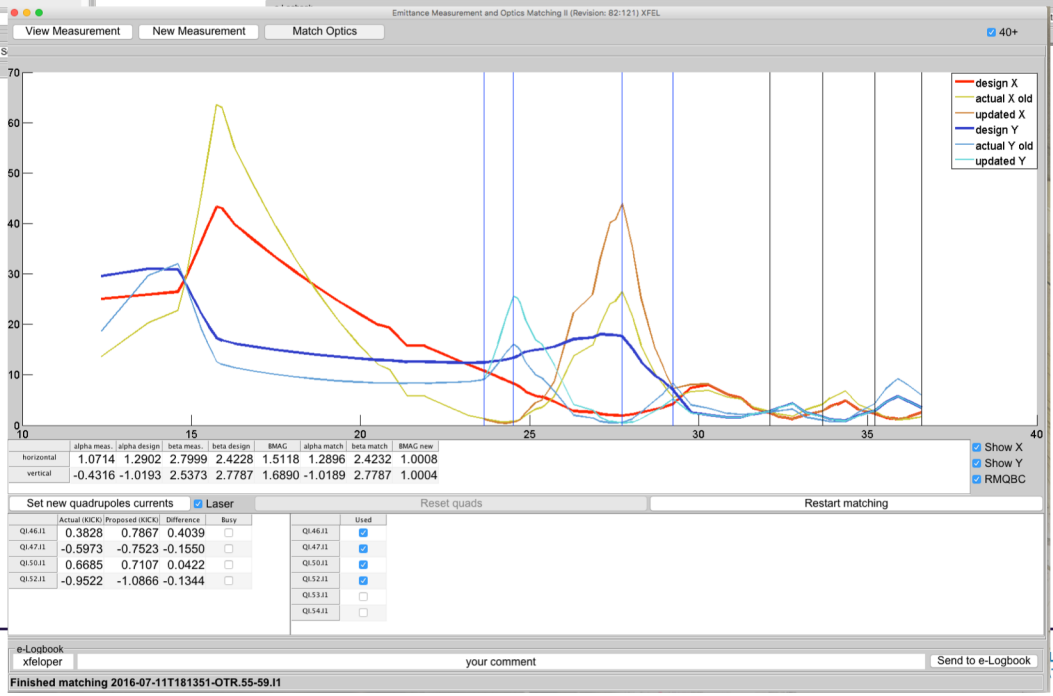




On-Axis Projected Measurements



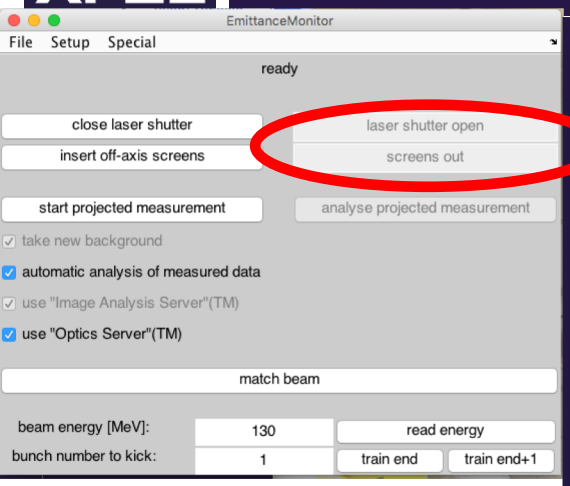


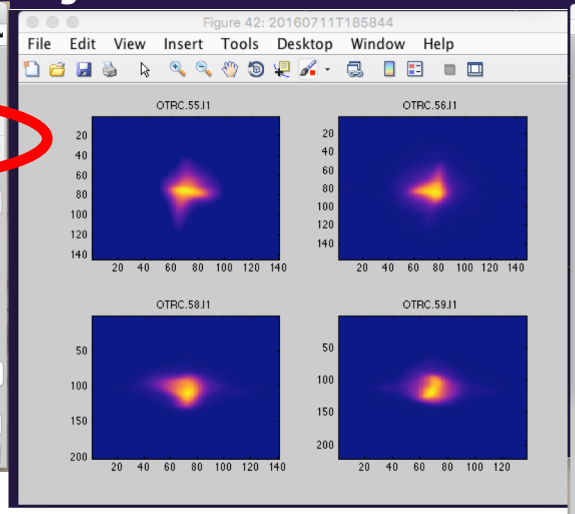


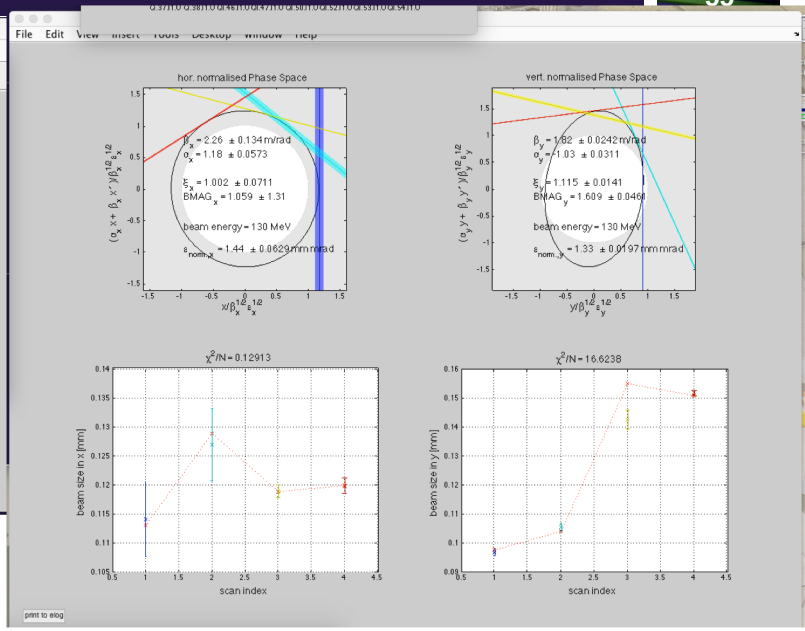
- Most reliable
- Takes more time than other methods (~ 5 minutes)
- Does not require kickers or TDS systems operational
- Only first bunch
- Should be the first choice for startup after shutdown etc.

European XFEL

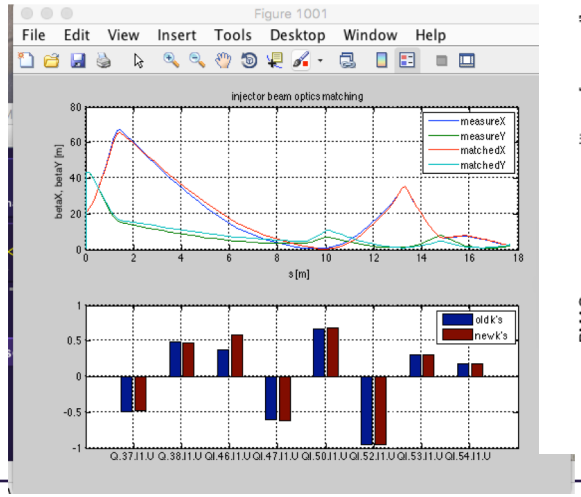
Off-Axis Projected Measurements

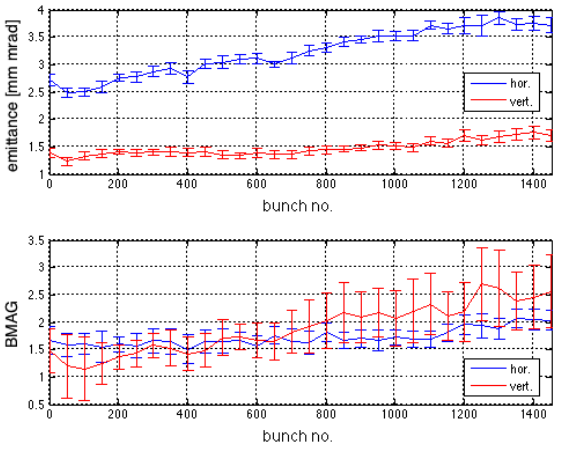






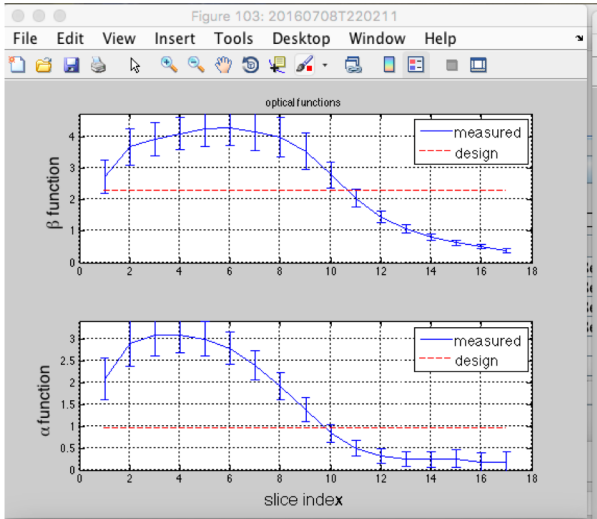
- Use of kickers allows for much faster measurements (about 20s)
- Orbit and optics mismatch needs to be good
- Allows for measurements of other than the first bunch
- Make sure that the energy chirp is removed
- Main tool for tuning of projected emittance

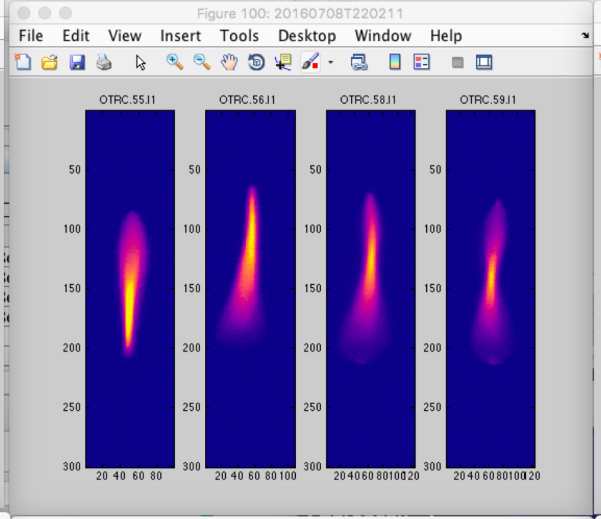


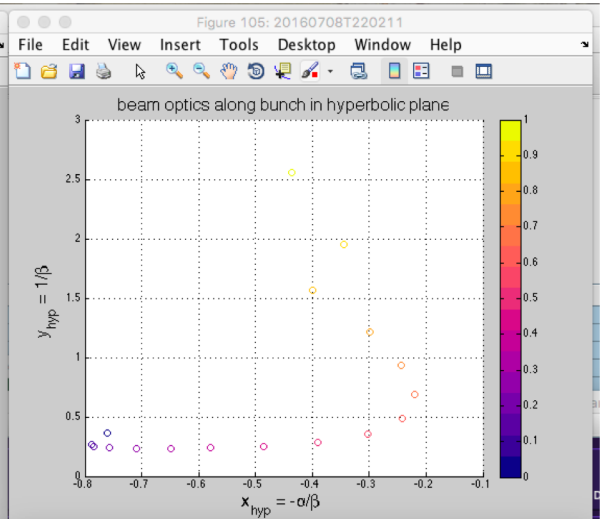


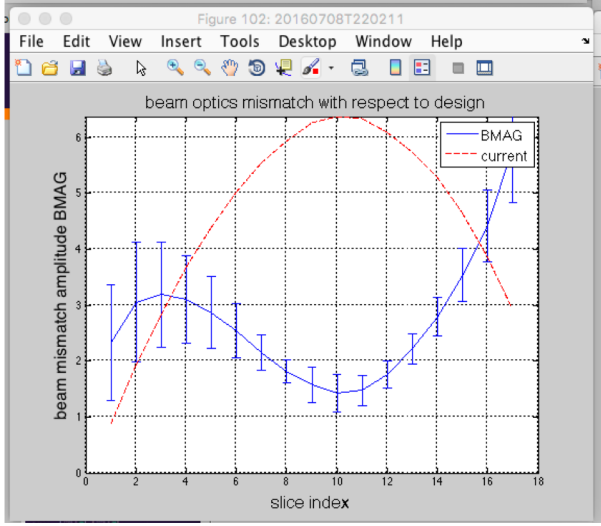
European XFEL

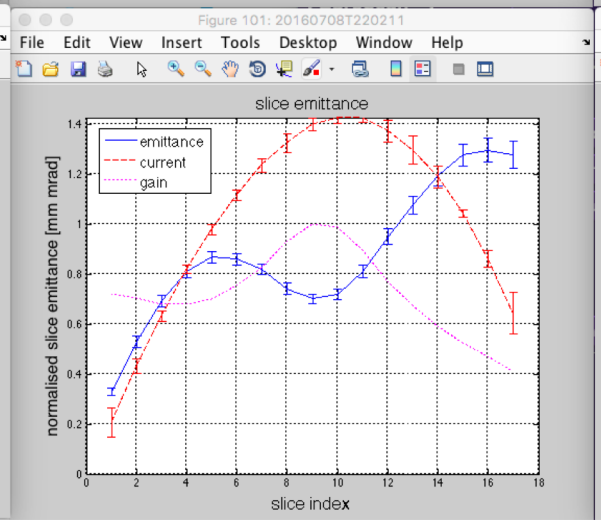
Slice Emittance Measurements

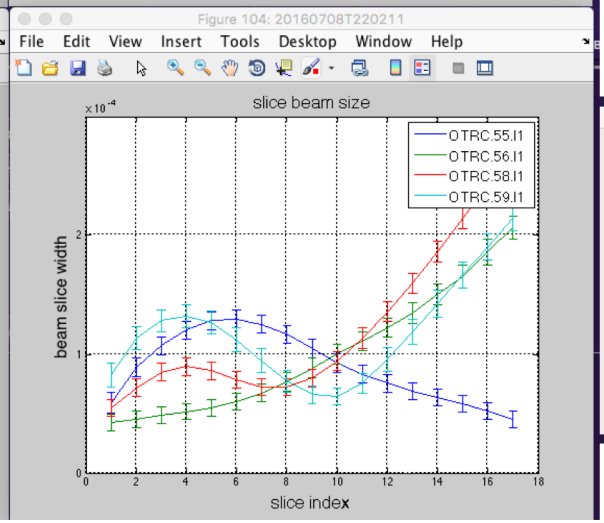




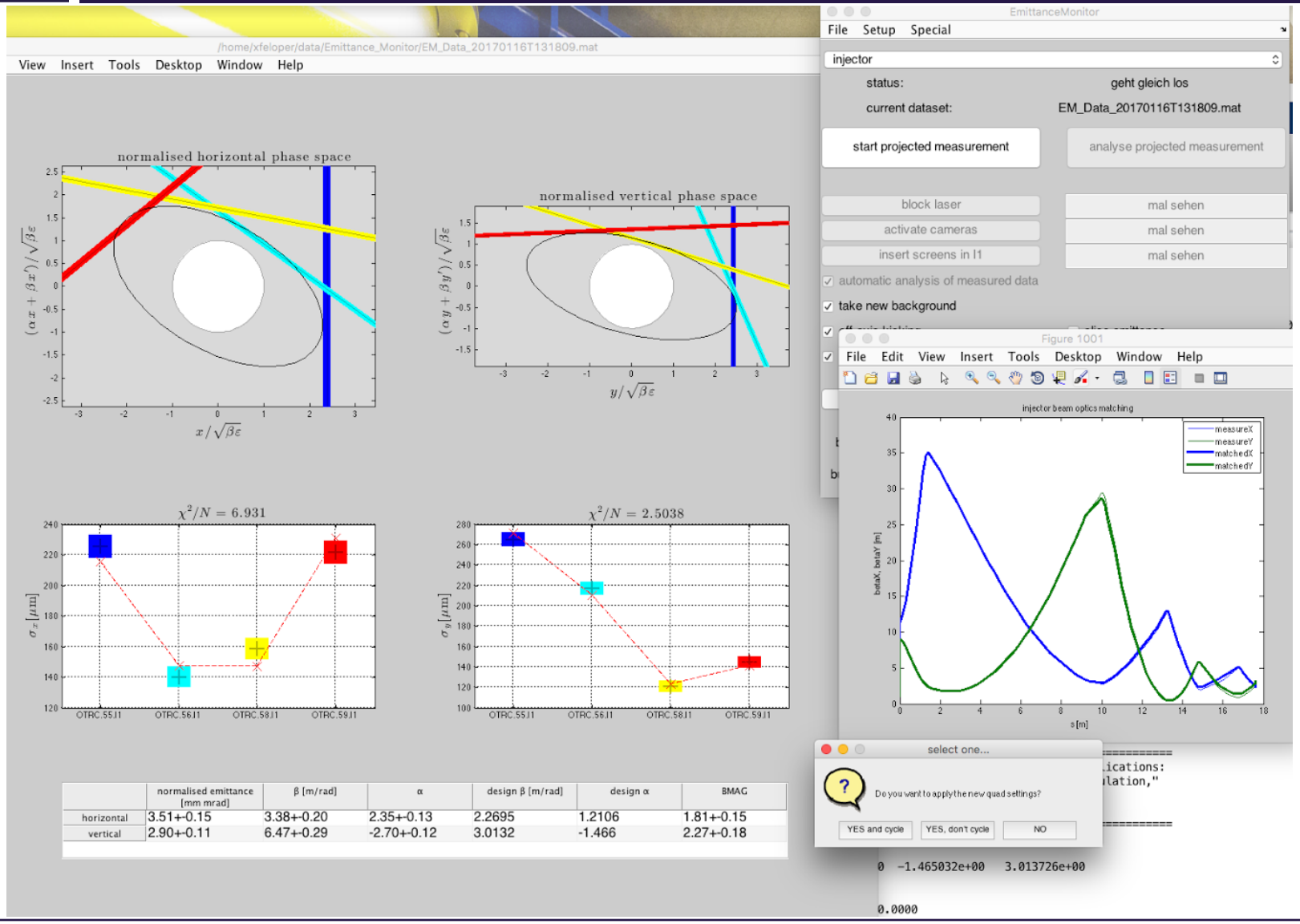




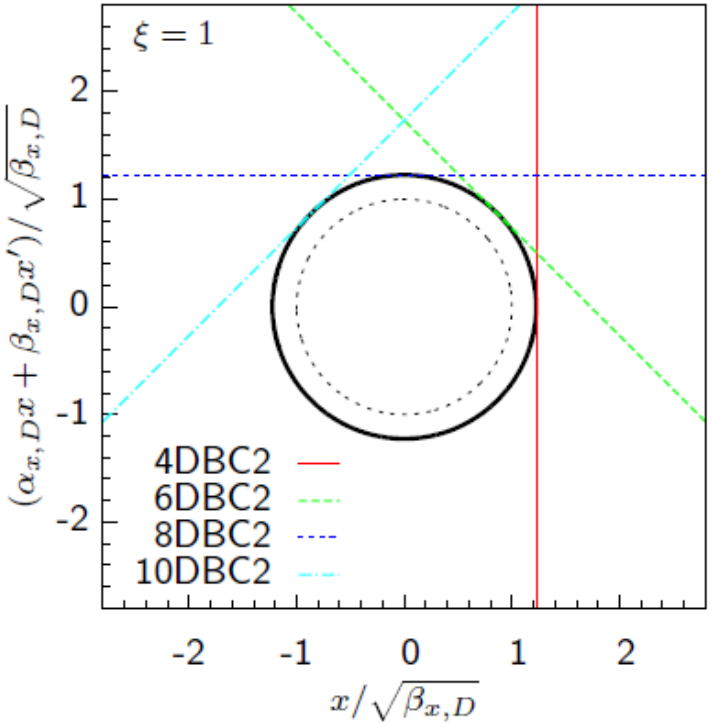


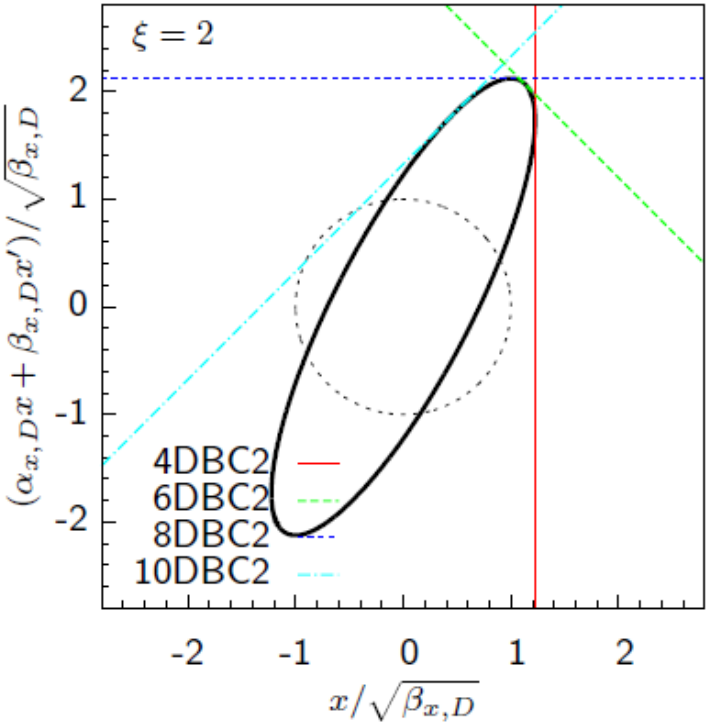


Combined Tool Results



	normalised emittance [mm mrad]	β [m/rad]	α	design β [m/rad]	design α	BMAG
horizontal	3.51+-0.15	3.38+-0.20	2.35+-0.13	2.2695	1.2106	1.81+-0.15
vertical	2.90+-0.11	6.47+-0.29	-2.70+-0.12	3.0132	-1.466	2.27+-0.18


$\xi = 1$
$(\alpha_{x,D}x + \beta_{x,D}x')/\sqrt{\beta_{x,D}}$
$x/\sqrt{\beta_{x,D}}$
4DBC2
6DBC2
8DBC2
10DBC2


$\xi = 2$
$(\alpha_{x,D}x + \beta_{x,D}x')/\sqrt{\beta_{x,D}}$
$x/\sqrt{\beta_{x,D}}$
4DBC2
6DBC2
8DBC2
10DBC2

Measurement errors

- A mismatched beam (with respect to design optics) is not only bad because of the resulting unknown beam transport – a mismatched beam makes the measurement itself unreliable
- If the beam is well matched in a periodic measurement lattice statistic beam size errors contribute with equal weights and partially compensate each other
- Do not trust measurements with mismatch higher than BMAG = 2
- Beam should be matched to BMAG < 1.1

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

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

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