



Elettra
Sincrotrone
Trieste

A FRAMEWORK FOR HIGH LEVEL MACHINE AUTOMATION BASED ON BEHAVIOR TREES

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on behalf the Sequencer TEAM

✓ Automation frameworks:

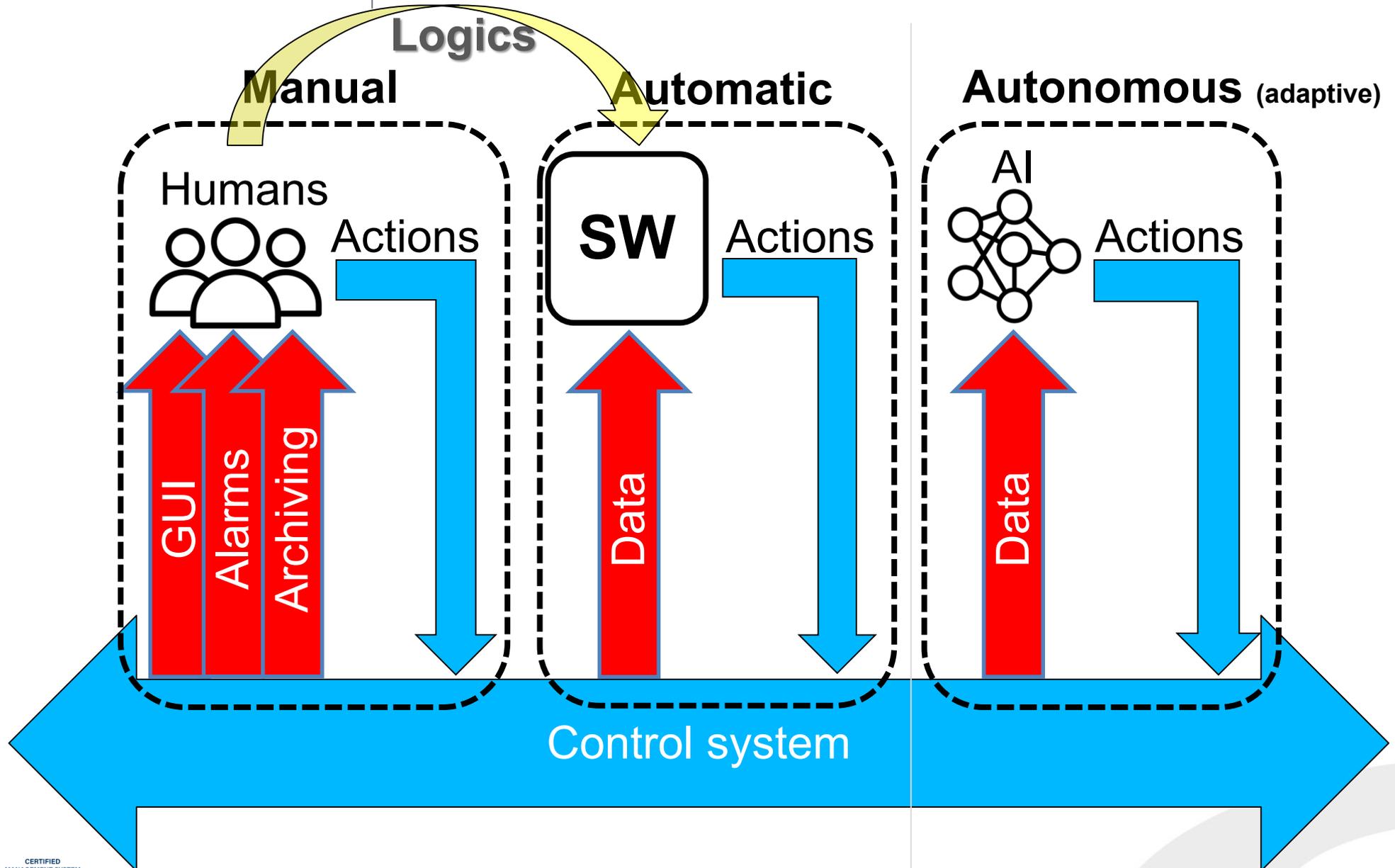
- *The Colliding Beam Sequencer (FNAL - PAC89)*
- *Automating ELETTRA Operation with One Button Machine (Elettra - IPAC97)*
- *The RIHC Sequencer (BNL - PAC01)*
- *A sequencer for LHC ERA (CERN - ICALEPCS09)*
- *Automated operation of ITER using behavior tree semantics (ITER – this conference **WEPV006**)*
-
- EPICS sequencer
-

SOLEIL, DESY....and many many others

Sorry if I haven't mentioned your work!



Toward full automation



Automation metric

- ✓ For a user facility like a synchrotron **full automation** means:
 - Recover from a beamdump, reinject and give a stable beam to the users without any human intervention
- ✓ A metric to measure human intervention is:
 - **Quantum of human-computer interaction (Qhci)**: one click on a keyboard/mouse in the control room during user and machine tuning shifts

$$AL(U) = \sum [Q_{hci}(U)]_{\text{per day}}$$

$$AL(T) = \sum [Q_{hci}(T)]_{\text{per day}}$$

↑

$$\text{Automation Level} = AL(U) + AL(T)$$

$$AL = 0 \text{ autonomous machine}$$

Scripting language

- ✓ Move logics from GUIs and stand alone scripts to server side applications (tango servers)
- ✓ Speed up the knowledge transfer by involving more people
- ✓ Minimize bugs by privileging configuration instead of programming
- ✓ **Home-made scripting language** (based on C++ Boost.Spirit parser)
 - Implement IF/ELSE (conditional ternary operator “? :”) and the “harmful” GOTO statements

Language syntax

```
stepN;[expression];[step description];[error message];[timeout ms.];[catch exceptions]
```

Sequence example (reset and turn ON a power supply):

```
step1;read(sr/ps/ch_s1.1/State)==FAULT ? command(sr/ps/ch_s1.1/Reset) && goto(2) : goto(3);Reset PS;Error resetting PS;3000  
step2;read(sr/ps/ch_s1.1/State) != OFF ? sleep(1) && goto(2) : goto(3);Waiting OFF state;Timeout waiting OFF state;6000  
step3;read(sr/ps/ch_s1.1/State) != ON ? command(sr/ps/ch_s1.1/On) && goto(4) : goto(5);Turn PS ON;Error turning ON PS;3000  
step4;read(sr/ps/ch_s1.1/State) != ON ? sleep(1) && goto(4) : goto(5);Waiting ON state;Timeout waiting ON state;6000
```

Description:

step1; If PS is in FAULT state then Reset and **go to step2**, otherwise **go to step3**

step2; if PS is not OFF then sleep one sec and check again (max 6 sec.), otherwise **goto step3**

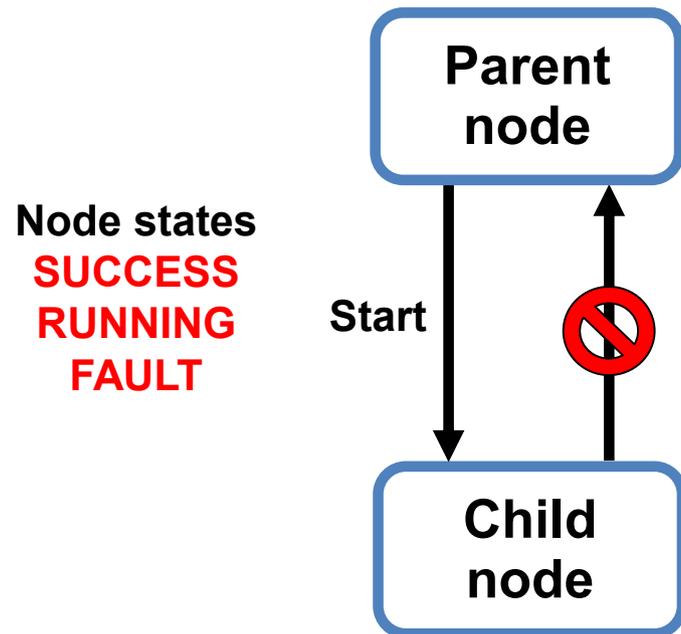
step3; if PS is not ON turn PS ON and **go to step4**, otherwise **go to step5** (exit)

step4;if PS is not ON then sleep one sec and check again (max 6 sec.), otherwise **go to step5** (exit)

Behavior Trees

✓ Used by AI in video games (Unreal Engine), UAV...

Direct Acyclic Graph



The **parent node starts** the execution of the **child node** and **waits** it to complete the task. If the **child node** goes in **FAULT** state then also the **parent node** will end in **FAULT** state.

Structural nodes:
sequence, composer, fallback,
selector, decorator

A node executes a **real action** or implements **the structure of the BT**:

- start child nodes in series
- start child nodes in parallel
- invert the returning state of a child node
- Execute at least one child node from a multitude
- Conditional execution between two child nodes
-

All nodes are implemented with the scripting language



Tree node: the Sequencer

The Sequencer is a Tango device implementing a task

Sequence
TXT file

Sequence
Tango DB property

TANGO

Sequencer

C++ Tango
server

Logs

sequence

Task

R/W
dynamic
attributes

Control system

Commands

START: starts the sequence
STOP: stops the sequence
ABORT: aborts execution
PAUSE: freezes the sequence
GOTO: jumps to a step

R/W dynamic attributes

Thresholds
Constants
Internal variables...

Start Matlab, Python,
bash scripts,....(exec
sys call)

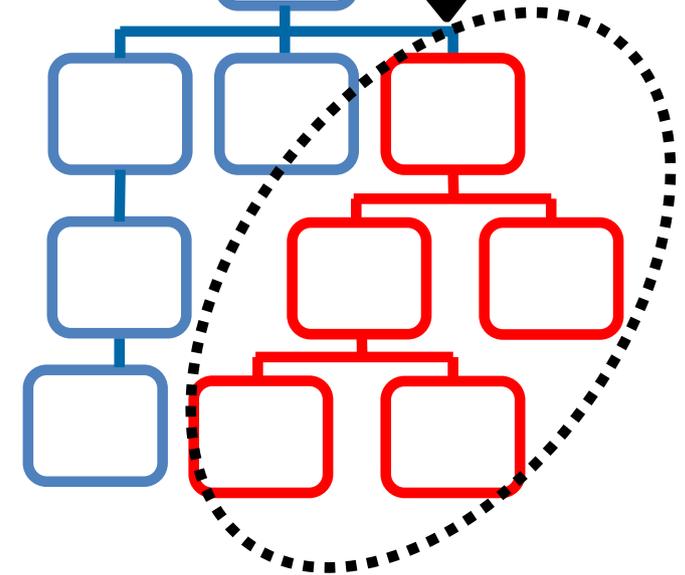
States

OFF: sequencer not running
RUNNING: sequencer is running
FAULT: sequencer failed
STANDBY: sequencer frozen
ALARM: syntax error

Start

Pause

Root
node

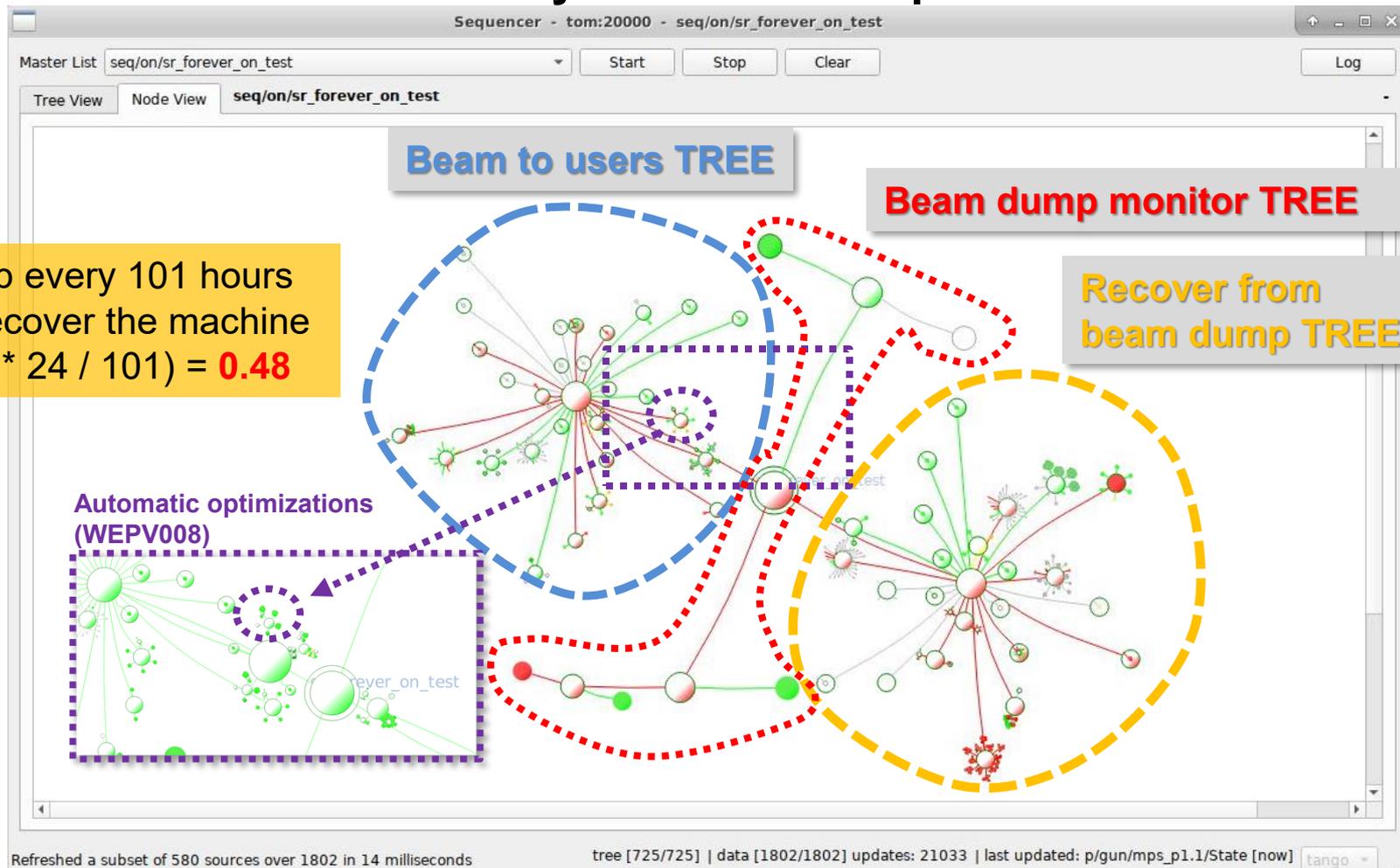


Can propagate **Stop**, **Abort** and
Pause command through a sub-
tree

Sequencer GUI (Node view)

All graphical interfaces (Qt-Cumbia) are automatically generated by getting information from the Tango Database and by dynamically exploring the Behavior Tree.

Elettra synchrotron autopilot



1 beamdump every 101 hours
2 clicks to recover the machine
 $AL(U) \geq (2 * 24 / 101) = 0.48$

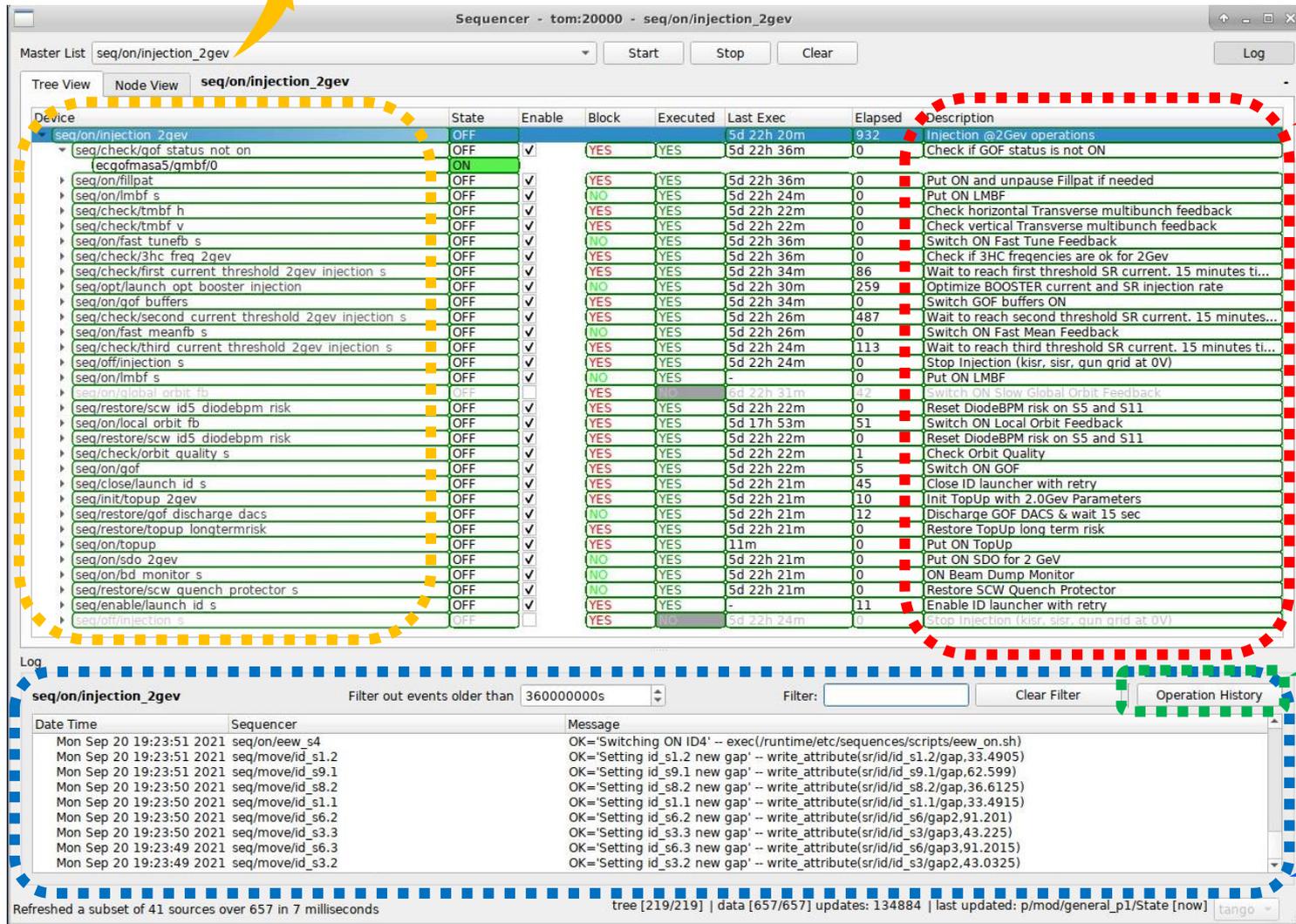
725 nodes

1802 attributes

Sequencer GUI (Tree View)

Sequencer that refills the storage ring till giving stable beam to the users

Sequence description



The screenshot shows the Sequencer GUI interface. At the top, there's a 'Master List' dropdown set to 'seq/on/injection_2gev' and buttons for 'Start', 'Stop', 'Clear', and 'Log'. Below this is a 'Tree View' section with a table of operations. A red dashed box highlights the 'Description' column of this table. Below the tree view is a 'Log' window with a filter and a table of recent events.

Device	State	Enable	Block	Executed	Last Exec	Elapsed	Description
seq/on/injection_2gev	OFF				5d 22h 20m	932	Injection @2Gev operations
seq/check/gof status not on	OFF	✓	YES	YES	5d 22h 36m	0	Check if GOF status is not ON
ecqofmasa5/gmbf/0	ON						
seq/on/llmpat	OFF	✓	YES	YES	5d 22h 36m	0	Put ON and unpaue Fillpat if needed
seq/on/lmbf s	OFF	✓	NO	YES	5d 22h 24m	0	Put ON LMBF
seq/check/tmbf h	OFF	✓	YES	YES	5d 22h 22m	0	Check horizontal Transverse multibunch feedback
seq/check/tmbf v	OFF	✓	YES	YES	5d 22h 22m	0	Check vertical Transverse multibunch feedback
seq/on/fast tune/b s	OFF	✓	NO	YES	5d 22h 36m	0	Switch ON Fast Tune Feedback
seq/check/3hc freq_2gev	OFF	✓	YES	YES	5d 22h 36m	0	Check if 3HC frequencies are ok for 2Gev
seq/check/first current threshold 2gev injection s	OFF	✓	YES	YES	5d 22h 34m	86	Wait to reach first threshold SR current. 15 minutes ti...
seq/opt/launch_opt booster injection	OFF	✓	NO	YES	5d 22h 30m	259	Optimize BOOSTER current and SR injection rate
seq/on/gof buffers	OFF	✓	YES	YES	5d 22h 34m	0	Switch GOF buffers ON
seq/check/second current threshold 2gev injection s	OFF	✓	YES	YES	5d 22h 26m	487	Wait to reach second threshold SR current. 15 minutes...
seq/on/fast mean/b s	OFF	✓	NO	YES	5d 22h 26m	0	Switch ON Fast Mean Feedback
seq/check/third current threshold 2gev injection s	OFF	✓	YES	YES	5d 22h 24m	113	Wait to reach third threshold SR current. 15 minutes ti...
seq/off/injection s	OFF	✓	YES	YES	5d 22h 24m	0	Stop Injection (kisir, sirs, gun grid at 0V)
seq/on/lmbf s	OFF	✓	NO	YES	-	0	Put ON LMBF
seq/on/global orbit fb	OFF	✓	YES	YES	5d 22h 31m	42	Switch ON Slow Global Orbit Feedback
seq/restore/scw id5 diode/bpm risk	OFF	✓	YES	YES	5d 22h 22m	0	Reset DiodeBPM risk on S5 and S11
seq/on/local orbit fb	OFF	✓	YES	YES	5d 17h 53m	51	Switch ON Local Orbit Feedback
seq/restore/scw id5 diode/bpm risk	OFF	✓	YES	YES	5d 22h 22m	0	Reset DiodeBPM risk on S5 and S11
seq/check/orbit quality s	OFF	✓	YES	YES	5d 22h 22m	1	Check Orbit Quality
seq/on/gof	OFF	✓	YES	YES	5d 22h 22m	5	Switch ON GOF
seq/close/launch id s	OFF	✓	YES	YES	5d 22h 21m	45	Close ID launcher with retry
seq/init/topup 2gev	OFF	✓	YES	YES	5d 22h 21m	10	Init TopUp with 2.0Gev Parameters
seq/restore/gof discharge dacs	OFF	✓	NO	YES	5d 22h 21m	12	Discharge GOF DACS & wait 15 sec
seq/restore/topup longtermrisk	OFF	✓	YES	YES	5d 22h 21m	0	Restore TopUp long term risk
seq/on/topup	OFF	✓	YES	YES	11m	0	Put ON TopUp
seq/on/sdo 2gev	OFF	✓	NO	YES	5d 22h 21m	0	Put ON SDO for 2 GeV
seq/on/bd monitor s	OFF	✓	NO	YES	5d 22h 21m	0	ON Beam Dump Monitor
seq/restore/scw quench protector s	OFF	✓	NO	YES	5d 22h 21m	0	Restore SCW Quench Protector
seq/enable/launch id s	OFF	✓	YES	YES	-	11	Enable ID launcher with retry
seq/off/injection s	OFF	✓	YES	NO	5d 22h 24m	0	Stop Injection (kisir, sirs, gun grid at 0V)

Date Time	Sequencer	Message
Mon Sep 20 19:23:51 2021	seq/on/eew_s4	OK='Switching ON ID4' -- exec(/runtime/etc/sequences/scripts/eew_on.sh)
Mon Sep 20 19:23:51 2021	seq/move/id_s1.2	OK='Setting id_s1.2 new gap' -- write_attribute(sr/id/id_s1.2/gap,33.4905)
Mon Sep 20 19:23:51 2021	seq/move/id_s9.1	OK='Setting id_s9.1 new gap' -- write_attribute(sr/id/id_s9.1/gap,62.599)
Mon Sep 20 19:23:50 2021	seq/move/id_s8.2	OK='Setting id_s8.2 new gap' -- write_attribute(sr/id/id_s8.2/gap,36.6125)
Mon Sep 20 19:23:50 2021	seq/move/id_s1.1	OK='Setting id_s1.1 new gap' -- write_attribute(sr/id/id_s1.1/gap,33.4915)
Mon Sep 20 19:23:50 2021	seq/move/id_s6.2	OK='Setting id_s6.2 new gap' -- write_attribute(sr/id/id_s6/gap2,91.201)
Mon Sep 20 19:23:50 2021	seq/move/id_s3.3	OK='Setting id_s3.3 new gap' -- write_attribute(sr/id/id_s3/gap3,43.225)
Mon Sep 20 19:23:49 2021	seq/move/id_s6.3	OK='Setting id_s6.3 new gap' -- write_attribute(sr/id/id_s6/gap3,91.2015)
Mon Sep 20 19:23:49 2021	seq/move/id_s3.2	OK='Setting id_s3.2 new gap' -- write_attribute(sr/id/id_s3/gap2,43.0325)

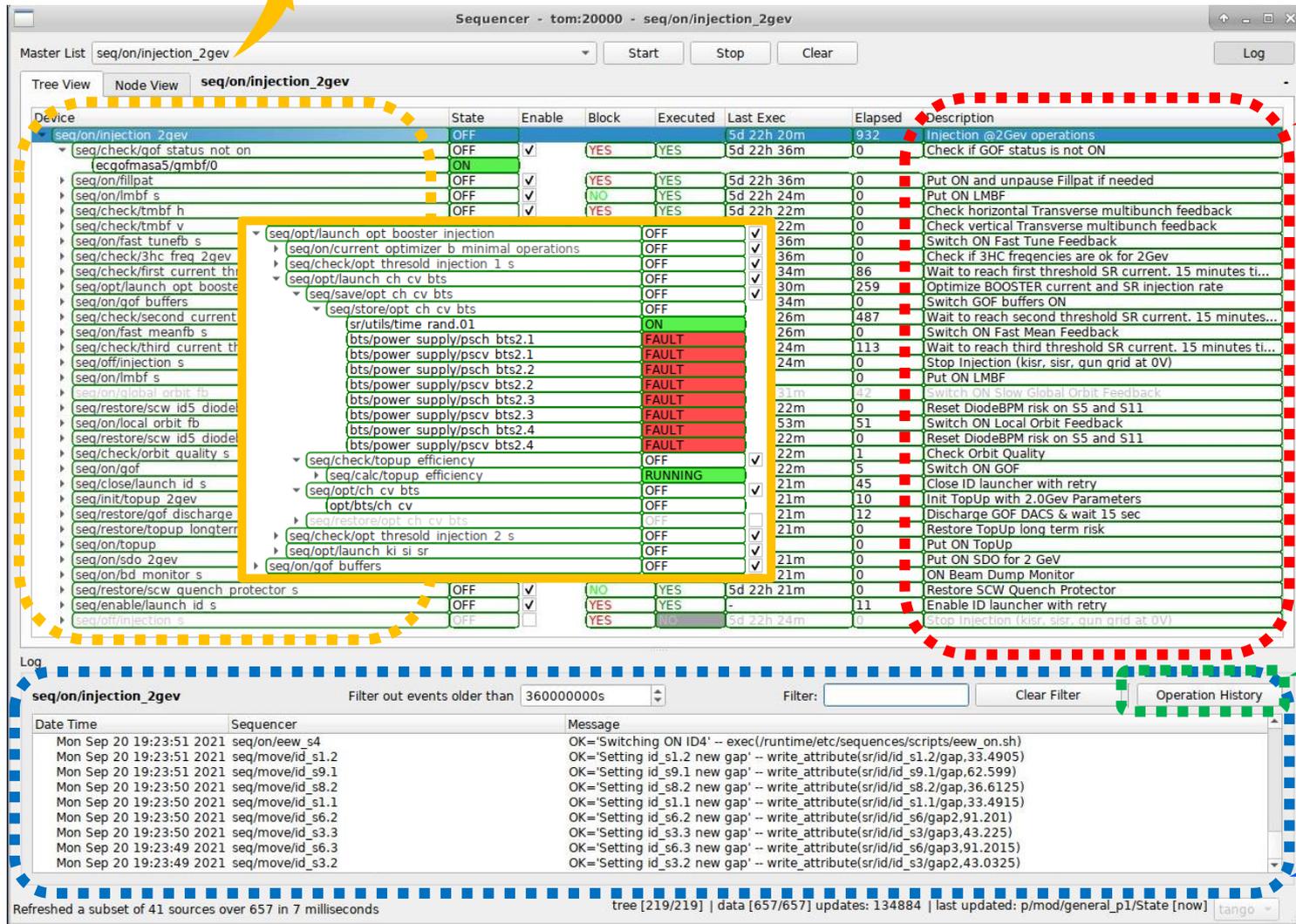
Historical logging

RT-logging based on events

Sequencer GUI (Tree View)

Sequencer that refills the storage ring till giving stable beam to the users

Sequence description



The screenshot shows the Sequencer GUI for the configuration 'tom:20000 - seq/on/injection_2gev'. The main window displays a tree view of the sequence steps, each with columns for State, Enable, Block, Executed, Last Exec, Elapsed, and Description. A yellow dashed box highlights a sub-section of the tree, and a red dashed box highlights the entire tree view. Below the tree view is a log window showing a list of events with columns for Date Time, Sequencer, and Message. The log shows various operations like 'seq/on/eev_s4', 'seq/move/id_s1.2', etc., with their corresponding messages.

Device	State	Enable	Block	Executed	Last Exec	Elapsed	Description
seq/on/injection_2gev	OFF				5d 22h 20m	932	Injection @2Gev operations
seq/check/gof status not on	OFF	✓	YES	YES	5d 22h 36m	0	Check if GOF status is not ON
ecqofmasa5/gmbf/0	ON						
seq/on/llmpat	OFF	✓	YES	YES	5d 22h 36m	0	Put ON and unparse Fillpat if needed
seq/on/lmbf s	OFF	✓	NO	YES	5d 22h 24m	0	Put ON LMBF
seq/check/tmbf h	OFF	✓	YES	YES	5d 22h 22m	0	Check horizontal Transverse multibunch feedback
seq/check/tmbf v	OFF	✓	YES	YES	22m	0	Check vertical Transverse multibunch feedback
seq/on/fast tune/b s	OFF	✓			36m	0	Switch ON Fast Tune Feedback
seq/check/3hc freq 2gev	OFF	✓			36m	0	Check if 3HC frequencies are ok for 2Gev
seq/check/first current th	OFF	✓			34m	86	Wait to reach first threshold SR current. 15 minutes ti...
seq/opt/launch opt booste	OFF	✓			30m	259	Optimize BOOSTER current and SR injection rate
seq/on/gof buffers	OFF	✓			34m	0	Switch GOF buffers ON
seq/check/second current	OFF	✓			26m	487	Wait to reach second threshold SR current. 15 minutes...
seq/on/fast mean/b s	OFF	✓			26m	0	Switch ON Fast Mean Feedback
seq/check/third current th	OFF	✓			24m	113	Wait to reach third threshold SR current. 15 minutes ti...
seq/off/injection s	OFF	✓			24m	0	Stop Injection (kisir, sirs, gun grid at 0V)
seq/on/lmbf s	OFF	✓			24m	0	Put ON LMBF
seq/on/global orbit fb	OFF	✓			31m	42	Switch ON Slow Global Orbit Feedback
seq/restore/scw id5 diode	OFF	✓			22m	0	Reset DiodeBPM risk on S5 and S11
seq/on/local orbit fb	OFF	✓			53m	51	Switch ON Local Orbit Feedback
seq/restore/scw id5 diode	OFF	✓			22m	0	Reset DiodeBPM risk on S5 and S11
seq/check/orbit quality s	OFF	✓			22m	1	Check Orbit Quality
seq/on/gof	OFF	✓			22m	5	Switch ON GOF
seq/close/launch id s	OFF	✓			21m	45	Close ID launcher with retry
seq/init/topup 2gev	OFF	✓			21m	10	Init TopUp with 2.0Gev Parameters
seq/restore/gof discharge	OFF	✓			21m	12	Discharge GOF DACS & wait 15 sec
seq/restore/topup longterr	OFF	✓			21m	0	Restore TopUp long term risk
seq/on/topup	OFF	✓			21m	0	Put ON TopUp
seq/on/sdo 2gev	OFF	✓			21m	0	Put ON SDO for 2 GeV
seq/on/bd monitor s	OFF	✓			21m	0	ON Beam Dump Monitor
seq/restore/scw quench protector s	OFF	✓	NO	YES	5d 22h 21m	0	Restore SCW Quench Protector
seq/enable/launch id s	OFF	✓	YES	YES	-	11	Enable ID launcher with retry
seq/off/injection s	OFF	✓	YES	NO	5d 22h 24m	0	Stop Injection (kisir, sirs, gun grid at 0V)

Historical logging

RT-logging based on events

Conclusions

- ✓ 995 sequencers in FERMI, 958 sequencers in Elettra
- ✓ 8 people have been involved (Controls + Operators + Physicists), now 1 FTE
- ✓ In operation in Elettra since 2019, almost all high level operations in control room driven by sequencers
- ✓ Introduced in FERMI in 2021
- ✓ Developer doesn't have to care of GUIs, logging, documentation...all out of the box
- ✓ “Framework” based on one C++ Tango server, two Qt-Cumbia panels and a sequence template that eases the implementation of the BT structure
- ✓ Short term to-do list:
 - Versioning of an entire BT logic (md5)
 - Log analysis to detect anomalies in terms of execution time and fault rate



Elettra
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Thank you!

P. Cinquegrana, G. Gaio, S. Krecic, G. Scalamera, G. Strangolino, F. Tripaldi, M. Trovo',
L. Zambon