Reaching 1 pm vertical emittance at the Swiss Light Source storage ring

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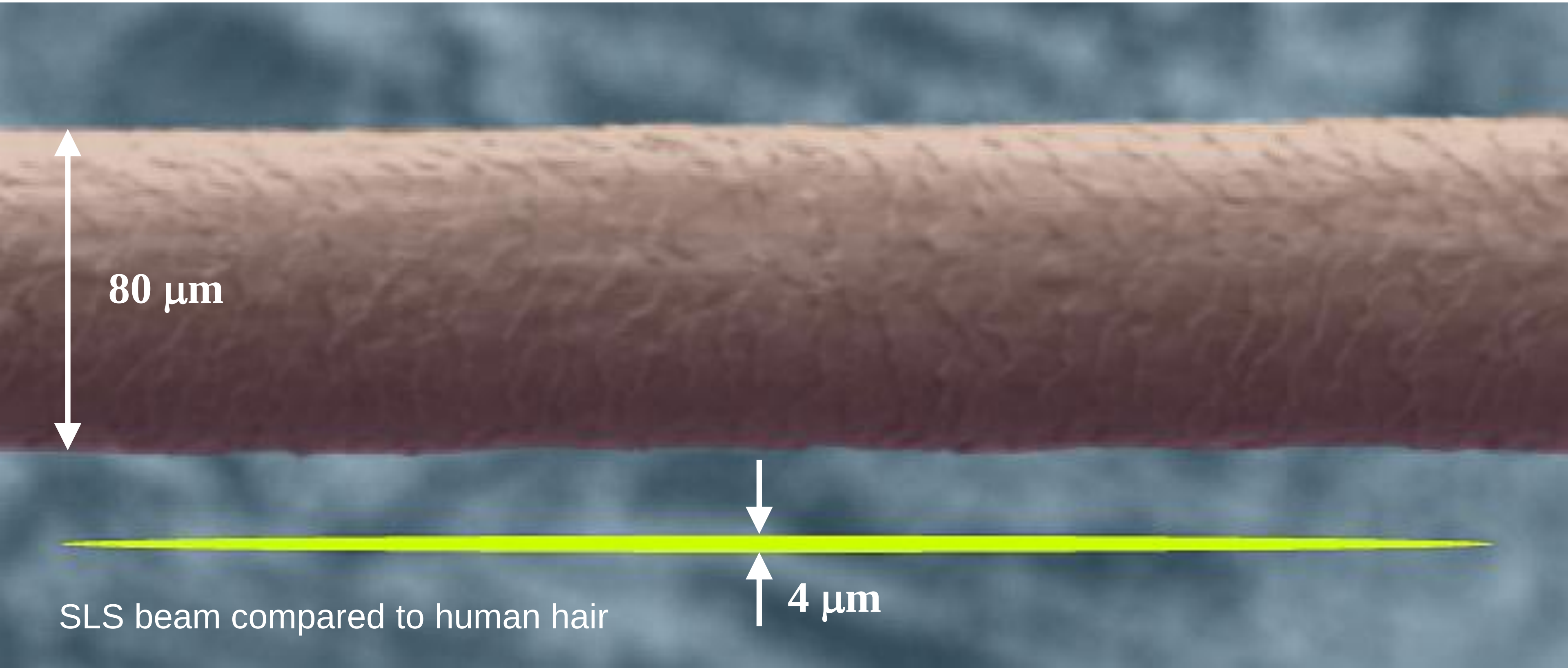
TIARA mid-term meeting, CIEMAT, Madrid, June 12-14, 2012



SLS beam compared to human hair

Contents

- TIARA work package 6 SVET
- The Swiss Light Source SLS
- Vertical emittance
- Instrumentation
  - Knobs for tuning
  - Beam profile monitor
- Methods for vertical emittance minimization
  - BPM roll error measurement
  - Magnet girder realignment
  - Correction of vertical dispersion and betatron coupling
  - Orbit manipulations and optics corrections
  - Random walk optimization
- Vertical emittance record
- Upgrade: high resolution beam profile monitor
- Summary and outlook

SLS Vertical Emittance Tuning (SVET)

Test Infrastructure and Accelerator Research Area
www.eu-tiara.eu
Work package 6 “SVET”

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“The main objective of SVET is to upgrade the Swiss Light Source (SLS) at PSI to enable R&D on ultra-low emittances. [...] SLS will – after this upgrade – be an R&D infrastructure suitable to investigate ultra-low vertical emittance tuning and control, in particular also in the regime of strong IBS. This is relevant for damping rings of future linear colliders and for next generation light sources.”

SVET partners

PSI → **SLS coupling suppression and control**
CERN → **CLIC damping ring design**
INFN/LNF → **Super-B factory design**
Max-IV-Lab → **MAX-IV emittance measurement and coupling control**

SVET activities

- **Verification of low vertical emittance**

  beam size (σ_y) & magnet optics (β_y) $\rightarrow$ emittance $\varepsilon_y = \sigma_y^2/\beta_y$

  $\Rightarrow$ High resolution beam size monitor

  PSI, MAX-IV-Lab

- **Minimization of vertical emittance**

  Optic correction & tuning methods and automation

  $\Rightarrow$ skew quadrupole and orbit settings

  PSI, INFN/LNF

- **IBS simulations and measurements**

  IBS = intra beam scattering:

  increase of emittance and energy spread for high current.

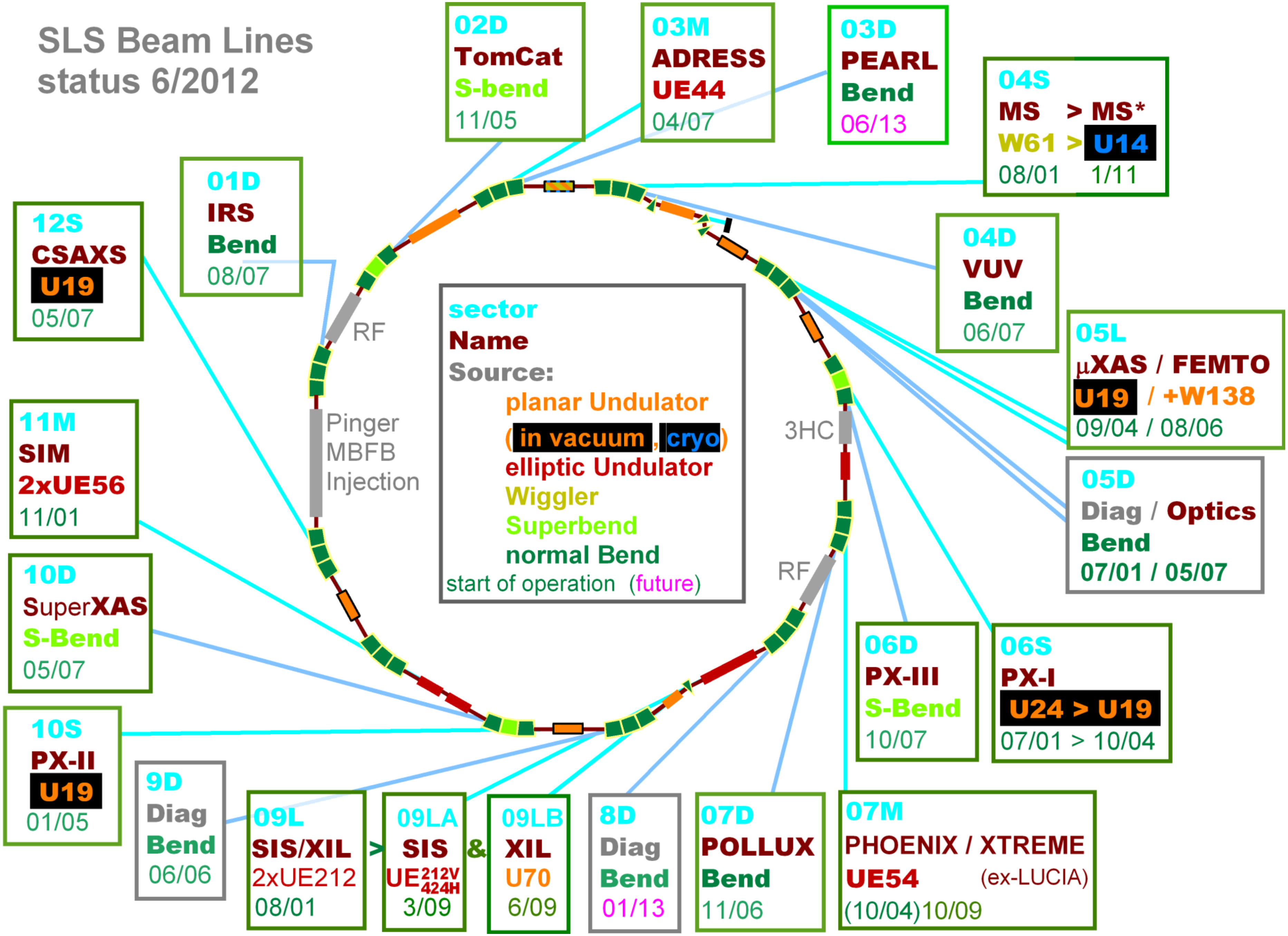
  $\Rightarrow$ low energy (1.6 GeV) operation of SLS

  CERN, INFN/LNF, PSI

The Swiss Light Source (SLS)

- Light source profile
  - compact lattice 288 m
  - medium energy 2.4 GeV
  - low emittance 5.5 nm
  - top up operation 400 ±1 mA
- User operation since 2001
  - 18 beam lines
  - 98% availability
  - 1 micron photon beam stability

SLS Beam Lines
status 6/2012

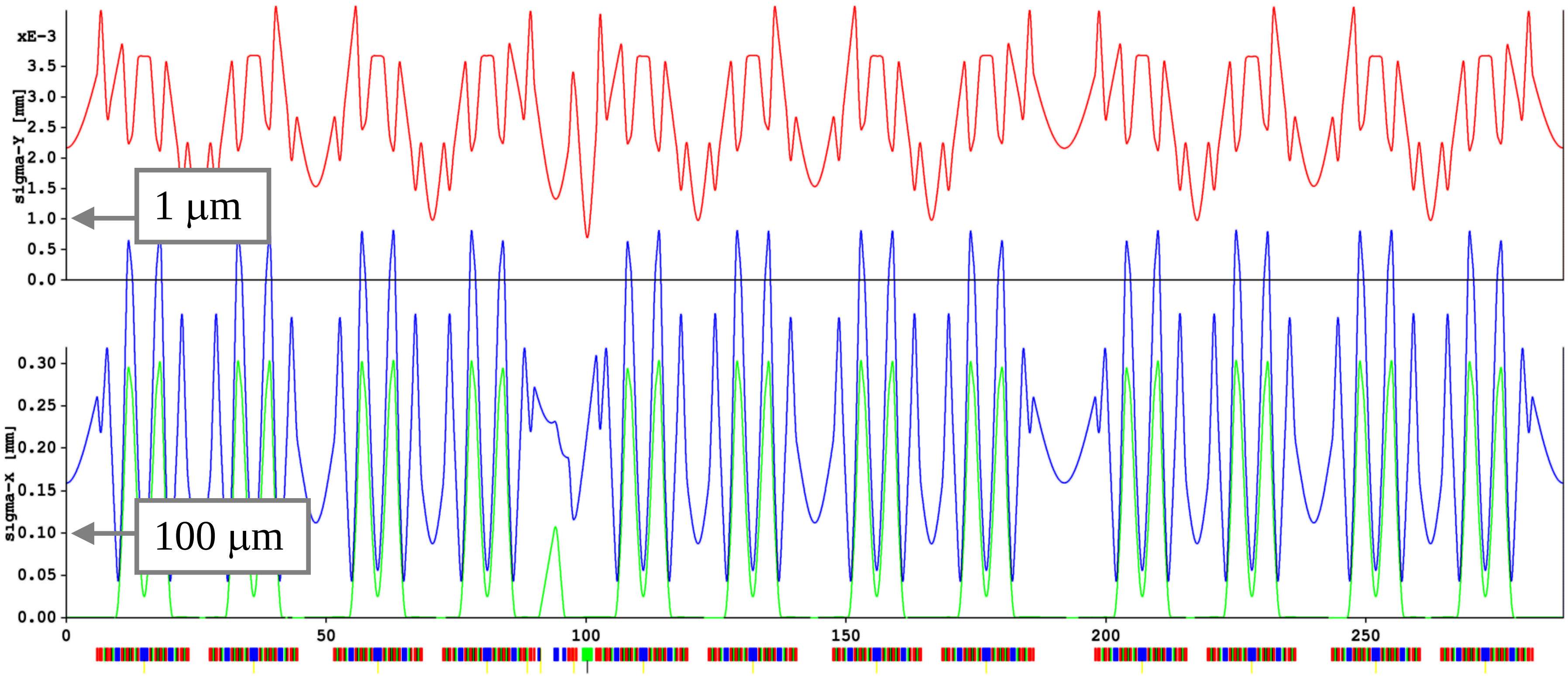


Why the SLS storage ring is well suited for vertical emittance tuning studies

- **Prerequisite**: high beam stability
  - Top up operation → thermal stability
  - Precise beam position monitors (~100 nm [<100Hz])
  - Fast orbit feedback system (0dB at 90 Hz)
- **Equipment** for vertical emittance tuning
  - High resolution beam size monitor
  - 36 skew quadrupoles for coupling control
  - Dynamic alignment system (girder movers)
- **Experience**: low coupling achieved in 2008
  - vertical emittance 3.2 pm (0.06% coupling)

RMS beam size in SLS

- Vertical beam size (σ_y) for ε_y = **1 pm**
- Horizontal beam size (σ_x) with ε_x = **5.5 nm**
  - dispersion contribution ($|D_x| \cdot \sigma_p$) with $\sigma_p = 0.09\ \%$



Vertical emittance limit

Quantum emittance

= vertical emittance for ideal, flat lattice

- direct photon recoil, $1/\gamma$ radiation cone

T. O. Raubenheimer, *Tolerances to limit the vertical emittance in future storage rings*, SLAC-PUB-4937, Aug.1991

- independent of energy
- examples:

SLS	**0.20 pm**
MAX-IV	0.05 pm
PETRA-III	0.04 pm

$$\epsilon_y = \frac{13}{55} C_q \frac{\oint \beta_y(s)|G^3(s)|ds}{\oint G^2(s)ds}$$

$G(s)$ =curvature, C_q = 0.384 pm

isomagnetic lattice

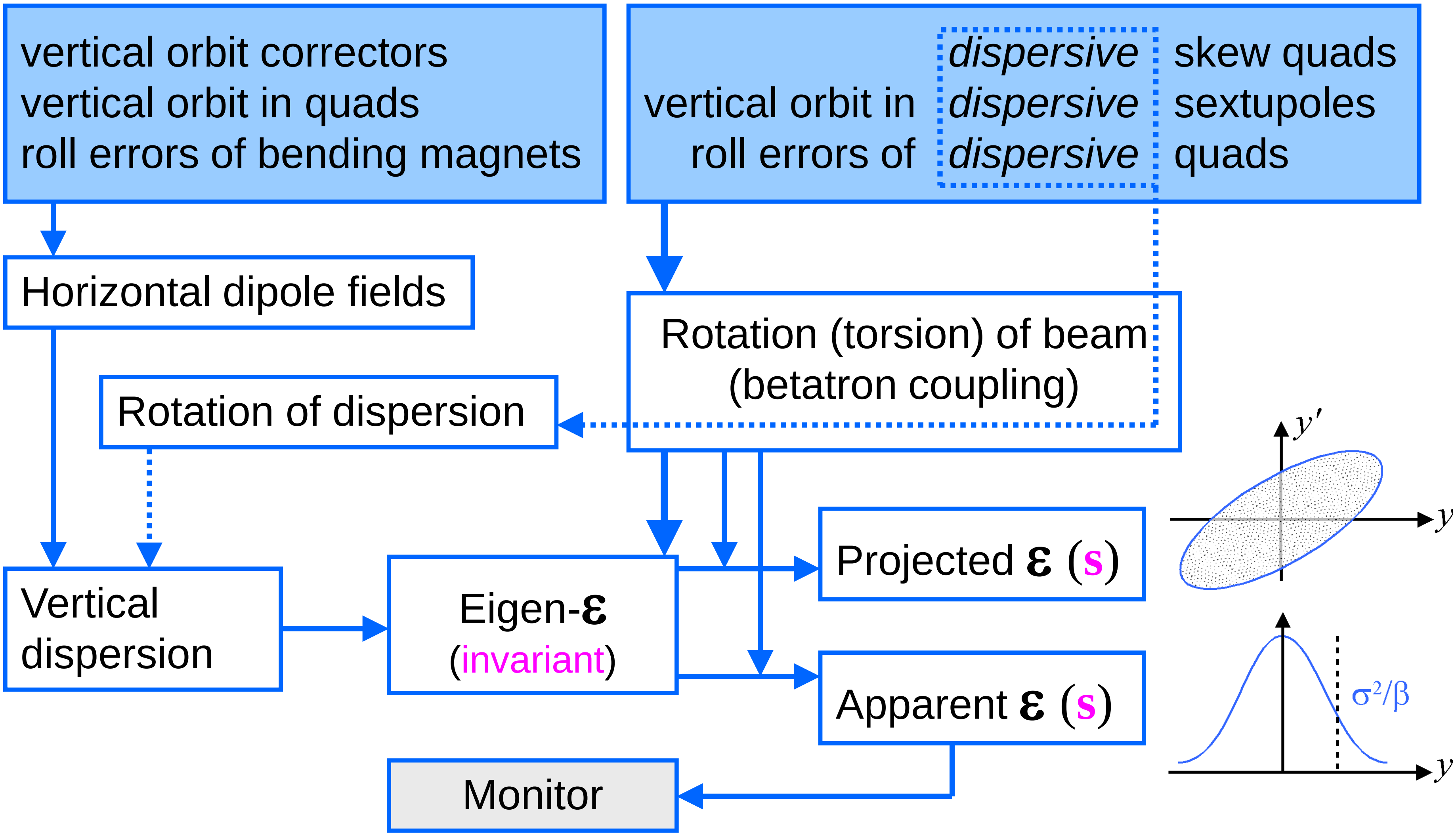
$$\varepsilon_y = 0.09\,\mathrm{pm} \cdot \frac{\langle \beta_y \rangle_{\mathrm{Mag}}}{\rho}$$

⇒ ultimate limit of vertical emittance

⇒ quantum emittance << coupling

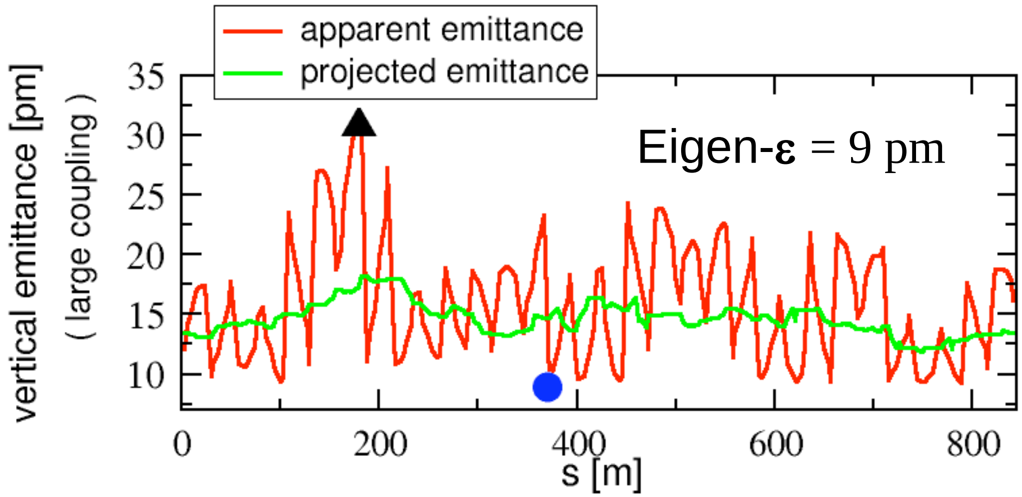
Vertical emittance from coupling

- A. W. Chao, *Evaluation of beam distribution parameters in an electron storage ring*, J. Appl. Phys. 50, 595 (1979)
- A. Franchi et al., *Vertical emittance reduction and preservation in electron storage rings via resonance drive terms correction,* PRSTAB 14, 034002 (2011)



Vertical emittance properties

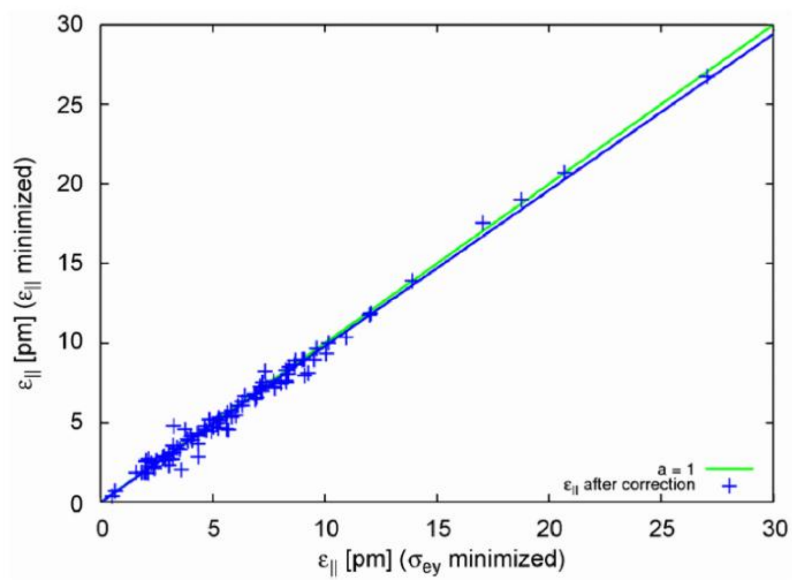
- Apparent-ε oscillates around the lattice.
  - Oscillation amplitude is low for low coupling.
- Projected-ε changes at skew quad kicks.
- Eigen-ε is invariant.
- Minimization of apparent ε at one location (monitor) minimizes eigen-ε too:



ESRF at *large* coupling, figure taken from A. Franchi, *Coupling correction through beam position data*, LER-2011.

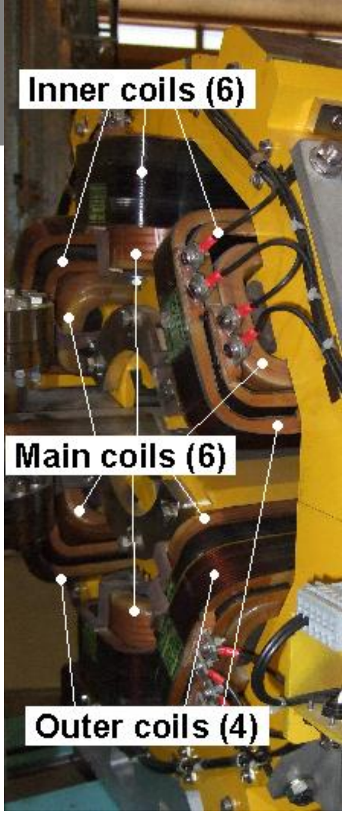
Simulation (TRACY, 100 seeds, SLS with 6 skew quads): Eigen-ε results, when optimizing on beam size at monitor (→) vs. optimizing on eigen-ε itself (↑).

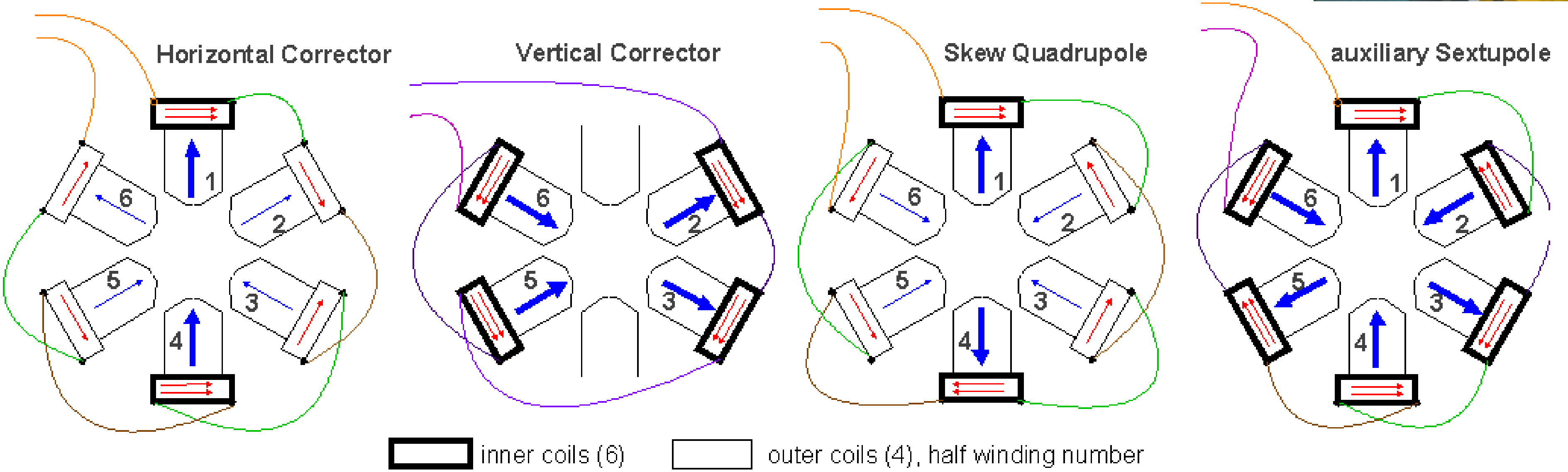
Å. Andersson et al., NIM A 592 (2008) 437



SLS knobs for coupling control

- 120 sextupoles with additional coils:
  - 72 wired as horizontal/vertical orbit correctors.
  - 12 wired as auxiliary sextupoles for sextupole resonance suppression.
  - 36 wired as skew quadrupoles:
    12 dispersive, 24 non-dispersive.
- Orbit bumps in 120 sextupoles:
  72 dispersive, 48 non-dispersive "skew quads"

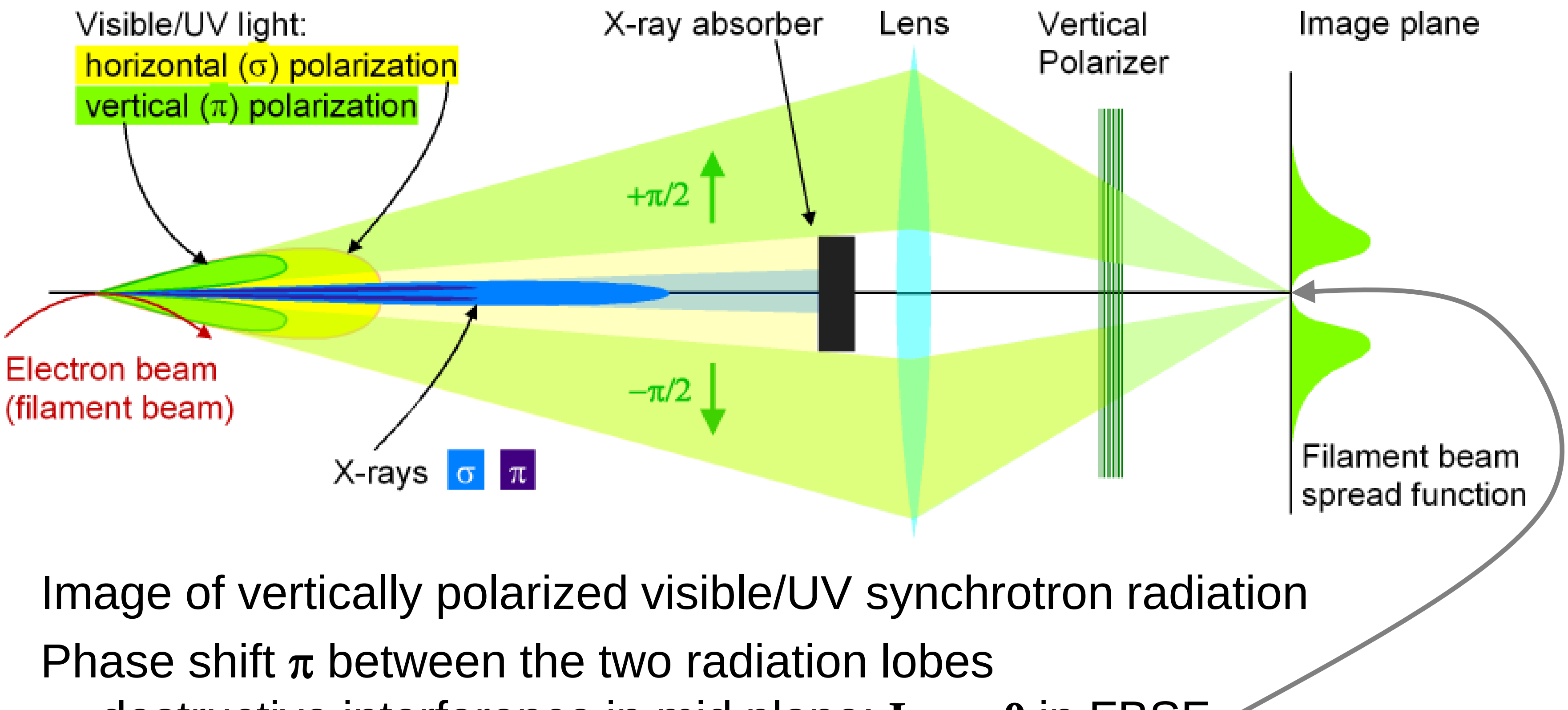




SLS beam profile monitor

The π-polarization method

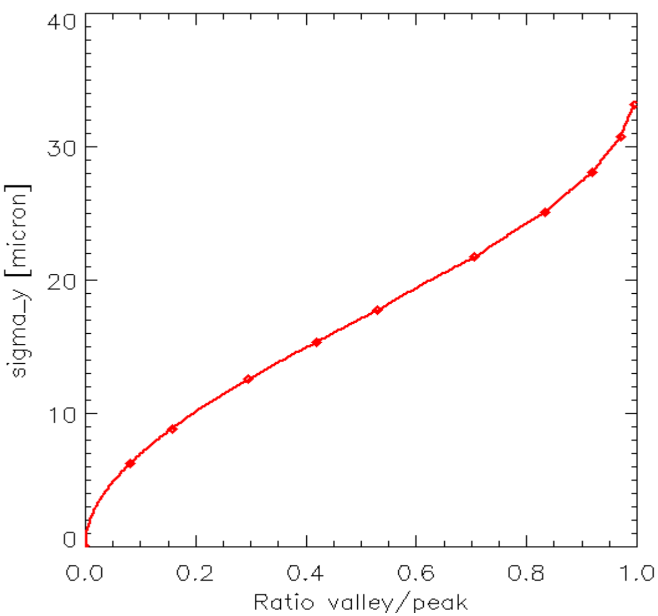
- Å. Andersson et al., *Determination of small vertical electron beam profile and emittance at the Swiss Light Source*, NIM A 592 (2008) 437-446

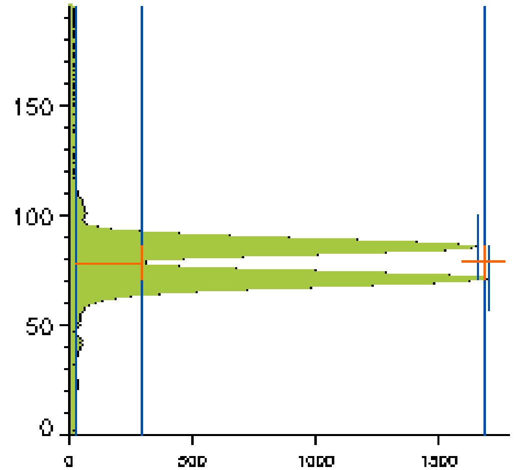


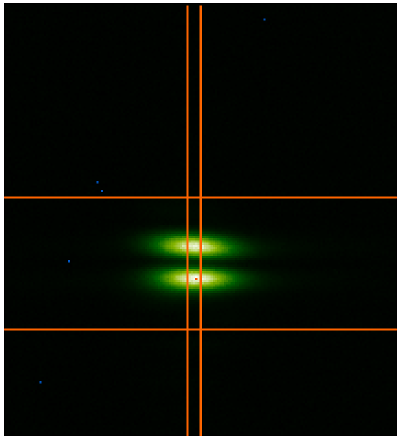
- Image of vertically polarized visible/UV synchrotron radiation
- Phase shift π between the two radiation lobes
  $\rightarrow$ destructive interference in mid plane: $\mathbf{I_{y=0} = 0}$ in FBSF
- Finite vertical beam size: $\mathbf{I_{y=0} > 0}$

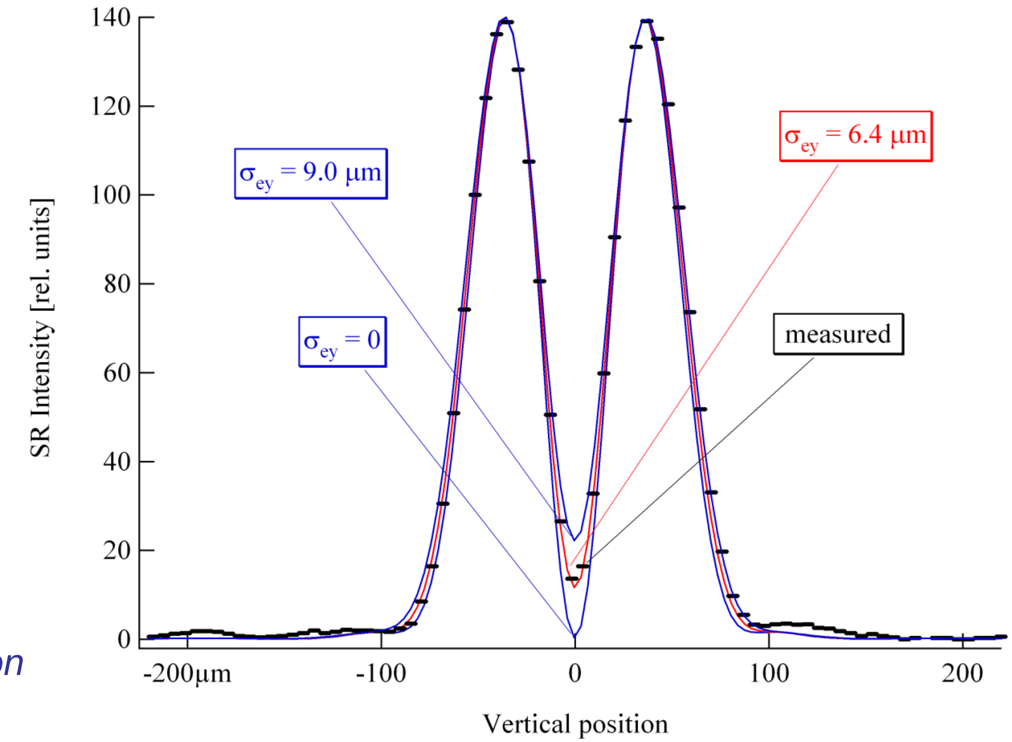
Measurement

- Wavelength 364 nm
- Get beam height from peak-to-valley intensity ratio
- Lookup-table of SRW* simulations:





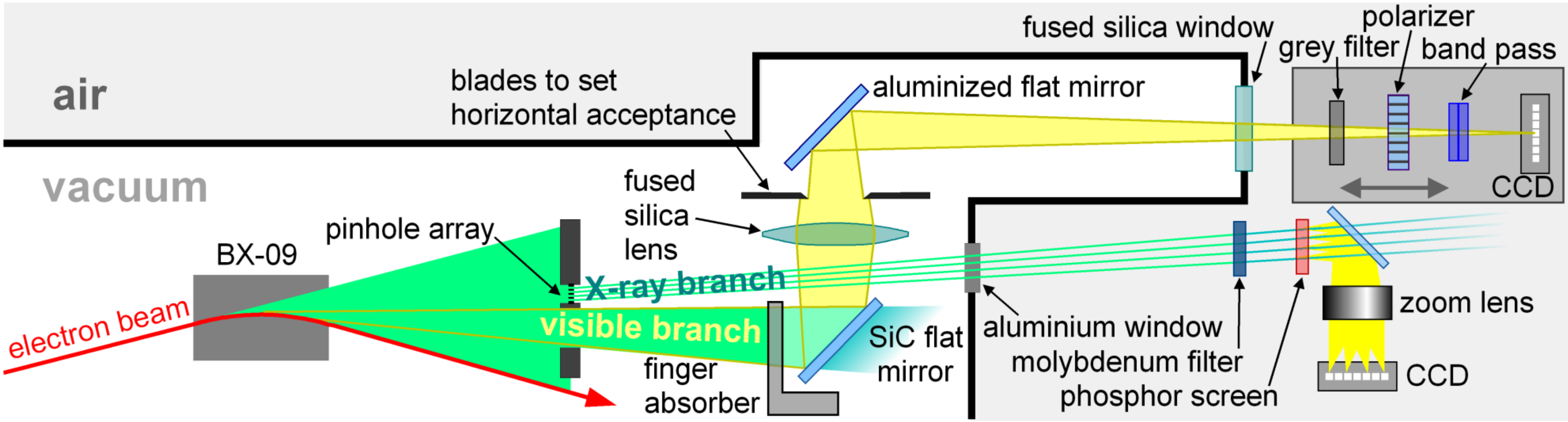




* Synchrotron Radiation Workshop

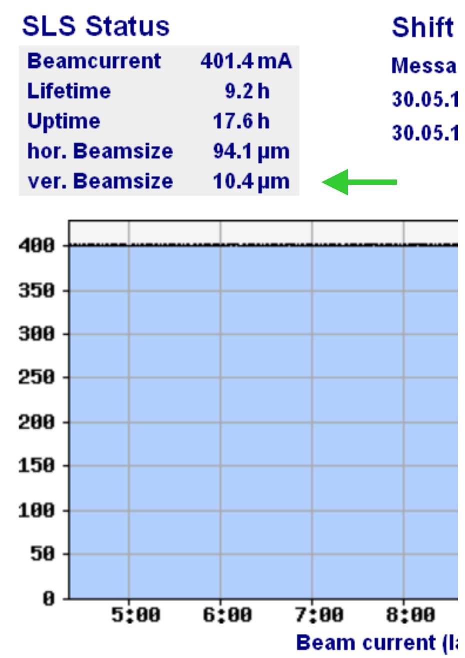
O. Chubar & P. Elleaume, *Accurate and efficient computation of synchrotron radiation in the near field region*, EPAC 1998.

Layout & performance



- **Precision**
  Beam height ±0.5 µm
- **Resolution**
  Beam height > ≈ 4 µm
  Emittance > ≈ 1 pm
- **Application**
  On-line measurement
  Display on status page

X-ray side branch
Pinhole array
Resolution > 10 µm



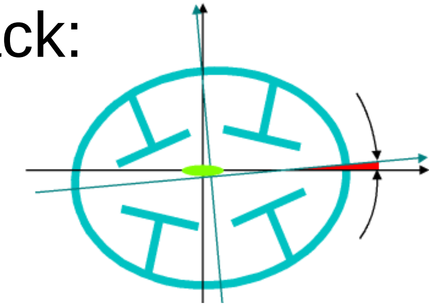
Methods for vertical emittance minimization

Overview

- Measurement of BPM roll errors
  ⇨ avoid “fake” vertical dispersion measurement.
  (roll error × horizontal dispersion > vertical dispersion.)
- Realignment of magnet girders
  ⇨ remove main sources of vertical dispersion.
  (dipoles for correction of steps between girders)
- Measurement and correction of
  vertical dispersion and betatron coupling
  using **skew quads**.
- Measurement and correction of
  vertical dispersion, betatron coupling & linear optics using
  skew quads and **orbit bumps**.
- Random walk optimization of
  vertical beam size at beam profile monitor
  using **skew quads**.

BPM roll error measurements

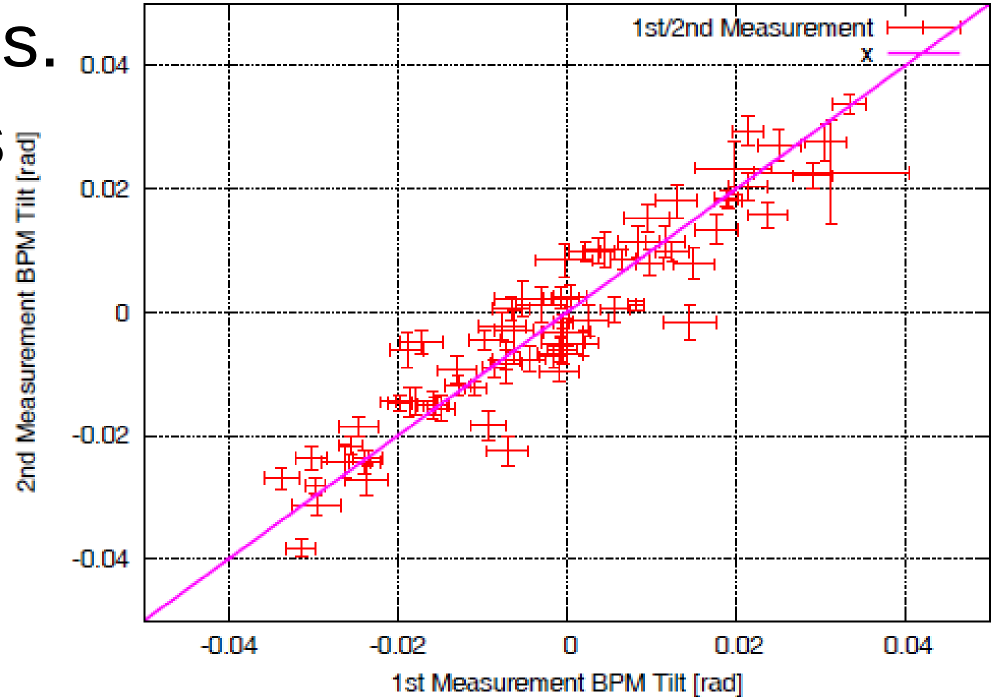
- Methods:
  - Local bumps ($\pm 150\ \mu m$) with fast orbit feedback: get BPM roll from corrector currents.
  - LOCO fit to response matrix.



- BPM roll: 17 mrad RMS.
- Origin: mainly electronics.
- ✘ Corrupts measurements of vertical dispersion.
- ⇒ Low level implementation as "3rd BBA* constant": BPM sway, heave & roll

(*BBA = "beam based alignment")

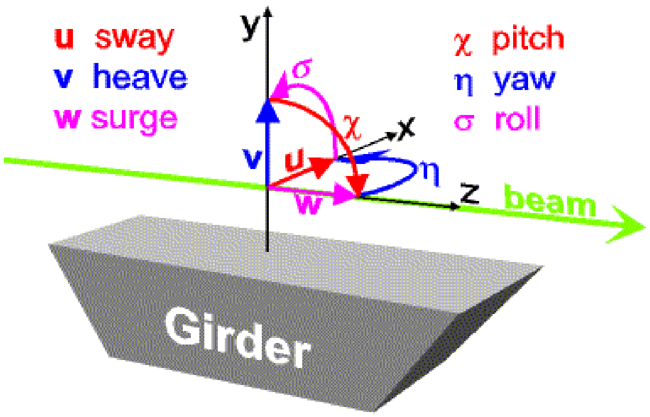
- M. Böge et al., *The Swiss Light Source – a test-bed for damping ring optimization,* Proc. IPAC-2010



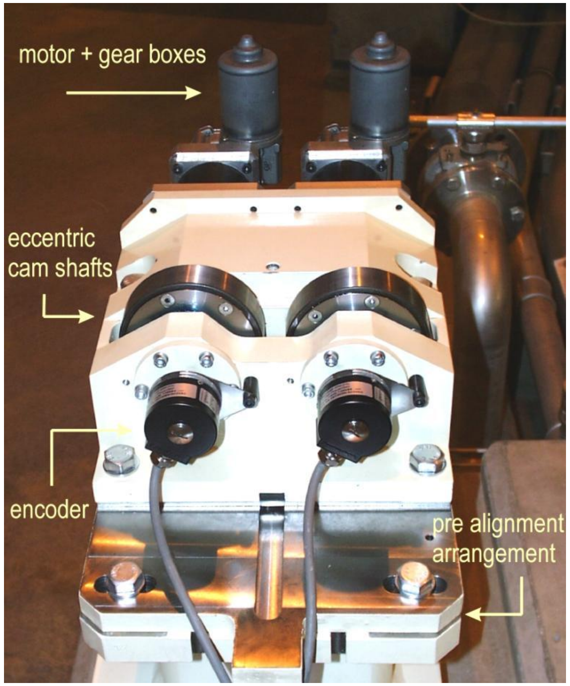
Correlation of two BPM roll measurements

BAGA (beam assisted girder alignment)

The SLS dynamic girder alignment system



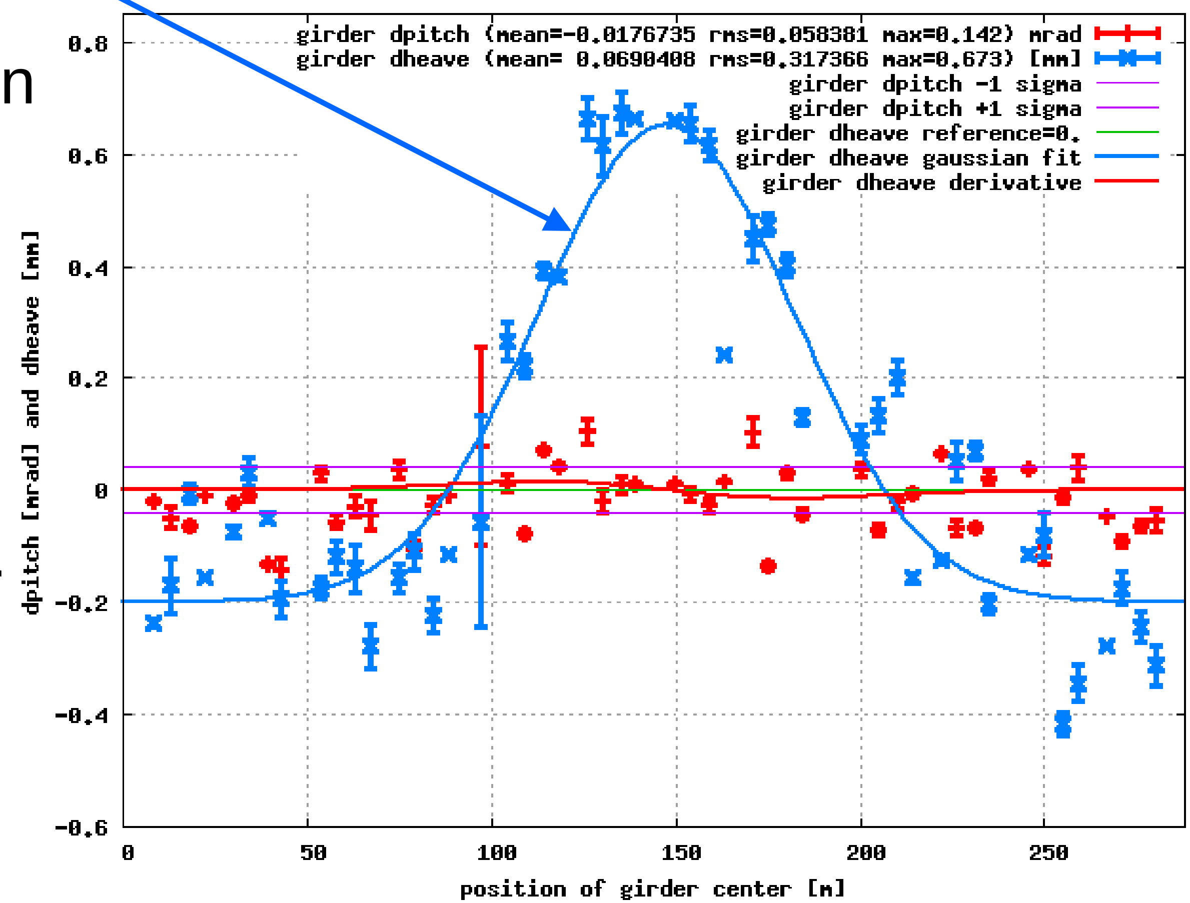
- Remote positioning of the 48 girders in 5 DOF (**u, v, χ, η, σ**) by eccentric cam shaft drives.
- 36 dipoles (no gradients) supported by adjacent girders.
  - except 3 super-bends: extra supports
  - except laser slicing insertion FEMTO
- Magnet to girder alignment < **50 μm**
  - girder rail 15 μm,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



S. Zelenika et al., *The SLS storage ring support and alignment systems, NIM A 467 (2001) 99*

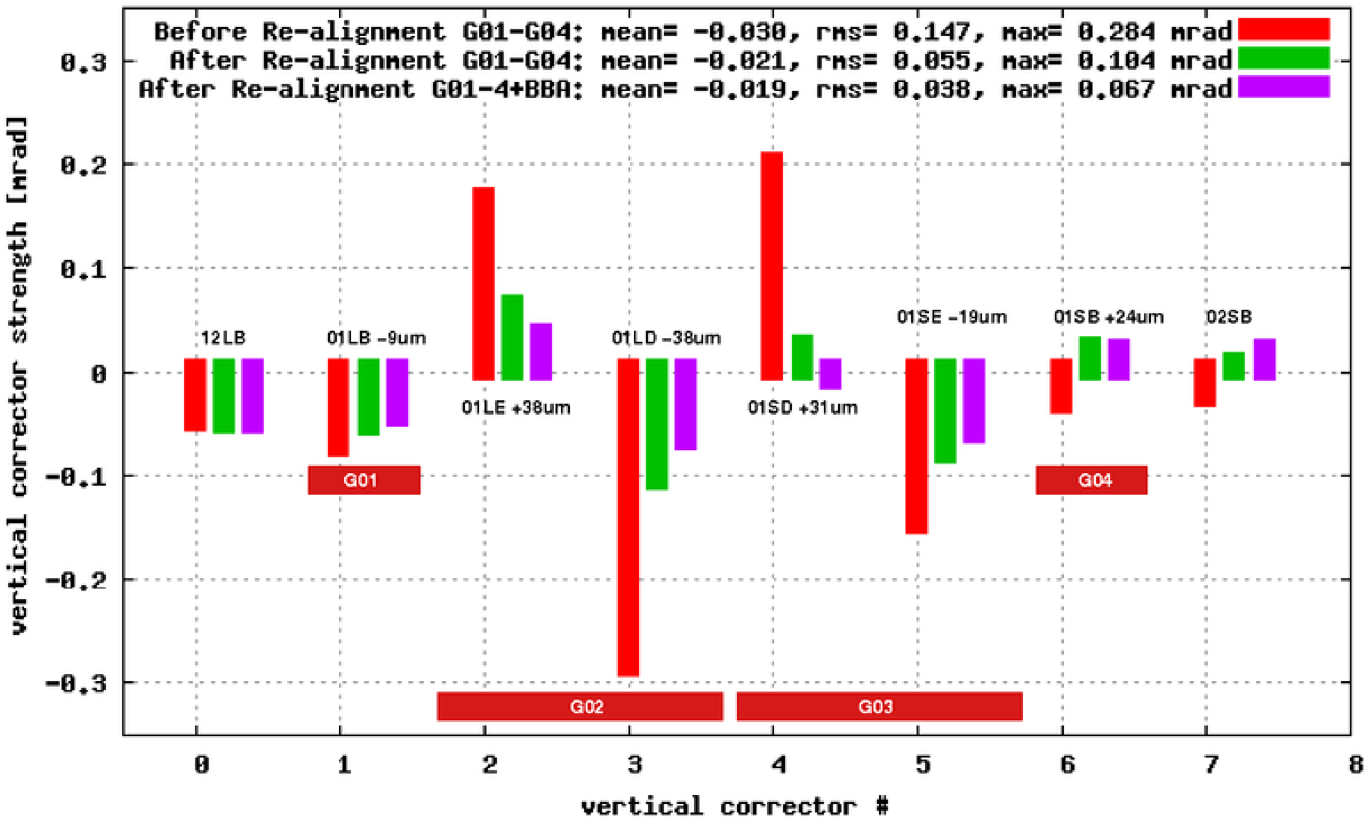
Survey based girder alignment

- Girder heave and pitch from survey
- Align girders to medium line
  (long wavelength machine deformation is not a problem)
- 400 mA stored beam current and fast orbit feedback active
  ↓
  Vertical corrector currents confirm girder move.



- M. Böge et al., *SLS vertical emittance tuning,* Proc. IPAC-2011

Decrease of corrector strengths through girder alignment



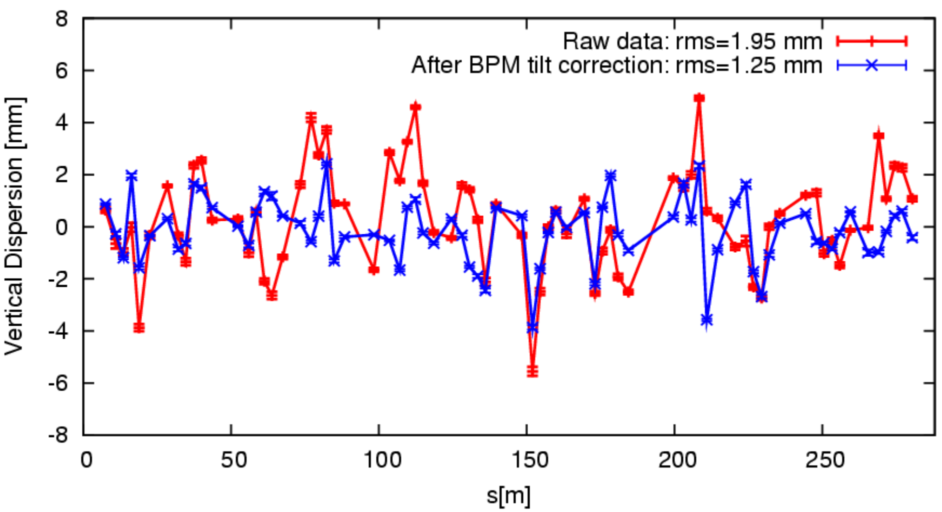
Corrector strengths before and after girder alignment, and after beam based BPM calibration* (BBA) (sector 1)
(*girder move causes vacuum chamber deformation)

⇒ Corrector strengths reduced from **130** to **50** **μrad** RMS.

Vertical dispersion suppression

Measurement

- Vertical orbit as function of energy at 73 BPMs
- Upgrade of RF oscillator for fast frequency shift
- Prerequisite: determination of BPM roll errors.



Correction

- 12 dispersive skew quadrupoles ($D_x \approx 33$ cm)

$\Rightarrow$ 73 × 12 dispersion response matrix

$\Rightarrow$ Suppression to <1.3 mm RMS.

> Vertical dispersion measurement
> Energy range ± 0.3% (–Δf = ± 920 Hz)
> 20 points
> 10 minutes
> 65 μm resolution

Betatron coupling suppression

Model

- Sensitivity of the coupled orbit response matrix (RM) on skew quad strengths $\{a_2\}$: Jacobian $\{\partial RM/ \partial a_2\}$.
- 24 non-dispersive skew quads
- 73 BPMs (**x**/**y**) and 73 CH/CV $\Rightarrow$ 146 × 146 × 24 tensor.
- Rearrange: 21316 × 24 matrix $\Rightarrow$ SVD-"inversion".

Measurement

- Coupled orbit response matrix.
  (horizontal | vertical excitation → vertical | horizontal orbit)

Correction

- Fit 24-vector $\{\Delta a_2\}$ of skew quad strengths.
- Apply inverse to machine: $-\{\Delta a_2\}$.
- Iterate – also iterate model fit for large errors.
- Compensates also betatron coupling increase from previous vertical dispersion suppression.

$\Rightarrow$ Vertical emittance = **1.2 pm**

Orbit manipulation

LET algorithm ("low emittance tuning")

Principle: double linear system

- Measurement vectors
  - vertical orbit
  - vertical dispersion
  - off-diagonal (coupling)...
  - horizontal orbit
  - horizontal dispersion
  - diagonal (regular)...

  ...parts of the orbit response matrix

- Knob vectors
  - vertical correctors
  - skew quadrupoles
    - and BPM roll errors
  - horizontal correctors

- Weight factors (α , ω)

S. Liuzzo et al., *Tests for low vertical emittance at DIAMOND using LET algorithm*, IPAC-2011.

$$\begin{pmatrix} (1-\alpha-2\omega)\,\vec{y} \\ \alpha\,\vec{\eta}_y \\ \omega\,\vec{\mathcal{ORM}}_{y,\theta_H} \\ \omega\,\vec{\mathcal{ORM}}_{x,\theta_V} \end{pmatrix} = \mathcal{M}_v \begin{pmatrix} \vec{\theta}_V \\ \vec{K} \\ \vec{T} \end{pmatrix}$$

$$\begin{pmatrix} (1-\alpha-2\omega)\,\vec{x} \\ \alpha\,\vec{\eta}_x \\ \omega\,\vec{\mathcal{ORM}}_{x,\theta_H} \\ \omega\,\vec{\mathcal{ORM}}_{y,\theta_V} \end{pmatrix} = \mathcal{M}_x \begin{pmatrix} \vec{\theta}_H \\ \vec{T} \end{pmatrix}$$

LET algorithm: "all in one"

- **Coupling suppression**
  suppression of vertical dispersion and betatron coupling
- **Optics correction**
  like LOCO: linear optics from closed orbit
- Exploits orbit bumps in sextupoles (b_3) to sample off-axis quad (b_2) and skew quad (a_2) down-feed.
- Uses dedicated skew quads for coupling suppression.
- Also includes fit to BPM roll errors.

$$B_x = b_3\, x\, y$$
$$B_y = b_3 (x^2 - y^2)/2$$
$$"b_2" = \frac{\partial B_x}{\partial y} = \frac{\partial B_y}{\partial x} = b_3 x$$
$$"a_2" = \frac{\partial B_x}{\partial x} = -\frac{\partial B_y}{\partial y} = b_3 y$$

Successfully applied to **DIAMOND, SLS, DAΦNE**

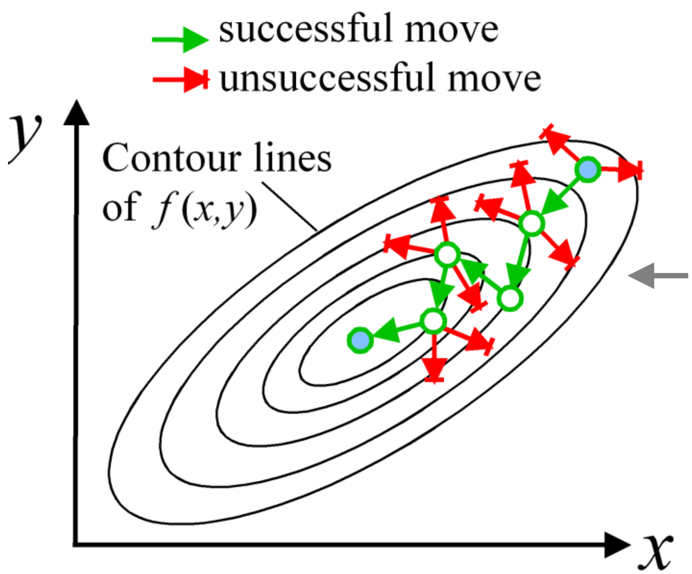
SLS: only 3 MD shifts $\Rightarrow$ emittance = **1.6 pm**

S. Liuzzo et al., *Tests of low emittance tuning techniques at SLS and DAΦNE,* IPAC-2012.

Random walk optimization

Model independent method

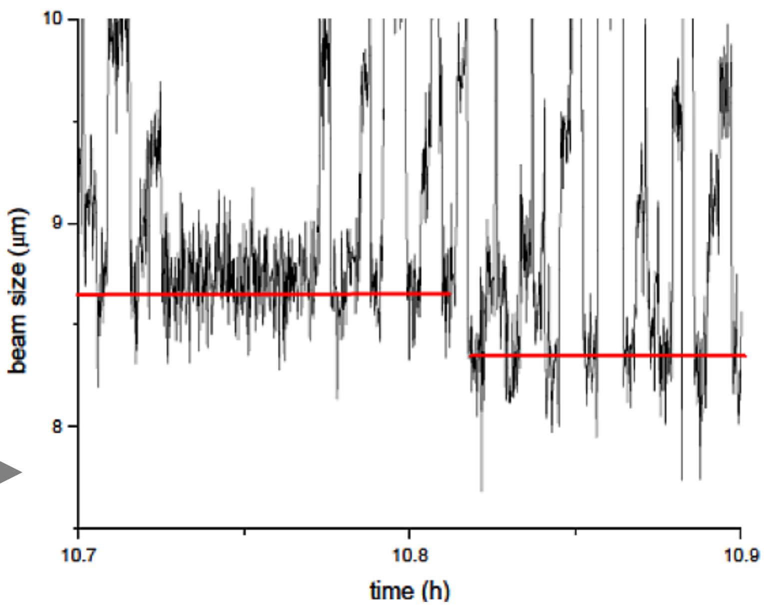
- overcomes measurement limitations: BPM noise, drifts, etc.
- overcomes model deficiencies.
- target function: vertical beam size at profile monitor.
- knobs: 24 non-dispersive skew quads.
- optimization algorithm: random walk (RWO)
  (small steps, works even in background during user runs)



RWO

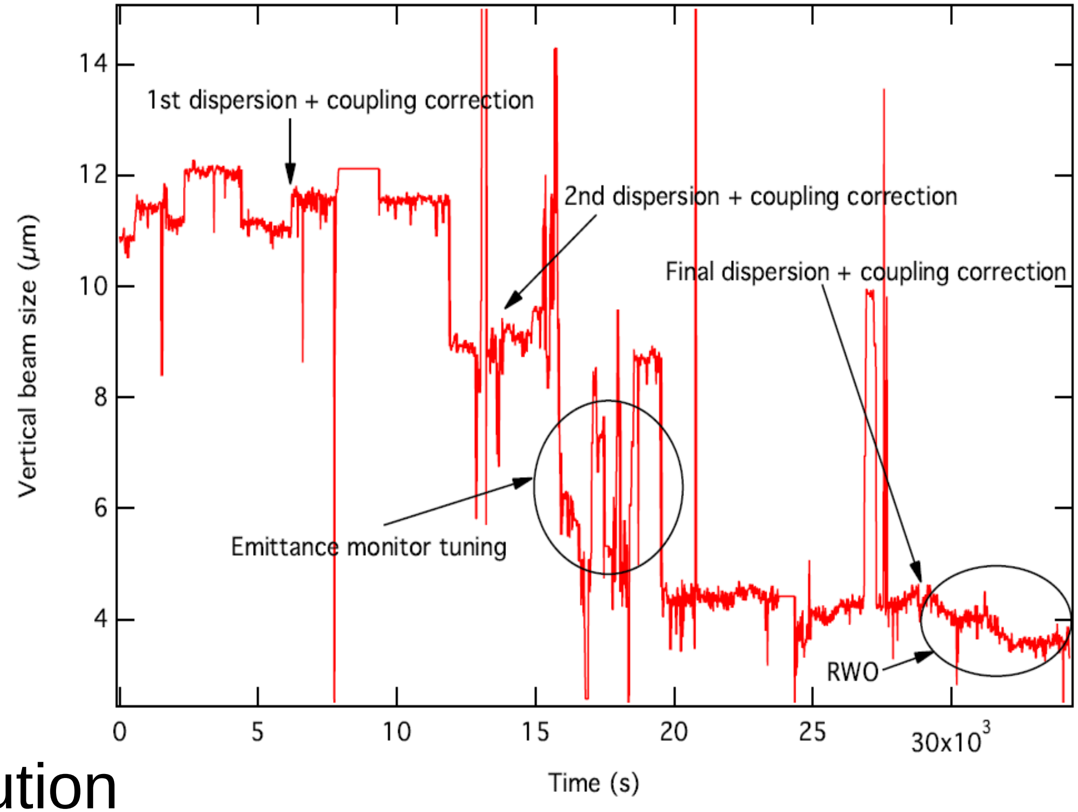
principle

example for successful move



RWO application

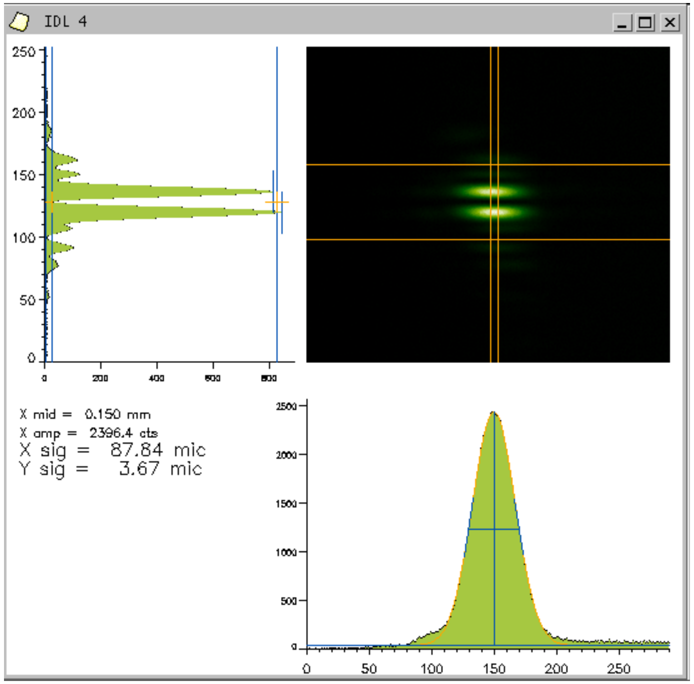
- Before:
  dispersion suppression
  & coupling suppression
  alternated and iterated
  ⇒ emittance = **1.3 pm**
- Required: fine tuning of emittance monitor.
- RWO ~1 hour
  ⇒ emittance = **0.9 pm**

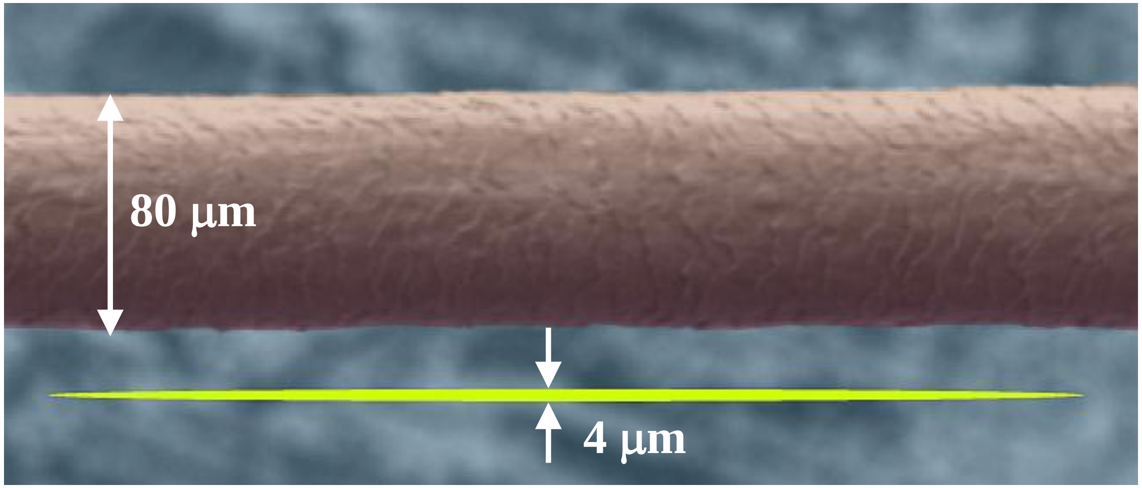


- Limitation: monitor resolution
- Found reduction of coupled response matrix (although beam size was observed only in one location!)
- Skew quad changes larger (×6) than expected from saturation of coupling suppression.

  ⇒ systematic correction limited by
  model deficiencies rather than measurement errors.

- Beam size **3.6 ± 0.6 μm**
- Emittance **0.9 ± 0.4 pm**
- Error estimate from beam size and beta function at monitor.
- Dispersion not subtracted.
- SLS beam cross section (in short undulator straight, 2σ) compared to a human hair:





Horizontal and vertical emittance of existing (●) and planned (●) storage rings

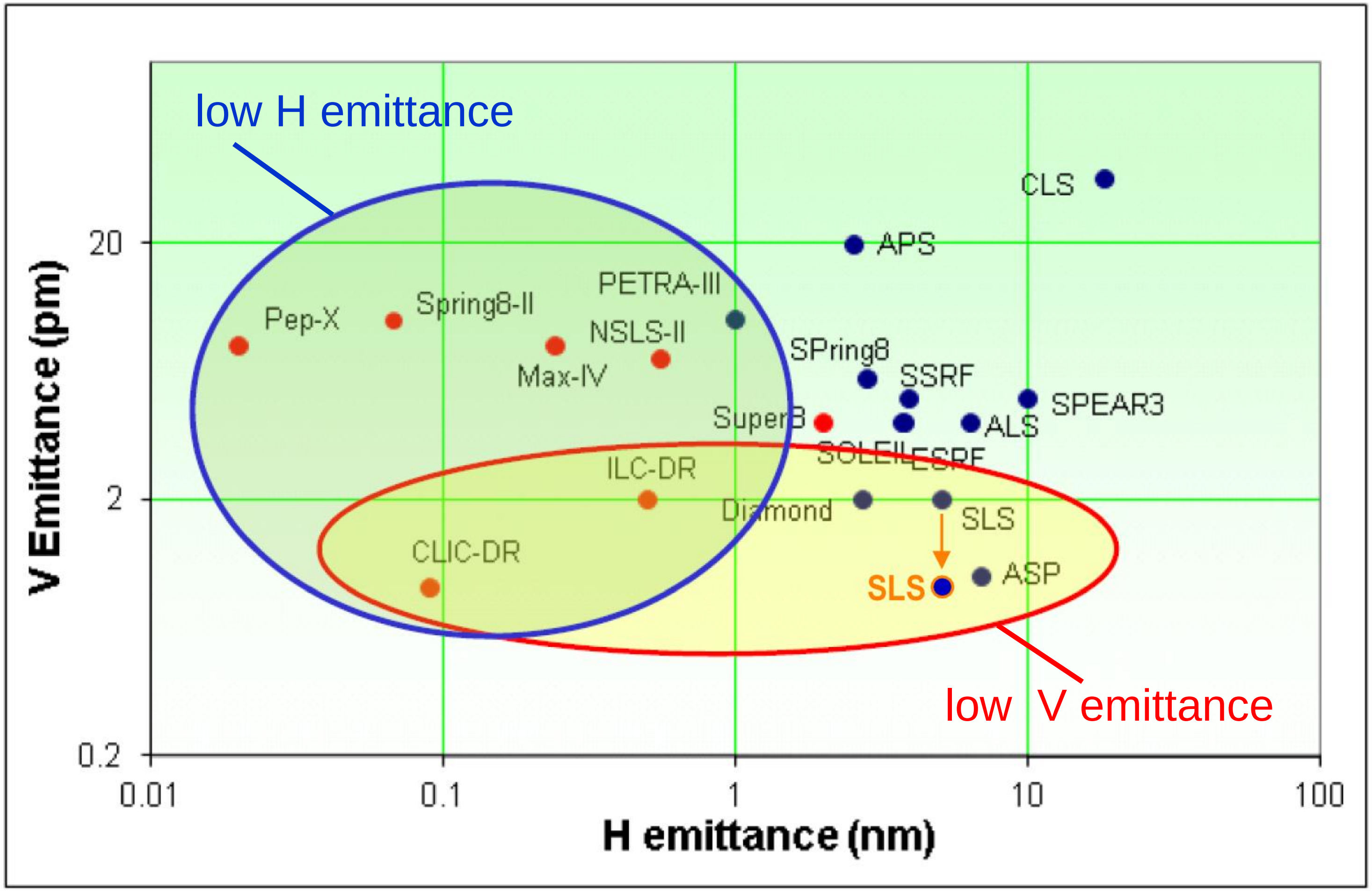


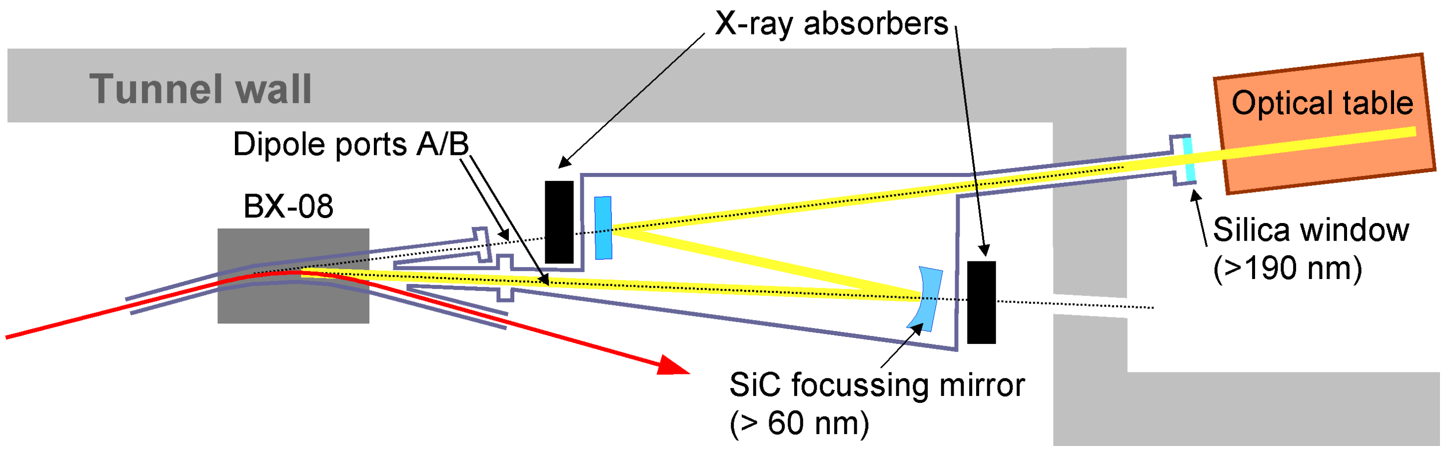
Figure taken from R. Bartolini, *Review of lattice design for low emittance ring,* LER-2011 – and **updated.**

High resolution beam profile monitor

Vertical emittance tuning limited by monitor resolution.

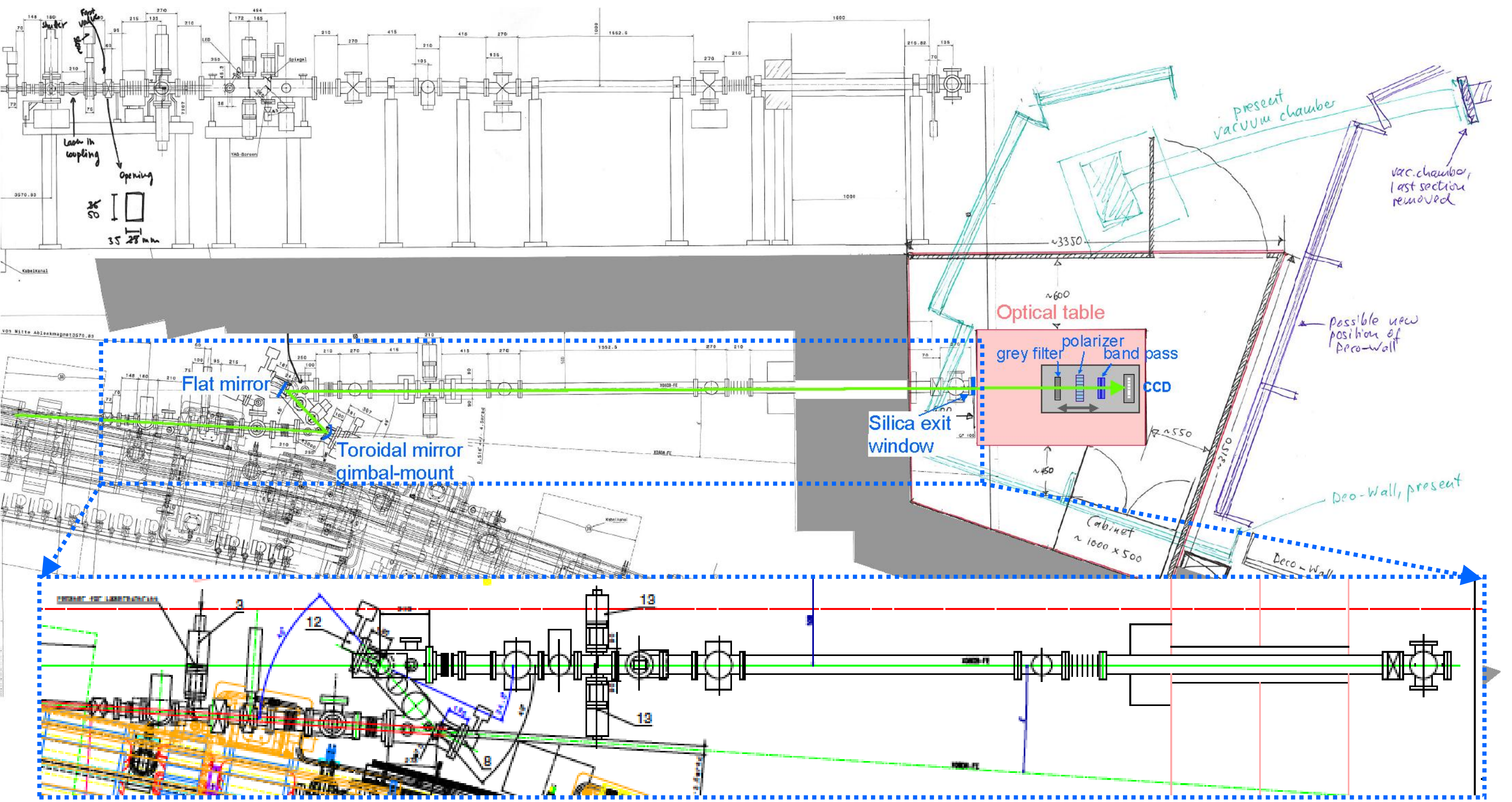
⇨ **WP6/SVET hardware investment : new monitor**

- Higher resolution: **2 µm** [existing monitor: 3.5 µm]
  - ⇒ Emittance: **0.3 pm** [1.0 pm]
- Shorter wavelength: 266 nm [364 nm]
- Larger magnification: 1.50 [0.84]
- Wavelength independent focusing:
  - reflective optics: toroid [refractive optics: lens]
- On-line access: extend out of tunnel [inside tunnel]
- Concept:



Layout of monitor beamline X08D

- Design specifications WP6 report **D_SPEC** due June 2012
- Installation: winter shutdown January 2013



Summary & Outlook

- Methods for vertical emittance tuning established:
  - **removing sources of vertical emittance**
    - **beam assisted girder alignment**
  - **model dependent correction**
    - **vertical dispersion and coupling suppression**
    - **LET algorithm including orbit manipulations**
  - **model independent optimization**
    - **random walk using beam size measurement**
- World record $\varepsilon_y = 0.9 \pm 0.4$ pm has been achieved.
- 2013 program
  - further minimization based on new monitor
  - automated coupling control (feedback)
  - experiments on intra beam scattering using low ε_y beam