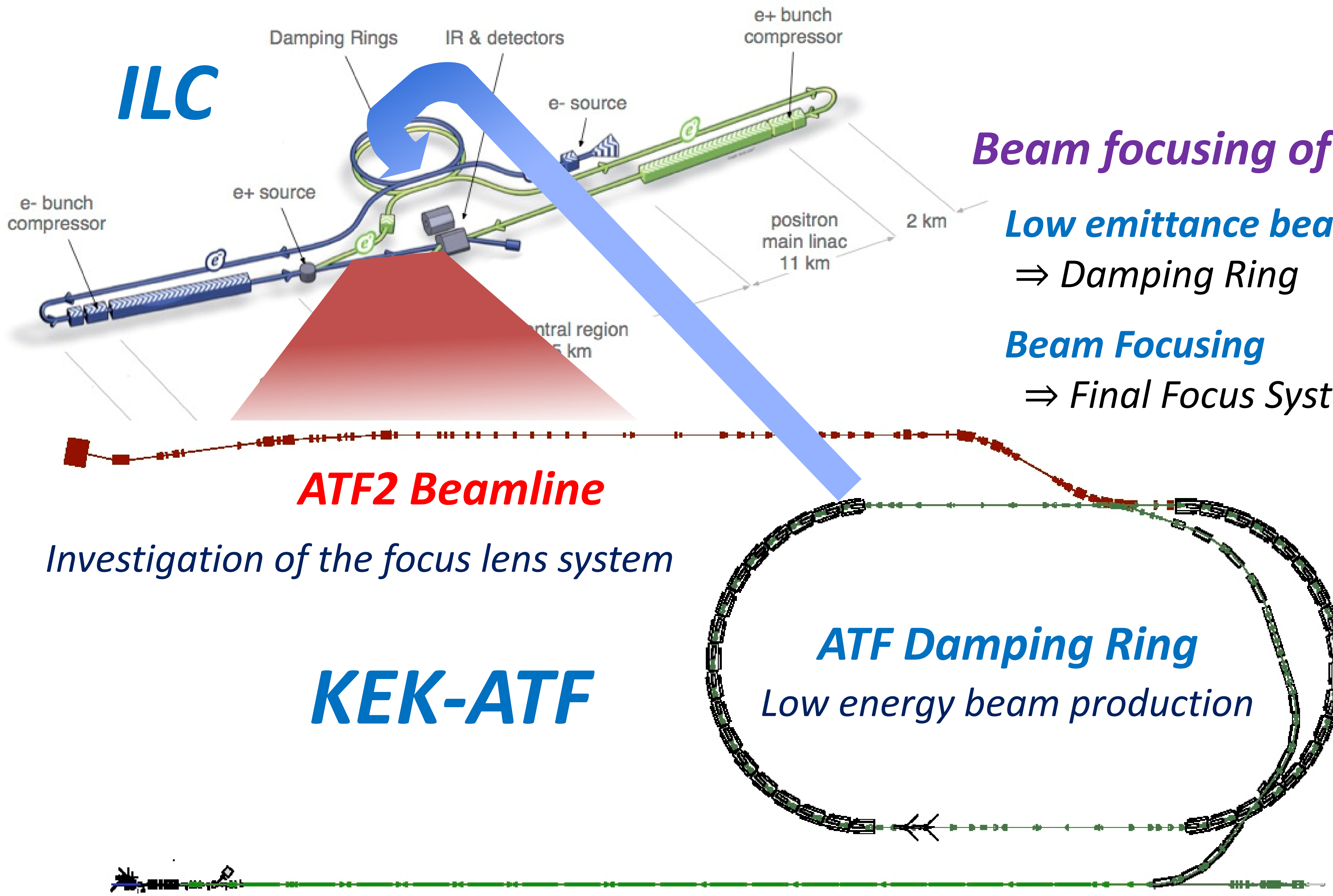
Introduction of the studies at ATF2 beamline

Toshiyuki OKUGI, KEK
IDT WG2 BDS group meeting
2023/ 03/ 01

ATF2 Project

Final focus test with ATF low emittance beam.

ATF2 project was proposed at 1st LCWS (2004 November).



Beam focusing of ILC

Low emittance beam

⇒ *Damping Ring*

Beam Focusing

⇒ *Final Focus System*

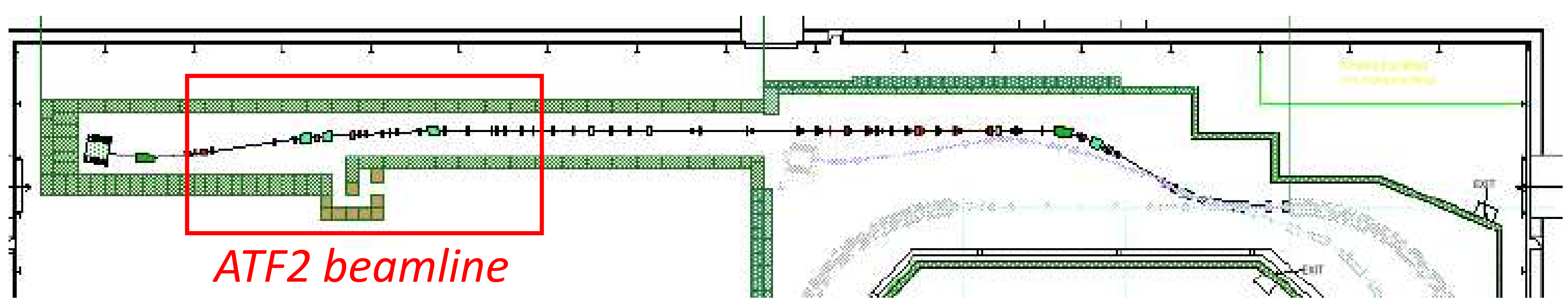
ATF2 Beamline

Test beamline for LC final focus test

Start construction at 2007

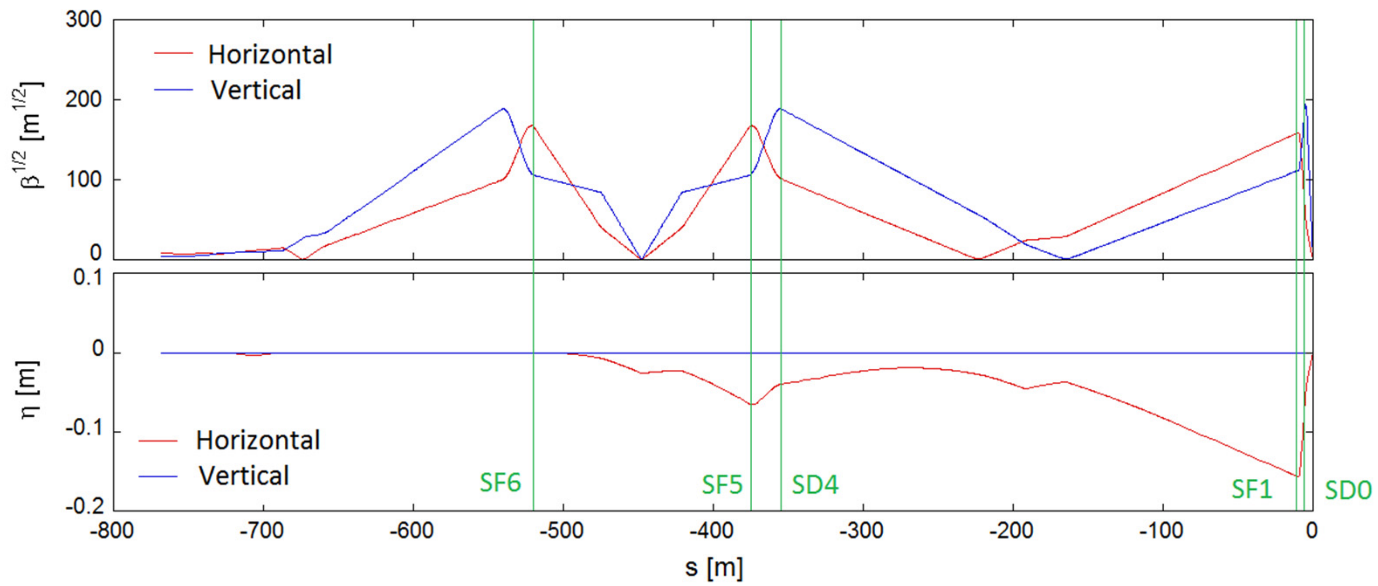
Design and construction were done by international collaboration.

ATF has been operating by international collaboration.

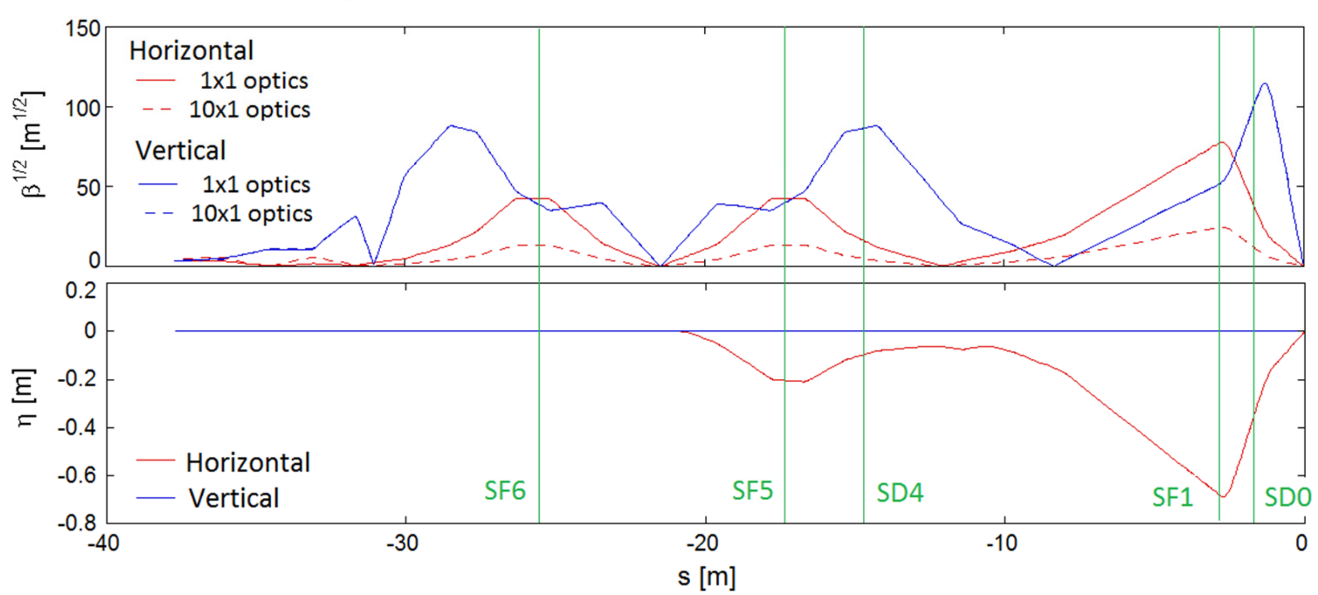


Beam Optics of ILC & ATF2

Beam optics of ILC final focus system



Beam optics of ATF2 beamline



ILC final Focus System

- ILC final focus systemand ATF2 beamline are both based on the Local Chromaticity Correction.

- Same magnet arrangement

ATF2 Beam Optics

1x1 optics

X&Y chromaticities are comparable to ILC FF.

10x1 optics

Since betax is 10 times larger than 1x1 optics, X chromaticity is one order smaller than ILC .*

Same concept of beamline design to ILC !

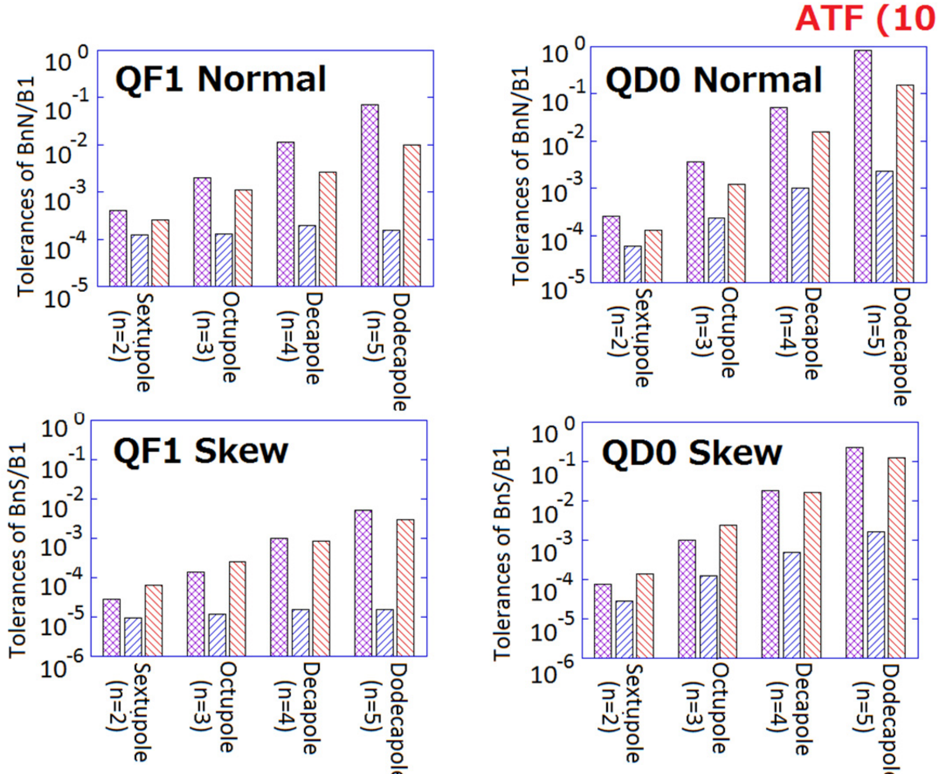
ATF2 Goal 1 *: Establish the beam tuning method for ILC final focus with same optics and compatible beam line tolerance*

ATF2 Beam Optics

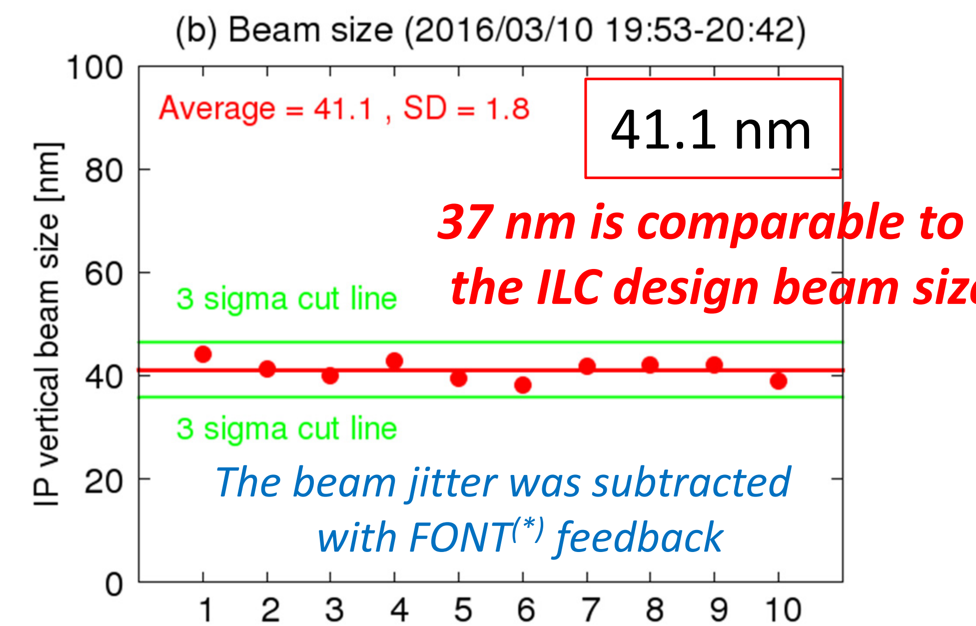
- ✓ *ILC final focus system and ATF2 beamline are both based on the Local Chromaticity Correction.*
- ✓ *Same magnet arrangement*

Multipole Field Error Tolerances (R=1cm)

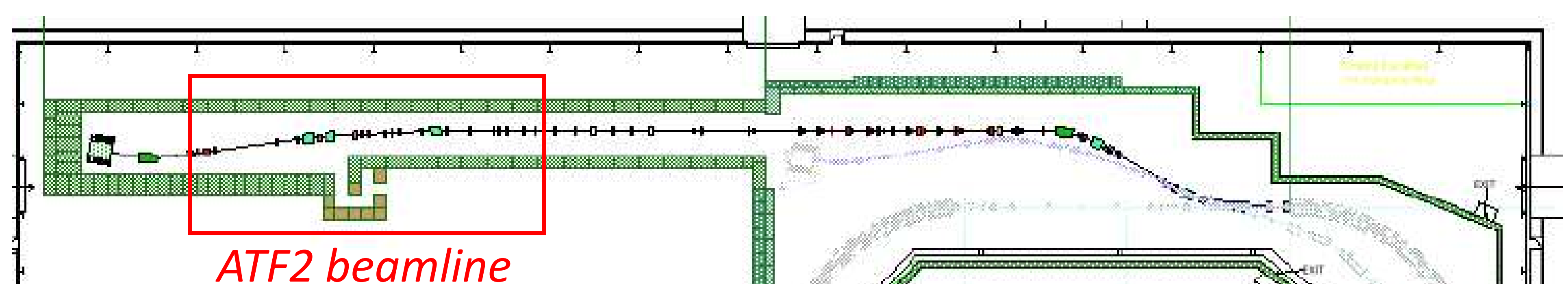
ILC
ATF (1 x 1)
ATF (10 x 1)



Minimum beam size (2016/03/10)



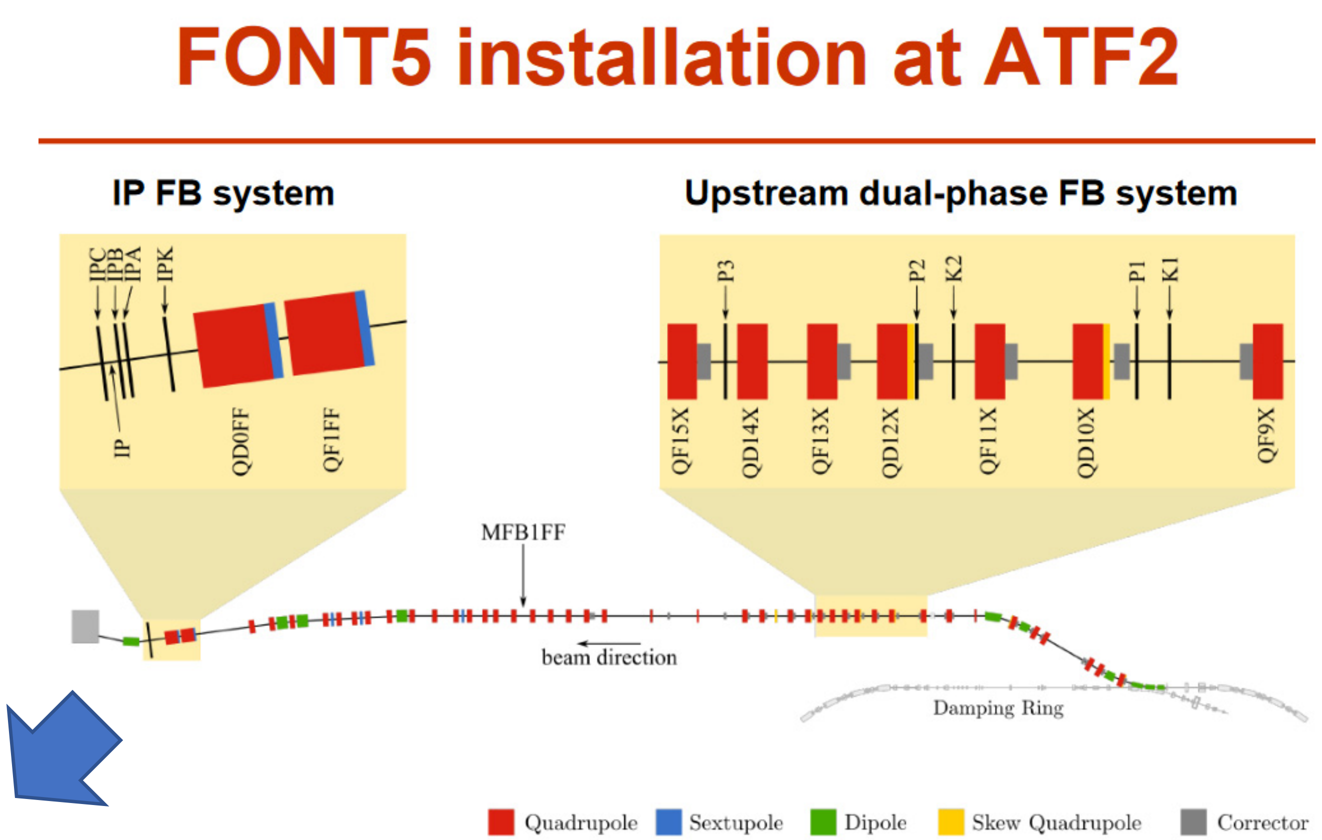
(*) Feedback On a Nanosecond Time scale, developing by Oxford Univ.



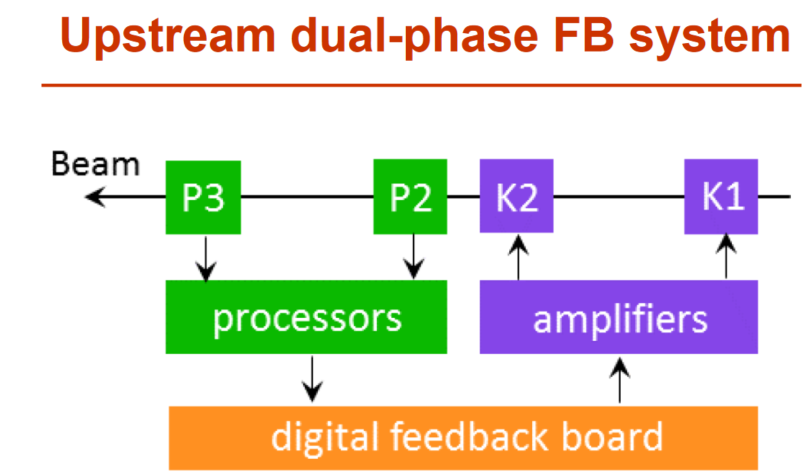
***ATF2 Goal 2** : Development a few nm position stabilization for the ILC beam interaction point*

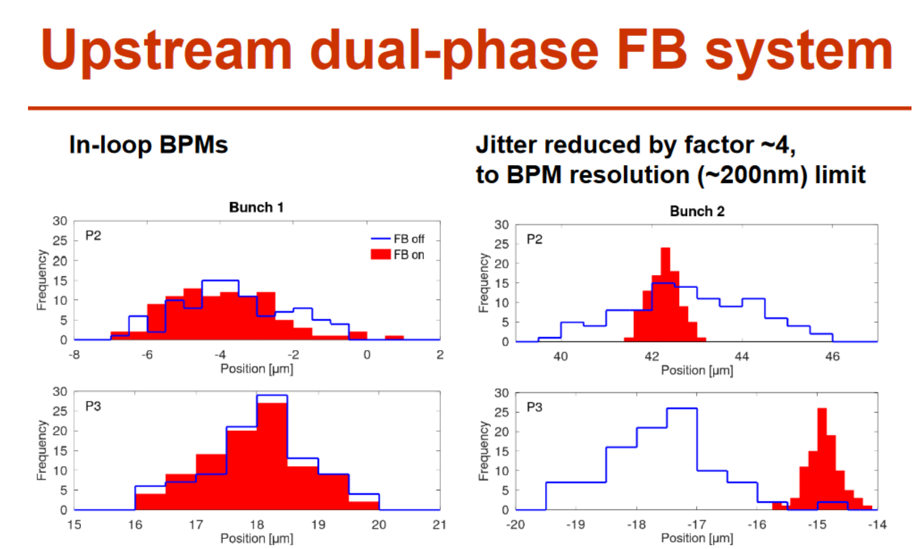
The IP beam position is stabilized up to the BPM resolution for both Upstream and IP.

P. Burrows at ATF review (2020)



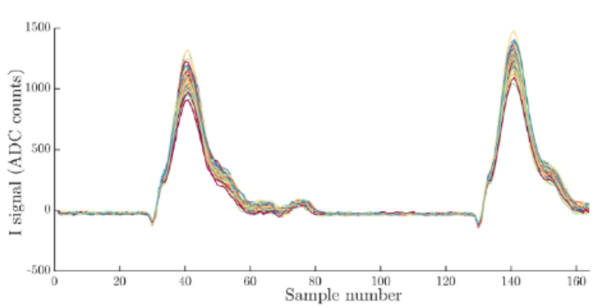
Upstream dual-phase FB

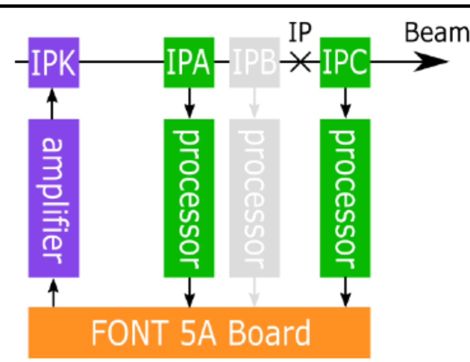




ATF2 IP feedback

Digitization of IP BPM waveform





	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	106 ± 16	106 ± 16
2	96 ± 10	41 ± 4

Remaining studies planned for the next few years at "ATF review 2020 report"

Our main study items in the near future are:

- ***Study of higher order aberrations and corrections***
  - ✓ *Study of 2nd order aberrations and corrections*
  - ✓ *Study of the energy bandwidth of the final focus*
  - ✓ *Study of the different optics that enhance the effects of aberrations (smaller beta/larger L*)*
- ***Study of intensity dependence***
  - ✓ *Qualitative agreement of our observations and simulations/calculations*
- ***Improvement of IPBSM laser system***
  - ✓ *New laser system*
- ***Stabilizing beam orbit and reducing beam jitter***
  - ✓ *Specify the main source of the orbit drift*
  - ✓ *Routine operation of the upstream FONT feedback system*

ATF3 proposal

Building on the achievements of the ATF2 project a follow-on, upgraded facility ('ATF3') for pursuing R&D aimed at maximising the luminosity potential of ILC is necessary. ATF3 would comprise an overhaul and upgrade of the existing ATF2 beamline so as to model more accurately the energy-scaled ILC final-focus system.

Time-critical WPs by the IDT WG2

WP-prime-15 : ATF (Priority A)

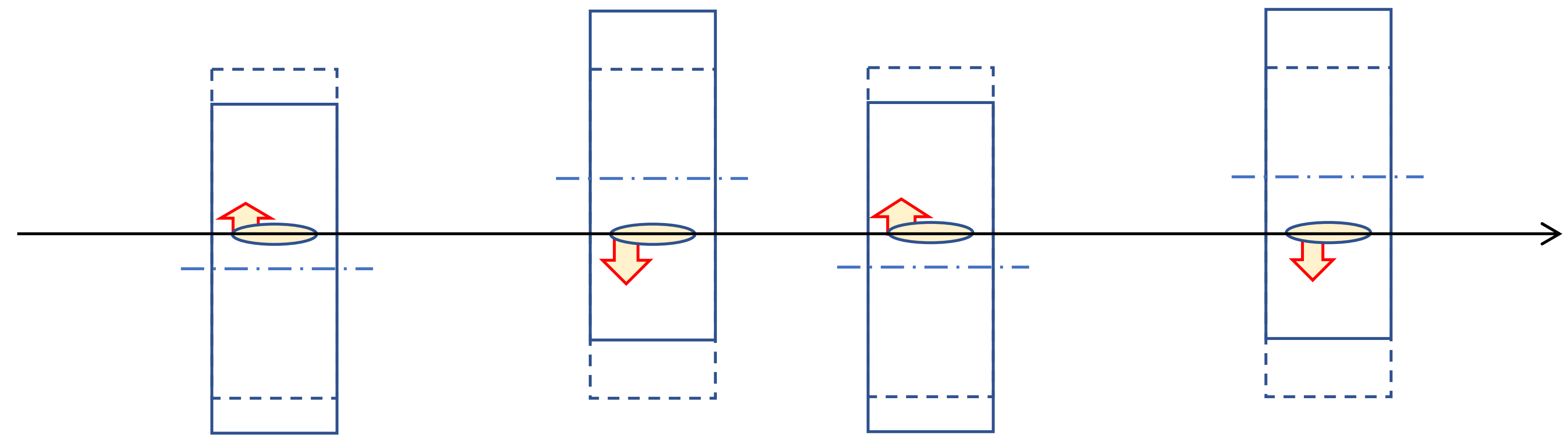
- *ATF is the only existing test accelerator in the world to test the final focus beamline of the linear collider, and the study of the final focus beamline at ATF is important for ILC.*
- *However, since some of the items listed in the TPD can be performed in the Pre-Lab period, it is appropriate for the time-critical WP to narrow down the items and to perform only the higher priority research topics.*
- *Therefore, the time-critical WP of theWP-15 is not be selected some items from the items listed in the technical preparation document, but be restricted the following three research topics to be carried out at ATF before the pre-lab starts. Then, the budgets that are evaluated to be necessary for these items.*

    1) ***wakefield mitigation***
    2) ***mitigation and correction of higher-order aberration***
    3) ***training for ILC beam tuning (ML etc.)***

- *As candidates for research laboratories, we decided to list all the laboratories that were also listed as candidate laboratories in TPD WP-15.*

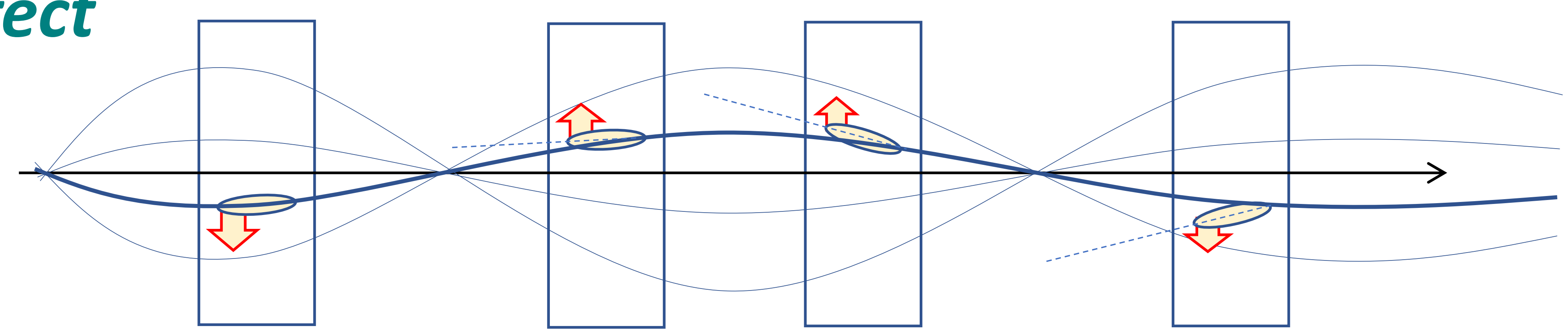
wakefield mitigation

Static wakefield effect



- The wakefield is generated by **the misalignment and/or the beam orbit offset of vacuum component.**
- Bunch tail is kicked by the wakefield, generated by the beam.
- ***The kicked amplitude is proportional to the beam position offset w.r.t. the chamber center.***

Dynamic wakefield effect



- The wakefield is generated by **the beam orbit jitter of the beam**.
- **The effect is superposed**, because polarities of (y, y') are changed for IP angle jitter, simultaneously.
- Bunch tail is kicked by the wakefield, generated by the beam.
- ***The kicked amplitude is proportional to the beam angular jitter amplitude.***

by K. Kubo at ATF review 2020

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 β_y	390 km	61 km	2.5	6.7
Total			0.11	0.032

Wakefield effect at ILC design bunch population (2×10^{10}e) corresponds to bunch population at ATF

0.2×10^{10}e for misalignment

0.06×10^{10}e for orbit jitter

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

Reported in LCWS2019

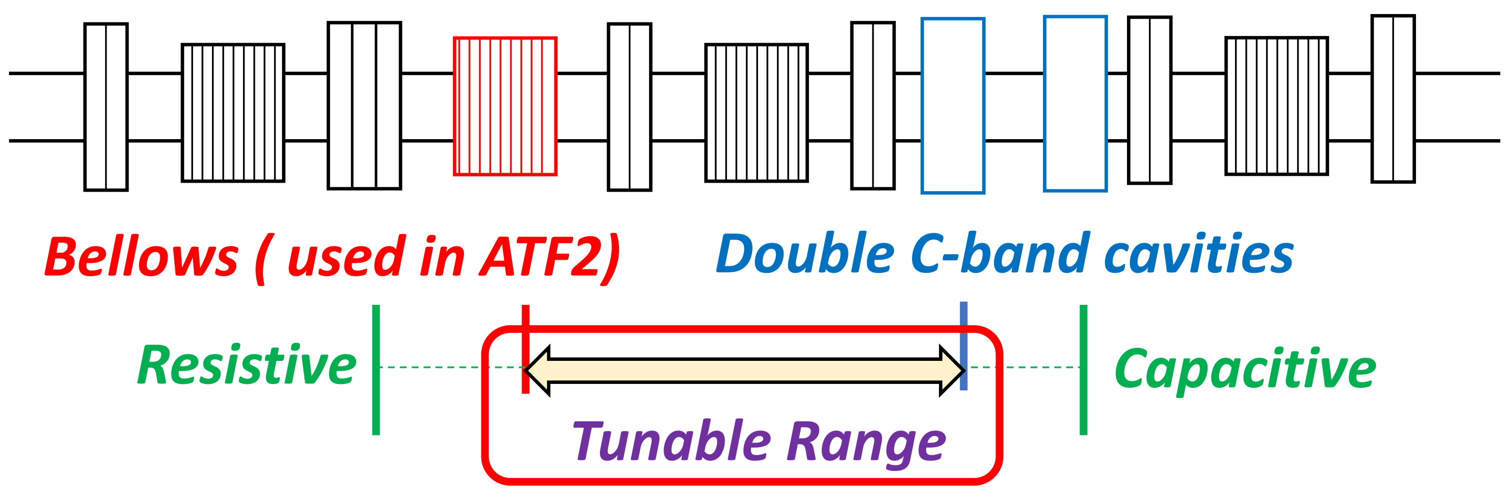
https://agenda.linearcollider.org/event/8217/contributions/44505/attachments/34913/53944/LCWS_intensity_dependence_oct2019.pdf

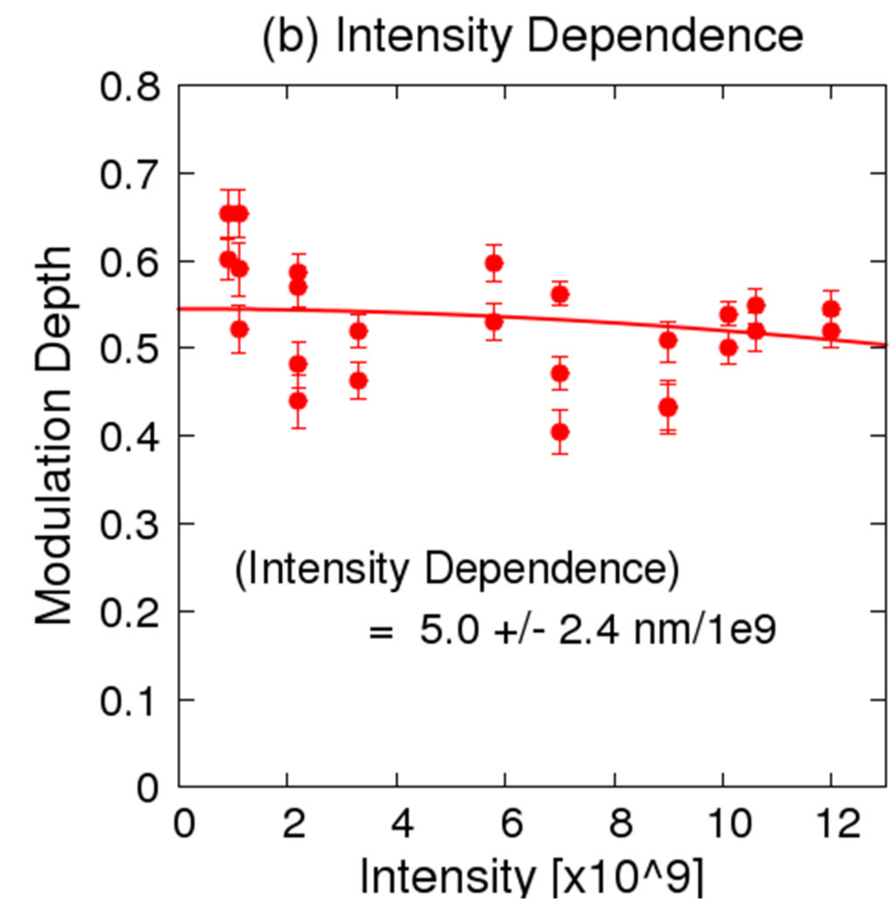
However, further experimental studies at ATF will

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

Wakefield compensation with 2 independence wake sources (static effect)

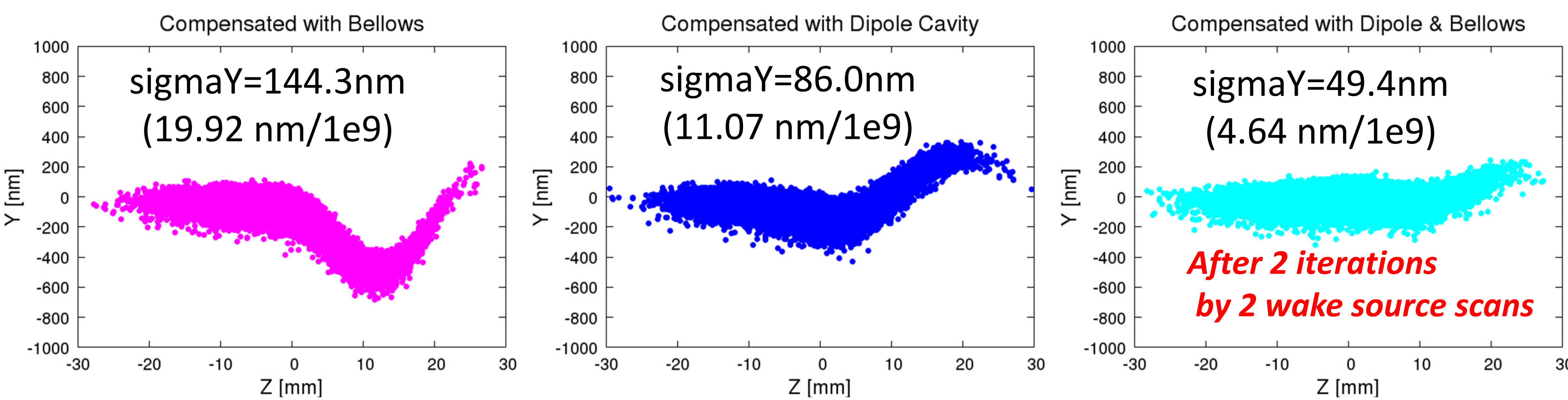
By using ATF2 nominal bellows (resistive), and C-band cavity (capacitive), the tunable range of the wakefield correction makes wider.





IP distribution after wake field compensation (simulation)

N = 7e9 , (MQD10AFF) = +0.5mm



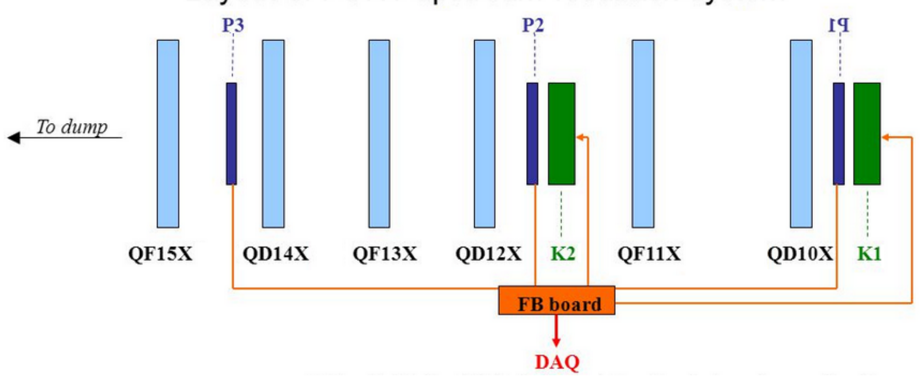
37 nm => 38.3 nm by static effect at N=2e9

IP angle jitter reduction with upstream FONT FB (dynamic effect)

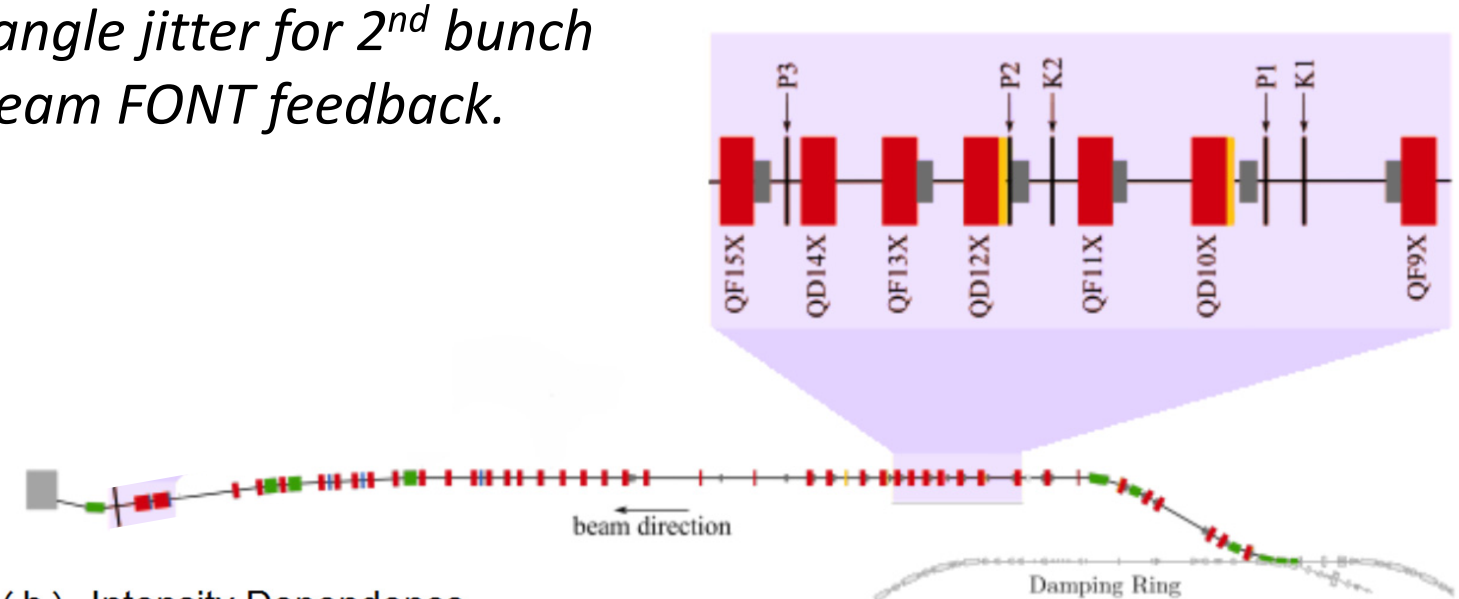
Special thanks to Oxford group for this demonstration

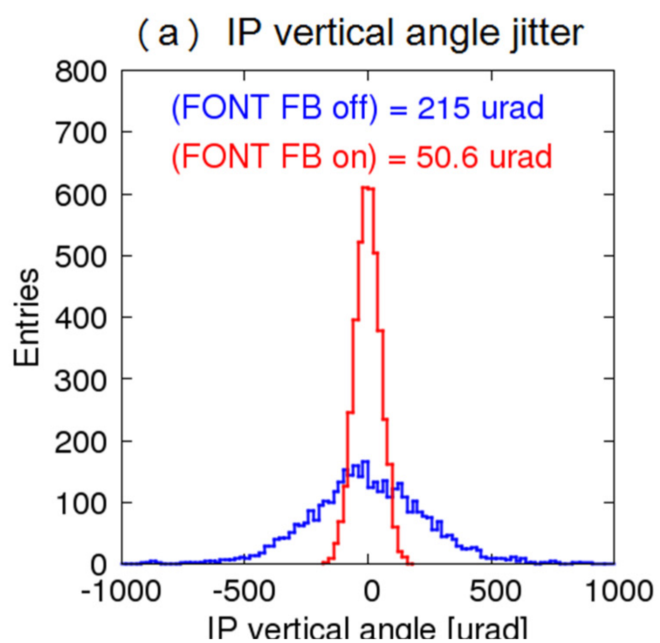
We can reduce the IP position and angle jitter for 2nd bunch by using 2 dimensional (y-y') upstream FONT feedback.

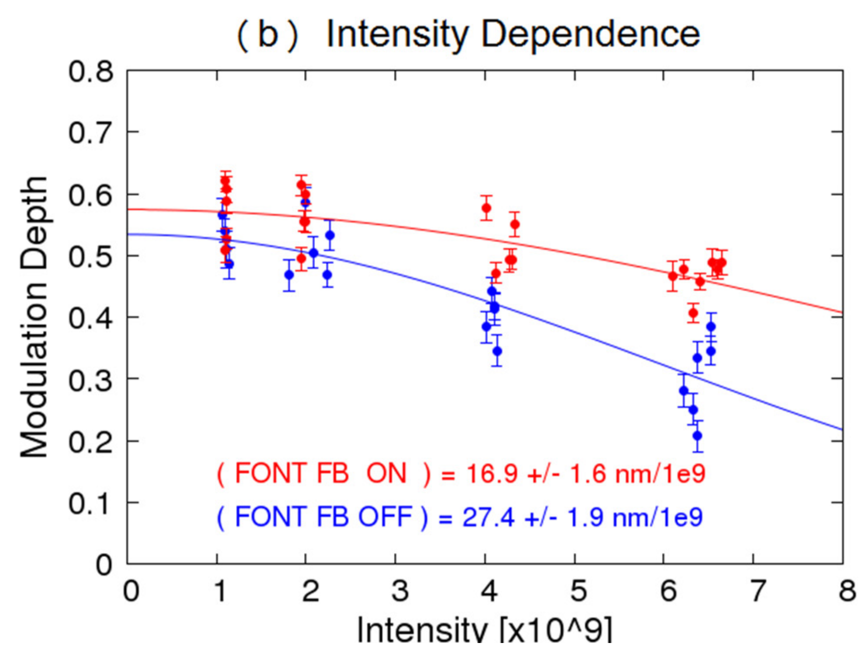
Layout of FONT upstream feedback system



Upstream system







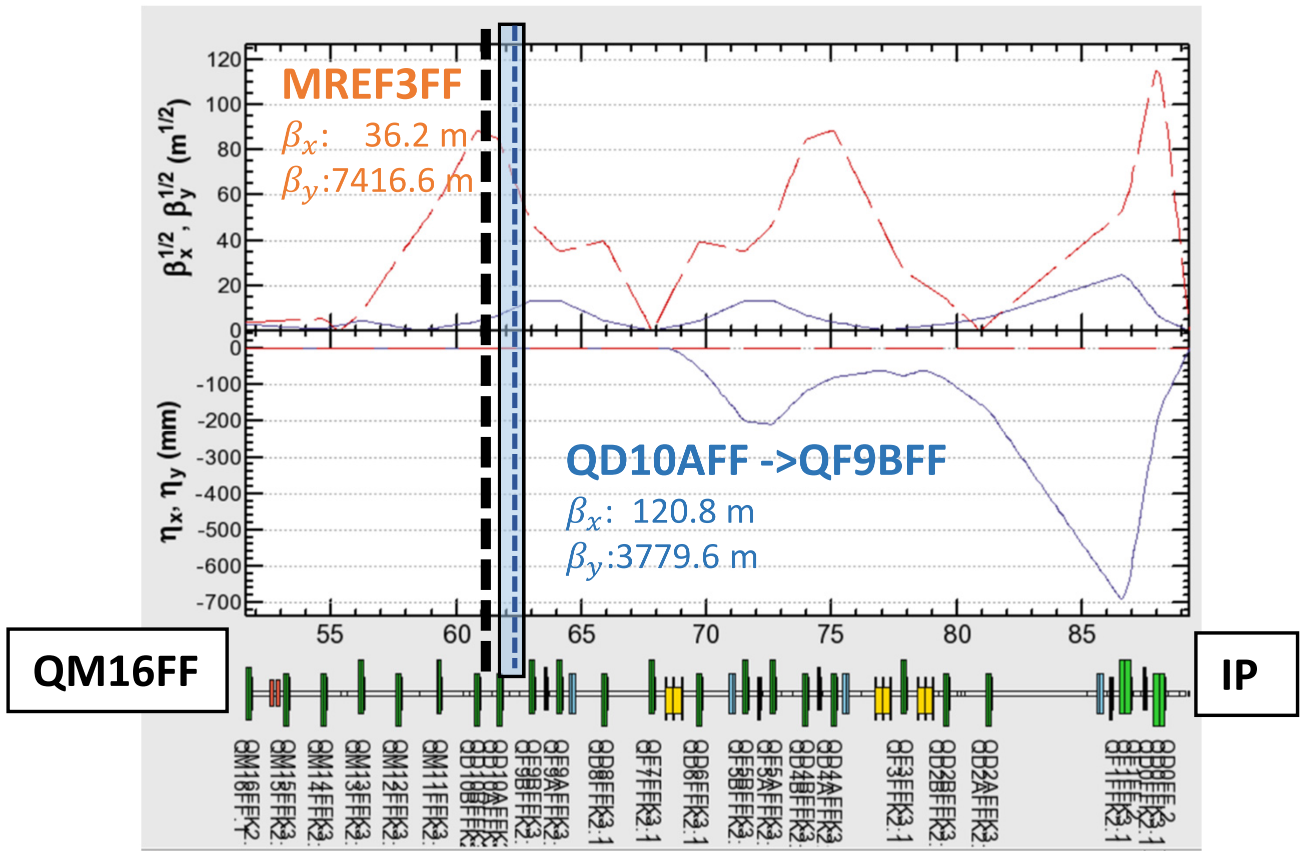
When the IP angle jitter was reduced by using the 2D upstream FONT FB, intensity dependence was also reduced.

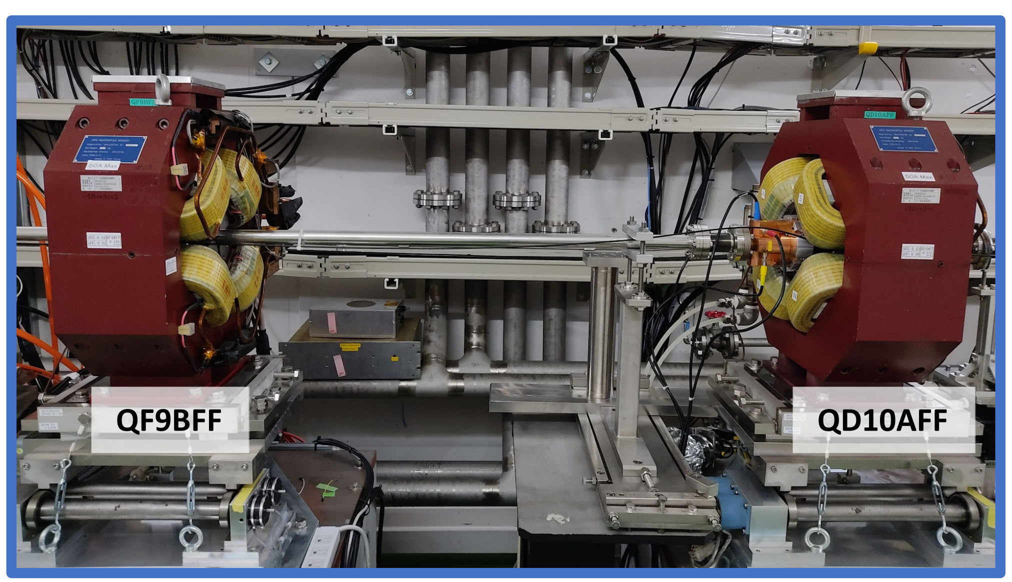
It was confirmed that the jitter reduction with FB is effective to reduce the intensity dependence.

	IP angle jitter	Intensity dependence
Single bunch operation	220 μrad	25.1 ± 1.5 nm$/1 \times 10^9 e^-$
2 bunch operation without FB	215 μrad	27.4 ± 1.9 nm$/1 \times 10^9 e^-$
2 bunch operation with FB	50.6 μrad	16.9 ± 1.6 nm$/1 \times 10^9 e^-$

by Y. Abe

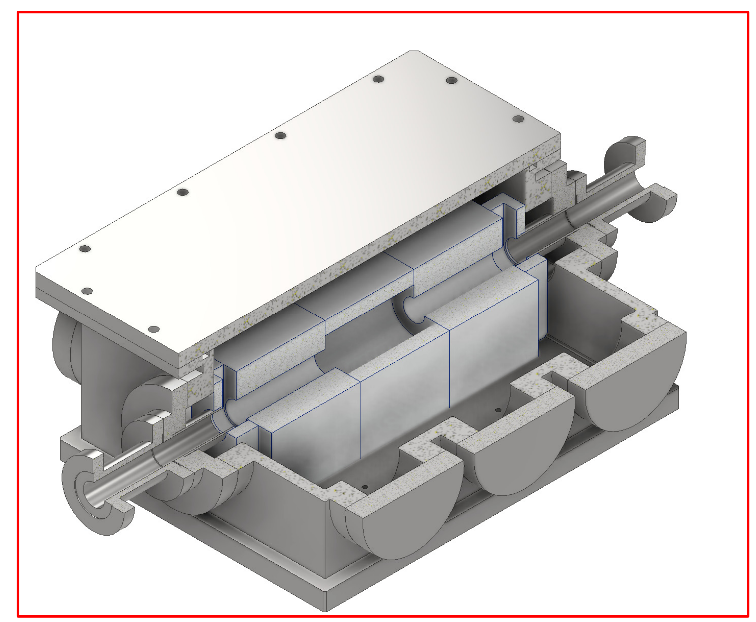
Wakefield test station in ATF2 beamline





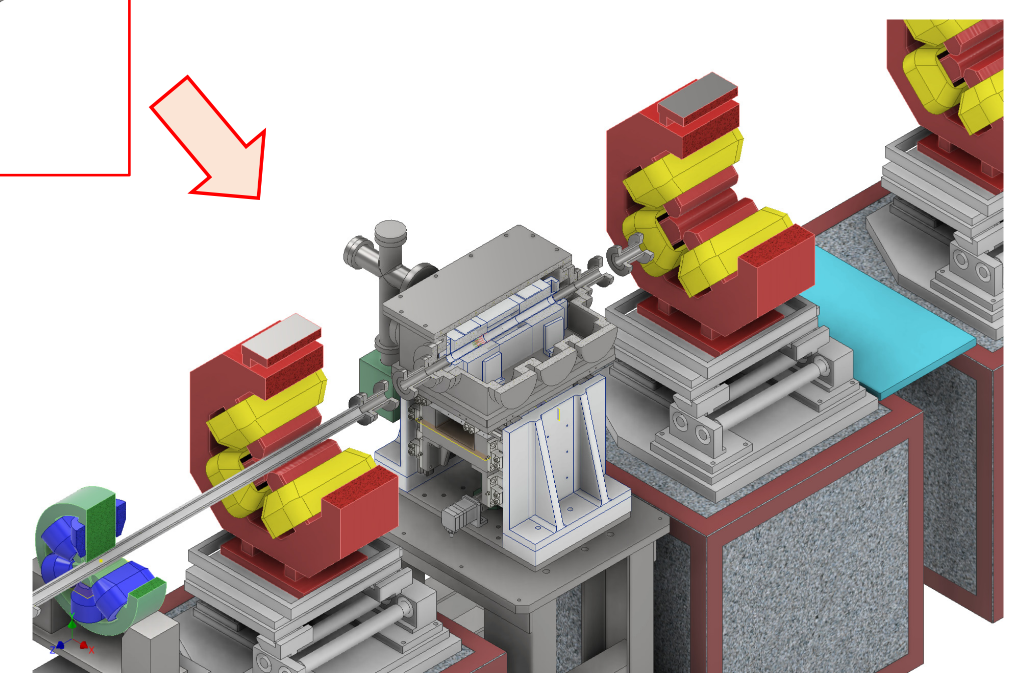
Subject of the study

- ✓ Minimization of wakefield effects on ATF2 beamlines
- ✓ Development of vacuum components to reduce wakefield effects



Preparing a wakefield test station

The vacuum chamber will be installed in ATF2 beamline in this autumn.



mitigation and correction of higher-order aberration

Linear Optics Tuning Knobs

Sextupole magnet is moved by Δx horizontally

$$x \to x_0 - \Delta x, \qquad y \to y_0$$

Normal quadrupole field

$$-\frac{q}{p_0}A_{s,2N} = \frac{k_{2N}}{6}(x_0^3 - 3x_0 y_o^2) - \underline{\underline{\frac{k_{2N}}{2}(x_0^2 - y_0^2)\,\Delta x}} + \mathrm{o}(\Delta x^2)$$

5 sextupoles in FF beamline.
Since SF5 is too weak to correct, we use 4 other sextupoles.

⇨ $\alpha_x^*, \alpha_y^*, \eta_x^*, \eta_x'^*$ *are changed.*

Orthogonal to make $\alpha_x^*, \alpha_y^*, \eta_x^*, \eta_x'^*$ correction knobs .

Sextupole magnet is moved by Δy vertically

$$x \to x_0, \qquad y \to y_0 - \Delta y$$

Skew quadrupole field

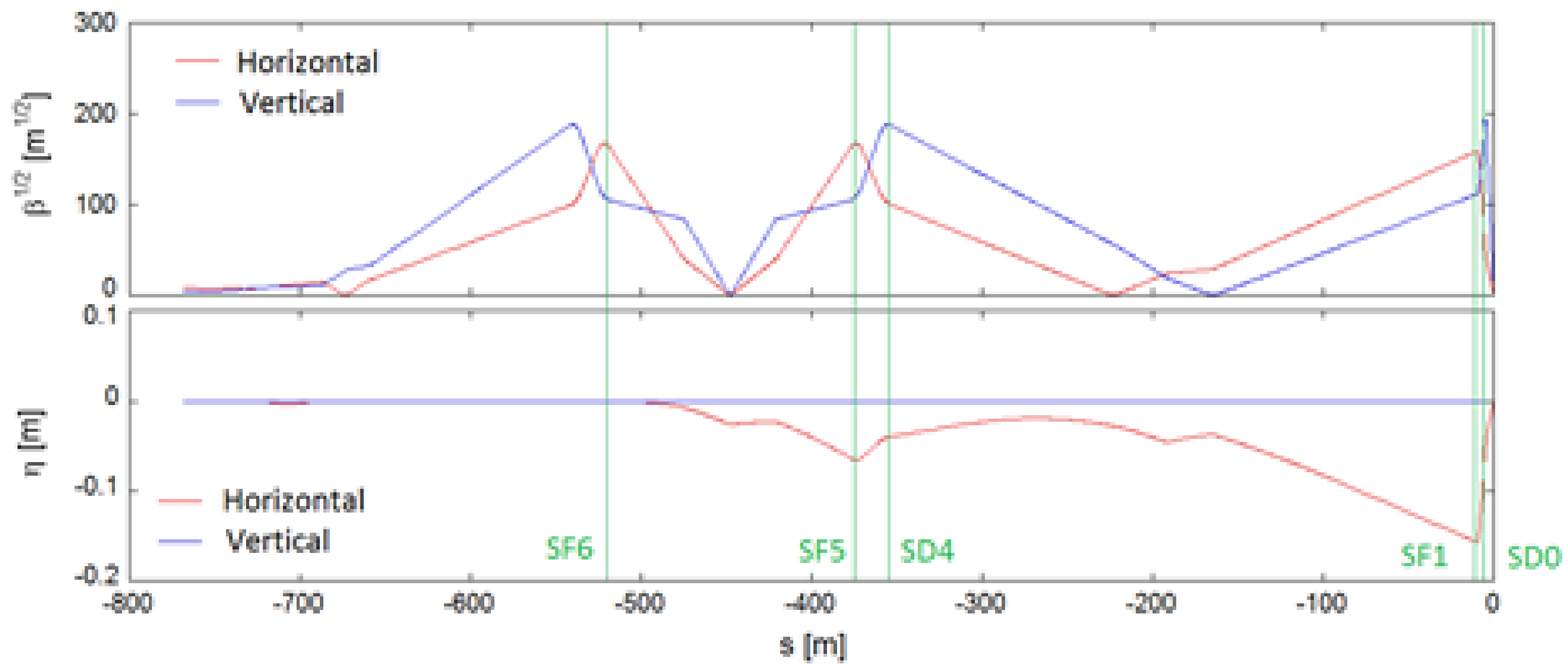
$$-\frac{q}{p_0}A_{s,2N} = \frac{k_{2N}}{6}(x_0^3 - 3x_0 y_o^2) + \underline{\underline{k_{2N} x_0 y_0\,\Delta y}} + \mathrm{o}(\Delta y^2)$$

5 sextupoles in FF beamline.
Since SF5 is too weak to correct, we use 4 other sextupoles.

⇨ $\langle xy \rangle_{IP}, \ \langle xy' \rangle_{IP}, \eta_y^*, \eta_y'^*$ *are changed.*

Orthogonal to make $\langle xy' \rangle_{IP}, \eta_y^*, \eta_y'^*$ correction knobs .

Sextupole Strength Change



Strength of normal sextupole magnet is changed by ΔK_2

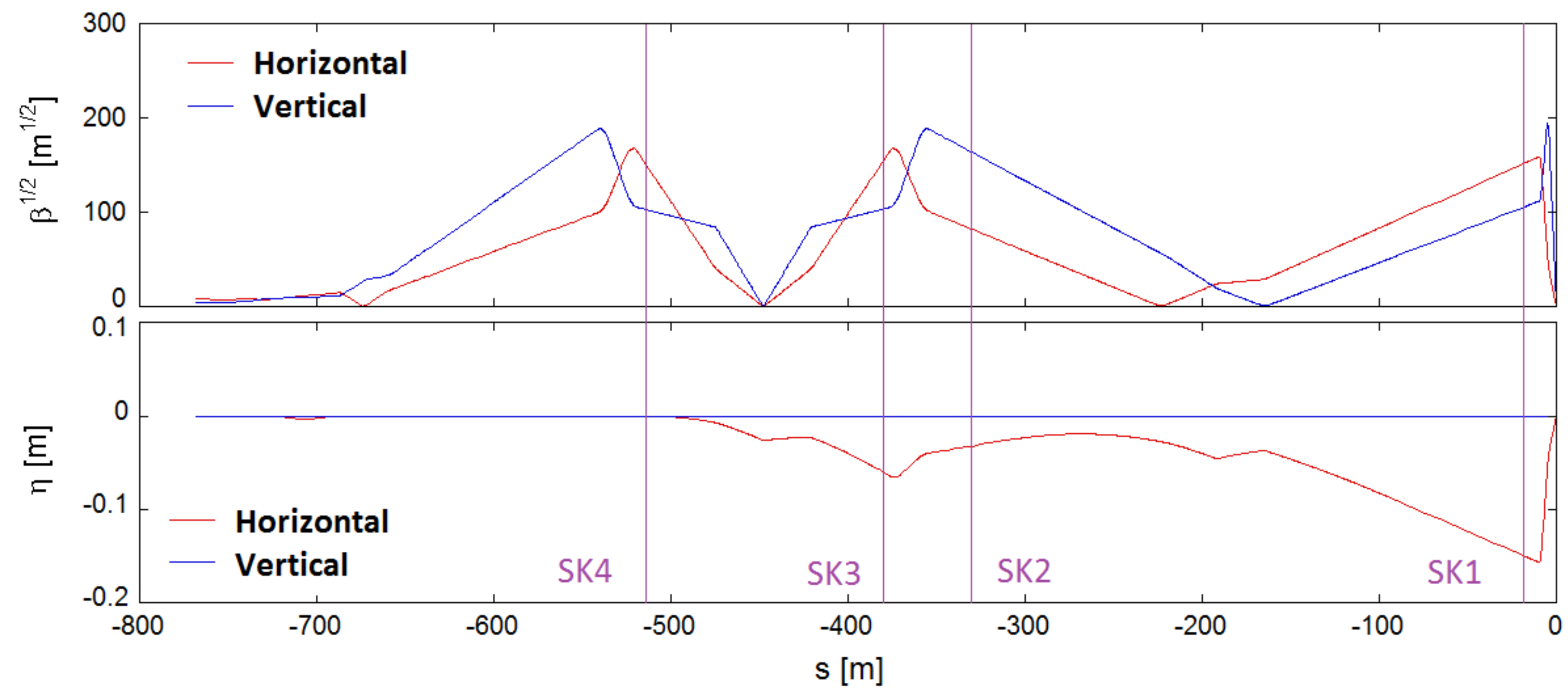
$$\frac{\Delta x_{IP}}{\sqrt{\beta_x^*}} = \underbrace{\left(-\beta_x^{3/2}\Delta K_2\right)}_{T_{122}} u_x^2 + \underbrace{\left(-2\eta_x\beta_x\Delta K_2\right)}_{T_{126}} u_x\delta + \underbrace{\left(-\eta_x^2\beta_x^{1/2}\Delta K_2\right)}_{T_{166}} \delta^2 + \underbrace{\left(\beta_x^{1/2}\beta_y\Delta K_2\right)}_{T_{144}} u_y^2$$

$$\frac{\Delta y_{IP}}{\sqrt{\beta_y^*}} = \underbrace{\left(2\beta_x^{1/2}\beta_y\Delta K_2\right)}_{T_{324}} u_x u_y + \underbrace{\left(+2\eta_x\beta_y\Delta K_2\right)}_{T_{346}} u_y\delta$$

Four 2nd order optics components are changed for IP horizontal position.
Two 2nd order optics components are changed for IP vertical position.

Skew Sextupoles for Optics Correction

In ILC Final Focus beamline, 4 skew sextupoles are arranged for optics correction.



Strength of skew sextupole magnet is changed by ΔK_2

$$\frac{\Delta x_{IP}}{\sqrt{\beta_x^*}} = \underbrace{\left(2\beta_x\beta_y^{1/2}\Delta K_2\right)}_{T_{124}} u_x u_y + \underbrace{\left(+2\eta_x\beta_x^{1/2}\beta_y^{1/2}\Delta K_2\right)}_{T_{146}} u_y\delta$$

$$\frac{\Delta y_{IP}}{\sqrt{\beta_y^*}} = \underbrace{\left(-\beta_x\beta_y^{1/2}\Delta K_2\right)}_{T_{322}} u_x^2 + \underbrace{\left(-2\eta_x\beta_x^{1/2}\beta_y^{1/2}\Delta K_2\right)}_{T_{326}} u_x\delta + \underbrace{\left(-\eta_x^2\beta_y^{1/2}\Delta K_2\right)}_{T_{366}} \delta^2 + \underbrace{\left(\beta_y^{3/2}\Delta K_2\right)}_{T_{344}} u_y^2$$

Two 2nd order optics components are changed for IP horizontal position.
Four 2nd order optics components are changed for IP vertical position.

2^{nd} order optics tuning knobs

	Horizontal beam size: Chromaticity	Horizontal beam size: Geometrical Aberration	Horizontal beam size: 2^{nd} order Dispersion	Vertical beam size: Chromaticity	Vertical beam size: Geometrical Aberration	Vertical beam size: 2^{nd} order Dispersion
Normal Sextupole	T_{126}	T_{122} T_{144}	T_{166}	T_{346}	T_{324}	
Skew Sextupole	T_{146}	T_{124}		T_{326}	T_{322} T_{344}	T_{366}

Ignored for small effect

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

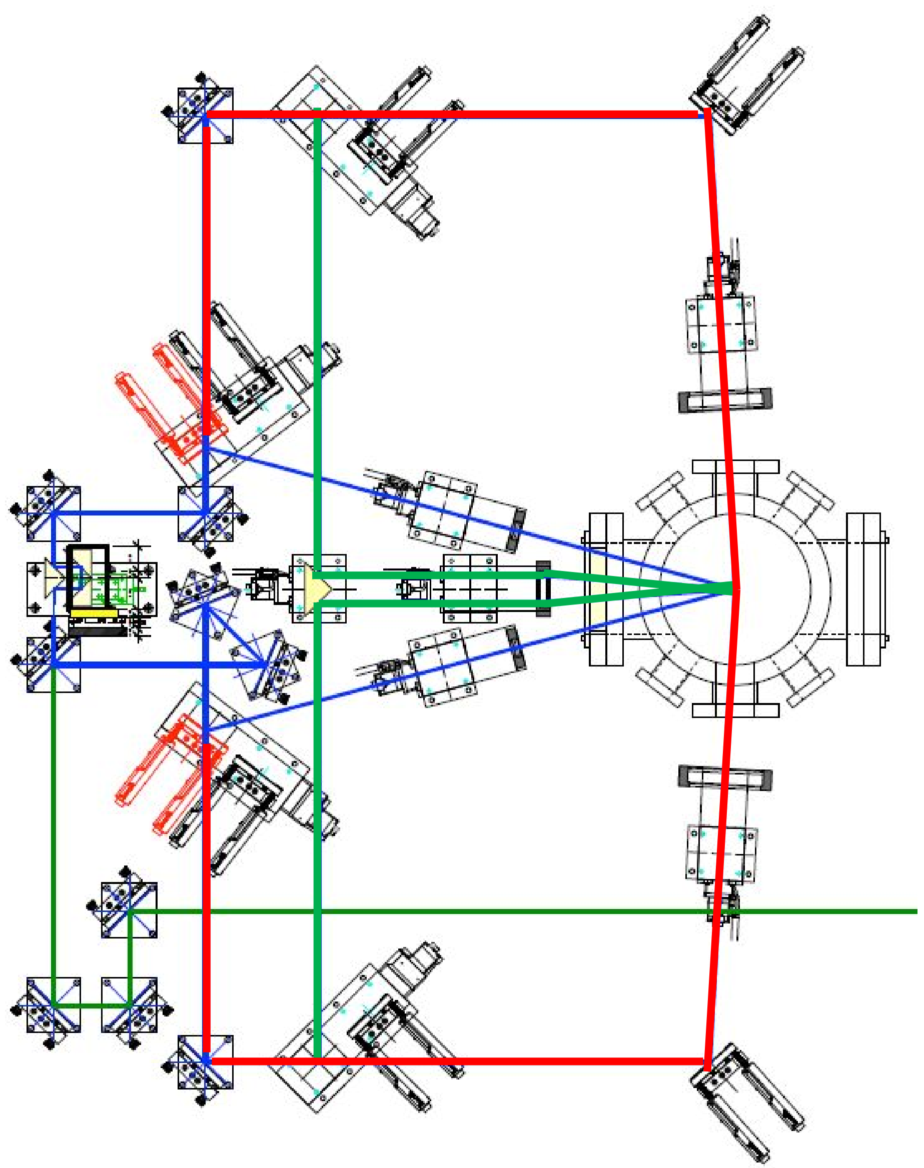
We use 5 sextupoles to correct 5 aberrations.

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.

IP-BSM (Shintake Monitor) for ATF2



Laser wave length was changed.

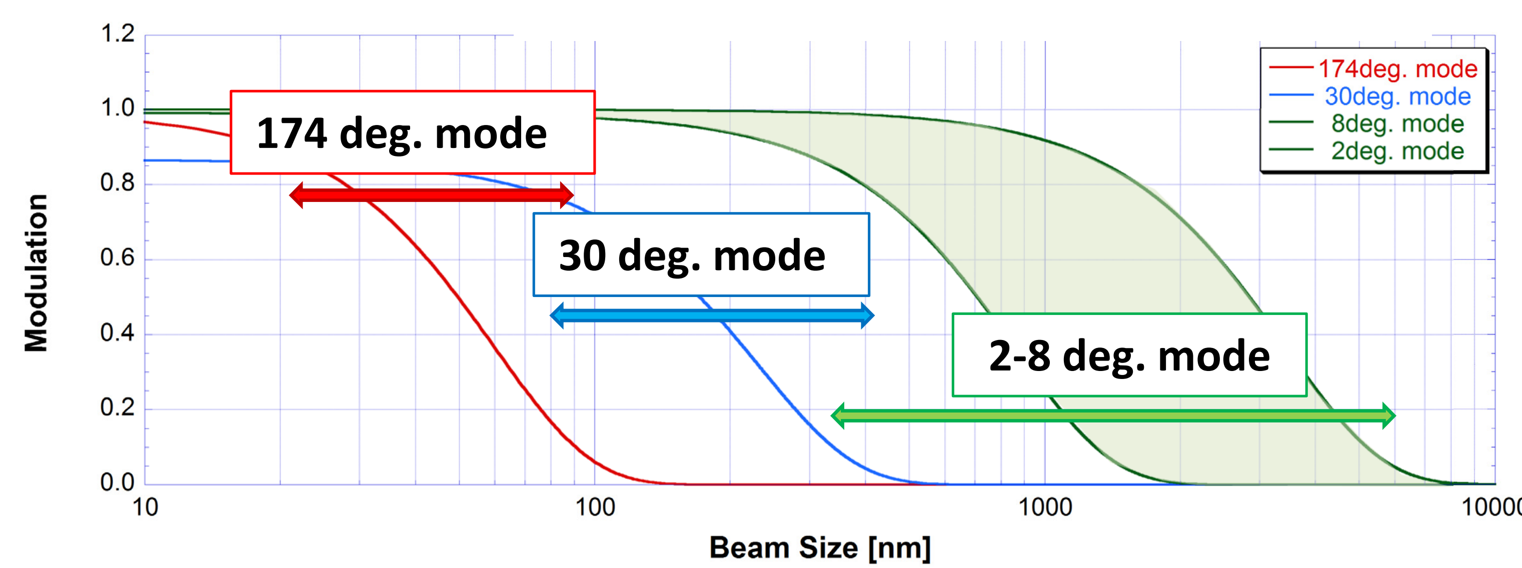
FFTB ; Nd:YAG fundamental mode (1064nm)

ATF2 ; Nd:YAG harmonic doubler (532nm)

Add the collision mode

FFTB	ATF2
174deg mode	174deg mode
30 deg mode	30 deg mode
	2-8deg mode

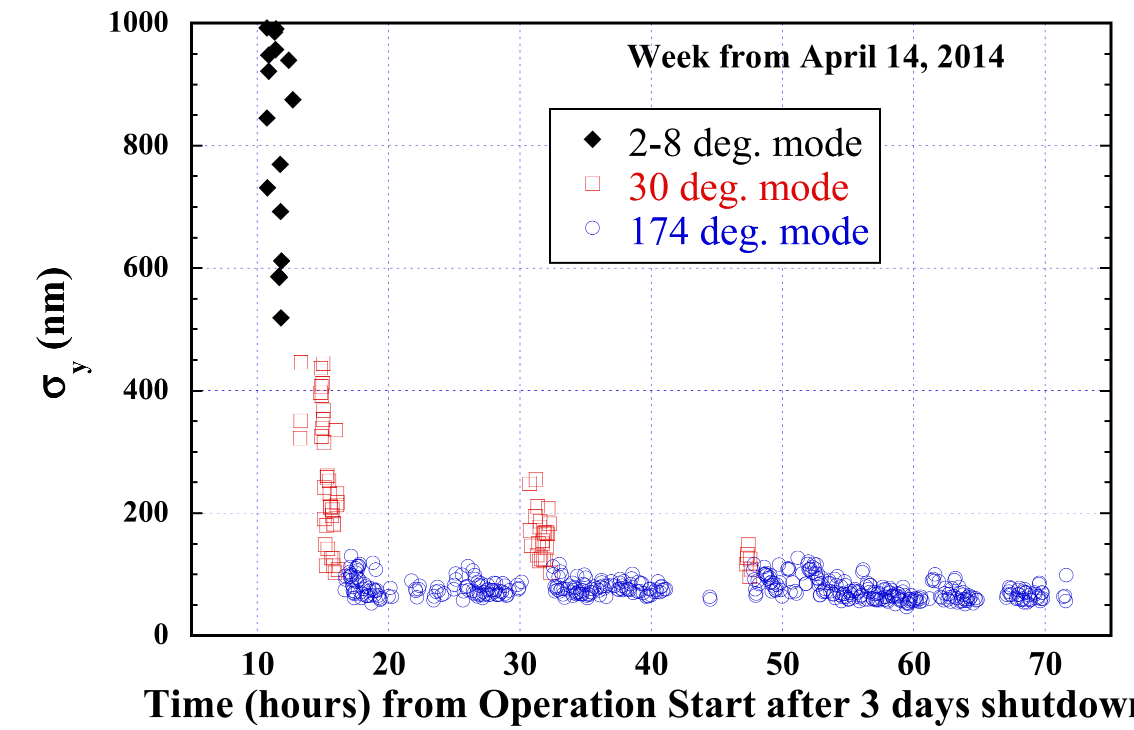
ATF2 IP-BSM (20 – 6mm)



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)*



presented by K.Kubo (KEK) at IPAC2014

FF sextupoles turned ON

Carbon Wire
- *AY knob*
- *EY knob*
- *Coup2 knob*

→

IP-BSM 8degree
- *AY knob*
- *EY knob*
- *Coup2 knob*

→

IP-BSM 30degree
- *AY knob*
- *EY knob*
- *Coup2 knob*
- *Y24 knob*
- *Y46 knob*

→

IP-BSM 174 degree
- *AY knob*
- *EY knob*
- *Coup2 knob*
- *Y24 knob*
- *Y46 knob*
- *Y22 knob*
- *Y26 knob*
- *Y66 knob*
- *Y44 knob*

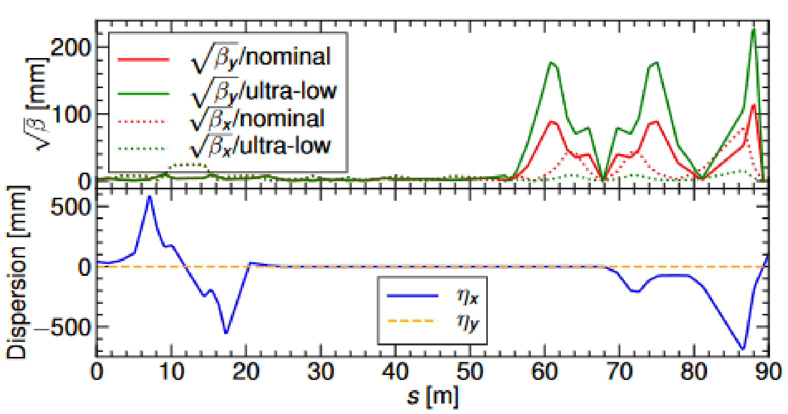
The ATF2 tuning procedure is same to ILC final focus beam line.

Ultra-low beta optics study at ATF2 to investigate of the correction of higher aberration

by R. Yang at ATF review 2020

- $0.25\beta_y^*$ 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**



Before 2016
$10\beta_x^*0.5\beta_y^*/25\beta_x^*\ 0.5\beta_y^*$

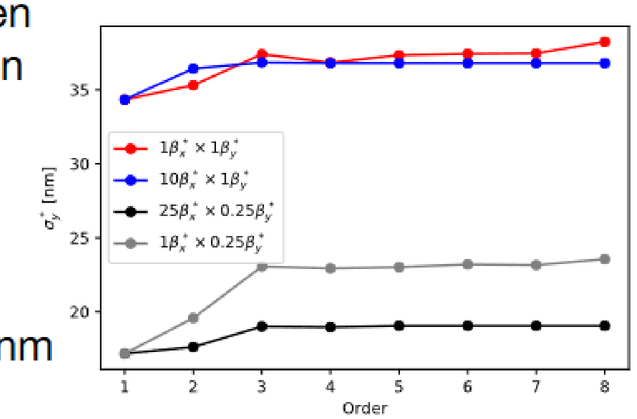
↓ 51 nm (2016)

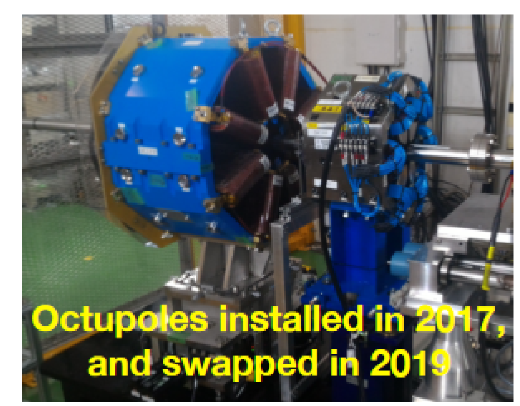
2016-present
$25\beta_x^*0.25\ \beta_y^*$

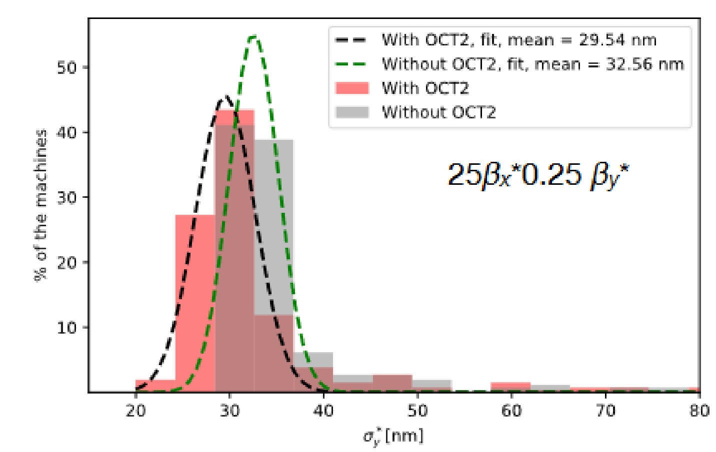
↓ 50 nm (2019)

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

- 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





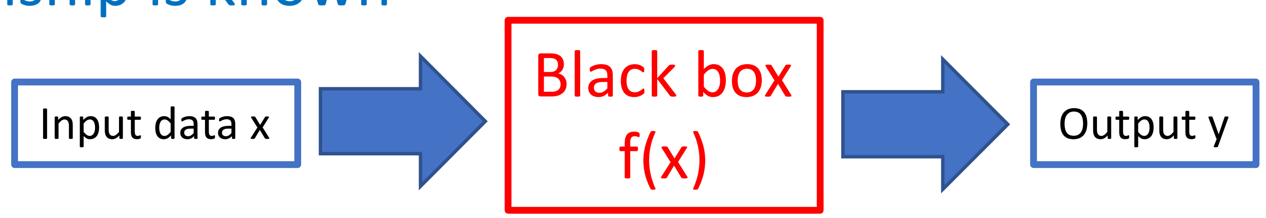


training for ILC beam tuning (ML etc.)

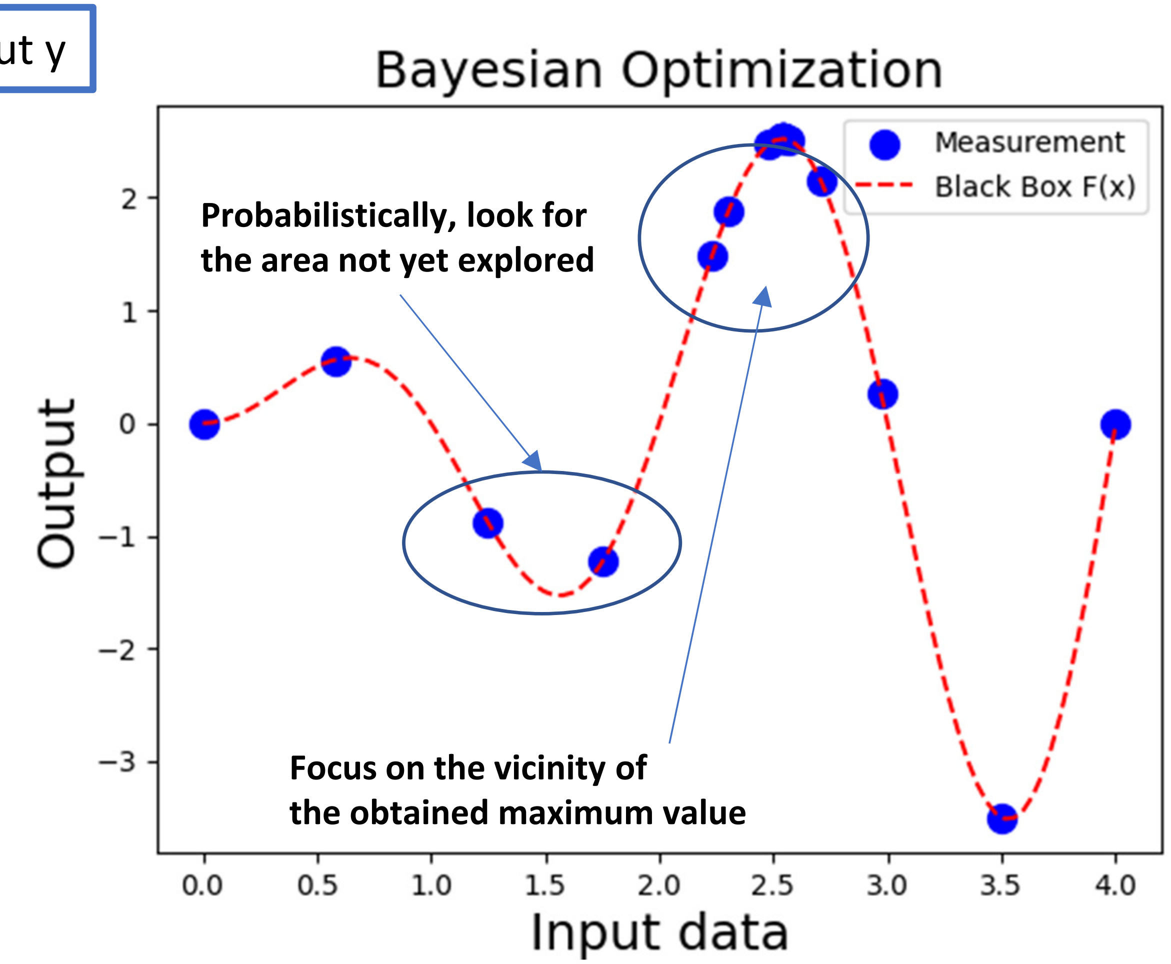
Auto-tuning using Machine Learning

by M. Kurata

- Realization of automatic beam-tuning
  - Minimize the number of tuning parameter searches: Reduce tuning time
  - Simultaneous optimization of multiple parameters: Better tuning including correlation
- Optimization of the beam = "Black-box Optimization"
  - Looking for the global maximum in situations where only the input-output relationship is known



  - Auto-tuning using "Bayesian Optimization"



Using the trial results so far, predict

- Parameter space not yet explored
- Parameter space close to maximum value

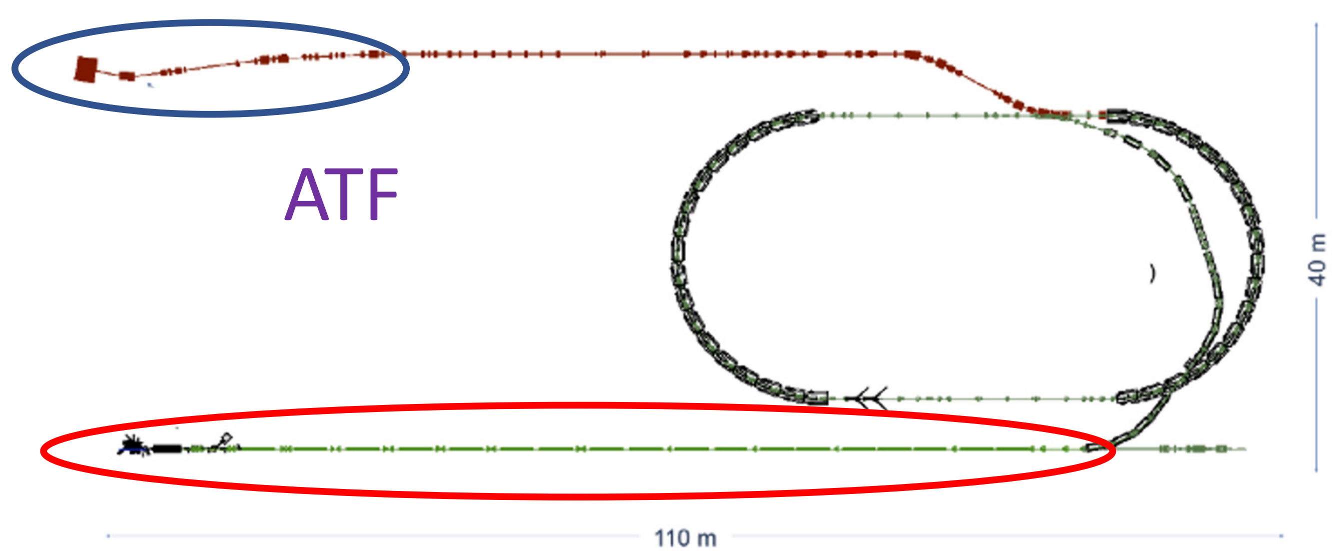
and search efficiently

Do not need "training", like neural-network

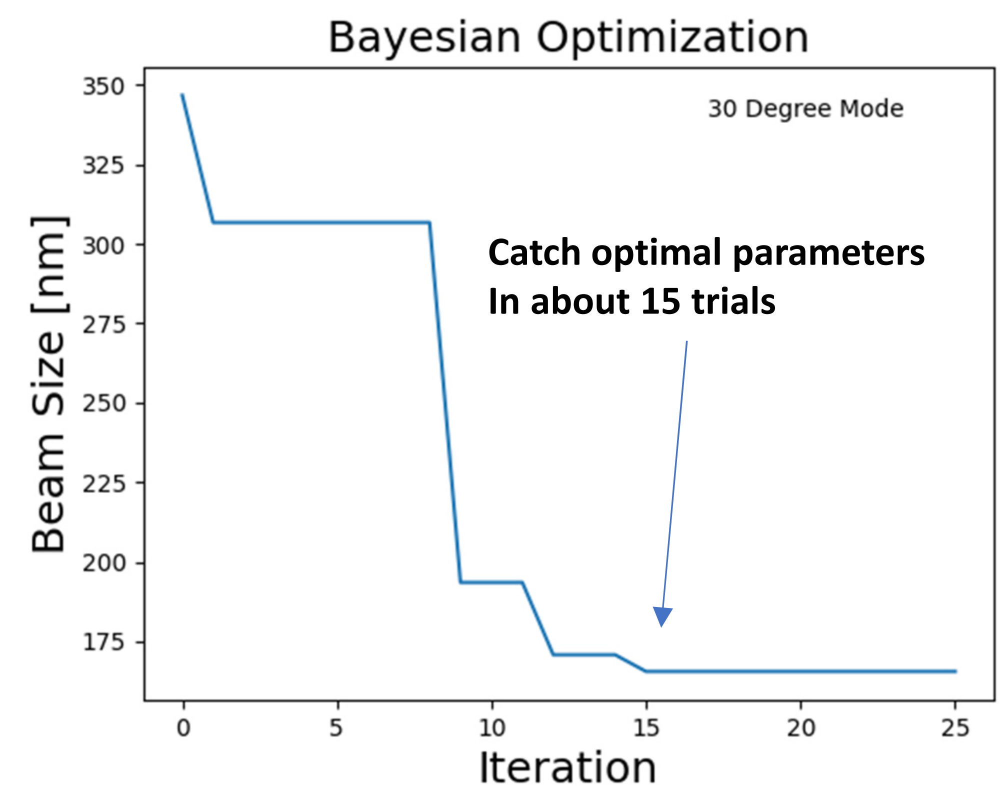
Bayesian Optimization @ATF

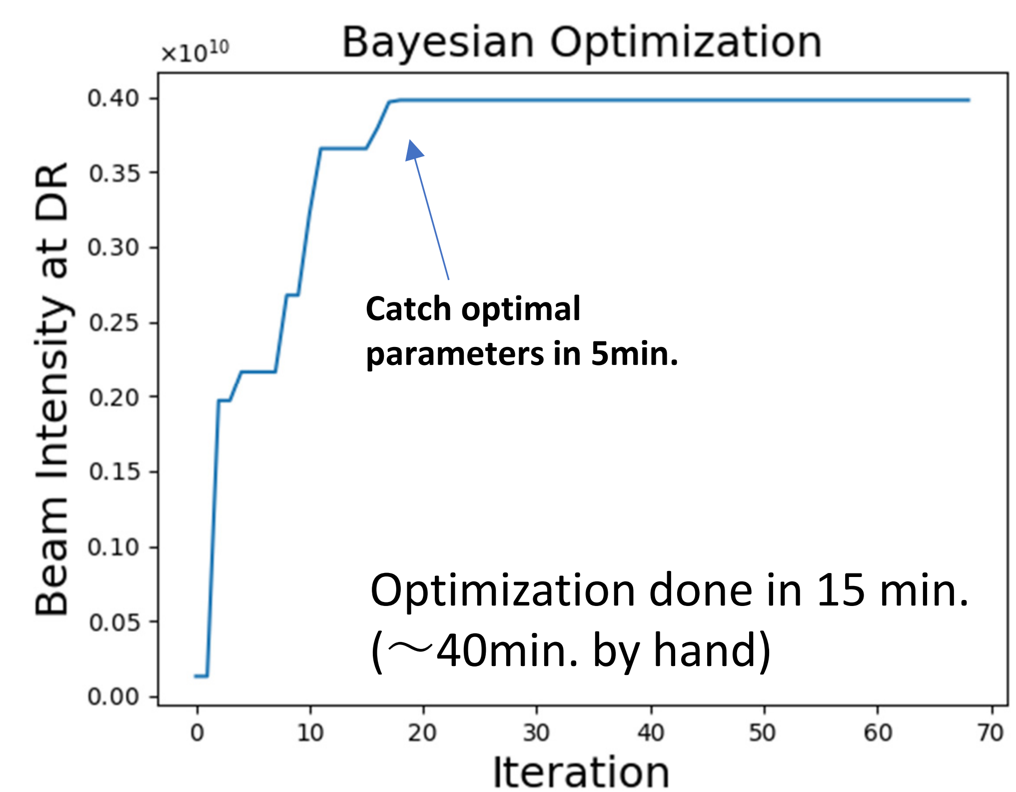
by M. Kurata

- Final Focus: Nano-beam tuning for the ILC
  - **Simultaneous optimization of multiple parameters**
    - Search for better parameters, including correlation
    - 3-parameter tuning: can obtain optimal value
    - Aiming for small beam by adjusting more parameters simultaneously



- Linac: Beam transportation to Damping ring
  - **Maximize transport efficiency to the damping ring**
  - Realize the auto-parameter optimization





If you are interested in doing research at ATF2 beamline, shall we do it together.