Issues and Plans on Beam Diagnostics in SuperKEKB

10th Feb. 2009, KEKB review committee

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1. Introduction
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3. Synchrotron Light Monitor
4. Gated Measurement
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1. Introduction

•Parameters of SuperKEKB related to the beam diagnostics

	HER	LER
Energy (GeV)	8	3.5
Current (A)	4.1	9.4
Bunch length (mm)	3	5
Number of bunches	5018	5018
Bunch separation (ns)	2	2
Emittance (nm)	18	24
Transverse damping time (ms)	47	84
Vacuum chamber	ante-chamber	ante-chamber
Chamber cross section (mm)	65x14(?)	50φ(?)

2. Beam Position Monitor

A)Requirement

- Requirement to the BPM system is not fully specified yet.
- We tentatively assumed that the required performance is same as the performance in present KEKB.

  resolution : several micron, accuracy : 40 micron (by beam based alignment)

- We also tentatively assumed that following functions are required according to discussions in KEKB group so far.

  a) Precise slow (about 1Hz) closed orbit measurement

  b) Turn-by-turn measurement during physics run to measure the betatron amplitude and phase at BPMs.

B) Items to be considered

a) Large beam current of about 10 A

- Large signal power to a detector, poor electrical contact and movement of BPM due to thermal deformation of a chamber

  ⇨ ◊Reduce the diameter of the button from 12mm to 6mm,
  ◊Use pin type inner conductor for tight electrical connection,
  ◊Use displacement sensors.

b) Use of ante-chambers

- Lowest cut-off frequency of a chamber is below 1 GHz which is a detection frequency in KEKB system (cut-off frequency is 768 MHz for a chamber of 50 mm ϕ).

  ⇨ ◊Change the detection frequency from 1018 MHz to 509 MHz,
  ◊Develop a new detection module for 509 MHz detection.

c) Maximal use of present system to save the cost

  ⇨ ◊Maximal use of present VXI modules, cables and so on.

d) Cold BPM

- Several BPMs around IP might be at He or N_2 temperature if cold bore magnets are used as recently discussed.

e) Turn-by-turn orbit measurement in large current operation

A proposed solution

1)Kick a pilot bunch, then measure its position.

2)Put a fast gate in front of a detection circuit to pick up a signal of the pilot bunch.

3)Increase the number of turn-by-turn BPMs.

Turn by turn BPM in KEKB

- 38 log-ratio detection modules are installed.
- Slow measurement and turn-by-turn measurement are switched by switch modules.
- 120 turn-by-turn detection modules can be housed at the maximum to present VXI mainframes.

◊Increase the number of turn-by-turn BPMs to 120.

◊These circuits cover 1/4 of BPMs in each ring.

◊A simulation shows that 90 BPM data are needed for the betatron phase measurement if the number of the power supplies of quadrupole is same as that in KEKB.

Button electrode

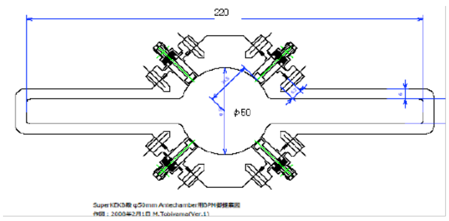
- A button electrode is under development. Prototypes are installed in ante-chambers in Nikko straight section for test.

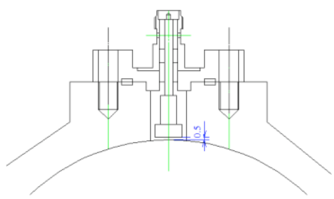
◊Diameter : 6mm

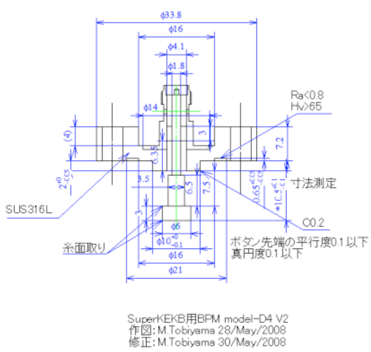
◊Flange type for easy replacement upon trouble

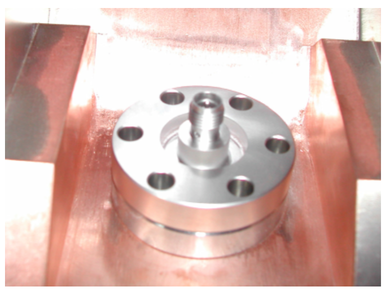
◊Pin-type inner conductor for tight electrical connection

◊Ceramic vacuum seal





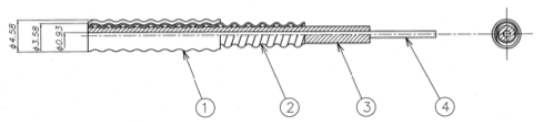




Radiation-resistant flexible PEEK coax-cable (3D)

- A radiation-resistant PEEK cable is being developed.
- It will replace a present semi-rigid cable which connects a button feed-through with a terminal.

A)Structure



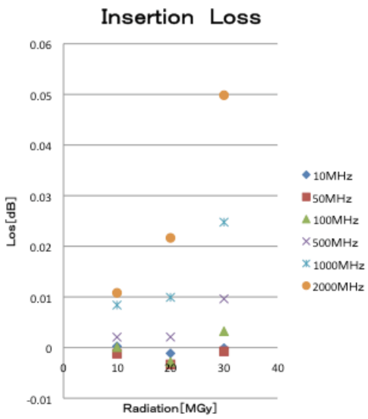
inner conductor (4)	copper lead
insulator (3)	PEEK
outer conductor (2)	corrugated copper duct
covering material (1)	fireproofed non-halogen polyolefin

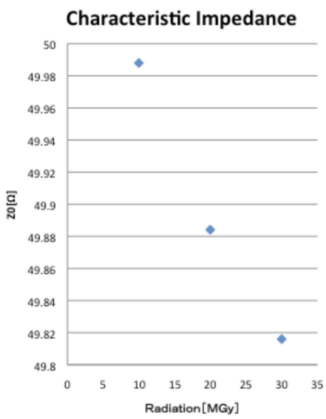
B)Electric characteristics

peak voltage	1000 V AC
characteristic impedance	50 Ω
VSWR	<1.15
attenuation	82 dB/km (50 MHz, 20 deg.)

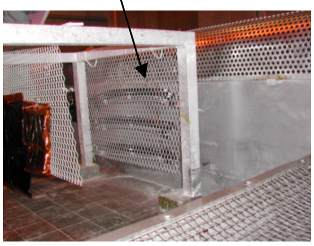
C) Irradiation test

Source : γ ray (Co-60)





cables under test



- No significant deterioration of electric characteristics was observed after irradiation of 30 MGy.
- Outer sheath was damaged after irradiation of 30 MGy (crack at bending).
- Estimated radiation level on the duct is 0.5MGy/year according to the data taken at KEKB in 2004.
- The cable will be tested in next run at KEKB.

509 MHz super-heterodyne detector

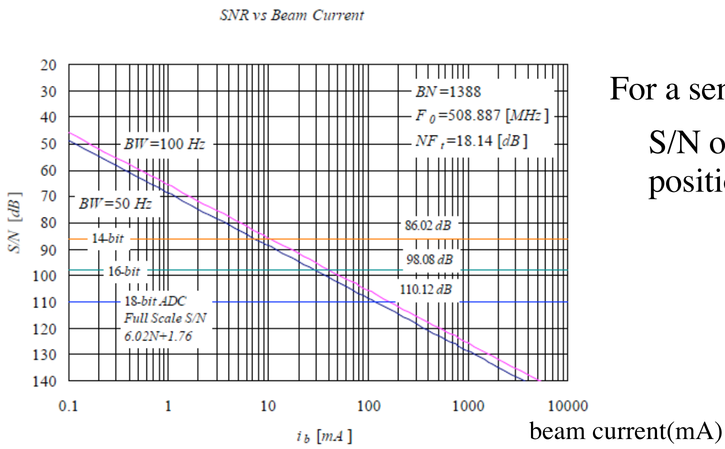
A 509 MHz detector is under development.

A) Consideration of signal to noise ratio (S/N) by thermal noise and position resolution

- Assume,
  - ◊Size of button : 6mm ϕ
  - ◊Detection freq. : 509 MHz
  - ◊Transmission loss of cable (100m) : 9.14 dB
  - ◊Noise Figure (NF) of a detector : 9 dB

signal voltage

position $$x = K\frac{V_1 + V_4 - V_2 - V_3}{V_1 + V_2 + V_3 + V_4}$$



For a sensitivity constant K of 30 mm,

S/N of 83.5 dB corresponds to position resolution of 1 μm.

$$\sigma_{x,y} \approx \frac{1}{2} K_{x,y} \frac{1}{(S/N)}$$

- Resolution less than 1 μm will be obtained at beam current of 30 mA which is a required minimum current for optics correction.

B) Specifications

Detection frequency	508.887MHz
S/N at signal power of -60 dBm	> 89.8 dB
Noise figure	< 7 dB
ADC (bits/sampling freq.)	18 bits / 102.4 kHz
Max. input power	-50 dBm
FFT points	2^N (N=4, 5, ..., 12)

VXI module

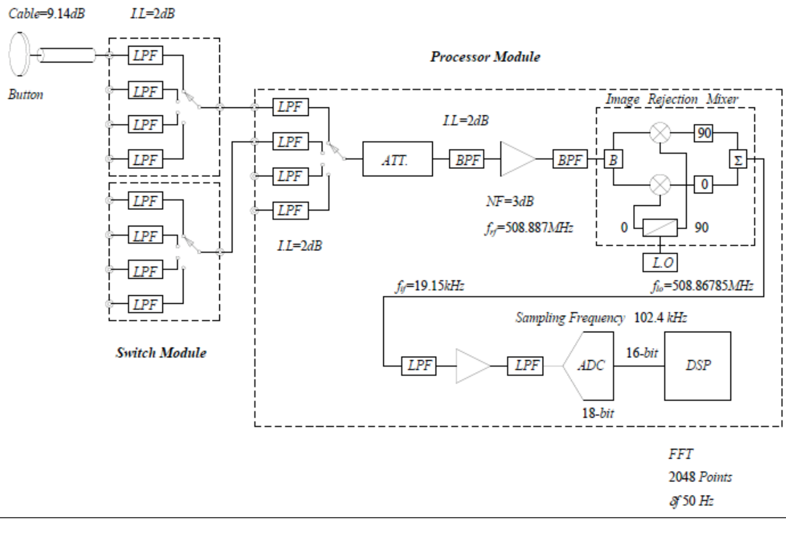
4ch Switch : PIN & FET

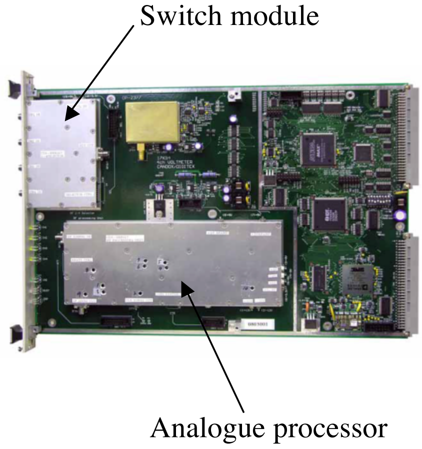
Mixer : Active image rejection mixer

ADC : 18 bits

FFT of IF signal by DSP

DSP : SHARC processor





C) Laboratory test

1) S/N

- Assume that the noise is represented by a noise floor of the signal spectrum.
- Measured $(S/N)_{noise\ floor}$ was 85.1 dB.
- The amplitude A was measured 16 times, then a scattering of A was calculated.

$$(S/N)_{amp.} \equiv \sigma_{r.m.s.}/\overline{A} \;=\; 60.9 \text{ dB}$$

⇨ resolution of 15μm

$(S/N)_{amp}$ is much worse than $(S/N)_{noise\ floor}$ and should be improved.

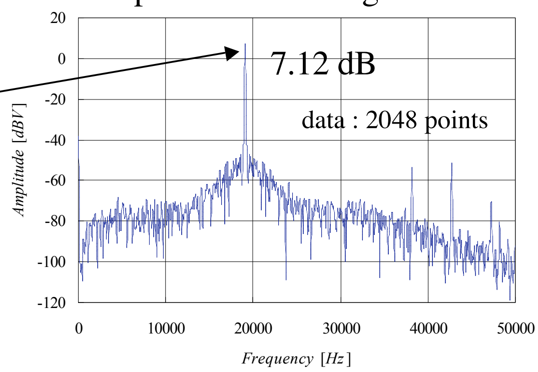
Some noise might be down-converted to IF (Intermediate Freq.).

- Measured NF (from the multiplexer input to output of 1st amp.) was 8 dB which is larger than the spec. (= 7 dB).

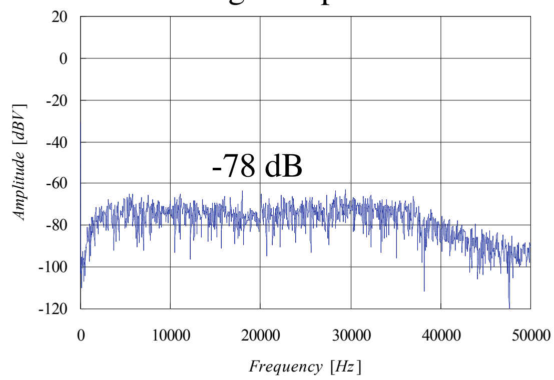
Insertion loss of switches ?

Results of FFT of IF signal

input : 508 MHz signal



no signal input



SNR=7.12-(-78)=85.1(dB)

2) Linearity

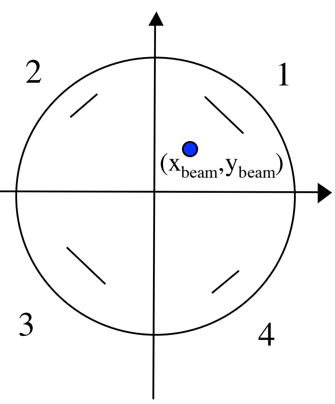
- Input vs. output characteristics of 4 channels was measured at the company and fit to a 3rd order polynomial as,

$$V_{out,i} = \sum_{j=0}^{3} a_{j,i} V_{in,i}^{j} \quad \text{i : ch no.}$$

Assume linear relations of

$$V_{in,1} = V_0\left(1+\frac{1}{K}(+x_{beam}+y_{beam})\right),\ V_{in,2} = V_0\left(1+\frac{1}{K}(-x_{beam}+y_{beam})\right),$$

$$V_{in,3} = V_0\left(1+\frac{1}{K}(-x_{beam}-y_{beam})\right),\ V_{in,4} = V_0\left(1+\frac{1}{K}(+x_{beam}-y_{beam})\right)$$



Positions are calculated as

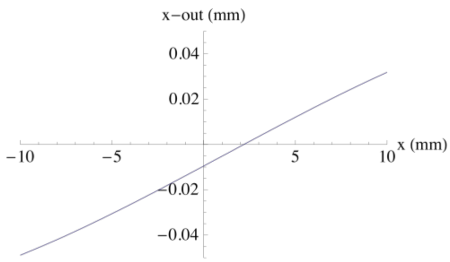
$$x_{out} = K\frac{V_{out,1}+V_{out,4}-V_{out,2}-V_{out,3}}{V_{out,1}+V_{out,2}+V_{out,3}+V_{out,4}},$$

$$y_{out} = K\frac{V_{out,1}+V_{out,2}-V_{out,3}-V_{out,4}}{V_{out,1}+V_{out,2}+V_{out,3}+V_{out,4}}$$

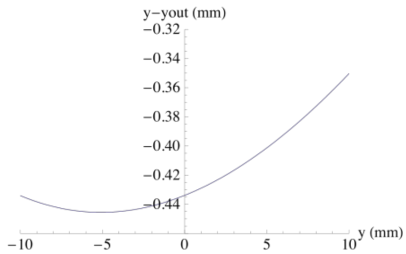
The x_{beam}-x_{out} was plotted as a function of x_{beam}.

•Result

$x_{beam} - x_{out}$ at y=0mm



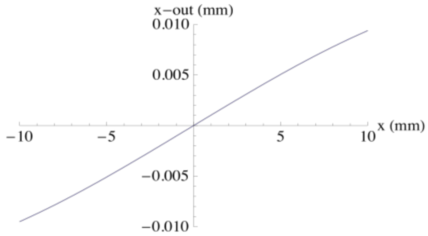
$y_{beam} - y_{out}$ at x=0mm

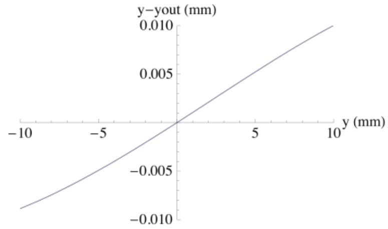


The error is about 0.1mm in -10 mm < x, y < 10 mm.

If offsets are removed and gains are equalized, position errors are 10μm within -5 mm < x, y < 5 mm.

$$V_{out,i} = \sum_{j=0}^{3} a_{j,i} V_{in,i}^{j} \qquad a_{i,0} = 0,\ \mathrm{i} = 1,4, \quad a_{1,1} = a_{2,1} = a_{3,1} = a_{4,1}$$



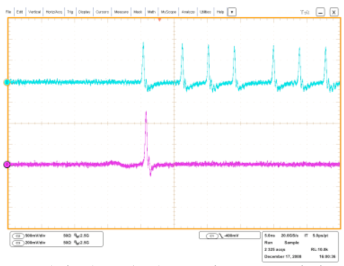


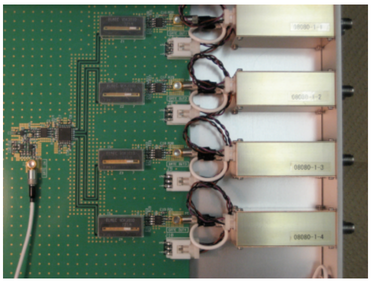
The tolerance of the nonlinearity to the operation should be estimated.

Four channel gate

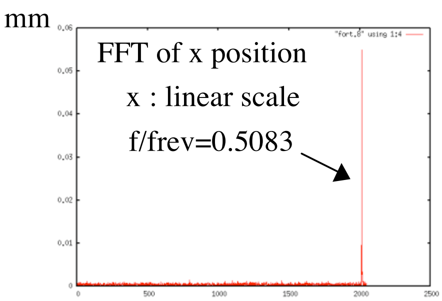
•A 4 ch gate was tested to measure the turn by turn orbit of a pilot bunch separated by typically 6ns from a bunch train.

•Switches of a gate module for the bunch by bunch diagnostics in KEKB are used.





•A bunch was kicked then its position was measured by a turn by turn BPM in KEKB.



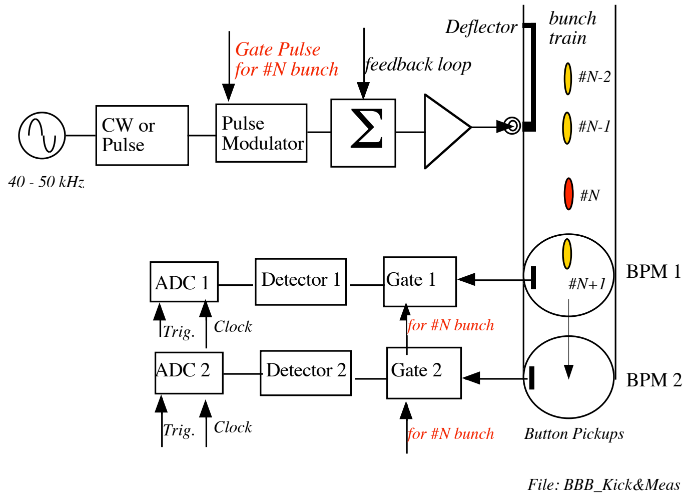
Specifications

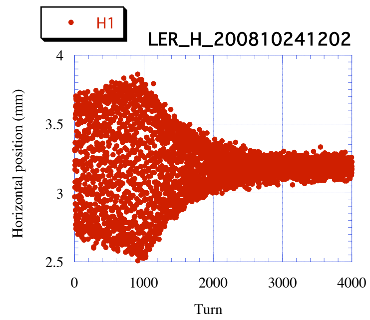
- Frequency Range: DC - 4 GHz
- Impedance : 50 Ohms
- Number of channels : 4
- ON/OFF isolation : > 60dB @ 2GHz
- Channel Isolation : ~ 80 dB @2GHz
- Insertion loss ~ 3 dB
- Control Voltage: NIM level

•The oscillation of the bunch was clearly identified.

Exciter of a bunch oscillation

- The oscillation of a bunch is excited by shaking the bunch at the frequency of a tune.

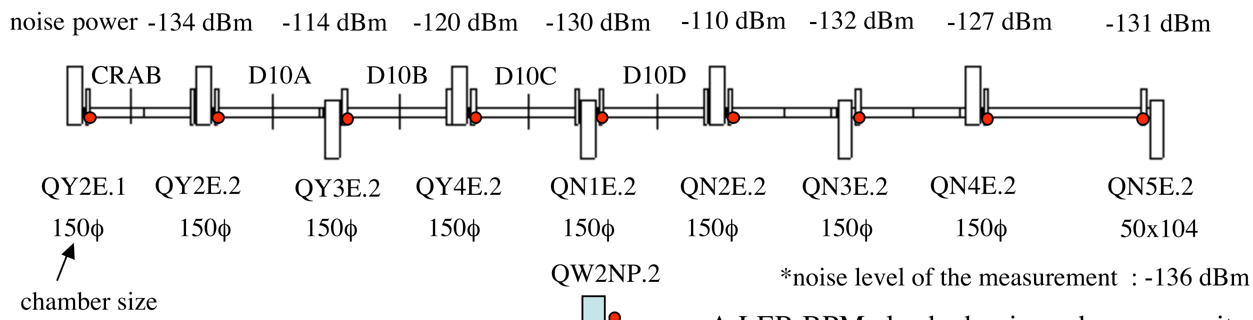




- A tracking exciter using PLL will be tried in next run in order to stably kick the bunch.

BPM noise at 509MHz

- In SuperKEKB the detection frequency is not 1 GHz but 509 MHz because antechambers will be used.
- Noise from RF system might be troublesome.
- 509 MHz signal was measured at Nikko straight section when RF cavities in HER were powered.



QW2NP.2

-118 dBm

*noise level of the measurement : -136 dBm

- A LER BPM also had noise, where no cavity in LER is in Nikko straight section.

- S/N from the measurement

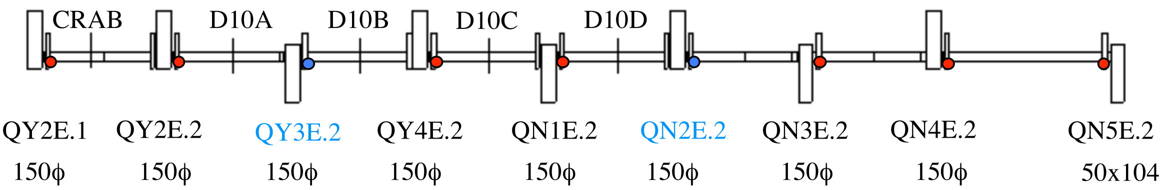
signal : -51 dBm@30mA

noise : -110 dBm (QN2E.2)

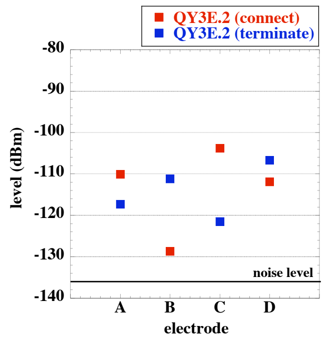
1/(S/N)=-110+51=-59 dB = 0.0011

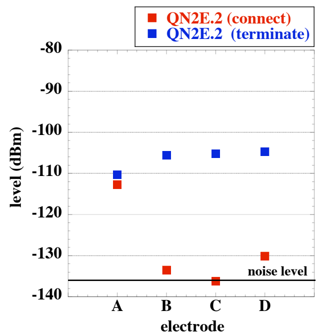
⇨ position error=1/2 x K x 1/(S/N)
=1/2 x 33mm x 0.0011
=18 μm

•Second measurement was done to assure the noise did not came from the cavities through the chamber.



•The signals from QY3E.2 and QN2E.2 were measured connecting cables to feed-through or terminating the cables to 50 ohm.





red : connected to the feed-through.
blue : terminated to 50 ohm.

•Almost same level or larger noise was observed when the cables were terminated.

⇩

•Noise comes from signal pass from a feed-through to a detector.

Shielding is necessary for better S/N.

Test of Libera Brilliance (Instrumentation Technologies)

•Libera Brilliance is used in several light sources such as Australian Synchrotron, DIAMOND, Elettra, Soleil and SSRF.

•Libera has several data paths.

◊Turn-by-turn Acquisition

◊Fast Acquisition (10kHz)

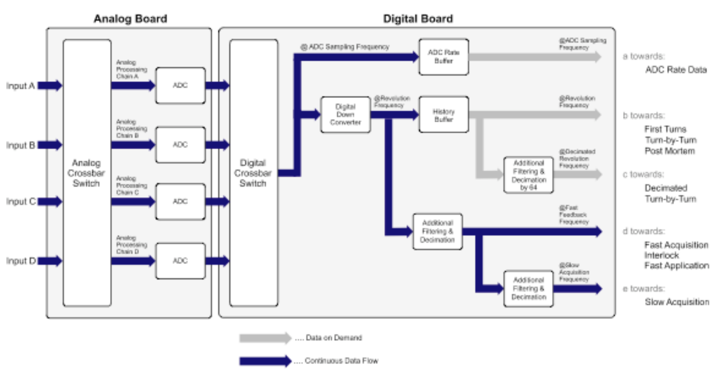
◊Slow Acquisition (about 10Hz)

•Libera might be a candidate of a signal processor for special use, for example for BPMs for IR orbit feedback where a fast (1kHz to 10 kHz ?) continuous measurement is required.

•A Libera Brilliance is under test in KEKB.

Specifications

Parameter	Range	Guaranteed performance, k= 10mm			
		Libera Brilliance (TBT= 131kHz)		Libera Brilliance (TBT= 1.15MHz)	
		non switched	switched	non switched	switched
Resolution (turn-by-turn)	→ -28 dBm	1 μm	1 μm	3 μm	3 μm
	→ -44 dBm	5 μm	5 μm	15 μm	15 μm
Beam Current Dependence	→ -24 dBm	1 μm		1 μm	
	→ -32 dBm	1,5 μm		1,5 μm	
	→ -50 dBm	2 μm		2 μm	
Fill Pattern Dependence	100%-20% duty cycle	1 μm		1 μm	
FA Resolution	→ -20 dBm	0,25 μm		0,25 μm	
Crosstalk		-45 dB to -70 dB			

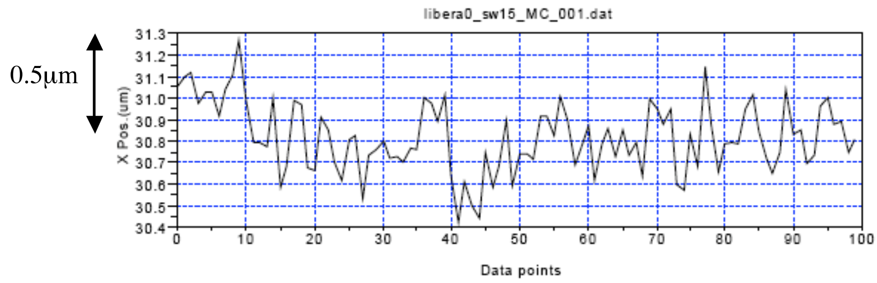


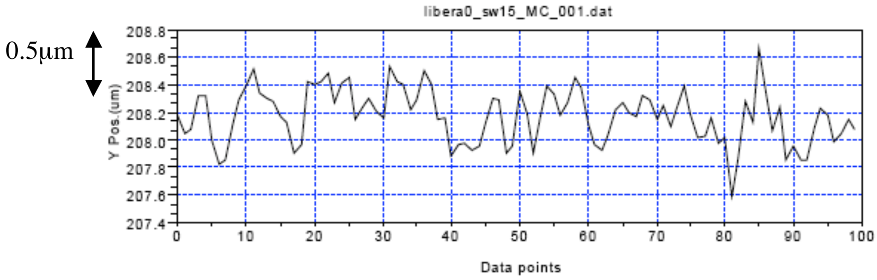
a) Laboratory test by a signal generator (Turn-by-turn Mode)

- Resolution

Kx=Ky=10mm, Libera att. 0dB, Libera input -20dBm

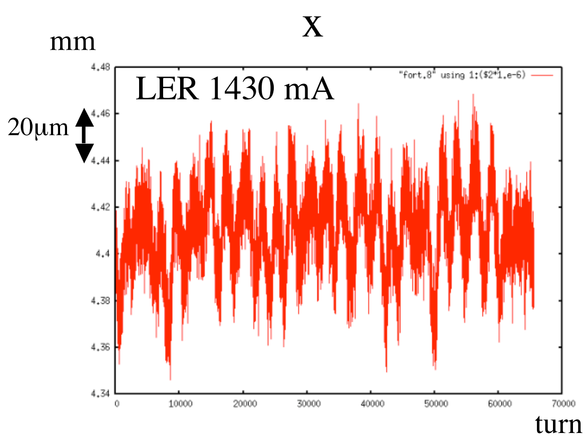
(Kx=Ky= about 30mm in KEKB)



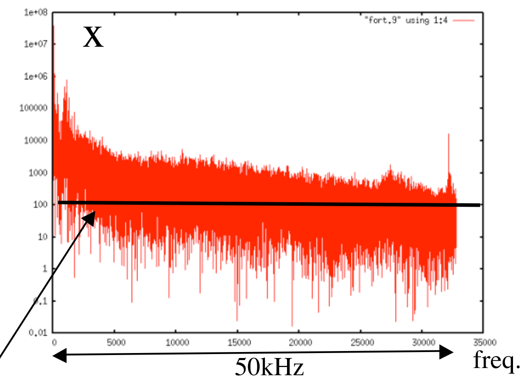


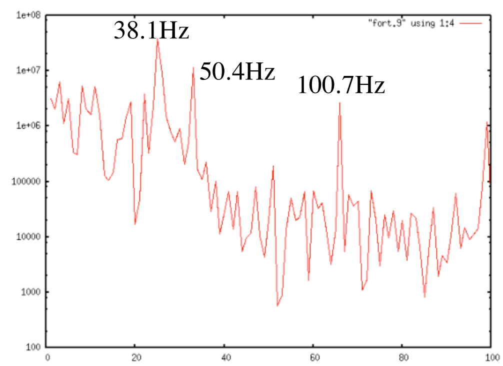
$\sigma_x = 0.18\mu m$, $\sigma_y = 0.18\mu m$ in 10000 data for K=10mm

b)Beam test (Turn-by-turn Mode)



FFT - 65536 points (power spectrum)





$$\sigma_x^2 = \int S(\omega)d\omega$$

S(ω) :power spectrum density of noise floor

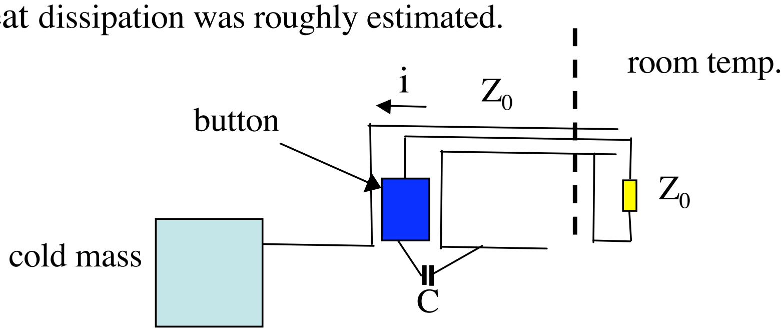
➡ σ_x : 3.2μm, σ_y : 2.4μm

$\sigma_{x,y}$ is not the resolution of the BPM. It could be affected by the movement of the beam.

*Sudden change of the data is observed in Slow Acquisition Mode. The reason is not clear yet.

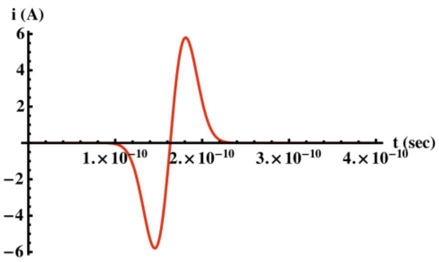
Cold BPM in IR

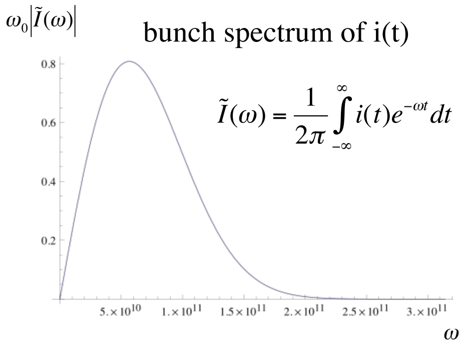
- Several BPMs in IR may be at low temperature (He or N_2 temperature).
- Heat dissipation was roughly estimated.



LER

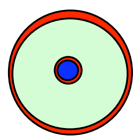
bunch current : 1.84 mA, bunch spacing : 2ns, bunch length : 5mm,
button diameter : 6 mm, chamber radius : 47 mm





$$R(\omega) = \frac{1}{2\pi}\left(\frac{1}{a}+\frac{1}{b}\right)\frac{\rho}{\delta}\cdot l = \frac{1}{2\pi}\left(\frac{1}{a}+\frac{1}{b}\right)\sqrt{\frac{\mu_0\omega\rho}{2}}\cdot l, \quad \delta = \sqrt{\frac{2\rho}{\mu_0\omega}}$$

red : copper conductor



ρ : resistivity, δ : skin depth, l : length of conductor

$$\overline{P} = \frac{1}{2}\sum_{p=-\infty}^{\infty}(\omega_0\tilde{I}(p\omega_0))^2 R(p\omega_0)$$

a=1.5 10^{-3} m, b=0.4 10^{-3} m (LHC BPM cable), l=0.1 m

4K for copper (He temp.) : ρ =9.3 10^{-11} Ωm

➡ δ =4.0 10^{-8} m, R=0.12Ω@15GHz, P=0.03 W

77K for copper (N_2 temp.) : ρ =1.55 10^{-9} Ωm

➡ P=0.14 W

- Questions
  - Is the heat load within the ability of the cryogenics ?
  - Structure of a feed-through, a connector and a signal cable ?
  - Alignment, movement of BPM at low temperature ?
- KEKB has no experience of this kind of BPM.

⇨ Need R&D if the cold BPM is really required.

3. Synchrotron Light Monitor

A)Visible light monitor

•Beam size at source points of light

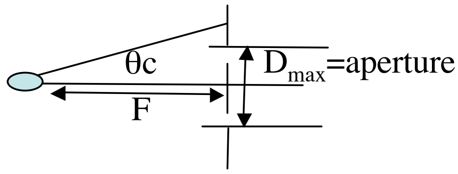
	LER1	LER2	HER
σ_x(μm)	490	420	730
σ_y(μm)	97	68	46
σ_{min} (μm) : minimum measurable beam size by an interferometer	12	13	24

$$\sigma_{min.} = \text{Minimum}(D_{max}/F,\ 2\theta_c)$$

D : slit separation,
F : distance from beam to slits,
θc : critical angle

•From standpoint of beam sizes, we can still use:

Interferometers
Streak Camera
Gated Camera

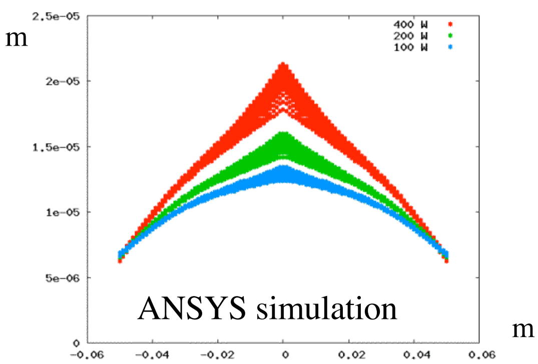


•Extraction mirror

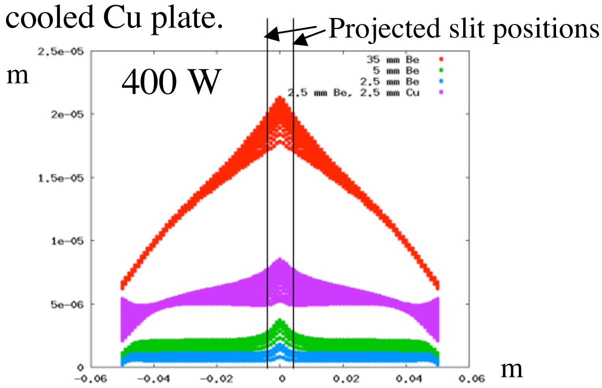
Heat load at high beam currents causes serious mirror distortions.

	LER1	LER2	LER1 (KEKB)	HER	HER (KEKB)
Energy(GeV)	**3.5**	**3.5**	**3.5**	**8**	**8**
Current(A)	**9.4**	**9.4**	**2**	**4.1**	**1.4**
Bending radius(m)	**180**	**120**	**60**	**1160**	**580**
Power(W/mrad/A)	**11.5**	**17.3**	**34.5**	**48.7**	**97.5**
Total incident power(W)	**231**	**204**	**147**	**364**	**248**

First step: increase bending radius of source magnets (HER 2x, LER1 3x, LER2 2x).



Next step: Investigate new mirror structures, e.g., thin Be on thin water-cooled Cu plate.



A simulation showed that deformation decreases to the level of KEKB with 2mm Be and a water channel. We are trying to find a better solution.

B) X-ray Monitor

- Purpose is to provide high-resolution bunch-by-bunch measurement capability, with low beam current dependence (low distortion).
- Currently we are investigating and developing (in collaboration with Cornell U. and U. Hawaii) an x-ray monitor system featuring:

  1) Coded Aperture Imaging

     Being tested in collaboration with Jim Alexander et al. at CesrTA at Cornell U..

  2) High-speed readout

     STURM readout being developed at U. Hawaii (Gary Varner).

1) Coded Aperture Imaging

- Technique developed by x-ray astronomers using a mask to modulate incoming light.
- Resulting image must be de-convolved through mask response (including diffraction and spectral width effects) to reconstruct object.
- Open aperture of 50% gives high flux throughput for bunch-by-bunch measurements.
- A heat-sensitive monochromator not needed.

P=O*A   * : convolution

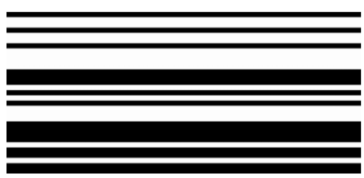
$$\hat{O} = P * G = O * (A * G)$$

$\hat{O}$: reconstructed object, P: picture, O: object,

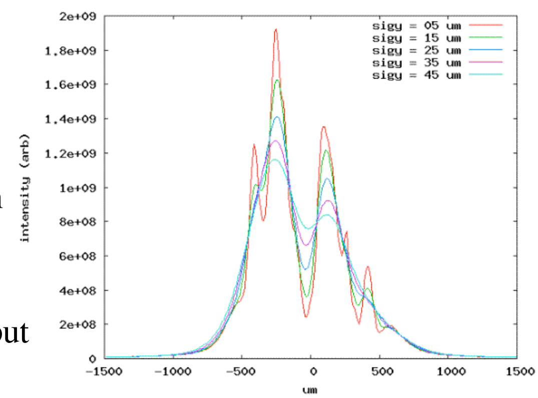
A : mask or aperture, G: post processing array

A*G : system point-spread function

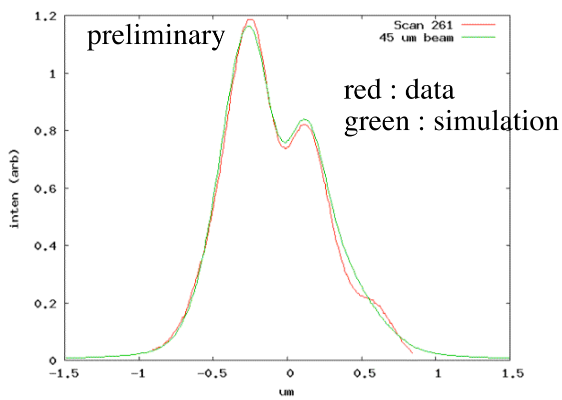
~ δ function



Uniformly Redundant Array (URA) mask being tested at CesrTA



Simulated detector response for various beam sizes



Example of beam size measurement at CesrTA (σ_y =~ 45 μm)

2) High-speed Readout: STURM
(Sampler of Transients for Uniformly Redundant Masks)

- •Designer: G. Varner, U. Hawaii (Belle)
- •8 Channels/ASIC, 32 samples/channel
- •Up to 8 external timing strobes
- •Each timing strobe can fire 4 timing samples, with minimum spacing < 5 ps.

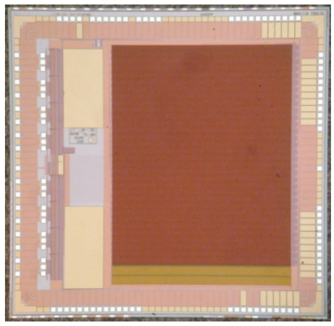
  Examples:
  8 bunches, 4 samples/bunch
  32 bunches
  8 trains, 4 bunches/train

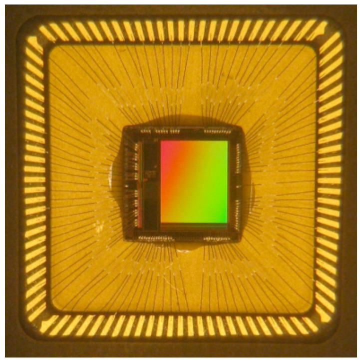
- •Total readout time 8 μs

  Turn-by-turn measurement is possible.

- •Beam test planned March 2009 at KEK PF
- •Detector

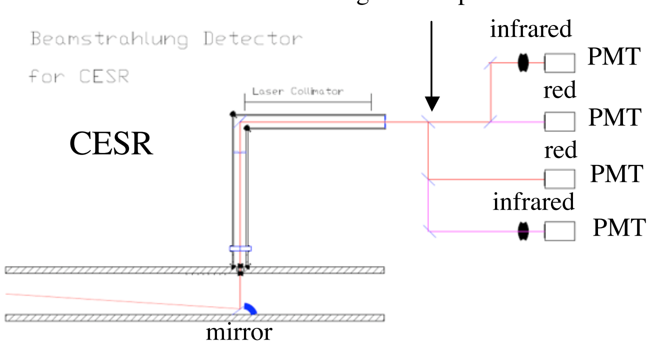
  Fermionics InGaAs sensor array being tested at CesrTA and KEK PF.



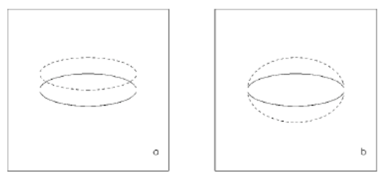


C) Beamstrahlung Monitor

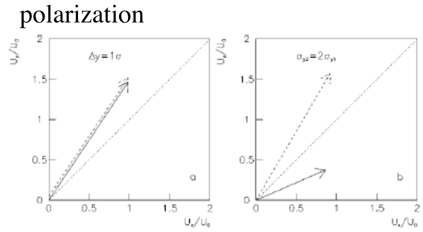
- •Developed by G. Bonvicini (Belle, Wayne State U.) originally for use at CESR.
- •Uses relative strengths of x- and y-polarization of wide-angle beamstrahlung to diagnose quality, e.g. beam separation, beam size, of collision.
- •Monitor and Vacuum groups are assisting Prof. Bonvicini with design of system for use at SuperKEKB.
- •Need to understand background due to halo in IR quadrupoles.
- •Need to make room for extraction mirror and window in beam pipes near IR, and evaluate resulting HOM.



Two beams at IP



polarization



G. Bonvicini et al., Phys. Rev. E 59, 4584 (1999)

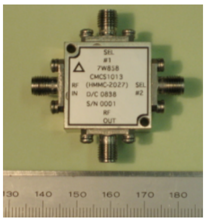
4. Gated Measurement for Bunch-Tune, -Orbit and -Phase

A) Development of a gate module

- A fast gate module is being developed for a fast gate to measure the tune, orbit and longitudinal phase of each bunch separated by 2ns.

- Two switches are being tested.

1) Agilent HMMC-2027



Specifications

Input/Output Impedance	50 Ω
Input Power	> +20 dBm
Bandwidth	1.0 MHz - 5.0 GHz
Switching Time	200 ps
ON/OFF Isolation	> 50 dB @2GHz
Insertion Loss	< 10 dB@2GHz
Control	0 - - 0.8 V

2) AVAGO AMMC-2008

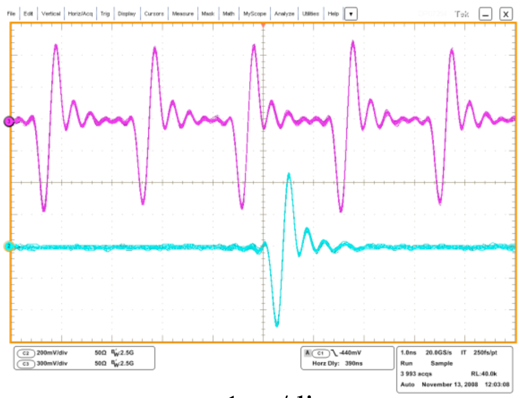
- Beam Test

HER: 0.5 mA/bunch

HMMC-2027

1 ns/div

AMMC-2008



1 ns/div

ON/OFF Isolation: >60dB@2GHz, Switching Time: <500 ps, VSWR ~1.5

- A compact 4 channel module will be fabricated and tested with beam in next fiscal year.

5. Summary

•Tentative plan of beam diagnostics system in SuperKEKB is as follows.

•BPM system

1) Flange type feed-through with a button electrode of 6mm ϕ,

2) All BPMs are processed by narrow band detection at 509 MHz,

3) 120 BPMs can be turn by turn BPMs with a fast gate,

4) Some BPMs, for example BPMs near IP, might be commercial products.

Issues to be solved or not addressed yet are

1) Improvement of S/N of the prototype 509 MHz detector and improvement of its linearity if necessary.

2) RF noise at 509 MHz in RF straight sections,

3) System of a cold BPM if it will be used.

•Synchrotron light monitor system

1) Visible light monitor

•Use of an interferometer, a streak camera and a gated camera like KEKB.

2) X-ray monitor

•Coded aperture imaging and high-speed readout for turn-by-turn or bunch-by-bunch measurements (a backup might be a pinhole mask for slow measurement).

Issues to be solved or not addressed yet are

1) Thermal deformation of an extraction mirror for visible light,

2) Design of a mirror chamber for reduced HOM losses at higher beam currents and short bunch length,

3) Design of an extraction chamber and a beam line for X-ray monitor.

•Gated measurement system with newly developed fast gates.

•Remaining instruments such as DCCT, CT and loss monitors will be straightforward extension of those in KEKB.