Status of MicroTCA-based System for Accelerators in KEK and J-PARC

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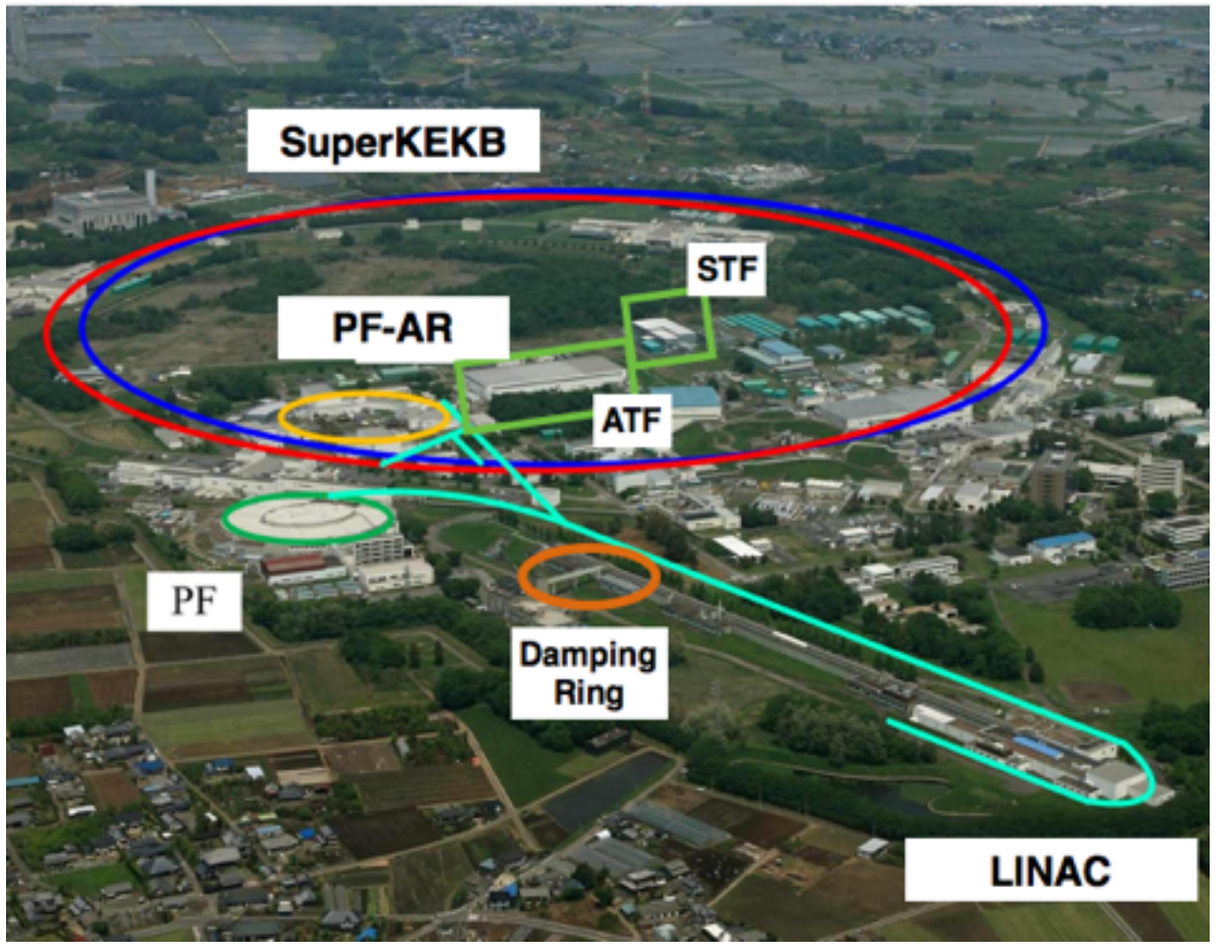
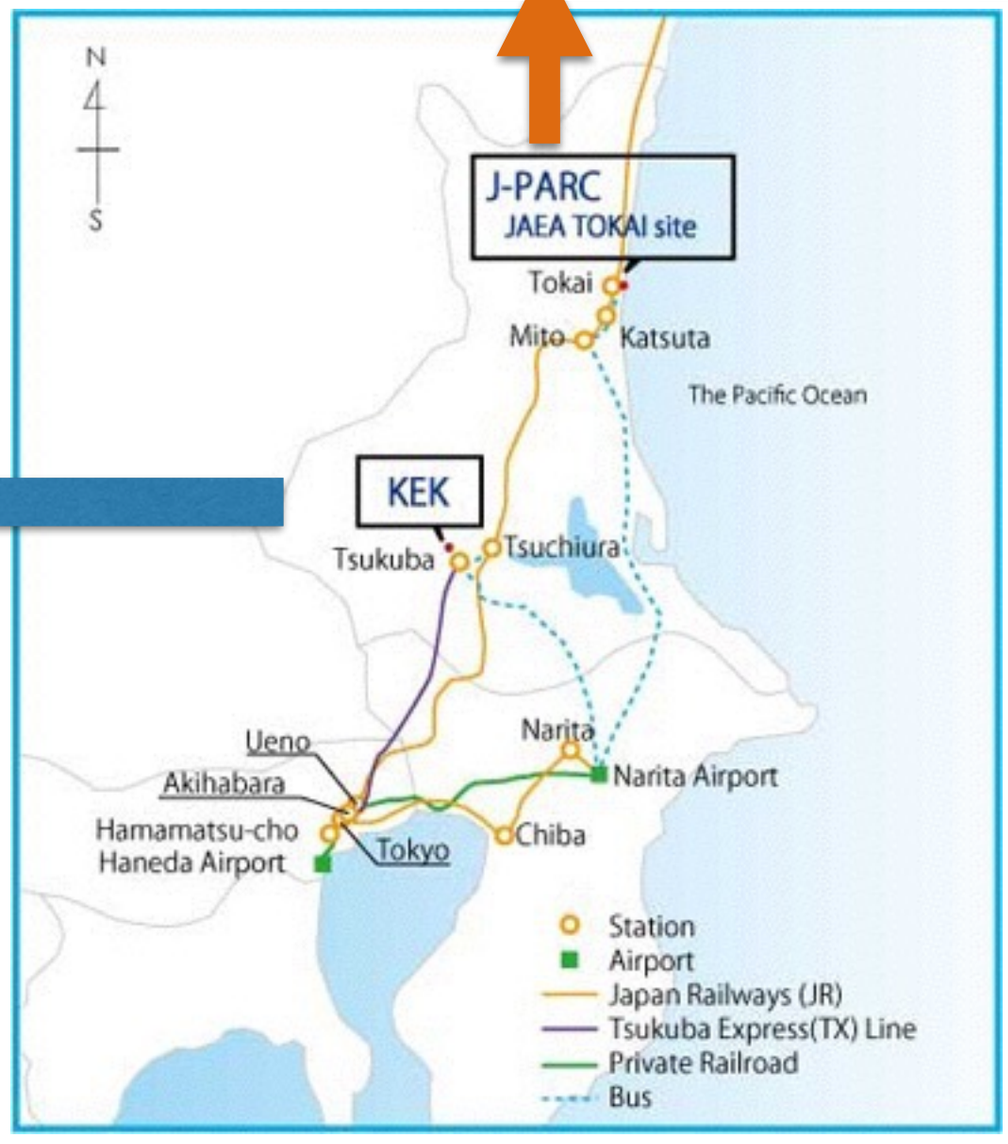
KEK

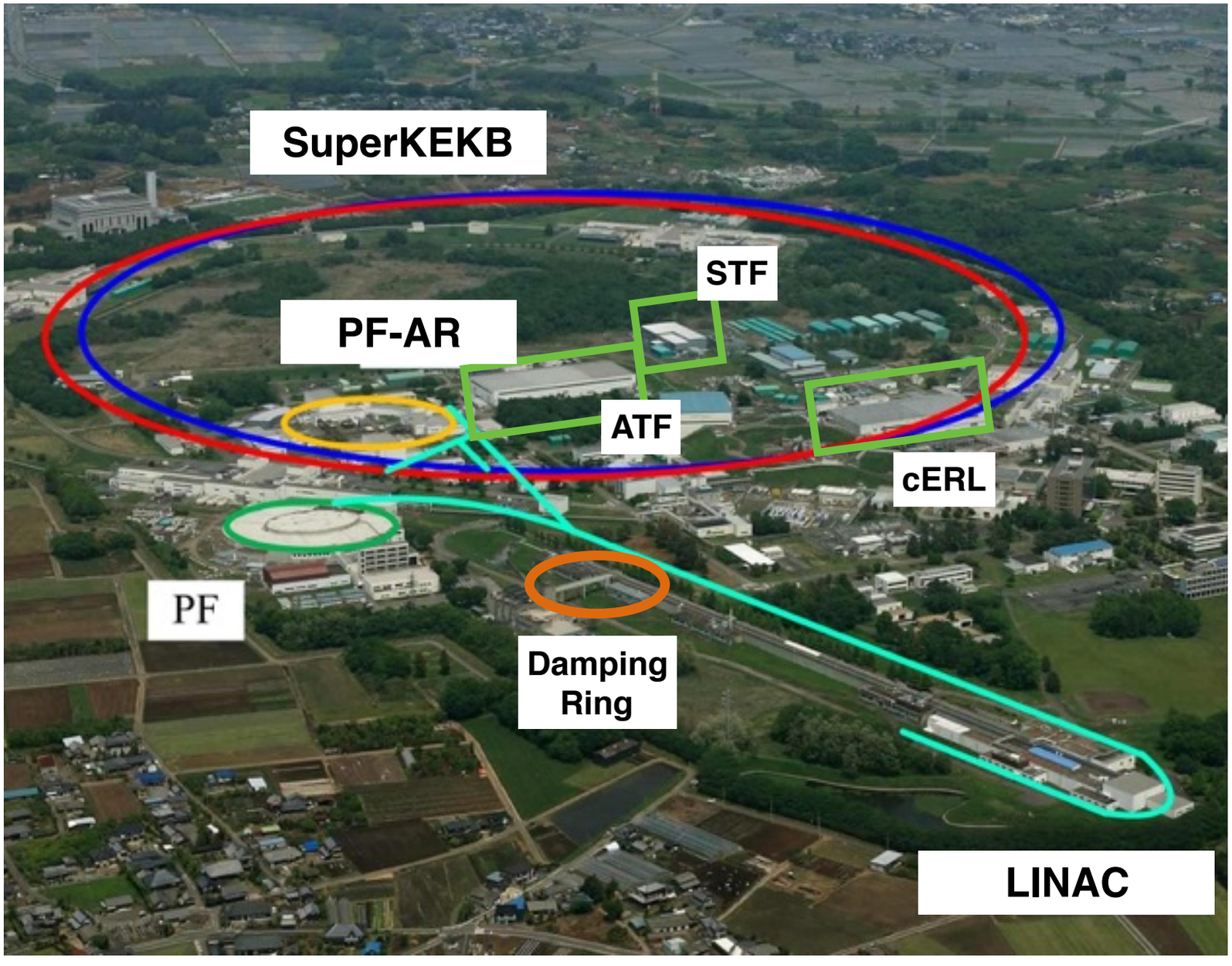
- National laboratory for High Energy Physics and accelerator systems.
- Two campus
  - KEK(Tsukuba campus): SuperKEKB,PF..
  - Tokai campus: J-PARC (inside JAEA)





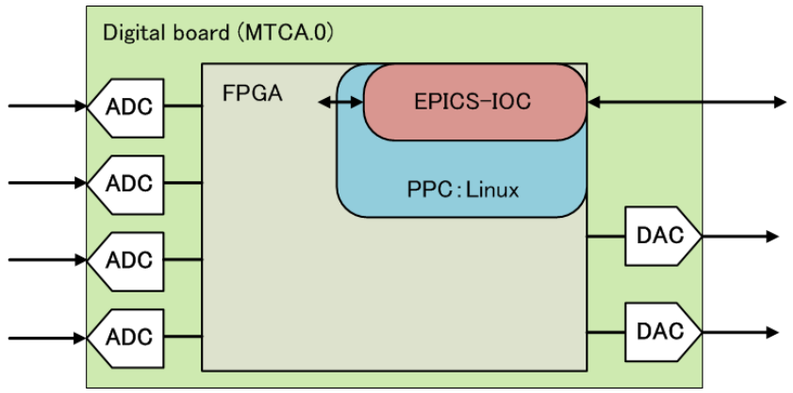
KEK (Tsukuba)

- $e^{\pm}$ accelerators complex
  - LINAC:
    Injector for synchrotrons
  - SuperKEKB: $e^{\pm}$ collider for HEP experiment (Belle2)
  - Photon Factory(PF) /PF-AR: SR photon source
  - STF: Superconducting RF Test Facility for ILC
  - ATF: Accelerator Test Facility for ILC
  - cERL: Test Facility for a future 3-GeV Energy Recovery LINAC (ERL)



MTCA module used in KEK

- Module made by **Mitsubishi Electric TOKKI systems Co.,Ltd**
  - EPICS-IOC is running on the LINUX installed on the CPU in the FPGA.
- In 2008, the development of digital board based on MTCA.0 was started for the aim of common use at RF control among SuperKEKB, cERL, and STF in KEK.
  - **Type1**:used for cav-voltage regulation and cav-tuning
  - **Type2**: used for RF direct (under) sampling method to monitor the slow (narrow band) phase change.



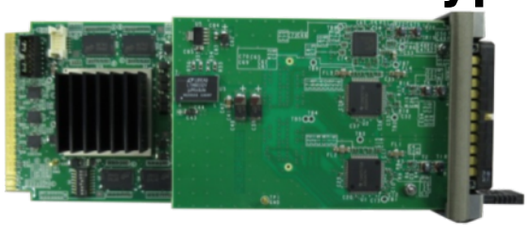
- In 2013, the development of the module based on MTCA.4 for the LLRF system of STF
  - **Type3**: SFP on the RTM is used to communicate with other module.

Type1

- FPGA (Virtex 5 FX),
- 4 x 16-bit ADCs (Max. 130MSPS)
- 4 x 16-bit DACs
- Digital I/O

Mitsubishi Electric TOKKI System Co., Ltd.

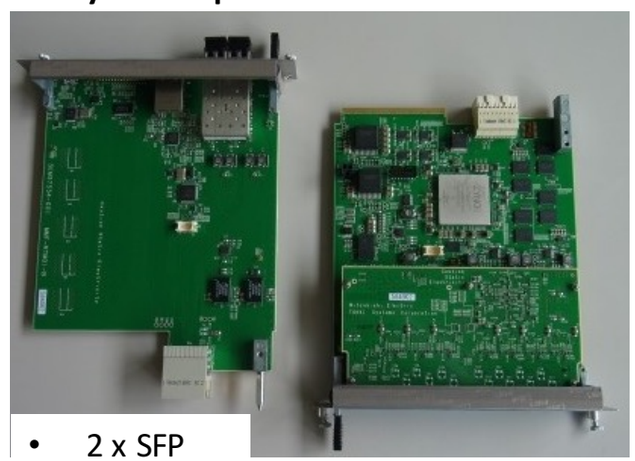
Type2



- FPGA (Virtex 5 FX),
- 2 x 14-bit ADCs (Max. 400MSPS)
- Digital I/O

Mitsubishi Electric TOKKI System Co., Ltd.

Newly developed board based on MTCA.4



Type3

- 2 x SFP
- 1 x RJ-45
- Digital I/O
- 2 FPGAs (Zynq-7000, Spartan 6)
- 14 x 16-bit ADCs
- 2 x 16-bit DACs

Mitsubishi Electric TOKKI System Co., Ltd.

Present status of KEK Accelerators using MTCAs

- **SuperKEKB Ring**

  LLRF control system (feedback control)

  => Newly installed at Damping Ring

  Reference system (feedback control)

  Beam Orbit feedback control at Interaction Point

- **SuperKEKB Linac**

  Reference system (monitor => feedback control)

- **STF (Superconducting rf Test Facility)**

  LLRF control system (feedback control)

  Reference system (monitor => feedback control)

- **cERL (Compact Energy Recovery Linac)**

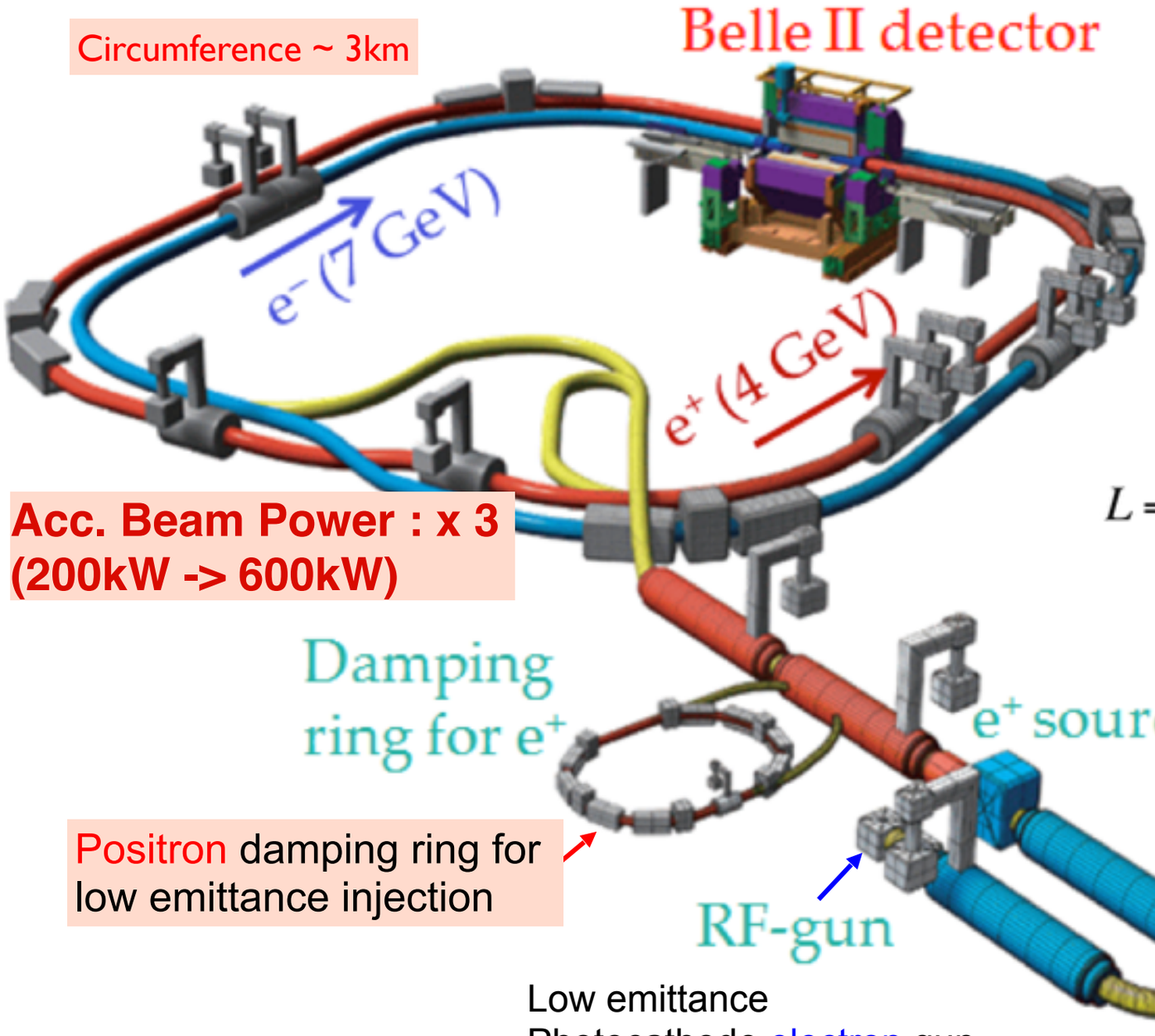
  LLRF control system (feedback control)

SuperKEKB Project

- KEKB is being upgraded to SuperKEKB.
- The first beam commissioning (Phase-1) was successfully accomplished 2016.
- The commissioning with beam collision (Phase-2) began in March of 2018.
- The Belle2 physics run (Phase-3) began in March of 2019.

Luminosity : KEKB x 40 !

Circumference ~ 3km



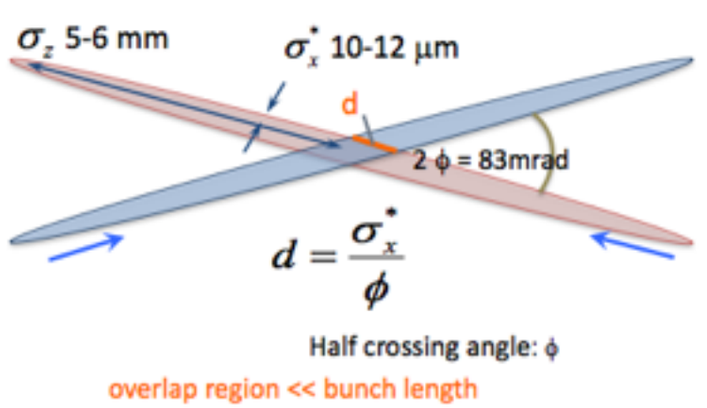
Acc. Beam Power : x 3 (200kW -> 600kW)

Positron damping ring for low emittance injection

Low emittance Photocathode electron gun

P. Raimondi

Nano-Beam Scheme SuperKEKB



Half crossing angle: ϕ

overlap region << bunch length

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

Beam Current: x 2

β_y @IP: 1/20

	KEKB Acieved		SuperKEKB Nano-Beam	
	LER	HER	LER	HER
I_{beam} [A]	1.6	1.2	3.6	2.6
β_y^* [mm]	5.9	5.9	0.27	0.30
ξ_y	0.09	0.12	0.088	0.081
Luminosity [cm^{-2} s^{-1}]	2.1×10^{34}		8.0×10^{35}	

SuperKEKB

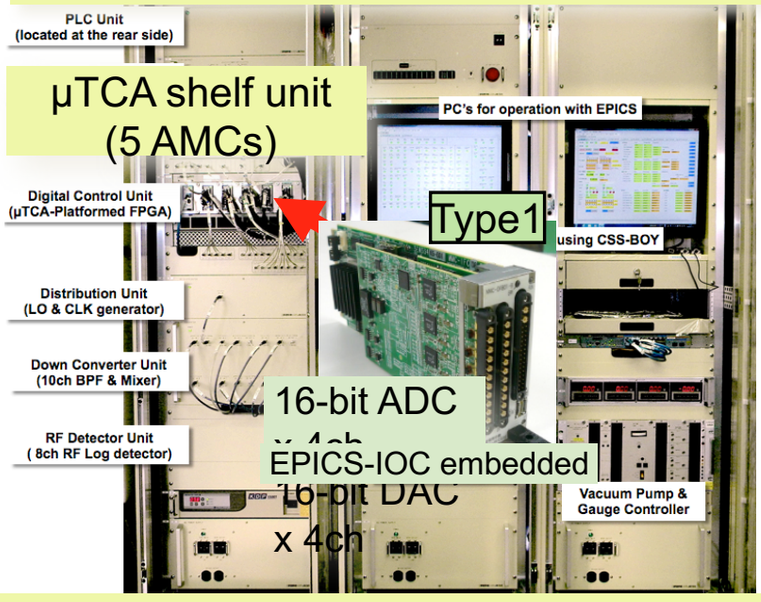
New LLRF control system

with high accuracy and flexibility for superKEKB

Existing analog LLRF system for KEKB

replace

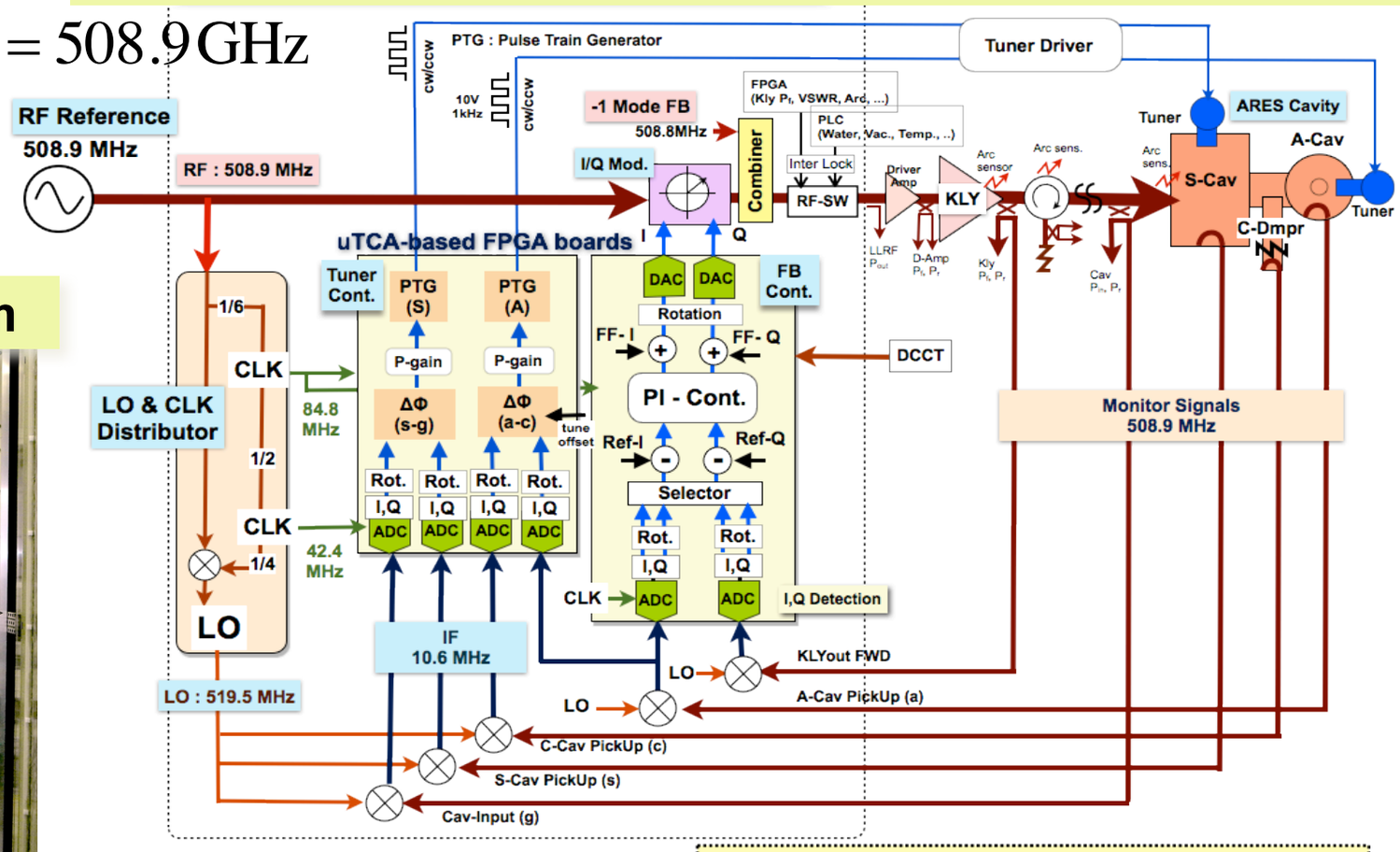
New LLRF Control System



Mitsubishi Electric TOKKI System Co., Ltd.

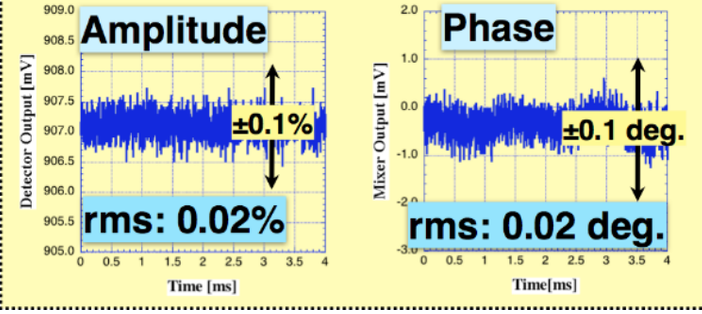
Block Diagram of Vc-FB & Tuner Control

$$f_{rf} = 508.9\,\mathrm{GHz}$$



I/Q-sampling for 10.6-MHz IF

ARES Cavity FB Control Stability measured by external "outside-the-loop" monitor in high power test.



- Consisting of μTCA-platformed **FPGA boards** & **PLC.**
- **Type1** board is used for Cav. field **FB control**, **Cavity Tuning** and RF-I/L.
- **EPICS-IOC** with Linux-OS embedded in each board.
- The regulation stability is **0.02%** in amplitude and **0.02 deg.** in phase.

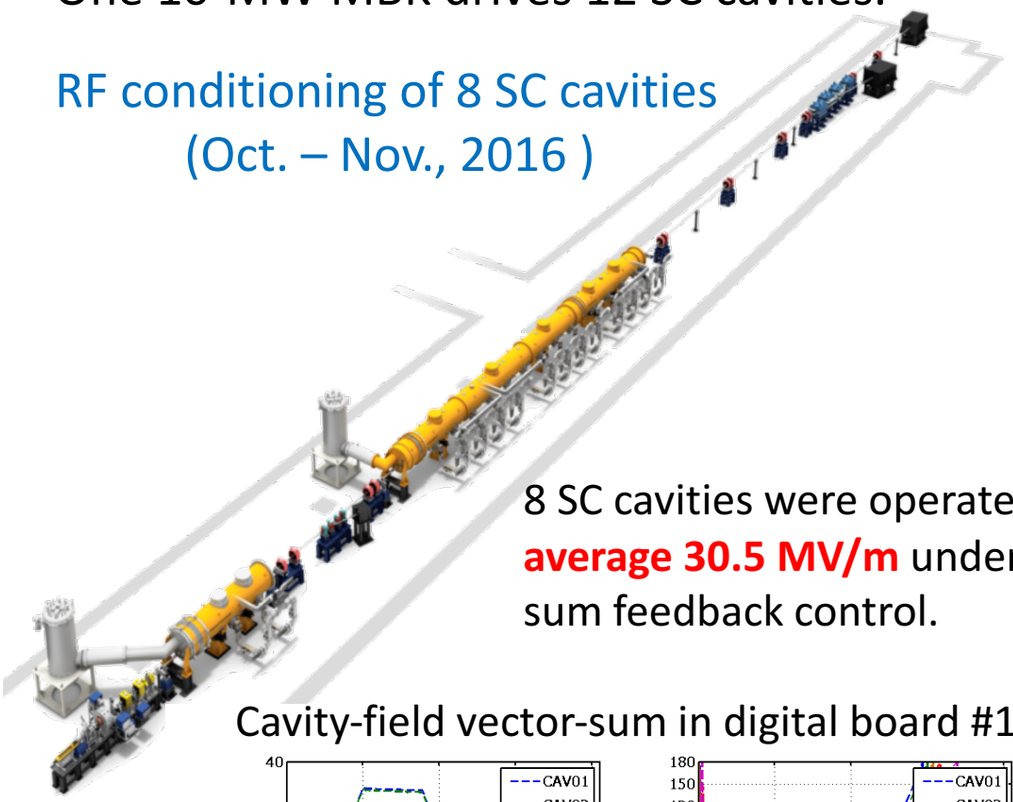
20

STF-2 : Prototype of ILC-TDR (2015-)

STF-2: Prototype of ILC-TDR

One 10-MW MBK drives 12 SC cavities.

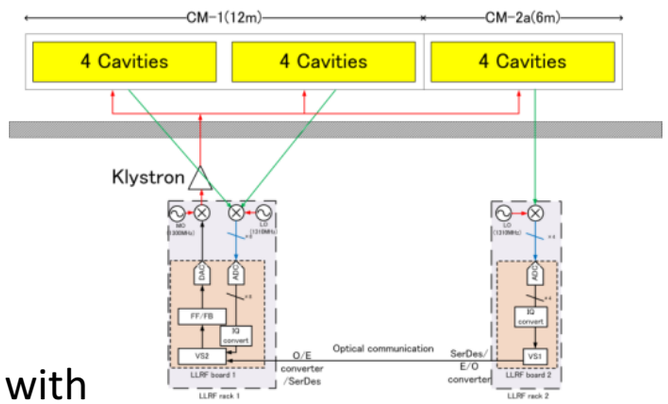
RF conditioning of 8 SC cavities
(Oct. – Nov., 2016)



8 SC cavities were operated with **average 30.5 MV/m** under vector-sum feedback control.

- In STF-2, two digital LLRF boards connected with optical communication are configured for operation.

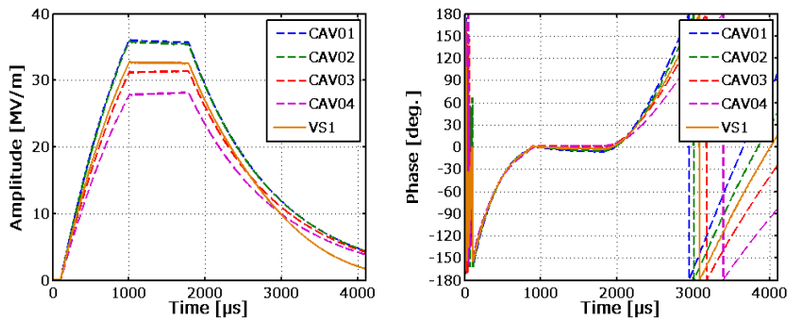
→ minimal combination of ILC LLRF system.



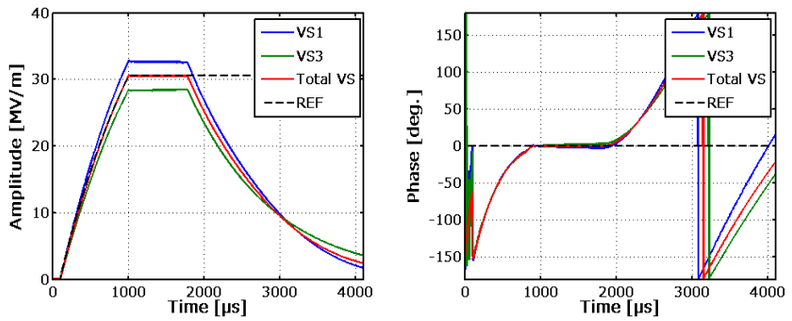
MTCA.4 standard board
2ch SFP connectors

Zynq-7000(XC7Z045):
ARM (Cortex-A9) → EPICS-IOC

Cavity-field vector-sum in digital board #1

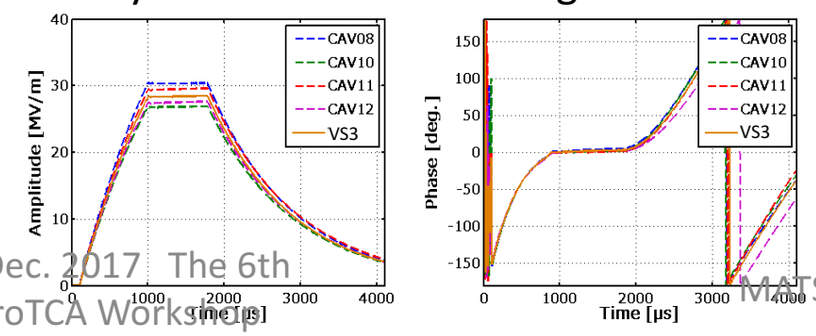


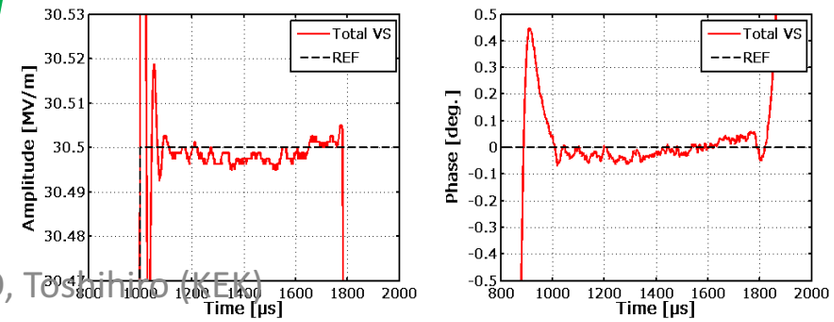
VS1



VS3

Cavity-field vector-sum in digital board #2





ΔA/A =0.006%rms
(0.07%@ILC)

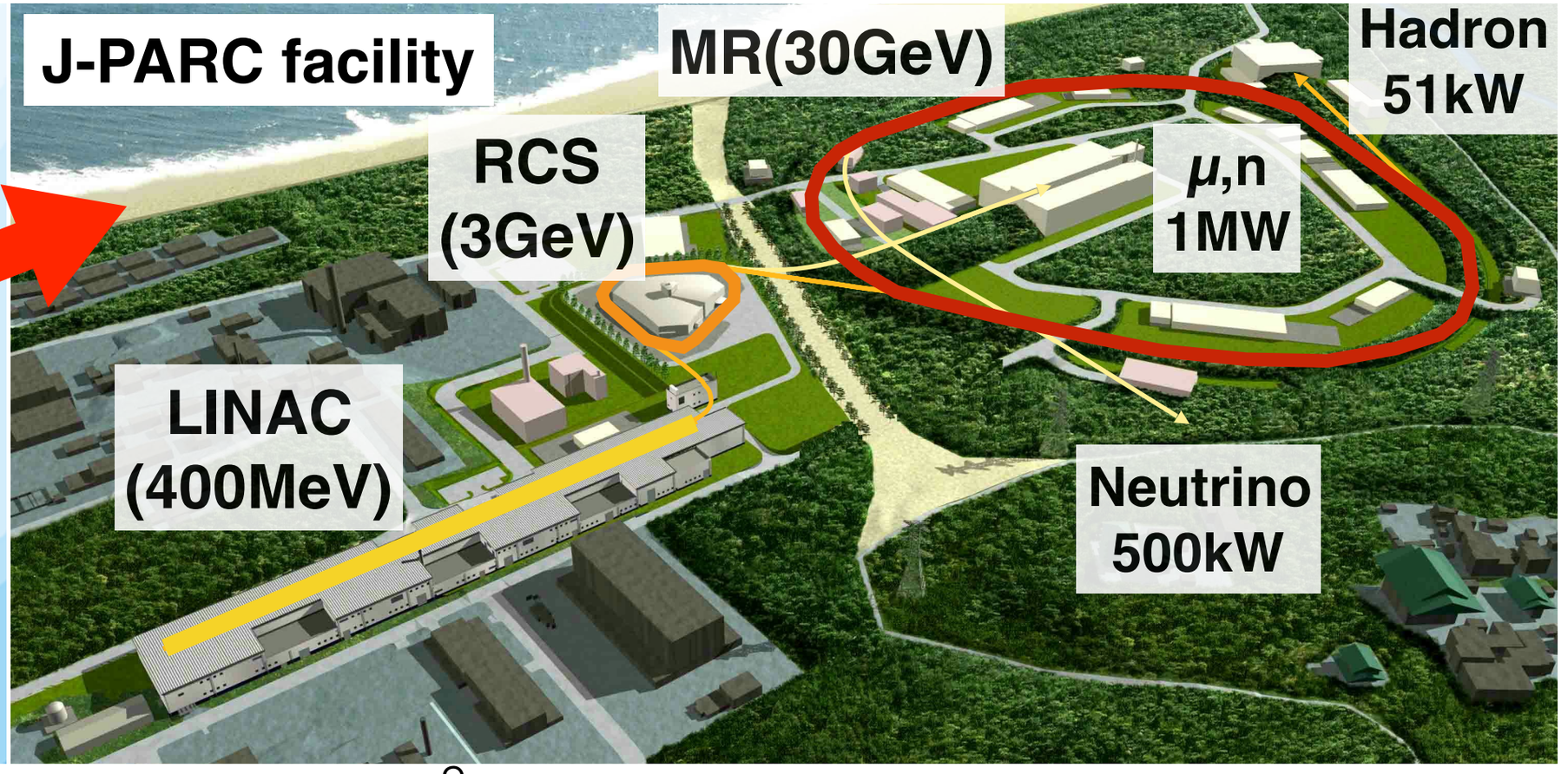
Δϕ = 0.03deg.rms
(0.35deg.@ILC)

J-PARC

(Japan Proton Accelerator Research Complex)

Joint Project
between KEK and JAEA

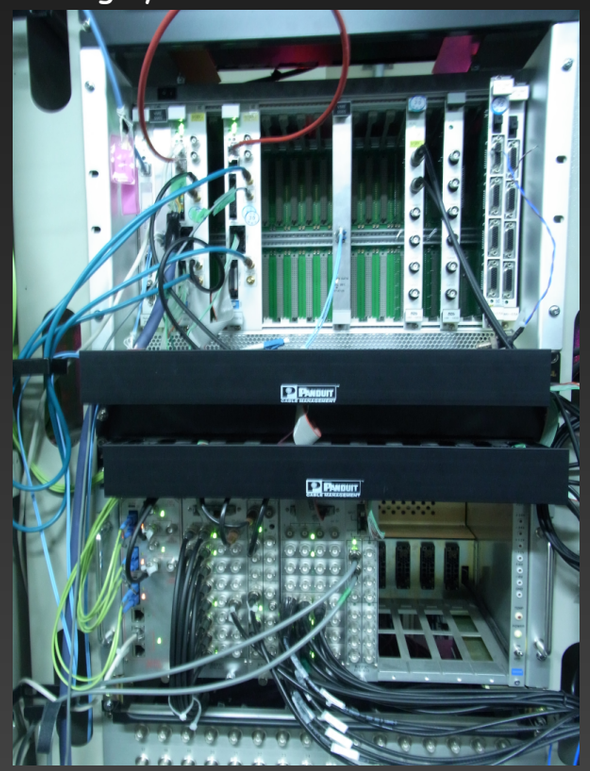
- High intensity Proton Accelerator with a LINAC and two synchrotrons.
- Started the beam commissioning from 2006 and achieved the high intensity proton delivery.
  - **LINAC**: 400MeV negative hydrogen ($\mathbf{H^-}$) with 40mA (25 Hz)
  - Rapid Cycle Synchrotron **(RCS)**: 3 GeV proton with 1 MW (25 Hz).
  - Main Synchrotron Ring **(MR)**: 30 GeV proton with 500 kW (2.48 s cycle) for the neutrino experiment, 51kW(5.52 s cycle) for the Hadron Experiment.



Platforms currently used in J-PARC accelerators

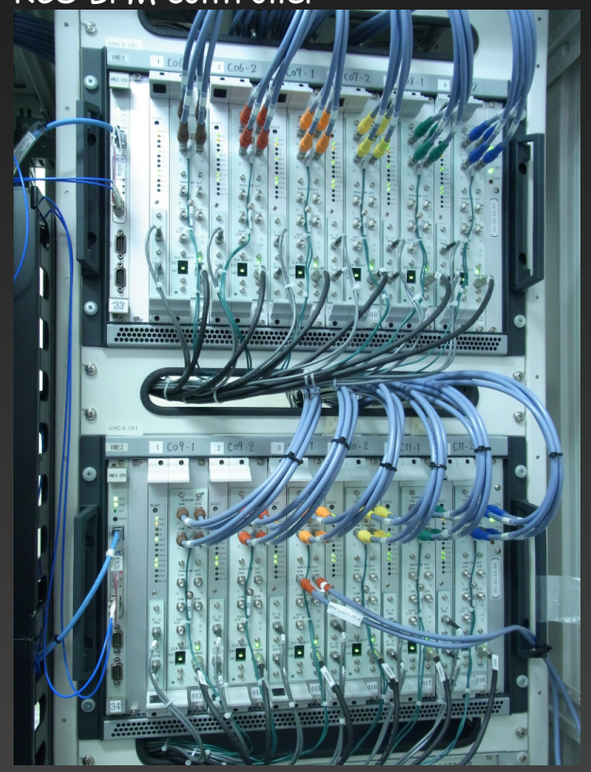
VME / cPCI systems used for high-end / complicated applications (timing, beam instrumentation, LLRF, etc.):

Timing system



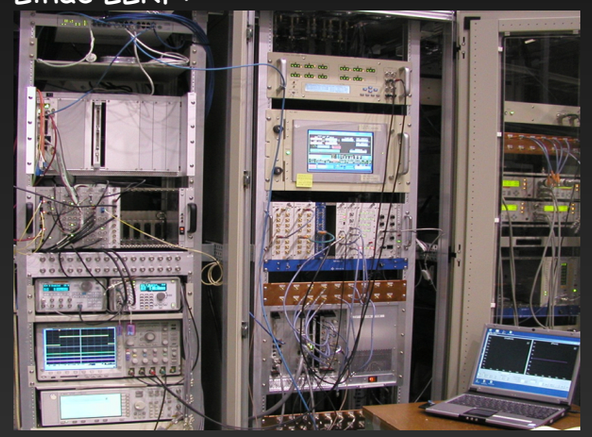
VME+NIM

RCS BPM controller



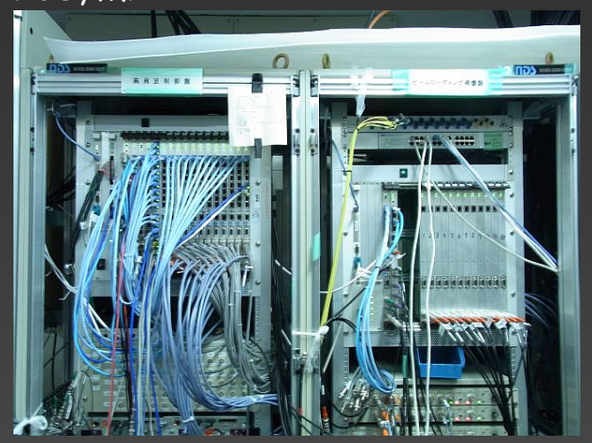
VME

Linac LLRF:



NIM (analog) + cPCI (digital)

RCS, MR:



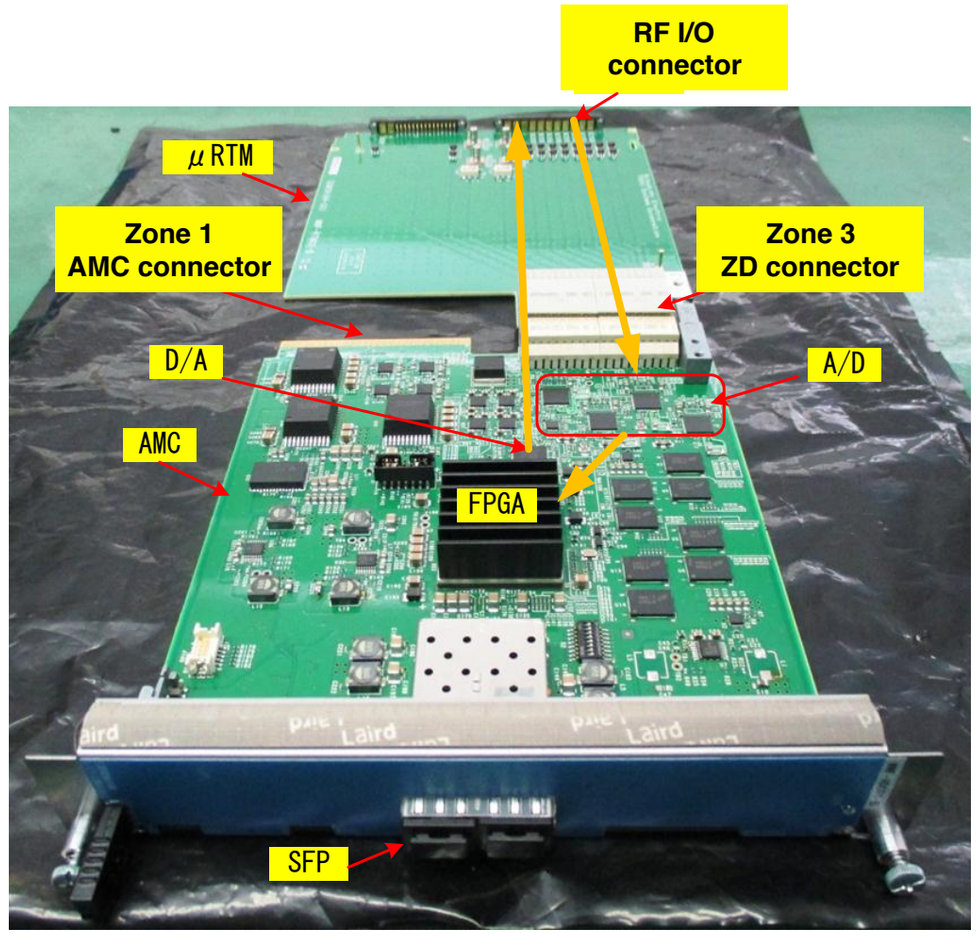
Specialized 9U VME

- **Modules with more than 10years old**
  =Difficulty in the maintenance due to discontinued modules and outdated FPGA.
- **Need more functionalities for higher intensities and stability.**

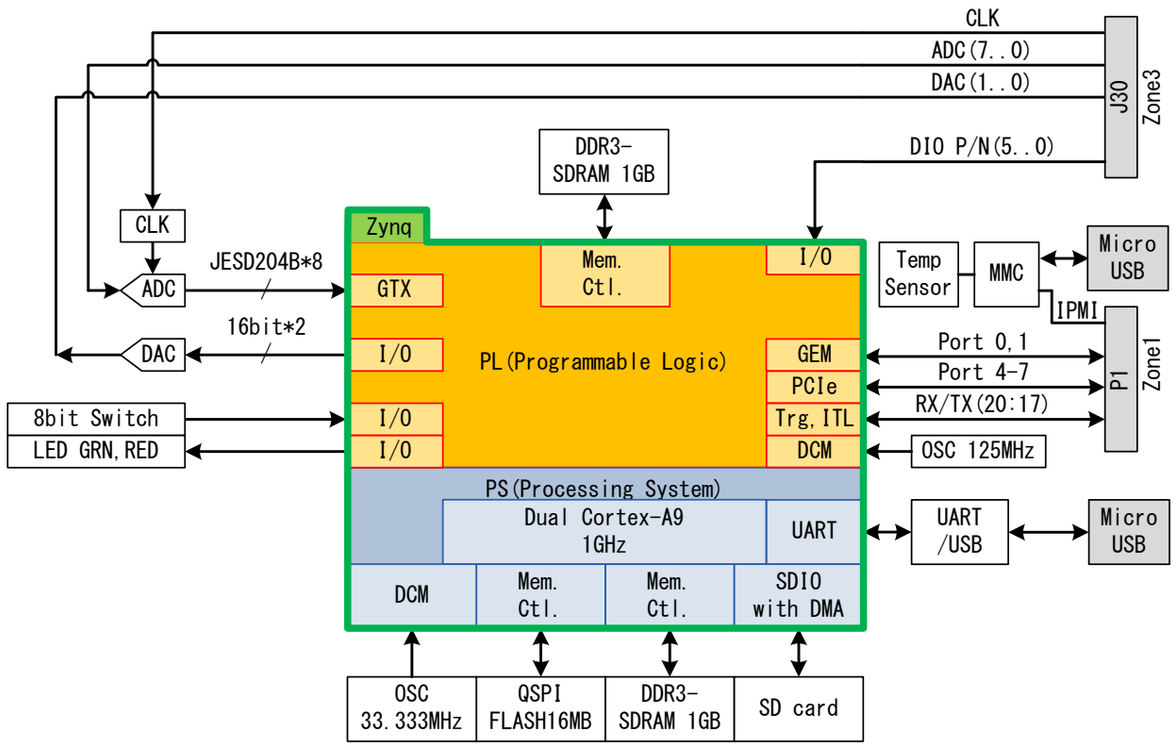
=> MTCA.4 as next platform!

A/D-D/A AMC module

- Developed by **Mitsubishi Electric TOKKI System Co.,Ltd**.
- 8 ADC and 2 DAC
  - Analog signal through Zone3 (ClassA1.1) Connector
- PCI-Ex and GbE through Zone1 AMC Connector
- EPICS-IOC running on embedded Linux on Zync FPGA

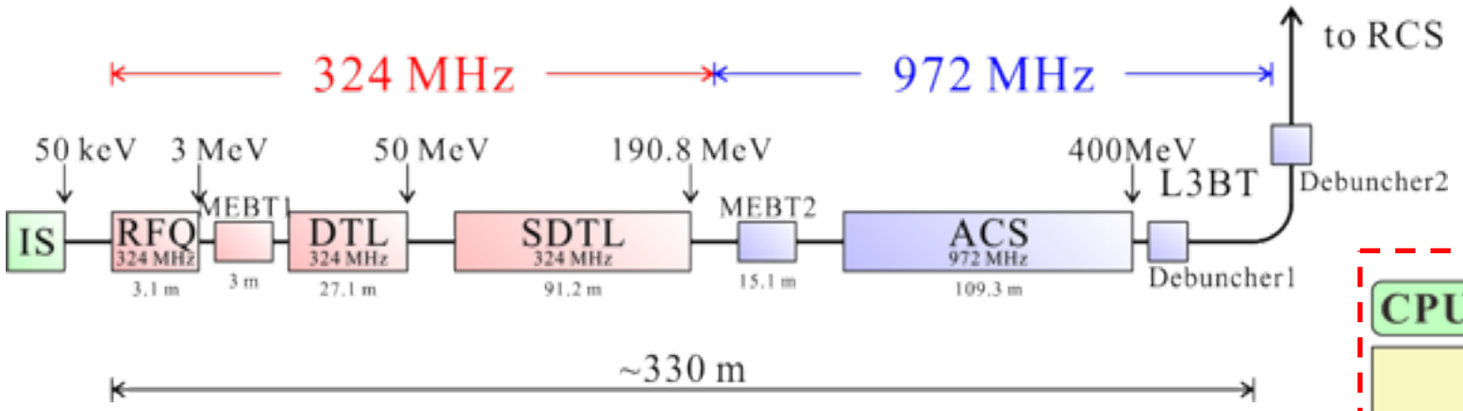


- Enables the remote control and the easy integration into the current control system.

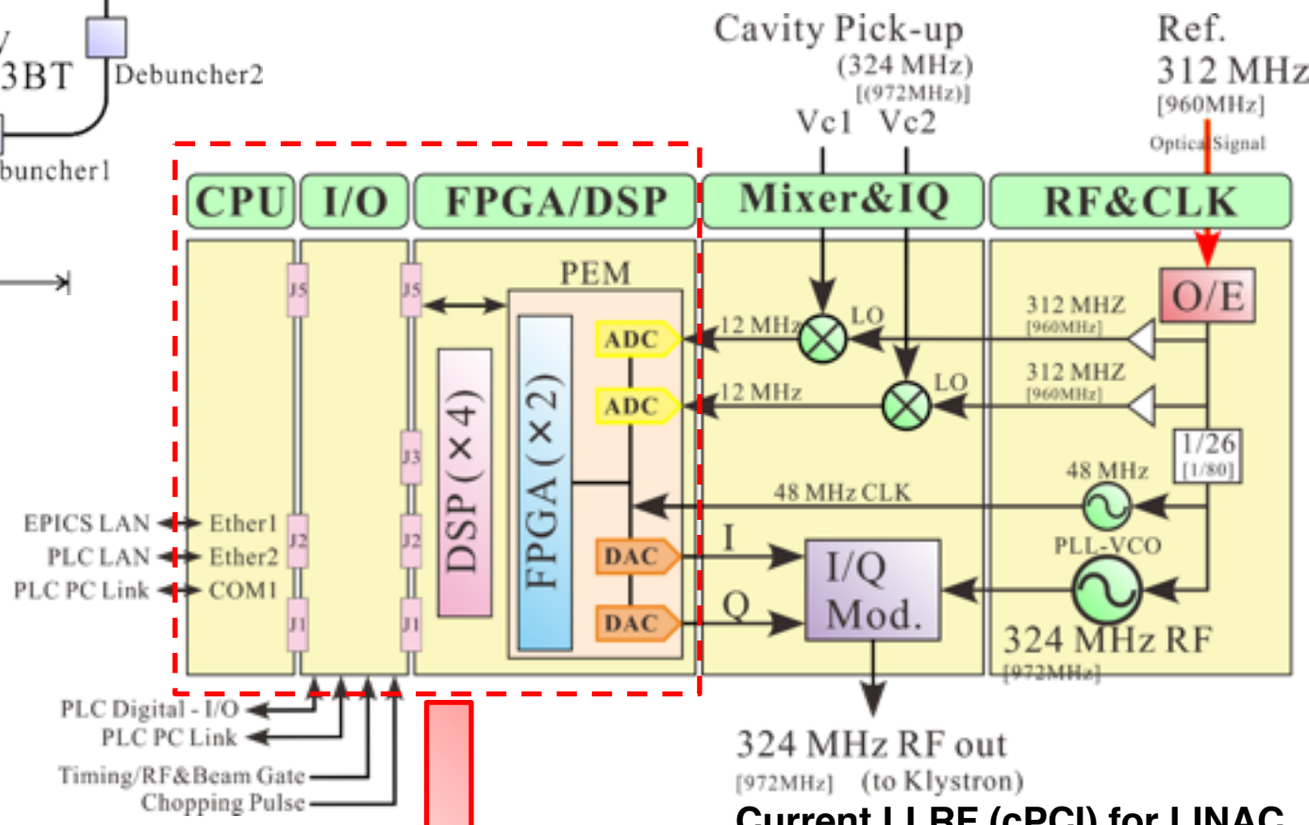


FPGA	Zynq　XC7Z045-1FFG900C
OS	Xilinx Linux (EPICS-IOC)
RAM	DDR3-SDRAM 1GiB×2 (PL, PS)
FPGA Configuration	QSPI FLASH-ROM 16MiB, SD Card, Remote Update
ADC	8ch, 16bit, 370MSPS max., BW 800MHz
DAC	2ch, 16bit, 500MSPS max.
Zone1 (AMC Connector)	Port[0:1]:1000BASE-BX, Port[4:7]: PCI Express Gen2 Port[17:20]:M-LVDS, IPMB: IPMI v1.5 support
Zone3 (ZD connector)	Class A1.1(RFin×8ch,DCout×2ch,CLKin×1,DIO×6pair,TCLKout)
SFP	2ports
Switch	8bit DIP-switch
Front Panel LED	Hot swap status (blue), Error status (red), Running status (green)
Size	PCIMG MTCA.4 Double-Width Full Size 148.5*28.95*181.5 [mm]

LLRF and monitor system in LINAC

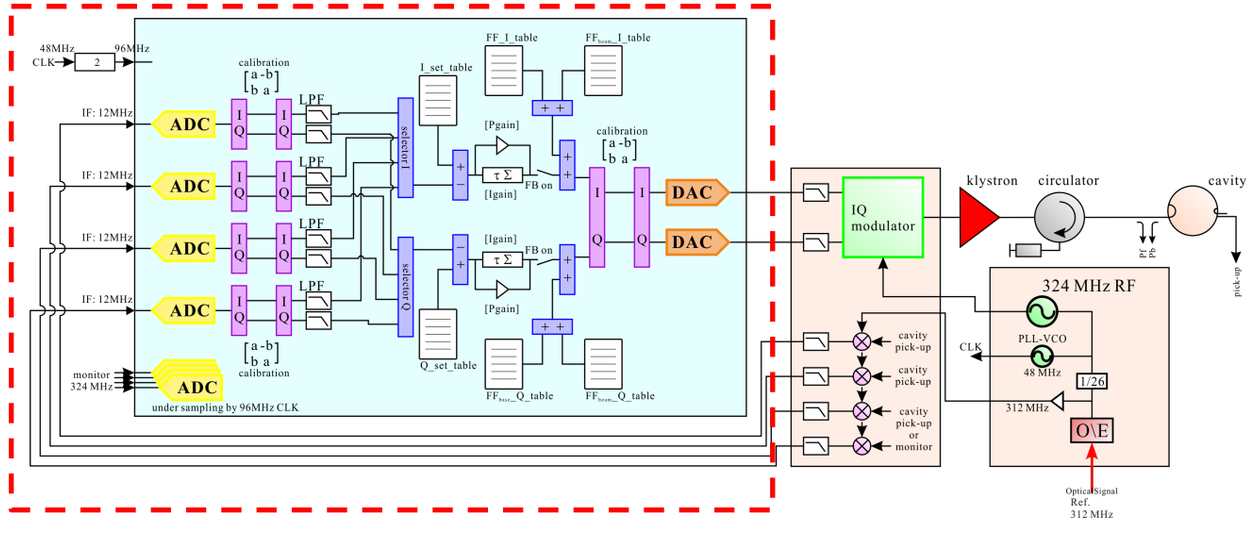


- **LLRF**
  - #station: 24 (324MHz), 25 (972MHz)
  - current LLRF system (cPCI) with the digital feedback/feedforward.
  - Upgrade development
    - Started the development of the digitizer part in the 324MHz LLRF system.
- **Monitor (FCT, BPM)**
  - Signal processed in analog system, and recorded by the digitizer system.
  - Upgrade development
    - Started the development of digitizer module.
      - Integrate signal processing and monitoring into the AMC module.



Current LLRF (cPCI) for LINAC

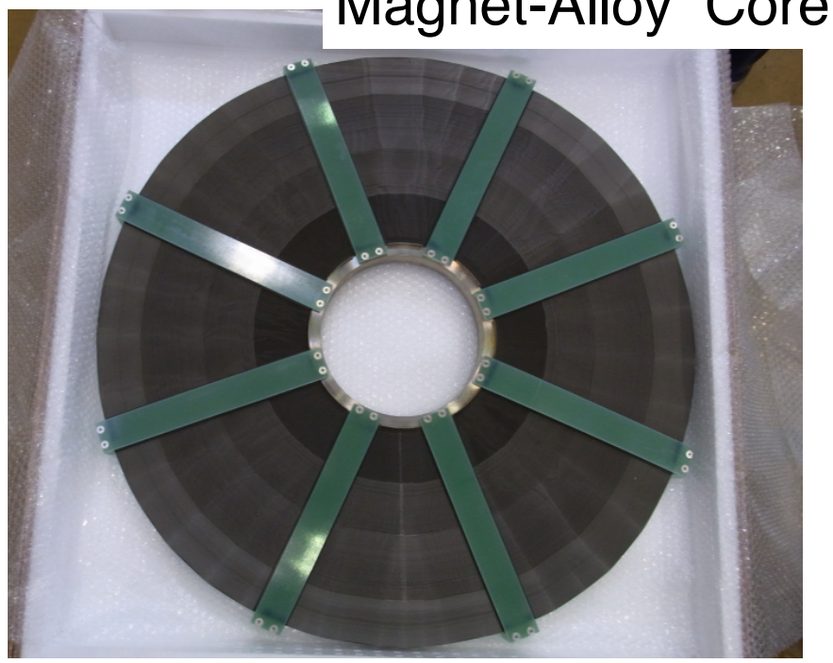
Replace with MTCA module

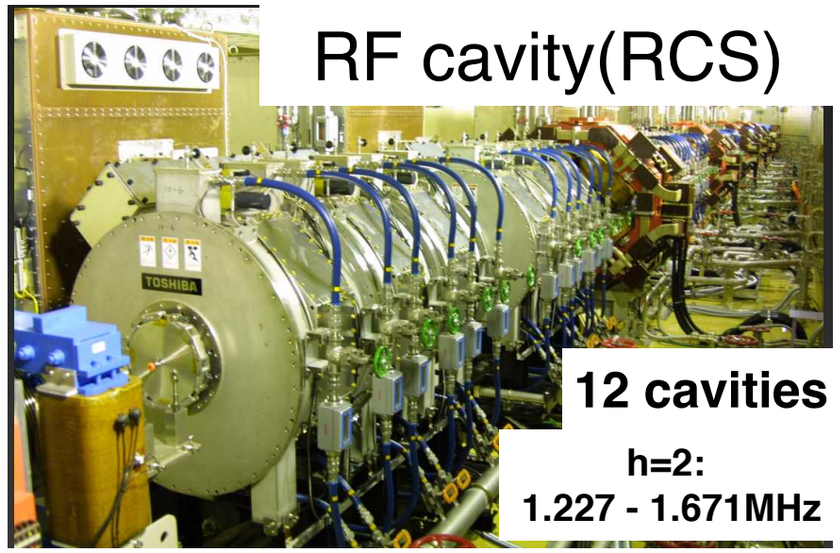


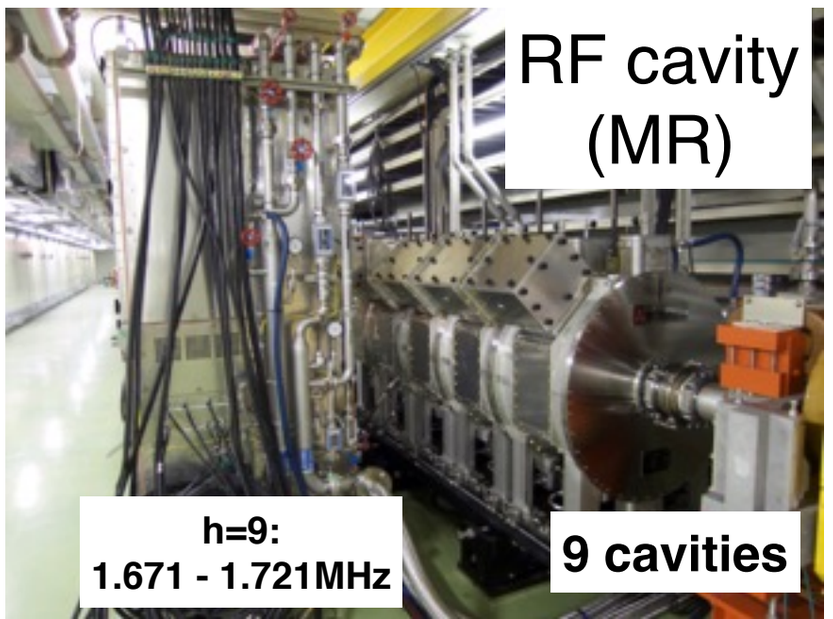
LLRF with MTCA.4 digitizer module

J-PARC Ring RF system

- J-PARC synchrotrons use the wide-band MA loaded cavity systems.
  - Beam loading compensation is necessary to achieve the high intensity operation.
- Required Function for LLRF.
  - **RF common function:**
    - Frequency pattern, Freq. &Phase FB
      - Vector Sum of Cavity Voltage
  - **Cavity Voltage Driver**
    - I/Q pattern generation and FB for Cavity
    - Feedforward for the beam loading compensation
- Development status with MTCA.4
  - new LLRF system for RCS
  - longitudinal oscillation FB for MR

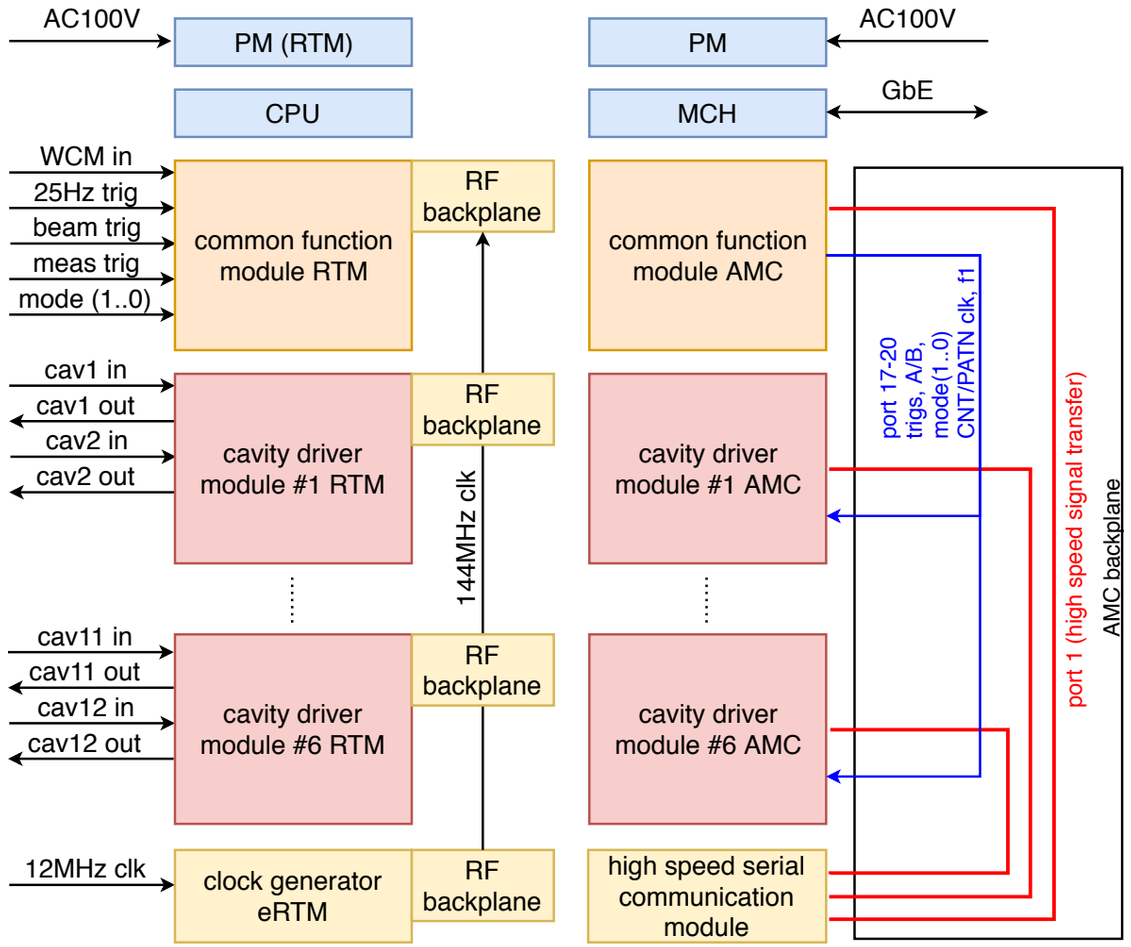


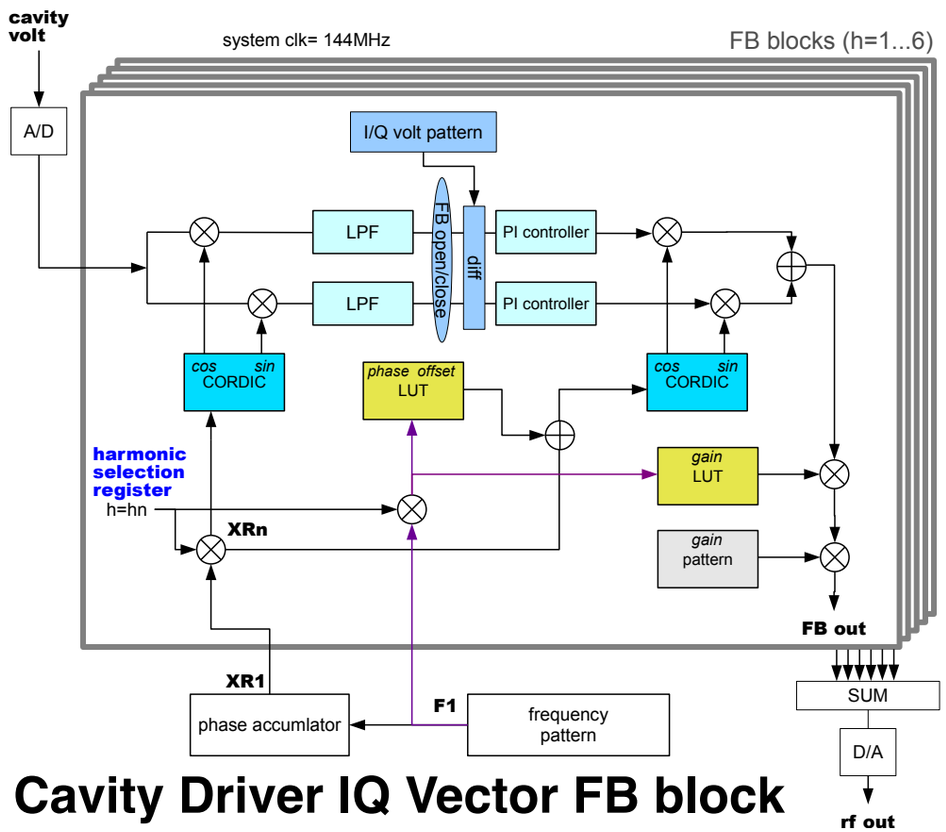




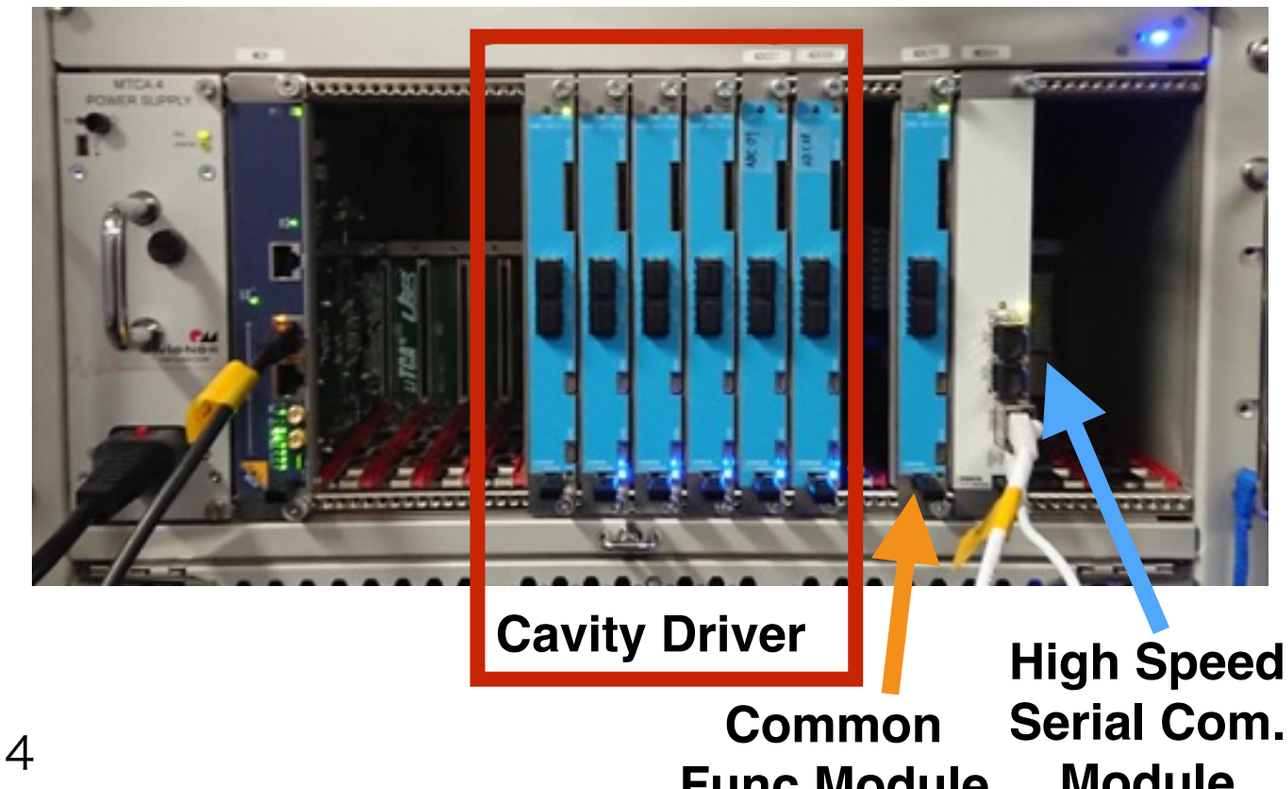
new LLRF for RCS

- Single MTCA.4 shelf can supports modules for the all the 12 cavities for RCS.
- Separate modules with functions
  - Common Function and cavity driver.
- Vector Sum is done by special module (High Speed Serial Com. module) in MCH2 slot
  - Collect, Sum, return the cavity voltage via Port#1
- Shelf and Modules are fabricated in FY2018 and under debug for the installation during this summer.





Cavity Driver IQ Vector FB block



Summary

- MTCA based modules have been used in KEK/J-PARC accelerators, especially in LLRF system.
  - Mainly the modules made by Mitsubishi Electric TOKKI
  - Embedded EPICS-IOC and LINUX-OS on FPGA of the AMC enable the remote-control and the easy integration into current system.
- At KEK Tsukuba campus, the development of LLRF control systems using MicroTCA standards was started as common-use hardware in SuperKEKB, STF and cERL.
  - started from MTCA.0 modules and MTCA.4 modules are developed.
  - Used in the LLRF, FB, monitoring system during the beam commissioning.
- In J-PARC, MTCA.4 based modules are considered as the new LLRF/monitor system for the replacement
  - LLRF system for RCS with RTM RF backplane is under test for installation in this summer.

Reference

- Most of pictures/plots/diagrams are from the slide at MTCA workshop in 2017,2018.

  - Fumihiko Tamura - MicroTCA.4 based LLRF control system of the J-PARC RCS: design and status https://indico.desy.de/indico/event/20703/session/6/contribution/59/material/slides/0.pdf

  - Toshihiro Matsumoto - Status of MicroTCA-based System for Accelerators in KEK https://indico.desy.de/indico/event/18211/session/16/contribution/42/material/slides/0.pdf

  - Yasuyuki Sugiyama - Applications of MTCA.4 to the J-PARC accelerators https://indico.desy.de/indico/event/18211/session/9/contribution/39/material/slides/0.pdf