Towards a bunch-resolved transverse beam-profile monitor for BESSY II and BESSY VSR

HZB Helmholtz Zentrum Berlin

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The BESSY VSR Project

See *Technical Design Study BESSY VSR*
Variable pulse-length **S**torage **R**ing
by A. Jankowiak et al. (June 2015)

BESSY VSR Project

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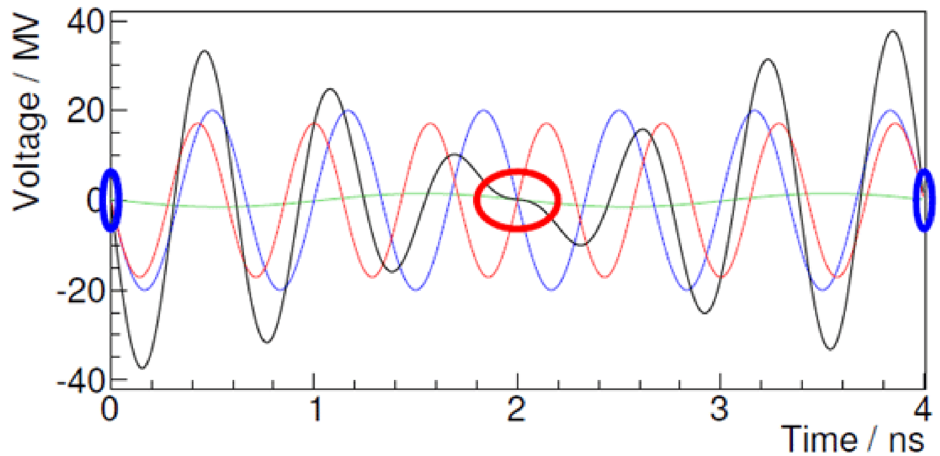
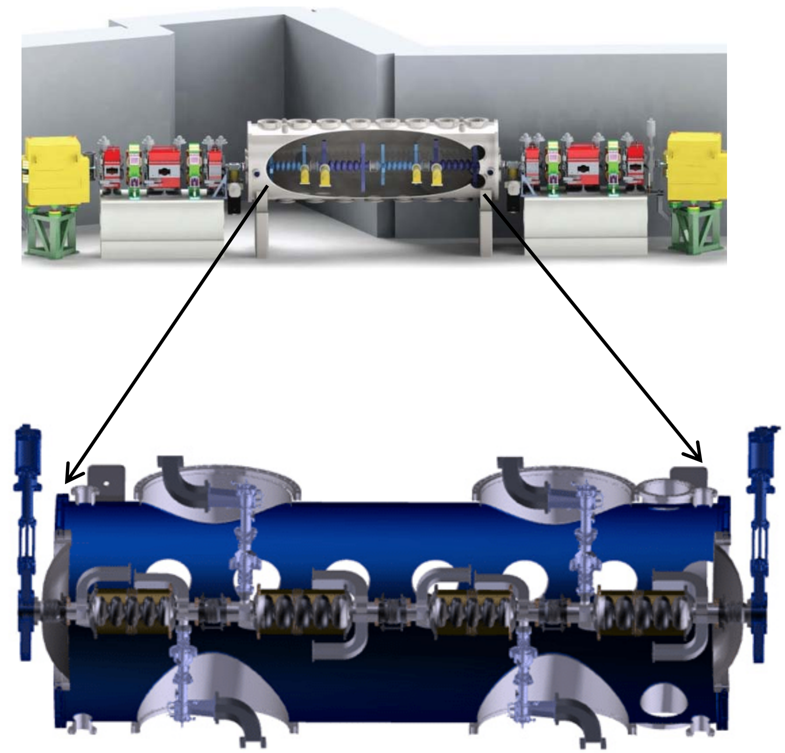


Superposition of 0.5 GHz (BESSY II) and additional 1.5 GHz and 1.75 GHz RF voltages for the BESSY VSR project. This leads to a beating field pattern and formation of short as well as long buckets every 2 ns.



The BESSY VSR cryo-module design-concept, showing 1.5 GHz and 1.75 GHz SRF cavities.

See also

- G. Wüstefeld et al., *„Simultaneous Long and Short Electron Bunches in the BESSY II Storage Ring“*, Proc. IPAC 2011, San Sebastian, Spain, 2011
- A.Velez et al. (2015)
BESSY VSR: A NOVEL APPLICATION OF SRF FOR SYNCHROTRON LIGHT SOURCES

BESSY VSR Project

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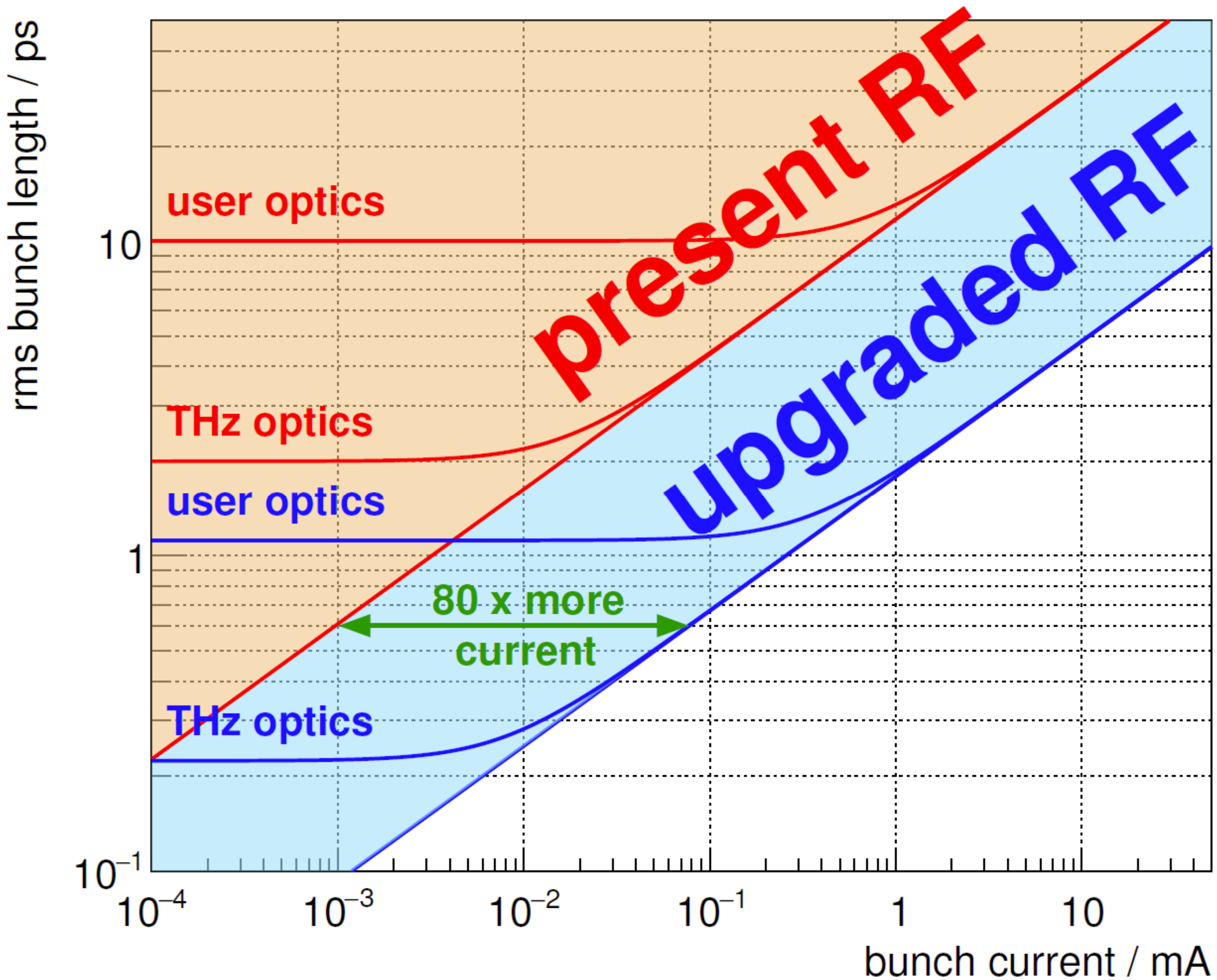

BESSY VSR Project

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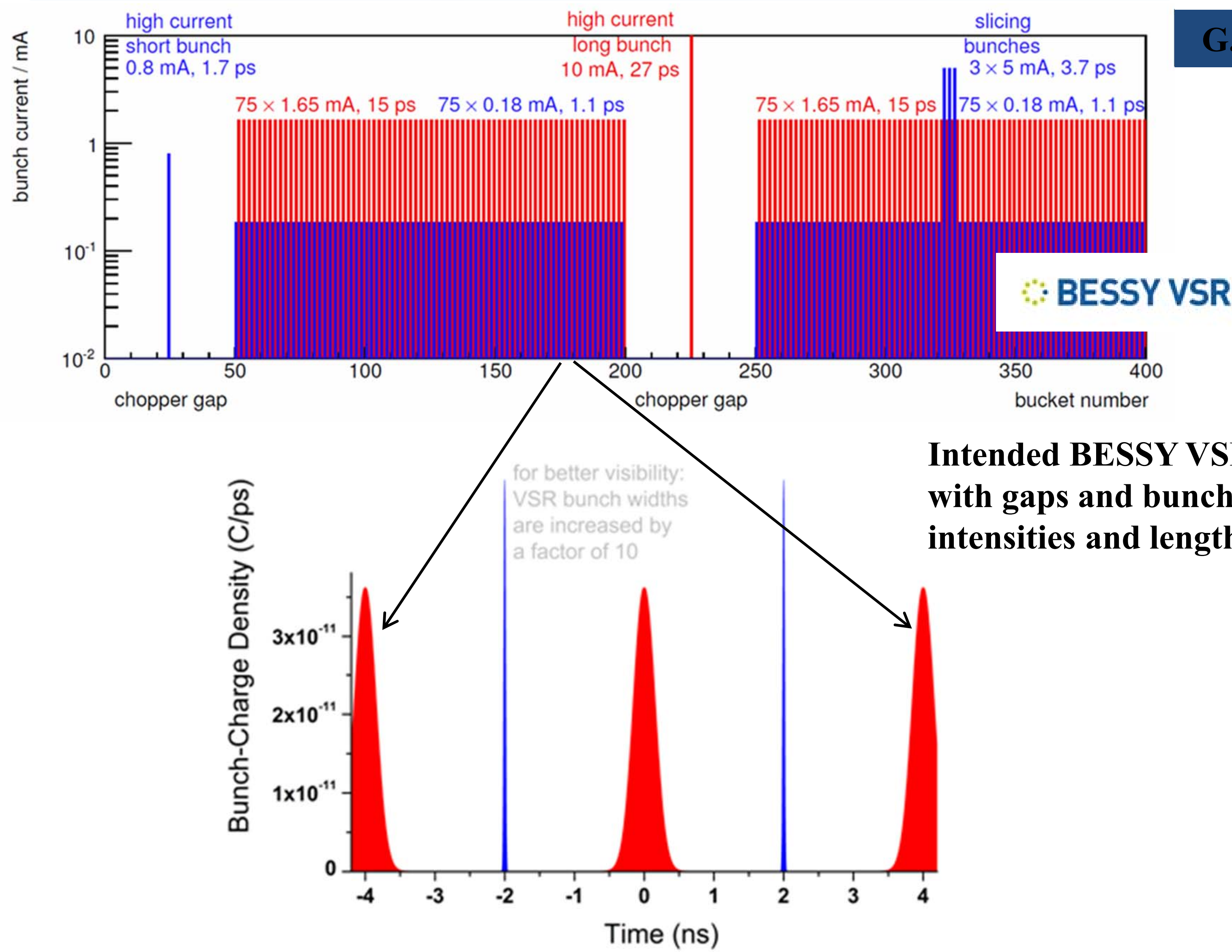

Intended BESSY VSR timing pattern with gaps and bunches of different intensities and lengths.

Requirements for Diagnostics @ BESSY VSR

Requirements

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- Nondestructive diagnostics of
  - beam position + lateral sizes or distributions f(z,x,y)
  - bunch-pattern as well as
    longitudinal bunch length and phase or time distribution f(z,t)

- Robust 24/7 bunch-by-bunch diagnostics @ BESSY VSR
  - use capacitive pick-up electrodes (button Beam Position Monitors)
  - use photons preferentially from dipole beamlines

- Use indirect beam imaging via photon-based methods
  - X-rays (pinhole monitors, bunch-pattern monitor,
    XBPMs and Staggered-Pair Monitors)
  - THz detection (fluctuations and spectral shape)
  - photons in the visible range (streak-camera timing measurements,
    halo monitor, direct source-point imaging, interferometry)

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New Beamlines for Optical Diagnostics

Beamlines

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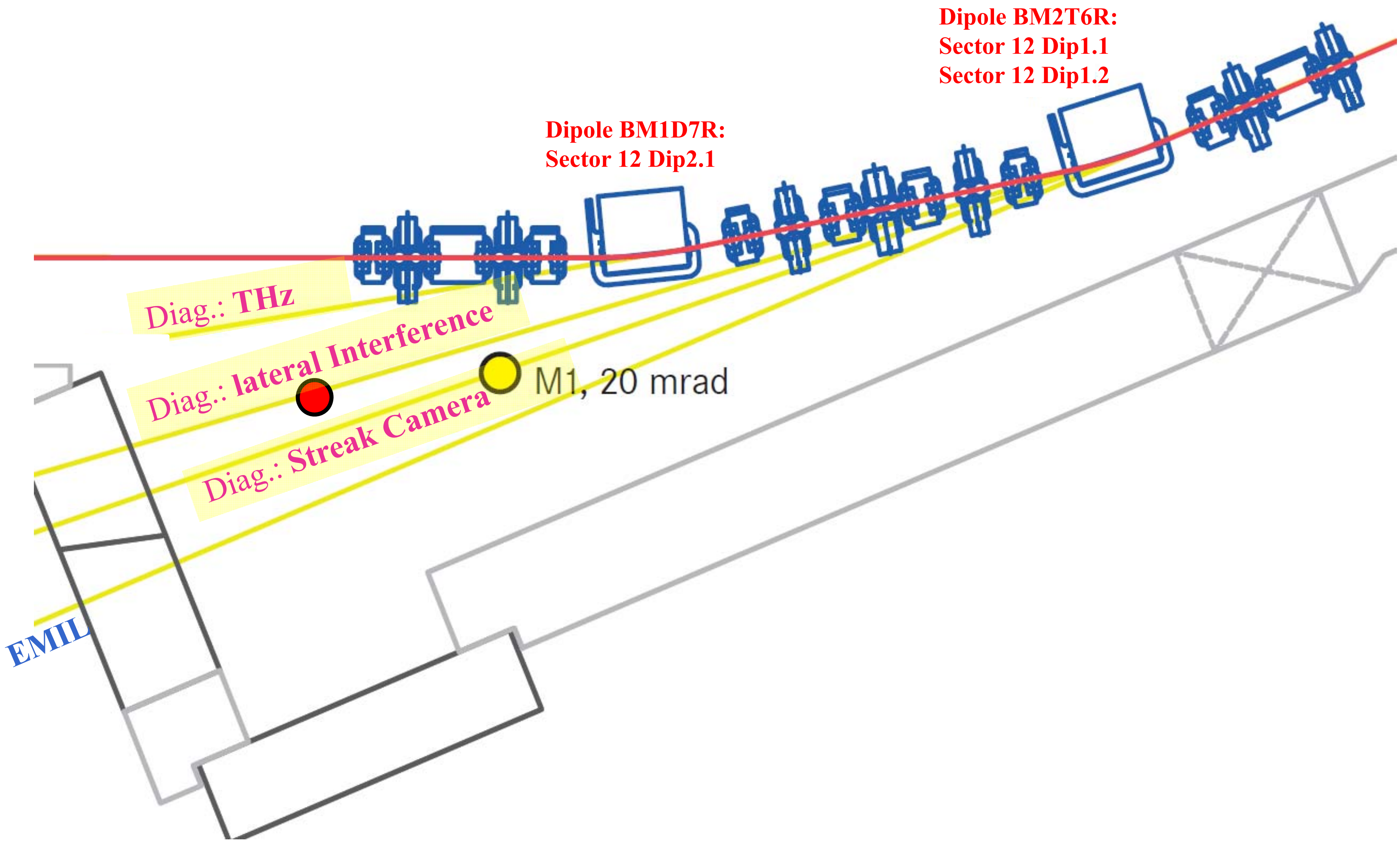

Beamlines

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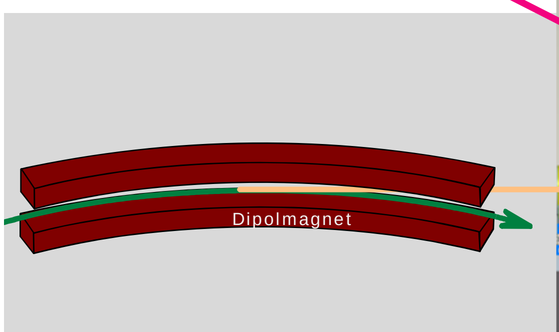
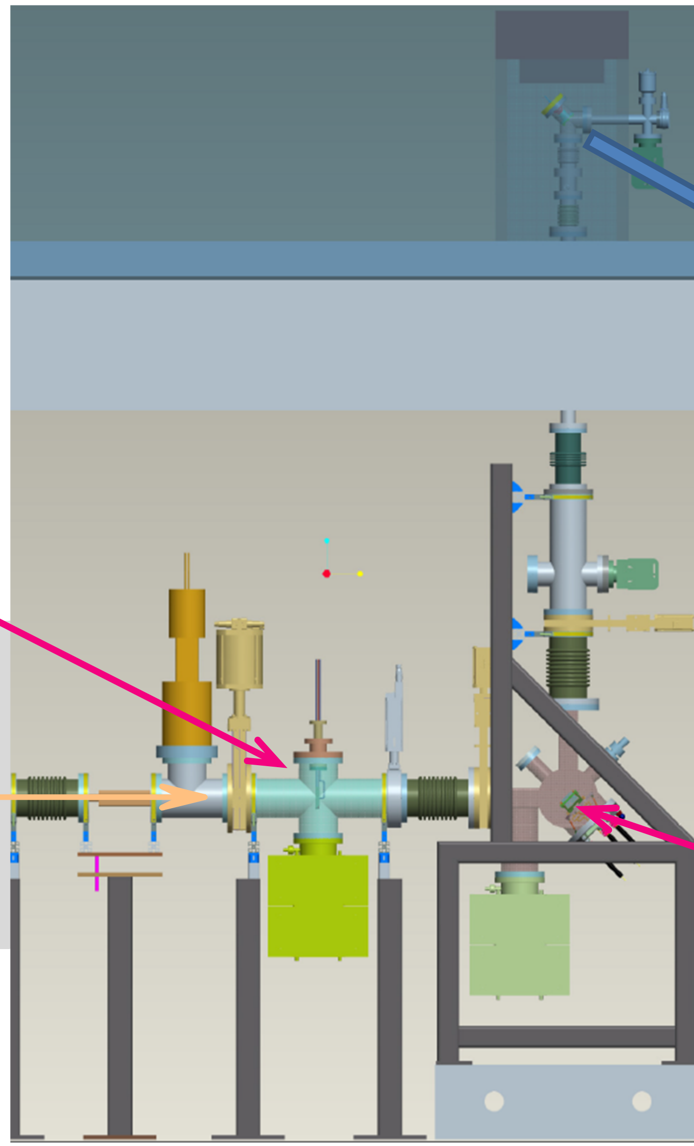
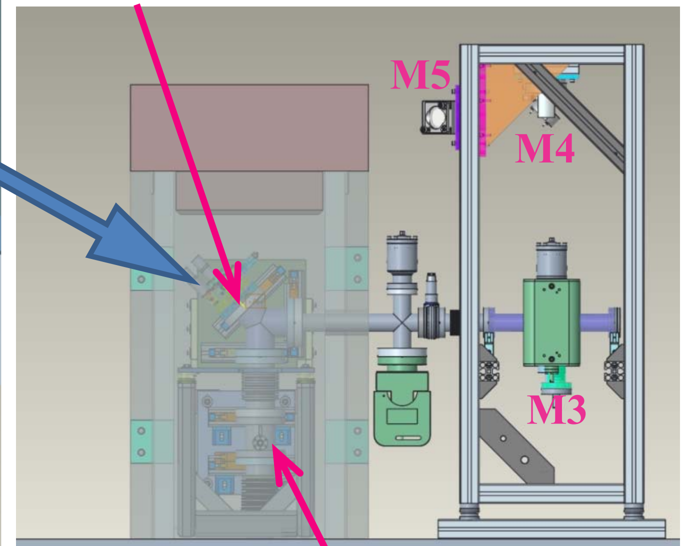
Sector 12 Dip1.1 - BM2T6R
Longitudinal Bunch Size
(timing: streak Camera etc.)







Beamlines

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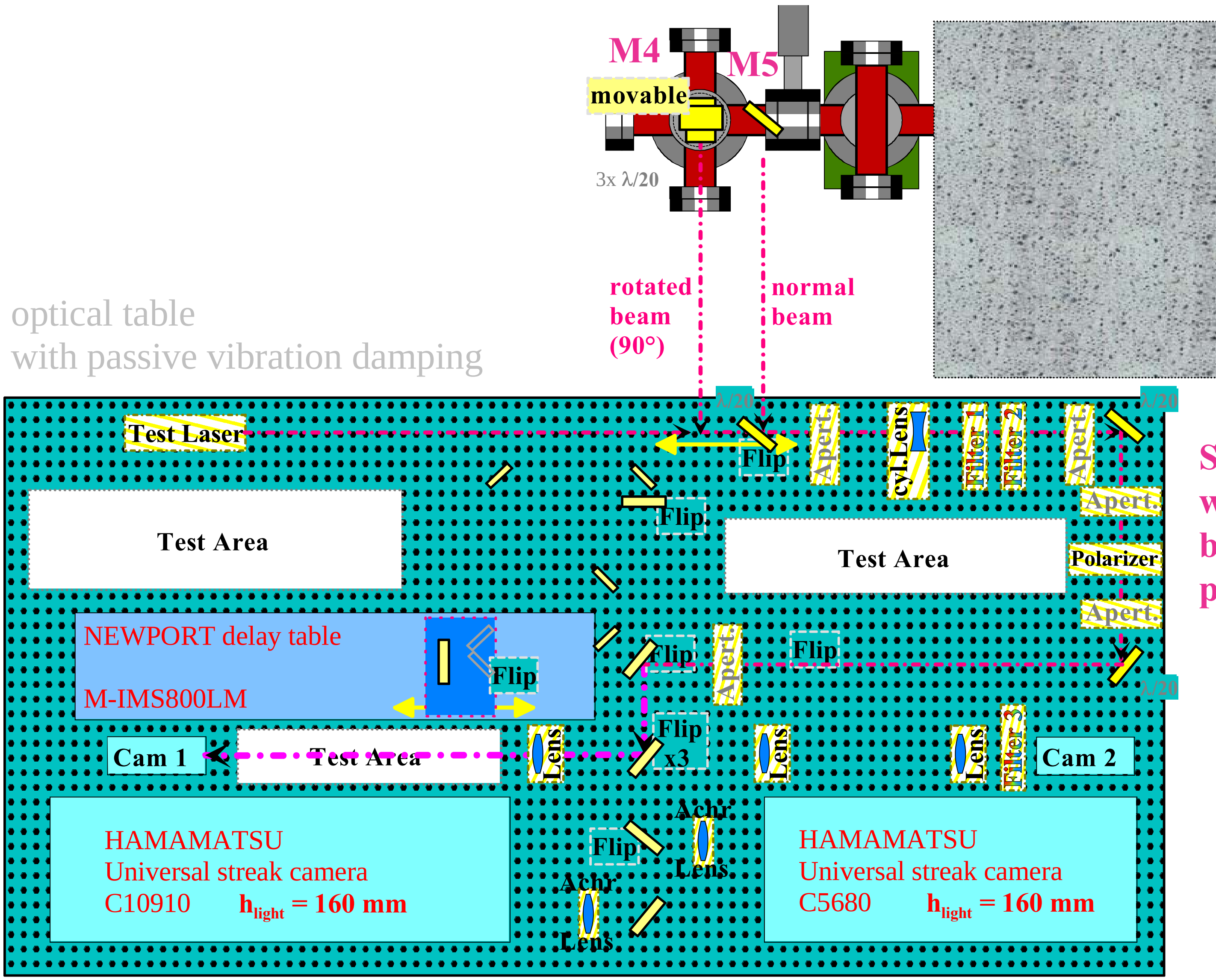
Select orientation of collimated light-beam

optical table
with passive vibration damping



Select wavelength, bandwidth and polarization

Beamlines

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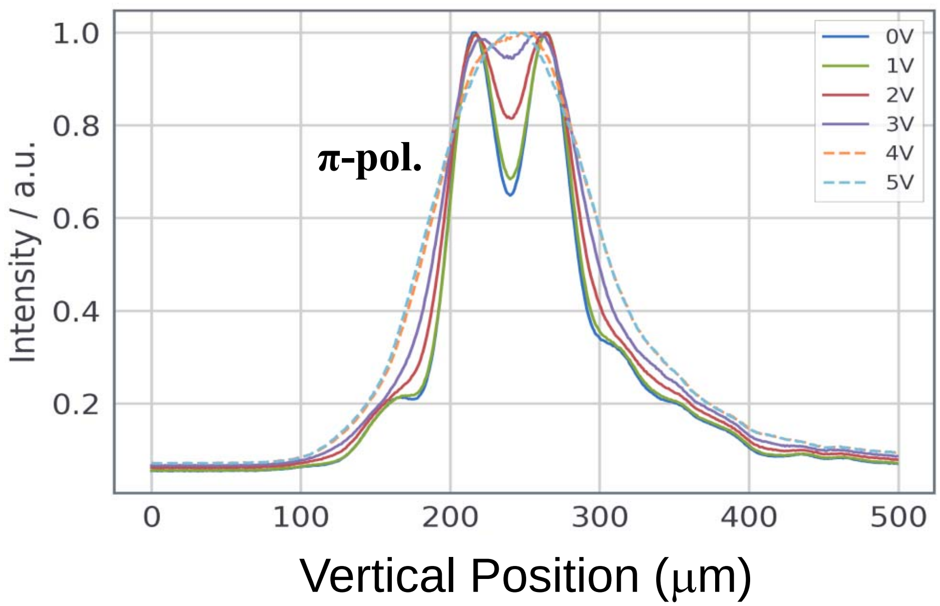
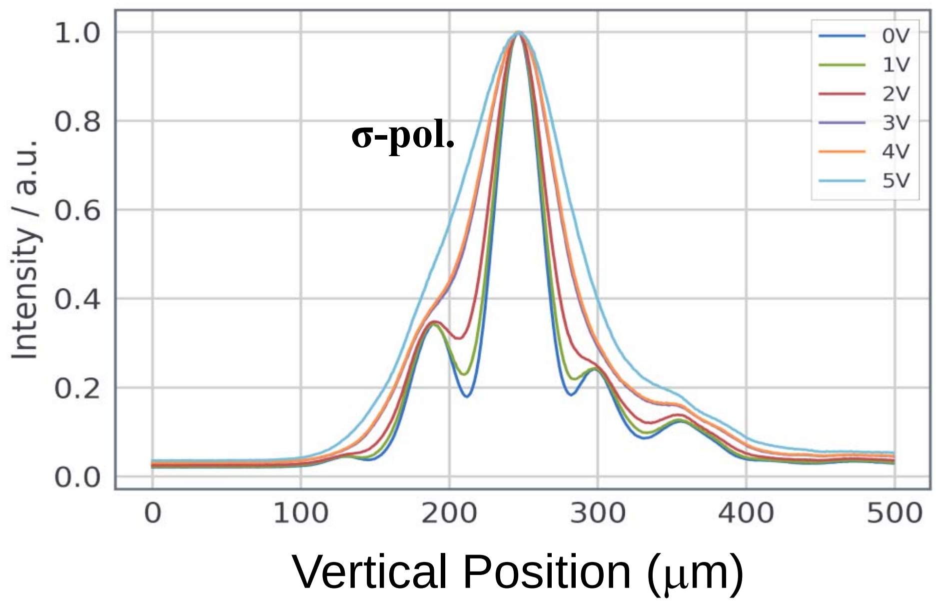
Direct imaging with CCD @ 800 nm
as function of the vertical noise excitation (0 to 5 V) of the beam





π-polarization at smaller beam sizes

- Strong interference minimum at the center position (X-Ray baffle method)
- Beam size may be obtained from the valley-to-peak ratio
- Wave-optical simulations are needed for quantitative evaluation

Å.Andersson, M.Böge, A.Lüdeke, V.Schlott, A.Streun, NIM-**A591**, 437–446 (2008).

σ-polarization at larger beam sizes

- Interference structures vanish if the beam size reaches Rayleigh's diffraction criterion (~ Abbe limit)

$$\Delta y \approx \frac{0.61 \cdot \lambda}{\sin\alpha} = \frac{0.61 \cdot 800\ nm}{0.0028} = 0.17\ mm$$

- Geometrical optics: lateral beam size and distribution may simply be determined from the known magnification and resolution of the optical system

Double-Slit Interferometry Using Visible Light

Interferometry

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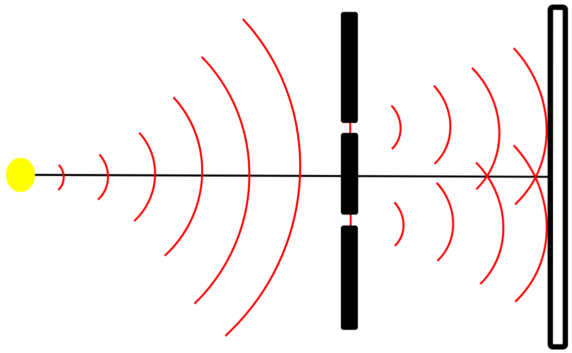

λ = wavelength
w = slit width
d = slit separation
R = distance between slits and screen
L = distance between source and slits
with *R*,*L* >> *d* >> *w* >> λ

A double slit is exposed by a point-like source at a large on-axis-distance. The Fraunhofer interference pattern of this double slit is given by

$$I(x) = 2I_0\, sinc^2\left(\frac{\pi w}{\lambda R}(\boldsymbol{x}-\boldsymbol{x_0})\right) cos^2\left(\frac{\pi d}{\lambda R}\,(x-x_0)\right);\ \text{with } sinc(x) = \frac{sin\,x}{x}\ ,$$

where the first term describes an incoherent sum of two single-slit distributions.

For a Gaussian-distributed light source, we have

$$I(x) = I_0\, sinc^2\left(\frac{\pi w}{\lambda R}(\boldsymbol{x}-\boldsymbol{x_0})\right)\left[\mathbf{1} + V\, cos\left(\frac{2\pi d}{\lambda R}\,(x-x_0)\right)\right],$$

where $V \cong (I_{max} - I_{min})/(I_{max} + I_{min})$ denotes the experimental visibility that is related to the rms source width σ via

$$\boldsymbol{\sigma} = \frac{\lambda L}{\pi d}\sqrt{\tfrac{1}{2}\, ln(1/V)}\,.$$

T. Mitsuhashi, *"Beam Profile and Size Measurement by SR Interferometer"*,
in Beam measurement, Ed. by S. Kurokawa et al., pp. 399 – 427, World Scientific 1999.

Interferometry

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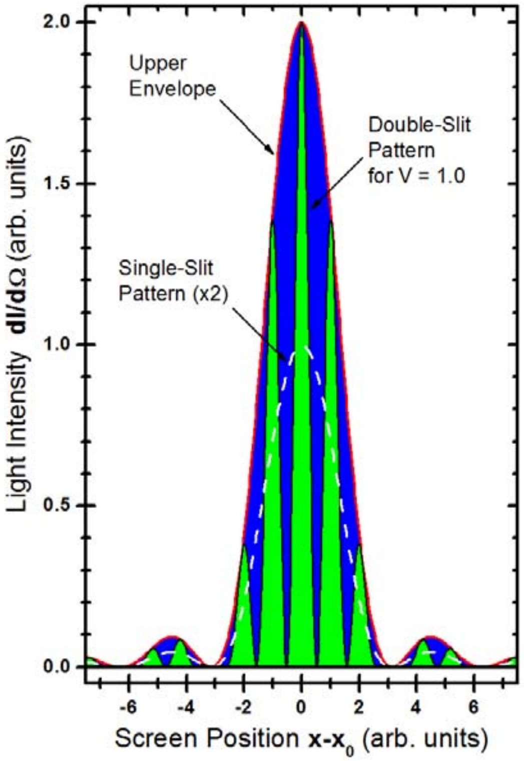
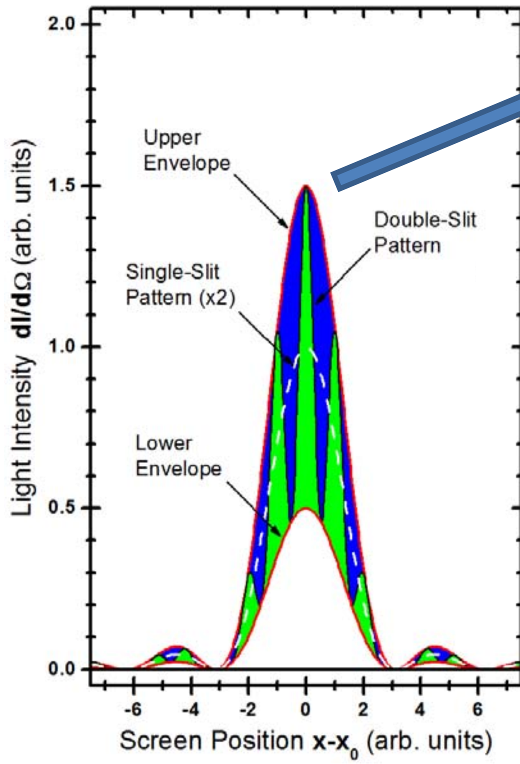
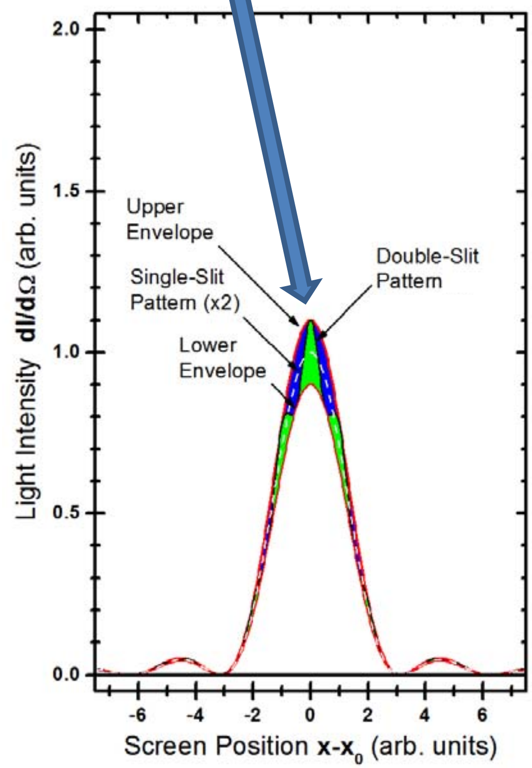


Full spatial coherence:
Point source visibility
V = 1.0



Reduced spatial coherence:
Visibility *V = 0.5*

Increase by a factor of *1.8* in σ



Reduced spatial coherence:
Visibility *V = 0.1*

Interferometry

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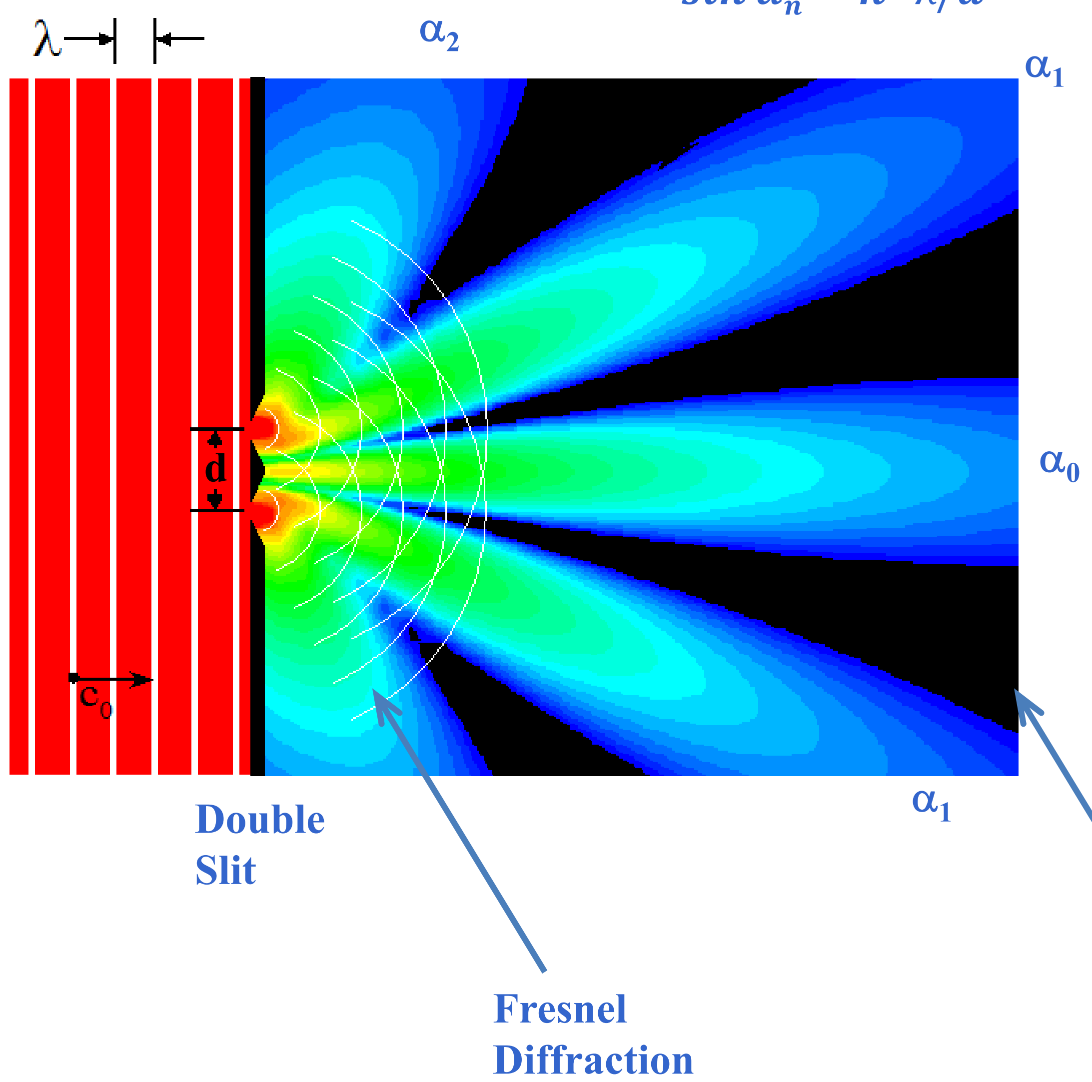
$$\sin \alpha_n = n \cdot \lambda / d$$



Interferometry

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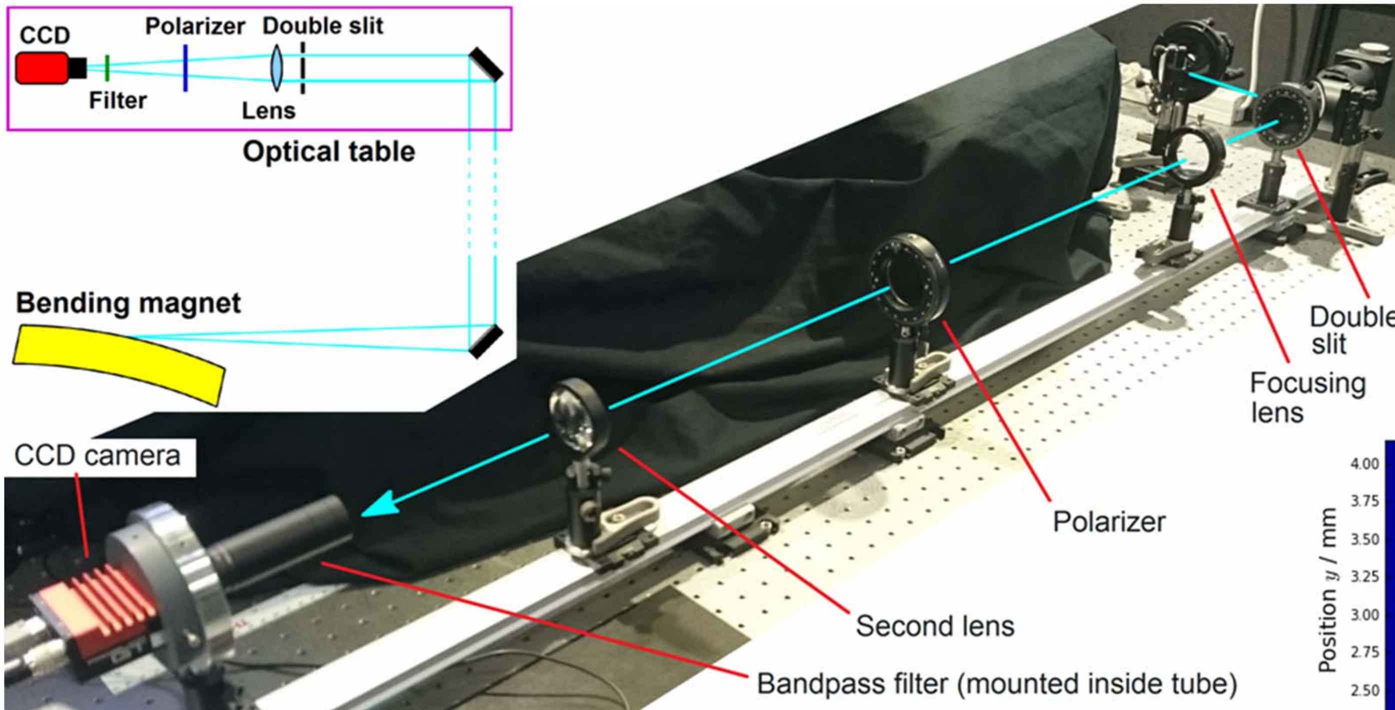

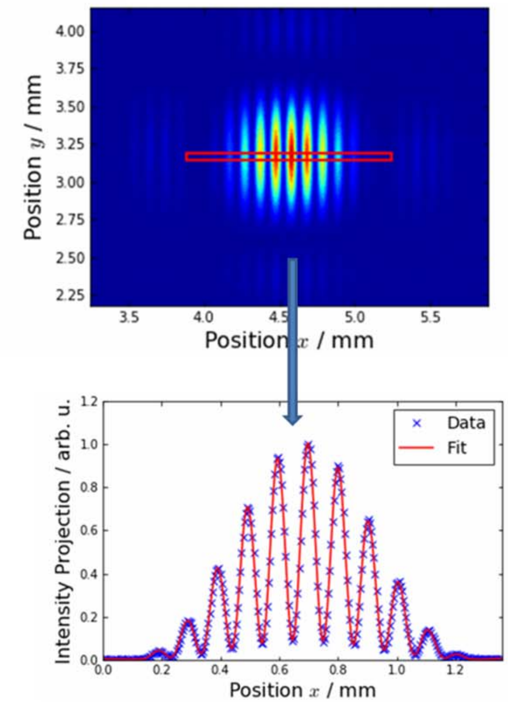

Master Thesis Marten Koopmans

Scheme and photo of the optical Interferometric Beam-Size Monitor (IBSM)

Interferometry

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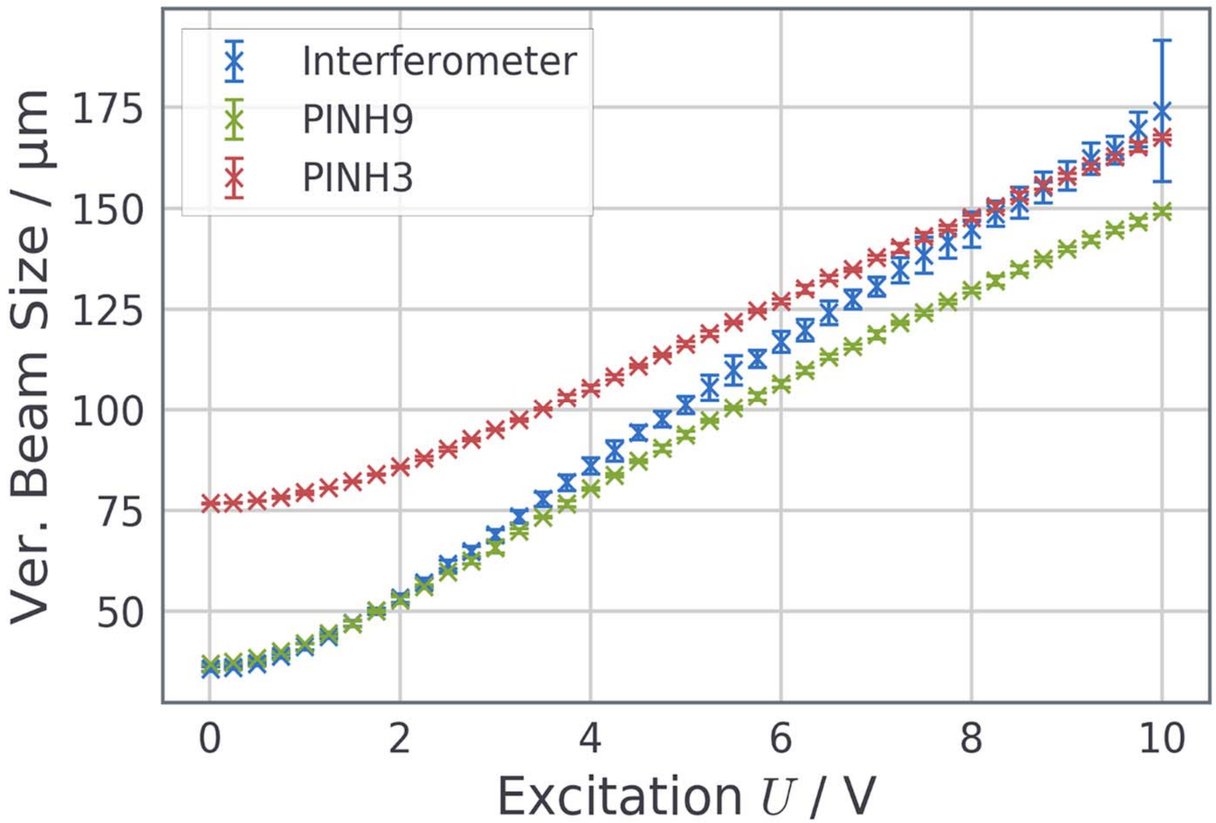
Measurements have been performed as function of

- Electron-beam energy E_e
- **Noise Excitation U**
- Rotation angle
- Slit distance Δd
- Linear polarization
- Filter wave-length λ
- Filter band-width Δλ
- **Camera-exposure time**



Interferometry

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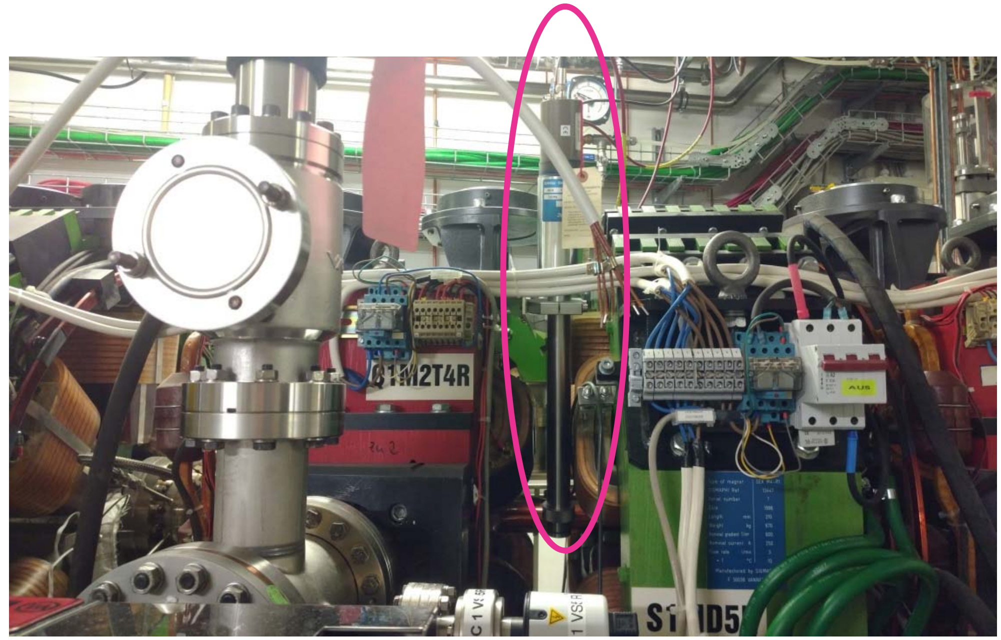
- Use the lifetime τ_{beam} as additional parameter sensitive to the size σ of the electron beam
- The reciprocal lifetime is proportional to the total particle Loss Rate (*LR*), as observed by beam-loss monitors
- Model ansatz: beam-size independent plus beam-size dependent term

$$LR = LR_{\text{const}} + LR_{\sigma}$$

with $LR_{\sigma} \propto \sigma^{-1}$



Method suggested by P. Kuske

Interferometry

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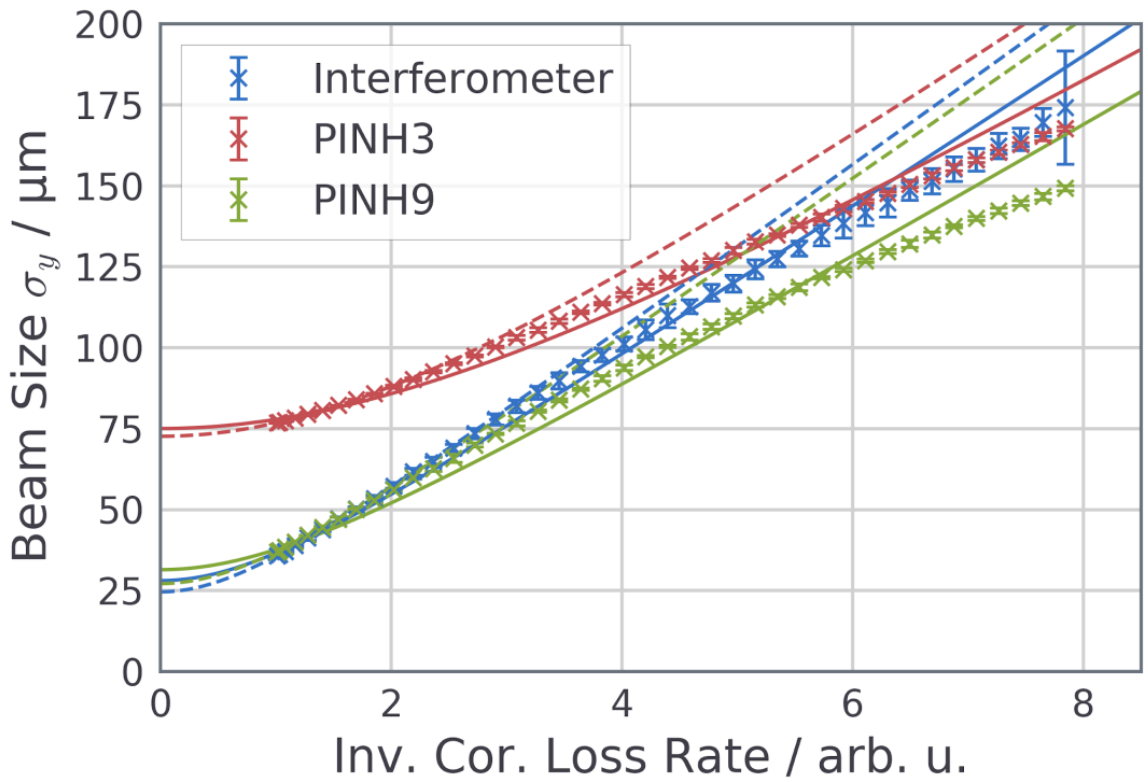

System	Data	σ_{res} / µm	σ_0 / µm
Interferometer	First 10	**24.6±0.2**	25.8±0.1
PINH3		**72.6±0.1**	24.9±0.1
PINH9		**27.2±0.3**	25.0±0.3

Problems and Solutions

Interferometry

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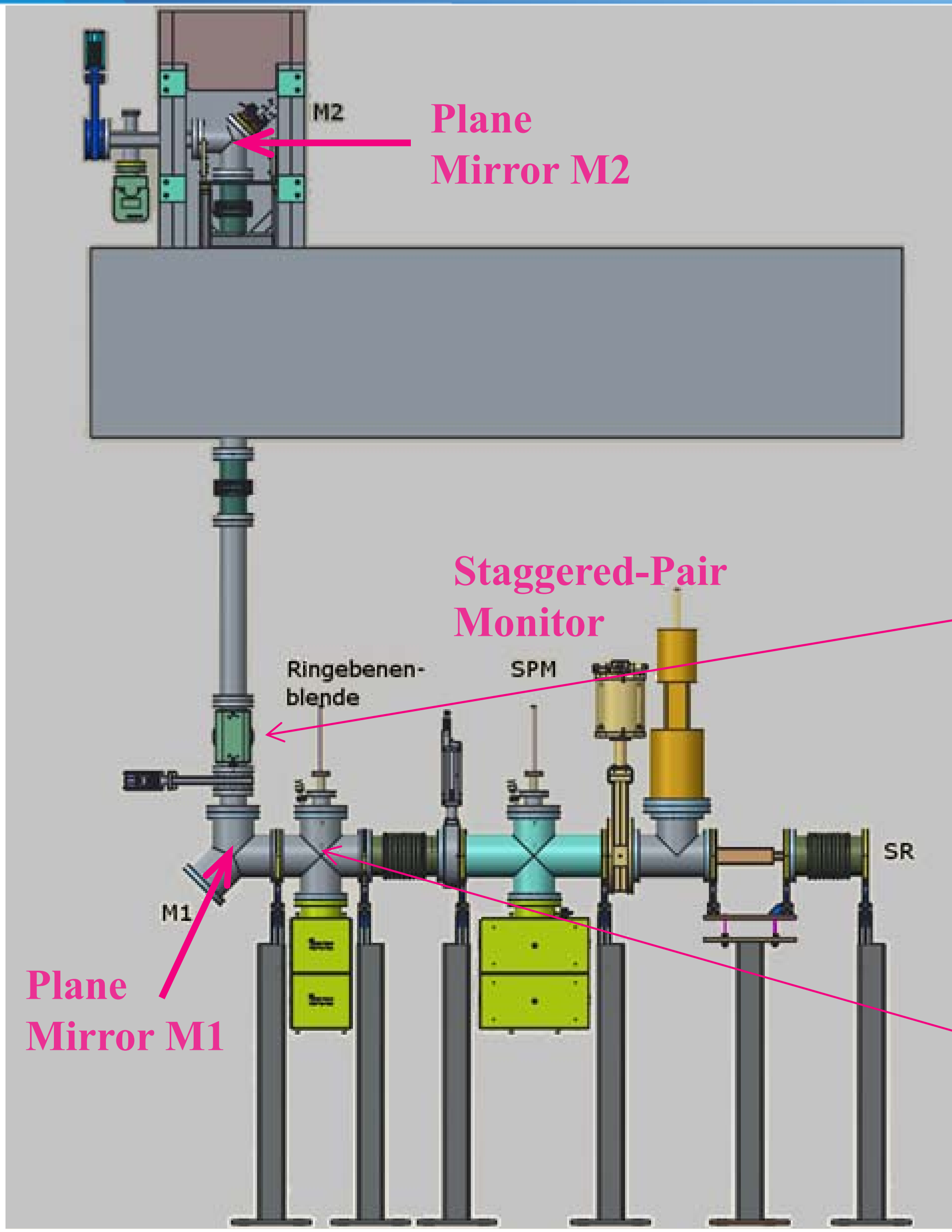

Sector 12 Dip1.2 - BM2T6R
Lateral Bunch-Size
Interferometry (ICCD)

Selectable/retractable
interference target
plus
retractable
achromatic lens

X-Ray Blocker

Problems and Solutions

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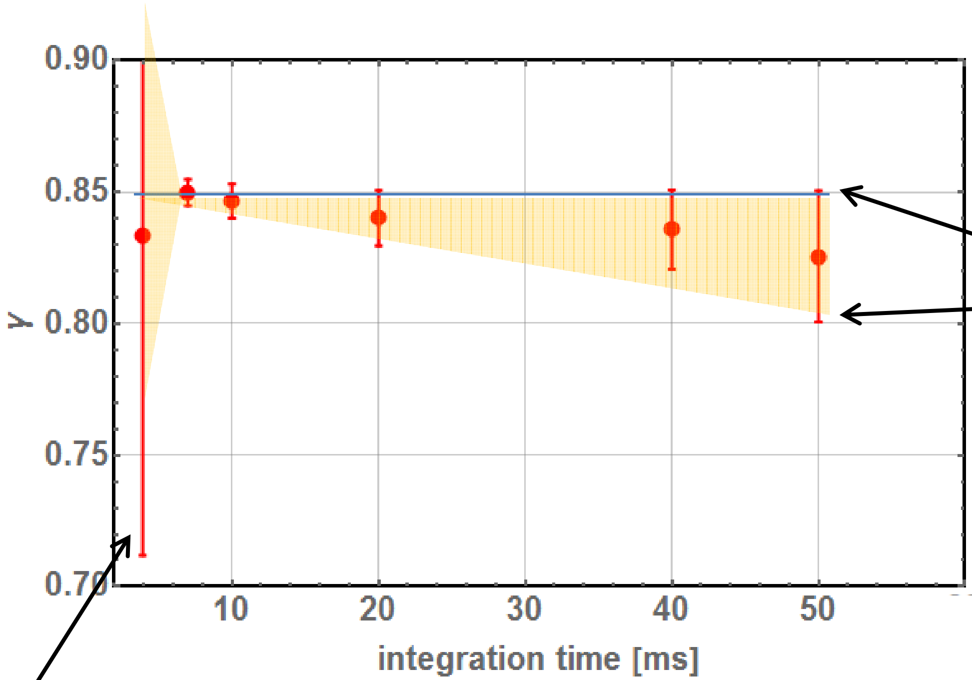
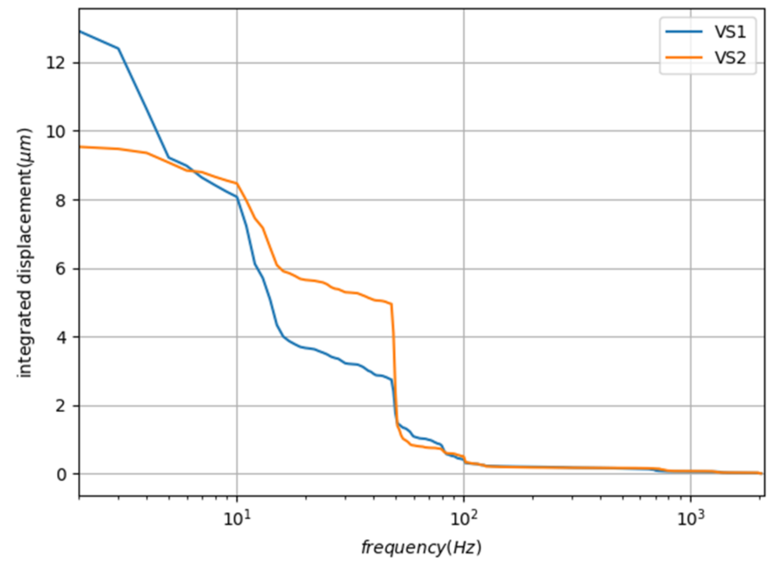


Significant variation of visibility V due to ground motion

Uncertainty of the fit due to insufficient light intensity

Measured displacement spectrum



Solution: passive damping

Problems and Solutions

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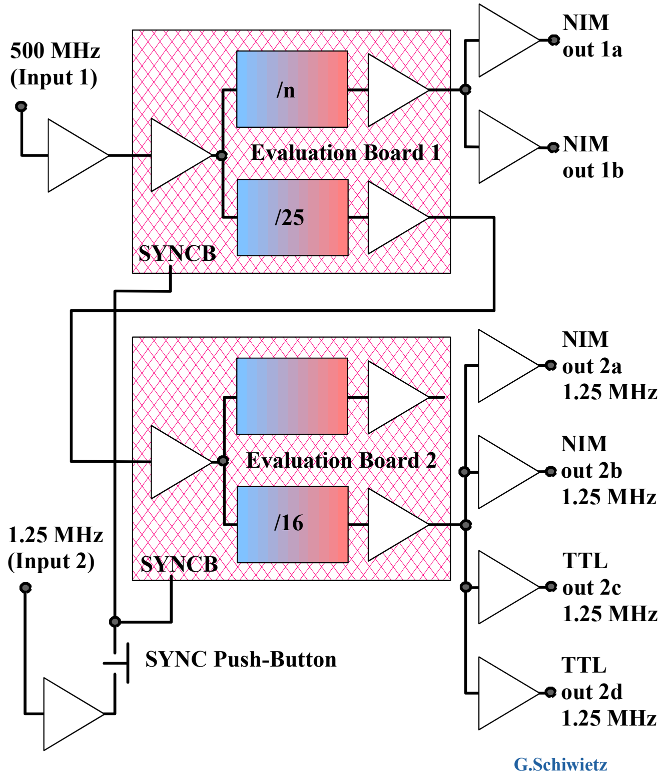
Fast Intensified CCD (ICCD)
Exposure time: 200 ps to 80 s
Low jitter : < 10 ps
Multiple-gate repetition frequency: < 2.0 MHz
High dynamic Range: 14 bit

Functional Block diagram
Precision Frequency Divider
(f/400 and f/n)



Problems and Solutions

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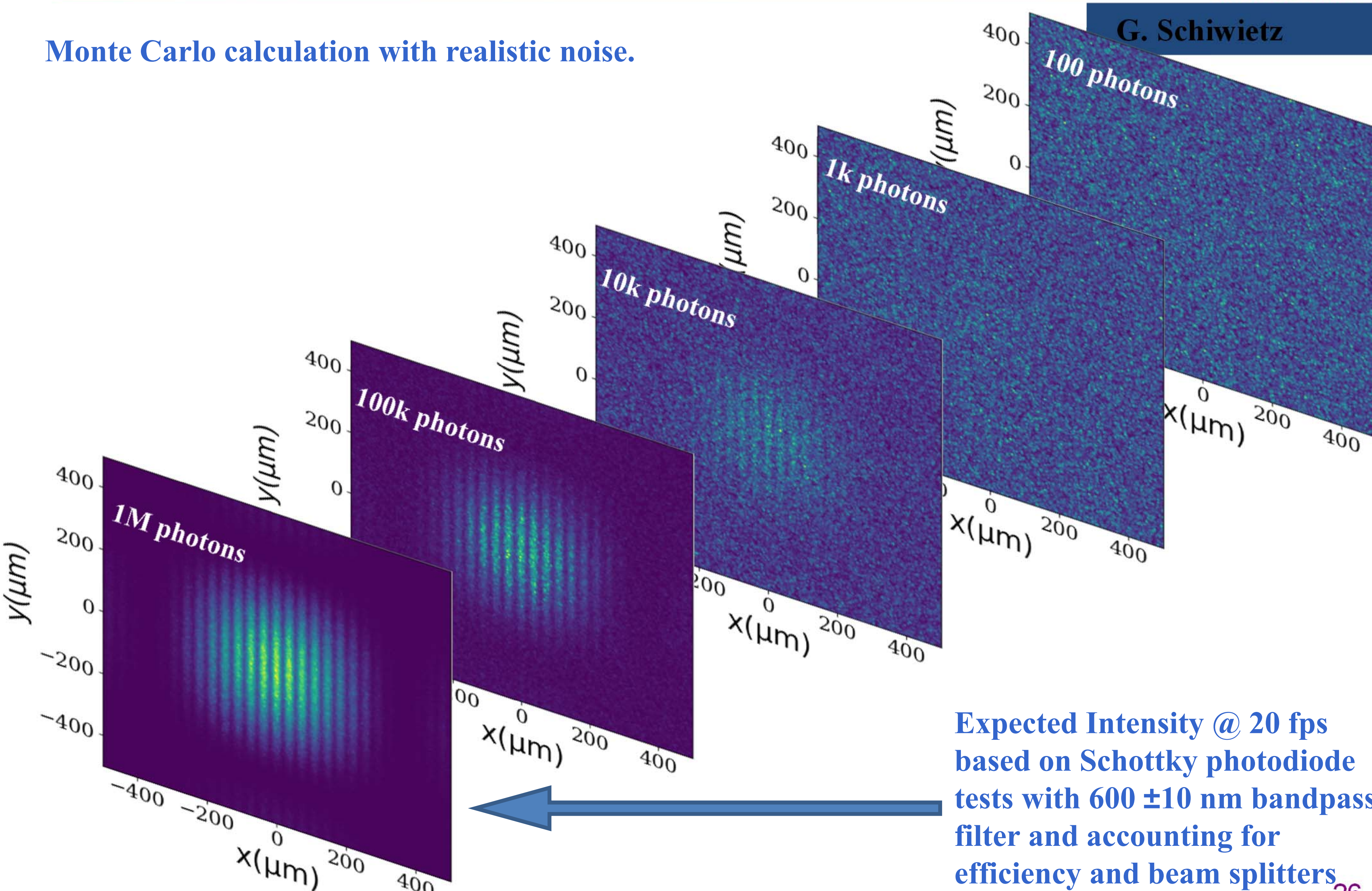
Monte Carlo calculation with realistic noise.



Expected Intensity @ 20 fps based on Schottky photodiode tests with 600 ±10 nm bandpass filter and accounting for efficiency and beam splitters in the ICCD

Problems and Solutions

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Large beam size (σ_x, σ_y > 70 µm rms):
Direct imaging works very well for the vertical direction
To be improved: new toroidal mirror, new slit(s),

Intermediate beam size (25 µm rms < σ_x, σ_y < 250 µm rms): :
Double-slit interference has been demonstrated at BESSY II
To be installed: new beamline with
- **X-ray beam stopper (no power on M1)**
- **intermediate target (improved intensity)**
- **improved optics (less losses and vibrations)**
- **vibration damping of optical table**
- **fast ICCD camera**

Small vertical beam size (σ_y < 50 µm rms):
X-Ray baffle method has been demonstrated at BESSY II
To be developed: quantitative evaluation procedure

Thank you for your attention !