OTR Emittance experience at ATF2

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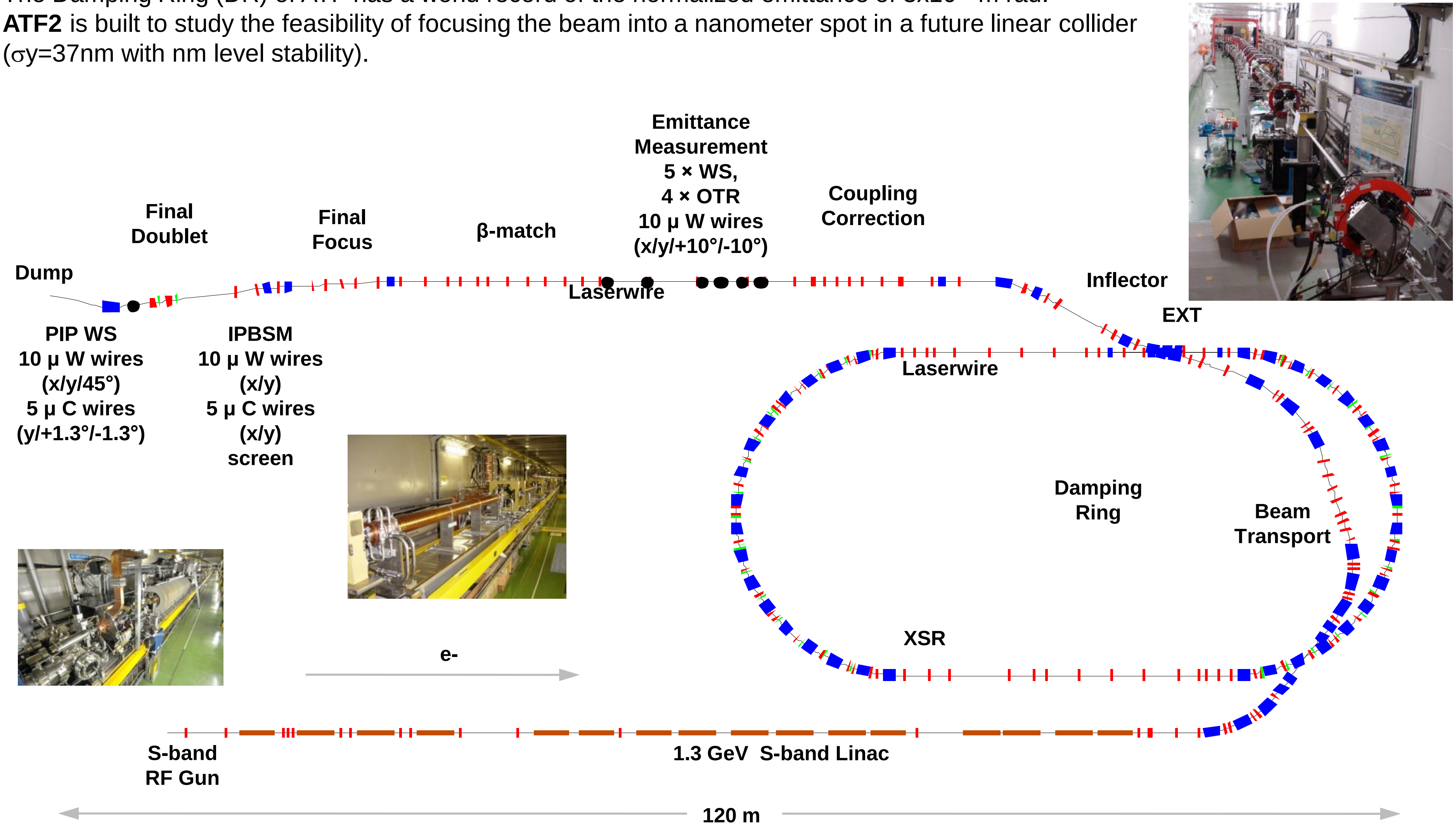
Multi-OTR System Outline

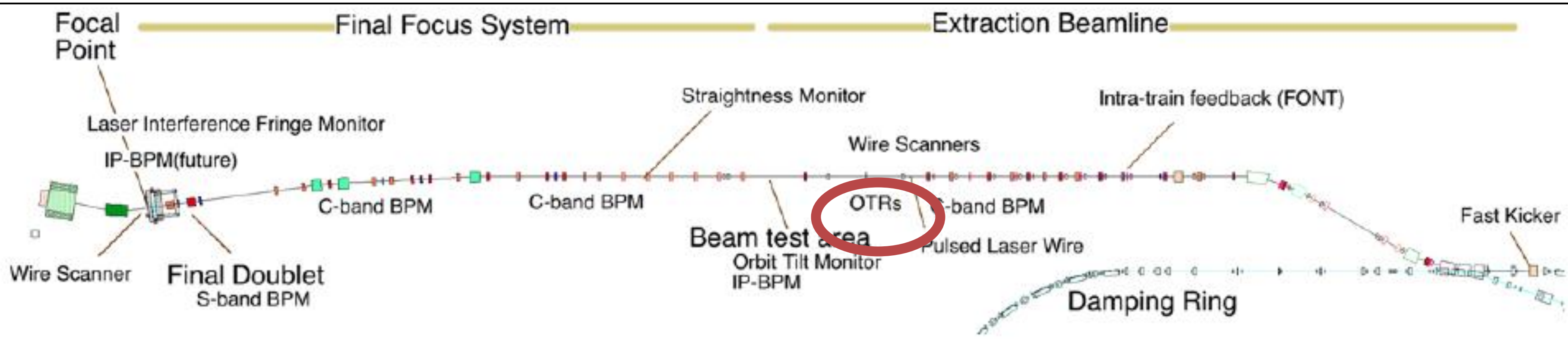
- Overview and Description
- Construction, Installation and first calibration test
- First Software Developments
- New Hardware Implementation: Demagnifier system
- Emittance reconstruction
- Coupling correction
- Systematic measurements

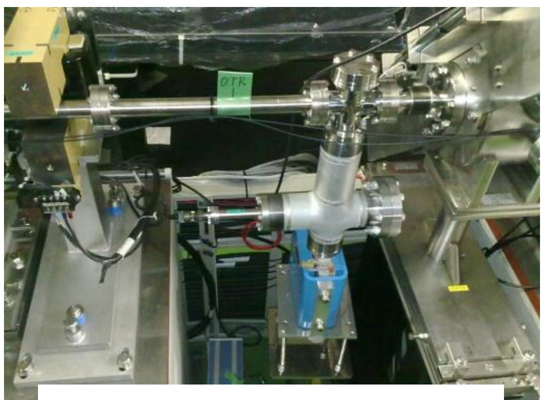
ATF/ATF2 Overview

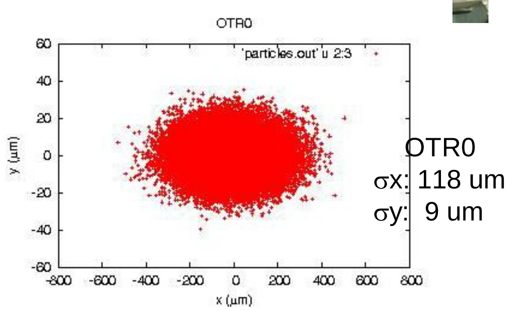
The Accelerator Test Facility (**ATF**) was built in KEK (Japan) to create small emittance beams.
The Damping Ring (DR) of ATF has a world record of the normalized emittance of 3×10^{-8} m rad.
ATF2 is built to study the feasibility of focusing the beam into a nanometer spot in a future linear collider (σy=37nm with nm level stability).



Multi-OTR System Overview

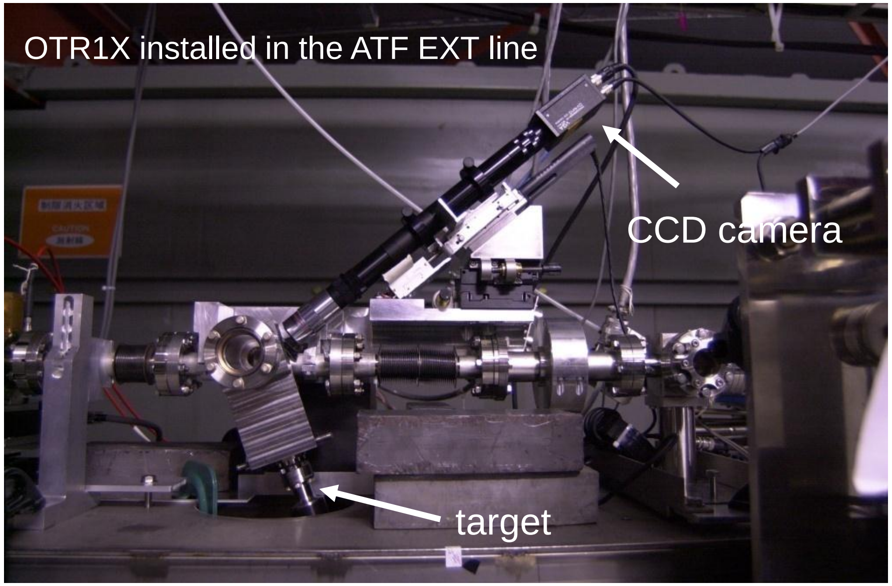


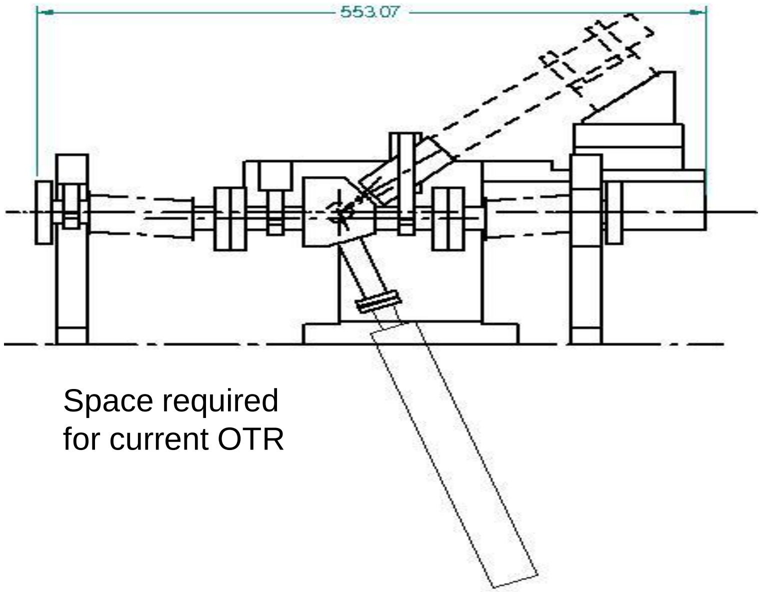




- The multi-OTR system is made of **4 OTRs** installed in the zero-dispersion part of ATF2 EXT line
- **Fast emittance measurements** (single shot for beam size, 1min for emittance) with high statistics with **2um measurement capabilities** with **$2x10^{10}$ single bunch** and **$2x10^{11}$ for 20 multi-bunched beam** (2.8 ns spacing)
- Design based on OTR1X at ATF EXT line (**5um resolution with $2x10^{10}$)** with improved features (compactness, calibration setup and demagnifier system)
- **Installed near WS** for comparison and confirmation of OTR as a beam emittance diagnostic device

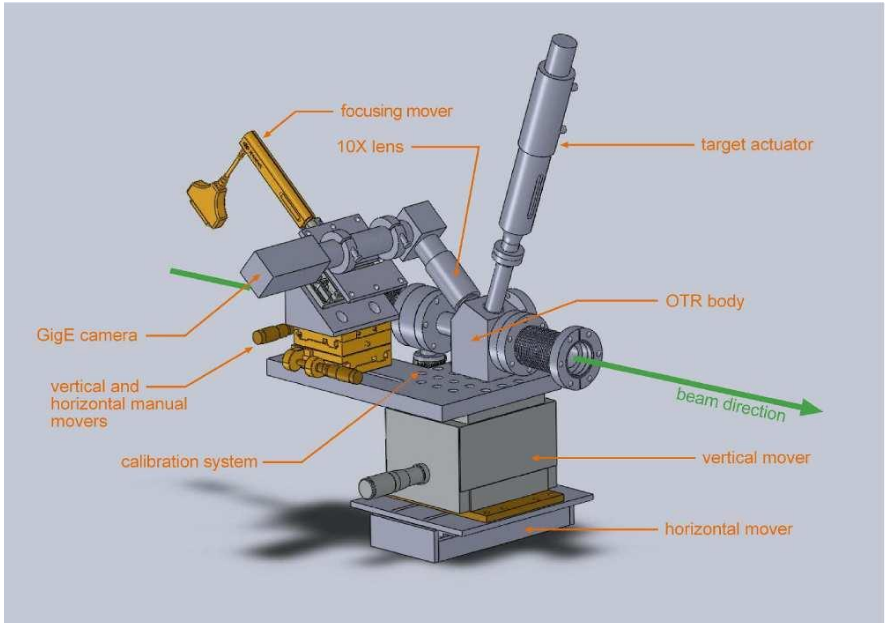
Multi-OTR System   The OTR1X





- The OTR1X was an **evolved design** rather than a **optimized one**. New parts were added to the existing OTR to add functionality. Instead of making new design they were added bit by bit. As a result the OTR1X is a patchwork of parts and takes up **a lot of beam line space**.
- The OTR **targets** were rather **thick**, about 0.5 mm of copper, beryllium or glassy carbon. This caused radiation darkening of the glass lens and camera damage.
- The camera **CCD** was **not parallel** to the **target**. This meant that the beam spot was in focus on only a small portion of the target. If the **beam moved**, the **image** had to be **refocused**.

Multi-OTR System   The new OTRs design

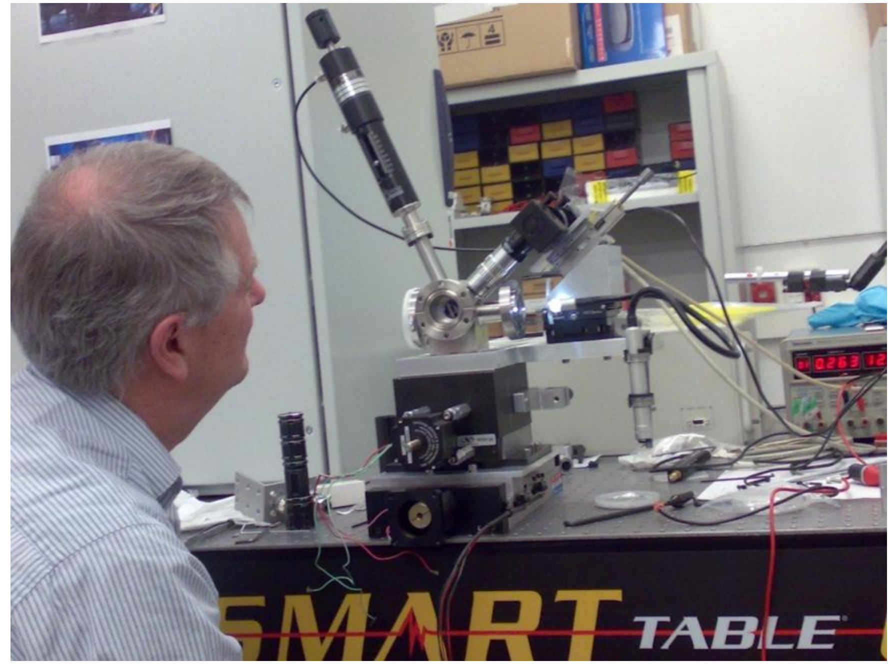


New OTRs will have **same controls** and **motion capabilities** as OTR1X with the following improvements:

- **Target actuator** relocated to the **top** (no interference with the girder) and smaller design, giving greater flexibility in the OTR placement
- **Thinner target** that **reduces** lens **radiation** darkening.

- The extreme **thinness** of the **aluminium** will **reduce** the **power deposition** in the aluminium and coupled to larger beam spot sizes should **eliminate target damage** problems.
- **CCD** camera "**parallel**" to **the target**. This will put the entire target into focus and **reduce** the need to **adjust focus** during normal operation giving greater depth of field.
- 12 bit **camera** for **more dynamic range** with **smaller pixel size** (3.75x3.75um) for more resolution (1280x960 pixels) with CCD sensor 1/3.
- **Calibration system** when there is no beam includes small lamp

Multi-OTR System   February 2010: Hardware Tests



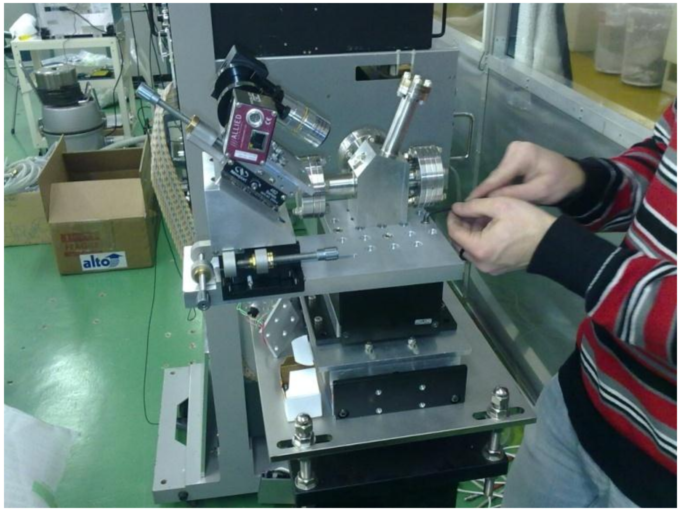
Assembling and **first tests** at SLAC and IFIC labs after fabrication

Vacuum test made at SLAC

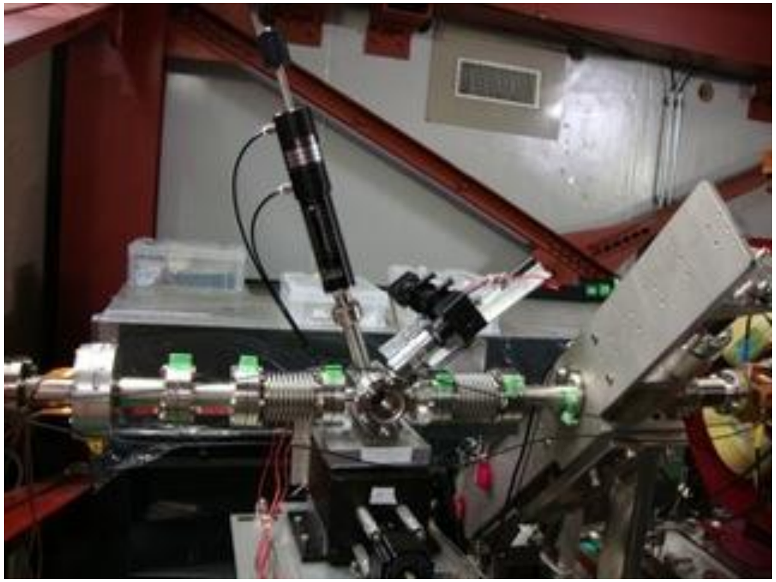
without OTR

with OTR

Multi-OTR System April / May 2010: Hardware Installation

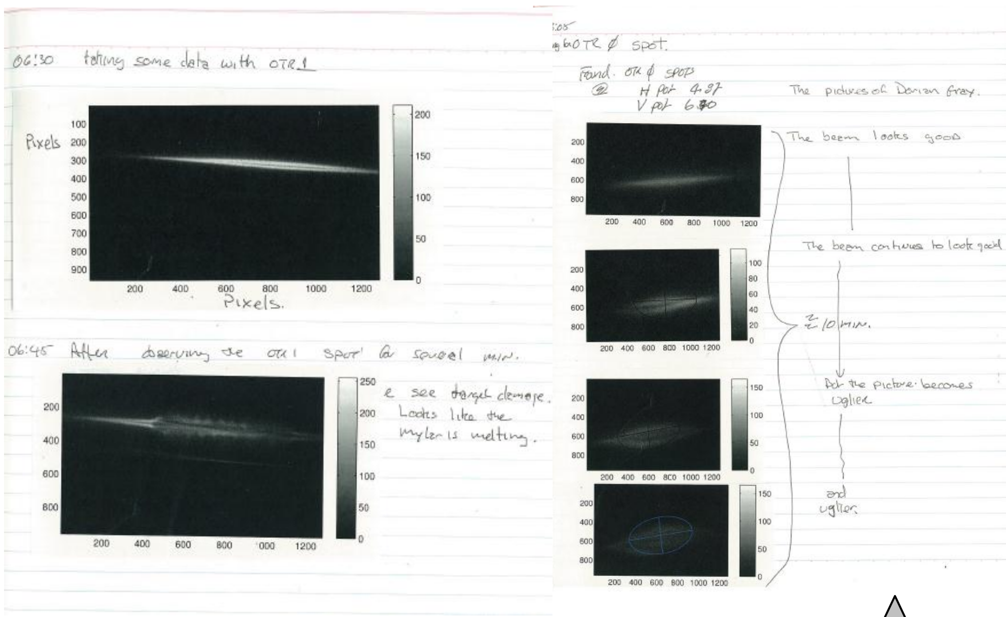


April: All **4 OTRs were assembled** at ATF clean room



May: All **4 OTRs installed** in the EXT line

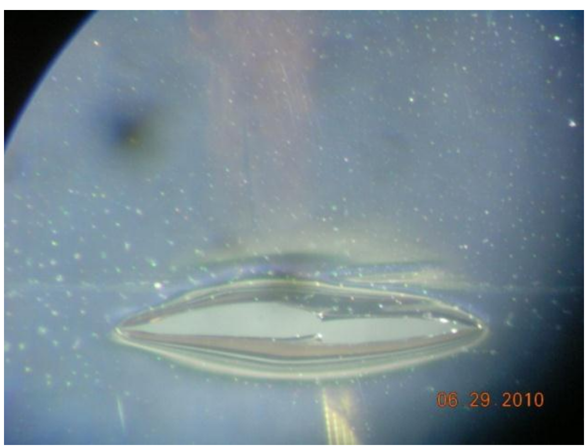
Multi-OTR System June 2010: First Measurements



- Exercise and **calibration** of vertical and horizontal **movers** and read-back **potentiometers**

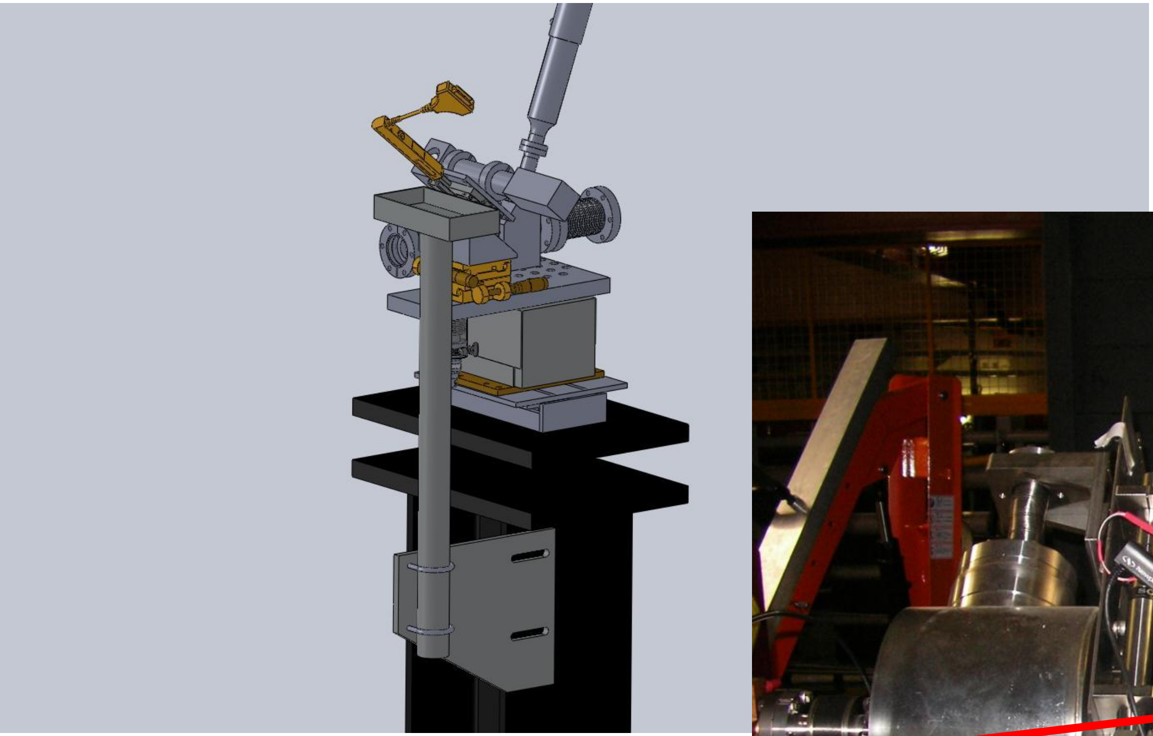
- Tests of 4 OTRs during beam time: beam seen but 3 **targets** (nitrocellulose coated aluminum)**were damaged** ($4x10^9$ e^- per pulse)

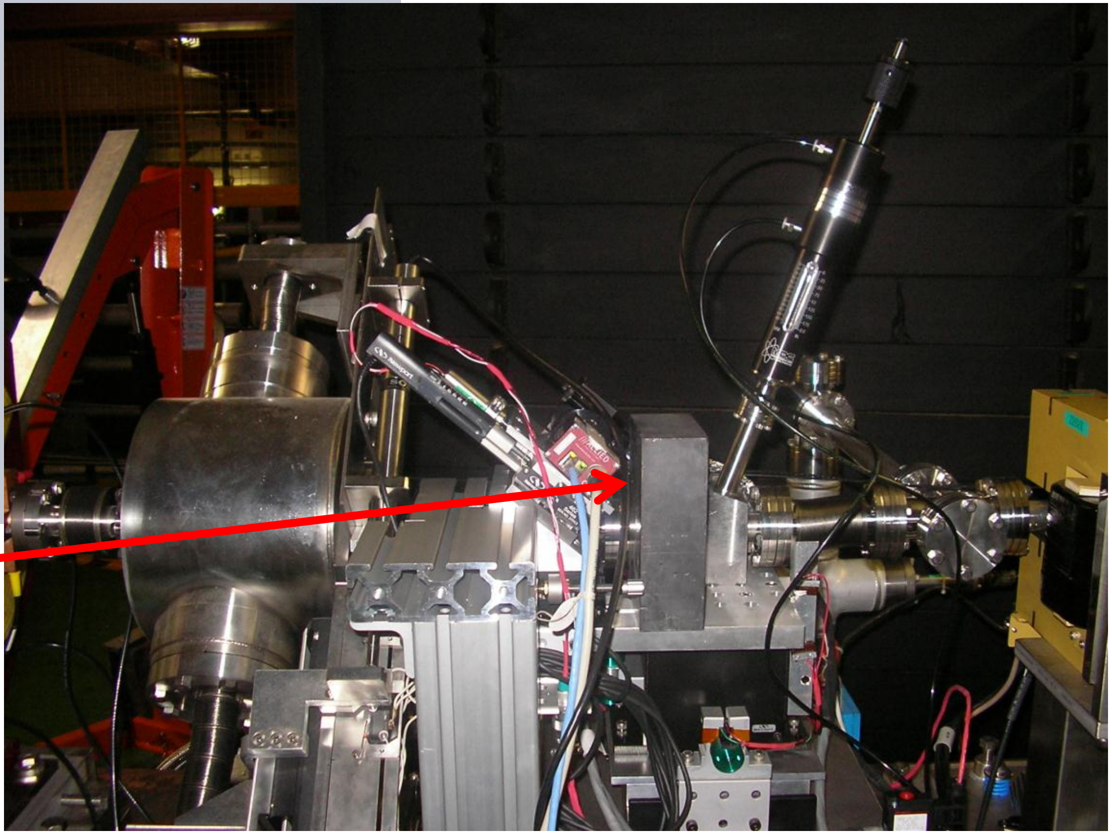
- CCD **Cameras** suffer from **radiation**, some pixel are dead.



Damaged target

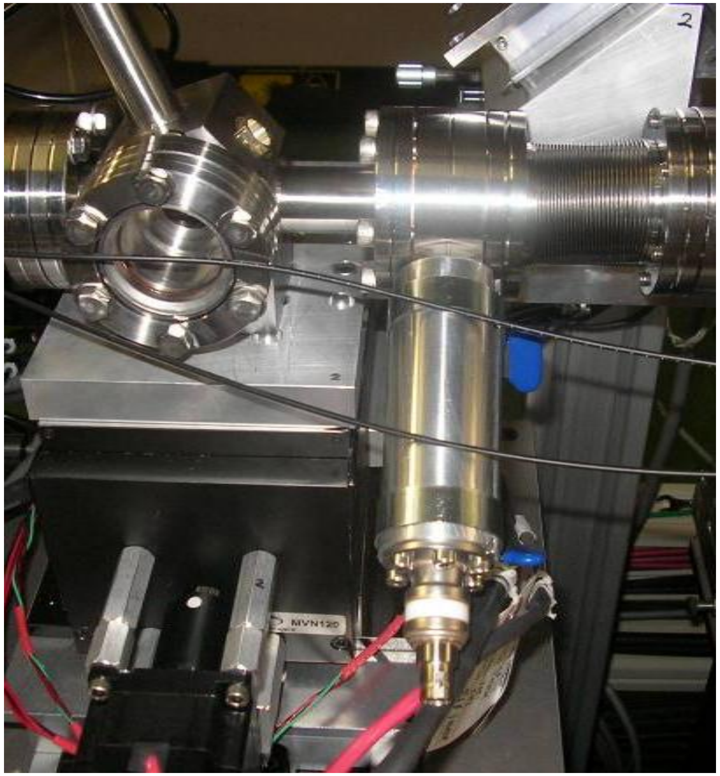
Multi-OTR System November 2010: Installation of cameras protection





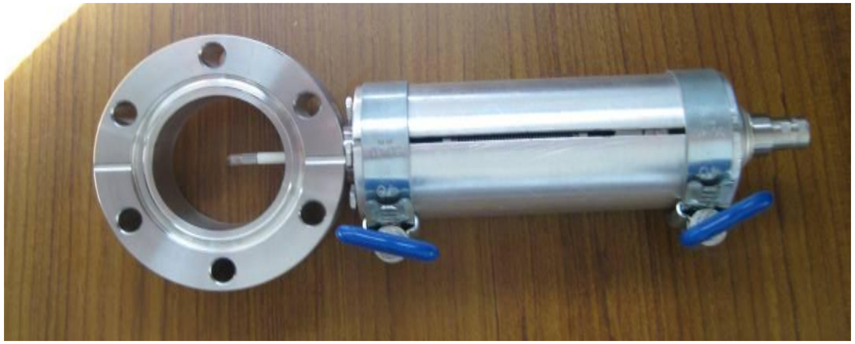
Lead blocks with a special holding support has been added to protect cameras from the radiation

Multi-OTR System   November 2010: Installation of calibration setup



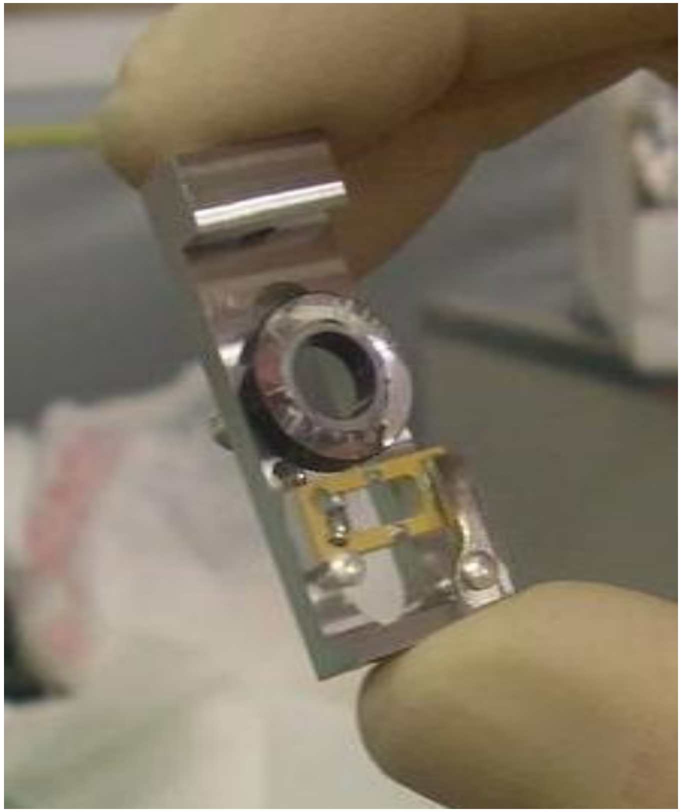
Illuminators were **installed** to facilitate calibrating tasks by **lighting** the **target** from the **beam direction,** when there is **no beam**

BNC feedthrough, copper connector, ceramic tube with bulb, stainless steel tube (ceramic tube holder), bellow and flange with port.



Aluminium tube and clamp to hold the bellow

Multi-OTR System   November 2010: New targets installed and tested

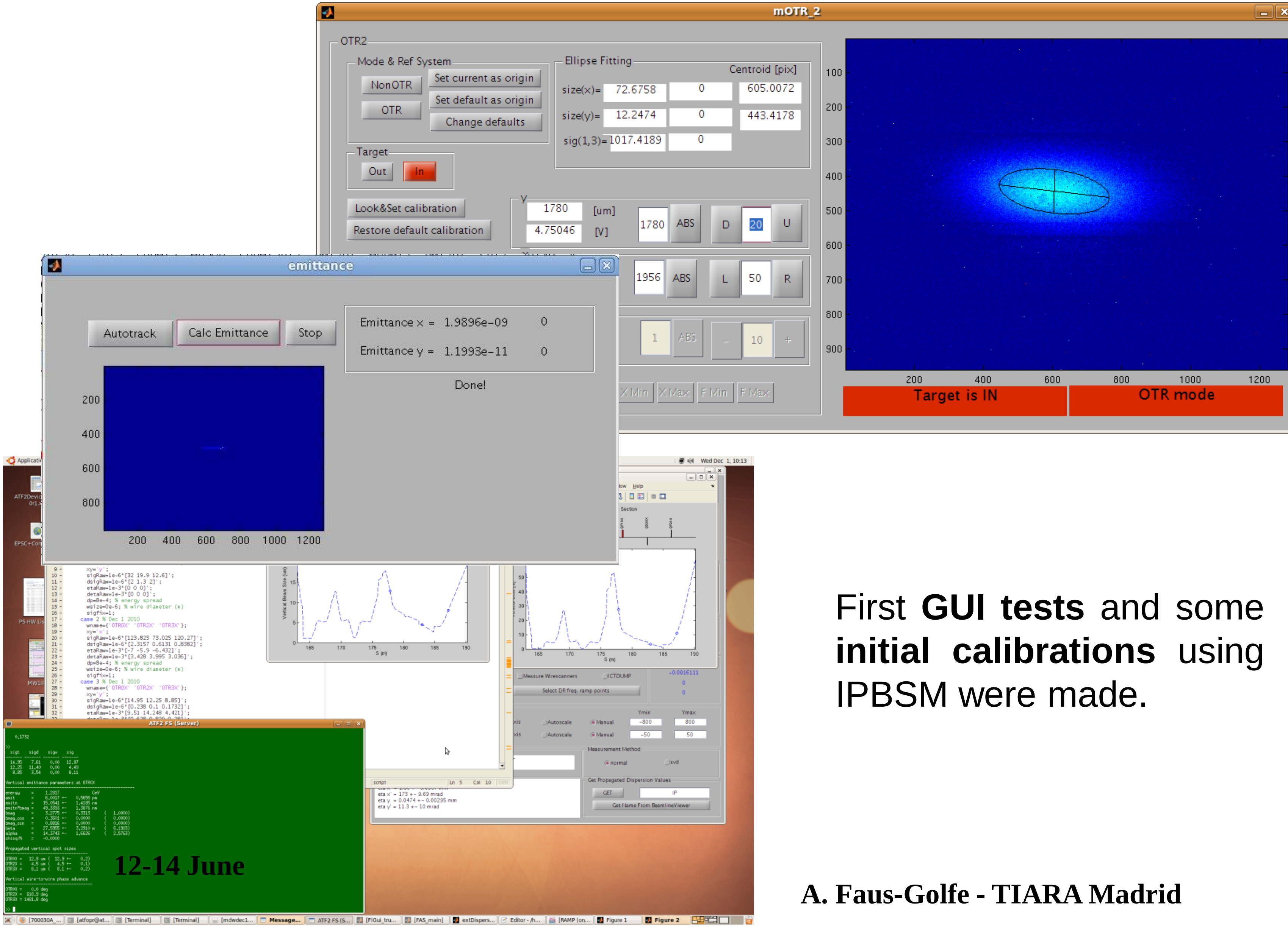


New targets could **stand the beam currents** for several minutes without being damaged

The **new targets** were installed, two made with **aluminium** (2um) **and** two with **aluminized kapton** (3-5um with 1200 Amstrongs Al coating). Besides, together with all them were installed the **wire targets, made with 4** wire (10um tungsten), one horizontal, one vertical and two tilted.

Multi-OTR System

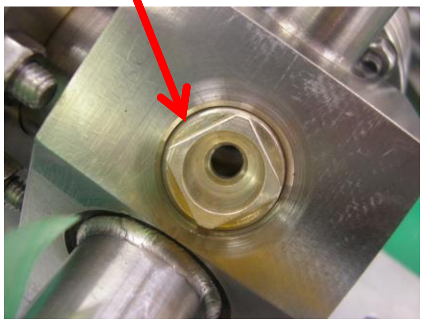
November 2010: First calibration of vertical scale and first software test

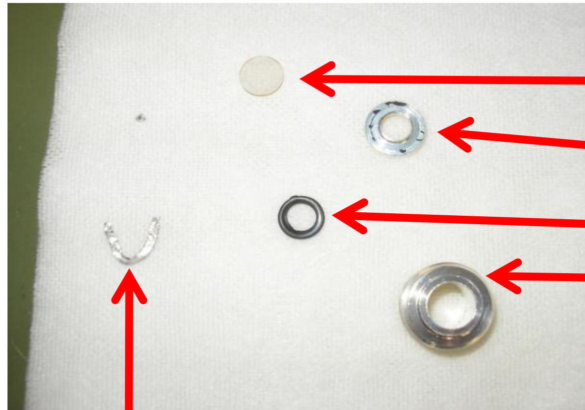


First **GUI tests** and some **initial calibrations** using IPBSM were made.

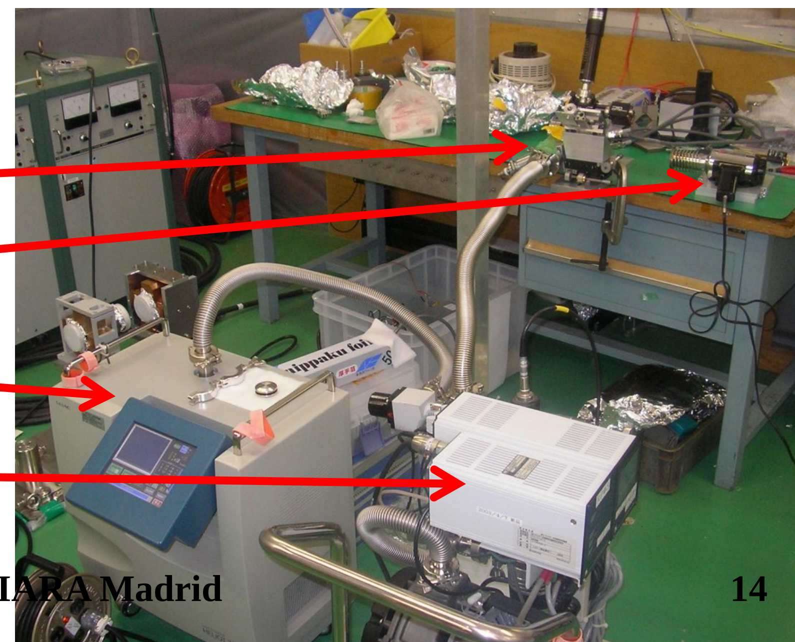
Multi-OTR System   December 2010: Vacuum leak repaired

Leak in the camera window





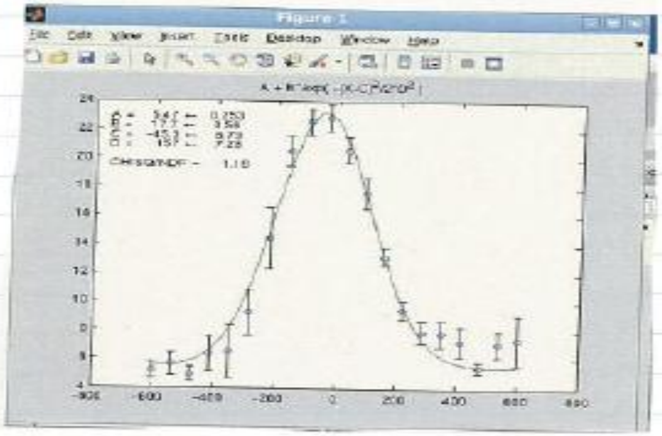
Important **vacuum leak** in the camera window of OTR2 was **repaired** by changing the indium washer



December 2010: OTR Wire Scans

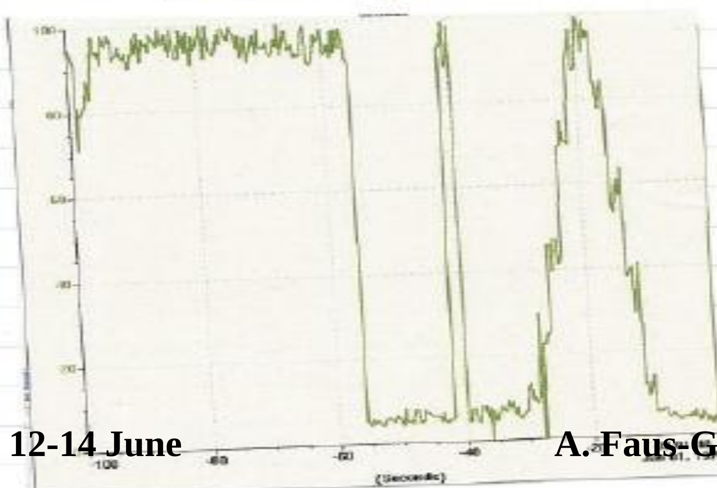
X wire scan from OTR3

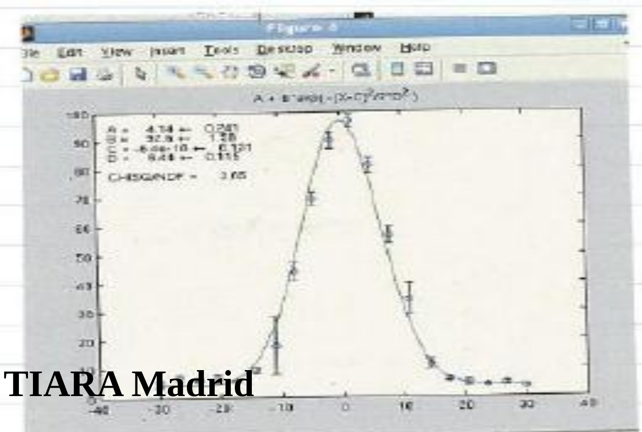
$\sigma = 157 \pm 7 \mu m$



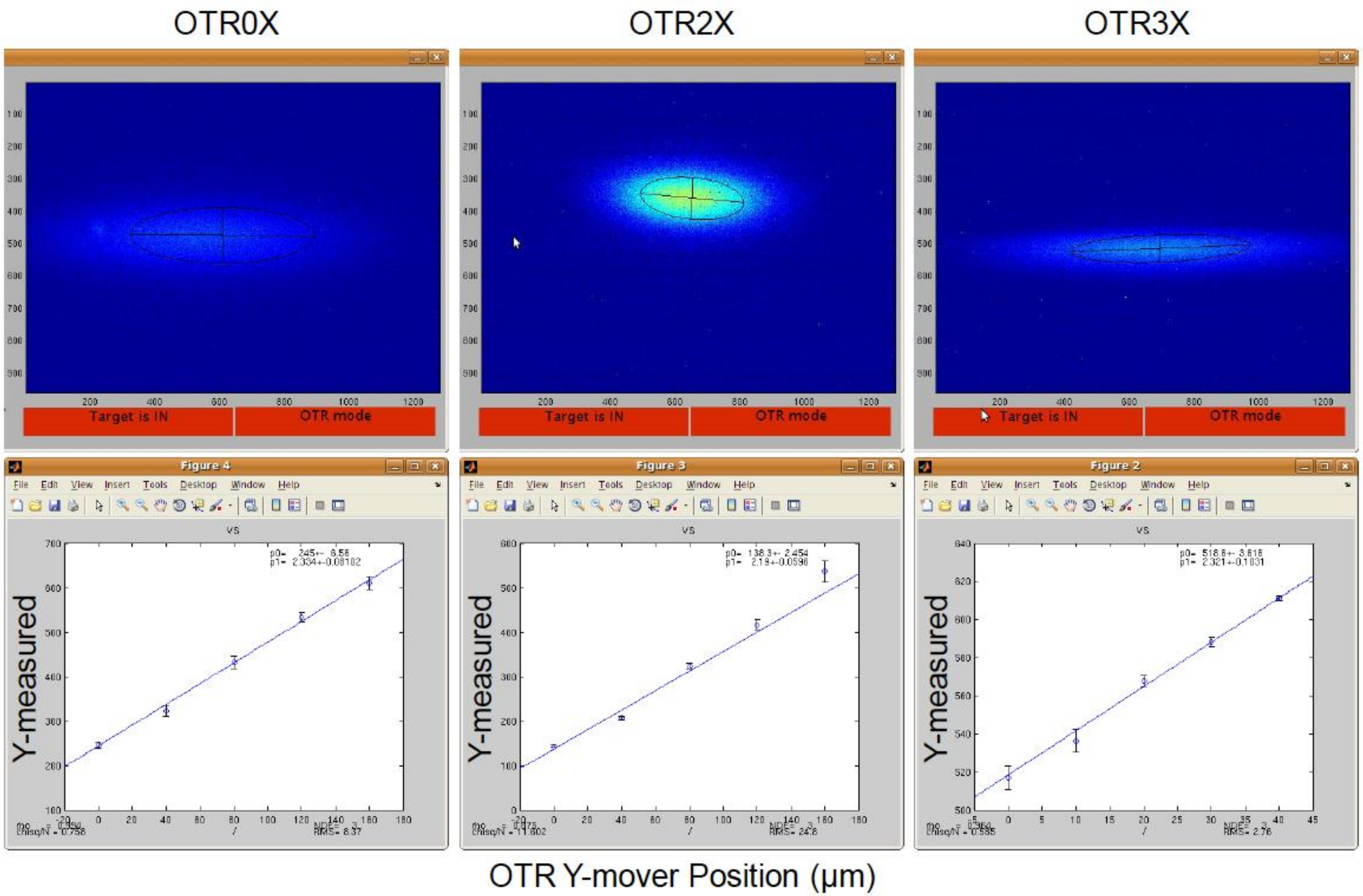
OTR Scan wires versus signal from **IPBSM background** detector.
Made to cross check wire scans with observed beam sizes. Numbers agree within fit errors.

Y wire scan from OTR3
BSM Signal



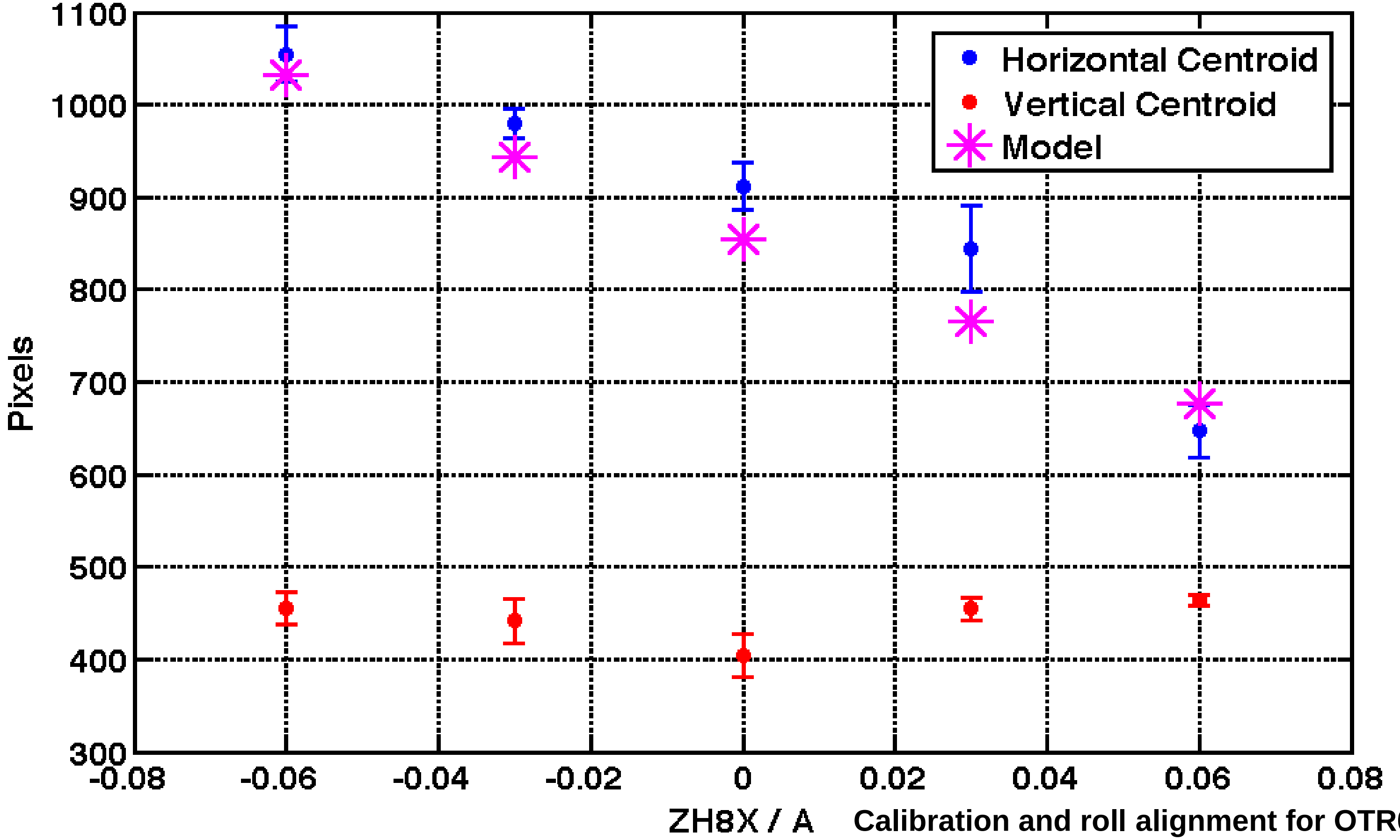


December 2010: Vertical scale calibration



Vertical scale calibration done by scanning the vertical mover stage and recording the motion of the observed beam centroid. Thus the vertical calibration factor um/pixel is obtained.

December 2010: OTR0x calibration test and roll alignment

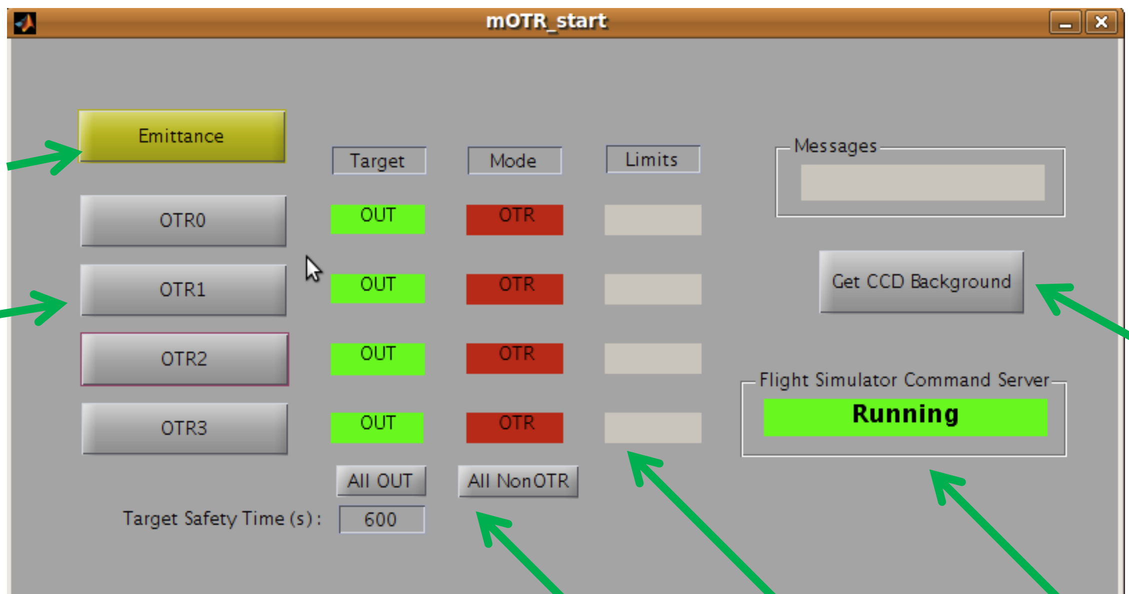


Calibration and roll alignment for OTR0X

To test the **calibration** an **upstream corrector is scanned** and the response is observed in the OTR. To test **roll alignment (of the OTR CCDs)** we have to look for **no motion in the opposite plane**.

- **OTR sofware** is an standalone compiled executable from **Matlab**.
- Some functions like **emittance calculation** or beam finder need the Flight Simulator running.
- OTR status reported and displayed on global **ATF alarm panel** showing **OTR actuator status**.
- All useful **data is stored in EPICS** PVs and archived in the EPICS archival system.

Main start panel



December 2010: Software development

Single OTR panel

number of measurements

Working mode & Reference system

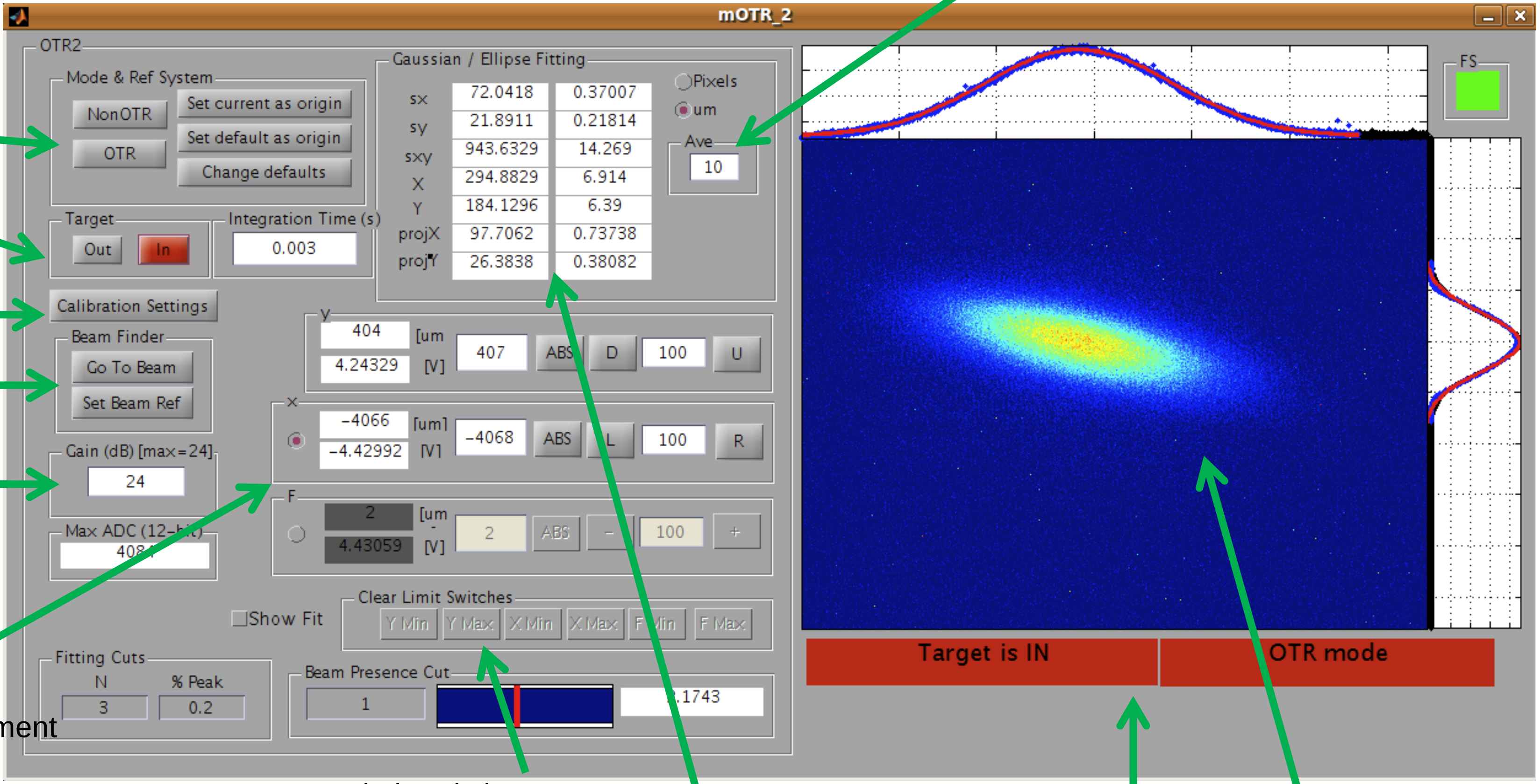
Target control

Calibrations

Beam finder

CCD Gain

Position & movement of the movers



Limit switches status

Ellipse fitting and analysis

Machine status

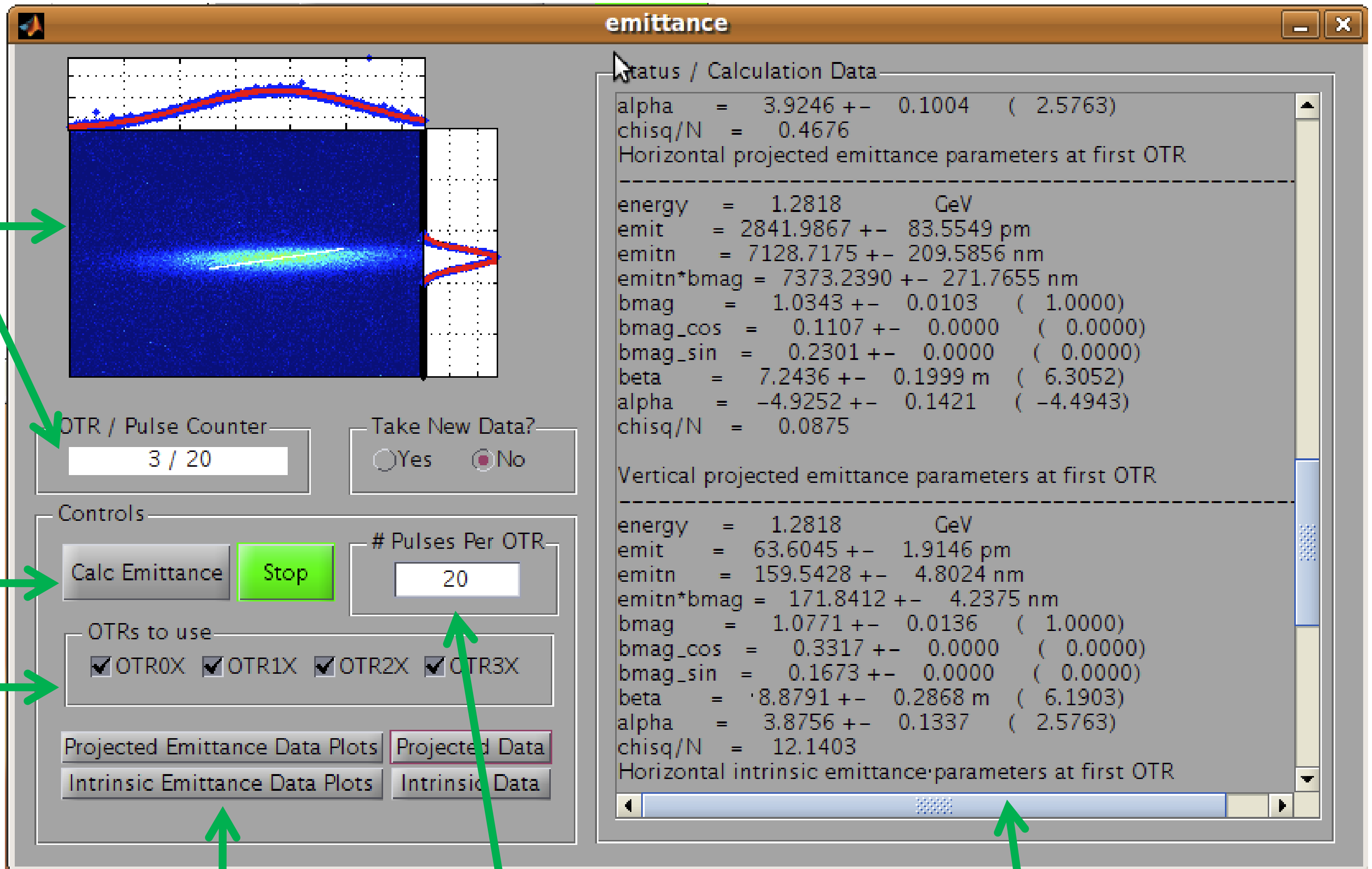
CCD image and beam fitting

Emittance panel

Current OTR info

Start/stop emittance procedure

Number of OTR to be used

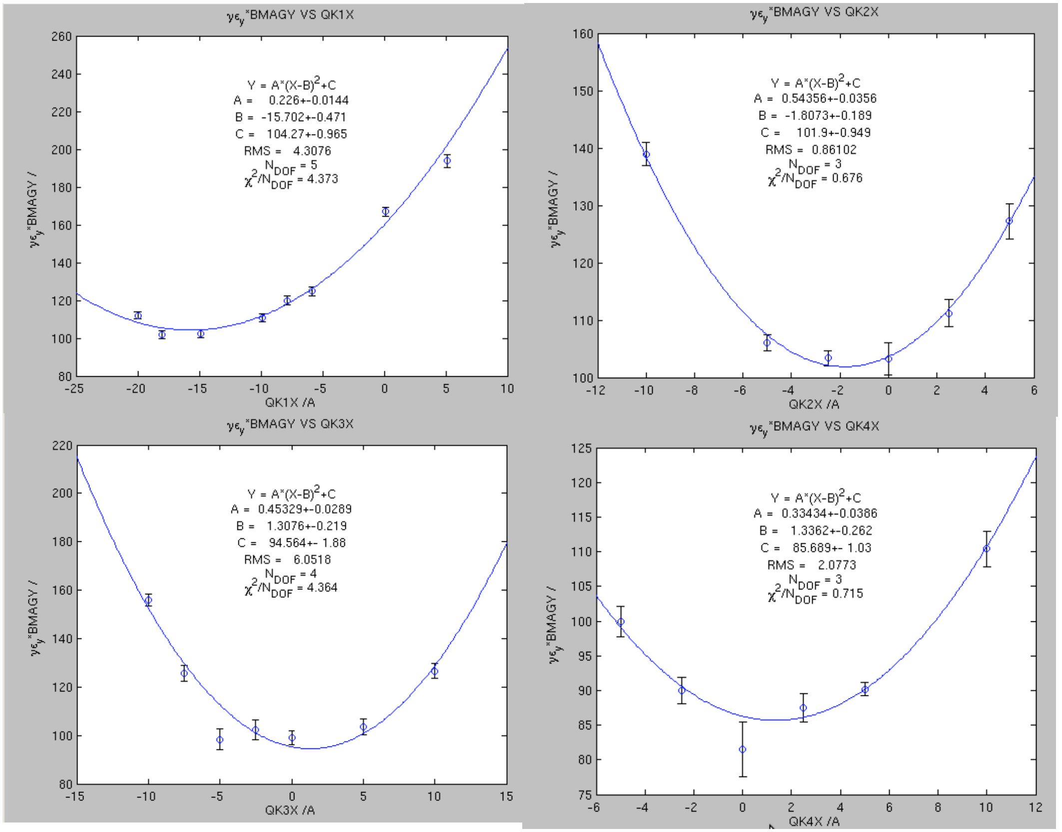


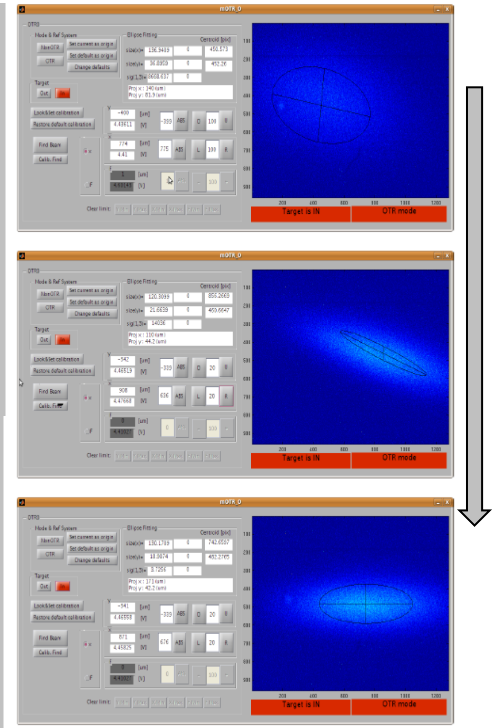
Data analysis and plots

number of measurements per OTR

Calculation data

December 2010: Coupling Correction





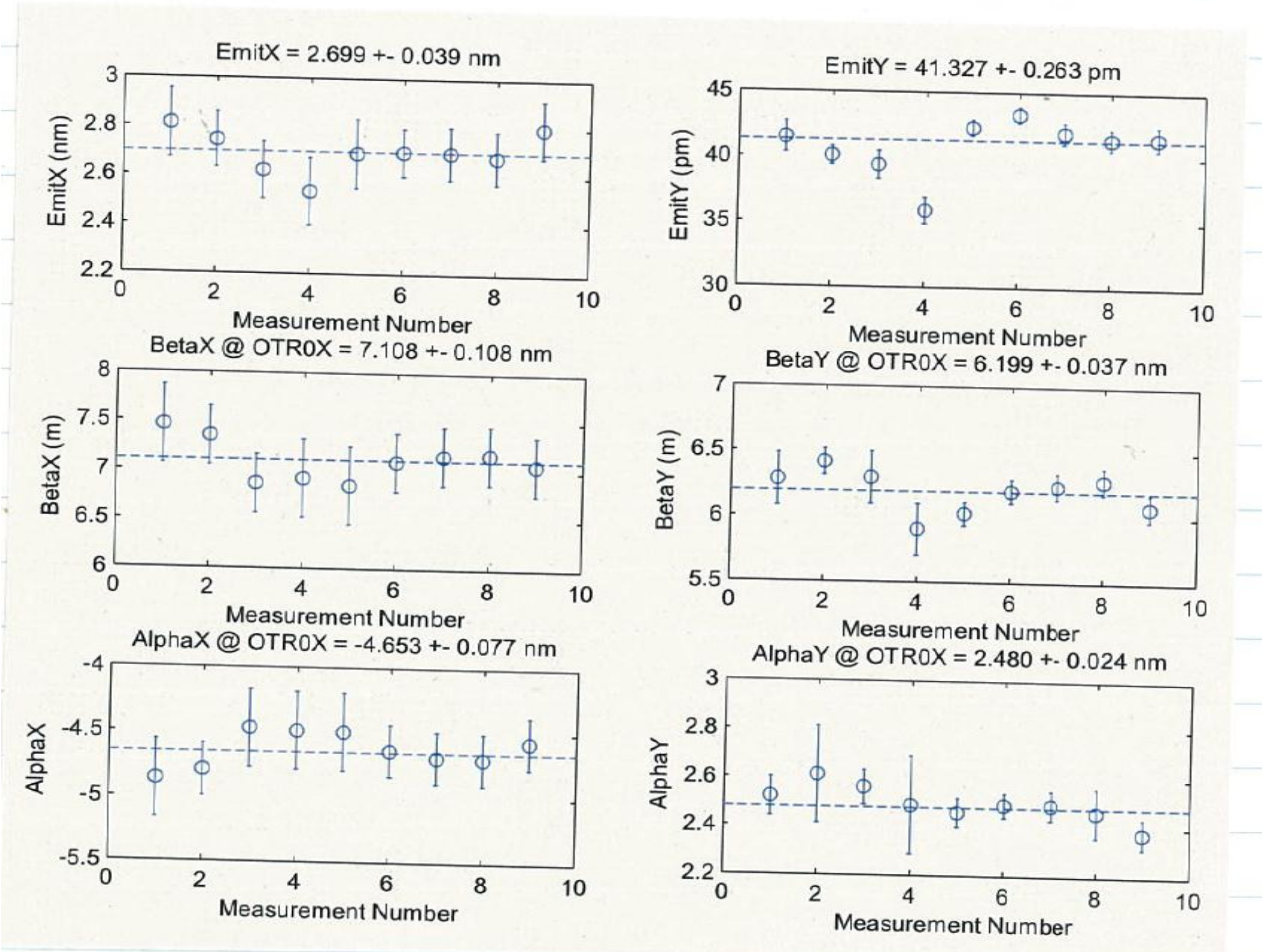
OTR0X before corrections

OTR0X after dispersion correction

OTR0X after coupling correction

Coupling correction in the EXT achieved by **scanning each of the 4 EXT skew quads**. For each scan the quantity **(vertical normalised emittance)*BMAGY** is plotted and taken the optimal from a parabolic fit.

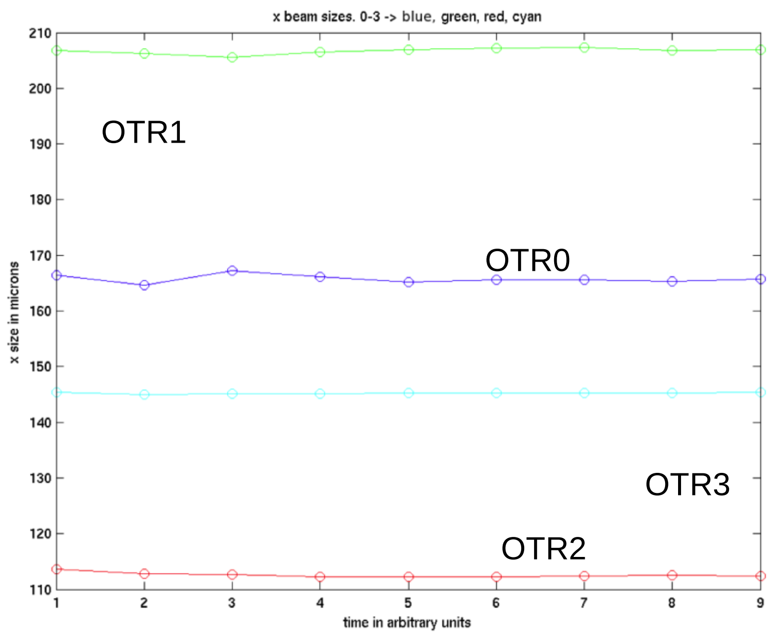
Multi-OTR System December 2010: Stability Measurement

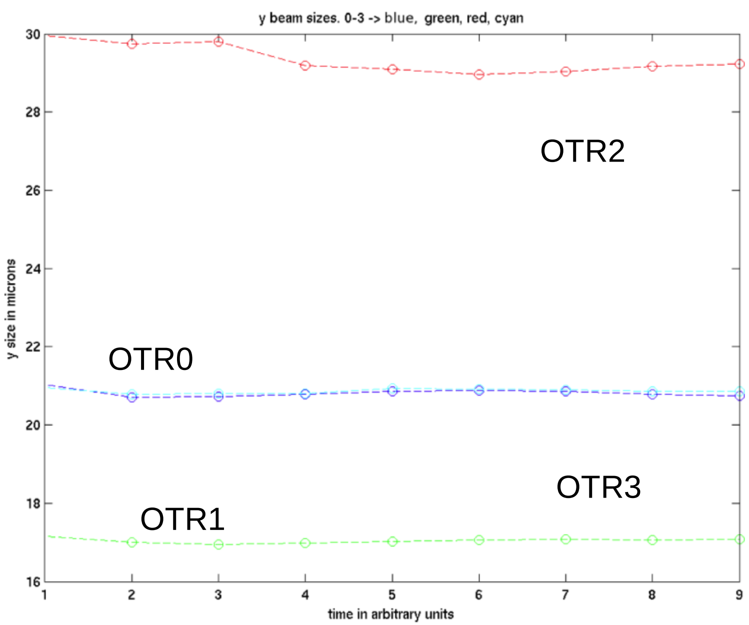


Multi-OTR System December/March 2010: Systematic Measurements

- **Calibrations** and **alignments** were made during the first part of the 2011 run period before to start a systematic measurement campaign

- A **systematic measurement** campaign was **started** in the first part of 2011

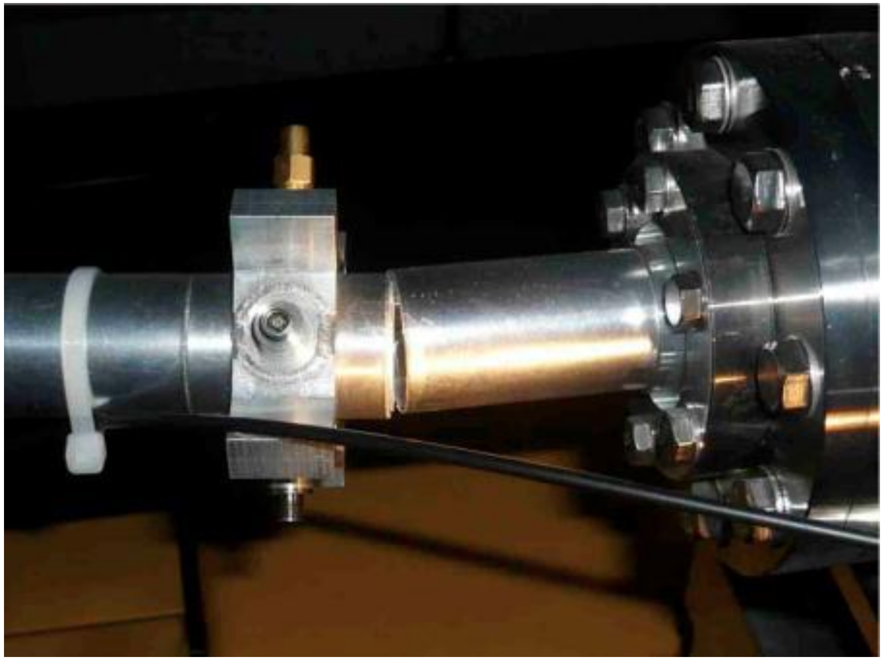




Multi-OTR System February 2011: LAN control power strip in-tunnel

A **LAN controllable power strip in-tunnel** and build in power cycle controls into the OTR software was installed. CCD cameras can be put into a mode of operation unresponsive to the OTR software and needs to be reset by power cycling the cameras being the power supplies in-tunnel.

Multi-OTR System March 2011: Earthquake



- Impossible to finish the systematic measurement campaign because of the earthquake
- After the earthquake the hardware has been checked and works fine

January/August 2011: Demagnifier system design

A demagnifier system to speed up the **beam finding** and to measure horizontal size when **beam** is **large** in x

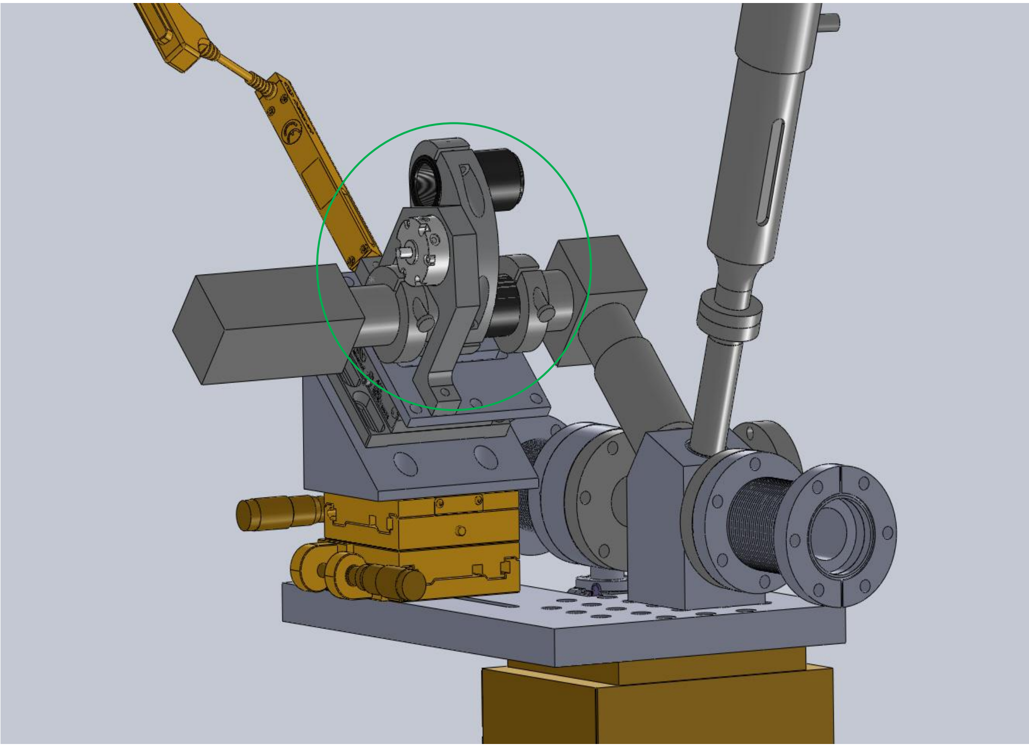
SWITCHABLE LENS INSERTED SYSTEM

Pros:

- Cheaper
- Less optical elements

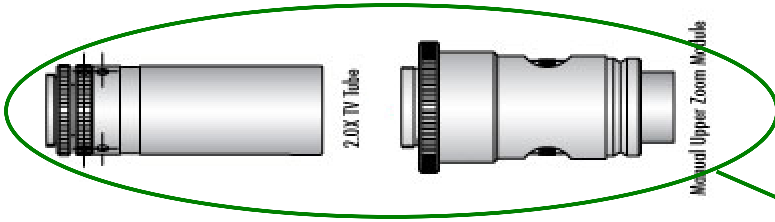
Cons:

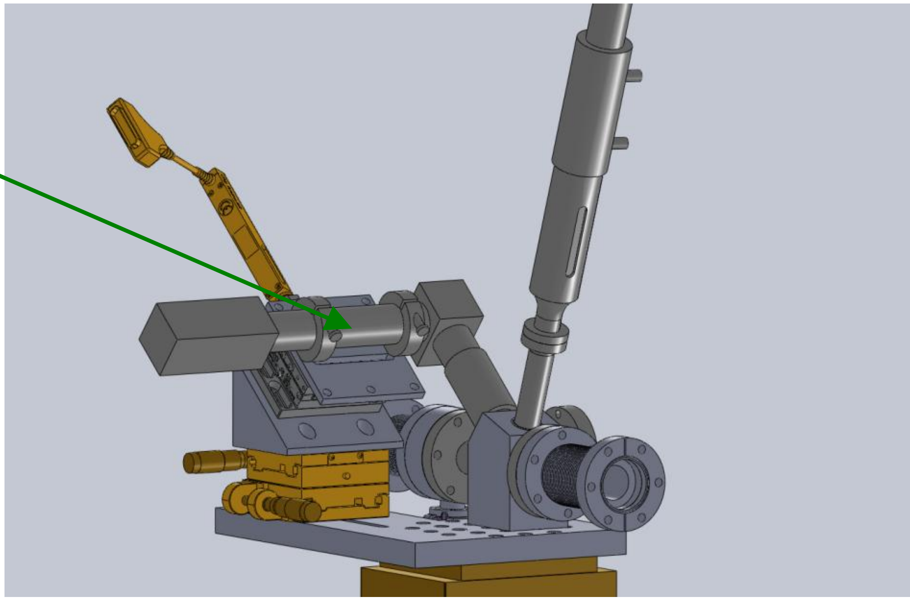
- Heavy and bulky
- Small room to install it
- Not good optical performance
- Possible alignment problems when inserting the lenses
- Only for beam finding (one lens system)



Multi-OTR System January/August 2011: Demagnifier system design

NEW MOTORIZED ZOOM STSYEM





- 2.0X TV Tube: Position the camera at the proper distance from the zoom
- Upper zoom module: Contains the core zoom system.
- It will be motorized by an independent step motor

Pros: - Lighter and less bulky than the switchable lens system, easier installation
- Better lenses performance
- Allows beam finding and measurements in 2 different magnification (5X and 10X) by calibrating the system in both states.

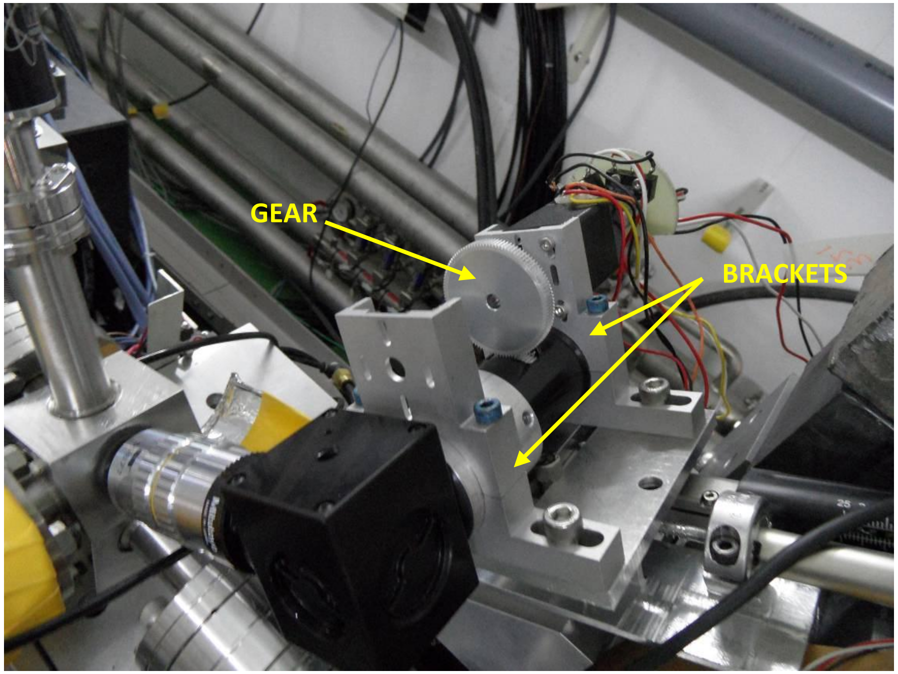
Cons: - Larger number of optical elements and therefore a greater light absorption, meaning slightly dimmer spots.

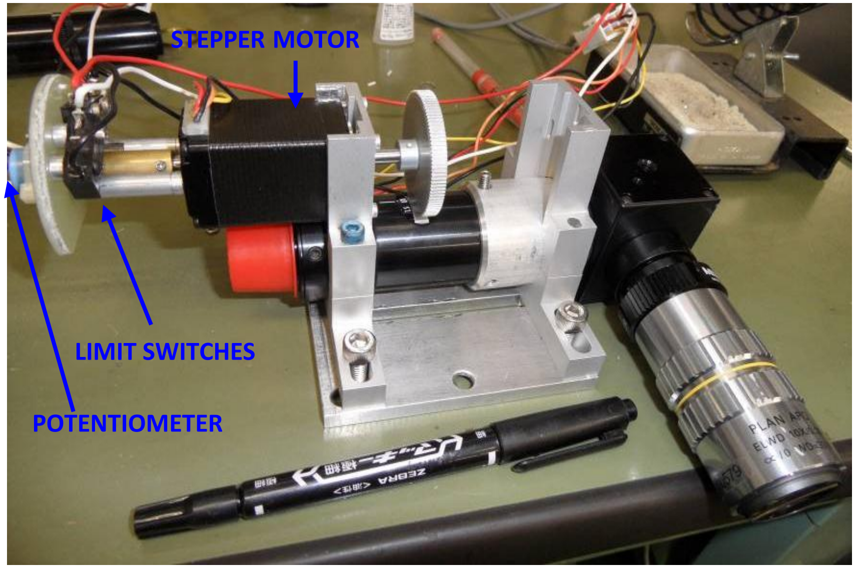
Multi-OTR System

January/August 2011: Demagnifier system installation

OTR Zoom System:

A demagnifier system was installed in summer 2011 to speed up the **beam finding** and to measure horizontal size when **beam** is **large** in x





By measuring the **beam sizes** in **4** places and knowing the optics in between the **beam matrix** could be reconstructed:

$$\begin{pmatrix} \sigma_1 & \sigma_2 & \sigma_3 & \sigma_4 \\ \sigma_2 & \sigma_5 & \sigma_6 & \sigma_7 \\ \sigma_3 & \sigma_6 & \sigma_8 & \sigma_9 \\ \sigma_4 & \sigma_7 & \sigma_9 & \sigma_{10} \end{pmatrix} \longrightarrow \begin{pmatrix} <x^2> & <xx'> & <xy> & <xy'> \\ <xx'> & <xx'^2> & <x'y> & <x'y'> \\ <xy> & <x'y> & <y^2> & <yy'> \\ <xy'> & <x'y'> & <yy'> & <y'^2> \end{pmatrix}$$

The emittances values are calculated by using the x and y sub-matrices: **2D emittance**.

X submatrix

$$\begin{pmatrix} \sigma_1 & \sigma_2 & \sigma_3 & \sigma_4 \\ \sigma_2 & \sigma_5 & \sigma_6 & \sigma_7 \\ \sigma_3 & \sigma_6 & \sigma_8 & \sigma_9 \\ \sigma_4 & \sigma_7 & \sigma_9 & \sigma_{10} \end{pmatrix} \begin{matrix} \longrightarrow \epsilon_x = \sqrt{\sigma_1\sigma_5 - \sigma_2^2} \\ \longrightarrow \epsilon_y = \sqrt{\sigma_8\sigma_{10} - \sigma_9^2} \end{matrix}$$

Y submatrix

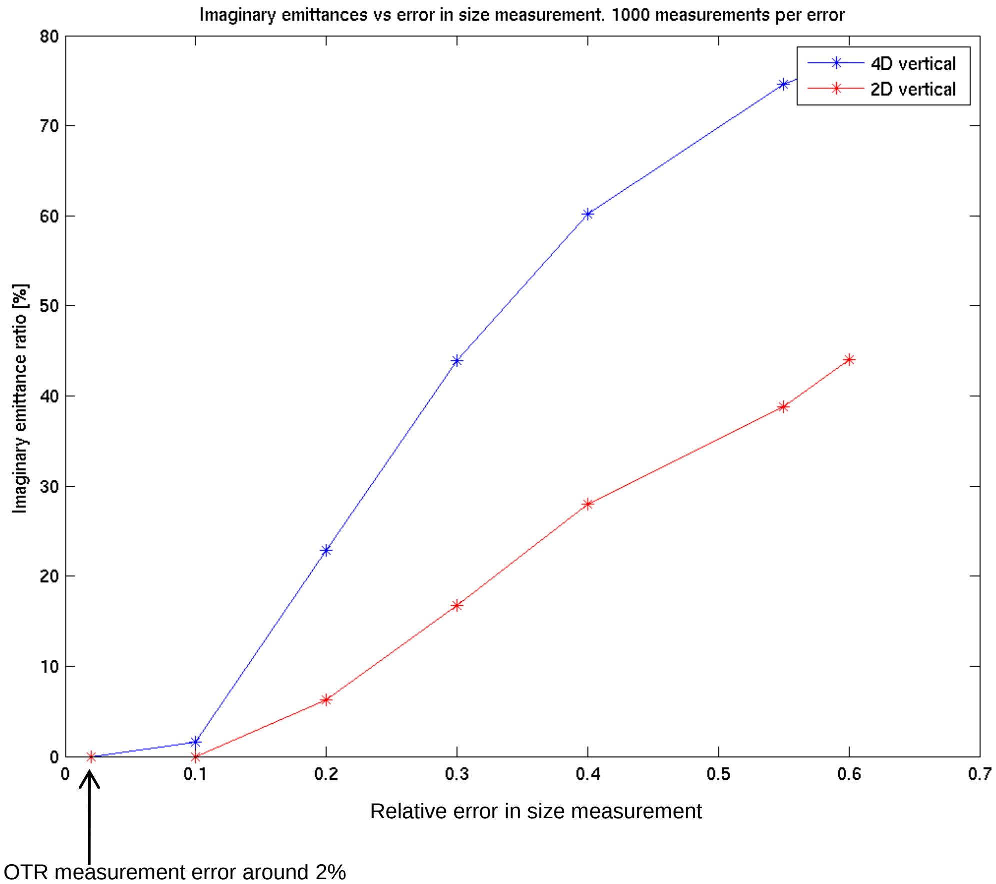
To take in account the coupling terms the diagonalising of the beam matrix is needed: **4D emittances** or intrinsic emittances

$$\begin{pmatrix} \sigma_1 & \sigma_2 & \sigma_3 & \sigma_4 \\ \sigma_2 & \sigma_5 & \sigma_6 & \sigma_7 \\ \sigma_3 & \sigma_6 & \sigma_8 & \sigma_9 \\ \sigma_4 & \sigma_7 & \sigma_9 & \sigma_{10} \end{pmatrix} \longrightarrow \begin{pmatrix} \varepsilon_1 & 0 & 0 & 0 \\ 0 & \varepsilon_1 & 0 & 0 \\ 0 & 0 & \varepsilon_2 & 0 \\ 0 & 0 & 0 & \varepsilon_2 \end{pmatrix}$$

- **2D** emittance reconstruction algorithm is **fully implemented** and it is working.
- **4D** algorithm is **under study**.
- The algorithm gives **emittance imaginary values** when errors in the measurements are considered.
  - **Simulations** of the emittance reconstruction in function of the beam size error measurement to find the ratio of the unphysical results (imaginary emittance)
  - **Analytical** study of the problem of solving a system of equations with more equations than unknowns that gives unphysical results (imaginary emittance) and of the diagonalization process for the 4D.

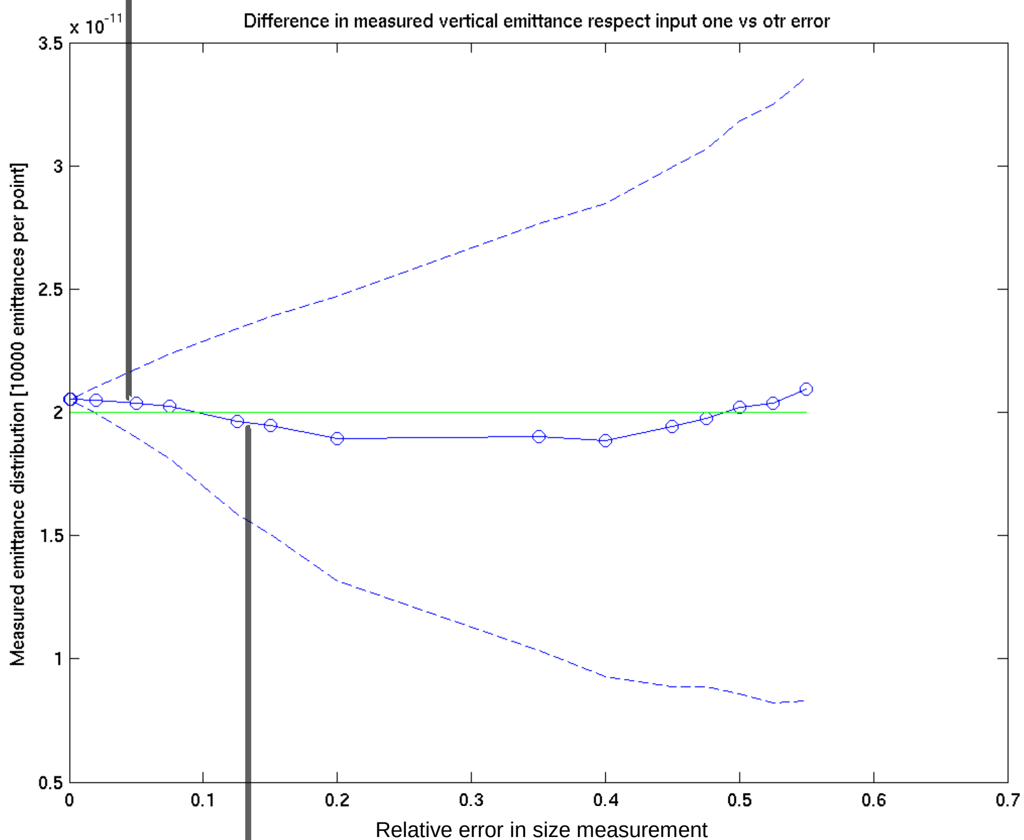
Simulation parameters:

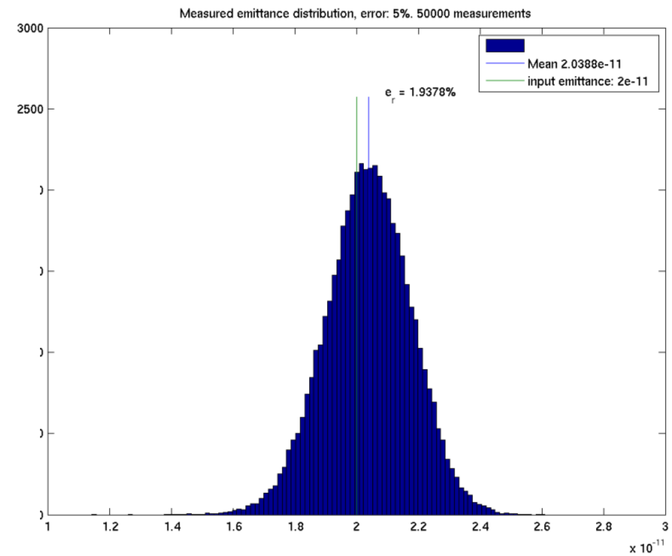
- 1000 emittance measurements per error.
- 50.001 particles.
- Standard nominal V3.1 optics
- Tracking with Lucretia

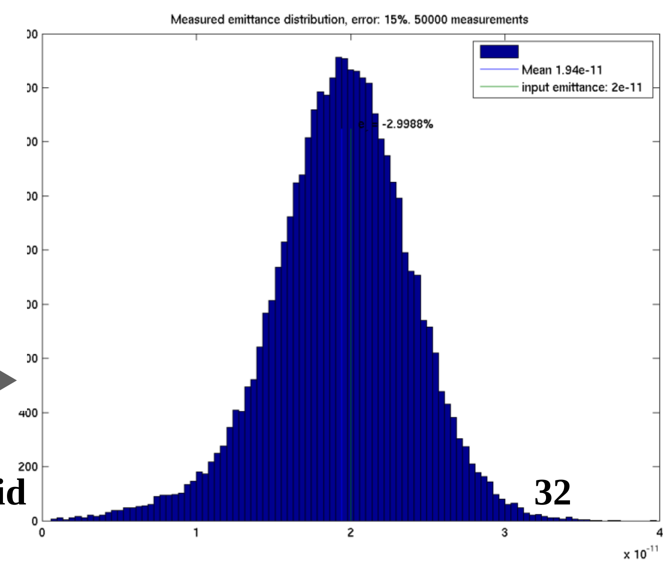


Emittances are vertical if not specified

Mean of measured value compared with input one





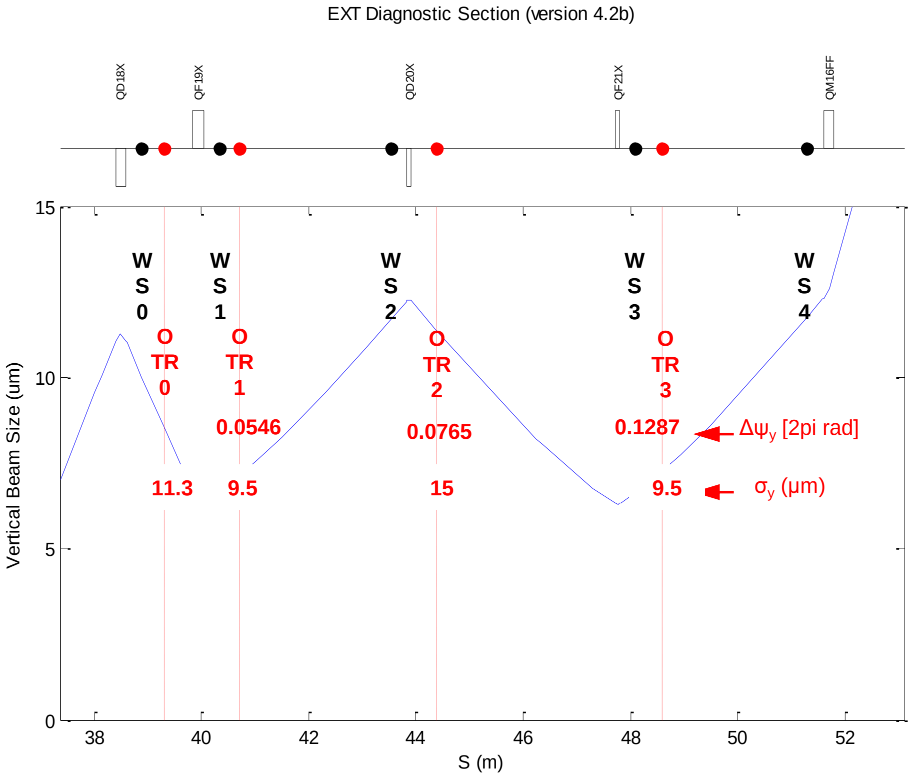


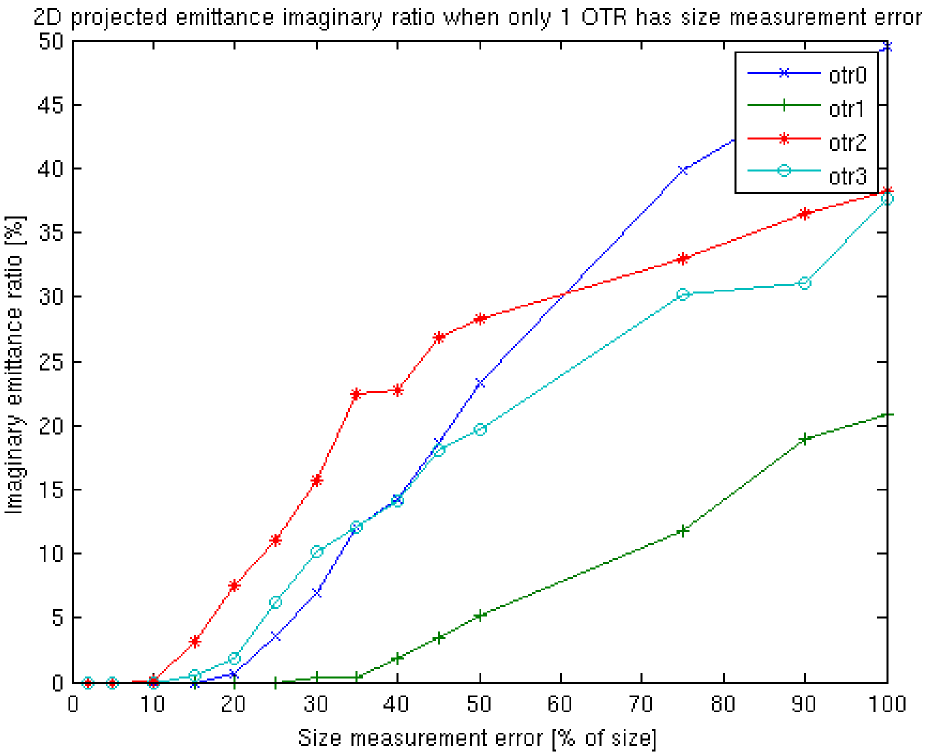
Input emittance

Mean of measured emittances

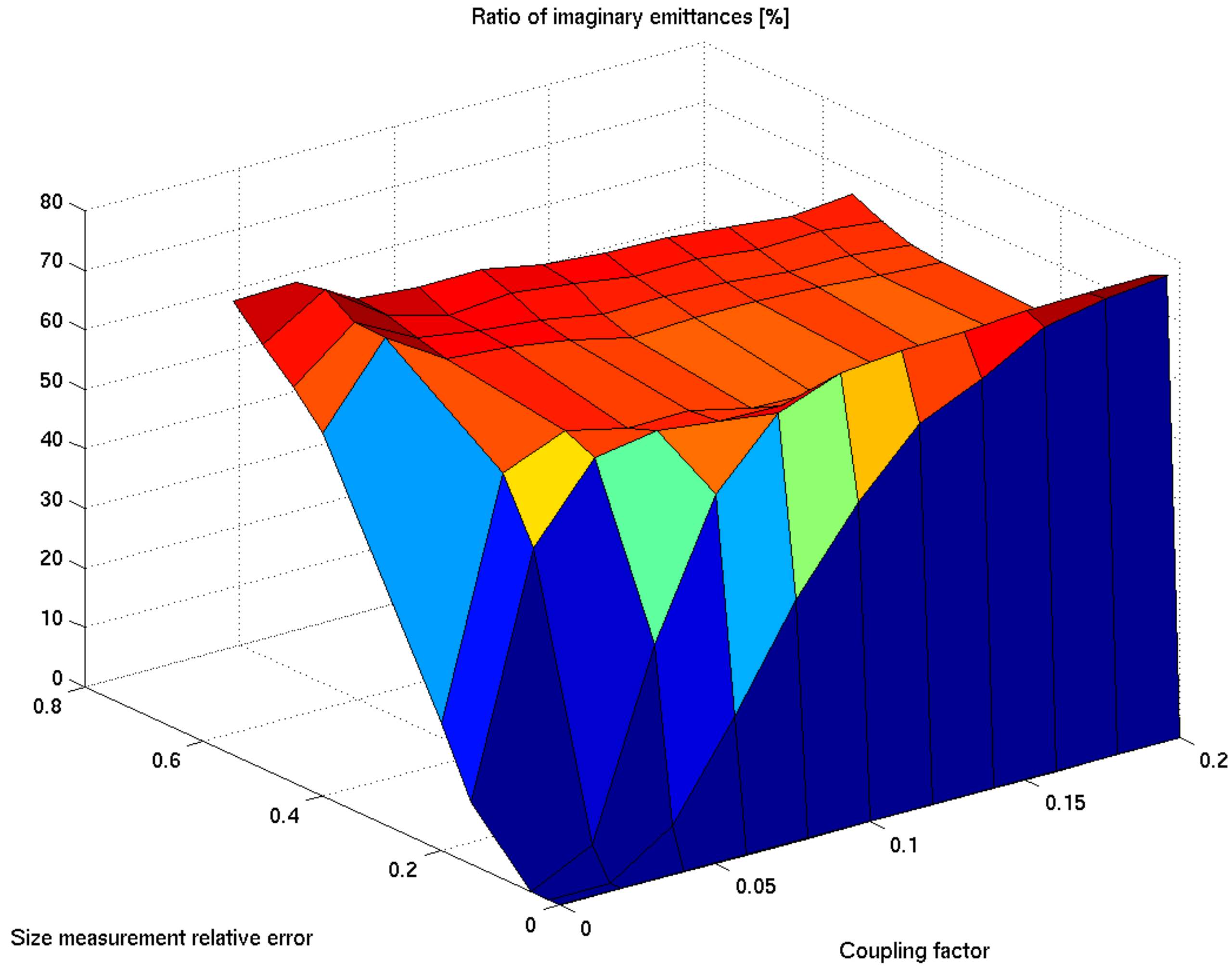
Standard deviation of measured emittances

Effect of each OTR in the emittance imaginary ratio





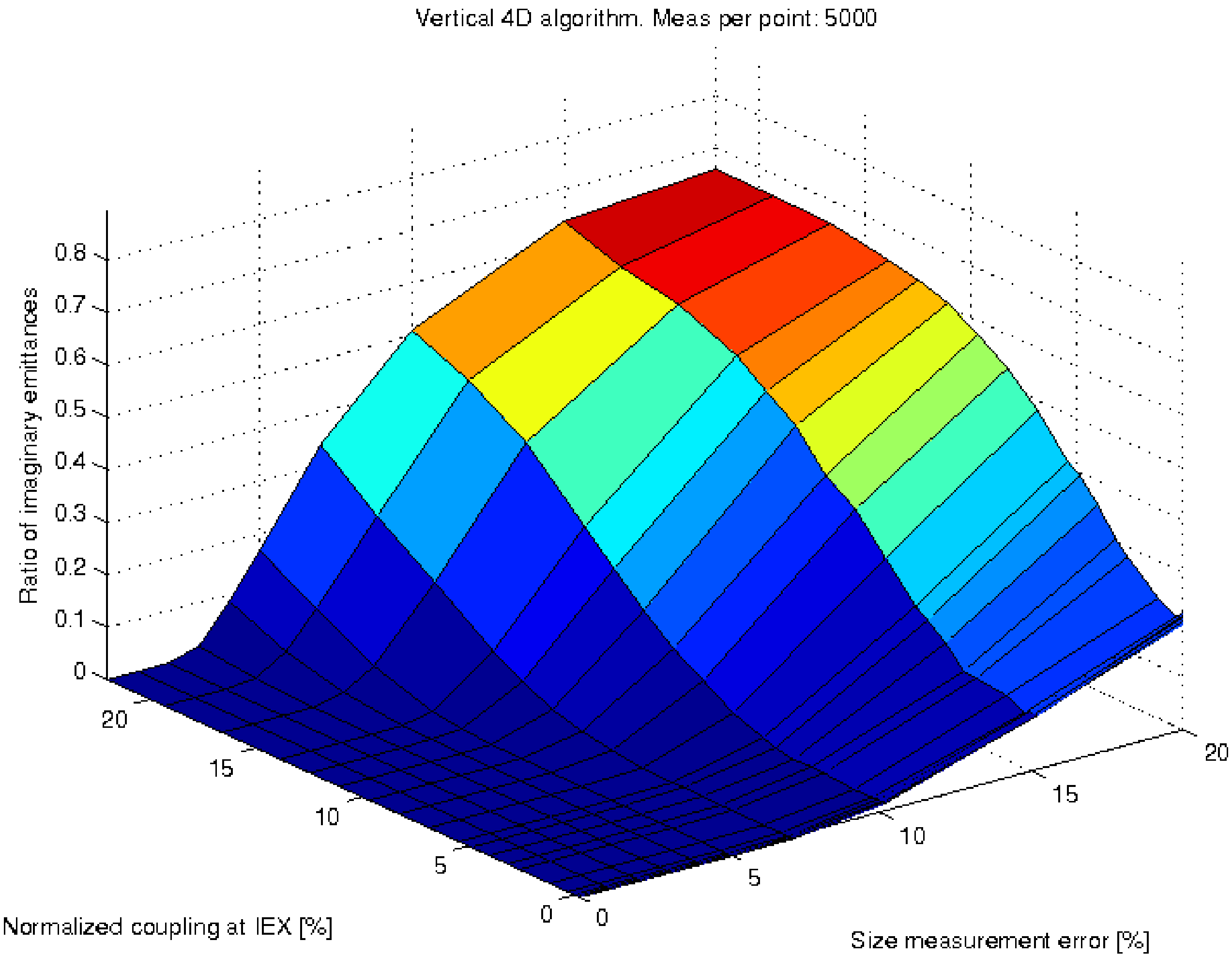
Effect of coupling in the emittance imaginary ratio



May/December 2011: Emittance reconstruction

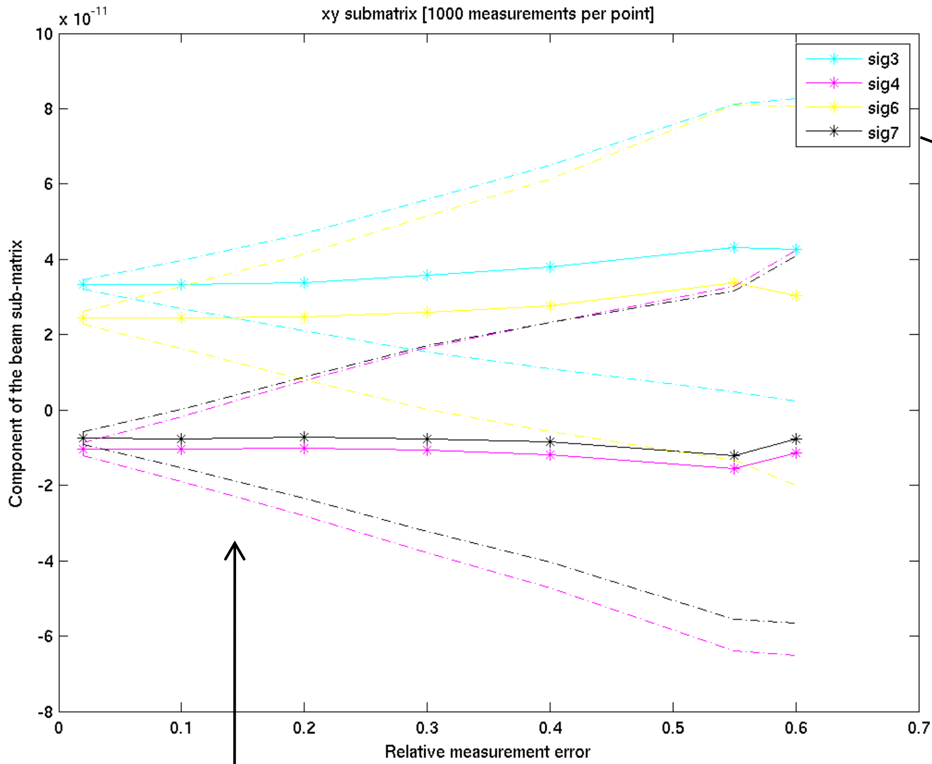
Studies on emittance reconstruction algorithm.

Imaginary emittances vs relative size error and coupling at IEX.

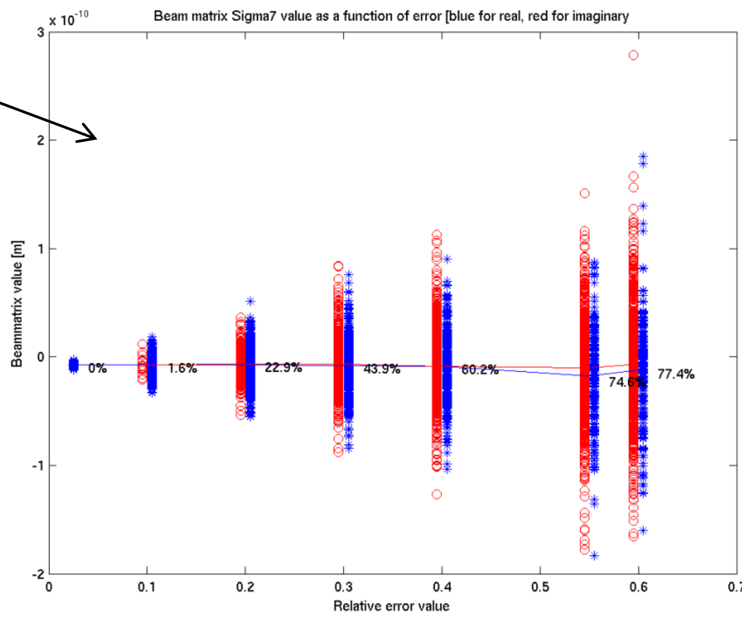


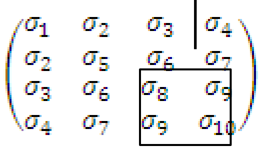
May/December 2011: Emittance reconstruction

Study of the reconstructed beam matrix elements



σ_7





Blue dots are beam matrix elements that lead to a real emittance value and red ones are for the imaginary value

May/December 2011: Emittance reconstruction

- **Analytical** study of the problem of solving a system of equations with more equations than unknowns that gives unphysical results (imaginary emittance) and the diagonalization process for the 4D.
    - The condition of that the emittance is always real positive is not taken into account when we solved the system. One option could be to use the Lagrange operators but the problem here is that we have an inequality, instead of an equality.
    - The other option we are studying is the diagonalization process itself (Cholesky options, N Poincare invariants for a definitive positive beam matrix)
    - Solving the system trying to find the range of solutions (4 OTRs)
- **4D** emittance reconstruction algorithm by using the Poincare invariants is **fully implemented** and it is being tested (January-March 2012)

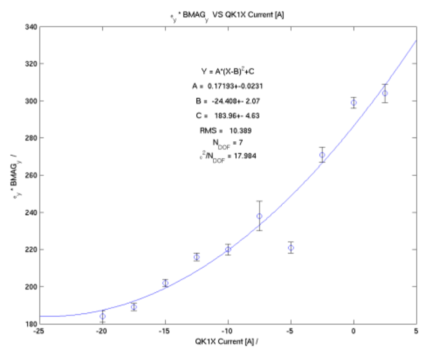
Manual Skew Quad Scanning Method: Procedure

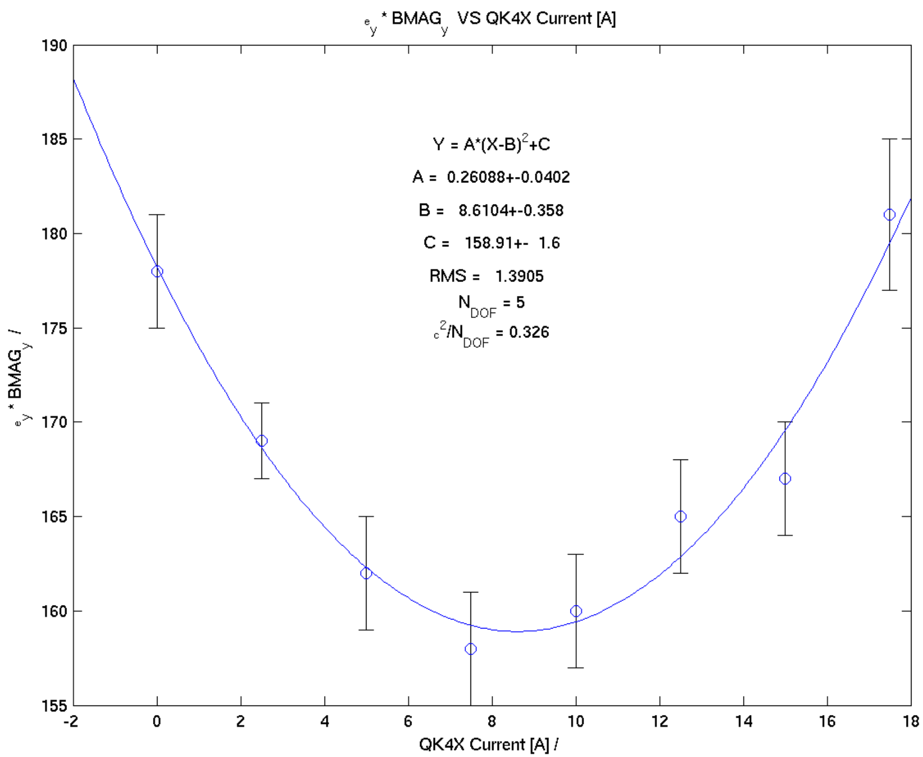
Scan a single skew quad and look for the intensity that minimises the measured emittance.
Do it for the 4 skew quadrupoles.

-Used normally for correction

-It takes several minutes to be done, half an hour the complete correction

-It can lead to optimal intensities beyond the skew limits [-20,20]A





Manual Skew Quad Scanning Method: Measurements with mOTR

Correction from 16th November 2011

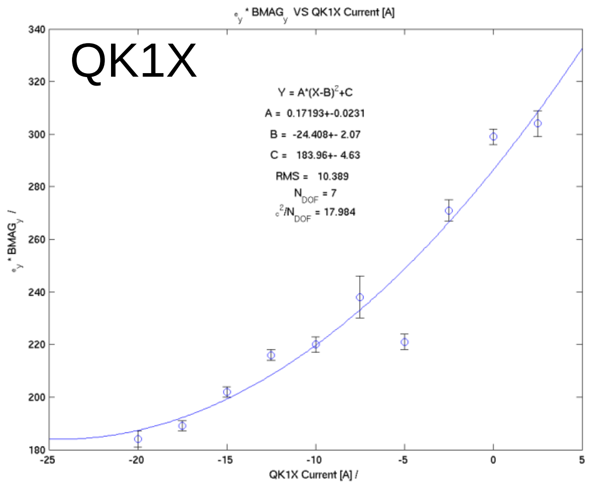
First all 4 skew set to 0

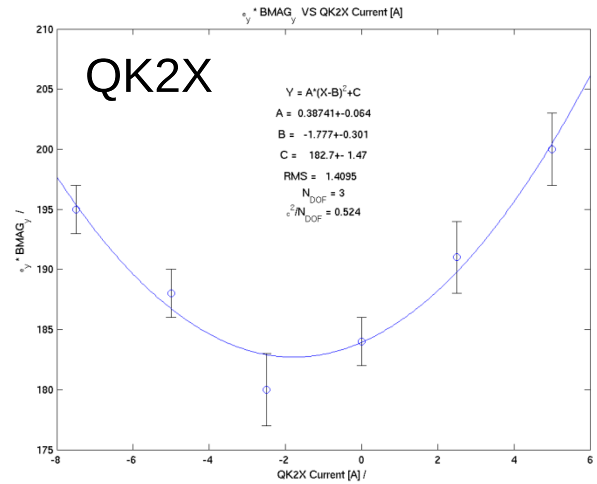
Emittance before:
Ey = 100 ± 1pm · rad

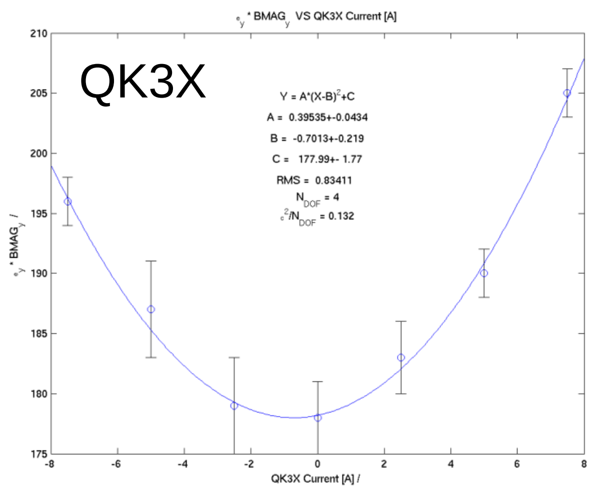
QK1X set to −20A
QK2X set to −1.8A
QK3X set to −0.7A
QK4X set to 8.6A

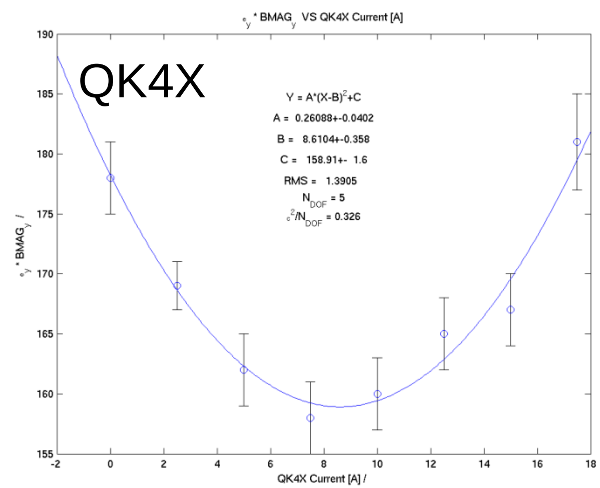
Emittance after:
62 ± 2pm · rad

Emittance is almost halved



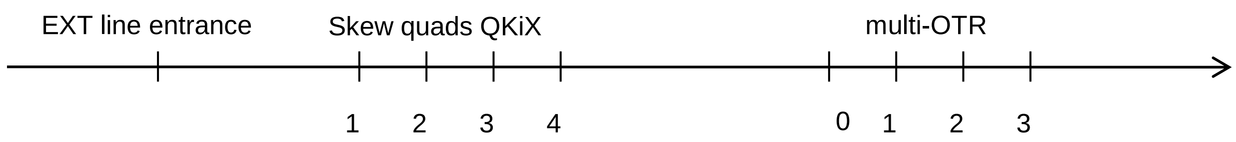






Multi-OTR System   September/December 2011: Coupling Correction

Response Matrix Method: Procedure



Using the nominal lattice scan each skew and fit linearly the response for the coupling term in each OTR: Cij is the linear coefficient.

$$\begin{pmatrix} \sigma_{13}^{OTR0} \\ \sigma_{13}^{OTR1} \\ \sigma_{13}^{OTR2} \\ \sigma_{13}^{OTR3} \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \\ C_{41} & C_{42} & C_{43} & C_{44} \end{pmatrix} \cdot \begin{pmatrix} I_{skew1} \\ I_{skew2} \\ I_{skew3} \\ I_{skew4} \end{pmatrix}$$

Build the response matrix that relates each skew with each OTR through the coefficient Cij.

Built by tracking

Measure the coupling term σ_{13} (<xy> term) in each of the OTRs.

Calculate the needed strength to correct this coupling using the pseudo-inverse response matrix

$$\begin{pmatrix} I_{skew1} \\ I_{skew2} \\ I_{skew3} \\ I_{skew4} \end{pmatrix} = pinv \begin{pmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \\ C_{41} & C_{42} & C_{43} & C_{44} \end{pmatrix} \cdot \begin{pmatrix} \sigma_{13}^{OTR0} \\ \sigma_{13}^{OTR1} \\ \sigma_{13}^{OTR2} \\ \sigma_{13}^{OTR3} \end{pmatrix}$$

Goal

Measured

Multi-OTR System Coupling Correction

Response Matrix Method: Measurements

-The method was implemented in December 2011 and it has been used successfully (but residual coupling at IP issue!)

-Corrects in few minutes [the time needed to measure the sizes]

-Converges to the Manual Skew Scanning value in three iterations.

-Leads to a more averaged intensities, not extreme ones.

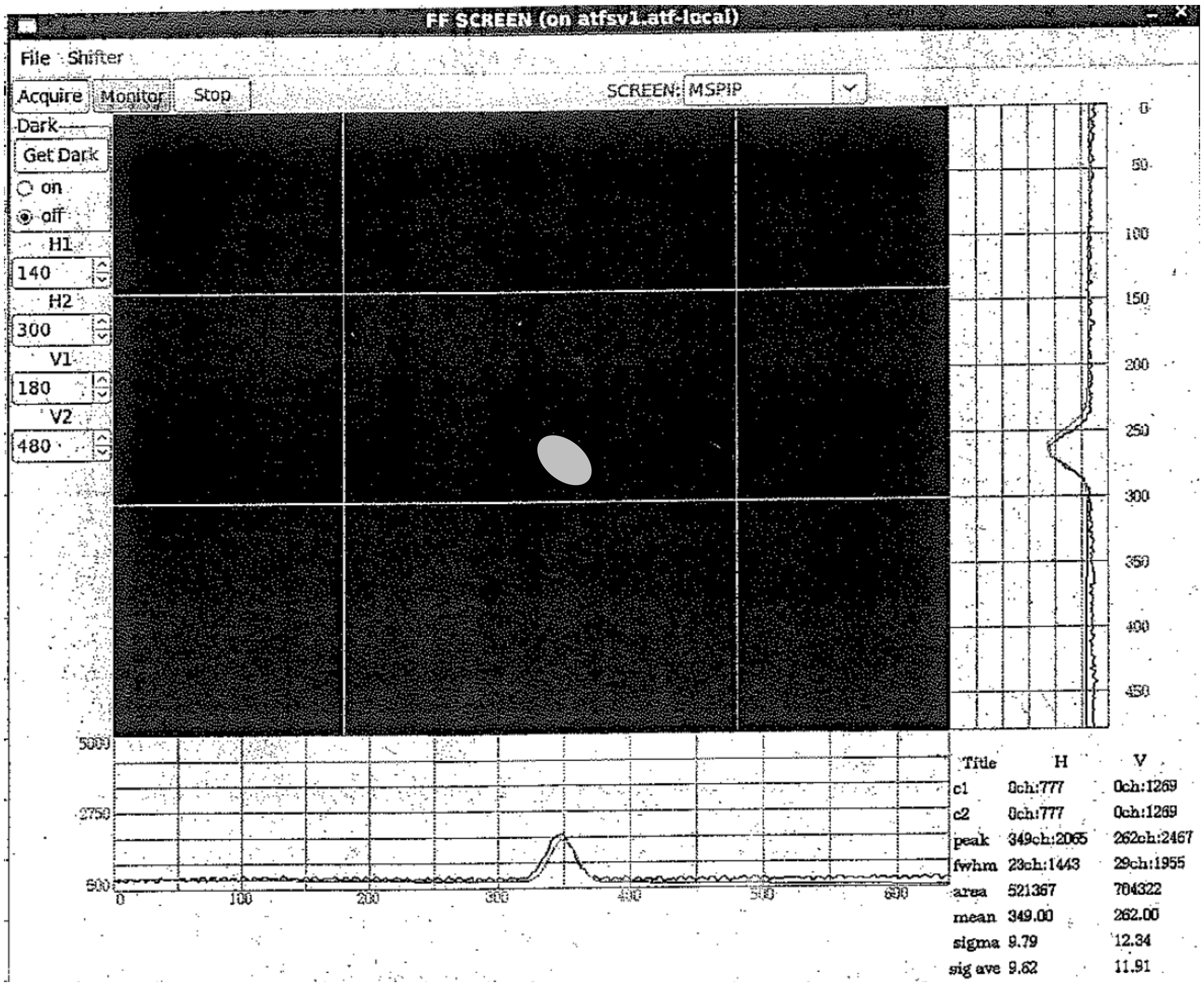
Correction made on shift 8th December 2011

	6th Dec.	Load 8th Dec.	Skews off	Iter. 1	Iter. 2	Iter. 3
$\epsilon_y [pmrad]$	41 ± 13	11 ± 11	16 ± 13	14 ± 12	12 ± 8	12 ± 9
QK1X $[A]$	-13.1	-13.1	0	-3.0	-5.1	-6.0
QK2X $[A]$	-4.0	-4.0	6.2!	3.6	2.1	1.8
QK3X $[A]$	-2.4	-2.4	0	-1.8	-3.3	-4.3
QK4X $[A]$	4.9	4.9	0	1.8	2.9	3.4

Presence of coupling at IP

16th December 2011:

After coupling correction with mOTR -> Big coupling at IP -> ~45 degrees tilt!



Response matrix method for 4 coupling terms

-May be due to nonzero angular coupling terms [only spatial one is cancelled].

- Install a ‘response matrix’-like algorithm that cancels all the 4 coupling terms in one location.

$$\begin{pmatrix} <xy> \\ <x'y> \\ <xy'> \\ <x'y'> \end{pmatrix} = pinv(M_{xy}) \cdot \begin{pmatrix} <xy>_{OTR0} \\ <xy>_{OTR1} \\ <xy>_{OTR2} \\ <xy>_{OTR3} \end{pmatrix}$$

Function of lattice

Measured

-Measure the 4 σ_{13} (<xy> term) and reconstruct the 4 coupling terms at OTR0.

$$\begin{pmatrix} I_{skew1} \\ I_{skew2} \\ I_{skew3} \\ I_{skew4} \end{pmatrix} = pinv \begin{pmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \\ C_{41} & C_{42} & C_{43} & C_{44} \end{pmatrix} \cdot \begin{pmatrix} <xy> \\ <x'y> \\ <xy'> \\ <x'y'> \end{pmatrix}$$

Goal

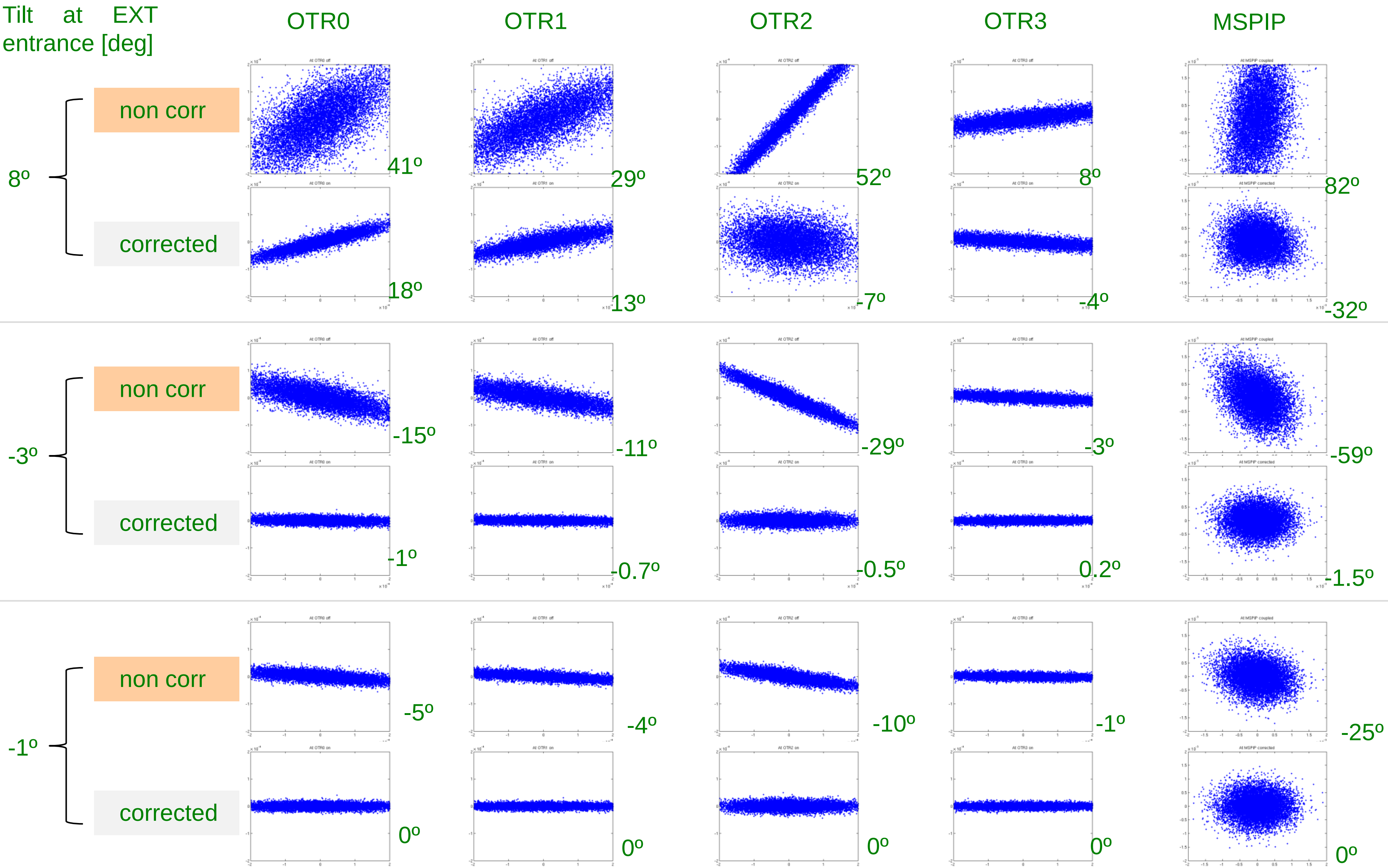
Built by tracking

Reconstructed from measurements

-Calculate skew intensities to correct the 4 coupling terms.

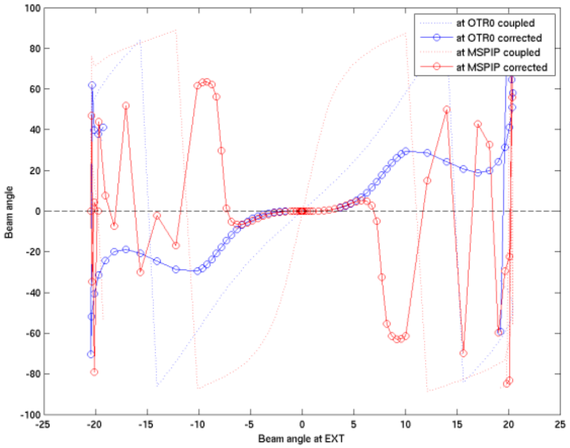
Multi-OTR System September/December 2011: Coupling Correction

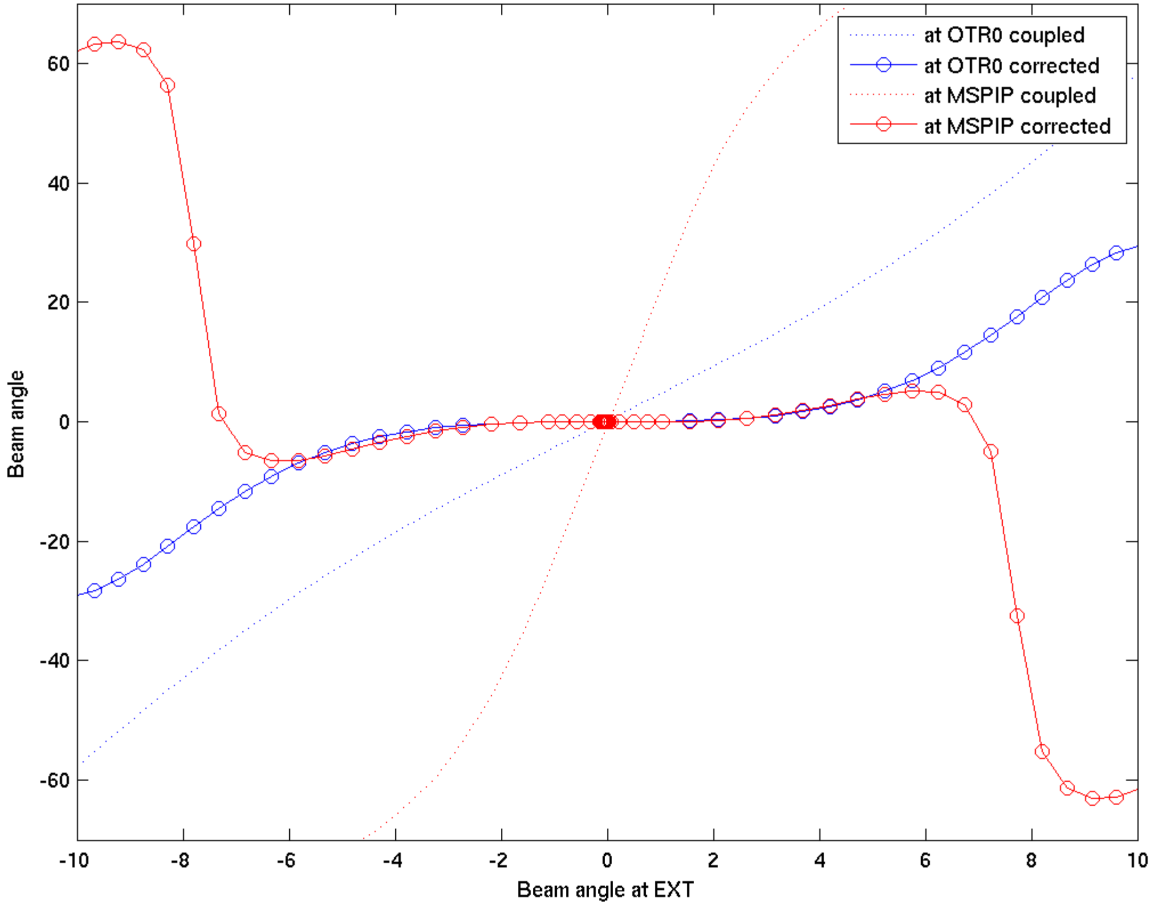
Response matrix method for 4 coupling terms



Multi-OTR System   September/December 2011: Coupling Correction

Response matrix method for 4 coupling terms

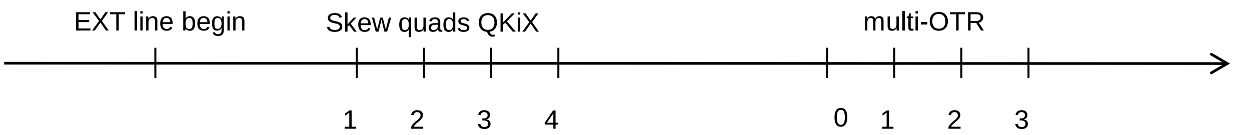




Multi-OTR System September/December 2011: Coupling Correction

Beam matrix as a function of skew intensities

Another approach: Solving the transport matrix



Given the beam matrix upstream it propagates towards downstream like:

$$R_i \cdot \sigma^u \cdot R_i^T = \sigma^{OTR0}$$

-Use the beam matrix reconstruction algorithm to obtain the beam matrix σ^u upstream of the skews.

- Build the transfer matrix from a point upstream through the skews to OTR0 leaving the skew strength explicit in the calculation:

$$R_i = (R_{4\to OTR0} \cdot R_{skew4} \cdot R_{3\to 4} \cdot R_{skew3} \cdot R_{2\to 3} \cdot R_{skew2} \cdot R_{1\to 2} \cdot R_{skew1} \cdot R_{u\to 1})$$

Beam matrix as a function of skew intensities

Another approach: Solving the transport matrix

- Transport the downstream beam matrix to OTR0 to get the 4 coupling terms as a function of the 4 skew strengths.

$$\begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} & \sigma_{14} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} & \sigma_{24} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} & \sigma_{34} \\ \sigma_{41} & \sigma_{42} & \sigma_{43} & \sigma_{44} \end{pmatrix}^d$$

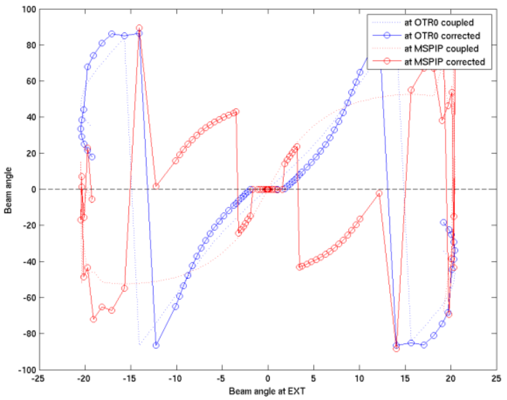
- Solve the 4 equations and 4 unknowns system to get the skew intensities that makes coupling terms equal 0.

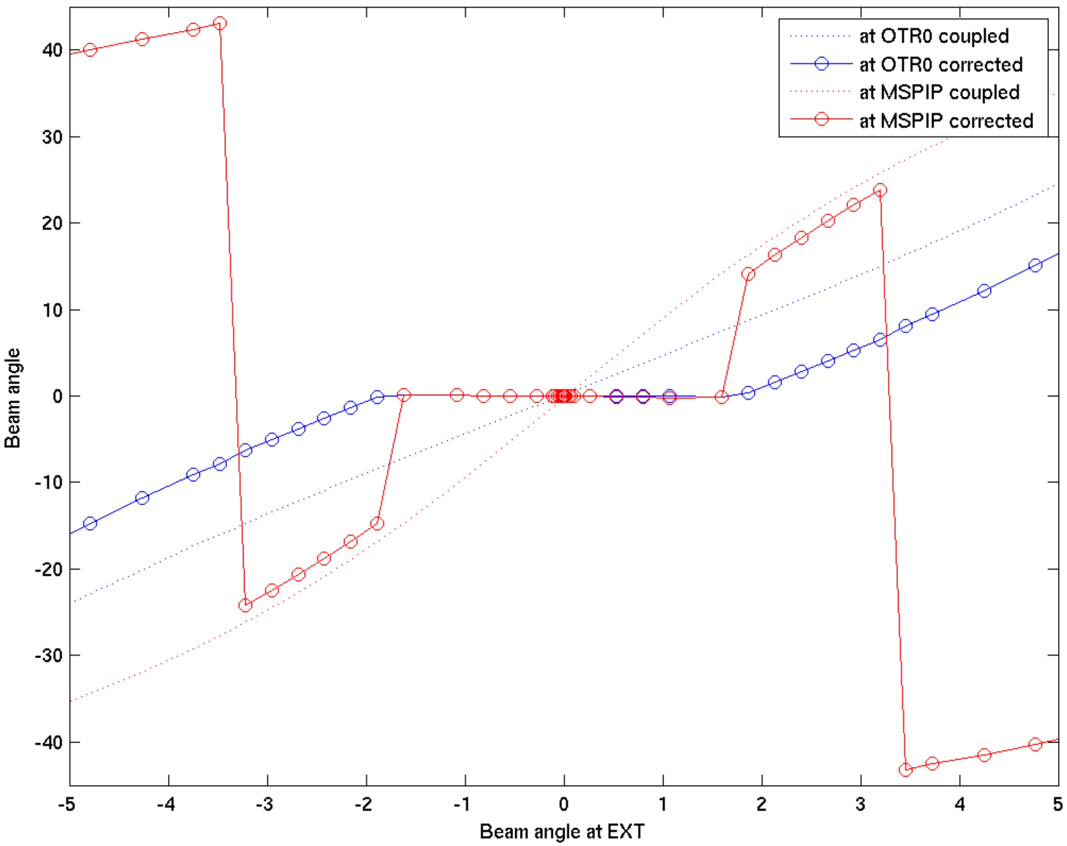
$$\left.\begin{aligned} \sigma_{13}(I_1, I_2, I_3, I_4) = 0 \\ \sigma_{14}(I_1, I_2, I_3, I_4) = 0 \\ \sigma_{23}(I_1, I_2, I_3, I_4) = 0 \\ \sigma_{24}(I_1, I_2, I_3, I_4) = 0 \end{aligned}\right\}$$

Multi-OTR System   September/December 2011: Coupling Correction

Beam matrix as a function of skew intensities

Another approach: Solving the transport matrix





Model optimizer method

Procedure:

- Use “lsqnonlin” minimization routine to **generate a Lucretia beam** which tracks to 4 OTR locations and **reproduces measured σ_{13} measured values** at each location.

- Using this beam, use “lsqnonlin” together with Lucretia beam tracking to **find 4 QK strength** settings which correct **σ_{13} terms**.

Only needs 1 set of measurements with beam.

Takes about 2 min. to complete [longer the worse the incoming coupling is].

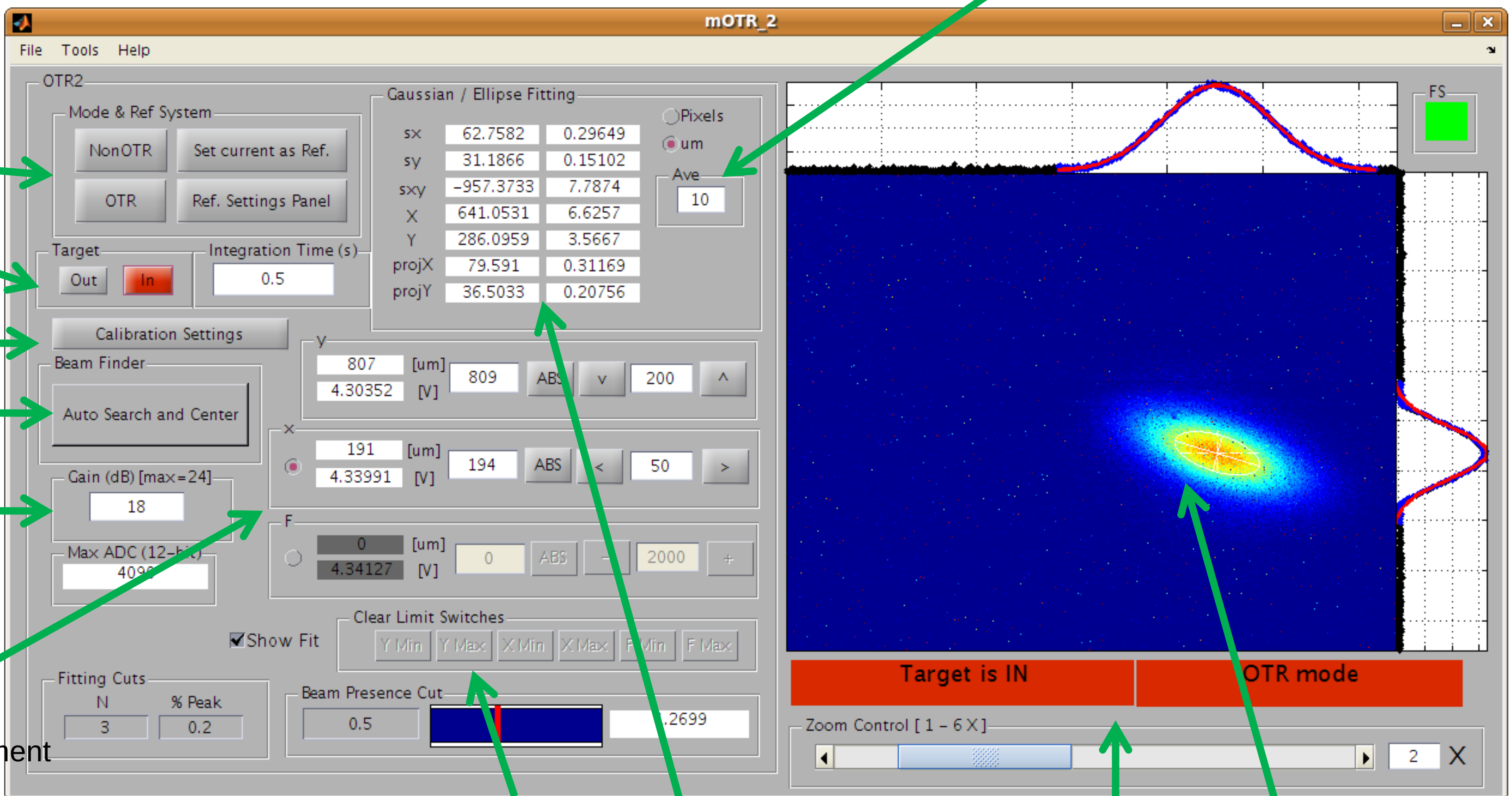
Simulations showed better behaviour than the response matrix procedure in some cases.

Being tested at ATF2.

Multi-OTR System

2012 Systematics measurements: Beam size measurements

Single OTR panel



Working mode & Reference system

Target control

Calibrations

Beam finder

CCD Gain

Position & movement of the movers

number of measurements

Limit switches status

Ellipse fitting and analysis

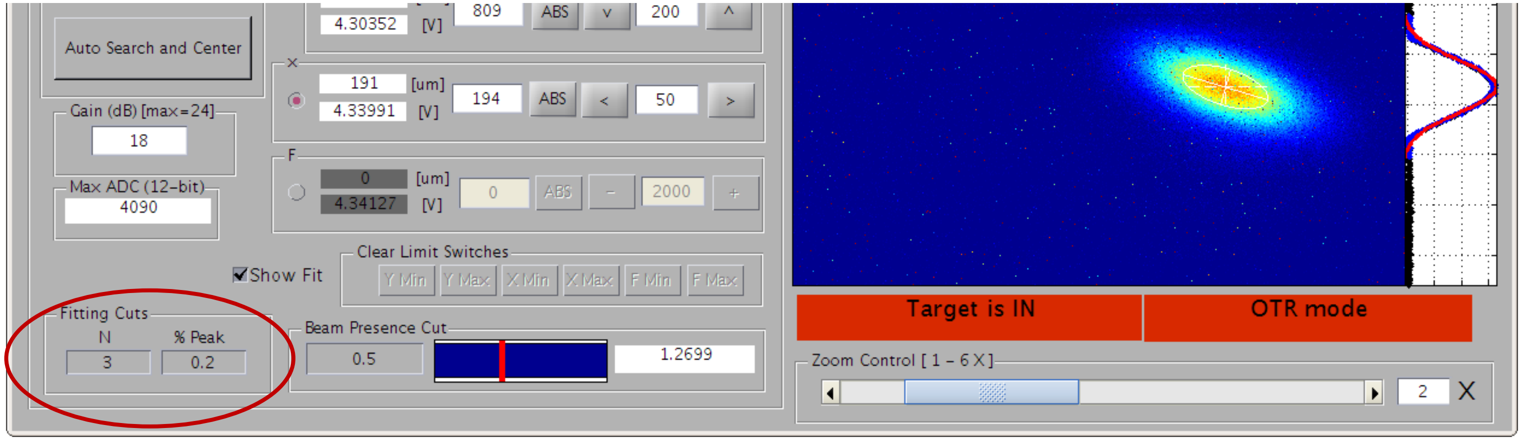
Machine status

CCD image and beam fitting

2012 Systematics measurements: Beam size measurements

Ellipse fitting parameters

Due to presence of background and dead pixels in the CCD camera one has to define a window to cut the image and to fit the ellipse.

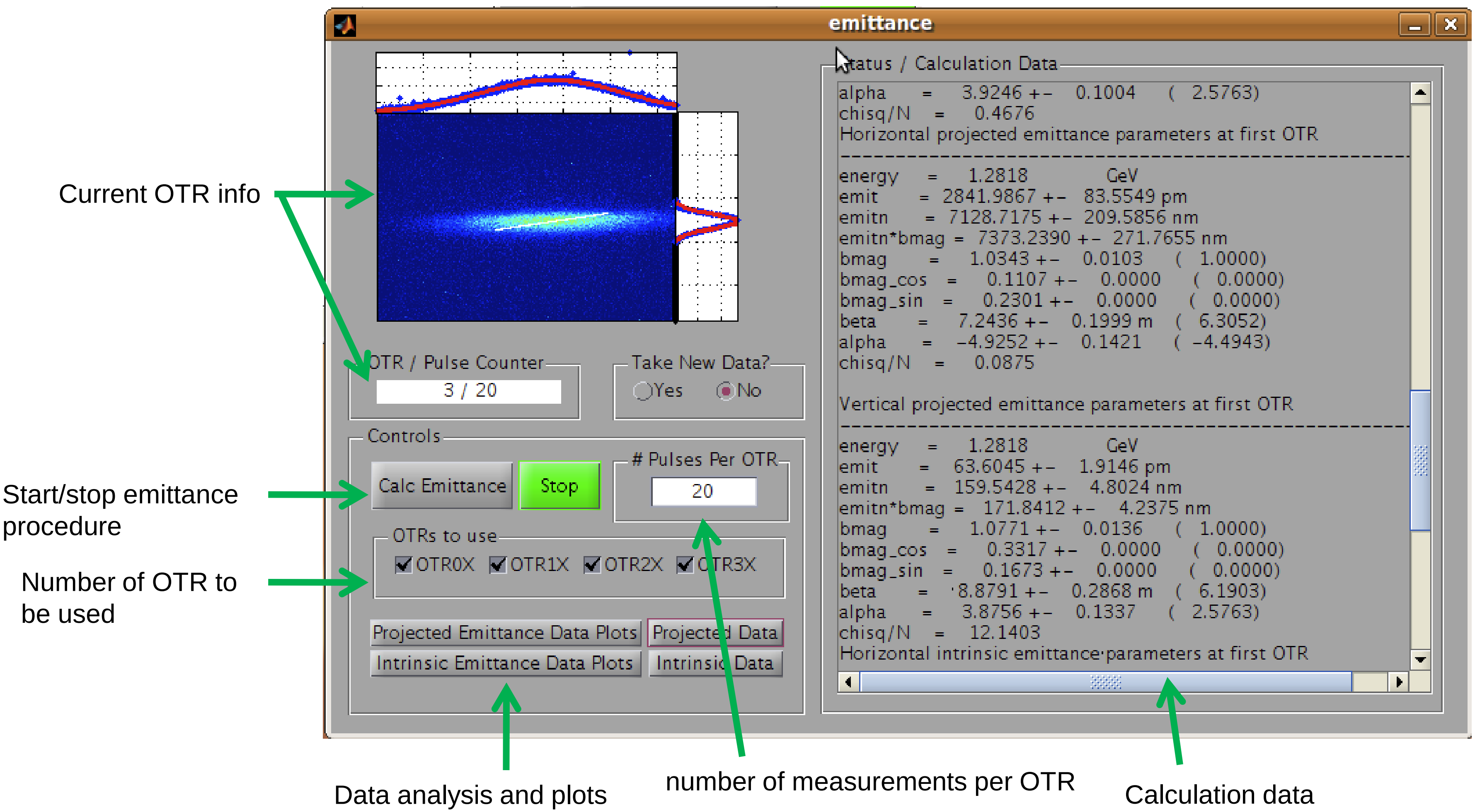


It has been lately seen that the measured size has high sensibility to this window.

This is to be studied and an agreement needs to be found in order to have reliable emittance values.

2012 Systematics measurements: Emittance measurements

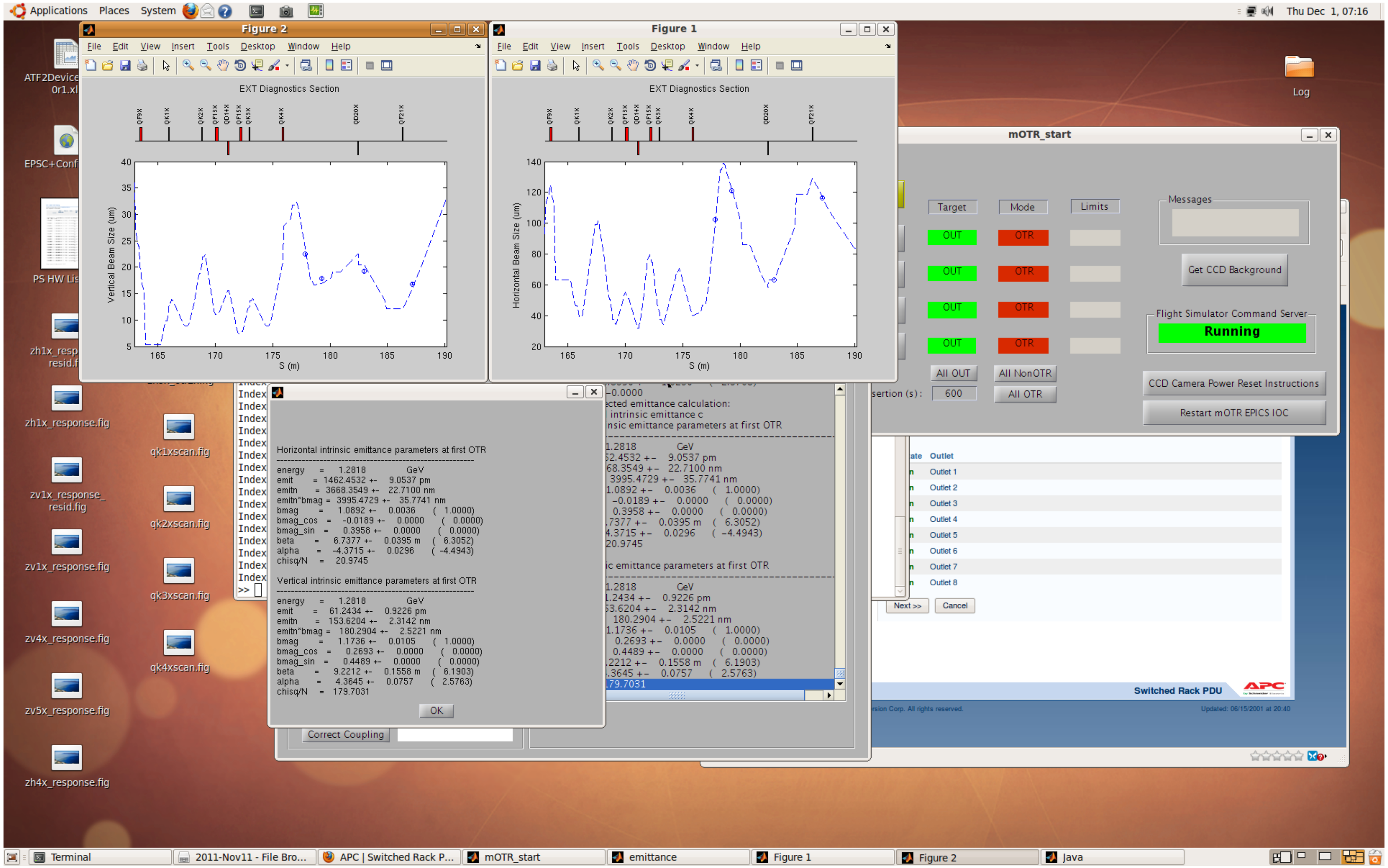
Emittance panel



Multi-OTR System

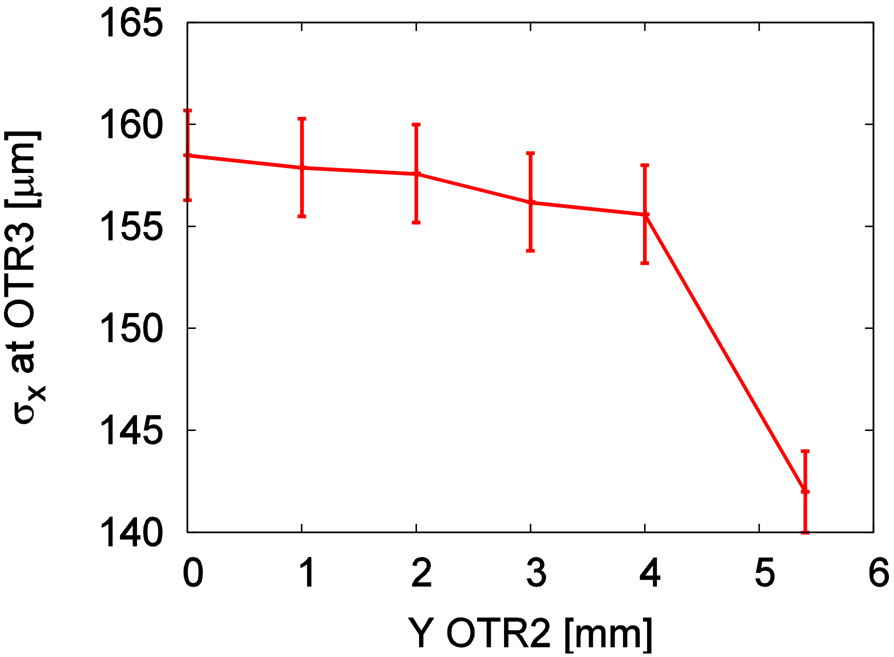
2012 Systematics measurements: Emittance measurements

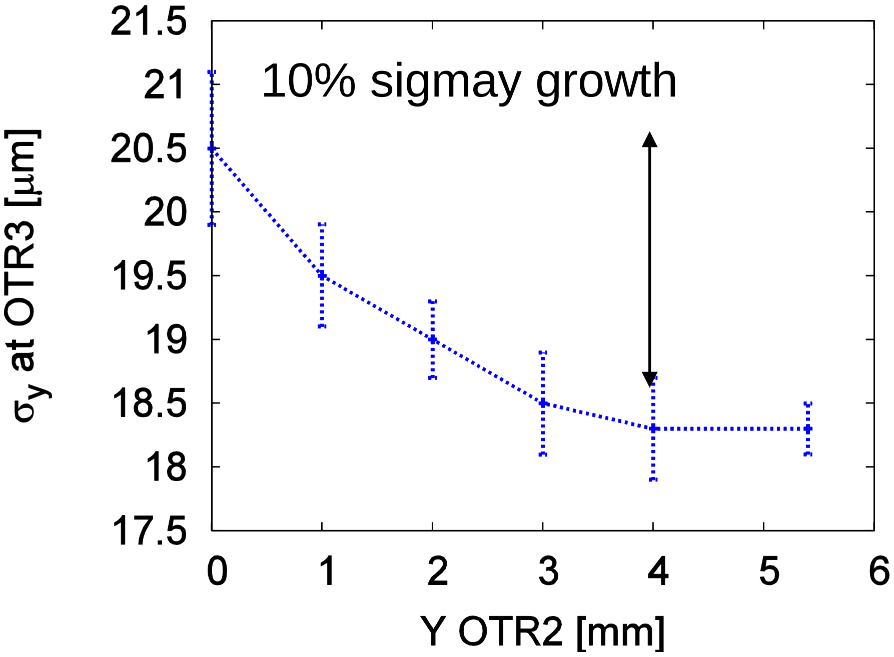
Emittance measurements are being done usually in the control room since last year.



2012 Systematics measurements: Emittance Measurements

Emittance growth due to wakefields in OTRs





Changing vertical position of the OTR2 body from 6 mm [non OTR position] to measure mode position (0 mm) in steps of 1 mm. Then, recording beam size at OTR3.

From ~ 4 mm down the effect is clear

10% sigma growth (20% emitt growth)

2012 Systematics measurements: Emittance Measurements

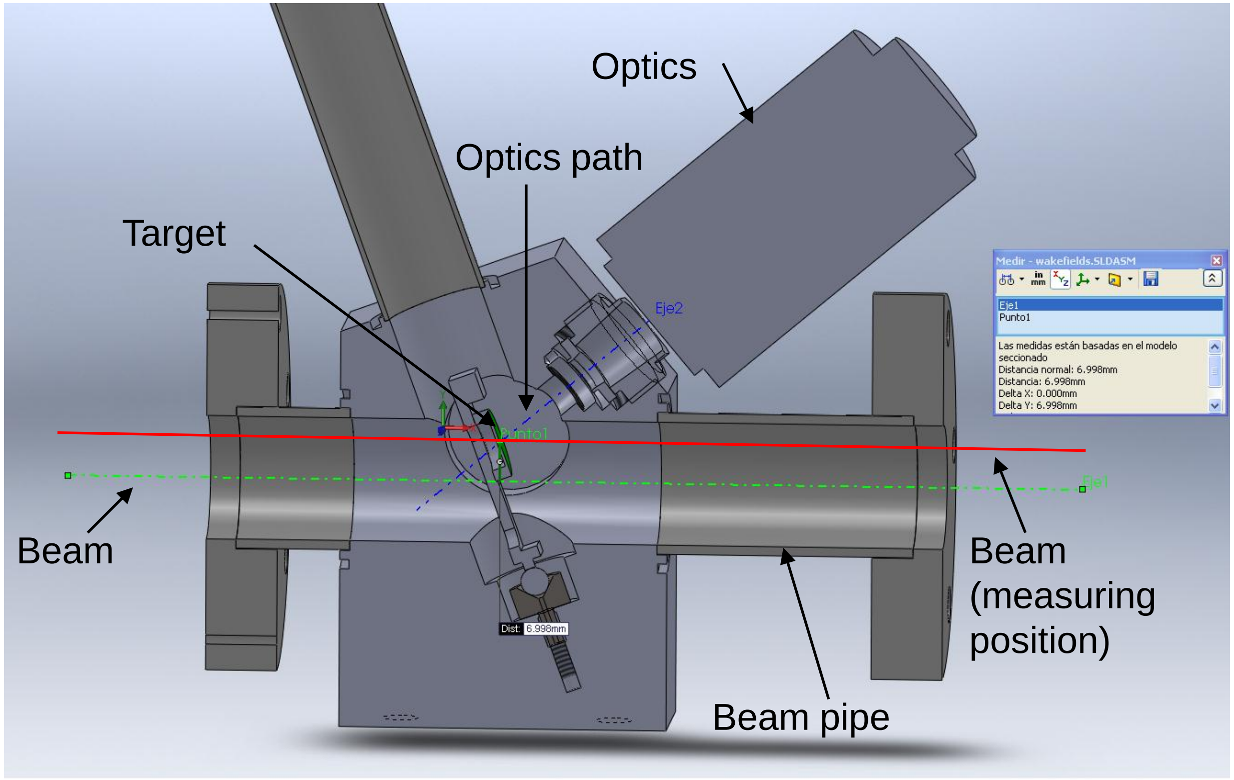
Current target position

-To make the beam intercept with the target, the OTR must be lowered by 7 mm to measure.

-Beam pipe ID = 22 mm.

- Due to this, the beam goes close to the beam pipe edge (4mm) when the OTR is in the measuring configuration causing wakefield effects.

-To avoid this effect a new design of the target holder is proposed in order to get the target lower.



Multi-OTR System

2012 Systematics measurements:Emittance Measurements

-The new holder host the target inside itself and place the target downstream and down.

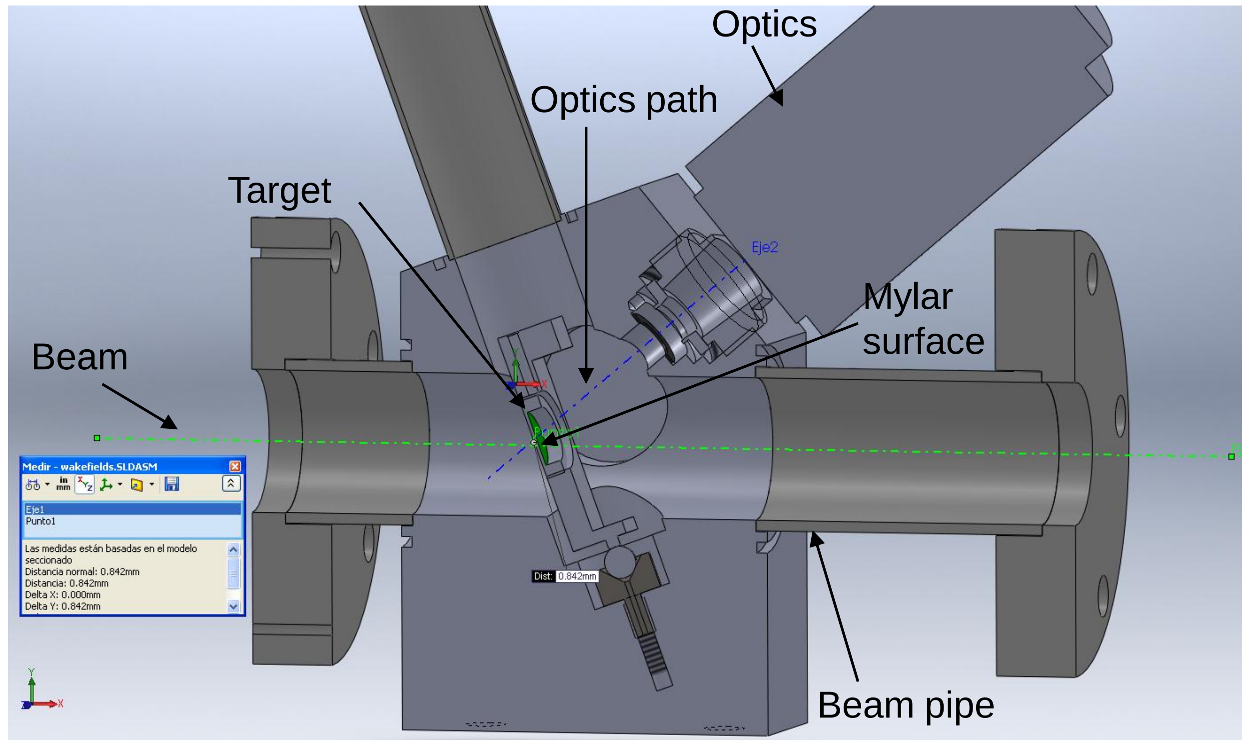
- By flipping the target over we achieve to get the center of the mylar surface (green face) even lower.

-With this set up the beam intercept the target without lowering the OTR.

-The beam remains centered within the beam pipe in the measuring configuration and do not produce wakefield effects.

-The target could be also smaller in diameter and thickness.

New target position



The mOTR system is working and usually speeding some routines in beam tuning.

Work to be done:

- Find an agreement for a reliable beam size measurement.

- Test of 4D emittance algorithm.

- Coupling at IP: Coupling source after OTRs?

  Coupling correction algorithm research?

-Wakefield problem for simultaneous measurement

Thanks for your attention