Final Focus Challenges – Highlights from ATF2

Philip Bambade

Laboratoire de l'Accélérateur Linéaire
IN2P3/CNRS – Université Paris-Sud, Orsay

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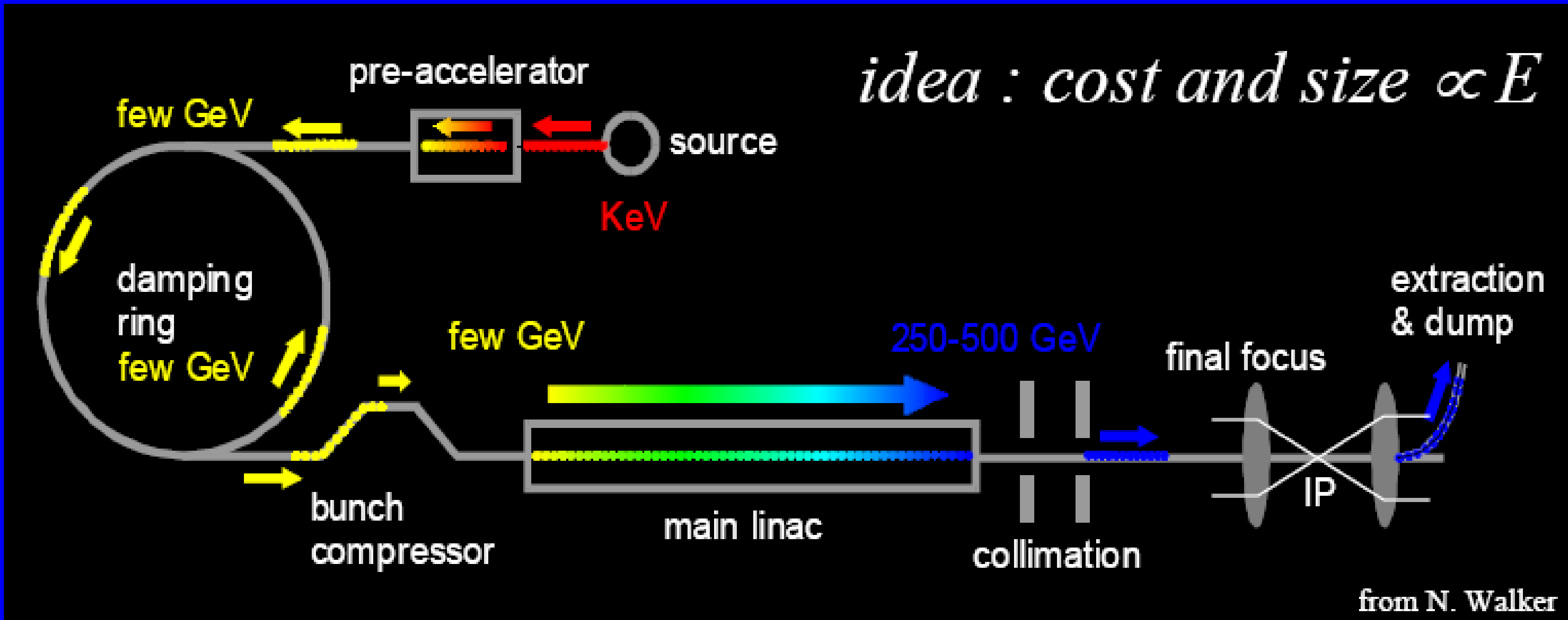
Linear collider concept



focus
- RF technology (gradient, efficient power transfer)
- beam phase-space control and stability

$$\textbf{Luminosity} \rightarrow \frac{efficiency \times power}{E} \sqrt{\frac{energy\ spread}{vertical\ emittance}}$$

Beam parameters (hidden) in LC luminosity scaling

$$L = \frac{n_b N^2 f}{4\pi\sigma_x\sigma_y} H_D \rightarrow \eta_{efficiency} \frac{P_{electrical}}{E_{CM}} \sqrt{\frac{\Delta E_{BS}}{\varepsilon_{N,y}}}$$

Optimization based on setting

$$\sigma_z = \beta_y \rightarrow \text{ bunch length } \leq \text{ "depth of focus" } \Rightarrow \text{ avoid "hour−glass effect"}$$

$$\beta_x \gg \beta_y \rightarrow \text{ very flat bunch profile } \Rightarrow \text{ minimize } \Delta E_{BS} \propto \frac{N^2}{\sigma_z(\sigma_x+\sigma_y)^2}$$

Consequences for final focus and additional considerations

- minimize β_y to maximize luminosity $\rightarrow$ only down to $\sim \sigma_z$
- $\beta_x \rightarrow$ balances high luminosity versus low ΔE_{BS}
  - $\beta_x \searrow \Delta E_{BS} \nearrow$ unless σ_z is reduced, however this then limits β_y smallness
  - $\beta_x \nearrow \Delta E_{BS} \searrow$ and β_y can be reduced to recover luminosity, but needs smaller σ_z
- 1st order chromaticity $\xi \sim L^*/\beta_y \rightarrow$ corrected with paired sextupoles

  $$\sigma_y^2 = \beta_y\varepsilon_y \left[1 + K_1 \left(\frac{L*}{\beta_y}\right)^2 \delta_E^2 + K_{ijk} \sum_{i,j,k} \left(\frac{L*}{\beta_x}\right)^i \left(\frac{L*}{\beta_y}\right)^j (\delta_E)^k \ldots\right], \text{ with } K_1 \sim 1 \rightarrow 0$$

  very small β_x and/or $\beta_y \Rightarrow$ more complex control of higher order optical aberration
- large L* and small ΔE_{BS} easier for detector and post-IP extraction

Design challenges in LC final focus

- Complex optics increases tuning difficulty of real system with errors

  local or non-local chromaticity correction
  for non-local correction → separated or interleaved
  use only sextupoles or also higher order magnets (e.g. octupoles…)
- Stabilization of two colliding beams with feedback (cf. FONT group)

  beam-beam deflection technique → ILC long train ⇒ MHz bandwidth
  (→ CLIC ⇒ requires also active mechanical stabilization)
- Collimation of beam halo for background control

  wakefield → emittance growth for case of very large optical demagnification (small β_y)
  can amplify input jitter → beam breakup → tighter tolerances for stabilization
- Beam instrumentation

Recent trends / approaches for final focus design

- Increasing β_x with reduced σ_z to lower ΔE_{BS} or raise luminosity

  Study of alternative ILC final focus optical configurations, D. Wang et al., NIMA 781 (2015) 14-19
- Increasing L*

  CLIC Beam Delivery System Rebaselining and Long L* Lattice Optimization, F. Plassard et al., IPAC2016-THPMR045
- Alternative chromaticity correction for better tuning ability

  Non-interleaved FFS design, O. Blanco et al., arXiv:1504.00162
  Final-focus systems for multi-TeV linear colliders, H. Garcia Morales et al., PRSTAB 17 (2014) 10, 101001

Study of alternative ILC final focus optical configurations ☆

Dou Wang [a,*], Philip Bambade [b], Yiwei Wang [a], Cecile Rimbault [b], Jie Gao [a]

[a] IHEP, Beijing, China
[b] LAL, Paris, France

NIMA 781 (2015) 14-19

D. Wang and Y. Wang

Reduced bunch length enables

1. Less beamstrahlung with the same luminosity, or
2. Higher luminosity with equal amount of beamstrahlung.

Approach is to use flatter beams

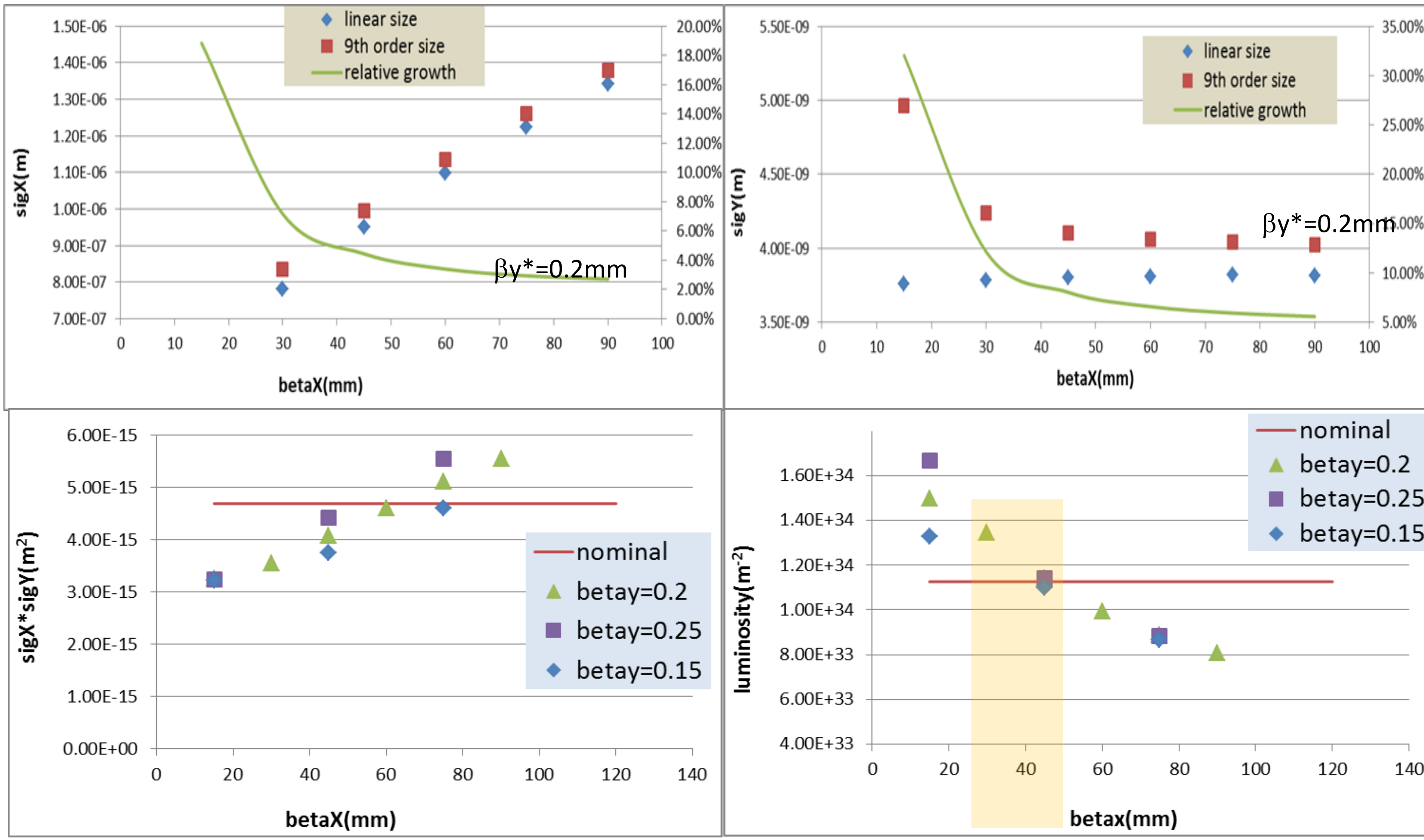
- Same magnets as in ILC nominal design, only refitting them
- Requires shorter bunch length than nominal (150 or 200 microns), it's the price to pay...

Benefits from less beamstrahlung

- Easier post-IP extraction line, with less losses...
- Less beam-beam induced effects (backgrounds...) for ILD and SiD

ILC FFS optics rematch and optimization

- Minimize $\sigma_x \times \sigma_y$ with fixed βy and σ_z (σ_z=150 μm)
- Chromaticity correction using 5 sextupoles with reasonable values
- Energy spread for both beams = 0.0006



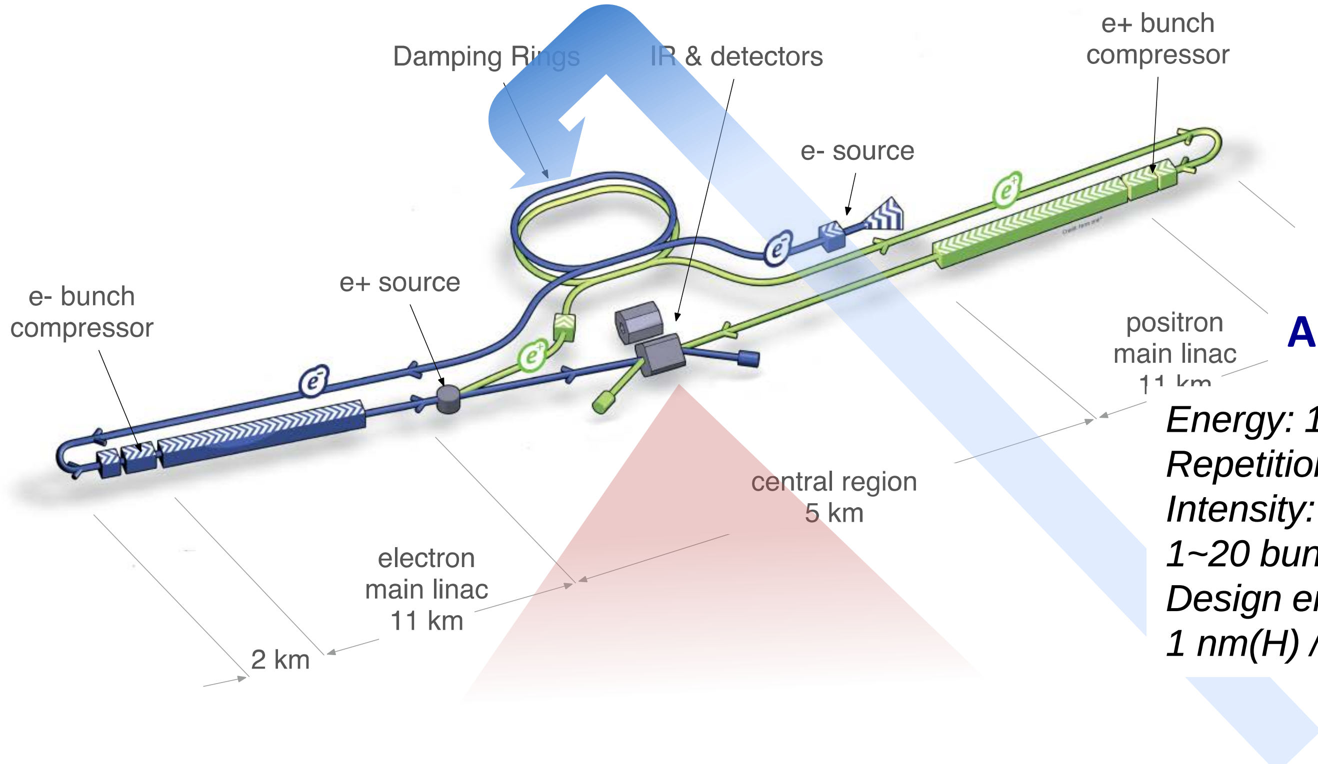
Maximum β_x to obtain higher luminosity than nominal → 45 mm

Alternative optical parameters for ILC FFS

	ILC RDR	ILC low BS	ILC high Lumi
Energy per beam (GeV)	250	250	250
N_e ($\times 10^{10}$)	2	2	2
σ_z (μm)	300	150	150
$\beta_{x/y}$ (mm)	15/0.4	45/0.2	20/0.2
A_y	0.75	0.75	0.75
$\sigma_{x/y}$ by MAPCLASS (nm)	594/7.89	994/4.10	750/4.6
$\sigma_x \times \sigma_y$ (nm^2)	4687	4075	3450
Luminosity per collision from guineapig++ ($\times 10^{34}$ m^{-2})	1.126	1.143	1.40
Beamstrahlung energy spread from guineapig++ (%)	2.8	1.8	2.8

- Larger luminosity with similar beamstrahlung as nominal design for $\beta_x < 45$ mm, or
- Less beamstrahlung keeping luminosity as in nominal design for 45 mm $= \beta_x$

Nanometre scale beam handling at ATF/ATF2



Accelerator Test Facility

Energy: 1.3 GeV
Repetition: 3.12 Hz
Intensity: 1-2x10^{10} e-/bunch
1~20 bunches/pulse
Design emittance:
1 nm(H) / 10 pm(V), Achieved 4 pm(V)

ATF2 beamline: Nano-meter beam R&D

Final focus system development
Technologies to maintain the luminosity at ILC
Goal 1: Beam size: 37 nm (design), **41 nm (achieved)**
Goal 2: Beam stabilization via feedback: **achieved 67 nm**
Beam instrumentation development

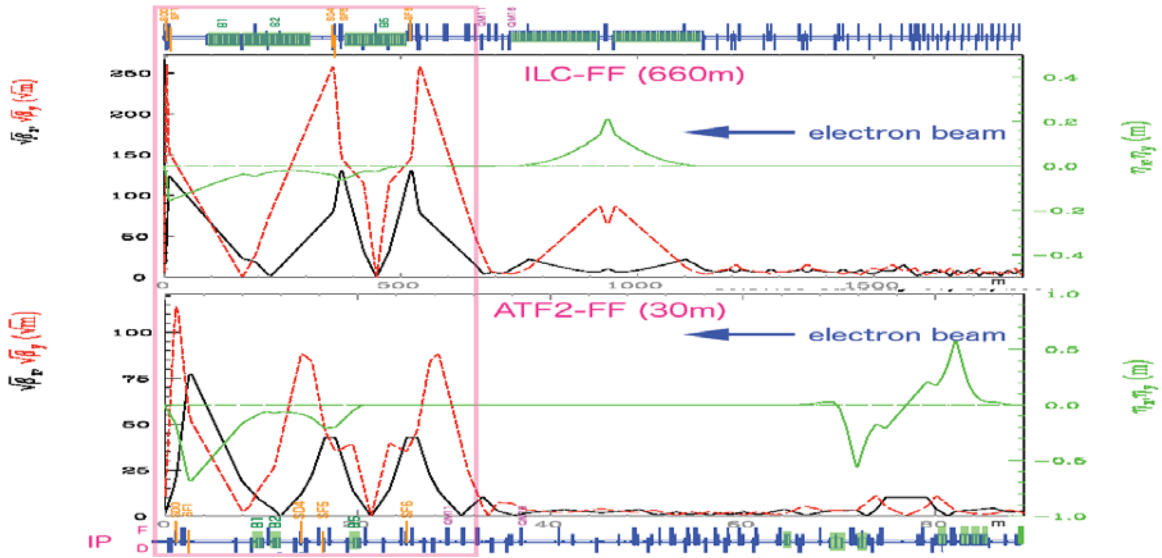
Damping Ring (~ 140m)
Low emittance beam

ATF2 = scaled ILC FFS

FFTB ➔ ATF2

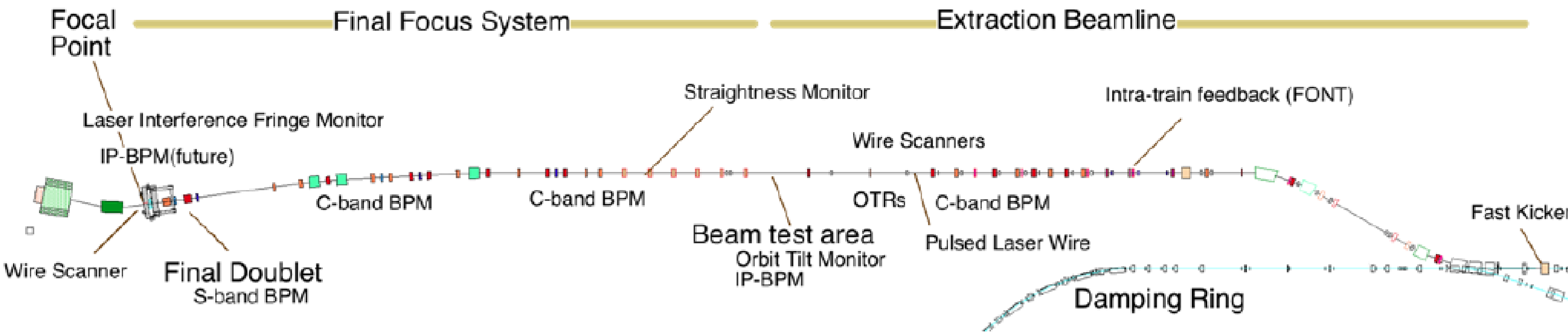
local chromaticity correction

- ✓ ***superior***
- ✓ ***more compact***

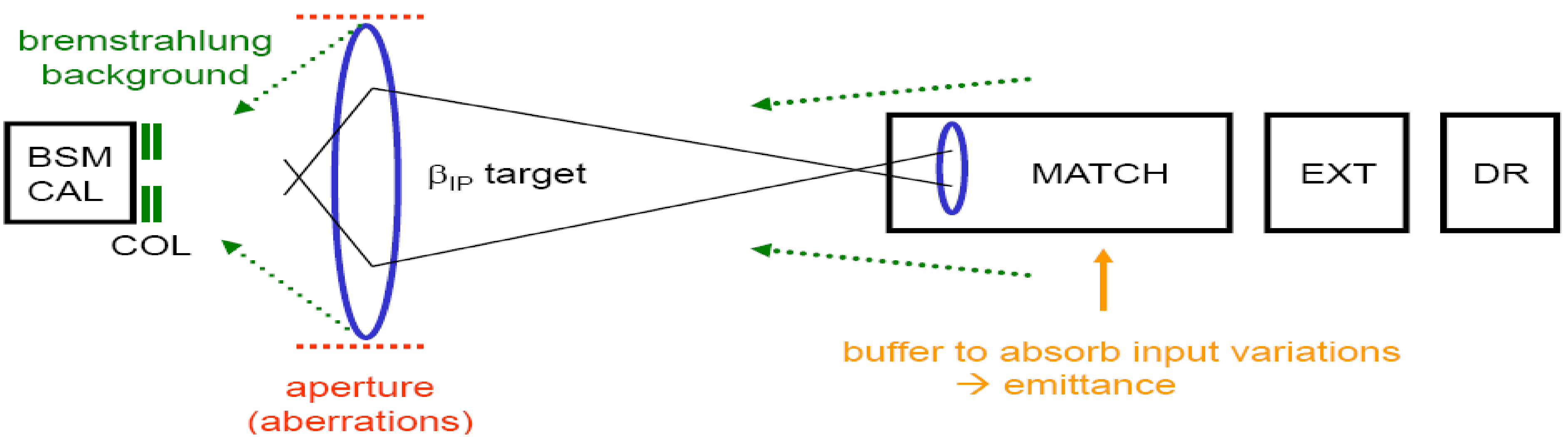


Parameters	ATF2	ILC	CLIC	SuperKEKB
Beam Energy [GeV]	1.3	250	1500	4-7
L* [m]	1	3.5 - 4.5	3.5	0.47-1.3
$\gamma\varepsilon_{x/y}$ [m.rad]	$5\ 10^{-6}$ / $3\ 10^{-8}$	10^{-5} / $4\ 10^{-8}$	$6.6\ 10^{-7}$ / $2\ 10^{-8}$	~ $3\ 10^{-5}$ / ~ $1\ 10^{-7}$
IP $\beta_{x/y}$ [mm]	4 / 0.1	21 / 0.4	6.9 / 0.07	25-32 / 0.27-0.41
IP η' [rad]	0.14	0.0094	0.00144	
δ_E [%]	~ 0.1	~ 0.1	~ 0.3	0.065
Chromaticity ~ L* / β*	~ 10^4	~ 10^4	~ $5\ 10^4$	$1.7\text{-}3.2\ 10^3$
Number of bunches	1-3	~ 3000	312	2500
Bunch population	$1\text{-}2\ 10^{10}$	$2\ 10^{10}$	$3.7\ 10^9$	
IP σ_y [nm]	37	5.7	0.7	59

Producing nanometre beams at ATF2



2nd order telescope	Match optics into FF	DR extraction
fine tuning of local errors	*buffer section for input errors*	*setup, stability*



2008

Is 37 nm vertical size the limit at ATF2 ?

Optical configurations with variable β* at different IP locations in ATF2, by S. Bai et al. ATF-08-05, LAL/RT-08-10

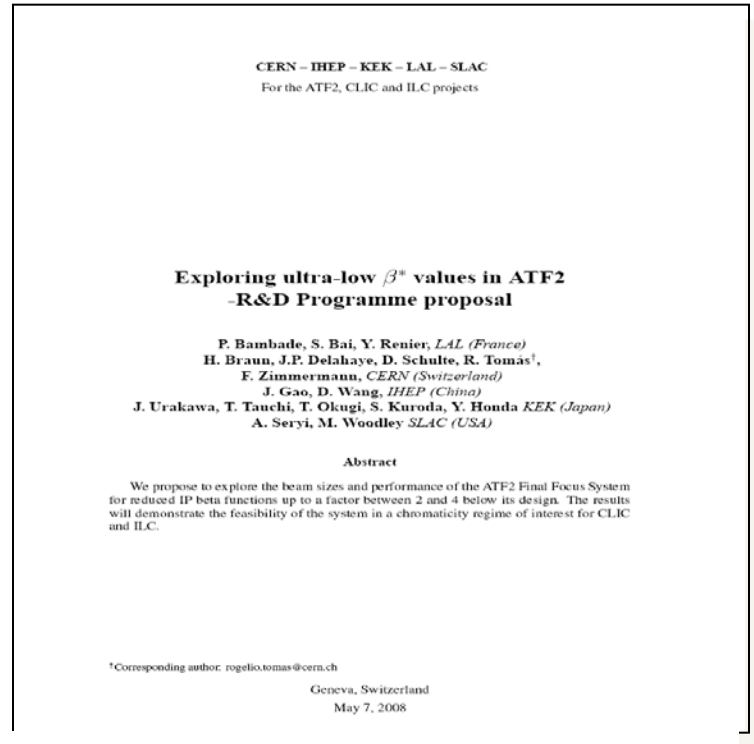
Variability of β_x and β_y ? (optical "zoom")

- Staged commissioning with larger $\beta_{x,y}$ for easier tuning with less sensitivity to errors and backgrounds
- Beam size down to ~ 17 nm may be possible !
  - Probe larger chromaticity of CLIC baseline and some of the alternative ILC parameters

Probing half β_y^* optics in the Accelerator Test Facility 2
M. Patecki (CERN) et al., PRAB 19 (2016) no.10, 101001

→ One of main CERN-CLIC R&D at ATF2

2016 : CERN installed 2 octupoles to facilitate demonstration of "ultra-low β optics"



CERN – IHEP – KEK – LAL – SLAC
For the ATF2, CLIC and ILC projects

Exploring ultra-low β^* values in ATF2 -R&D Programme proposal

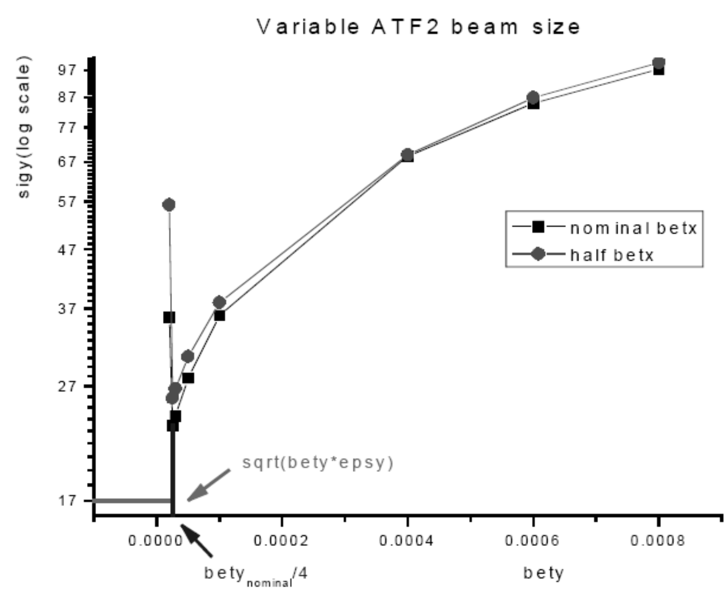
P. Bambade, S. Bai, Y. Renier, *LAL (France)*
H. Braun, J.P. Delahaye, D. Schulte, R. Tomás[†],
F. Zimmermann, *CERN (Switzerland)*
J. Gao, D. Wang, *IHEP (China)*
J. Urakawa, T. Tauchi, T. Okugi, S. Kuroda, Y. Honda *KEK (Japan)*
A. Seryi, M. Woodley *SLAC (USA)*

Abstract

We propose to explore the beam sizes and performance of the ATF2 Final Focus System for reduced IP beta functions up to a factor between 2 and 4 below its design. The results will demonstrate the feasibility of the system in a chromaticity regime of interest for CLIC and ILC.

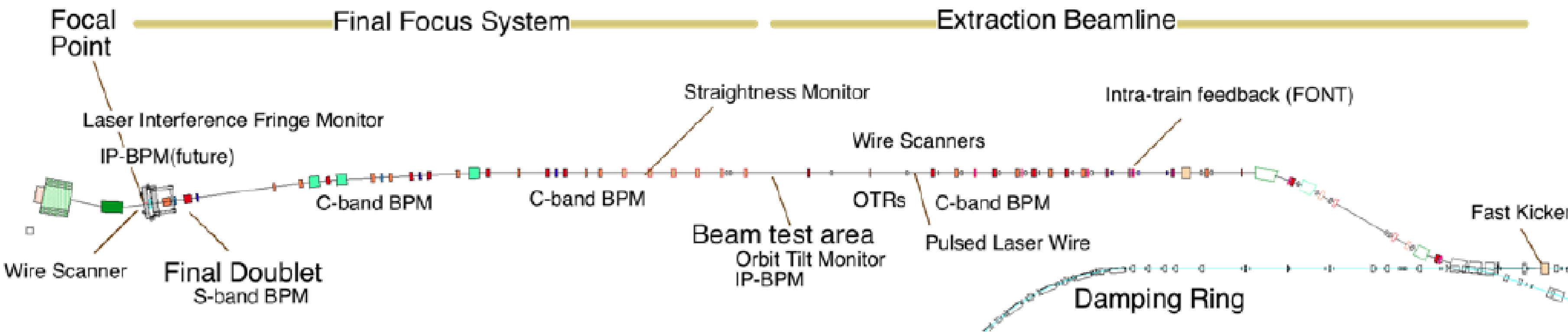
[†]Corresponding author: rogelio.tomas@cern.ch

Geneva, Switzerland
May 7, 2008

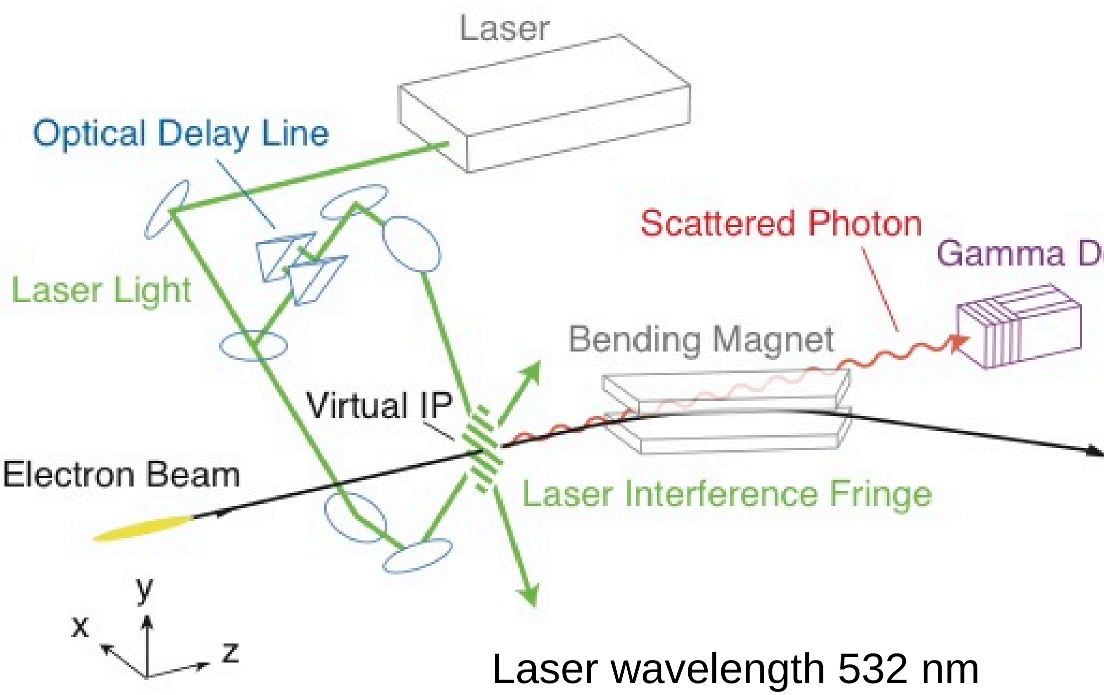


S.Bai, ATF-08-05, PhD thesis, IHEP (2010)

Measuring nanometre beams at ATF2

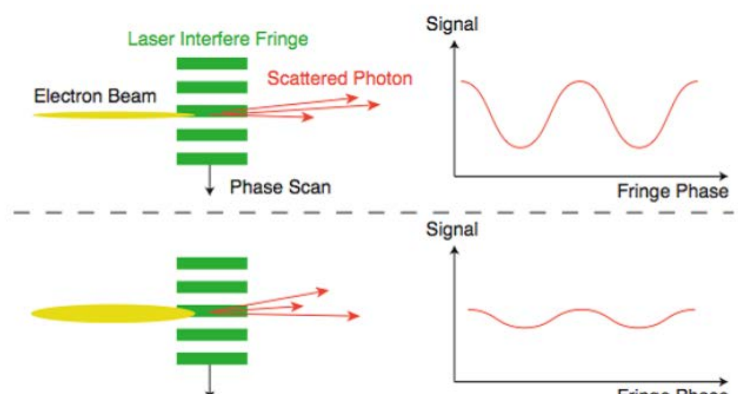


→ **37 nm vertical size**

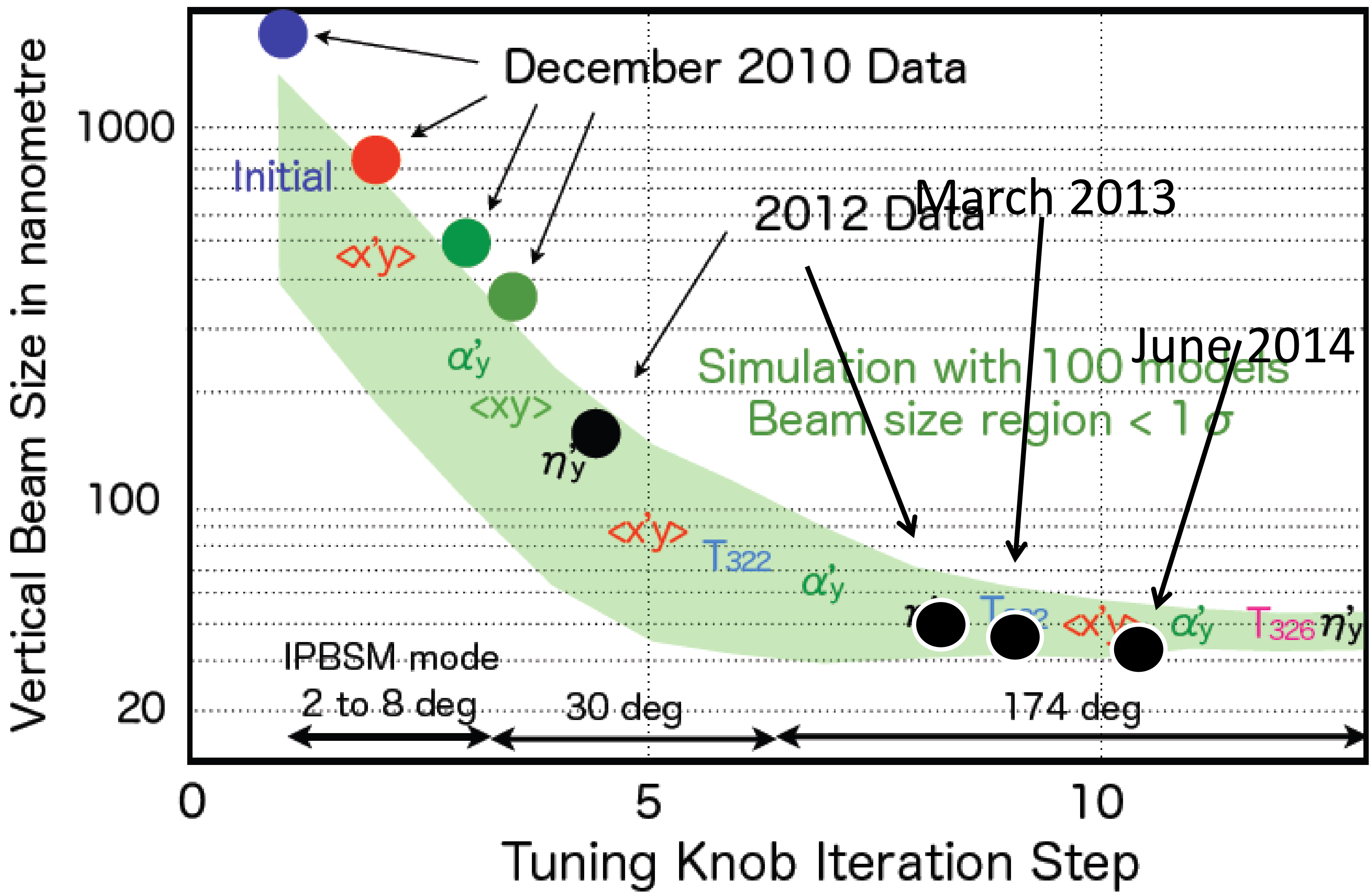


Laser wavelength 532 nm

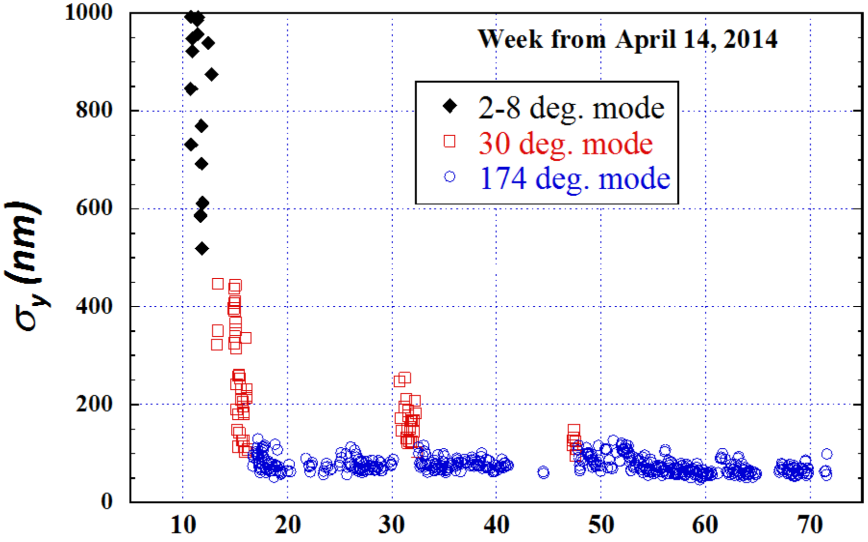
Modulation of Compton scattered photon rate from beam interaction with laser interference fringe pattern



History of minimum beam size in ATF2



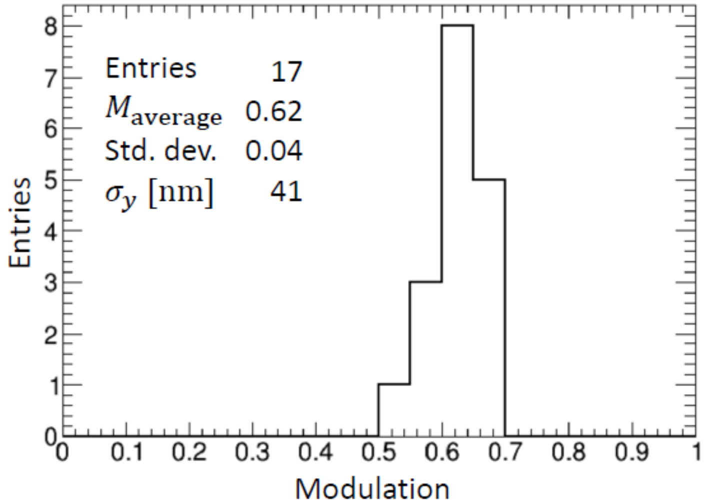
Experimental Validation of a Novel Compact Focusing Scheme for Future Energy-Frontier Linear Lepton Colliders, by G. White et al. (ATF2 Collaboration): Phys.Rev.Lett 112, 034802 (2014)



Time (hours) from operation start after 3 days shutdown

Fast recovery after stop

Result of consecutive measurements with FONT upstream feedback on



Beam intensity = 0.7×10^9 /bunch
ATF2(MFB1FF) FB off

Largest Modulation was achieved

Stability

$\sigma_y \sim 41$ nm

smallest vertical beam size ever achieved

ATF2 : further challenges and limitations

- ATF2 reproducibly achieves design $\sigma_y \rightarrow$ 40 nm, but
  - 10^9 electrons / bunch < nominal $10^{10} \Rightarrow$ strong intensity-dependence
  - $\beta_x = 10 \times$ nominal $\Rightarrow$ some observation of σ_y degradation when $\beta_x \searrow$

    $\rightarrow$ ILC Final Focus really validated ?

  Yes $\rightarrow$ both parameters consistent with ILC after proper (energy) scaling of higher order multipole and wakefield effects
- $\beta_y = 10^{-4}$ m (nominal value) $\rightarrow$ can smaller σ_y be achieved with "ultra-low β_y" optics ?

  On-going test with pair of newly installed octupoles
- Feedback stabilization (cf. FONT) $\rightarrow$ limits σ_y reduction ?

  On-going assessment & improvements of BPM instrumentation
- Background control / halo collimation $\rightarrow$ limits σ_y reduction ?

  Seems not major problem from recent studies

Conclusions and outlook

- Final focus challenges well identified and researched
  - mature for engineering design with certain rules / limits
  - ILC design conservative, validated w.r.t. final focus
  - certain variations / flexibility in parameters are possible

- ATF2 reproducibly achieves smallest σ_y in the world
  - expect running to end 2018
    - $\rightarrow$ close remaining issues
    - $\rightarrow$ probe limits beyond original parameters (e.g. ultra-low β)
  - invaluable "real system" experience & training (many PhD students !)

Extra slides

Wakefield in ILC FF compared with ATF2

- Effects of transverse wakefield will be much smaller than in ATF2
  - High energy, short bunch length (see next slide)
  - Beam pipe aperture will be similar
    - Except for collimators (special care will be necessary)
  - Careful design of beam pipe and structures in the beam line
- But, understanding the intensity dependence and comparison between observations and calculations are important

See
http://atf.kek.jp/twiki/pub/ATF/CompareWakeILCAT2/wakecompare-ILCATF-v3.pdf

and next slide

Kiyoshi Kubo, KEK

Misalignment

	ILC	ATF2	Dependence	Ratio of effect ILC/ATF2
Beam Energy	250 GeV	1.3 GeV	1/E	0.0052
Bunch length	0.3 mm	7.0 mm	Shape pf wake	~0.5
Emittance	0.07 pm	12 pm	$1/\sqrt{\varepsilon}$	13
Sum of Beta-function	310 km	58 km	$\sqrt{\sum \beta}$	2.3
Total			0.078	0.078

Orbit jitter

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Sum of Beta-function	310 km	58 km	$\sum \beta$	5.3
Total			0.014	0.014

Misalignment

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Sum of Beta-function	310 km	58 km	$\sqrt{\sum \beta}$	2.3

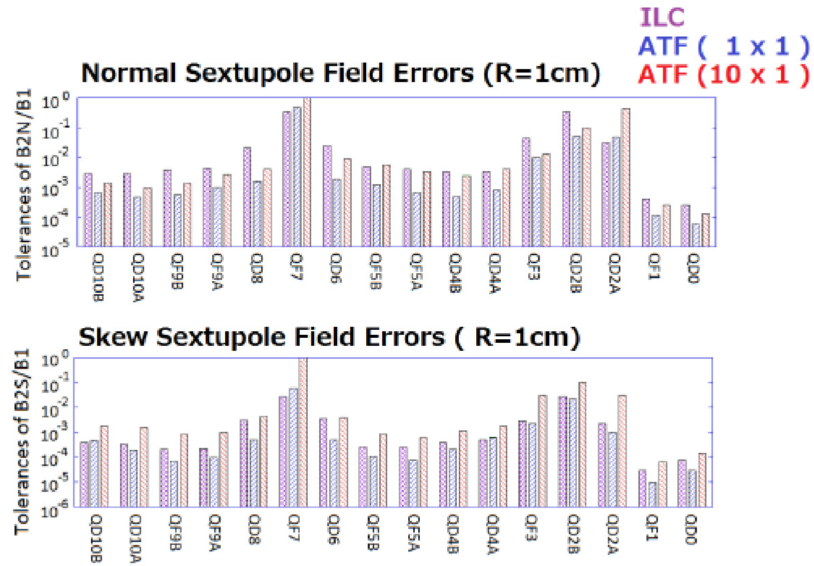
Effect of misalignment at ILC with bunch population 2E10 will be similar to that at ATF with bunch population 0.16E10.

Effect of betatron oscillation at ILC with bunch population 2E10 will be similar to that at ATF with bunch population 0.03E10.

Bunch Length	0.3 mm	7.0 mm	Shape pf wake	~0.5
Sum of Beta-function	310 km	58 km	$\sum \beta$	5.3
Total			0.014	0.014

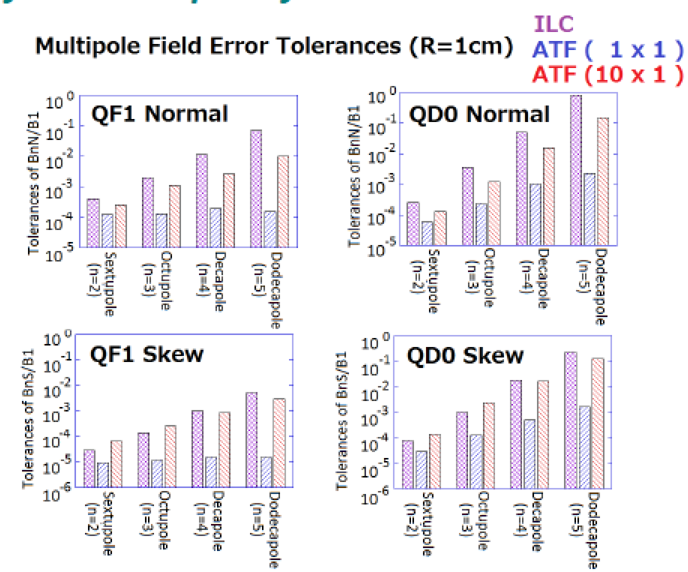
Tolerances of sextupole field error to IP vertical beam size

Toshiyuki Okugi, KEK



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

Tolerances of FD multipole field error to IP vertical beam size



Linear and second order optics corrections for the KEK Accelerator Test Facility final focus beam line,
T. Okugi *et al.*,
PRSTAB 17, 023501 (2014)

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