Online Bunch Length Monitoring for Storage Ring using a Fast Photodiode

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POHANG ACCELERATOR LABORATORY

Contents

PLS-II @ Pohang Accelerator Laboratory

PLS-II Parameter	Value	Unit
Beam Energy	3	GeV
Beam Current	400	mA
Circumference	281.82	m
RF Frequency	499.97	MHz
RMS Bunch Length	21.3	ps

- PLS-II operates a hybrid filling pattern to support pump-probe experiments.
- Online information of bunch lengths and fill-pattern could be worth for users

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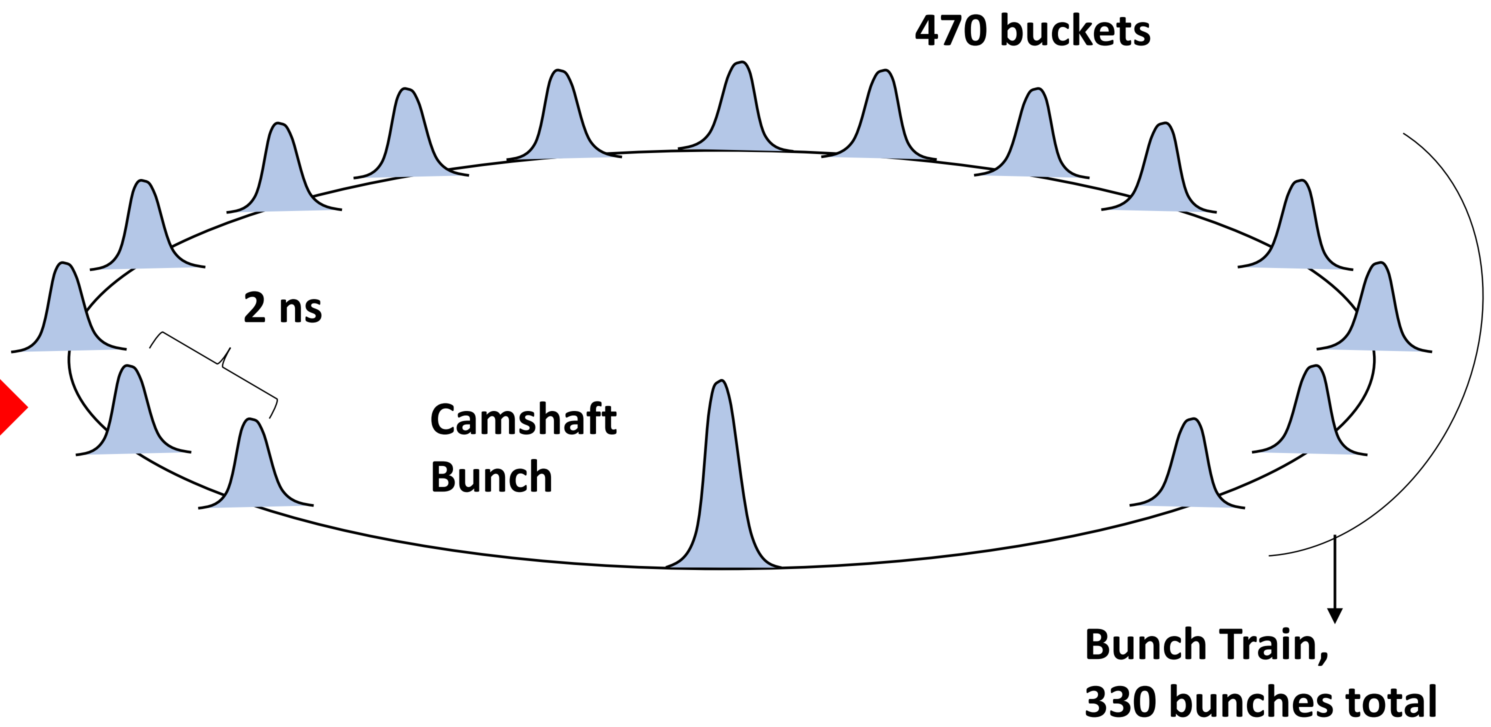
PLS-II @ Pohang Accelerator Laboratory



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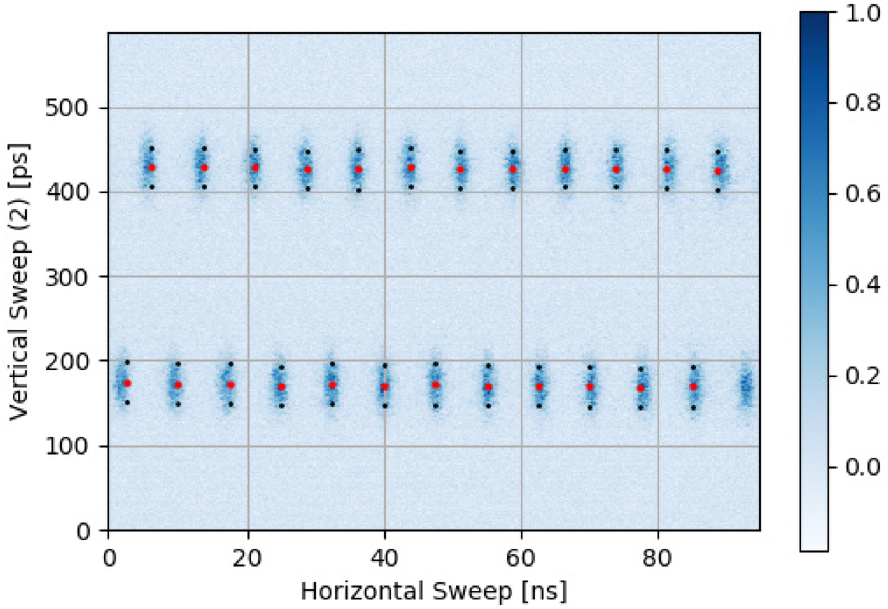
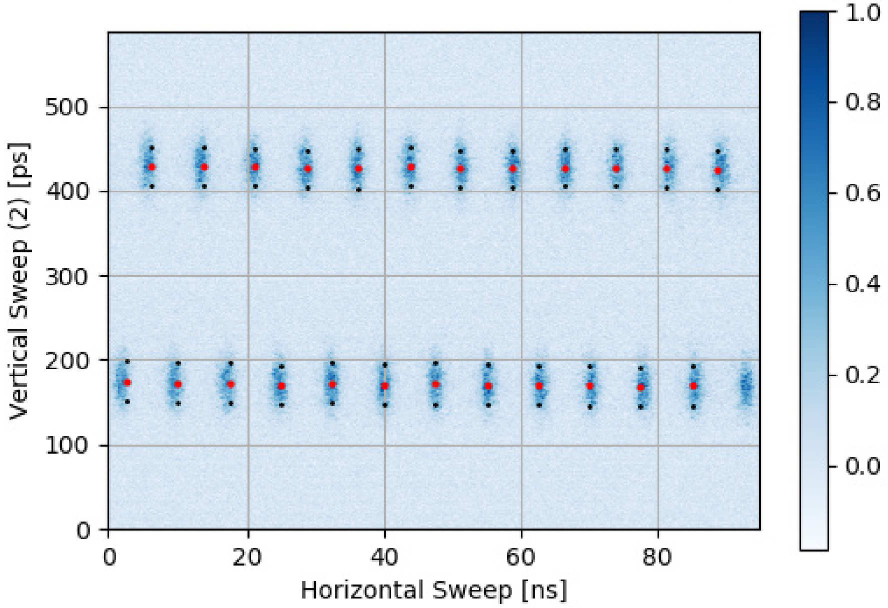
Bunch Length



Streak Camera

- High temporal resolution (< RMS 1 ps)
- Slow acquisition rate
- Incompatible for turn-by-turn me asurements

Bunch Length



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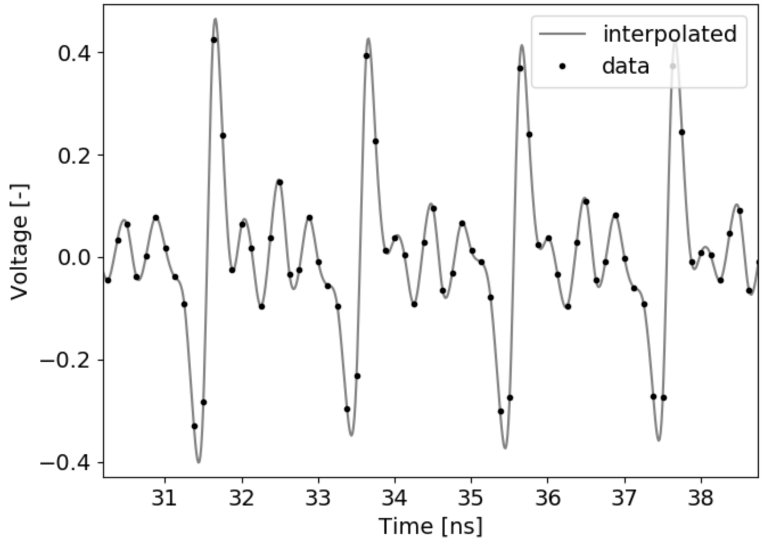
Fill-Pattern

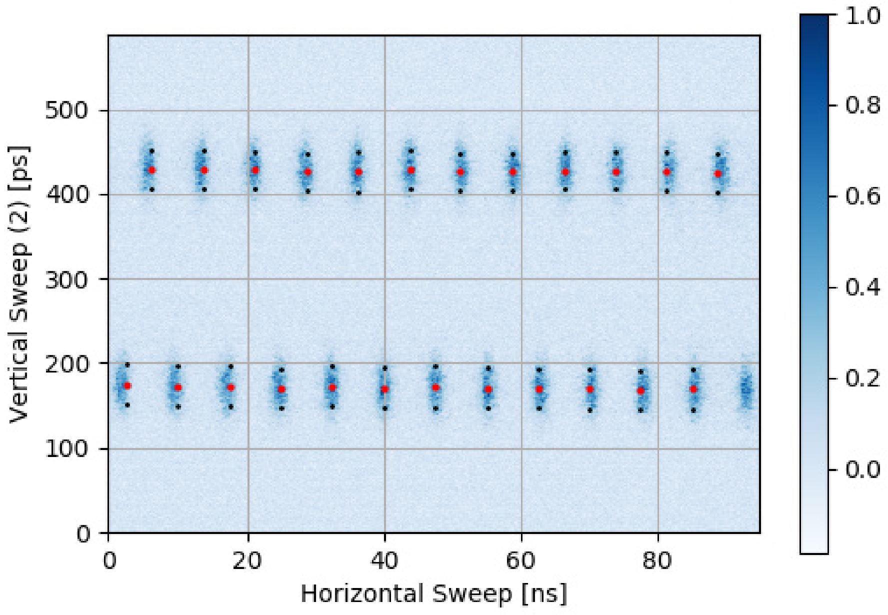


BPM pick-up / FCT

- Fill-pattern monitoring
- Limited bandwidth
- Moderate accuracy
- Non-linear behavior causes an intolerable error

Longitudinal Beam Diagnostics

Bunch Length



Streak Camera

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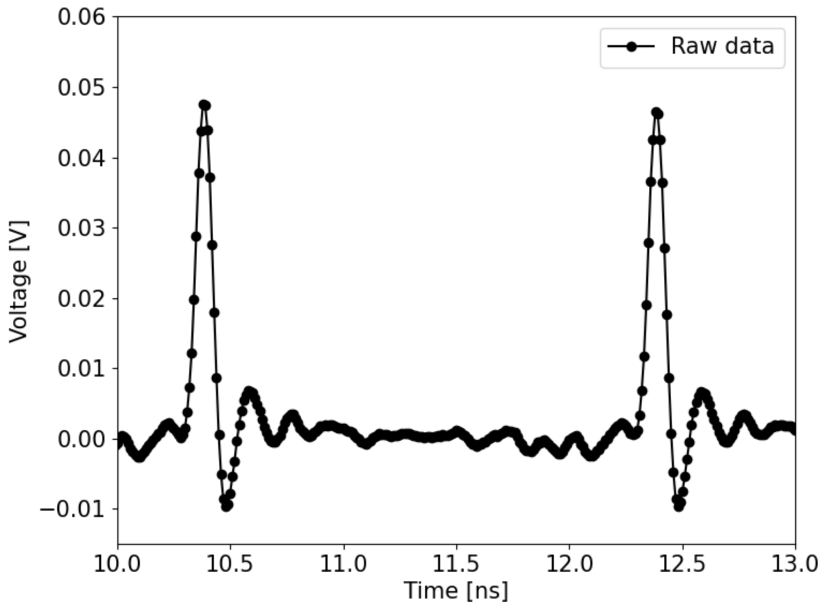
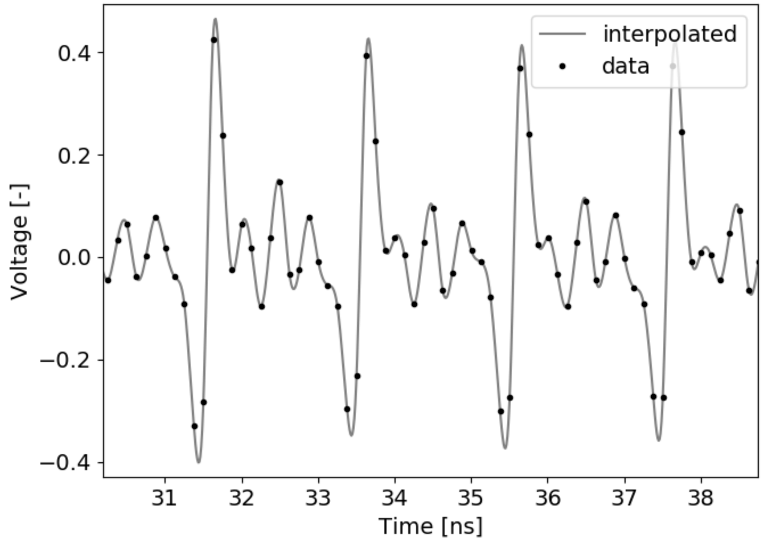
Bunch Length + Fill-Pattern

Fast Photodiode

- Intermediate resolution (~2 ps)
- Bunch length and fill-pattern real-time measurement



Fill-Pattern



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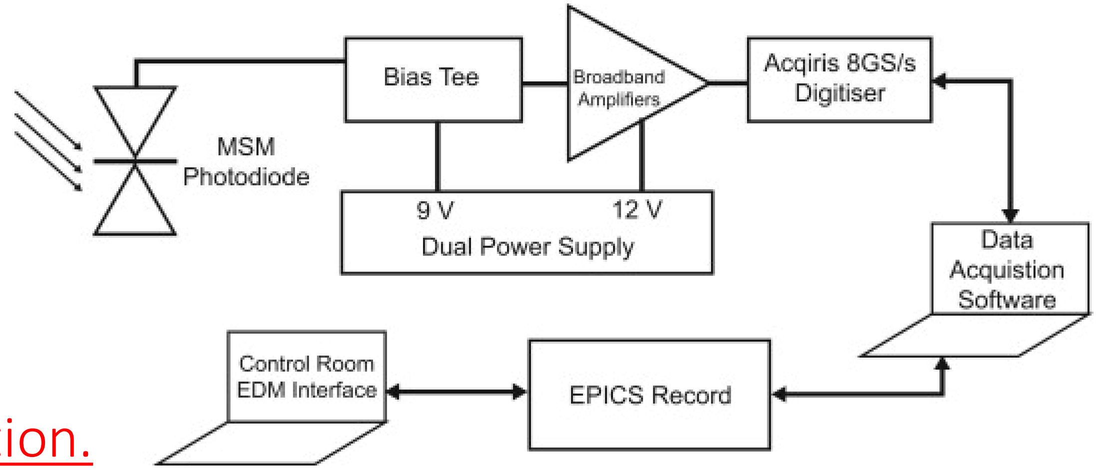
Previous studies

- **Australian Synchrotron [1]**
  - Successful online fill-pattern (FP) measurement
  - We could not find analog input bandwidth information of bias tee, digitizer or cables.

  → We use similar experimental set-up
  BUT chose all devices' ABW near 15 GHz for bunch length detection.



[1] D. J. Peake *et al.,* "Measurement of the real time fill-pattern at the Australian Synchrotron", NIM. A. (2008)

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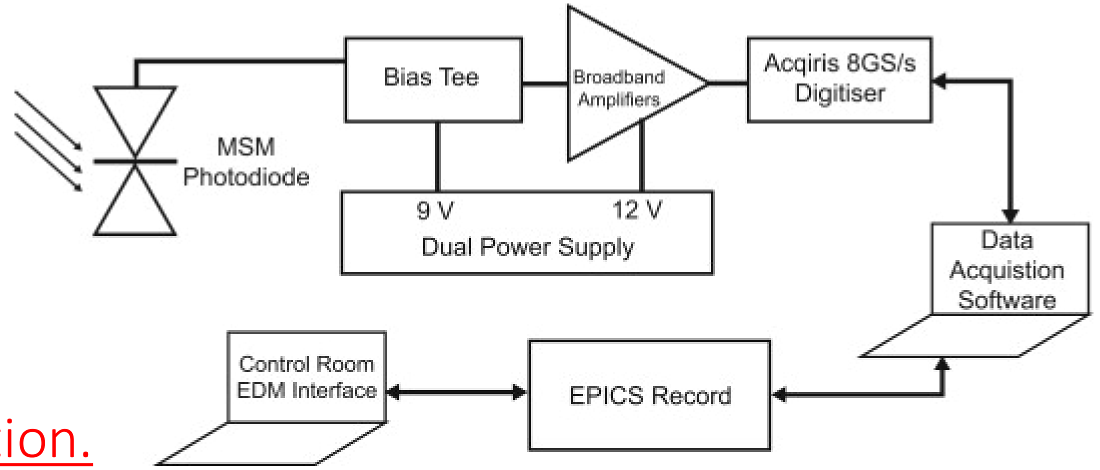
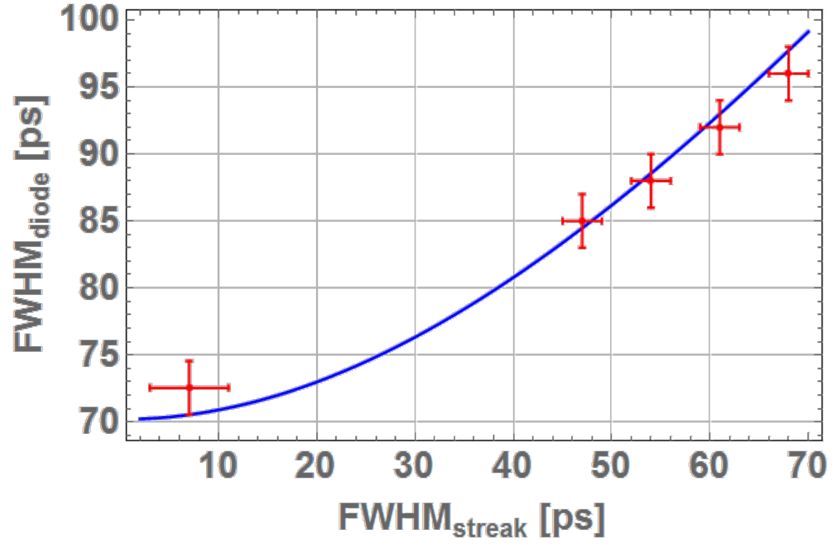


- **Bessy-II, HZB [2]**
  - Successful online bunch length, fill-pattern, and phase measurement.
  - Bunch length data fit result seemed valid locally.

  → We developed a new analysis method
  to handle nonlinear frequency response of the system.



[1] D. J. Peake *et al.,* "Measurement of the real time fill-pattern at the Australian Synchrotron", NIM. A. (2008)

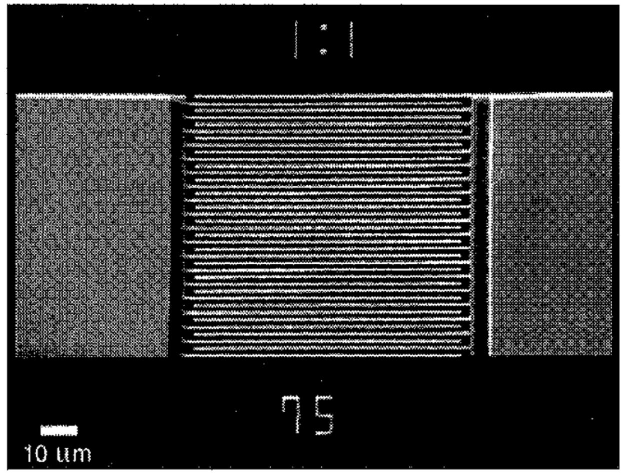
[2] J. Hwang, Bunch length measurement by using a fast photodiode, Private Discussion, (2019)

MSM Photodiode

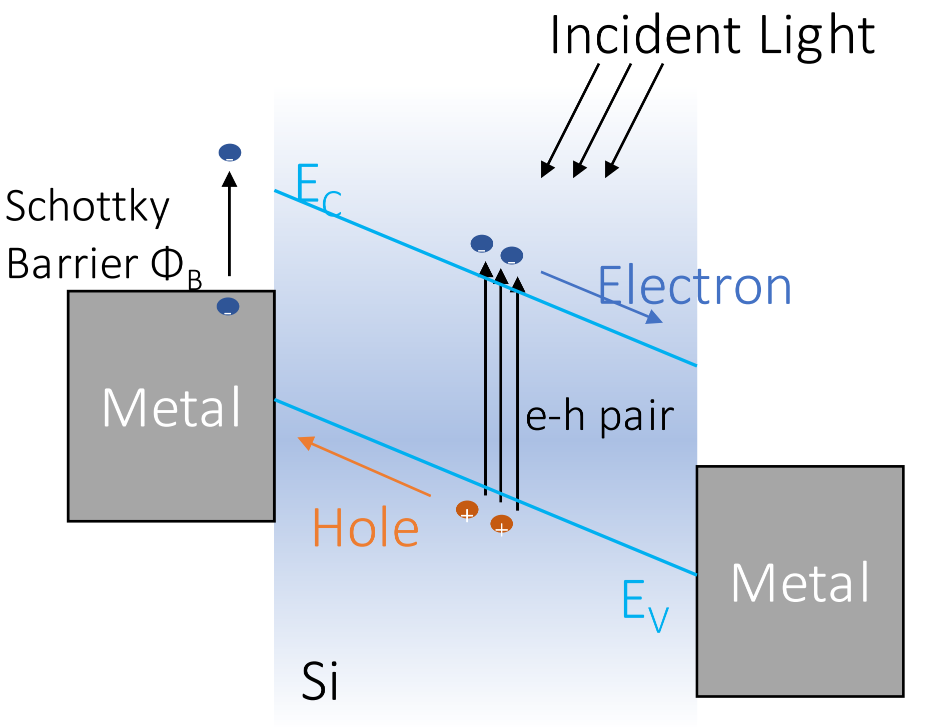
- Metal-Semiconductor-Metal Photodiode
  - Metal-semiconductor Junction

→ Schottky diode's potential barrier is ruled by the metal and silicon work functions.

MSM photodiode with wedge-comb structure has fast and strong response.



P. R. Berger, 1996



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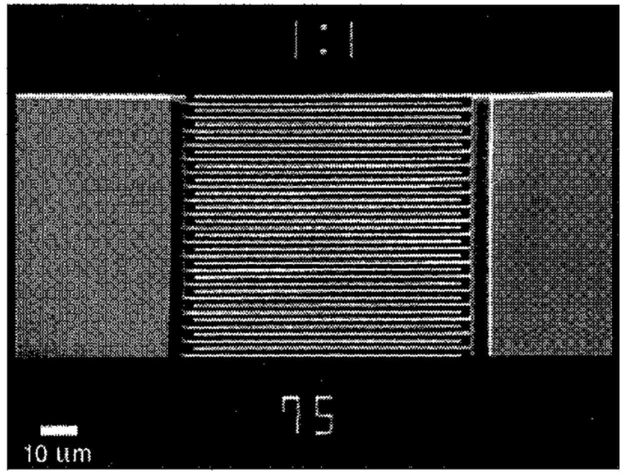

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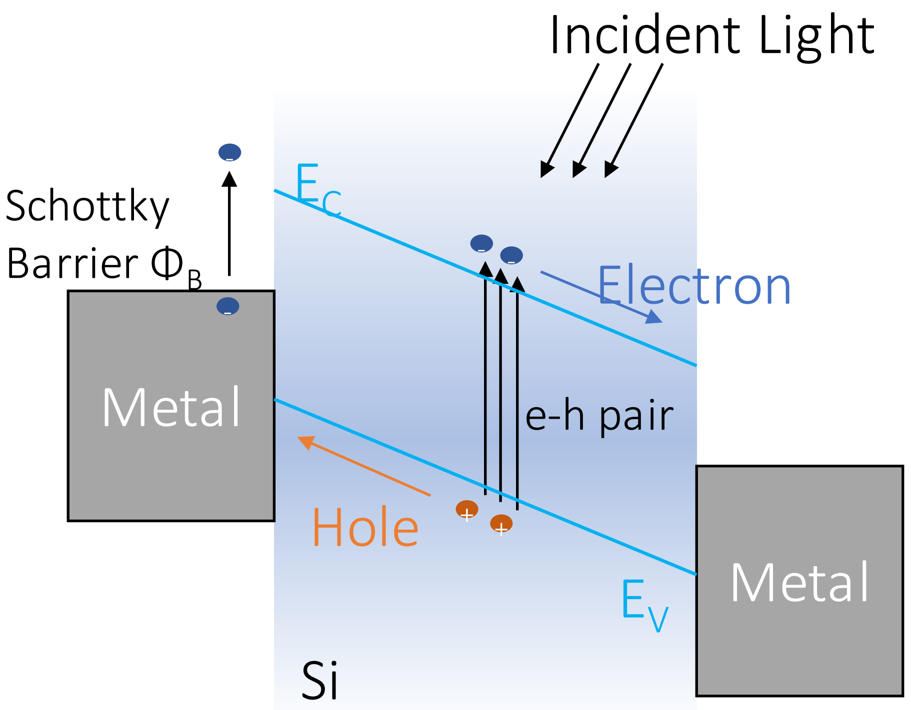
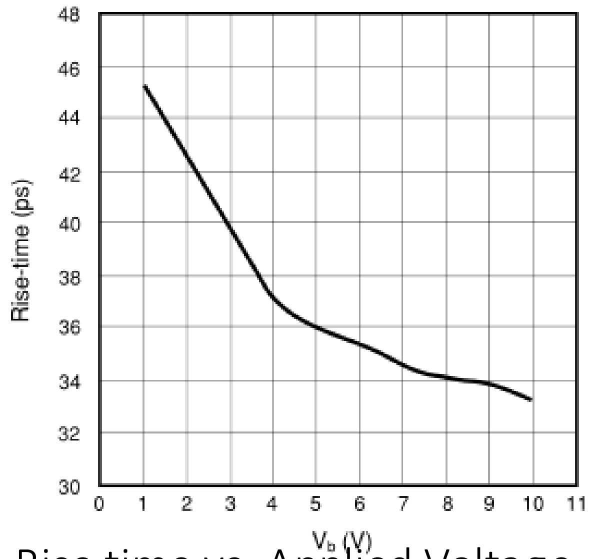
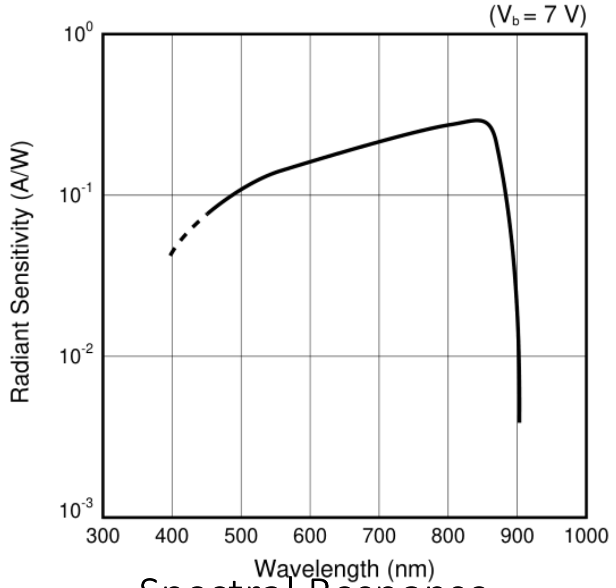


- Hamamatsu G4176-03 (GaAs MSM photodiode)
  - Rise time ~ 35 ps @ 7 V bias
  - Active area : 200 μm^2
  - Dark current : 100 pA @ Ta = 25 °C



Rise time vs. Applied Voltage

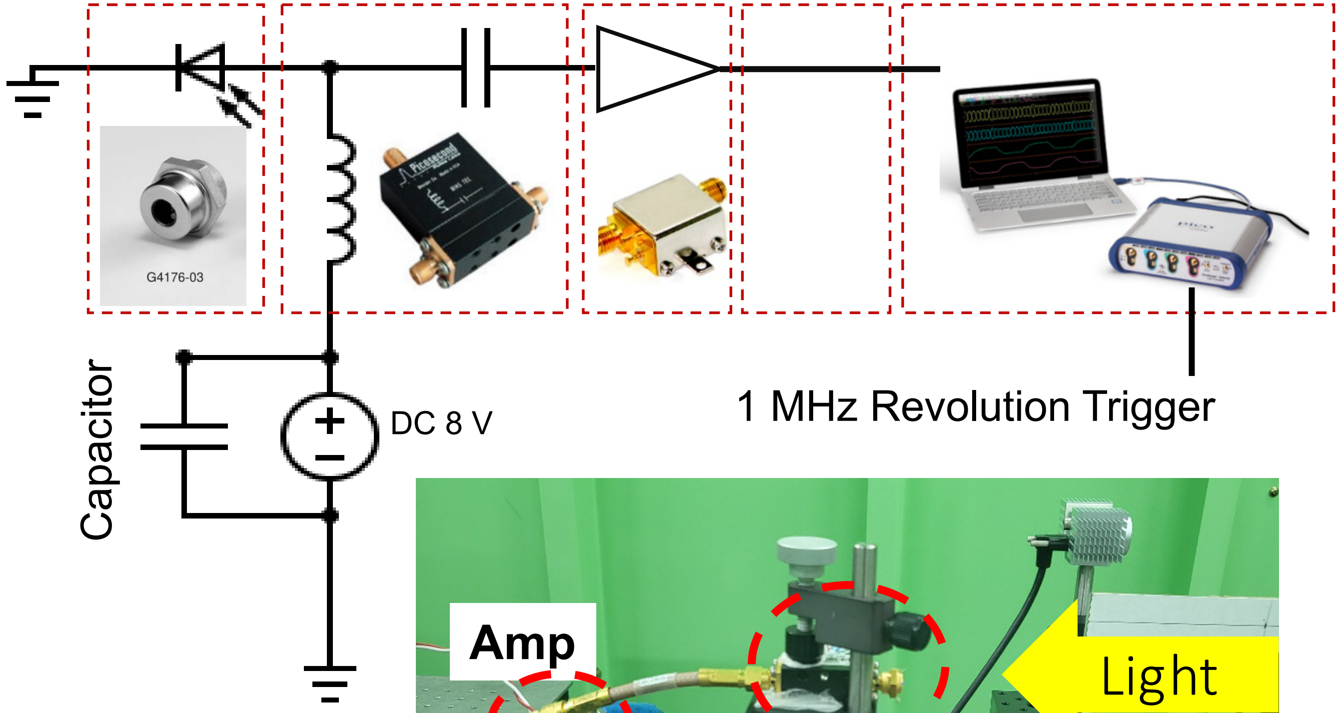


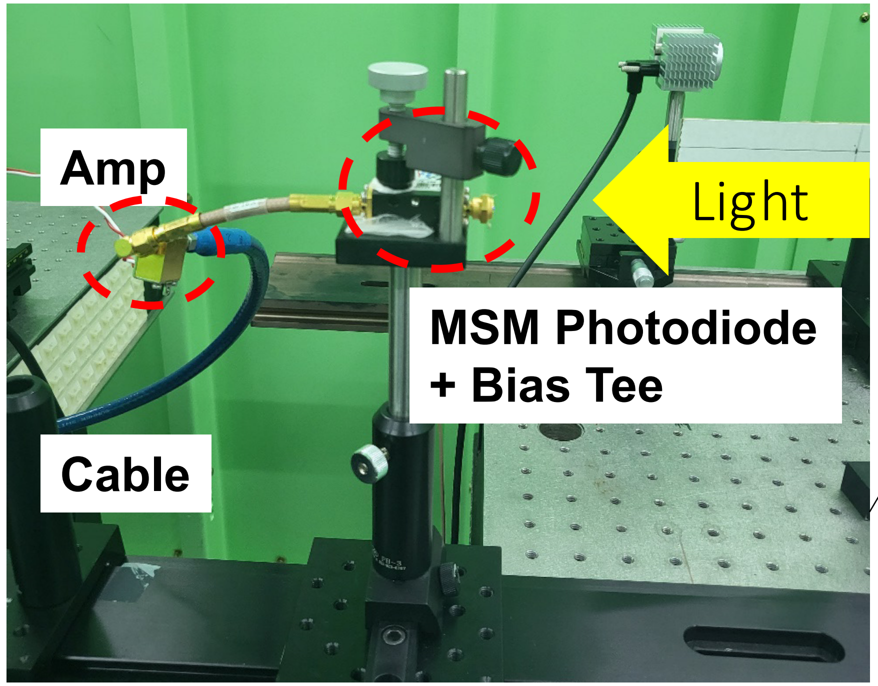
Spectral Response

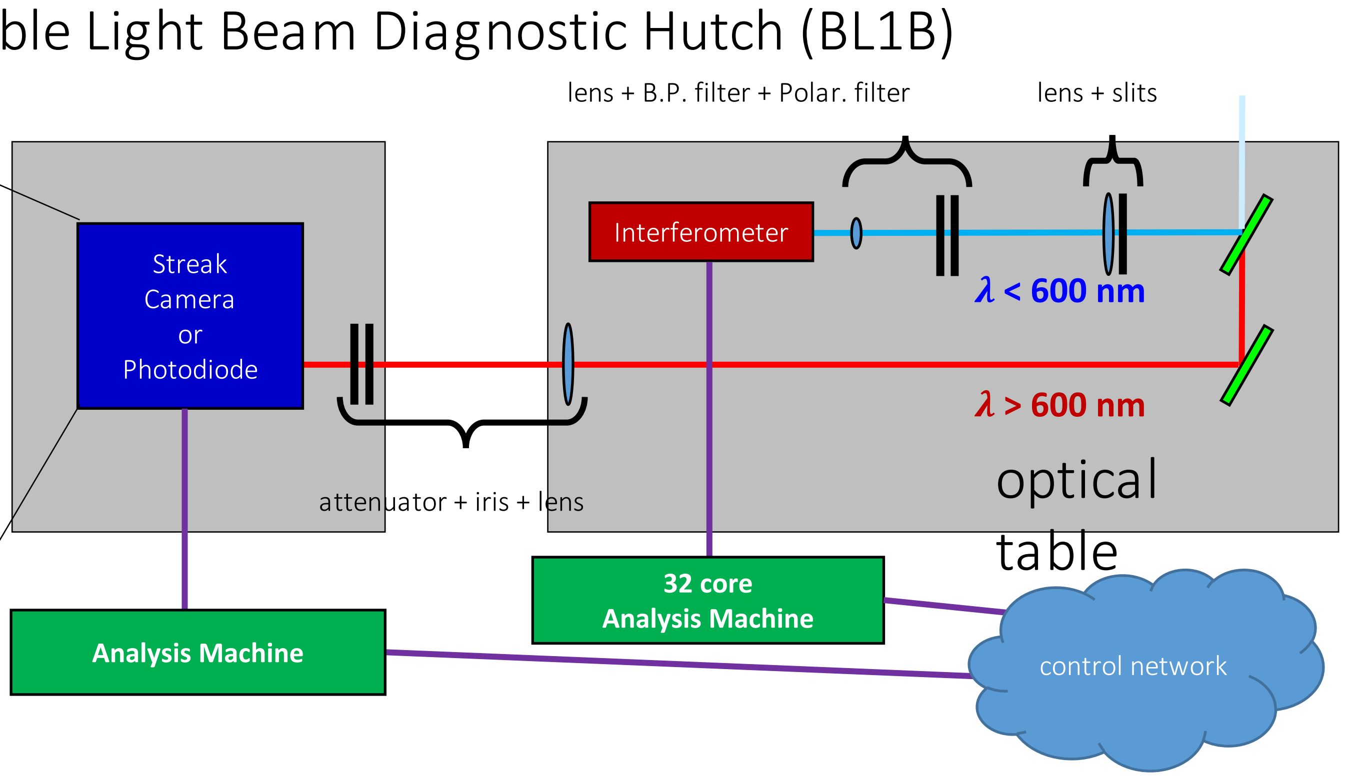
Experimental Setup (1/2)

Visible part (600~900 nm λ) of synchrotron radiation –

Photodiode – Bias Tee – Amp – Cable – Digitizer – PC





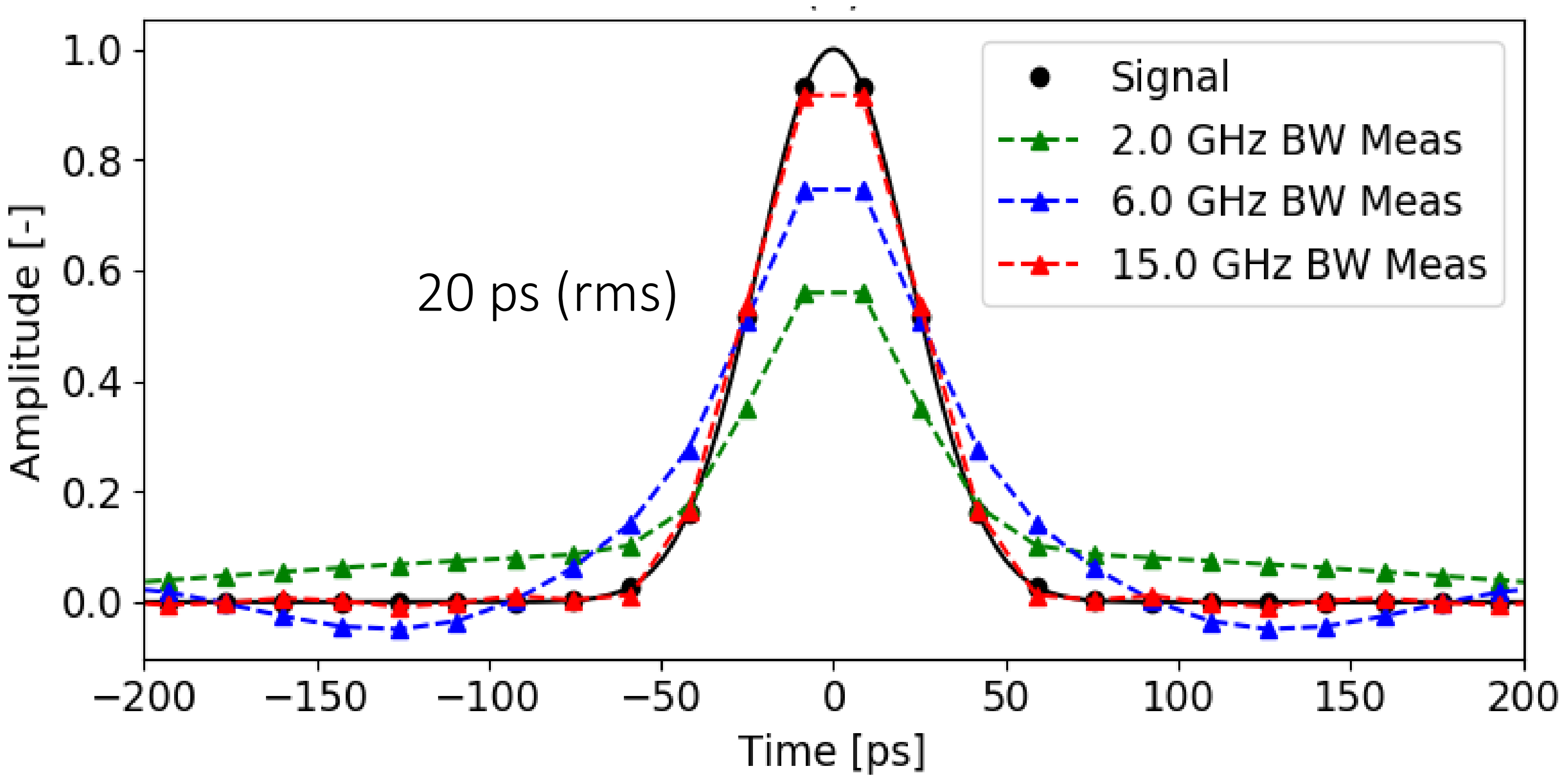


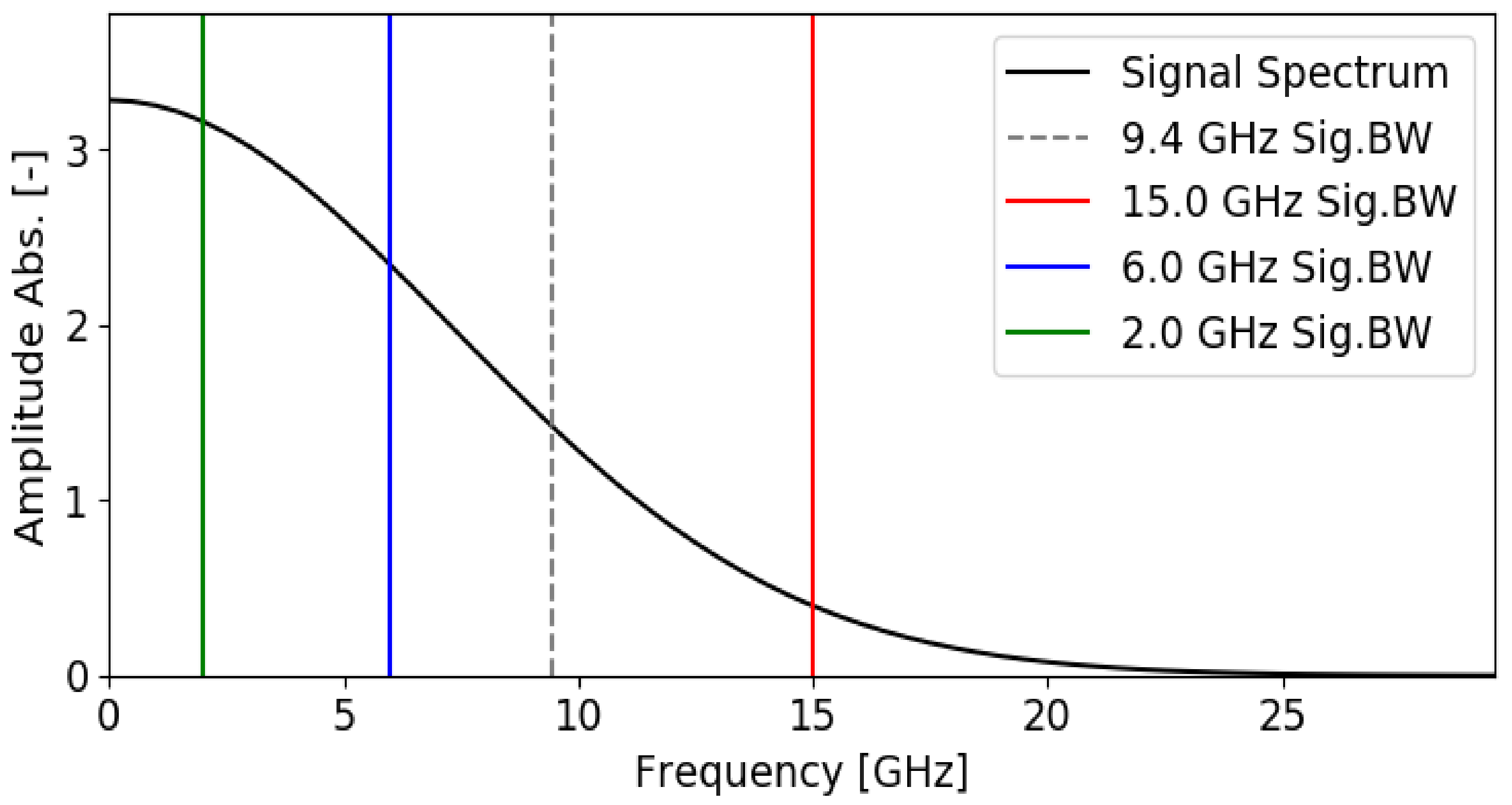
- To maximize gain and efficiency, dichroic mirror was used.
  - higher than 600 nm for photodiode
  - lower for interferometer
- Beam splitter was used for simultaneous measurement with photodiode and streak camera.
- Multi-channel DC P/S 8 - 12V was installed to feed the voltage to the photodiode (connected at the bias tee) and the amplifier.

Experimental Setup (2/2)

Component	Model	Analog Bandwidth (-3 dB)	Etc.
Photodiode	G4176-03, Hamamatsu	~ 10.4 GHz *	No Freq. Response Info.
Bias Tee	5541A, Picosecond(Tektronix)	26 GHz	
Amplifier	ZX60-14012L-1+, Mini-Circuits	14 GHz	
Cable	Lab-made	26.5 GHz	
Digitizer	Picoscope9404-16, Pico Technology DPO71304SX, Tektronix	16 GHz 13 GHz	2 TS/s sequential, 0.5 GS/s real time sample 50 GS/s real time sample

Experimental Setup (2/2)





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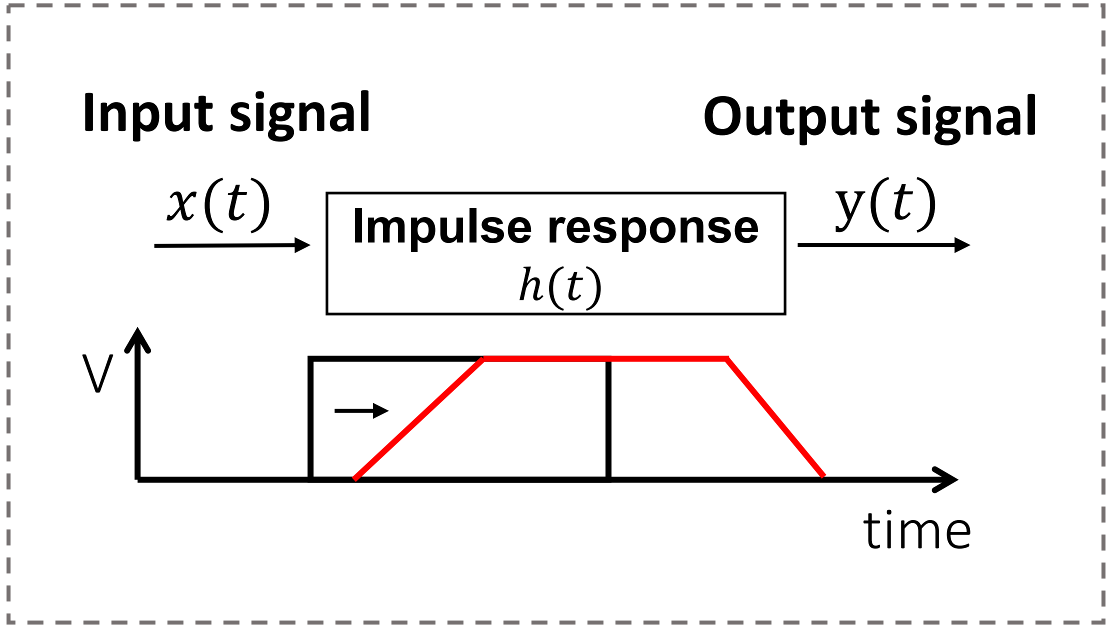
Analytic Gaussian Deconvolution (AGD)



$$y(t) = x(t) * h(t) = \int x(\tau)h(t-\tau)d\tau$$

⇧

System response function

: $h_{sys} = h_{PD} * h_{bias\,T} * h_{amp} * \cdots$

$$\sigma_y^2 = \sigma_x^2 + \sigma_h^2$$

- The input signal is reconstructed by analytically deconvolving the output signal with a Gaussian kernel.
- The system's impulse response is used as a deconvolution kernel.

	Analytic Gaussian Deconvolution
Pros	• Practical • Fast
Cons	• Inaccuracy (Error with Gaussian assumption)

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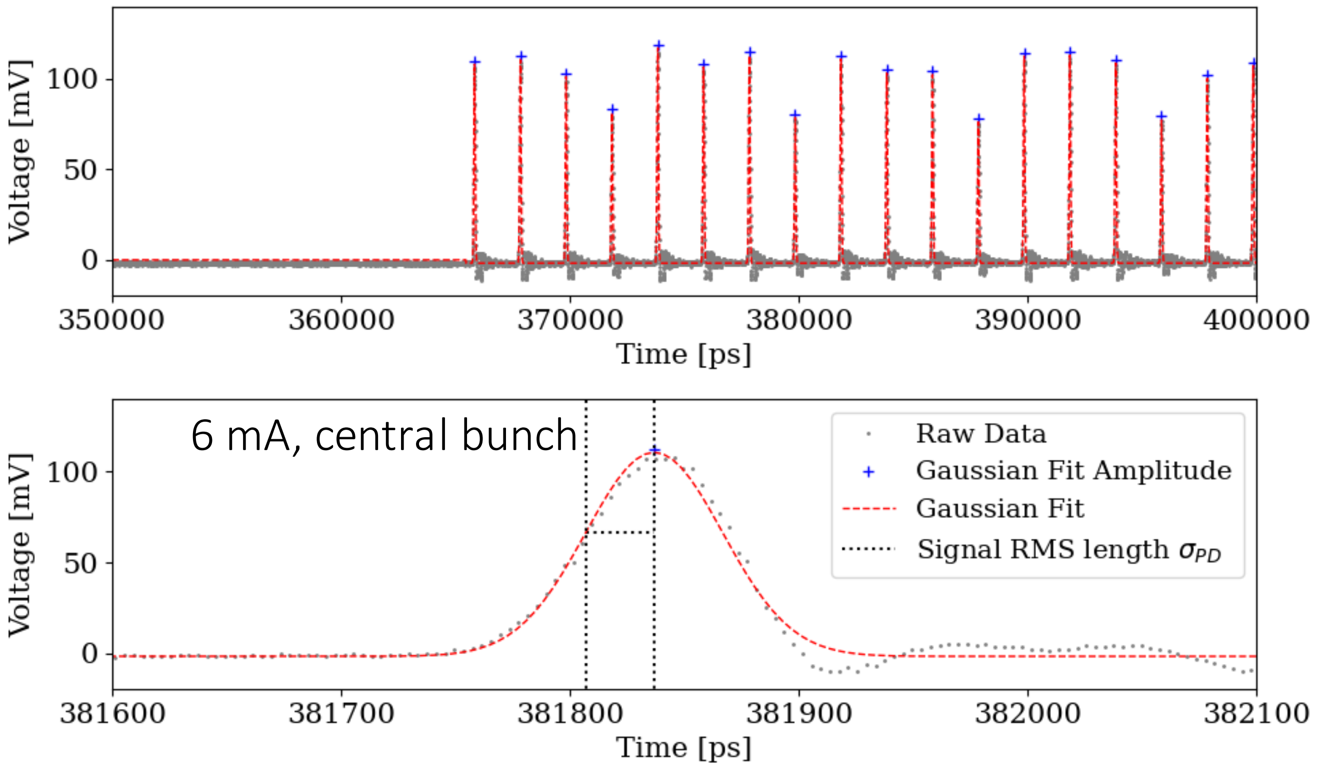
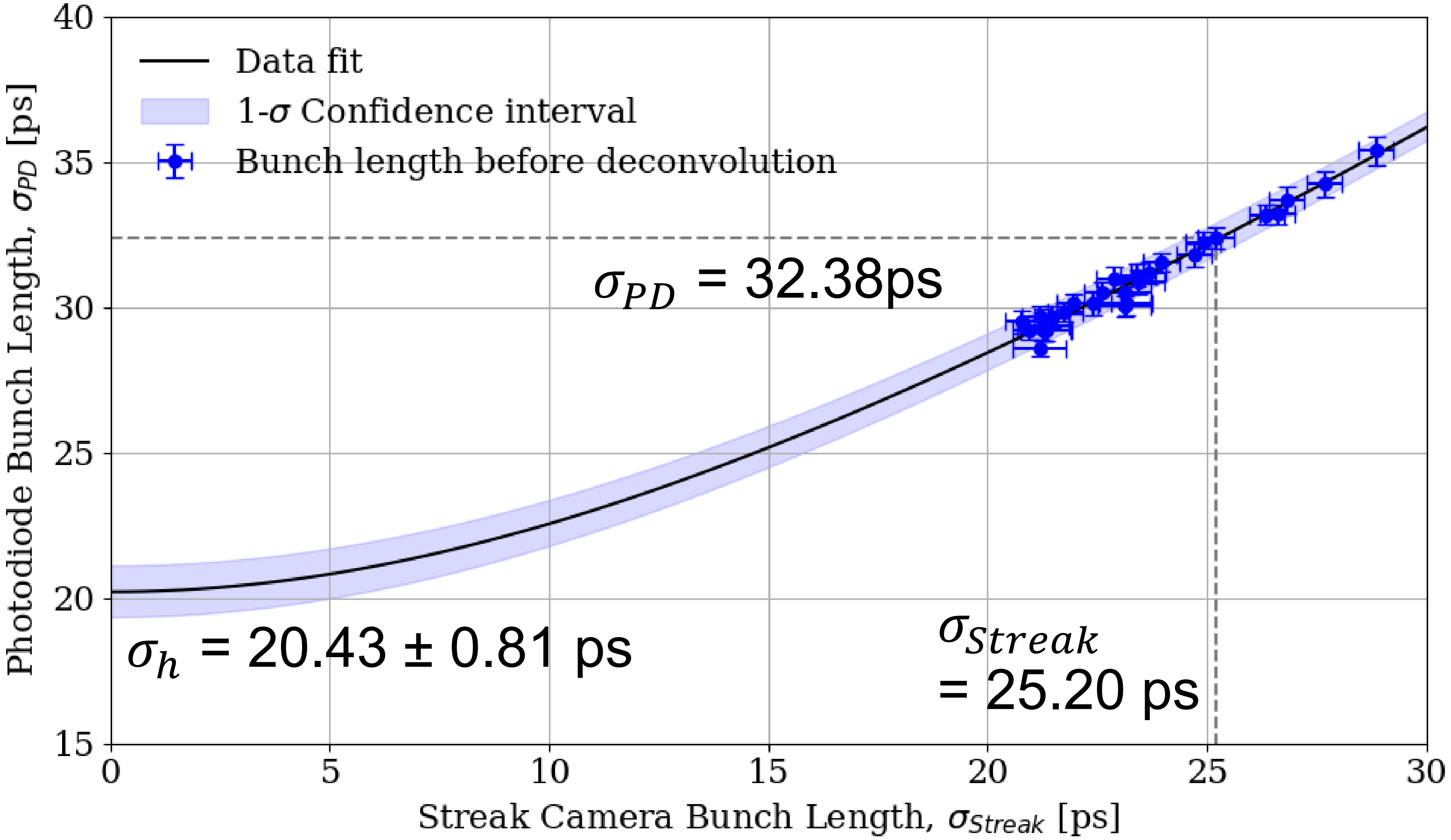
AGD Measurement Results



Bunch Length Measurement



- The noise level (without beam, room temperature, hutch-door closed) was equivalent to a bunch current of 3 μA.
- The wideband system enables the bunch-resolved current measurement.
- Applying the fit form of typical Gaussian deconvolution, we obtained a calibration curve for photodiode measurement.
- Is the Point Spread Function $\sigma_{h,AGD}$ true?

Fit form : $\sigma_{PD} = \sqrt{\sigma_{streak}^2 + A^2}$

Fit result : $A \Rightarrow \sigma_{h,AGD} = 20.43 \pm 0.81\ ps$

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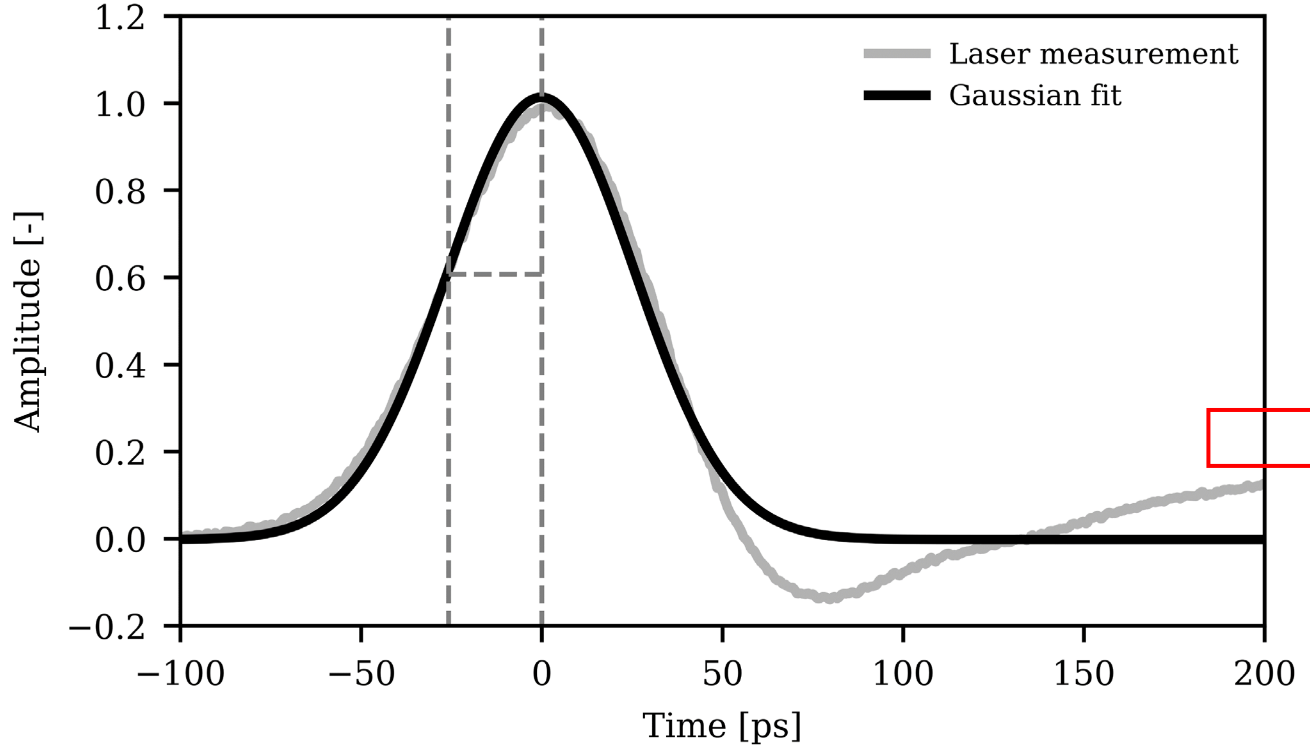
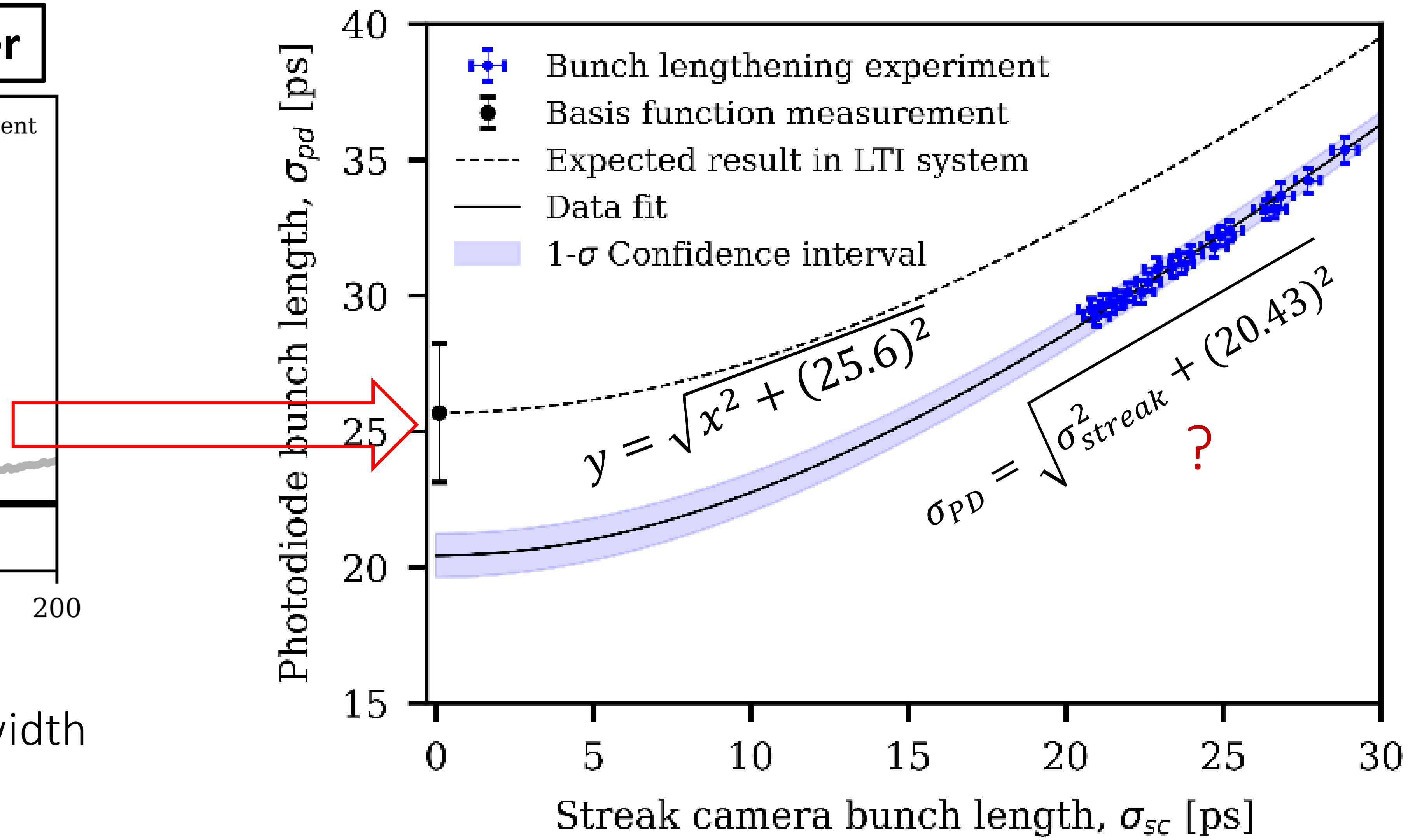
AGD Processed PD Bunch Length

Cross-check, Using Femtosecond Laser

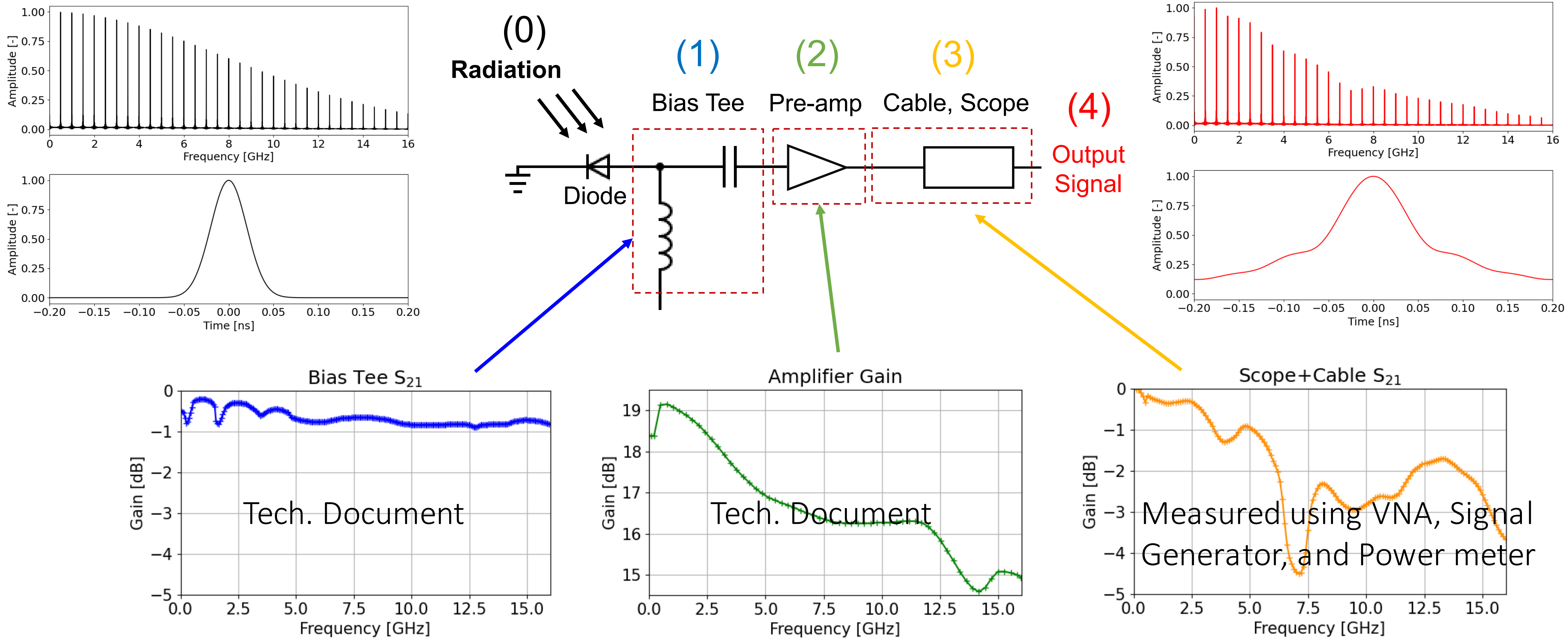




- The PSF was measured with a laser pulse width of ~ 200 fs, as a delta function.
- RMS PSF(Gaussian Fit) was obtained about 25.68 ± 2.56 ps which is way out of 1-sigma confidence interval.

- AGD PSF is inconsistent with the measured response function !

Numerical Compensation (NC)



→ **The measured signal is distorted strongly by the frequency response of analog components.**

Transmission Ratios

- **Ultra-fast Photodiode**
  - rise time(t) = ~35 ps @ 7 V (bias)
  - Eq. bandwidth = 0.35/t ~ 10 GHz
  - Eq. point spread function = 20.7 ps

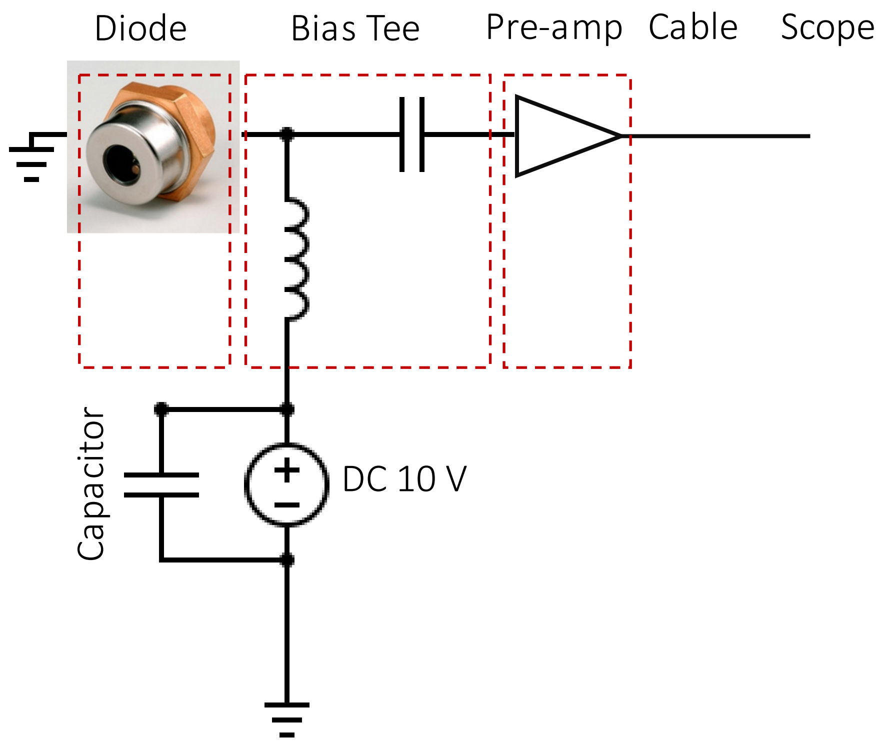
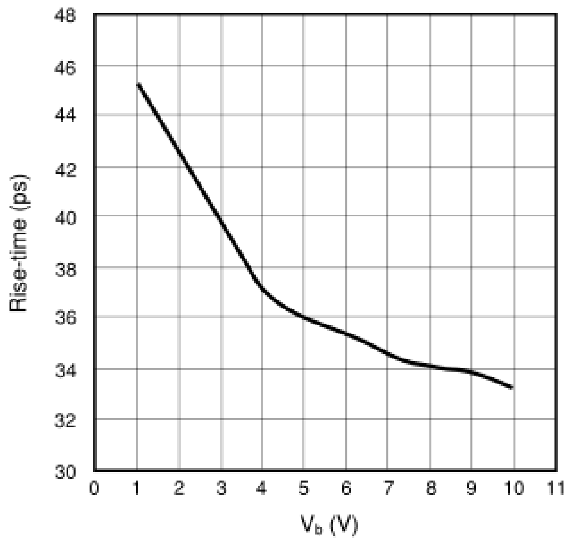
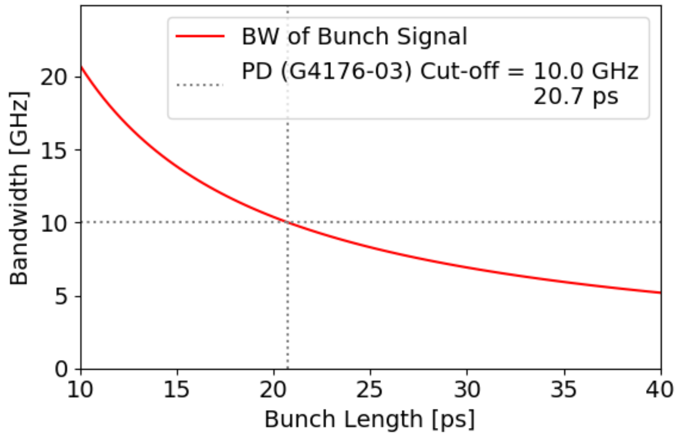
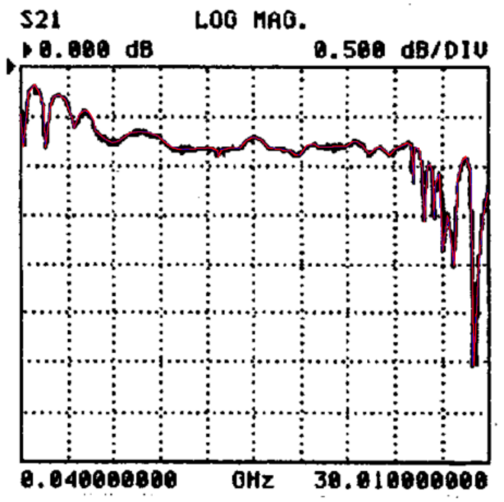


Figure 3: Rise Time vs. Applied Voltage (G4176-03)

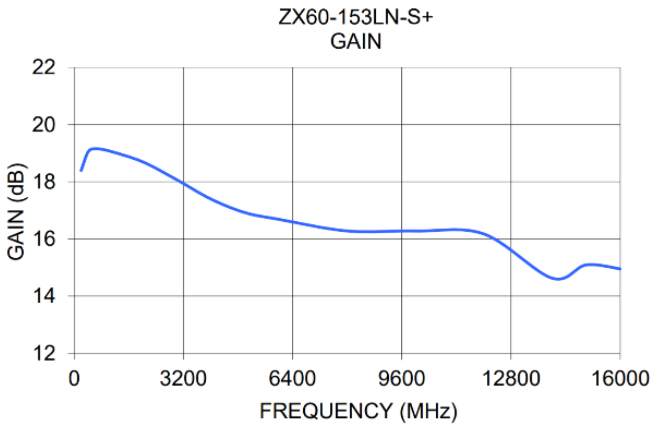




- **Bias Tee**
  - Gain



- **Pre-amp**
  - Gain



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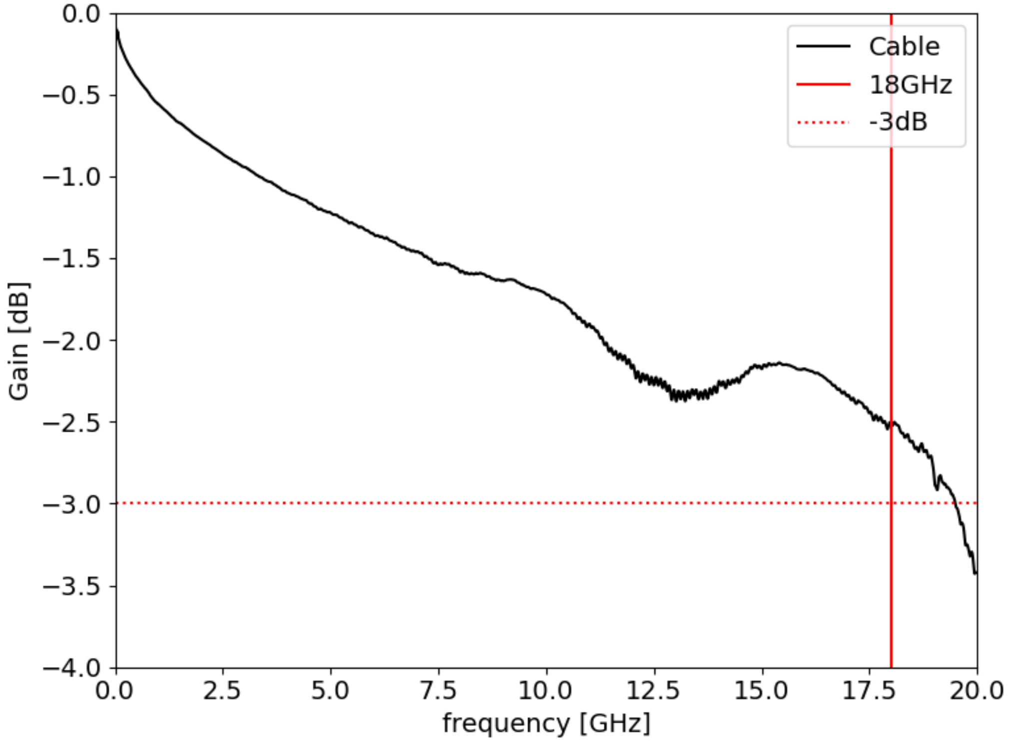
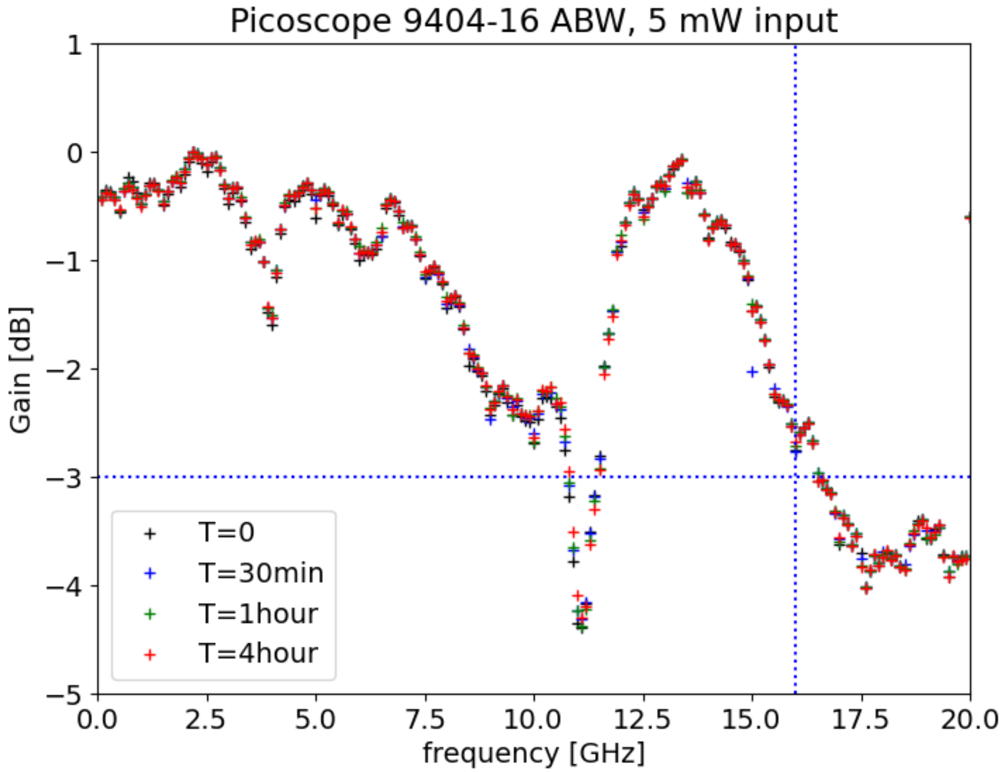
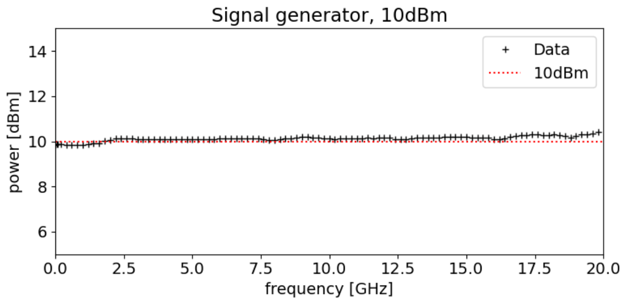
Transmission Ratio Measurement

- **Cable ABW Measurement**
  - Tr. Ratio (S21, **VNA**)
  - Spec. was 26.5 GHz but obtained 19.5 GHz as -3 dB level



- **Scope ABW Measurement (16 GHz-ABW, 2 TS/s EQ)**
  - Tr. Ratio -> Gain (By well calibrated signal generator, we scanned frequency, and we measured voltage level at the digitizer)





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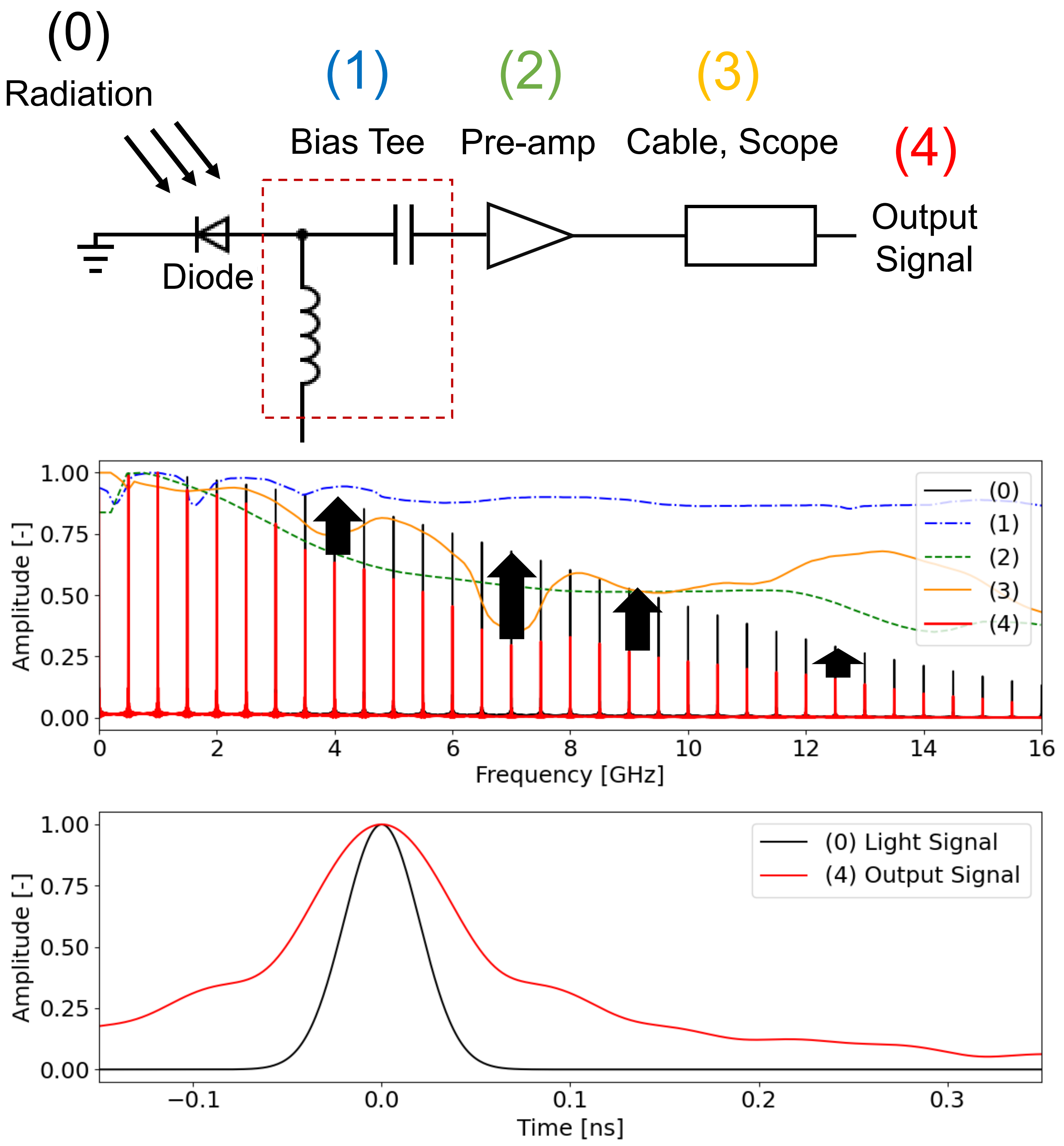
Numerical Compensation



1. Calculate the overall frequency response map R by convolution of all real frequency response maps

$$R(\omega) = R_1(\omega) \cdot R_2(\omega) \cdot R_3(\omega) \cdot R_4(\omega)$$

2. Measurement data was Fourier-transformed, And recovered by R

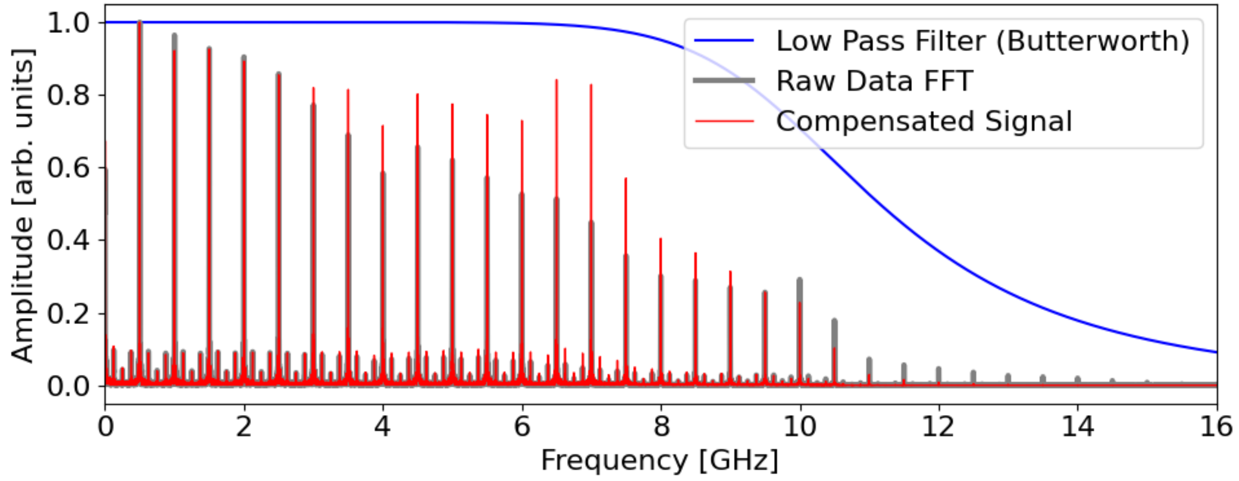
$$h'(t) = \boldsymbol{F}^{-1}\left[\frac{\boldsymbol{F}[\,h(t)]}{R(\omega)}\right] \qquad \boldsymbol{F} : FFT \quad \boldsymbol{F}^{-1} : iFFT$$

Loop over

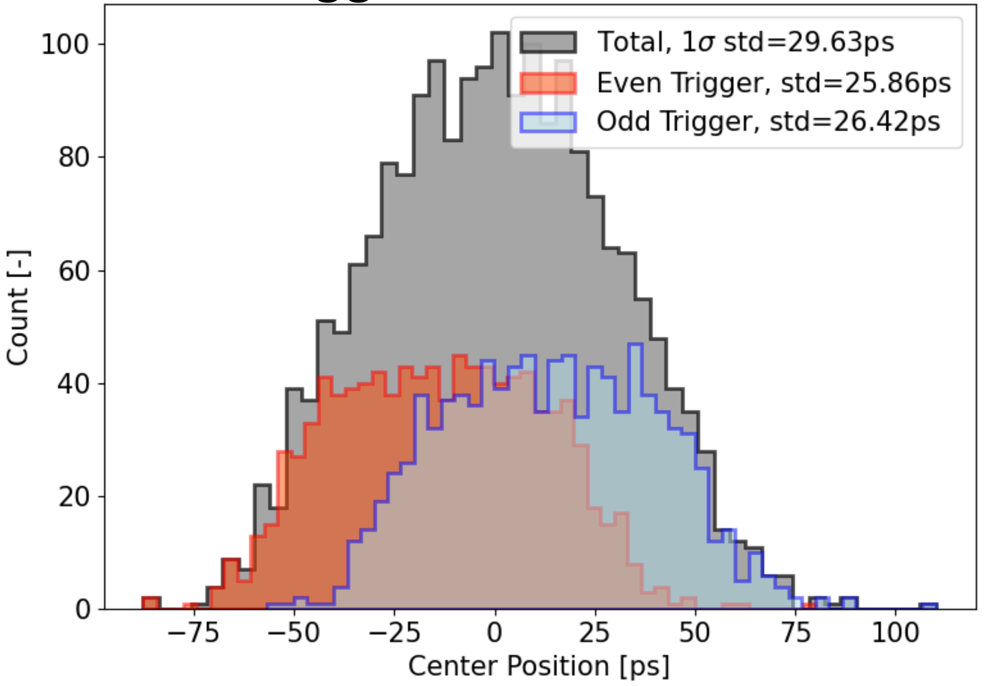
3. To find the bunch length, calculate Gaussian fit, FWHM or whatever

	Numerical Compensation
Pros	• Still fast • Accurate
Cons	• Frequency response can be changed according to circumstance. (ex. Temp, Connection …)

Numerical Compensation (in detail)



Rev. Trigger Jitter Measurement



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1.1 Accumulate data to reduce error caused by revolution trigger jitter (Typically 30-120 seconds using the Picoscope9400. We are currently using Tektronix DPO71304SX which is independent from the Rev. trigger jitter)

1.5. Apply low pass filter G (Butterworth, -3 dB at 16 GHz), to remove HF noise

2. Measurement data was Fourier-transformed, And recovered by R

$$h'(t) = \boldsymbol{F}^{-1}\left[\frac{\boldsymbol{G}(\omega)\boldsymbol{F}[\,h(t)]}{R(\omega)}\right] \qquad \boldsymbol{F} : FFT \quad \boldsymbol{F}^{-1}: iFFT$$

2.5 Partitioning data-points into every RF bucket and converting time to phase

3. To find the bunch length, perform Gaussian fit

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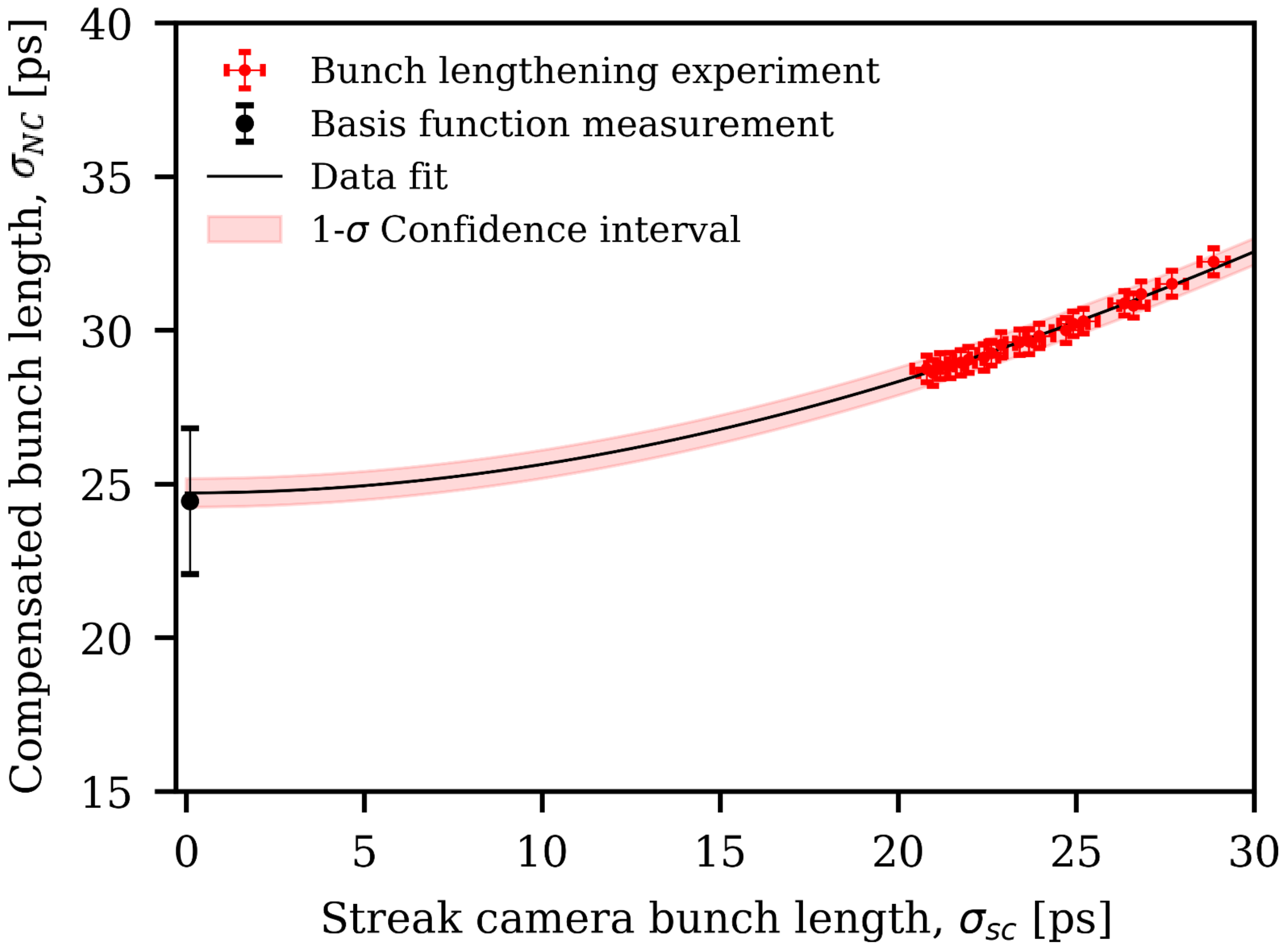
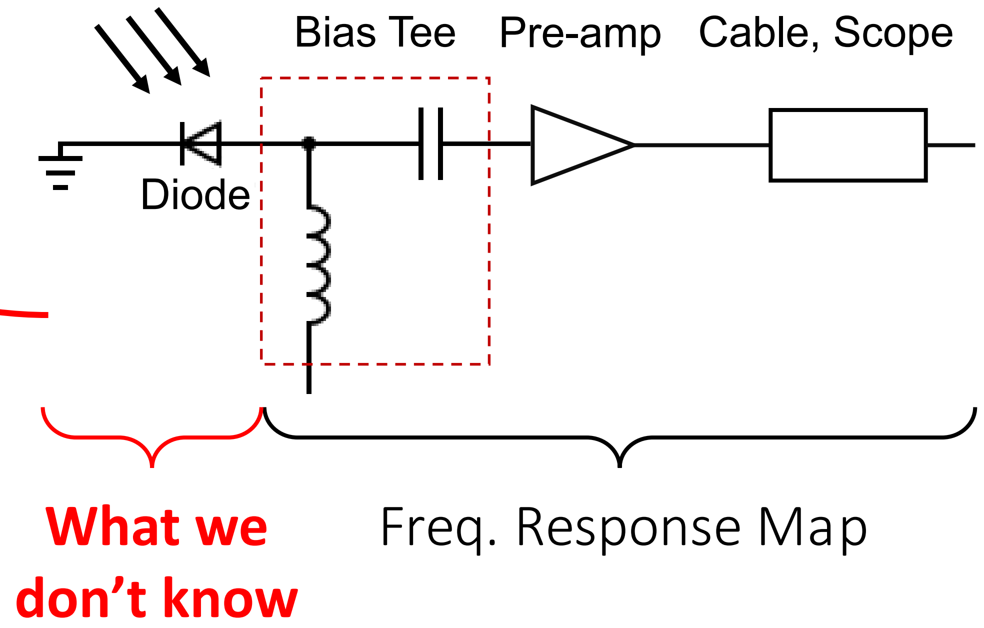
Bunch Lengthening Experiment

$$\sigma_{NC} = \sqrt{\sigma_{SC}^2 + A^2} + B$$





- The numerical compensation method lacks completeness since we don't know a Freq. response of the photodiode.
- However, in contrast to AGD, slope of quadratic curve was well matched.
- The extrapolated quadratic curve (Y interception point) is consistent with the laser experiment.
- Not perfect, but it is still a good method to provide longitudinal information in the operation range.

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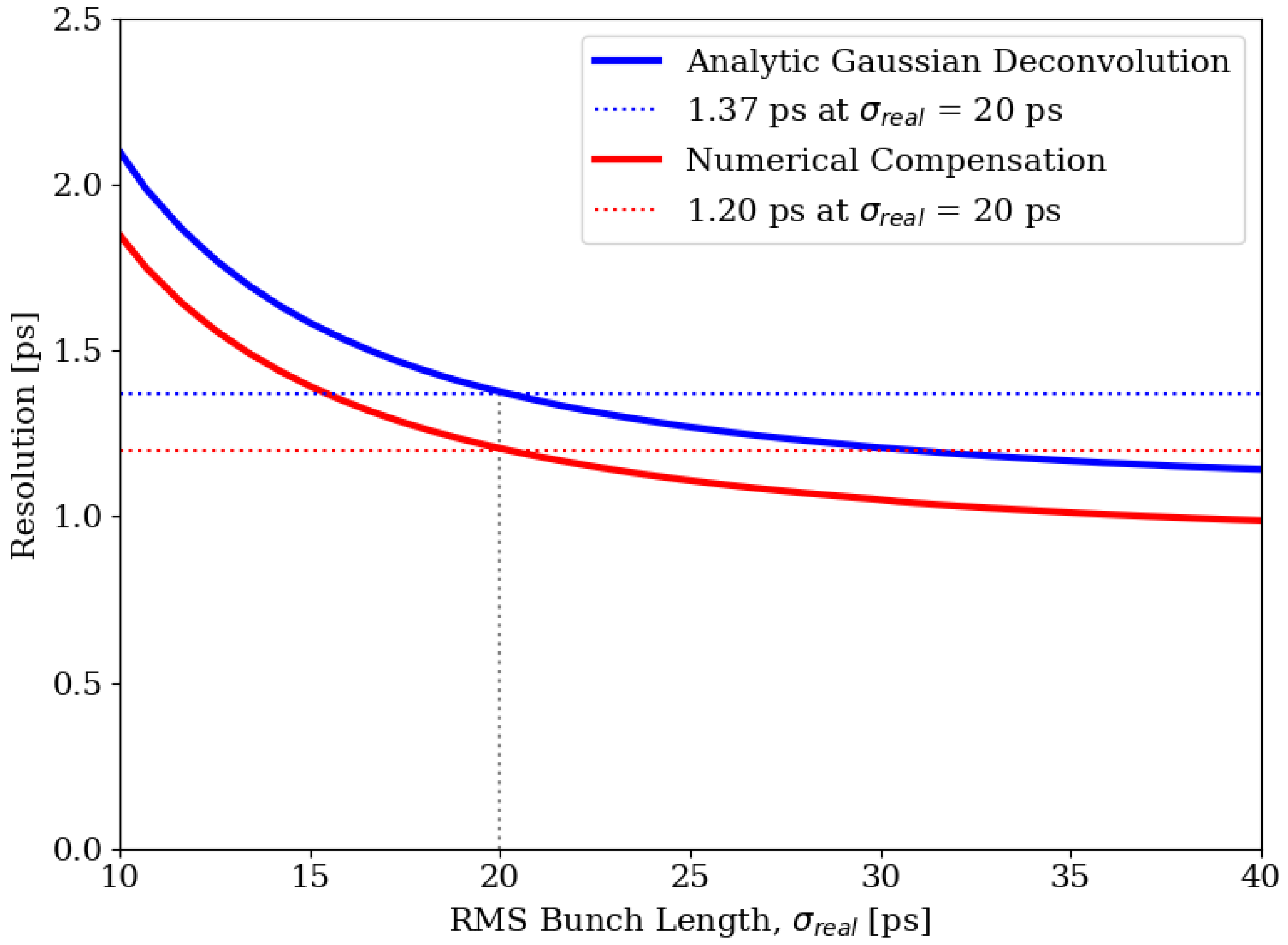
Statically Estimated Resolution, by Monte Carlo Study



1. Artificially generate time domain signals $h_{MC}(t, \sigma_0)$

$$h_{MC}(t,\sigma_0) = h_{PSF,PD}(t)_{\sigma_0=0} * h_{IGB}(t,\sigma_0) * h_{BW}(t) + h_{MC\ NOISE}(t,\sigma_0)$$

$h_{PSF,PD}|_{\sigma=0}(t)$: Point spread function (Gaussian profile $\sigma = 25.68$ ps)
$h_{IGB}(t,\sigma_0)$: Ideal bunch-train profile
$h_{BW}(t)$: Overall frequency response (PD, Amp, cable & digitizer)
$h_{MC\ NOISE}(t,\sigma_0)$: Digitizer noise (random error based on technical note)

2. Calculate bunch length using both methods

$\sigma_{AGD} \pm \sigma_{AGD\ fit\ error}$ $\quad$ $\sigma_{NC} \pm \sigma_{NC\ fit\ error}$

3. Definition of systematic error

$$\sigma_{sys\ err} = \sqrt{\left(\frac{\sigma_{trigger\ jitter}}{N_{\#\ of\ meas}}\right)^2 + \sigma_{fit\ error}^2}$$

$\sigma_{trigger\ jitter} = 30\ ps,\ \ N_{\#\ of\ meas} = 500,\ \ \sigma_{fit\ error} = \sigma_{AGD\ fit\ error}\ ||\ \sigma_{NC\ fit\ error}$

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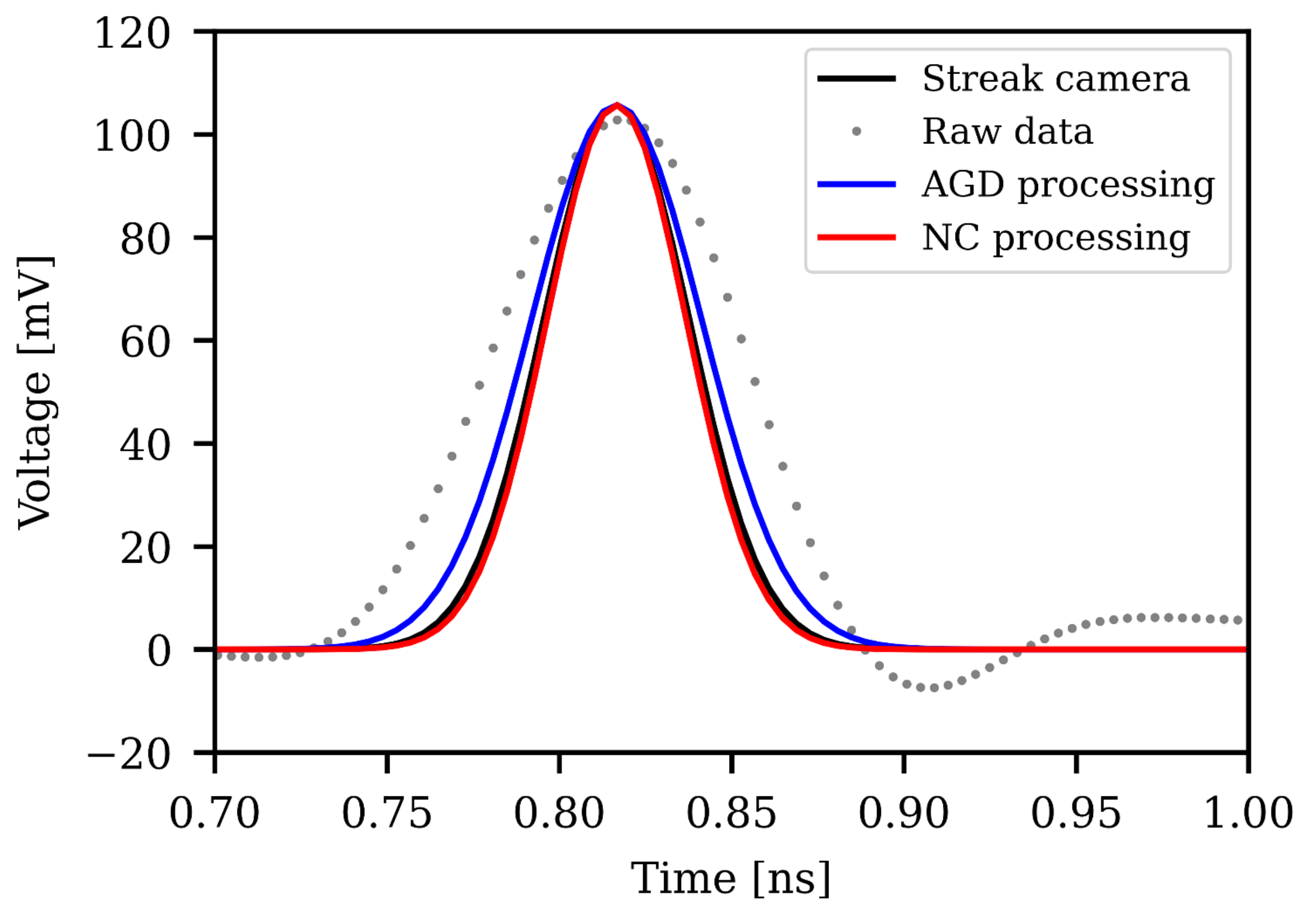
Discussion



- The NC results are closest to the ideal curve, despite the absence of the photo-diode's frequency response
- BUT still we could not understand why the fit form looks like below

$$\sigma_{NC} = \sqrt{\sigma_{SC}^2 + A^2} + B$$

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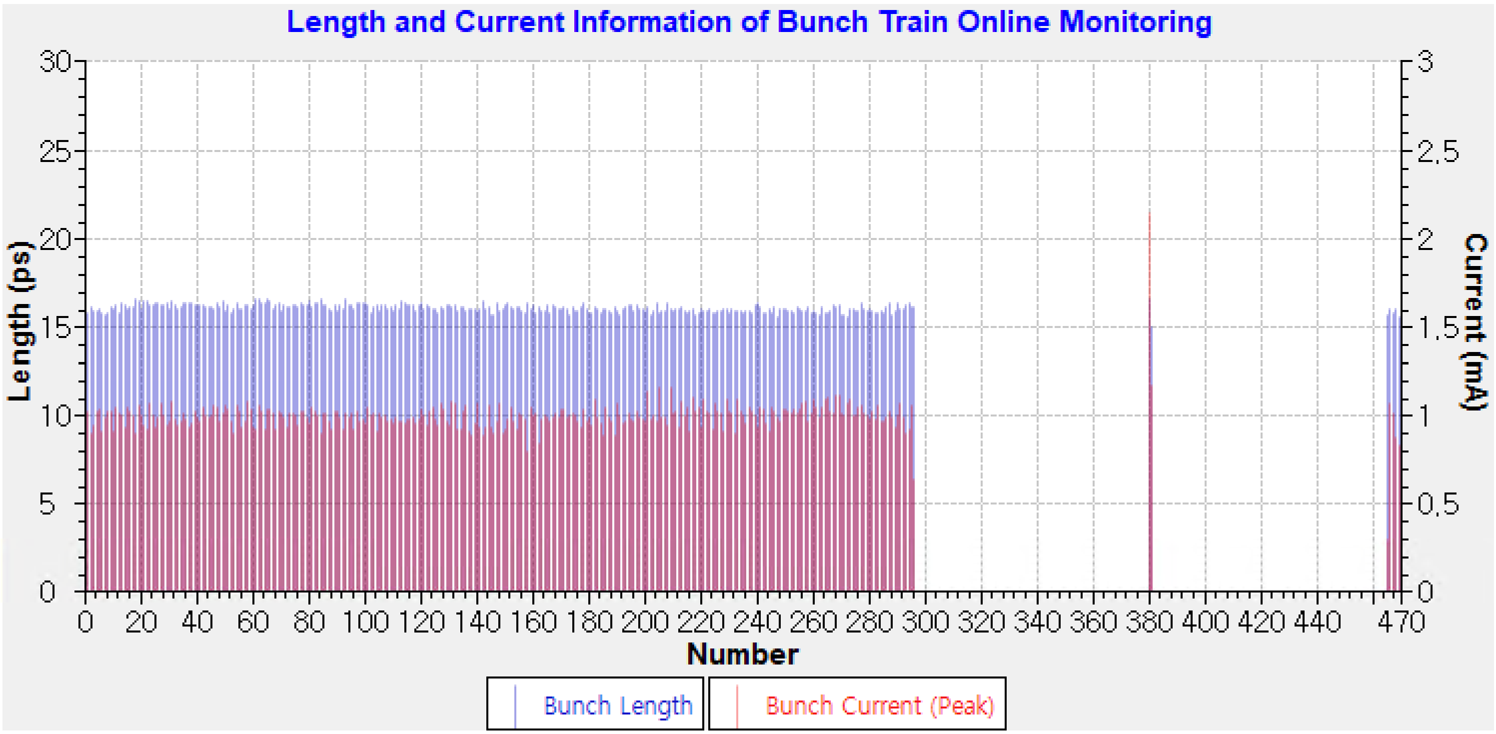
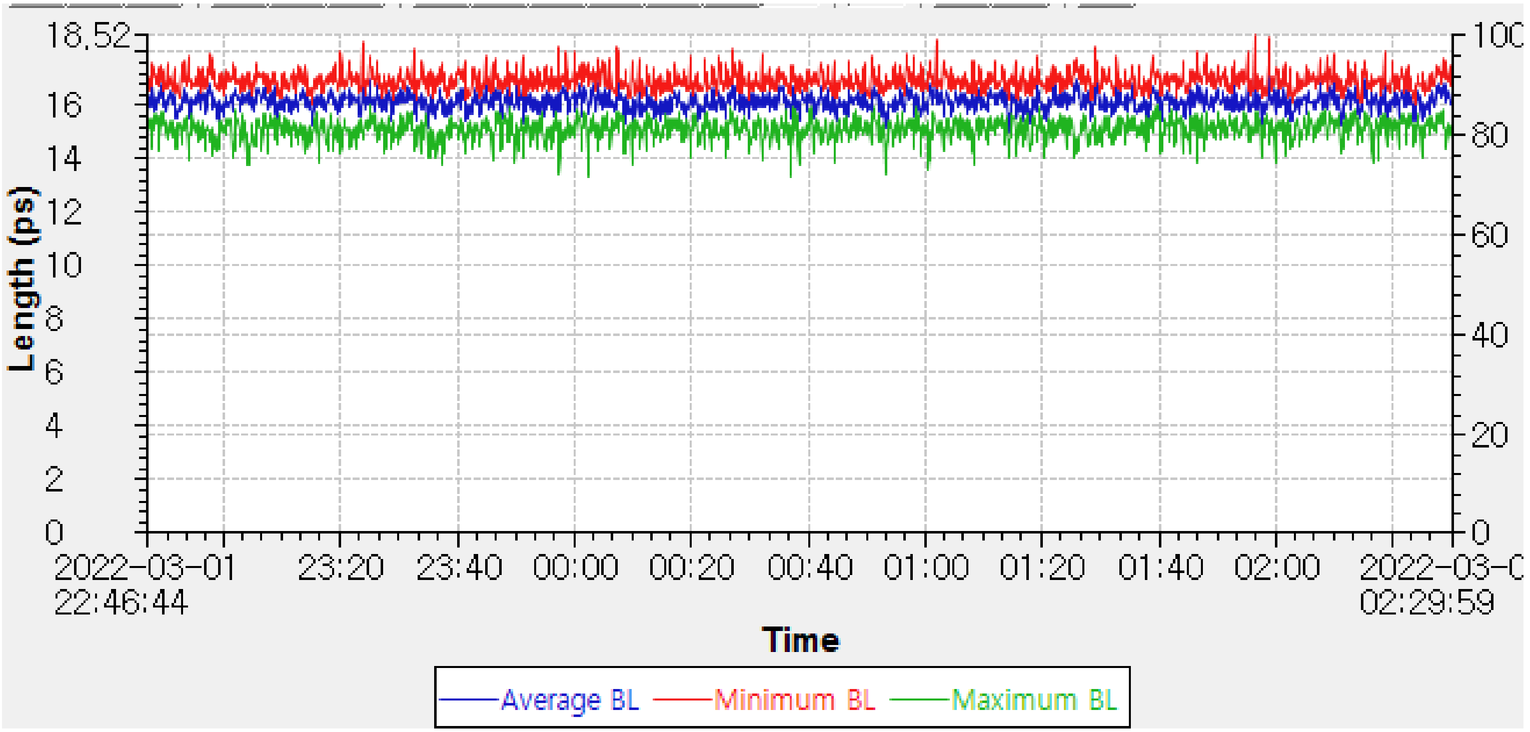
Current Status

We are monitoring bunch length online



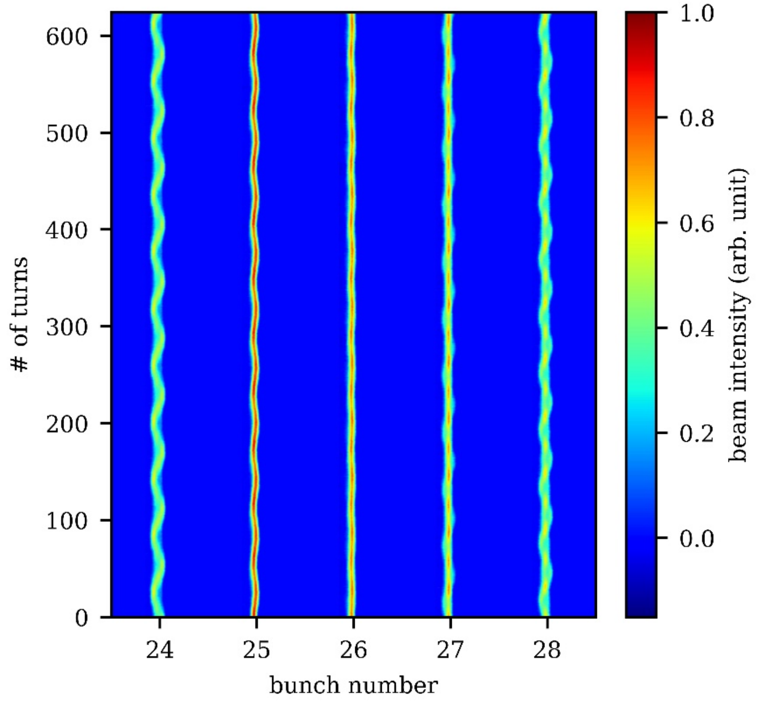


Old system (with Picoscope-9404-16, Pico Technology):

- Data acquisition time : 30 ~ 120 seconds for statistically mitigating the error mainly due to the revolution trigger jitter of 30 ps and vertical noise of the scope.

New system (with DPO71304SX, Tektronix):

- Real time data acquisition : PV updating rate is about 0.1 ~ 1.0 Hz (mostly data transferring time)
- Trigger jitter free (non-averaged)



Summary

- We have experimentally demonstrated a compact monitor that enables filling pattern (~ 3 μA resolution) and bunch length (~ 1 ps resolution) monitoring with visible light at the PLS-II storage ring
- Both analytical Gaussian deconvolution and numerical compensation methods were investigated to improve measurement accuracy

  → We achieved better resolution with numerical compensation method
- Recently we installed a new digitizer for online Turn-by-turn and Bunch-by-bunch measurements are under contemplation as a future upgrade project.

Thank you for your attention

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