Beam instrumentation at SuperKEKB

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for the KEKB beam monitor group

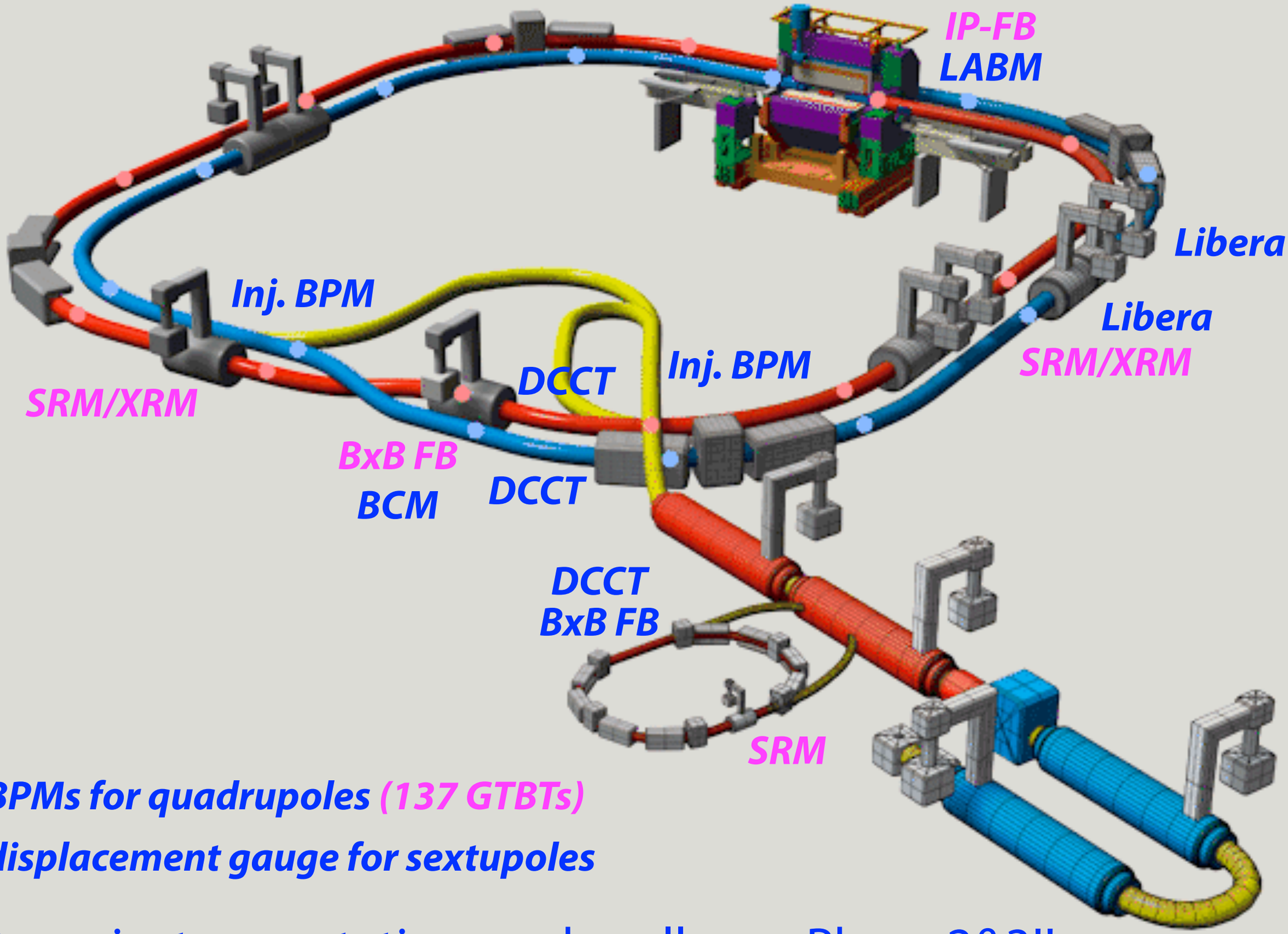
The 23rd KEKB Accelerator Review
8-10 July 2019

Outline

- Overview of the beam instrumentation at SuperKEKB
- Recent updates & future prospects in the SuperKEKB beam monitors
  - Optics measurements by gated turn-by-turn monitors
  - Beam size measurements by synchrotron radiation monitors
  - Bunch-by-bunch feedback system
  - Fast IP-orbit feedback system
- Summary

Beam abort system was reported by H. Ikeda.

The SuperKEKB beam instrumentation



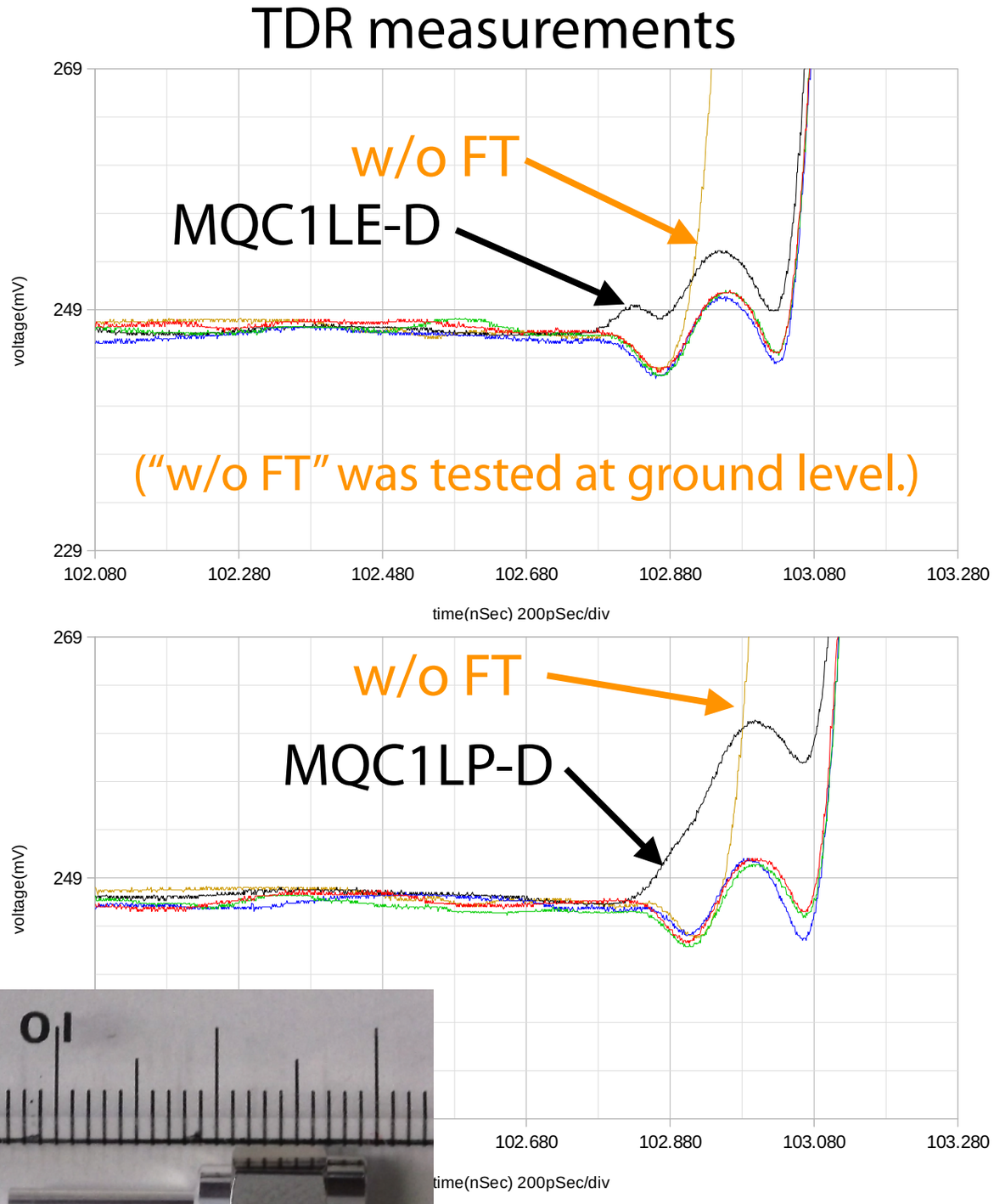
902 BPMs for quadrupoles (137 GTBTs)

218 displacement gauge for sextupoles

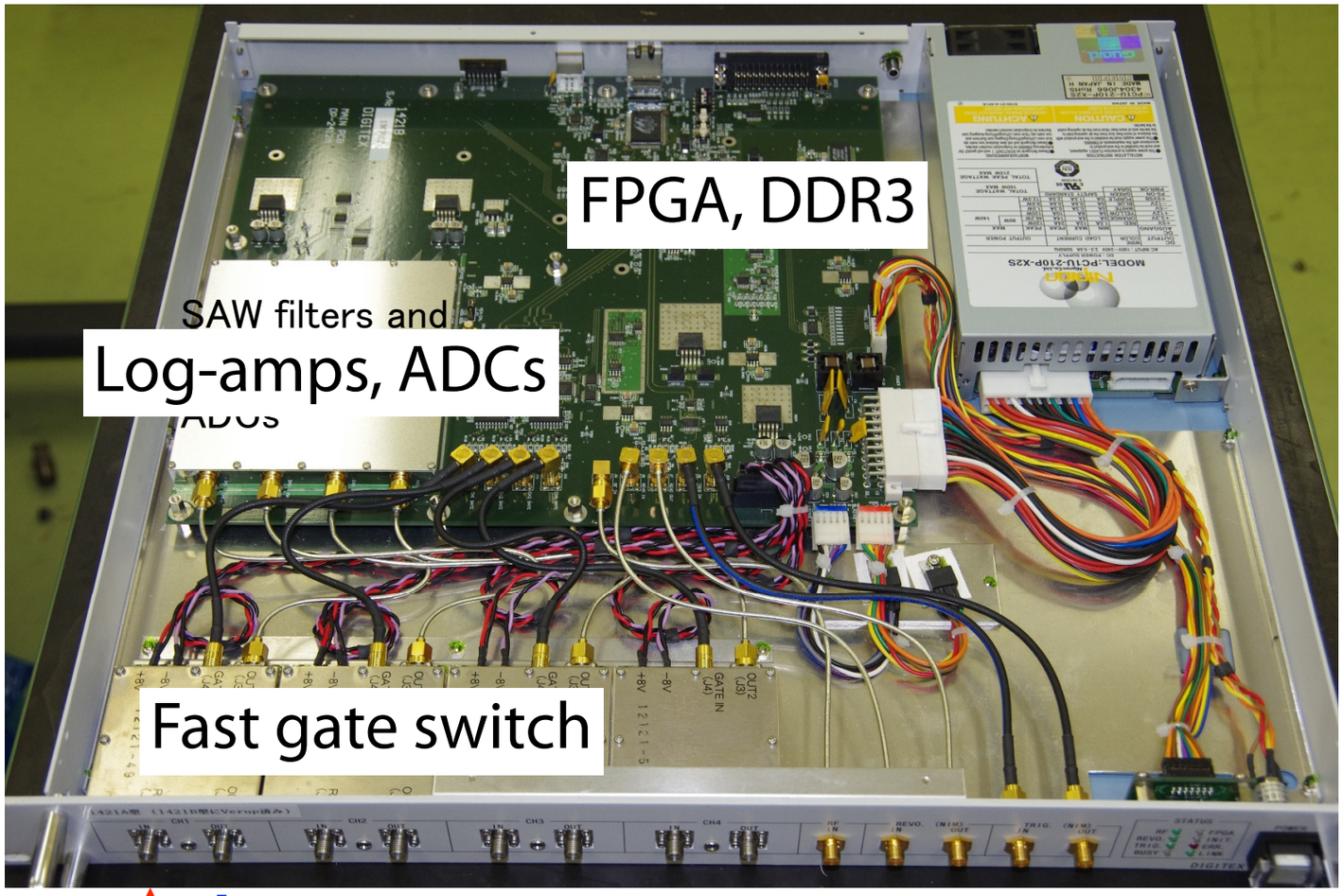
Beam instrumentation work well over Phase 2&3!!

Connection failure in MQC1LE/LP

- Most likely the outer conductor was damaged by strong crimping.
- Smooth operation with healthy three electrodes
- Plan to replace with new cables having a modified SMA connector in middle August



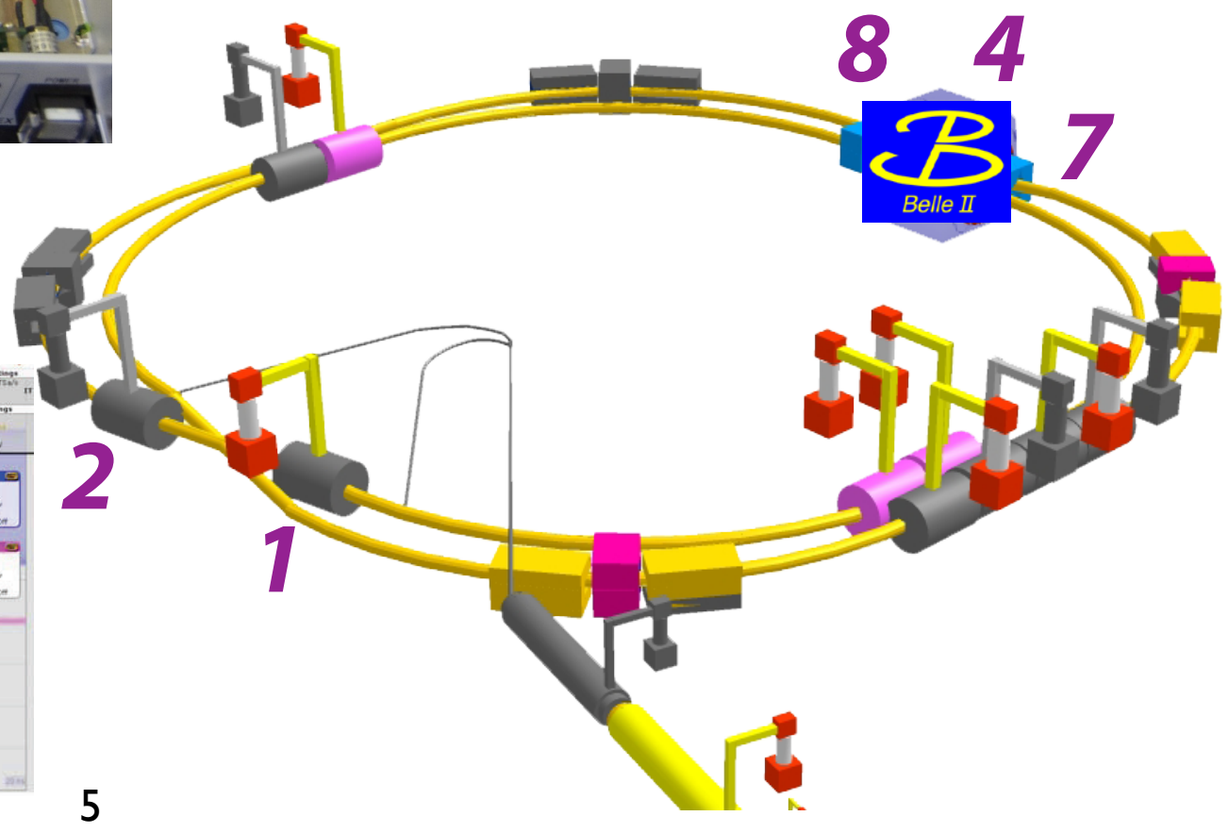
Gated turn-by-turn monitors (GTBT)



- Fast RF switch : Hittite HMC232LP4
- Log amplifier : AD ADL5513
- ADC : BurrBrown 14-bit ADS850
- FPGA : Spartan6 XC6SLX100T

68 and 69 GTBTs in HER and LER

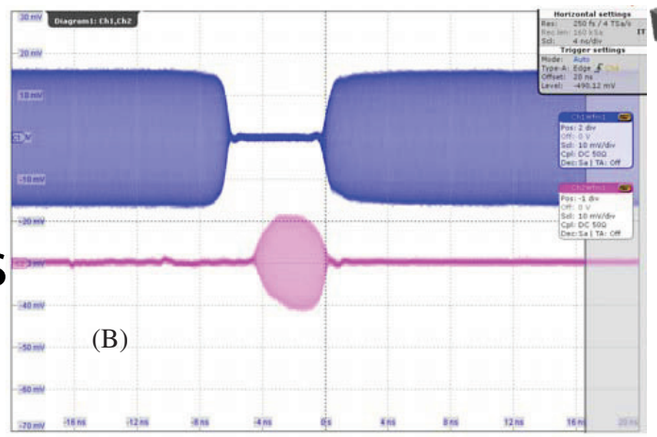
22 GTBTs added since Phase 2



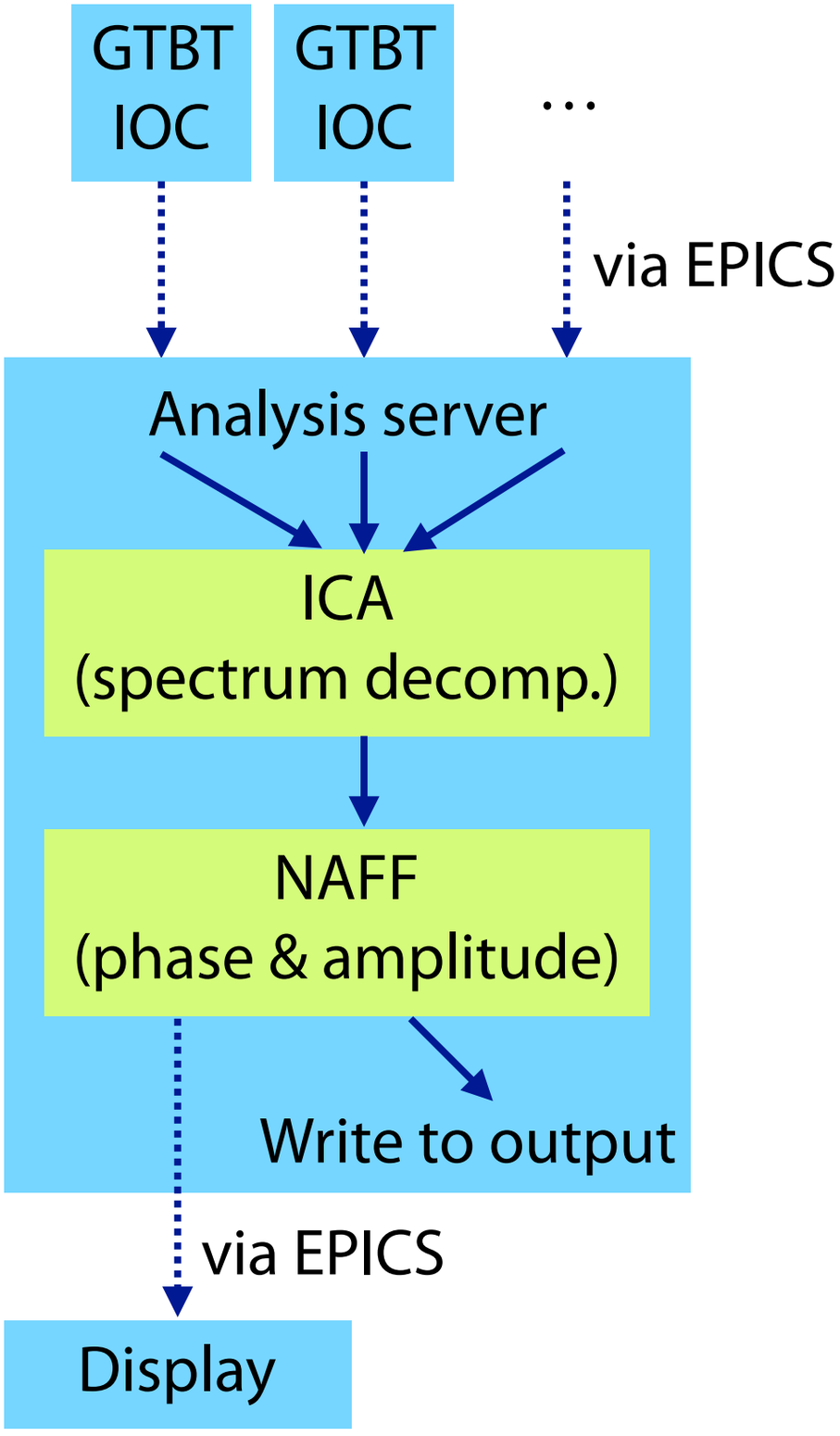
508MHz narrow band detector (COD)

BPM electrode

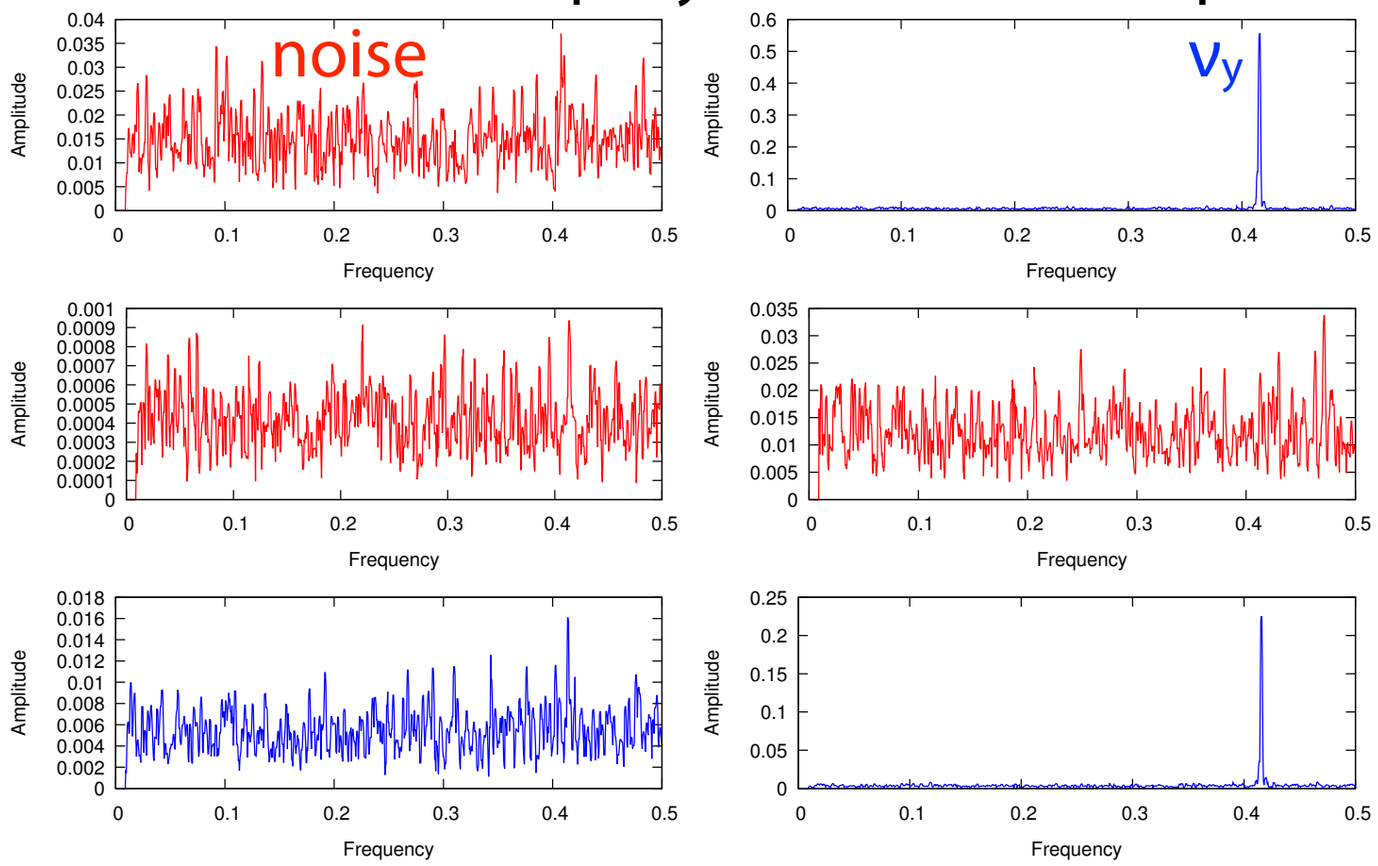
- Switching noise 2 mVpp
- Fast rise/fall time ~0.6 ns
- Good isolation > 80 dB

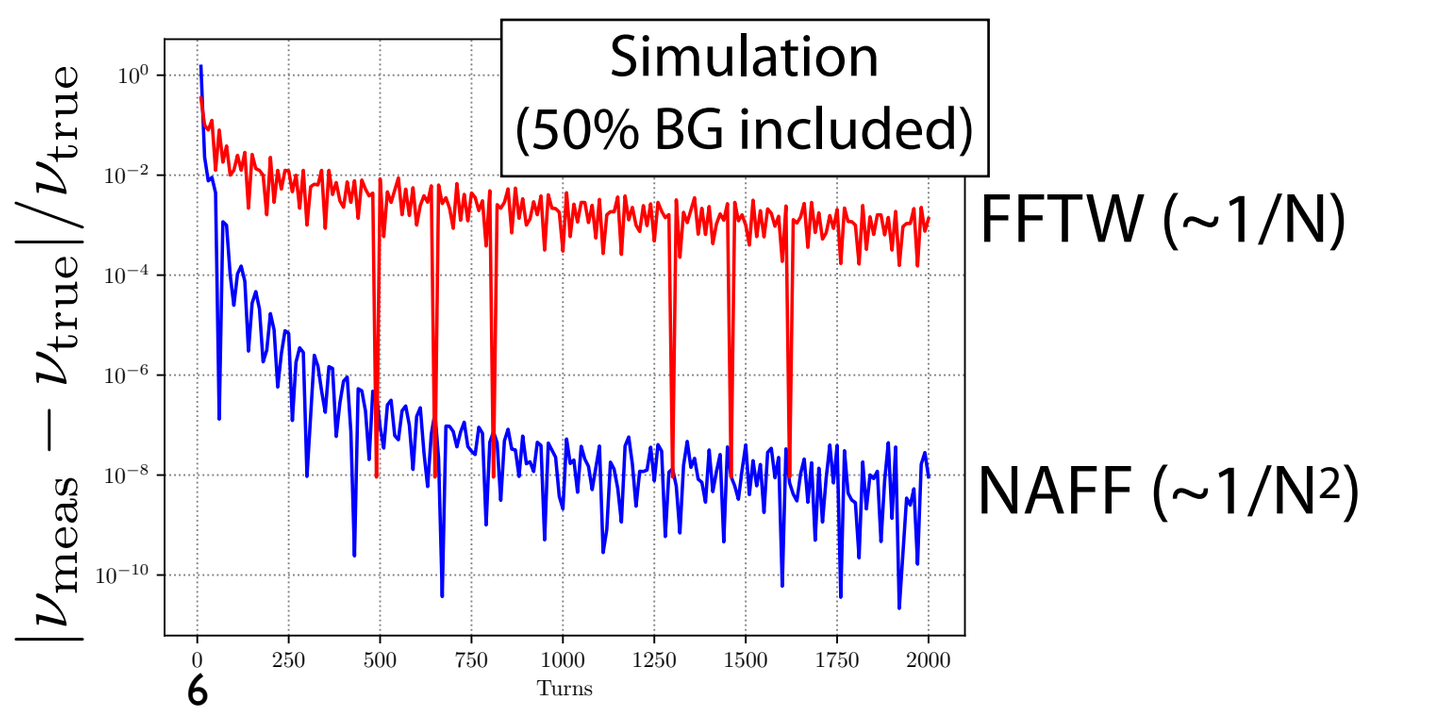


GTBTs' data pipeline

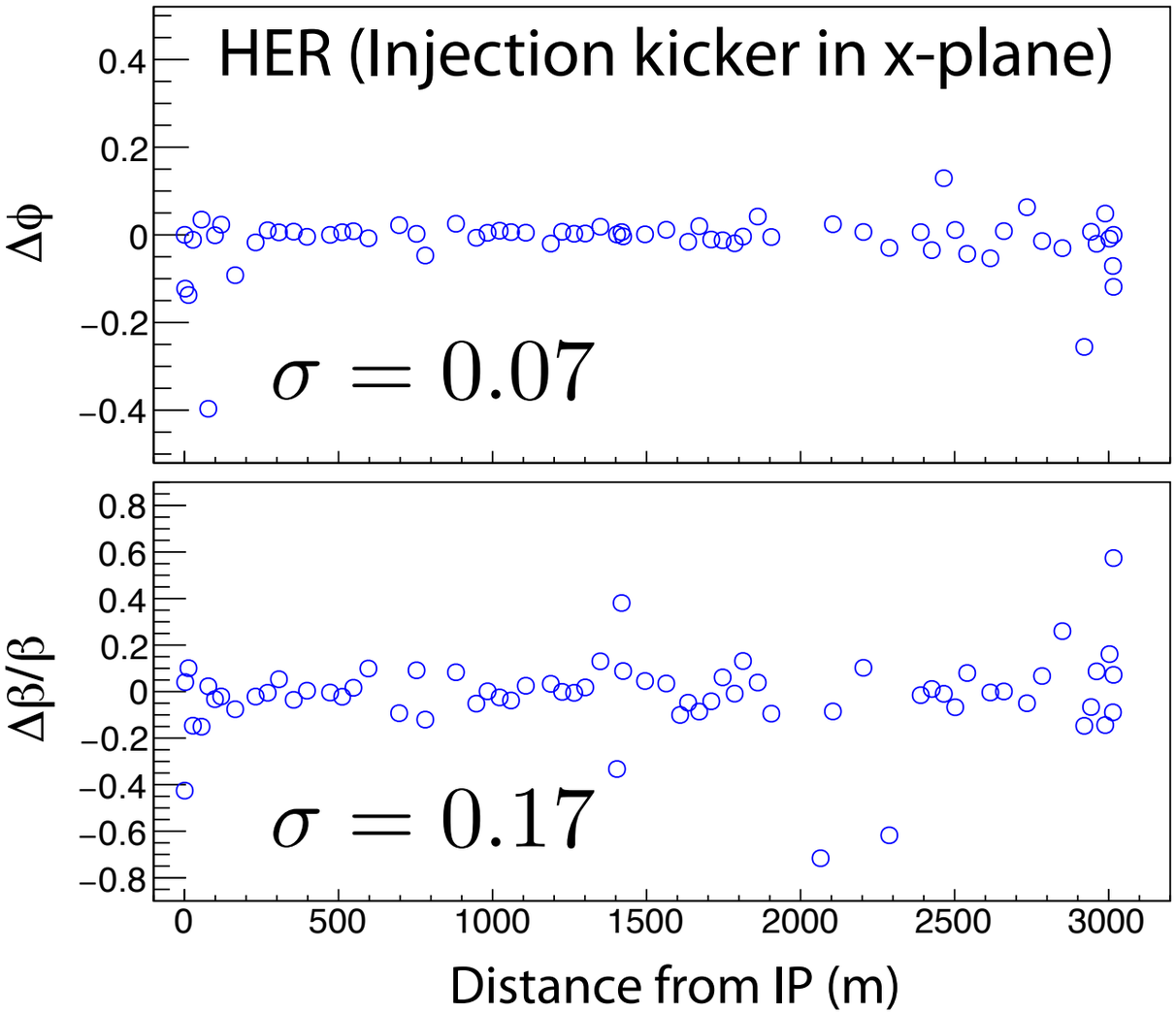


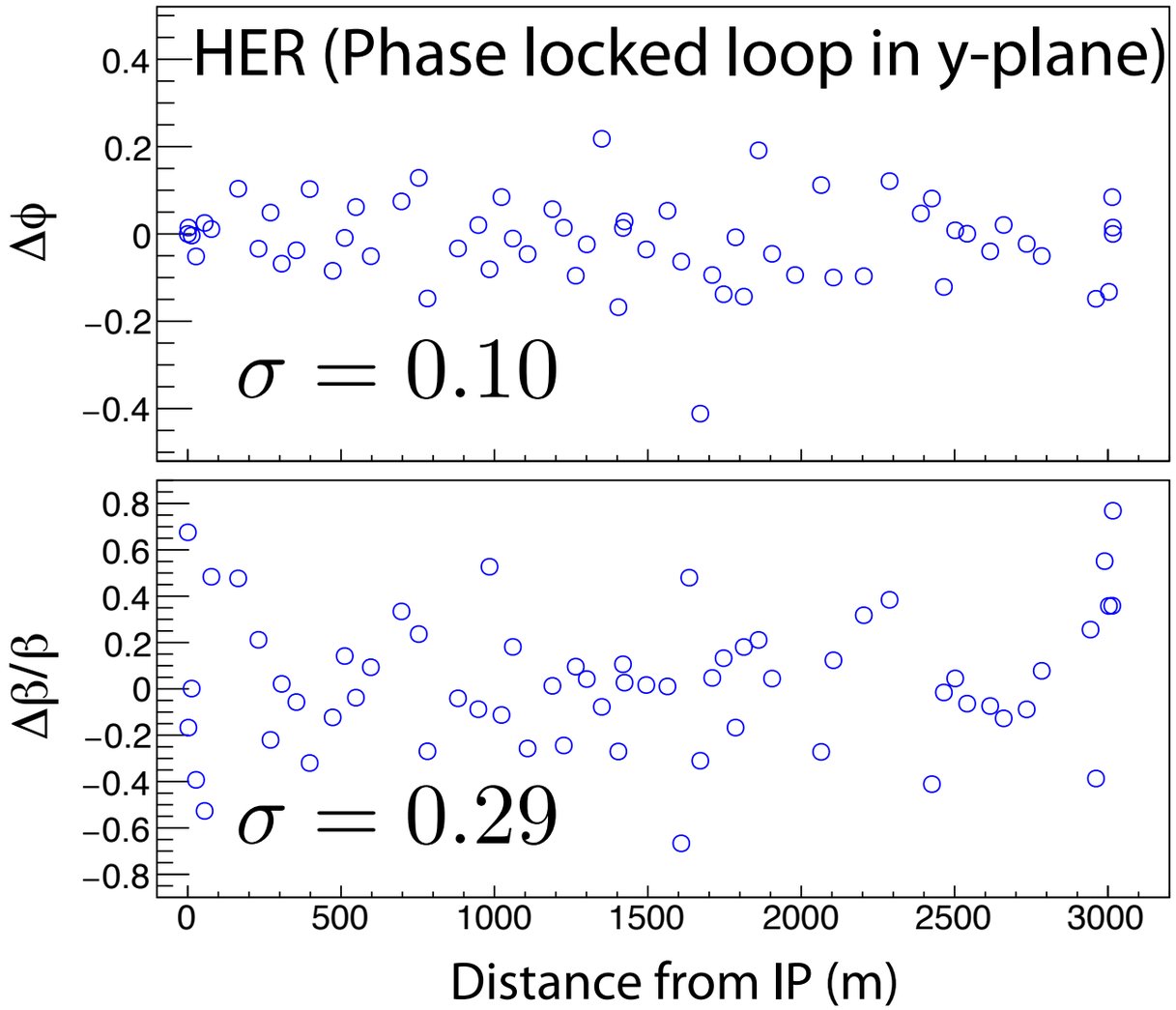
Data into 6 comp. by ICA (blue = accepted)





Phase advance and β function measurements

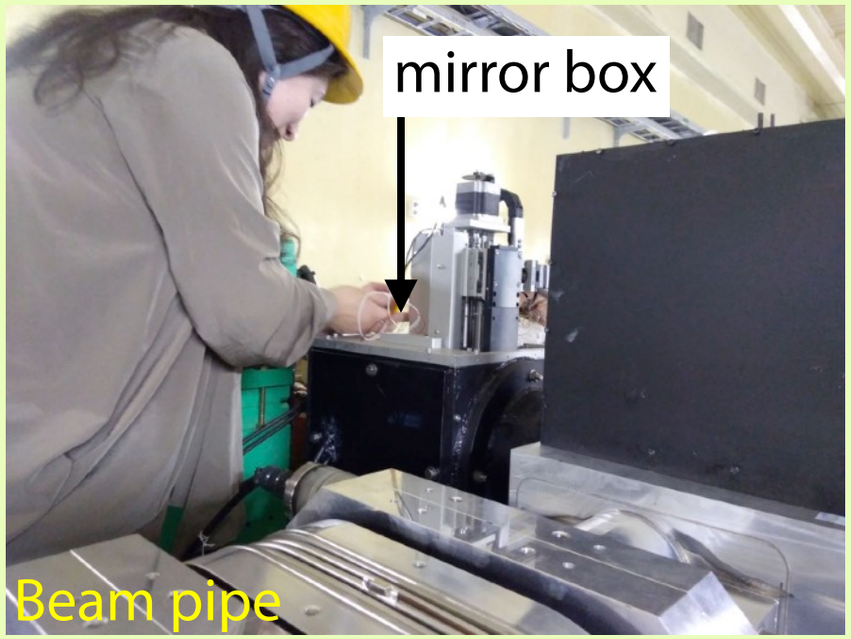


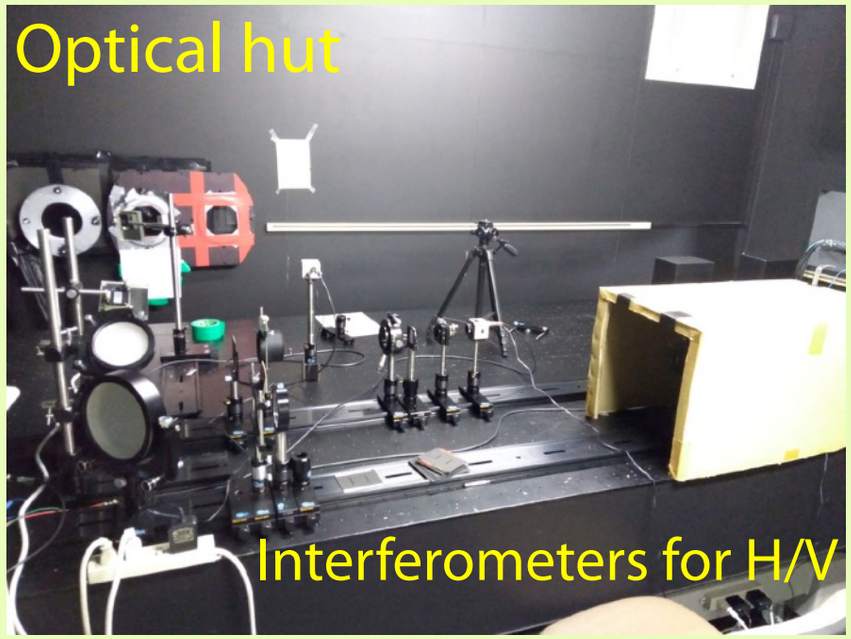


- β measurements are sensitive to GTBT gain calibration.
- Excitation by injection kicker gives better results than that by PLL, since PLL limits kick amplitude lower to avoid quick beam loss.
- Extended to investigations on chromatic coupling, K-modulation, etc.

Synchrotron radiation beam size monitors

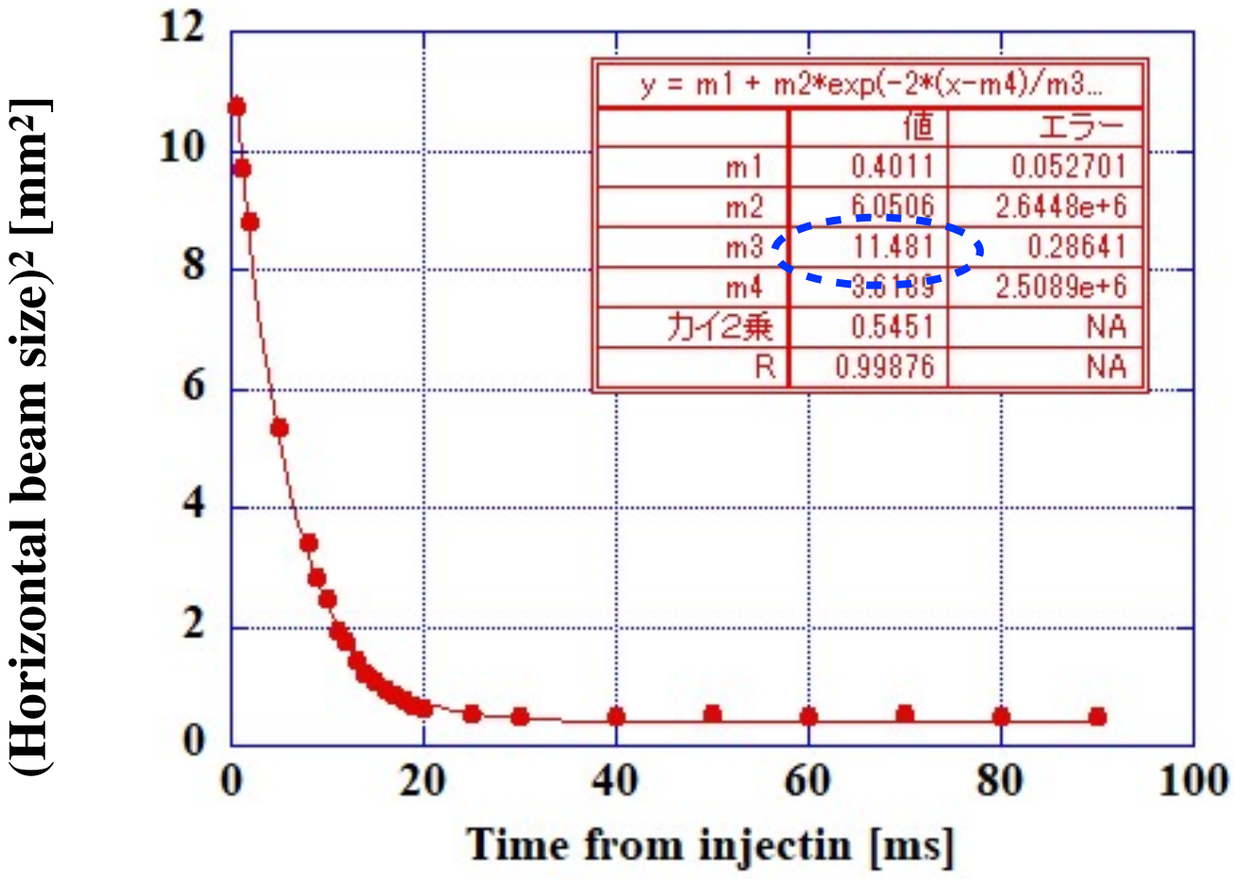
"Visible" SR monitor

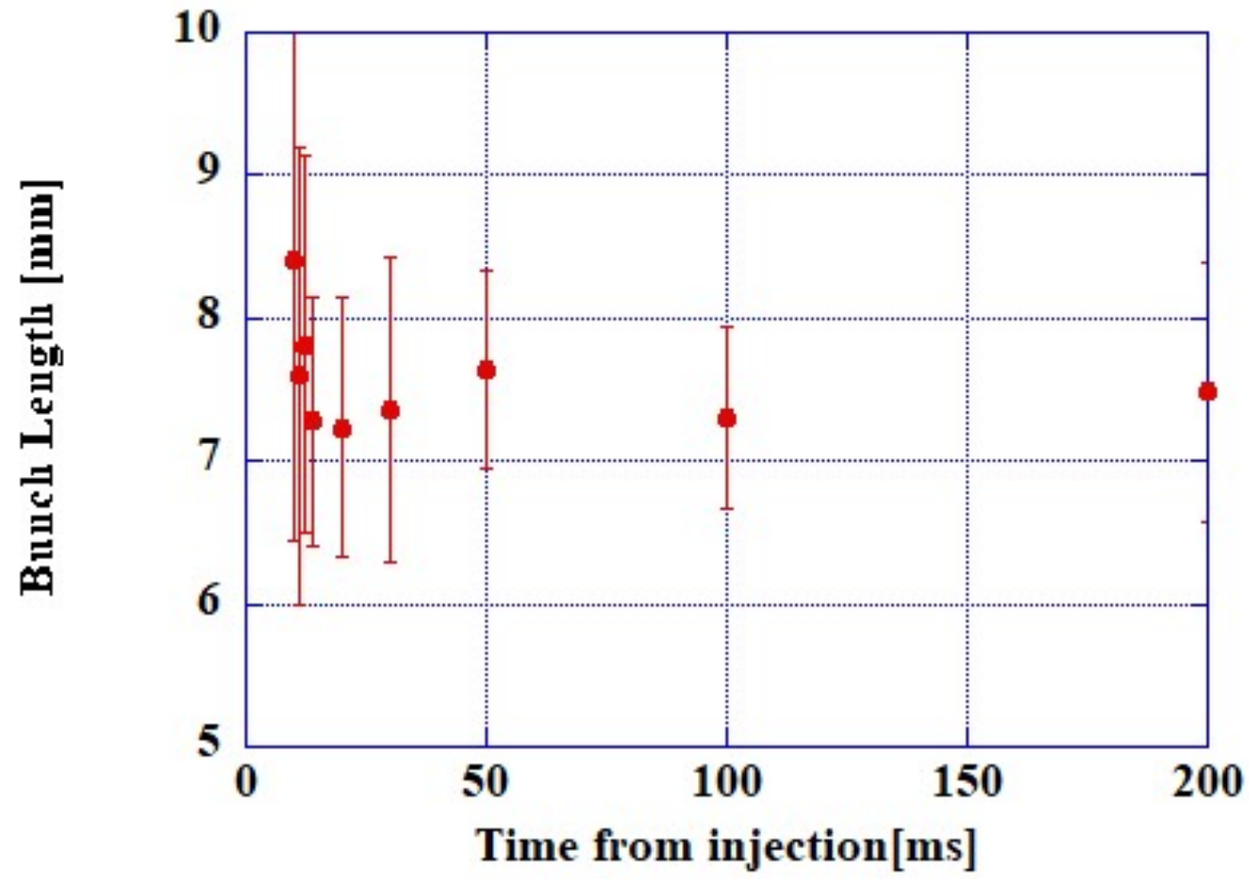




X-ray monitor

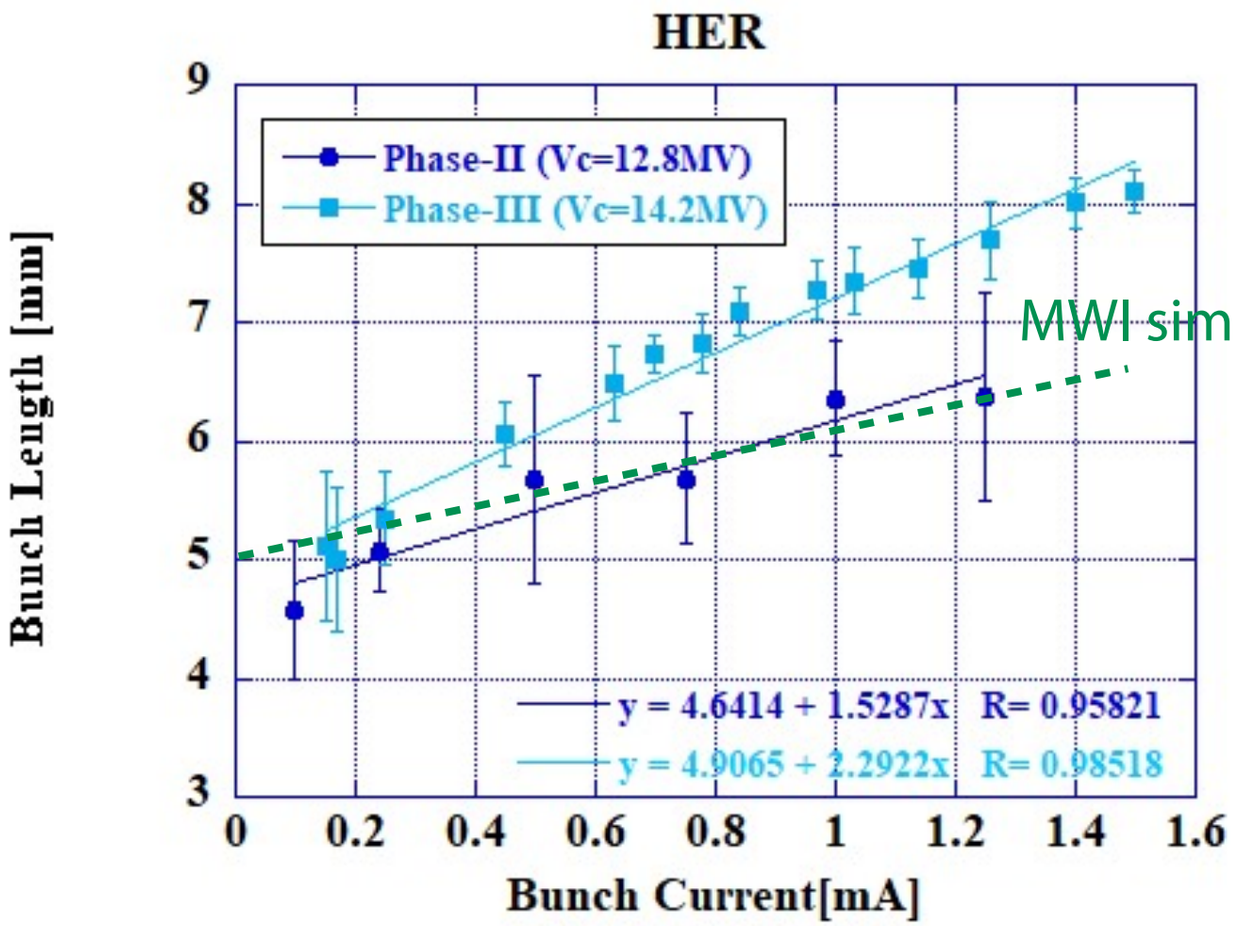
Beam size measurements in DR

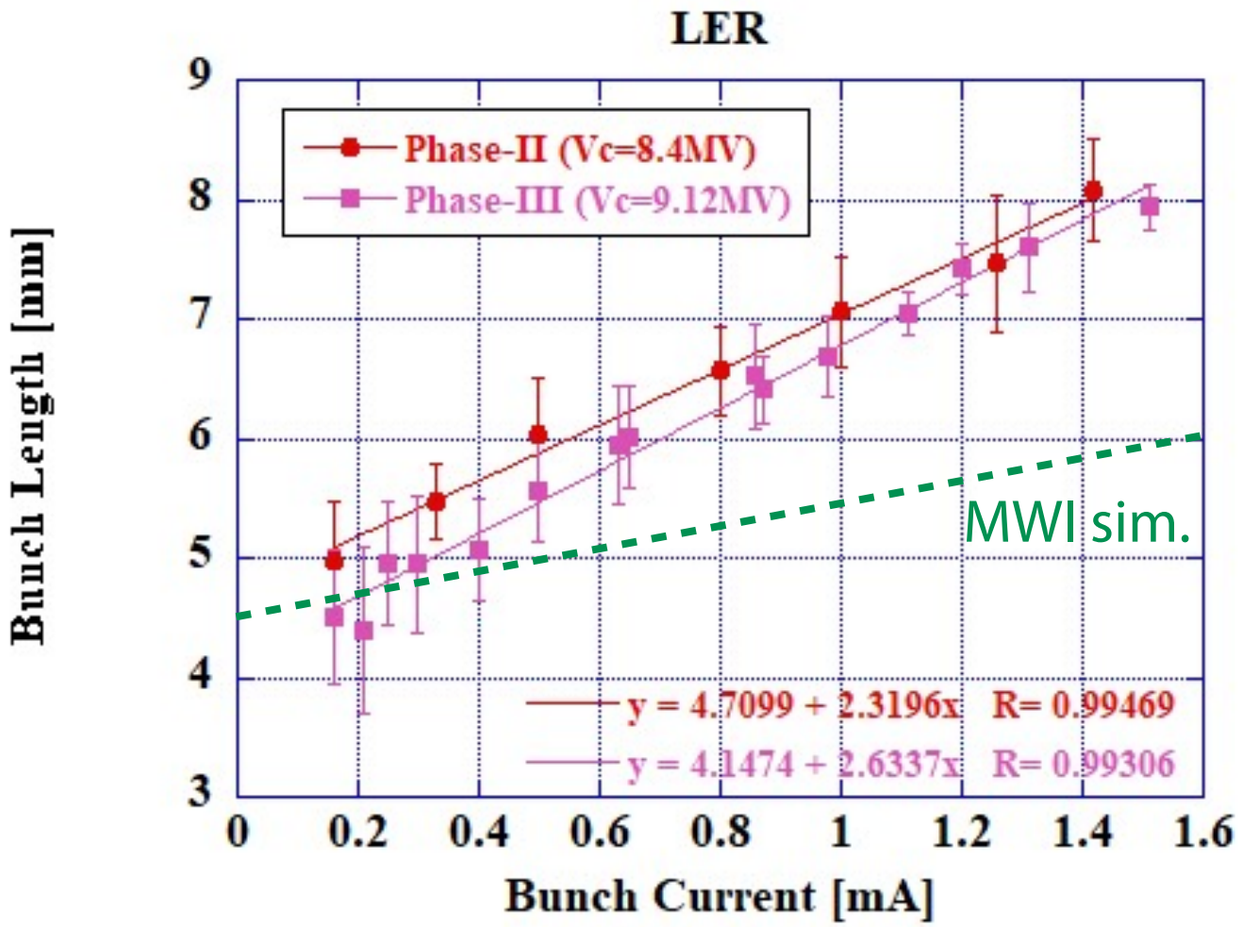




- Horizontal beam size measurements by gated camera
  - The Bestfit damping time 11.5 ms is consistent with the design value (11 ms).
  - Refraction optics in Phase 1-2 was replaced with reflection optics in Phase 3.
  - Increased light intensity enabled a single-shot measurement.
- Bunch length measurements by streak camera
  - Well damped before the extraction ~40 ms

Bunch length measurements in HER & LER

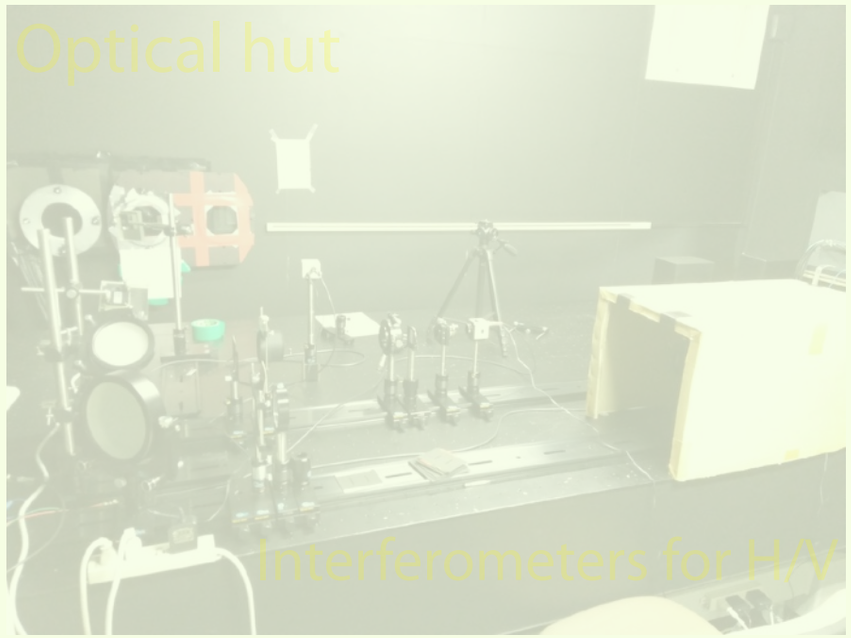




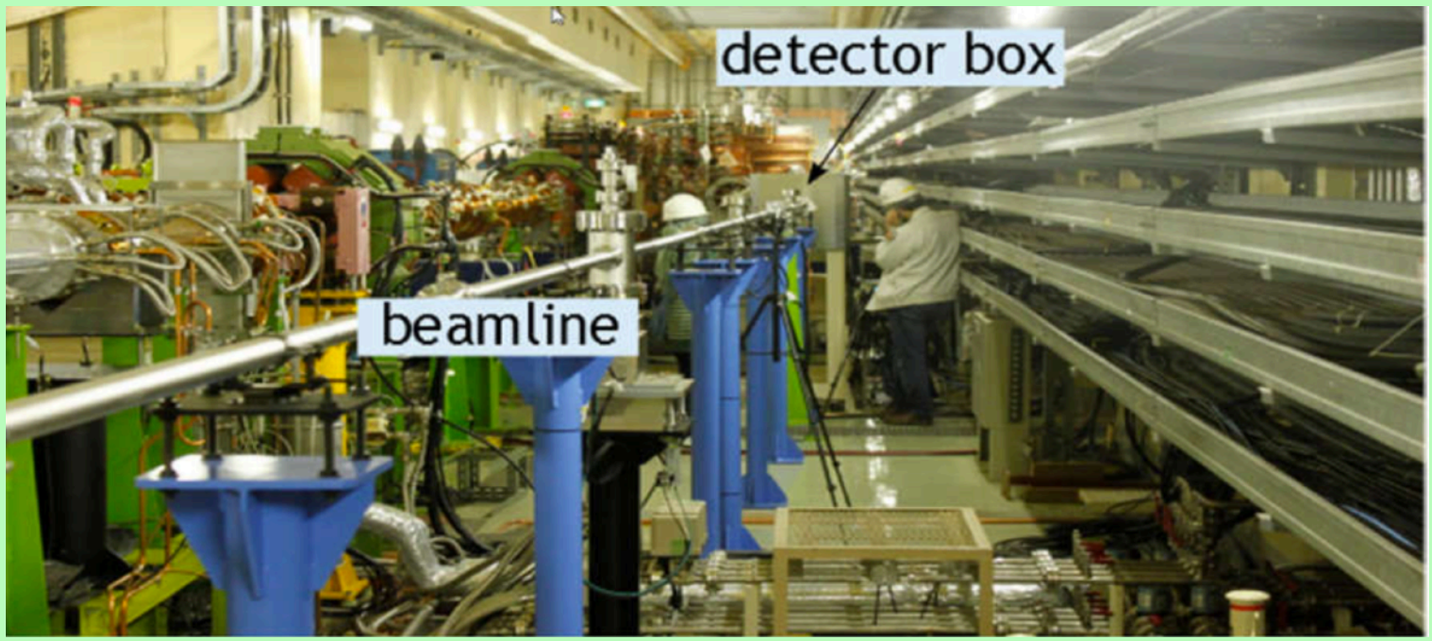
- HER
  - Bunch length in Phase 3 increases faster than in Phase 2.
  - Bunch length in Phase 2 is similar with MWI sim. in Phase 3 (thanks to D. Zhou).
- LER
  - Similar results are obtained in the Phase 2 and 3 measurements.
  - Sizable discrepancy between measurements and simulation remains.

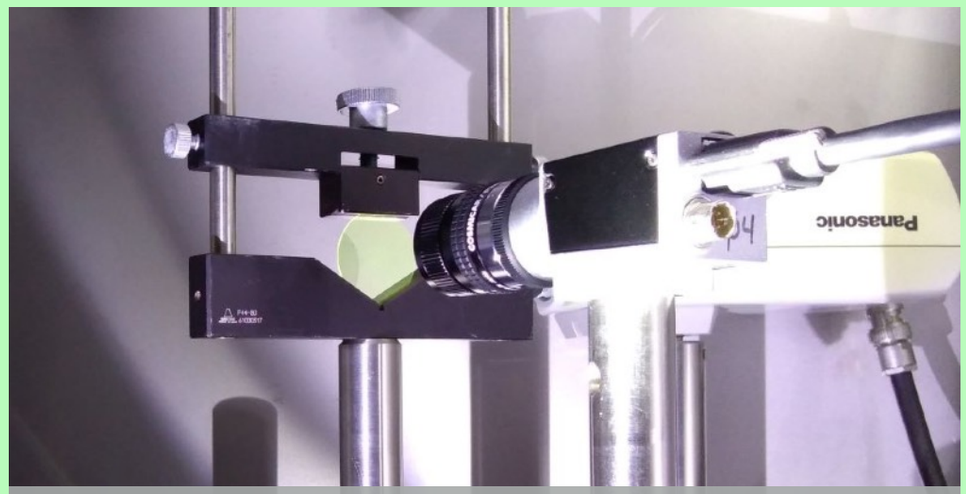
Synchrotron radiation beam size monitors

"Visible" SR monitor



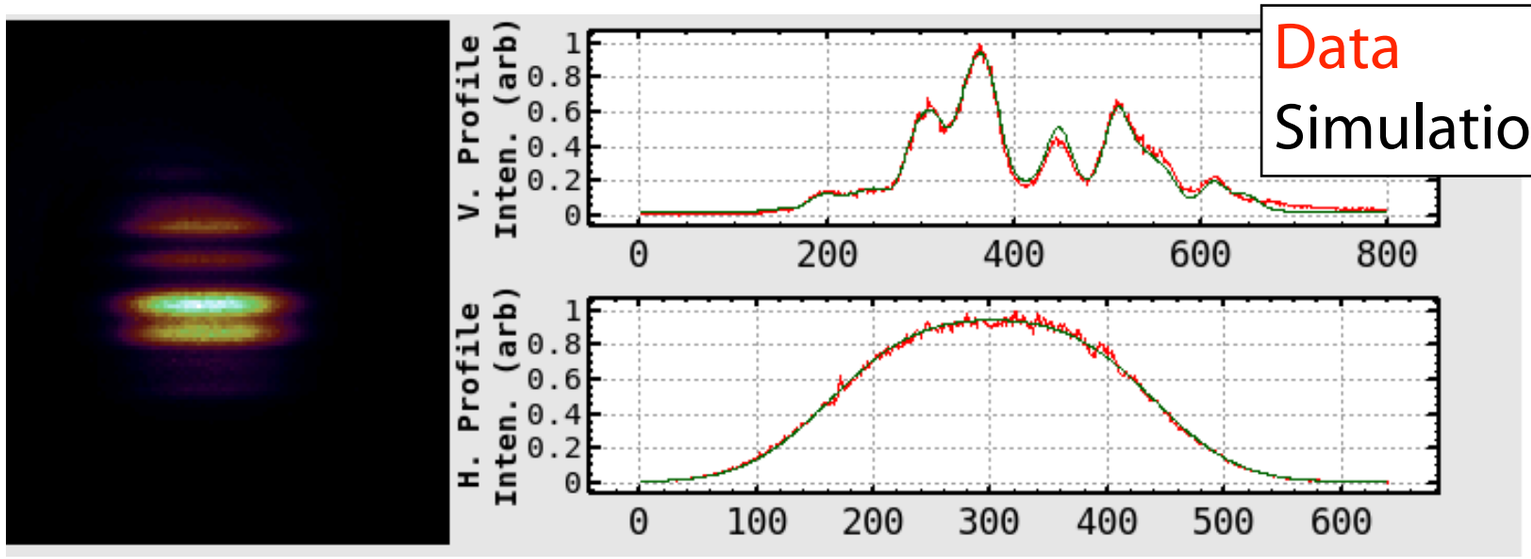
X-ray monitor





Measuring transverse sizes through the projected image on sci. screen

Calibration of the X-ray monitors



Finite resolution,
Be filters, etc.

$$\sigma_{y,meas}^2 = \sigma_{y,true}^2 + \sigma_s^2$$

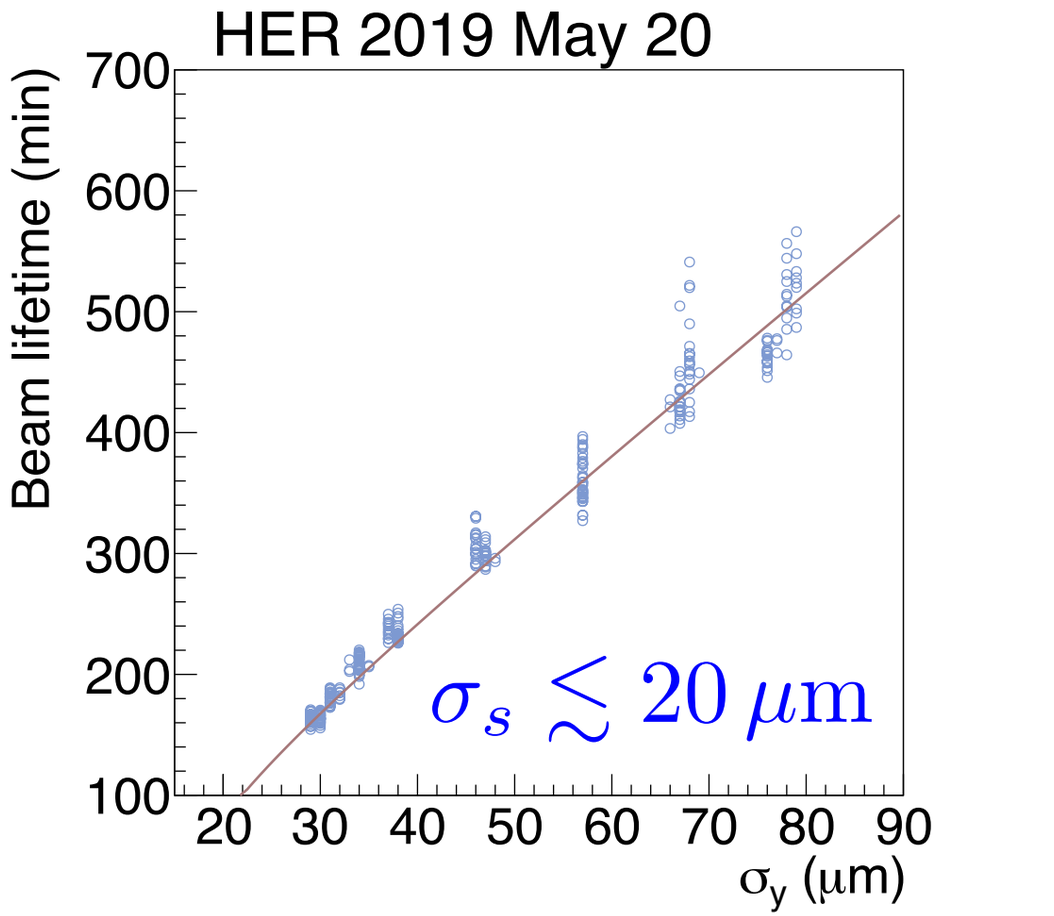
Understanding and reducing σ_s is crucial to extract small $\sigma_{y,true}$.

Toucheck lifetime vs. σ_y

$$\frac{1}{\tau} = \left\langle \frac{c r_e^2 n_p}{8\pi\gamma^2 \sigma_z \sigma_x \sigma_y (\Delta p/p)^3} F(\xi) \right\rangle$$

$$\tau \longrightarrow \left\langle k \frac{\sigma_z}{I_b} \sigma_y \right\rangle = \left\langle k \frac{\sigma_z}{I_b} \sqrt{\frac{\sigma_{y_{meas}}^2}{cal^2} - {\sigma_s}^2} \right\rangle$$

Streak camera measurements
or MWI simulation (Zhou)



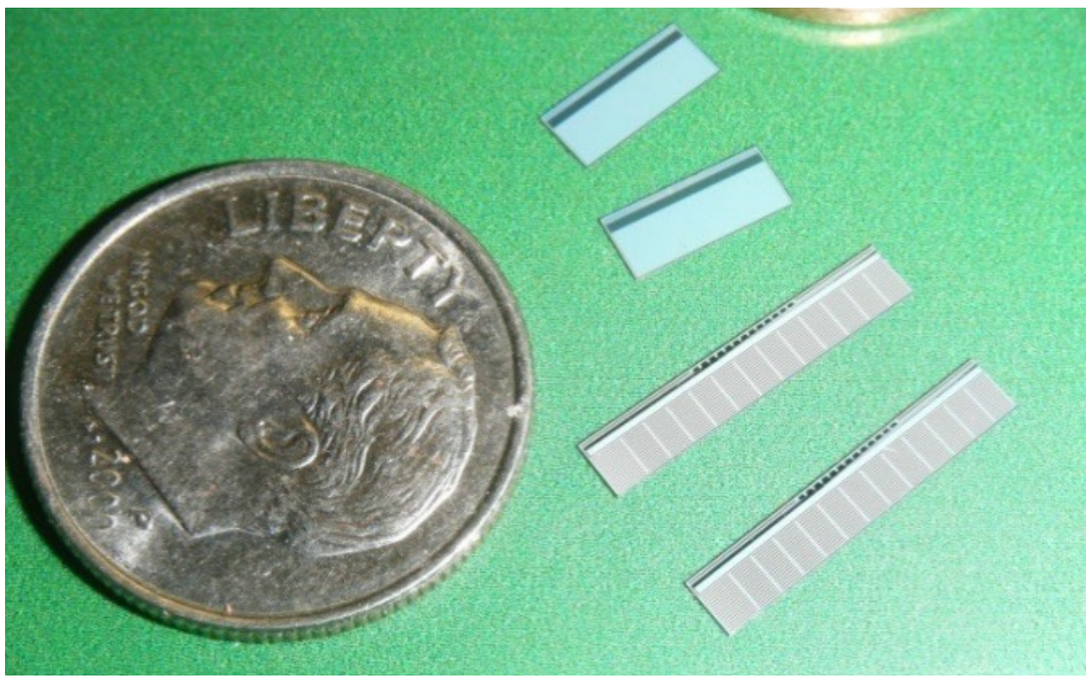
Same level as Phase 2 (@β_y = 28 m)

New X-ray monitor using Si-pixel sensor

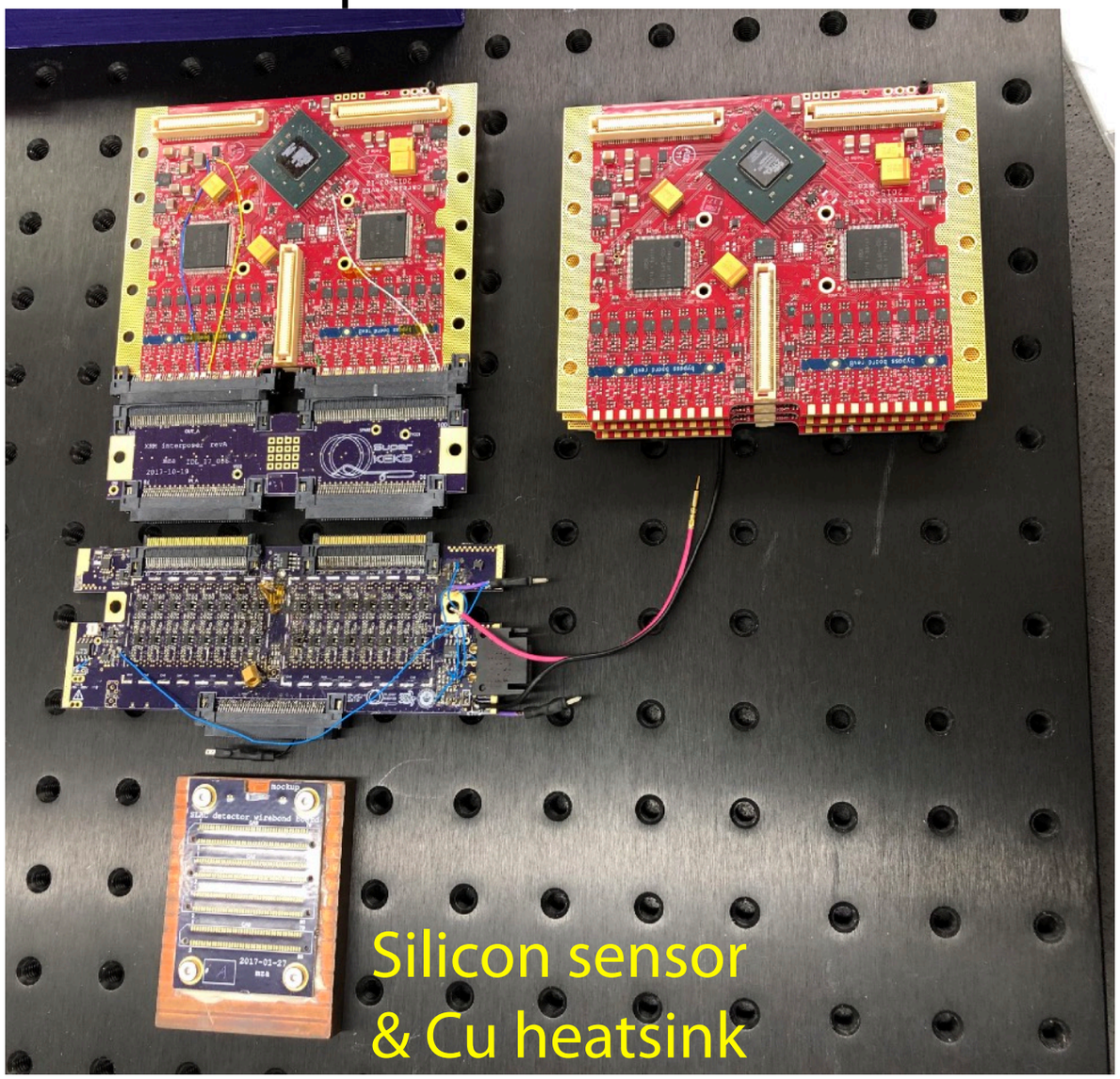
US-Japan Collaboration (U. Hawaii, SLAC, Cornell U., and KEK)

- New system directly catching X rays by a silicon sensor can take bunch-by-bunch snapshots.
- σ_y per bunch helps understanding of beam instabilities.

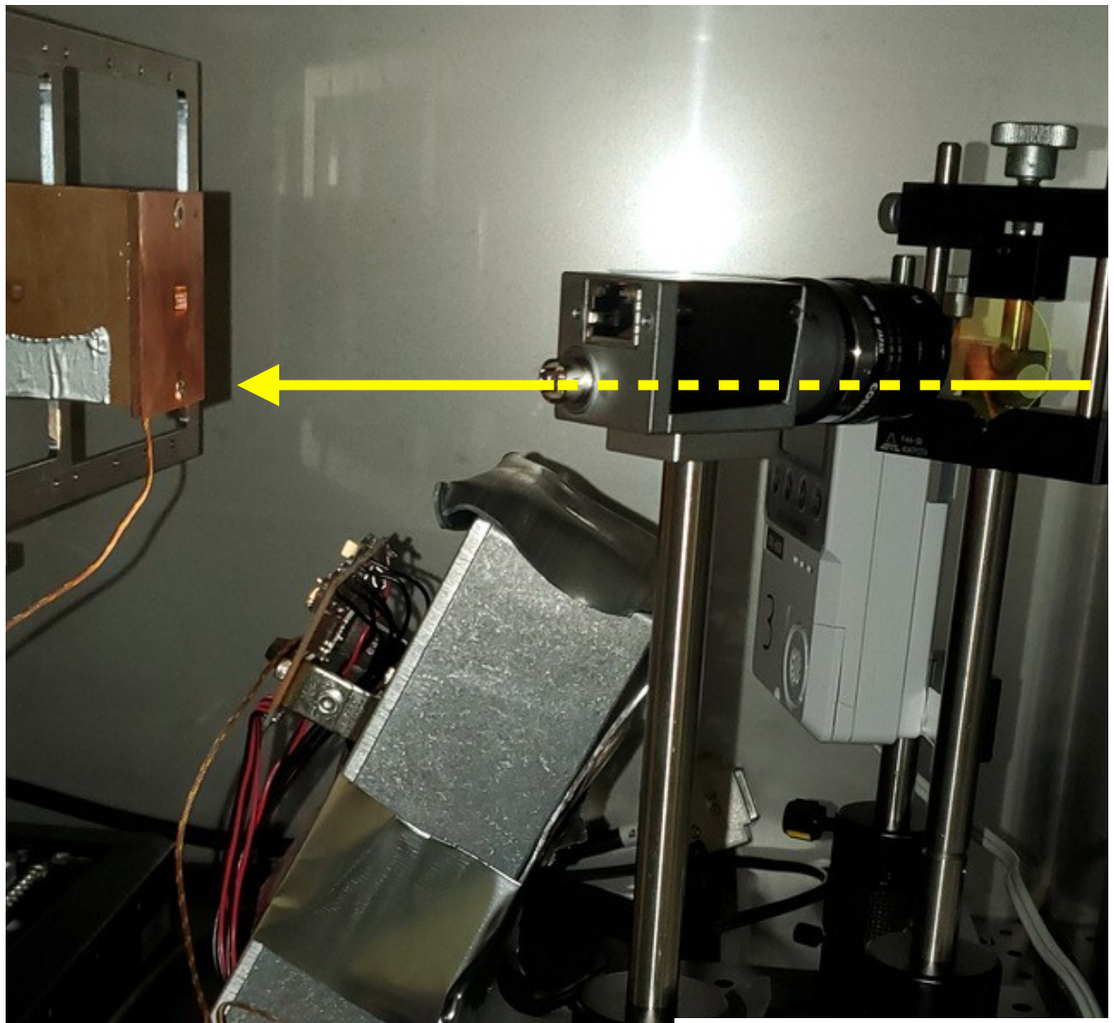
Silicon-pixel detector and spectrometer chips developed at SLAC



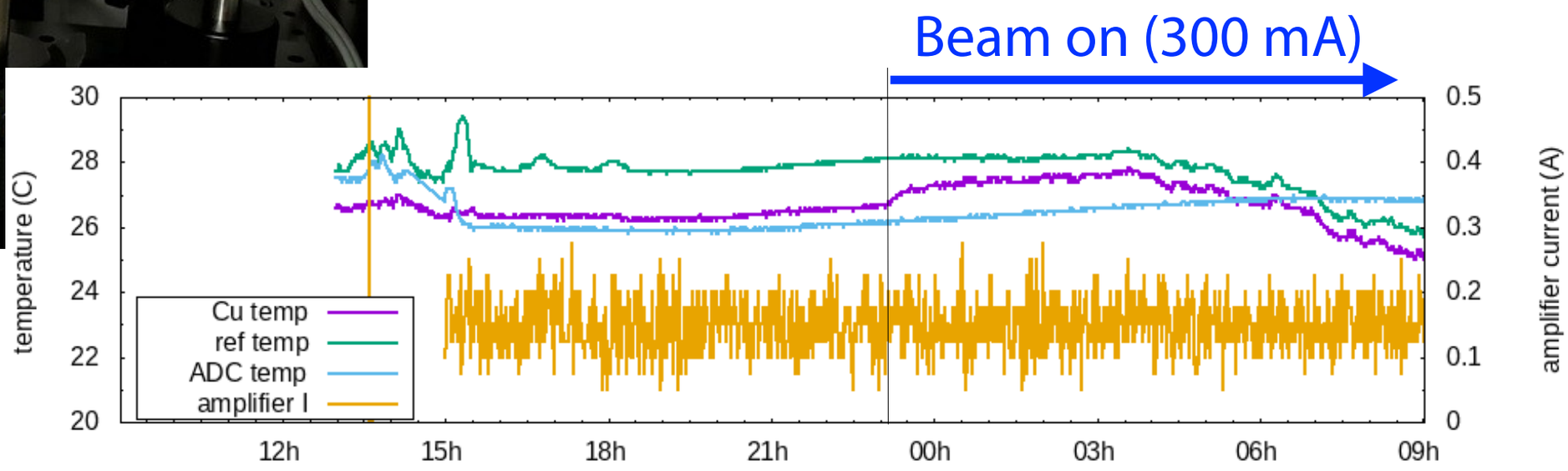
High-speed readout electronics developed at U. Hawaii



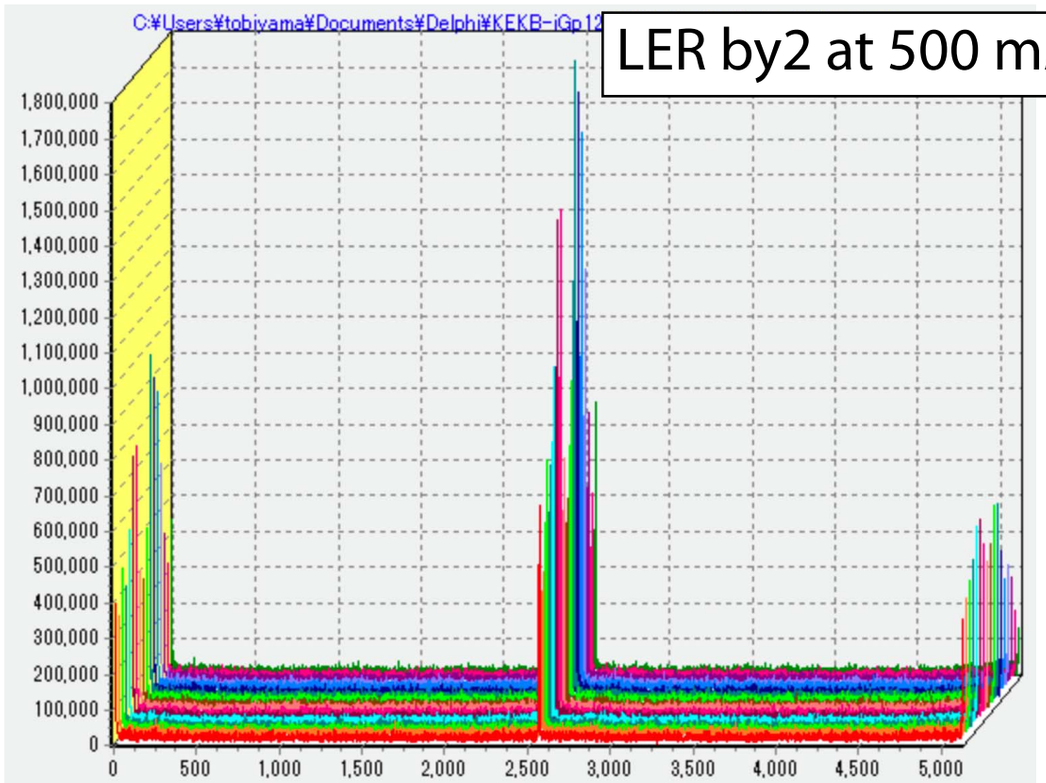
Testing Si-pixel X-ray monitor in HER

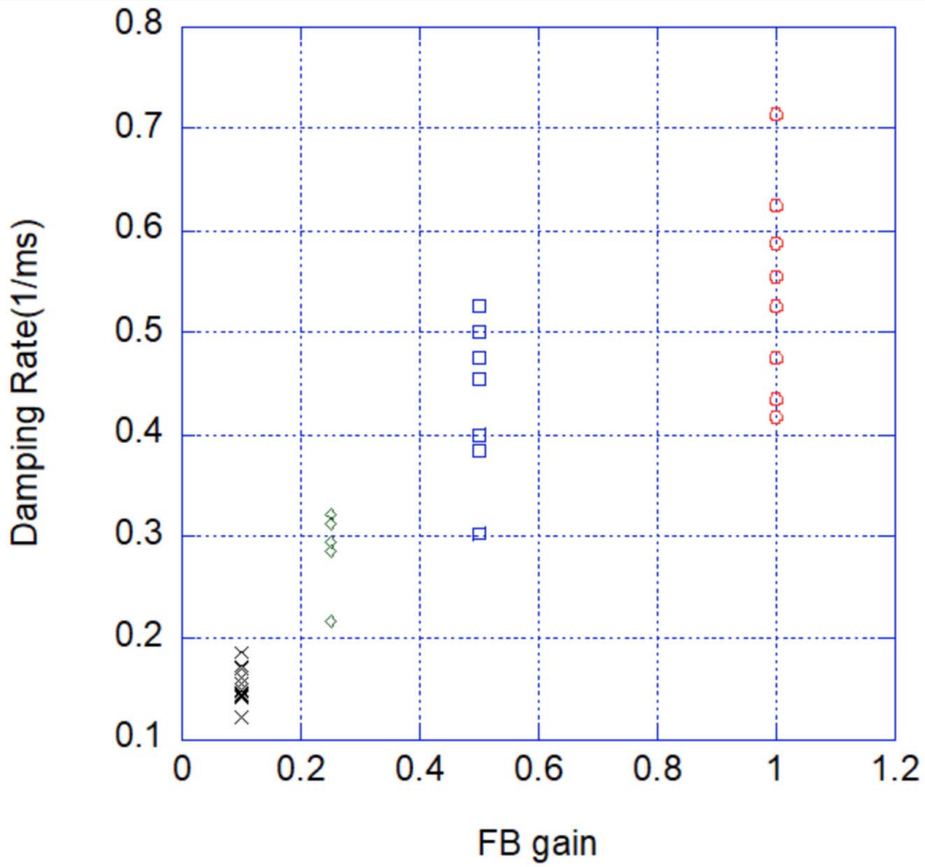


- Temperature on the Cu heatsink has been measured in the detector box in HER.
- No significant temperature increase was found after beam on (~4℃ at 900 mA). Air cooling (instead of water cooling) would be good enough.
- Dose inside the detector box ~15 Gy for 2 weeks
- Plan to install Si-sensor and detector in summer shutdown, which will be operated together with the present camera-based system.

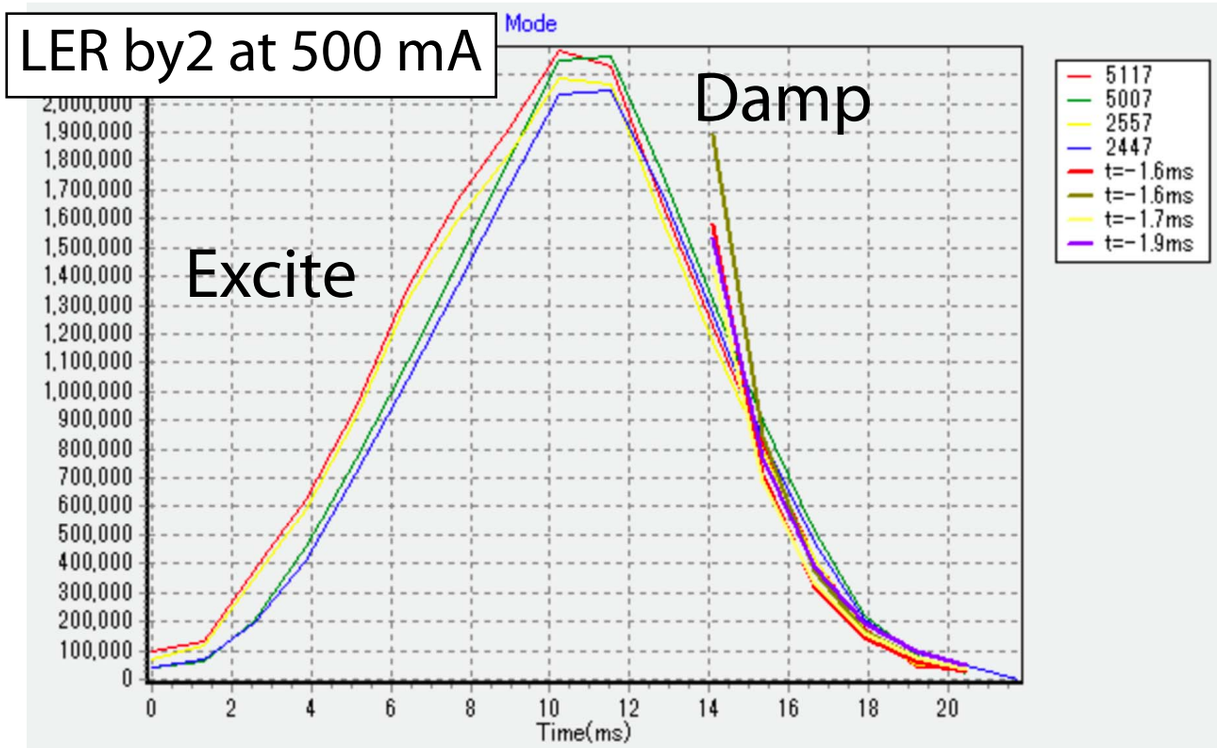


Bunch-by-bunch longitudinal feedback



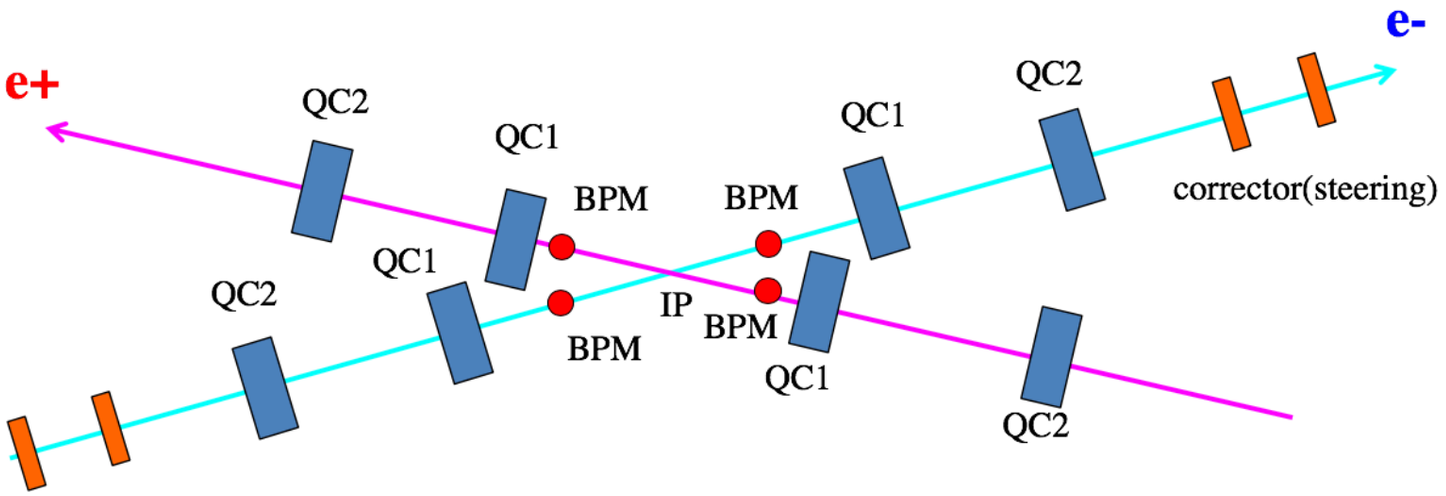


- Work with Prof. John Fox in May 2019
- No apparent instability ~1 sec after FB turning off for filling by 2 (500 mA) and by 3 (575 mA)
- Damping ~1.7-1.9 ms are observed in excite-damp measurements.



- Damping rate almost linearly increases as FB gain.

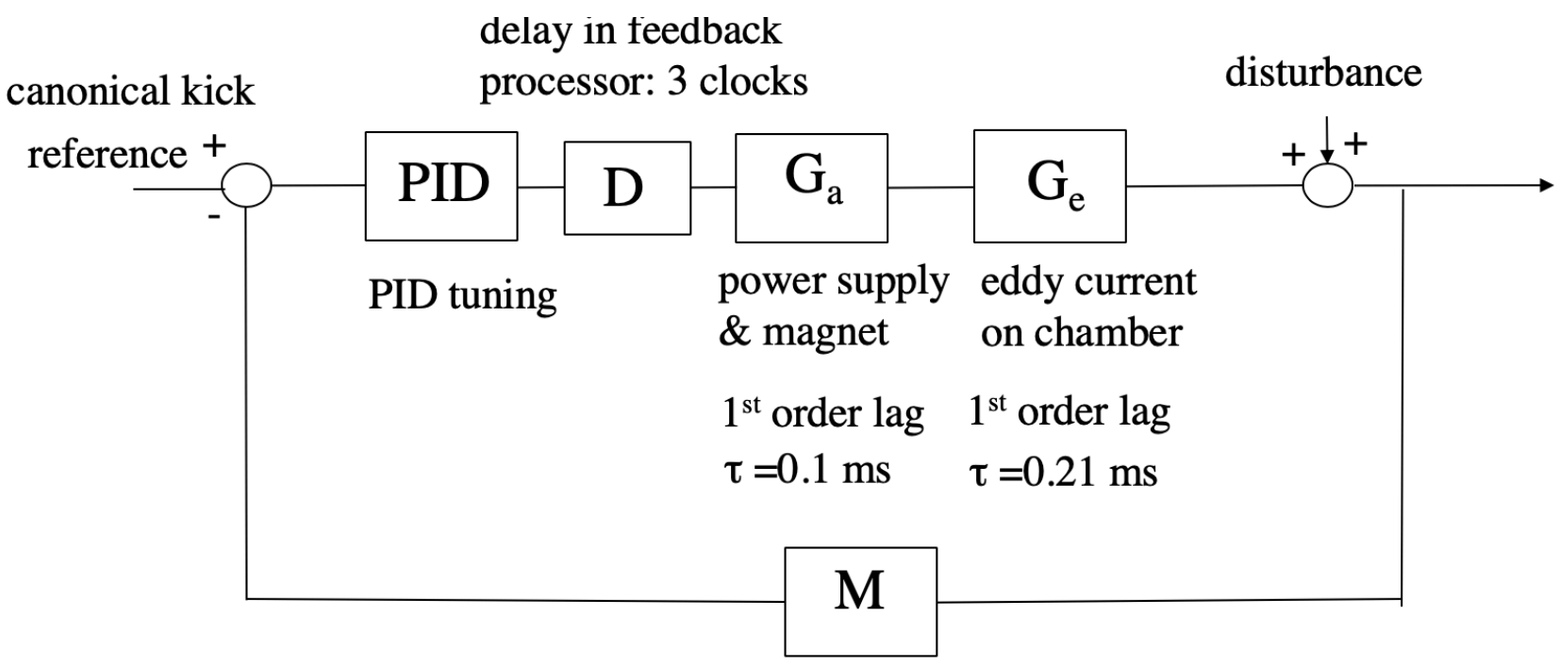
Fast IP-orbit feedback system



Canonical kick $\Delta y^*_{can} = \frac{1}{2}\left[\left(y_{MQC1LE} + y_{MQC1RE}\right) - \left(y_{MQC1LP} + y_{MQC1RP}\right)\right]$

$= -K_y \Delta y^*$

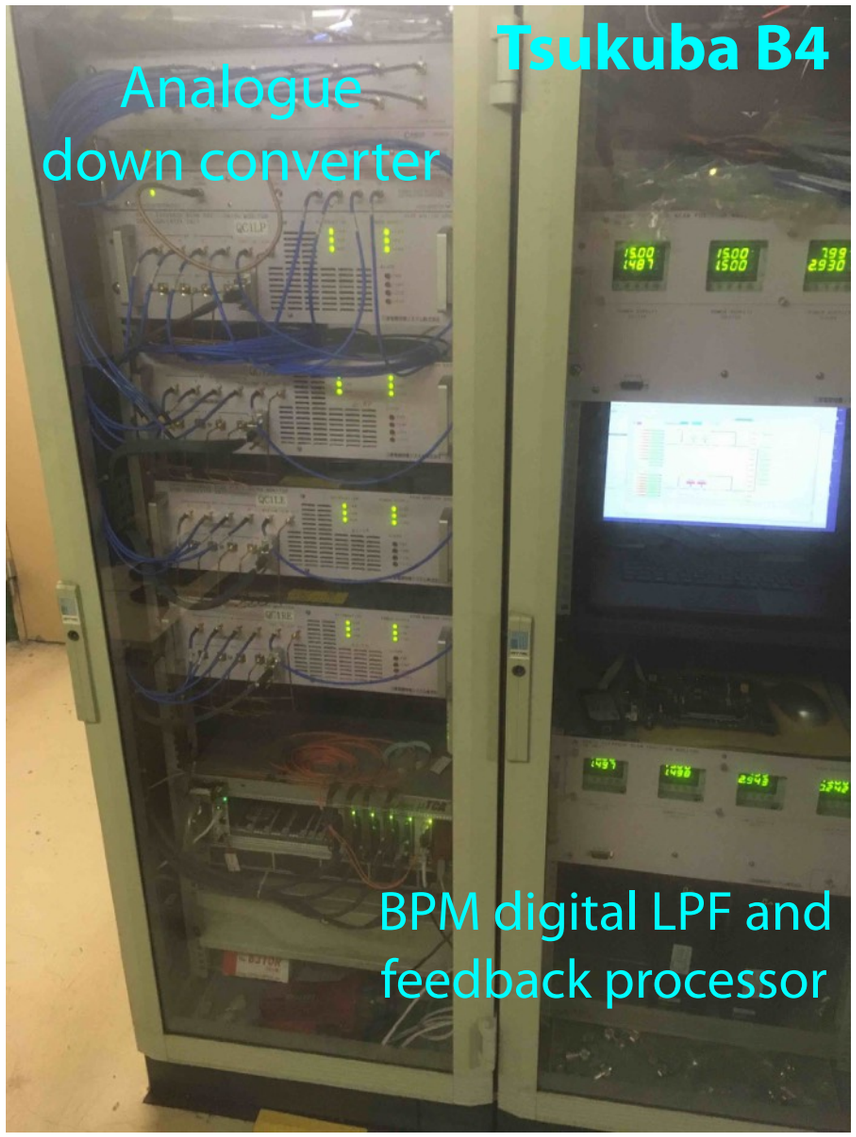
y_{MQC1**}: orbit at BPM MQC1**.
Δy^*: orbit separation
between two beams at IP



Processing rate = 32kHz

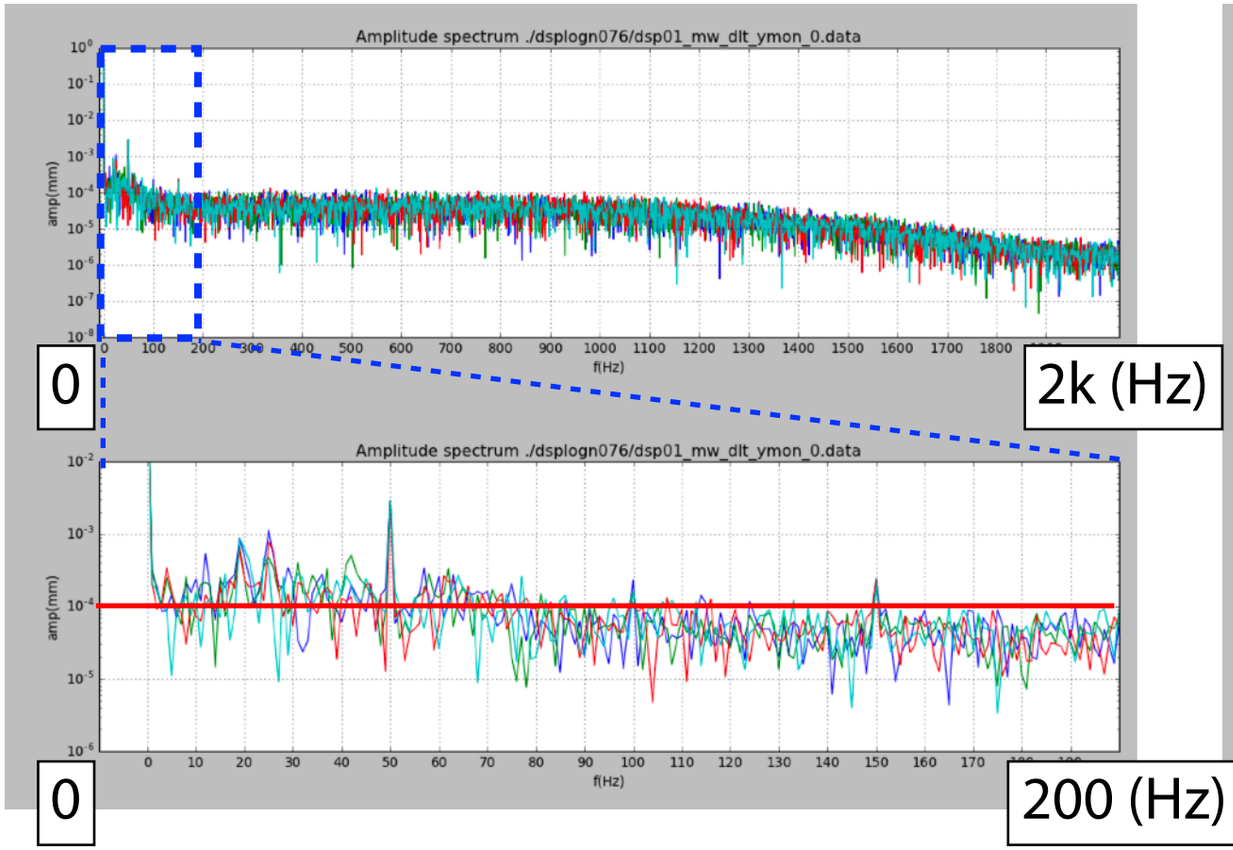
Feedback bandwidth <100Hz

LPF (equiripple FIR)

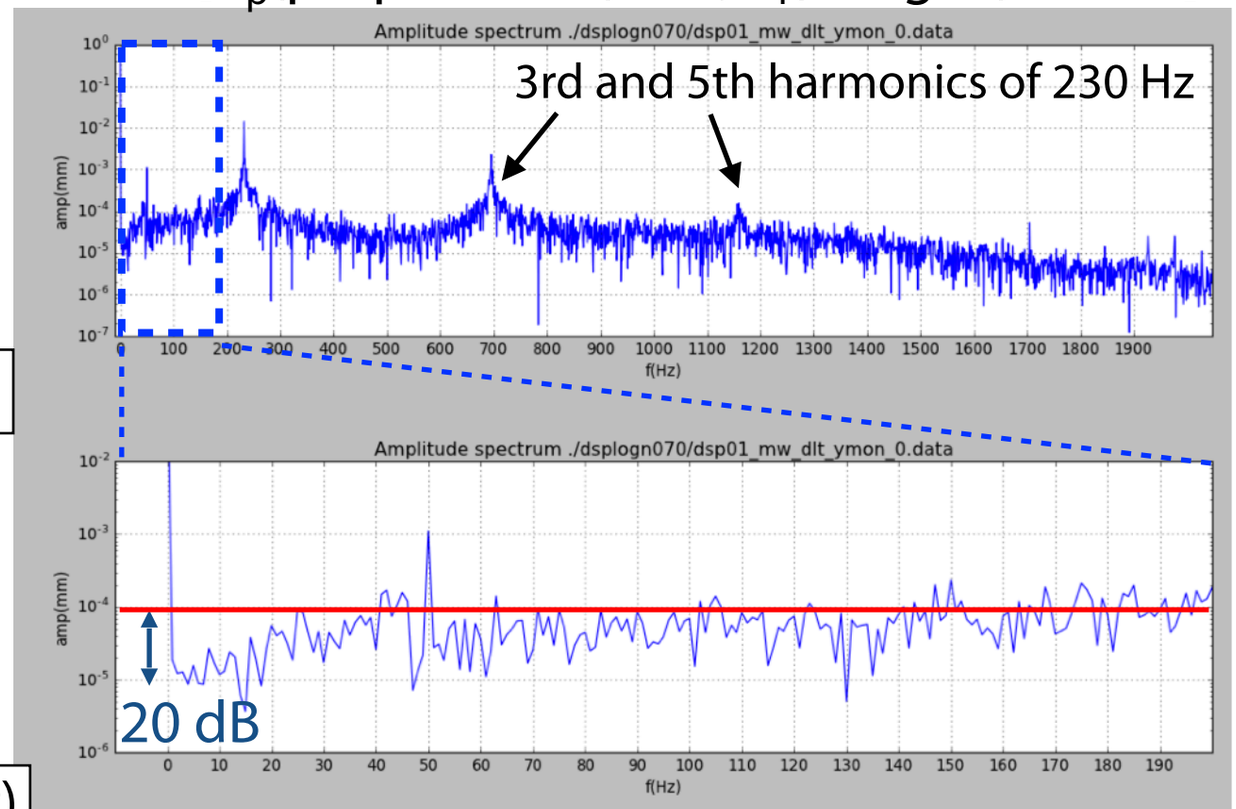


Spectrum of canonical kick with FB off/on

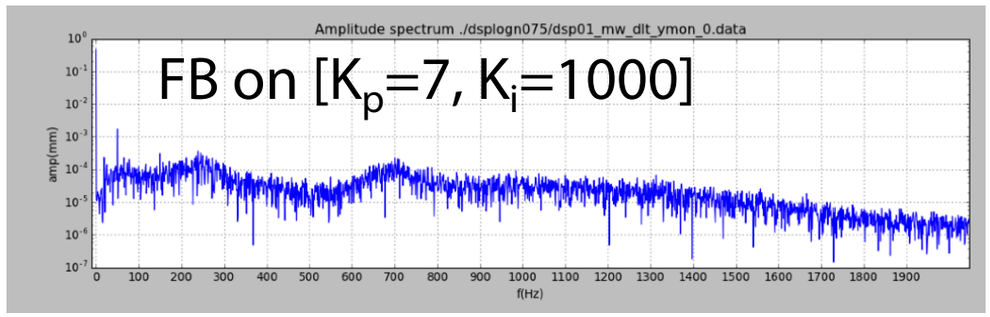
FB off

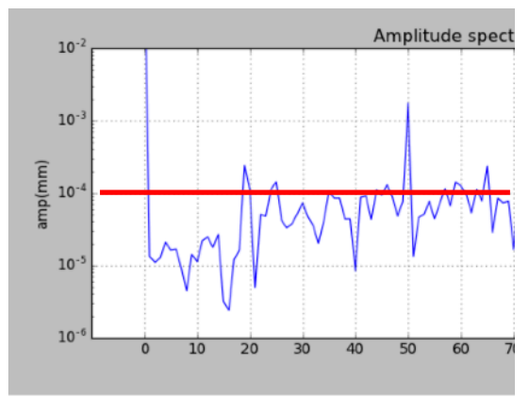


FB on [K_p(proportional)=10, K_i(integral) =1000]



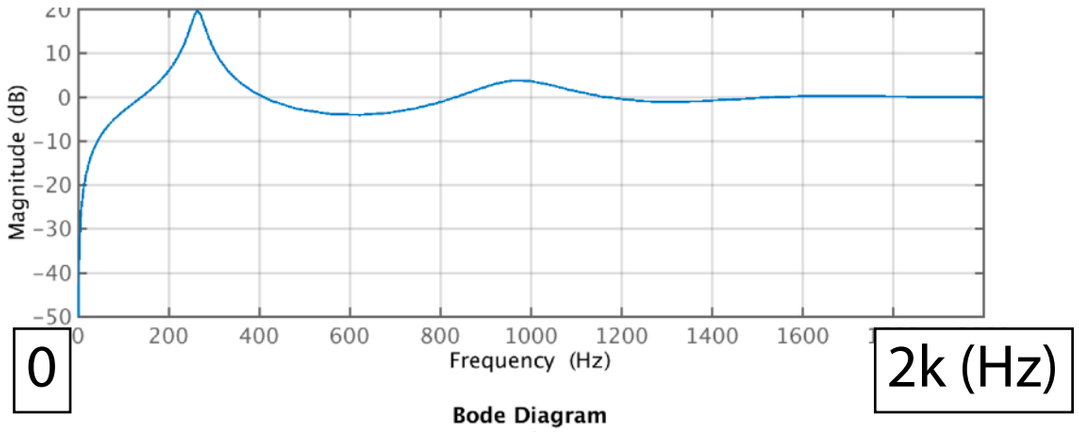
- FB on
  - ~20 dB reduction of the osc. amp. found at 10Hz
  - Luminosity drops down probably owing to large excitation at 230 Hz.
- FB on with changing K_p from 10 to 7
  - The peak 230 Hz peak gets tamed and luminosity keeps.
  - Reduction power < 30 Hz goes smaller.

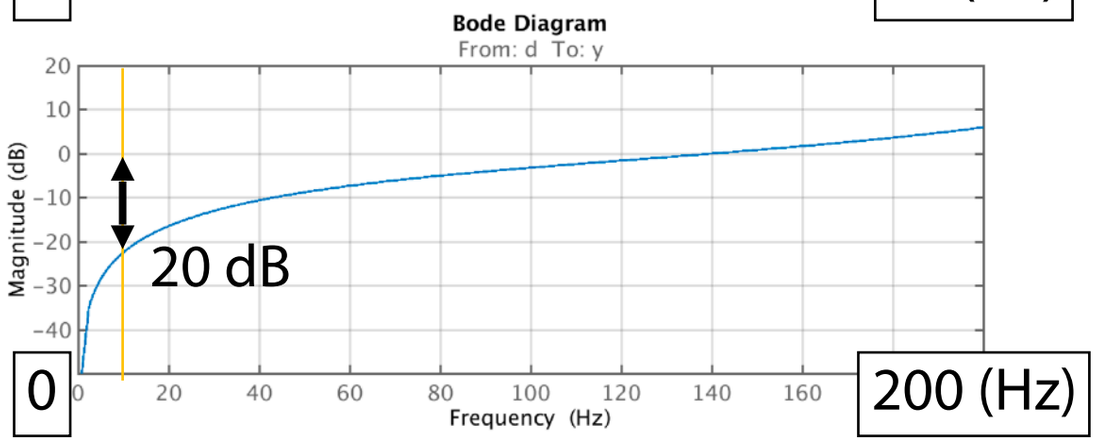




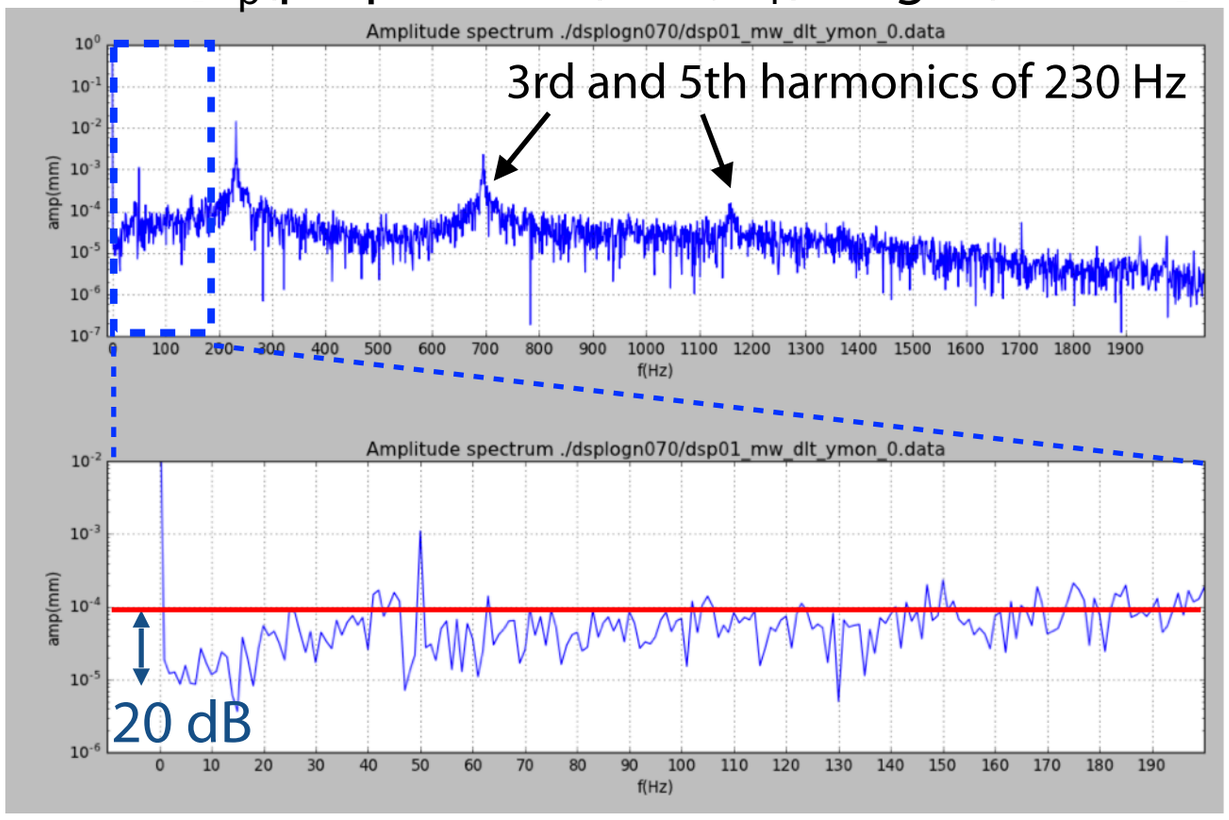
Comparisons with MATLAB simulations

MATLAB simulation (K_p=10, K_i =1000)





FB on [K_p(proportional)=10, K_i(integral) =1000]



- The MATLAB simulation shows a peak at 260 Hz (cf. at 230 Hz in data).
- Reduction powers are ~20 dB at 10 Hz in both sim. and the measurement.
- Future prospects
  - Need to understand the origin of the 230 Hz peak
  - Trying a new FIR filter with small group delay; changing a delay 1.1 to 0.2 ms improves a reduction power 11.6 to 20.4 dB at 20 Hz.

New ideas

- New GTBT monitors
  - 1st round of prototype testing this year
  - Embedded FFT in Zynq FPGA enables realtime phase and amplitude monitoring etc.

- Injection synchrotron oscillation monitor
  - checking injection related BGs in both rings with 12-bit resolution or more

- Synchrotron radiation beam size monitors
  - Good and old interferometers (since KEKB-era) will be renewed.

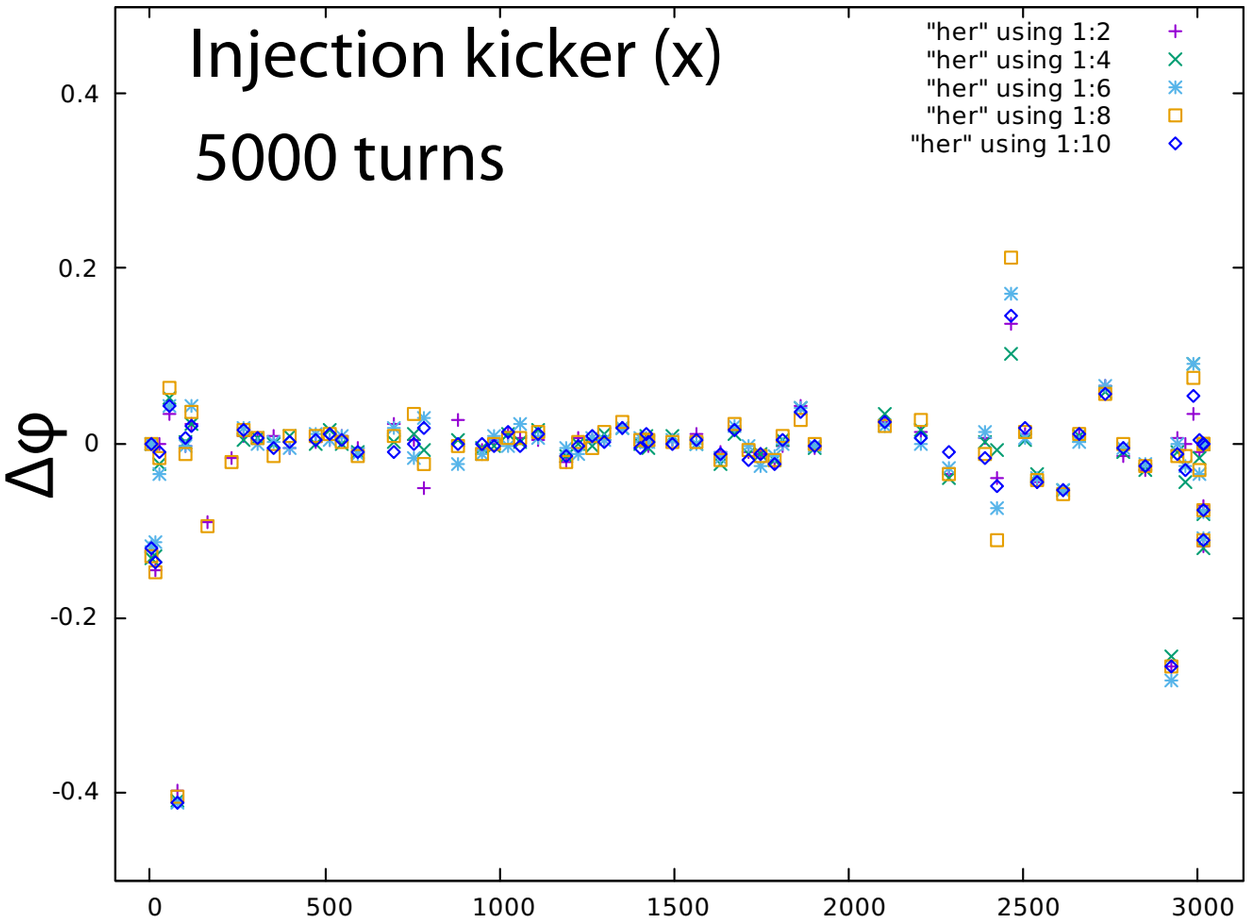
- Radiation monitors
  - RADFET+Raspberry pi = realtime and EPICS controllable rad. monitor.

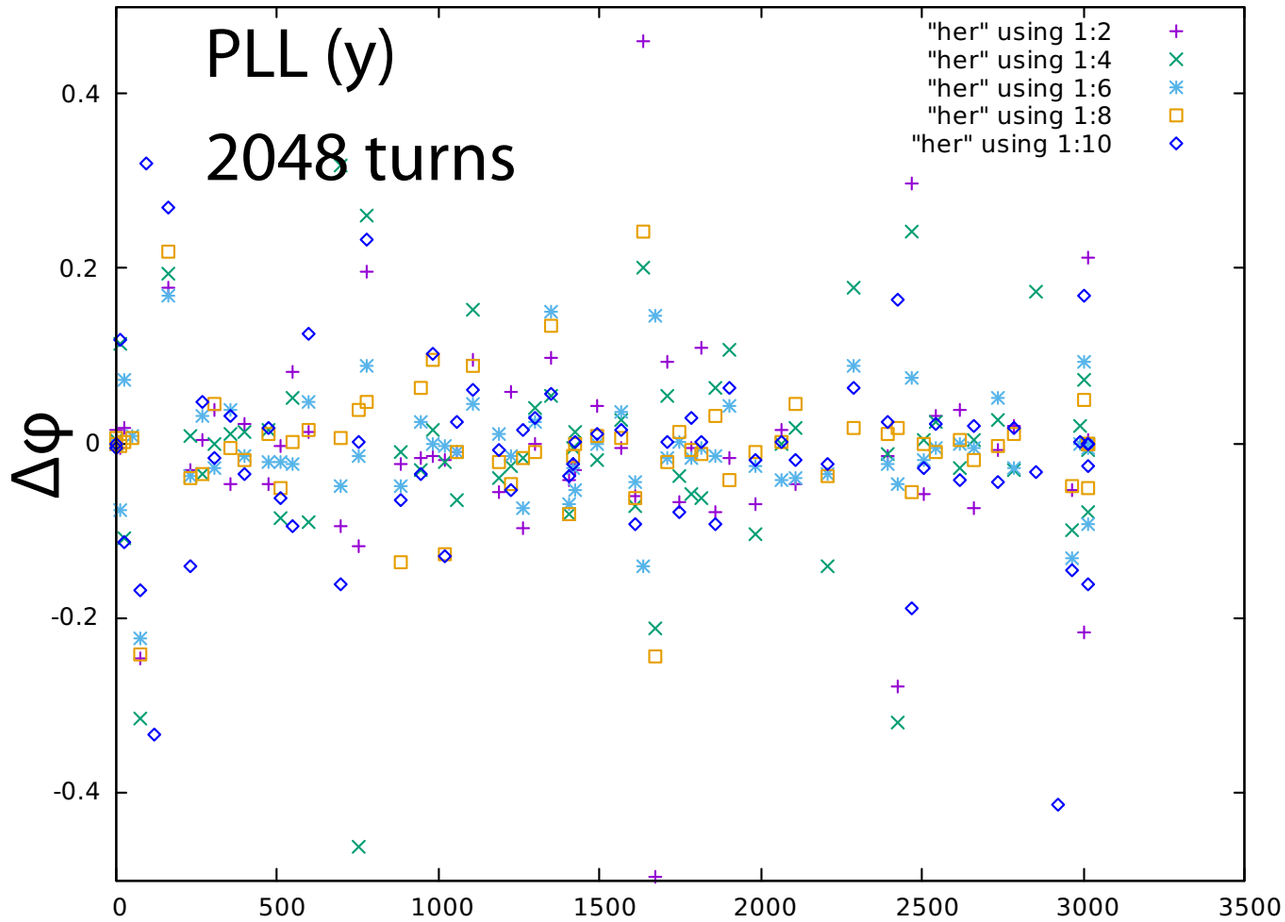
Summary

- 1 out of 4 channels of each MQC1LE/LP seems damaged, although no significant effect to operation. Replacement with new cables in August.
- No other major problem in the beam monitors, work well over Phase 2&3
  - Promising capability of GTBTs for optics measurements
  - Well calibrated beam size monitors provide fundamental information to the beam commissioning, and may contribute to beam dynamics study.
  - Bunch-by-bunch FB system stably operated
  - Tuning of the fast IP-orbit FB underway, will be involved into daily operation if necessary
- R&D of new detectors are running in parallel.

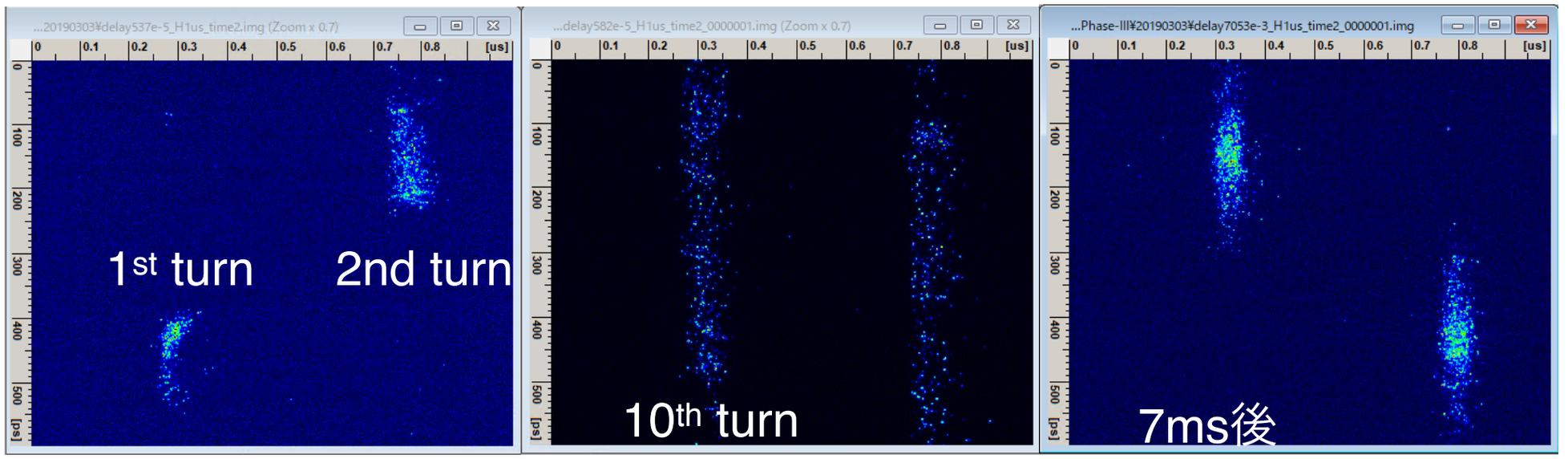
Backup

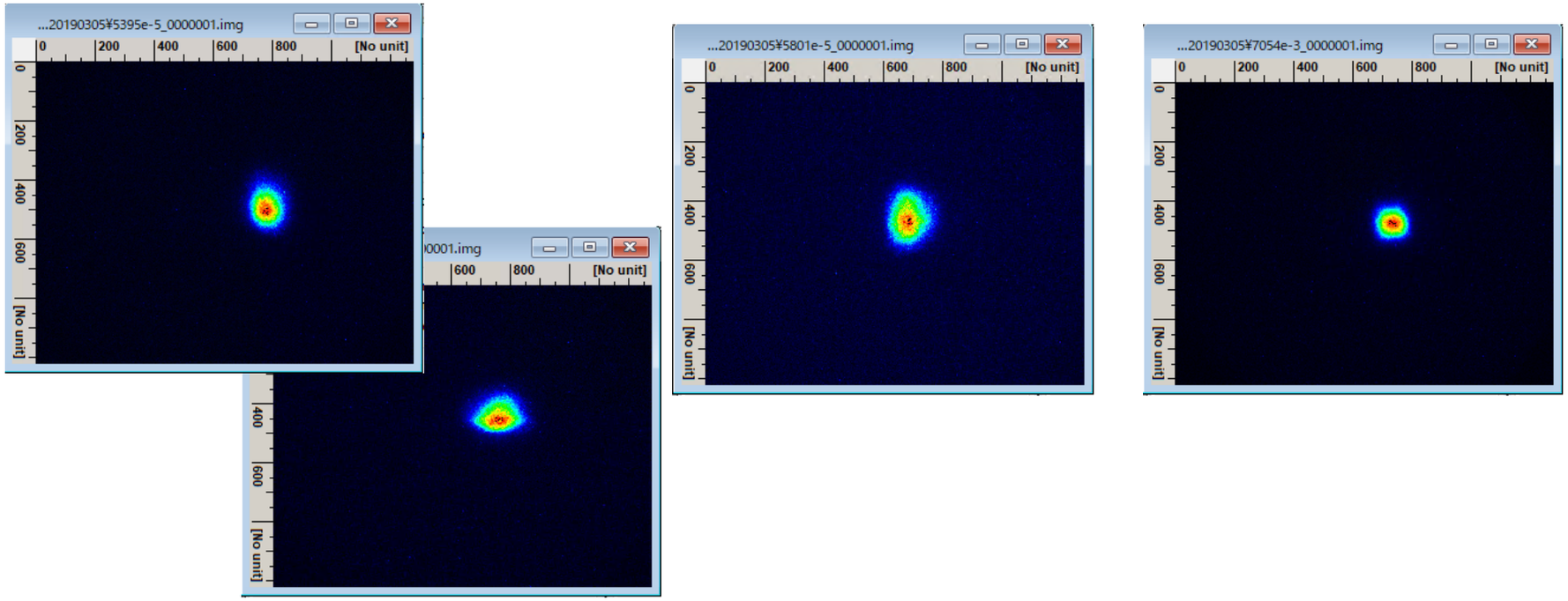
Variation among 5 data sets



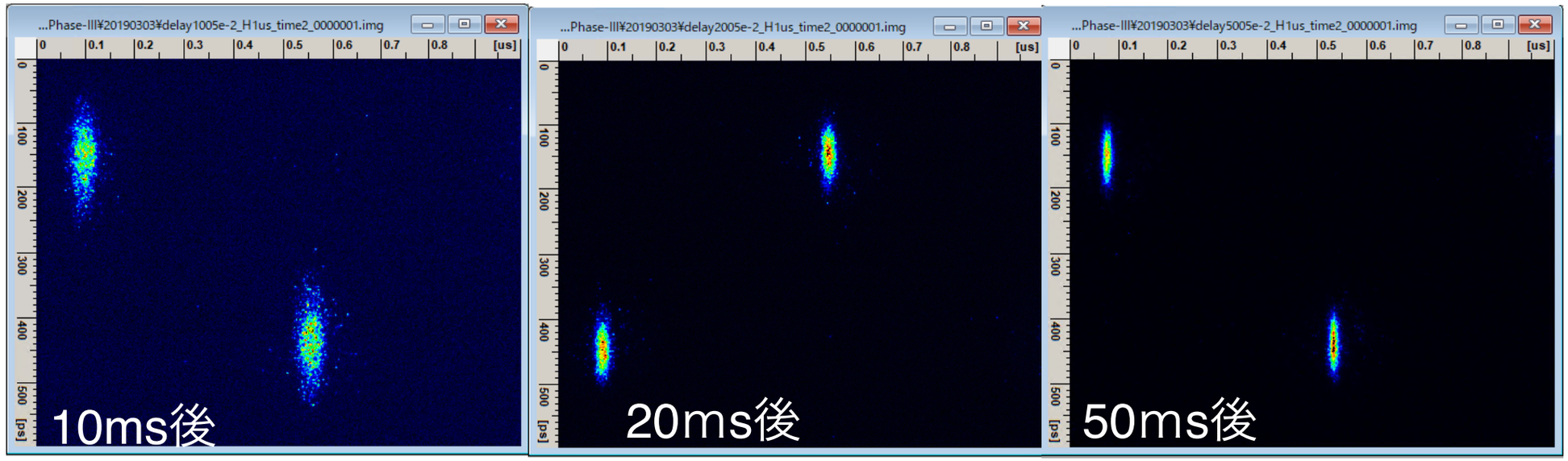


streak camera





gated camera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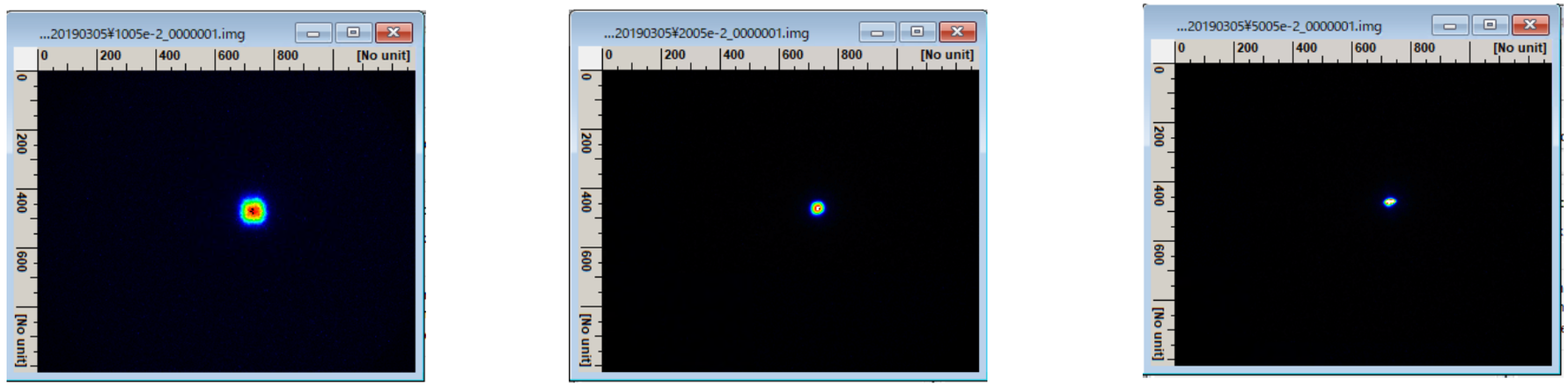
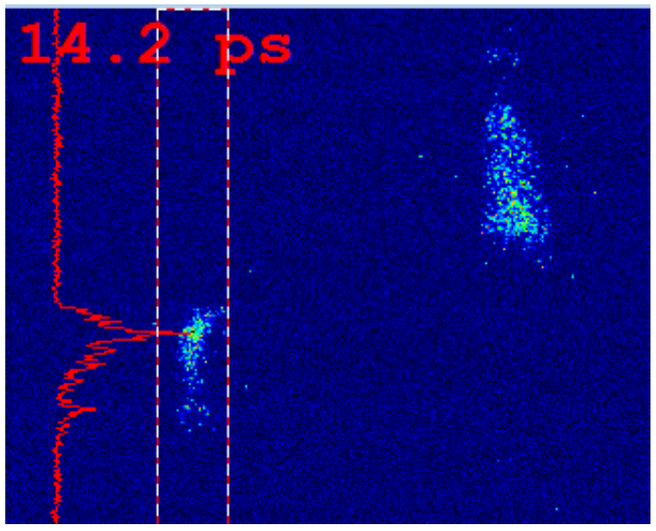
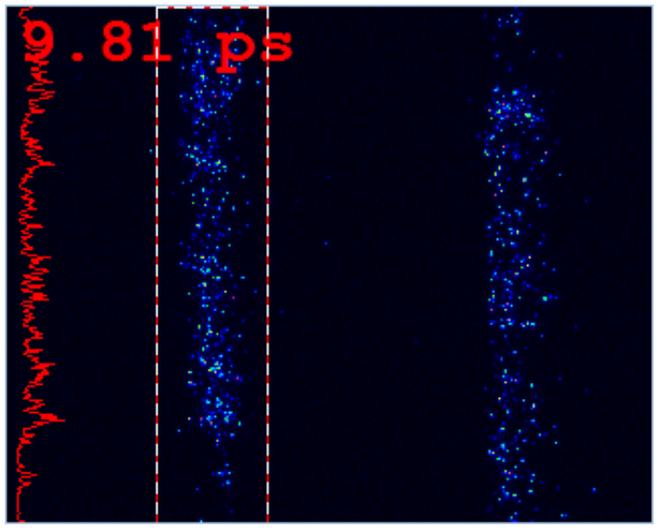
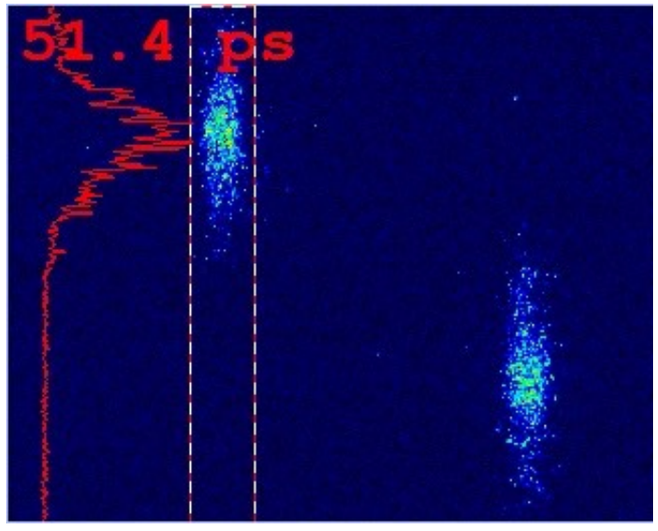
...Phase-III¥20190303¥delay2005e-2_H1us_time2_0000001.img
...Phase-III¥20190303¥delay5005e-2_H1us_time2_0000001.img
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 [us]
0 100 200 300 400 500 [ps]
10ms後
20ms後
50ms後


...20190305¥1005e-2_0000001.img
...20190305¥2005e-2_0000001.img
...20190305¥5005e-2_0000001.img
0 200 400 600 800 [No unit]
0 200 400 600 [No unit]


14.2 ps


9.81 ps


51.4 ps

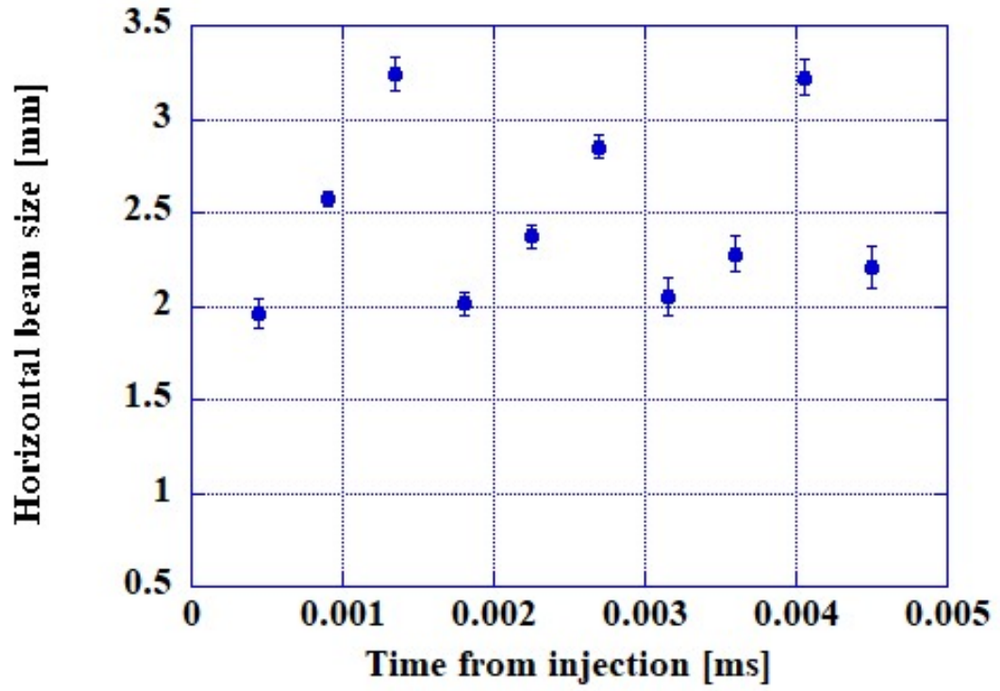
A comparison of Phase 1 and 2 XRM measurement

At HER using URA mask

Phase 1		**Parameters**	**Min. $\sigma_{y(meas)}$**
1	22 Jun 2016	I = 188~ 250mA, $\beta_y = 7.64\ m$ and 1576 bunches	32 um
2	24 Jun 2016	I = ~20 mA, $\beta_y = 7.64\ m$ and 1576 bunches	30 um
Phase 2			
1	16 Jun 2018	I = 20 ~ 16 mA, $\beta_y = 28\ m$ 250 ~ 230 bunches	26 um
2	04 Jul 2018	I = 40 ~ 30 mA, $\beta_y = 28\ m$ 64 ~ 42 bunches	21 um
3	10 Jul 2018	I = 100 ~ 63 mA, $\beta_y = 7.64\ m$ 788 bunches	14 um

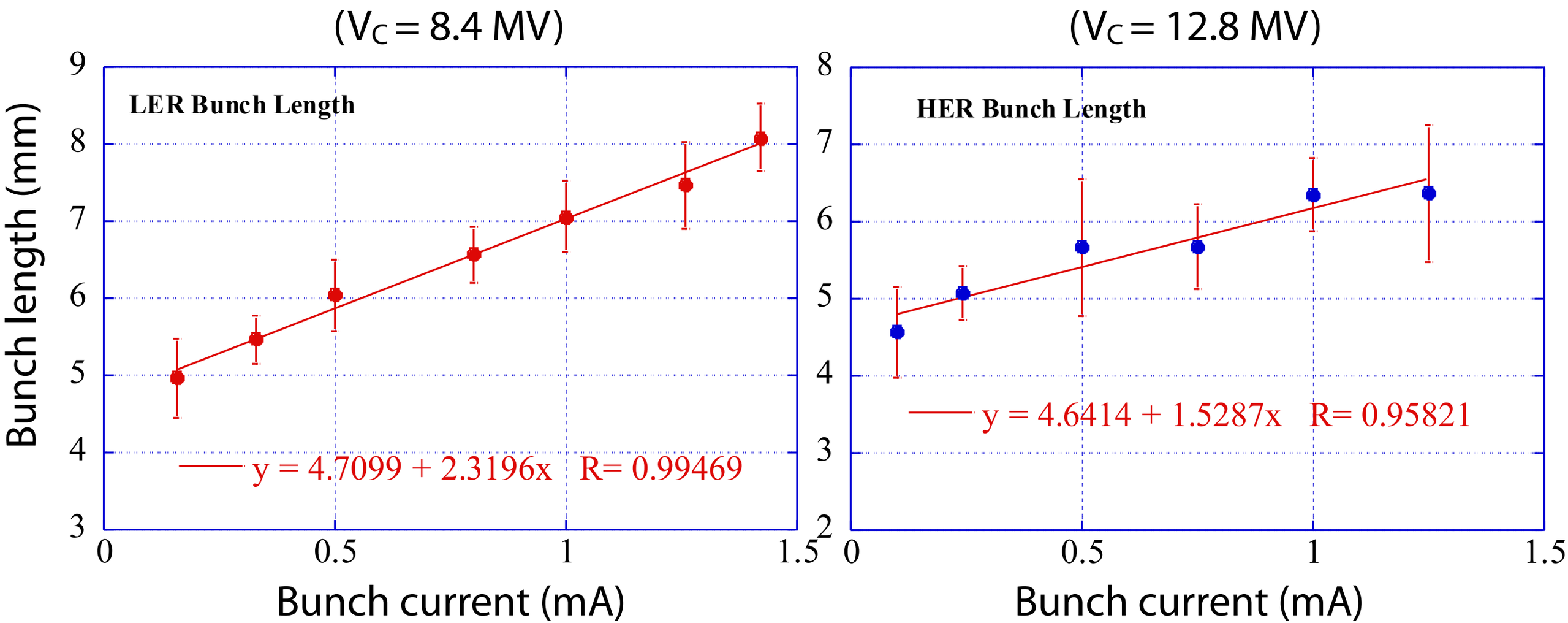
	Phase 1	**Phase 2**	**unit**
σ_s	31.58 ± 0.72	6.6 ± 0.73	um

A good improvement, PSF factor is ~ 5 times smaller than phase 1.



- Gate camera data (first to 10th turn)

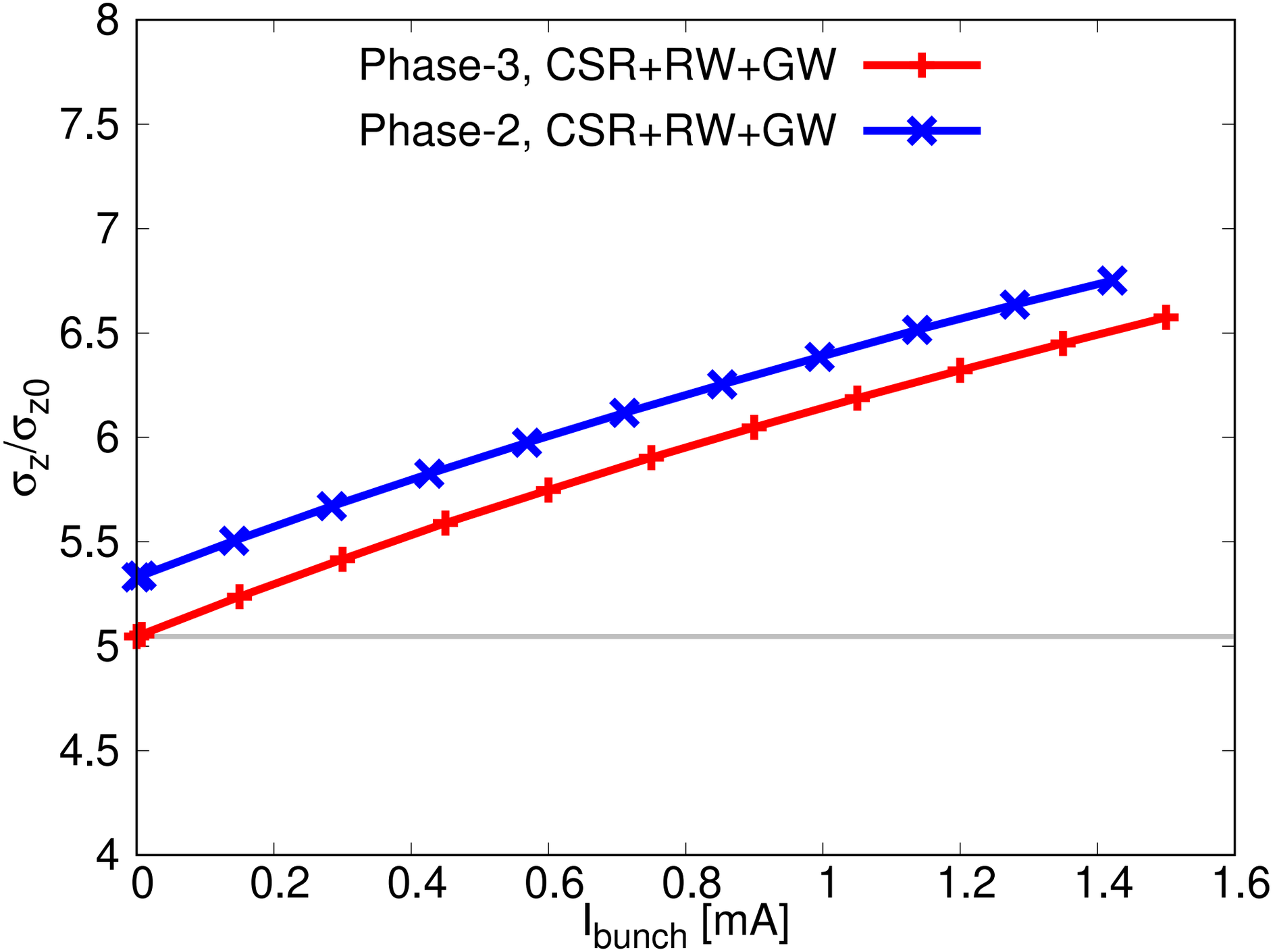
Bunch length measurements in the MR



- MWI simulation shows thresholds are ~1.9 mA (LER) and 2.7 mA (HER).
- Measured bunch lengthening might be due to potential well distortion.
- The HER result is comparable with the simulation (Zhou and Ohmi), but huge discrepancy between measurements and simulation remains in the LER.

Blue line: Phase-2, 2018.07.04

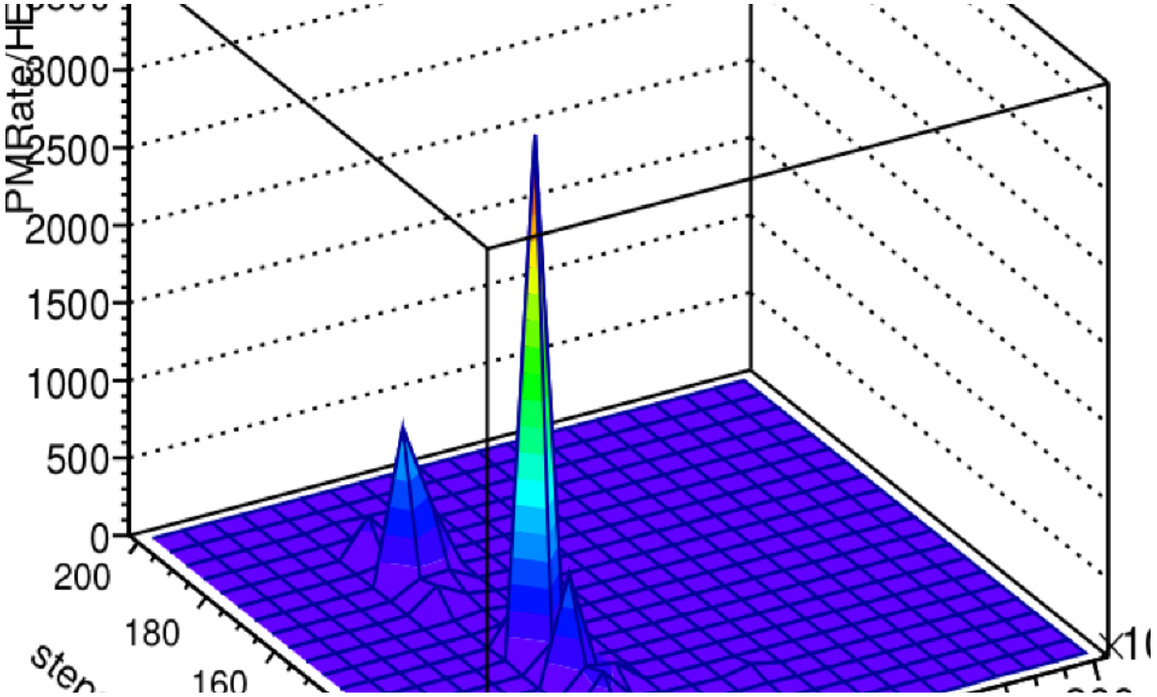
Red line: Phase-3, 2019.05.20

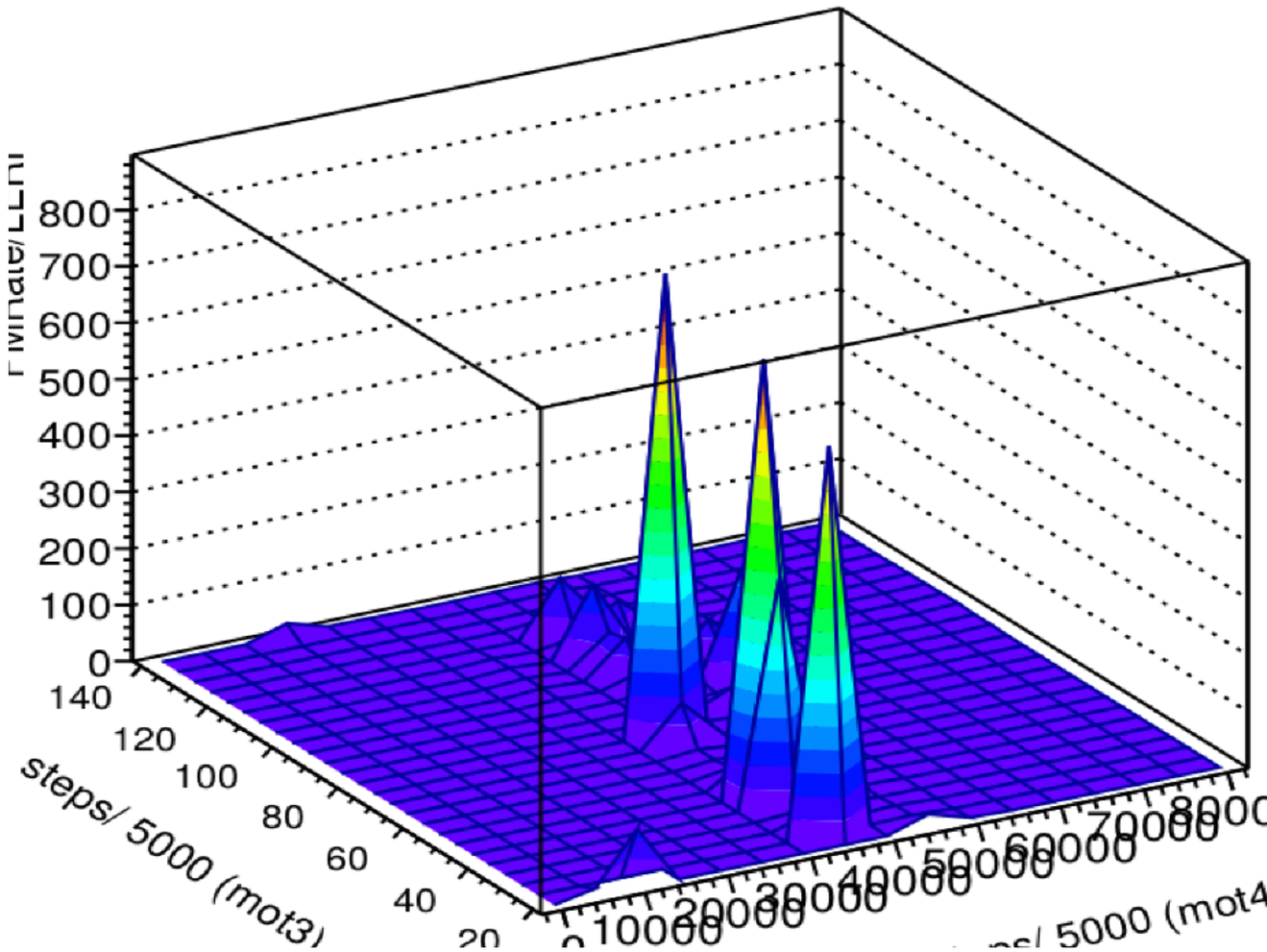


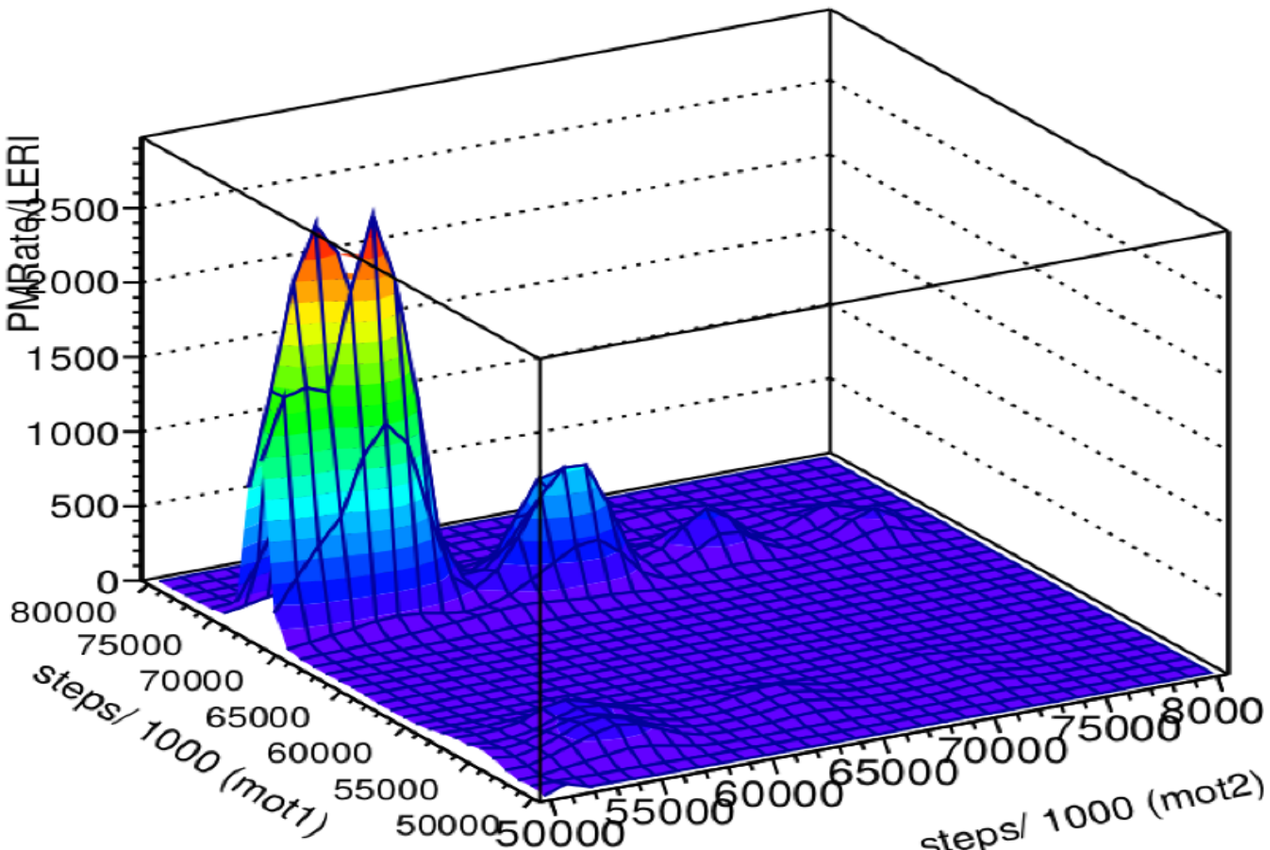
14 modifications during Fall 2018

- Mostly aimed at making the alignment system more robust
- However the funds were released too late to implement them all before installation
- One that we could not do in time was making the primary mirrors so they could be opened and reset in situ

IP found in 3 of 4 telescopes at first scan

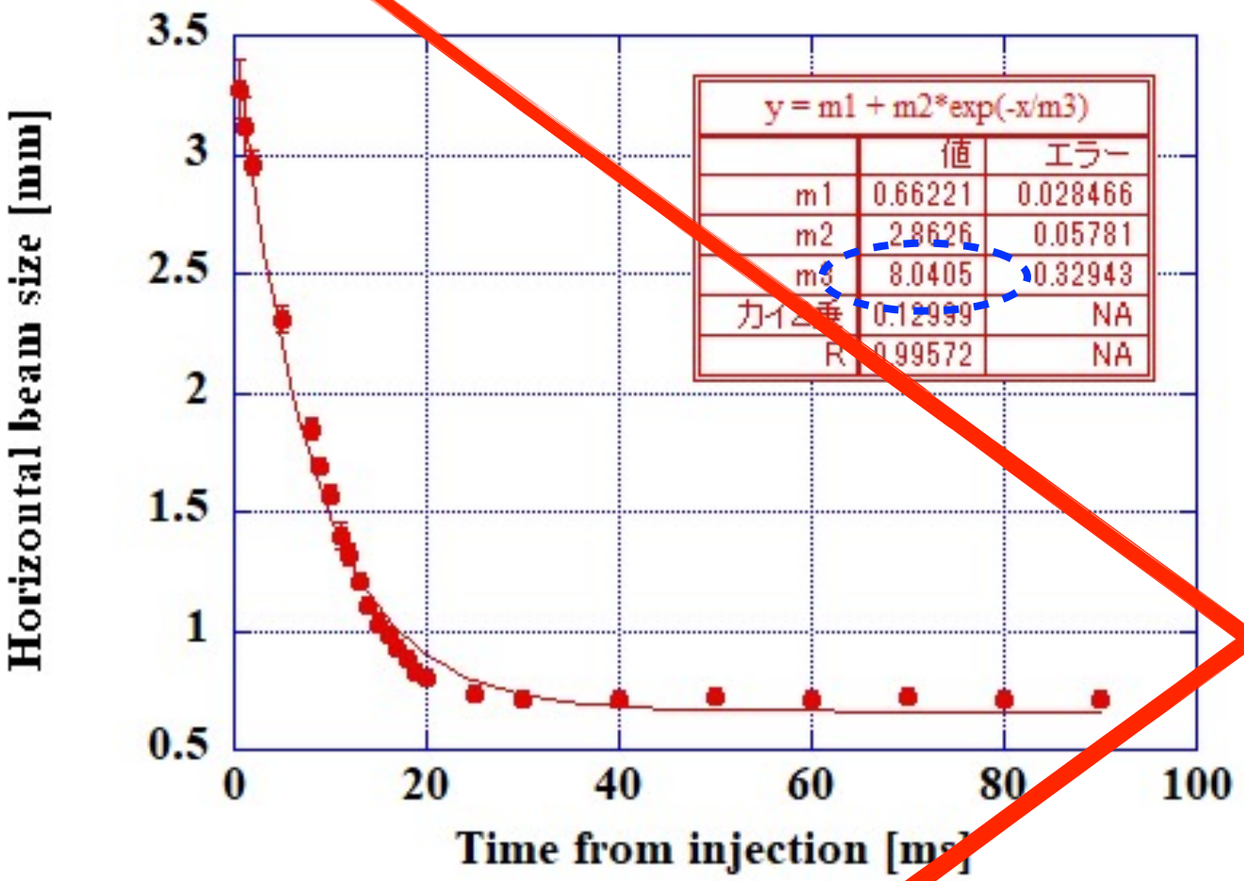


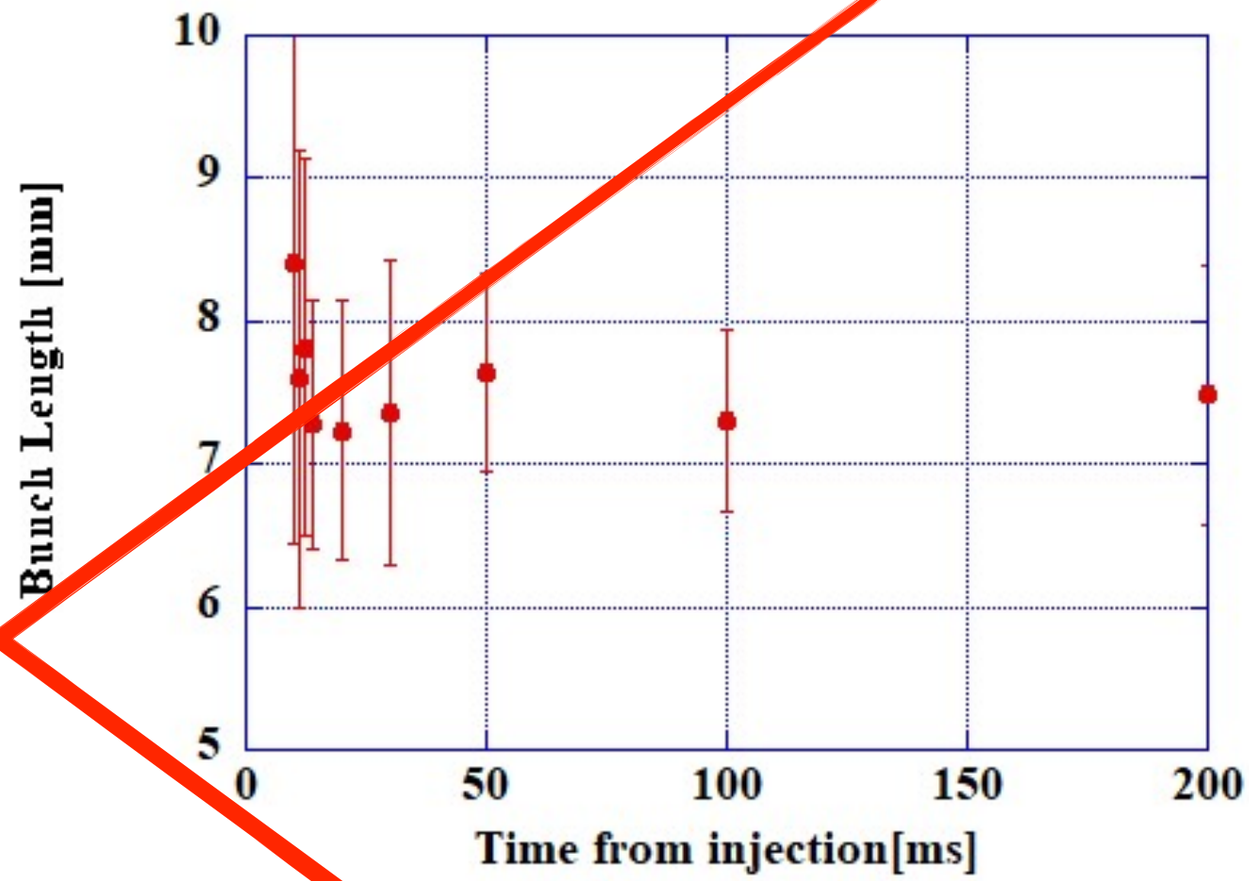




- However in a single shift, and before telescope 4 could be examined, a shifter sent all 4 primaries out of tolerance. They could not be reset because they could not be opened (we tried)
- We are modifying the primaries this summer and we have changed software to set hard limits to primary movement
- Nevertheless the new alignment system much improved and installation time is halved.

Beam size measurements in DR





- Horizontal beam size measurements by gated camera
  - The Bestfit damping time 8 ms is slightly faster than the design value (11 ms).
  - Refraction optics in Phase 1-2 was replaced with reflection optics in Phase 3.
  - Increased light intensity enabled a single-shot measurement.
- Bunch length measurements by streak camera
  - Well damped before the extraction ~40 ms