Optical Beam Profiling @ BESSY II: Imaging, interferometry and more

HZB Helmholtz Zentrum Berlin

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What do we need?

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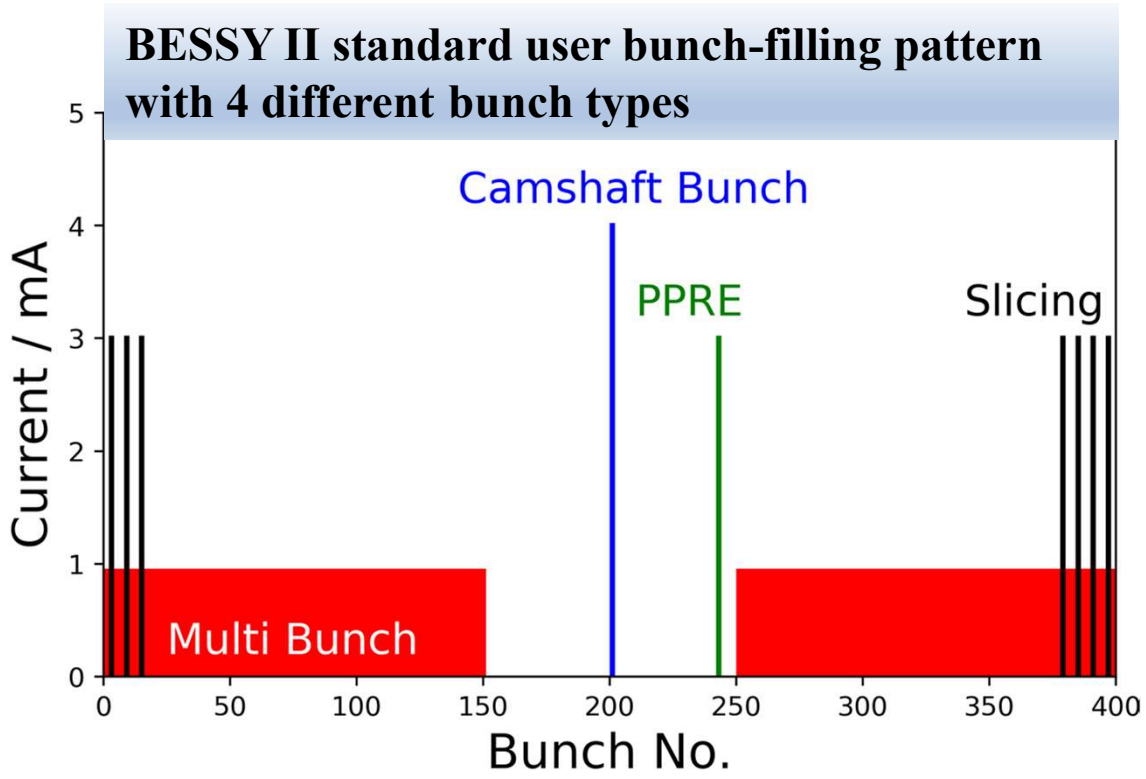
New Beamlines for Bunch-Resolved Optical Beam Diagnostics



What do we need?

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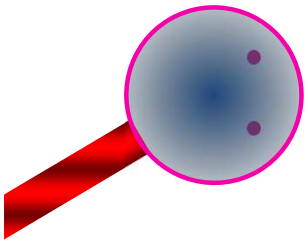
New Beamlines for Bunch-Resolved Optical Beam Diagnostics

Necessary Properties:

- Nondestructive *detailed* diagnostics for complex fill patterns
- Robust operation and 24/7 availability → **dipole beamlines**
- Bunch-resolved measurements (BII, B-VSR, BIII) → **$\Delta t \ll 1$ ns**

- longitudinal bunch parameters (*t*): phase* + length + shape
- **lateral bunch parameters (*x,y*):** position*# + size# + shape
- **2D detection methods (*for x, y, t*): *x vs. t, y vs. t, x vs. y***



* measured also by BESSY-II bunch-by-bunch feedback sensors / BPMs

\# measured also by BESSY-II pinhole monitors

Hardware: Beamlines @ Sector L 12

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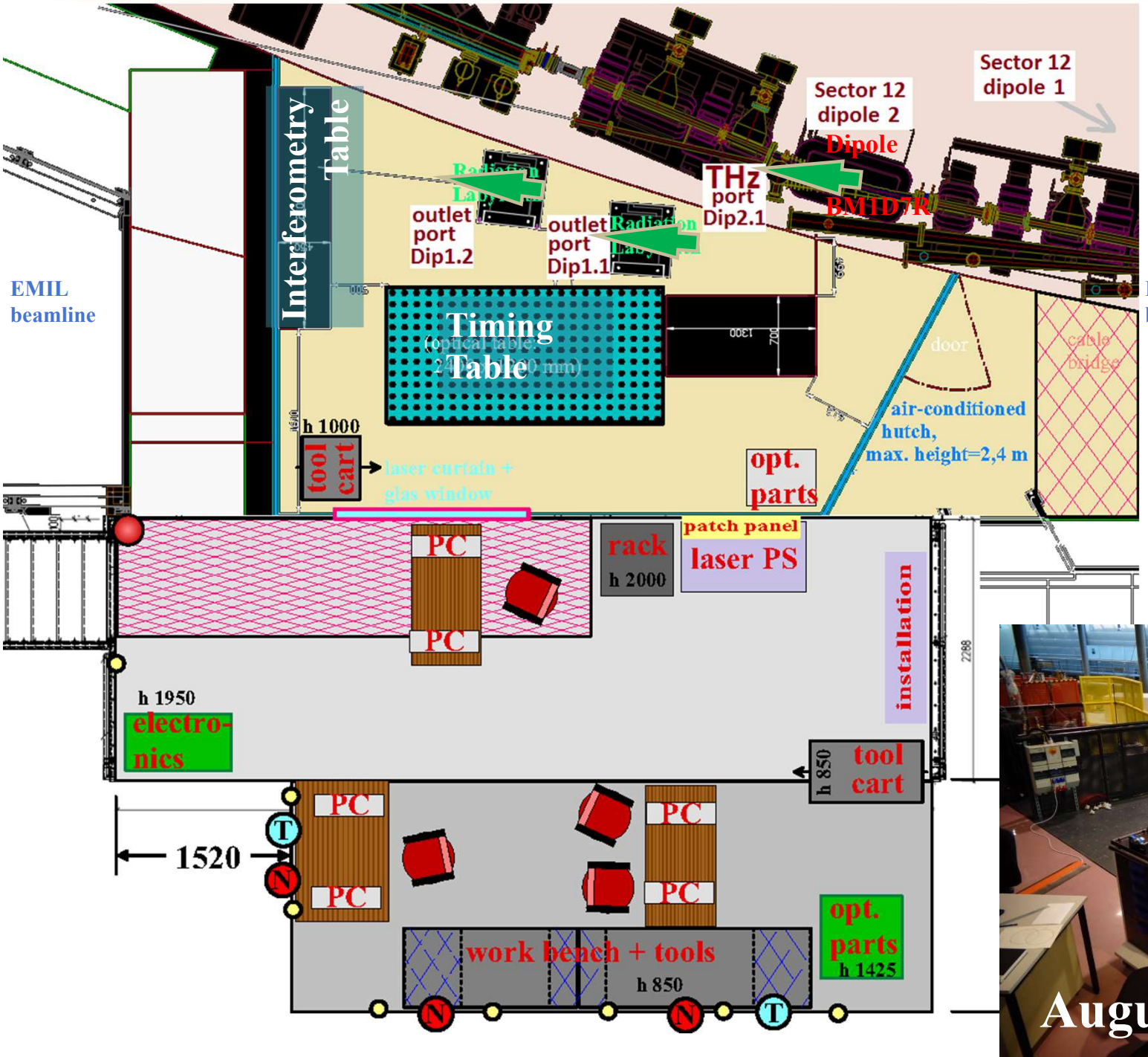

Dipole
BM2T6R

Schematic Top View Sector L12

Hardware: Detectors @ Sector L 12

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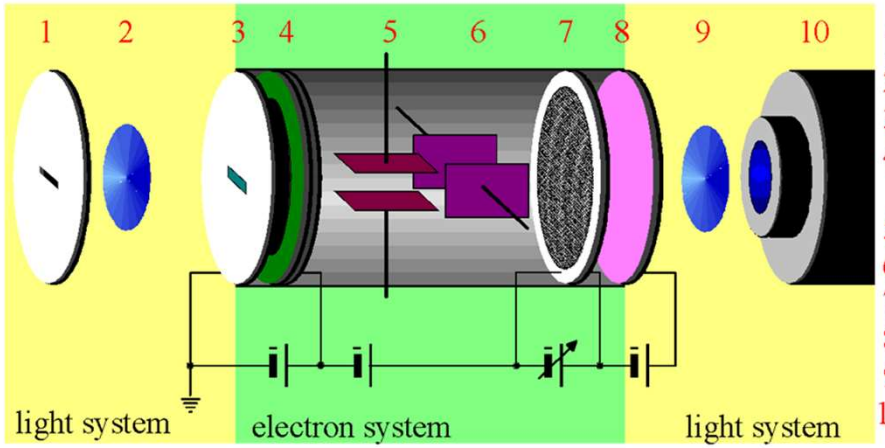
Fast gated Intensified CCD (**ICCD**),
4 channels w. MCP amplifiers @ 14 bit
Exposure Time: ≈ **400 ps** to 80 s,
sequence mode
Low Jitter : ≈ **10 ps rms**
Multiple-gating Repetition Frequency:
100 kHz (→ **1.5 MHz**)
Cont. Data Rate: < 20 stored frames /s /cam

CCDs: Prosilica GT1920
by Allied Vision
Sensor: Sony ICX674 @ 14 bit, (Magnif. ≈ 0.9)
Pixel Size: 4.54 µm × 4.54 µm, 2.8 Mpxl
Exposure Time: 10 µs to 26 s
Frame Rate: < 41 stored frames /s

Fast Synchro-Scan Streak Camera: **C10910-05**
by Hamamatsu (total time resolution = **0.6 ps rms**)
CMOS-Sensor: 16 bit, Image Magnification ≈ 0.6 (total)
Pixel Size: 6.5 µm × 6.5 µm, 1.4 Mpxl
Repetition frequency, horizontal scan: **1 kHz**
Streaking Time Range: 100 ns to 1 µs (or above)
Frame rate: < 70 stored frames /s



1 – entrance slit
2 – input optics
3 – photo cathode
4 – acceleration plus focussing electrode
5 – vertical sweep
6 – horizontal sweep
7 – Multi-Channel Plate
8 – phosphor screen
9 – output optics
10 – CCD camera

Transverse Beam Size: Interferometry vs. Geometrical Optics

Lateral interferometry

Direct imaging of an isotropic emitter is determined by the Abbe limit or Rayleigh criterion (for a 1D slit)

$\Delta l_{FWHM} = 0.5\ \lambda / \sin(\alpha_{1/2})$,

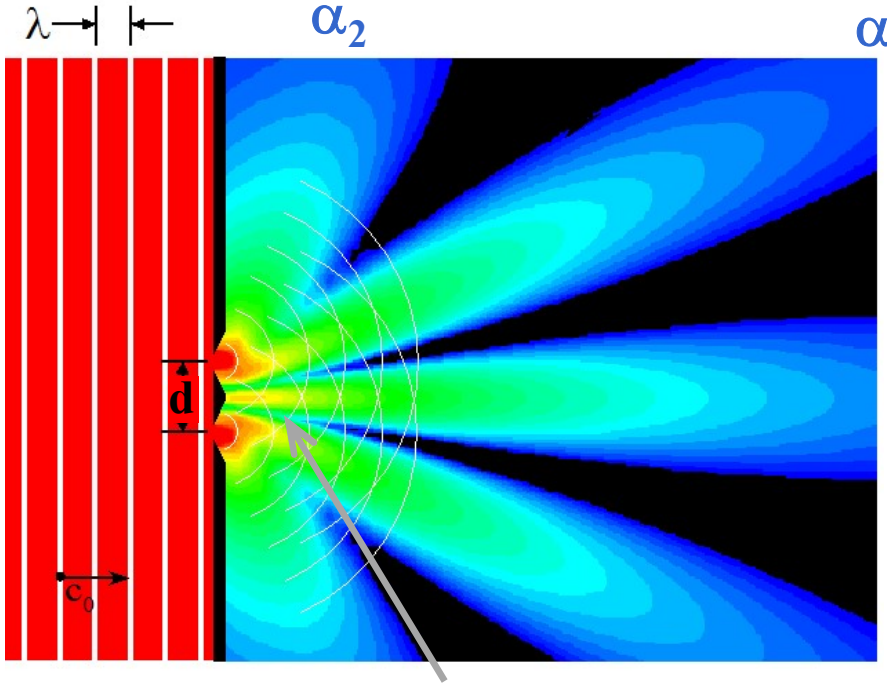
with $\alpha_{1/2}$ = *half source-opening angle*

For a circular 2D aperture, we have

$\Delta l \approx 0.61\ \lambda / \sin(\alpha_{1/2})$

λ_{mean} / direction	$\alpha_{1/2}^{slit}$ (mrad)	$\alpha_{1/2}^{rad.\,cone}$ (mrad)	Image Resolution: σ_{RMS} (μm)
550 nm / horizontal	±10	±3.55	45 μm [84 RAY#, 60 meas.*]
550 nm / vertical	±2.80	±3.55	75 μm [135 RAY#, 115 meas.*]

* CCD white-light fit to central peak + σ pol. @Dip.1.1 after 16 m # incl. slope errors



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

Following T. Mitsuhashi, "Beam Profile and Size Measurement by SR Interferometer", Beam measu-rement, Ed. by S.Kurokawa et al., pp. 399, World Scientific 1999:

$\sigma_{RMS} \gtrsim 0.05\ \lambda / \alpha$,

with sin(α) = d/ℓ and

ℓ as source-to-obstacle distance

for visibility V = 0.95

→ Double-slit interferometry may improve the resolution by a factor of 10 to 20, assuming the same source-opening angle and the same wavelength.

Lateral interferometry

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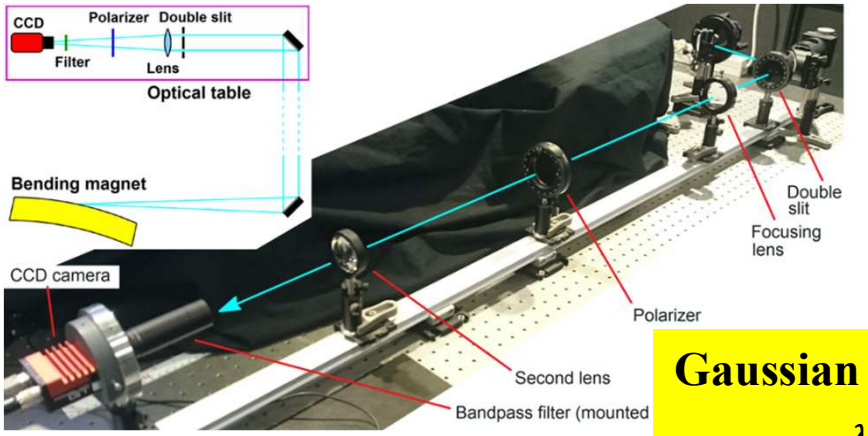

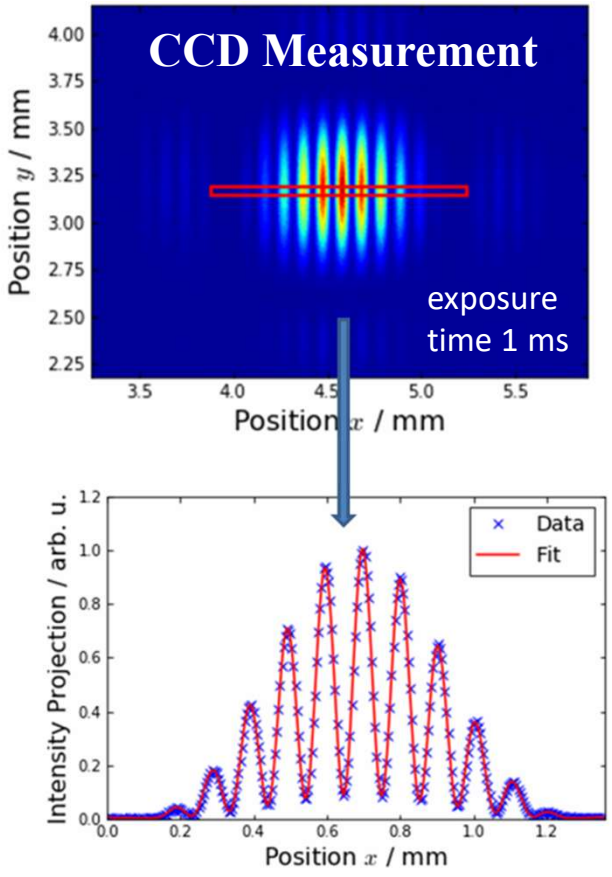

Gaussian distribution yields

$$\sigma = \frac{\lambda R}{\pi d}\sqrt{\frac{1}{2}\, ln\, \frac{1}{V}}$$

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High resolution at small beam sizes requires

- Small λ
- Large photon-emission angles $\alpha_{em} \approx d/R$

- - - - - - - - - - - - - - - - - - -

Reliable curve fitting (determination of V) requires

- Strong light **intensity**
- Low **vibration** amplitudes
- Low **vibration** frequencies
- High quality of focusing **optics** (lenses, bandpass filter, maybe vacuum window)

Master thesis **M. Koopmans:**
Resolution = **11 µm rms**
@ 400 nm *(at old test beamline that was never intended for precision measurements)*

successful tests of double-slit method (slit separation, wavelength, rotation angle, polarization, interference pattern), see also

- **T. Mitsuhashi in: Beam measurement (ed. by S. Kurokawa et al., pp. 399–427, World Scientific 1999).**
- **M. Koopmans et al., "Applications of the Interferometric Beam Size Monitor at BESSY II", WEPAK009, IPAC2018 Proc., Vancouver, Canada. (2018), 2103-2106.**
- **M. Koopmans et al., "Vertical Beam-Size Measurement at the BESSY II Storage Ring and Their Resolution Limits", WEPGW012, IPAC2019 Proc. , Melbourne, Australia (2019), 2491-2494.**

Lateral interferometry (NEW)

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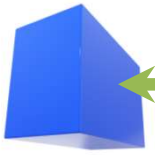
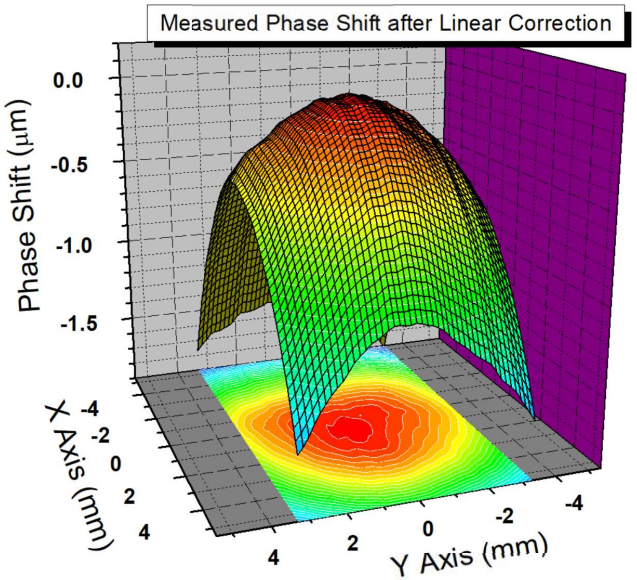
Hartmann-Shack-Sensor



$\Delta\phi_{RMS} = \lambda/11$



Spherical wave front (plus baffle-interference pattern ?)

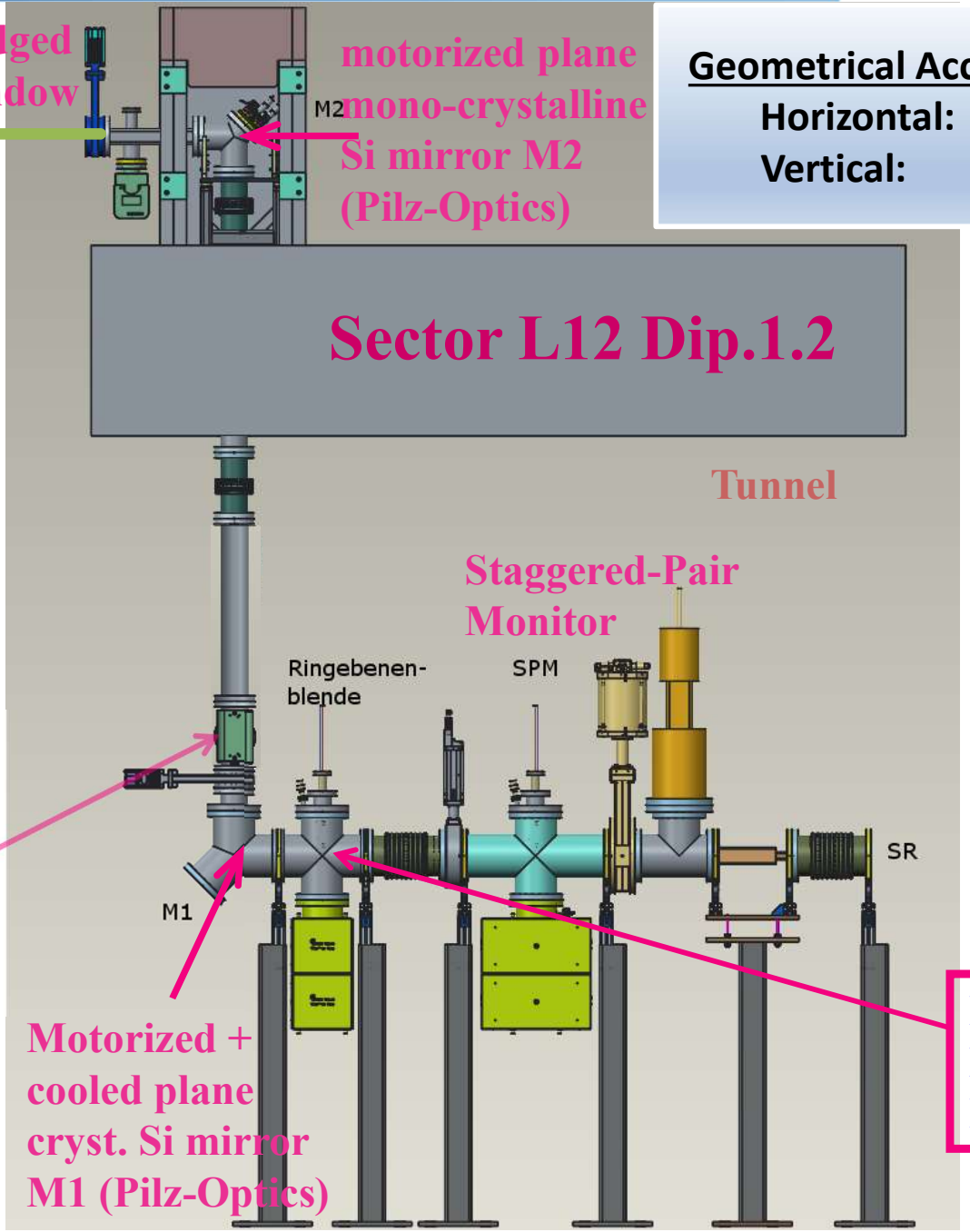
Wedged Window

motorized plane mono-crystalline Si mirror M2 (Pilz-Optics)

Geometrical Acceptance Angles

Horizontal: ±3.02 mrad

Vertical: ±2.16 mrad



BM2T6R

Motorized + cooled plane cryst. Si mirror M1 (Pilz-Optics)

Motorized X-Ray Blocking Baffle

Selectable/retractable interference targets Plus achromatic lens (f = 3.3 m)

Lateral interferometry

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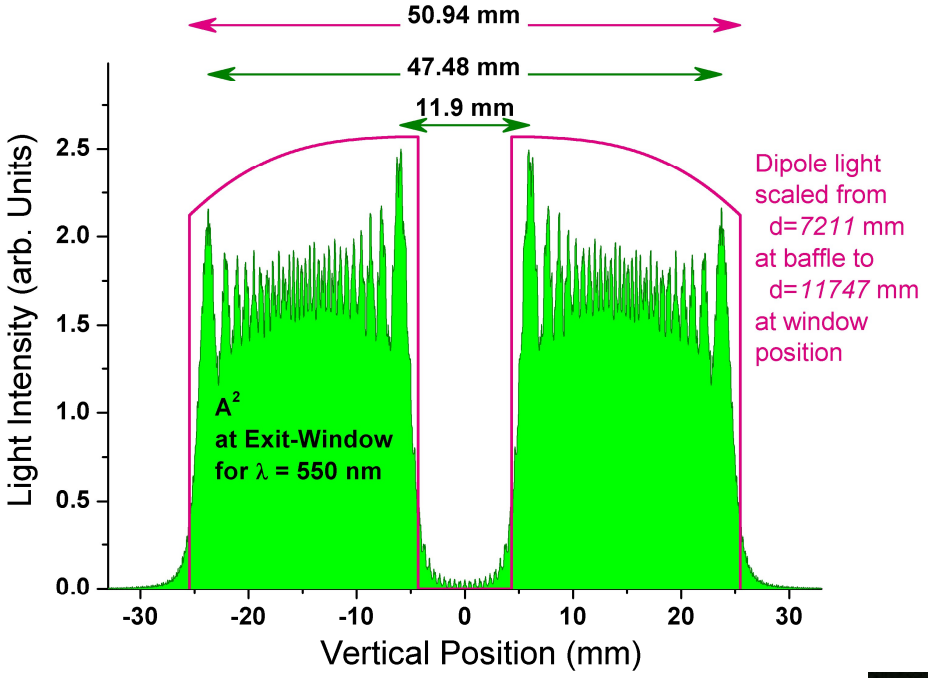


Geometrical Acceptance Angles

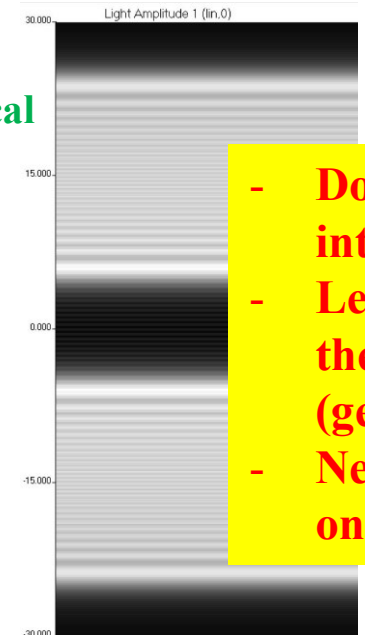
Horizontal: ±3.02 mrad

Vertical: ±2.16 mrad

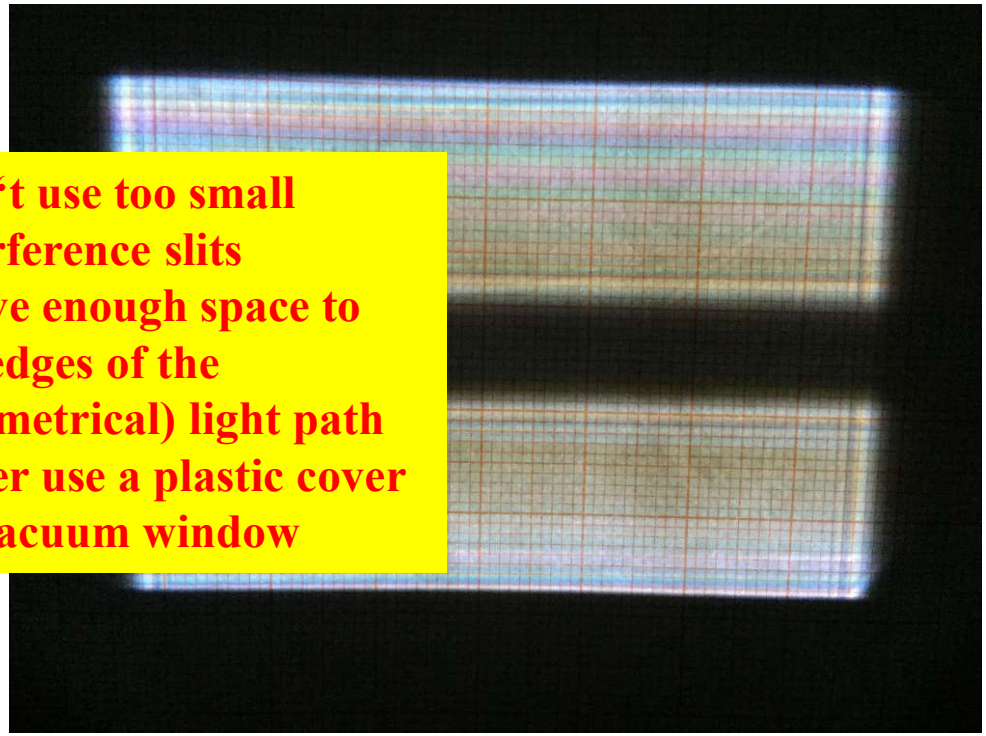
→ ca. ±3.5 mrad

Sector L12 Dip.1.2

Model calculation for 550 nm based on a converged numerical solution of a Kirchhoff diffraction integral (a complex scalar treatment based on superposition of elementary spherical waves by neglecting the large-angle obliquity factor) with realistic SR properties (Schwinger theory) for BESSY II



- **Don‘t use too small interference slits**
- **Leave enough space to the edges of the (geometrical) light path**
- **Never use a plastic cover on vacuum window**



Lateral interferometry w. ICCD

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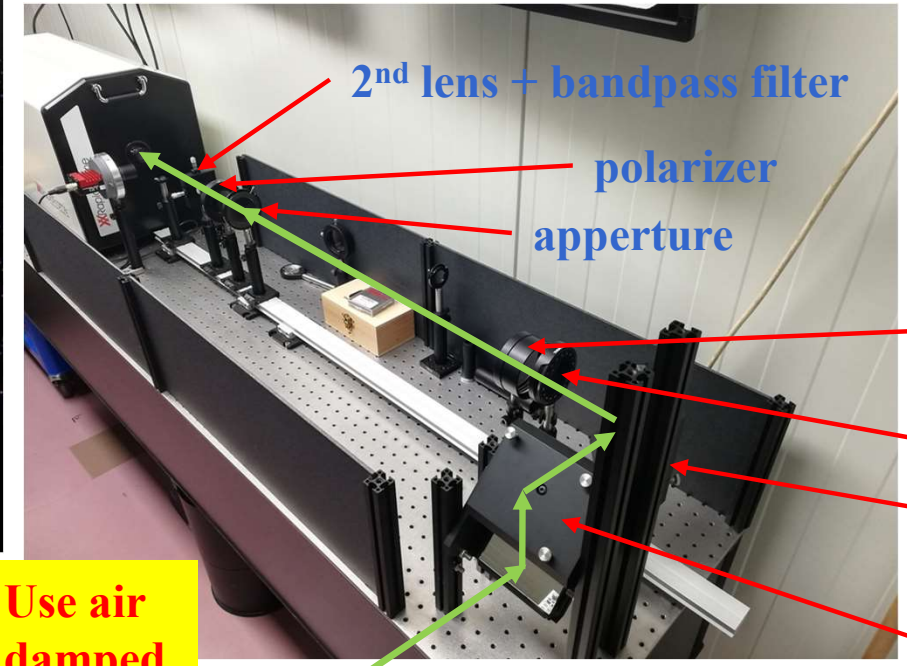

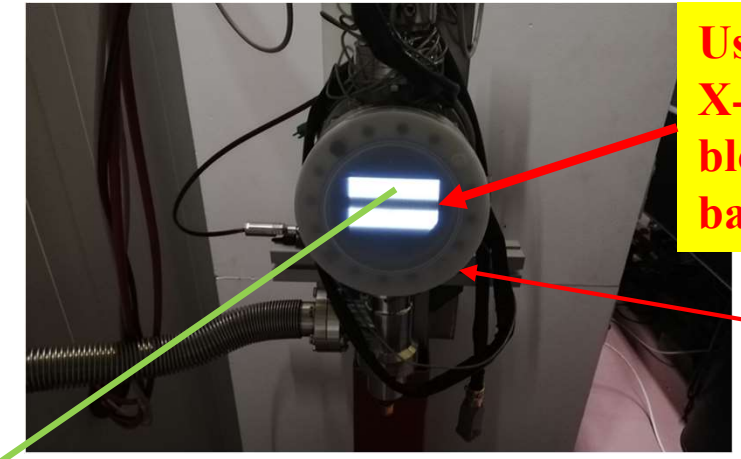

Lateral interferometry w. ICCD

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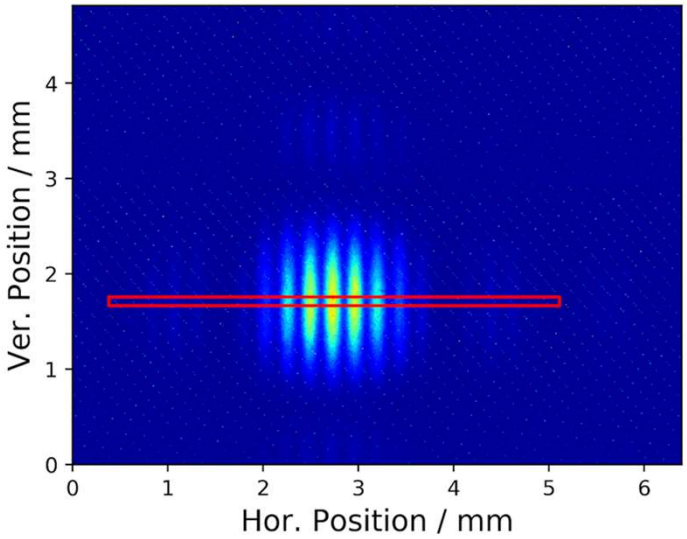
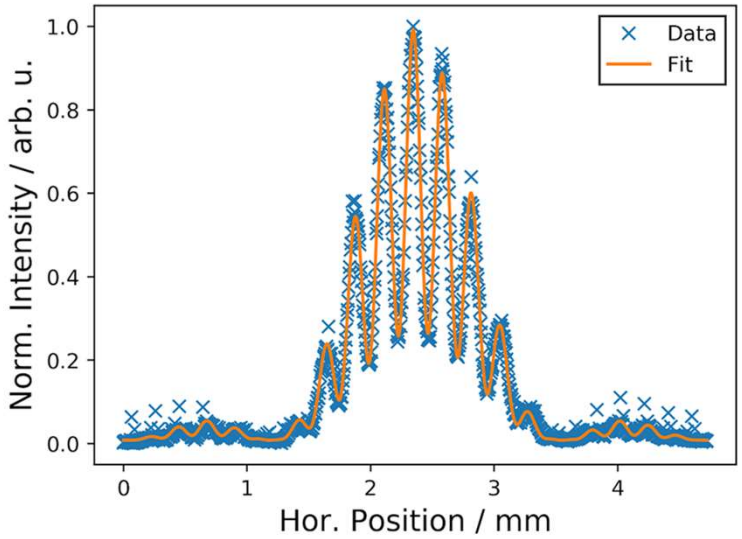
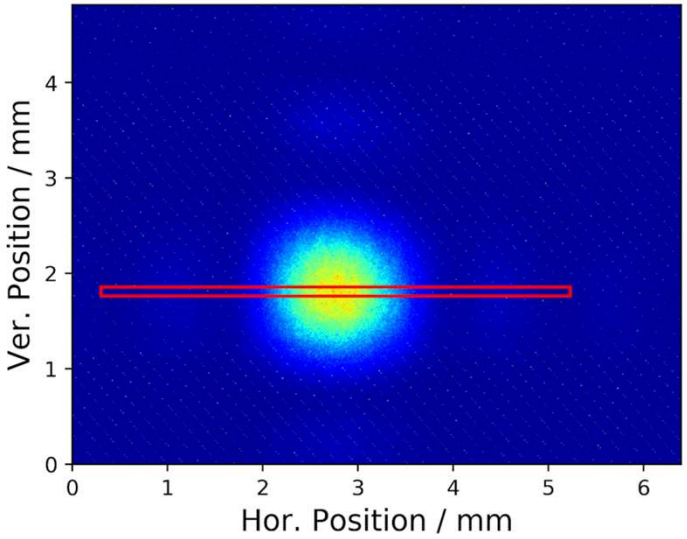
ICCD illumination @ 20 kHz trigger rate (all light on one camera only, no faceplate) for 200 ms = 4000 triggered turns

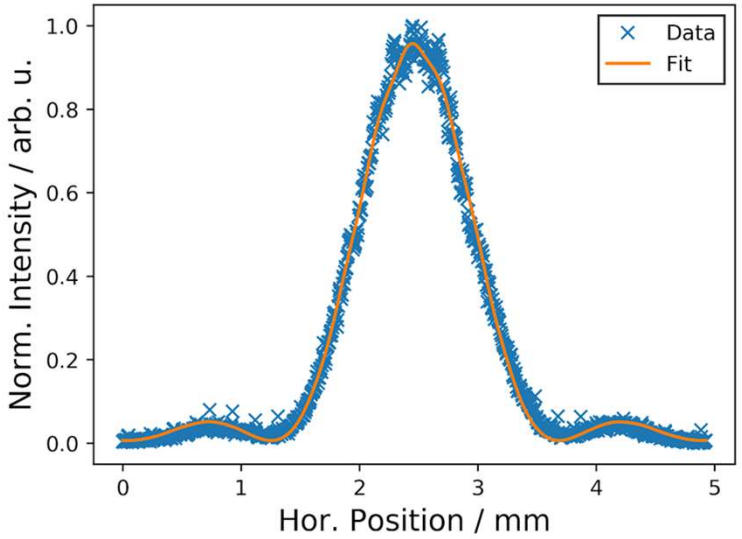
Camshaft bunch
$\Delta t_{bunch} = 1$ *ns*





PPRE bunch
$\Delta t_{bunch} = 1$ *ns*





2D Streak-Camera Modes: High Time Resolution ($\ll 1\ ps\ rms$) and Transverse-Size Information

More is possible: 2D analysis

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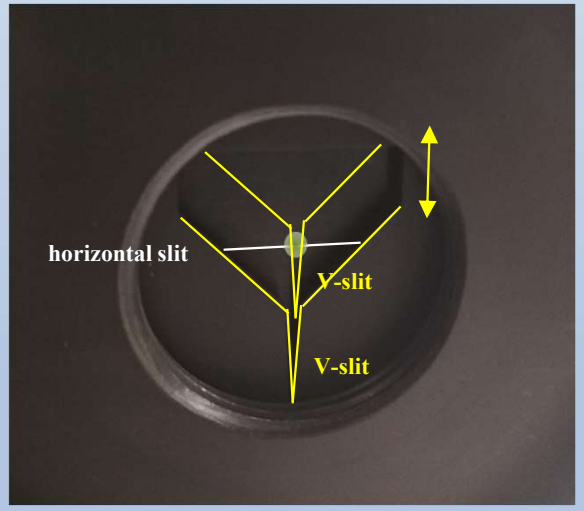
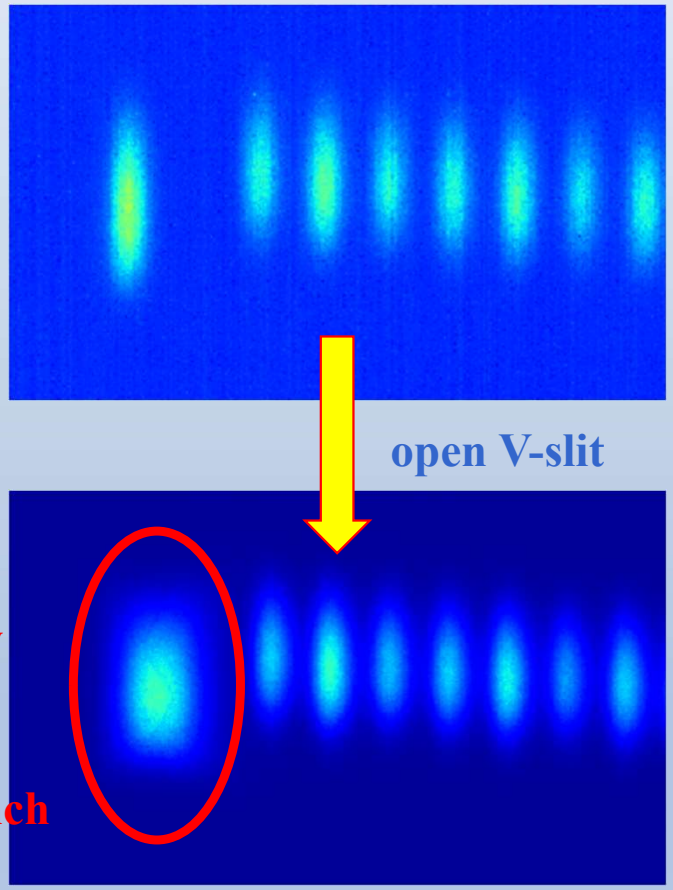
- ➢ Good imaging properties at beamline
- ➢ Wide streak camera aperture (V-slit)

  ⇒ Additional transverse information





Time vs. bunch number

Time vs. horizontal position and size (+ bunch number)

Marten Koopmans, DPG Spring Meeting, Dortmund, 2021

G. Schiwietz et al., *"Bunch-resolved diagnostics for a future electron-storage ring"*, NIM-A990, 164992 (2021)

Vertical π-polarization interference

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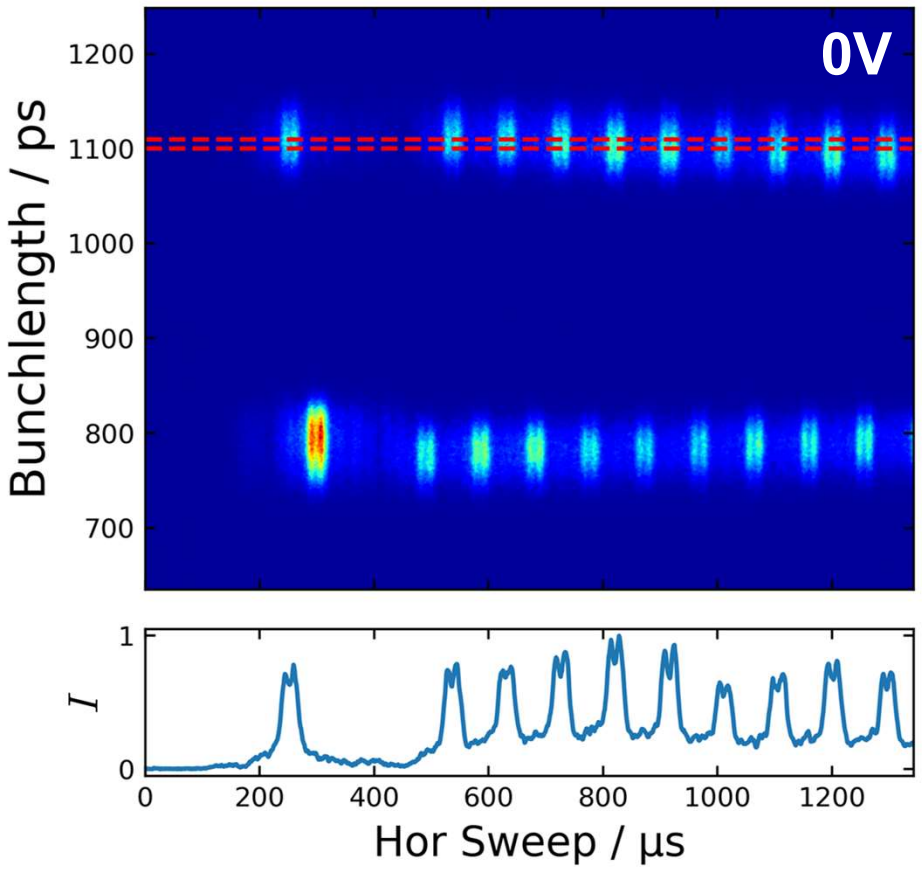
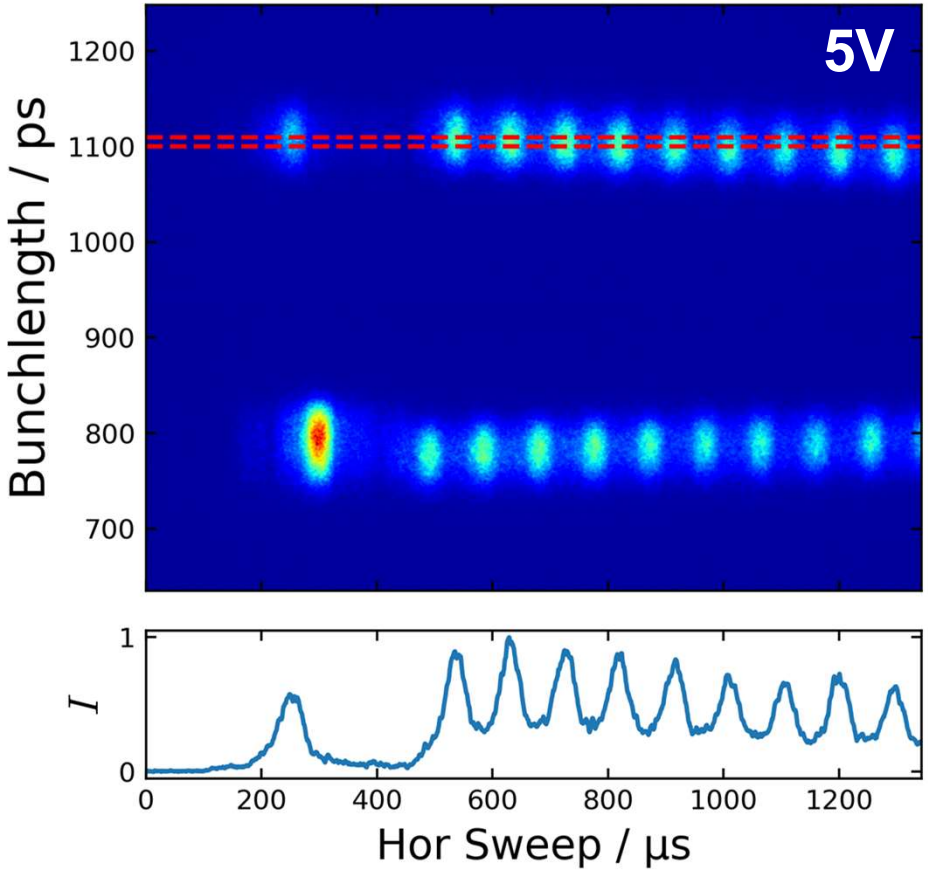
- Measurement at streak camera (t/y mode)

  pi-polarisation @ λ = 700 nm

  plus white-noise excitation (0V … 5 V)





Analog integration over about *1000 x Δt* *(Δt=100 ms)*

Conclusions

Ongoing beamline commissioning:

actual lower limits have still to be determined

Lateral Beam Size (Bunch Resolved Detection)

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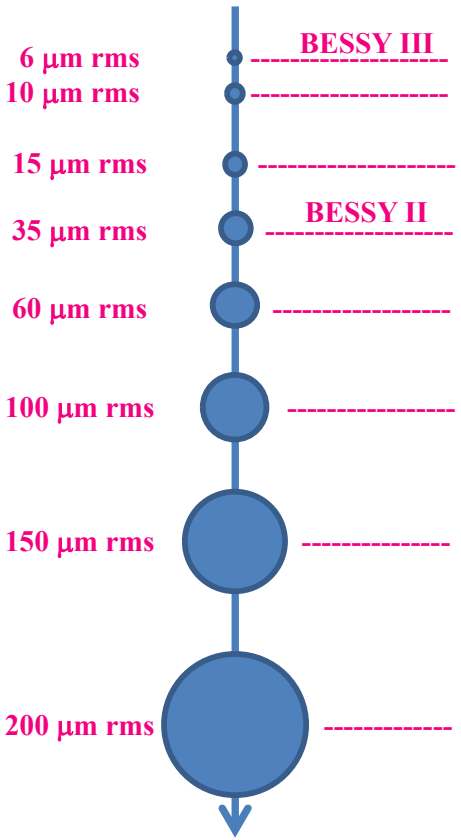


σ_y = 4 .. 50 µm rms → π-polarization interference

4 µm rms < σ_x, σ_y < 200 µm rms → Double-slit interference

2D combination with ICCD is possible

σ_x > 60 µm rms
σ_y > 115 µm rms
→ Direct imaging

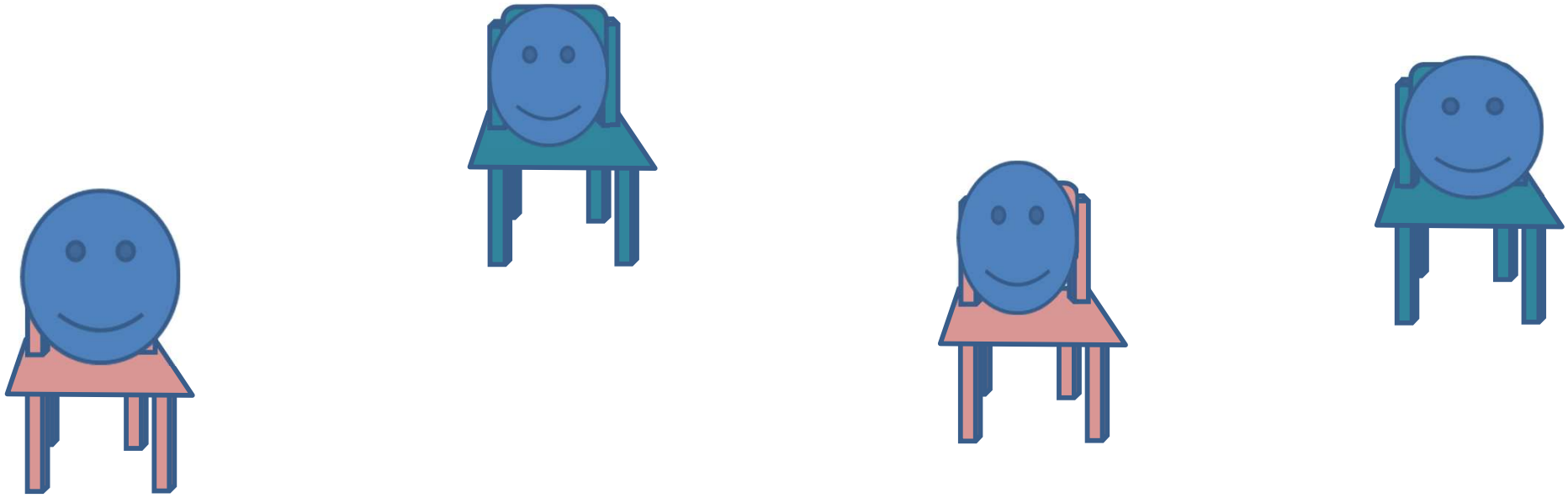
(limited by Rayleigh criterion + opt. quality)

2D combination with streak camera is possible

Open Problems

- Quality for 2D interferometry and extended re-adjustment time changing slit structures (quality of focussing elements +detoriation +edge-diffraction)
- Absolute lateral interferometry with ICCD

Thank you for your attention !



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