A Light for Science

Vertical Emittance Reduction and Preservation in the ESRF Electron Storage Ring

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European Synchrotron Radiation Facility

Outlines

- Vertical emittances in the presence of coupling
- Coupling correction via Resonance Driving Terms
- 2010: Application in the ESRF storage ring
- 2010: Preserving small vertical emittance during beam delivery
- 2011: Towards ultra-small vertical emittance

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- Vertical emittances in the presence of coupling

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CAUTION!

Next considerations are valid for

- **_lepton machines (subject to radiation damping and diffusion)_**

AND

- **_machines the tunes of which are separated by several integers (@ ESRF Qx=36.44 , Qy=13.39 , Qx-Qy=26.05) but not for those with the same integer part (like the CERN SPS Qx≈Qy=26.6)_**

ESRF

Electron Storage Ring

- 3rd gen. light source
- Energy: 6 GeV
- Circumference: 844 m
- Max current: 200 mA
- (300 mA)
- DBA lattice
- 16-fold symmetry (32 mirrored foc. cells)

...s of which are separated by several integers (@ ESRF Qx=36.44 , Qy=13.39 , Qx-Qy=26.05) but not for those with the same integer part (like the CERN SPS Qx≈Qy=26.6)

Vertical emittance in the absence of coupling

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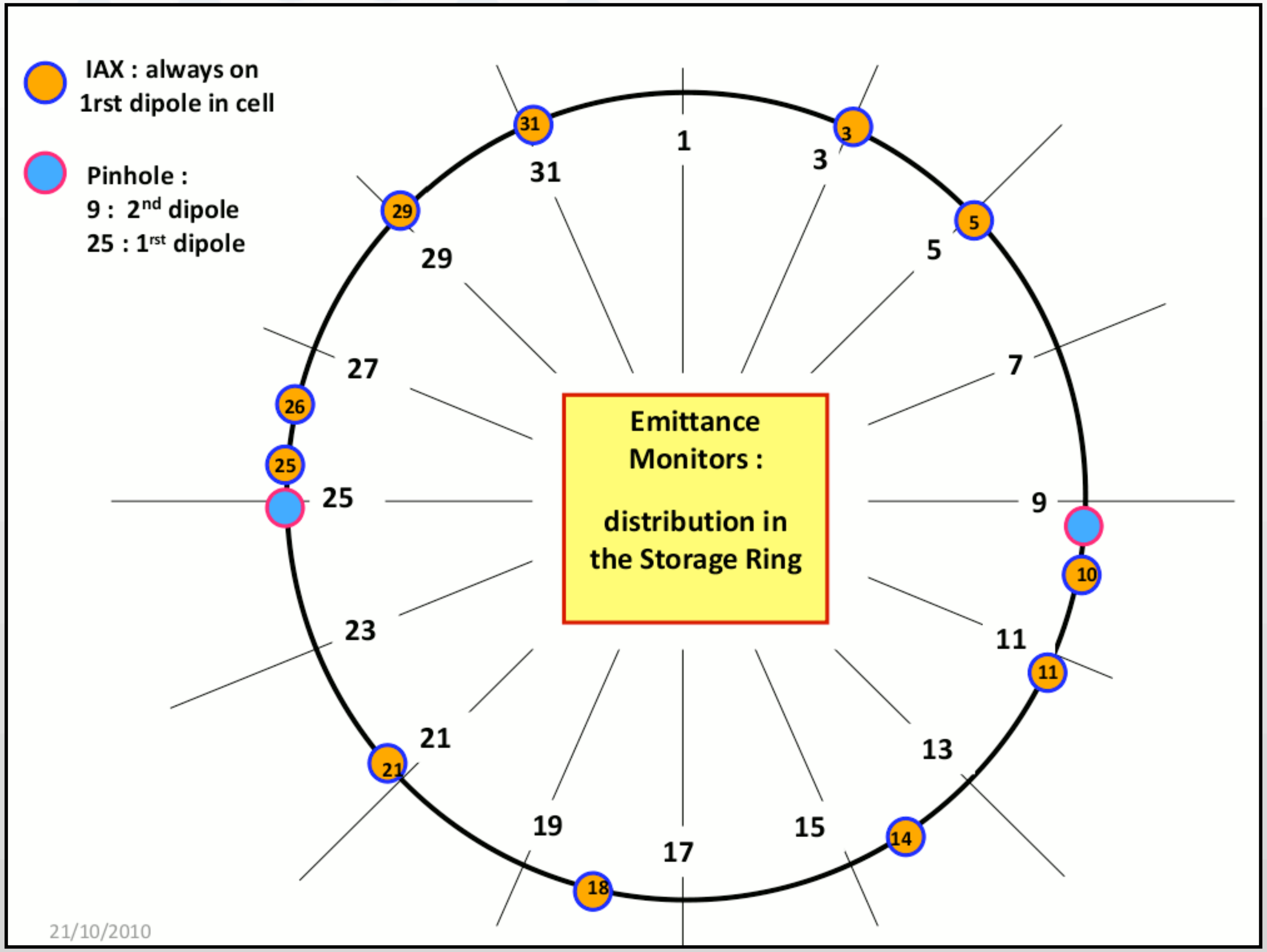
$\mathcal{E}_v = \epsilon_y = \mathrm{E}_y =$ const.

With zero vertical dispersion, $\mathcal{E}_v = \epsilon_y = \mathrm{E}_y \cong 0$

Meas. vertical emittance Ey from RMS beam size

ESRF SR equipment:

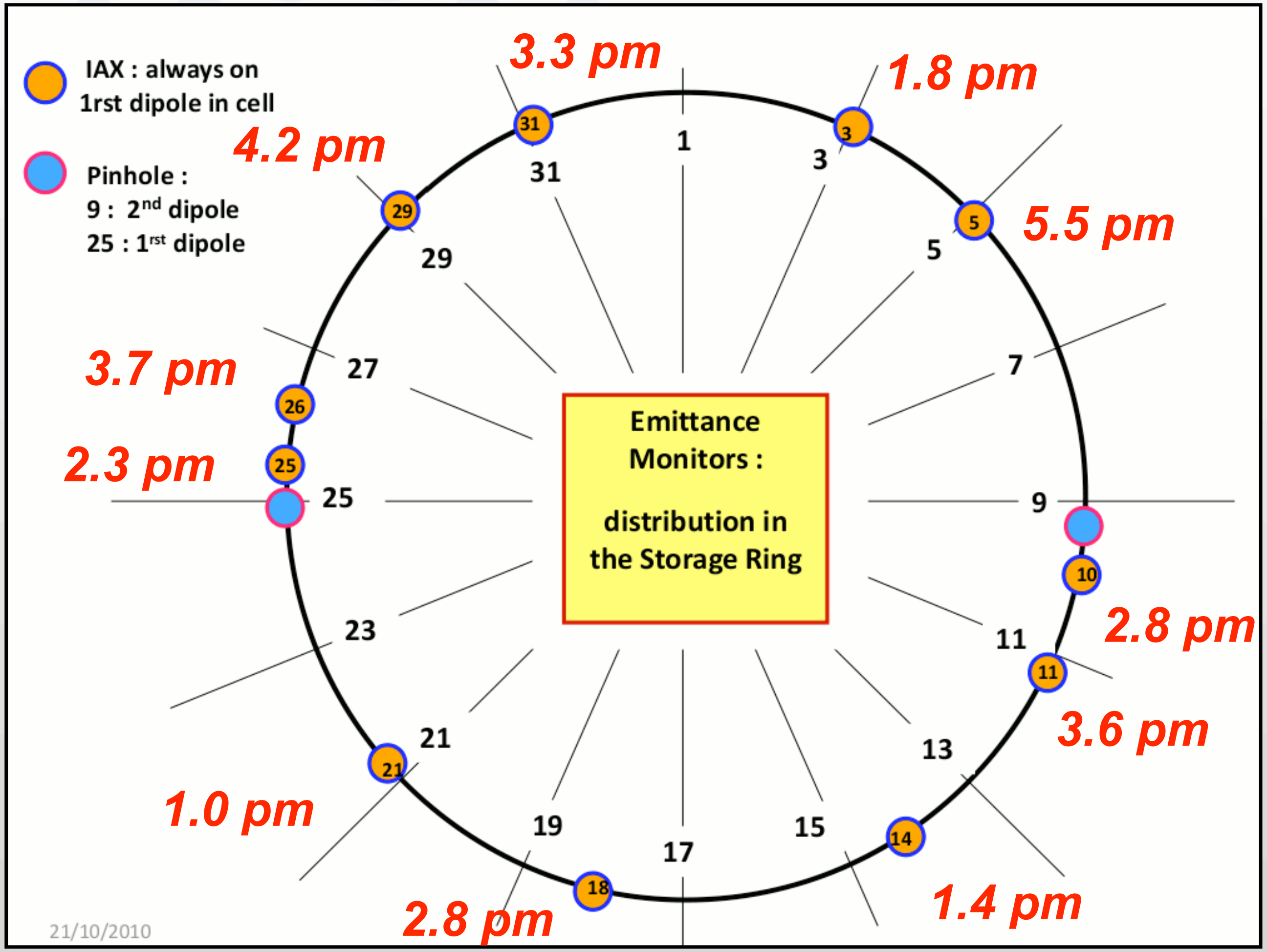
- 11 dipole radiation projection monitors (IAX)
- 2 pinhole cameras



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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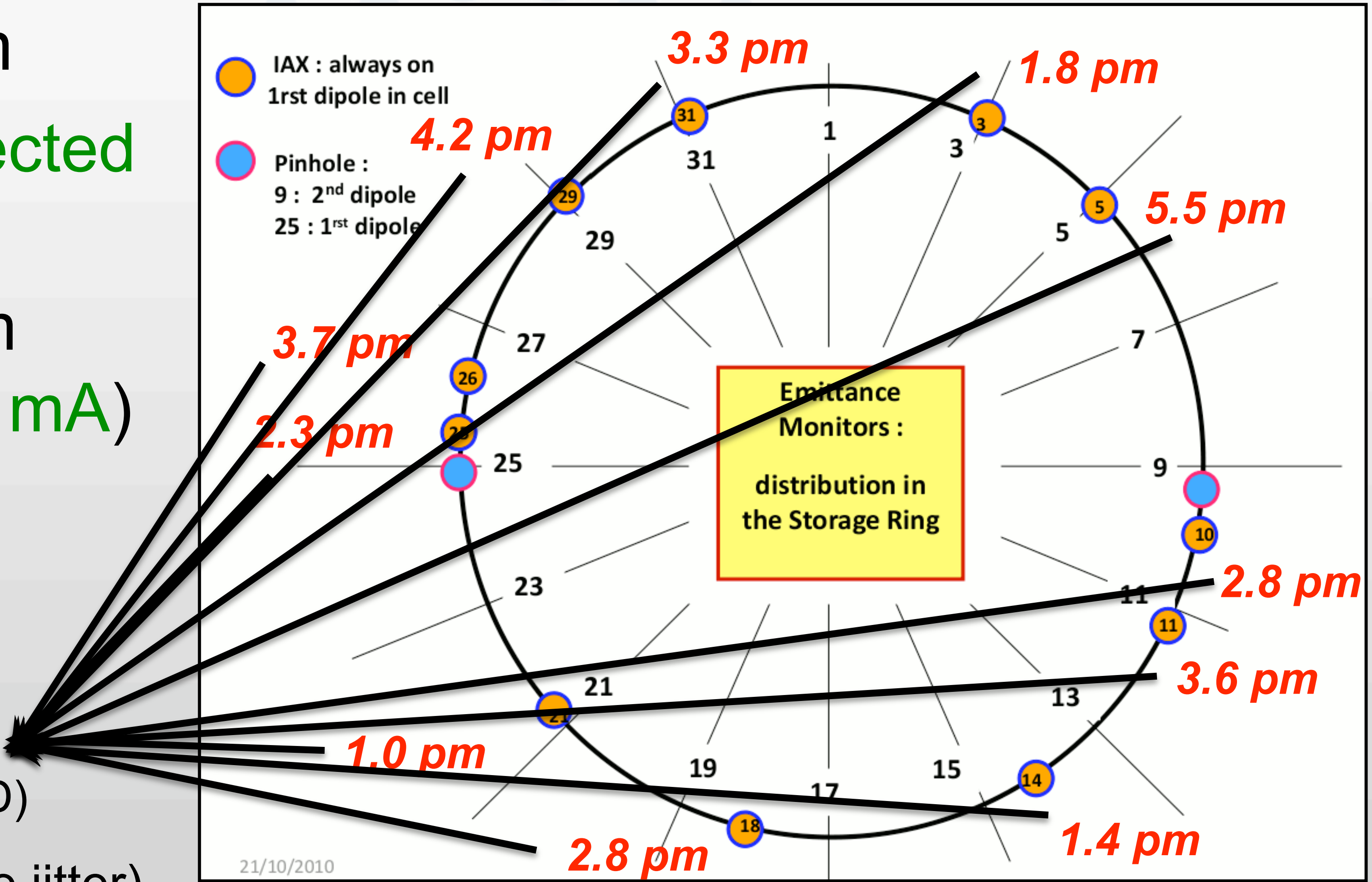
$\overline{E}$y=3.0 pm

±1.3 (STD)

±0.15 (time jitter)



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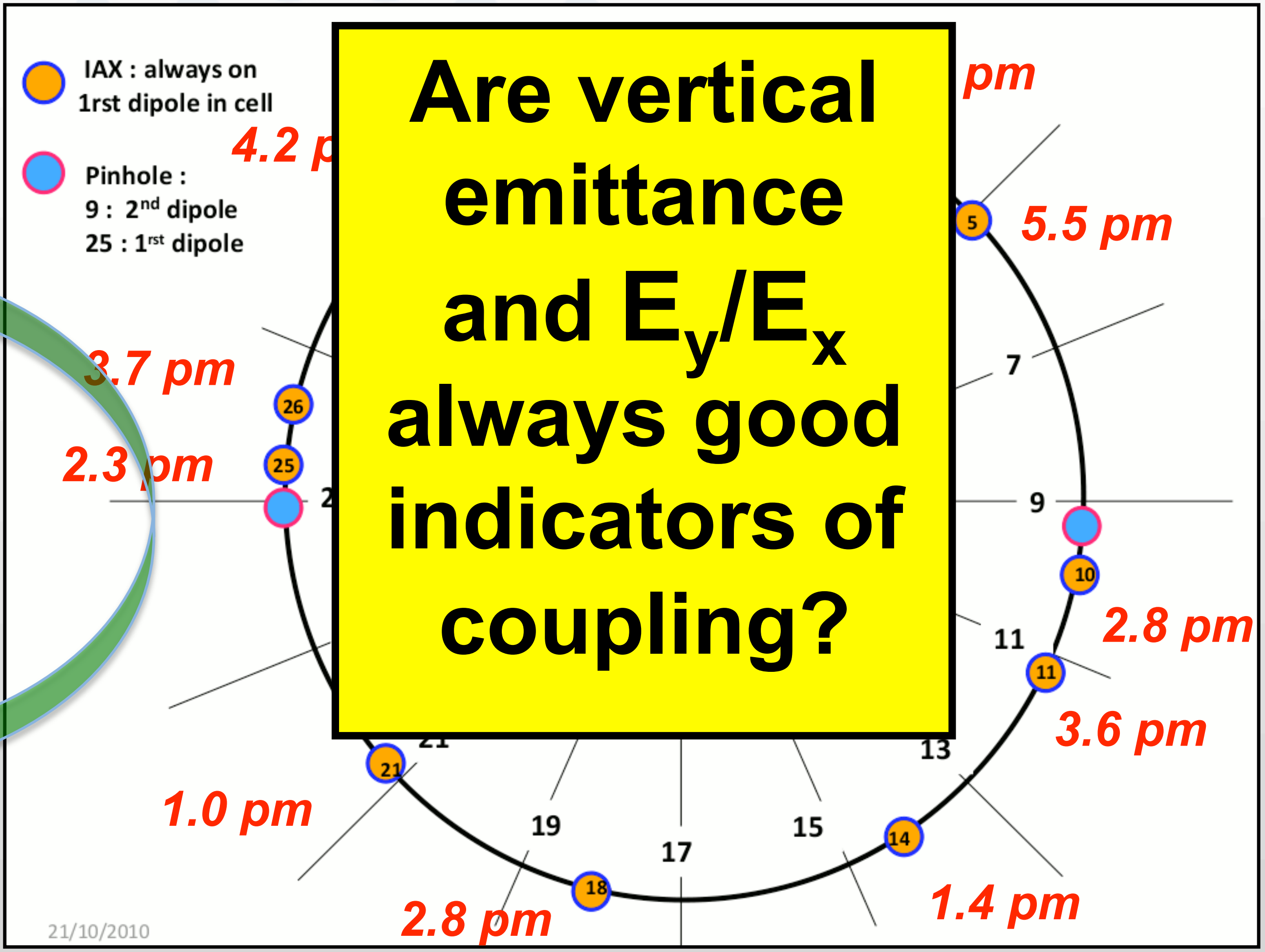

Meas. vertical emittance Ey from RMS beam size

Fixed low coupling

Stored beam current [mA]	Measured Vertical emittance [pm] INCREASING ION TRAPPING	
20	3.0 ± 1.5 (STD) ±0.15 (TJ)	
100	5.7 ± 1.7 (STD) ±0.07 (TJ)	
160	10.1 ± 2.0 (STD) ±0.12 (TJ)	
200	17.2 ± 1.8 (STD) ±0.35 (TJ)	

- STD =standard deviation from 11 IAX monitors
- TJ=Time Jitter over 30 s from 1-Hz sampling

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200	17.2 ± 1.8 (STD) ±0.35 (TJ)	
200*	4.2 ± 1.4 (STD) ±0.05 (TJ)	← with bunch-by-bunch feedback

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Meas. vertical emittance E_y from RMS beam size

Fixed low coupling		Fixed low beam current	
Stored beam current [mA]	**Measured Vertical emittance [pm]** **INCREASING ION TRAPPING**	**Corrector skew quad (S13C1) current [A]**	**Measured Vertical emittance [pm]** **INCREASING COUPLING**
20	3.0 ± 1.5 (STD) ±0.15 (TJ)	0	3.1 ± 1.5 (STD) ±0.20 (TJ)
100	5.7 ± 1.7 (STD) ±0.07 (TJ)	0.08	5.7 ± 1.8 (STD) ±0.20 (TJ)
160	10.1 ± 2.0 (STD) ±0.12 (TJ)	0.15	10.0 ± 2.7 (STD) ±0.20 (TJ)
200	17.2 ± 1.8 (STD) ±0.35 (TJ)	0.18	17.2 ± 3.2 (STD) ±0.20 (TJ)

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2 different physical phenomena,
same average vertical emittance

- STD =standard
- TJ=Time Jitter over 30 s from 1-Hz sampling

Meas. vertical emittance Ey from RMS beam size

Fixed low coupling | Fixed low beam current

Stored beam current [mA]	Measured Vertical emittance [pm] INCREASING ION TRAPPING	Corrector skew quad (S13C1) current [A]	Measu [pm] INCRE
20	3.0 ± 1.5 (STD) ±0.15 (TJ)	0	3.1 ±
100	5.7 ± 1.7 (STD) ±0.07 (TJ)	0.08	5.7 ±
160	10.1 ± 2.0 (STD) ±0.12 (TJ)	0.15	10.0 ±
200	17.2 ± 1.8 (STD) ±0.35 (TJ)	0.18	17.2 ±

Are vertical emittance and E_y/E_x always good indicators of coupling?

Maybe not

2 different physical phenomena, same average vertical emittance

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Meas. vertical emittance E_y from RMS beam size

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20% larger STD

110% larger STD

- STD =standard deviation from 11 IAX monitors
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Fixed low coupling — Fixed low beam current

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The spread among vertical emittance measurements along the ring increases with coupling. Why?

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Vertical emittances in the presence of coupling

- Eigen-emittance $\mathcal{E}$: still **constant** along the ring, but $\mathcal{E}v\neq 0$
- Non measurable projected ***s*-dependent** RMS emittance:

$$\epsilon_y(s)=\sqrt{\sigma_y(s)\sigma_p(s)-\sigma_{yp}^2(s)}$$

- Measurable apparent ***s*-dependent** emittance from RMS beam size:

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

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$\mathcal{E}_v$=const ≠ εy(s) ≠ Ey(s)

Vertical emittances in the presence of coupling

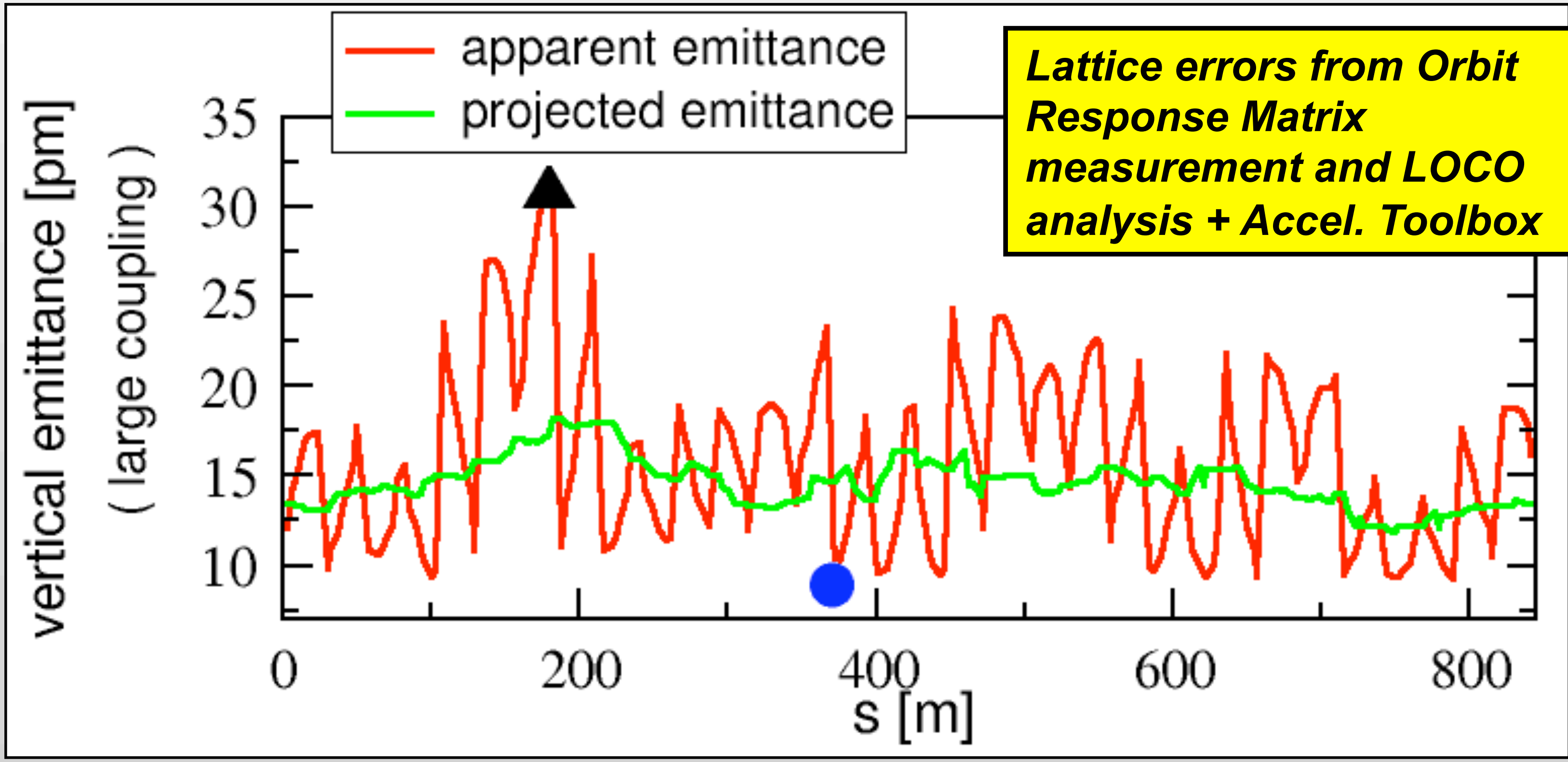
Measurable apparent emittance:

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

Non measurable projected emittance:

$$\epsilon_y(s) = \sqrt{\sigma_y(s)\sigma_p(s) - \sigma_{yp}^2(s)}$$

$\mathcal{E}_v$= 9 pm



Lattice errors from Orbit Response Matrix measurement and LOCO analysis + Accel. Toolbox

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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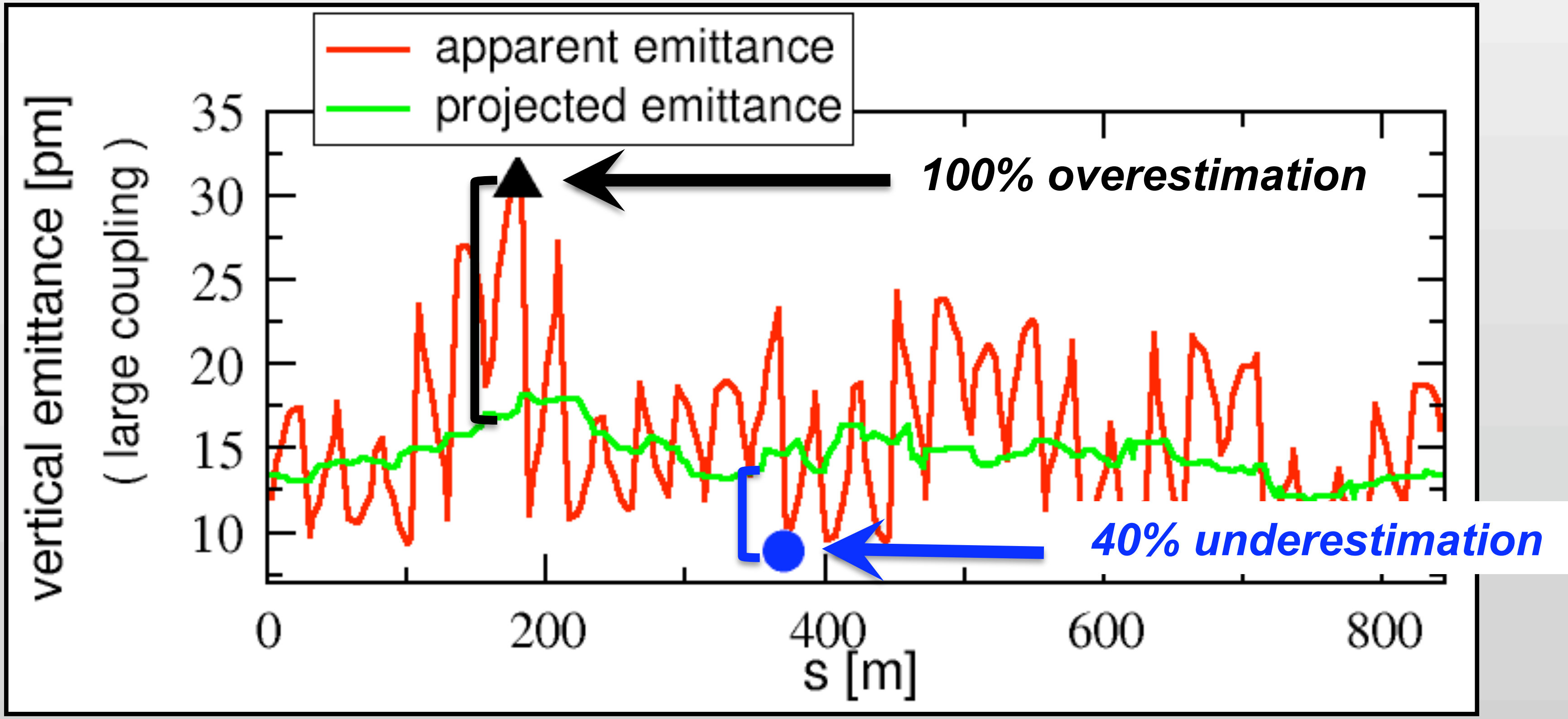

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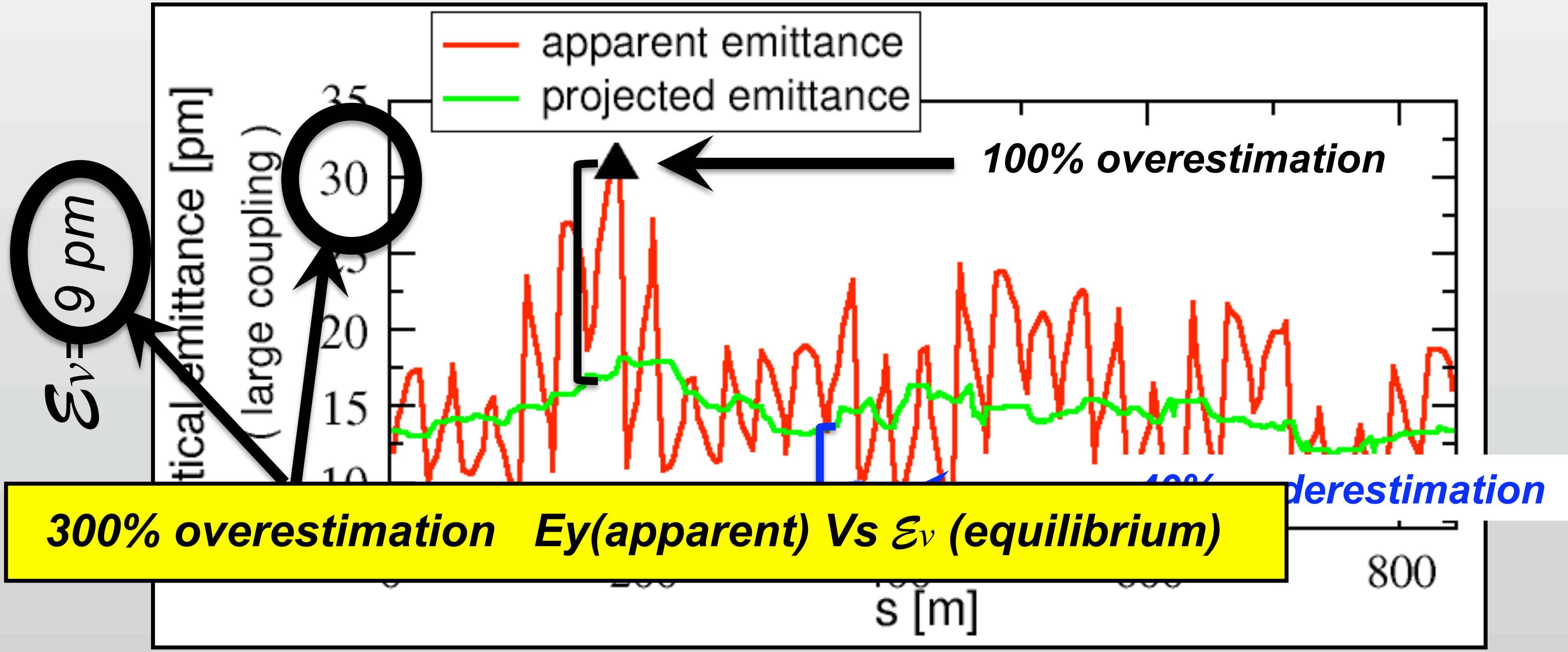

300% overestimation Ey(apparent) Vs $\mathcal{E}_v$ (equilibrium)

Vertical emittances in the presence of coupling

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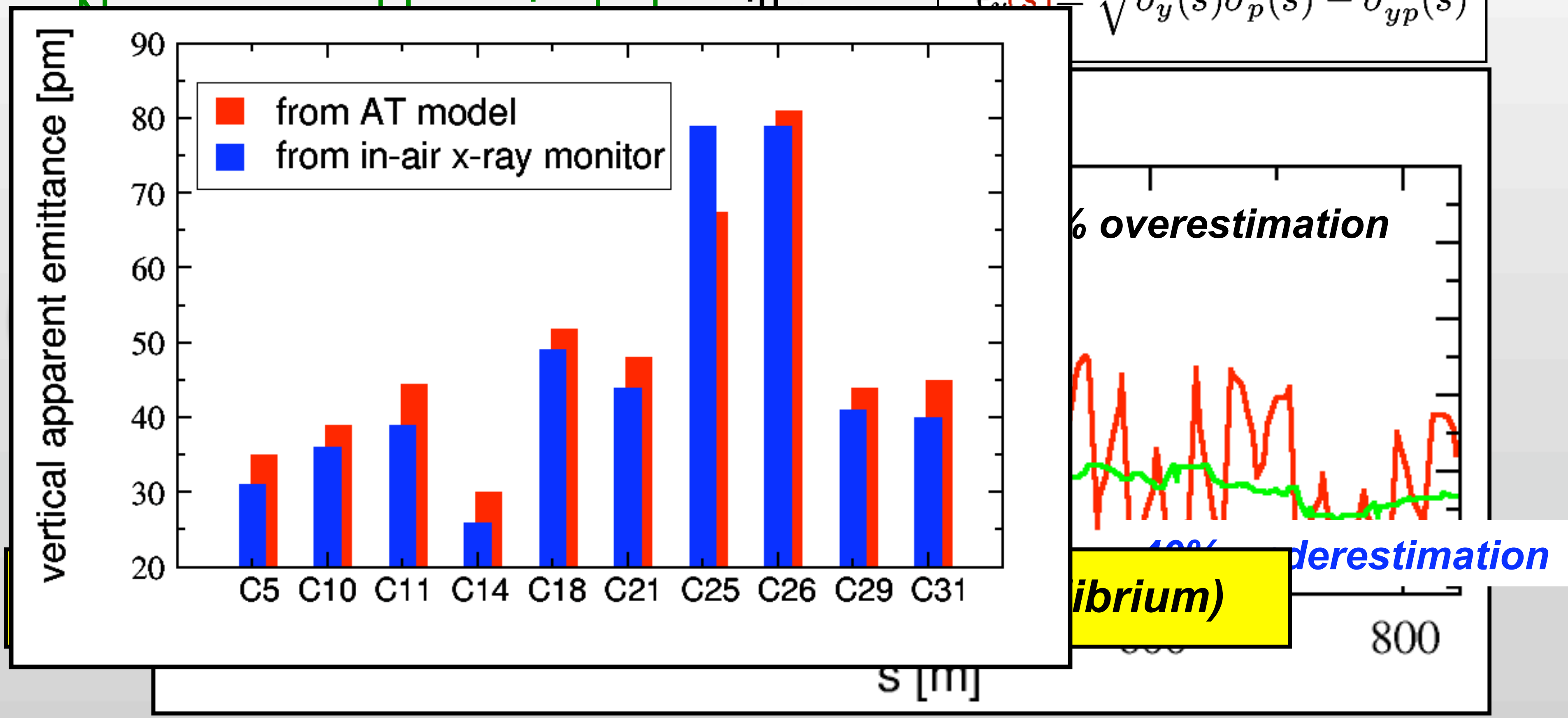

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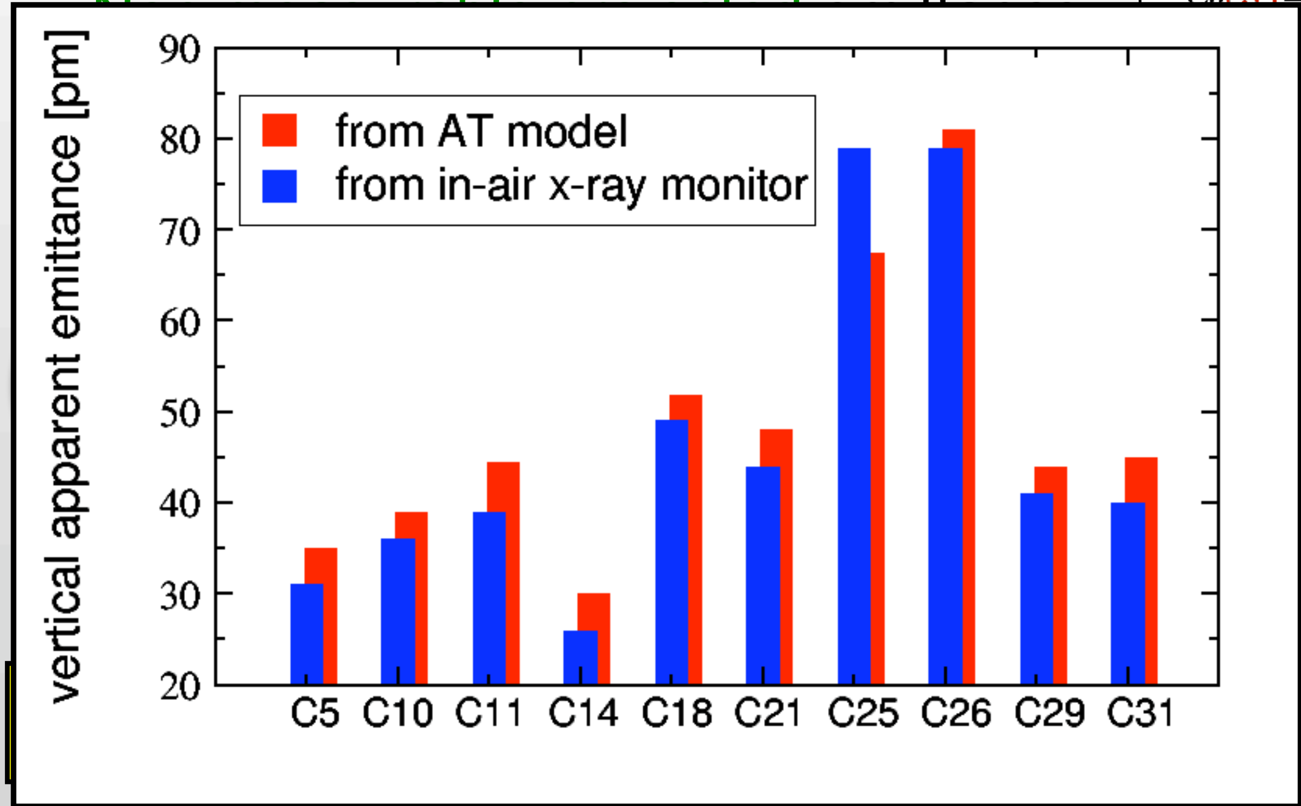
Measurable apparent emittance: $\mathbb{E}_y(s) = \frac{\sigma_y^2(s)}{\beta_y(s)} = \frac{< y^2(s) > -(\delta D_y(s))^2}{\ldots}$

$\epsilon_y(s) = \ldots$



...ibrium)

800

s [m]

Which "vertical emittance" shall we choose, then?

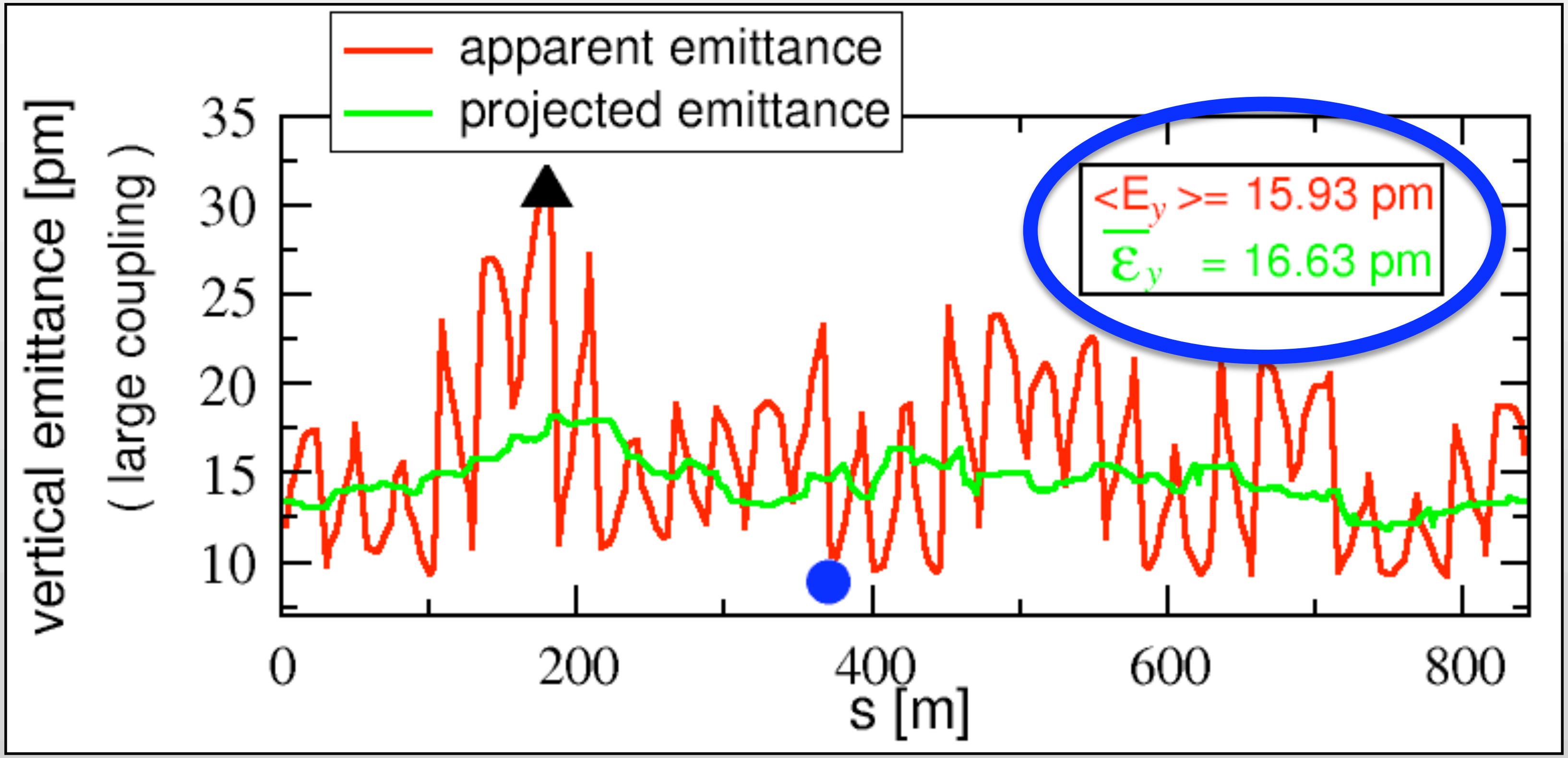
Vertical emittances in the presence of coupling

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

Average over the ring

Non measurable projected emittance: $<\epsilon_y(s)> = \sqrt{\sigma_y(s)\sigma_p(s) - \sigma_{yp}^2(s)}$

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



Vertical emittances in the presence of coupling

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Non measurable projected emittance:

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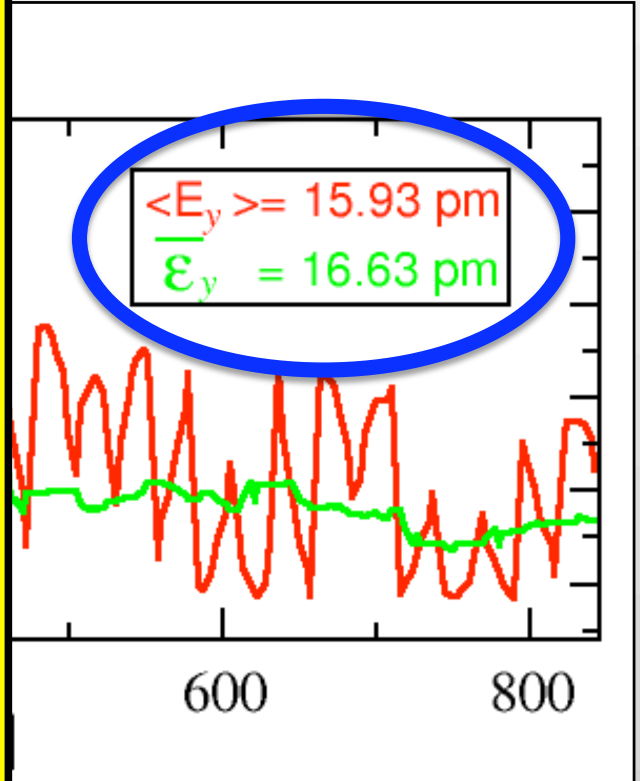
Definition of vertical emittance @ ESRF:

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

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

More details in PRSTAB-14-012804 (2011)



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Vertical emittance reduction in the storage ring

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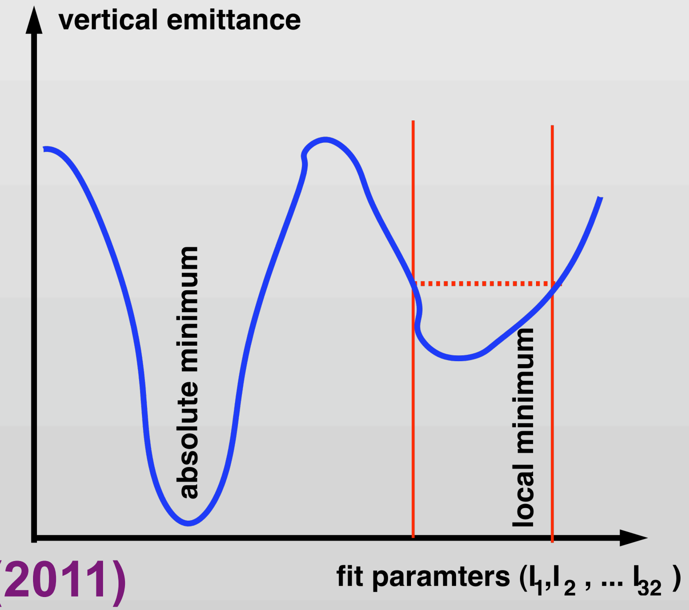
- Until 2009 their currents were computed by trying to minimize the apparent vertical emittance along the machine ➔ non-linear fitting
  - time consuming
  - may get stuck into a local minimum value



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

Vertical emittance reduction in the storage ring

- Coupling (x-y & y-δ) correction @ ESRF SR is carried out with independent skew quadrupoles ($V=J_1xy$) distributed along the machine.
- As of 2010 their currents are computed by trying to minimize other quantities: Resonance Driving Terms, obtained from orbit measurements (for x-y) and vert. disp. (for y-δ). This automatically minimizes vertical emittance ➔ linear fitting

    - faster

    - gets directly to absolute minimum value

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

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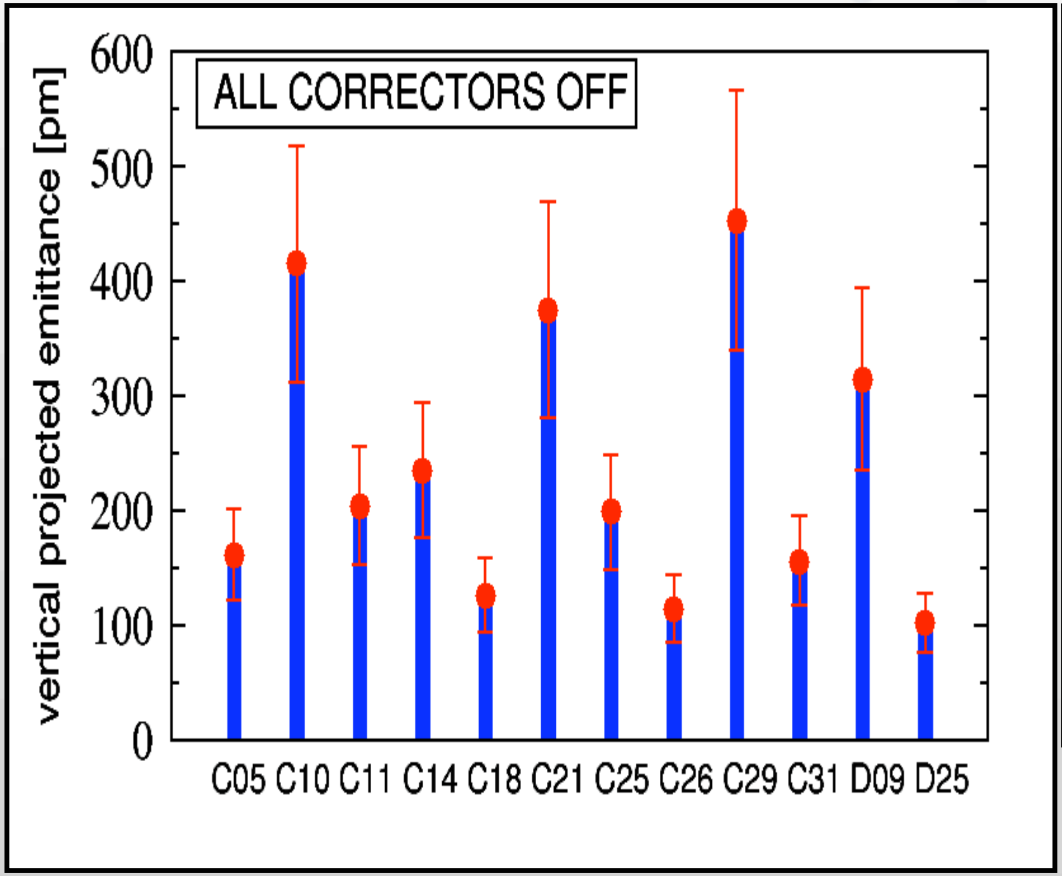
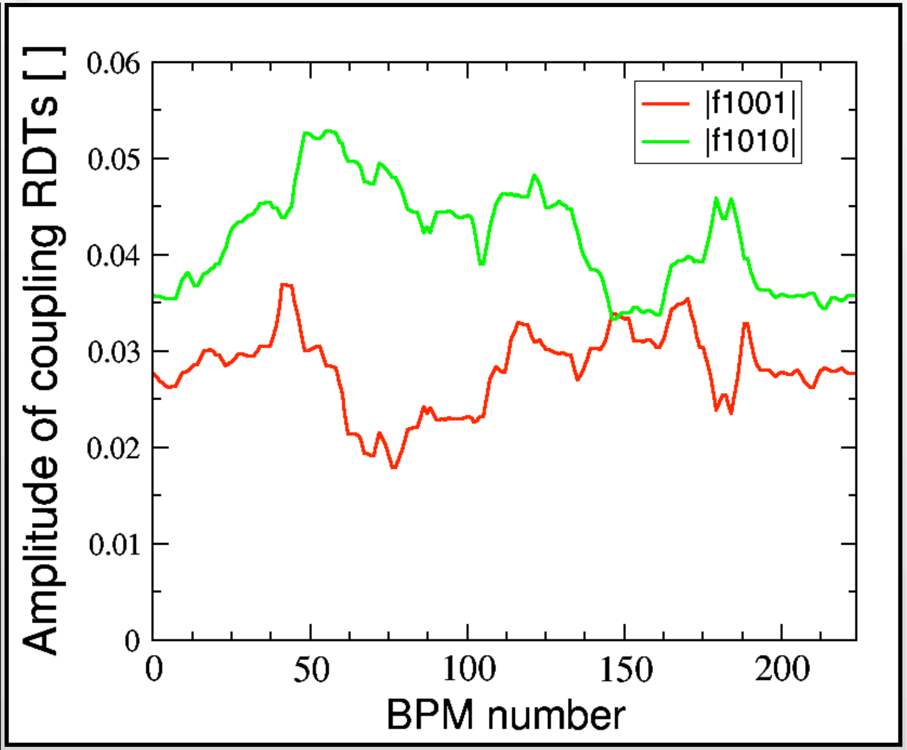
2010: Application in the ESRF storage ring

First RDT correction: January 16th 2010

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

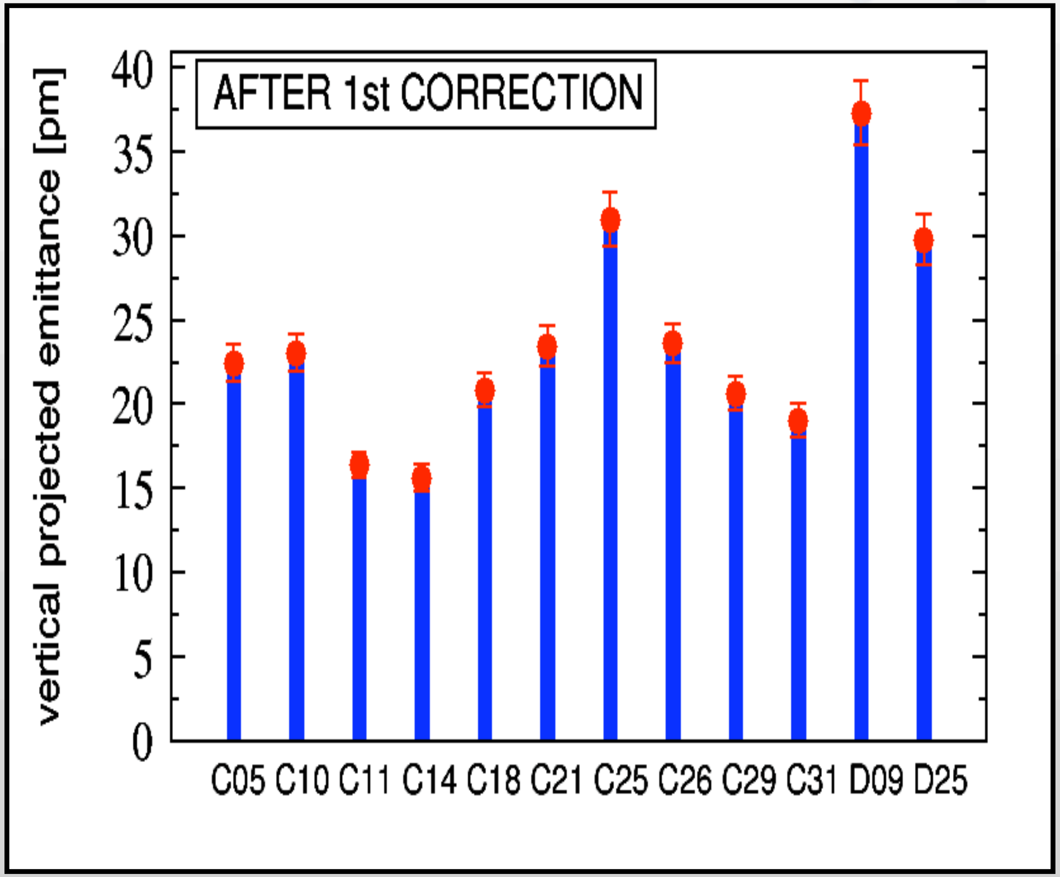


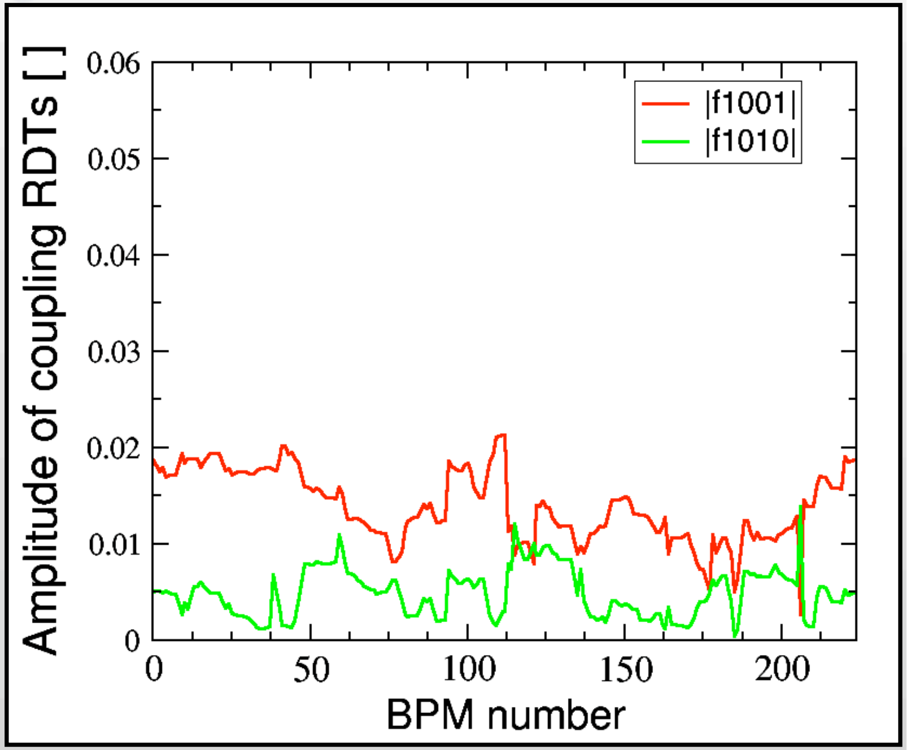


2010: Application in the ESRF storage ring

First RDT correction: January 16th 2010

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



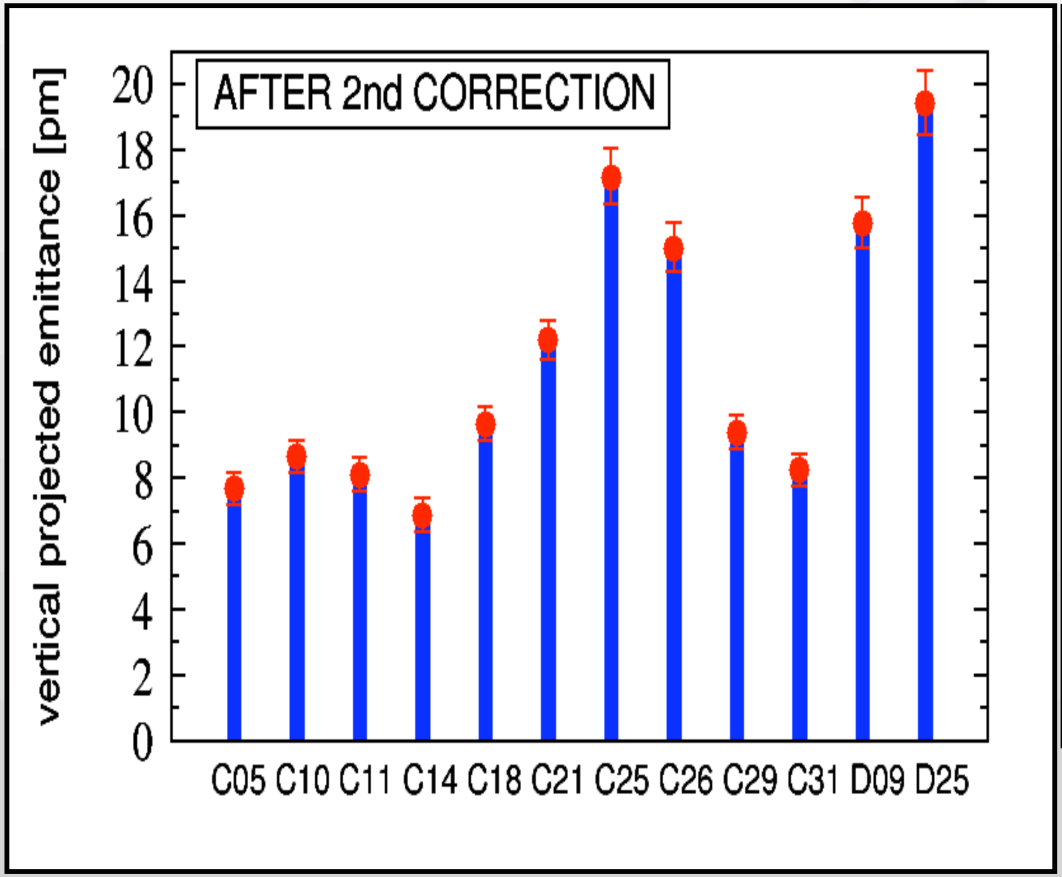


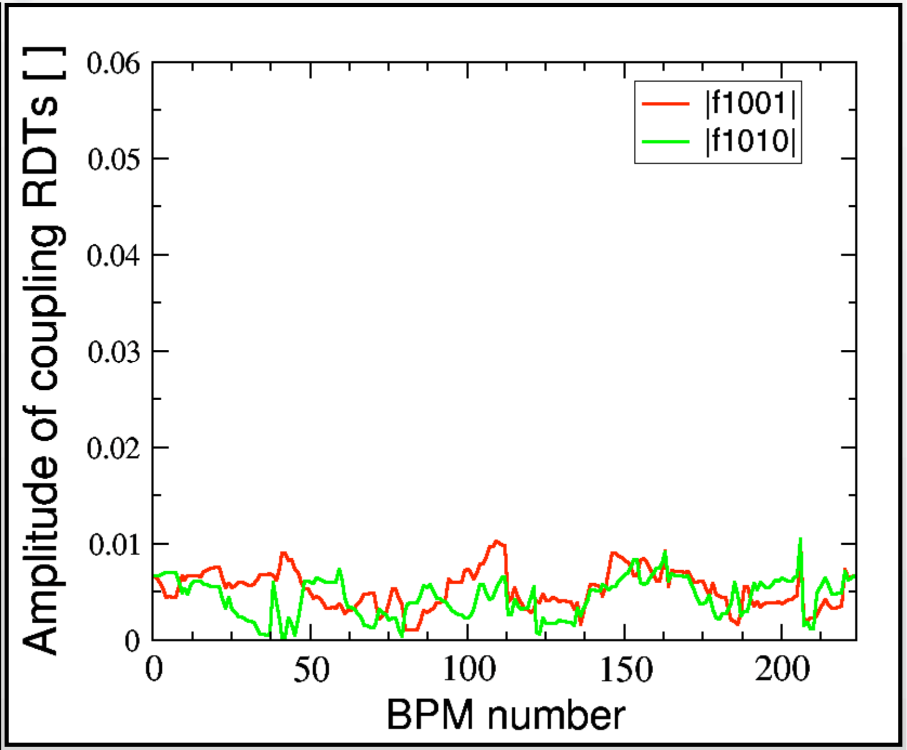
~20 min. for ORM
a few seconds for RDT correction

2010: Application in 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



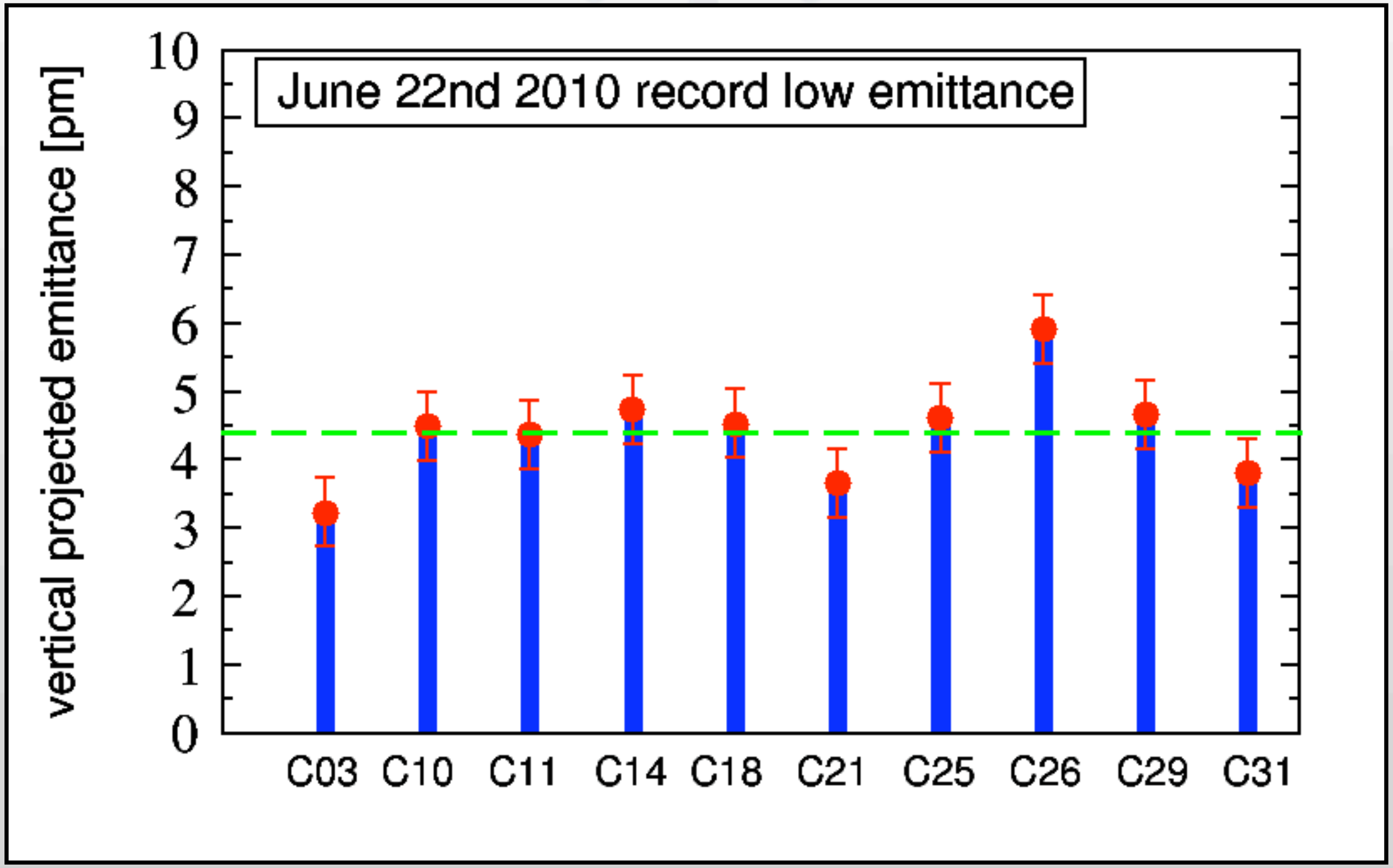


~20 min. for ORM
a few seconds for RDT correction

2010: Application in the ESRF storage ring

ESRF 2010 **temporary** record-low vertical emittance: June 22nd

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



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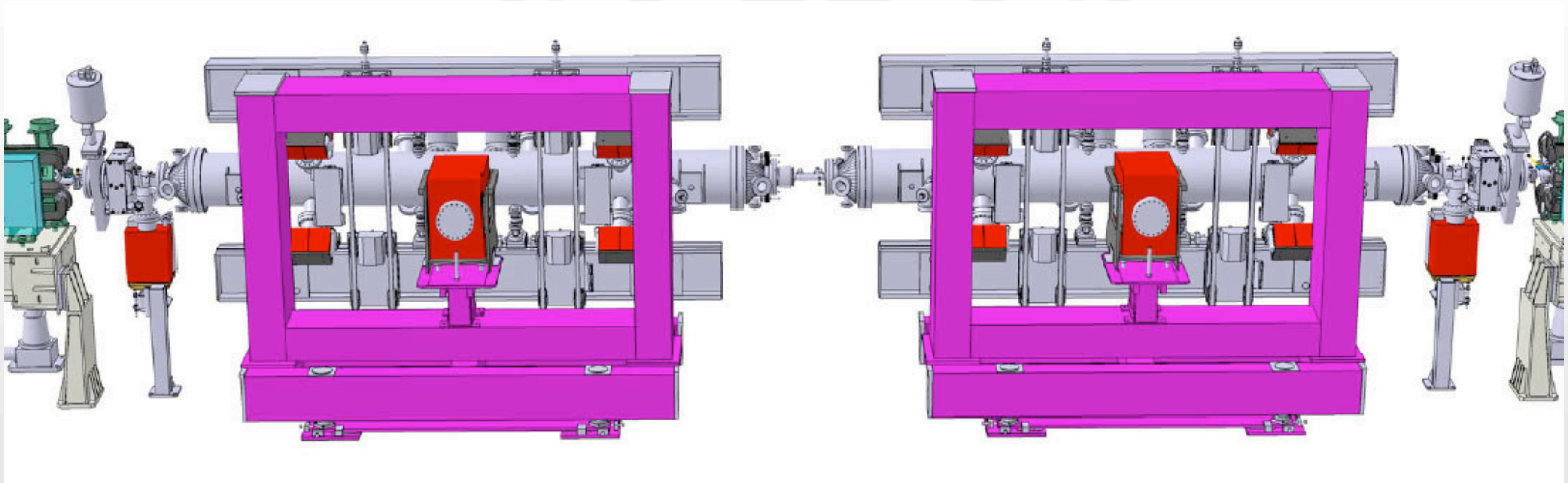
2010: Preserving vertical emittance during beam delivery

- 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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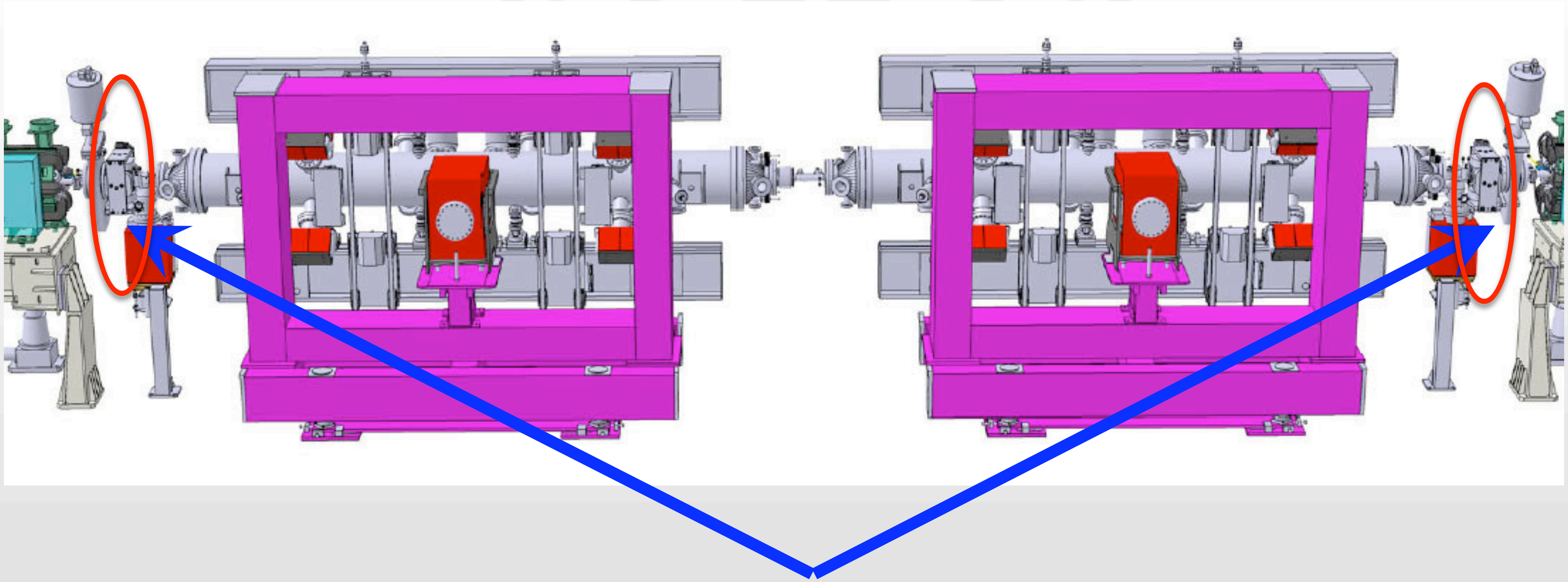
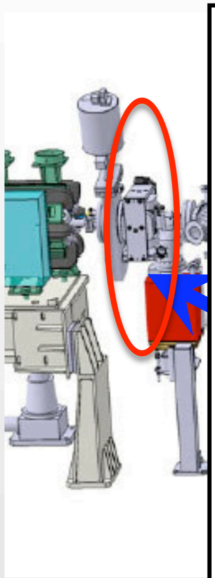
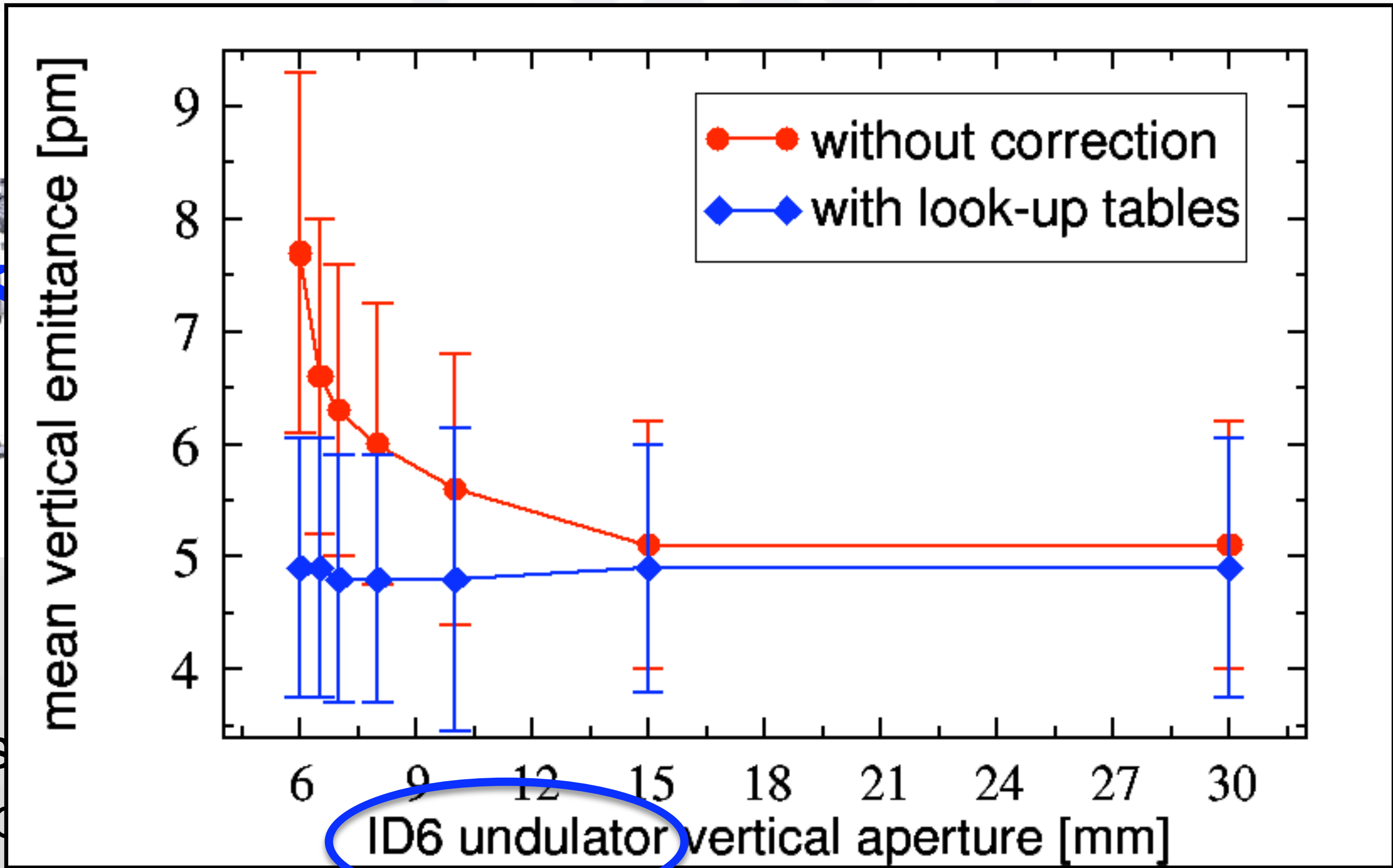


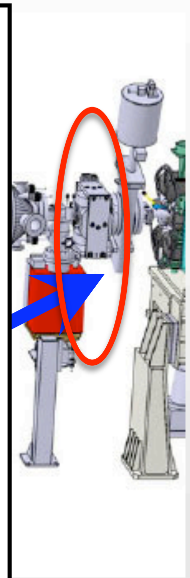
•H-V steerers at the ends of an ID straight section were cabled so as to provide skew quad fields.

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

2010: Preserving vertical emittance during beam delivery







•H-V s … led so
as to p

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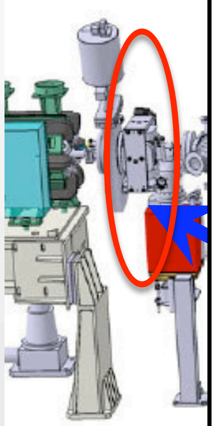
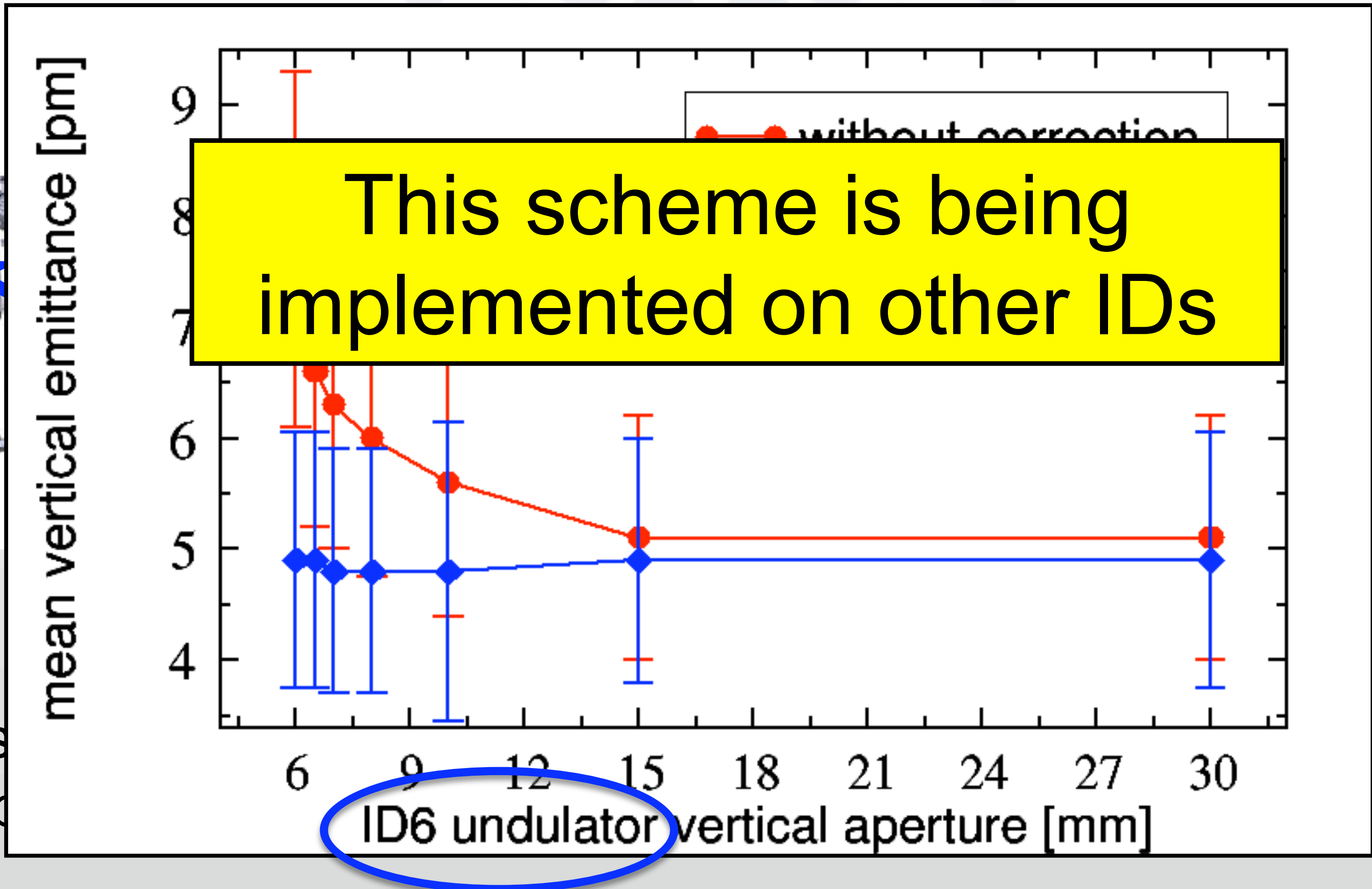
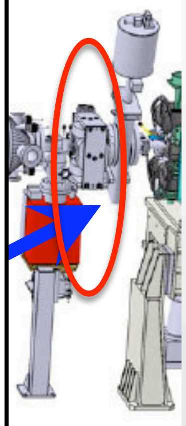
2010: Preserving vertical emittance during beam delivery





This scheme is being implemented on other IDs



•H-V s… …led so as to p…

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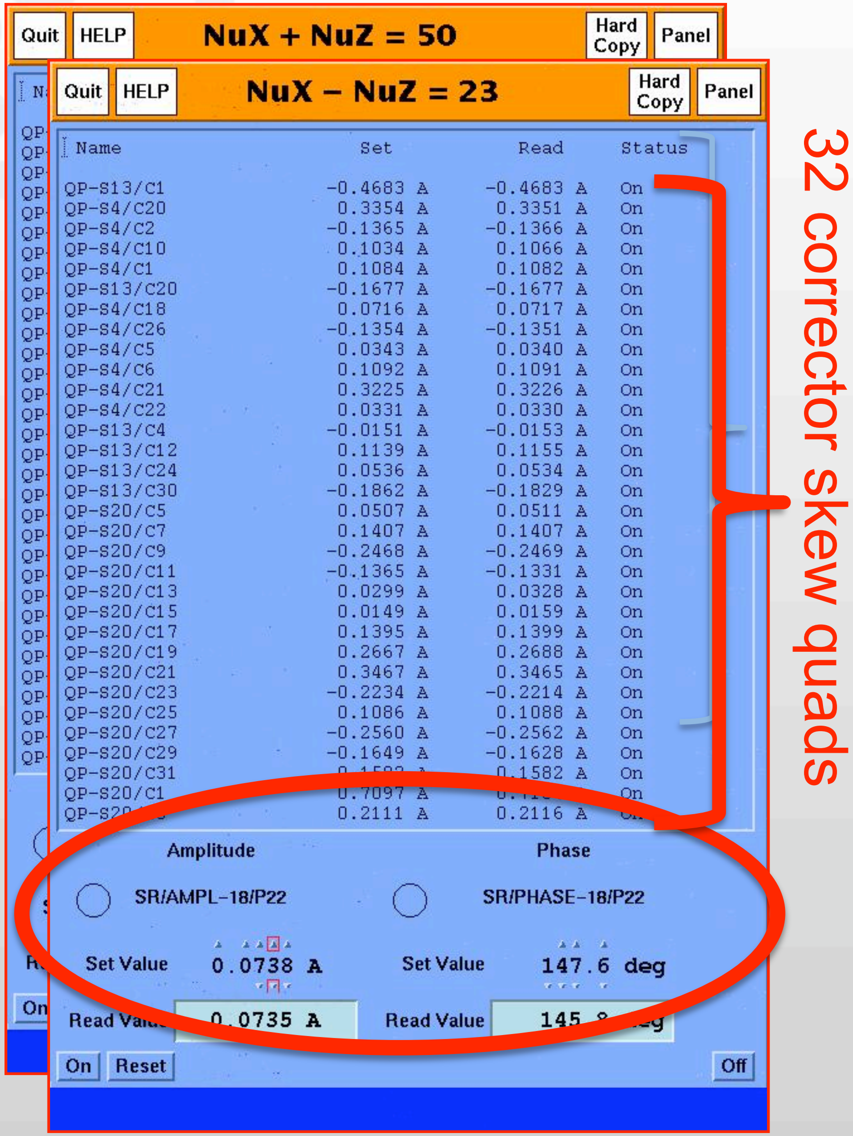
2010: Preserving vertical emittance during beam delivery

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

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

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



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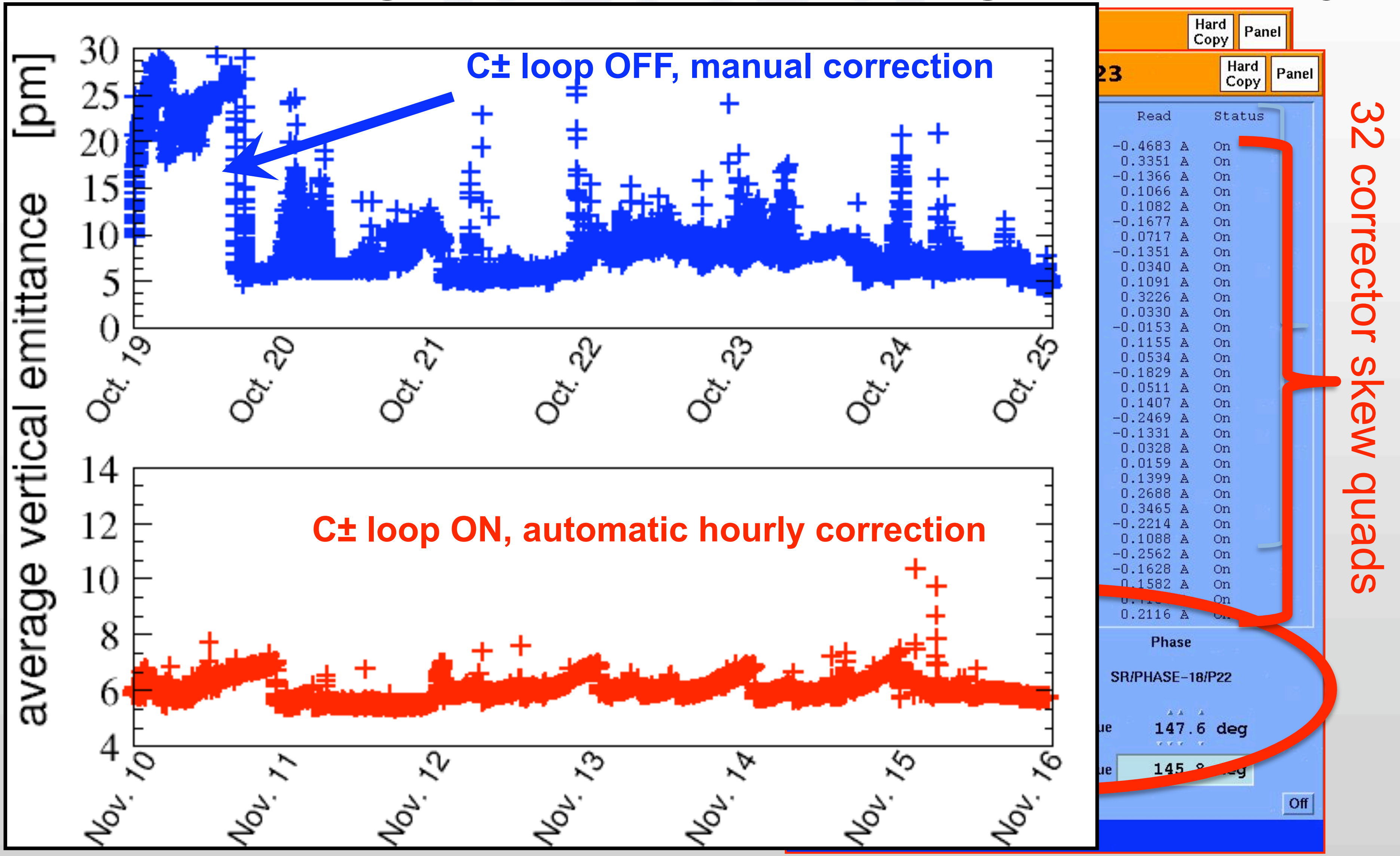

Outlines

- Vertical emittances in the presence of coupling
- Coupling correction via Resonance Driving Terms
- 2010: Application in the ESRF storage ring
- 2010: Preserving small vertical emittance during beam delivery
- 2011: Towards ultra-small vertical emittance

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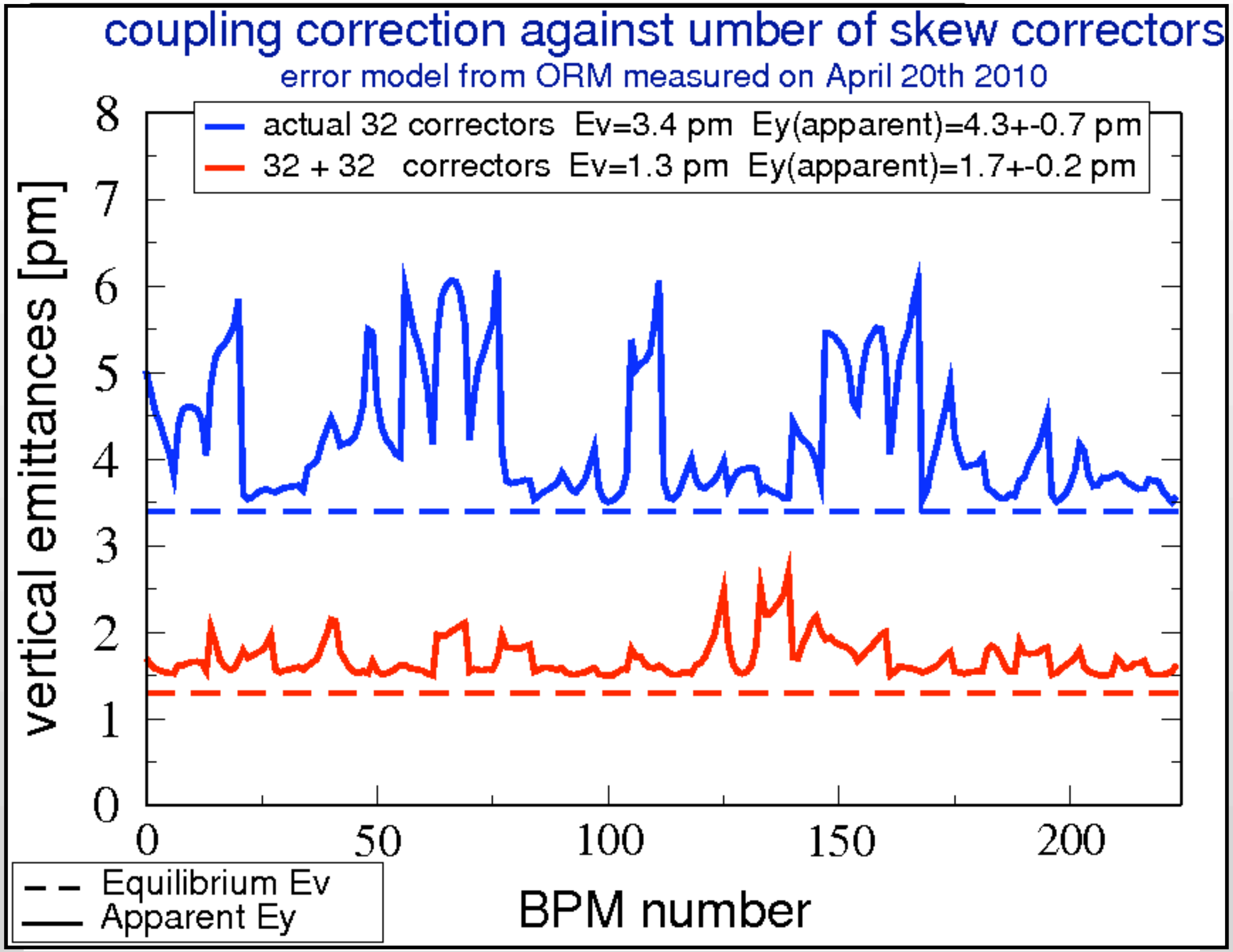

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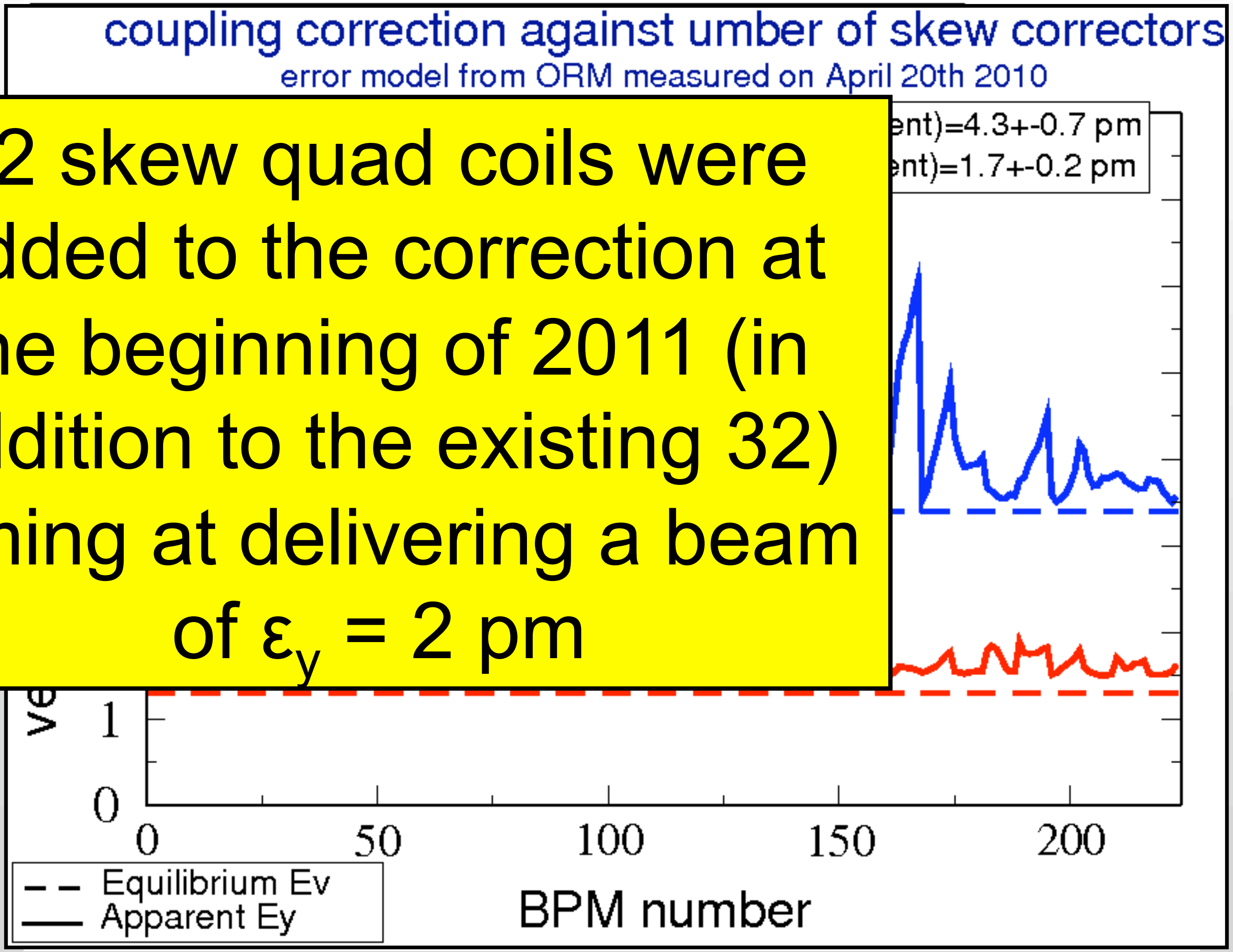
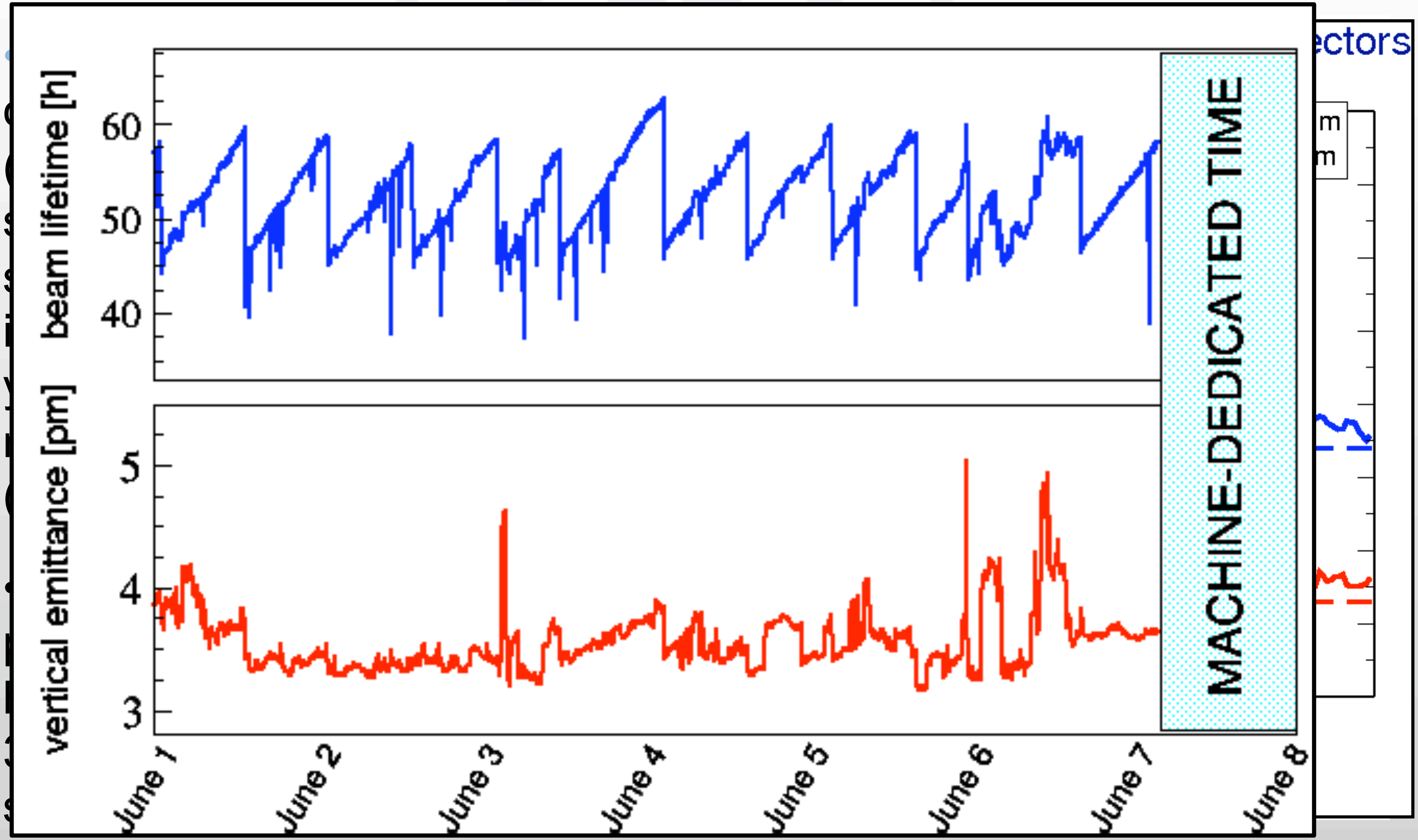


32 skew quad coils were added to the correction at the beginning of 2011 (in addition to the existing 32) aiming at delivering a beam of ε_y = 2 pm

2011: Towards ultra-small vertical emittance



2011: Towards ultra-small vertical emittance

ESRF 2011 record low (ε_x=4.2 nm):

- ε_y = 2.6 ± 1.1 pm @ low beam current (20 mA)
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- Observed intensity-dependent vertical coherent motion (both at low and high frequencies: ion-trapping instability + resistive wall impedance) may account for the larger ε_y @ high beam current

Conclusion

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- Final goal: to deliver a beam of ε_y = 2 pm.

EXTRA : Caution with Guignard's formula

- At very low coupling ε_y may be smaller than monitor/camera resolution and hence non measurable.
- One may be then tempted to use Guignard's formula

$$\epsilon_y = g\,\epsilon_x$$

$$g = \frac{(|C^-|/\Delta)^2}{(|C^-|/\Delta)^2 + 2}$$

The "large" ε_x easier to measure and "g" evaluated from tune measurements (closest tune approach). Δ = Qx-Qy (fractional part, $|C^-|$ is the difference resonance stop band.

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@ ESRF SR

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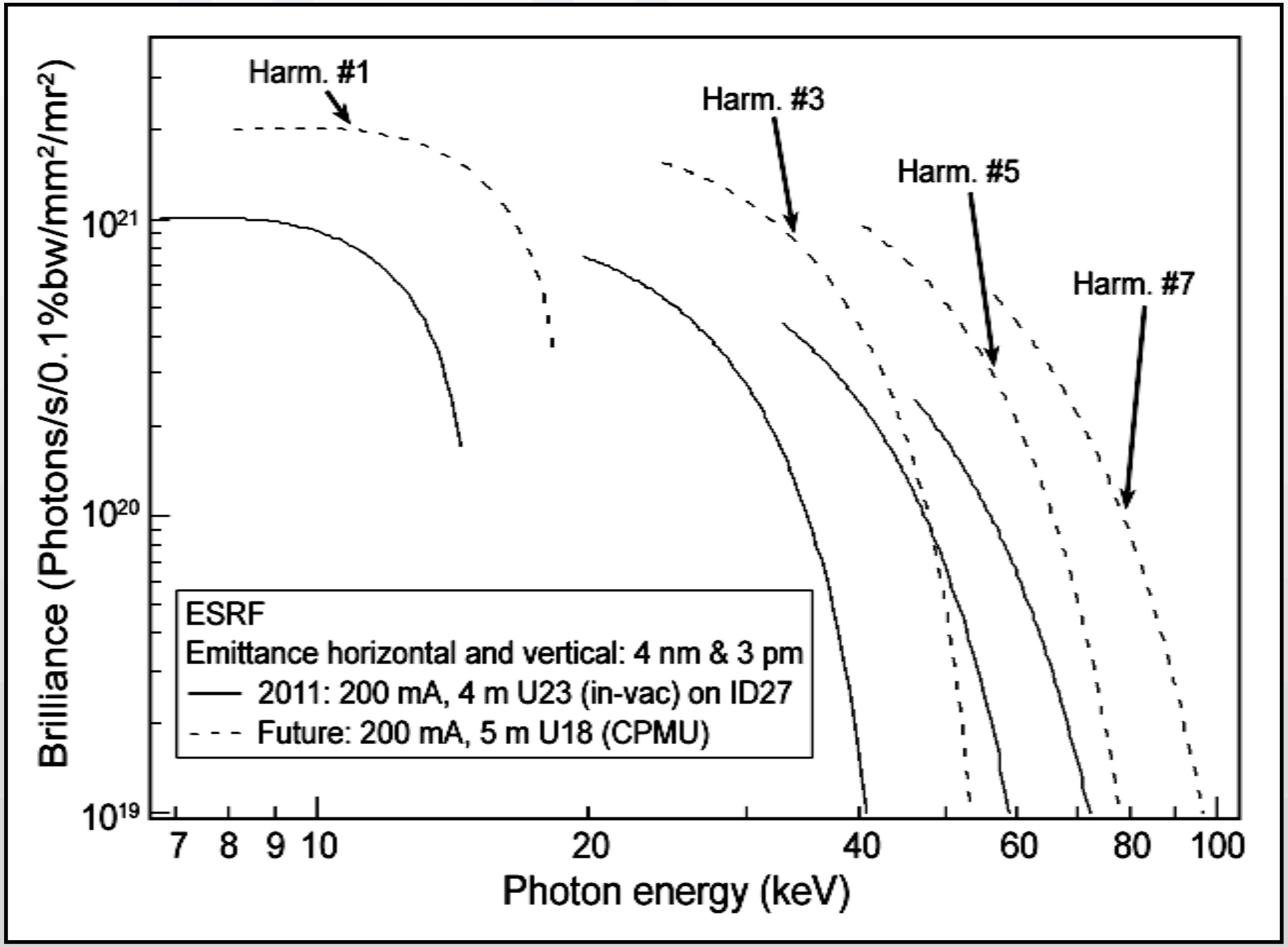
  - ✓ Vert. dispersion Dy contribution to ε_y > betatron coupling contribution (0.94 pm, 0.65 pm)

EXTRA: 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.



EXTRA: Why correcting coupling?

- Lower coupling (x-y & y-δ) ➔ lower vertical emittance ➔
  - ✓ higher brilliance (luminosity for colliders)
  - ✓ smaller vertical beam size ➔ lower ID gaps
    ➔ higher ID magnetic field ➔ higher photon flux
- Lower coupling ➔ lower radiation dose during injection, as the (unavoidable) large oscillations of the incoming electrons induce limited vertical oscillations and hence beam loss (the latter occurs mainly in the vertical plane)
- But lower bunch volume ➔ higher probability of electron collisions (Touschek) ➔ lower lifetime