INTEGRATED TIMING SYSTEM FOR THE EBIS PRE-INJECTOR *

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Abstract

The Electron Beam Ion Source (EBIS) began operating as a pre-injector in the Collider-Accelerator Department (C-AD) RHIC accelerator complex in 2010. Historically, C-AD RHIC pre-injectors, like the 200MeV Linac, have had largely independent timing systems that receive a minimal number of triggers from the central C-AD timing system to synchronize the injection process. The EBIS timing system is much more closely integrated into central C-AD timing, with all EBIS machine cycles included in the master supercycle that coordinates the interoperation of C-AD accelerators. The integrated timing approach allows better coordination of pre-injector activities with other activities in the C-AD complex. Independent pre-injector operation, however, must also be supported by the EBIS timing system. This paper describes the design of the EBIS timing system and evaluates experience in operational management of EBIS timing.

INTRODUCTION

Electron Beam Ion Source

The Electron Beam Ion Source (EBIS) began operating as a pre-injector in the C-AD RHIC accelerator complex in 2010. Beam from the EBIS pre-injector is delivered to the Booster Synchrotron via the 37m long EBIS to Booster (ETB) transfer line. EBIS replaces two existing Tandem Van de Graaff accelerators as the heavy ion pre-injector for both the Relativistic Heavy Ion Collider (RHIC) and NASA Space Radiation Laboratory (NSRL). The last 4m section of the ETB transfer line is shared with the Tandem to Booster (TTB) transfer line. [1]

An Electron Beam Ion Source traps ions around an electron beam. Ions of the desired species are introduced into the C-AD EBIS trap from one of two ion sources. A third ion source is being installed in fall of 2013. [2] Ions are step-wise ionized while held in the trap and extracted from EBIS when the desired charge state is reached. The charge state of the extracted ions is a function of the time of confinement in EBIS. [3] Typical EBIS confinement times are less than 100ms. EBIS can operate at a 5Hz rate.

C-AD Timing

The C-AD accelerator complex consists of the EBIS heavy ion pre-injector, the 200 MeV Linac proton pre-injector, the Booster Synchrotron, the Alternating Gradient Synchrotron (AGS), the Relativistic Heavy Ion Collider (RHIC), the transfer lines that connect these accelerators, and the extraction line for the NSRL facility. All C-AD accelerators other than RHIC support Pulse to Pulse Modulated (PPM) operation in which accelerator equipment rapidly switches between PPM contexts to serve different accelerator programs. Timed coordination of machine activities at C-AD is accomplished using a supercycle link with events marking major milestones for each C-AD machine. For example, supercycle events mark the start of machine cycles and switching of PPM contexts for the EBIS, Linac, Booster, and AGS accelerators. Placement of events on the supercycle event link is specified in terms of 60hz clock ticks synchronized with AC line power. Supercycle events, along with accelerator-specific intracycle events, are delivered to controls equipment on accelerator-specific event links. [4] C-AD supercycles are typically 3 to 5 seconds in length.

Operational Scenarios

EBIS is operated in two distinct modes with different timing requirements. When EBIS beam is used for RHIC or NSRL programs, EBIS beam cycles must be synchronized at the microsecond level with the operation of the Booster Synchrotron. During stand-alone operation, ions are injected into EBIS and extracted down the ETB line but not delivered to Booster. In stand-alone mode, EBIS beam cycles do not need to be synchronized with the operation of the rest of the C-AD complex. C-AD Main Control Room operators play no role in stand-alone EBIS operation. Stand-alone mode is used for the development of new beams or for tuning beams in preparation for delivery to RHIC or NSRL. Supercycles can include a mix of stand-alone and Booster synchronized EBIS beam cycles with different PPM contexts.

EBIS TIMING SYSTEM

EBIS Intracycle Timing

Timing signals are delivered to EBIS equipment by one of two mechanisms. Many timing signals are delivered by a local trigger system that is built from a generic 16 bit function generator module that is widely used in the C-AD control system. Each output bit of the function generator can be used as an independent trigger. The EBIS application interface allows an EBIS operator to specify start time and pulse length for each trigger. The function generator module is then programmed to provide a two state output function for each of the 16 bits. Two such modules are used to provide 32 local triggers. Trigger times are specified relative to the start of the EBIS cycle (EBIST0). The function generator module provides 10us timing resolution. For triggers that require finer timing, the output of the function generator is used to trigger a standard C-AD controls delay module with 100ns timing resolution.

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The standard C-AD event link mechanism is used for other EBIS timing signals. EBIS shares an event link with the C-AD 200MeV Linac pre-injector. EBIS uses the event link primarily for synchronization with other C-AD activity. For example, the EBIST0 event signaling the start of a new EBIS cycle is delivered on the event link. The event link is also used to deliver significant milestone events during the EBIS cycle, such as the "prepare to extract" event. Milestone events in the EBIS cycle are defined in the local trigger system and published on the Linac event link. A small number of outputs from the local trigger system are dedicated to the purpose of publishing these milestone events. Once they are published on the event link, they become available to any EBIS controls equipment using standard trigger mechanisms.

Placing Booster-synchronized EBIS Cycles

Booster-synchronized EBIS beam cycles are placed in the supercycle using the C-AD master supercycle manager (SuperMan) application. SuperMan applies a set of rules to determine supercycle code placement based on a high level supercycle description supplied by Main Control Room operators. Three events are placed on the C-AD supercycle to define an EBIS beam cycle – a PPM user code to define the PPM context for cycles that follow, a start of cycle event, and a group end event to define the completion of a single cycle or a group of cycles that share the same PPM context. In order to allow time for ion injection and confinement in EBIS, the EBIS start of cycle event (ET0) is typically placed 100ms or more before the associated Booster start of cycle event (BT0).

A separate PPM context, with separate supercycle events, has been defined for equipment in the ETB transfer line. This allows ETB equipment to begin moving to setpoint in anticipation of EBIS cycles. The ETB start of cycle event typically precedes the start of EBIS cycle by one second.

Fine Synchronization of EBIS and Booster

Two requirements must be satisfied for fully synchronized operation of EBIS and Booster. EBIS requires that confinement time be controlled to the level of one millisecond or better in order to produce the desired charge state. The process of injecting the EBIS beam into the Booster requires synchronization with fast ramping orbit "bump" magnets. This requires synchronization at the level of microseconds.

Placement of supercycle events, with their 1/60 second granularity, can only provide approximate synchronization of EBIS with the Booster Synchrotron. In order to achieve the required level of synchronization, the Booster "prepare for injection" event is transferred to the Linac event link where it is published as a "prepare to extract" event for use by EBIS equipment. The delay from "prepare to extract" to actual EBIS extraction can be fine tuned, along with fine tuning of Booster injection bump delays, to precisely line up EBIS extraction with Booster injection.

Booster timing, therefore, defines the end of the EBIS cycle. In order to achieve the desired EBIS confinement time, the start time of the EBIS cycle must be properly placed. The supercycle event ET0 defines a reference point for the start of the EBIS cycle. A delay module is used to provide fine control of the placement of EBIST0, the event that actually starts the EBIS cycle, on the Linac event link. The size of the delay is managed by a server process (specManEbis) that monitors the key parameters that affect EBIS timing. The size of the EBIST0 delay is calculated based on EBIS cycle timing (defined by EBIS operators), Booster injection timing (defined by MCR operators), and the relative location in the supercycle of EBIS and Booster cycle start events.

Since the specManEbis server reacts to changes in these three timing inputs after they have already been made, it typically takes one supercycle to correctly place EBIST0 after timing changes. Mistimed cycles can cause EBIS equipment trips if an extraction event is received too early in the EBIS cycle or the cycle is truncated by an early Group End event. Three techniques have been employed to avoid this problem. (1) The EBIS application interface and specManEbis server use a handshake protocol to ensure that changes in EBIS intracycle timing and EBIS cycle placement are made in the proper order to avoid cycle truncation. (2) Booster injection requests are disabled (administratively) before making any large changes in the time of Booster injection. (3) Placement of ET0 in the supercycle is determined by a static rule in the SuperMan application that is only changed by experts. It is placed sufficiently in advance of the Booster cycle to accommodate all anticipated confinement times for a running period.

Scheduling Stand-alone EBIS Cycles

Though synchronization with other C-AD operations is not required during stand-alone EBIS operation, EBIS beam cycles still must be defined in the C-AD supercycle. Historically, C-AD supercycle timing has only been managed by Main Control Room operators using the C-AD master supercycle manager (SuperMan) application. A new application developed for the management of stand-alone timing (EbisLocalUserControl) allows an EBIS operator to specify the number, period, and PPM context of requested EBIS beam cycles. The EbisLocalUserControl application merges stand-alone EBIS cycles into the running C-AD supercycle without making any changes supercycle timing for any other C-AD activities. Booster-synchronized EBIS cycles are always given priority over requests for stand-alone Booster cycles. EBIS operators can graphically preview their stand-alone cycle requests to determine what requests will be accepted. Figure 1 shows a supercycle with Booster-synchronized and stand-alone cycles.

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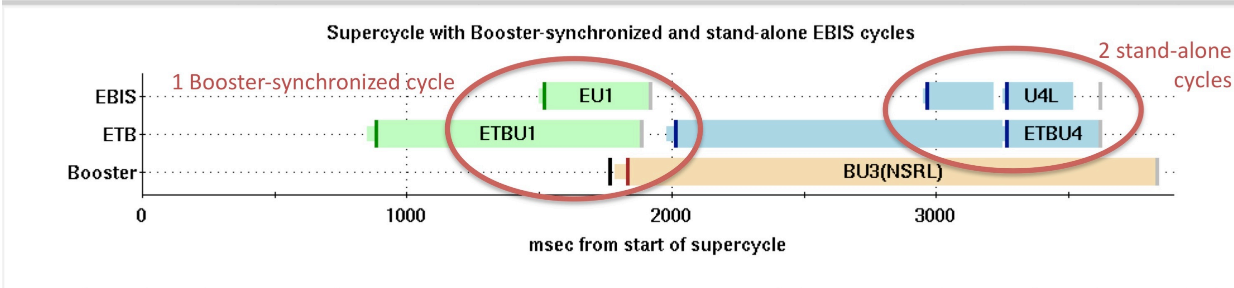

Figure 1: Timing diagram of supercycle with EBIS stand-alone and Booster-synchronized cycles.

EBIS OPERATIONAL EXPERIENCE

RHIC 2012 Ion Run

In 2012, EBIS supplied ion beams for RHIC physics for the first time. U, Cu, and Au beams were delivered. In order to optimize EBIS performance, a variety of EBIS timing configurations were used. An alternating supercycle arrangement (one with beam-one without beam) was used to deliver 8 consecutive U beam pulses to Booster while limiting the overall EBIS duty factor. Stand-alone EBIS Cu cycles were paired with Booster-synchronized Au cycles (and vice versa) to maintain stable EBIS performance of both beams during the Au-Cu RHIC run. The flexibility of EBIS timing and close integration with C-AD complex timing was critical to the success of the 2012 RHIC ion runs.

Operation in Stand-alone Mode

EBIS operators have been able to effectively manage timing for stand-alone operation. Software has been modified to offer more stand-alone cycle placement options as experience with the system has grown.

It was important to demonstrate that the supercycle could be modified for EBIS stand-alone timing changes without impacting any other C-AD activities. During early stages of EBIS operation, beams from the Tandem Van de Graaff were still being used in C-AD. On several occasions, EBIS timing changes adversely affected Tandem beams due to conflicts in the common ETB/TTB section. Changes in software and operational procedures addressed these problems. Some time was needed to restore confidence after these early problems.

The goal of stand-alone operation is to prepare beams for injection into Booster. EBIS operators have observed that beam characteristics (e.g. intensity, stability) in stand-alone operation do not always precisely match beam characteristics in Booster-synchronized operation for the same EBIS setup. Extensive investigation has shown that beam characteristics change with changes in the phase of EBIS cycles relative to AC line power. Since EBIS cycles begin on a delay from supercycle events, their phase changes as the size of this delay changes. Further investigation is needed to better understand and resolve this problem.

Timing Transitions

The mechanisms employed to avoid problems during timing transitions have been largely but not completely effective. Use of larger confinement times than anticipated led to a need for mid-run changes in the static supercycle rule for ET0 placement. Manual editing of supercycles by Main Control operators caused misplacement of the EBIS Group End event and truncation of EBIS cycles. Software changes are planned to allow easier, but protected, adjustment of ET0 events in the supercycle. A more controlled mechanism of Booster injection time management is also being considered.

CONCLUSION/PLANS

The EBIS timing system has effectively supported EBIS operation as pre-injector for NSRL and RHIC. The EBIS timing system has also effectively supported stand-alone operation of EBIS for beam tuning and development of new beams. EBIS timing software evolved during the first years of operation to expand flexibility and improve reliability. Software modifications are planned to accommodate the addition of a new ion source at EBIS and to better ensure smooth handling of timing transitions.

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