POHANG ACCELERATOR LABORATORY

Online bunch-by-bunch length monitoring using Synchrotron Radiation

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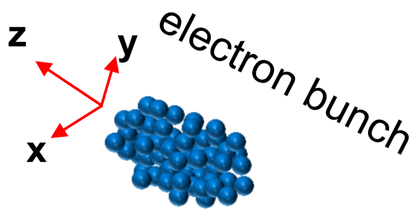
Longitudinal Beam Diagnostics

Conserved quantity in accelerators

1. Charge represents the number of electrons in a bunch (= Bunch charge/current).

Real space



U(1) gauge transformation
symmetry of electromagnetism

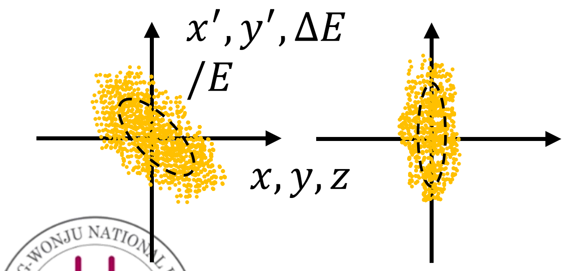
$$[Q,H] = 0$$

where H is the Hamiltonian and
Q represents the charge.

→ Bunch charge / fill pattern

2. Emittance is an area of the particles in th e phase-space (Liouville's theorem).

Phase space

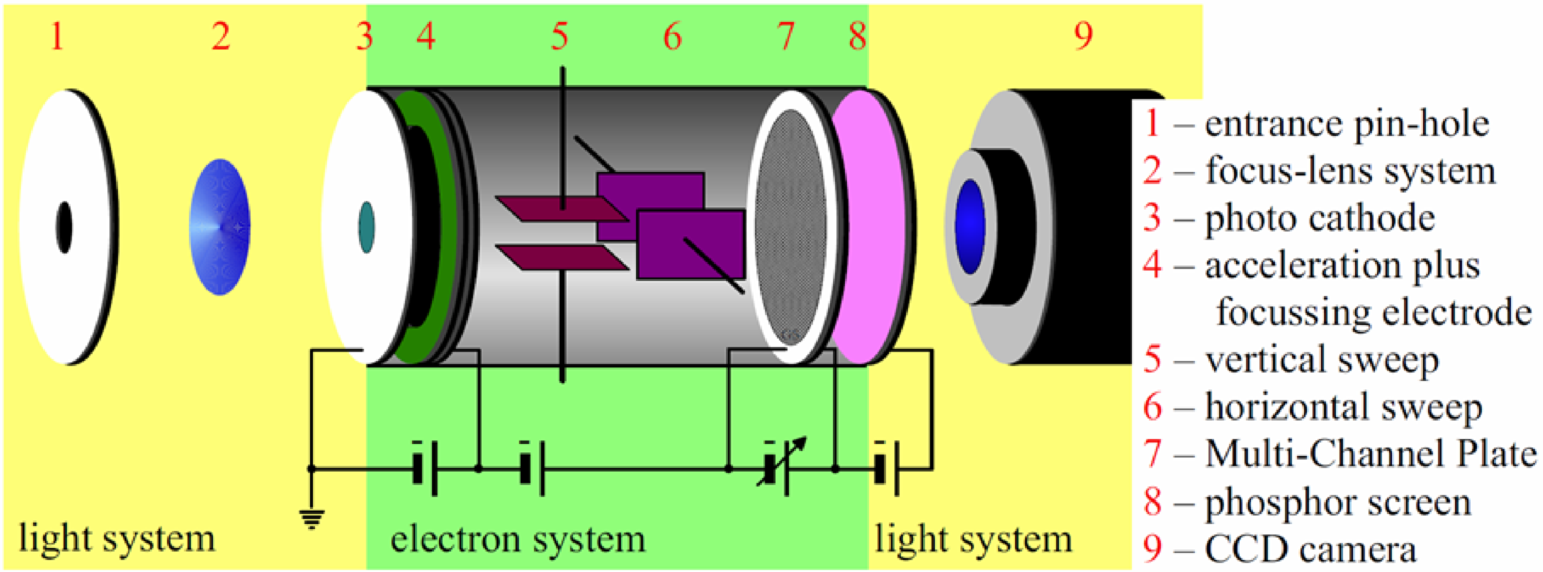


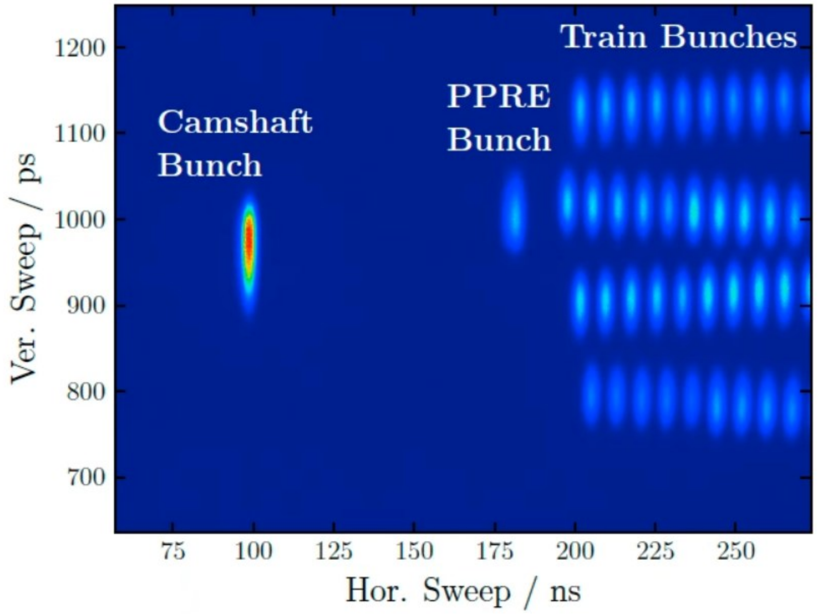
Hamiltonian system:
1) no velocity dependent forces
2) no individual forces on particles
3) no (or very slow) time dependance, $\partial H / \partial t = 0$

$$Area = \varepsilon_{(x,y,z),e-} = const.$$

→ Distribution in real space

Streak camera: common longitudinal diagnostics

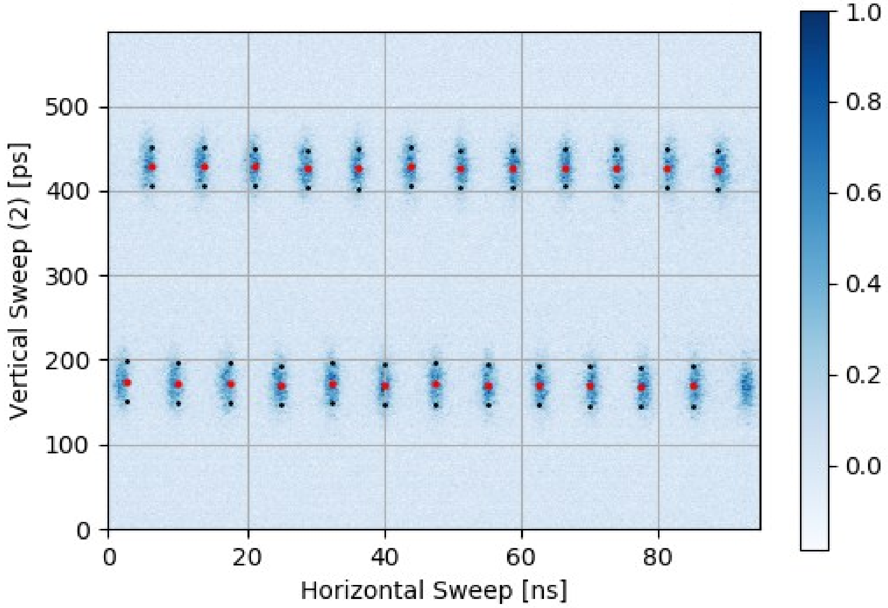




BESSY II VIS beamline

Longitudinal Beam Diagnostics

Bunch Length



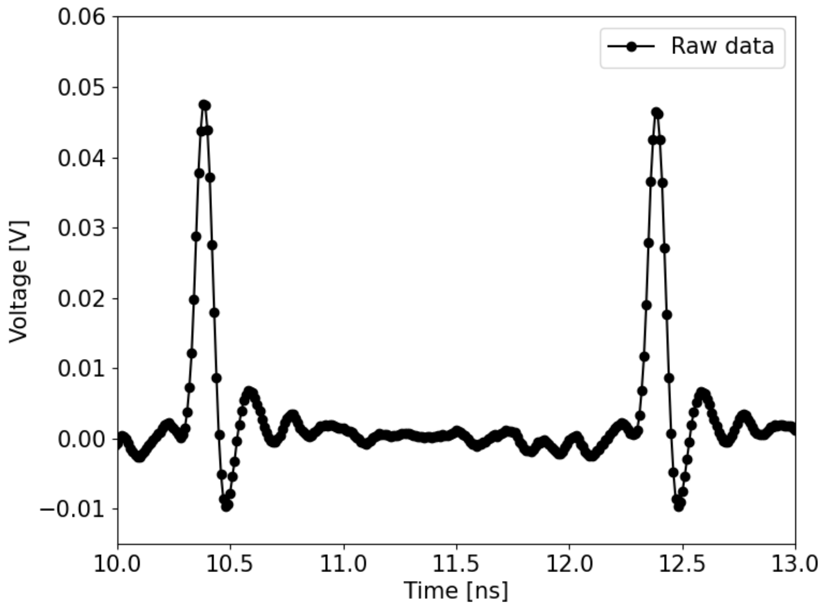
Streak Camera

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

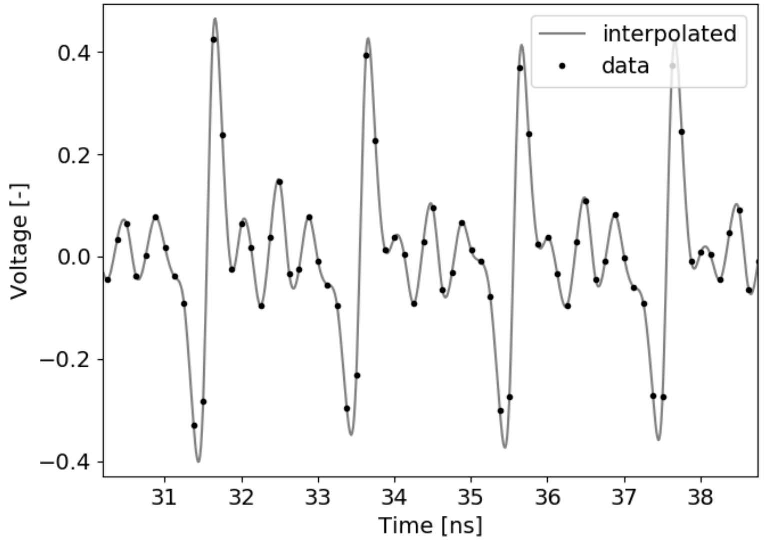
Bunch Length + Fill-Pattern

Fast Photodiode

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



Fill-Pattern



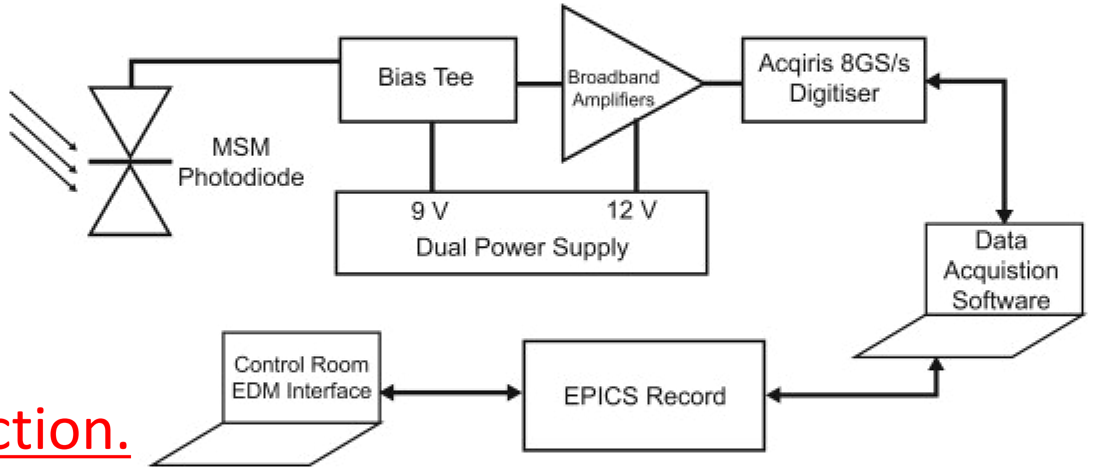
BPM pick-up / FCT

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

Previous studies

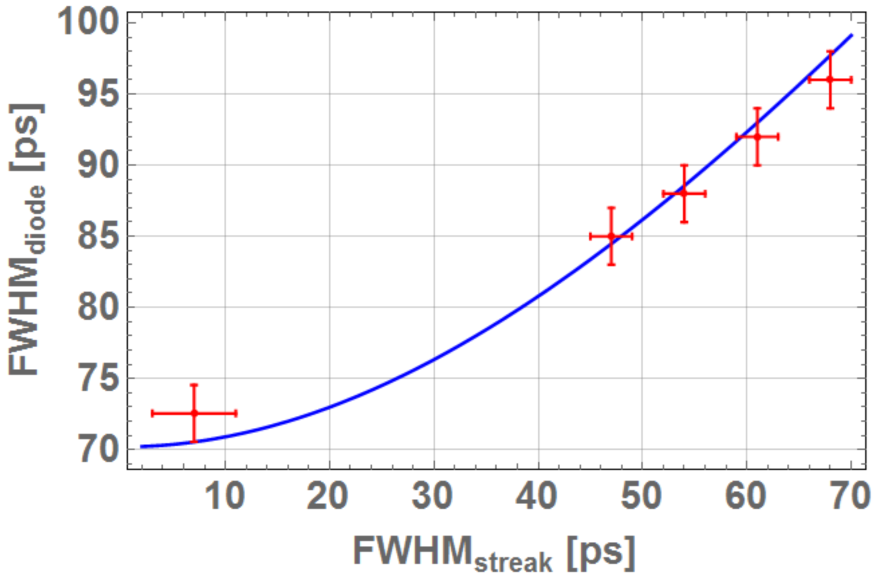
- **Australian Synchrotron [1]**
  - Successful online fill-pattern measurement
  - We could not find Analogue BandWidth (ABW) information of bias tee, digitizer, and cables.

  → We use a similar experimental setup
  BUT chose all device's ABW near 15 GHz for bunch length detection.



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

  → We developed a new and online analysis method
  to handle the 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)

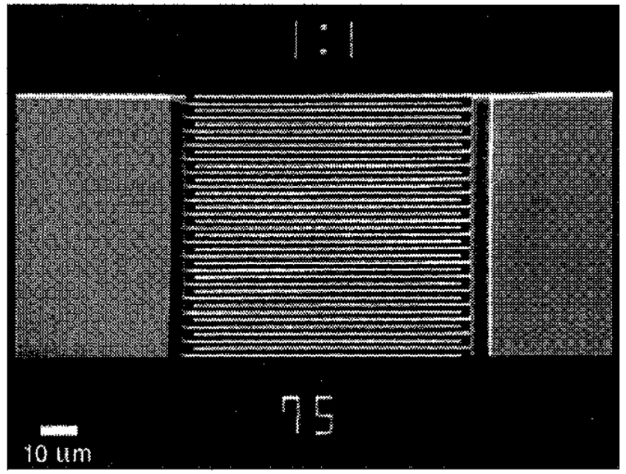
[2] J. Hwang, Bunch length measurement by using a fast photodiode, Private Discussion, (2019)

MSM Photodiode

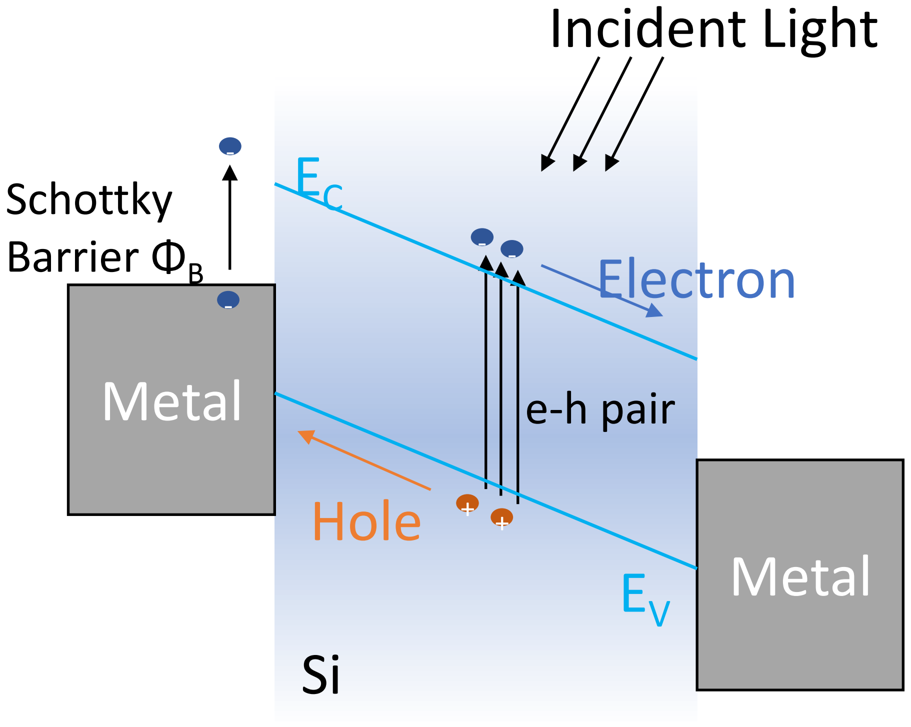
- Metal-Semiconductor-Metal Photodiode
  - Metal-semiconductor Junction

  → 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.

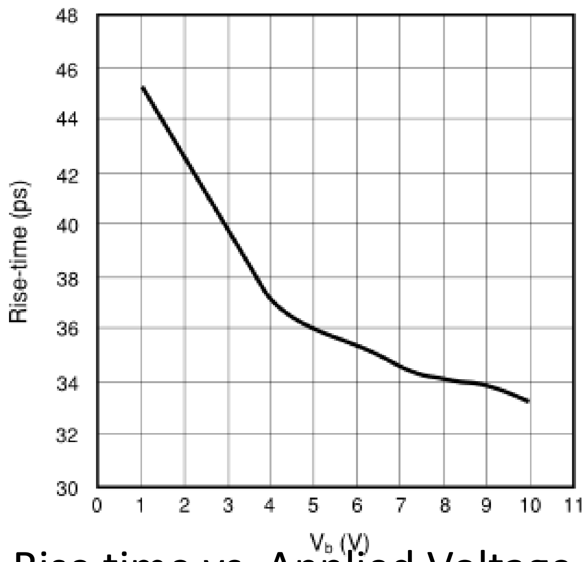


P. R. Berger, 1996

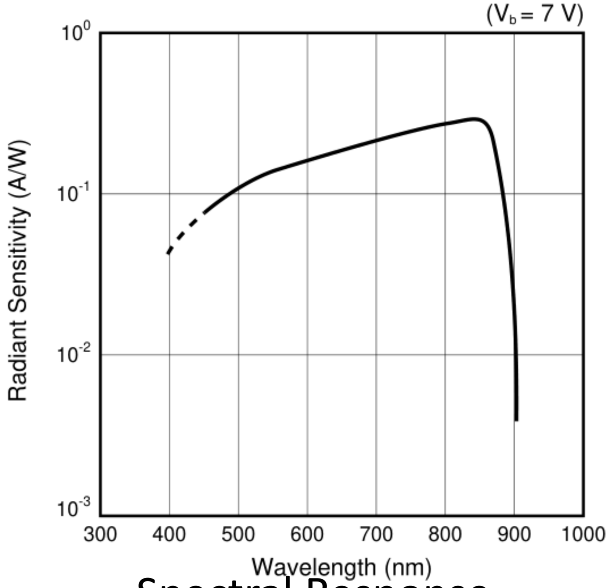


- Hamamatsu G4176-03

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

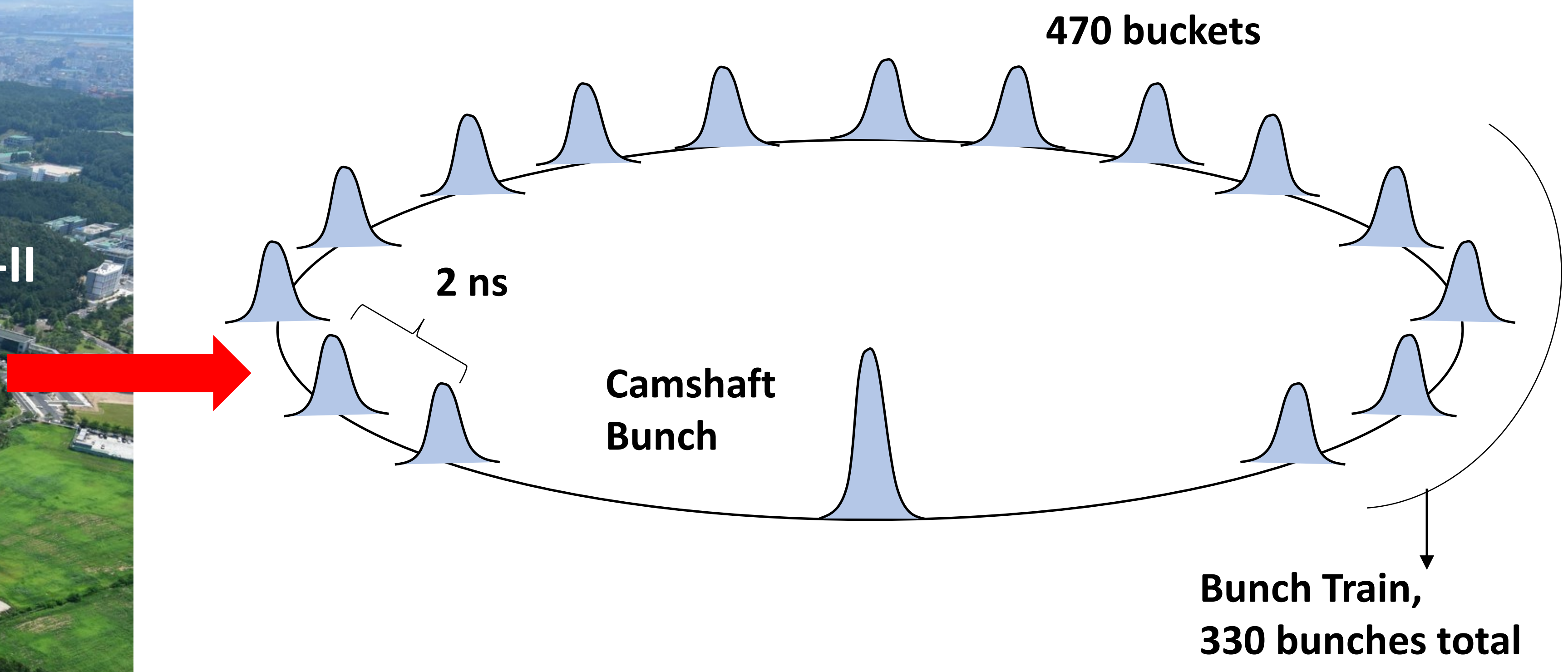


Rise time vs. Applied Voltage



Spectral Response

PLS-II @ Pohang Accelerator Laboratory



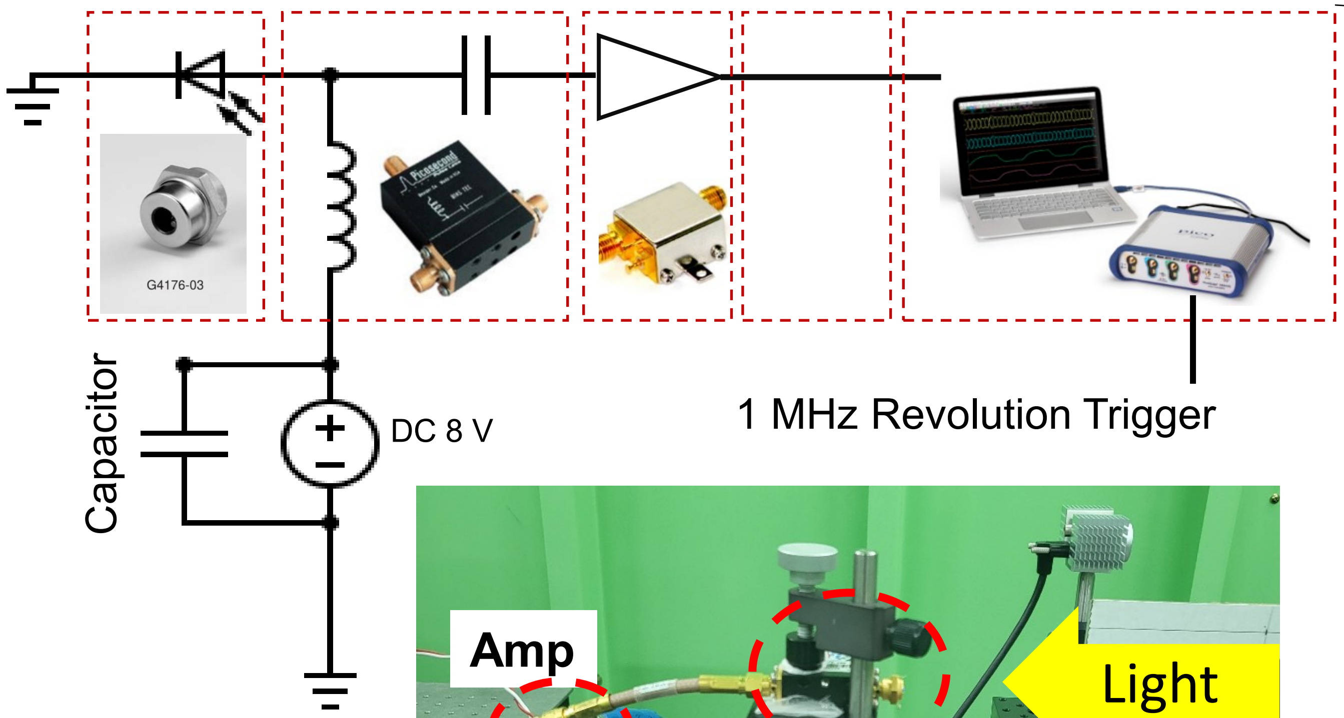
PLS-II Parameter	Value	Unit
Beam Energy	3	GeV
Beam Current	400	mA
Circumference	281.82	m
RF Frequency	499.97	MHz
RMS Bunch Length	21.3	ps

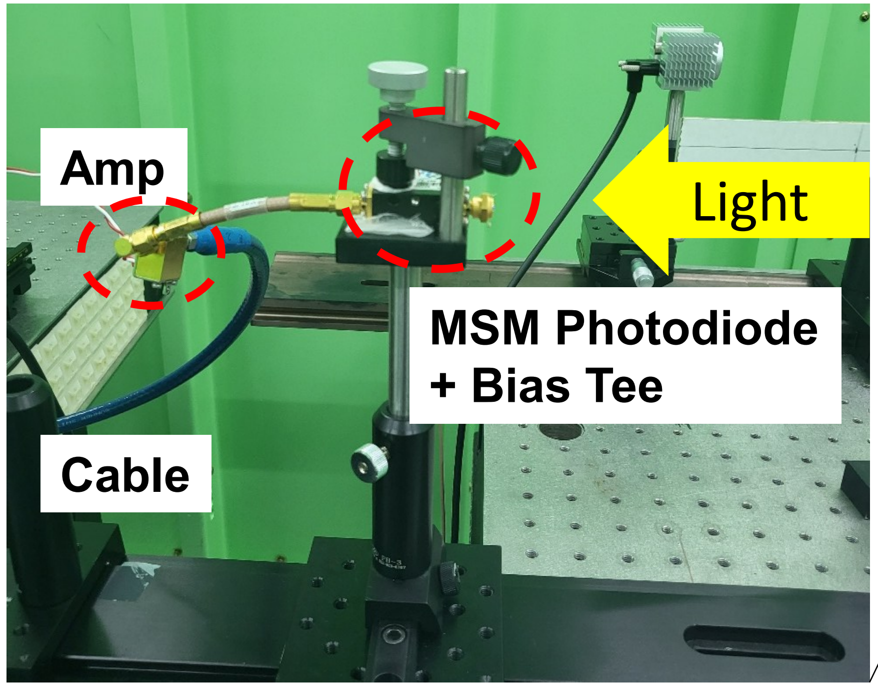
- PLS-II operates a hybrid filling pattern to support pump-probe experiments.
- Online information of bunch lengths and filling-pattern could be worth for users

Experimental Setup (1/2)

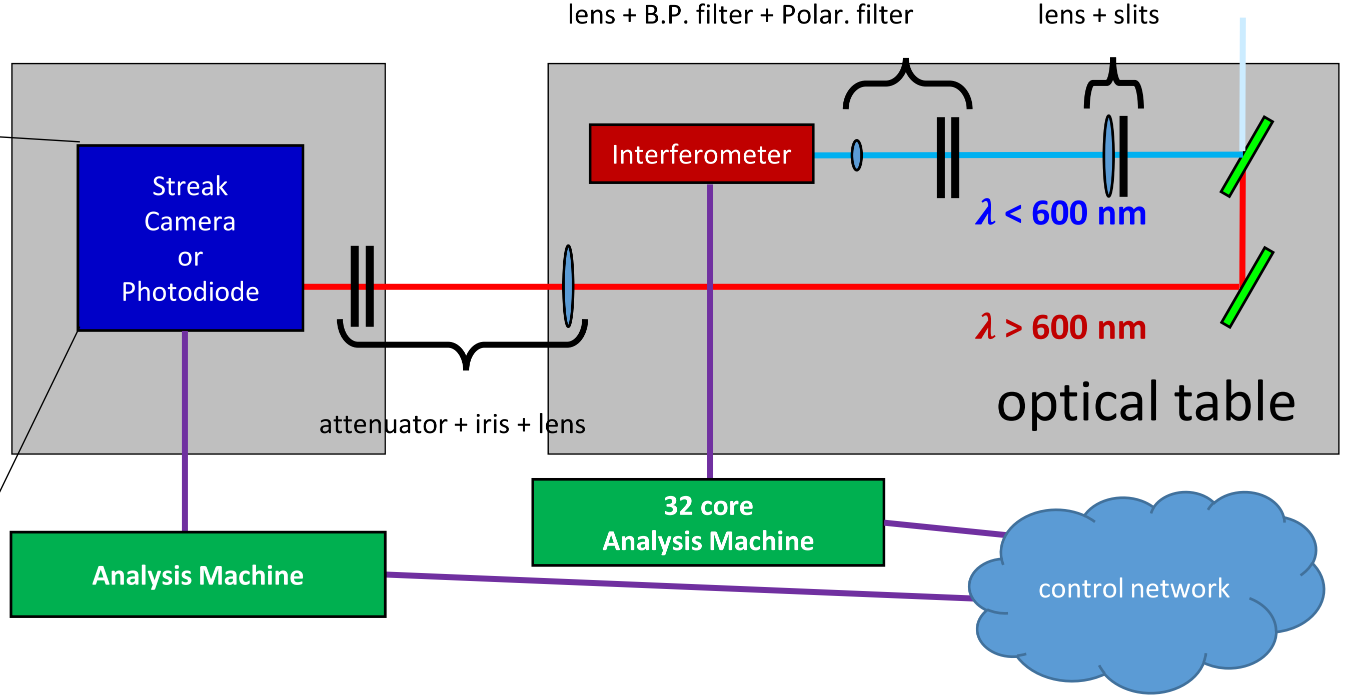
Visible part (600~900 nm λ) of synchrotron radiation –

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



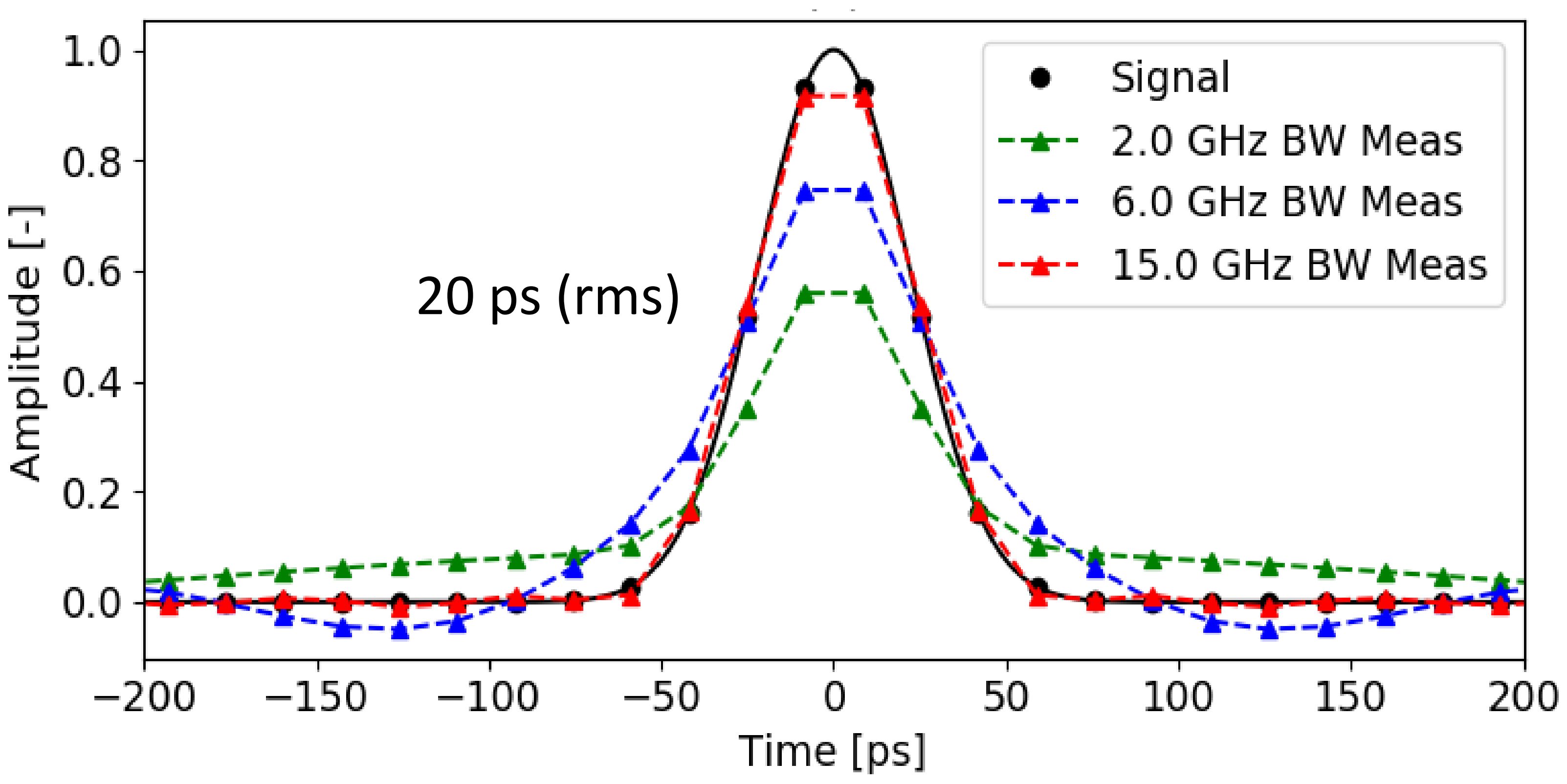


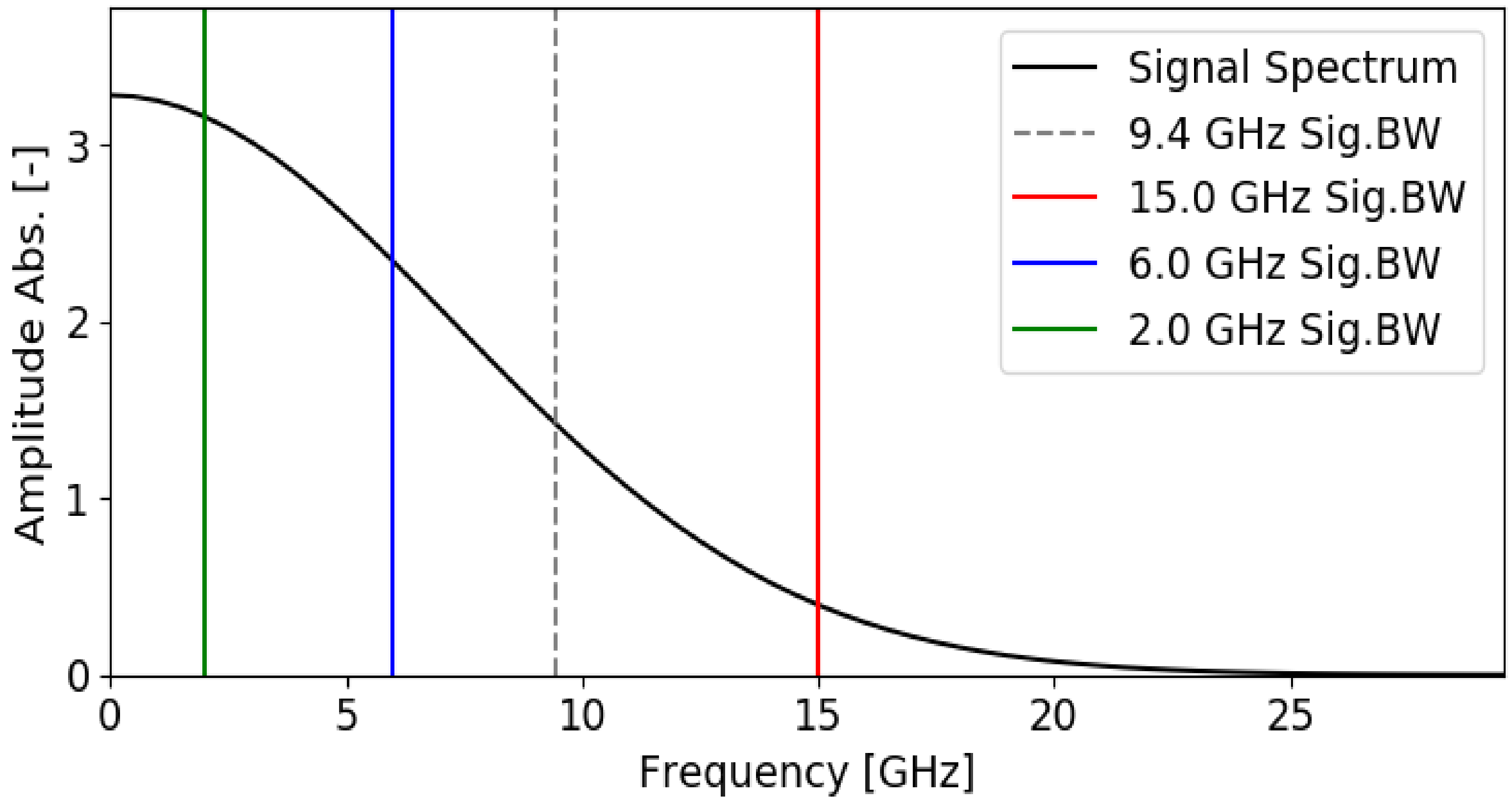
Visible Light Beam Diagnostic Hutch (BL1B)



- 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.

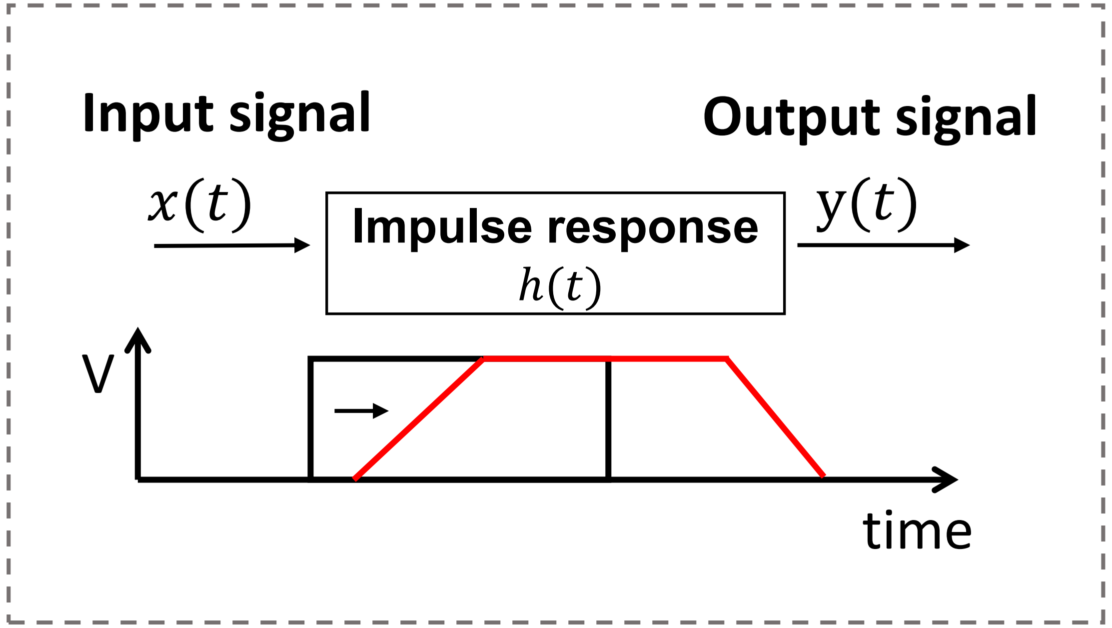
Experimental Setup (2/2)





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

Analytic Gaussian Deconvolution (AGD)



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

⇧

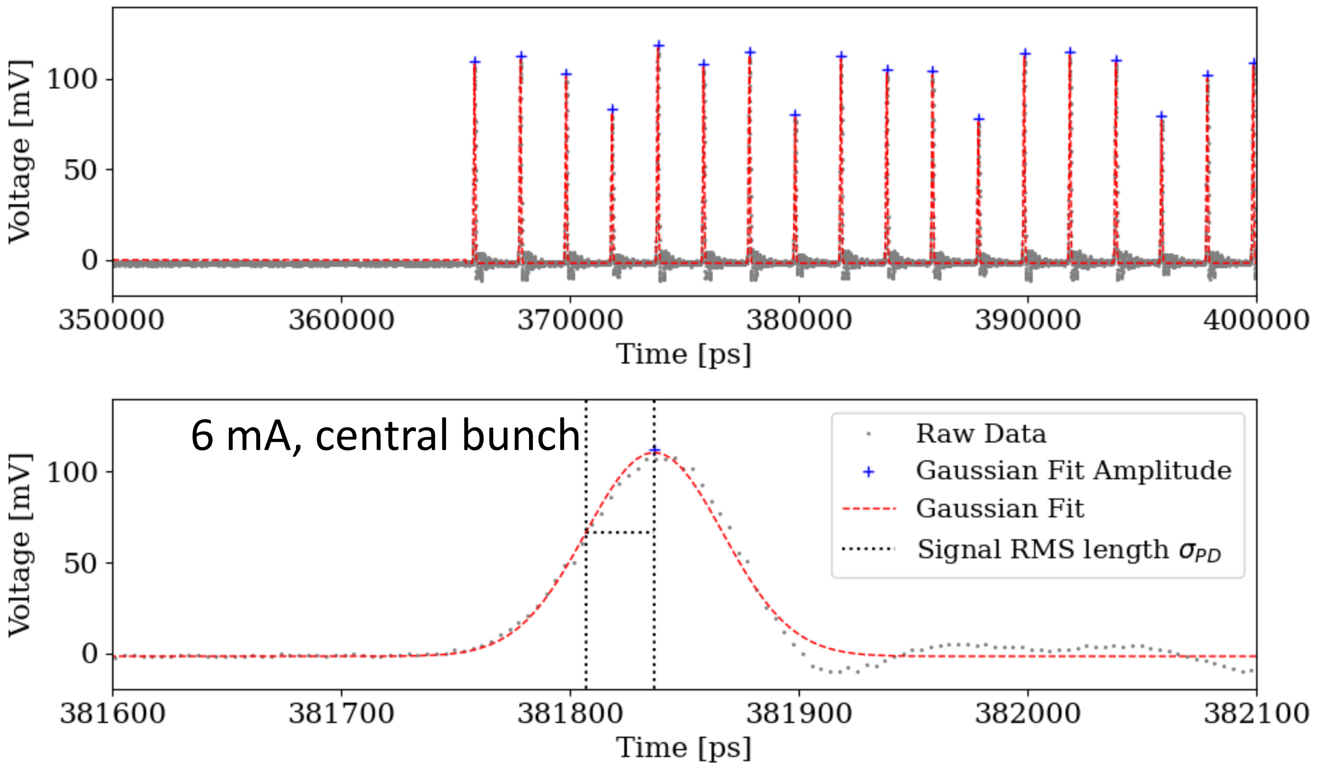
System response function
: $h_{sys} = h_{PD} * h_{bias\,T} * h_{amp} * \cdots$

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

- 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.

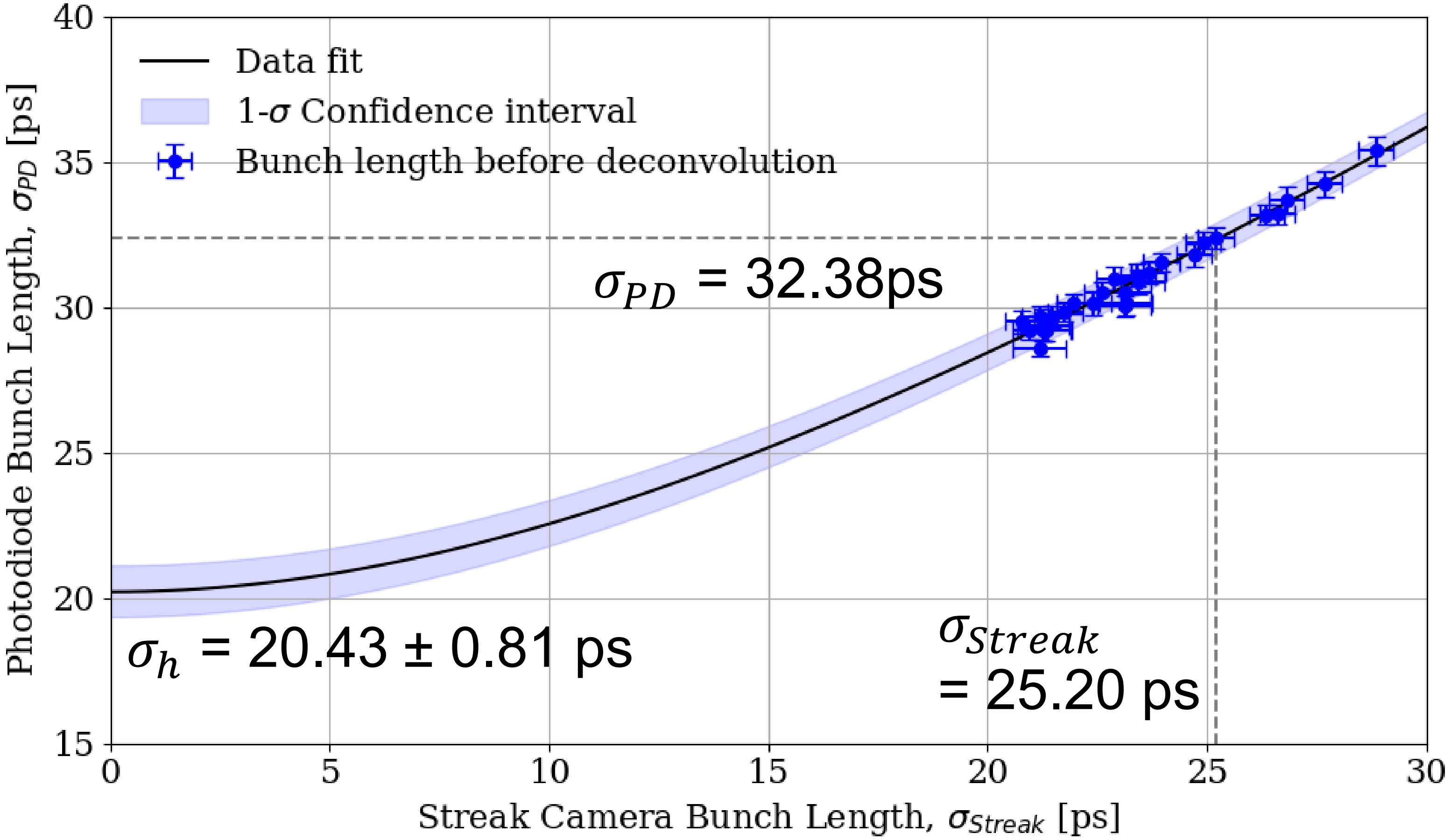
	Analytic Gaussian Deconvolution
Pros	• Practical • Fast
Cons	• Inaccuracy (Error with Gaussian assumption)

AGD Measurement Results



- 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?

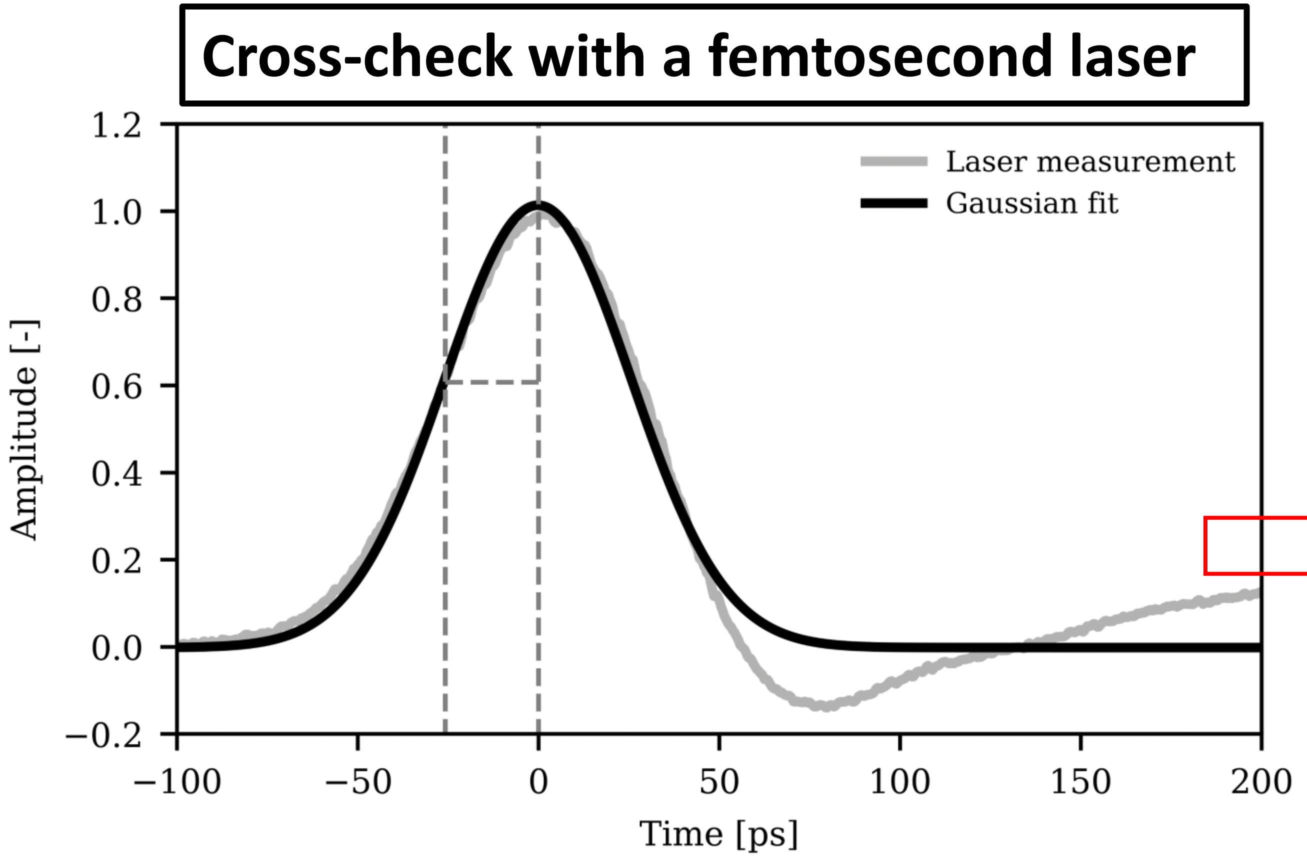
Bunch Length Measurement

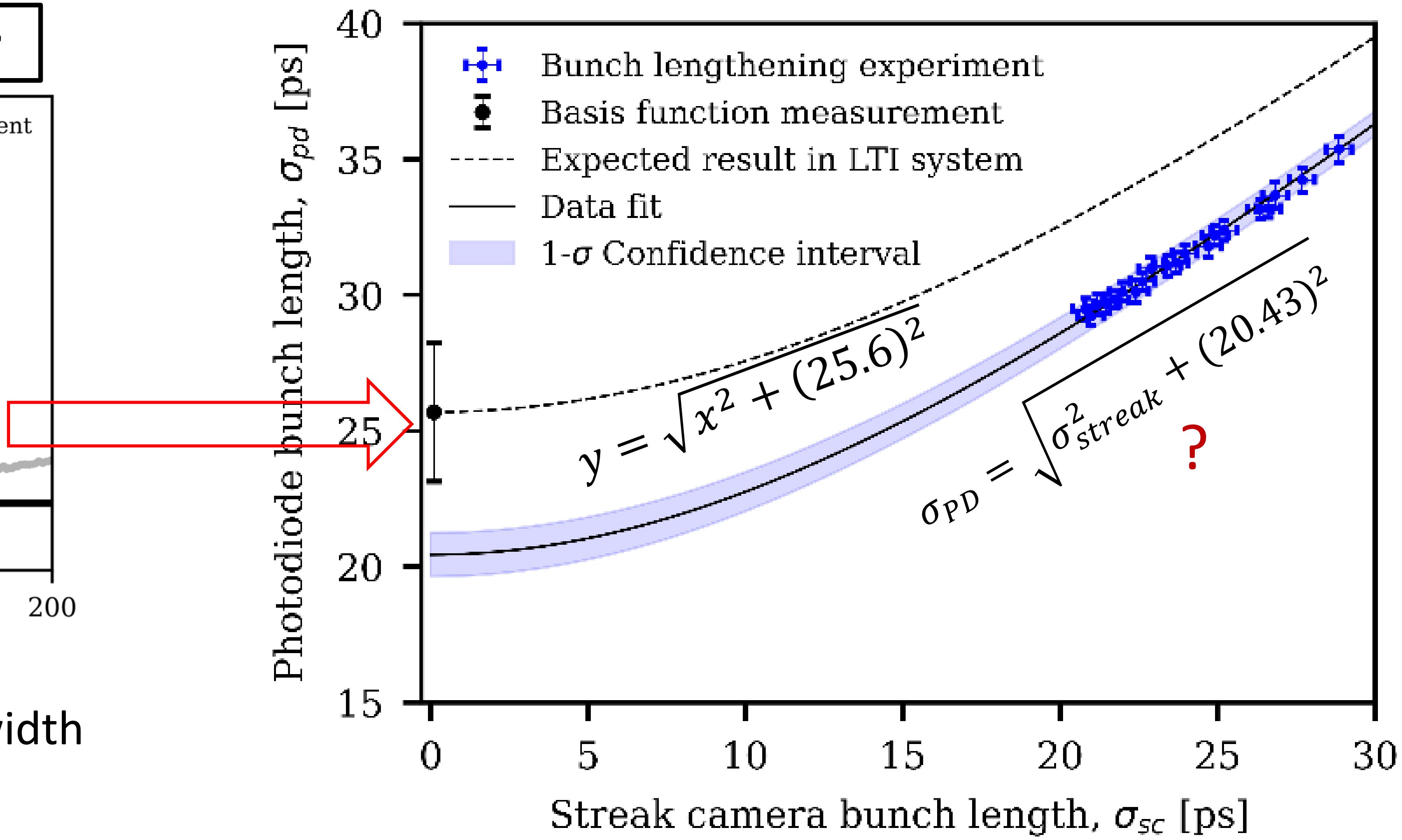


Fit form : $\sigma_{PD} = \sqrt{\sigma_{streak}^2 + A^2}$

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

AGD Processed PD Bunch Length

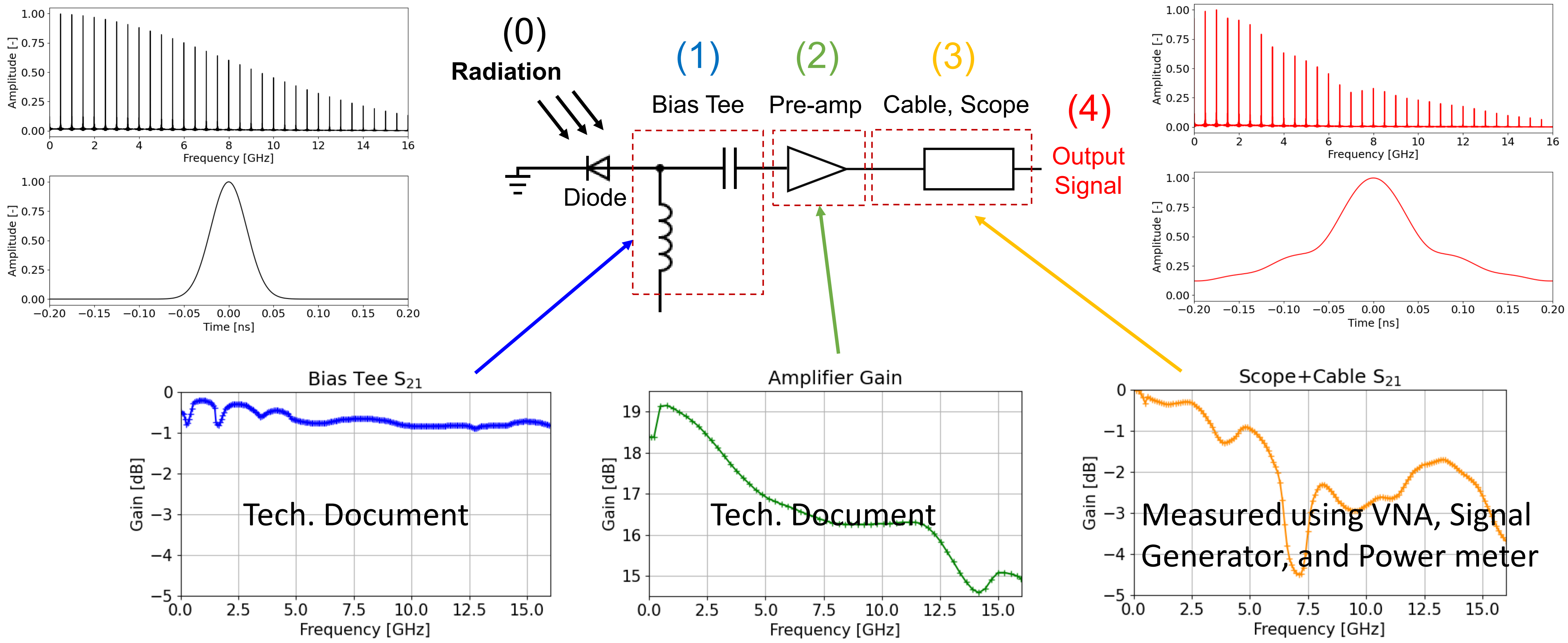




- The PSF was measured with a laser pulse width of ~ 200 fs, as a delta function.
- RMS PSF(Gaussian Fit) was obtained about 25.68 ± 2.56 ps which is way out of 1-sigma confidence interval.

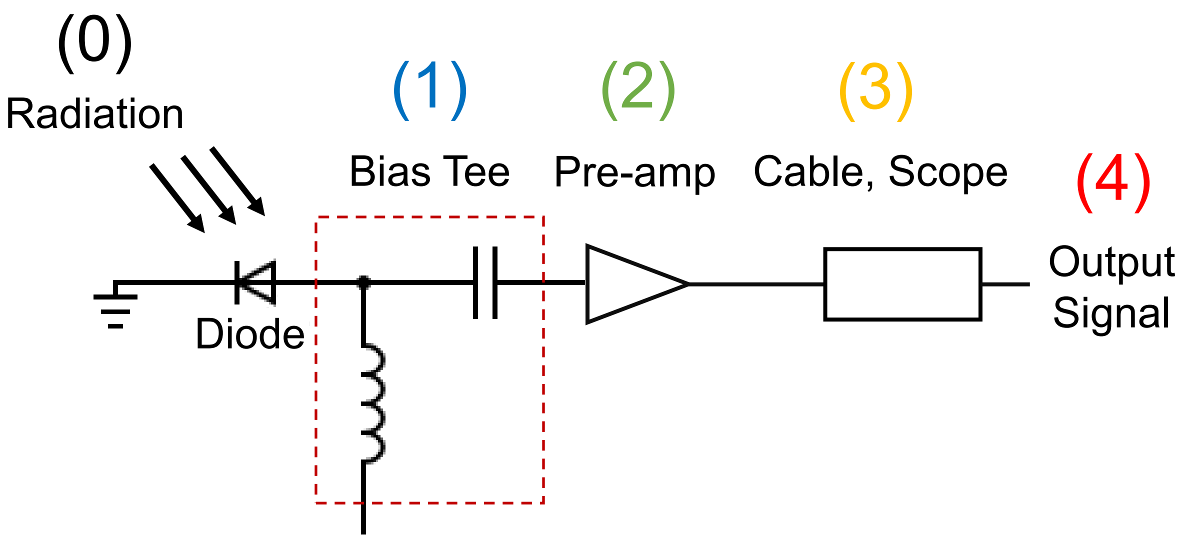
- AGD PSF is inconsistent with the measured response function !

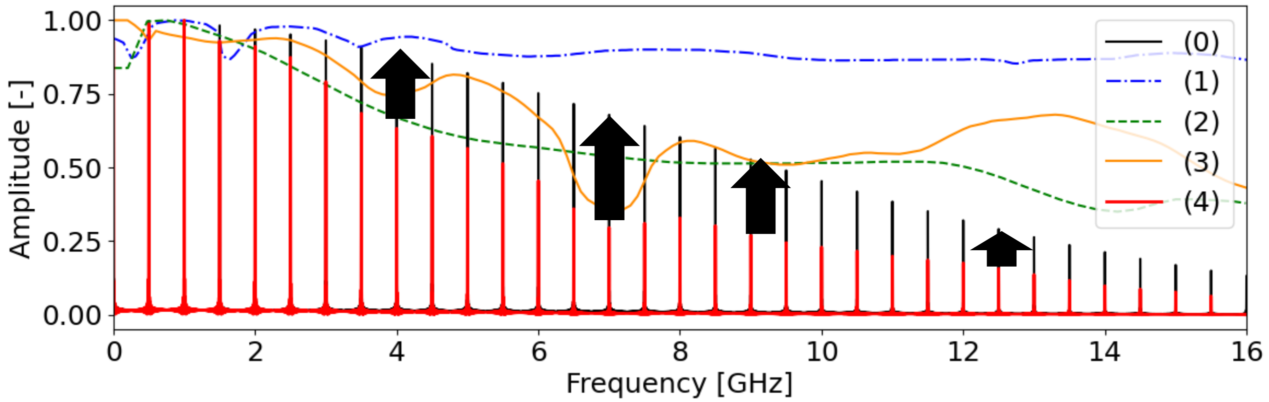
Numerical Compensation (NC)

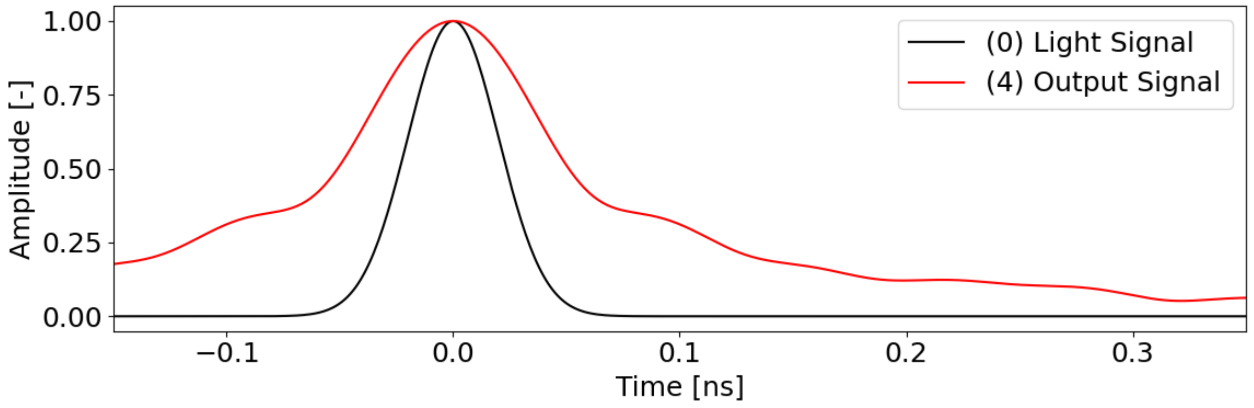


→ **The measured signal is distorted strongly by the frequency response of analog components.**

Numerical Compensation







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

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

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

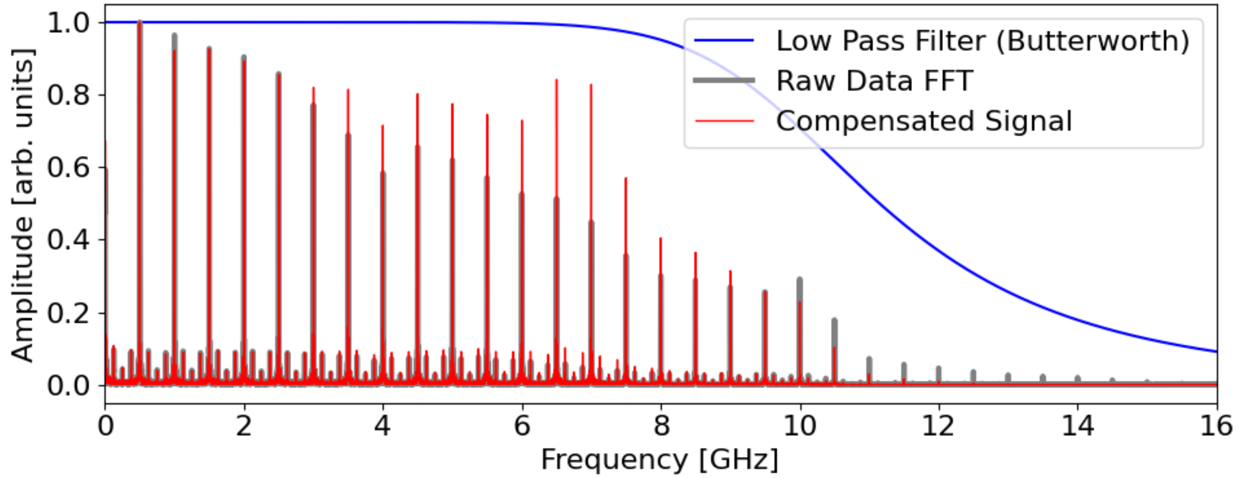
2. Measurement data was Fourier-transformed, And recovered by R

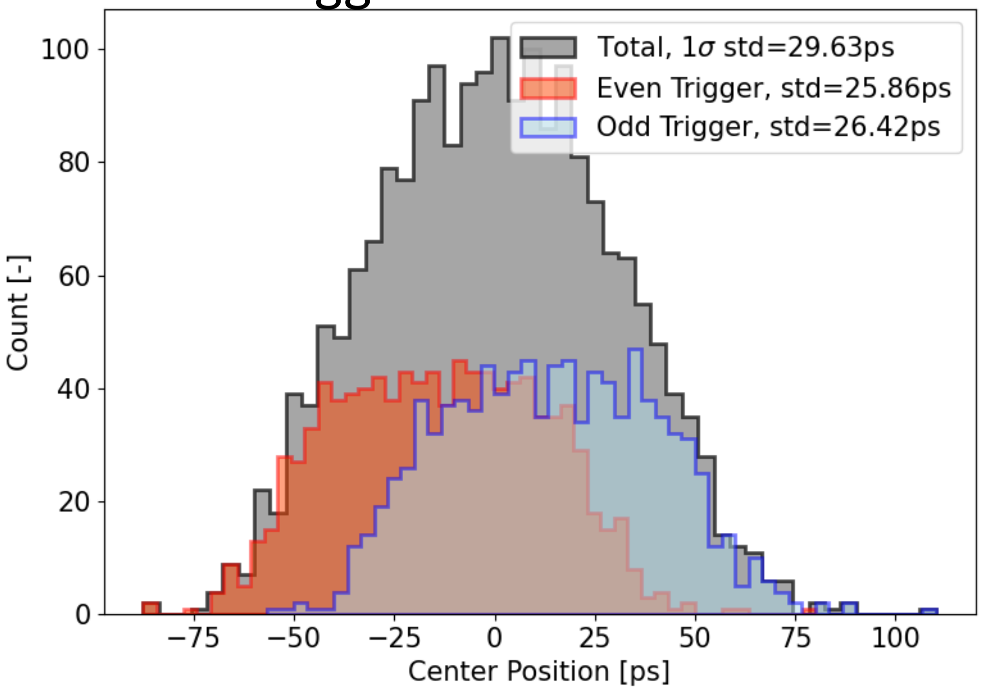
$$h'(t) = \boldsymbol{F}^{-1}\left[\frac{\boldsymbol{F}[\,h(t)]}{R(\omega)}\right] \qquad \begin{array}{l}\boldsymbol{F} : FFT \\ \boldsymbol{F}^{-1} : iFFT\end{array}$$

Loop over

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

Numerical Compensation (in detail)





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

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

1.1 Averaging data to reduce statistical error, caused by revolution trigger jitter. (~30-120 seconds using the Picoscope9400. We are currently using Tektronix DPO71304SX which is independent to 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

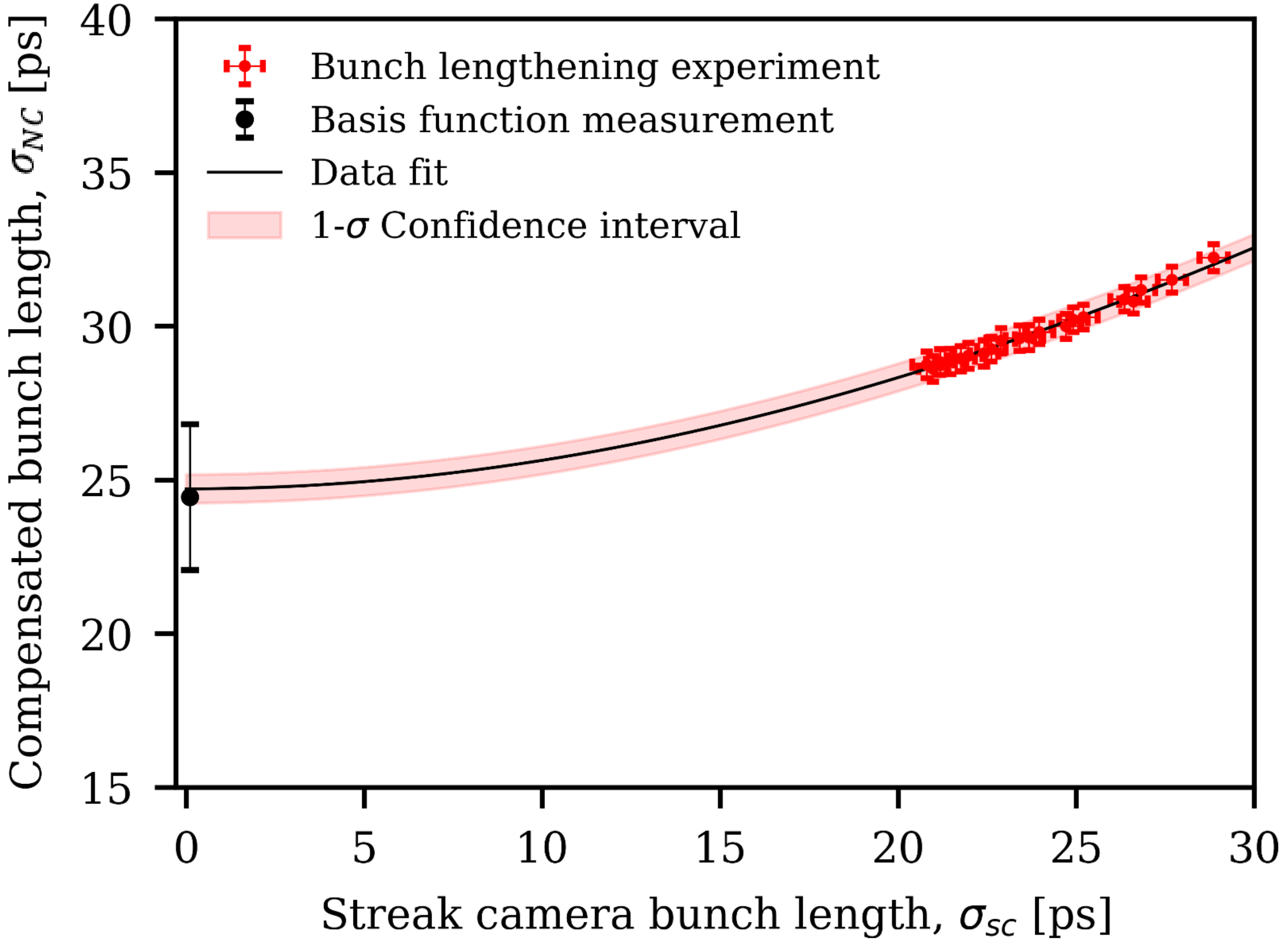
$$h'(t) = \boldsymbol{F}^{-1}\left[\frac{\boldsymbol{G}(\omega)\boldsymbol{F}[\,h(t)]}{R(\omega)}\right] \qquad \boldsymbol{F}: FFT \quad \boldsymbol{F}^{-1}: iFFT$$

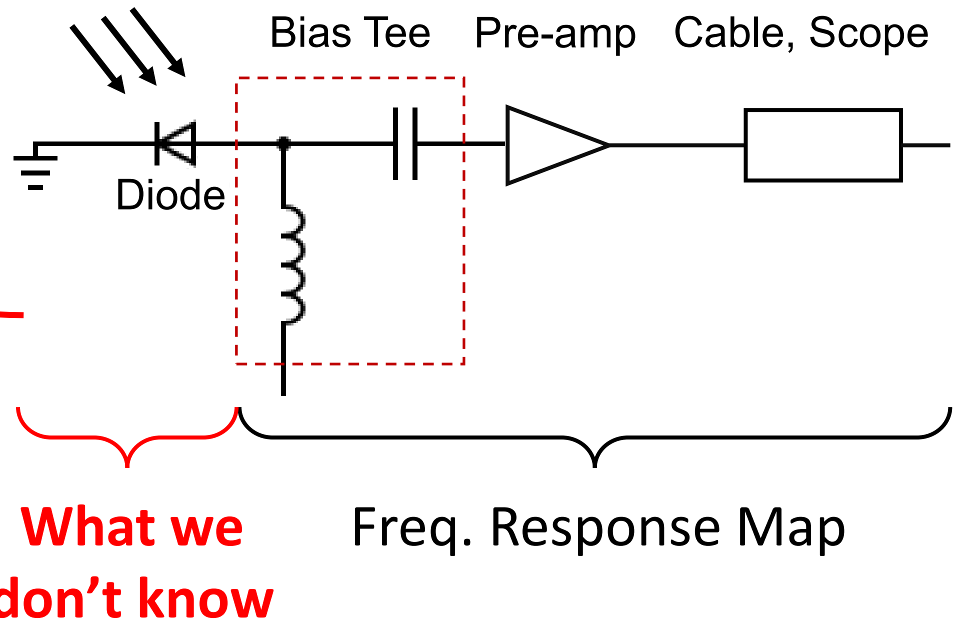
2.5 Partitioning data-points into every RF bucket and convert time to phase

3. To find the bunch length, perform Gaussian fit

Bunch Lengthening Experiment

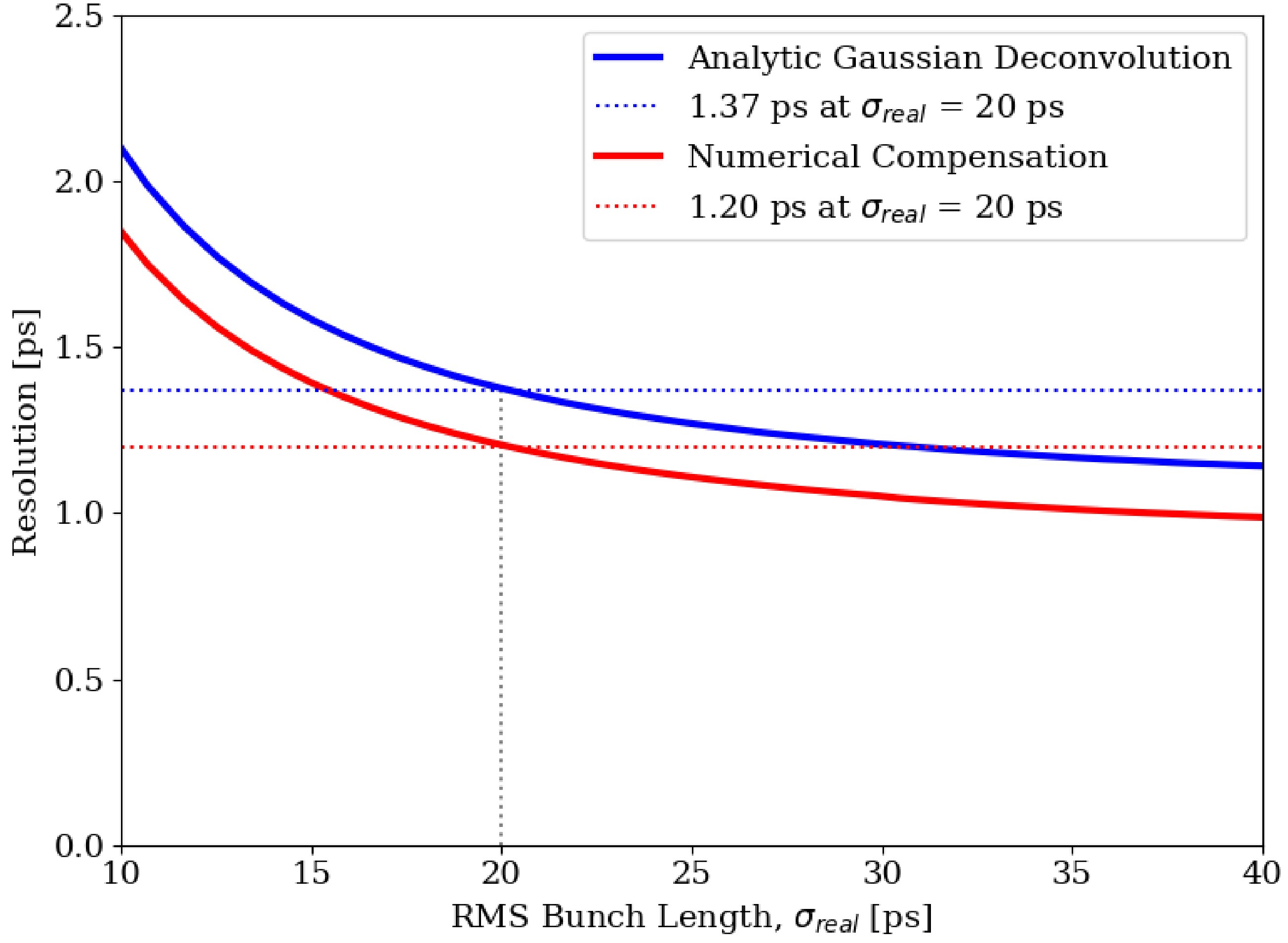
$$\sigma_{NC} = \sqrt{\sigma_{SC}^2 + A^2} + B$$





- 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 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.

Statically Estimated Resolution, by Monte Carlo Study



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

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

$h_{PSF,PD}\vert_{\sigma=0}(t)$	: Point Spread Function (Gaussian profile σ = 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

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

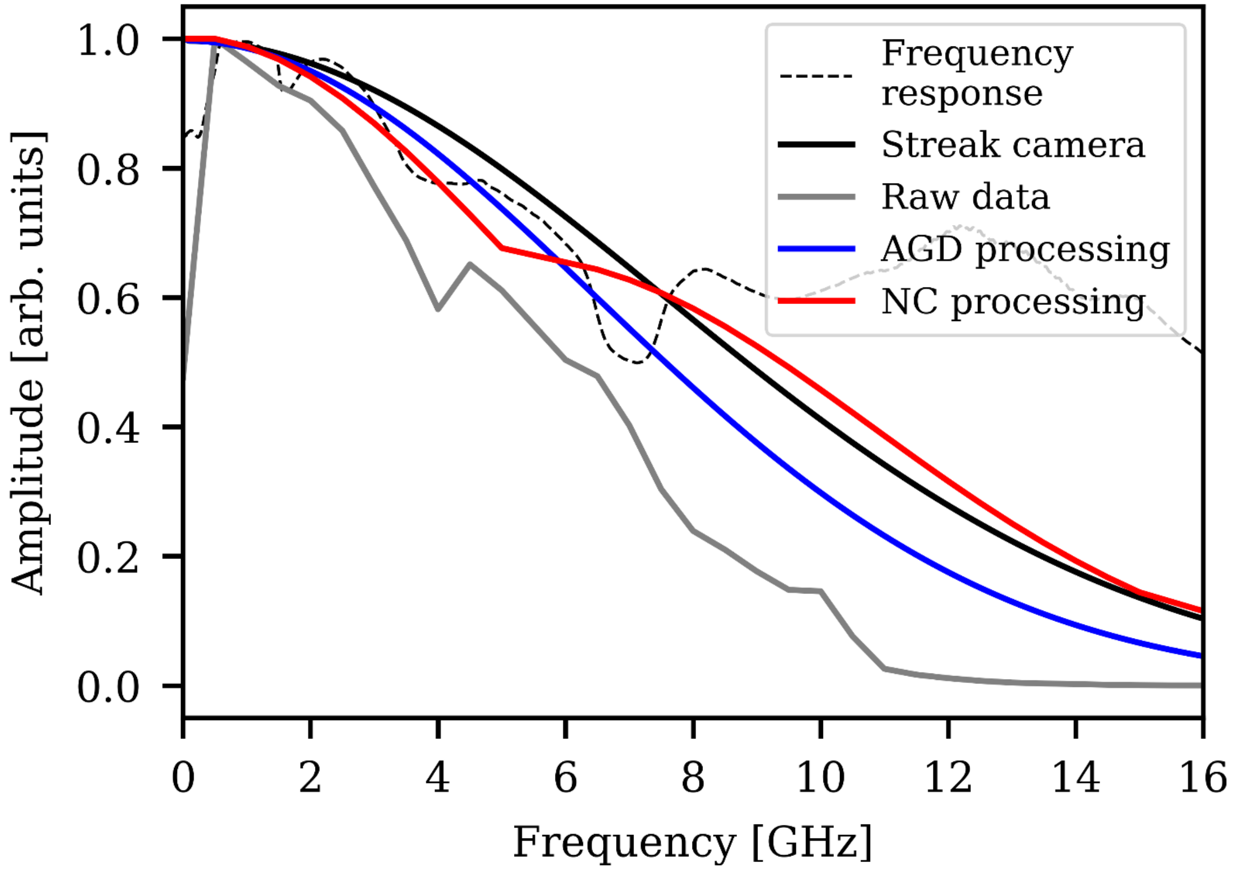
3. Definition of systematic error

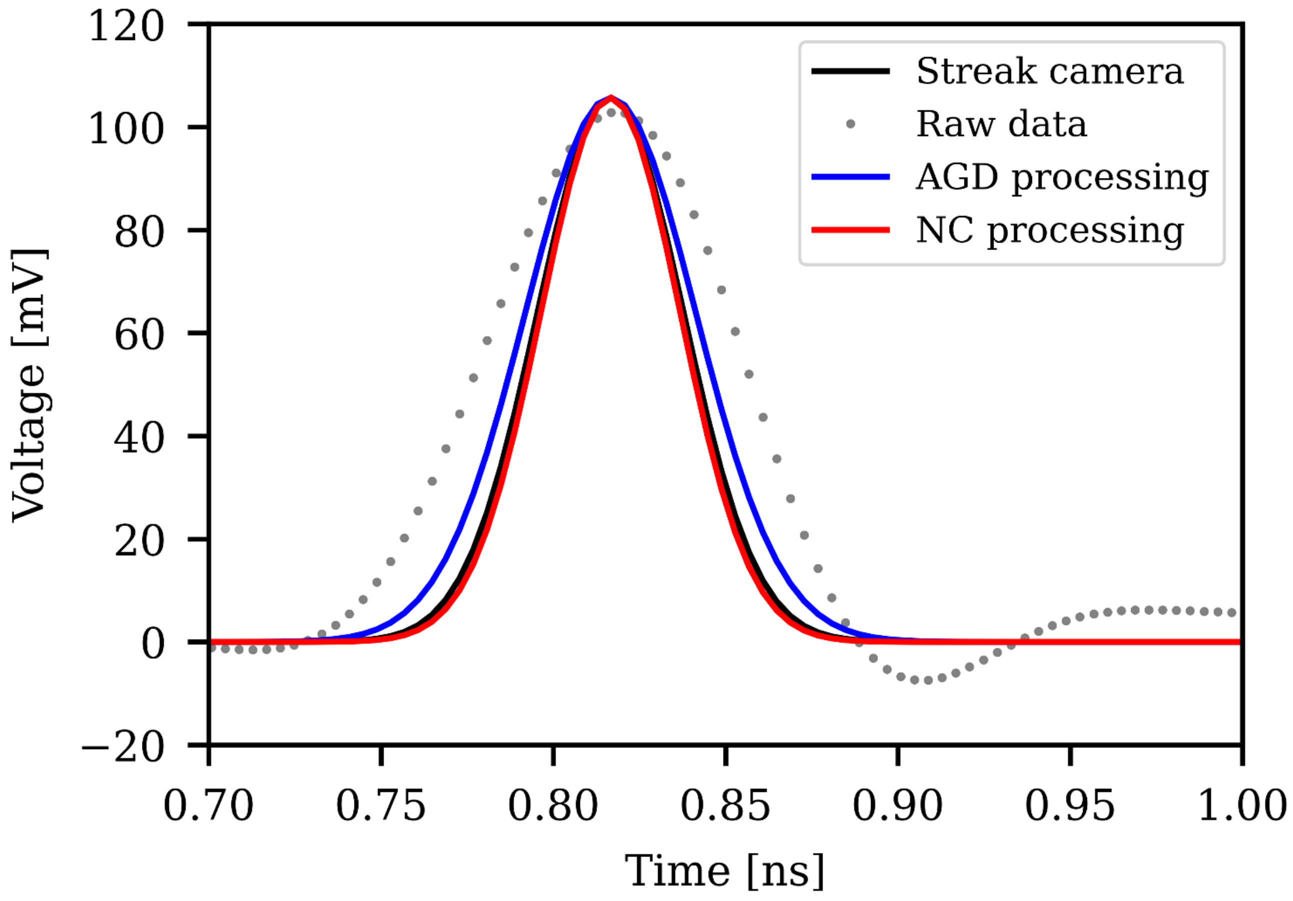
$$\sigma_{sys\ err} = \sqrt{\left(\frac{\sigma_{trigger\ jitter}}{N_{\#\ of\ meas}}\right)^2 + \sigma_{fit\ error}^2}$$

$$\sigma_{trigger\ jitter} = 30\ ps, \quad N_{\#\ of\ meas} = 500,$$

$$\sigma_{fit\ error} = \sigma_{AGD\ fit\ error}\ ||\ \sigma_{NC\ fit\ error}$$

Discussion

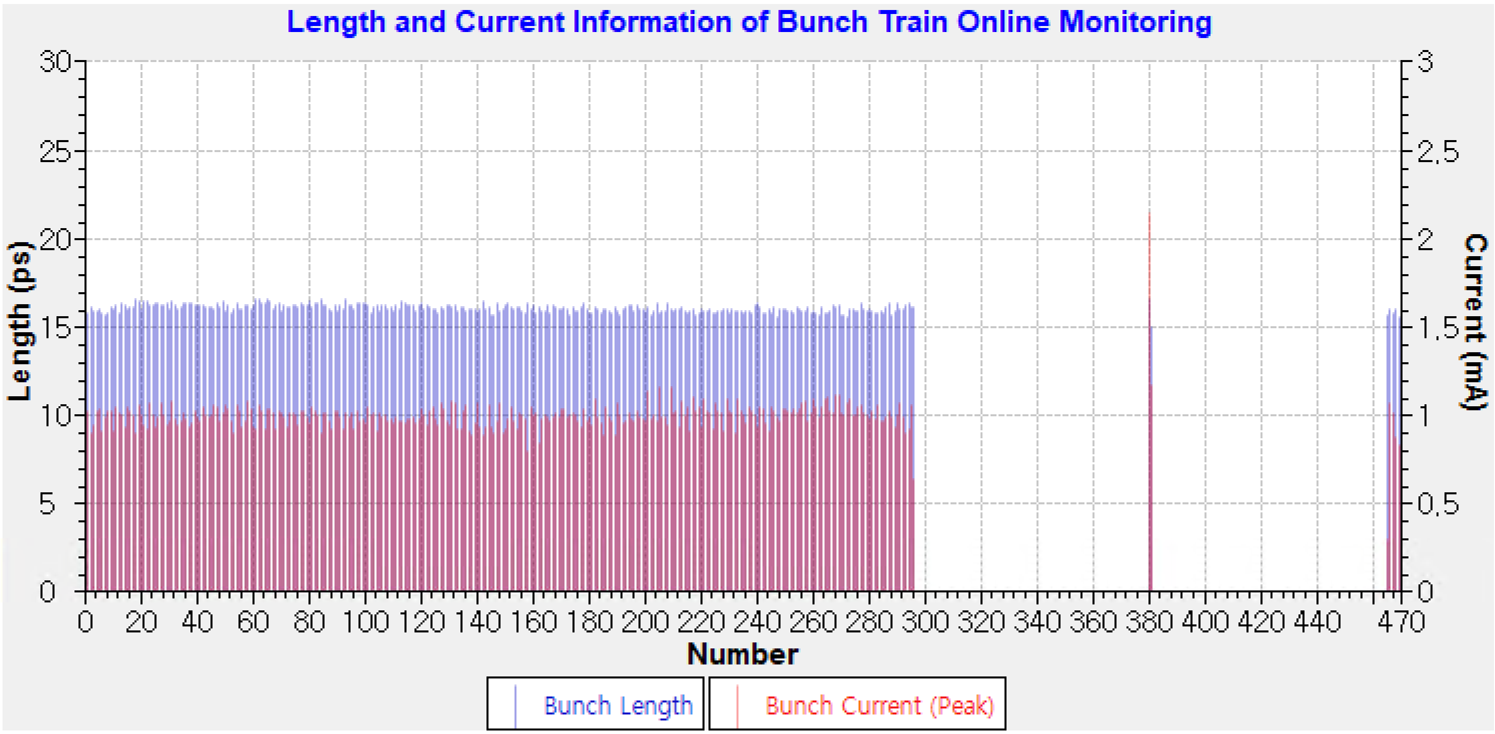


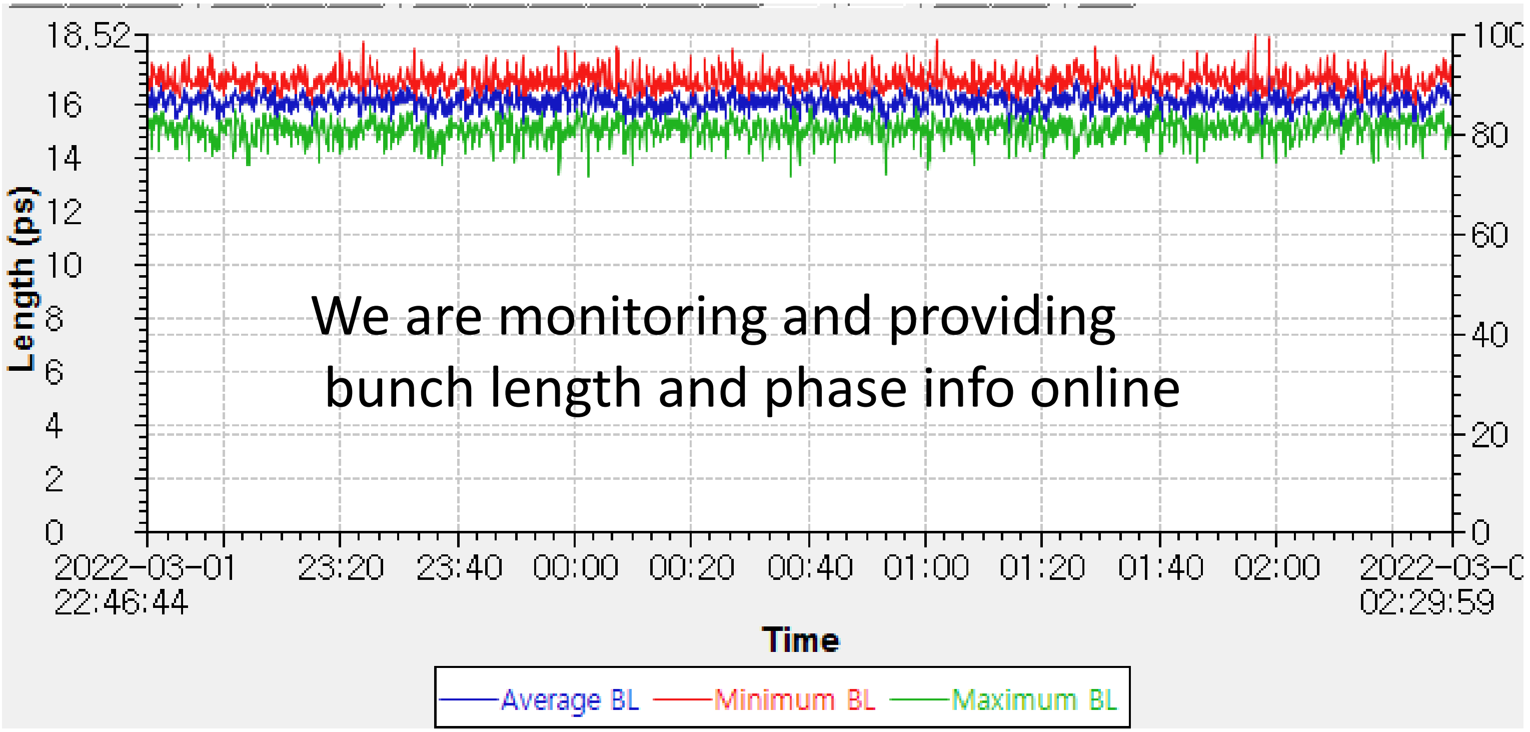


- The NC results are closest to the ideal curve, despite the absence of the frequency response of the photodiode
- BUT still we could not understand why the fit form looks like below

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

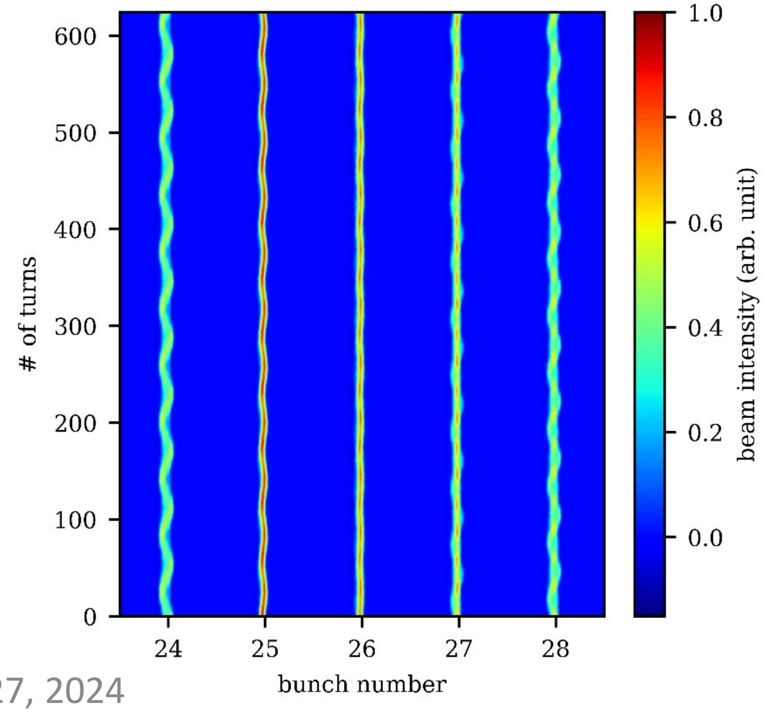
Current Status





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)

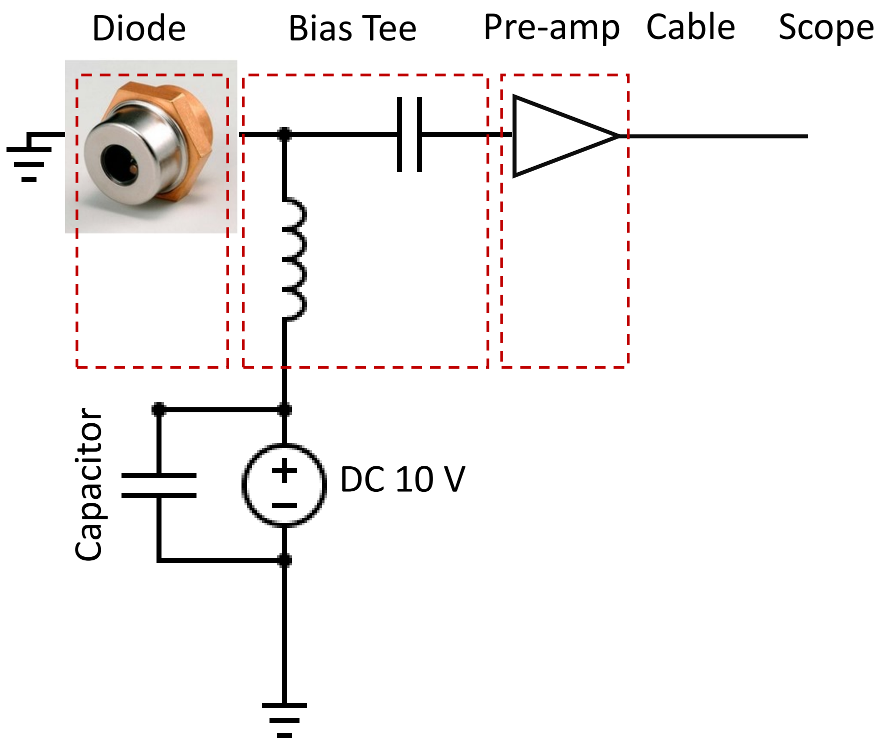


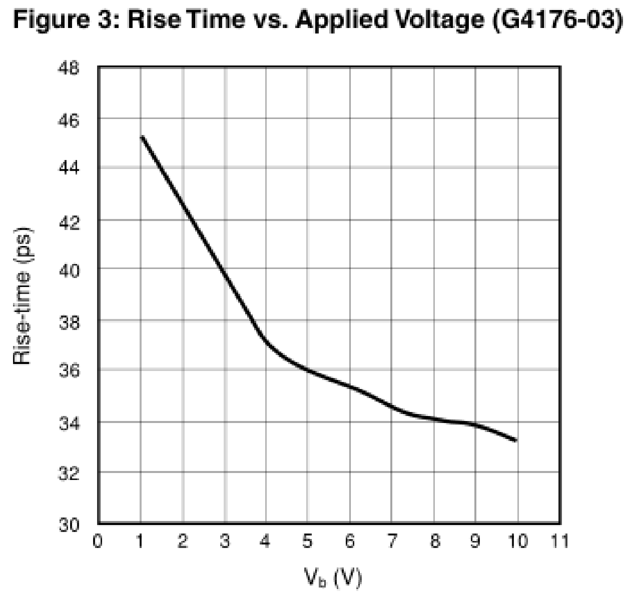
Summary

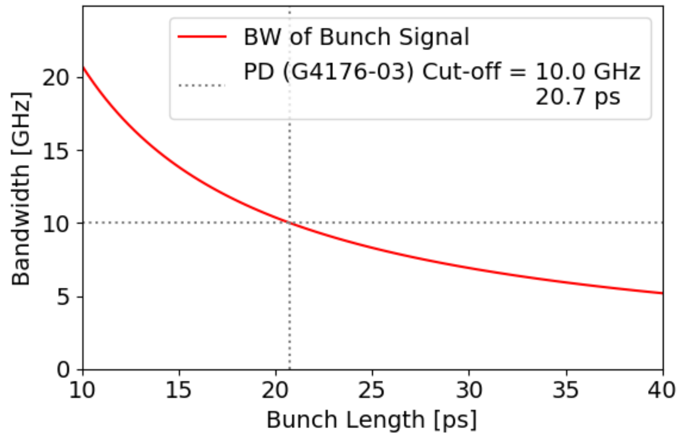
- We have experimentally demonstrated a compact monitor that enables filling pattern (~ 3 μA resolution) and bunch length (~ 1 ps resolution) monitoring with visible light at the PLS-II storage ring.
- Both analytical Gaussian deconvolution and numerical compensation methods were carefully evaluated to improve measurement accuracy
  → We achieved better resolution with the numerical compensation method
- A real-time digitizer has been newly implemented for online Turn-by-turn and Bunch-by-bunch measurements. This enables an observation of the fast dynamics of the stored beam.

Transmission Ratios

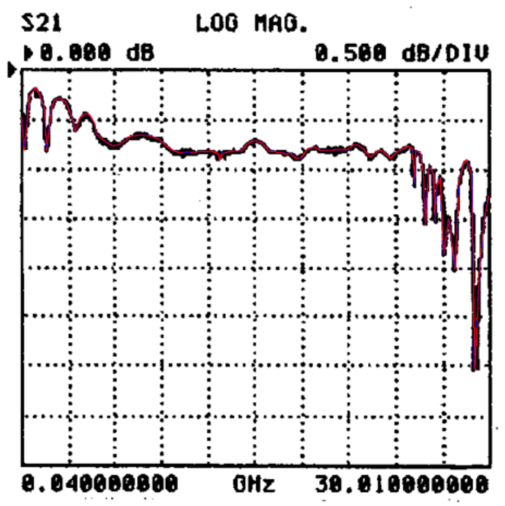
- MSM Photodiode
  - rise time(t) = ~35 ps @ 7 V (bias)
  - Eq. bandwidth = 0.35/t ~ 10 GHz
  - Eq. point spread function = 20.7 ps



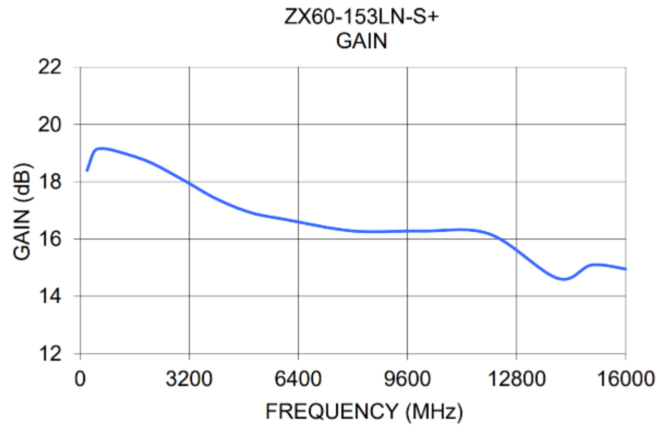




- **Bias Tee**
  - Gain

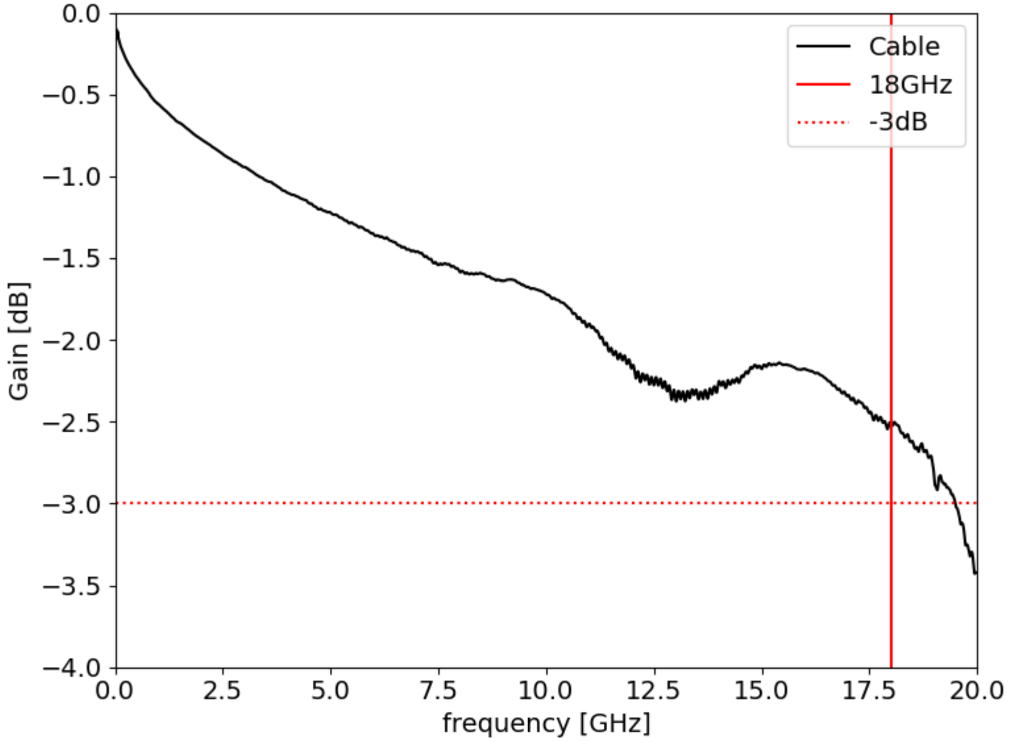


- **Pre-amp**
  - Gain



Transmission Ratio

- **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 (Well Calibrated Sig. Generator scanned frequency, and measured voltage level at digitizer)