# ATF2 small beam, Wakefield

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ATF Review Meeting - September 29th 2020

# ATF2 Final Focus Design

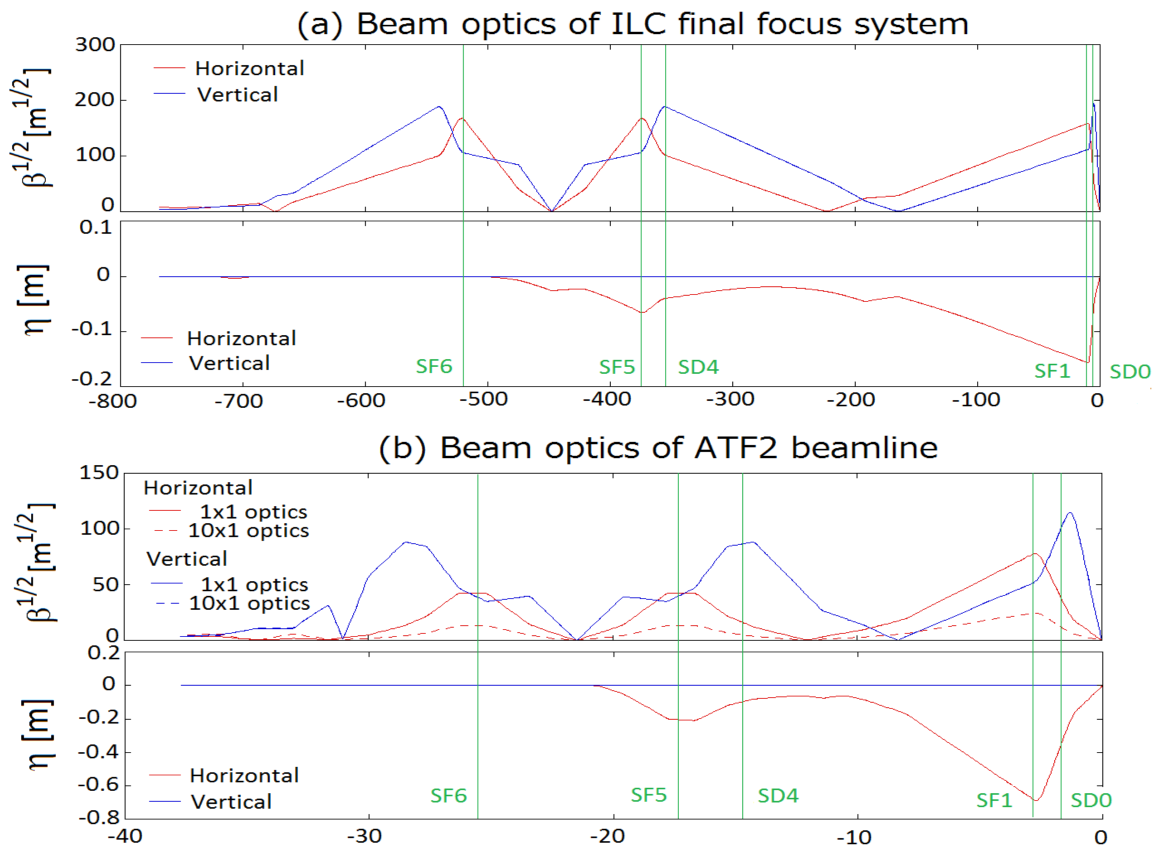
**Prototype of ILC Final Focus beam line (Local Chromaticity Correction)**

- Almost the same configuration of the beam line.
    - Magnets have the same names
- Same tuning method

ILC

Final Focus Line
$\beta$ and $\eta$ functions

ATF



# Original ATF2 design optics → 10x1 optics

- Original design
  - **Similar chromaticity** (~$L^*/\beta^*$) in both x and y directions as ILC
  - Tighter tolerances of multipole field error, due to larger ATF beam physical emittance
- 10x1 optics (10 times larger $\beta^*_x$, same $\beta^*_y$)
  - Smaller chromaticity in x direction
  - **Similar multi-pole field error tolerances** as ILC

Chromaticity of ATF and ILC Final Focus

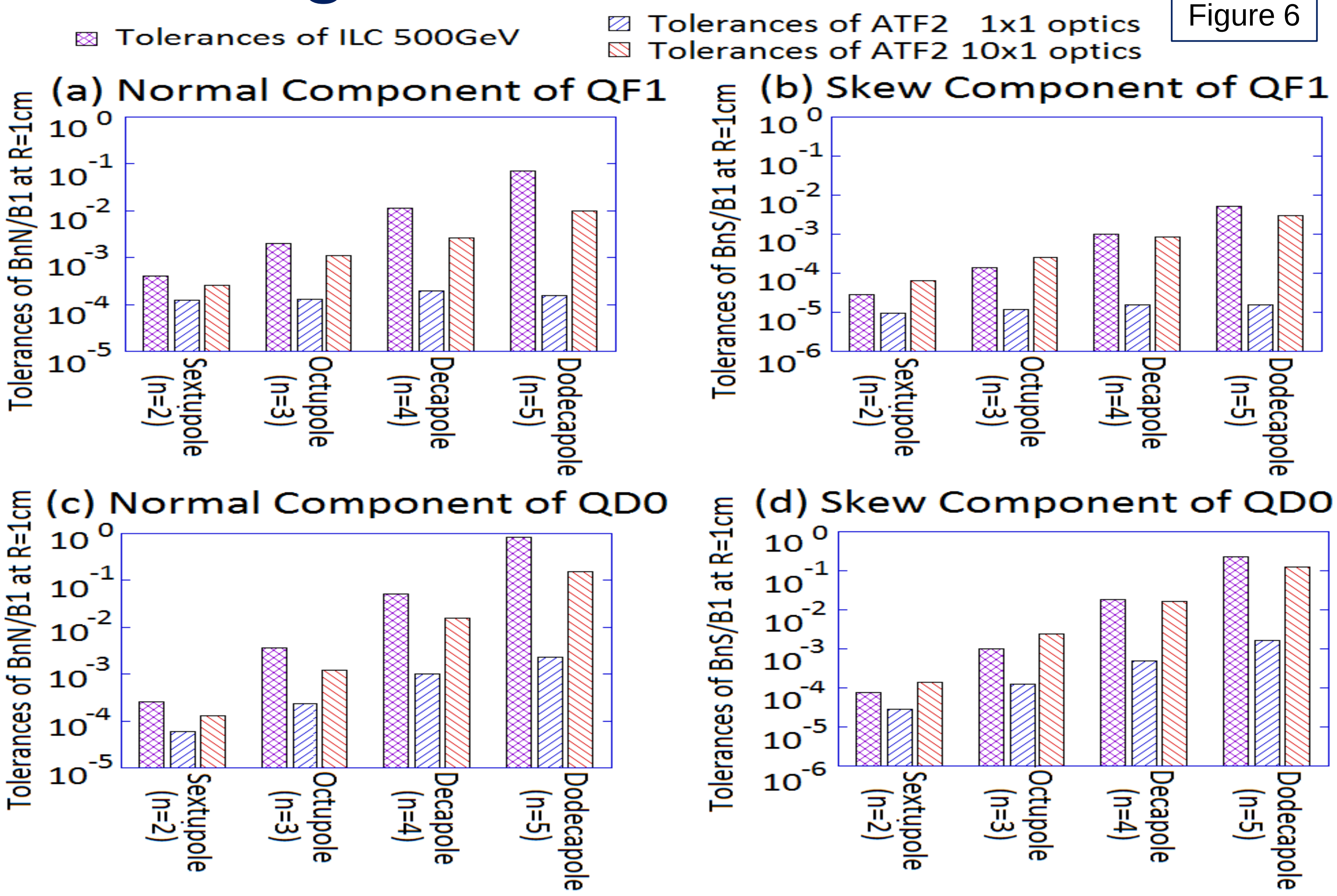
| | ATF Original | ATF 10x1 | ILC |
|---|---|---|---|
| $L^*/\beta^*_x$ | 250 | 25 | 320 |
| $L^*/\beta^*_y$ | 10,000 | 10,000 | 10,000 |

($L^*$: distance from final Q to IP)

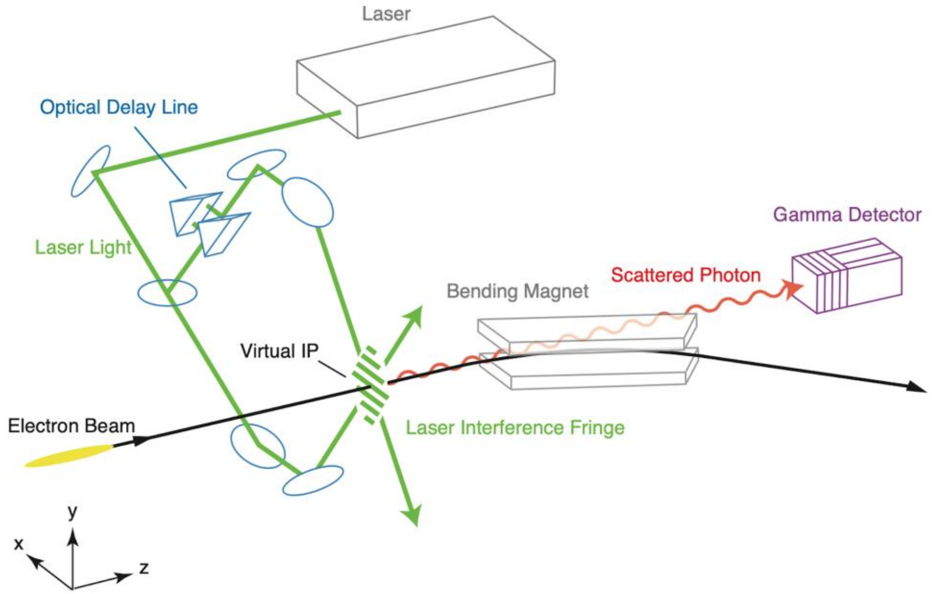
# Tolerances of multi-pole field error of Final doublet magnets

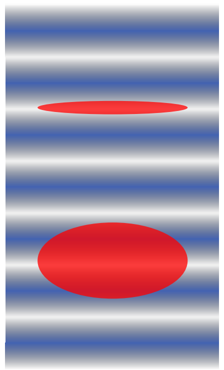
Figure 6

ILC and ATF 10x1 have similar tolerances



# Beam Size Monitor at IP (IPBSM)



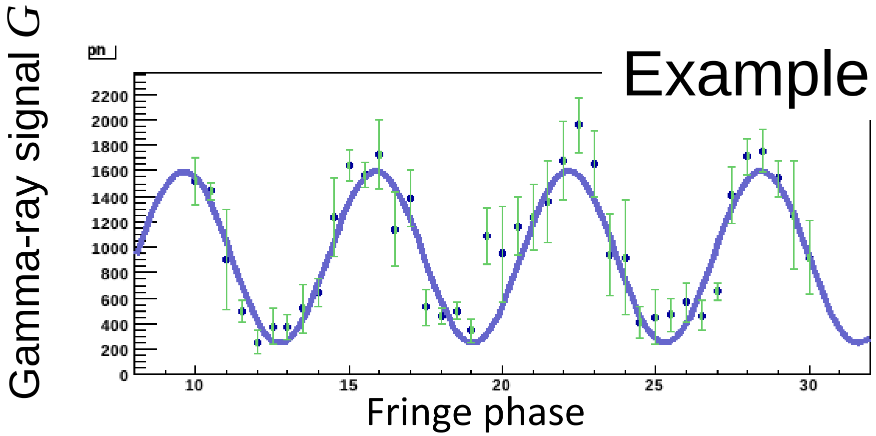



Small beam ↓ Large $M$

Large beam ↓ Small $M$

Scan interference fringe phase.
Fit modulation $M$:

$$G(\phi) = G_0\left(1 + M\cos(\phi + \phi_0)\right)$$

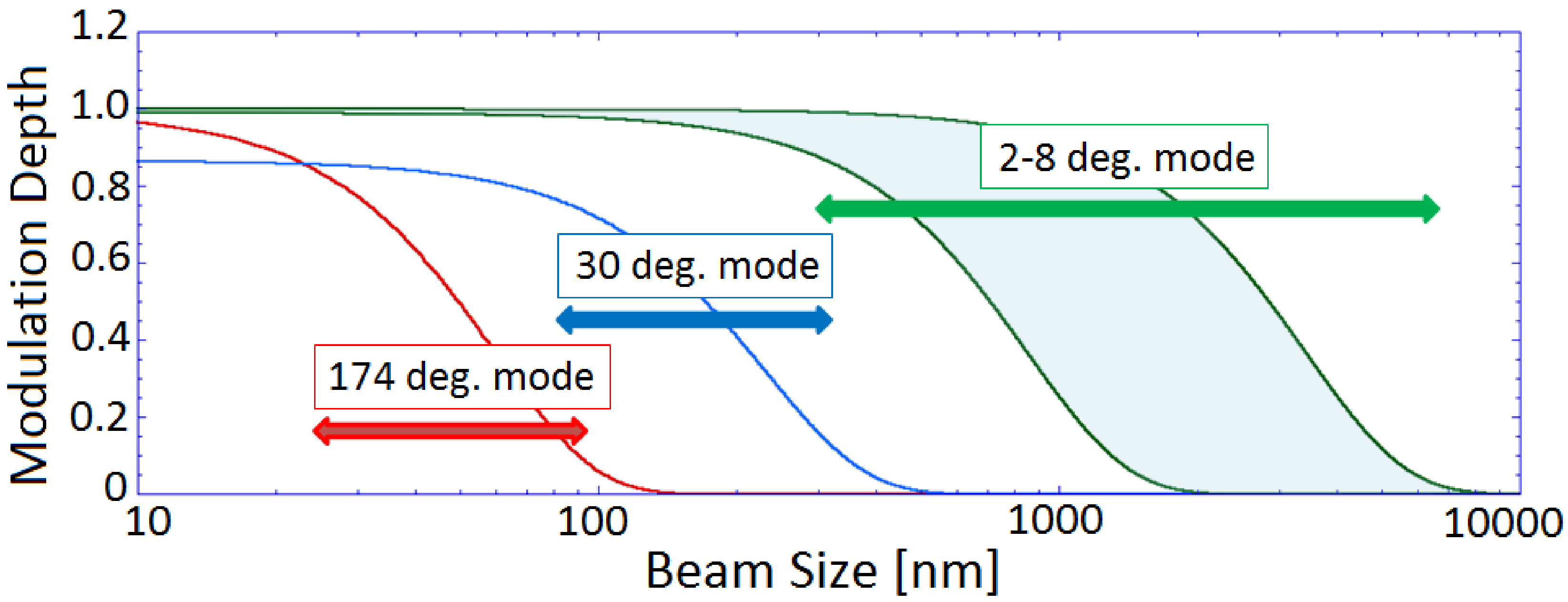


# Beam Size Monitor at IP (IPBSM)

3 laser crossing angle modes for different tuning stages

$$\text{fringe pitch} = \frac{\text{wave length}}{2\sin(\text{crossing angle})}$$

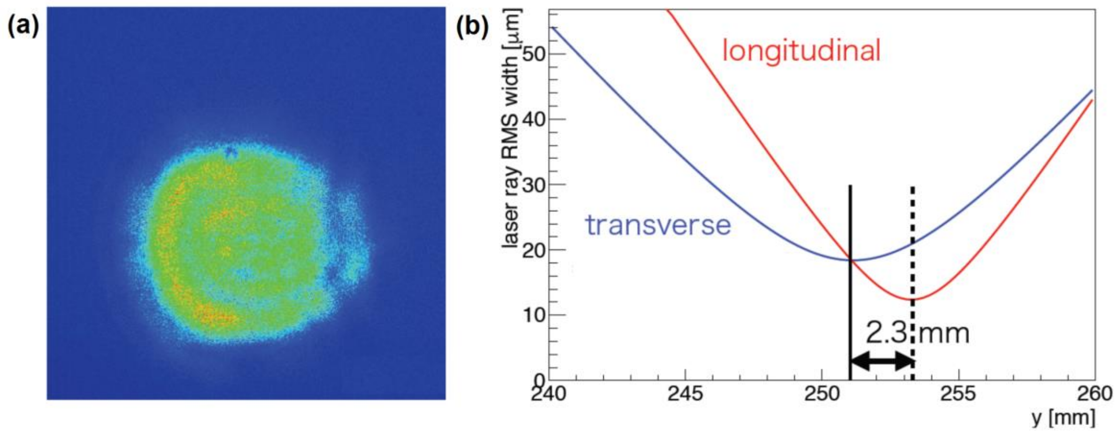
Sensitive beam size regions of different crossing angle modes of IPBSM



# Quality and stability of IPBSM Laser: Suspected to be one of major problems in small beam size measurement.

Transverse laser profile
Laser beam waist sizes and positions are different in two directions

Figure 9




Laser position drift observed.
Modulation (then, measured beam size) is sensitive to change of laser path.

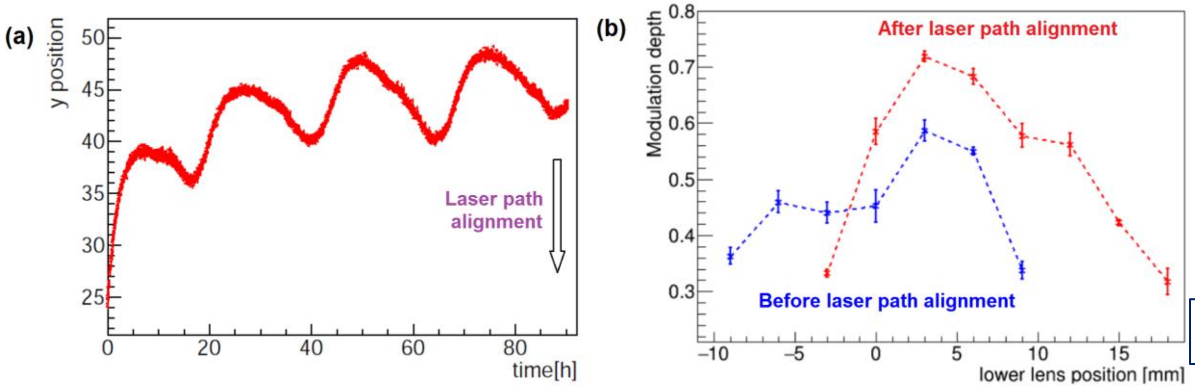



Figure 10

**Evaluated beam size is upper limit of real size.**

**Measurement is not very stable, affecting precise tuning.**

# Tuning knobs for Vertical Beam Size at IP (Final stage of beam tuning)

| | Changing parameters | Corrected coupling |
|---|---|---|
| **Linear knobs** (Linear Optics adjustment) | 6-poles horizontal moves | $yy'$ (Focal Position) (AY) |
| | 6-poles vertical moves | $yE$ (Dispersion) (EY) |
| | | $x'y$ (x-y coupling) (R32) |
| **Non-linear knobs** (2nd order optics adjustment) | 6-poles strength | $x'yy'$ |
| | | $yy'E$ (chromaticity) |
| | Skew 6-poles strength | $xxy$ |
| | | $xyE$ |
| | | $yEE$ (2nd order dispersion) |
| | | $yy'y'$ |

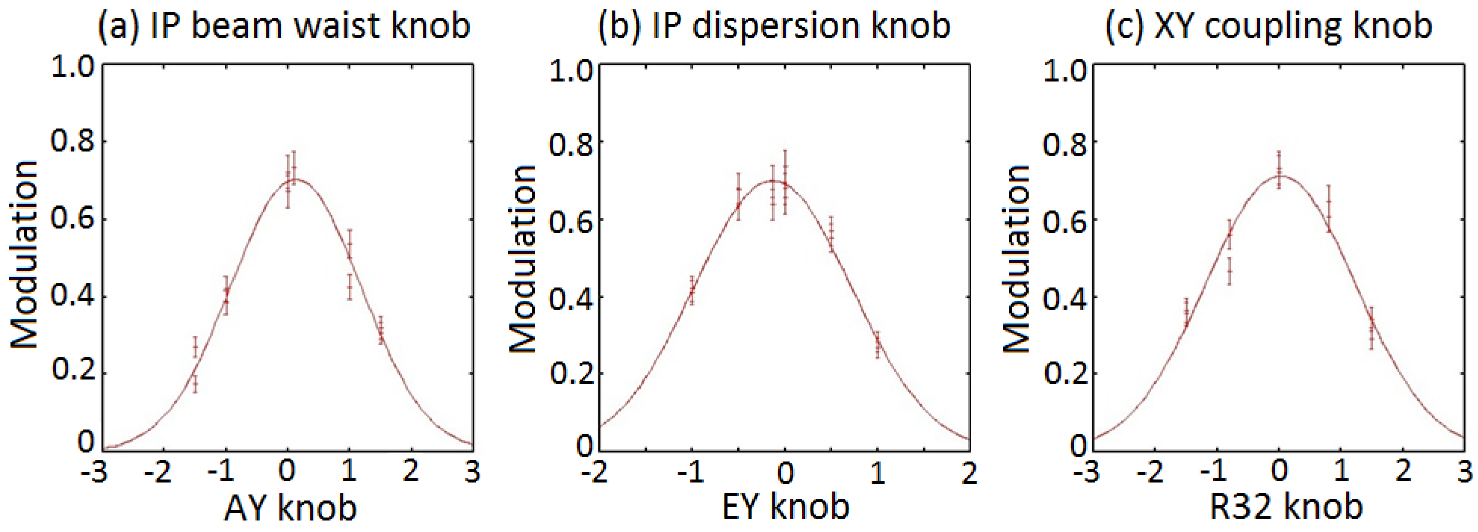
**Each knob changes one coupling (correlation) term.**

# Tuning with Linear Optics Knobs

## Procedure of linear optics correction (linear knobs) established

- QF1 and QD0 (final doublet) strength tuning using wire scanner at IP
- Linear-knob scans, IPBSM 2-8$^{o}$ (~6$^{o}$) mode → 30$^{o}$ mode → 174$^{o}$ mode

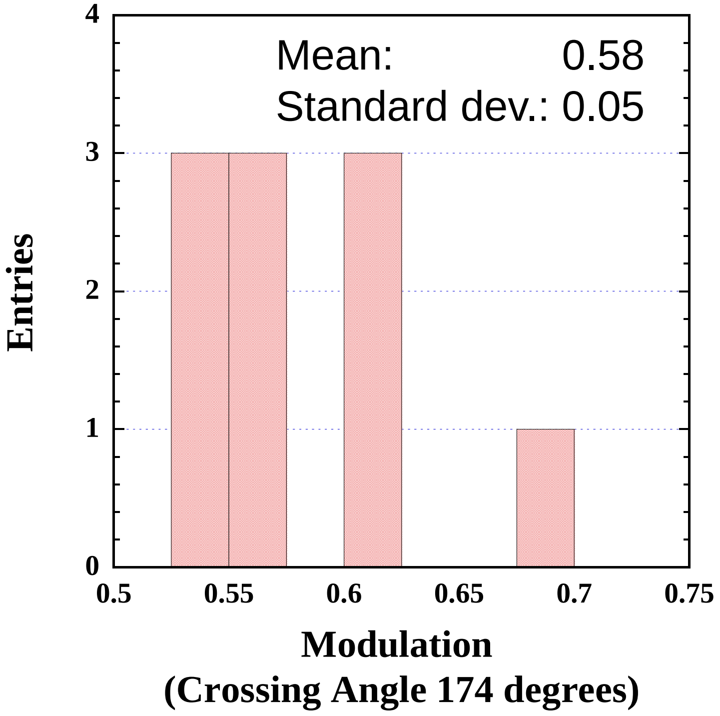
Examples of tuning with linear knobs | Figure 11



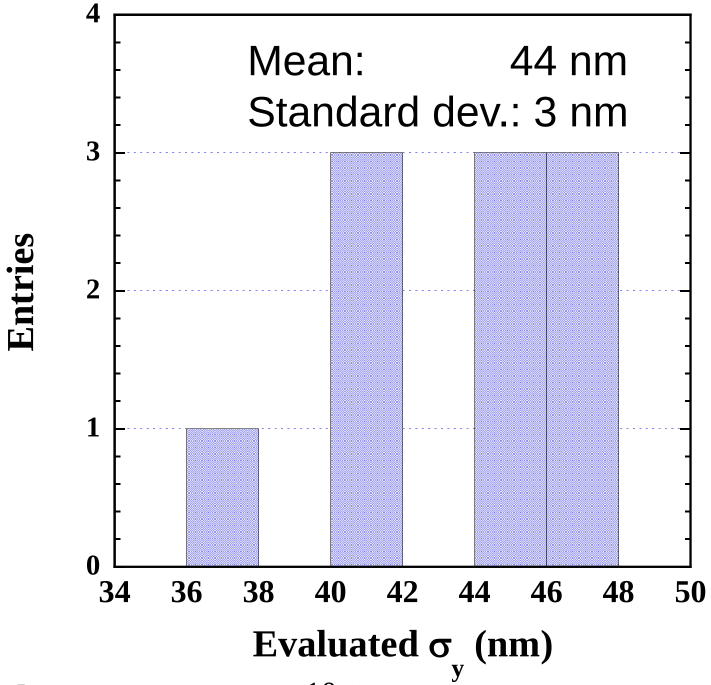

After each knob scan, the knob is set at the peak of the Modulation.

# Example of small beam size data (2014 June)

IPBSM Modulation
(174 degree Crossing angle)




Beam Size Evaluated from Modulation
(no systematic error assumed)




(Bunch charge ~ $0.1 \times 10^{10}$e)

Reported in IPAC2014,
http://accelconf.web.cern.ch/IPAC2014/papers/weza01.pdf

# Final Focus Scheme of ILC Validated

**Confirmed smallest beam size ~41 nm (2016)**

**Local Chromaticity Correction Demonstrated**

Without chromaticity correction,

expected beam size ~ 300 nm

Beam size without chromaticity correction

$$\sigma = \sigma_0 \sqrt{1 + (\sigma_\delta \xi)^2}$$

Chromaticity: $\xi \approx L^*/\beta^* \approx 10^4$

Energy spread: $\sigma_\delta \approx 10^{-3}$

# Tuning with non-linear (2nd order) knobs

- Non-linear knobs are sets of strength changes of normal and skew sextupole magnets
- Successfully integrated into tuning procedure
- **Systematic study and correction of non-linear aberrations have not been fully demonstrated yet.**
- Effects are expected to be visible only at very small beam (IPBSM 174$^{o}$ mode)
- Need stable beam and monitor

# Example of beam size after tuning including 2nd order knobs

Modulations after tuning

Modulations after tuning, turn off skew sextupoles (But, linear knobs were not optimized)

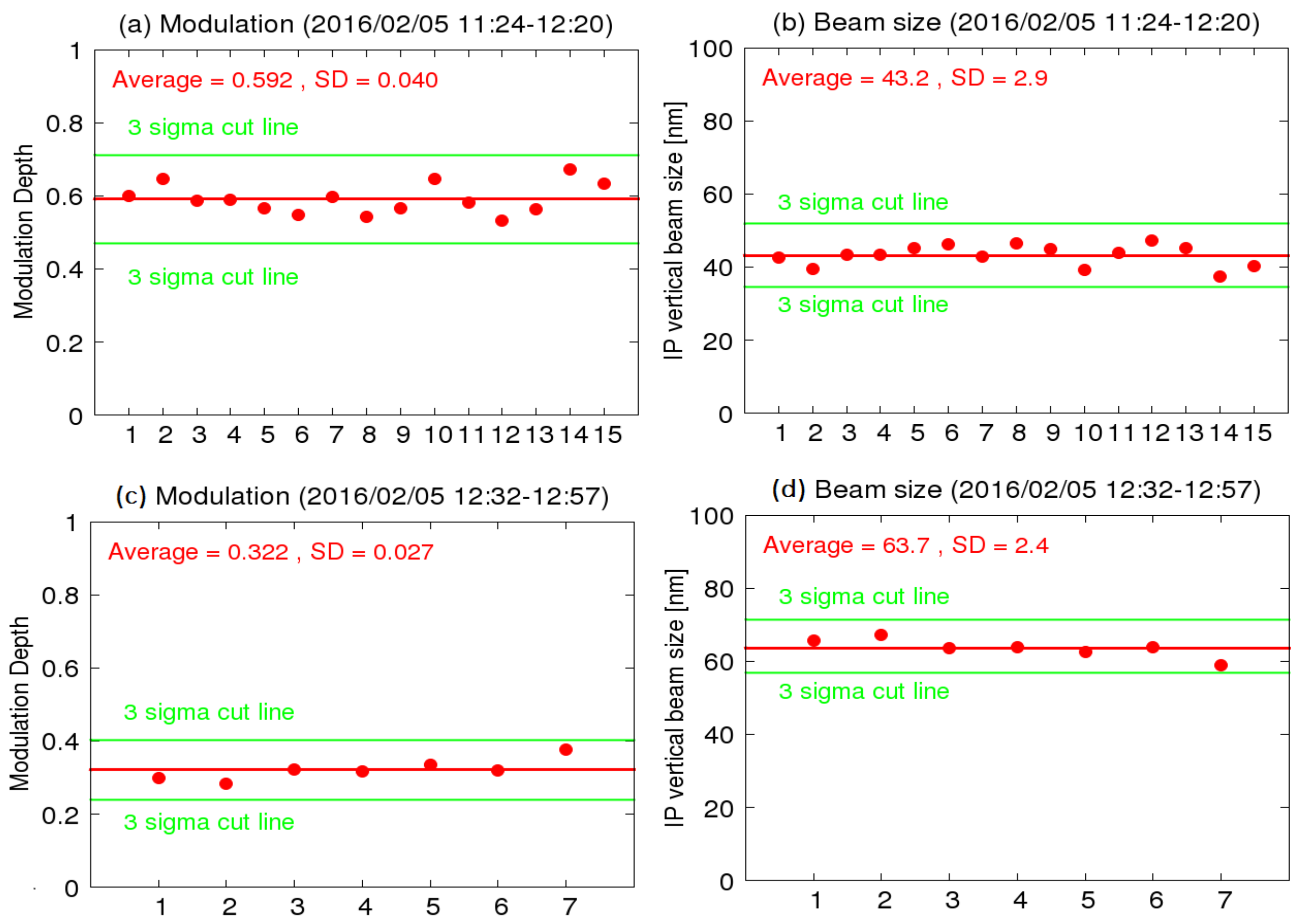
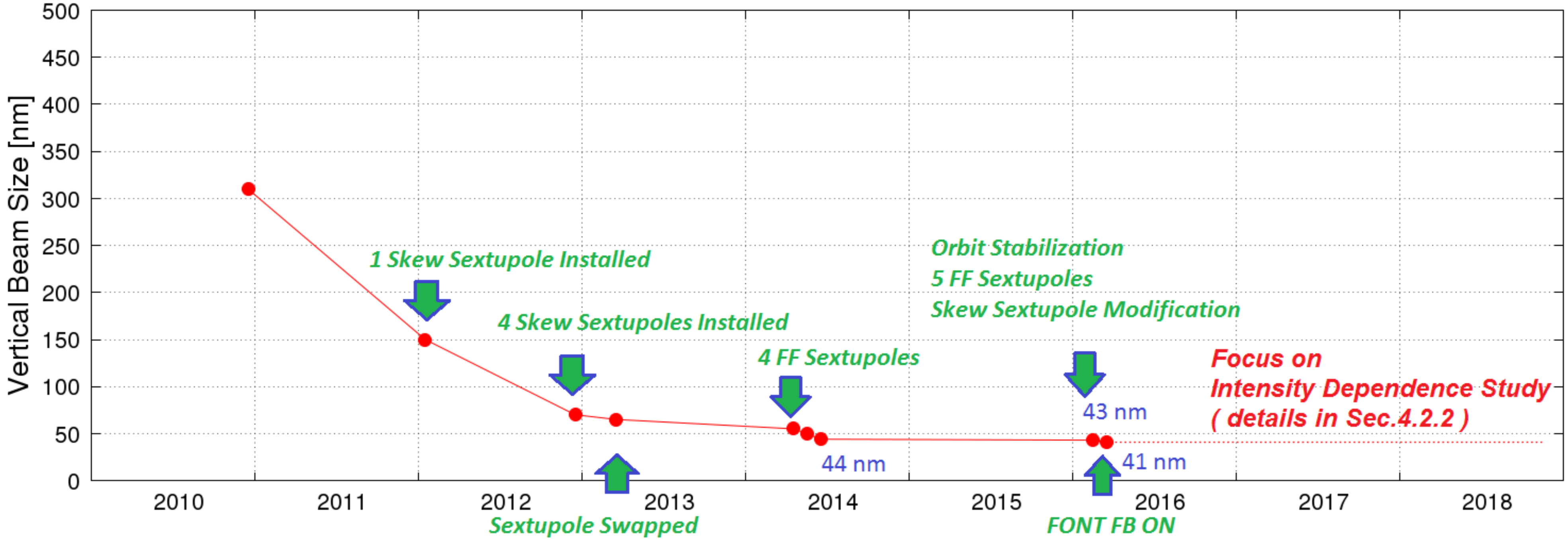



Figure 13

# History of measured smallest beam size

Figure 12



# Beam Size Intensity Dependence Wakefield Studies

**Small beam size can be observed only at low bunch intensity.**

Example of Measured IPBSM Modulation vs. bunch population

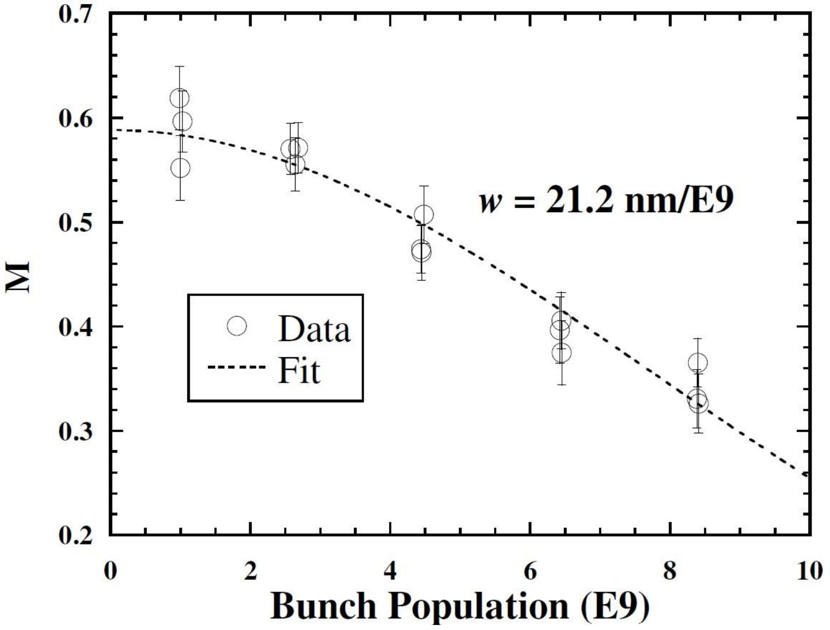



Figure 18

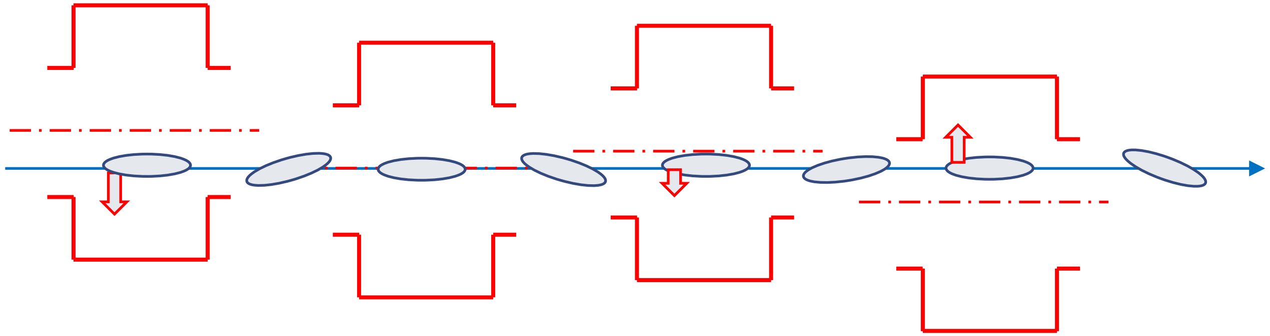
Fitting:
$\sigma^2 = \sigma_0^2 + w^2 N^2$

Beam size growth ~21nm/ $1 \times 10^{10}$e

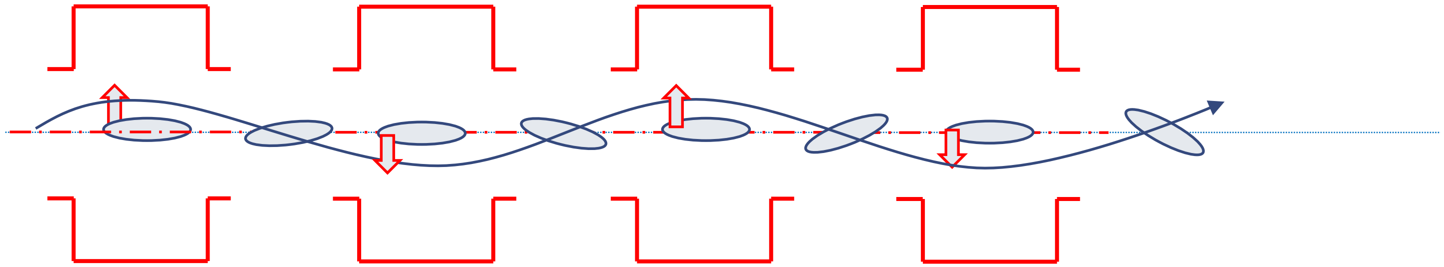
**Transverse wakefield is dominant cause of the dependence.**

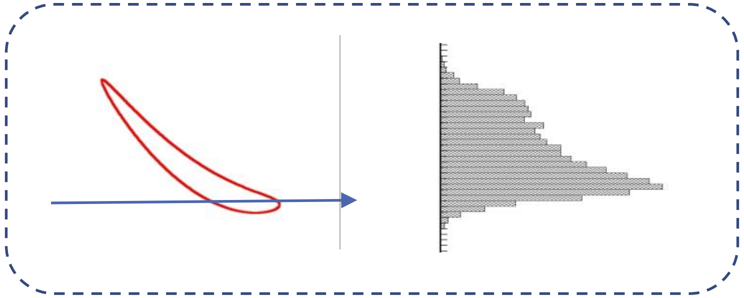
# Effects of transverse wakefield to beam size

Misalignment of beam line components



Beam orbit





**Effects can be divided into static and dynamic:**

**Static: misalignments and fixed beam orbit**

**Dynamic: orbit jitter**

# Special Characteristics of Final Focus Beam Line

Effectively,
all wakefield sources are
at phase $(n+1/2)\pi$
to Focal Point (IP)

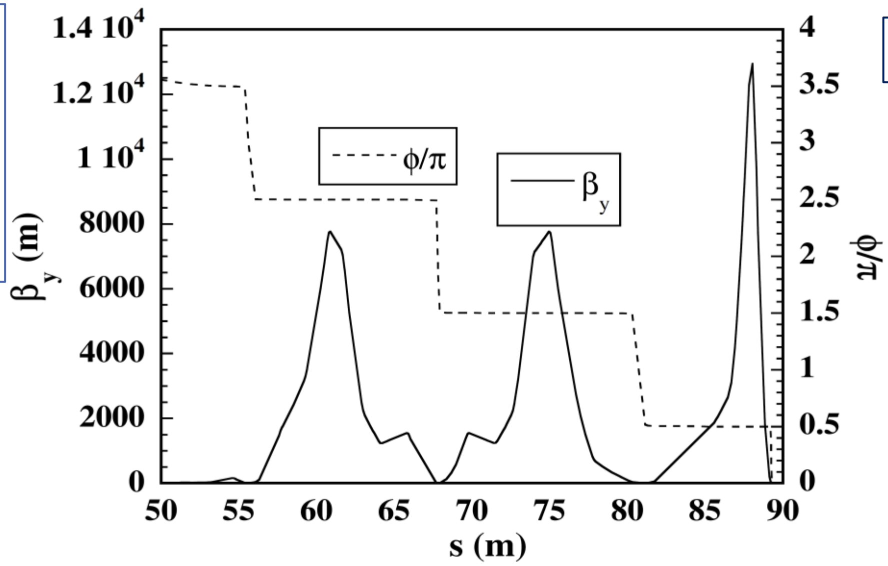



Figure 20

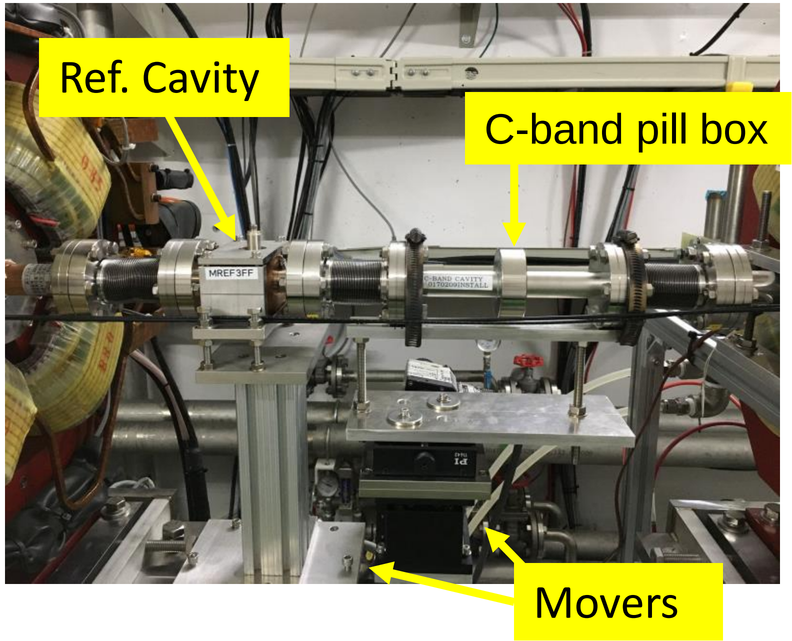
- **"Position at IP" phase orbit does not induce wakefield effects.**
- **"Angle at IP" phase orbit is important for wakefield effects.**

- **Wakefield changes only "position at IP" phase orbit.**
  - **Wakefield effect is simply linear sum of effects of all sources.**

# Wakefield source on mover

Wakefield sources (Cavities or Bellows) on movers are installed in beam line.

Present setup



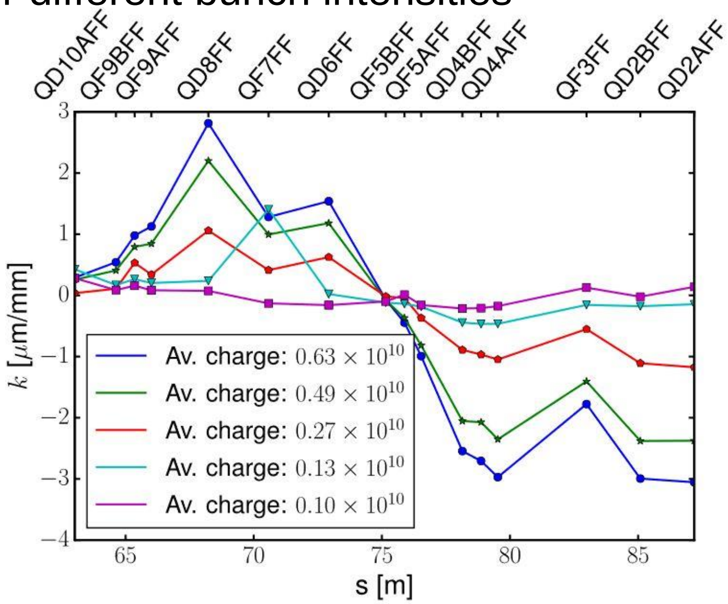

Experiments

- Downstream orbit change as function of mover position.
  - Good agreement with calculations
- Beam size at IP
  - Cancellation of wakefield in beam line
  - Estimation of wakefield strength in beam line

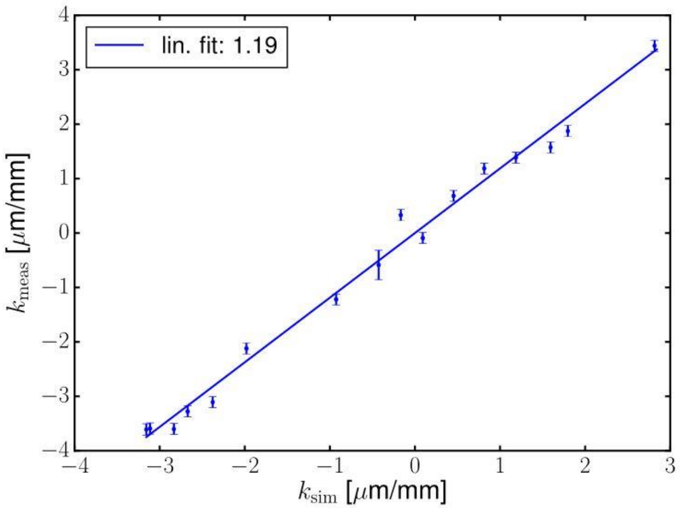
# Orbit change by wake source on mover
# Consistent with simulations

Bunch center orbit is changed by wakefield.
Orbit change dependence on mover position was measured.

(orbit change at BPM)/(mover position change)
for different bunch intensities




Measurement vs. calculation




Phys. Rev. Accel. Beams 19, 091002 (2016)

**Wakefield calculation of moving part agreed with measurement. (Difference is about 20%)**

# Wakefield cancellation by wake source on mover

**"Static" wakefield is cancelled by adjusting the mover position, for wakefield sources with similar shape of wake-potential.**

**"Wakefield effect is simply linear sum of effects of all sources."**

Wake-potential of major components

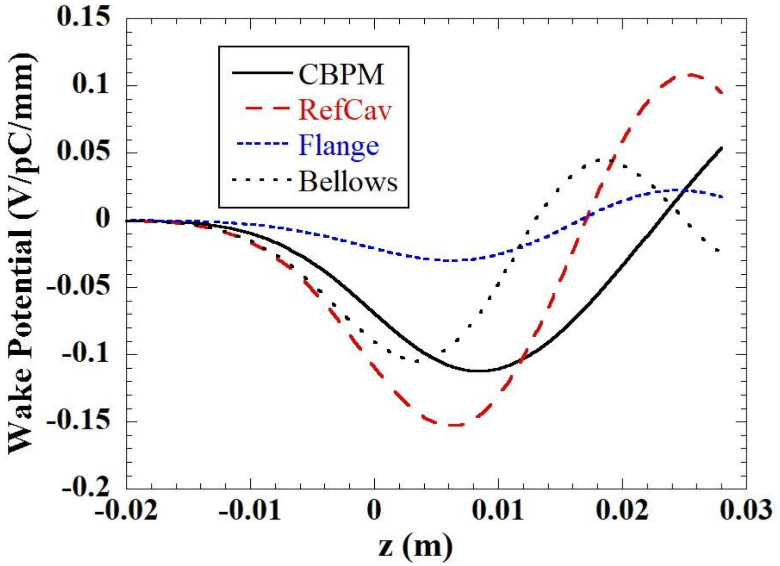
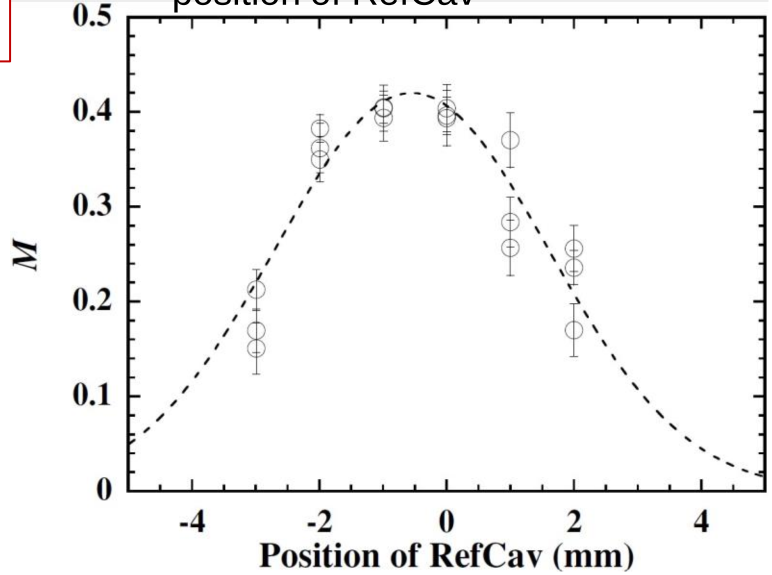



Figure 19

Example of cancellation

IPBSM modulation vs. mover position of RefCav

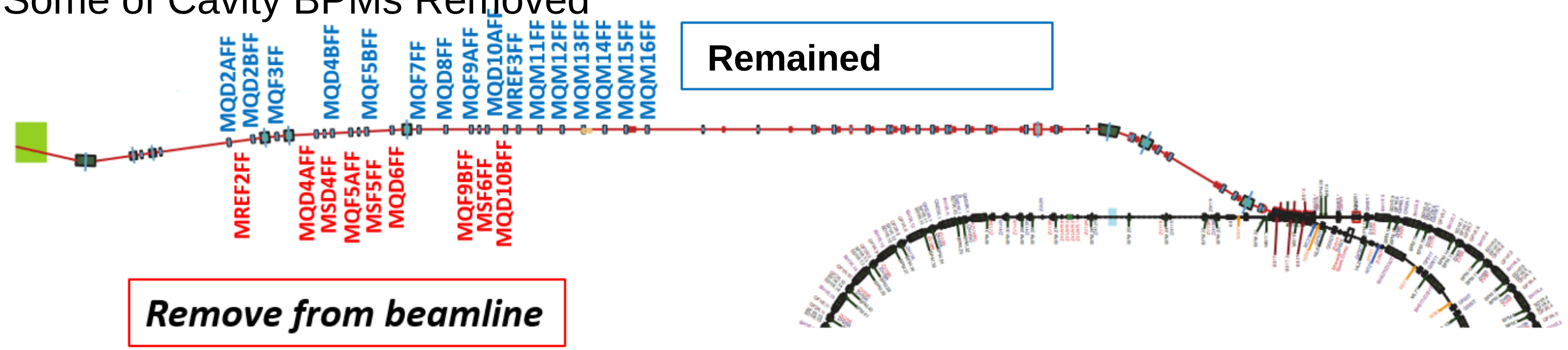
Figure 24




Optimizing position of "structure on mover", intensity dependence reduced, but larger than expected (factor ~2).
Possibility: Unknown wakefield sources with different wakefield shape, which cannot be canceled by the structures installed on mover.

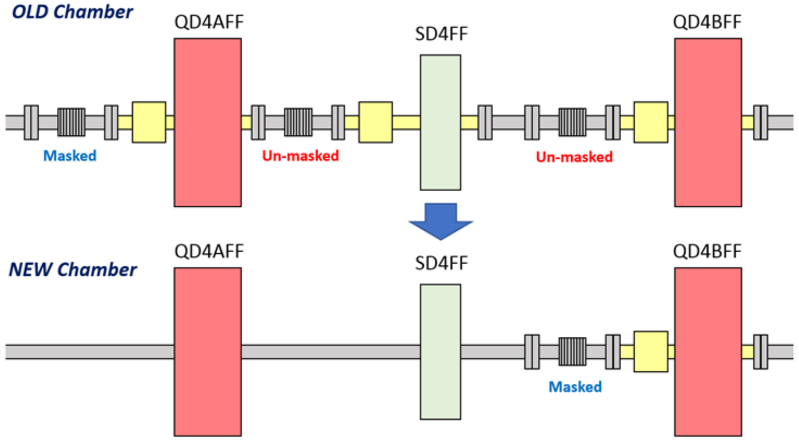
# Reduction of wakefield in November 2016

Some of Cavity BPMs Removed




Example: Around SD4FF

Bellows and Flanges Reduced




- Remove some BPMs, bellows, flanges.
- Shield bellows
- Shield flange gaps, etc.
- Etc.

# Confirmation of wake reduction

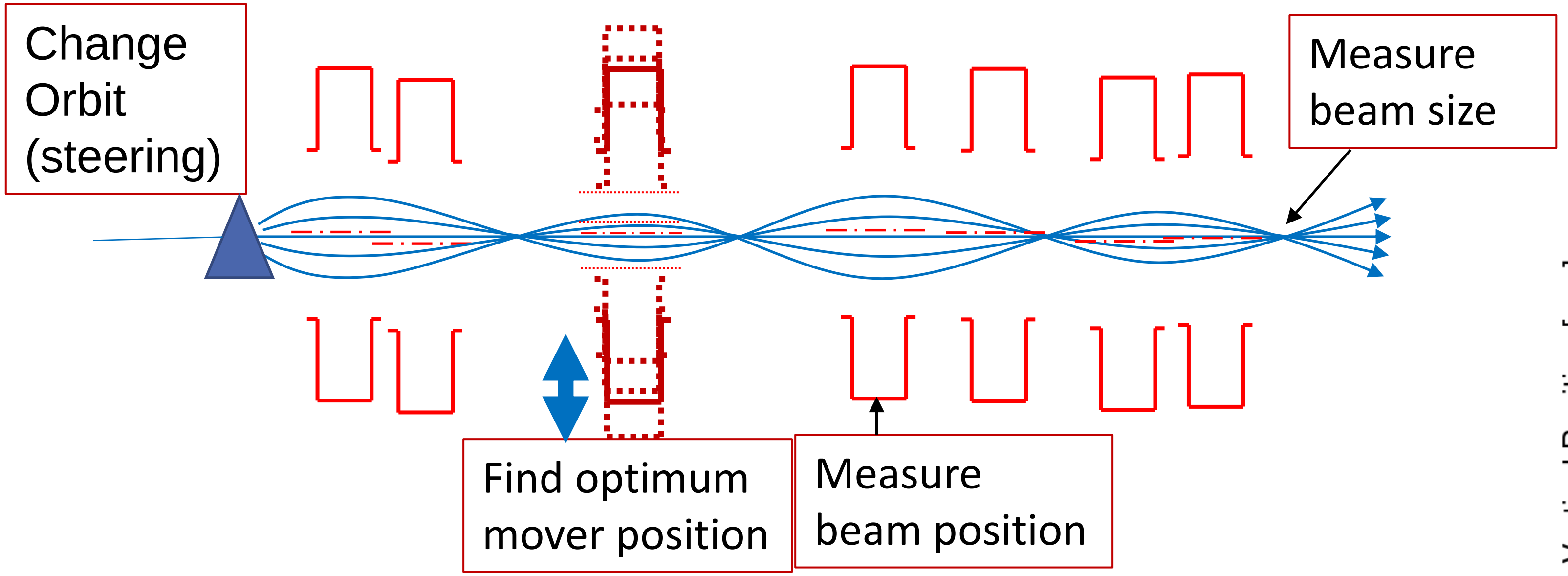
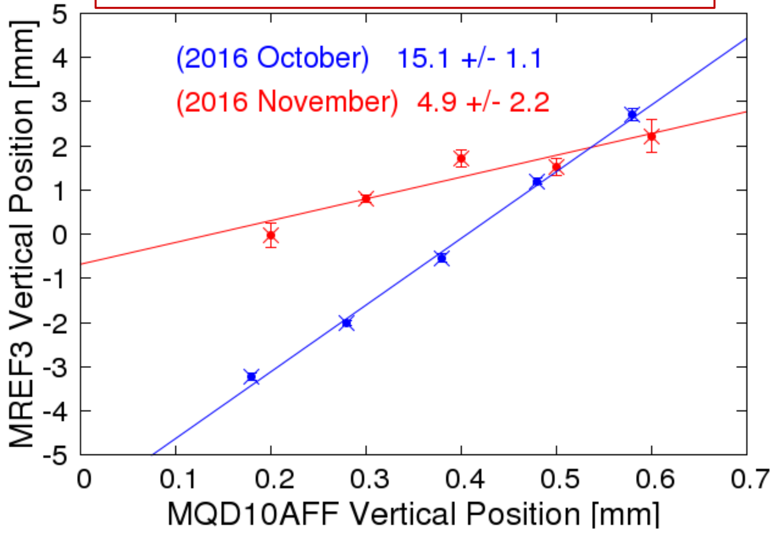



Figure 25

optimum mover position vs. orbit change

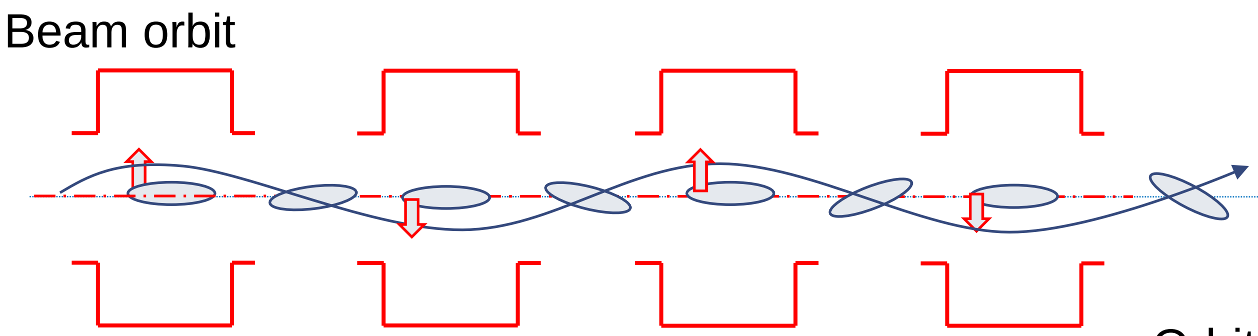


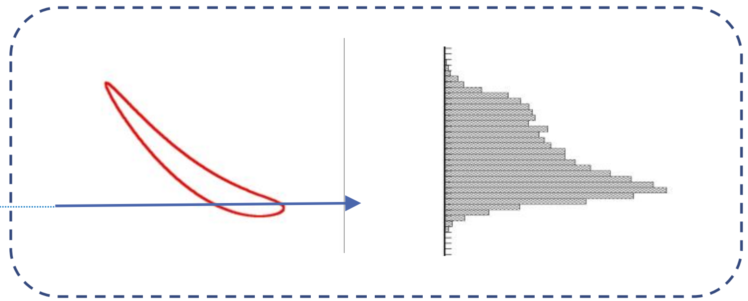

$$\frac{\text{(optimum mover position change)}}{\text{(orbit change)}} \approx \frac{\text{(wakefield strength in the beam line)}}{\text{(wakefield strength of moved structure)}}$$

**→ Total wakefield strength can be estimated**

**Change of slope:**
**15.1+-1.1 -> 4.9+-2.2**
**Showed wakefield reduction.**
**Consistent with calculated reduction factor about 2.0.**

# Dynamic wakefield effect



Orbit jitter → Beam shape changing pulse by pulse

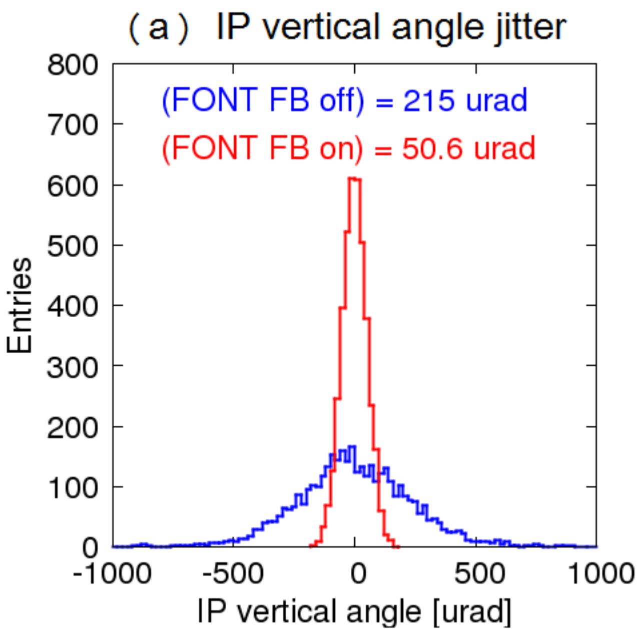
**Our monitor measures beam size of sum of many pulses.**

Observed orbit jitter is about 0.1-0.3$\sigma$.
"angle at IP" phase jitter causes significant beam size growth due to wakefield.
Direct effect of "position at IP" phase orbit jitter is very small.
(0.3$\sigma$ orbit jitter induces beam size growth of only 0.044$\sigma$, $\sigma \rightarrow \sqrt{1+0.3^2}\sigma$ )

# Mitigation of “Dynamic” wakefield effect to beam size by orbit jitter reduction

Beam size measured with and without orbit feedback (FONT: later presentation).
2-bunch operation. Beam size of $2^{nd}$ bunch.

Reduction of angle jitter




Reduction of beam size intensity dependence

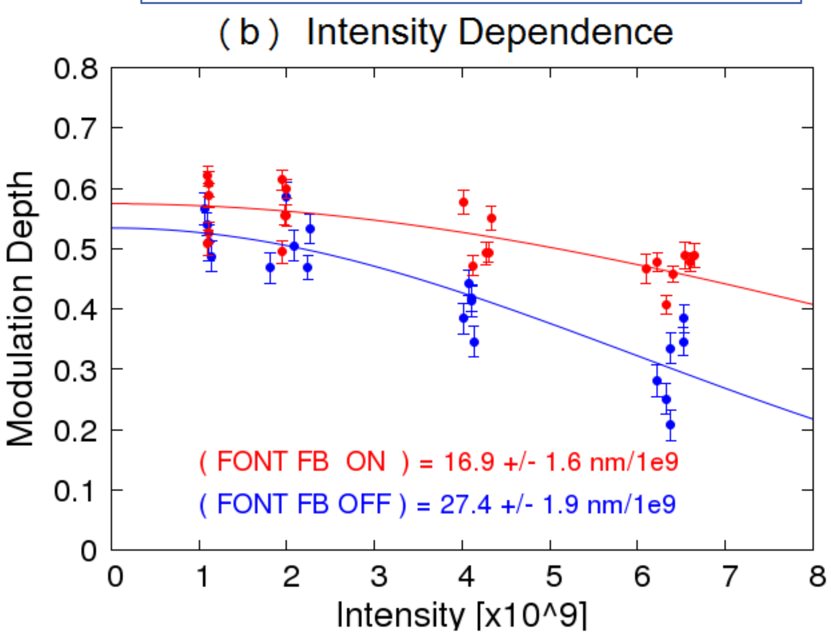



Figure 27

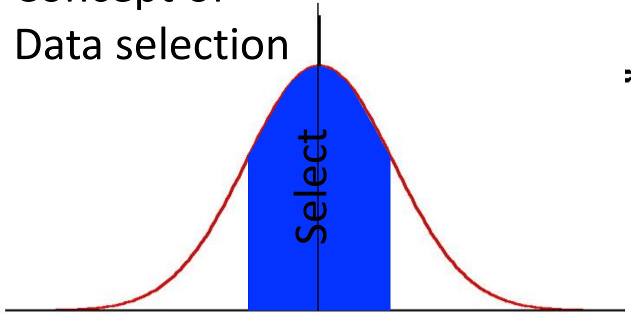
# Confirmation of “Dynamic” wakefield effect to beam size by data selection

Data selections by orbit angle at IP for beam size data.
Bam size intensity dependence evaluated for each of different angle limits.

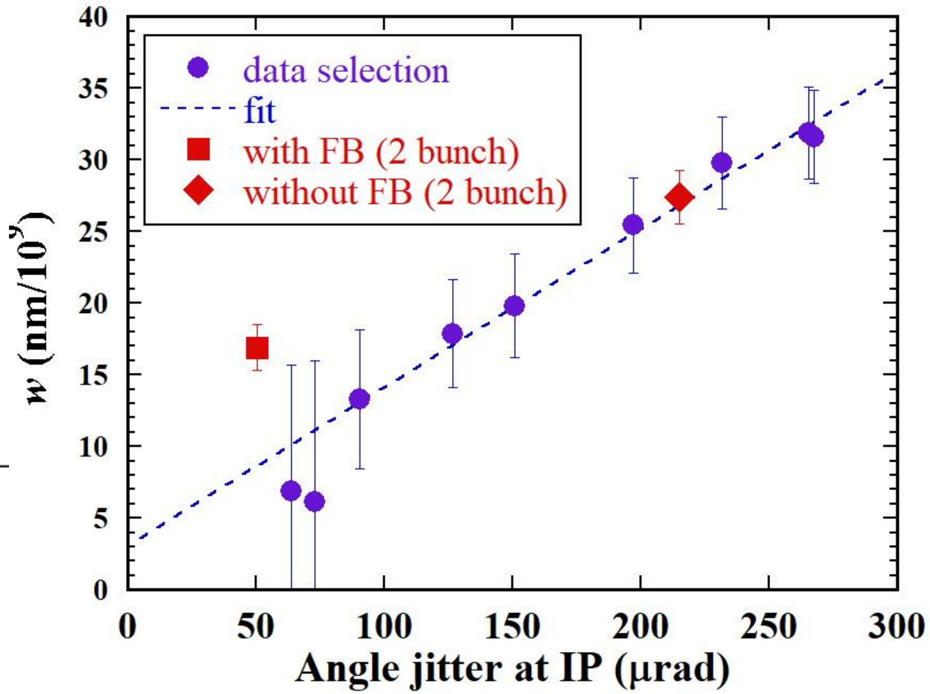
Intensity dependence parameter vs. (resulted) RMS angle jitter

Figure 29

Concept of
Data selection




Angle at IP evaluated
from BPMs data




**Slope of he fitted line is steeper than simulations by a factor about 1.5~2**

**Small jitter data does not on the fitted line.**
**Significant “static” effect?**

# Another set of data with angle orbit selection

Similar analysis of data (Oct. 2016, before wakefield reduction).
Intensity dependence parameter vs. (resulted) RMS angle jitter, for 3 different optics.

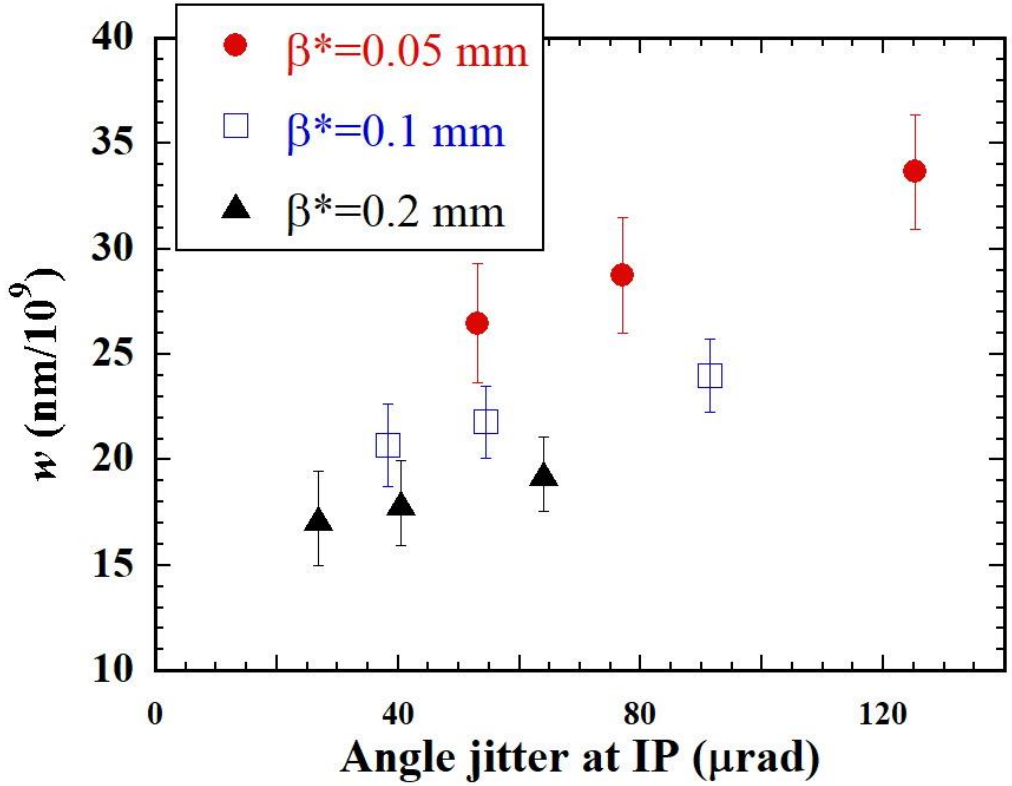



Figure 30

Not on a single line.
No simple explanation found.

**Only a part of intensity dependence can be explained as "dynamic" effect.**

# Wakefield at ILC Final Focus will not be significant

Comparison of wakefield effect to IP beam size at ILC and ATF from simple scaling (Table 4)

| | ILC | ATF | Ratio of effect (ILC/ATF) | |
|---|---|---|---|---|
| | | | misalignment | orbit jitter |
| Beam Energy | 125 GeV | 1.3 GeV | 0.01 | 0.01 |
| Bunch Length | 0.3 mm | 7.0 mm | 0.5 | 0.5 |
| Emittance | 0.16 pm | 12 pm | 8.7 | 1 |
| Sum of $\beta_y$ | 390 km | 61 km | 2.5 | 6.7 |
| Total | | | 0.11 | 0.032 |

**Wakefield effect at ILC design bunch population ($2\text{x}10^{10}$e) corresponds to bunch population at ATF**

**$0.2\text{x}10^{10}$e for misalignment**

**$0.06\text{x}10^{10}$e for orbit jitter**

**More detailed simulation showed wakefield effect at ILC Final Focus very small.**

Reported in LCWS2019

https://agenda.linearcollider.org/event/8217/contributions/44505/attachments/34913/53944/LCWS_intensity_dependence_oct2019.pdf

**However, further experimental studies at ATF will**

- **Improve the reliability of our calculations of wakefields and their effects**
- **Give important information for the design of the ILC beamline**

# Summary - Achieved

Final Focus

- ILC Final Focus Scheme (local chromaticity correction) demonstrated
- Linear optics tuning procedure established
- Tuning including $2^{nd}$ order knobs performed

Intensity Dependence (Wakefield)

- Dependence was reduced by removing structures in the beam line.
- “Static” wakefield cancellation by “structure on mover” was confirmed.
- Significant “Dynamic” wakefield effect was confirmed and partly reduced by orbit feedback.

# Summary - Issues to be studied

**Final Focus**

- Systematic study/correction of 2nd order aberrations needed
  - Effectiveness of 2nd order knobs has not been fully confirmed.
- Accurate measurement of energy band width still needed

**Intensity Dependence (Wakefield)**

- Even after optimizing position of “structure on mover”, intensity dependence is larger than expected from “dynamic” wakefield effects.
- There is some “static” effect remained?
  - Unknown wakefield sources, which cannot be canceled by the structures installed on mover.
- Unknown strong non-linear aberrations?

**For further studies, stable beam and stable IPBSM are essential.**

- Accurate beam size measurement with various conditions (parameters) changes