



ATF2 ultralow β^* optics

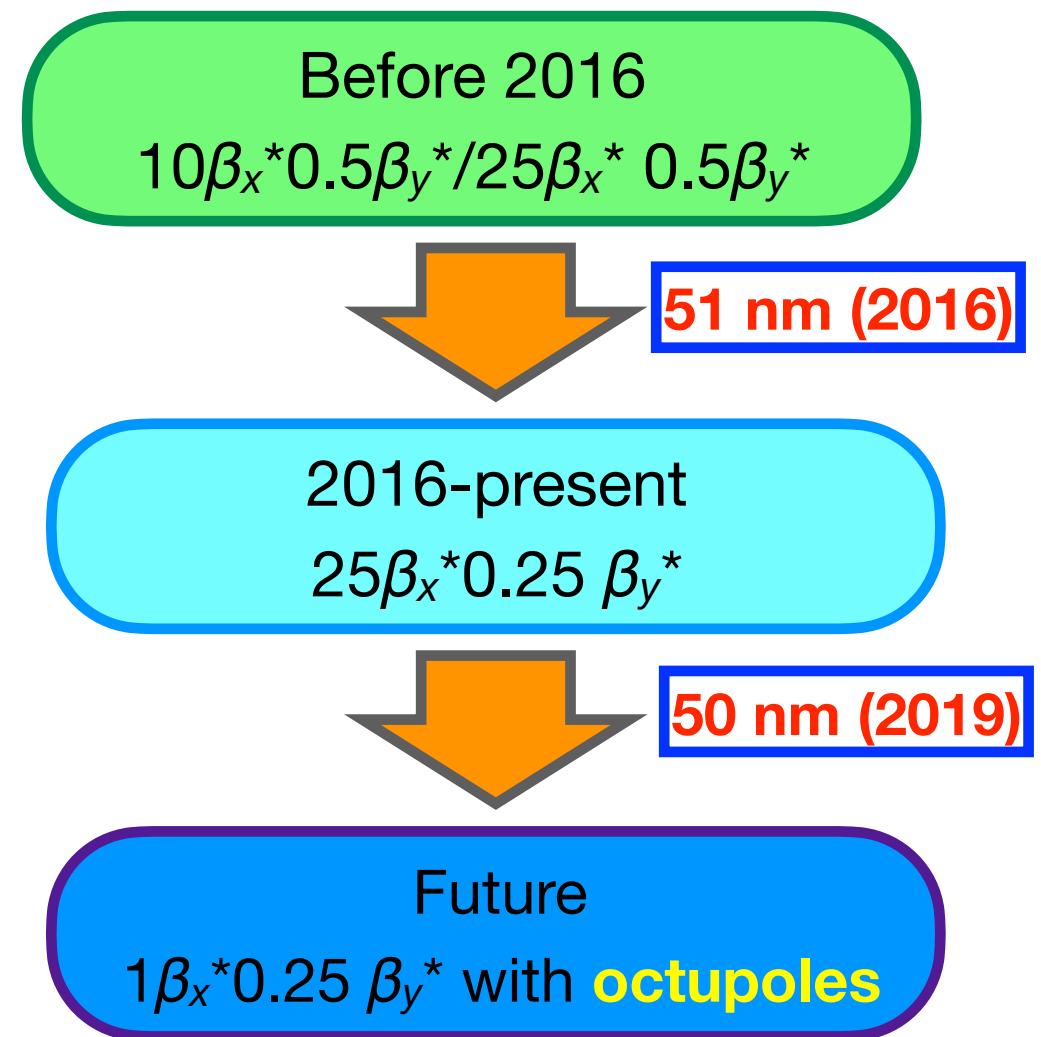
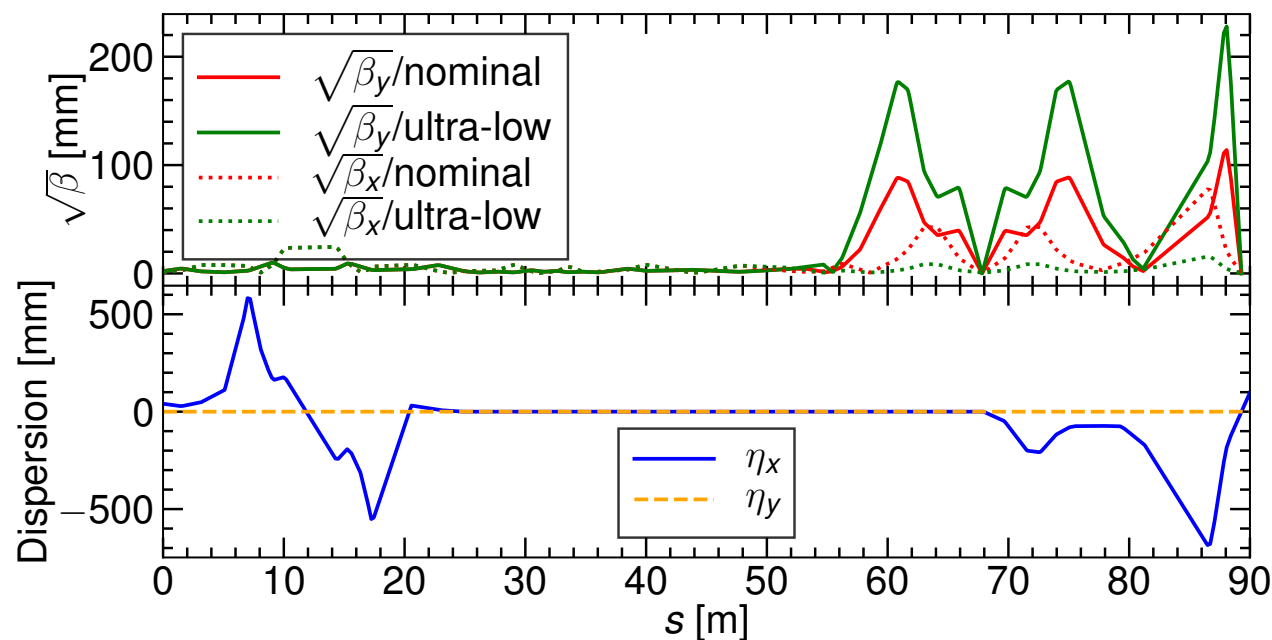
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Thanks to M. Bergamaschi, V. Cilento, A. Pastushenko, F. Plassard, A. Latina, R. Tomas, A. Aryshev, K. Kubo, S. Kuroda, T. Naito, T. Okugi and N. Terunuma

Ultralow β^* optics

- ◆ $0.25\beta_y^*$ optics to demonstrate the tightest focusing possibility with a higher chromaticity beyond ILC & approaching CLIC
- ◆ Exploring the uncharted chromaticity territory; pushing the limits of ATF2

	L^* [m]	β_y^* [μm]	Chromaticity (L^*/β_y^*)	σ_y^* [nm]
CLIC	6	120	5×10^4	1
ATF2 (nominal)	1	100	1×10^4	37
ATF2 (ultra-low)	1	25	4×10^4	23



Tuning procedures&difficulties

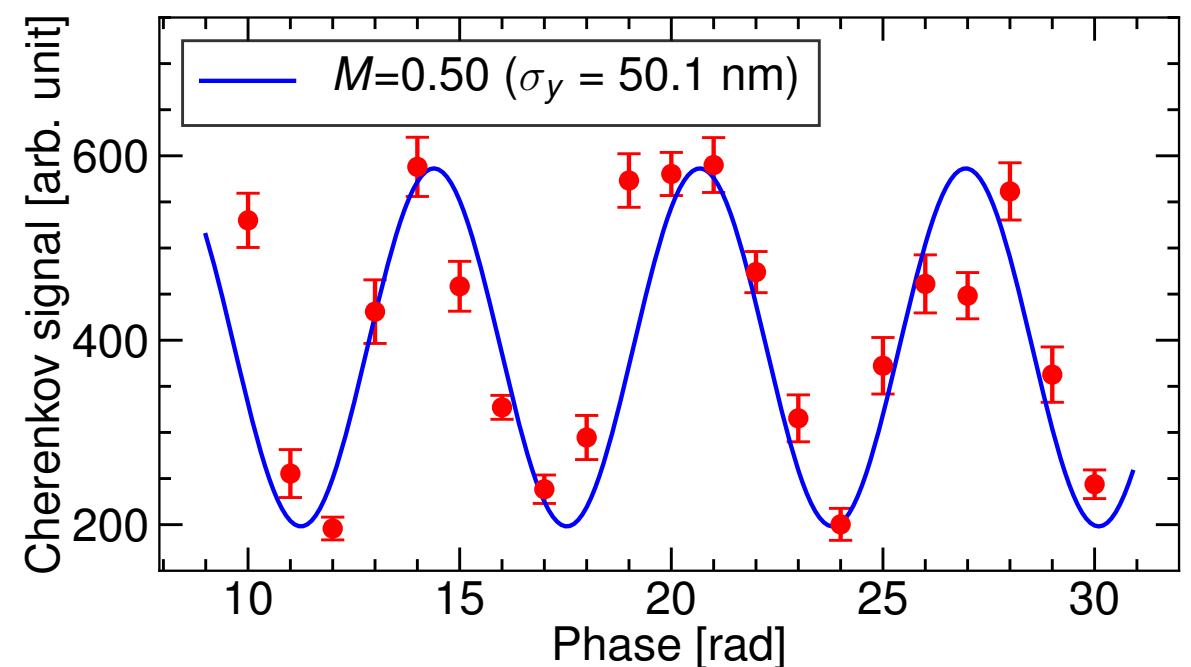
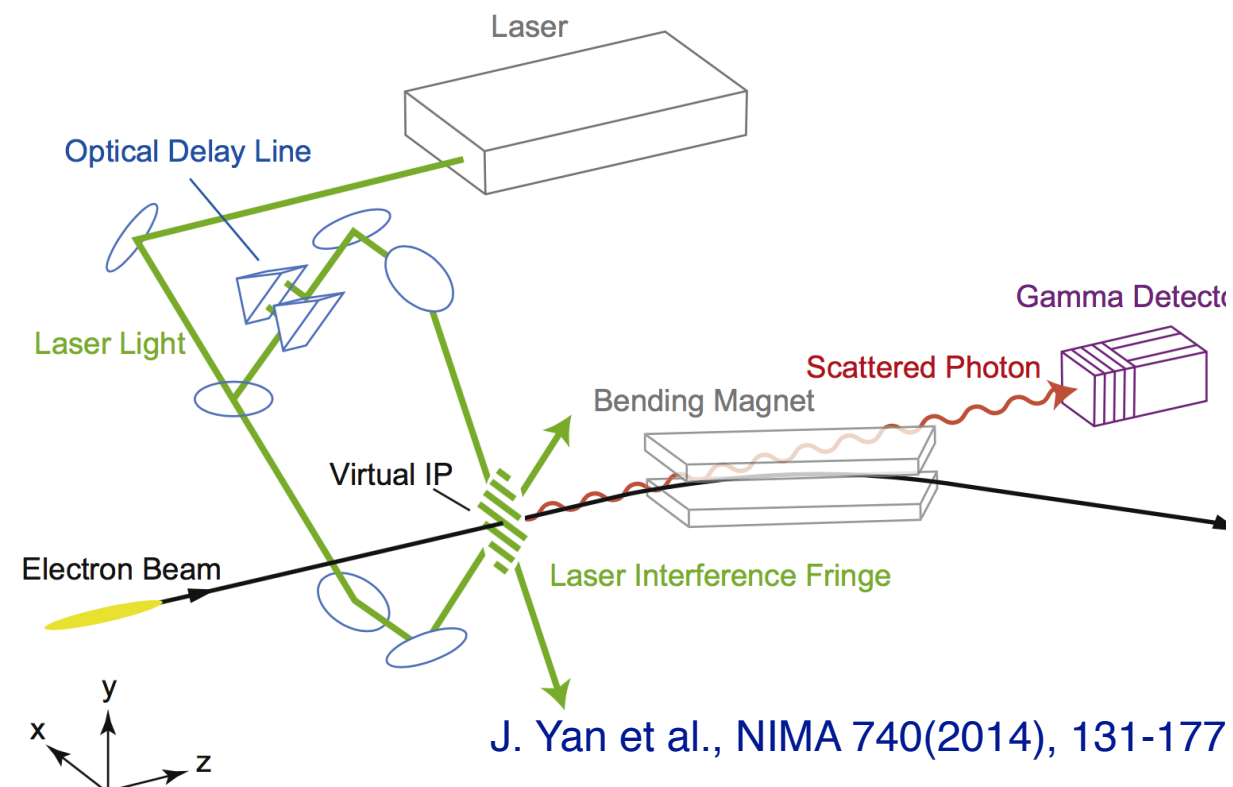
◆ General tuning procedure (~1 week)

1. DR tuning → beta/emittance measurement → BPM calibration
2. Optics matching → FFS orbit/dispersion/coupling correction → sext./skew-sext. BBA → **IPBSM** setup
3. Iteration of linear&non-linear tuning knobs → Octupoles (?)

◆ IPBSM: laser interferometer covering beam size from ~ μm to ~20 nm*

◆ Major difficulties

static&dynamic imperfections, machine-condition drift, hardware breakdown, in-consecutive beam operations, ...



* To be demonstrated!

Simulation predictions

- ◆ Measured multipoles, static machine errors (misalignment, magnet strength error), **dynamic imperfections evaluated from measurements**

Major dynamic errors

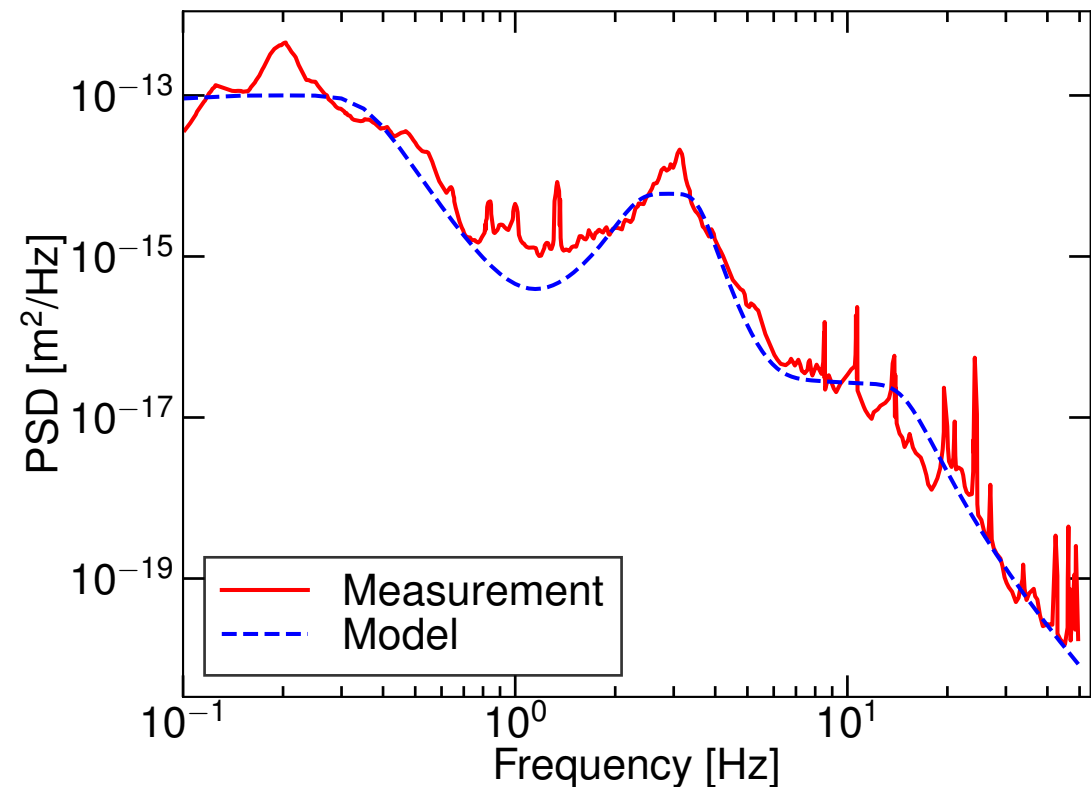
GM (fast)	ATF2 model
GM (slow)	ATL law $A=27 \mu\text{m}^2/(\text{m}\cdot\text{s})$
Vibration of FD	10 (6.5) nm
Mover accuracy	<1 μm
Power supply setting accuracy	0.001% (FFS)
Initial beam jitters	10 %

Fast Ground motion generator:

- traveling wave
- random $t: 0 < t < 3$ mins

$$\Delta y(t, s) = \sum_i \frac{1}{\sqrt{2}} a(w_i, k_i) \cos(-k_i s - w_i t + \phi_0)$$

$a(w_i, k_i)$ amplitude from PSD function



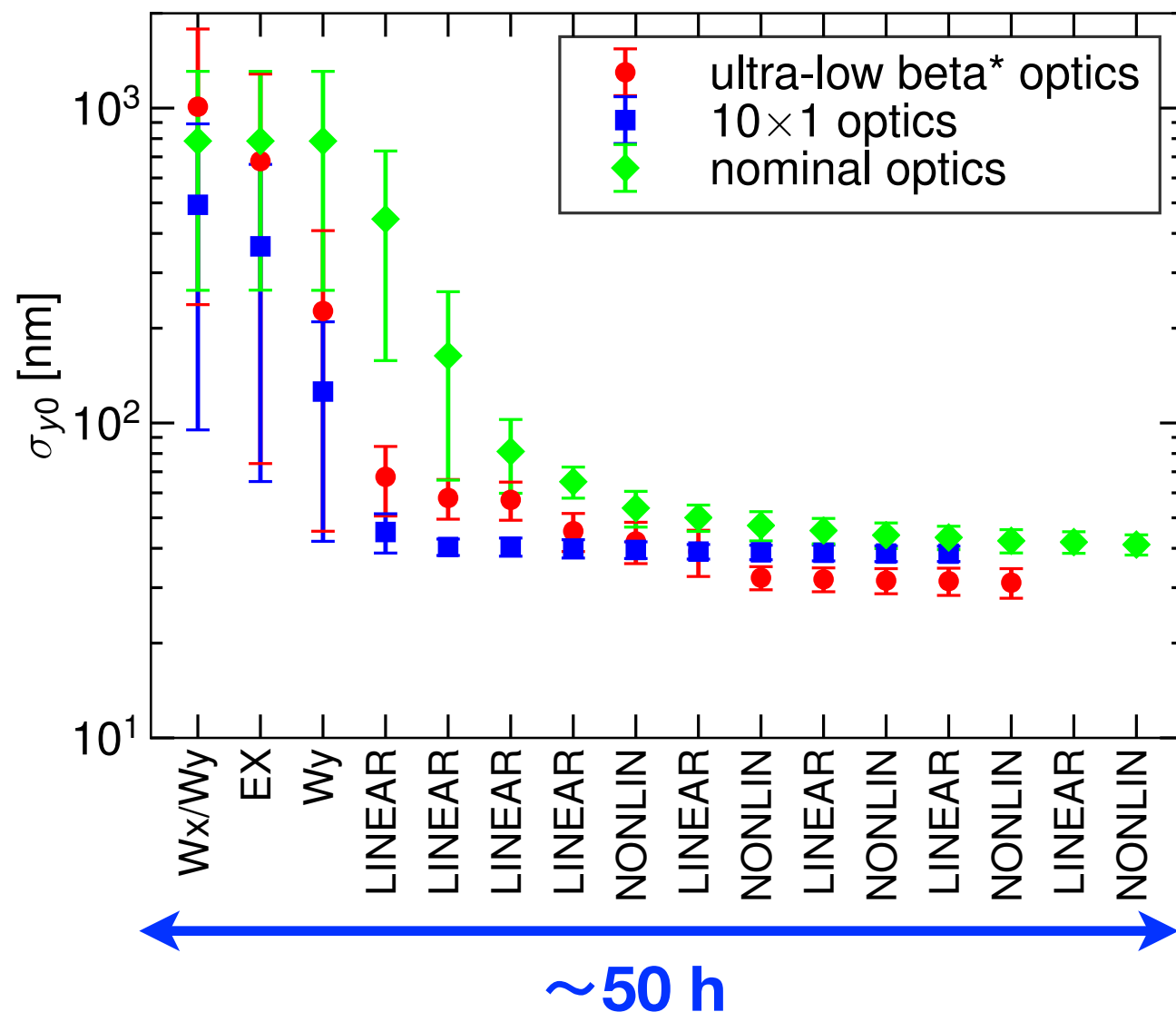
[1] B. Bolzon et al., PAC09, TH5RFP086

[2] P. Bambade et al., PRST-AB, **13**, 042801 (2009)

[3] G. White, ATF2 optics design, Beam dynamic newsletter 61 (2013)

Simulation predictions

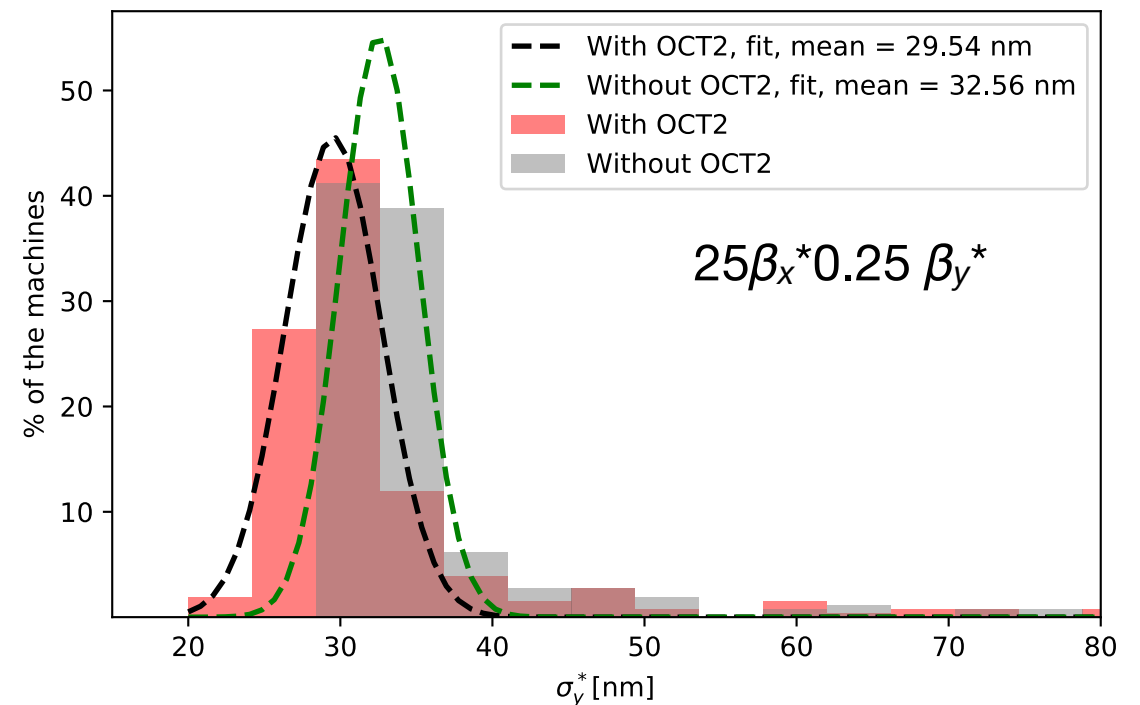
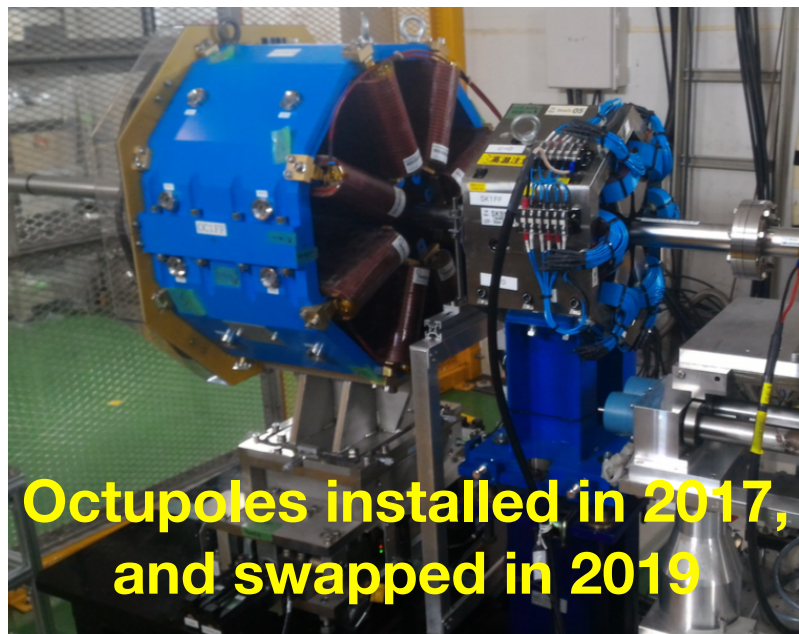
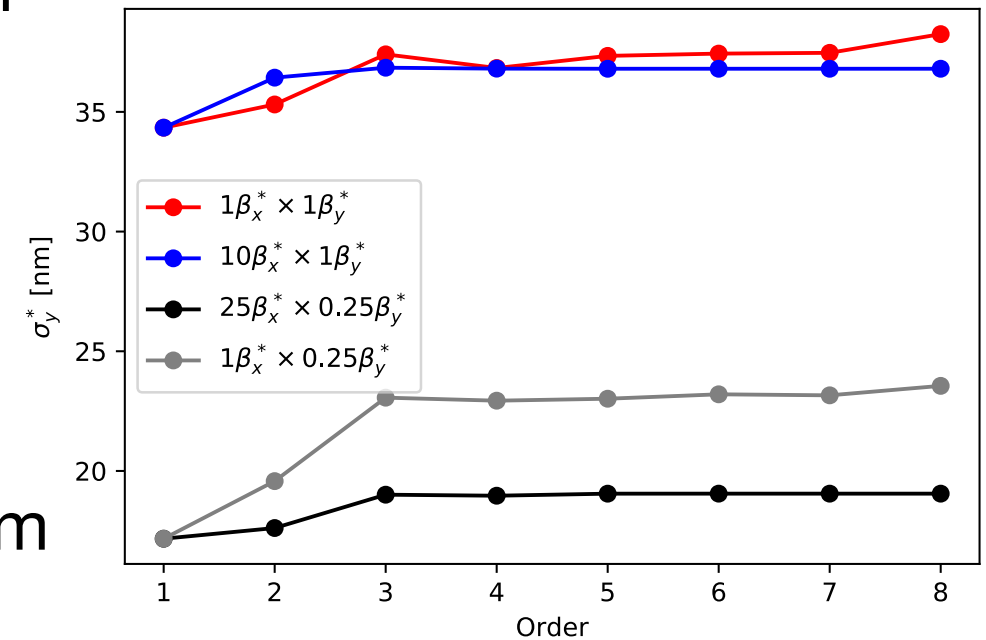
- ◆ Measured multipoles, static machine errors (misalignment, magnet strength error), dynamic imperfections evaluated from measurements
- ◆ Dedicated linear/nonlinear tuning knobs for ultralow β^* optics
- ◆ **Single-shot IP beam size of ~ 32 nm, limited by 3rd-order chromaticity and aberrations; multi-shot beam size enlarged by beam jitter (~ 20 nm)**



	$\sigma_{y,\beta}^*$ [nm]	$\sigma_{y,0}^*$ [nm]	$\sigma_{y,m}^*$ [nm]
ultra-low β^*	17.3	32.2 \pm 4.5	38.3 \pm 3.8
10x1	34.6	38.8 \pm 2.8	44.9 \pm 2.4
nominal	34.6	40.9 \pm 3.3	46.4 \pm 2.9

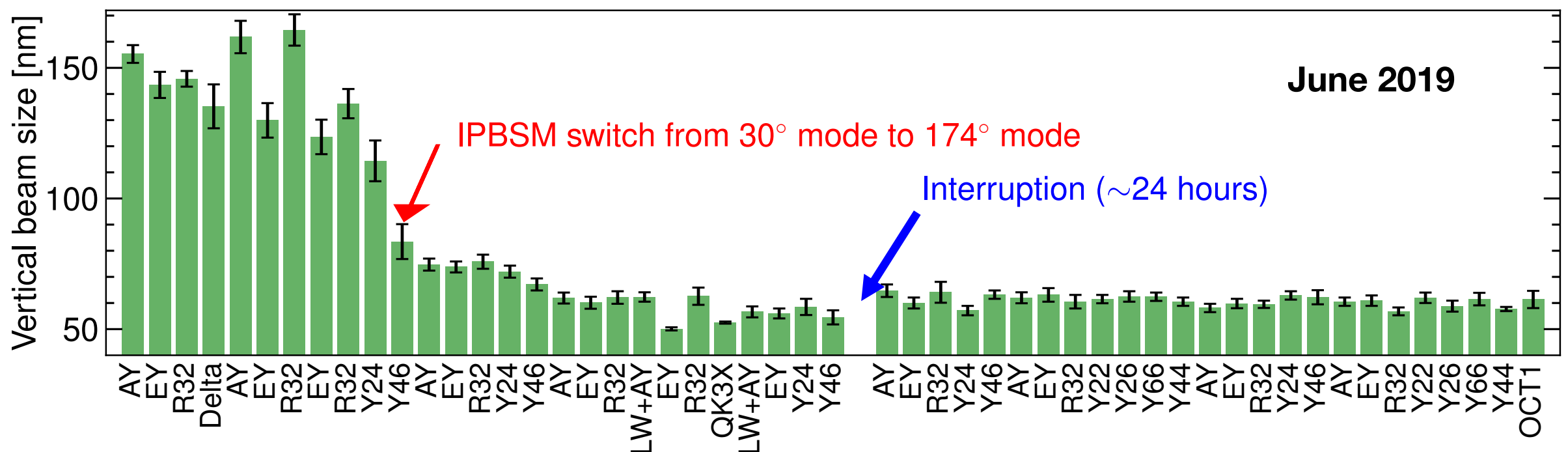
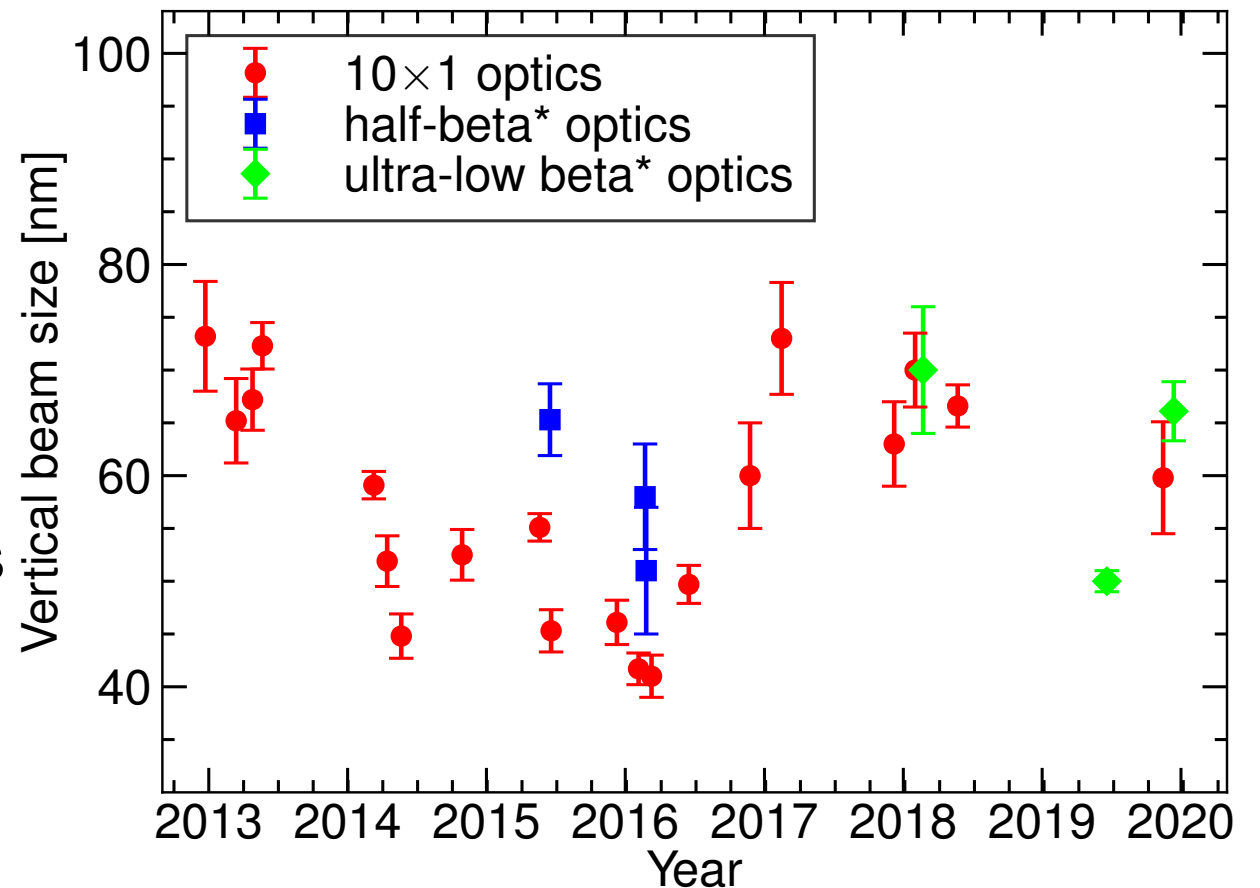
High-order aberrations

- ◆ 3rd-order terms become dominating when entering sub-25 nm region! → correction using octupoles
- ◆ Two octupoles (larger & small, $K_3L = 740$ and 90 m^{-3}), fabricated by CERN, have been placed in the FFS
- ◆ Higher probability of obtaining a sub-30 nm beam size thanks to the octupoles



Small beam size achievements

- ◆ The record smallest beam size of **41.1±0.7 nm** was achieved in 10x1 optics in 2016 (2-bunch mode)
- ◆ IP beam size of less than 60 nm has been successfully demonstrated
- ◆ In ultralow β^* optics, an IP beam size of <60 nm (min. as **50.1±0.6 nm**) was obtained and stabilized over long periods in June 2019 (single-bunch)



Limitations to achieved beam sizes

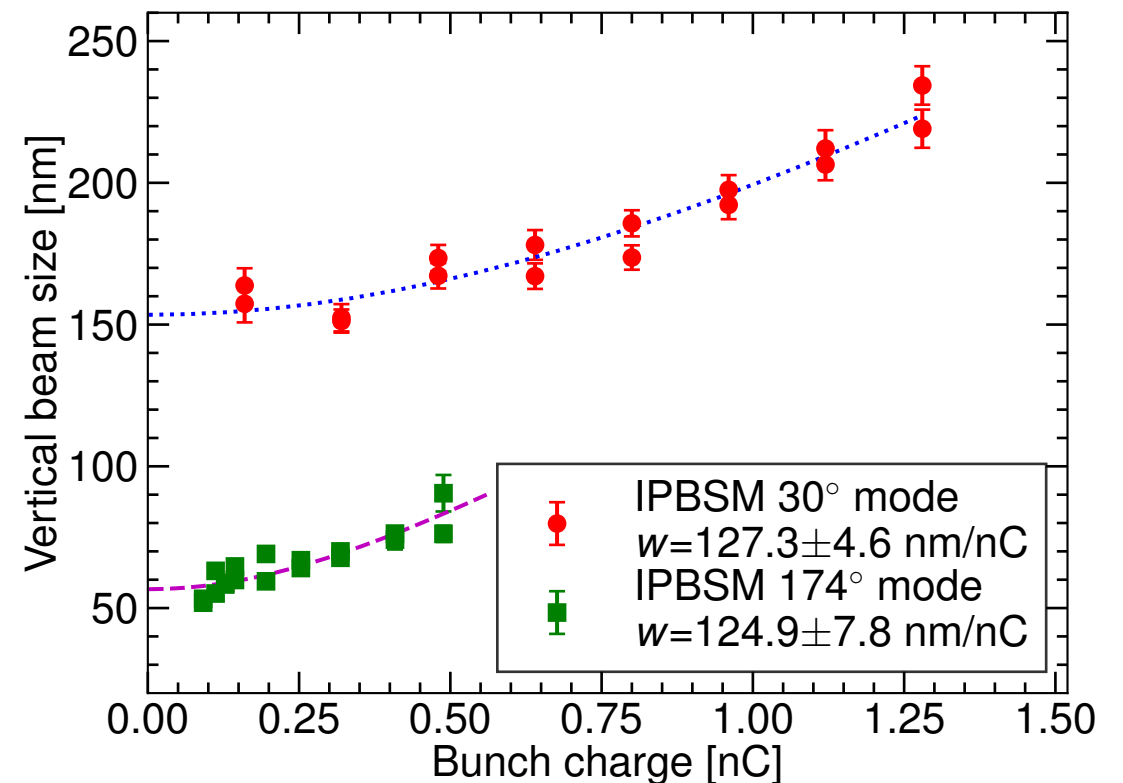
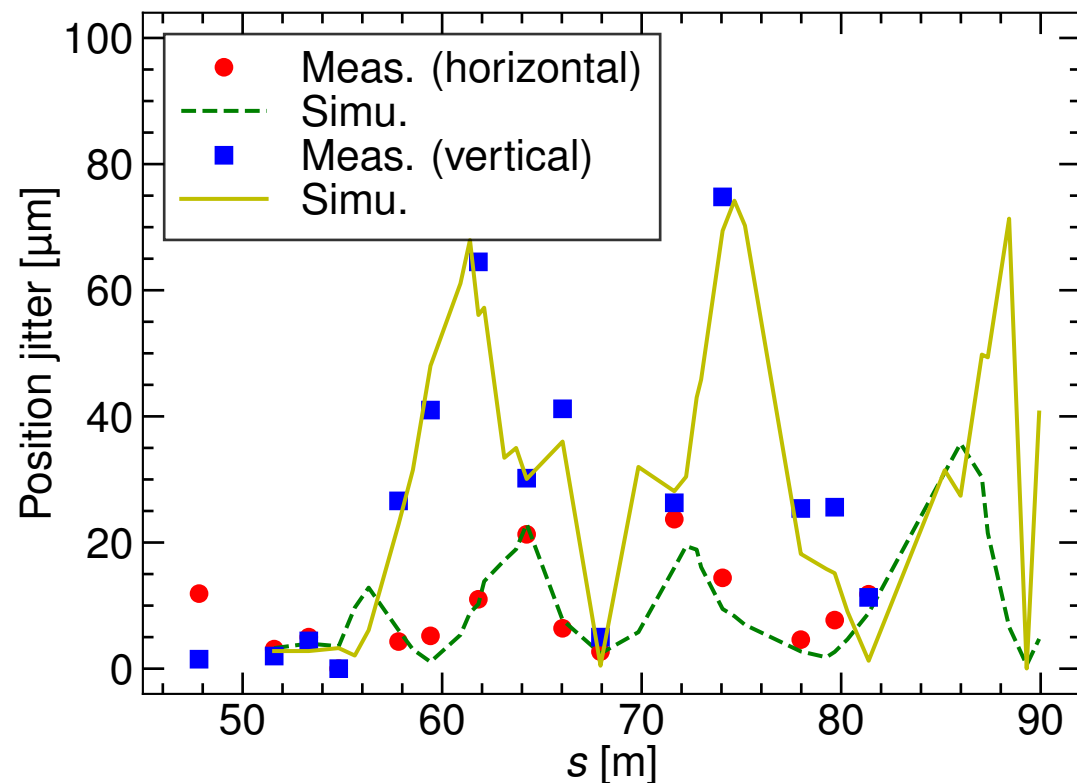
- ◆ ~10 and ~20 nm gaps for 10x1 and ultralow β^* optics
- ◆ Contributions from beam jitter, beam size growth due to wakefield and diagnostic errors

$$\sigma_y = \frac{1}{2k_y} \sqrt{2[2k_y^2(\sigma_{y0}^2 + \sigma_{dy}^2 + \sigma_w^2) + \sum_i \log C_i]}$$

σ_{dy} : beam position jitter (~20 nm w/o correction)

$\sigma_w = wq$: beam size growth due to wakefield ($w \approx 125$ nm/nC from measurements)

C_i : modulation reduction (~0.91 by analytical assessments)

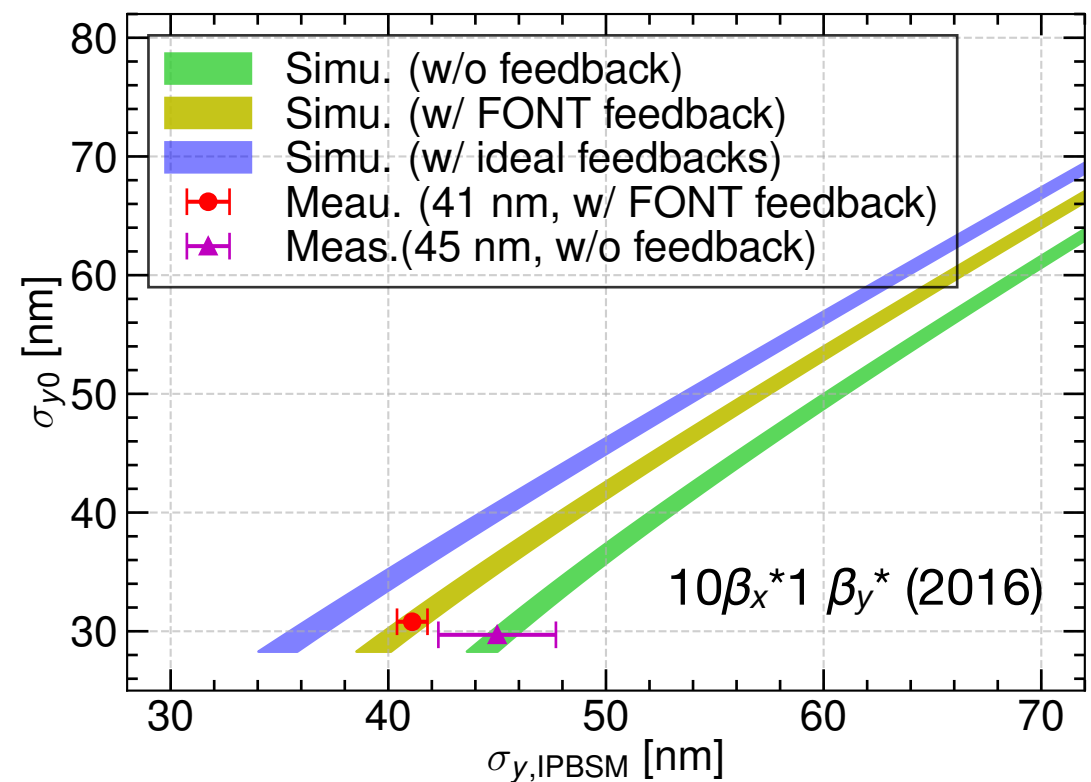
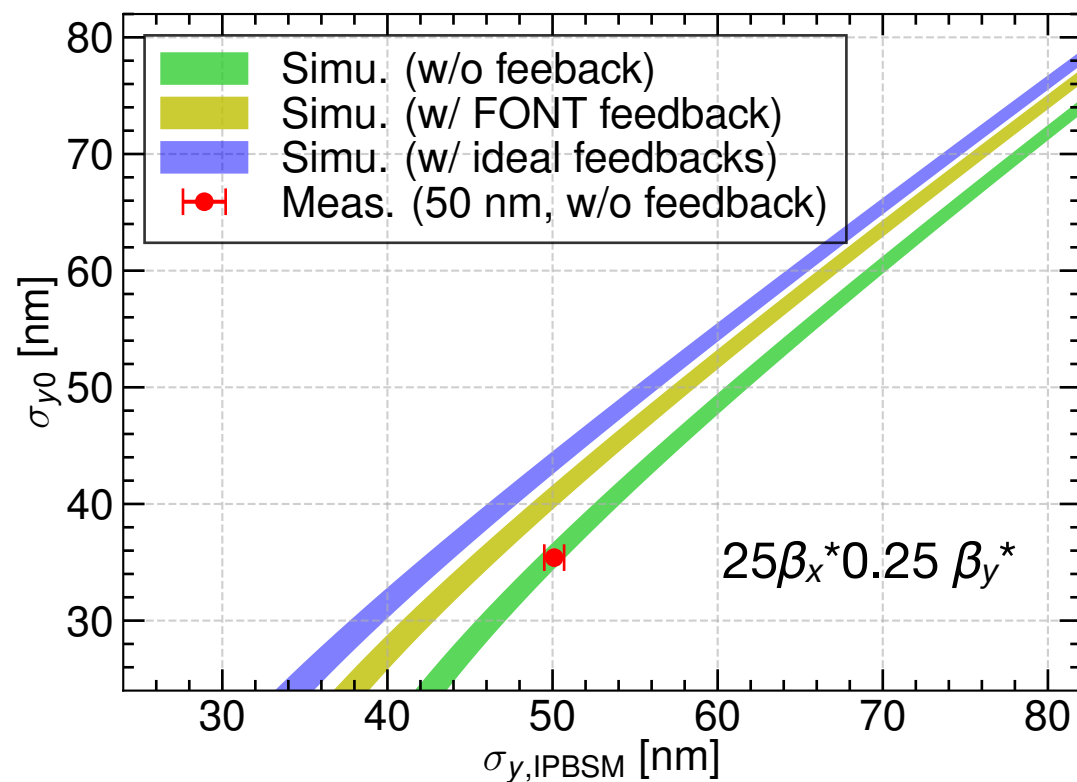


Realistic FFS jitter + GM/Vibration $\rightarrow \sigma_{dy}$

Limitations to achieved beam sizes

◆ IPBSM beam-size correction $\sigma_y \rightarrow \sigma_{y0}$

- 50.1 nm@ultralow β^* optics ($Q=0.16$ nC, $\varepsilon_y=12$ pm)
 $\rightarrow \sigma_{y,0}^* \sim 35.5$ nm *close to simulation!*
- 41.1 nm@10x1 optics ($\varepsilon_y=8.0$ pm, $\sigma_w \approx 17.8/20.3$ nm)
 $\rightarrow \sigma_{y,0}^* \sim 30$ nm *approaching $\sigma_{y,\beta}^*$!*
- Beam jitter, wakefield and IPBSM systematic errors play similar role!

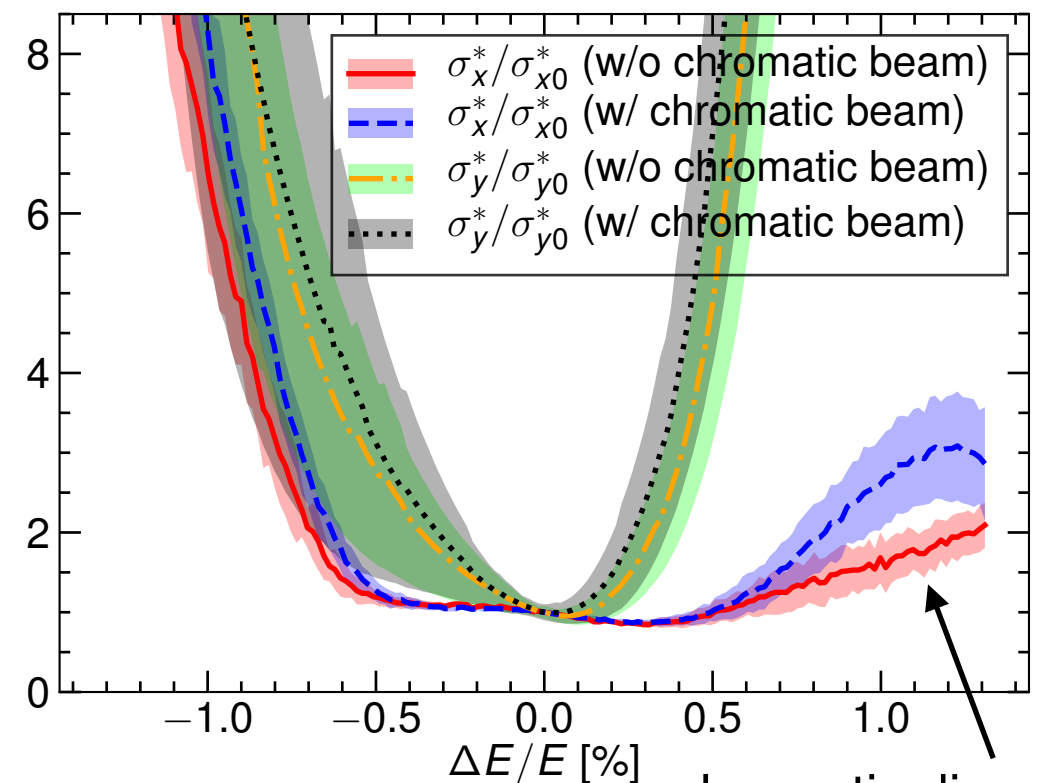
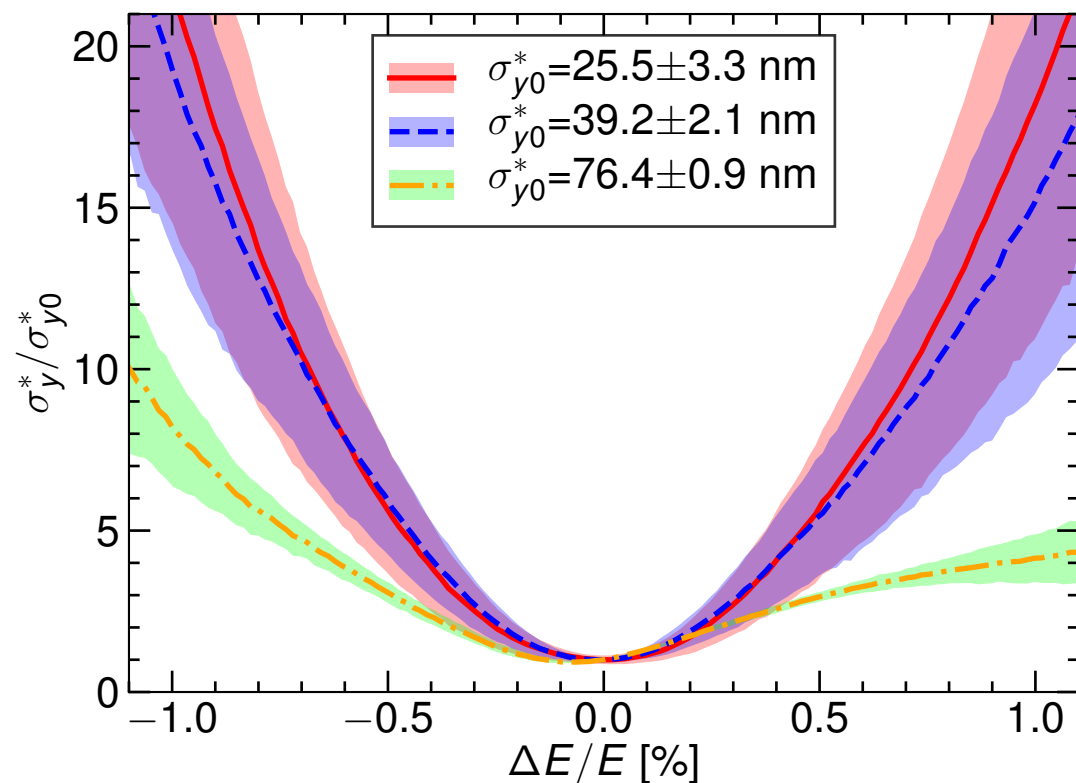


◆ $\sigma_{y,0} \rightarrow \sigma_y$

23 nm \rightarrow 32.3 nm and 37 nm \rightarrow 40.0 nm for ultralow β^* and 10x1 optics, even with orbit stabilization ($\sigma_{dy}=10$ nm) !! **Barriers to break towards goal beam sizes!**

Momentum bandwidth

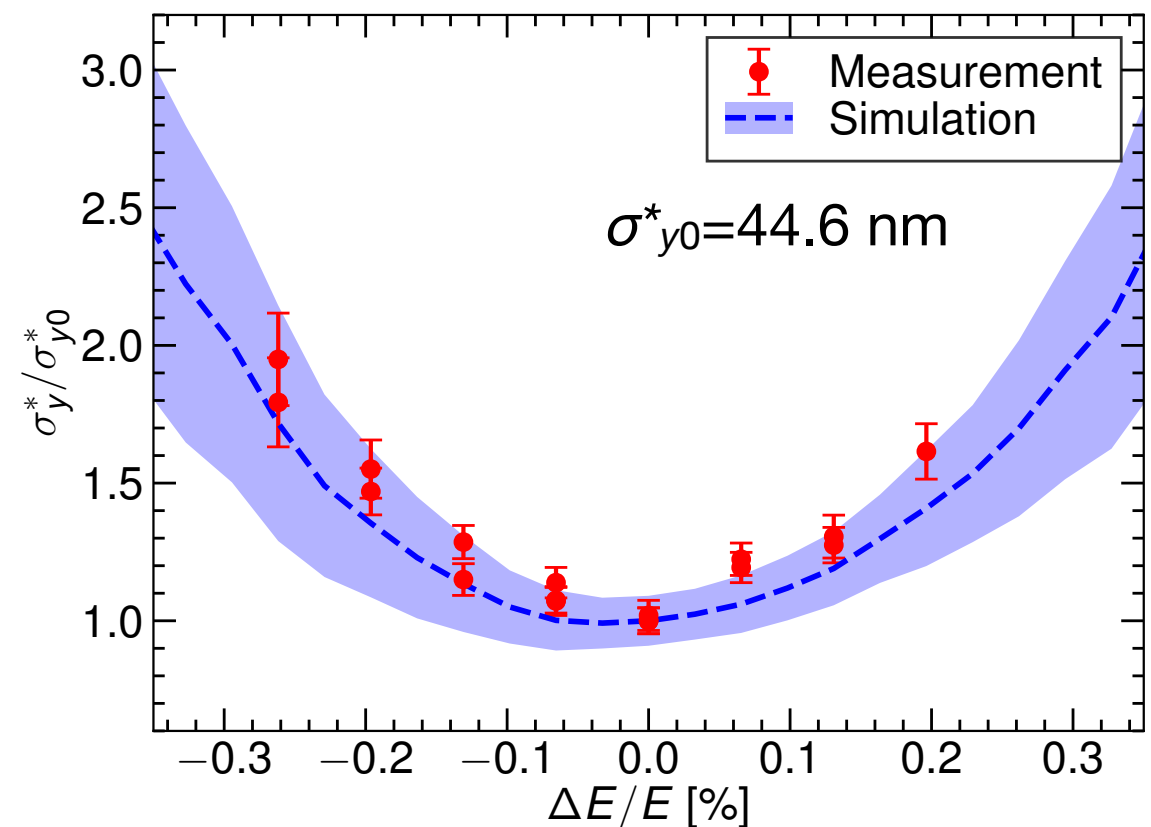
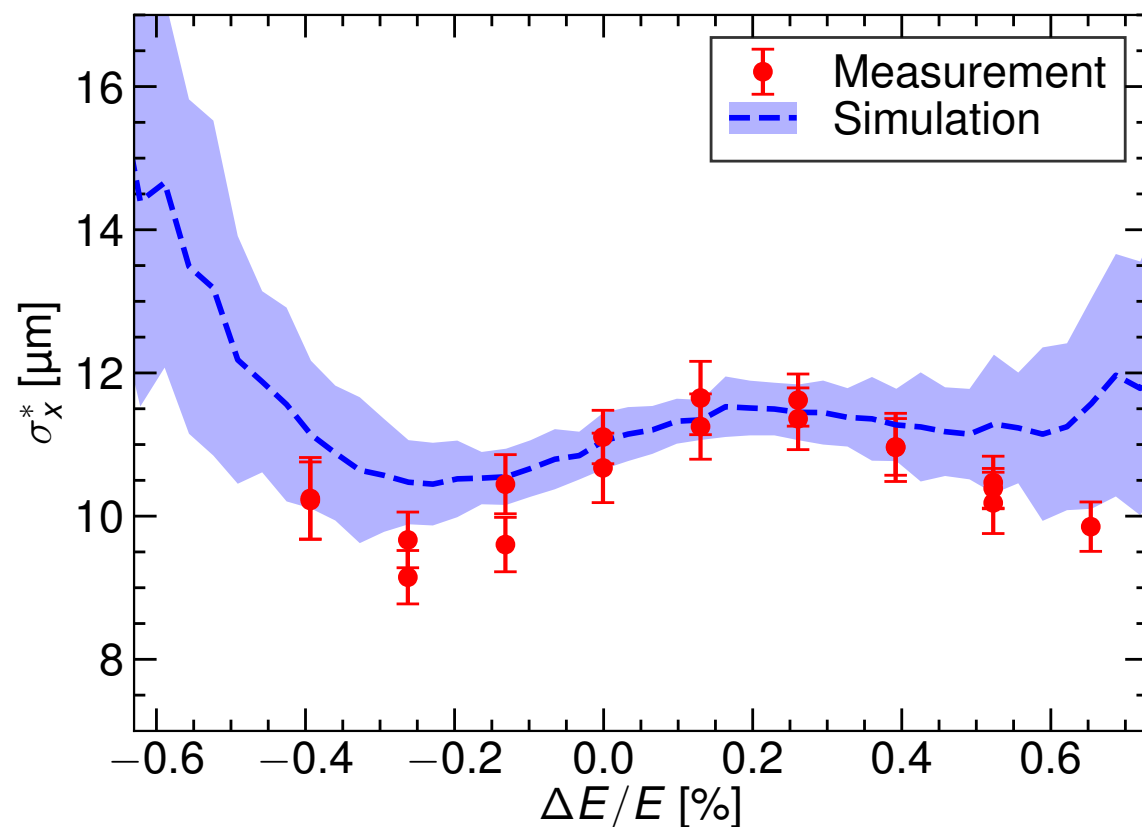
- ◆ Characterizing the preservation of design optics against marginal beam-energy errors and energy-spread blowup
- ◆ Probable distortions to energy-bandwidth measurement
 - ✓ Mismatched FFS optics → realistic FFS optics model
 - ✓ Unsatisfactory IP tuning & larger σ_y^* (residual 2nd-order terms)
 - non-linear knobs correction; reproductions w/ comparable σ_{y0}^*
 - ✓ Chromatic emittances, Twiss and dispersions of extracted beam
 - may deform horizontal bandwidth; not easy to measure/control



chromatic dispersions at the extraction 10

Momentum bandwidth

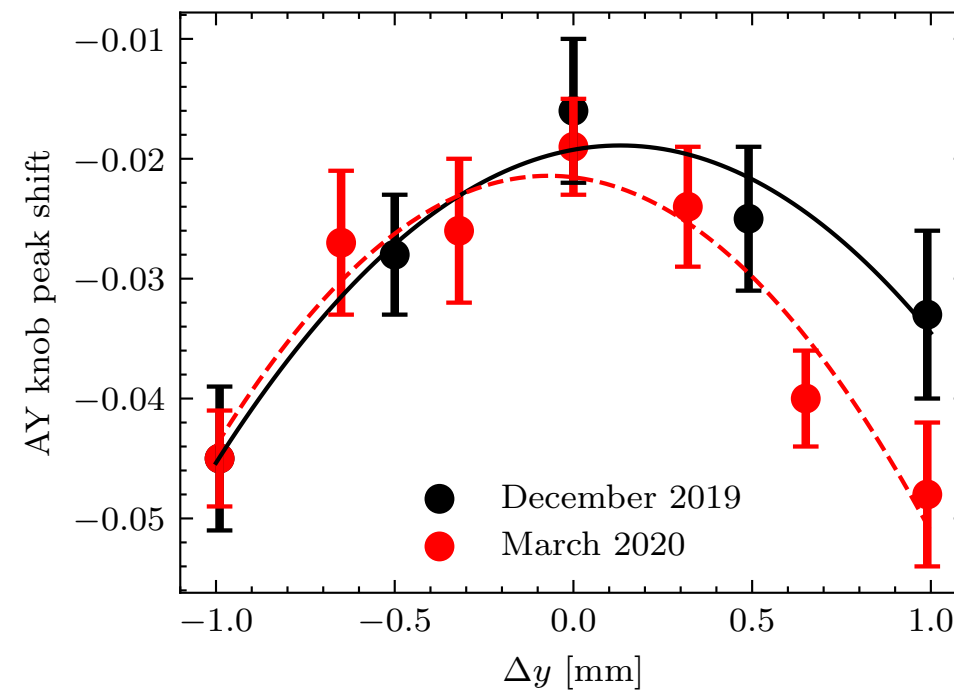
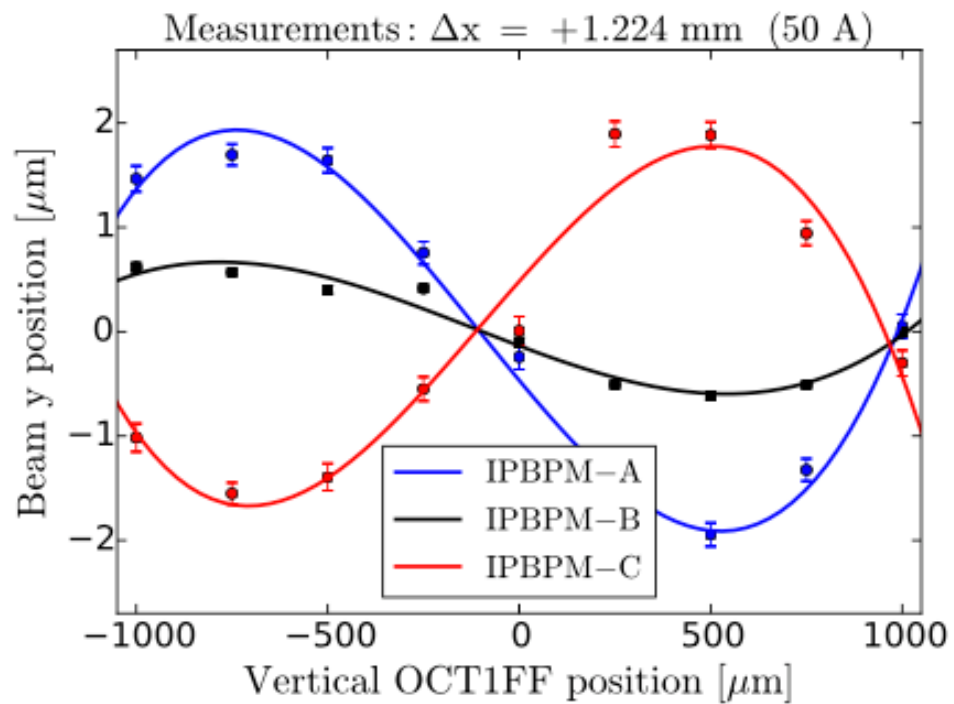
- ◆ Measurements@ultralow β^* optics are roughly consistent with simulations based on operational optics model!
- ◆ The 10% bandwidth* is $<0.2\%$, much smaller than CLIC and ILC ($\sim 0.6\%$), because the current optics is solely optimized for small-beam tuning at nominal energy
- ◆ Further measurements with optimized sextupole configurations, and in 10x1 optics are strongly recommended!



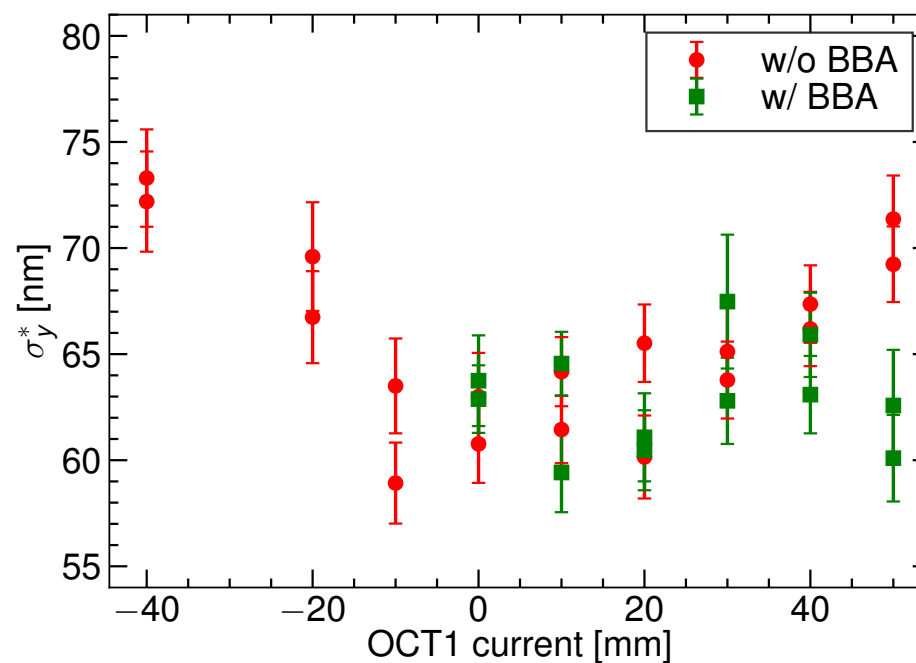
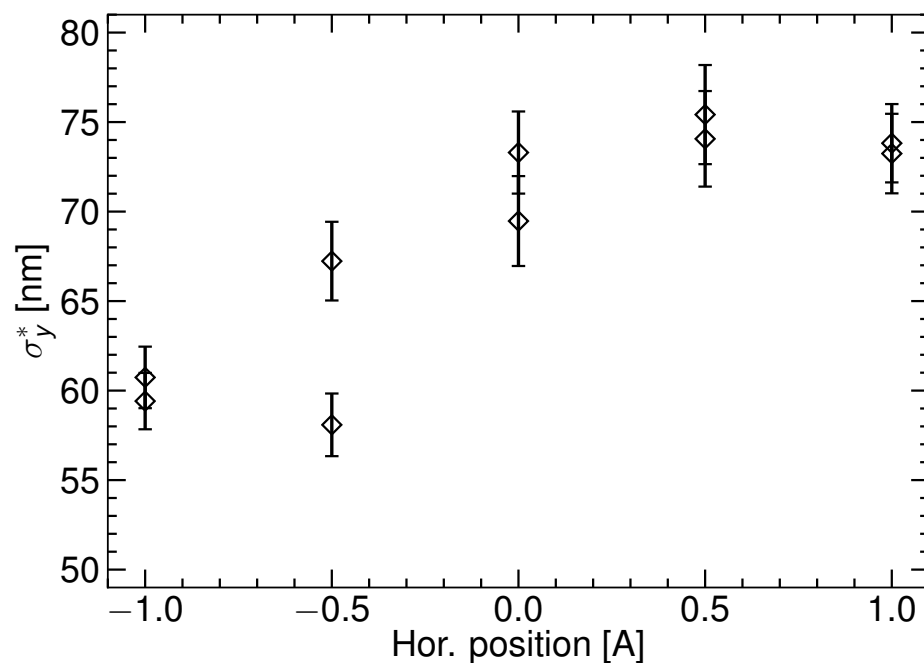
* Defined as a 10% increase of either horizontal or vertical IP spot size for mono-energetic beam.

Octupole studies

- ◆ Demonstrations of octupole BBA methods
 - ✓ Using dipole component (w/ IPBPMs) and quadrupole component (waist shift)



- ◆ Not yet observed beam-size reduction by the octupoles (poor BBA? too large σ_y^* ?)



Summary

◆ Achievements

- Small beam sizes of less than 60 nm (min. ~50 nm) have been obtained in both half β^* and ultralow β^* optics
- BBA strategies for the new installed octupoles have been evaluated
- Momentum bandwidth has been demonstrated in ultralow β^* optics

◆ Lessons & Limitations & solutions

- Vertical IP position jitter (~20 nm) —> FB/FF
- Wakefield effects (125 nm/nC) —> FB & wakefield compensation
- Systematic diagnostic errors —> modulation corrections (jitter-free?)
- Possible larger multipoles of FD quads. —> new measurements + consecutive dedicated operations for tuning (1-2 weeks)

◆ Far future (ATF3=ATF2+R&D beyond LC)...

- ◆ Moving to $10\beta_x^*0.25\beta_y^*$ and $1\beta_x^*0.25\beta_y^*$ optics
- ◆ New optics with long L^* (modifying IP configurations)

Thank you!
Question?

