Summary of KEK llrf system (KEK-Tsukuba and J-PARC)

Shin MICHIZONO, KEK

KEKB

- Crab cavity operation
- Bunch-by-bunch FB

Poster session: M.Tobiyama:
Bunch-by-bunch Feedback System Using iGp Feedback Signal Processor

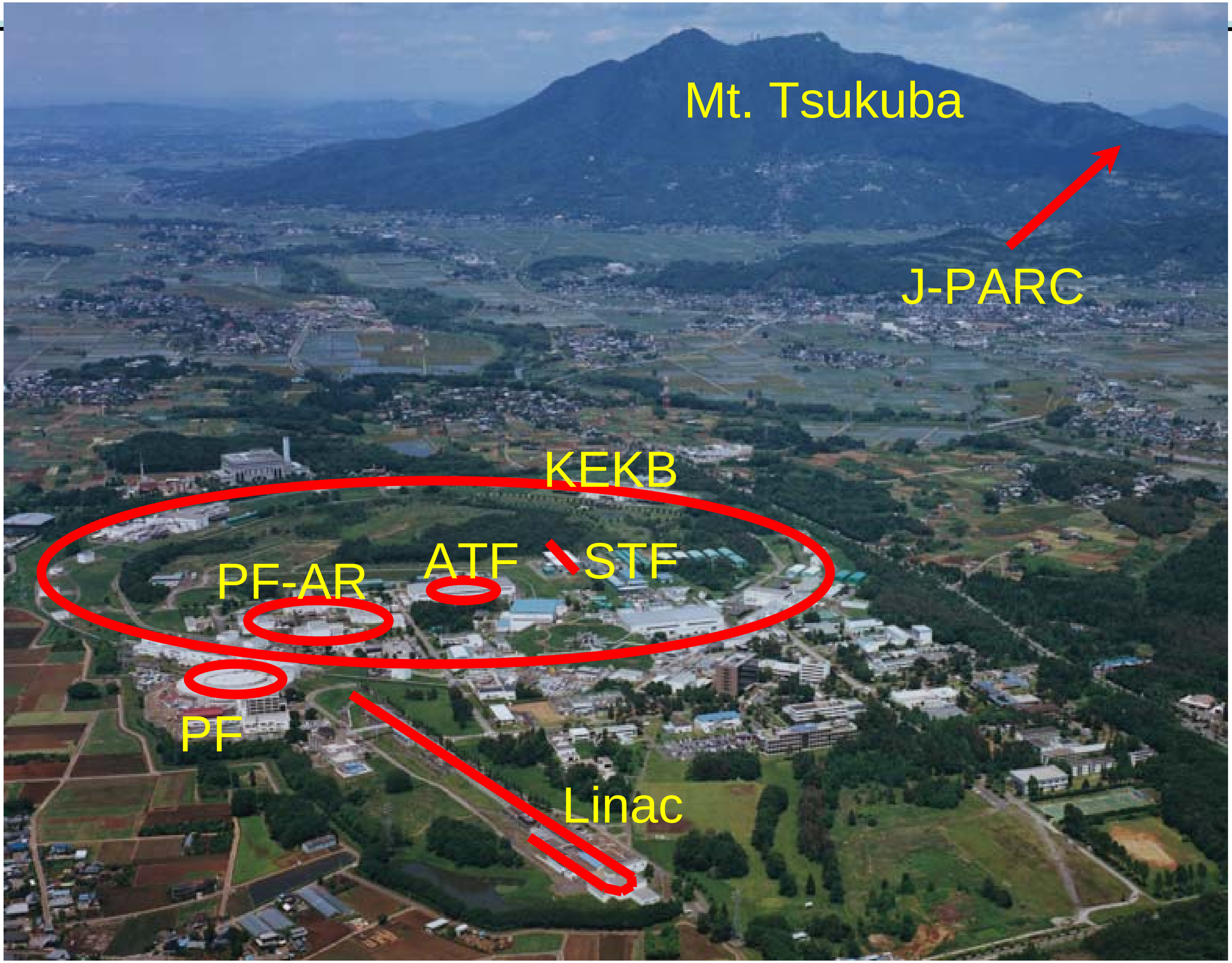
J-PARC

- Linac llrf — ***Monday's talk T.Kobayashi:*** **Performance of J-PARC Linac RF System**
- Synchrotrons — ***Wednesday's talk F.Tamura:*** **LLRF Control Systems for J-PARC Synchrotrons**

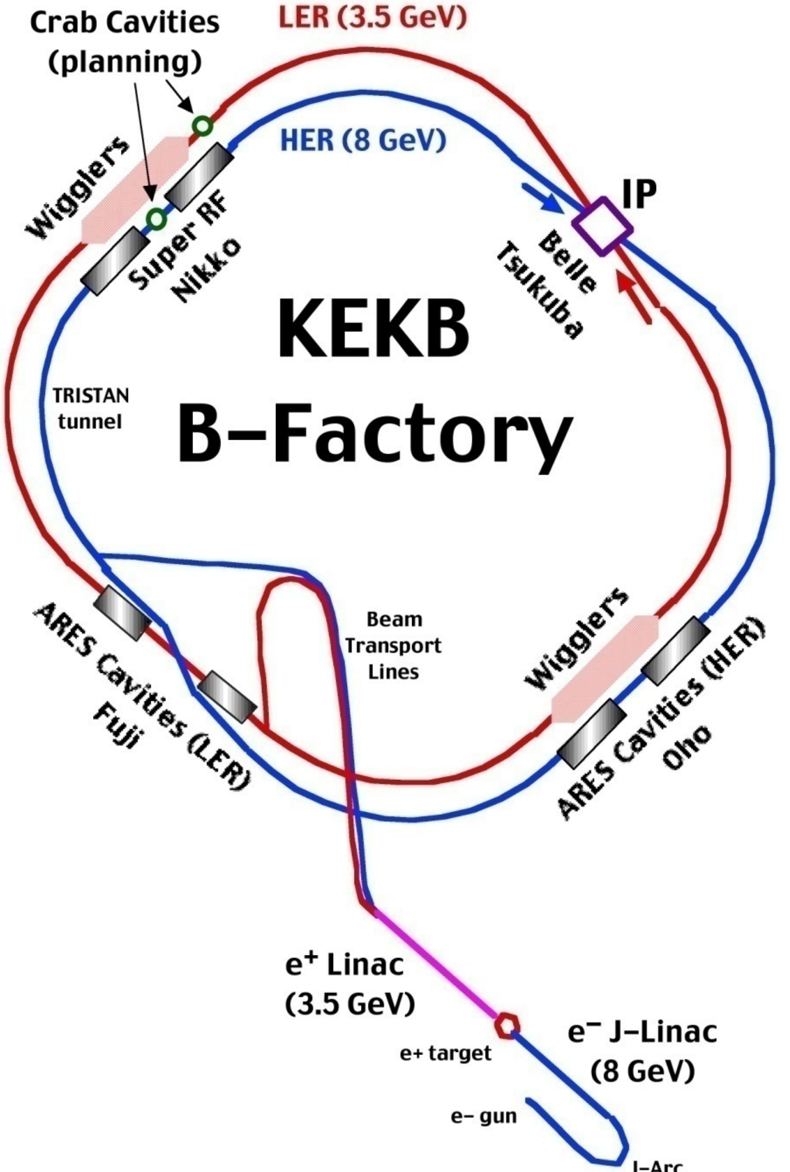
STF (Superconducting rf test facility)

- Status of STF llrf — ***Poster session S.Michizono:*** **Status of the low-level RF system at KEK-STF**
- IF mixture — ***Poster session T.Matsumoto:*** **Development of Low-level RF System using IF Mixture Technique**

ERL


Mt. Tsukuba
J-PARC
KEKB
ATF
STF
PF-AR
PF
Linac

KEKB Accelerator



- **Beam energy**
  - **8GeV (electron)**
  - **3.5GeV (positron)**
- **Circumference**
  - **~3018m**
  - **Use TRISTAN tunnel**
- **RF system**
  - **f_{RF} ~ 509MHz**
  - **ARES (LER)**
  - **ARES+SCC (HER)**
- **Injector Linac**
  - **No Damping rings**
  - **2 bunch injection (e+)**

K. Akai et al., SRF2007 workshop, WEP57

First Crab Cavity Operation

Crab cavities installed in KEKB

Beam currents and crab voltage In four months operation

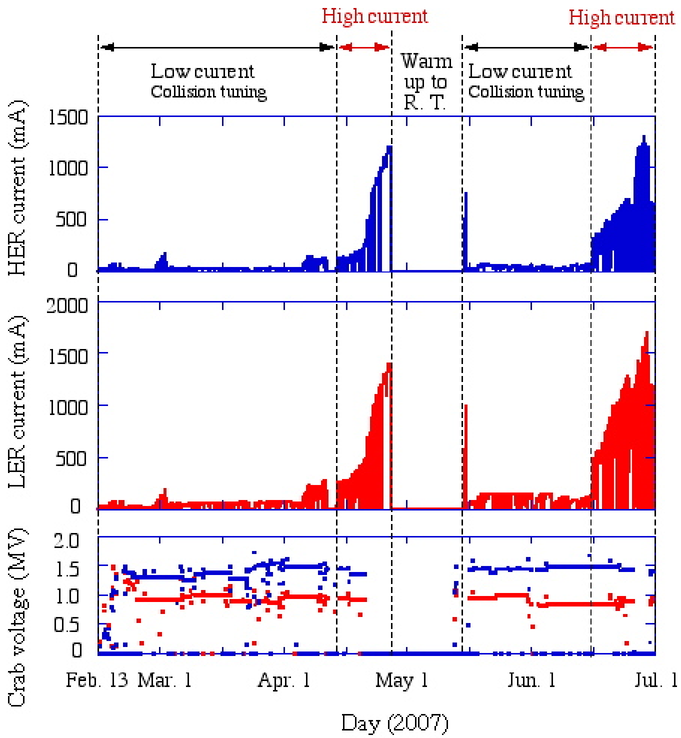
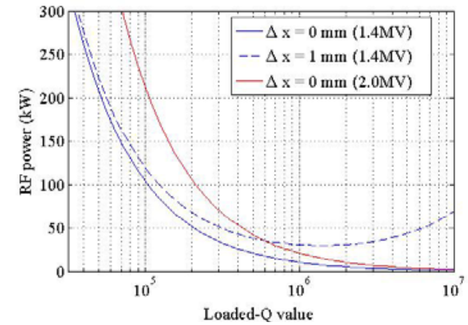


Table 2: Achieved parameters during beam operation.

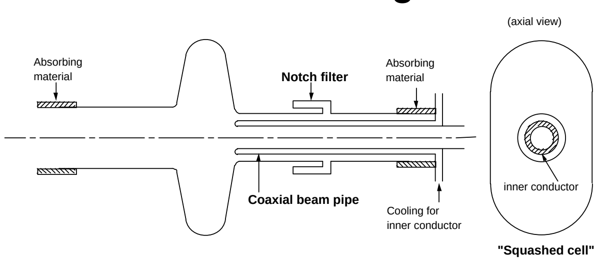
	LER	HER	unit
Beam current (detuned)	1700	1350	mA
Beam current (crab ON)	1300	700	mA
Number of bunches	1389	1389	
Crab voltage (max)	1.5→1.1	1.8	MV
Crab voltage (operation)	0.9	1.45	MV
Tuner phase stability	±15	±1	deg
Crab phase stability	±0.1	±0.1	deg
HOM power	11.5	12	kW
Average trip frequency	1.57	1.27	/day

Beam-loading on crab cavity



$$P_g = \frac{1}{4\left(\frac{R_\perp}{Q_0}\right)Q_L}\left\{V_c + I_b\left(\frac{R_\perp}{Q_0}\right)Q_L k \Delta x\right\}^2$$

Baseline design

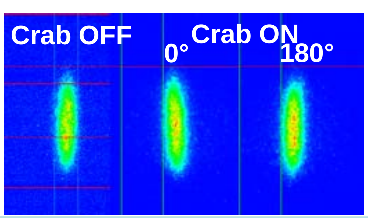


Squashed Crab cavity for B-factories

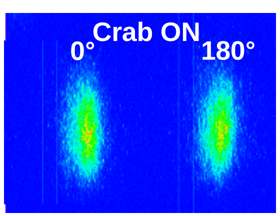
(K. Akai et al., Proc. B-factories, SLAC-400 p.181 (1992).)

Tilts by the crabbing (H. Ikeda)

HER



LER



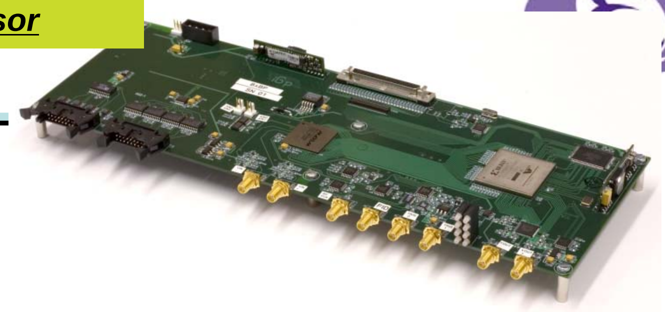
The phase fluctuation faster than 1 kHz is less than ± 0.01°, and slow fluctuation is about ± 0.1°. They are much less than the allowed phase error for the crabbing beams in KEKB.

Bunch-by-bunch feedback systems using iGp feedback singal processor

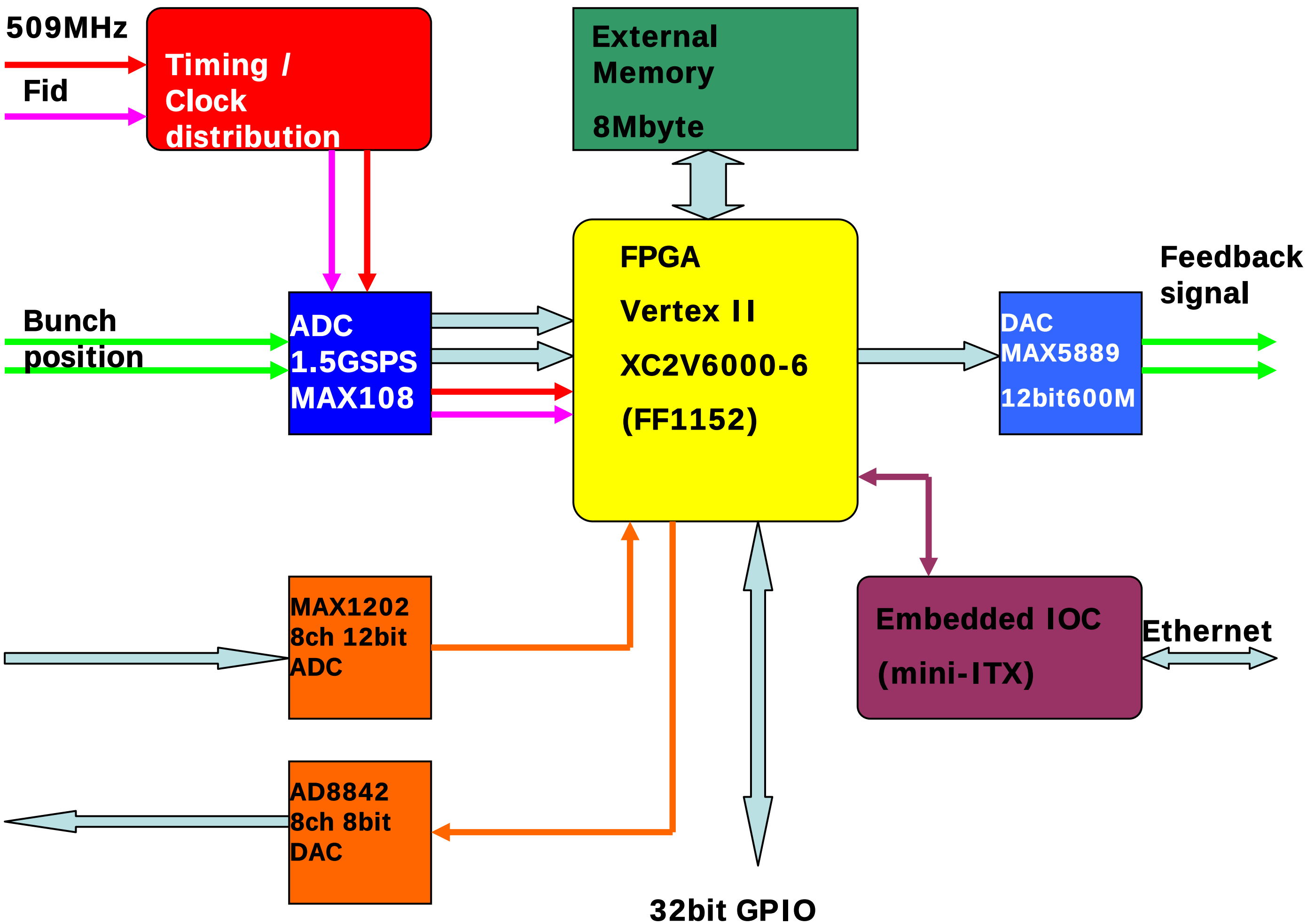
M.Tobiyama, J.W.Flanagan, T.Obina, M.Tadano(KEK),J.D.Fox, D.Teytelman, J.Dusatko(SLAC), A.Drago(INFN-LNF)

Supported by US-Japan collaboration in High Energy Physics

Poster session: M.Tobiyama:
Bunch-by-bunch Feedback System Using iGp Feedback Signal Processor

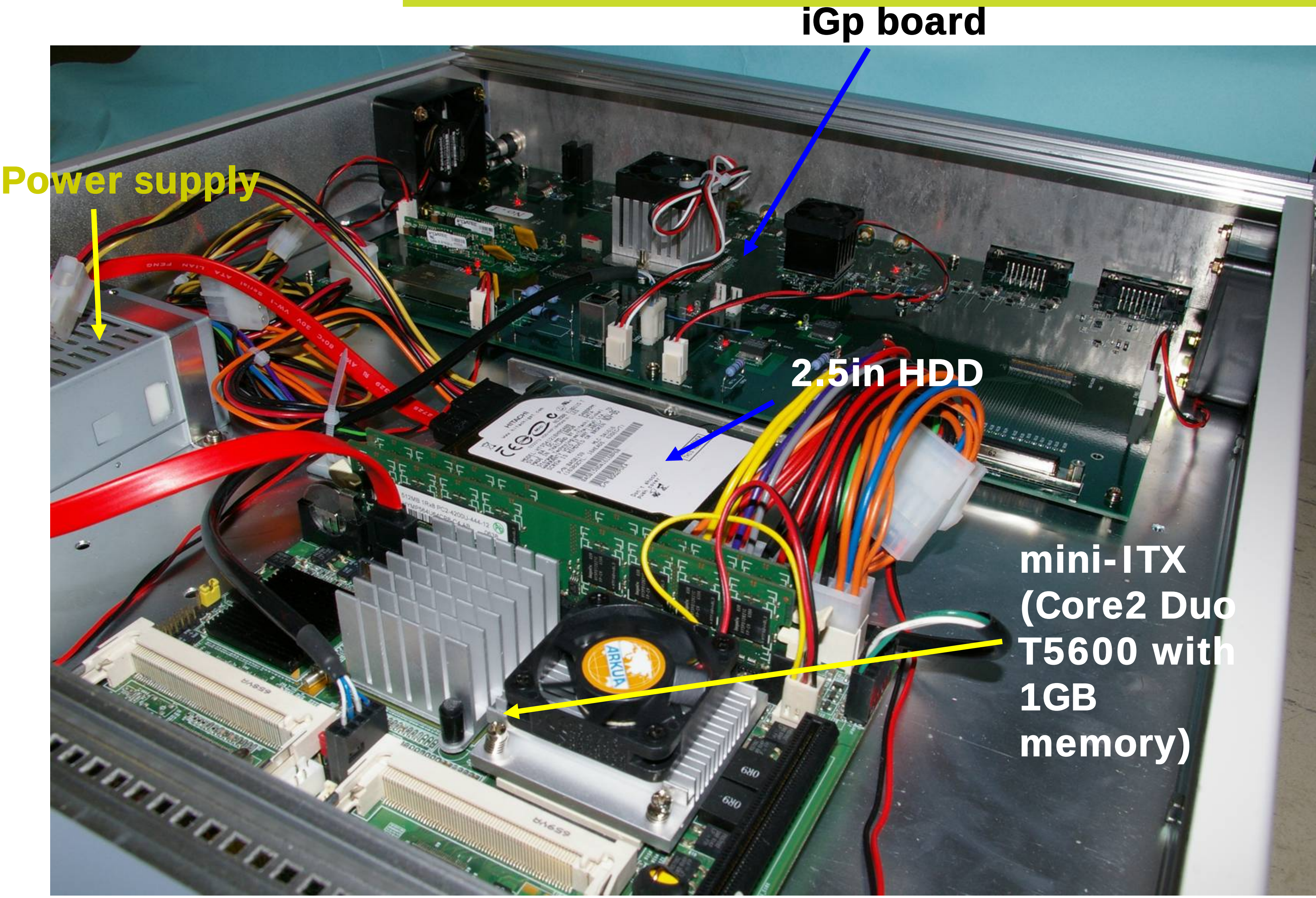


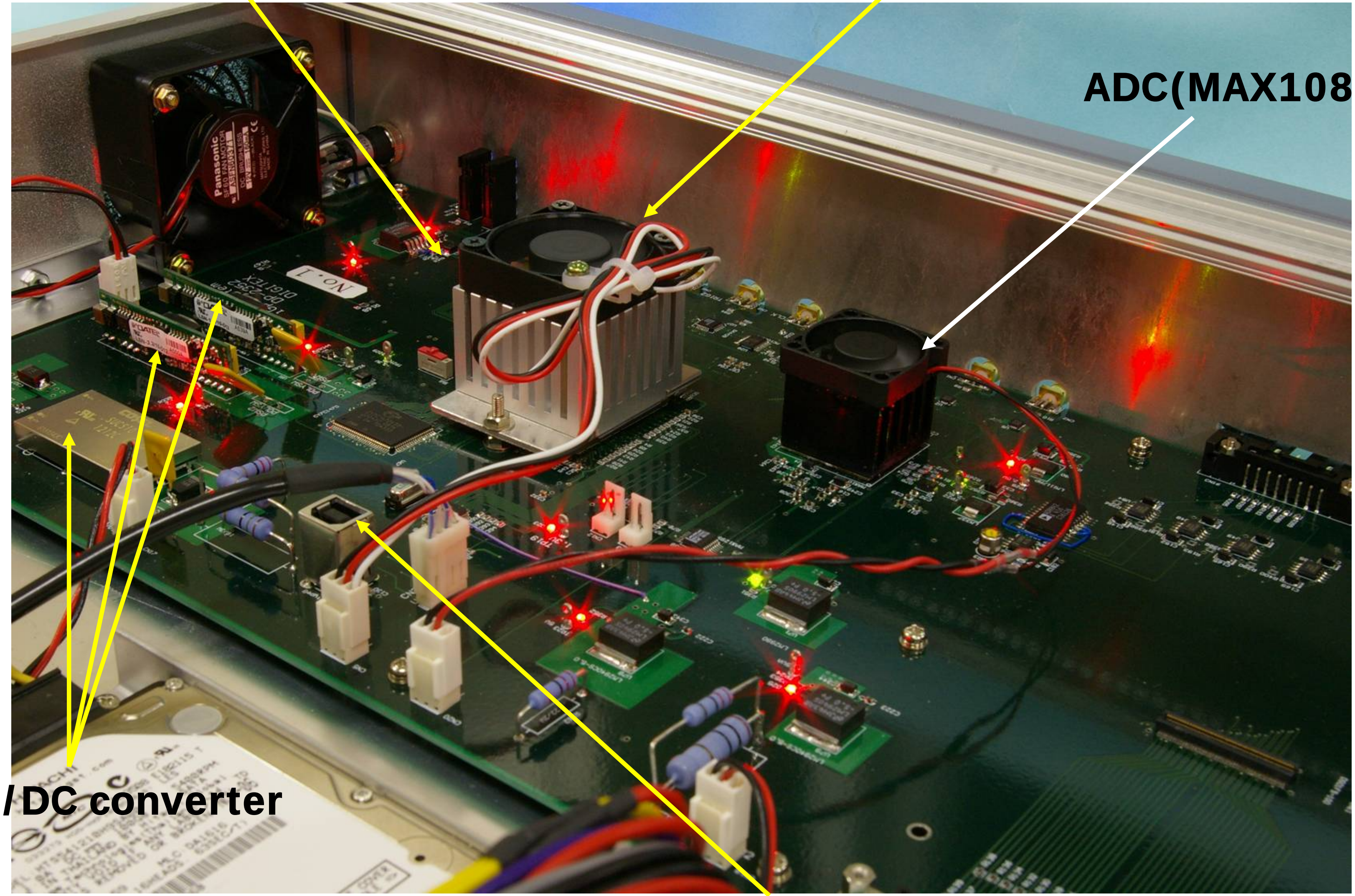
Block diagram



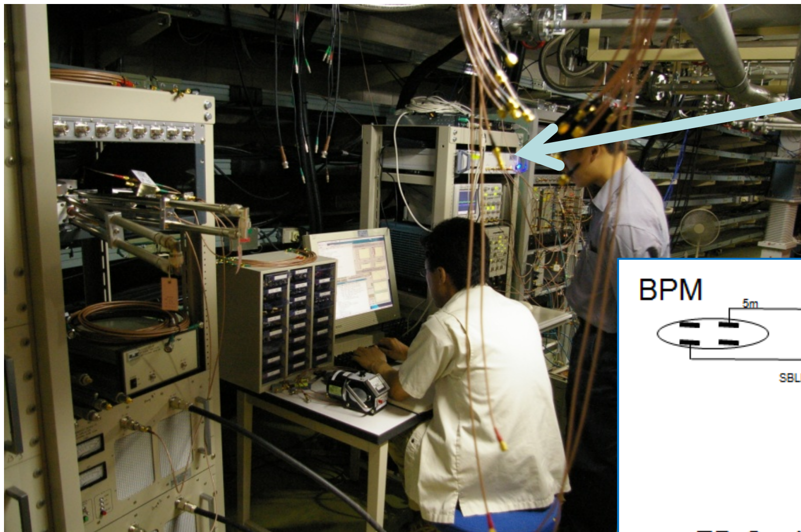
iGp 2nd board (KEKB)

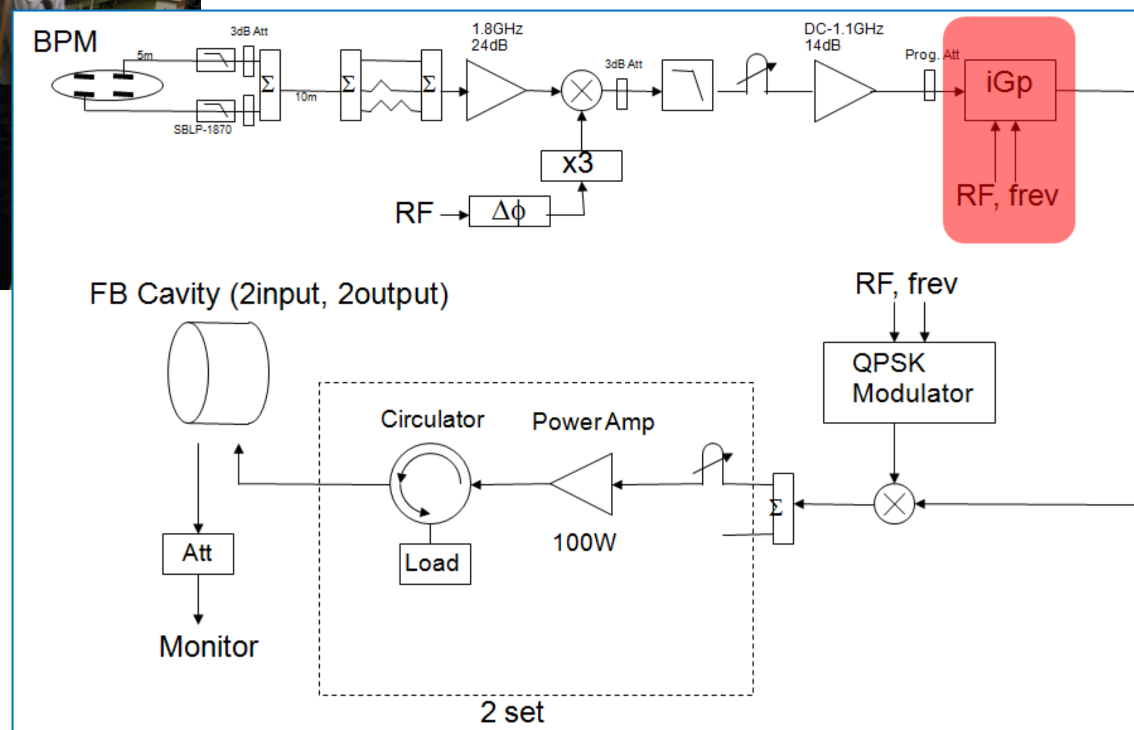
Poster session: M.Tobiyama:
Bunch-by-bunch Feedback System Using iGp Feedback Signal Processor




DAC(MAX5889)
FPGA(XC2V6000)
ADC(MAX108)
DC/DC converter
USB IF(FT2232L)

Longitudinal feedback experiment at KEK-PF





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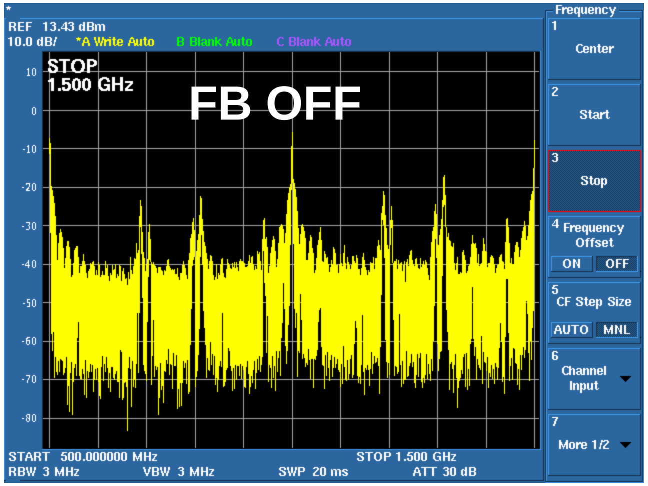
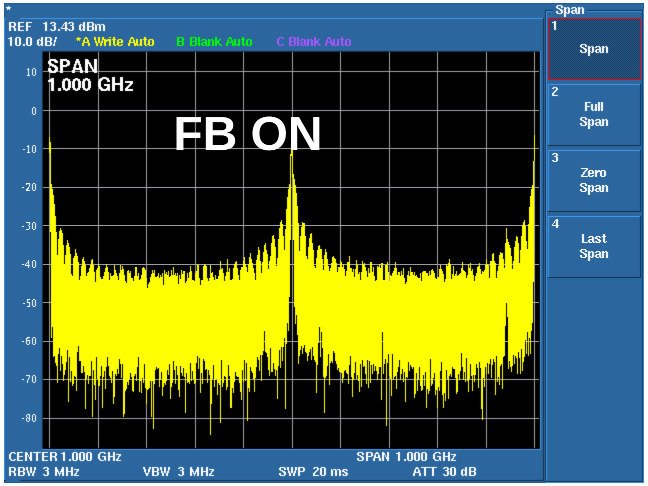
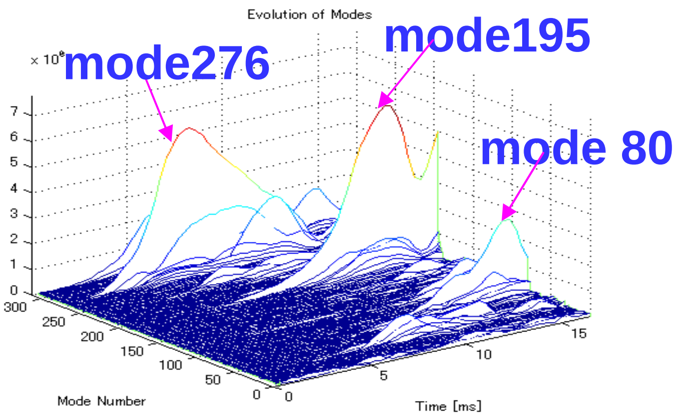
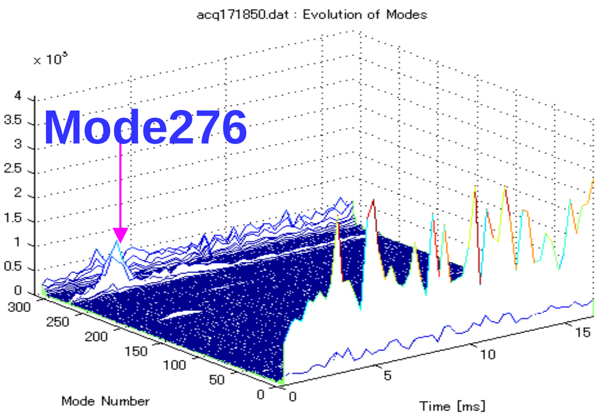




Transient domain analysis using grow/damp function of iGp





For detail, contact at poster session

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→ ***J-PARC***

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•Synchrotrons

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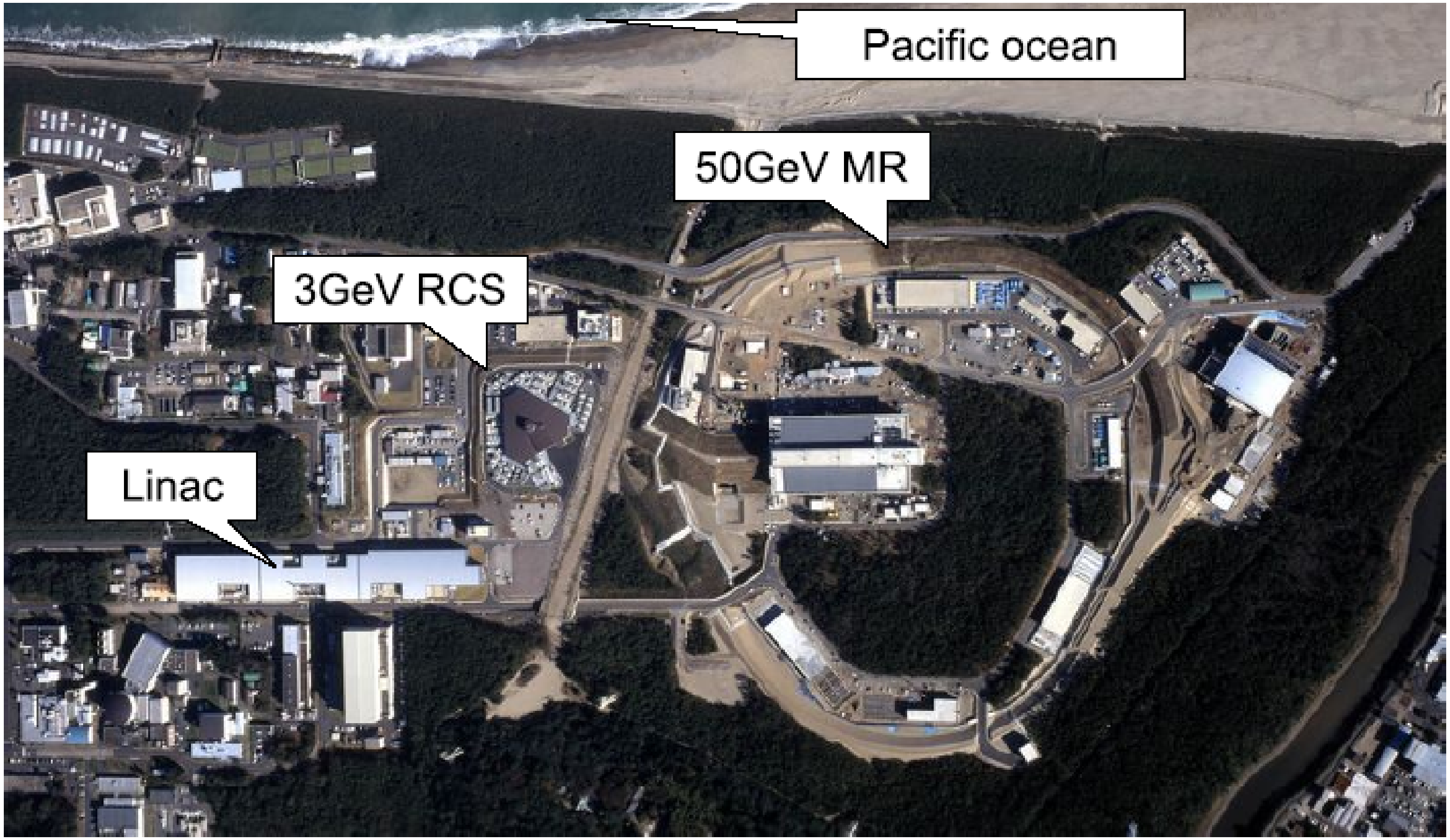
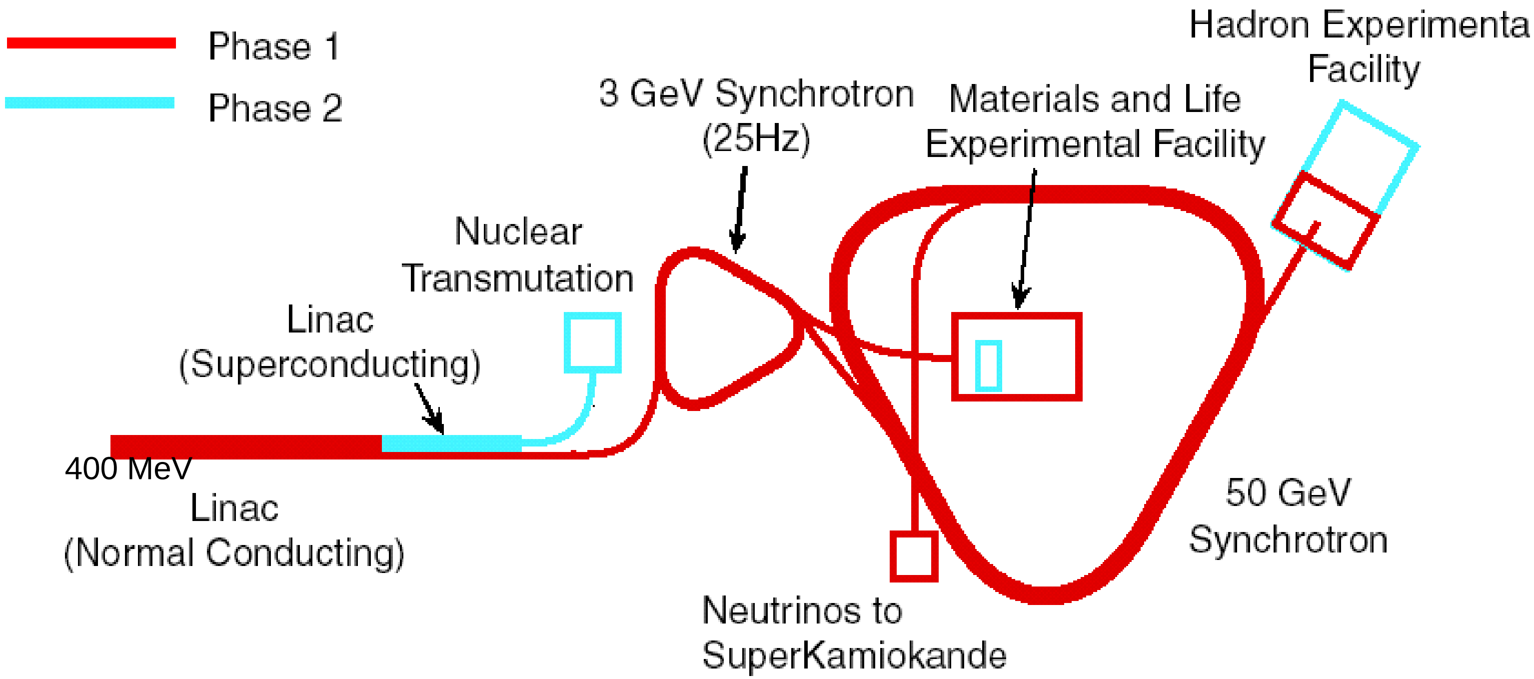
ERL

Introduction ..(1) -- J-PARC Facility



RCS beam commissioning began in October 2007,
MR first beam is to be in May 2008.

J-PARC Facility



The Japan Proton Accelerator Research Complex (J-PARC) will be one of the highest intensity proton accelerators in the world.

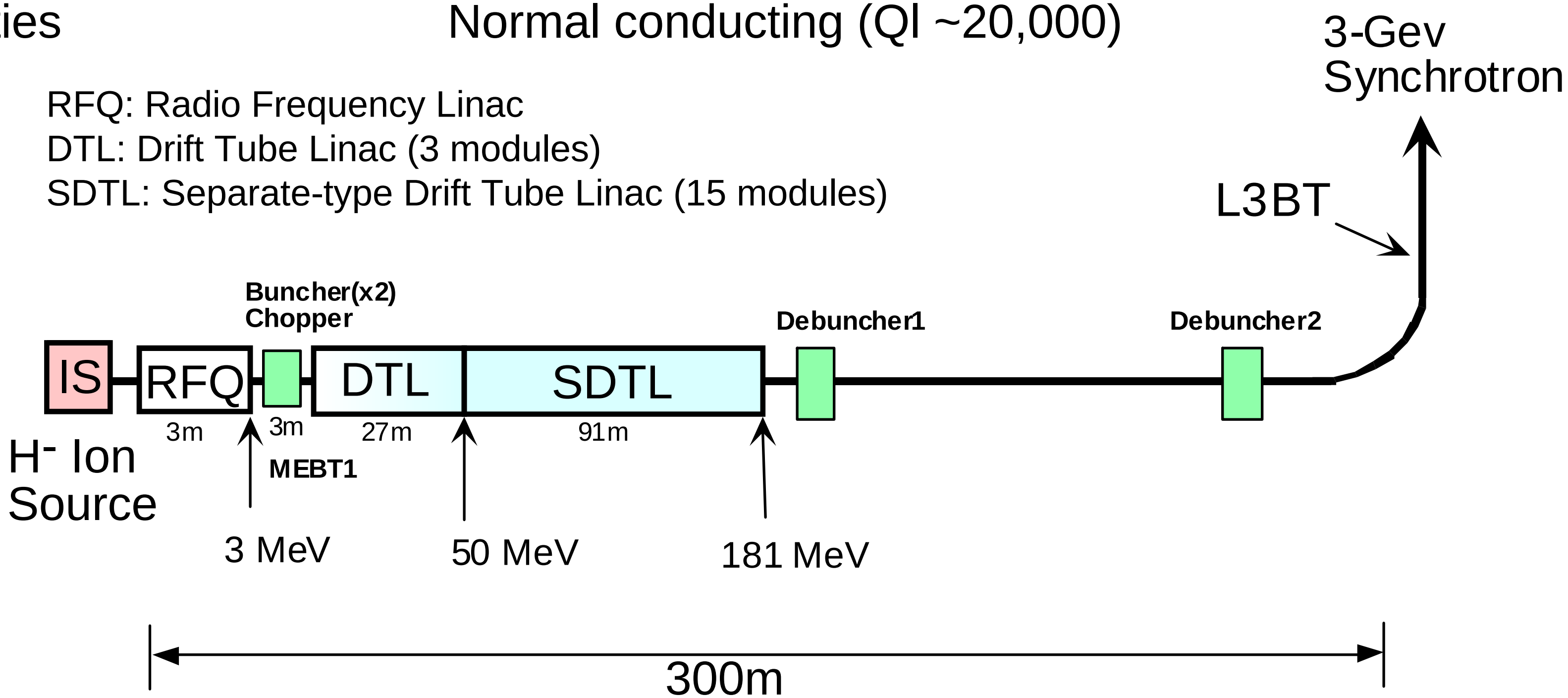
It consists of a 400-Mev H^- linac, a 3-GeV 1-MW rapid-cycling synchrotron (RCS), and a 50-GeV synchrotron (main ring, MR)

J-PARC Linac

(Present State)

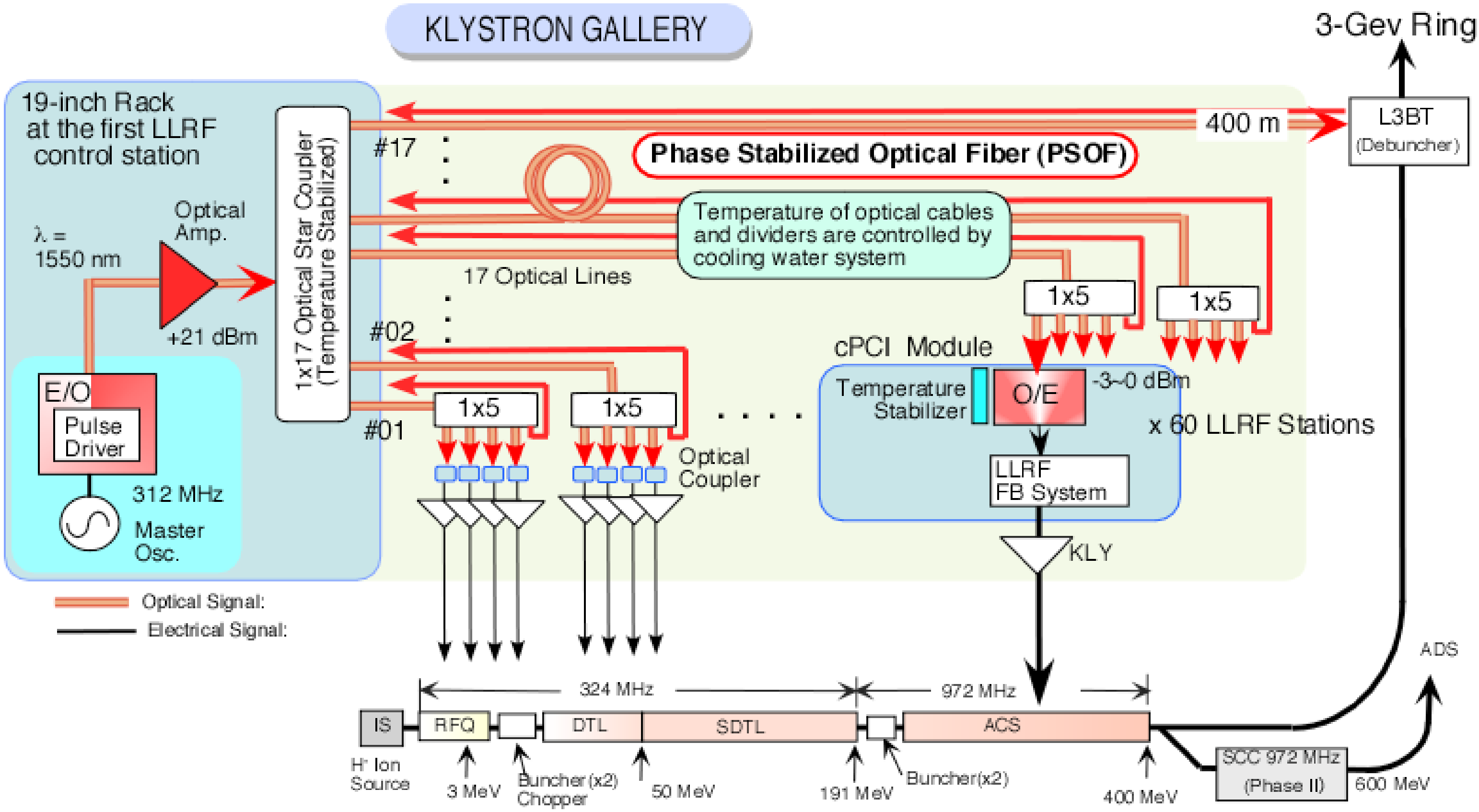
- Accelerated particles:	H^- (negative hydrogen)
- Energy:	181 MeV, The last two SDTLs are debunchers
- Peak current:	30 mA (50 mA for 1MW at 3GeV)
- Repetition:	25 Hz
- Pulse width:	500 us (Beam), 650 us (RF)
-Acceleration Frequency	324 MHz
-Cavities	Normal conducting (Ql ~20,000)

RFQ: Radio Frequency Linac
DTL: Drift Tube Linac (3 modules)
SDTL: Separate-type Drift Tube Linac (15 modules)



Shin MICHIZONO

RF Reference Distribution System



The 312-MHz RF reference is distributed to all LLRF control systems through optical links.

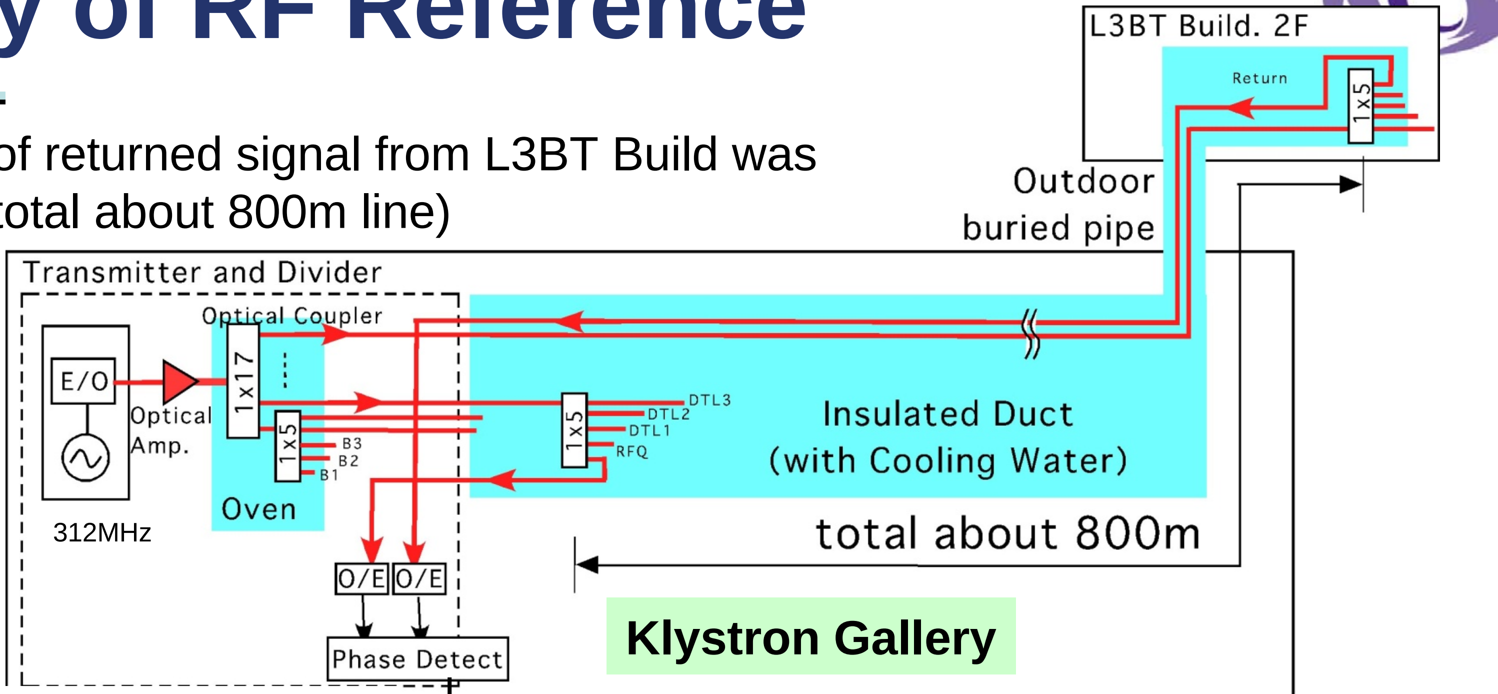
It is optically amplified and divided into 17 transfer lines, then furthermore divided into 5; one of them is returned back to the first station for phase monitor.

Optical cable is the Phase Stabilized Optical Fiber (PSOF). (The thermal coefficient is 0.4 ppm/^{o}C.)

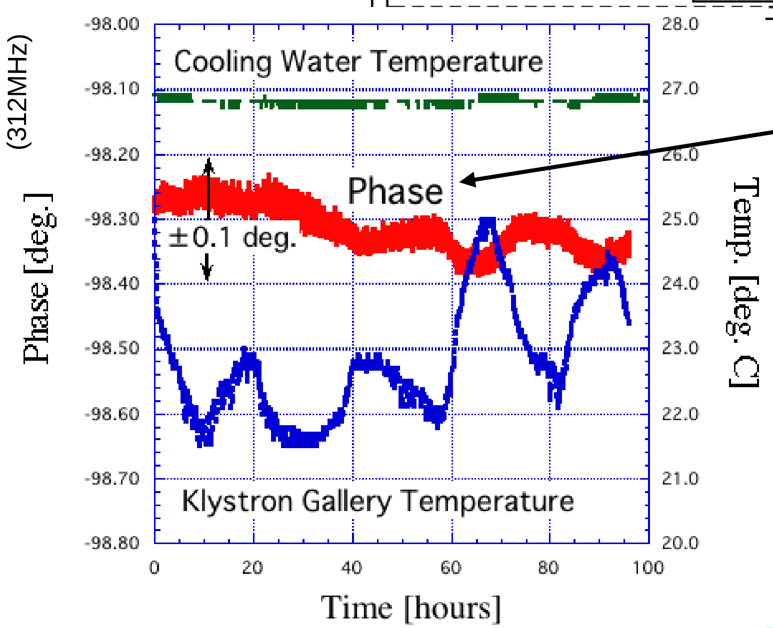
Temperature of the optical components (E/O, O/E, cables, couplers) are controlled to be constant.

Stability of RF Reference

- The phase of returned signal from L3BT Build was measured. (total about 800m line)



Phase trend for 4 days

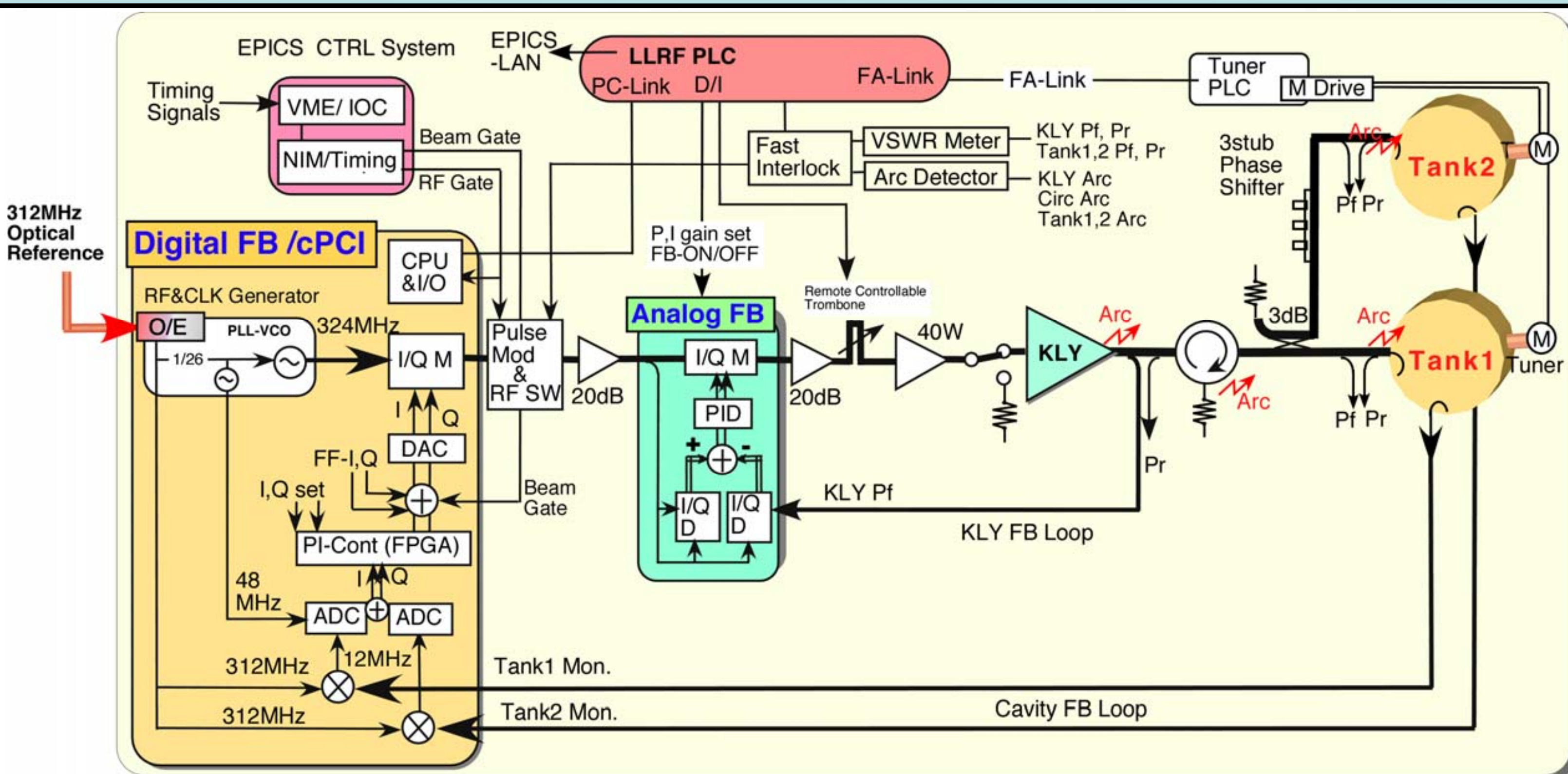


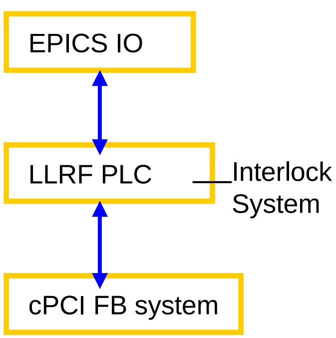
Monday's talk T.Kobayashi: **Performance of J-PARC Linac RF System**

Stability	Measured Result	Spec.
Gallery Temp.	±1.7 °C	within ±2°C
Phase of Ref.	**±0.06°**	**within ±0.3°**

Low Level RF System

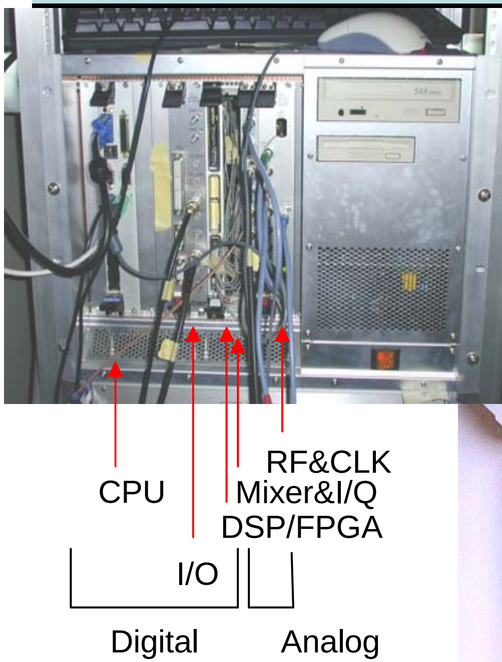
Monday's talk T.Kobayashi: **Performance of J-PARC Linac RF System**





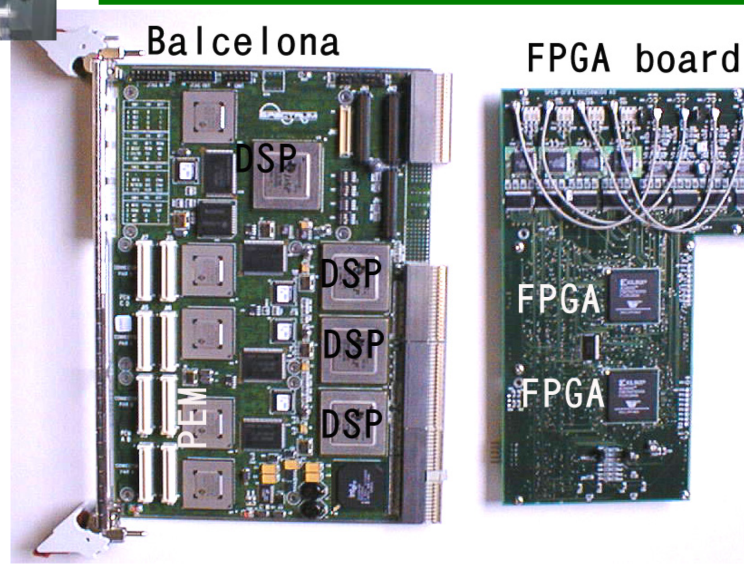
- **One klystron supplies powers 2 cavities in SDTL section.**
- **Digital FB system (FPGA & DSP) is used for the cavity field stabilization.**
- **The FB system controls the vector sum of the 2 cavity fields. The RF reference is 312-MHz optical signal (received by O/E converter) .**
- **Cavity-tuners are controlled from cPCI by way of PLC.**
- **Fast hardwire interlock is connected to Pulse Modulator (outside cPCI).**
- **Analog fast FB will be used for klystron FB loop. (It is optional.)**

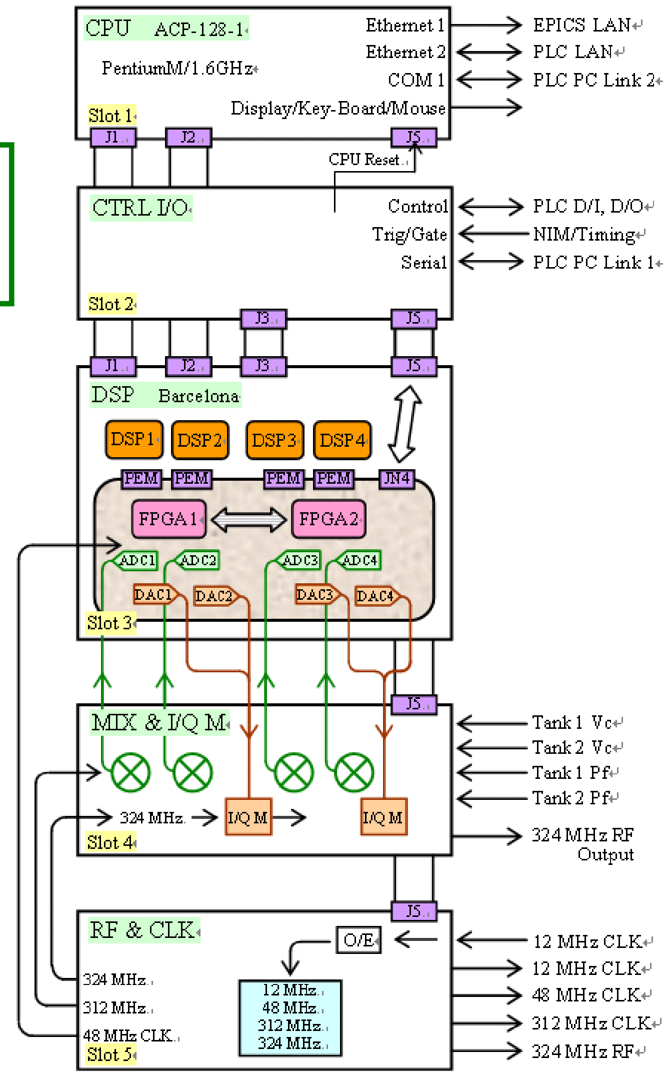
J-PARC linac Digital FB Control System



cPCI is adopted for the crate.

FPGA based digital FB system
FPGA: Mezzanine card of the commercial DSP board





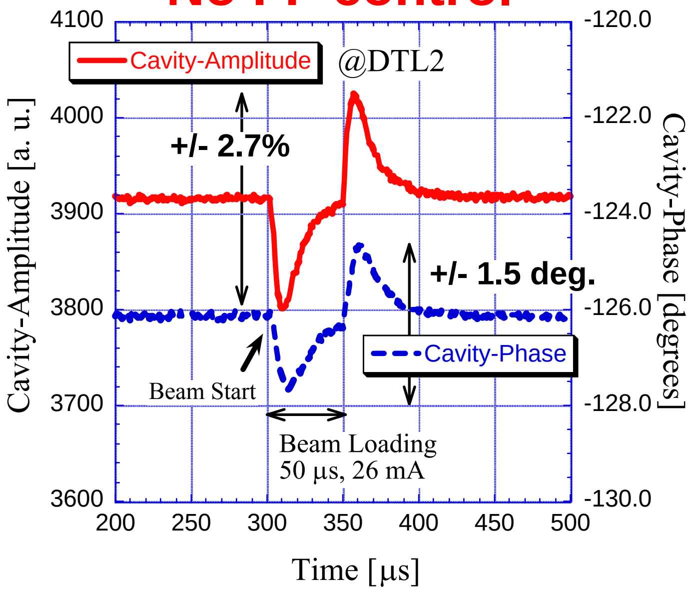
- **2-FPGAs (**2x VirtexII 2000) **are installed with 4x**14bit-ADCs and4x14bit-DACs at 48 MHz sampling
- DSP board enables to calculate complex diagnostics such as cavity control.
- FPGAs are used only for fast feedback.

Monday's talk T.Kobayashi: **Performance of J-PARC Linac RF System**

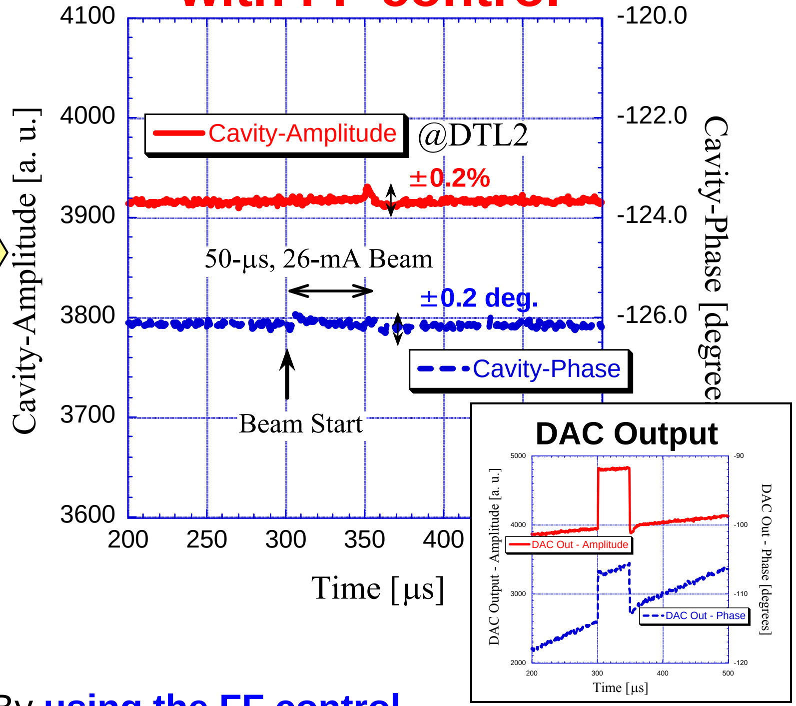
Beam Loading Compensation

with Feed-forward (FF) control

No FF control



with FF control



Beam Loading in DTL cavity field with only FB control.
Peak Current: **26 mA**, Pulse width: **50 us**,

The amplitude change: ±2.7% ,
Phase Change: ±1.5 degrees

By **using the FF control**
the beam loading was **successfully compensated**.
(Amplitude change: ±0.2% , Phase change: ±0.2 deg.)

However, it is necessary to adjust a timing of a control gate by 0.1-us step for optimization.

Optimum values of the FF amplitude and phase **depend on beam current**.

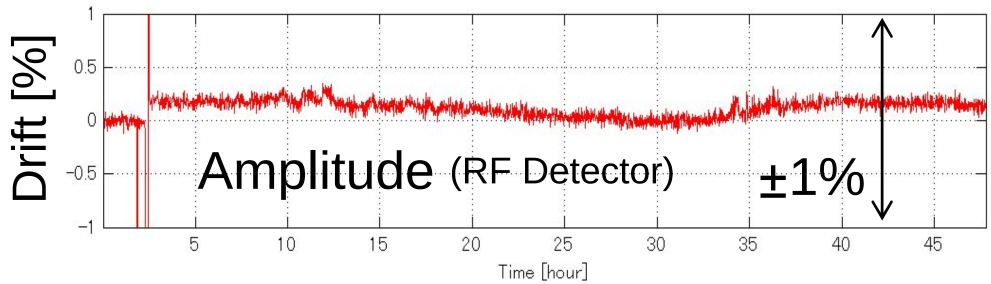
Monday's talk T.Kobayashi: **Performance of J-PARC Linac RF System**

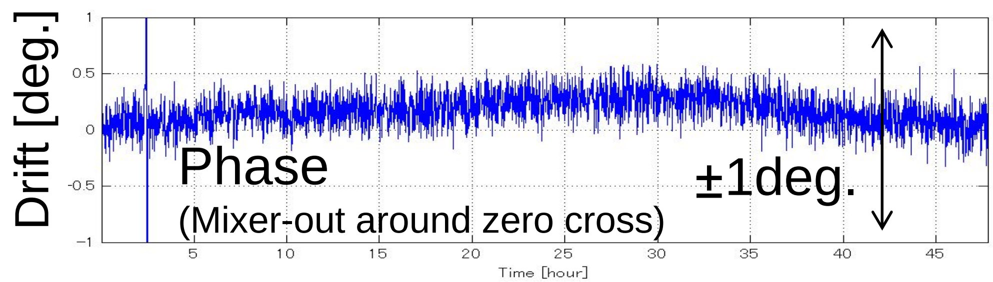
Long Term Stability

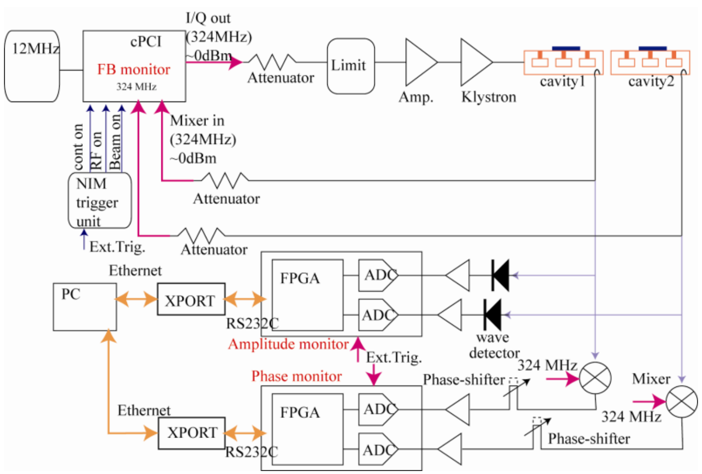
The stability of the RF feedback system in long-duration operation was evaluated.

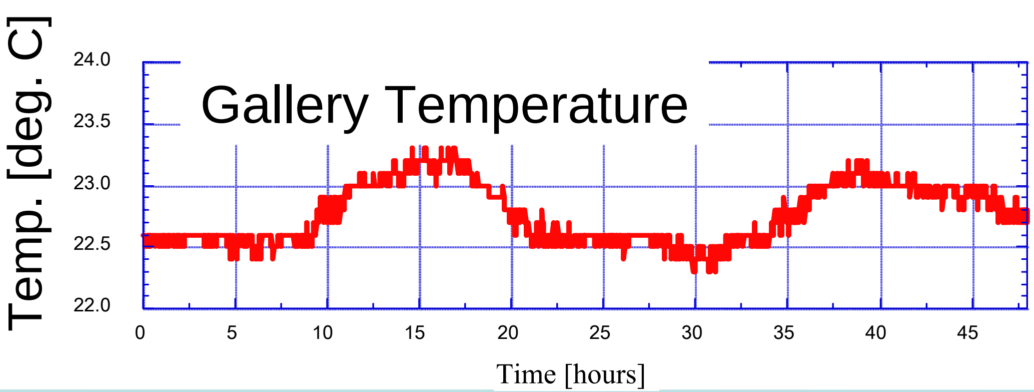
The trends of the amplitude and phase of the DTL2 Cavity (Input Power 1MW)
measured by external monitor (independent of FB system) **for 2 days**

Monday's talk T.Kobayashi: **Performance of J-PARC Linac RF System**









(during 2 days.)

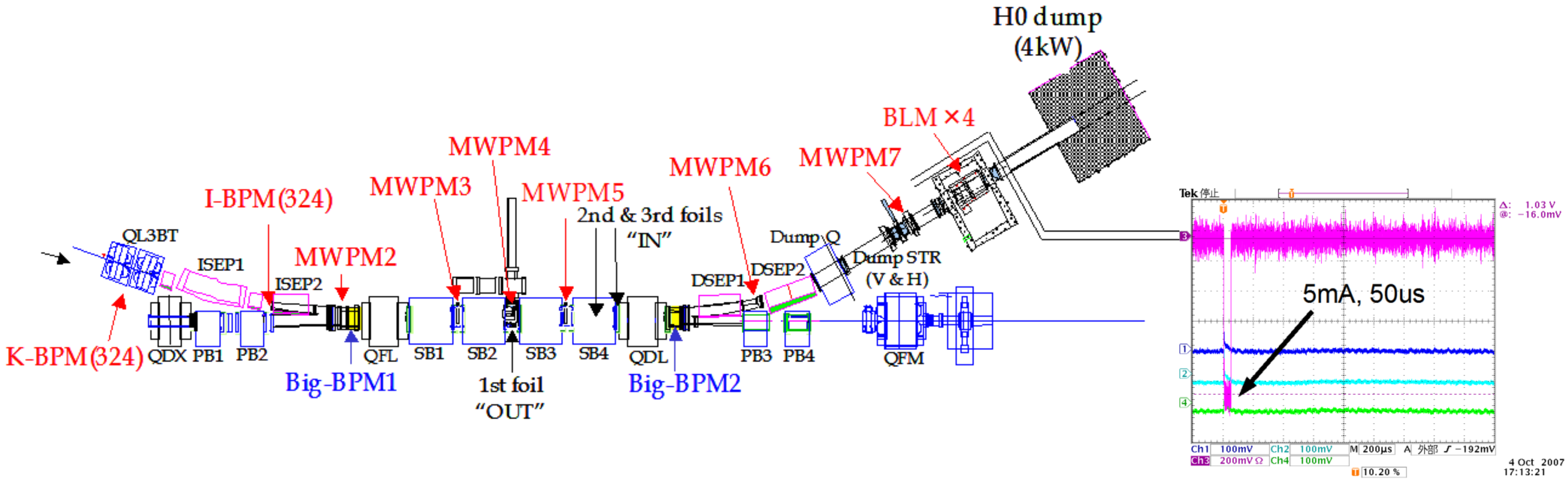
Amplitude drift is ±0.15%.

Phase drift is ±0.15 degrees.

RCS and MR machine status

Wednesday's talk F.Tamura: **LLRF Control Systems for J-PARC Synchrotrons**

- RCS beam commissioning started in Oct 07
- MR 1st beam will be in May 08



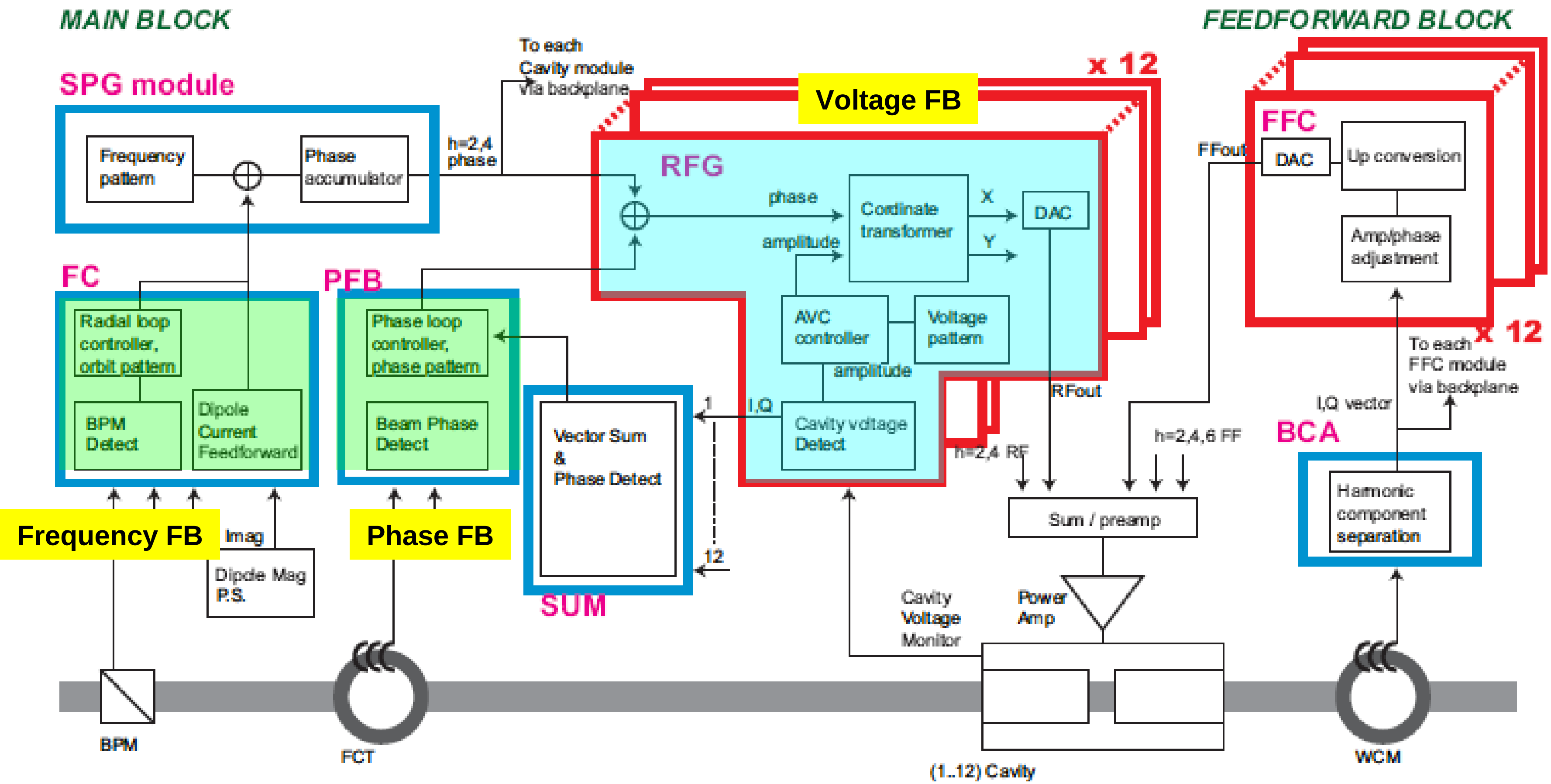
RCS: "H0-dump mode" only, beam has not yet been circulating

LLRF for RCS and MR

Wednesday's talk F.Tamura: **LLRF Control Systems for J-PARC Synchrotrons**

- Cavity Q=2 (RCS), 10~20 (MR)
- LLRF systems are designed to handle multi-harmonic RF signals
  - **acceleration**
  - **bunch shaping**
- Full-digital, DDS (direct digital synthesis) based
  - **Multi-harmonic RF generation for cavity drive and signal detection**
- Common feedbacks for stabilizing the beam
  - **AVC, auto cavity voltage control**
  - **Phase FB (RF phase)**
  - **Radial FB (frequency)**
- Beam feedfoward system for compensating the heavy beam loading.

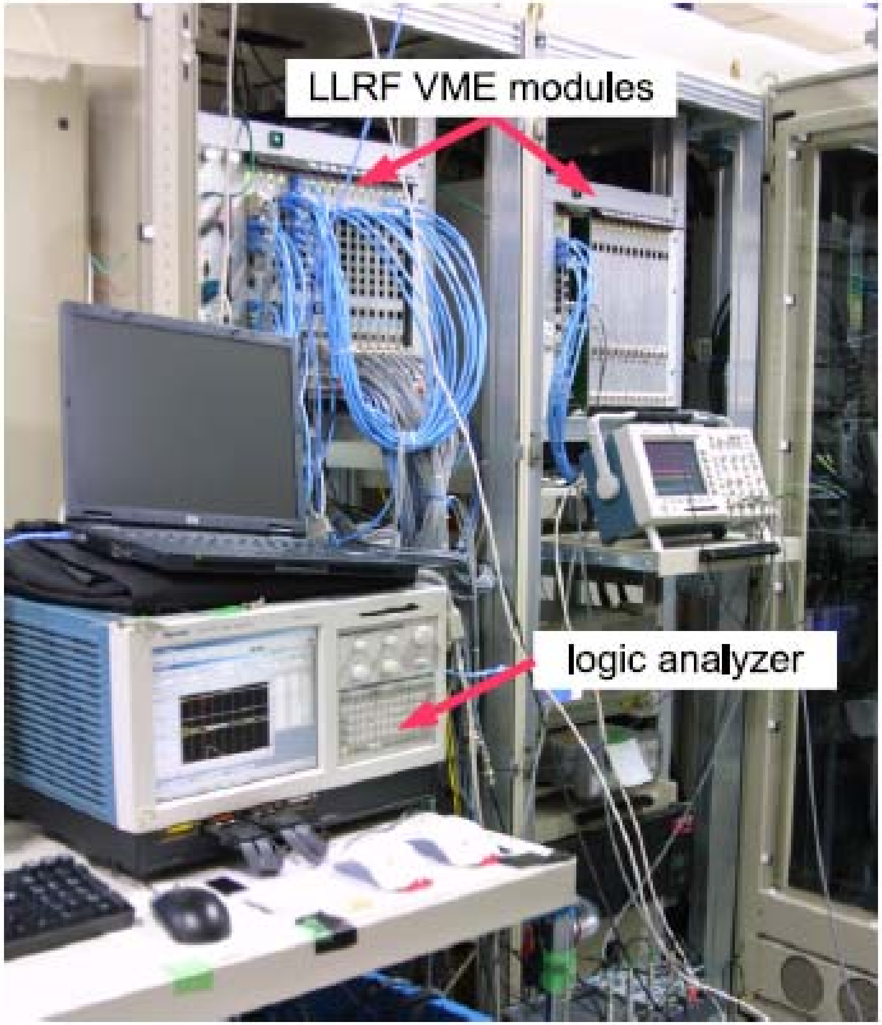
RCS LLRF block diagram (MR is similar)

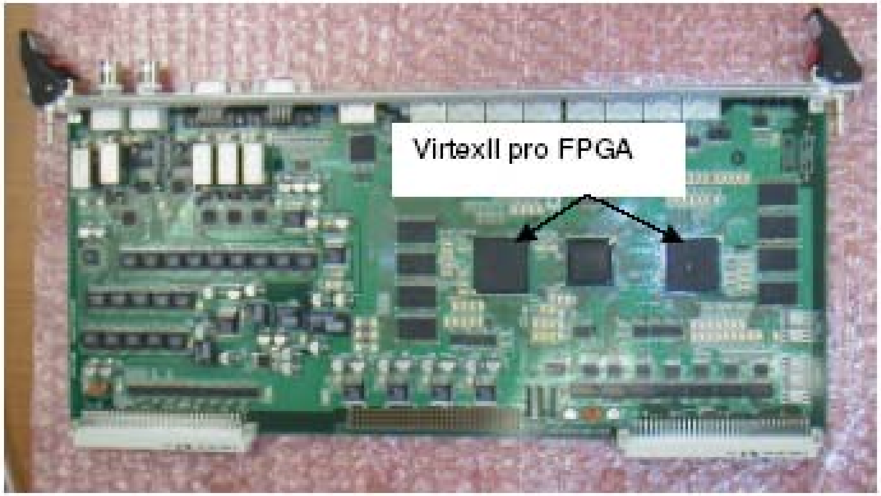


Block diagram of RCS LLRF system (MR LLRF has similar blocks)

Blue: common for the whole system, Red: for each of the 12 cavities

Wednesday's talk F.Tamura: **LLRF Control Systems for J-PARC Synchrotrons**

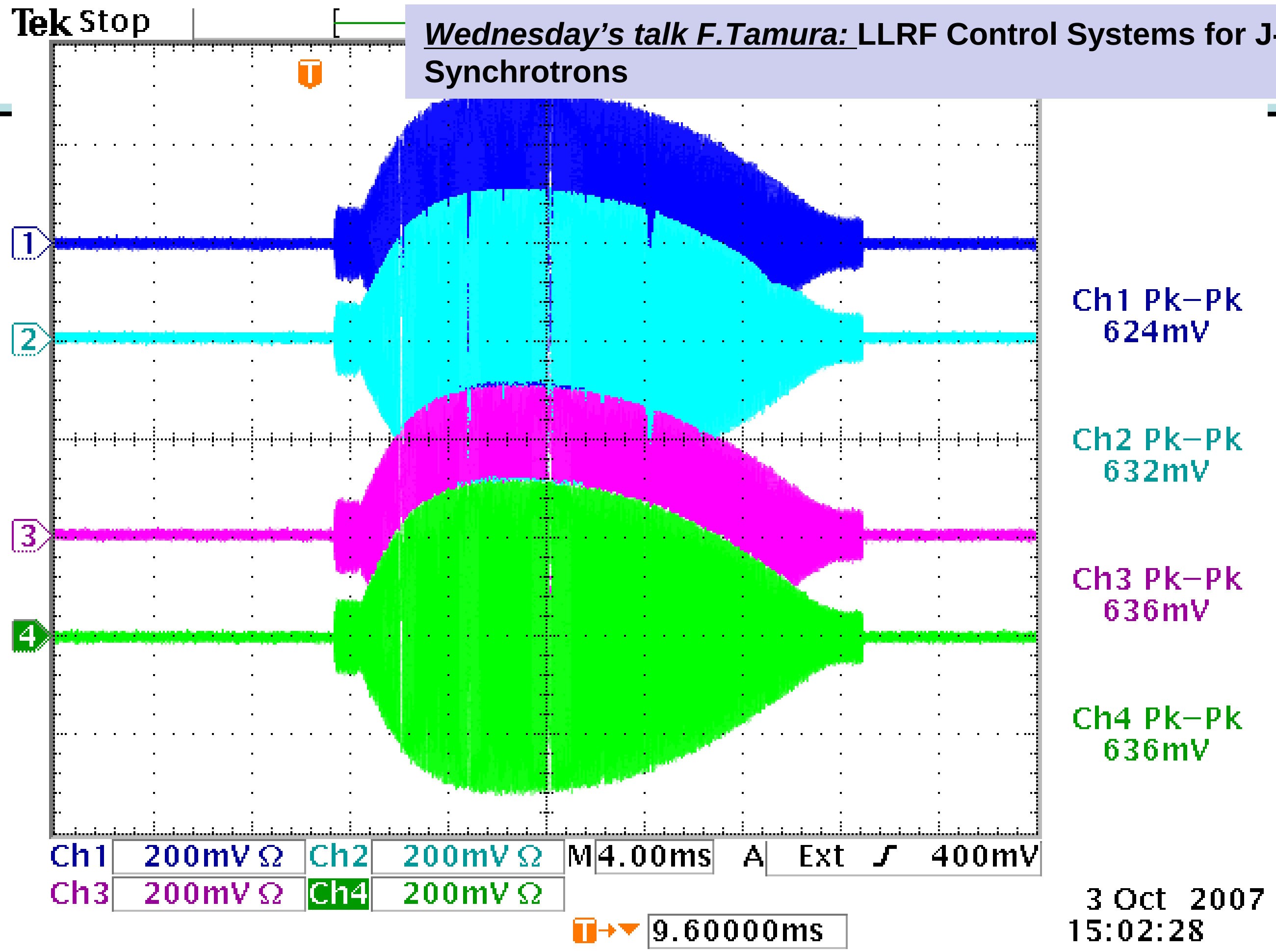




RFG board

- RCS hardware completed, MR ongoing
- VME based, 9U boards
- FPGA (Virtex-II etc.)
  - strong computing power

Wednesday's talk F.Tamura: **LLRF Control Systems for J-PARC Synchrotrons**



Voltage monitor signals of four cavity (12.5kVpeak) , AVC is working

- **RCS LLRF has been tested with high-power system**
- **3 GeV acceleration will be in November-December**

LLRF at J-PARC synchrotron can be discussed at Dr. Tamura's talk tomorrow.

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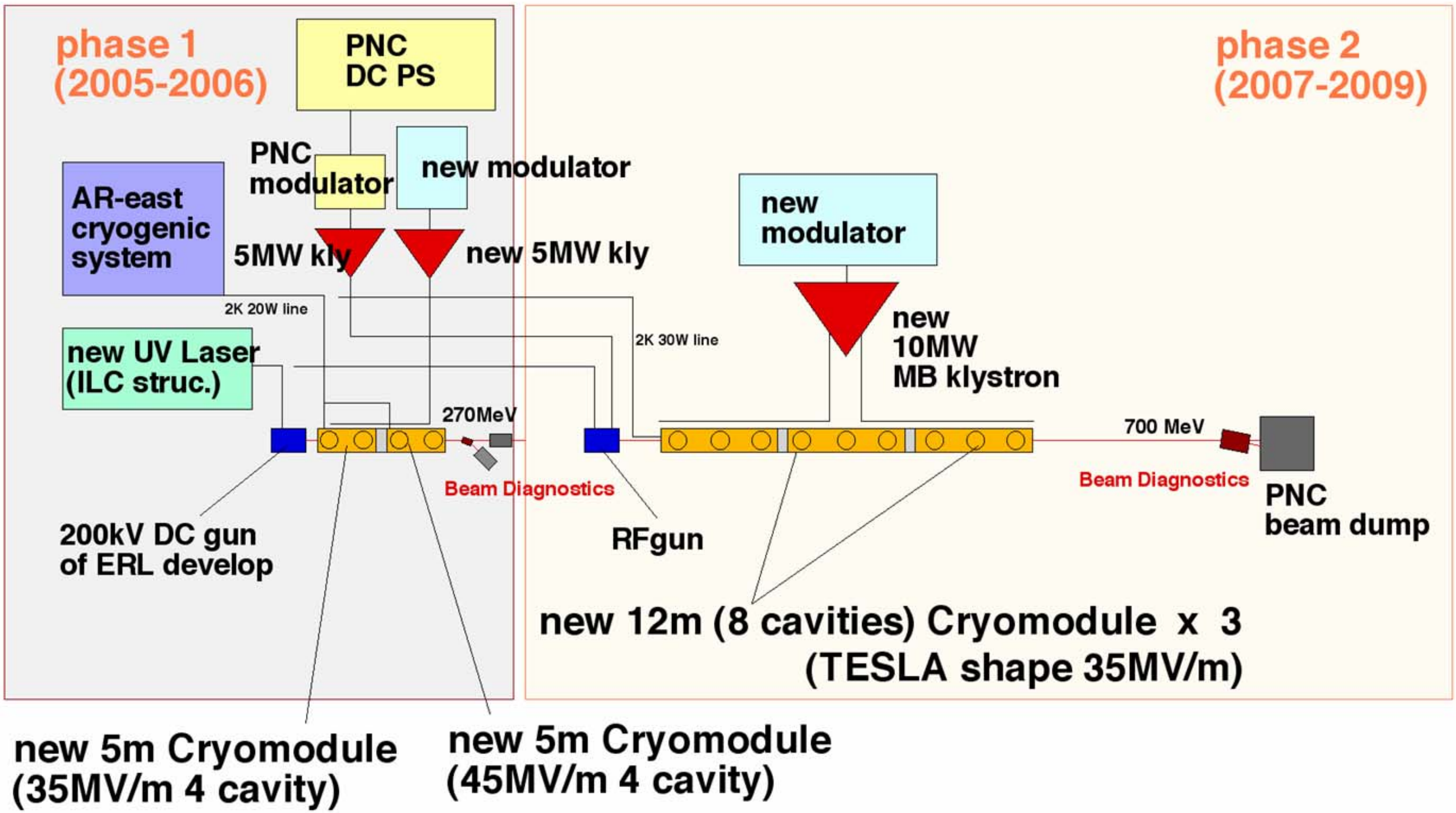
ERL

Plan of Superconducting RF Test Facility (STF)

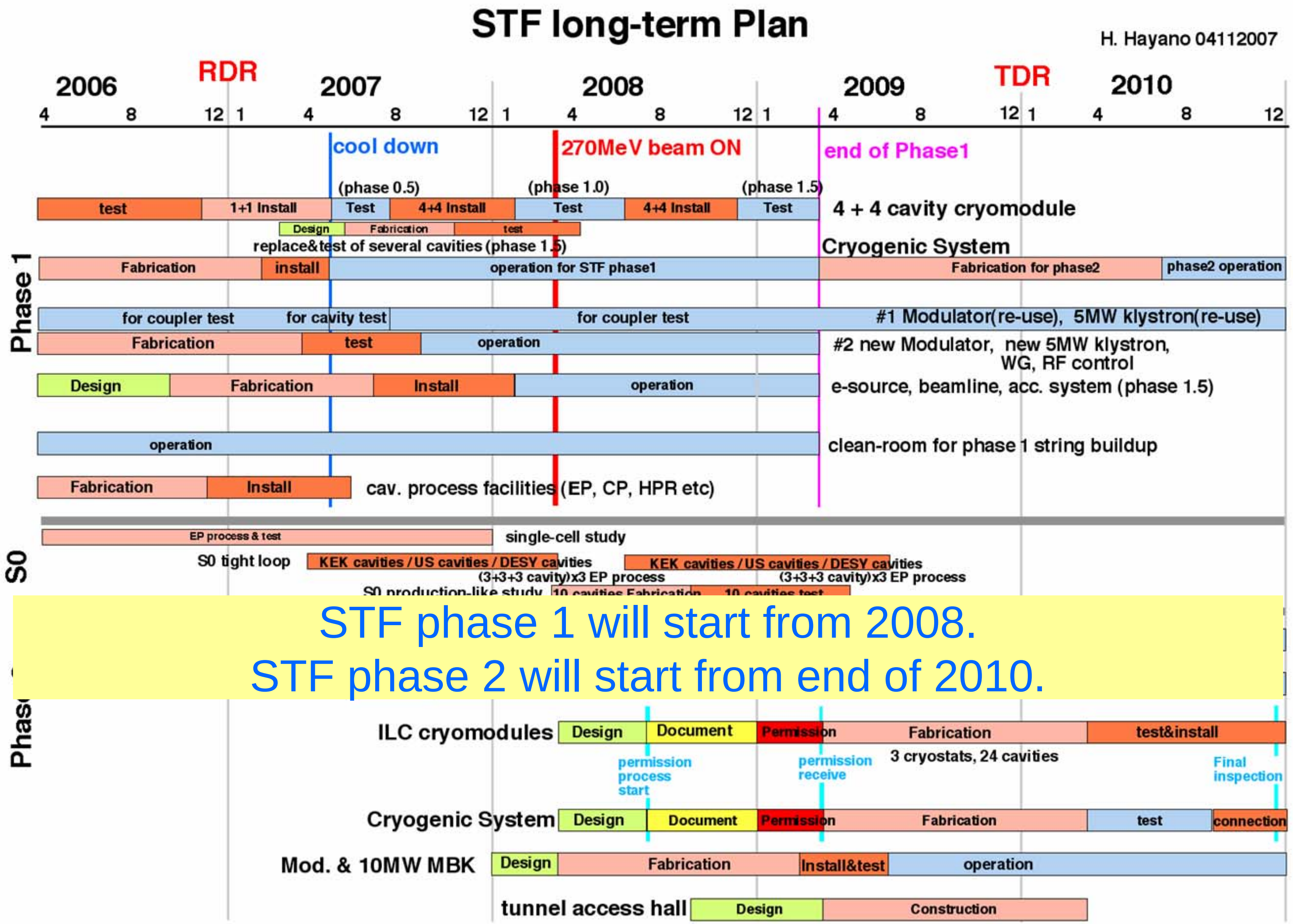


V3.0 Hitoshi Hayano, 12/02/2005

STF phase 1 / phase 2

- **Phase 1 (2005 -2008)**
  - Operate 8 cav. Vector sum with cPCI digital FB system
  - Stability requirements: 0.3% in amplitude and 0.3 deg. in phase
  - Install EPICS to the llrf and other systems and operate with EPICS
  - Data acquisition using EPICS
  - FB algorithm development
  - Survey of field stability and perturbation (shared with world-wide LLRF team)

- **Phase 2 (2008 -2010)**
  - Operate 26 cav. Vector sum with HA digital FB system
  - Stability requirements: 0.3% in amplitude and 0.3 deg. in phase
  - Install EPICS to the llrf and other systems and operate with EPICS
  - Develop 32ch receivers and FPGA board (or IF-mixture)



STF phase 1 will start from 2008.

STF phase 2 will start from end of 2010.

Digital LLRF FB control @STF phase1

JPARC linac LLRF

324 MHz
Max. 2 cav.
IF=12 MHz
LO=312 MHz
Sampling=48 MHz

→

STF phase-1

1300 MHz
Max. 8 cav.
16 bit ADCs
IF=10 MHz
LO=1310 MHz
Sampling=40 MHz

→

STF phase-2

1300 MHz
Max. 26 cav.
IF=10 MHz
LO=1310 MHz
Sampling=40 MHz

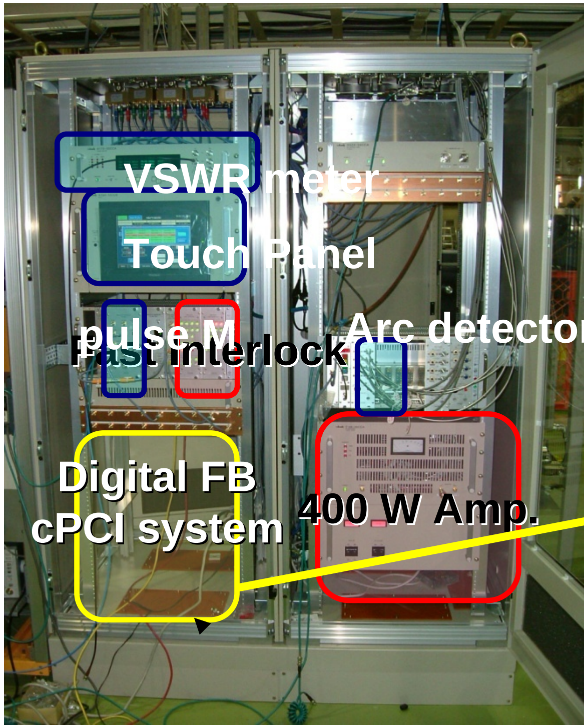
Digital cavity simulator

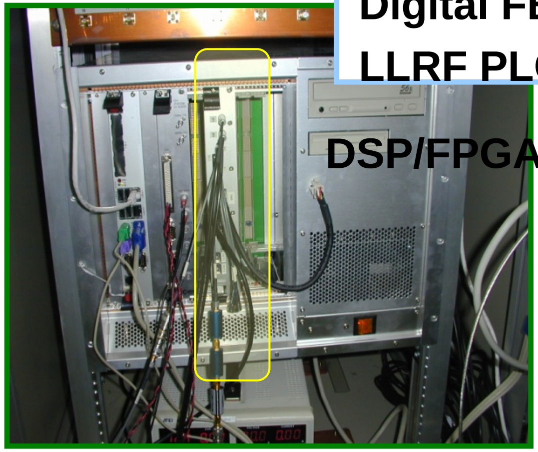
	J-PARC	STF Phase-1
Cavity	Normal	Super
Frequency	324 MHｚ	1300 MHｚ
Q-value	2e4	2e6
Rise time	100 us	500 us
Pulse width	650 us	1.5ms
Phase difference	～30deg.	～60deg.
	Pulse voltage	Lorentz detuning
others		Microphonics
Amp. Stability	±1％	0.3%rms
Phase stability	±1deg.	0.3deg.rms
FB loop	＜1us	＜3us

Concept of the digital system is based on J-PARC.
We developed new custom FPGA board for STF.

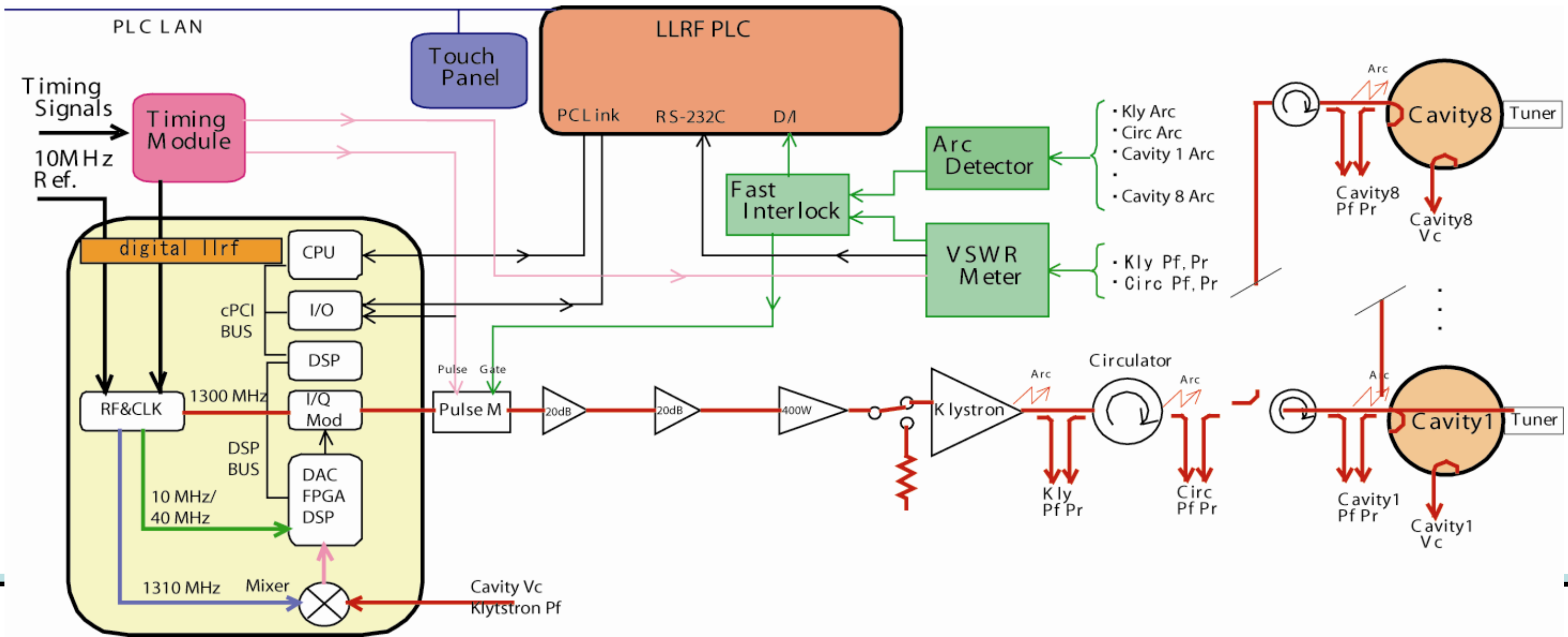
LLRF system @STF Phase1

J-PARC based LLRF system
Digital FB system using a FPGA board
LLRF PLC system control digital FB





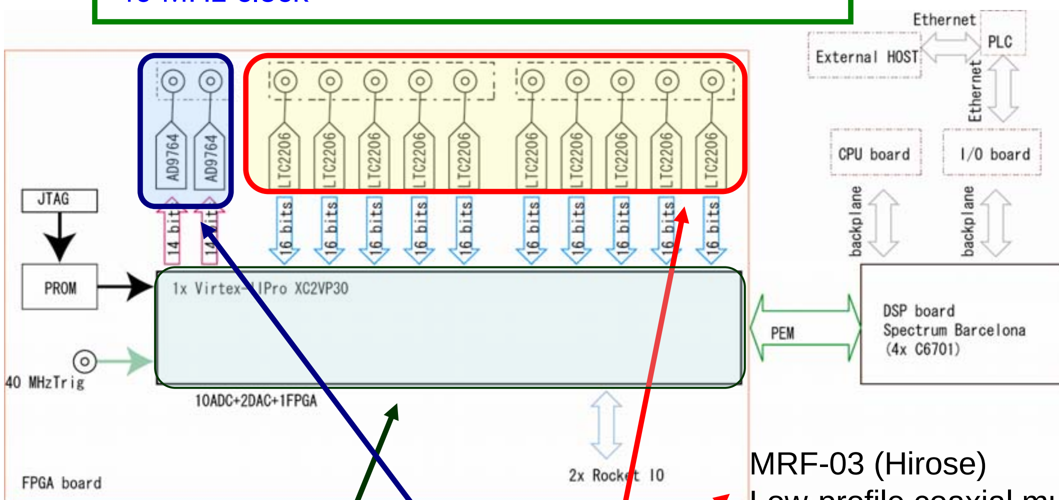
DSP/FPGA board



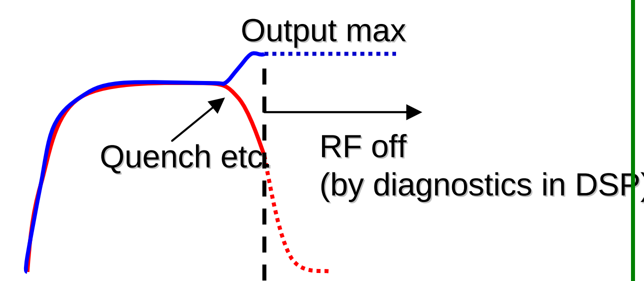
FPGA & DSP boards @STF Phase1

Custom FPGA board
: Mezzanine card of the commercial DSP board
10 **16bit-ADCs** and 2DACs + 2Rocket IO
40 MHz clock

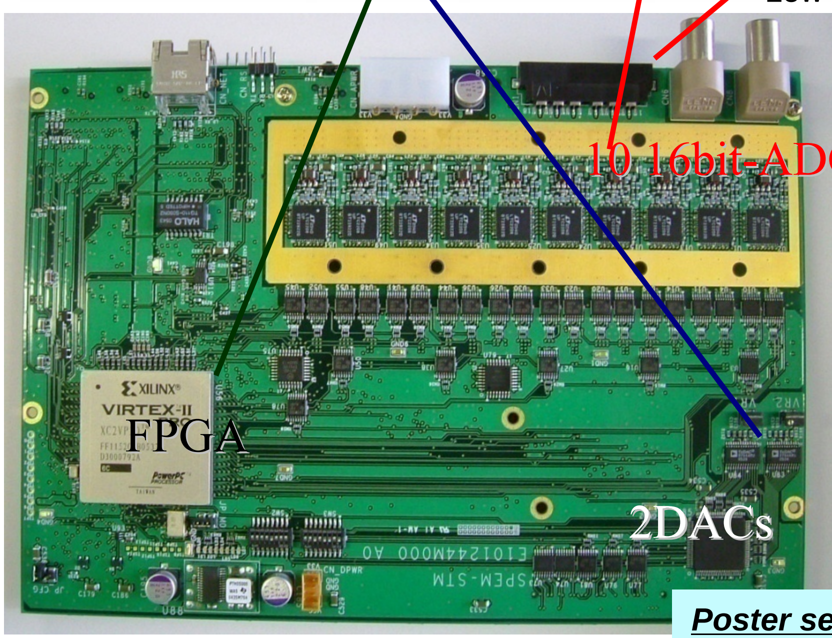
Commercial DSP board (Barcelona)
(same to J-PARC system)
:4x TI C6701 DSPs
Can access to FPGA like an external memory of DSP

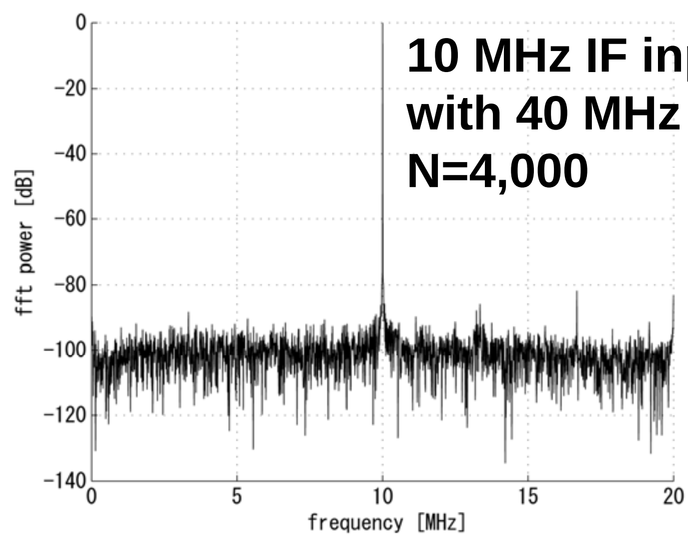


Real time intelligent diagnostics by DSP board



MRF-03 (Hirose)
Low-profile coaxial multiple contact connector

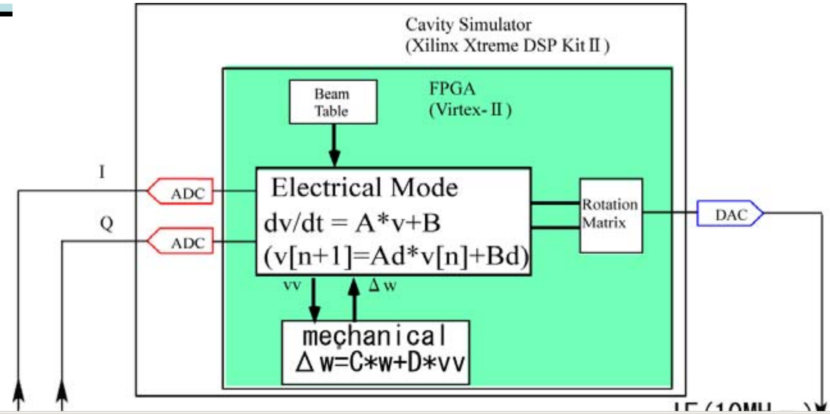


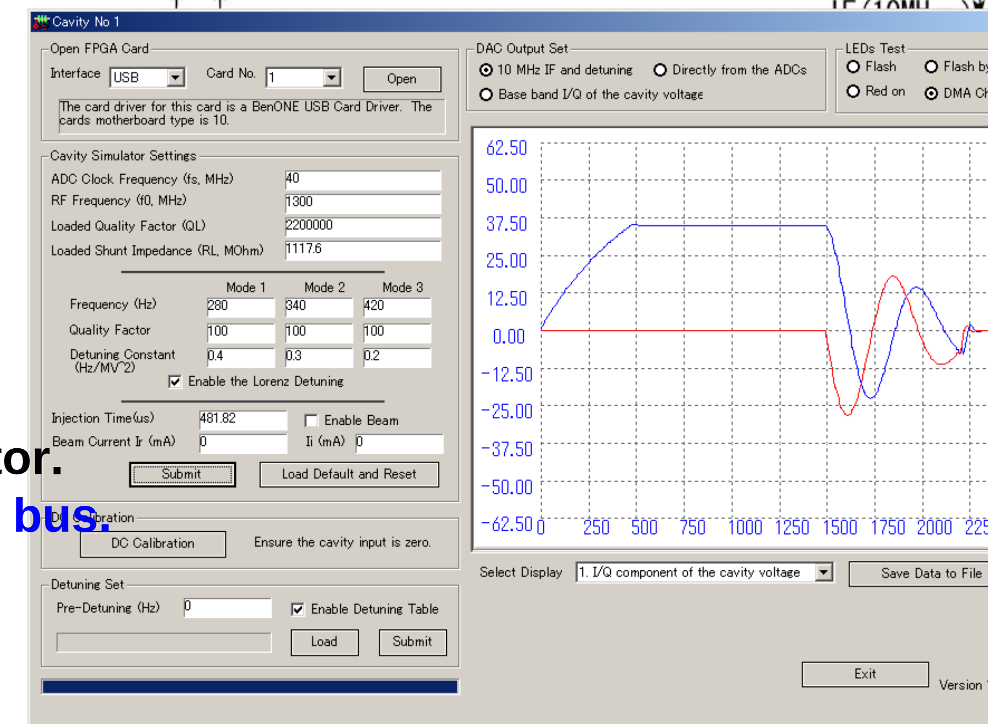


10 MHz IF input with 40 MHz sampling N=4,000

Poster session S.Michizono: **Status of the low-level RF system at KEK-STF**

Cavity simulators installed into PC



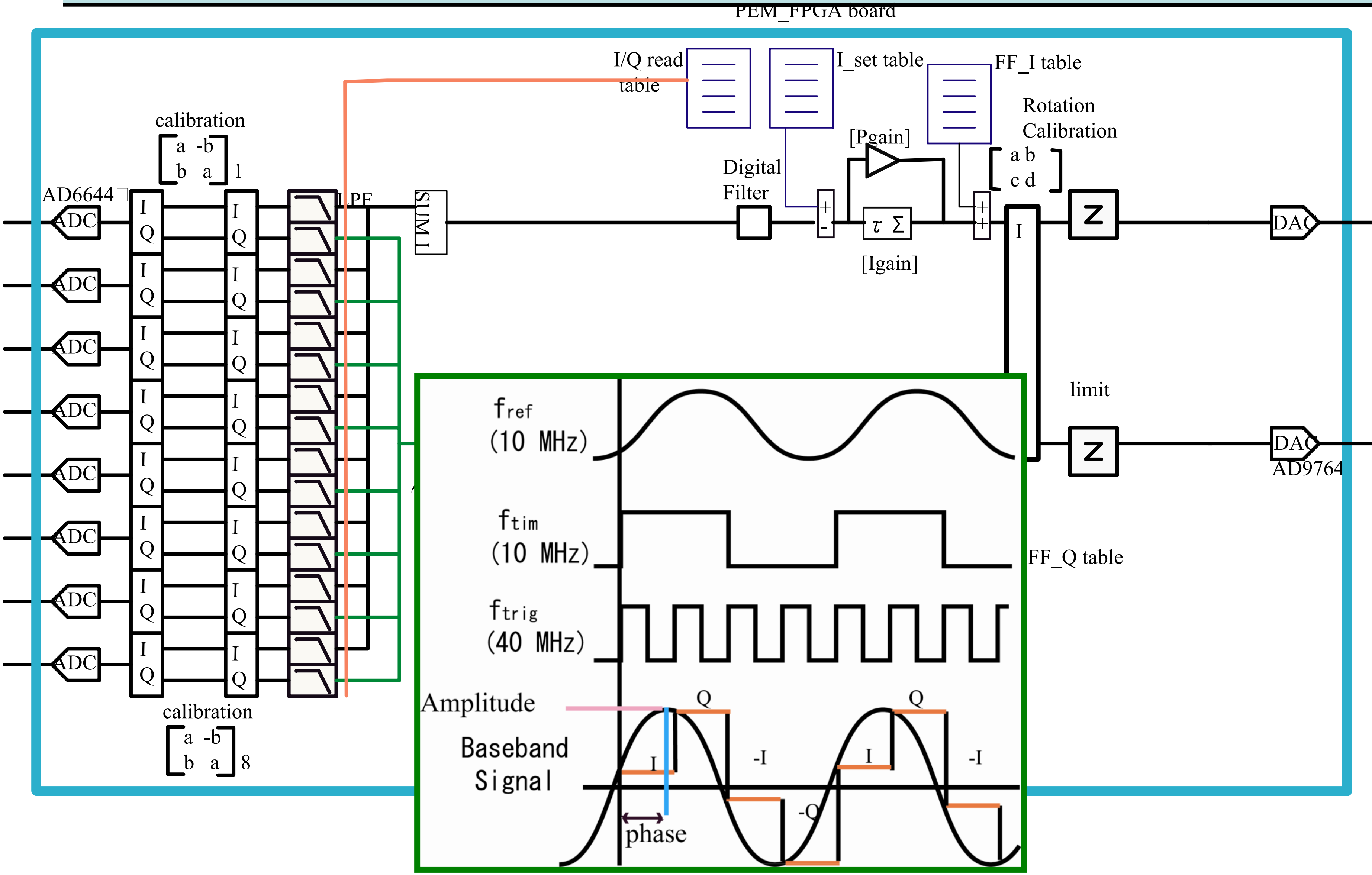


- XtremeDSP was used for cavity simulator.
- **Four XtremeDSPs are installed into PCI bus.**

(corresponding 4 cavity simulators)

Poster session S.Michizono: **Status of the low-level RF system at KEK-STF**

FB algorism

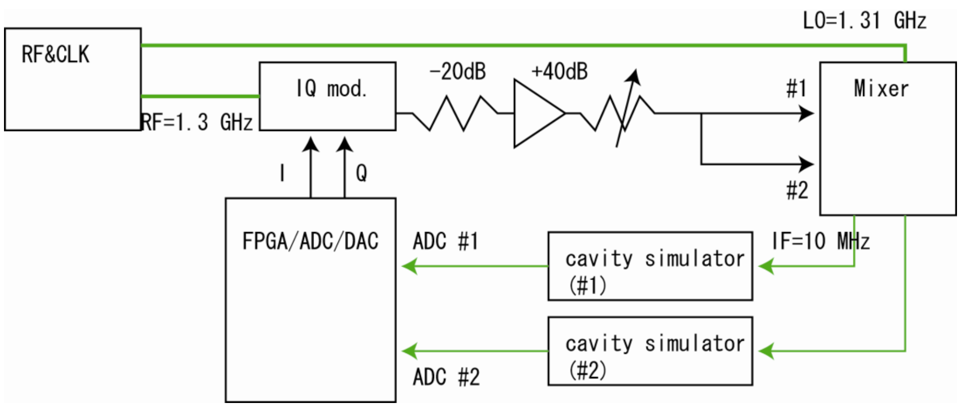


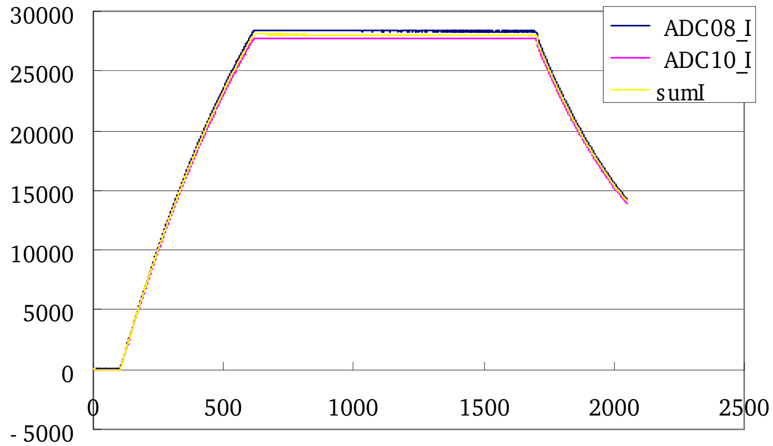
Simple Vector-sum and PI control

Poster session S.Michizono: **Status of the low-level RF system at KEK-STF**

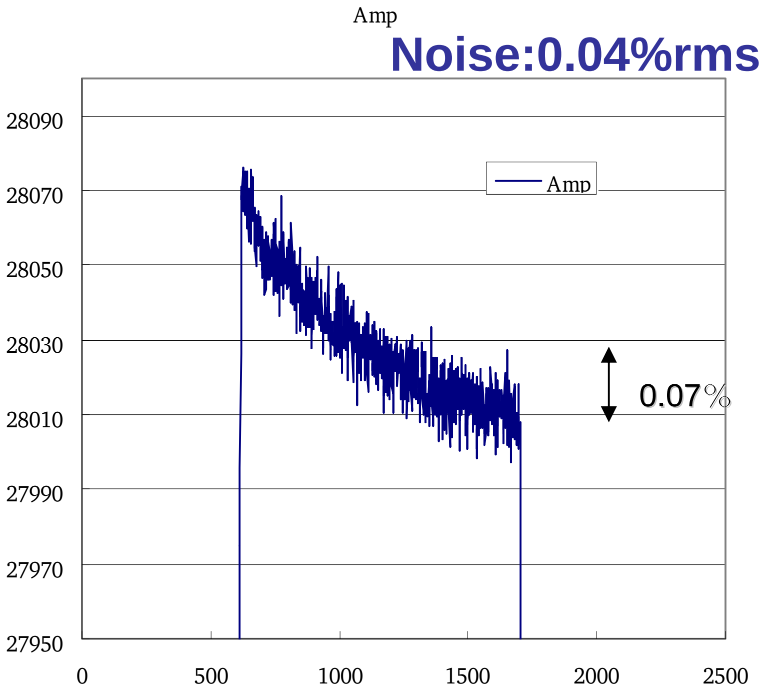
FB results

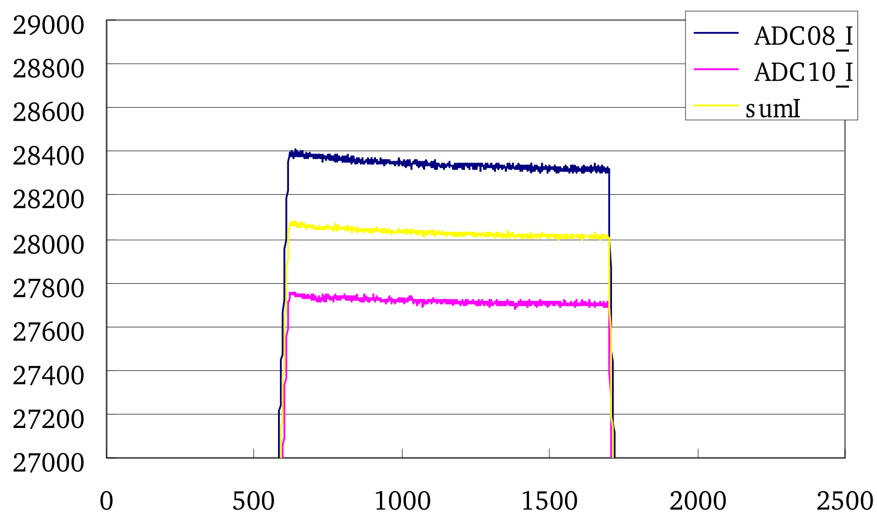
Poster session S.Michizono: Status of the low-level RF system at KEK-STF





Noise:0.04%rms(amplitude), 0.03deg.rms (phase)

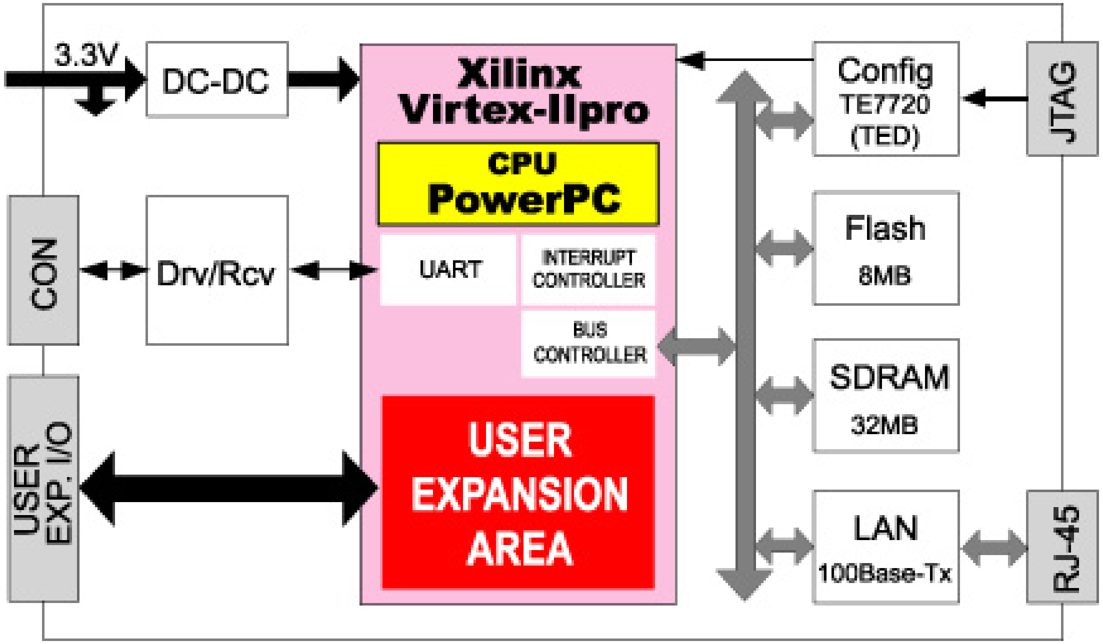




STF-llrf R&D(1) -FPGA interlock system-

Poster session S.Michizono: **Status of the low-level RF system at KEK-STF**

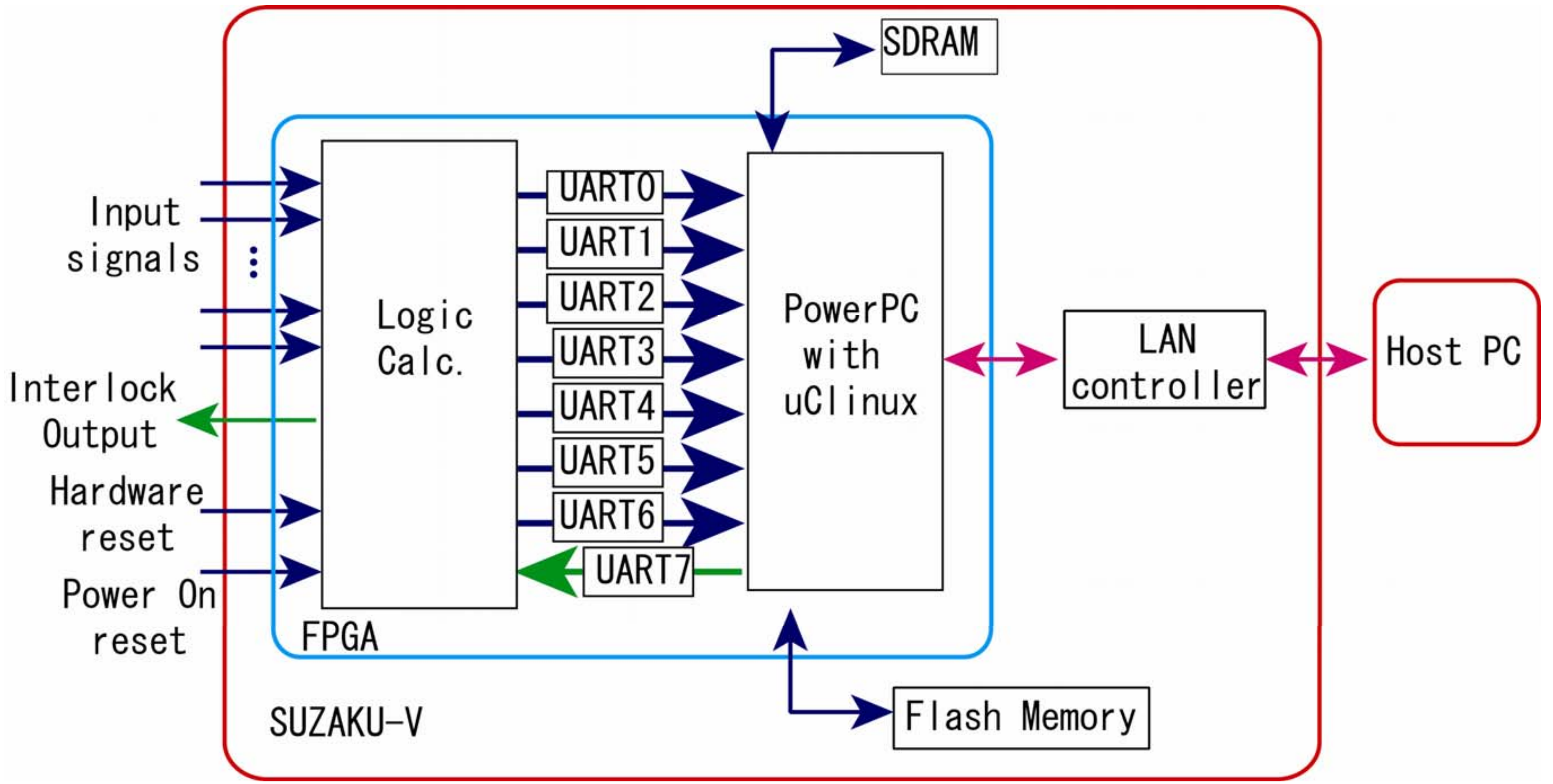
SUZAKU-V (SZ310-U00) by ATMARK TECHNO
FPGA(XC2VP4) with 70 I/O and LAN
OS: Linux
MPS by FPGA and monitor by Ethernet



Cheap commercial FPGA card

Interlock system inside FPGA

Poster session S.Michizono: **Status of the low-level RF system at KEK-STF**

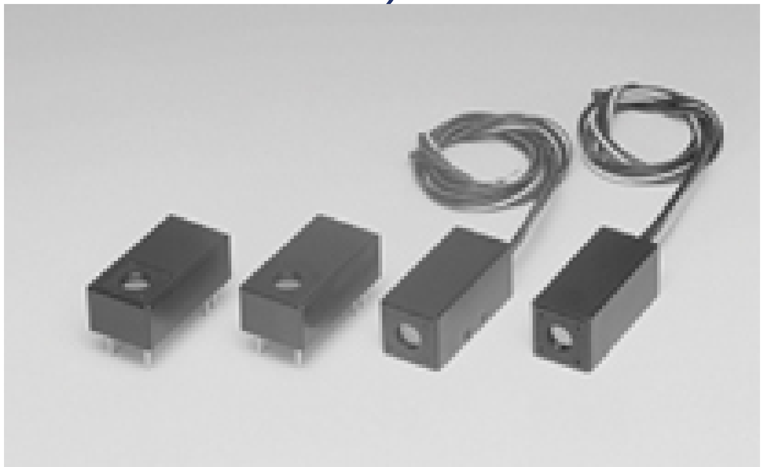


- Fast interlock detection is done at inside logic circuit.
- Communication between host and FPGA is via Linux, which can be slow.
- This is our first step to use PowerPC inside FPGA at new FPGA board for llrf control.

STF-llrf R&D(2) -Arc detection-

Poster session S.Michizono: **Status of the low-level RF system at KEK-STF**

- Conventional arc detectors are photo-coupler with thick optical fiber (such as 1 mm in diameter).
- Instead of this, we adopted high sensitive photosensor (H5783).
- Owing to the high sensitivity, we can use commercial multi-mode optical fiber (50 um in diameter)

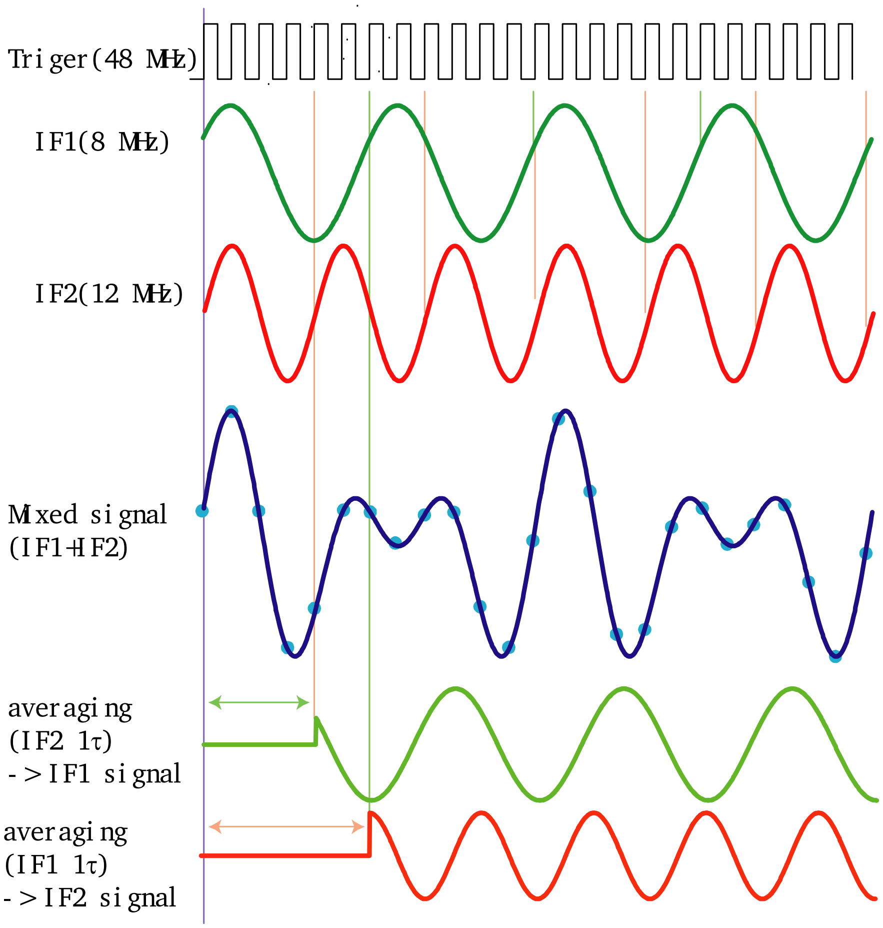


- Head on module using Metal package PMT Spectral response of 300nm - 650nm. Has no amp and uses a low power consumption HV supply
- Capable of detecting light levels 1/10000 as low as those detectable with semiconductor photodiodes.

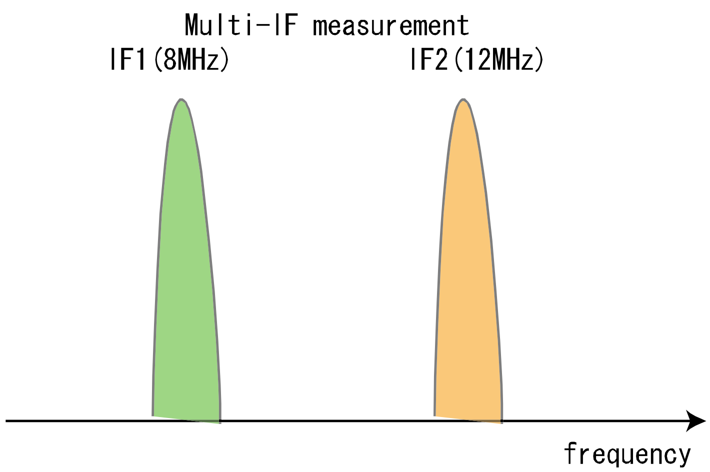
For detail, contact at poster session

STF-llrf R&D(3) -IF-mixture-

Poster session T.Matsumoto: **Development of Low-level RF System using IF Mixture Technique**



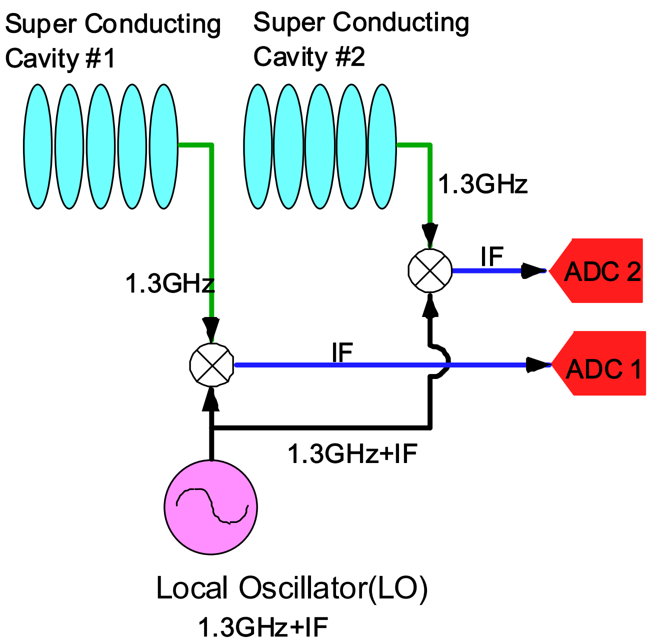
- Concept is like digital receiver
- Two IF are mixed in analog circuits.
- Two signals are separated at digital processing.



Concept of the IF-mixture technique

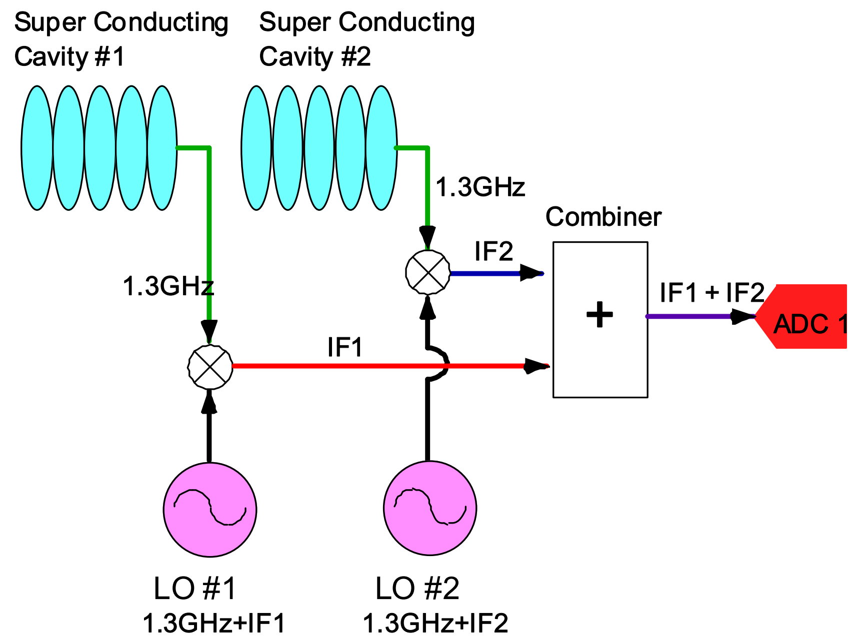
Poster session T.Matsumoto: **Development of Low-level RF System using IF Mixture Technique**

・ Conventional single IF method



- One Local Oscillator (Common IF)
- No. of ADCs = No. of Cavities

・ IF-mixture technique



- **Two Local Oscillators with Different Frequency**
- **Each IQ component of cavities are calculated by DSP inside FPGA**
- **No. of ADCs = half (No. of Cavities)**

-Advantages

# of ADCs reduce 1/4 (In case of 4 IF)

-Disadvantages

Need 4 LO

less bit-resolution/signal

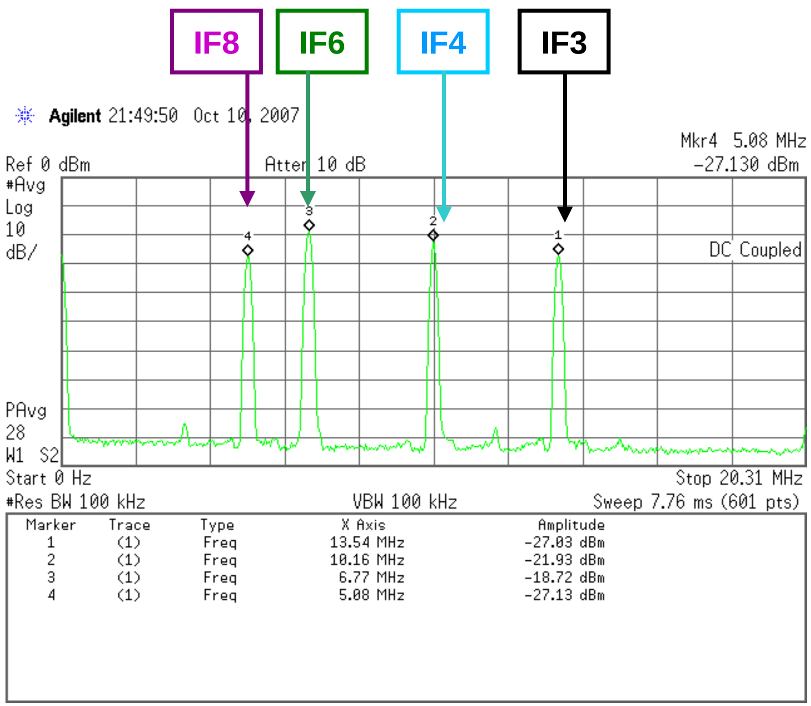
more latency

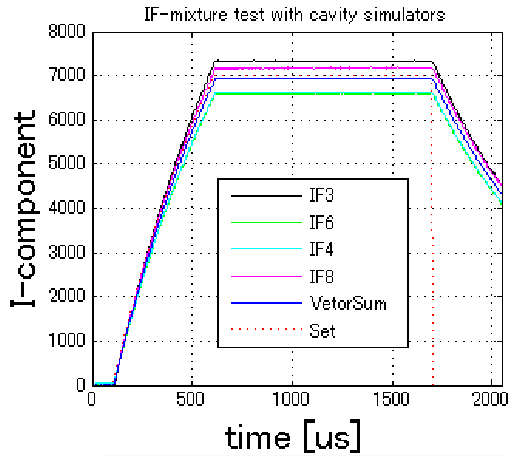
Performance of IF-mixture technique (4 IF signals)

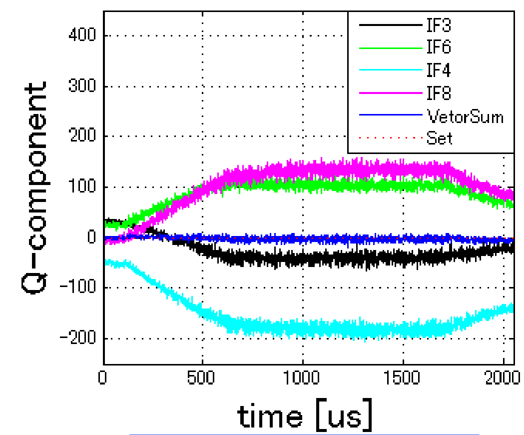
Poster session T.Matsumoto: **Development of Low-level RF System using IF Mixture Technique**

- **ADC Sampling Frequency, FPGA Clock: 40.625MHz**
- **IF3: 13.542MHz (= 40.625MHz/3)**
- **IF4: 10.156MHz (= 40.625MHz/4)**
- **IF6: 6.771MHz (= 40.625MHz/6)**
- **IF8: 5.078MHz (= 40.625MHz/8)**

- **FB operation (P control only)**
  set point of flattop: 7000, P gain: 98

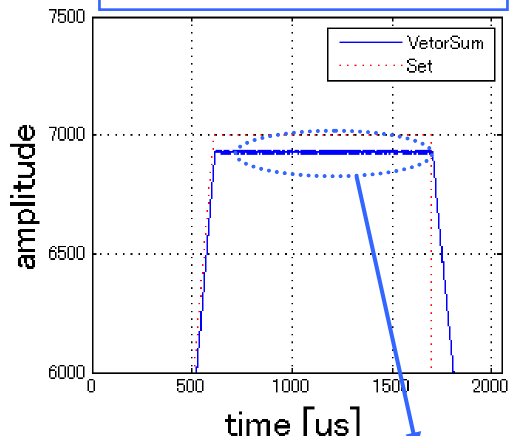


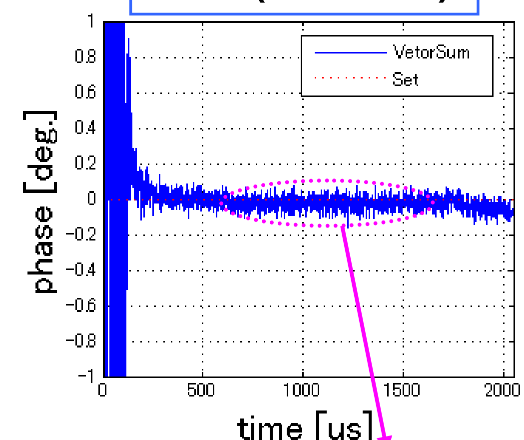




Amplitude (Vector sum)

Phase (Vector sum)



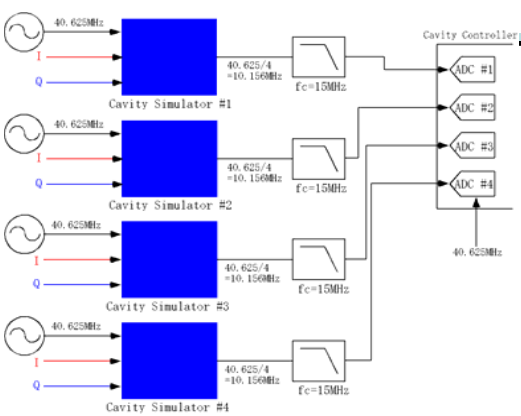


⊿A/A = 0.043% (RMS)

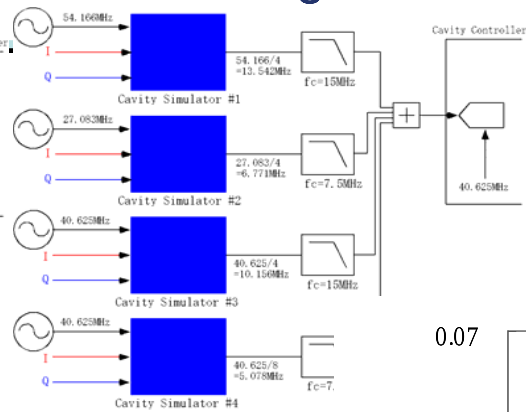
⊿φ = 0.036deg. (RMS)

- **Frequency Spectrum of combined IF signals**
  (Input signal to ADC)

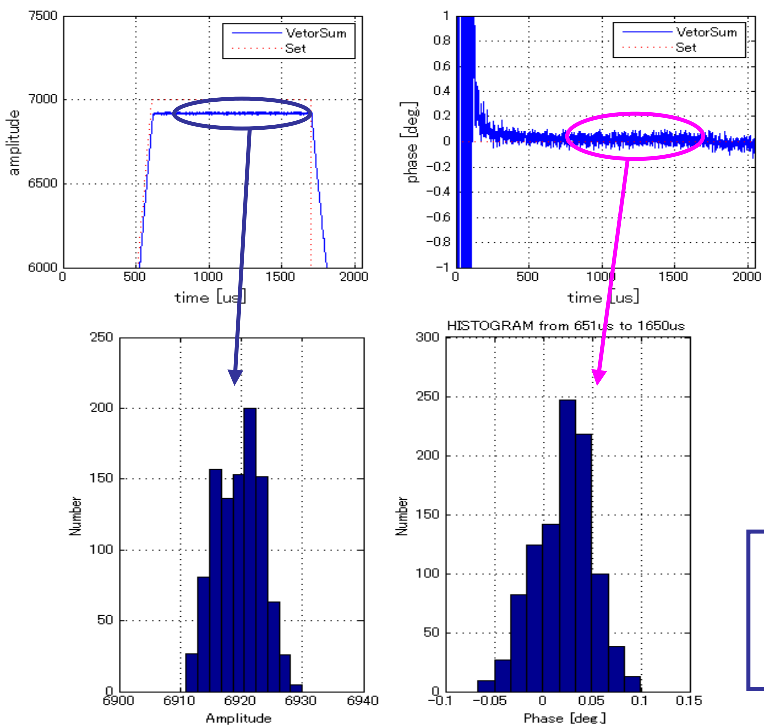
Comparison with conventional single IF method



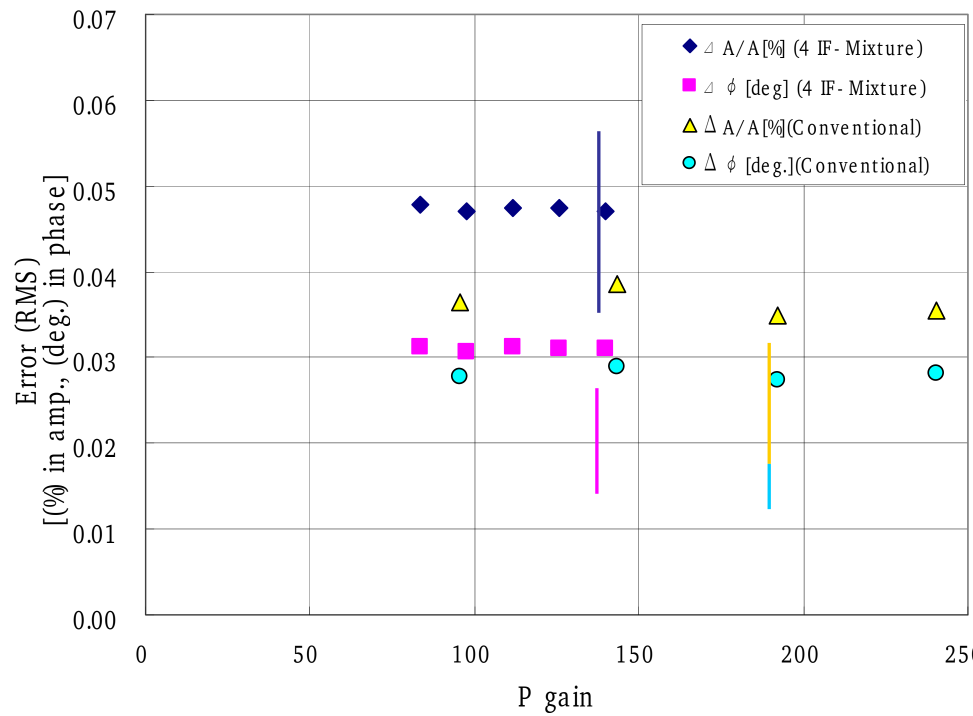
- conventional single IF



- 4 IF-Mixture



Poster session T.Matsumoto:
Development of Low-level RF System using IF Mixture Technique



Errors (RMS)

Conventional: 0.036%(amplitude), 0.029deg.(phase)

4 IF Mixture : 0.047%(amplitude), 0.031deg.(phase)

For detail, contact at poster session

Summary of KEK llrf system (KEK-Tsukuba and J-PARC)

Shin MICHIZONO, KEK

KEKB

- Crab cavity operation
- Bunch-by-bunch FB

Poster session: M.Tobiyama:
Bunch-by-bunch Feedback System Using iGp Feedback Signal Processor

J-PARC

- Linac llrf
- Synchrotrons

Monday's talk T.Kobayashi: **Performance of J-PARC Linac RF System**

Wednesday's talk F.Tamura: **LLRF Control Systems for J-PARC Synchrotrons**

STF (Superconducting rf test facility)

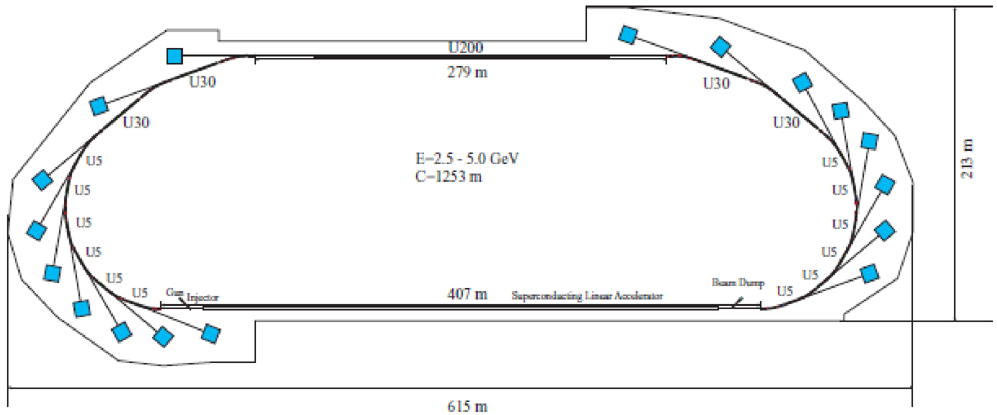
- Status of STF llrf
- IF mixture

Poster session S.Michizono: **Status of the low-level RF system at KEK-STF**

Poster session T.Matsumoto: **Development of Low-level RF System using IF Mixture Technique**

→ ***ERL***

Proposed 5-GeV ERL for the Future Light Source in Japan



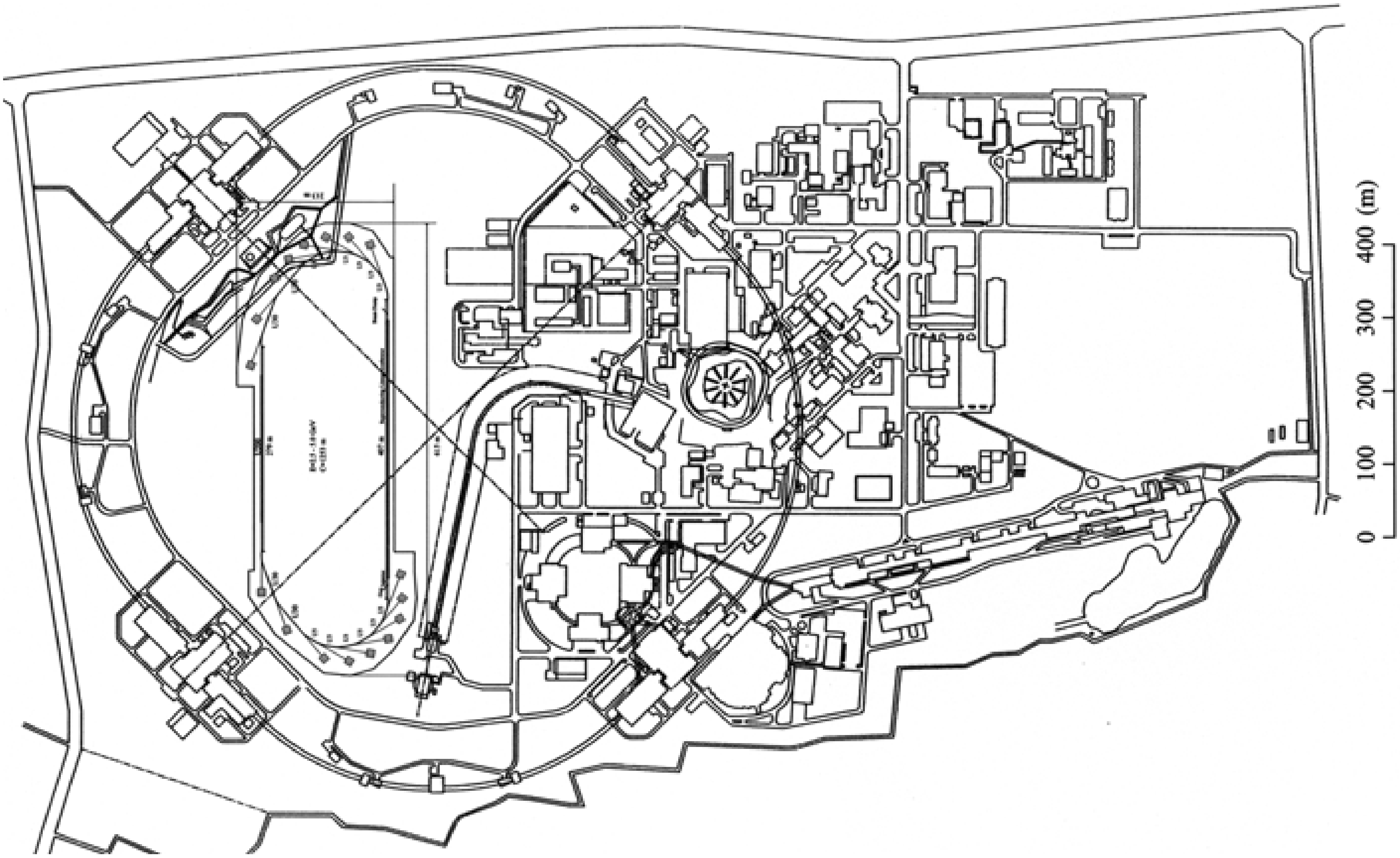
Machine parameters

Beam energy	5 GeV
Average beam current	100 mA
Circumference	1253 m
Normalized emittance ε_n	1 - 0.1 mm·mrad
Beam emittance at 5 GeV	100 - 10 pm·rad
Energy spread (rms)	4×10^{-5}
Bunch length (rms)	1 - 0.1 ps
RF frequency	1.3 GHz
Accelerating gradient	10 – 20 MV/m

Light source parameters

Spectrum range	30 eV – 30 keV
Brilliance from ID's (@ 0.1 nm)	10^{21} – 10^{23} ph/s/0.1%/mm^2/mrad^2
Average flux	> 10^{16} ph/s/0.1%
Bunch length (rms) (short pulse mode)	< 100 fs
Number of insertion devices	20 – 30

Possible layout of the 5-GeV ERL



Planned ERL test facility

In the East Counter Hall at KEK. Approved to use the building.

Tentative parameters of the test ERL

Injection energy	5 MeV (10-15 MeV)
Injector beam power	500 kW (1 MW)
Beam energy in arcs	~60 MeV (160-200 MeV)
SC cavities for main linac	9cells × 4: single module (two modules)
Normalized emittance	1 mm·mrad (0.1 mm·mrad)
Beam current	10 mA (100 mA)
Rms bunch length	Usual mode : σ_τ = 1-2 ps Short bunch mode : σ_τ ~ 100 fs?
Test undulator	No undulators (with an undulator)

Initial goals. Final goals are in ( ).

LLRF requirements are

10^-3 in amplitude and 0.1deg. in phase (initial)

10^-4 and 0.01 deg. (final).

Summary

- KEKB started crab cavities operation.
- Fast FPGA board is used for beam FB at KEKB.
- LLRF of J-PARC linac stabilizes rf field ~+/-0.2%, +/-0.2 deg.
- Synchrotron at J-PARC is ready for beam.
- STF's llrf system is based on J-PARC linac and stability is <0.1% and <0.1 deg.
- Baseband experiments of IF mixture (to reduce the number of ADCs) shows similar performance.
- ERL is under designing of the test facility.

- Many of these topics are presented at posters or talks in this LLRF-07.

Poster session: M.Tobiyama:
Bunch-by-bunch Feedback System Using iGp Feedback Signal Processor

Monday's talk T.Kobayashi: Performance of J-PARC Linac RF System

Wednesday's talk F.Tamura: LLRF Control Systems for J-PARC Synchrotrons

Poster session S.Michizono: Status of the low-level RF system at KEK-STF

Poster session T.Matsumoto: Development of Low-level RF System using IF Mixture Technique