Beam size and Emittance measurement at the EXT line of ATF2

A. Faus-Golfe

on behalf of mOTR team:
A. Faus-Golfe, J. Alabau, C. Blanch, J. Resta Lopez J. Navarro Faus
IFIC Valencia
D. McCormick, G. White, J. Cruz, M. Woodley, E. Marin
SLAC
with
KEK support

Outline

- Introduction and Objectives
- Technical Description and Capabilities
  - Hardware and Software
  - First measurements
  - Beam size and Emittance measurements
  - Other applications: Coupling correction, Beta matching, Energy spread measurement
- Emittance reconstruction analysis
- Lessons learned and implications to ILC
- Conclusions

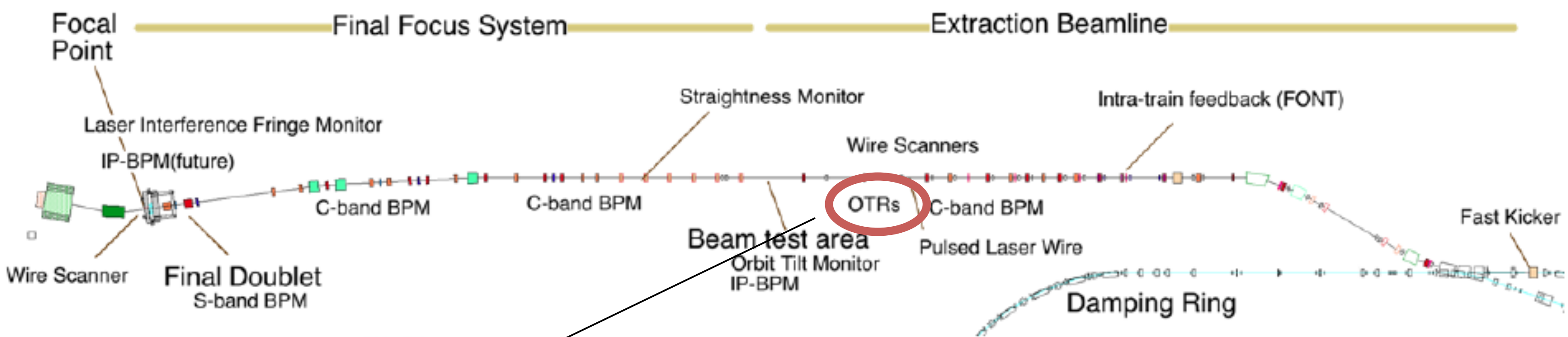
Introduction and Objectives

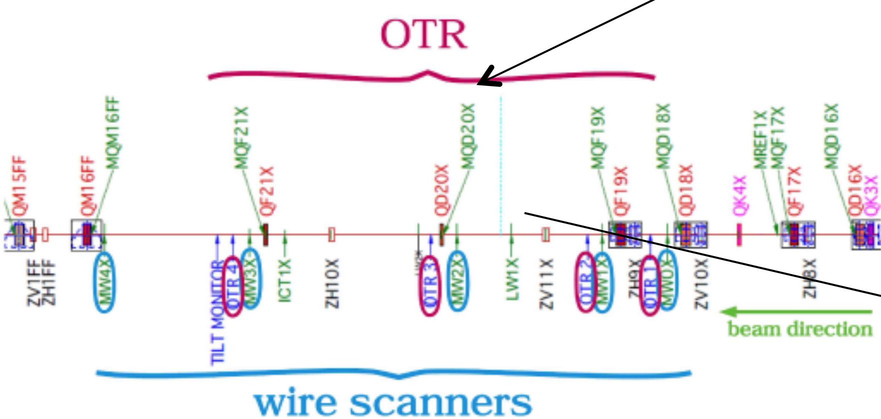
- The multi-OTR system is made of **4 OTRs** installed in the zero-dispersion part of ATF2 EXT line

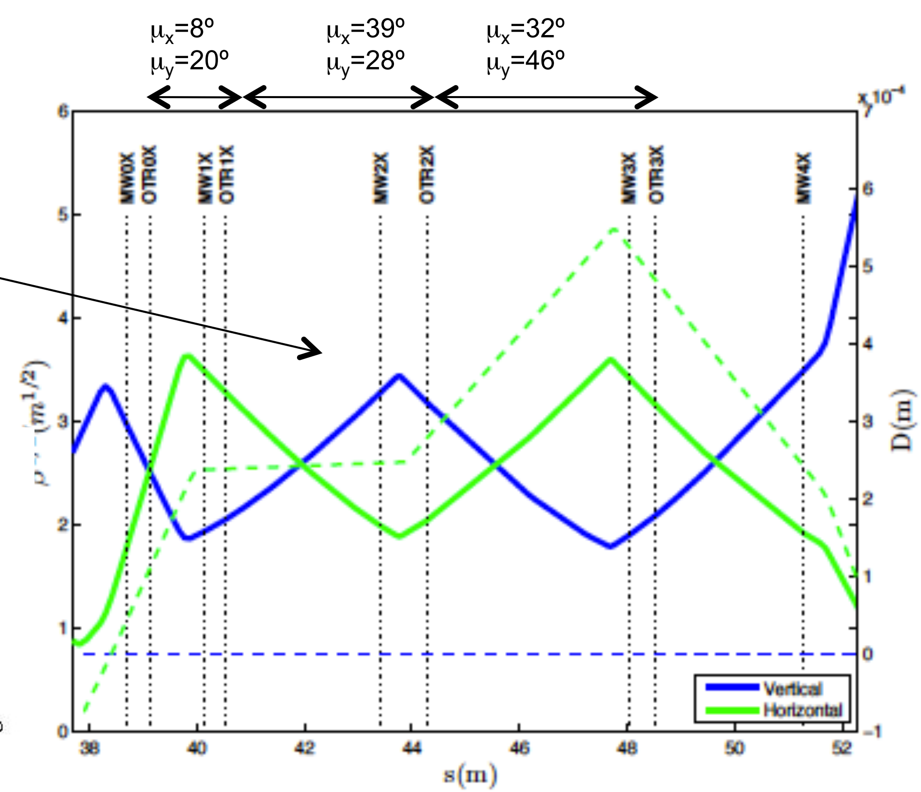
- The objective of this project is the **fast measurement of the emittance** (single shot for beam size, 1min for emittance) with:
  - high statistics
  - **2um** resolution
  - **$2x10^{10}$ single bunch** and **$2x10^{11}$** for **20 multi-bunched** beam (2.8 ns spacing)

- The design is based on OTR1X at ATF EXT line (**5um resolution with $2x10^{10}$**) including improved features (compactness, calibration setup, demagnifier system..)

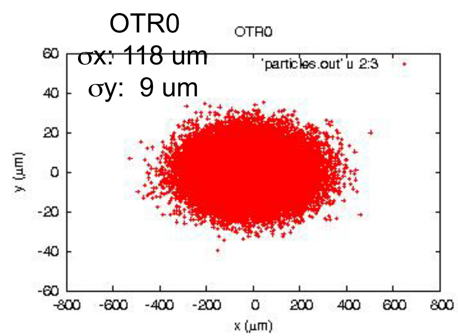
- The system **is installed near WS** for comparison and confirmation of OTR as a beam emittance diagnostic device







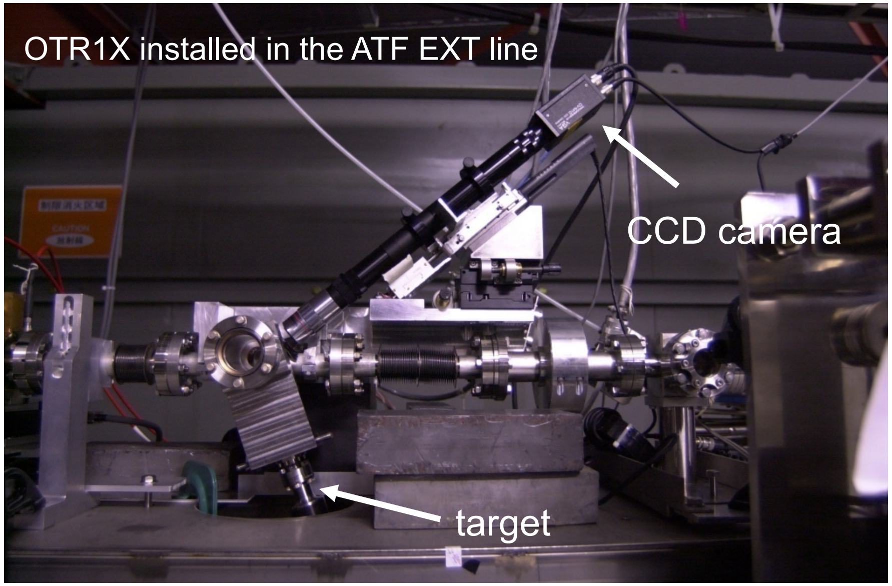
Location is not optimized, free space criteria has been taken into account

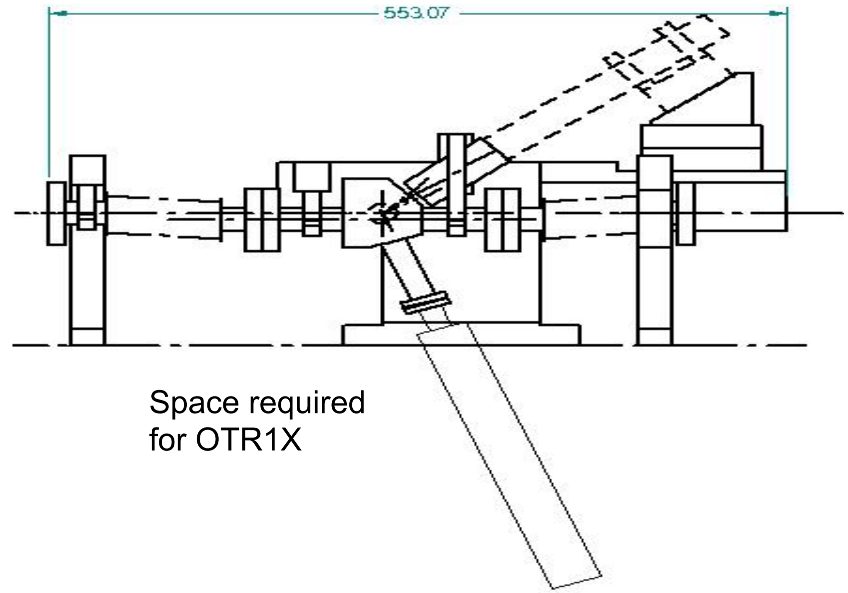


Timeline

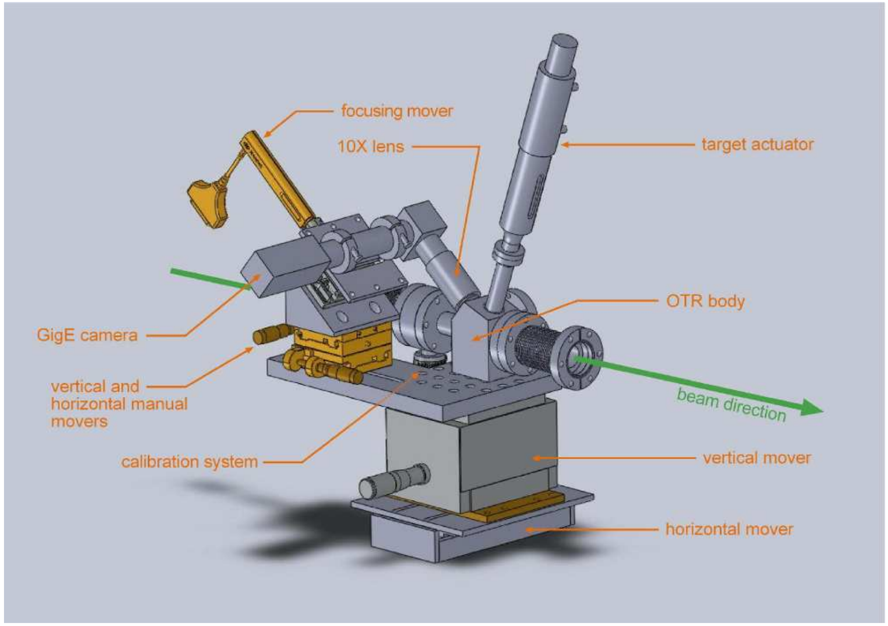
- **Proposal to ATF2 collaboration** June 2009
- **Design and Construction** Fall 2009
- **Calibration at IFIC and SLAC labs** February 2010
- **Installation in the ATF2 EXT line** April-May 2010
- **First Test with beam** June 2010
- **Test, Software Developments for beam size and emittance reconstruction and implementation in ATF2 control system** Fall 2010
- **New targets, Calibration system and Camera protection system** November 2010
- **Software Developments, Calibration and First Beam Measurements** Nov-Dec 2010
- **New LAN Control system** February 2011
- **Systematic Measurements I (before Tohoku earthquake)** January-March 2011
- **Design and Construction of a Demagnifier system** January-April 2011
- **Installation of the Demagnifier system** August 2011
- **Development of Coupling correction software algorithms** from September 2011
- **Systematic Measurements II (after Tohoku earthquake)** Nov 2011- Dec 2012
- **Proposal of new Target holders and Optical system** September 2012
- **Design and Construction of new Target holders** February-December 2012
- **New Target holder Installation** February 2013
- **Systematic measurements III** from March 2013

Technical Description HW I — 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 a new design. As a result the OTR1X was a patchwork of parts, taking 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**.

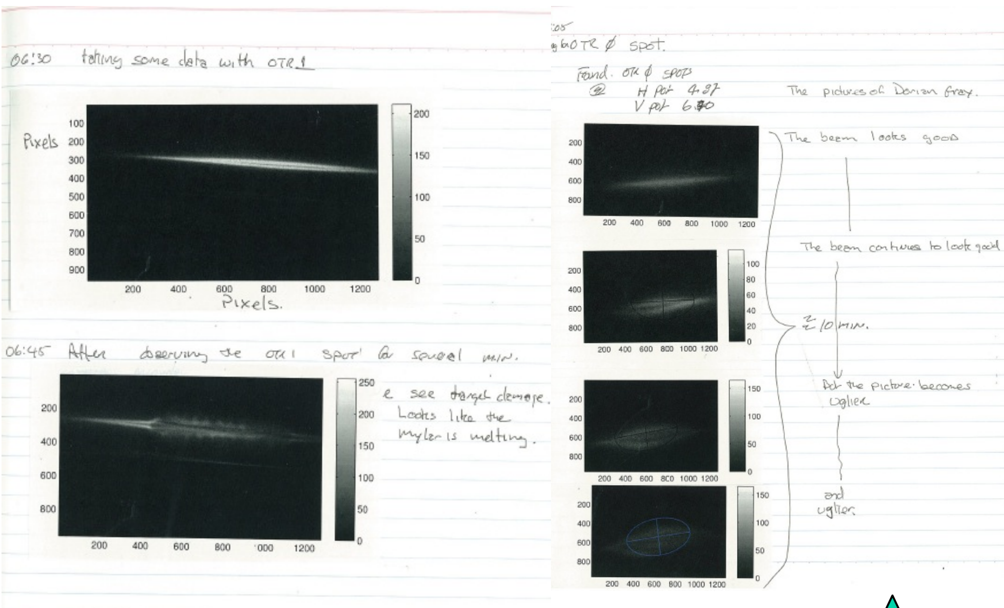


New OTRs have **same controls** and **motion capabilities** as OTR1X with the following improvements:

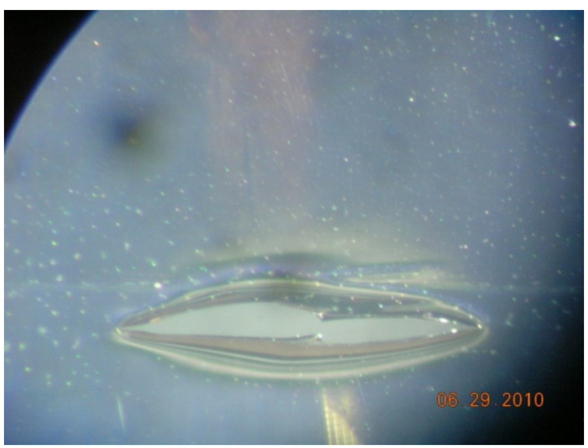
- **Target actuator** relocated to the **top** (no interference with the girder) and smaller design, giving greater flexibility in the OTR placement
- **Thinner target** that **reduces** lens **radiation** darkening

- The extreme **thinness** of the **aluminium target reduces** 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 puts the entire target into focus and **reduces** 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

June 2010: Target test



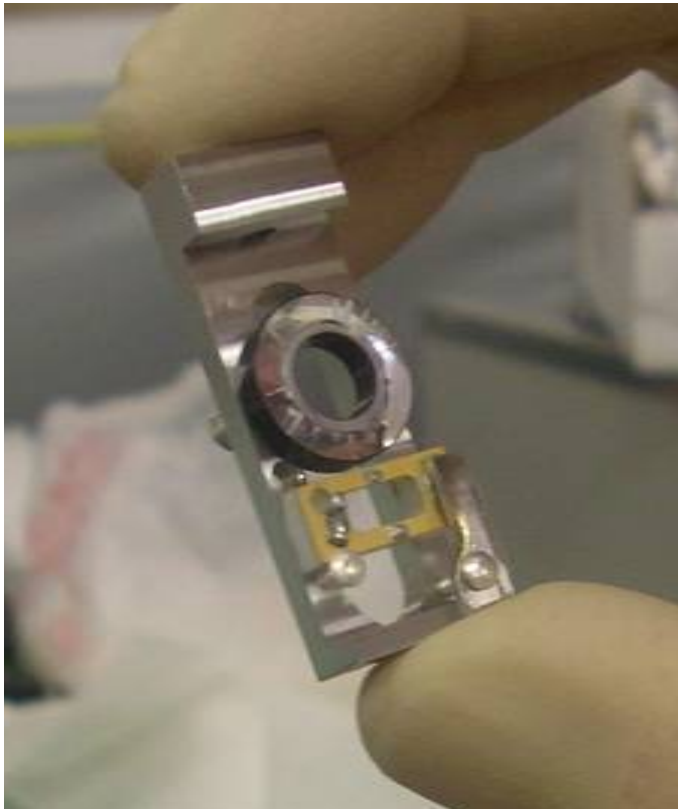
- Exercise and **calibration** of vertical and horizontal **movers** and read-back **potentiometers**
- Tests of 4 OTRs during beam time: beam seen but 3 **targets** (nitrocellulose coated aluminum) were **damaged** ($4x10^9$ e^- per pulse)
- CCD **Cameras** suffer from **radiation**, some pixel are dead



Damaged target

Technical Description HW I

November 2010: New targets installed and tested

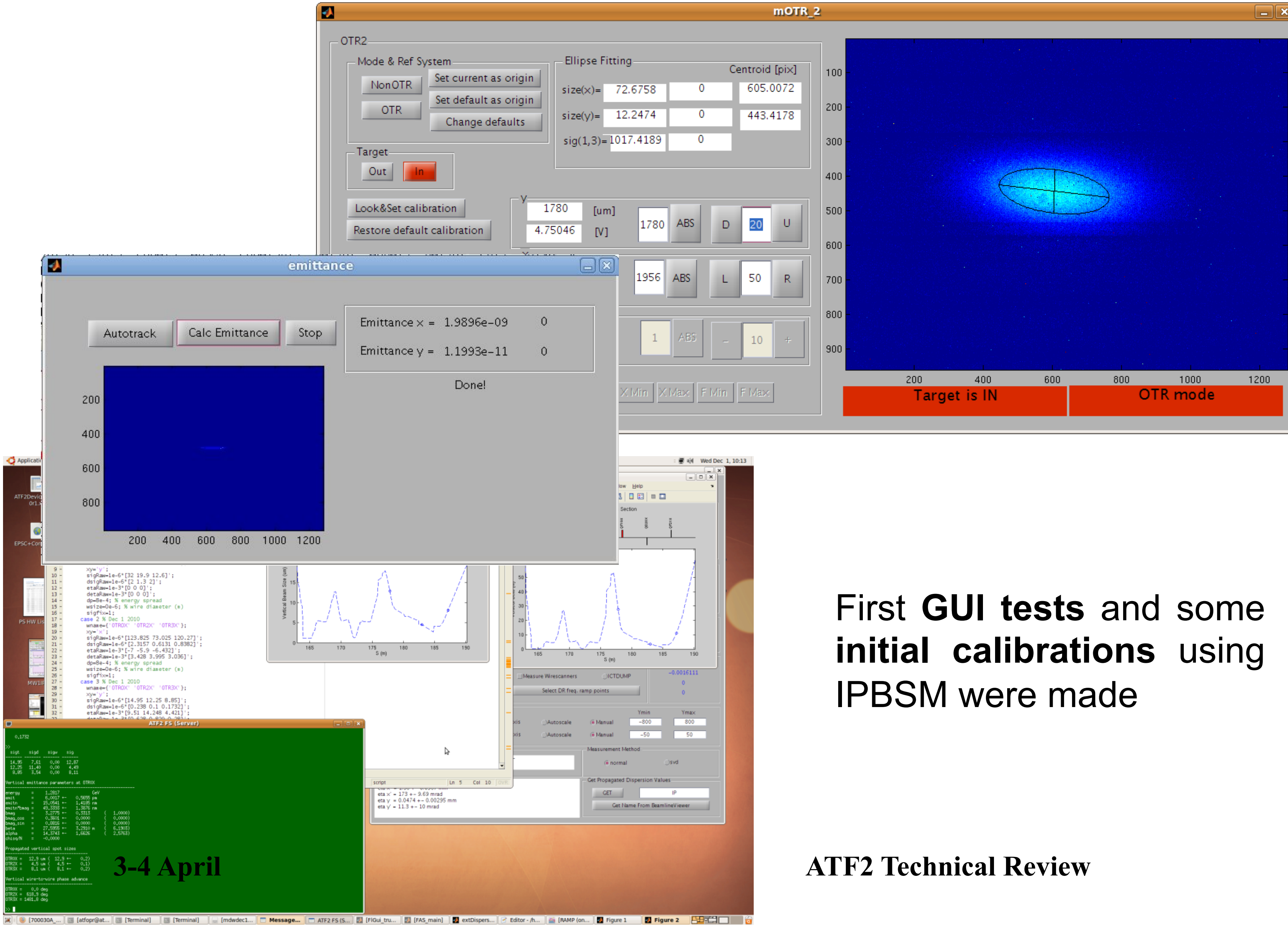


New targets could **stand the beam currents** for several minutes without being damaged

Two **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, the **wire targets, made with 4** wire (10um tungsten), one horizontal, one vertical and two tilted were installed.

Technical Description SW I

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

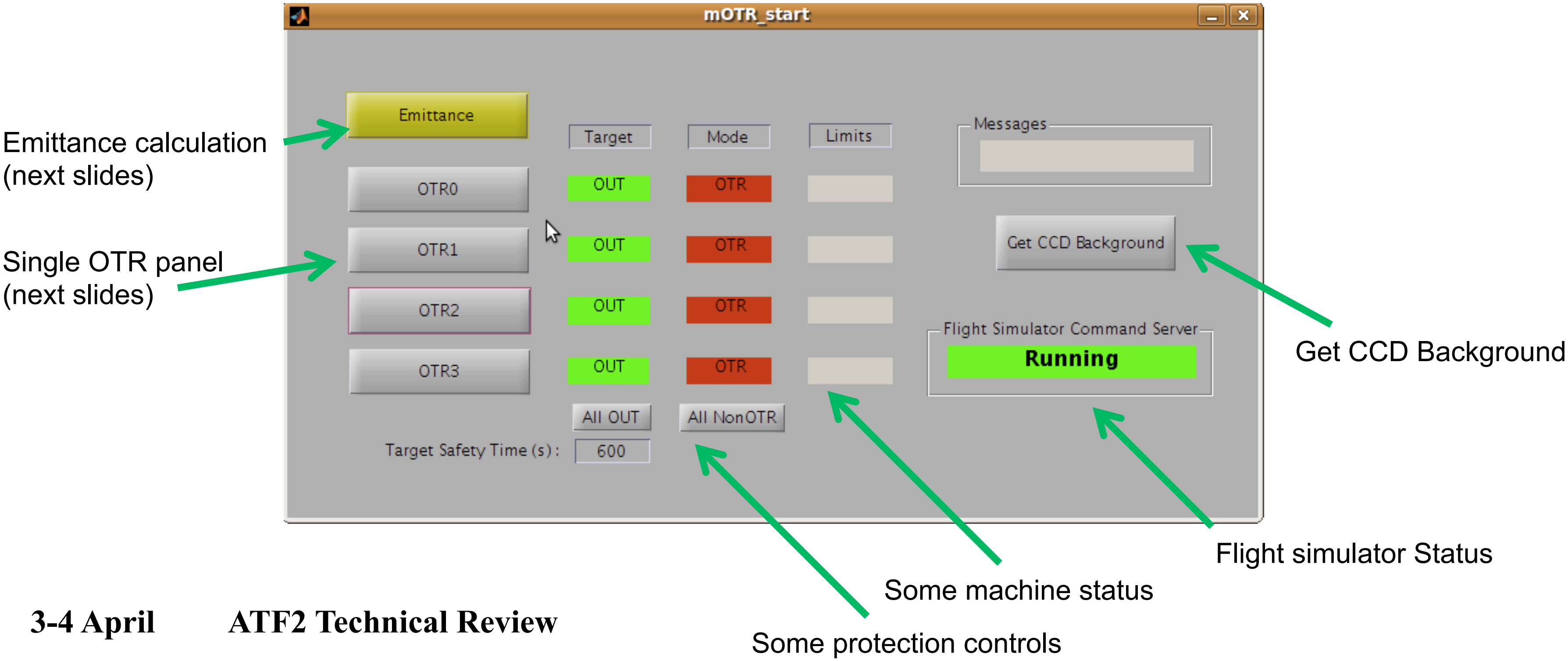


First **GUI tests** and some **initial calibrations** using IPBSM were made

Technical Description SW I

- **OTR software** 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 are stored in EPICS** Process Variables and archived in the EPICS archival system.

Main start panel



December 2010: Beam size and Emittance

Single OTR panel

number of measurements

Working mode & Reference system

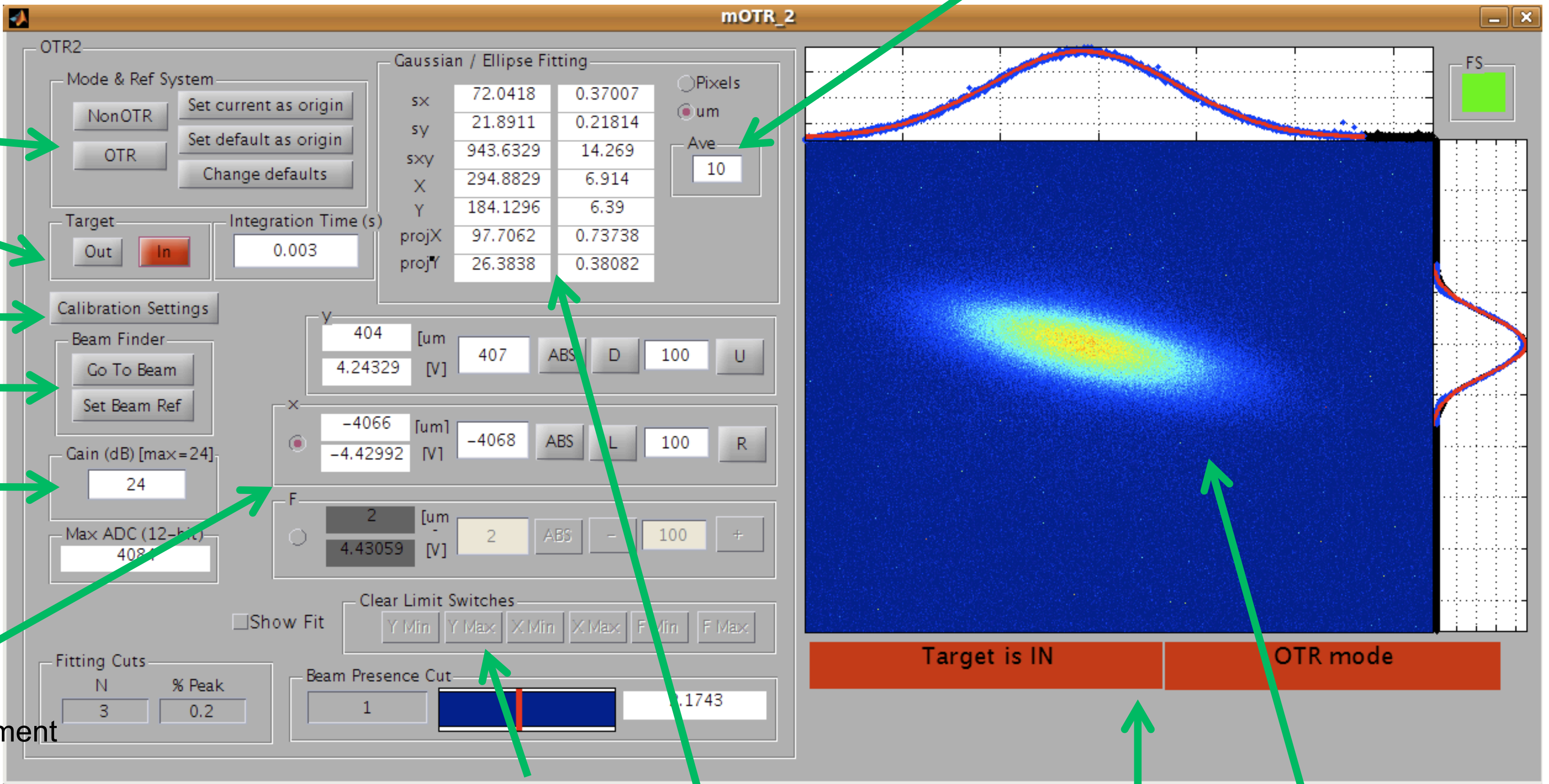
Target control

Calibrations

Beam finder

CCD Gain

Position & movement of the movers



Limit switches status

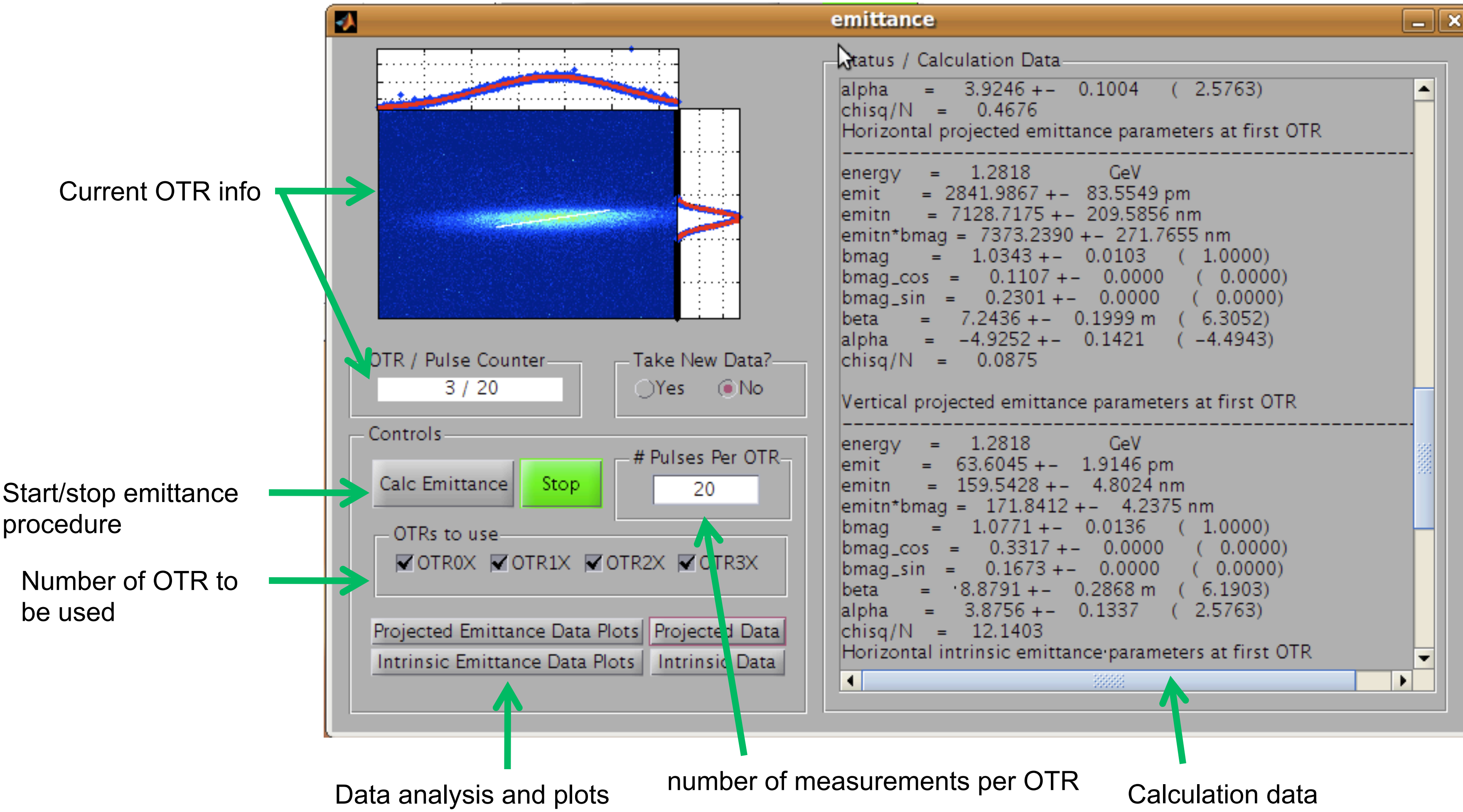
Machine status

Ellipse fitting and analysis

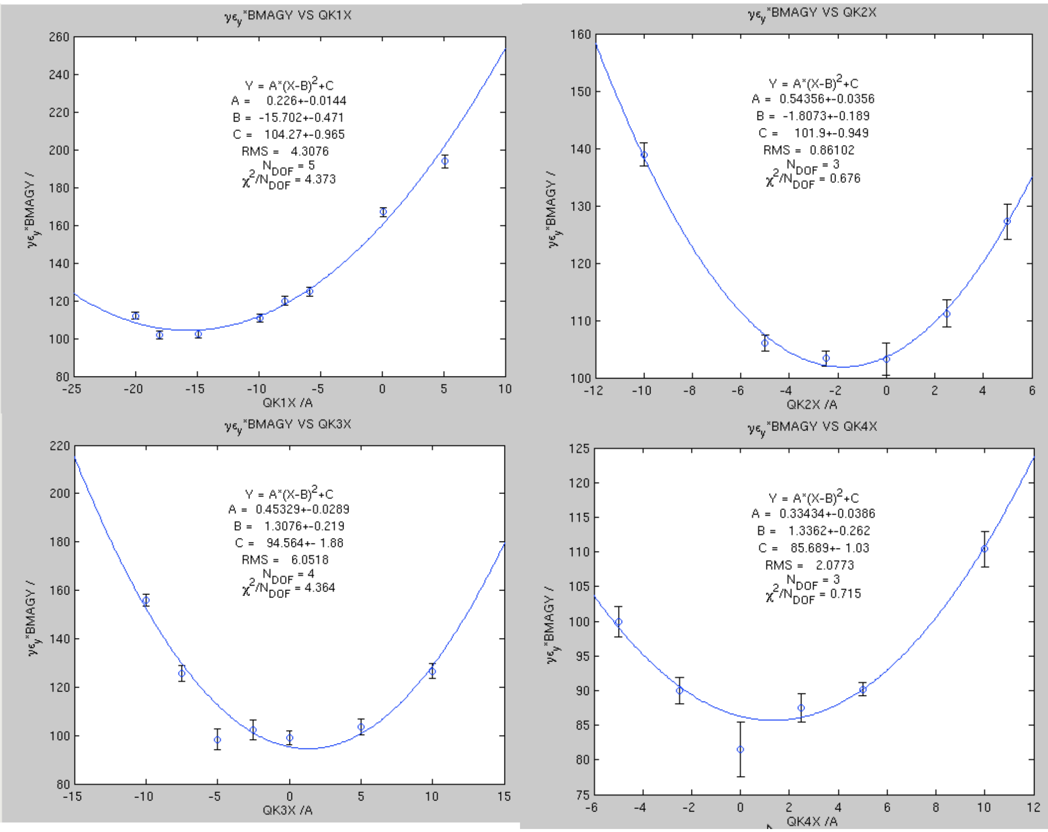
CCD image and beam fitting

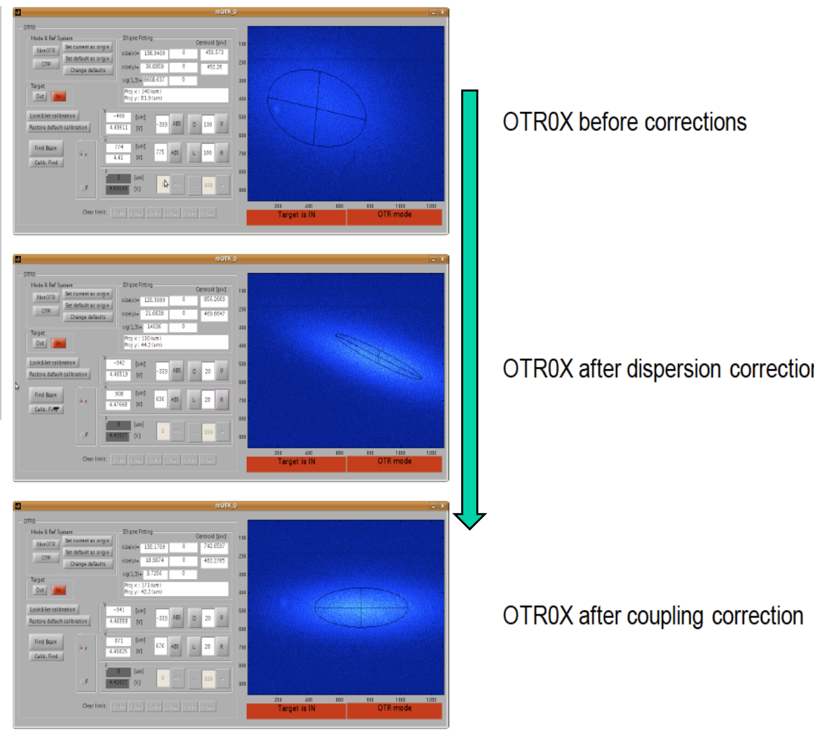
December 2010: Beam size and Emittance

Emittance panel



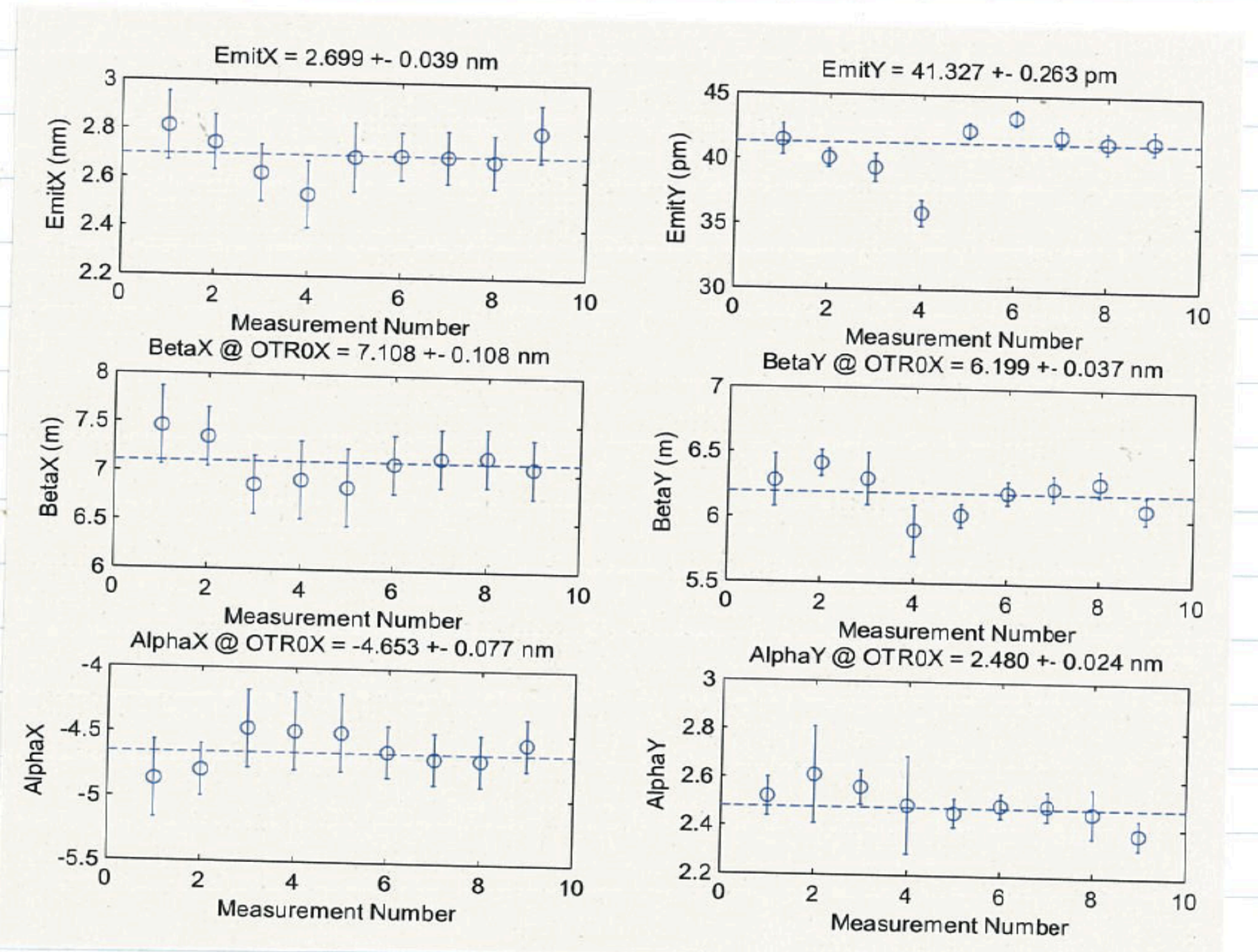
December 2010: Coupling Correction





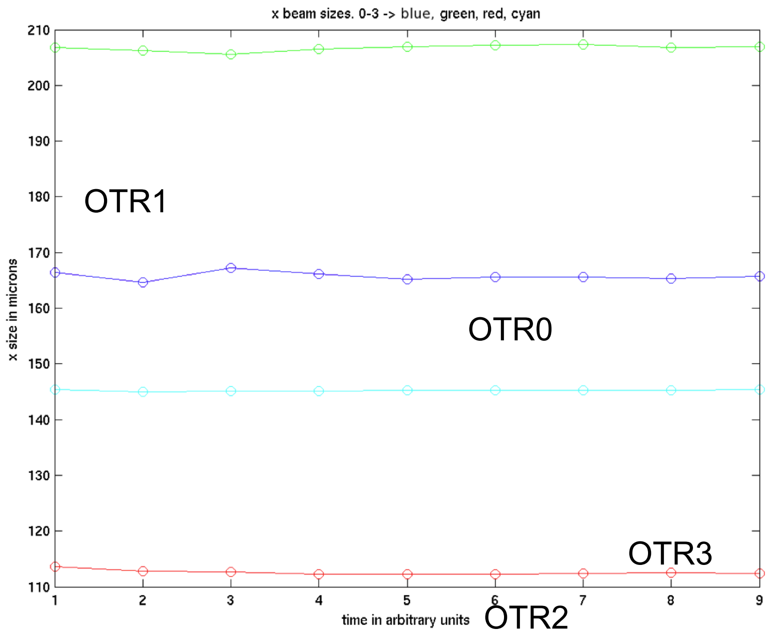
Coupling correction in the EXT line was achieved by **scanning each of the 4 EXT skew quads**. For each scan the quantity: $\gamma\varepsilon_y$***BMAGY** is plotted and the optimal value of the skew quad comes from the parabolic fit.

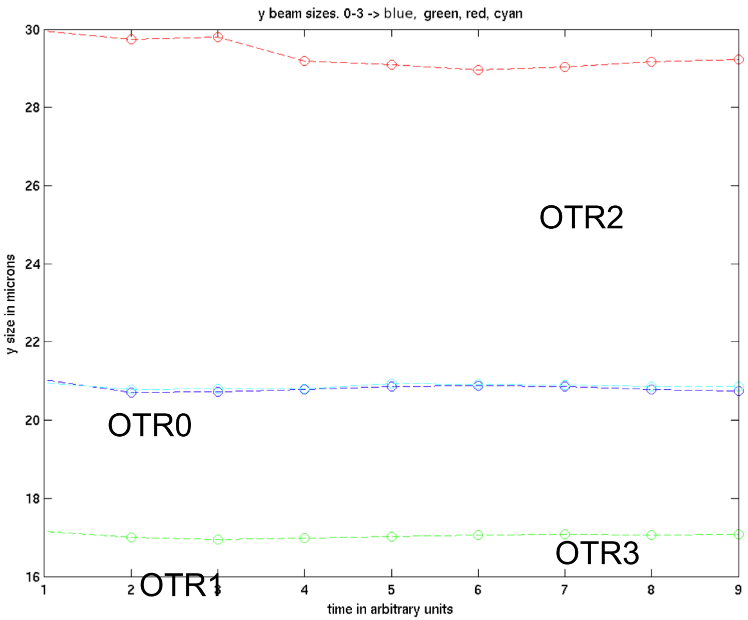
December 2010: Stability Measurement



January/March 2011: Systematic Measurements I

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

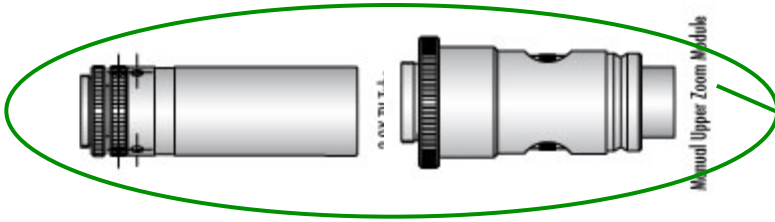




Technical Description HW II

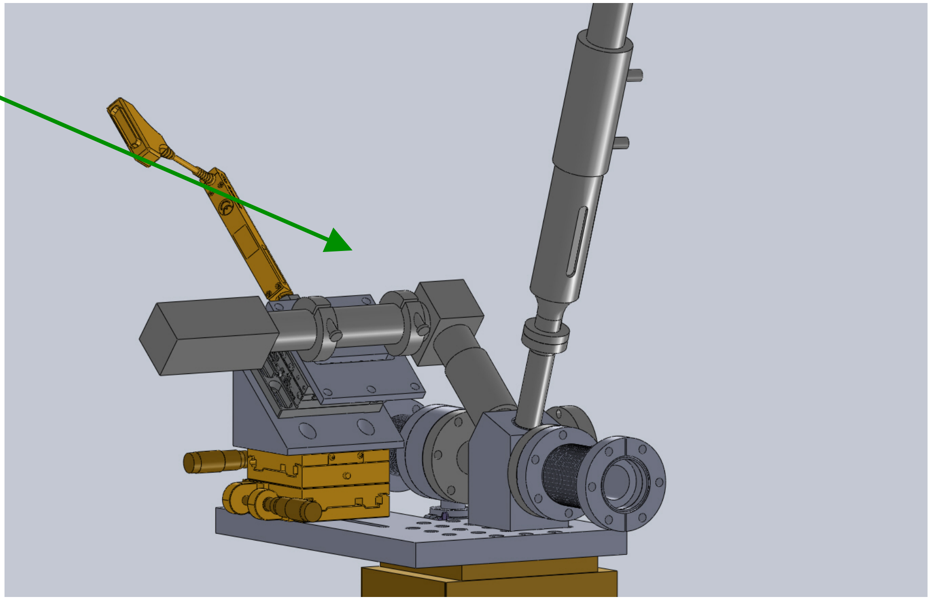
January/August 2011: Demagnifier system Design, Construction

A **demagnifie**r system to speed up the **beam finding** and to measure **horizontal** size when **beam** is **large** in x was designed



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

NEW MOTORIZED ZOOM STSYEM

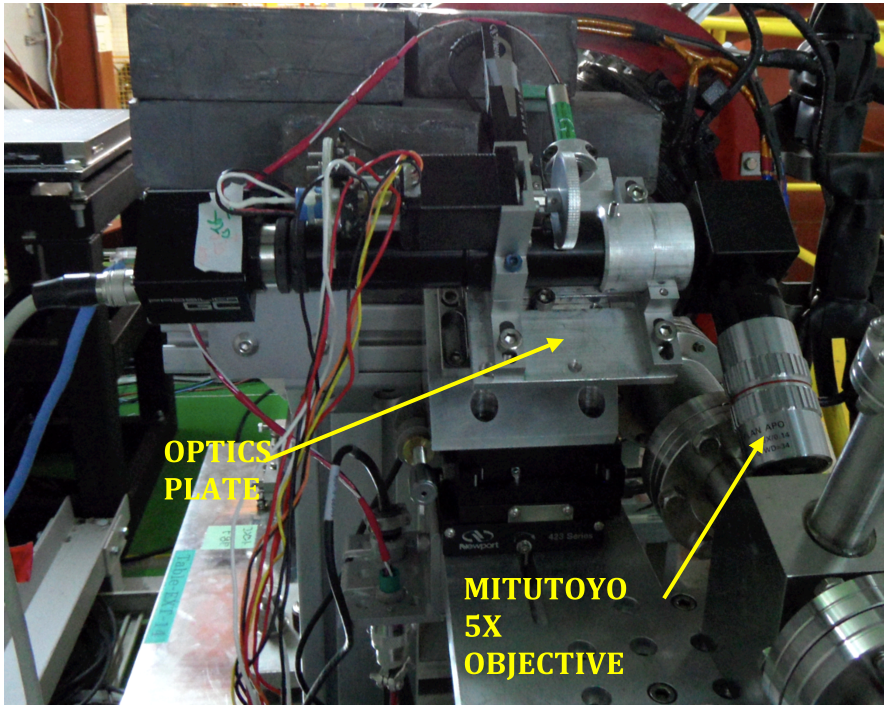


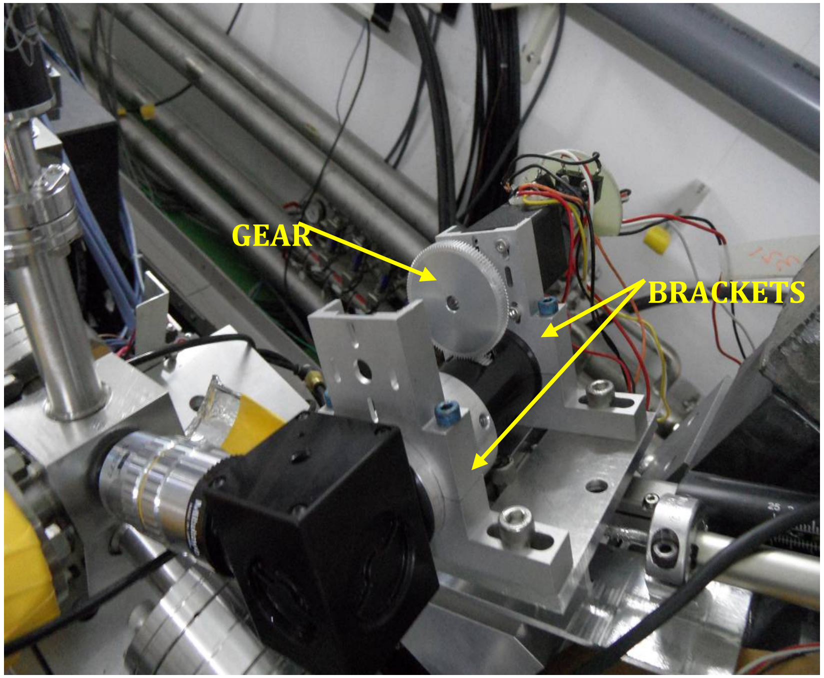
Pros: - Lighter and less bulky than the switchable lens system, easier installation
- Better lenses performance
- Allows beam finding and measurements in 2 different magnification (5X and 10X) by calibrating the system in both states.

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

January/August 2011: Demagnifier system Installation

The **demagnifier zoom** system was **installed** in August 2011

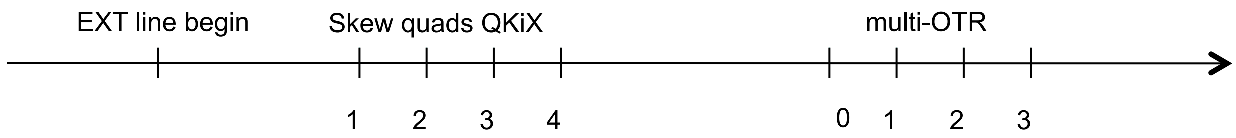




The zoom system was installed in the same place where before an empty optic tube was located, between the 45º mirror and the CCD camera.

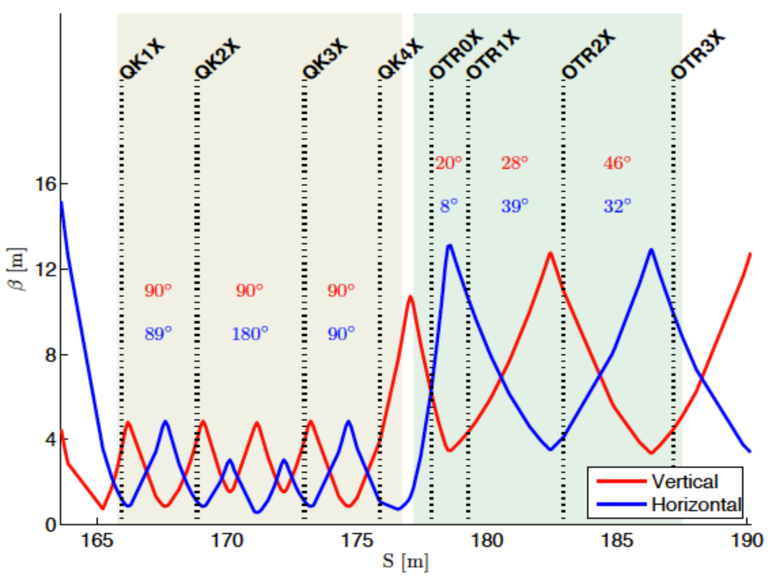
The Mitutoyo 10X lenses were substituted by a 5X lenses allowing the system to operate in a range of **magnification** between **3.6X** and **25X**

Response Matrix method

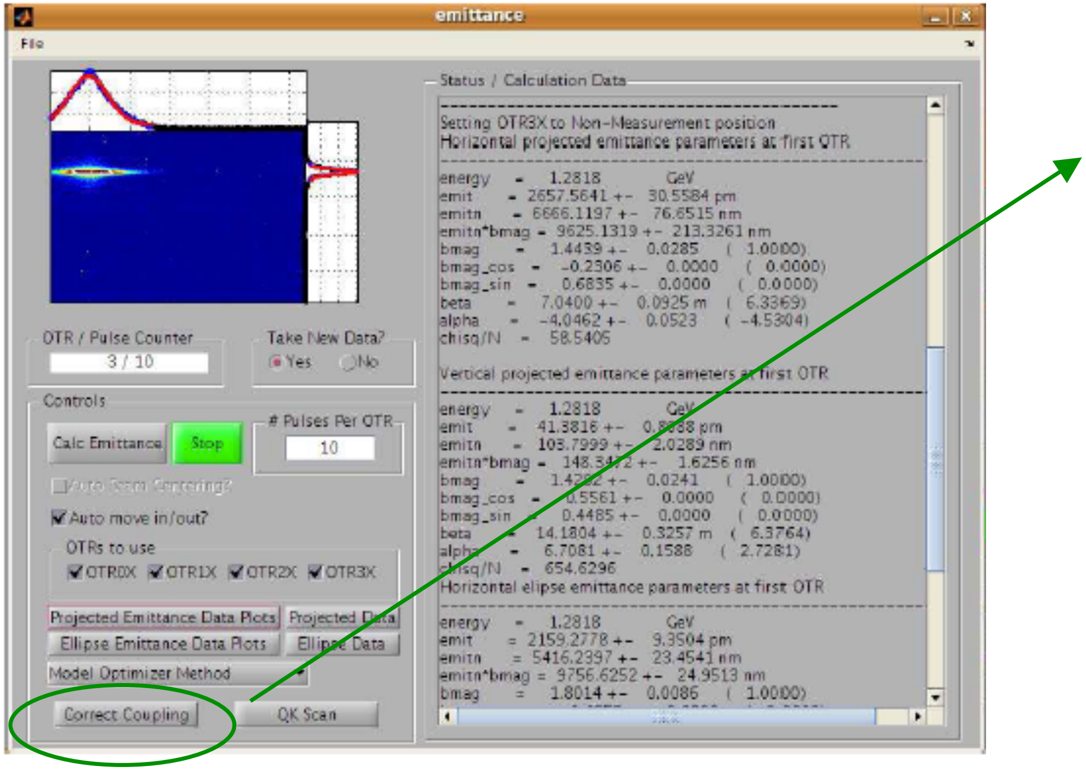


- **Measure** the **beam size** and **tilt** in the 4 OTR locations.
- Reconstruct the **beam matrix** upstream at **EXT line entrance** (σ_0) assuming no coupling and skews switch-off.
- **Transport** it from EXT line entrance to **OTR0** (σ_i) with the skews switch-on **determining** which **skew strengths** lead to an **uncoupled OTR0** beam matrix (minimise as possible the coupling terms) by solving a 4 equations system with 4 unknowns with constrains in the skew strengths values.

$$R_{0\to i} = R_{4\to i} R_{skew4} R_{3\to 4} R_{skew3} R_{2\to 3} R_{skew2} R_{1\to 2} R_{skew1} R_{0\to 1}$$



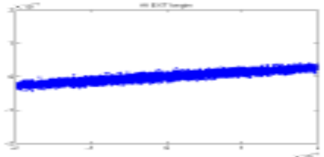
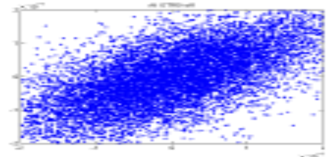
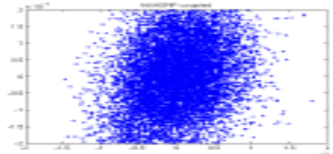
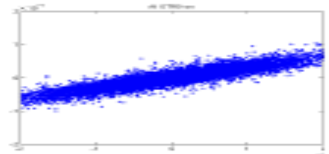
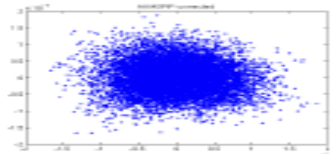
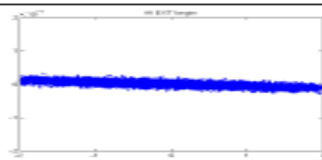
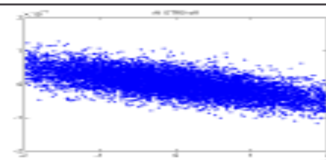
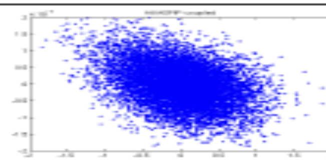
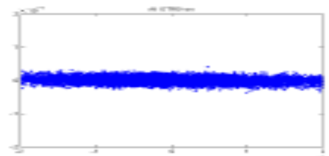
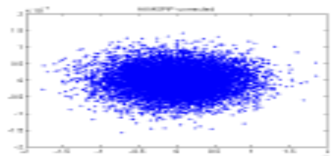
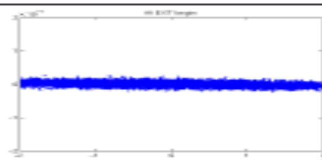
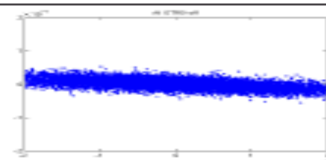
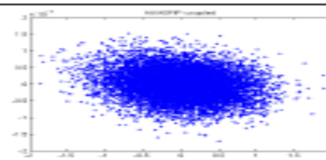
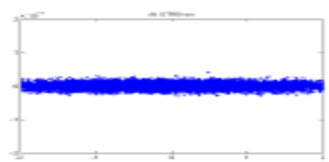
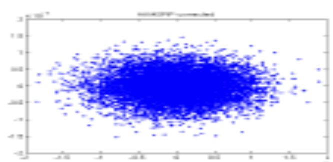
$$R_{0\to i}\sigma_0 (R_{0\to i})^T = \begin{pmatrix} \sigma_1 & \sigma_2 & \sigma_3 & \sigma_4 \\ \sigma_2 & \sigma_5 & \sigma_6 & \sigma_7 \\ \sigma_3 & \sigma_6 & \sigma_8 & \sigma_9 \\ \sigma_4 & \sigma_7 & \sigma_9 & \sigma_{10} \end{pmatrix}$$



- The **response matrix method coupling** correction method was **installed** and **tested** in **ATF2 control system** in December 2011
- This gives the possibility to have an **automatic coupling correction** for each nominal lattice using the OTR measurements. The method is **iterative** and **fast converging**, saving a lot of time in comparison with the standard scanning method.

- Different methods: **scan**, **response matrix** and **solve transport matrix** methods have been studied and **compared** with **simulations** and real **measurements**. In comparison with the scan method (non-model dependent), the response method is faster but sometimes present some unstable results.

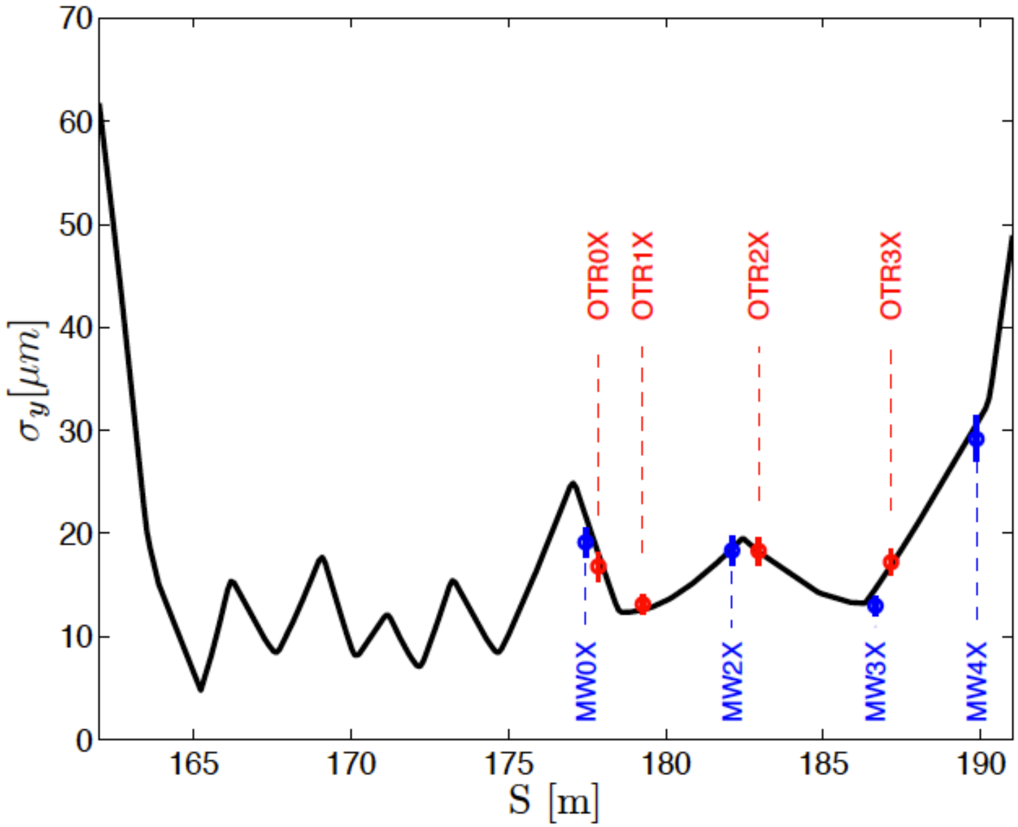
December 2011: Coupling correction algorithms implementation

Input	Correction	EXT begin	OTR0X	MSPIP
1	Off	 7.73	 41.46	 82.05
	On		 17.63	 -32.46
2	Off	 -3.24	 -14.79	 -59.50
	On		 -1.04	 -1.53
3	Off	 -1.11	 -4.82	 -25.34
	On		 -0.03	 -0.03
		[deg]	[deg]	[deg]

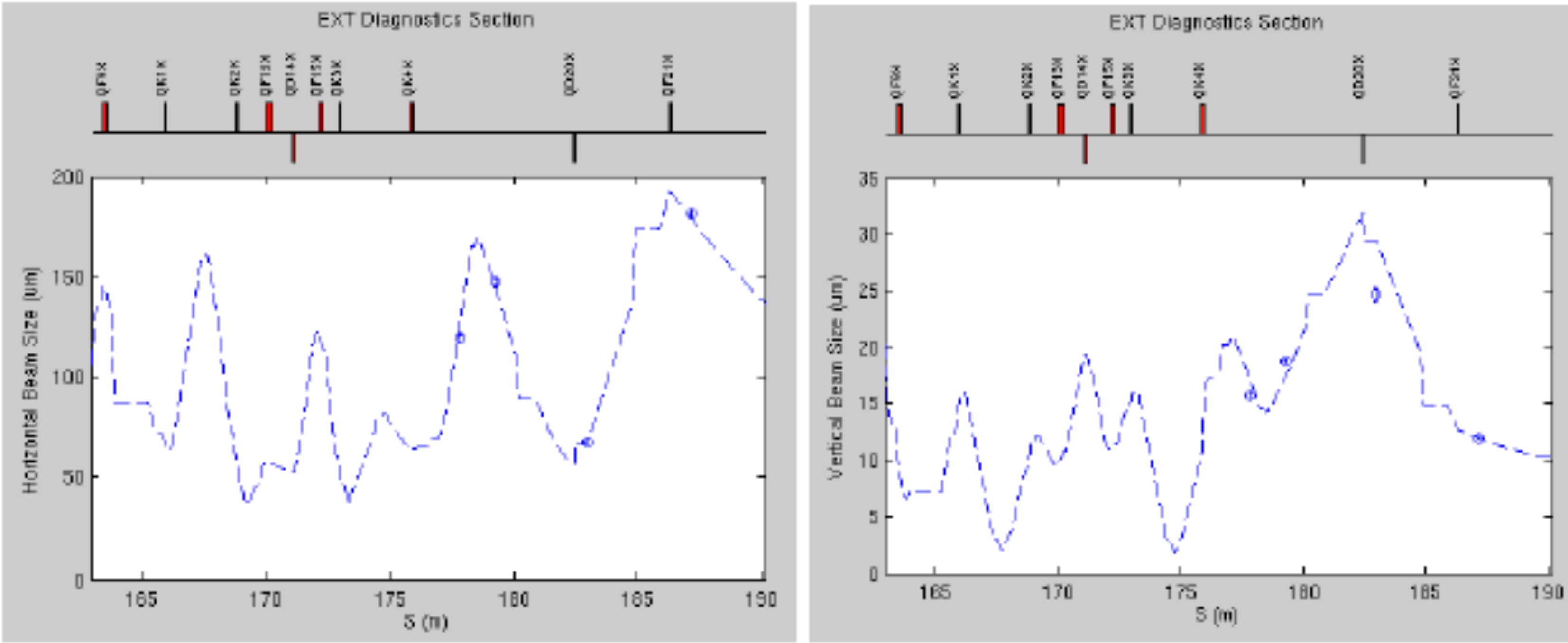
Coupling correction with the **response matrix method**

November 2011/December 2012: Systematic Measurements II

Comparison between **OTR** and **WS** measurements made on Dec. 14th 2011

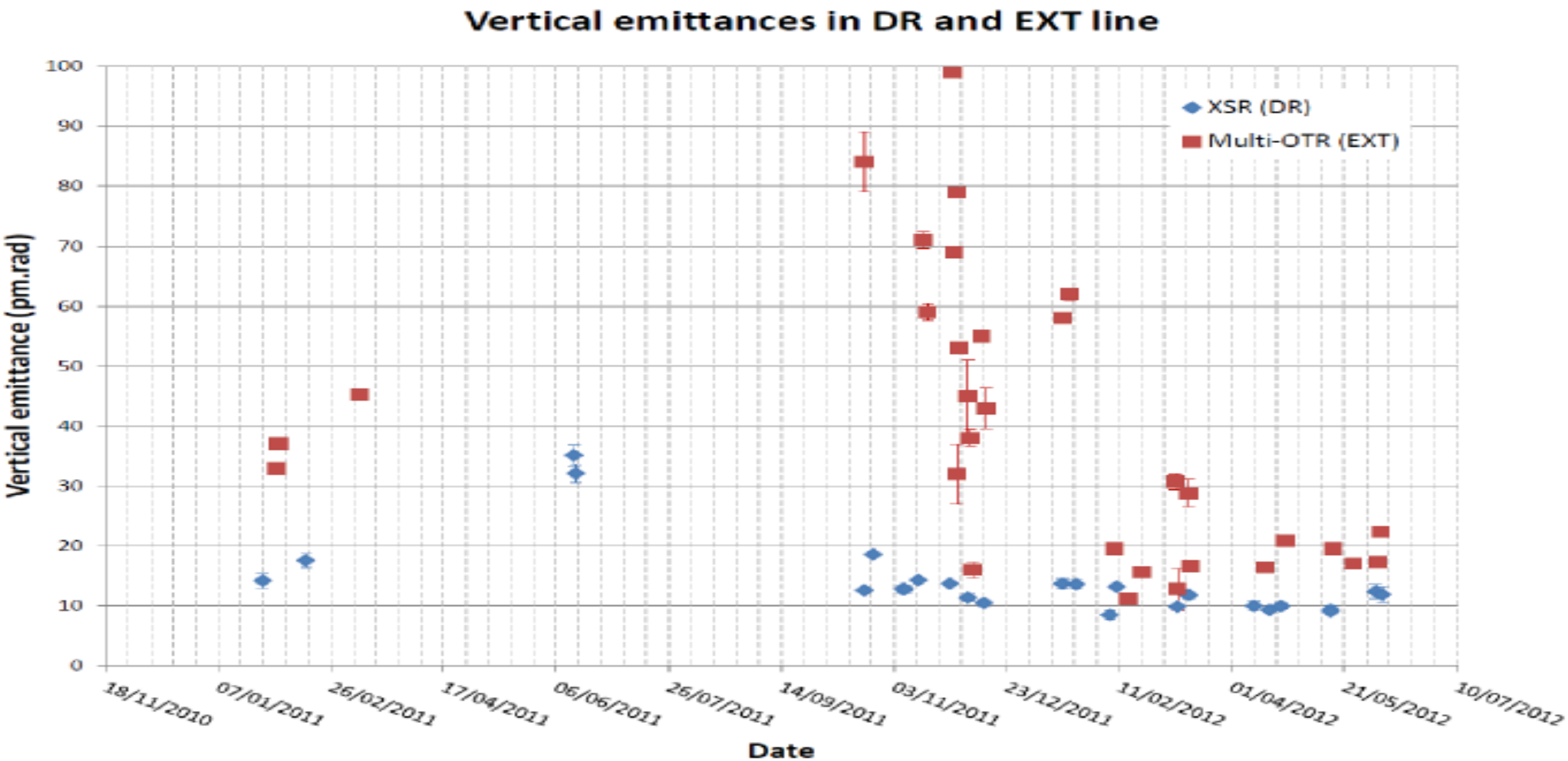


November 2011/December 2012: Systematic Measurements II



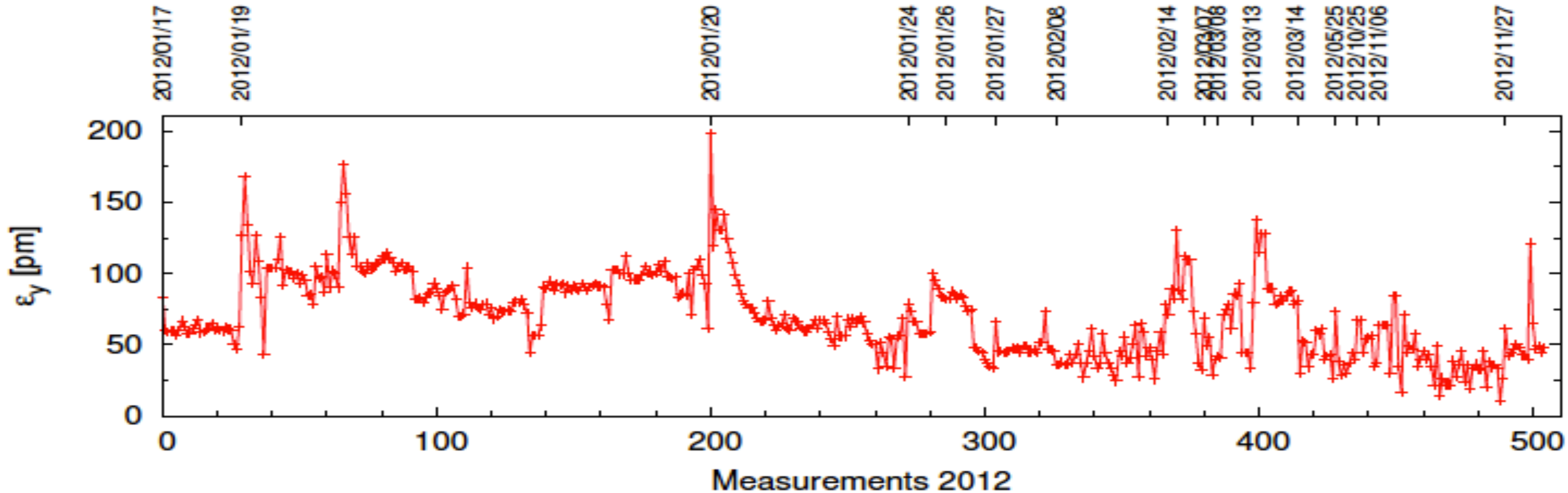
Measurement of the **beam sizes** and **comparison** with the **model** made on 8th March 2012

Comparison of **DR** and **EXT** line vertical **emittance** measurements during 2011 and half 2012.



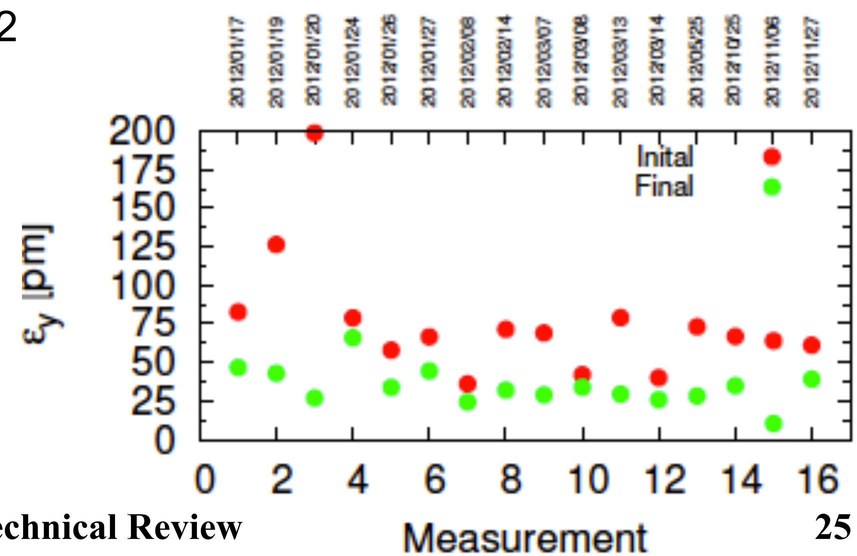
Beam size and Emittance

November 2011/December 2012: Systematic Measurements II



Vertical **emittance** measurements during 2012

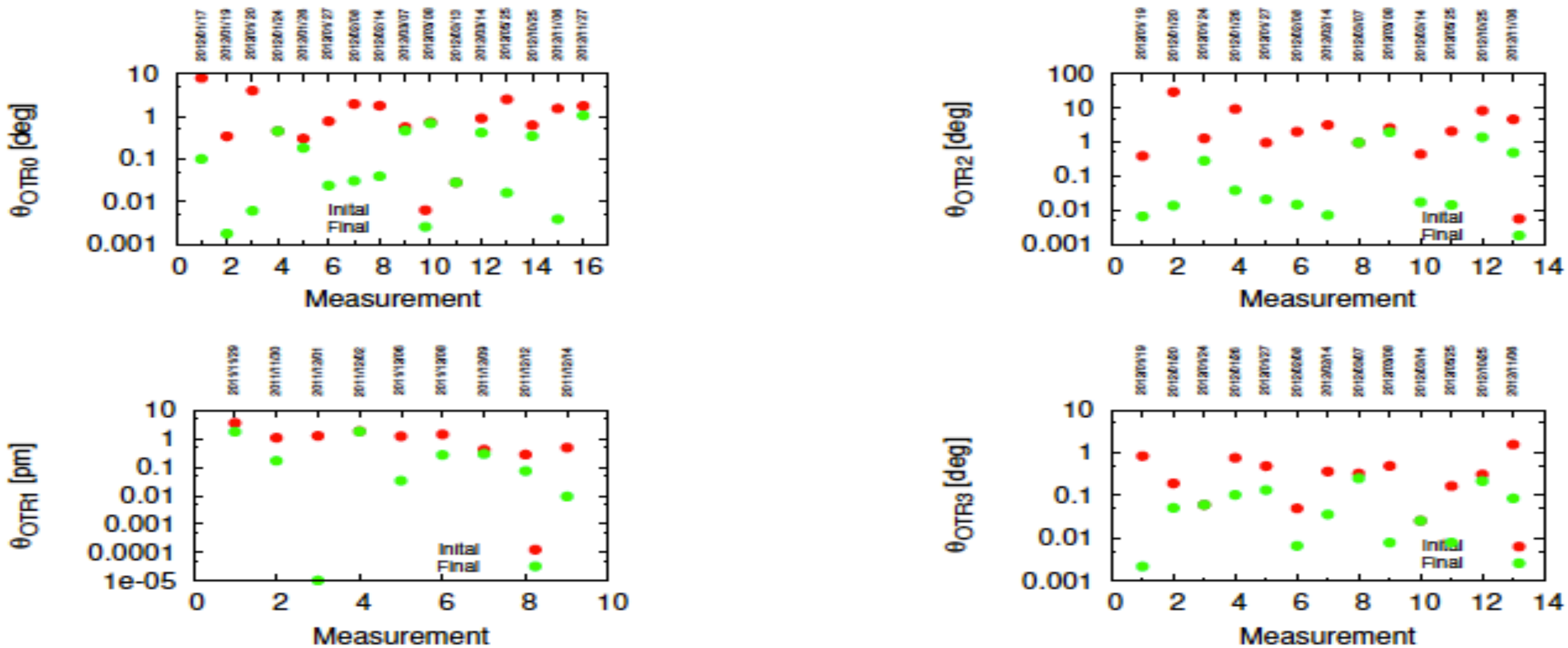
- **Initial** (before coupling correction):
  ε_y =76±39 pm
- **Final** (after coupling correction):
  ε_y = 34±12 pm



Beam size and Emittance

November 2011/December 2012: Systematic Measurements II

Beam **Tilts** at OTRs measurements during 2012:

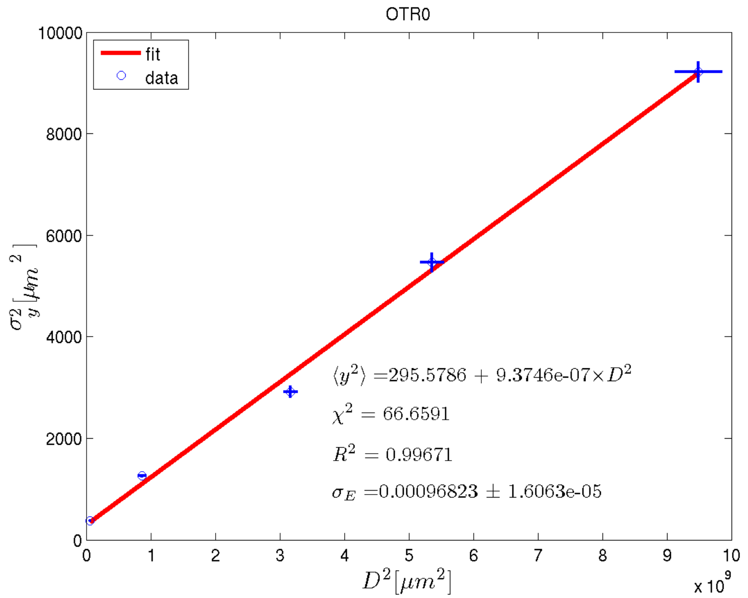


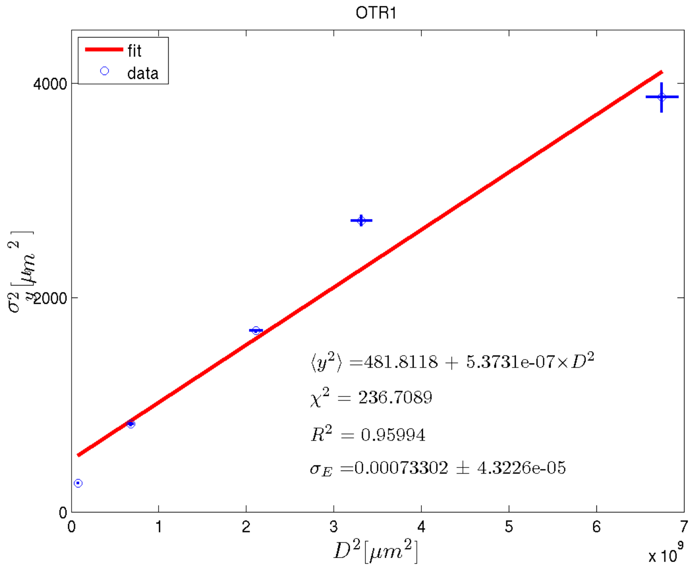
Mean of the |Tilt| values before and after correction:

OTR0 $\Rightarrow \theta_0 = 1.7 \pm 1.9$ deg	Final $\theta_0 = 0.3 \pm 0.3$ deg
OTR1 $\Rightarrow \theta_1 = 1.5 \pm 1.7$ deg	Final $\theta_1 = 0.2 \pm 0.2$ deg
OTR2 $\Rightarrow \theta_2 = 5.0 \pm 7.6$ deg	Final $\theta_2 = 0.4 \pm 0.6$ deg
OTR3 $\Rightarrow \theta_3 = 0.4 \pm 0.4$ deg	Final $\theta_3 = 0.1 \pm 0.1$ deg

Measured Initial tilts below 10 deg

Energy spread measurement

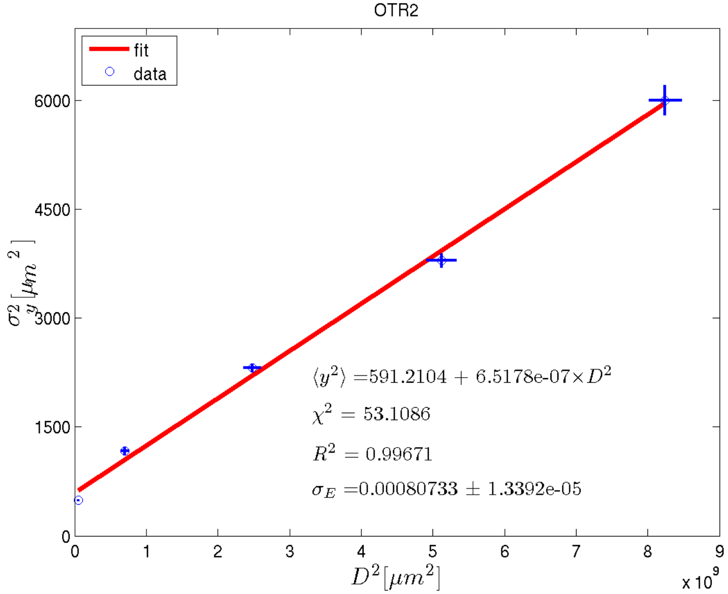




Obtain the **energy spread** by changing the dispersion (QS1X and QS2X) and measuring the change in size

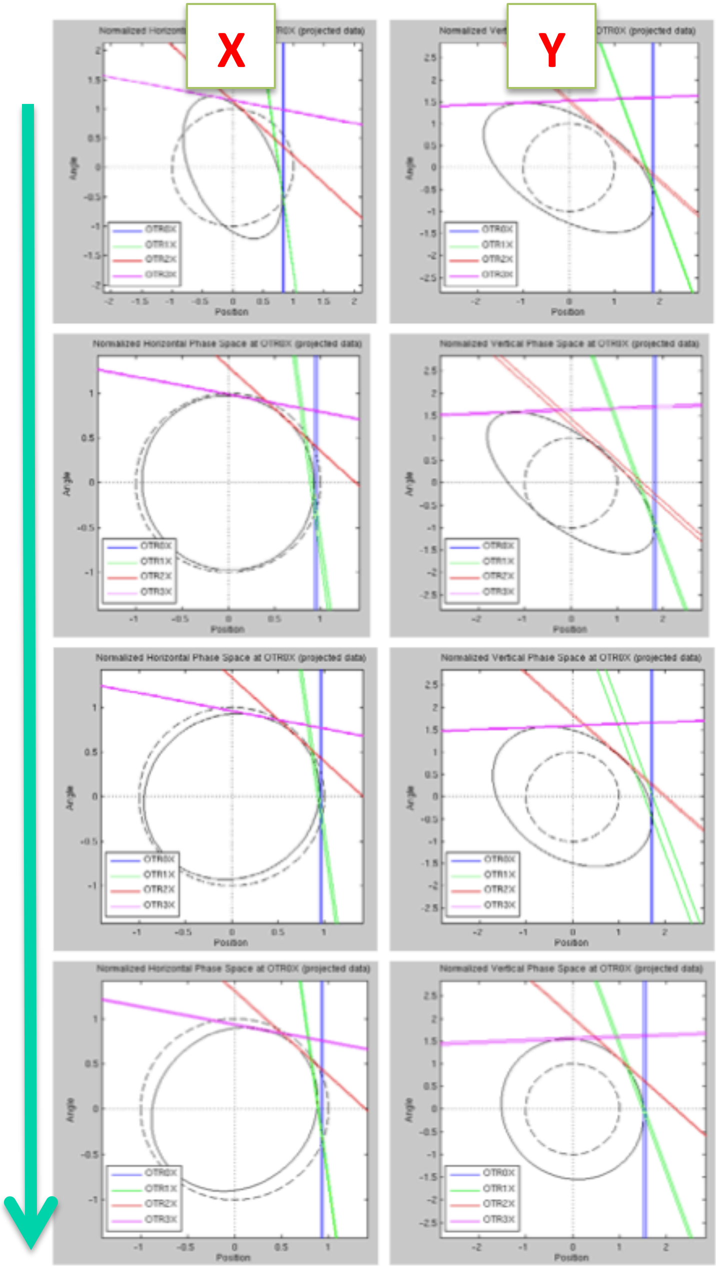
$$\sigma_y^2 = \beta_y \varepsilon_y + D_y^2 \sigma_E^2$$

First measurement: $\sigma_E = (8.4 \pm 1.2)10^{-4}$



Other Applications

November 2011/December 2012: Systematic Measurements II



Beta matching

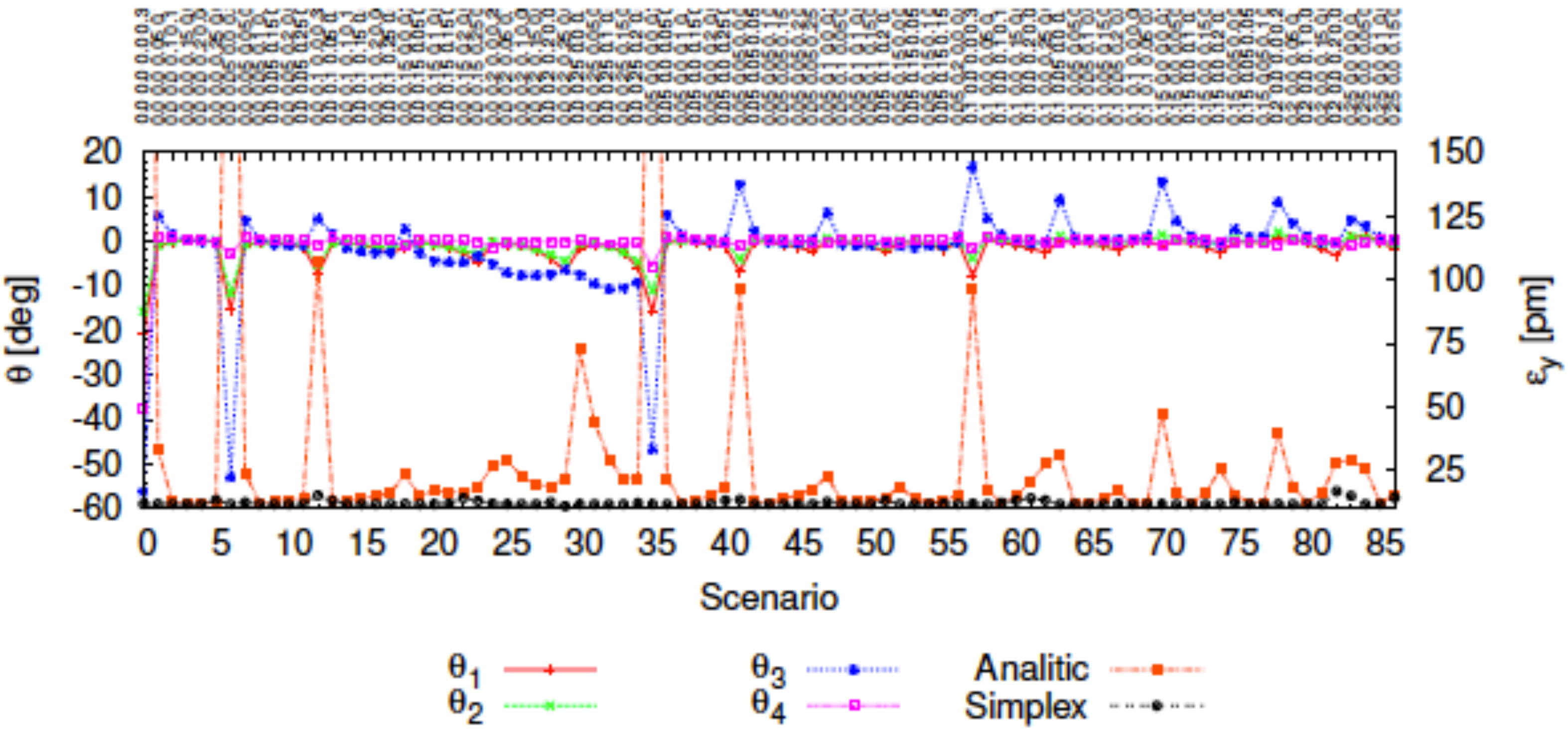
name	match0	match1	match2	match3	design
file	054152	061717	080625	084346	
EmitX	1.7894	1.8228	1.7587	1.5860	
BmagX	1.1946	1.0013	1.0026	1.0076	1.0000
EmBmX	2.1376	1.8251	1.7633	1.5981	
BetaX	4.7239	6.0386	6.4327	6.2257	6.3052
AlphaX	-2.8890	-4.2795	-4.6550	-4.5596	-4.4943
EmitY	28.4846	25.7572	30.8175	28.2300	
BmagY	1.2000	1.3489	1.0554	1.0034	1.0000
EmBmY	34.1808	34.7439	32.5253	28.3262	
BetaY	9.1308	9.4923	7.1151	6.0766	6.1903
AlphaY	4.4037	4.8369	3.2854	2.6087	2.5763

- Matching performed using quads in inflector, upstream of OTR system
  - Can easily iterate matching to converge on well matched solution
  - Have to take care not to destroy dispersion & coupling correction system
- Propagate match to IP using online model
- Check match at IP using quad scan technique
  - Scan QD0FF/QF1FF vs. IP Carbon wire scanner
- Typically find good agreement for vertical match at ~10-20% level, a little worse for horizontal

During 2012: Coupling correction algorithms studies

The considered algorithms for correcting the coupling:

- **Response matrix** method (zeroing the measured tilts of the beam at the OTRs using the strength of 4-skew quadrupoles to compensate the measured tilts at the OTRs)
- **Simplex** algorithm that minimises the **emittance**

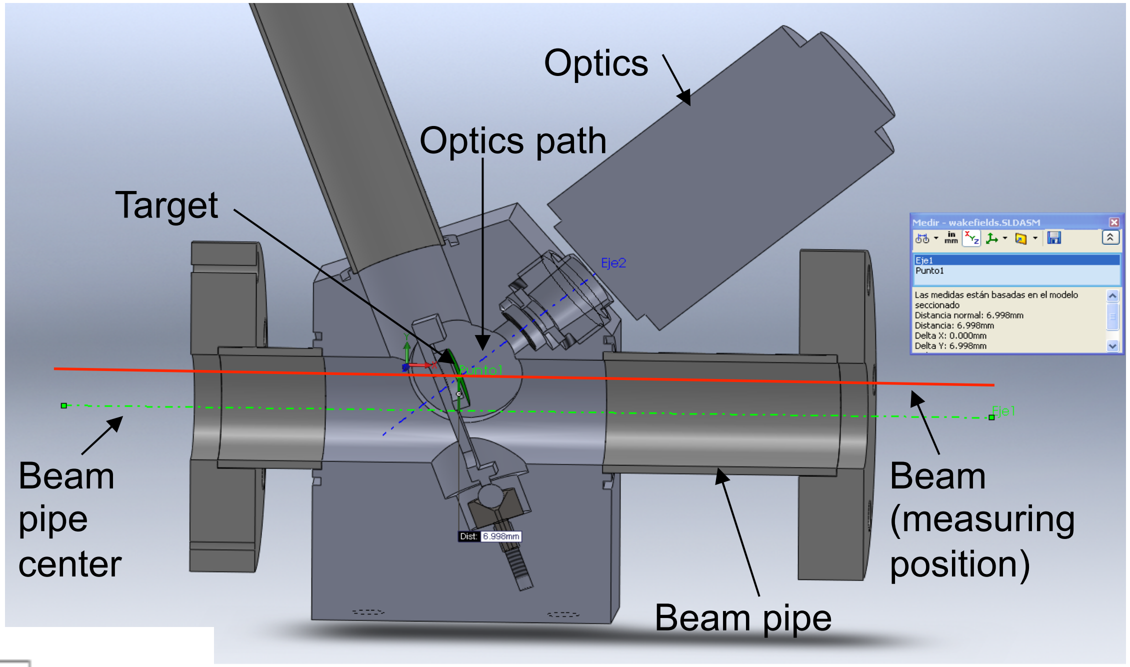


Simplex is **more efficient** but the cases where the analytical method is not correcting are not realistic in the ATF2 case. With the OTR upgrade the emittance could be measured parasitically and the Simplex method could be **easily implemented**.

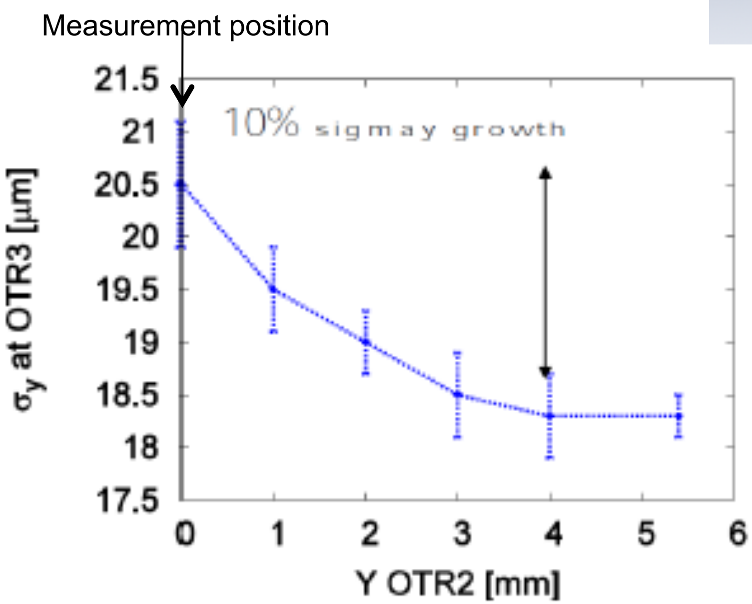
September 2012: Proposal of new Target holder and Optical system

When OTR is not measuring the beam is in the beam pipe centre.

For **measuring** the beam size the mOTR body is **lowered** about **7 mm** for intercepting the beam.

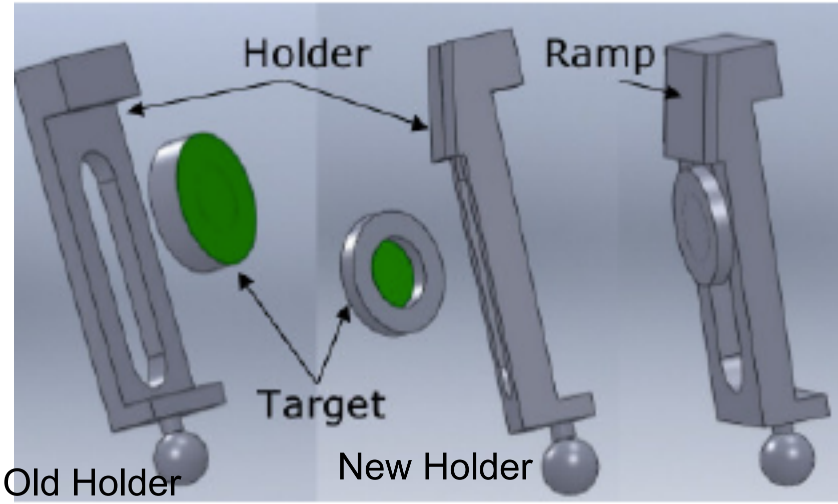


Current target position

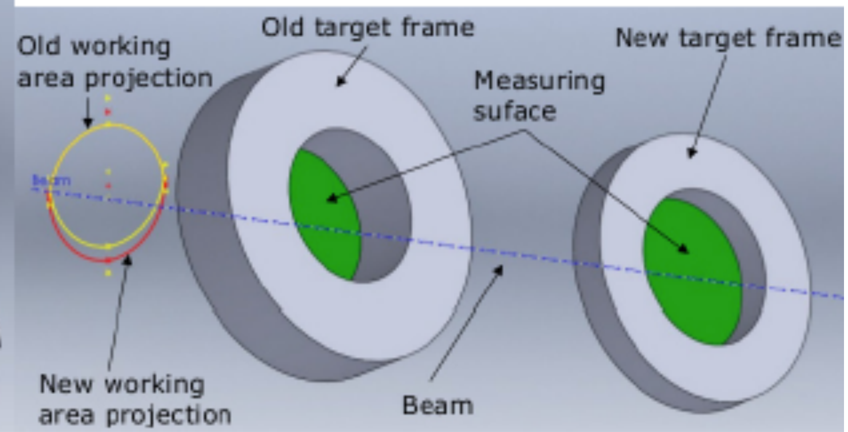


Wakefields are generated when lowering the **OTRs** for a **simultaneous measurement**

February-December 2012: Design and Construction of new Target holder and Optical system

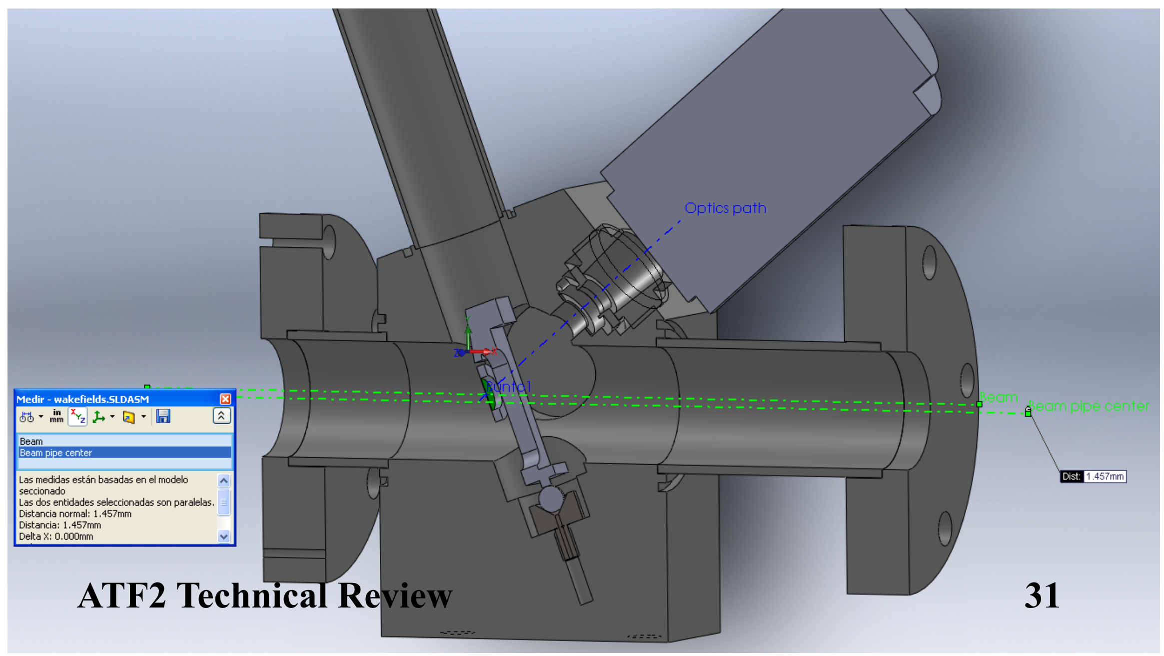


New Target holder and Target



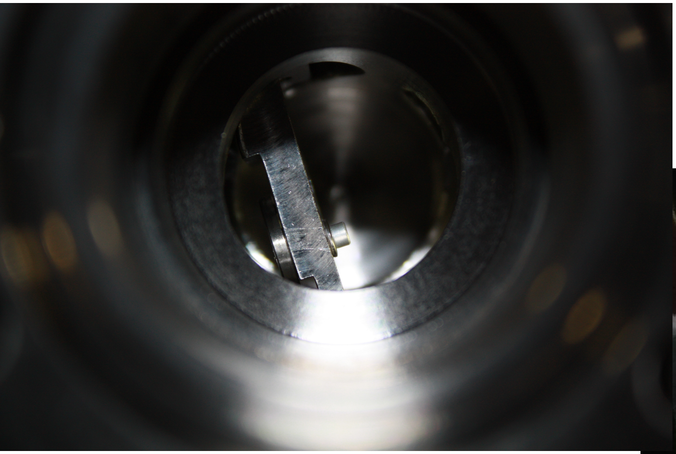
New target position

The required distance to be **lowered** for intercepting the beam is reduced from **7 mm** down to **1.5 mm**

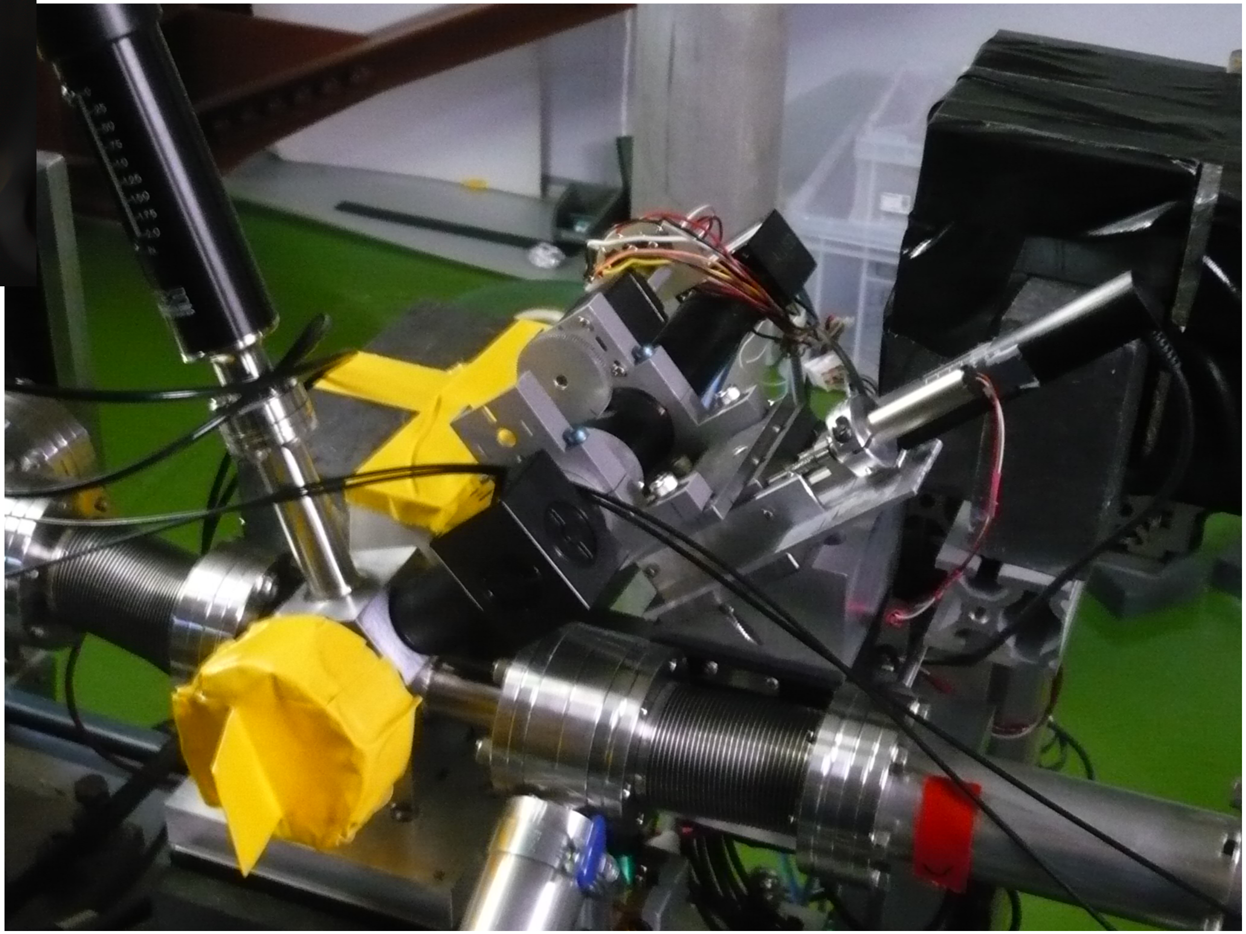


Technical Description HW III

February 2013: Installation of new Target holder and Optical system



OTR0 long working distance target external view



Long working distance target side view

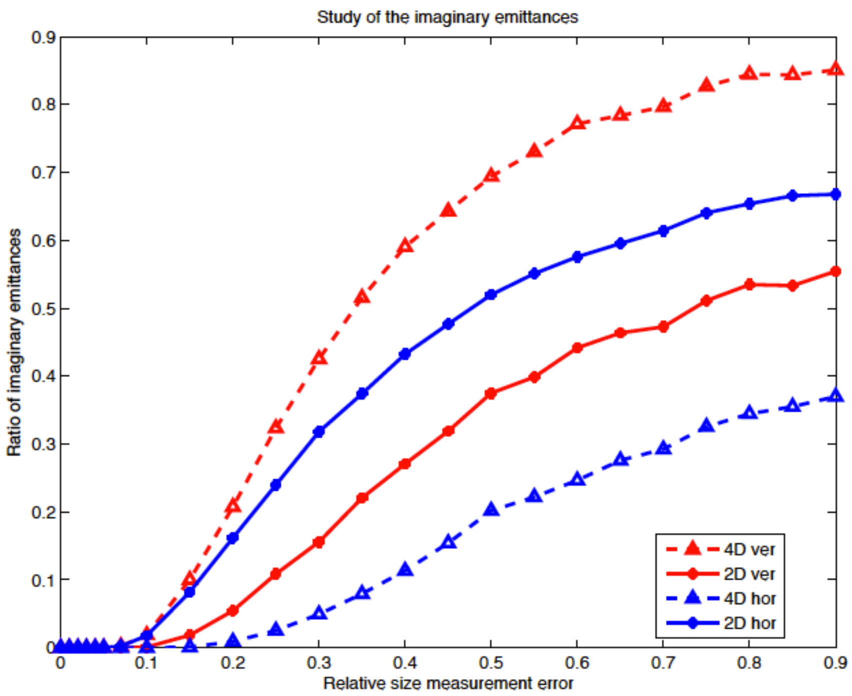
Installation of new target holders and optical system was made in **February 2013.**
Some test has been made after the installation and the system is working properly.

- The **mOTR** system is the **principal** method to **characterize** the beam in the ATF2 EXT line. Some specific points to be signalled:
  - **Resolution** and **Stability** of the system were well demonstrated by **repeated measurements**
  - **Correctness** of the measurements were demonstrated by **comparison** with previous well tested measurement system the **existing WSs**, also with and additional WS wire embedded into the OTR target devices
  - The **model** fitting and **emittance/twiss calculations** are **corroborated** against the **existing WSs**
  - Achievements and stability of the **emittance**, **coupling** and other **corrections** has been **compared** with **simulations**

- Although the OTR technique is **not new,** the **complete measurement** and **correction system** of the mOTR system in ATF2 is a **significant evolution** in the state-of-the-art of such solutions. Of special note it is the large degree of **automation** and **integration** with the **online modelling** systems. It represents a highlight of **modern beam instrumentation**. Similar monitor systems can now be deployed at **FLC** and linac-based synchrotron light sources.

Emittance Reconstruction   Introduction and Objectives

The **emittances** could be reconstructed from the **beam size measurements** at different locations along the beamline. The **2D** (transverse) and **4D** (intrinsic) emittances could be obtained by **solving numerically three separated systems** of coupled equations. When the number of measurement stations is greater than four, these **systems are overdetermined**, and the numerical solutions can lead to unphysical results. The incidence of such meaningless results usually increases if the measurements are noisy. Numerical rules can be used to study the conditioning of these systems.



The **main objective** of this work is to **study analytically** the conditions of **solvability of these systems of equations** and its implication in the emittance reconstruction algorithms used in the accelerators. The aim is to give some hints about the **optical constrains** and the **location** of the **measurement stations**.

Emittance Reconstruction   The formalism

The transverse beam envelope matrix:

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

The projected emittances (2D) ε_x and ε_y are:

X submatrix

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

Y submatrix

$$\varepsilon_x = \sqrt{\sigma_1\sigma_5 - \sigma_2^2}$$

$$\varepsilon_y = \sqrt{\sigma_8\sigma_{10} - \sigma_9^2}$$

Diagonalization of the beam matrix yields the intrinsic emittances ε_1 and ε_2 (4D) :

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

Experimentally only the horizontal σ_1 vertical $\boldsymbol{\sigma_8}$ are directly measured. The coupling term $\boldsymbol{\sigma_3}$ can be deduced by measuring the beam size along a tilted axis at an angle respect to the horizontal beam size.

At least **ten measurements** are required to **reconstruct the beam matrix**. The ten values could be obtained by changing the optics in a controlled manner at the location of the measurements or by **measuring the beam size** at **different locations**.

Emittance Reconstruction   The formalism

Assuming ***N*** measurement stations, for each measurement station labelled as ***i*** one obtain the following **systems of coupled equations**:

$$\hat{\sigma}_1^{(i)} = R_{11}^{2(i)}\sigma_1 + 2R_{11}^{(i)}R_{12}^{(i)}\sigma_2 + R_{12}^{2(i)}\sigma_5$$

$$\hat{\sigma}_8^{(i)} = R_{33}^{2(i)}\sigma_8 + 2R_{33}^{(i)}R_{34}^{(i)}\sigma_9 + R_{34}^{2(i)}\sigma_{10}$$

$$\hat{\sigma}_3^{(i)} = R_{11}^{(i)}R_{33}^{(i)}\sigma_3 + R_{11}^{(i)}R_{34}^{(i)}\sigma_4 + R_{12}^{(i)}R_{33}^{(i)}\sigma_6 + R_{12}^{(i)}R_{34}^{(i)}\sigma_7$$

$$\longrightarrow \quad M_X\begin{pmatrix}\sigma_1\\ \sigma_2\\ \sigma_5\end{pmatrix} = \begin{pmatrix}\hat{\sigma}_1^{(1)}\\ \hat{\sigma}_1^{(2)}\\ \dots\\ \hat{\sigma}_1^{(N)}\end{pmatrix} \quad M_Y\begin{pmatrix}\sigma_8\\ \sigma_9\\ \sigma_{10}\end{pmatrix} = \begin{pmatrix}\hat{\sigma}_8^{(1)}\\ \hat{\sigma}_8^{(2)}\\ \dots\\ \hat{\sigma}_8^{(N)}\end{pmatrix} \quad M_{XY}\begin{pmatrix}\sigma_3\\ \sigma_4\\ \sigma_6\\ \sigma_7\end{pmatrix} = \begin{pmatrix}\hat{\sigma}_3^{(1)}\\ \hat{\sigma}_3^{(2)}\\ \dots\\ \hat{\sigma}_3^{(N)}\end{pmatrix}$$

- with **3** stations only the projected emittance (**2D**) could we reconstructed
- with **4** stations **coupled** beam matrix could be reconstructed but the first two systems are **overdetermined**
- with **>4** stations **coupled** beam matrix could be reconstructed but the three systems are **overdetermined**.

Emittance Reconstruction Analytical conditions: Projected Emittance (2D)

In the general case of ***N*** measurement stations. The system has **unique solution (σ_1 σ_2 σ_5)** if and only if the rank of both M_X and $M_X{}^*$ is equal to three. This give us two conditions:

Condition1: $$\phi_x^{(ji)} \neq n\pi, \forall(i,j)$$

The **measurement** stations should be **located** at places where the **phase advances** correspond to **different snapshots** of the beam. This is the only required condition in the case of **3** measurement stations.

For **4 or more stations** a second condition is required to get a unique solution.

Condition 2: $$-\hat{\sigma}_1^{(i)}\Delta_{3x}(jkl)+\hat{\sigma}_1^{(j)}\Delta_{3x}(ikl)-\hat{\sigma}_1^{(k)}\Delta_{3x}(ijl)+\hat{\sigma}_1^{(l)}\Delta_{3x}(ijk)=0,\forall(ijkl)$$

$$\Delta_{3x}(ijk)=2\beta_x^{(i)}\beta_x^{(j)}\beta_x^{(k)}\sin\phi_x^{(ji)}\sin\phi_x^{(ki)}\sin\phi_x^{(kj)}$$

$$A_{4x}(ijkl)=-\hat{\sigma}_1^{(i)}\Delta_{3x}(jkl)+\hat{\sigma}_1^{(j)}\Delta_{3x}(ikl)-\hat{\sigma}_1^{(k)}\Delta_{3x}(ijl)+\hat{\sigma}_1^{(l)}\Delta_{3x}(ijk)$$

Condition 2 involve the β and the **measurements**, one can see that **in general** the **equality cannot be exactly satisfied**. One could replace the **zero** by some previously **fixed error value**, related with the error of the **measurements**.

Idem for vertical plane.

Emittance Reconstruction

Analytical conditions: Coupling Terms

In the general case of ***N*** measurement stations we have M_{XY} and M_{XY}^*, the system has **unique solution ($\sigma_3\ \sigma_4\ \sigma_6\ \sigma_7$)** if and only if the rank of both M_{XY} and M_{XY}^* is equal to four. This give us two more conditions:

Condition 3:

$$\begin{aligned}
&\cos(\varphi_x^{(ji)}+\varphi_x^{(lk)})\left[\cos(\varphi_y^{(ki)}+\varphi_y^{(lj)})-\cos(\varphi_y^{(ki)}-\varphi_y^{(lj)})\right]\\
&+\cos(\varphi_x^{(ki)}+\varphi_x^{(lj)})\left[\cos(\varphi_y^{(ji)}-\varphi_y^{(lk)})-\cos(\varphi_y^{(ji)}+\varphi_y^{(lk)})\right]\\
&+\cos(\varphi_x^{(ji)}-\varphi_x^{(lk)})\left[\cos(\varphi_y^{(ji)}+\varphi_y^{(lk)})-\cos(\varphi_y^{(ki)}+\varphi_y^{(lj)})\right]\neq 0,\forall(ijkl)
\end{aligned}$$

This is the only required condition in the case of **4** measurement stations. In the particular case where **$\phi_x^{(ji)}=\phi_y^{(ji)}$** the system has **no solution.**

For **5 or more stations** an additional condition is required to get a **unique solution**.

Condition 4:

$$\hat{\sigma}_3^{(i)}\Delta_4(jklm)-\hat{\sigma}_3^{(j)}\Delta_4(iklm)+\hat{\sigma}_3^{(k)}\Delta_4(ijlm)-\hat{\sigma}_3^{(l)}\Delta_4(ijkm)+\hat{\sigma}_3^{(m)}\Delta_4(ijkl)=0,\forall(ijklm)$$

$$\begin{aligned}
-8(\beta_x^{(i)}\beta_y^{(i)}\beta_x^{(j)}\beta_y^{(j)}\beta_x^{(k)}\beta_y^{(k)}\beta_x^{(l)}\beta_y^{(l)})^{-1/2}\Delta_4(ijkl)&=\cos(\varphi_x^{(ji)}+\varphi_x^{(lk)})\left[\cos(\varphi_y^{(ki)}+\varphi_y^{(lj)})-\cos(\varphi_y^{(ki)}-\varphi_y^{(lj)})\right]\\
+\cos(\varphi_x^{(ki)}+\varphi_x^{(lj)})\left[\cos(\varphi_y^{(ji)}-\varphi_y^{(lk)})-\cos(\varphi_y^{(ji)}+\varphi_y^{(lk)})\right]&+\cos(\varphi_x^{(ji)}-\varphi_x^{(lk)})\left[\cos(\varphi_y^{(ji)}+\varphi_y^{(lk)})-\cos(\varphi_y^{(ki)}+\varphi_y^{(lj)})\right]
\end{aligned}$$

One could replace the **zero** by some previously **fixed error value**, related with the error of the **measurements**.

Emittance Reconstruction Partial Conclusions

- We have studied **analytically** the conditions of **solvability of the systems** of equations involved in the process of emittance reconstruction and we have obtained some **conditions** about the **locations** of the measurements to avoid unphysical results.

- These conditions have been **tested analytically** in various systems as in the NLC diagnostic section and in **ATF2 EXT line**, giving good results. **Simulations** are being made to test the robustness in **high coupling scenarios** and **large measurement errors**.

- The results of these studies will be very **useful** to better **determine** the **location** of the **emittance measurement stations** in the diagnostic sections of FLCs.

ILC implications

m-OTR system for the ILC RTML: exploratory study

The **m-OTR system** of the ATF2 EXT line has **demonstrated** its performances as a fast (1min) and **reliable system** to measure the beam size and the emittance. The system is **totally integrated** in the **online model** and it is **crucial** for **tuning procedures** of the beamline as: coupling correction, beta matching, energy spread measurements…

↓

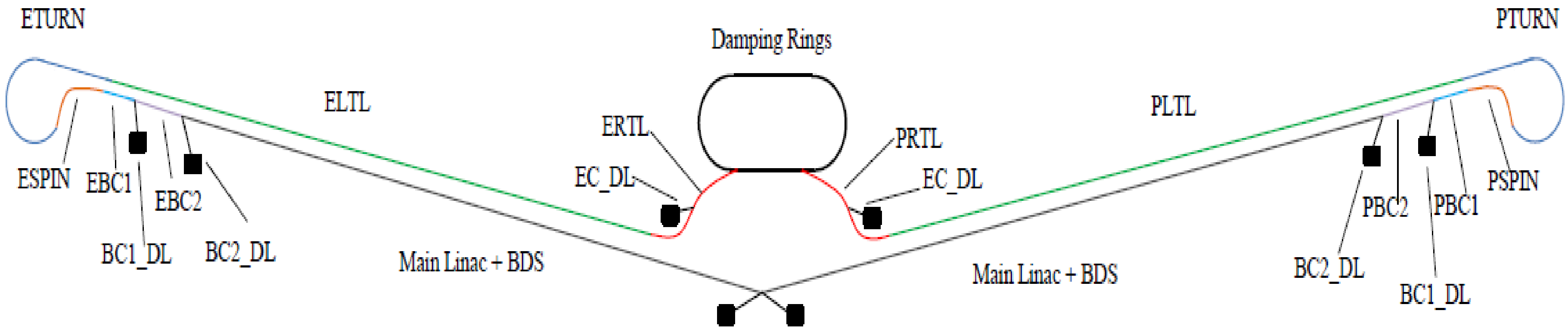
▪ OTR monitors are **mature** and **reliable diagnostic** tools that could be very suitable for the setup and tuning of the machine in single-bunch mode. It can be very useful during start up and commissioning phases of the **ILC RTML**

↓

▪ We explore the **feasibility** of using a **m-OTR system** in **transfer lines** of the **ILC RTML**

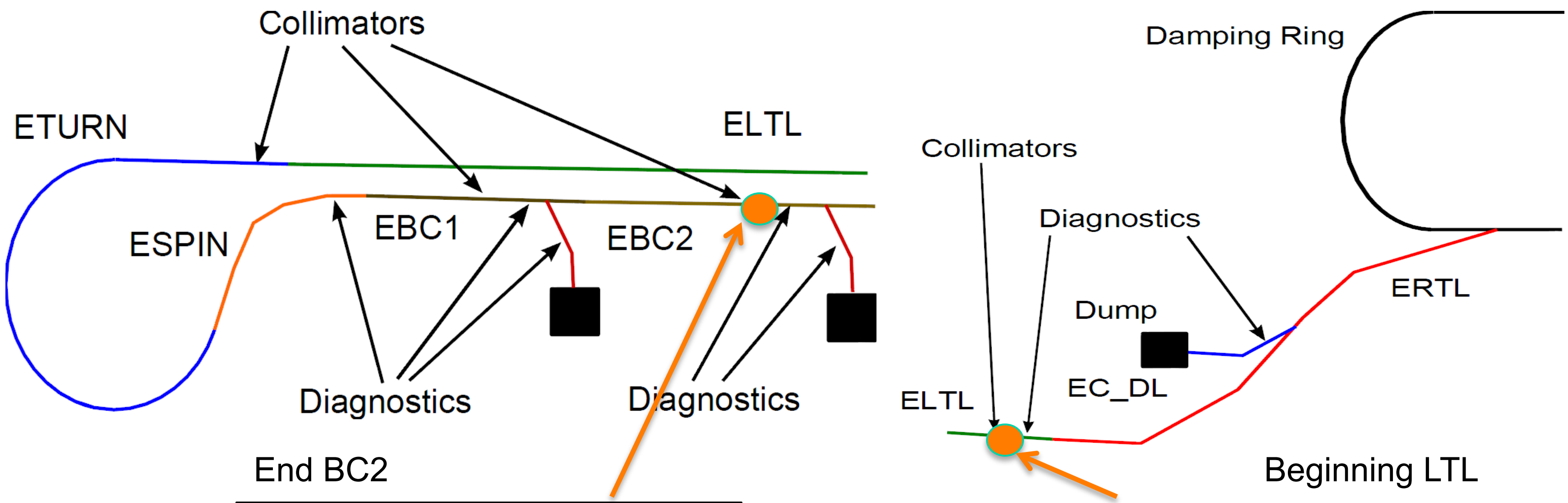
▪ We investigate different **materials** for the **OTR target** and possible limitations of operation

ILC RTML beamlines



- ERTL/PRTL: e^-/e^+ Ring-to-Line from DR to Main Tunnel (+ Dump Line)
- ELTL/PLTL: e^-/e^+ Long-Transfer-Line
- ETURN/PTURN: e^-/e^+ Turn-Around
- ESPIN/PSPIN: e^-/e^+ Spin rotator
- EBC1/PBC1: e^-/e^+ 1st stage of Bunch Compressor (+ Dump Line)
- EBC2/PBC2: e^-/e^+ 2nd stage of Bunch Compressor (+ Dump Line)

Possible positions for m-OTR systems

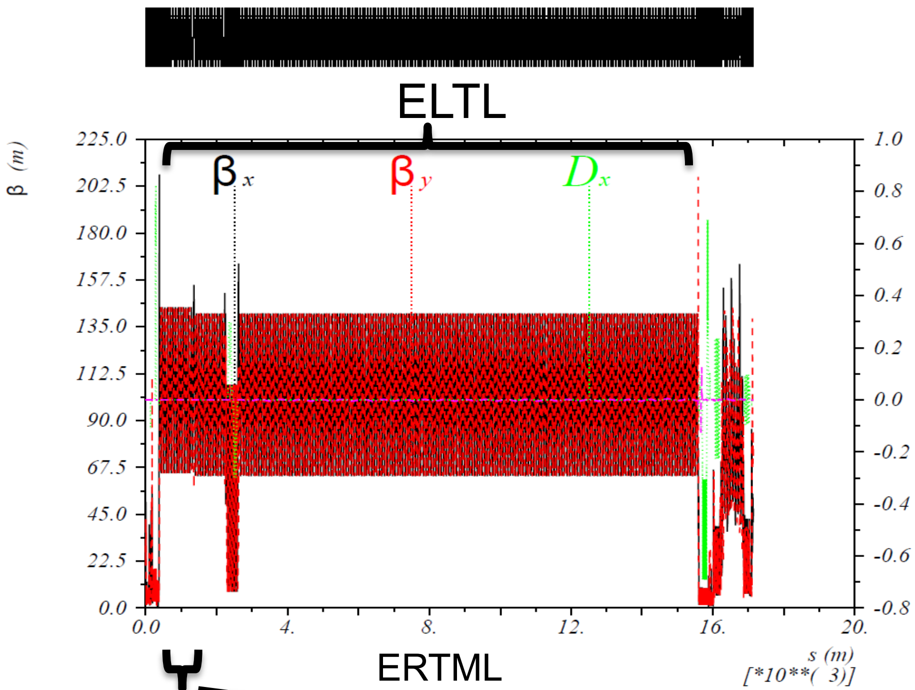


E=15 GeV
N_e=2x10^{10} particles per bunch
σ_z=0.3/0.15 mm
Energy spread=1.07%
$\gamma\varepsilon_x$ =8 μm
$\gamma\varepsilon_y$ =20 nm

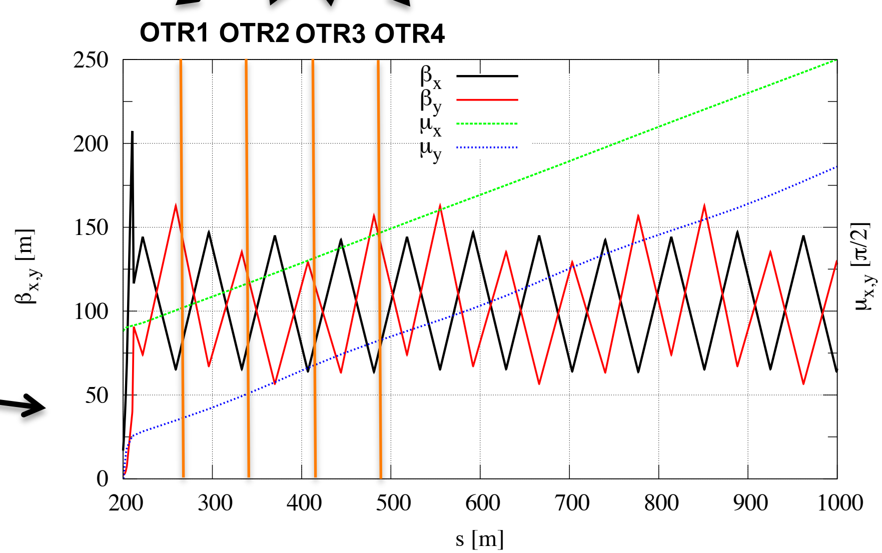
E=5 GeV
N_e=2x10^{10} particles per bunch
σ_z=6 mm
Energy spread=0.13%
$\gamma\varepsilon_x$ =8 μm
$\gamma\varepsilon_y$ =20 nm

ILC RTML has been designed with 7 diagnostic sections: beginning of LTL, end of spin rotator SPIN, end of BC1 and BC2 and in each extraction line

RTML Long Transfer Line



Beginning LTL: 4 OTRs monitors



E=5 GeV
N_e=2x10^{10} particles per bunch
σ_z=6 mm
Energy spread=0.13%
$\gamma\varepsilon_x$=8 μm
$\gamma\varepsilon_y$=20 nm

OTR target study for beginning LTL : Temperature rise of material per pulse

- Peak of instantaneous temperature rise:

$$\Delta T_{inst} = \frac{1}{\rho C_p}\left(\frac{dE}{dz}\right)\frac{N_b N_e}{2\pi\sigma_x\sigma_y}$$

ρ: material density
C_p: specific heat
N_b: number of bunches per pulse (N_b=1, single bunch mode)
N_e: number of particles per bunch ($N_e=2\times10^{10}$)
$\sigma_x \approx 239.14$ µm, $\sigma_y \approx 17.49$ µm ($\beta_x \approx 70$ m, $\beta_y \approx 150$ m)
dE/dz: Collision stopping power in a thin material (< X_0) (calculated from the Bethe-Bloch formula)

- Comparison with fracture limit due to thermal stress:

σ_{UTS}: ultimate tensile stress
α_T: thermal expansion coefficient
Y: Young modulus

$$\Delta T_{fr} \cong \frac{2\sigma_{UTS}}{\alpha_T Y}$$

Material	$\frac{1}{\rho}\frac{dE}{dz}$ $\left[\frac{\text{MeV}\cdot\text{cm}^2}{g}\right]$	Density ρ $\left[\text{g/cm}^3\right]$	$\frac{dE}{dz}$ $\left[\frac{\text{MeV}}{\text{cm}}\right]$	ΔT_{inst} [K]	ΔT_{fr} [K]	T_{melt} [K]
Kapton	2.322	1.42	2.297	18.096	9240	Does not melt, decomposes at 793 K
Al	2.14	2.7	5.778	28.675	63.662	933.37
Be	2.002	1.85	3.704	12.682	222.28	1546
Ti	2.007	4.54	9.112	46.35	441.06	1923
W	1.677	19.3	32.366	152.6	1059.7	3643

For all the cases studied: $\Delta T_{inst} < \Delta T_{fr}$ (fracture limit) and T_{melt} (melting point),

No damage operating in low charge (single bunch) mode

OTR target study for beginning LTL: Long Term heating

Heat transfer by conduction in a cylindrical system (OTR target) for a Gaussian bunch and thin targets

- The equilibrium temperature:

$$\Delta T_{eq} = T(0) - T(R) = \frac{dE}{dz} \cdot \frac{N_b N_e f_{rep}}{4\pi k} \ln\left(\frac{R^2}{2\sigma_r^2}\right)$$

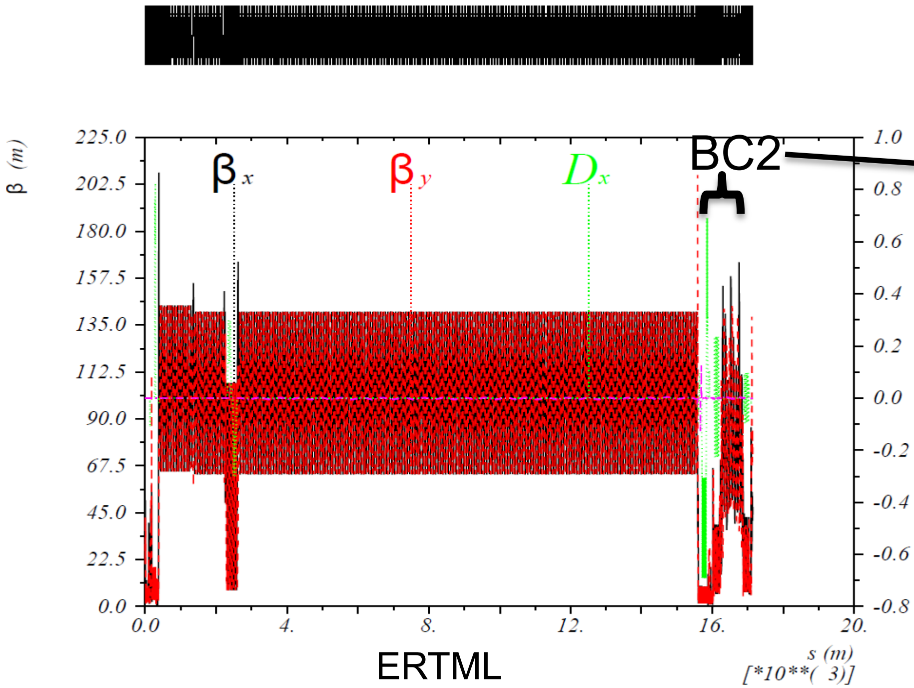
Target radius R=6 mm (same as for ATF2 OTR prototype)
Repetition frequency f_{rep}=5 Hz
k: thermal conductivity
$\sigma^2_r=\sqrt{(\sigma_x\sigma_y)}$

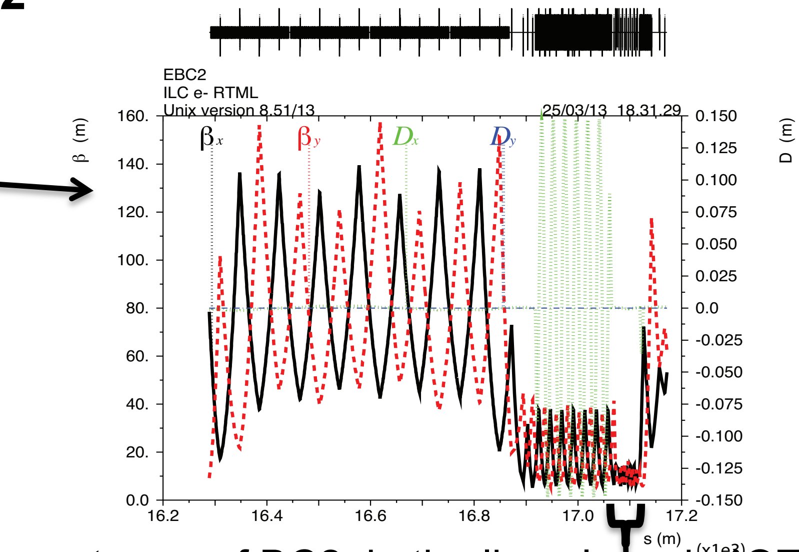
Material	k $[\mathrm{W\cdot m^{-1}\cdot K^{-1}}]$	$\frac{dE}{dz}$ $\left[\frac{\mathrm{MeV}}{\mathrm{cm}}\right]$	ΔT_{eq} [K]
Kapton	0.12	2.297	20.42
Al	210	5.778	0.03
Be	200	3.704	0.02
Ti	17	9.112	0.57
W	163	32.366	0.21

Over many pulses (1 bunch each) these materials have no problem because they conduct the heat appearing in the beam area very quickly to the rest of the target.
No damage

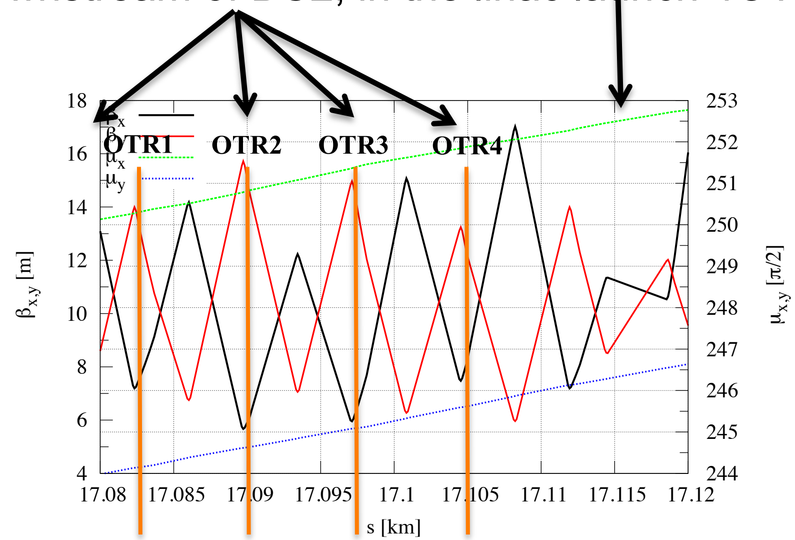
m-OTR system for the ILC RTML: exploratory study

RTML BC2





Downstream of BC2, in the linac launch 4OTRs



E=15 GeV
N_e=2x10^{10} particles per bunch
σ_z=0.3/0.15 mm
Energy spread=1.07%
$\gamma\varepsilon_x$=8 μm
$\gamma\varepsilon_y$=20 nm

OTR target study for end BC2 : Temperature rise of material per pulse

- Peak of instantaneous temperature rise:

$$\Delta T_{inst} = \frac{1}{\rho C_p}\left(\frac{dE}{dz}\right)\frac{N_b N_e}{2\pi\sigma_x\sigma_y}$$

ρ: material density
C_p: specific heat
N_b: number of bunches per pulse (N_b=1, single bunch mode)
N_e: number of particles per bunch (N_e=2x10^{10})
Σ_x≈75.62 μm, σ_y≈5.34 μm (β_x≈7 m, β_y≈14 m)
dE/dz: Collision stopping power in a thin material (< X_0) (calculated from the Bethe-Bloch formula)

- Comparison with fracture limit due to thermal stress:

σ_{UTS}: ultimate tensile stress
α_T: thermal expansion coefficient
Y: Young modulus

$$\Delta T_{fr} \cong \frac{2\sigma_{UTS}}{\alpha_T Y}$$

Material	$\frac{1}{\rho}\frac{dE}{dz}$ $\left[\frac{\text{MeV}\cdot\text{cm}^2}{g}\right]$	Density ρ $[\text{g/cm}^3]$	$\frac{dE}{dz}$ $\left[\frac{\text{MeV}}{\text{cm}}\right]$	ΔT_{inst} [K]	ΔT_{fr} [K]	T_{melt} [K]
Kapton	2.58	1.42	3.665	298.81	9240	Does not melt, decomposes at 793 K
Al	2.22	2.7	5.996	307.96	63.662	933.37
Be	2.066	1.85	3.822	135.43	222.28	1546
Ti	2.067	4.54	9.386	494.12	441.06	1923
W	1.745	19.3	33.678	1643.3	1059.7	3643

In this case, stress fractures may be generated for targets made of Al, Ti and W. In principle, these calculations indicate that Kapton and Be might avoid damage. However, the use of Be could be discouraged due to costs and difficulties of machining (toxicity). **Kapton could be a good candidate!**

OTR target study for end BC2 : Long Term heating

Heat transfer by conduction in a cylindrical system (OTR target) for a Gaussian bunch and thin targets

- The equilibrium temperature:

$$\Delta T_{eq} = T(0) - T(R) = \frac{dE}{dz} \cdot \frac{N_b N_e f_{rep}}{4\pi k} \ln\left(\frac{R^2}{2\sigma_r^2}\right)$$

Target radius R=6 mm (same as for ATF2 OTR prototype)
Repetition frequency f_{rep}=5 Hz
k: thermal conductivity
$\sigma^2_r = \sqrt{(\sigma_x \sigma_y)}$

Material	k $[\mathrm{W \cdot m^{-1} \cdot K^{-1}}]$	$\frac{dE}{dz}$ $\left[\frac{\mathrm{MeV}}{\mathrm{cm}}\right]$	ΔT_{eq} [K]
Kapton	0.12	3.665	41.68
Al	210	5.996	0.04
Be	200	3.822	0.03
Ti	17	9.386	0.75
W	163	33.678	0.28

Over many pulses (1 bunch each) these materials have **no problem** because they conduct the heat appearing in the beam area very quickly to the rest of the target. Therefore the long term heating (assuming 5 Hz pulse repetition frequency) is not a problem. The real problem is caused by the thermal stress during the instantaneous deposition of energy.

Final Conclusions

- The **m-OTR system** of the ATF2 EXT has demonstrated its performances as a **fast** (1min) and **reliable** system for measuring the beam size and the emittance. The system is **totally integrated** in the **online model** and it is **crucial** for **tuning procedures** of the beamline as: coupling correction, beta matching, energy spread measurements…Studies to ameliorate these procedures are under study

- A **systematic measurement campaign** to determine if the new target configuration is able to avoid the **wakefield effect** of the **simultaneous measurement** of the 4 OTRs has to be made and also a **intensity** beam size **dependence** measurement and its implications in the resolution

- We have **studied analytically** the **conditions of solvability** of the systems of equations involved in the process of emittance reconstruction and we have obtained some rules about the **locations** of the **measurement stations** to avoid unphysical results. **Simulations** are being made to test the robustness with high coupling scenarios and measurement errors. The results of these studies will be very **useful** to better determine the location of the emittance measurement stations in the **diagnostic sections** of **FLC**s.

- OTR monitors are **mature** and **reliable** diagnostic tools that could be **very suitable** for the setup and tuning of the machine in single-bunch mode. It can be very useful during **start up** and **commissioning** phases of the **RTM**L. The **feasibility** of using a m-OTR system in **transfer lines** of the **ILC RTML** as well as a study of the different **materials** for the OTR **target** and possible limitations of operation is ongoing.

References

[1] ATF Collaboration, *Present status of the final focus beam line at the KEK Accelerator Test Facility*. Physical Review Special Topics Accelerators and Beams 13, 042801 (2010).

[2] ATF collaboration*, Instrumentation for the ATF2 Facility.* IPAC10.

[3] J. Alabau Gozalvo, C. Blanch, A. Faus-Golfe, J.V. Civera, J.J. Garcia-Garrigos, D. McCormick, G. White, J. Cruz, *Multi Optical Transition Radiation System for ATF2.* IPAC10.

[4] J. Alabau Gonzalvo, C. Blanch-Gutiérrez, A. Faus-Golfe, J. J. García-Garrigos, D. McCormick, J. Cruz, M. Woodley, G. White, *Multi Optical transition Radiation System for ATF2*, DIPAC2011

[5] J. Alabau-Gonzalvo, C. Blanch Gutierrez, A. Faus-Golfe, J. J. Garcia-Garrigos , J. Cruz, D. McCormick, G. White, M. Woodley, *Optical Transition Radiation System for ATF2*, IPAC2011.

[6] J. Alabau Gozalvo, C. Blanch, A. Faus-Golfe, D. McCormick, G. White, J. Cruz M. Woodley, *Multi-OTR system for ATF2*, Physics Procedia TIPP2011.

[7] J. Alabau-Gonzalvo, C. Blanch-Gutierrez, J. Cruz, A. Faus-Golfe, J. J. Garcia-Garrigos, D. McCormick, J. Resta-Lopez, G. White, M. Woodley, *Optics and Emittance Studies Using the ATF2 Multi-OTR System*. IPAC2012, New Orleans, Louisiana, USA, 2012.

[8] J. Alabau-Gonzalvo, C. Blanch-Gutierrez, J. Cruz, A. Faus-Golfe, J. J. Garcia-Garrigos, D. McCormick, J. Resta Lopez, G. White, M. Woodley, *Optics and Emittance Studies Using the ATF2 Multi-OTR System*, IBIC2012, Tsukuba, Japan, 2012.

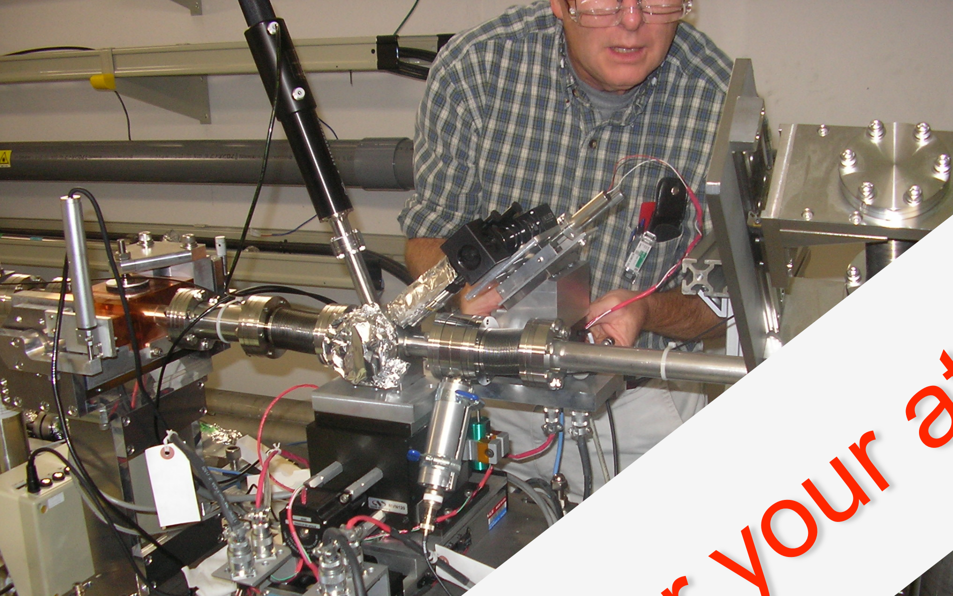
[9] A. Faus-Golfe, J. Navarro, *Emittance reconstruction from measured beam sizes,* to be published

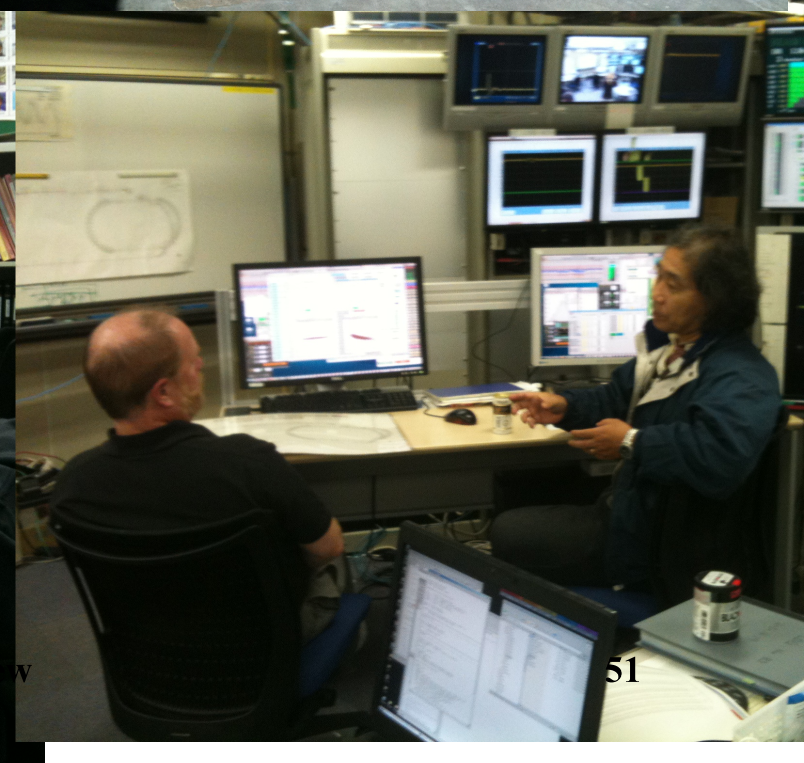
[10] J. Alabau-Gonzalvo, C. A. Faus-Golfe, J. Resta, R. Apsimon, A. Latina, *Multi-OTR system for Linear Colliders*, IPAC2013 ongoing

[11] J . Alabau-Gonzalvo, C. Blanch Gutierrez, A. Faus-Golfe , J. Cruz, E. Marin, D. McCormick, J. Resta, G. White, M. Woodley, *Upgrade and Systematic Measurement Campaign of the ATF2 Multi-OTR System,* IPAC2013 ongoing

[12] J. Giner Navarro, C. A. Faus-Golfe, J. Resta, J. Navarro, J. Fuentes, *Emittance Reconstruction from Measured Beam Sizes* , IPAC2013 ongoing

[13] *Beam Size and very low-emittance with a muti-OTR system in ATF2*, Thesis J.Alabau





Thanks for your attention

Back-up Slides

Technical Description HW

February 2010: Calibration at IFIC and SLAC

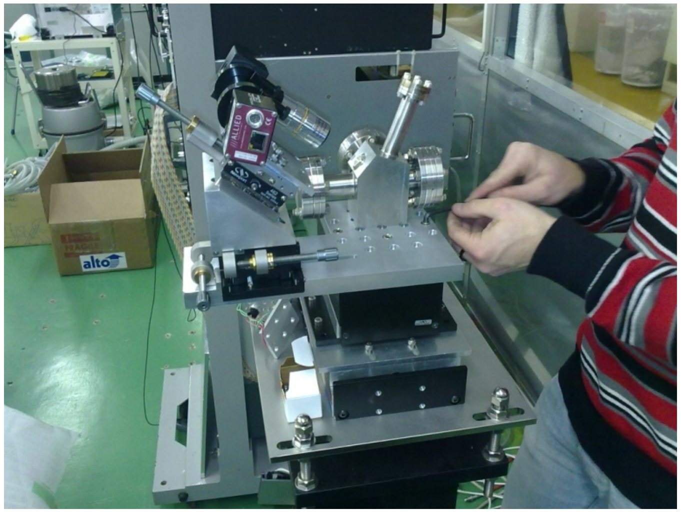
Assembling and **first tests** at SLAC and IFIC labs after fabrication

Vacuum test made at SLAC

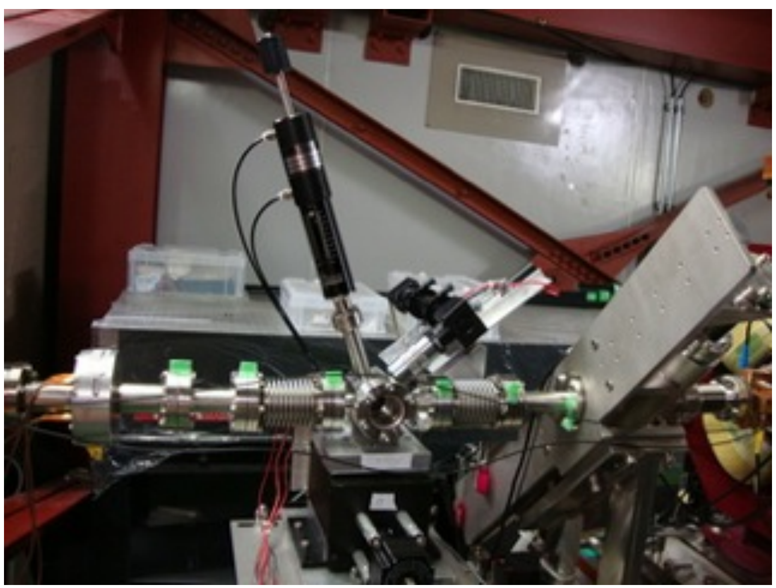
without OTR

with OTR

Technical Description HW April / May 2010: Hardware Installation

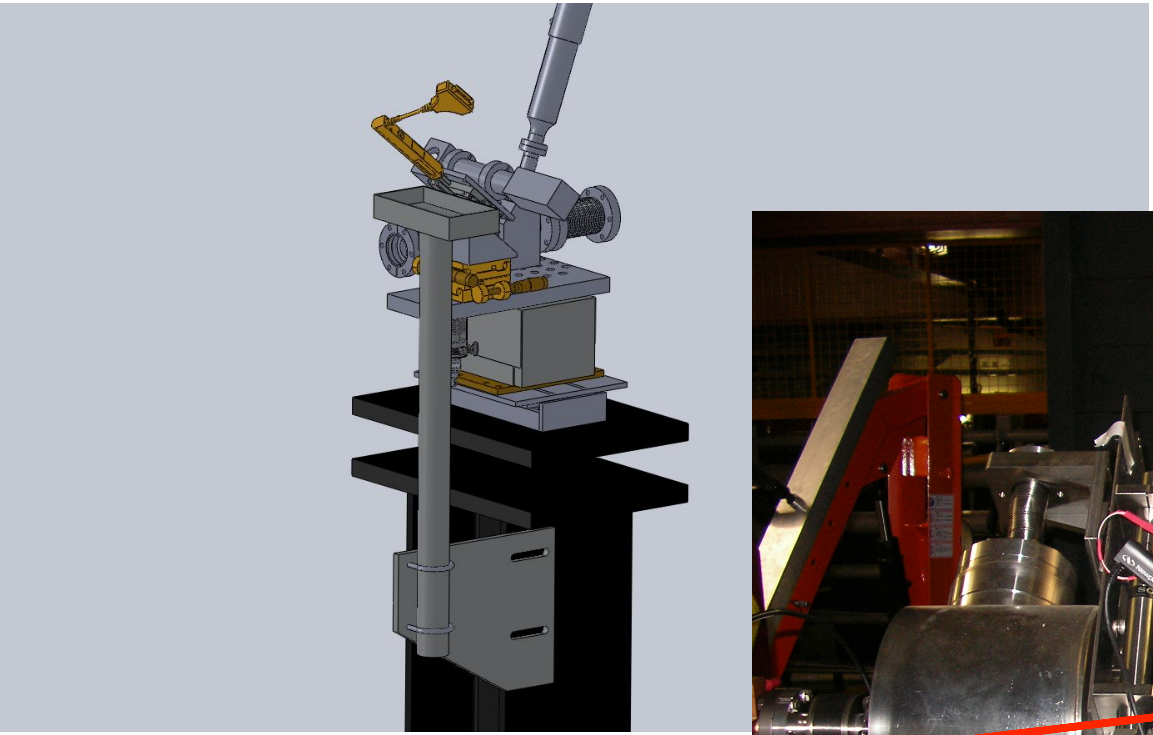


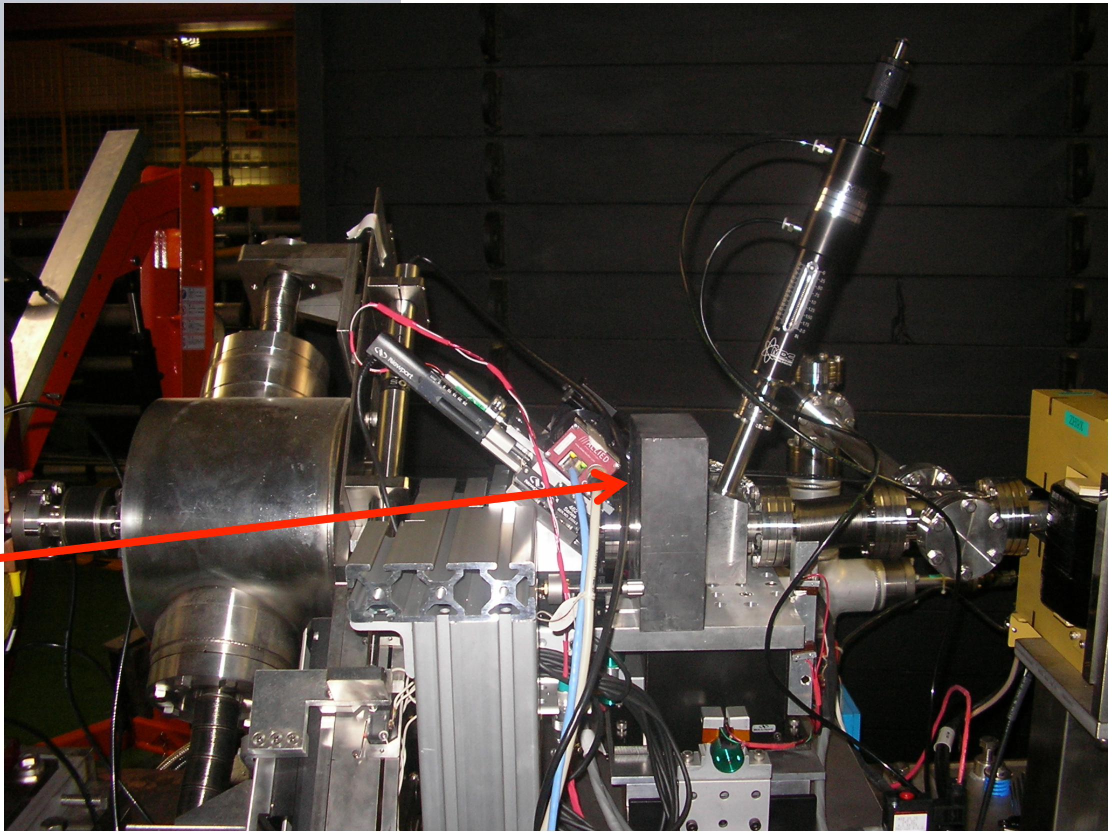
April: All **4 OTRs were assembled** at ATF clean room



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

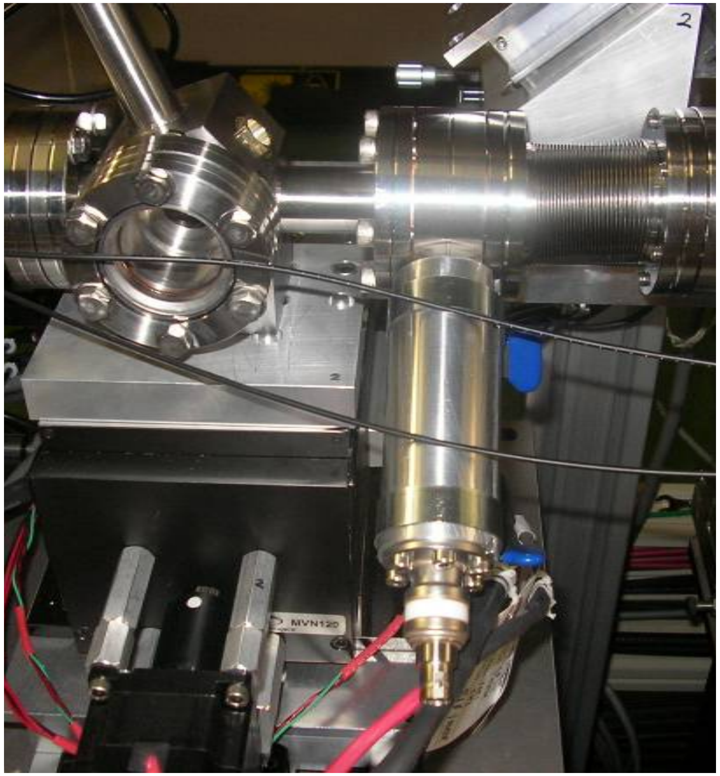
November 2010: Installation of cameras protection





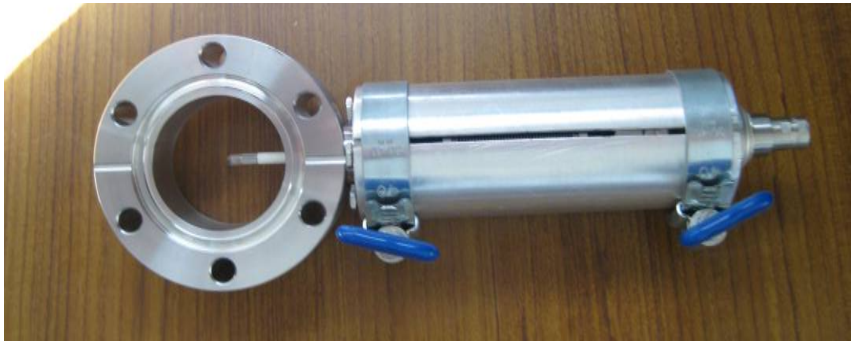
Lead blocks with a special holding support has been added to protect cameras from the radiation

Technical Description HW 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**

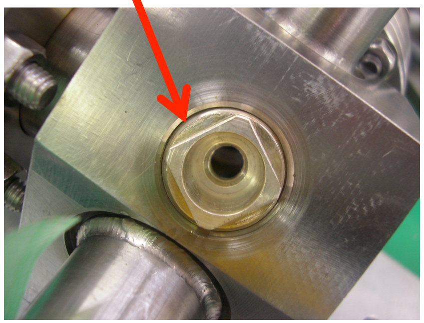
BNC feedthrough, copper connector, ceramic tube with bulb, stainless steel tube (ceramic tube holder), bellow and flange with port.

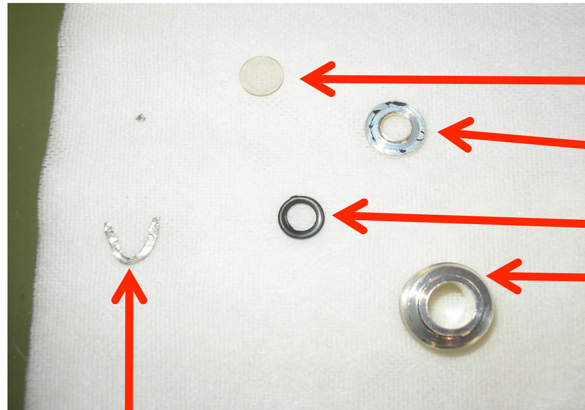


Aluminium tube and clamp to hold the bellow

Technical Description HW   December 2010: Vacuum leak repaired

Leak in the camera window





window

Thrust washer

O-ring

Nut

Old indium washer

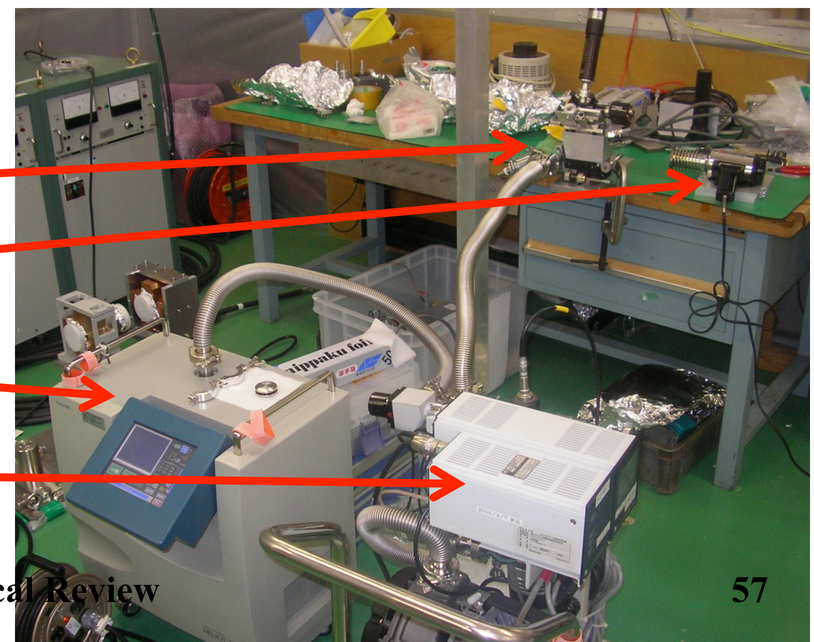
Important **vacuum leak** in the camera window of OTR2 was **repaired** by changing the indium washer

OTR

Heat gun

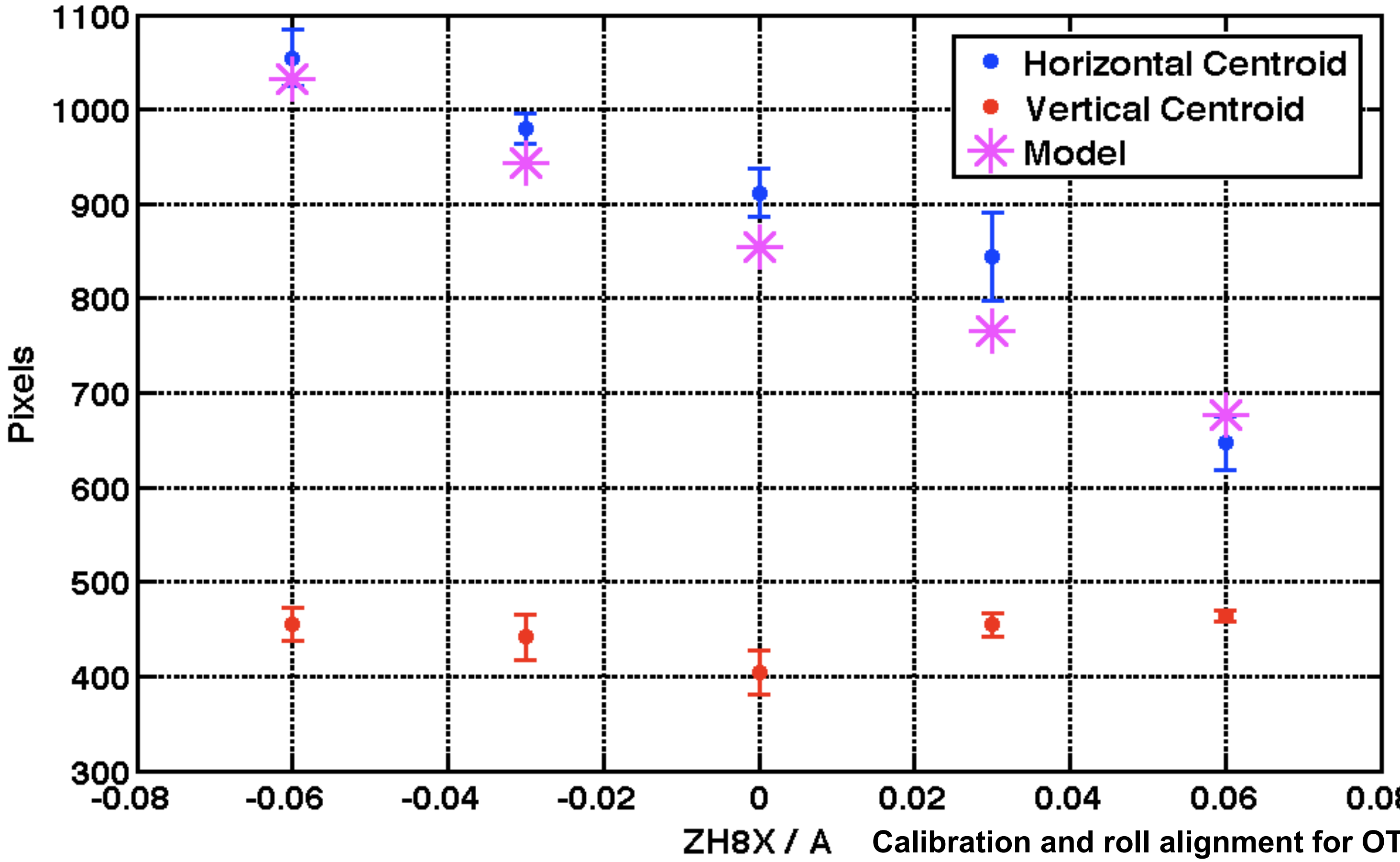
Helium leak check

Vacuum pump



1st Measurements

December 2010: OTR0x calibration test and roll alignment



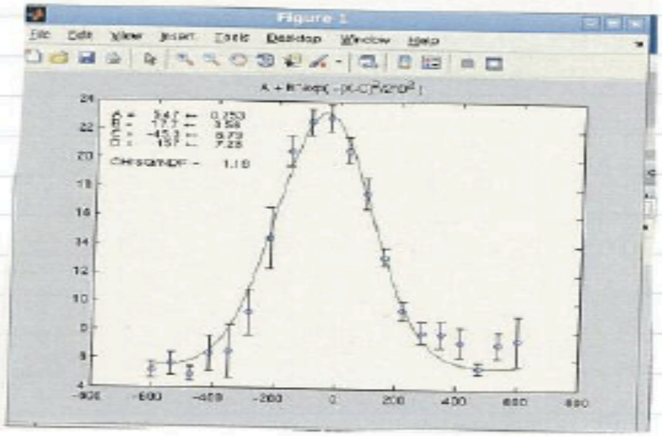
Calibration and roll alignment for OTR0X

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**.

December 2010: OTR Wire Scans

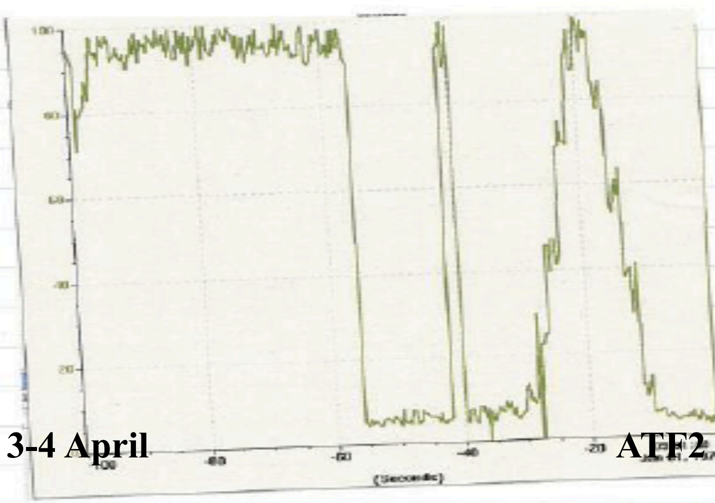
X wire scan from OTR3

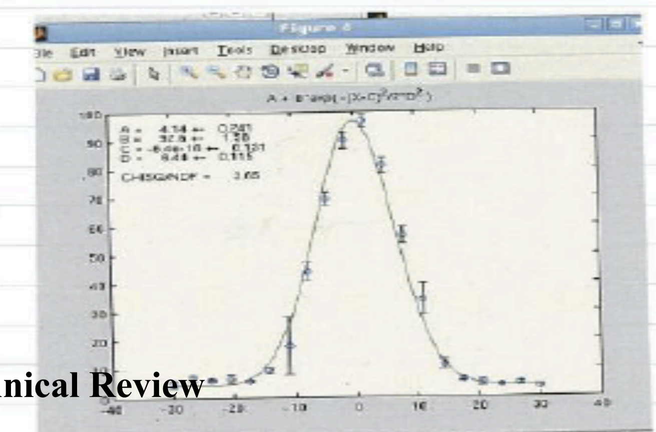
σ = 157 ± 7 μm



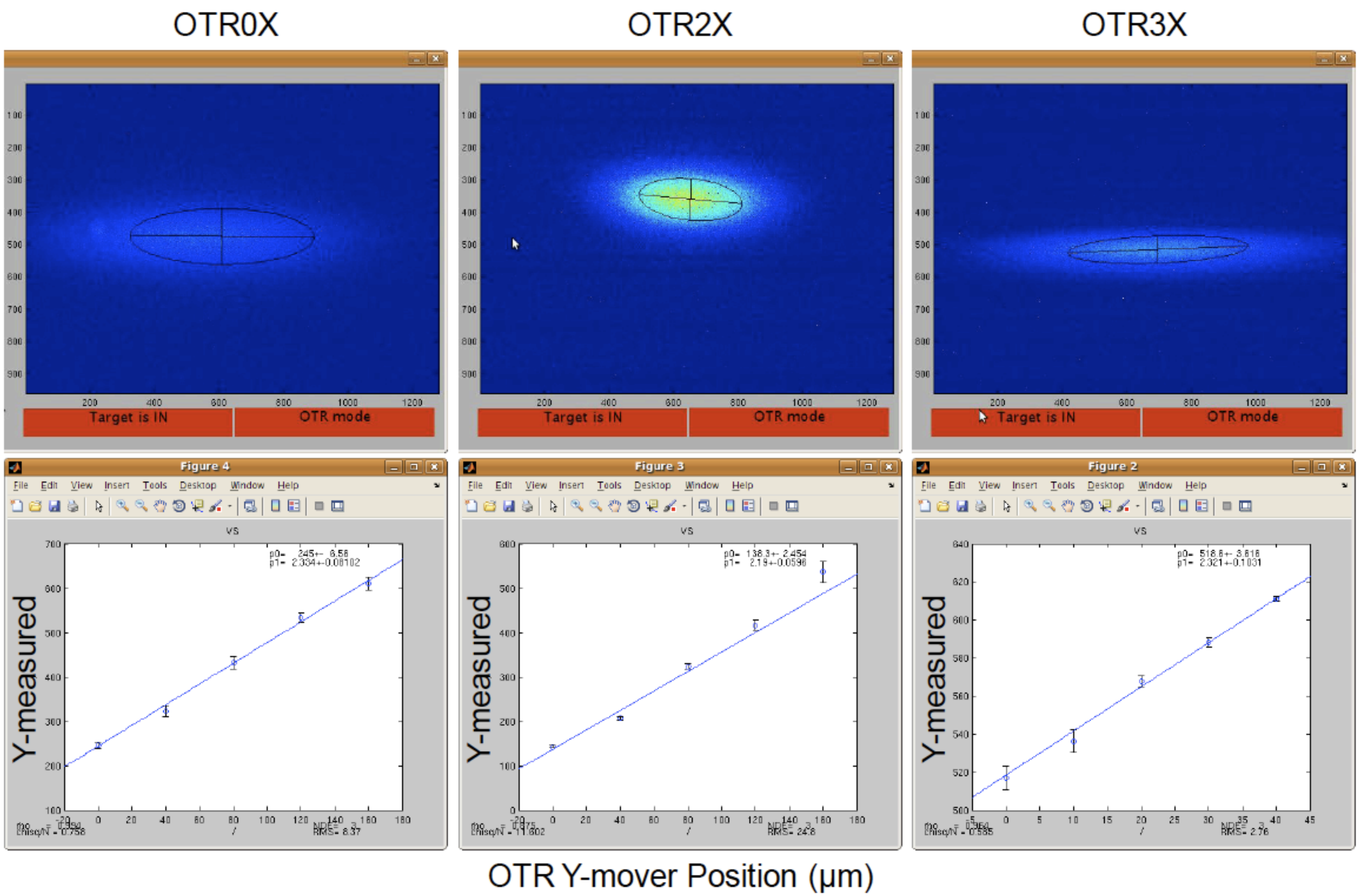
OTR Scan wires versus signal from **IPBSM background** detector. Made to cross check wire scans with observed beam sizes. Numbers agree within fit errors.

Y wire scan from OTR3
BSM signal





December 2010: Vertical scale calibration

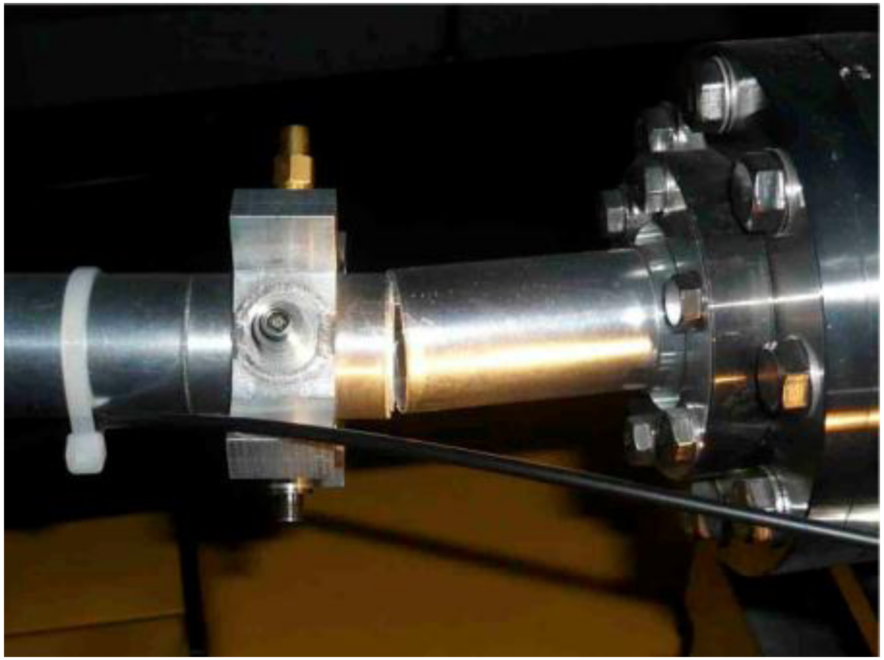


Vertical scale calibration done by scanning the vertical mover stage and recording the motion of the observed beam centroid. Thus the vertical calibration factor um/pixel is obtained.

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.

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

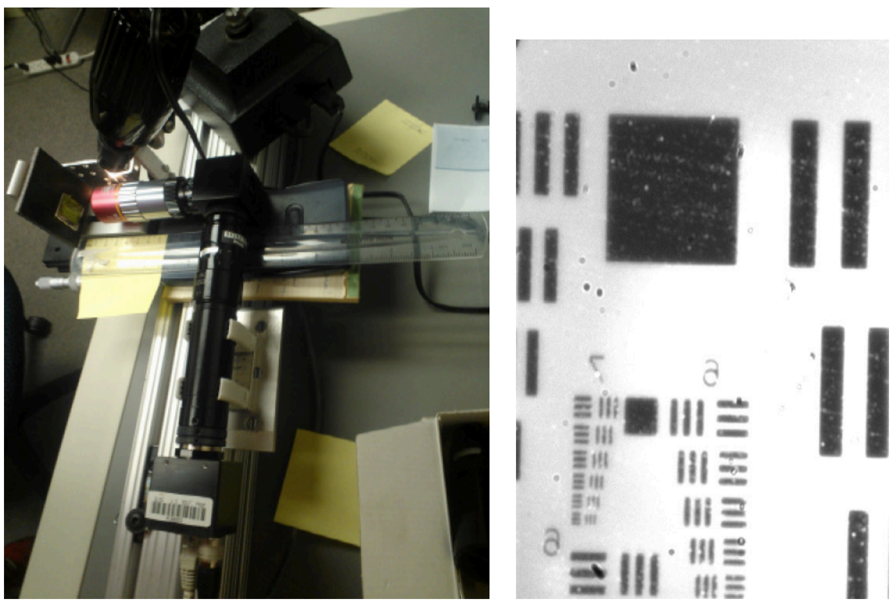
Technical Description HW

February-December 2012: Design and Construction of new Target holder and Optical system

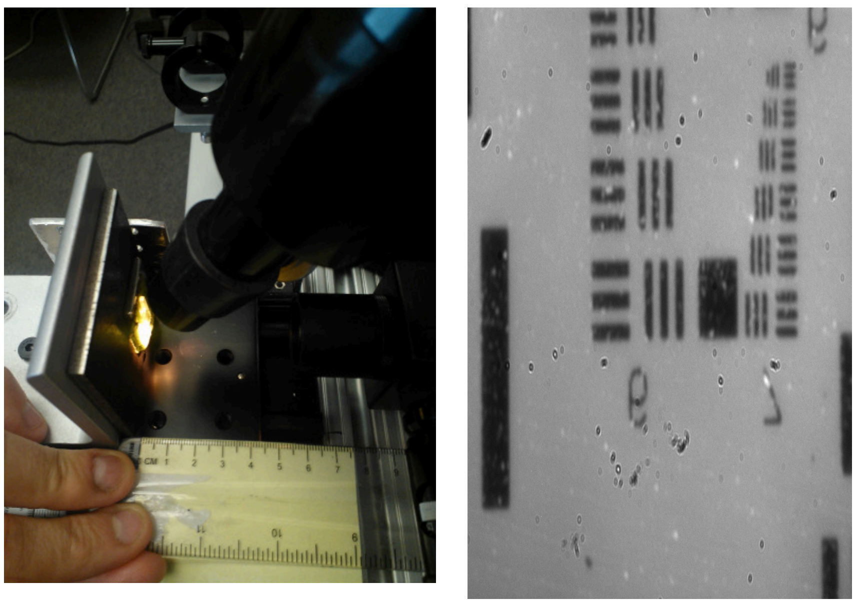
The present optical device (Mitutoyo lens) implemented by the mOTR system features a working distance of 34 mm and provides a resolution of 10%.

We have designed a new optic device (Achromat lens) that features a working distance of about 55 mm.

To determine the resolution of the new optical system we used an optical bench that accommodates the CCD camera, a tube lens, zoom device, square box with a 45º mirror and the optical system that faces a test target.



Mitutoyo device and CCD image



Achromat new lens and CCD image