Vertical emittance reduction via coupling resonance driving terms correction: theory and experimental results at the ESRF

J. Chavanne, F. Ewald, L. Farvacque, A. Franchi, B. Nash, T. Perron, K. Scheidt

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Outlines

- Vertical emittances in presence of coupling
- Coupling correction via Resonance Driving Terms
- Application to the ESRF storage ring
- Preserving small vertical emittance during beam delivery
- Towards ultra-small vertical emittance

Vertical emittance in absence of coupling

Eigen-emittance:

$$\mathcal{E}_u = \frac{1}{2}\frac{\oint\{\mathcal{H}_x^2(s)\mathrm{d}(s)\}ds}{\oint\{\mathrm{b}_{RF}(s) - D_x(s)\mathrm{b}_{\delta x}(s)\}ds}$$

$$\mathcal{E}_v = \frac{1}{2}\frac{\oint\{\mathcal{H}_y^2(s)\mathrm{d}(s)\}ds}{\oint\{\mathrm{b}_{RF}(s) - D_y(s)\mathrm{b}_{\delta y}(s)\}ds}$$

RMS emittance:

$$\epsilon_r = \sqrt{\sigma_r(s)\sigma_p(s) - \sigma_{rp}^2(s)}$$

Measurable emittance:

$$\mathbb{E}_r = \frac{\sigma_r^2(s)}{\beta_r(s)} = \frac{< r^2(s) > -(\delta D_r(s))^2}{\beta_r(s)}$$

The three definitions are equivalent and

Ey=$\mathcal{E}v$=ℇy=const. If vert. disp. Dy=0, Ey=$\mathcal{E}v$=ℇy≅0

Vertical emittances in presence of coupling

Constant eigen-emittance [See B. Nash *et al*. PRSTAB 9, 032801, 2006]:

$$\mathscr{E}_v = \frac{1}{2}\frac{\oint \mathrm{d}(s)\left\{\mathcal{C}^2\mathcal{H}_y^2(s) + \left[\mathcal{S}_-^2 + \mathcal{S}_+^2\right]\mathcal{H}_x^2(s)\right\}\ ds}{\oint \left\{\mathrm{b}_{RF}(s) - \mathcal{C}^2 D_y(s)\mathrm{b}_{\delta y}(s) - \left[\mathcal{S}_-^2 - \mathcal{S}_+^2\right] D_x(s)\mathrm{b}_{\delta x}(s)\right\} ds}$$

RMS projected ***s*-dependent** emittance:

$$\epsilon_y = \sqrt{\sigma_y\,\sigma_p - \sigma_{yp}^2} = \sqrt{\left(\mathcal{C}^2\mathscr{E}_v + \left[\mathcal{S}_-^2 + \mathcal{S}_+^2\right]\mathscr{E}_u\right)^2 - \left(2\mathcal{S}_+\mathcal{S}_-\mathscr{E}_u\right)^2}$$

Measurable apparent ***s*-dependent** emittance:

$$\mathbb{E}_y = \frac{\sigma_y^2}{\beta_y} = \mathcal{C}^2\mathscr{E}_v + \left[\mathcal{S}_-^2 + \mathcal{S}_+^2 - 2\mathcal{S}_-\mathcal{S}_+\cos\left(q_+ - q_-\right)\right]\mathscr{E}_u$$

In absence of coupling C=1, $S_-=S_+=0$ and $E_y=\mathcal{E}_v=\varepsilon_y$=const

Vertical emittances in presence of coupling

- Coupling sources (tilted quads, misaligned sextupoles, ID error fields, etc.) generate skew quad fields $\boldsymbol{J_1}$(s)

- $\boldsymbol{J_1}$(s) generate two *Resonance Driving Terms* (RDTs) f(s)

$$f_a = M_{ab}(\beta,\varphi)\, \boldsymbol{J_{b,1}}$$

<u>Linear dependence</u>!!

$$\mathcal{C} = \cosh\left(2\mathcal{P}\right) ,$$

$$\mathcal{S}_- = \frac{\sinh\left(2\mathcal{P}\right)}{\mathcal{P}} |f_{1001}| ,$$

$$\mathcal{S}_+ = \frac{\sinh\left(2\mathcal{P}\right)}{\mathcal{P}} |f_{1010}| ,$$

$$\mathcal{P} = \sqrt{-|f_{1001}|^2 + |f_{1010}|^2} ,$$

$$f_{\substack{1001\\1010}} = \frac{\sum_w^W J_{w,1}\sqrt{\beta_x^w \beta_y^w}\, e^{i(\Delta\phi_{w,x} \mp \Delta\phi_{w,y})}}{4(1 - e^{2\pi i(Q_u \mp Q_v)})}$$

$$q_- = \arg\{f_{1001}\} , \qquad q_+ = \arg\{f_{1010}\}$$

Vertical emittances in presence of coupling

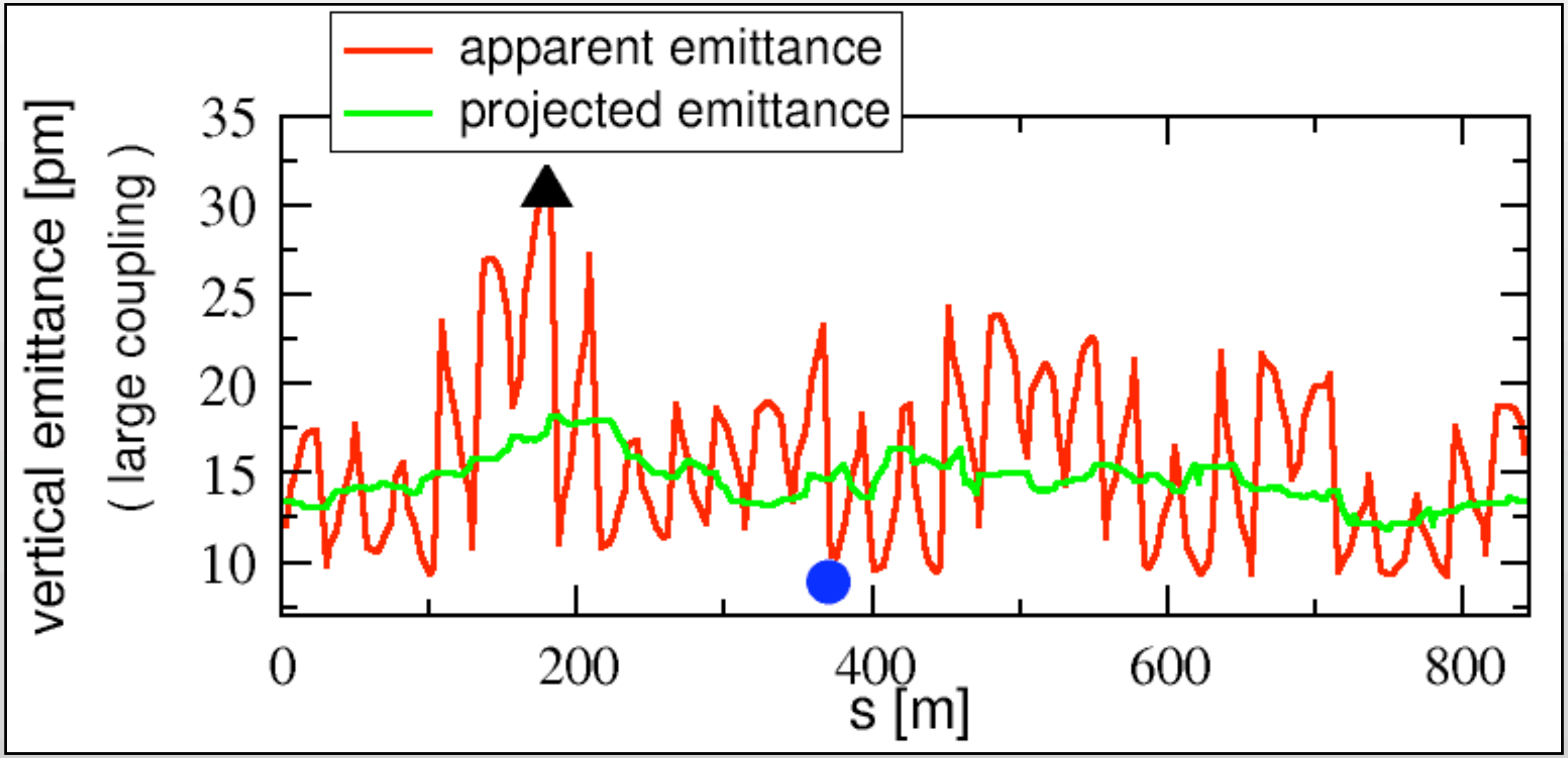
Apparent emittance:

$$\mathbb{E}_y = \mathcal{C}^2 \mathscr{E}_v + \left[\mathcal{S}_-^2 + \mathcal{S}_+^2 - 2\mathcal{S}_-\mathcal{S}_+ \cos\left(q_+ - q_-\right)\right] \mathscr{E}_u$$

Projected emittance:

$$\epsilon_y = \sqrt{\left(\mathcal{C}^2 \mathscr{E}_v + \left[\mathcal{S}_-^2 + \mathcal{S}_+^2\right] \mathscr{E}_u\right)^2 - \left(2\mathcal{S}_+\mathcal{S}_-\mathscr{E}_u\right)^2}$$

$\mathcal{E}_v = 9$ pm



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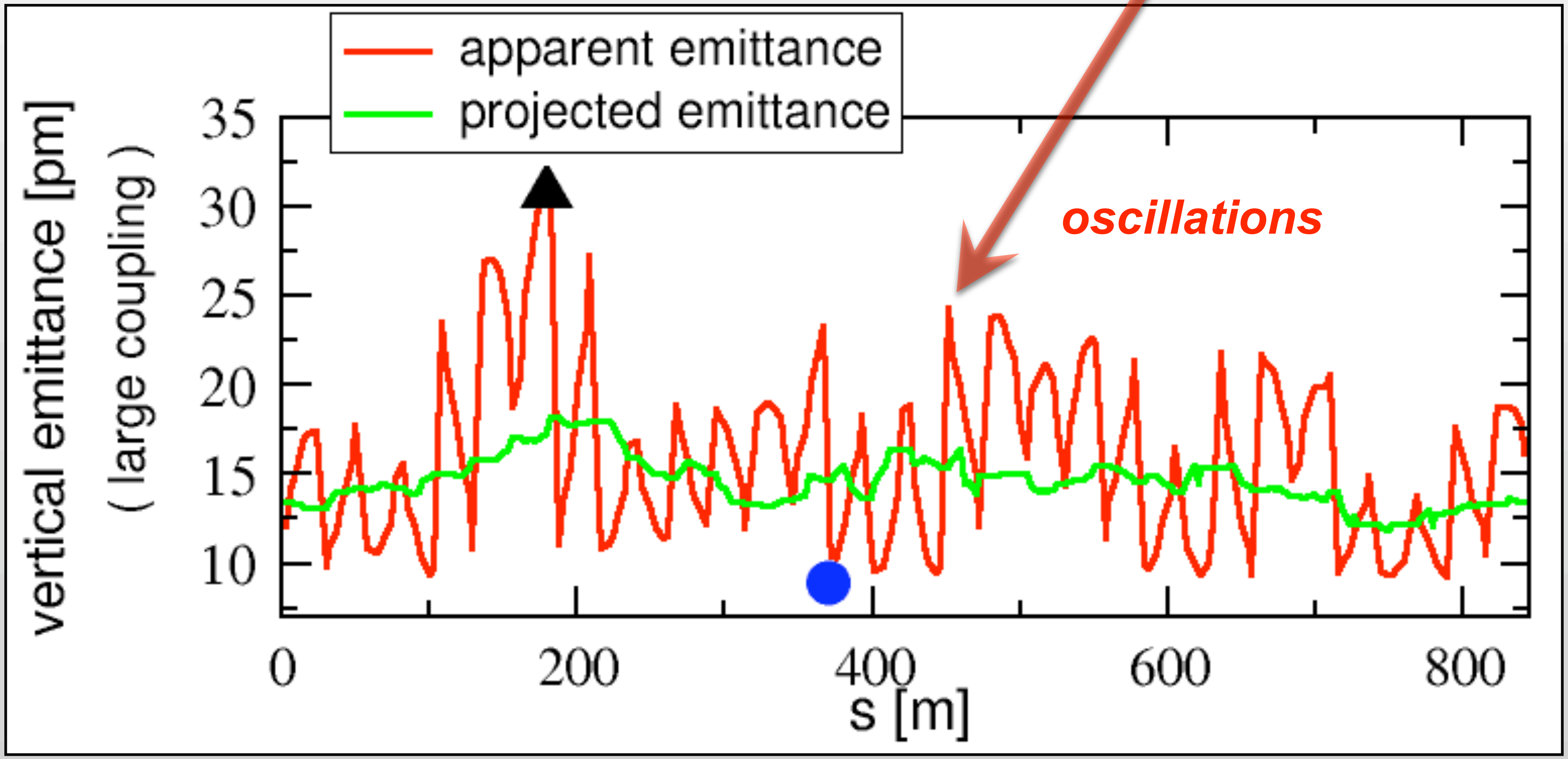

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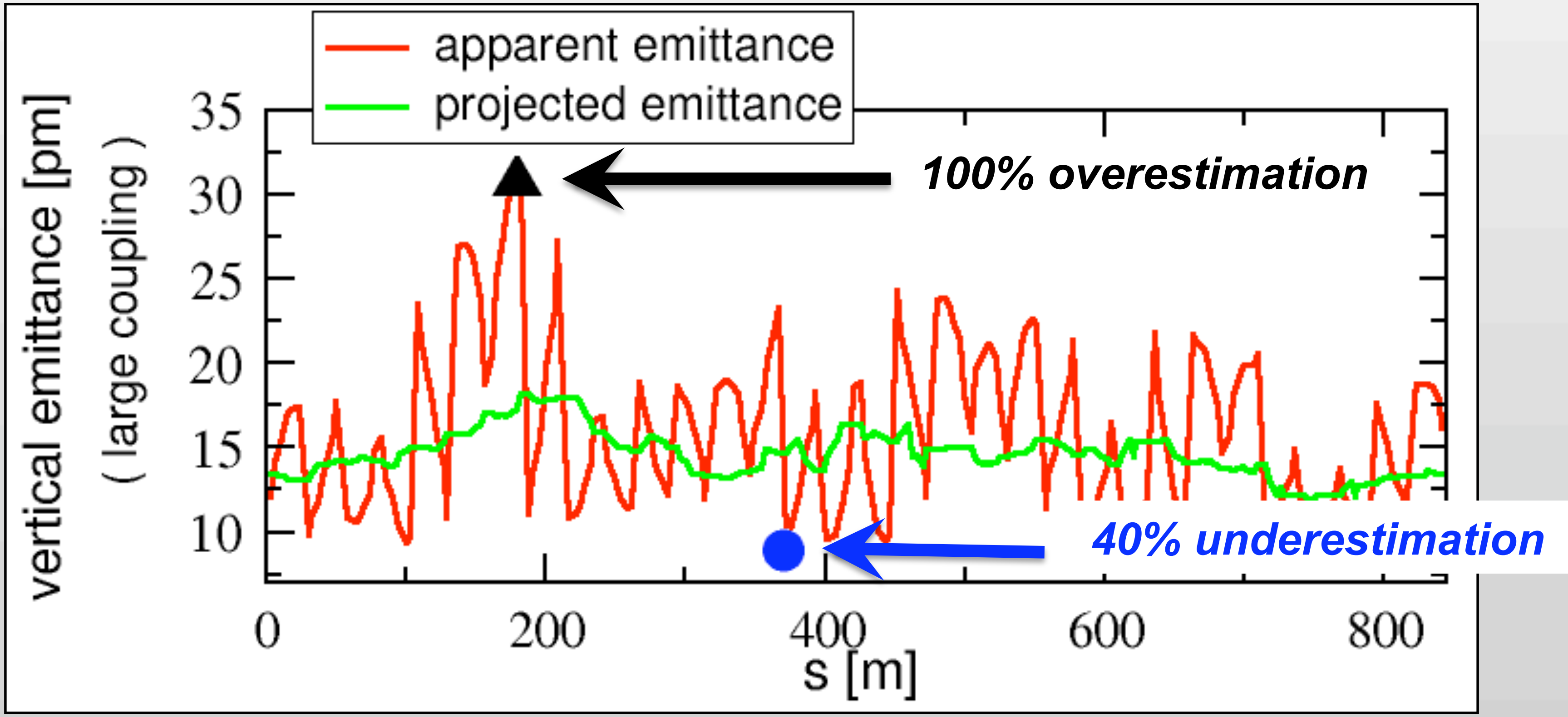

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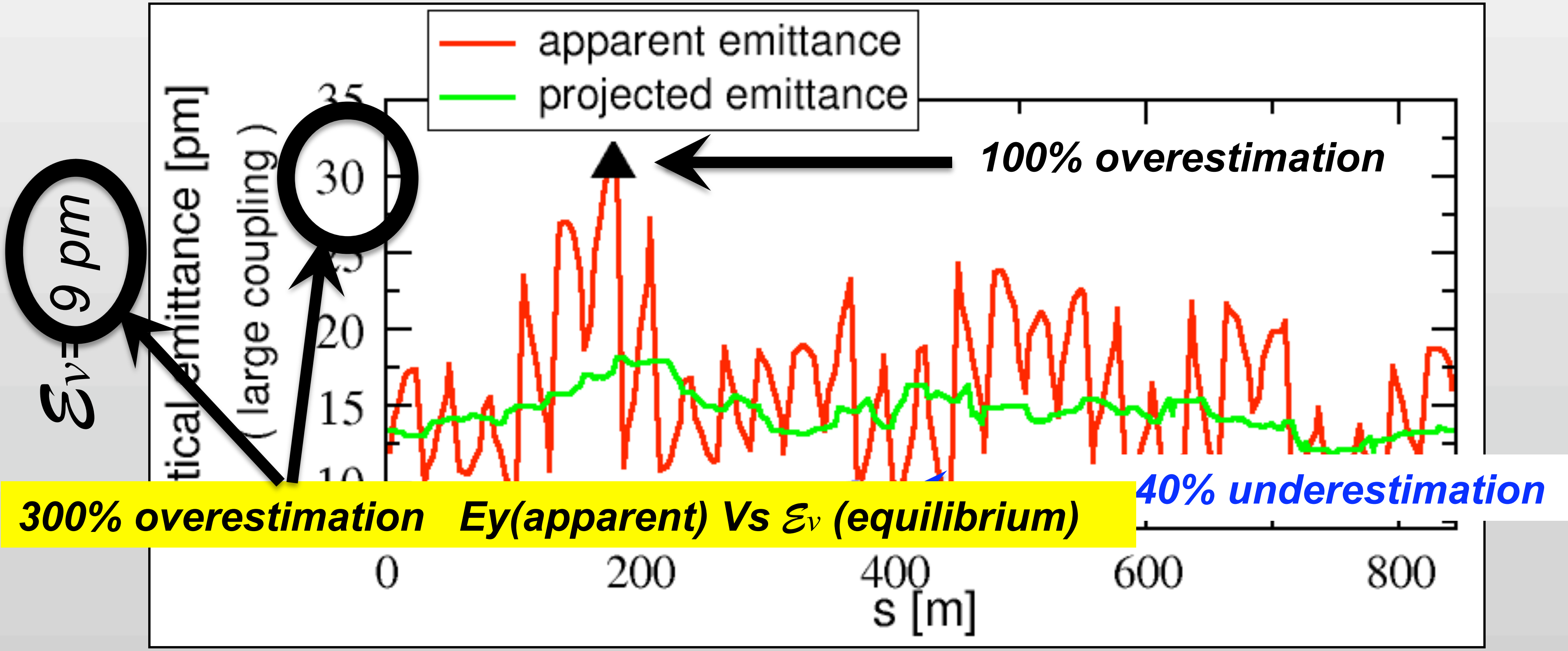

Vertical emittances in presence of coupling

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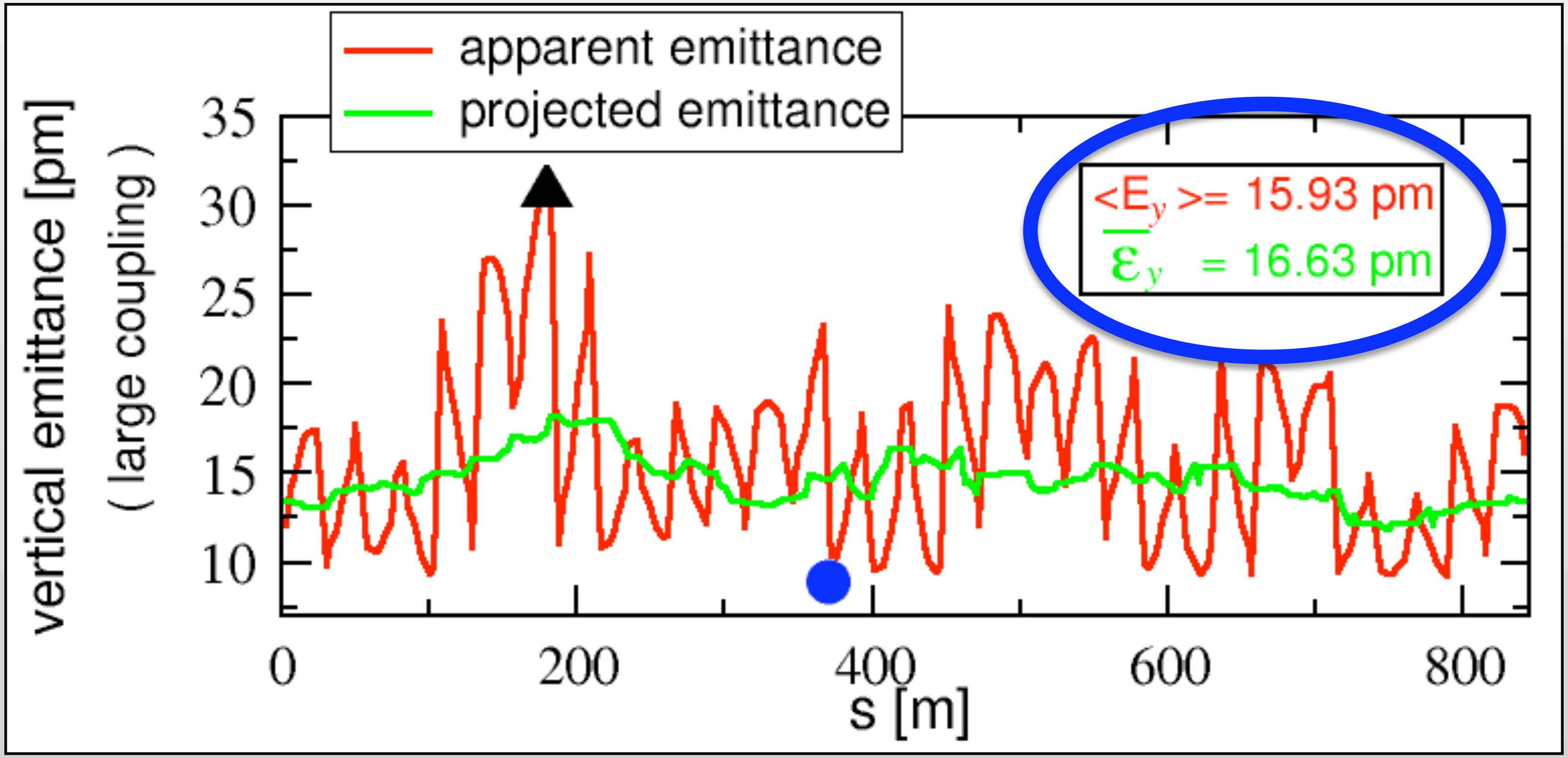
Average over the ring

Projected emittance: $\langle \epsilon_y \rangle = \sqrt{\left(\mathcal{C}^2 \mathscr{E}_v + \left[\mathcal{S}_-^2 + \mathcal{S}_+^2\right] \mathscr{E}_u\right)^2 - \left(2\mathcal{S}_+\mathcal{S}_-\mathscr{E}_u\right)^2}$

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



Coupling correction via Resonance Driving Terms

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

- Vertical dispersion Dy is linear in the skew quad strengths J_1 : once measured may be corrected via SVD of its response matrix
- Coupling RDTs are linear in J_1 too, and a response matrix may be easily defined and used for correction (fast, direct, no iteration needed)

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

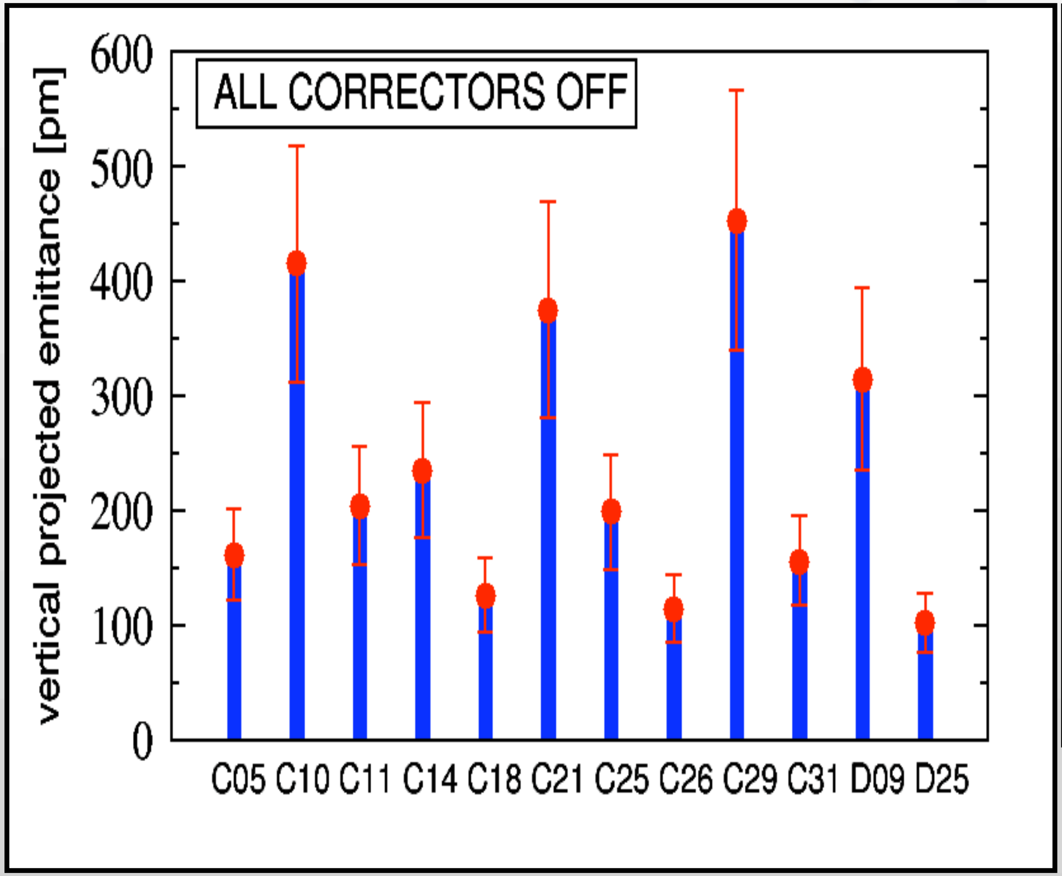
1. Define an error lattice model (quad tilts, etc. from ORM or TbT BPM data) => RDTs and Dy $\vec{F}$
2. Evaluate response matrix of the available skew correctors **M**
3. Find via SVD a corrector setting $\vec{J}$ that minimizes both RDTs and Dy

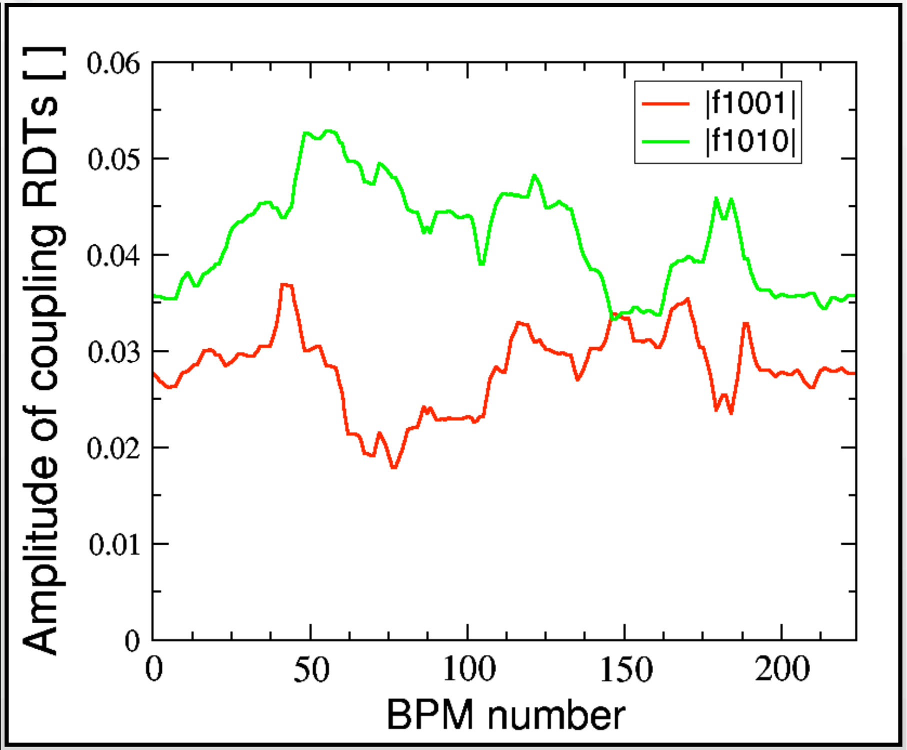
$$\vec{J} = -M \vec{F}$$ **to be pseudo-inverted**

Application to 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

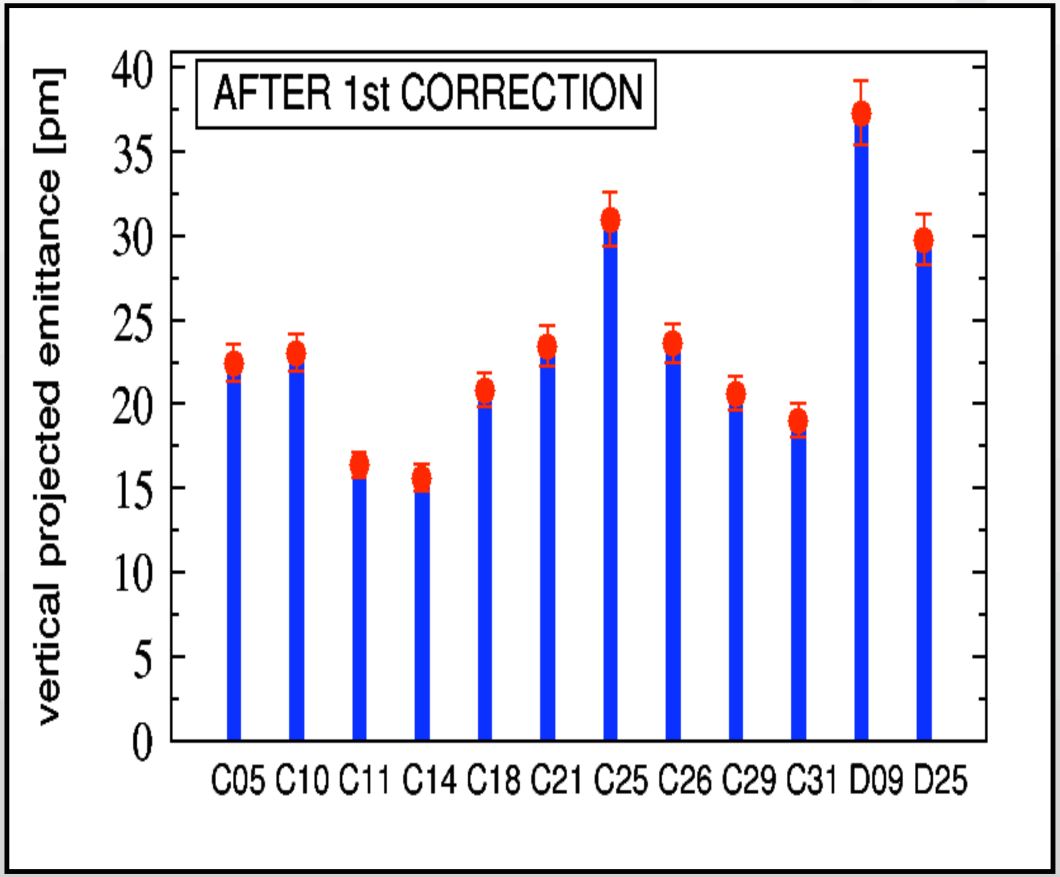


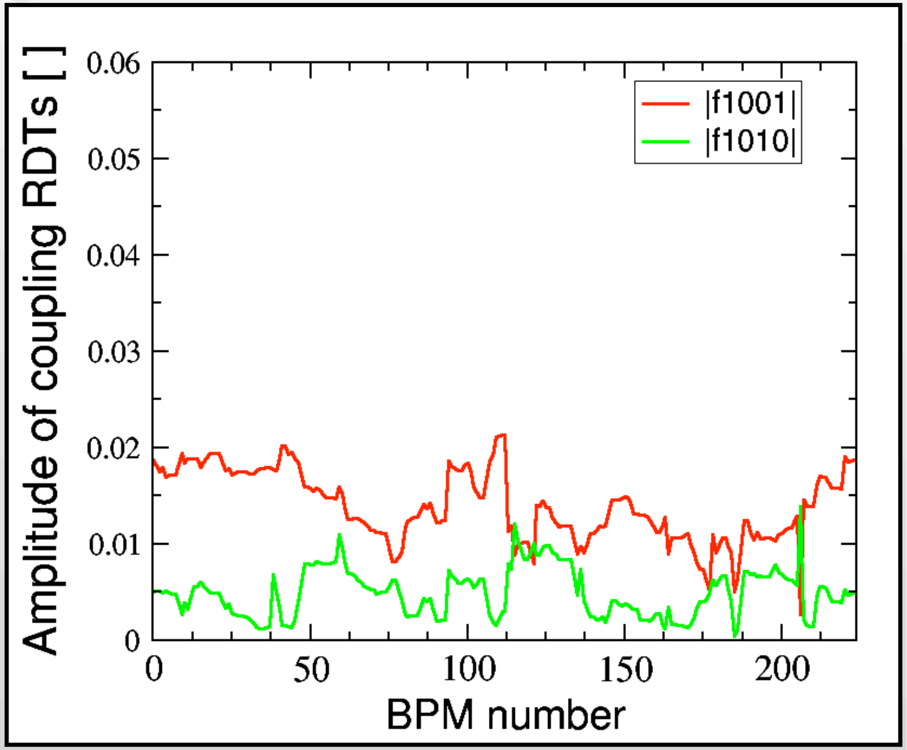


Application to the ESRF storage ring

First RDT correction: January 16th 2010

1st ORM measur. and RDT correction: $\bar{\varepsilon}_y \pm \delta\varepsilon_y = 23.6 \pm 6.3$ pm



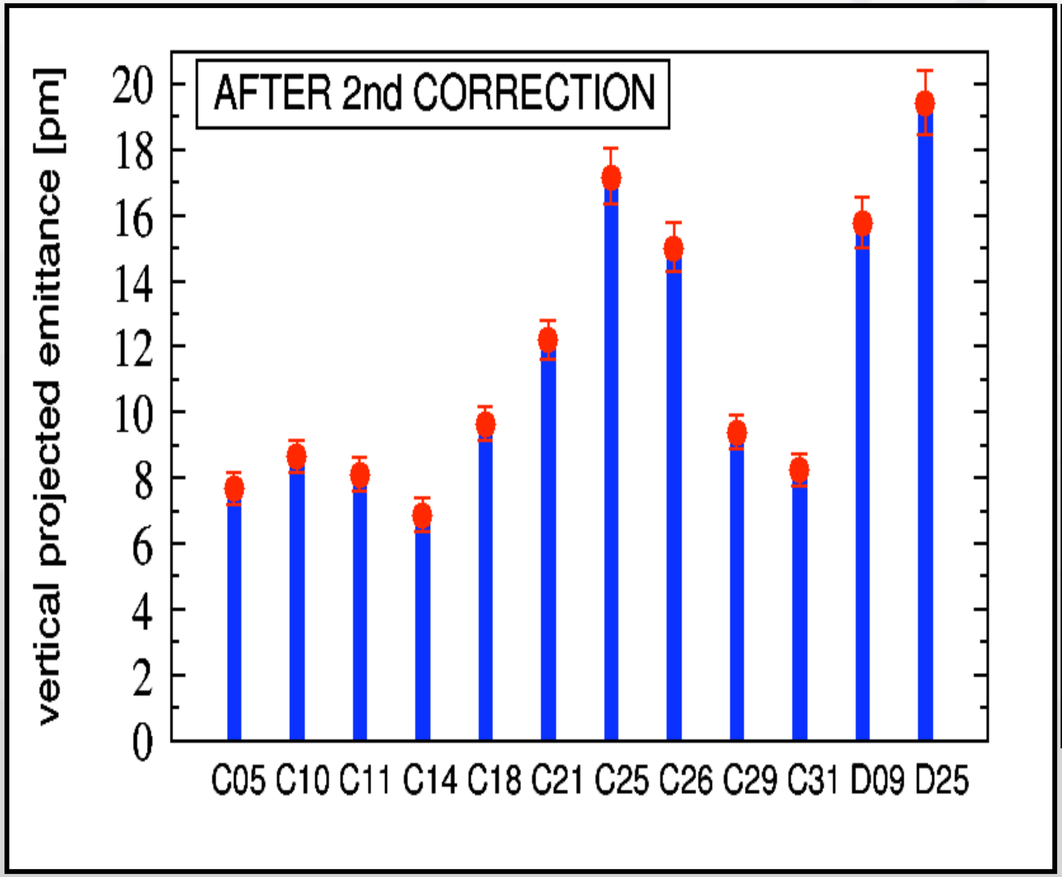


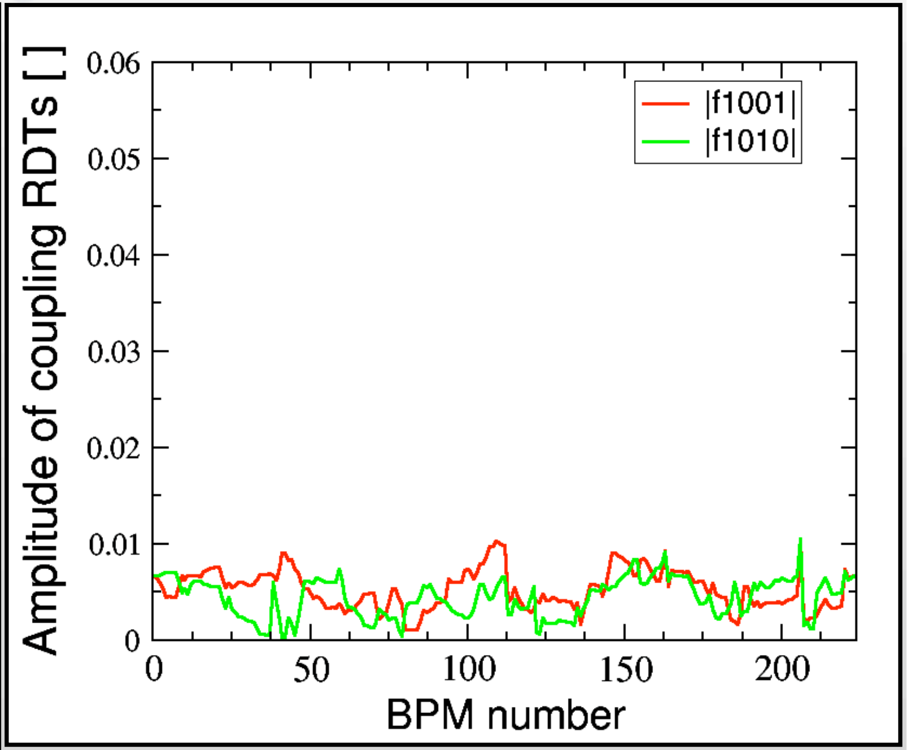
~20 min. for ORM
a few seconds for RDT correction

Application to the ESRF storage ring

First RDT correction: January 16th 2010

2nd ORM measur. and RDT correction: $\bar{\varepsilon}_y \pm \delta\varepsilon_y = 11.5 \pm 4.3$ pm



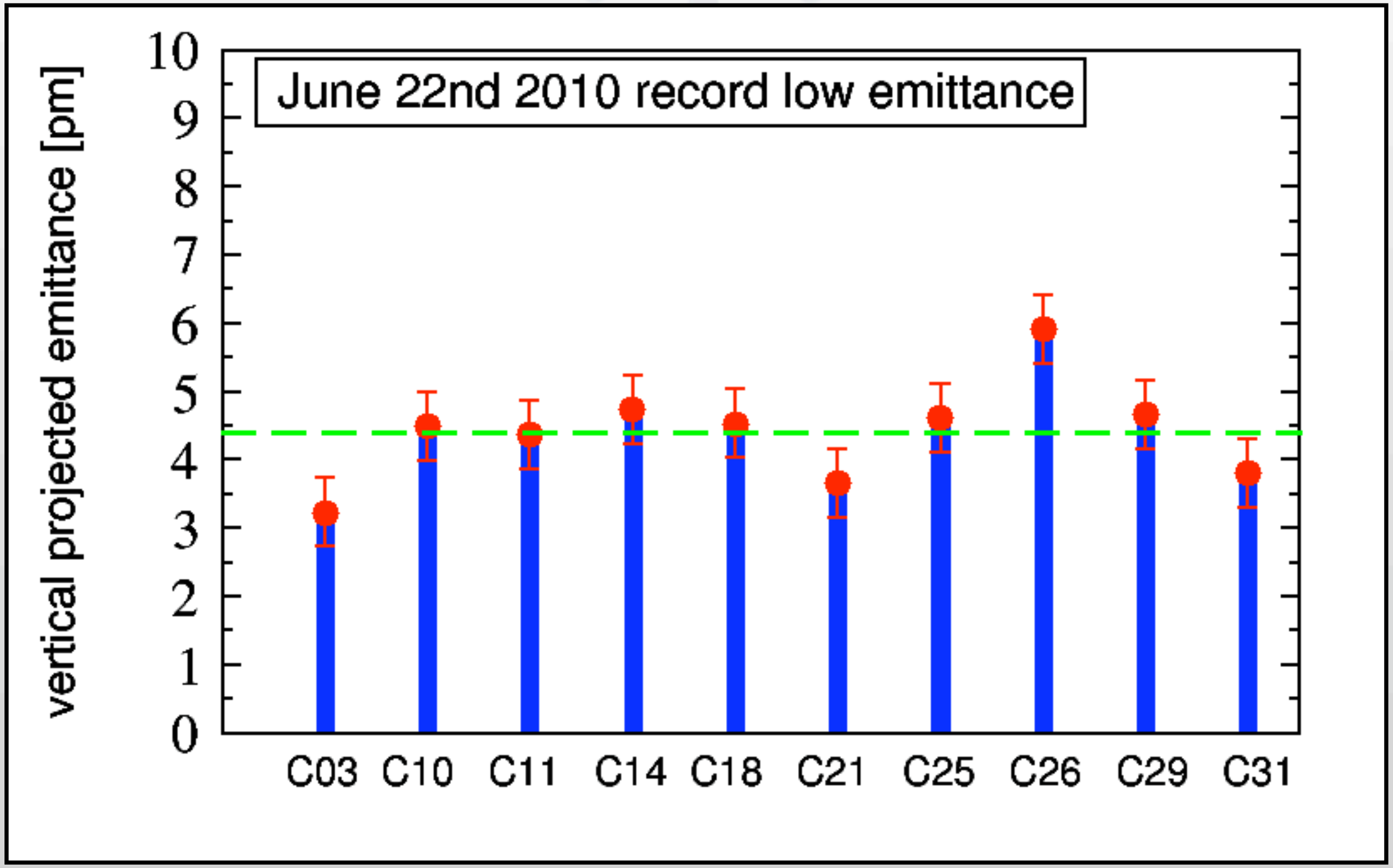


~20 min. for ORM
a few seconds for RDT correction

Application to the ESRF storage ring

ESRF record-low vertical emittance: June 22nd 2010

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

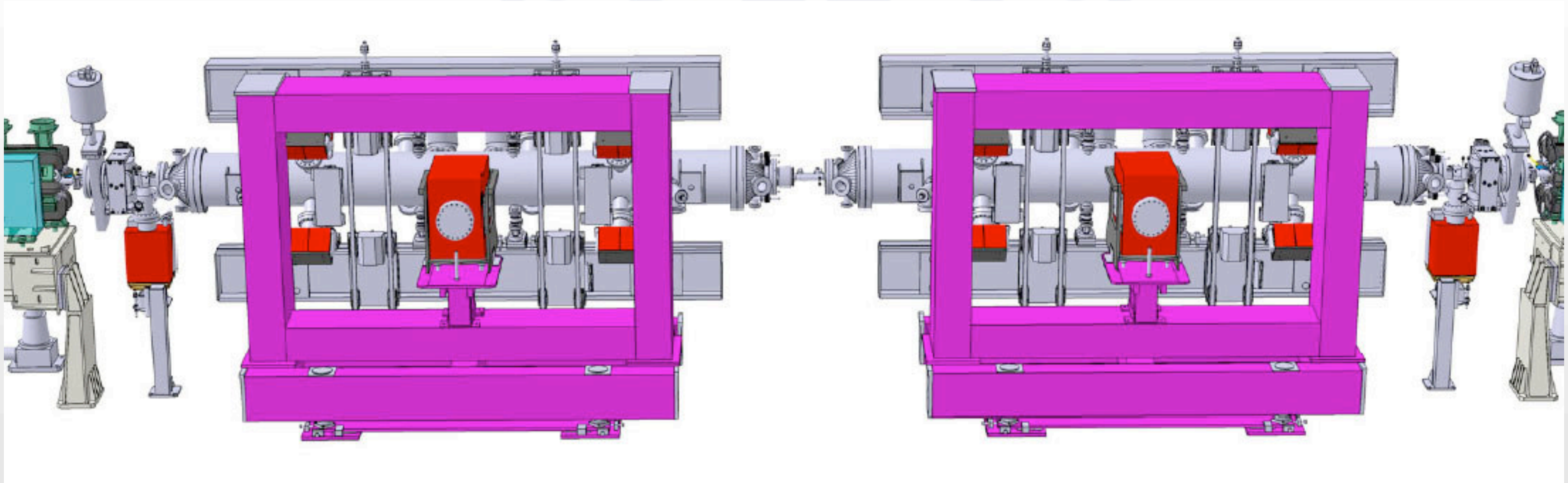


Preserving small vertical emittance during beam delivery

- 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 14 monitors on Jan. 20th 2010, during beam delivery and movements of two ID gaps movements

Preserving small vertical emittance during beam delivery



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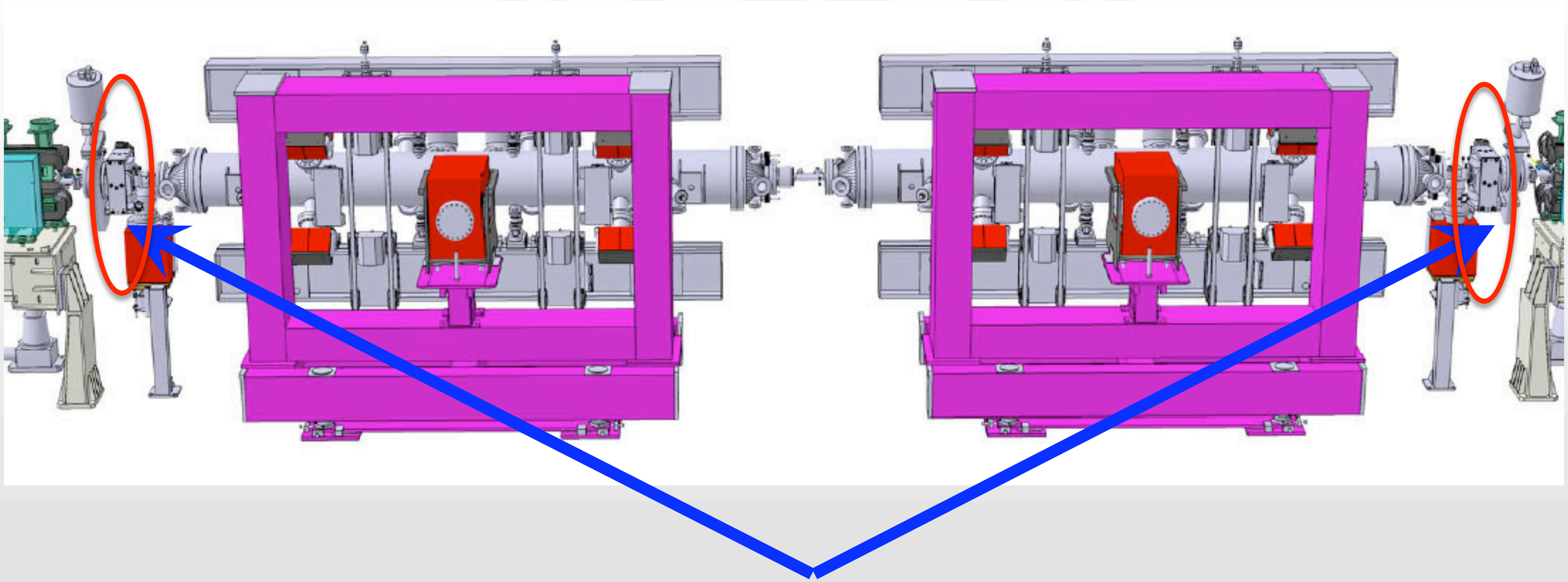
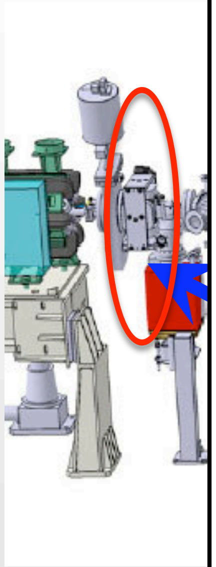
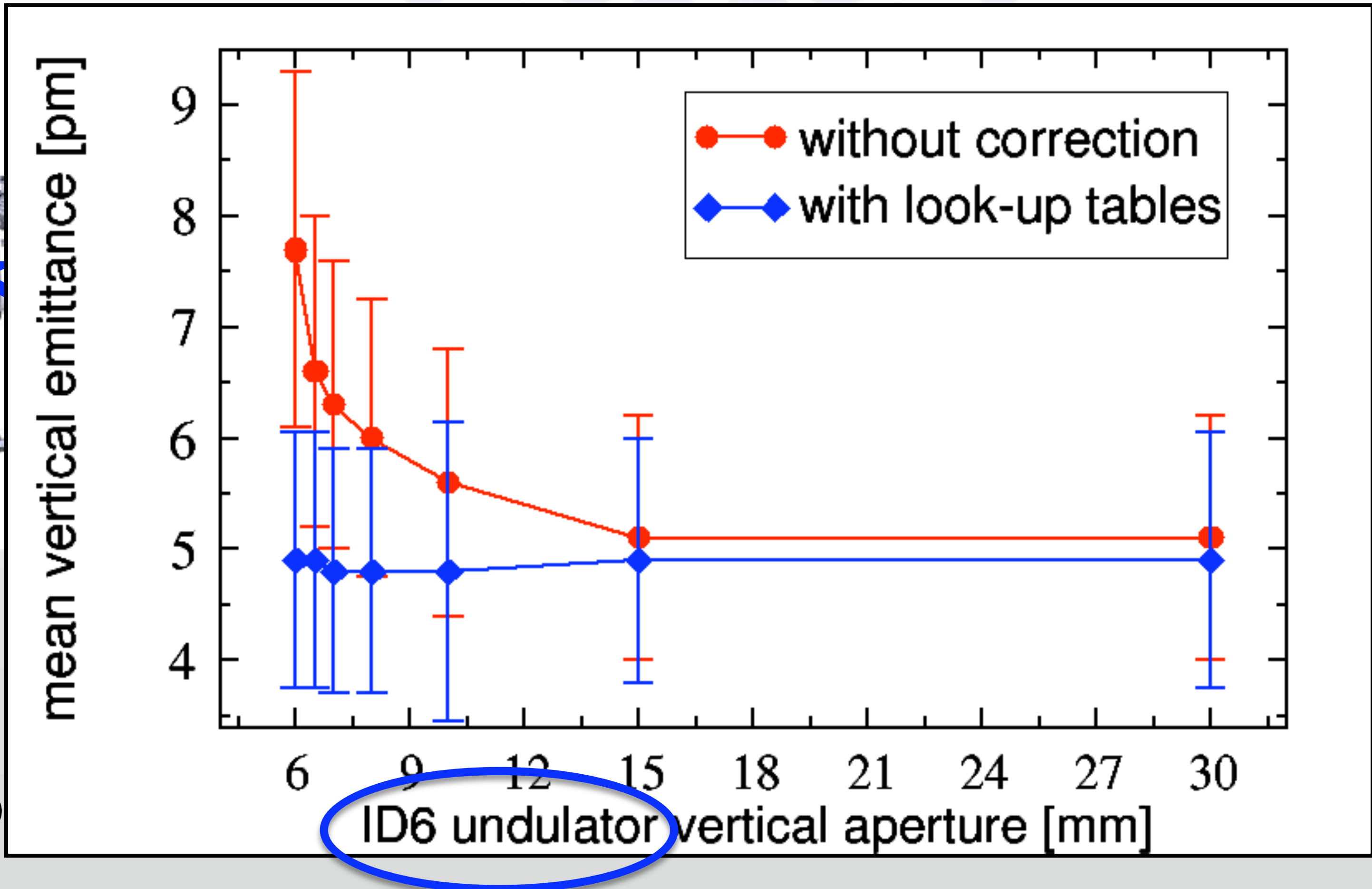


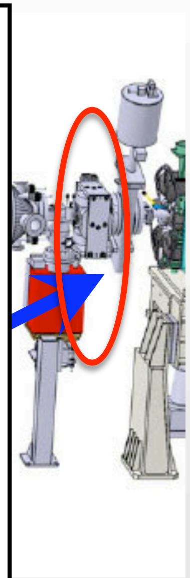
•H-V steerers at the ends of an ID straight section were cabled so to provide skew quad fields

•Look-up tables (corrector currents Vs ID gap aperture) were defined so to preserve the vertical emittance at any gap value.

Preserving small vertical emittance during beam delivery







•H-V … bled so to …

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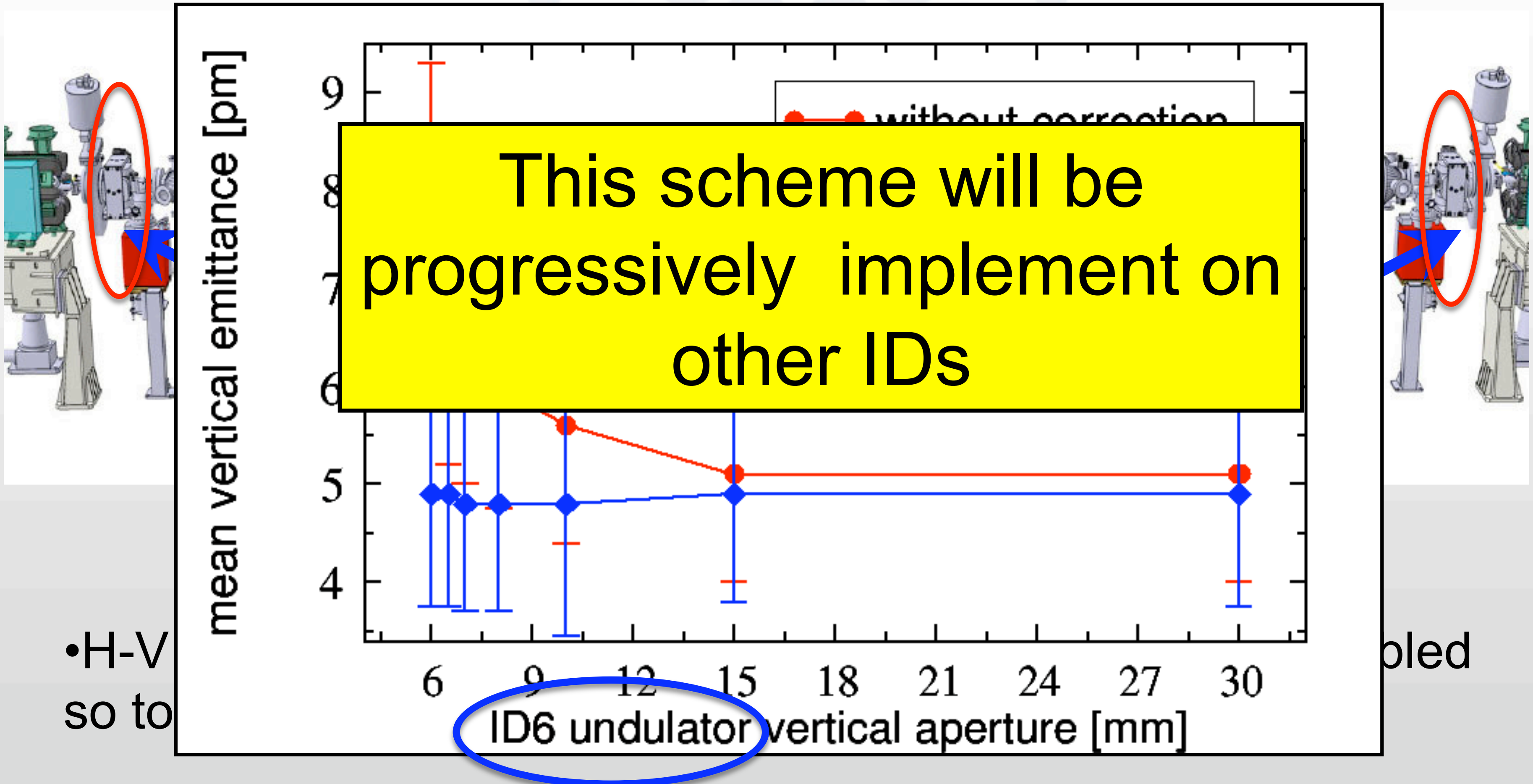


This scheme will be progressively implement on other IDs

•H-V ... bled so to ...

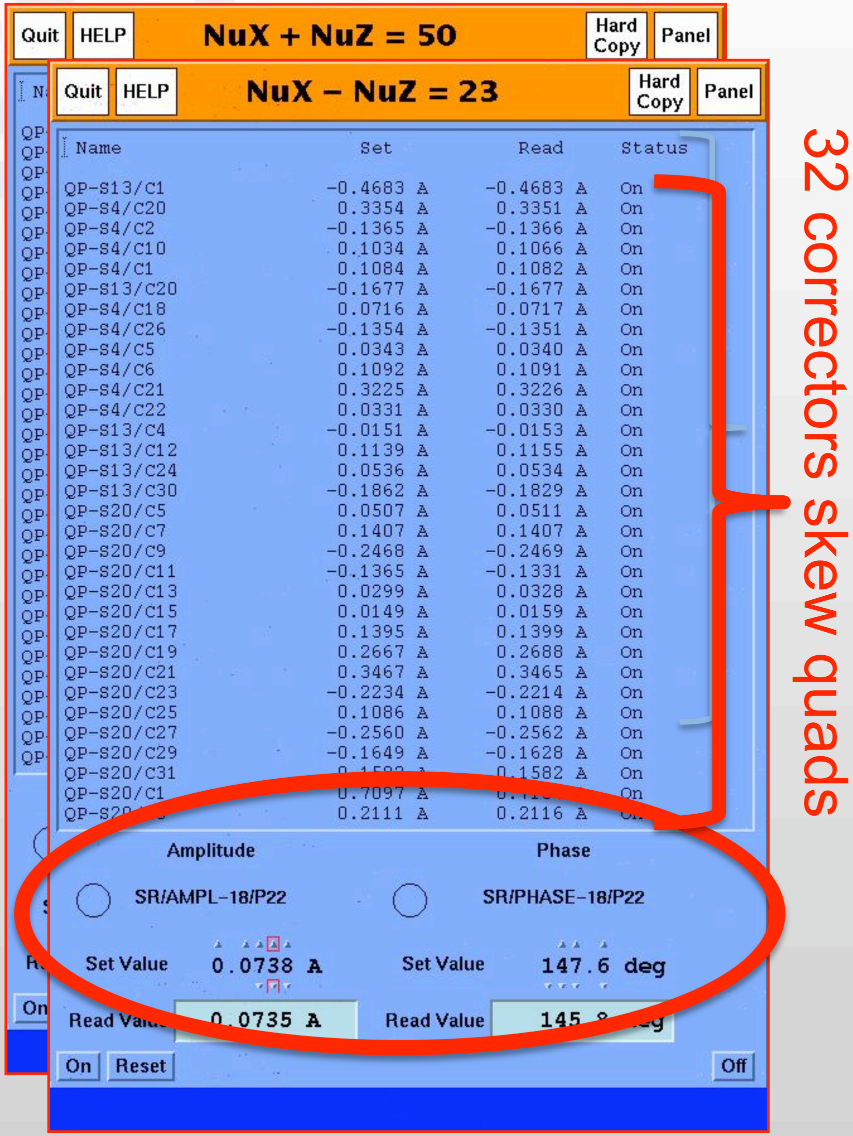
•Look-up tables (corrector currents Vs ID gap aperture) were defined so to preserve the vertical emittance at any gap value.

Preserving small vertical emittance during beam delivery

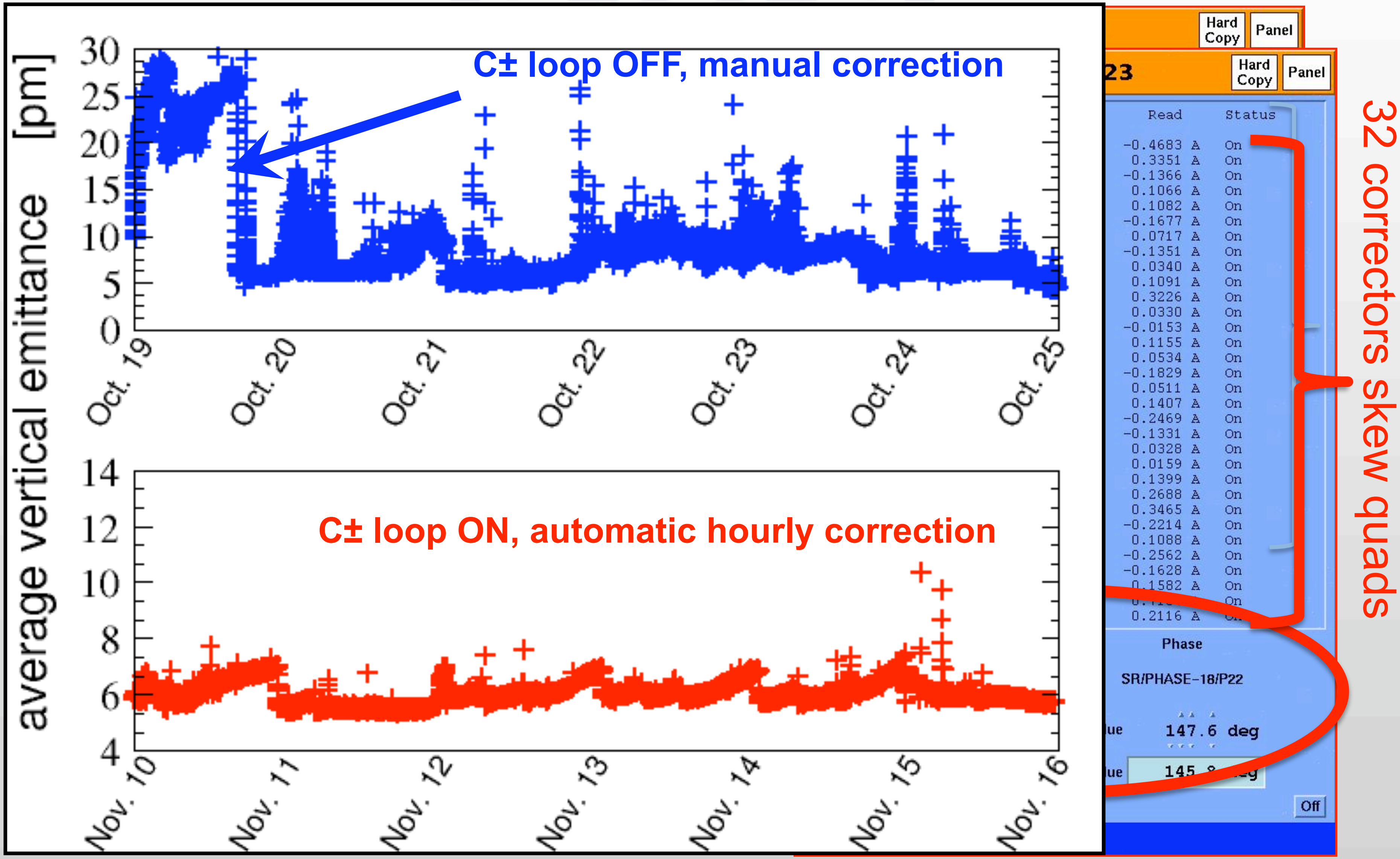
- Coupling may be represented by two complex vectors (for the sum and difference resonances respectively) $C\pm=|A\pm|e^{i\varphi\pm}$.

- At the ESRF storage ring, on top of the RDT static correction, C± may be dynamically varied so to catch up coupling variations induced by ID gap movements.

- A new software minimizes automatically C± by looking at the average vertical emittance



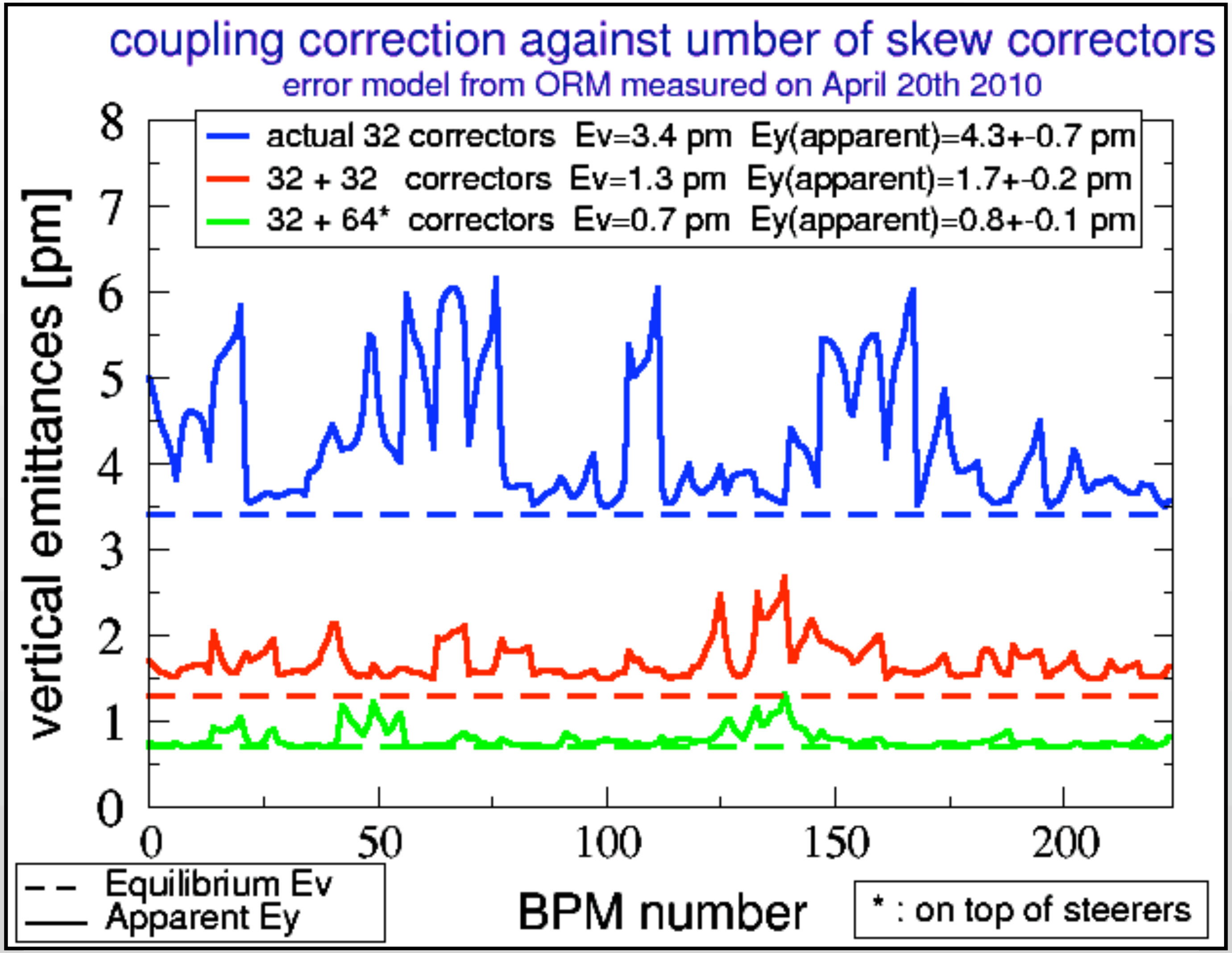
Preserving small vertical emittance during beam delivery



Towards ultra-small vertical emittance

- At the ESRF SR corrector coils (dipole, quad, skew quad & sextupole) are installed on the yokes of the main sextupoles (7 per 32 cell).

- 52 coils may be powered so to have more than 32 corrector skew quads.



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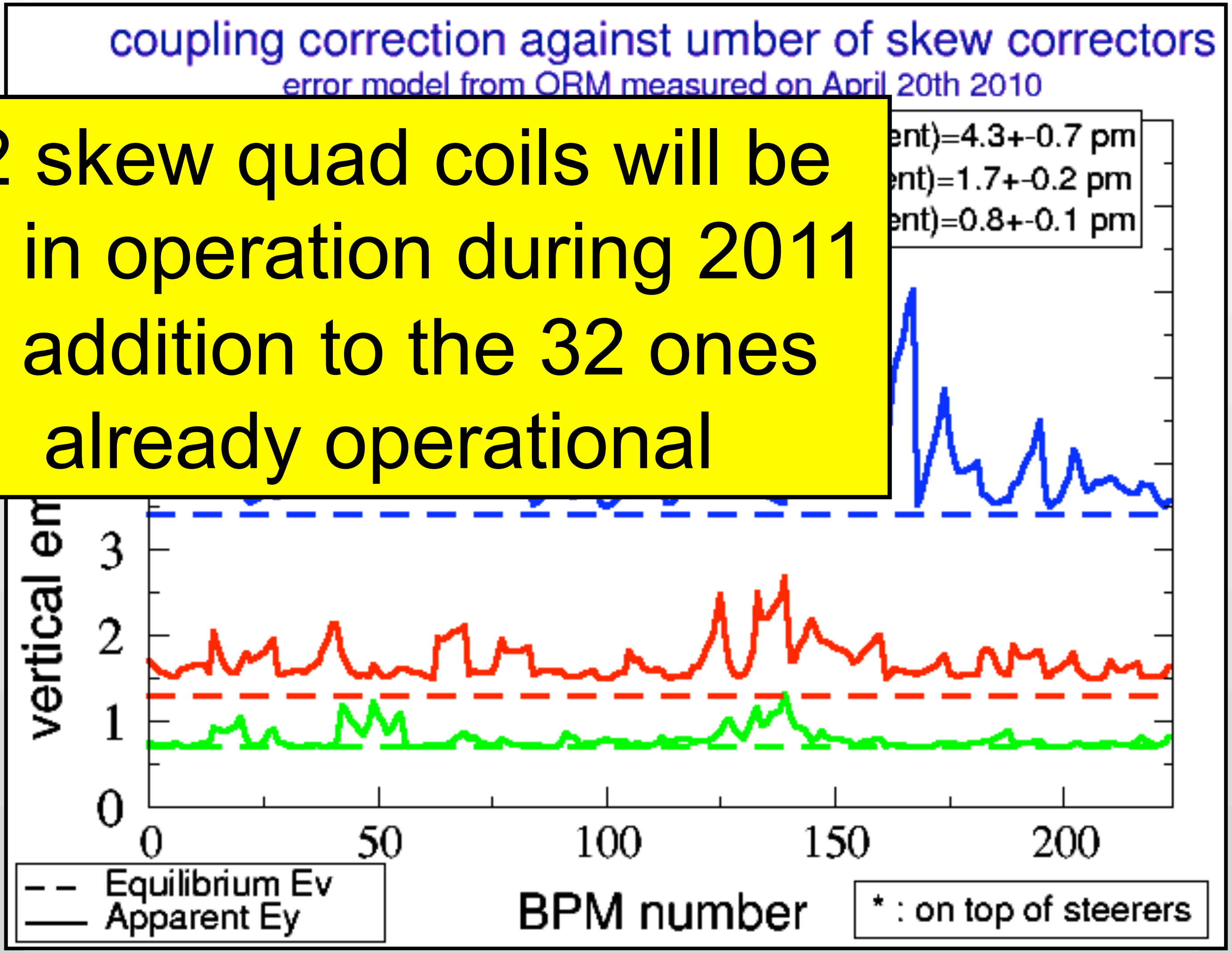
32 skew quad coils will be put in operation during 2011 in addition to the 32 ones already operational

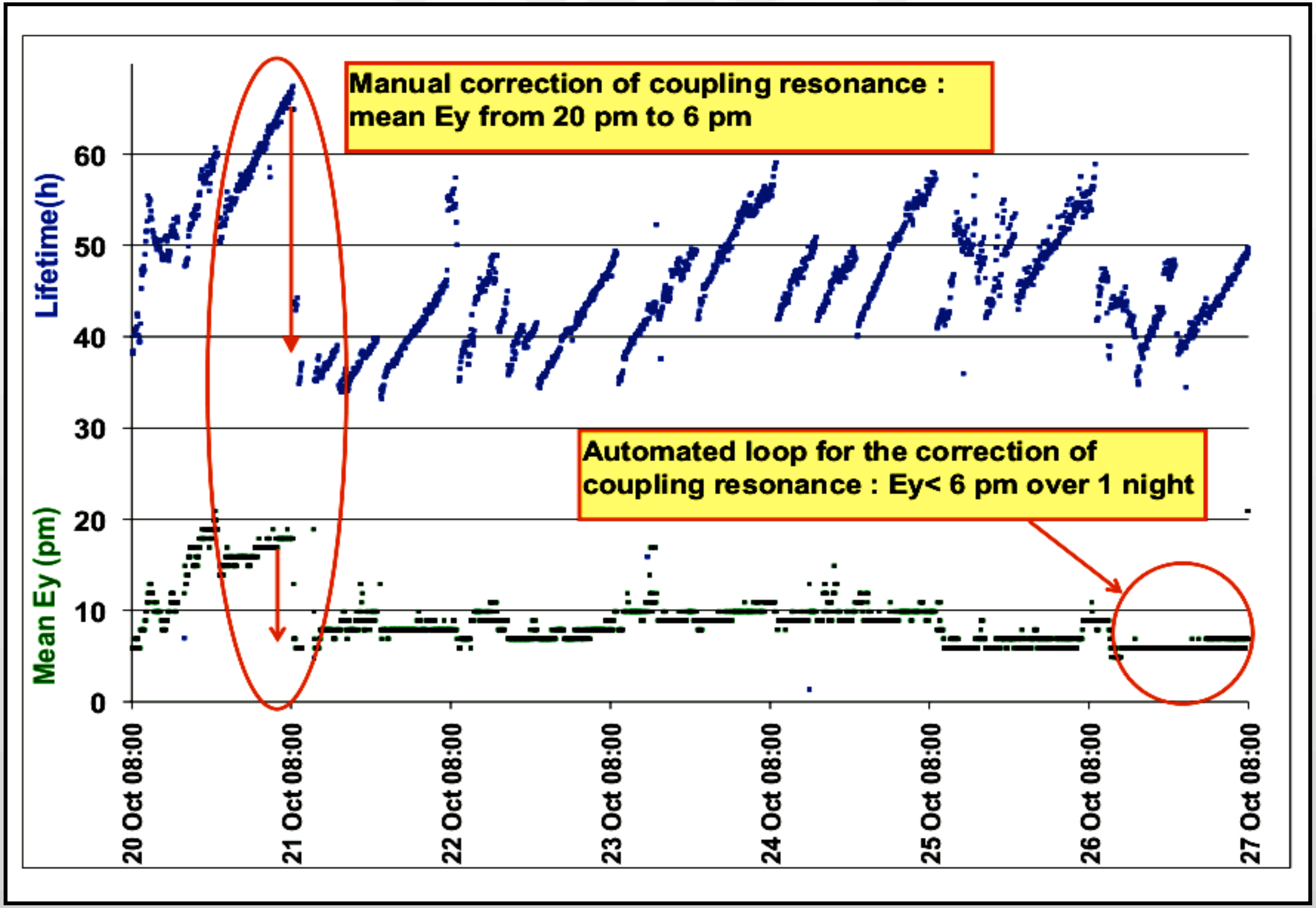


Conclusion

- The Resonance Driving Terms formalism helps clarifying the various significances of "vertical emittance" in presence of coupling and allows a straightforward, linear, correction algorithm.
- Applications to the ESRF storage ring led to vertical emittance of ε_y = 4.4 ± 0.7 pm, a record low for this machine (ε_x =4.2 nm => $\varepsilon_y/\varepsilon_x \approx$ 0.1%).
- A number of procedures to preserve small vertical emittance during beam delivery was successfully tested: stable ε_y = 6-7 pm (7/8 +1 filling) delivered as of November '10
- 32 new skew quads will be added during 2011 with the aim of delivering beam of ε_y = 2 pm.

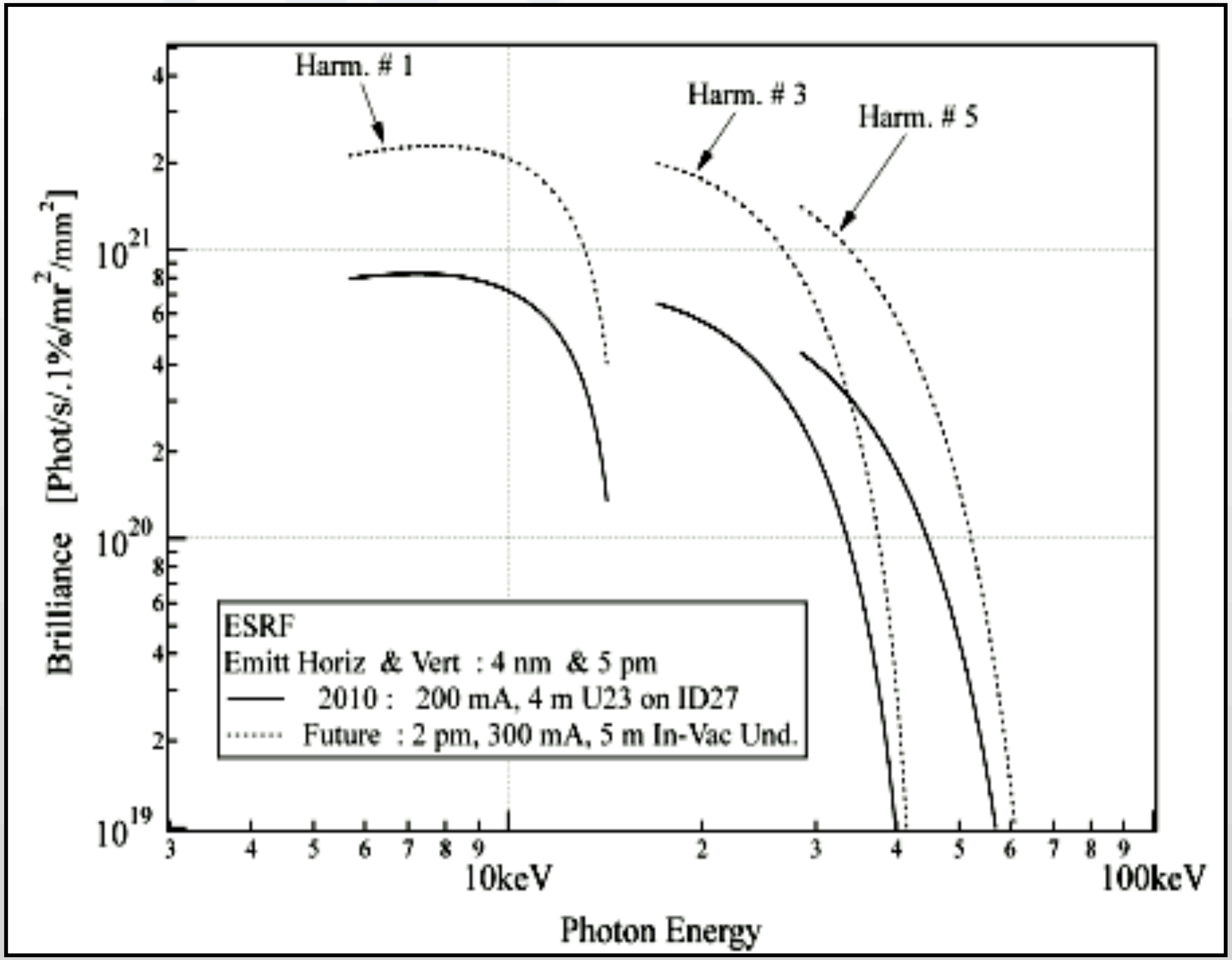
More details in a paper submitted to PRSTAB

Extra: vertical emittance Vs lifetime (7/8+1 filling)



EXTRA: Brilliance @ ε_y = 5 pm@200 mA (2 pm@300mA)

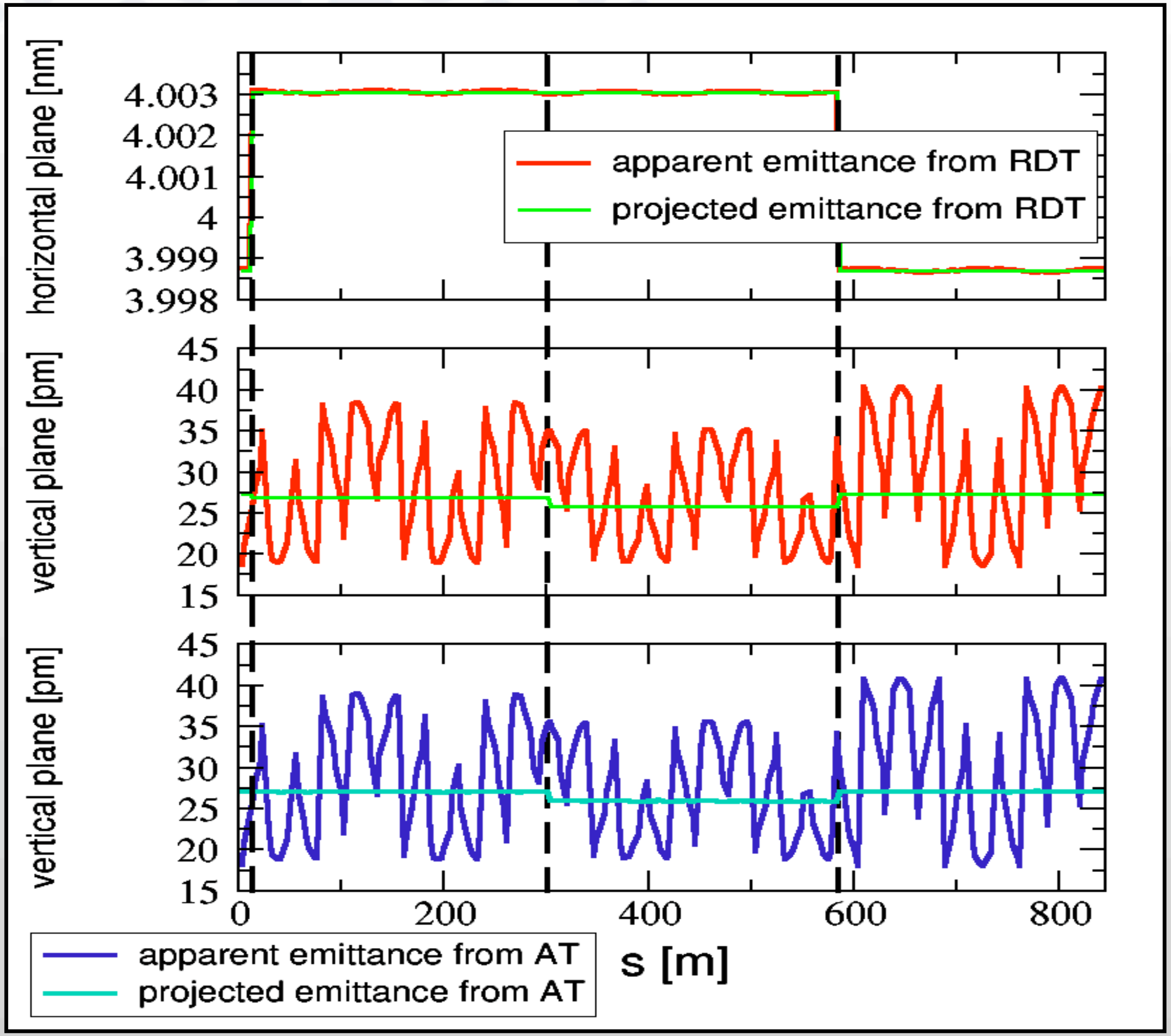
Solid curve: Brilliance of the X-ray beam emitted from the two in-vacuum undulators installed on ID27 (High Pressure beamline). Each undulator segment has a period of 23 mm, a length of 2 m and is operated with a minimum gap of 6 mm.



EXTRA: comparing RDT formula and optics codes

- ESRF lattice with three sources of coupling only (black dashed lines): apparent and projected emittances along the ring, from RDT formulas and AT (Ohmi's formalism)

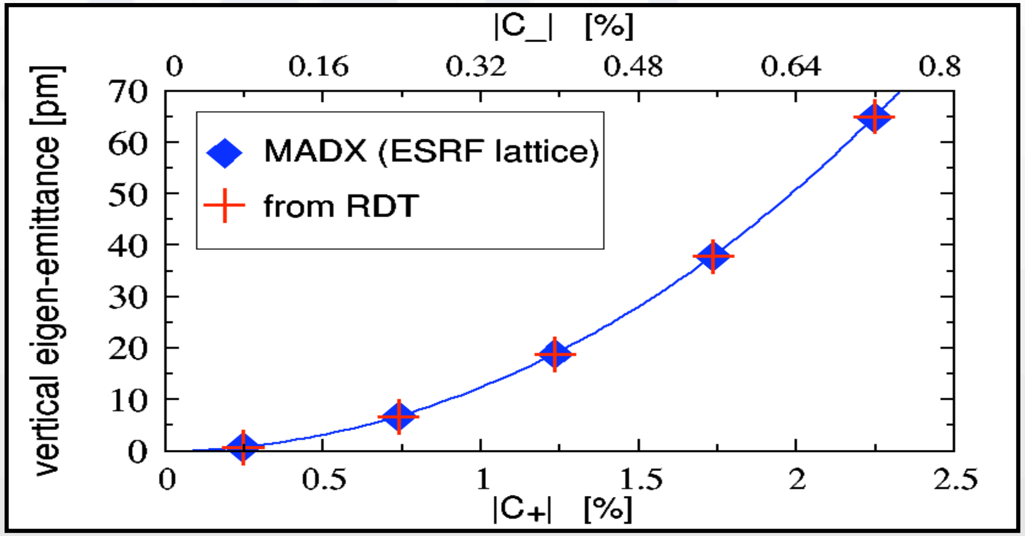
Agreement < 0.1%

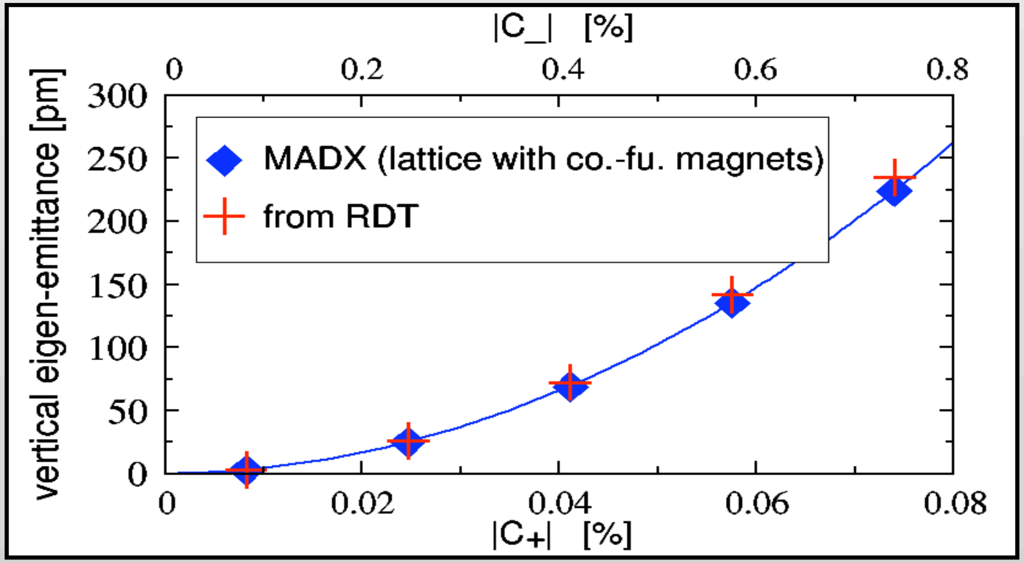


EXTRA: comparing RDT formula and optics codes

- ESRF lattice (top) and lattice with quadrupole fields in bending magnets (bottom): comparing vertical eigen-emittance between RDT formula and MADX (Chao's formalism)

Agreement < 1% (top), ~5% (bottom)





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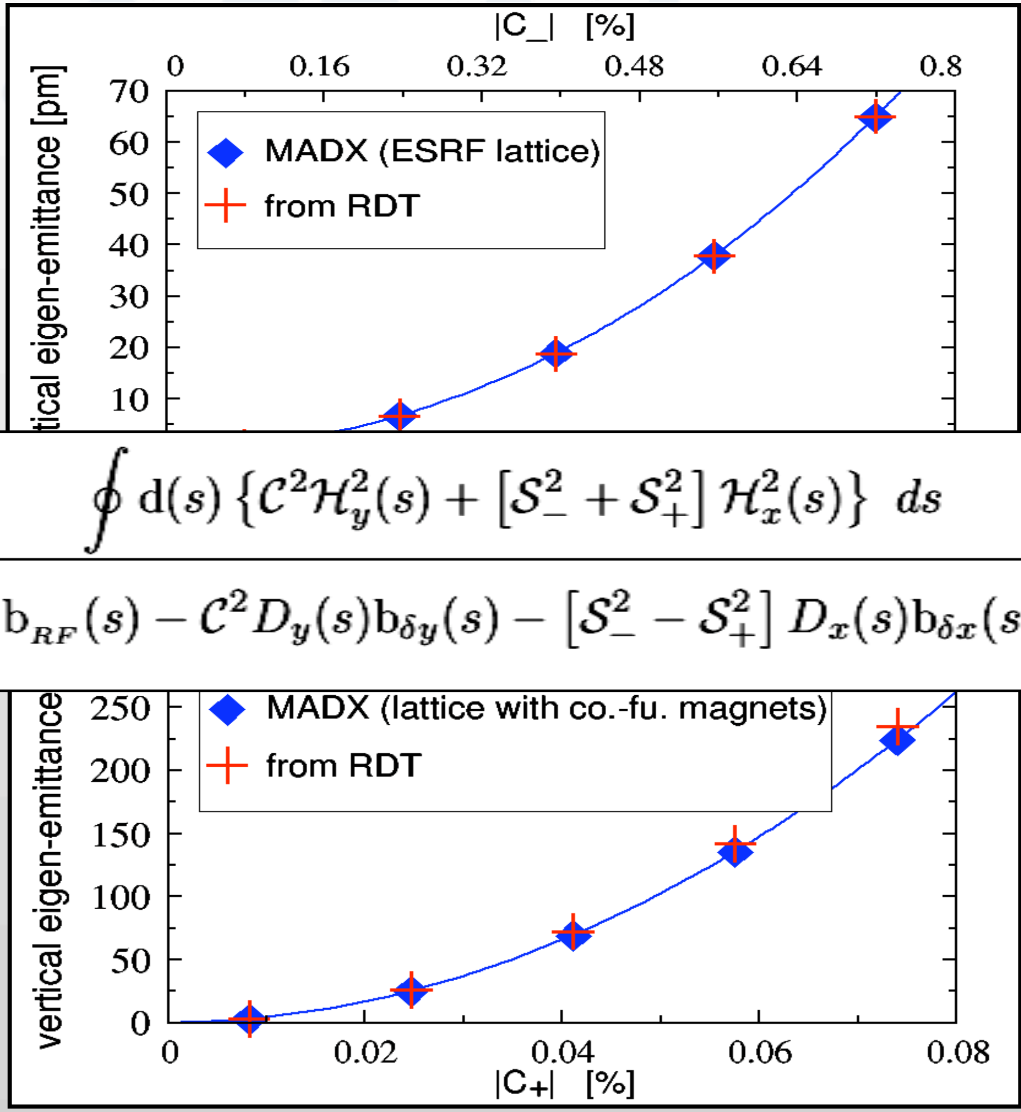
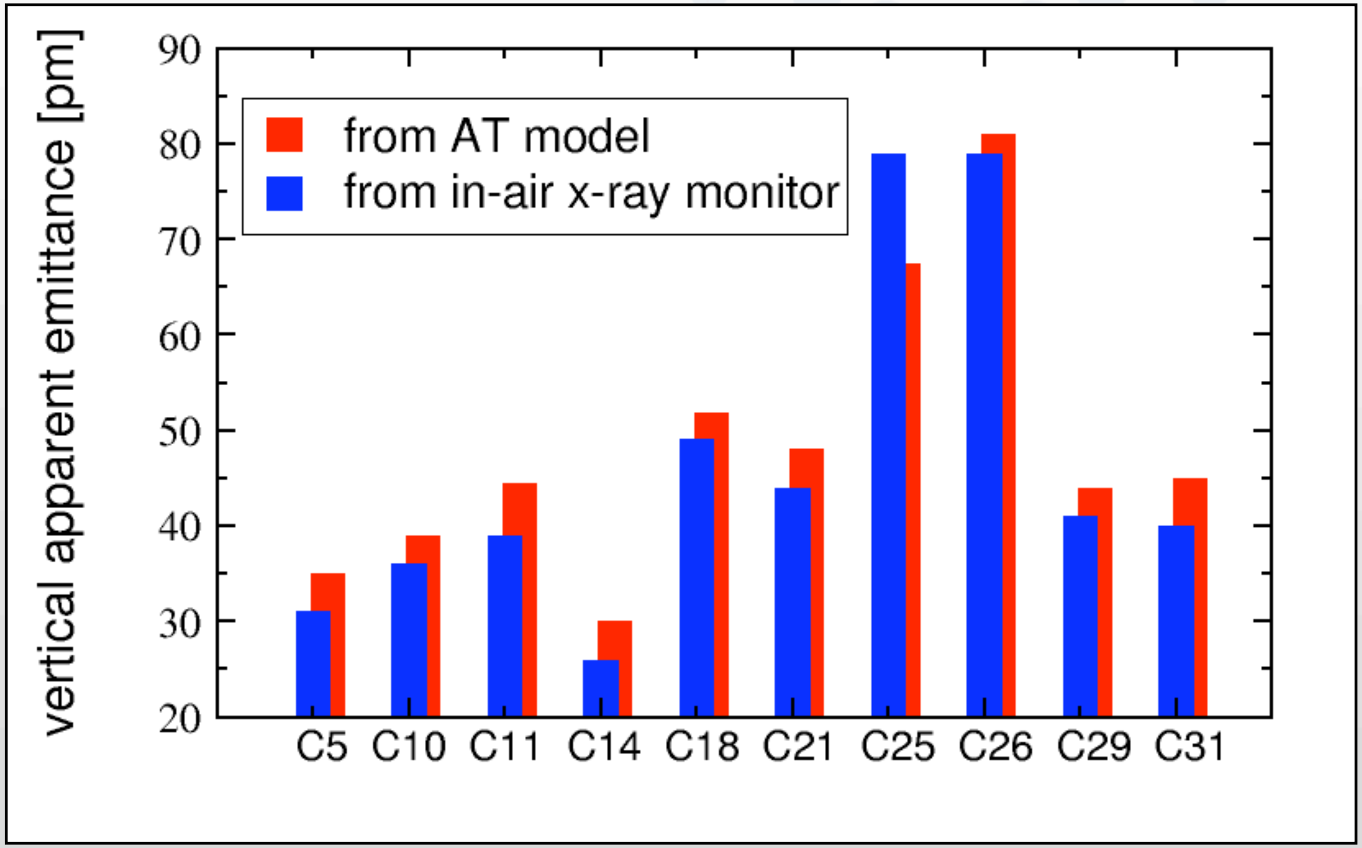


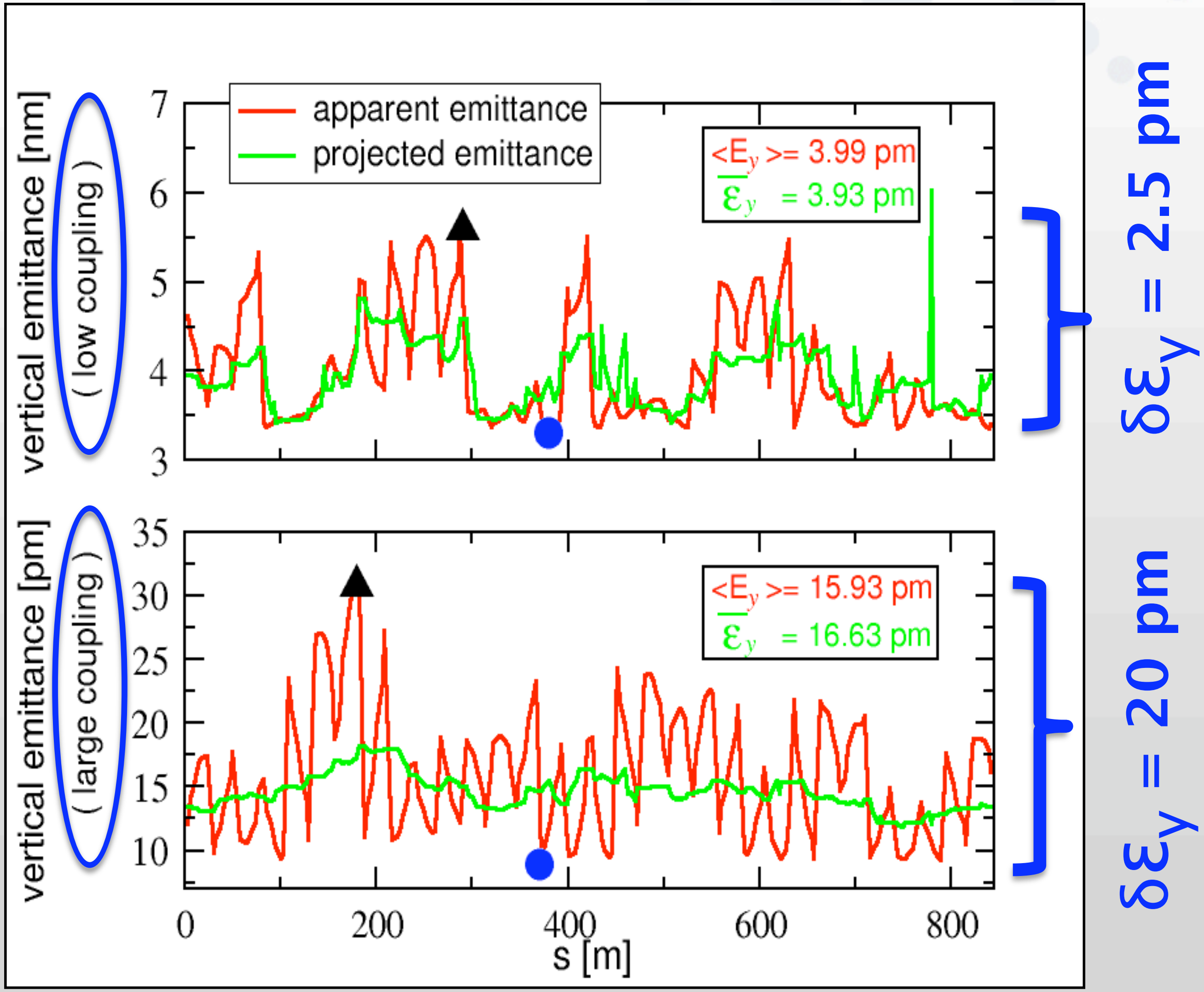
EXTRA: Vertical apparent emittance "spread"



Measurement of Jan. 16th 2010, before correction

- The larger the coupling, the larger is the "*spread*" among the measured apparent vertical emittance along the ring (don't blame "bad" emittance monitors for larger-than-expected measured values)

EXTRA: Vertical apparent emittance "spread"



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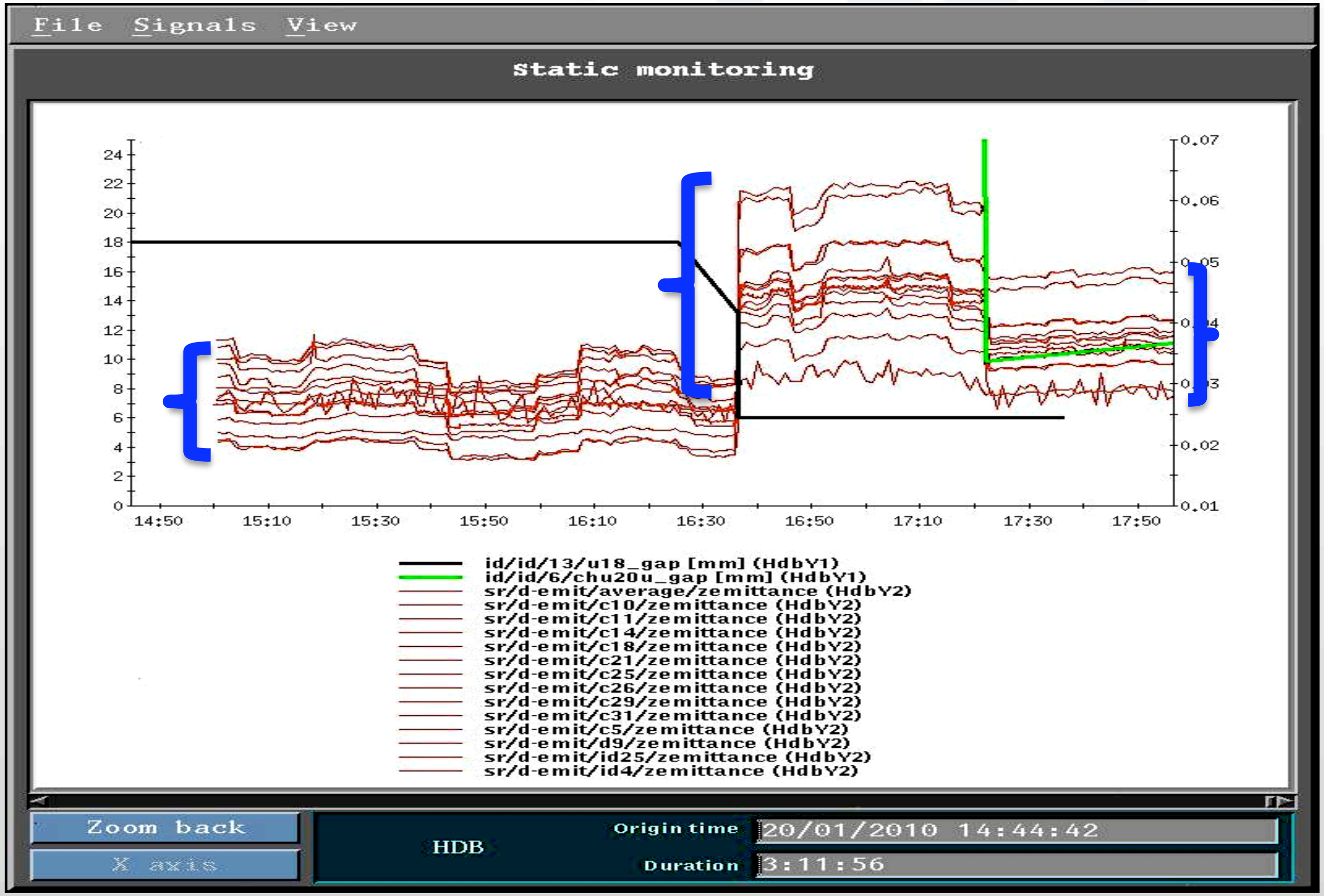

Apparent emittance measured at 14 monitors on Jan. 20th 2010, during beam delivery and movements of two ID gaps movements

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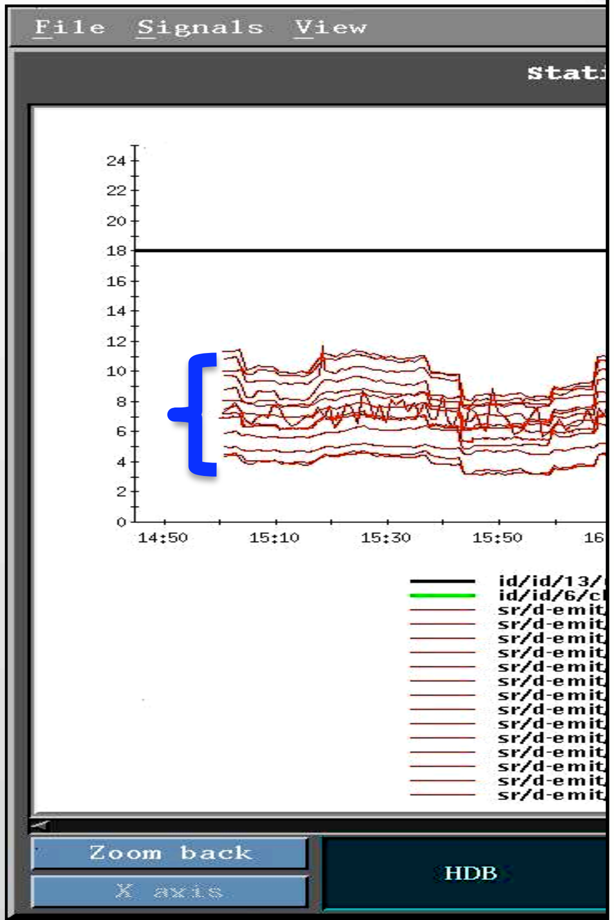
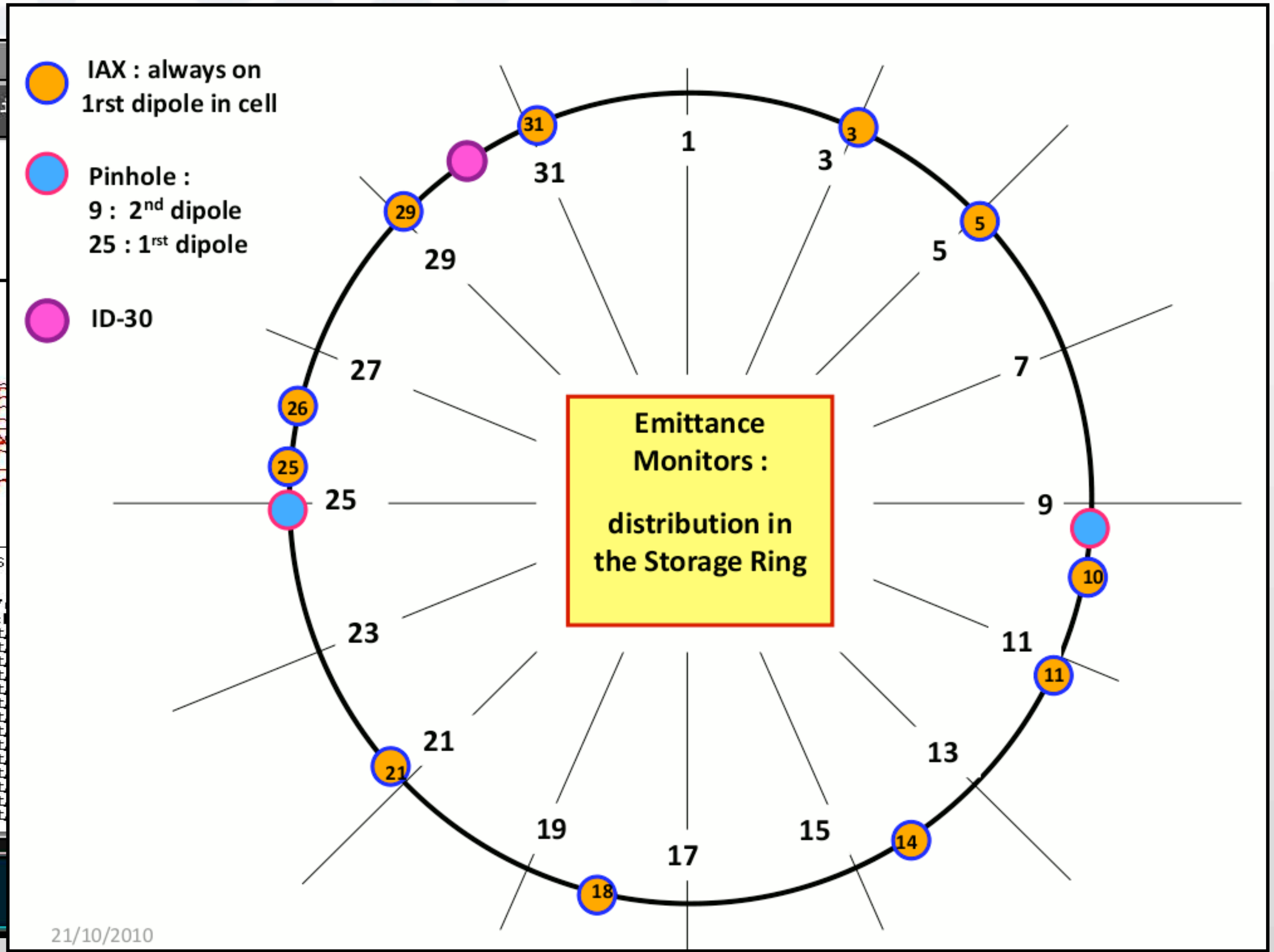
EXTRA: vertical emittance monitors in the ESRF SR





Apparent emittance measured at 14 monitors on Jan. 20th 2010, during beam delivery and two ID gaps movements

expected measured values)

EXTRA: ESRF SR correctors matrix

- At the ESRF SR corrector coils (dipole, quad, skew quad & sextupole) are installed on the yokes of the main sextupoles (7 per 32 cell).
- 52 coils may be powered so to have more than 32 corrector skew quads.

cell\sext.	S04	S06	S13	S19	S20	S22	S24
4	norm. quad	steeerer	skew quad	steeerer	norm. quad	steeerer	
5	skew quad	steeerer		steeerer	skew quad	steeerer	norm. quad
6	skew quad	steeerer	norm. quad	steeerer		steeerer	
7		steeerer		steeerer	skew quad	steeerer	norm. quad
8		steeerer	norm. quad	steeerer	norm. sext	steeerer	norm. sext
9		steeerer	norm. quad	steeerer	skew quad	steeerer	norm. sext
10	skew quad	steeerer		steeerer		steeerer	norm. quad
11		steeerer	norm. quad	steeerer	skew quad	steeerer	
12		steeerer	skew quad	steeerer	norm. quad	steeerer	
13		steeerer	norm. quad	steeerer	skew quad	steeerer	
14	norm. quad	steeerer		steeerer		steeerer	norm. quad
15		steeerer	norm. quad	steeerer	skew quad	steeerer	
16		steeerer		steeerer	norm. sext	steeerer	norm. sext
17		steeerer	norm. quad	steeerer	skew quad	steeerer	
18	skew quad	steeerer		steeerer		steeerer	norm. quad
19		steeerer	norm. quad	steeerer	skew quad	steeerer	
20	skew quad	steeerer	skew quad	steeerer	norm. quad	steeerer	
21	skew quad	steeerer	norm. quad	steeerer	skew quad	steeerer	
22	skew quad	steeerer	norm. quad	steeerer		steeerer	
23	norm. quad	steeerer		steeerer	skew quad	steeerer	norm. sext
24		steeerer	skew quad	steeerer	norm. sext	steeerer	norm. sext
25		steeerer	norm. quad	steeerer	skew quad	steeerer	
26	skew quad	steeerer		steeerer		steeerer	norm. quad
27		steeerer	norm. quad	steeerer	skew quad	steeerer	
28	norm. quad	steeerer		steeerer		steeerer	norm. quad
29		steeerer	norm. quad	steeerer	skew quad	steeerer	norm. sext
30		steeerer	skew quad	steeerer	norm. quad	steeerer	
31		steeerer	norm. quad	steeerer	skew quad	steeerer	
32		steeerer	norm. quad	steeerer	norm. sext	steeerer	norm. sext
1	skew quad	steeerer	skew quad	steeerer	skew quad	steeerer	
2	skew quad	steeerer		steeerer		steeerer	norm. quad
3		steeerer	norm. quad	steeerer	skew quad	steeerer	norm. sext

96 steeerers

32 norm. quads

32 skew quads

12 norm. sext.s

Free channels: 52