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

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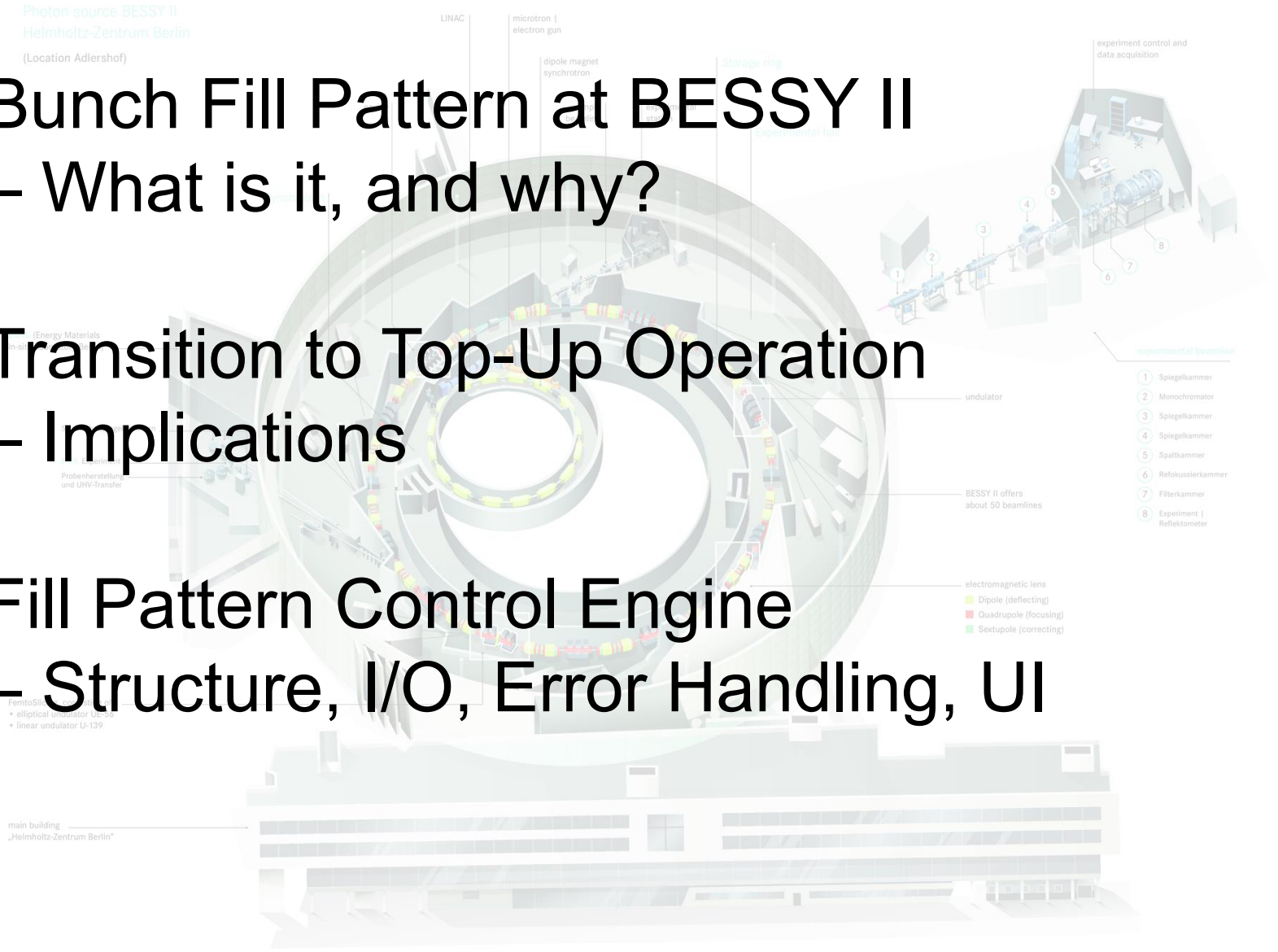
Contents

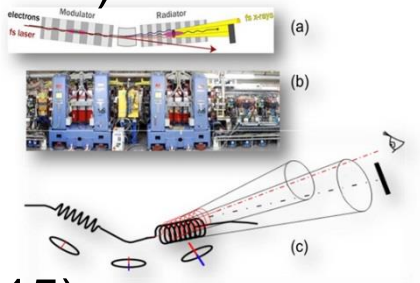
- Bunch Fill Pattern at BESSY II
  - What is it, and why?
- Transition to Top-Up Operation
  - Implications
- Fill Pattern Control Engine
  - Structure, I/O, Error Handling, UI

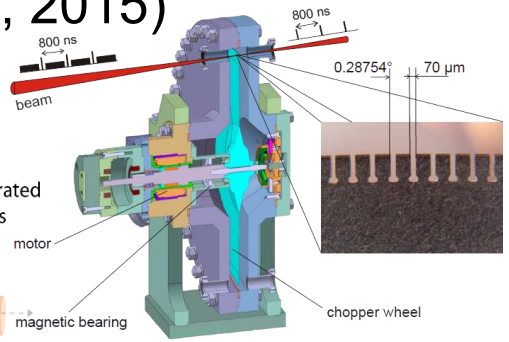


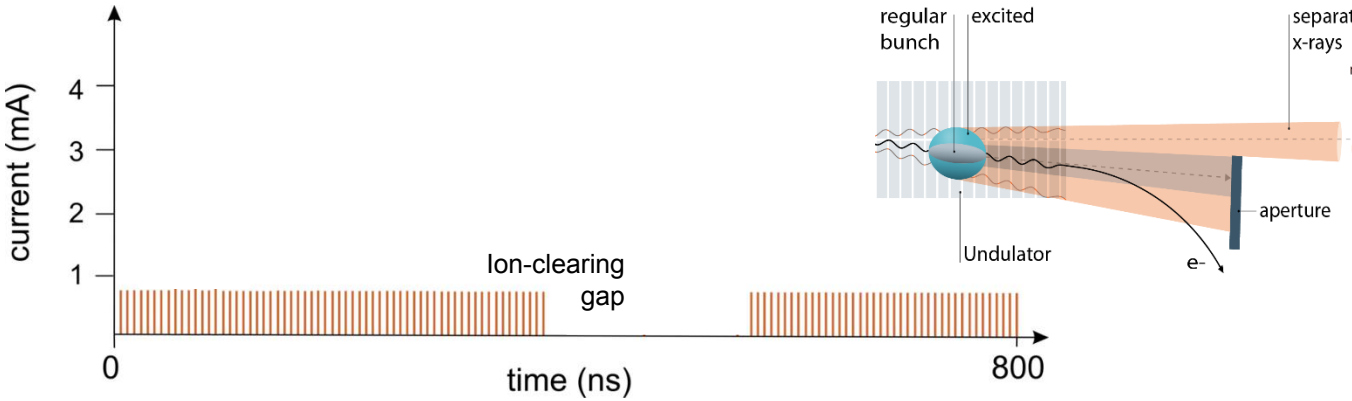
What is the Bunch Fill Pattern at BESSY II?

- 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!

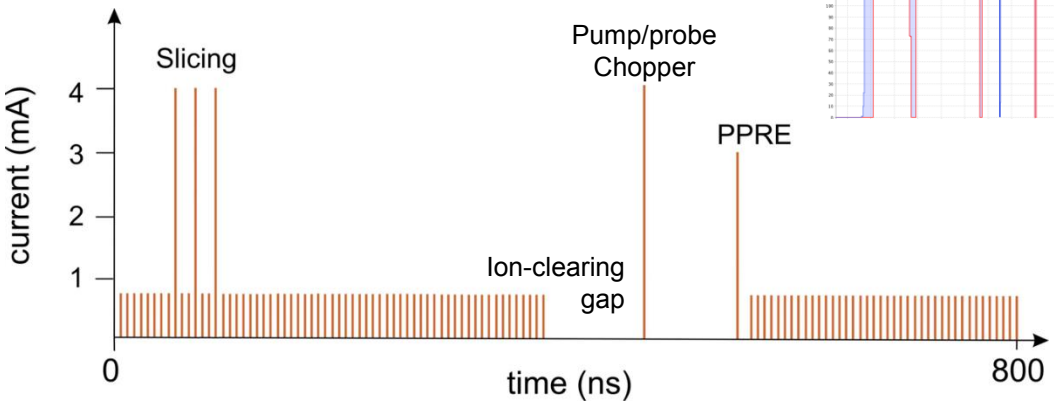


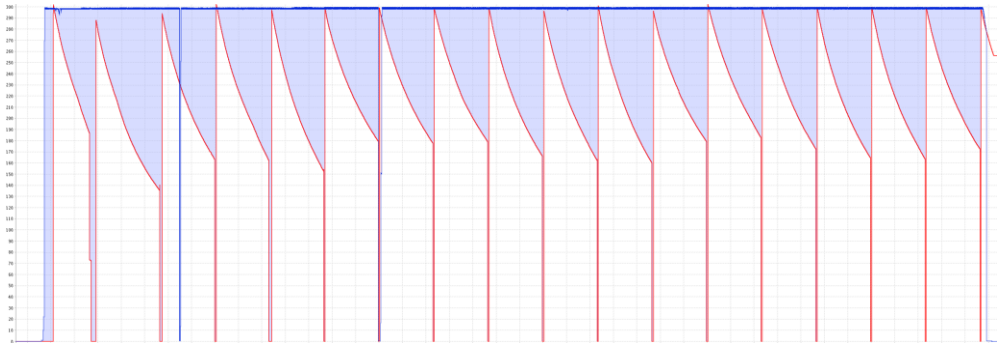




Transition to Top-Up Operation (2012)

- **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





Beamcurrent over one week
before top-up – decaying beam (1998-)
after switching to topup (2012-)
net gain of photons

Top-Up – Constraints: Radiation Safety

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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 τ > 5 h (curr. 180-260 mA at τ > 4.4 h)

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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

Fill Pattern Control Engine

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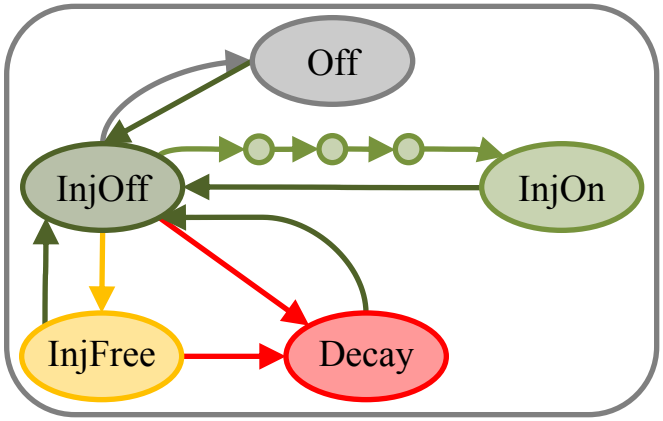
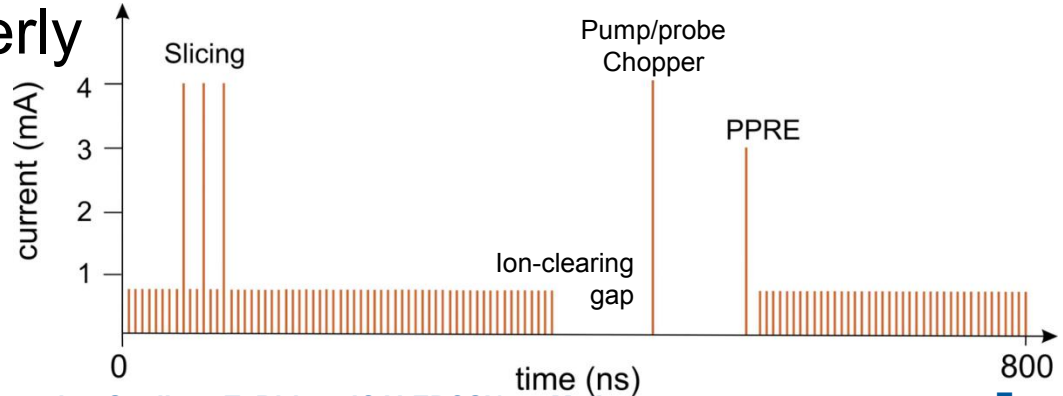
Tasks of the Fill Pattern Control Engine:

- 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. ~ 1.6 mA / shot resp. ~ 0.3 mA / bunch / shot → variation < 0.5 %
  - Injections every 10 s - 200 s average ~ 120 s
- Handle exceptions properly
  - Top-Up interlocks
  - Injector failures
  - Timing flaws
  - …





Fill Pattern Control: Program Structure

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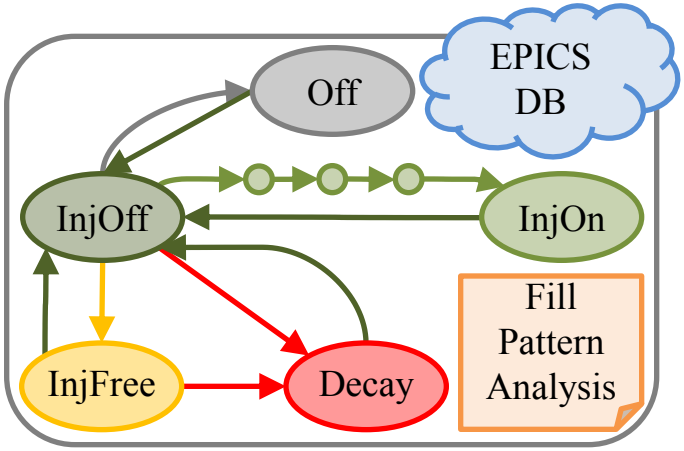
Consists of three parts

Finite State Machine controls injections

- 5 core states + ~10 transitional states

Fill Pattern Analysis

- Asynchronous on every fill pattern
- Determines next shot configuration

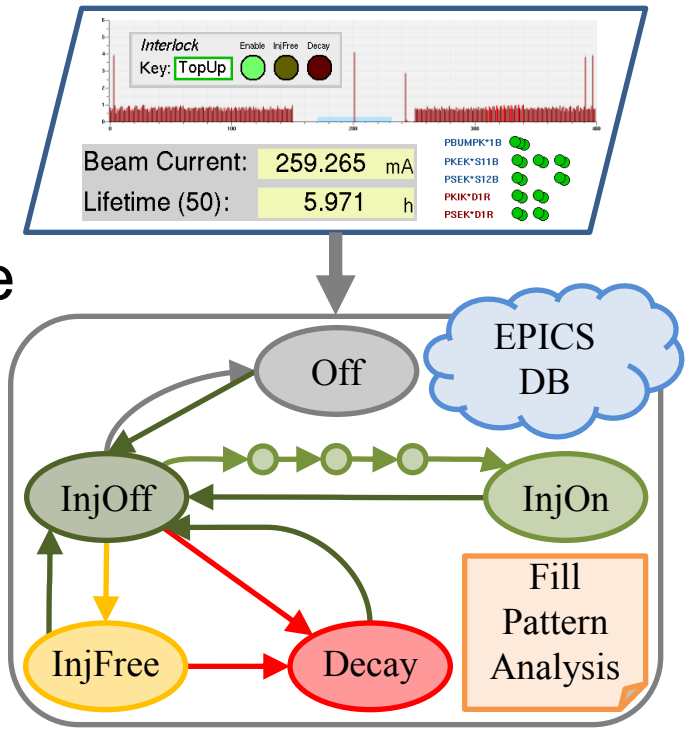


EPICS realtime database

- 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



Fill Pattern Control: Controlled Elements

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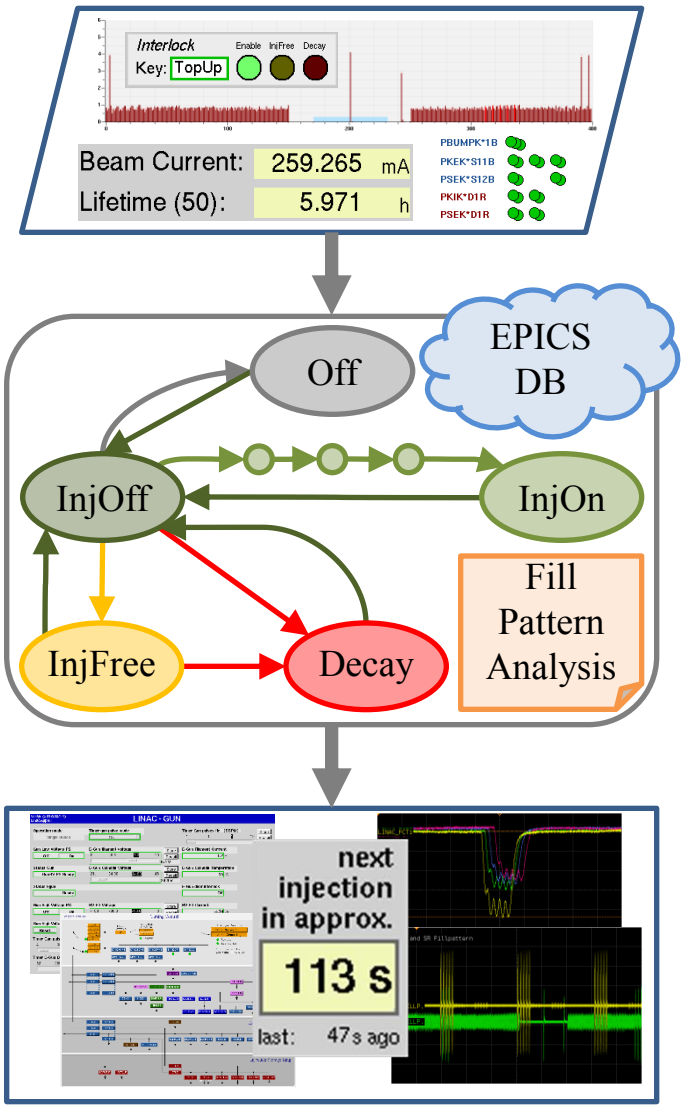
Injection Setup

- 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 predicion 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



Fill Pattern Control: Configuration

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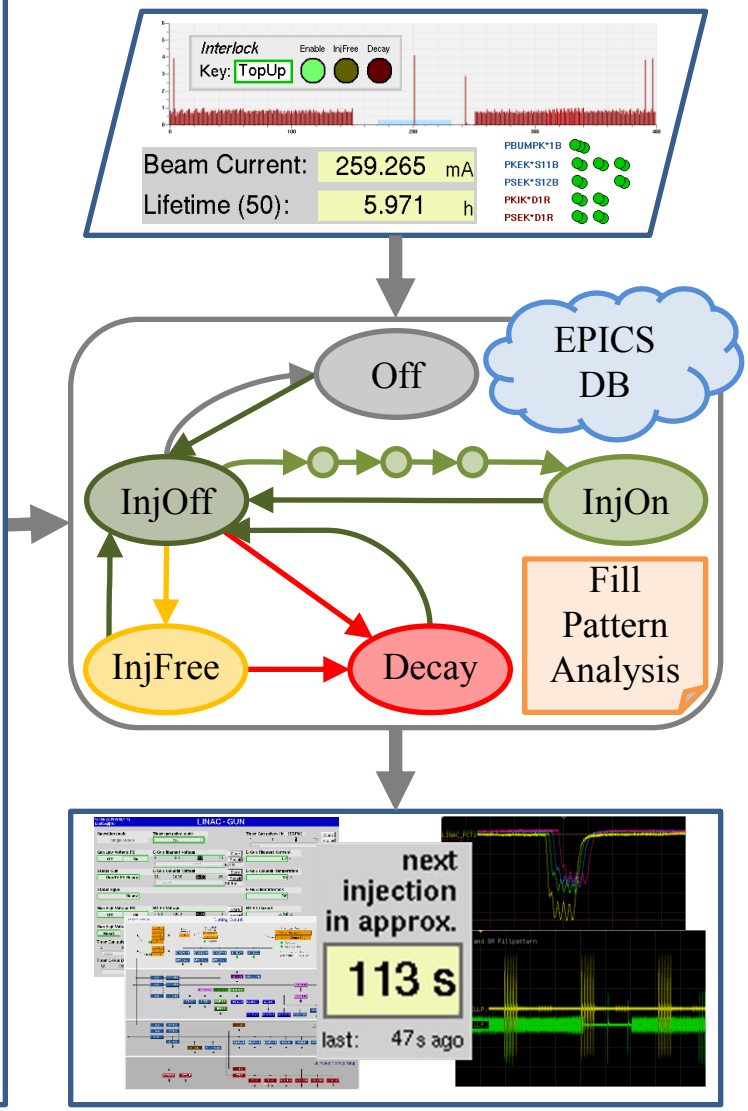
User Input:

- 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*



Fill Pattern Control: Error Handling

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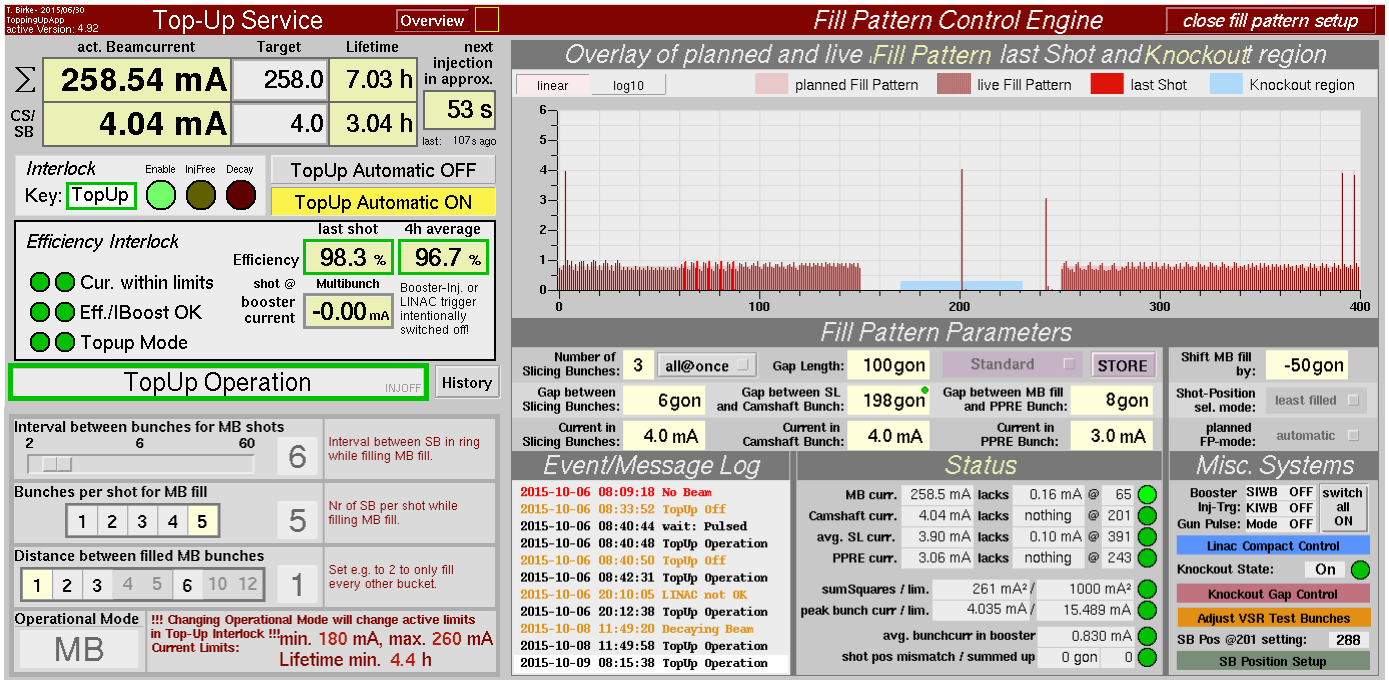
- **Top-up interlock**
  - May pause or terminate to-up operation due to violation of radiation safety constraints
- **Injector problems/failure**
  - Detected by monitoring linac status and
  - Current accelerated in booster synchrotron
- **Positioning mismatch**
  - No exact positioning possible – fallback to round-robin
- **I^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



Fill Pattern Setup

Multibunch Fill Setup

Informational Area

Next steps

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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 curent
- Enables even more special fillpatterns
  - BESSY-VSR studies
  - Lowest-current bunches (down to 5 µA)

Overhaul of User Interface

Conclusion

- *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.