KEKB Crab Cavity Commissioning

Rama Calaga

BNL/LARP, March 15, 2007

Outline

- Crab Cavity Design, RF Controls & Conditioning

- Beam Commissioning

- Optics & Collision tuning

日本語 → Translation → ME → Interpretation → YOU
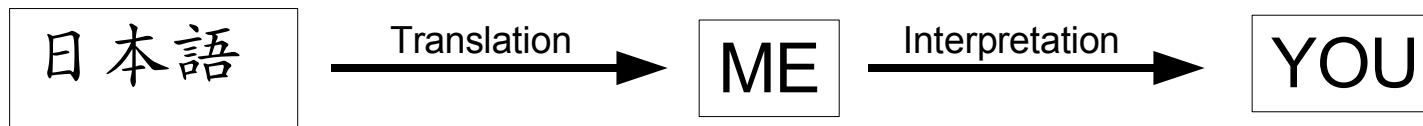
Picture is worth a thousand words...

Getting There

Entrance

Dorm 2

KEKB Control Room

On my way

No parking problem

Better buy slip-on

KEKB Control Room

Design Luminosity ~ 10^{34}
circa 1994

$\mathcal{L} = 1.7 \times 10^{34}$ cm^{-2}

祝 世界記録更新

Solenoid Winding Samples
for e-Cloud

Lots of Luminosity

Main Monitors

祝 $\int \mathcal{L} = 700^{fb}$ 世界記録更新中
DEC-11-2006

Main Controls

祝 $\int \mathcal{L} = 700^{fb}$ 世界記録更新中
DEC-11-2006

Keep Enemies Closer

PEP II Luminosity & Currents

To More Serious Things
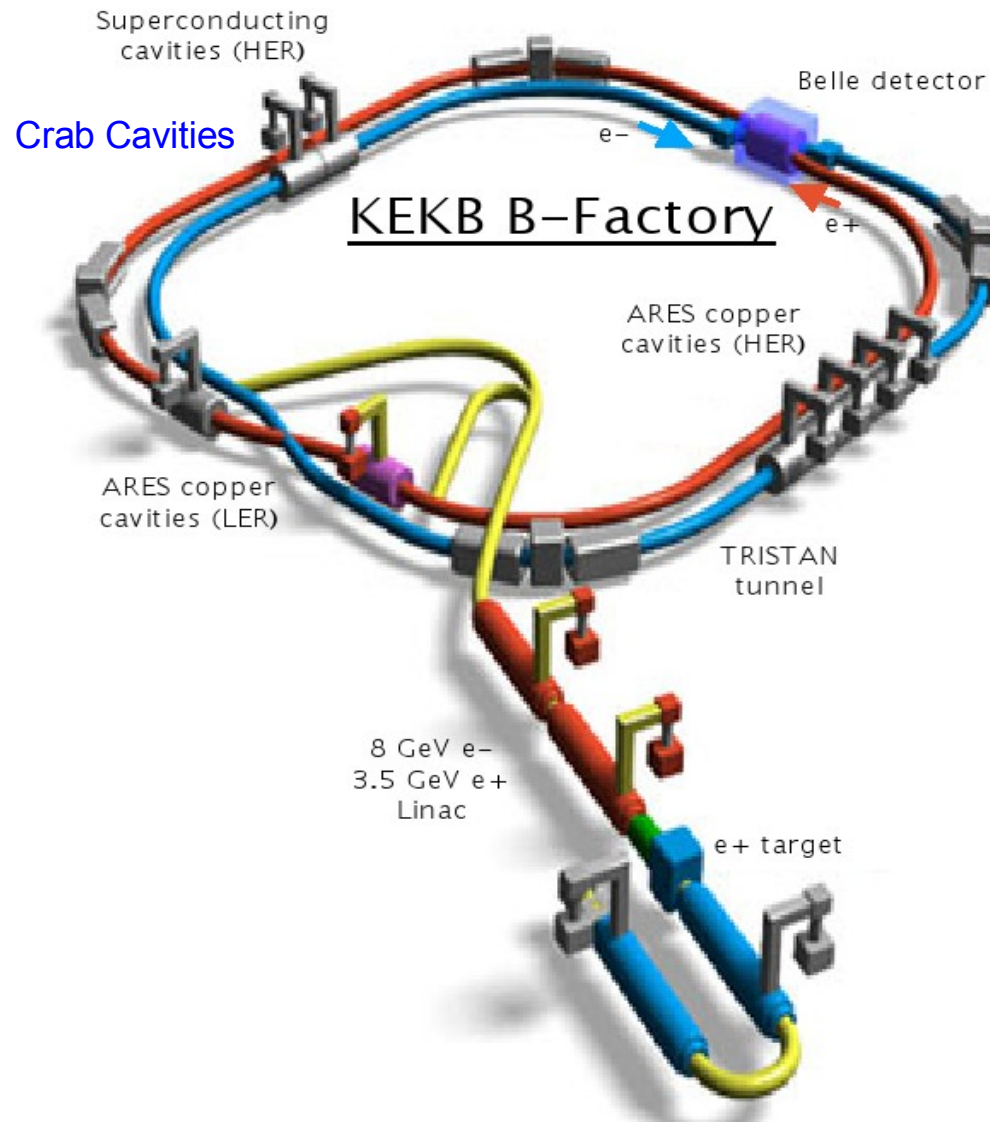
Machine Parameters

|	HER	LER
Energy	8 GeV	3.5 GeV
Beam Current	1.662 A	1.34 A
Number of Bunches	1388	1388
Bunch Current	1.2 mA	0.965 mA
Betatron Tune	45.505/43.534	44.509/41.565
Beta Function IP	59/0.65 cm	56/0.59 cm
Bunch Spacing	2.1 m (7 nS)	
Bunch Length	6 mm	
RF & Crab Frequency	508.88 Mhz	

Crossing Angle (22 mrad)

KEKB Interaction Region
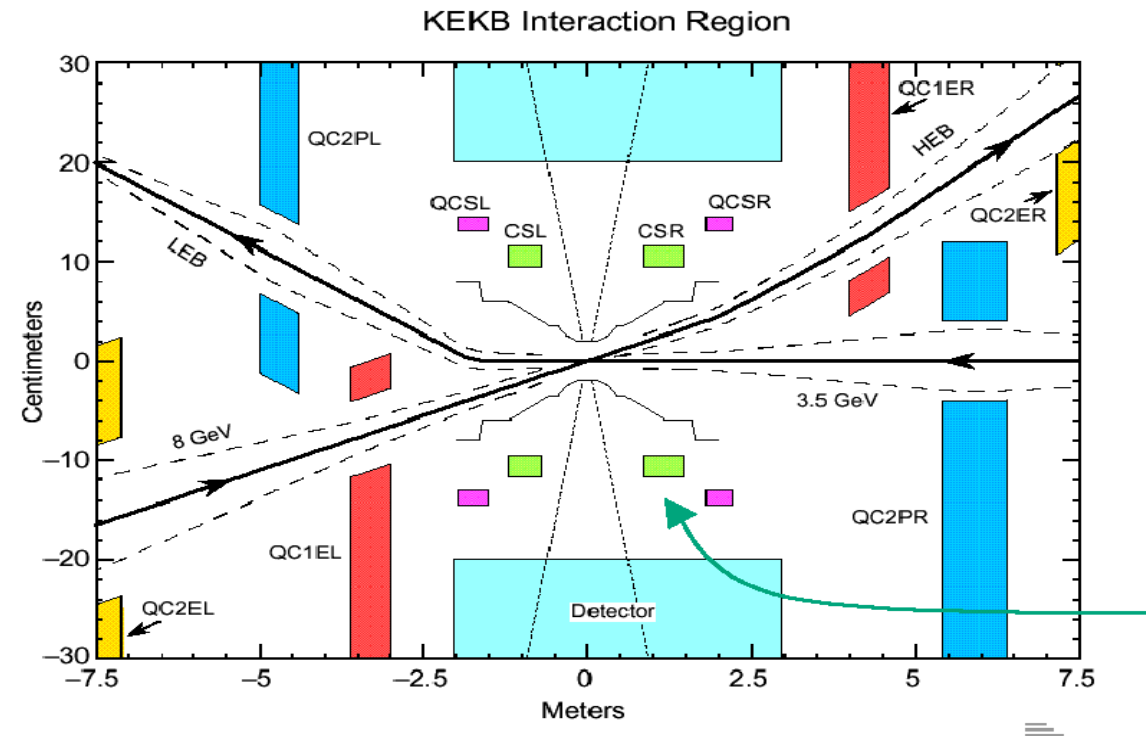
- Simple IR Design

- No bend for incoming beam

- Solenoid compensation for smaller β

- Smaller bunch spacing (e-cloud)

- Parasitic interactions ??

Crossing angle induces z-dependent dispersion at IP

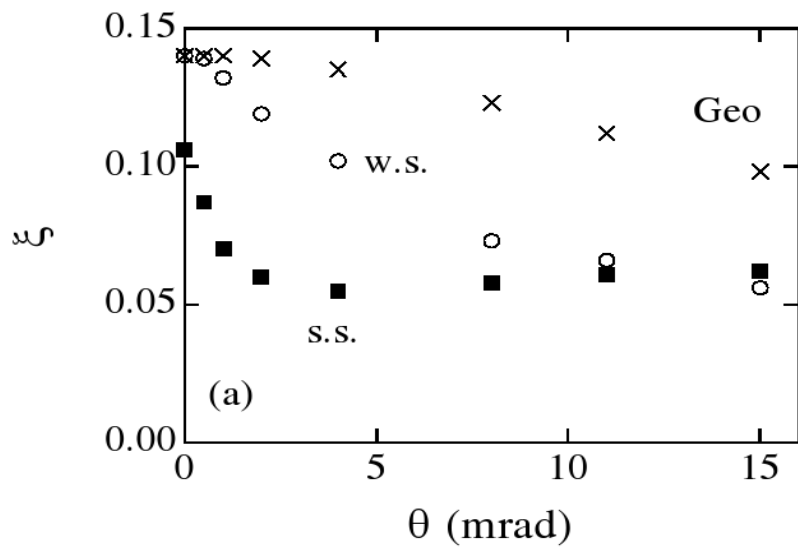$$\zeta_x = \delta\, x / z$$

- Geometric luminosity reduction (~ 20%)

- Max achievable BB parameter due x-z coupling (~ factor of 2 smaller)

Courtesy K. Oide

BB Parameter
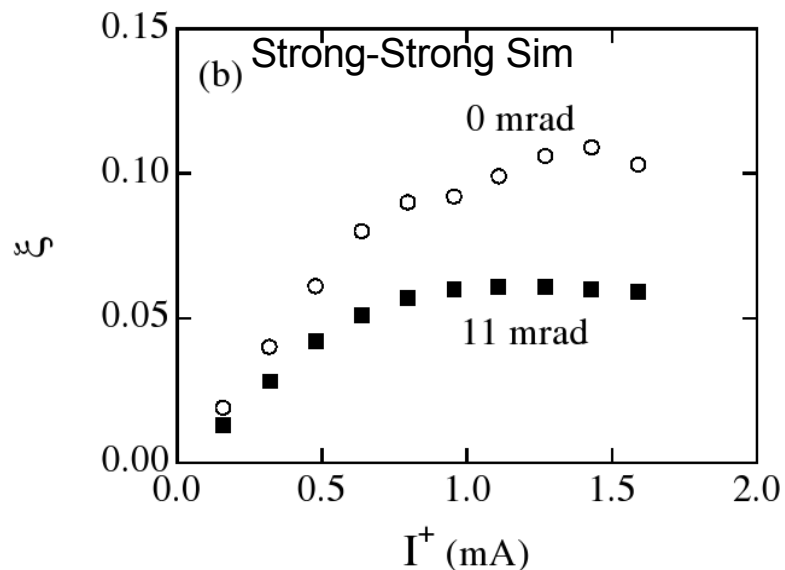
- Max ξ_y with 22mrad crossing angle ~ 0.05

- **$\xi_y \geq 0.1$ with crab cavities** (SS & WS Sim)

- Crab phase tol ~ 0.1 deg (Not Difficult!!)

Luminosity degradation due to
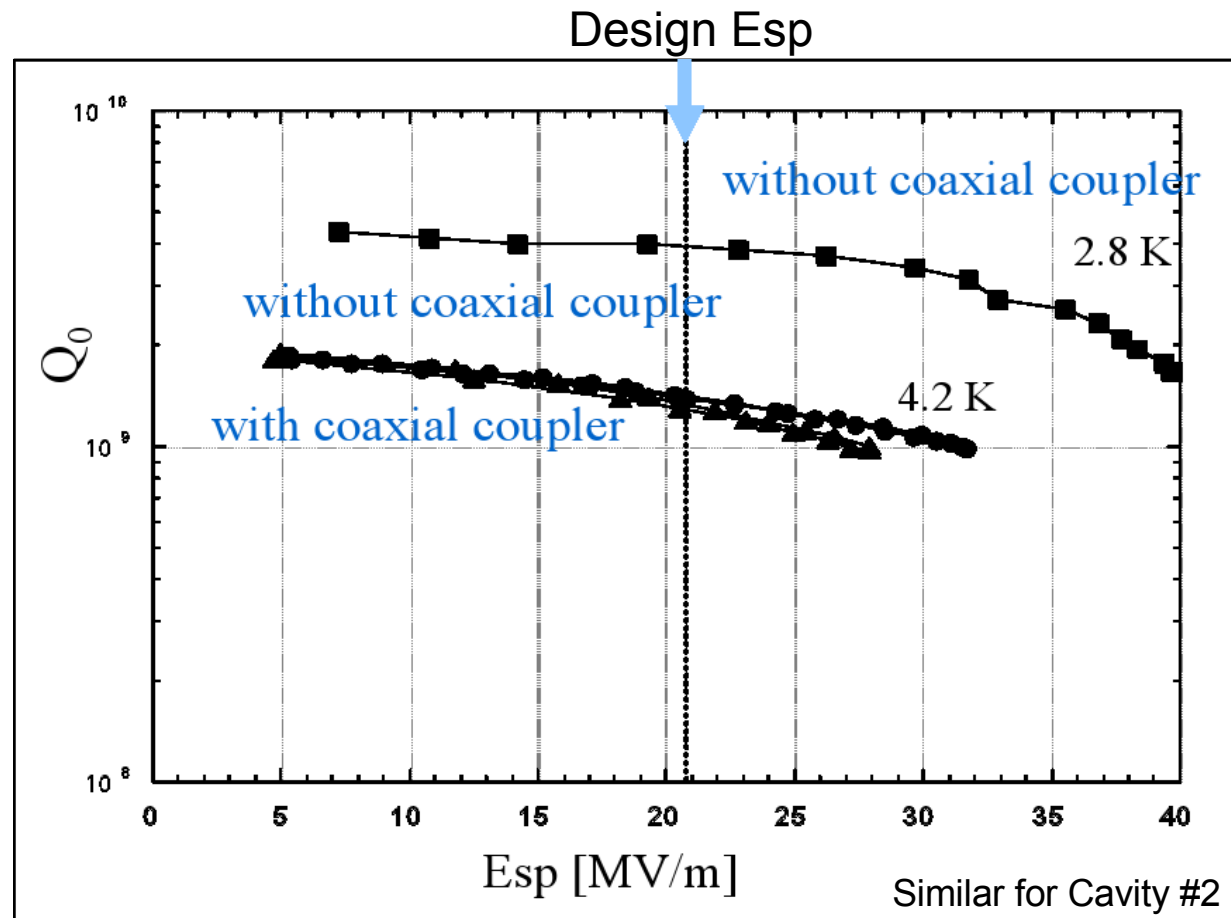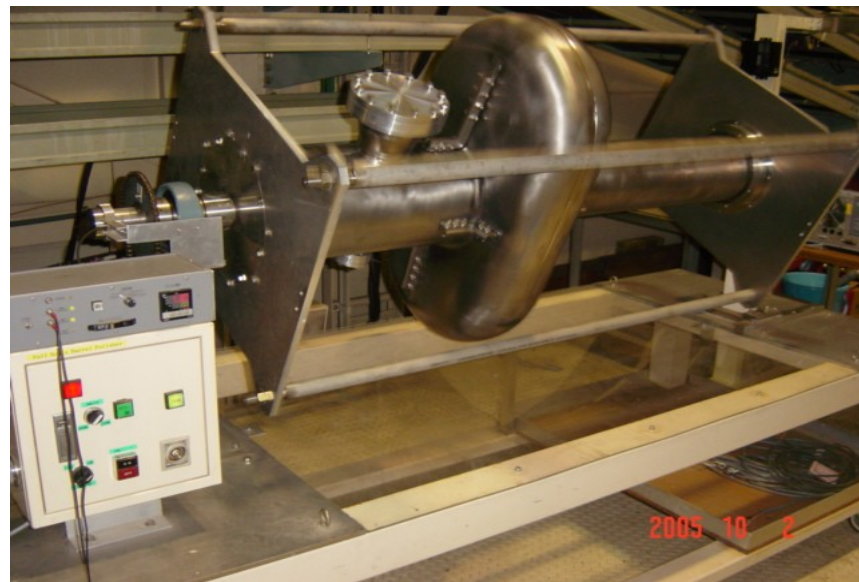
vertical diffusion induced by crossing angle

Ohmi et al., Phys. Rev. ST Accel. Beams 7, 104401 (2004)

Crab Cavity & RF

Cavity & Components

Top View

Input coupler

Magnetic Shield (Jacket Type)

Frequency Tuning by Adjusting Distance

RF Absorber

~ 18 kW

RF Absorber

~ 8 kW

Stub Support

I.D. 240

Coaxial Coupler

I.D. 100

Monitor Port

Main He Vessel

Bellows

Crab Mode Reject Filter

80 K LN2 Radiation Shield

Sub Liq. He Vesse

at LER 1.6 A 1300 bunch

508.9 Mhz, Squashed TM$_{110}$ Cavity
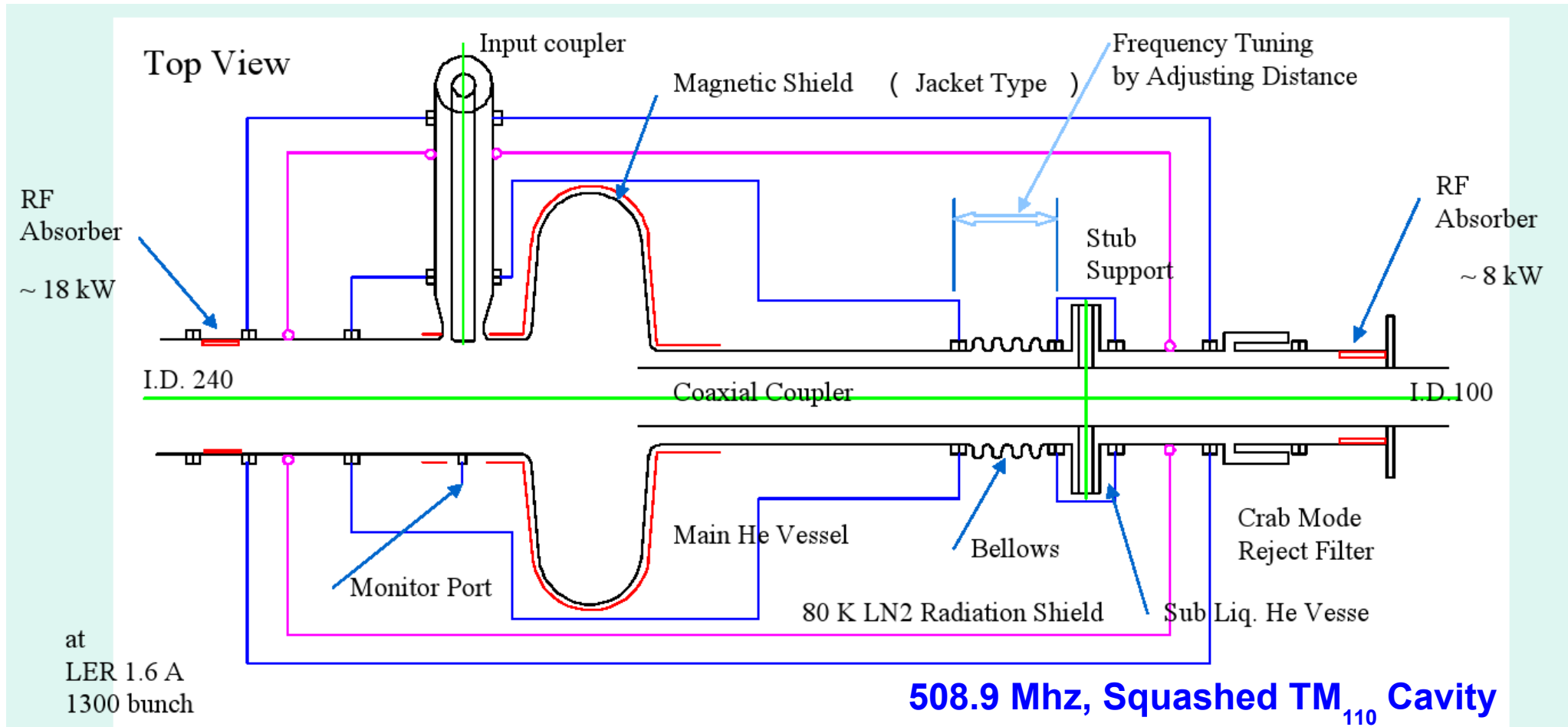
Frequency Tuning: Coax-Coupler (adjust Long. & Hor)

Courtesy K. Akai, K. Hosayama et al.

Cavity #1 Performance

Courtesy K. Hosayama et al.

Cavity Installation
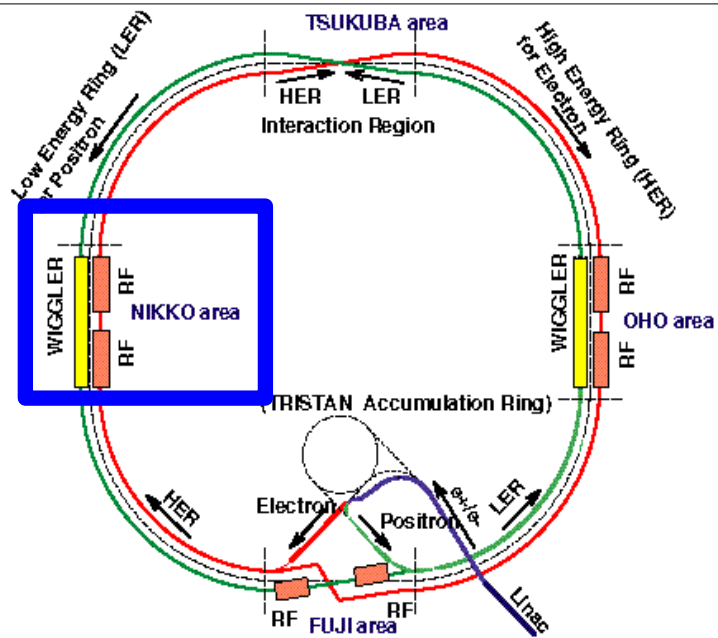
Global Crab Cavities 1/ring @NIKKO Area

Use existing cooling for Acc. SRF Cavities

Courtesy K. Hosayama et al.

In the Tunnel

HER Installation
2007.01.08 10:57

2007.01.08 17:08
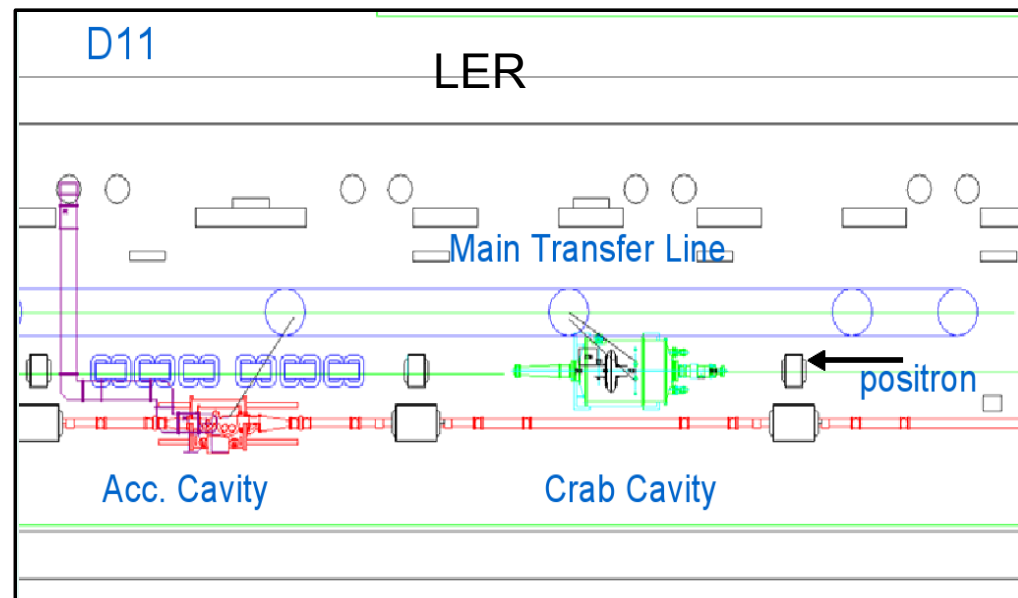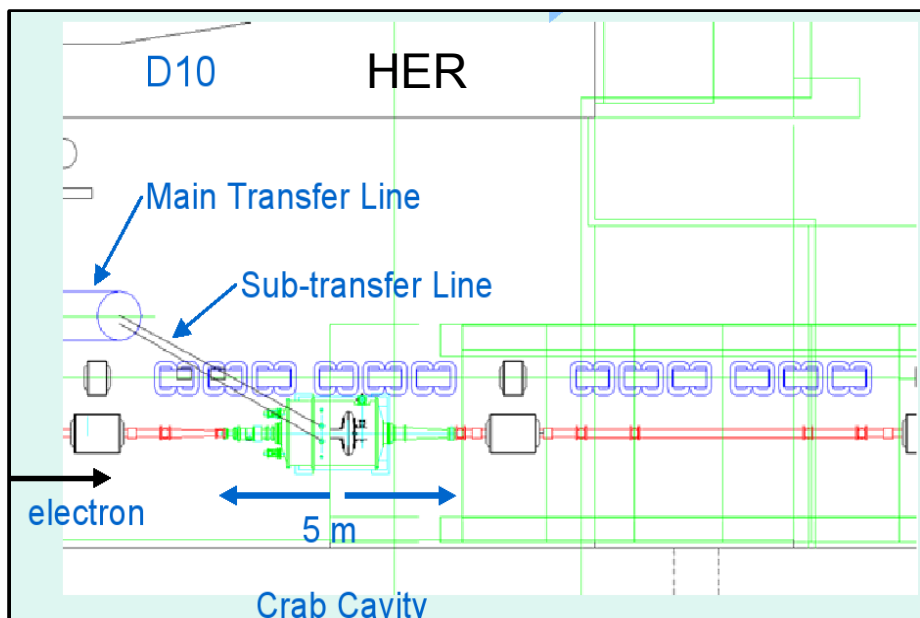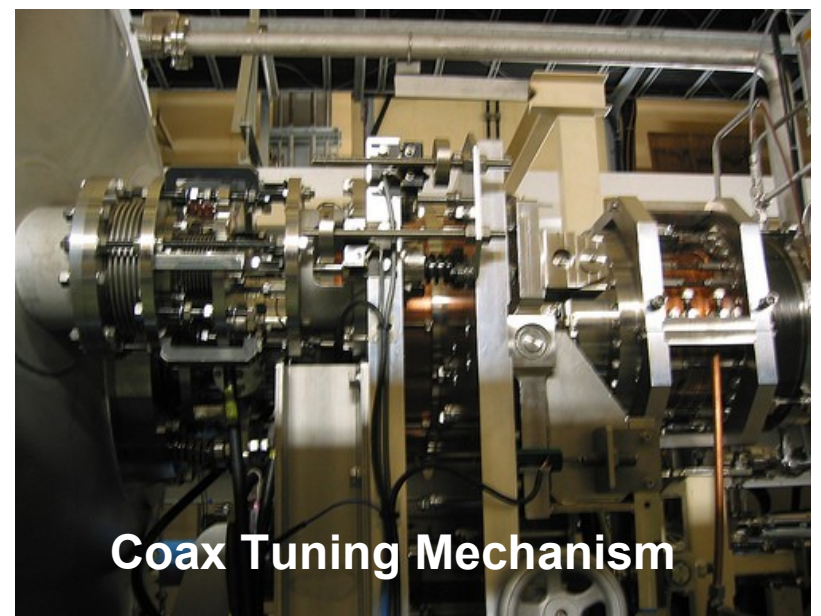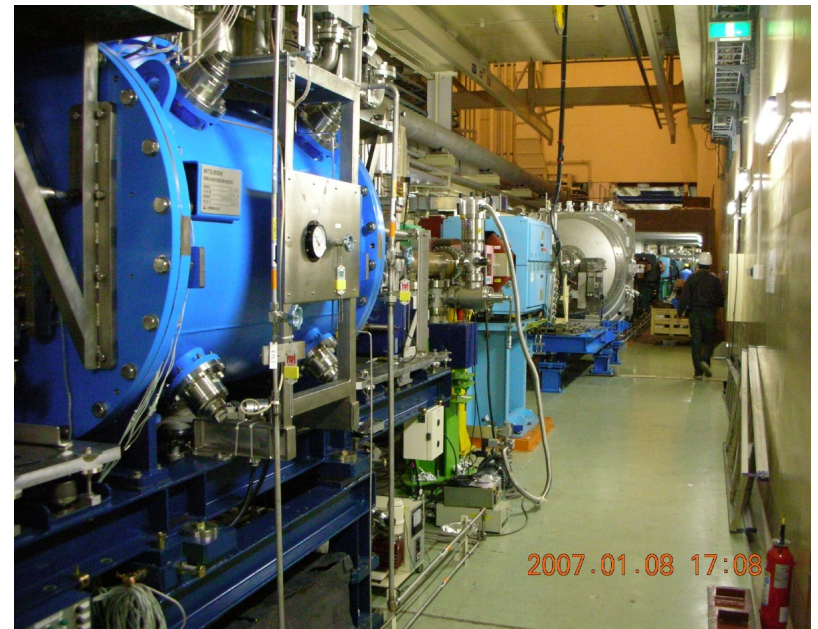
ME
They are doing the work, I am just posing for the camera

Coax Tuning Mechanism

KEKB Tunnel Patrol

RF Power & Detuning

(Beam current = 2A)

$Q_L \sim 2 \times 10^5$

200 kW enough 2 MV

V=2MV (dx=0mm)

V=1.4MV (dx=1mm)

V=1.4MV (dx=0mm)

Growth rate   Coupled Bunch Instabilities

$\pm 30^0$
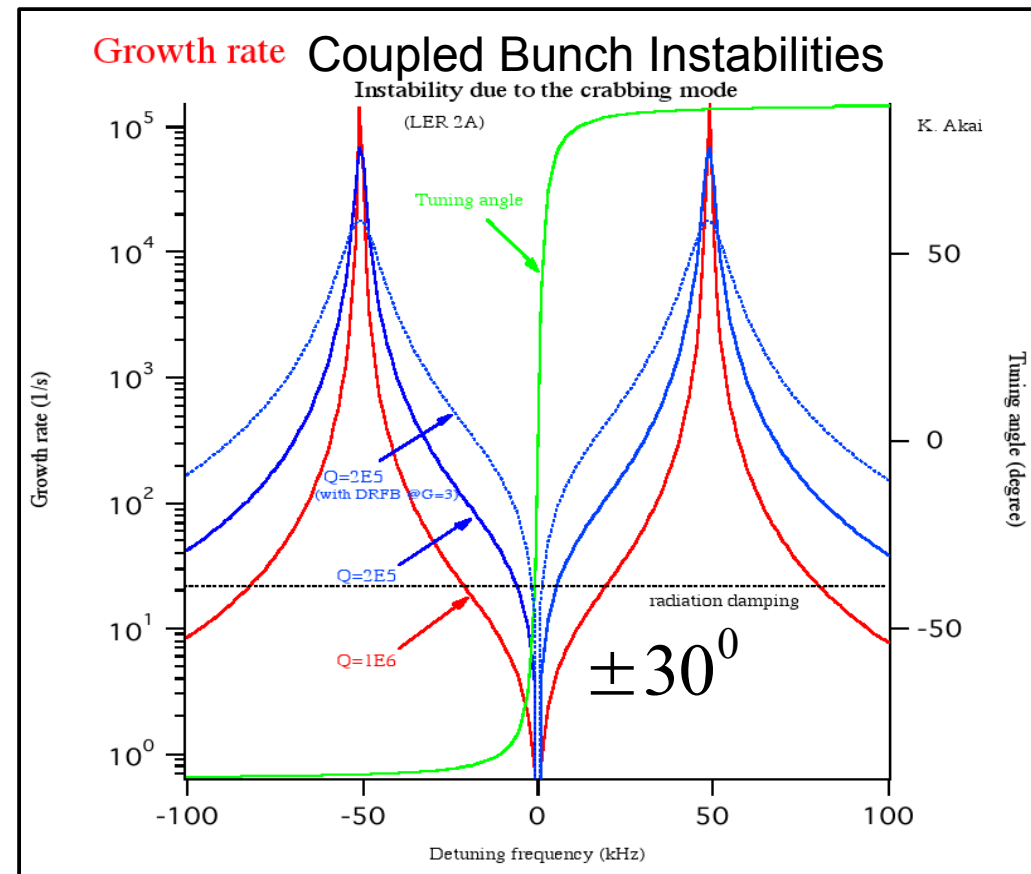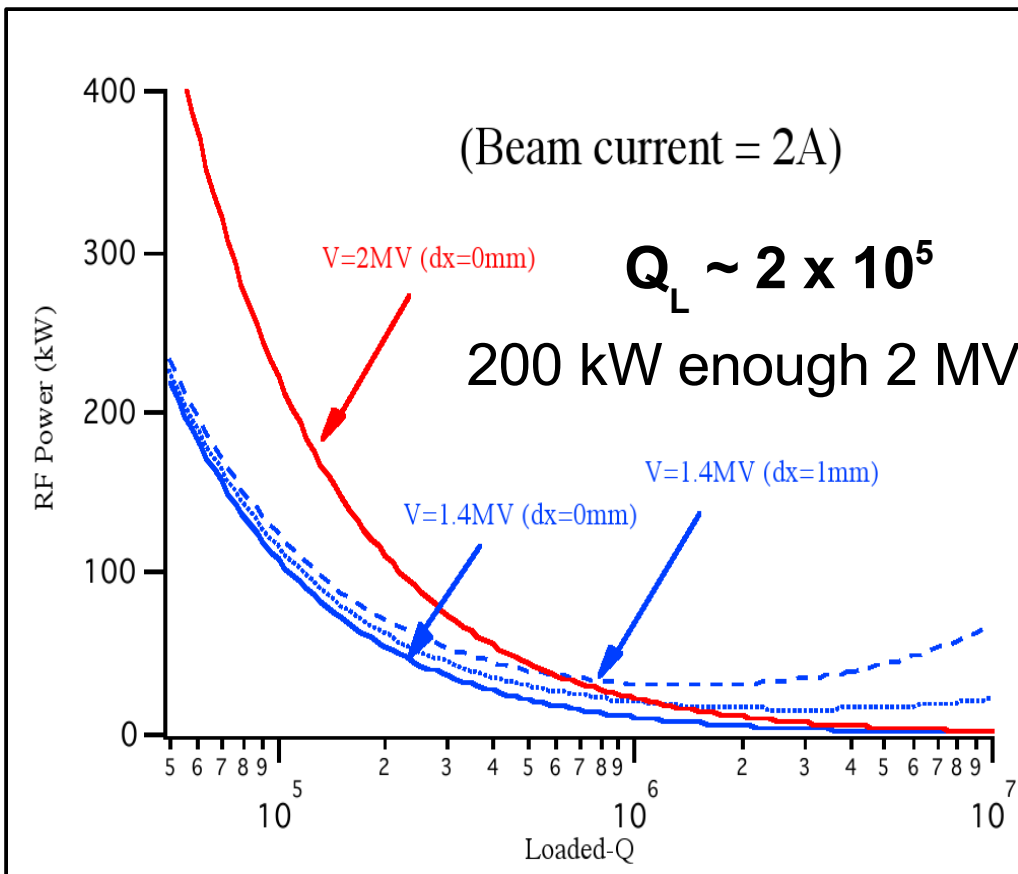
- Frequency is parked far away from $\frac{1}{2}F_{rev}$

- Bunch by bunch feedback to cure CBI

Courtesy K. Akai

RF Control & Feedback

~ 600 kW
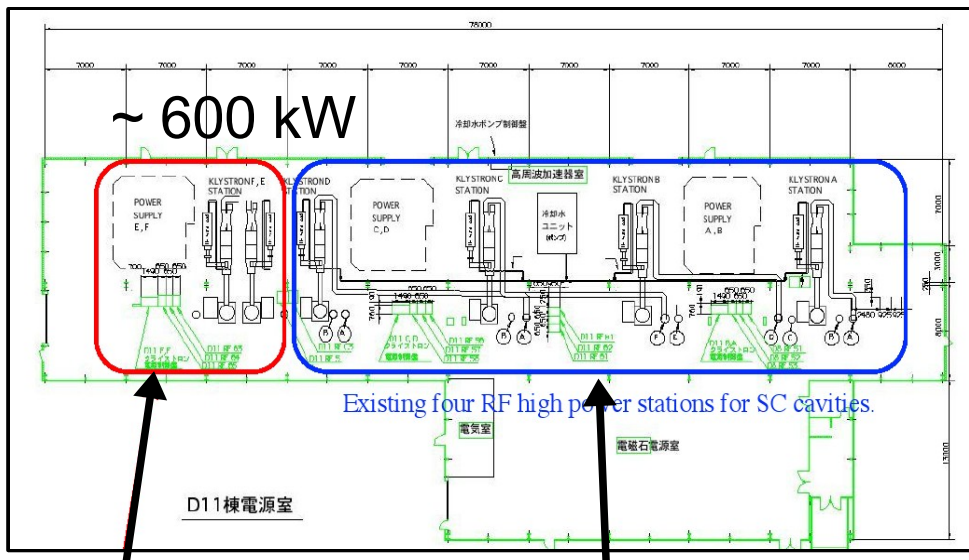
Crab Station

Acc Cavity Station

HER Low Level RF Control

Reference Signal

Klystron Loop

Tuning Loop
(slow loop)

Amplitude & Phase Loop (fast loop)

Courtesy K. Akai
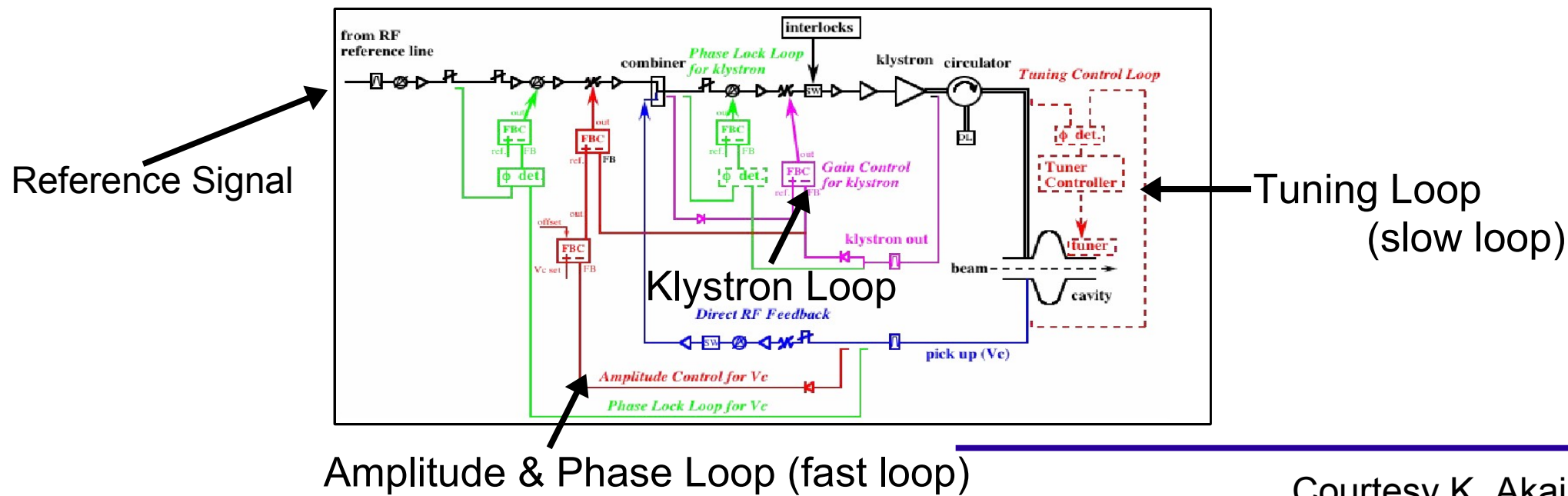
Tuner Response

Commissioning for HER Crab Cavity ('07/2/10)

Kick Voltage

Coax Position

Phase ± 2 deg

Tuner Load

Piezo Voltage

Commissioning for LER Crab Cavity ('07/2/10)

± 30 deg

Courtesy N. Yamamoto
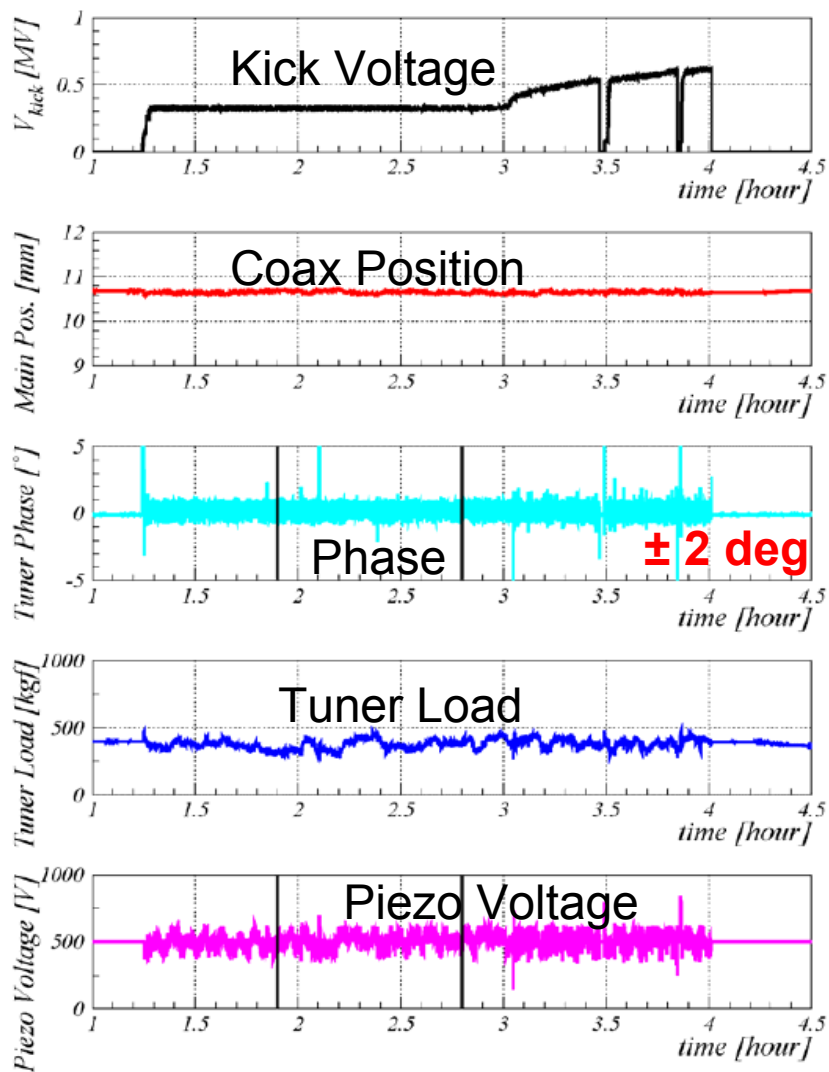
LER号機のTuner Response②

Commissioning for LER Crab Cavity ('07/2/10)

Commissioning for LER Crab Cavity ('07/2/10)

$V_{kick}=0.3MV$

Piezo On

±35°

Piezo Off

±40°

Manual

±35°

何もしないで放っておくとしばらくは中心にいるが、一度外れた後で元に戻そうとすると、一旦逆方向に動いてから戻るため拡がりは変わらないことになる。
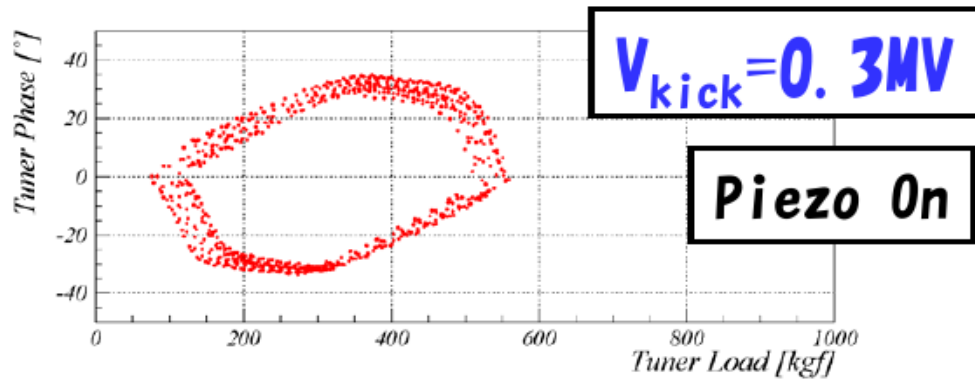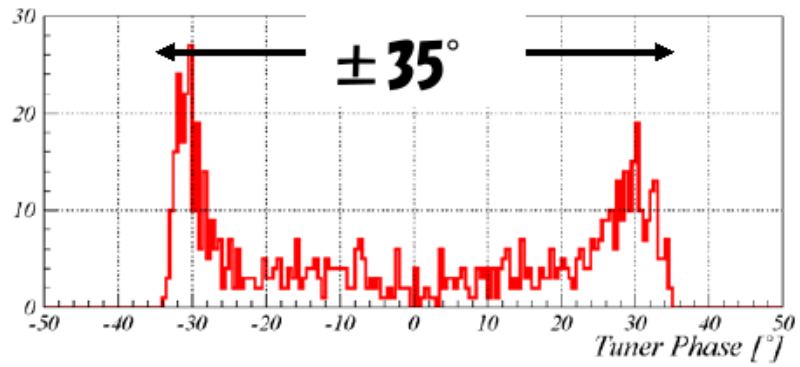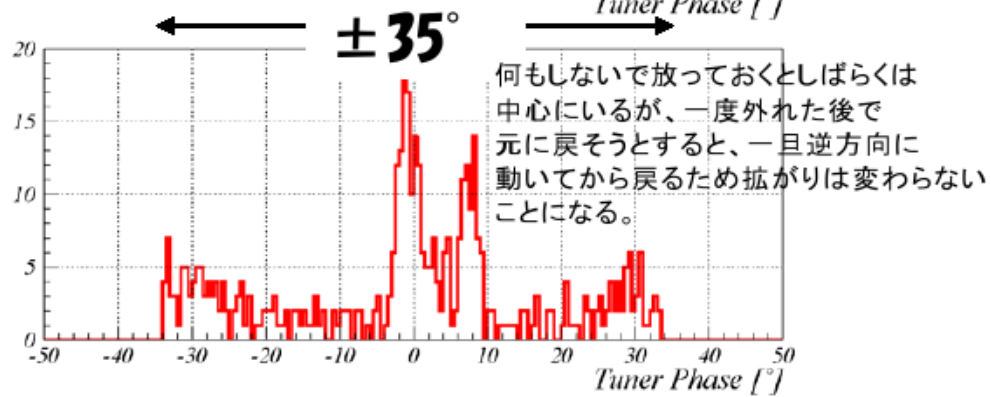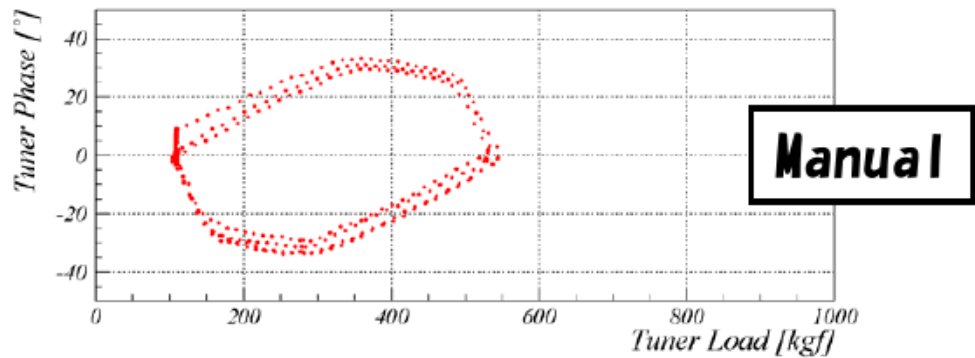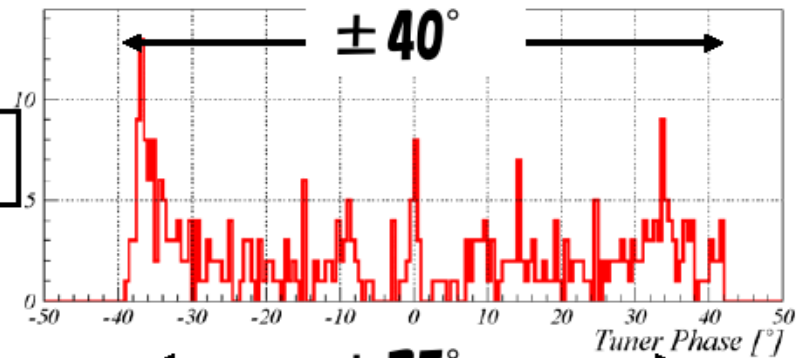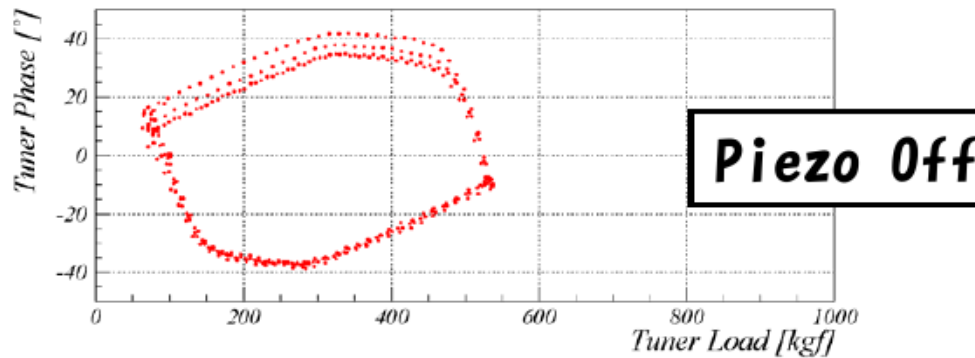
チューナーロード

チューナー位相

ヒステリシスの傾向は3つのモードの間で違いは無いように見える。
位相の振れ幅は、ピエゾが働いている時の方が若干狭いことがわかる。

Improvement
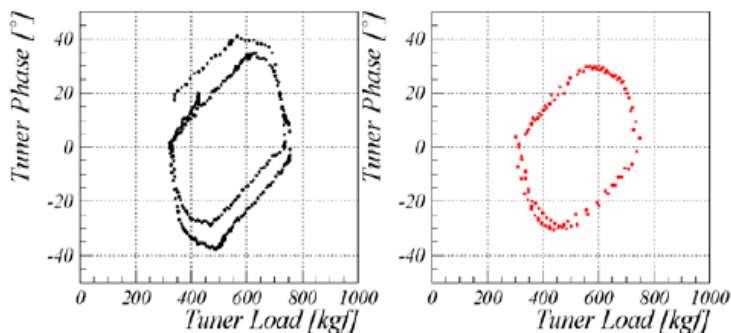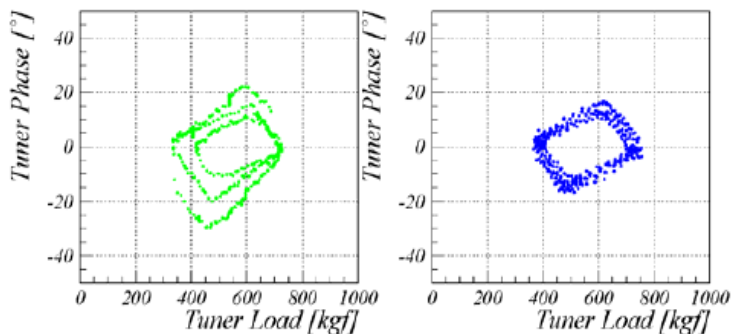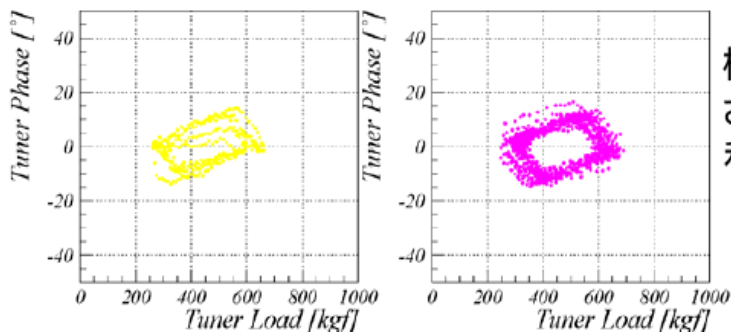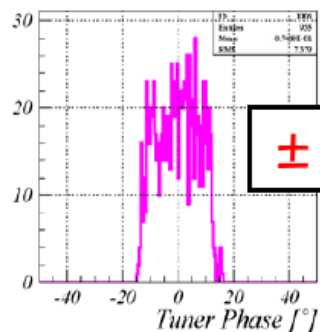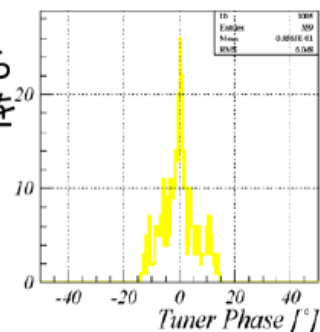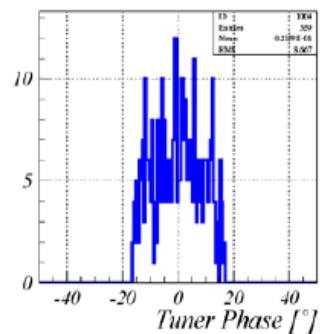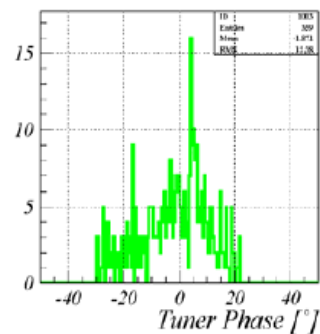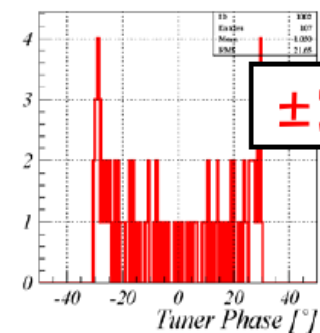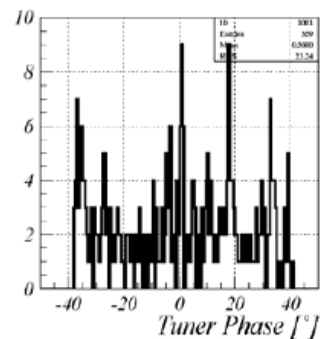
- Bulging of screw holding the tuner plate was observed.
- Extra support to the tuning plate with special clamps improved phase stability

RF Conditioning
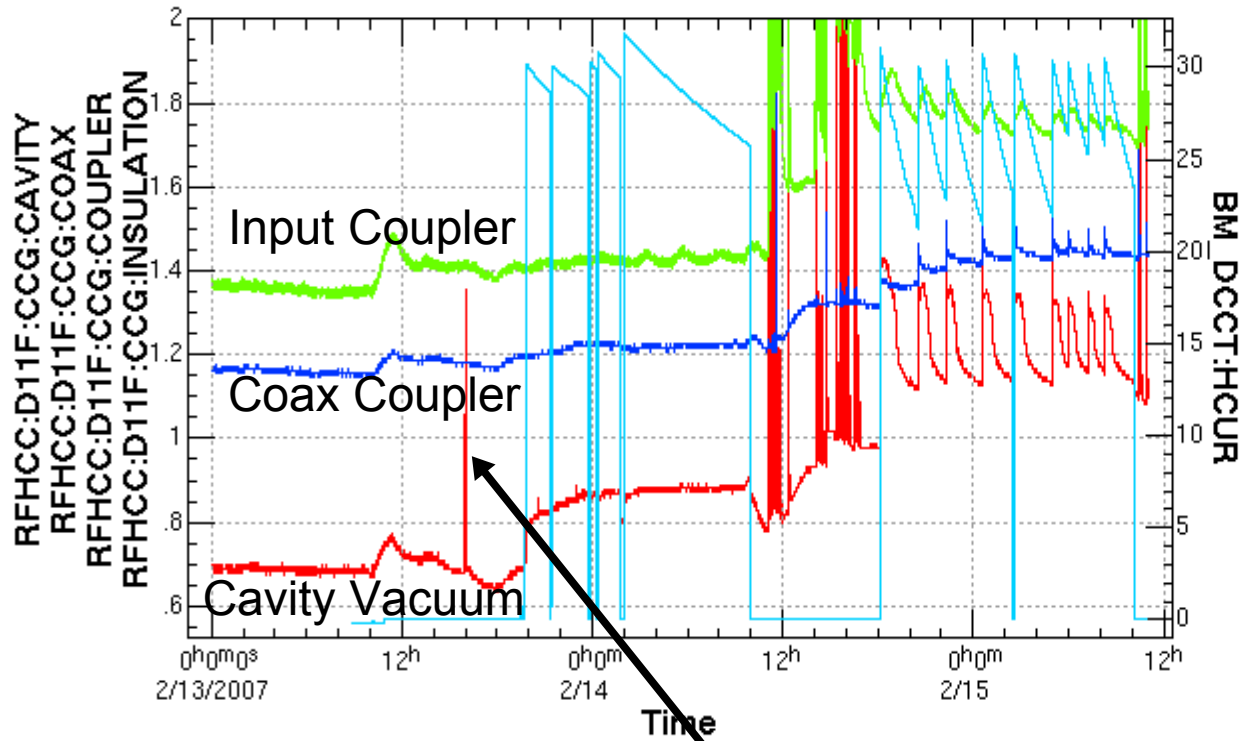
Courtesy RF Group

Crab Cavity with Beam

Approx Chronology

- Feb 13 – 18:

  - Mornings: High power RF conditioning (1.6MV/1.4MV CW)

  - Evenings: Beam with Detuned Cavity

    - 2 Modes – 30mA, 30 bunches/Multi-bunch

    - BPM Calibration, Orbit, Optics, Coupling & Dispersion

    - Cavity Field Center, RF Phase..

- Feb 19 – Present: Beam with Crab On

  - Some gradient degradation observed (1.4MV/1.1MV CW)

  - Optics (β_x increased), Dispersion & Coupling Correction, Crab Orbit Feedback

  - Collision Tuning

    - Low Currents (~30 mA with 30 Bunches)
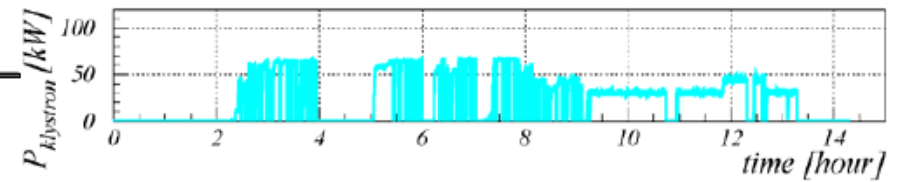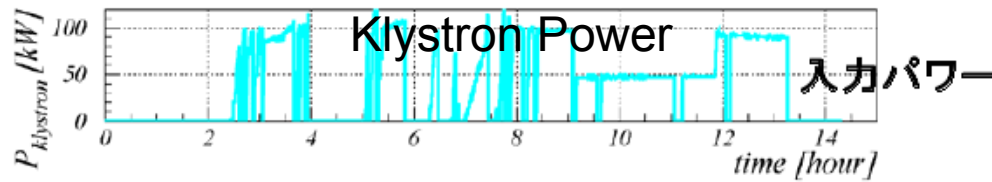
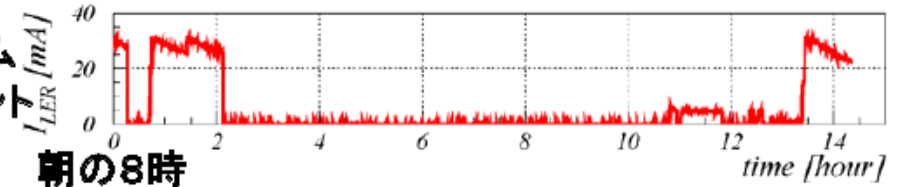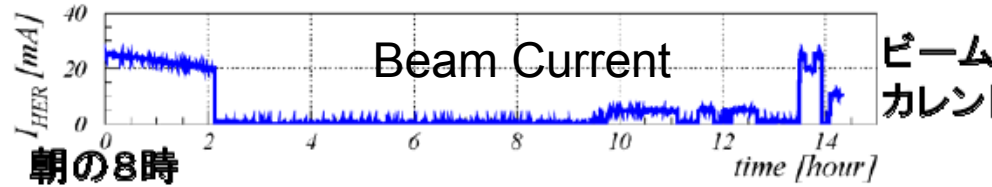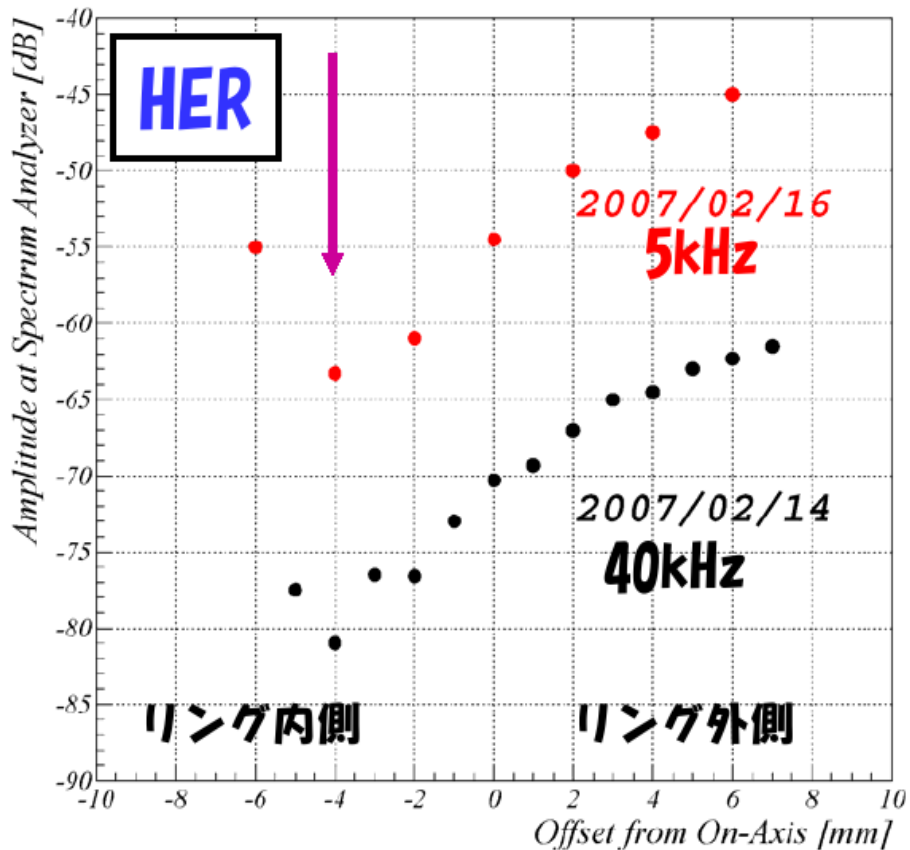   - IR Scan (BB Kick, σ_y, Coupling, η_y, Waist...)

First Beam Test with Crab "ON"① (2/19)

HER

LER

Commissioning for HER Crab Cavity ('07/2/19)
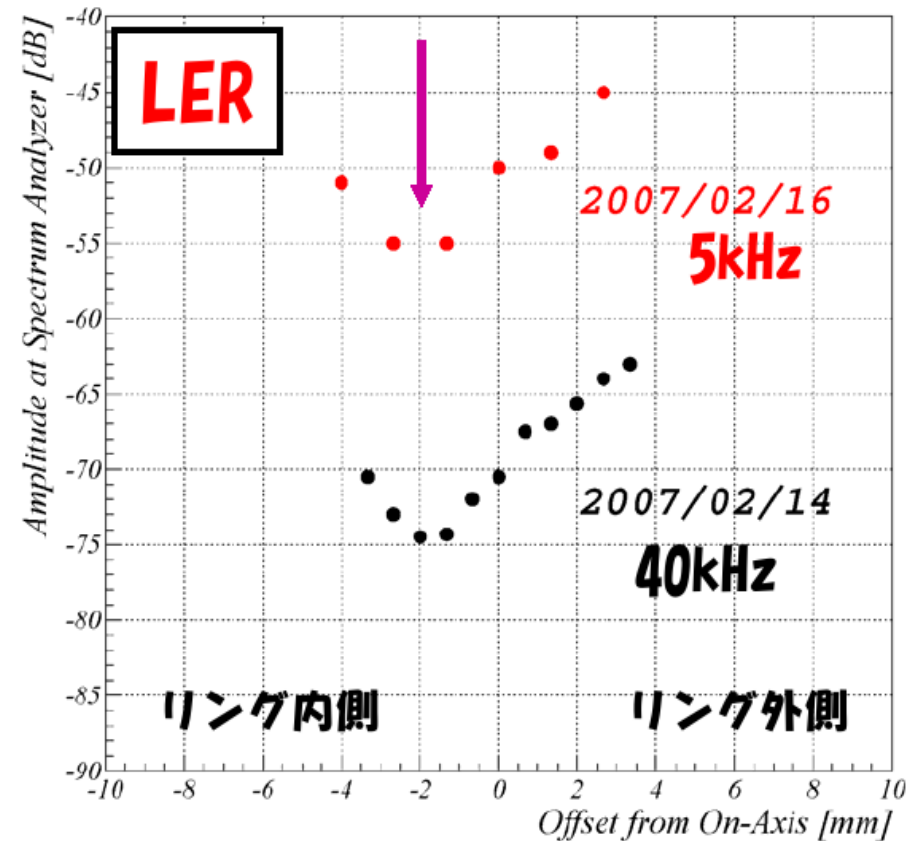
Commissioning for LER Crab Cavity ('07/2/19)
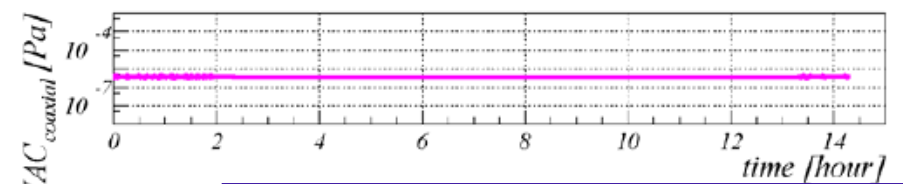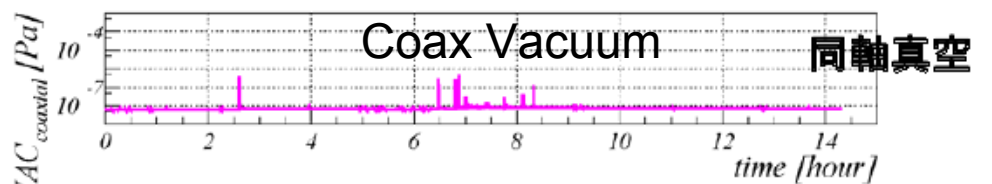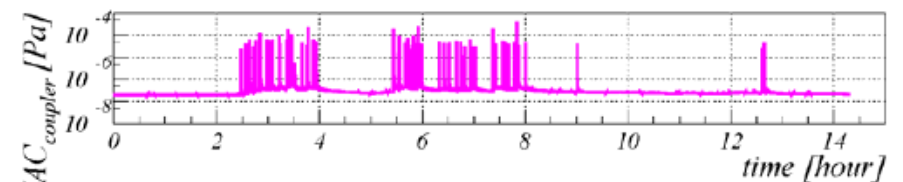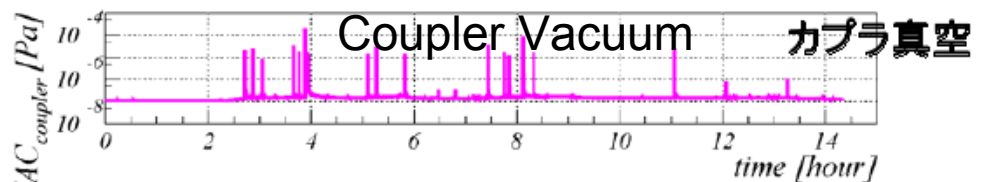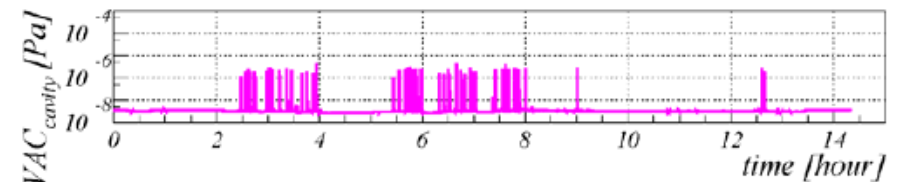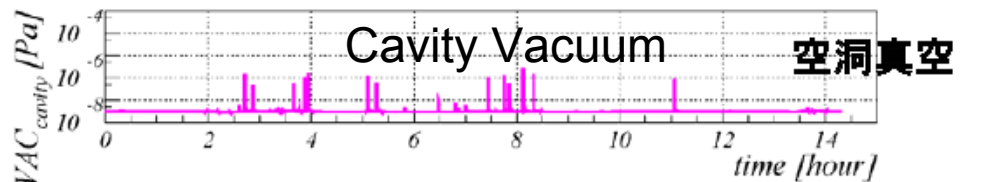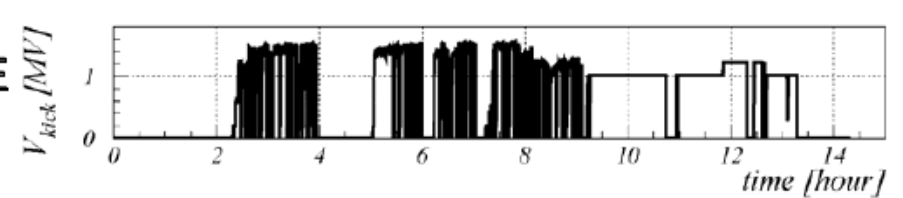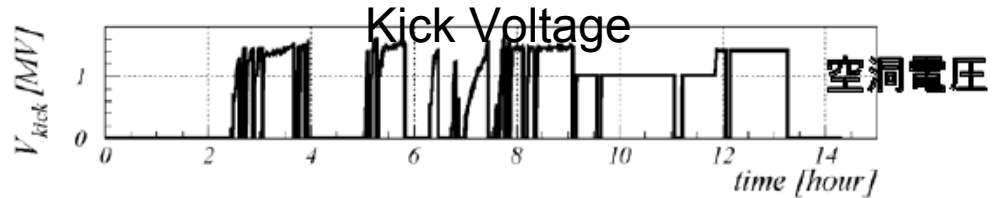
Beam Current ビーム
カレント

朝の8時

Klystron Power 入力パワー

Kick Voltage 空洞電圧

Cavity Vacuum 空洞真空
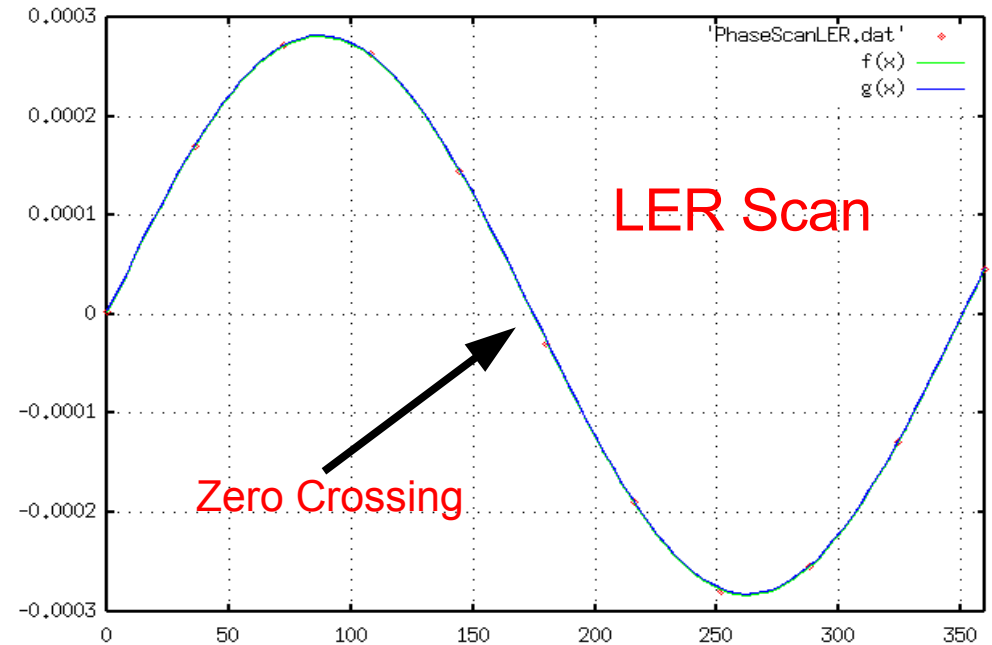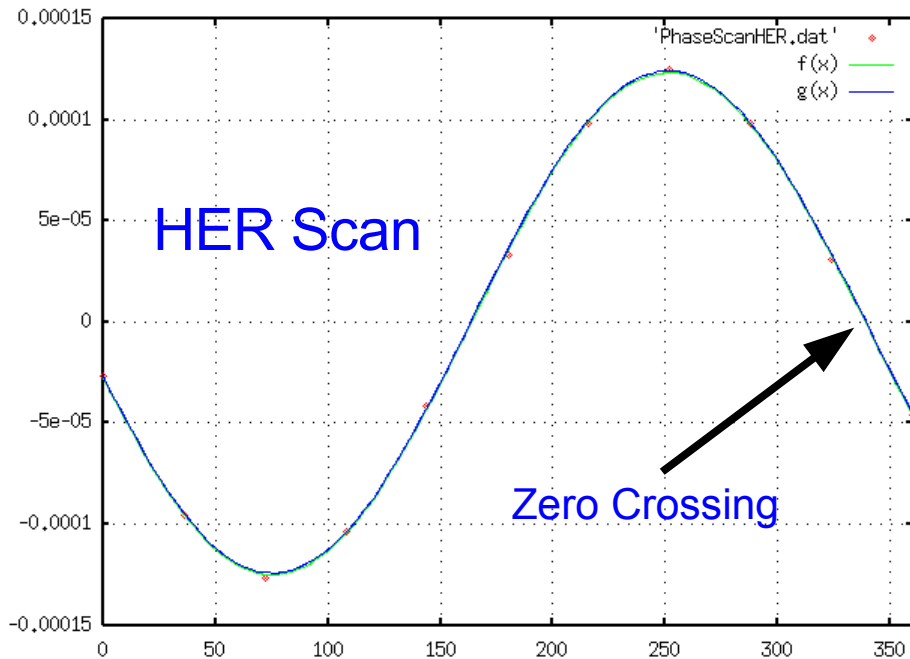
Coupler Vacuum カプラ真空

Coax Vacuum 同軸真空

Courtesy N. Yamamoto

Cavity Field Center

Record output power as a function of horizontal orbit (dipole mode)

Crab Cavity Phase Scan

- Zero crossing & sign of the slope not known

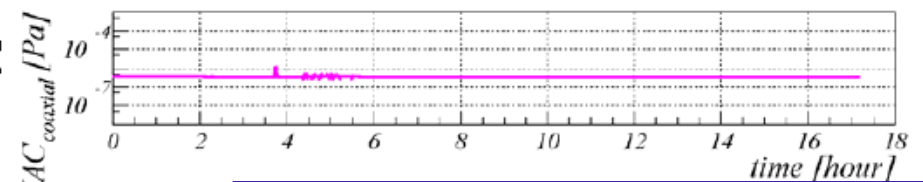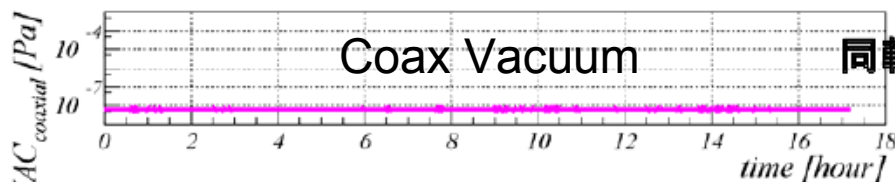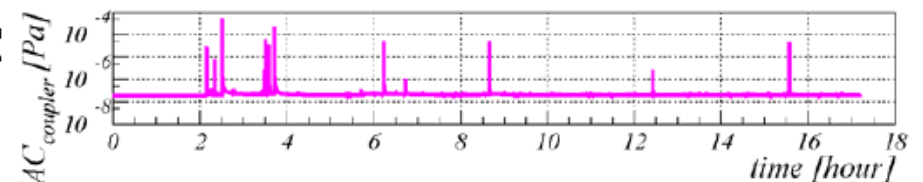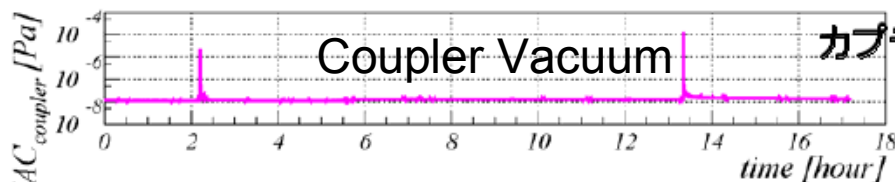- **2π** phase scan vs. relative orbit deviation

First Beam Test with Crab Crossing① (2/21)

HER

LER

Commissioning for HER Crab Cavity ('07/2/21)

Commissioning for LER Crab Cavity ('07/2/21)

Beam Current

ビームカレント

朝の8時

朝の8時

Klystron Power

入力パワー

Kick Voltage

空洞電圧

Cavity Vacuum

空洞真空

Coupler Vacuum

カプラ真空

Coax Vacuum

同軸真空
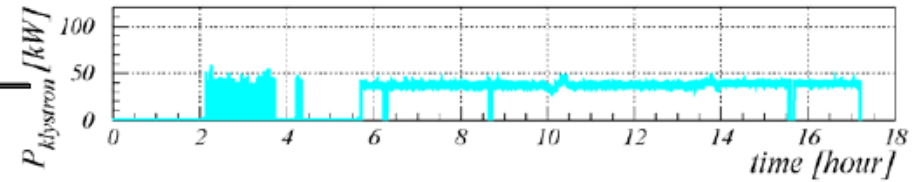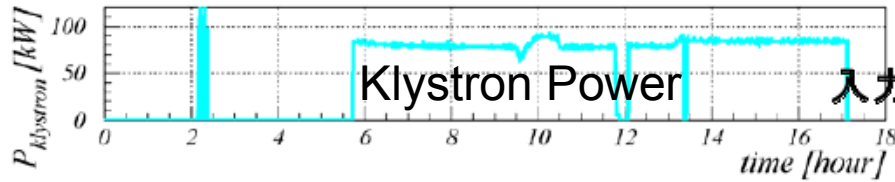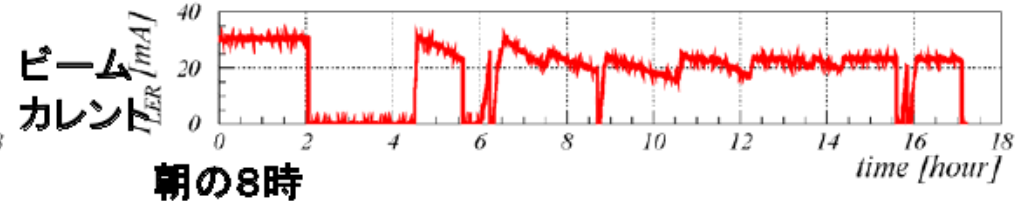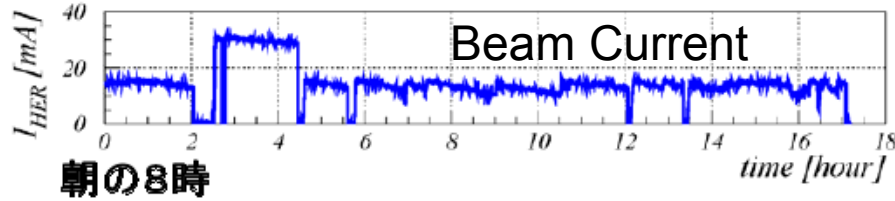
Courtesy N. Yamamoto
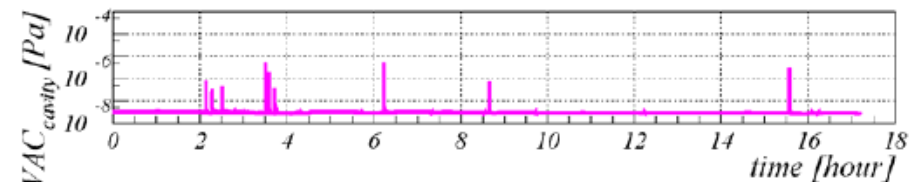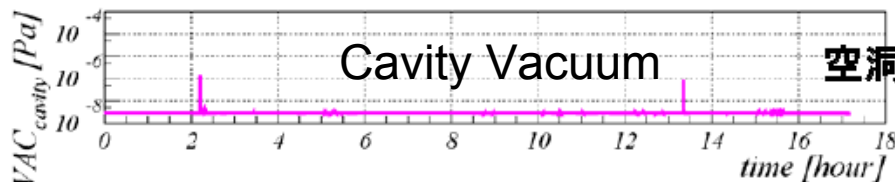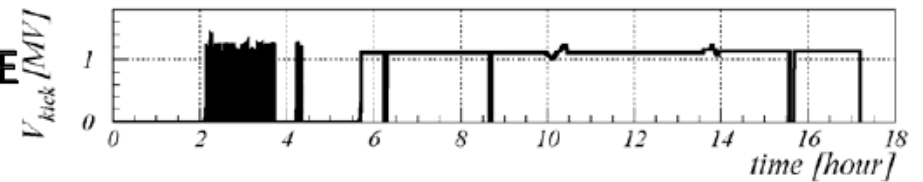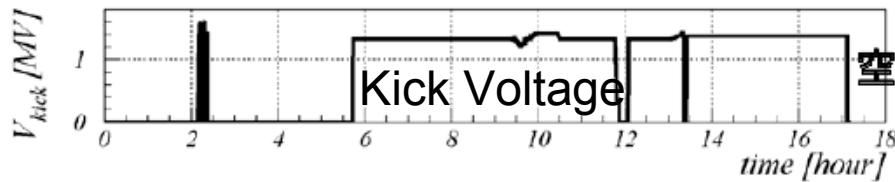
Phase Stability during Beam Test
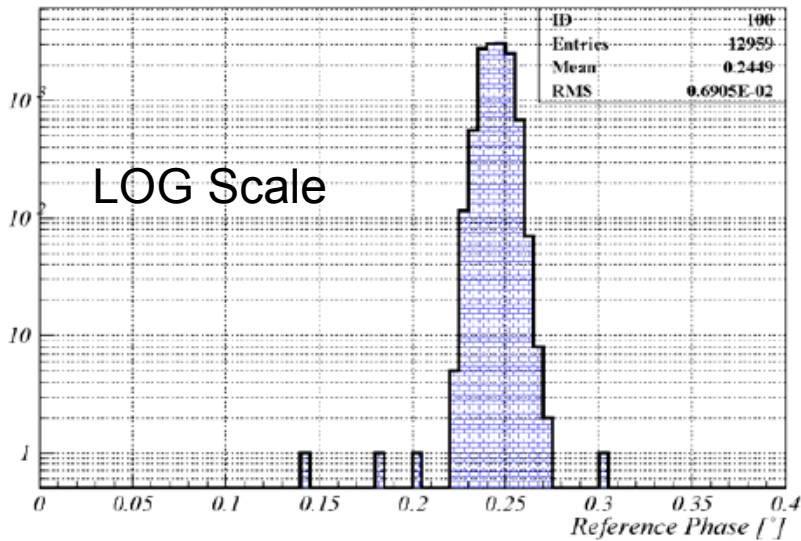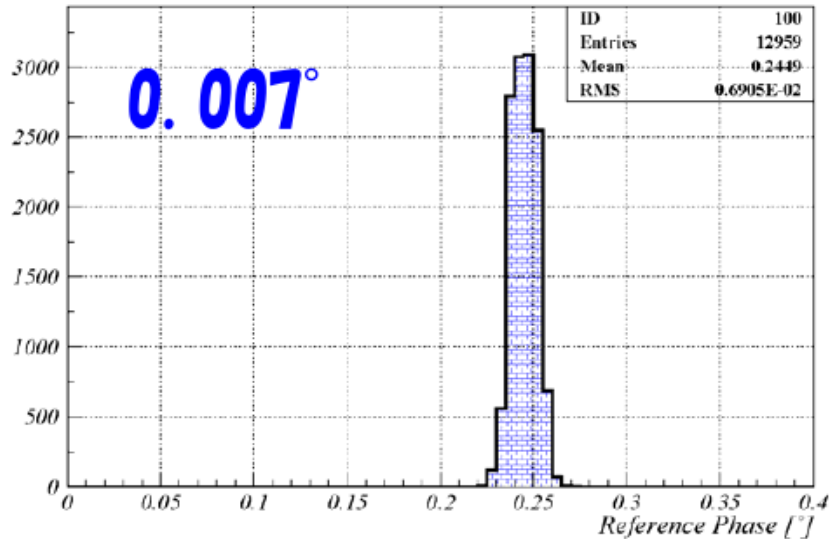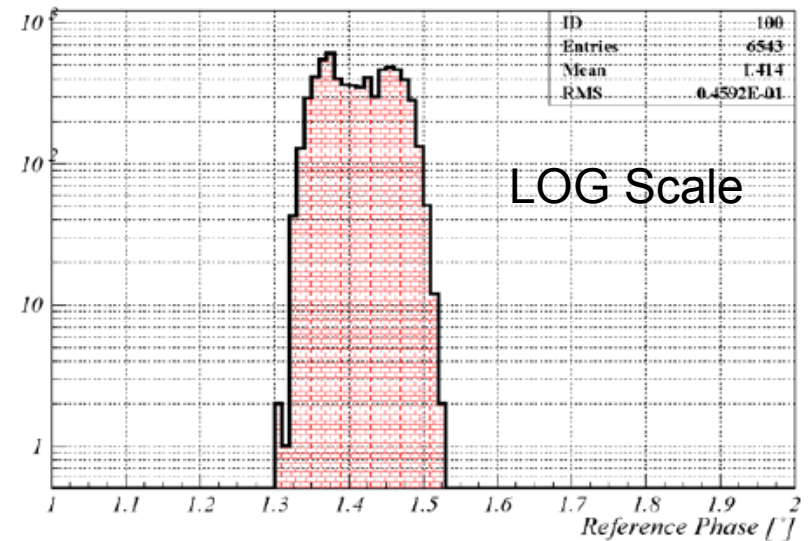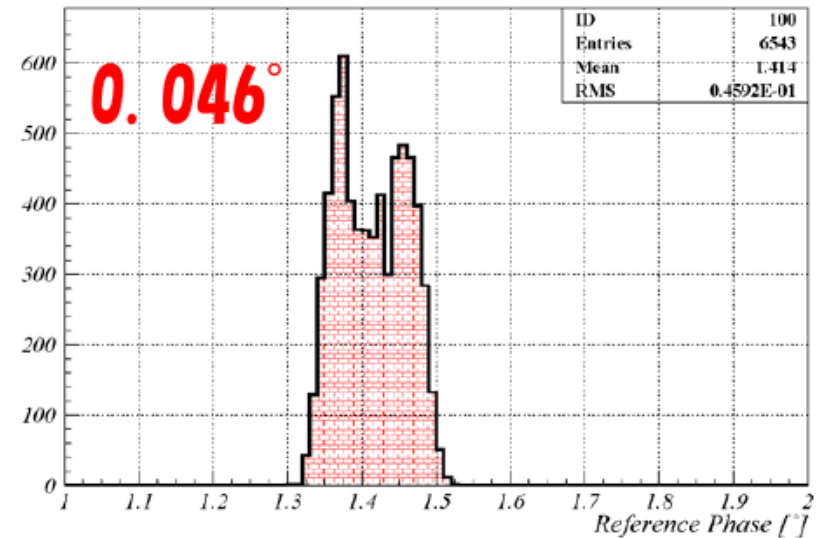
空洞電圧一定モード時の位相の分布（上はlinearで、下はlogである）

Phase Noise Spectrum
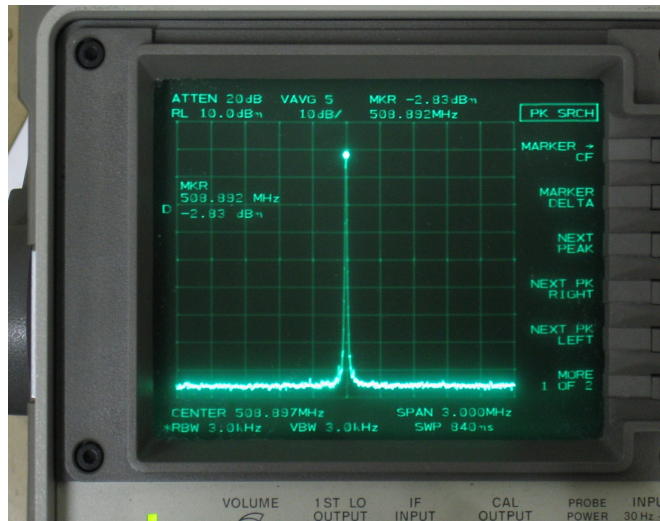
Span 3MHz
No significant sidebands seen.
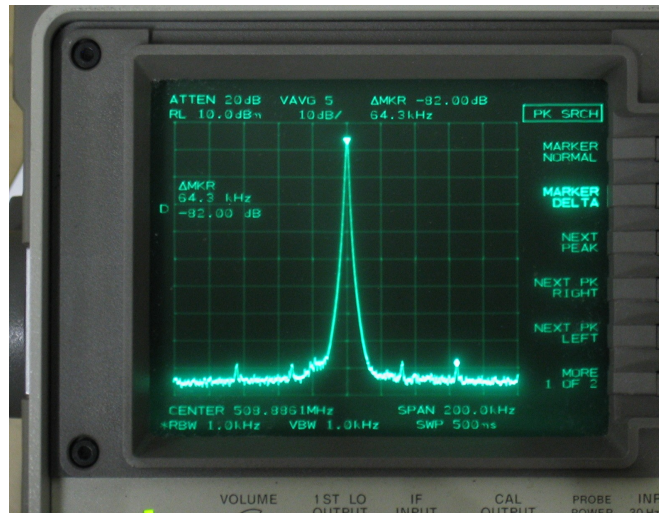
Span 200 kHz
Sideband peaks at 32kHz, 64kHz.
Phase error < ± 0.01 deg (fast)
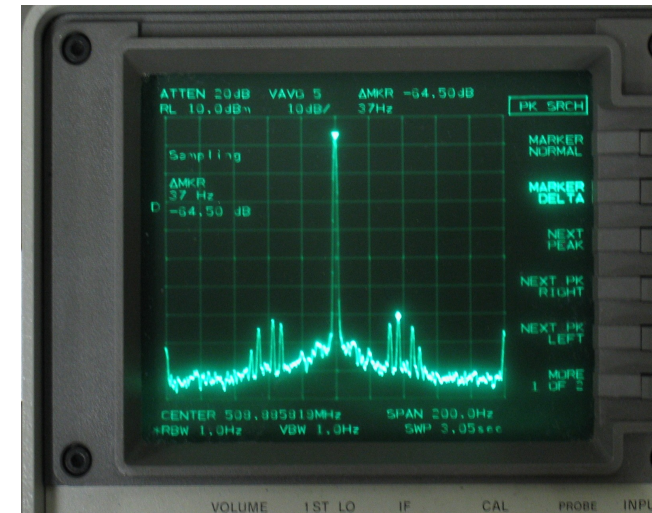
Span 200 Hz
Sideband peaks
at 32, 37, 46, 50, 100 Hz.
Phase error < ± 0.07 deg (slow)
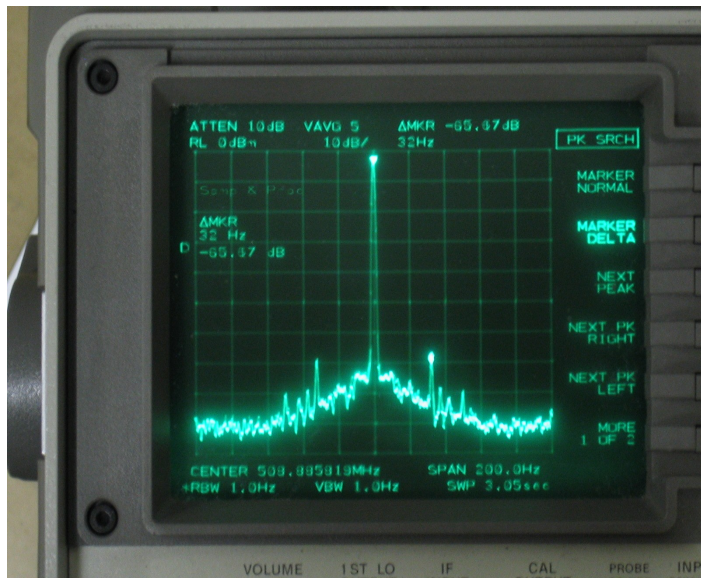
Some of the peaks are also found
in the reference line.
(upstream of the crab station)

Use this spectrum for LHC simulations ?

Courtesy K. Akai

Machine & Collision Tuning

BPM Gain (450 Dual Plane BPM)
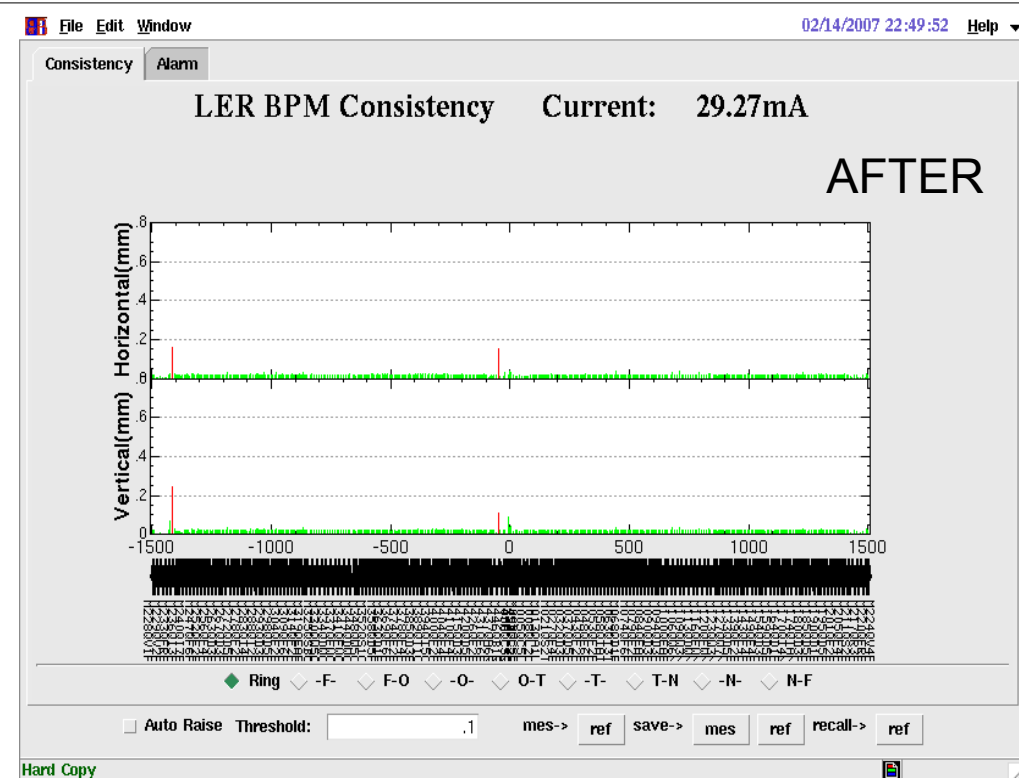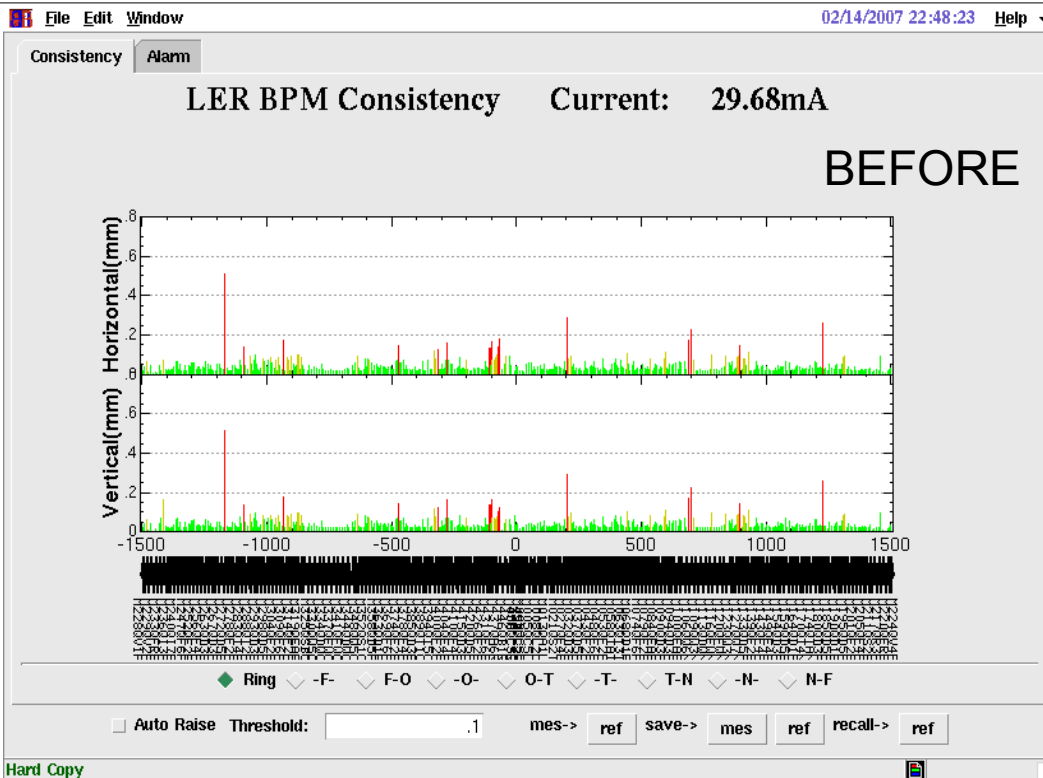
- Use combinations of 3 electrodes to determine position

- ABC, BCD, CDA, DAB should coincide

- Consistency: STDEV(4 Combinations) < 0.1mm

$$V_i = g_i\, q\, F(x, y), [i = 1...4]$$

F(x,y): 4th Order Polynomial Fit & Non-Linear Least Squares

4 electrodes & m orbits (m > 4)

Courtesy M. Tejima
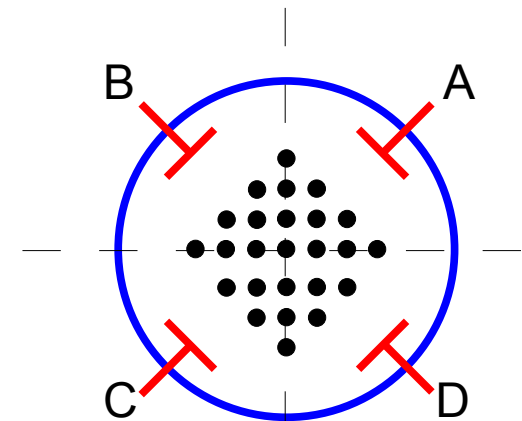
BPM Offset: Quad Modulation

Courtesy H. Koiso et al.
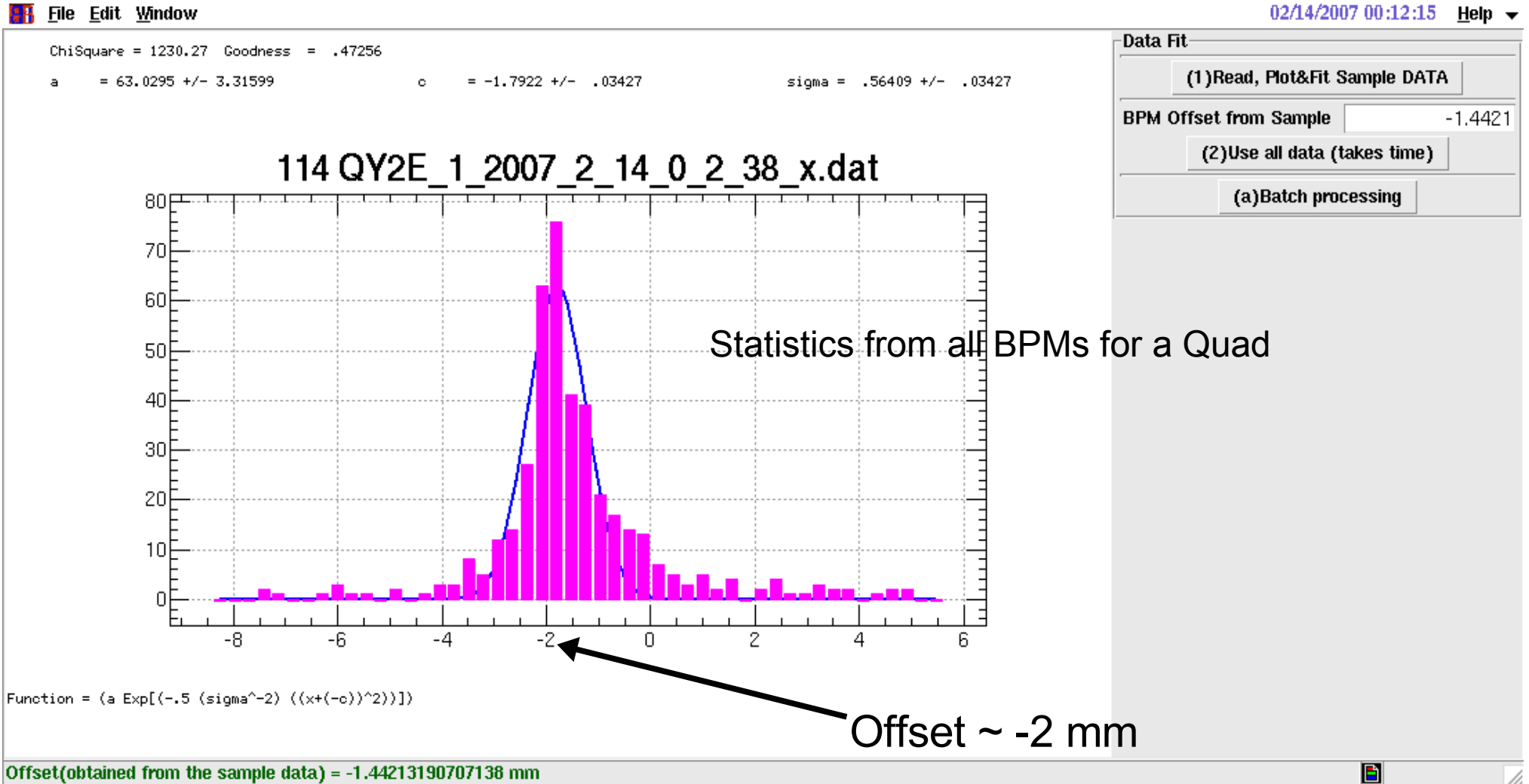
Online Optics Model
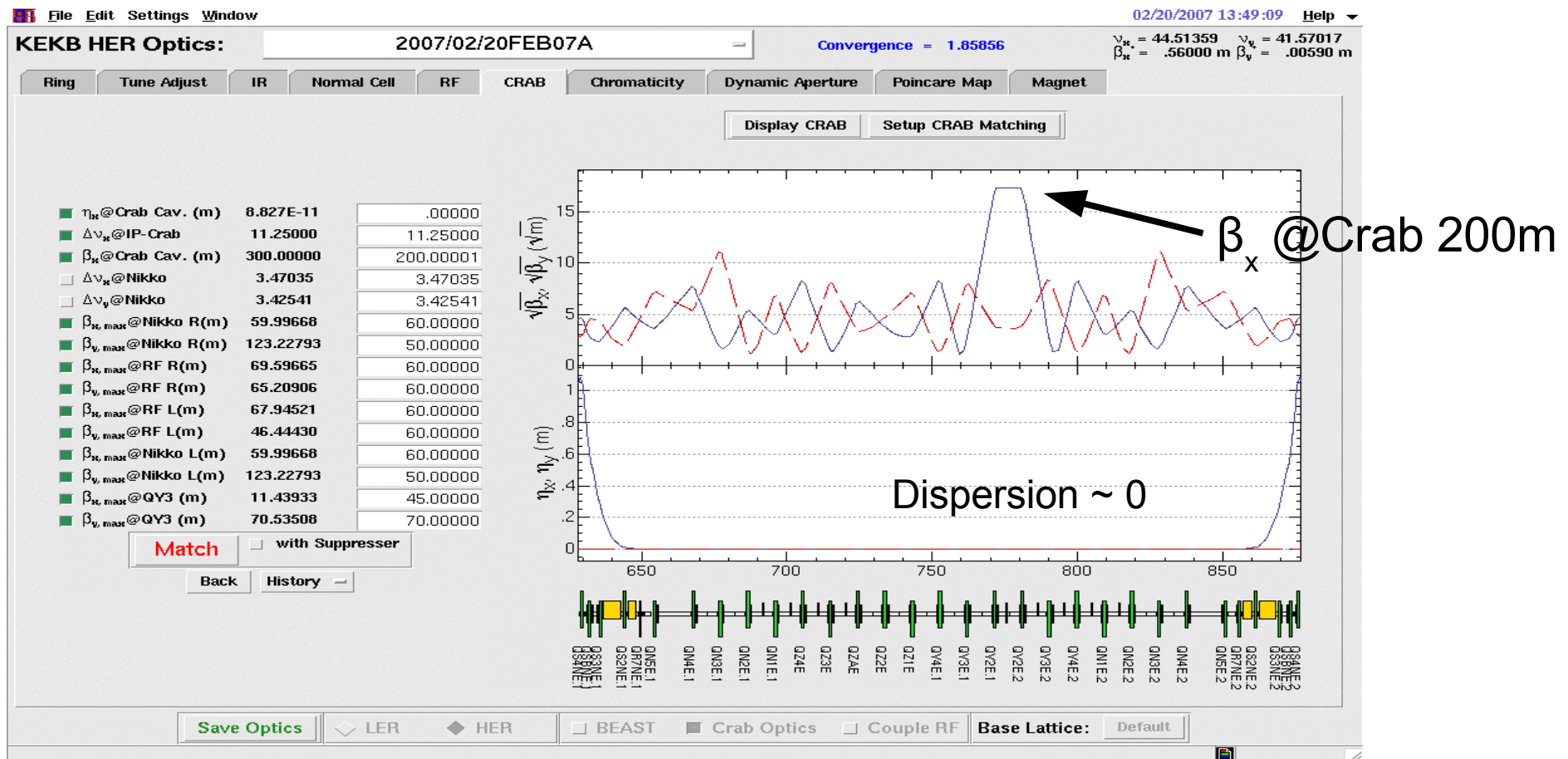
- SAD based online optics (Tk interface)
- Easily change $Q_{\{x,y\}}$, $\beta_{\{x,y\}}$, $\xi_{\{x,y\}}$
- Re-Match and send to power supplies

Courtesy K. Oide, H. Koiso

Tune Measurement
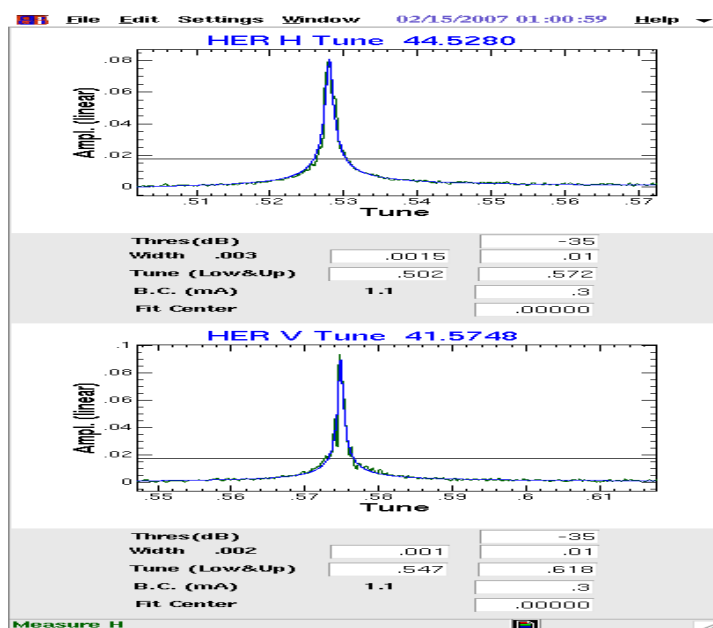
Pilot Bunch Tune
Tune Feedback

Luminosity & Lifetime Vs. Tune

Courtesy KEKB AP Group
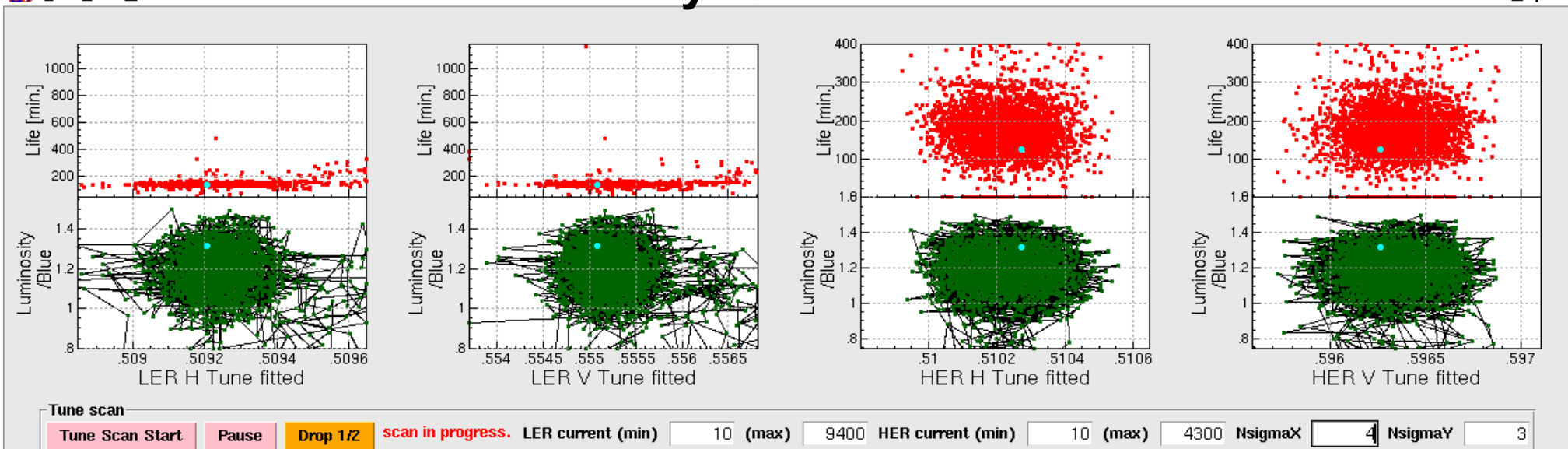
Tune (Freq Sweep)
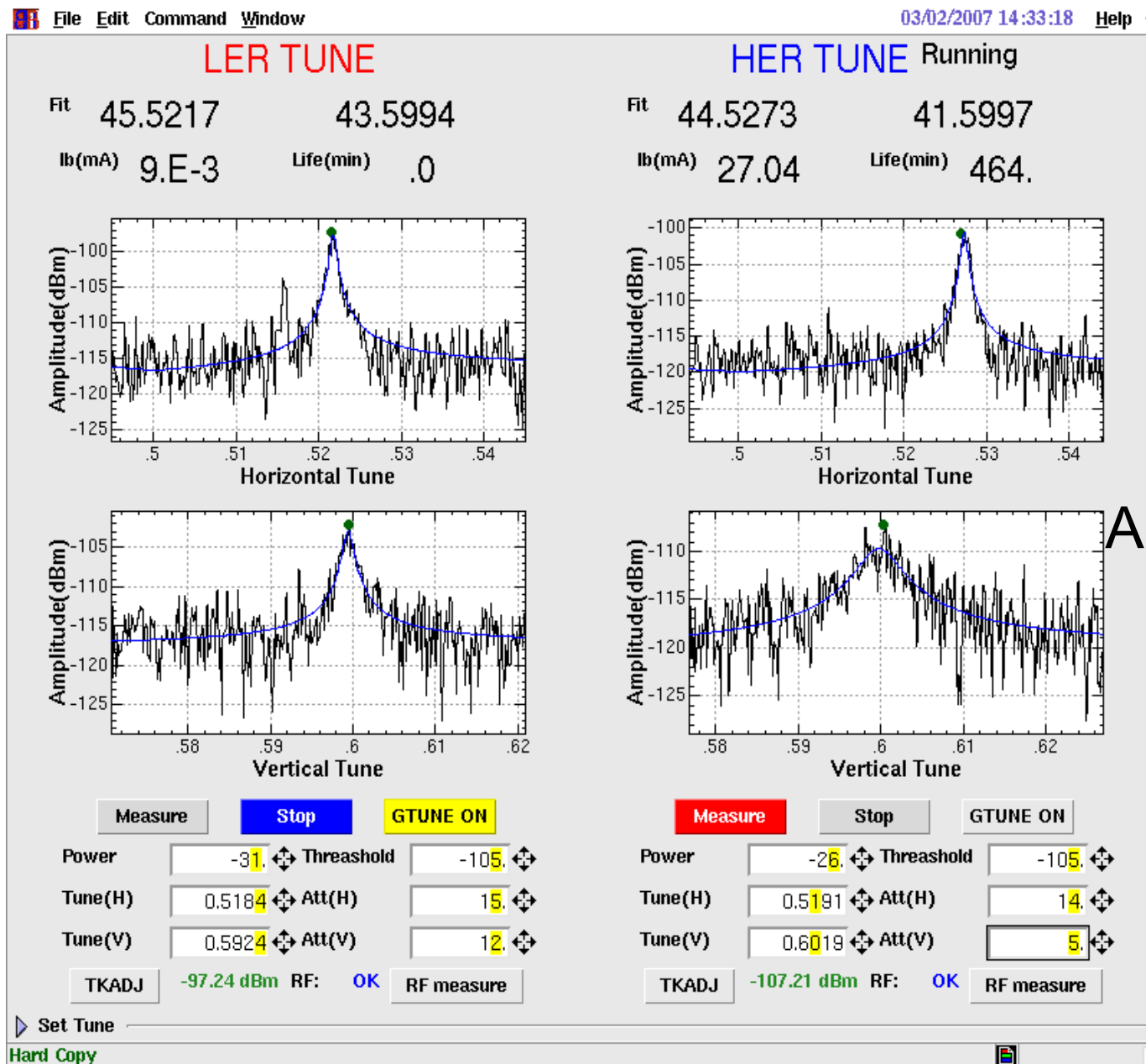
All Bunches

Optics Correction
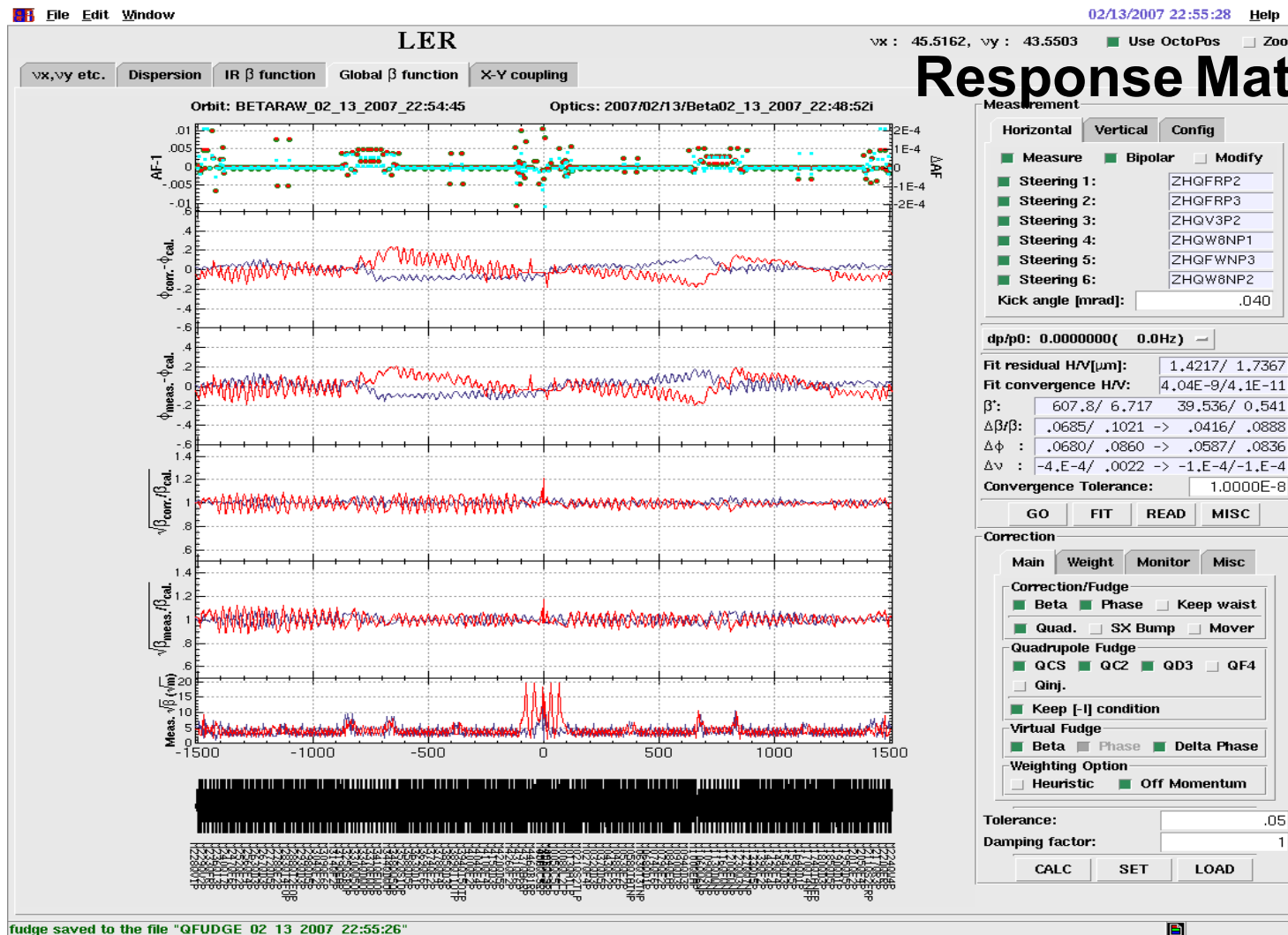
Response Matrix + QUAD Circuits

~ 3-4% Beta-Beta
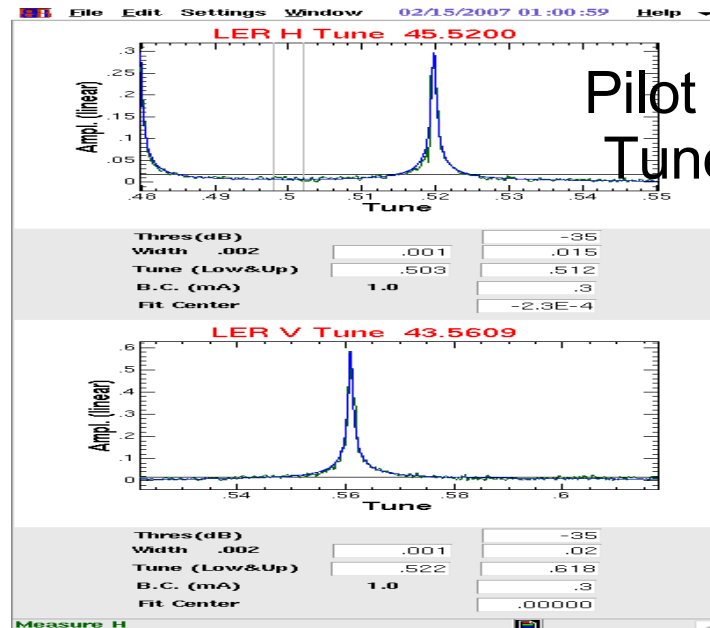~ 0.04 deg Phase-Beat

6 Correctors:

$$x_{ik} = f_k \cos(\pi \nu - |\mu_i - \mu_j|) \equiv F(i, \beta_i, \mu_i, f_k, \mu_k)$$

Least Squares Minimize:

$$\sum_{ik} (x_{ik} - F_{kick})^2$$

Courtesy A. Morita

X-Y Coupling
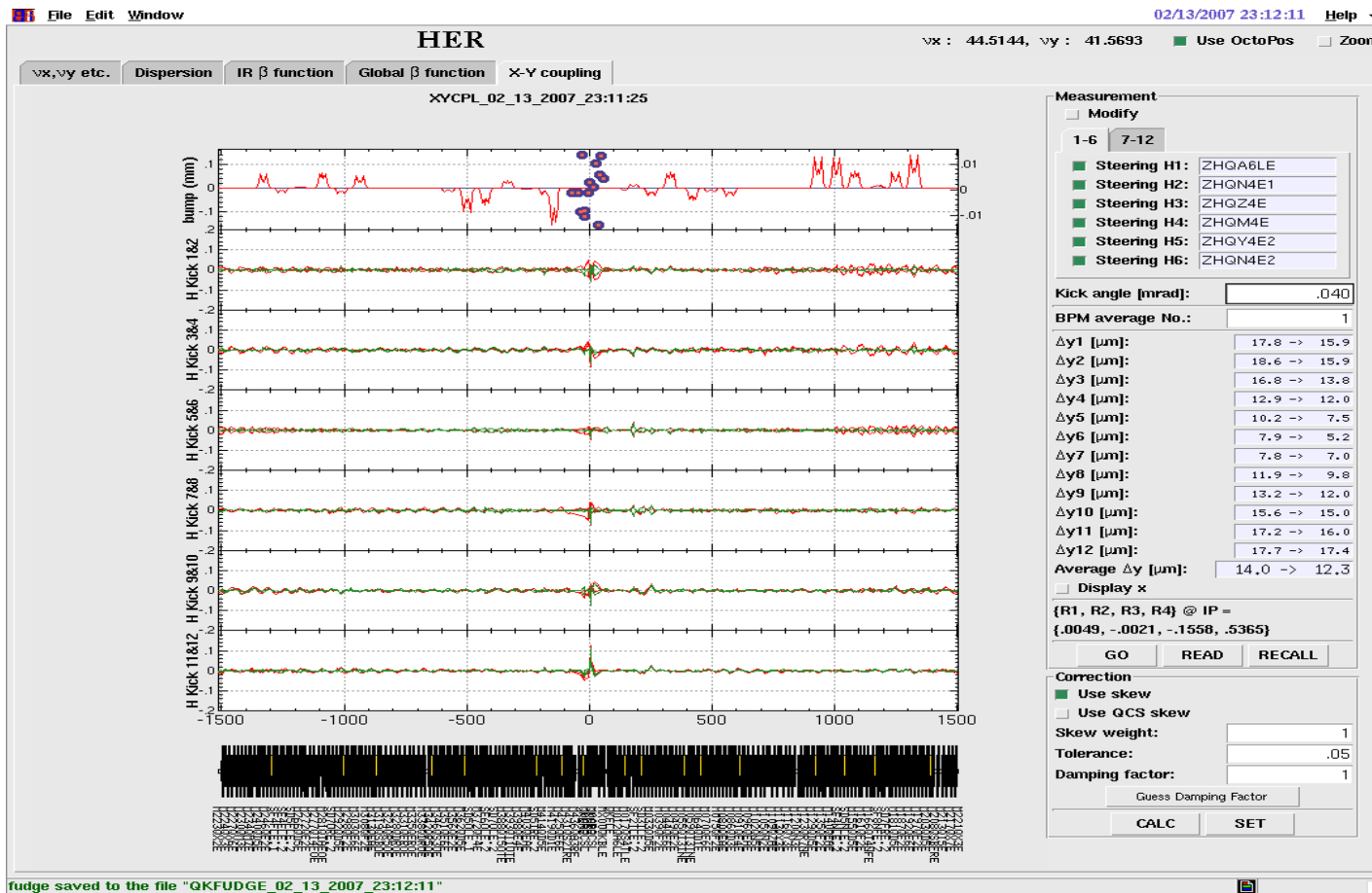
$$\Delta y_{rms} < 20 \mu m$$

Observe vertical leakage from horizontal steering magnets (reduce ε_y)

Correct:

- IR skew quads LER (8), HER (12) (local IR correction)
- Symmetric vertical bumps @SD sextupoles

Courtesy A. Morita

Dispersion Correction
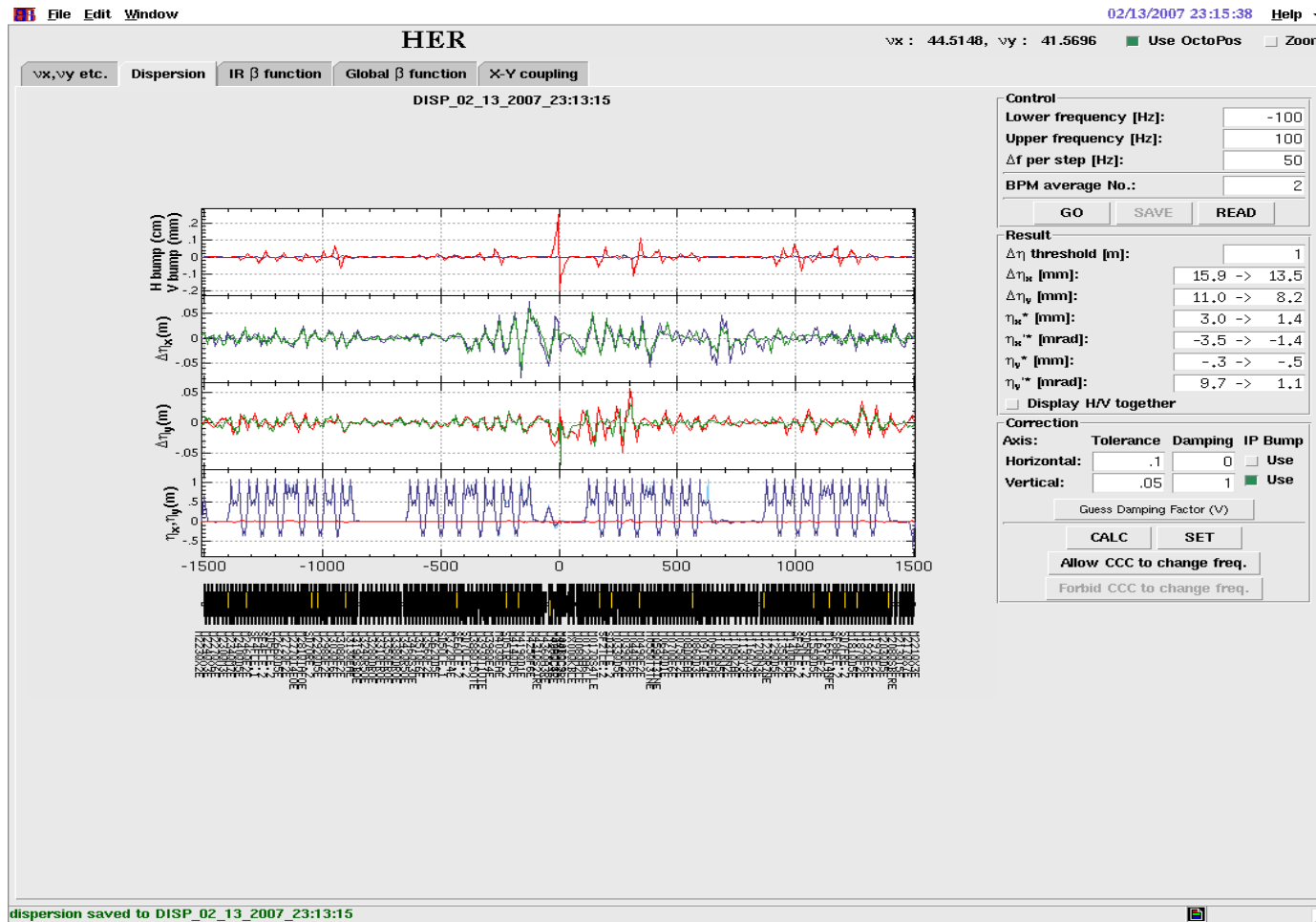
Typically:

$$\Delta \eta_{(x,y)} < 2\,cm$$

$$\Delta \eta_{(ip,y)} < 1\,mm$$

Measure using RF radial loop method

Correct:
- Asymmetric X&Y bumps @SF & SD sextupoles

Closed Orbit Correction

Crab Phase Scan

Correction ~ every 10 sec

Crab Orbit Feedback

- 4 correctors for each ring

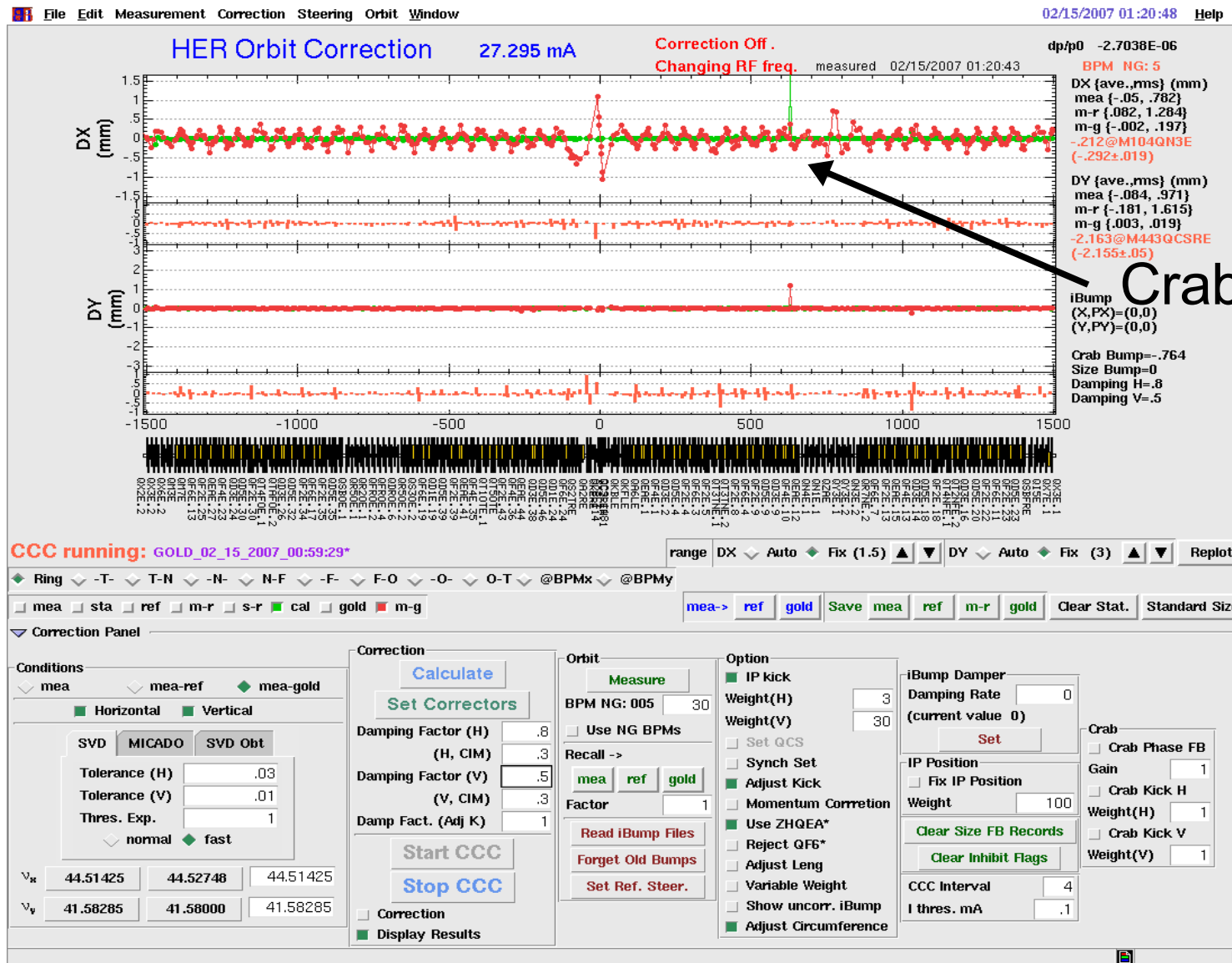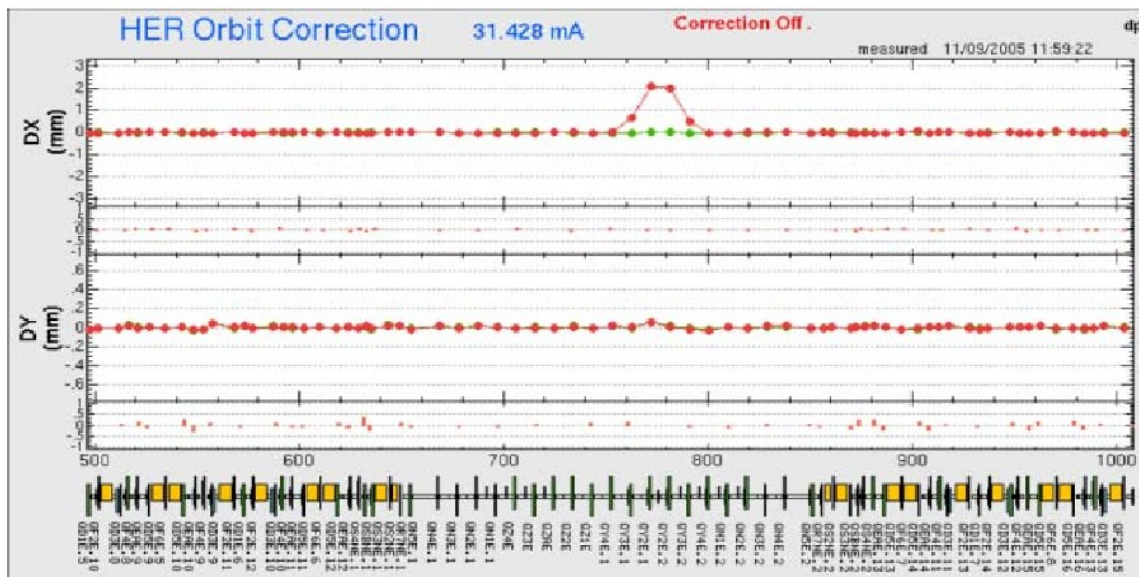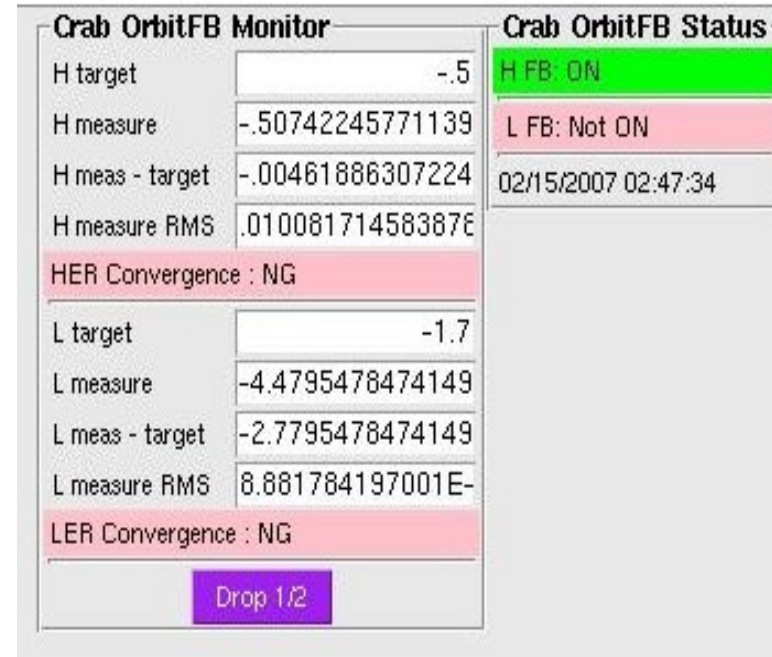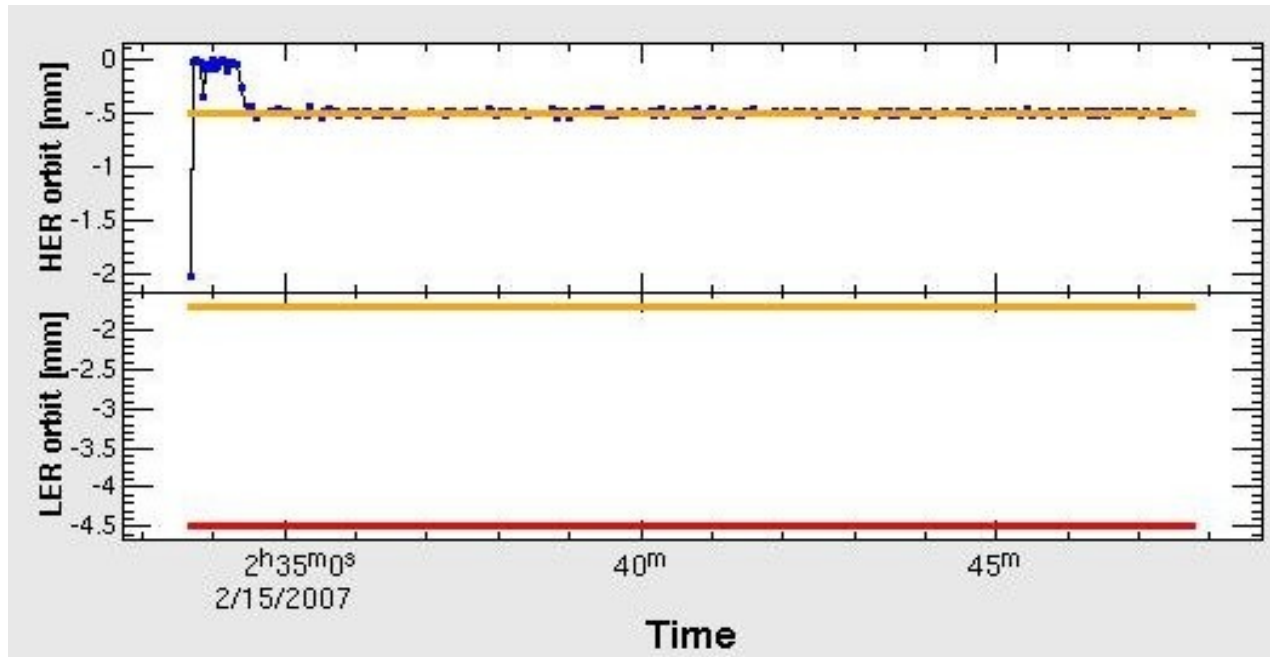- 1 Hz correction feedback

- Much faster than CCC

Courtesy M. Mazuzawa, Y. Funakoshi

Streak Camera

Courtesy H. Ikeda, H. Koiso
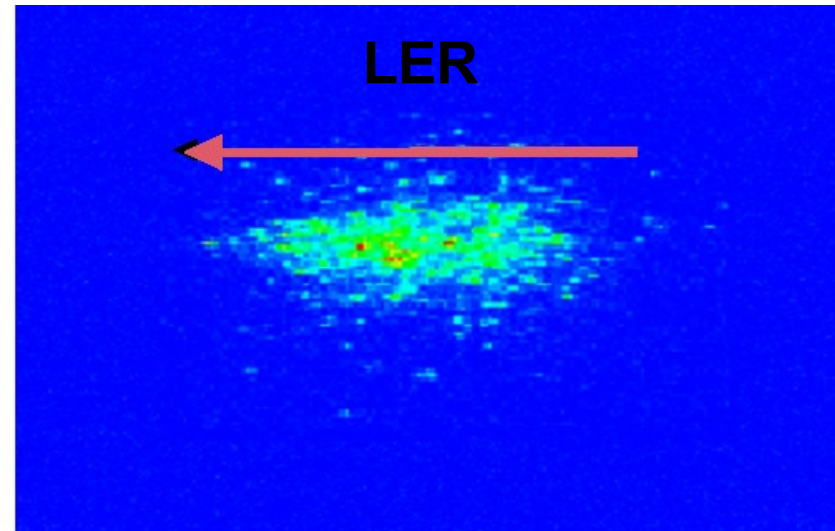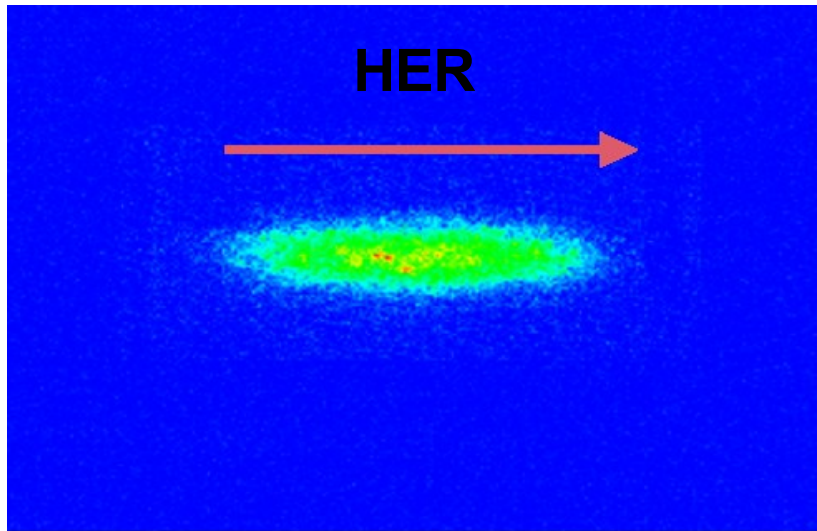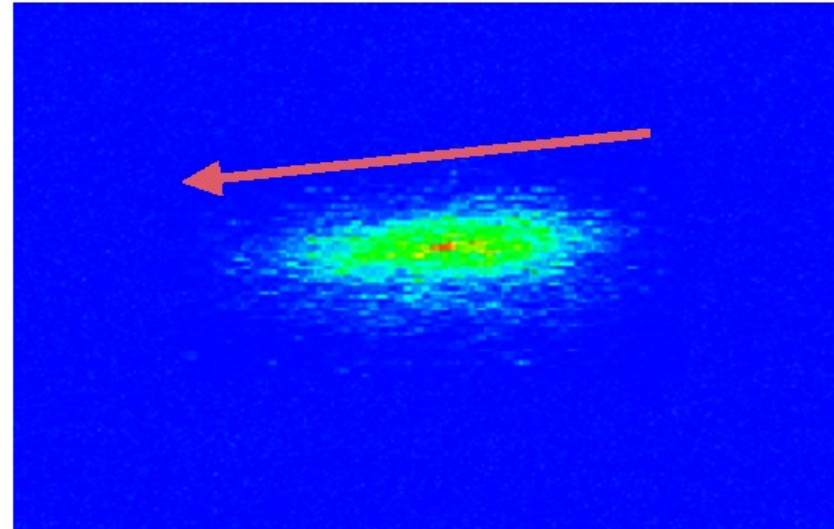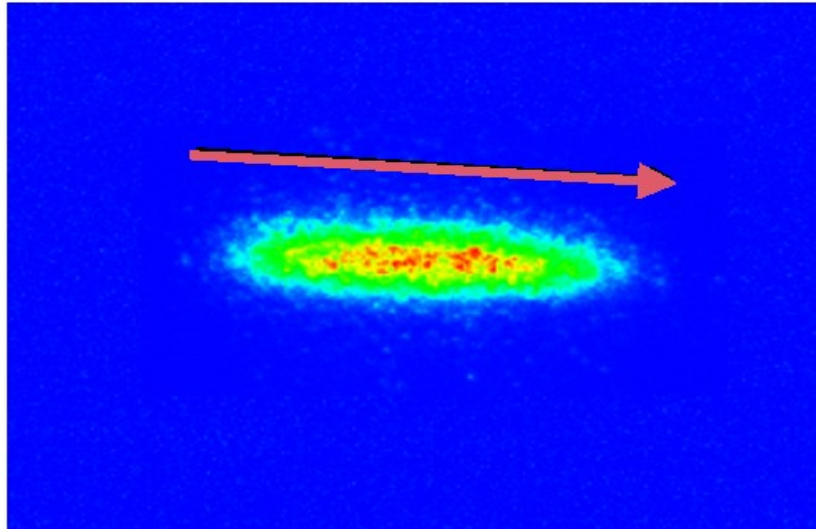
Beam Size Optimization & SR Monitor

- Optimum empirical Ratio of $\sigma_y^{LER} / \sigma_y^{HER}$

- η_y of HER beam controlled by local Horizontal bump in IR

- X-Y local coupling is compensated by skew quads or vertical bumps

- Beam size measured by SR monitors

Courtesy KEKB AP Group
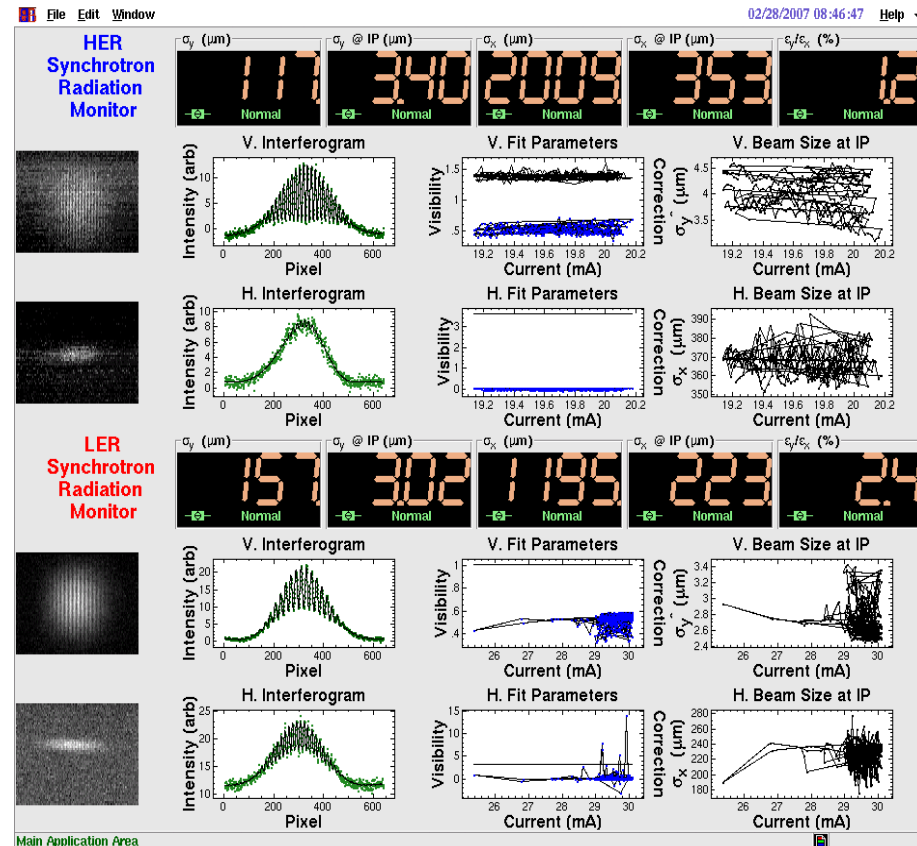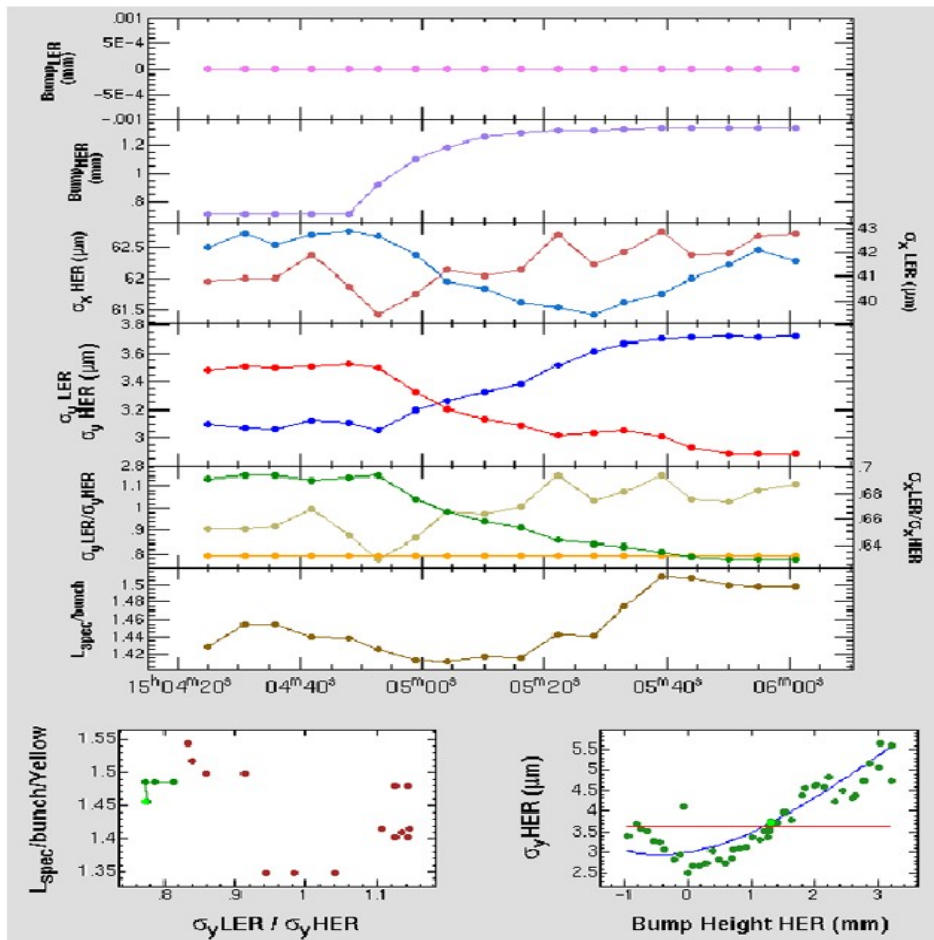
IR Orbit Scan

- 12 Local dipole correctors: 4-Hor & 8-Ver

- 4 dedicated BPMs for HER & LER

- Scan orbit to find optimum position with beam-beam

Lifetime better with a small offset
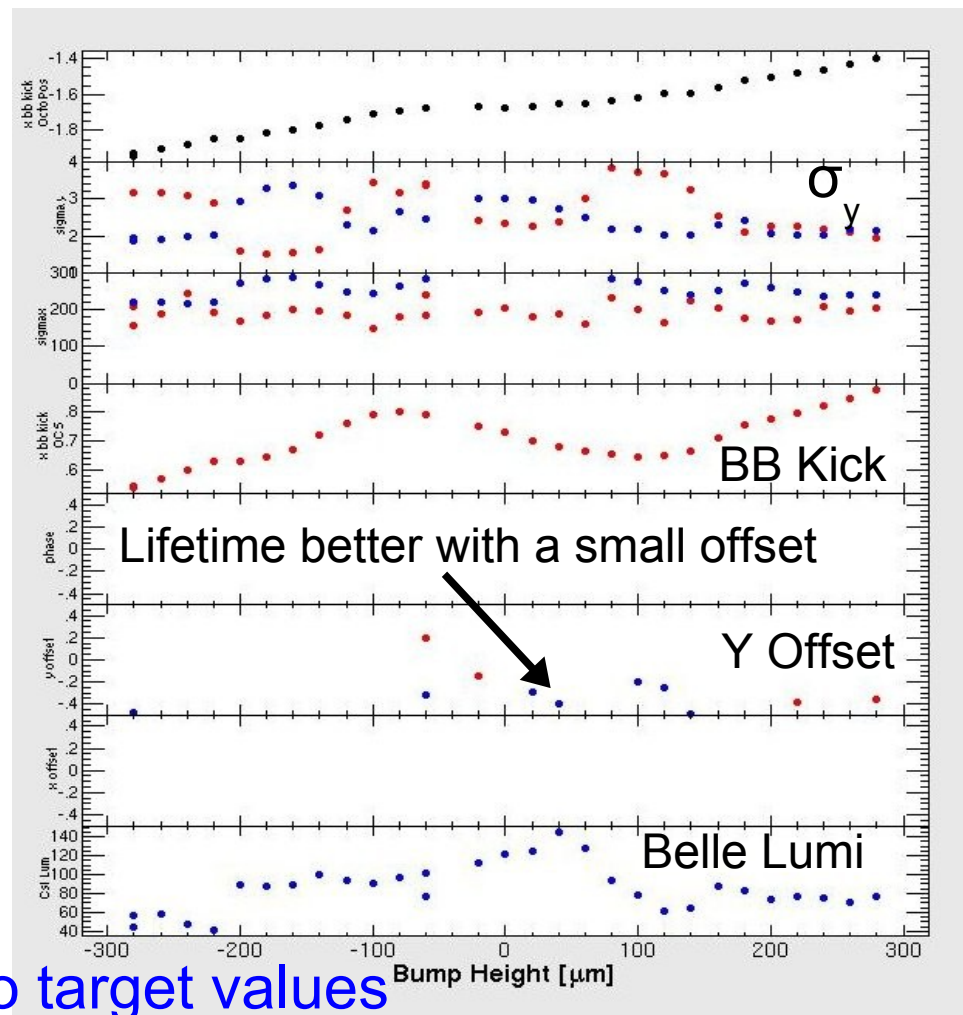
Feedback on canonical BB Kick & θ_c to target values

IR Waist Scan

- Vary IR quadrupole (Δφ ~ π/2, localized β modulation)
- Measure luminosities, lifetime, and beam size

Courtesy Y. Funakoshi, H. Koiso et al.
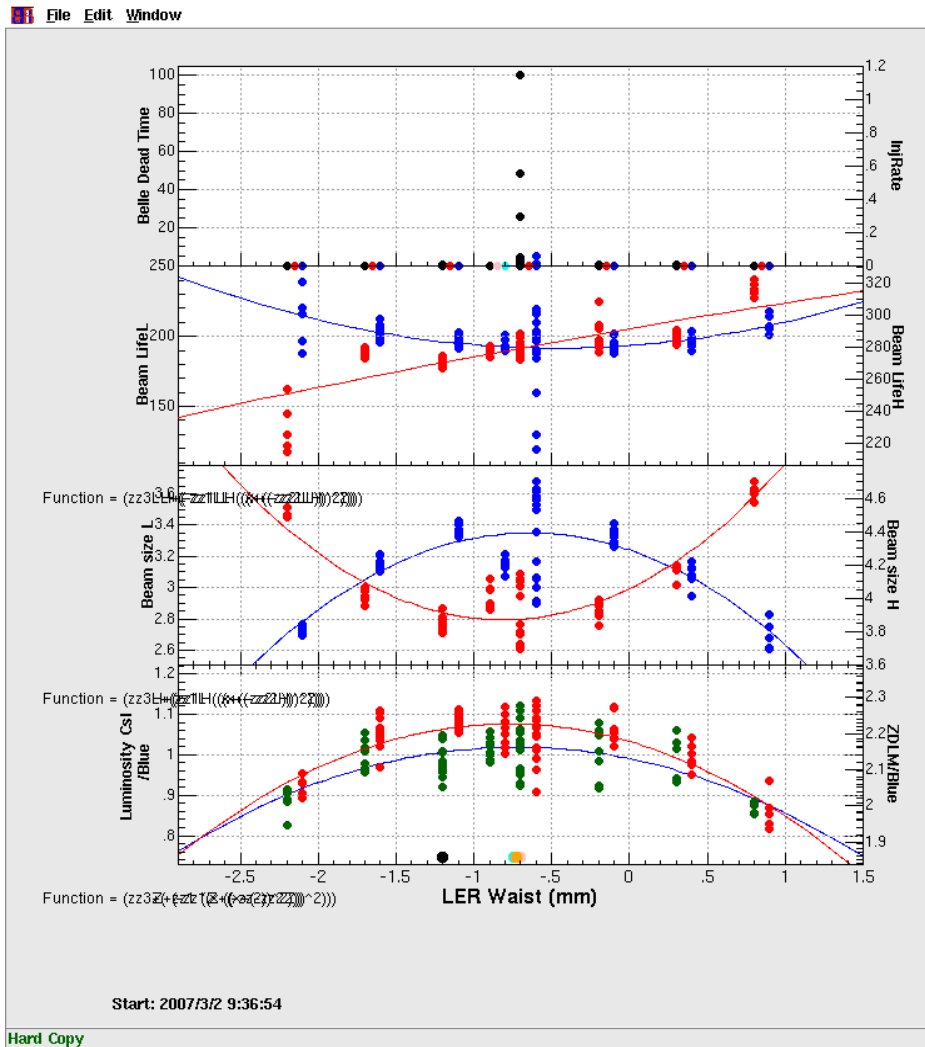
IP Knob Scan Data

Orbit Bumps in the 4 pairs of Sextupoles in the IR

Knob 1
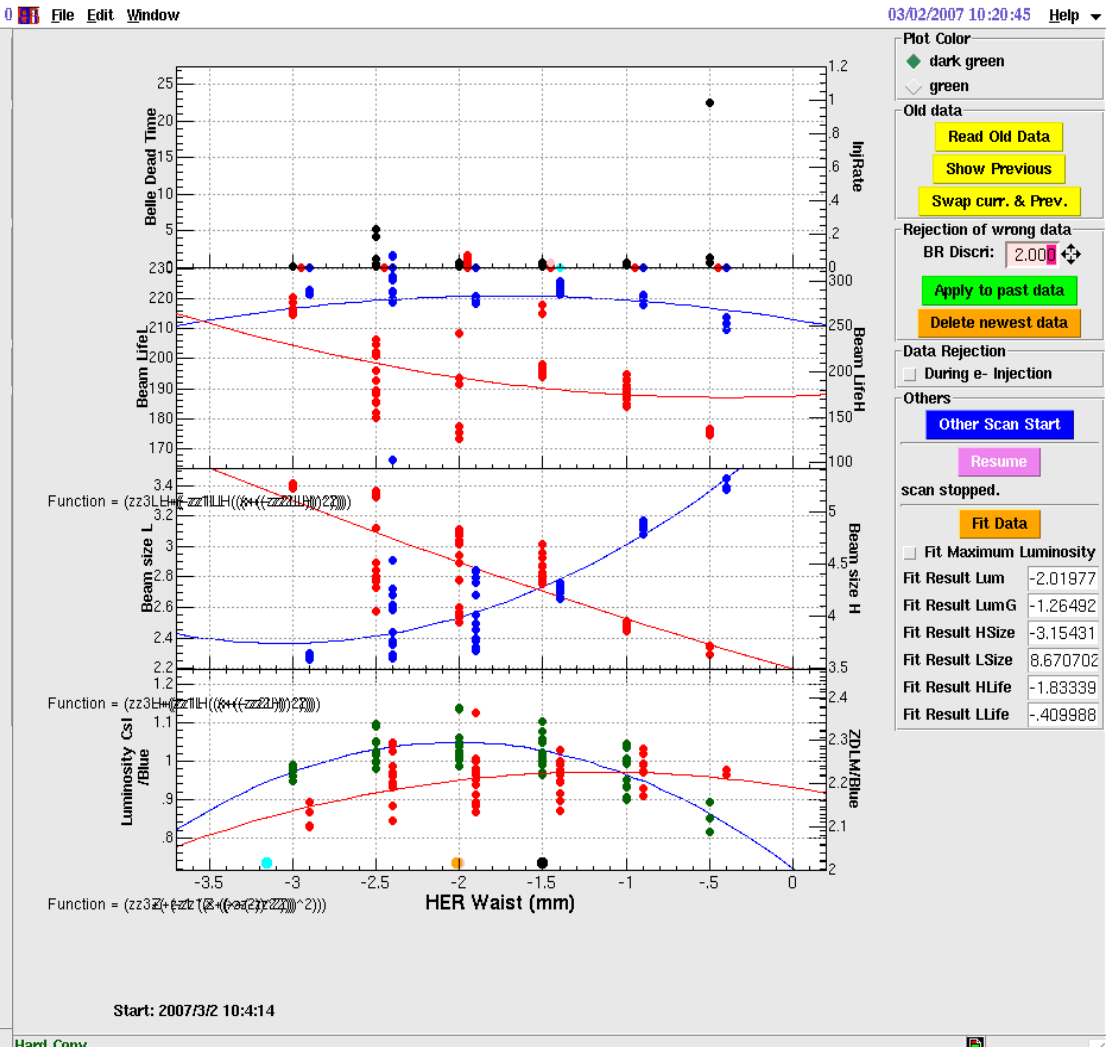
Waist
Dispersion
Coupling

Knob 2

Beam Size
Tunes
Chromaticities
Chromatic Derivatives

Knob 3 — **All Sextupoles**

Beta Functions
Dispersion
Coupling
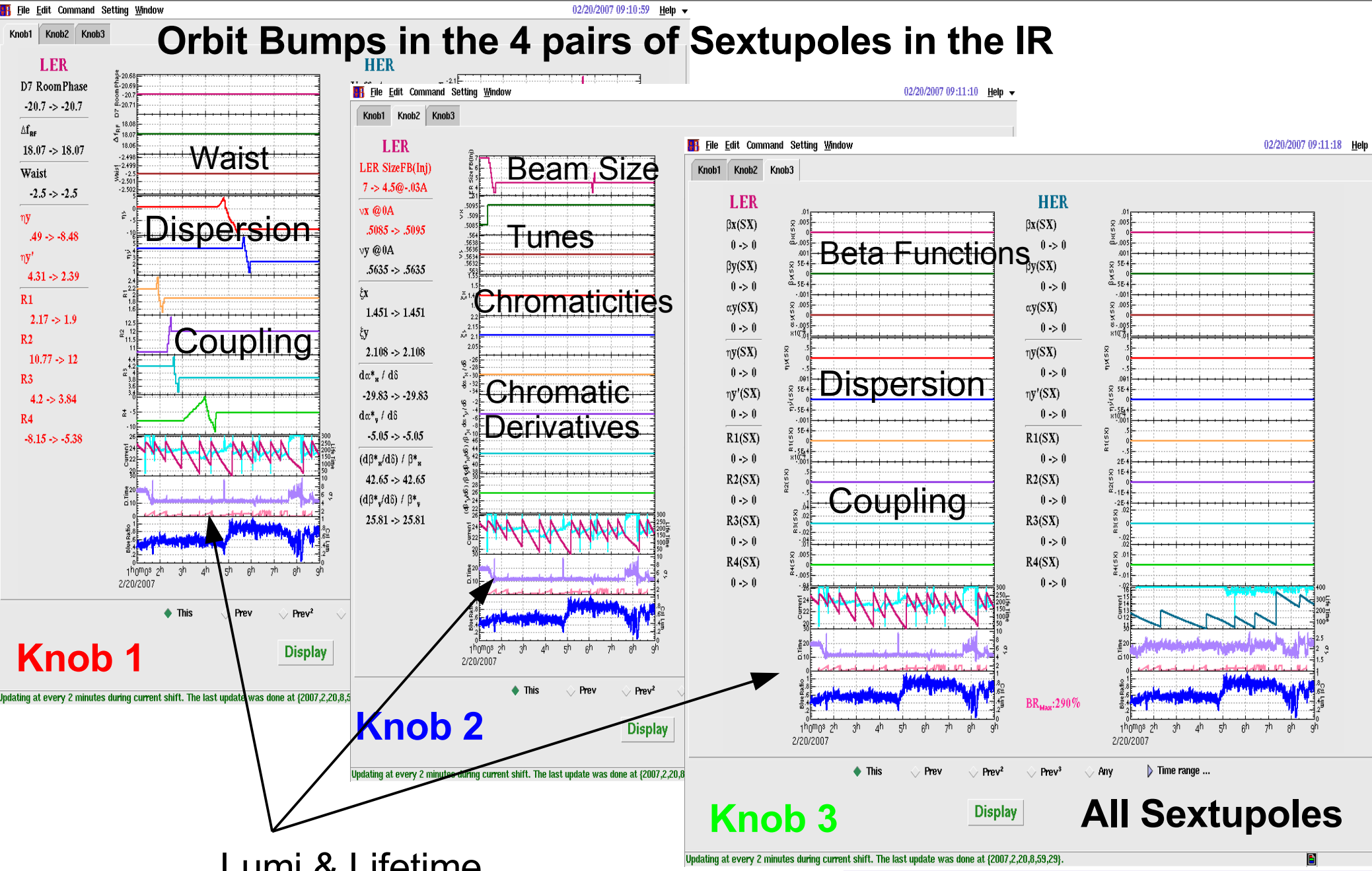
Lumi & Lifetime

Courtesy Y. Funakoshi, H. Koiso et al.

Beam & Crab On
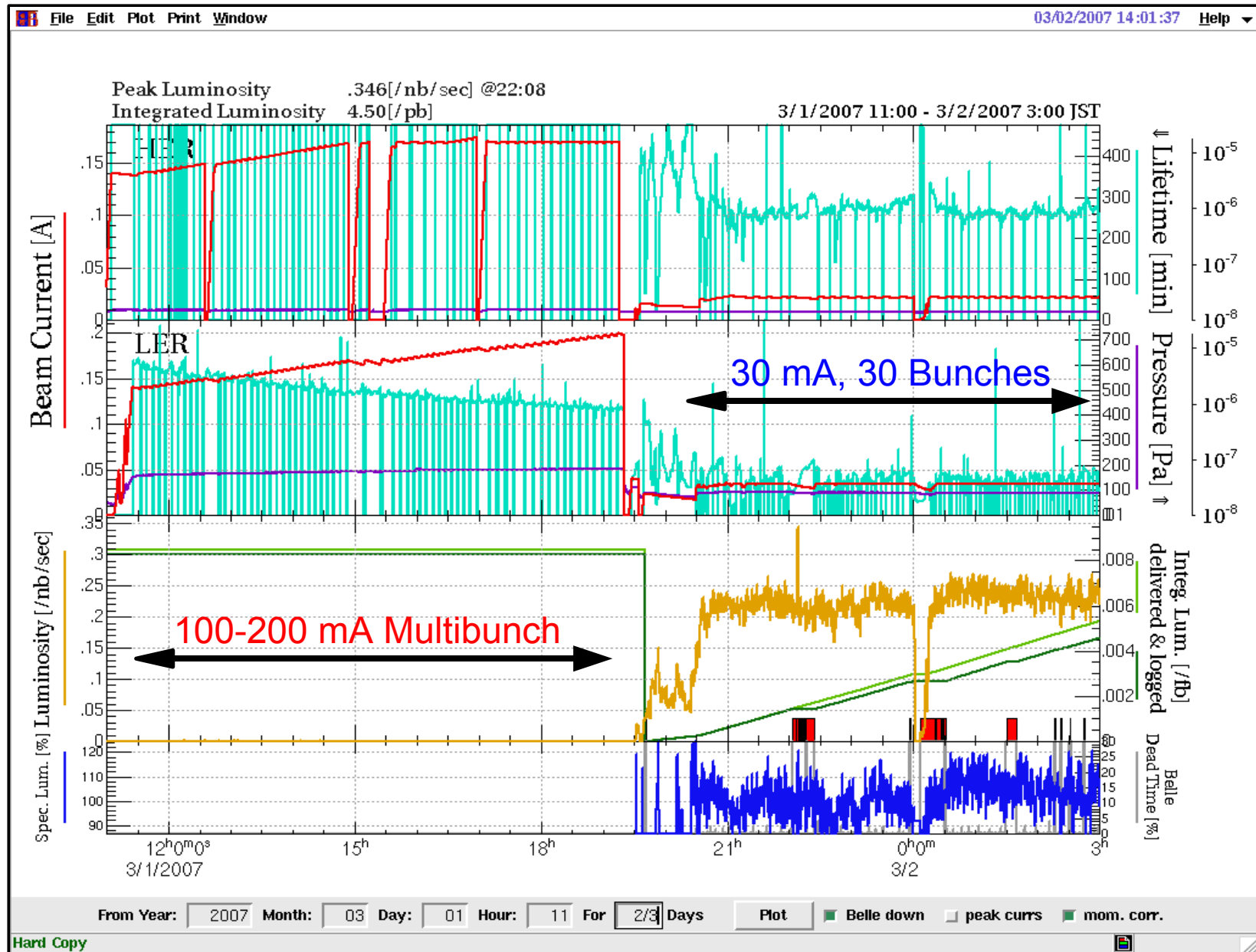
Specific Luminosity

Courtesy H. Koiso
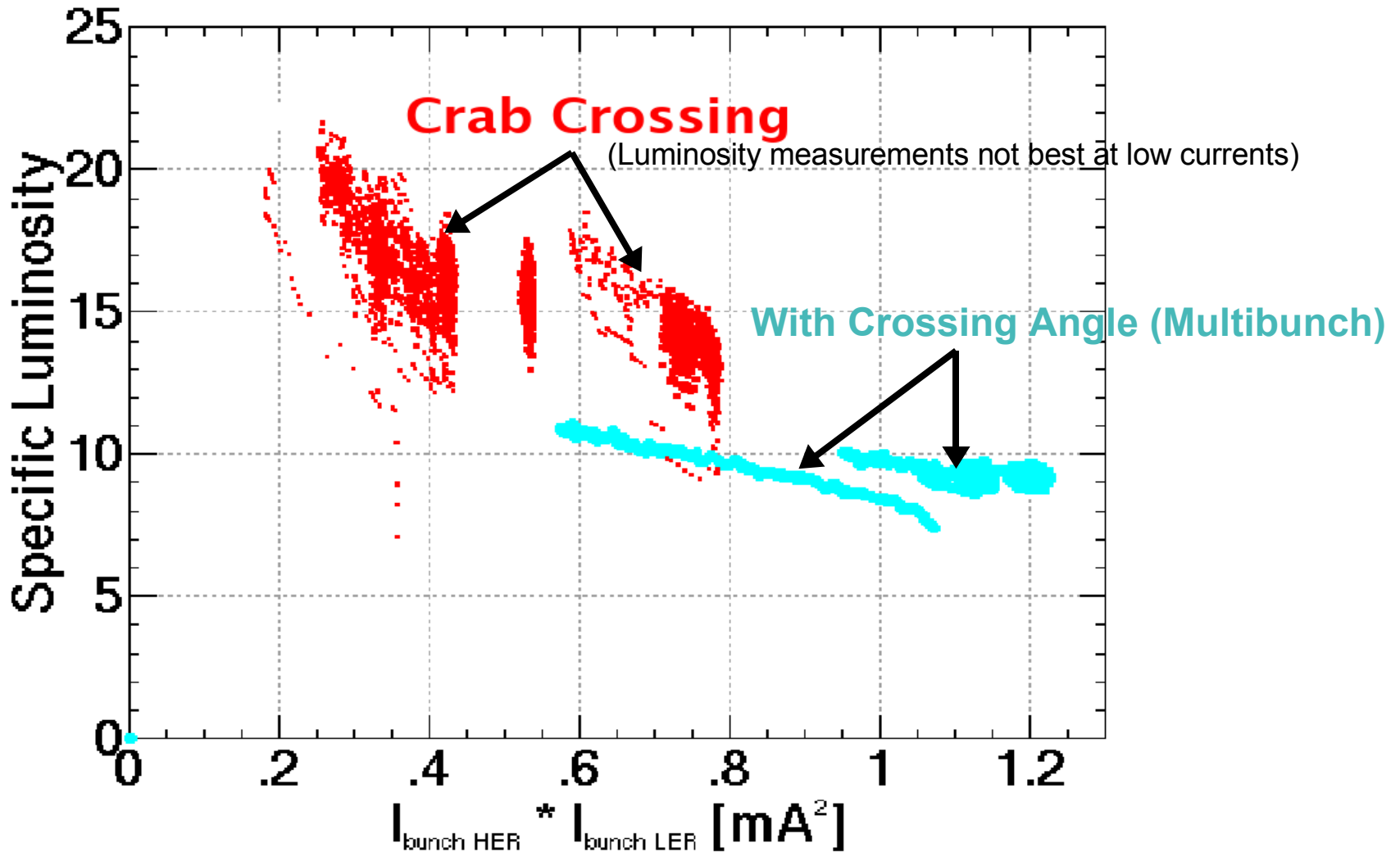
Conclusions

- Almost 15 yrs of R&D on the idea of crab cavities

- Two cavities installed Jan 2007 and successfully crabbed the beam

- More tuning needed for luminosity optimization, also increase LER $V_{crab} \sim 1.4$ MV

- Stability and vacuum issues at high currents ??

- Next milestone ~ 200 mA to observe benefits from head-on collision

Need to benchmark Ohmi's Beam-Beam code with HEADTAIL (or others) including

LHC sector map + crab cavity for phase tolerances and such for LHC

KEK-B group enthusiastic about LHC crab proposal, future collaboration foreseen

Many Thanks to K. Oide, K.Ohmi & KEKB Team !!

And Good Bye Japan...