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Design and Expected Performance of the New SLS Emittance Monitor

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- **Motivation** – **EU-Project TIARA WP-6 SVET**
- **Swiss Light Source** – **1 pmrad Vertical Emittance**
- **Measurement Principles** – **π-Polarization Method**
  Interferometric Method
- **New Monitor Design** – **New Features & Improvements**
- **Critical Issues and Components**
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Test Infrastructure and Accelerator Research Area
www.eu-tiara.eu
Work Package 6 “SVET”

Partially funded by the European Commission under the FP7-INFRASTRUCTURES-2010-1/ INFRA-2010-2.2.11 project TIARA (CNI-PP). Grant agreement no 261905.

SVET: SLS Vertical Emittance Tuning

→ investigate ultra-low vertical emittance tuning and control in the regime of strong IBS

→ relevance for damping rings of future linear colliders & for next generation light sources

→ upgrade Swiss Light Source to enable R&D on ultra-low emittances

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

1. verification of low vertical emittance

beam size measurement: σ_y
magnet optics control: β_y

emittance $\varepsilon_y = \sigma_y^2 / \beta_y$

➡ design of a high resolution beam size monitor at SLS (PSI and Max-Lab)

2. minimization of vertical emittance

beam-assisted SLS storage ring alignment and optics correction

tuning methods and automation

➡ skew quadrupole corrections and orbit settings (PSI and INFN / LNF)

3. intra beam scattering simulations and measurements

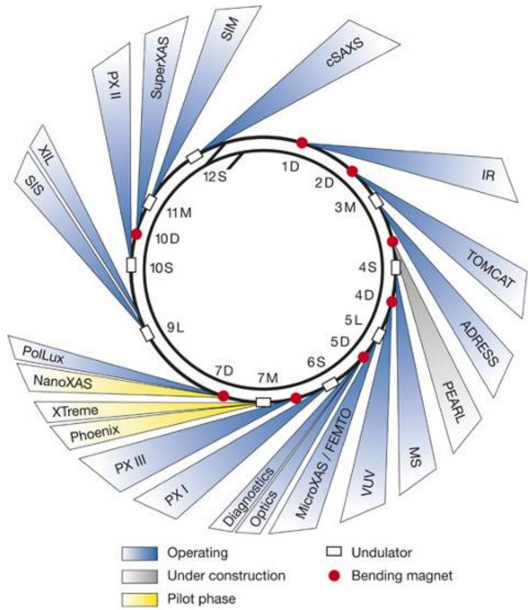
emittance and energy spread increase at high currents

➡ low energy (1.6 GeV) operation of SLS (PSI, CERN)

Swiss Light Source – Some Key Parameters

- Beam Energy 2.4 GeV
- Circumference 288 m
- Emittances
  - horizontal 5.5 nm rad
  - vertical 1 … 7 pm rad
- Coupling 0.02 % … 0.13 %
- Energy Spread 0.09 %
- Beam Current 400 mA (top-up operation)
- Life Time ~ 3 – 10 h
- Stability < 1 µm (photon beam at front end)

SR User Facility with 19 Beam Lines (Status 2012)



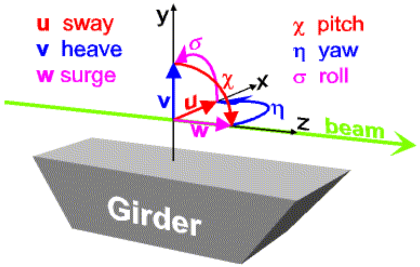
Pre-Requisites and Tools for SLS Vertical Emittance Tuning

1. high beam stability as a pre-requisite

top-up operation → high thermal (long term) stability

precise BPMs: ~ 100 nm rms (< 100 Hz)
fast orbit feedback
} orbit control & short term stability

2. procedures & equipment for vertical emittance tuning



re-alignment (beam-assisted girder alignment) of storage ring

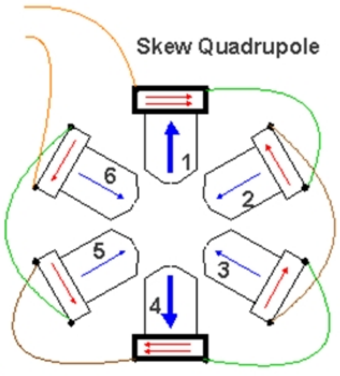
→ remote positioning of 48 girders in 5 DoF (eccentric cam shafts drives)

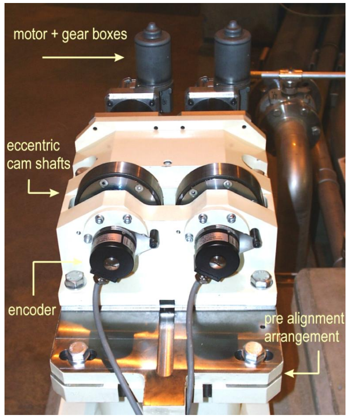
skew quadrupoles for coupling control (36 in case of SLS)

→ sextupoles with additional coils

high resolution beam size monitor

→ π polarization method





Procedure for SLS Vertical Emittance Tuning

1. measurement and correction of BPM roll error

   → avoid "fake" vertical dispersion readings (from 48 dispersive BPMs with $\eta_{hor} \neq 0$)

2. realignment of magnet girder to remove main sources of vertical dispersion

   → reduction of rms vertical correction kick from ~ 130 μrad to ~ 50 μrad

3. measurement & correction of linear optics

   → model-based quadrupole corrections

4. measurement & correction of vertical dispersion and betatron coupling

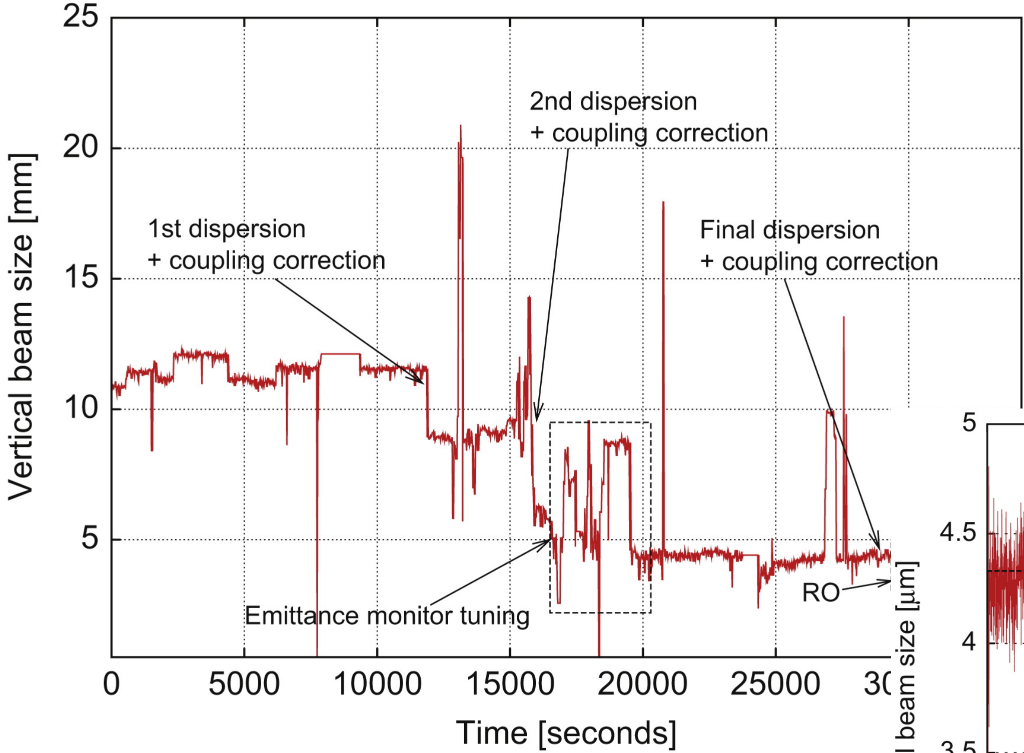
   → model-based skew quadrupole corrections (12 dispersive and 24 non-dispersive skew quads)

5. "random walk" optimization of vertical beam size

   → skew quadrupole corrections using beam size measurements from profile monitor

   works in the background (small steps), overcomes measurement limitations and model deficiencies

SLS Vertical Emittance Optimization – Results



Iterative Minimization Procedure

- → BPM roll error corrections
- → beam-based girder alignment
- → **dispersion & coupling corrections**
- → **beam size monitor tuning**
- → **random walk optimization**

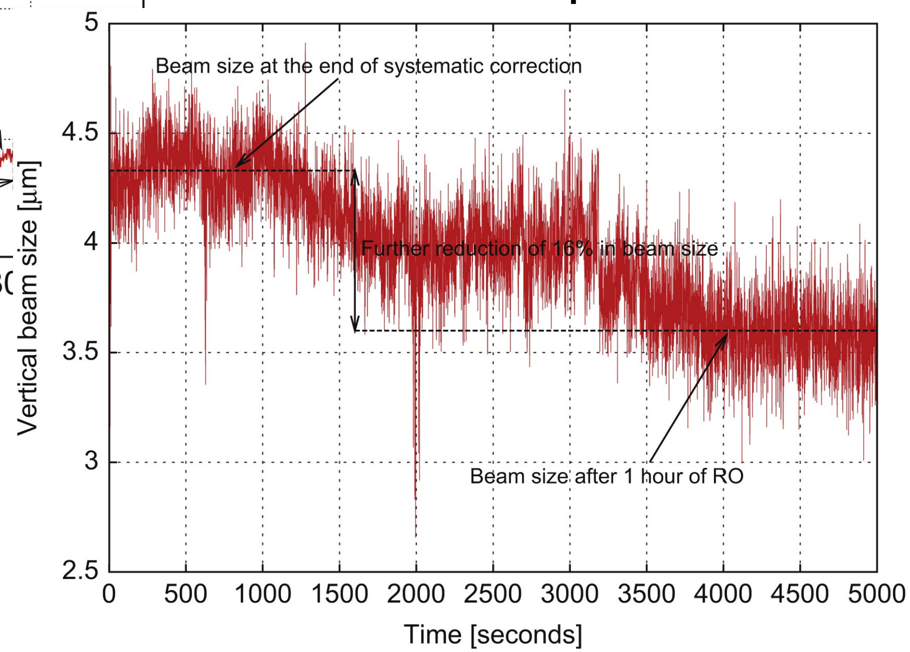
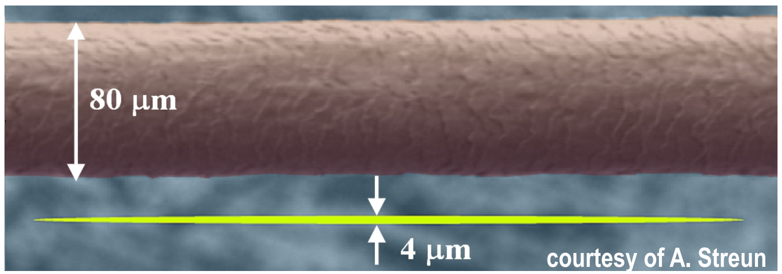


Illustration of SLS Beam Size (short ID straight – 2σ)

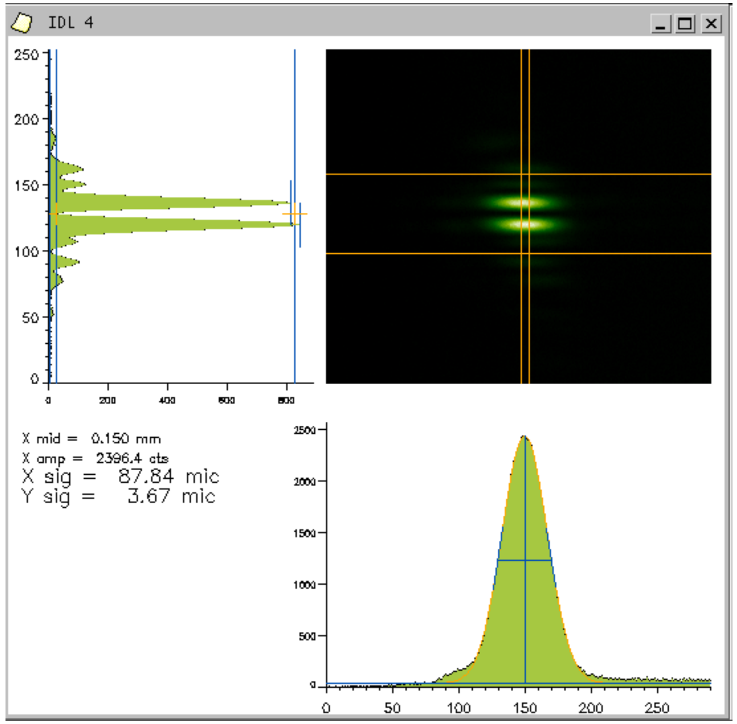


M. Aiba, et al., *Ultra Low Vertical Emittance at SLS Through Systematic and Random Optimization,* NIM-A 694 (2012) 133-139

SLS Vertical Emittance Optimization – Results

- **vertical beam size: 3.6 μm ± 0.6 μm**
- **vertical emittance: 0.9 pm ± 0.4 pm**
- **error estimate from beam size and β-function at monitor**
- **dispersion not subtracted**

Beam Size Display from SLS π-Polarization Monitor



Horizontal and Vertical Emittances of Storage Rings

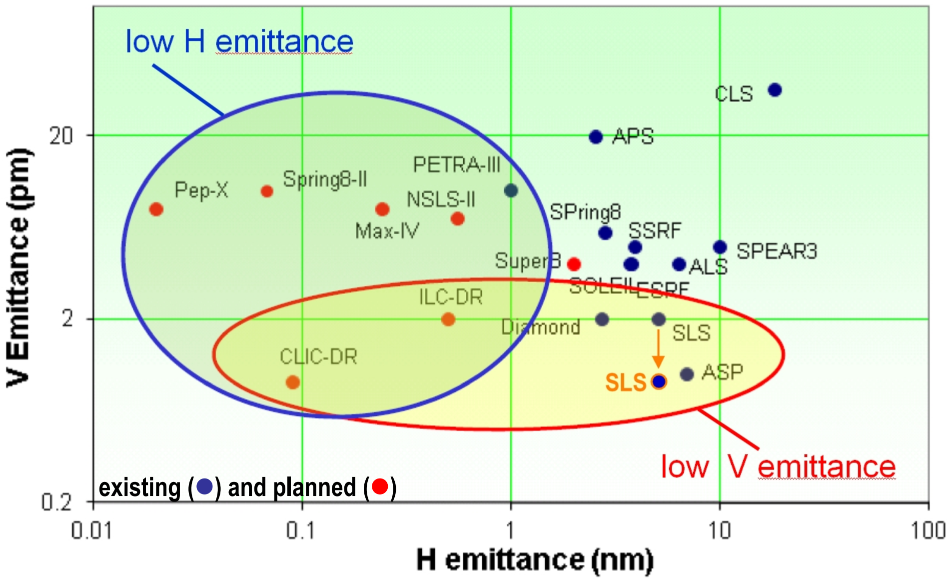
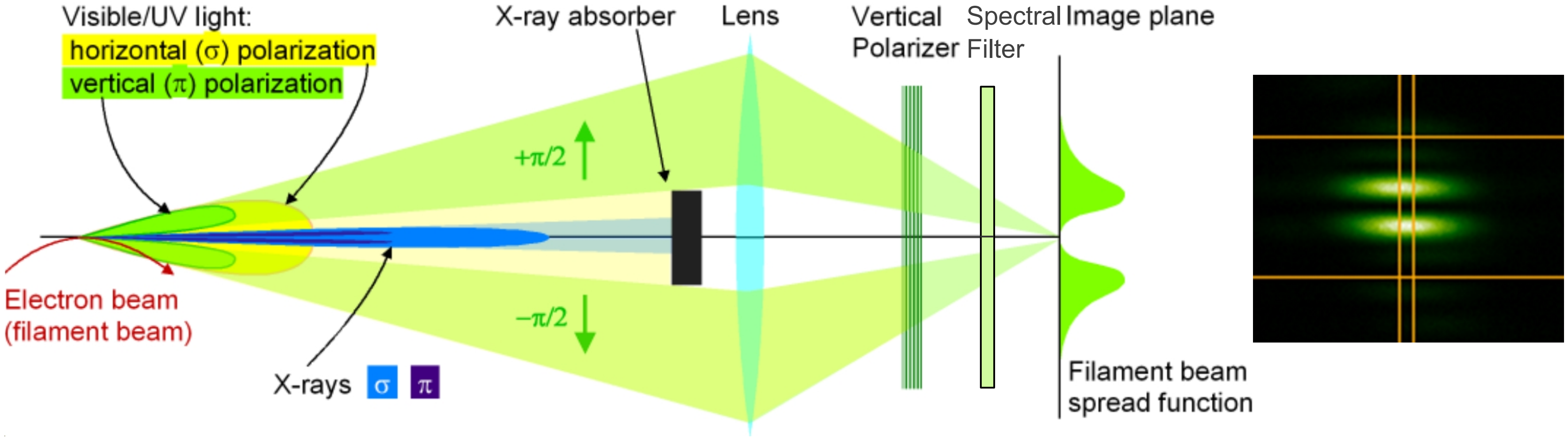


Figure taken from:
R. Bartolini, Low Emittance *Ring Design,* ICFA Beam Dynamics Newsletter, No. 57, Chapter 3.1, 2012 – and updated.

Principle of the SLS Beam Size 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



- imaging of vertically polarized SR in the visible / UV
- phase shift of π between two radiation lobes
  → destructive interference in the mid plane
  → $I_{y=0} = 0$ in FBSF (filament beam spread function)
- finite vertical beam size → $I_{y=0} > 0$ in FBSF
- modeling by SRW* (Synchrotron Radiation Workshop)

O. Chubar & P. Elleaume, *Accurate and Efficient Computation of Synchrotron Radiation in the Near Field Region,* EPAC 1998

2-D Electric Field Distribution (in image plane)

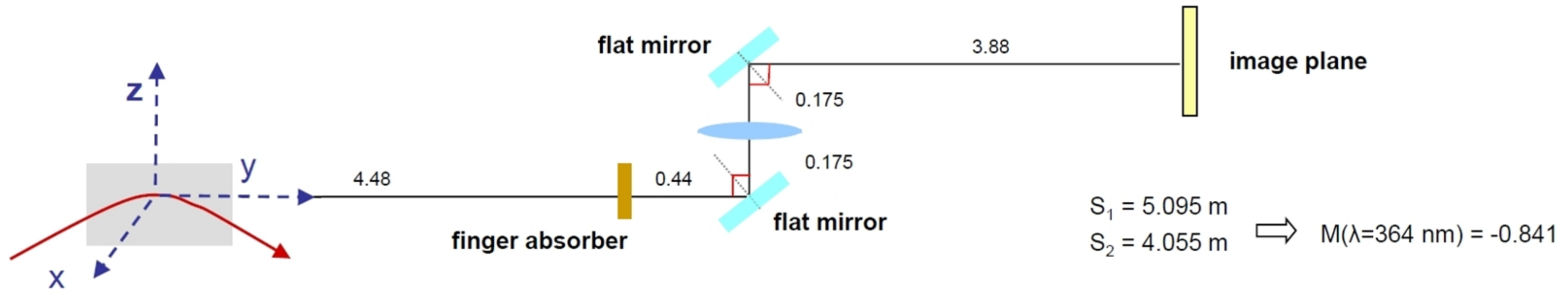
$$E_\pi(x,y) = E_{\pi 0}\,\mathrm{sinc}\left(\frac{2\pi x_c}{\lambda p'}x\right) \times \int_0^{+\infty}\left(1+\xi^2\right)^{1/2}\xi K_{1/3}\left(\frac{1}{2}\frac{\lambda_c}{\lambda}\left(1+\xi\right)^{3/2}\right)\sin\left(\frac{2\pi p}{\lambda\gamma p'}y\xi\right)d\xi$$

2-D Intensity Distribution (in image plane)

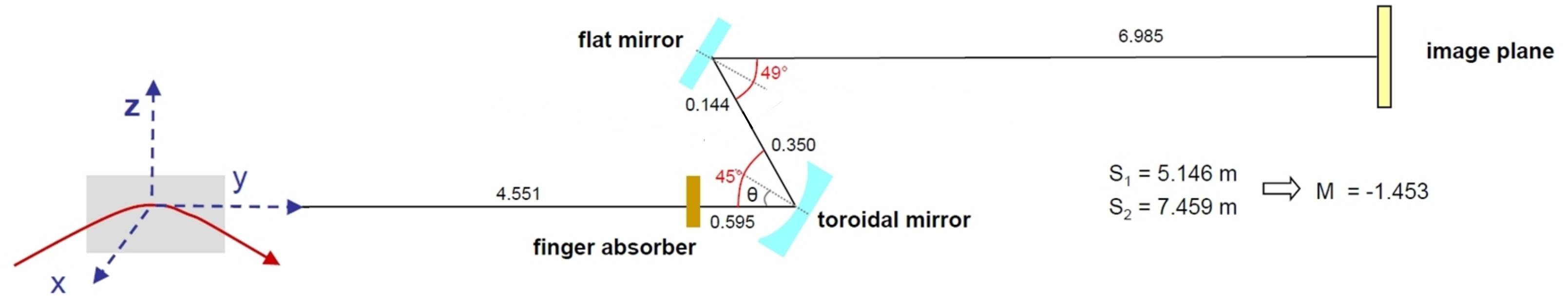
$$I_\pi(x,y) \sim \mathrm{sinc}^2(x) \times \left|\frac{\cos(\psi)-1}{\psi}\right|^2 \quad with\ \psi = \frac{2\pi\theta y}{\lambda}$$

Comparison of the "Old" and "New" SLS Beam Size Monitor

- operating wavelength: 403 / 364 / 325 nm
- opening angle: 7 $mrad_H$ x 9 $mrad_V$
- finger absorber to block main SR intensity
- imaging by fused silica lens
- magnifications: 0.854 / 0.841 / 0.820
- surface quality of optics: < 30 nm (λ/20 @ 633 nm)



- operating wavelength: variable (266 nm)
- opening angle: 7 $mrad_H$ x 9 $mrad_V$
- finger absorber to block main SR intensity
- imaging by toroidal mirror
- magnification: 1.453
- surface quality of optics: < 20 nm (λ/30 @ 633 nm)



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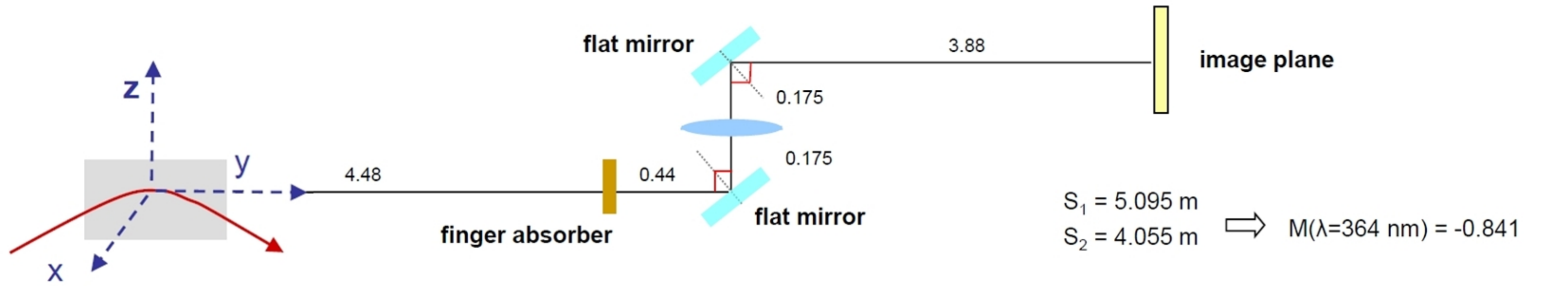

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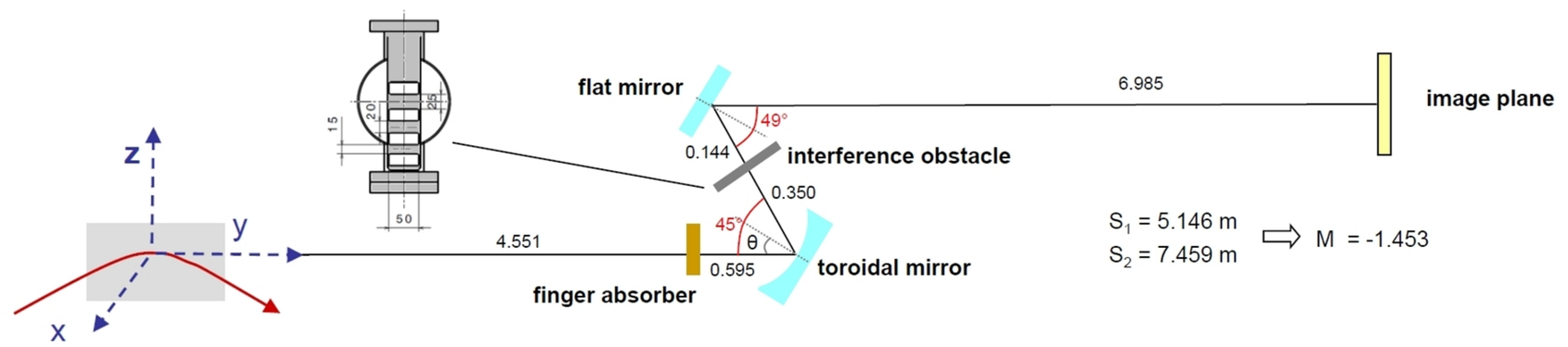
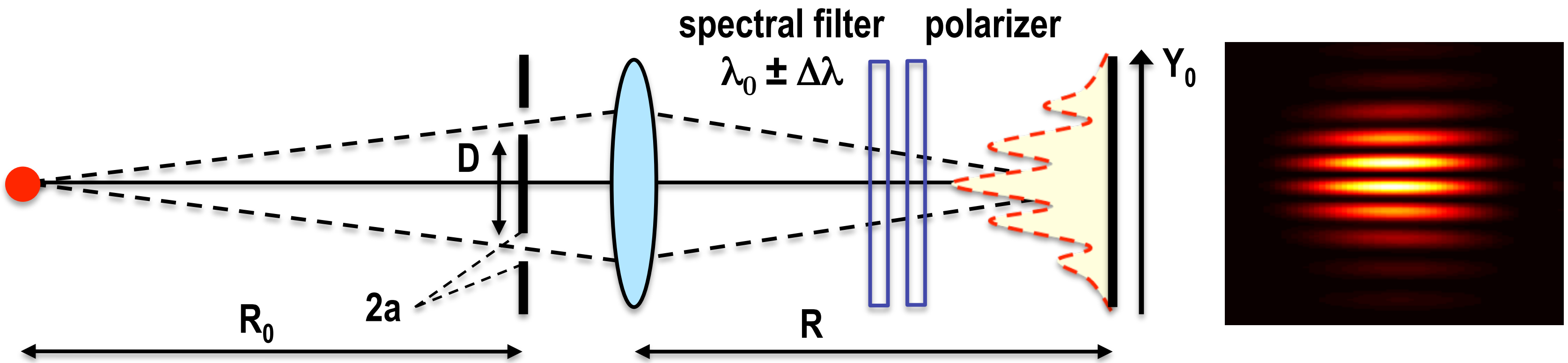
- surface quality of optics: < 20 nm (λ/30 @ 633 nm)

- π-polarization or interferometric method selectable



"New" SLS Beam Size Monitor – 2^{nd} Method: SR Interferometry

T. Mitsuhashi, *Spatial Coherency of the SR at the Visible Light Region and its Application for Electron Beam Profile Measurement,* Proc. PAC 1997, Vancouver, p. 766



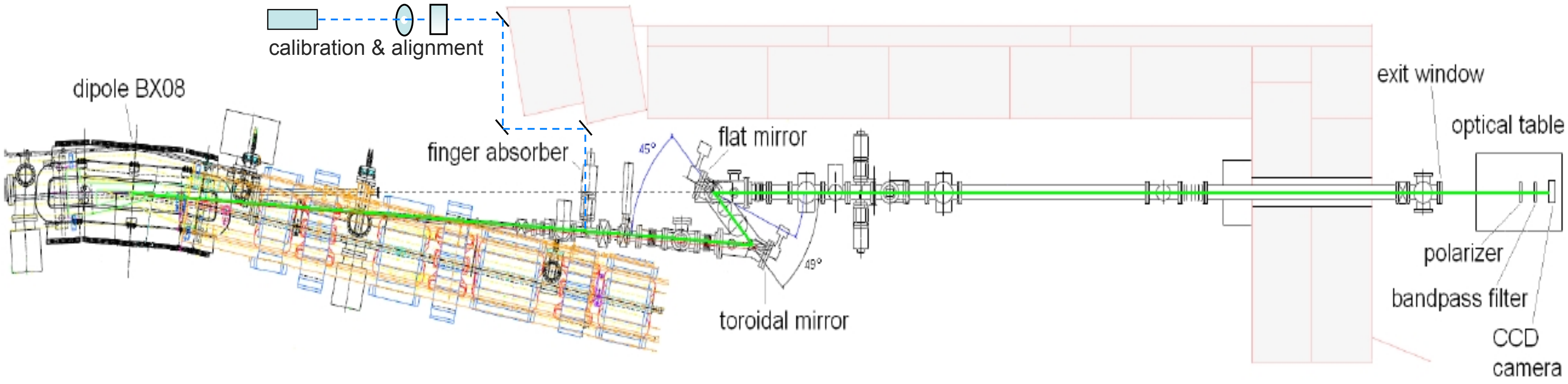
- double slit Michelson interferometer adapted for beam size measurements by T. Mitsuhashi (see WEIC02)
- van Citert-Zernike's theorem relates transverse distribution *f(y)* via FFT with spatial coherence *γ(y)*

<u>Intensity of Interference Pattern</u>

$$I(y_0,D) = (I_1 + I_2)\left[\operatorname{sinc}\left(\frac{\pi\, a\, \chi(D)}{\lambda R}\, y_0\right)\right]\cdot\left[1+|\gamma|\cos\left(\frac{2\pi D}{\lambda}\cdot\left(\frac{y_0}{R}+\psi\right)\right)\right]$$

→ spatial coherence $\gamma = \left(\frac{2\sqrt{I_1 \cdot I_2}}{I_1+I_2}\right)\cdot\left(\frac{I_{max}-I_{min}}{I_{max}+I_{min}}\right)$ provides rms beam size $\sigma = \frac{\lambda R}{\pi D}\sqrt{\frac{1}{2}\ln\left(\frac{1}{\gamma}\right)}$

The "New" SLS Beam Size Monitor – Beam Line X08DA



Main Features of the "New" SLS Beam Size Monitor

- X08-DA allows for longer beam line → optics table fully accessible outside of accelerator bunker
- higher magnification ratio (M = -1.45) → increase of measurement precision
- toroidal mirror as focusing element → free selection of SR wavelength without shift of image plane
  → shorter wavelength increases resolution
- π-polarization & interferometric method → matched operating ranges (nominal and high resolution)
  → cross-checking of results
- alignment & calibration set-up → online inspection of monitor at 266 nm and 532 nm

The "New" SLS Beam Size Monitor – Critical Elements and Issues I

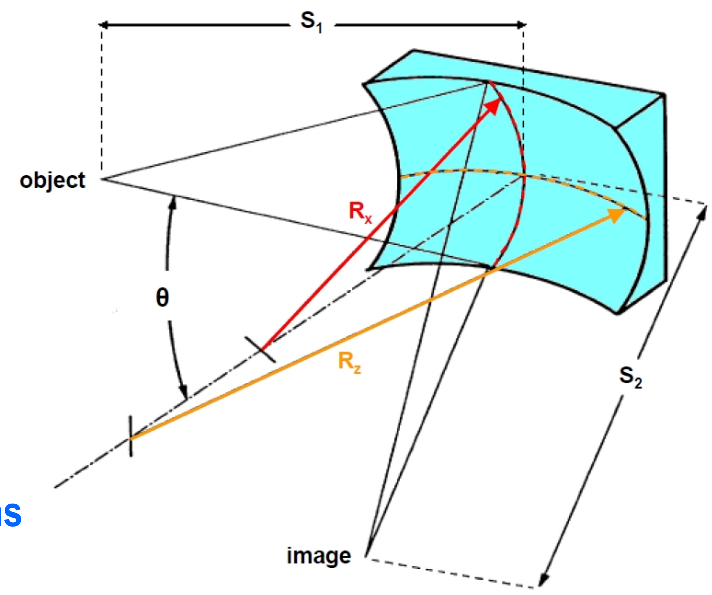
Focusing Element – Toroidal Mirror

- S_1 = 5.146 m
- S_2 = 7.459 m

} → M = - 1.453

- R_X = 6.592 m
- R_Z = 5.627 m
- Θ 22.5°

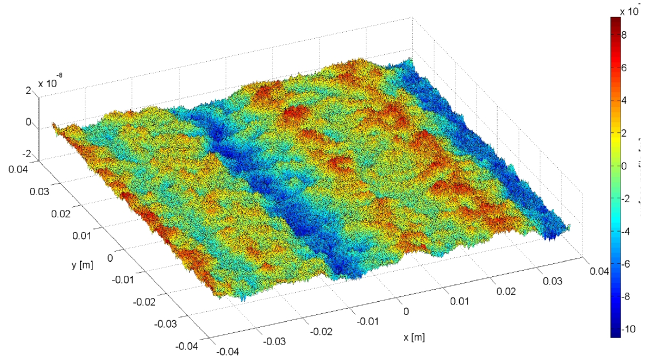
} → $F_X = F_Z$ = 3.045 m

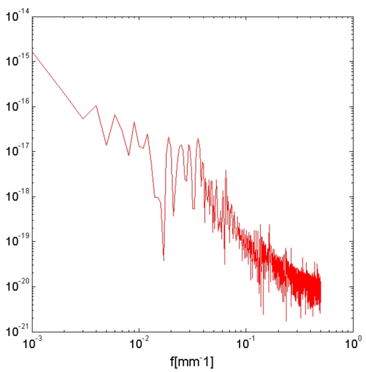


- Material: SiC (silicon carbide), Al-coated (UV enhanced)
- Surface Quality:

slope error	0.2 arcsec
roughness	21 nm pp (λ/30) , < 4 nm rms
waviness	horizontal, vertical, radial

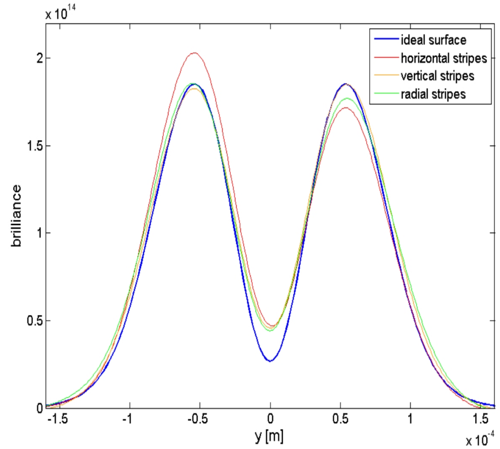
Modelling of Toroidal Mirror Surface Quality





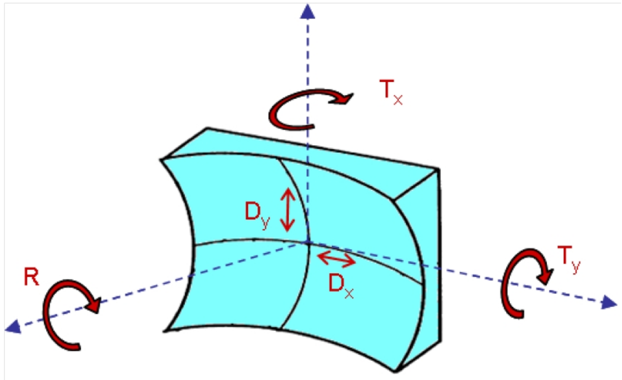
horizontal stripes
→ asymmetry

vertical & radial stripes
→ acceptable



The "New" SLS Beam Size Monitor – Critical Elements and Issues II

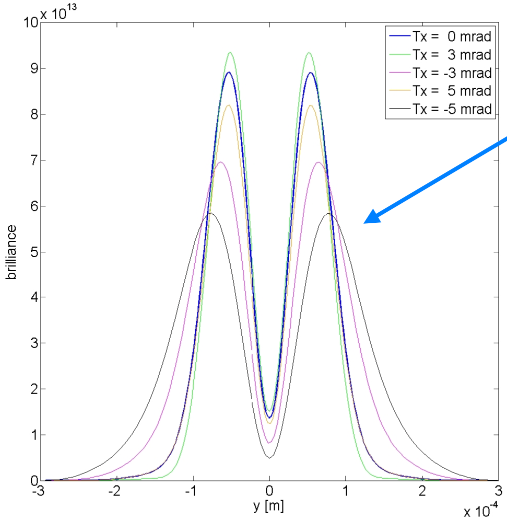
Toroidal Mirror – Offsets & Misalignments



- horizontal offset D_X
- vertical offset D_Y

} → not critical within ± 50 μm

Influence of Tilts (T_X, T_Y) and Axis Rotation

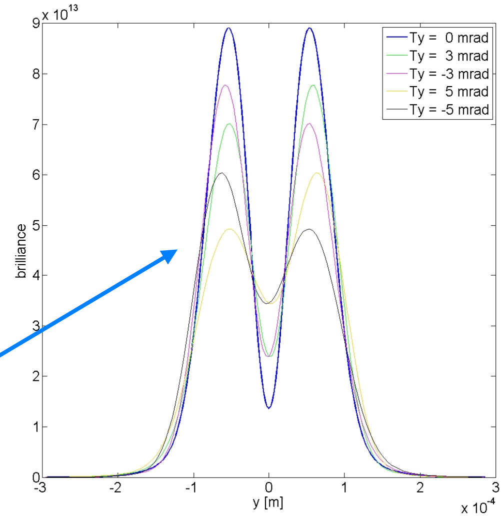


horizontal tilt T_X

symmetric broadening and
and washing out of peak-to-valley pattern

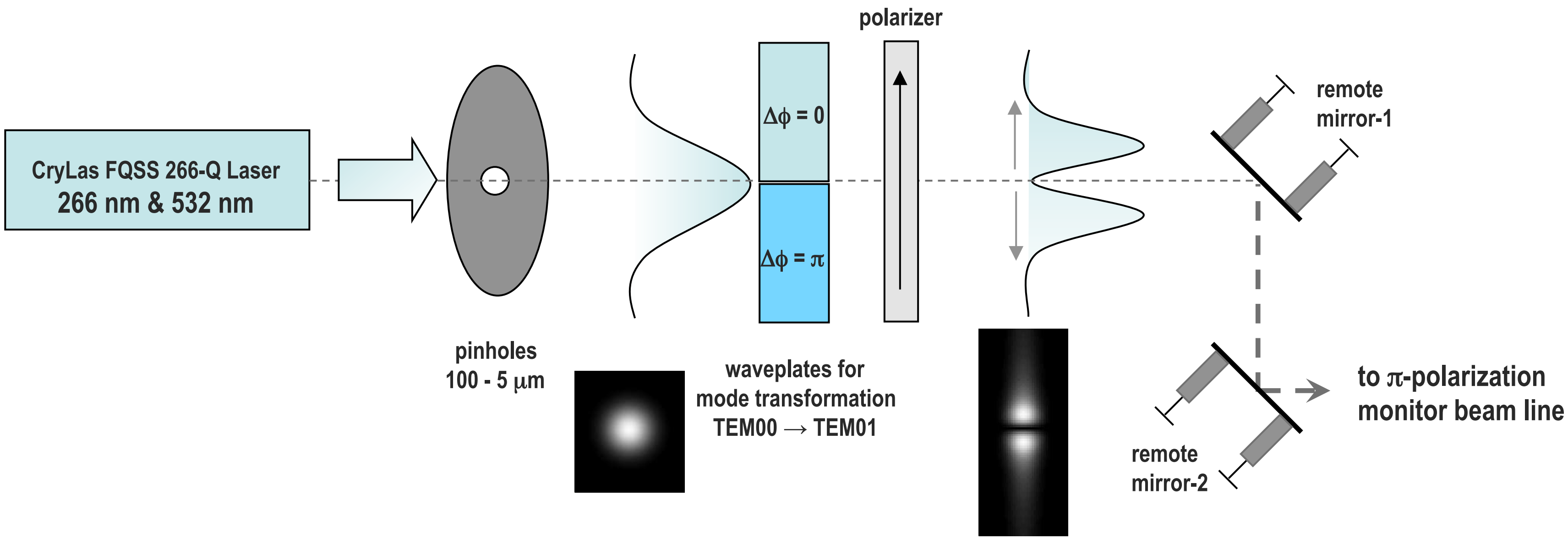
rotation around mirror axis R and vertical tilt T_Y

asymmetric washing out of
peak-to-valley pattern for R & T_Y



The "New" SLS Beam Size Monitor – Calibration & Alignment

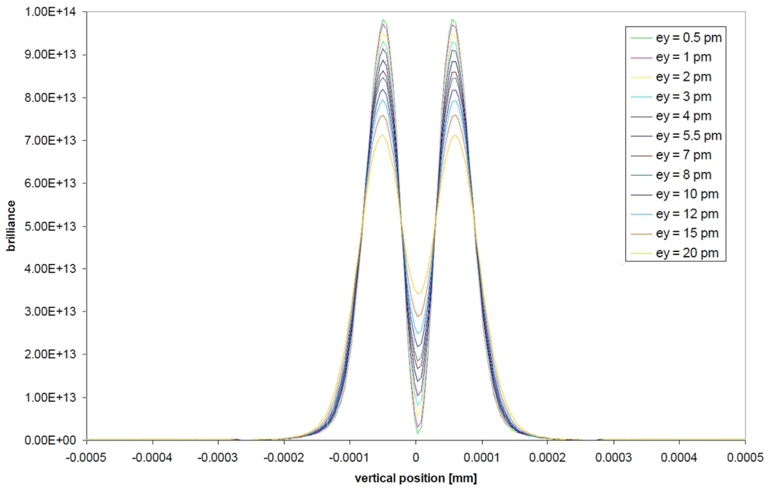
mode images from: Meyrath et al., Opt. Express, Vol. 13, Issue 8, pp. 2843-2851 (2005)



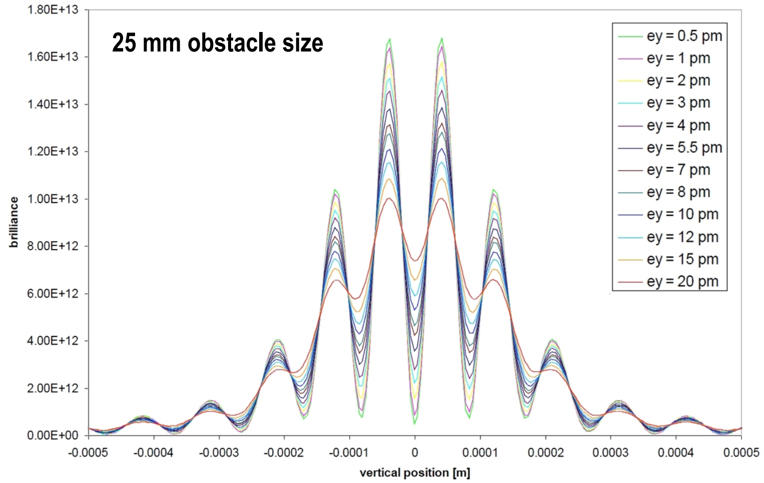
- CryLas FQSS 266-Q Laser…: λ_1 = 266 nm, λ_2 = 532 nm, vertically polarized (100:1), TEM_{00}
- pinholes as virtual source…: diameters of 100 μm, 50 μm, 25 μm, 15 μm, 10 μm, 5 μm, 1 μm
- "mode transformation"
  "polarization rotation"…: λ/2 waveplates at 0° (upper half) and 90° (lower half)
- remote controlled mirrors…: for beam transfer into π-polarization beam size monitor

The “New” SLS Beam Size Monitor – Expected Performance

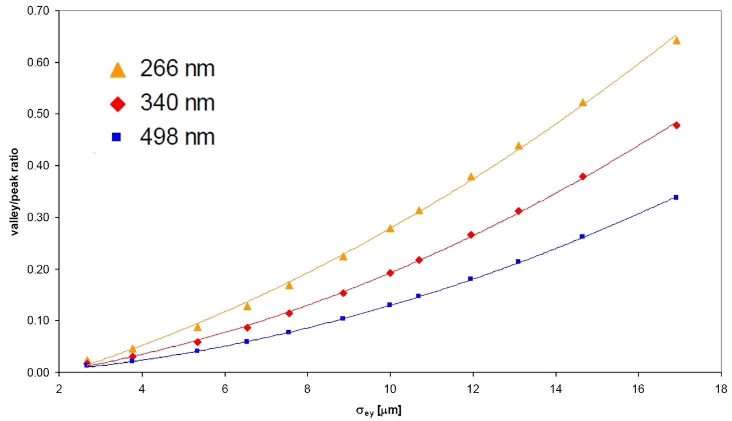
π-Polarization Branch – Emittance Resolution



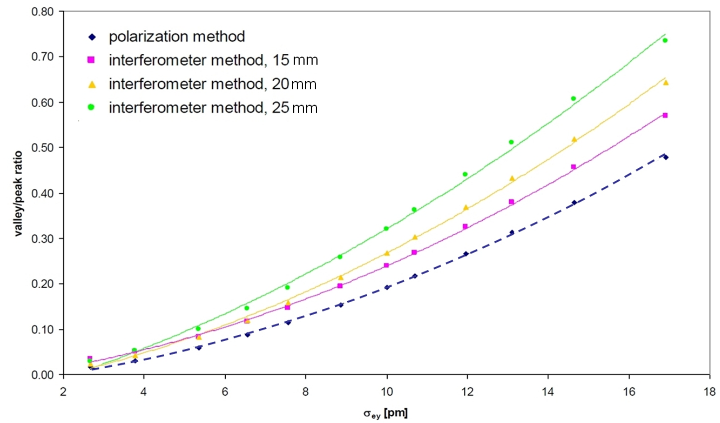
Interferometer Branch – Emittance Resolution



π-Polarization Branch – Resolution vs Wavelength

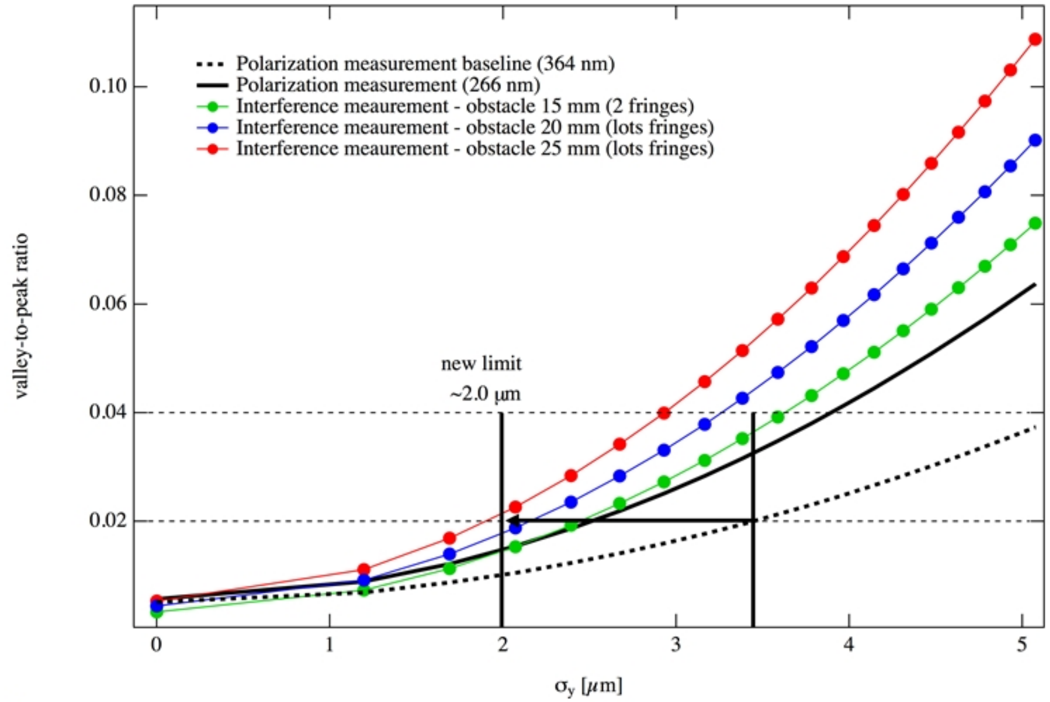


Interferometer Branch – Resolution vs Obstacle Size



The "New" SLS Beam Size Monitor – Expected Performance

Comparison: π-Polarization Branch – Interferometer Branch



- **improved resolution** → ~ 4 μm (old monitor) **to ~ 2 μm (new monitor)**
- **two measurement methods** → **π-polarization for nominal SLS operation**
  → **interferometer for low emittance studies**
- **calibration & alignment path** → **online check of monitor performance**

Summary and Outlook

- methods for emittance tuning established at SLS (within TIARA-SVET collaboration)
  - → lowest vertical emittance of 0.9 ± 0.4 pmrad
- design of "new" high resolution beam size monitor at SLS
  - → application of π-polarization and interferometeric methods
  - → overlapping sensitivity ranges for nominal SLS operation and low emittance studies
  - → mirror optics (toroidal focusing mirror) provides free selection of SR wavelength
  - → sensitivity study using SRW provides specifications for optical elements
  - → calibration and alignment branch allows for online monitor performance check
  - → expected measurements resolution for vertical beam height ~ 2 μm
- next steps…:
  - → installation of "new" monitor in SLS X08DA beam line in January 2013
  - → further ε_y minimization by mid of 2013 (towards SLS quantum emittance limit of 0.2 pmrad)
  - → automated coupling feedback using "new" beam size monitor in 2013

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many thanks to…:

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→ Pavel Chevtsov & Colin Higgs for control system interfacing & support

→ Helge Brands for CCD read-out and image processing

→ Christian Lüscher & Stefan Speckert for safety & interlock systms (EPS & MIS)

→ Nazareno Gaiffi & the SLS vacuum group for UHV & installation support

→ Elmar Zehnder & Beat Sommer for cabling & electrical installations

→ Peter Oggenfuss & Roger Sommer for SLS floor coordination

→ Tino Höwler & the alignment group for alignment of all components

→ many more for their support and fruitful discussions

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