BESSY II
Light Source

Approaching an optimum time resolution for synchroscan streak-camera measurements with visible synchrotron light

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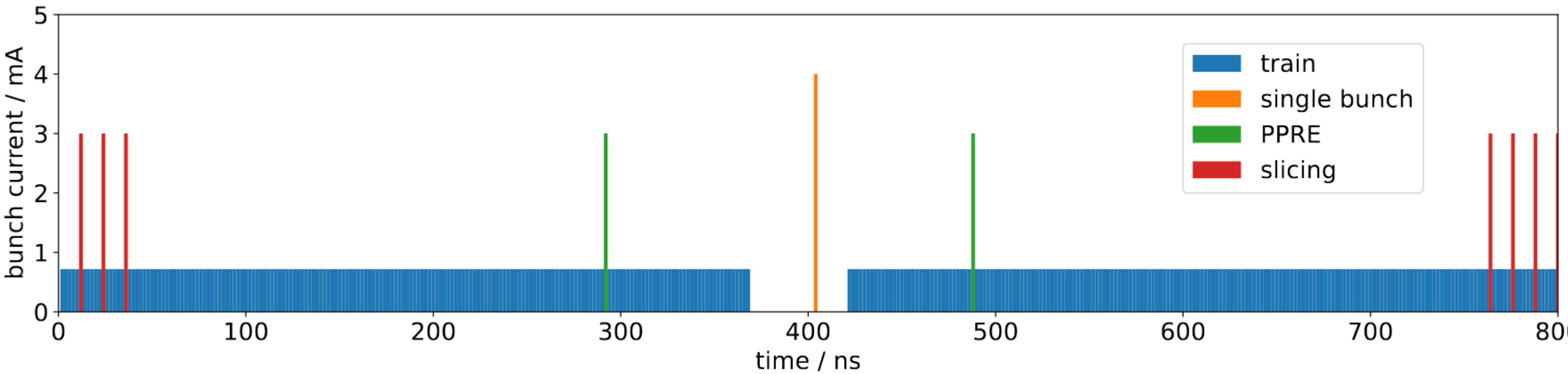
Outline

BESSY II

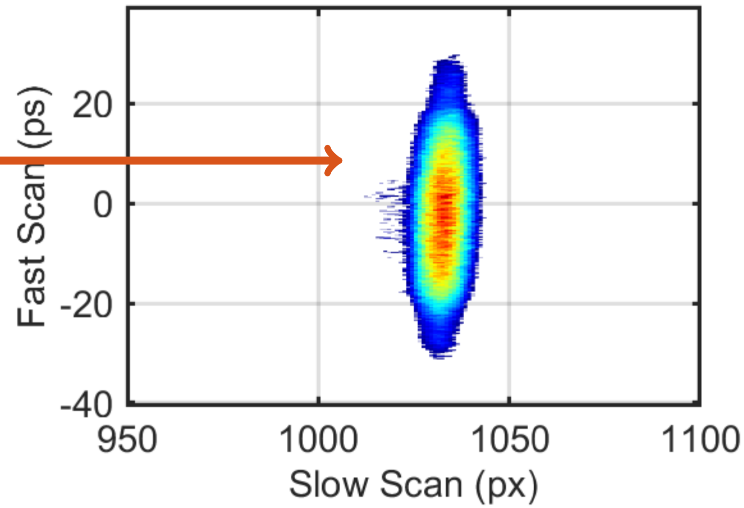
TopUp	Value
Beam Energy (GeV)	1.7
Rel. Energy Spread (%)	7×10^{-4}
Beam Current (mA)	300
Beam emittance (nm)	5
Coupling (%)	2
H Beam size (μm)	64
V Beam size (μm)	47
RMS Bunch-length (ps)	20
Bunch Separation (ns)	2
Number of bunches/buckets	350/400
RF Frequency (MHz)	500
Bending Magnet Field (T)	1.3
Circumference (m)	240

- slicing facility, superconducting wavelength shifter (x2), in-vacuum undulator
- hybrid filling pattern operation:
  - flux / brightness
  - brilliance (4×10^{19} avg, 6×10^{21} peak)
  - timing / dynamics
- single bunch, few bunch
  - timing / dynamics
  - pulse length: 100 ps
- low-alpha: coherent THz radiation (timing) 2 ps

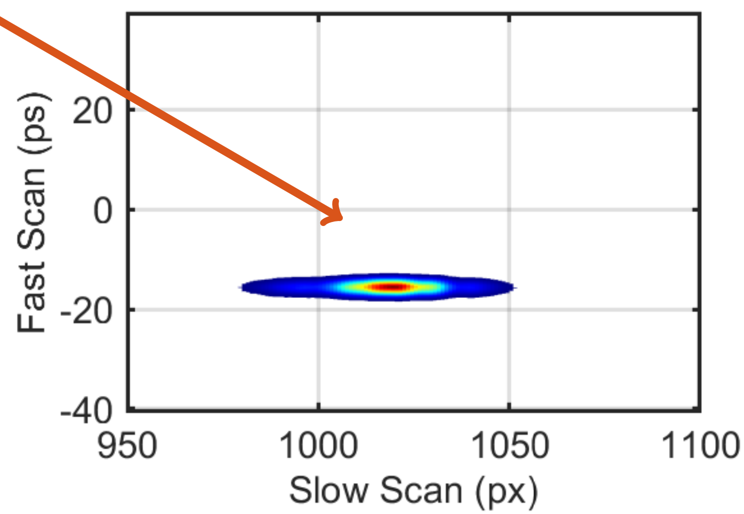


Motivation

Standard Operation	Value
Beam Current (mA)	300
RMS Bunch-length (ps)	20
Emittance (nm)	5
α	7.3×10^{-4}



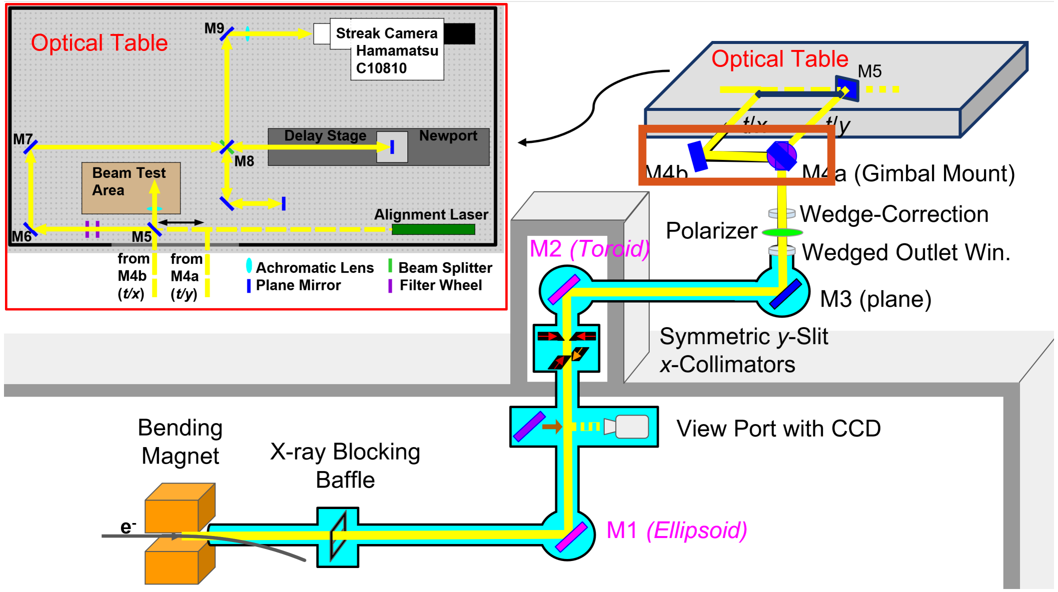
Low α Operation	Value
Beam Current (mA)	100
RMS Bunch-length (ps)	1
Emittance (nm)	40
α	3.5×10^{-5}



Sub-ps resolution required:

- broadening in optical media
- broadening inside the streak-camera
- jitter broadening

Beamline Overview



Parameter	Value
Beam Energy	1.7 GeV
Bending Radius	4.35 m
Critical Energy	2.5 K eV

Opening angle 20x3.5 mm
5.5 mW after X-Ray Blocker

Zeiss ellipsoidal focusing mirror: intermediate focal point

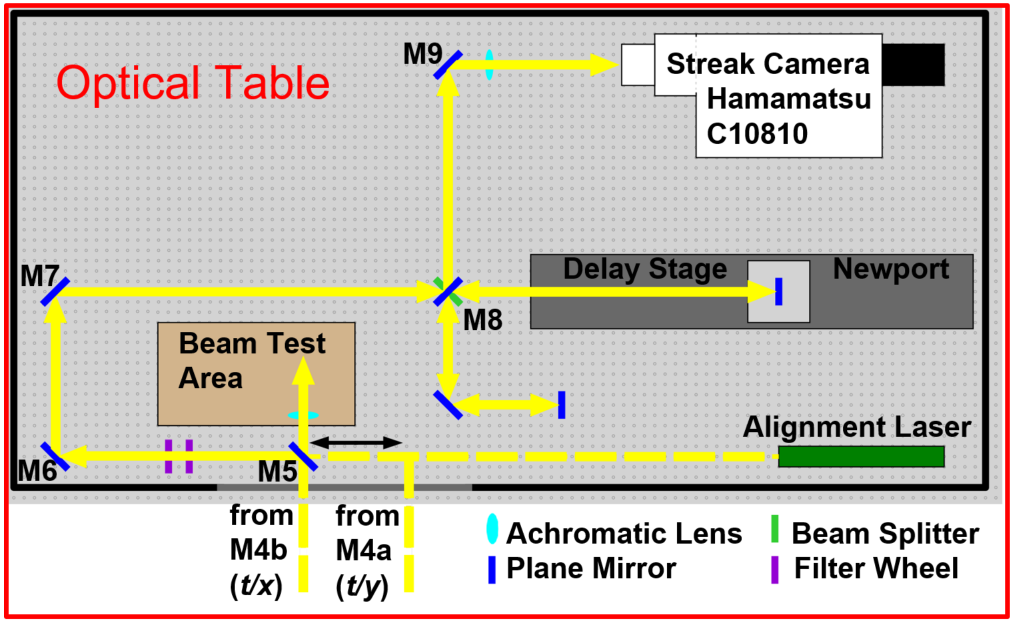
WinlightX toroidal mirror: beam collimation

Wedge/anti-wedge window (3 mm fused silica); $180^\circ \longrightarrow$ position dispersion

Polarizer: π-polarized with X-Ray blocker

Gimbal mount mirrors: 2D additional info

Beamline Overview



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2 Filter wheels: BPF and HP edge filters

Newport delay stage

Alignment laser

Achromatic lens: final focus

Hamamatsu C10810

5 m light path in the table

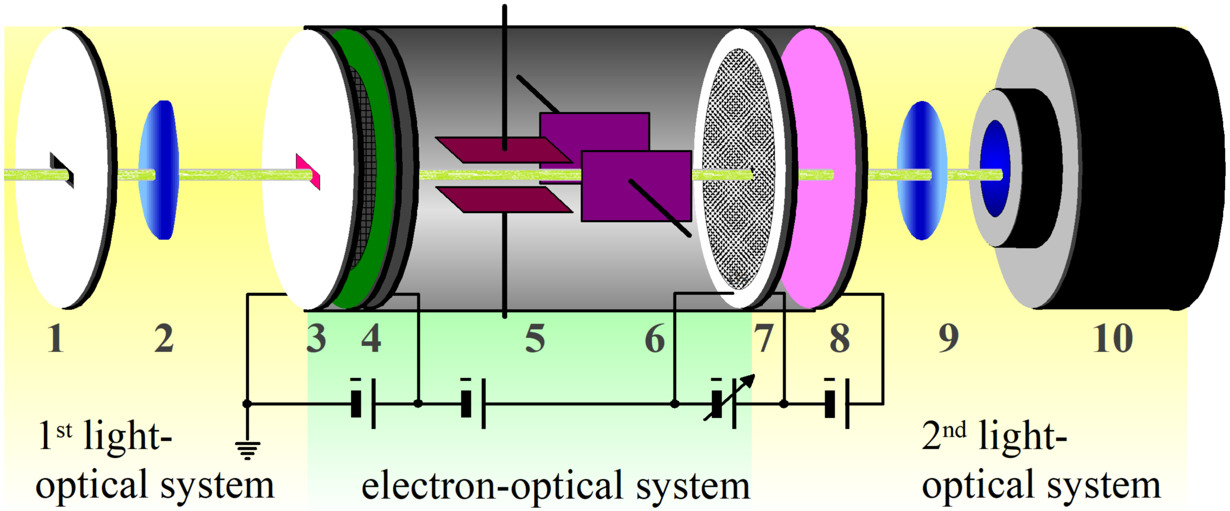
HQ plane mirror (surface flatness $\lambda/20$):

Good SNR $\longrightarrow$ 1 to 2000 dynamic range

Maximize light and minimize dispersion:

No beam splitters nor polarizer

Streak Camera Overview



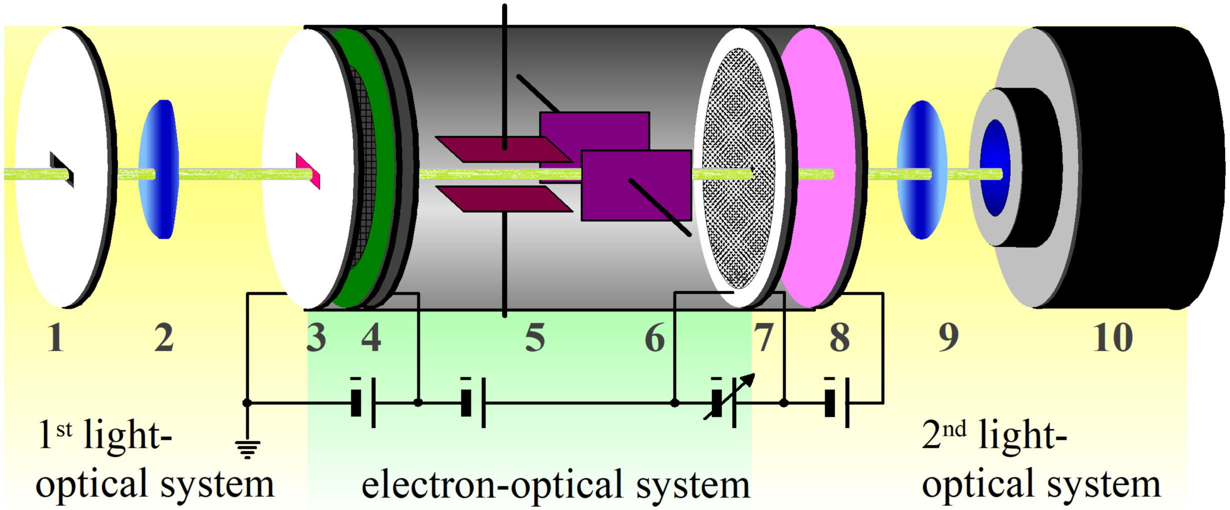
OPTRONIS 500 MHz to 125 MHz divider
8 ns bunch distance

1. **Entrance slit**: 5 mmx14 µm
2. **Lens**: focus on the cathode
3. **S-20ER Photocathode**: tx-type $\longrightarrow$ emits inside the tube
4. **Closely spaced mesh** to accelerate electrons and reduce dispersion
5. **V sweep electrodes**: vertical sweep with freq. 125 MHz
6. **H sweep electrodes**: slow saw-tooth type to separate individual bunches

7/8. **MCP/phosphor screen**: single-electron sensitivity with 10^3 to 10^6 photons per converted electron

9/10. **Detector system**: focus the light to the detector

Streak Camera Overview



OPTRONIS 500 MHz to 125 MHz divider
Hamamatsu M10916-01 dual time-base unit: from 100 ns to 1 µs at 1 kHz
Sweep calib. via 3rd order poly: bunch structure for H, delay stage for V

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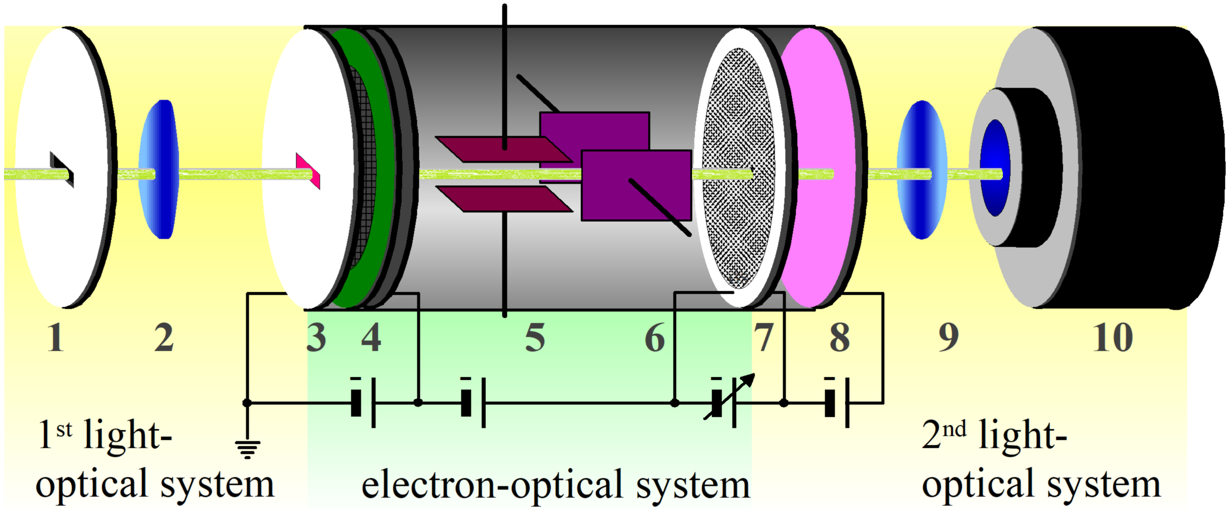

ORCA Flash 4.0 V3 CMOS with 1344×1016 at 60 Hz

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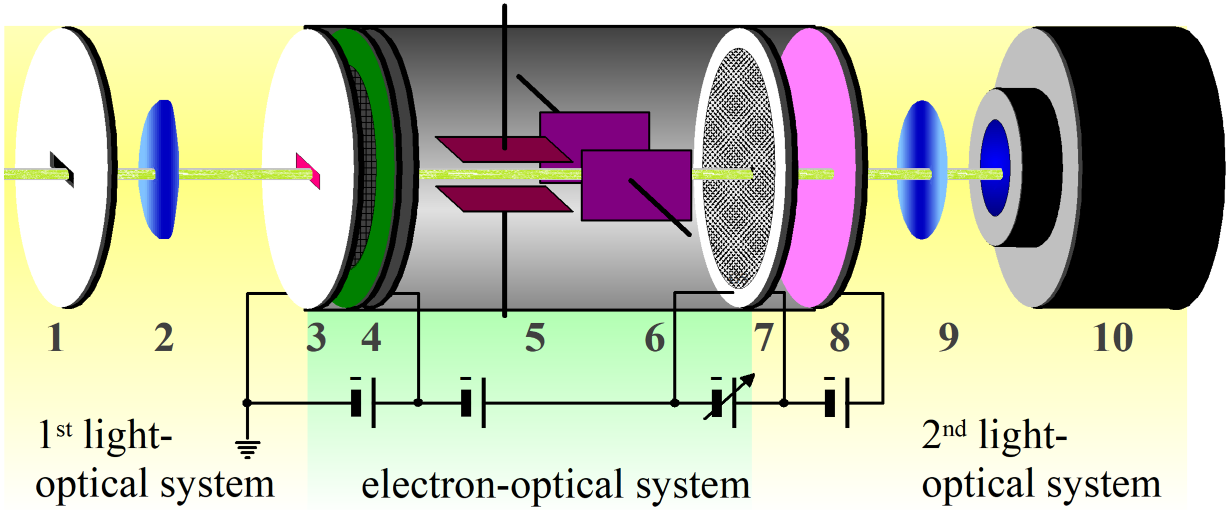

Single-turn illumination or many-turns accumulation

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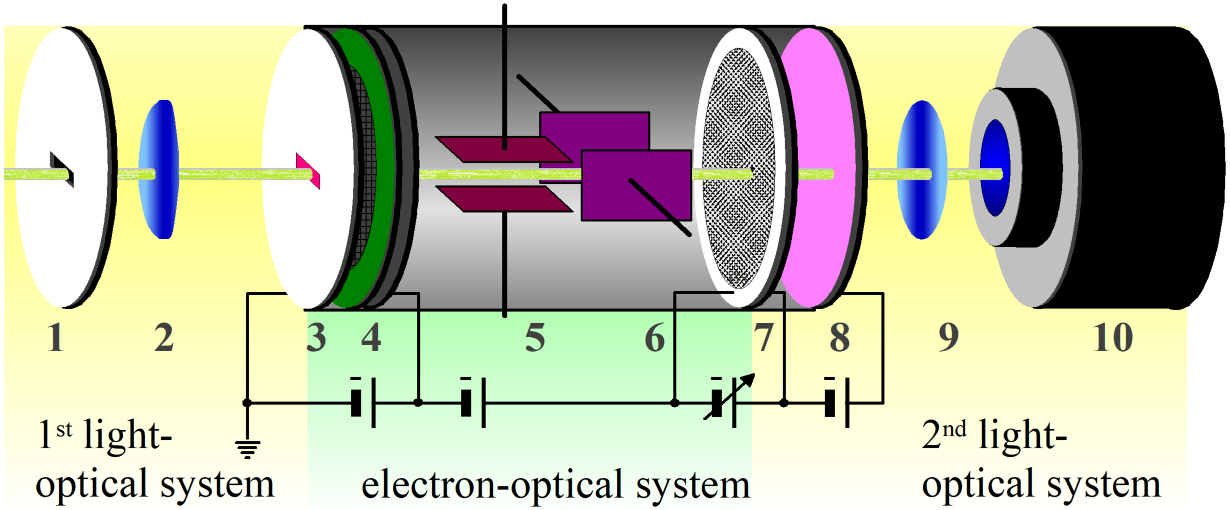

Continuous 1 kHz accumulation of 5000 frames with T_{exp} =20 ms: 100 s, 10^5 turns

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Wavelength Independent Contribution

HZB BESSY II Light Source

Path-length Variation:

-$\beta_L \neq 1$

-Surface roughness and slope error

Uncertainty angle in wedge/anti-wedge vacuum window ($\Delta\theta \approx 0.1°$):

$\Delta t_{wedge} = \sin(\Delta\theta) h_{beam}(n_{fs} - 1)/c$

Mechanical vibration:

$\Delta t_{vibration} = \Delta x_{vibration}/c$

Air-damped legs $\longrightarrow$ vibration below 12 Hz

Time-delay Variation:

-Air pressure: 10 fs after few hours

-Convective air flow: minutes time scale

Geometrical components:

$\Delta t_{slit} = M \Delta y_{slit} \Delta t_{pixel} / \Delta y_{pixel}$

Trigger:

$\Delta t^{trigger}_{RMS} = 0.145 ps [t_{acq}/s]^{0.154}$

Parameter	RMS Value (fs)
$\Delta t_{beamline}$	< 1.3
Δt_{wedge}	5.5
$\Delta t_{vibration}$	13
Δt_{air}	<20
Δt_{slit}	220
$\Delta t_{trigger}$	0 ... 295

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$h_{beam} = 2$ mm

$n_{fs} = 1.46$

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Countermeasure:

Mild cooling (<2 K below exp. hall) at low air flux
Partial shielding of optical path
FSC as only power consumer
Test with hot-air gun

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Δy_{slit} =10 µm: ref value

$M = 1.84$

Δy_{pixel} =6.5 µm

Δt_{pixel} =78 fs in "Time Range 1"

In operation Δy_{slit} =14 µm: 63 fs additional broadening

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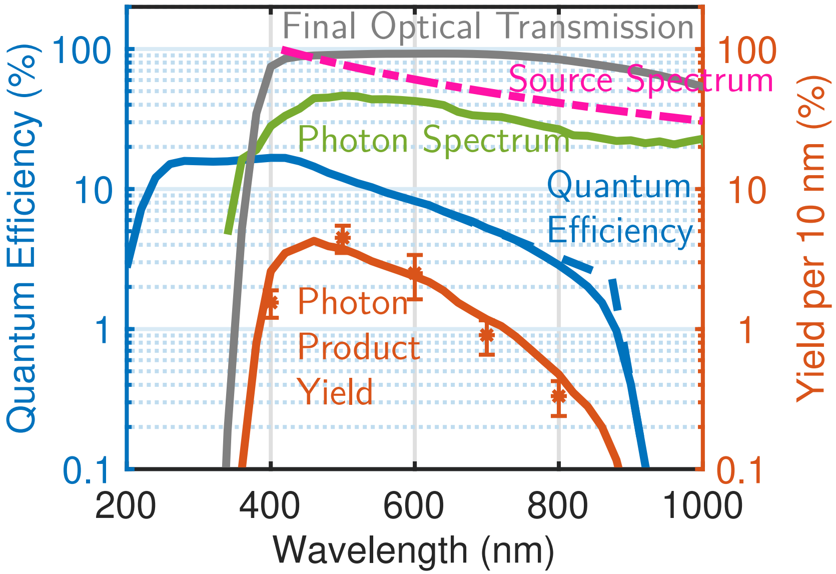
Negligible for T_{acq} less than 7 turns due to FSC PLL circuit
Longer time: noise spectrum and short-time drifts

SR Spectra

Parameter	Value
Beam Energy	1.7 GeV
Dipole Magnetic Field	1.3 T

- **Source Spectrum:** Theoretical SR estimate for low frequency ($\propto \lambda^{-4/3}$)
- **Photon Spectrum:** Measured after M4 with spectrometer
  - losses at lower wavelength
- **Final Optical Transmission** coefficient at the streak camera entrance
  - Maximum at plateau of $90\,\%$
  - Strong absorption losses below 400 nm
- **Quantum Efficiency** of the cathode (1)
  - $16.5 \pm 0.5\,\%$ at $\lambda =$[$270 - 440$ nm]
  - asymptotic slope due to the Fermi edge
  - Work function $\phi = 1.43$ eV at 0 K
- **Photon Product Yield:** product of photon spectrum with optical transmission and quantum efficiency.



(1) Hamamatsu test report

The Photon product yield will be used as wavelength dependent weighting

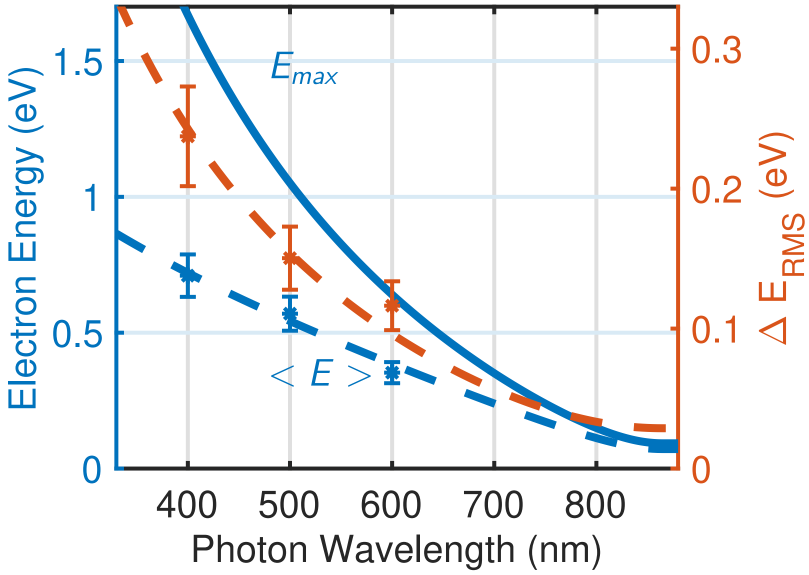
Max emission energy $E_{max} = E_{photon} - \Phi$
To be added quadratically to 93 meV
Data point taken from (1)
Fit (dashed lines) used for timing simulation.

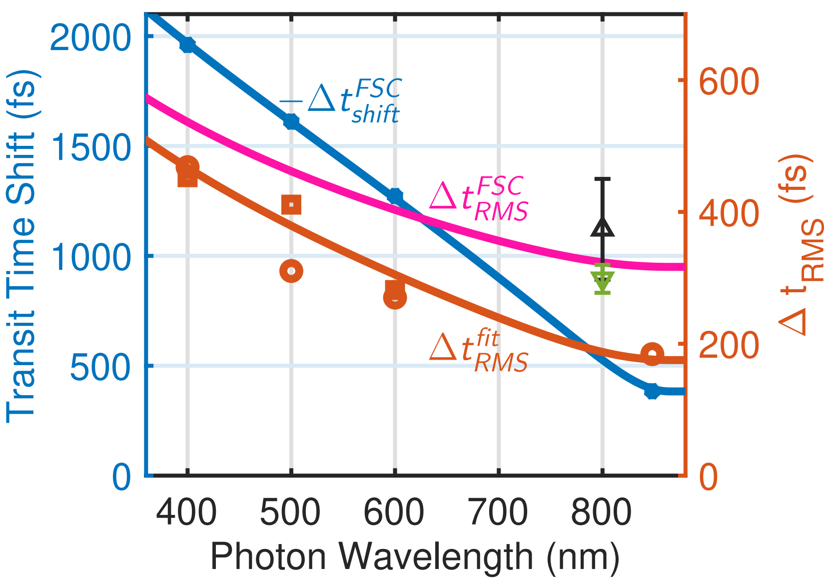
Width:
(1) Data taken from Hamamatsu Paper (Squares)

Relativistic Estimate (Circles)
Laser Test at HZB (Triangles)
Hamamatsu Laser Test (Triangles)

Time Shift:
Relativistic Estimate (asterisks)

Δt_{RMS}^{FSC}: Quadratic some of Δt_{RMS}^{fit} with wavelength independent contributions (264 fs)





Optical Media Broadening

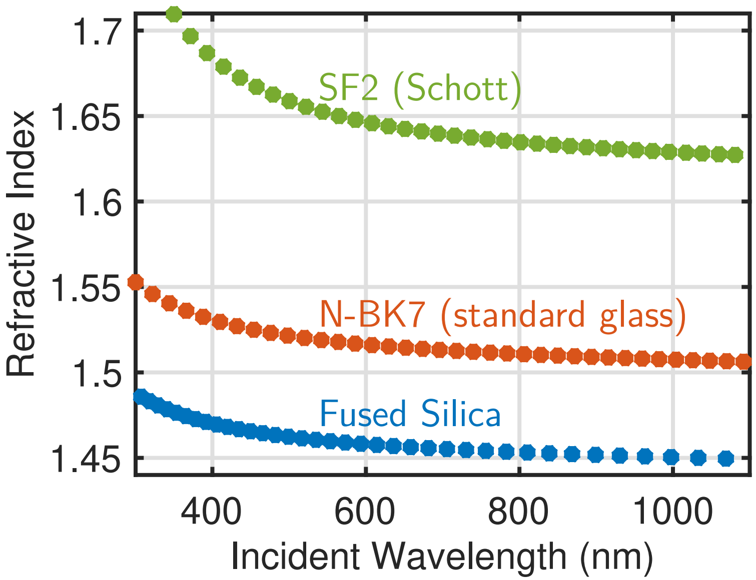
Peak shift and broadening of streak-camera time projections (Δt^{OTS}_{shift}) due to thickness and $n(\lambda)$.
Anti-reflection Coating (<1 mm) can be neglected.

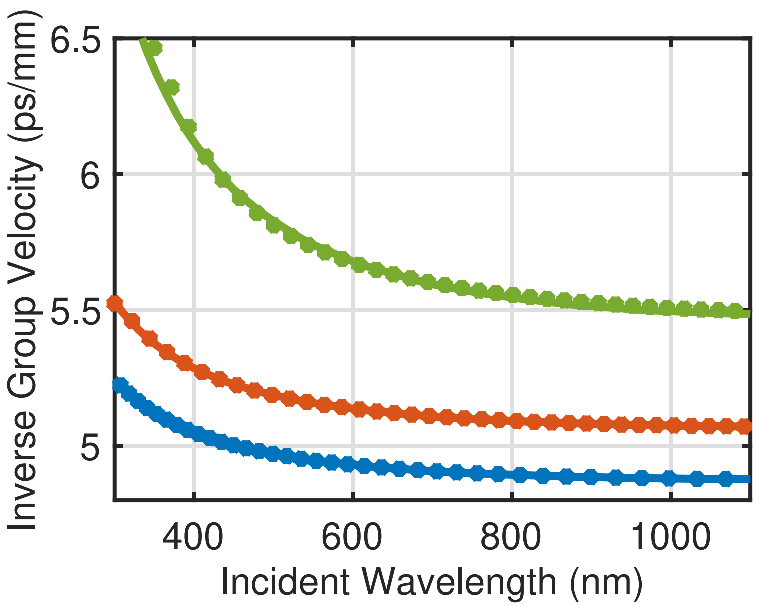
$$\Delta t^{OTS}_{shift} = \sum_j l_j / v_{g,j}$$

1. Lack of data for several wavelength for several materials;
2. Only fuse silica is well documented;
3. Find scaling properties to infer the missing data.

$$\frac{1}{v_{g,j}} = P_{1,j} \left(\frac{\partial K}{\partial \omega} \right)_{Silica} + P_{2,j}$$

Material	P_1	P_2 **(ps/mm)**
N-BK7 (std glass)	1.245	-0.803
SF2 (Schott)	3.673	-3.384
Soda Lime	1.200	-0.630
SF5 (Schott)	4.086	-3.516





Time Resolution Simulation

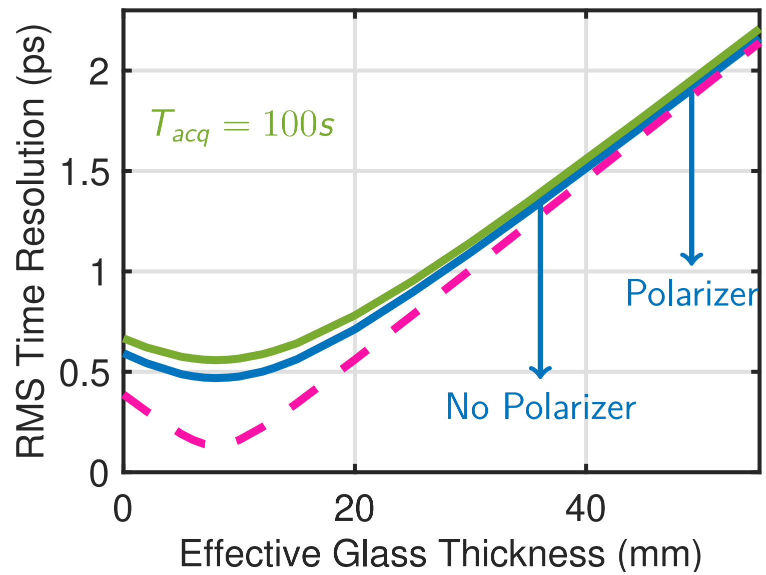
White-light through optics of only silica.
$t_{acq} << 5\,\mu s \longrightarrow$ FSC phase-lock suppress external trigger-jitter.

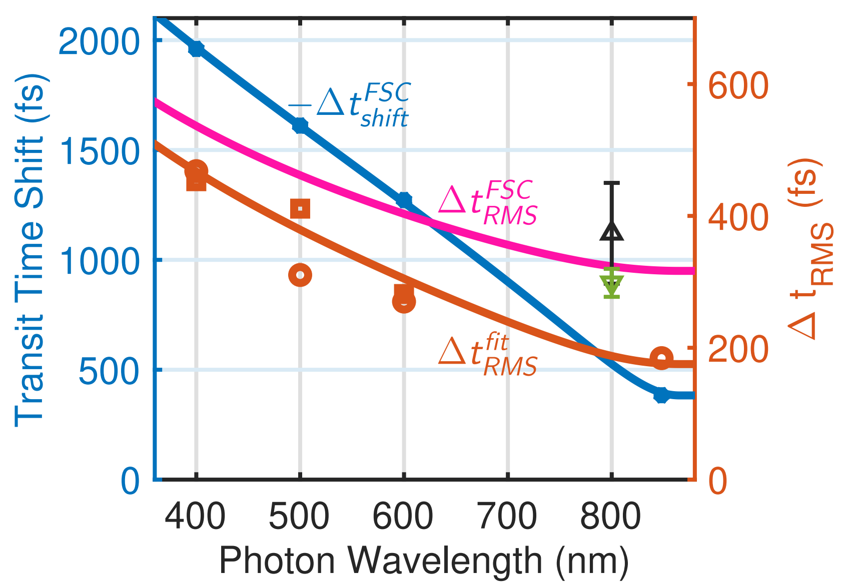
Deterministic Simulation $\longrightarrow$ due to Δt_{shift}^{OTS} and Δt_{shift}^{FSC}:
-Min due to delay-time cancellations at 8 mm;
-Min$\neq 0$ due to wavelength dependencies.

Full Simulation $\longrightarrow$ includes also Δt_{RMS}^{FSC}:
-Significant effects below 16 mm;
-Above 18 mm Δt_{shift}^{OTS} is dominant.
-S.O.: 47 mm $\longrightarrow 1.8$ ps RMS.
-wo Pol.: 34 mm $\longrightarrow 1.3$ ps RMS.

Long Acquisition Time $\longrightarrow$ additional trigger jitter contribution

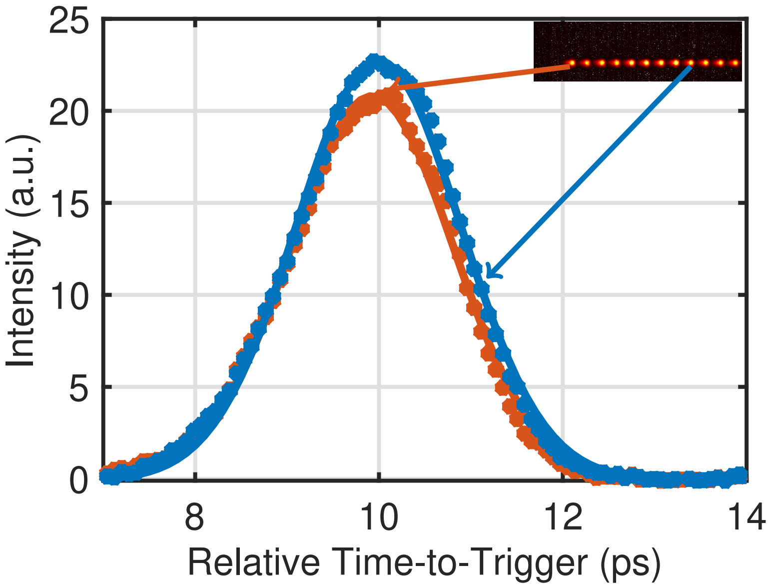
$$\Delta t_{RMS}^{trigger} = 0.145 ps [t_{acq}/s]^{0.154}.$$





Beam Profile Measurements

- Low current ($850\,$nA) $\longrightarrow$ negligible collective effects
- $\alpha \to 0$: small bunch length
- 336 buckets filled with uniform filling pattern
- $t_{acq} = 100\,$s $\longrightarrow \Delta t^{trigger}_{RMS} = 295\,$fs
- BPF at $700\,$nm with BW of $50\,$nm



$\sigma_t = 881 \pm 2\,$fs
$\sigma_t = 895 \pm 2\,$fs

Mean bunch length of $894\,$fs
Relative variation of $1.5\,\%$
Position variation below $40\,$fs

Edmund BPFs $3.5\,$mm thick

BW of $10\,$nm at 400, 500, 600 and $700\,$nm and BW of $50\,$nm at $700\,$nm

Thorlabs FELH edge filters $2\,$mm thick

Cut-off frequency of 500, 600 and $700\,$nm

Time Resolution

Delay Time:

Depends only on time shift on FSC and OTS

Simulation and experiment agrees

Difference due to filter thickness

Pulse Width:

Dashed curves $\longrightarrow$ time resolution

Blue $\longrightarrow \Delta t^{FSC}_{RMS}$

Red $\longrightarrow$ also Δt^{FSC}_{shift} and Δt^{OTS}_{shift}

$\Delta t^{bunch}_{RMS} = 0.75 \pm 0.01$ ps $\longrightarrow$ spectroscopy of coherent THz

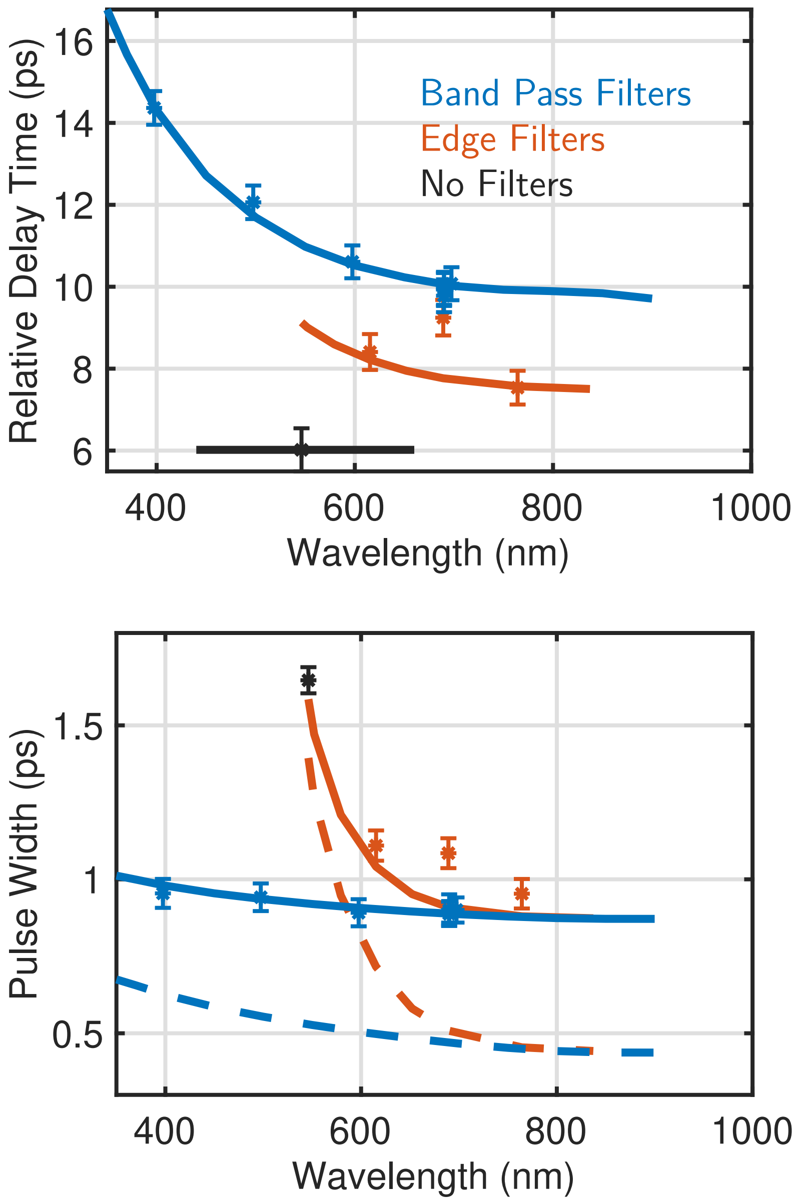
600 nm Edge filter:

No defect at optical inspection

hyp.: resonance-like delay and broadening effect

Edge filter:

$6\,\%$ $\longrightarrow$ hyp.: neglected higher order effects



Time Resolution vs Bandwidth

Several BPF simulated

Filtered photon fluence constant $\longrightarrow$ increased T_{acq} and $\Delta t_{RMS}^{trigger}$

10 nm at 600 nm with T_{acq} $=100$ s $\longrightarrow$ reference value

Left side $\longrightarrow$ increased jitter and resolution

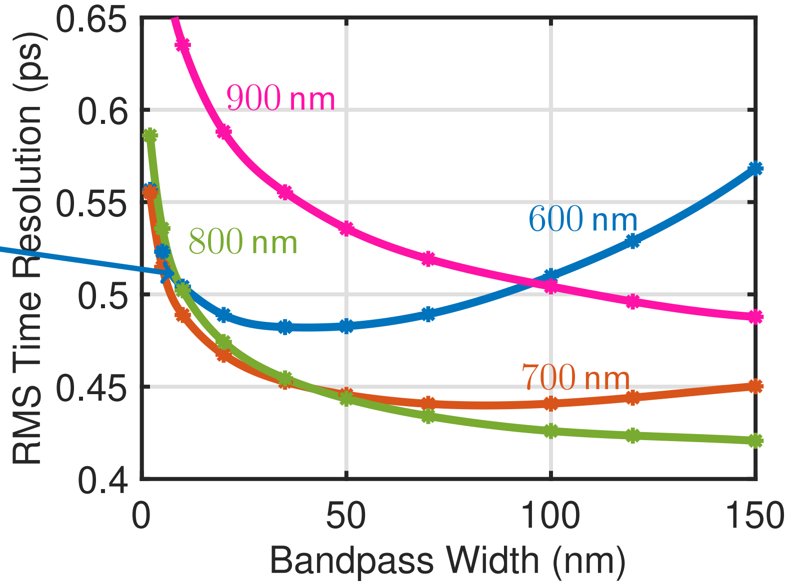
Higher λ and $\Delta\lambda_{bp}$ is better

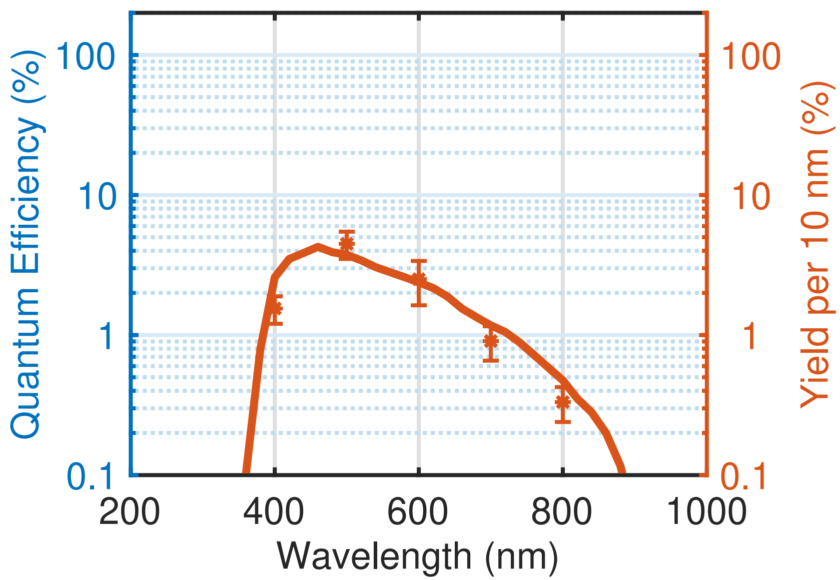
900 nm is worst $\longrightarrow$ jitter dominated

Best for 150 nm at 800 nm $\longrightarrow$ 0.42 ps

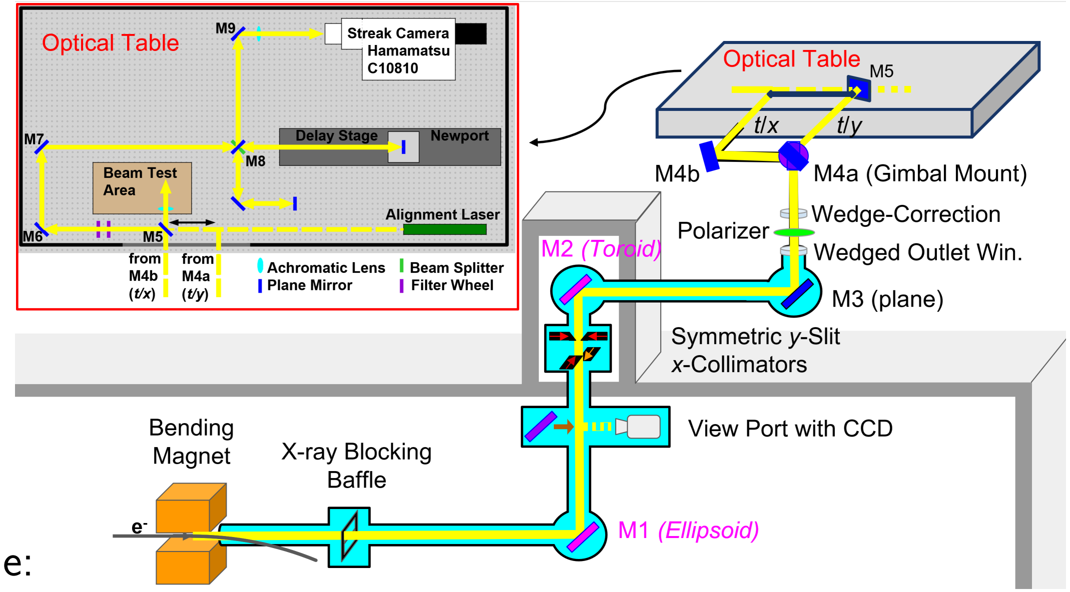
Such high quality filter does not exist

Best obtained is 0.47 ps at 700 nm



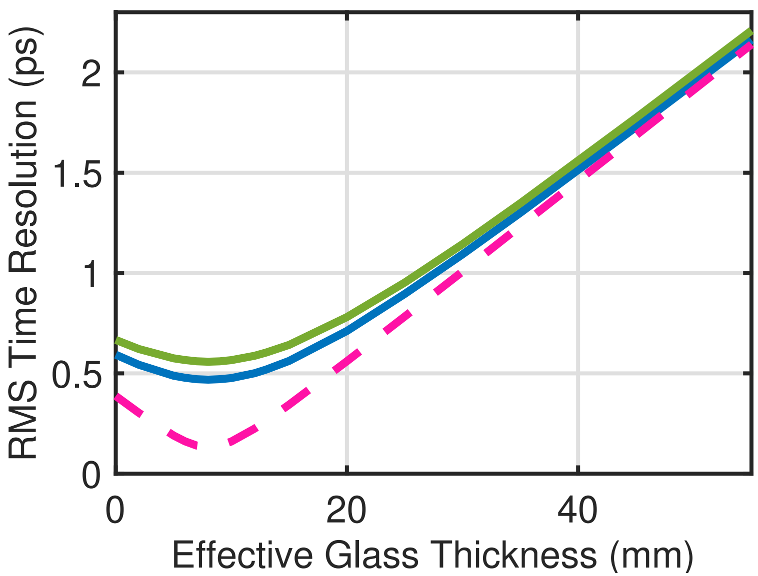


HZB BESSY II Light Source



- Characterization of the beamline:
  - Optical media
  - Streak camera
- Analysis of broadening mechanism:
  - find major source of broadening
  - improve resolution
- 1.3 ps resolution obtained (single-shot with white-light)
- 0.47 ps resolution obtained (long acquisition time)
- 0.4 ps potentially achievable with a BPF of 150 nm BW at 800 nm.

Conclusion



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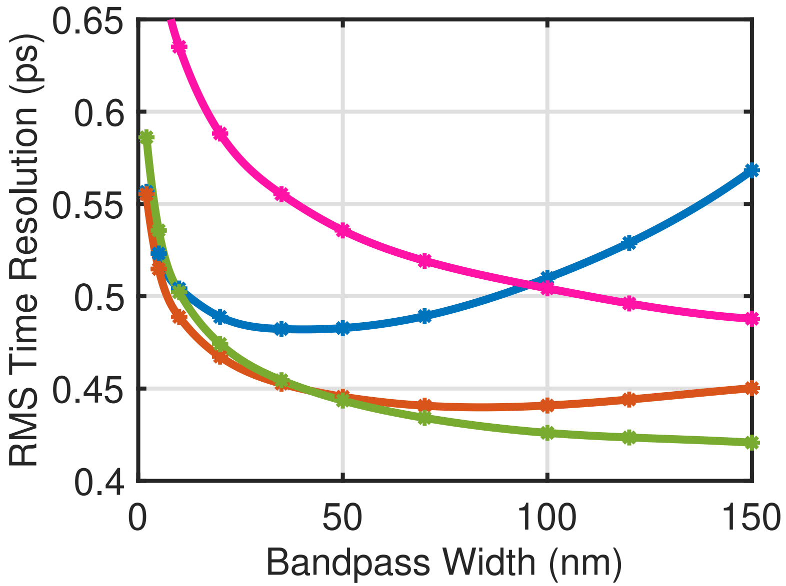

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Acknowledgments

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  - I. Müller from HZB

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  - Th. Birke from HZB
  - I. Seiler from HZB

- Incorporation of realistic time structures into the ray-tracing code RAY-UI:
  - P. Baumgärtel from HZB

- Very helpful discussions and information:
  - I. Grill from the Hamamatsu support group
  - Th. Franzl from the Hamamatsu support group