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Development of LLRF control system for J-PARC RCS

J-PARC Ring-RF Group

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Overview

- Introduction
  - J-PARC accelerators
  - RCS RF parameters
- The RCS LLRF system, and picked-up features
  - Multi-harmonic RF generation
  - Beam loading compensation
- Summary

Introduction (1)

- J-PARC is a project of high-intensity proton accelerator complex
  - 400 MeV linac
  - 3-GeV rapid cycling synchrotron (RCS)
  - 50-GeV synchrotron (MR)
- To accelerate the ultra-high intensity proton beam, the LLRF control systems of the J-PARC synchrotrons must be very stable and precise
- Magnetic Alloy (MA) loaded cavities are used to achieve high accelerating voltages

Introduction (2)

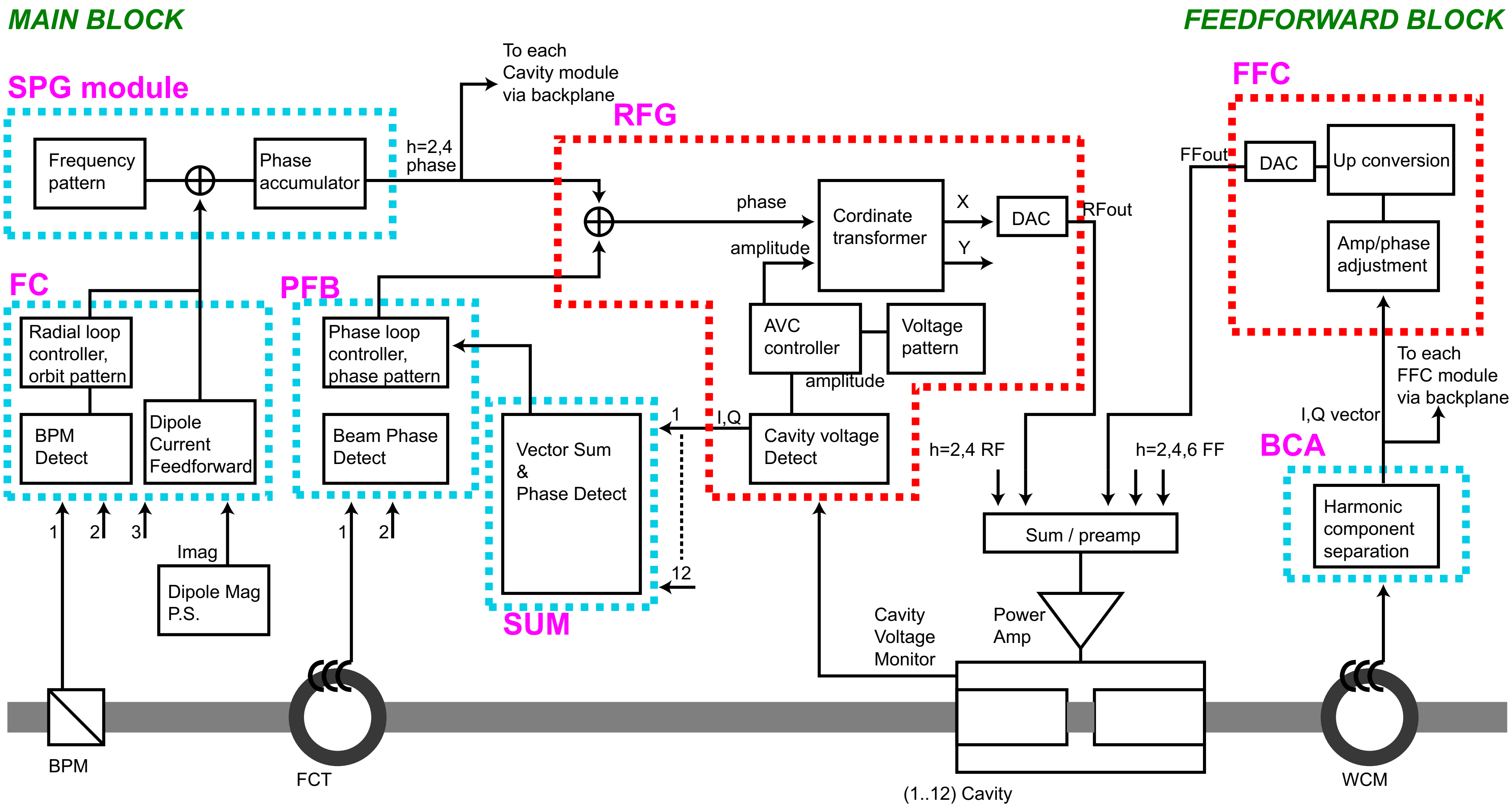
parameter	RCS	MR
circumference	348.3 m	1567.9 m
energy	0.181–3 GeV	3–50 GeV
Accel. freq.	0.94–1.67 MHz	1.67–1.72 MHz
harmonic number	2	9
max RF-voltage	450 kV	280 KV
repetition period	40 msec	3.64 sec
duty (power)	30%	60%
No. of cavities	12	6
Q-value	2	10–20
No. of gaps	3 per cavity	3 per cavity
average power	120 kW/cavity	240 KW/cavity

Table 1: Parameters of the J-PARC synchrotron RF

Introduction (3)

- Low Q-value, wide-band cavity: $Q = 2$
  - no tuning loop is necessary, more simple control
  - A single cavity is driven by the superposition of multi-harmonic RF signals
    - the fundamental RF $(h = 2)$: for acceleration of the beam
    - the second harmonic RF $(h = 4)$: for the bunch shape control by modifying the RF bucket.
  - Bucket distortion by the higher harmonic beam current is an issue

LLRF system (1)



Block diagram of RCS LLRF system

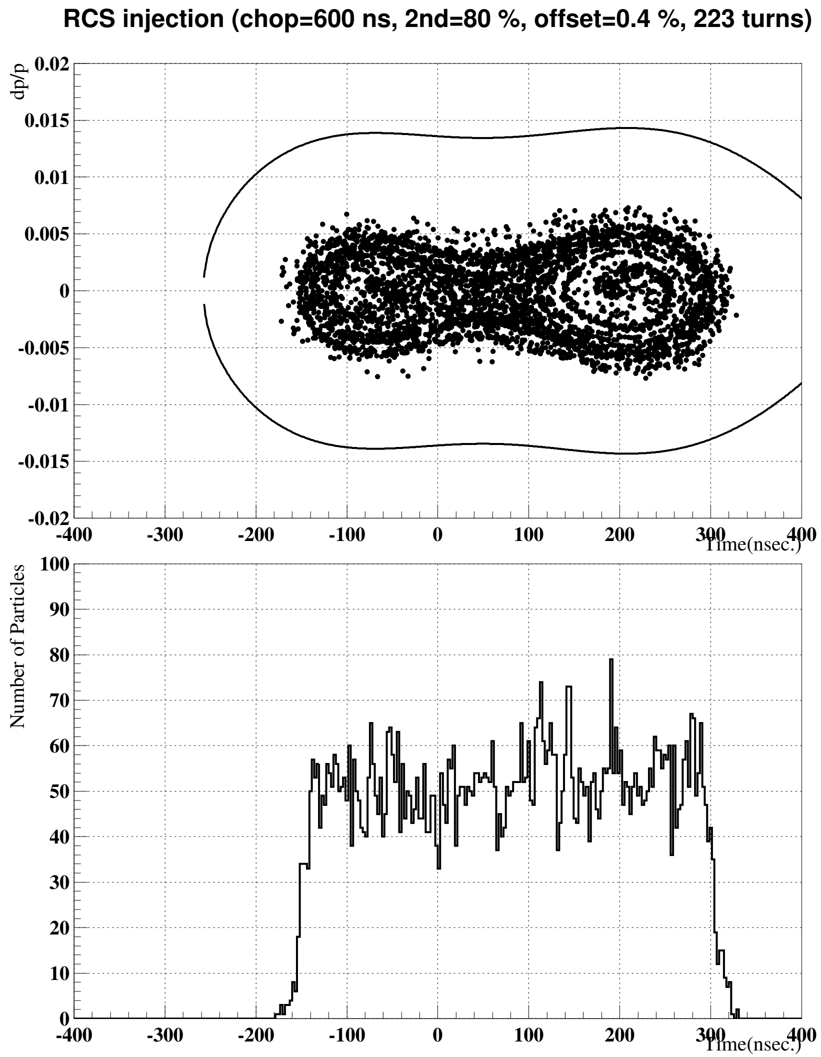
Blue: common for the whole system, Red: for each of the 12 cavities

LLRF system (2)

- LLRF functions:
  - the multi-harmonic RF generation $(h = 2, 4)$ for the acceleration and the longitudinal bunch shaping
  - the common feedbacks for stabilizing the beam
    * dual-harmonic AVC, cavity voltage control
    * phase FB (RF phase)
    * radial FB (frequency)
  - the beam feedforward for compensating the heavy beam loading
  - miscellaneous functions; synchronization, chopper timing
- The system is a full-digital system based on direct digital synthesis (DDS).
- RCS LLRF system is now under construction
  - to be completed in this fiscal year

Multi-harmonic RF generation (1)

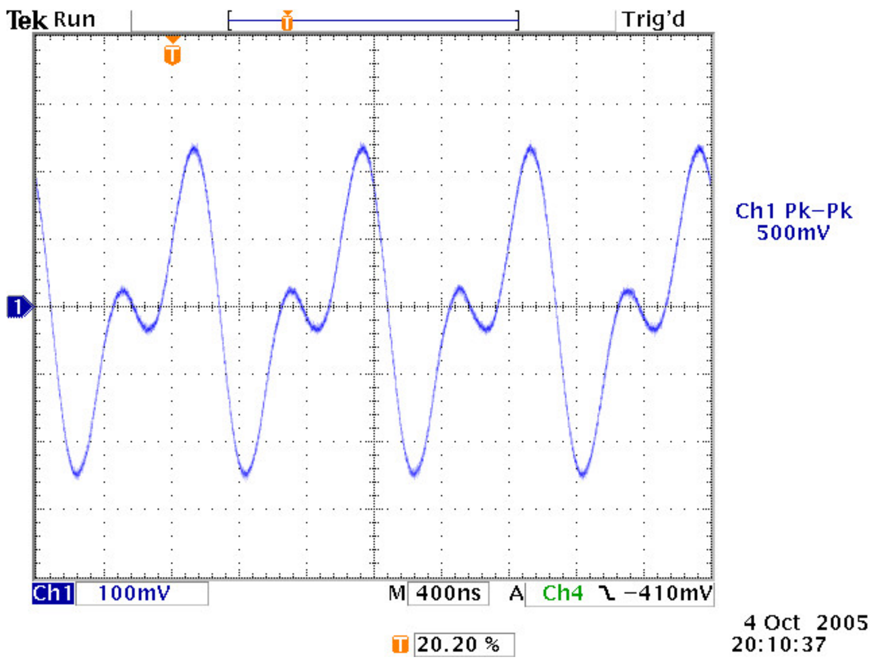
- A single cavity is driven by the superposition of $h = 2, 4$
- Flat bunches are to be generated by applying the second-harmonic voltage ($V_4/V_2 = 0.8$) and using the momentum-offset injection scheme.
- Reducing space-charge effects

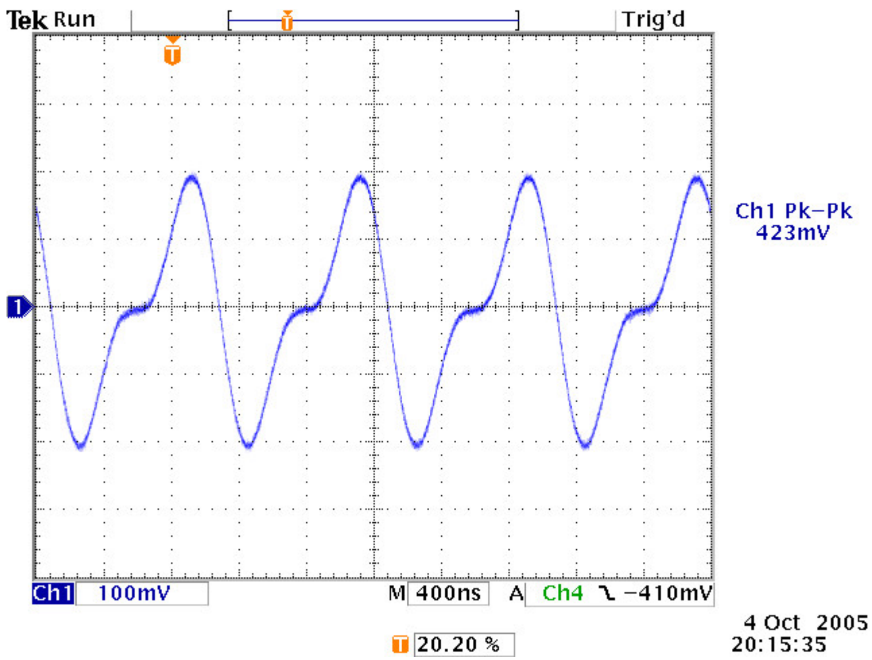


Simulated bunch shape after injection with the second harmonic RF

Multi-harmonic RF generation (2)

- The harmonic signals are generated by the DDS; they are easily synchronized.
- Each of $h = 2, 4$ has its own voltage control loop. Also the phases of both harmonics are individually controlled.

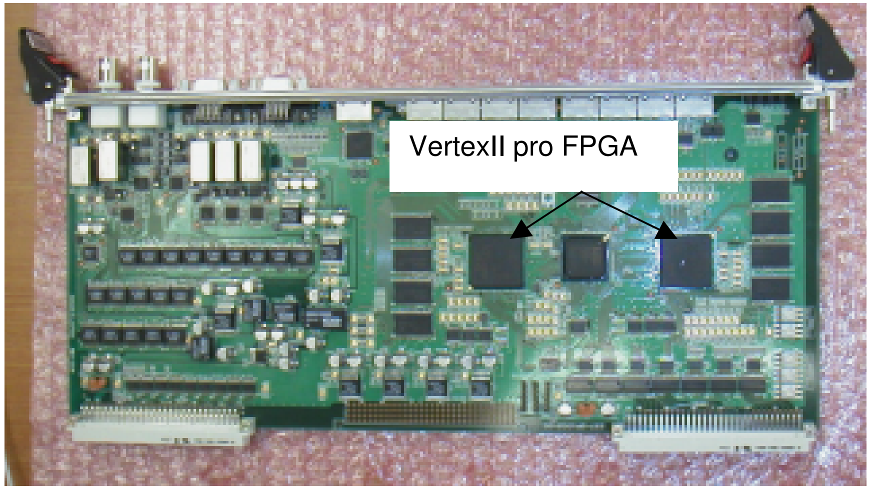


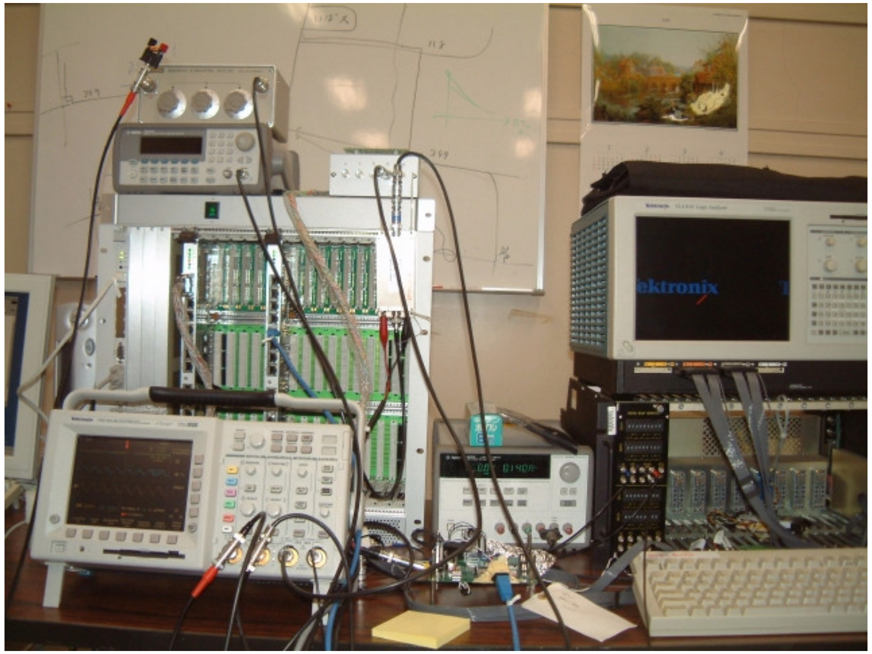


superposition of the harmonics generated by **"RFG" module**. $V_4/V_2 = 0.8$ *and* 0.5. *AVC is ON for both harmonics. phase control module is not implemented yet.*

Multi-harmonic RF generation (3)

SPG, RFG, the test setup at JAEA.

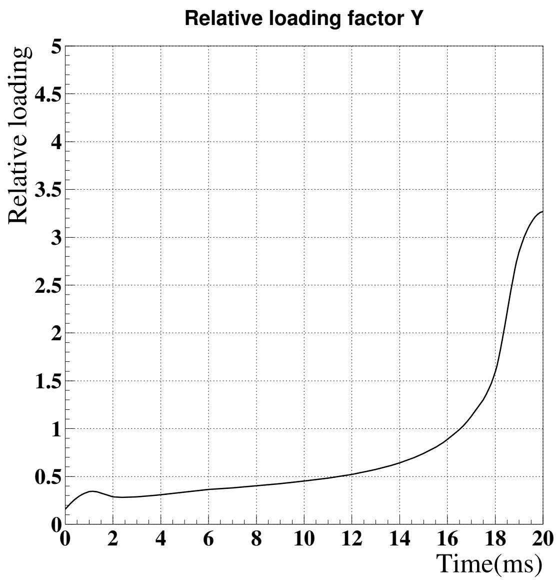


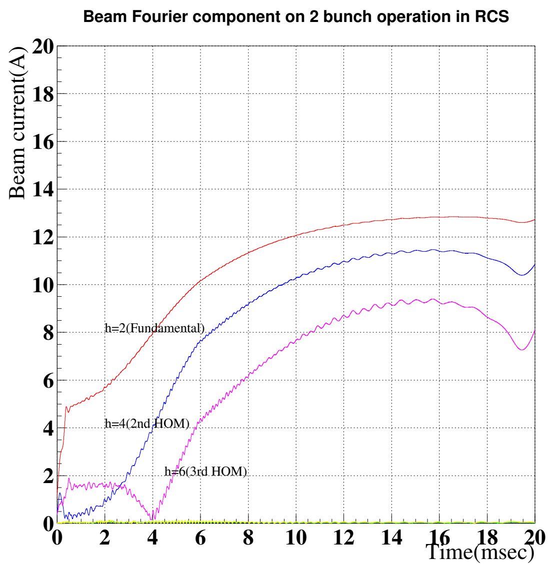


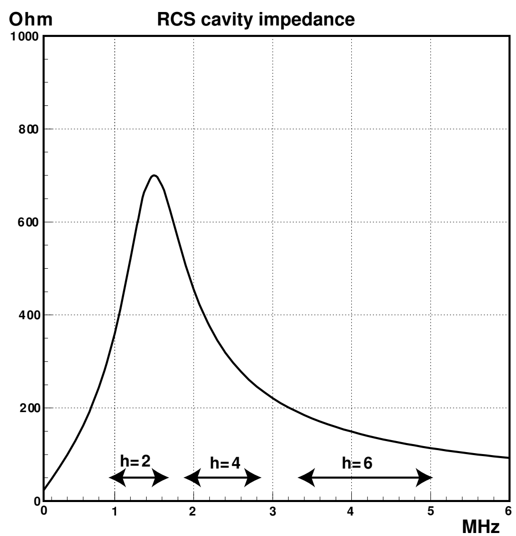
- high-performance arithmetic functions of FPGA are especially important for the realization of FIR filters which are necessary for the RF signal detection
- re-programmable feature makes the debugging more efficient

Beam loading compensation (1)

- Beam loading compensation is a key issue
  - high beam current
    - large relative loading factor Y (especially near extraction)
  - wide bandwidth ($Q = 2$) of the MA-loaded cavities
    - bucket distortion by the harmonic components of the beam



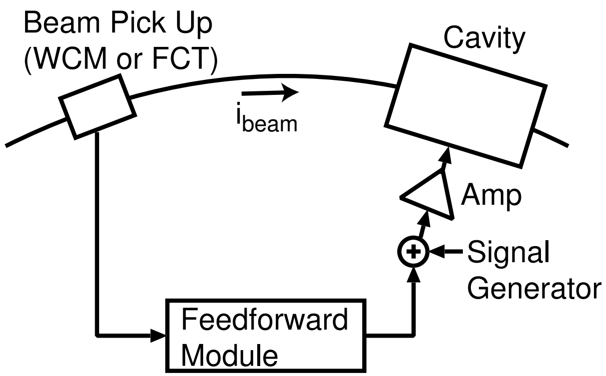




relative loading factor, harmonic components of beam current, and the frequency response of the cavity

Beam loading compensation (2)

- Beam feedforward method is used:
  - RF compensation signal is generated so that the final amplifier generates a current $(-i_{beam})$ which cancels the wake voltage by using WCM beam signals
  - the wake voltage consists of not only the fundamental accelerating RF component $(h = 2)$, but also the other harmonics $(h = 4, 6)$.
  - All of $h = 2, 4, 6$ wake voltages are to be compensated.
    - each harmonic component must be adjusted in amplitude and phase because of the frequency response of the system.



Summary

- In the J-PARC RCS, MA-loaded RF cavities are employed to achieve high accelerating gradient. The MA-loaded cavity has wide bandwidth (Q=2).
- The DDS-based full-digital LLRF control system is designed to accelerate the ultra-high proton beam current in the order of 10A. The common feedback loops are used; AVC, phase loop and radial loop. The RCS LLRF system is now under construction. The system will be completed in this fiscal year
- The multi-harmonic RF signals are fed into a single cavity for longitudinal bunch control.
- The beam feedforward method is employed for compensating the heavy beam loading.

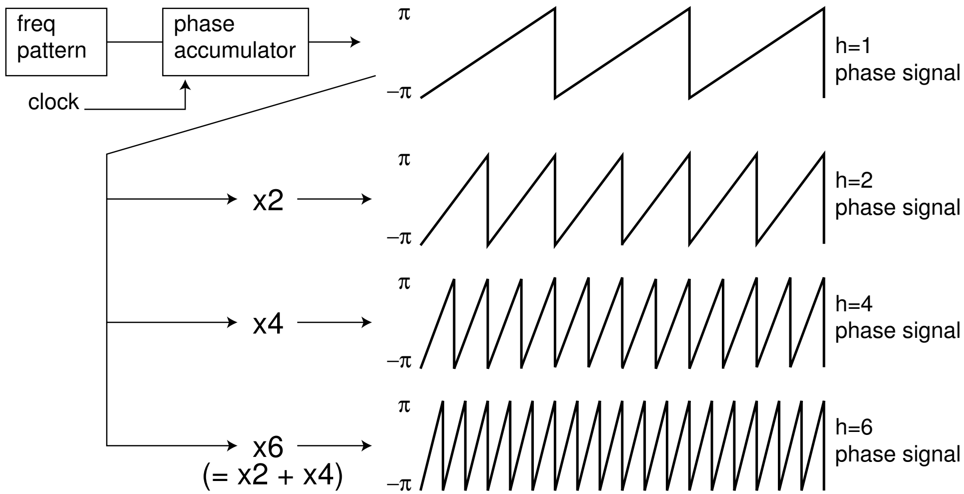
Appendix: system details

- the system clock is fixed; 36 MHz.
- huge computing power: one thousand of hardware multipliers are in the whole LLRF system.
  - many FIR filters for I/Q signal processing
  - modern FPGAs make the implementation possible

Appendix: DDS details

Multi-harmonic RF generation by DDS (Direct Digital Synthesis)

- multi-harmonic RF signal
  - for driving cavities
  - as reference for detecting signals (I/Q mod, etc.)
- the pattern generator gives a phase-increment at each clock cycle
- the phase accumulator generates a saw-tooth phase signal at the beam revolution frequency
- the phase signal is converted into sine-wave by coordinate transformer
- by basic arithmetic operation, higher harmonic phase signals are generated



advantages:

- no PLLs
- the harmonic signals are *perfectly* synchronized
- Realized in "SPG (main synthesizer)" and "RFG (RF generation board)"

Appendix: main feedback loops

- Common feedback loops are employed
  - auto voltage control (AVC) to follow the programmed voltages
    - for both $h = 2$ and $h = 4$.
    - each cavity has AVC
    - realized in RFG module
  - radial loop
    - controls the RF frequency referring the beam orbit
    - three beam position monitors (BPM) are used and the signals from the BPMs are averaged with proper weights
    - realized in FC board
  - phase loop is for damping the synchrotron oscillations
    - compares the beam phase picked up by fast current transformers (FCT) and the vector-sum of the RF voltage of the 12-cavities
    - realized for $(h = 2)$ and $(h = 4)$
    - dependency can be selected (who is master and who is slave)
    - realized in PFB board

Appendix: miscellaneous functions

- other miscellaneous functions : necessary to receive and send the beam to the other facilities in the J-PARC
  - Timing of the beam chopper in the linac is generated by the RCS RF system
  - synchronization of the beam in the RCS to the MR or the neutron choppers
- now under design

Appendix: AVC performance (1)

- preliminary tests of AVC loops performed
  - SPG and RFG modules
  - the low-level RF output is connected to the cavity voltage input with an external variable attenuator
  - RF frequency: 1 MHz
  - AVC has a PID controller with the gains of X_p, X_i, X_d for the proportional, integral and differential part, respectively.
- Figure 3 shows the step responses of the error signals with the stable condition
  - A stable condition: $X_p = 1$, $X_i = 0.12$, $X_d = 0$
  - the error signal goes to zero in 100 μsec
- Tests in more realistic situation are to be done

Appendix: AVC performance (2)

Figure 1: 9U VME chassis, SPG, RFG modules

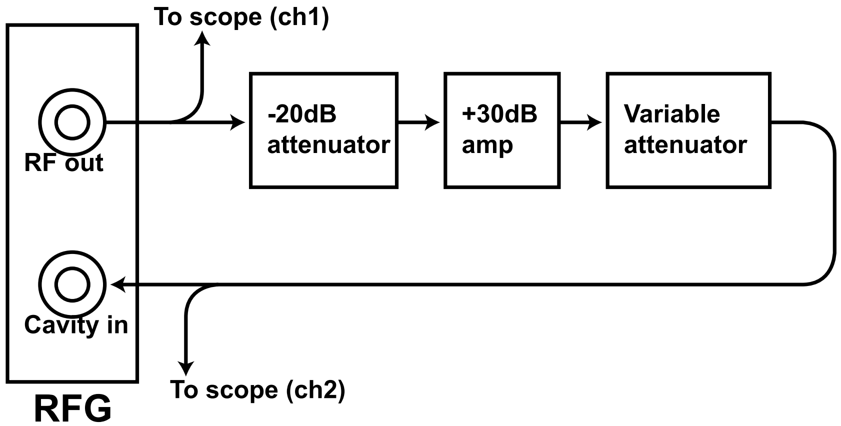
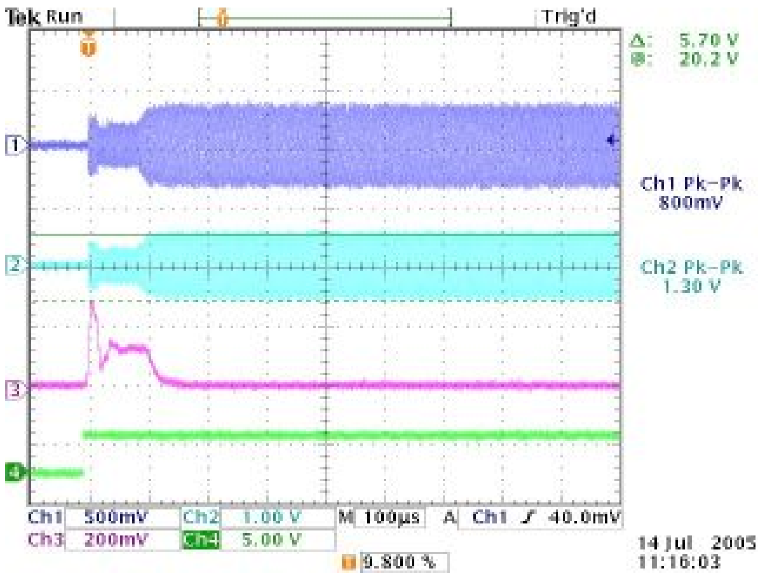


Figure 2: Test diagram

Appendix: AVC performance (3)

ch1: RF out, ch2: cavity in, ch3: error signal, ch4: trigger

t=0: amplitude step 0 to 8192



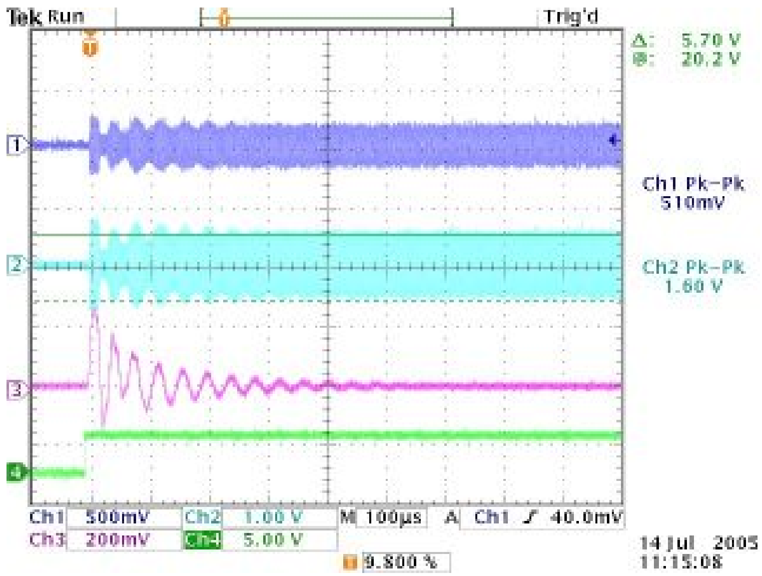


Figure 3: Stable condition: $X_p = 1$, $X_i = 0.12$, $X_d = 0$, external attenuator -6 dB, the error signal shows no ringing

Figure 4: Near instability. With external att. 0 dB, the error signal shows some ringing

Appendix: feedforward details

- modules:
  - BCA (beam current analysis) module properly selects the harmonic component of the beam signals picked up by the wall current monitor (WCM).
  - I/Q vectors of the selected harmonics are sent to the individual FFC (feedforward cavity driver) modules. Proper RF signals are generated by the FFC.
- we start with the feedforward method:
  - limited performance of FF
    - system drifts, etc.
  - cavity voltage FB method is also considered
    - replacement of AVC with "vector AVC"
  - we can handle separately AVC and FF. More simple.
  - FF and FB are not exclusive; we can have both. There are possibilies of extension of the system

Appendix: Abstract

The J-PARC Rapid cycling synchrotron (RCS) requires a very stable and precise low level RF (LLRF) control system to handle the ultra-high proton beam currents. The MA-loaded low-Q cavities for the RCS are driven by the superposition of the dual-harmonic RF signal for both the acceleration and the longitudinal bunch shaping. We employ a full-digital system based on direct digital synthesis (DDS). The multi-harmonic RF signals generated by the DDS are easily synchronized without PLLs. We describe the design and the structure of the LLRF blocks. The common feedback loops are used for the stabilizing the beam orbit and phase as well as the RF voltages of the cavity. The heavy beam loading effect is compensated by using the beam feedforward method. We also present the test results of the recently manufactured modules.