Design of the CAFE-2 Synchronous Timing Trigger System

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Abstract

CAFE-2 is a superconducting linear accelerator constructed in 2021 by the Institute of Modern Physics, Chinese Academy of Sciences, for research on superheavy new nuclide synthesis, chemical properties of superheavy elements, and the structure and properties of superheavy nuclei. The synchronous timing trigger system constitutes a critical subsystem of CAFE-2, playing a pivotal role in its operation. To accommodate the distinct operational timing and synchronous triggering requirements under both accelerator commissioning and terminal operation modes, the main synchronous timing system of CAFE-2 employs a classical event-based timing scheme. Additionally, through the design of coupling circuits and interlock logic, the synchronous pulse signal modulated by the rotating target is coupled with the trigger signal in the main timing CW (Continuous-wave) mode during terminal operation, thereby resolving the challenge of synchronizing trigger signals with rotating target pulse signals in CAFE-2' s terminal operation mode. This paper introduces the architecture of the CAFE-2 synchronous timing trigger system and elaborates on its working principles and implementation schemes across different operational modes.

Full Text

Design of the CAFE-2 Synchronized Timing and Trigger System

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Abstract

CAFE-2 (China Accelerator Facility for superheavy Elements) is a superconducting linear accelerator constructed by the Institute of Modern Physics, Chinese Academy of Sciences (IMP) in 2021 for research on superheavy nuclide synthesis, chemical properties of superheavy elements, and nuclear structure studies. The synchronized timing and trigger system serves as a critical subsystem in CAFE-2, playing a key role in its operation. To meet the diverse timing and synchronization requirements across two operational modes—accelerator commissioning and terminal operation—CAFE-2 employs a classical event-based timing architecture. Through innovative coupling circuit and interlock logic design, the system synchronizes the rotating target' s modulated trigger pulses with the main timing system' s CW (Continuous-wave) trigger signals during terminal operation, successfully addressing the challenge of maintaining trigger synchronization with the rotating target. This paper presents the architecture of the CAFE-2 timing system and elaborates on its operating principles and implementation schemes under different operational modes.

Keywords: superconducting linear accelerator; superheavy elements; timing system; synchronous trigger; CAFE-2; rotating target; operation mode

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The discovery and synthesis of new elements to extend the periodic table has long been a frontier research area in nuclear physics and chemistry [1, 2, 3]. The Institute of Modern Physics, Chinese Academy of Sciences (IMP) initiated superheavy nuclide synthesis research in 2001 [4]. In 2021, IMP upgraded the CAFE (China ADS Front-end demo) superconducting linear accelerator [5, 6, 7] and added the superheavy experimental terminal SHANS2 [8, 9] (Spectrometer for Heavy Atoms and Nuclear Structure-2), establishing the China Accelerator Facility for superheavy Elements (CAFE-2) dedicated to superheavy element research.

Superconducting linear accelerators exhibit strong "self-damage" characteristics, imposing stringent requirements on the CAFE-2 control system design. As a core subsystem, the synchronized timing and trigger system precisely controls beam generation, injection, and acceleration. It provides stable and accurate time references for timing-dependent equipment throughout the accelerator and superheavy experimental terminal, generates and distributes low-jitter synchronous clock and trigger signals, and timestamps data acquired by beam diagnostic devices distributed along the beamline to ensure temporal consistency.

CAFE-2 comprises a superconducting linear accelerator and the superheavy experimental terminal SHANS2. The accelerator delivers energy-tunable high-intensity heavy ion beams and includes: an Electron Cyclotron Resonance (ECR) ion source, Low-Energy Beam Transport (LEBT), Radio-Frequency Quadrupole (RFQ) accelerator, Medium-Energy Beam Transport (MEBT), superconducting acceleration sections (CM1-4), and High-Energy Beam Transport (HEBT). SHANS2 consists of a differential pumping system, target assembly, main deflection magnet, small-angle deflection magnet, three quadrupole magnets, working gas maintenance system, and collection/measurement system. The CAFE-2 layout is shown in [Figure 1: see original paper].

The CAFE-2 driver beam is accelerated through low-energy, medium-energy, high-energy, and superconducting sections before bombarding rare elements on a rotating target at the terminal, inducing fusion-evaporation reactions to produce target nuclei of interest. To maintain target temperature below its melting point, CAFE-2 employs a rotating target illustrated in [Figure 2: see original paper]. The target rotates at 2000 rpm with 20 sector-shaped target zones uniformly distributed on the disk, separated by 20 rectangular apertures. To prevent disk irradiation by the beam, infrared emitter-receiver pairs and photoelectric conversion circuits installed perpendicular to the apertures generate delay- and pulse-width-adjustable synchronous trigger pulses as the target rotates, which modulate the accelerator' s CW beam to produce pulses synchronized with the rotating target.

1. CAFE-2 Timing System Requirements

Like all large, complex particle accelerators [10, 11, 12, 13], CAFE-2 requires a high-precision, high-reliability, low-jitter global timing system to synchronize subsystems and equipment distributed around the accelerator, such as RF transmitters, chopper power supplies, LLRF low-level feedforward control, Beam Position Monitors (BPM), Beam Loss Monitors (BLM), and AC Current Transformers (ACCT). This ensures precise generation of beams required by the superheavy terminal, with acceleration, extraction, and accurate bombardment of the 20 sector target zones on the uniformly rotating target. Given the high cost of the superheavy terminal' s rotating target and rare elements, CAFE-2 must implement two primary operational modes to prevent unpredictable damage from high-energy beams: (1) accelerator commissioning mode and (2) terminal operation mode.

The timing system must satisfy the following requirements in both modes: 1. In accelerator commissioning mode, generate and distribute low-jitter, high-precision clock and trigger signals (TTL trigger levels/software trigger events) throughout the facility. 2. In accelerator commissioning mode, provide precise time references for data acquired by beam diagnostics to ensure temporal consistency. 3. In terminal operation mode, synchronize trigger signals with rotating target pulses.

When CAFE-2 is in startup, fault, or beam parameter adjustment states, it must operate in accelerator commissioning mode with pulsed beams (repetition rate

1–50 Hz, pulse width ≤ 20 s). Operators preset all timing system parameters (clock pulse width, delay, event codes, output channels, etc.) via upper-level software and download them to all subsystem nodes. All accelerator equipment and subsystems strictly follow the preset timing sequence. Based on an accurate time reference, the timing system triggers the ion source microwave transmitter and high-voltage chopper at precise moments to generate and inject microsecond-scale pulses, while synchronously triggering the RFQ acceleration field and beam diagnostics with precisely delayed pulses. The triggered equipment is listed in . The beam accelerates through low-energy, medium-energy, high-energy, and superconducting sections before striking a dump in the high-energy beamline, with superheavy terminal equipment remaining inactive.

** Synchronized Trigger Equipment List**

Trigger Equipment Type	Trigger Action Target	Equipment Location
LEBT chopper	Microwave power fed into ion source arc chamber to generate pulsed beam	Ion source
High-voltage chopper	Chops ion source beam to control accelerator beam pulse duty cycle	LEBT
LLRF feedforward	Feedforward compensation of cavity amplitude and phase	RFQ, MEBT, superconducting sections
BPM, BLM, FC, other diagnostics	Defines measurement intervals for beam diagnostics	LEBT, MEBT, superconducting sections, HEBT

Operators monitor and adjust beam status in real time. Only when accelerator equipment and beam conditions meet superheavy terminal requirements can CAFE-2 switch to terminal operation mode. In this mode, the accelerator operates with CW beam to supply the superheavy terminal while the rotating target spins at 2000 rpm, generating delay- and pulse-width-adjustable pulses that modulate the CW beam to produce target-synchronized pulsed beams.

Timing diagrams for both operational modes are shown in [Figure 3: see original paper] and [Figure 4: see original paper]. [Figure 3: see original paper] illustrates the accelerator commissioning mode, where the timing system generates periodic, delay- and pulse-width-adjustable digital trigger pulses based on preset parameters (repetition rate, pulse width, delay) to trigger the ion source microwave transmitter and chopper high-voltage power supply, producing microsecond-to-millisecond pulses. Simultaneously, it synchronously triggers the LLRF control system and beam diagnostics for feedforward compensation of RFQ cavity power, amplitude, and phase, as well as synchronous data acquisition and analysis.

[Figure 4: see original paper] shows the terminal operation mode, where the timing system enters CW trigger mode (100% duty cycle). All superheavy terminal equipment participates in operation, and through coupling modulation circuits, the rotating target' s synchronous pulses modulate the timing system' s CW trigger signals, ensuring all triggers remain synchronized with the target pulses.

2. CAFE-2 Timing System Design

To meet CAFE-2 timing requirements, a relatively independent timing system based on the EPICS (Experimental Physics and Industrial Control System) software architecture was designed, as shown in [Figure 5: see original paper]. The system comprises two parts: (1) the accelerator central timing system and (2) the accelerator-target coupling modulation system. The central timing system employs a classical event-based timing system to generate and distribute reference clocks and synchronous triggers to equipment and subsystems throughout the accelerator and superheavy experimental terminal. The coupling modulation system uses analog circuits to modulate the accelerator' s CW ion beam with pulses from the rotating target' s photoelectric conversion system, generating target-synchronized pulsed beams. Depending on the operational mode, different internal interlock logic couples the central timing system' s hardware safety interlock signals with the target output pulses.

2.1 Accelerator Central Timing System

The accelerator central timing system utilizes an event-based timing architecture [14, 15, 16]. Due to the superconducting linear accelerator' s high intensity and power, which create strong self-destruction risks, commissioning must use microsecond-to-millisecond pulsed beams. Low-duty-cycle pulses verify component functionality while phase sweeping determines longitudinal phase to ensure beam quality. In commissioning mode (Accelerate Mode=0), operators generate precisely delayed digital pulses via the central timing system to trigger the particle source, low-level RF, beam control, and diagnostics at correct times.

Key design parameters are listed in . CAFE-2 operates at 1-50 Hz repetition rate, synchronized with the facility' s 50 Hz AC power supply. The central timing system' s reference clock is phase-locked to the RF frequency (RF freq) with timing jitter below 10 ps. With division factor n, the event clock period is n/(RF freq), coarse delay step depends on the RF reference and division factor as (n/(RF freq))/20, and fine delay step is 5 ps using dedicated chips. n is set to 2.

** Central Timing System Design Parameters**

Parameter	Value
Beam repetition frequency	1–50 Hz (AC freq/n)

Parameter	Value
RF frequency	162.5 MHz
Event clock frequency (RF frequency/2)	81.25 MHz
RMS jitter	<10 ps
Trigger coarse delay step	0.615 ns
Trigger fine delay step	5 ps
Operational modes	Accelerator commissioning/Terminal operation

As shown in [Figure 5: see original paper], the CAFE-2 central timing system consists of a central timing IOC (Input-Output Controller) server, Event Generator (EVG) modules, Fan-Out (FOUT) modules, Event Receiver (EVR) modules, and high-speed fiber optic links connecting them. This high-performance, scalable event timing system is based on standard VME (Versa Module Eurocard) industrial computers, FPGA technology, and high-speed fiber communication, supporting VME backplane buses and EPICS software integration. The EVG broadcasts event data frames via fan-out modules and a star-topology fiber network to EVRs. Each event frame comprises an 8-bit event code and 8-bit distributed data bus, encoded using 8B/10B. EVRs receive and decode timing information from the EVG, outputting defined trigger pulses. The star-topology network using fan-out modules and multimode fiber ensures reliability, safety, and interference immunity. The IOC server runs base-3.14.12-based IOC under vxWorks, enabling data communication and information exchange between the timing system and EPICS. The Operator Interface (OPI) uses CS-Studio (Phoebus-4.6.0) for human-machine interface development, enabling parameter configuration, real-time status monitoring, and control.

The central timing system divides the 162.5 MHz RF master oscillator frequency by 2 to generate the event clock, using integer multiples of this clock to define macro-pulse lengths and ensure RF-beam phase locking. The beam cycle repetition rate is 1–50 Hz, synchronized to the 50 Hz AC power line phase to mitigate power ripple effects.

Most major accelerator laboratories employ commercial event timing systems, such as the MRF-based system from Finland [17]. CAFE-2 utilizes a domestically developed system from the Shanghai Institute of Applied Physics (SINAP) [18, 19], shown in [Figure 6: see original paper]. This system employs FPGA chips as EVG and EVR controllers, using 2.5 Gbps SFP optical modules over 10 Gbps fiber. The EVG receives a 162.5 MHz high-frequency signal (3–5 dBm sine wave) via "RF IN" and a 50 Hz AC signal via "AC IN" to generate event cycles. Eight fiber outputs connect to EVR upstream inputs. Each EVR channel provides programmable delays: coarse resolution of 1/20 event clock period (0.615 ns) and fine resolution of 5 ps. The timing network uses OM3 multimode fiber operating at 2.5 Gbps over distances exceeding 250 meters, with equal fiber lengths at each stage to minimize thermal drift.

By employing standard commercial timing modules and a high-reliability, lowlatency fiber network integrated with flexible EPICS software, the central timing system achieves <10 ps jitter and 0.615 ns clock synchronization precision across EVR output channels, meeting CAFE-2 commissioning mode requirements.

2.2 Accelerator-Target Coupling Modulation System

The 2021 upgrade of the superconducting linear accelerator into a superheavy element research facility presented a new challenge: in terminal operation mode, EVR output trigger pulses must maintain original timing performance while being synchronized with pulses from the superheavy terminal' s rotating target. To address this, CAFE-2 added an accelerator-target coupling modulation system to the central timing system. Through coupling circuit design, the timing system supports both operational modes, enabling rapid switching from commissioning to terminal mode by changing the accelerator mode signal state, thereby synchronizing all trigger signals with rotating target pulses.

The control logic is shown in [Figure 7: see original paper]. Pulses from the rotating target' s photoelectric conversion system are fed into the coupling modulation circuit via high-speed fiber, along with accelerator mode signals, terminal beam permit signals, and mechanical safety/beam protection interlock signals. Through combinational logic, the system outputs two TTL levels to INH ports of two EVR groups. EVR1 triggers chopper and LLRF equipment, with outputs inhibited by MPS and BPS interlock signals. EVR2 triggers beam diagnostics, with outputs synchronized to rotating target pulses in terminal mode.

The system leverages the "interlock" function of EVR channels. When enabled, channel output is controlled by the INH port input: if the external interlock signal is 0, the EVR immediately terminates output. EVR1' s interlock function remains enabled in both modes, while EVR2' s status changes with mode switching. As shown in [Figure 5: see original paper], after beam commissioning in accelerator mode (Accelerate Mode=0), operators manually switch to terminal mode (Accelerate Mode=1) via the OPI central timing interface. The OPI automatically loads terminal mode parameter recipes, configures the timing system for CW trigger mode (100% duty cycle for continuous beam), and enables EVR2 channel interlocks.

In commissioning mode (Accelerate Mode=0), EVR1' s INH input receives only MPS and BPS interlock signals, independent of target pulses. In terminal mode (Accelerate Mode=1), when MPS, BPS, and Beam Permit signals are all 1, the processed Target signal is delivered as a TTL level to EVR1' s INH port, synchronizing chopper and LLRF equipment with target pulses via the interlock function. If any MPS, BPS, or Beam Permit signal is 0, EVR1 terminates output. Additionally, the inverted target pulse directly feeds EVR2' s INH port, synchronizing beam diagnostics with target pulses.

Through analog coupling modulation circuit design, the system meets terminal mode synchronization requirements, achieving <25 ns synchronization error between EVR trigger pulses and target pulses. During equipment or beam anomalies, the timing system rapidly cuts trigger outputs to stop beam generation, ensuring CAFE-2 equipment and beam safety.

2.3 Timing System Software Design

The CAFE-2 timing system software comprises IOC and OPI components, enabling status monitoring, run/stop control, and remote configuration of delay and pulse width parameters for each EVR channel.

As shown in [Figure 5: see original paper], the OPI connects to the IOC via the facility LAN, communicating through EPICS Channel Access (CA) protocol. Operators select operational modes and parameters via the OPI, which downloads all parameters and commands via high-speed Ethernet to the IOC in the timing server.

EPICS (Experimental Physics and Industrial Control System), developed in the early 1990s by Los Alamos and Argonne National Laboratories, creates distributed real-time control systems for large accelerators and scientific facilities. CAFE-2 employs EPICS for software integration and development, ensuring excellent scalability and stability. The central timing system provides necessary EPICS interfaces.

The timing system IOC runs on VxWorks in the VME controller. The server uses a VME-based industrial computer housing VME PowerPC boards, SINAP VME-EVG, SINAP VME-Fanout, and SINAP VME-EVR modules. The controller connects to the facility LAN via a 1000 Mbps Ethernet interface. Through IOC and network configuration, all VME crate boards (EVG, EVR, FOUT) publish parameters as Process Variables (PVs) on the LAN for remote OPI access.

The CAFE-2 timing system OPI uses CS-Studio (Phoebus-4.6.0). CS-Studio is a collection of tools for monitoring and controlling large-scale control systems like accelerator controls. Originally based on Eclipse RCP, the "Phoebus" variant eliminates Eclipse dependencies while providing Display Builder, Data Browser, Probe, PV Tree, Alarm, Scan, and integrated email/logging in a more compact package. The operational OPIs are shown in [Figure 8: see original paper] (commissioning mode) and [Figure 9: see original paper] (terminal mode).

3. System Testing

The China Accelerator Facility for superheavy Elements completed equipment installation and successful beam commissioning in 2021. Timing system performance was tested during laboratory and operational runs. As shown in [Figure 10: see original paper], the left panel shows initial fixed delay (460 ps); the middle panel sets channel 2 (green) coarse delay steps to 0 and fine delay steps to 200, yielding 1.38 ns delay relative to channel 1 (yellow); the right panel sets channel 2 coarse delay steps to 2 and fine delay steps to 0, yielding 1.64 ns delay. Calculations show fine delay steps of 4.6 ps and coarse delay steps of 0.6 ns under operational conditions.

Oscilloscope measurements of EVR trigger signals demonstrate timing jitter standard deviation below 10 ps, meeting physics requirements. [Figure 11: see original paper] shows an EVR trigger signal with 6.333 ps standard deviation.

The accelerator-target coupling modulation response was also tested. In terminal operation mode with constant target rotation, the coupling modulation signal combines the target’ s synchronous pulses with the timing system’ s CW pulses, synchronizing all triggers with target pulses. [Figure 12: see original paper] shows single-cycle waveforms: yellow (CW continuous pulses), green (rotating target synchronous pulses), and pink (coupled modulation output).

The coupling modulation signal delay relative to target pulses is shown in [Figure 13: see original paper]: 22.8 ns delay for both rising (left) and falling (right) edges, with channel 1 (yellow) as the target pulse and channel 2 (green) as the coupled output.

The CAFE-2 timing system has operated online for over two years without any trigger interruptions or misfires caused by timing system failures, demonstrating proven reliability and stability through field operation.

This paper presents the CAFE-2 timing system design, proposing and implementing a coupling modulation-based timing control solution that resolves conflicts between different signal sources in the two operational modes. The system architecture, hardware/software design, and implementation enable flexible mode switching, satisfying CAFE-2’ s stability and flexibility requirements. As a core subsystem of the CAFE-2 control system, the timing system plays a vital role in stable beam delivery and provides the foundation for superheavy element and nuclide synthesis research.

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Note: Figure translations are in progress. See original paper for figures.