Experience on Coupling Correction in the ESRF electron storage ring

Laurent Farvacque & Andrea Franchi,
on behalf of the
Accelerator and Source Division

Future Light Source workshop 2012
Jefferson Lab, Newport News, VA, 5th to 9th March 2012

Outlines

- Vertical emittances in the presence of coupling
- Coupling correction via Resonance Driving Terms
- Experience in the ESRF storage ring (2010)
- Experience in the ESRF storage ring (2011)
- Benefits and drawbacks; operational considerations

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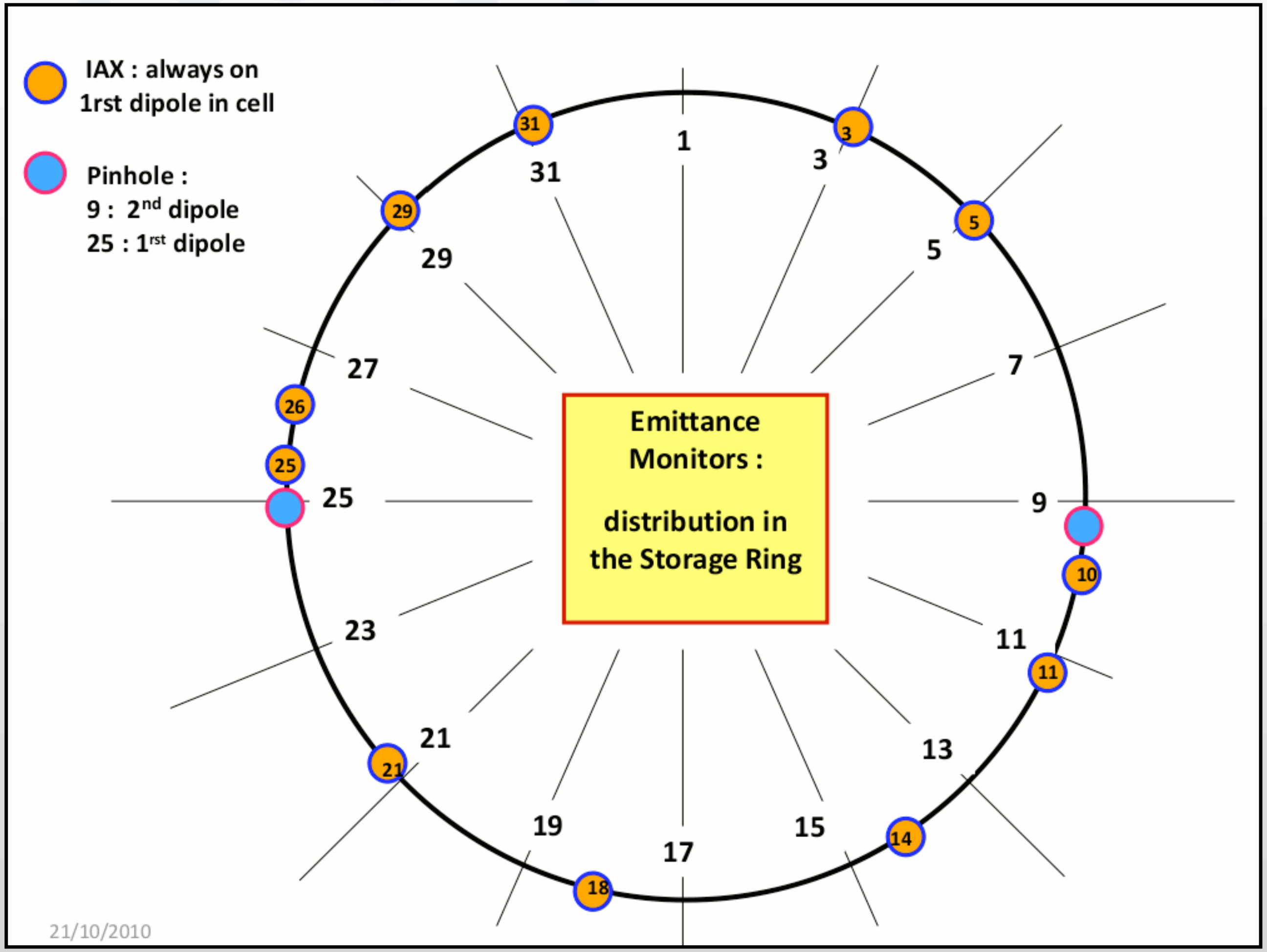
Meas. vertical emittance E*y* from RMS beam size

ESRF SR equipment:

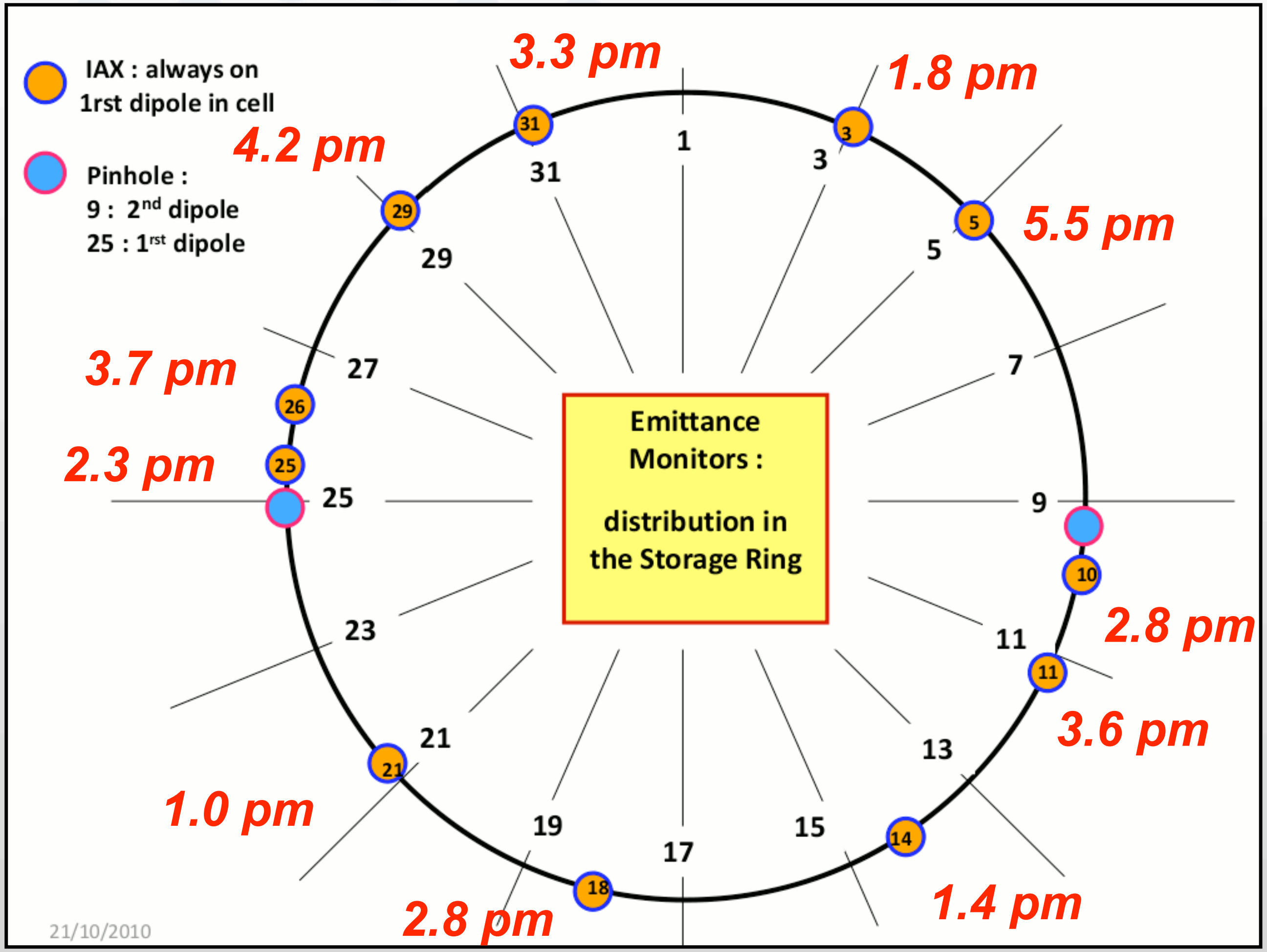
- 11 dipole radiation projection monitors (IAX)
- 2 pinhole cameras



Meas. vertical emittance Ey from RMS beam size

Ex=4.2 nm

- Well corrected coupling
- Low beam current (20 mA)



Meas. vertical emittance Ey from RMS beam size

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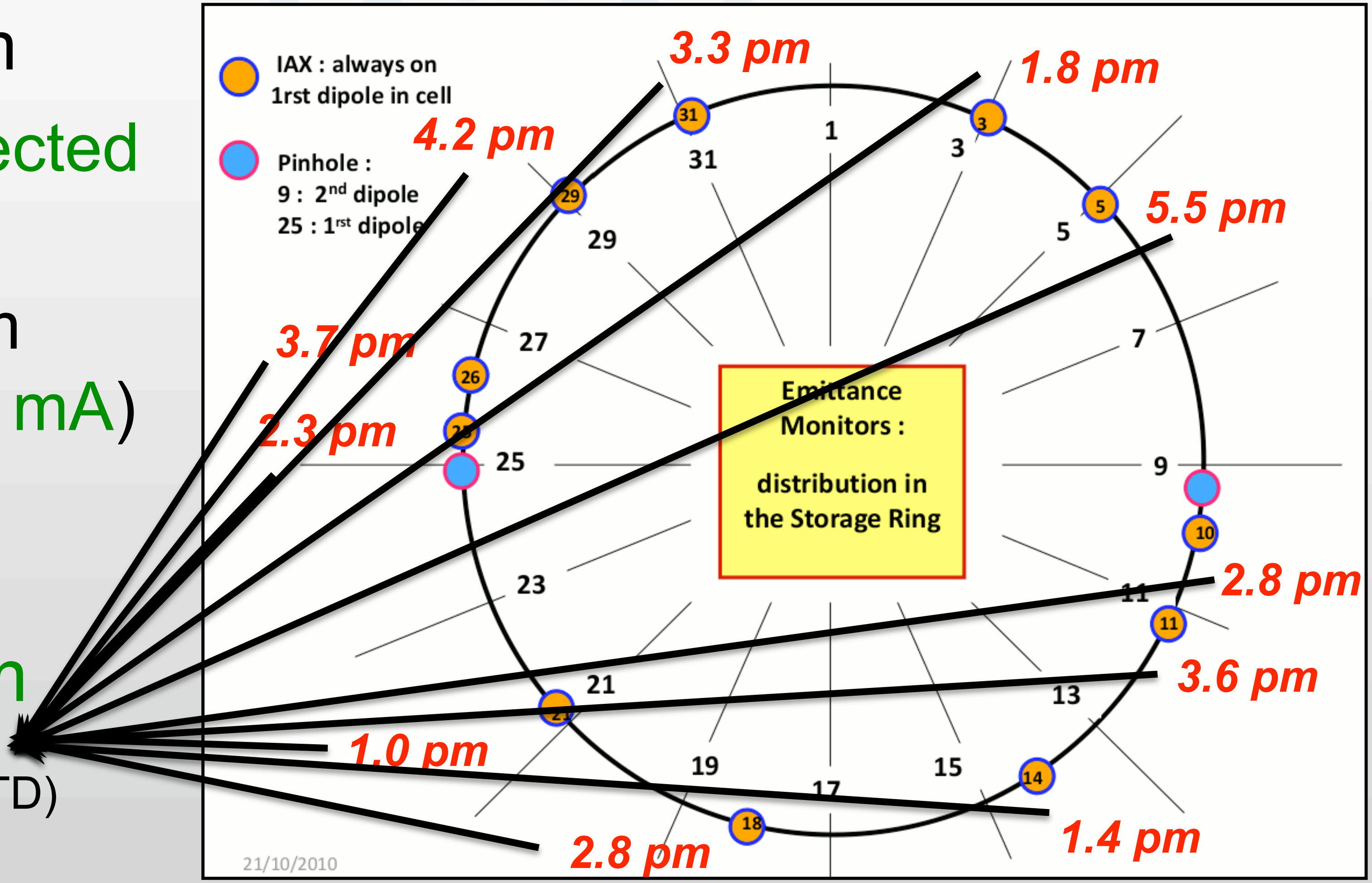
$\overline{\mathrm{Ey}}$=3.0 pm

±1.3 (STD)

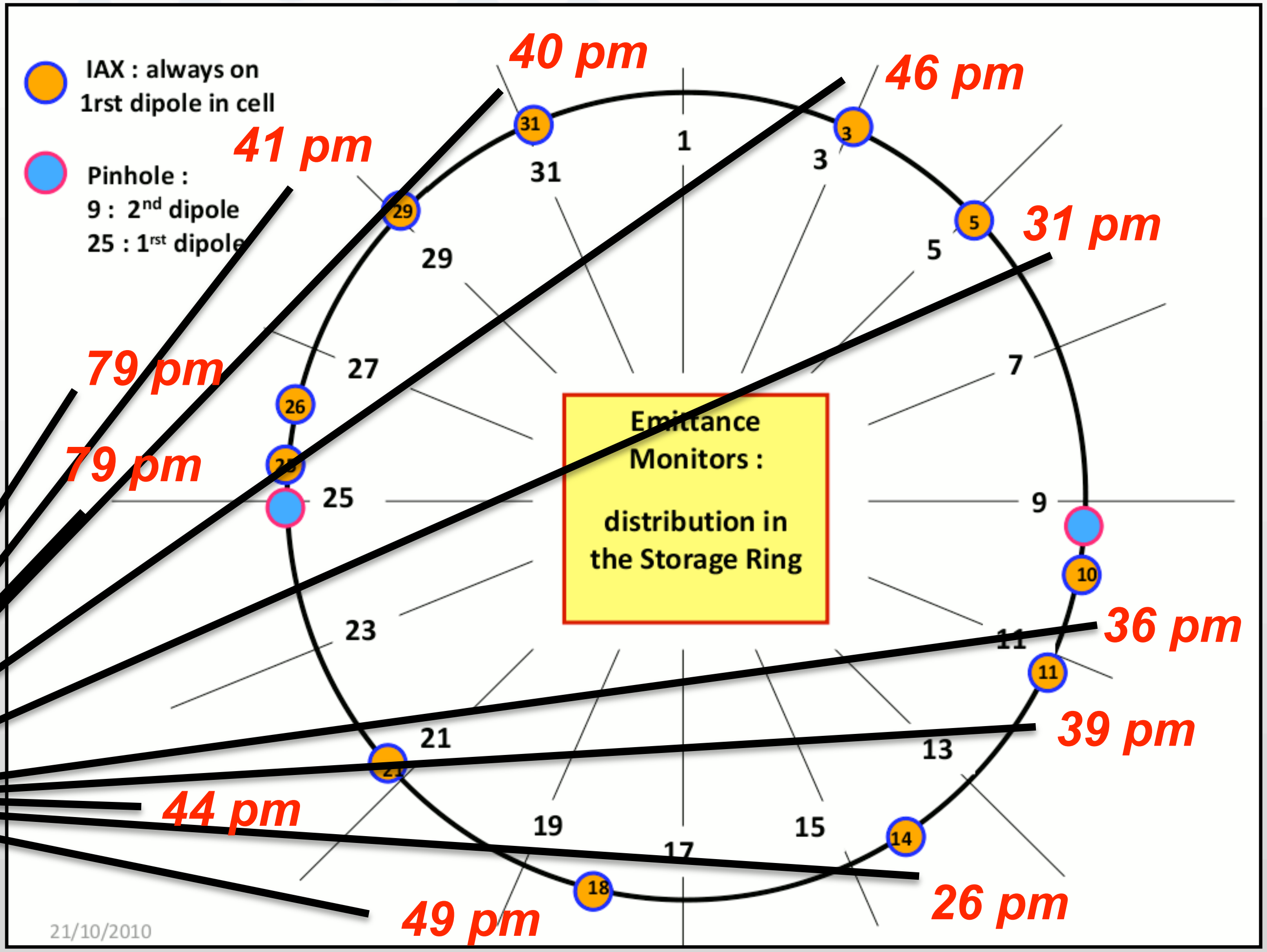


Meas. vertical emittance Ey from RMS beam size

Ex=4.2 nm

- Uncorrected coupling
- Low beam current (20 mA)

$\overline{\text{Ey}}$=46 pm ±18 (STD)



Vertical emittances in the presence of coupling

Measurable apparent emittance:

$$\mathbb{E}_y(s) = \frac{\sigma_y^2(s)}{\beta_y(s)} = \frac{< y^2(s) > -(\delta D_y(s))^2}{\beta_y(s)}$$

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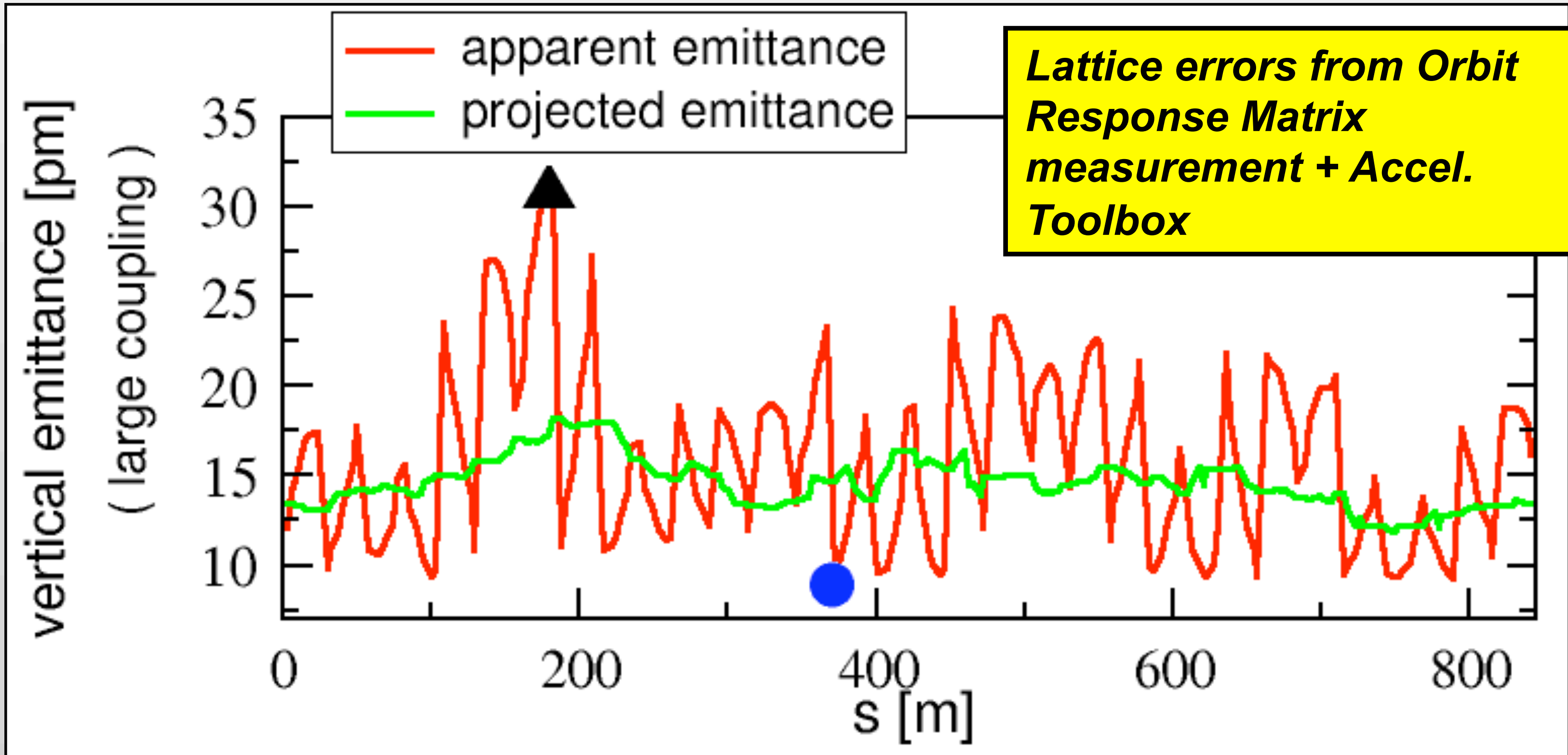

Lattice errors from Orbit Response Matrix measurement + Accel. Toolbox

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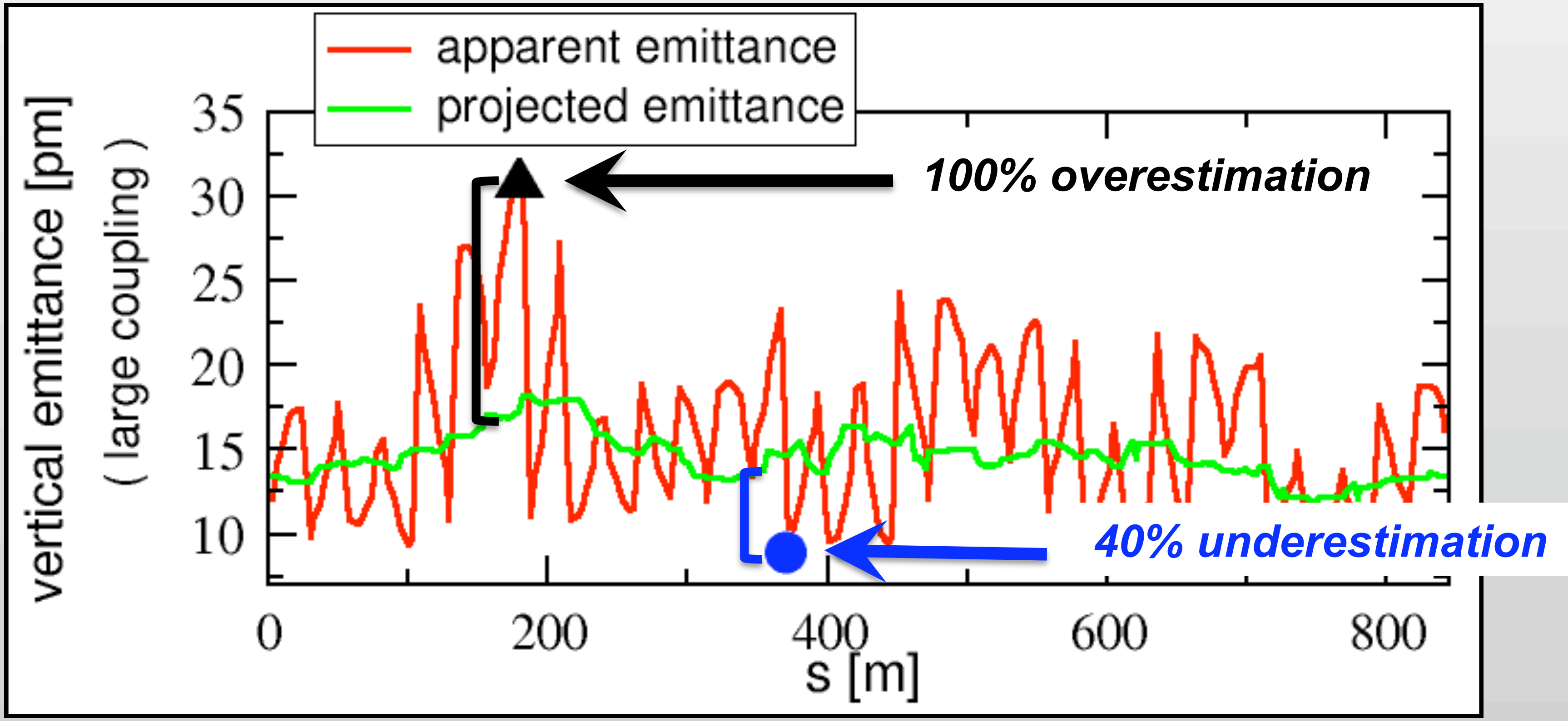

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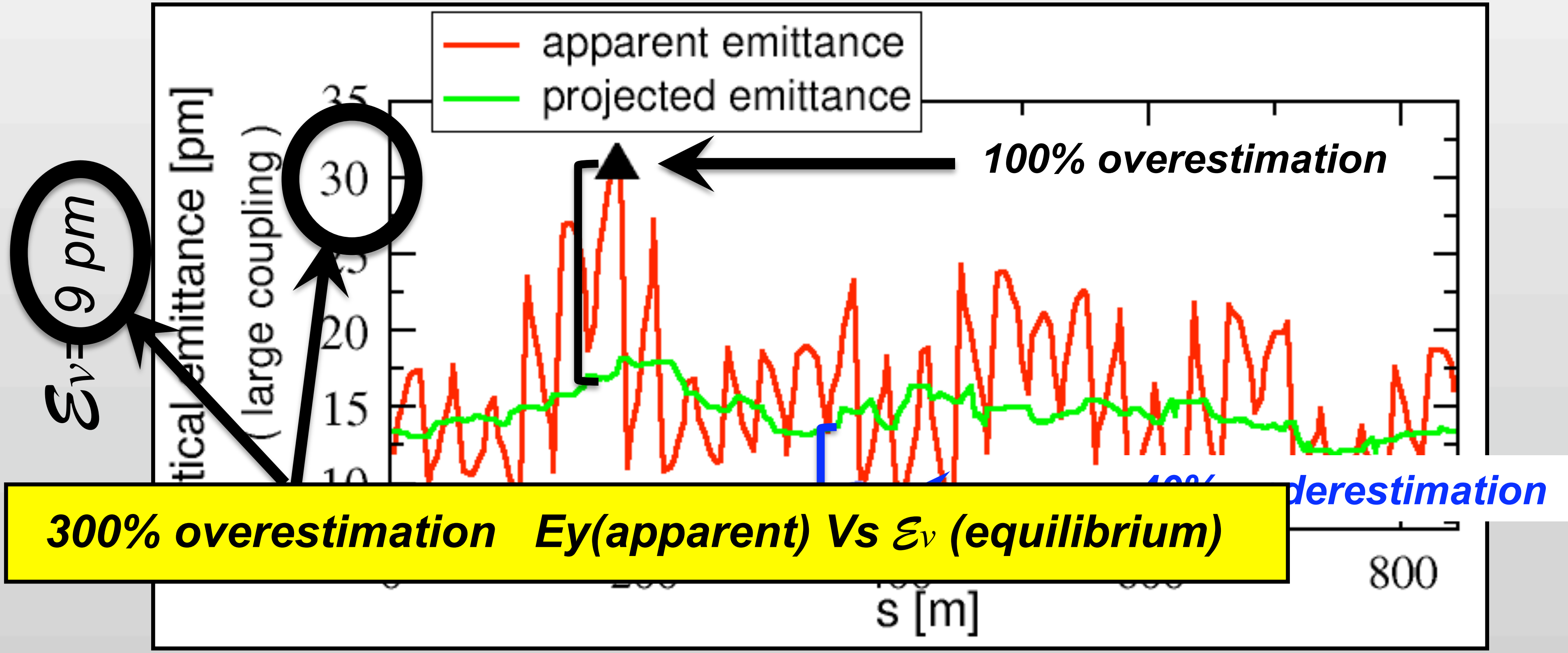

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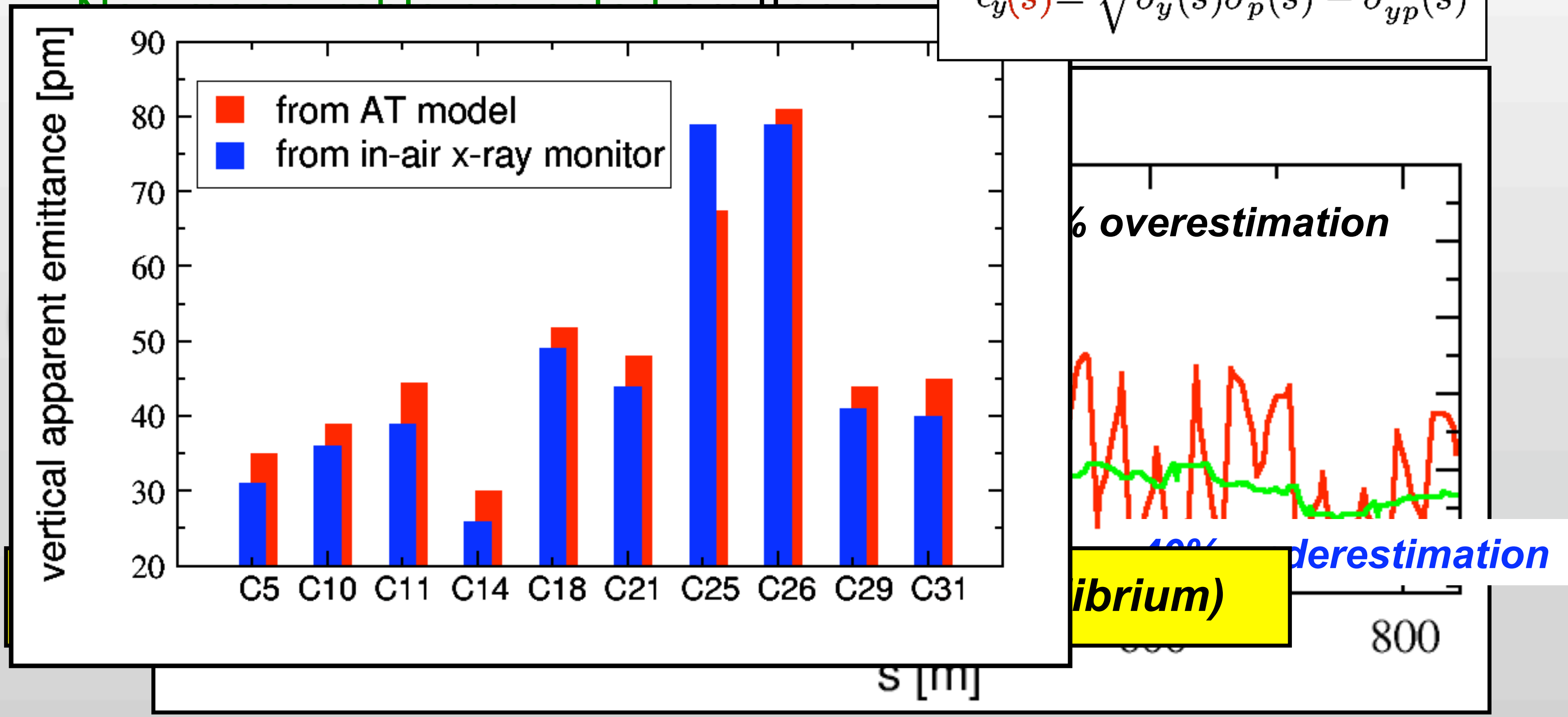

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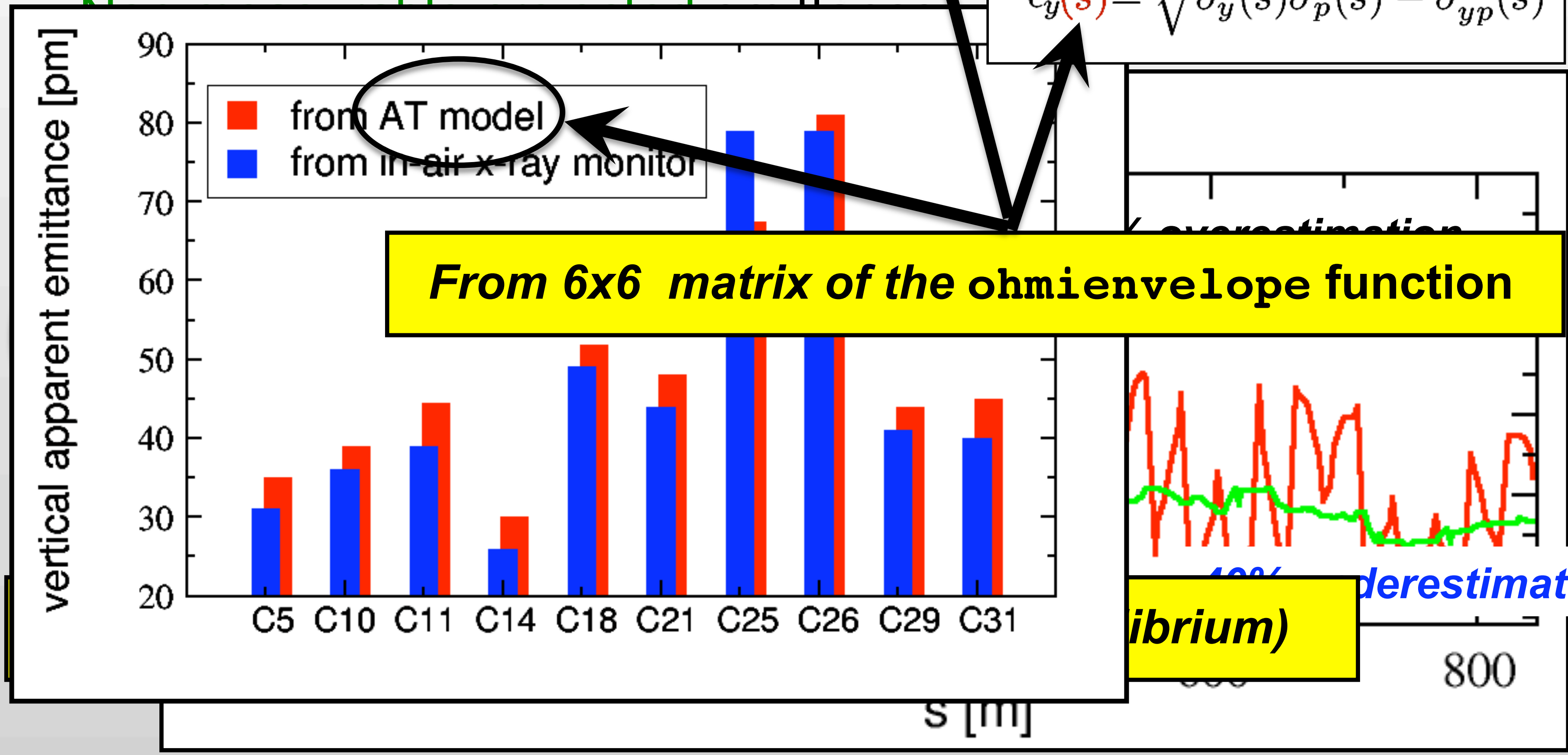

From 6x6 matrix of the `ohmienvelope` function

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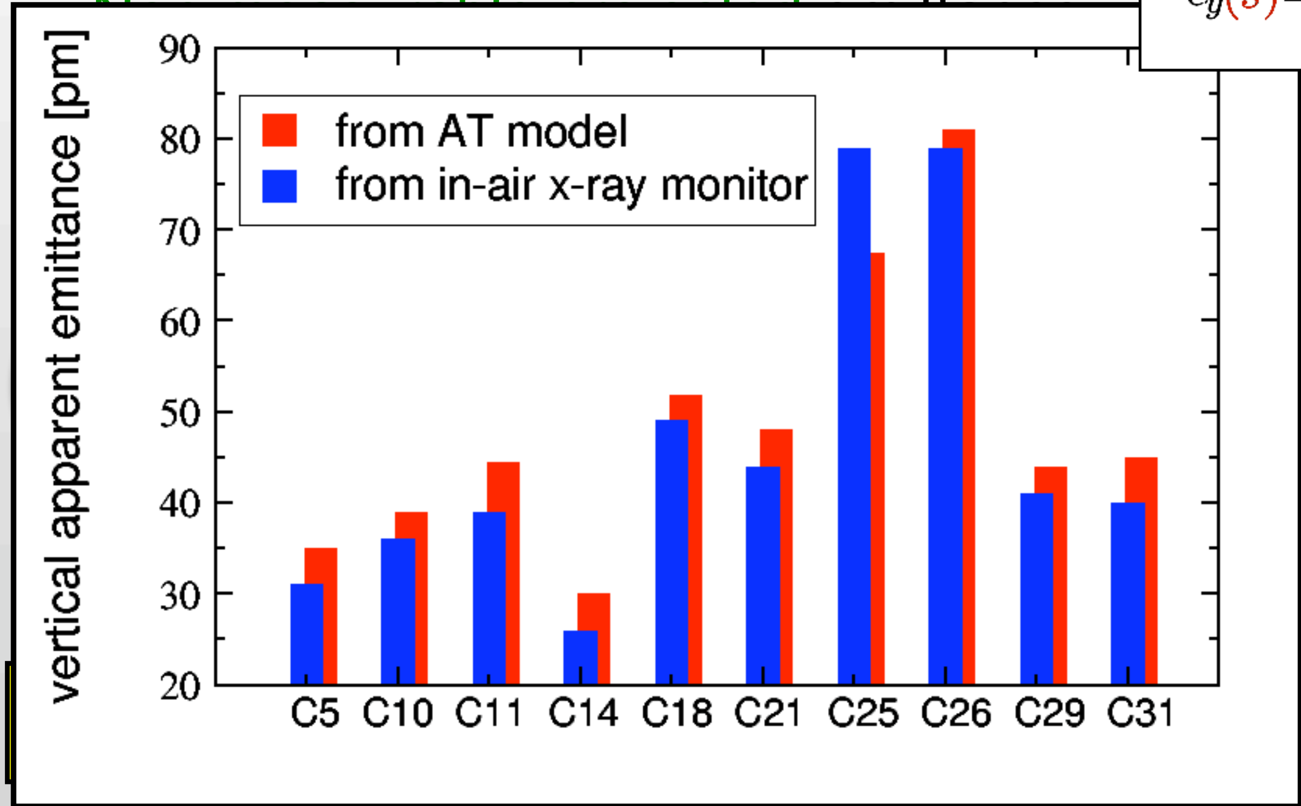
$\epsilon_y(s) =$



ibrium)

800

s [m]

Which "vertical emittance" shall we choose, then?

Vertical emittances in the presence of coupling

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Average over the ring

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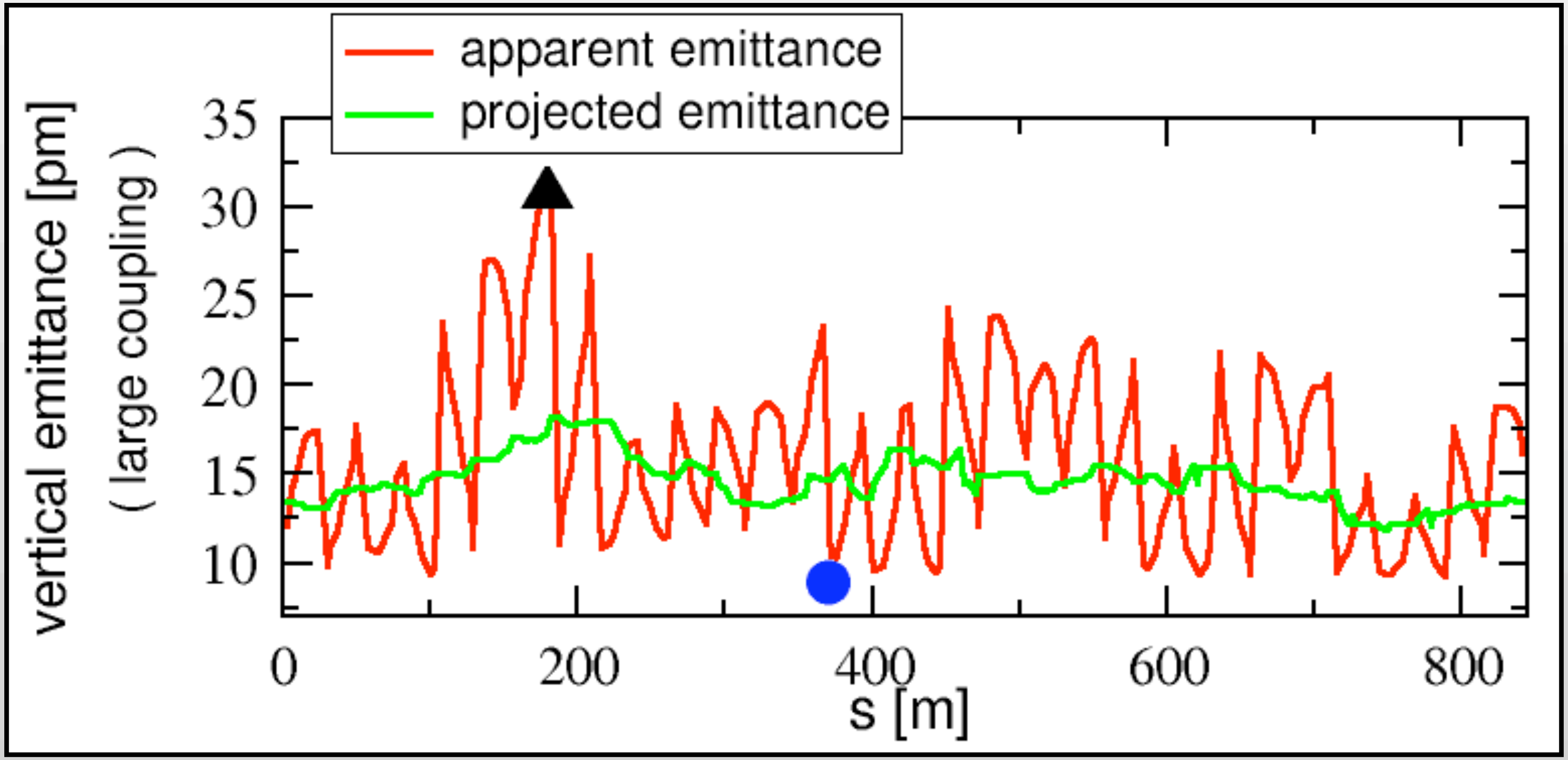
$\mathcal{E}_v = 9\ pm$



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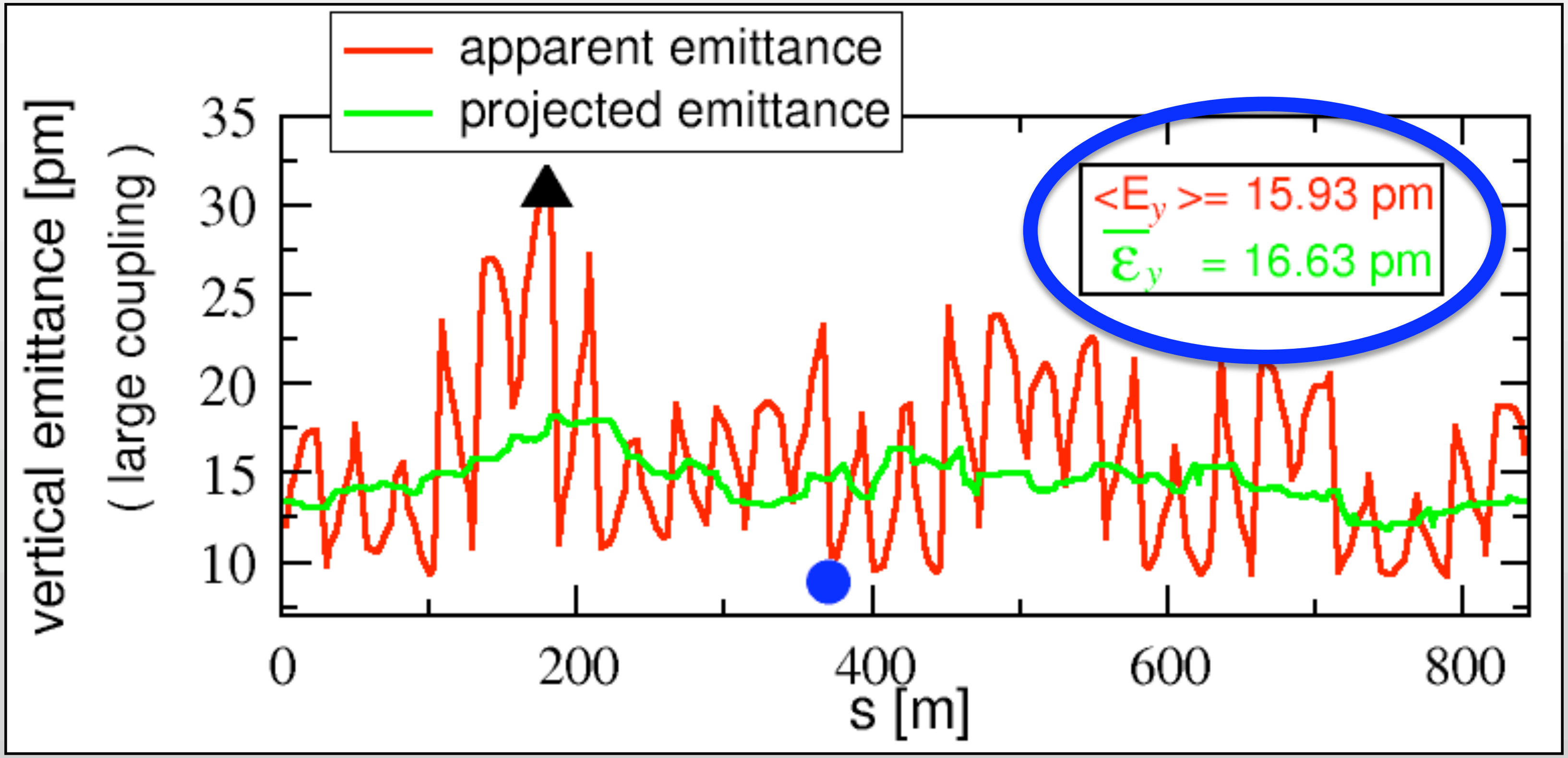

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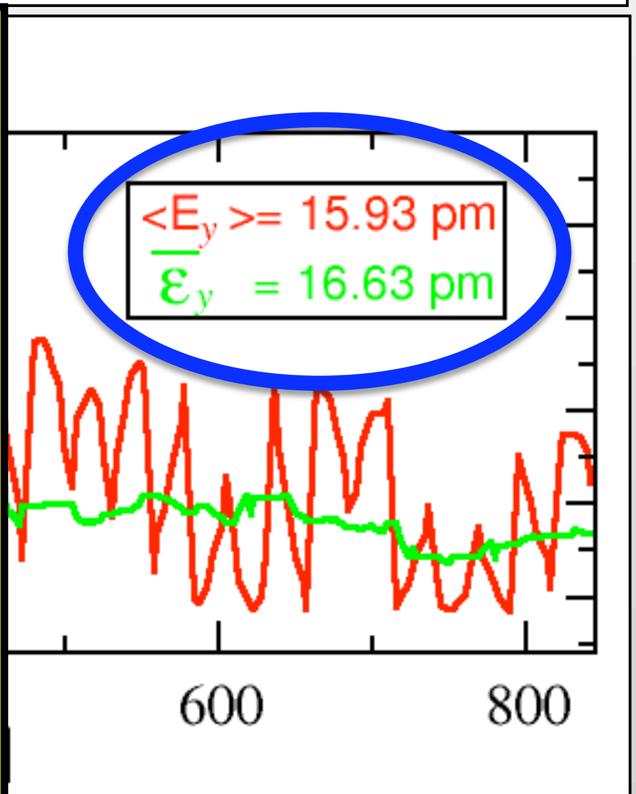

Definition of vertical emittance @ ESRF:

$$\bar{\epsilon}_y = \frac{1}{C}\oint \epsilon_y(s)ds \simeq < \mathbb{E}_y > = \frac{1}{N}\sum_{n=1}^{n=N} \mathbb{E}_{y,n}$$

$$\delta\epsilon_y = \left(\sum_n (\mathbb{E}_{y,n} - < \mathbb{E}_y >)^2/N\right)^{1/2}$$

More details in PRSTAB-14-012804 (2011)

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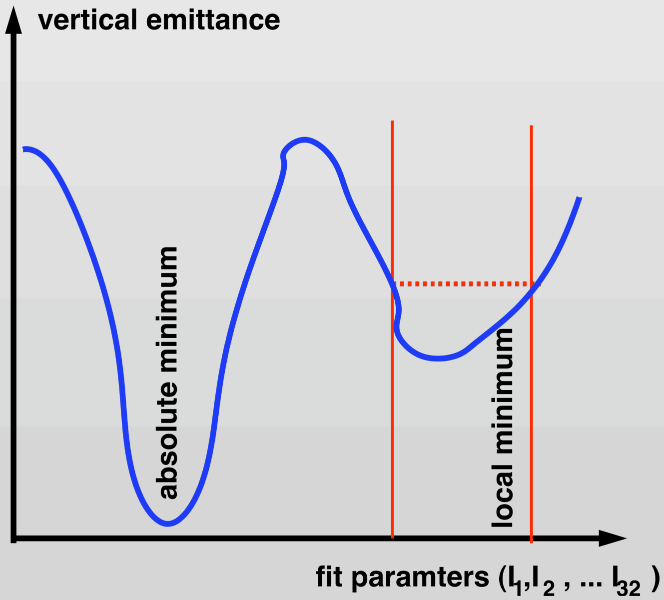

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Details and formulas in PRSTAB-14-012804 (2011)

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  - faster
  - gets directly to absolute minimum value

Details and formulas in PRSTAB-14-012804 (2011)

Coupling correction via Resonance Driving Terms

The lower the vertical dispersion and the coupling RDTs, the smaller the vertical emittances

Procedure [already independently developed by R. Tomas (for ALBA)]:

1. Build an error lattice model (quad tilts, etc. from Orbit Response Matrix or turn-by-turn BPM data) => RDTs and Dy

$$\vec{F} = (a_1{}^*f_{1001},\ a_1{}^*f_{1010},\ a_2{}^*Dy)\ ,\quad a_1+a_2=1$$

1. Evaluate response matrix of the available skew correctors **M**
2. Find via SVD a corrector setting $\vec{J}$ that minimizes both RDTs and Dy

$$\vec{J} = -M\,\vec{F}$$ **to be pseudo-inverted**

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$$\mathrm{ORM} = \begin{pmatrix} O_{xx} & O_{xy} \\ O_{yx} & O_{yy} \end{pmatrix}$$

Orbit Response Matrix at 224 BPMs after exciting 16x2 steerers (H,V)

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Fitting measured diagonal blocks from ideal ORM => focusing errors ΔK_1 .

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Fitting measured off-diagonal blocks from ideal ORM => effective quadrupole tilts θ (accounting for sextupole ver. misalignments)

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Vertical dispersion Dy is measured at all 224 BPMs

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$$\ldots_{,1}\sqrt{\beta_x^w\beta_y^w}\,e^{i(\Delta\phi_{w,x}\mp\Delta\phi_{w,y})} \over 4(1-e^{2\pi i(Q_u\mp Q_v)})$$

$$m_{w,c} = \frac{\sqrt{\beta_x^{(c)}\beta_y^{(c)}}\,e^{i(\Delta\phi_{w,x}^{(c)}-\Delta\phi_{w,y}^{(c)})}}{4(1-e^{2\pi i(Q_u-Q_v)})} \quad \text{for } w \leq 224,$$

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From MADX or AT

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From MADX or AT

$$m_{w,c} = \frac{\Delta D_y^{(w)}}{\Delta J_1^{(c)}},$$

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$\vec{J} = -M\vec{F}$ **to be pseudo-inverted**

Coupling correction via Resonance Driving Terms

$$\begin{pmatrix} a_1\vec{f}_{1001} \\ a_1\vec{f}_{1010} \\ a_2\vec{D}_y \end{pmatrix}_{\text{meas}} = -\mathbf{M}\vec{J}_c,$$

a_2=0.7 (2010) , 0.4 (2011)

$a_1+a_2=1$

Different weights on f_{1001} and f_{1010} tried, best if equal.

1. Build an error lattice model (quad tilts, etc. from Orbit Response Matrix or turn-by-turn BPM data) => RDTs and Dy

$$\vec{F} = (a_1{*}f_{1001},\ a_1{*}f_{1010},\ a_2{*}Dy) \quad , \quad a_1+a_2=1$$

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- Coupling correction via Resonance Driving Terms
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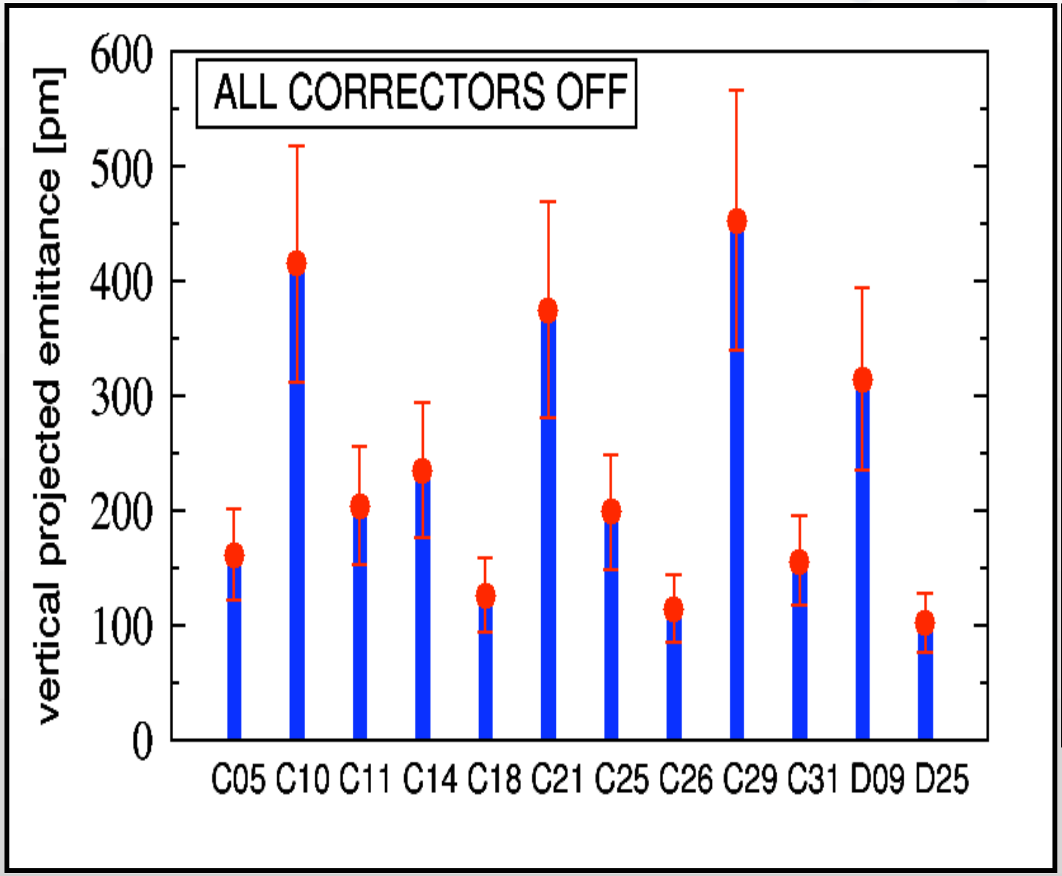
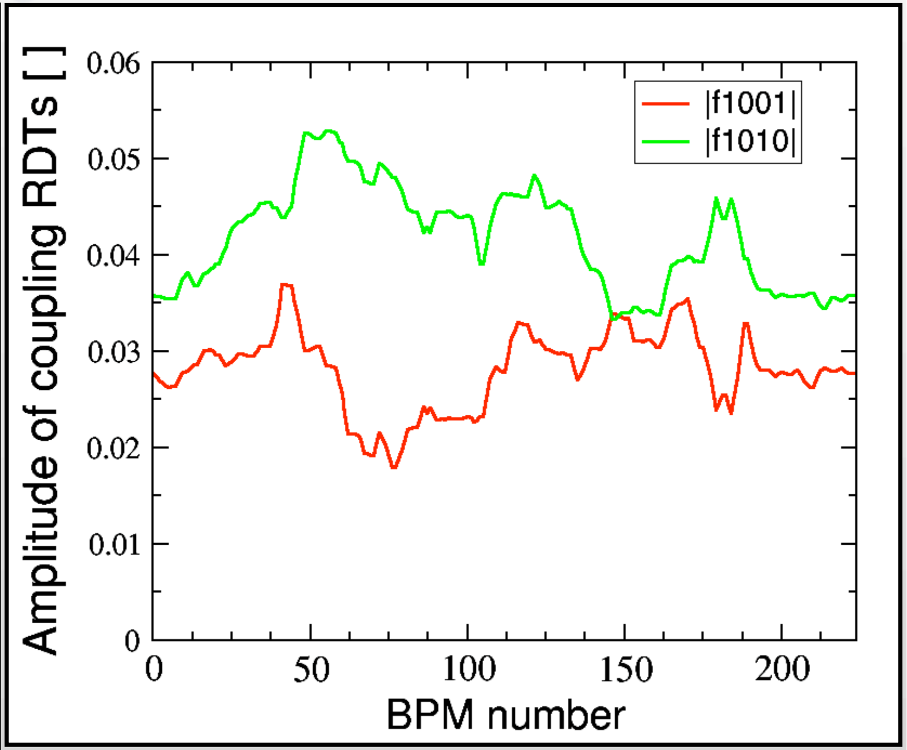
2010: Application in the ESRF storage ring

First RDT correction: January 16th 2010

All skew correctors OFF: $\bar{\varepsilon}_y \pm \delta\varepsilon_y = 237 \pm 122$ pm

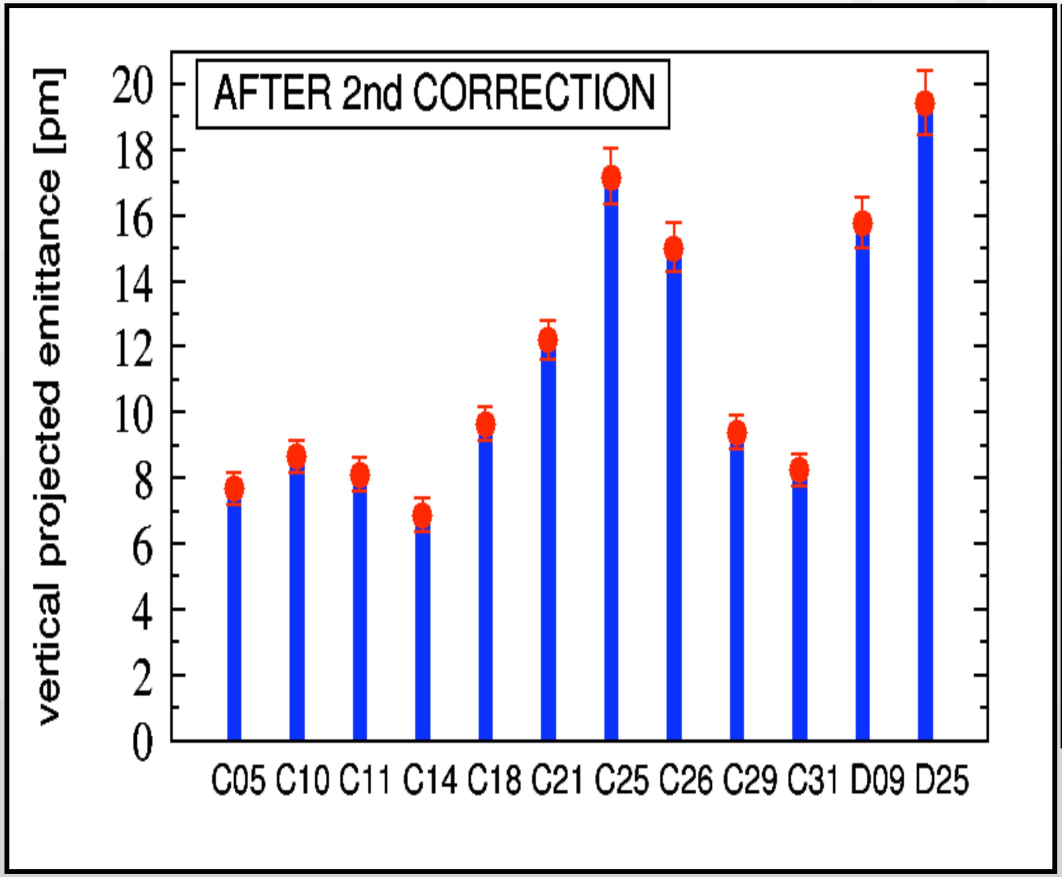


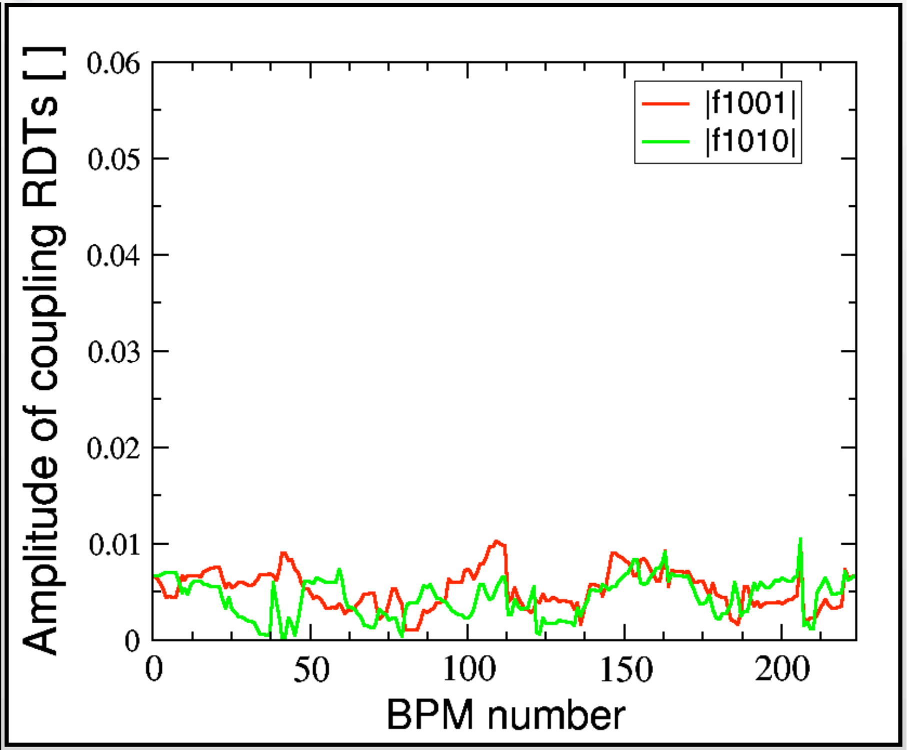


2010: Application in the ESRF storage ring

First RDT correction: January 16th 2010

After ORM measur. and RDT correction: $\bar{\varepsilon}_y \pm \delta\varepsilon_y = 11.5 \pm 4.3$ pm





~20 min. for ORM
a few seconds for RDT correction

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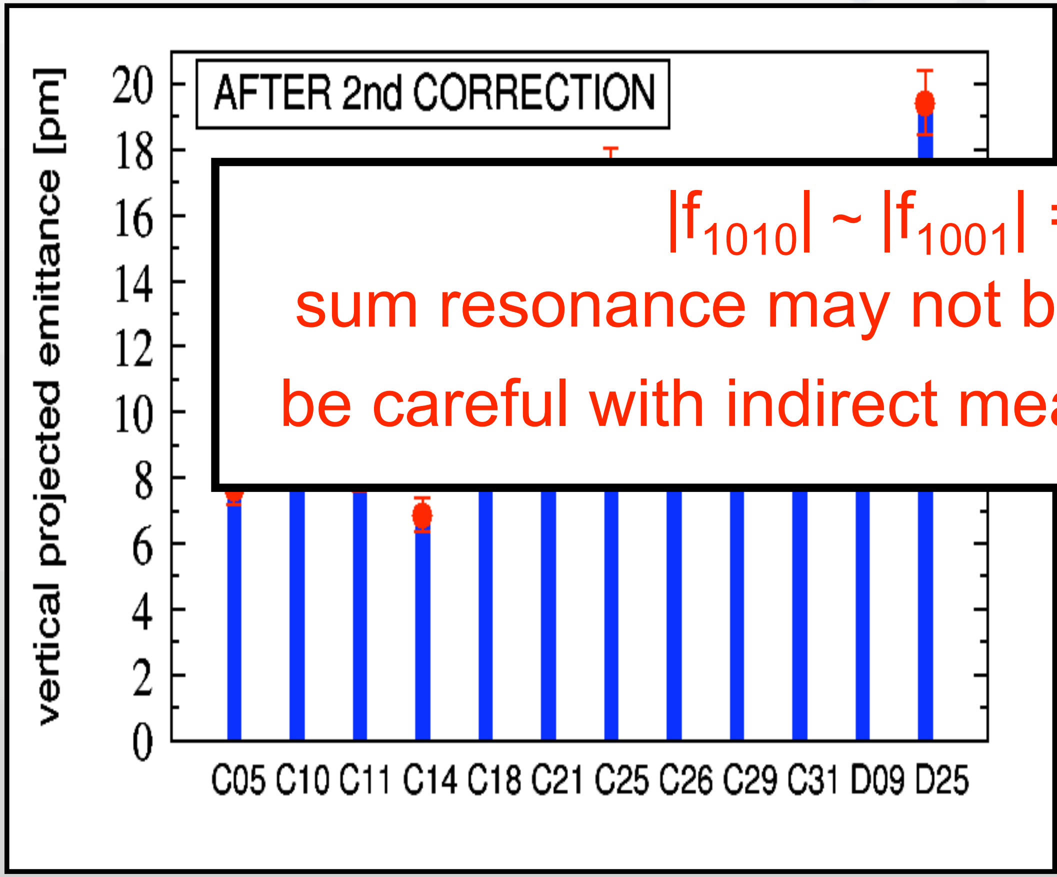
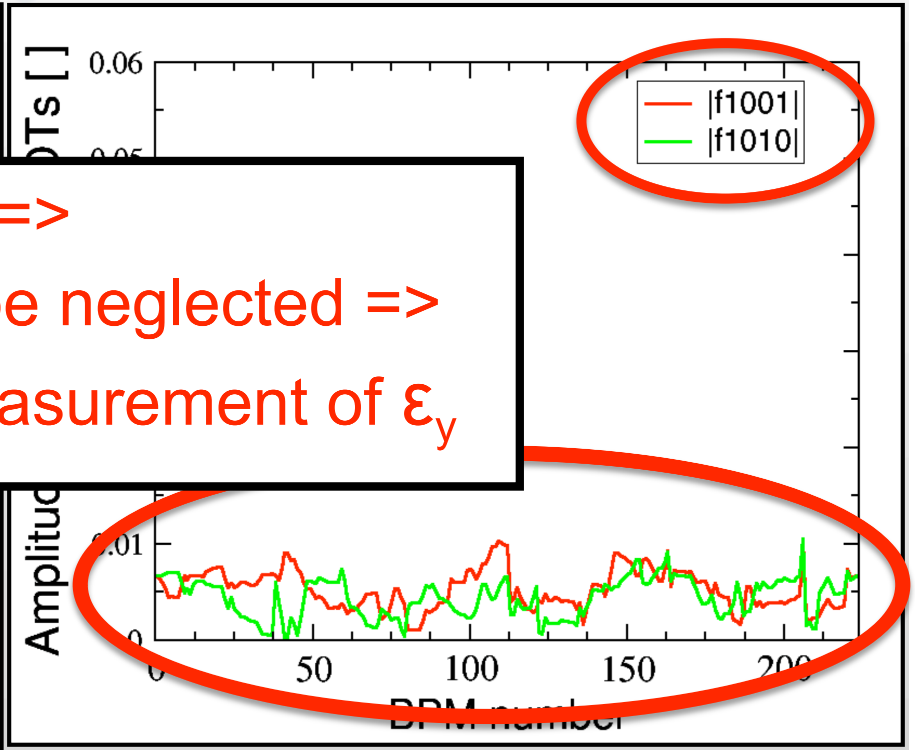




$|f_{1010}| \sim |f_{1001}|$ =>

sum resonance may not be neglected =>

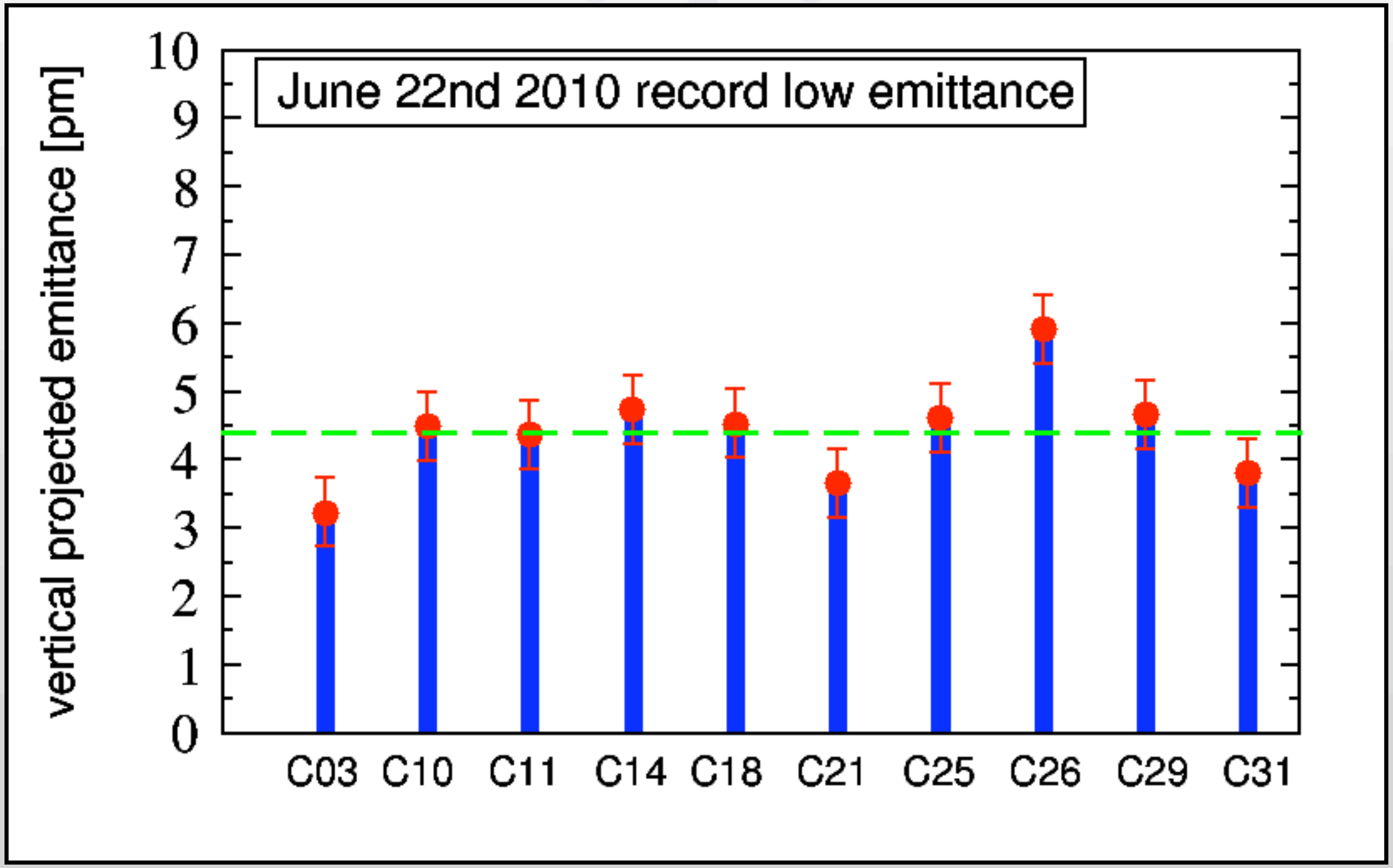
be careful with indirect measurement of ε_y

~20 min. for ORM
a few seconds for RDT correction

2010: Application in the ESRF storage ring

ESRF 2010 **<u>temporary</u>** record-low vertical emittance: June 22nd

At ID gaps open: $\bar{\varepsilon}_y \pm \delta\varepsilon_y = 4.4 \pm 0.7$ pm

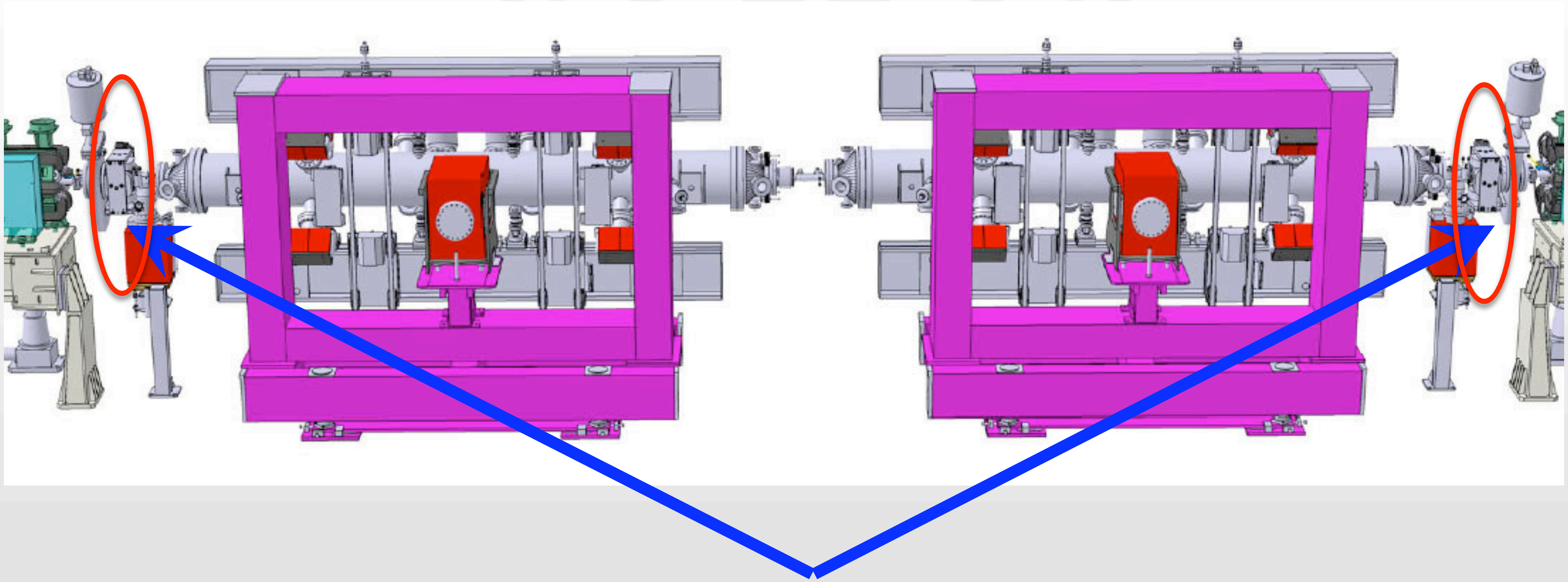


2010: Preserving vertical emittance during beam delivery

- Low coupling may not be preserved during beam delivery because of continuous changes of ID gaps that vary coupling along the ring

Apparent emittance measured at 13 monitors (red) on Jan. 20th 2010, during beam delivery and movements of two ID gaps (black & green)

2010: Preserving vertical emittance during beam delivery



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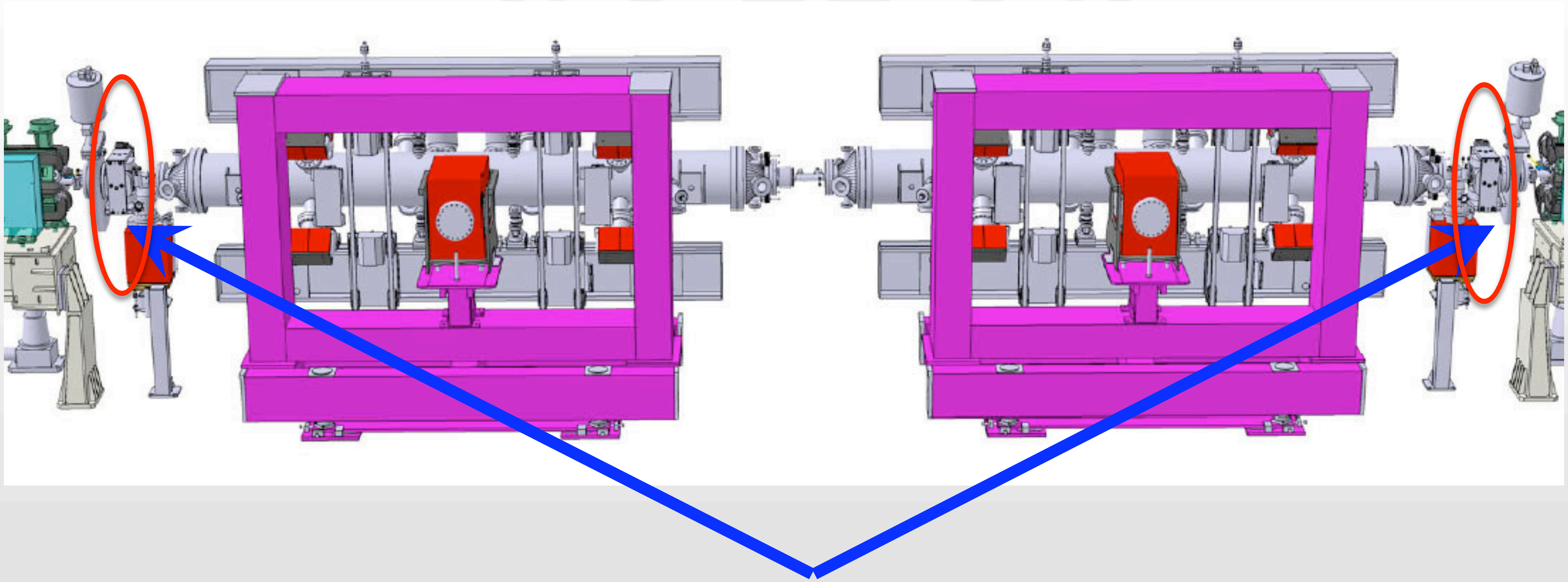

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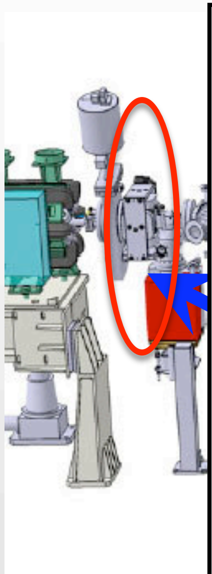

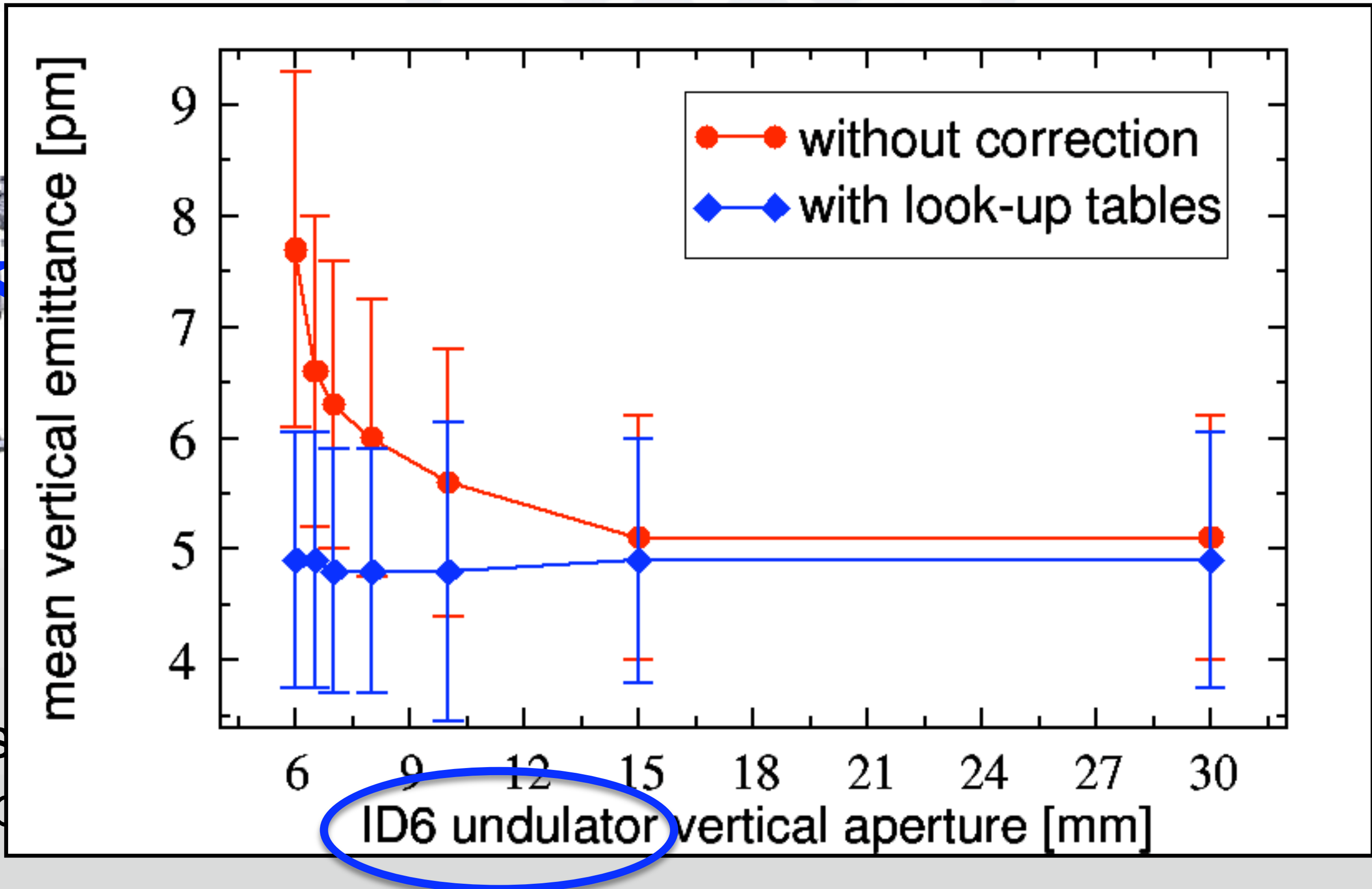

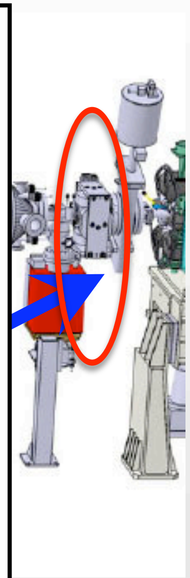

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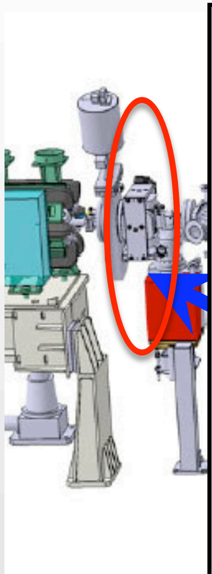
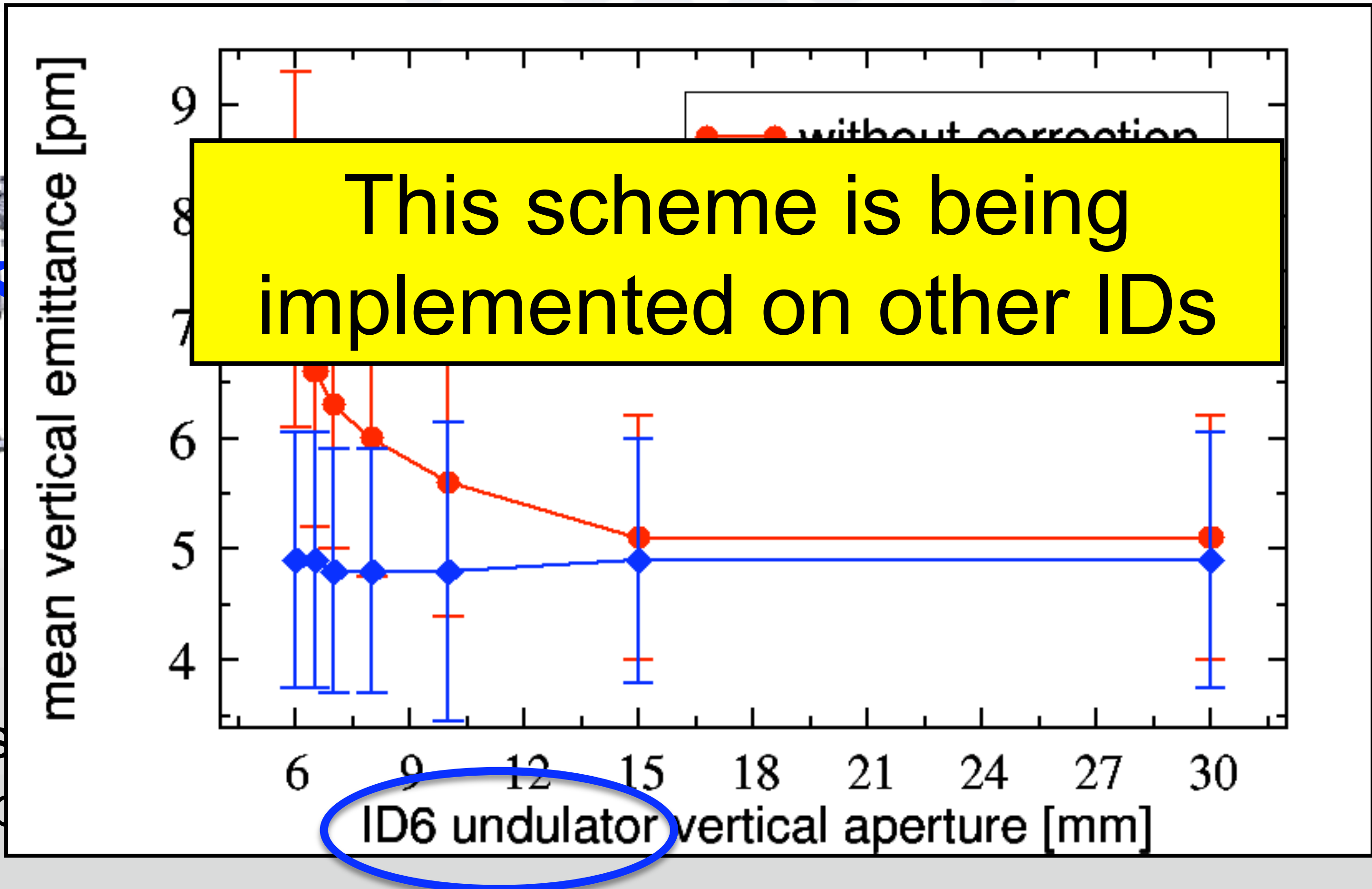
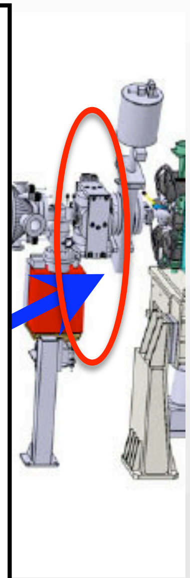




This scheme is being implemented on other IDs



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2010: Preserving vertical emittance during beam delivery

- Coupling may be represented by two complex vectors (for the sum and difference resonances respectively) $C^{\pm}=|A^{\pm}|e^{i\varphi\pm}$.

$$\boxed{C^{-} = -\frac{1}{2\pi}\oint ds\ j(s)\sqrt{\beta_x(s)\beta_y(s)}e^{-i(\phi_x(s)-\phi_y(s))+is/R\Delta}}$$

$$\boxed{C^{+} = -\frac{1}{2\pi}\oint ds\ j(s)\sqrt{\beta_x(s)\beta_y(s)}e^{-i(\phi_x(s)+\phi_y(s))+is/R\Delta}}$$

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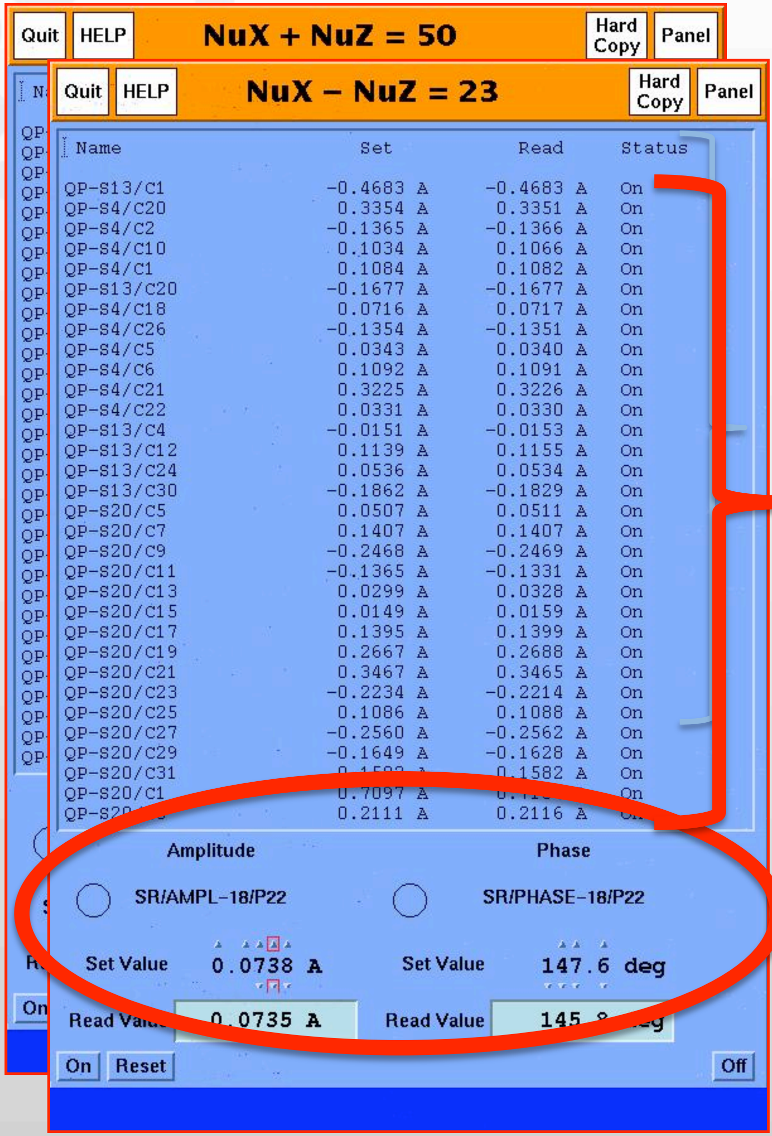
•In the ESRF storage ring, on top of the RDT static correction, $C^{\pm}$ may be dynamically varied in order to catch up coupling variations induced by ID gap movements.



32 corrector skew quads

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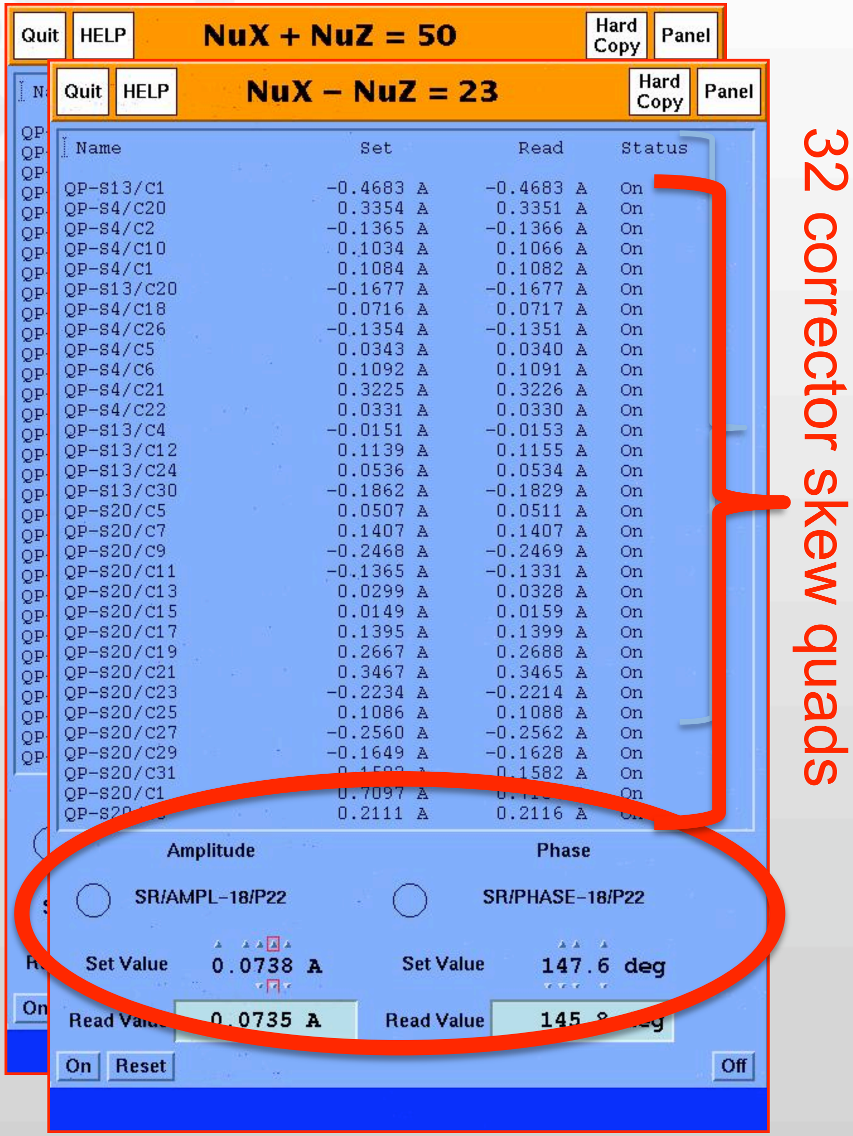
- A new software automatically minimizes $C^{\pm}$ by looking at the average vertical emittance



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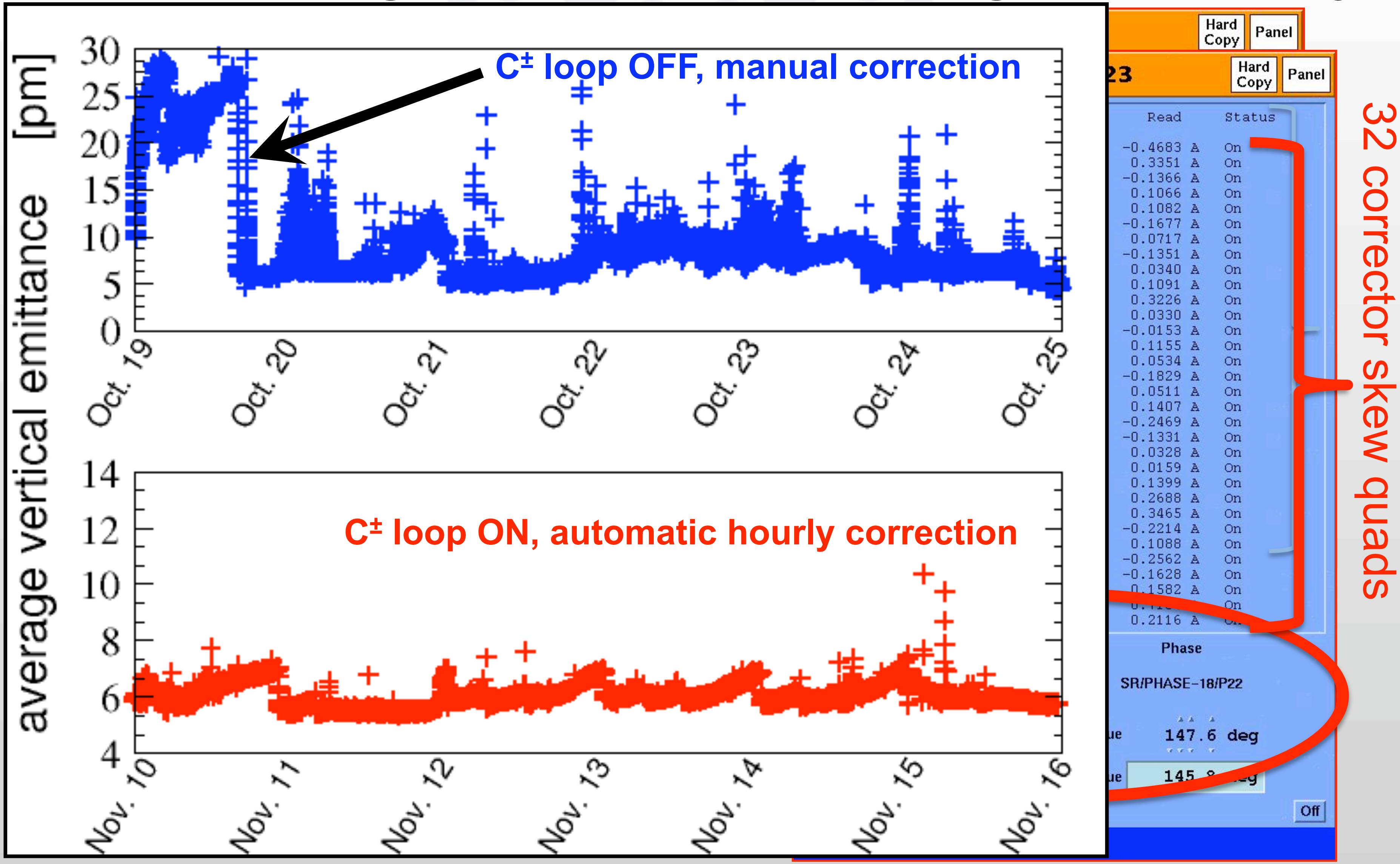

Outlines

- Vertical emittances in the presence of coupling
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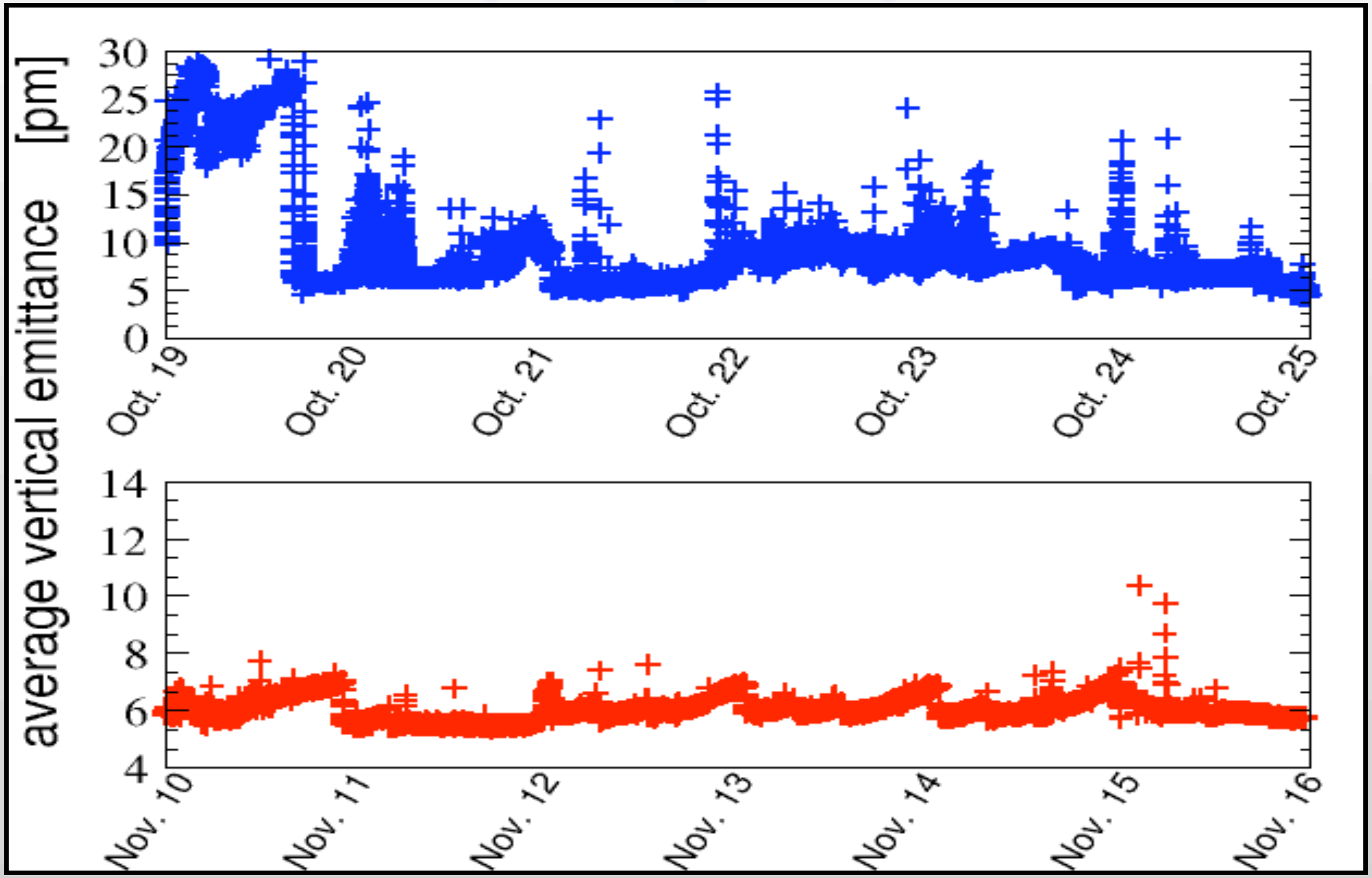
- **Experience in the ESRF storage ring (2011)**
- Benefits and drawbacks; operational considerations

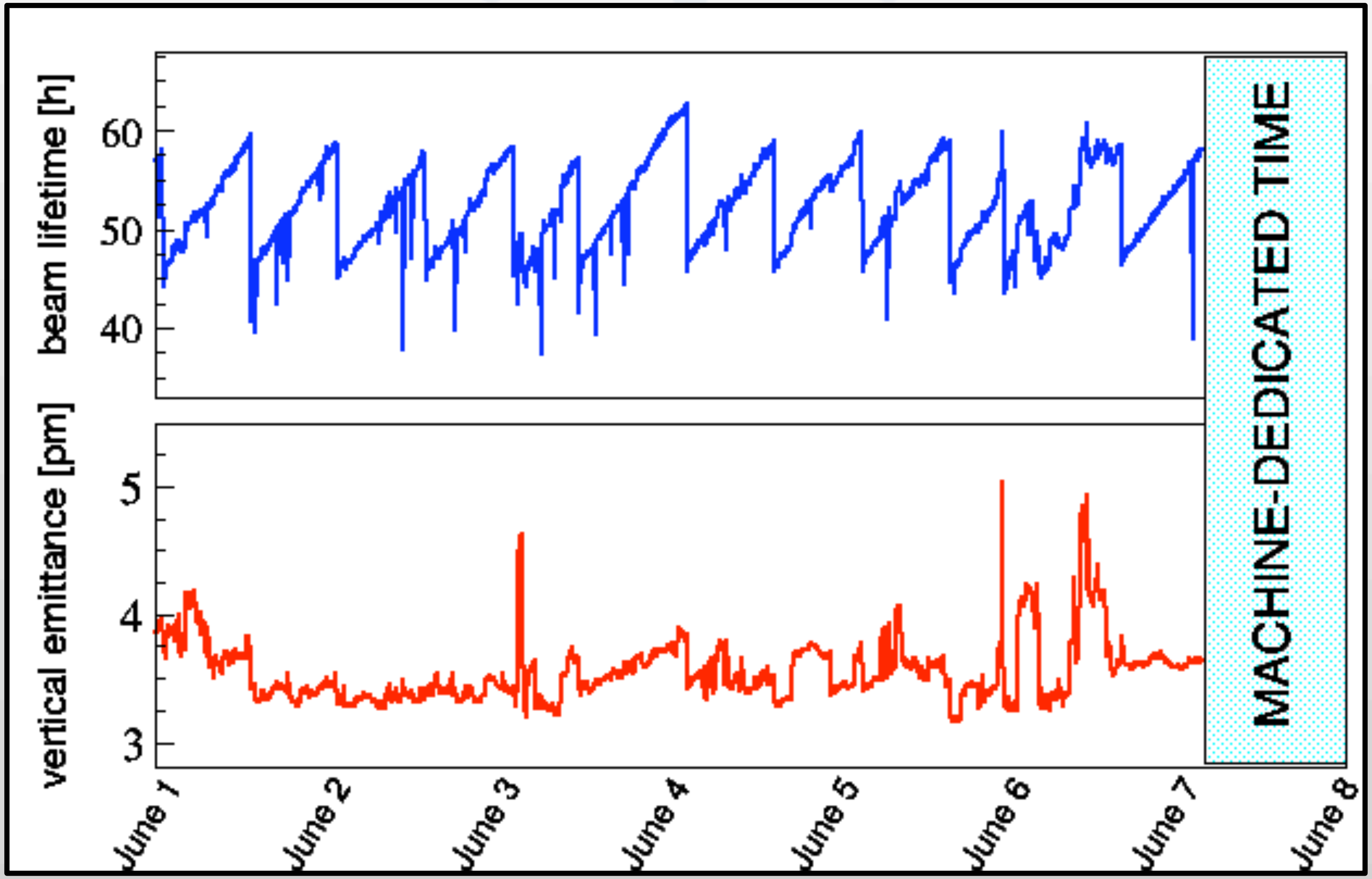
2011: Towards ultra-small vertical emittance

2010, with 32 skew quad correctors



2011: Towards ultra-small vertical emittance

2011, with 64 skew quad correctors



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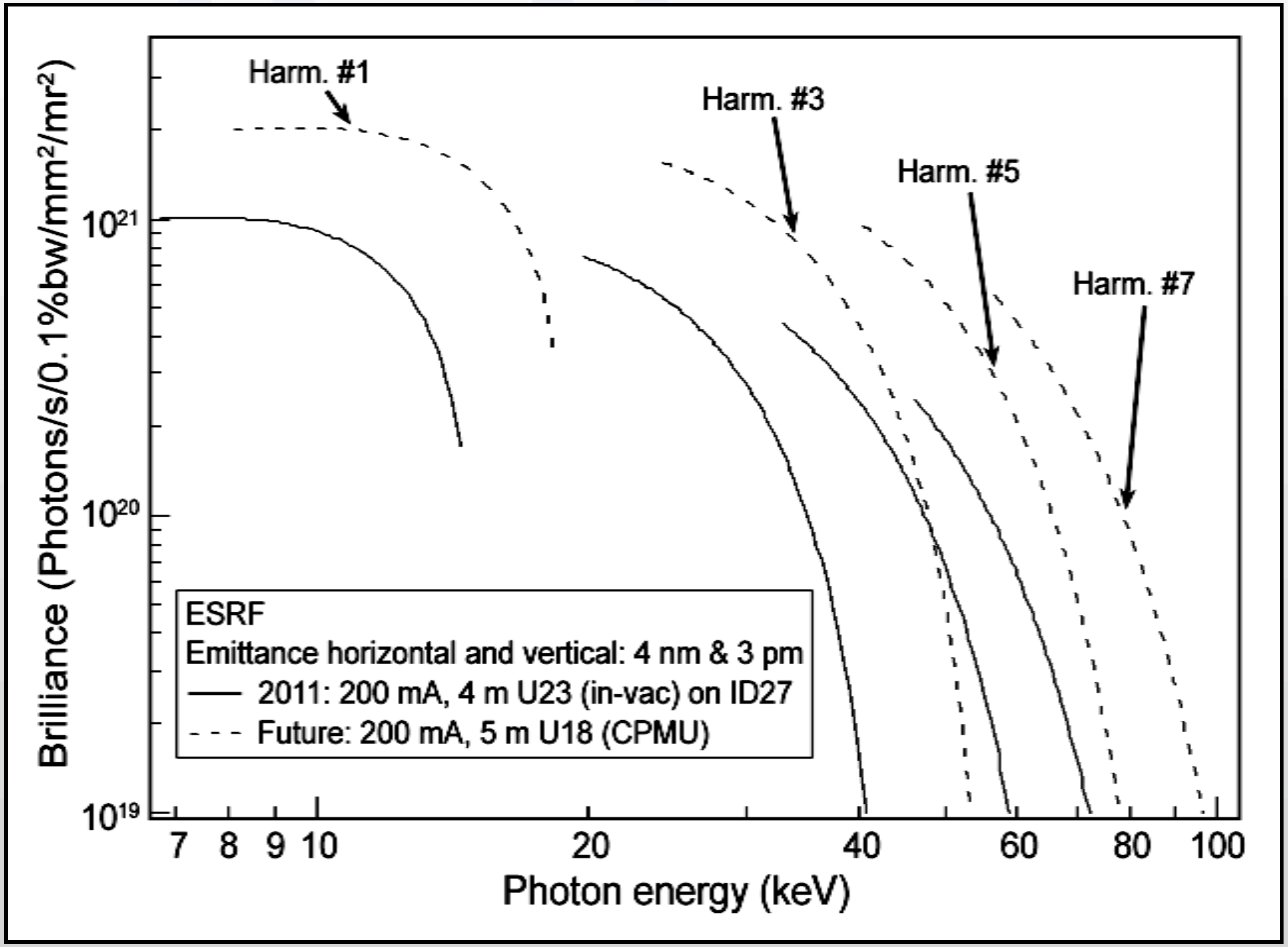
Benefit: Brilliance @ ε_y = 3 pm @200 mA

Solid curve: Brilliance of the X-ray beam emitted from the two in-vacuum undulators installed on ID27 (High Pressure beamline). Each undulator segment has a period of 23 mm, a length of 2 m and is operated with a minimum gap of 6 mm.



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Filling mode	**inj. eff. until 2009 operation**	**inj. eff. as of 2010 operation**	**inj. eff. as of 2010 open IDs & scrapers**
16 bunches (92mA)	30-50%	50-70% (*)	~100% (*)
7/8 +1 (200mA)	50-70%	70-90% (^)	~100% (^)

(*) with new optics (^) with lower chromaticity

Drawback: reduced lifetime (7/8 +1 filling mode, @ 200 mA)

- LT in 2009 (@ ε_y = 30 pm) : 55-60 h

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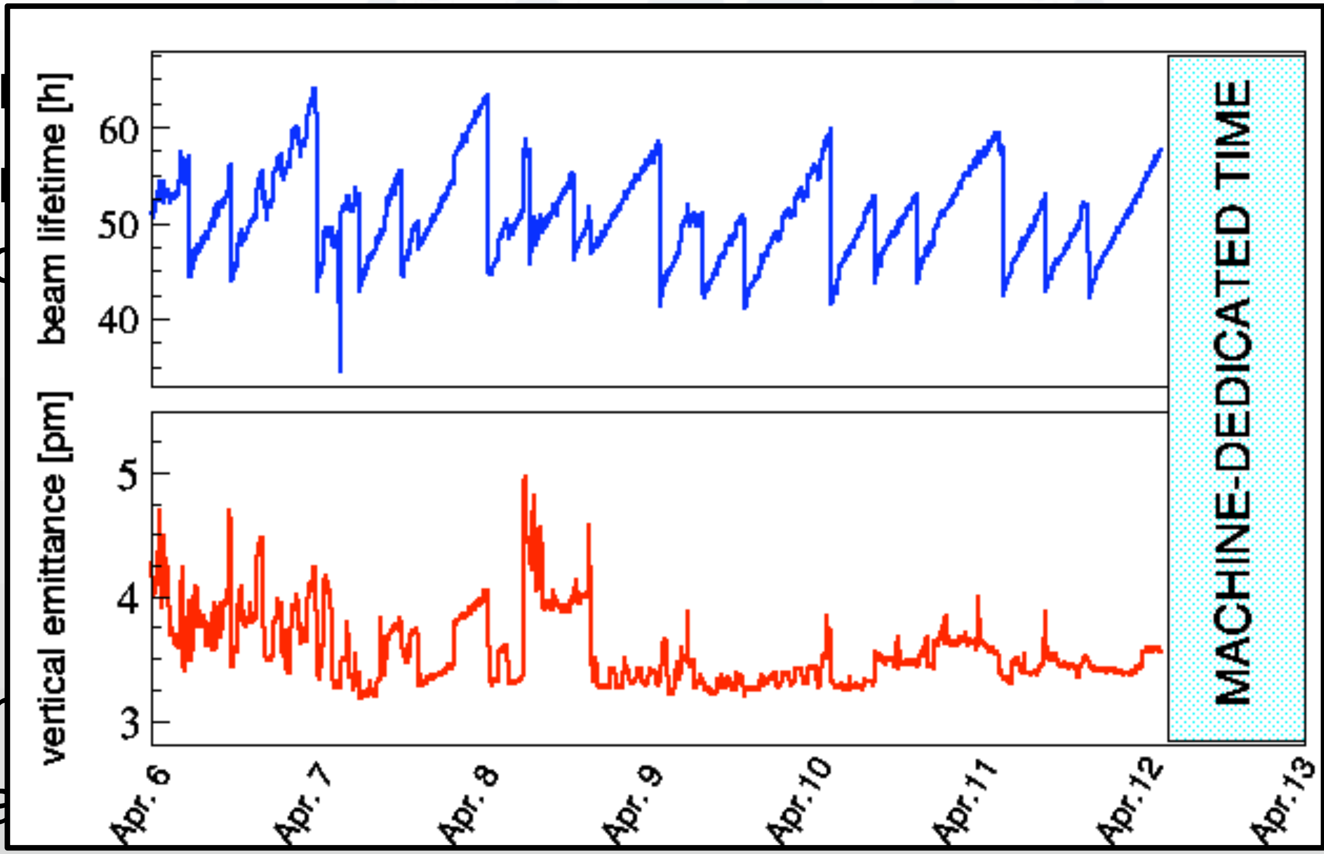

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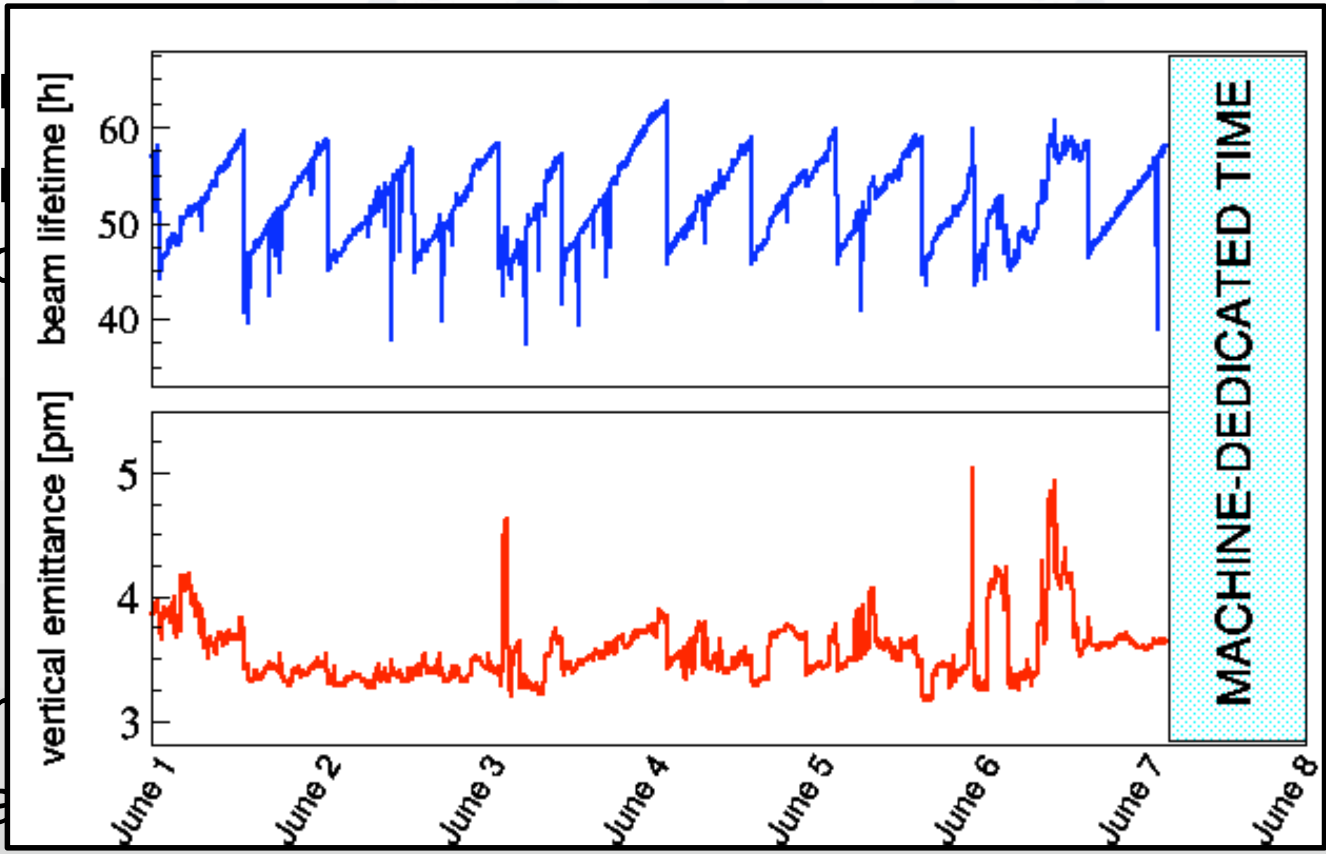

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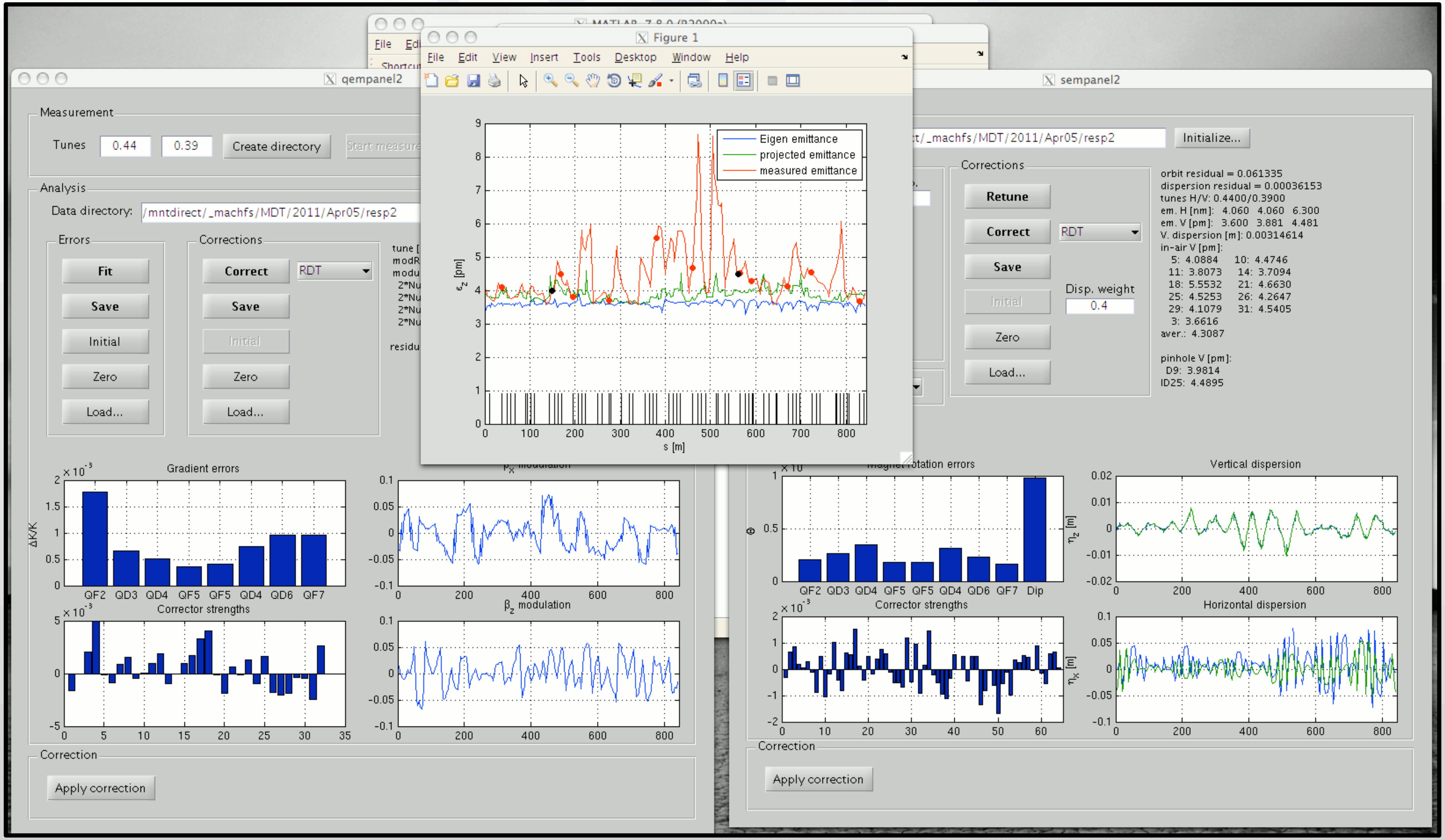

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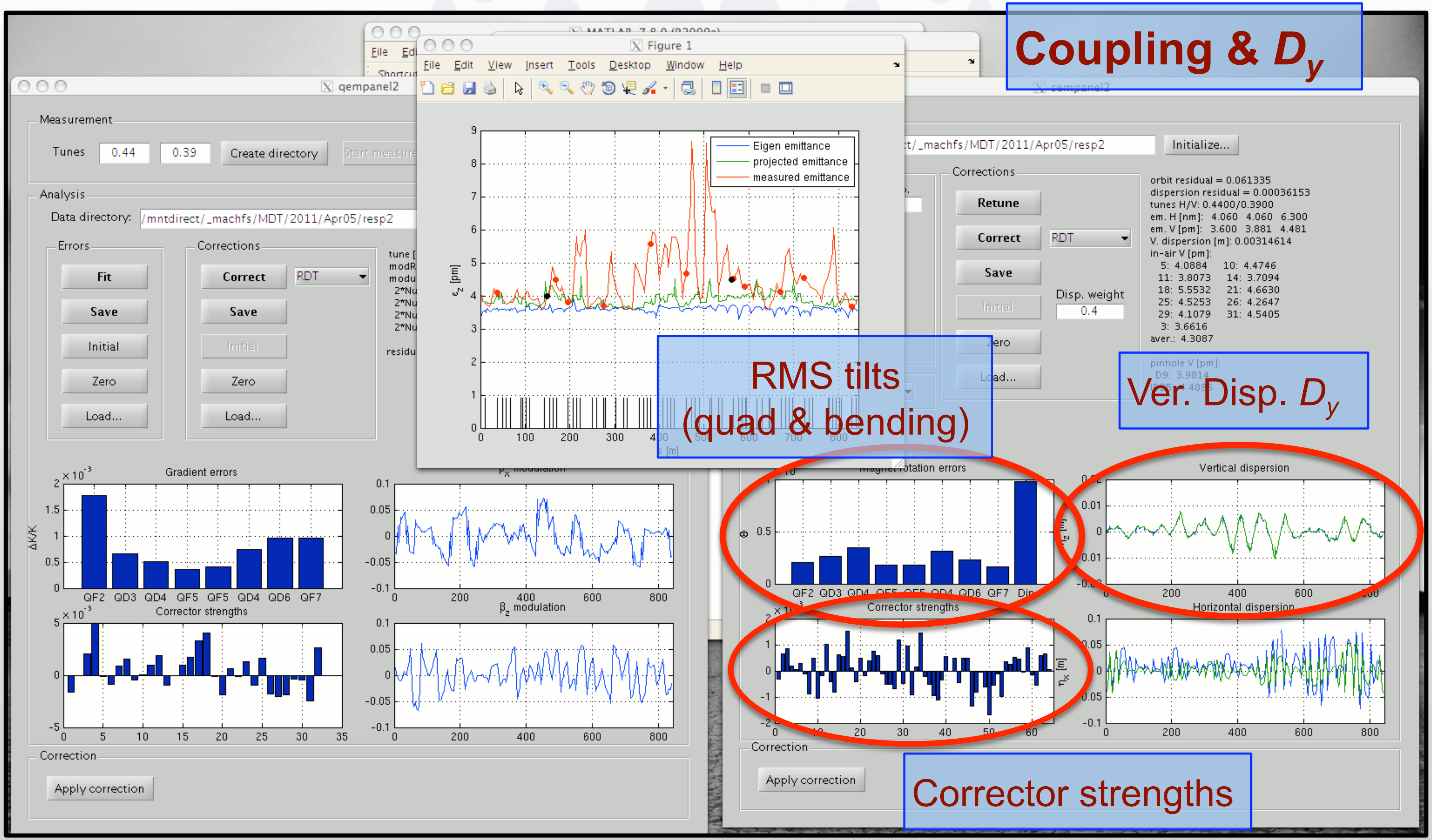

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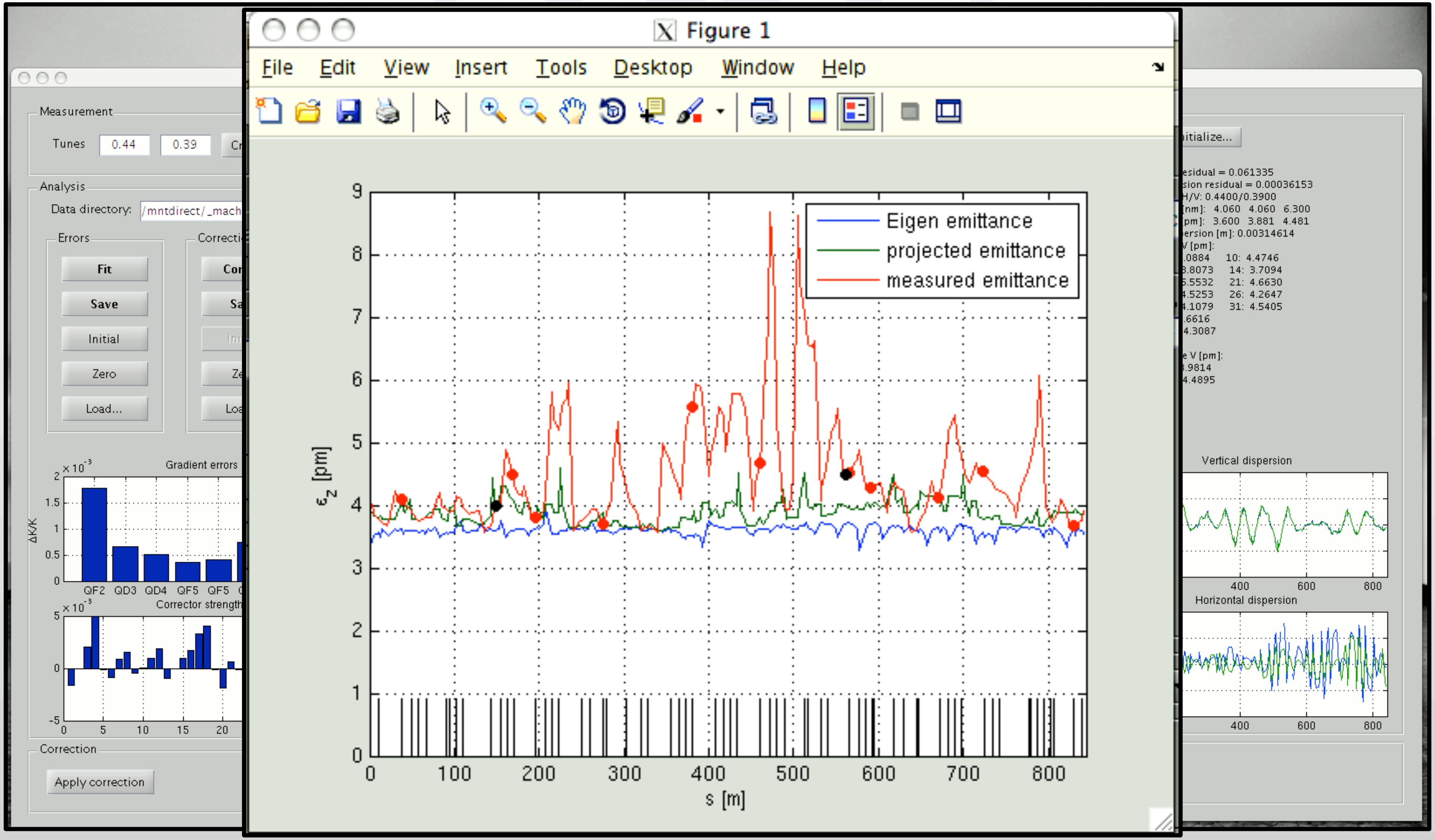

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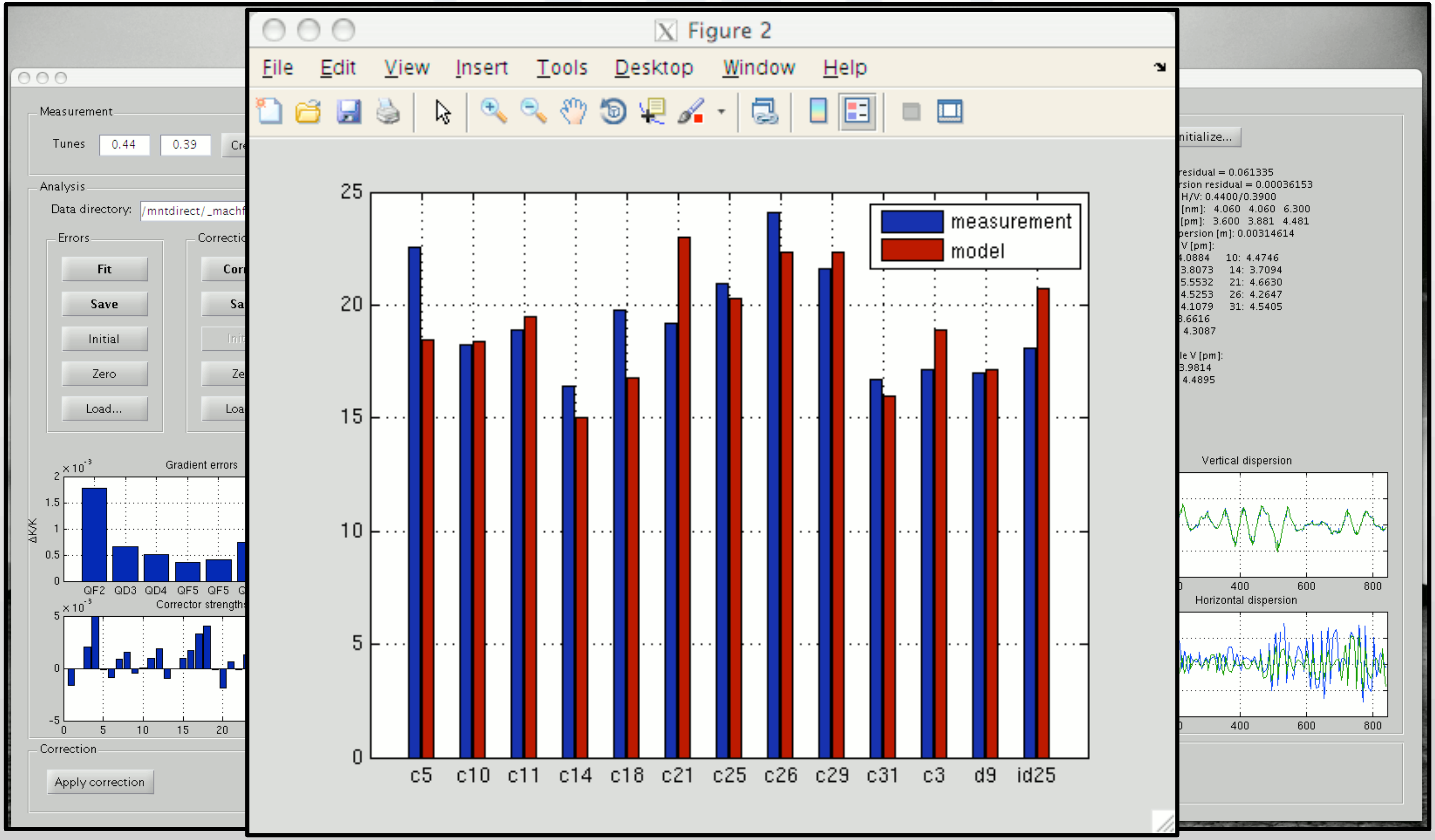

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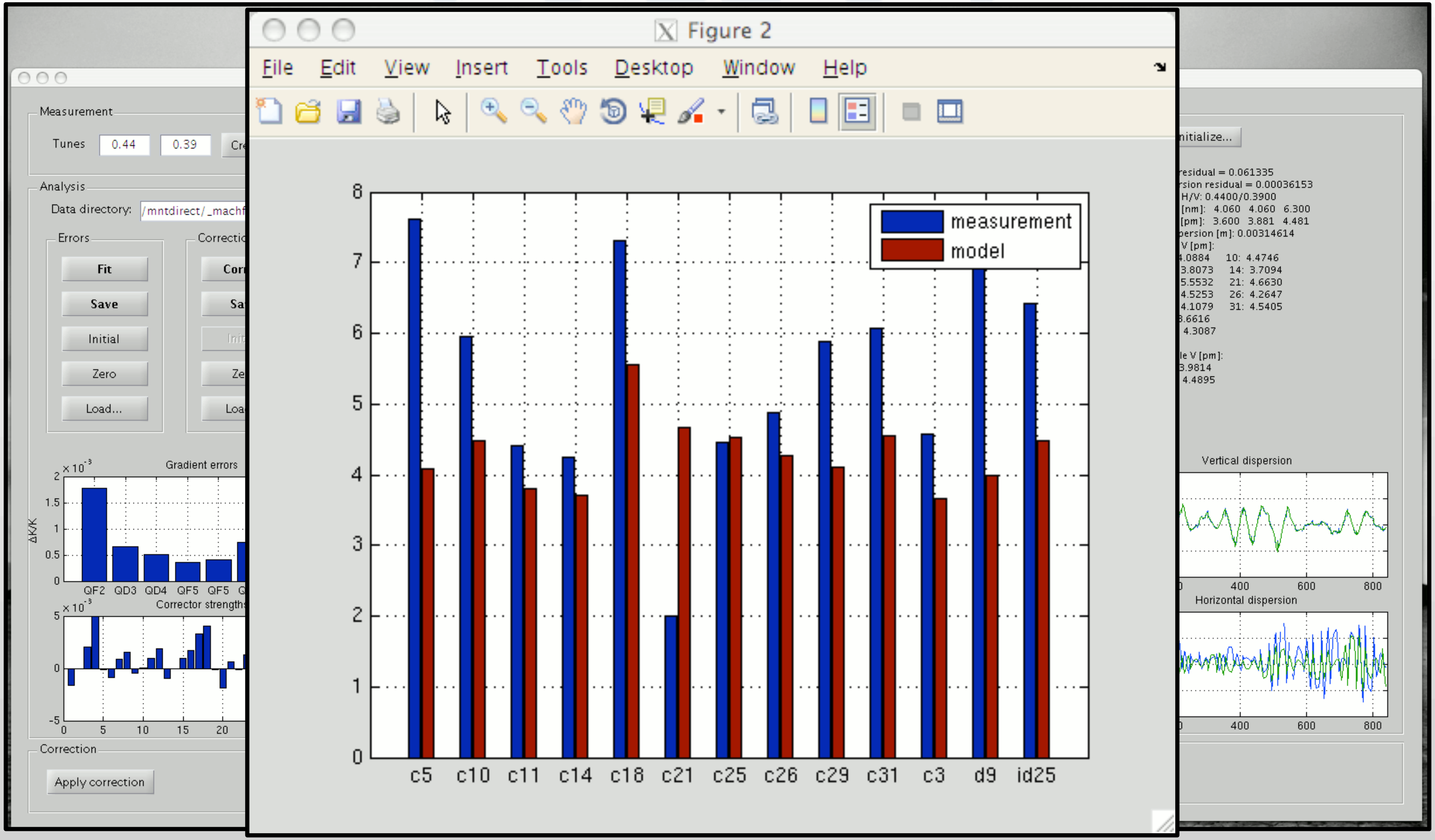

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- Looking into the future: under study the possibility of using the new AC orbit correction system to perform fast ORM measurements on all steerers in parallel (at different frequencies, ORM retrieved from harmonic analysis)

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- Applications in the ESRF storage ring led to vertical emittance of ε_y = 2.8 ± 1.1 pm, a record low for this machine (ε_x=4.2 nm => $\varepsilon_y/\varepsilon_x \approx$ 0.06%, a factor 10 lower than in the past).

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- Applications in the ESRF storage ring led to vertical emittance of ε_y = 2.8 ± 1.1 pm, a record low for this machine (ε_x=4.2 nm => $\varepsilon_y/\varepsilon_x \approx$ 0.06%, a factor 10 lower than in the past).
- Two procedures to preserve small vertical emittance during beam delivery were successfully tested: as of spring 2011 stable ε_y = 3.2-4.5 pm delivered to users (lifetime of 45 hours after refilling @ 200 mA, 10 hours less than in the past only).