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DEVELOPMENT OF MULTI-CHANNEL TIME-DIVISION MULTIPLEXING RF SIGNAL CONDITIONING FRONT-END FOR CAfe2 BPM SYSTEM

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Abstract

The construction of the China Accelerator Facility for Superheavy Elements (CAFe2) is advancing, building upon the foundation of the Chinese ADS Front-end Demo Linac (CAFe). However, the existing BPM read-out electronics from CAFe are insufficient to accommodate the increased number of BPM probes required for CAFe2 and cannot meet the measurement demands for low-intensity heavy ion beams. To address these issues, a high-speed RF switch array was developed, featuring multi-channel multiplexing, tunable gain and filtering, and web-based parameter configuration. This device functions as a front-end for RF signal conditioning, offering microsecond-level channel switching capabilities, and is capable of receiving, filtering, and amplifying multiple beam signals. When integrated with the existing RF front-end and digital signal processing platform, the new BPM read-out electronics system can support simultaneous measurement of 32 signals from 8 BPM probes. Test results indicate that the high-speed RF switch array achieves channel isolation exceeding 60 dB, with phase differences between channels less than 6° and amplitude discrepancies under 4%. These results demonstrate excellent amplitude-phase consistency and channel isolation performance, fully meeting the BPM measurement requirements of CAFe2.

INTRODUCTION

CAFe2 is designed to provide an advanced experimental platform for the synthesis of superheavy elements [1]. To ensure the provision of highly stable, low-energy spread beams, precise beam trajectory measurements are required, necessitating a sufficient number of BPM systems. According to the design, the Medium Energy Beam Line and Cryogenic Modules (CM1–CM4) of CAFe2 are equipped with 24 BPM probes along the beamline, with a required beam current of 10pμA. However, expanding the system using the existing approach would result in high costs and complex structures, and cumulative device errors could lead to inconsistencies in the input-output response curves of each channel, ultimately degrading the overall BPM system performance [2]. Moreover, the existing system can only measure beam currents down to 10 mA, which is inadequate for low-intensity beams.

Therefore, an upgrade to the existing CAFe BPM read-out electronics is needed. This paper proposes a high-speed RF switch array as a front-end for RF signal conditioning. This solution increases the number of accessible signal channels without altering the existing hardware structure, enabling the CAFe2 BPM system to achieve multi-channel time-division multiplexing measurements of low-intensity heavy ion beams across varying beam currents.

DESIGN SCHEME FOR HIGH-SPEED RF SWITCH ARRAY

The high-speed RF switch array consists of four modules: high-speed switching, tunable filtering, tunable gain, and logic control, as shown in Fig. 1. RF IN 1 to RF IN 8 correspond to 8 selectable switch paths, each with 4 inputs (*X, Y, X', Y'*), supporting 32 signals from 8 BPM probes. The tunable filter selects different center frequencies, and the gain module adjusts levels. The logic control module manages signal interfaces, triggering switch control (FPGA SW CTL) for switching, filtering, and gain adjustment. Web-based configuration allows remote management and real-time parameter updates during measurements.

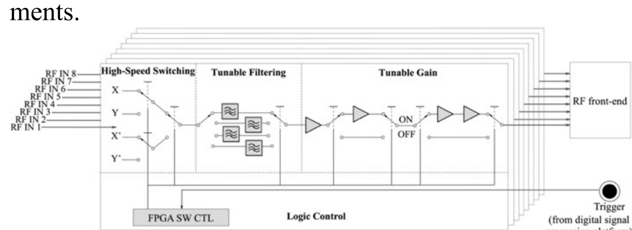

Figure 1: Schematic diagram of the high-speed RF switch array.

High-speed Switching Module

The high-speed switching module consists of three cascaded dual-channel SPDT switches (HMC199AMS8, Analog Devices, Inc.). The outputs of the first two switches connect to the inputs of the third, forming a four-channel selectable switch path. The module contains eight such paths, each independently controllable, and supports two operation modes. In fixed-channel mode, each switch remains on a specific path, functioning as a fixed 8-channel system. In automatic switching mode, the cycle for switching among four signals is configurable on a microsecond scale, with the logic control module managing switch states. This enables high-speed switching among four signals on a single channel, allowing multiple beam signals to be processed by one module, achieving multi-channel time-division multiplexing across the entire RF switch array.

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As shown in Fig. 2, the introduction of the RF switch array, leveraging the multi-channel time-division multiplexing function of the high-speed switching module, expands the measurement capacity of a single CAFe2 readout system to 32 channels, supporting simultaneous measurement of up to 8 BPM probes.

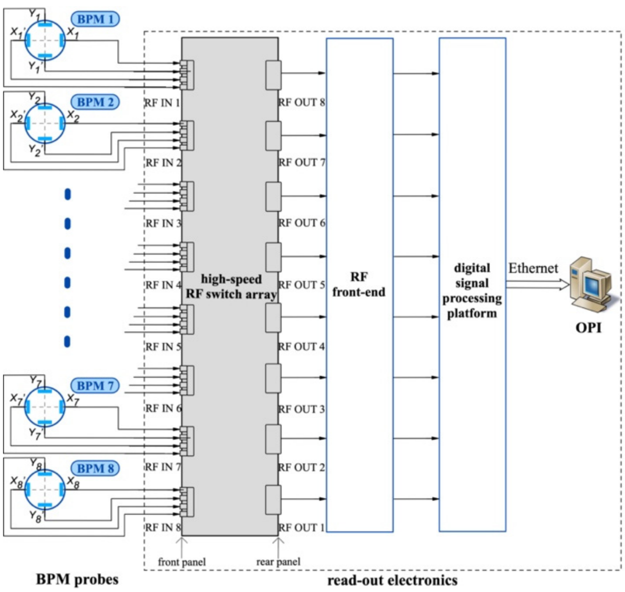

Figure 2: Simplified diagram of BPM system architecture after introducing the high-speed RF switch array.

Tunable Filtering Module

The signal spectrum output by the CAFe2 BPM probes is broad, containing multiple harmonics, including the operating frequency of 162.5 MHz. These additional frequency components can interfere with beam signal measurements, necessitating signal filtering to condition the high-amplitude, wide-band signals into a measurable form. As shown in Fig. 3, a bandpass filter is used to extract a signal with a center frequency of 162.5 MHz and a bandwidth of 20 MHz, representing the beam information of CAFe2. To prevent signal aliasing effectively, a high-performance anti-aliasing SAW filter (B39162B9482P810, TDK) is selected as the bandpass filter. SAW filters feature a narrow passband and high out-of-band rejection, allowing them to preserve the desired signal while significantly suppressing other harmonics introduced by nonlinear components such as RF amplifiers.

The BPM read-out electronics equipped with the high-speed RF switch array are not only implemented in CAFe2 but are also planned for deployment in the China initiative Accelerator Driven System (CiADS) [3]. Given the differing operating frequencies of these accelerators, a tunable filter module is designed in addition to filtering out frequency components outside the (162.5 ± 10) MHz range. Each filter channel contains SAW filters with varying center frequencies, which are selected via the FPGA SW CTL signal generated by the logic control module. This ensures that signals with different center frequencies can be extracted, accommodating both the 162.5 MHz operating frequency of CAFe2 and the 81.25/325/650 MHz frequencies required by CiADS.

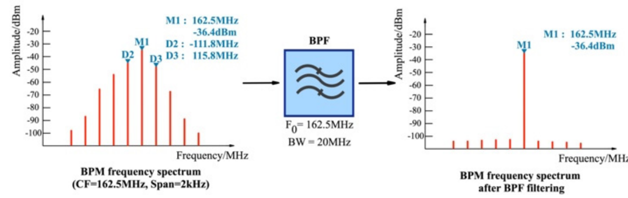

Figure 3: Schematic diagram of beam signal extraction.

Tunable Gain Module

CAFe2 accelerates a variety of heavy ions (e.g. $^{51}V^{17+}$, $^{54}Cr^{18+}$), each corresponding to different beam intensities. The existing BPM read-out electronics, with fixed gain, cannot accommodate the varying amplification needs across different beam intensities. Therefore, a tunable gain module based on a cascaded Low Noise Amplifier (LNA) design was developed. This module features a cascaded structure consisting of four single-pole double-throw (SPDT) switches and four LNAs. The signal generated by the logic control module uniformly controls the four SPDT switches, allowing selection of different gain settings.

To cover a broad signal input range and avoid overload from exceeding the ADC range, a step-size gain adjustment of 23 dB was chosen. As shown in Fig. 4, this design provides a signal input range from 1 µA to 41 mA, with gain settings of 11 dB, 34 dB, 57 dB, and 80 dB. This allows for selection of the appropriate gain setting based on the beam intensity range.

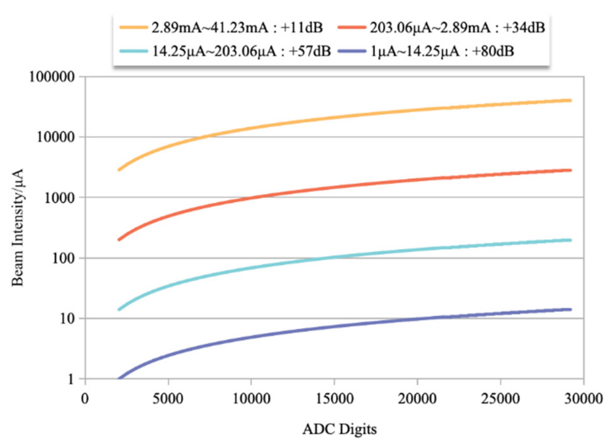

Figure 4: Schematic diagram of the gain cascade scheme.

SYSTEM TEST AND VERIFICATION

Performance Test

As a multi-channel system, the high-speed RF switch array requires performance testing to ensure accuracy in subsequent BPM measurements. Signal crosstalk between channels or discrepancies in phase and gain can negatively impact measurement precision.

The isolation test evaluates signal shielding between channels [4]: A 162.5 MHz, −15 dBm sine wave is applied

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to the RF IN 1 path of the switch array, with the remaining ports left open. The output is measured using a vector network analyzer. By calculating the power difference between RF IN 1 and RF IN 8, the signal leakage into other channels is quantified. This process is repeated for all eight channels. For RF IN 1, the isolation exceeds 60 dB, with greater isolation observed between channels spaced further apart.

The consistency test assesses the amplitude and phase alignment across all channels [5]: A 162.5 MHz signal is split into eight paths using a power splitter (ZCSC-8-1+, Mini-Circuits) and fed into the RF IN 1 to RF IN 8 paths of the switch array. Outputs are connected to an eight-channel oscilloscope (DHO5000, RIGOL) via SMA cables. As shown in Fig. 5, the phase difference between channels is less than 6°, and the amplitude difference is under 4%, demonstrating excellent amplitude and phase consistency.

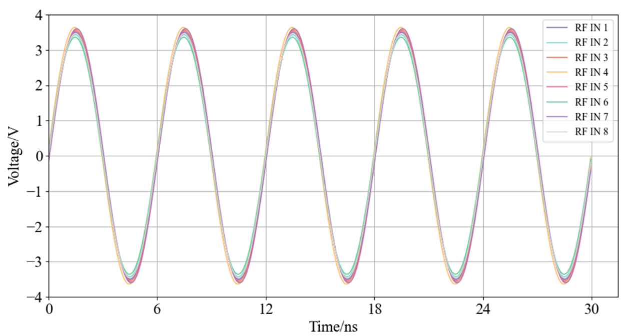

Figure 5: Result of channels consistency testing for high-speed RF switch array.

Functional Verification

After completing the performance tests, an experimental platform (Fig. 6) was constructed to verify the feasibility of controlling the high-speed RF switch array for multi-channel high-speed switching using an external trigger signal. The external trigger signal was input to the RF switch array, and the output signals were observed to evaluate the high-speed switching functionality.

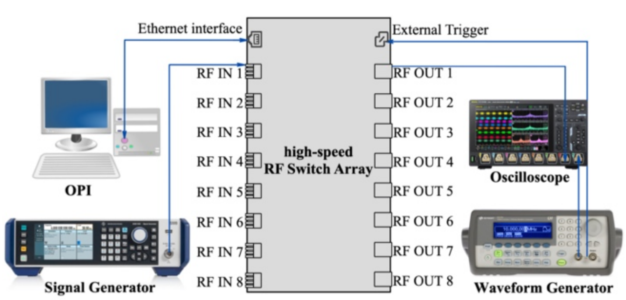

Figure 6: Experiment platform for high-speed RF switch array switching function. It consists of a signal generator, a waveform generator (33210A, KEYSIGHT), an oscilloscope and a host computer.

In the experiment, a waveform generator produces a pulse signal with a 1 kHz period and a high-level duration of 500 µs, which is displayed on an oscilloscope. Simultaneously, a synchronized signal serves as an external trigger input to the high-speed RF switch array. A 162.5 MHz, −15 dBm sine wave is fed into RF IN 1 to simulate one of the four signals from the BPM probe outputs. The RF IN 1 is configured for automatic switching mode with a 5 µs interval through the WEB interface. The output signal is then connected to the oscilloscope, where Figure 7 illustrates the comparison between the trigger signal (blue waveform) and the output signal (red waveform).

In Figure 7(left), the RF switch array initiates switching at the falling edge of the trigger signal and cycles during the low level, validating the feasibility of external trigger control for switching. Figure 7(right) shows a switching cycle of 20 µs, consistent with the configured 5 µs switching interval, demonstrating the microsecond-level switching capability of the RF switch array.

Notably, the slight misalignment of the switch transitions with the trigger signal's falling edge in Figure 7(right) indicates that electrical noise from the switches does not affect subsequent operations. This reliability is attributed to the internal trigger circuitry, which introduces an appropriate delay after detecting the falling edge, thus avoiding interference from initial signal noise.

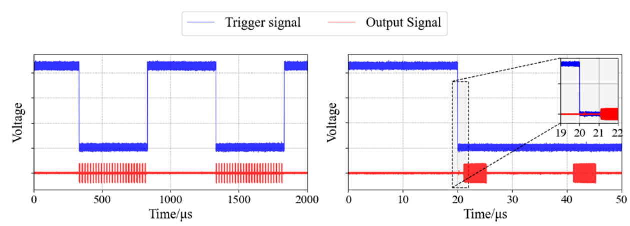

Figure 7: Waveform of the triggering signal and the output signal (The oscilloscope sampling rate is 2 GSa/s). LEFT: Sampling Time Span:2000 µs. RIGHT: Sampling Time Span:50 µs.

CONCLUSION

This study presents the development of a high-speed RF switch array tailored to meet the demands of the CAFe2 BPM system. Acting as the RF signal conditioning front-end, the array upgrades the existing readout electronics. Compared to traditional readout systems, the integration of the high-speed RF switch array significantly improves system integration and multiplexing capabilities. It enables accurate measurement of low-intensity beams across varying beam currents and frequencies. Additionally, the array allows simultaneous input from multiple BPM probe signals, enhancing support for differential BPM measurement schemes and improving the precision of beam position measurements. Overall, the high-speed RF switch array offers an efficient and reliable solution for multi-channel time-division multiplexed BPM measurements.

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