The Beam Diagnostics of SuperKEKB rings

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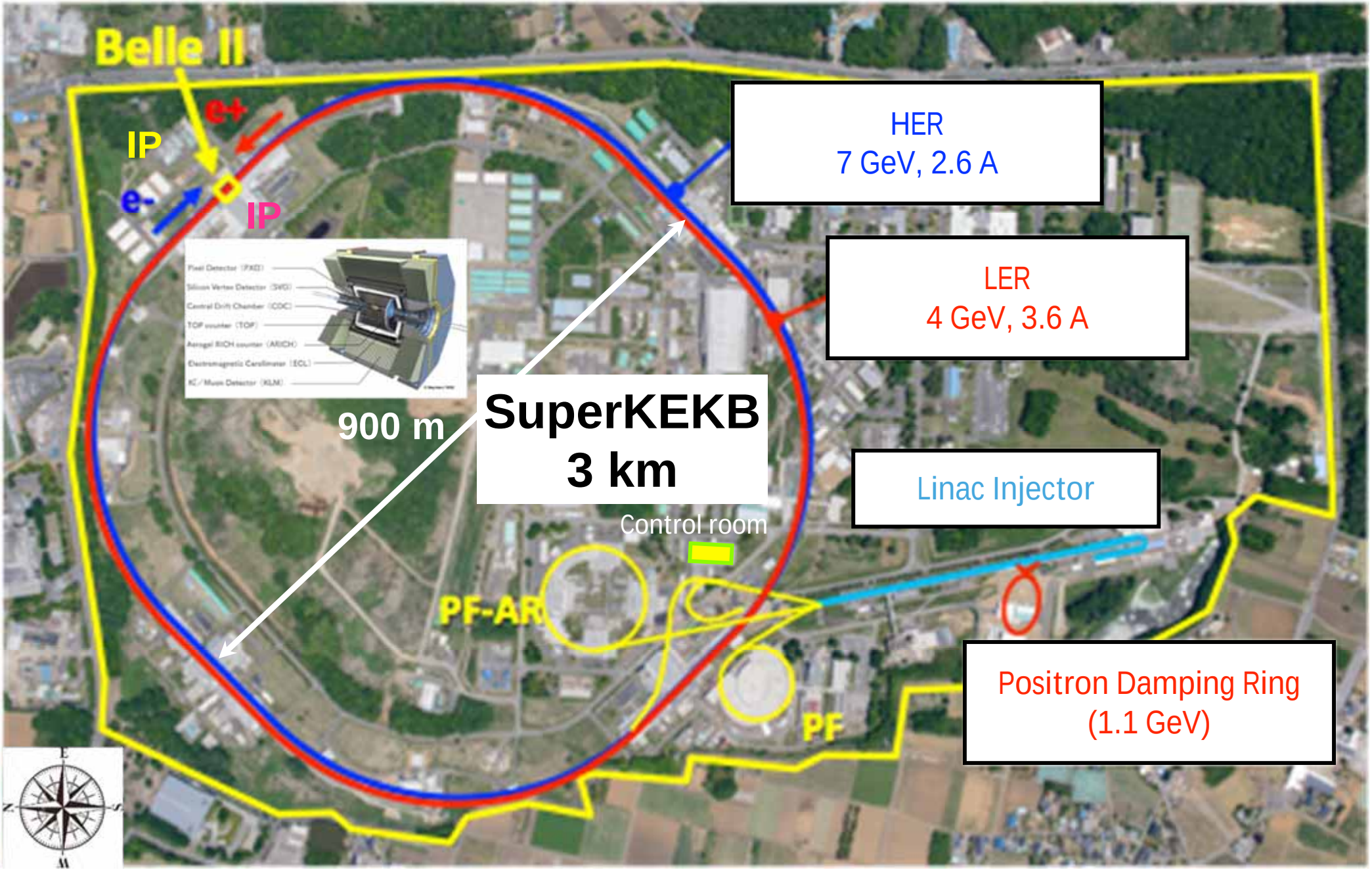
KEK Accelerator Laboratory


Belle II
e+
IP
e-
IP
900 m
SuperKEKB
3 km
HER
7 GeV, 2.6 A
LER
4 GeV, 3.6 A
Linac Injector
Control room
PF-AR
PF
Positron Damping Ring
(1.1 GeV)

Introduction

System	Quantity		
	HER	LER	DR
Beam position monitor (BPM)	466	444	83
Displacement sensor (relative to sextupole)	110	108	0
Transverse bunch feedback system/plane	2	2	1
Longitudinal bunch feedback system	0	1	0
Visible SR size monitor	1	1	1
X-ray size monitor	1	1	0
Large Angle Beamstrahlung Monitor	1	1	0
Betatron tune monitor	1	1	1
Beam loss monitor	207+		34
DCCT	1	1	1
CT	1	1	0
Bunch current monitor	1	1	1

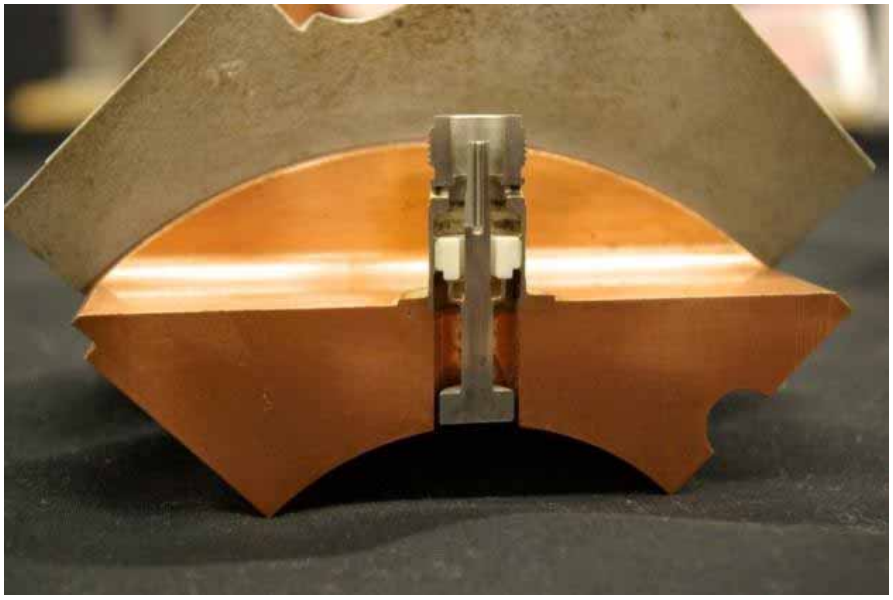
BPM systems

Type	Function	Resolution	Repetition	Number of units
1GHz Narrow-band system from KEKB	Closed orbit correction, CCC, optics measurement	3μm	0.25Hz	109
New narrow-band with 509MHz detection	As above	2 to 3 μm	0.25Hz	133
Gated turn by turn	Injection tuning, optics measurement	50 - 100μm	100kHz/data	117
Medium-band(Libera)	Measurement of orbit variation	< 2 to 3 μm	10kHz	4
Fast orbit deviation (Libera)	Orbit deviation abort	~10μm <10 turn	100kHz	4

One narrowband detector covers four BPMs.

Button Heads

- **HER**
  - N-type connector
  - 12mm diameter
- **LER**
  - SMA(R) connector
  - 6mm diameter

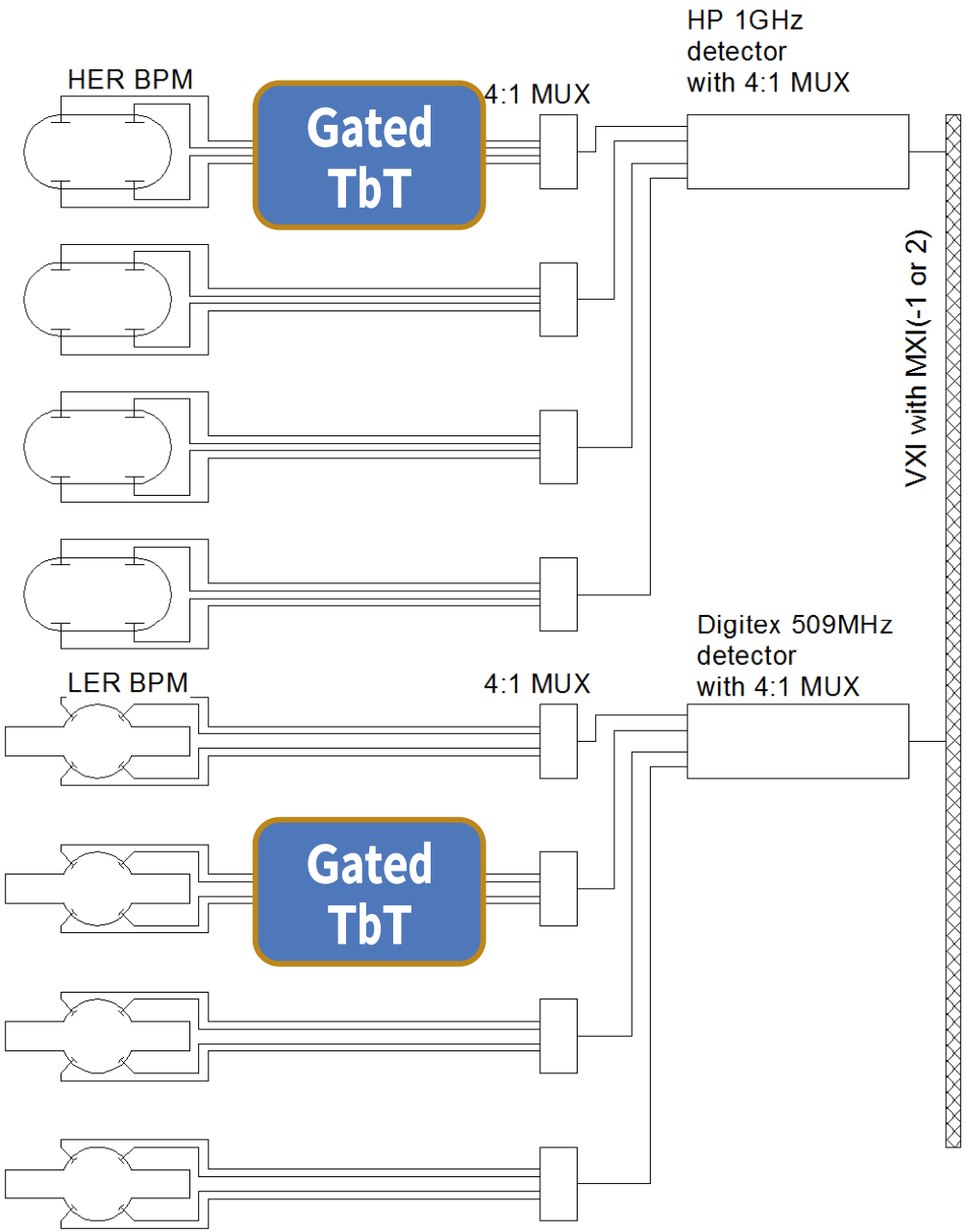


Cable length (4-in-one 9D coax cable) from BPM to local control room 100~200m

Beam position monitors at MR

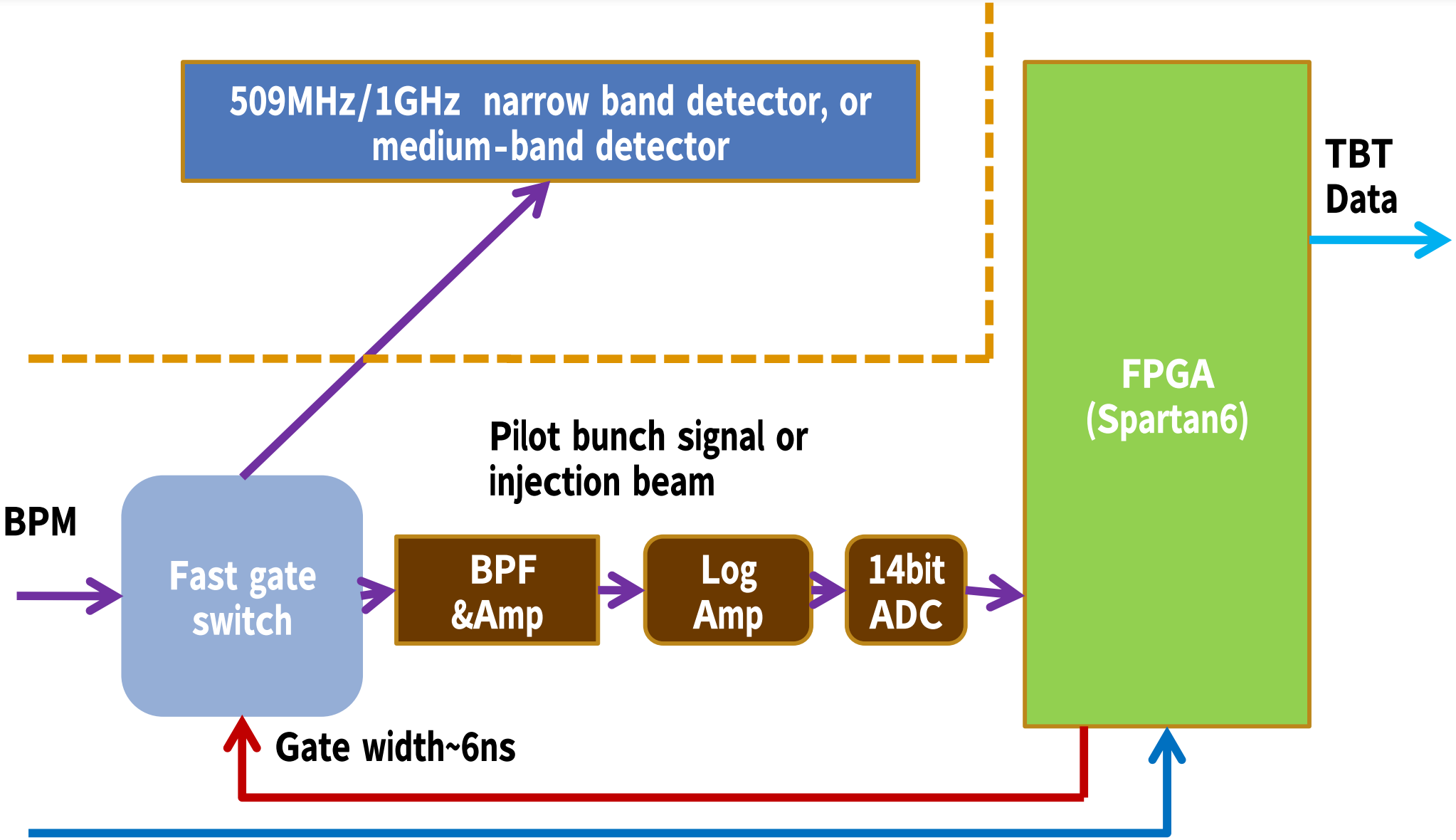
- Still using VXI-MXI based systems from KEKB time. All VXI main frames have been renewed and re-installed from KEKB to SuperKEKB.
- Software-works in progress (EPICS database, OPI).

Configuration of main BPM system

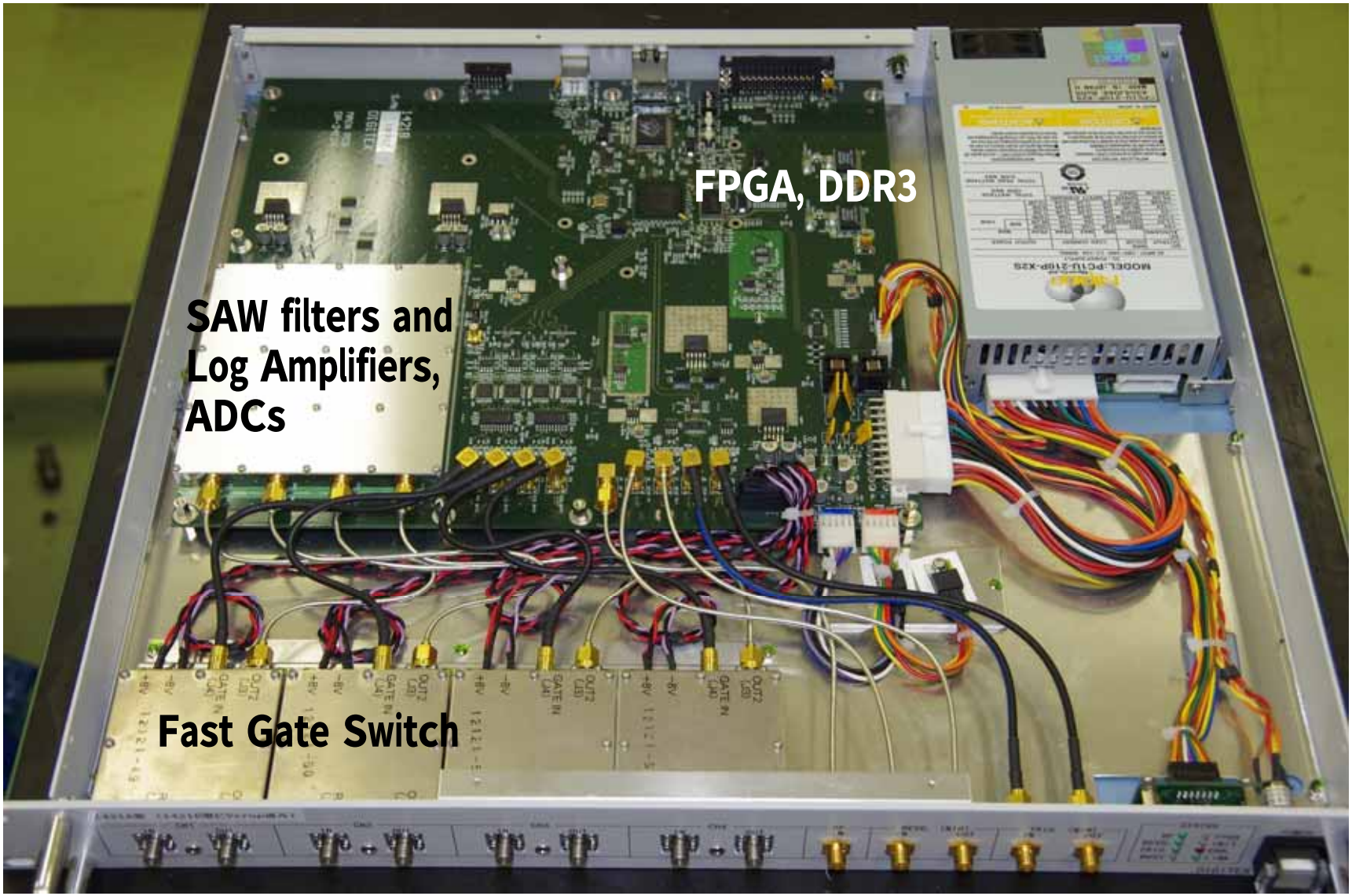


- **Separate HER and LER BPM systems.**
  - **Cutoff freq. of LER chamber lower than 1GHz (989MHz).**
- **Continue to use VXI system with MXI (1/2) connection.**
- **Selected 117 BPMs have gated turn-by-turn monitoring function.**

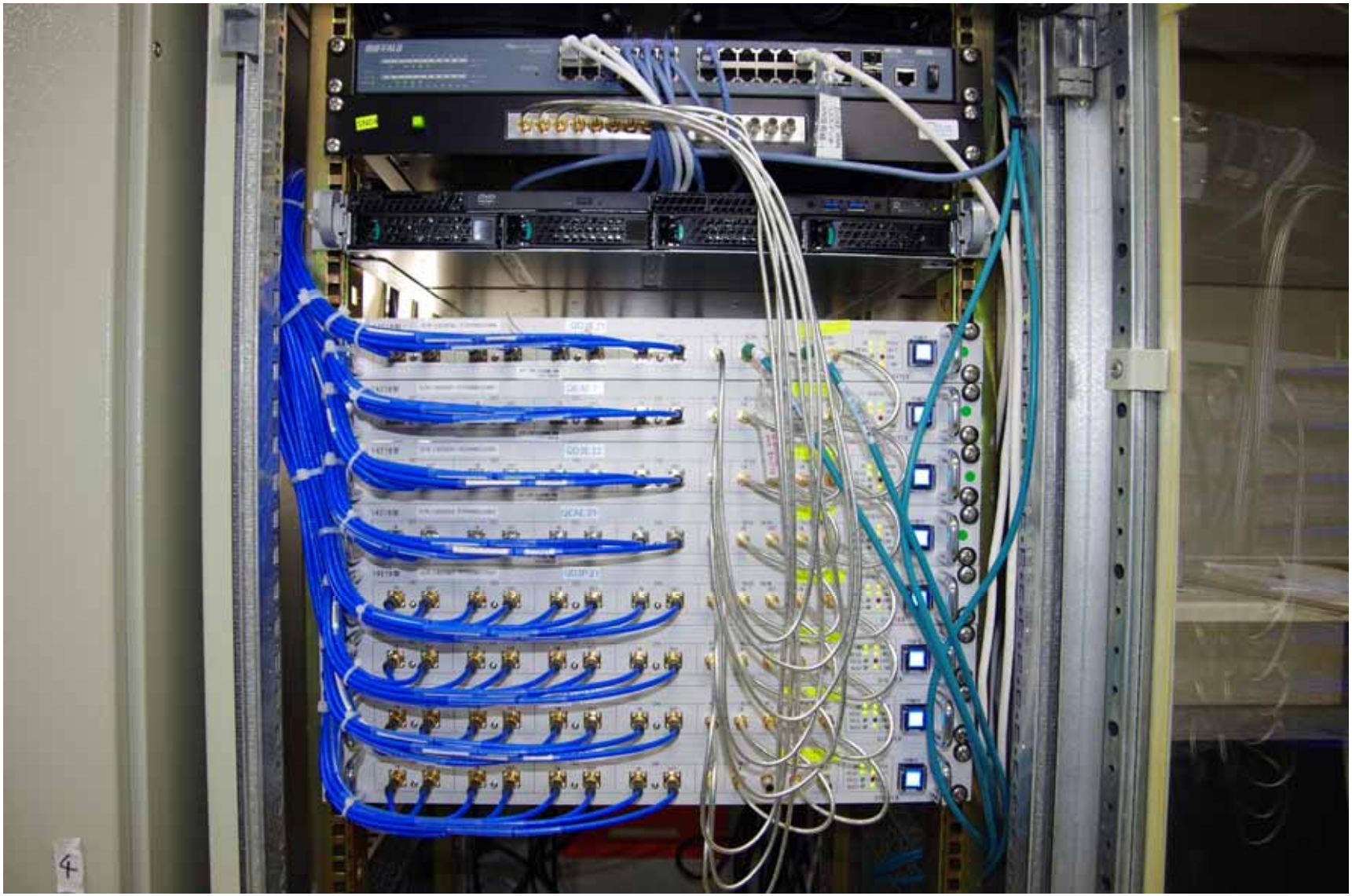
Gated turn-by-turn monitor



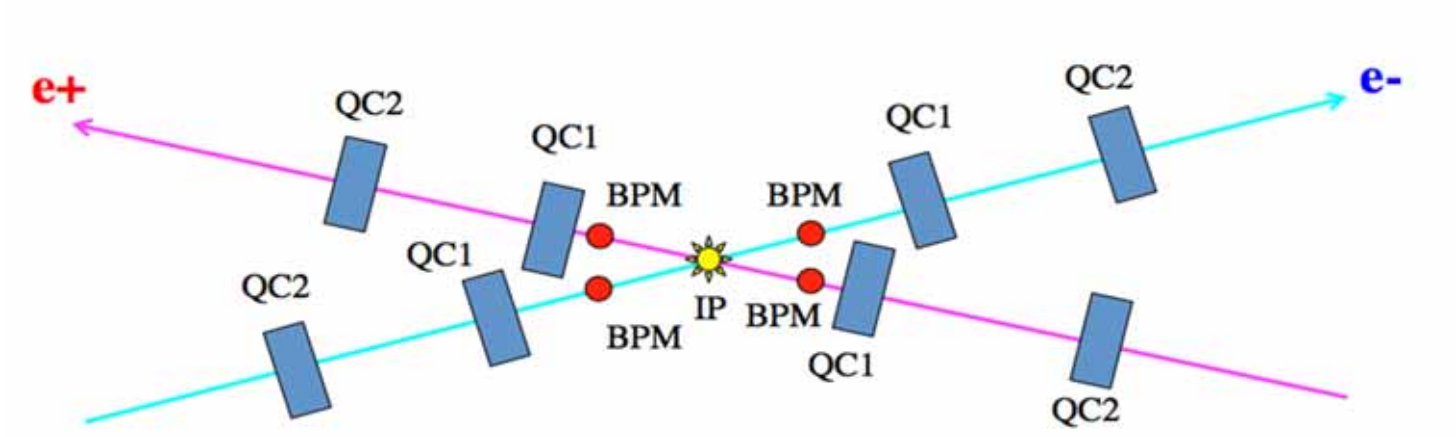
1421B Gated turn-by-turn monitor



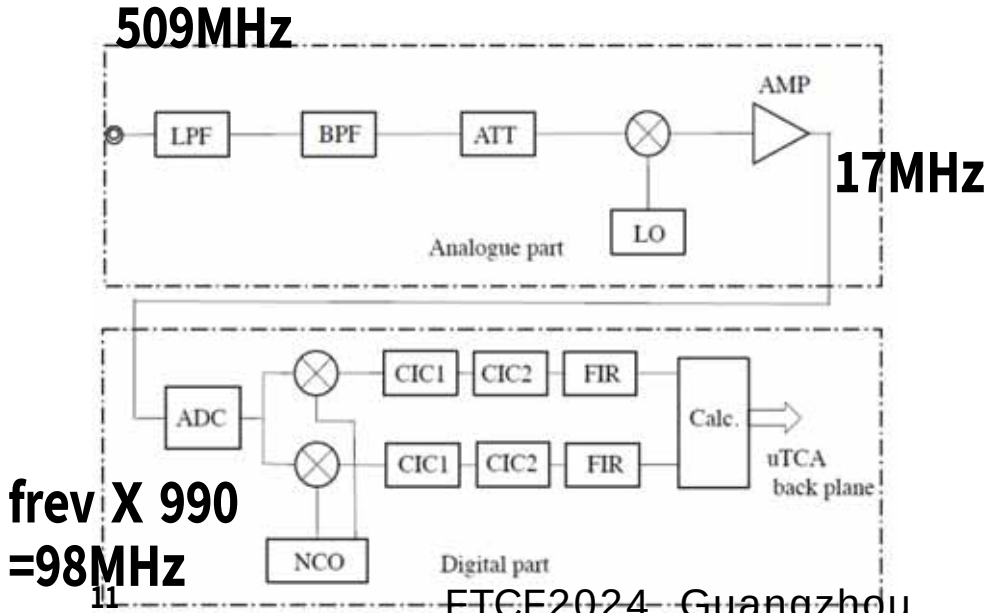
117+ units have been installed



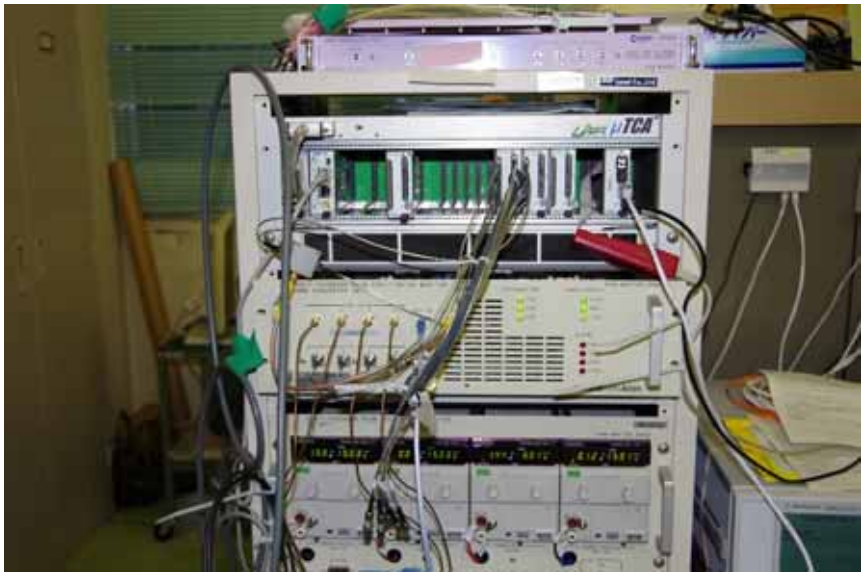
IP orbit feedback detector



- **Specification**
  - Resolution <1um
  - Repetition 32 kHz
  - Bandwidth <100 Hz (FB)



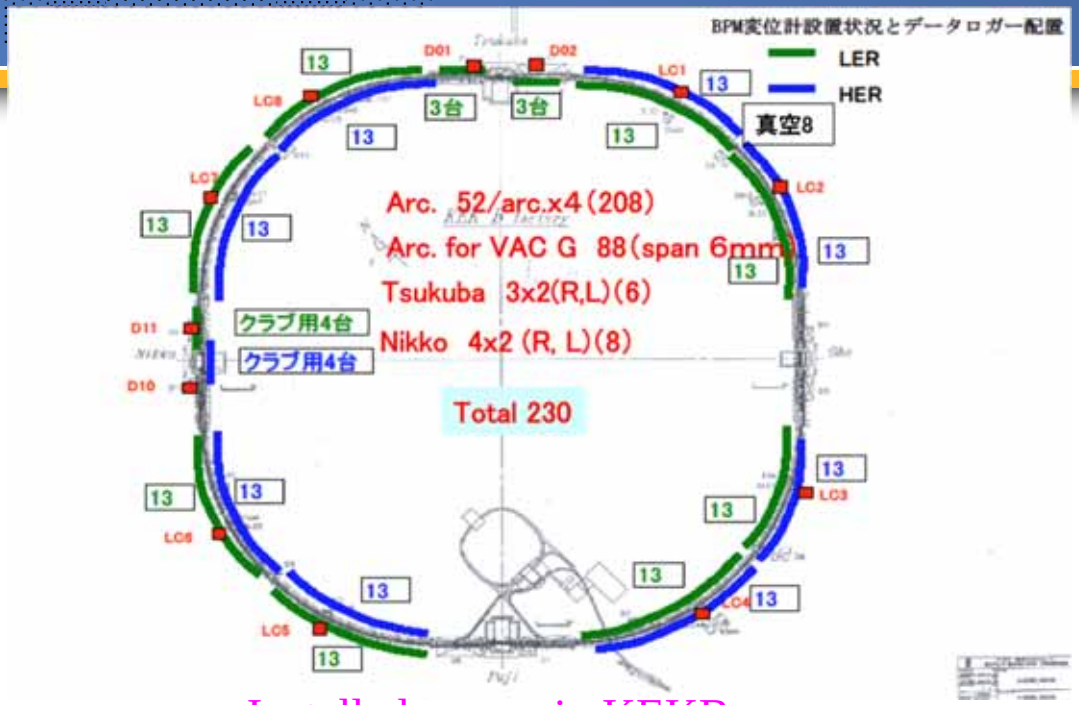
Detector/Processor/PS controller



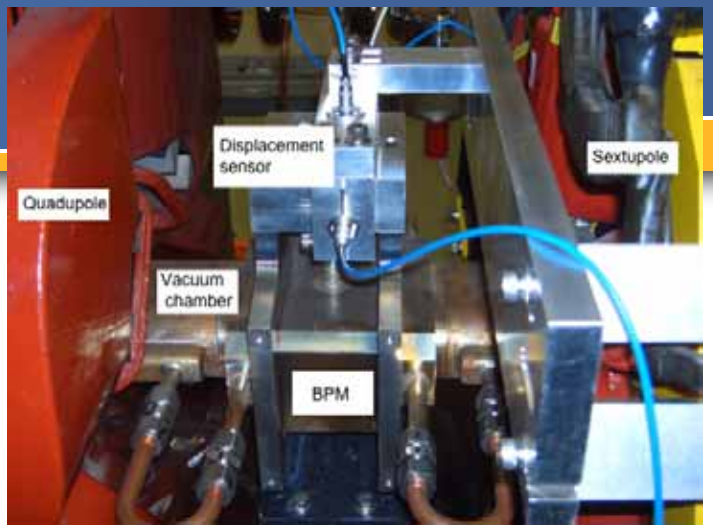
MicroTCA form factor based on LLRF processors (STF and KEKB)
Vertex5 FPGA (with PPC)
ADCs on mezzanine card
Built-in EPICS on PPC

MTCA.4 form factor
Zynq FPGA with built-in EPICS controller

Displacement sensors



Installed sensor in KEKB



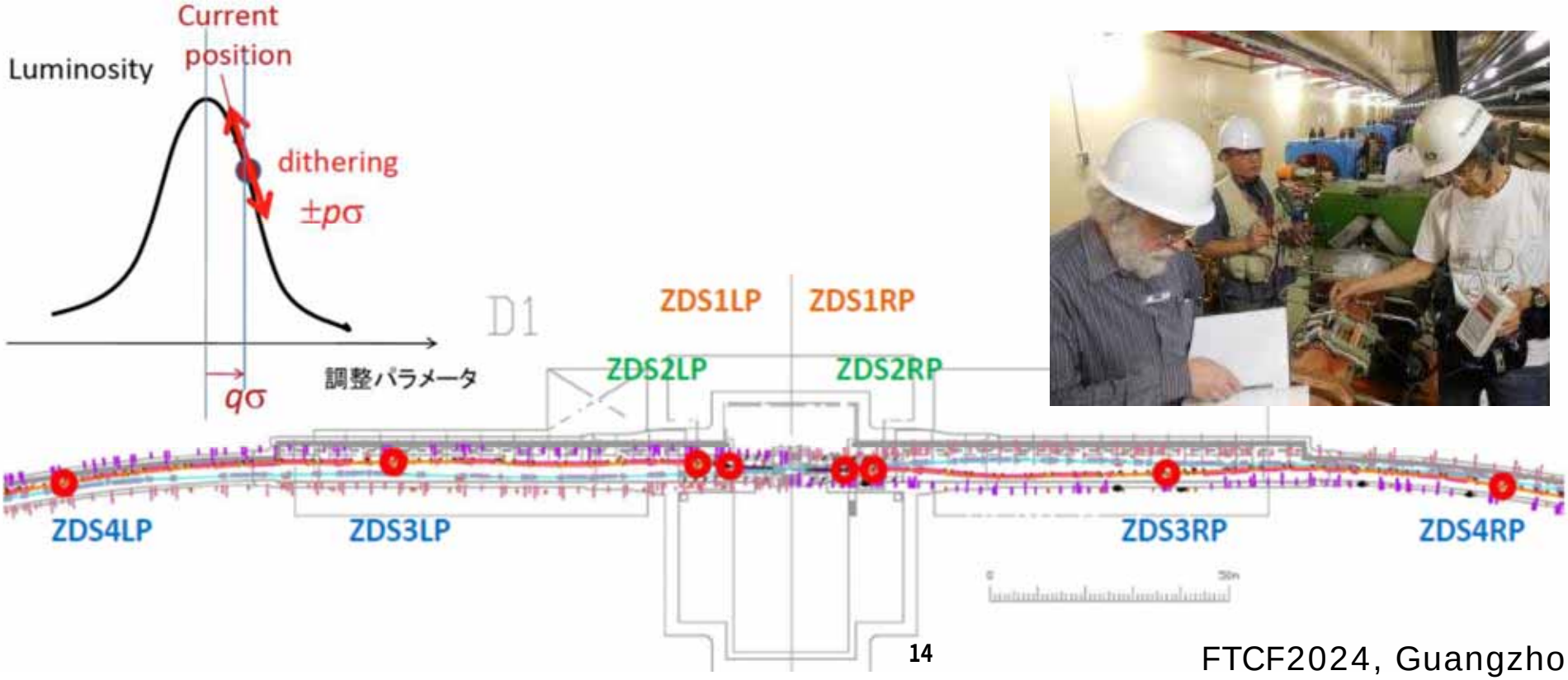
Gap detector developed for KEKB.

Specifications

method	electrostatic (capacitive)
channels	2
range (mm)	0.5 - 2.5
resolution (μm)	< 0.2
nonlinearity (%)	< ±0.3
frequency response (Hz)	0 - 100
temperature coefficient (μm/deg.)	< 0.2

Dithering based IP Luminosity FB

- **Constructing Dithering feedback systems collaborating with SLAC**
  - **Modulate IP positions and angles with a sinusoidal signal (~70Hz) and detect the frequency and phase response of luminosity monitor using lock-in amplifiers.**



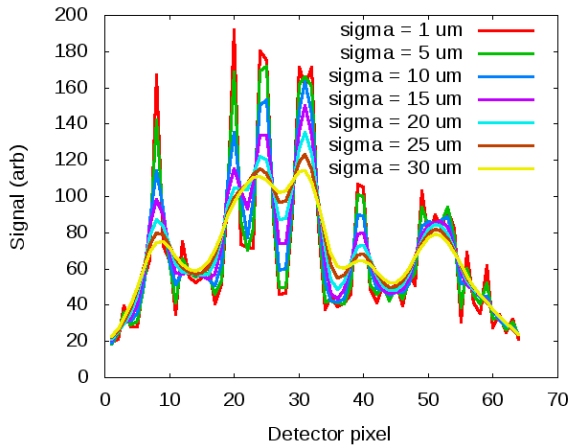
Photon Monitors

- **SRM: Synchrotron Radiation Monitor**
  - Visible light monitor. Interferometer, streak, gated camera, coronagraph etc.
    - σ_z, σ_x (σ_y)
- **XRM: X-ray Monitor (US-Japan:U. Hawaii, SLAC, Cornell)**
  - Pinhole, Coded Aperture mask, etc.
    - σ_y (σ_x)
- **LABM: Large Angle Beamstrahlung Monitor (IR)**
  - Wayne St. Univ (US-Japan)
  - SR-like radiation from interaction point (~300-600 nm)
  - Can measure size ratios and relative offsets at collision point.

X-ray size monitor

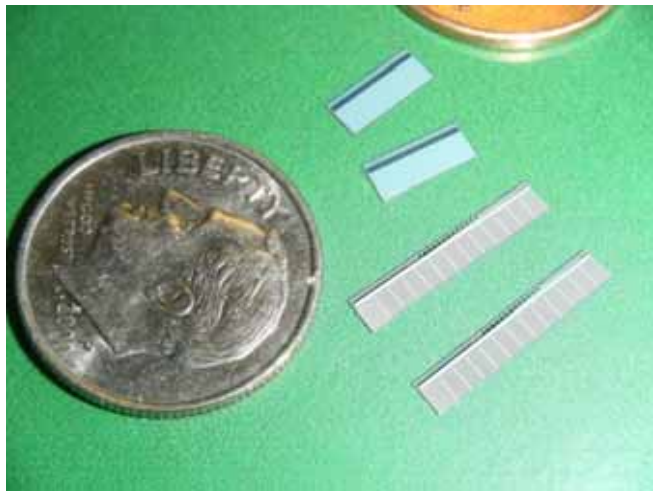
X-ray beam line at LER

Simulated detector response for various beam sizes at SuperKEKB LER



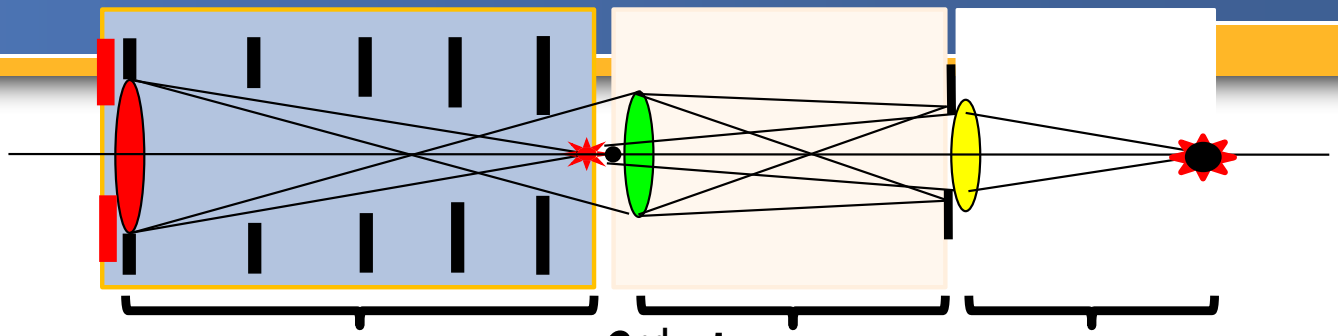
Deep Si pixel detector and spectrometer chips for the X-ray monitor, being developed at SLAC.

High-speed readout electronics for the X-ray monitor, being developed by U of Hawaii.



US-Japan Collaboration (Cornell U, U. Hawaii, SLAC)

Observation of beam halo

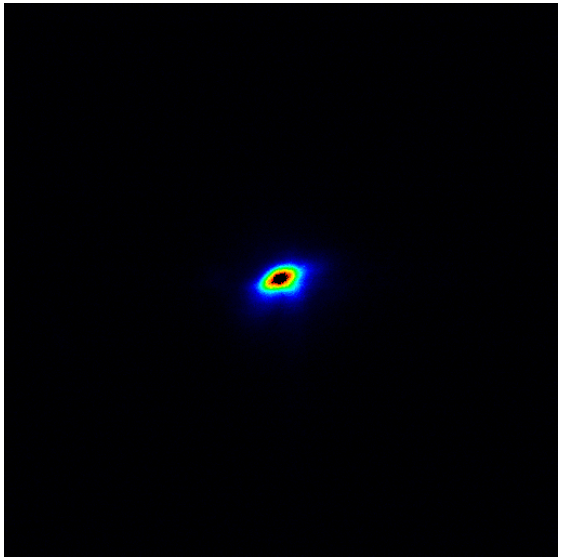


1st stage:
Objective lens system

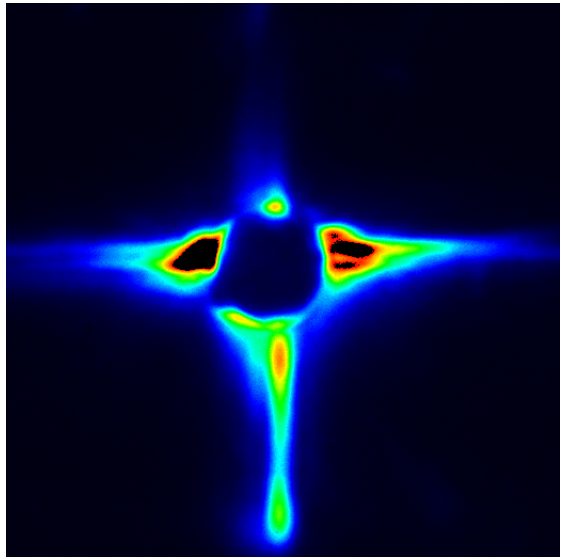
2nd stage:
Re-diffraction system

3rd stage:
Relay lens

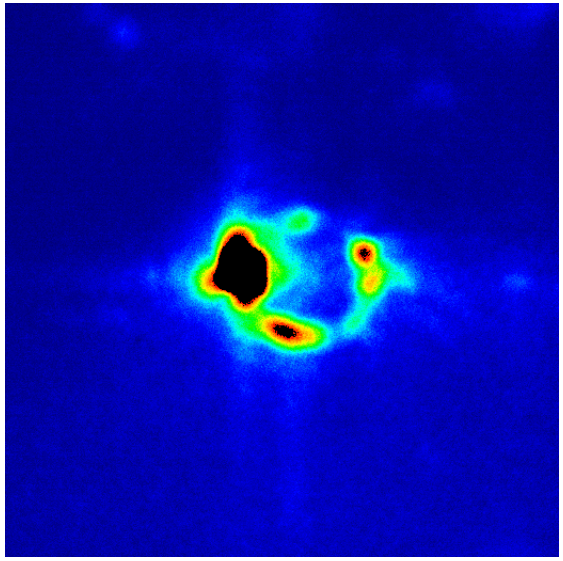
Beam core



Core blocked by a Φ3mm disk

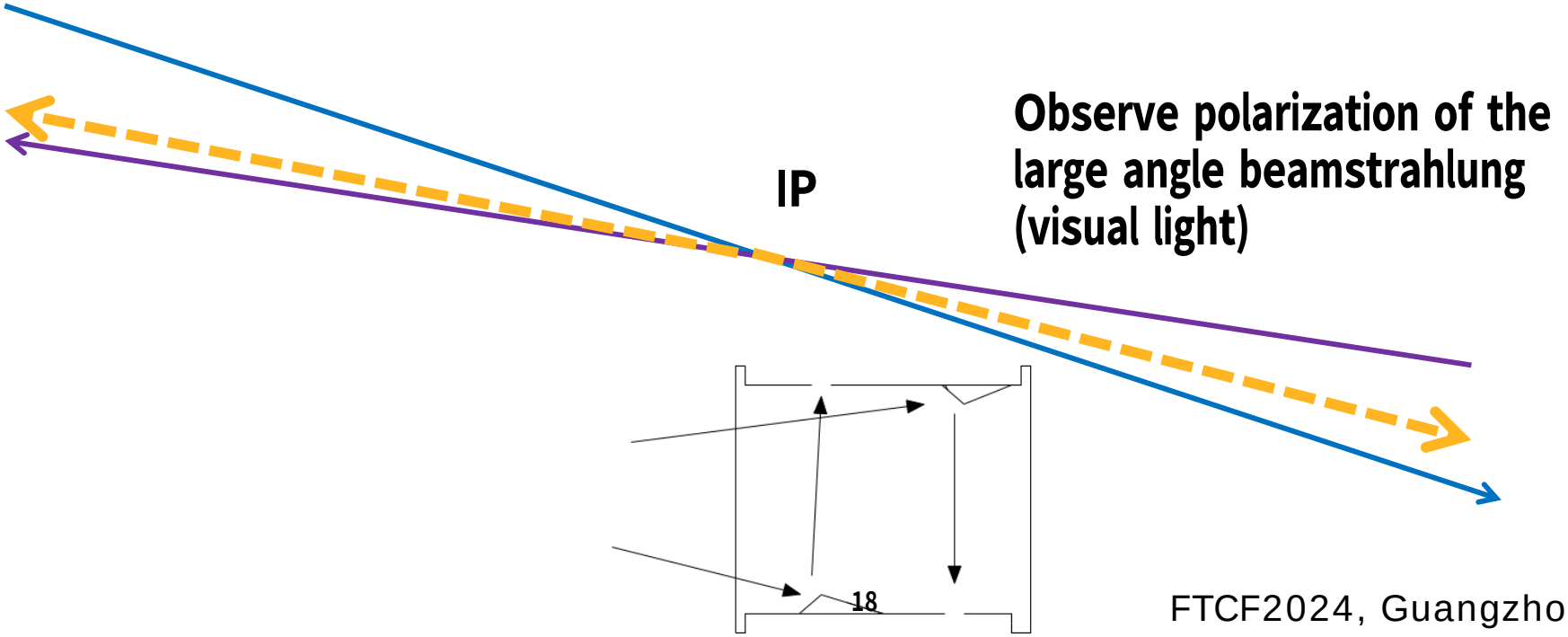


Re-diffraction fringes blocked by the Lyot stop

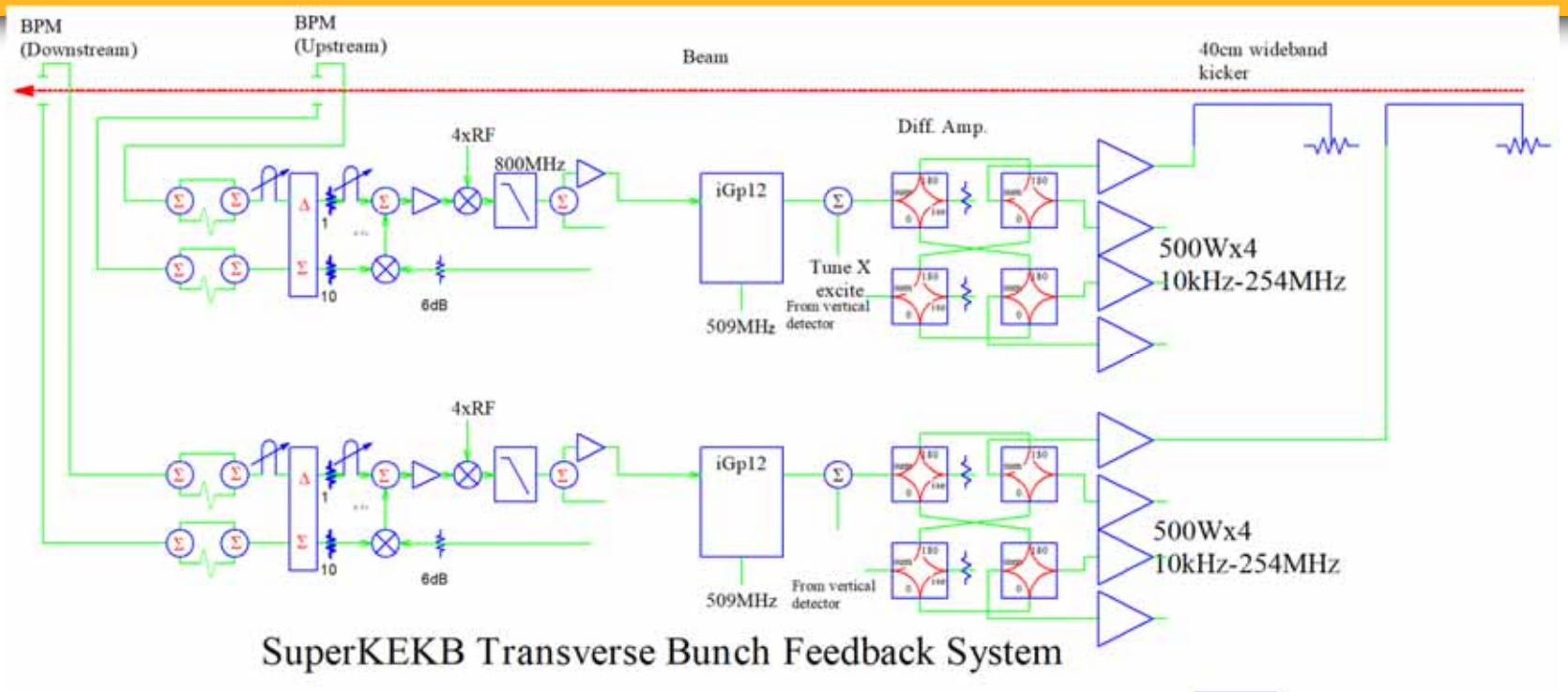


Beamstrahlung monitor for SuperKEKB (Wayne State U.)

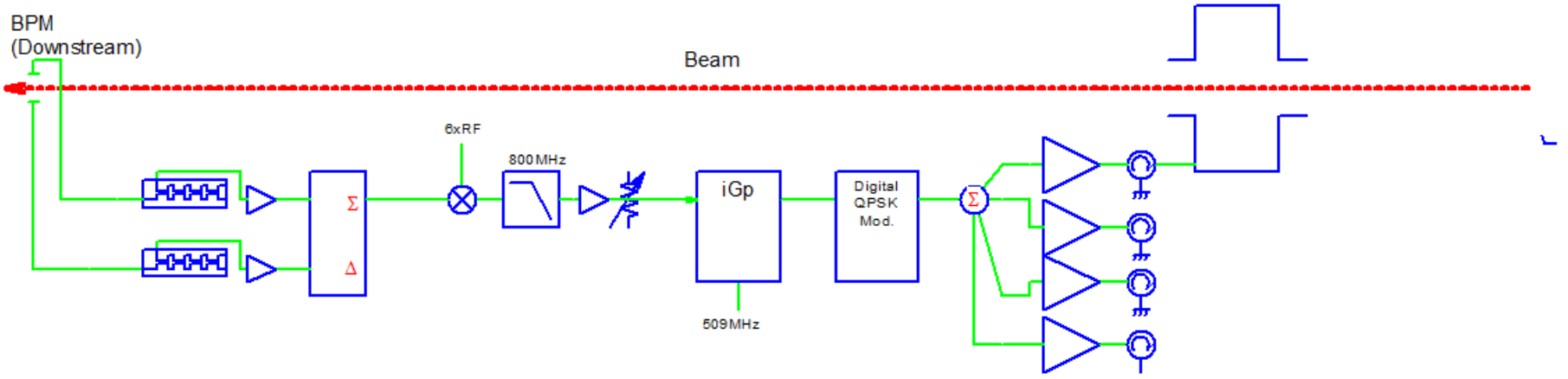
- **Beamstrahlung: The radiation of the particles of one beam due to the bending force of the EM field of the other beam. Many similarities with SR but also some substantial difference due to very short "magnet".**
- **Beamstrahlung polarization at specific azimuthal points provides unique information about the beam-beam geometry.**



SuperKEKB BxB FB systems

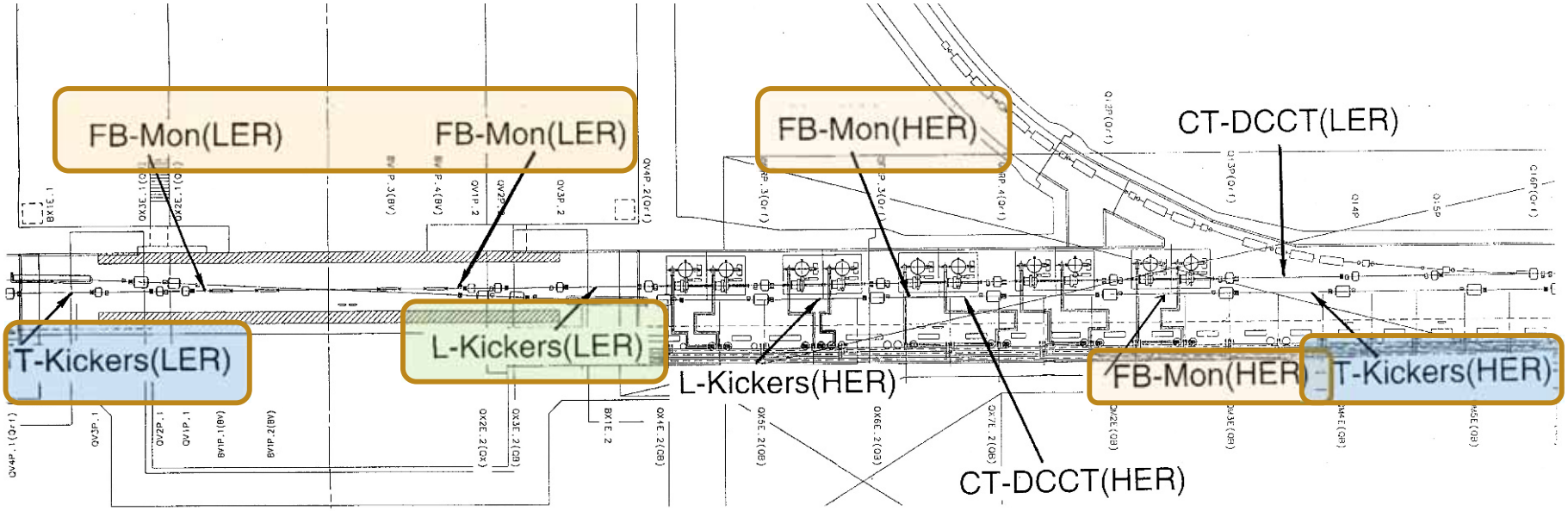


SuperKEKB Transverse Bunch Feedback System

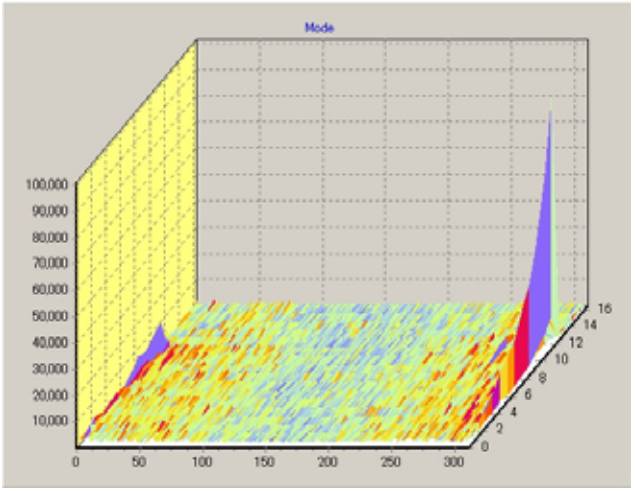


SuperKEKB Longitudinal Bunch Feedback System

SuperKEKB Fuji straight section

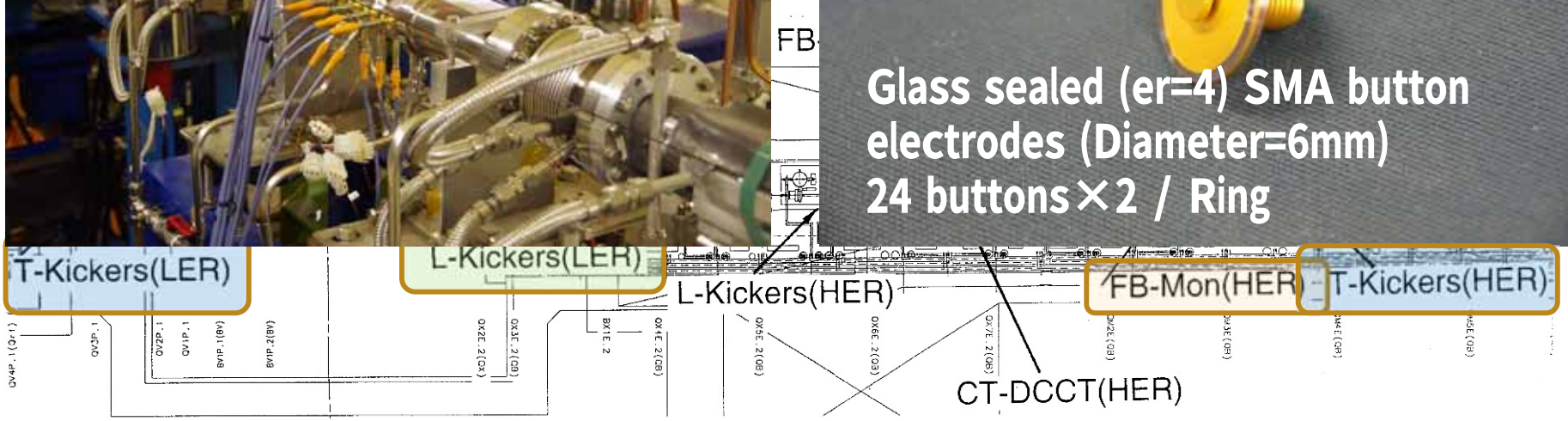


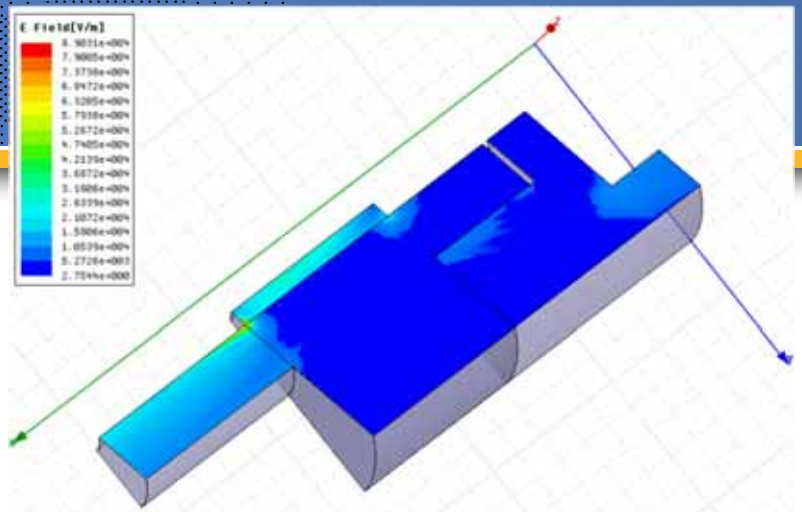
iGp12 digital feedback filter



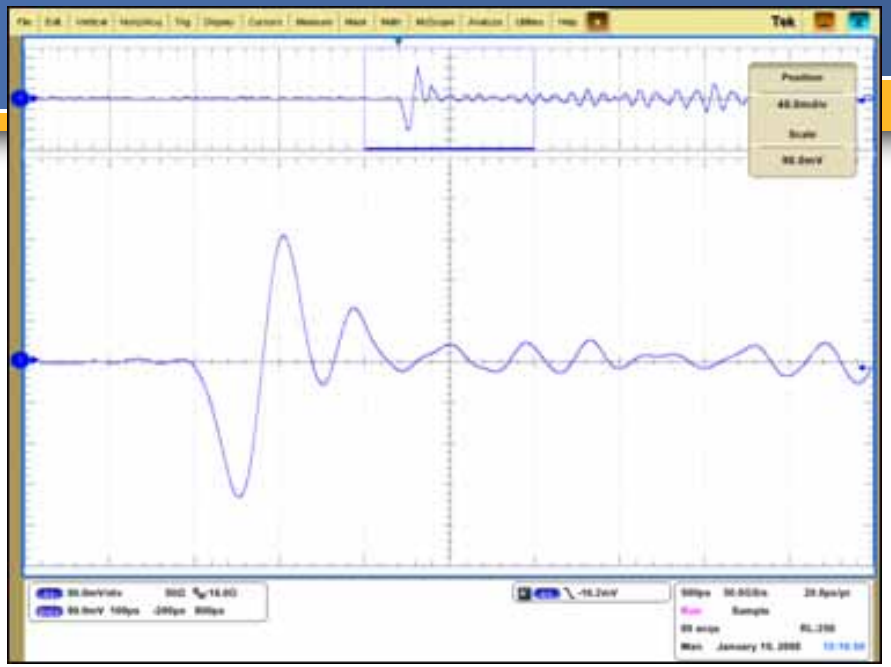
- **Sucessor of iGp digital filters developed under US-Japan collaboration with SLAC.**
  - 12bit ADC/DAC
  - 4-18 tap FIR filter
  - 12MB memory to analyze instabilities
- **10 iGp12s are ready**
  - 8 with larger FPGA (VSX95T)
  - 2 with normal FPGA (VSX50T)
- **Single bunch excitation using PLL**

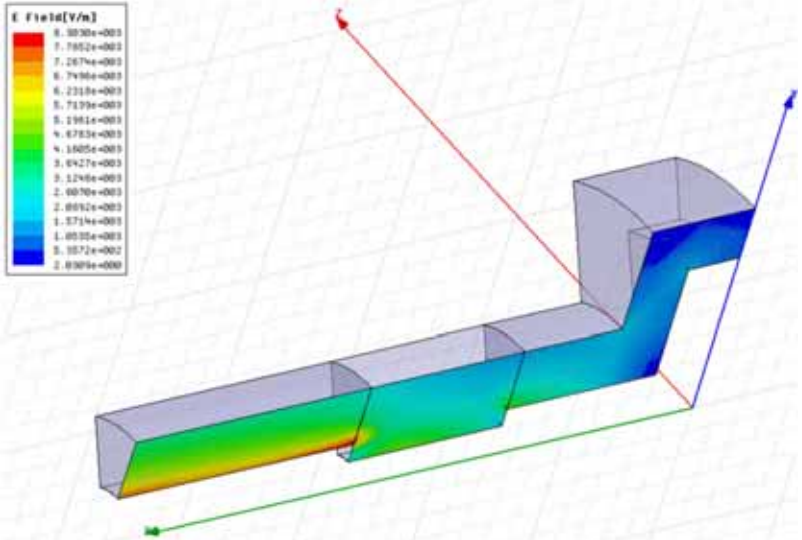
SuperKEKB Fuji straight section



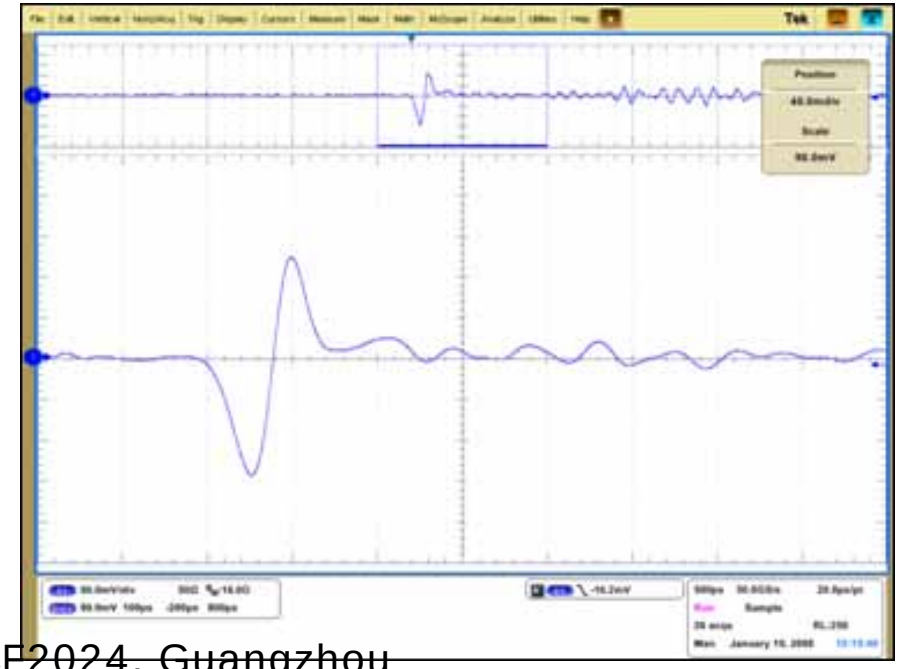


KEKB feedthrough for FB

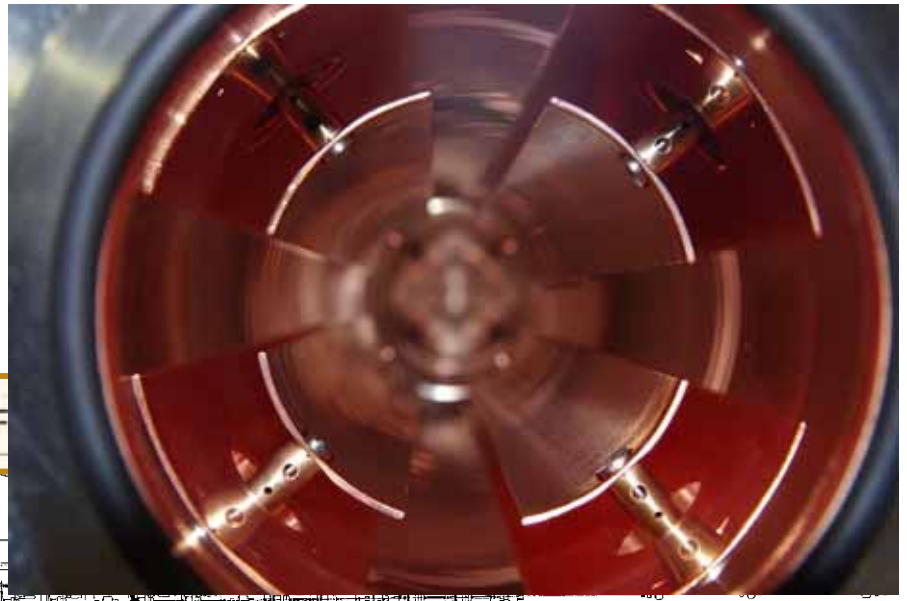




SuperKEKB FT for FB



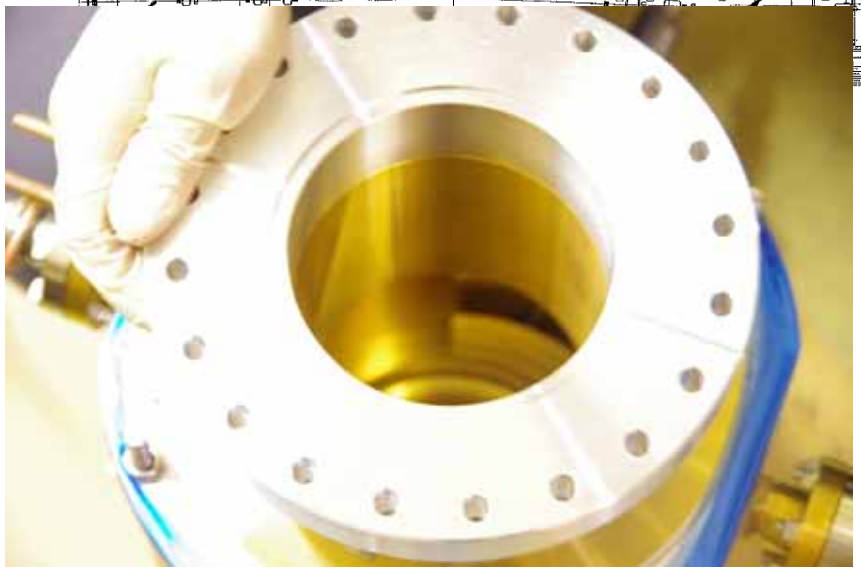
SuperKEKB Fuji straight section

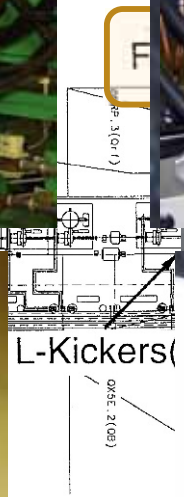


SuperKEKB Fuji straight section

Overdamped-type Longitudinal kickers (LER)
Rsh~1.6kΩ、Q~5 x4

Absorptive type LPF and wide-band circulators

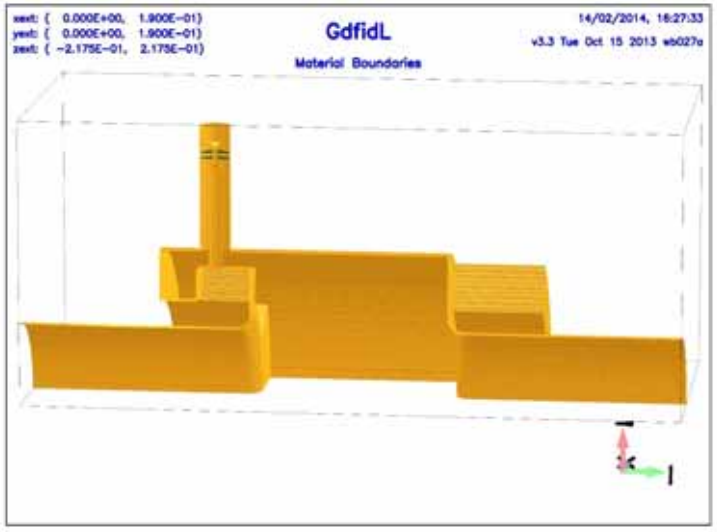


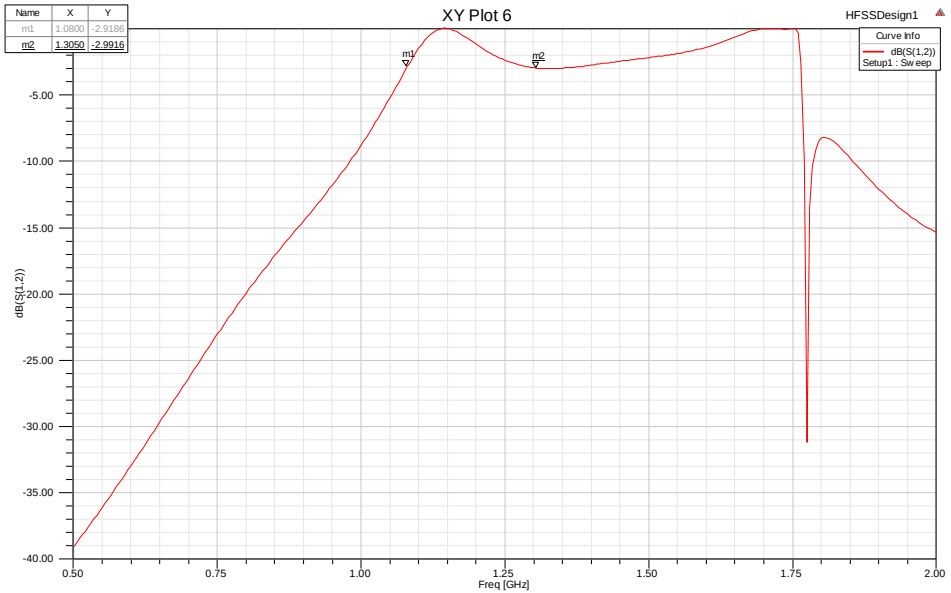


UHF Amplifiers (800M-2GHz, 500W) for L-FB (8 for LER)

Longitudinal kicker

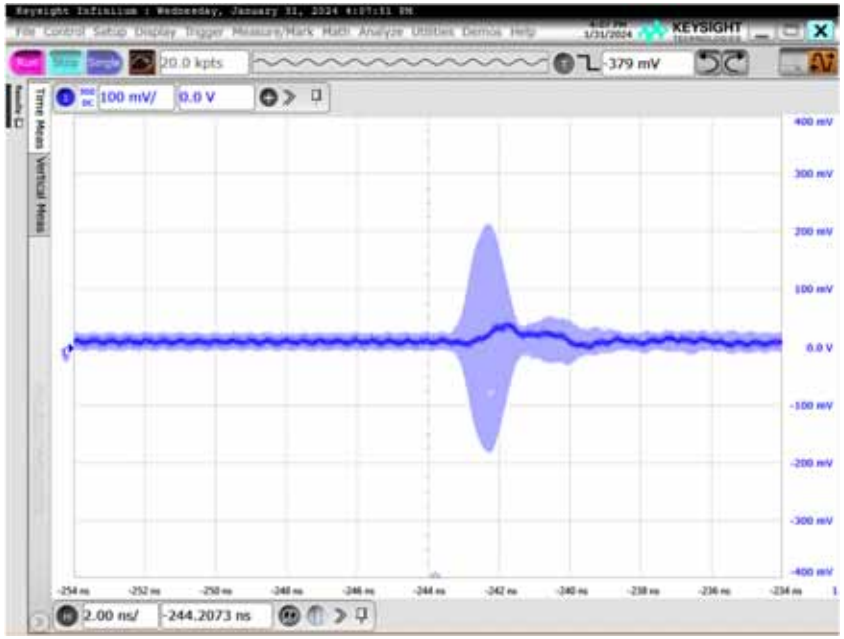
- 2-input, 2-output, DAFNE type kicker.
- center frequency =2.25 x fRF (1150 MHz)
- Bandwidth ~ 250MHz
- 8 wideband UHF amplifiers (R&K) are working (800M-1.8GHz, Po=500W).

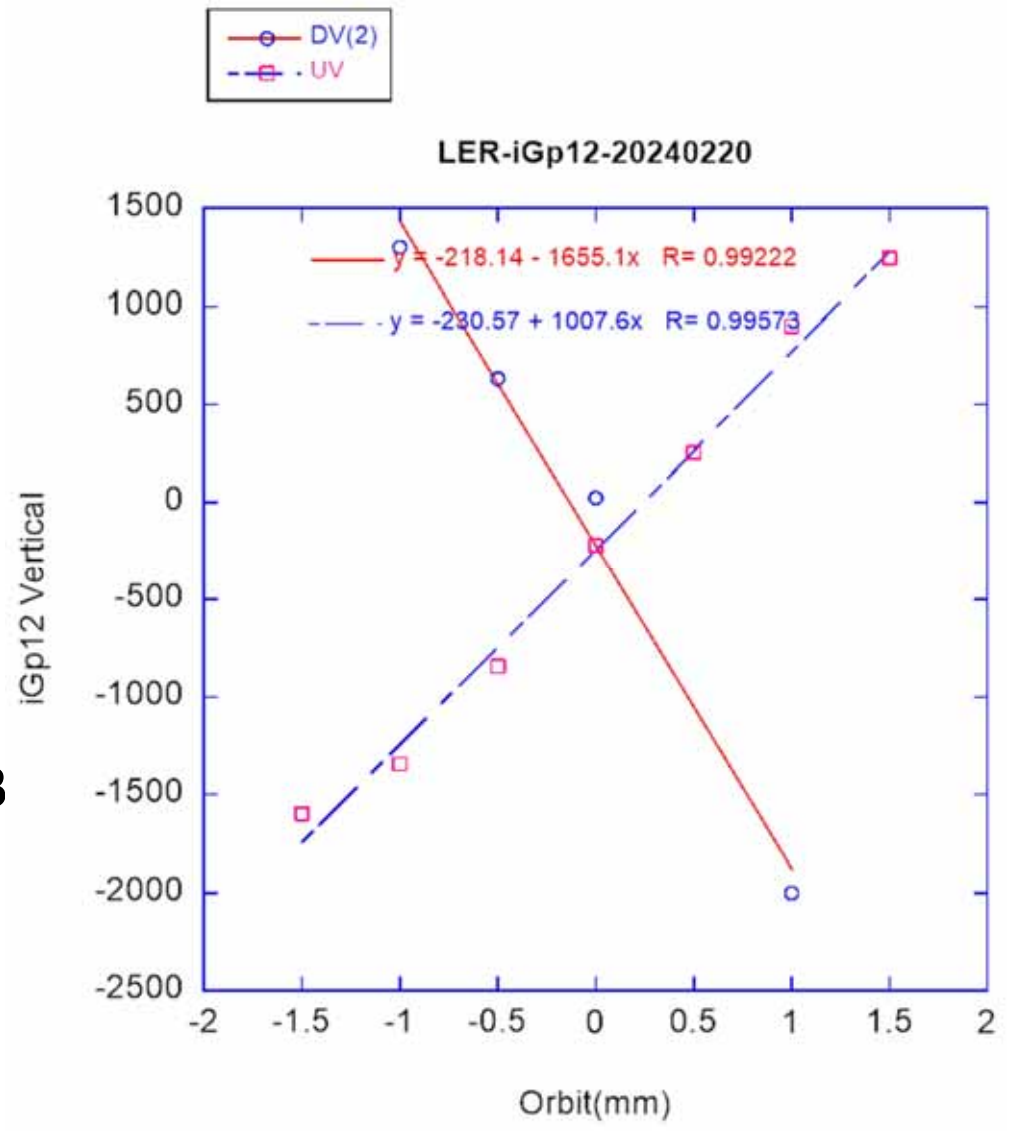




Q~ 5, Rsh ~ 1.6kΩ by HFSS calculation

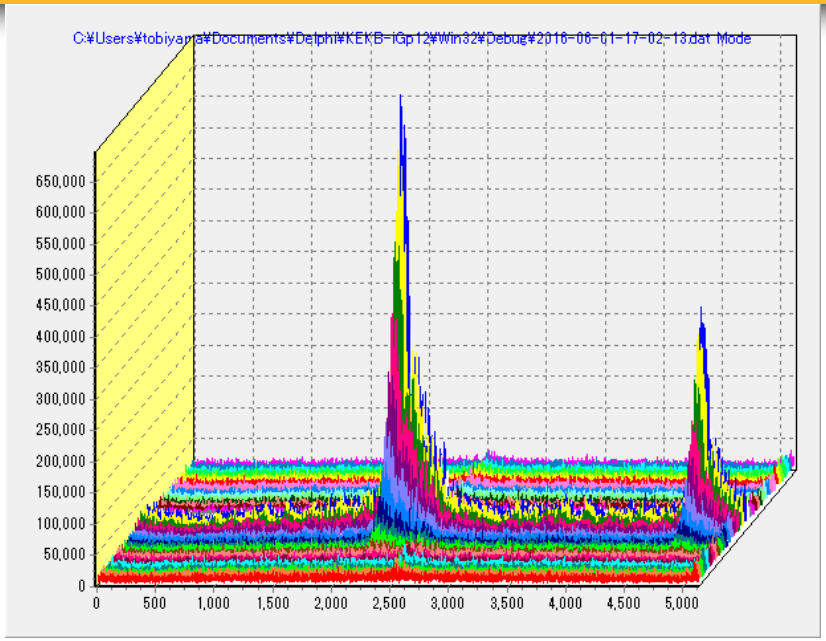
Detector output/sensitivities

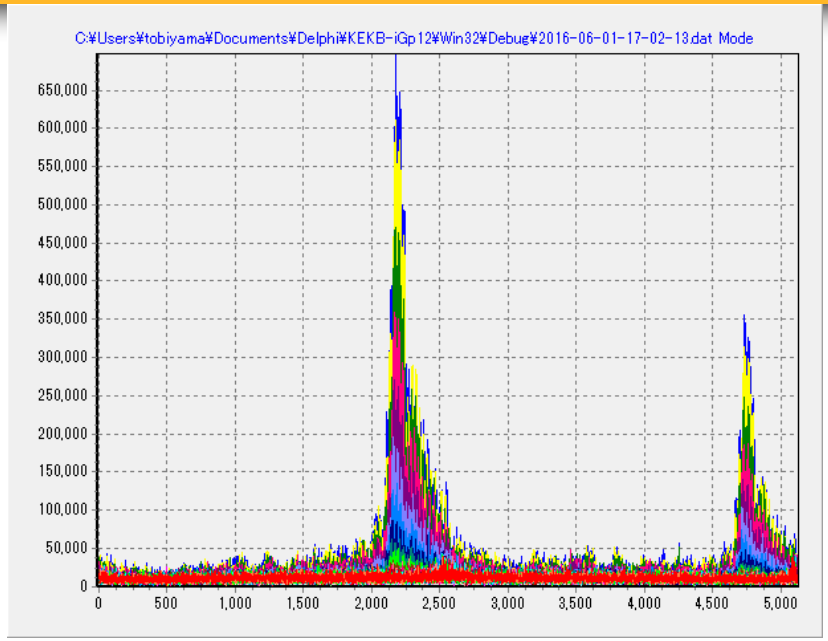


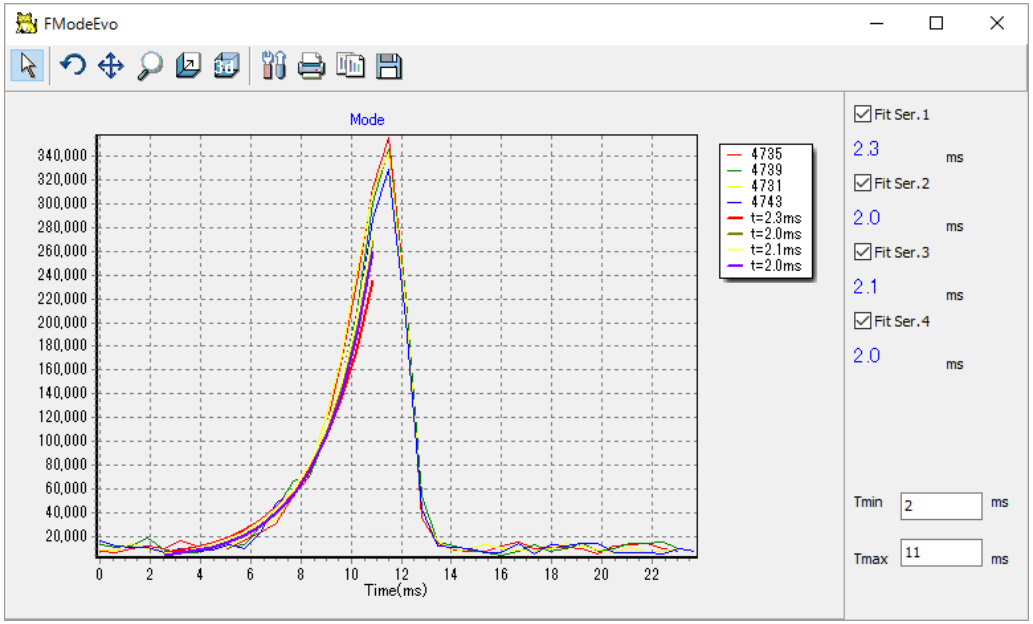


Dynamic range <+- 1.5mm /0.4mA @FB detector

Example of by 2 LER vertical (200mA)

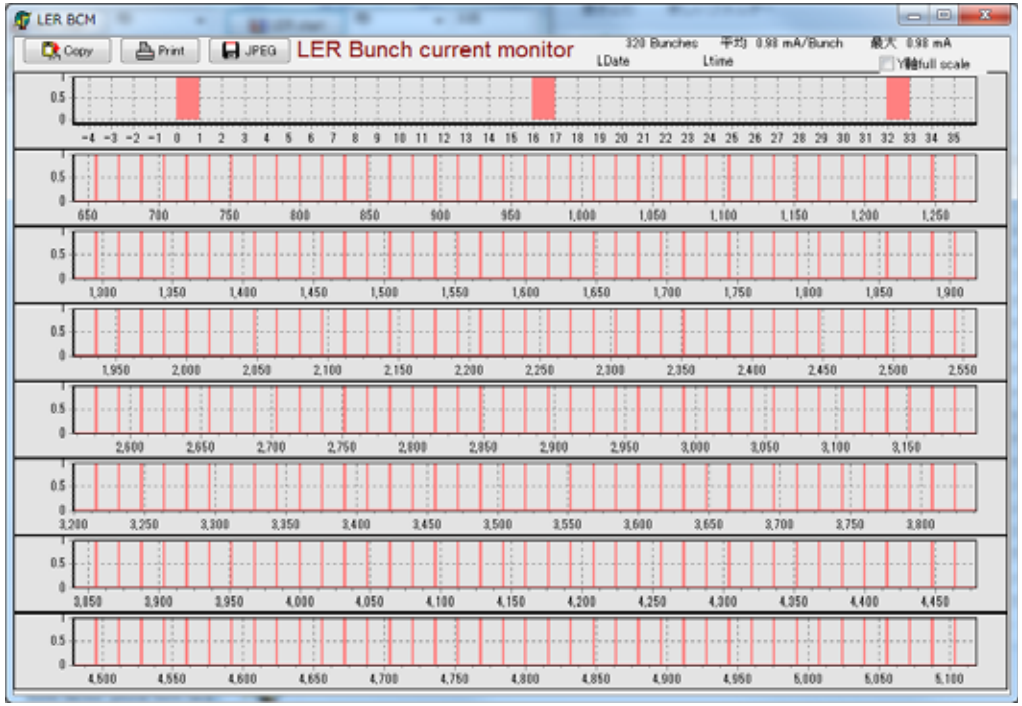






By2 200mA Vertical
Growth time~ 2.0ms
Damp < 0.5ms

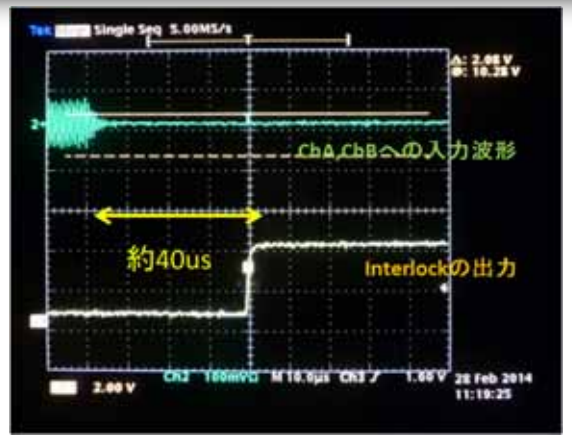
Bunch current monitor/BOR



MAX108 8bit ADC
Spartan6 FGPA
VME 2W size

Bunch current information will be sent through reflective memory (real-time) to the bucket selection system during injection period.

Other monitors



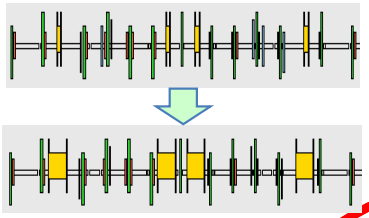
- **Orbit interlock**
  - Libera Brilliance+
    - turn-by-turn mode, latency <10 turns
    - Evaluation in progress: Latency < 4 turns
- **Medium-band detector**
  - Libera Brilliance+, FA mode (10kHz)
  - Oho straight section and south arc section
- **DCCT/CT**
  - Max beam current ~10A
  - Faster data acquisition using fast digitizer (Agilent 34410A)

Summary

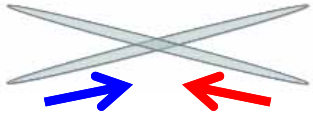
- **Overview of beam instrumentation of SueprKEKB rings (HER, LER and DR)**
  - **COD measurement systems**
  - **Gated turn-by-turn beam position monitor**
  - **Beam monitors for collision feedback**
  - **Photon monitors (Visual and X-ray)**
  - **Bunch feedback systems and their application (bunch current, bunch oscillation)**

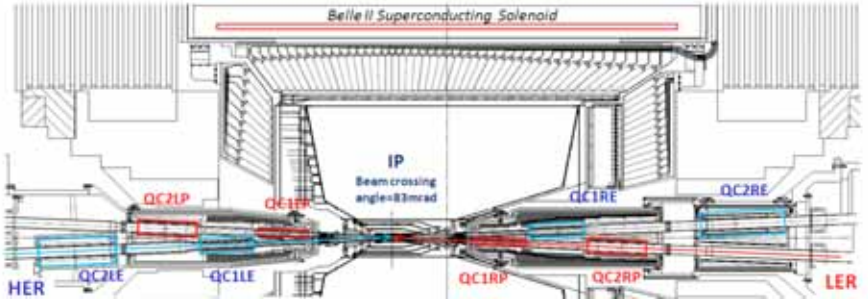
backup

Redesign the lattice to squeeze the emittance (replace short dipoles with longer ones, increase wiggler cycles)

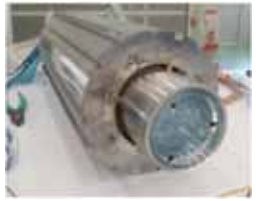


Colliding bunches





New superconducting final focusing magnets near the IP



e^+ 3.6A

e^- 2.6A

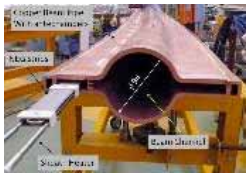
SuperKEKB

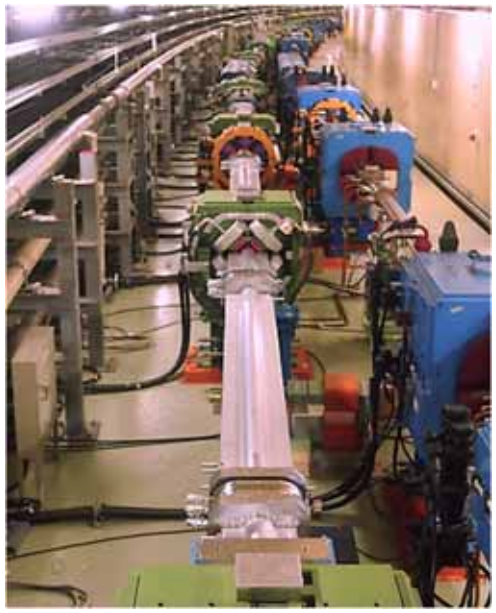
◆Nano-Beam scheme
extremely small β_y^*
low emittance

◆Beam current double

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

40 times higher luminosity
2.1×10^{34} --> 8×10^{35} $cm^{-2}s^{-1}$





Replace beam pipes with TiN-coated antechamber-type ones

Wiggler sections upgrade

Improve monitors and control system

Injector Linac upgrade
- RF electron gun
- improve e+ source

New e+ Damping Ring

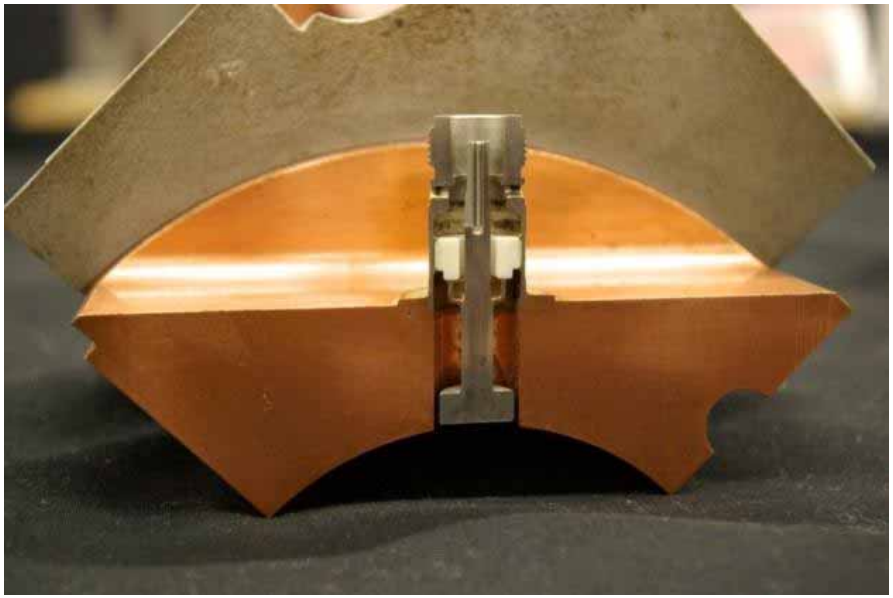
Reinforce RF systems for higher beam currents

International Collaboration

- **US-Japan Collaboration on High Energy Physics**
  - "R&D for SuperKEKB and the next generation high luminosity colliders", M. Tobiyama (KEK) and J. T. Seeman(SLAC)
  - SLAC, Cornell Univ., Univ. Hawaii, Wayne State Univ, LBNL, FNAL, BNL, …
  - Supported by US-Japan Collaboration since FY2003.
- **Multi-National Partnership Project (MNPP-01)**
  - IHEP, CERN, IJC-Lab, INFN, SLAC +

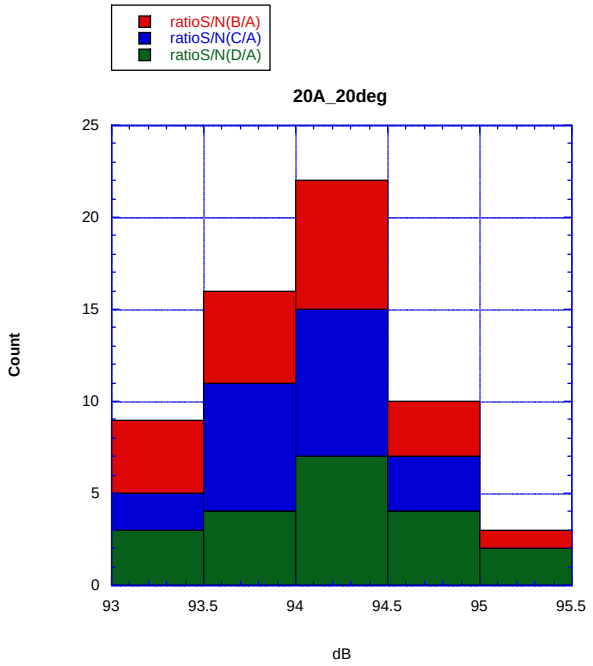
Button Heads

- **HER**
  - N-type connector
  - 12mm diameter
- **LER**
  - SMA(R) connector
  - 6mm diameter

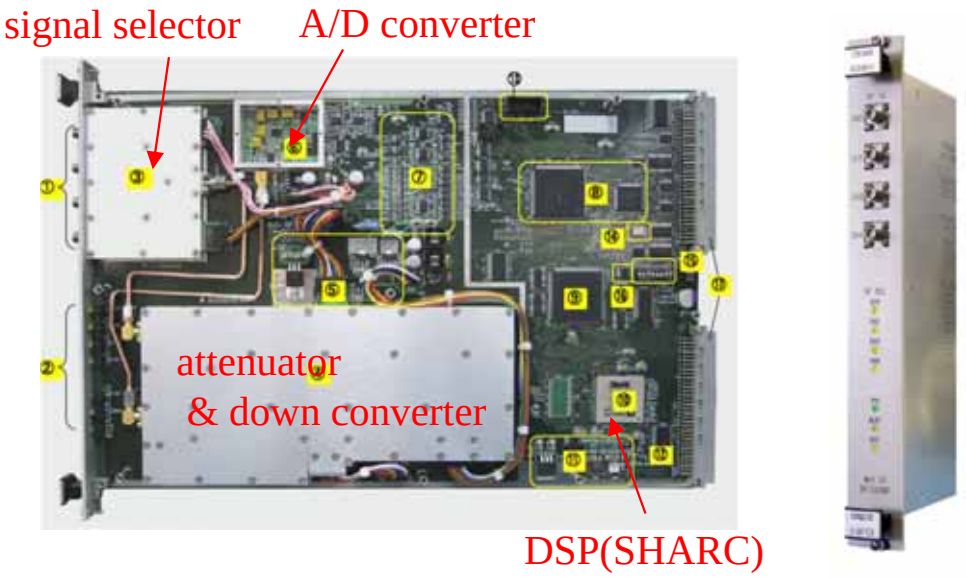


509MHz narrowband detector

- 120 Narrowband(509 MHz) detectors have been installed.
- Ratio S/N's have been confirmed to be better than 90dB.

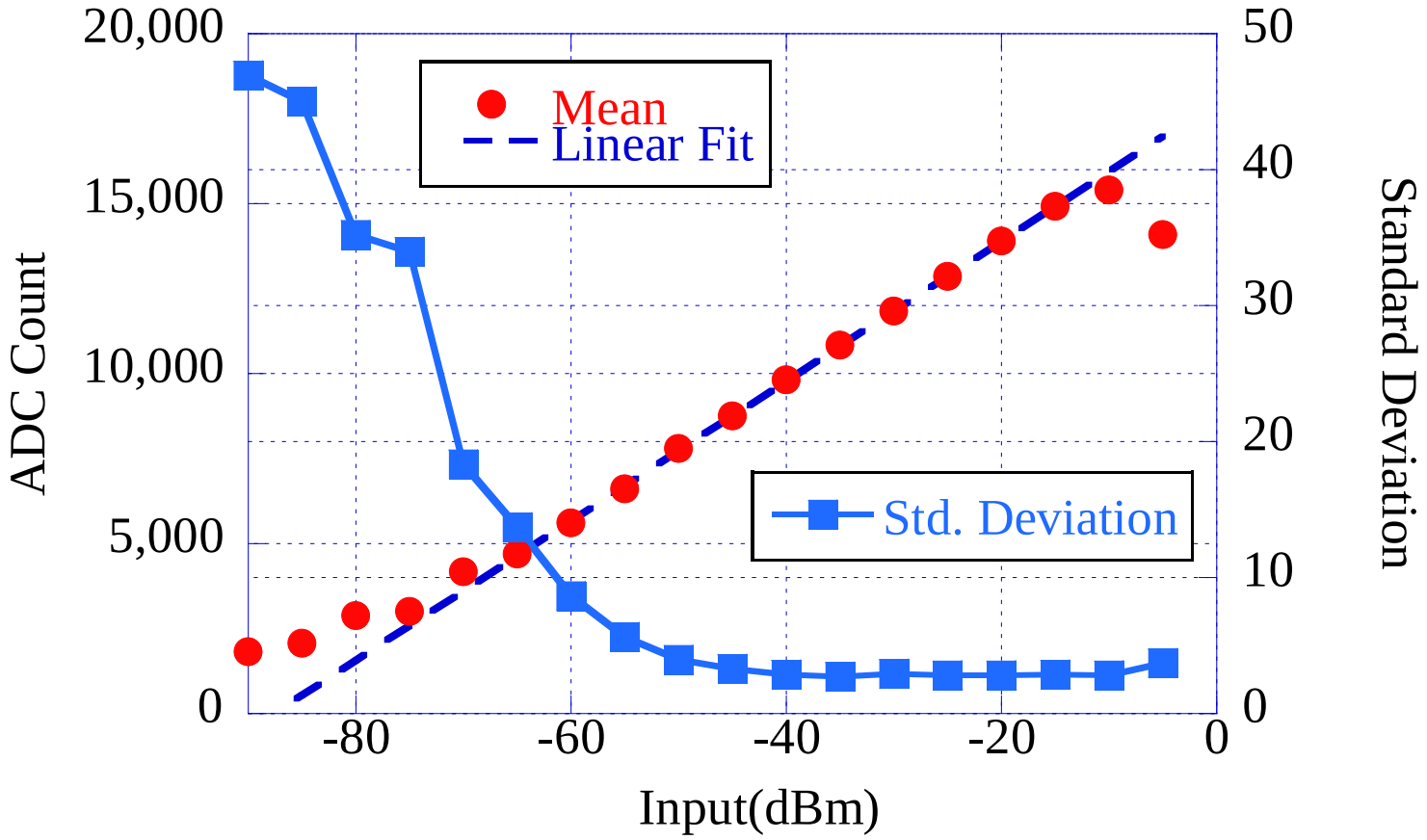


Ratio S/N of first 20 modules



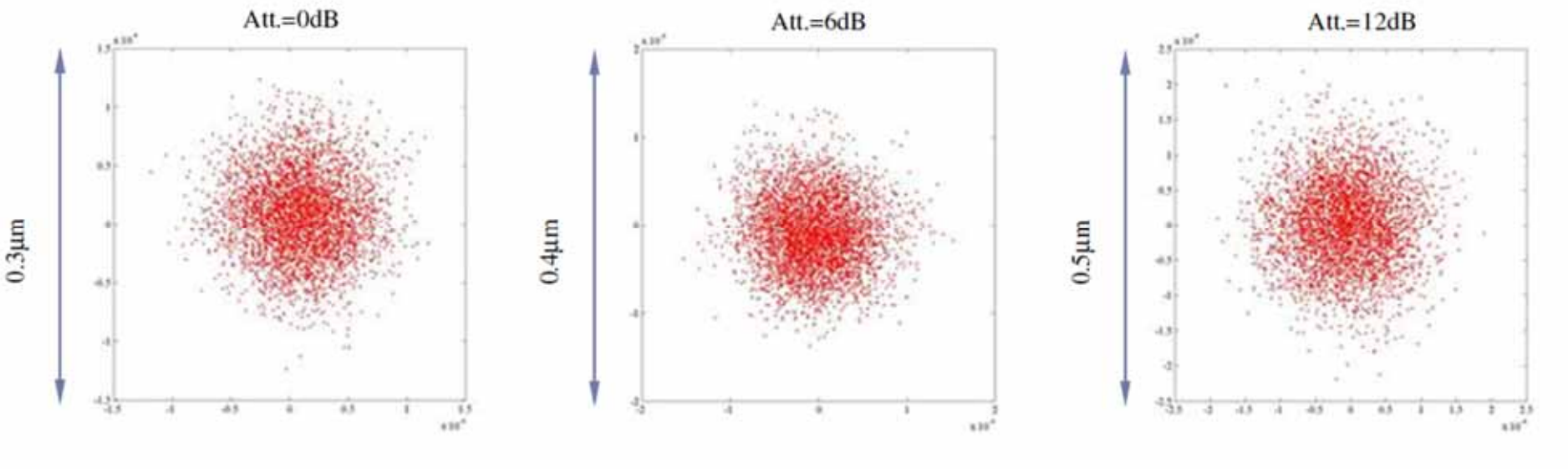
A 509 MHz narrowband detector

Position error



Standard deviation of ADC from -50dBm to -10dBm corresponds roughly 30um of position jitter.

Position resolution



- R&D of a down-converter has completed. Ready to fabricate (scheduled on FY2016).
- Power supply controller (PS I/F) prototype(mTCA4) has been fablicated and tested in FY2015. Fixing bugs.

SRM: Extraction mirrors and chambers

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Diamond extraction mirror for visible light beam size monitor in holder

Mirror mounted in extraction chamber.

Extraction chamber installed in tunnel. (Vac. Group)

- Diamond mirrors for visible light monitors have been installed in extraction chambers and aligned.

XRM: X-Ray Monitor

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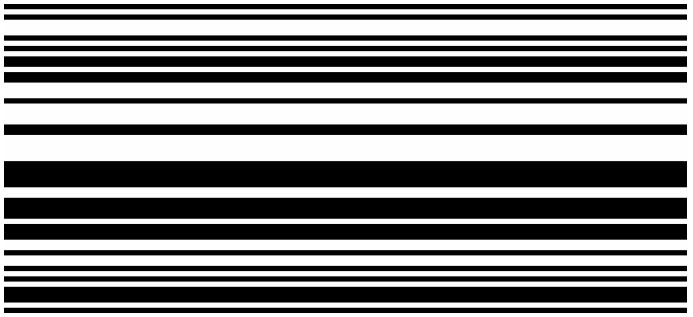
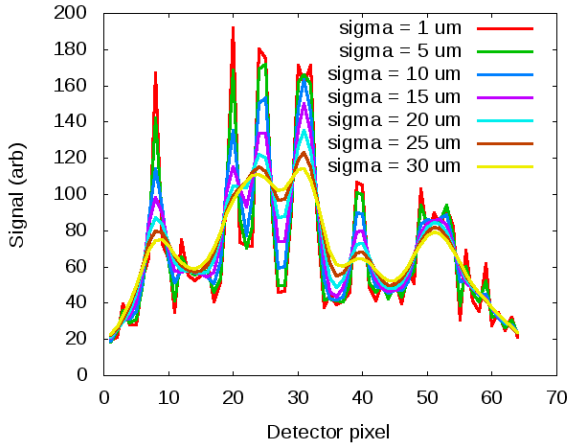
Xray Source Bend Par.	S-LER (BS2FRP.1)	S-HER (BS2E.82)	Units
ε_x	3.20E-09	4.60E-09	m
κ	0.27%	0.24%	
ε_y	8.64E-12	1.10E-11	m
β_y	50.0	11.5	m
σ_y	20.8	11.3	μm
Beam Energy	4	7	GeV
Effective length	0.89	5.9	m
Bend angle	28.0	55.7	mrad
ρ	31.7	105.9	m
Critical Energy	4.4	7.1	keV



59-element Uniformly Redundant Array mask pattern

- Coded Aperture Mask:
  - In-hand :
    - High-power, 59-element, 10 μm/element URA
    - 10 μm Au mask on 625 μm Si substrate
  - Under development:
    - 20 μm Au mask on 500 μm CVD diamond (monocrystalline) substrate
      - Substrates manufactured.
      - New pattern being designed for improved resolution (E. Mulyani)
- Detector:
  - 64-pixel (Phase 1), later 128-pixel, 50 μm pitch linear array
  - InGaAs detectors in hand (same type as used at CesrTA)
  - Deep Si detectors in development for better detection efficiency at high energy (SLAC)

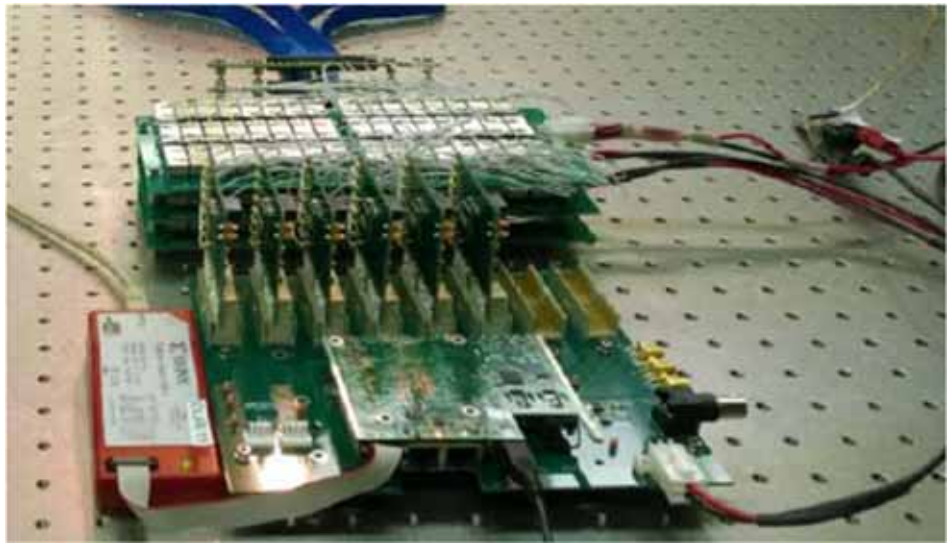


Simulated detector response for various beam sizes at SuperKEKB LER

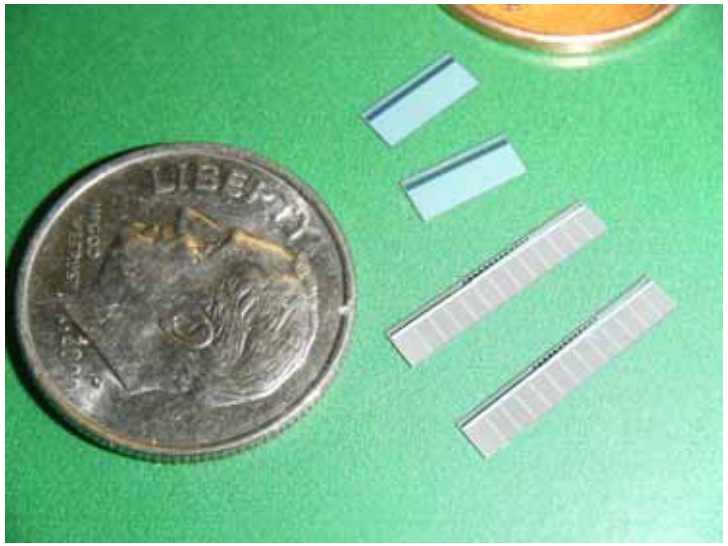
XRM: Hardware

J.Flanagan

- Beamline components have been installed. Vacuum conditioning in progress.
- 64-channel prototype high-speed readout system and detector mount made (U. Hawaii). Firmware under development (US-Japan).
- High-energy detector wafers processed and diced, and detector and spectrometer chips undergoing leakage testing. (SLAC, US-Japan)
  - Chips from first wafer show high leakage currents. Second wafer chips being tested.
  - Need for second wafer run to be evaluated based on yield.
  - Heat-sinking and mounting design of detector to follow.



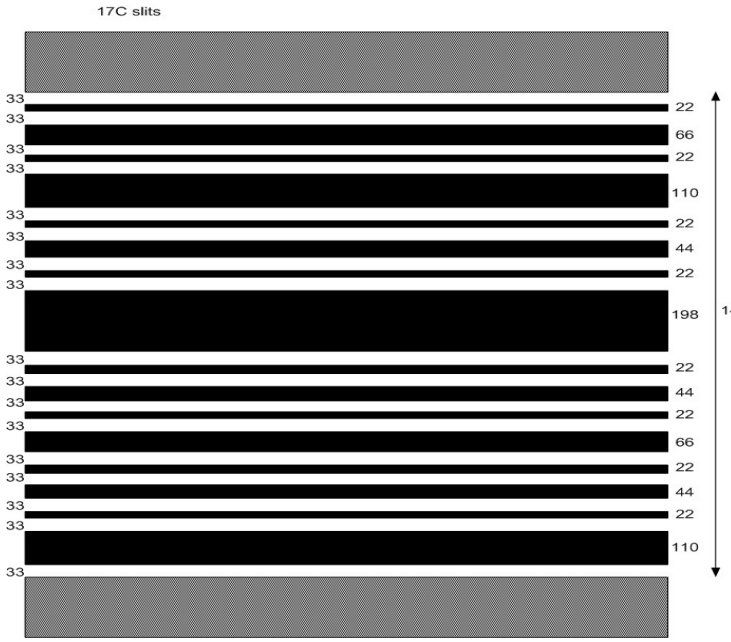
High-speed readout electronics for the X-ray monitor, being developed by U of Hawaii.

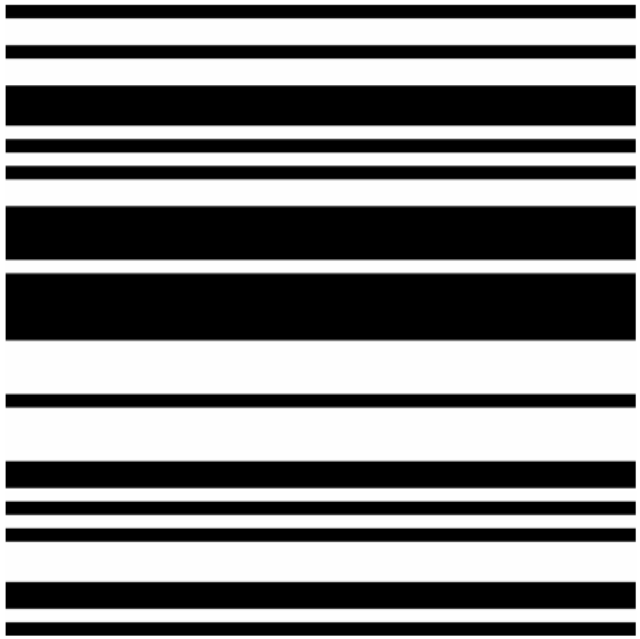


Deep Si pixel detector and spectrometer chips for the X-ray monitor, being developed at SLAC.

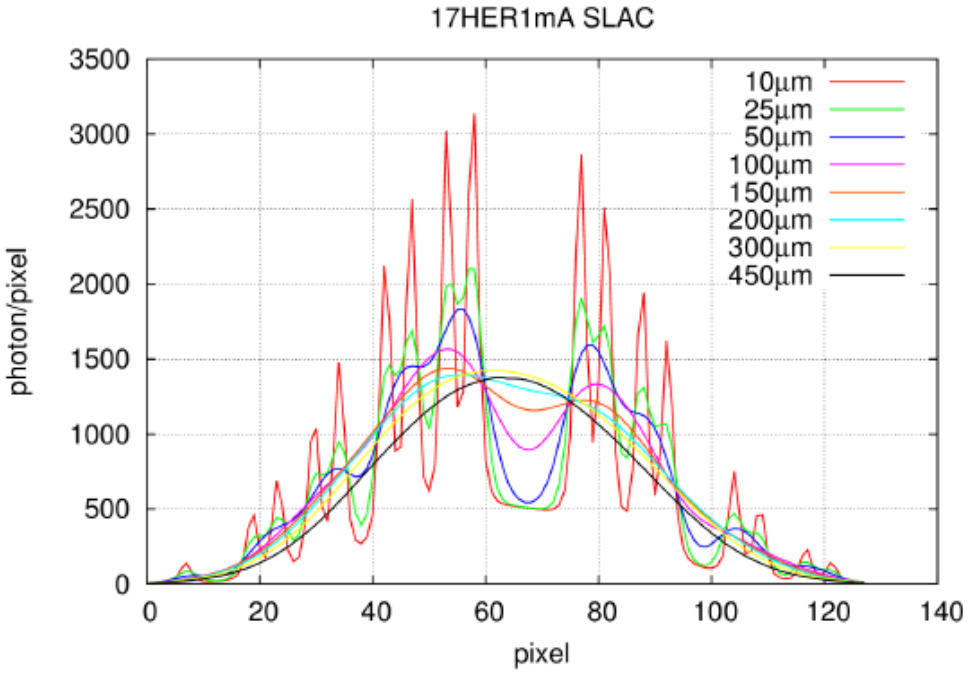
XRM Beamline + Optics Box

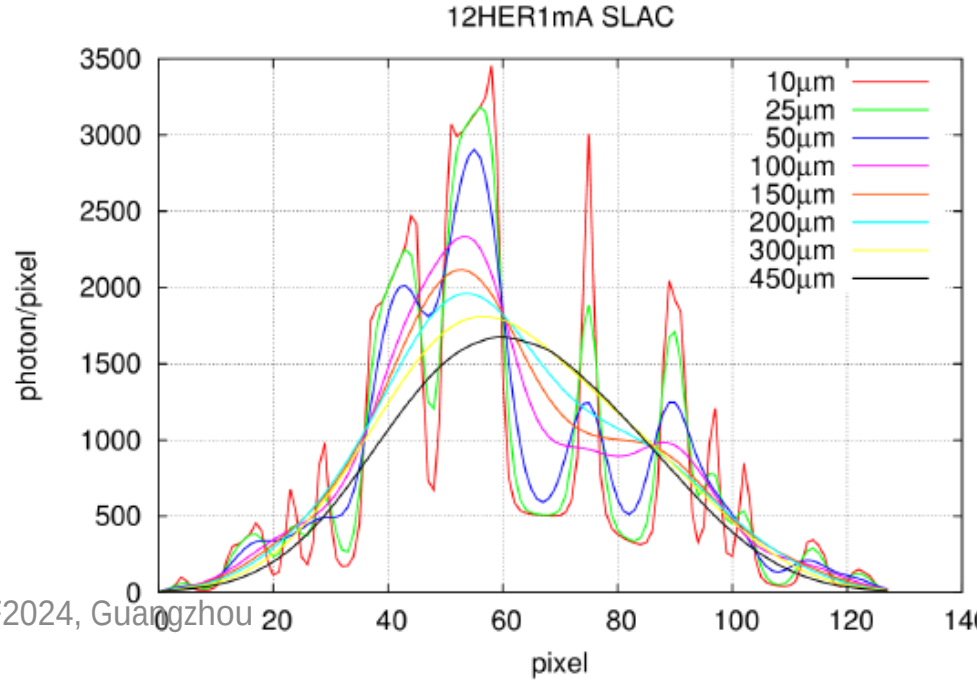
Coded Aperture Mask Patterns





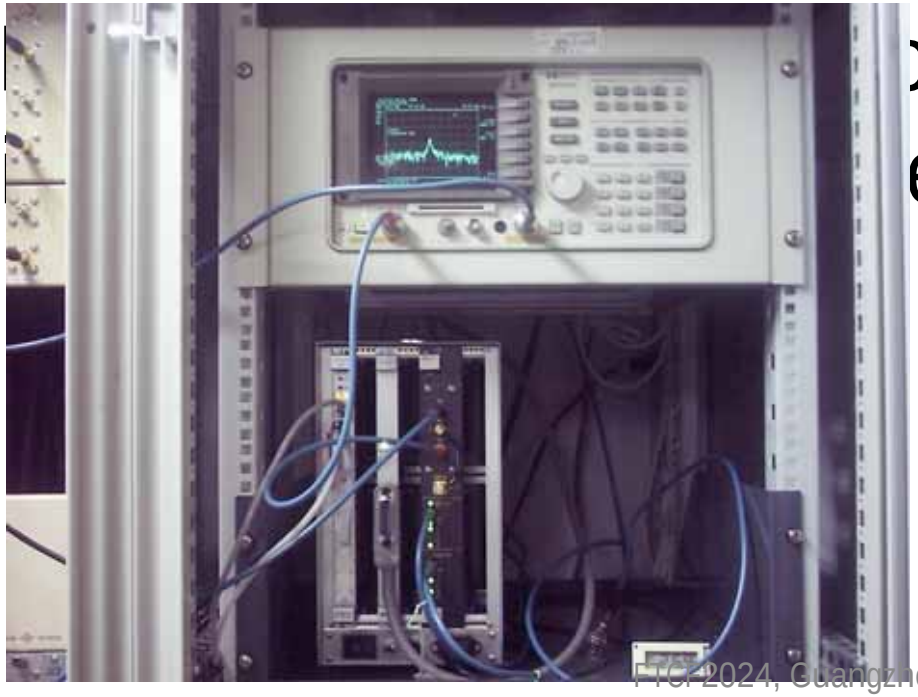
Detector Images

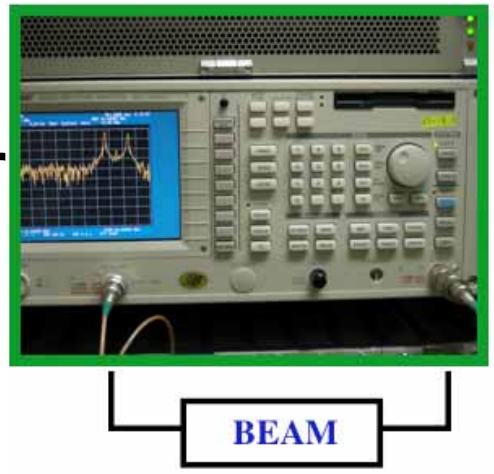




Betatron Tune

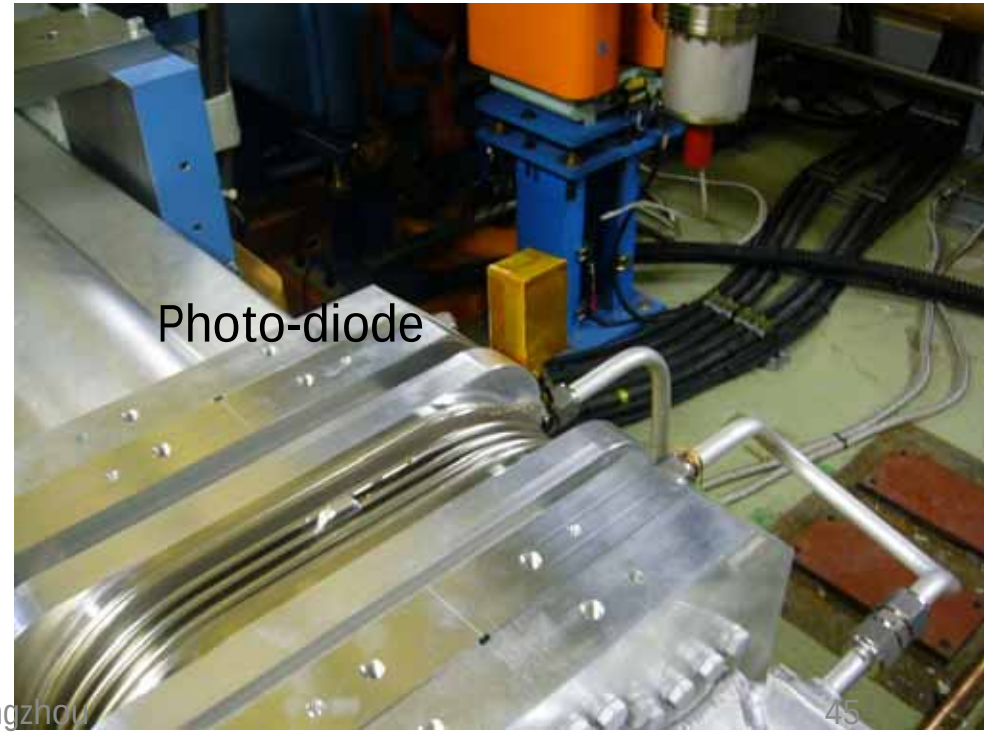
- Global tune measurement for multi-bunch, small beam current
- Gated tune measurement for pilot bunch only
- [illegible]ot
  [illegible]er





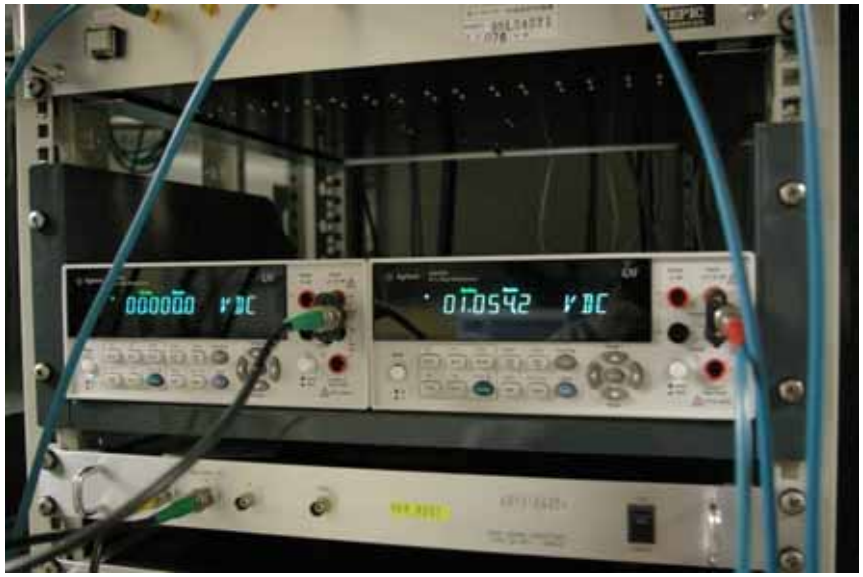
Loss Monitor

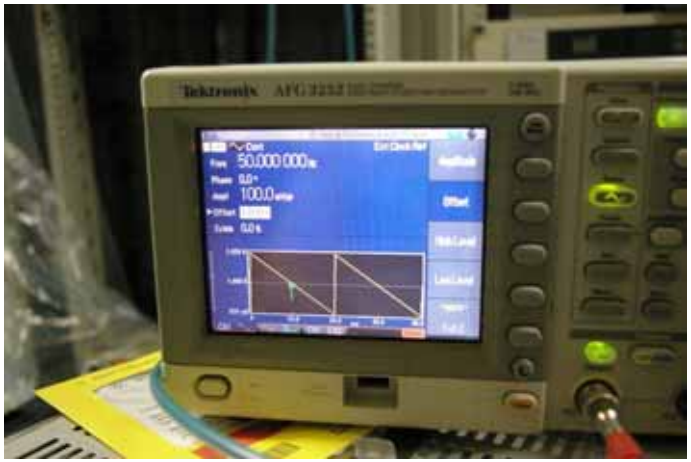
- Installation of LM cables and sensors has finished except for IR region.
- Read-out modules (integrator + interlock module, ADC) are prepared and cabling in control room will be done soon.



Fast beam decay measurement system

- Keysight 34410A DVM
  - Can transfer ~5ksps data to the host without data gap.
- Calculate using EPICS sequencer
  - Mean, Injection rate, Decay rate, Injection counts.
  - 1st order fit to get decay slope.
- Good agreement with the input signal.





US-Japan collab. overview

- Development and fabrication of accelerator components important to the construction and operation of the SuperKEKB accelerator
  - Collaborate with SLAC to develop
    - IP collision feedback systems
    - Fast luminosity monitor
    - Beam collimators
    - Beam background, Machine Detector Interface
    - Accelerator Physics
      - Main Ring commissioning
      - Damping Ring commissioning
      - Linac commissioning
    - BPM for Linac/BT
    - X-band deflecting cavity
    - Stripline kicker for high beam current
    - X-ray detector
    - Flux Concentrator to increase capture efficiency of positrons
    - Beam energy calibration using laser Compton scattering

(cont)

- R&D on accelerator technology important for the next generation of high luminosity colliders.
  - Development of general purpose bunch-by-bunch feedback systems (KEK, SLAC)
  - Development of bunch-by-bunch X-ray beam size monitor using coded aperture mask (KEK, Univ. Hawaii, Cornell Univ., SLAC)
  - Development of Large Angle Beamstrahlung Monitor for collision monitoring (KEK, Wayne State U.)

LABM Beamlines