INTRODUCING THE MULTI-HARMONIC RF FEEDFORWARD IN THE J-PARC SYNCHROTRONS

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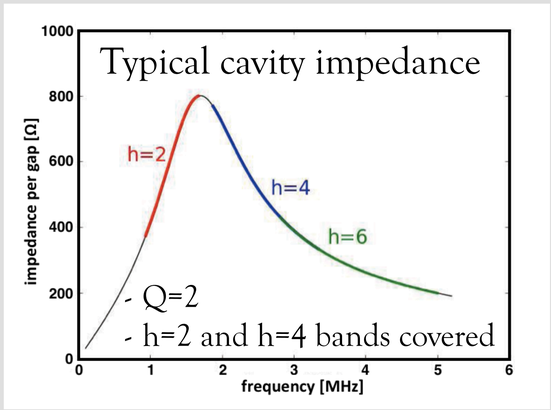
J-PARC is a MW-class proton accelerator facility, which consists of 181 MeV Linac, 3 GeV rapid cycling synchrotron (RCS) and 50 GeV Main Synchrotron (MR). 3 GeV RCS and 50 GeV MR are the first high intensity proton machines, which use the magnetic alloy loaded accelerating cavities instead of the conventional ferrite loaded rf systems. Magnetic alloy is a low-Q material. However, the μQf-product of the material is high enough to realize the required electrical field gradient (>20kV/m). The R/Q of the cavity becomes large. The beam loading compensation is an essential issue. In the J-PARC RF systems, the full digital low-level control is employed to realize a stable and reproducible operation supported by a feed-forward beam loading compensation scheme indispensable for high beam intensity. Especially in RCS, the Q-value of the cavity is set to 2, which can cover both the accelerating frequency range (h=2) and the second harmonic (h=4) for bunch shape manipulation. RCS RF systems are operated with a dual harmonic by superposing the RF signals. In JFY2010, we completed the multi-harmonic RF feedforward for all 11 RCS systems. The feedforward patterns of all 11 systems have been optimized by using a 300 kW equivalent proton beam. About 30 dB suppression of the impedance seen by the beam is achieved. The trial in compensating heavy beam loading by using a multi-harmonic RF feedforward proved successful.

Introduction:

Wide-band magnetic alloy cavities used in the J-PARC RCS.

- high accelerating field gradient >20 kV/m achieved (Max. 400 kV with 11 cavities)
- cavity impedance covers frequency sweep (0.938 - 1.671 MHz) and second harmonic frequency for bunch shaping.
- the cavity is a "passive load", no tuning loop provided



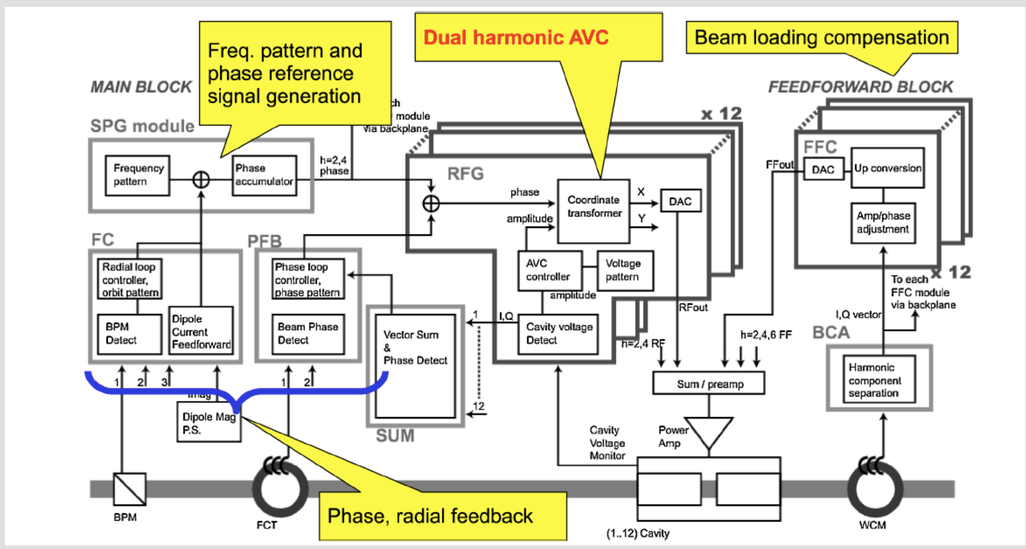
400 kW beam operation achieved in RCS

- alleviating space charge effects and compensation of beam loading are indispensable

➡ We developed a Multi-harmonic RF feedforward system.

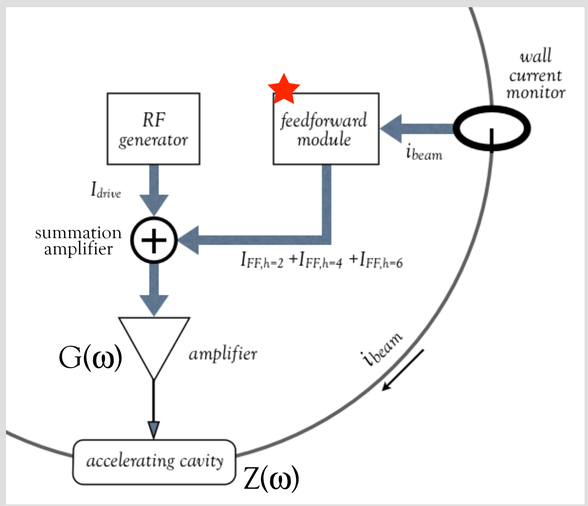
DDS based full digital LLRF control system employed

- best-match with MA loaded cavity
- reliability and reproducibility realized



Multi-harmonic RF feedforward:

- ✦ The feedforward module analyzes the harmonic components of beam current by using I/Q modulation technique.
- ✦ I/Q modulation signal for each harmonic contains the gain and phase.
- ✦ The gain and phase are adjusted so that the wake voltage of each harmonics is cancelled.
- ✦ Finally, the module generates the compensation signals for 11 cavities.
- ✦ The feedforward signal is sent to the summation amplifier and summed with the LLRF driving signal.



$G(\omega)\cdot(I_{FF,h=2}+I_{FF,h=4}+I_{FF,h=6}) \approx -i_{beam}$

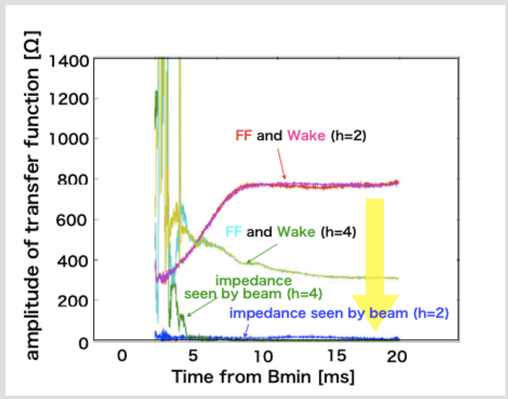
The wake voltage:

$V_{cav.wake}(\omega) = Z(\omega)\cdot i_{beam}$

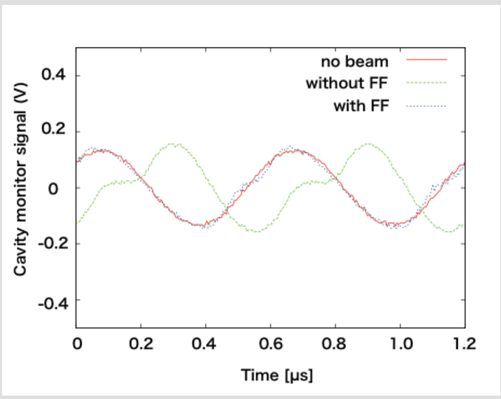
The accelerating voltage:

$V_{cav.acc}(\omega) = G(\omega)\cdot Z(\omega)\cdot I_{drive}$

RCS beam commissioning :



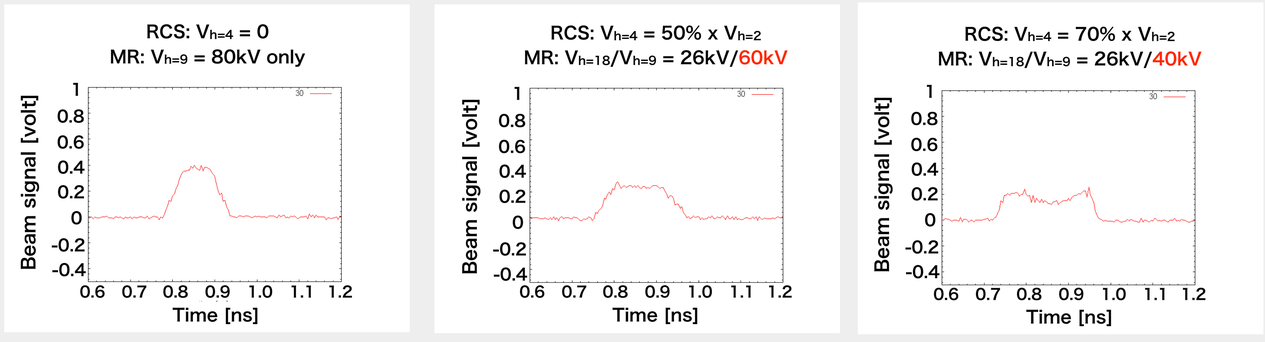
Comparison of the feedforward transfer function and the impedance seen by the beam, in the case of with and without feedforward. The impedance seen by the beam is kept less than 25Ω during the whole acceleration period.



Comparison of the cavity voltage monitor waveforms just before extraction, in the case of no beam, without feedforward and with feedforward. The beam intensity is 300 kW equivalent. The waveform distortion and delay are reduced with feedforward.

Since October 2010, the feedforward is used in routine operation.

MR beam commissioning:



Mountain views and Bunch shapes at the MR injection

- MR requires a flat bunch to alleviate space charge effects of high intensity proton beam.
- by adding 2nd harmonic voltage near RCS extraction, bunch can be flattened
- preliminary beam studies with MR end harmonic cavity started from last year
- bunching factor was improved by 70%.

See also: F. Tamura, et al.: "Multi-harmonic rf feedforward system for beam loading compensation in wide-band cavities of a rapid cycling synchrotron", Phys. Rev. ST Accel. Beams, 14, 051004 (2011).

Conclusions:

- ✦ The multi-harmonic RF feedforward loading compensation was implemented in all 11 RCS RF systems.
- ✦ Commissioning of the multi-harmonic feedforward system in RCS was carried out with 300 kW-equivalent beam.
- ✦ The commissioning was successful and the impedance seen by the beam can be reduced by 30 dB.
- ✦ From October 2010, the feedforward is used in normal beam operation.
- ✦ Thanks to the multi-harmonic feedforward, the bunch shape manipulation in MR works properly.
- ✦ The performance of the multi-harmonic feedforward is promising for the achievement of the design beam power, 1 MW in RCS.