Experience on Coupling Correction in the ESRF electron storage ring

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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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• 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
Meas. vertical emittance $E_y$ from RMS beam size

ESRF SR equipment:
• 11 dipole radiation projection monitors (IAX)
• 2 pinhole cameras
Meas. vertical emittance $E_y$ from RMS beam size

$E_x = 4.2$ nm

- Well corrected coupling
- Low beam current (20 mA)
Meas. vertical emittance $E_y$ from RMS beam size

$E_x = 4.2$ nm
- Well corrected coupling
- Low beam current (20 mA)

$E_y = 3.0$ pm
$\pm 1.3$ (STD)
Meas. vertical emittance $E_y$ from RMS beam size

$E_x = 4.2$ nm

- Uncorrected coupling
- Low beam current (20 mA)

$E_y = 46$ pm ± 18 (STD)
Vertical emittances in the presence of coupling

Measurable apparent emittance:

\[
\mathbb{E}_y(s) = \frac{\sigma_y^2(s)}{\beta_y(s)} = \frac{< y^2(s) > - (\delta D_y(s))^2}{\beta_y(s)}
\]
Vertical emittances in the presence of coupling

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\[ \mathbb{E}_y(s) = \frac{\sigma_y^2(s)}{\beta_y(s)} = \frac{\langle y^2(s) \rangle - (\delta D_y(s))^2}{\beta_y(s)} \]

Non measurable projected emittance:

\[ \epsilon_y(s) = \sqrt{\sigma_y(s)\sigma_p(s) - \sigma_{yp}^2(s)} \]
Vertical emittances in the presence of coupling

Measurable apparent emittance:

\[
\bar{\varepsilon}_y(s) = \frac{\sigma_y^2(s)}{\beta_y(s)} = \frac{\langle y^2(s) \rangle - (\delta D_y(s))^2}{\beta_y(s)}
\]

Non measurable projected emittance:

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

Lattice errors from Orbit Response Matrix measurement + Accel. Toolbox
Vertical emittances in the presence of coupling

Measurable apparent emittance:

$$E_y(s) = \frac{\sigma^2_y(s)}{\beta_y(s)} = \frac{\langle y^2(s) \rangle - (\delta D_y(s))^2}{\beta_y(s)}$$

Non measurable projected emittance:

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

![Graph showing emittance over distance with annotations for 100% overestimation and 40% underestimation.]

- Apparent emittance
- Projected emittance

$E_y = 9$ pm

$\epsilon_y = 9$ pm (large coupling)
**Vertical emittances in the presence of coupling**

Measurable apparent emittance:

\[
E_y(s) = \frac{\sigma_y(s)}{\beta_y(s)} = \frac{<y^2(s)> - (\delta D_y(s))^2}{\beta_y(s)}
\]

Non measurable projected emittance:

\[
\epsilon_y(s) = \sqrt{\sigma_y(s)\sigma_p(s) - \sigma_{yp}(s)}
\]

300% overestimation \( E_y(\text{apparent}) \) Vs \( \varepsilon_v(\text{equilibrium}) \)

100% overestimation

40% underestimation

\( \varepsilon_v = 9 \text{ pm} \)
Vertical emittances in the presence of coupling

**Measurable apparent emittance:**
\[ \mathcal{E}_y(s) = \frac{\sigma_y(s)}{\beta_y(s)} = \frac{\langle y^2(s) \rangle - (\delta D_y(s))^2}{\beta_y(s)} \]

**Non measurable projected emittance:**
\[ \epsilon_y(s) = \sqrt{\sigma_y(s)\sigma_p(s) - \sigma_{yp}^2(s)} \]

![Graph showing vertical apparent emittance vs. S with data points for different TES values. The graph compares emittance from AT model and in-air x-ray monitor.](image)
Vertical emittances in the presence of coupling

Measurable apparent emittance:

\[ \mathcal{E}_y(s) = \frac{\sigma_y^2(s)}{\beta_y(s)} = \frac{\langle y^2(s) \rangle - (\delta D_y(s))^2}{\beta_y(s)} \]

Non measurable projected emittance:

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

From 6x6 matrix of the ohmienvelope function

From 6x6 matrix of the ohmienvelope function
Vertical emittances in the presence of coupling

Measurable apparent emittance:

\[ E_y(s) = \frac{\sigma_y(s)}{\beta_y(s)} \quad <y^2(s) > = -(\delta D_y(s))^2 \]

Non measurable projected emittance:

\[ \epsilon_y(s) = \frac{1}{2} \left( \frac{\sigma_y(s)}{\beta_y(s)} \right)^2 \]

Which "vertical emittance" shall we choose, then?

![Graph showing vertical emittance measurements from AT model and in-air x-ray monitor for various beamlines (C5 to C31).]
Vertical emittances in the presence of coupling

Measurable apparent emittance:
\[ \mathbb{E}_y(s) = \frac{\sigma_y^2(s)}{\beta_y(s)} = \frac{\langle y^2(s) \rangle - (\delta D_y(s))^2}{\beta_y(s)} \]

Average over the ring

Non measurable projected emittance:
\[ \langle \epsilon_y(s) \rangle = \sqrt{\sigma_y(s)\sigma_p(s) - \sigma_{yp}^2(s)} \]

\[ \mathbb{E}_y = 9 \text{ pm} \]

Graph showing apparent and projected emittance as a function of position (s).
**Vertical emittances in the presence of coupling**

Measurable apparent emittance:

\[
\mathbb{E}_y(s) = \frac{\sigma_y^2(s)}{\beta_y(s)} = \frac{\langle y^2(s) \rangle - (\delta D_y(s))^2}{\beta_y(s)}
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Non measurable projected emittance:

\[
\langle \epsilon_y(s) \rangle = \sqrt{\sigma_y(s)\sigma_p(s) - \sigma_{yp}^2(s)}
\]

<table>
<thead>
<tr>
<th>Vertical emittance [pm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_v = 9 pm</td>
</tr>
</tbody>
</table>

(apparent emittance)

(projected emittance)

\[\langle E_y \rangle = 15.93 \text{ pm} \]

\[\mathcal{E}_y = 16.63 \text{ pm}\]
Vertical emittances in the presence of coupling

Measurable apparent emittance:

\[ \langle E_y(s) \rangle = \frac{\langle y^2(s) \rangle - (\delta D_y(s))^2}{\beta_y(s)} \]

Average over the ring

Non measurable projected emittance:

\[ \langle \epsilon_y(s) \rangle = \sqrt{\sigma_y(s) \sigma_p(s) - \sigma_{yp}(s)} \]

Definition of vertical emittance @ ESRF:

\[
\bar{\epsilon}_y = \frac{1}{C} \int \epsilon_y(s) ds \sim \langle E_y \rangle = \frac{1}{N} \sum_{n=1}^{n=N} E_{y,n}
\]

\[
\delta \epsilon_y = \left( \sum_n (E_{y,n} - \langle E_y \rangle)^2 / N \right)^{1/2}
\]

More details in PRSTAB-14-012804 (2011)

\[ \langle E_y \rangle = 15.93 \text{ pm} \]

\[ \bar{E}_y = 16.63 \text{ pm} \]
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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.
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.
- 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
Vertical emittance reduction in the storage ring

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AT code + Matlab `fminsearch` function
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AT code + Matlab `FMINSEARCH` function
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Details and formulas in PRSTAB-14-012804 (2011)
Vertical emittance reduction in the storage ring

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Vertical emittance reduction in the storage ring

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• 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.

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Vertical emittance reduction in the storage ring

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- 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)
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
   \[ F = (a_1 f_{1001}, a_1 f_{1010}, a_2 Dy), \quad a_1 + a_2 = 1 \]
2. Evaluate response matrix of the available skew correctors \( M \)
3. Find via SVD a corrector setting \( J \) that minimizes both RDTs and Dy
   \[ J = -M F \] to be pseudo-inverted
Coupling correction via Resonance Driving Terms

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   \[ \vec{J} = -\mathbf{M} \vec{F} \] to be pseudo-inverted
Coupling correction via Resonance Driving Terms

\[
\text{ORM} = \begin{pmatrix}
O_{xx} & O_{xy} \\
O_{yx} & O_{yy}
\end{pmatrix}
\]

Orbit Response Matrix

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

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

\[
\mathbf{F} = (a_1 f_{1001}, a_1 f_{1010}, a_2 Dy), \quad a_1 + a_2 = 1
\]

1. Evaluate response matrix of the available skew correctors \( \mathbf{M} \)

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\mathbf{J} = -\mathbf{M} \mathbf{F} \text{ to be pseudo-inverted}
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\[ \vec{J} = -M \vec{F} \] to be pseudo-inverted

Fitting measured diagonal blocks from ideal ORM => focusing errors \( \Delta K_1 \).
Coupling correction via Resonance Driving Terms

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

Fitting measured off-diagonal blocks from ideal ORM $\Rightarrow$ effective quadrupole tilts $\theta$
(accounting for sextupole ver. misalignments)

1. Build an error lattice model (quad tilts, etc. from Orbit Response Matrix or turn-by-turn BPM data) $\Rightarrow$ 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
   $$\vec{J} = -M \vec{F} \quad \text{to be pseudo-inverted}$$
Coupling correction via Resonance Driving Terms

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

$$J_1 = -[K_1 + \Delta K_1] \sin(2\theta)$$

1. Build an error lattice model (quad tilts, etc. from Orbit Response Matrix or turn-by-turn BPM data) => RDTs and Dy
   $$\vec{\Phi} = (a_1 * f_{1001}, a_1 * f_{1010}, a_2 * Dy), \ a_1 + a_2 = 1$$

1. Evaluate response matrix of the available skew correctors M
2. Find via SVD a corrector setting \( \hat{J} \) that minimizes both RDTs and Dy
   $$\hat{J} = -M \vec{\Phi}$$ to be pseudo-inverted

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

Andrea Franchi

Vertical Emittance reduction @ ESRF
Coupling correction via Resonance Driving Terms

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

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

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

(accounting for sextupole ver. misalignments)
Coupling correction via Resonance Driving Terms

Vertical dispersion $D_y$ is measured at all 224 BPMs

1. Build an error lattice model (quad tilts, etc. from Orbit Response Matrix or turn-by-turn BPM data) => RDTs and $D_y$
   \[ \mathbf{F} = (a_1 f_{1001}, a_1 f_{1010}, a_2 D_y), \quad a_1 + a_2 = 1 \]

1. Evaluate response matrix of the available skew correctors $\mathbf{M}$
2. Find via SVD a corrector setting $\mathbf{J}$ that minimizes both RDTs and $D_y$
   \[ \mathbf{J} = -\mathbf{M}^{\dagger} \mathbf{F} \text{ to be pseudo-inverted} \]
Coupling correction via Resonance Driving Terms

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

\[ \mathbf{F} = (a_1 f_{1001}, a_1 f_{1010}, a_2 \text{Dy}), \quad a_1 + a_2 = 1 \]

1. Evaluate response matrix of the available skew correctors \( \mathbf{M} \)
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\[ \mathbf{J} = -\mathbf{M} \mathbf{F} \] to be pseudo-inverted
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1. Build an error lattice model (quad tilts, etc. from Orbit Response Matrix or turn-by-turn BPM data) => RDTs and Dy
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2. Find via SVD a corrector setting \( \mathbf{J} \) that minimizes both RDTs and Dy
   \[ \mathbf{J} = -\mathbf{M} \mathbf{F} \] to be pseudo-inverted

\[ f_{\frac{1001}{1010}} = \sum_{w} W J_{w,1} \sqrt{\beta_{x}^{w} \beta_{y}^{w}} e^{i(\Delta \phi_{w,x} + \Delta \phi_{w,y})} \]
\[
\frac{1}{4(1 - e^{2\pi i(Q_{u} + Q_{v})})}
\]
Coupling correction via Resonance Driving Terms

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

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

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

\[\vec{F} = (a_1 f_{1001}, a_1 f_{1010}, a_2 \text{Dy}) \quad , \quad a_1 + a_2 = 1\]

1. Evaluate response matrix of the available skew correctors \(\mathbf{M}\)

2. Find via SVD a corrector setting \(\mathbf{J}\) that minimizes both RDTs and Dy

\[\mathbf{J} = -\mathbf{M} \vec{F} \quad \text{to be pseudo-inverted}\]
**Coupling correction via Resonance Driving Driving Terms**

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

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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

   \[ \vec{J} = -M \vec{F} \quad \text{to be pseudo-inverted} \]
Coupling correction via Resonance Driving Terms

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

\[
RDTs = (a_1 * f_{1001}, a_1 * f_{1010}, a_2 * Dy), \quad a_1 + a_2 = 1
\]

1. Evaluate response matrix of the available skew correctors \( M \)

2. Find via SVD a corrector setting \( \mathbf{J} \) that minimizes both RDTs and Dy

\[
\mathbf{J} = -M \mathbf{F} \quad \text{to be pseudo-inverted}
\]

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

\[
m_{w,c} = \frac{\sqrt{\beta_x^{(c)} \beta_y^{(c)}} e^{i(\Delta \phi_{w,x}^{(c)} + \Delta \phi_{w,y}^{(c)})}}{4(1 - e^{2\pi i (Q_u + Q_v)})} \quad \text{for } w > 224,
\]
Coupling correction via Resonance Driving Terms

\[
\begin{pmatrix}
a_1 \hat{f}_{1001} \\
a_1 \hat{f}_{1010} \\
a_2 \hat{D}_y
\end{pmatrix}_{\text{meas}} = -M J_c,
\]

\[a_2 = 0.7 \ (2010) , \ 0.4 \ (2011)\]

\[a_1 + a_2 = 1\]

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

\[\hat{F} = (a_1 * f_{1001}, a_1 * f_{1010}, a_2 * Dy), \ a_1 + a_2 = 1\]

1. Evaluate response matrix of the available skew correctors \(M\)

2. Find via SVD a corrector setting \(\hat{J}\) that minimizes both RDTs and Dy

\[\hat{J} = -M \hat{F} \text{ to be pseudo-inverted}\]
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2010: Application in the ESRF storage ring

First RDT correction: January 16\textsuperscript{th} 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
2010: Application in the ESRF storage ring

First RDT correction: January 16\textsuperscript{th} 2010

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

$|f_{1010}| \sim |f_{1001}| \Rightarrow$

sum resonance may not be neglected $\Rightarrow$

be careful with indirect measurement of $\varepsilon_y$

~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 22\textsuperscript{nd}

At ID gaps open: $\overline{\varepsilon}_y \pm \delta \varepsilon_y = 4.4 \pm 0.7 \ p\text{m}$
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. 20\textsuperscript{th} 2010, during beam delivery and movements of two ID gaps (black & green)
2010: Preserving vertical emittance during beam delivery

- H-V steerers at the ends of an ID straight section were cabled so as to provide skew quad fields.
2010: Preserving vertical emittance during beam delivery

- 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.
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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

![Graph showing mean vertical emittance vs vertical aperture with data points for 'without correction' and 'with look-up tables']

- ID6 undulator
- Vertical aperture [mm]
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.

This scheme is being implemented on other IDs.

2010: Preserving vertical emittance during beam delivery

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

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

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

\[
C^+ = -\frac{1}{2\pi} \oint ds \, j(s) \sqrt{\beta_x(s)\beta_y(s)} e^{-i(\phi_x(s) + \phi_y(s)) + is/R\Delta}
\]
2010: Preserving vertical emittance during beam delivery

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32 corrector skew quads
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Outlines

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

2010, with 32 skew quad correctors
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• Benefits and drawbacks; operational considerations
 Benefit: Brilliance @ $\varepsilon_y = 3$ 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.
Benefit: Injection Efficiency

- Injection tuning after shutdown (steering in the transfer line, septa optimization) observed to be more effective if performed after coupling correction in the storage ring
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<table>
<thead>
<tr>
<th>Filling mode</th>
<th>inj. eff. until 2009 operation</th>
<th>inj. eff. as of 2010 operation</th>
<th>inj. eff. as of 2010 open IDs &amp; scrapers</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 bunches (92mA)</td>
<td>30-50%</td>
<td>50-70% (*)</td>
<td>~100% (*)</td>
</tr>
<tr>
<td>7/8 +1 (200mA)</td>
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</table>

(*) with new optics  (^) with lower chromaticity
Drawback: reduced lifetime (7/8 +1 filling mode, @ 200 mA)

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Focusing errors

RMS quad err.  Beta Beating

Corrector strengths
Operational considerations: the ORM+correction software

- Coupling & $D_y$
- RMS tilts (quad & bending)
- Ver. Disp. $D_y$
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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)
Conclusion

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• Two procedures to preserve small vertical emittance during beam delivery were successfully tested: as of spring 2011 stable $\varepsilon_y = 3.2$-4.5 pm delivered to users (lifetime of 45 hours after refilling @ 200 mA, 10 hours less than in the past only).