FREQUENT FILL TOP-OFF INJECTION AT SPEAR3*

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Abstract

SPEAR3 beam is now delivered to users in a "frequent fill" mode in which beam is injected into the storage ring, with beam-line shutters open, on a periodic schedule so that the beam current is kept constant to within 1% of its average value. This goal was achieved with the constraints of having the SPEAR3 injector run at very high reliability and ensuring that there would be no challenges to the beam containment system in this operational mode. This paper presents the accelerator development, the hardware changes, and the software developed to implement this operational mode.

INTRODUCTION

The injector used for SPEAR3 was built in 1990 to inject beam into SPEAR2 [1]. Since that time the SPEAR complex has evolved. SPEAR3 was built, an emittance upgrade to SPEAR3 has been made, the machine current is now 300 mA (500 mA running will occur in the near future), and top-off mode, beam injection with beam-line shutters open, has been introduced [2]. Once top-off was approved, a frequent fill injection program was required to keep the beam current nearly constant so that the users see a nearly current flux of photons on their experiments.

The injector had been designed to operate for only three scheduled injections per day. Prior to a fill, the machine operator would turn on the machine and tune it for the required injection. Since the machine was typically on for only a short time, issues such as component lifetime, power consumption, thermal heating of components, and stability were not major issues. Having the injector ready continuously changes these considerations. Producing frequent, repeatable, and reliable injection using the existing injector components therefore meant that these issues had to be properly considered while maintaining “constant” beam current. Periodic cycling of the main power supplies addressed the lifetime and thermal issues; multiple feedback loops addressed the repeatability issues.

Frequent filling was initiated on and has been continuously operated since June 7, 2010.

MACHINE PARAMETERS

The injector is designed to inject a single bunch of beam into a single bucket of SPEAR3. It is a periodic machine that cycles at 10 Hz. A thermionic RF gun accelerates a few S band (2856 MHz) bunches to 2.5 MeV. These bunches are accelerated through three LINAC sections to 120 MeV. Finally, the injector accelerates them to the SPEAR3 energy of 3.0 GeV. About 80 pC of charge is injected into SPEAR3 each cycle, corresponding to a fill rate of 60 mA / min.

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MAGNET SUPPLIES

Operating Parameters

All of the main injector ring magnets, along with large inductors and capacitor banks, form an oscillating circuit, known as a White circuit [3]. One large DC supply powers a pulser that drives the oscillation and another provides the DC offset current for the circuit. The supplies provide 530 kW of power to the White circuit. This power places electrical and thermal stresses on the capacitors in the circuit and the semiconductors in the supplies. It also places mechanical stresses on the coils and laminations of the magnets and inductors. The main magnets in the transport line between the injector and SPEAR3 are powered by another large supply that outputs 94 kW. Reducing the duty cycle of these supplies was necessary in order to reduce the heat load and improve system reliability. Our goal was to top-off every 10 minutes, powering the supplies only when needed.

Power Supply Control

A precision current transducer measures the exact White circuit current and has been used to accurately determine the ejection time of the beam from the injector. In order to improve the circuit stability we used the this current as the sensor from which to accurately regulate the two supplies. We digitize the transducer output at a 10 kS / s rate during approximately half of each 100 ms cycle. Since the circuit has a high quality factor, we know that at this time the circuit very closely approximates a biased 10 Hz sinusoid. Therefore we use an efficient algorithm to project out the DC and 10 Hz amplitude and phase each cycle. These calculated values are then fed back to the set points of the supplies. With this method we achieve 100 ppm current stability, which is more than adequate for our system.

We tuned up both the hardware and software responses of the systems so that they can typically achieve their set point in about 20 s; we ramp the supplies up 50 s before the fill time to ensure that they are always ready. The transport line supply is also ramped up and down at this time. We experimentally verified that the magnetic fields in the transport line magnets were reproducible under these periodic ramps.

We ramp the supplies between an "idle" value (1% of the output power) that keeps the regulation circuits in their active regions. We reduce the power dissipation by 90% and reduce stress on the system components. The temperature of the warmest magnetic element increases by only 2 °C above ambient during normal operation. We have had no equipment failures in either of these systems for the past two years, including during the time of the frequent filling which started on June 7, 2010.

OTHER STABILIZATION MEASURES

Characterization

Prior to implenting frequent filling, we spent much time characterizing the performance of the injector as it existed. Since we had access to the functioning machine we could optimize our resources by characterizing the various elements of the injector and concentrating on improving the performance only in the areas where necessary. Sometimes the work involved the addition of hardware. Always it involved the addition of feedback loops.

LINAC

The main hardware modification to the LINAC involved the addition of additional diagnostics. Over the last few years we have improved our amplitude and phase detectors of the various radio frequency (RF) signals. We use commercial diode detectors for the amplitude and low level integrated circuits for phase detection. In order to stabilize the detectors we have placed them in a temperature regulated, ovenized chassis in an air conditioned rack. The temperature in the rack is held to within 0.5 °C; the chassis is an order of magnitude more stable.

All of our signals go into commercial digitizer boards, sampling at 100 MS / s.. We use these boards to digitize the pulsed signals and average the signals over the region of interest to further improve the measurement accuracy. The digitizers are also located in the air-conditioned rack.

We have feedback around our gun cathode heater to keep the total electron output current constant. Only a fraction of the electrons emitted from the gun cathode leave the gun; the rest back-bombard the cathode and heat it ballistically. The feedback keeps the total emission stable.

There are also feedback loops on our klystron amplitudes and phases. The amplitudes are stabilized to within about 500 ppm. The phases are held to within a fraction of a degree.

LINAC to Injector Transport Line

Our transport line from the LINAC to the injector turned out to be a weak link in our system [4]. A combination of magnet mis-alignments and insufficient magnet power supply regulation made capture in the injector difficult. The power supply initially used for the bend magnet in question had insufficient resolution to stabilize the magnet to the tight tolerance required. A smaller trim winding on the magnet was used for the fine control. This combination was adequate to keep the system stable for minutes, but excessive drifts occurred on longer time scales. After discovering that the resolution was inadequate we installed a Hall probe and regulated the power supply on the measured field. We then installed a new supply and controller which, with a more than adequate regulation of 10 ppm.

A realignment of the transport line was done during the extended downtime last year, allowing for easier tuning of the injection from the LINAC.

Injector Ring

In addition to the reduced duty cycle implemented in the main magnet supplies, improved power supply controllers were also installed. They allow the supplies to be ramped up more quickly and reliably than the controllers that they replaced.

Injector to SPEAR3 Transport Line

Much work was done on the transport line between the injector and SPEAR3 [5]. The vacuum system was improved by unifying the previously separate injector and SPEAR3 systems. Removal of the windows between the systems greatly reduced the emittance of the injected beam and improved capture. Work was also done with single turn electron beam position monitor (BPM) electronics and streak cameras to measure and then minimize injection oscillation transients caused by energy, phase, and lattice mismatches between the injector and SPEAR3.

A feedback system on the trajectory down the transport line has also been implemented. Electron BPM electronics measure the trajectory and an inverse response matrix is applied to the transport line correctors to keep the orbit stable. Currently this feedback is manually run by the operation staff as needed. Plans exist to automate this feedback by measuring and correcting during each fill.

FREQUENT FILL ALGORITHM

Injection Protocol

We selected our injection protocol as a compromise between providing uniform, stable beam to the users while not putting excessive strain on our injector. With a SPEAR3 beam lifetime of 14 hours, we can keep the current stable to 1% by filling every 10 minutes. This tolerance was chosen after co-ordinating experiments with our beamline scientific staff to ensure that the ripple on the SPEAR3 current and the transients did not compromise the integrity of their data collection.

We chose to fill the ring at times determined by the clock rather than beam current. We want the users to easily know when the next fill will occur if they want to synchronize their data collection with the fills. The injection starts exactly on every tenth minute of the clock. We also make software and hardware signals available to the beamlines, but few experimenters use these signals.

We depend on averaging to keep the ring fill uniform. The charge in each injected pulse is approximately one tenth that of a stored bunch in SPEAR3. The control system cycles through the desired fill pattern; fluctuations between the various bunches average out over time. A typical fill cycle injects tens of pulses over several consecutive seconds.

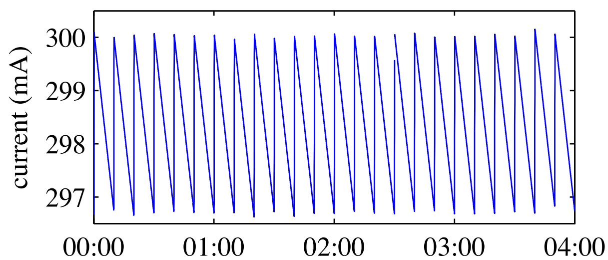

Figure 1: SPEAR3 current during frequent filling.

Software Implementation

The algorithm was written using MATLAB [6] and the LabCA [7] interface to communicate with the EPICS [8] based control system. Programming in the MATLAB environment is typically much quicker than in a standard high level language such as C and the program can be developed and debugged from the interactive mode of the MATLAB development environment. Once the code works as desired, the MATLAB code is compiled via a *make* application to produce a stand-alone executable. Once compiled, the code is another soft IOC that is run by the control system.

The program acts at a high level. It depends on the underlying control system to store configuration setpoints, interface with the hardware, etc. Therefore it is independent of the specific machine configurations. Most of the feedback loops are also handled by the control system. This program only tells the feedback systems to go to the desired setpoints, leaving the details of the individual feedback routines to the control system.

Other Considerations

Another major function of the frequent fill program is to help ensure that the machines perform at a level that minimizes any potential radiation hazard. The SLAC Radiation Physics group ensures by means of appropriate shielding, radiation monitors, administrative controls, etc., that all personnel around SPEAR3 are protected against radiation exposure. This program adds an additional layer of safety to ensure that errors in hardware and/or software do not challenge the radiation safety system.

The program monitors various diagnostic equipment around the accelerator. From this equipment it can determine if beam is available when and where it should be. For example, if the beam has not been detected within five seconds of starting the injection process or the injection rate into SPEAR3 decreases below a minimum acceptable level, the injection cycle is terminated, beam stoppers are inserted, and an alarm message to the operator is displayed.

During each cycle the program monitors the efficiency of the various sections of the injection process and records these efficiencies in the History database. Operators monitor these efficiencies to know when and where to tune the machine to keep it running smoothly. There are typically only a few adjustments that need to be made each day.

CONCLUSION

SSRL has implemented a frequent fill program for top-off injection at SPEAR3. The implementation was completed with a minimum of hardware upgrades. Thorough study and analysis led to specifications and implementation of numerous feedback loops that stablized the twenty year old injector and allowed it to perform extremely reliably. A strategy of topping off SPEAR3 every ten minutes and operating the high power equipment only when needed for injection adds to the system reliability.

SPEAR3 has been using this frequent fill program, without interruption, since June 2010. Less than 1% of the scheduled fills have been missed due to equipment failure during that time.

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