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

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Comprehensive Fill Pattern Control Engine: Key to Top-Up Operation Quality – T. Birke – ICALEPCS’15 – Melbourne

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- Transition to Top-Up Operation – Implications
- Fill Pattern Control Engine – Structure, I/O, Error Handling, UI
What is the Bunch Fill Pattern at BESSY II?

- BESSY II provides specific support for time resolved experiments
- Pioneered low-α mode with coherent THz radiation and ps-pulses (2002)
- Most advanced fs-slicing endstation with 100ps pulses (2004)
- High current single bunch in ion-clearing gap
  - Pump/probe experiments (2004)
  - Singlebunch experiments at full or reduced intensity
    - Mechanical chopper (2013)
    - Pulse Picking by Resonant Excitation (PPRE, 2015)

Possible because any particular bunch may be filled and topped up to a configured intensity!
Transition to Top-Up Operation (2012)

- **Top-Up**: Refill decaying beam and keep stored beam current at level while beamshutters are open
- Thermal equilibrium – stabilized machine
- Higher average and close to constant intensity in photons
  - Integrated Ah/week increased by ~30%
- All configured bunches have to be topped up with minimal variation to programmed intensities

**Graphs:**
- Beamcurrent over one week before top-up – decaying beam (1998-)
  after switching to topup (2012-)
- Net gain of photons
Goal: No additional radiation in experimental hall
- Analysis of facility properties and malfunction scenarios
- Make sources of minimal damages measurable
  - Accurate efficiency and current measurements
- Guarantee minimized losses by setting up constraints
  - Interlocks block further injections on any violation

⇒ Defined Constraints for Top-Up Operation:
- Injection efficiency > 60 % for every shot (booster → ring)
- 4h-average of injection efficiency > 90 %
- Max. injection frequency 0.1 Hz
- Min. current in booster for reliable efficiency-measurement
- Min. and max. current limit in ring with corresponding minimum lifetime („normal“ losses < ~ 60 mA / h):
  - nom. 200-300 mA at \( \tau > 5 \) h (curr. 180-260 mA at \( \tau > 4.4 \) h)
Top-Up – Constraints: Interlocks

Top-Up Efficiency Interlocks
- Two separate systems check all constraints
  - Currents, lifetime, efficiency
- Both have to approve top-up operation to continue
- Violation inhibits further injections until conditions fixed
  - Injection free time or decay mode
  - Closing beamshutters may be necessary

Top-Up Interlock
- Extension of Personnel Safety Interlock (PSI)
- Ensures base injection trigger is at 0.1 Hz
- Together with PSI and efficiency interlocks
  → Grants or denies injection- and beamshutter-permission
Tasks of the Fill Pattern Control Engine:

- Manage the entire injection process to fill storage ring
- Fill it according to the configured bunch fill pattern
- Keep stored currents in any bunch as stable as possible with minimal variations
  - Currently max. $\sim 1.6 \text{ mA} / \text{shot}$ resp. $\sim 0.3 \text{ mA} / \text{bunch} / \text{shot}$ → variation $< 0.5 \%$
  - Injections every 10 s - 200 s average $\sim 120 \text{ s}$
- Handle exceptions properly
  - Top-Up interlocks
  - Injector failures
  - Timing flaws
  - …
Consists of three parts

Finite State Machine controls injections
- 5 core states + ~10 transitional states

Fill Pattern Analysis
- Asynchronous on every fill pattern
- Determines next shot configuration

EPICS realtime database
- Configuration interface
- Reflects internal status of state machine and analysis
- PVs visible everywhere on the network: alarmhandler, archiver, information systems for users, web based status displays...
- Fill pattern control engine is a pure software device
Fill Pattern Control: Input Signals

- State and processed data of top-up interlock systems
- Fill pattern measurement system
  - PXI based fast ADC and stripline
  - Down to 100 nA per bunch current resolution
  - Averaged data provided at 1 Hz by LabVIEW application
- Global overall beamcurrent and lifetime measurement
- State of extraction- and injection-elements as well as the overall injector status from linac to booster synchrotron
Injection Setup
- Linac setup (number and interval of pulses)
  - 1-5 pulses at typical interval of 12 ns
    (12 ns = resolution of slicing laser timing)
- Suspend/resume injector
- Pulsed elements for extraction & injection
- Global timing for shot-positioning
- Global trigger enable/disable

Reliable Countdown
- Sensitive experiments need reliable prediction of duration of decay phases between injections
- Calculated after injection shot based on actual stored current, average lifetime and configured target current
- Promise to users: No injections before countdown expires
User Input:

- Total target current
- Shape of bunch train from linac
- 4 groups of bunches:
  - Multibunch fill
    - gap length and position
  - Camshaft bunch
    - current
  - Slicing bunches
    - number, position, interval and current
  - PPRE bunch
    - position and current

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Fill Pattern Control: Error Handling

- **Top-up interlock**
  - May pause or terminate to-up operation due to violation of radiation safety constraints

- **Injector problems/failure**
  - Detected by monitoring linac status and
  - Current accelerated in booster synchrotron

- **Positioning mismatch**
  - No exact positioning possible – fallback to round-robin

- **$l^2$-limit exceeded**
  - Impedance induced power deposit in components scales with sum of squares of bunch currents.
    - Software "interlock" to protect sensitive hardware

- **Persistent efficiency problems** during beamscrubbing
  - Top-up inactive, so software has to prevent damages
Fill Pattern Control: User Interface

Top-Up Service and Fill Pattern Control Panel

Overall Status

Bunch Fill Pattern Display

Multibunch Fill Setup

Informational Area

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Extend possibilities of fillpattern definition

- Overcome limitations of fillpattern configuration
- Define arbitrary number of separate bunch groups
  - Range of bunches to fill: `startpos:endpos:stepwidth`
  - Current per bunch
  - Priority of group
  - Scalability of current to match overall total current
- Enables even more special fillpatterns
  - BESSY-VSR studies
  - Lowest-current bunches (down to 5 µA)

Overhaul of User Interface
The standard tool to fill machine in any operational mode
  - Top-Up operation (Multibunch-Hybrid and Single Bunch)
  - Commissioning & machine studies
    - Low-α (decaying beam, 1-2 injections per day)

Automation of injection procedure to maximum degree
Working horse since day one of Top-Up Operation
Provides exactly the programmed bunch fill pattern (even with on-the-fly changes) with smallest possible variations.