Measurement of Nanometer Electron Beam Sizes with Laser Interference using IPBSM

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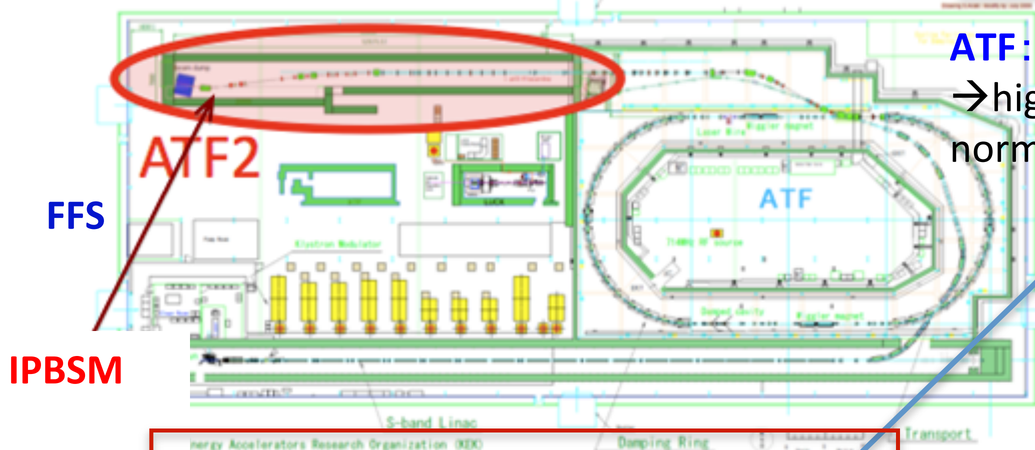
Role of IPBSM (Shintake Monitor) at ATF2

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

For **high luminosity** must **focus** **vertical beam size** at IP !!

flat beam : $\sigma_y << \sigma_x$

ATF2: Linear Collider FFS test facility@KEK



ATF: 1.28 GeV LINAC , DR

→high quality e- beam with extremely small normalized vertical emittance $\gamma\varepsilon_y$

ATF2 Goal 1 :

focus **σ_y* to design size 37 nm**

➔verify Local Chromaticity Correction

ATF2 Goal 2:

O(nm) **beam trajectory stabilization**

IPBSM is crucial for achieving ATF2 's Goal 1 !!

OUTLINE

measurement scheme, performance, beam tuning roles

Beam Time results 2011～2012 → **upgrades**

Summary & Goals

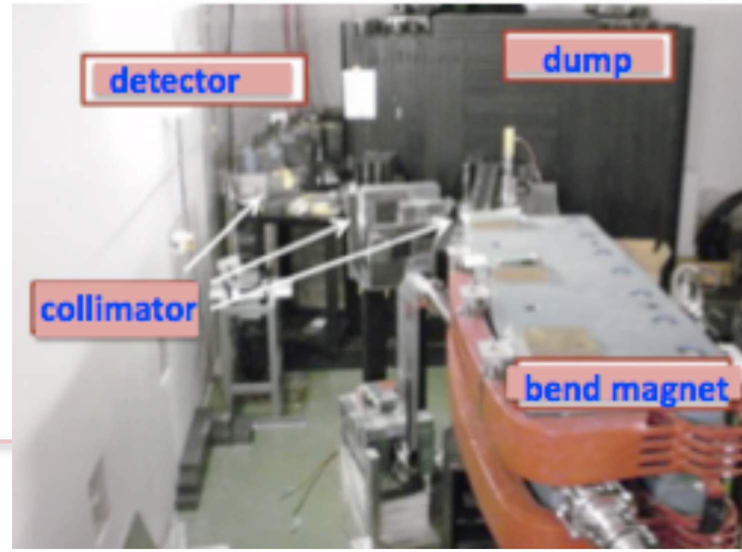
Measurement Scheme

use **laser interference fringes** as target for e- beam

Only device able to measure σ_y < 100 nm !!

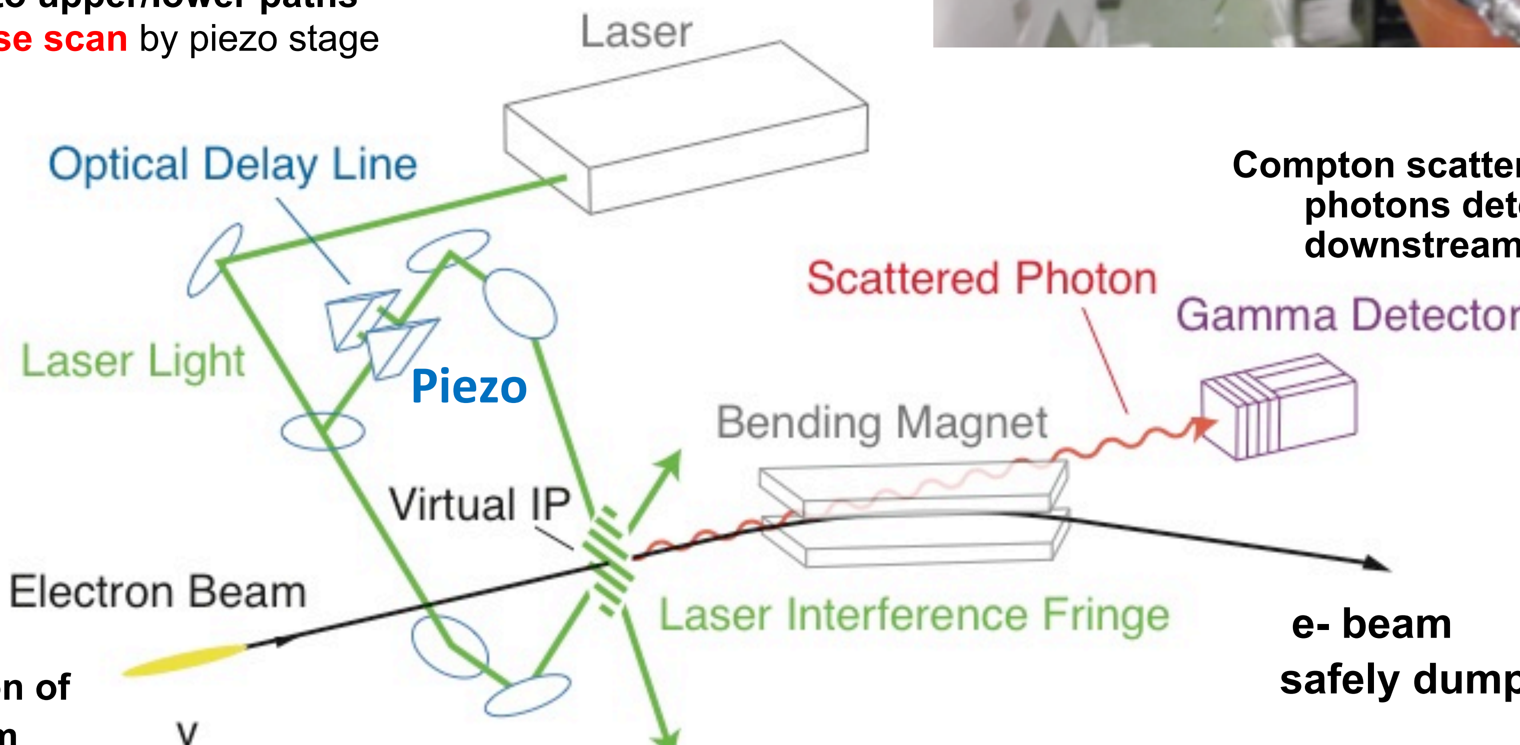
•Crucial for beam tuning

→ *realization of future linear colliders*



Split into upper/lower paths

→ **phase scan** by piezo stage



Compton scattered photons detected downstream

e- beam safely dumped

Collision of e- beam with laser fringe

upper, lower laser paths cross at IP

→ form Interference fringes

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

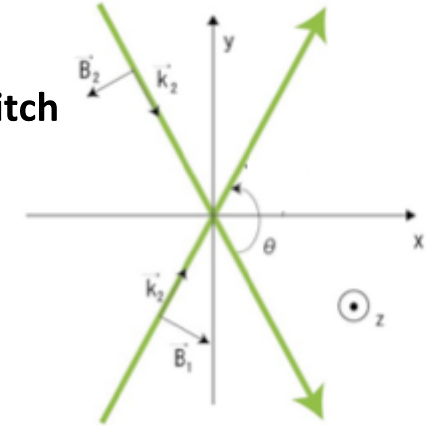
$$\mathbf{M} = \frac{N_+ - N_-}{N_+ + N_-} = \left|\cos(\theta)\exp\left(-2(k_y\sigma_y)^2\right)\right|$$

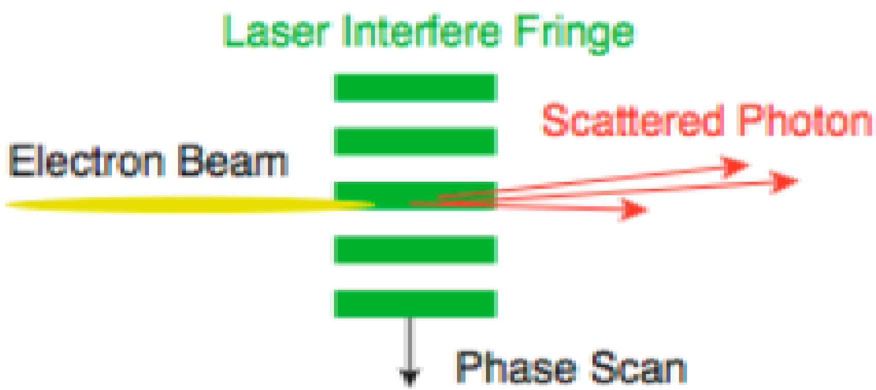
$$\Rightarrow \quad \sigma_y = \frac{d}{2\pi}\sqrt{2\ln\left(\frac{|\cos(\theta)|}{M}\right)}$$

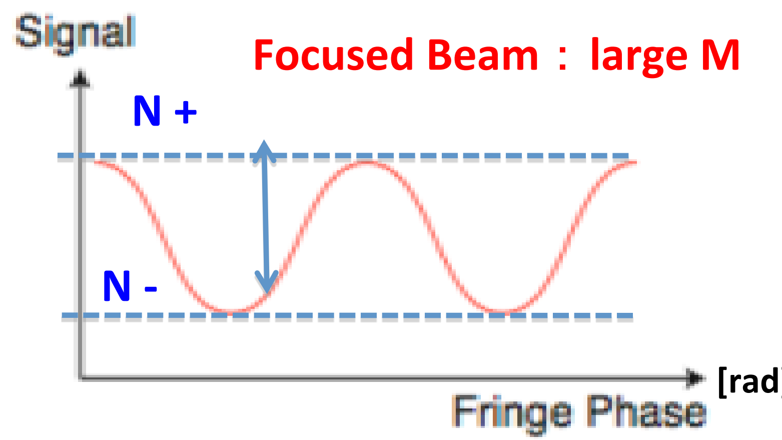
measurable range
determined by **fringe pitch**

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

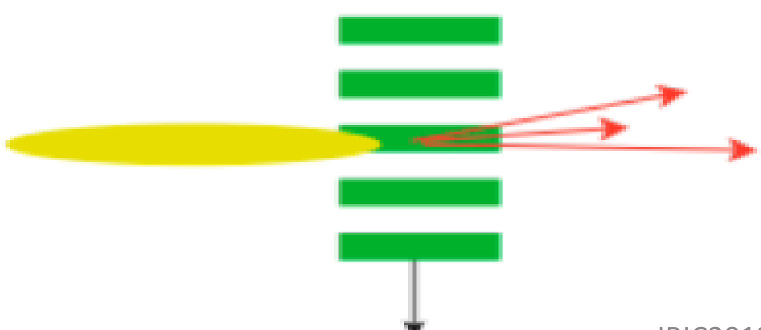
depend on
crossing angle θ (and λ)

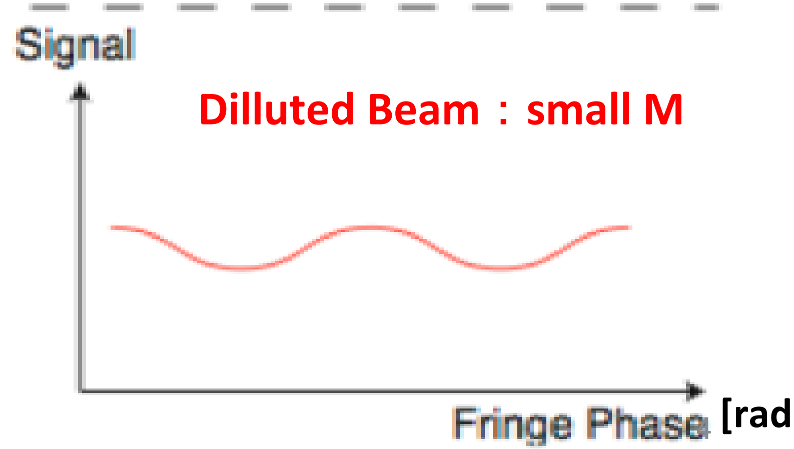






N: no. of Compton photons
Convolution between e- beam profile and fringe intensity





Crossing angle θ	174°	30°	8°	2°
Fringe pitch $d = \frac{\pi}{k_y} = \frac{\lambda}{2\sin(\theta/2)}$	266 nm	1.03 μm	3.81 μm	15.2 μm
Lower limit	20 nm	80 nm	350 nm	1.2 μm
Upper limit	110 nm	400 nm	1.4 μm	6 μm

Expected Performance

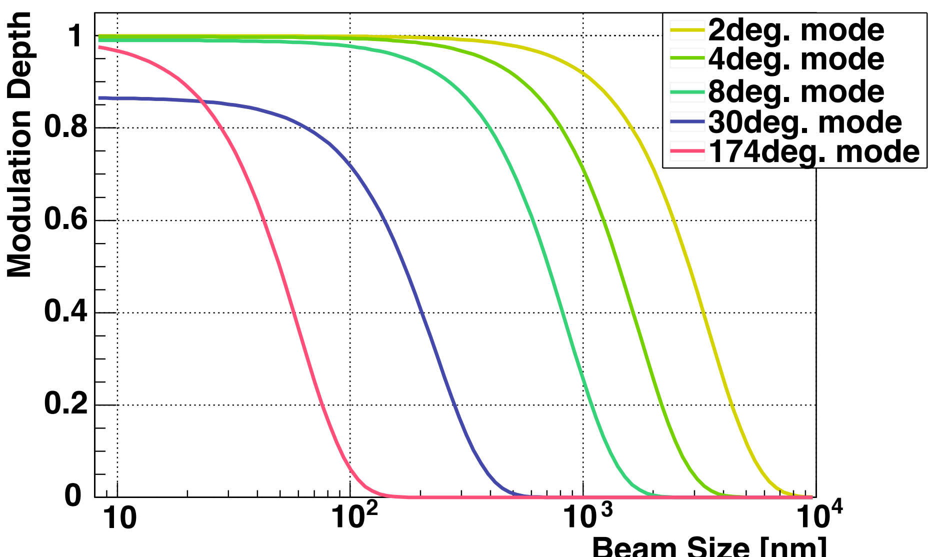
$$37 \pm 2\,(\text{stat.})\;^{-0}_{+4}\,(\text{syst.}) \quad \text{nm}$$

Measures
σy* = 20 nm ～few μm
with < 10% resolution

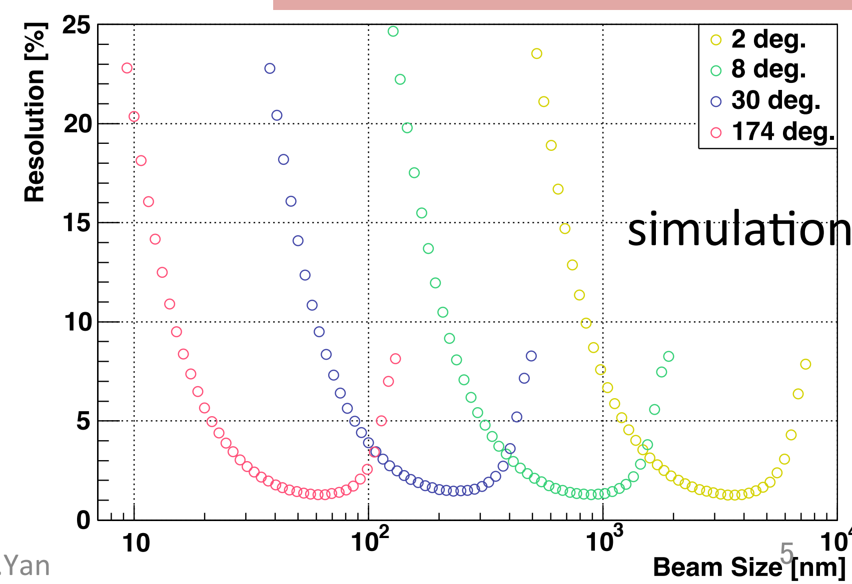
$$\sigma_y = \frac{d}{2\pi}\sqrt{2\ln\left(\frac{|\cos(\theta)|}{M}\right)}$$

must select appropriate mode according to beam focusing

σy*and M for each θ mode



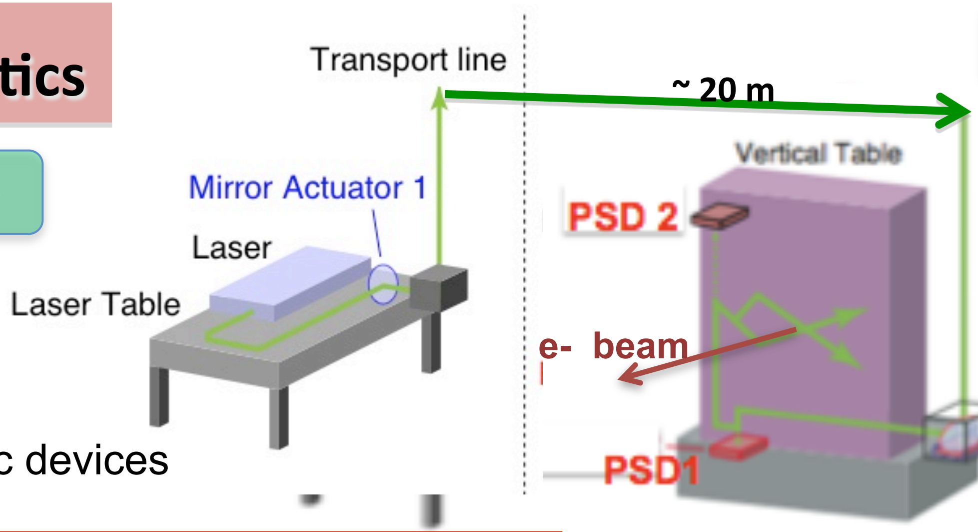
Resolution for each θ mode



Laser Optics

Laser table

- Source (SHG)
- diagnostic devices



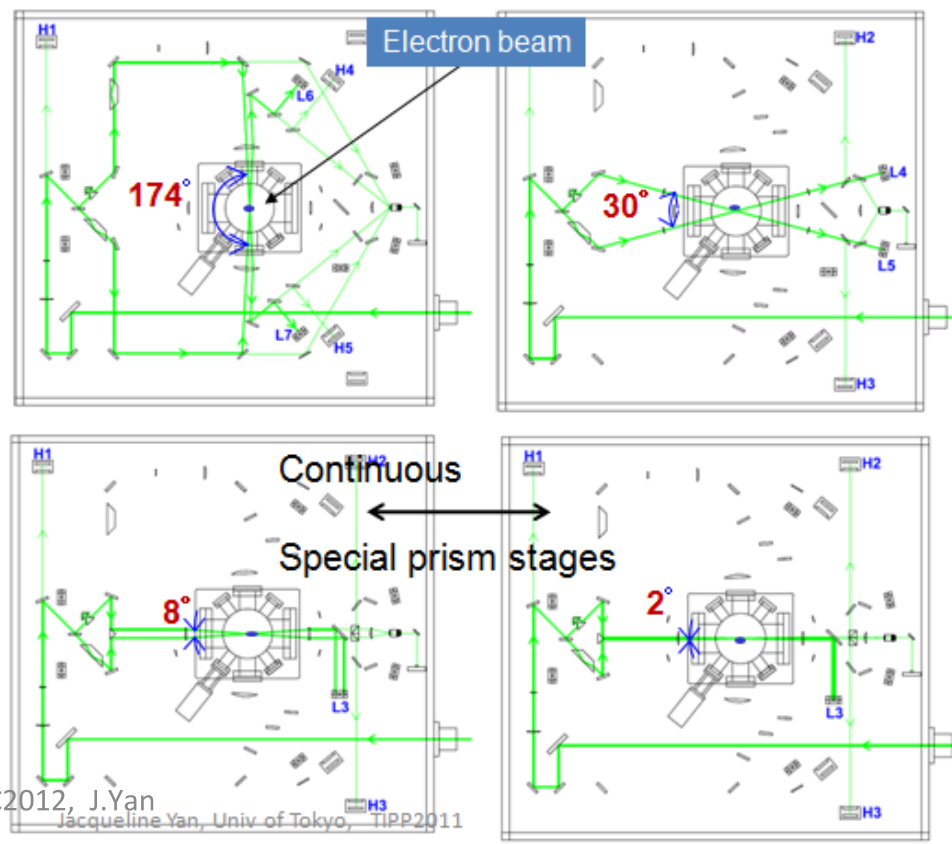
Vertical table **Interferometer**

- **Phase control**
  → piezo stage
- **construct path for each θ mode**
  （auto-stage + mirror actuators ）

Nd :YAG
Q-Switch laser

PRO350
Spectra Physics

Wavelength	532 nm (SHG)
Pulse Energy	1.4 J
Peak power	164 MW
Pulse Width	8 ns (FWHM)
f_{rep}	6.25 Hz
Line Width	$< 0.003\ cm^{-1}$
Timing Stability	< 0.5 ns
Energy Stability	± 3%



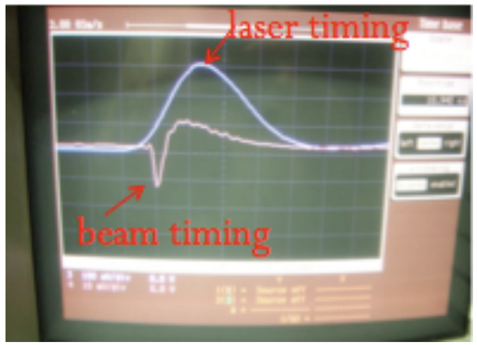
Role of IPBSM in Beam Tuning

1 **path construction**: access to IP, confirm precision with “ eyes & hands”

switch e- beam ON → remote control

2 **Timing alignment**

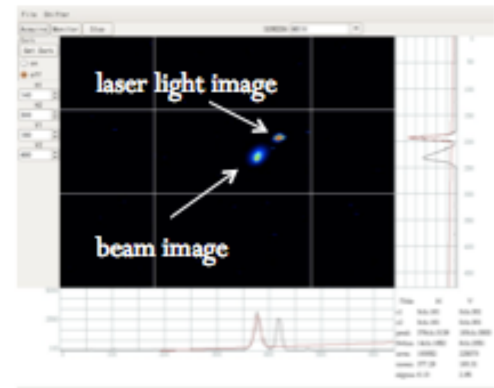
Timing scan of laser Q-SW and e- beam
→ matched with precise TD2



3 **Preliminary position alignment**

Overlap laser and e- beam spots on screen monitor

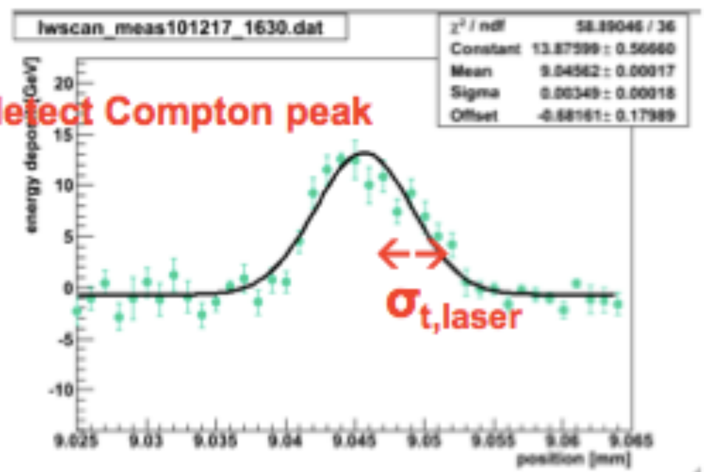
(within ∼20 μm)



extremely precise position alignment

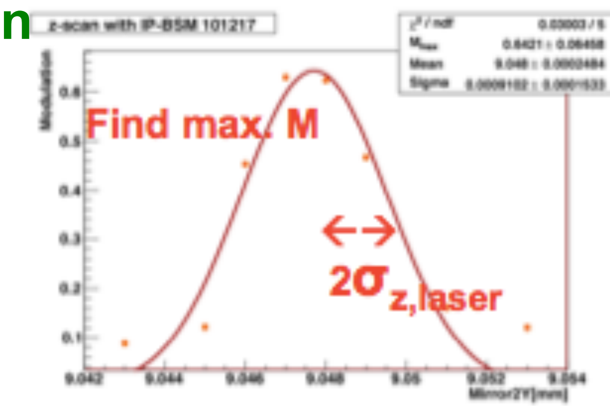
4 **transverse** : **detect Compton peak**

laser wire scan



5 **Longitudinal**:

z scan



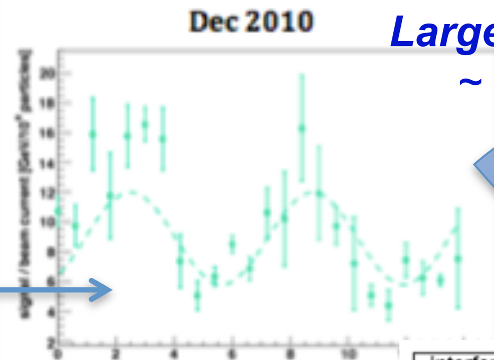
6 **After all preparations ....**

continuously measure σ_y^* using interference mode

→ Feed back to beam tuning

post-earthquake recovery and upgrade in 2011

- overall stabilization of laser optics
- **suppress signal jitters**



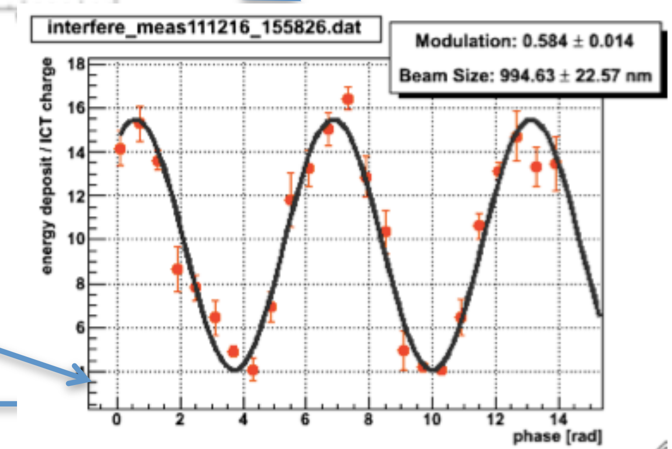
Large jitters ~ 30%

Hardware upgrade

Beam Time (autumn～)

σy* focused down to **~ 1 μm**
(beam tuning issues)
IPBSM resolution improved
（2 – 8 deg mode ）

much smaller jitters
clear contrast



overcome signal jitter sources
(example)

fast M detection ➔ scan under stable conditions

Beam size jitter

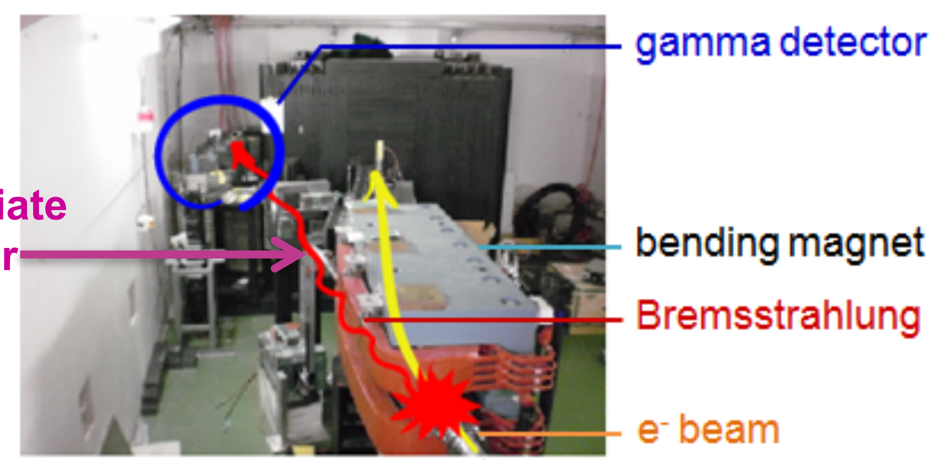
high response , effective status monitors & scan software
introduced to ATF2

➔ **monitor instability factors on beam/laser profile**

High BG

extra bremsstrahlung at post-IP dipole

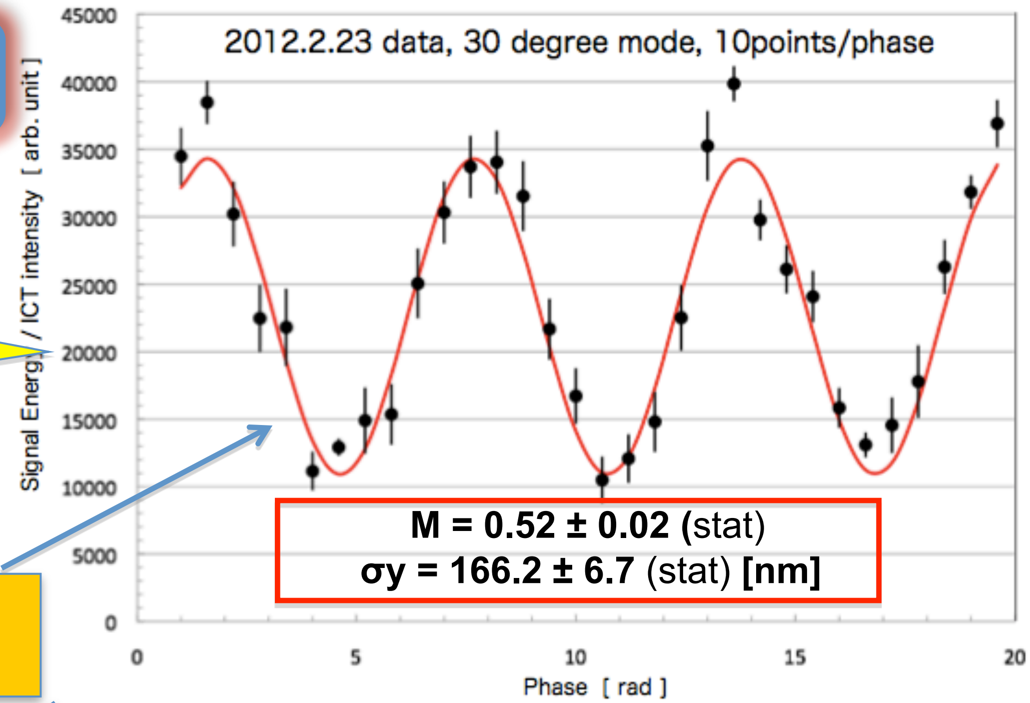
intermediate collimator
installed



Beam time status in 2012

full commissioning of 30° mode
First Modulation detection
(10 x β_x*, 10 x β_y* optics)

stably measure σy* ~ 160 nm
(10 x β_x*, 3 x β_y* optics)



2 - 8 ° mode

Measured larger σy（～few 100 nm ）
with clear **contrast**
（i.e. high M : 0.8 – 0.9)

➔ **Syst error study**
✓ **upper limit on M_meas**
✓ **consistency of σy_meas**

Began commissioning of 174 ° mode

- **hardware check**
- **Optimization of scan strategies**

Obstacles (2012 Feb)
•Beam condition drift (over many hours)
•Not very focused σy* (still at 3 x β_y* optics)

one more step before full commissioning of 174 ° mode i.e. consistent fringe scans

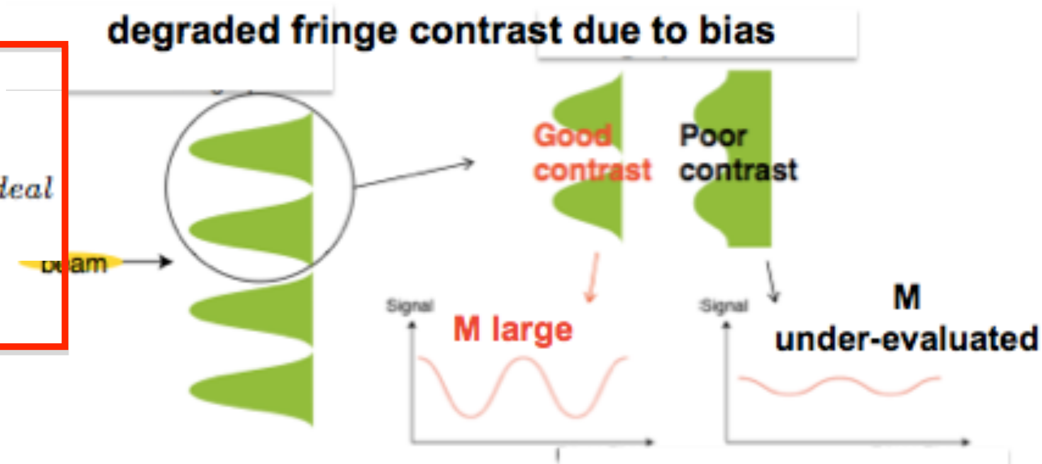
Systematic Error Study

Interpretation of M under-evaluation / σy* over-evaluation)

Modulation Reduction Factor

$$M_{meas} = C_1 C_2 .... M_{ideal} = \left(\prod_i C_i\right) M_{ideal}$$

$$\sigma^2_{y,ideal} + \frac{1}{2k_y^2}\left|\sum lnC_i\right|$$



Example of syst error evaluation
（June, 2012 ,4 deg mode ）

major bias factors →

Laser profile imbalance	compare **Compton signal of upper / lower path** laser wire scans
Fringe tilt	limited by **alignment precision**
Phase jitter (relative position)	C_{phase} > 95%
Laser path alignment	Ct,pos : ~ 100%, Cz,pos : > 99.5% *M reduction "worst limit"*
polarization	> 98% *adjusted to nearly pure S state*

From actual data :
upper limit on M (= "fringe contrast") Ctotal = 0.8 – 0.9

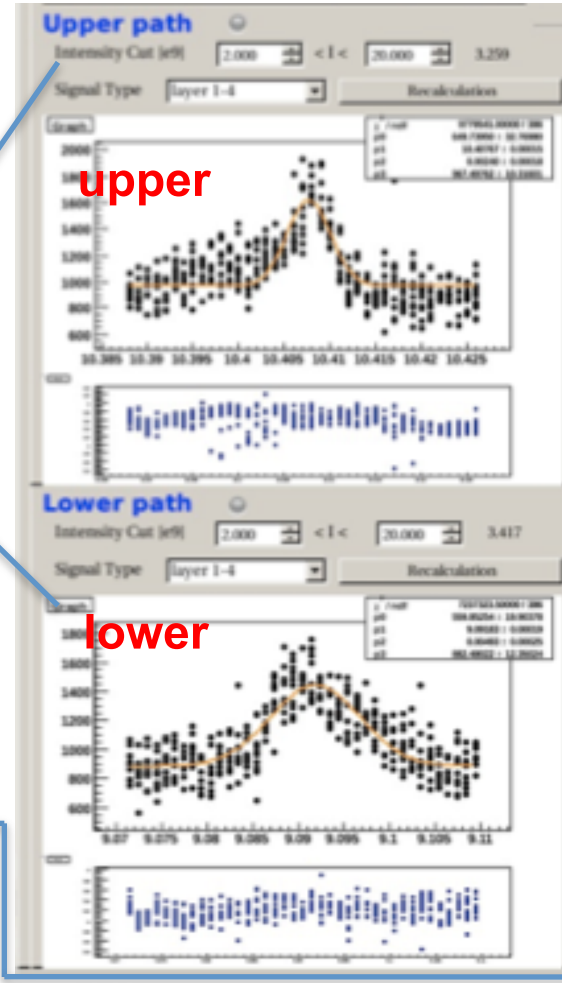
Dominant Systematic Errors (2012 continuous run)

Improve through 2012 summer upgrade

Profile Imbalance

- ✓ **peak power**
- ✓ **IP spot size σ_{laser}**

2 times difference in laser-wire Compton signals (**N_{av} = 20)**



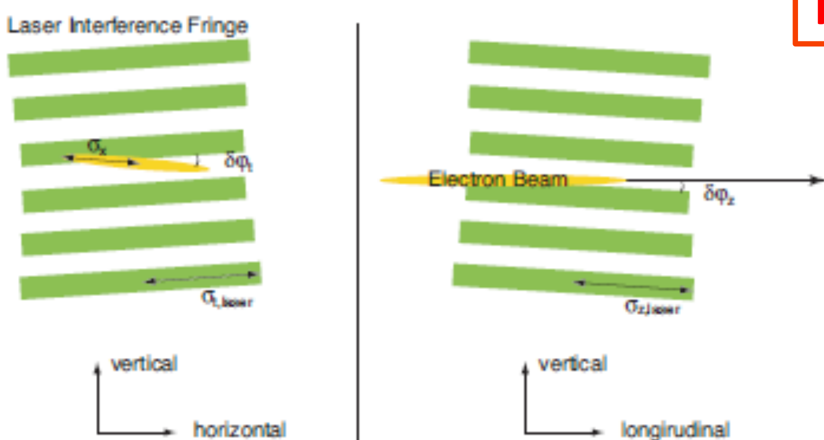
◆ partially: optical components related loss
(transmission, reflection, delay line
total $P_l = 0.88$)

$$M' = CM = \frac{2\sqrt{P_l}}{1+P_l} M$$

◆ **lens misalignment**
→ Difference in focal point position

$$P_l \equiv P_U / P_D$$

Fringe Tilt



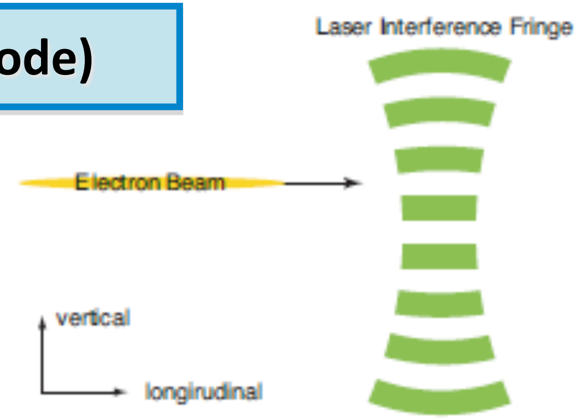
transverse longitudinal

fringe not formed perpendicular to e- beam axis

→ **improve alignment precision on final focus lens before IP**

observable limit: Δ = 3 - 5 mm
←→ tilt δφt,z : 5 - 20 mrad

Syst. Errors specific to very small σ_y^* (174 deg mode)

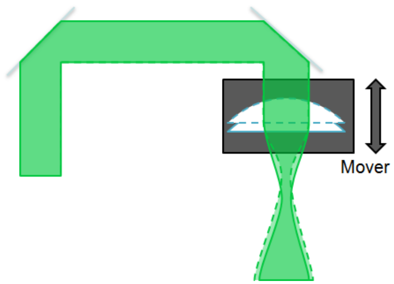


Spherical wavefronts

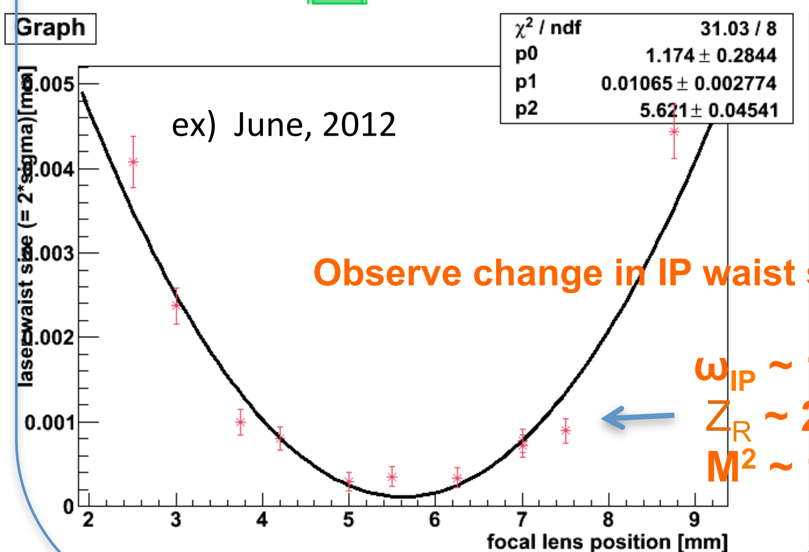
Offset of ultra-focused e- beam vs laser waist → distorted fringes

Csphere > 99.7 %

Solution is **focal point scan**



attach mover to lens
→ **align focal point to IP within < 100 µm**
(~0.1*Raylegh length Z_R)



ex) June, 2012

Observe change in IP waist size ω_{IP}

ω_{IP} ~ 10 µm
Z_R ~ 2.2 mm
M^2 ~ 1.2

Change of σy* within fringes

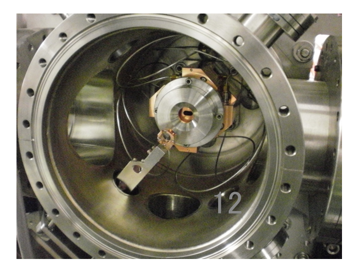
due to strong focusing,

Cgrowth ~ 99.7%

Tiny σy* is very sensitive to **relative position jitter ! !**

IPBPM (O(nm) design resolution) under commissioning

- beam pos. monitoring
- feedback correction

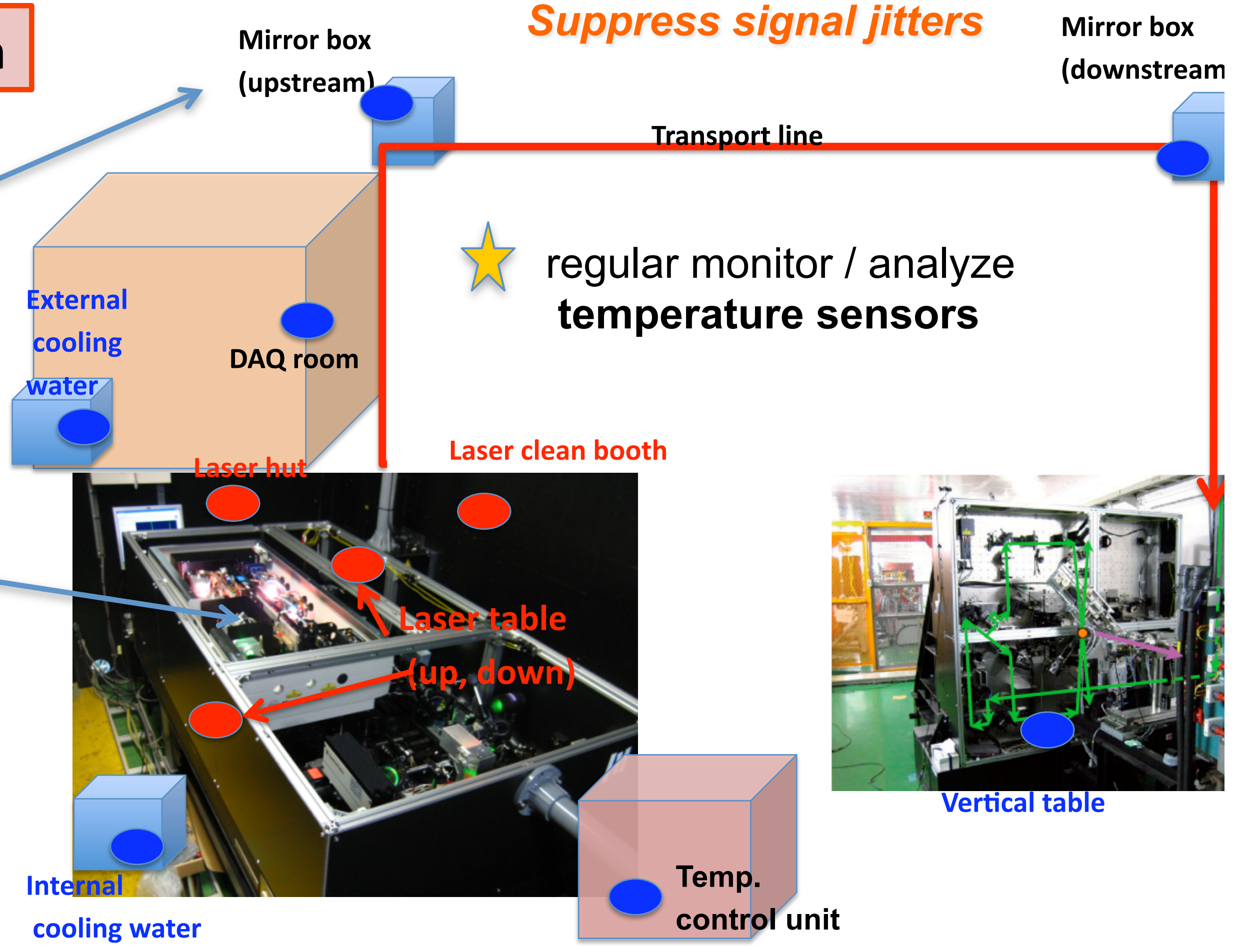


Stabilization of laser system

Insulated mirror box

★ **transport line**
➔ insulation,
anti-vibration

Suppress signal jitters



★ regular monitor / analyze
temperature sensors

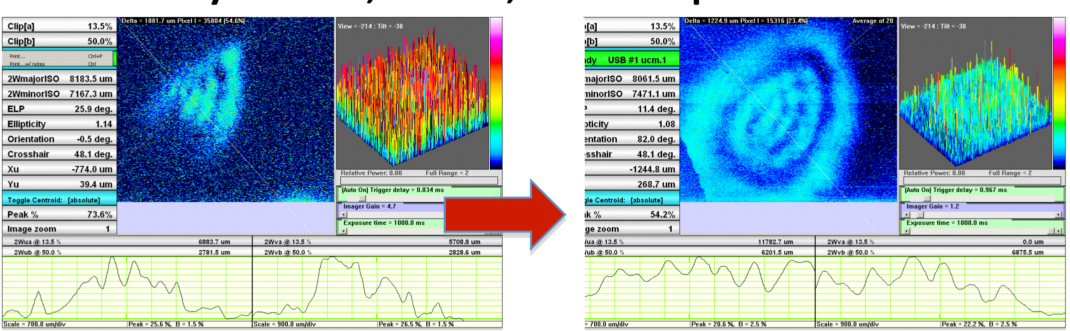
long term path stabilization

★ **Beamlok** (piezo feedback)
added to laser cavity

Improved pointing stability
< ±50 μrad → < ±25 μrad

improve oscillation, profile

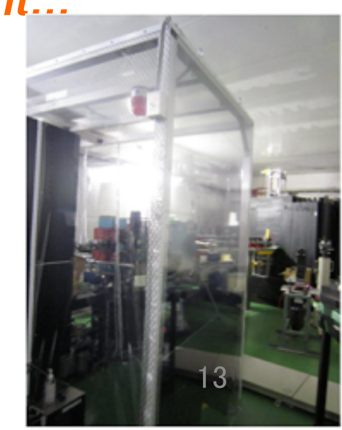
★ **Tuning / exchange of**
cavity mirrors, seeder, flash-lamp



cleaner environment…

★ protectve booth
@ IP vertical table

★ Maintain dust-free
component surfaces



2012 summer: **major upgrade of laser optics**
Goal: **alignment precision & reproducibility**

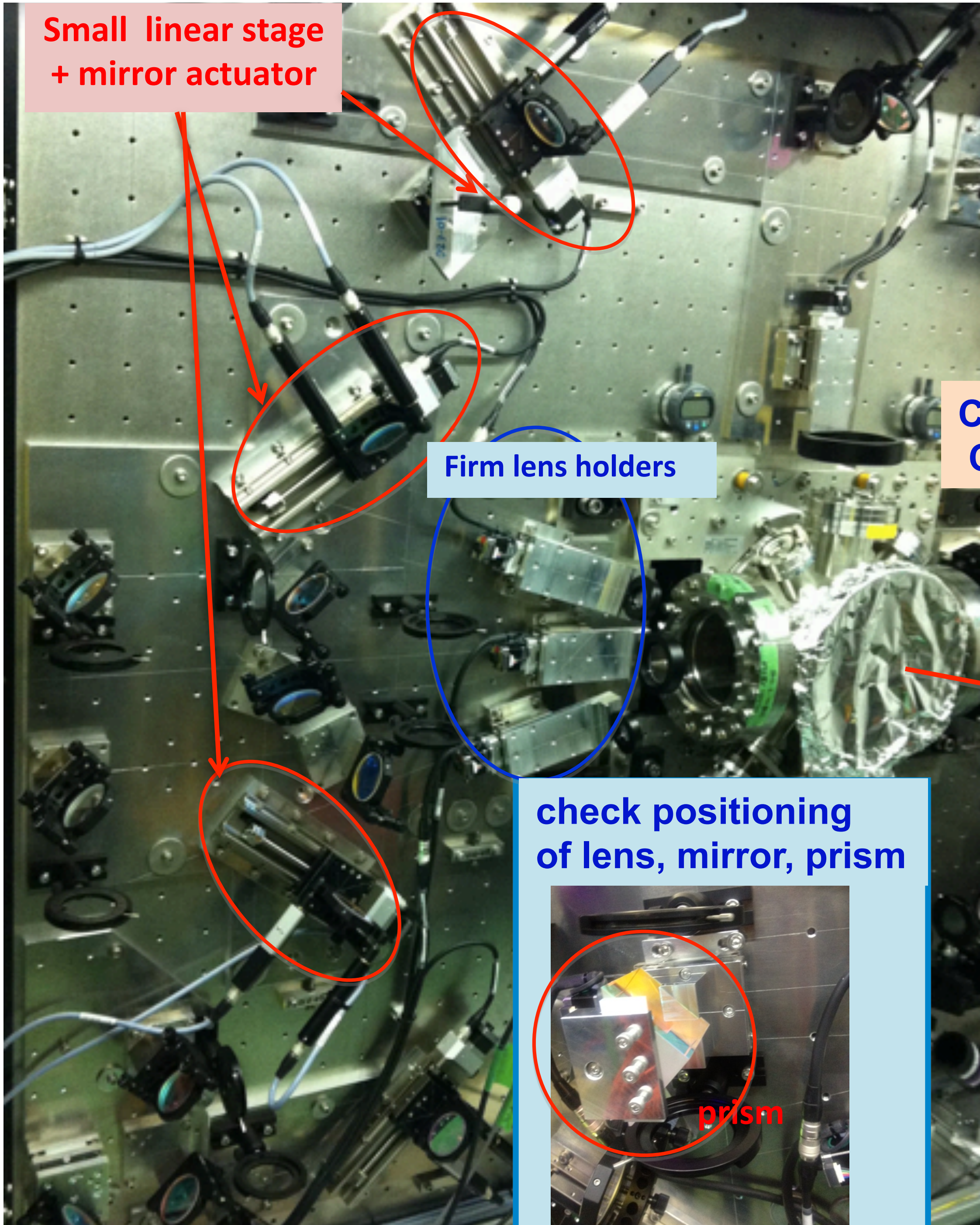
- suppress syst. errors
- effective small **σy*** tuning

- better conditions to accomplish goals in autumn beam run

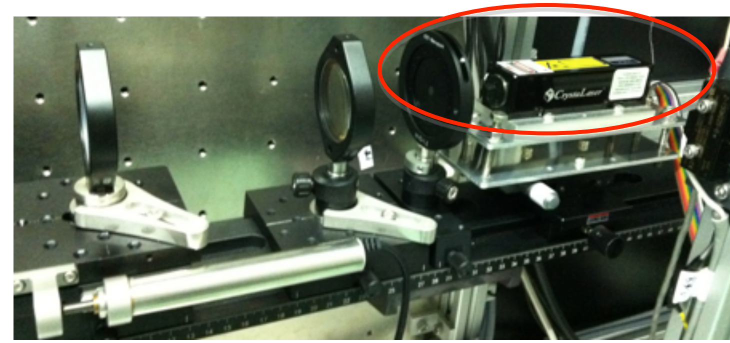
BEAM TIME GOAL:

- **Full commissioning of 174° mode**
  - → **stably measure σy* < 100 nm**
  - → **focus down to σy* ~ 37 nm**

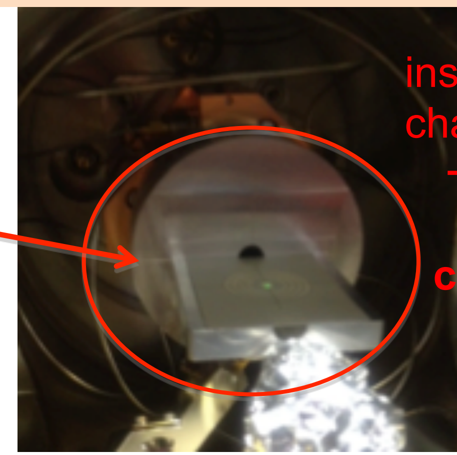
improvements	details
easier alignment match focal point to IP Injection position / angle into lens	• focal point scan for all modes • redefine clear reference lines on new base plates
consistency , reproducibility esp. before / after mode switching	• **new θ switching method** **{small linear stage + mirror actuators }** independent for each mode (instead of shared rotating stages) • re-commission **PSD system** → monitor jitters / drifts
profile imbalance focal point difference between upper/lower paths	• suppress path length difference in new design



just after injection onto vertical table



Confirm fine alignment using CW laser and transparent IP target



check positioning of lens, mirror, prism

prism

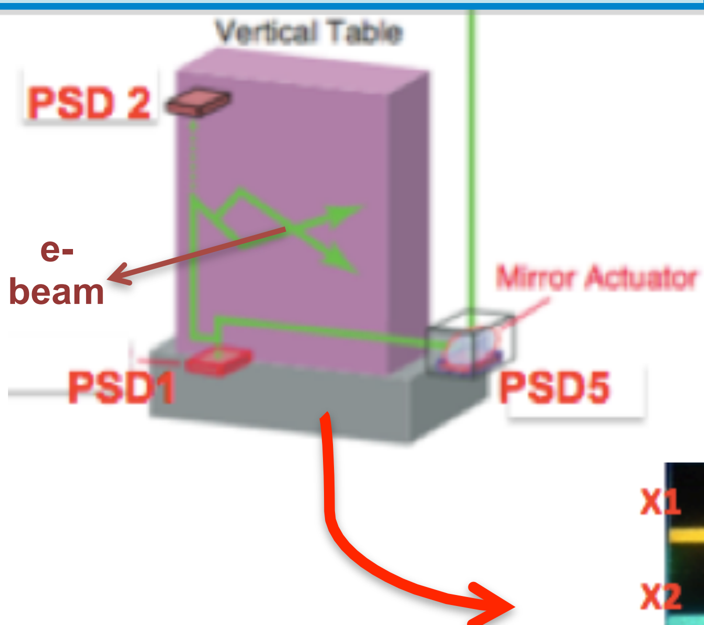
Schedule:

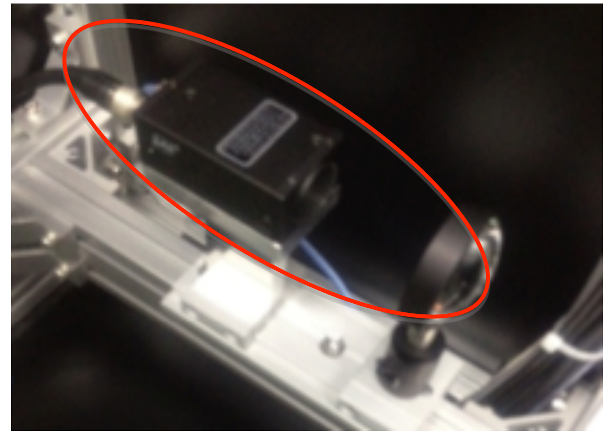
assembling of new setup completed

❖ Now（Sep, 2012）: **Beam off tests** prepare for autumn run (10/15~)

Hardware (re)commissioning PSDs, phase monitor, profile monitors, DAQ modules, ect….

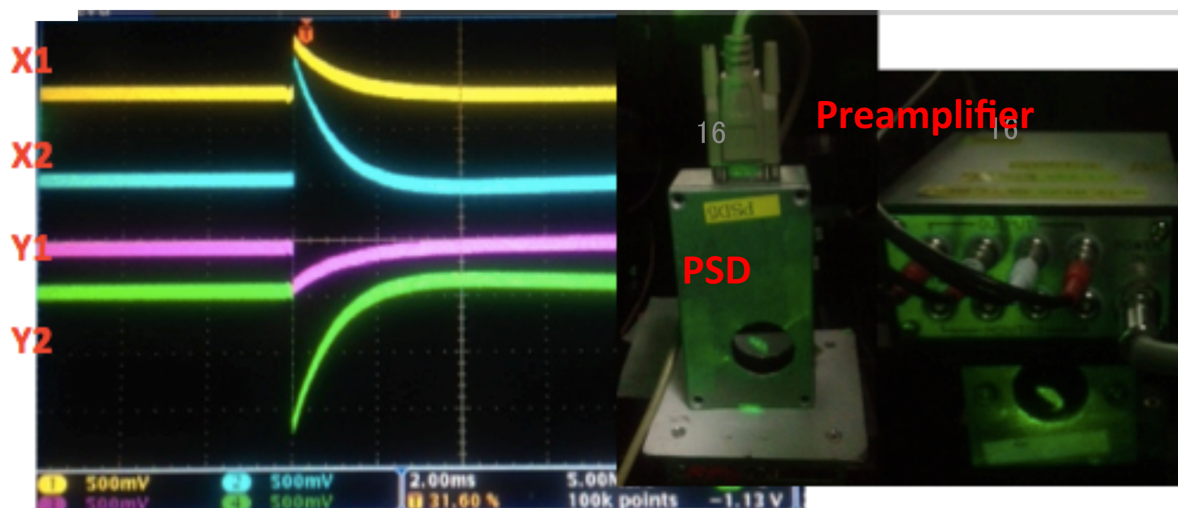
Tests of PSDs (+ preamps, readout circuit)





CCD camera as profile monitor

Signal output from PSD electrodes



SUMMARY

IPBSM ("Shintake Monitor") installed at ATF2 IP

- use **laser interference fringes**
  → **only device capable of measuring σy* < 100 nm**
- Crucial for beam tuning → realization of future linear colliders

< Status >

❖ **Stable measurements of σy* ~ 160 nm (**30° mode)

❖ dedicated systematic error study (2 – 8 °mode)

<upgrades>

- suppress jitters & bias factors
- stabilize laser system
- **reliability & reproducibility in laser optics alignment**

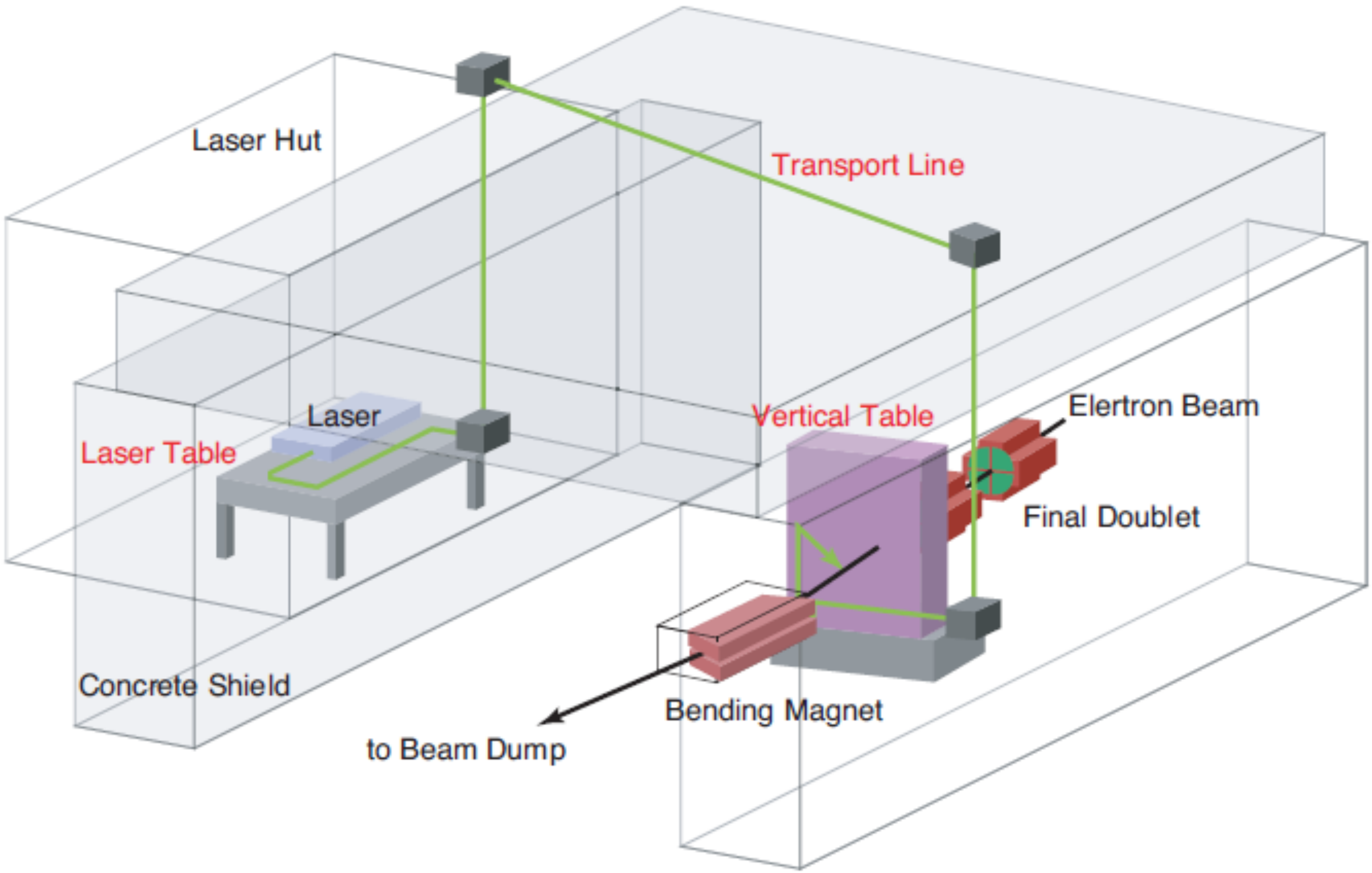
< Goals for 2012 autumn beam run>

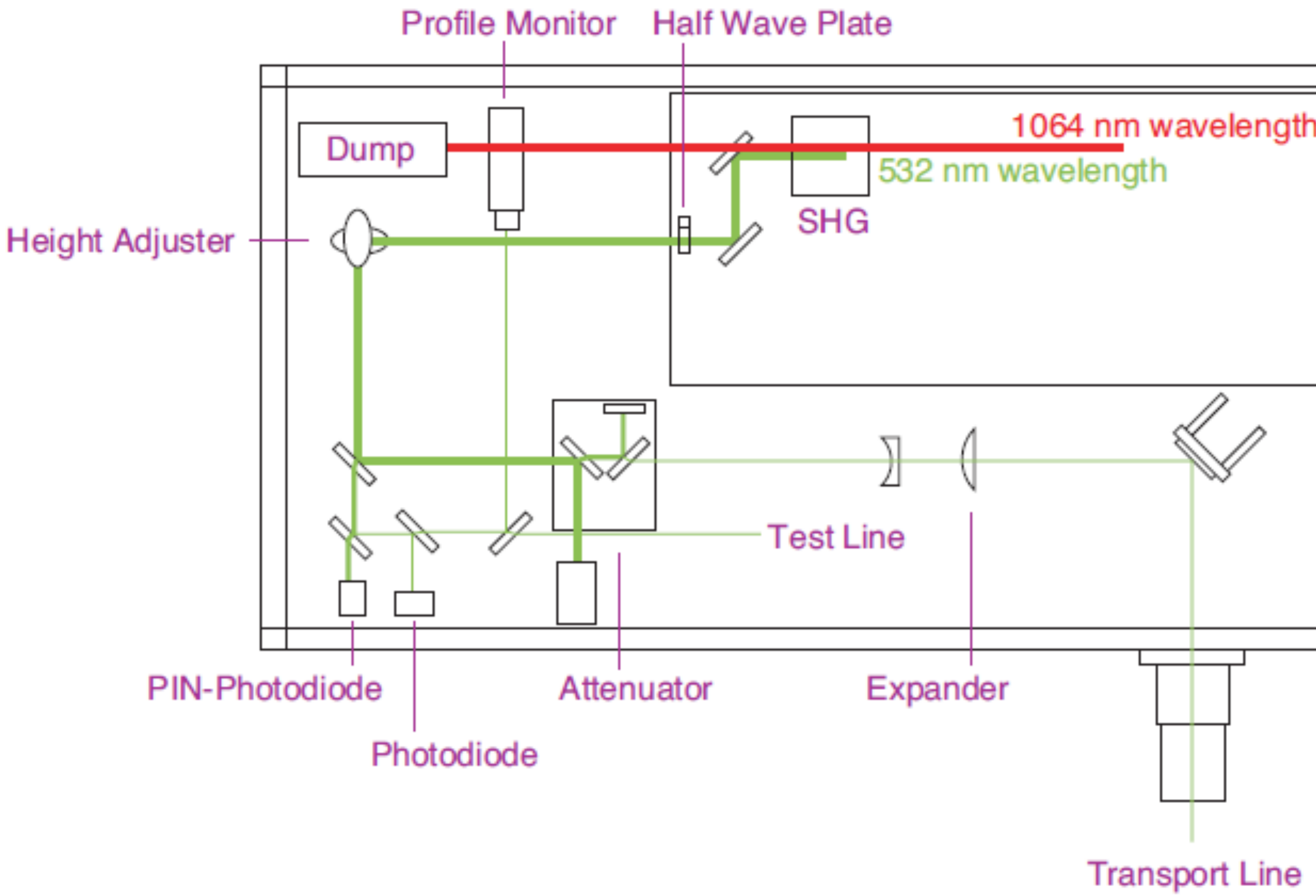
◆ full commissioning of 174 ° mode

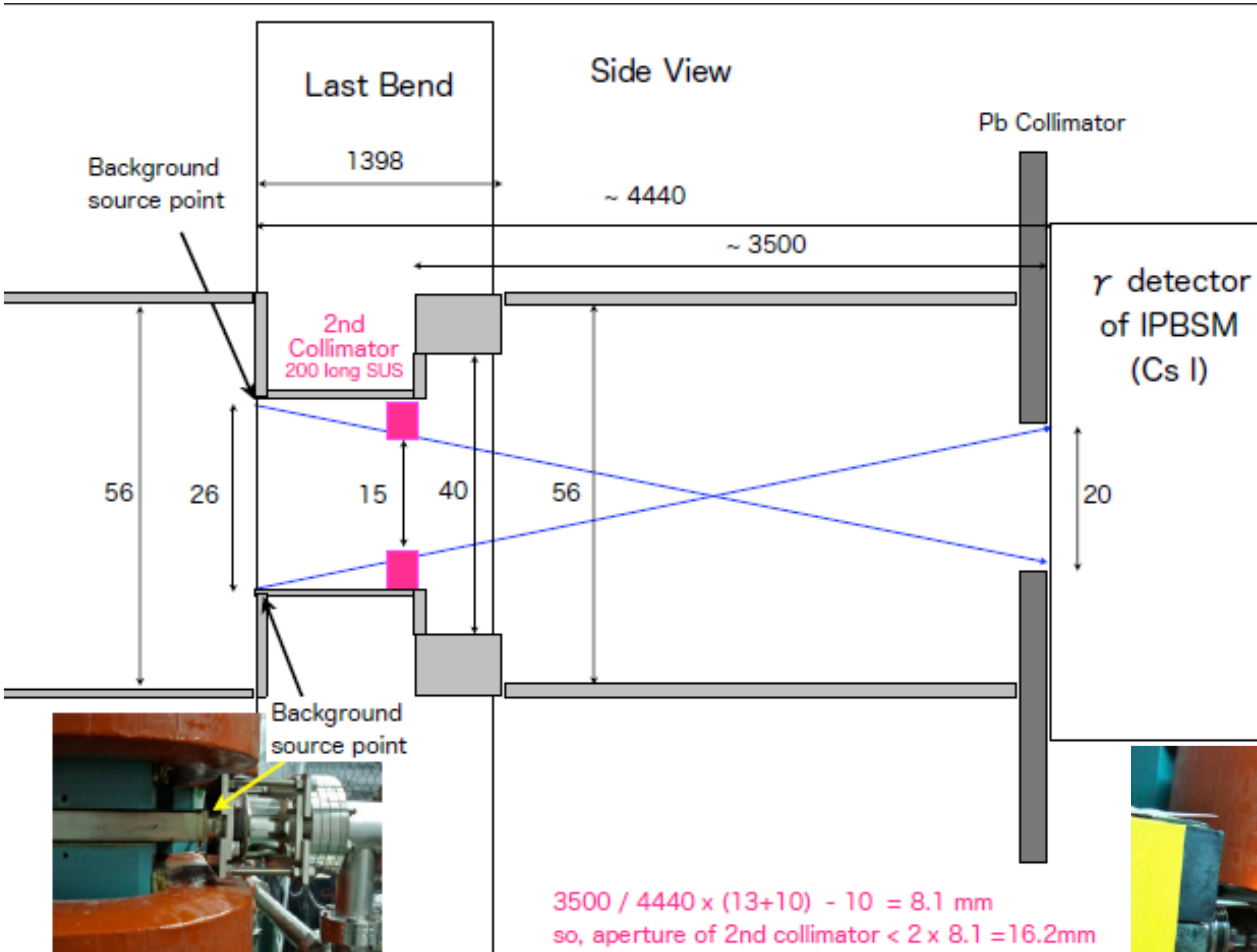
◆ stable measurement of σy* < 100 nm

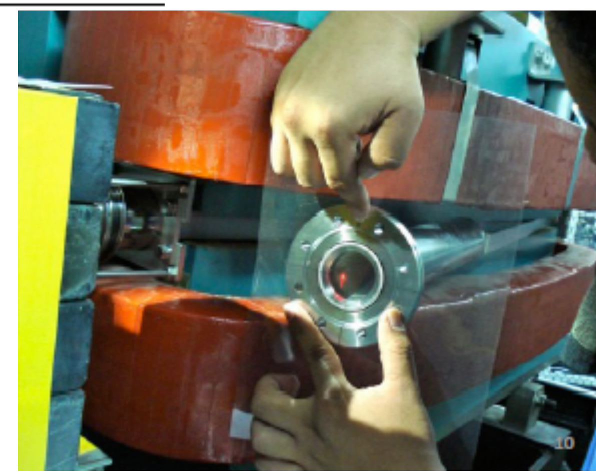
→ achieve focusing down to σy* ~ 37 nm

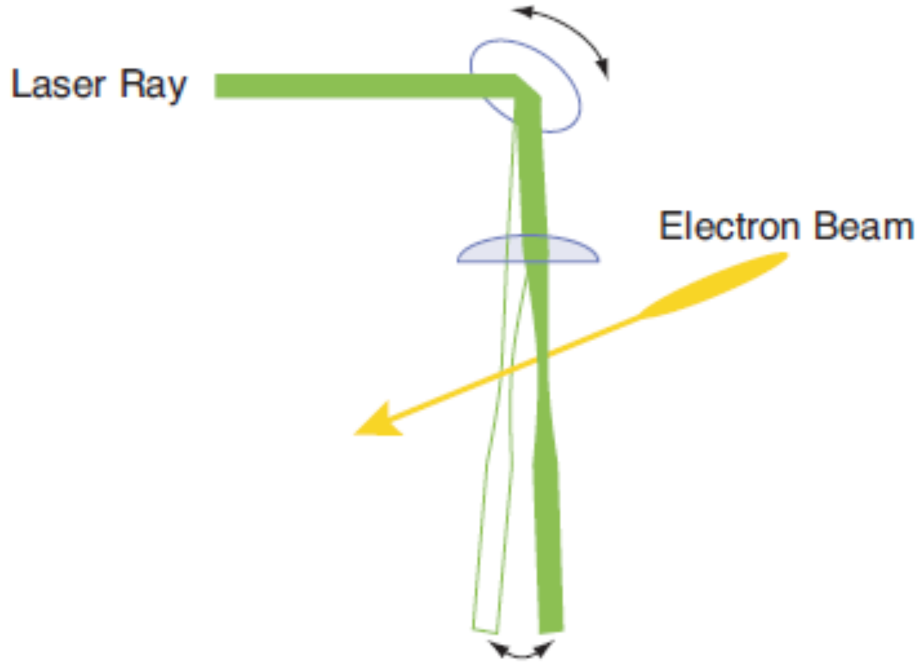
BACKUP

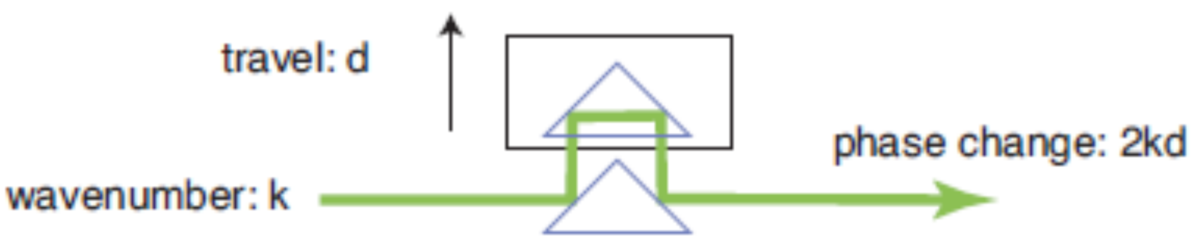

Laser Hut
Transport Line
Laser
Laser Table
Vertical Table
Elertron Beam
Final Doublet
Concrete Shield
Bending Magnet
to Beam Dump


Profile Monitor
Half Wave Plate
Dump
1064 nm wavelength
532 nm wavelength
SHG
Height Adjuster
Test Line
PIN-Photodiode
Photodiode
Attenuator
Expander
Transport Line

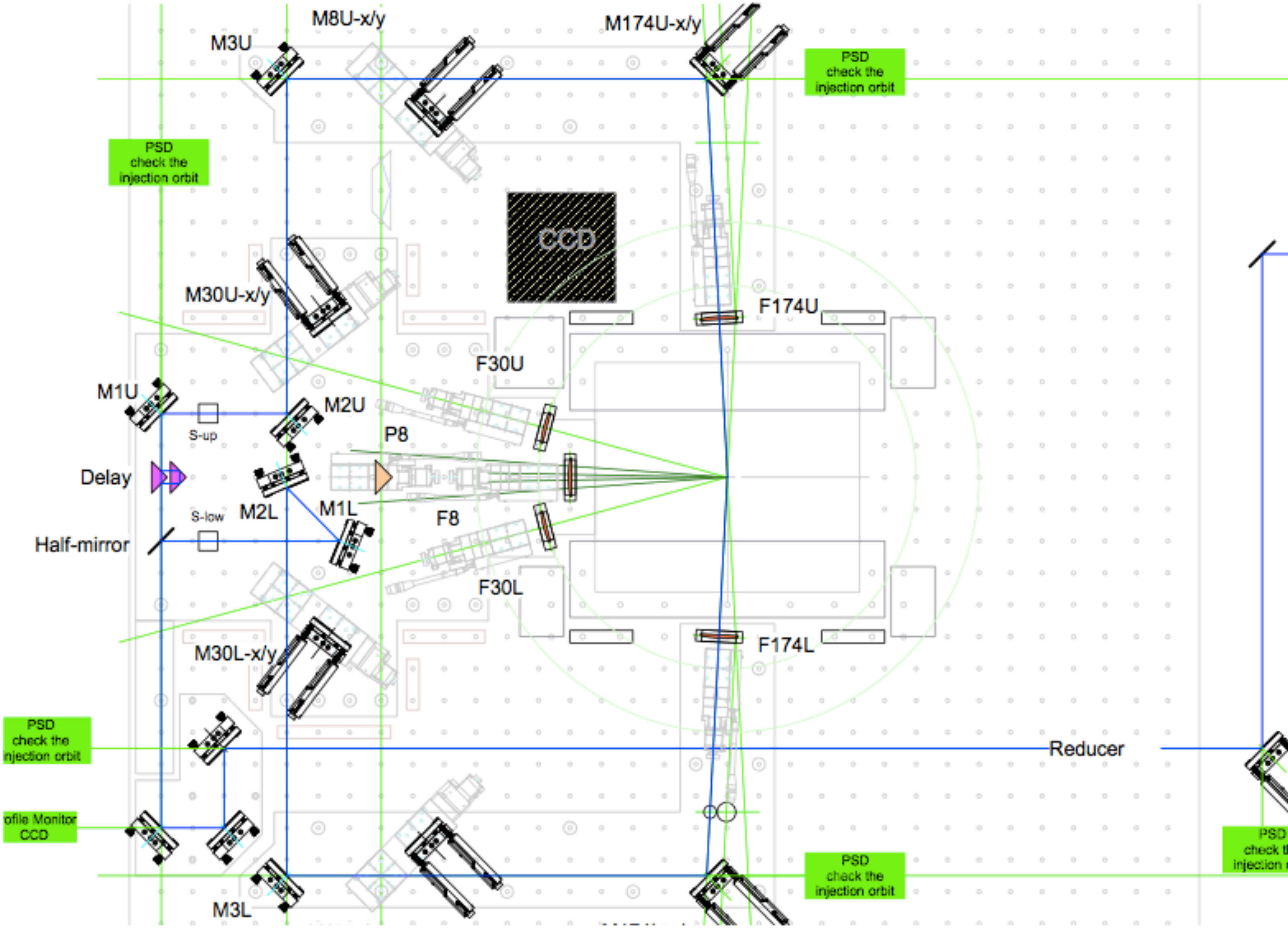

Side View
Last Bend
1398
~ 4440
~ 3500
Pb Collimator
Background source point
γ detector of IPBSM (Cs I)
2nd Collimator
200 long SUS
56
26
15
40
56
20
Background source point
3500 / 4440 x (13+10) - 10 = 8.1 mm
so, aperture of 2nd collimator < 2 x 8.1 =16.2mm

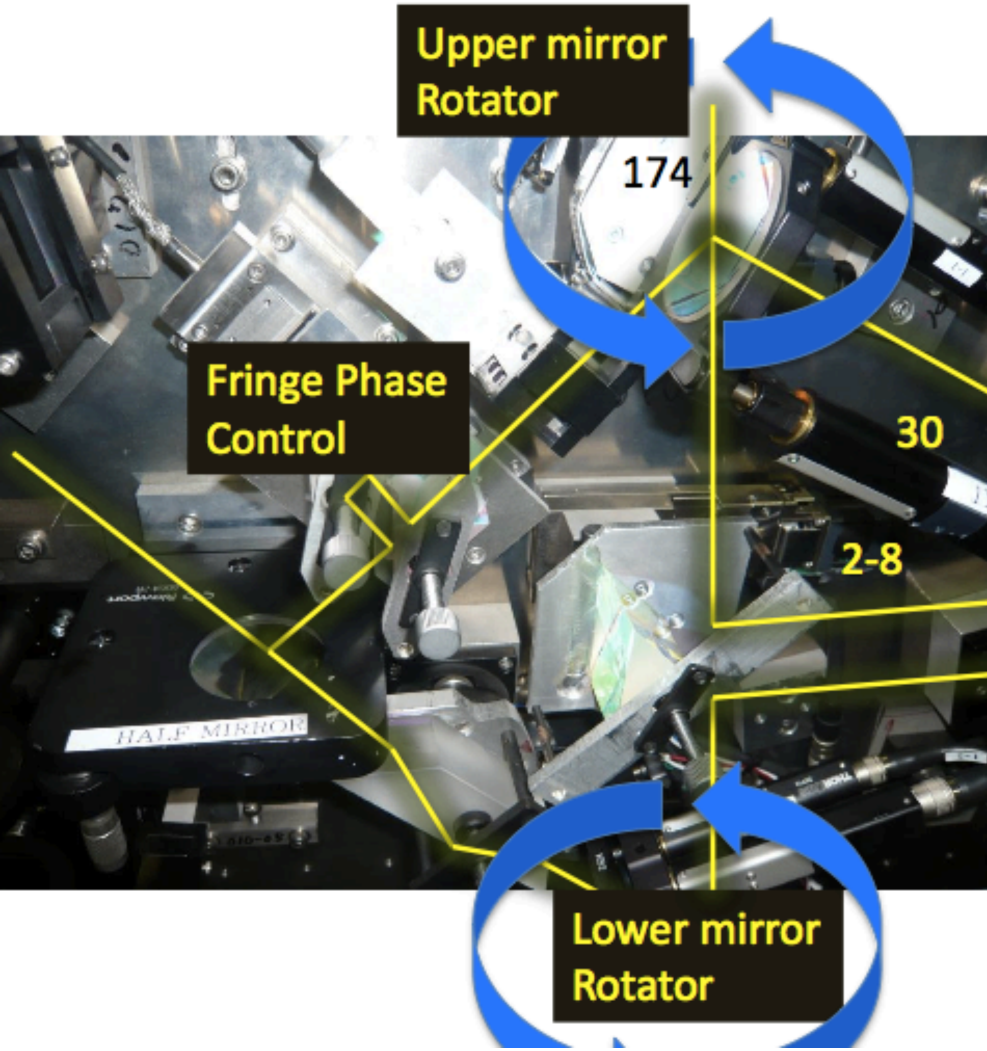



Laser Ray
Electron Beam


travel: d
phase change: 2kd
wavenumber: k

New 174 mode


M8U-x/y
M174U-x/y
M3U
PSD
check the
injection orbit
PSD
check the
injection orbit
CCD
M30U-x/y
F174U
F30U
M1U
M2U
S-up
P8
Delay
M2L
M1L
S-low
F8
Half-mirror
F30L
M30L-x/y
F174L
PSD
check the
injection orbit
Reducer
ofile Monitor
CCD
PSD
check the
injection orbit
M3L


Upper mirror
Rotator
174
Fringe Phase
Control
30
2-8
HALF MIRROR
Lower mirror
Rotator

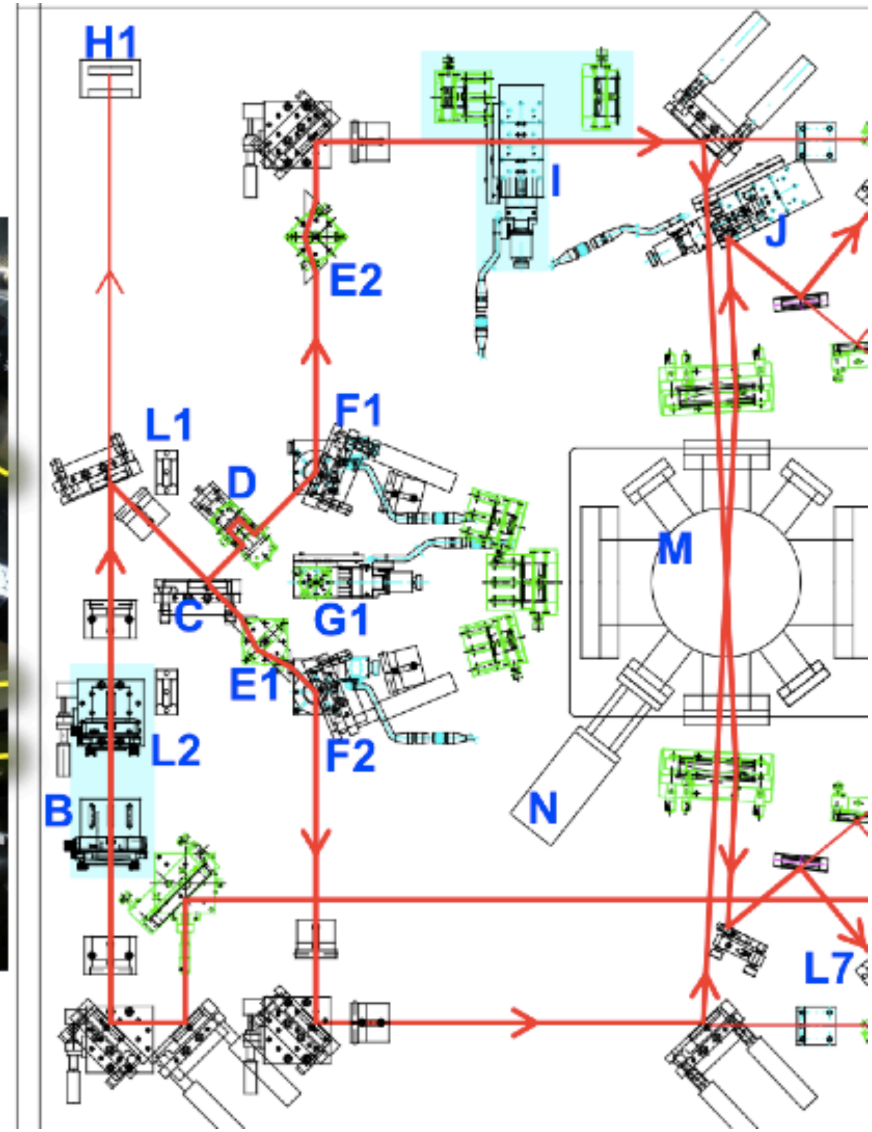

H1
E2
I
J
L1
F1
D
M
C
G1
E1
L2
F2
B
N
L7

Table 3: Upper limits of each M reduction factor predicted for measuring the design σ_y^* = 37 nm at ATF2. Assumed here are nominal laser and ATF2 beam parameters, as well as implementation of specific correction functions for the sensitive 174 deg mode used in this case[6].

Modulation reduction factor	**37 nm at 174 deg**
Total power imbalance	> 99.8 %
Relative position jitter	> 98.0 %
Fringe tilt	> 97.2% (tilt < 1 mrad)
Alignment (t, z)	(> 99.6%, > 99.1 %)
Spatial coherence	> 99.9%
Spherical wavefronts	> 99.7%
Beam size growth within fringe	> 99.7%

Table 4: Upper limits of dominant M reduction factors for measuring σy^* ~ 500 nm at 4 deg mode, estimated using data from June, 2012

Modulation reduction factor	**O(500) nm at 4 deg**
Profile imbalance (t, z)	(> 94%, > 89 %)
Relative position jitter	> 95 %
fringe tilt (t, z)	> 95% (tilt < 20 mrad)
Alignment (t, z)	(> 95%, > 99 %)
Polarization	> 98%

laser path misalignment

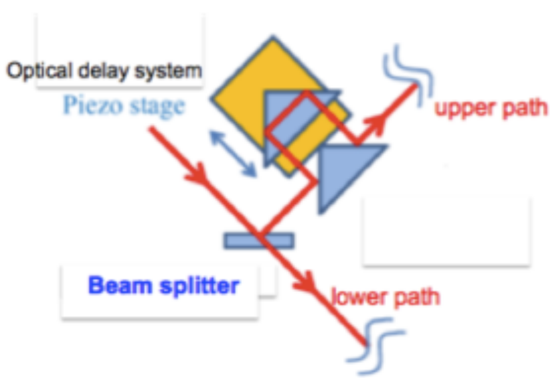
1 . **Laser profile imbalance**
misalignment of final lens focal point
divergence angle affected by reducer setup

In past:
replaced damaged optical components
optimized lens / reducer setup, alignment methods

2. Laser position offset from IP (beam center)
→ not a concern,
mirror actuators finely adjust to 1/10 of σlaser
long. : Cz- pos > 99.5 %
transv : Ct-pos ~ 100%

Polarization related errors

→ **imbalance in intensity/ profile**
→ half mirror R = 50% only for pure S state
elliptical components（P contamination)



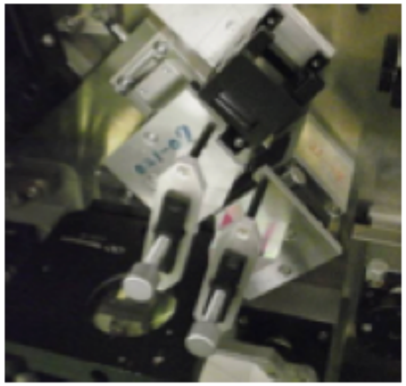


Figure 4.7: [Left] The optical delay system for controlling fringe phase. [right] The piezoelectric stage

adjust to S state by rotating λ /2 wave plate
•measured in past :
half mirror properties,
eccentricity Es : Ep = 1: 0.13

→ Cpol = 97.8 ± 12.8 · tanθ ± 0.1% (2-8, 30 deg)

Cpol = 97.2 ± 1.3 · tanθ ± 0.1% (174 deg)

for now assume Cpol ~ 98 %

顕著な系統誤差　(2012連続ランより)

夏の光学系アップグレードで系統誤差を改善

Profile Imbalance

✓ Compton peak power の違い:　C_{pow} ~ 98%
✓ IP spot size σ_{laser}の違い:　C_{pro} ~ 90 – 95%

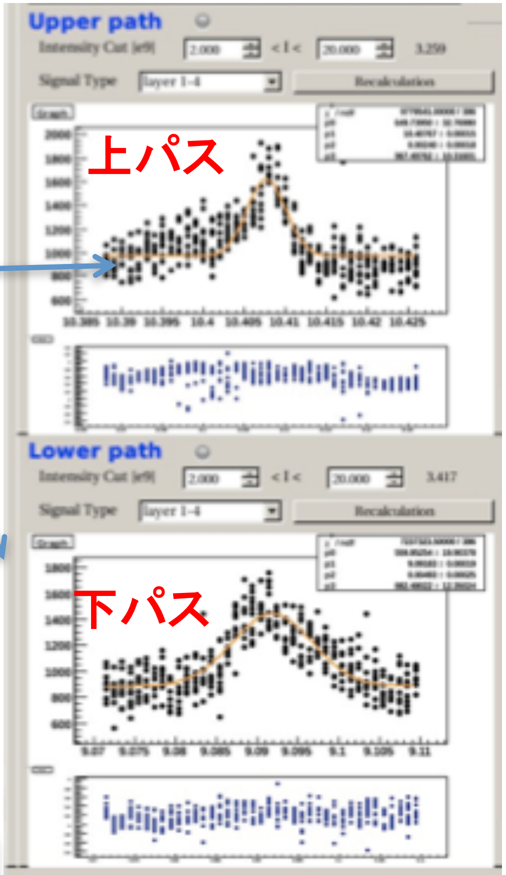
◆一部は光学素子由来のロス
(反射・透過率、光路長差ect…)
total　P_l = 0.88 ←→ C = 99.8%

$$M' = CM = \frac{2\sqrt{P_l}}{1+P_l} M$$

◆lensのalignment精度
(→ 焦点位置のばらつき)

$$P_l \equiv P_U / P_D$$

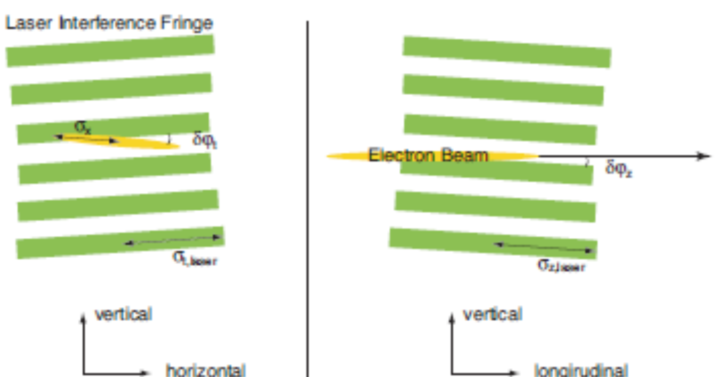
実laserwire scan



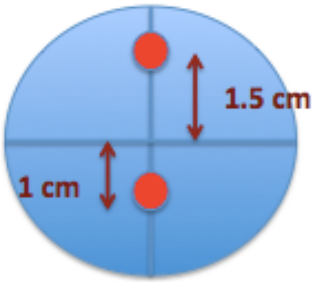
上図）2倍の信号量の差

Fringe Tilt

干渉縞がbeam軸に垂直でない場合

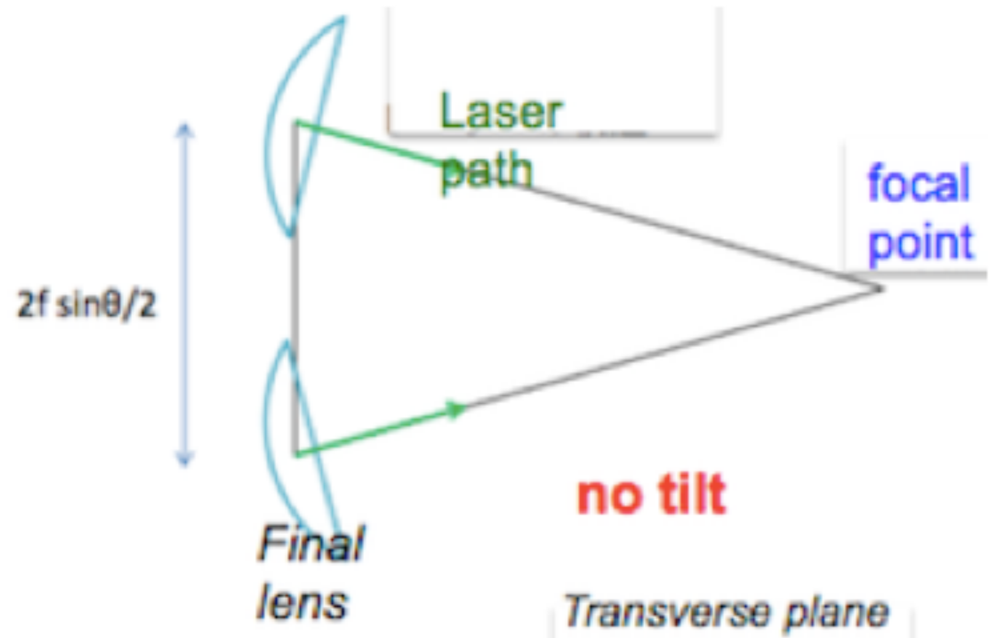


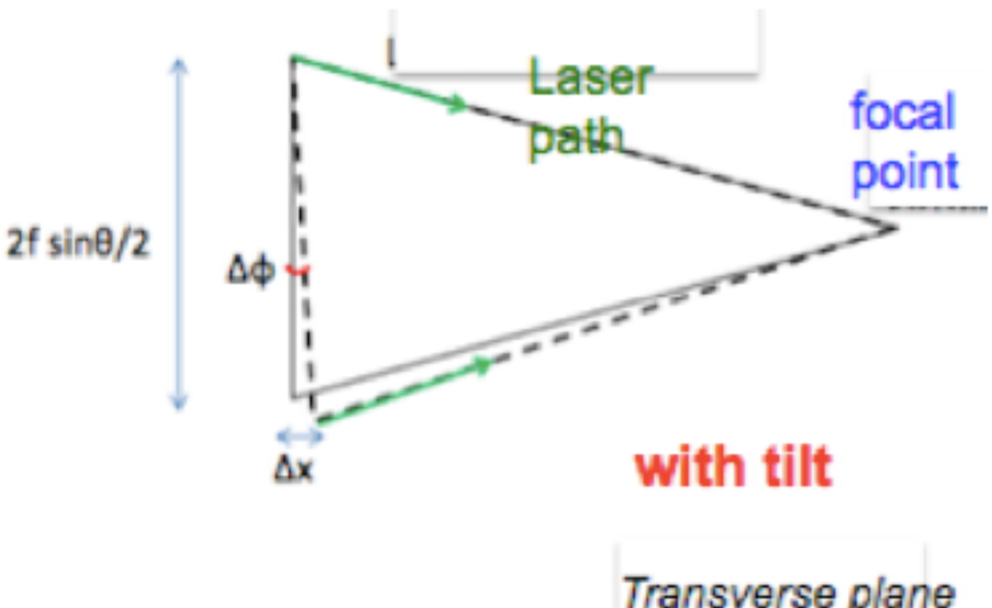
transverse　　　longitudinal



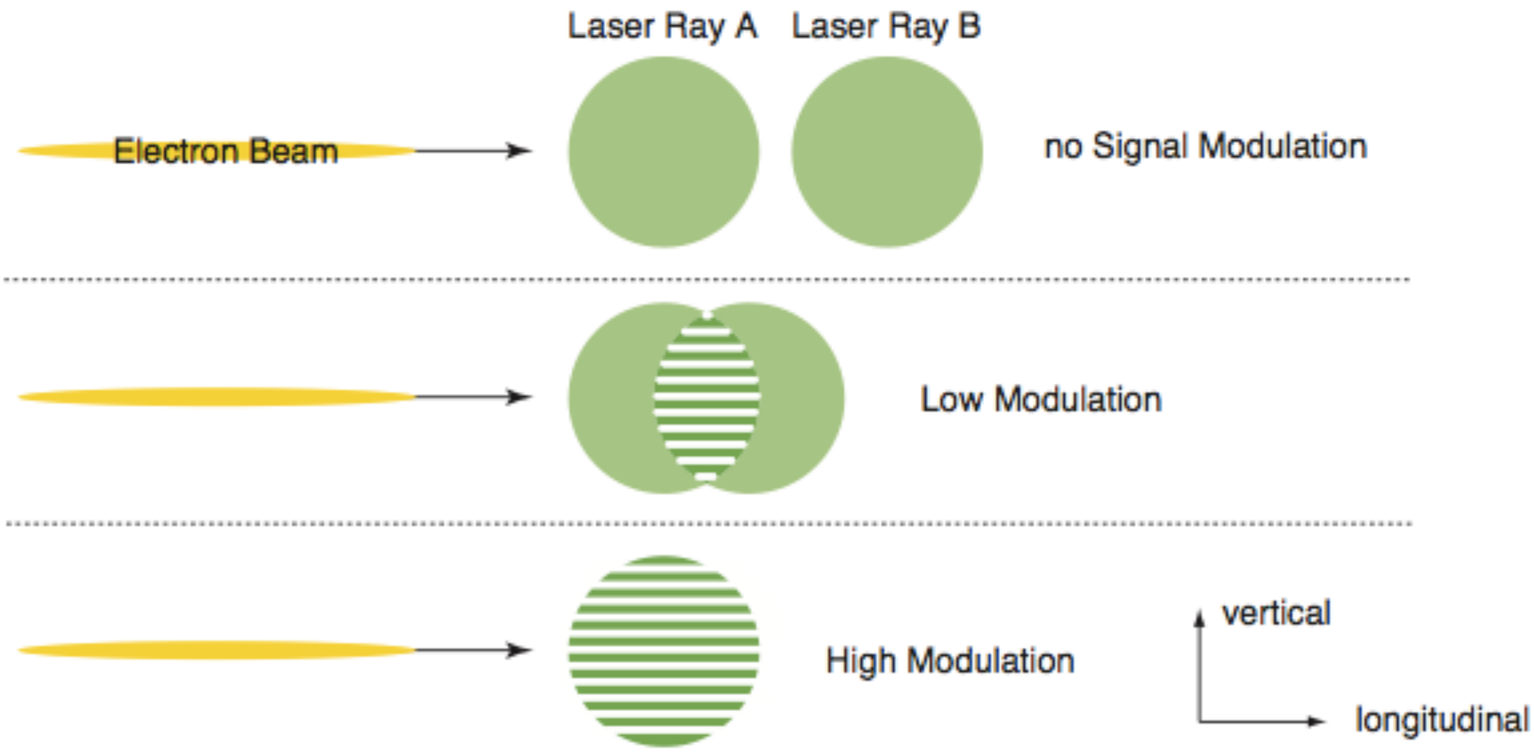
見積もり方:
収束レンズ中心からの相対的オフセット　Δt,z

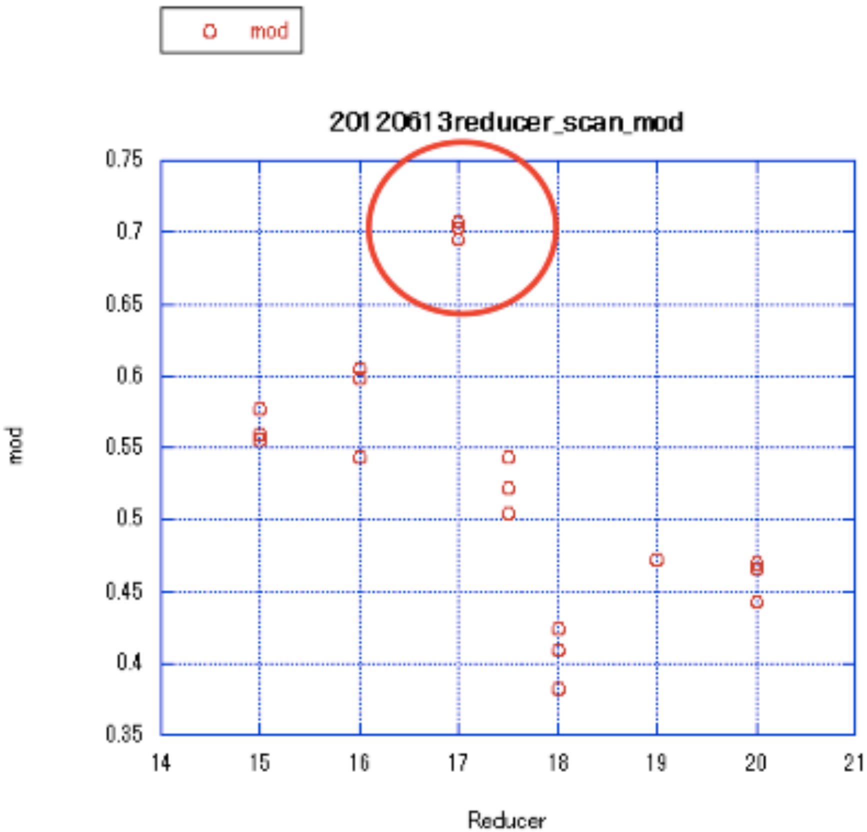
光路精度 Δ < 3 mm
➔ 傾き:　δφt <10 mrad　　**Ct-tilt > 95.3%**
　　　　δφz < 5 mrad　　**Cz-tilt > 99.8%**



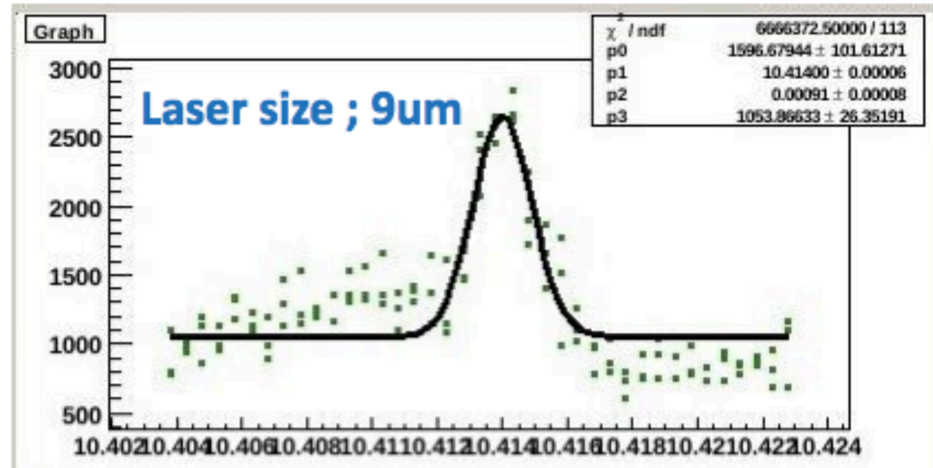


$\tan \Delta\phi = \Delta x / 2f \sin\theta/2$

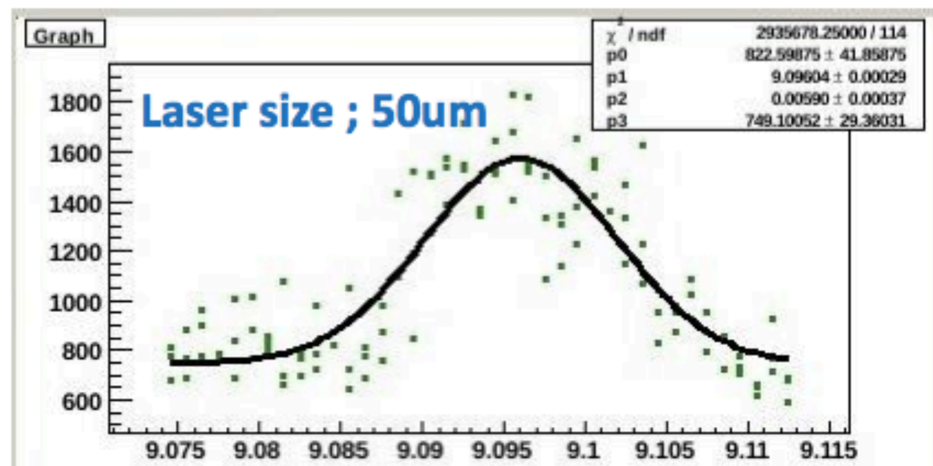

Laser Ray A
Laser Ray B
Electron Beam
no Signal Modulation
Low Modulation
High Modulation
vertical
longitudinal



Very narrow optimum setting



Beam profile of lower path



Current status of laser system

relative timing	Stabilized by **timing scans** **TDC, TD2** modules
Intensity	• **Stability ~ 1%** • optics damaged by high intensity laser in March • Safe at ~ **40% power** for now
Oscillation	**currently stable** •**exchanged flash lamps and seeder** • **cavity mirror tuning**
profile	Triangular (**non-Gaussian**) profile at IP **dark spots** →Improved by **rear mirror tuning**
Major upgrades in laser optics	• **Beamlok** • new laser table box • additional mirror for **precise injection onto vertical table** • changed **reducer and expander lens** (AR coating , magnification)

Stat errors

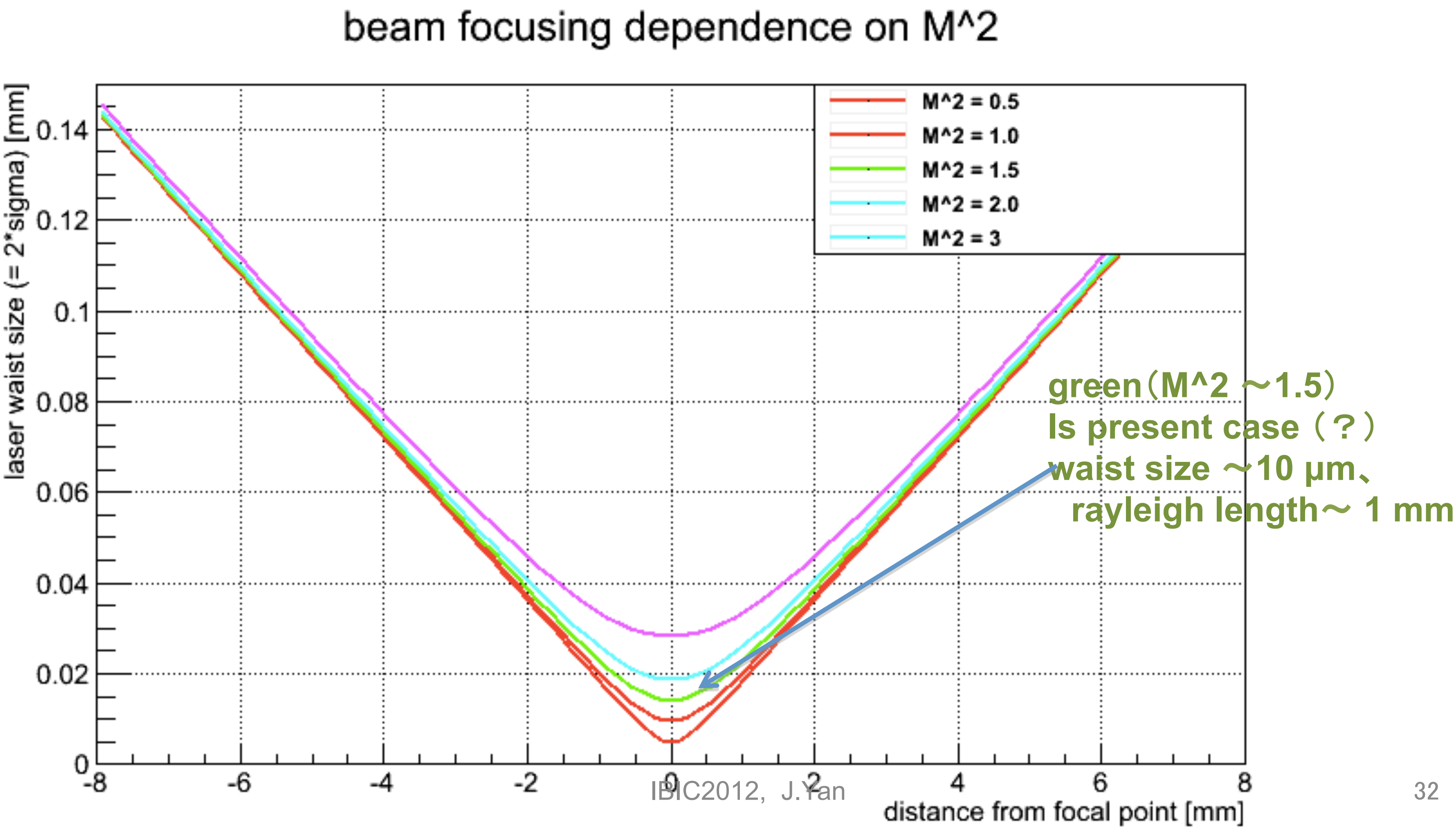
Laser timing	**1 - 3 %**
Laser intensity	**1.5%**
Beam intensity jitters	**ICT monitor resolution: 2-5%** (Measured energy is normalized by ICT)
Laser pointing stability	**10 ~ 15%**
Beam position jitters	unknown

M^2 :   0.5 – 3.0

near field to few times of rayleigh length

•Assume injected size of ω = 4.5 mm,

• fix focal point to 5.6 mm (lens mover position)

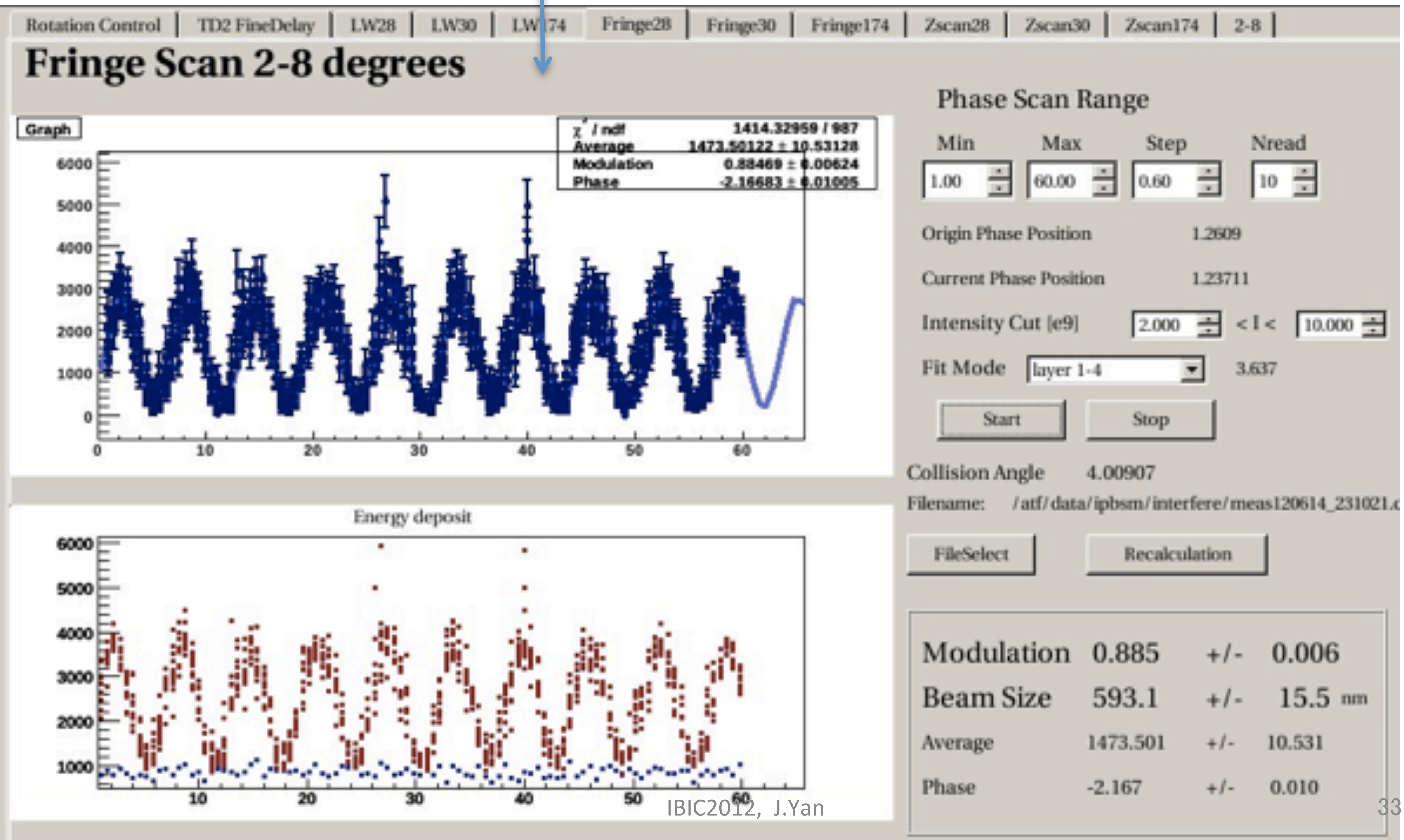


4 consistent measurements at 4 deg mode :

including **long range fine scan** (60 rad, Nav = 10)

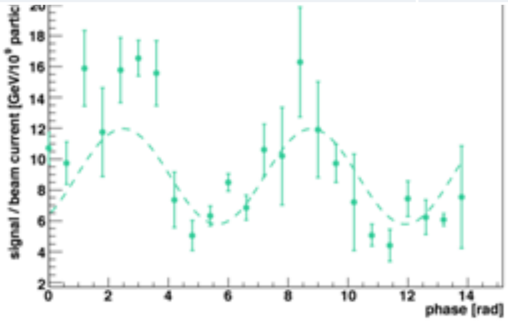
M = 0.887 ± 0.005 (stat only) **σy = 589 ± 13 nm**

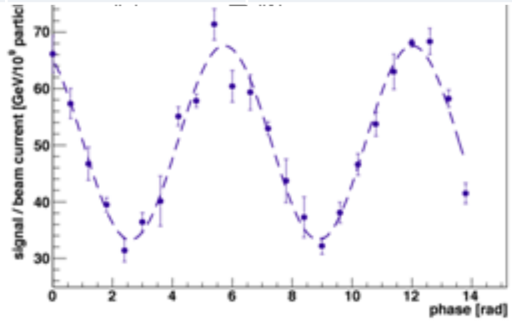
init. phase: -2.162 ±0.009 rad *phase drift ~ 18 mrad (~ 0.8 % only)*



optics for recent run	S/N	BG [GeV]	Sig. jitter
10x βy* (ex: 30 deg)	**4**	**5**	**15 – 25%**
3 x βy* (ex: 2- 8 deg)	**1**	**15**	
1 x βy* (ex: 174 deg)	**0.5**	**20**	

BG のふらつき
〜10 – 15 %

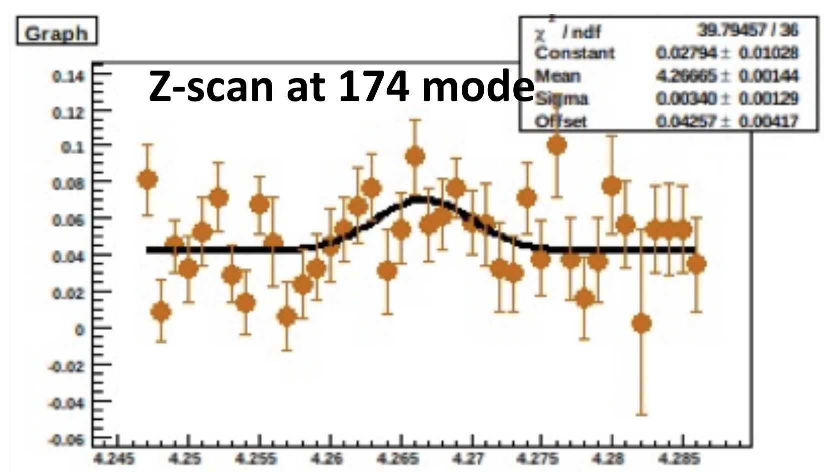




シグナルジッター: 30%

シグナルジッター < 10%

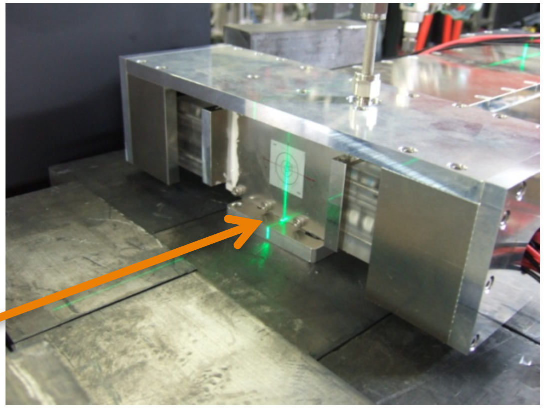
ハードウエアアップグレード



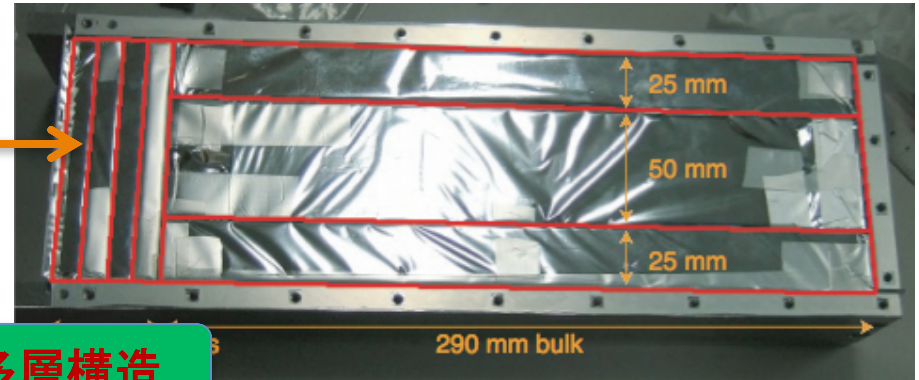
ガンマ線検出器

カロリーメータ型CsI(Tl)シンチレータ

γ



γ

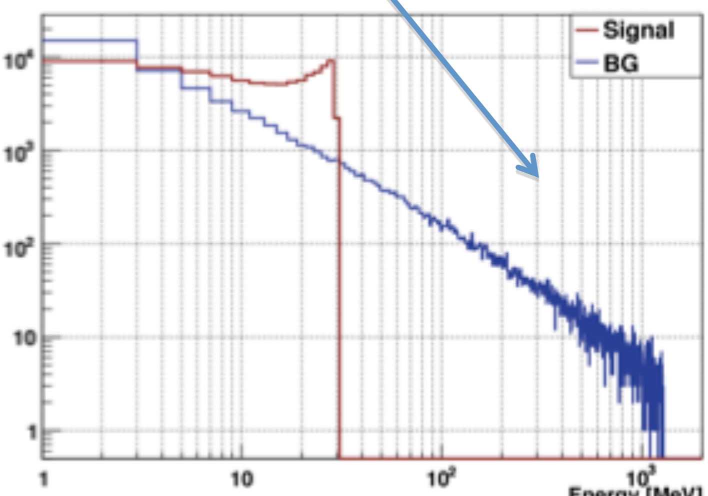


多層構造

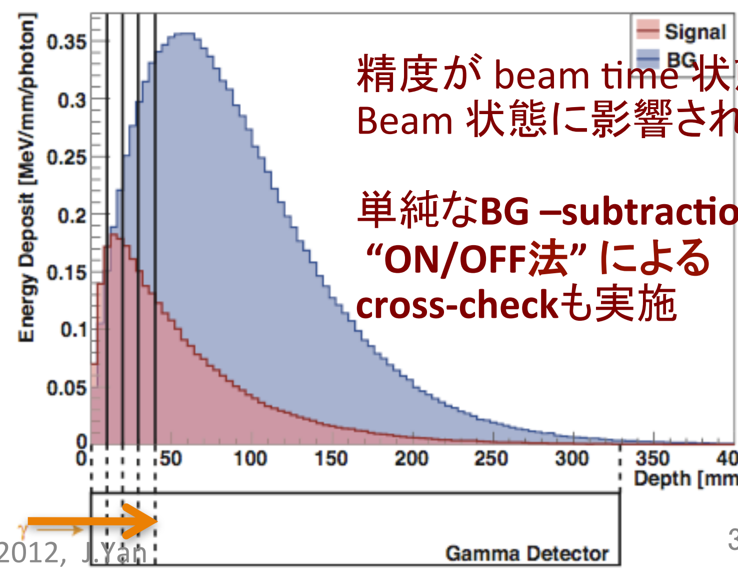
前4層 （10 mm x 4) ＋ 後ろの ”bulk” (290 mm)

高いシグナル･BG分離能

ATF2 でsignalとBGエネルギースペクトル
が大きく違うことを活用



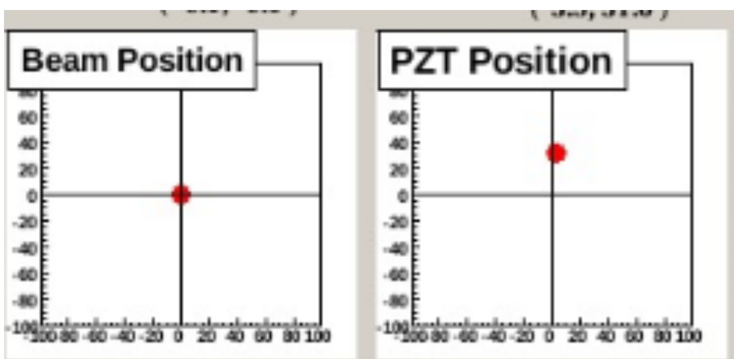
各層でのシャワー発展を測定
→参照シャワーでfitting



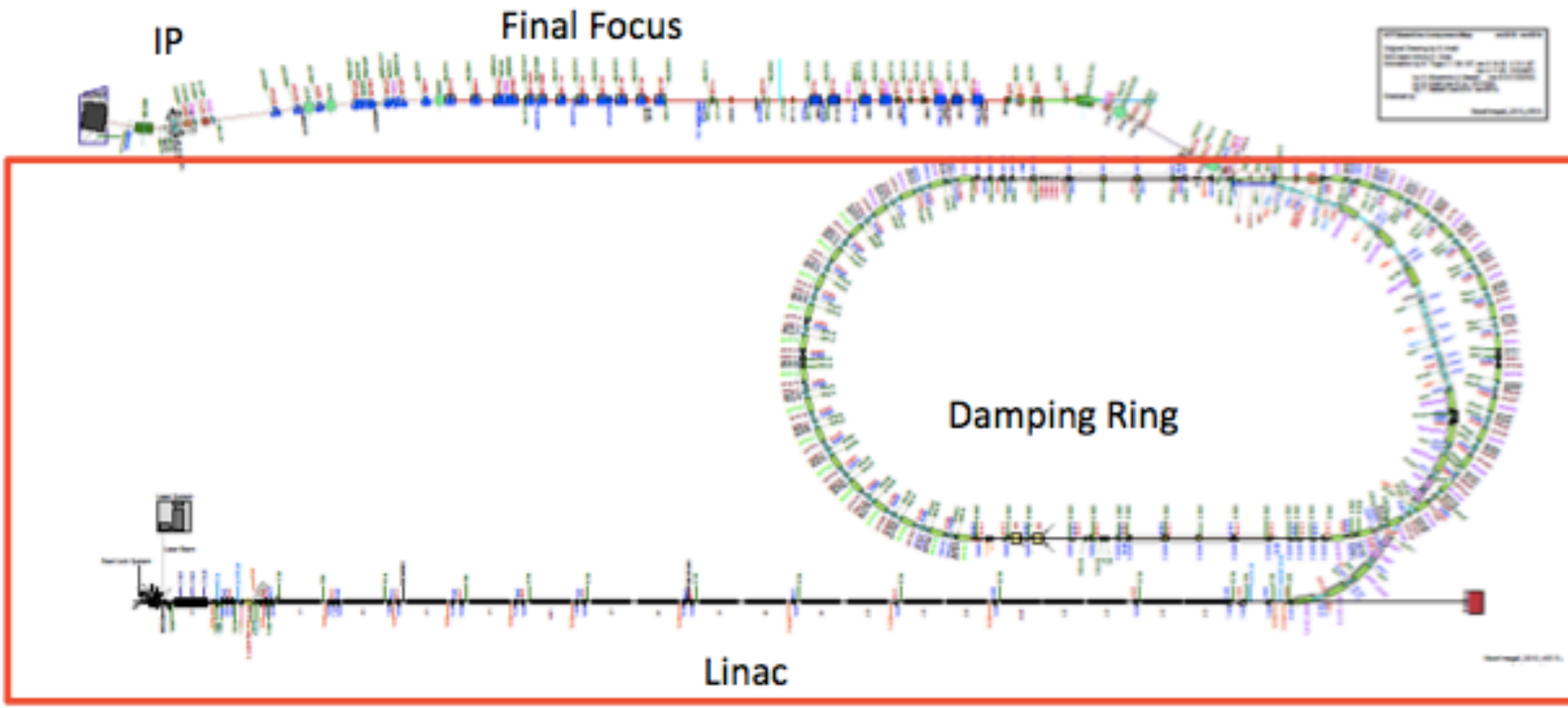
精度が beam time 状態が
Beam 状態に影響されないように、

単純な**BG –subtraction**
“ON/OFF法” による
cross-checkも実施

BeamLok Specifications	Standard Pro Series	With BeamLok/D-Lok
Beam Pointing Stability[12]	<±50 µrad	<±25 µrad
Beam Divergence[13]	<0.5 mrad	<2 x initial level
Lamp Lifetimes[14]	30 million pulses	40 million pulses
Linewidth		
Standard	<1.0 cm^{-1}	
Injection Seeded[15]	<0.003 cm^{-1}	
Timing Jitter[16]	<0.5 ns	

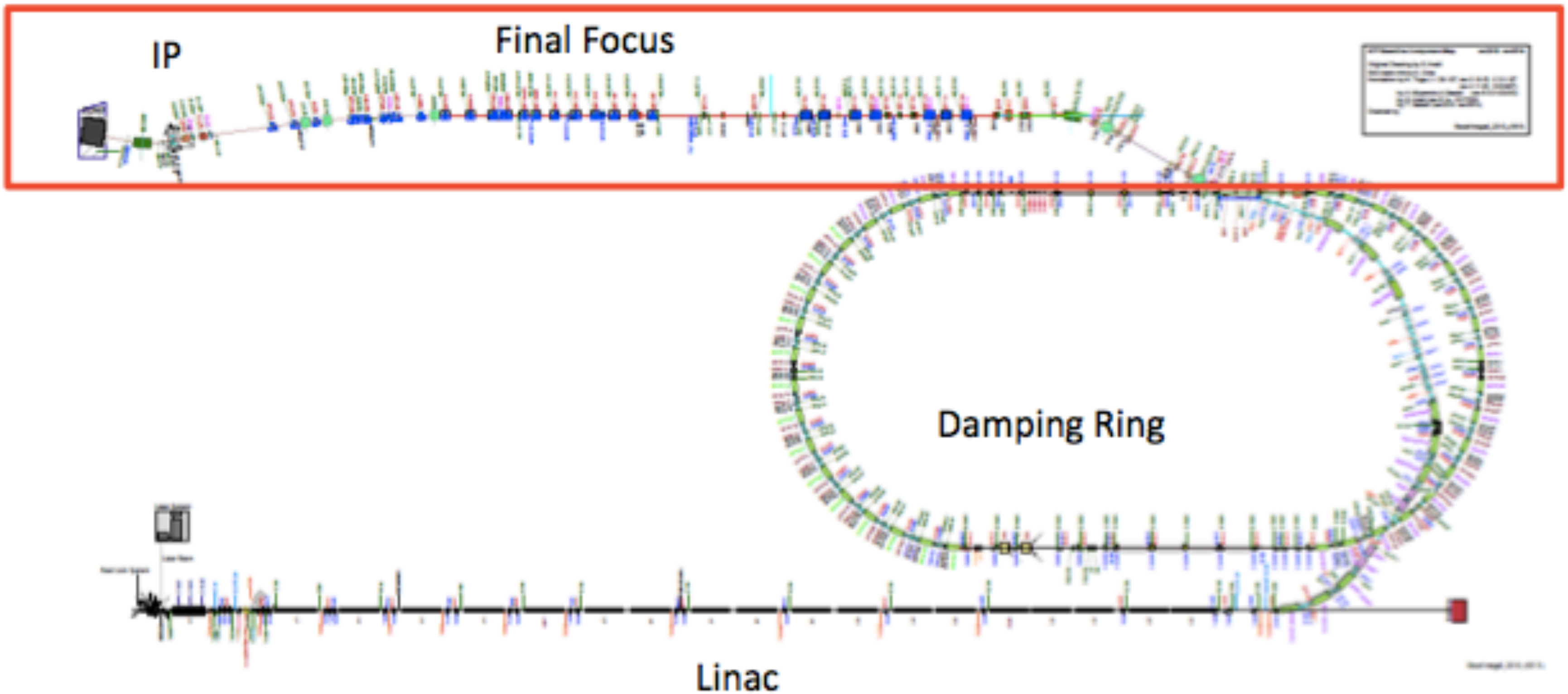


ATF



Linac: ビームエネルギー1.3 GeV
Damping Ring: 鉛直エミッタンス11 pm・rad → 規格化鉛直エミッタンス30 nm・rad
ILCでの規格化エミッタンス35 nm・rad

ATF2

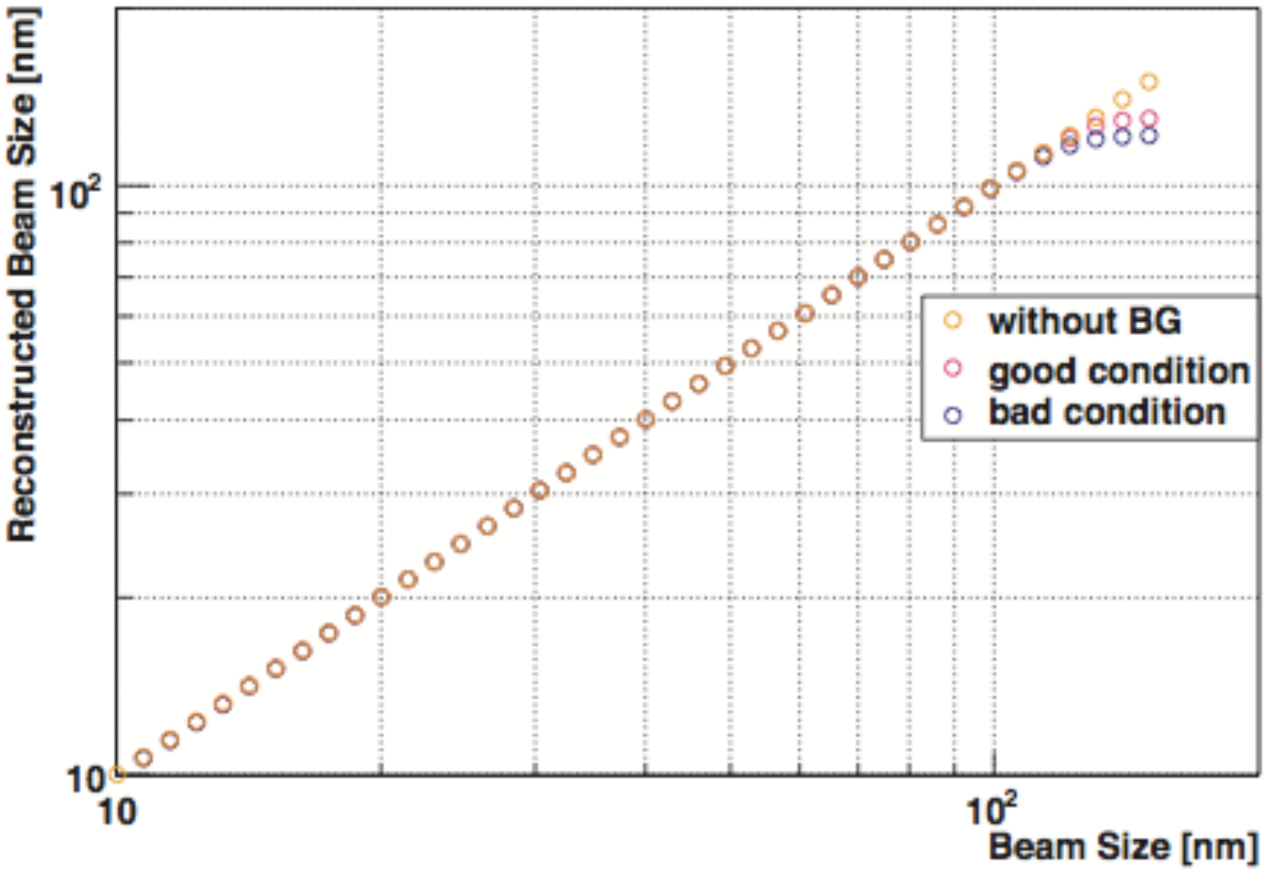


Final Focus: 局所色収差補正に基づいた設計
・37 nmの鉛直ビームサイズ → 新竹モニタで測定
・nmレベルのビーム安定化
100 nm以下のビームサイズ測定に実績

FFTB vs ATF2

Table 2: Typical e- beam and IPBSM parameters: ATF2 vs FFTB[2, 4]

	FFTB	ATF2
Beam energy	46.6 GeV	1.28 GeV
1 photon energy	8.6 GeV	15 MeV
rep. rate	30 Hz	1.56 Hz (3 Hz)
e- / bunch	1×10^{10}	1×10^{10}
Bunch length	3 ps	16 ps
(σ_x^*, σ_y^*) at IP	(900, 60) nm	(2200, 37) nm
Laser wavelength	1064 nm	532 nm (SHG)
Range for σy*	40-720 nm	20 nm-6μm


Reconstructed Beam Size [nm]
10²
10
10
10²
Beam Size [nm]
without BG
good condition
bad condition