

ATF2 IP Beam Size Measurement Systematics

5-10 October 2014
Hyatt Regency and Crowne Plaza, Belgrade

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Role of Shintake Monitor at ATF2

ATF2: test prototype of final focus system for ILC

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x\sigma_y} H_D$$

High luminosity
requires $O(\text{nm})$
vertical beam size at IP



ATF: 1.3 GeV LINAC , DR
→ wextremely small vertical e beam emittance

ATF2 Goal 1:
verify Local Chromaticity Correction
scheme by focusing σ_y to design 37 nm

Goal 2: $O(\text{nm})$ beam position stabilization

Shintake Monitor is the only device capable of measuring $\sigma_y < 100 \text{ nm}$

2014 Spring: made new records in stable measurement of $\sigma_y < 45 \text{ nm}$

ATF2 Goal 1 (almost ?) achieves

→Successful verified FFS design featuring the Local chromaticity Correction scheme

large step towards demonstarting feasibility of realizing ILC

Outline of this talk

Introduction

Beam Time Status

Focus of this talk

Performance precise
evaluation of systematic
errors to precisely
evaluate the beam size

Summary

Introduction

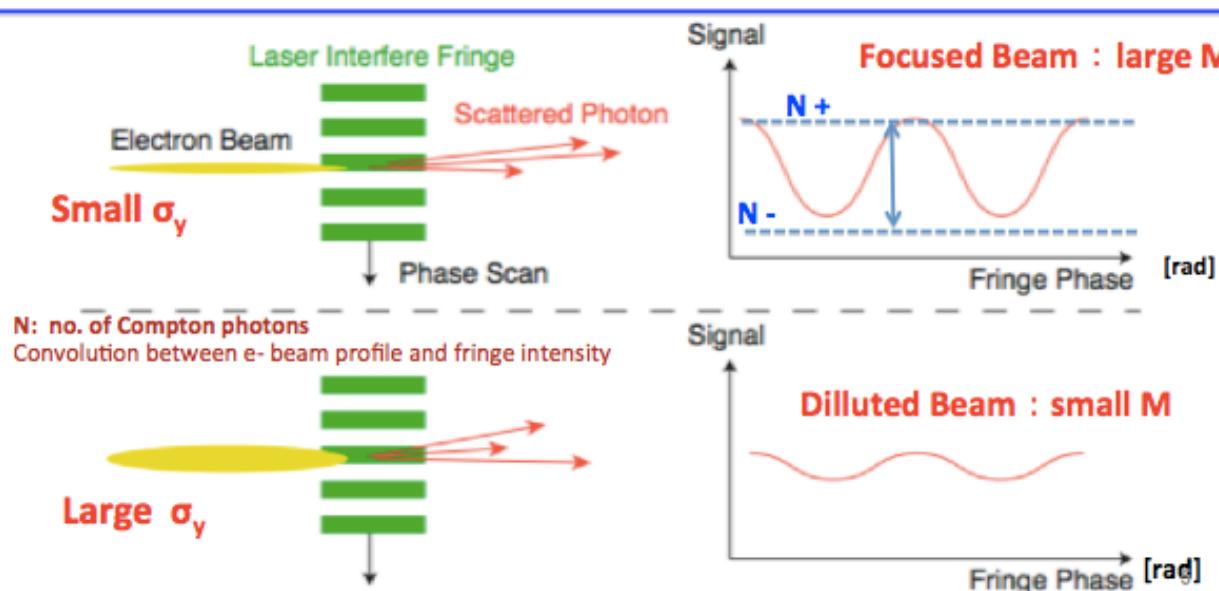
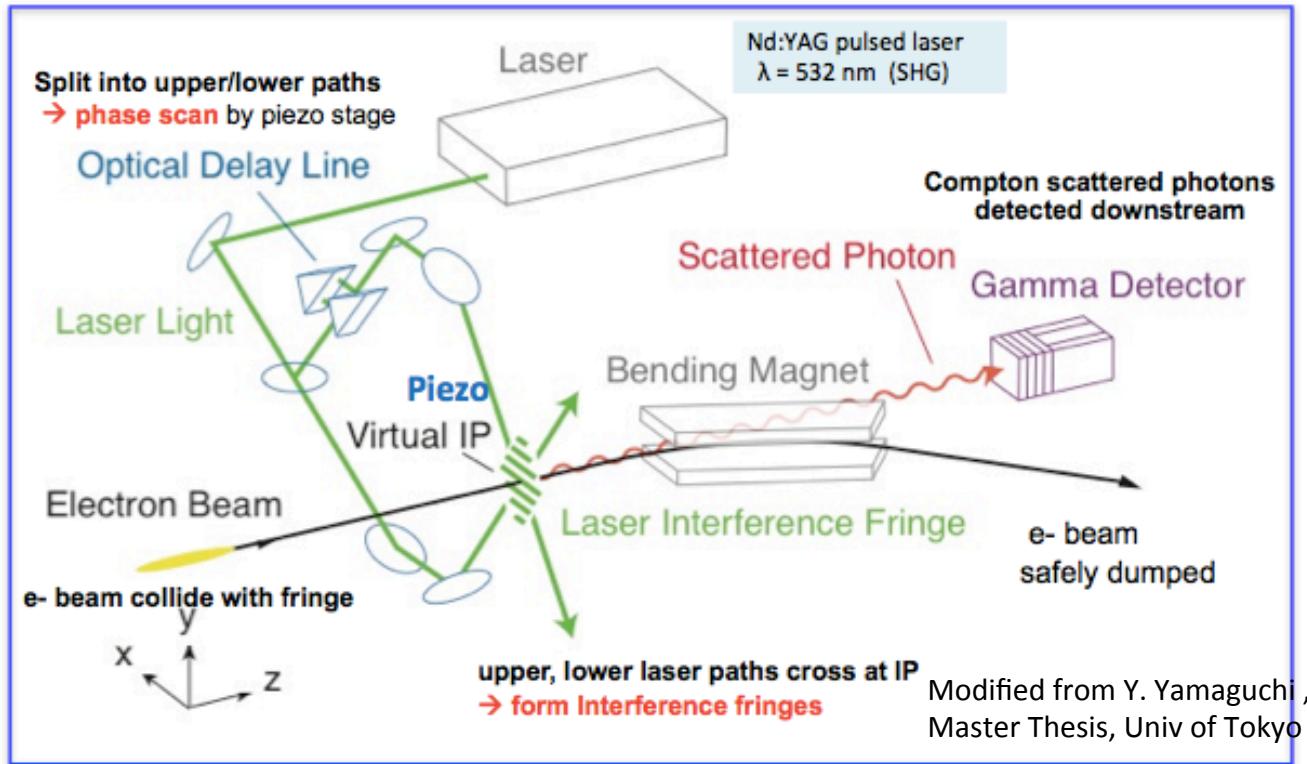
**Measurement Scheme
Expected Performance
Role in Beam Tuning**

Measurement Scheme

measurable range
determined by **fringe pitch**

$$d = \frac{\pi}{k_y} = \frac{\lambda}{2 \sin(\theta/2)}$$

depend on
crossing angle θ (and λ)



Detector measures
signal **Modulation Depth "M"**

$$M = \frac{N_+ - N_-}{N_+ + N_-} = |\cos(\theta)| \exp(-2(k_y \sigma_y)^2)$$

$$\Rightarrow \sigma_y = \frac{d}{2\pi} \sqrt{2 \ln \left(\frac{|\cos(\theta)|}{M} \right)}$$

Crossing angle θ	174°	30°	8°	2°
Fringe pitch	266 nm	1.03 μm	3.81 μm	15.2 μm
$d = \frac{\pi}{k_y} = \frac{\lambda}{2 \sin(\theta/2)}$				
Lower limit	25 nm	80 nm	350 nm	1.2 μm
Upper limit	110 nm	400 nm	1.4 μm	6 μm

Expected Performance

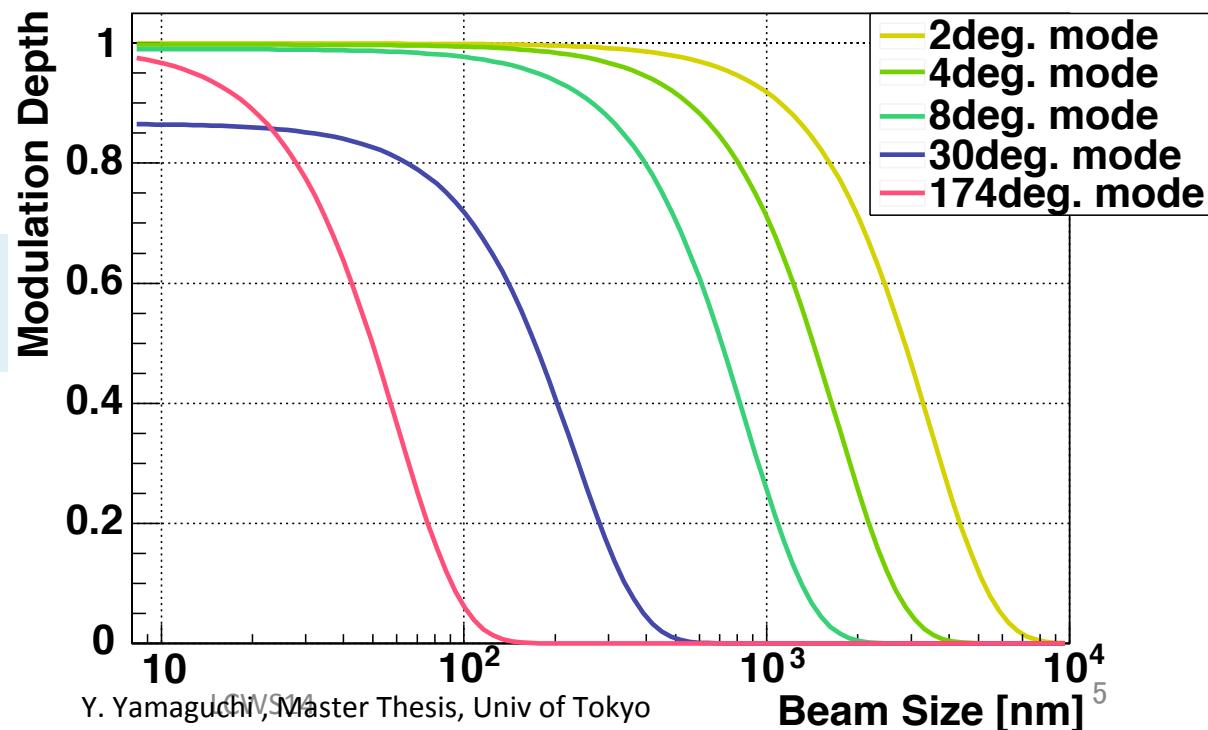
Measures

$\sigma_y^* = 25 \text{ nm} \sim 6 \mu\text{m}$
with < 10% resolution

$$\sigma_y = \frac{d}{2\pi} \sqrt{2 \ln\left(\frac{|\cos(\theta)|}{M}\right)}$$

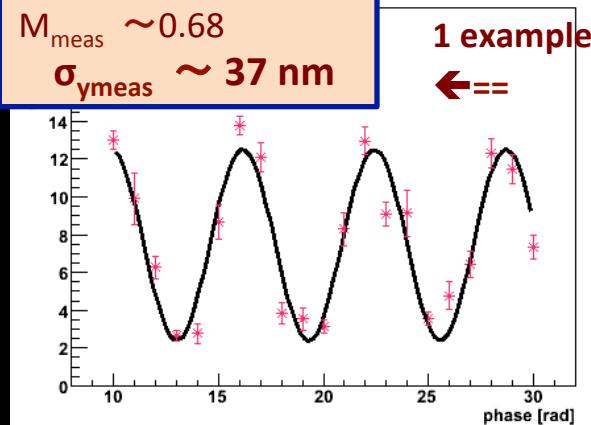
σ_y and M
for each θ mode

select appropriate mode
according to beam focusing

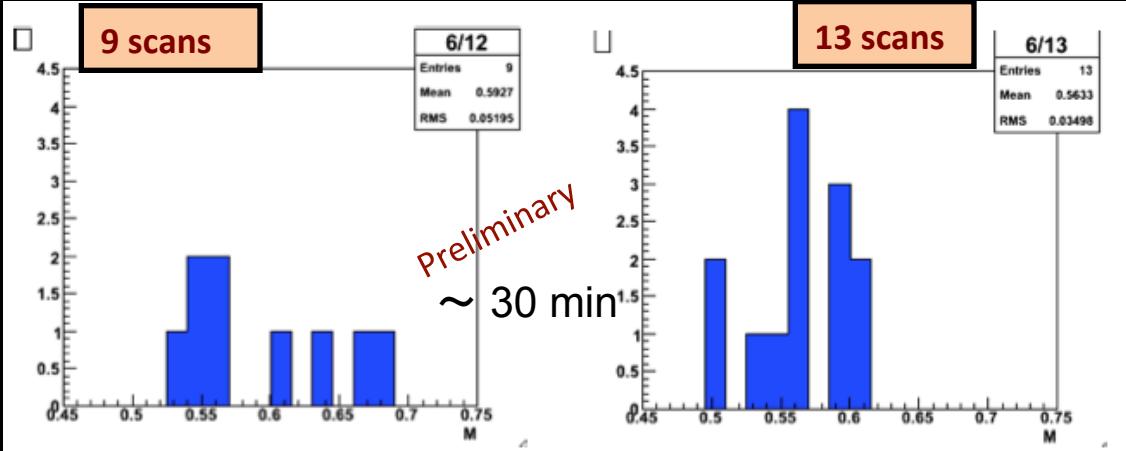


Recent Beam Time Status

Newest Beam time status



"record continuous scans" (June 2014)



These are the results before correction of systematic errors

Focus of this talk is evaluation of "M reduction factors"

→ show that the actual σ_y is smaller after compensation of systematics

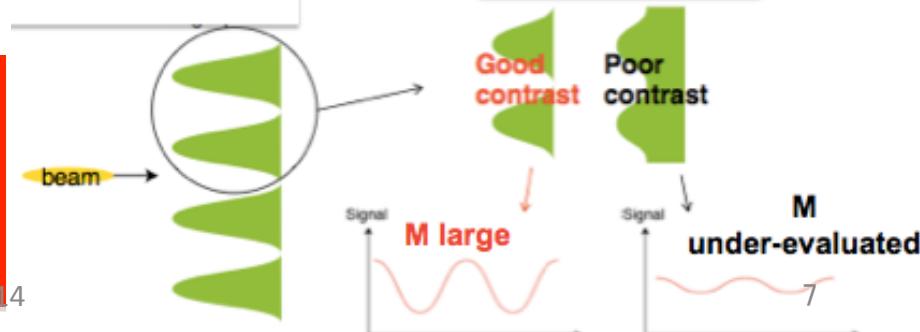
best measurement stability $\sim 5\%$

date	Preliminary	M_{meas}	$\sigma_{\text{meas}} [\text{nm}]$	stability
6/12		0.589 ± 0.053 (S.D.)	43.3 ± 3.7 (S.D.)	9.0%
6/13		0.563 ± 0.038 (S.D.)	45.2 ± 2.7 (S.D.)	6.7%

Reference:

- K. Kubo et al: IPAC14 :TOWARDS INTERNATIONAL LINEAR COLLIDER: EXPERIMENTS AT ATF2
- S. Kuroda et al : ICHEP14 , "ATF2 for Final Focus test Beam for Future Linear Colliders",

degraded fringe contrast due to bias



M under-evaluation

$$M_{\text{meas}} = C_1 \cdot C_2 \cdot \dots \cdot M_{\text{ideal}}$$

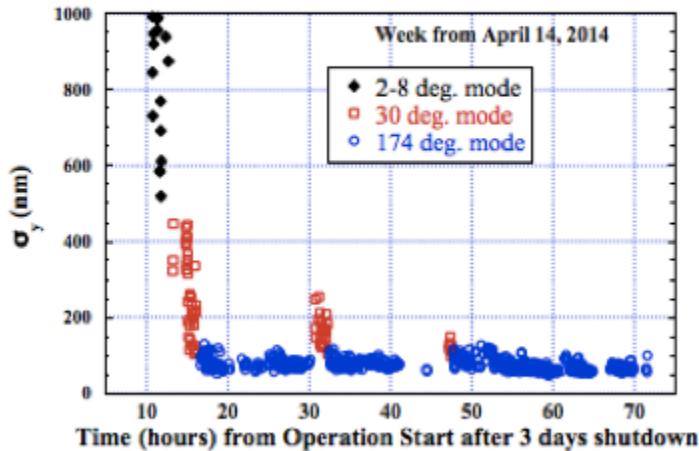
σ_y over-evaluation

$$\sigma_y \rightarrow \sqrt{\sigma_y^2 + \sum_i |\ln(C_i)| / (2k_y^2)}$$

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Beam time performance

Beam Size Tuning after 3 days shutdown
Small beam (~60 nm) observed
~16 hours from operation start



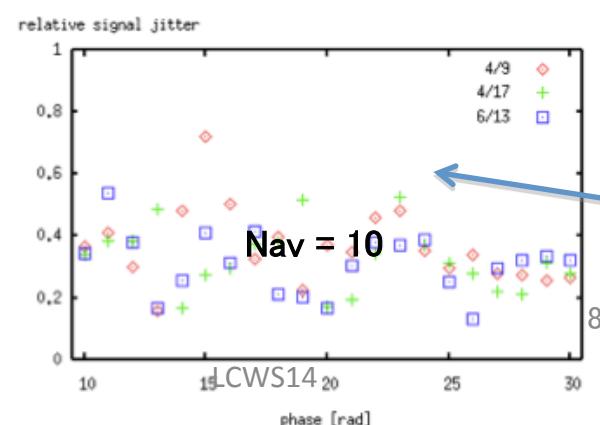
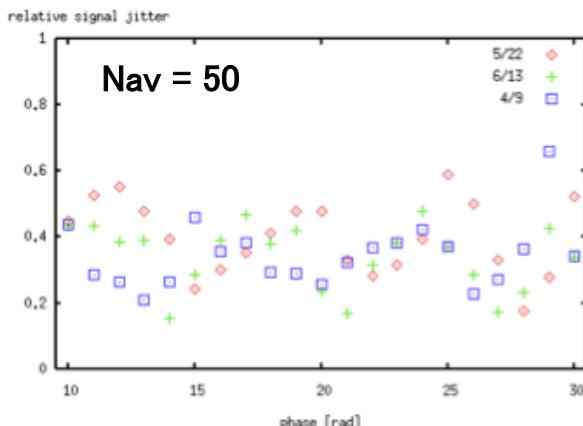
K. Kubo et al: IPAC14 :TOWARDS INTERNATIONAL LINEAR COLLIDER
Week 2014 April 14

HIGHLIGHTS of PERFORMANCE

Consistent measurement of high M @ 174°

• effective linear / nonlinear knob tuning

$\sigma_y > 150 \text{ nm} \rightarrow \sigma_y < 60 \text{ nm}$ within half a day !!



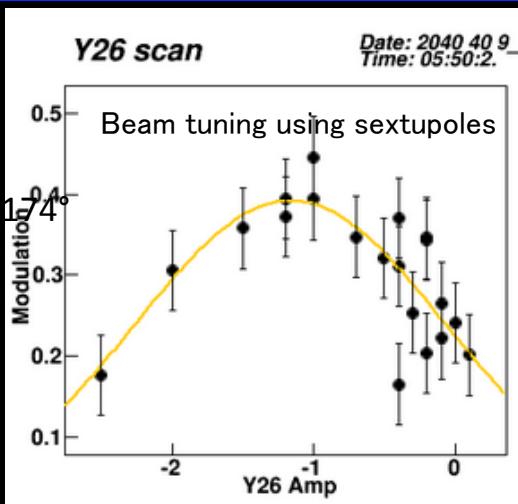
Progress owes to improvements of both IPBSM and beam

IPBSM:

- reduction in signal jitters/ drifts by hardware improvement
laser profile tuning, detector collimation, Q-Switch timing
- Speed up IPBSM control software : 1 Hz → 3 Hz
reduced effect from drifts (?)
- reinforcement of detector shielding :

Electron Beam :

- stabilize beam orbit
- exchange of magnets
- suppress wakefield sources in beamline



Relative signal jitter in 174 deg mode fringe scans
Generally 15–50%,
depending on phase

M reduction Factors

$$M_{\text{meas}} = C_1 \cdot C_2 \cdot \dots \cdot M_{\text{ideal}}$$

Priorities

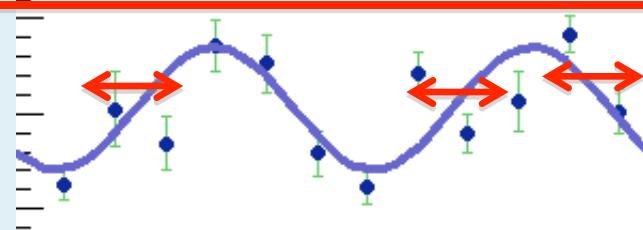
- 1) improve hardware to suppress error sources by IPBSM group at KEK
- 2) Evaluate residual errors

Phase jitter ($\Delta\phi$)

== relative position jitter (Δy) between laser and beam

causes:

- laser pointing jitter, mirror vibration
- e beam jitter $\Delta\varphi = 2k_y\Delta y \quad \sigma_y^2 \rightarrow \sigma_y^2 + \Delta y^2$
change over time, hard to evaluate quantitatively



Suppress by careful alignment:

- ◆ **laser misalignment (position & profile)** shot-by-shot profile fluctuation
- ◆ **fringe tilt (roll and pitch)** → Optimization by “**tilt scan**”

Others:
insignificant effect

- ◆ **Power imbalance**
- ◆ **Polarization** : optimize by “ **$\lambda / 2$ plate scan**”
- ◆ **Phase drift (linear)**
- ◆ **spherical wave front effects**
- ◆ **growth of σ_y within fringes**

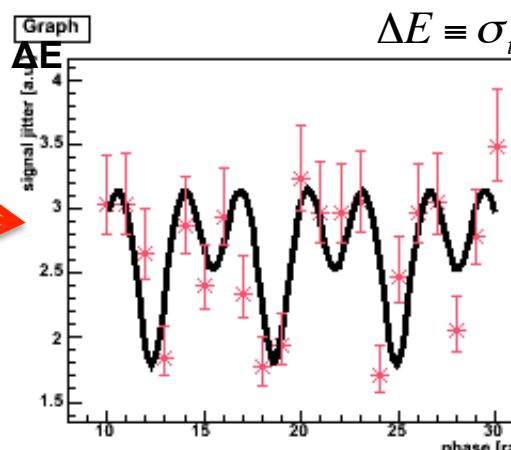
$\Delta\phi$ is one of the most dominant limit on small σ_y measurement

my personal focus:

develop original method for deriving $\Delta\phi$

- ➔ demonstrate precision of method using simulation
- ➔ Analysis of beam time data

Plot signal jitter as a function of phase fitting: convolute phase jitter and vertical jitters



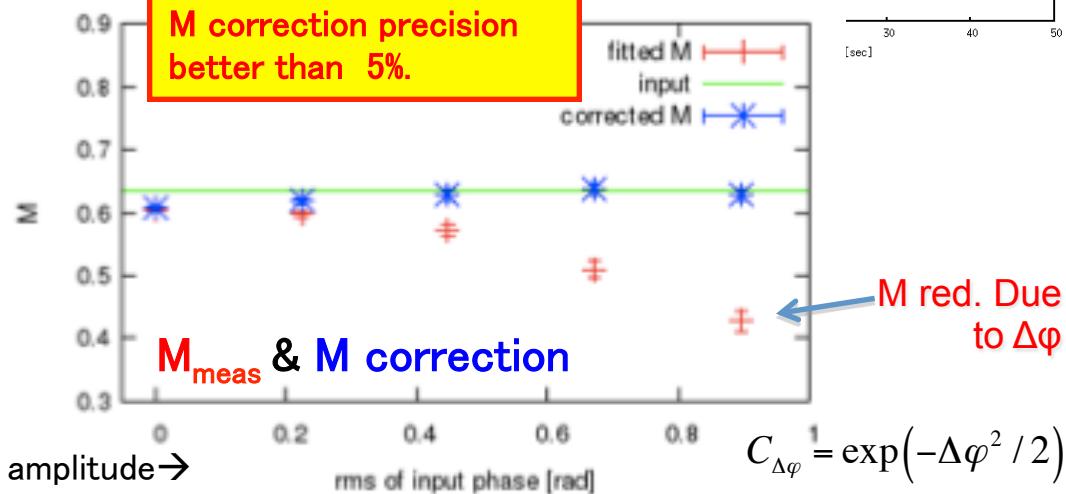
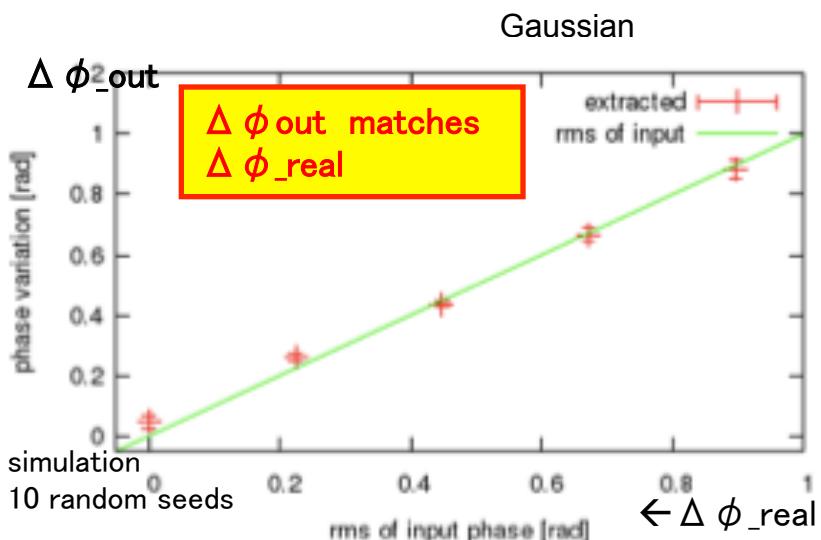
$$\Delta E \equiv \sigma_{\text{tot}} = \sqrt{\sigma_V^2 + \sigma_p^2}$$

Fix M from regular fitting

simulation test of $\Delta\phi$ extraction and compensation

Fringe scan simulation input:
past measured $\Delta\phi$
(change amplitude)

- + realistic long range phase drift
- + vertical jitter



Apply verified method to actual data analysis

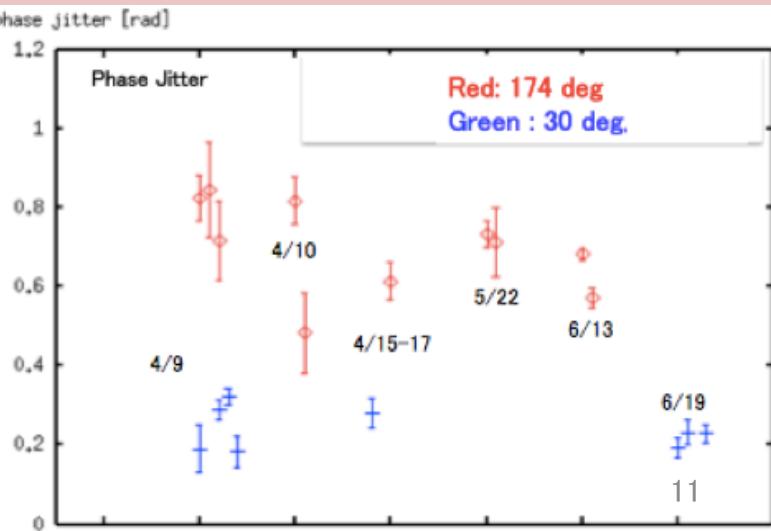
174 °: typically $\Delta\varphi = 0.4\text{-}0.75$ rad
contribute 5-9 nm to σ_y

Less for 30 °: typically $\Delta\varphi < 0.3$ rad
-174 deg mode is more sensitive to e- beam jitter
- 174 deg mode has longer path length after half mirror

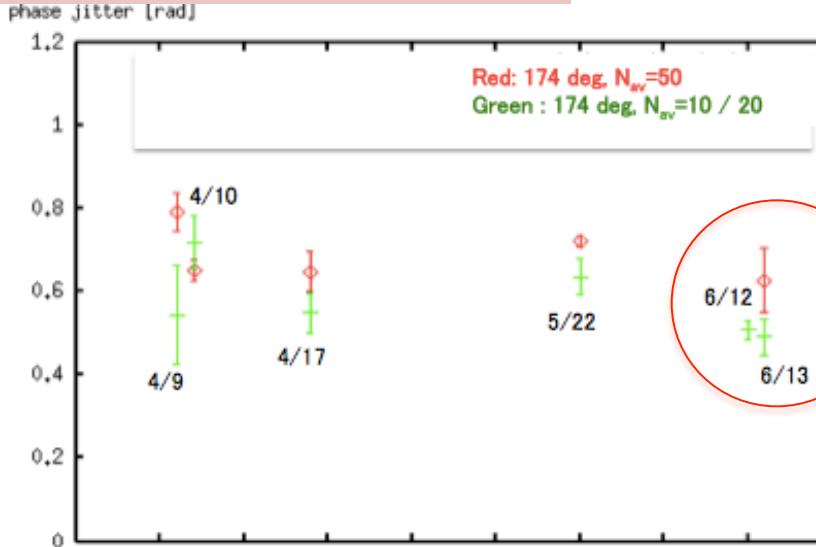
$\Delta\phi$ is combination of jitter and slow drifts
effect on M depend on scan time structure

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History of estimated $\Delta\phi$ in randomly sampled scans



History of estimated $\Delta\phi$ in continuous scans (174 deg)



Overall evaluation

M reduction factors for the two record sets of scans in June 2014

Preliminary

date	6/12 (9 scans)	6/13 (12 scans)
$C_{\Delta\varphi}$	0.878	0.886
$C_{t,align}$	> 0.987	> 0.996
$C_{z,align}$	> 0.911	> 0.970
C_{tilt}	> 0.999	> 0.999
C_{pitch}	> 0.988	> 0.988
C_{sphere}	> 0.997	> 0.997
C_{growth}	> 0.9937	> 0.997
C_{drift}	> 0.999	> 0.999
C_{power}	> 0.999	> 0.999
C_{pol}	100%	100%
C_{total}	> 0.773	> 0.838

Full beam size evaluation for smallest σ_y
Taking into account systematic errors

Preliminary

date	6/12 (9 scans)	6/13 (12 scans)
M	$0.589 \pm 0.019(stat)^{+0.173}_{-0.000}(syst)$	$0.563 \pm 0.011(stat)^{+0.109}_{-0.000}(syst)$
σ_y	$43.3 \pm 1.3(stat)^{+0.0}_{-12.4}(syst)$ nm	$45.2 \pm 0.8(stat)^{+0.0}_{-7.7}(syst)$ nm

Demonstrates ATF2 Goal 1 is met within error ranges even for stable consecutive scans

Uncertainty of error evaluation

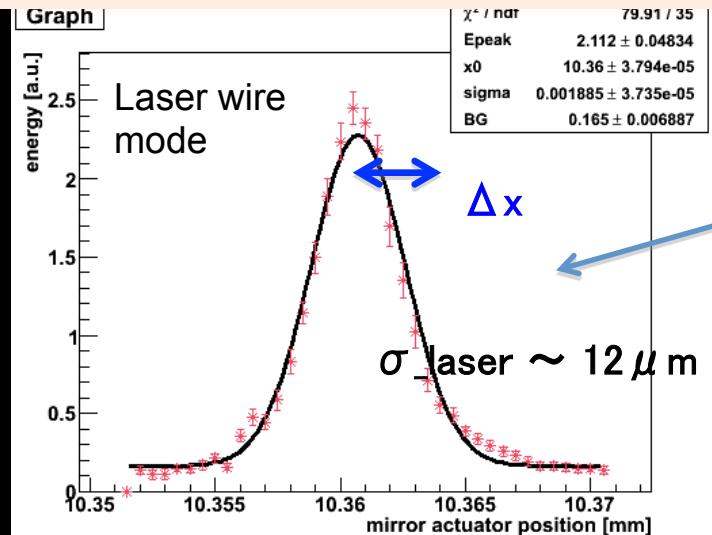
$$\Delta M_{corr} = \frac{M_{meas}}{C_{tot}^2} \Delta C_{tot} = M_{corr} \frac{\Delta C_{tot}}{C_{tot}} = M_{corr} \sqrt{\sum_i \left(\frac{\Delta C_i}{C_i} \right)^2}$$

Uncertainty of the dominant $\Delta C_{\Delta\phi}$: 5–10%
 \rightarrow 5–10% for ΔM_{corr} ,
 2–4 nm for $\sigma_y = 45$ nm

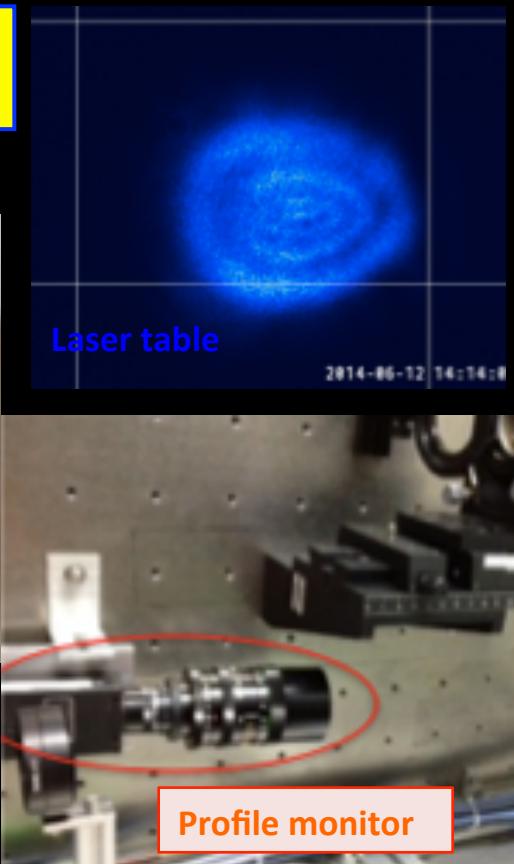
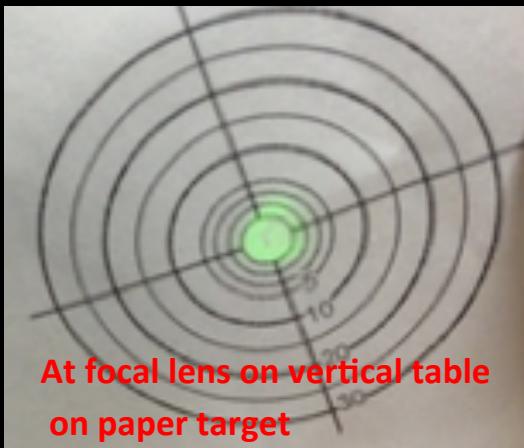
Laser pointing stability

x relative position jitter : $\Delta x_{\text{rel}} \sim 2.5 \mu\text{m}$

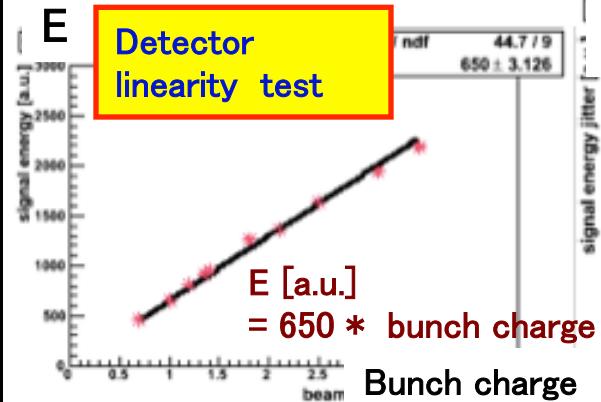
laser pos. jitter : $\Delta x_{\text{laser}} / \sigma_{\text{laser}} \sim 15 \%$



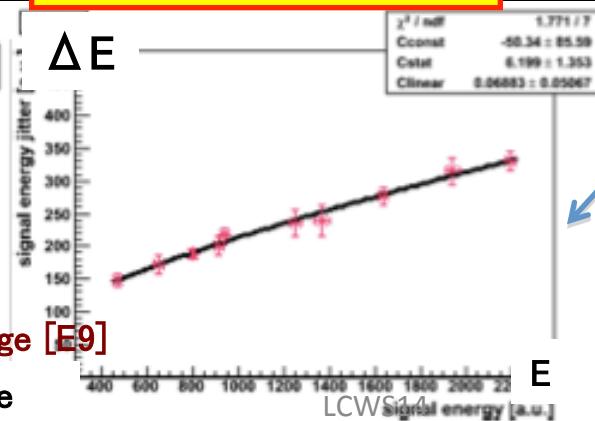
Laser profile (spot size, shape, focusing)



CsI detector calibration



Statistical fluctuation



info. used in $\Delta \phi$ analysis

dominnat
 $C_{\text{stat}} = 6.2 \times \text{sqrt}(\text{unit of } E)$

$$\Delta E = \sqrt{C_1^2 + (C_{\text{stat}}\sqrt{E})^2 + (C_2 E)^2}$$

Direct Laser power measurement



174 deg U vs L path, vertical table vs laser table

Power balance better than 95 %
→ Cpower > 0.99 (M reduction)

results	location	174 U	174 L	vertical table	laser table
power [W] (mean±RMS)		0.356±0.002	0.3573±0.003	0.799±0.004	0.857±0.005
power jitter = RMS/mean		0.5%	0.8%	0.5%	0.6%

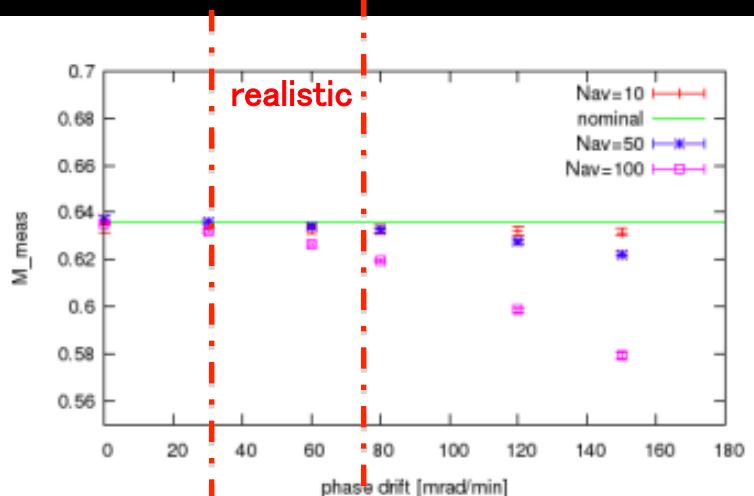
Total power jitter < 1%

Loss in transport line < 7 %

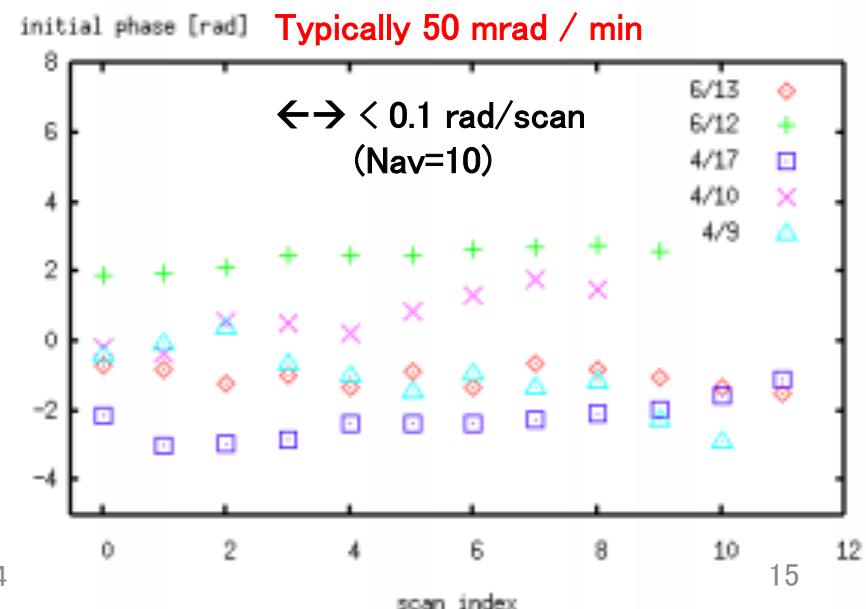
Phase drift (long range)

Simulation of M red due to linear phase drift

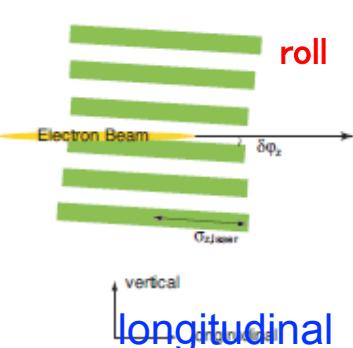
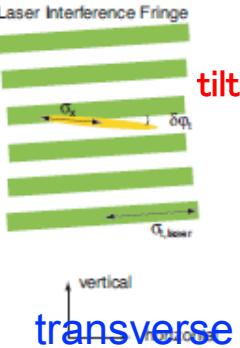
Cdrift > 0.99 for Nav=10, 50



drift of initial phase (fitted) in continuous scans



Fringe tilt / pitch



Mis-match of fringe and beam axis

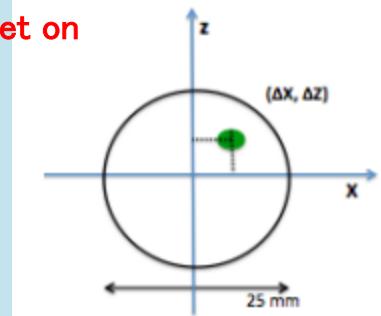
Due to laser path misalignment:

if tilt ~ 5 mrad : $\sigma_y^{*} = 40$ nm $\rightarrow 65$ nm

$$\text{tilt } \sigma_{y,\text{meas}}^2 = \sigma_{y0}^2 + \sigma_x^2 \cdot \Delta\Phi_{\text{tilt}}$$

$$\text{roll } \sigma_{y,\text{meas}}^2 = \sigma_{y0}^2 + \sigma_{z,\text{laser}}^2 \cdot \Delta\Phi_{\text{pitch}}$$

Offset on lens



- Position drift over time
- e beam itself is rotated in x-y

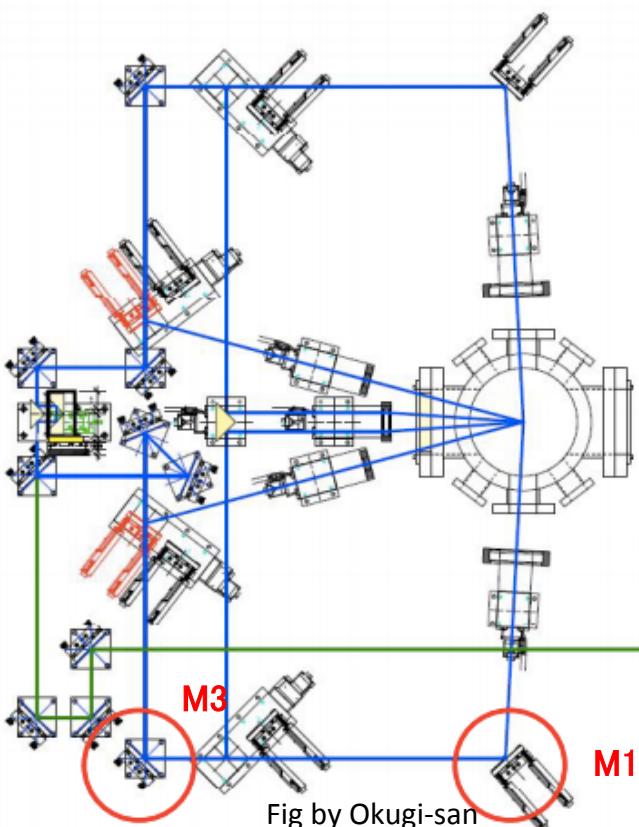


Fig by Okugi-san

Use interaction with beam as reference to correct tilt/pitch

Remote control of mirror actuators

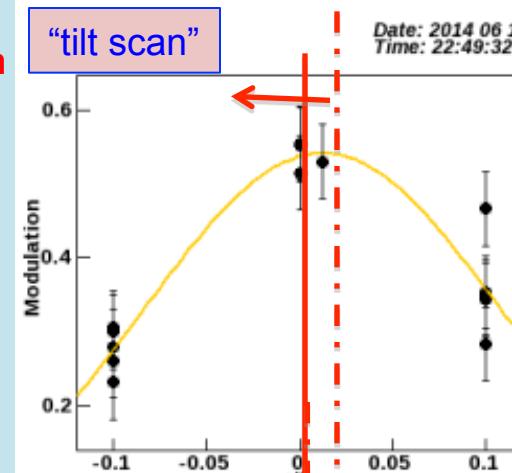
From precision of M3 setting
(peak search)

Ctilt,roll >~ 0.99

Big improvement of M

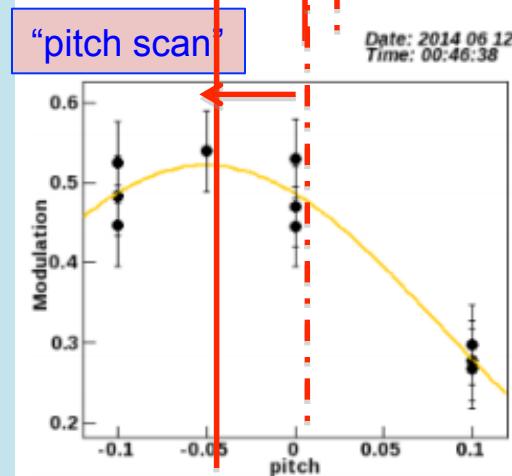
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Beam time



Fit results: $A \cdot \exp(-(x-B)/C)^{2/2}$
Modulation: 0.541 ± 0.025
Center: 0.012 ± 0.005
Sigma: 0.097 ± 0.006
Chi2/ndf: $9.0670e+00 / 11$

Fringe tilt corrected by about 0.5 mrad



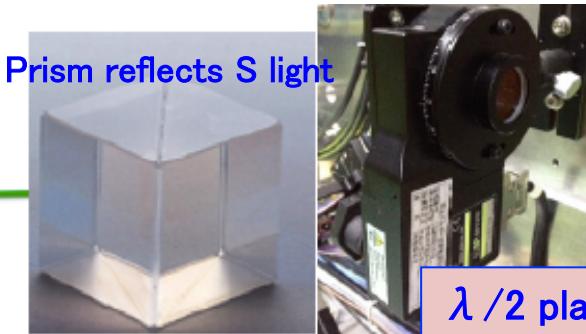
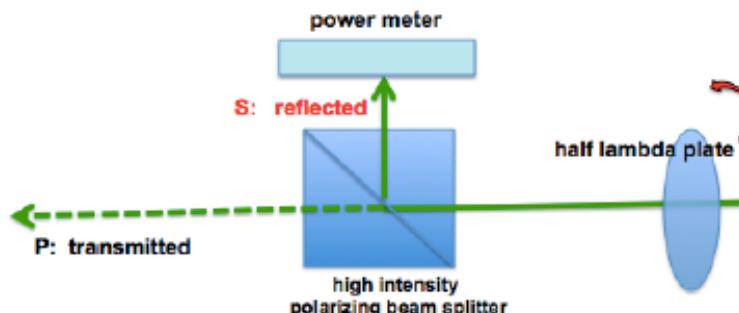
Fit results: $A \cdot \exp(-(x-B)/C)^{2/2}$
Modulation: 0.522 ± 0.024
Center: -0.050 ± 0.015
Sigma: 0.135 ± 0.020
Chi2/ndf: $3.0978e+00 / 7$

Fringe pitch corrected by about 2 mrad

Data file:
tilt_fringe_140611_224932.dat
pitch_fringe_140612_004638.dat

Laser polarization measurement

Optics is made for S linear Polarization
P “contamination” lead to power → M reduction

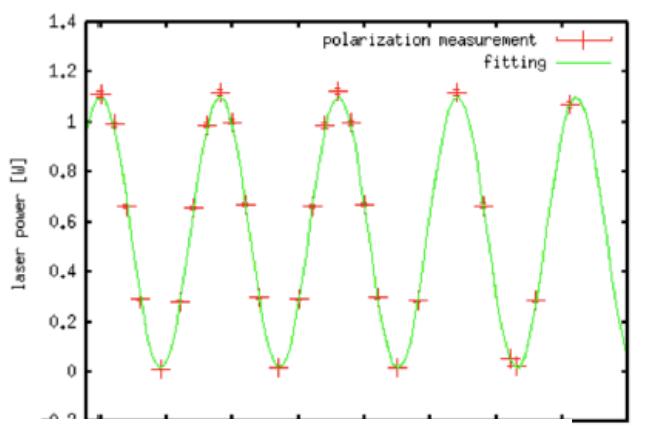


Method:
measure power while
rotating polarization
using $\lambda/2$ plate

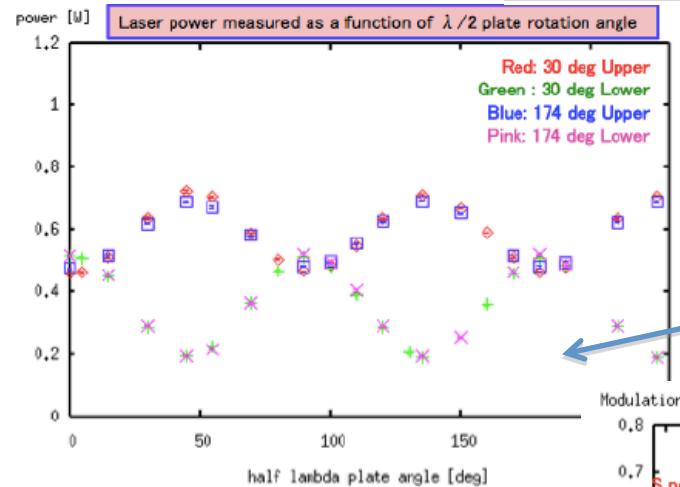
$$\tan \chi = \frac{E_{y0}}{E_{x0}} = \sqrt{\frac{P_p}{P_s}}$$

Result: very close to pure S state : $P_p/P_s < 1.5 \%$

ϕ [deg]	P_p/P_s [%]	$\tan \chi$	χ [deg]
86.8 ± 3.0	1.47 ± 0.06	0.121 ± 0.002	6.9 ± 0.1

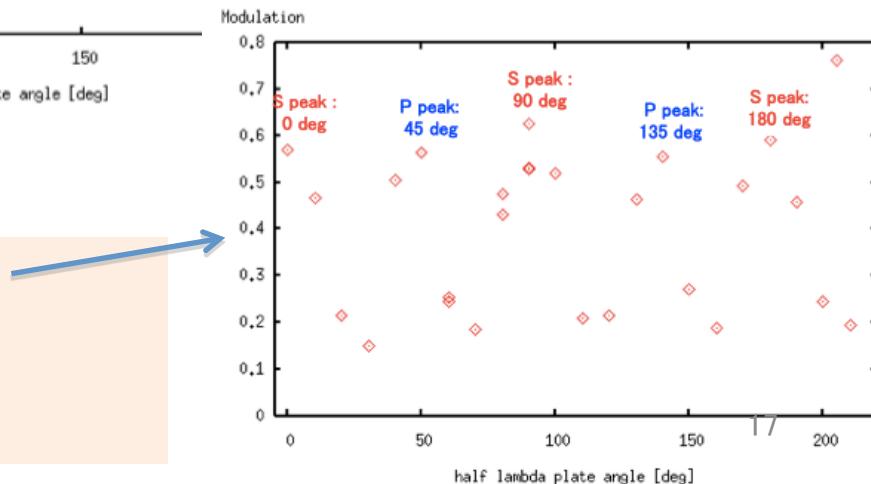


$$P = \frac{P_0}{2} (1 + C_1 \cos 4\theta + C_2 \sin 4\theta)$$



Laser power measurement

by setting $\lambda/2$ plate to “S peak angles”
cut out residual P light
→ confirm best power balance



“ $\lambda/2$ scan” during beamtime
by setting $\lambda/2$ plate to “S peak angles”,
confirm M is maximized
→ Should be almost no M reduction

Summary of performance of laser interferometer type beam size monitor IPBSM

various improvements made on IPBSM hardware and e beam stabilization

Stable beam size measurements (stability $\sim 5\%$) contributed to
Successful verification of a FFS for ILC

- ❖ **dedicated study of systematic errors** data analysis & simulation
- ❖ after correction for one of the dominant M reduction factors **phase jitter** :
→ demonstrates ATF2 Goal 1 is (nearly ?) achieved within error ranges

Preliminary evaluation of “best” measurements (June 2014)

date	6/12 (9 scans)	6/13 (12 scans)
M	$0.589 \pm 0.019(stat)^{+0.173}_{-0.000}(syst)$	$0.563 \pm 0.011(stat)^{+0.109}_{-0.000}(syst)$
σ_y	$43.3 \pm 1.3(stat)^{+0.0}_{-12.4}(syst)$ nm	$45.2 \pm 0.8(stat)^{+0.0}_{-7.7}(syst)$ nm

Goals

- continue stable measurement for study of wake field effects
→ achieve small σ_y with higher beam charge
- investigate possibility of usage for ILC initial beamline commissioning
(shorter wavelengths, stabilization)

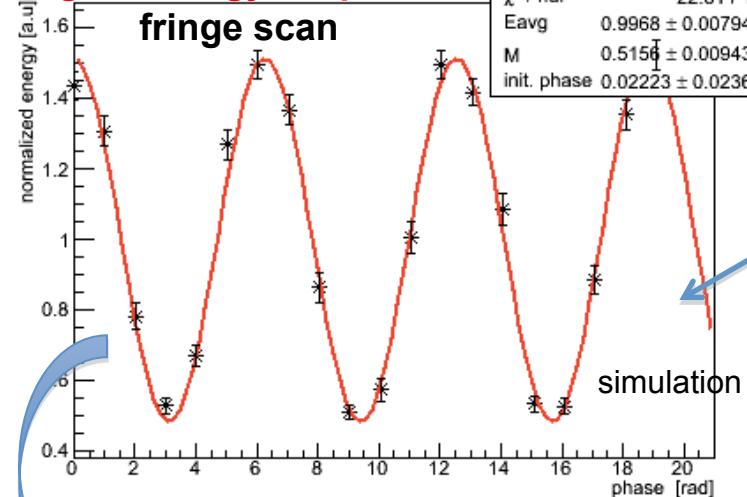
References

- ❖ J.Yan et al: **Measurement of Nanometer Electron Beam Sizes with Laser Interference using Shintake Monitor** in Nucl. Instrum. and Meth. In Phys, Research A740 (2014) 131-137
- ❖ J.Yan et al, **Measurement of Nanometer Electron Beam Sizes Using Laser Interference by Shintake Monitor**, Proceedings of Science, Proceedings of TIPP14, in preparation
- ❖ The ATF Collaboration: “**Experimental validation of a novel compact focusing scheme for future energy frontier linear lepton colliders**”, Phys. Rev. Lett. 112, 034802

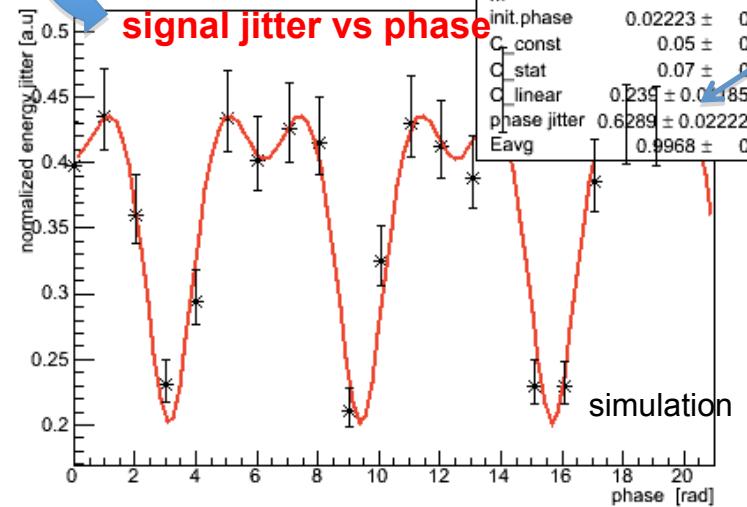
BACKUP SLIDES

Simulation study of $\Delta\phi$ extraction precision

Signal energy vs phase



fix $\{M, \varphi_0, E_{\text{avg}}, C_{\text{const}}, C_{\text{stat}}, t\}$ to jitter plot



input: $\sigma_{y0} = 40 \text{ nm}$, 174° mode
 $\Delta\phi = 0.7 \text{ mrad}$, 24.5 % vertical jitter

STEP1: generate fringe scan assume "realistic" ATF2 conditions

$$E = E_{\text{avg}} \cdot \{1 + M \cdot \cos \varphi\}$$

$$\varphi \equiv \varphi_{\text{set}} + \varphi_0$$

$$\varphi \rightarrow \varphi \pm \Delta\varphi$$

Random $\Delta\varphi$ input

$$E_{\text{avg}} \cdot \left\{1 + M \cdot \cos(\varphi + (\text{Random} \rightarrow \text{Gaus}(0, \sigma_{\varphi})))\right\}$$

$$\sigma_{V,\text{input}} = \sqrt{C_{\text{const}}^2 + (C_{\text{stat}} \sqrt{E})^2 + (C_{\text{linear}} \cdot E)^2}$$

BG statistical laser

vertical jitter input

STEP2: extract $\Delta\varphi$ from fitting

Model

$$\Delta E \equiv \sigma_{\text{tot}} = \sqrt{\sigma_V^2 + \sigma_p^2}$$

Sig jitter

= convolution of phase jitter and vertical jitter

Jitter from $\Delta\varphi$

$$\sigma_p = E_{\text{avg}} M \sqrt{\frac{1}{2} \left[1 - 2 \cos^2 \varphi \exp(-\Delta\varphi^2) + \cos(2\varphi) \exp(-2\Delta\varphi^2) \right]}$$

$\Delta\varphi$, Clinear (2 free parameters)

fixed parameters: M, φ_0 , Eavg, Cconst, Cstat: (estimated)

Potential Sources of Signal Jitters

Status

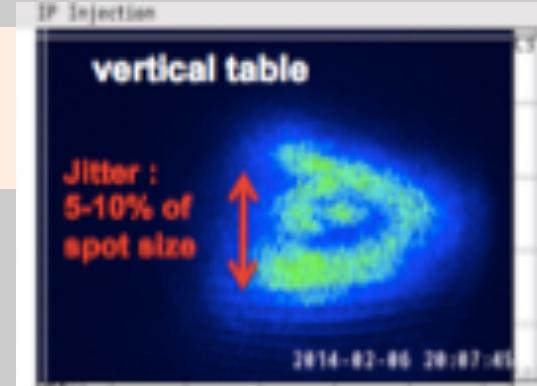
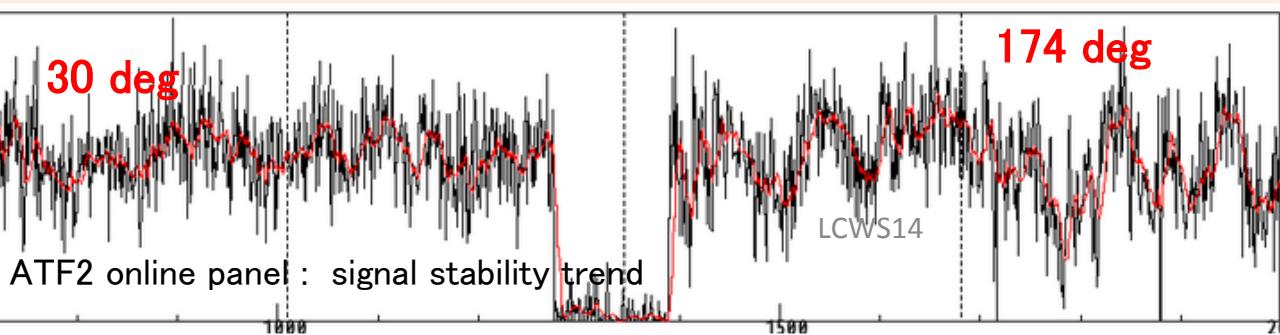
Laser pointing jitters (H relative position jitter “ Δx ”)	<ul style="list-style-type: none"> observed by profile monitor & laser wire mode : ~ 5-10% of laser profile radius <p><i>Varies with beam condition</i></p>
Phase jitter $\Delta\phi$ Vertical laser-beam relative position jitter “ Δy ” Also a M reduction factor	<p>Estimated by fitting of jitters in fringe scans Still need independent measurement of either laser or beam jitter</p> $\sigma_{E,\Delta\phi} = E_{avg}M \sqrt{\frac{1}{2} [1 - 2\cos^2(\phi)\exp(-\Delta\phi^2) + \cos(2\phi)\exp(-2\Delta\phi^2)]}$
Laser power jitter <i>From PIN-PD signal</i>	< 10%
Timing jitter	1 – 3 ns peak to peak, add < few % to signal jitters
statistical fluctuations	Depend on photon statistics : detector properties, collimation, beam intensity, etc....
<u>Other minor factors</u>	
<ul style="list-style-type: none"> BG fluctuation, e- beam current monitor resolution 	< 5 % each, BG is not a issue recently with high S/N

Further measurements and simulations ongoing to comprehend impact from each source

- observe overall sig jitter in fringe scan ~ 20-40% depend on phase drifts are hard to separate from jitters sometimes

issue of “oscillating” Compton signal jitters (period~few min)

- ◆ pointing jitters related to complex internal structure of laser profile@ IP
eg. non-Gaussian multi- components

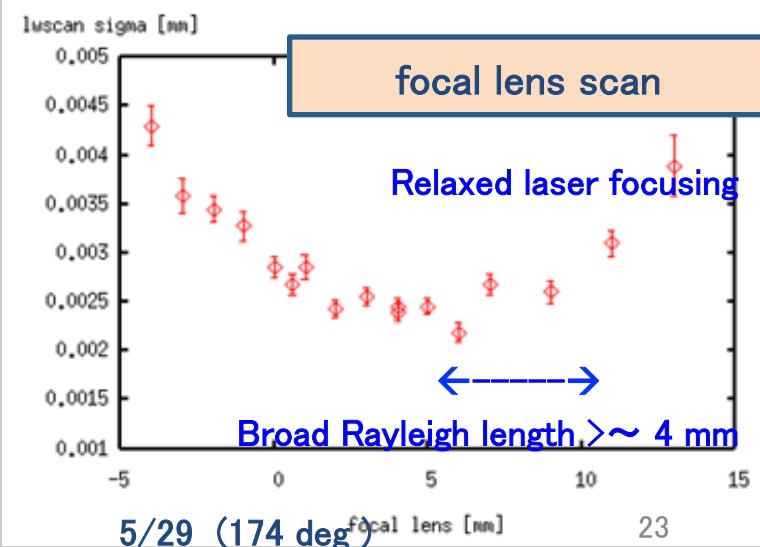


Hardware improvements to stabilize measurements in 2014

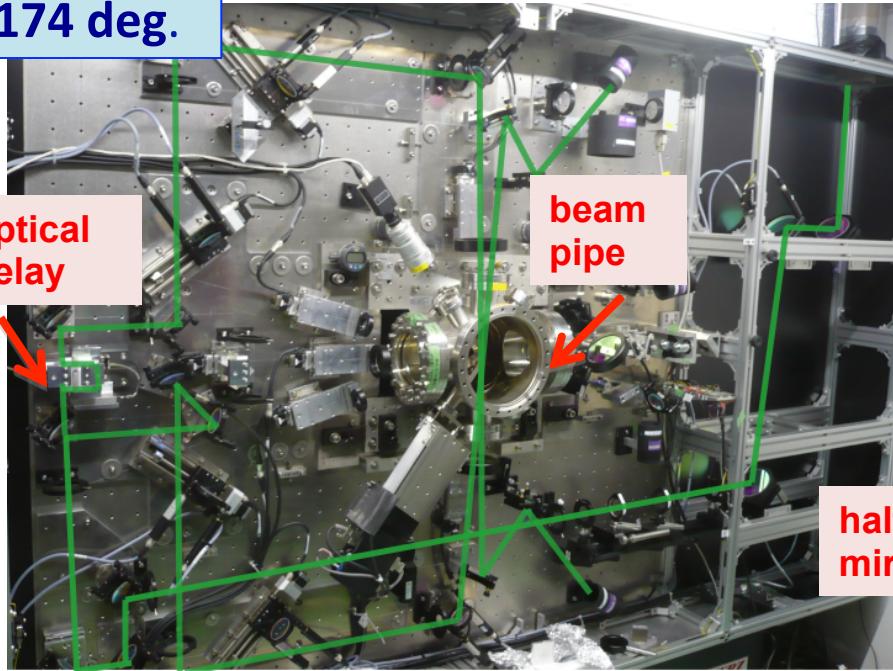
by Shintake Monitor group@ATF2

- (1) reinforcement of detector shielding (Pb and parafine)
- (2) Stabilization of e- beam improved tuning multiknobs, orbit feedback
- (3) speed up DAQ software : reduced effect from drifts
- (4) Adjust laser profile and focusing → Reduce pointing jitter at IP
- (5) improved buildup and Q-switch timing stability

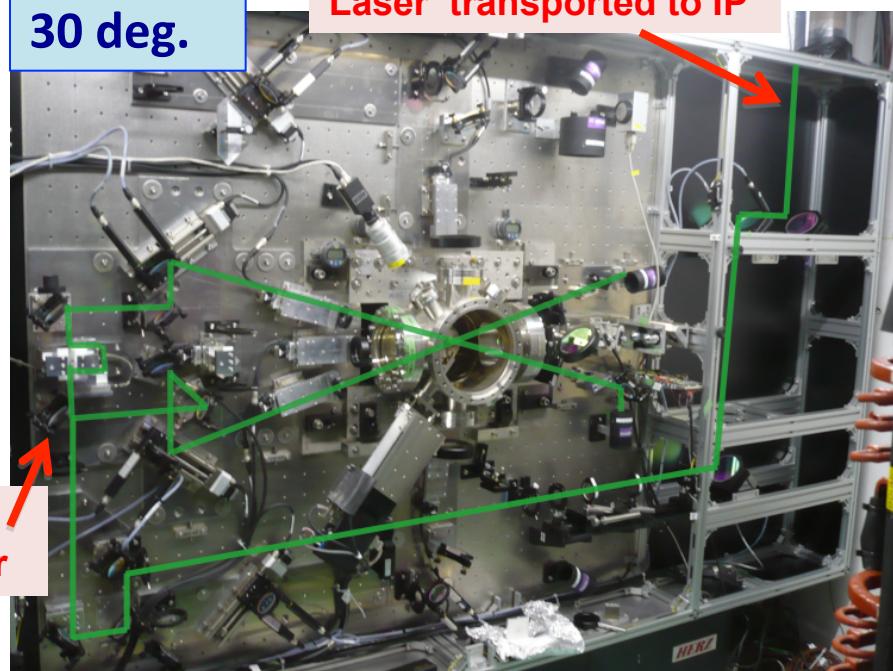
Regular laser tuning by laser company engineer



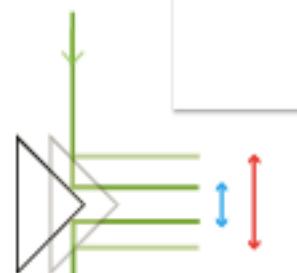
174 deg.



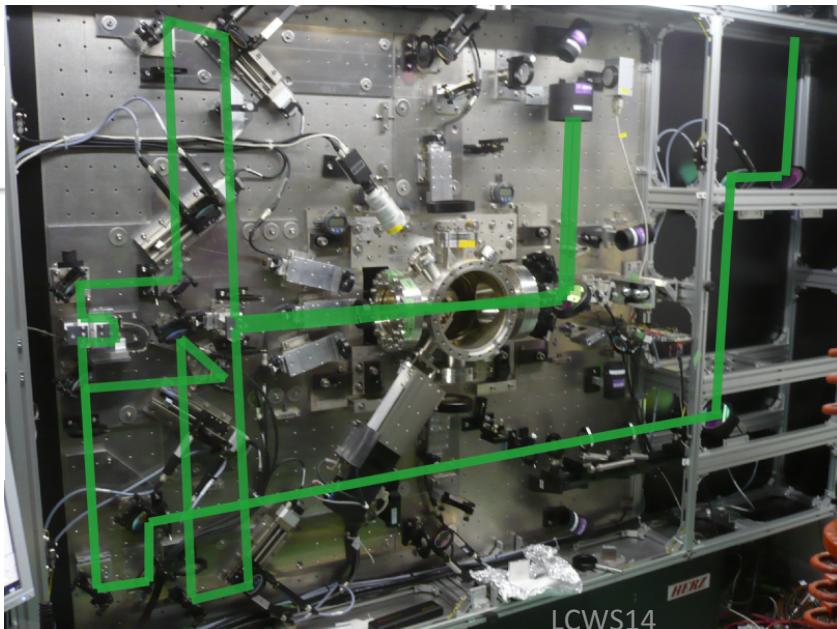
30 deg.



2 - 8 deg



Crossing angle
continuously
adjustable by
prism



Laser transported to IP

Vertical table

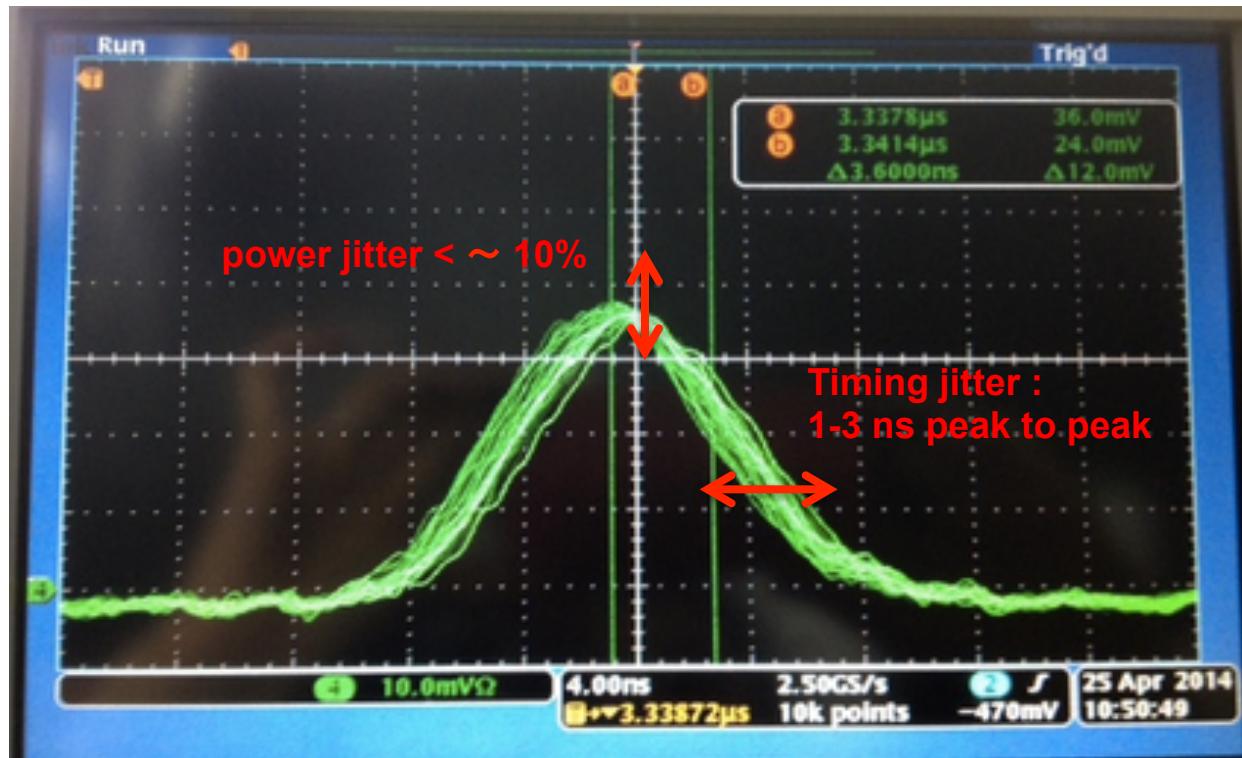
1.7 (H) x 1.6 (V) m

- Interferometer
- Phase control (piezo stage)

path for each θ mode
(auto-stages + mirror actuators)

Timing and Power Stability

Observe signal of PIN-Photodiode @laser hut



Laser Power and Profile Measurements (Apr, 2014)

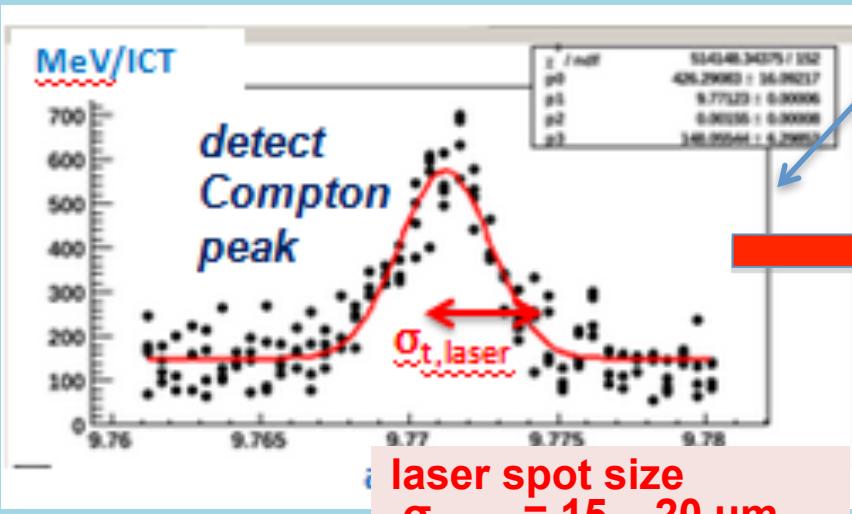
- Parallel propagation to final focal lenses
- balanced profiles and power (~ 95%) between U and L paths
- loss in transport (laser hut → IP) < 7%



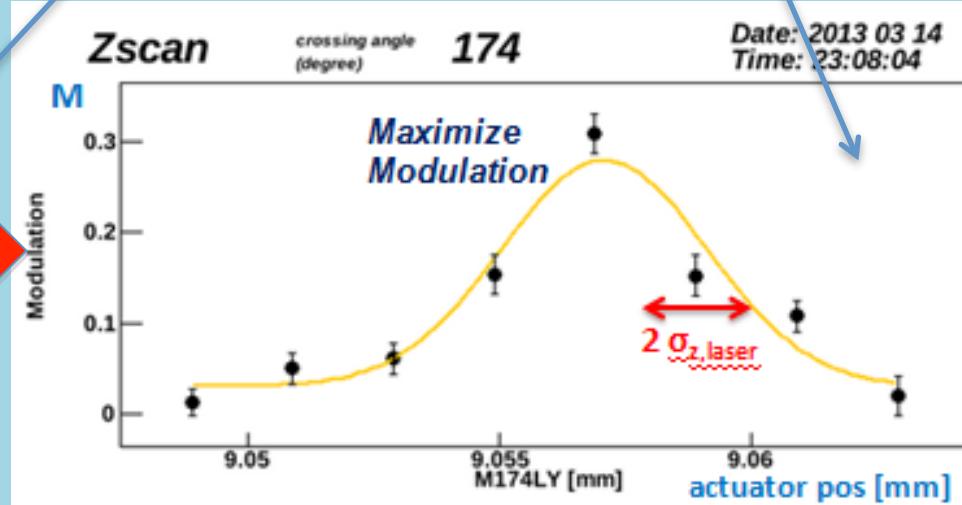
Role of IPBSM in Beam Tuning

beforehand
 Construct & confirm laser paths, timing alignment
precise position alignment by remote control

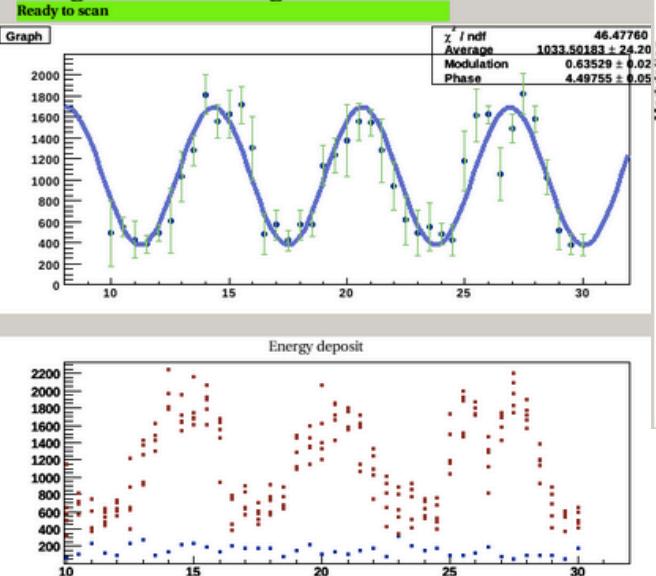
transverse : laser wire scan



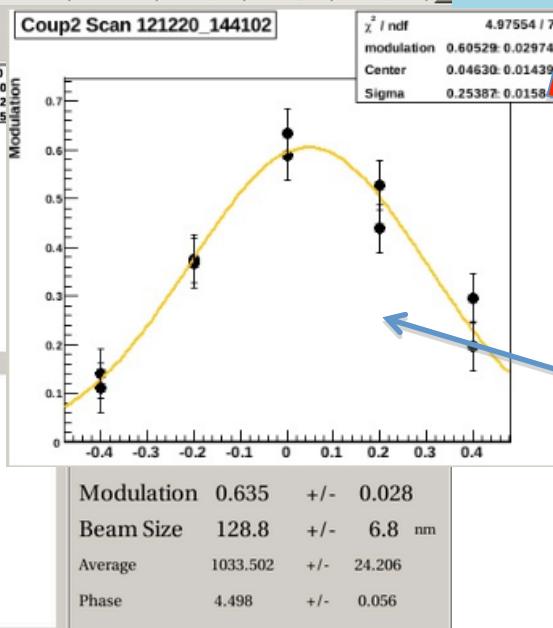
Longitudinal : z scan



Fringe Scan 30 degrees



Coup2 Scan 121220_144102



After all preparations
continuously measure σ_y using fringe scans
 → Feed back to multi-knob tuning