Low vertical emittance at the SLS

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SVET collaboration

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ESLS XIX meeting, Aarhus, Nov. 23-24, 2011
SVET Collaboration

Test Infrastructure and Accelerator Research Area
www.eu-tiara.eu
Work package 6 “SVET” (SLS Vertical Emittance Tuning)

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SVET main collaborators

**PSI** → **SLS coupling suppression and control**
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**Max-IV Lab** → **MAX-IV emittance measurement and coupling control**
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1. Vertical emittance

1.1 Quantum limit

- direct photon recoil, \(1/\gamma\) radiation cone


- independent of energy!

- examples:
  - SLS: 0.20 pm
  - MAX-IV: 0.05 pm
  - PETRA-III: 0.04 pm

\(\Rightarrow\) lower limit of vertical emittance

\(\Rightarrow\) quantum emittance \(<\!<\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\! \)
1.2. Vertical emittance with coupling

A. Franchi et al., *Vertical emittance reduction and preservation in electron storage rings via resonance drive terms correction*, PRSTAB 14, 034002 (2011)

Coupling (diff. and sum resonances) from skew quads, sextupole heaves and quad rolls.

Vertical correctors, bend rolls, quad heaves

Eigen-ε (invariant) → Projected ε (s) → Apparent ε (s) → y'

Vertical dispersion

Projected ε (s) → y'

Apparent ε (s) → y'

Coupling terms: $h_{10010} \& h_{10100}$

Vertical emittance $h_{00101}$
Vertical emittance properties

- Apparent-$\epsilon$ oscillates around the lattice.
  - Oscillation amplitude is lower for low coupling
- Projected-$\epsilon$ changes at skew quad kicks.
- Eigen-$\epsilon$ is invariant.
- Minimization of apparent $\epsilon$ at one location minimizes eigen-$\epsilon$ too:

Simulation (TRACY, 100 seeds, SLS with 6 skew quads):
Eigen-$\epsilon$ results, when optimizing on beam size at monitor (→) vs. optimizing on eigen-$\epsilon$ itself (↑).

Å. Andersson et al., NIM A 592 (2008) 437-446
2. Machine preparation

2.1 BPM roll measurements

- **Methods:**
  - Local bumps (150 μm) with fast orbit feedback: get BPM roll from corrector currents.
  - LOCO fit to response matrix.
- **BPM roll:** 17 mrad RMS.
- **Origin:** electronics.

Spoils measurements of vertical dispersion.

\[ \Rightarrow \text{Low level implementation as "3rd BBA constant": BPM sway, heave & roll} \]

\[ \Rightarrow \text{M. Böge et al., The Swiss Light Source – a test-bed for damping ring optimization, Proc. IPAC-2010} \]

Correlation of two BPM roll measurements
2.2 Knobs for coupling control

- **120 sextupoles (9 families) with additional coils:**
  - 72 wired as horizontal/vertical orbit correctors.
  - 12 wired as auxiliary sextupoles for sextupole resonance suppression (empirical).
  - 36 wired as skew quadrupoles:
    - 12 dispersive, 24 non-dispersive.

- **Skew quads from orbit bumps in 120 sextupoles:**
  - 72 dispersive, 48 non-dispersive “skew quads”

\[ a_2 = 2b_3 y_o \]
2.3 Emittance (beam size) monitor

- \( \pi \)-polarization method: image of vertically polarized visible-UV synchrotron radiation.
- Get beam height from peak-to-valley intensity ratio: lookup-table of SRW simulations.
- Resolution:
  - Beam height \( \pm 0.5 \, \mu m \)
  - Emittance \( \pm 0.7 \, \mu m \) (incl. dispersion subtraction)

Å. Andersson et al., NIM A 592 (2008) 437-446
Existing monitor (364 nm) inside tunnel:
- Aging problems (UV radiation damage?)
- Upgrade: operate at 250 nm for higher resolution ($\rightarrow 3$ μm beam height)

Proposal for new monitor:
- Magnification $\times 2..3$. Reflective optics. Optical table outside tunnel.
3. Girder realignment

3.1 The SLS dynamic girder alignment system

- **Remote** positioning of the 48 girders in 5 DOF \((u, v, \chi, \eta, \sigma)\) by eccentric cam shaft drives.
- 36 dipoles (no gradients) supported by adjacent girders.
  - except 3 super-bends: extra supports
  - except laser slicing insertion FEMTO
- Magnet to girder alignment \(< 50 \ \mu m\)
  - girder rail 15 \ \mu m, magnet axis 30 \ \mu m

\[\text{S. Zelenika et al., The SLS storage ring support and alignment systems, NIM A 467 (2001) 99}\]
3.2 Beam based girder alignment

- 48 girders (shift & angle) = 96 “correctors”
- Response & correction matrices for
  - orbit correction (saves 75% CH, 100% CV strength !),
  - or, vertical dispersion suppression.
- Orbit based remote girder alignment rejected:
  - Mistrust in girder moving procedures.
  - Possible negative impact on user operation.
3.3 Survey based girder realignment

- Girder **heave** and **pitch** from survey
- Align girders to medium line (long wavelength machine deformation is not a problem)
- Fast orbit feedback active ↓ correctors confirm girder move.

M. Böge et al., *SLS vertical emittance tuning*, Proc. IPAC-2011
Corrector strengths before and after girder realignment, and after beam based BPM calibration* (sector 1) (*girder move causes vacuum chamber deformation)

⇒ Factor ≈ 4 reduction of rms CV kick in sector (= 4 girders)
Status (Sep. 2011) : done, partially done, malfunction

Sector 1 2 3 4 5 6 7 8 9 10 11 12

Vertical corrector kick (all CV) 140 \(\Rightarrow\) 81 \(\mu\text{rad}\) rms
(expect \(\approx\)60 \(\mu\text{rad}\) rms after repair of sectors 4,9,11)

\[\uparrow\text{Re-establishment of "train link" between G06 and G07}\]
G07 pitch 70 \(\mu\text{m}\), confirmed by hydrostatic leveling system \(\rightarrow\)
Manual alignment of super-bend between G06/G07
\(\Rightarrow\) Improvement for beam line too.
4. Emittance minimization

4.1 Vertical dispersion measurement

- Vertical orbit as function of energy
- Upgrade of RF oscillator for fast frequency shift
- Prerequisite: determination of BPM roll errors.

Vertical dispersion measurement

Energy range ± 0.3% \((-\Delta f = \pm 920 \text{ Hz})\)

20 points

10 minutes

65 \(\mu\)m resolution
4.2 Vertical dispersion suppression

- 12 dispersive skew quadrupoles \( D_x \approx 33 \text{ cm} \)
- 73 BPMs \(\Rightarrow 73 \times 12\) dispersion response matrix
- Feed in measured \( D_y \Rightarrow \) apply \(\Rightarrow\) measure again.
- Best results up to now: \( D_y \approx 1 \text{ mm RMS} \).

\[
D_y(s) = \frac{\sqrt{\beta_y(s)}}{2 \sin \pi Q_y} \int_C F(s') \sqrt{\beta_y(s')} \cos \left( |\mu(s) - \mu(s')| - \pi Q_y \right) ds'
\]

\[
F(s) = b_2 y_{co} + 2b_3 D_x y_{co} - a_2 D_x + a_1
\]

- Orbit bump in quadrupole
- Orbit bump in dispersive sextupole
- Vertical dipole
- Dispersive skew quadrupole
4.3 Betatron coupling correction

- 24 non-dispersive skew quads.
- From model: coupled response matrix as function of skew quad strength: Jacobian \( \{ \partial \mathbf{R}\mathbf{M}/ \partial a_{2k}\} \).
- 73 BPMs and CH/CV: \( \Rightarrow 146 \times 146 \times 24 \) tensor.
- Rearrange: \( 21316 \times 24 \) matrix \( \Rightarrow \) SVD-inversion.
  - Alternative: use only coupled \( \mathbf{R}\mathbf{M} \)-quadrants: \( 73 \times 73 \times 24 \) tensor \( \Rightarrow 5329 \times 24 \) matrix.
- Feed in measured orbit response matrix.
- Fit 24-vector \( \{ \Delta a_2 \} \) of skew quad strengths.
- Apply inverse to machine: \( -\{ \Delta a_2 \} \).
- Iterate within model for large errors.
- Compensates also betatron coupling increase from previous vertical dispersion suppression.
4.4 Orbit manipulation

“dispersion free steering”

- Orbit bumps:
  - get skew quads from sextupoles
  - get vertical dipoles from quadrupoles

- Simultaneous suppression of vertical dispersion and betatron coupling.

- Individual corrector method: use all correctors with additional constraints on orbit and optics

- 3-bump method: closed orbit bumps for compatibility with user operation.

- M. Aiba et al., *Coupling and vertical dispersion correction in the SPS, Proc. IPAC-2010*
- Application of the individual corrector method:
- Reduction $D_y = 1.4 \rightarrow 1.1 \text{ mm RMS.}$
- Orbit $310 \mu\text{m RMS.}$
- Dispersion spikes resistant to correction $\Rightarrow$ steps between girders

- Recent (Aug. 30) MD-shift ($S. \text{ Liuzzo, M. Aiba, M. Böge}$): $\Rightarrow$ vertical emittance $3.6 \text{ pm}$ with all skew quads off.
4.5 Emittance achievements

- Best result up to now (March 16, 2011):
  
a) coupling correction
b) vertical dispersion suppression $\rightarrow$ 1.4 mm RMS
c) 2 iterations of coupling correction
  ! no orbit manipulations

$\Rightarrow$ Beam height $5 \pm 0.5 \, \mu m$ RMS $\Rightarrow \varepsilon_y = 1.9 \pm 0.4 \, pm$

( dispersion not subtracted )
Outlook

- **Next steps**
  - repair malfunctioning girder movers and realign
  - iterate further dispersion and coupling correction
  - orbit manipulations on top of skew quad correction

- **Emittance monitor maintainence & upgrade**
  - understand and cure aging problems
  - operate existing monitor at lower wavelength for higher resolution (Dec. 2011)
  - design, construction and commissioning of a new monitor with even higher resolution (2012).