Achievement of small beam size at ATF2 beamline

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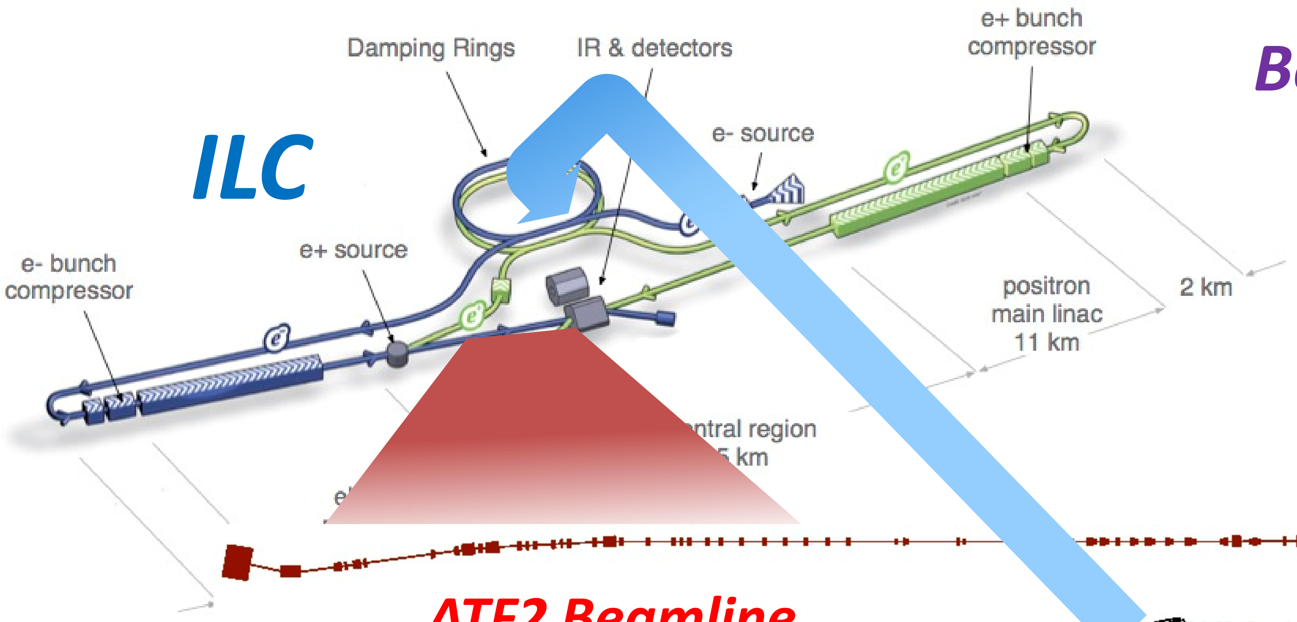
ATF International Collaboration

2016/09/26
LINAC2016
East Lansing, USA

KEK-ATF for ILC beam focusing

ILC



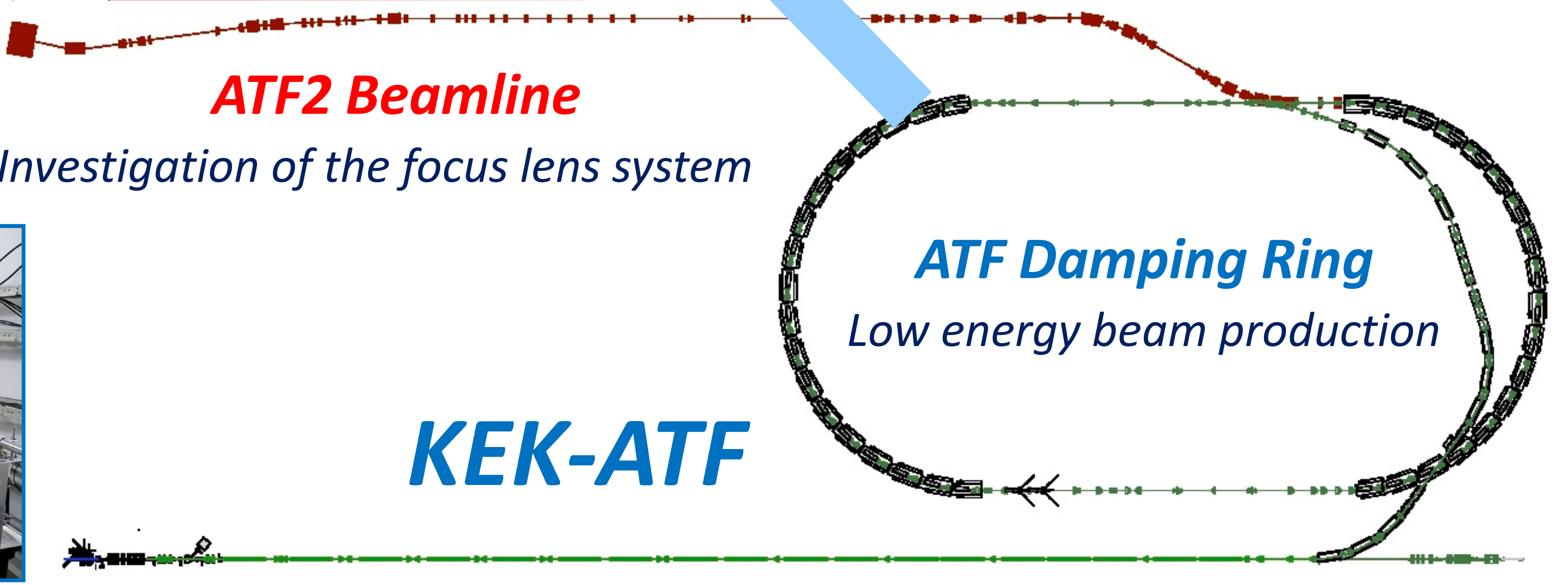
Beam focusing of ILC

Low emittance beam
⇒ *Damping Ring*

Beam Focusing
⇒ *Final Focus System*

ATF2 Beamline

Investigation of the focus lens system



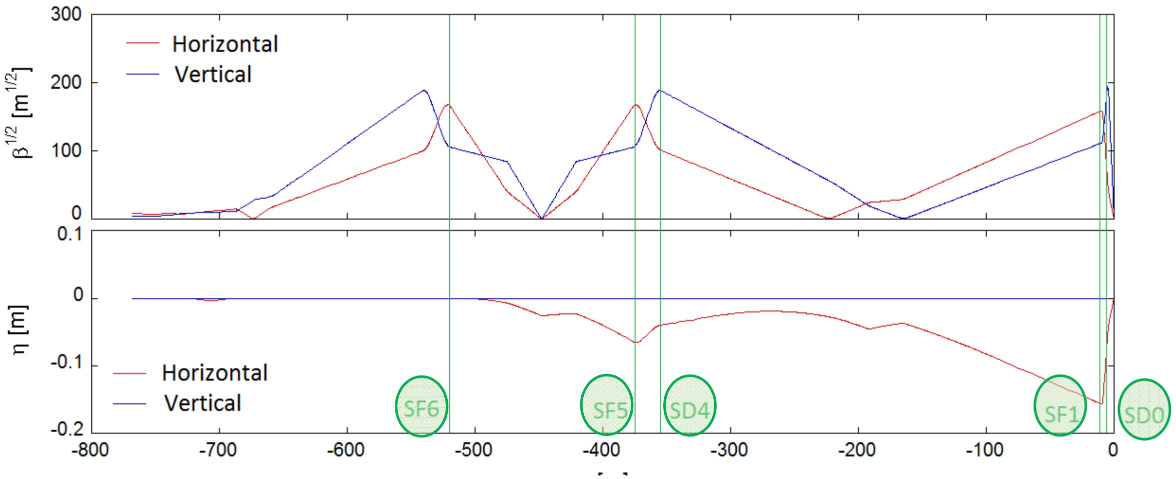
ATF Damping Ring

Low energy beam production

KEK-ATF

Beam Optics of ILC Final Focus System

ILC final Focus System



Local Chromaticity Correction

Sextupole magnets are put beside the quadrupoles, which have large chromaticities.

Benefits

- *Compact*
- *Large L**
- *Small detector background*

Demerits

- *Complex tuning system*

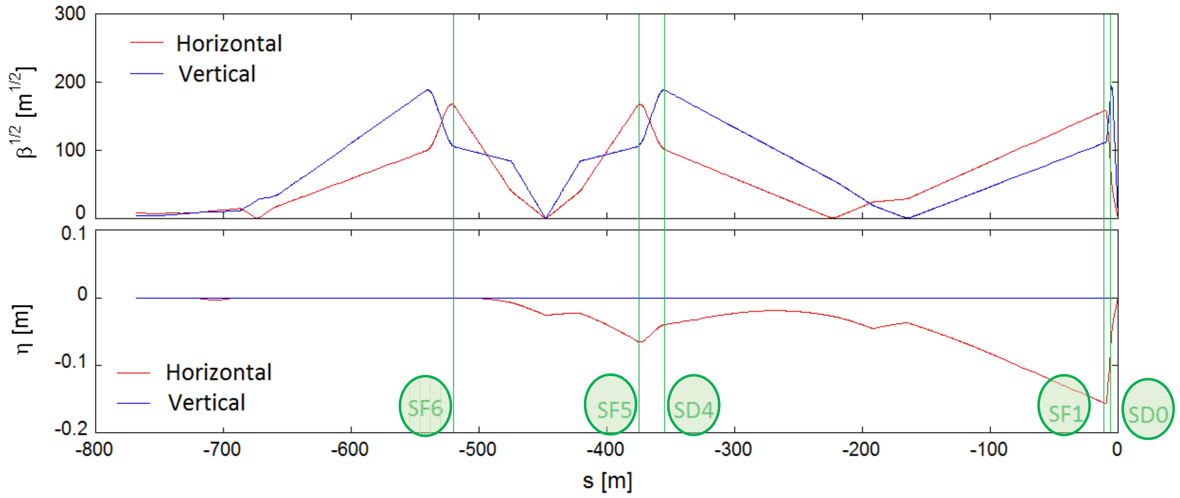
Chromaticities are corrected within the FF lens system

Chromaticity List of ILC FF beamline

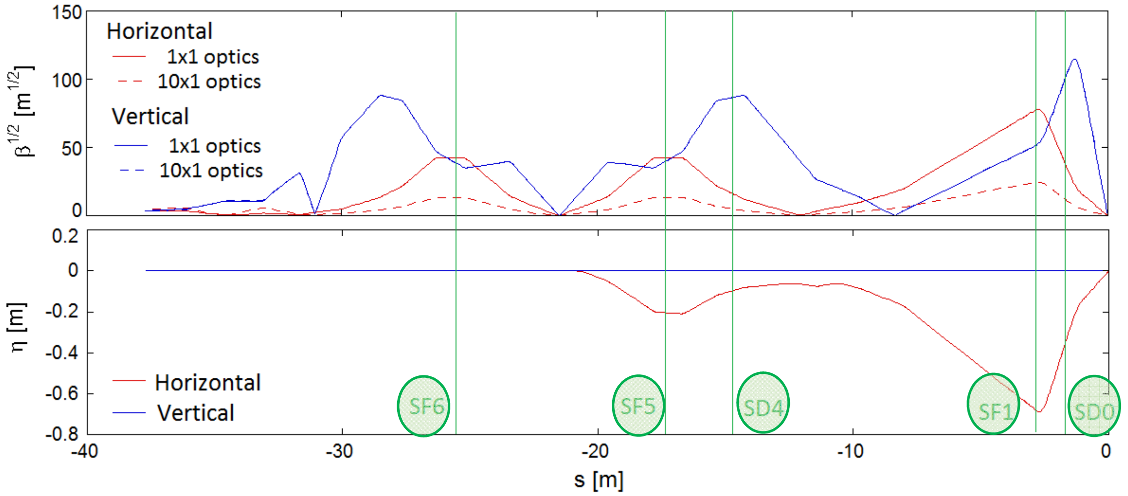
Name	X	Y
QD10B	131.9	-757.6
QD10A	168.7	-673.4
QF9B	-437.4	377.5
SF6	0.0	0.0
QF9A	-460.6	295.4
QD8	45.0	-379.0
QF7B	-0.2	1.2
QF7A	-0.2	1.2
QD6	45.0	-379.0
QF5B	-460.9	295.6
SF5	-155.6	112.9
QF5A	-437.6	377.8
QD4B	162.6	-650.6
SD4	-1238.1	6089.7
QD4A	126.0	-736.6
QD2B	0.0	3.9
QF3	-5.8	7.5
QD2A	13.7	-0.1
SF1	9095.3	-4954.9
QF1	-4830.8	2934.4
SD0	-2497.5	12835.6
QD0	1002.9	-14564.7
Total	266.5	236.9

Beam Optics of ATF2 Beamline

ILC final Focus System



ATF2 Beam Optics



ATF2 is a prototype of the ILC final focus system

- *Same magnet arrangement*
- *Same tuning procedure*

1 x 1 Optics (original design)

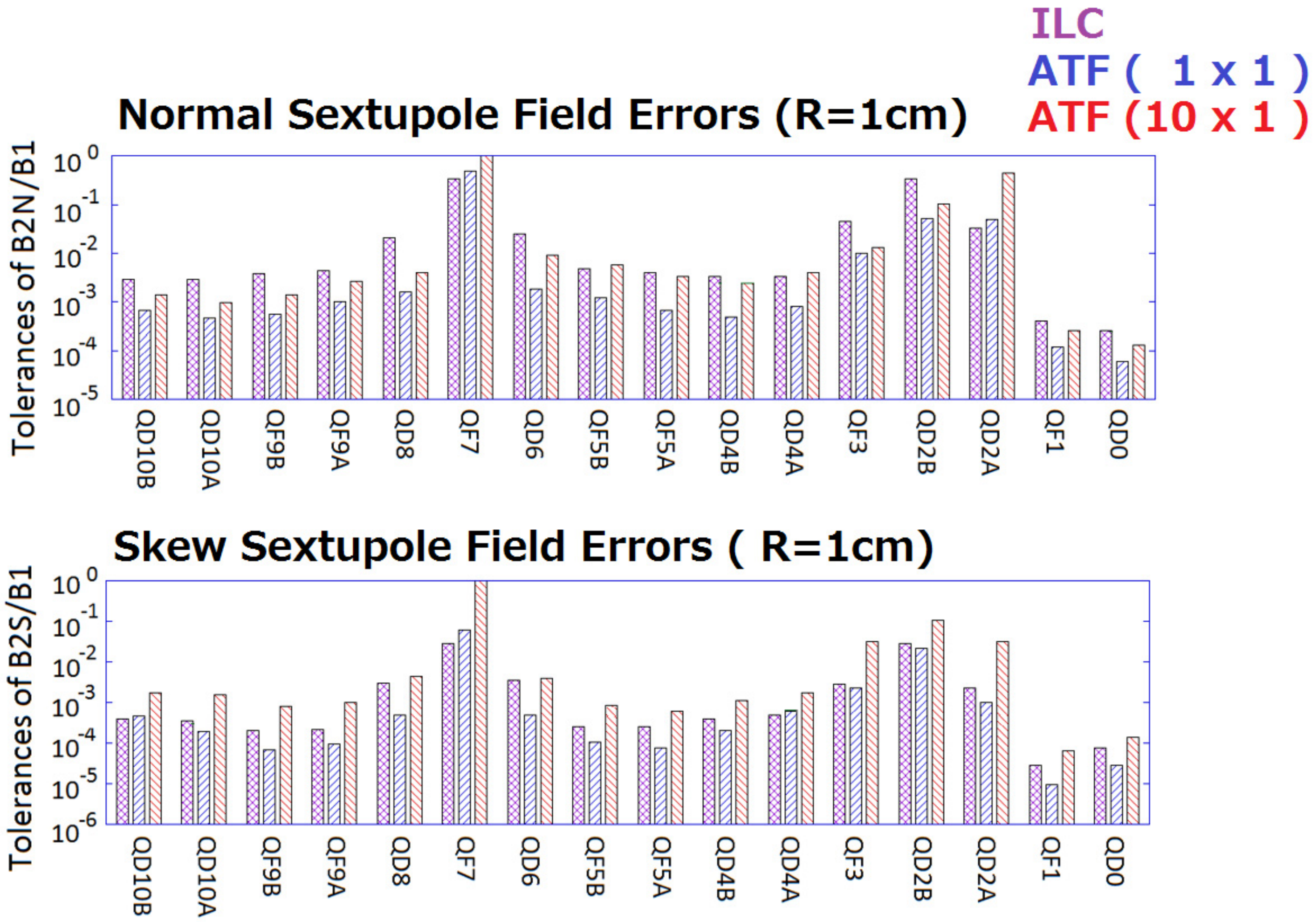
- Same X and Y chromaticities of ILC

10 x 1 Optics (used in recent operation)

- 10 times larger β_x^* than original.
- Same β_y^* to original.

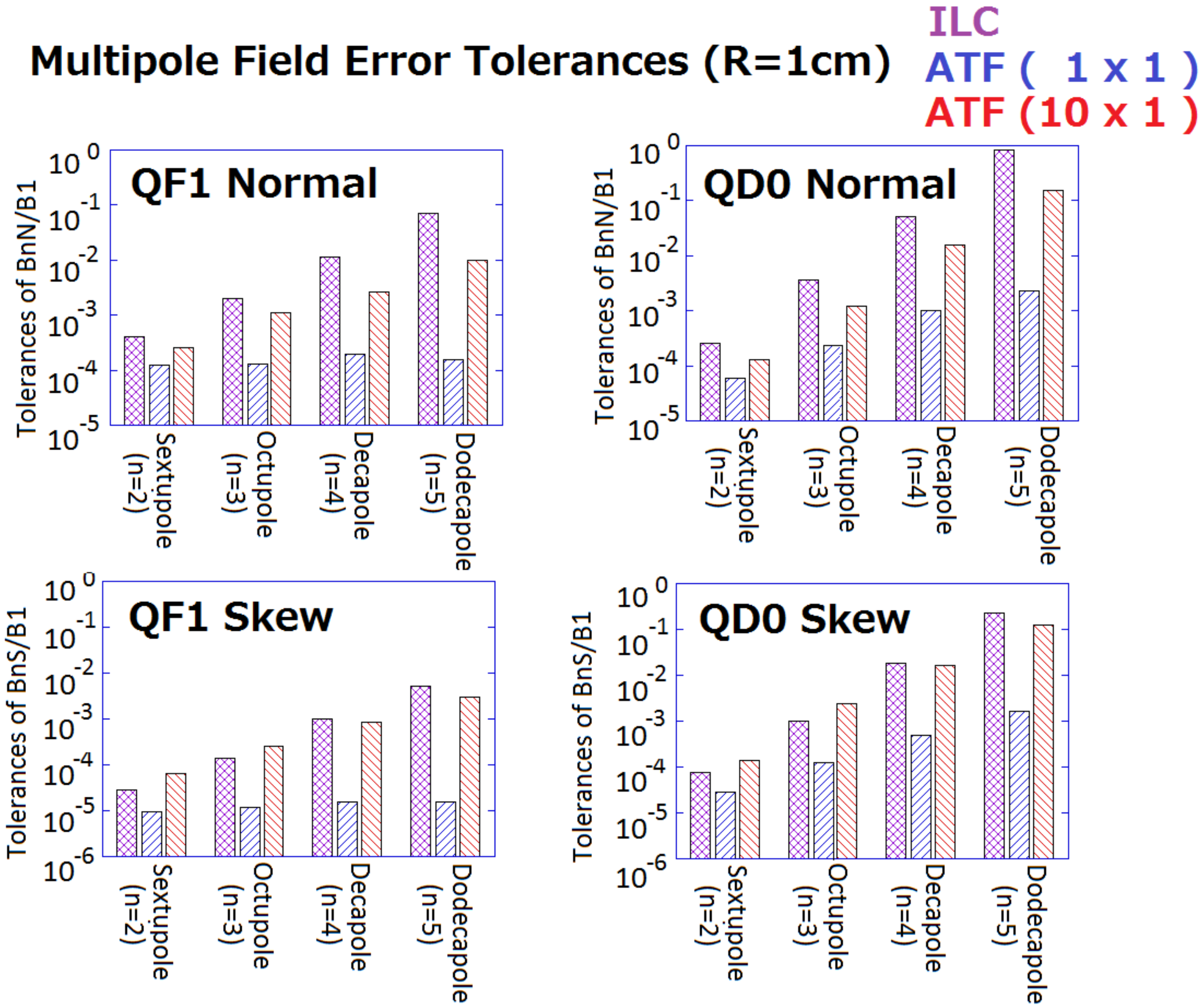
⇒ Same difficulty of IP vertical beam size tuning

Tolerances of sextupole field error to IP vertical beam size



The tolerances of sextupole errors for ATF2 10x1 optics is comparable to ILC.

Tolerances of FD multipole field error to IP vertical beam size



The tolerances of FD multipole errors for ATF2 10x1 optics is comparable to ILC.

2^{nd} order optics correction at ILC & ATF2

	Horizontal beam size		Vertical beam size	
	Geometrical Aberration	Chromaticity	Geometrical Aberration	Chromaticity
Normal Sextupole	T122	T126	T324	T346
	T144	T166 (2^{nd} order Dispersion)		
Skew Sextupole	T124	T146	T322	T326
			T366	T344

Ignored

Sextupole magnets are used for chromaticity correction.
But, the sextupoles generate other 2^{nd} order aberrations.

We use 5 sextupoles to correct 5 aberrations.

The aberrations are generated by the multipole errors of quad.

We use 4 skew sextupoles to correct 4 vertical aberrations.

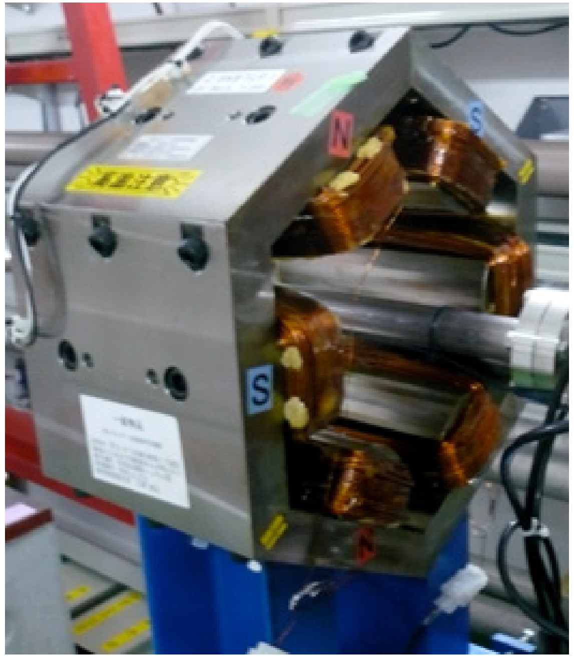
*T. Okugi et al., Physical Review Special Topics - Accelerators and Beams **17**(2014) 023501.*

Skew sextupole magnets for 2nd order correction

Install at 2011 Autumn

Install at 2012 Summer

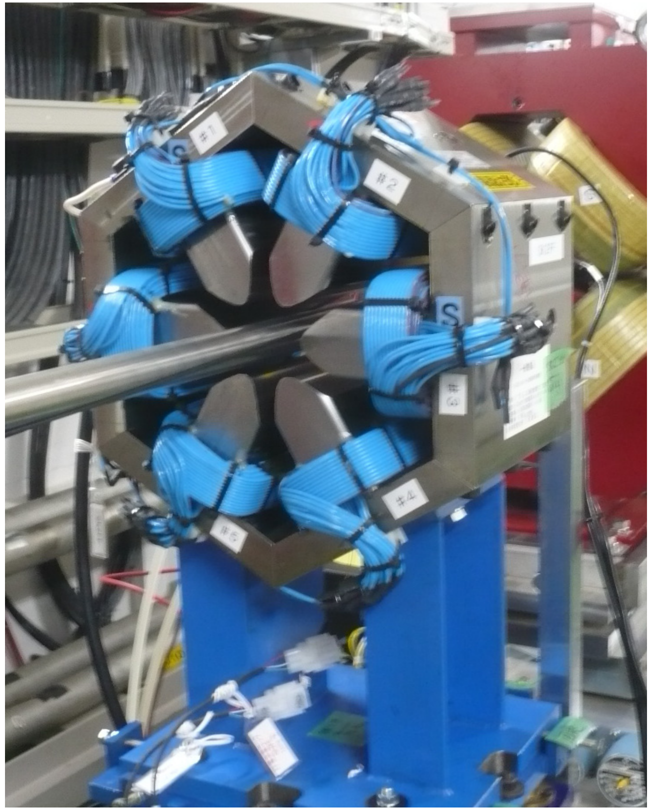
Borrowed from KEKB



Too weak for knob optimization

Modified in 2016 January

160mmϕ ⇒ 60mmϕ



ATF2 beam tuning procedures of IP beam size

FF sextupoles turned OFF

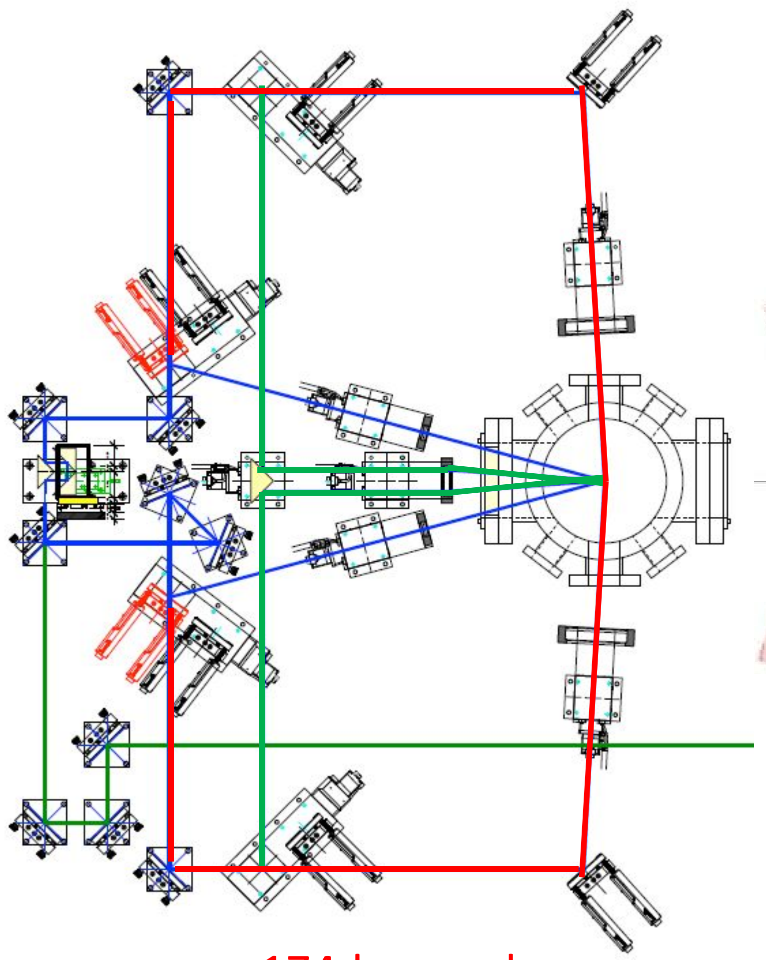
- Orbit tuning
- QF1FF strength optimization (Carbon wire; Horizontal beam size)
- QD0FF strength optimization (Carbon wire; Vertical beam size)
- QD0FF rotation optimization (Carbon wire; Coupling)
- FF normal and sextupole BBA (Magnetic center)

FF sextupoles turned ON

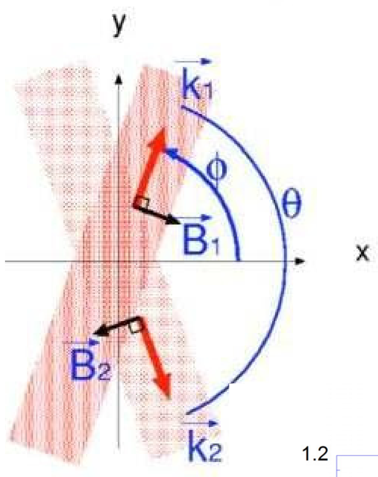
Carbon Wire	→	IP-BSM 8degree	→	IP-BSM 30degree	→	IP-BSM 174 degree
AY knob		AY knob		AY knob		AY knob
EY knob		EY knob		EY knob		EY knob
Coup2 knob		Coup2 knob		Coup2 knob		Coup2 knob
				Y24 knob		Y24 knob
				Y46 knob		Y46 knob
						Y22 knob
						Y26 knob
						Y66 knob
						Y44 knob

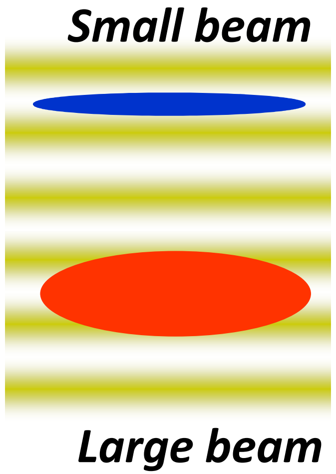
The ATF2 tuning procedure
is same to ILC final focus beam line.

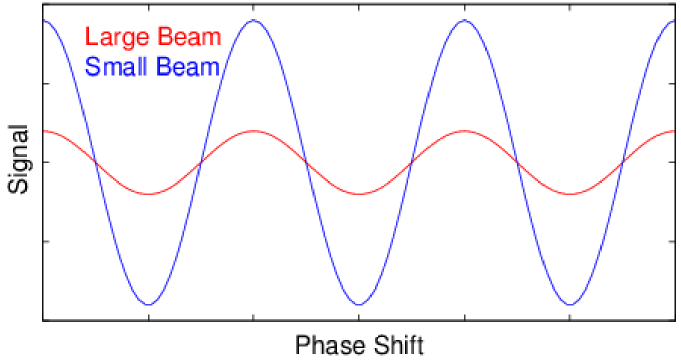
IP-BSM (IP Beam Size Monitor; Shintake Monitor) for ATF2

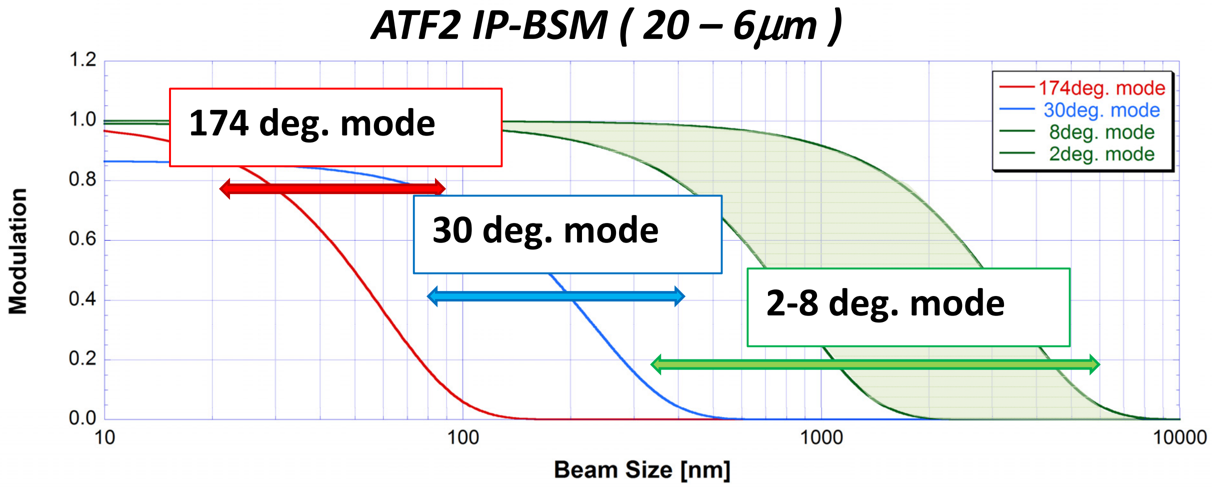


174deg mode
30 deg mode
2-8deg mode

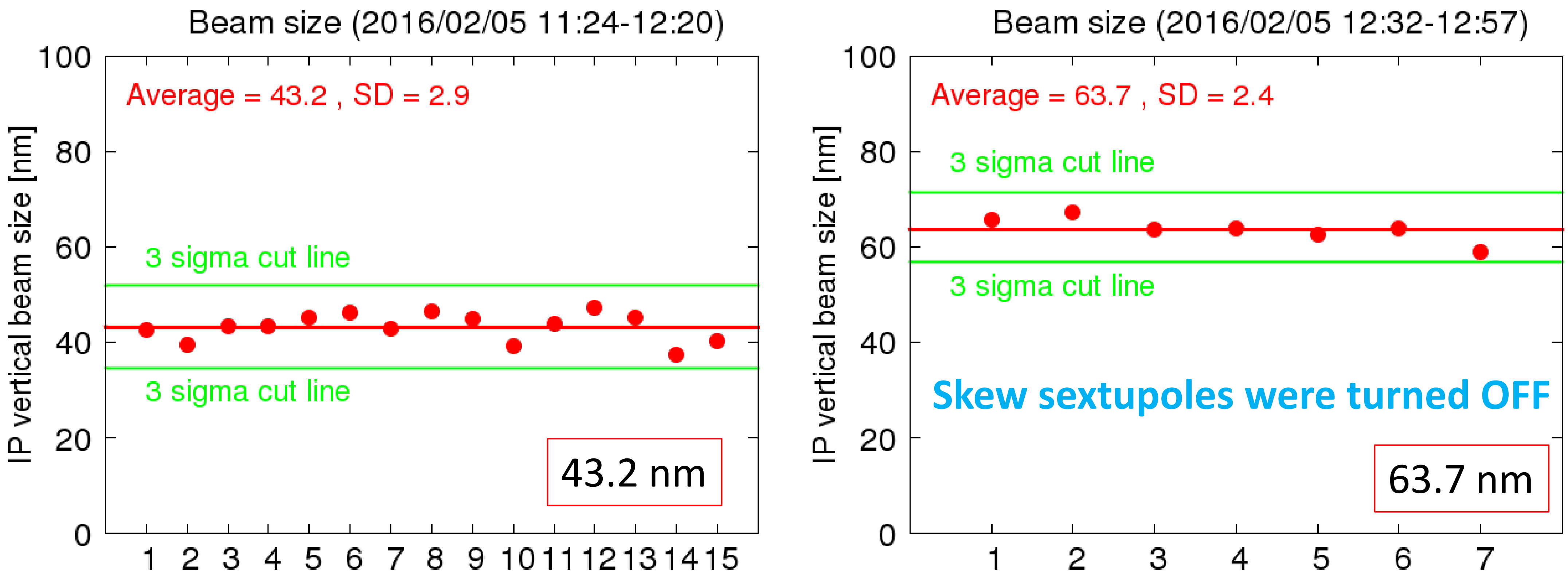








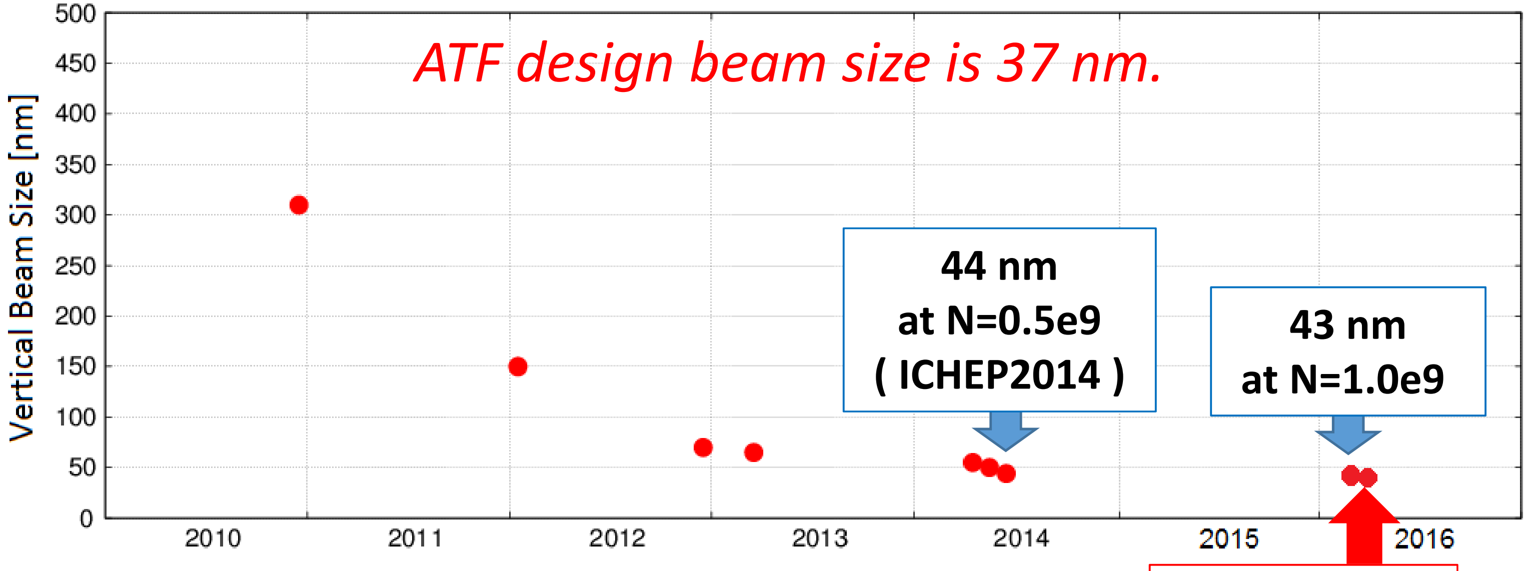
Beam size tuning results on 2016/02/05



- *The correction with skew sextupoles worked well (same scheme of ILC).*
- *IP beam sizes were evaluated by assuming the perfect laser fringe contrast.*
- *The bunch population at the measurement was* $\mathrm{N} = 1.0 \times 10^9$.

IP beam size trend of ATF2 beam size

Minimum beam size of ***41 nm*** *was measured on 2016/03/10 by using FONT orbit jitter correction at N=0.7e9.*

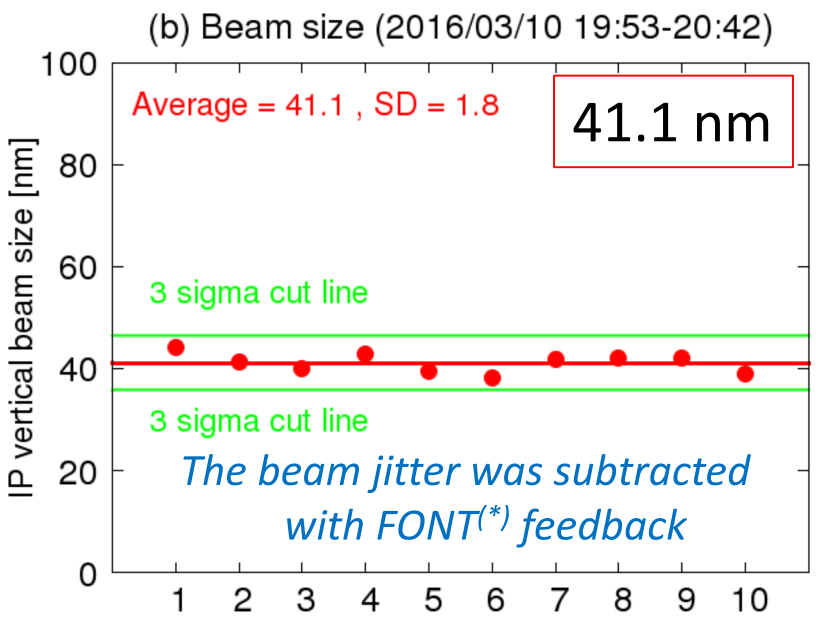


2014/06 ; 44 nm at N=0.5e9
2016/02; 43 nm at N=1.0e9
2016/03; 41 nm at N=0.7e9 with FONT

The reason why bunch population was smaller than ILC is its strong intensity dependence. (*ILC* ; $\mathrm{N} = 2 \times 10^{10}$)

Minimum beam size (2016/03/10)

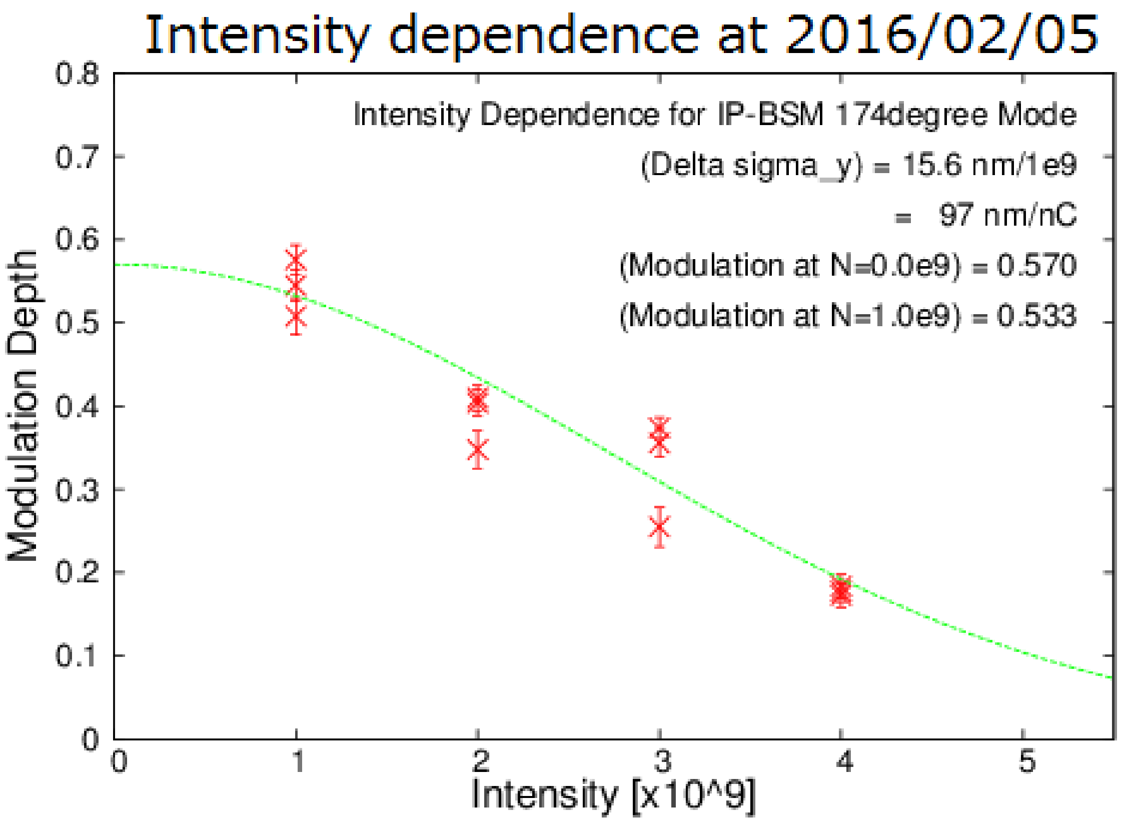
presented by Y. Kano and T. Okugi at ECFA LC workshop 2016.



(*) Feedback On a Nanosecond Time scale, developing by Oxford Univ.

The detail of FONT is in “ N. Kraljevic et al., Proc. of IPAC16, THPOR035”

Typical Intensity Dependence of ATF2 IP beam size



- The typical intensity dependence is $15\ \mathrm{nm}/10^9$ electrons.

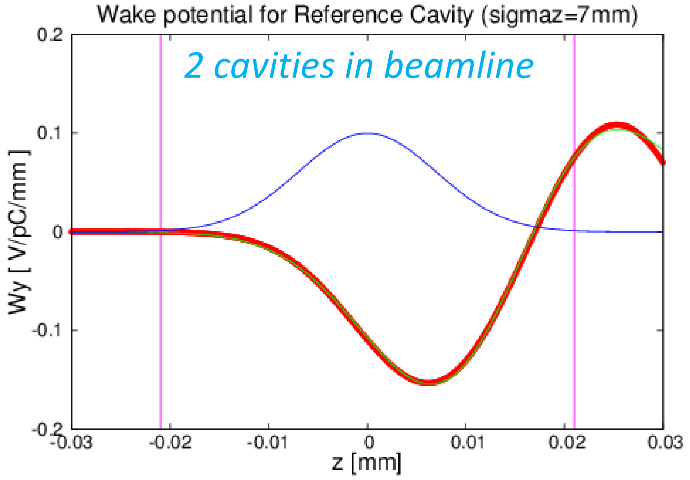
  $\Rightarrow$ 150 nm at $\mathrm{N} = 1 \times 10^{10}$.

- The candidate of the intensity dependence is ***IP angle jitter via wakefield.***

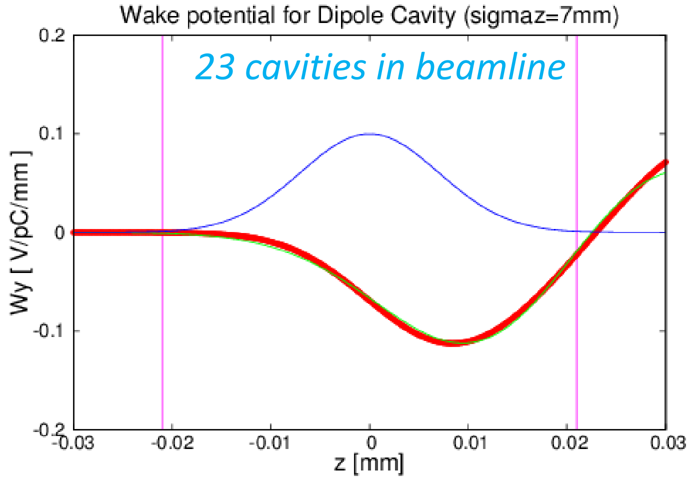
Wakefield sources in the ATF2 beamline

wakefield was calculated by Alexey Lyapin

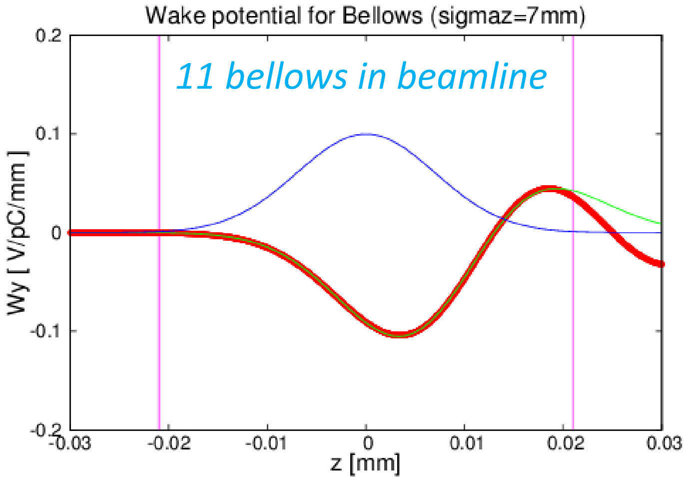
C-band reference cavity



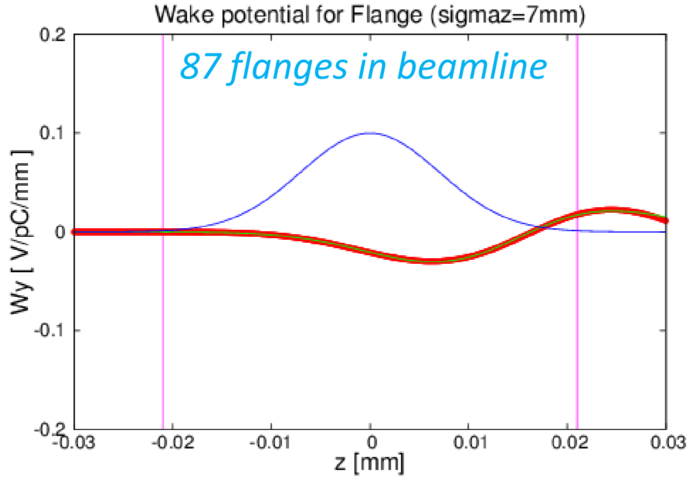
C-band sensor cavity



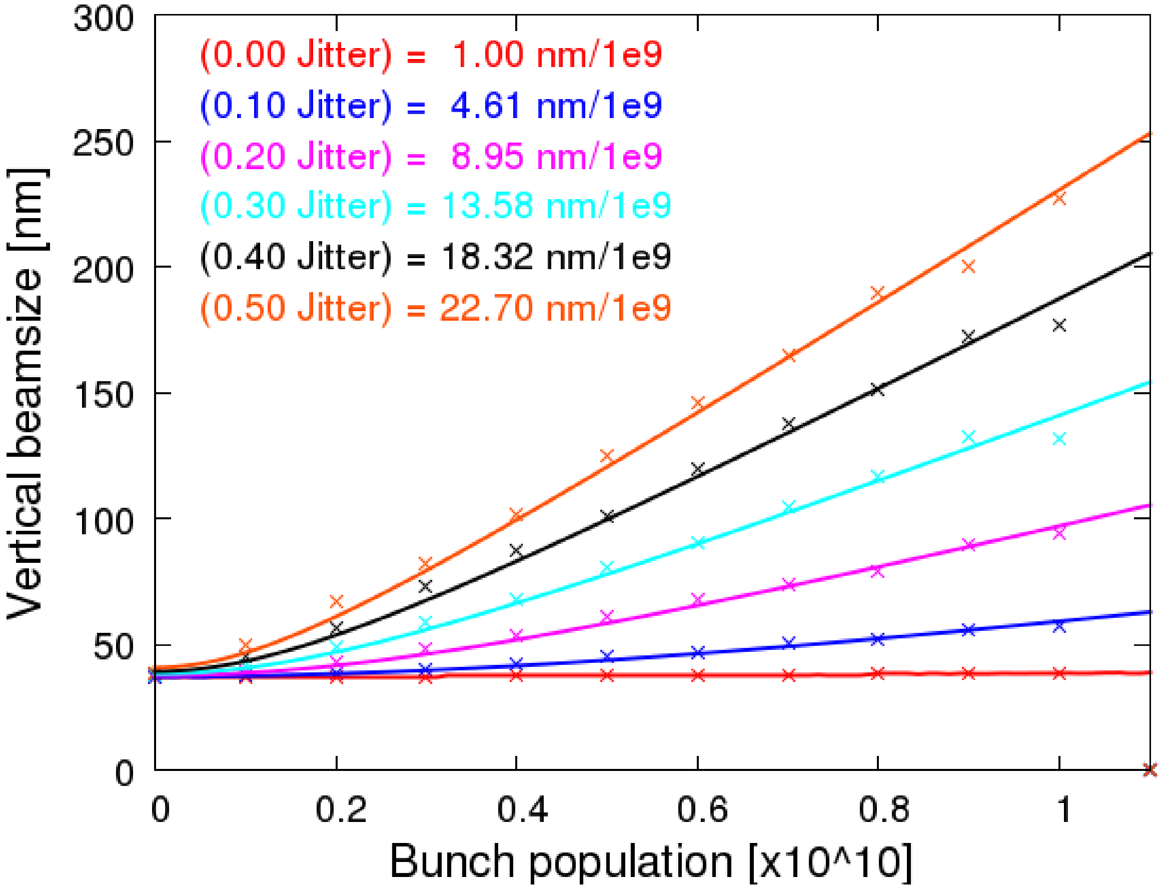
Un-masked bellows



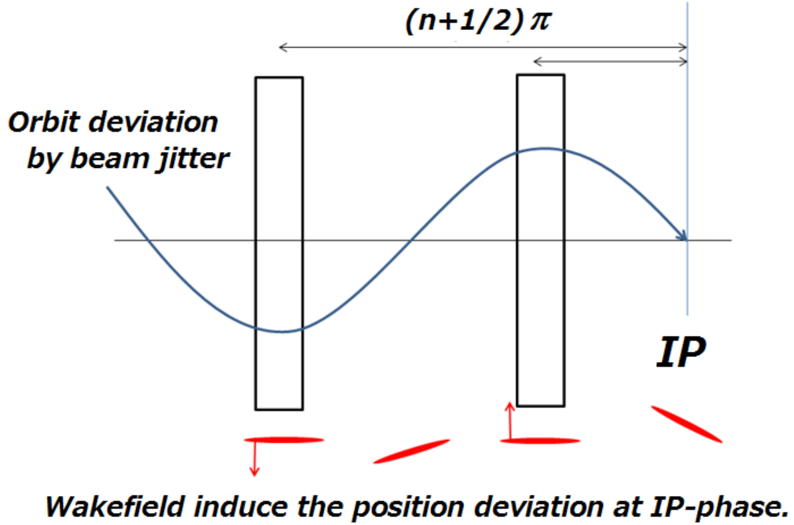
ICF70 Flange



Intensity dependence simulation for IP angle jitter via wakefield



by K. Kubo at ECFA LC workshop 2016.



Simulation conditions

- *Beam jitters were assumed only for FD phase.*
- *Wakes for cavities, flanges and bellows were assumed.*
- *The following IP beam parameters were assumed.*

$$\varepsilon_x = 2.0\ \mathrm{nm}\,,\quad \beta_x^* = 40\ \mathrm{mm}$$
$$\varepsilon_y = 12\ \mathrm{pm}\,,\quad \beta_y^* = 0.1\ \mathrm{mm}$$

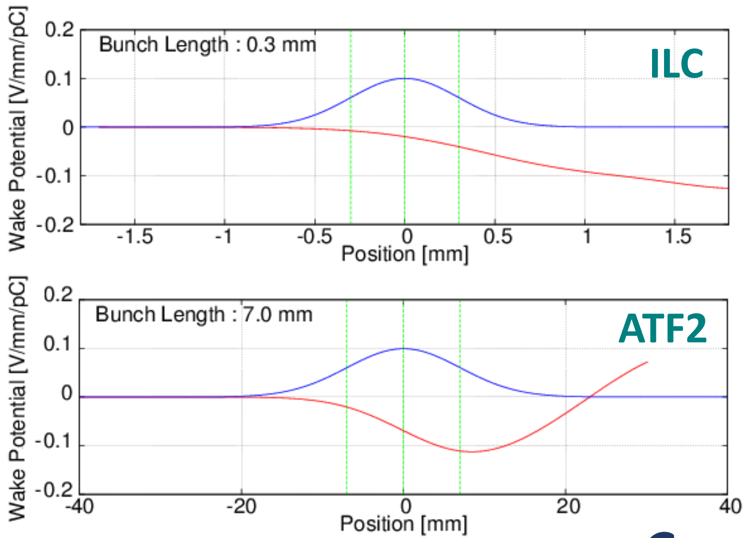
The consistent with the intensity dependence

for 30-40% of angle jitter (Typical value is 15 nm/1e9).

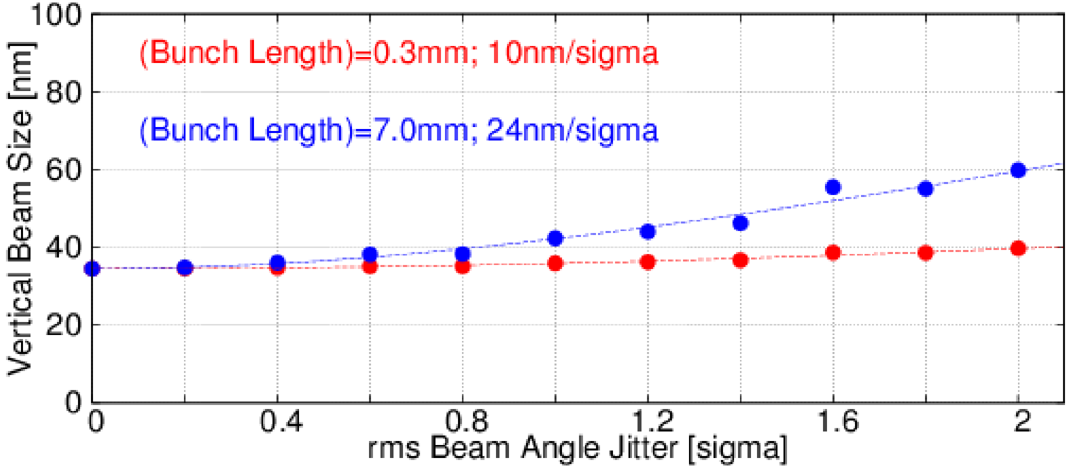
Intensity dependence for ILC

Wakepotential difference of bunch length

wakefield was calculated by Alexey Lyapin



Simulation of ATF2 IP beam size with two different bunch length (N=1e9)



Comparison of (ATF2 at N=1e9) and (ILC at N=2e10)

	ATF2	ILC-500GeV	ILC/ATF2
Energy ($1/E$)	1.3 GeV	250GeV	0.0052
N	1×10^9	2×10^{10}	20
Bunch Length	7 mm	0.3 mm	0.4
Emittance (Constant)	12 pm	0.07 pm	1
Beta Function ($\sum \beta_y$)	58350 m	310584 m	5.32
Total			0.22

The effect of beam angle jitter via wake field for ILC N=1e9 is much smaller than ATF2.

Summary

ATF2 beamline is designed to be the same scheme and the same magnet arrangement as ILC.

The tuning difficulties of IP vertical beam size for ILC and ATF2 10x1 optics are comparable.

Beam size was focused to less than 41 nm at $\mathrm{N} = 0.7 \times 10^9$ *(43 nm at* $\mathrm{N} = 1.0 \times 10^9$ *).*

- The design IP beam size is 37 nm.

The reason why the small bunch charge is its strong intensity dependence.

- The ILC design is $\mathrm{N} = 2 \times 10^{10}$.

- The typical intensity dependence is $\Delta\sigma_y^*/\mathrm{N} = 15\ \mathrm{nm}/10^9$.

The candidate of the strong intensity dependence for ATF2 is the IP angle jitter via wakefield.

- The effect of ATF2 at $\mathrm{N} = 1 \times 10^9$ *is much stronger than ILC at* $\mathrm{N} = 2 \times 10^{10}$.

If so, the strong intensity dependence at ATF2 is not insignificant for ILC.

- The comparative study of the intensity dependence will be planned in 2016 autumn beam operation.

Backup

Effect of nonlinear field to IP beam size

When we assumed the beam size at quadrupoles as $\sigma_{x,y} \propto L^* \sqrt{\frac{\varepsilon_{x,y}}{\beta^*_{x,y}}}$,

the effect of multipole field to IP beam size can be roughly scaled as

$$Y_{24} \propto L^{*2} \sqrt{\frac{\varepsilon_x \varepsilon_y}{\beta^*_x \beta^*_y}} \Big/ \sqrt{\varepsilon_y \beta^*_y} = L^{*2} \varepsilon_y \sqrt{\frac{\varepsilon_x}{\beta^*_x}} \qquad (5th\ order\ aberration) \propto L^{*5} \frac{\varepsilon_x^2}{\beta_x^{*2}} \sqrt{\frac{\varepsilon_x}{\beta^*_x}} \Big/ \sqrt{\varepsilon_y \beta^*_y} = L^{*5} \frac{\varepsilon_x^2}{\beta_x^{*2}} \sqrt{\frac{\varepsilon_x \varepsilon_y \beta^*_y}{\beta^*_x}}$$

etc.

		ILC	ATF2(1x1)	ATF2(10x1)
2nd order	Y46	1	0.89	0.89
	Y24	1	6.62	2.10
	Y22	1	3.83	0.38
	Y26	1	0.52	0.16
	Y66	1	0.07	0.07
	Y44	1	11.46	11.46
	X22	1	0.51	0.05
3rd (vertical)		1	18.32	0.58
4th (vertical)		1	87.62	0.88
5th (vertical)		1	419.13	1.33

Y chromaticity (Y46)

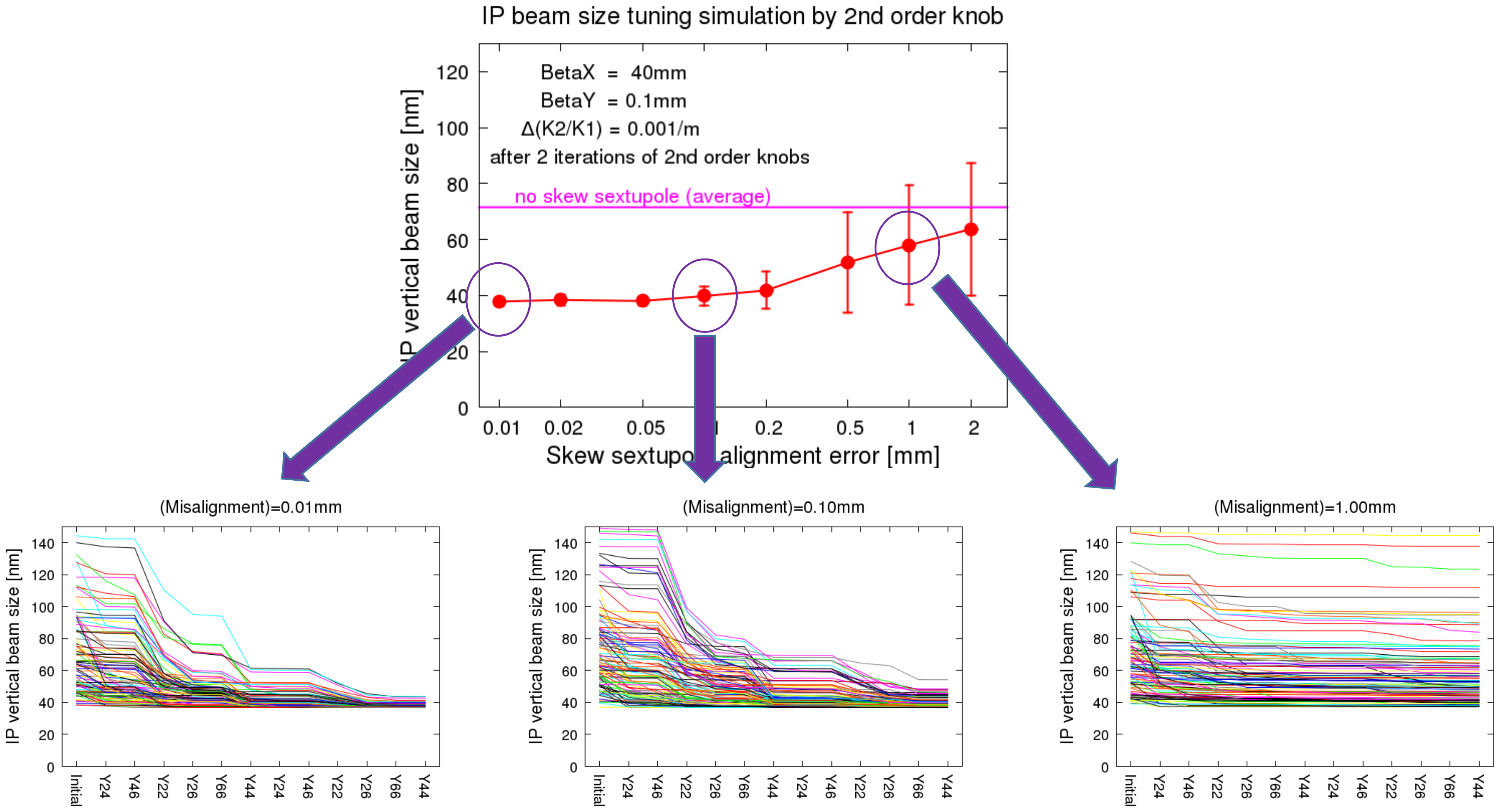
Y geometrical aberration (Y24)

X chromaticity (X22)

Allowed component of quadrupoles (5th)

The beam energy of ATF2 is much smaller than that of ILC,
⇒ Beam size at quadrupole is much larger than ILC.

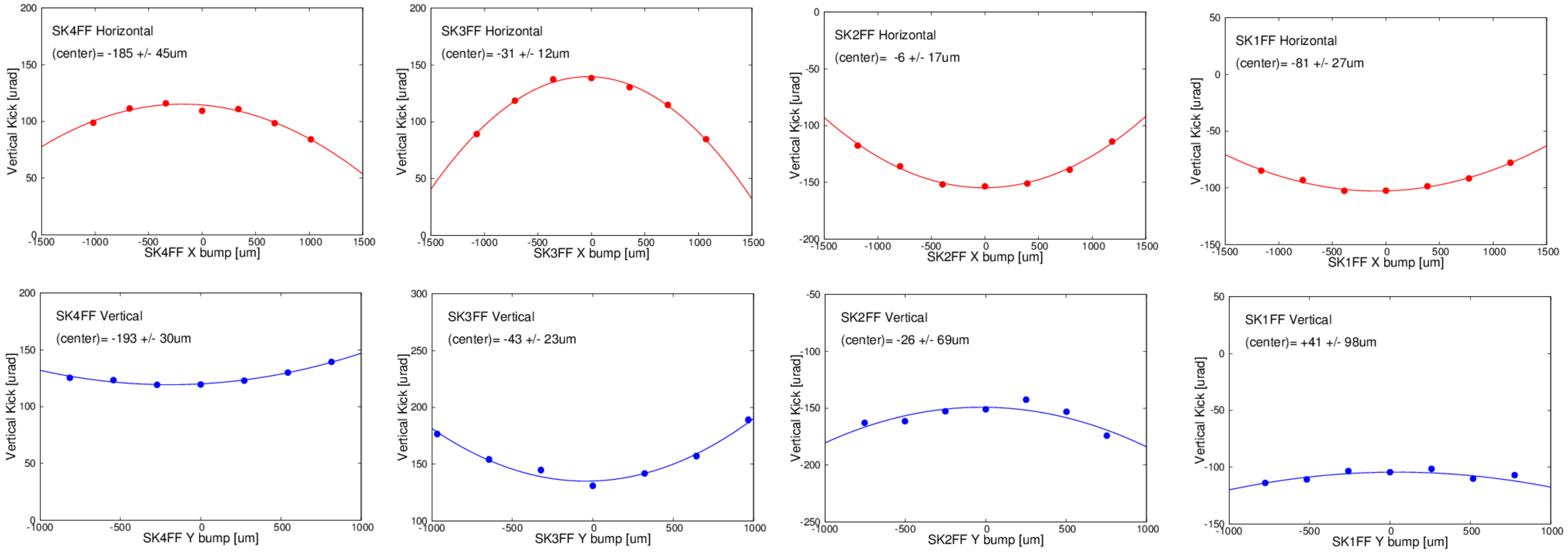
Initial alignment for skew sextupole magnets (simulation)



In order to apply the 2nd order knob effectively, we must align the magnets within 100um.

Magnetic center measurement for skew sextupoles

We did the mechanical position alignment of FF skew magnet, because the magnets don't have movers.



	SK4FF		SK3FF		SK2FF		SK1FF	
	X [um]	Y [um]	X [um]	Y [um]	X [um]	Y [um]	X [um]	Y [um]
2016/01/28	+527	+69	-94	-762	-12	-138	-137	+282
2016/02/03	-185	-193	-31	-43	-6	-26	-81	+41

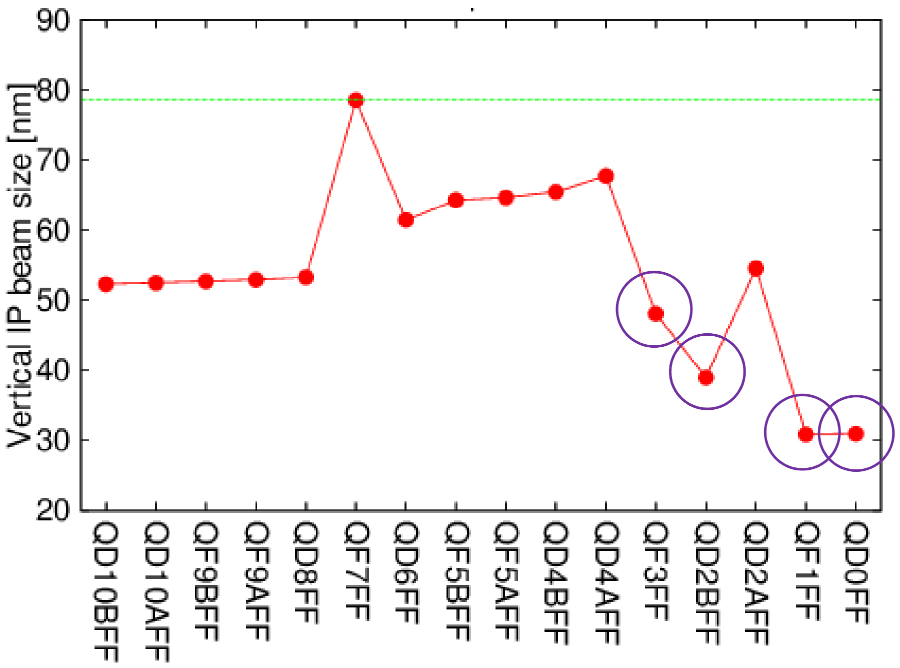
Magnetic center was within the requirement after the mechanical alignment.

Normal Sextupole Magnet Setting

Beam size was minimized in simulation for the normal sextupole settings by applying the normal sextupole errors for 1-by-1 quadrupole.

Normal sextupole settings	IP vertical beam size at model
Design setting w/o sextupole errors in quads	35.2nm
Magnet settings after nonlinear knobs	**78.7nm**

Minimum IP vertical beam size after beam size minimization



Candidates of error sources

(K2N/K1) at R=1cm

QF3FF - 0.17756

QD2BFF +0.97074

QF1FF - 0.00232

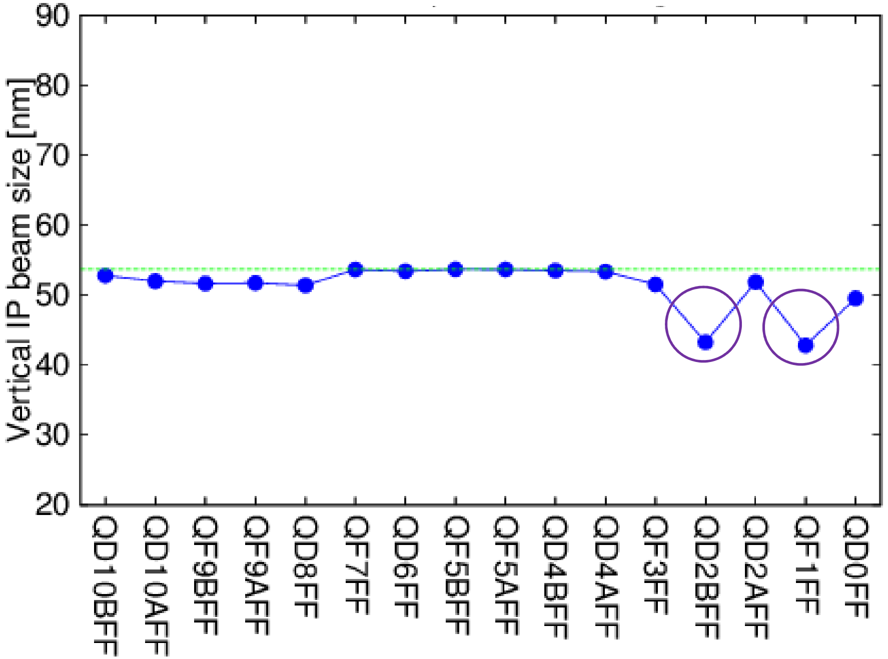
QD0FF +0.00117

Skew Sextupole Magnet Setting

Beam size was minimized in the simulation for the skew sextupole settings by applying the skew sextupole errors for 1-by-1 quadrupole.

Normal sextupole settings	IP vertical beam size at model
Design setting w/o sextupole errors in quads	35.2nm
Magnet settings after nonlinear knobs	**53.7nm**

Minimum IP vertical beam size after beam size minimization



Candidates of error sources

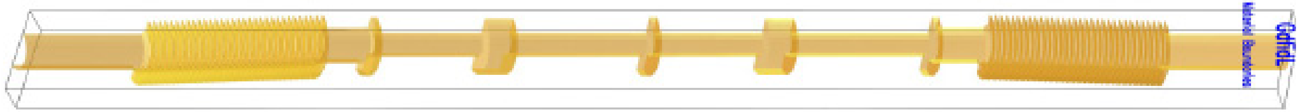
(K2S/K1) at R=1cm

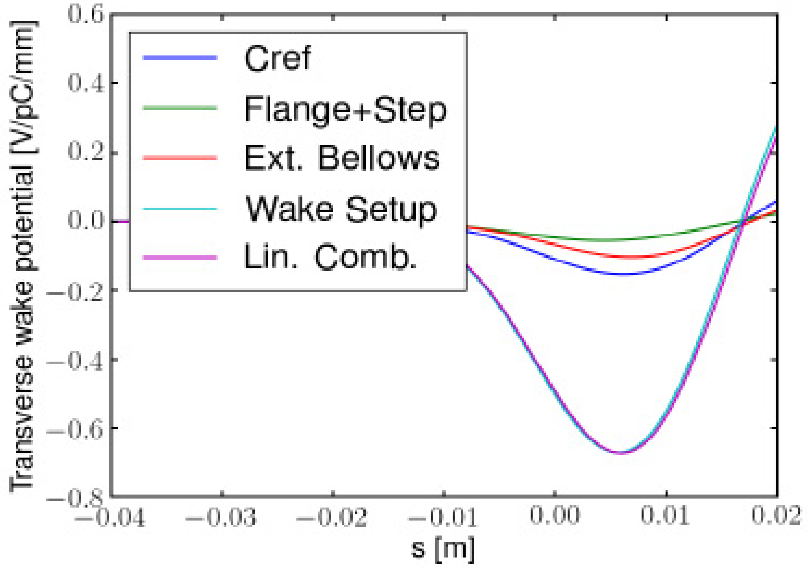
QD2BFF - 0.27321

QF1FF - 0.00030

Wakefield measurement with single wake component (Reference cavity for cavity BPM)

Experiment showed 20% larger orbit change than new calculation.
(J. Snuverink, et.al.,PR-AB 19, 091002 (2016))



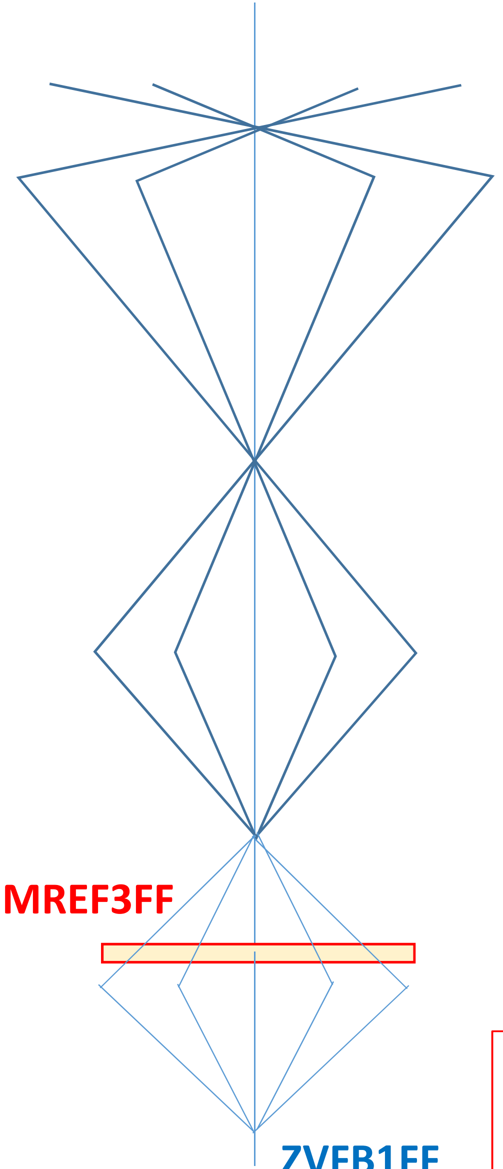


Simulated wakefield of whole setup increased by 30% wrt earlier simulations

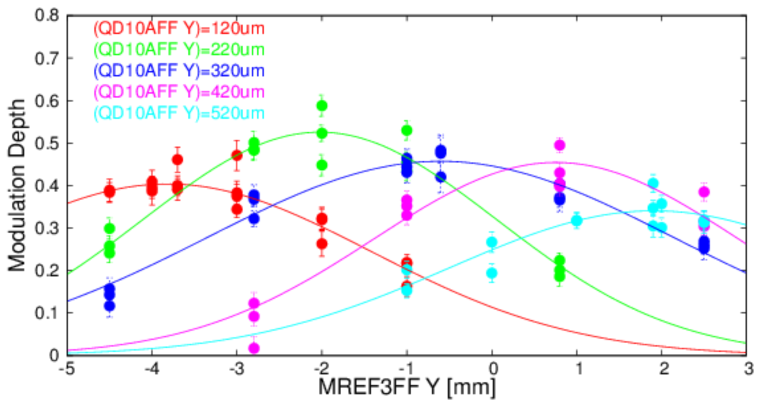
Combined setup and linear combination by adding individual components agree

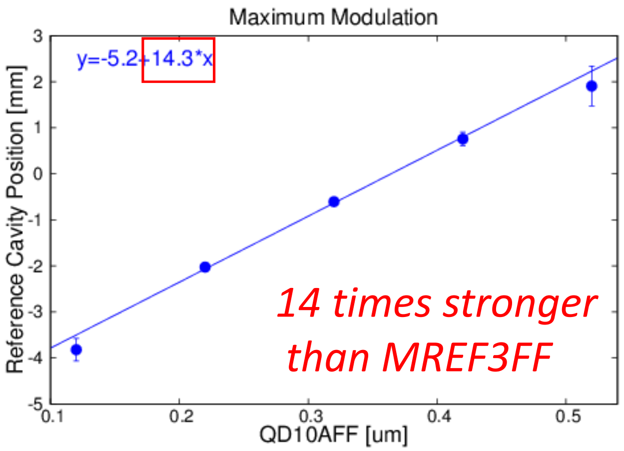
Evaluation of the total wakefield in ATF2 beamline

Beam intensity ; N=7e9

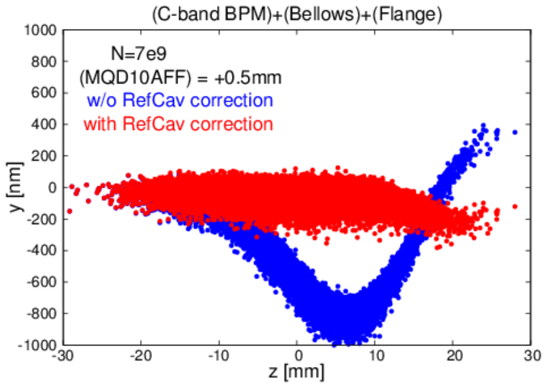


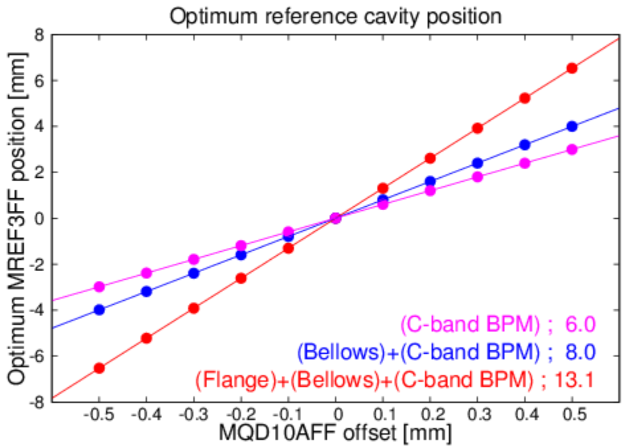
Measured Results





Simulation Results

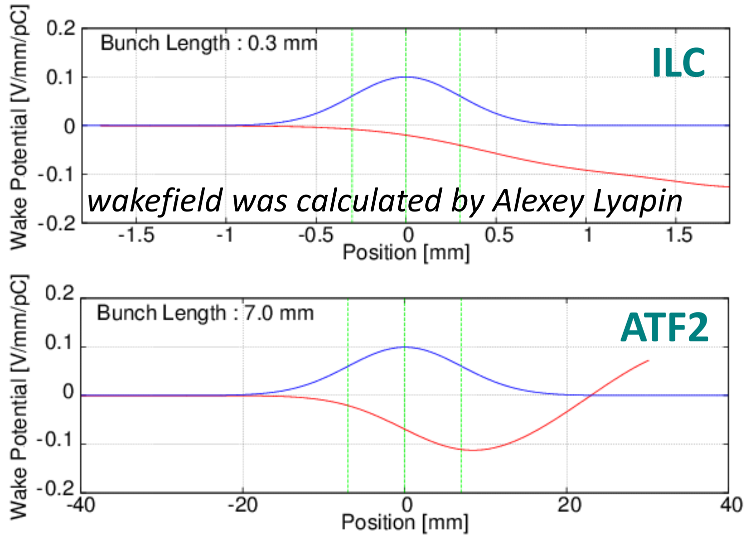




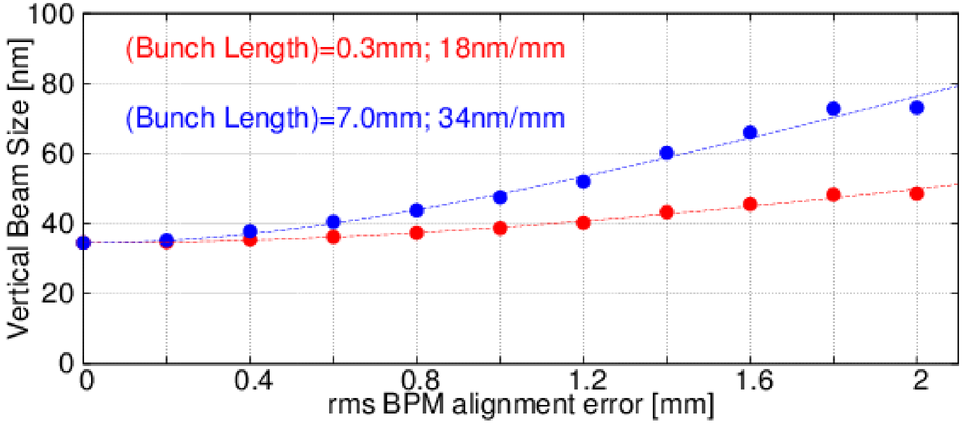
Beam kick effect by the wakefield for BPMs, bellows and flanges is consistent with the evaluation of wakefield sources.

Intensity dependence by the alignment error and wakefield

Wakepotential difference of bunch length



Simulation of ATF2 IP beam size with two different wakefield (N=1e10)

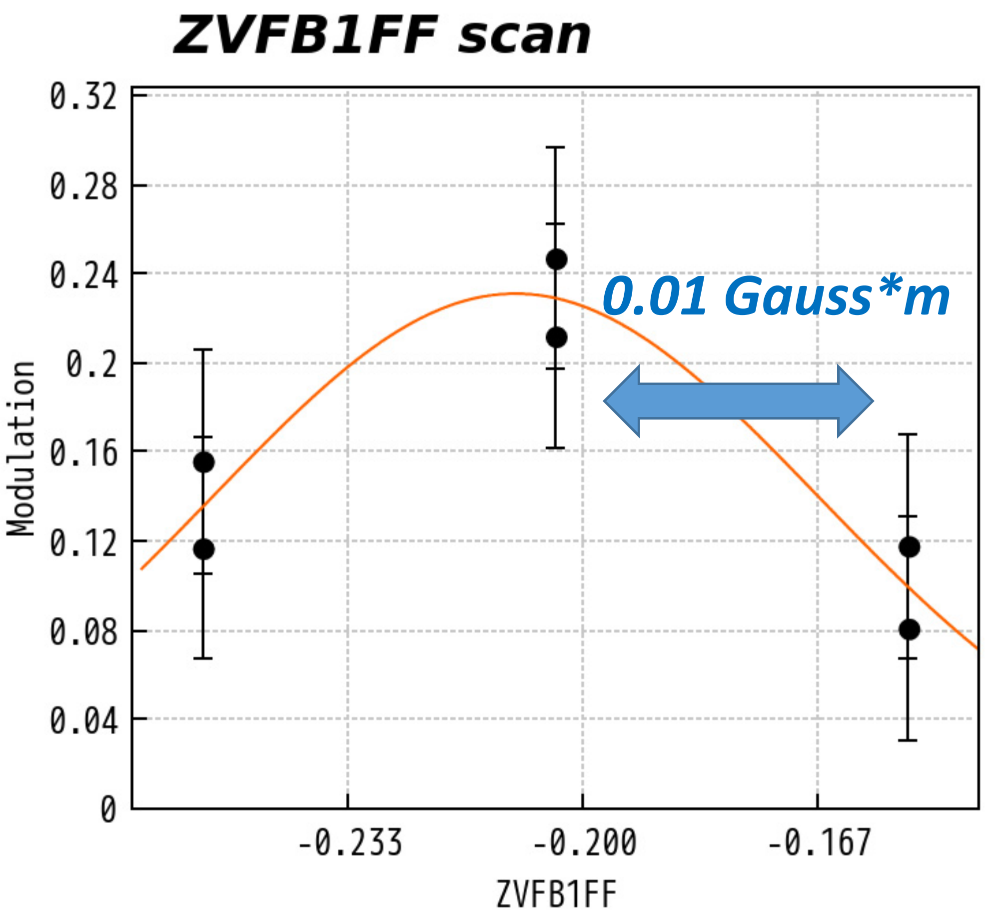


Comparison of (ATF2 at N=1e9) and (ILC at N=2e10)

	ATF2	ILC-500GeV	ILC/ATF2
Energy ($1/E$)	1.3 GeV	250GeV	0.0052
N	1×10^9	2×10^{10}	20
Bunch Length	7 mm	0.3 mm	0.5
Emittance ($1/\sqrt{\varepsilon_y}$)	12 pm	0.07 pm	13.1
Beta Function ($\sqrt{\sum \beta_y}$)	241 $m^{1/2}$	557 $m^{1/2}$	2.31
Total			1.57

The effect of alignment error via wake field for ATF2 N=1e9 is much smaller than ILC.

Requirement of orbit stability (FD phase)



Date: 2016/01/20   Time: 13:29:18

Fit results: A*exp(-((x-B)/C)^2/2)

Modulation: 0.232 +/- 0.036

Center: -0.210 +/- 0.008

Sigma: 0.043 +/- 0.009

Chi2/ndf: 8.2300e-01 / 3

Data file:

ZVFB1FF_fringe_160120_132918.dat

Orbit stability for FD phase is sensitive to IP beam size.

DR Cooling Water Temperature (2014/12/01 – 2014/12/21)

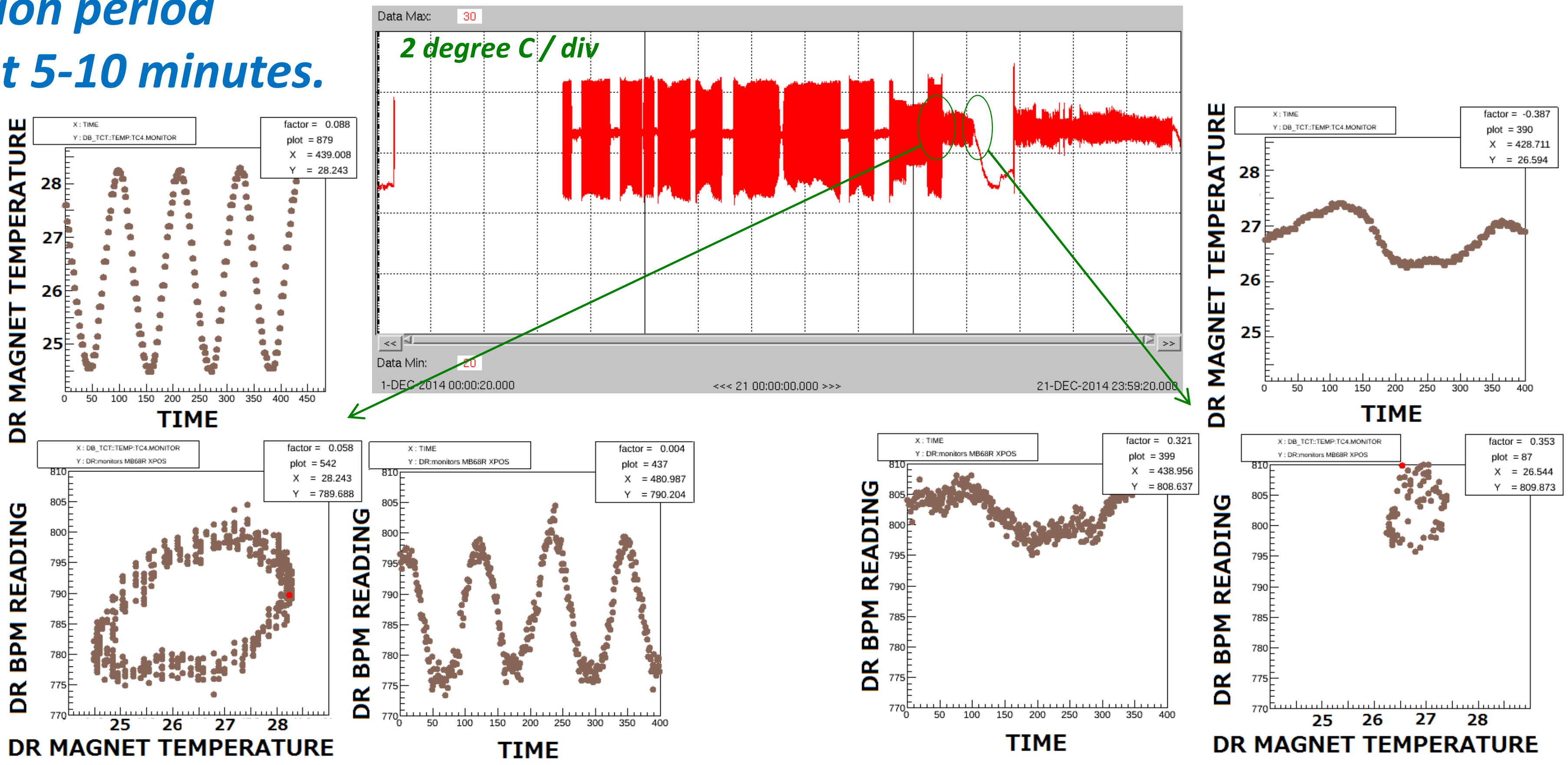
The DR horizontal orbit was oscillated with the DR cooling water temperature.

The FF vertical orbit was also oscillated with DR cooling water temperature.

- The frequency of FF orbit oscillation was twice as DR cooling water temperature.

- DR horizontal orbit oscillation was converted to FF oscillation through skew sextupole field at septum.

Oscillation period is about 5-10 minutes.

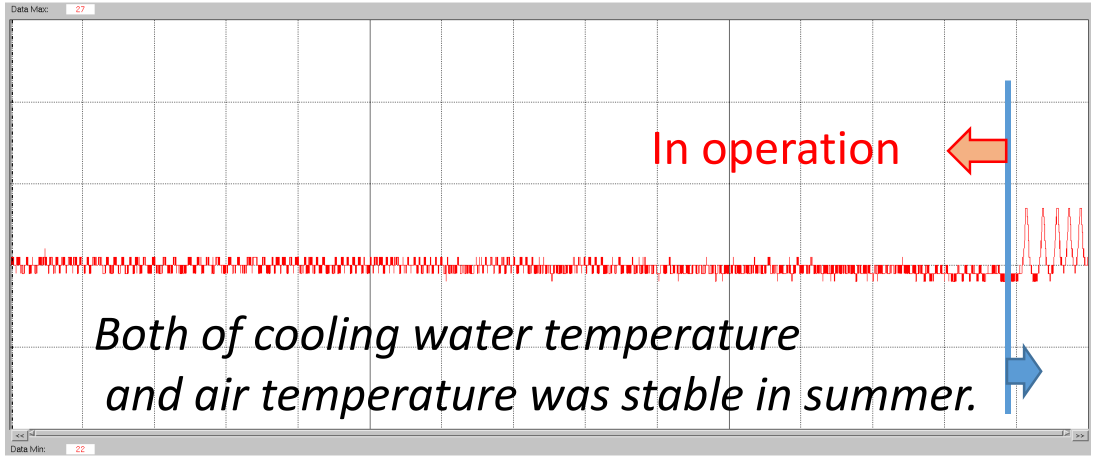


Air temperature variation in DR room

Since the cooling tower is outside of the hall,
the cooling power was much different in summer and winter season.

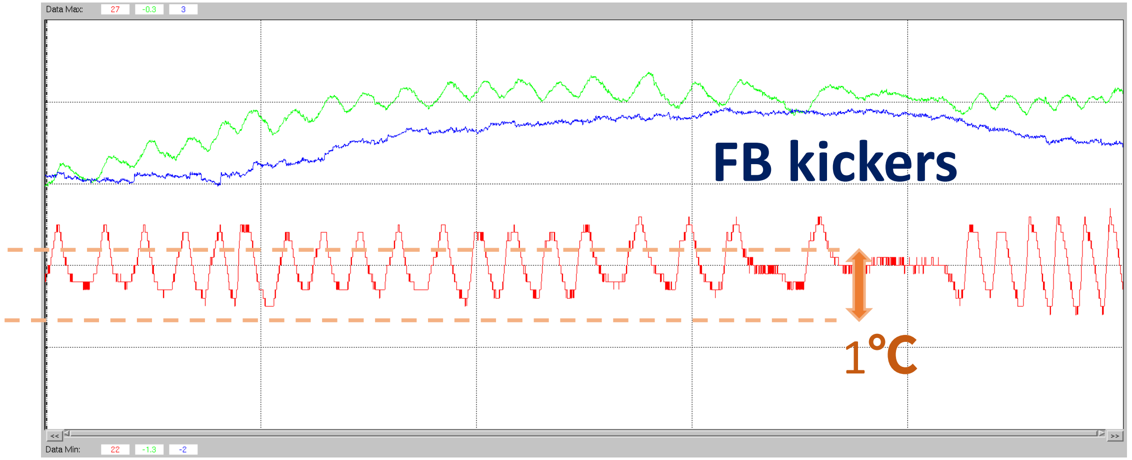
It is difficult to cure only by changing the parameter of cooling system.
Because, the load and the cooling power are much different in winter.

2015/06



Stop operation

2016/02



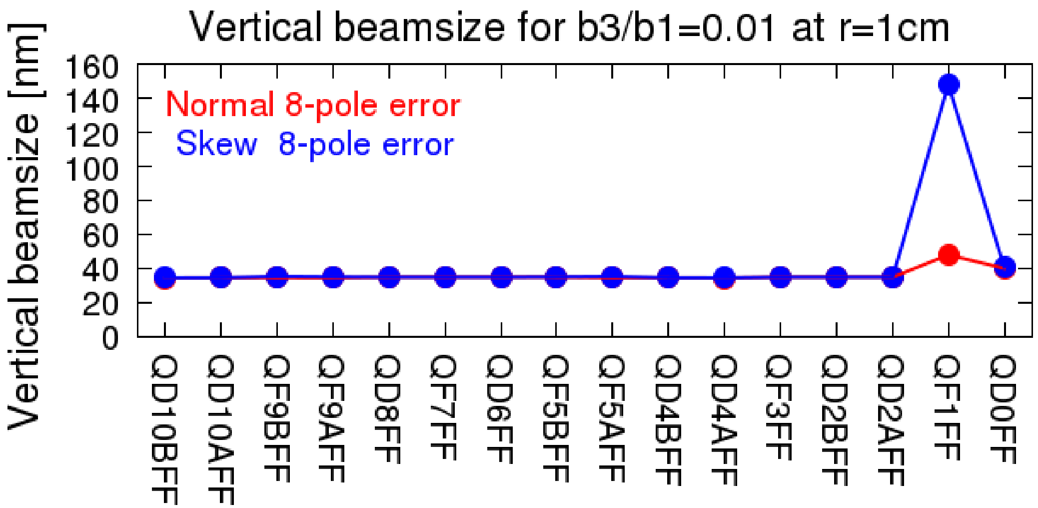
1degree is within the specification of air conditioner system

Oscillation period is about 1 hour.

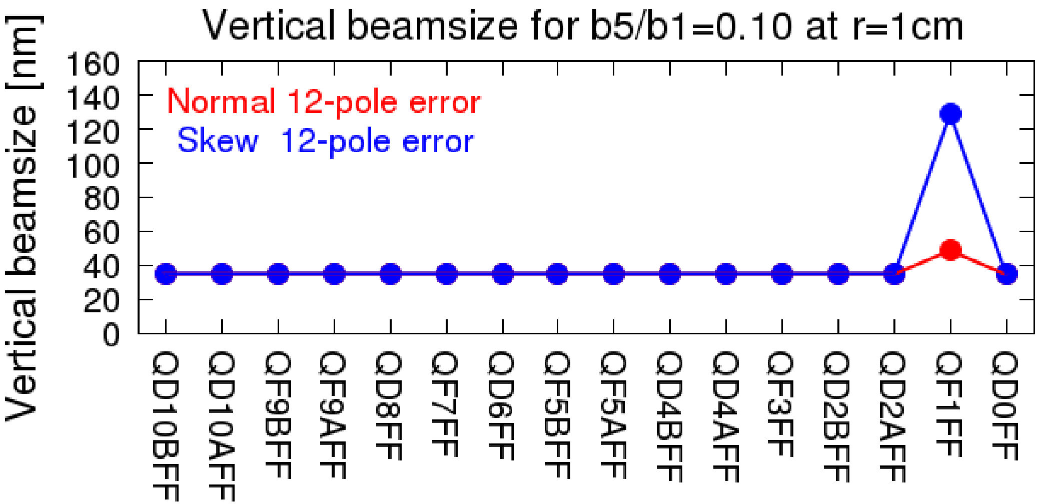
From 2016 operation,
we put 6 air-core steering magnets for slow orbit FB.

Sensitivities of higher order multipole field

Octupole Error (No jitter)



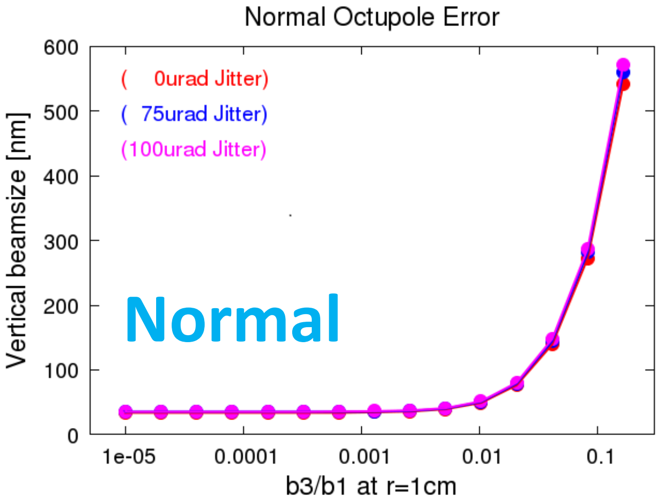
Dodecapole Error (No jitter)

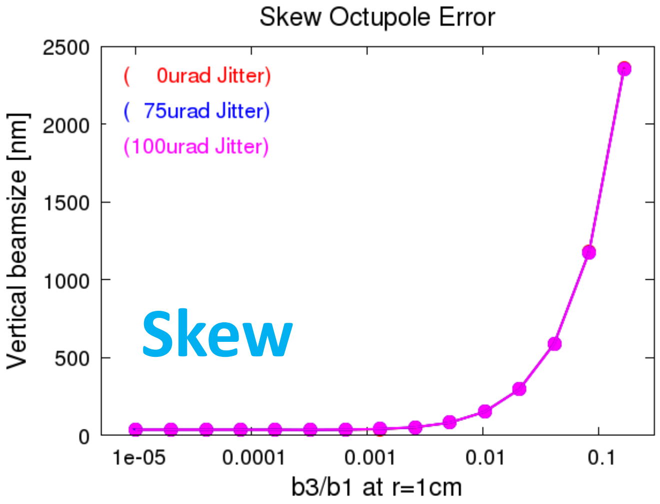


Since QF1FF is most sensitive both for octupole and dodecapole errors, the IP beam size growth by multipole errors via QF1FF was checked.

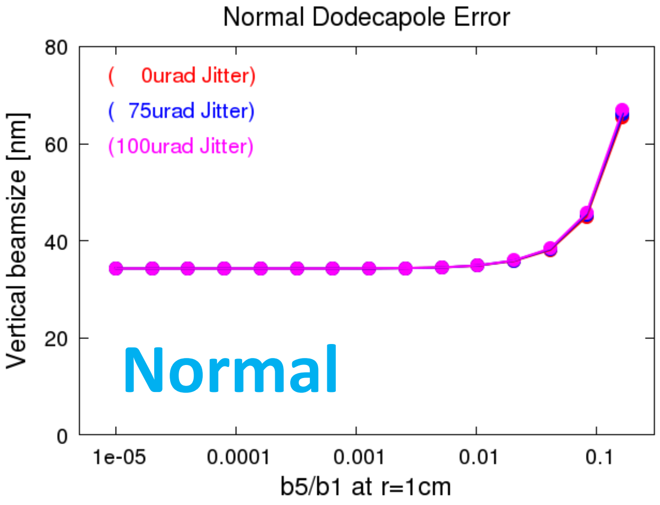
Simulation with multipole field error and IP beam angle jitter

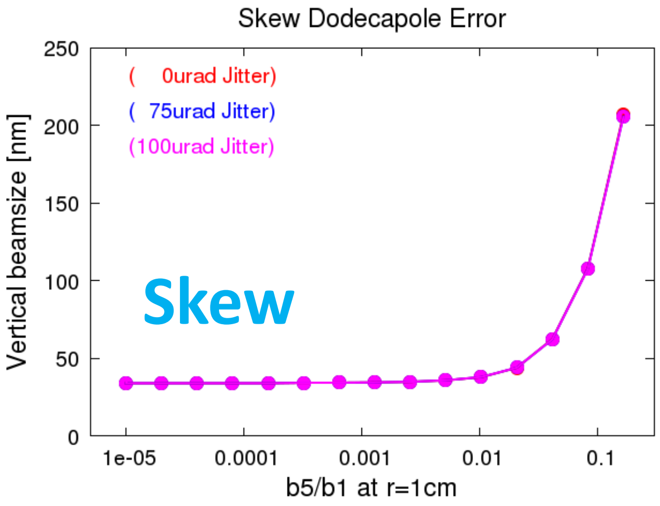
QF1FF
Octupole Error





QF1FF
Dodecapole Error





Vertical jitter is small impact for large multipole field error,
because the horizontal beam size at quad is dominant.