



Elettra
Sincrotrone
Trieste

A FRAMEWORK FOR HIGH LEVEL MACHINE AUTOMATION BASED ON BEHAVIOR TREES

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on behalf the Sequencer TEAM

Introduction

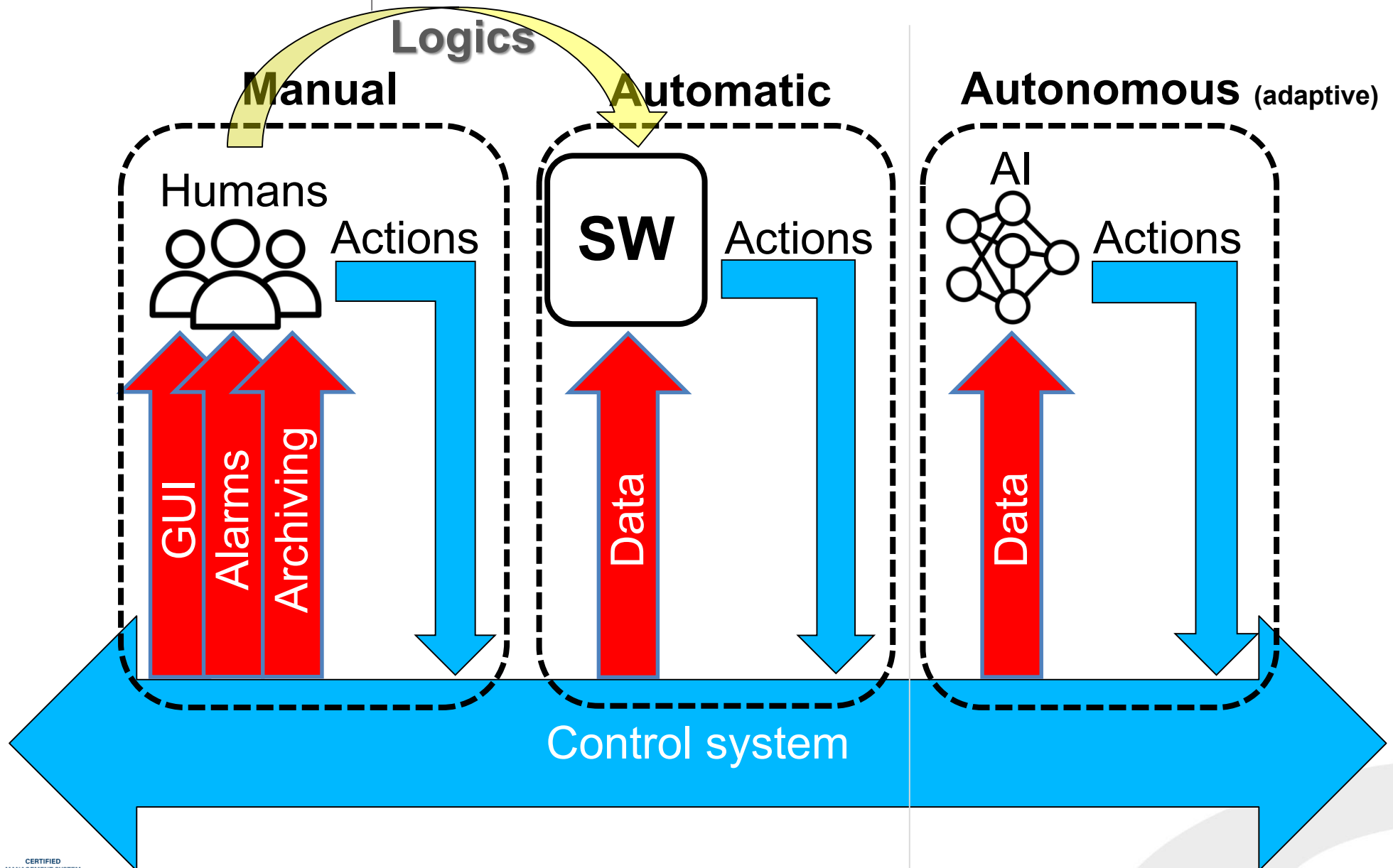
✓ Automation frameworks:

- *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 (Q_{hci})**: one click on a keyboard/mouse in the control room during user and machine tuning shifts

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

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

↑

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

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

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
```

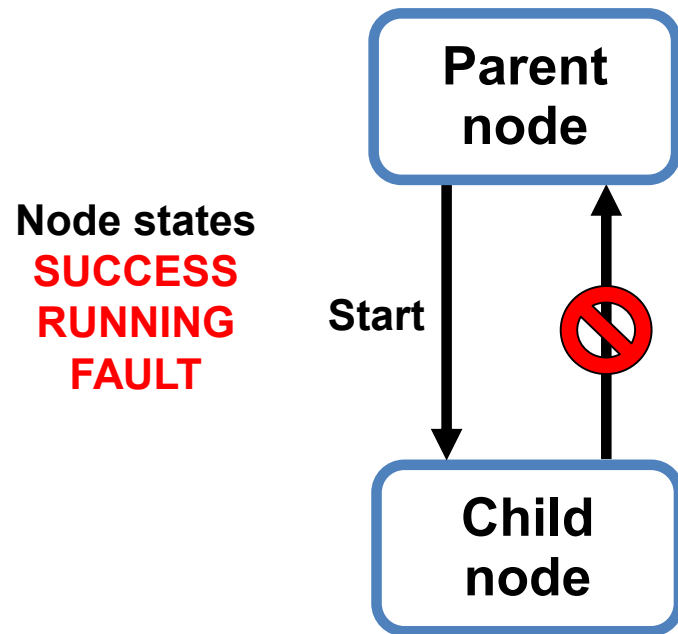
Description:

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

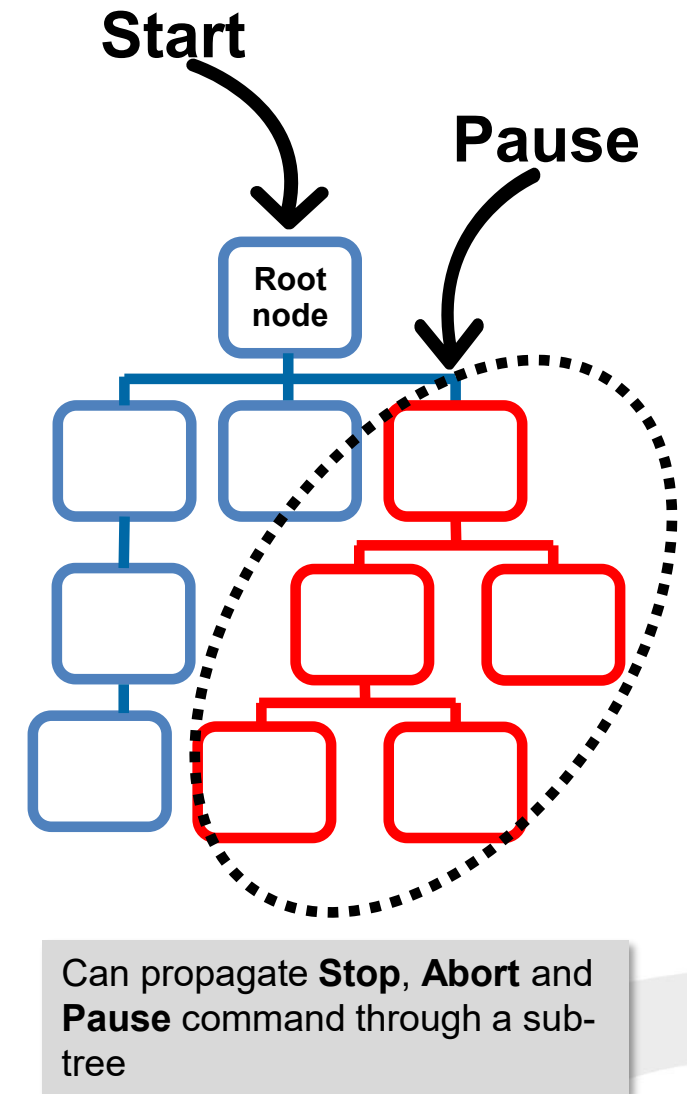
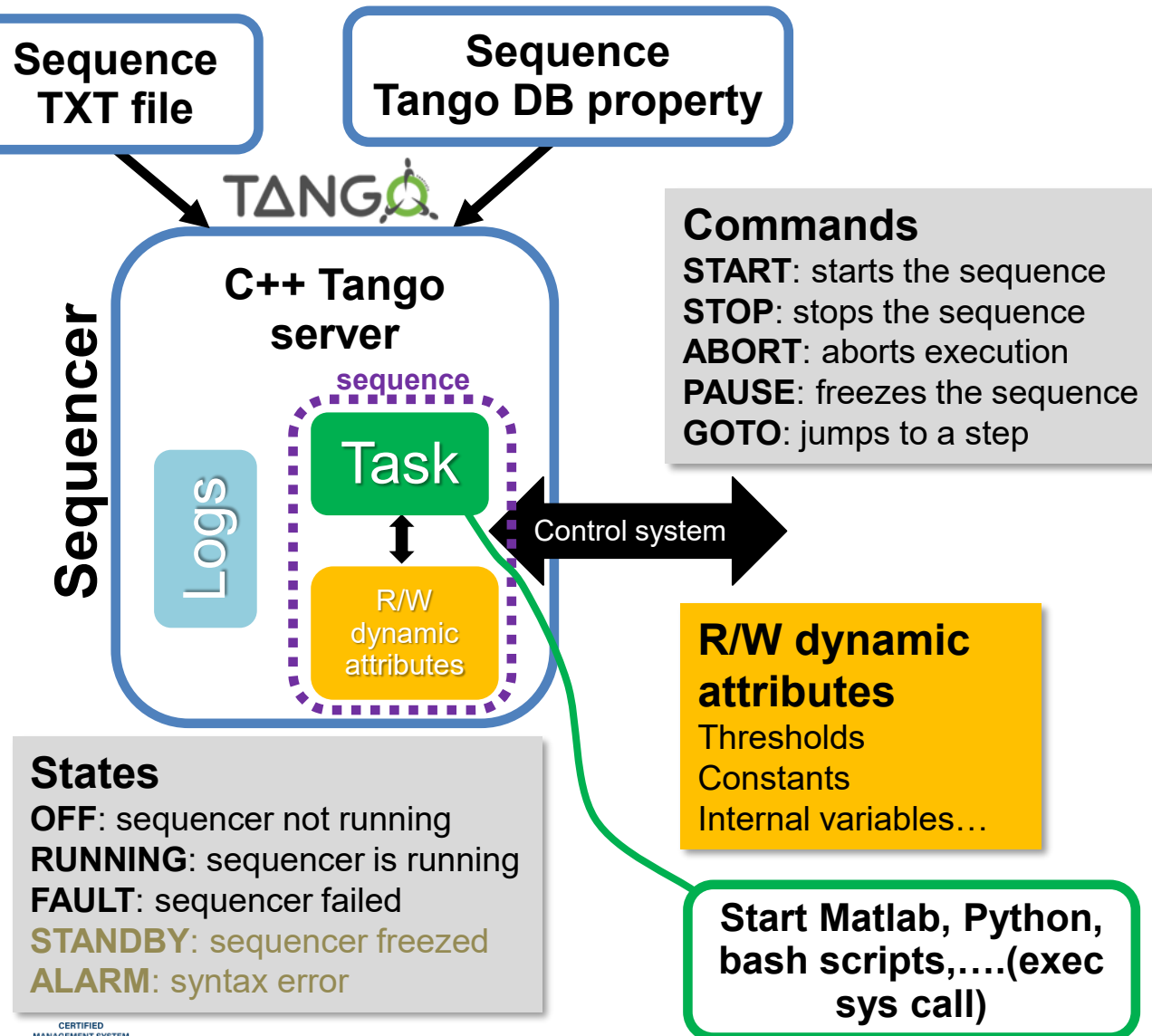
A node executes a **real action** or implements **the structure of the BT**:

- 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

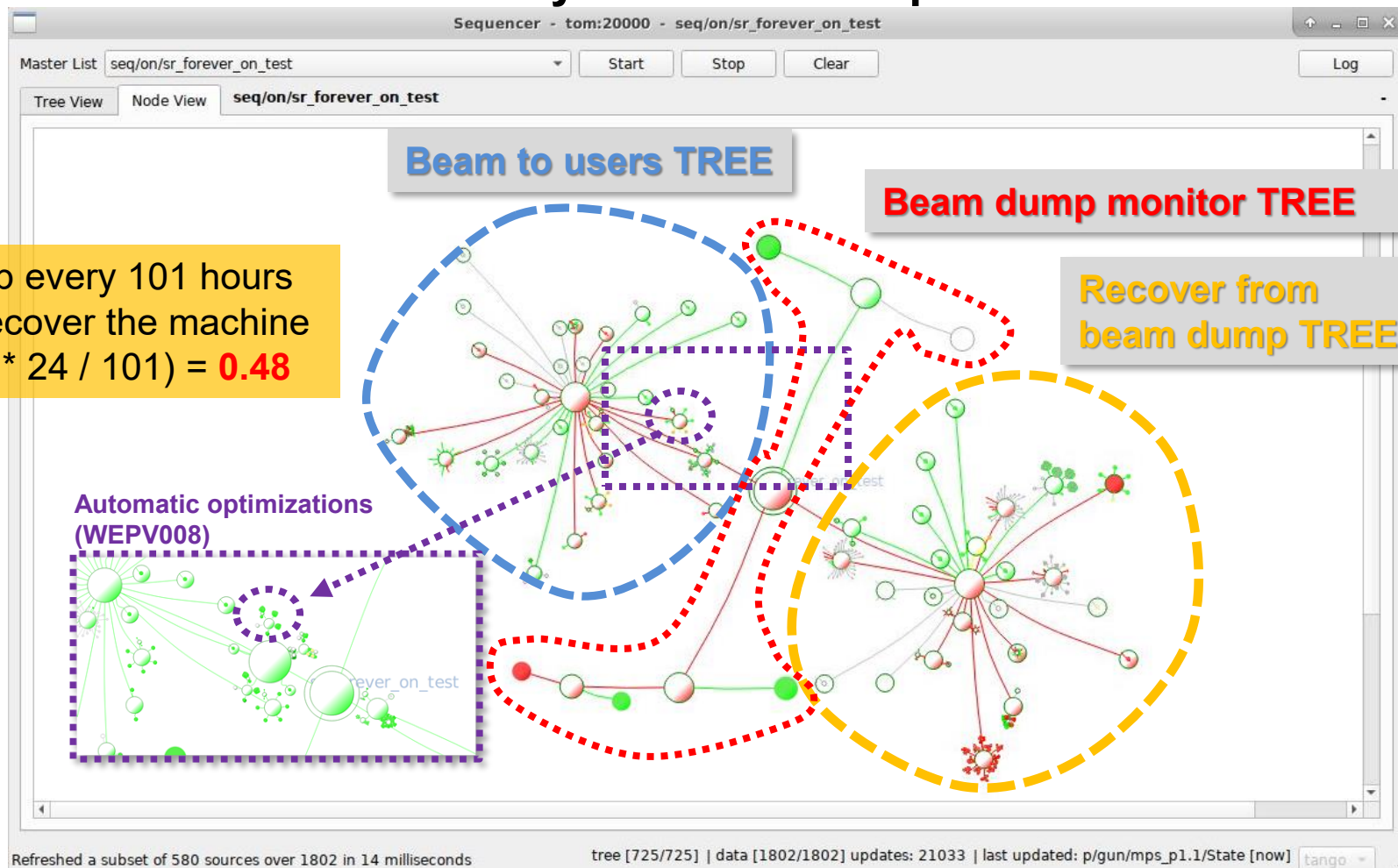
The Sequencer is a Tango device implementing a task



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
 $AL(U) \geq (2 * 24 / 101) = 0.48$

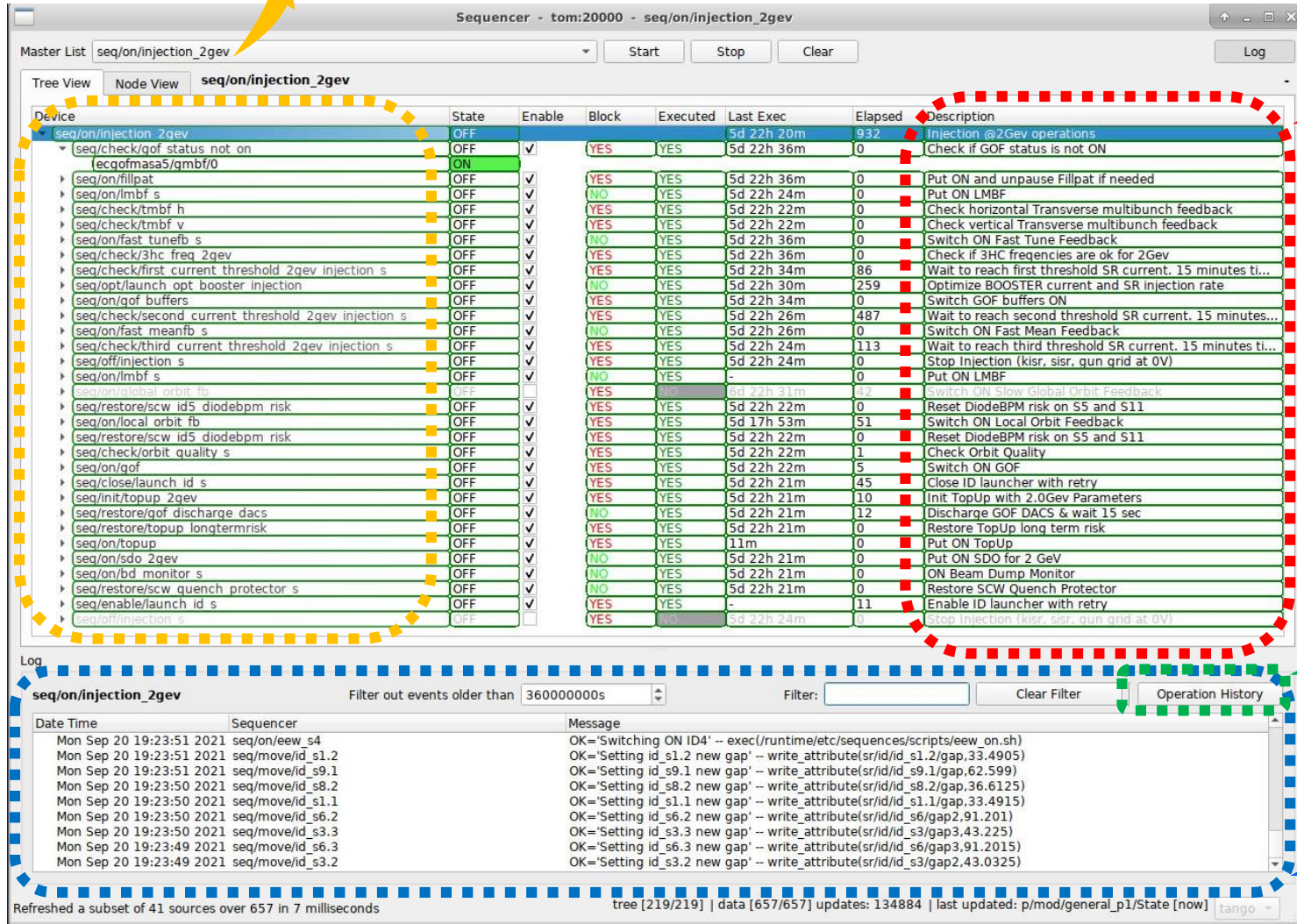
725 nodes

1802 attributes

Sequencer GUI (Tree View)

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

Sequence
description



Sequencer - tom:20000 - seq/on/injection_2gev

Master List: seq/on/injection_2gev [Start] [Stop] [Clear] [Log]

Tree View | Node View | seq/on/injection_2gev

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
seq/on/llmpat	ON	✓					
seq/on/llmpat	OFF	✓	YES	YES	5d 22h 36m	0	Put ON and unpause 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 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 meanfb 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 (kiss, 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 diodebpm 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 diodebpm 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/enale/launch id s	OFF	✓	YES	YES	-	11	Enable ID launcher with retry
seq/off/injection s	OFF	✓	YES	YES	5d 22h 24m	0	Stop Injection (kiss, sirs, gun grid at 0V)

Log

seq/on/injection_2gev Filter out events older than 360000000s Filter: [] Clear Filter [] Operation History []

Date Time	Sequencer	Message
Mon Sep 20 19:23:51 2021	seq/on/eww_s4	OK='Switching ON ID4' -- exec(/runtime/etc/sequences/scripts/eww_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_s6.2/gap,2.91.201)
Mon Sep 20 19:23:50 2021	seq/move/id_s3.3	OK='Setting id_s3.3 new gap' -- write_attribute(sr/id/id_s3.3/gap,3.43.225)
Mon Sep 20 19:23:49 2021	seq/move/id_s6.3	OK='Setting id_s6.3 new gap' -- write_attribute(sr/id/id_s6.3/gap,3.91.2015)
Mon Sep 20 19:23:49 2021	seq/move/id_s3.2	OK='Setting id_s3.2 new gap' -- write_attribute(sr/id/id_s3.2/gap,2.43.0325)

Refreshed a subset of 41 sources over 657 in 7 milliseconds

tree [219/219] | data [657/657] updates: 134884 | last updated: p/mod/general_p1/State [now] | tango

Historical
logging

RT-logging
based on
events



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Sequencer GUI (Tree View)

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

Sequence
description

The screenshot displays the Sequencer GUI for the 'seq/on/injection_2gev' sequence. The interface includes a 'Master List' dropdown, 'Start', 'Stop', 'Clear', and 'Log' buttons. The 'Tree View' tab is active, showing a hierarchical tree of sequence steps. A yellow dashed box highlights the 'seq/opt/launch opt booster injection' subtree, which includes steps like 'seq/opt/current optimizer b minimal operations', 'seq/check/opt threshold injection 1 s', and 'seq/opt/launch ch cv bts'. A red dashed box highlights the 'seq/on/injection_2gev' root node and its immediate children. A green dashed box highlights the 'Log' tab at the bottom, which shows a list of events with columns for 'Date Time', 'Sequencer', and 'Message'. The log entries show the sequence starting at 19:23:51 on Sep 20, 2021, with messages like 'OK=Setting id_s1.2 new gap' and 'OK=Setting id_s3.2 new gap'. A blue arrow points from the 'Log' tab to the 'RT-logging based on events' callout. A red arrow points from the 'Sequence description' callout to the 'seq/on/injection_2gev' node. A green arrow points from the 'Historical logging' callout to the 'Log' tab. A yellow arrow points from the 'Sequencer that refills the storage ring...' text to the 'seq/opt/launch opt booster injection' subtree.

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
seq/on/llmpat	ON						Put ON and unpause Fillpat if needed
seq/on/lmbf s	OFF	✓	YES	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 s	OFF	✓	YES	YES	5d 22h 22m	0	Switch ON Fast Tune Feedback
seq/check/3hc freq 2gev	OFF	✓	YES	YES	5d 22h 24m	0	Check if 3HC frequencies are ok for 2Gev
seq/check/first current th	OFF	✓	YES	YES	5d 22h 24m	0	Wait to reach first threshold SR current. 15 minutes ti...
seq/opt/launch opt booste	OFF	✓	YES	YES	5d 22h 24m	0	Optimize BOOSTER current and SR injection rate
seq/on/gof buffers	OFF	✓	YES	YES	5d 22h 24m	0	Switch GOF buffers ON
seq/check/second current	OFF	✓	YES	YES	5d 22h 24m	0	Wait to reach second threshold SR current. 15 minutes...
seq/on/fast meanfb s	OFF	✓	YES	YES	5d 22h 24m	0	Switch ON Fast Mean Feedback
seq/check/third current th	OFF	✓	YES	YES	5d 22h 24m	0	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	✓	YES	YES	5d 22h 24m	0	Put ON LMBF
seq/on/global orbit fb	OFF	✓	YES	YES	5d 22h 24m	0	Switch ON Slow Global Orbit Feedback
seq/restore/scw id5 diode	OFF	✓	YES	YES	5d 22h 24m	0	Reset DiodeBPM risk on S5 and S11
seq/on/local orbit fb	OFF	✓	YES	YES	5d 22h 24m	0	Switch ON Local Orbit Feedback
seq/restore/scw id5 diode	OFF	✓	YES	YES	5d 22h 24m	0	Reset DiodeBPM risk on S5 and S11
seq/check/orbit quality s	OFF	✓	YES	YES	5d 22h 24m	0	Check Orbit Quality
seq/on/gof	OFF	✓	YES	YES	5d 22h 24m	0	Switch ON GOF
seq/close/launch id s	OFF	✓	YES	YES	5d 22h 24m	0	Close ID launcher with retry
seq/init/topup 2gev	OFF	✓	YES	YES	5d 22h 24m	0	Init TopUp with 2.0Gev Parameters
seq/restore/gof discharge	OFF	✓	YES	YES	5d 22h 24m	0	Discharge GOF DACS & wait 15 sec
seq/restore/topup longter	OFF	✓	YES	YES	5d 22h 24m	0	Restore TopUp long term risk
seq/on/topup	OFF	✓	YES	YES	5d 22h 24m	0	Put ON TopUp
seq/on/sdo 2gev	OFF	✓	YES	YES	5d 22h 24m	0	Put ON SDO for 2 GeV
seq/on/bd monitor s	OFF	✓	YES	YES	5d 22h 24m	0	ON Beam Dump Monitor
seq/restore/scw quench protector s	OFF	✓	YES	YES	5d 22h 24m	0	Restore SCW Quench Protector
seq/enable/launch id s	OFF	✓	YES	YES	5d 22h 24m	0	Enable ID launcher with retry
seq/off/injection s	OFF	✓	YES	YES	5d 22h 24m	0	Stop Injection (kisir, sirs, gun grid at 0V)

Log

seq/on/injection_2gev

Filter out events older than 360000000s

Filter: Clear Filter

Operation History

Date Time	Sequencer	Message
Mon Sep 20 19:23:51 2021	seq/on/eww_s4	OK='Switching ON ID4' -- exec(/runtime/etc/sequences/scripts/eww_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)

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tree [219/219] | data [657/657] updates: 134884 | last updated: p/mod/general_p1/State [now] | tango

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

Thank you!

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