ATF2 and Perspective of ATF3

Philip Burrows

Director, John Adams Institute for Accelerator Science,

Oxford University

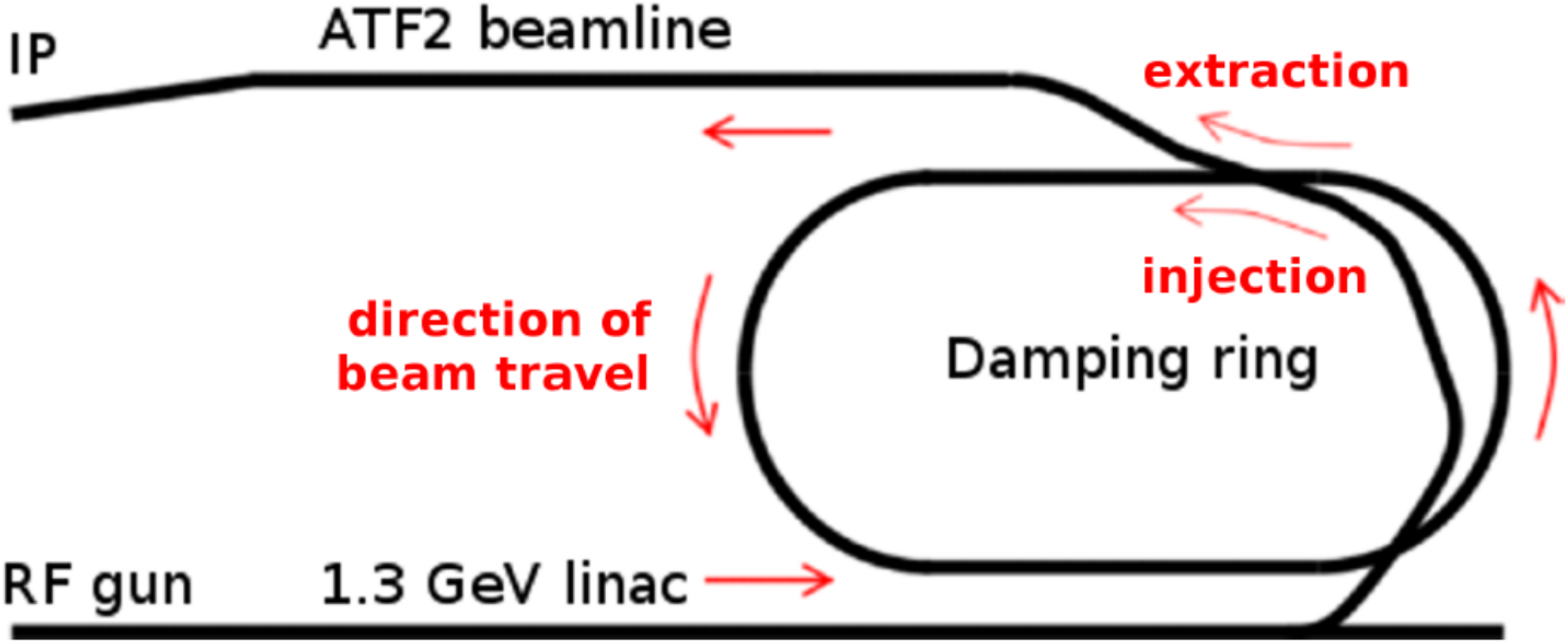
Thanks to:

Yuki Abe, Alex Aryshev, Angeles Faus-Golfe, Kiyoshi Kubo, Shigeru Kuroda,

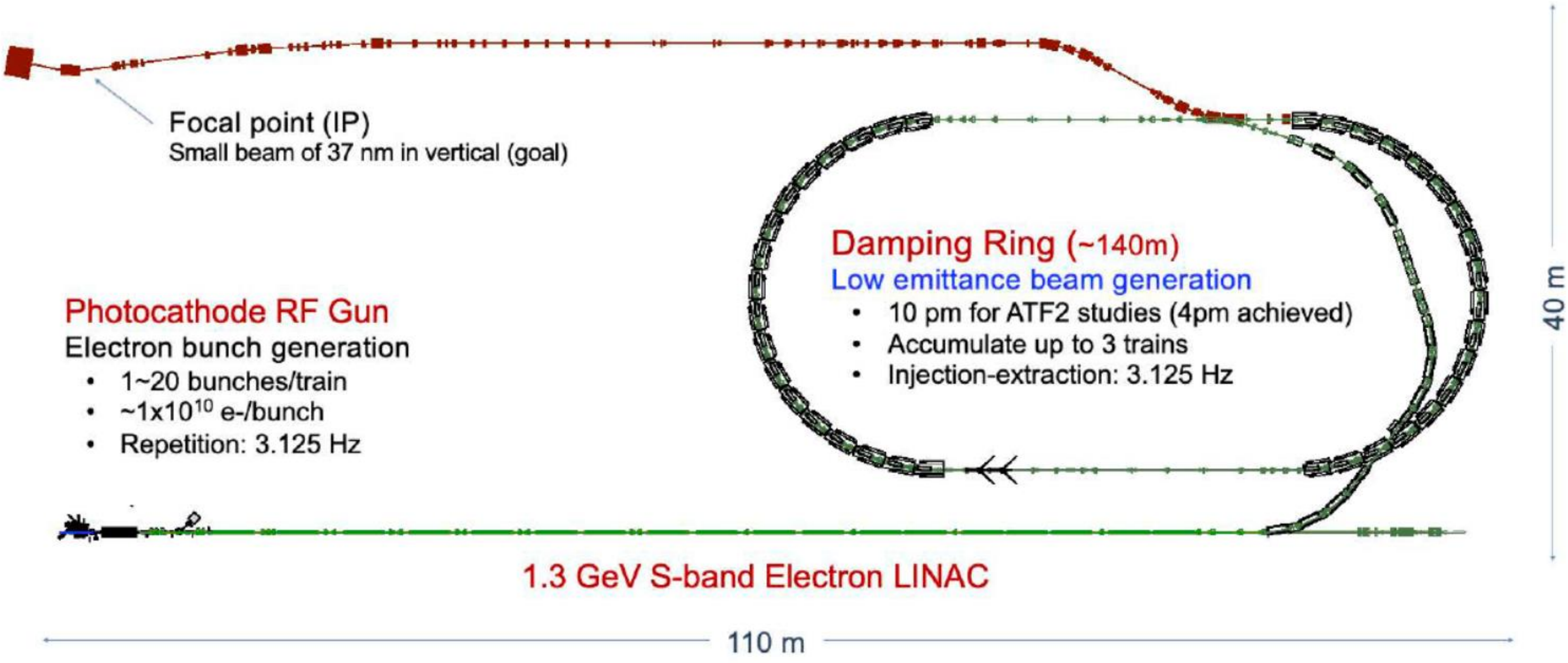
Toshiyuki Okugi, Nobuhiro Terunuma

KEK/ATF

https://www-atf.kek.jp/atf/



ATF systems



ATF2 final focus test beamline

Nanometer beam development

- Final focus System R&D
- Intra-train ultra-fast beam feedback

Advanced Beam Instruments R&D

Application of Low-emittance beam

Focal point (IP)

Small beam of 37 nm in vertical (goal)

Damping Ring (~140m)

Low emittance beam generation

- 10 pm for ATF2 studies (4pm achieved)
- Accumulate up to 3 trains
- Injection-extraction: 3.125 Hz

Photocathode RF Gun

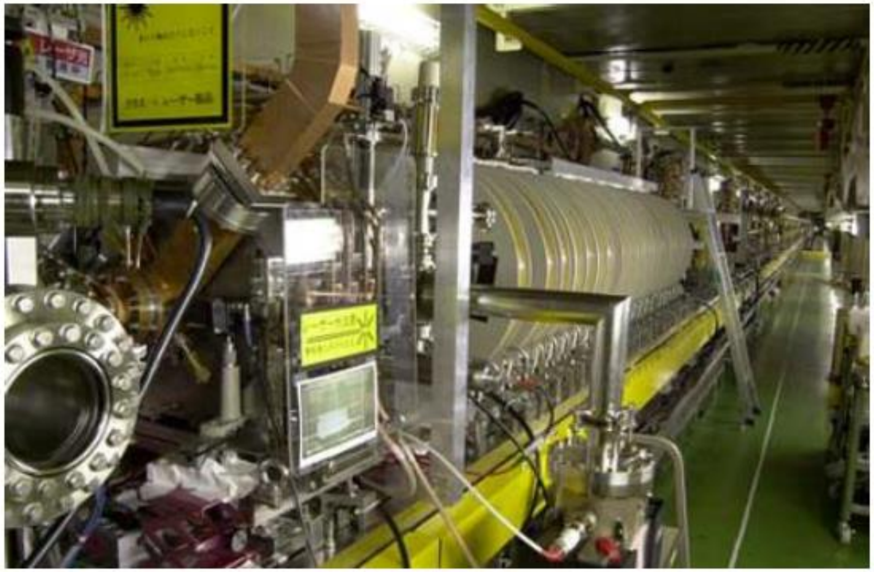
Electron bunch generation

- 1~20 bunches/train
- ~1x10^{10} e-/bunch
- Repetition: 3.125 Hz

1.3 GeV S-band Electron LINAC

ATF linac

- Beam Energy 1.3 GeV
- Up to 4E10 e-/bunch (usually 1E10)
- Up to 10 bunches/pulse
- Rep. rate ~6.25 Hz (usually 3.125 or 1.5625 Hz)
- Acceleration system
  - RF frequency 2.856 MHz (S- band, same as SLAC)
  - 19 accelerating structures + 2 energy compensation structures,
  - 3 m long each



Kuroda

ATF damping ring

$E=1.3GeV, C=140\ m$

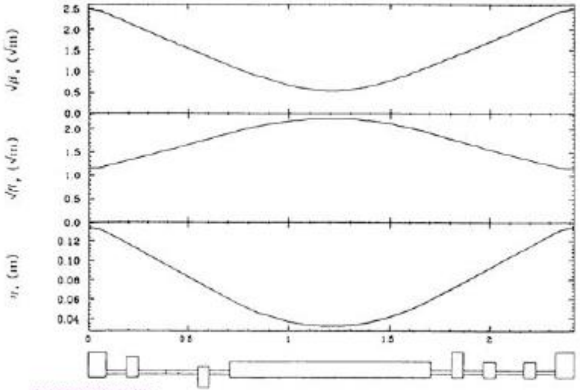
$Ne=0\sim 2x10^{10}\ e\text{-}/bunch$

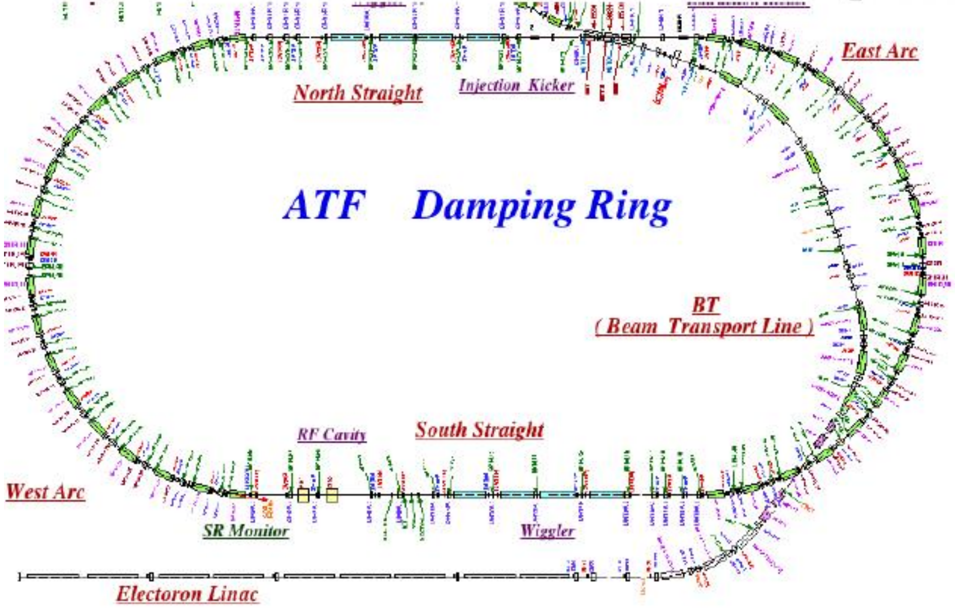
1 ~ 10 bunches/train

1~3 trains/ring

$\gamma\varepsilon_x = 2.5E\text{-}6$ **(at 0 intensity)**

$\gamma\varepsilon_y < 2.5E\text{-}8$ **(at 0 intensity)**





Low vertical emittance beam production was one of the main goal of ATF.

Much effort has been done for emittance tuning(including monitor R&D).

↓

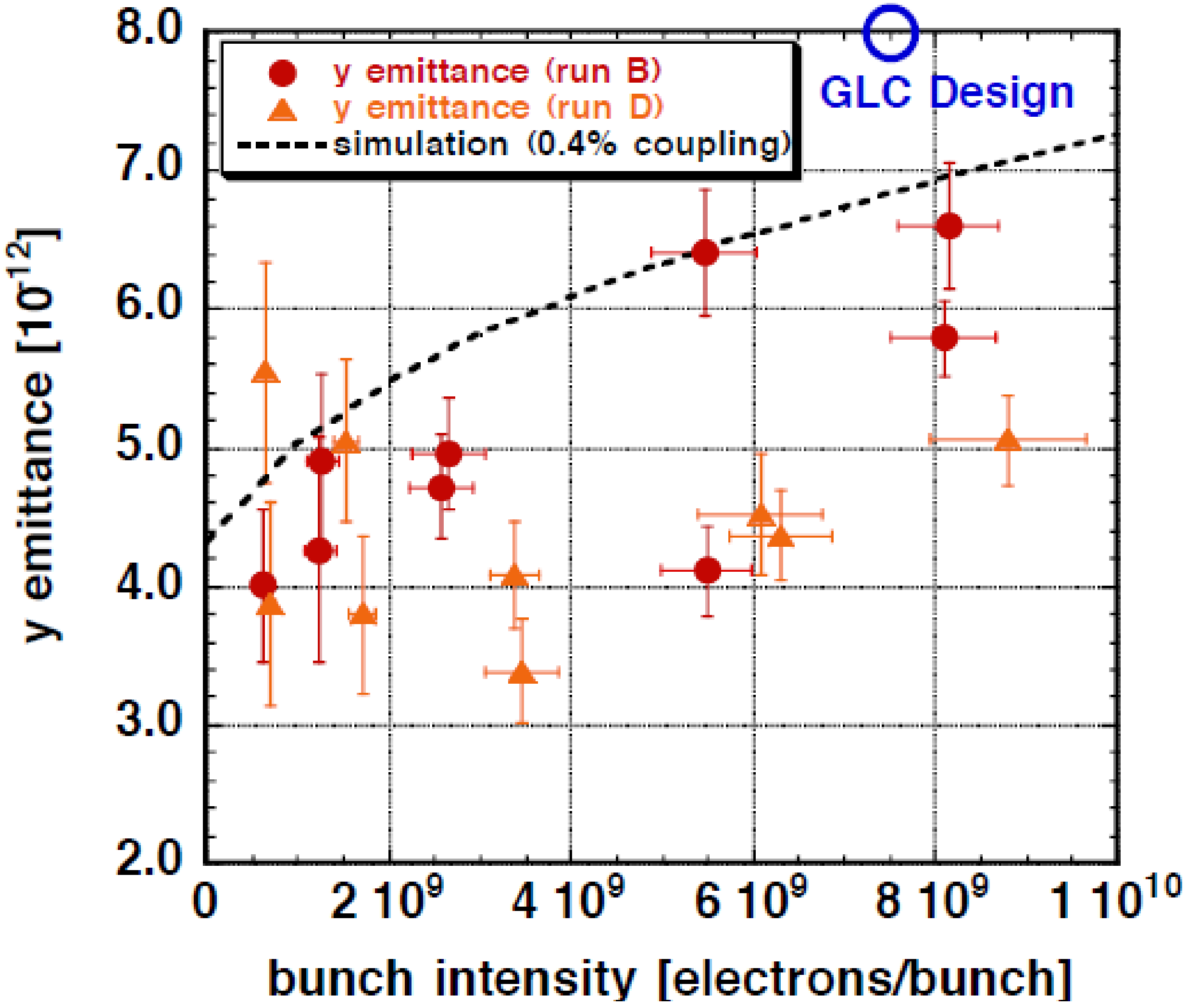
Quick tuning(≈ 1 shift) with

vertical dispersion correction

x-y coupling correction

→ ≈ 10 pm vertical emittance

Vertical emittance



Kuroda

ATF2 lattice

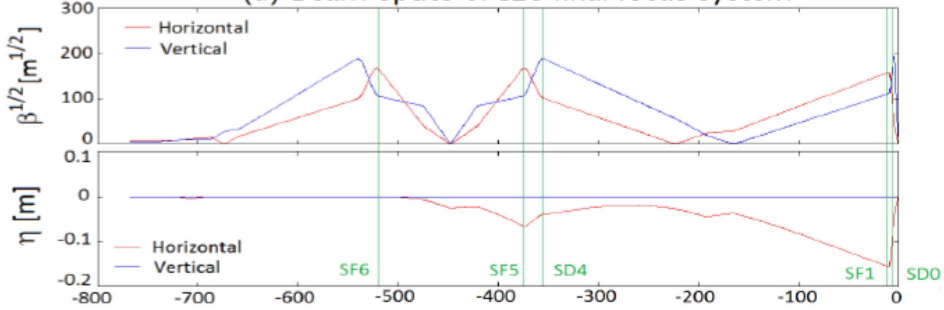
Scale model of Linear Collider Raimondi-Seryi final-focus system (for ILC)

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

Final Focus Line
β and η functions

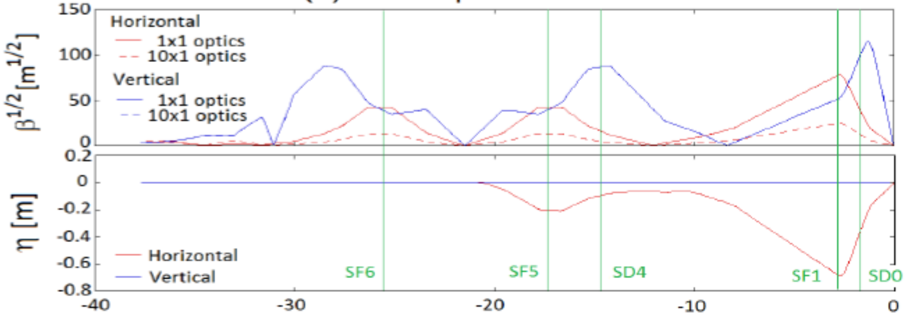
ILC

(a) Beam optics of ILC final focus system



ATF

(b) Beam optics of ATF2 beamline



ATF2 beamline

ATF2 optics

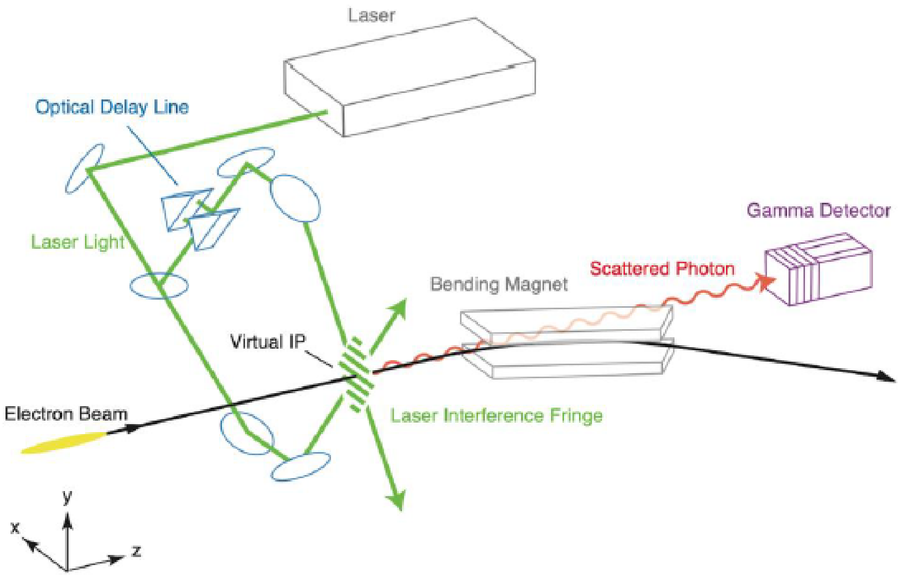
- Original design
  - **Similar chromaticity** (~L*/β*) in both x and y directions as ILC
  - Tighter tolerances of multipole field error, due to larger ATF beam physical emittance
- 10x1 optics (10 times larger β*_x, same β*_y)
  - Smaller chromaticity in x direction
  - **Similar multi-pole field error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

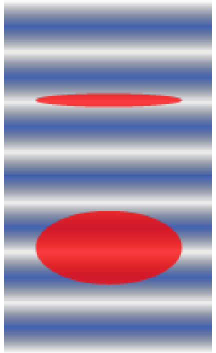
Chromaticity of ATF and ILC Final Focus

	ATF Original	ATF 10x1	ILC
L*/β*_x	250	25	320
L*/β*_y	10,000	10,000	10,000

(L*: distance from final Q to IP)

IP beam size monitor



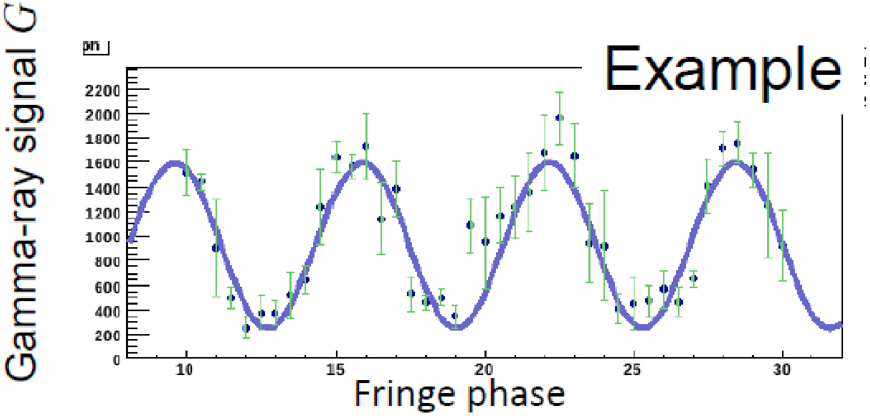


Small beam
↓
Large M

Large beam
↓
Small M

Scan interference fringe phase.
Fit modulation M:

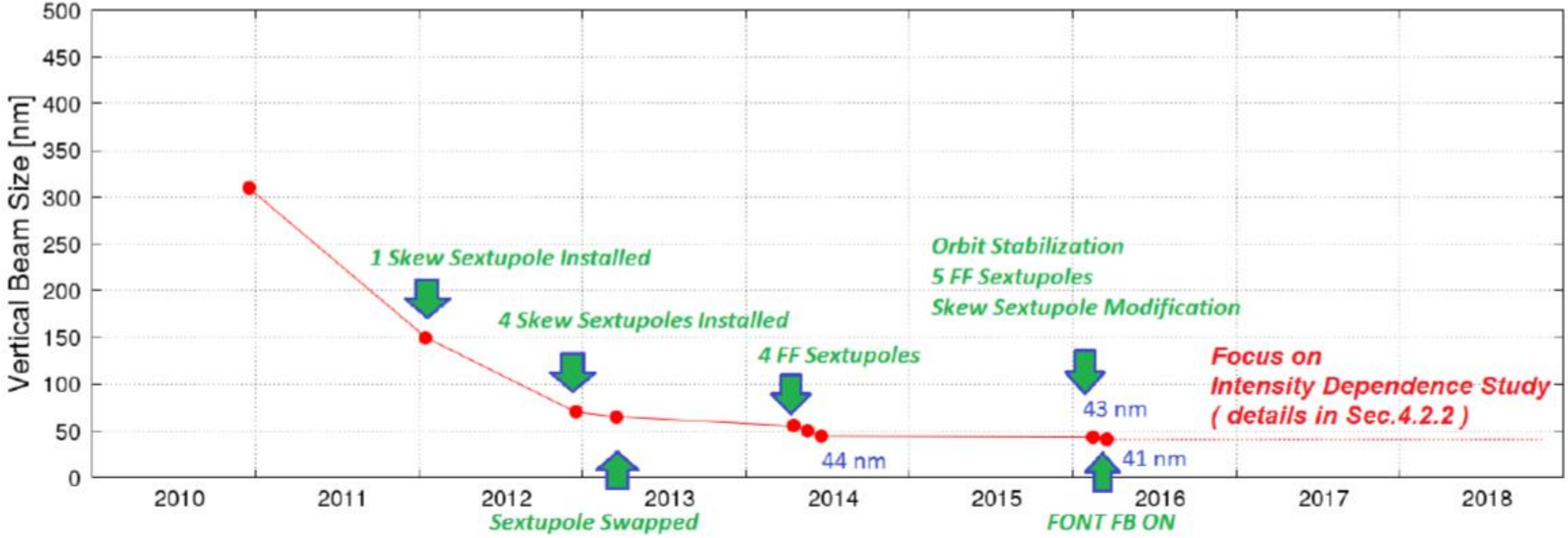
$$G(\phi) = G_0\left(1 + M\cos(\phi + \phi_0)\right)$$



IP beam size monitor

Terunuma

IP beam size history



Focus on
Intensity Dependence Study
(details in Sec.4.2.2)

Smallest beam size achieved ~ 41 nm ←→ 7 nm @ ILC

Kubo

IP beam size limitation

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

Example of Measured IPBSM Modulation vs. bunch population

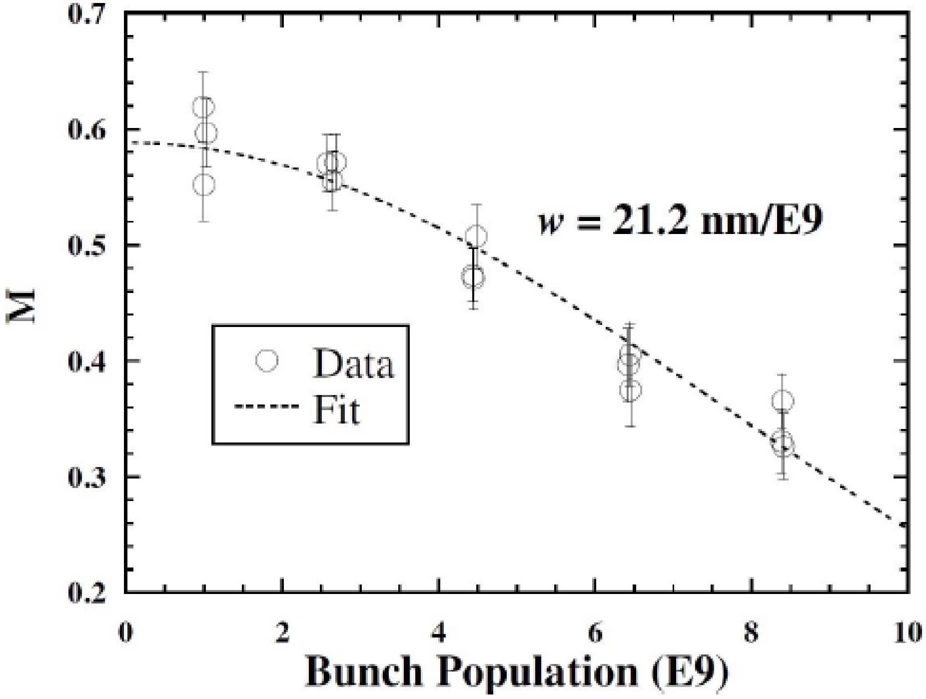


Figure 18

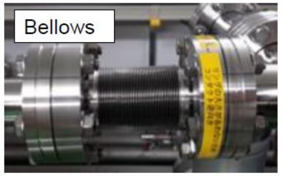
Fitting:
$\sigma^2 = \sigma^2_0 + w^2 N^2$

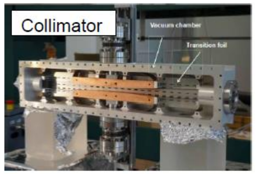
Beam size growth ~21nm/ 1x10^{10}e

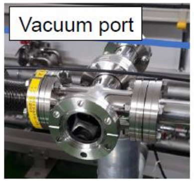
Transverse wakefield is dominant cause of the dependence.

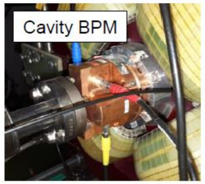
Kubo

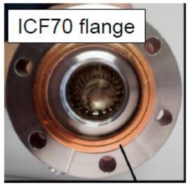
Wakefield sources


Bellows

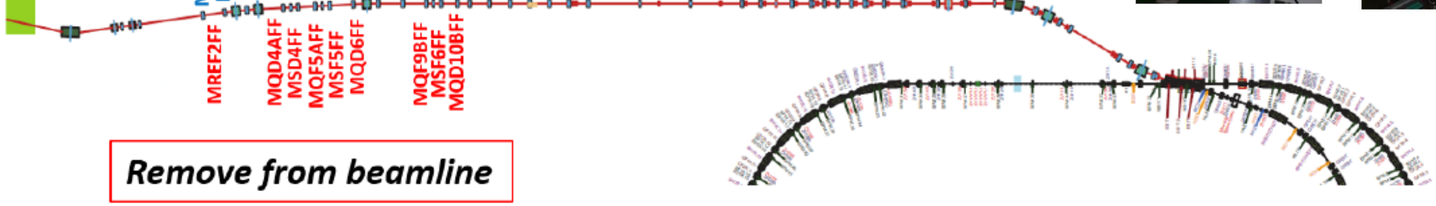

Collimator


Vacuum port


Cavity BPM


ICF70 flange

Some of Cavity BPMs Removed

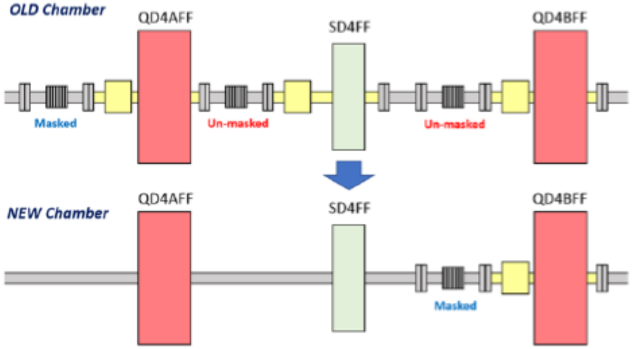


Remained

Remove from beamline

Bellows and Flanges Reduced

Example: Around SD4FF

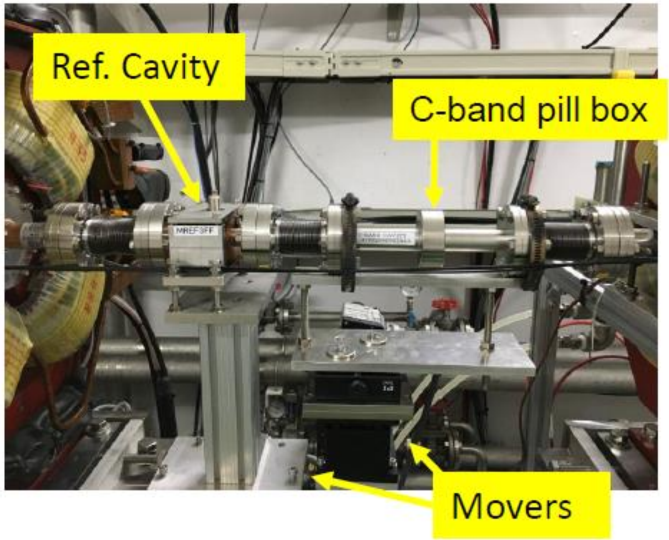


- Remove some BPMs, bellows, flanges.
- Shield bellows
- Shield flange gaps, etc.
- Etc.

Controlled wakefield source

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

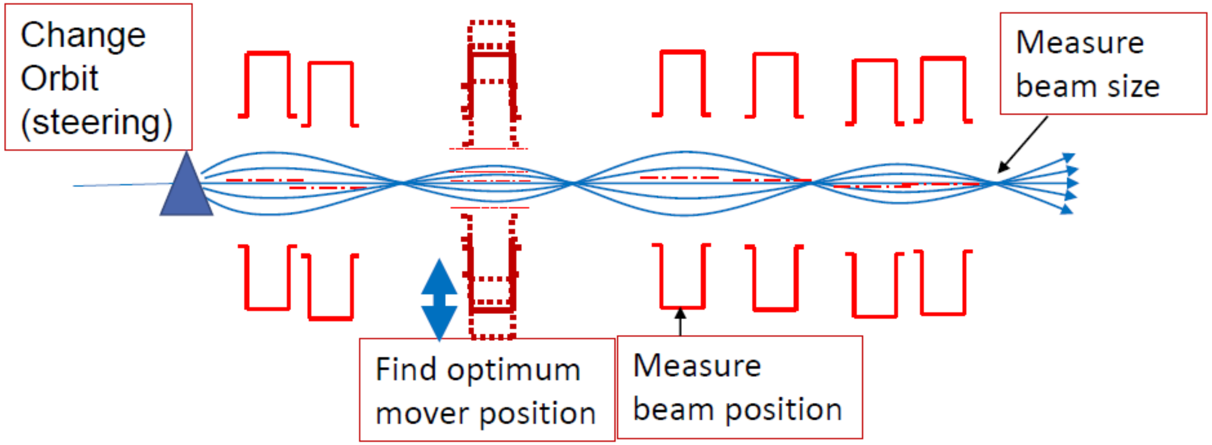
Present setup



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

Wakefield reduction



Change Orbit (steering)

Measure beam size

Find optimum mover position

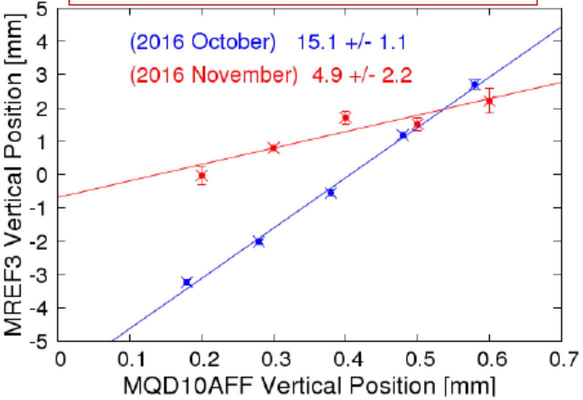
Measure beam position

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

→ Total wakefield strength can be estimated

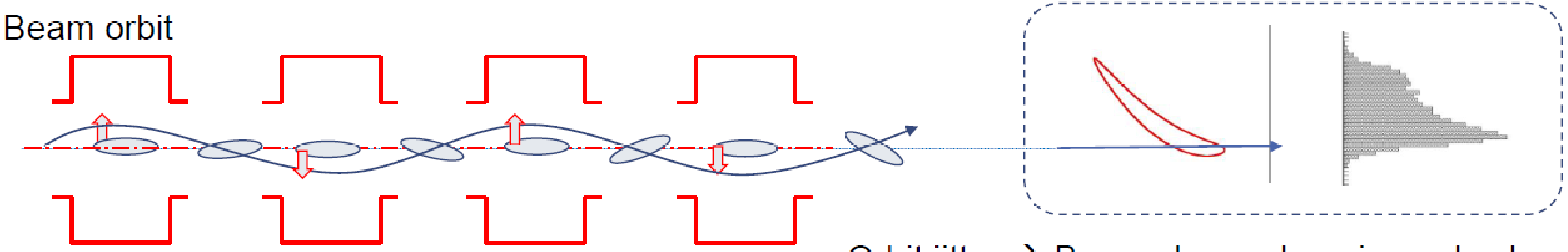
Figure 25

optimum mover position vs. orbit change



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

Dynamic effects



Orbit jitter → Beam shape changing pulse by pulse

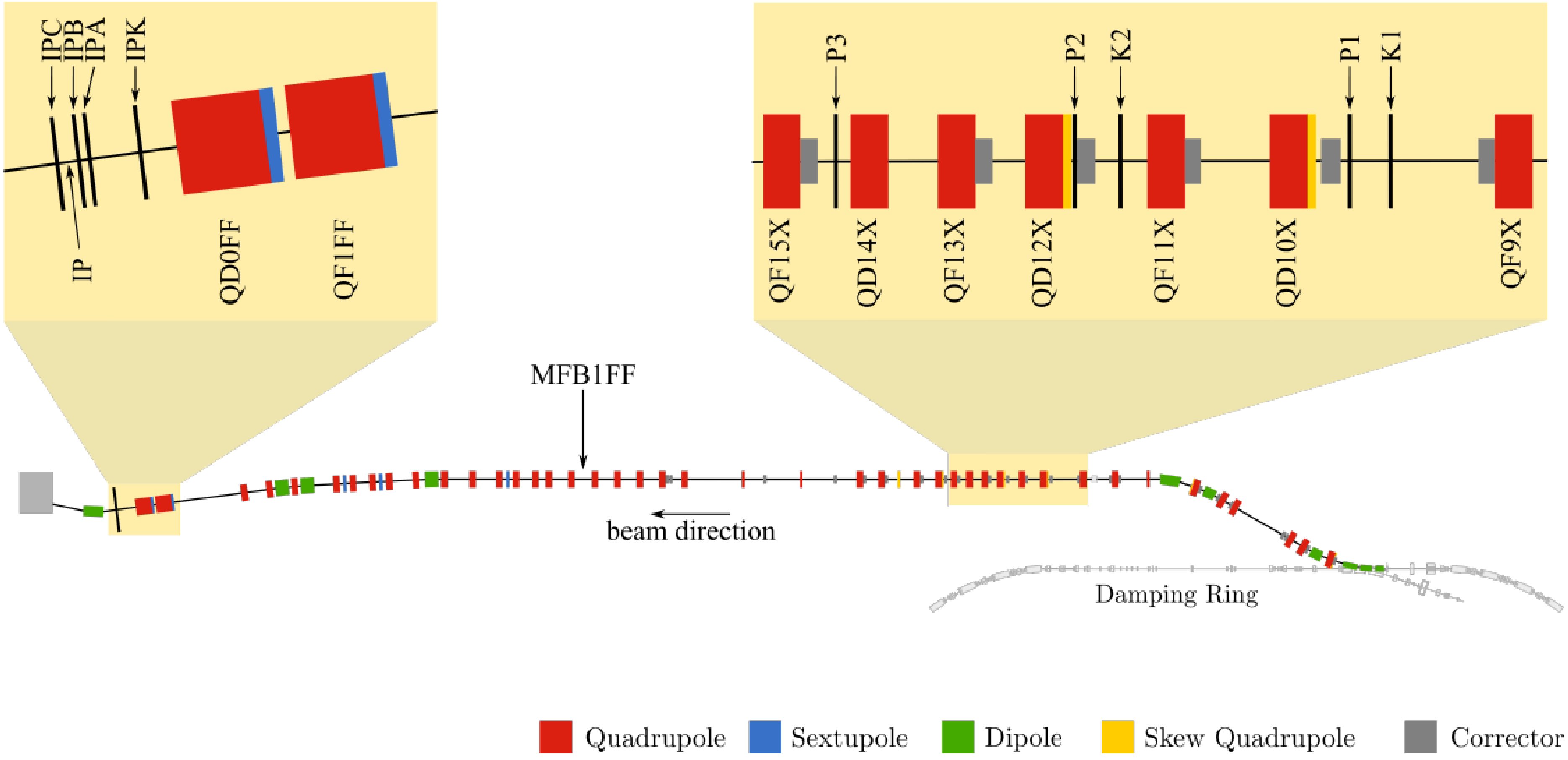
Our monitor measures beam size of sum of many pulses.

Observed orbit jitter is about 0.1-0.3σ.
"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.

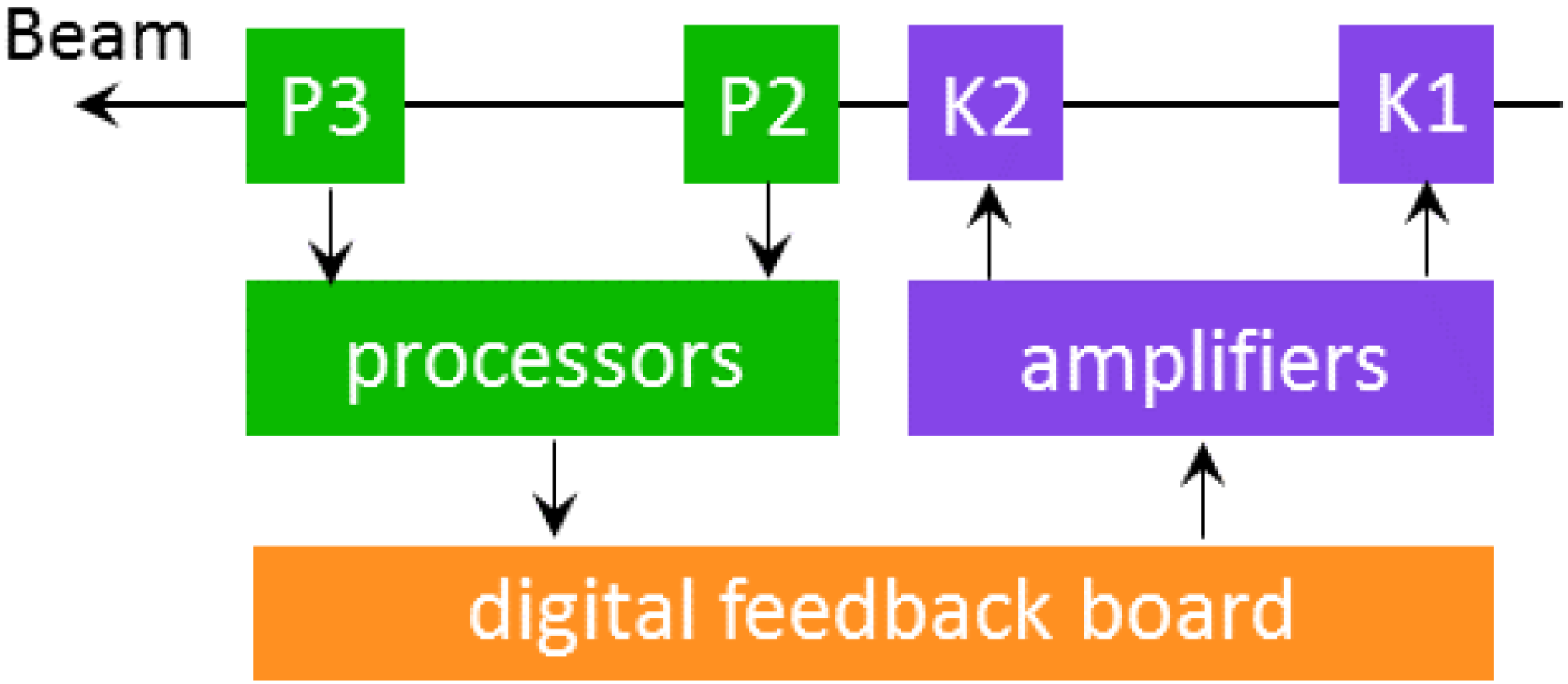
FONT FB installation at ATF

IP FB system

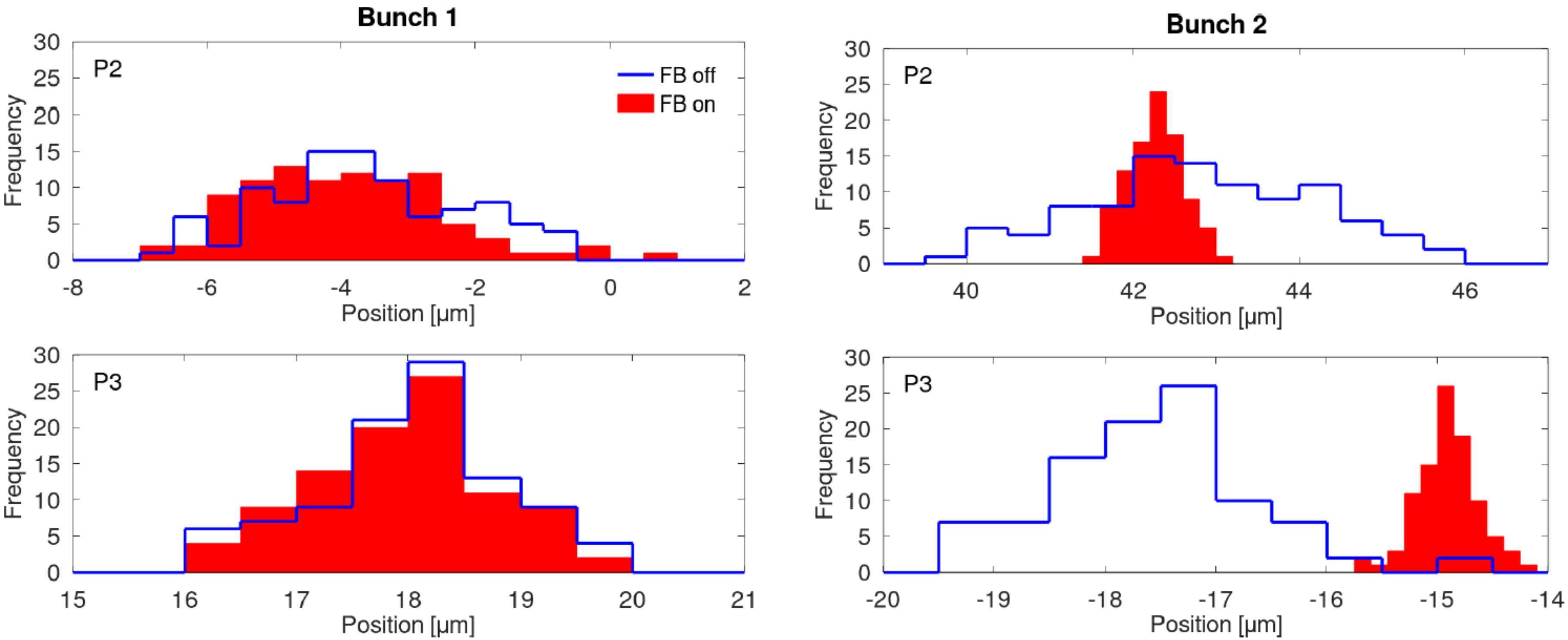
Upstream FB system



Upstream y-y’ FB system



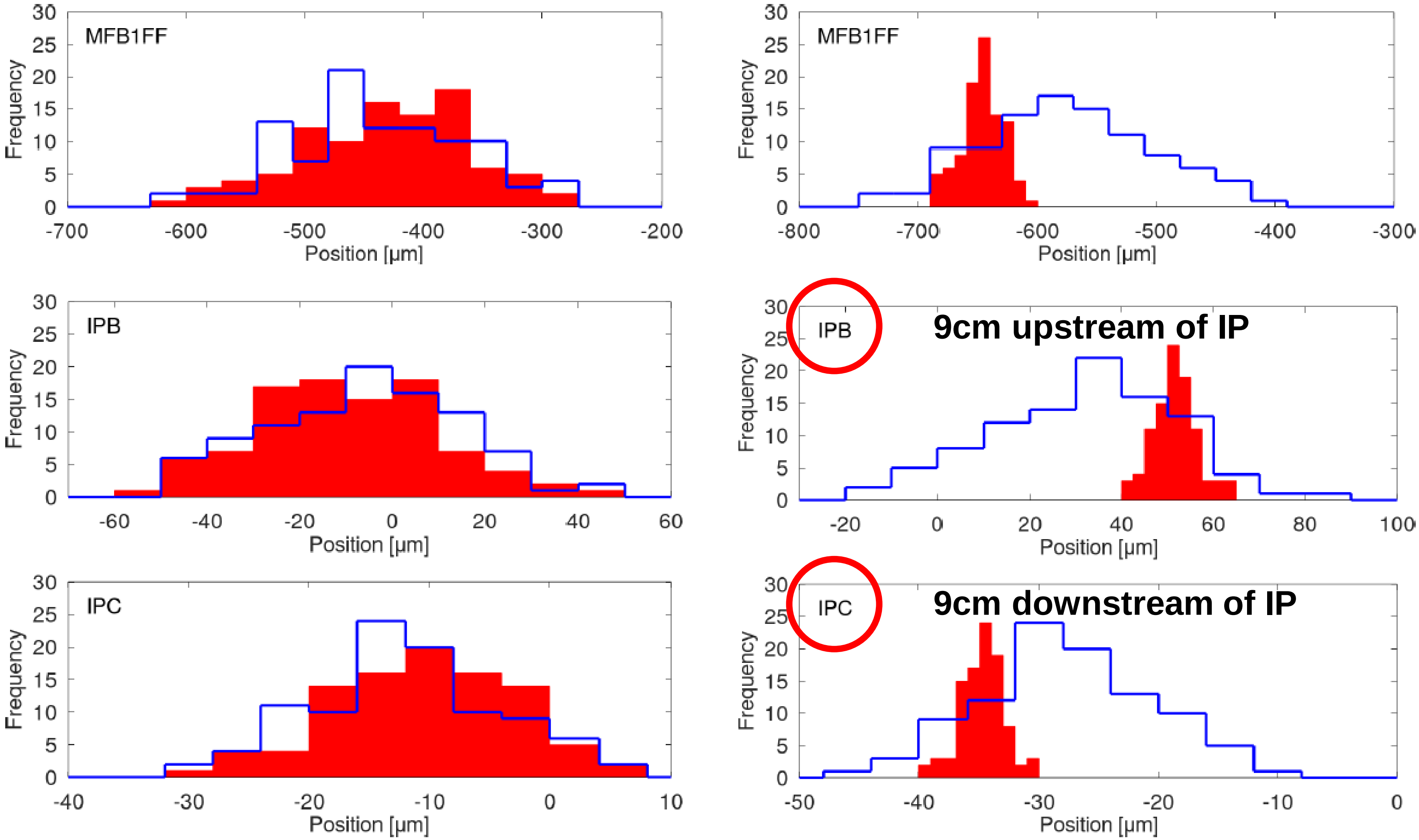
In-loop BPMs



Jitter reduced by factor ~ 4, to BPM resolution (~200nm) limit

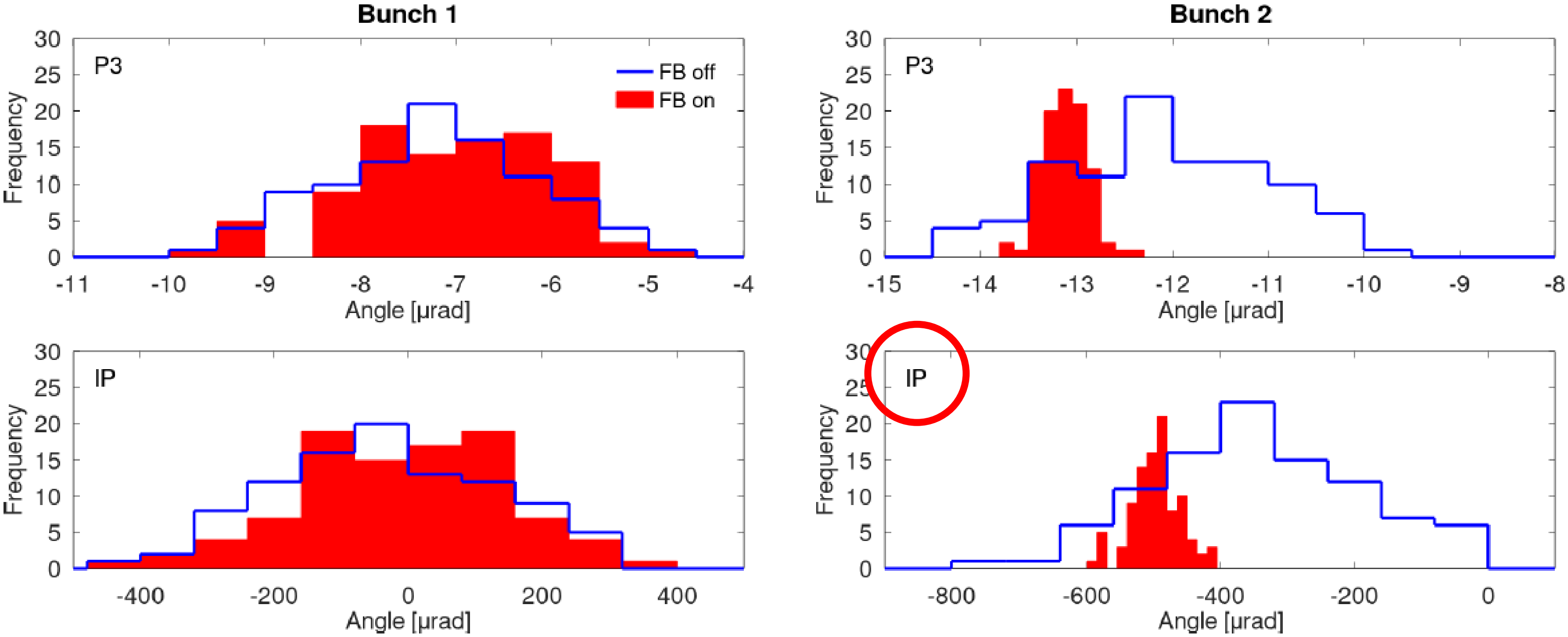
Downstream witness BPMs

Position jitter reduced by factor ~4 at IP

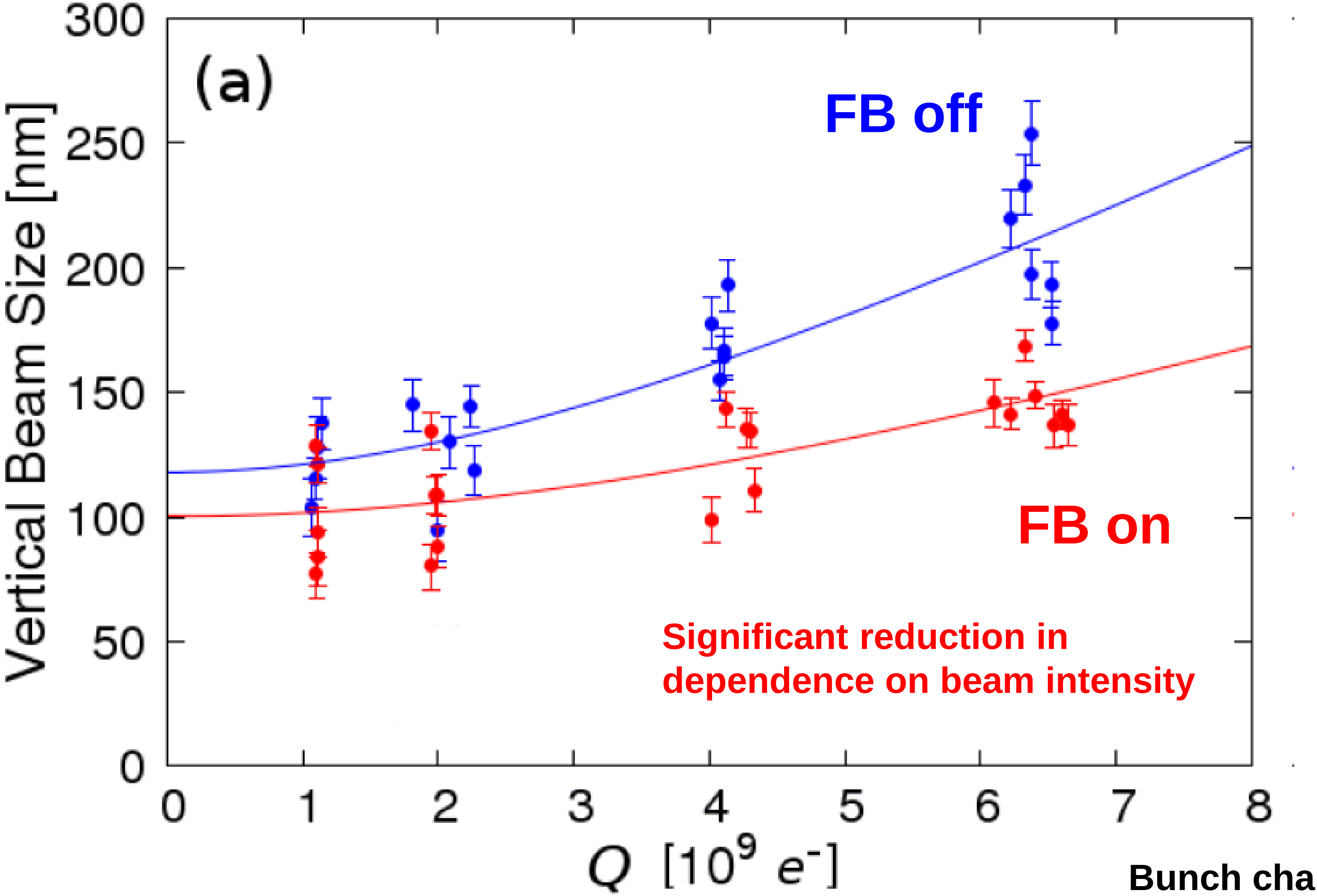


Results in terms of beam angle

Angle jitter reduced by factor ~4



Application of upstream y-y’ feedback to reduction of beam-size growth due to wakefields



Significant reduction in dependence on beam intensity

Bunch charge

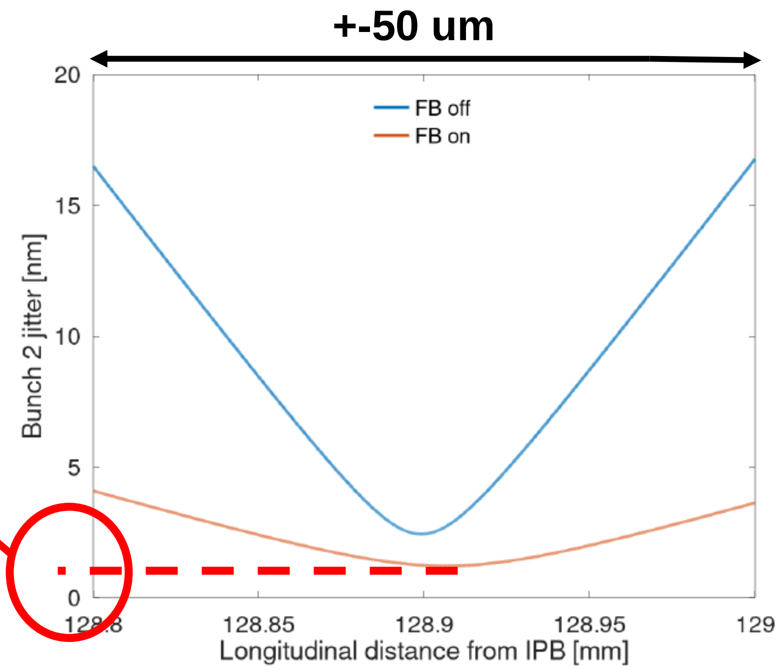
Extrapolation to IP

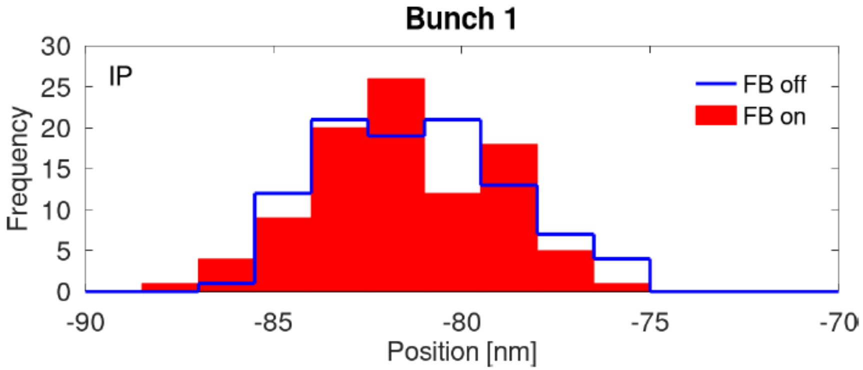
Track beam data from upstream region to IP using MADX model

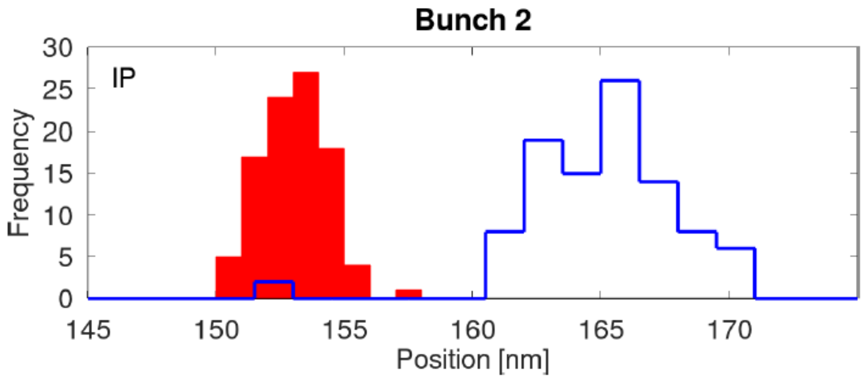
→ **beam stabilised to ~1nm at IP**

→ correction limited by upstream FB BPM resolution

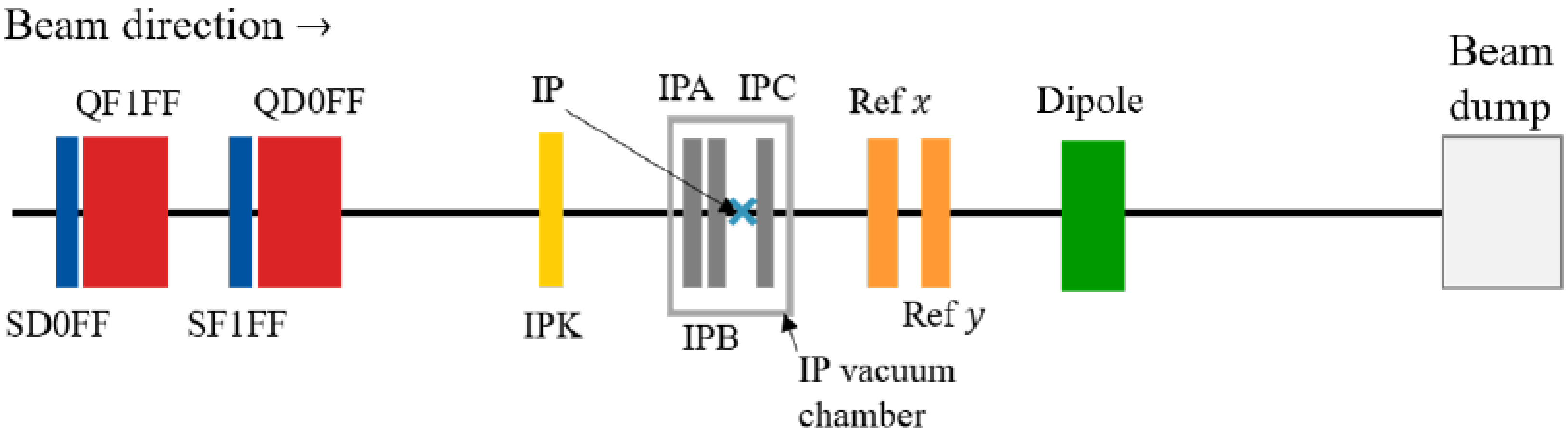
→ not possible to measure directly with 1nm resolution!

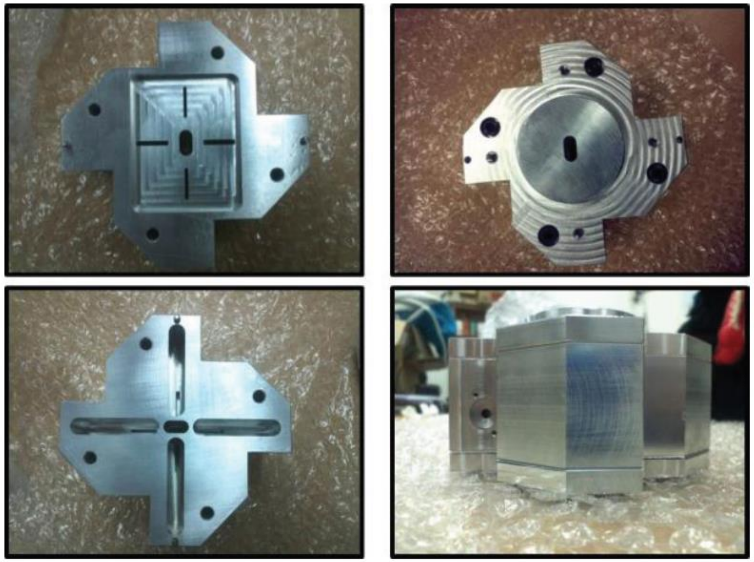






ATF2 'IP' FB system

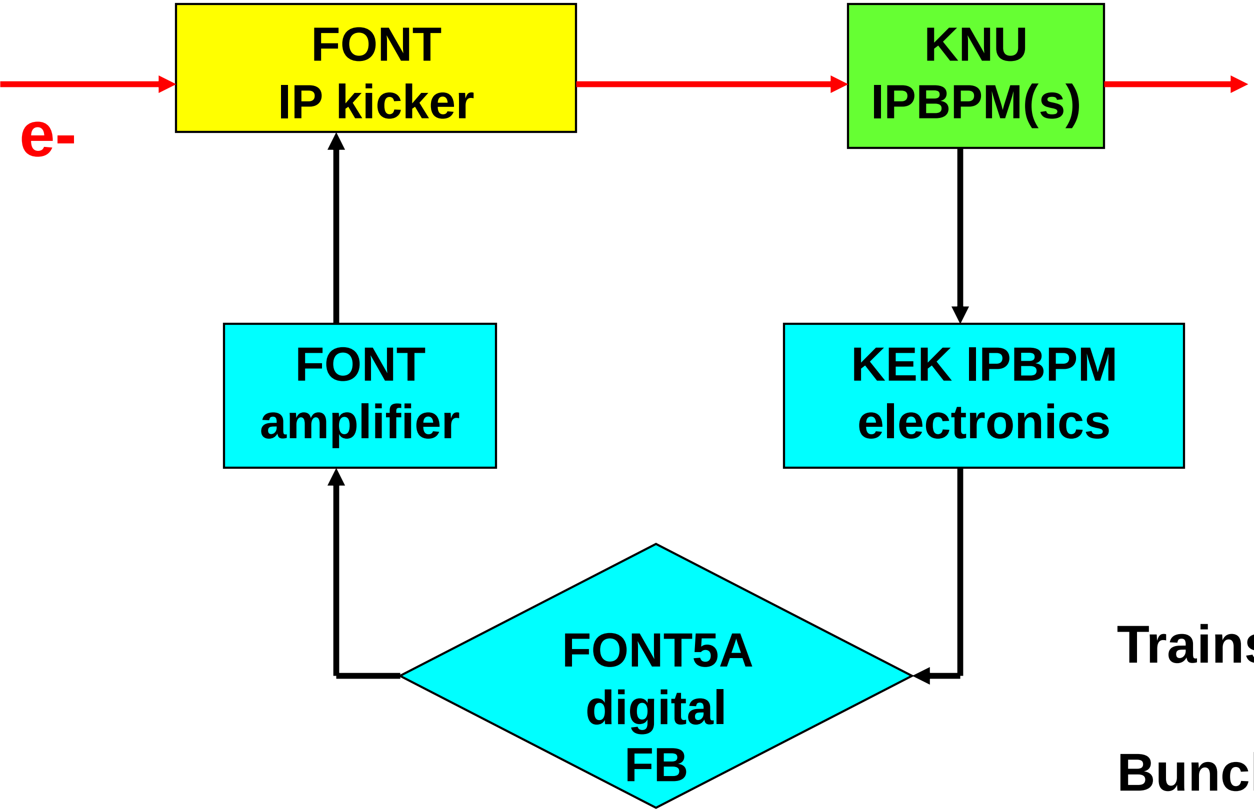




BPM cavity	Design frequency (GHz)	Measured frequency (GHz)	Decay time (ns)
Dipole IPA (x-port)	5.712	5.705	25
Dipole IPB (x-port)	5.712	5.706	25
Dipole IPC (x-port)	5.712	5.704	23
Dipole IPA (y-port)	6.426	6.428	26
Dipole IPB (y-port)	6.426	6.427	22
Dipole IPC (y-port)	6.426	6.428	21
Reference (x-cavity)	5.711	5.705	14
Reference (y-cavity)	6.415	6.428	14

Siwon Jang et al (KNU)

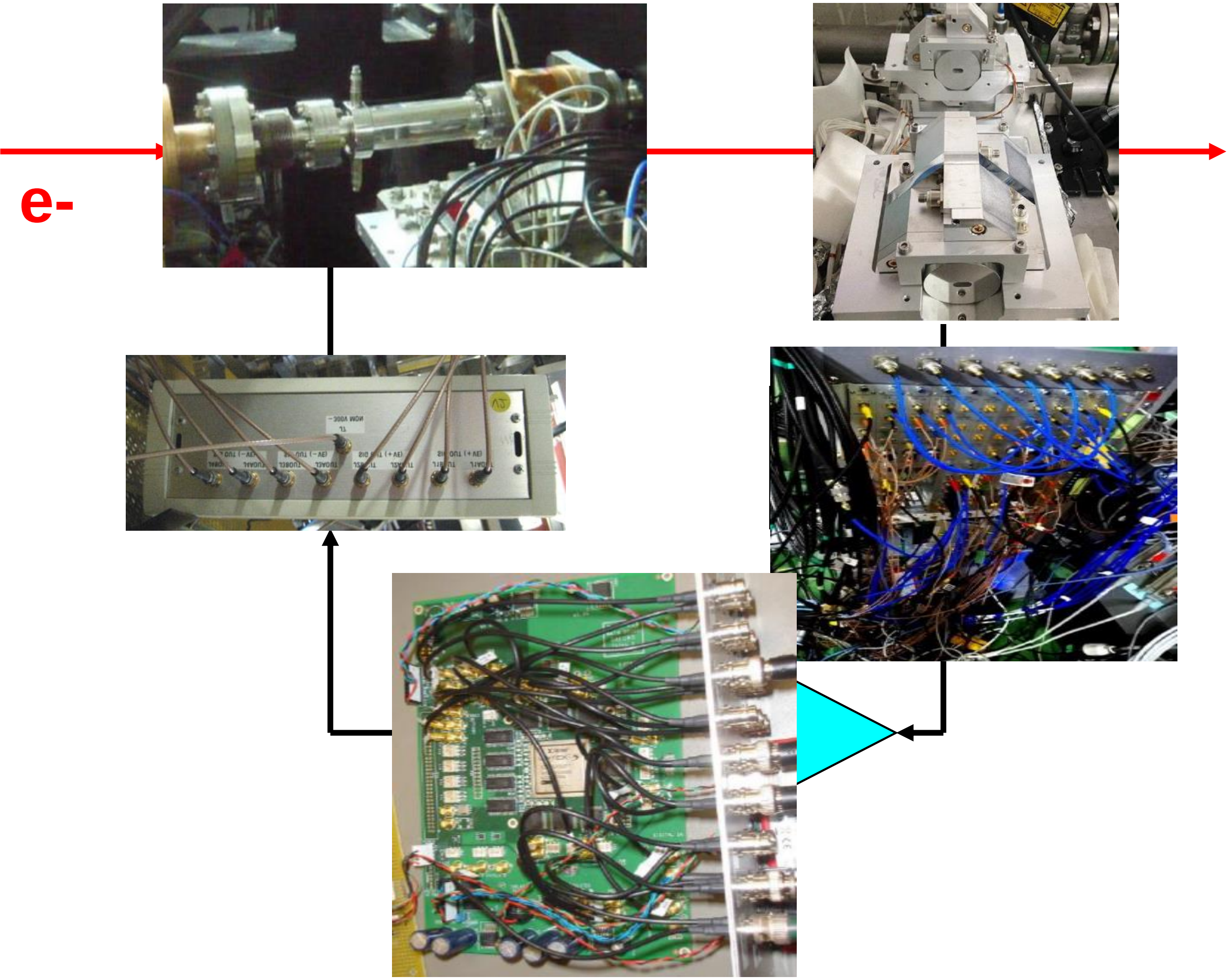
ATF2 ‘IP’ FB system



Trains of 2 bunches

Bunch separation c. 280 ns

ATF2 ‘IP’ FB system



Real-time position resolution

Ballistic beam

Use geometry of 3-BPM system to predict beam position at 3rd BPM using position measured at other two BPMs:

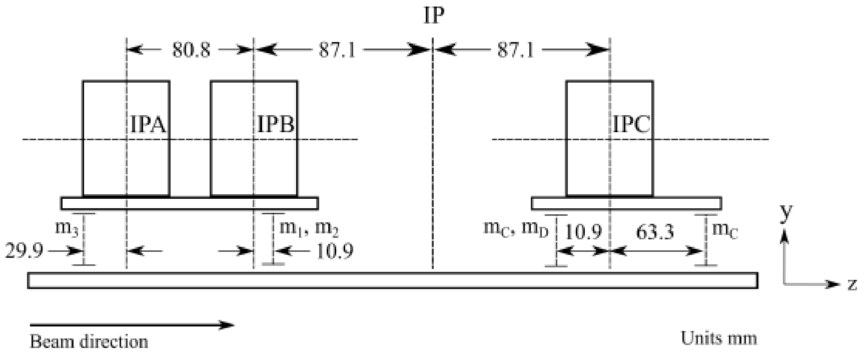
$$y_i^{\text{pred}} = A_{ij} y_j^{\text{meas}} + A_{ik} y_k^{\text{meas}}$$

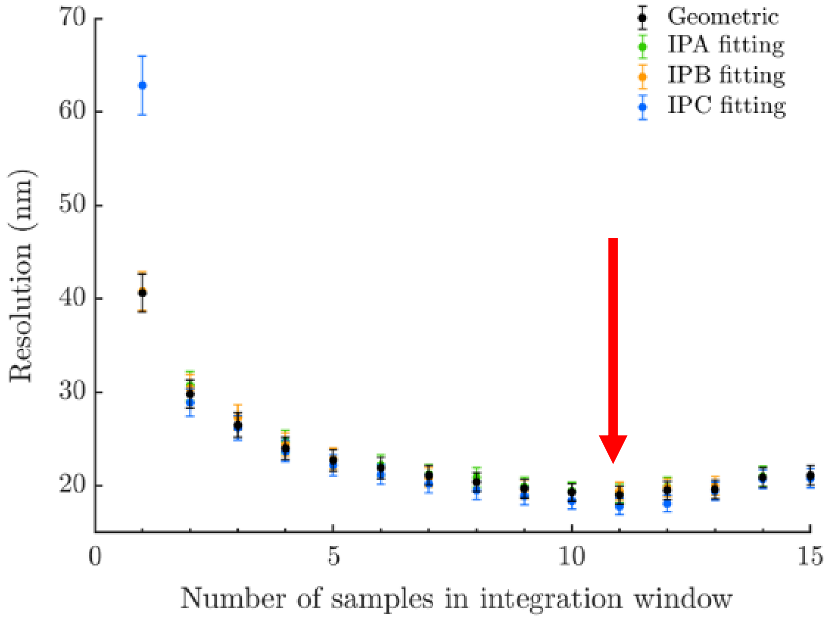
Resolution determined from distribution of residuals:

$$\sigma = \text{std}\left\{ \frac{(y_i^{\text{meas}} - y_i^{\text{pred}})}{\sqrt{1 + A_{ij}^2 + A_{ik}^2}} \right\}_{ijk}$$

Best real-time resolution ~ 19 nm

(< 25nm routine, depends on beam)



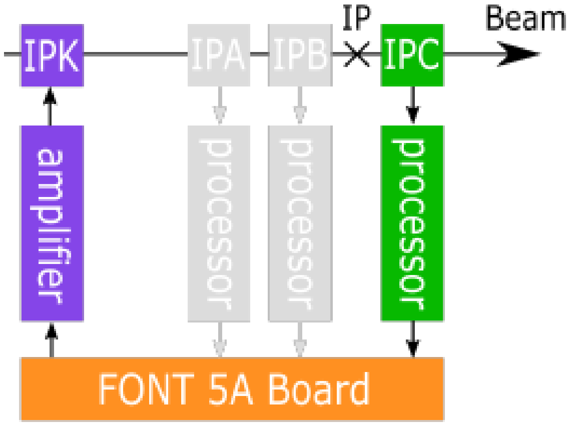


ATF2 ‘IP’ FB results

Nanobeam vertical focus placed at one BPM

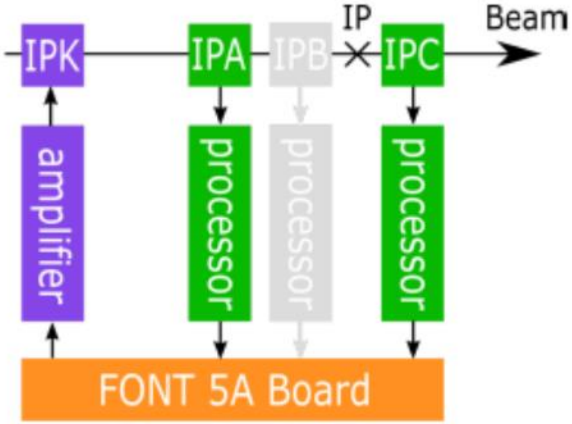
Two FB modes used to correct bunch 2:

1. Only IPC used



Bunch	Position jitter (nm) Feedback off	Feedback on
1	109 ± 11	118 ± 8
2	119 ± 12	50 ± 4

2. IPA and IPC used to correct at IPB



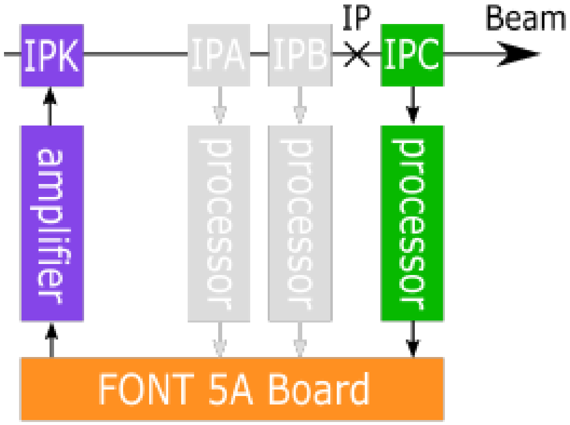
Bunch	Position jitter (nm) Feedback off	Feedback on
1	106 ± 16	106 ± 16
2	96 ± 10	41 ± 4

ATF2 ‘IP’ FB results

Nanobeam vertical focus placed at one BPM

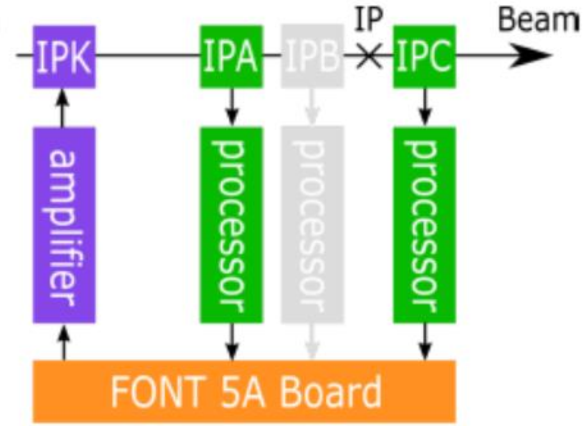
Two FB modes used to correct bunch 2:

1. Only IPC used



	Position jitter (nm)	
Bunch	Feedback off	Feedback on
1	109 ± 11	118 ± 8
2	119 ± 12	50 ± 4

2. IPA and IPC used to correct at IPB



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

References

P.N. Burrows, 'Fast beam-collision feedbacks for luminosity optimisation at next-generation lepton colliders', Nucl. Part. Phys. Proc. 273-275 (2016) 188.

G.R. White et al, 'Experimental Validation of a Novel Compact Focusing Scheme for Future Energy-Frontier Linear Lepton Colliders', Phys. Rev. Lett. 112 (2014) 3, 034802.

R.J. Apsimon et al, 'Performance of a high resolution, low latency stripline beam position monitor system', Phys. Rev. ST Accel. Beams 18, 032803 (2015).

D. Bett et al, 'Compensation of orbit distortion due to quadrupole motion using feed-forward control at KEK ATF', Nucl. Instrum. Meth. A895 (2018) 10.

R. J. Apsimon et al, 'Design and operation of a prototype interaction point beam collision feedback system for the International Linear Collider', Phys. Rev. Accel. Beams 21, 122802 (2018).

P. Korysko et al, 'Wakefield effects and mitigation techniques for nanobeam production at the KEK Accelerator Test Facility 2', Phys. Rev. Accel. Beams 23 (2020) 121004.

D.R. Bett et al, 'A sub-micron resolution, bunch-by-bunch beam trajectory feedback system and its application to reducing wakefield effects in single-pass beamlines', J. Inst. 16 (2021) P01005.

D.R. Bett et al, 'A high-resolution, low-latency, bunch-by-bunch feedback system for nano-beam stabilisation', Phys. Rev. Accel. Beams 25 (2022) 022801.

ATF2 achievements summary

Beam size:

- **Local chromaticity correction final-focus scheme demonstrated**
- **Linear optics tuning procedure established**
- **Tuning performed including 2nd order knobs**

41nm beam size demonstrated, limited by wakefield effects

- **Wakefield dependence reduced by removing sources from beamline**
- **Impact of static wakefield sources reduced by using source on mover**
- **Dynamic wakefield effects partly reduced by FONT orbit feedback**

Beam stability:

- **Using FONT orbit FB system, beam stabilisation to 1nm is implied by model**
- **Direct IP beam stabilisation to 40nm measured using IPFB system**

Remaining issues

- **Systematic study of 2nd order aberrations**

  → Confirm effectiveness of 2nd order tuning knobs
- **Accurate measurement of energy bandwidth**
- **Further wakefield studies: ‘unknown’ sources?**
- **Unknown strong non-linear aberrations?**
- **Reproducibility and long-term stability**

→ more stable beam and IPBSM system would facilitate measurements

ATF2 → ATF3

- **Overhaul beamline to replicate ILC more accurately:**
  - **replace magnets with poor field quality**
  - **remove/replace wakefield sources**
  - **relocate cavity BPMs to ILC-like locations**
- **Upgrade IPBSM laser for stable, long-term operations**
- **Ultra-low beta* studies with octupoles (CLIC)**

→ test-bed for LC luminosity optimisation studies

ATF2 → ATF3

Improvements completed, in progress or planned:

- **Replace QD0FF (2023) and QF1FF (2025)**
- **Upgrade skew sextupoles and put on movers**
- **Upgrade mover controls on sextupoles**
- **Upgrade IPBSM system (laser table, optical transport, vertical table …)**
- **Replace IPBSM laser (2025) → better laser spot profile**
- **Upgrade timing system**
- **Upgrade LLRF system / FB**
- **New beam chamber for wakefield studies**
- **Linac BPM readout upgrade**
- **Consolidation to reduce risks of failures**
- **Development of ML/AI techniques for faster/better tuning**

Longer term possibilities

- **Superconducting device test bench:**

  Final doublet
  Crab cavity
  Helical undulator for polarised positron source

- **Permanent magnet test bench**

- **Polarised electron source test bench**

Thanks for your attention

Extra material

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

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

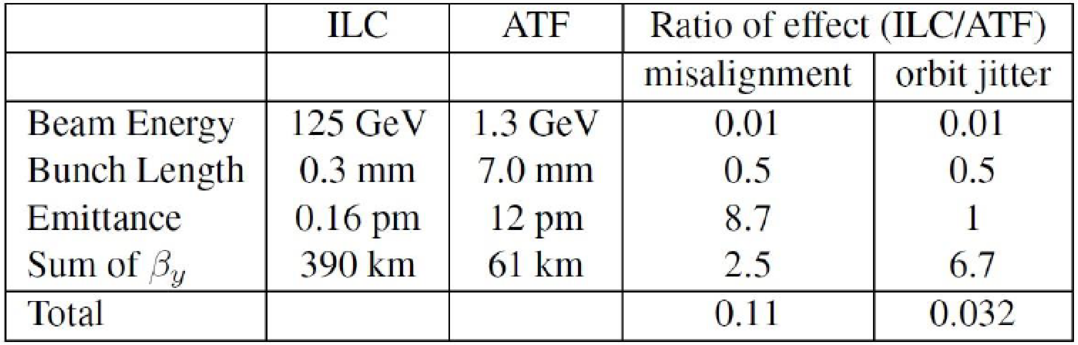
Chromaticity: $\xi \approx L^* / \beta^* \approx 10^4$

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

Implications for ILC

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**

Kubo