COMPREHENSIVE FILL PATTERN CONTROL ENGINE: KEY TO TOP-UP OPERATION QUALITY*

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Abstract

At the light source BESSY II numerous experiments as well as machine development studies benefit from a very flexible and stable fill pattern. The fill pattern control engine is based on a state machine that controls the full chain from gun timing, linac pulse trains, injection and extraction elements as well as next shot predictions allowing triggering the next user experiment DAQ cycle. Architecture and interplay of the software components as well as implemented functionality with respect to hardware control, performance surveillance, reasoning of next actions and radiation safety requirements are described.

INTRODUCTION

After starting user operation in 1998, the 3rd generation light source BESSY II provided users with synchrotron radiation in decaying beam mode with three injections per day for 14 years. During this time BESSY II offered specific support for time-resolved experiments, pioneered low-α mode with coherent THz-radiation and ps-pulses and established the most advanced femtosecond slicing [1] endstation with 100 fs pulses. A purity controlled high current camshaft bunch in the ion clearing gap enables pump/probe experiments as well as pseudo singlebunch experiments at full intensity with a mechanical chopper.

Switching to top-up mode [2] extended these possibilities with a thermally stabilized machine and higher average intensity. Today, more pseudo single bunch experiments with reduced intensity are possible by using pulse picking by resonant excitation (PPRE) [3] with a selected bunch close to the end of the gap.

All these specific bunches have to be topped up with minimal variation to programmable intensities.

CONSTRAINTS

Radiation Safety

Based on analysis of facility properties and various malfunction scenarios, several restrictions and modifications have been set up to guarantee minimized losses and to make all sources of possible damages measurable and hence allow beamshutters to be kept open during injections:

- Injection efficiency must be >60% for every shot.
- Average injection efficiency must be >90% over 4 h-blocks.
- Maximum allowed injection frequency is 0.1 Hz.
- Maximum increase in stored current per injection shot: 2 mA.
- Minimum current in booster. For reliable and accurate efficiency measurement, a minimum current of 0.3 mA during an injection is mandatory.
- Minimum and maximum current of stored beam together with a corresponding minimum lifetime. To control and limit the normal average loss, a limit of max. 60 mA/h has been defined. The nominal limits are 200 mA-300 mA stored beam with a minimum lifetime of 5 h.

Top-Up Interlocks

Two separate systems are responsible for efficiency measurement and interlock. During top-up operation, both have to permanently check all relevant parameters for compliance with the top-up radiation protection restrictions and approve top-up operation to continue. The efficiency interlock systems are part of the radiation protection system.

Any violation of any of the restrictions will activate the top-up interlock system and pause or terminate top-up operation while beamshutters are free to open. Top-up injections are continued as soon as all top-up conditions are restored. This may happen automatically (e.g lifetime temporarily below limit) or may have to be accomplished by operations staff after closing beamshutters (e.g. last injection efficiency below 60%).

The fill pattern control engine operates in both top-up user-runs (beamshutters unlocked and free to open) and commissioning or machine development runs (beamshutters closed and locked). The latter is possible even without switching interlock systems to top-up mode. So the strict limitations of top-up mode are not enforced in this case and the top-up interlocks are inactive.

Injection Frequency and Timing

A proper compromise between minimizing variation in bunch currents and minimizing the number of disruptions due to injection kicker pulses had to be settled. The currently consolidated injection-scheme is, to fill a maximum of 5 bunches (reduced to e.g. 1 or 3 when filling dedicated single- or slicing-bunches) at every multibunch injection shot with the highest possible bunch currents. The decay phase between two injections currently ranges from 10 s to 200 s with an average of 120 s and every injection shot adds between 0.3 mA to 1.8 mA to the stored beam (ring current variation during top-up operation: ~0.5%).

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TOP-UP SERVICE AND FILLPATTERN CONTROL ENGINE

These core automation center for top-up operation at BESSY II is the "Top-Up Service and Fillpattern Control Engine" that has been developed during tests, setup and commissioning of top-up operation mode.

It is implemented as a standard EPICS state-machine together with a corresponding realtime database hosted on a dedicated Software I/O-Controller (SoftIOC).

During runtime, this system communicates via EPICS ChannelAccess (CA) with several other I/O-controllers (IOCs).

Input Signals

State and processed data of top-up interlock systems During top-up operation, the status of all top-up interlock systems is monitored to decide whether to continue top-up injections or to provide information about the reason of a top-up interruption. If efficiency decreases, a possible injection-free time at the beginning of the next 4h-block is indicated.

If top-up mode is not active and therefore the beamshutters are locked, it is not necessary to obey the top-up restrictions stringently. All this information has to be processed and displayed and may initiate state transitions.

Fillpattern Monitor To decide which positions and bunch combinations to fill on the next injection shot, the fill pattern monitor is the central source of information and core diagnostic components for proper top-up operation.

It is implemented using a stripline based high-performance ADC that delivers per bunch current measurement with high accuracy (up to 100 nA resolution) [4]. Delivering an accurate fill pattern measurement of bunchcurrents of all 400 possible bunches every second, it builds the foundation to decide where and how to place the next injection shot.

The fill pattern monitor needed to be reclassified when preparing of BESSY II for top-up operation. In the transition from an optional diagnostic element to an essential core system of top-up operation, it has been duplicated with a hot spare system and can be complemented with high-resolution photon counter based on an avalanche diode that produces an accurate measurement of the fill pattern every 15 s – 30 s.

Global beam current and lifetime measurement Used to determine whether and when an injection shot is expected to be initiated.

Other inputs like the state of extraction- and injection-pulsers as well as the overall injector status from linac to booster synchrotron are monitored and evaluated to decide whether top-up injections can be carried on or not.

Controlled Elements

After an injection, the injector is switched into suspend mode by switching off the extraction trigger pulse for the linac-gun as well as the trigger for the booster-injection-pulsers. This measure is taken to avoid activation of the septum as well as to protect the electron gun and the pulser klystrons from premature aging, because the complete injector is operated with a 1 Hz repetition rate.

When preparing for an injection, the injector is resumed, and the linac is set up to produce the determined number of pulses with the corresponding time interval in between. Currently, the number of pulses varies between 1 and 5 while the interval is typically 12 ns. This satisfies the requirements of the currently used fill pattern (induced by the timing granularity of slicing laser systems), but may change anytime.

When all preconditions are met and an injection shot is imminent, the timing system is configured to place the injected bunches at the selected position in the storage ring and the global injection trigger is switched on.

Program Structure

The main program consists of three independent parts:

The finite state machine implements the core engine that controls and reflects the state of the top-up system and the storage ring. It consists of five main states and some few transitional states (see Figure 1).

Combining all incoming status information from interlocks, measurements and configuration setup and performing the appropriate state transitions, the state machine provides full automation of the injection process for filling the machine from scratch as well as running BESSY II in top-up operation mode.

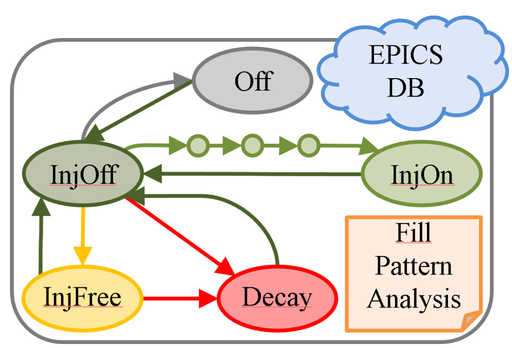

Figure 1: Simplified state diagram showing only main states and companion modules.

The fill pattern analysis asynchronously processes the measured fill pattern and decides which bunch group would be topped up with the next injection shot regardless of when it would actually happen.

This is a process that is triggered every second on incoming fill pattern measurement data. According to the current planned fill pattern, all possible positions and bunch groups to aim an injection shot at are checked, and the combination that lacks the most total current relative to the desired fill pattern is chosen.

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The EPICS realtime database is the sole interface to control the state machine as well as the fill pattern analysis. It also reflects the internal status of the fill pattern control engine and holds many informational parameters for operations staff, analysis and statistics.

The advantage of using an EPICS realtime database as the sole control- and monitoring-interface to a background server process is, that all parameters, whether they are configuration or information, are provided as standard EPICS process variables (PVs) and hence integrate perfectly into the underlying control system. Other applications may access these PVs just like any other PV in the control system. They are archived and alarm-monitored and can be monitored and controlled from any control system console as well as displayed on user-information monitors and in web-based status displays.

In terms of control system infrastructure, the Top-Up Service and Fillpattern Control Engine behaves just like any other device in the BESSY II control system.

Human Machine Interface

The verbose user interface panel (see Figure 2) provides access to all configurable parameters of the control engine as well as all relevant diagnostic and interlock information and several parameters internal to the control software.

Target current and positions of all currently supported bunch-groups are configured through this interface and define the desired planned fill pattern.

A simple event/message log provides a quick overview of overall top-up operation events, and a reduced set of informational PVs like the result of the fill pattern analysis is displayed in this panel. The full set of internal status information is accessible in a separate more verbose panel.

Links to a few auxiliary software modules like injector standby/resume, linac controls and RF-knockout gap control are also provided for easy access.

The fill pattern diagram shows the current live fill pattern as well as the underlying desired fill pattern calculated from the configuring parameters. It also displays the position and scaled up shape of the latest increase in the measured fill pattern, which is the last seen injection shot. Optionally the range cleared by RF-knockout during every shot for 50 ms, to maintain a high purity of the camshaft bunch, is also displayed.

The top-up service determines some further diagnostic information that are not of immediate relevance for the top-up interlock systems, but might point to subsequent problems if not taken care of. An example is the per bunch booster current, that prevents injections on camshaft- or PPRE-bunch if it does not exceed the minimum limit.

Fillpattern Control Engine — Configuration

Development over the last three years lead to the current scheme of defining the desired fill pattern. The overall total current and four groups of bunches can be configured to match the current needs:

Multibunch fill The part of the ring that will be populated with equally filled bunches is defined by exclusion. The length and position of the ion-clearing gap are configured and hence define the multibunch fill, which can in turn be setup to have every single or every n-th bunch filled.

Camshaft bunch A single bunch at a fixed position in the purity-controlled gap. Only the current stored in this bunch can be configured. This bunch is used for standard pump/probe experiments, but also for single-bunch experiments at full rate and intensity using the phase locked MHz pulse selector [5], a chopper wheel synchronized to the circulating beam opening a 70 ns window for the light pulse at 1.25 MHz.

PPRE bunch For a different scheme of pseudo single bunch experiments, a dedicated single bunch in configurable distance, but close to the end of the gap, is filled.

Slicing bunches For femtosecond experiments, a group of three bunches, usually opposite of the camshaft bunch, are filled with higher currents than the standard multibunch bunches. These are to be sliced one at a time with a fs-laser at a 6 kHz rate.

All these four groups or any subset may be configured, defining the desired fill pattern for the next user-run.

Error Handling

Problems that may occur during top-up mode are divided into five classes:

Top-up interlock Causes pausing or termination of top-up operation (includes full or partial beamloss).

Positioning mismatch A shot that is not appearing at the position it was targeted at may be caused by a timing failure, or a diagnostic problem. No further reliable exact positioning is possible until resolved. Immediate fallback to round-robin positioning of injection shots.

Injector failure Resulting in insufficient booster current will suspend injections for some or all bunch groups.

Depending on the actual available booster current, the fill pattern control engine may leave out any bunch-groups that could not be filled without violating the minimum booster current limit for a proper injection efficiency measurement.

I^2-limit exceeded Impedance related power deposit in components scales with the sum of the squared bunch currents. To protect sensitive components, an appropriate limit is defined.

Persistent efficiency problems Since top-up interlocks are inactive during beamscrubbing, the fill pattern control engine itself will suspend injections to avoid activation of components and damages.

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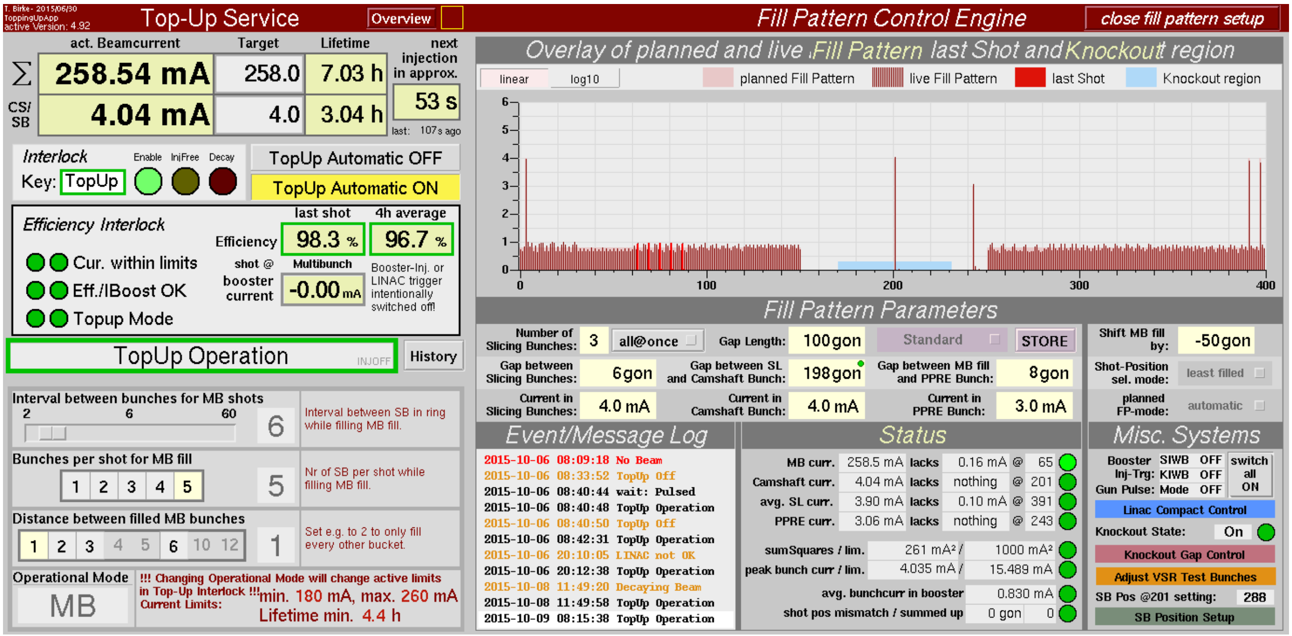

Figure 2: Top-Up Service and Fillpattern Control panel in standard multibunch hybrid mode. It contains a multibunch train, a purity controlled high current camshaft bunch in an ion clearing gap for pump/probe experiments and a mechanical pulse picking chopper, three high current bunches for femtosecond slicing and a specific bunch at the end of the gap for PPRE.

All these error conditions are handled properly by either suspending injections until the error-condition disappears or falling back into decay mode until problems are fixed manually by operations staff.

Reliable countdown

Sensitive experiments require a reliable prediction of start and end of the decay-phases between two injections.

In top-up operation mode, after each shot an estimation is made on when the next injection shot will be necessary depending on actual current and lifetime of the stored beam. Users can rely on this countdown, so even if beam-lifetime is decreasing e.g. due to insertion devices moving at low gaps, no injection is triggered before the reliable countdown has elapsed.

Fillpattern Control Engine – Next Steps

An update to the fill pattern control engine is currently in development, that has a more general approach. It will enable configuration of an arbitrary number of bunch-groups with a few general parameters:

- Affected bunches – range definition in MATLAB notation: *startpos:endpos:stepwidth*.
- Current to be stored in every bunch of this group.
- Additional flags e.g. whether the given current may be adjusted to match the desired overall target current.
- Prioritization of bunch groups.

Besides the currently supported fill patterns, this scheme will enable special fill patterns like alternating bunches with high and low current which is used as a test setup for BESSY-VSR [6] studies, or additional bunches with varying currents (down to 5 μA) for even shorter pulses in low-α mode.

CONCLUSION

A fully automated injection control software is absolutely essential for top-up operation with a fill pattern tailored to the users needs at BESSY II.

It has also completely replaced the manual injection procedure during low-α runs, machine- and beamline-commissioning and machine studies as well as for beam-scrubbing at high stored currents.

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