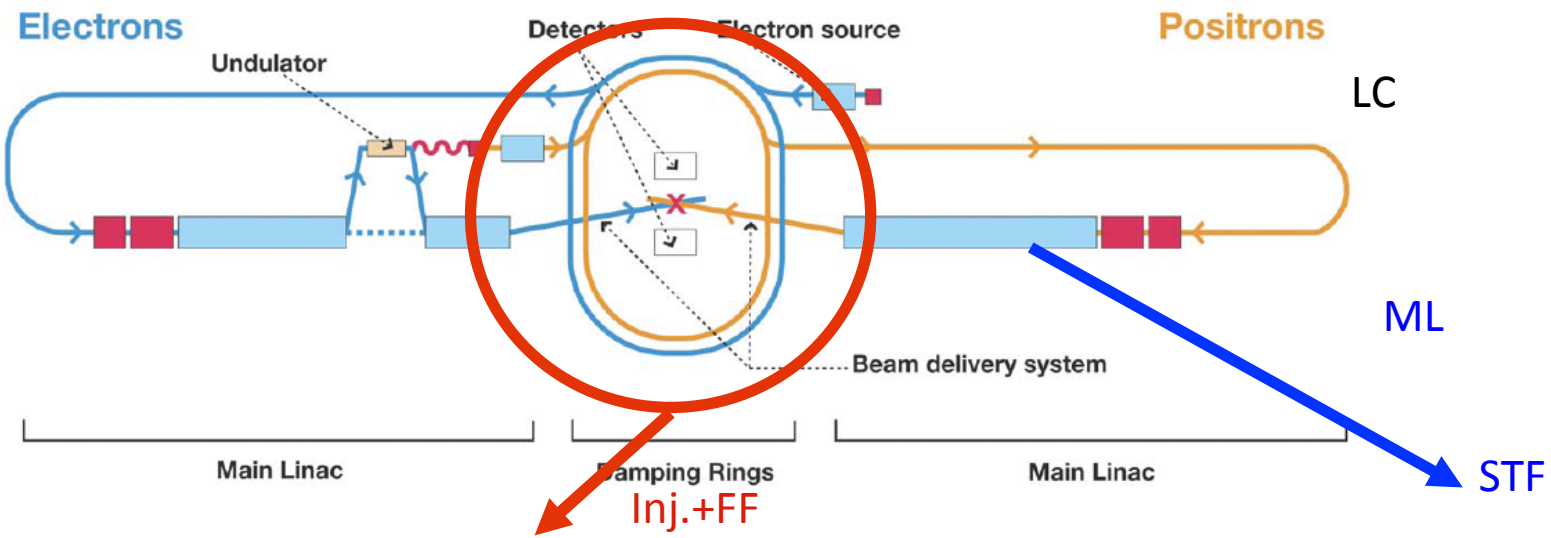
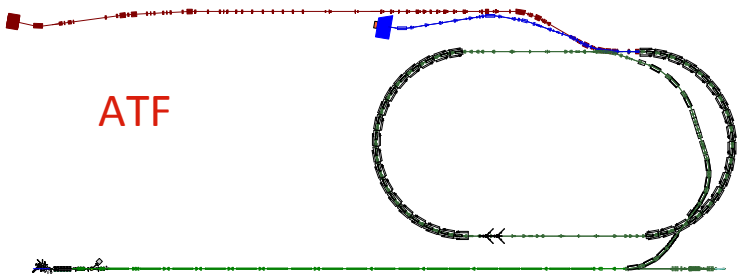
ATF/ATF2 について

S.Kuroda(KEK)

ATF/ATF2 Introduction





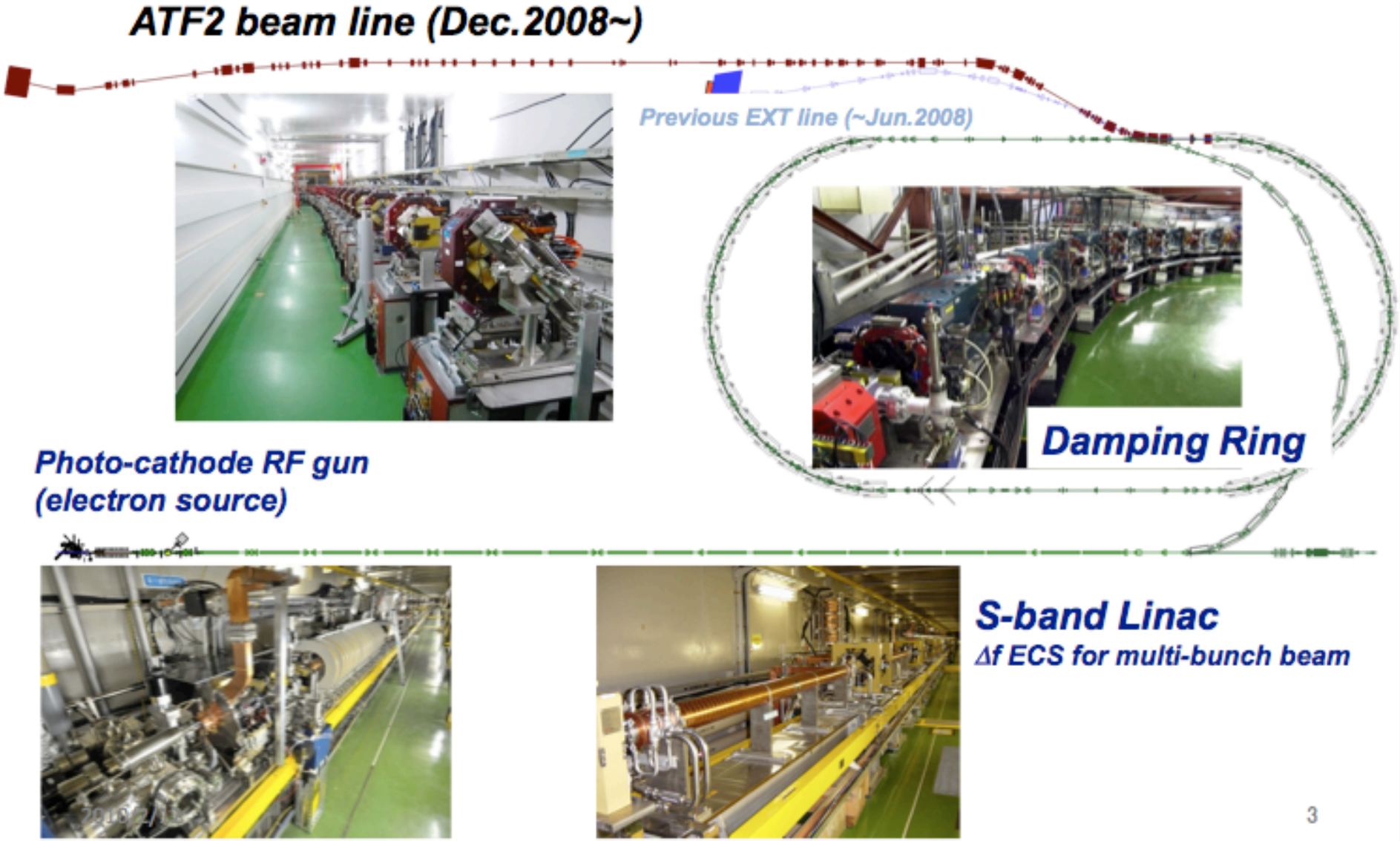
History

~1990 design started
1997 beam operation started
~2000 εy<5pm
2002 photo-cathode RF gun
2004 ITRP recommendation
2008 ATF2 commissioning

Accelerator R&D
Main goal
1. Low emittance generation
   Done in ~2000
2. Multi-bunch operation
   Multi-bunch generation is OK by RF Gun.
   Still study is needed for instabilities.

Other studies, e.g. LW, e+,…
ATF2 goal
small beam size as 37nm and its stable operation

ATF accelerator complex



DRのエミッタンス調整

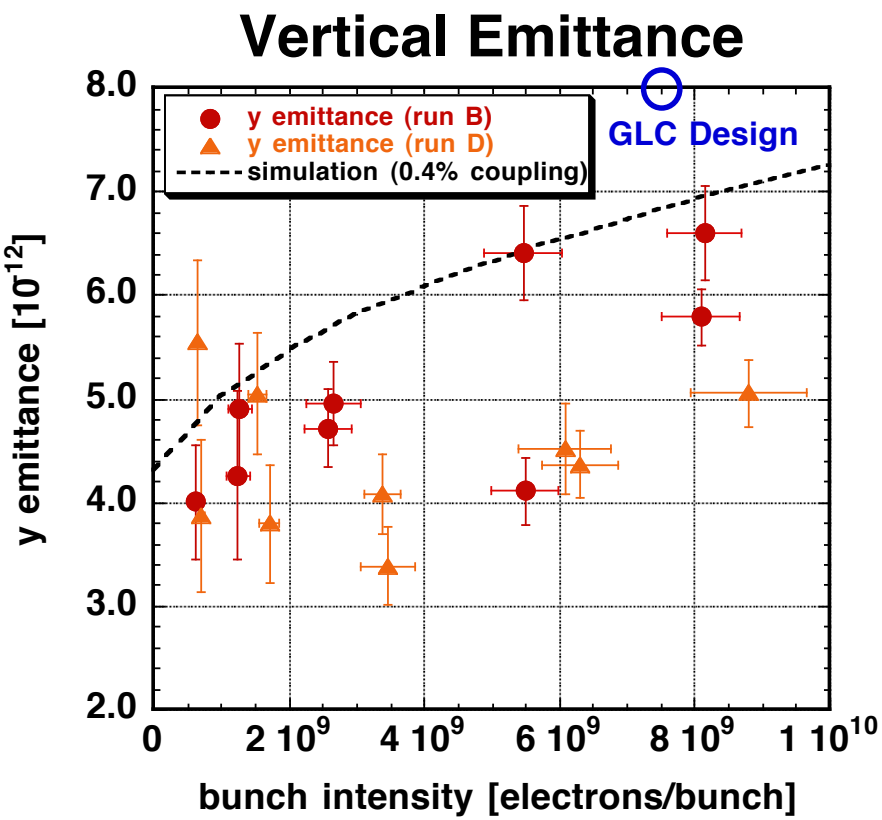
歴史

現状

EXTでのエミッタンス測定

Emittance History in DR

- There were great efforts to achieve low vertical emittance since DR commissioning.
- From the end of 2000 to 2002, we observed very low vertical emittance in DR about 10 pm.
- After further improvement of hardware, with software and simulation works, we constantly achieved lower than 5 pm at low intensity (N →0), and lower than 8 pm at high intensity (N~1E10)., which was lower than "designed" emittance. (2003)



Emittance History in DR (2)

After this low emittance achievement

We have not really pursued lower emittance.

R&D of instrumentations were main tasks at ATF.

Emittance was as large as 20~30 pm (from 2006 ?) !!

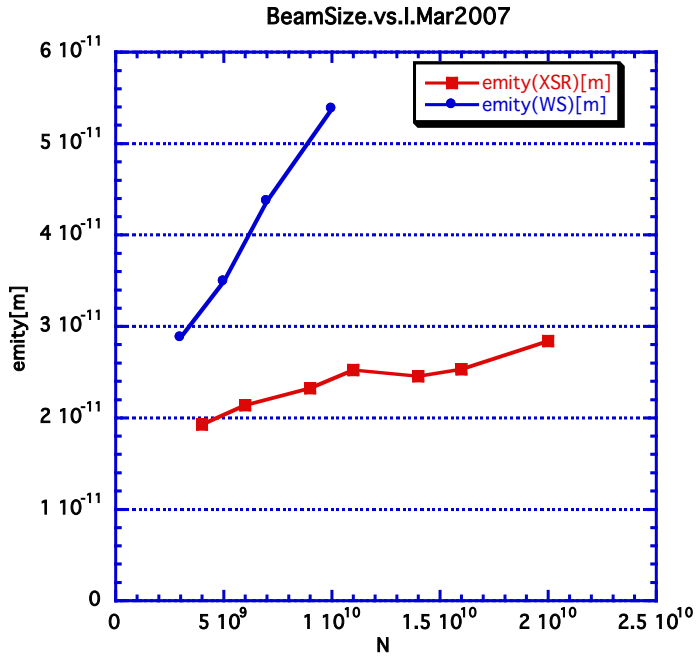
Why?

– No clear answer.

We have to make it small again

(smaller than before if possible)

– For ATF2



XSR meas. βx=1.69m 13Mar2007

WS meas. $\Delta p/p$=9e-4 15Mar2007

Here, EXT line was old, which was renewed with ATF2.

Emittance meas. was done by WSs.

Reason of the emittance growth was not clear. Non-linear field, wake, jitter,…?

Recovery to Low Emittance in 2009

- Hardware issue
  - Re-alignment of magnets in DR
  - Introduction of electric load to correct DR main bend.
  - Beam size monitor improvement →following slides
- Start with 'design optics'
- Beam tuning method
  - β beat correction
    - Correction with QM18R.1&QM15R.2 trim.
  - Dispersion correction
    - η_x in straight section is corrected by QM trim
    - η_y is corrected by correctors
  - Coupling correction
    - Correction of vertical leakage of the horizontal kicks by a couple of horizontal correctors.
    - Correction is done by Skew Q winding trim coil of SX.

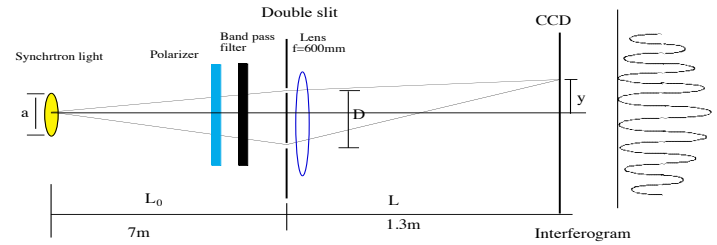
DR Emittance Measurement

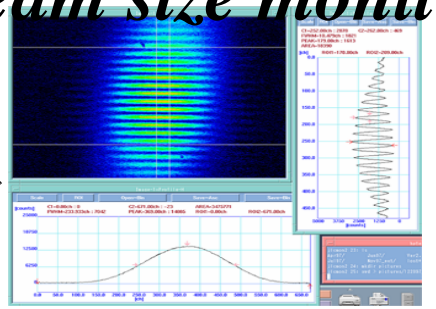
- Beam size measurement
  - SR Interferometer
    - Quick measurement, 5ms
    - Minimum beam size can be measured is ~5-6um
    - Suffering from mechanical vibration
  - XSR monitor
    - Quick measurement, 20ms→50Hz oscillation?
    - Minimum beam size can be measured is ~5-6um
    - Less mechanical vibration but still.
  - Laser wire
    - A few ten minutes requires for measurement
    - ‘design’ laser waist size is 6.5um→going to higher mode, beam size of 1um can be measured.
- Beta function measurement
  - Fitting β of Qs nearby which were obtained from tune slope.

Beam Size Measurement in DR

SR interference beam size monitor

Layout of the SR-interferometer

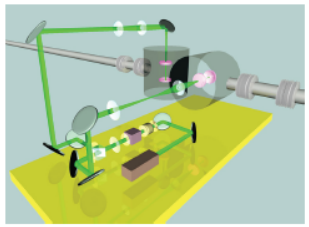


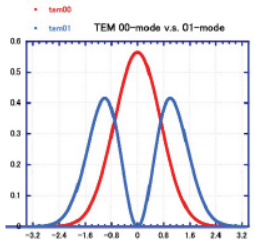


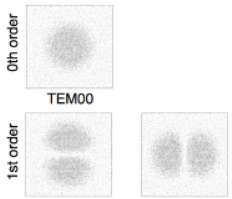
1.6.1997 T.Naito

$$I = \pi a J_0\{1+\exp[-(\frac{2\pi D a}{\lambda L_0})^2]\cdot\cos(\frac{2\pi D y}{\lambda L})\}$$

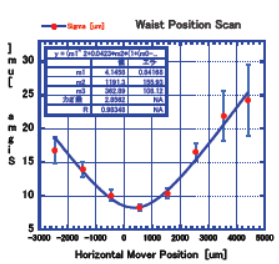
Laser wire beam size monitor in DR

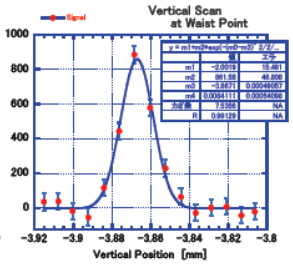






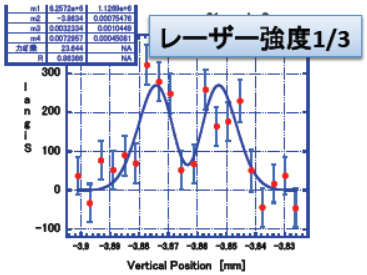
Fundamental mode(00 mode)





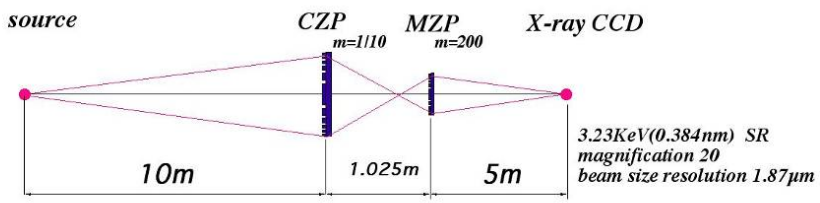
σ_e=4.1±0.8um

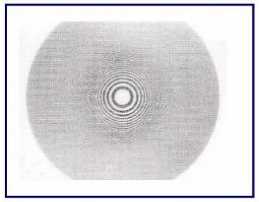
Higher order mode(01 mode)



σ_e=3.2±1.0um

X-ray SR monitor using zone plate (Tokyo Univ.)

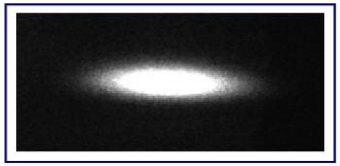




microscope image of zone plate

CZP : 3mm dia.
6497 zone rings
minimum zone width 108nm

MZP : 75μm dia.
584 zone rings
minimum zone width 127nm



Beam image (x:46.2, y:10.2μm)

ビームサイズモニターの性能向上(2009年)

- SR interferometer
  - 光路の再アラインメント
  - スリット間隔 40 mm → 60 mm

    → ~4 micron vertical beam size
- X-ray SR profile monitor
  - 機械的振動の低減

    → ~4 micron vertical beam size
- Laser Wire
  - Storage mode だけでなく通常の運転（ビーム取り出し）モードでも測定できるように変更
    - ビームタイムを占有することなく測定可能 （測定に要する時間は長い）

今後、レーザーの交換（大出力）の計画あり

- **測定時間の短縮**

K.Kubo

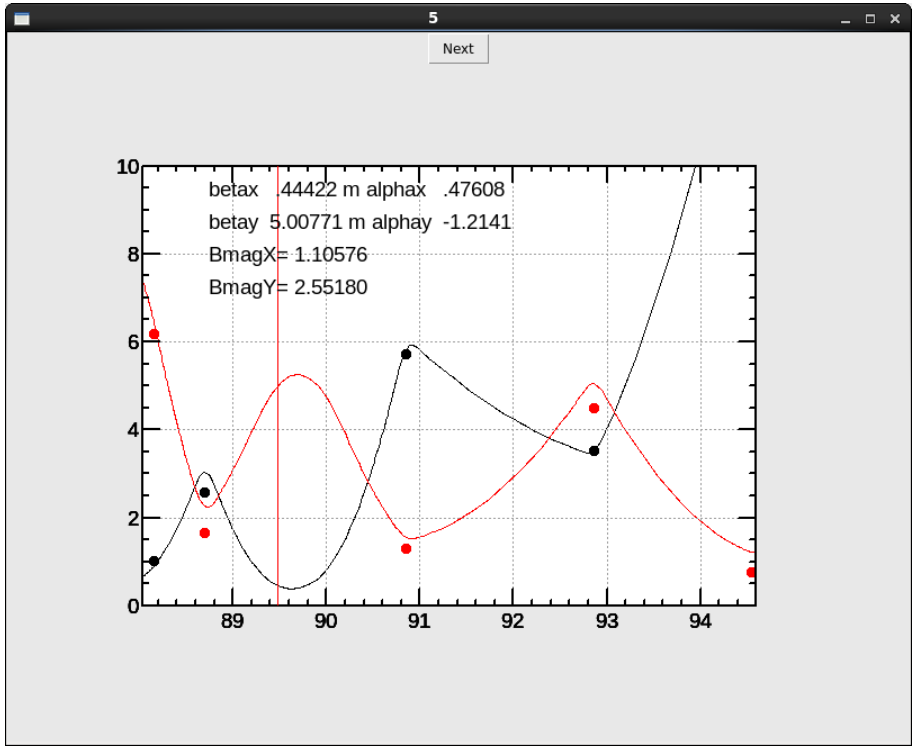
Beta Measurement

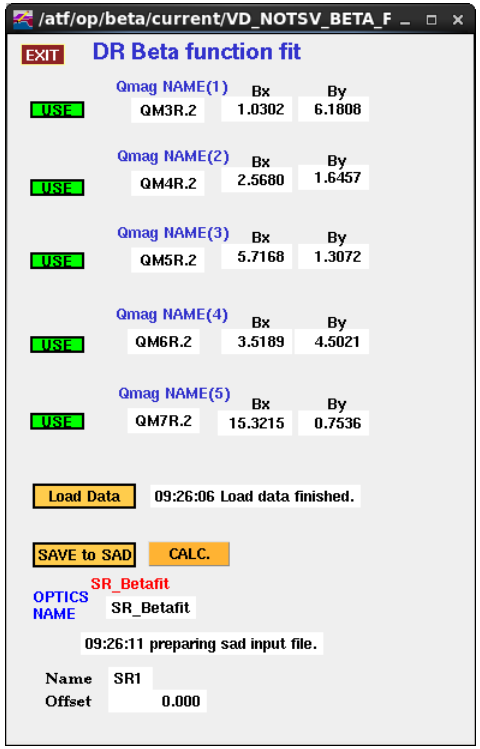
- Emittance is calculated by the formula;

$$\sigma_y^2 = \beta_y \, \varepsilon_y$$

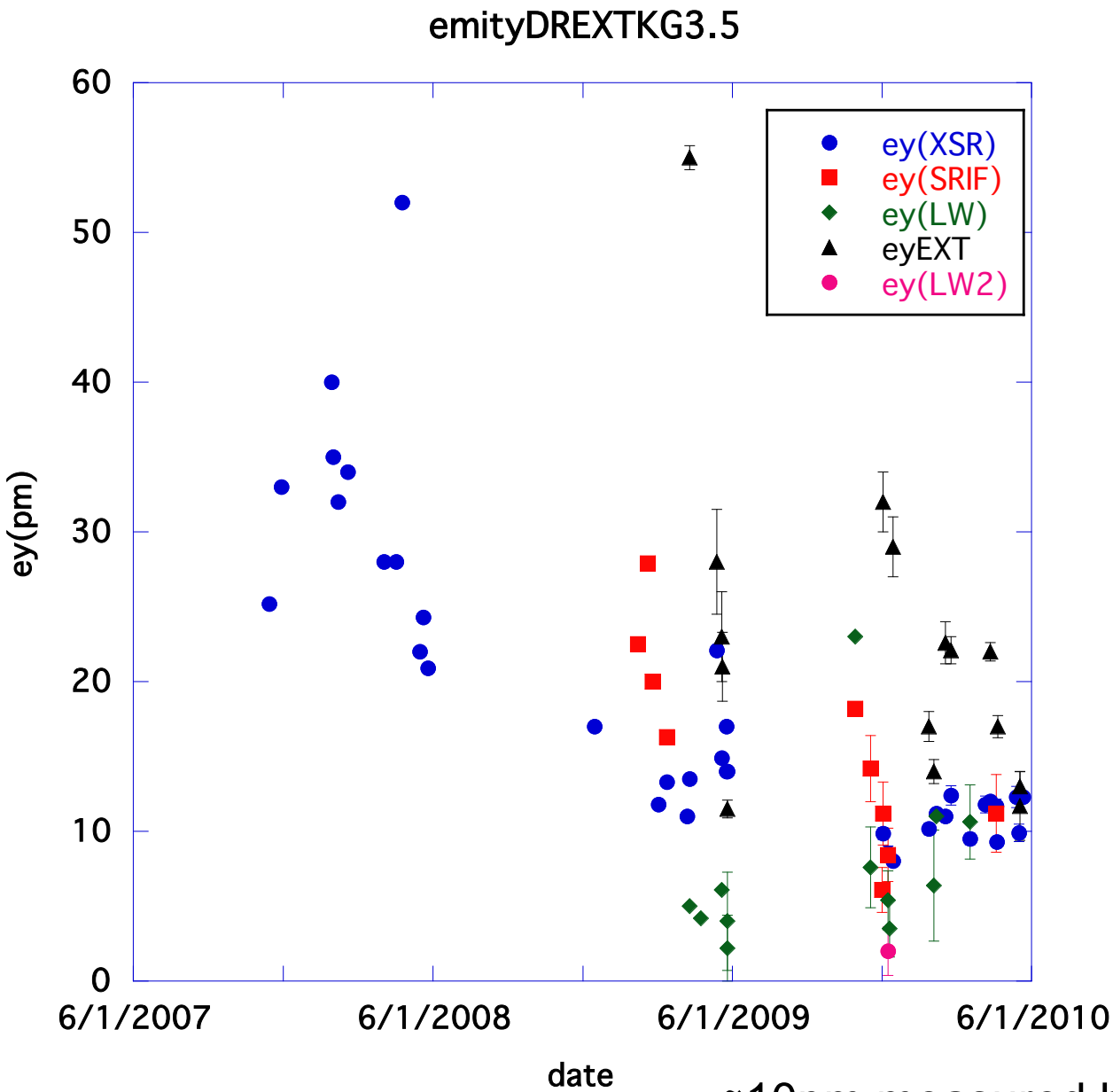
β is calculated by fitting the β s at near Qs, which are measured by tune slope.

ex.)->





DR Emittance Summary

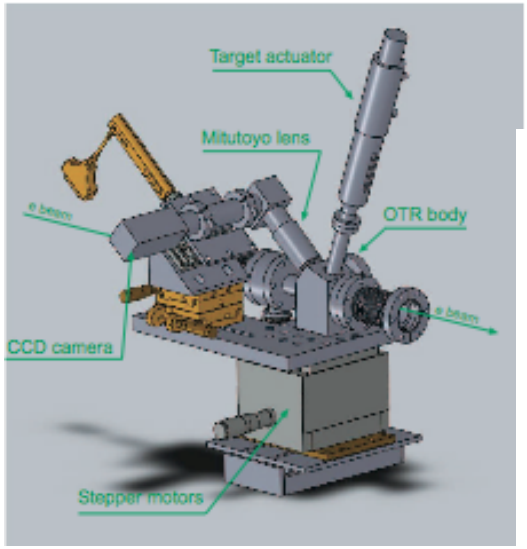


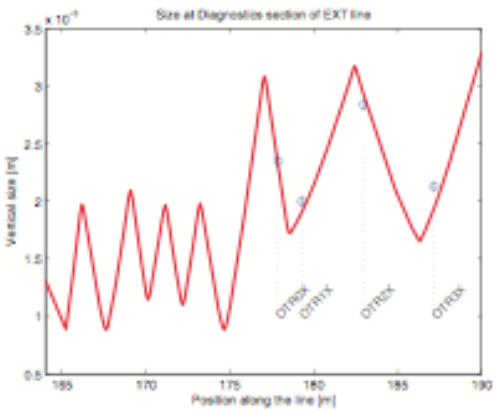
Terunuma, Kuroda

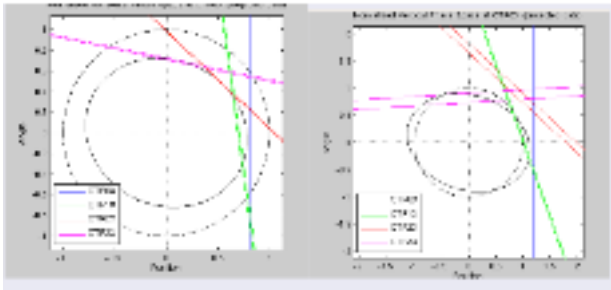
$\varepsilon_y \cong 10$pm measured by XSR/ EXT WS.

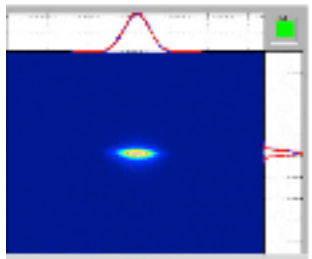
Emittance Tuning in EXT

- Dispersion correction
  - η_x is corrected by QF1X & QF6X
  - η_y is corrected by QS sum knob +orbit bump
- Coupling correction
  - QK and QS dif knob
- Emittance measurement by mOTR

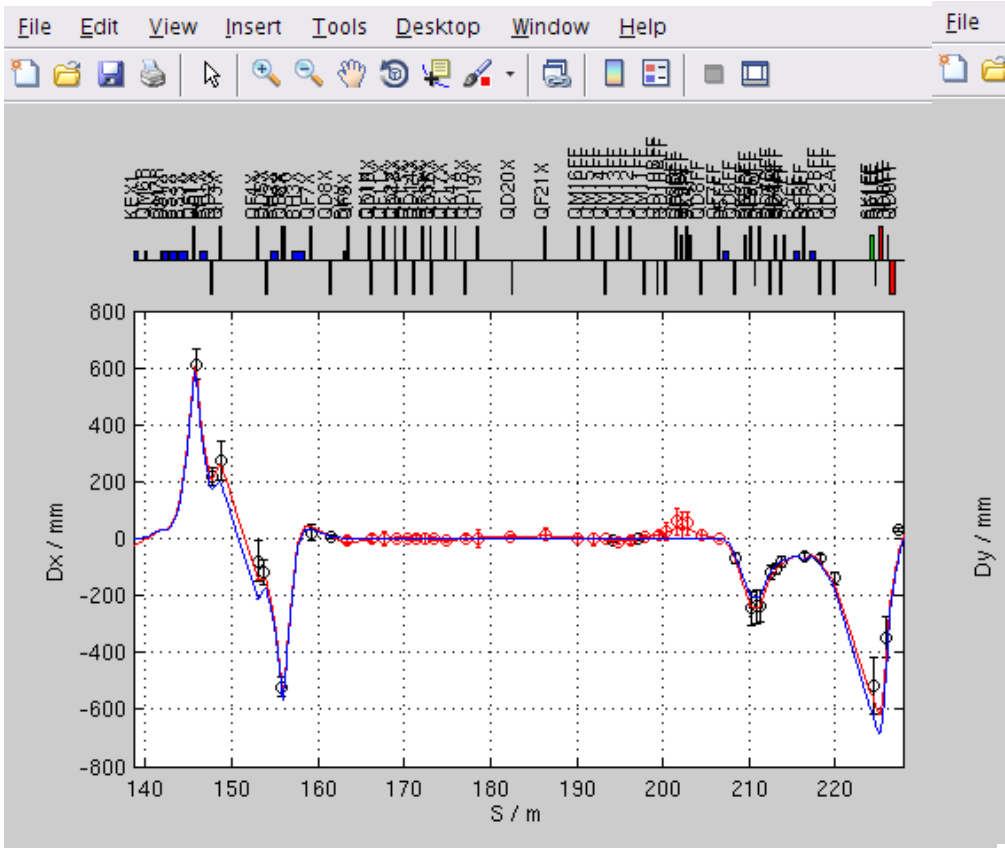


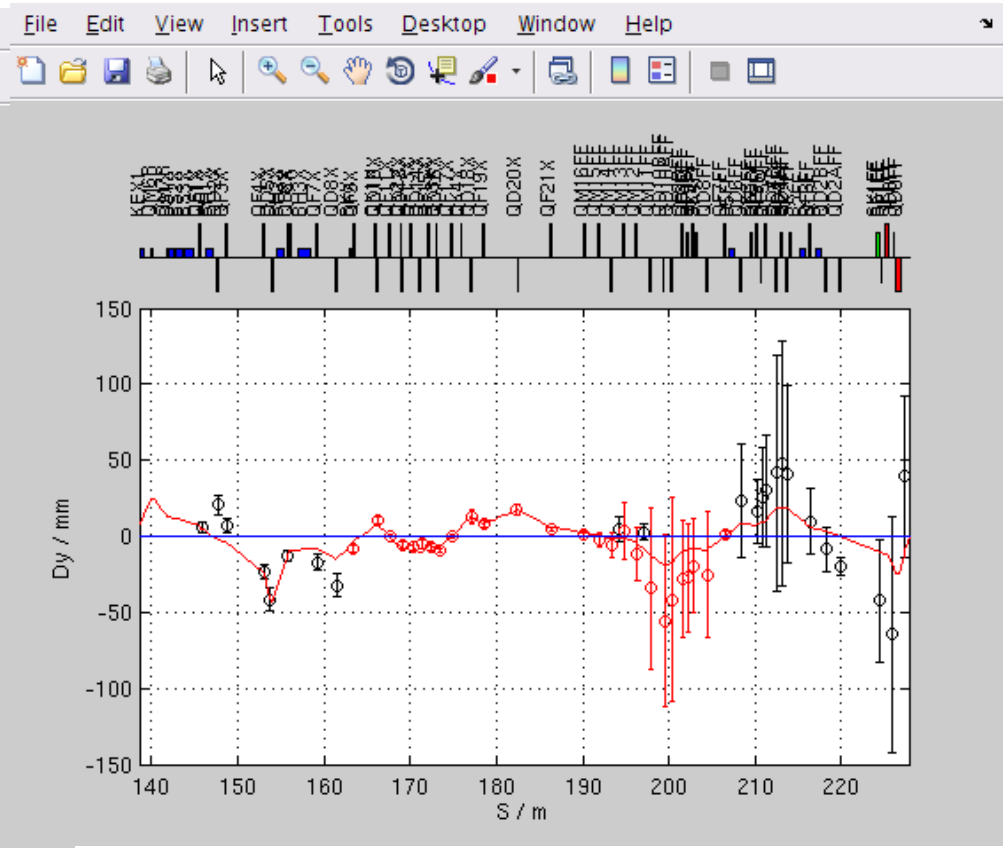






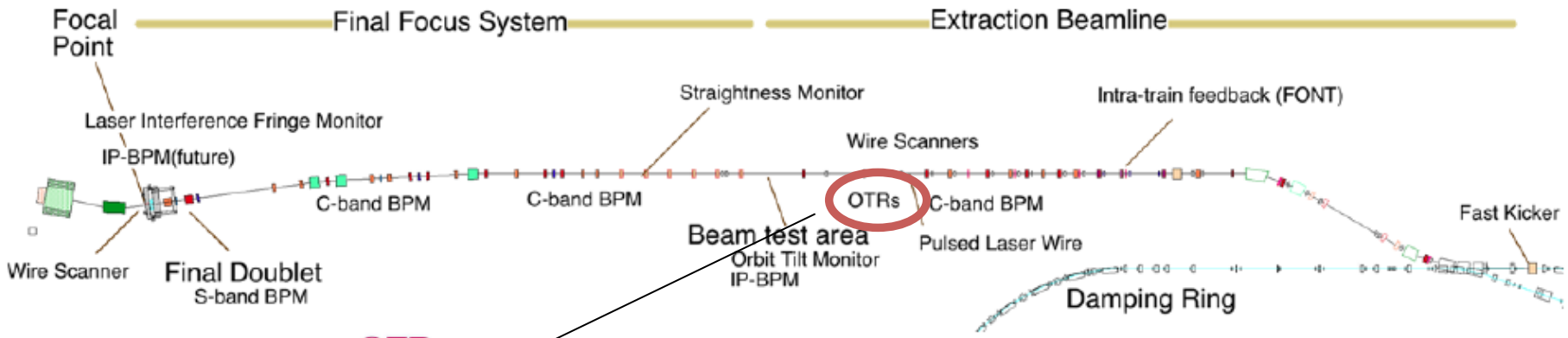
Example:
dispersion correction

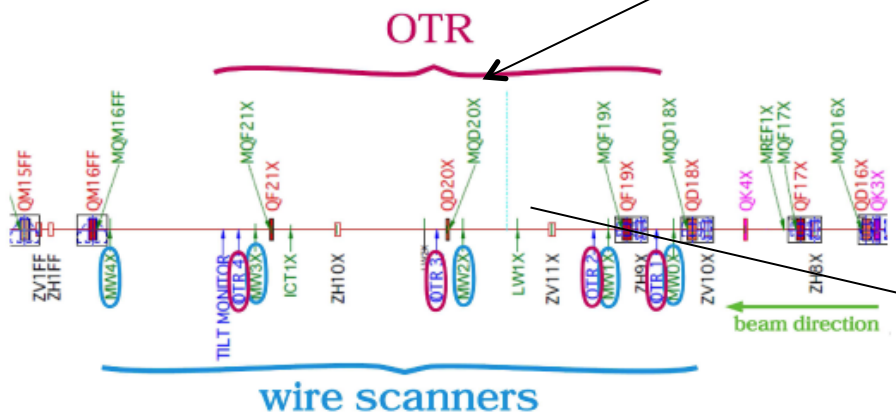


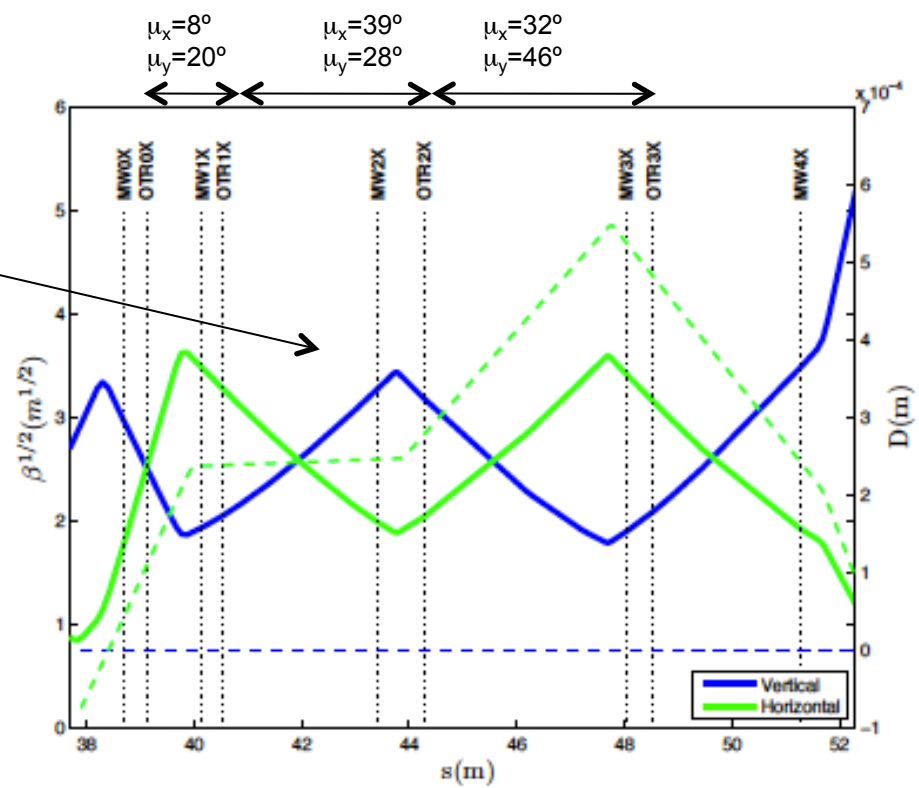


ATF2 Beam Line

Location and Optics



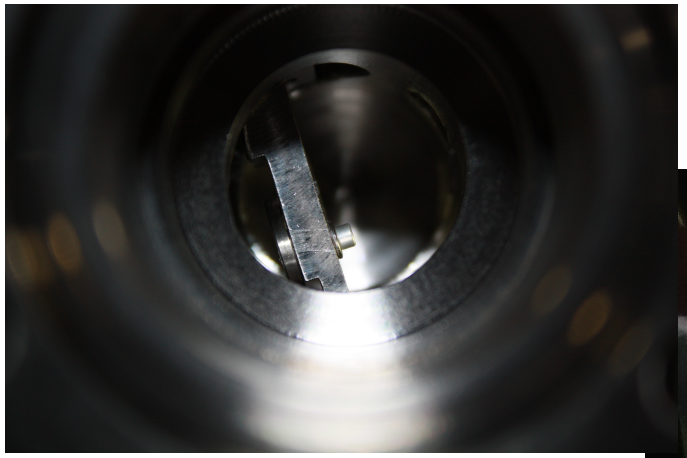




QM6R, which is common for DR and EXT, was replaced with big bore one in order to reduce non-linear field.

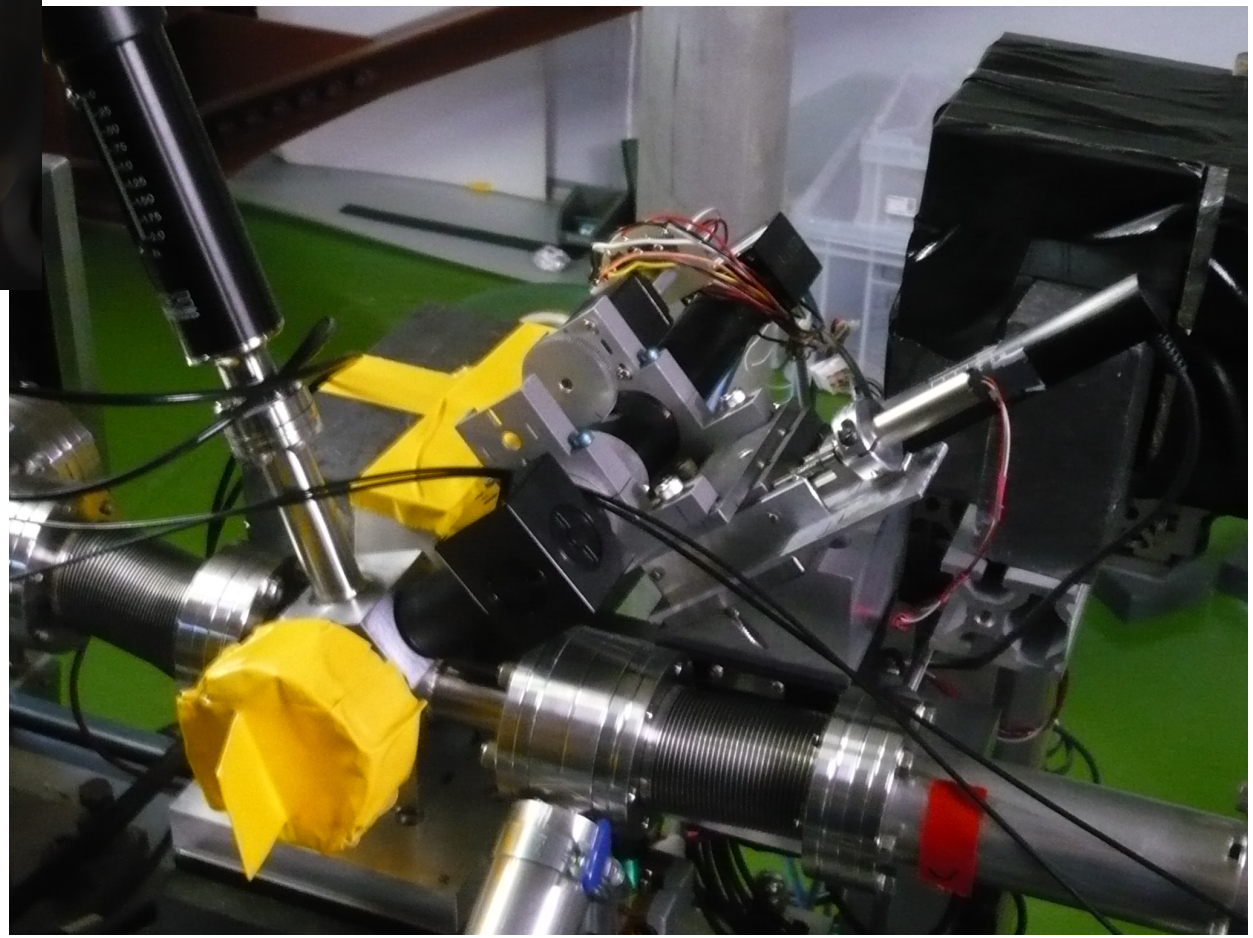
Technical Description HW III

February 2013: Installation of new Target holder and Optical system



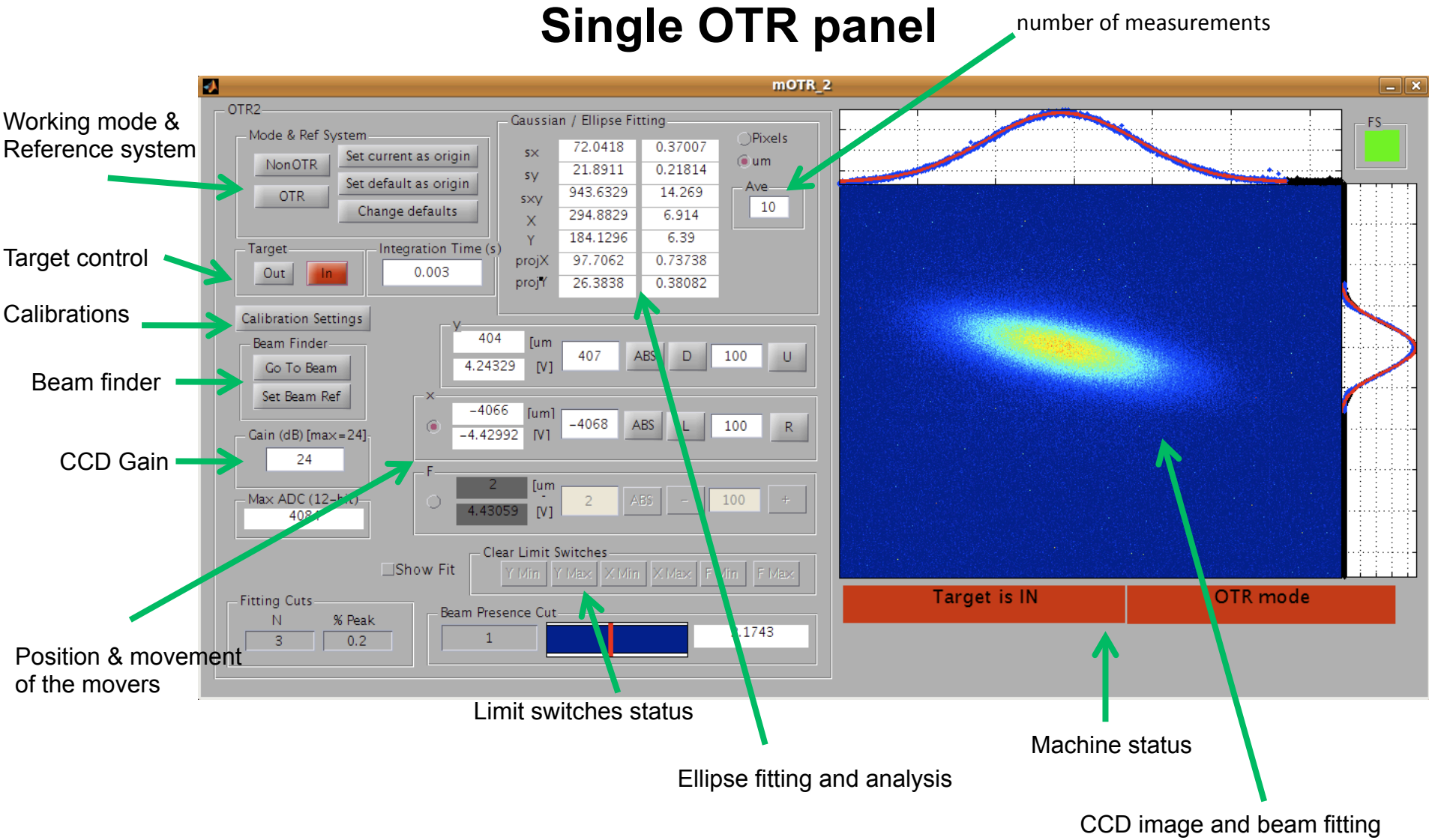
Long working distance target side view

OTR0 long working distance target external view

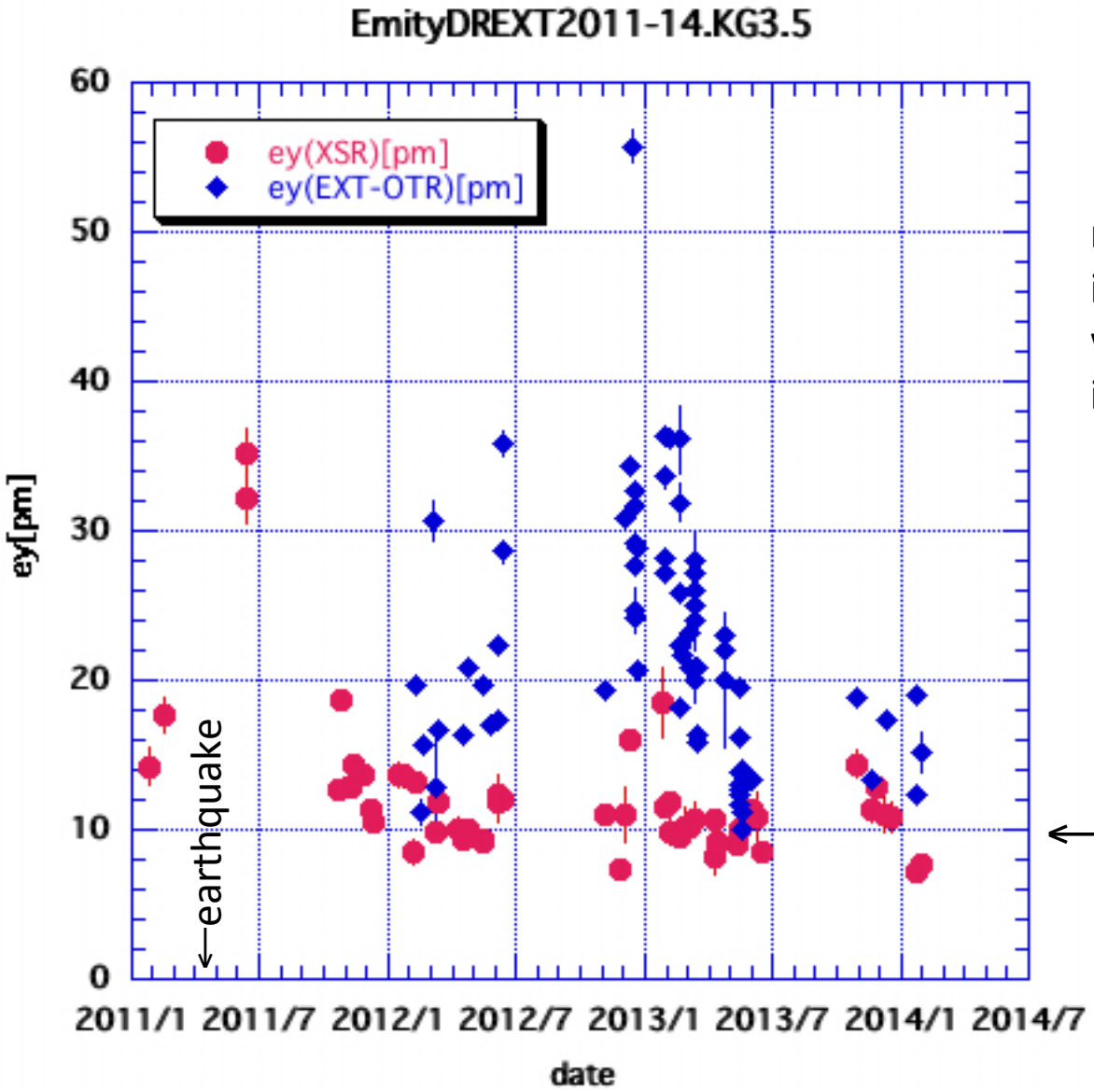


Installation of new target holders and optical system was made in **February 2013.** Some test has been made after the installation and the system is working properly.

Single OTR panel



Summary of ε_y of ATF-DR 2011-2014

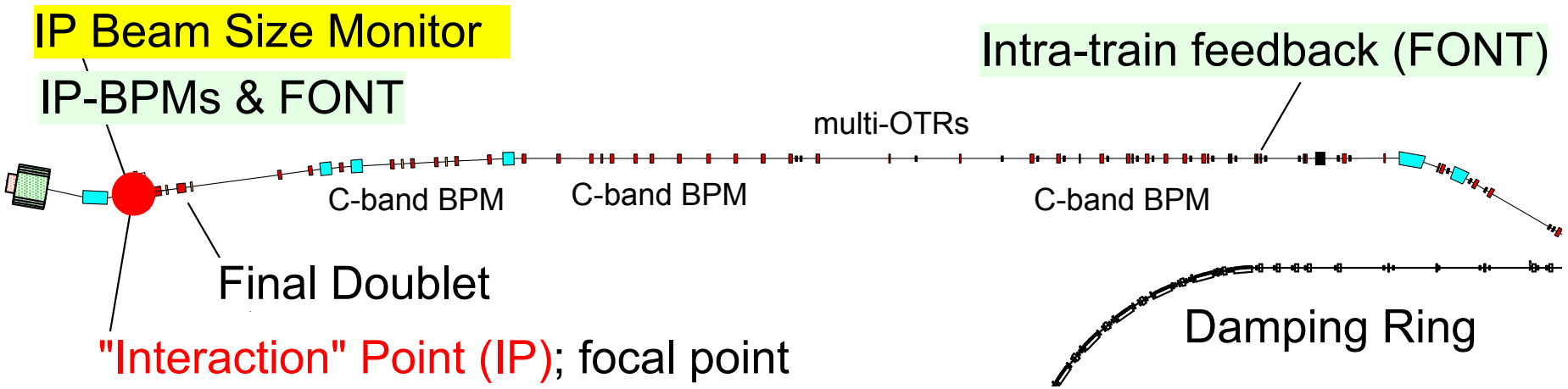


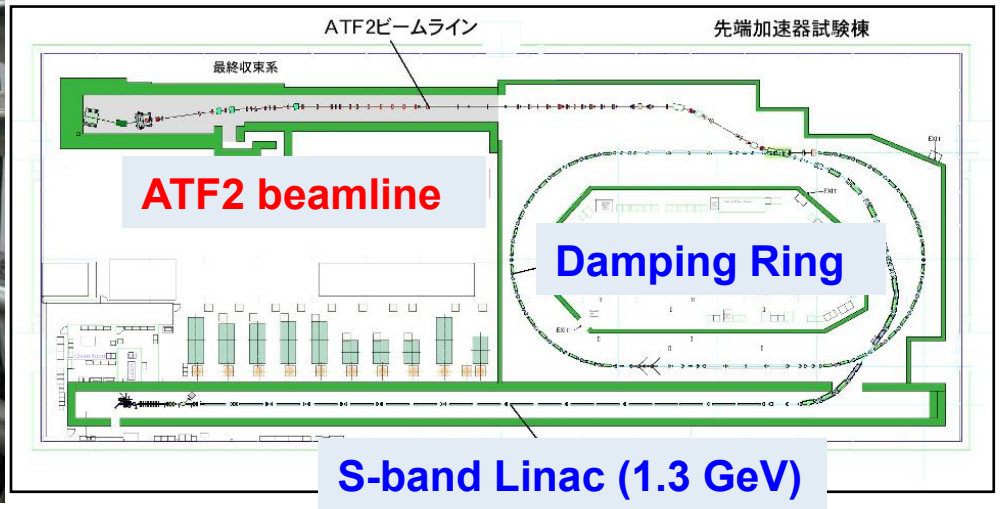
Emittance in the DR was measured with N≈5e9, while in the EXT, measurement was done with various intensity.

←ε_y≈10pm

ATF2

Final Focus Test Beamline (ATF2)





ATF2 International Collaboration
Design, Construction, Operation

ATF Main Institutes

CERN

Germany
- DESY

France
- IN2P3; LAL, LAPP

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.

2+1 Goals of ATF2

- Small beam size (Goal 1)
  - 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
- Small beam size with high intensity(Goal 1')
  - So far small beam size was measured with low intensity only

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
Horizontal beta function at IP (β^*_y) [mm]	11	4
Vertical beta function at IP (β^*_y) [mm]	0.48	0.1
Horizontal emittance ε_x[nm]/$\gamma\varepsilon_x$ [μm]	0.02/10	1.1/2.8
Vertical emittance ε_y[pm]/$\gamma\varepsilon_y$ [nm]	**0.07/35**	**12/31**
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

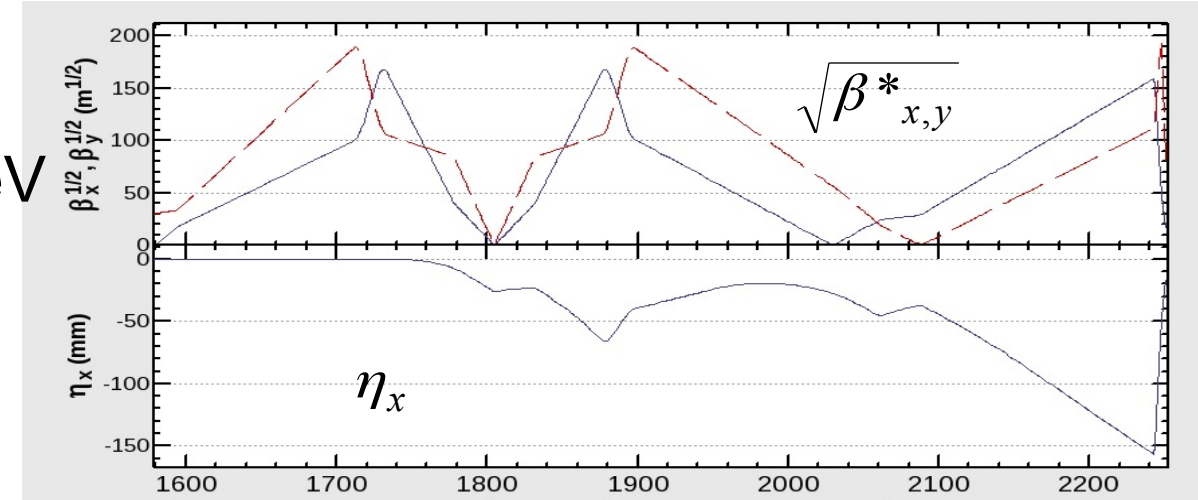
ATF2 Collaboration, "ATF2 Proposal," (2005)

Final Focus Optics, ILC and ATF2

Same magnet configuration, Almost identical optics

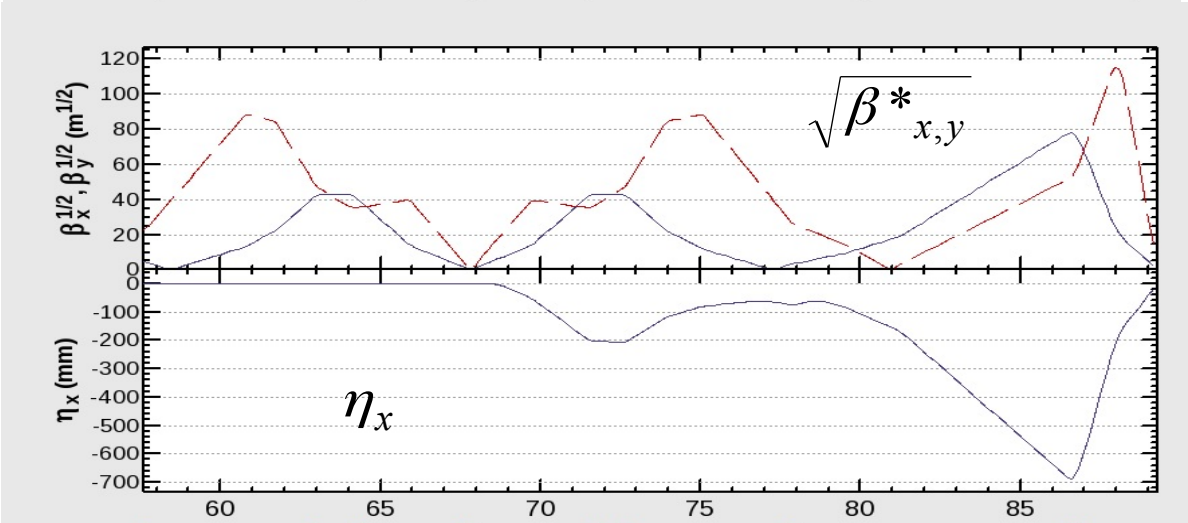
ILC

Up to 500 GeV
~700 m



ATF2

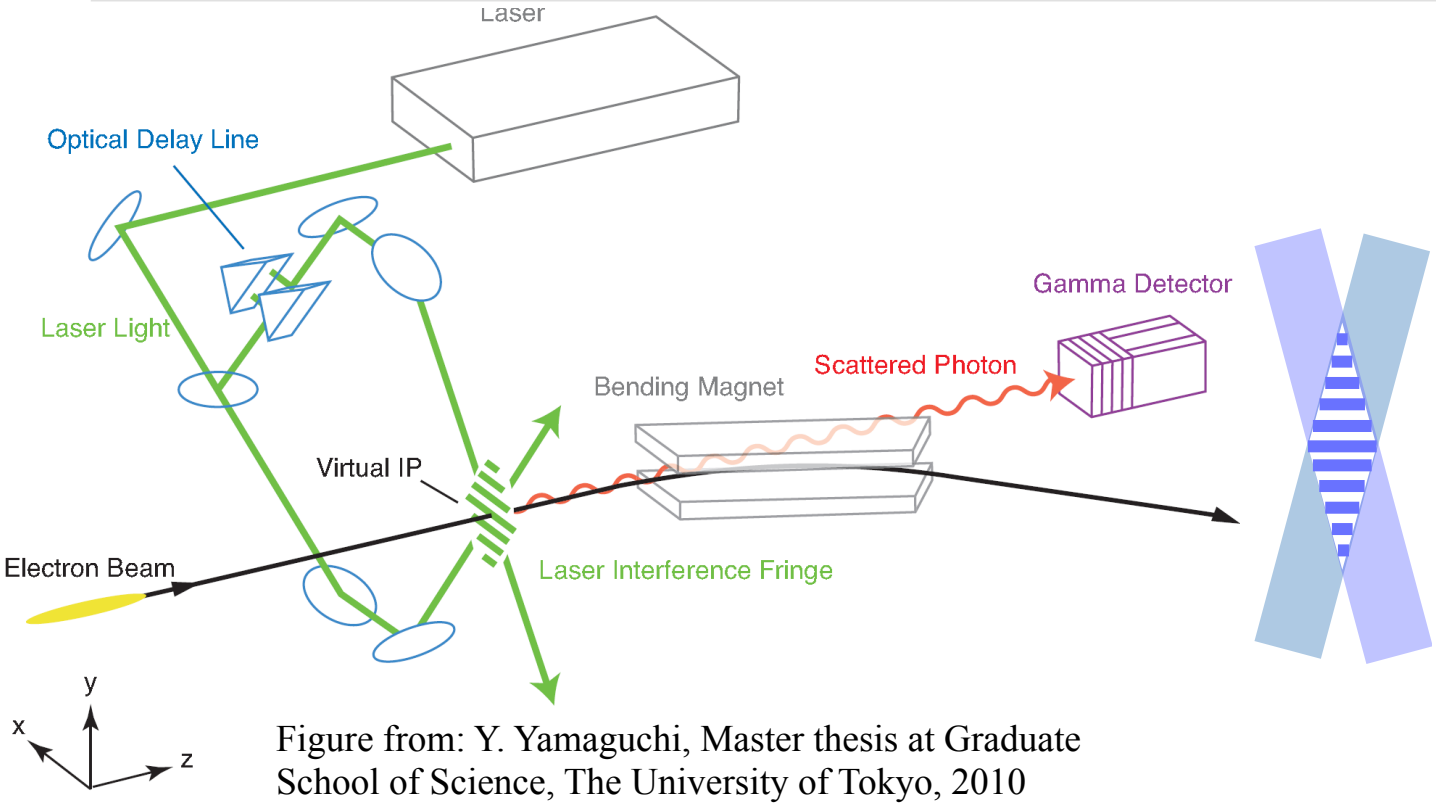
1.3 GeV
~30 m



K.Kubo IPAC14

Measurement of Beam Size at ATF2 Focal Point

Interference of two laser beams; Shintake-monitor



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

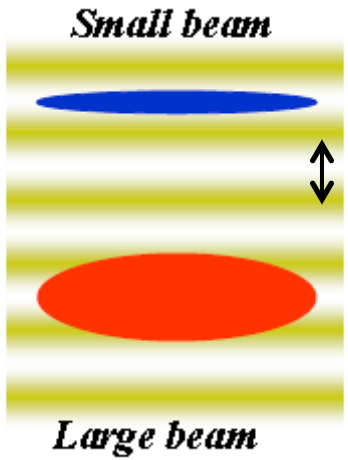
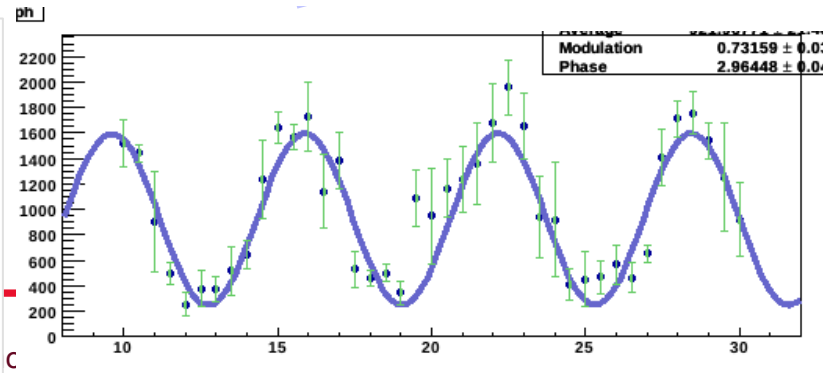


Figure from: Y. Yamaguchi, Master thesis at Graduate School of Science, The University of Tokyo, 2010

$$\text{Modulation} = \frac{\text{peak} - \text{bottom}}{\text{peak} + \text{bottom}}$$

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



Beam size measurement

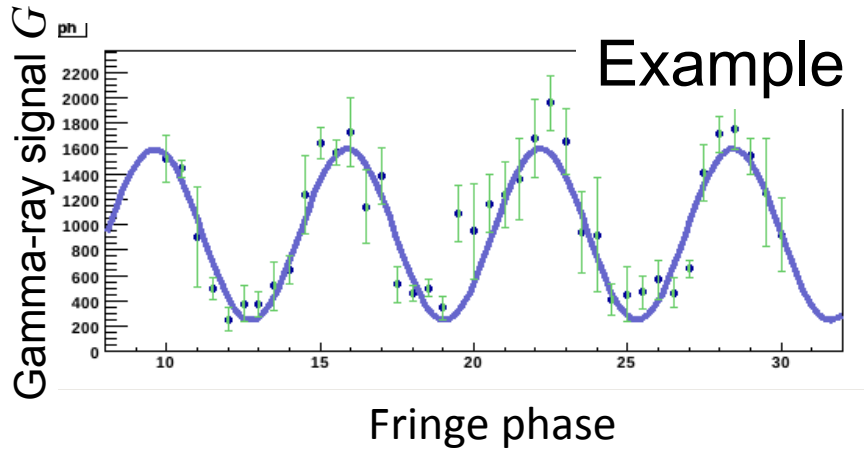
Pitch of interference fringe: $h = \dfrac{\lambda}{2\sin(\theta/2)}$

Contrast of interference fringe: $|\cos\theta|$

Scan interference fringe phase.
Fit modulation M:

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

M is proportional to amplitude of Fourier component of beam profile at $2\pi/h$



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.

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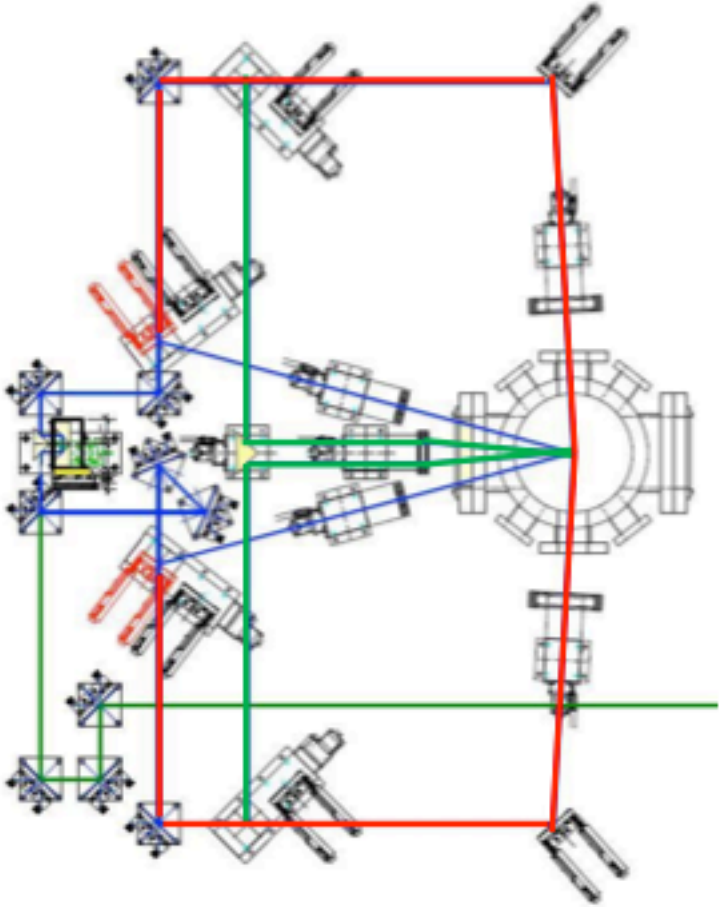
IP-BSM for ATF2



Laser wave length was changed.

FFTB ; Nd:YAG fundamental mode (1064nm)

ATF2 ; Nd:YAG harmonic doubler (532nm)

Add the collision mode

FFTB	**ATF2**
174deg mode	174deg mode
30 deg mode	30 deg mode
	2-8deg mode

T.Okugi

Measureable Beam Size Range of IPBSM

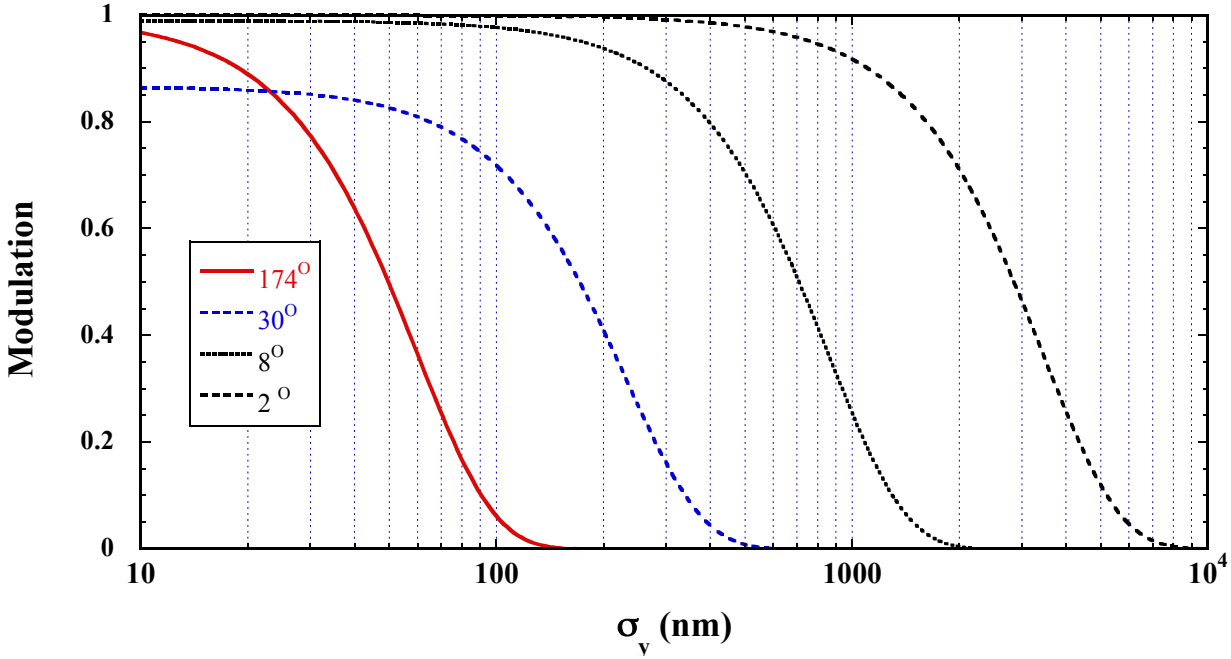
Sensitive beam size range depends on crossing angle (θ) of two laser beams.

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

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



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Beam Size Tuning

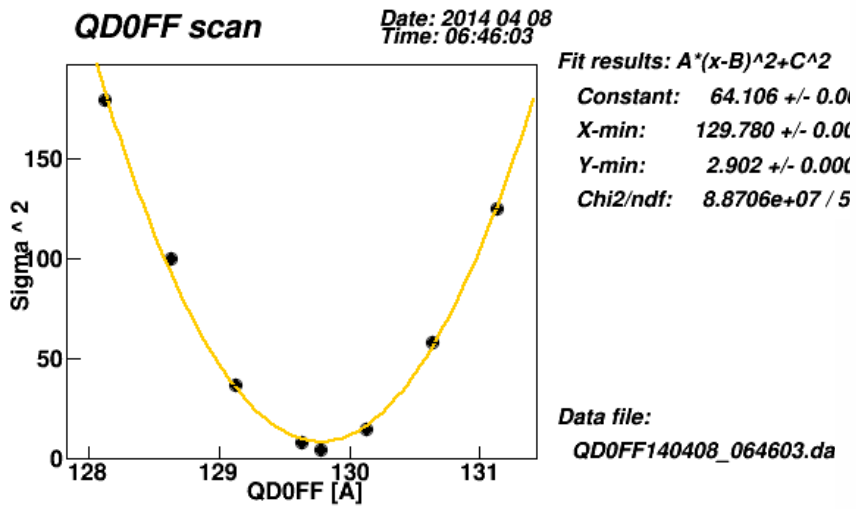
Orbit tuning

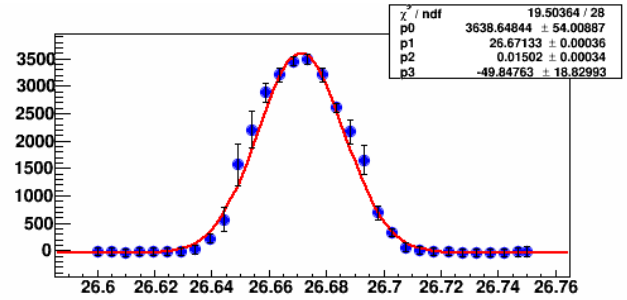
Dispersion correction (EXT)

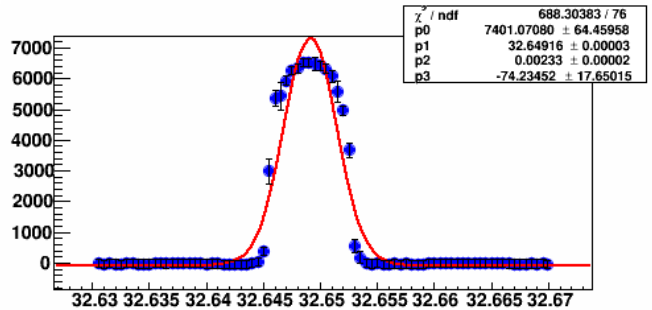
Coupling correction (EXT)

OTR measurement -> matching

IP beam size tuning by Carbon WS







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 (2nd order optics adjustment)	6-poles strength	$x'yy'$
		$yy'E$ (chromaticity)
	Skew 6-poles strength	xxy
		xyE
		yEE (2nd order dispersion)
		$yy'y'$

Each knob changes one coupling term.

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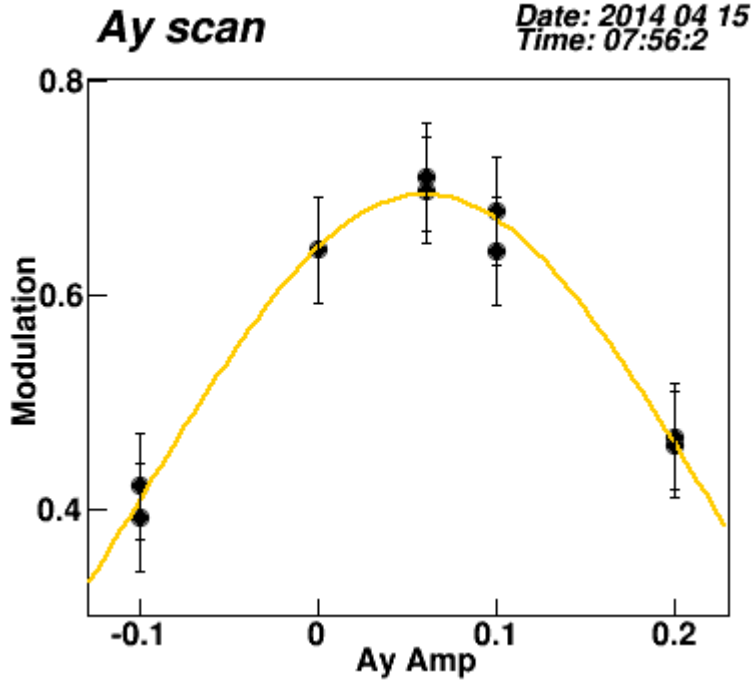
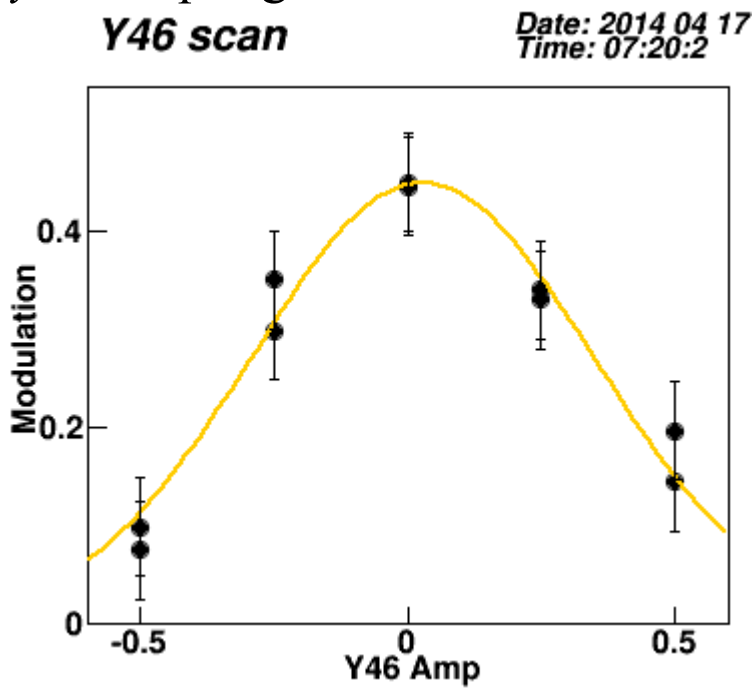
Examples of Tuning knob Scans

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.

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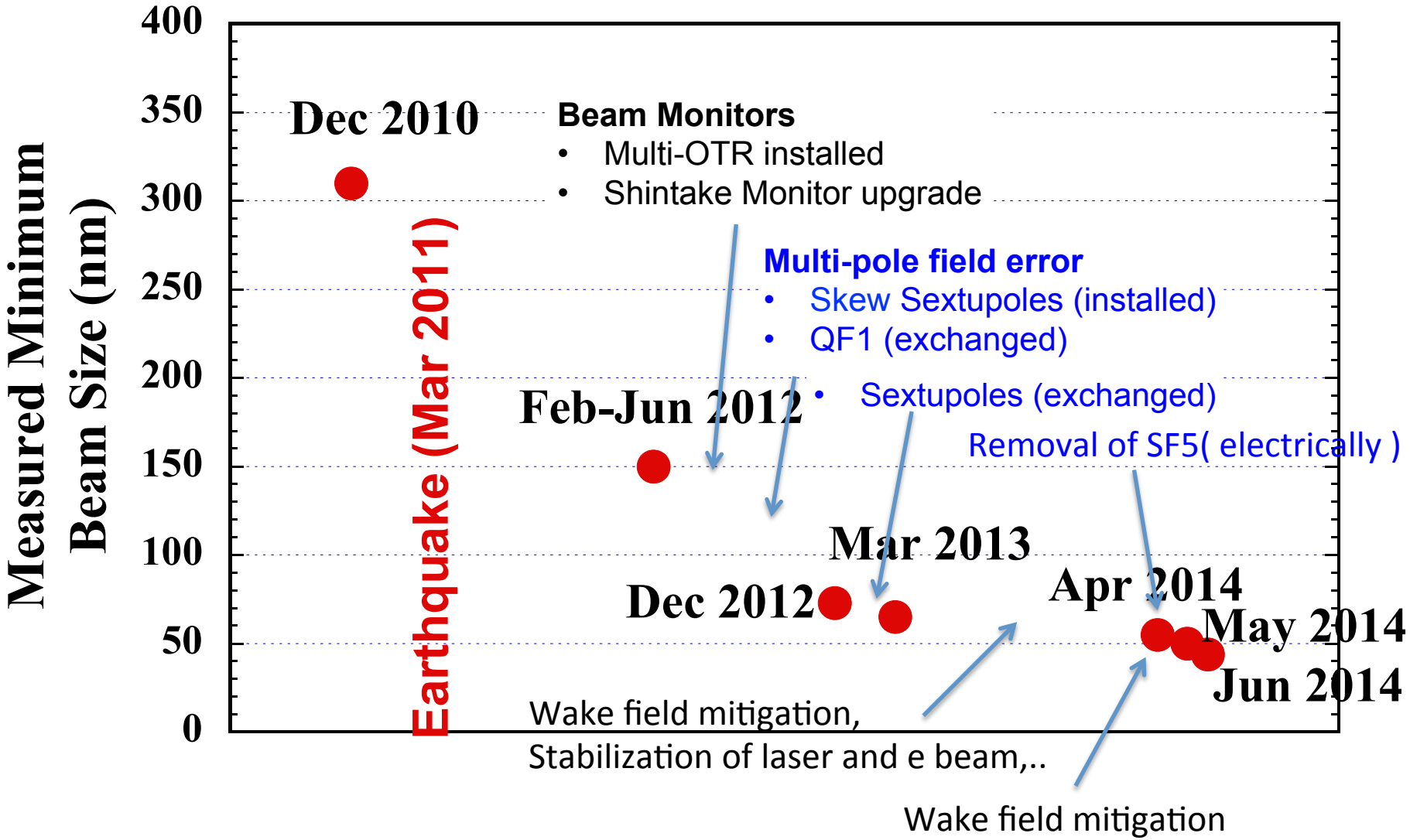
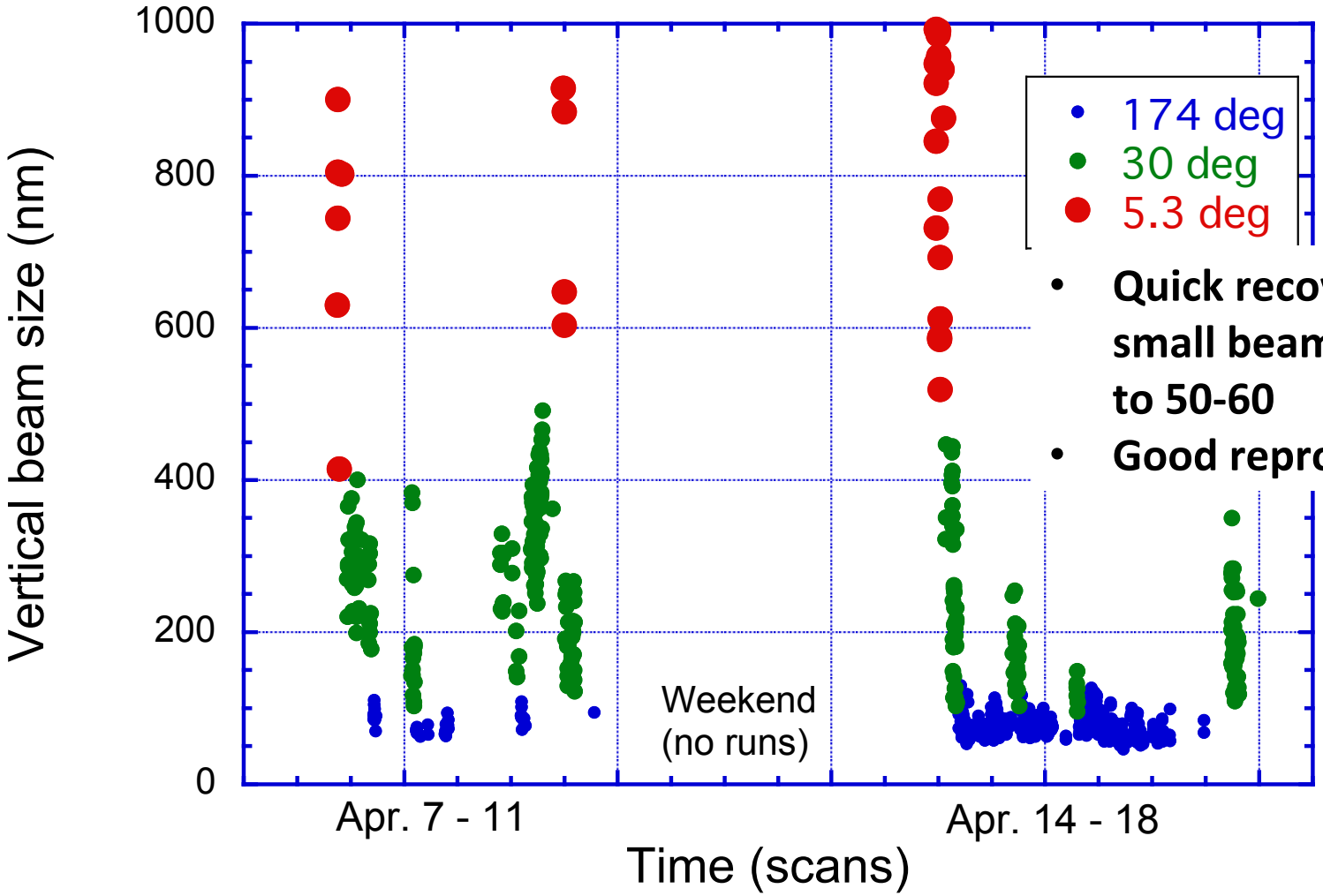
History of measured minimum beam size

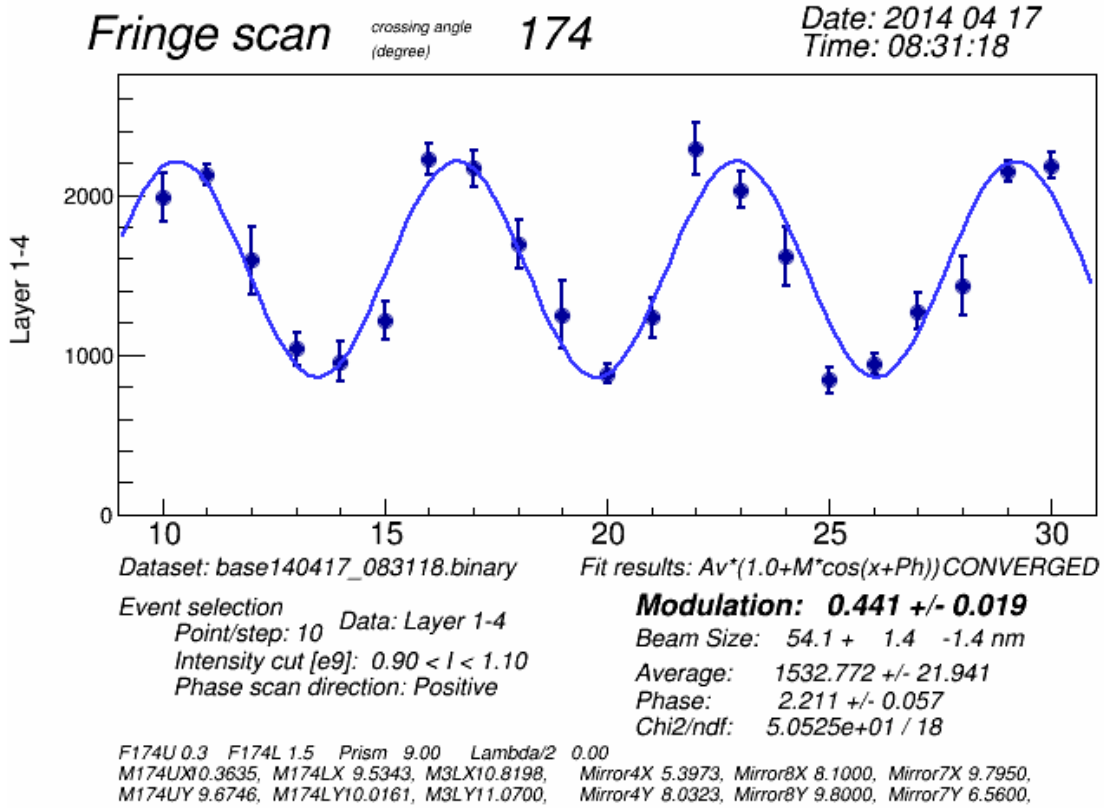


History of beam size tuning, April 2014 runs



- **Quick recovery of the small beam size, down to 50-60**
- **Good reproducibility**

Example of vertical beam size measurement (On-Line Fringe Phase Scan)



Data on April 17, 2014.
IPBSM with a crossing angle of 174 degrees. Bunch charge ~0.16 nC.
Fitted modulation is 0.44, evaluated beam size 54 nm

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

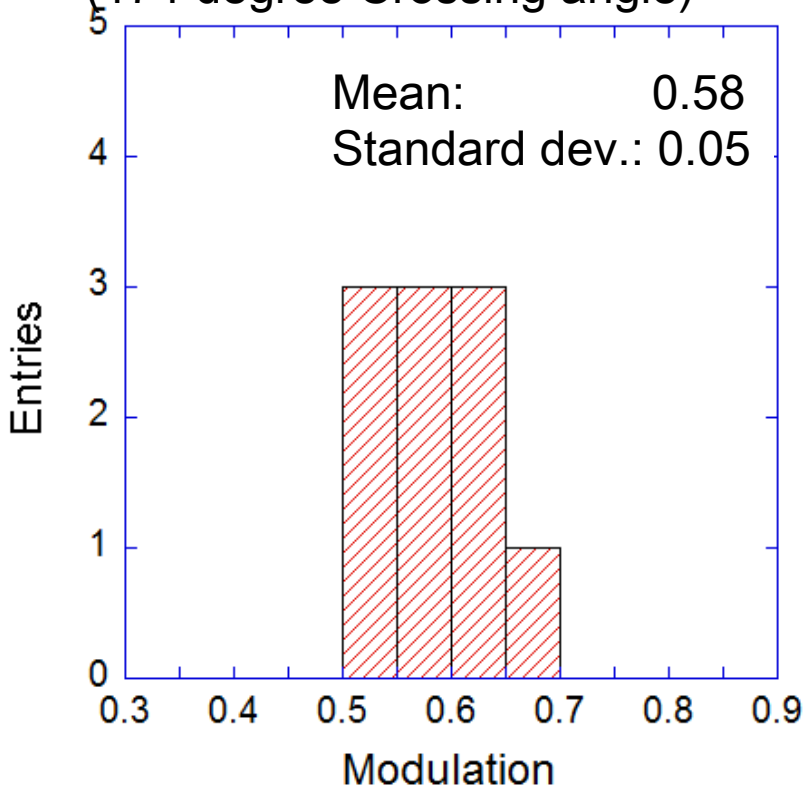
Off-line analysis is on-going about monitor systematics and errors.

Study for fast electron beam orbit FB is also on-going(goal 2).

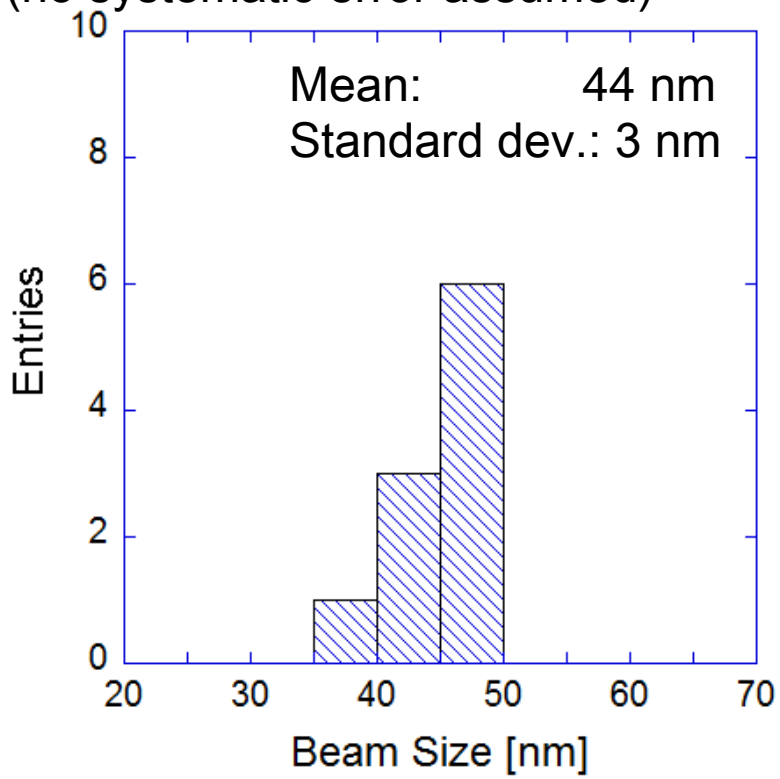
Study for magnets vibration is planned.

Beam is stable for 30 – 60 min. without tuning.
Examples of consecutive beam size measurements
(Data of 12th June 2014)

IPBSM Modulation
(174 degree Crossing angle)

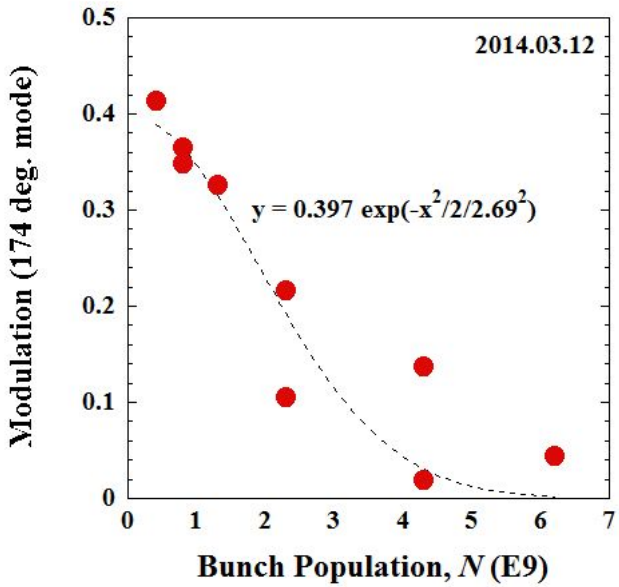


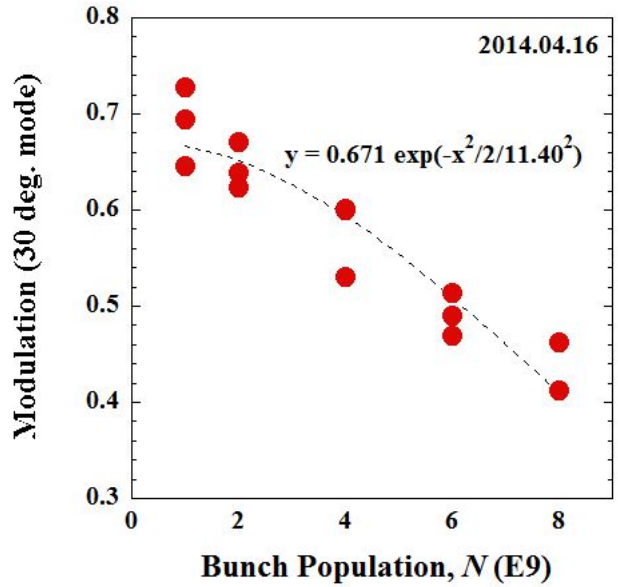
Beam Size Evaluated from Modulation
(no systematic error assumed)



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.

The effect is bigger than wake field calculation of Cav.BPM, bellows,…

➔ Need to find out sources

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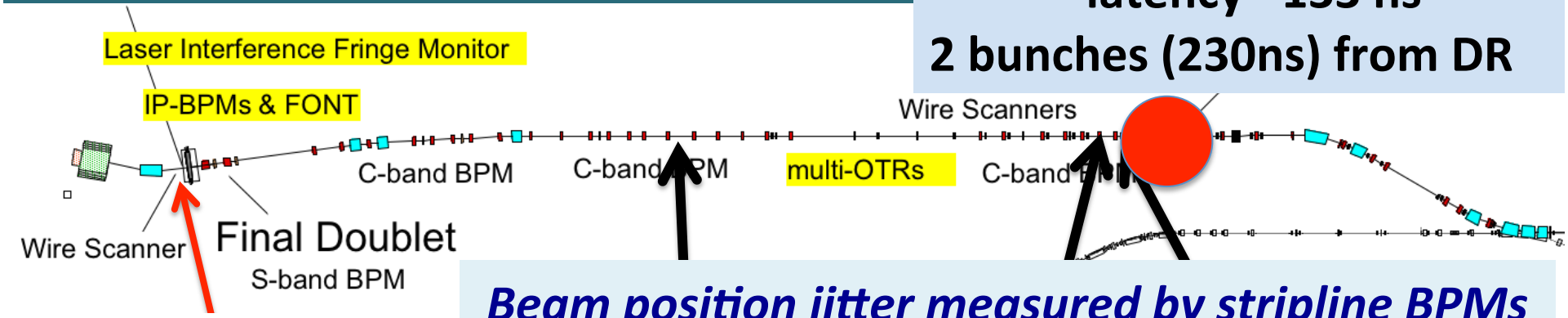
Beam Stabilization at ATF-EXT
— Intra-train Fast Feedback—

FONT feedback loop
latency ~133 ns
2 bunches (230ns) from DR

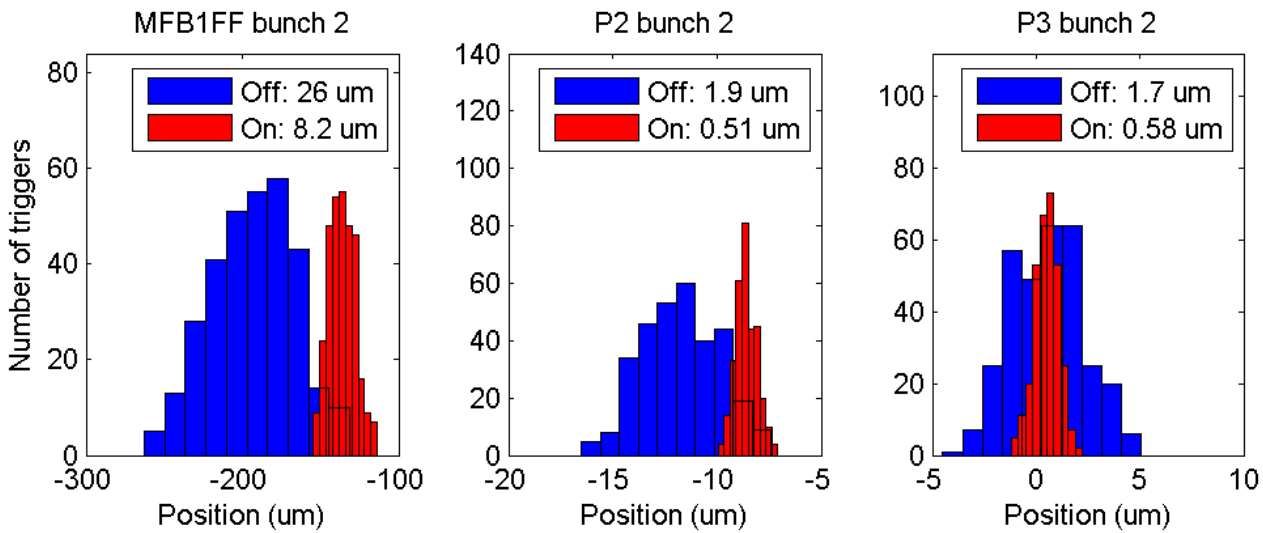


Beam position jitter measured by stripline BPMs 2014/Jan

IP-FONT
by IP Cavity BPM

(1) jitter meas. i.e., witness of the upstream feedback

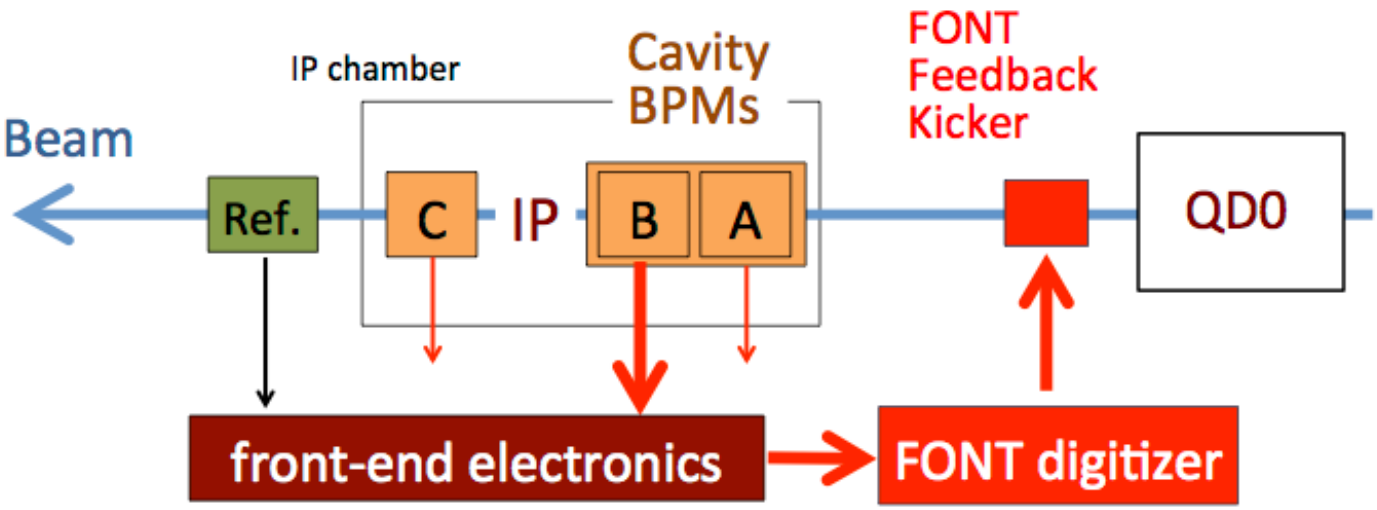
(2) Intra-train feedback at IP; nanometer level stabilization



Nanometer level beam position stabilization

IP-FONT(Intra-train feedback loop "at ATF2-IP")

- **Cavity BPMs optimized for ATF2-IP (2 nm Resolution) on the piezo movers**
- Stripline kicker for the second bunch correction



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.

SUMMARY

ATF/ATF2 is in successful operation.

ATF/ATF2 gives good opportunity for young physicists to handle real beam closely.

Back-up

加速器内でのビーム

加速器の中ではビームはかたまり(bunch)をつくる。
Bunchの記述→分布→2次のモーメント(<xx>, <xp> 等)

1次のモーメント、<x>等は0になるようにデザイン軌道をとっておく。

簡単のため、1方向のみを考える。

$$R = \left\langle \begin{pmatrix} x \\ p \end{pmatrix} \begin{pmatrix} x & p \end{pmatrix} \right\rangle = \begin{pmatrix} \langle x^2 \rangle & \langle x\ p \rangle \\ \langle x\ p \rangle & \langle p^2 \rangle \end{pmatrix}$$ がわかればよい。

$R_2 = MR_1M^T$

M:Transfer Matrix これはHamiltonianより
導かれたものなのでsymplectic。$M^TSM=S$
2x2 symplectic ↔ detM=1

ここで $S = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

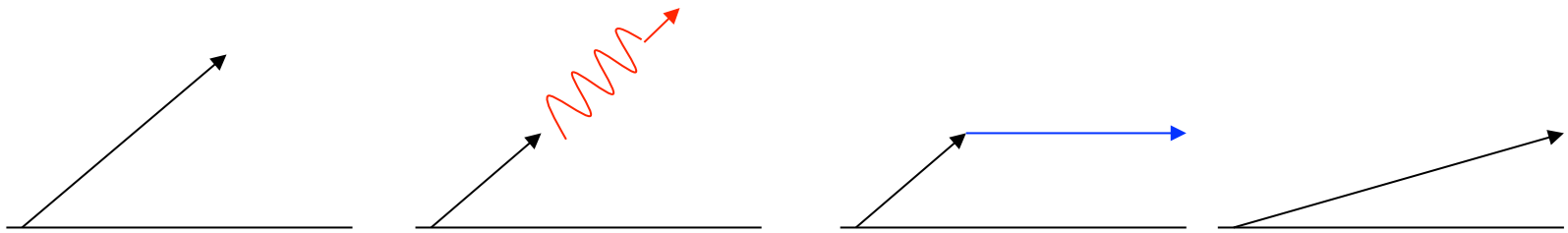
detRはビームライン上で不変:$\det R = \varepsilon^2$

ε:エミッタンス $\varepsilon^2 = \langle x^2 \rangle \langle p^2 \rangle - \langle xp \rangle^2$

平衡エミッタンス

リング加速器では、横方向の運動も同様にdampingとexcitationがある。

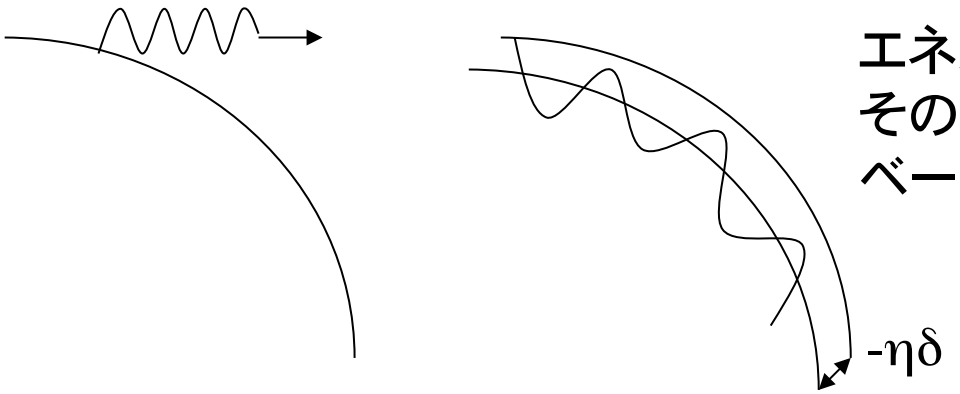
放射減衰



放射による
エネルギー損失

RF Cavityで
エネルギー補充

量子励起



エネルギーを失った粒子は
その平衡軌道-ηδのまわりで
ベータトロン振動を始める。

平衡エミッタンス（続き）

$$\tau_u \approx \frac{2T\,E_0}{U} \qquad \varepsilon_u \approx 2\left\langle \frac{1+\alpha_u{}^2}{\beta_u}\eta_x{}^2 + 2\alpha_u\eta_x\eta_x' + \beta_u\eta_x'^2 \right\rangle \langle \delta^2 \rangle$$

ただし、分散関数を含む平均はベンドのなかでのみ行う。

横方向は縦方向にくらべて約2倍はやく減衰する。

分散関数が0であるy方向の平衡エミッタンスは0?
理論的にはシンクロトロン放射が、1/γのひろがりをもつことにより、
制限される。ただし、これによるエミッタンスは非常に小さい。
現実的には、垂直方向の平衡エミッタンスは、種々の誤差により
決まってしまう。

磁石の設置誤差や強さの誤差→垂直方向の分散関数、x-yカップリング

小さな垂直エミッタンスを得るためには良い磁石を作り、精度良く
設置することが必要。

Twiss Parameterの測定(Ring)

$$M_{1turn} = U^{-1}\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} U = \begin{pmatrix} \cos\theta + \alpha\sin\theta & \beta\sin\theta \\ -\frac{1+\alpha^2}{\beta}\sin\theta & \cos\theta - \alpha\sin\theta \end{pmatrix}$$

θ: tune

measured by FFT of TBT beam position data

Perturbation by quad strength

$$\begin{pmatrix} \cos\theta + \alpha\sin\theta & \beta\sin\theta \\ -\frac{1+\alpha^2}{\beta}\sin\theta & \cos\theta - \alpha\sin\theta \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -dk & 1 \end{pmatrix} = \begin{pmatrix} \cos\theta' + \alpha\sin\theta' & \beta'\sin\theta' \\ -\frac{1+\alpha'^2}{\beta'}\sin\theta' & \cos\theta' - \alpha\sin\theta' \end{pmatrix}$$

Taking trace

$$d\theta = \beta\, dk / 2$$

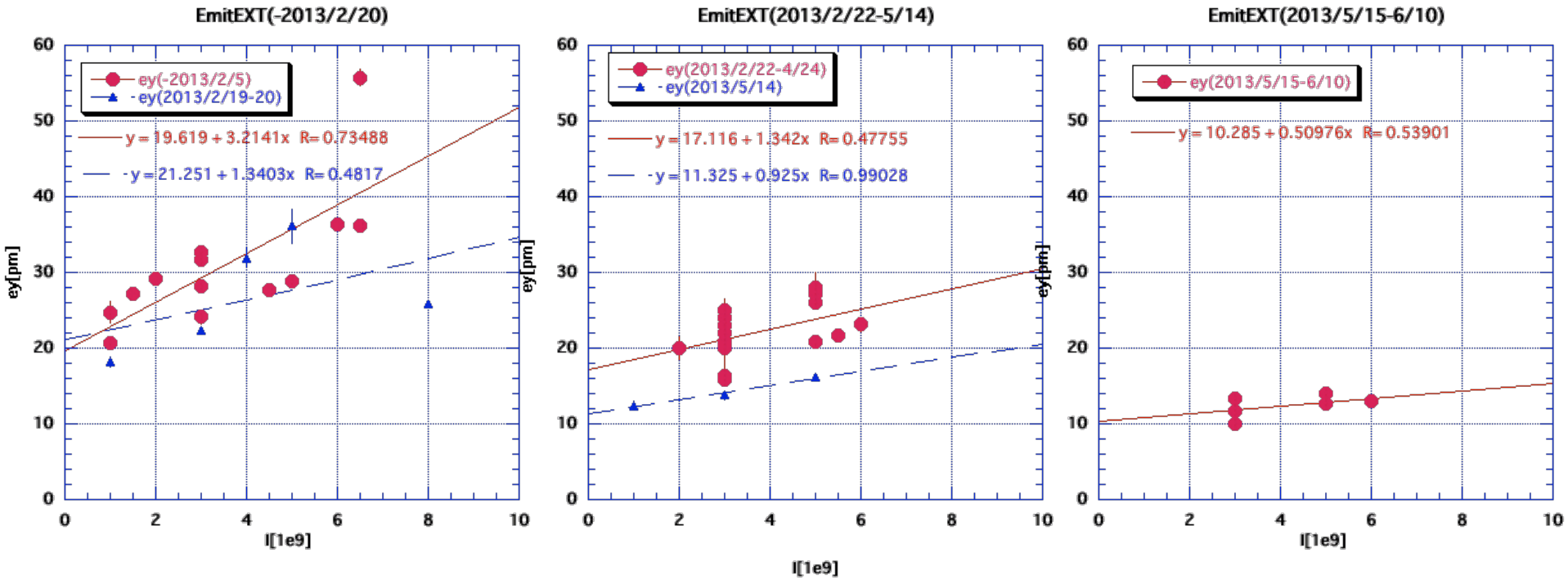
Measurement of beam size σ, β → emittance=σ^2/β

Works in ATF-EXT 2012-2013

Date	mOTR Monitor	Coupling Correction	General
		QK	
2012/Dec.			1.Remove possible wake sources[1)] 2.Ref.cav on mover for wake effect correction
-2013/Jan.	OTR3 not well-tuned		
2013/2/18		QS[2)]	
2013/2/20	New target system		
2013/5/9			Almost all bellows with shield
2013/5/15	OTR tuned[3)]	QS+QK	

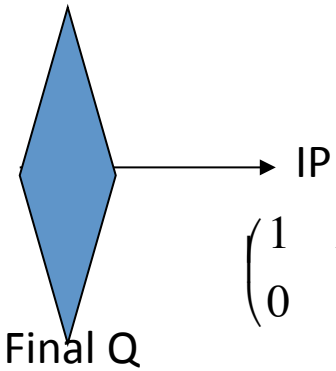
1) http://atf.kek.jp/twiki/bin/view/ATFlogbook/Log20121212m
2) QS magnets are used independently, and QKs are set to 0.
3) Report by G.White in ATF operation meeting 2013/5/17

Summary of ε_y of ATF-EXT 2012-2013



- -2012/2/20 large ε_y and strong I dep.
- Monitor tuning and coupling correction made ε_y closer to DR one.

Chromaticity Correction



$$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -k & 1 \end{pmatrix} = \left(\begin{pmatrix} 1 & 0 \\ \alpha * & 1 \end{pmatrix}\begin{pmatrix} \frac{1}{\sqrt{\beta *}} & 0 \\ 0 & \sqrt{\beta *} \end{pmatrix}\right)^{-1} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} 1 & 0 \\ \alpha_{in} & 1 \end{pmatrix}\begin{pmatrix} \frac{1}{\sqrt{\beta_{in}}} & 0 \\ 0 & \sqrt{\beta_{in}} \end{pmatrix}$$

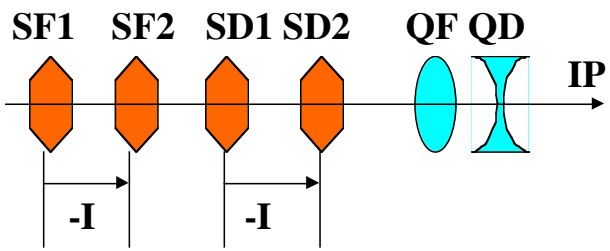
Momentum dependence of Q strength k→k/(1+δ)
Assuming a*=0 and b* is very small,

$$\beta *(\delta) = \beta * + 2kL\beta *\delta + \frac{k^2 L^4}{\beta *}\delta^2 + \ldots$$

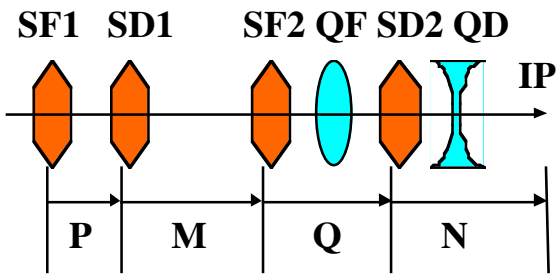
k L~O(1), the term of δ is negligible if δ~O(1e-3), but not term of δ^2.
$k^2L^4/\beta^* = \beta^*(k\,\beta_Q)^2$, $k\,\beta_Q$:chromaticity
Chromaticity can be corrected by SX magnets in dispersion region.

Correction of Geometric Aberration

Introduction of SX→nonlinear field
Cancellation/correction needed



FFTB



Local chromaticity correction
ILC→tested at ATF2

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 β_x 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 (?)

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)

Goal 3 : 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