Non-destructive Beam Position Monitoring in Two-Beam Section of cERL

Takashi OBINA
KEK

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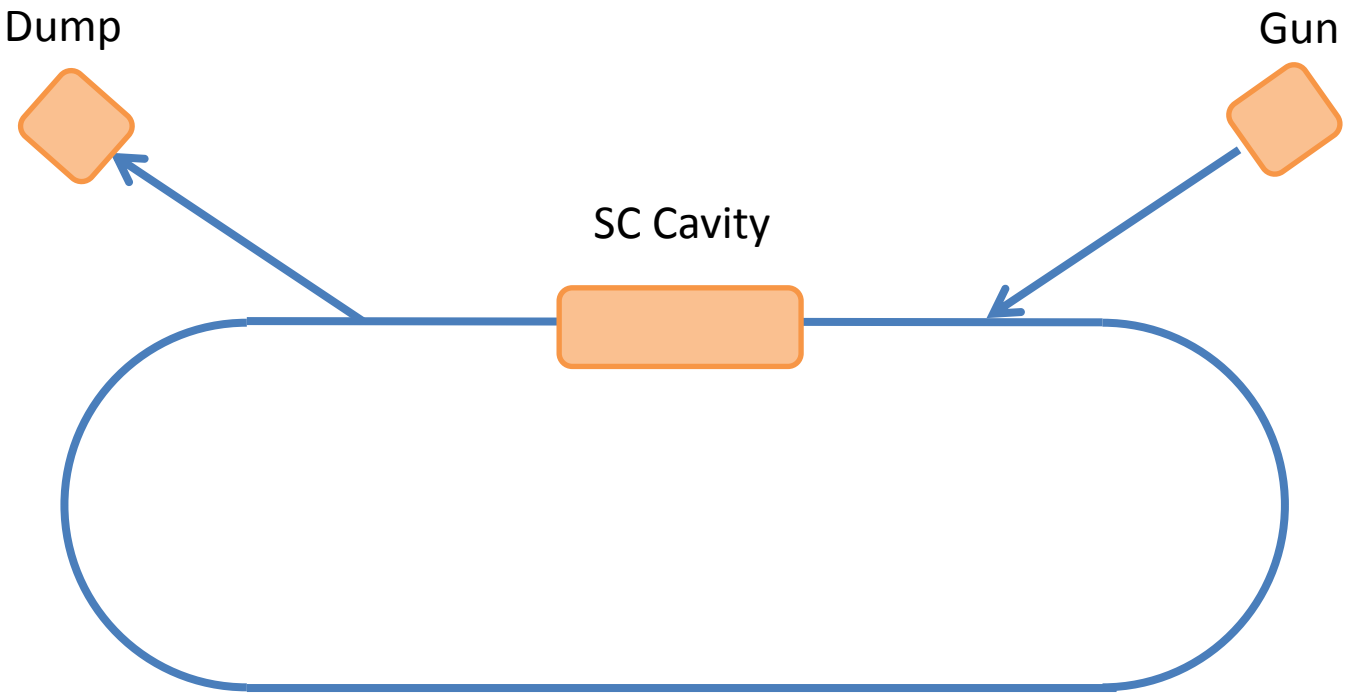
1. Requirements

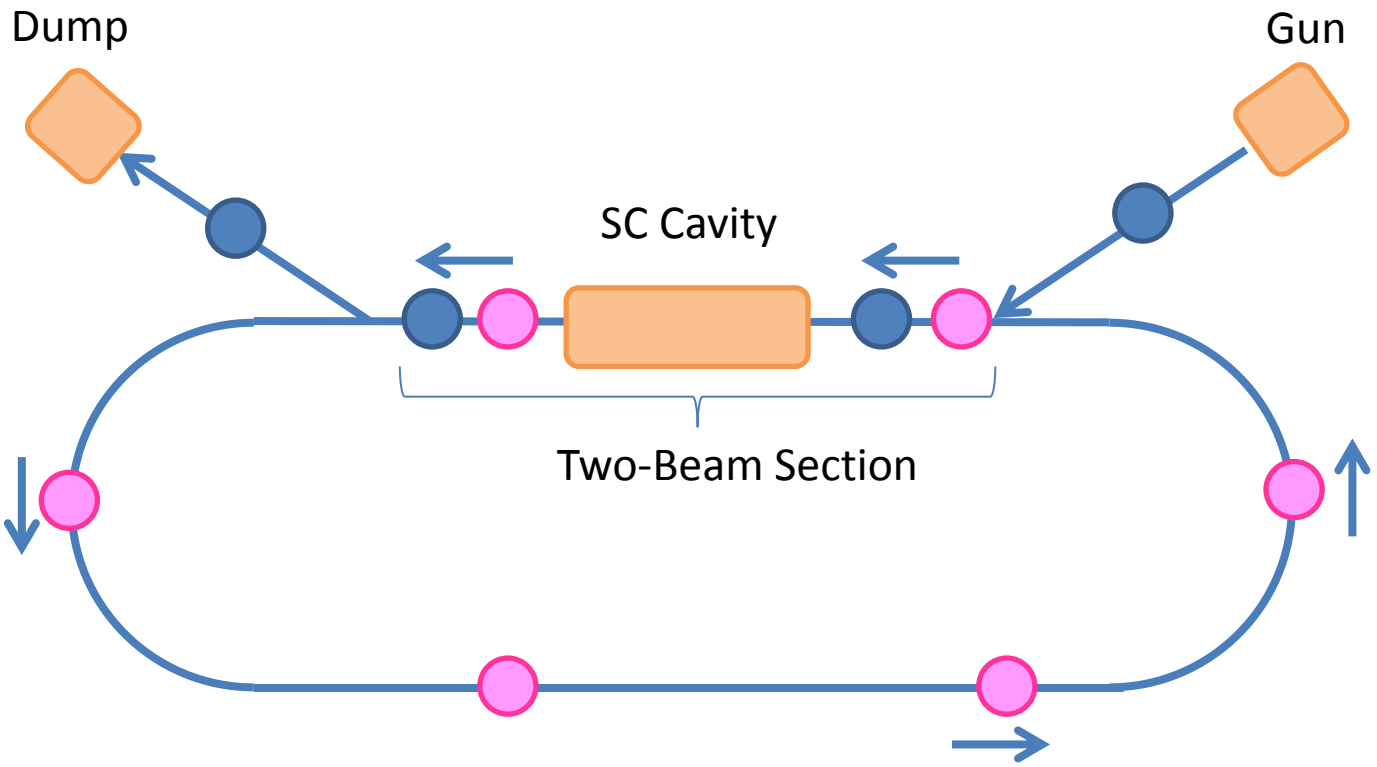
- Needs to measure beam position at "Two-Beam Section" in the ERL

Simple Layout Example



Requirements

- Needs to measure beam positions at "Two-Beam Section" in the ERL
  - Separation of high-energy and low-energy beam is mandatory for beam commissioning and beam tuning.
  - Must work under "Burst" and "CW" beam condition.



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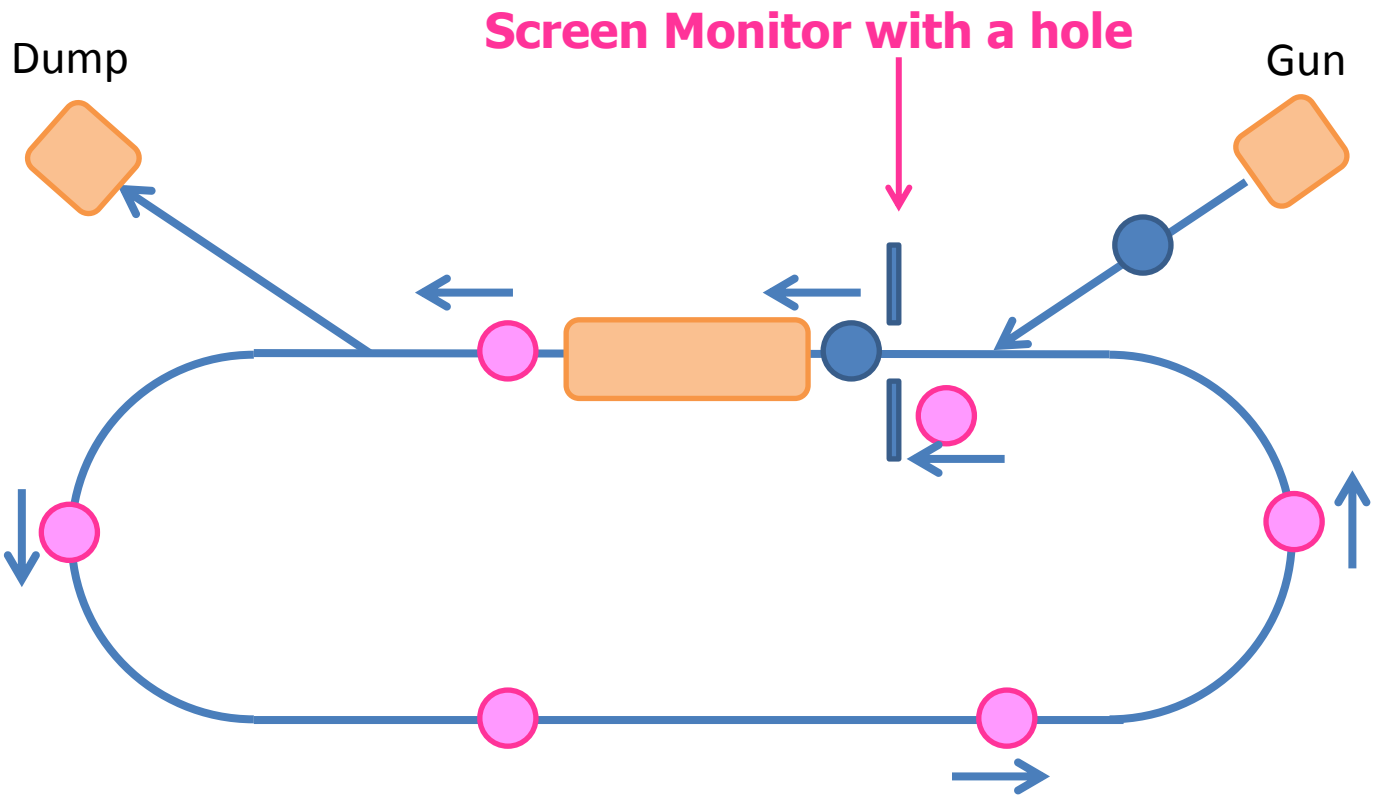
Candidate 1 : Screen monitor with a hole

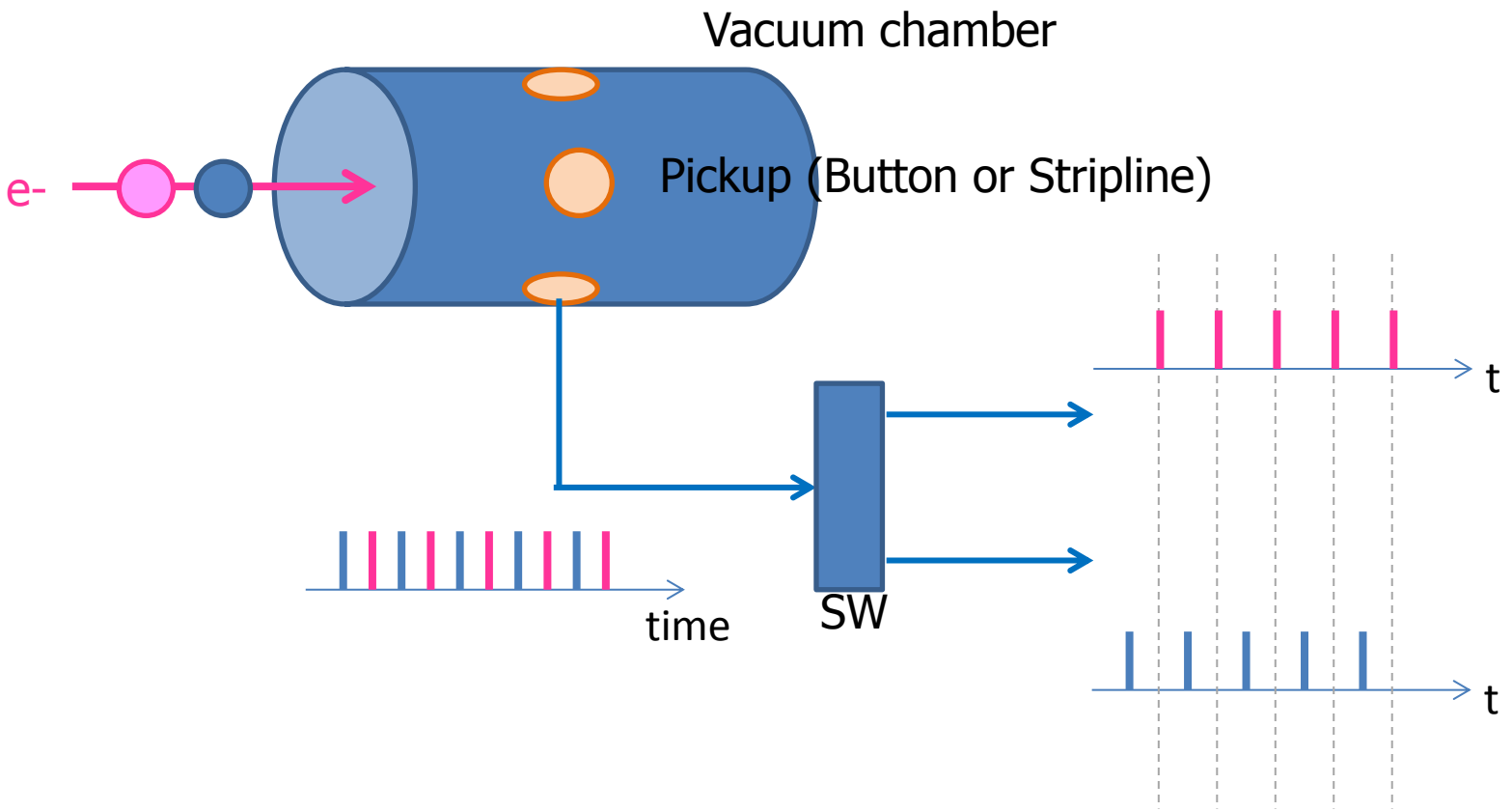
- Conventional tool to observe high energy beam
  - Disadvantage : Destructive
  - Cannot be used during CW operation

We need non-destructive position measurement.



Candidate 2 : Fast Switch

- Separate a BPM signal with Fast PIN-Diode (or GaAs) Switch
  - SPDT switch



(Real pickup electrode generates bipolar signal.)

Pros and Cons to use Fast Switch

- Advantage
  - Simple and Straightforward method
  - Easily available in the market
  - Can be used any kind of beam patterns such as Bust,CW, etc

- Limitations
  - ON/OFF ratio : typically 30 - 50 dB (in high speed)
  - Switching speed : typically 2 - 5 ns

- Disadvantages
  - Needs switch timing signal
  - Require two sets of detection circuit
  - Long-term stability (?)

Beam repetition rate

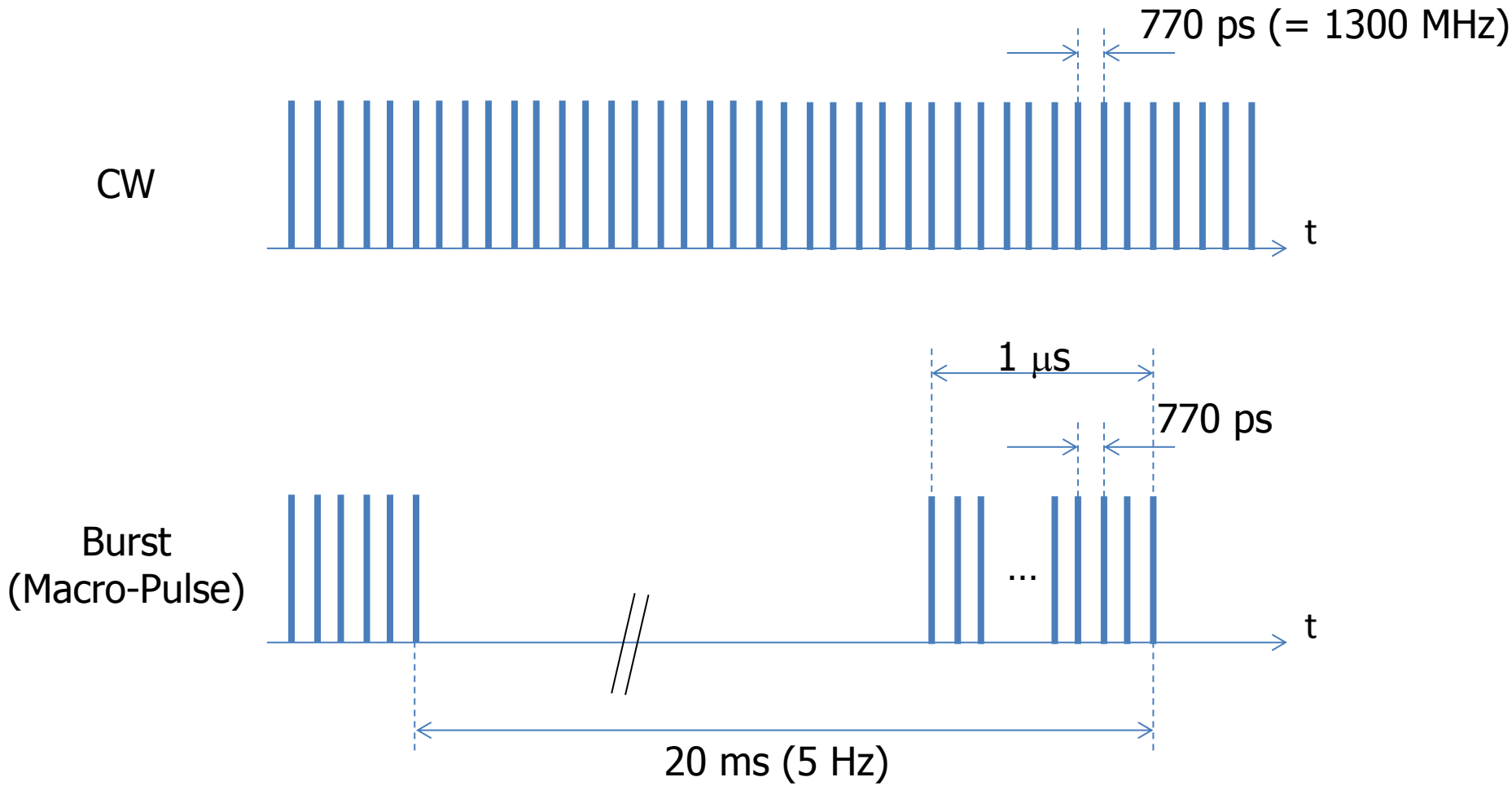
- Most of existing ERL facilities use much lower frequency than RF (1300 MHz) frequency.
  - from several MHz to 80 MHz or 160 MHz
  - Fast switch is a good candidate

- cERL at KEK uses 1300 MHz as a beam rep-rate.
  - Requirement from SC cavity (to avoid HOM)
  - Beam rep-rate at two-beam section is 2600 MHz!!
  - Almost impossible to separate in time domain

Utilize time domain and frequency domain information

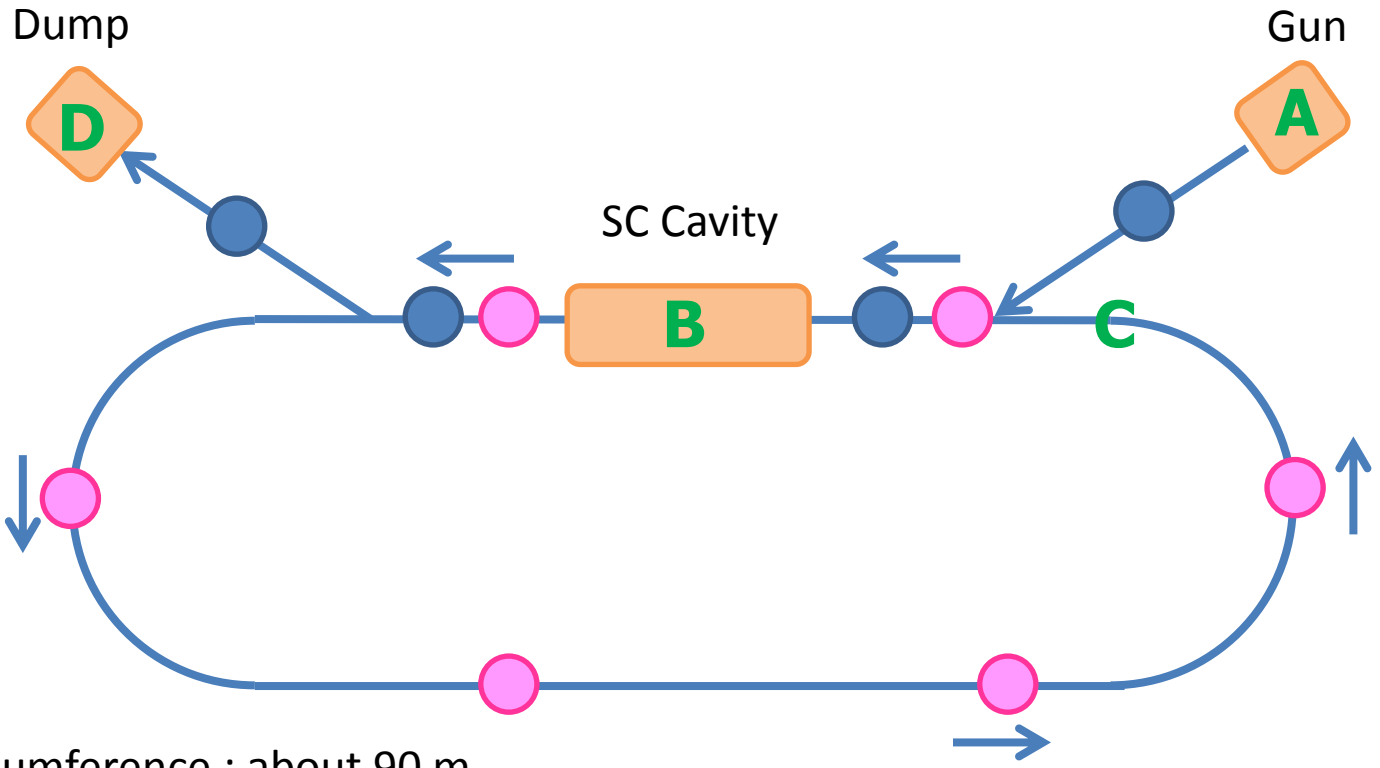
Typical beam pattern of cERL

- 1300 MHz CW for high current
- 1 μs burst (macro-pulse) for beam tuning



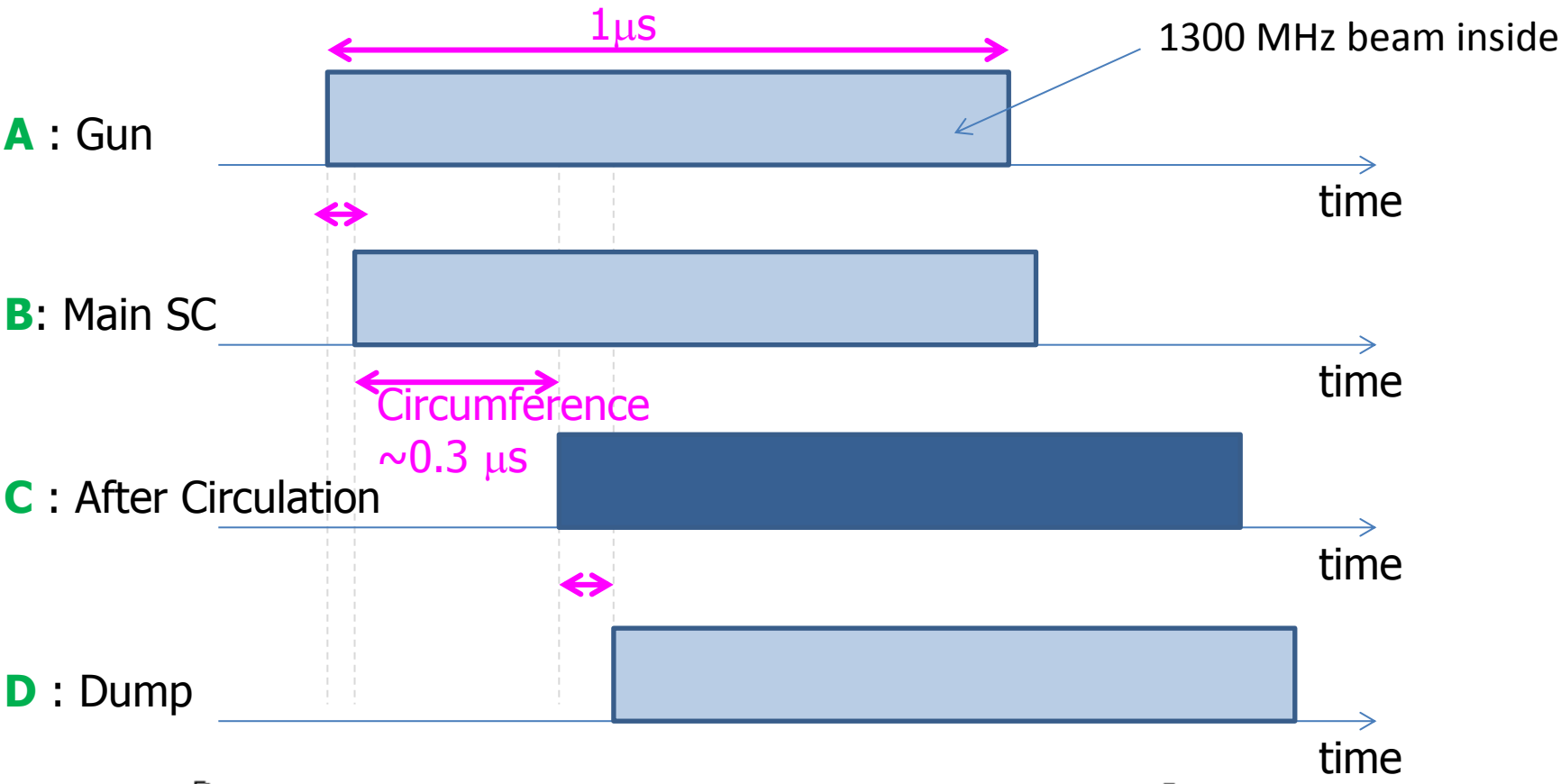
Beam signal under ideal condition

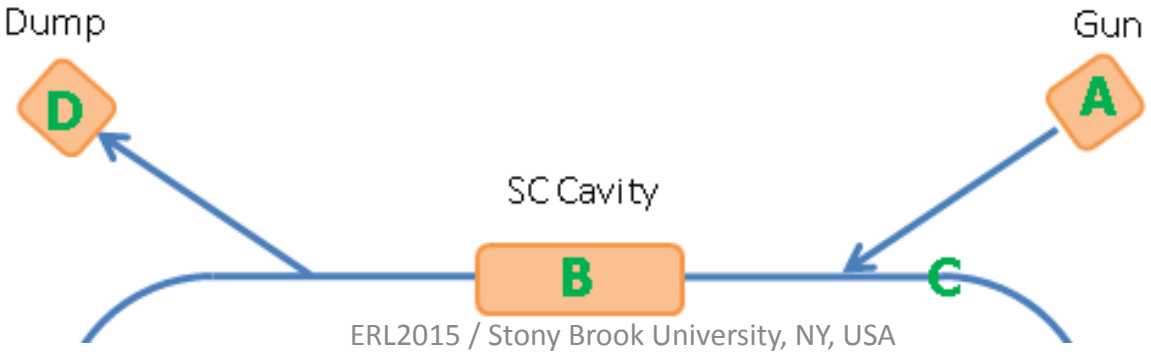
- Consider a signal at location **A, B, C, D** in the figure
- Simplified case
  - No difference in bunch charge, bunch length during the circulation
  - Detect 1300 MHz component of the beam
  - Perfect energy recovery condition



KEK-cERL Circumference : about 90 m

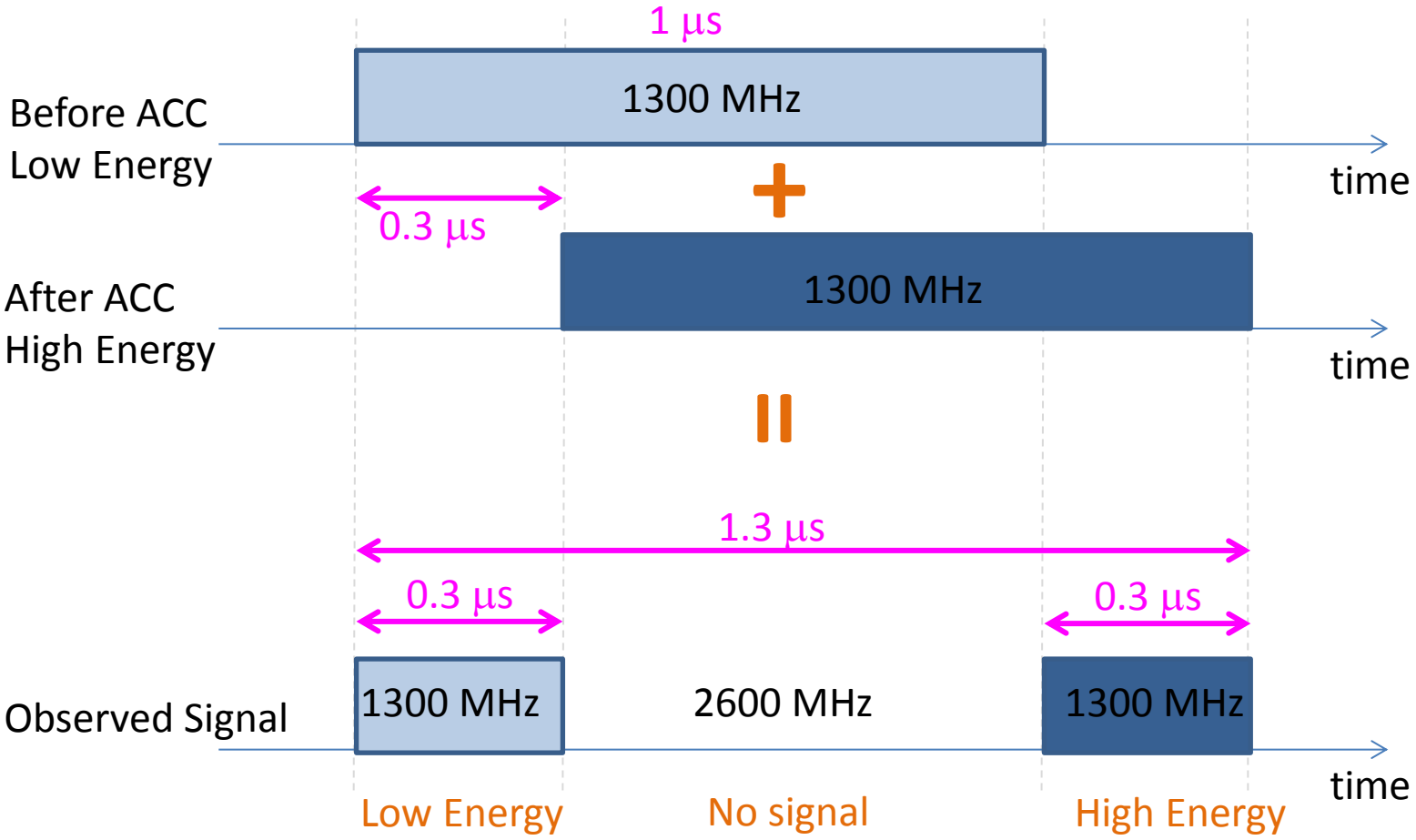
1 μs burst measured with Oscilloscope





1300 MHz signal at the center of SC cavity

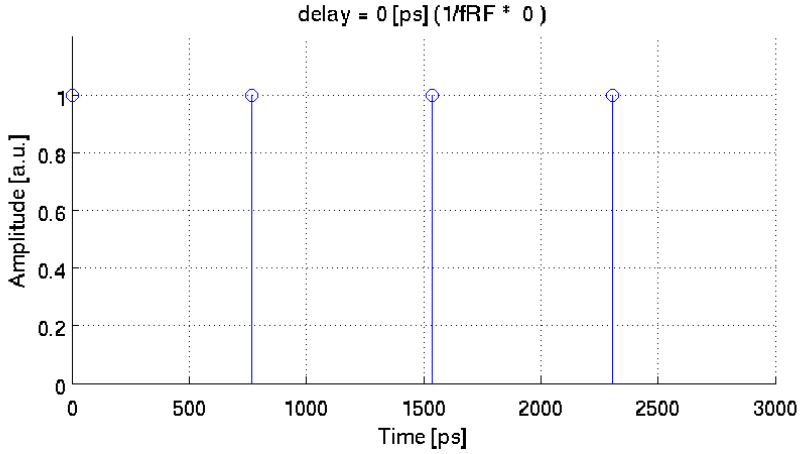
- Beam signal with 180 deg phase difference (Energy Recovery)
- Overlapped part generates harmonics of 2600 MHz. No 1300 MHz.



We can measure the beam position separately.

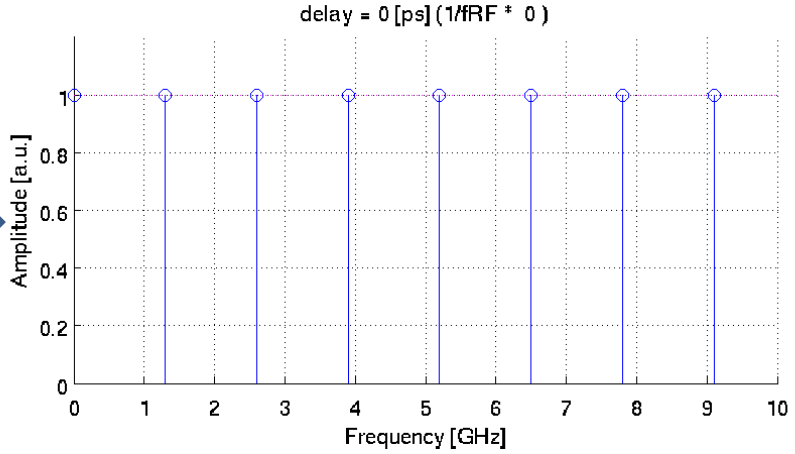
1300 MHz (~ 770 ps) pulse train

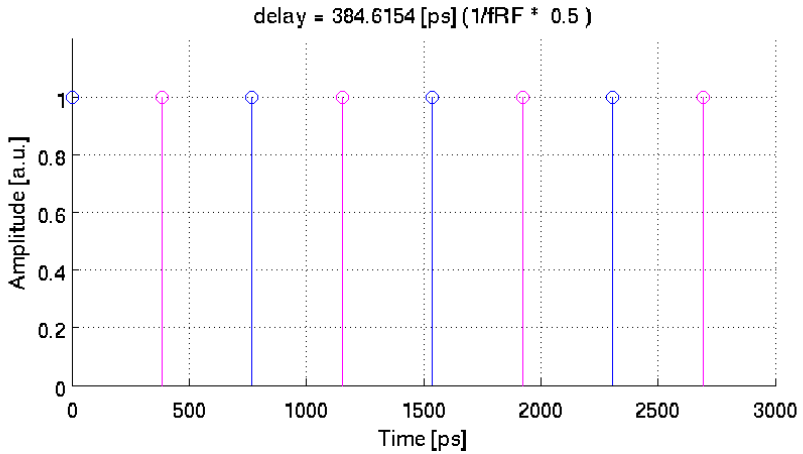
Time Domain

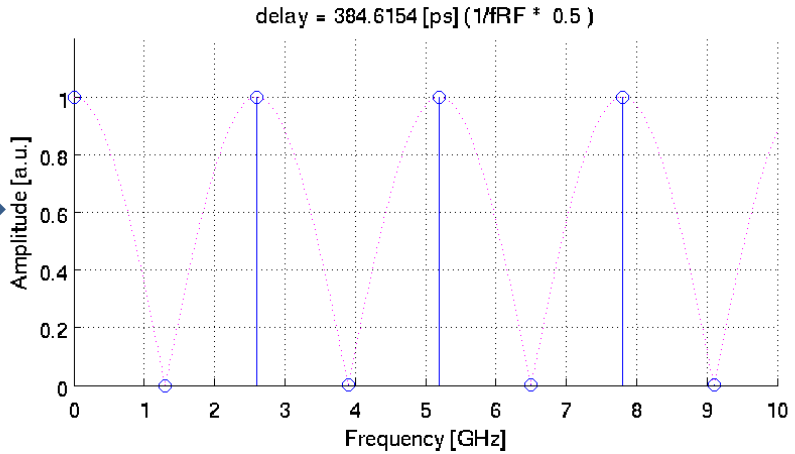


F.T.

Frequency Domain







Assume no beam loss in recirculation loop,
The bunch length affects only on much higher frequency components.

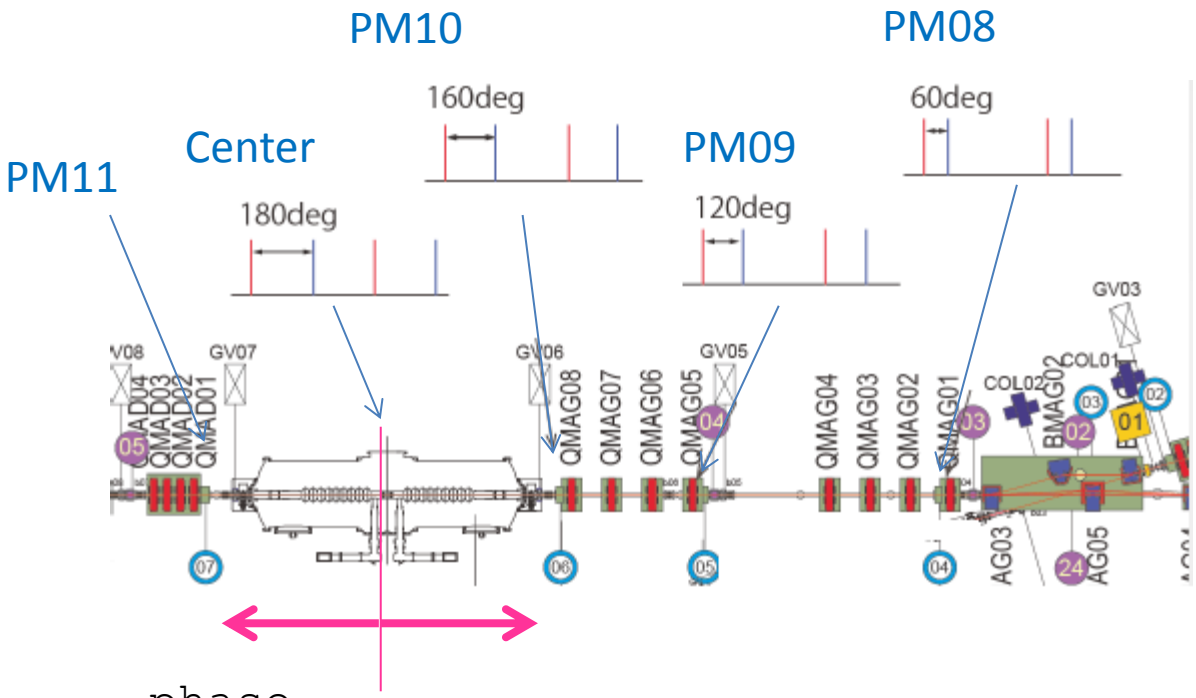
Comments

- Non-overlapped part
  - Time duration depends only on the circumference.
    - Less position resolution in small machine
  - Needs to select proper bandwidth of the detection circuit.

- Overlapped part
  - Signal of the overlapped part depends on
    - Difference of beam charge before/after acceleration
    - Bunch arrival time after acceleration

speed of electron is slower than speed of light

- 180 deg difference at the center of the main SC cavity
- Injector beam is much slower than high energy beam



# name	phase
PM08:BPMAG01	60deg
PM09:BPMAG05	120deg
PM10:BPMAG08	160deg
center	180deg
PM11:BPMAD01	200deg

Phase difference of BPM #10 and #11 is same
(same distance from SC cavity center)
→ we adjusted beam timing by BPM signal
at the early stage of commissioning.

time-shift of Fourier transform

- Fourier transform of impulse train

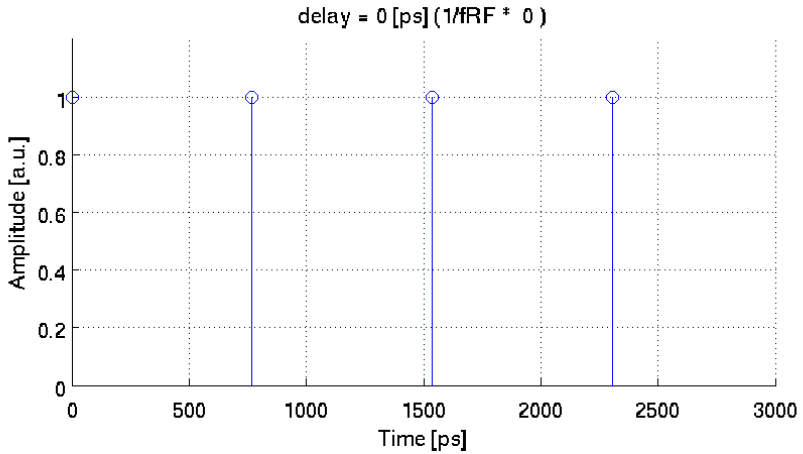
$$f(t) \leftrightarrow F(\omega)$$

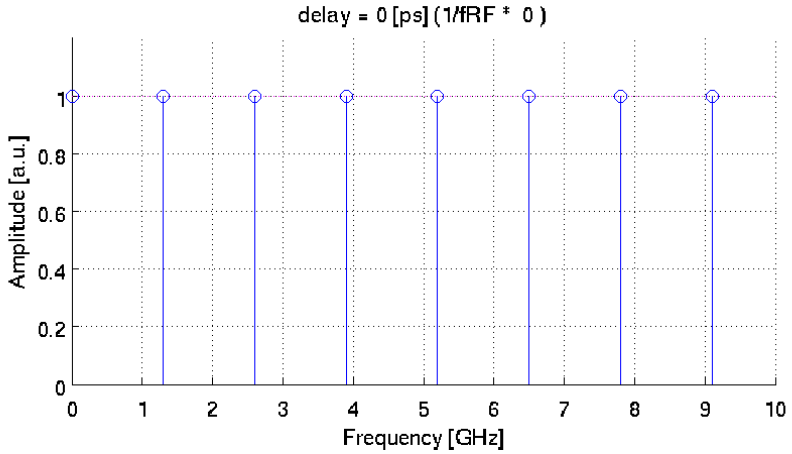
- Beam after acceleration can be represented as time shift.
- A shift in time corresponds to a change in phase in the FT

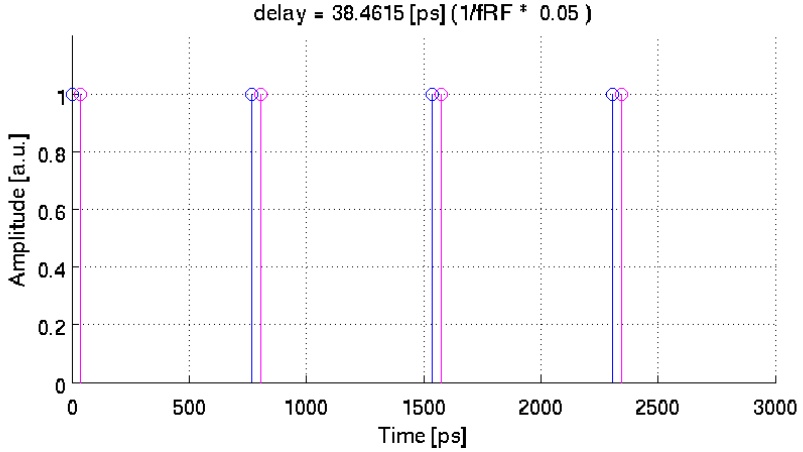
$$f(t - t_0) \leftrightarrow F(\omega)e^{-j\omega t_0}$$

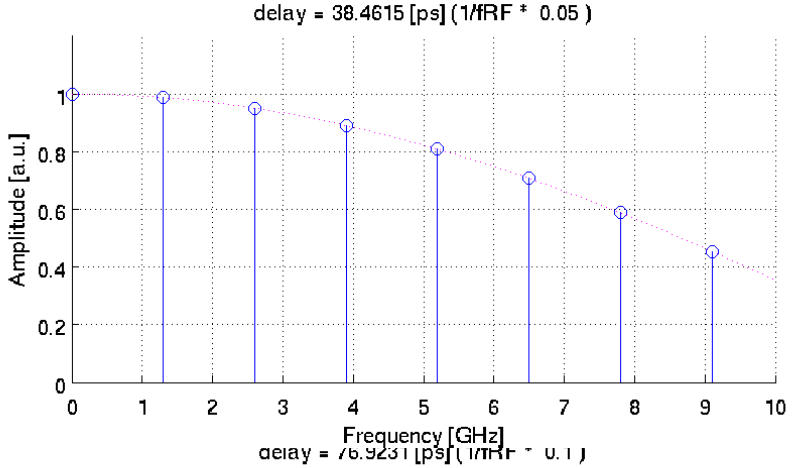
- Overlapped part can be expressed like

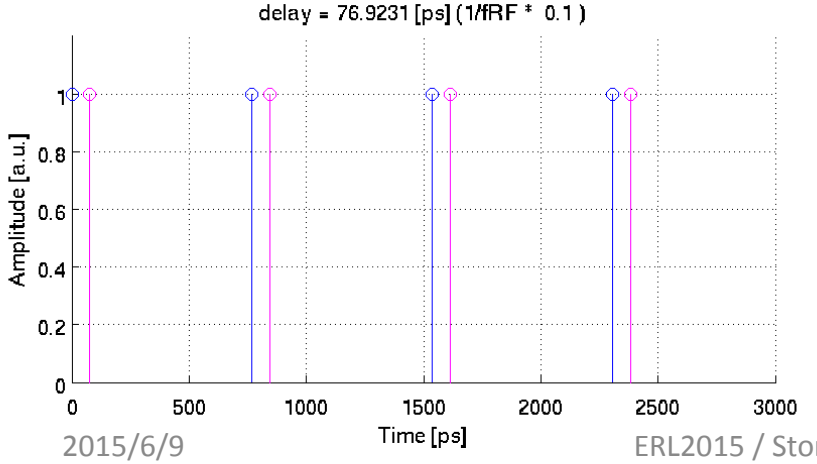
$$f(t) + f(t - t_0) \leftrightarrow F(\omega)(1 + e^{-j\omega t_0})$$


delay = 0 [ps] (1/fRF * 0)
Amplitude [a.u.]
Time [ps]


delay = 0 [ps] (1/fRF * 0)
Amplitude [a.u.]
Frequency [GHz]


delay = 38.4615 [ps] (1/fRF * 0.05)
Amplitude [a.u.]
Time [ps]


delay = 38.4615 [ps] (1/fRF * 0.05)
Amplitude [a.u.]
Frequency [GHz]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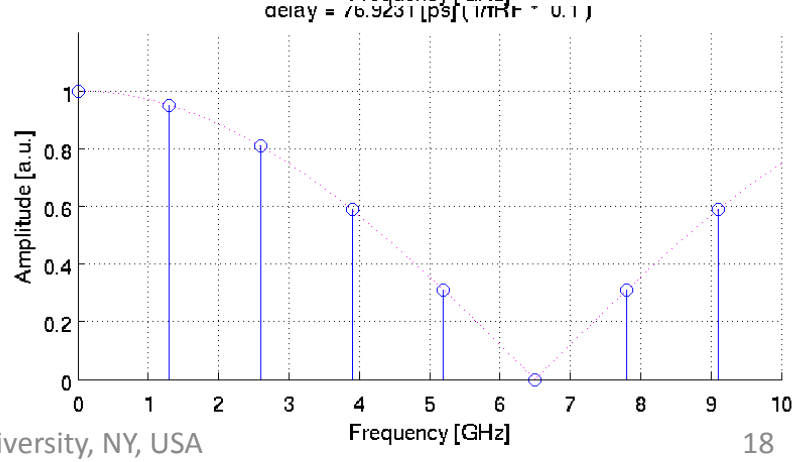
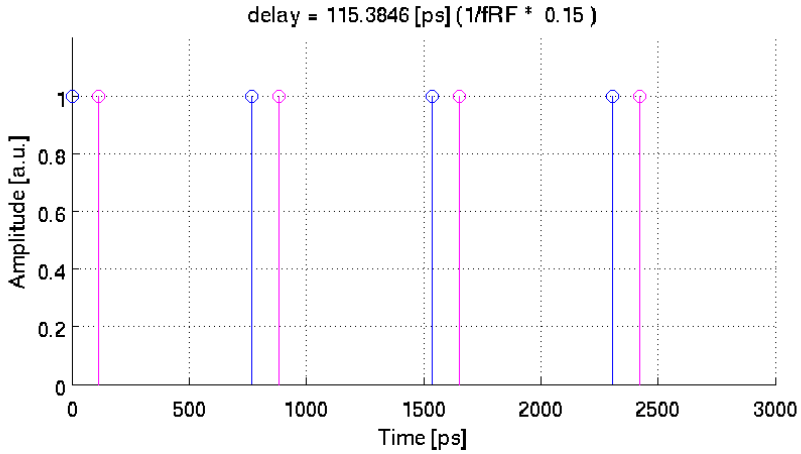
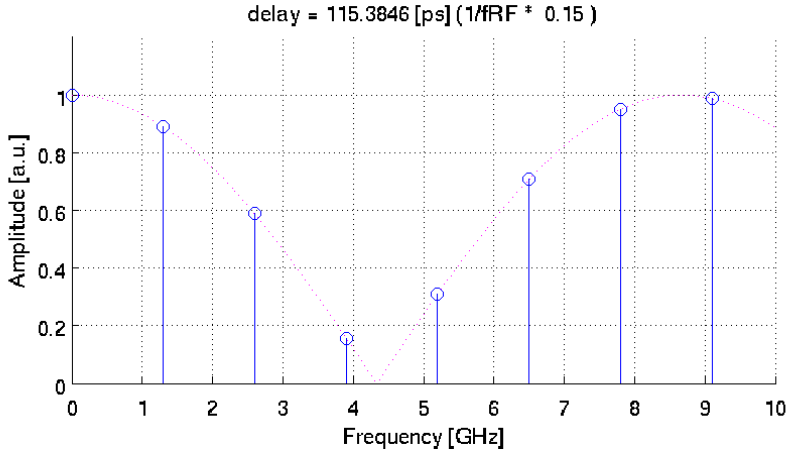
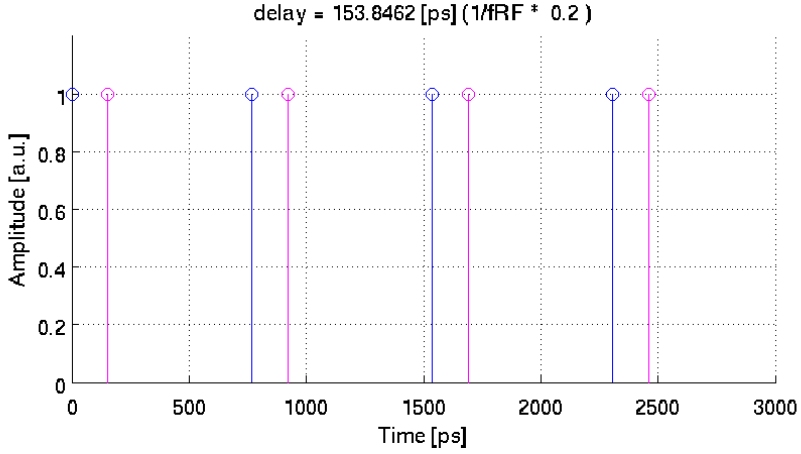
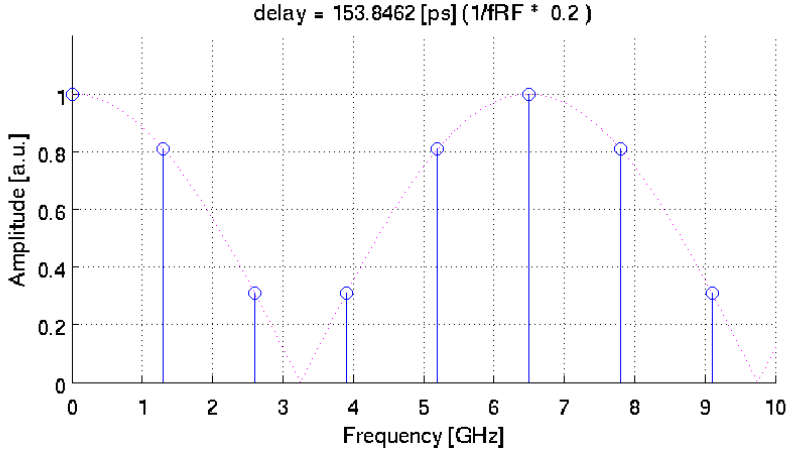
Amplitude [a.u.]
Time [ps]

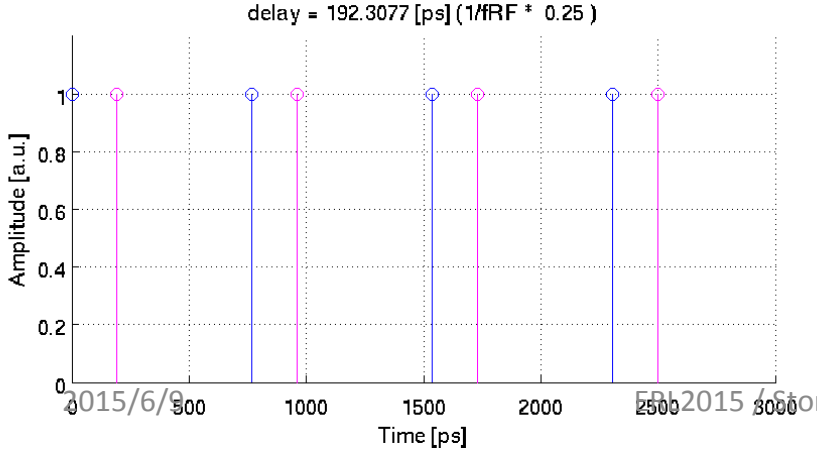

Amplitude [a.u.]
Frequency [GHz]

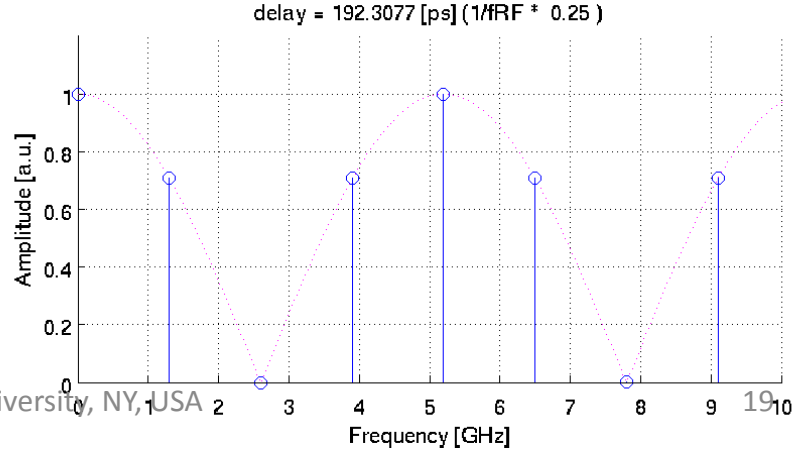

delay = 115.3846 [ps] (1/fRF * 0.15)
Amplitude [a.u.]
Time [ps]

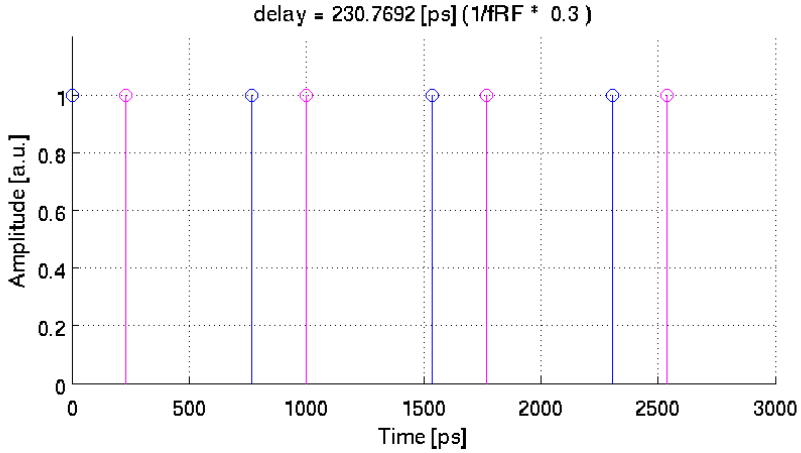

delay = 115.3846 [ps] (1/fRF * 0.15)
Amplitude [a.u.]
Frequency [GHz]

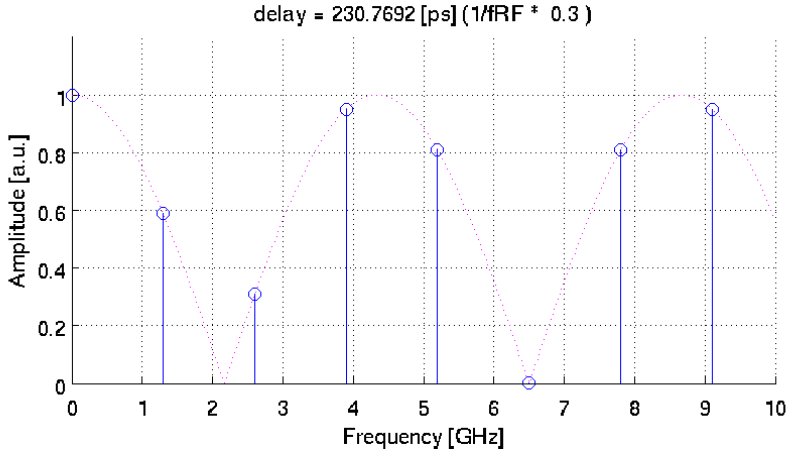

delay = 153.8462 [ps] (1/fRF * 0.2)
Amplitude [a.u.]
Time [ps]

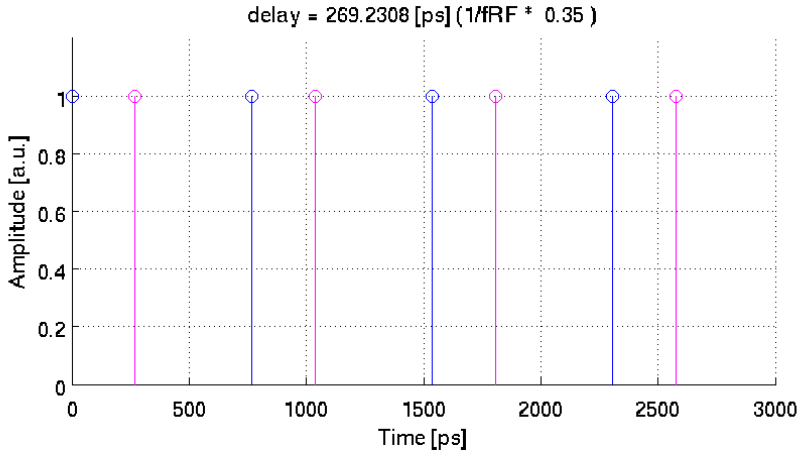

delay = 153.8462 [ps] (1/fRF * 0.2)
Amplitude [a.u.]
Frequency [GHz]

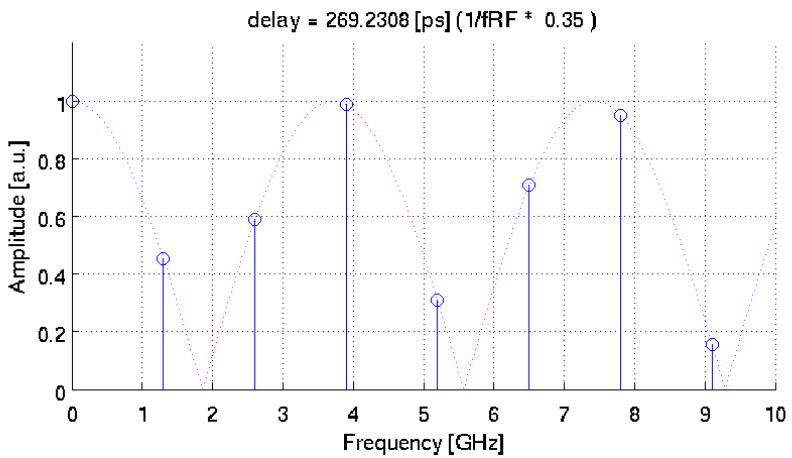

delay = 192.3077 [ps] (1/fRF * 0.25)
Amplitude [a.u.]
Time [ps]

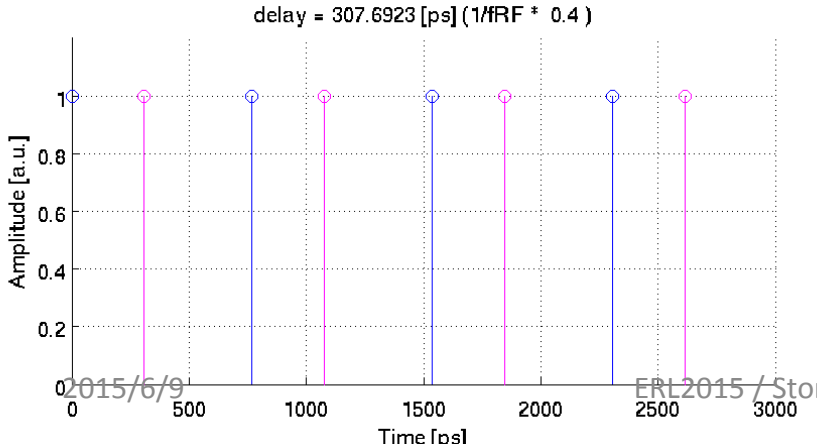

delay = 192.3077 [ps] (1/fRF * 0.25)
Amplitude [a.u.]
Frequency [GHz]

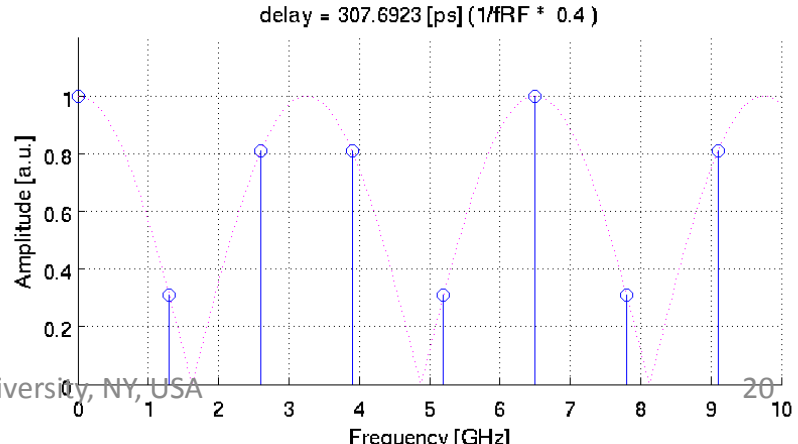

delay = 230.7692 [ps] (1/fRF * 0.3)
Amplitude [a.u.]
Time [ps]

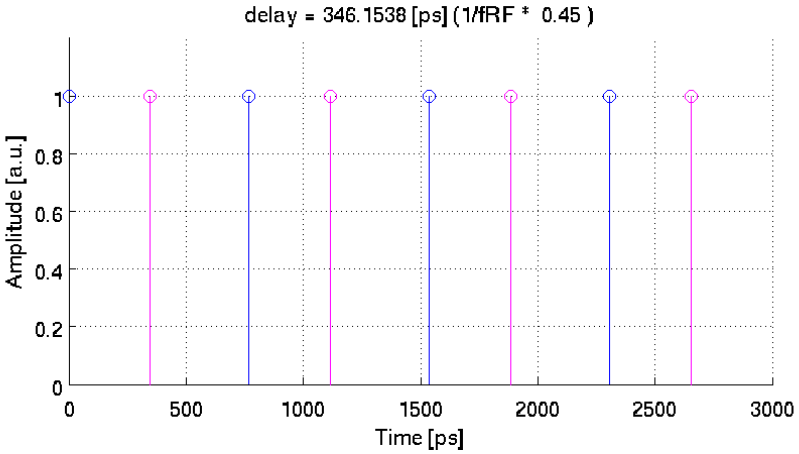

delay = 230.7692 [ps] (1/fRF * 0.3)
Amplitude [a.u.]
Frequency [GHz]

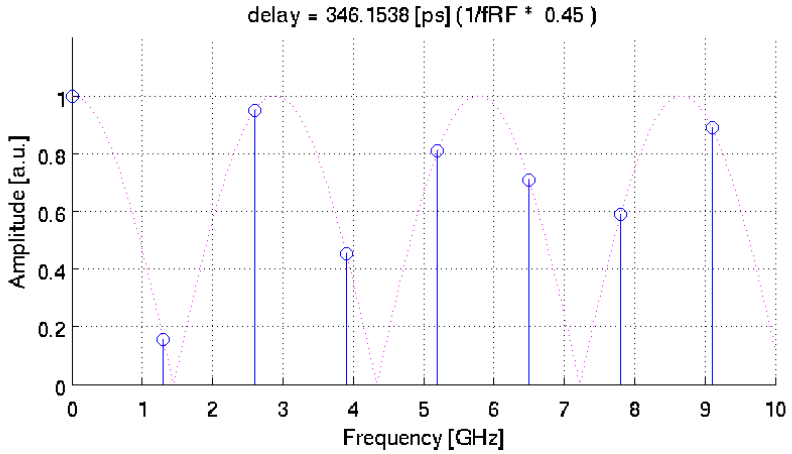

delay = 269.2308 [ps] (1/fRF * 0.35)
Amplitude [a.u.]
Time [ps]

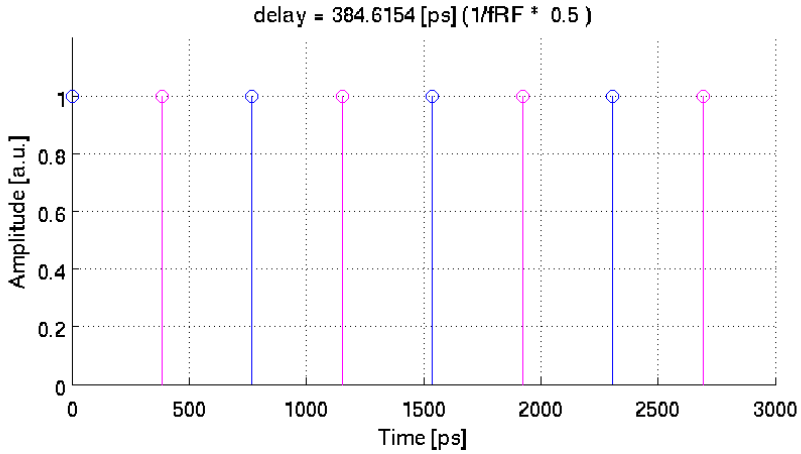

delay = 269.2308 [ps] (1/fRF * 0.35)
Amplitude [a.u.]
Frequency [GHz]

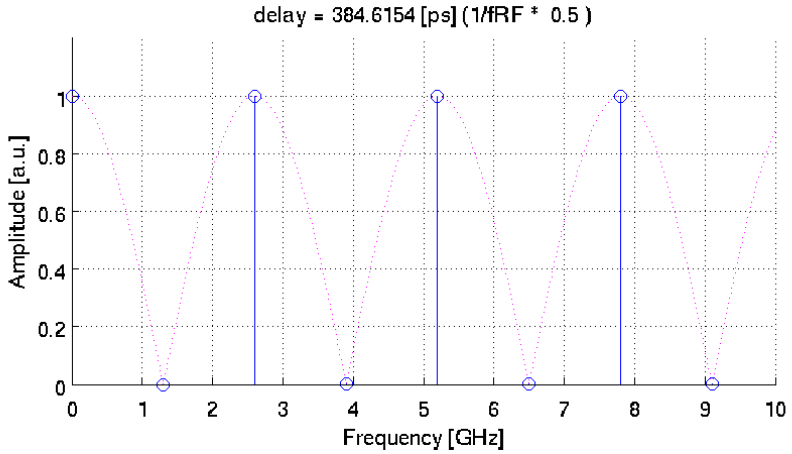

delay = 307.6923 [ps] (1/fRF * 0.4)
Amplitude [a.u.]
Time [ps]


delay = 307.6923 [ps] (1/fRF * 0.4)
Amplitude [a.u.]
Frequency [GHz]





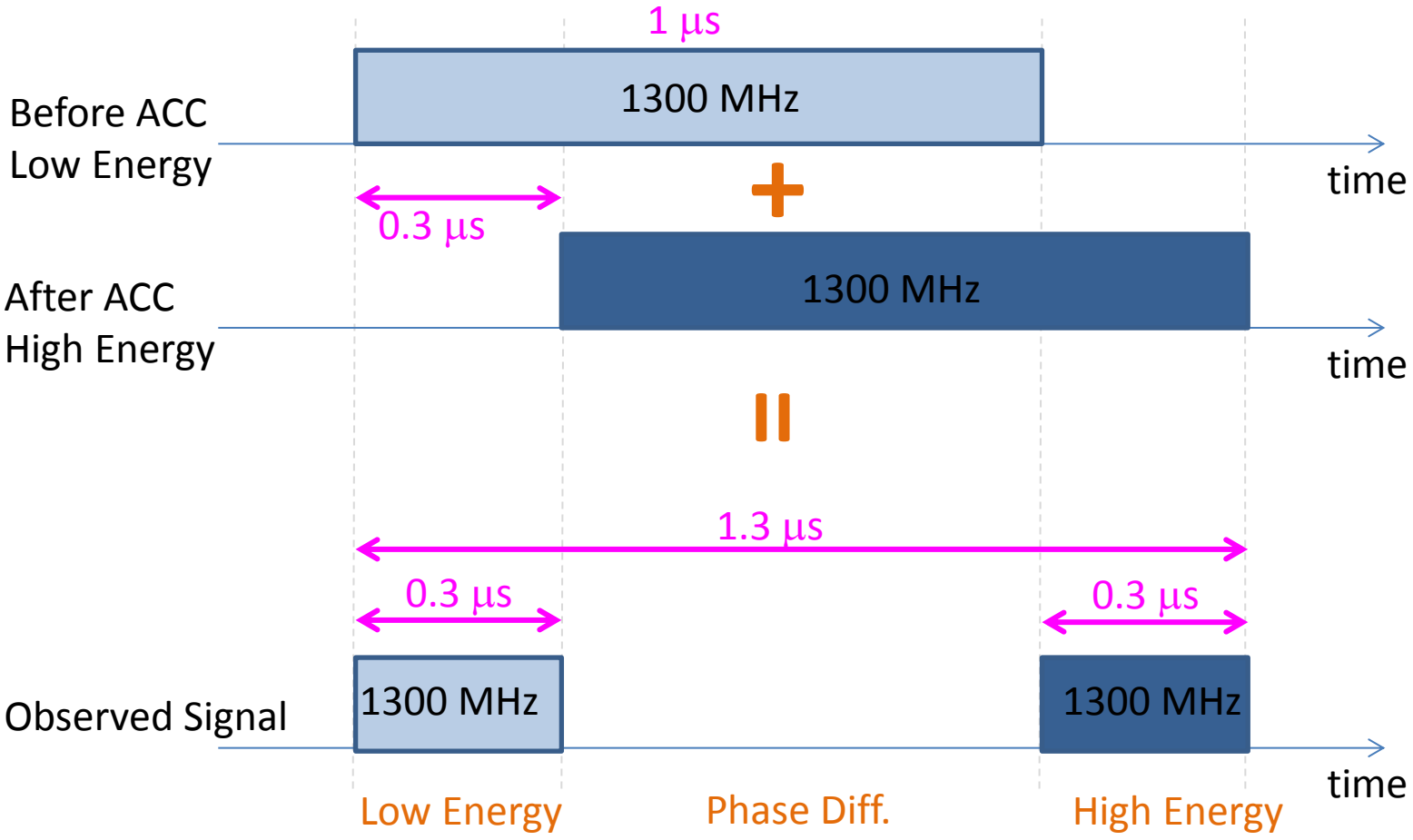




1.3 GHz component is proportional to phase difference
(Also proportional to amplitude difference)

simple summary

- Head and tail part is useful to detect beam position.
- Overlapped part is useful to detect beam phase.



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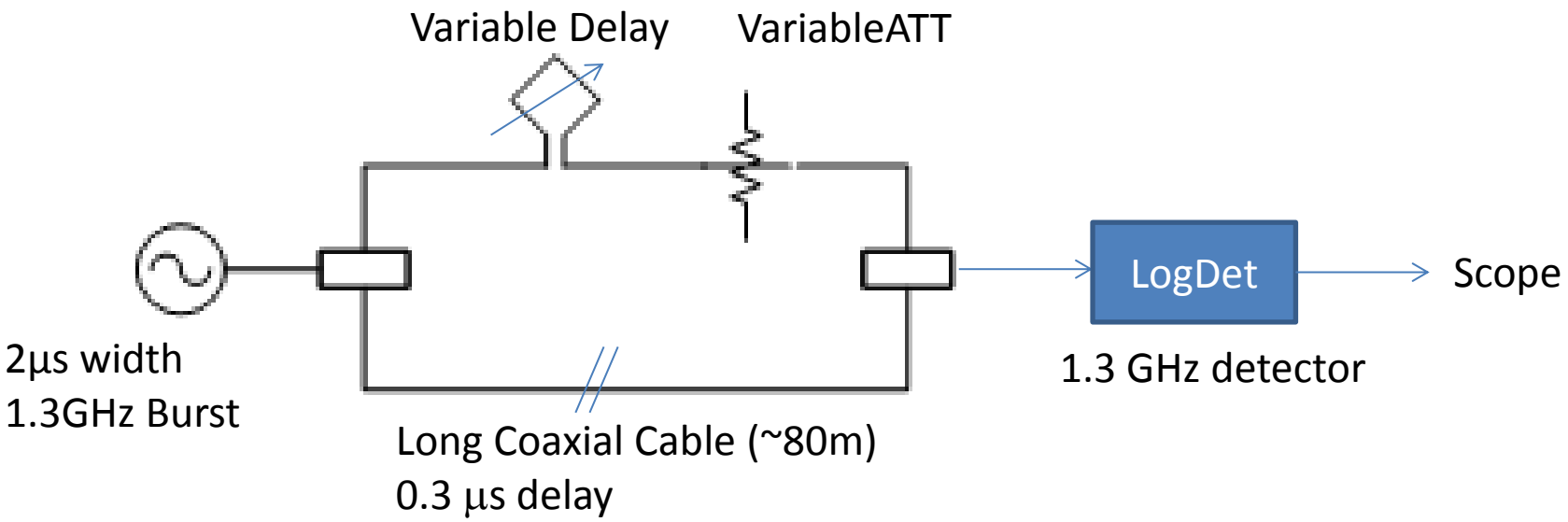
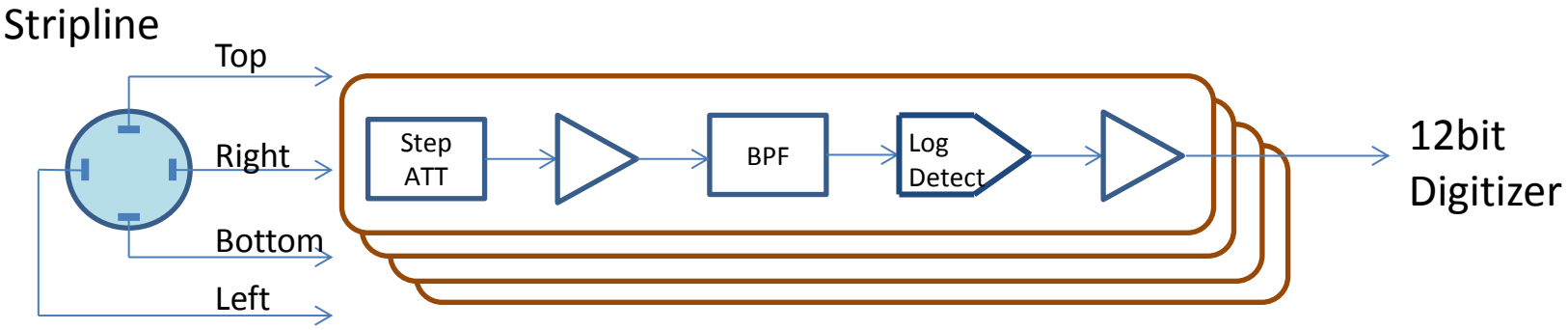
3. Bench Test

- 1.3 GHz burst signal -> Split -> Delay -> combine
- Variable attenuator to adjust cable attenuation
- Variable delay to simulate beam delay



Block Diagram of Log-Ratio Detector

- 1.3 GHz
- Log detector for BPM
- NIM module



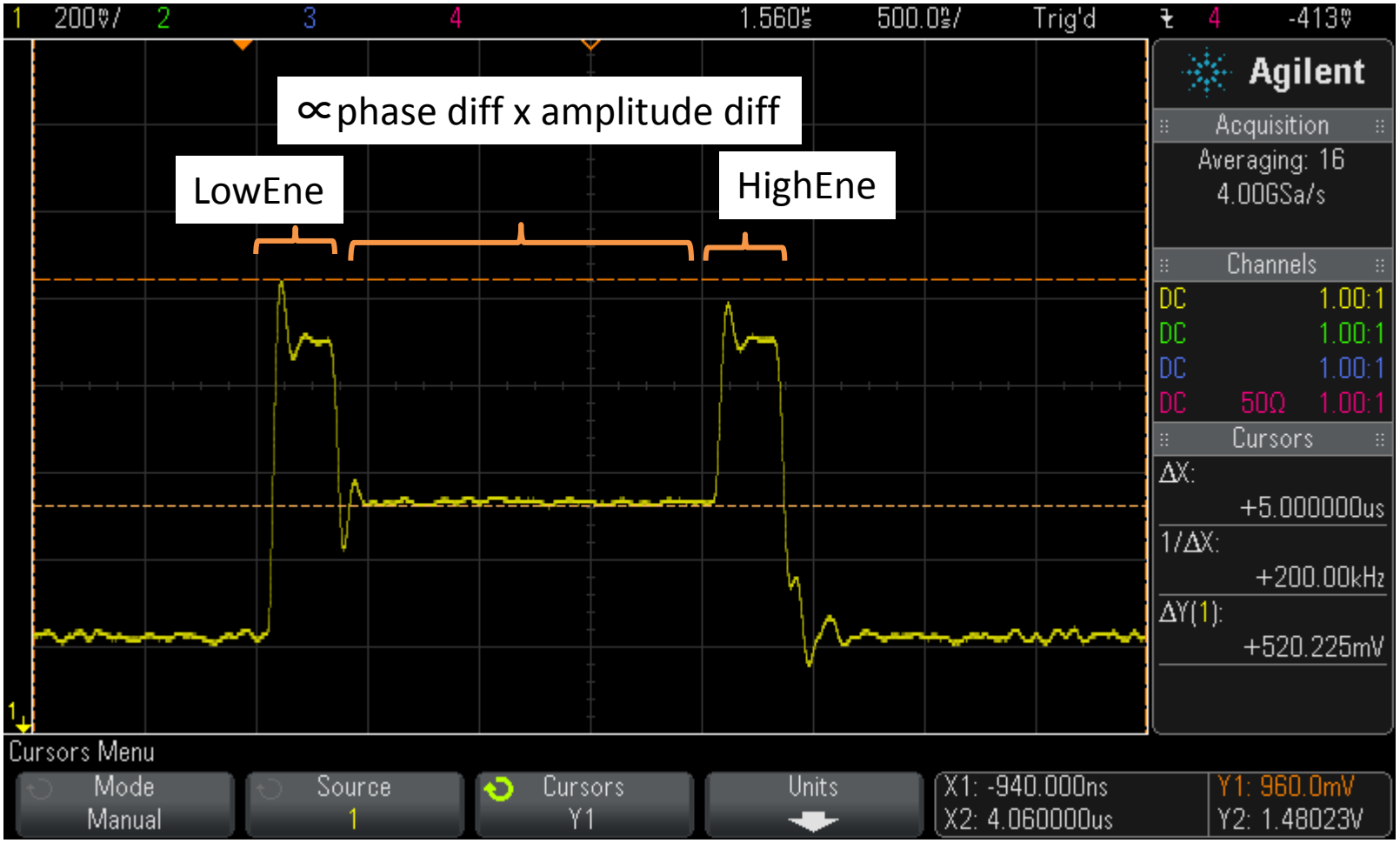
Bandwidth ~ 10MHz
Digitizer : Yokogawa SL1000, 100MS/s

Example 1

- Variable attenuator is adjusted to simulate "no beam loss"
- Phase shifter is adjusted to cancel 1.3 GHz component

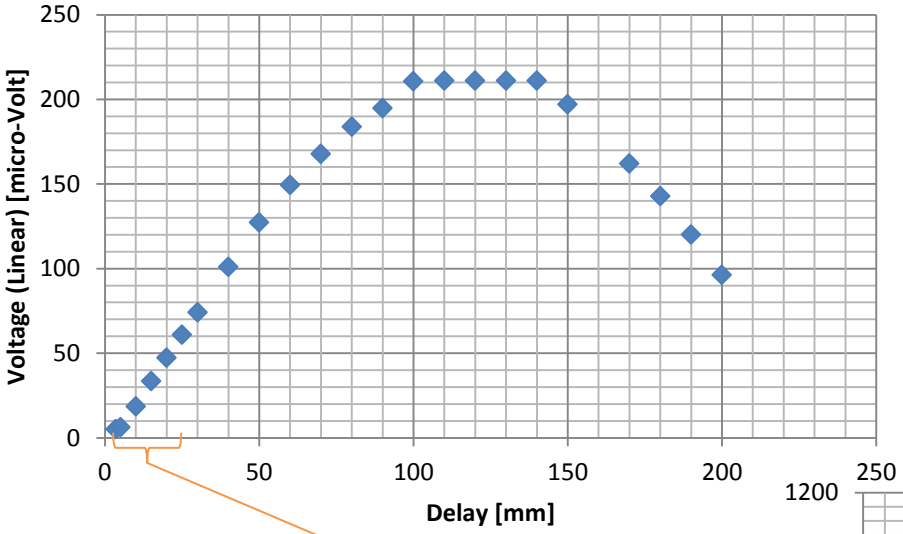
Example 2

- Introduce some phase delay



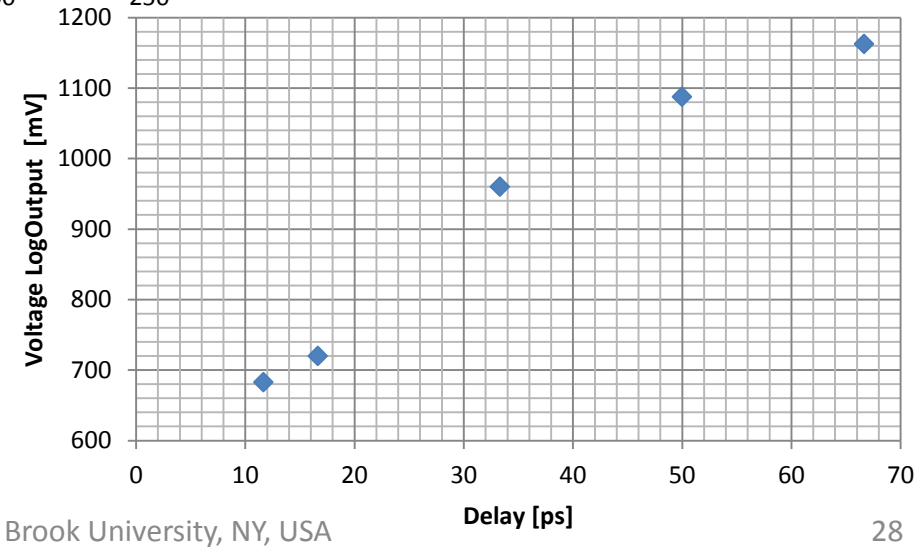
Phase sensitivity

- Delay length [mm] vs Output Voltage
- Enough for rough adjustment (several pico-sec order)



1300 MHz = 770 ps = 230 mm

$\lambda/2$ = 115 mm



Delay [ps] vs Log Detector

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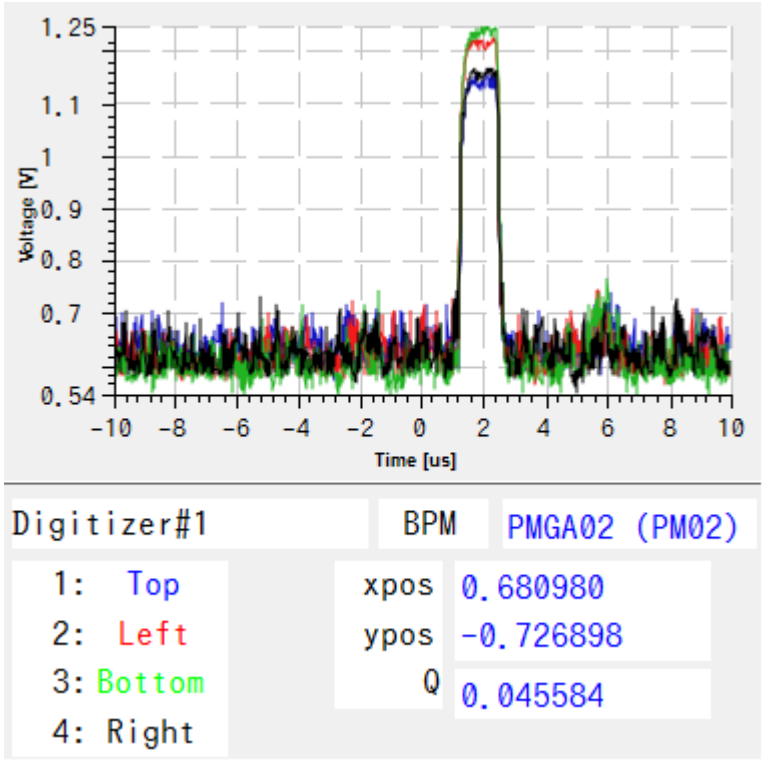
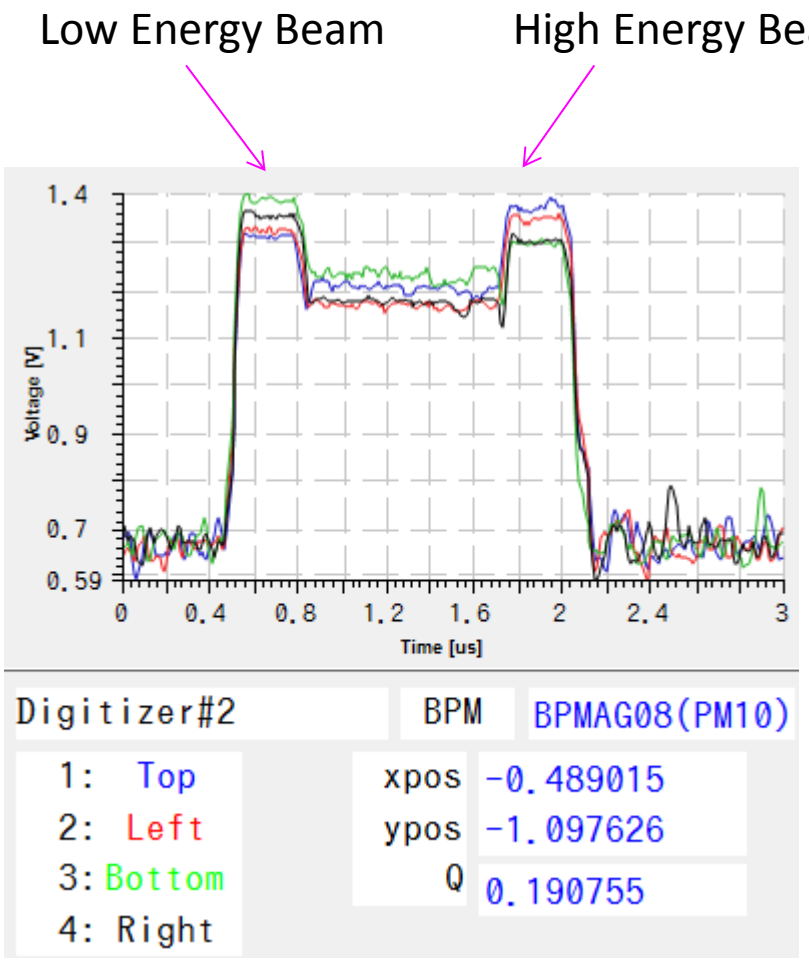
4. Beam Measurement : Burst Beam

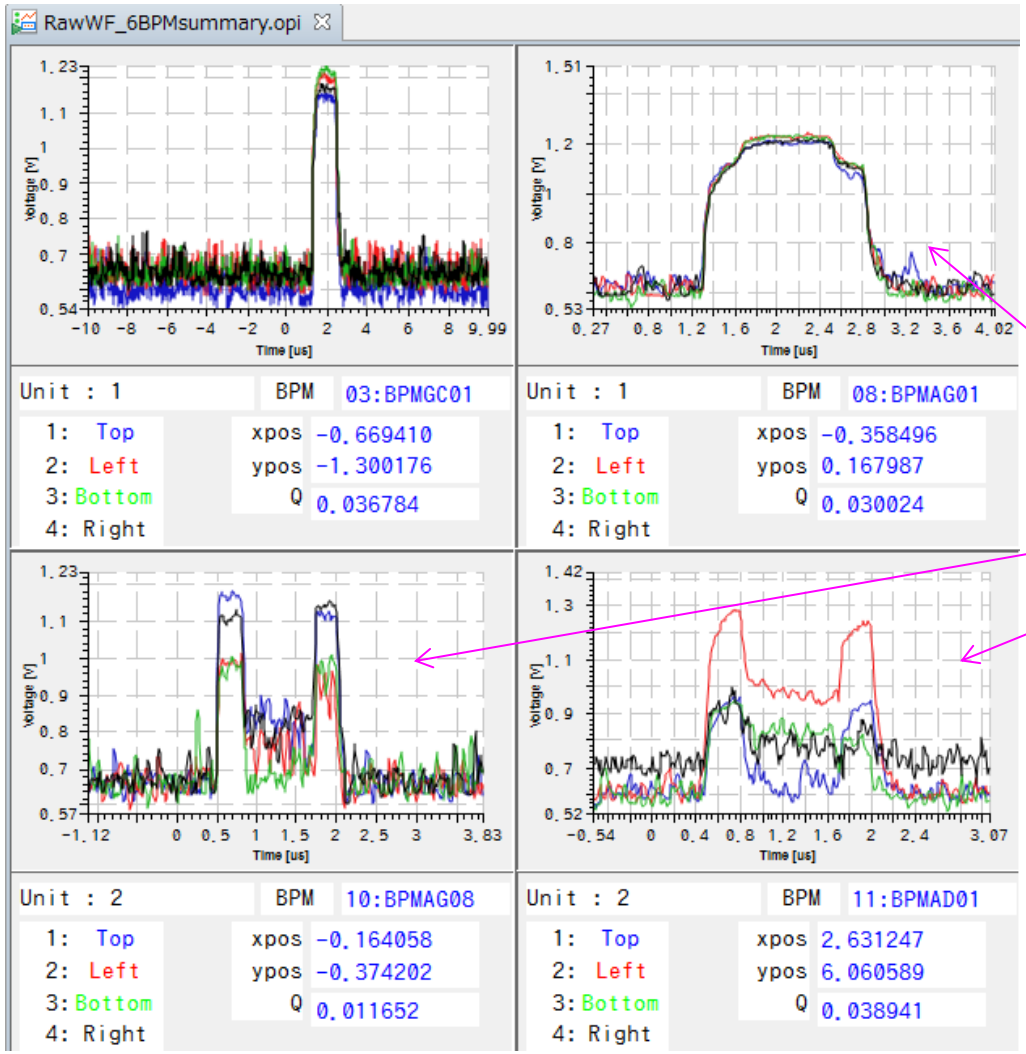
- Example : signal of single-beam section
  - 1 μs pulse duration from GUN
- Output signal of Log-ratio detector



Burst beam at two-beam section



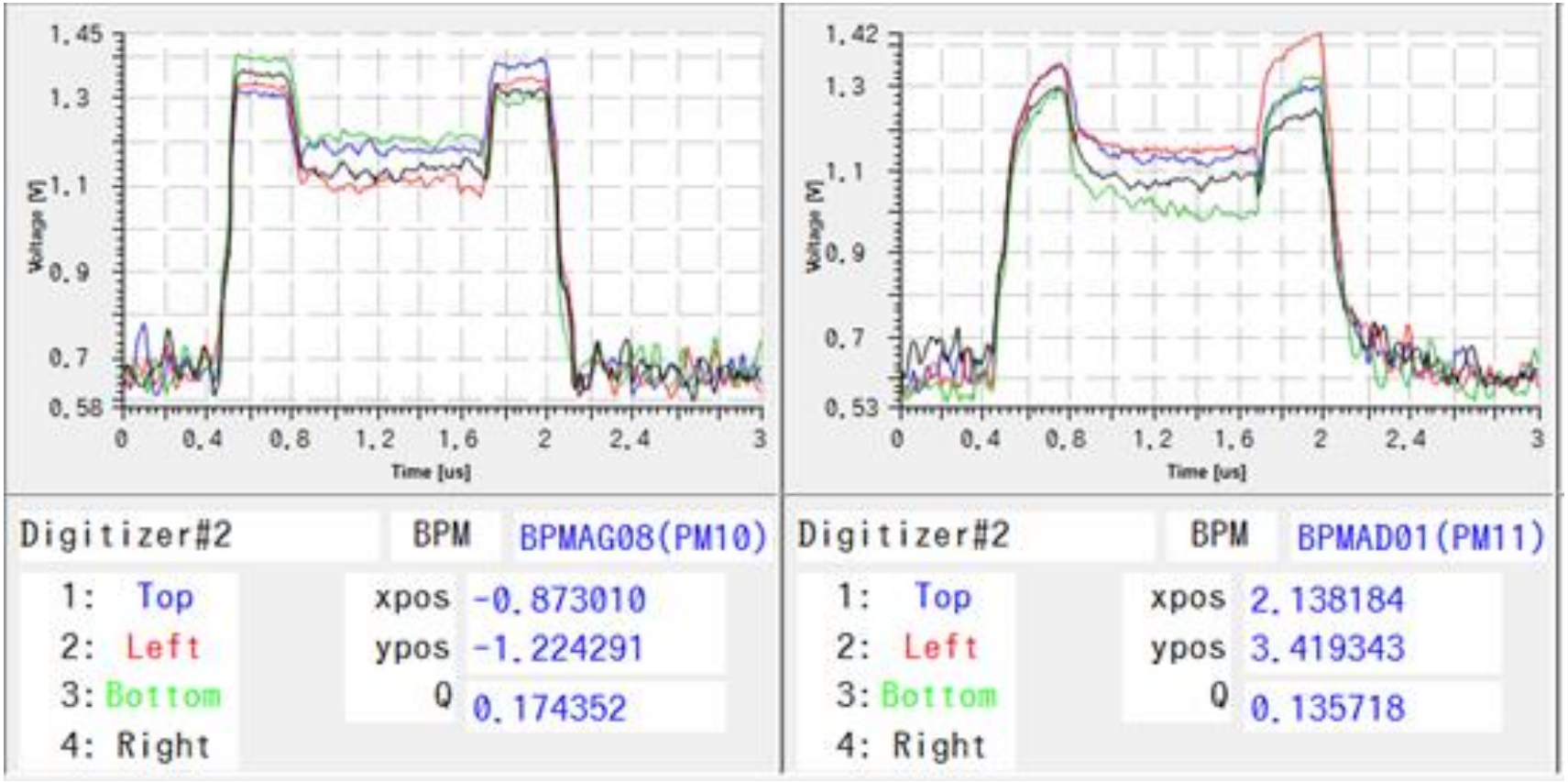
During the beam tuning



Different location

Beam Phase before/after SC cavity

- PM10, 11 signal
  - (almost) same distance from SC cavity center
  - Useful to adjust initial bunch phase



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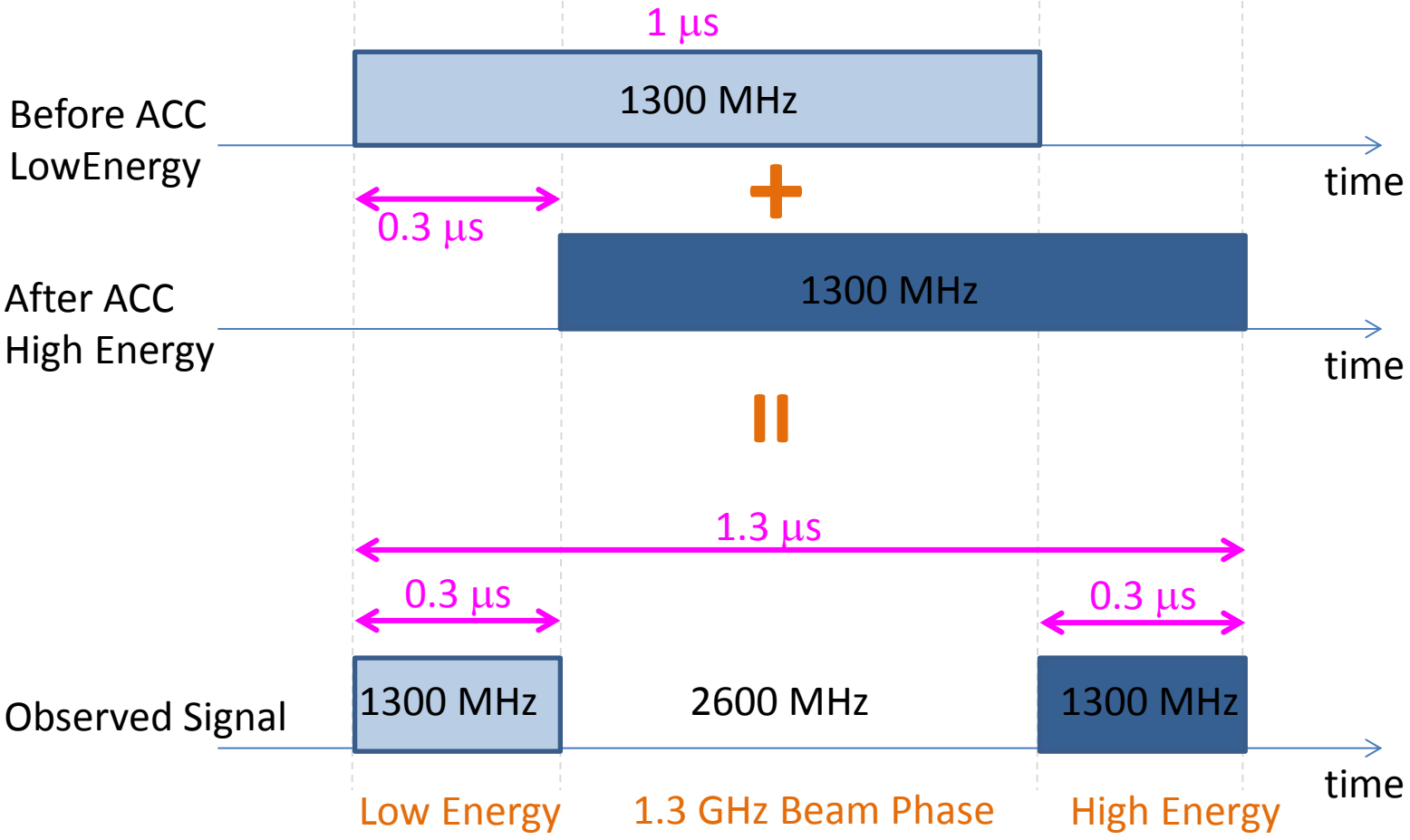
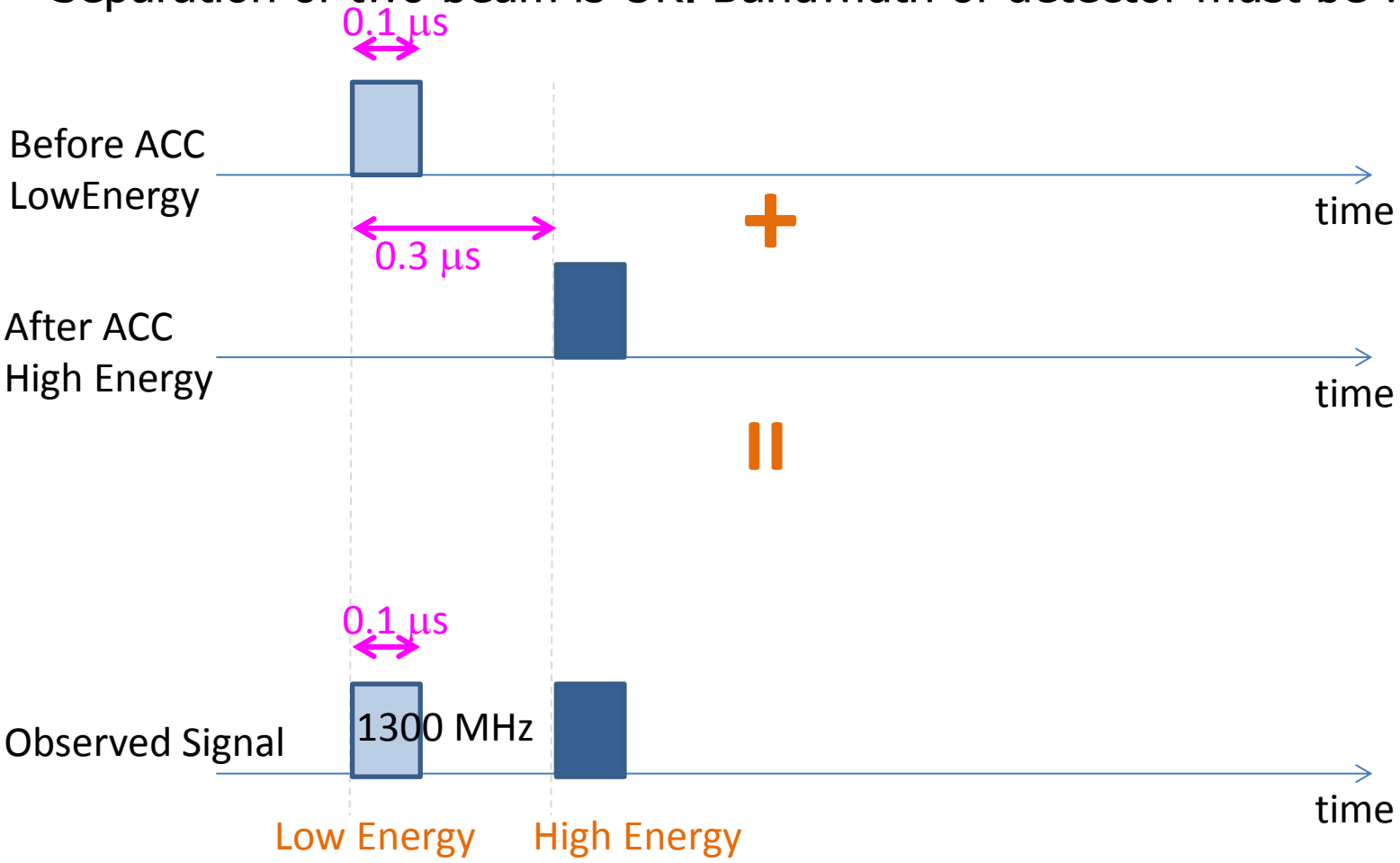
Before discussion of CW beam ...

- Start from 1 μs pulse again. (same figure as previous example)



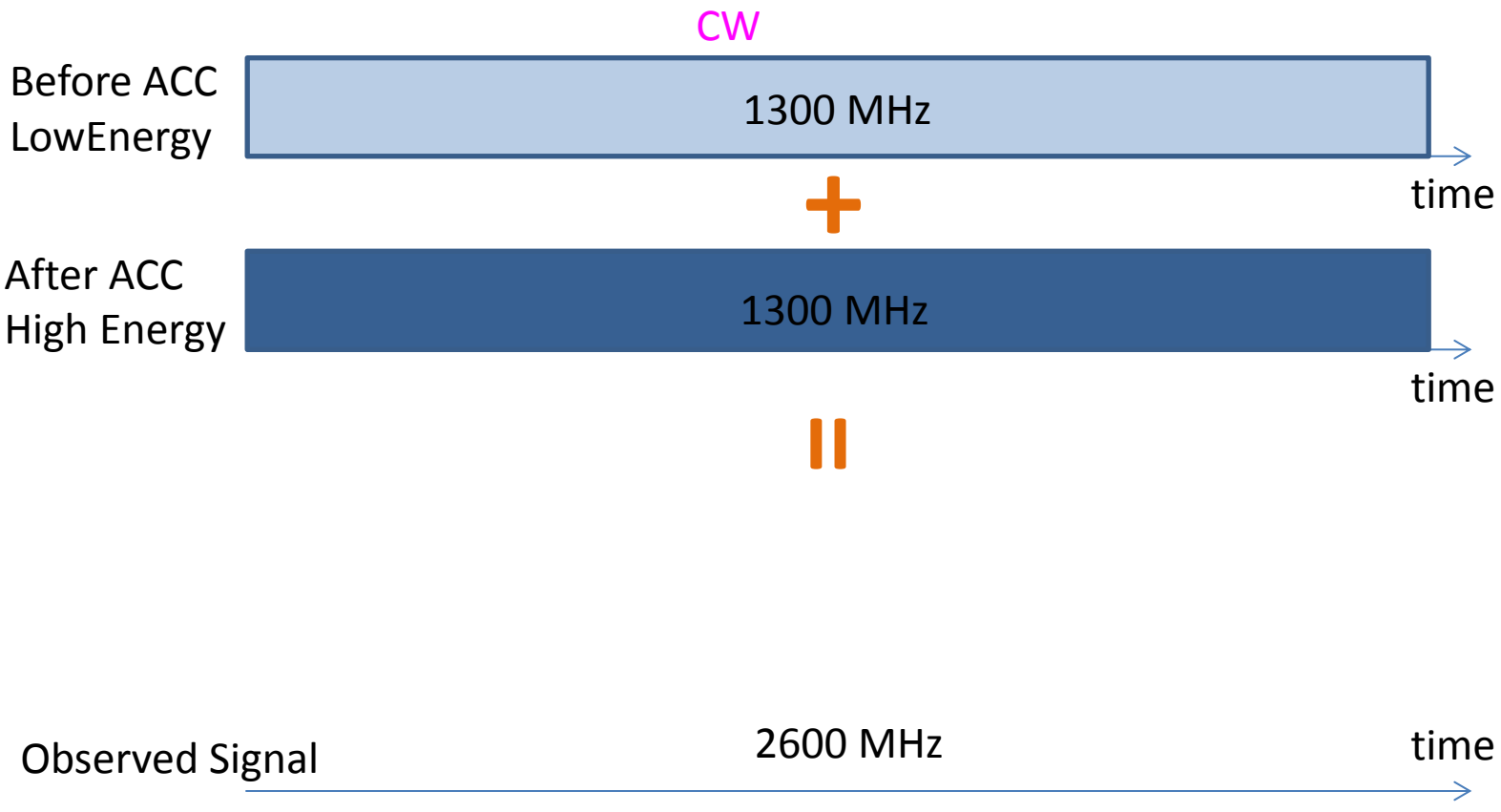
Short macro-pulse (or single bunch)

- Example : 100 ns pulse (shorter than circumference)
- Separation of two beam is OK. Bandwidth of detector must be wide.



Shorter pulse width will result in less position resolutions.

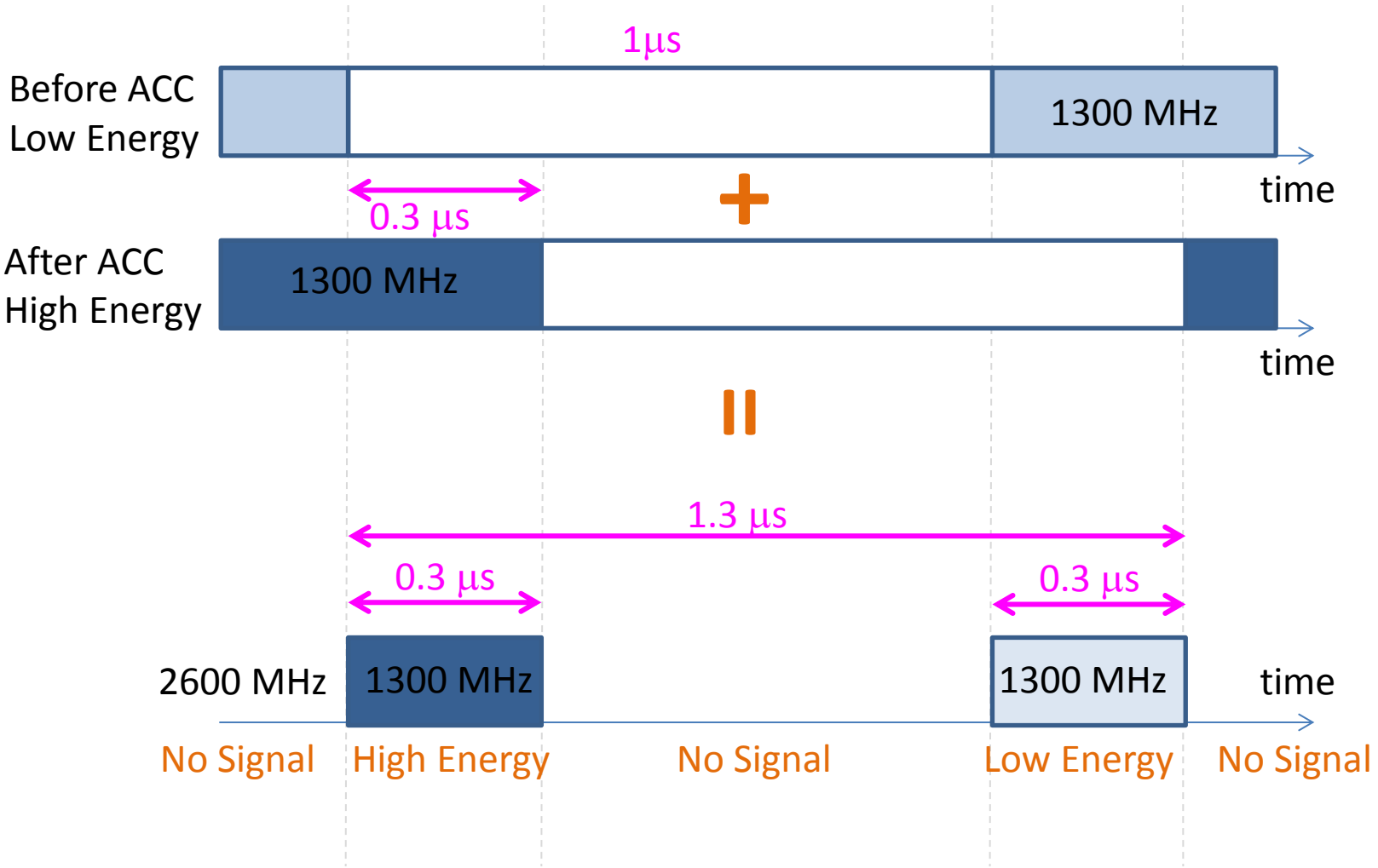
In case of CW Beam ...



No Signal in 1300 MHz !!

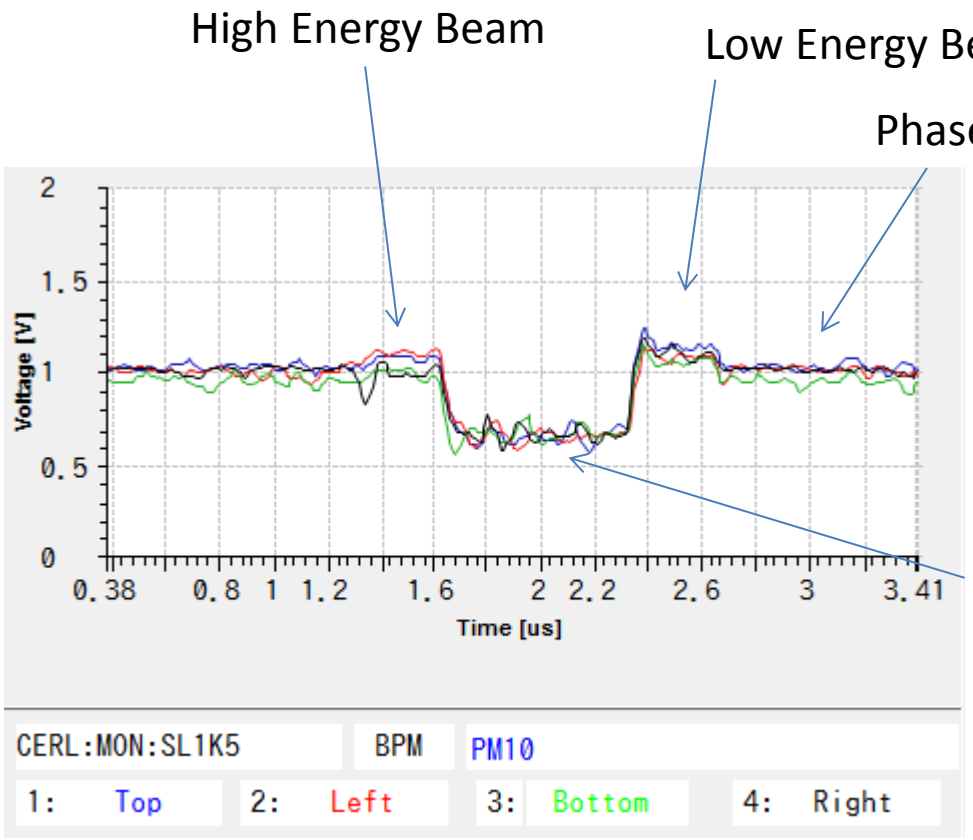
(Just the phase difference x current difference of two beams)

CW Beam with "Short Gap"



1μs gap with 5 Hz is negligibly small compared to CW beam current.
Short gap can be easily introduced by a Pockels cell.

Measurement Example during CW operation



Summary

- Non-destructive beam-position measurement technique at the two-beam section of cERL has been presented
  - This very simple method can be applied any type of 1-turn ERLs.
  - We didn't install screen monitors with a hole.
- Measurement with beam was successfully performed
- Phase sensitive part was very effective at the early-stage of the beam commissioning
- Beam position under CW beam condition is achieved by introducing a short gap in laser.

Thank you for your attention!