



**HELMHOLTZ  
ZENTRUM BERLIN**  
für Materialien und Energie

# **Automated Operation of the Metrology Light Source Storage Ring**

**Thomas Birke**

based on work of

T. Birke, M. Abo-Bakr, D. Engel, J. Feikes, B. Frankesen, M. v. Hartrott, G. Wüstefeld, ...

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## What is the Metrology Light Source (MLS)?

- Low energy  $e^-$  storage ring
- Metrology and technological developments in UV/XUV as well as IR and THz
- Optimized for generation of coherent SR in FIR/THz
- Owner:  
**Physikalisch-Technische Bundesanstalt (PTB)**  
German national metrology institute
- Built according to PTB specifications and operated by **BESSY** which is now part of the new **Helmholtz-Zentrum Berlin für Materialien und Energie GmbH**
- In regular user operation since April 2008





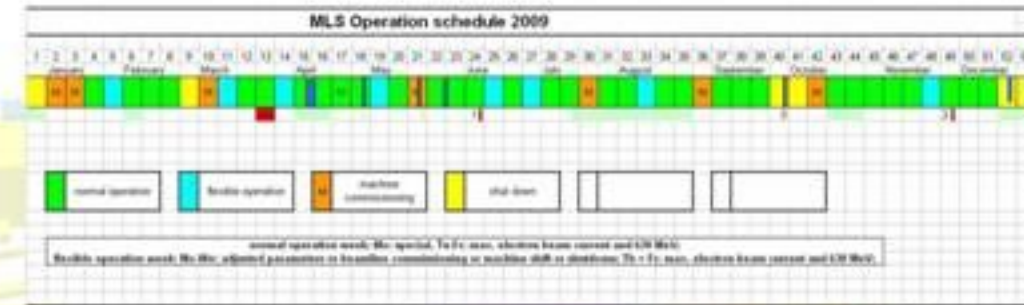
## Operating the Metrology Light Source

- Wide range of operating modes and parameter settings
  - Current: **1 pA** (a single electron) up to **200 mA**
  - Energy: **105 MeV – 629 MeV**
  - Momentum compaction factor  $\alpha$ : varies by factor of **~1000**
- Electromagnetic Undulator
  - strong **non-linear fields enforce compensation** with correction coils using fully automatic **feed-forward system**  
– otherwise impossible to accumulate and store beam
- Injection setup differs from operation setup
  - Orbit bump
  - Asymmetric sextupole settings
  - RF frequency modified



## Operating the Metrology Light Source

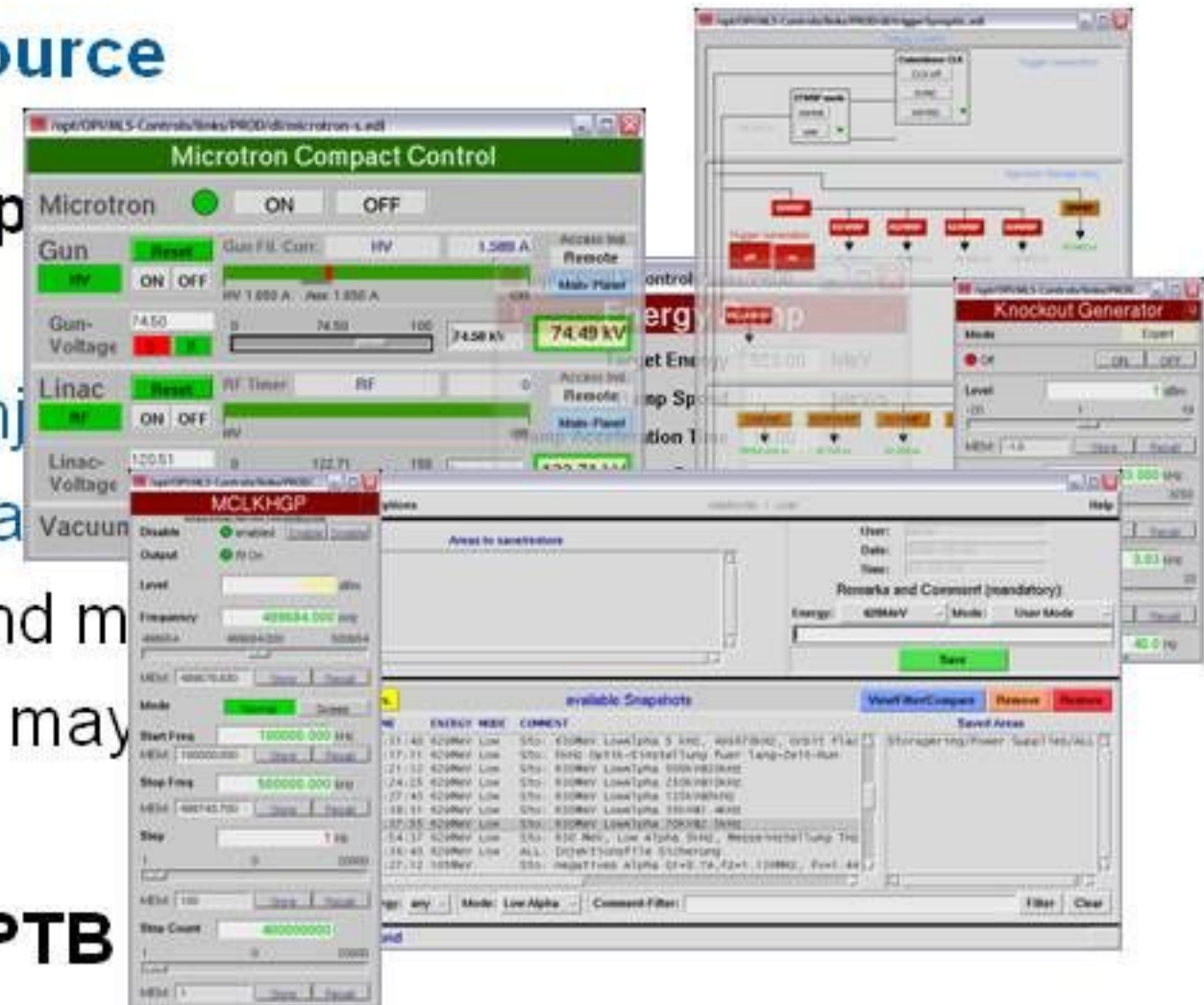
- Specialties require complex procedures
- Setup changes often according to user demands
  - Even **on short notice**
- **Energy Ramp** before and after injection with minimum loss of beam
  - **Special procedure**
  - **also used as degaussing cycle**
  - But: Magnets not driven into full saturation*
  - Machine performance is very sensitive to magnet-setting-errors
- **Optics Change** program to change momentum compaction factor
  - **Another special procedure** (similar to Energy Ramp)





## Operating the Metrology Light Source

- Several tasks to be performed by operator
  - Inject up to desired current
  - Ramp energy – before and after injection
  - Change optics (momentum compaction)
- All tasks require **several actions** and many steps
- Any **error** (esp. in magnet settings) may affect performance
- Operated by **BESSY/HZB** staff for **PTB**
  - Paid customer service
  - Deliver **high operational reliability** with maximum transparency and minimum personnel effort
- **High degree of automation required!**





## Software System – Status at the Beginning

- Several localized sub-tasks already realized in separate applications
  - Energy Ramp, Optics Change (Momentum Compaction Factor)
  - Optimizing microtron output
  - Orbit Correction, RF Master Clock Controller, ID-controls...
- **What** action to perform **how** and **when**? – Organized by operator
  - Expertise is in the heads – sometimes even documented
  - All signals needed to decide what to do and when are available in control system (**EPICS** – Experimental Physics and Industrial Control System)
- Decided to develop one **central application** to coordinate necessary tasks
  - **Operation Master**
  - Software model: **Finite State Machine**



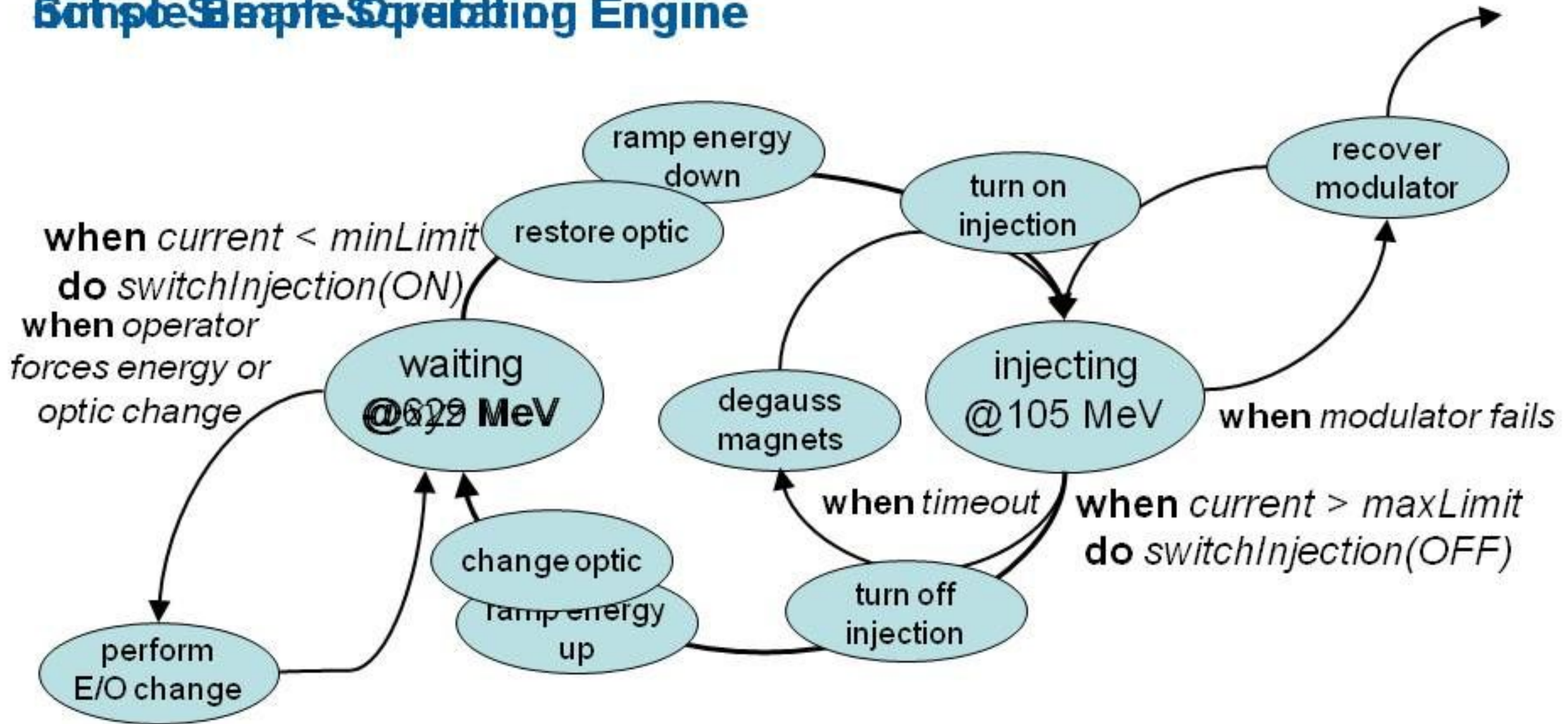
## Software System – Finite State Machine (FSM)

- Set of **States** of a described system
  - *States* represent all possible (known) states of the machine
  - *Active state* resembles current machine-state
  - Software and machine are to be kept in sync
- **Transitions** between these states
  - Well defined conditions unambiguously force *transitions* into other states
  - All *transitions/conditions* of active state checked on every incoming event
    - Change of a control system process variable
    - Timeout
- **Actions** may be performed on transition and/or when entering a state



# Software System – Finite State Machine

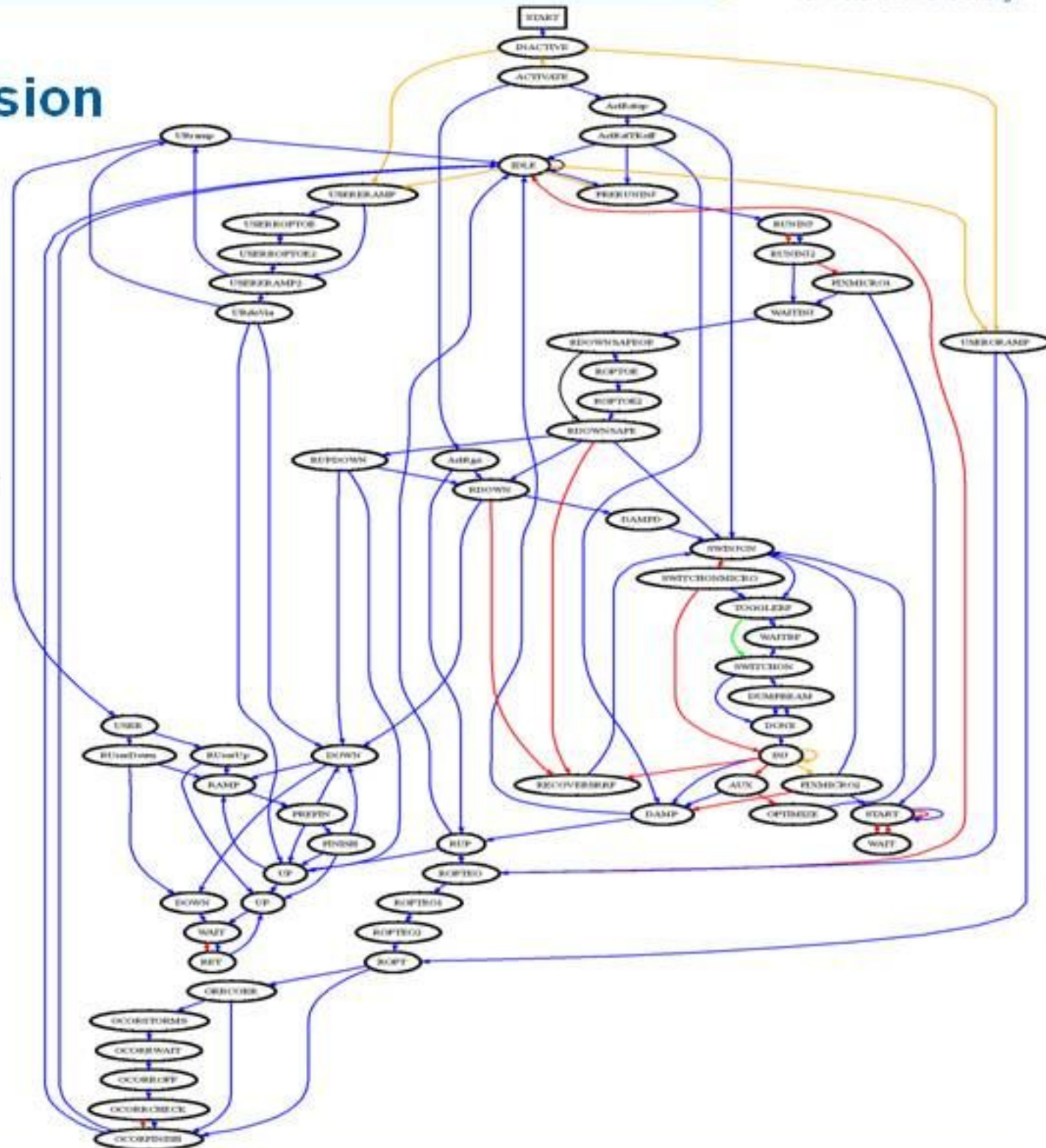
## Sample Spreading Engine





## State Machine – Current Version

- **Blue**
  - In-Sequence transitions “expected”
- **Orange**
  - Out-of-Sequence transitions “unexpected” or Operator interaction
- **Red**
  - Error transitions
- Image created by *GraphViz* ([www.graphviz.org](http://www.graphviz.org))
- Input to *GraphViz* created by *Operation Master*









## Operation Master – Development

- Whole system *not* developed by design according to full specification
  - **State Engine** – as generic as possible/necessary
  - **State Machine** – unspecified, very simple first version
- **Evolutionary** development process (still going on after 18 months)
  - **Experiences** of **commissioning** and **daily use** of application itself
  - Yet unhandled states only identified when using the application
  - Solutions to problems often roughly sketched → **refinement phase**
  - Clear view of solution often arises during discussions between developer and users/scientists → **close cooperation** drives development
  - Numerous **small development steps**
    - Some removed in favor of other solution or have proven obsolete during further commissioning



MLS Operation Master

Settings  
Mode | Injection | Energy Ramp

Beam Scrubbing User Operation

act. Current: 109.4476 mA  
act. Energy: 630.0 MeV  
Injection/Trigger: off  
RF-Freq: 499884.000 kHz

Waiting for min. current (80mA)

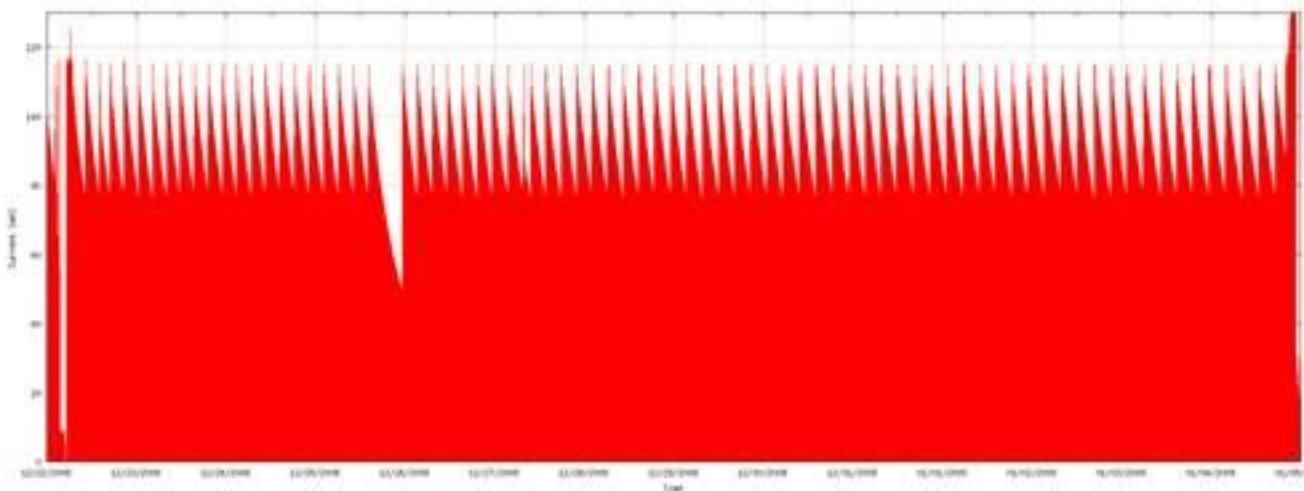
Command  
Force Injection now!

Log  
08:52:55 waiting for RF-Freq to reach 499884kHz  
08:53:10 switching injection ON  
08:53:17 switching injection OFF  
08:53:17 Beamstop finished  
08:53:19 Waiting for min. current (80mA)



## Operation Master – First successful longer Run

- Performed well for two unmanned weeks during holiday break 2008/2009
  - Just one unidentified problem with microtron modulator PLC
  - Manual intervention necessary
  - Action became part of command sequence to recover from PLC errors



beamcurrent over two weeks





## Operation Master – Implementation

- First version written in **Tcl/Tk**
  - Proper choice for **rapid prototyping**
  - **Monolithic** application
    - State machine, subprocess-control graphical user interface (GUI)

**MLS Operation Master** [About]

Settings  
Mode: **Injection** | Energy Ramp

**Beam Scrubbing** | User Operation

Minimum Current: 80 mA [set]  
Maximum Current: 110 mA [set]  
Aux. Current (if Inj. timed out): 80 mA [set]

**Force Injection now!**

Readbacks and Status  
act. Current: **109.4476** mA  
act. Energy: **630.0** MeV  
Ramp-State: **Stop**  
Ramp-Tables: **static.up**  
Injection/Trigger: **off**  
RF-Freq: 499684.000 kHz

Waiting for min. current (80mA)

Commands  
**Active!** [Stop] [Standby] [Quit]

History  
08:52:54 change RF-Freq  
08:52:55 waiting for RF-Freq to reach 499684kHz  
08:53:10 switching injection ON  
08:53:10 Injection running (110mA)  
08:53:17 Target Current reached  
08:53:17 Damping  
08:53:17 switching injection OFF  
08:53:17 Damping finished  
08:53:17 Ramping up  
08:53:17 tables reloaded  
08:53:19 Ramping finished  
08:53:19 Waiting for min. current (80mA)

**MLS Operation Master** [About]

Settings  
Mode: **Injection** | Energy Ramp

Damping Time before Ramp Up: 0.1 s [set]  
Target Energy to ramp up to: 450 MeV [set]

**Ramp to specified Energy**

previous ramp direction: Down  
changing ramp direction will need to ramp through the end-point of the ramp in current ramp-direction (105MeV req. 620MeV)

Force RF-voltage to be energy ramped

**Cycle Magnets using Energy Ramp**

Readbacks and Status  
act. Current: **105.2140** mA  
act. Energy: **470.2** MeV  
Ramp-State: **Go**  
Ramp-Tables: **static.down**  
Injection/Trigger: **off**  
RF-Freq: 499684.000 kHz

Ramping

Commands  
**Active!** [Stop] [Standby] [Quit]

History  
08:59:22 Target Current reached  
08:59:22 Damping  
08:59:22 switching injection OFF  
08:59:22 Damping finished  
08:59:22 Ramping up  
08:59:22 tables reloaded  
08:59:24 Ramping finished  
08:59:26 Waiting for min. current (80mA)  
08:59:27 Ramping Energy in Operation-Stop  
08:59:33 Ramping to 450 MeV  
08:59:33 switching ramp-tables to static.down  
08:59:34 tables reloaded

### • But:

- Only one instance can be running at a time
- Application only visible on a single screen
- **Idea:** split FSM and GUI, simplify interfaces
- Rewrite in *Python* considered



## Operation Master – ~~Future~~ (as planned in spring 2009) and modified

- Operation Master redesigned and ~~new implementation in progress~~
    - **Headless server** process
      - State machine and state engine only
      - ~~Written in Python programming language~~
    - All interaction using **control system process variables**
    - **Remote-control** from other applications
  - Use of **standard control system tools** (EPICS-Toolkit) for
    - **Display** – graphical display manager can be run on **any screen**
      - EPICS Channel Access Security used to control permissions
    - **Alarm monitoring** and **logging** – operator notification and analysis
    - **Archiving** – for later analysis and debugging
- to keep the well-known, easily maintainable and settled but still evolving State Machine code*



## Operation Master – Implementation

- Current version written in **Tcl/Tk**
  - **GUI** has been factored out
  - All interaction via **EPICS PVs**
    - User as well as other software components (IPC)

MLS Operation Master Remote Control Panel  
Version of MLS Operation Master: V2.11 - (rel. 090329-1349)

**Settings**

Mode: **Injection** | Energy Ramp | Optic Ramp

Injection Timeout: 15 min  
RF-Freq. for Injection: 499710 kHz  
max. RF-Freq. step-size: 50 kHz

Dump Beam before next Injection  
 Set RF-Frequency before Injection  
 Toggle V01PMP between Injections  
 Switch off Microtron between Inj.  
 Set Septum to 0.0 between Injections  
 Run Microtron-optics during Inj.

**Readbacks and Status**

act. Current: 119.803 mA  
act. Lifetime: 9.550 h  
act. Energy: 629.0 MeV  
Ramp-State: Stop  
Ramp-Tables: Up  
Synchr.-Freq.: 5 kHz  
Injection/Trigger: off  
RF-Freq (rdbk): 499710.000 kHz

getting msll

**Commands**

**Active!** | Deactivate

**History**

09:24:57 switching injection ON  
 09:24:57 injection running (120mA)  
 09:25:52 Target Current reached  
 09:25:52 Damping  
 09:25:57 Damping finished  
 09:25:57 Ramping up  
 09:25:58 tables reloaded  
 09:26:14 Ramping finished  
 09:26:14 checking existence of Optic Ramp tables  
 09:26:14 switching to LowAlpha tables  
 09:26:14 preparing to ramp Optic S->O  
 09:26:15 Ramp Optic S->O  
 09:26:20 Ramp Optic  
 09:26:20 getting msll  
 09:26:25 running automatic Orbit Correction for a few seconds

MLS Operation Master Remote Control Panel  
Version of MLS Operation Master: V2.11 - (rel. 090329-1349)

**Settings**

Mode: **Injection** | Energy Ramp | Optic Ramp

Minimum Current: 60 mA  
Maximum Current: 120 mA  
Aux. Current (if Inj. timed out): 90 mA

**Readbacks and Status**

act. Current: 87.780 mA  
act. Lifetime: 0.088 h  
act. Energy: 105.0 MeV  
Ramp-State: Stop  
Ramp-Tables: Up  
Synchr.-Freq.: nan kHz  
Injection/Trigger: on  
RF-Freq (rdbk): 499710.000 kHz

Injection running (120mA)  
Timeout: 4:01 min

**Commands**

**Active!** | Deactivate

**History**

08:57:55 tables reloaded  
 08:58:06 Ramping finished  
 08:58:06 tables reloaded  
 08:58:06 Switching injection ON  
 08:58:06 Damping  
 08:58:11 Damping finished  
 08:58:11 Microtron On?  
 08:58:11 Microtron is on  
 08:58:11 change RF-Freq  
 08:58:11 waiting for RF-Freq to reach 499710kHz  
 08:58:12 switching injection ON  
 08:58:12 dumping beam  
 08:58:21 partial beam-loss (11.8 mA -> 4.1 mA, 65% loss)  
 08:58:21 beam dumped  
 08:58:21 injection running (120mA)

• **So:**

- *Operation Master* now is a windowless background process (run on a central server)
- Can be monitored/controlled from anywhere
- Simplified interfaces lead to even more stable machine operation



## Conclusion

- *Operation Master*: **indispensable operator instrument** since day one
- **Minimizes errors** by performing complex command sequences
- Implements **standard mechanisms** to set up certain states as well as to recover from failure situations
- Will be **extended** to cover all **future standardized tasks** at MLS as well

*Experiences and success encourage using the same system for existing as well as future projects at BESSY/HZB*