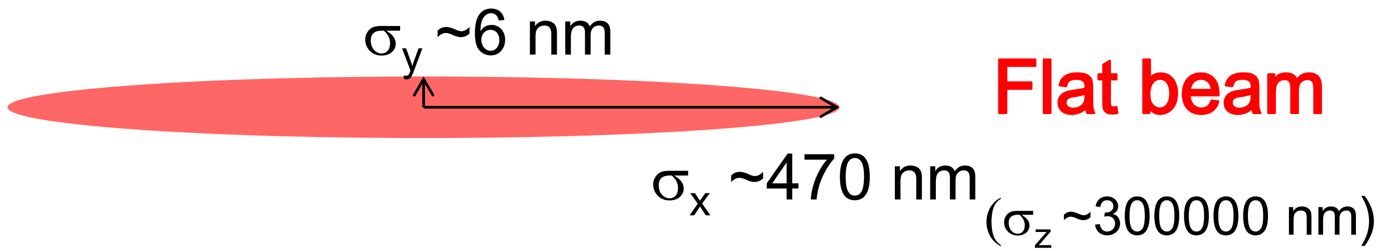
Towards International Linear Collider: Experiments At ATF2 (Final Focus Test)

K. Kubo (KEK)
ATF2 Collaboration

2014.06.18 IPAC14

ILC beam at Interaction Point (Focal point) For High Luminosity



Horizontal beam size is limited by beam-beam force (beamstrahlung)

↓

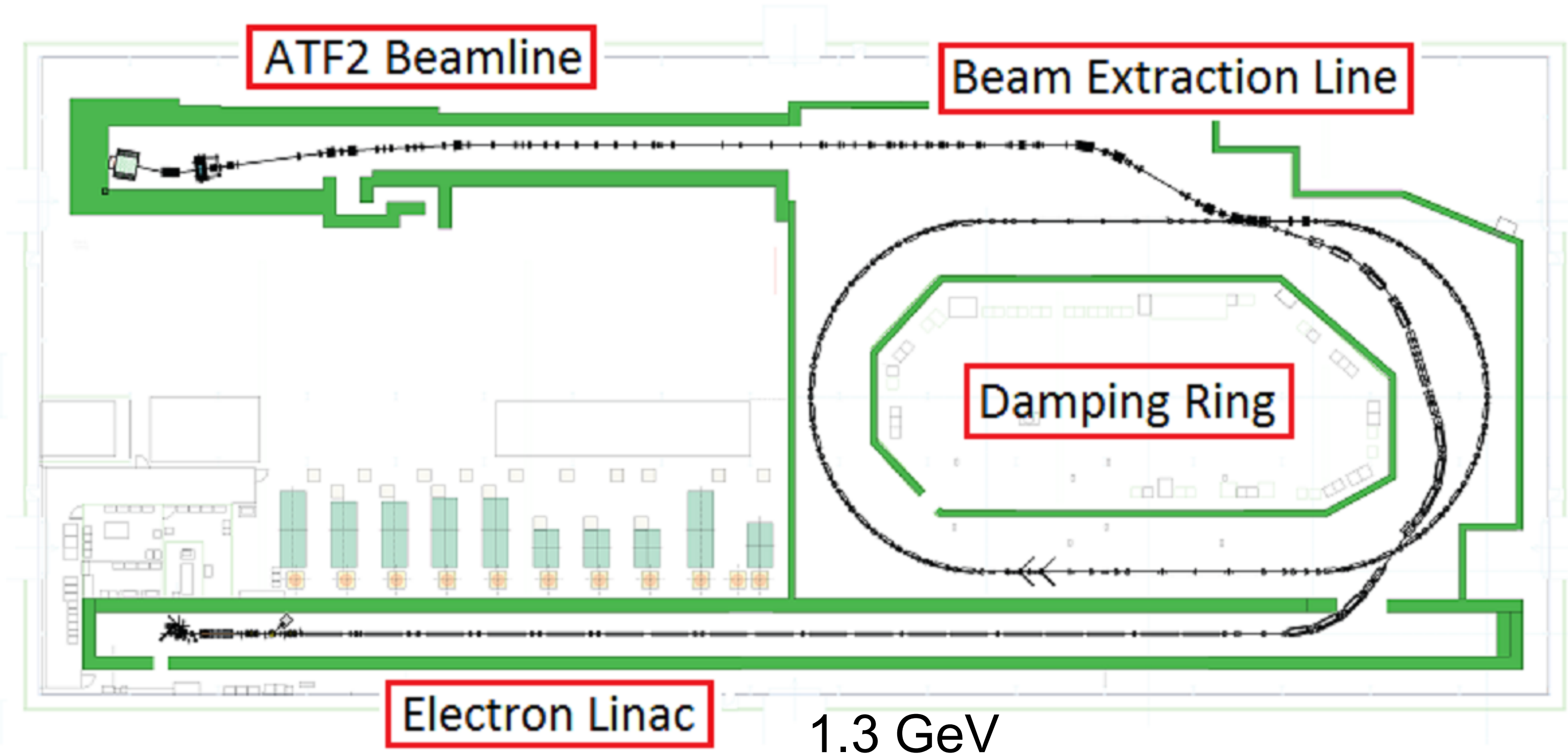
Luminosity limited by vertical beam size

For small beam we need

- **Low vertical emittance**
- **Small aberrations in Final Focus System**

Being tested at ATF(Accelerator Test Facility at KEK)

ATF, Accelerator Test Facility at KEK



ATF2 International Collaboration
Design, Construction, Operation

ATF Main Institutes

CERN

Germany
- DESY

France
- IN2P3; LAL, LAPP, LLR

UK
- Univ. of Oxford
- Royal Holloway Univ. of London
- STFC, Daresbury
- Univ. of Manchester
- Univ. of Liverpool
- Univ. College London

Italy
- INFN, Frascati

Spain
- IFIC-CSIC/UV

Russia
- Tomsk Polytechnic Univ.

Japan
- KEK
- Tohoku Univ.
- Univ. of Tokyo
- Waseda Univ.
- Nagoya Univ.
- Kyoto Univ.
- Hiroshima Univ.

China
- IHEP

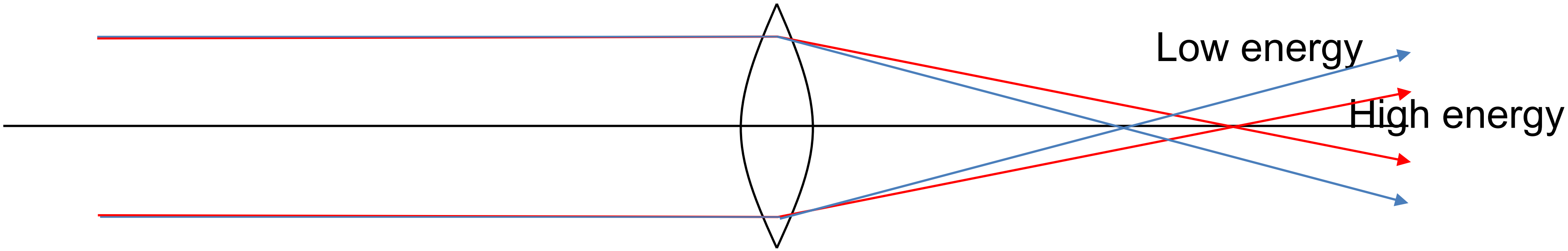
Korea
- PAL
- KNU

India
- RRCAT

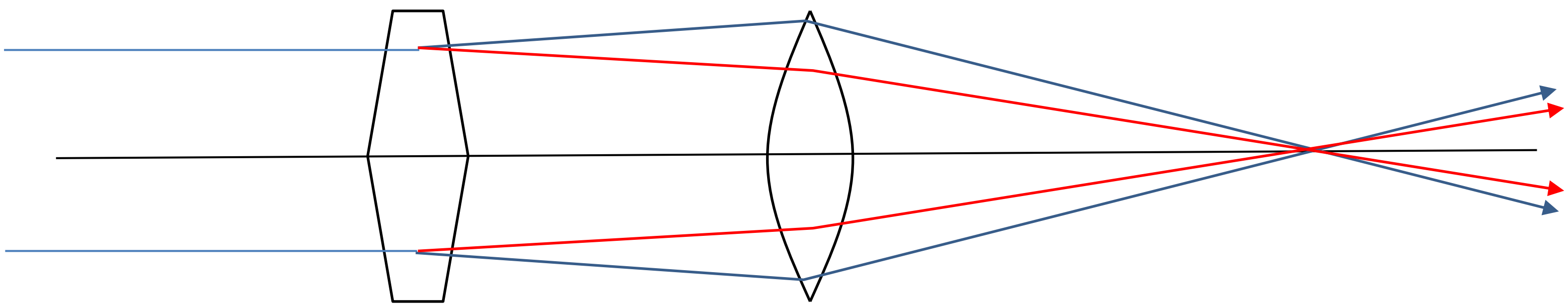
USA
- SLAC
- LBNL
- FNAL
- LLNL
- BNL
- Cornell Univ.
- Notre Dome Univ.

Chromatic Aberration in Final Focus

Different focal points for different energy particles in beam.
Energy spread causes large beam size.



Correction: Sextupole magnets located at Horizontal Dispersion
Focal strength proportional to particle energy cancels chromatic aberrations.



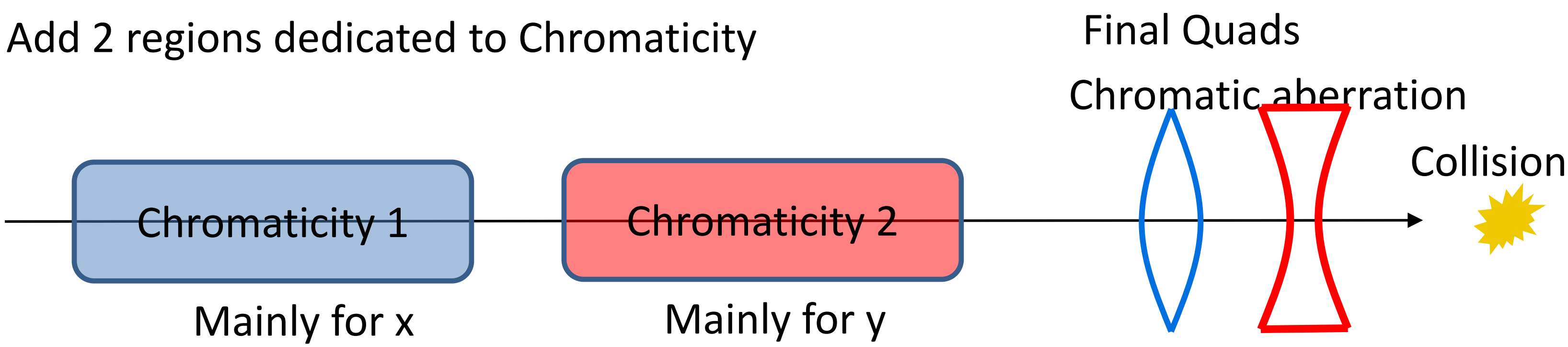
NOT SO SIMPLE

Other aberrations (geometrical aberration) created by the sextupole field

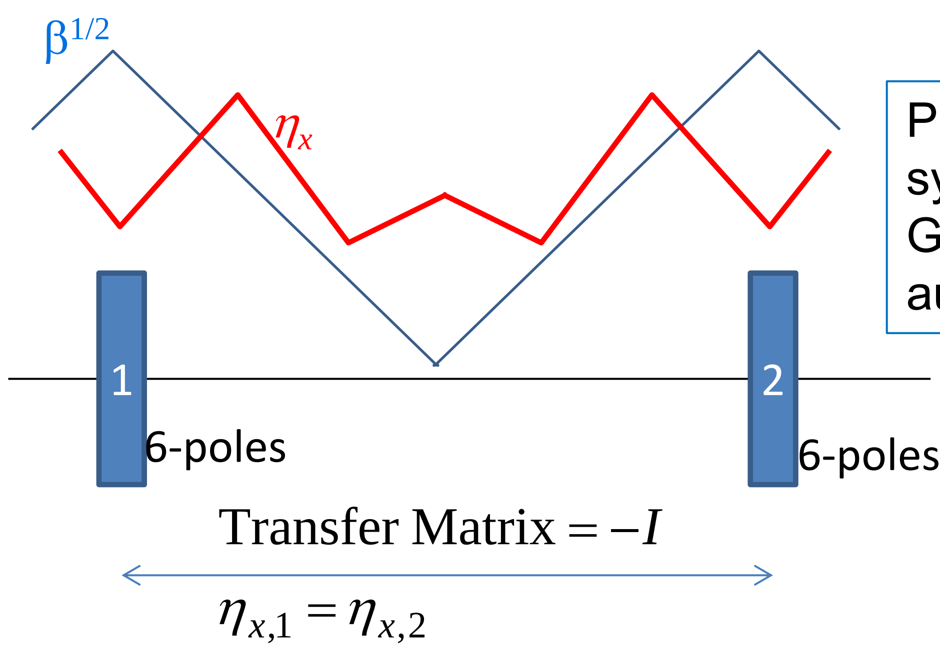
Because of energy-independent position spread (beam size)

Global chromatic correction

Add 2 regions dedicated to Chromaticity



Chromaticity

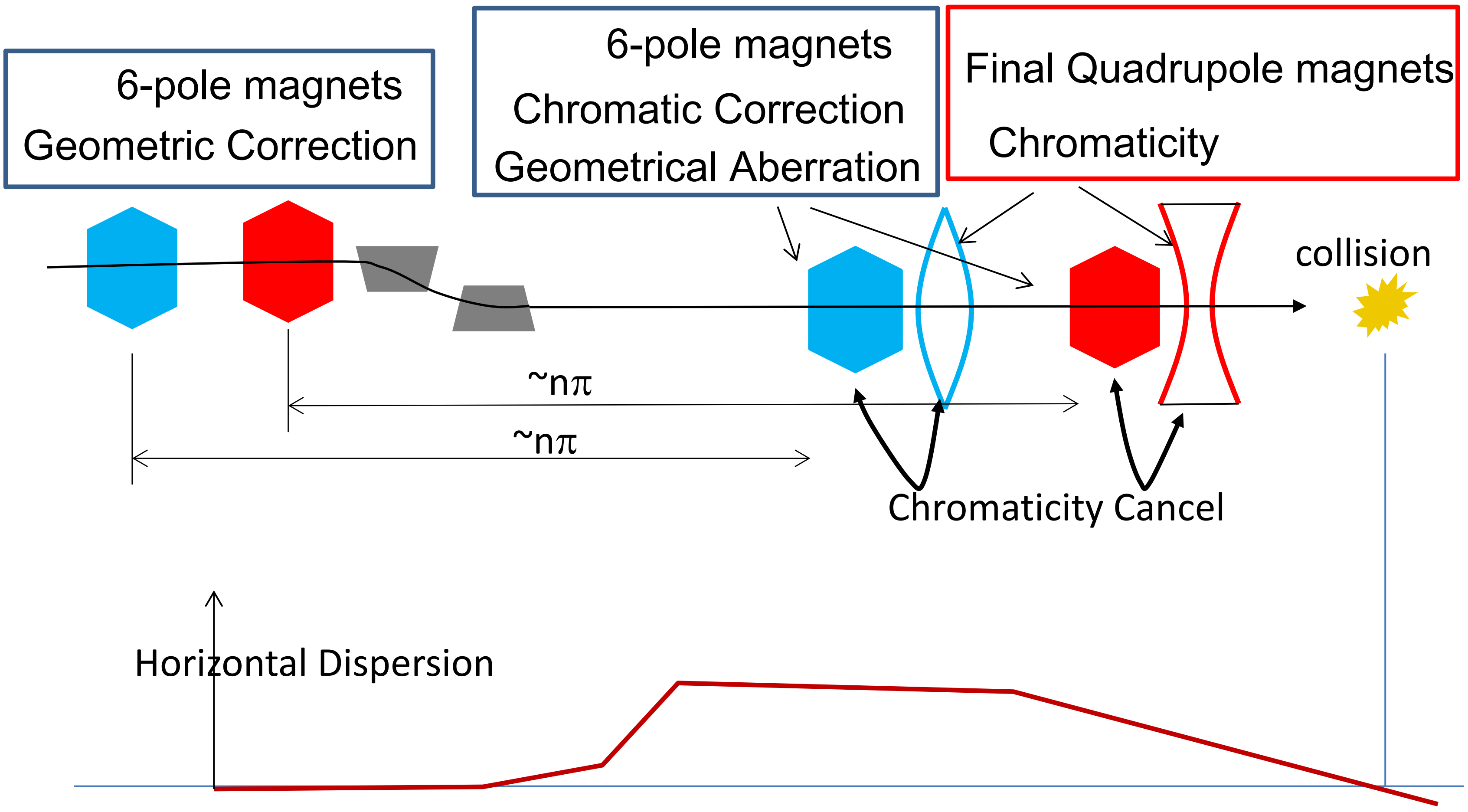


Put two 6-pole magnets symmetrically.
Geometrical aberrations automatically cancelled.

Local chromatic correction

(P.Raimondi and A.Seryi, Phys. Rev. Lett. 86, 3779 (2001))

Put 6-pole magnet next to each of Final Quads for Chromatic correction
Correct geometrical aberration in upstream



Comparison of Chromaticity Correction Methods

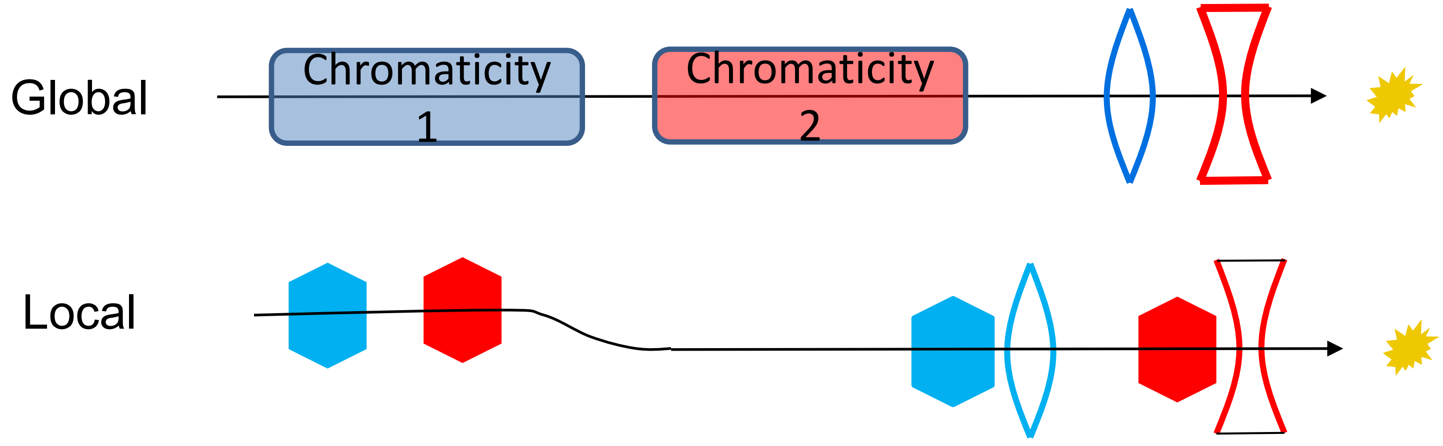
Advantages of "Local" correction

Chosen for ILC

- **Shorter beam line**
- Better designed performance (Large energy acceptance. Small halo at final quads.) (P.Raimondi and A.Seryi, Phys. Rev. Lett. 86, 3779 (2001))

Disadvantage?

- **Complicated design**
- **Difficulties in tuning (operation)**



Expected Difficulties/Complications In Local Chromatic Correction

- For Designing
  - No obvious (simple) symmetries for cancelling aberrations
- In Operation
  - Interleaved sextupoles → Interference between horizontal and vertical parameters
  - Nonzero angle dispersion at focal point
  - Many aberrations can be coupled

Expected difficulties: Motivation of ATF2 Project.

Test of Local Correction

Global Correction was successfully tested in 1994 at SLAC:
FFTB（Final Focus Test Beam)
(V. Balakin et al., Phys. Rev. Lett. 74, 2479 (1995))

Two Goals of ATF2

ATF2 Collaboration, "ATF2 Proposal," (2005)

- Small beam size (Goal 1) : This Report
  - Demonstration of a compact final focus system based on local chromaticity correction
  - Designed beam size: 37 nm
  - (Without chromatic correction, beam size is ~450 nm.)
- Control of beam position (Goal 2)
  - Demonstration of beam orbit stabilization with a few nanometer precision at the IP
    - Establishment of beam jitter controlling techniques at the nanometer level with an ILC-like beam

Design parameters of ILC and ATF2 Final Focus

Parameter	ILC	ATF2
Beam Energy [GeV]	**250**	**1.3**
Energy Spread (e^+/e^-) [%]	**0.07/0.12**	**0.06~0.08**
Final quad – IP distance (*L**) (SiD/ILD detector) [m]	3.5/4.5	1.0
Vertical beta function at IP (β^*_y) [mm]	0.48	0.1
Vertical emittance [pm]	**0.07**	**12**
Vertical beam size at IP (σ^*_y) [nm]	**5.9**	**37**
L^*/β^*_y (~natural vertical chromaticity, SiD/ILD detector)	**7300/9400**	**10000**

ILC Technical Design Report, https://www.linearcollider.org/ILC/Publications/Technical-Design-Report

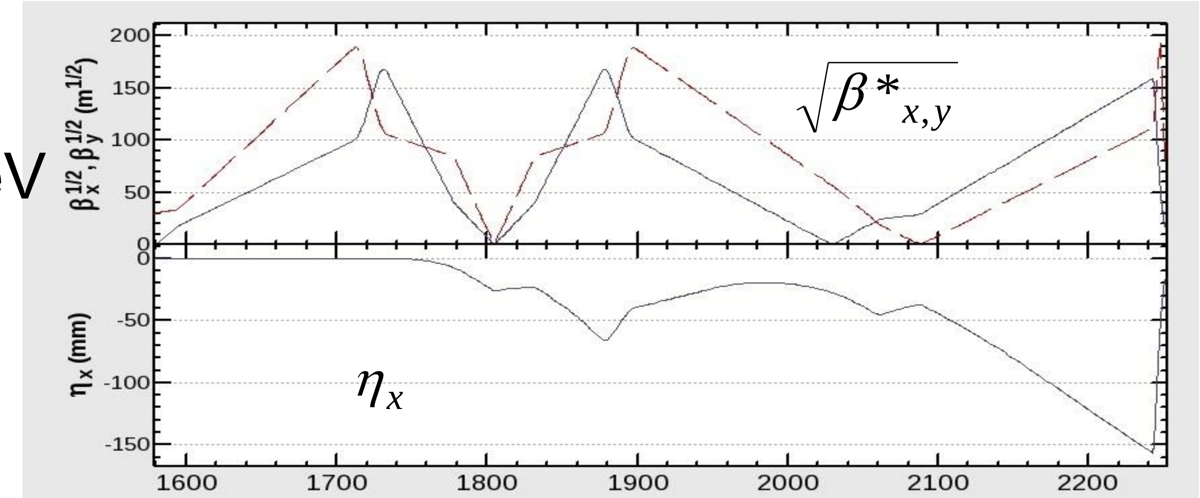
ATF2 Collaboration, "ATF2 Proposal," (2005)

Final Focus Optics, ILC and ATF2

Same magnet configuration, Almost identical optics

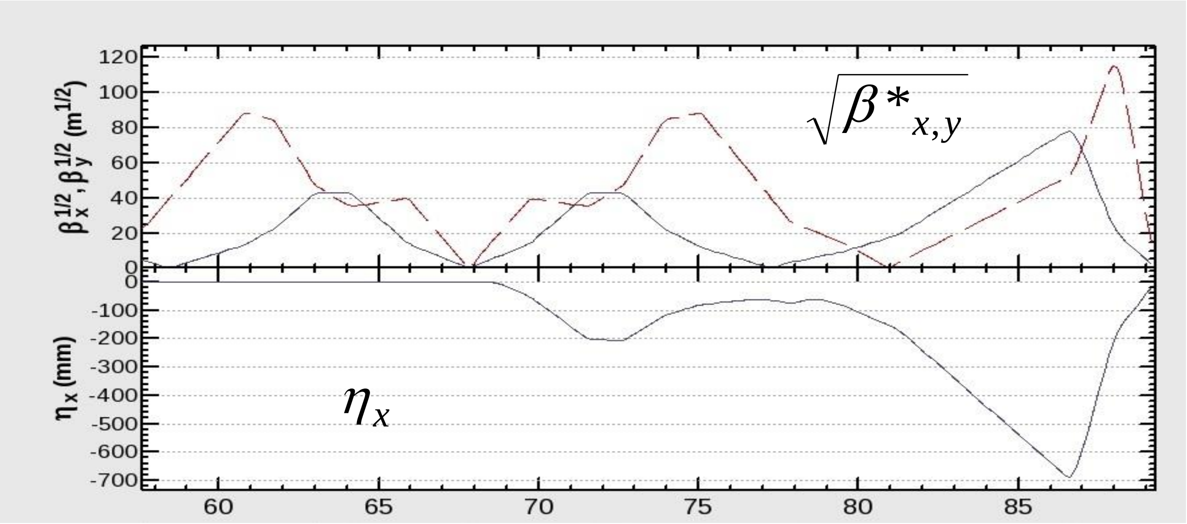
ILC

Up to 500 GeV
~700 m



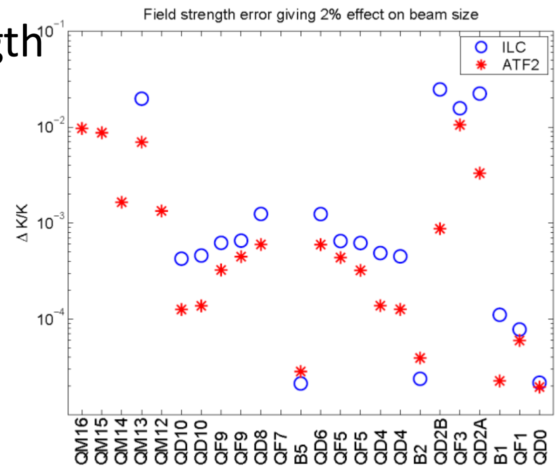
ATF2

1.3 GeV
~30 m

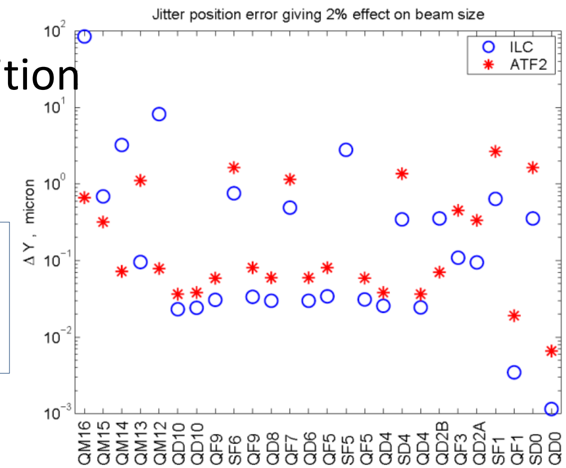


Tolerances for Final Focus System Magnet Errors
Comparison of ILC and ATF2

Field strength



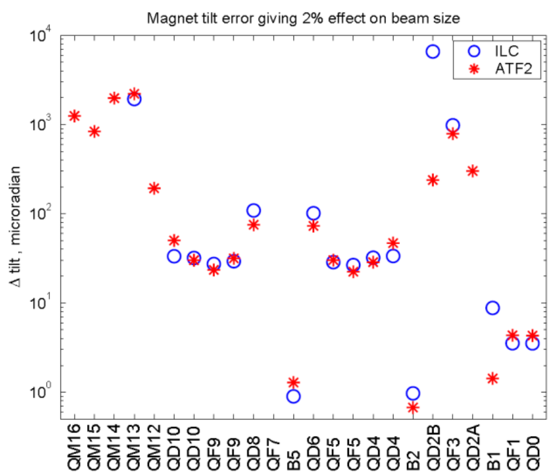
Jitter position



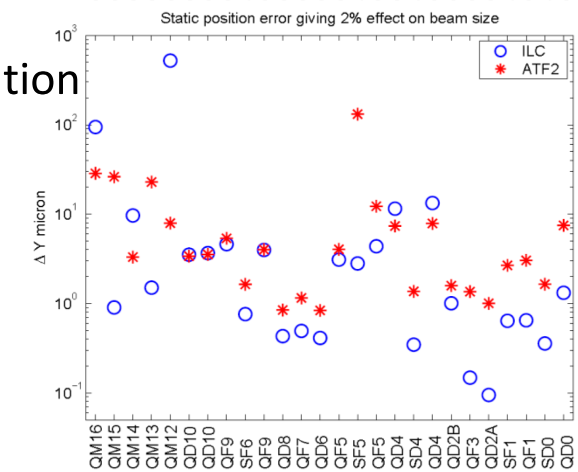
ILC

ATF2

Rotation



Static position



Same magnet names, similar tolerances.

ATF2 Collaboration, “ATF2 Proposal,” (2005)

Beam Size Monitor at Focal Point (IPBSM)

Shintake Monitor, using interference of laser beam

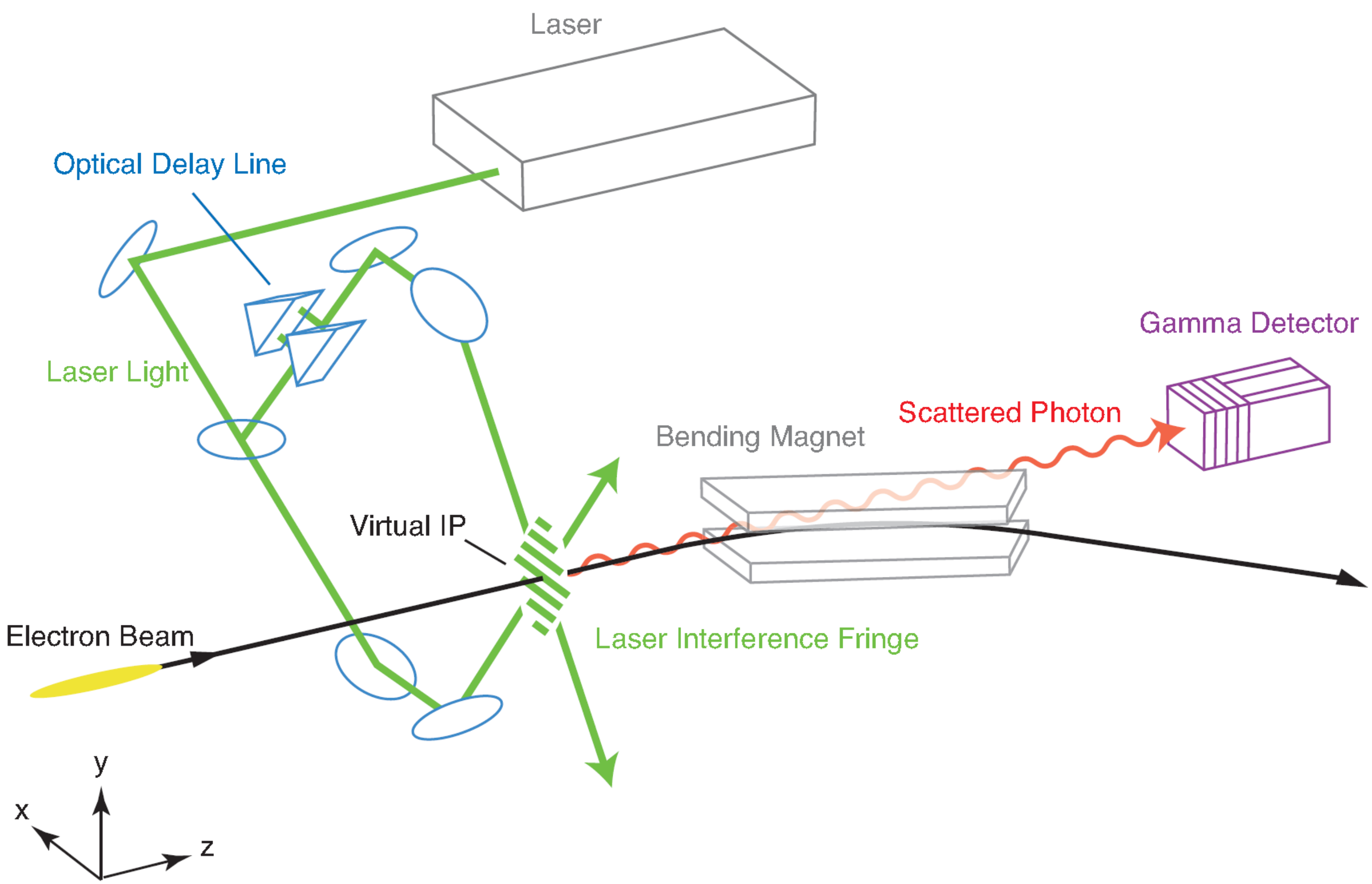
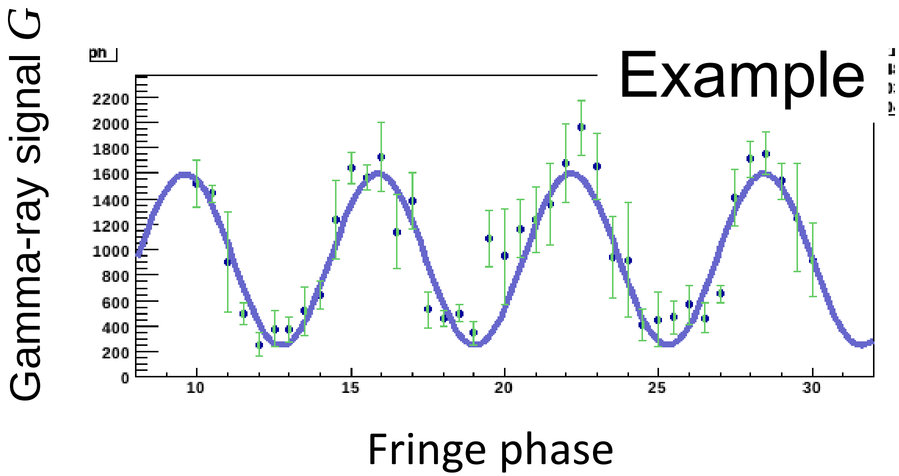


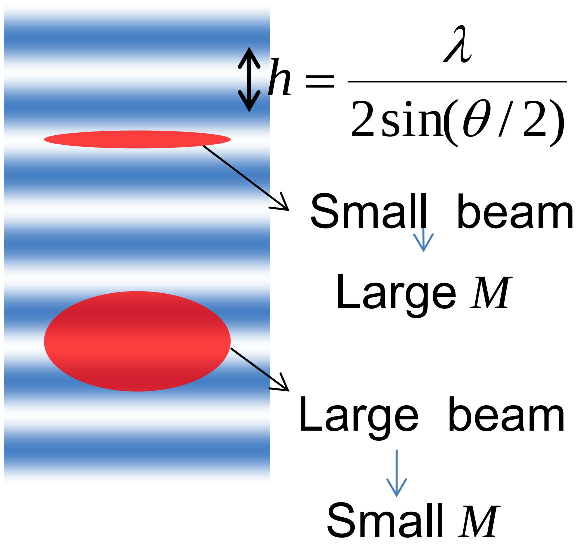
Figure from: Y. Yamaguchi, Master thesis at Graduate School of Science, The University of Tokyo, 2010

Beam size measurement

Scan interference fringe phase.
Fit modulation M:

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





$$h = \frac{\lambda}{2\sin(\theta/2)}$$

For Gaussian beam profile

$$M = |\cos\theta|\exp\left(-\frac{2\pi^2\sigma^2}{h^2}\right)$$

Possible errors reduce M and make apparent beam size larger.
Measured size: Upper limit

Evaluate beam size, σ, from this expression.

Measureable Beam Size Range of IPBSM

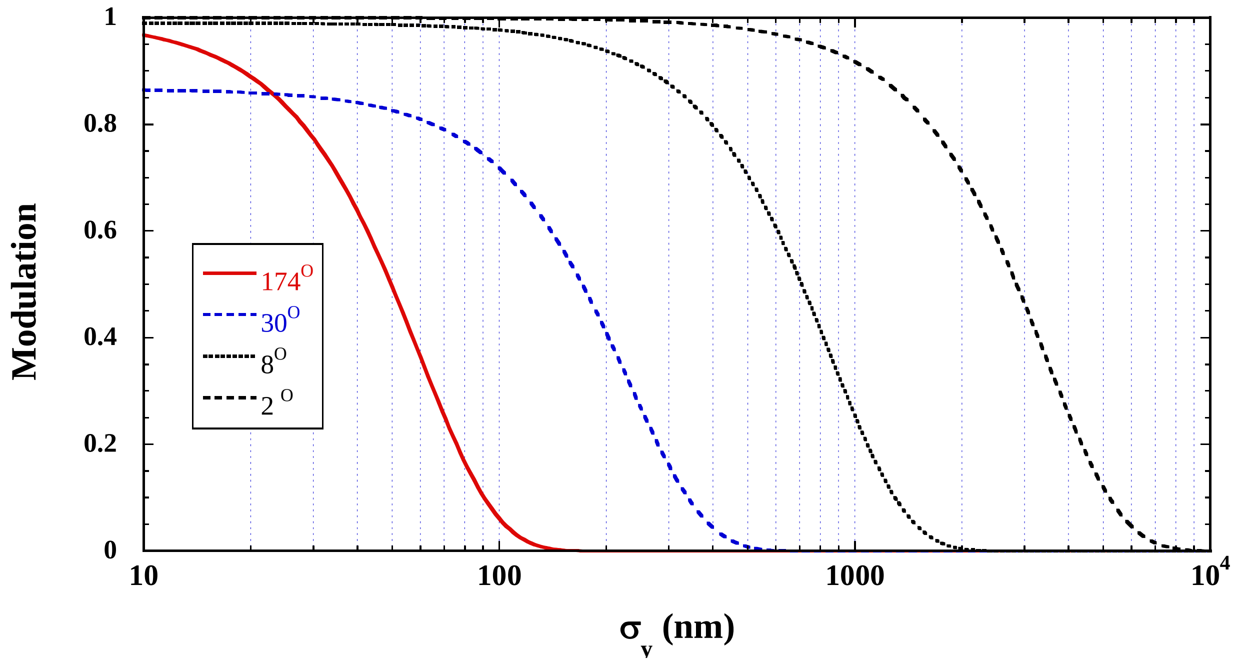
Sensitive beam size range depends on crossing angle (θ) of two laser beams.

Pitch of interference fringe: $$h = \frac{\lambda}{2\sin(\theta/2)}$$

There are 3 different crossing angle modes for covering wide range.

Crossing angle mode
174 deg.
30 deg.
2-8 deg. continuously adjustable

Covers
25 nm – 6000 nm



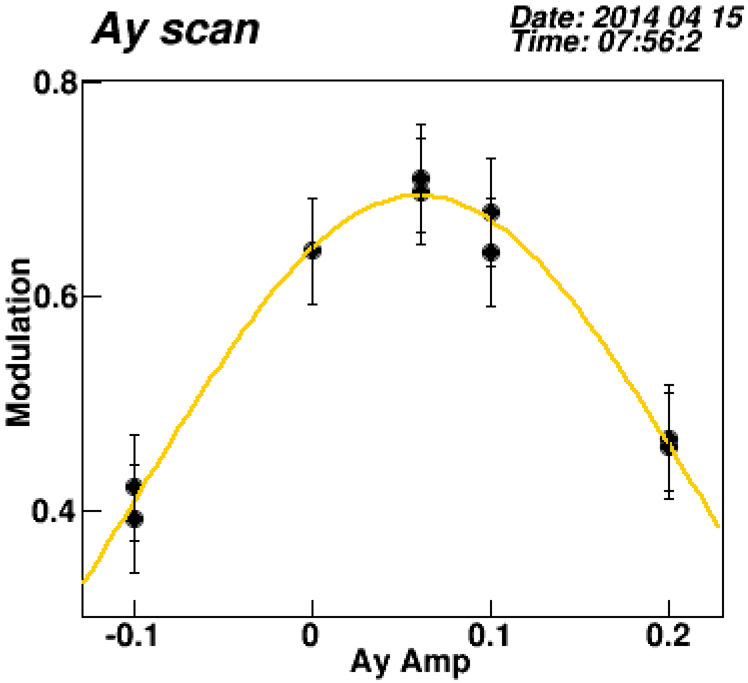
Vertical Beam Size Tuning
(Final stage of beam tuning)

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

Each knob changes one coupling term.

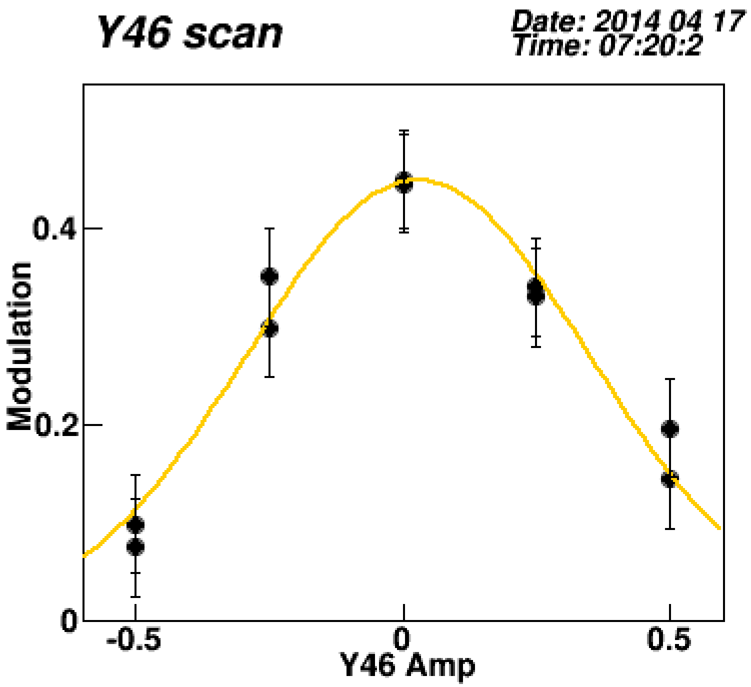
Examples of Tuning knob Scans

yy' coupling knob



M vs. knob strength
IPBSM 30 deg. mode

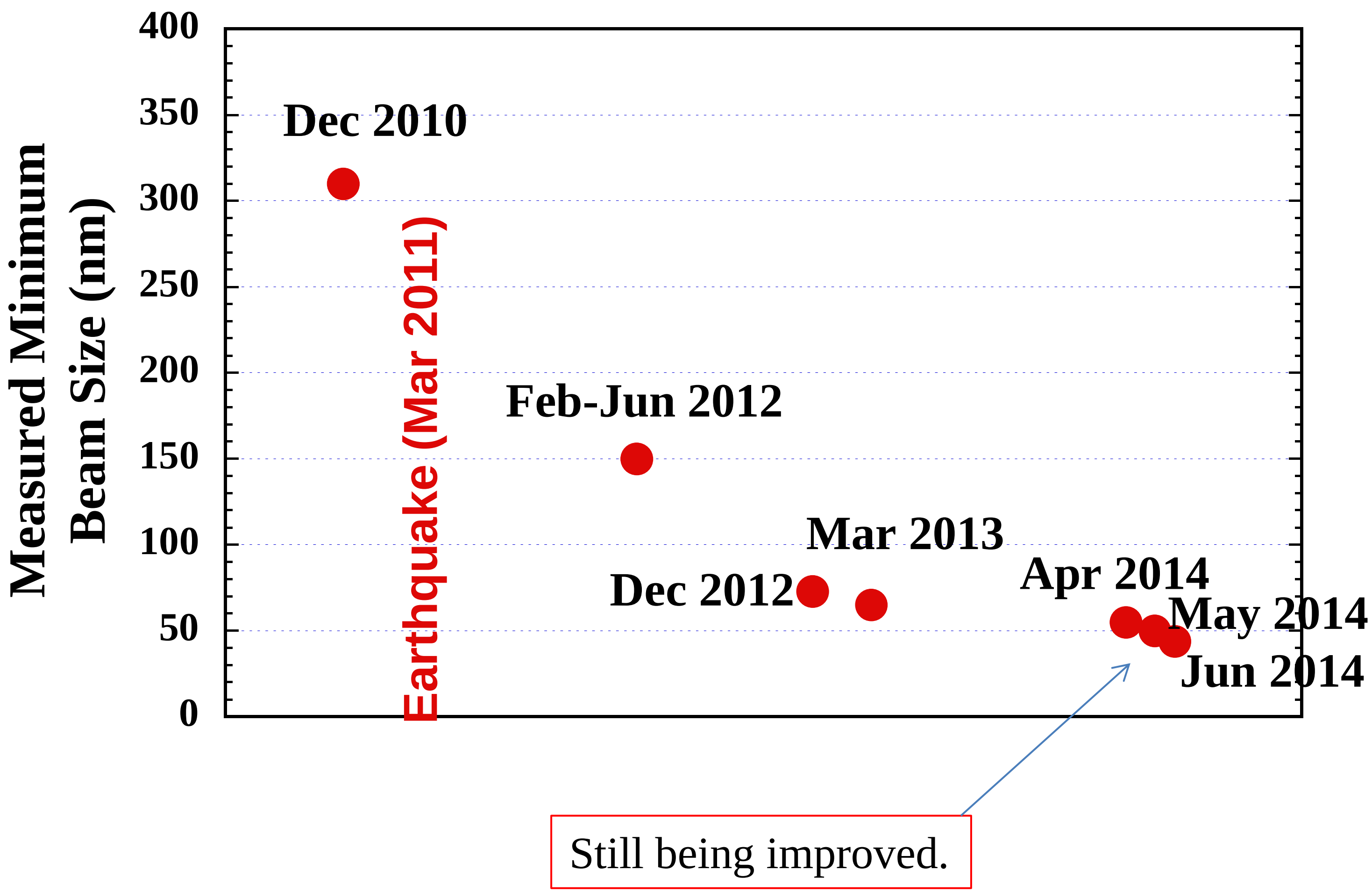
yy'E coupling knob



M vs. knob strength
IPBSM 174 deg. mode

After each scan, "knob" was set at the peak of the fitted line.

History of measured minimum beam size



What Contributed to Improvement?

- **Cures for Higher Order Magnetic Field Errors.**
  - Multi-pole field components of Quadrupole magnets
    - Adopt optics with 10 times larger β^*_x than nominal, smaller beam size at magnets → reduce x-y coupling effects
    - Replace final QF magnet

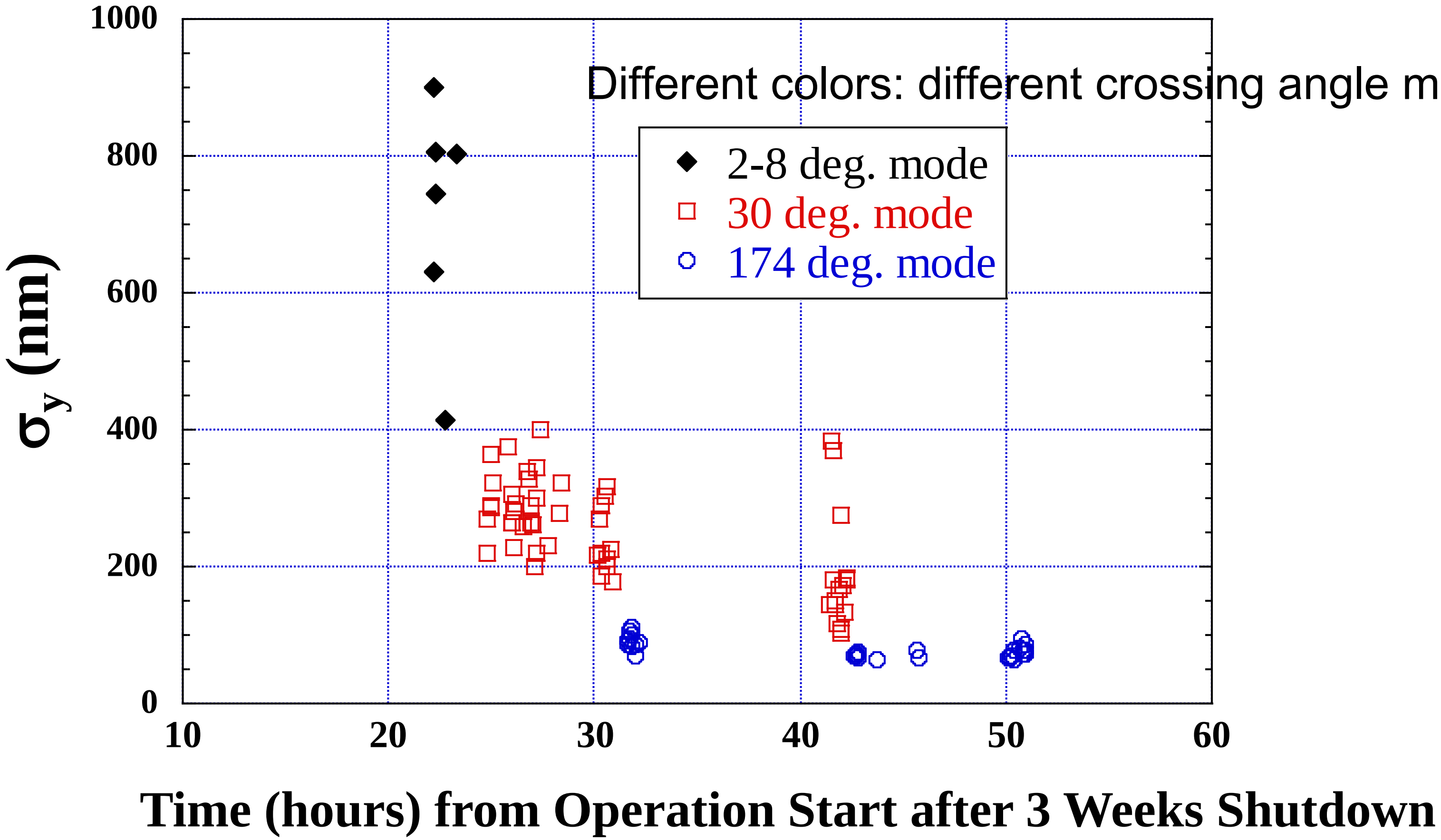
      (Small aperture, strong multi-pole fields

      → Large aperture, weak multi-pole fields)
- **Found one coil of strongest 6-pole magnet was shorted**
  - Exchange with weakest one (January 2013)
  - Turned off, by changing 2nd order optics (April 2014)
- Suppress Orbit Drifts in Final Focus Beam Line
  - **Improvement of orbit feedback**
- **Improvement of Beam Size Monitor**
- Wakefield reduction (?)

Beam Size Tuning after 3 weeks shutdown

Small beam (~60 nm) observed
~32 hours from operation start

Different colors: different crossing angle modes

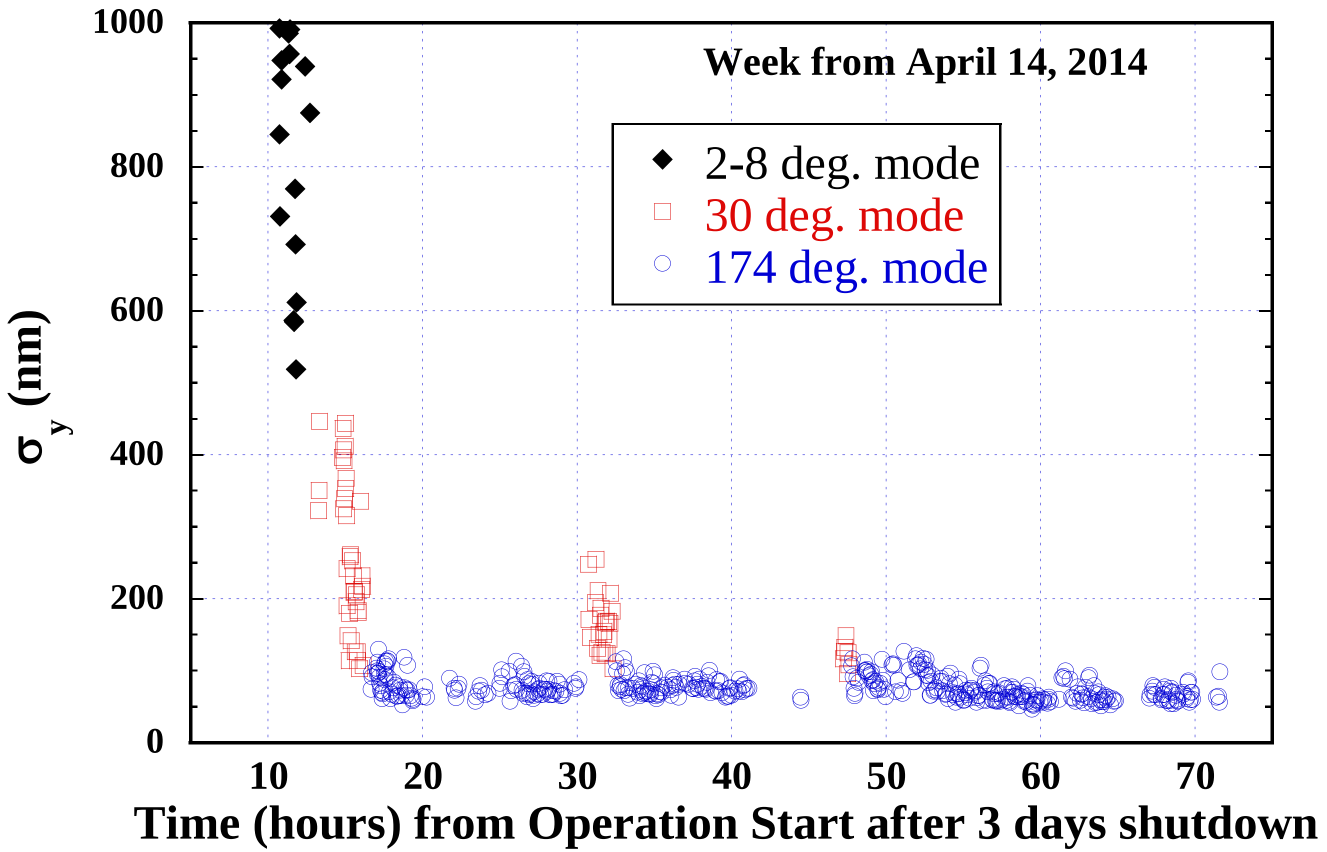


Week 2014 April 7

Beam Size Tuning after 3 days shutdown

Small beam (~60 nm) observed

~16 hours from operation start



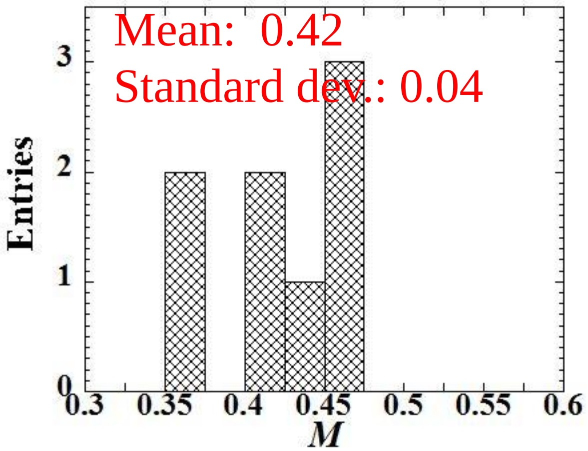
Week 2014 April 14

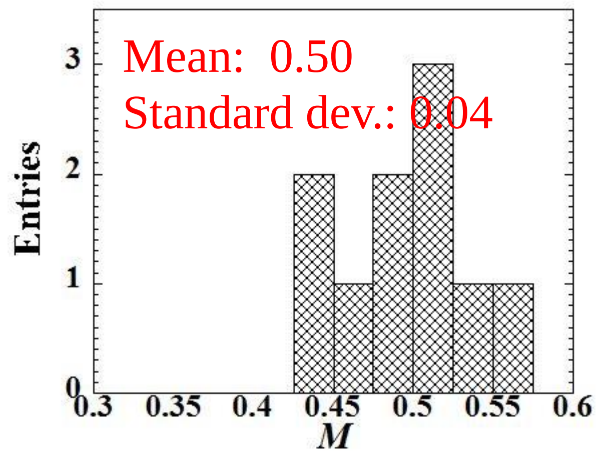
Beam is stable for 30 – 60 min. without tuning.

Examples of consecutive beam size measurements

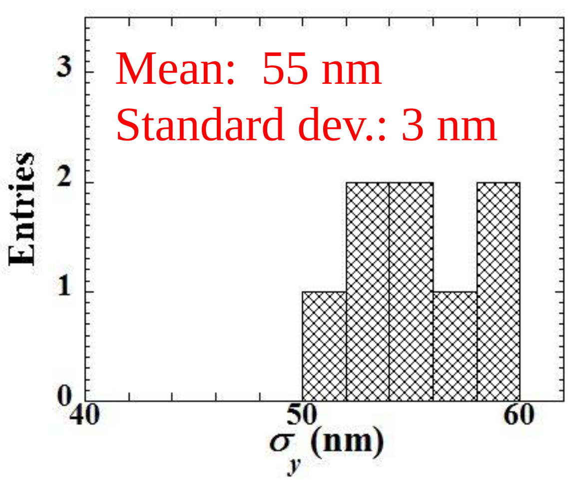
April 17, 2014 | May 22, 2014

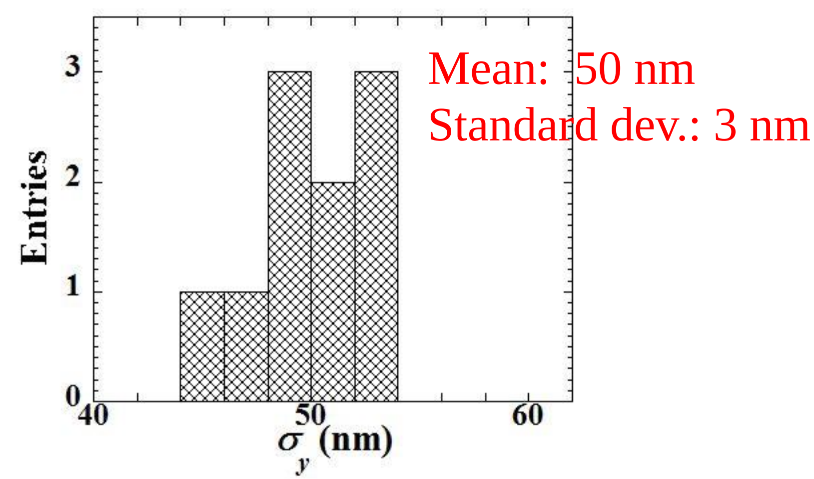
IPBSM Modulation (174 degree Crossing angle)





Beam size Evaluated from Modulation (no systematic error assumed)

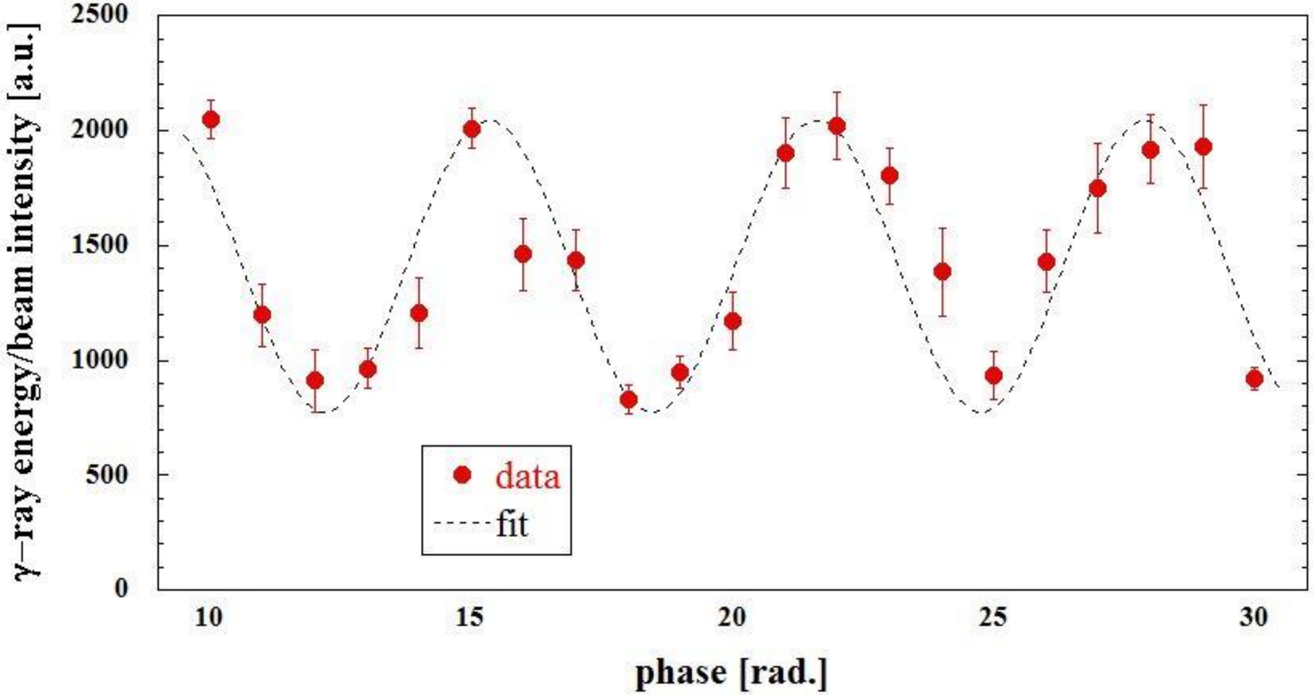




Bunch charge ~ 0.16 nC

Bunch charge ~ 0.09 nC

Example of vertical beam size measurement (Fringe Phase Scan)

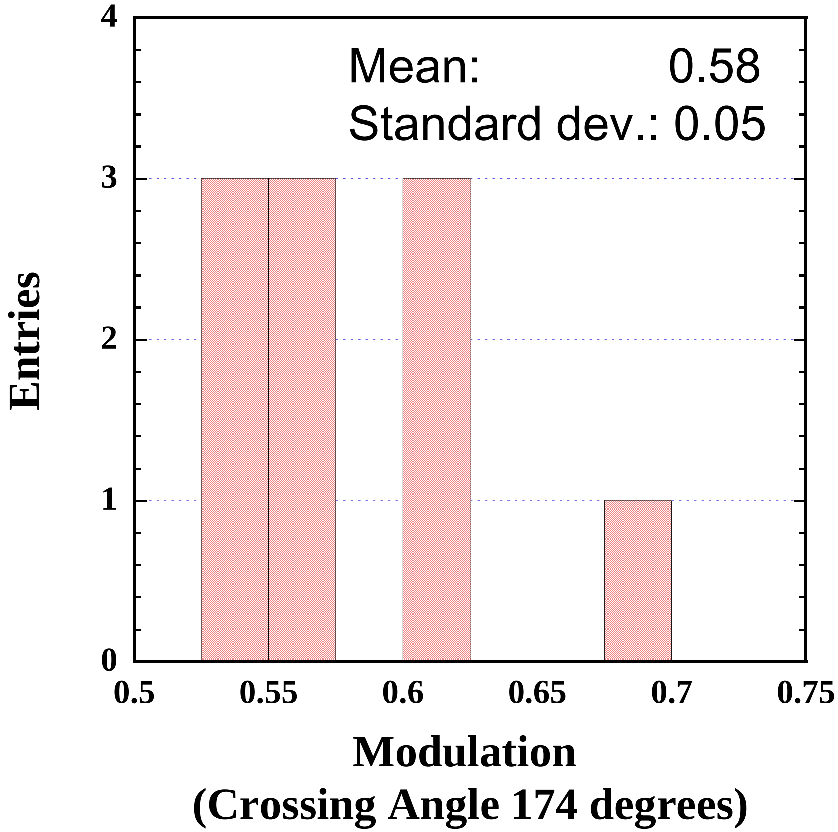


Data on April 17, 2014.
IPBSM with a crossing angle of 174 degrees. Bunch charge ~0.16 nC.
Fitted modulation is 0.45, evaluated beam size 53 nm

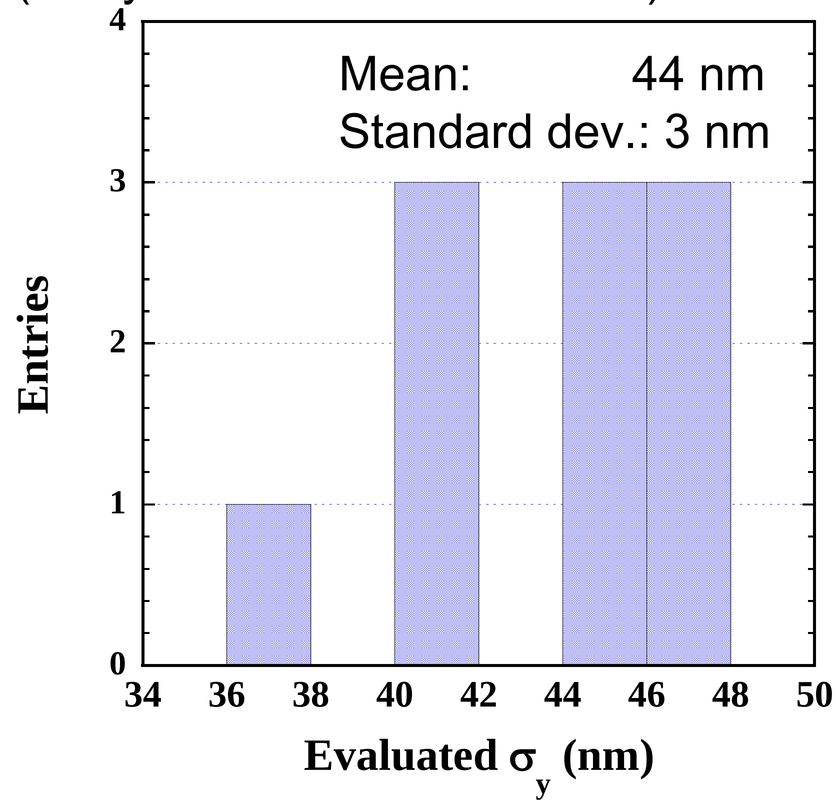
There must be some systematic errors, drift of beam position or monitor’ laser, etc., which tend to reduce modulation and make apparent beam size larger.

Data of Last Week (June 12)

IPBSM Modulation
(174 degree Crossing angle)

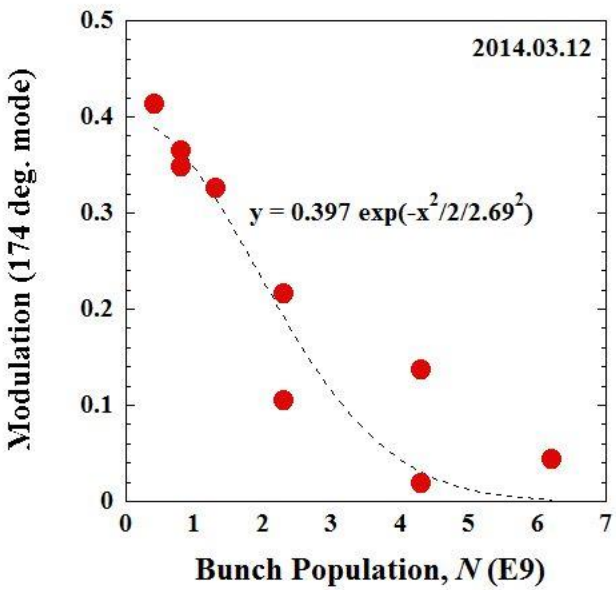


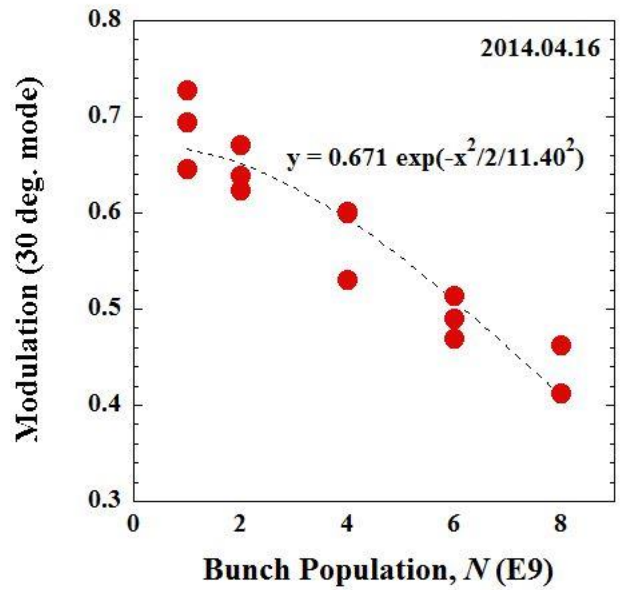
Beam Size Evaluated from Modulation
(no systematic error assumed)



Bunch charge ~ 0.16 nC

Beam Size Depends on Bunch Intensity





IPBSM modulation as function of bunch population. Measured with crossing angle 174 degrees (left) and 30 degrees (right).

Assuming $\sigma_y^2(q) = \sigma_y^2(0) + w^2 q^2$, w is fitted as 100 nm/nC.

$\Rightarrow$ Measured minimum beam size (at 0.1 - 0.16 nC) may be larger than zero - intensity beam size by 2 - 3 nm.

Intensity Dependence

- Beam size strongly depends on bunch intensity.
  - Most probably, due to transverse wakefield.
  - Compare with ILC, much stronger effects:

    Low beam energy (1.3 GeV/250 GeV) and

    Long bunch (7 mm/0.3 mm)
- **Estimation of effects of Wakefield**
  - Wakefield of Cavity BPMS, Bellows, Steps are calculated.
  - Experimental studies by introducing wakefield source on mover.
- **Reduction of wakefield**
  - Shield discontinuities in beam line
  - Remove possible strong wakefield sources
  - Move possible sources from high beta region to low beta region

Remaining Issues for Goal 1 (small beam)

Beam Size Still Slightly Larger Than Designed 37 nm

- Confirm emittance of incoming beam
- Confirm optics matching (β^*_y)
- Further Improvement of beam size monitor
- Detect/correct beam position drift/jitters
  - High resolution BPMs at IP region will solve the question. (related to Goal 2, stabilization of beam orbit)

Study of intensity dependence (Wakefield)

Status of Goal 2 (Stable beam)

- Intra-pulse, bunch to bunch feedback successfully demonstrated
  - Sub-micron to micron level stability. Limited by BPM resolution and bunch to bunch uncorrelated jitters.

- For nanometer level stabilization
  - High resolution BPMs installed around focal point.
  - Basic BPM performance studies on going.
  - Feedback is being prepared.

Other reports in this conference.

ID: 2811, TUPME009, P. Burrows, et.al.

ID: 2781, THOAA02, N. Blaskovic, et.al.

SUMMARY

Small beam

- **Performance of Final Focus System of ILC, Local Chromatic Correction, Has Been Demonstrated.**
  - **Vertical beam size ~45 nm was confirmed at low intensity.**
- **Beam size tuning method for this beam size level established**
  - **Small beam routinely observed.**

Stable beam

- Feedback system successfully tested.
- Nanometer level stabilization being prepared.