ICALEPCS09, 2009/10/15

STABILIZATION OF BEAM EXTRACTION TIMING IN J-PARC RCS

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Overview

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  - timing requirements
- Stabilization of beam extraction timing
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- Summary and outlook

Introduction

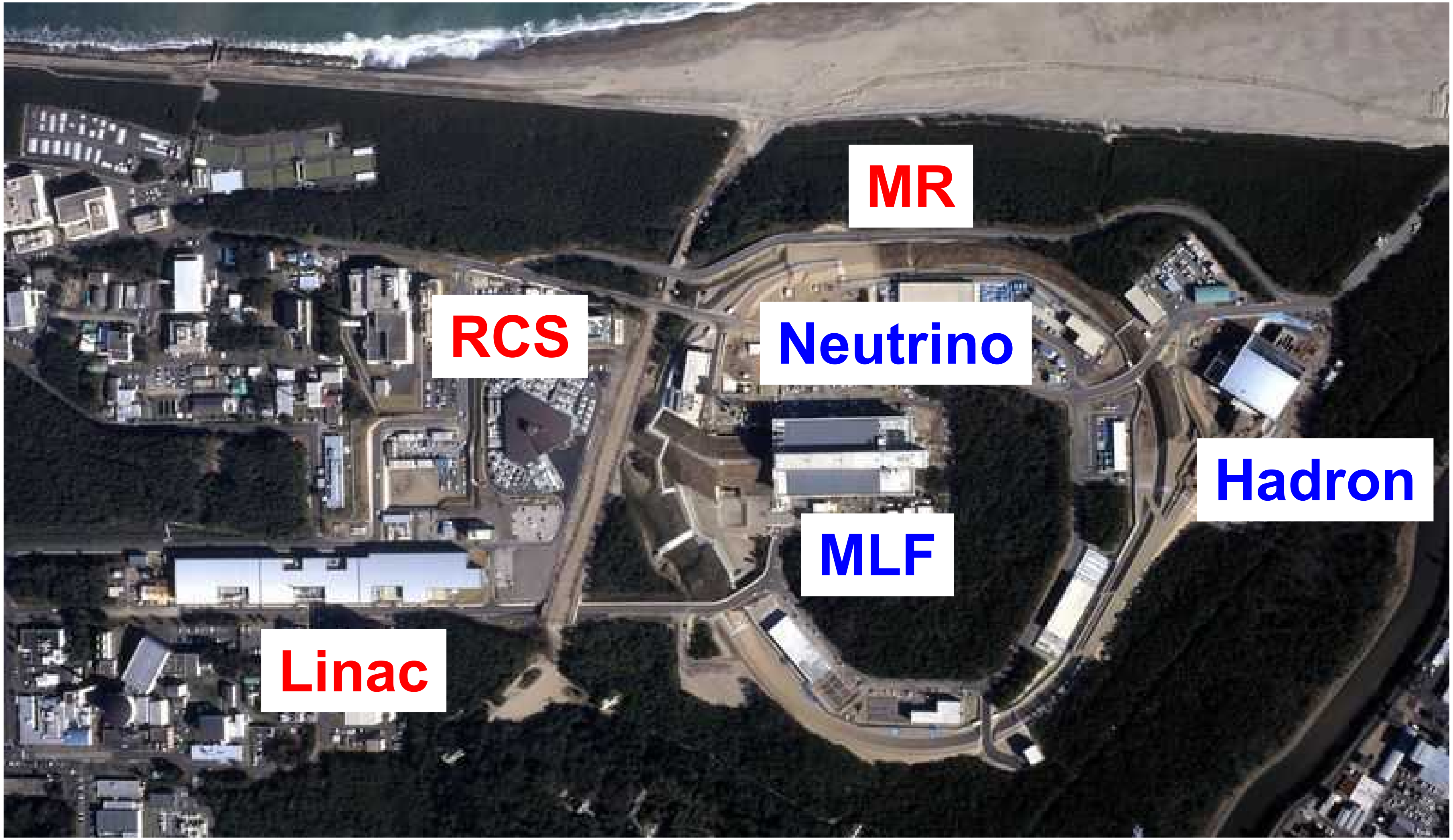


Fig. 1: The beams from the RCS are delivered to the MLF (materials and life science facility) and MR. Typically 4 pulses to MR, 87 pulses to MLF.

RCS parameters

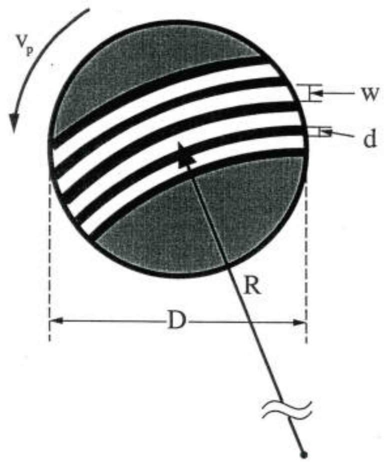
Table 1: Parameters of the J-PARC RCS.

circumference	348.333 m
energy	0.181–3 GeV
accelerating frequency	0.938–1.671 MHz
harmonic number	2
repetition	25 Hz
cavity Q-value	2

Timing requirement: MLF

Fermi chopper spectrometer: a key of MLF

- A fast rotating iron, 500 Hz to 1 kHz
- Chopper and proton beam must be synchronized within 300 ns
  - high resolution / efficient use of neutrons



- Large inertial moment, difficult to change quickly the rotating phase

→ Rotating speed fixed, extracted beam timing must be very stable and must have low jitters

Timing requirement: MR

- Bucket-to-bucket transfer
  - MR: $h = 9$, RCS: $h = 2$
  - To fill the 8 RF buckets in 9 buckets, 4 RCS cycles are used
  - Injection period: over 120 ms
- Must be injected into the proper RF buckets
- A precise phase control is required to avoid the dipole oscillation in the MR

Timing requirement

For both of MLF and MR, very stable beam timing is necessary

Common sense?

- Accelerators should be synchronized to the AC power line for stable operations
- Without strong RF feedback loops, the proton acceleration in a synchrotron is impossible

$\longrightarrow$ the beam timing is under the influence of both

AC line: 0.1% frequency variation

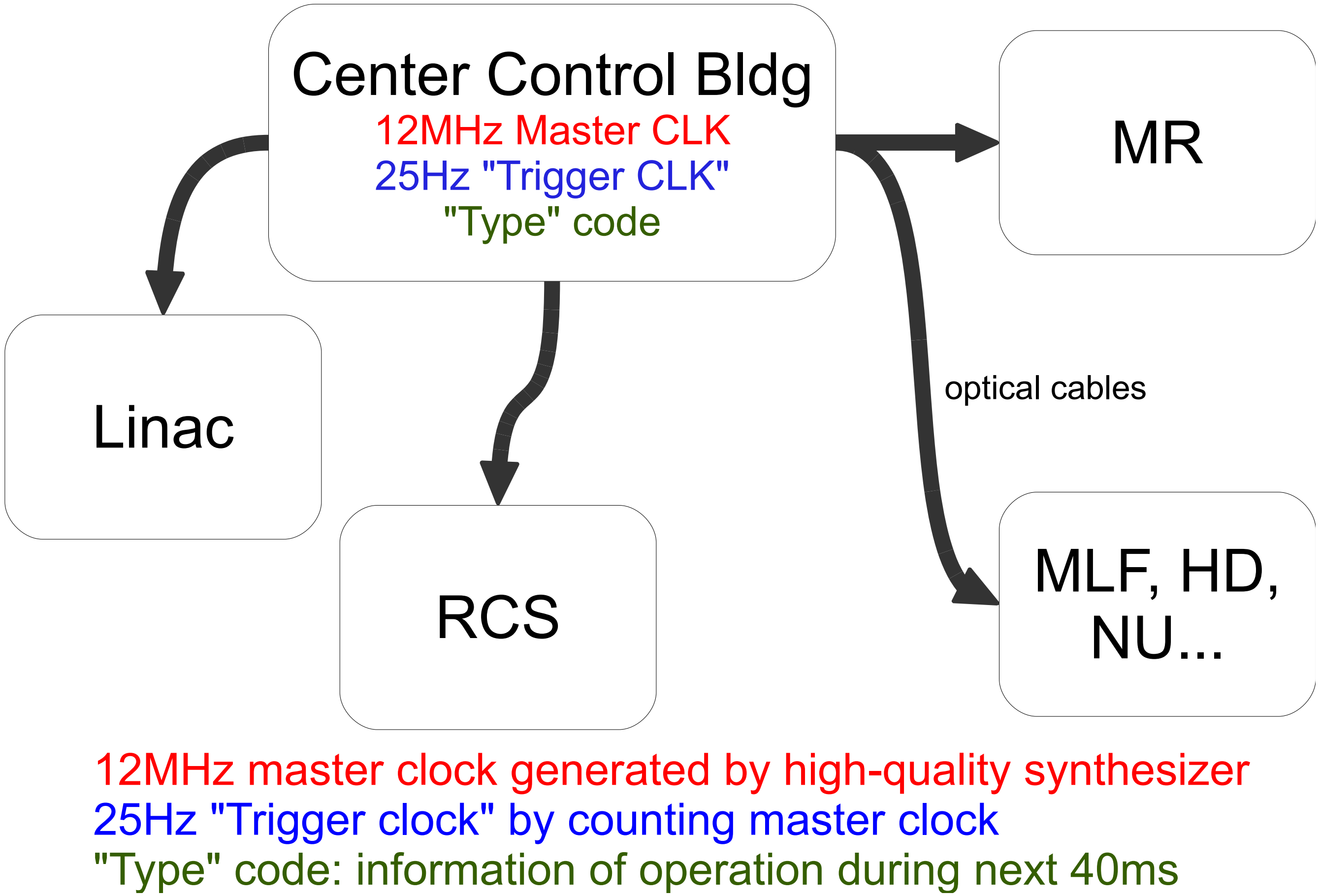
KEK PS-booster: beam timing accuracy is $\sim 10\mu$s

In J-PARC case:

- Non-AC-line-synchronized timing system is employed. The accelerators are operated without synchronization to the AC power line
- Radial feedback loop is not necessary to accelerate the proton beam in the J-PARC RCS, thanks to the magnetic alloy cavity, the digital LLRF, stable B-field

$\longrightarrow$ the beam timing is very stable!

Non-AC-line-synchronized timing system



- CCB to all J-PARC accelerator bldg via fan-outs and optical cables, star configuration

Non-AC-line-synchronized timing system

- Master clock: also used as reference of system clocks of digital systems, such as the digital LLRF control systems of the synchrotrons
- Trigger: defined by a delay from trig clk

Overall trigger jitter: several hundred ps

Power supply stability

Question: Power supplies operated with non-AC-line-synchronized timing is stable?

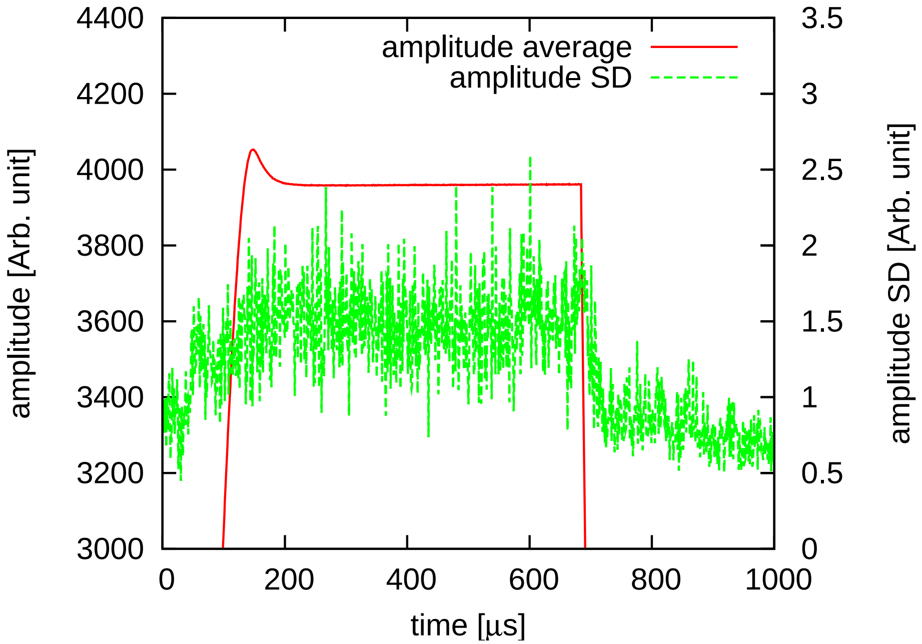
- Synchrotrons: switching power supplies, not affected by the AC line
- Klystron DC power supplies (linac) may get influence
  - Amplitude/phase variations of linac RF: output energy fluctuation

Linac RF stability

- RF feedback system for the compensation of the voltage sag and long-term drift of the klystron DC power supply
- With FB: amplitude/phase controlled in $\pm 1\%$ and ± 1 [deg] (meets requirements)
  - without FB: $\pm 5\%$ and ± 15 [deg]
- Cycle-to-cycle variations: also kept small

Linac RF stability

- SD of amplitude/phase: less than 2 [Arb. unit] / 0.05 [deg] (over 20 RF pulses)



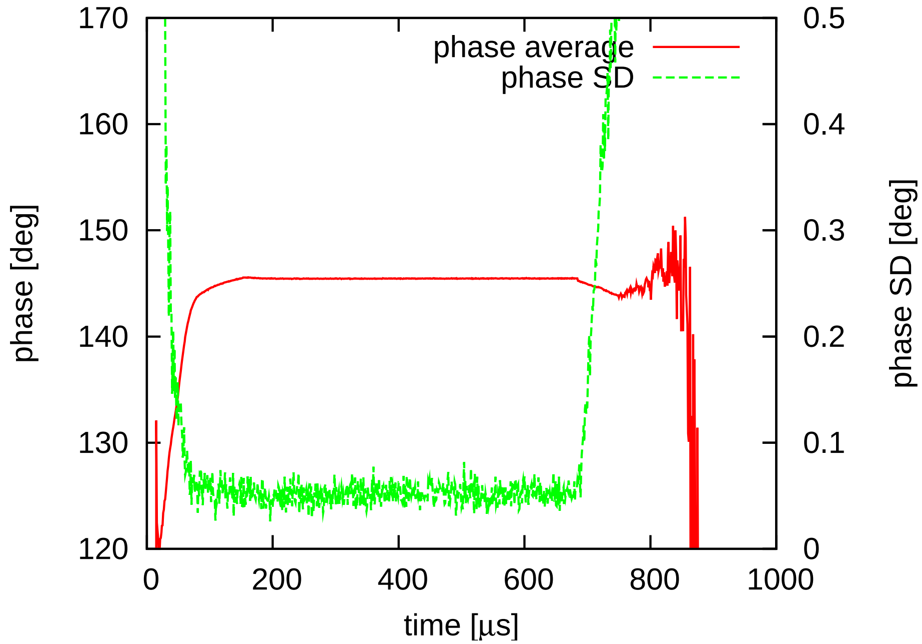


Fig. 2: Amplitude and phase variations over 20 RF pulses. Red: average, green: standard deviation.

Variation of the linac beam energy: ±0.01%

Magnetic Alloy (MA) cavity

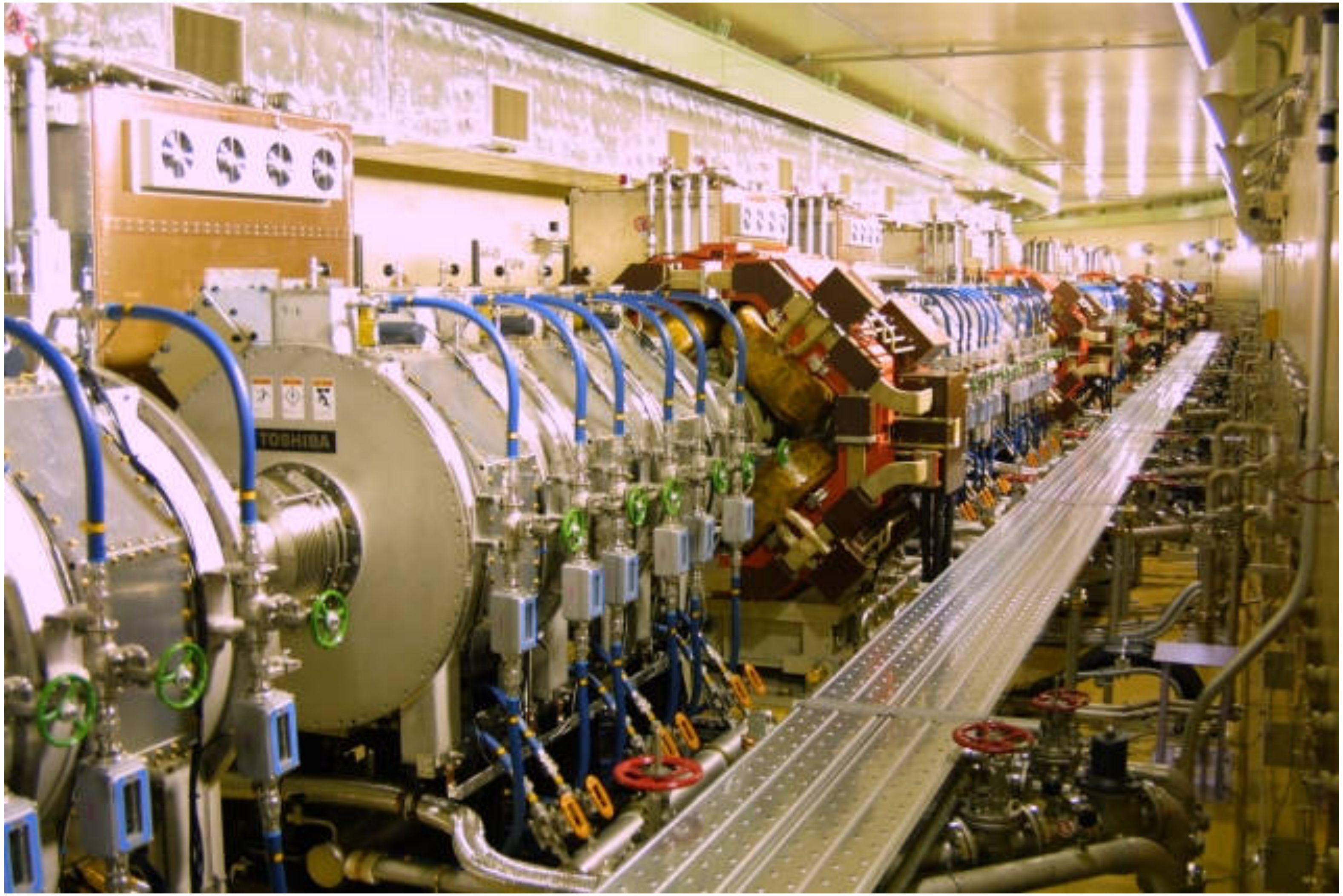


Fig. 3: RCS RF system

Magnetic Alloy (MA) cavity

- Twice high Acc. field to ferrite cavity
- Wide-band ($Q = 2$): no tuning control necessary to cover frequency sweep: treated as a passive device
- Response is predictable and reproducible
- Simple Low-level RF (LLRF) control

Digital Low-level RF (LLRF) control

- Full-digital LLRF based on DDS (direct digital synthesis)
  - $\mathbf{10^{-7}}$ frequency resolution, stable, reproducible
  - Analog VCO: only $\mathbf{10^{-4}}$

No radial feedback loop necessary with MA cavity, digital LLRF, stable B-field

Stable beam timing possible

Beam stability measurement

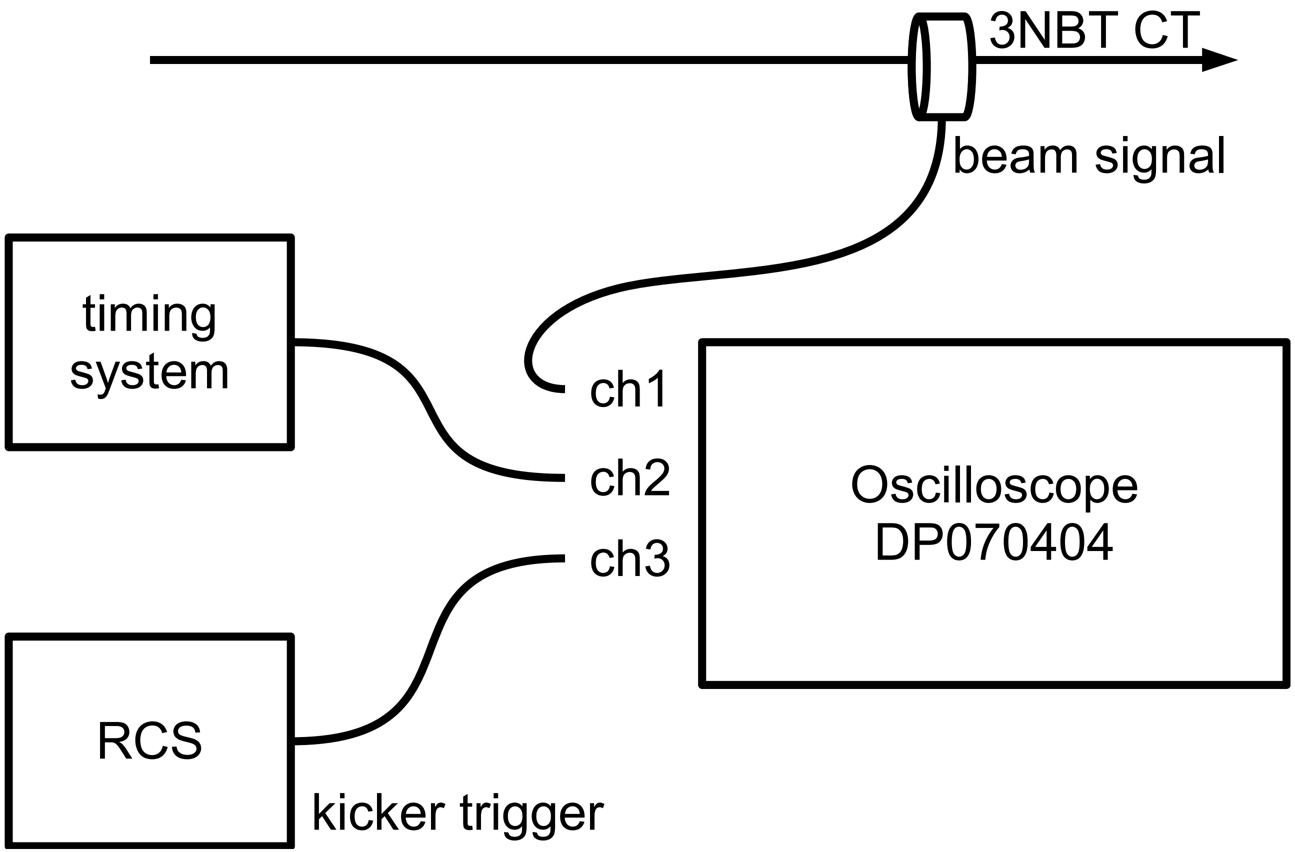


Fig. 4: Beam stability measurement setup.

Delay from trigger to beam was measured

Beam stability measurement

Table 2: Beam parameters.

repetition	25 Hz
macro pulse width	100 μs
linac peak current	5 mA
chopping width	560 ns
number of bunch	2
beam power	18 kW

Beam stability measurement

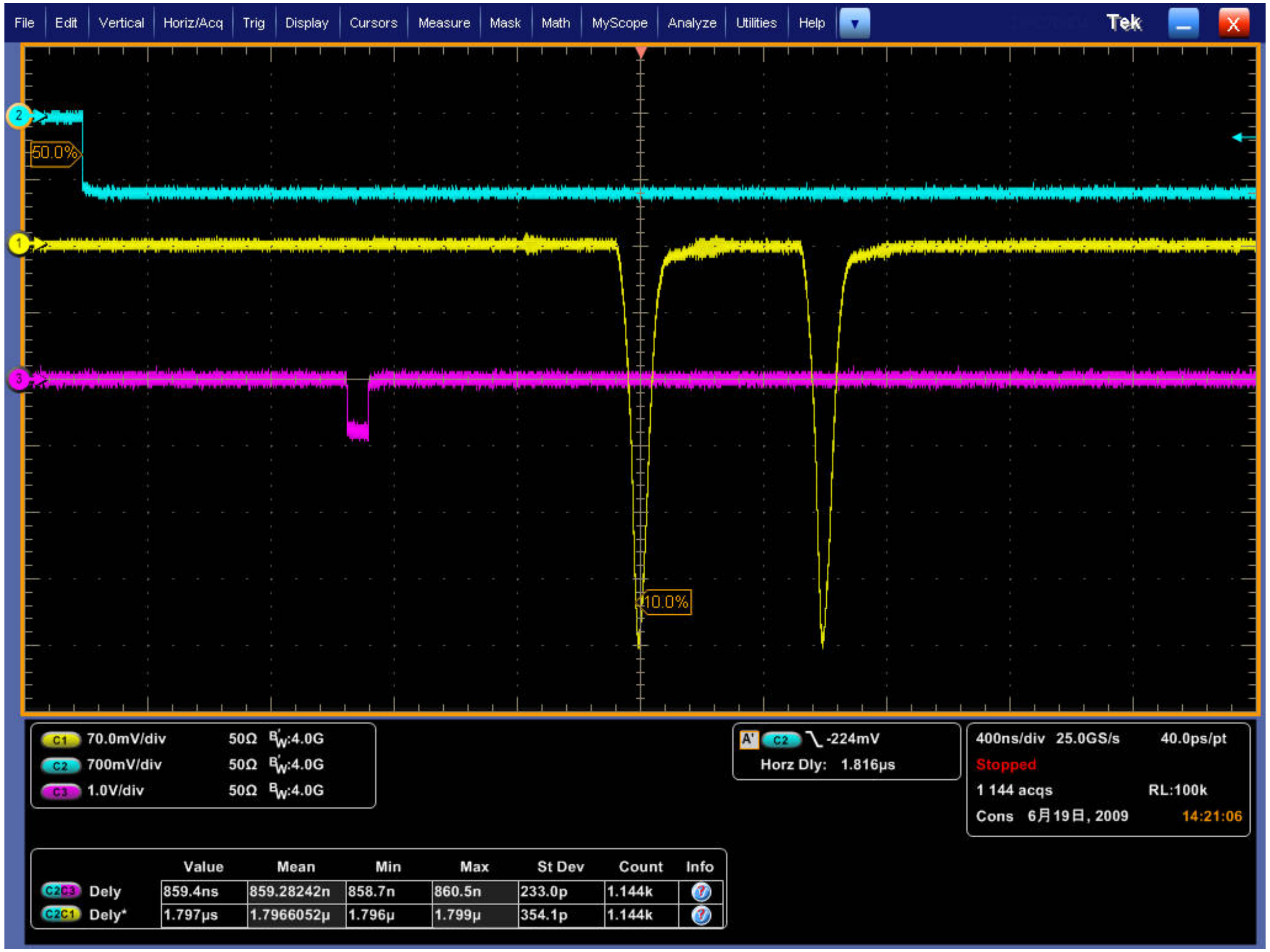


Fig. 5: Measured beam signals. Ch.2 (blue): the trigger signal, Ch.1 (yellow): the beam signal, Ch.3 (pink): the kicker trigger signal.

Beam stability measurement

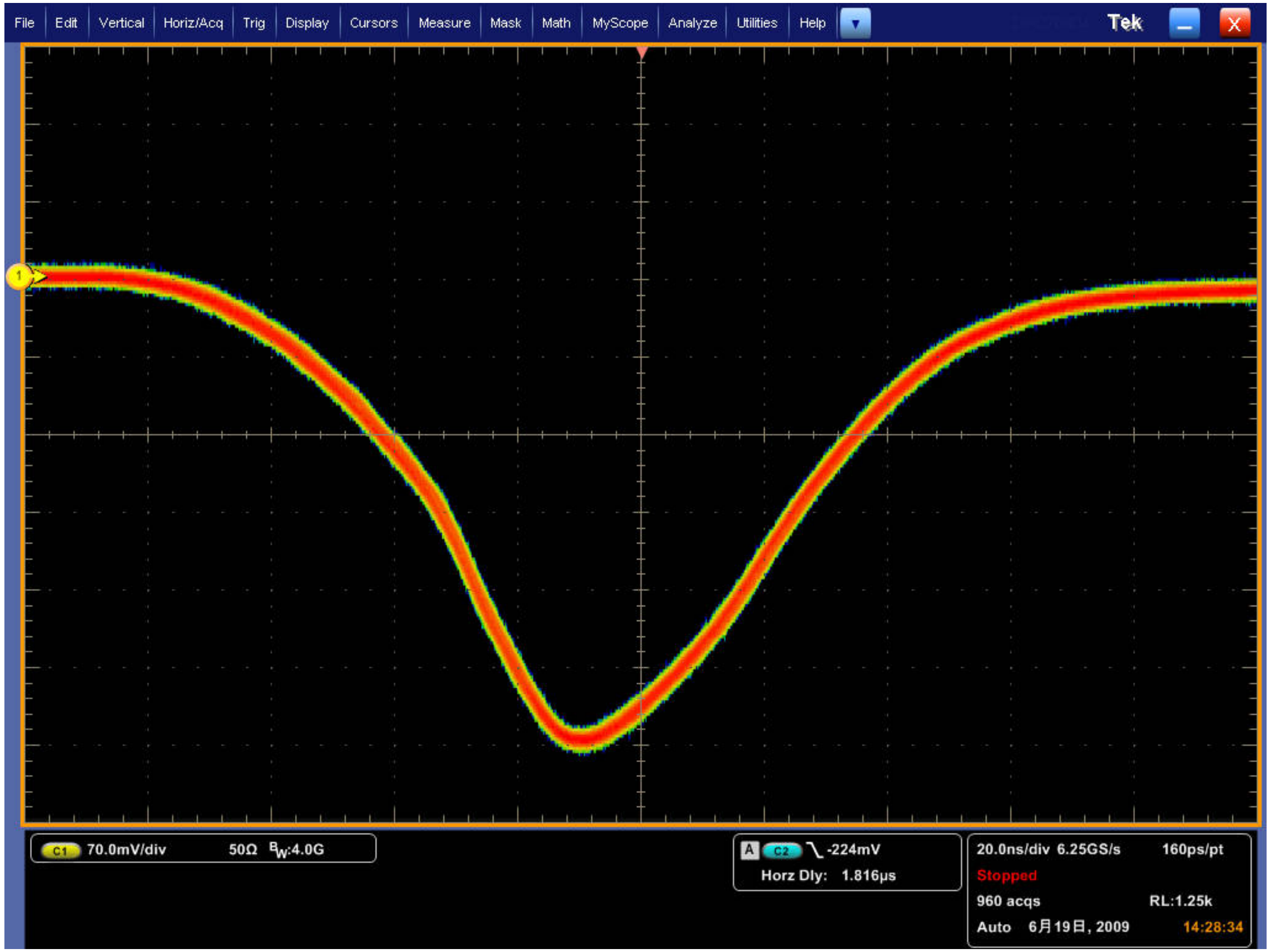


Fig. 6: Magnified view of the beam signal (the first peak) with an infinite persistence.

Beam stability measurement

Table 3: Measurement results of 1144 beam pulses.

	mean	max	min	St. Dev.
Beam	1.797 μs	1.796 μs	1.799 μs	354 ps
Kicker Trig.	859.3 ns	858.7 ns	860.5 ns	233 ps

Extremely low jitter!

Multi-batch injection to MR

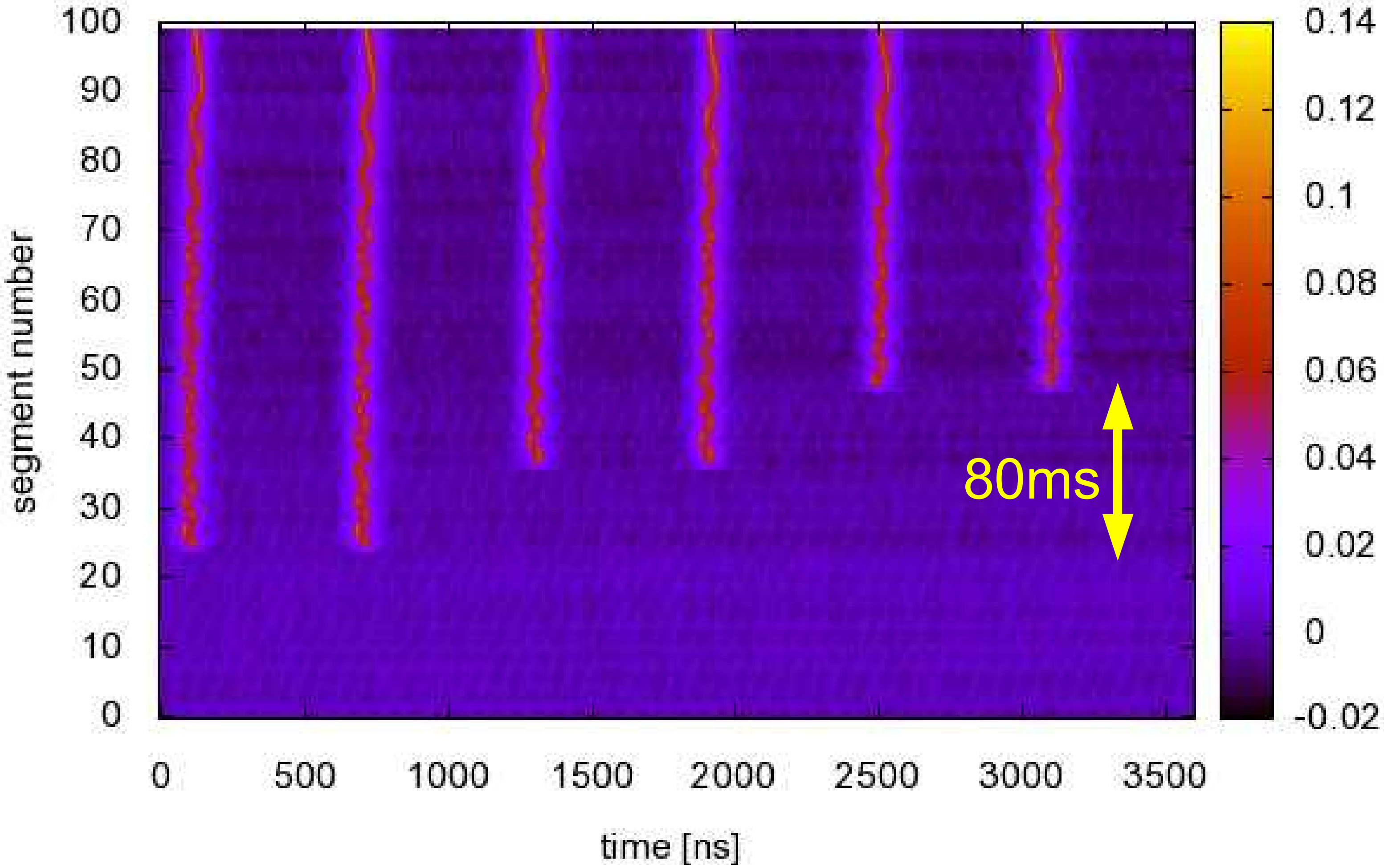


Fig. 7: Three batches are injected without synchronization (only bucket selection)

Summary and outlook

- Beam jitter less than 1 ns is achieved
  - Non-AC-line-synchronized timing
  - Wide-band MA cavity
  - Digital LLRF control based on DDS
- For high intensity, phase FB is necessary
  - beam phase is affected
  - should be still reproducible
  - beam loading compensation, synchronization system are prepared