ATF2 ultralow β^* optics

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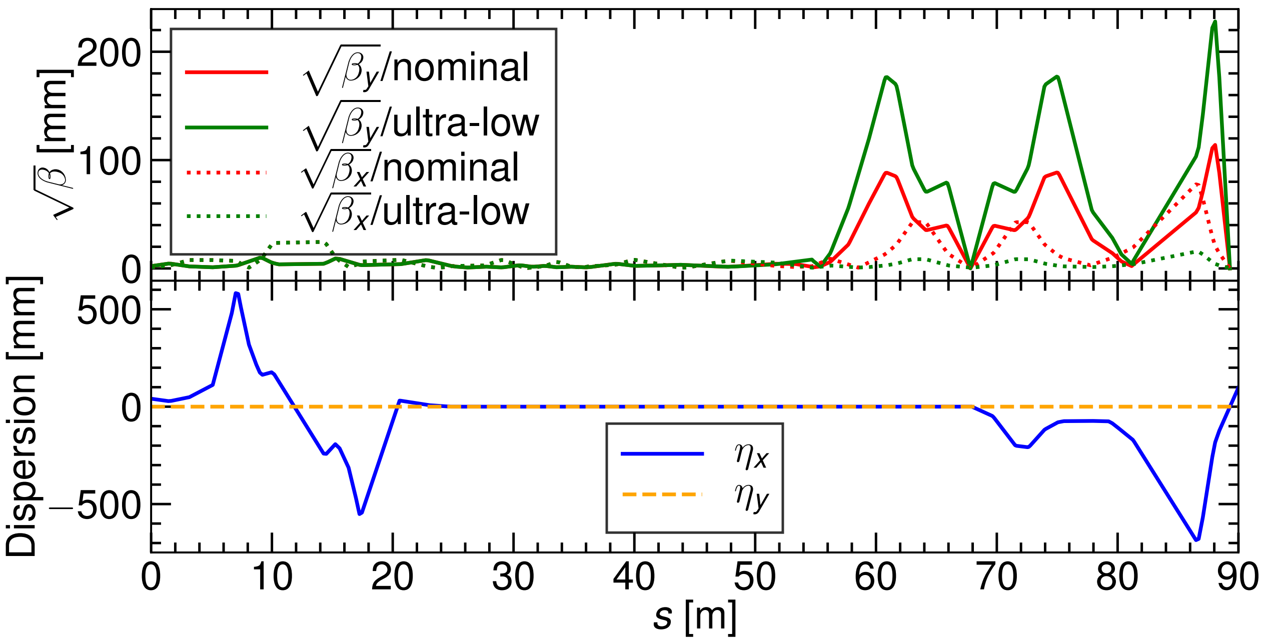
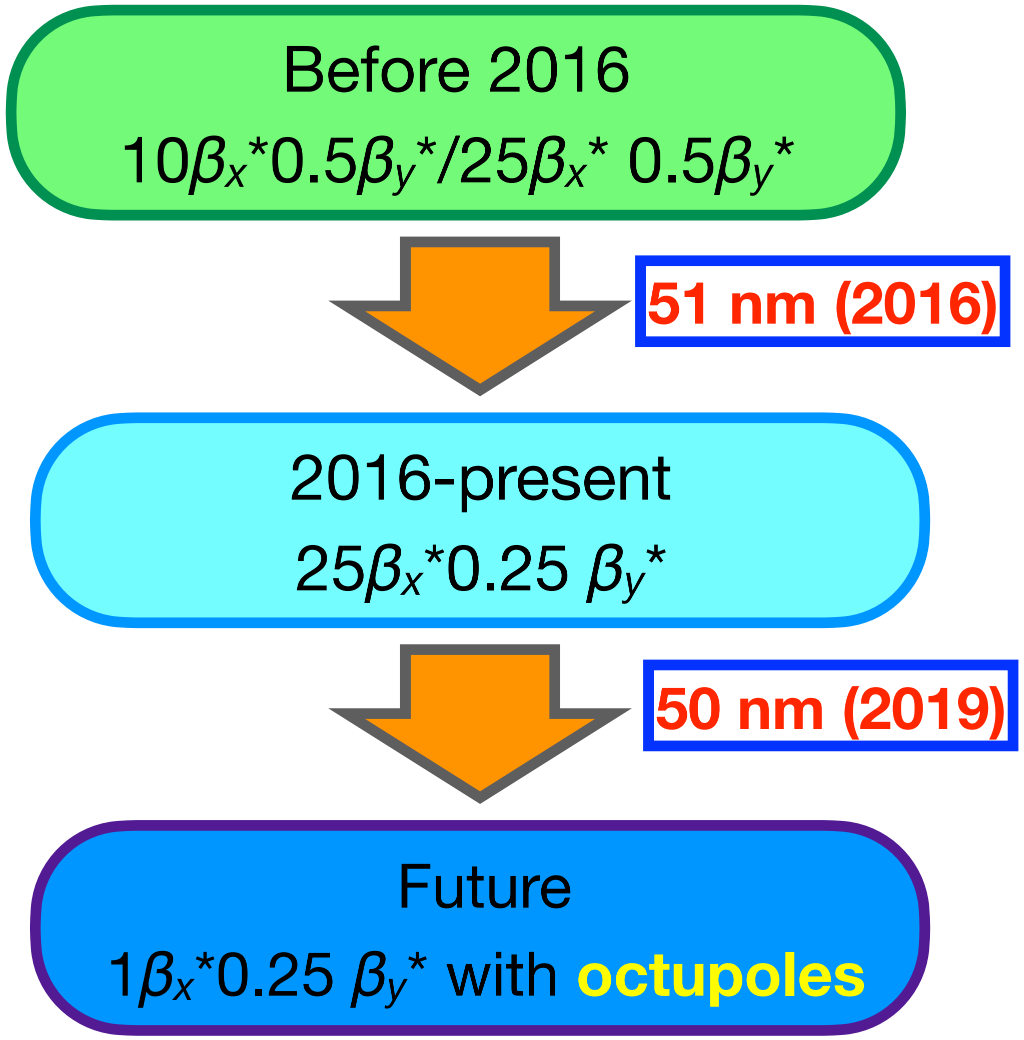
Ultralow β^* optics

- ◆ $0.25\beta_y^*$ 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	$5\text{x}10^4$	1
ATF2 (nominal)	1	100	$1\text{x}10^4$	37
ATF2 (ultra-low)	1	25	**$4\text{x}10^4$**	**23**





Before 2016

$10\beta_x^*0.5\beta_y^*/25\beta_x^*\ 0.5\beta_y^*$

51 nm (2016)

2016-present

$25\beta_x^*0.25\ \beta_y^*$

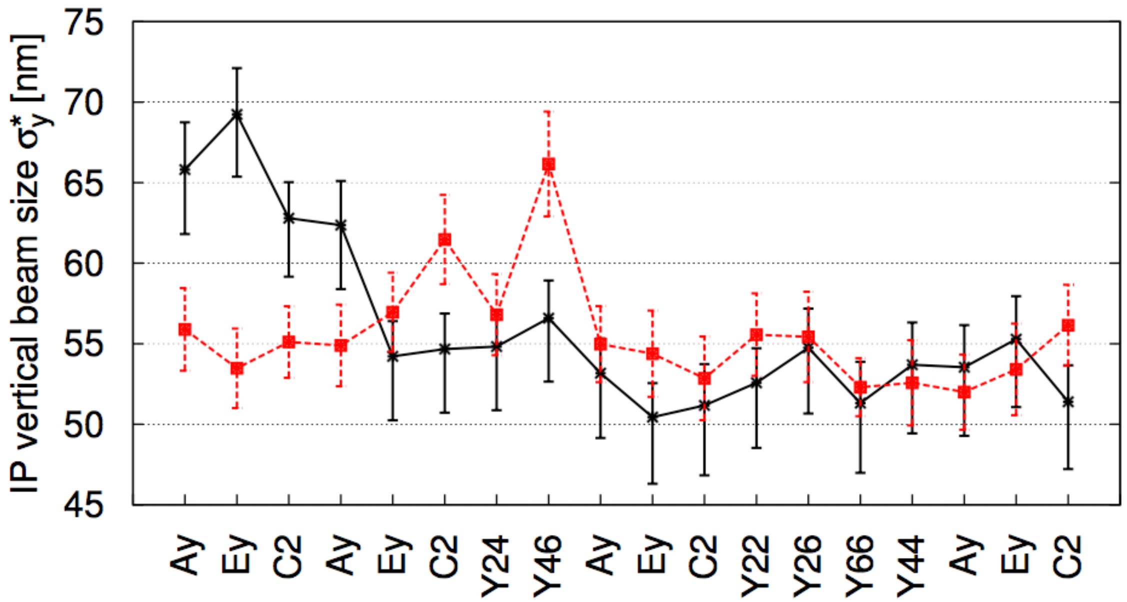
50 nm (2019)

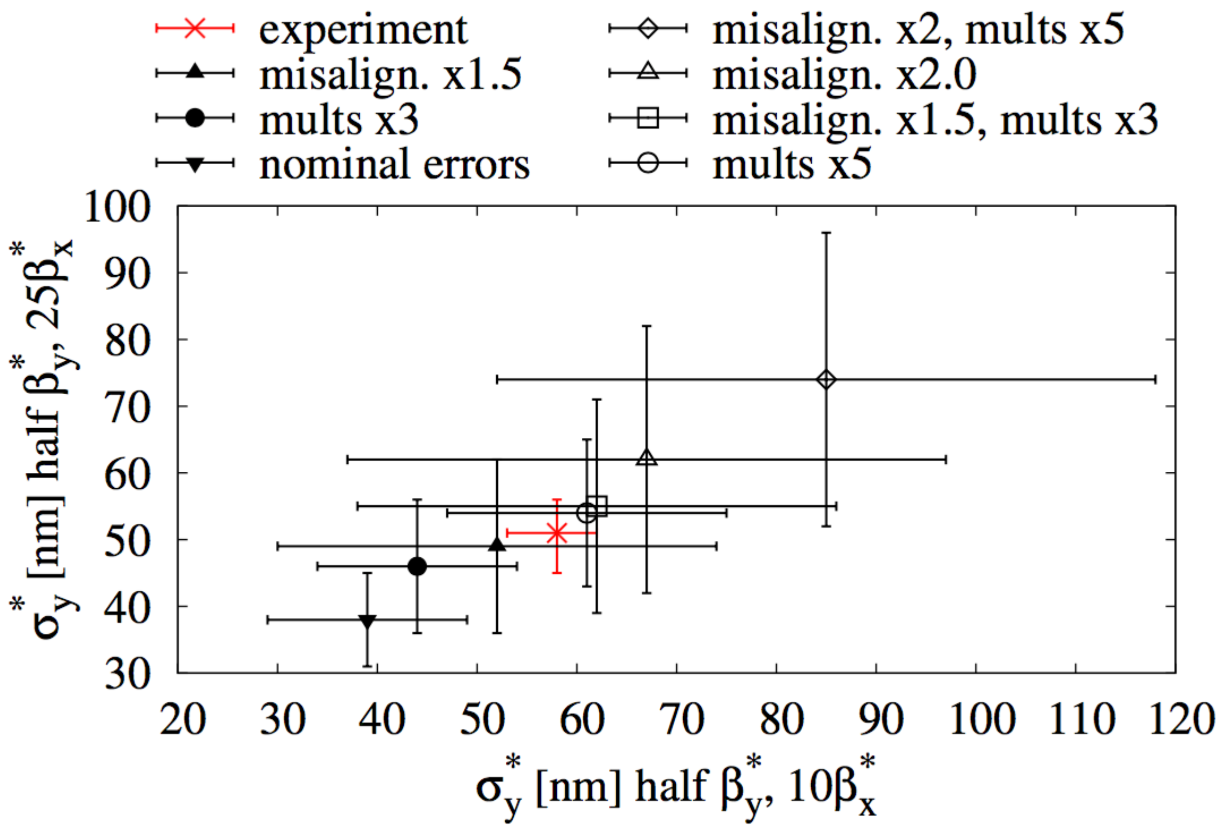
Future

$1\beta_x^*0.25\ \beta_y^*$ with **octupoles**

half *β** optics

- Halfway moderated step towards ultralow β^* tuning; study the possible limits of beam focusing with higher chromaticity
- Achieving ~51 nm min. beam size in $25\beta_x^* 0.5\beta_y^*$ optics; residual discrepancy from the design reveals possible larger static machine errors





[1] M. Patecki et al., Phy. Rev. Accel. Beams 19, 101001 (2016)
[2] M. Patecki, PhD. thesis, Warsaw University of Technology, 2016

Simulation predictions

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

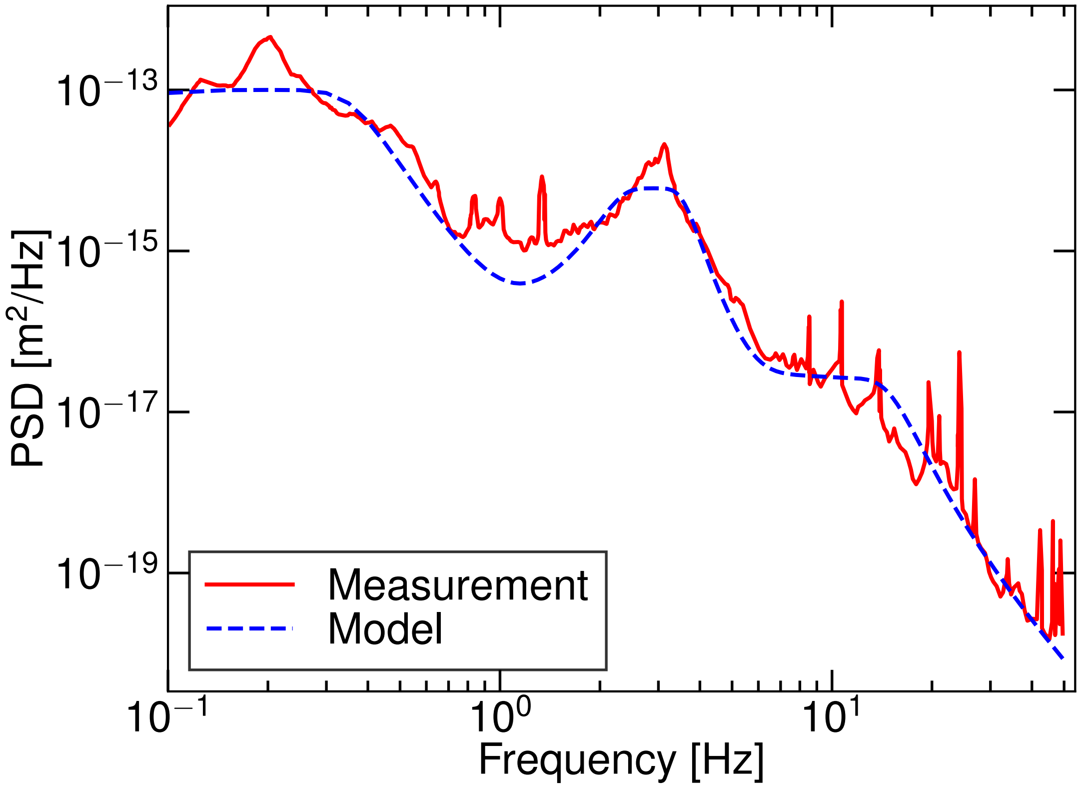
Major dynamic errors

GM (fast)	ATF2 model
GM (slow)	*ATL* law *A*=27 µm²/(m.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

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

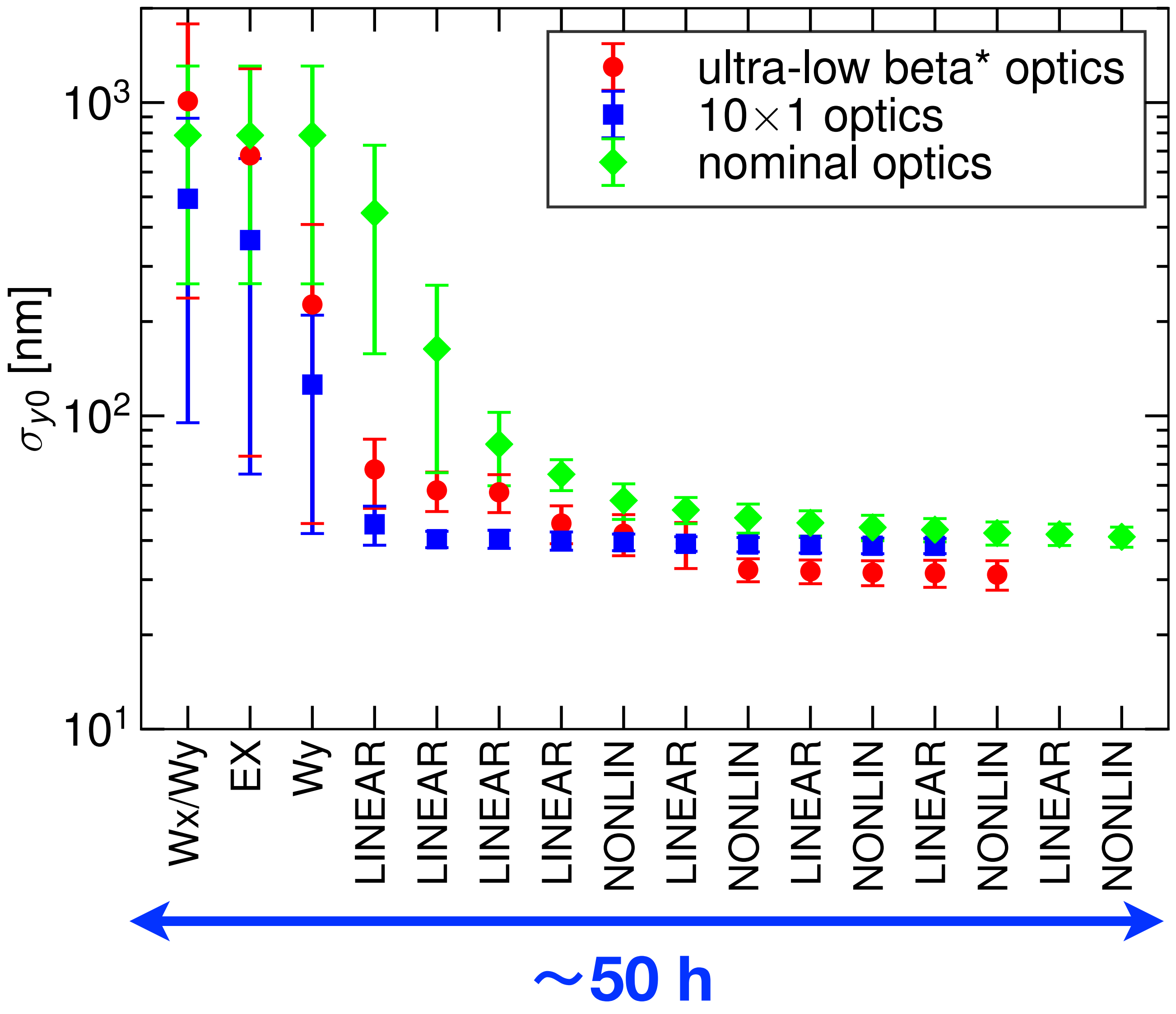
$a(w_i, k_i)$ amplitude from PSD function



[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

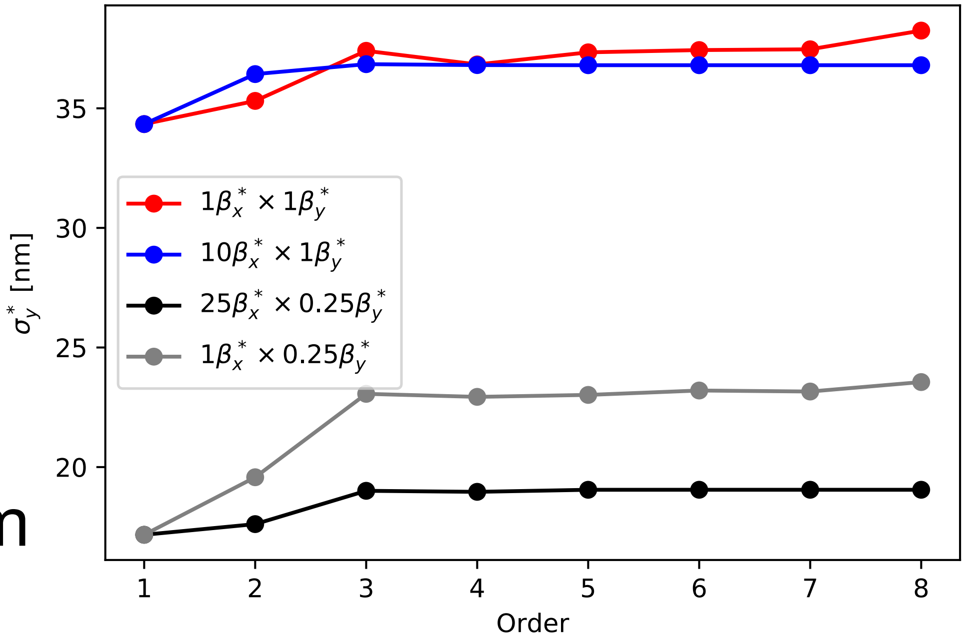
- Measured multipoles, static machine errors (misalignment, magnet strength error), dynamic imperfections evaluated from measurements
- Dedicated linear/nonlinear tuning knobs for ultralow *β** optics
- **Single-shot IP beam size of ~32.2 nm, limited by 3rd-order chromaticity and aberrations; multi-shot beam size enlarged by beam jitter (~20 nm)**

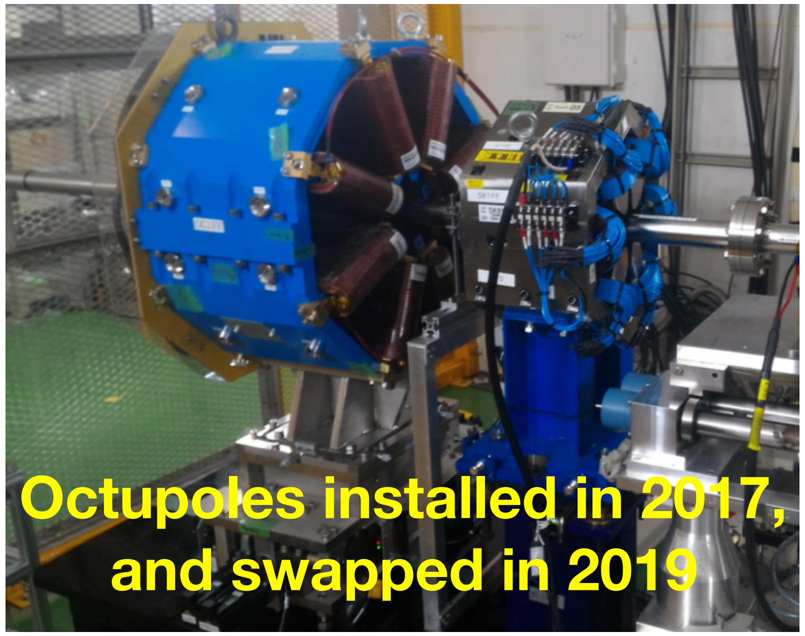


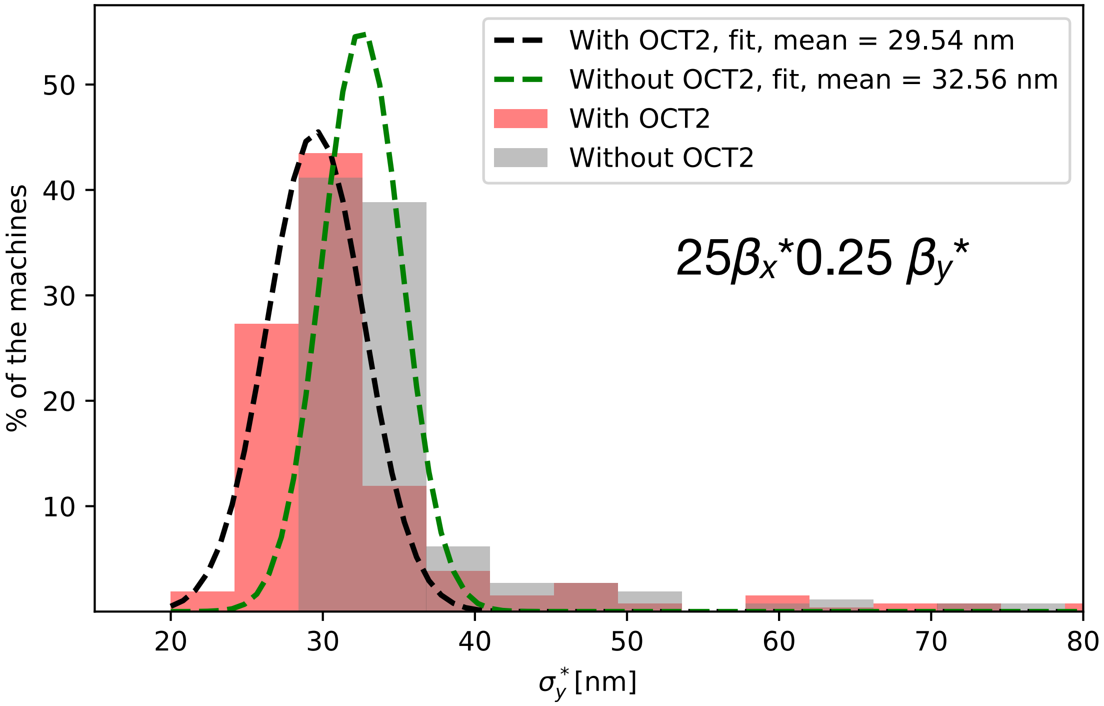
	$\sigma^*_{y,\beta}$ [nm]	$\sigma^*_{y,0}$ [nm]	$\sigma^*_{y,m}$ [nm]
ultra-low *β**	17.3	32.2±4.5	38.3±3.8
10x1	34.6	38.8±2.8	44.9±2.4
nominal	34.6	40.9±3.3	46.4±2.9

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



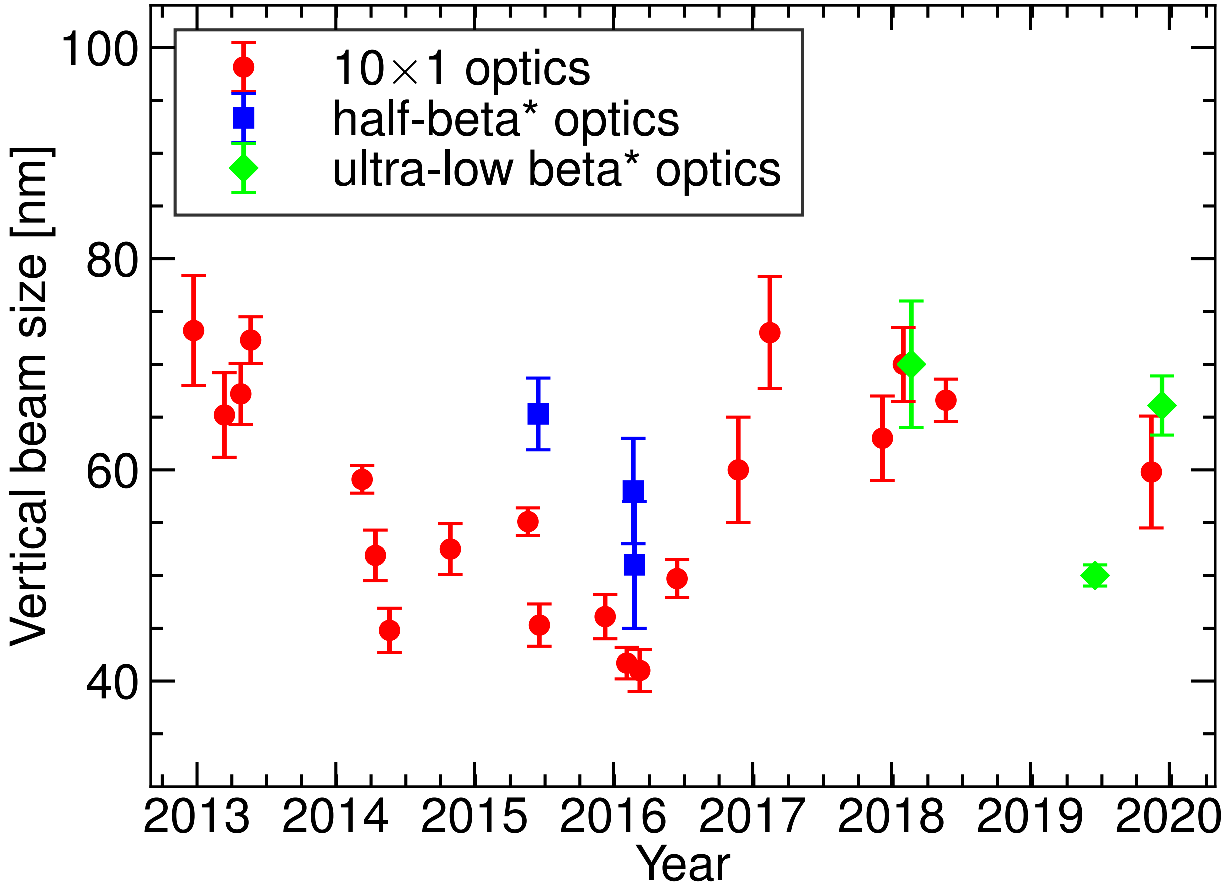

Octupoles installed in 2017, and swapped in 2019

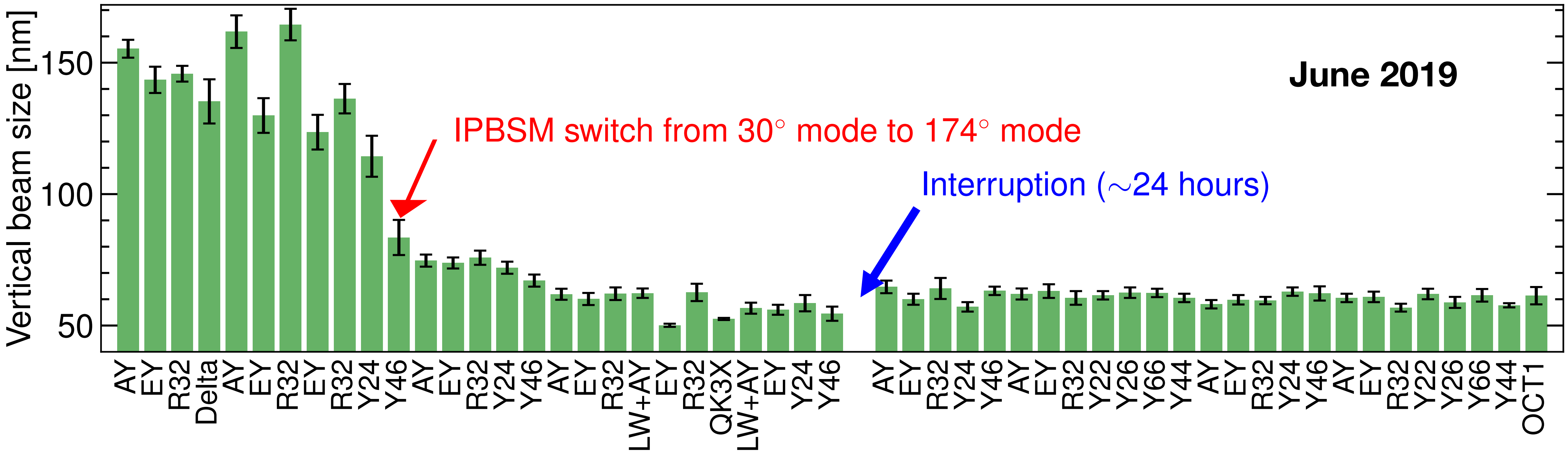


$25\beta_x$*0.25 β_y*

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

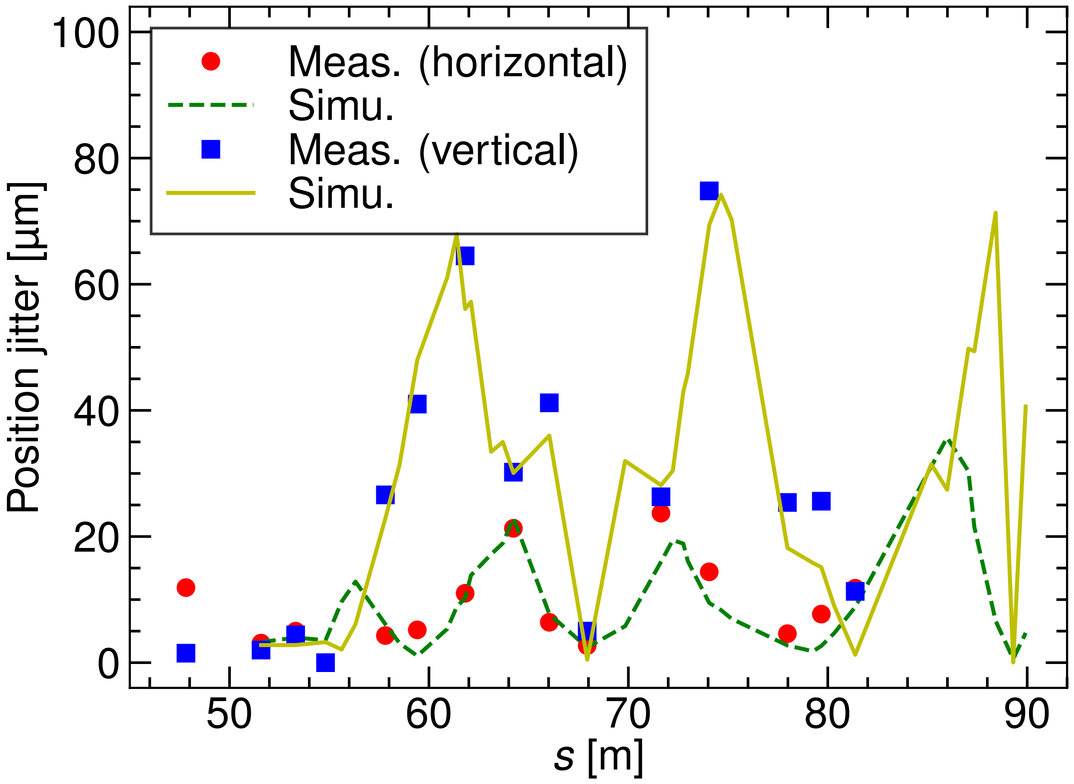
- ~10 and ~20 nm gaps for 10x1 and ultralow *β** optics
- Contributions from beam jitter, beam size growth due to wakefield and diagnostic errors

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

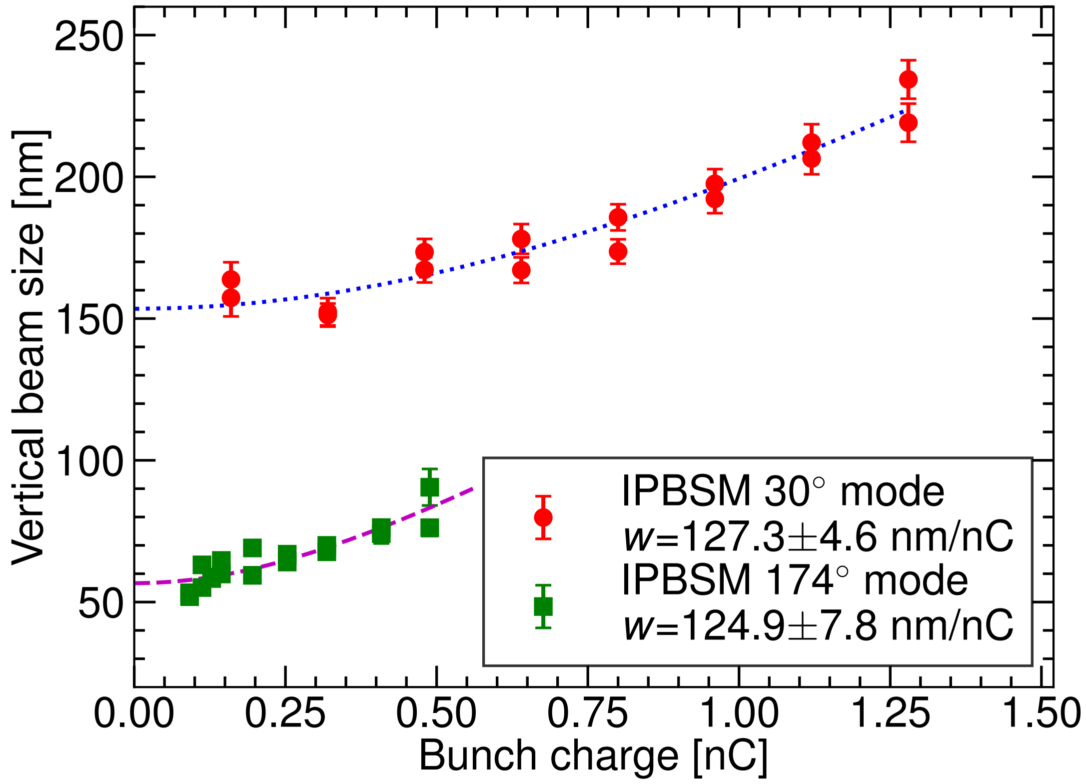
σ_{dy}: beam position jitter (~20 nm w/o correction)

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

C_i: modulation reduction (~0.91 by analytical assessments)



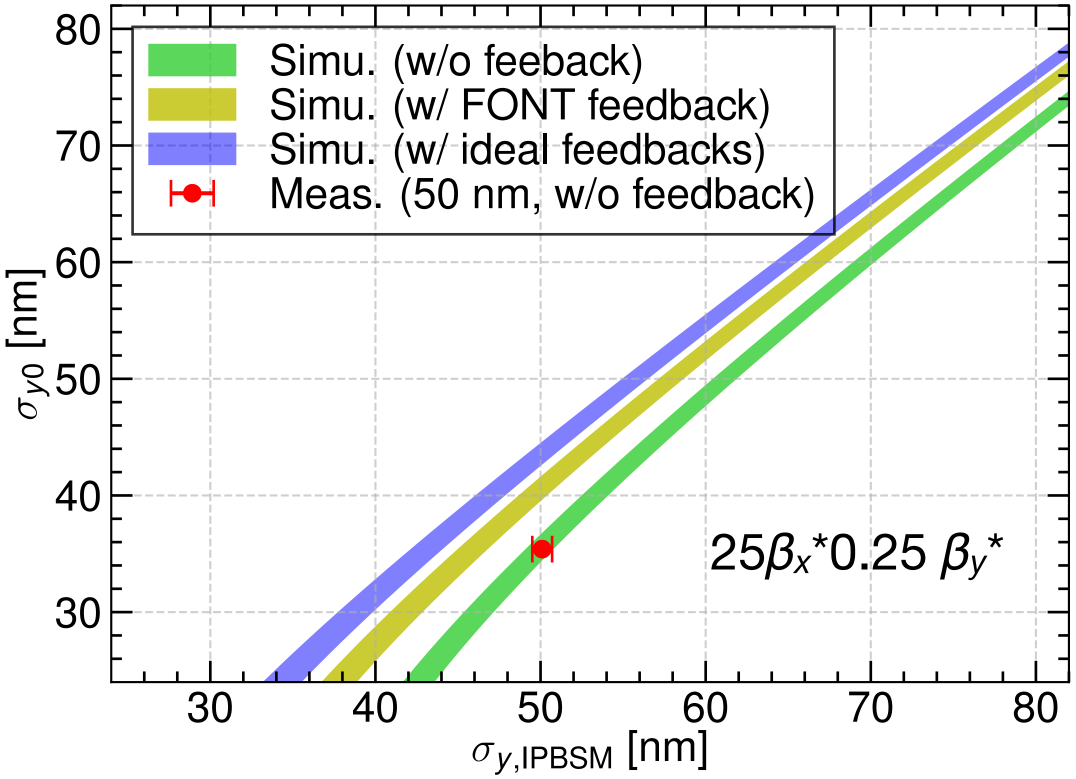
Realistic FFS jitter + GM/Vibration —> σ_{dy}

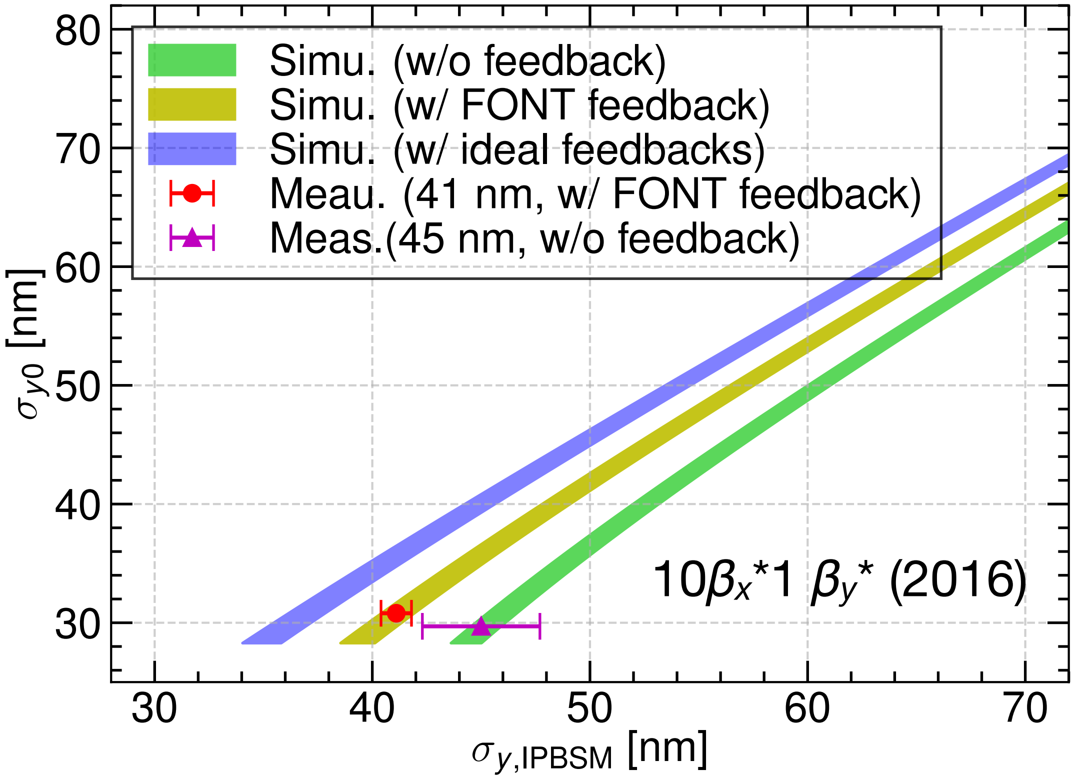


Limitations to achieved beam sizes

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

- 50.1 nm@ultralow β^* optics (Q=0.16 nC, ε_y=12 pm)
  —> $\sigma^*_{y,0}$~**35.5 nm** *close to simulation!*
- 41.1nm@10x1 optics (ε_y=8.0 pm, σ_w≈17.8/20.3 nm)
  —> $\sigma^*_{y,0}$~**30 nm** *approaching $\sigma^*_{y,\beta}$!*
- Beam jitter, wakefield and IPBSM systematic errors play similar role!



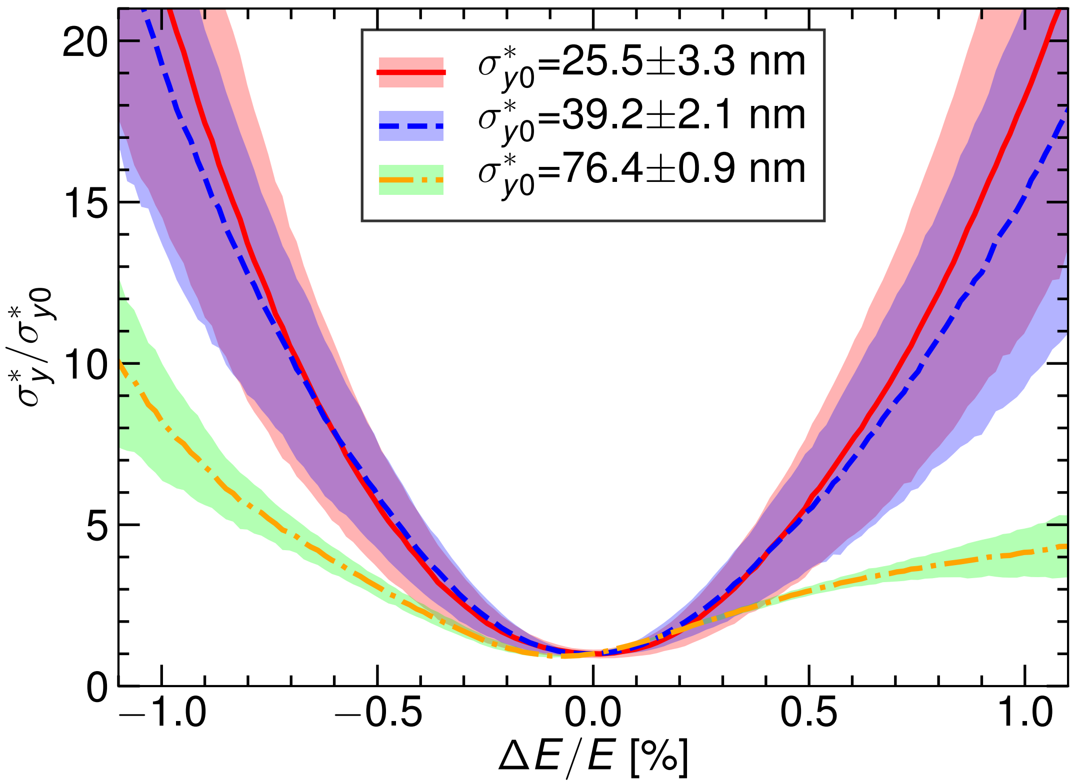


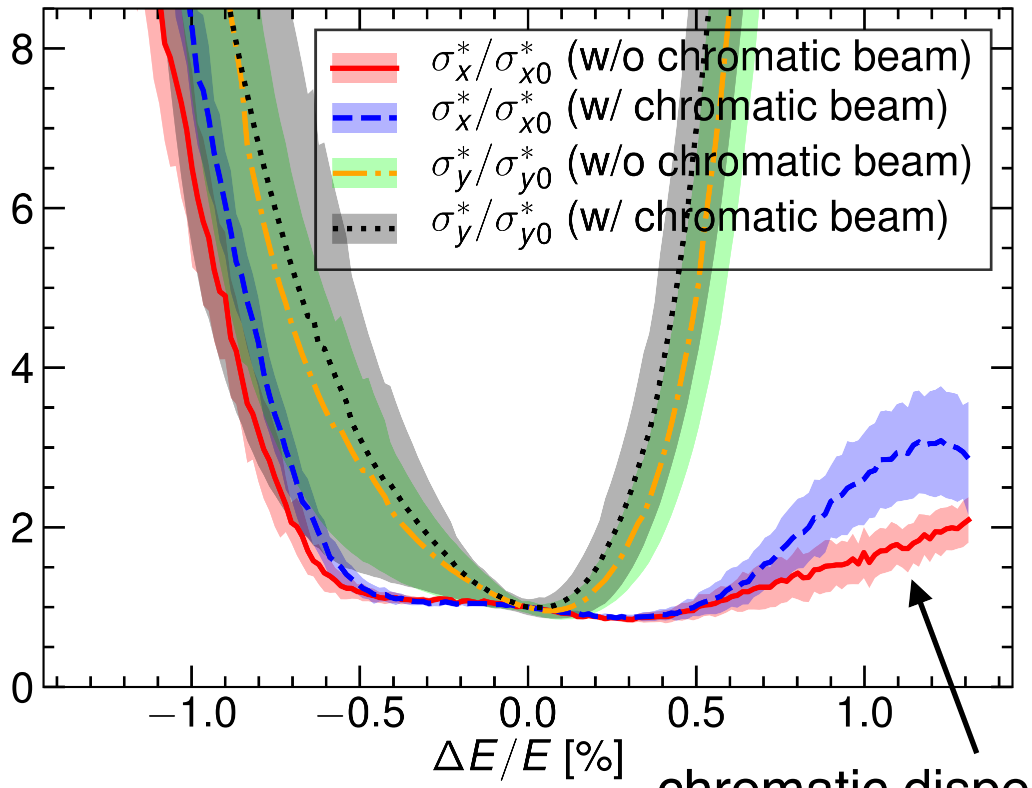
◆ $\sigma_{y,0} \rightarrow \sigma_y$

23 nm —> 32.3 nm and 37 nm—> 40.0 nm for ultralow β^* and 10x1 optics, even with orbit stabilization (σ_{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

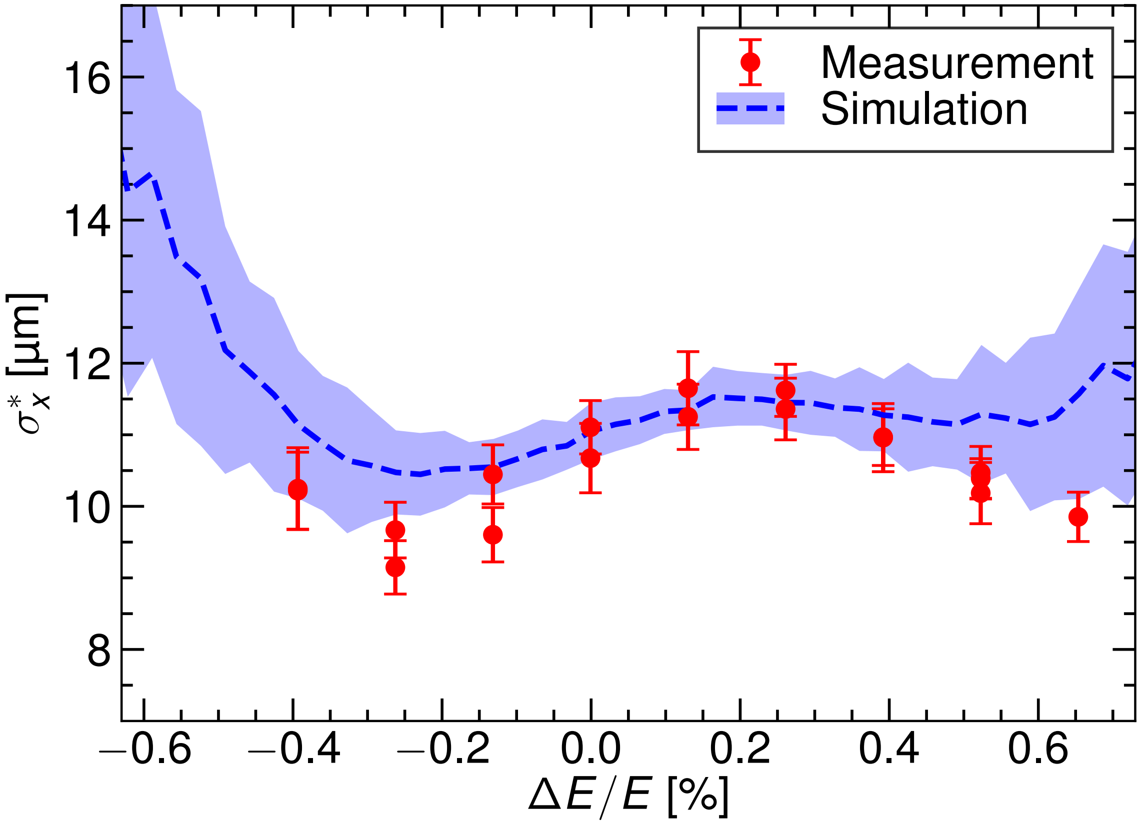


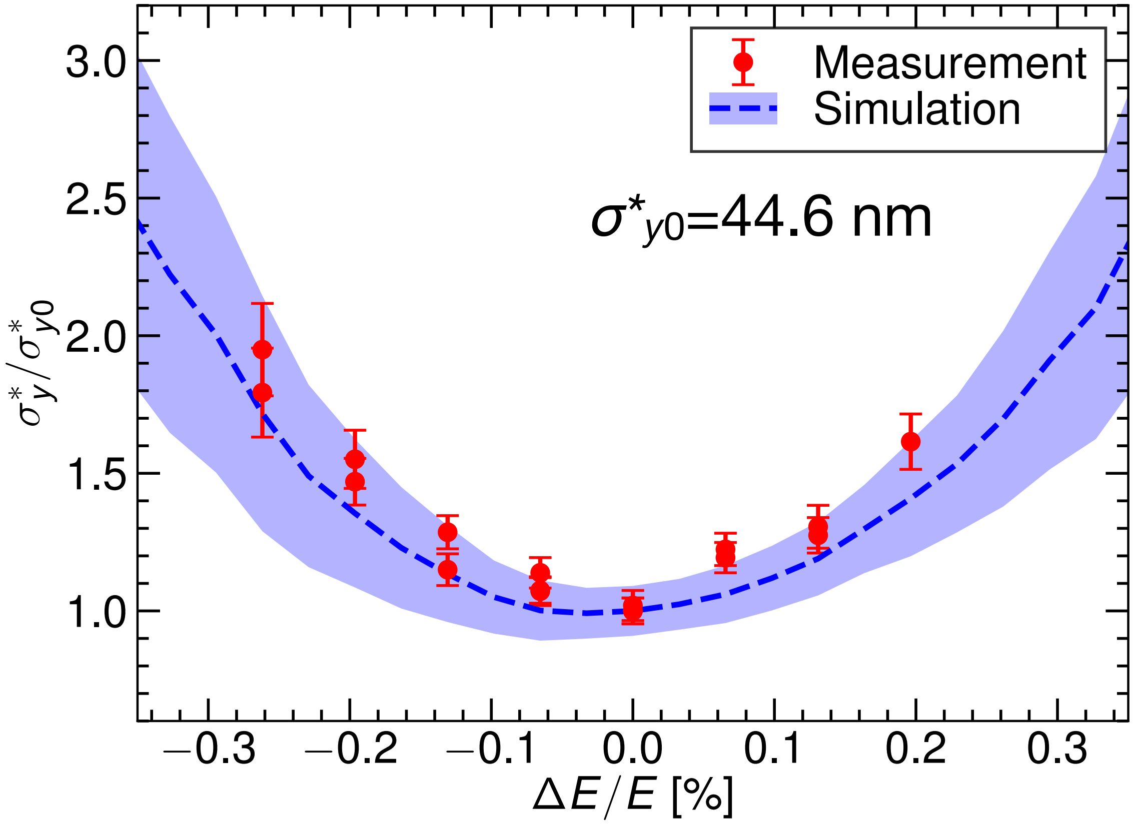


chromatic dispersions at the extraction

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 (0.36% and ~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!





σ^*_{y0}=44.6 nm

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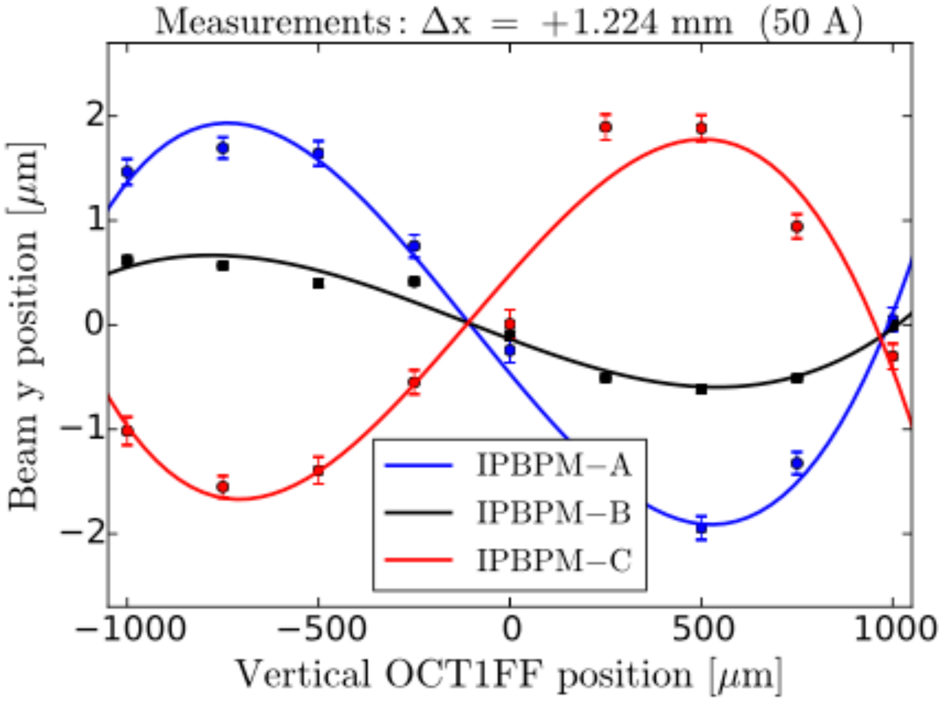
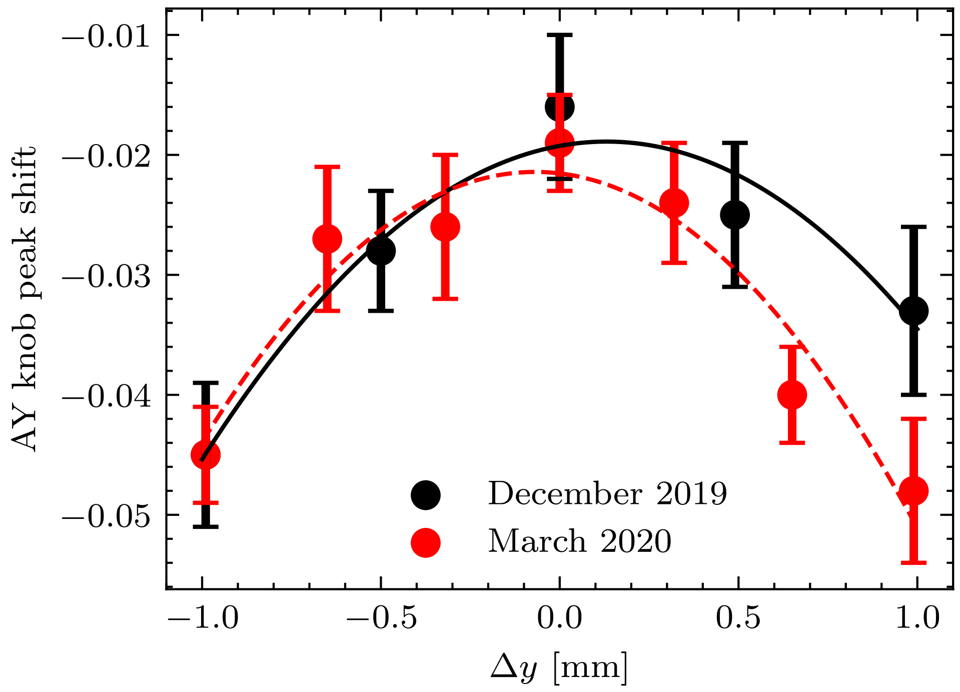
* Defined as a 10% increase of either horizontal or vertical IP spot size for mono-energetic beam.

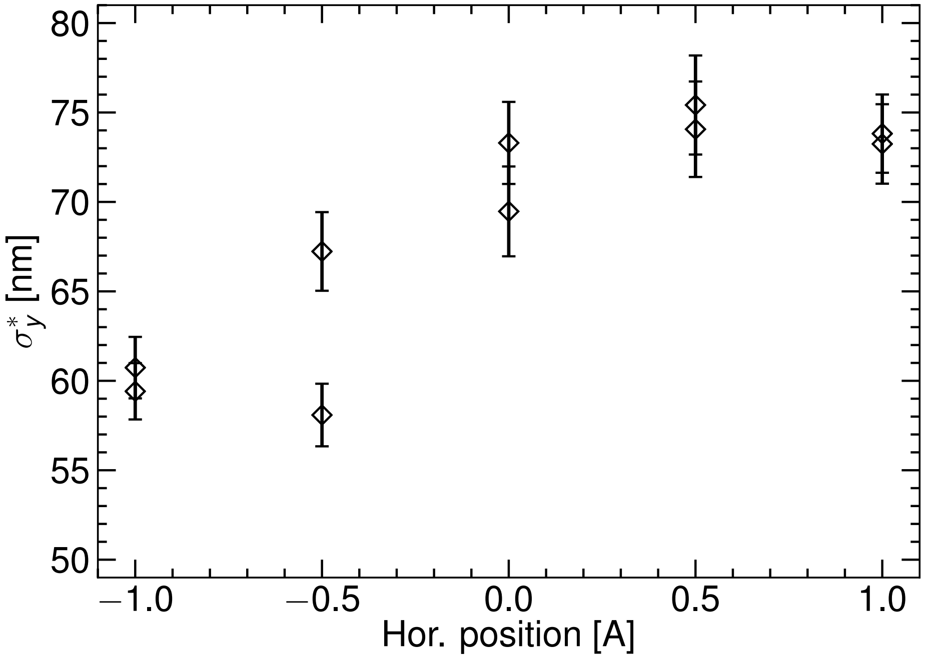
Octupole studies

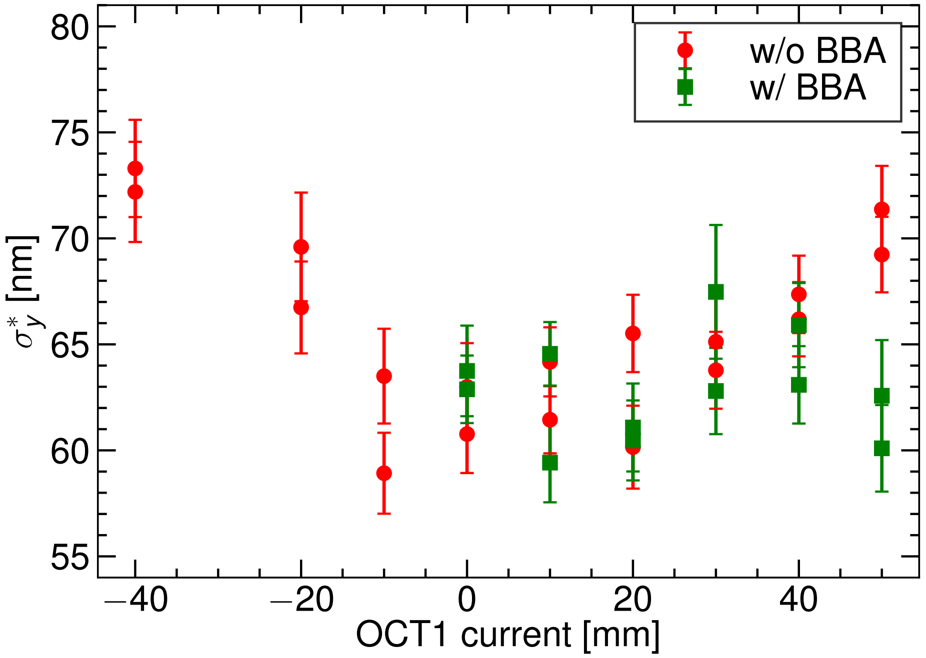
- Demonstrations of octupole BBA methods
  - ✓ Using dipole component (w/ IPBPMs) and quadrupole component (waist shift)





- 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
- **Limitations & solutions to small-beam tuning**
  - 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** (w/ ATF3)…
  - ✦ **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?