

Status of ultra-low β_y^* optics tuning

R. Yang, M. Bergamaschi, V. Cilento, P. Korysko
A. Pastushenko, A. Latina and R. Tomas

CERN

A. Aryshev, K. Kubo, S. Kuroda, T. Naito,
T. Okugi and N. Terunuma

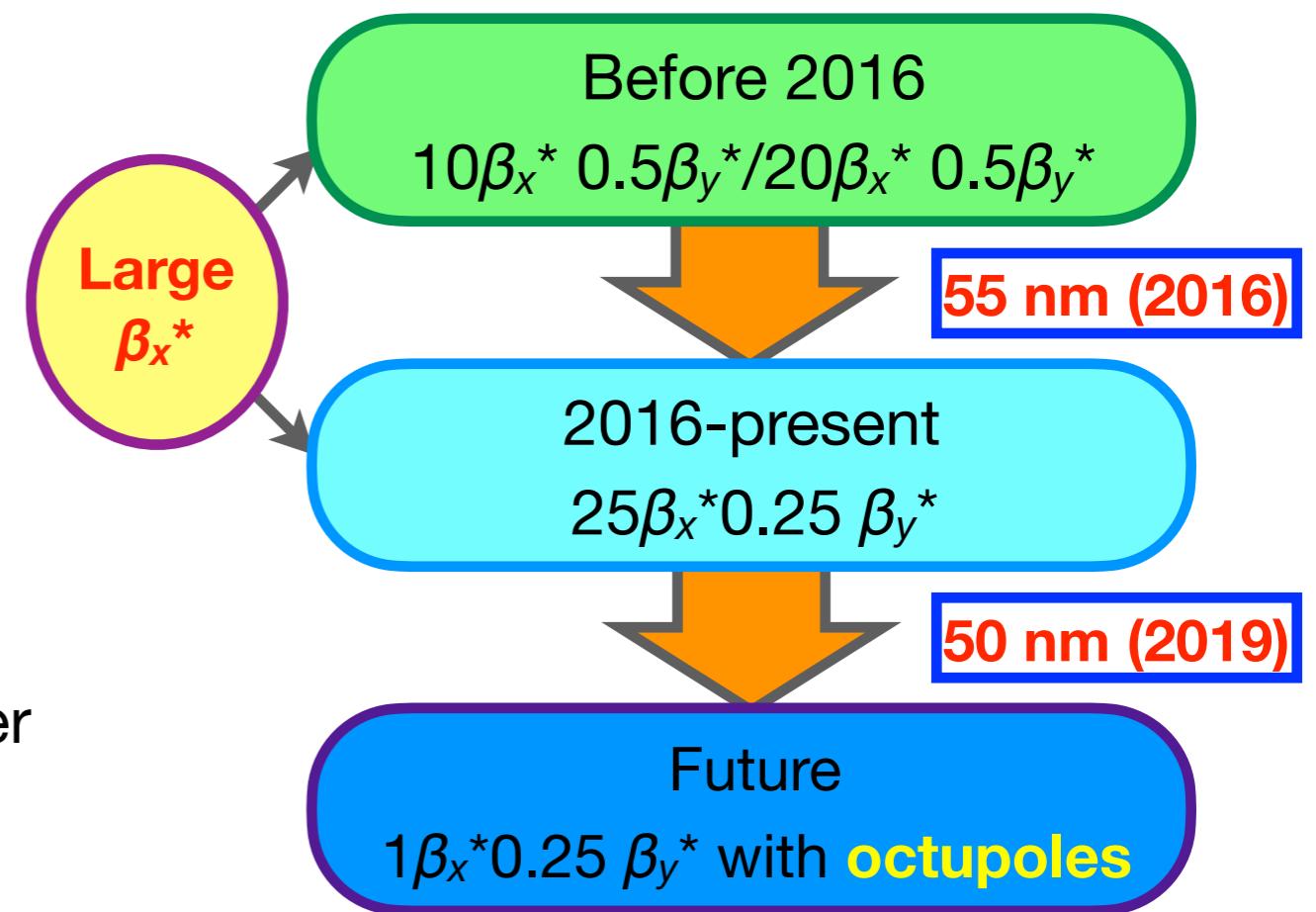
KEK

LCWS2019, Sendai
October 29, 2019

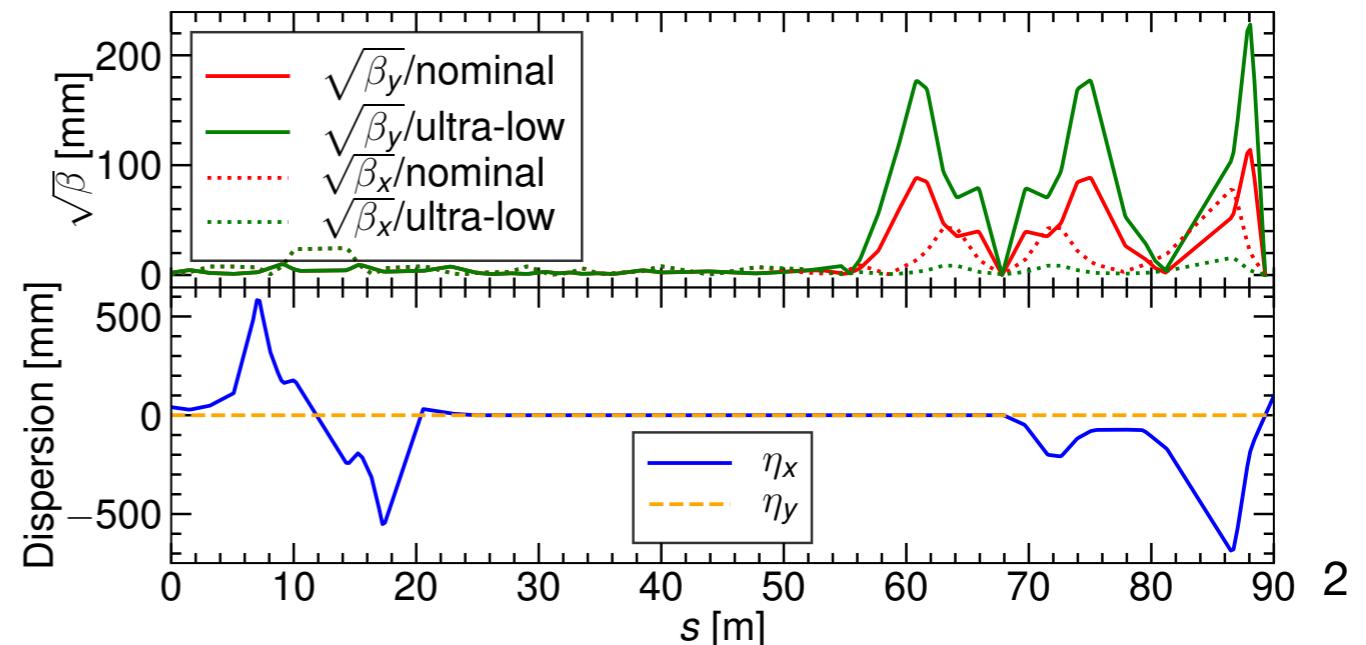
Ultra-low β_y^* optics@ATF2?

- ◆ To demonstrate the nanobeam tuning in the CLIC FFS chromaticity level with the local chromaticity correction scheme.

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

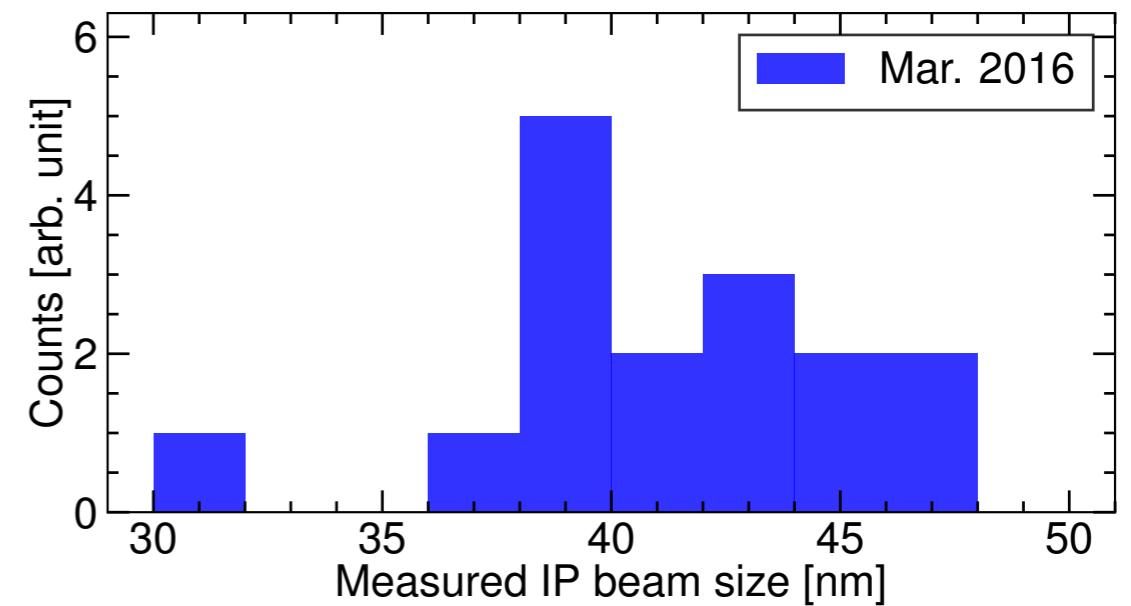
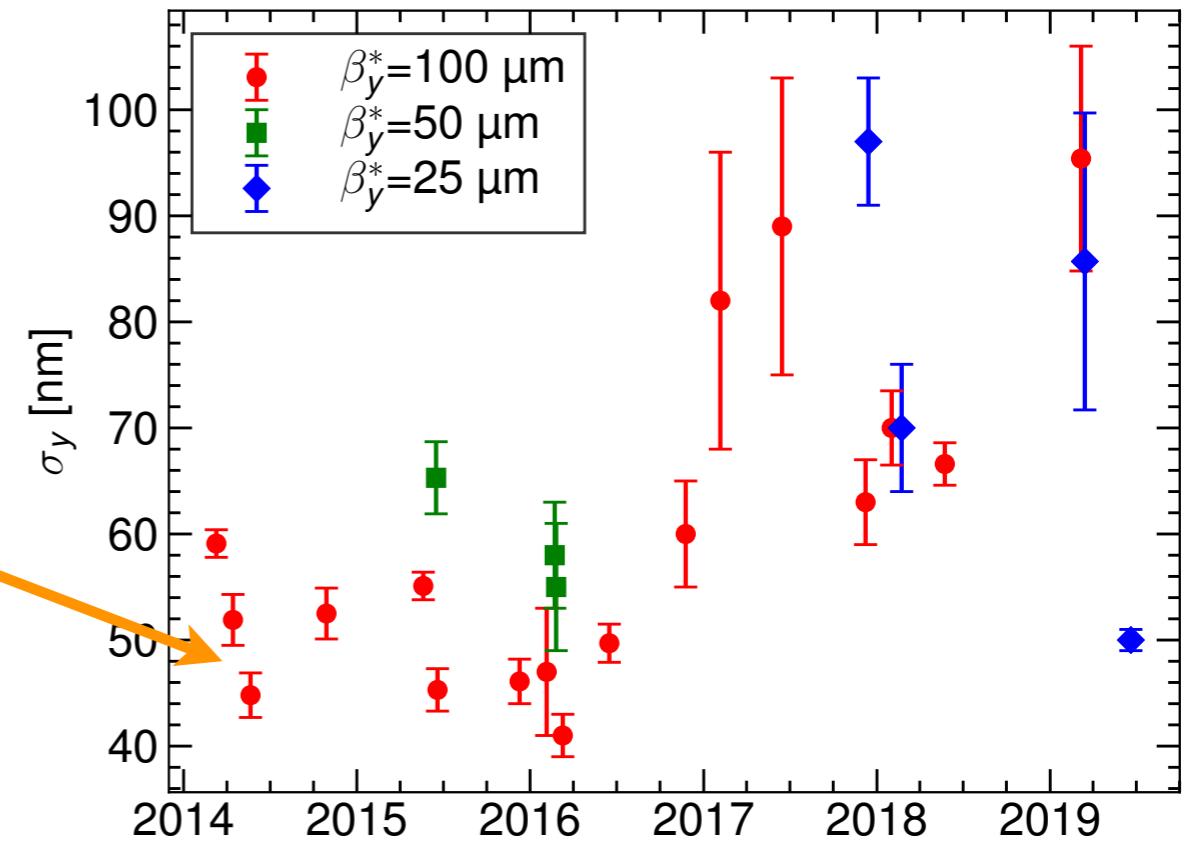


- ◆ Higher local chromaticity means higher sensitivity to machine errors (static/dynamic) and more difficult for tuning!



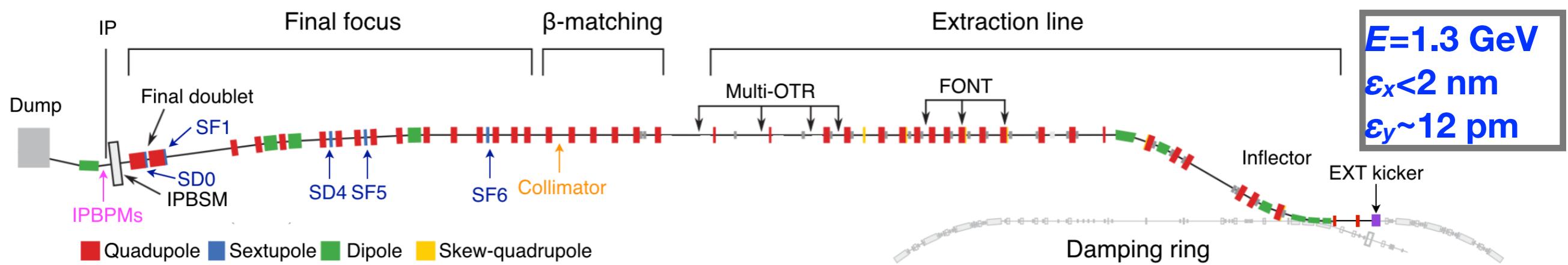
Small beam size tuning at ATF2

- ◆ Increased β_x^* to loose the tolerance on the multipole components
 - >> 10x1 optics
 - >> 10x0.5 or 20x0.5 optics
 - >> 25x0.25 optics (ultra-low β_y^*)
- ◆ A small beam size less than 60 nm has been successfully obtained in Jan. 2014-Jun. 2016
- ◆ A smallest beam size **41.1 nm** was achieved in 10x1 optics (Mar. 2016)!
- ◆ Ultra-low optics tuning:
 - ※ Two octupoles were installed in 2017 for future ultra-low β_y^* tuning
 - ※ Several ultra-low β_y^* weeks were allocated since Dec. 2017
 - ※ **A minimum beam size of 50 nm was observed in Jun. 2019**



General tuning procedure

- ◆ Require few days to apply all the tuning knobs
- ◆ Key: satisfactory upstream stability and IPBSM performance



1) mOTR
commissioning
2) BPM calibration
3) sextupole BBA
4) IPBSM checking

1) DR tuning
2) EXT dispersion
3) Twiss/Emittance
measurements
4) optics matching

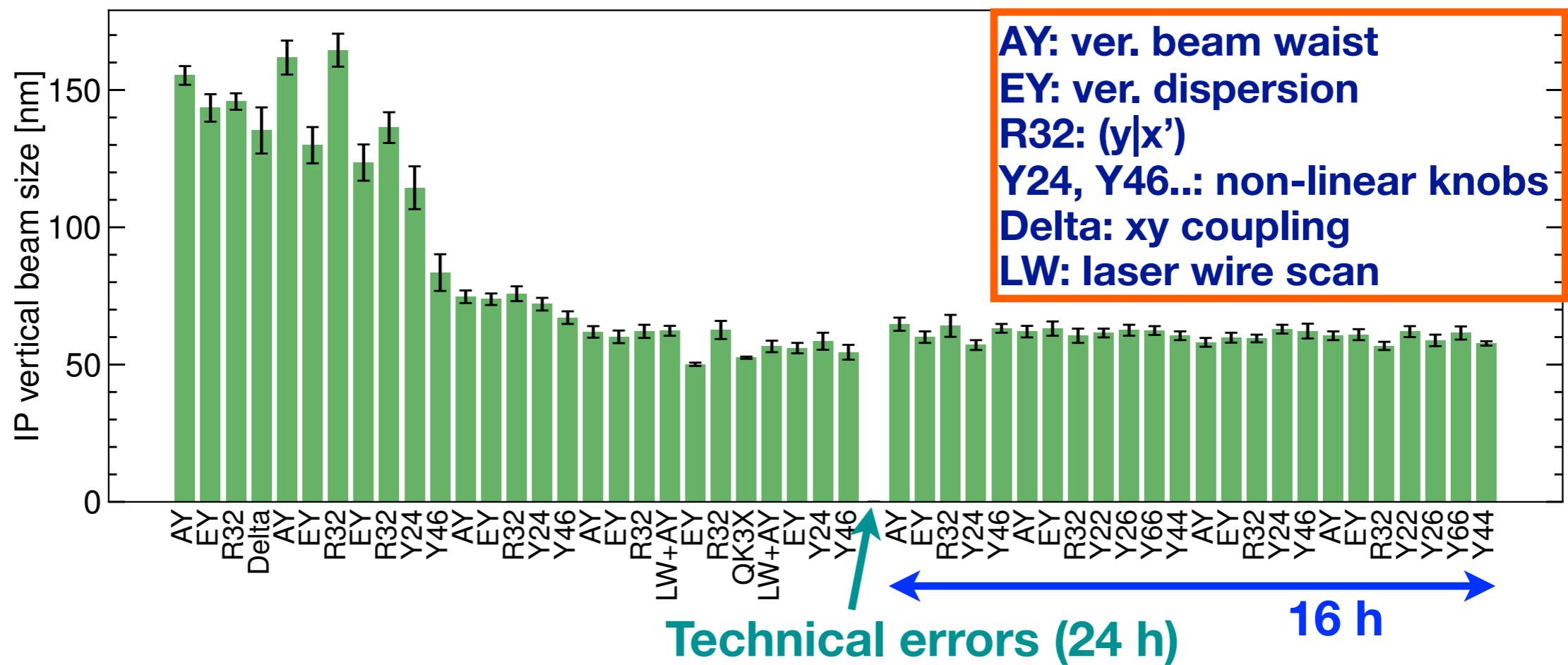
1) orbit/dispersion/
coupling correction
2) IPBSM setup
3) linear knobs
4) non-linear knobs
5) octupoles (?)

*before tuning week

*FONT feedback?

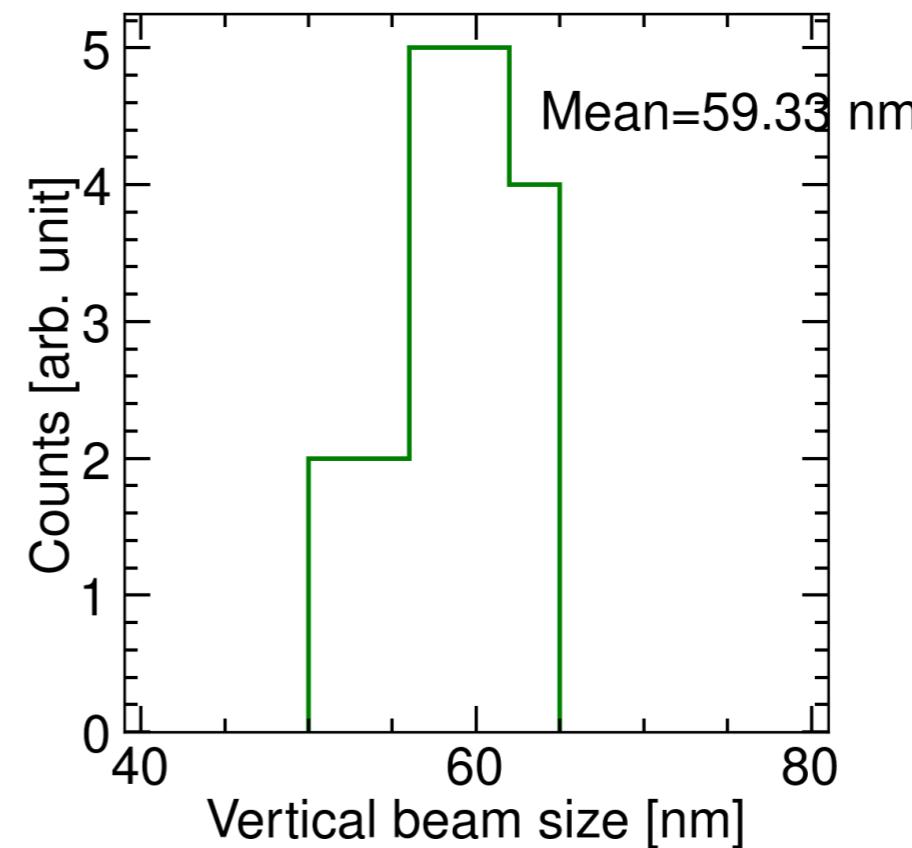
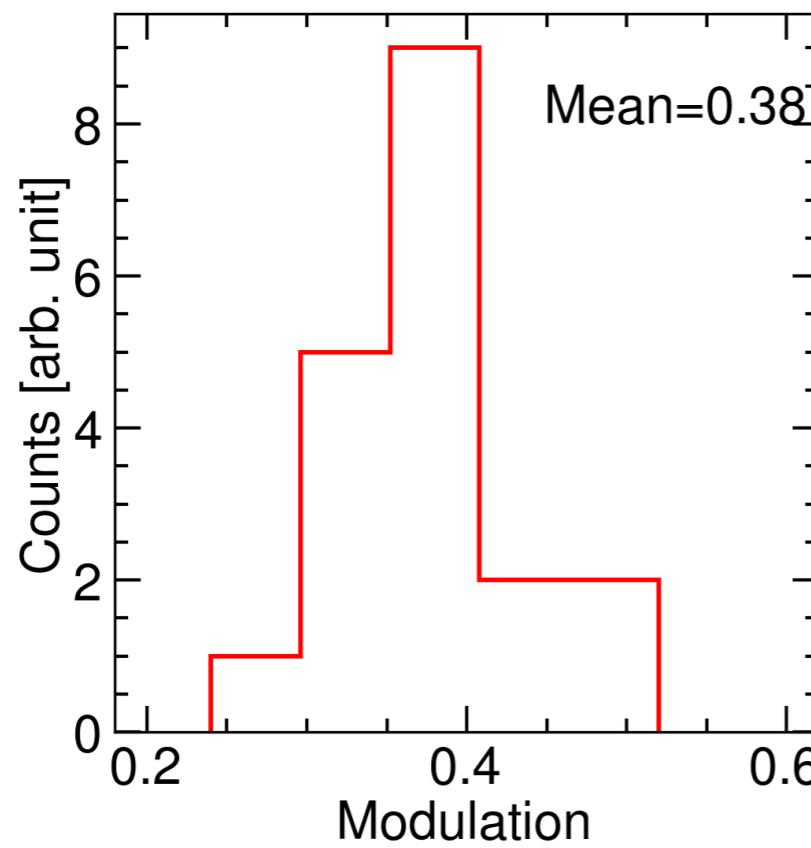
Small beam size achievement

- ◆ Dec. 2018 and Mar. 2019 tunings were hampered by troubles with IPBSM laser —> no clear modulation in IPBSM 174 deg mode
- ◆ June 17-21, 2019
 - reach 174 deg mode and observed a minimum beam size of 50 nm and then stabilized at ~60 nm for the whole week
 - couldn't reduce more beam size using all linear/non-linear knobs



Small beam size achievement

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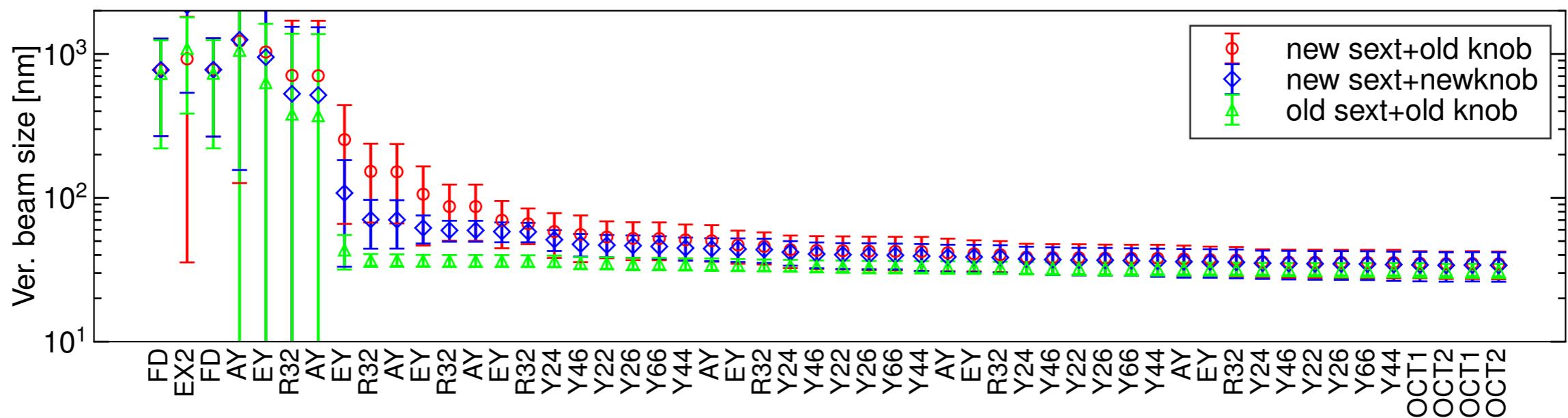
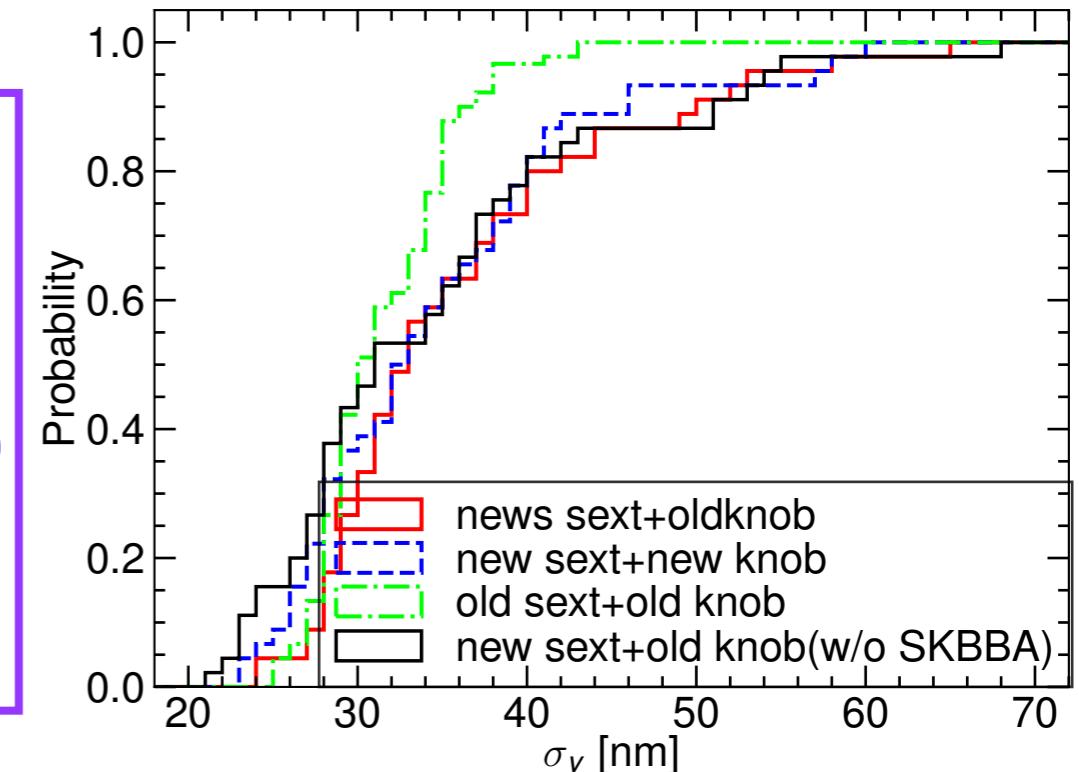


=> What limit the small beam size tuning?
residual aberration? dynamic error? wakefield? IPBSM errors?

Optimum sextuple strength&knobs

- ◆ Sextupole strength was optimized for chromaticity correction (new sext)
- ◆ knobs: ones for nominal optics (old knob) and new defined (new knob)
- ◆ Static errors

- ◆ oldsext+oldknob: fastest converge and smallest beam size (28.6 nm)
- ◆ new defined knobs converge faster but couldn't reduce more beam size (31 nm)
- ◆ Impact of skew-sextuple misalignment seems small



Dynamic errors

- ◆ Ground motion, vibration of FD, magnet mover accuracy, magnet power supply setting accuracy and BPM scale factor errors and resolutions
- ◆ Built into tuning simulation (SAD)

Major dynamic errors

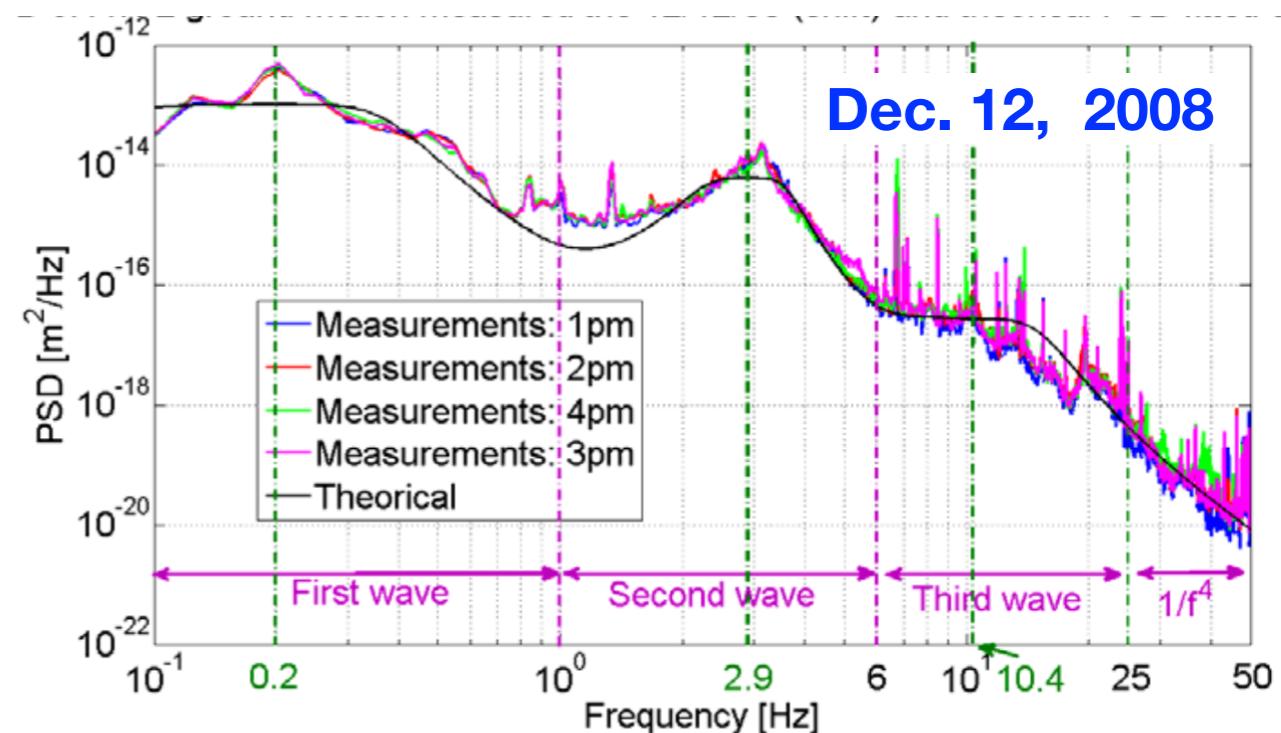
GM (fast)	ATF2 model
GM (slow)	ATL law $A=27 \mu\text{m}^2/(\text{m.s})$
Vibration of FD	6.5 nm
Mover accuracy	<<1 μm (x/y)
Power supply setting accuracy	0.001% (FFS)
Initial beam jitter	??

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.



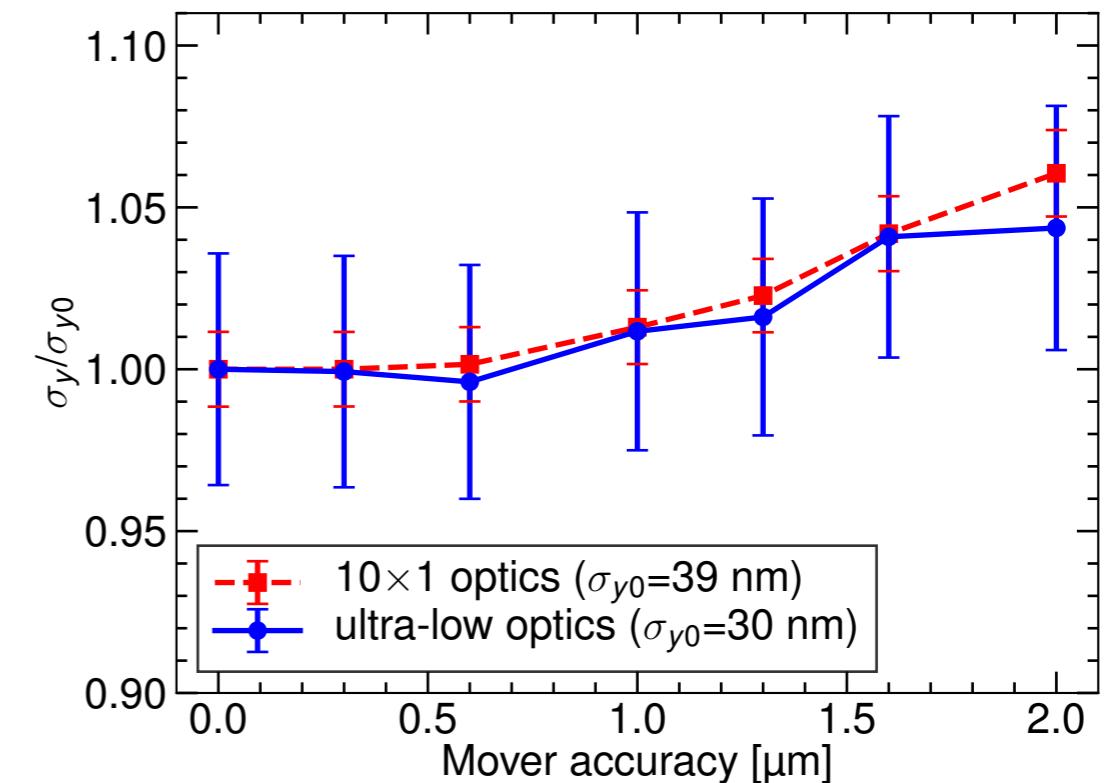
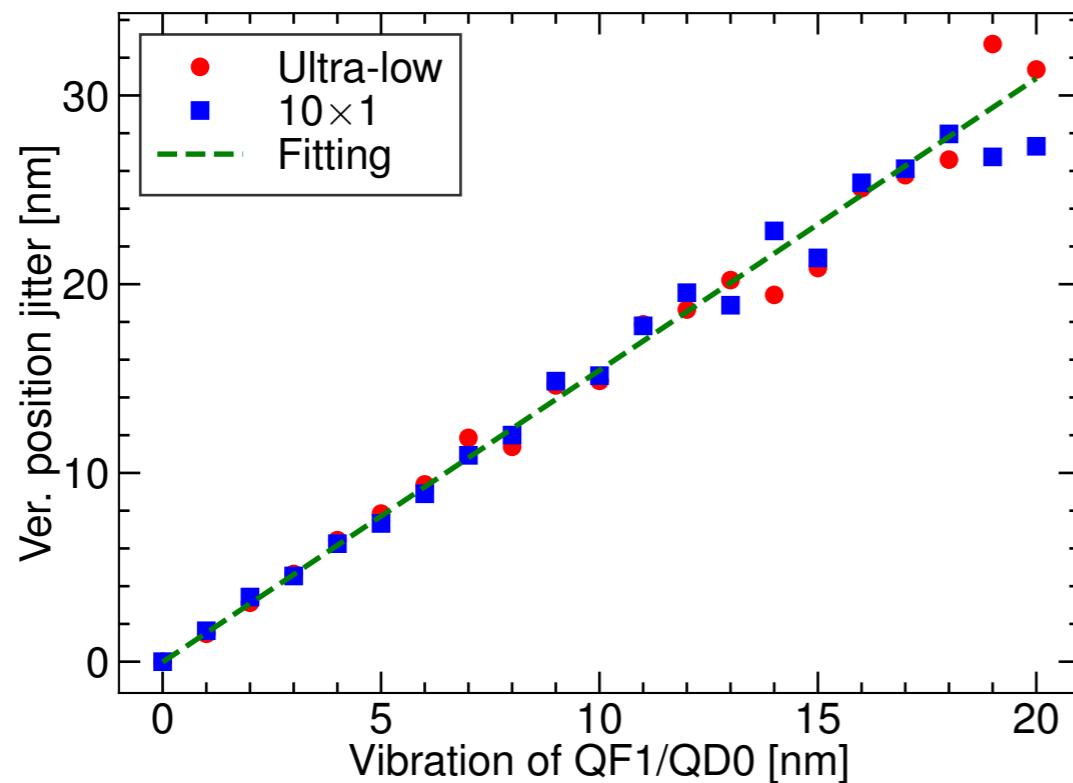
[1] B. Bolzon et al., PAC09, TH5RFP086

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

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

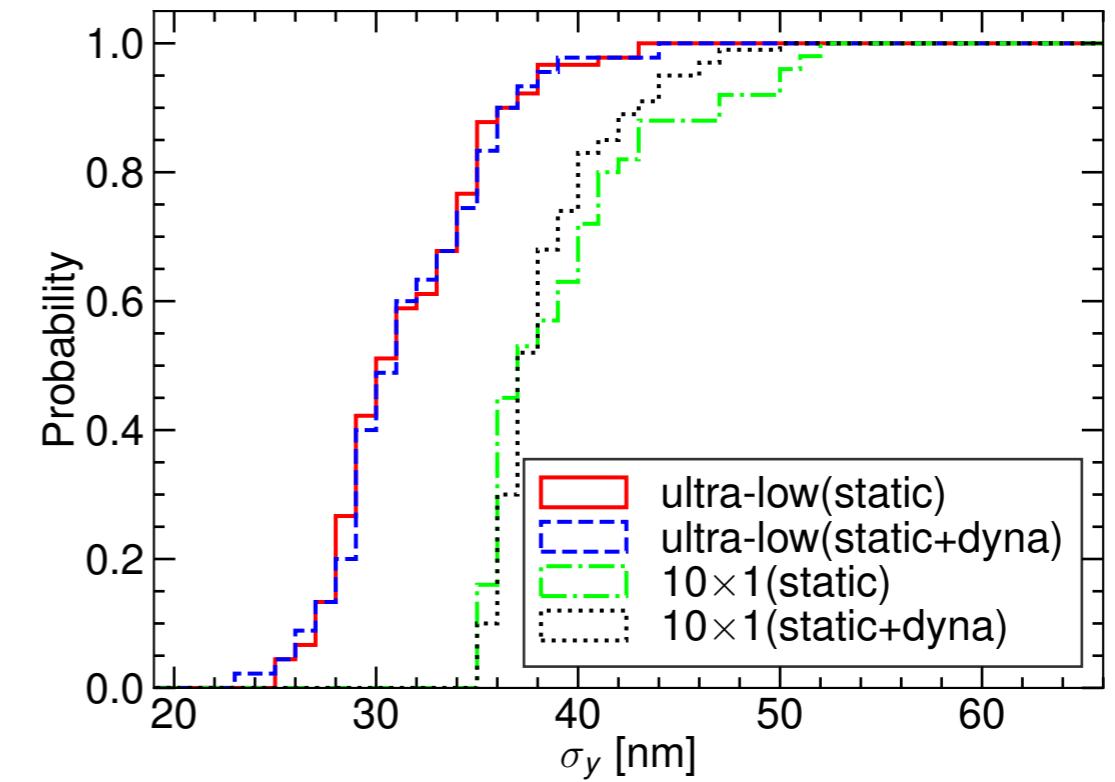
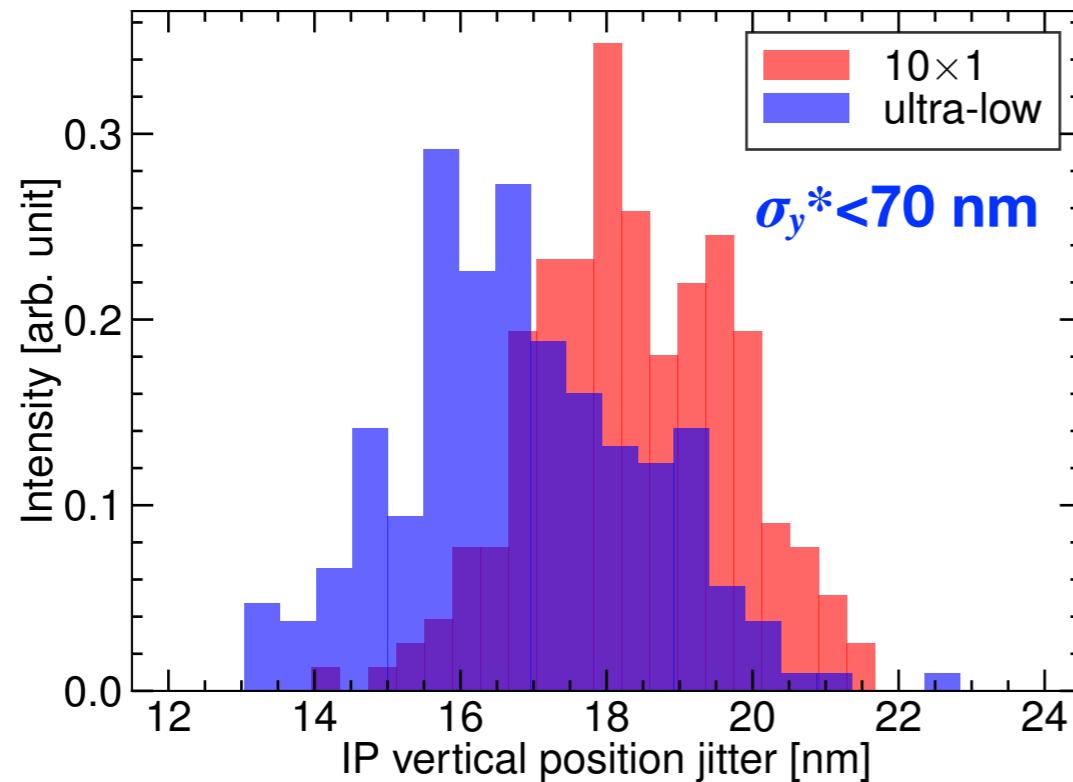
Impact of dynamic errors

- ◆ FD Vibration (jitter): $\approx 1.54\sigma_{\text{vib}}$
- ◆ Mover accuracy: negligible ($1 \mu\text{m} \rightarrow 1.1\%$ IP beam size growth)
- ◆ Fast ground motion (jitter)
15.5 nm and 15.9 nm for ultra-low β_y^* ($\sigma_y=18.7 \text{ nm}$) and 10x1 optics ($\sigma_y=36 \text{ nm}$)
- ◆ Fast GM+FD vibration (jitter)
perfect lattice: 16.5 nm and 16.3 nm for ultra-low β_y^* and 10x1 optics
Imperfect lattice ($\sigma_y^*<70 \text{ nm}$): 16.8 nm and 18.4 nm for ultra-low β_y^* and 10x1 optics



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> mainly vertical IP position jitter from fast GM and FD vibration!

Impact of Wakefield

- ◆ One major limitation on small beam size tuning

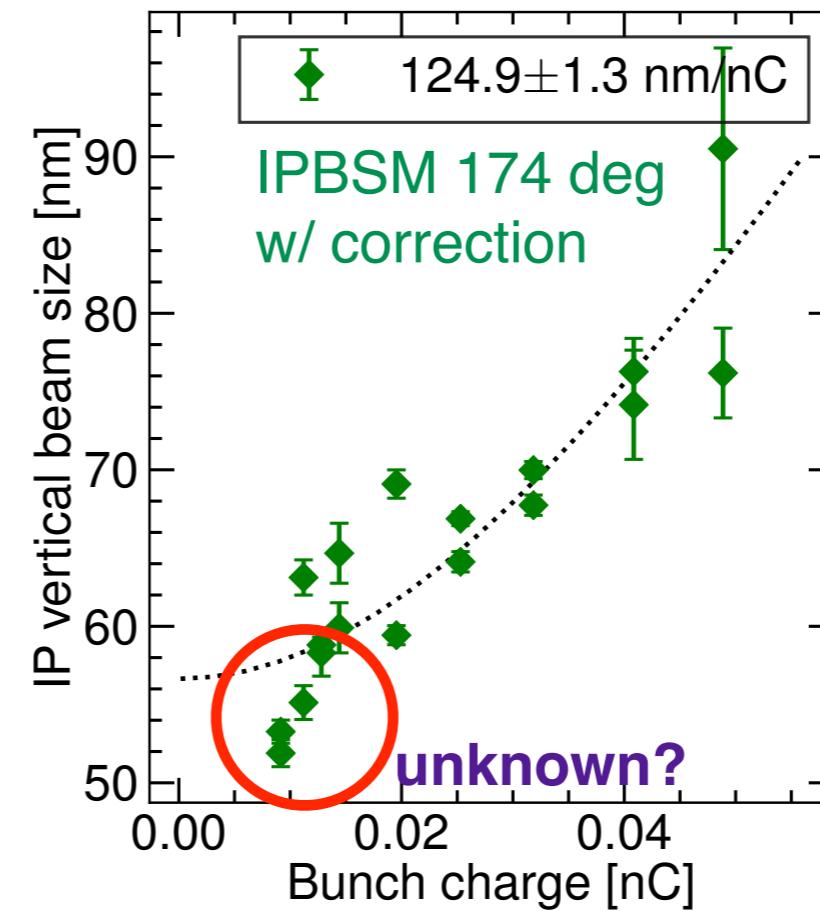
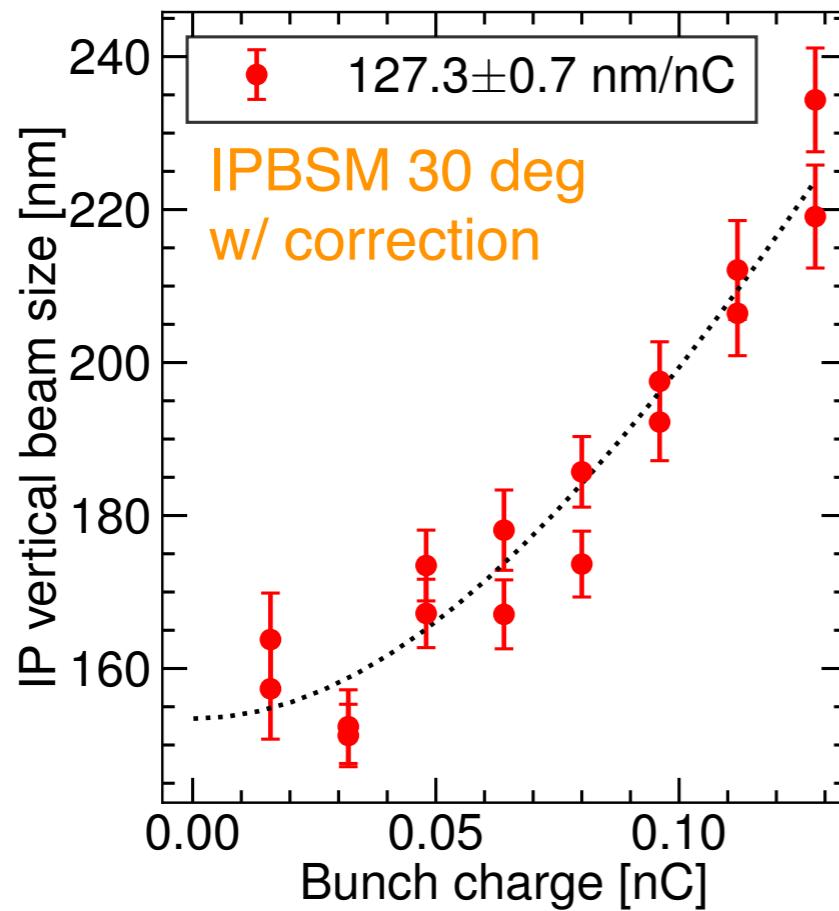
$$\sigma_y^2 = \sigma_{y0}^2 + (w_1^2 + w_2^2)Q^2$$

$w_1=55$ nm/nC (static, measured)

$$w = \sqrt{w_1^2 + w_2^2} \approx 131 \text{ nm/nC}$$

$w_2=118.6$ nm/nC (dynamic, predicted wrt. measurements in 10x1 optics)

- ◆ Measured intensity dependence factor: 125 nm/nC, consistent with preliminary predictions!



**Q=0.16 nC
=> $\sigma_{yw}=20$ nm**
More robust wakefield correction?



IPBSM errors

- ◆ Beam size is evaluated from the observed modulation M with phase scan

$$\sigma_{\text{SM}} = \frac{d}{2\pi} \sqrt{-2 \left[\log\left(\frac{M_0}{|\cos \theta|}\right) + \sum_i \log C_i \right]}$$

$d = \lambda/\sin(\theta/2)/2$ fringe pitch

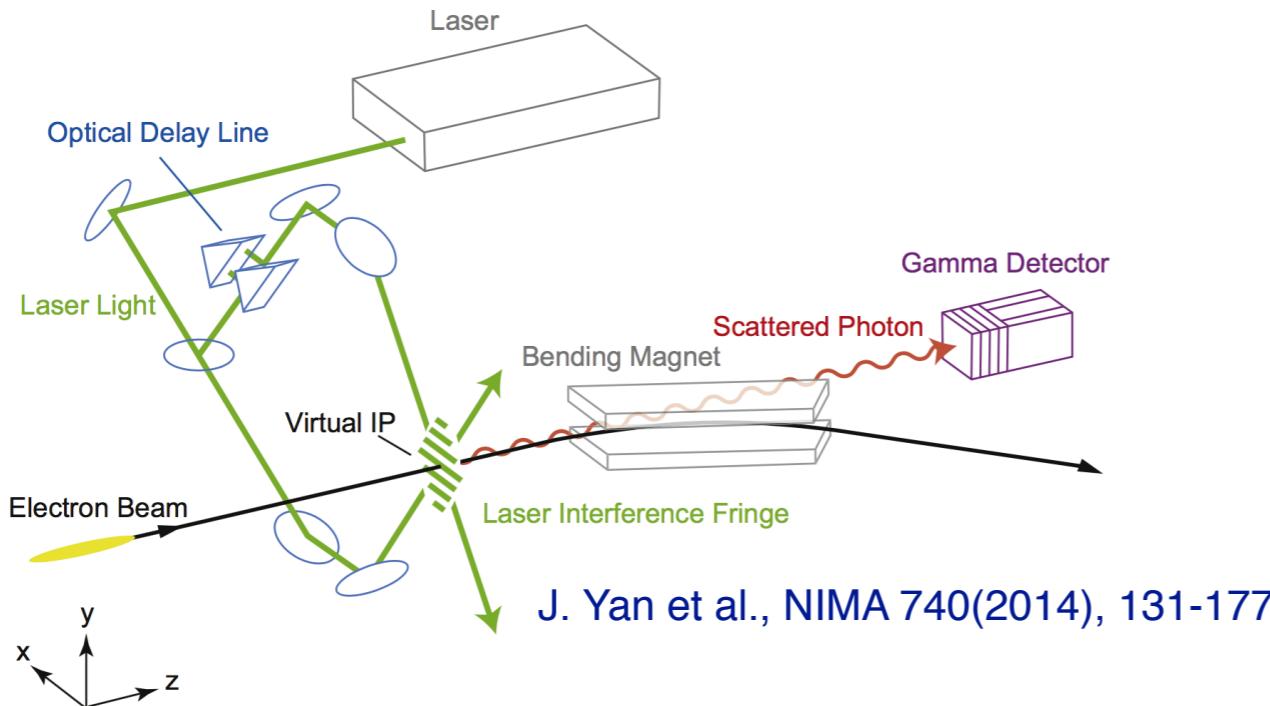
M_0 : modulation w/o detector error

$$M_0 = |\cos \theta| \exp(-2k_y^2 \sigma_{y0}^2)$$

θ crossing angle (2-8, 30 and 174 deg)

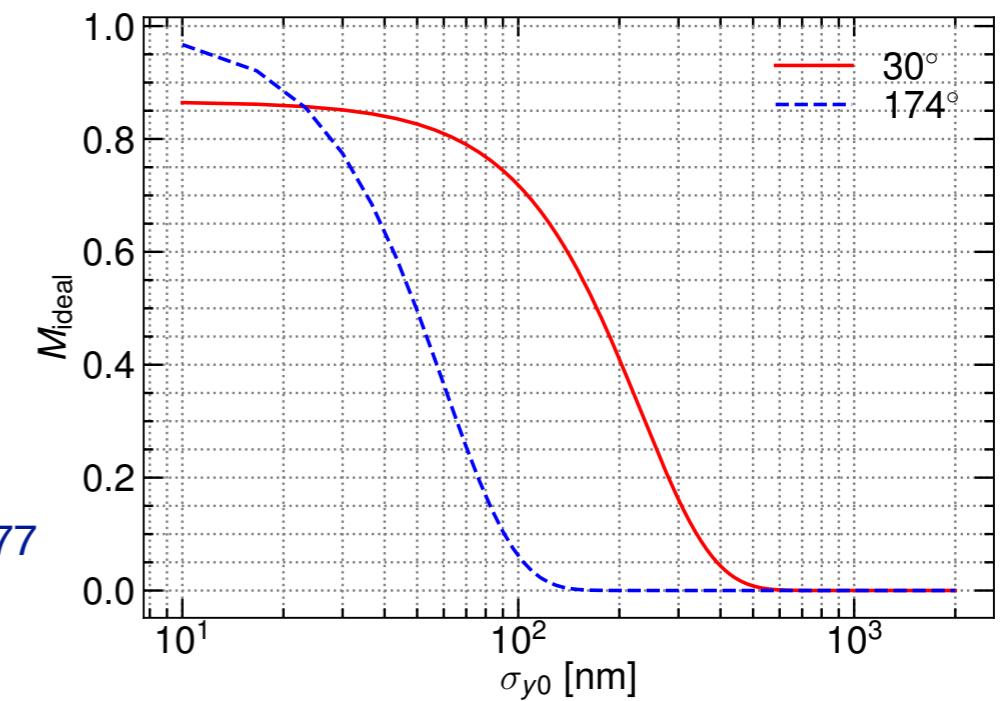
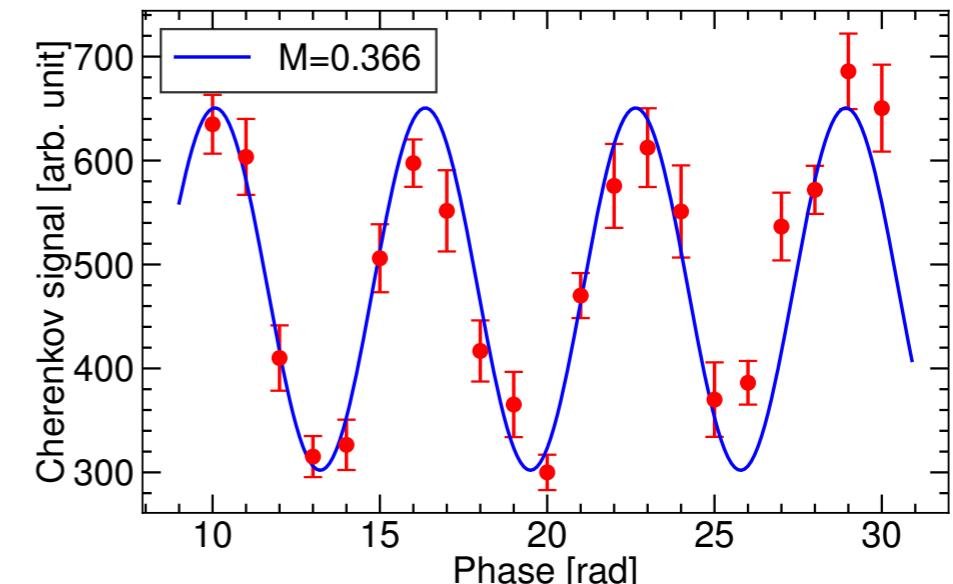
C_i reduction factor due to errors

- ◆ Observed modulation $M = M_0 C_1 C_2 .. C_n$



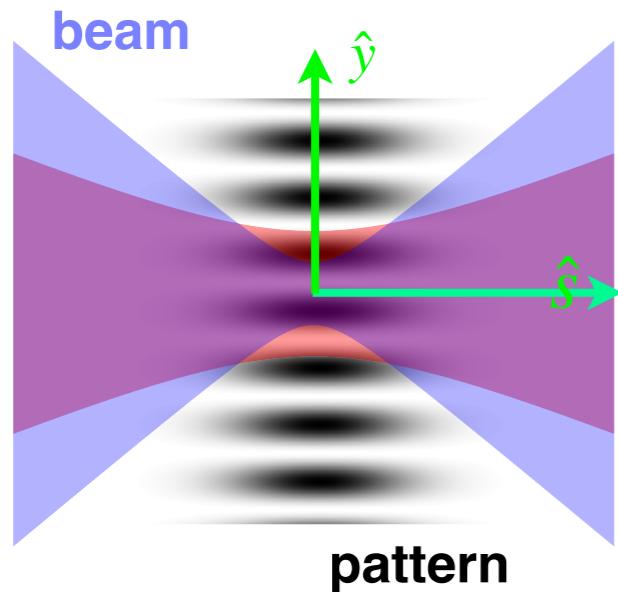
$\Rightarrow \sigma_{\text{SM}} > \sigma_{y0}$

$\Rightarrow C=?$ How to correct measured σ_{SM} ?



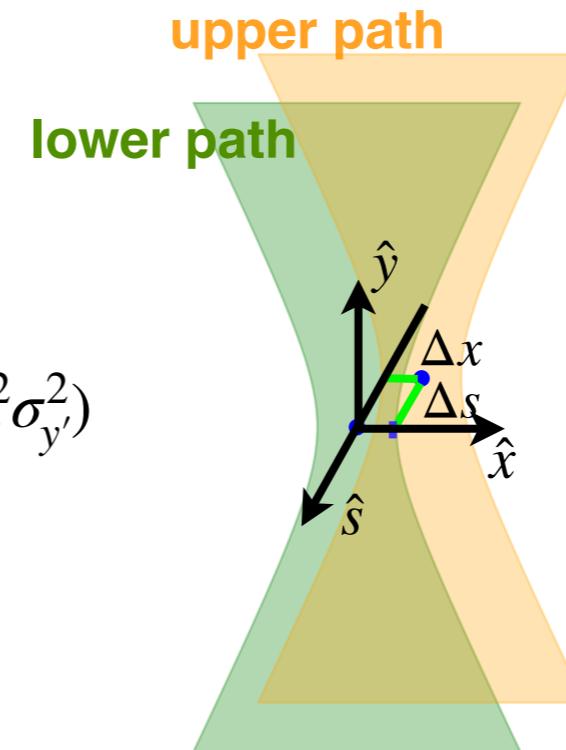
Modulation reduction sources

- ◆ Analytical formulas to characterize modulation reduction



length of fringe pattern in \hat{s}

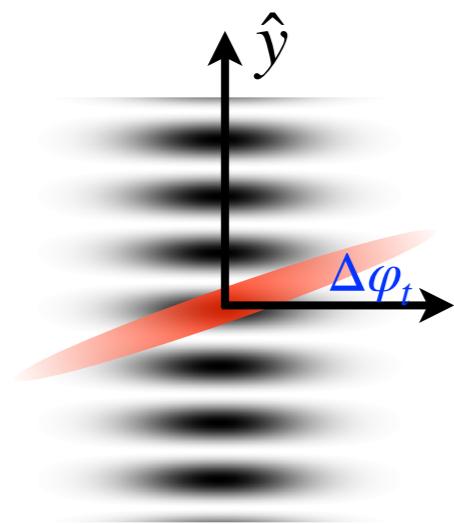
$$C_w = \exp(-2k_y^2 \sigma_z^2 \sigma_{y'}^2)$$



misalignment of two laser paths

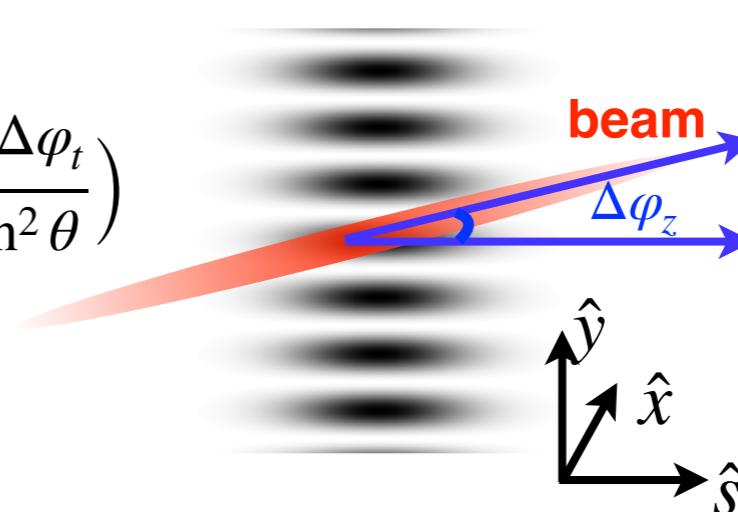
$$C_{\Delta x} = \frac{2 \exp(\frac{-\Delta x^2}{4\sigma_t^2})}{1 + \exp(\frac{-\Delta x^2}{2\sigma_t^2})}$$

$$C_{\Delta s} = \exp(\frac{\Delta s^2}{8\sigma_l^2})$$



transverse tilt

$$C_{\varphi_t} = \exp\left(\frac{-2k_y^2 \sigma_x^2 \sin^2 \Delta\varphi_t}{1 + \sigma_x^2 \sigma_t^{-2} \sin^2 \theta}\right)$$



$$C_{\varphi_z} = \exp(-2k_y^2 \sigma_l^2 \sin^2 \Delta\varphi_z)$$

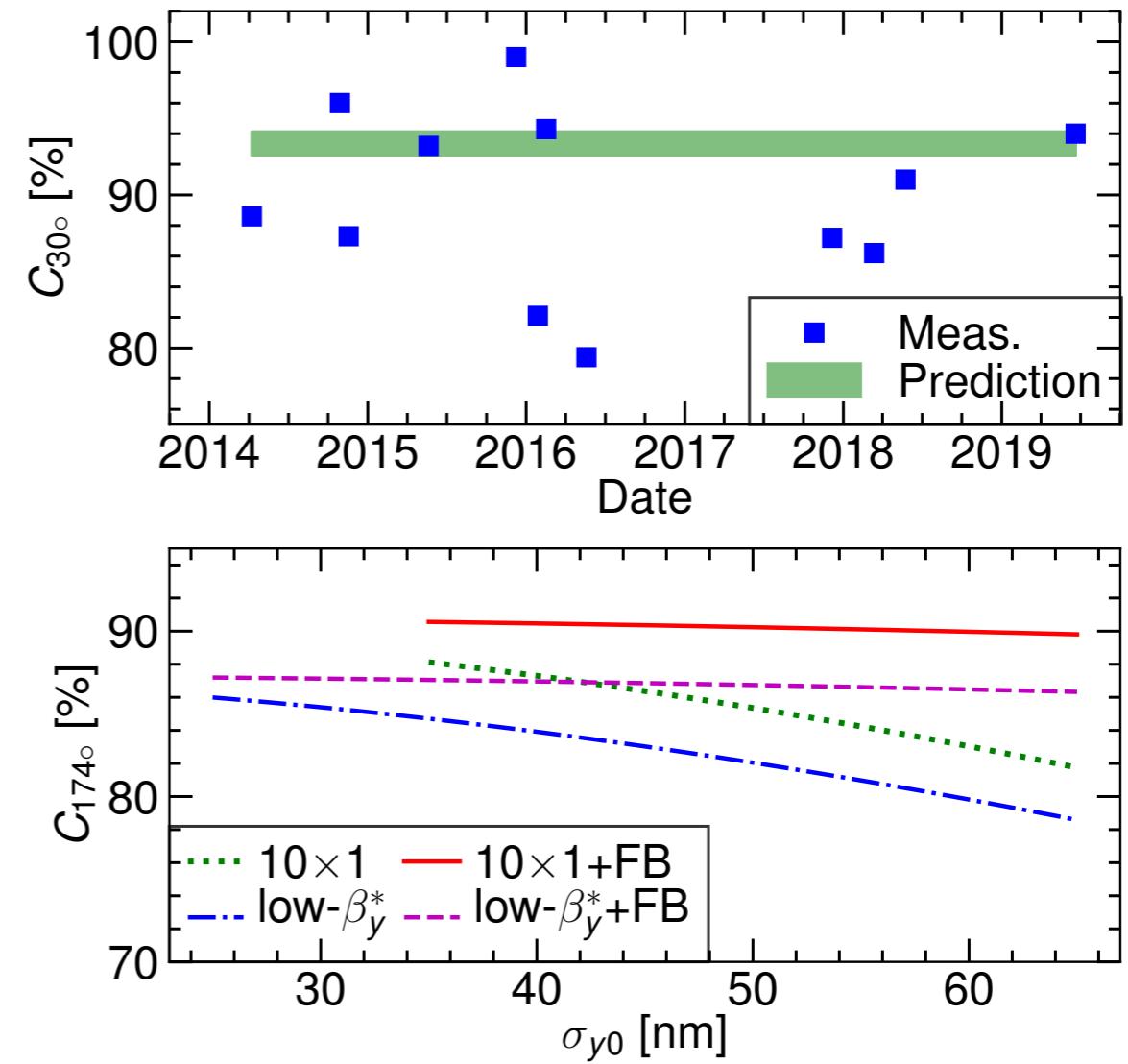
- ◆ others, e.g., phase jitter, beam position jitter, laser temporal coherence, laser spherical wavefront, laser polarization, laser power imbalance, etc.

IPBSM modulation reduction

- ◆ For 30 deg/174 deg in 10x1/ultra-low β_y^* optics and with feedback on/off
 - 30 deg: <94% roughly agrees with observations (2014-present)
 - 174 deg (w/o FB): <88% and <85% for 10x1 and ultra-low β_y^* optics
 - 174 deg (w/ FB): ~90% and ~87% for 10x1 and ultra-low β_y^* optics (<50 nm)
- ◆ Assumptions
 - 1) no cross-angle error
 - 2) ideal BG subtraction
 - 3) Gaussian laser profile
 - 4) emitx=1.2 nm, emity=12 pm

IPBSM parameters

Tilt/Pitch [mrad]	Longi. misalignment of two lasers	Trans. misalignment of two lasers
0.56	30% $\sigma_{z,\text{laser}}$	30% $\sigma_{x,\text{laser}}$
Trans. offset of two laser paths [m]	Phase jitter [mrad]	Beam position jitter (w/o FB)
<2x10 ⁻⁴	240	30% σ_y



IPBSM modulation reduction

- ◆ Concerning wakefield effects and IPBSM modulation reduction for 10x1 and ultra-low β_y^* optics with a bunch charge of 0.11 nC

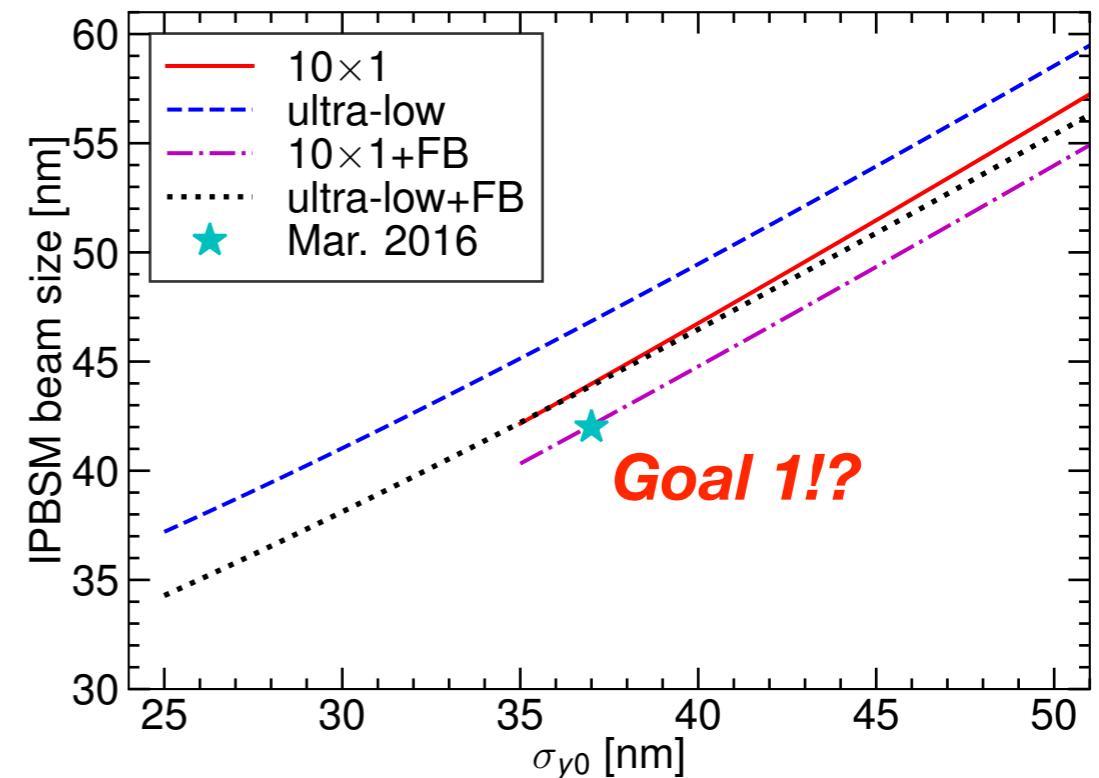
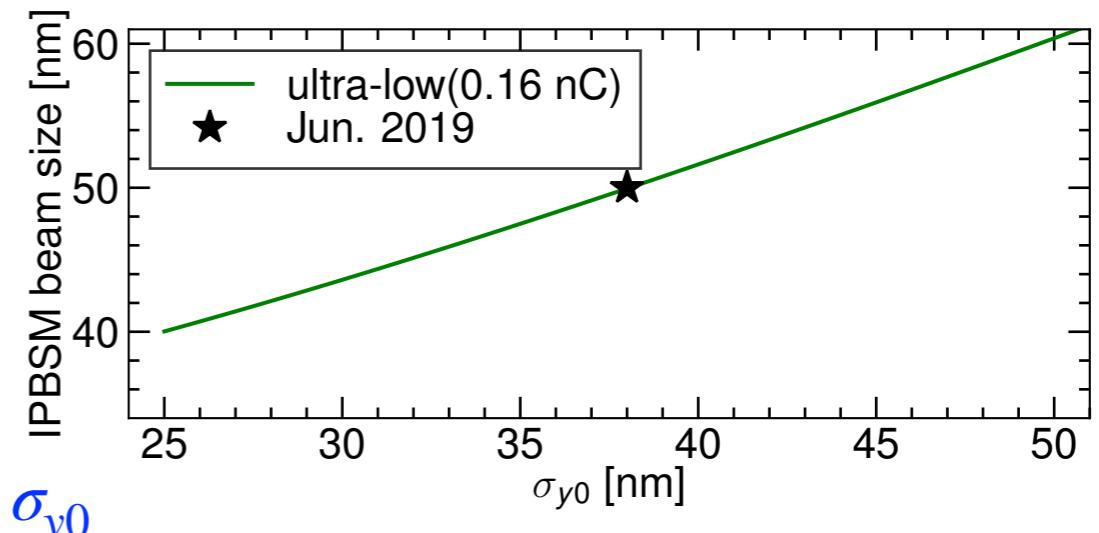
$$\sigma_y = \frac{1}{2k_y} \sqrt{2[2k_y^2(\sigma_{y0}^2 + \sigma_w^2) + \sum_i \log C_i]}$$

σ_w : contribution from wakefield

C_i : modulation reduction

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

- Min. IPBSM beam sizes are **42/40 nm** and **37/34 nm** for 10x1 and ultra-low β_y^* optics (w/o and w/ FB)!
- Achieved beam size
41.1 nm (10x1, 0.11nC, Mar. 2016)
→ **37 nm** optical beam size
50 nm (ultra-low, 0.16 nC, Jun. 2018)
→ **38 nm** optical beam size



To observe a sub-40 nm beam size: ultra-low β_y^* ? upstream FB?

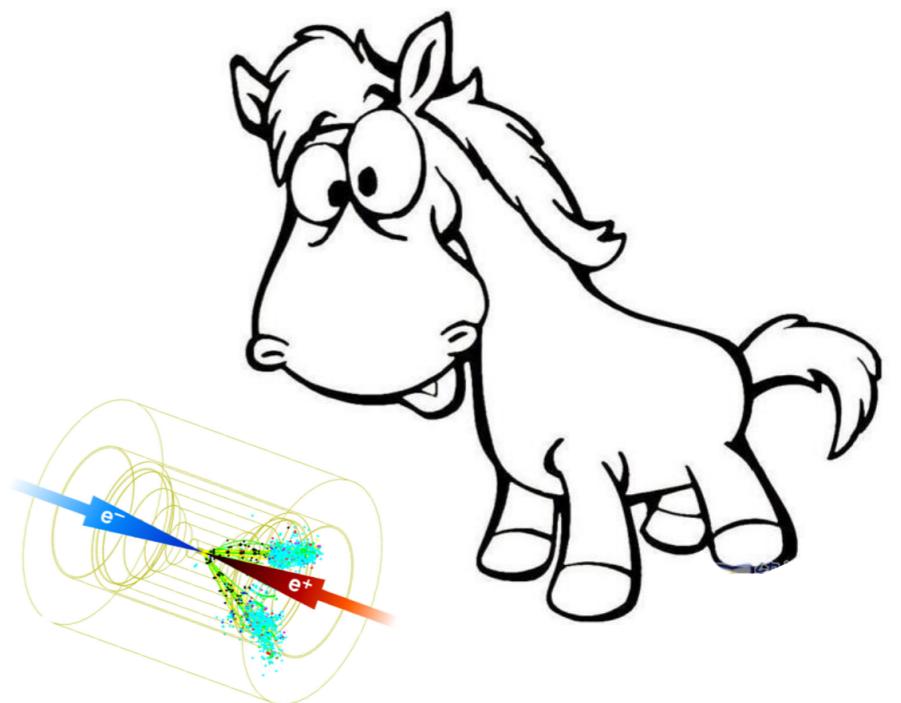
Conclusions

- ◆ The IP beam size was stabilized at 60 nm in the ultra-low β_y^* optics with a minimum beam size of 50 nm in June 2019!
- ◆ Tuning simulation with static machine errors and two different tuning knobs definitions suggest a final beam size about 30 nm
- ◆ What held the small beam tuning?
 - dynamic errors induce mainly vertical IP position jitter (16.8 nm)
 - beam size dilution from wakefield is measured as 125 nm/nC
 - IPBSM modulation reduction can be a barrier to the goal beam size observation. Modulation correction and upstream feedback will be essential for the sub-40 nm beam size achievement!
- ◆ Future plan
 - ◆ **A beam size <40 nm in $25\beta_x^*0.25\beta_y^*$ optics**
 - ◆ **Tuning in $10\beta_x^*0.25\beta_y^*/1\beta_x^*0.25\beta_y^*$ optics with octupole**
 - ◆ **Tuning with long L^* and at the similar chromaticity**



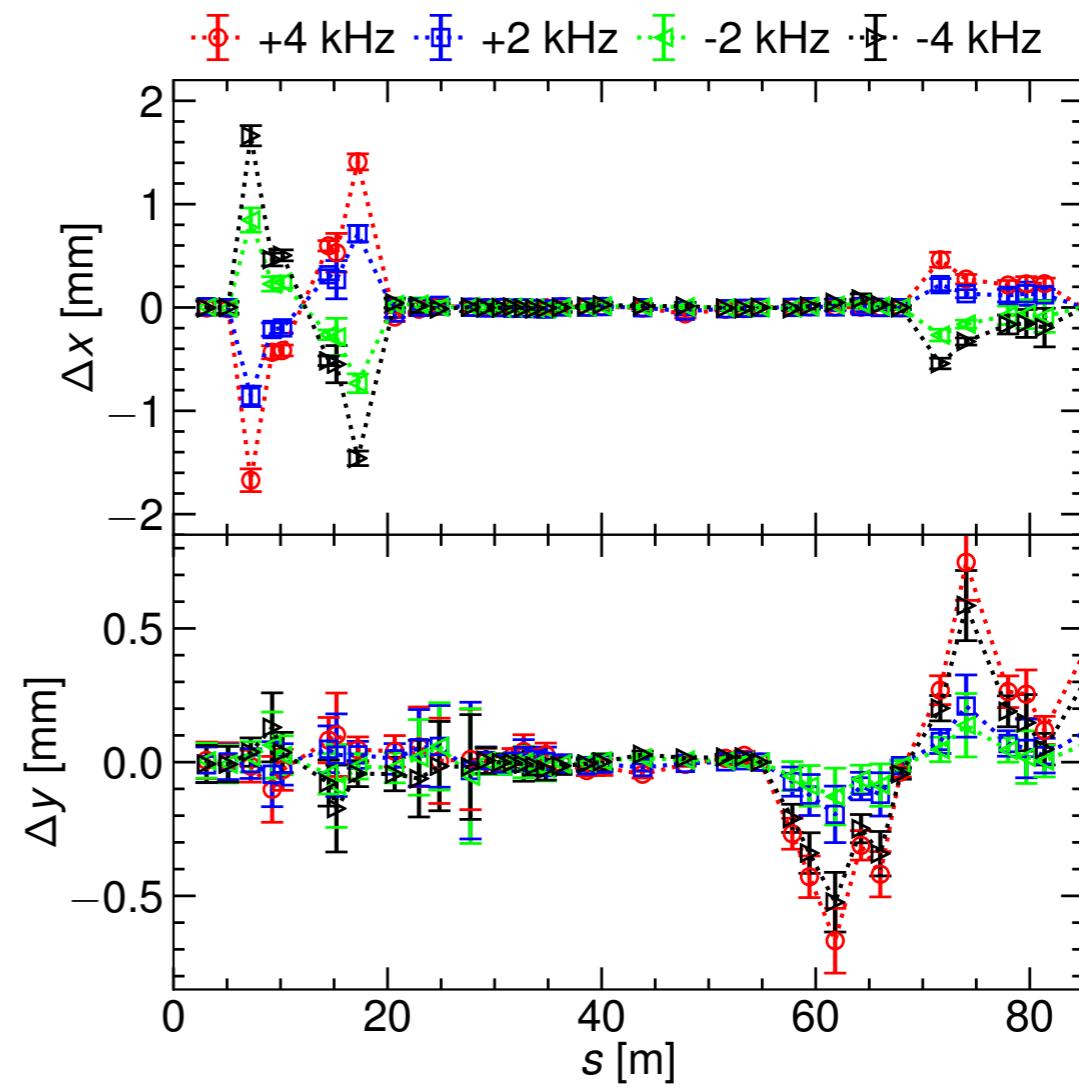
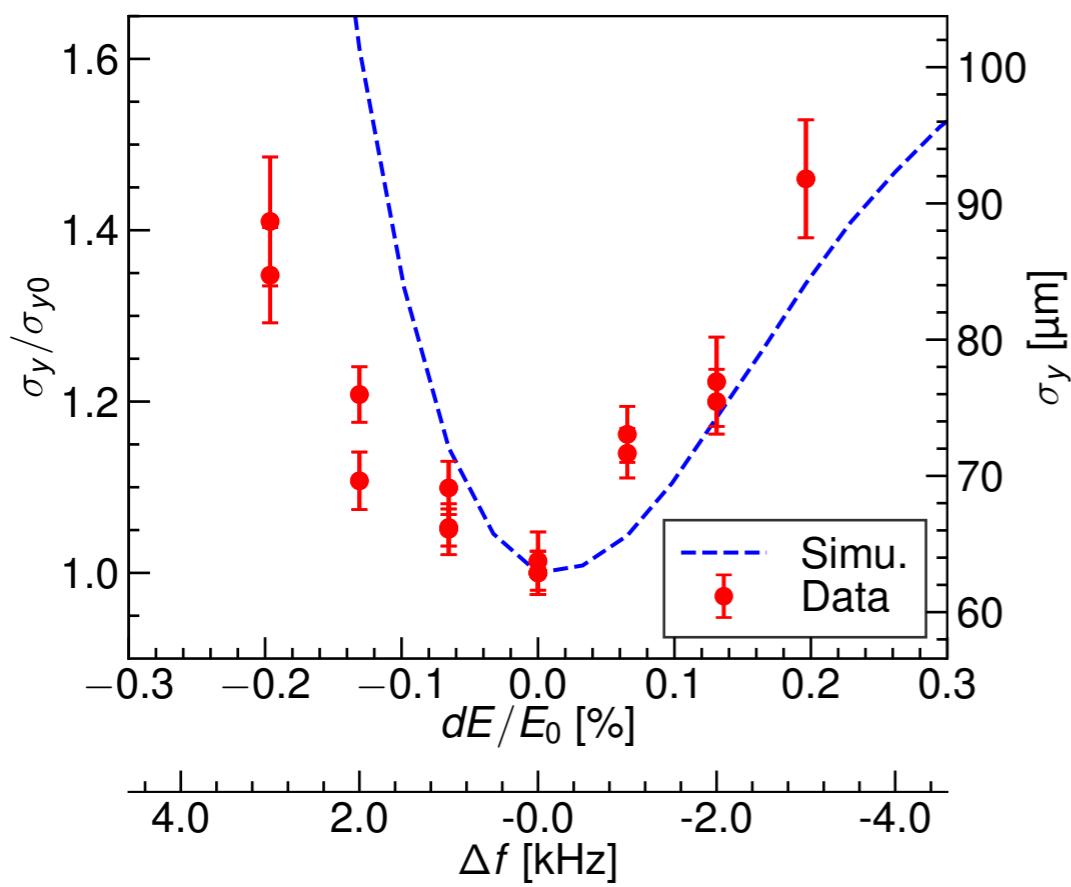
Grateful acknowledgement for the invaluable support from KEK-ATF and ATF collaboration!

**Thank you!
Question?**



IP bandwidth

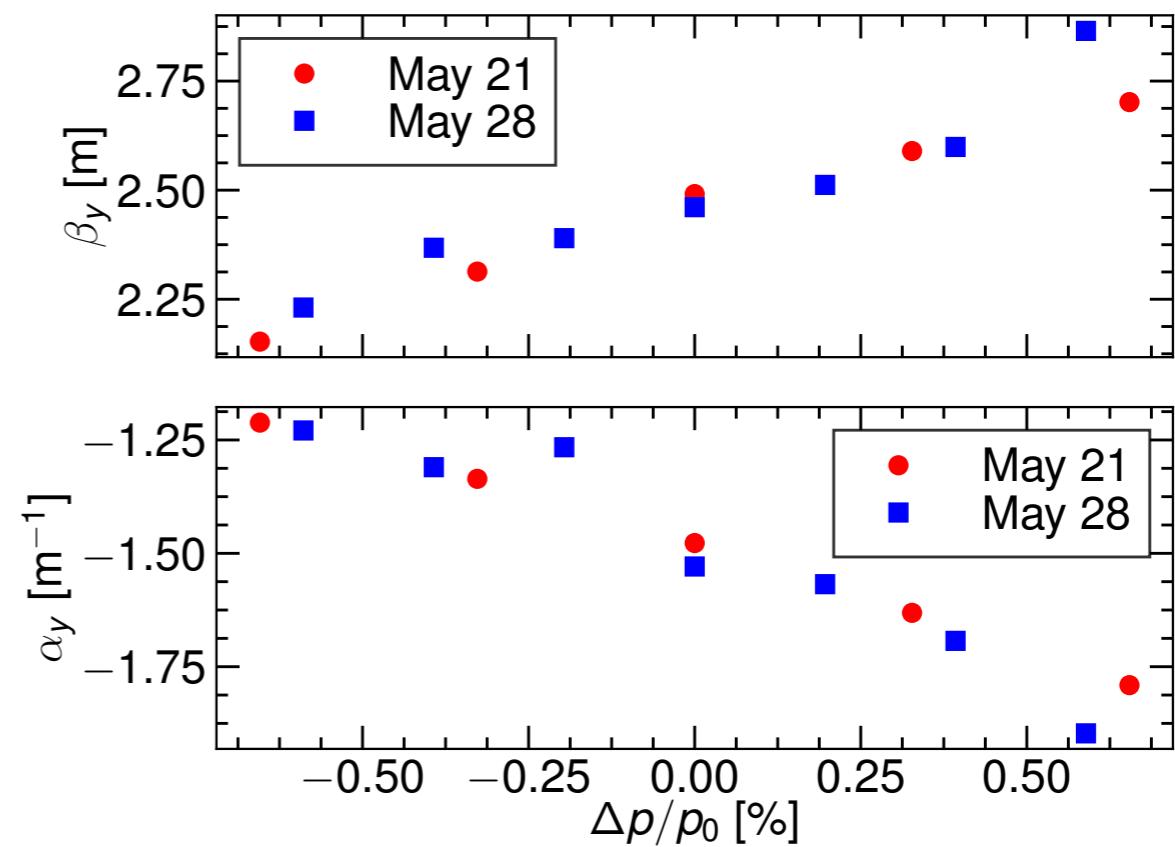
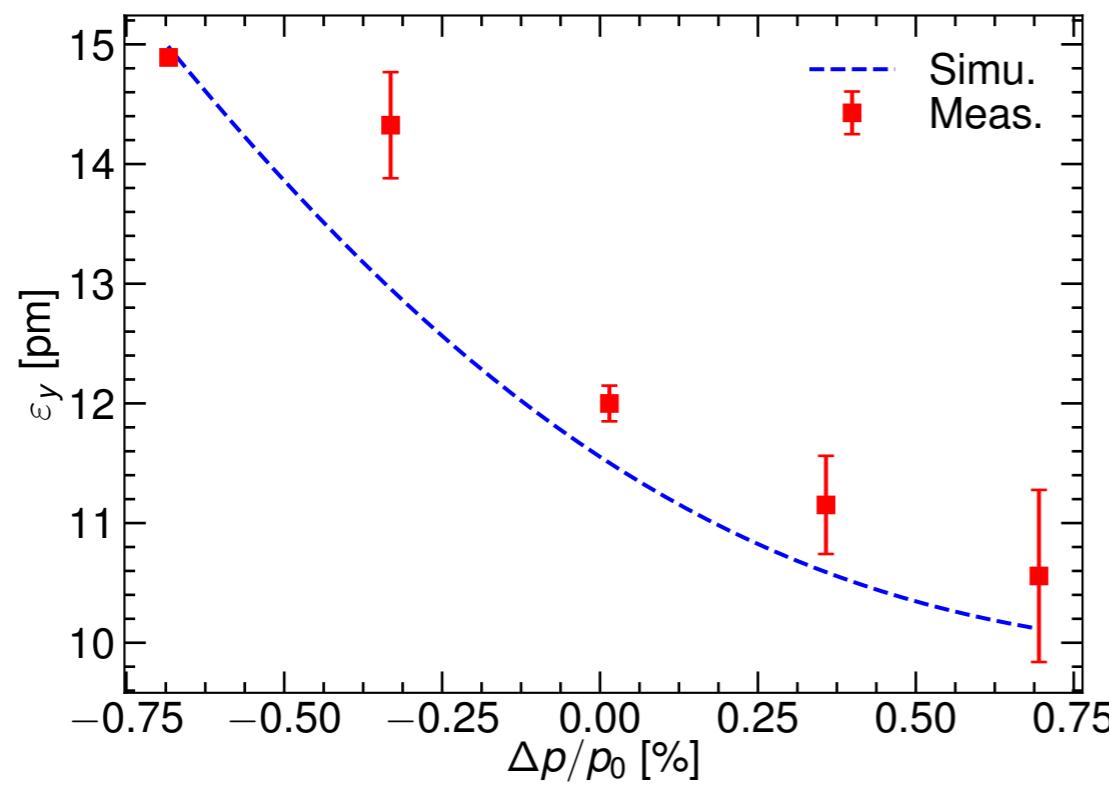
- ◆ First observation in the ultra-low β_y^* optics
- ◆ Looks agree with the simulation (w/o chromatic IEX parameters)
- ◆ Large vertical off-moment orbit distortion in the FFS (T_{366} ?)



→ require further analysis and simulations!

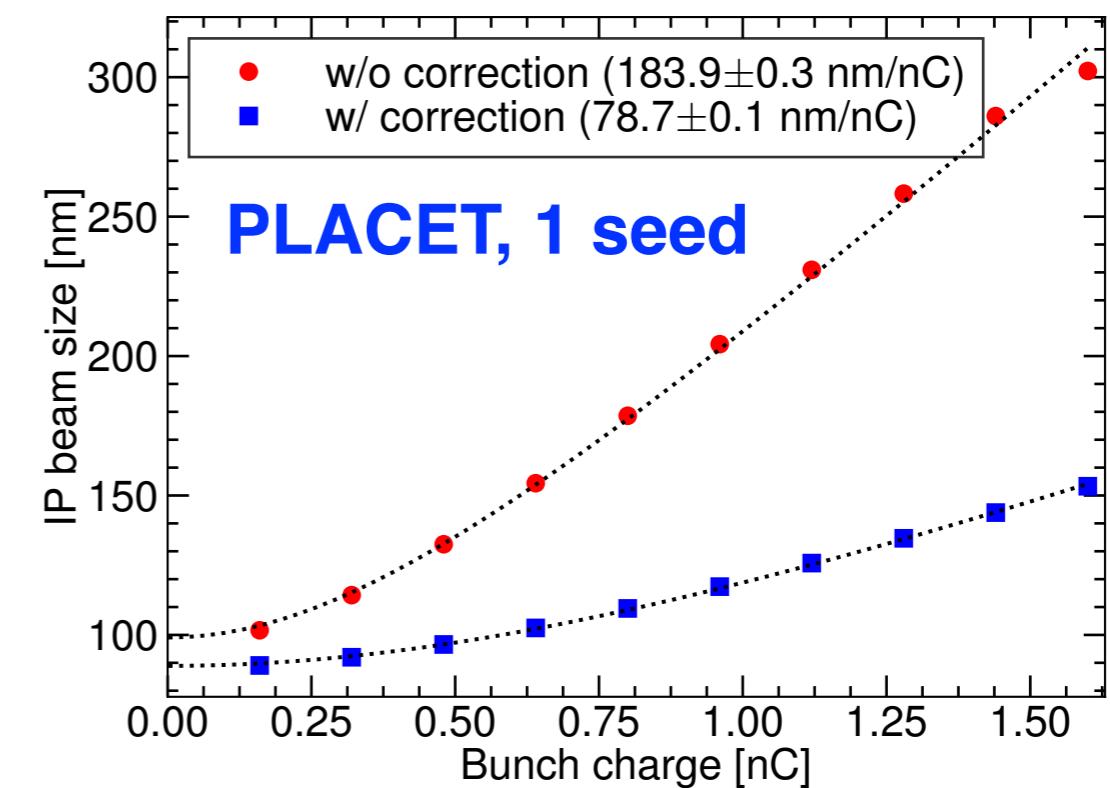
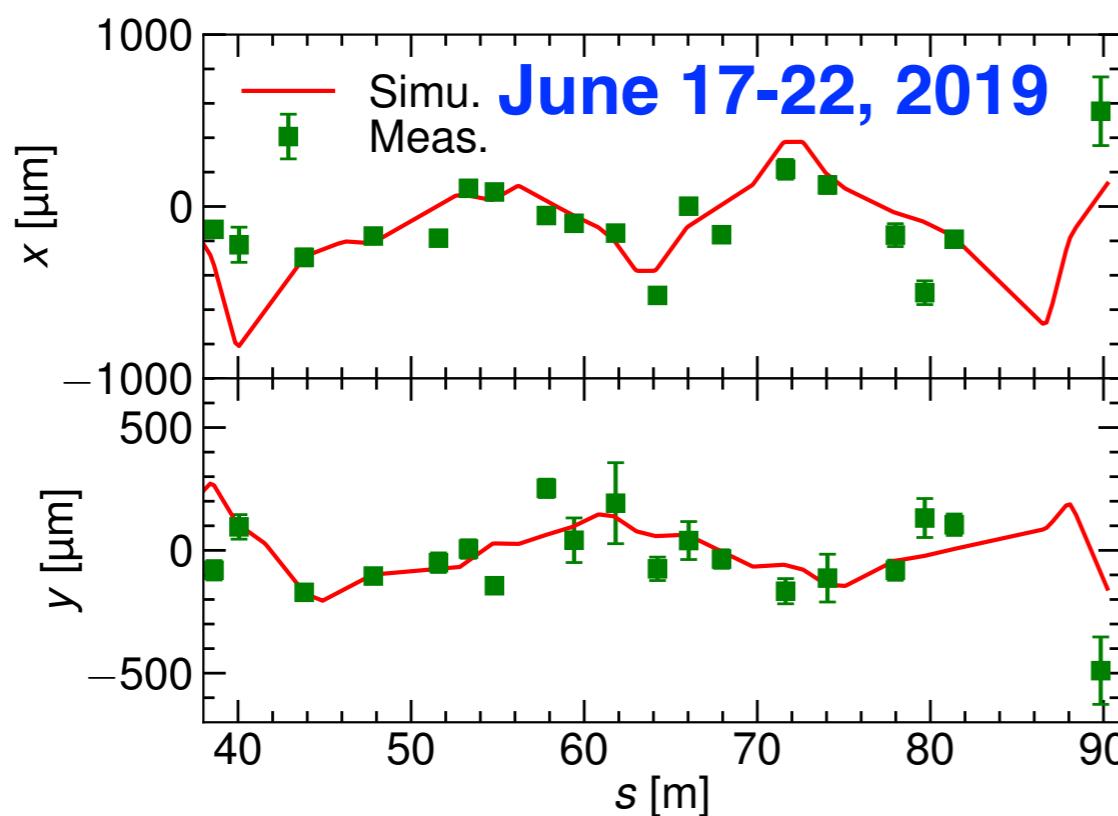
Chromatic optical parameters at IEX

- ◆ Measured off-momentum vertical dispersion seems agree with SAD simulations (realistic COD → ver. dispersion)
- ◆ Twiss parameters at the extraction (IEX) was extrapolated from measurements at adjacent quadrupoles



Impact of Wakefield – simulation

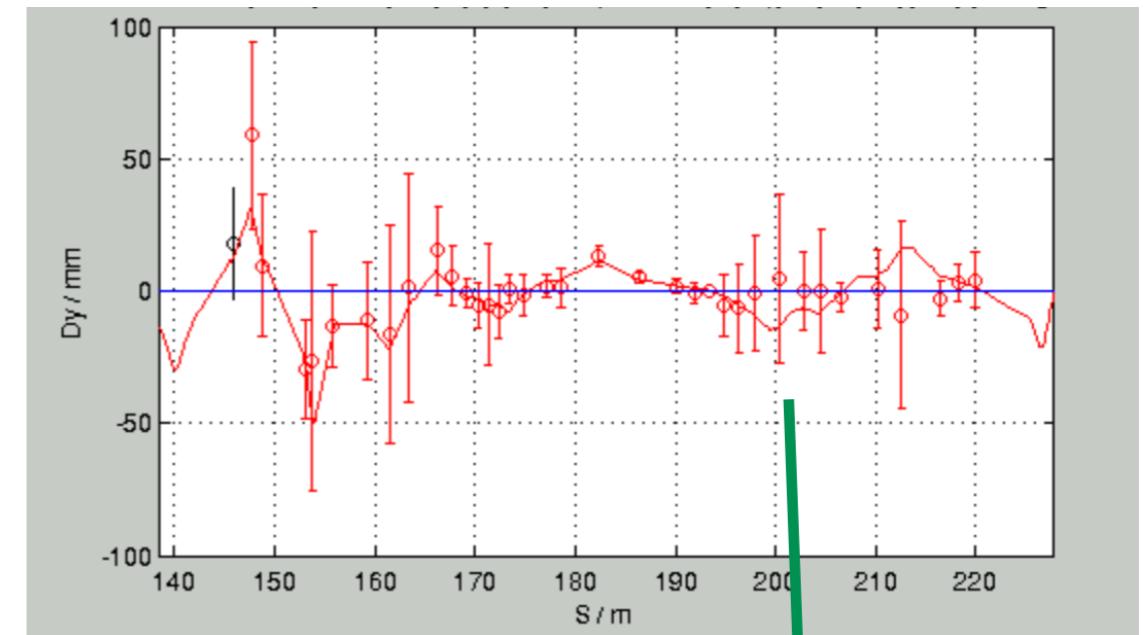
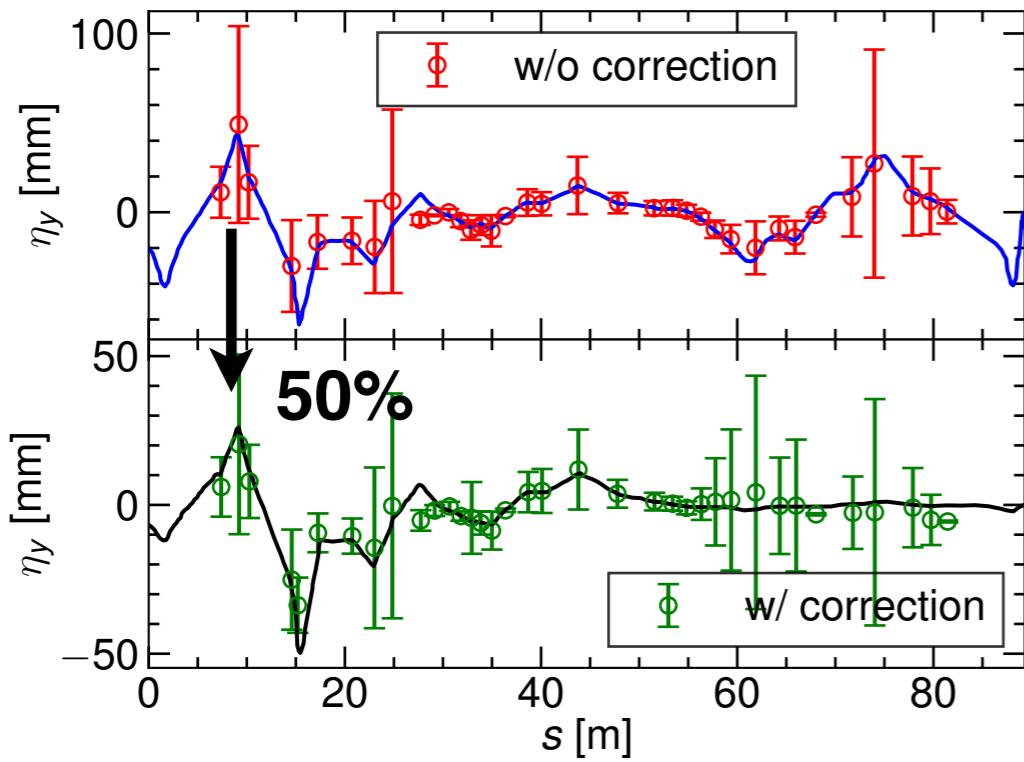
- ◆ Ultra-low β_y^* optics; sources (bellow, cavity BPM) in the FFS
- ◆ With the operation orbit distortions (FFS, extra orbit bump)
- ◆ Intensity dependence factor between 78.7 to 183.9 nm/nC with an imperfect wakefield correction! —> agree with measurements!



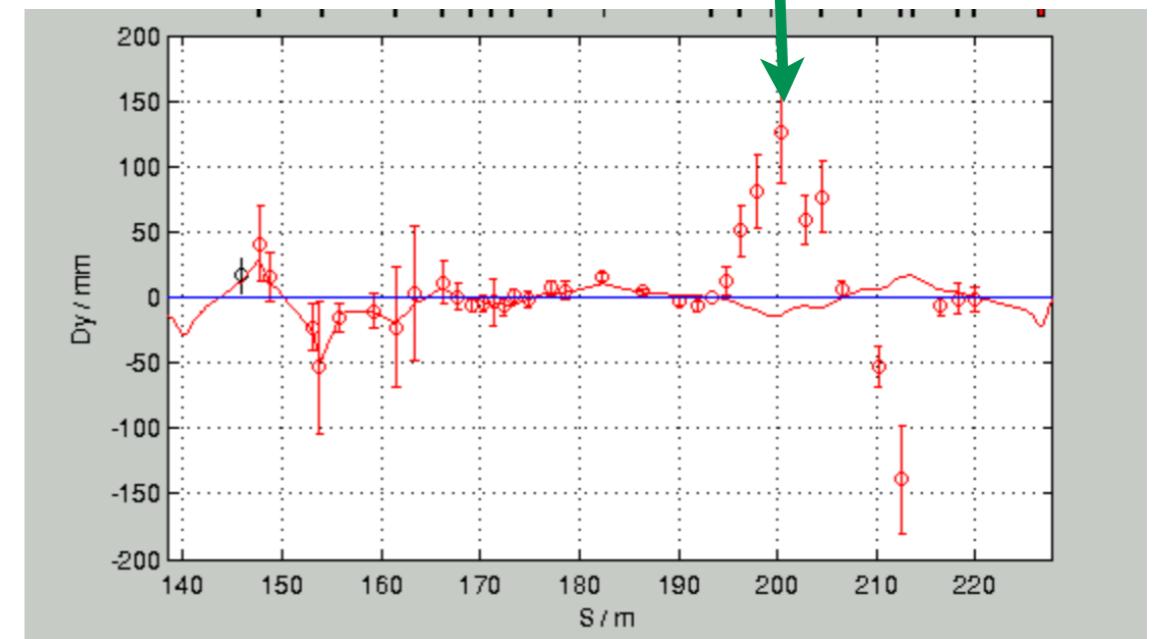
=> Tuning in low beam intensity (<0.16 nC)

EXT dispersion

- ◆ EXT dispersion correction via local orbit bump in the DR
- ◆ observe FFS dispersion increase during tuning (June 2019)

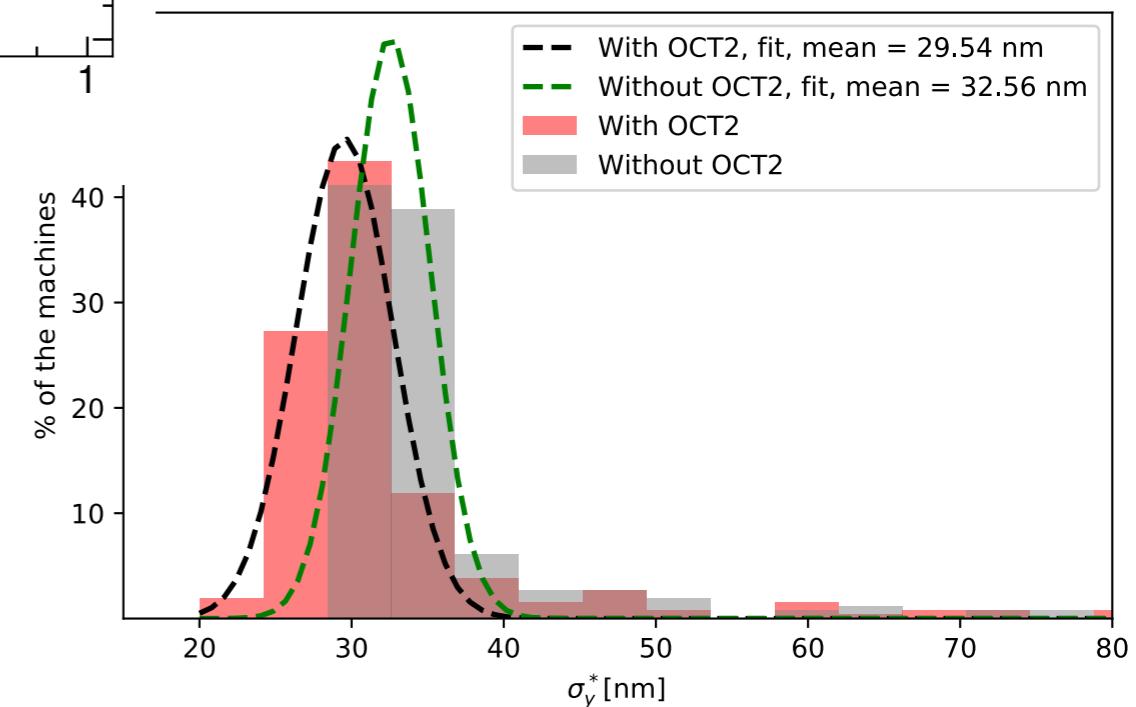
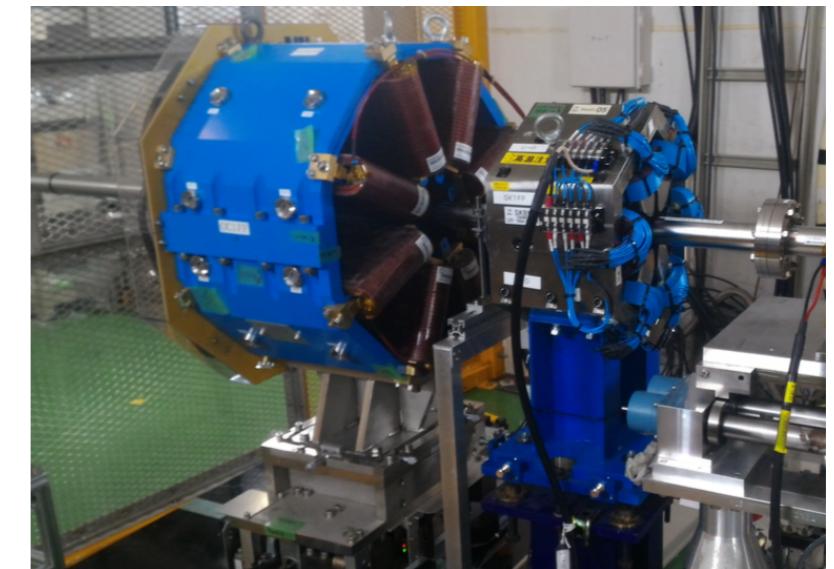
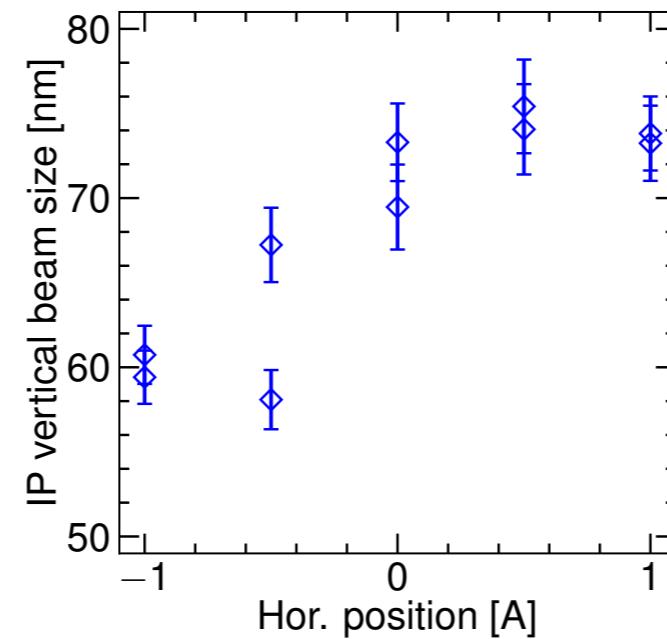
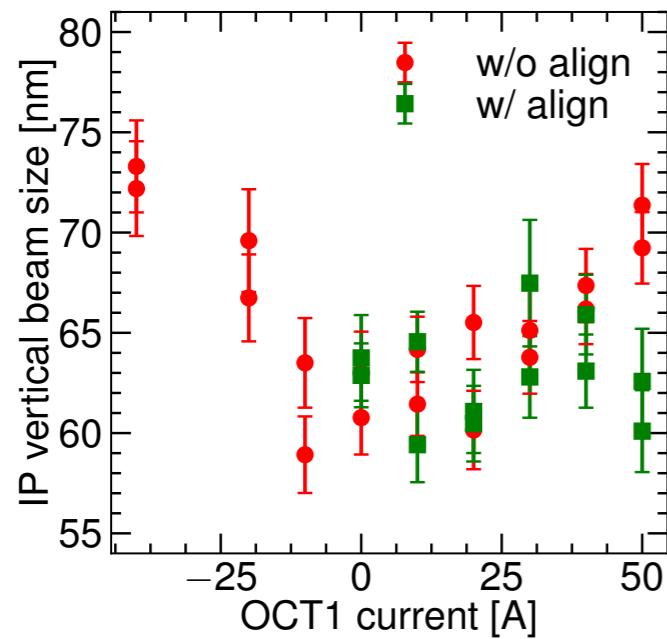


after 1.5 shift



Octupole studies

- ◆ 3rd order aberration correction using octupole is essential for $1\beta_x \times 0.25\beta_y$ optics
- ◆ Hor. scan of oct1. (40 A) found max. modulation 0.36 (same to that w/o oct1) at -1 mm
- ◆ Oct1. current scan give similar modulation => no impact on IP beam size?(beam through oct1. center?)



- ◆ Swapping the two octupoles may help observing smaller beam size
- ◆ Test in Dec. 2019

IPBSM modulation reduction

- Analytical prediction with the assumptions
 - 1) no cross-angle error; perfect BG subtraction
 - 2) Gaussian laser profile; s linear polarization
 - 3) emitx=1.2 nm, emity=12 pm
 - 4) position/angular jitter can be reduced by a factor 3 w/ FONT FB
- IPBSM parameters

Laser power imbalance	Laser spot size [um]	Laser size (longi.) [um]	Longi. fringe tilt [mrad]	Trans. fringe tilt [mrad]
P1/P2<1.2	19.2/23.2	18.7/24.4	0.56	0.56
Phase jitter [mrad]	Trans. misalignment of two lasers	Longi. misalignment of two lasers	Beam position jitter (w/o FB)	Trans. offset of two laser paths [m]
240	30 %	30 %	30% beam size	<2x10 ⁻⁴

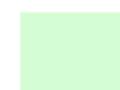
- [1] T. Shintake, Annu. Rev. Nucl. Part. Sci. 49:125-162 (1999)
- [2] Y. Yamaguchi et al., arXiv:1006.3370v2
- [3] J. Yan et al, NIMA 740: 131-137 (2014)
- [4] T. Yasui, master thesis, Tokyo university (2018)
- [5] R. J. Apsimon, PRAB 21, 122802 (2018)

Shift plan for Nov-Dec operation

- ◆ Preparation:
 - ◆ Octupole swapping and laser alignment;
 - ◆ Normal and skew sextuple alignment (Okugi-san...)
 - ◆ mOTR commissioning
- ◆ Shift request:

mOTR (Michele, Alex. and Renjun): 2
ultra-low week: Dec. 9-13 (w/ two shifts in the week before?)

November 2019						
Su	Mo	Tu	We	Th	Fr	Sa
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30



Beam operation



Ultra-low β_y shift

December 2019						
Su	Mo	Tu	We	Th	Fr	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28