ELI Beamlines
Overview of a control system of a high-power laser facility

Karel Majer

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MINISTRY OF EDUCATION,
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FZU Institute of Physics of the Czech Academy of Sciences

ELI (Extreme Light Infrastructure)

World's largest and most advanced high-power laser infrastructure and a global technology and innovation leader in high-power, high-intensity, and short-pulsed laser systems.

First ESFRI Landmark constructed in the Central Eastern European Member States. Three world-class high-power, high-repetition-rate laser facilities have been established in Czech Republic (ELI Beamlines), Hungary (ELI-ALPS) and Romania (ELI-NP).

The commissioning of the facilities is foreseen to be completed in 2022-2023.

ELI facilities

ELI Beamlines (Prague, CZ)

4 high-power fs laser systems
Particle acceleration, X-ray generation, plasma science

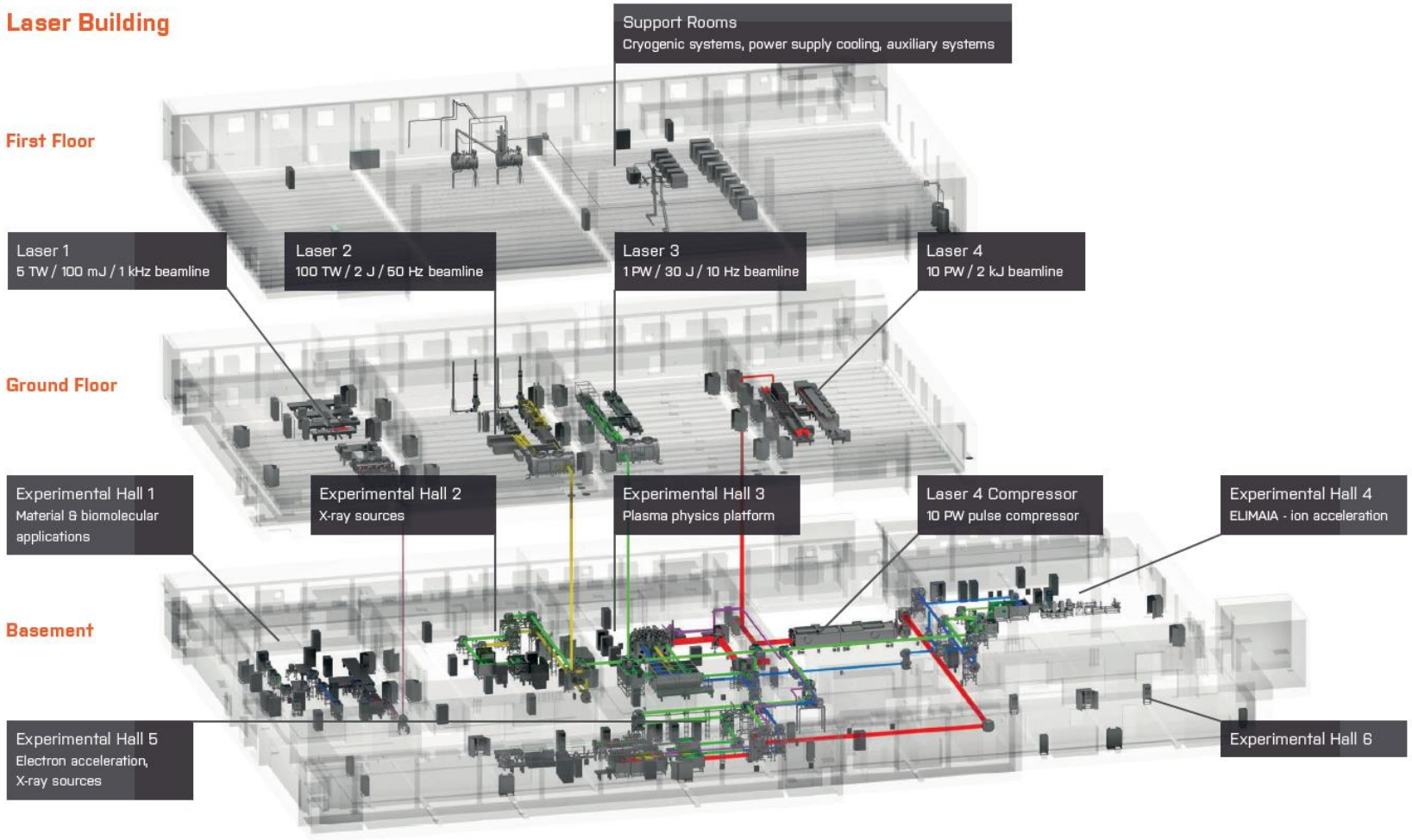
ELI-ALPS (Szeged, HU)

Ultra-short pulses from THz to X-rays
Attosecond science (electron processes, chemical reactions)

ELI-NP (Magurele, RO)

2x10 PW laser
Gamma beam source (to 19 MeV)
Nuclear physics

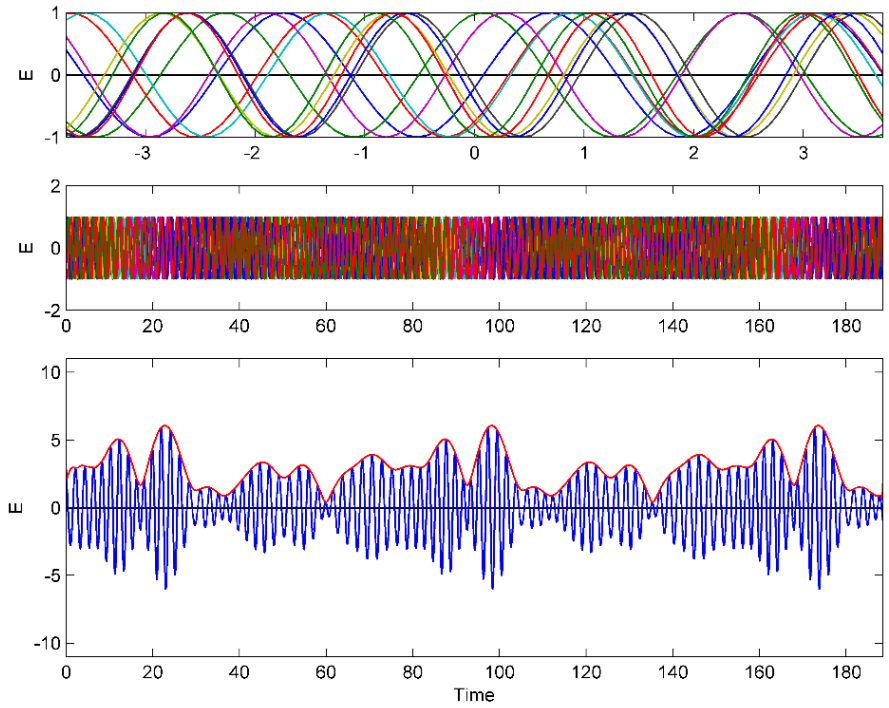
ELI Beamlines facility

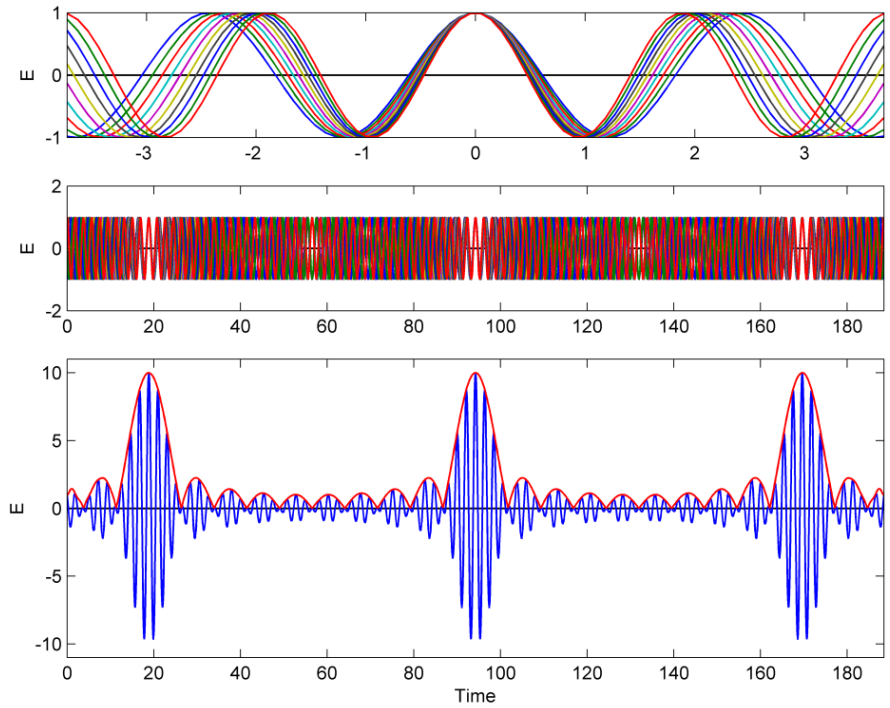


ELI Beamlines lasers

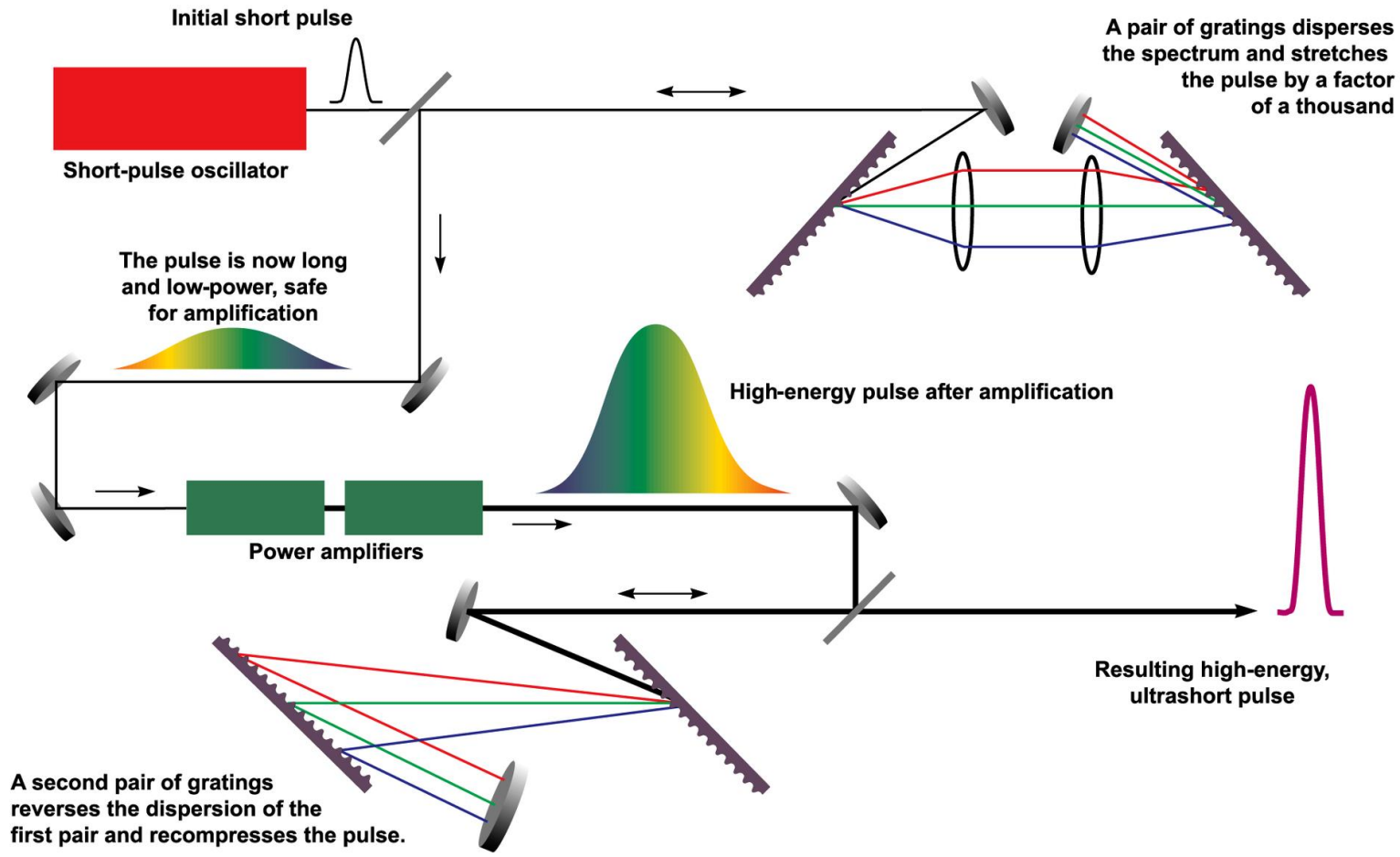
Beamline	L1	L2	L3	L4
Peak power	5 TW	100 TW	1 PW	10 PW
Pulse energy	100 mJ	2 J	30 J	1,5 kJ
Pulse length	20 fs	15 fs	30 fs	150 fs
Re. rate	1 kHz	50 Hz	10 Hz	0,1 Hz
Developer	ELI Team	ELI Team + Rutherford Appleton Laboratory	Lawrence Livermore National Laboratory + ELI Team	National Energetics + Ekspla + ELI Team
Technology	Diode pumping, OPCPA	Diode pumping, OPCPA	Square beam 214 mm x 214 mm, Ti:Sapphire amps and diode and Nd:glass pump lasers	Square beam 625 mm x 625 mm, Discharge lamp pumped Nd:glass amps + OPCPA pre-amps

Mode locking





Chirped pulse amplification



L4 compressor chamber

ELI Beamlines experiments

Bio/molecular research

Plasma physics

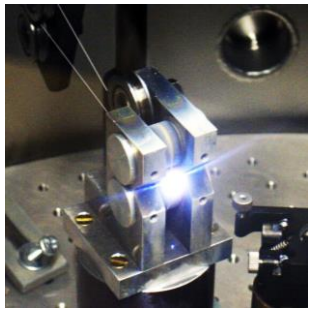
Particle acceleration

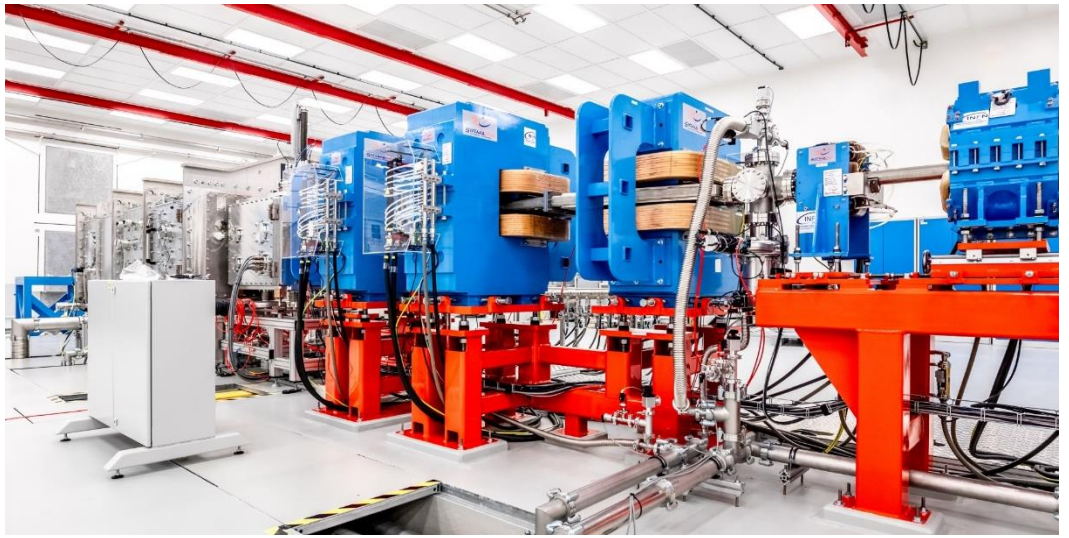
X-ray sources

Exotic physics

Laser as X-ray source:

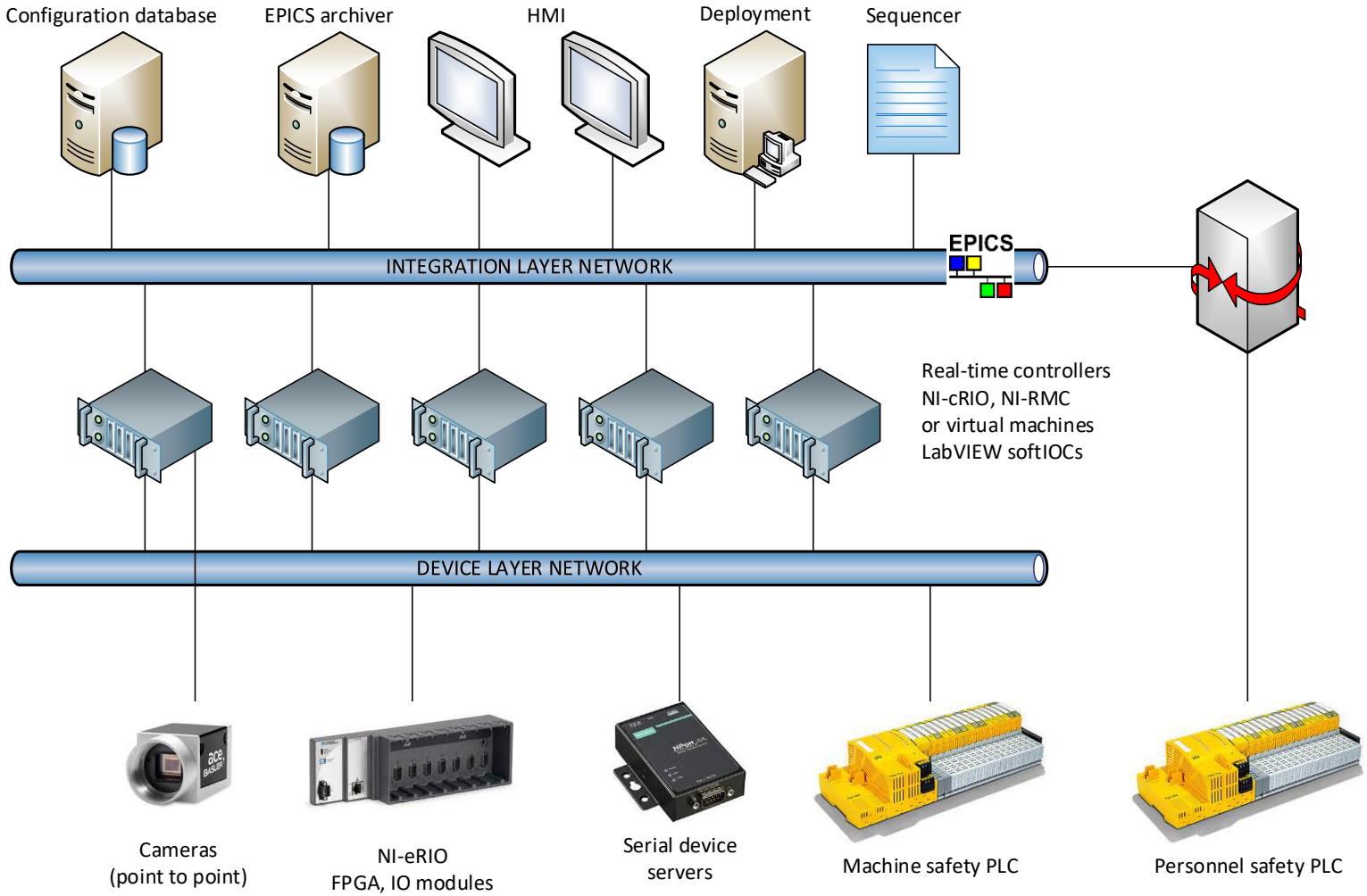
Laser beam -> plasma -> electrons accelerated by EM field -> X-ray beam





ELIMAIA – ion acceleration

ELI Beamlines laser control system



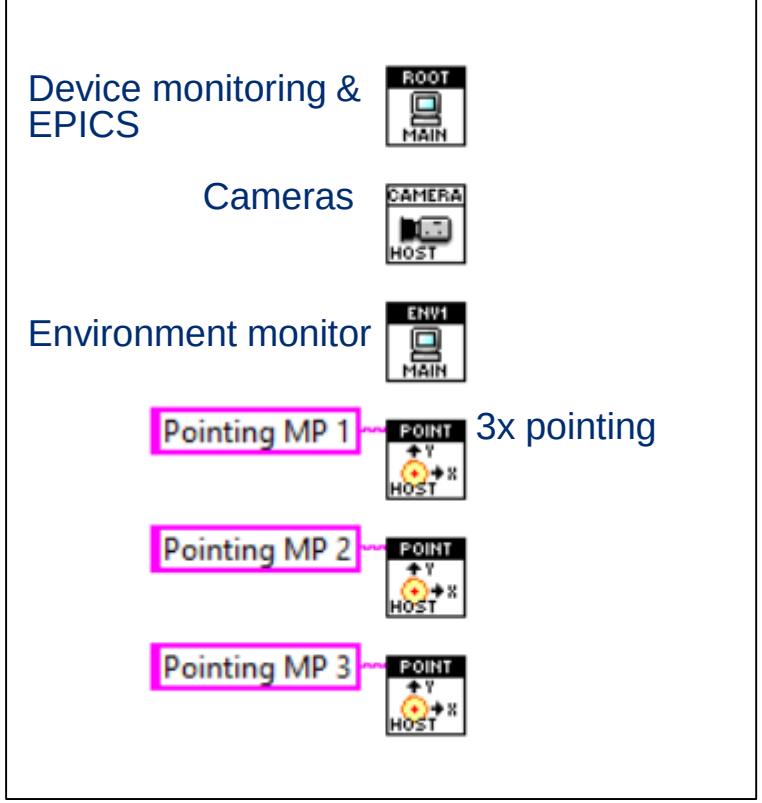
Software architecture

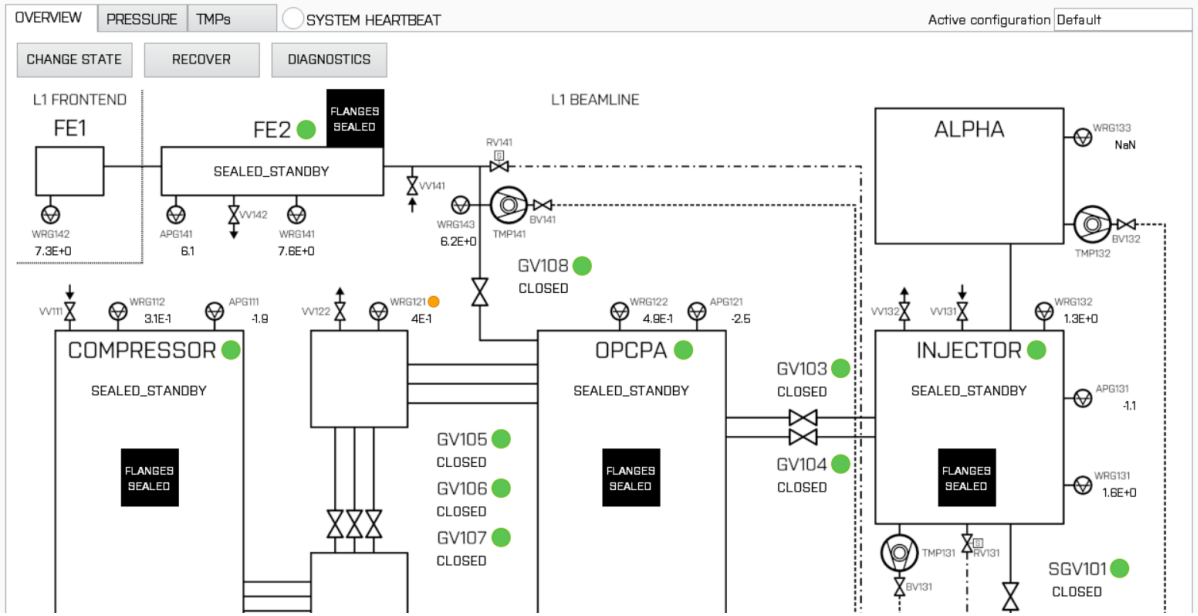
Mostly programmed in LabVIEW – many parallel processes on each controller

LabVIEW-native EPICS implementation (Obsevatory Sciences, modified by ELI)

Easy setup of PVs in MySQL configuration database

LabVIEW framework for creating EPICS-based GUIs





Safety systems

Personnel safety

- Pilz PLCs (SIL rating)
- Controls when laser may be turned on and propagated
- State machine paradigm for each area
  - No emission
  - Low power
  - High power
- Radiation confined to experimental halls, separate monitoring system (contractor)

Machine safety

- Pilz or B&R PLCs
- Guarantees valid laser beampath
- Beamline divided into zones
  - No emission, low power, high power

Vacuum control

- NI RIO (with FPGA) or B&R PLCs
- Big volumes, separate roughing and forevacuum primary pumps
- Abstraction to a set of state machines

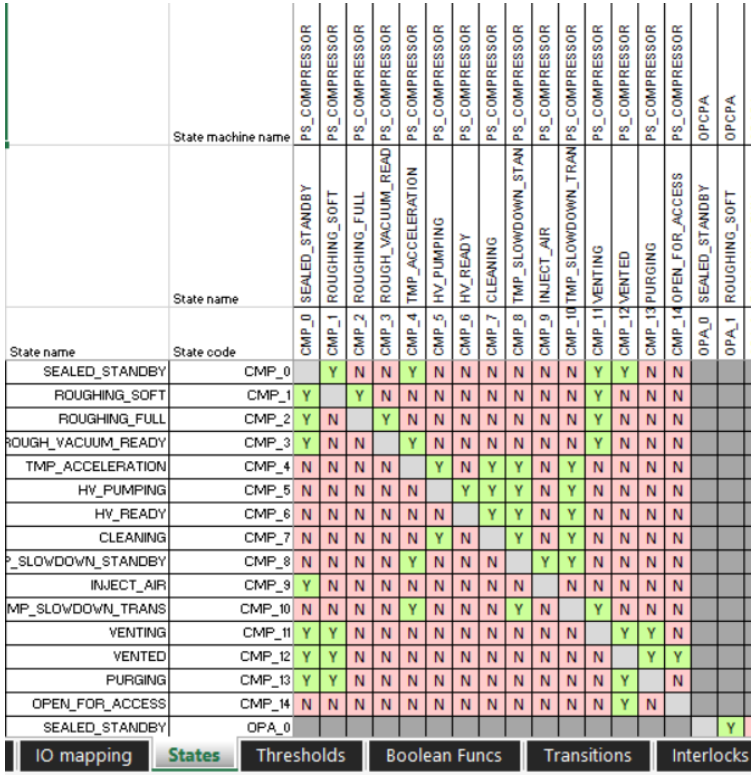
Common system description

We can abstract many systems to a set of Mealy state machines:

- Personnel safety (6)
- Machine safety (7)
- Vacuum control (10+)
- Pneumatics control (2)
- Environment monitors
- Fast interlock for 1 kHz laser

Unified description format for all of them

Systems fully described in Excel spreadsheets



	State machine name	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	OPCPA	OPCPA
	State name	SEALED_STANDBY	ROUGHING_SOFT	ROUGHING_FULL	ROUGH_VACUUM_READ	TMP_ACCELERATION	HV_PUMPING	HV_READY	CLEANING	TMP_SLOWDOWN_STAN	INJECT_AIR	TMP_SLOWDOWN_TRAN	VENTING	VENTED	PURGING	OPEN_FOR_ACCESS	SEALED_STANDBY	ROUGHING_SOFT
State name	State code	CMP_0	CMP_1	CMP_2	CMP_3	CMP_4	CMP_5	CMP_6	CMP_7	CMP_8	CMP_9	CMP_10	CMP_11	CMP_12	CMP_13	CMP_14	OPA_0	OPA_1
SEALED_STANDBY	CMP_0		Y	N	N	Y	N	N	N	N	N	N	Y	Y	N	N		
ROUGHING_SOFT	CMP_1	Y		Y	N	N	N	N	N	N	N	N	Y	N	N	N		
ROUGHING_FULL	CMP_2	Y	N		Y	N	N	N	N	N	N	N	Y	N	N	N		
ROUGH_VACUUM_READY	CMP_3	Y	N	N		Y	N	N	N	N	N	N	Y	N	N	N		
TMP_ACCELERATION	CMP_4	N	N	N	N		Y	N	Y	Y	N	Y	N	N	N	N		
HV_PUMPING	CMP_5	N	N	N	N	N		Y	Y	Y	N	Y	N	N	N	N		
HV_READY	CMP_6	N	N	N	N	N	N		Y	Y	N	Y	N	N	N	N		
CLEANING	CMP_7	N	N	N	N	N	Y	N		Y	N	Y	N	N	N	N		
TMP_SLOWDOWN_STANDBY	CMP_8	N	N	N	N	Y	N	N	N		Y	Y	N	N	N	N		
INJECT_AIR	CMP_9	Y	N	N	N	N	N	N	N	N		N	N	N	N	N		
TMP_SLOWDOWN_TRANS	CMP_10	N	N	N	N	Y	N	N	N	Y	N		Y	N	N	N		
VENTING	CMP_11	Y	Y	N	N	N	N	N	N	N	N	N		Y	Y	N		
VENTED	CMP_12	Y	Y	N	N	N	N	N	N	N	N	N	N		Y	Y		
PURGING	CMP_13	Y	Y	N	N	N	N	N	N	N	N	N	Y			N		
OPEN_FOR_ACCESS	CMP_14	N	N	N	N	N	N	N	N	N	N	N	Y	N				
SEALED_STANDBY	OPA_0																	Y

IO mapping | States | Thresholds | Boolean Funcs | Transitions | Interlocks

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Description in a spreadsheet

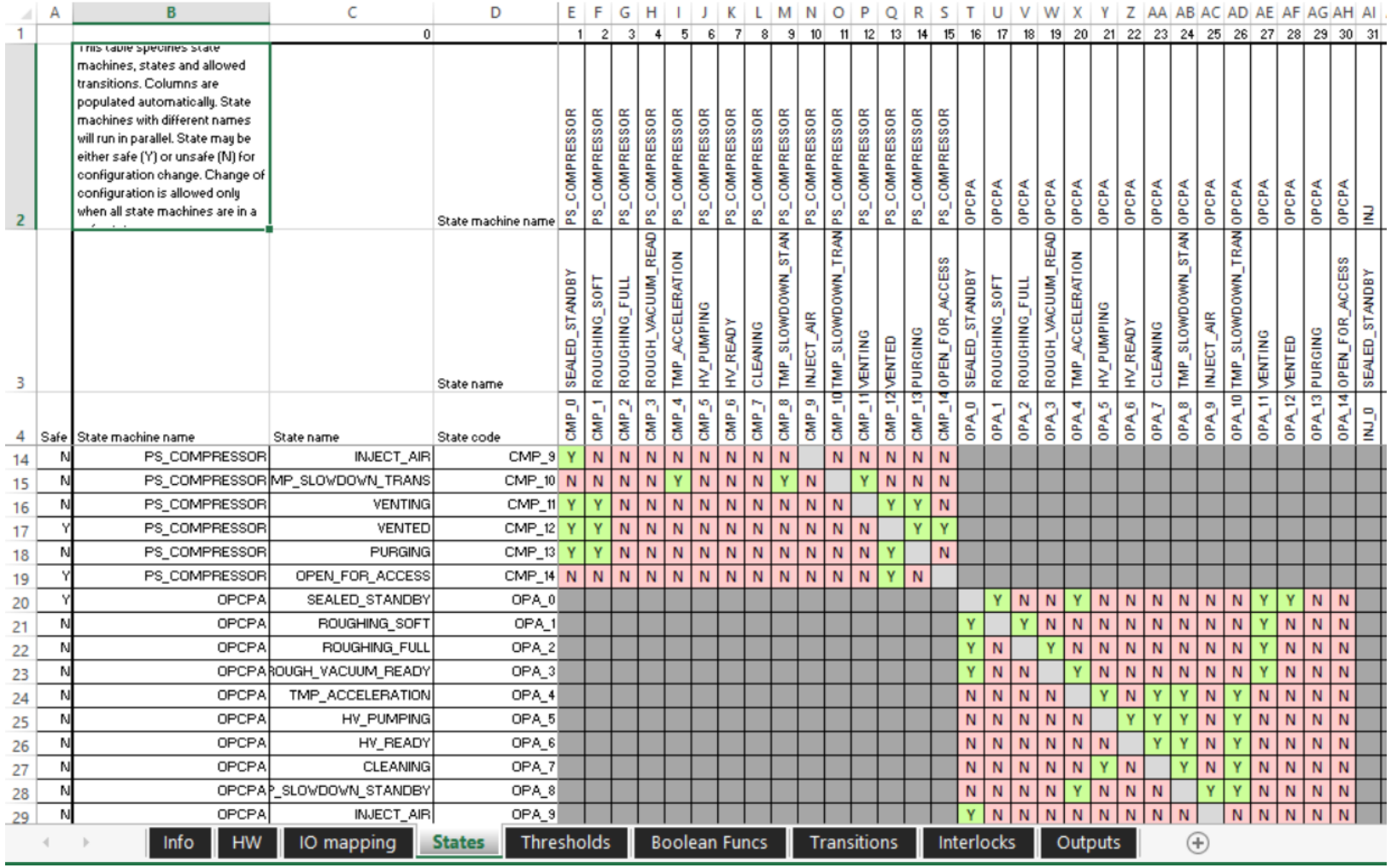
IO declaration

	Category	Signal Name	Type	Unit	Module	IO #	Active/Inactive	Description	TON	TOF	Alias	AI Conversion
109	OUTPUT_GATE_VAL	SGV101_CLOSED_NC	INPUT	RIO114	3	0	ACTIVE		50			
110	OUTPUT_GATE_VAL	SGV101_OPEN_NC	INPUT	RIO114	3	1	ACTIVE		50			
111	MSS	CMP_VENT_PERMISSION	INPUT	RIO114	3	2	ACTIVE		10			
112	MSS	CMP_PUMP_PERMISSION	INPUT	RIO114	3	3	ACTIVE		10			
113	MSS	OPCPA_VENT_PERMISSION	INPUT	RIO114	3	4	ACTIVE		10			
114	MSS	OPCPA_PUMP_PERMISSION	INPUT	RIO114	3	5	ACTIVE		10			
115	MSS	BT_VENT_PERMISSION	INPUT	RIO114	3	6	ACTIVE		10			
116	MSS	BT_PUMP_PERMISSION	INPUT	RIO114	3	7	ACTIVE		10			
117	MSS	INJ_VENT_PERMISSION	INPUT	RIO114	3	8	ACTIVE		10			
118	MSS	INJ_PUMP_PERMISSION	INPUT	RIO114	3	9	ACTIVE		10			
119	MSS	CENTRAL_ROUGHING_VACUUM_GOOD	INPUT	RIO114	3	12	ACTIVE		10			
120	MSS	CENTRAL_BACKING_VACUUM_GOOD	INPUT	RIO114	3	13	ACTIVE		10			
121	MSS	E1_READY_FOR_SHOT	INPUT	RIO114	3	14	ACTIVE		10			
122	MSS	GV103_4_OPEN_PERMISSION	INPUT	RIO114	3	22	ACTIVE	INVERTED	10			
123	MSS	GV108_OPEN_PERMISSION	INPUT	RIO114	3	23	ACTIVE	INVERTED	10			
124	MSS	GV105_6_7_OPEN_PERMISSION	INPUT	RIO114	3	24	ACTIVE	INVERTED	10			
125	MSS	GV103_4_CLOSE_PERMISSION	INPUT	RIO114	3	25	ACTIVE	ALSO PERM TO LEAVE HV	10			
126	MSS	GV108_CLOSE_PERMISSION	INPUT	RIO114	3	26	ACTIVE	ALSO PERM TO LEAVE HV	10			
127	MSS	GV105_6_7_CLOSE_PERMISSION	INPUT	RIO114	3	27	ACTIVE	ALSO PERM TO LEAVE HV	10			
128	ROUGHING_VALVE	RV121_MAIN_CLOSED	INPUT	RIO114	3	28	ACTIVE					
129	ROUGHING_VALVE	RV121_MAIN_OPEN	INPUT	RIO114	3	29	ACTIVE					
130	ROUGHING_VALVE	RV131_MAIN_CLOSED	INPUT	RIO114	3	30	ACTIVE					
131	ROUGHING_VALVE	RV131_MAIN_OPEN	INPUT	RIO114	3	31	ACTIVE					
132	TMP	TMP121_START	OUTPUT	RIO114	4	0	ACTIVE					
133	BACKING_VALVE	BV121_COIL	OUTPUT	RIO114	4	1	ACTIVE					
134	TMP	TMP131_START	OUTPUT	RIO114	4	2	ACTIVE					
135	BACKING_VALVE	BV131_COIL	OUTPUT	RIO114	4	3	ACTIVE					
136	TMP	TMP141_MOTOR_DRIVE	OUTPUT	RIO114	4	4	ACTIVE					
137	BACKING_VALVE	BV141_COIL	OUTPUT	RIO114	4	5	ACTIVE					
138	TMP	TMP111_START	OUTPUT	RIO114	4	6	ACTIVE					
139	BACKING_VALVE	BV111_COIL	OUTPUT	RIO114	4	7	ACTIVE					
140	ROUGHING_VALVE	RV111_MAIN_COIL	OUTPUT	RIO114	4	8	ACTIVE		5000			
141	ROUGHING_VALVE	RV111_SOFT_COIL	OUTPUT	RIO114	4	9	ACTIVE		5000			
142	ROUGHING_VALVE	RV141_SOFT_COIL	OUTPUT	RIO114	4	10	ACTIVE		5000			
143	ROUGHING_VALVE	RV141_MAIN_COIL	OUTPUT	RIO114	4	11	ACTIVE		5000			
144	ROUGHING_VALVE	RV121_SOFT_COIL	OUTPUT	RIO114	4	12	ACTIVE		5000			
145	ROUGHING_VALVE	RV121_MAIN_COIL	OUTPUT	RIO114	4	13	ACTIVE		5000			
146	ROUGHING_VALVE	RV131_MAIN_COIL	OUTPUT	RIO114	4	14	ACTIVE		5000			
147	ROUGHING_VALVE	RV131_SOFT_COIL	OUTPUT	RIO114	4	15	ACTIVE		5000			
148	VENTING_VALVE	VV112_COIL	OUTPUT	RIO114	4	16	ACTIVE					
149	VENTING_VALVE	VV111_COIL	OUTPUT	RIO114	4	17	ACTIVE		5000			

Info | HW | IO mapping | States | Thresholds | Boolean Funcs | Transitions | Interlocks | Outputs

Description in a spreadsheet

Transition matrix



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI
1			0		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2		This table specifies state machines, states and allowed transitions. Columns are populated automatically. State machines with different names will run in parallel. State may be either safe (Y) or unsafe (N) for configuration change. Change of configuration is allowed only when all state machines are in a		State machine name	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	PS_COMPRESSOR	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	INJ
3				State name	SEALED_STANDBY	ROUGHING_SOFT	ROUGHING_FULL	ROUGH_VACUUM_READ	TMP_ACCELERATION	HV_PUMPING	HV_READY	CLEANING	TMP_SLOWDOWN_STAN	INJECT_AIR	TMP_SLOWDOWN_TRAN	VENTING	VENTED	PURGING	OPEN_FOR_ACCESS	SEALED_STANDBY	ROUGHING_SOFT	ROUGHING_FULL	ROUGH_VACUUM_READ	TMP_ACCELERATION	HV_PUMPING	HV_READY	CLEANING	TMP_SLOWDOWN_STAN	INJECT_AIR	TMP_SLOWDOWN_TRAN	VENTING	VENTED	PURGING	OPEN_FOR_ACCESS	SEALED_STANDBY
4	Safe	State machine name	State name	State code	CMP_0	CMP_1	CMP_2	CMP_3	CMP_4	CMP_5	CMP_6	CMP_7	CMP_8	CMP_9	CMP_10	CMP_11	CMP_12	CMP_13	CMP_14	OPA_0	OPA_1	OPA_2	OPA_3	OPA_4	OPA_5	OPA_6	OPA_7	OPA_8	OPA_9	OPA_10	OPA_11	OPA_12	OPA_13	OPA_14	INJ_0
14	N	PS_COMPRESSOR	INJECT_AIR	CMP_9	Y	N	N	N	N	N	N	N	N		N	N	N	N	N																
15	N	PS_COMPRESSOR	MP_SLOWDOWN_TRANS	CMP_10	N	N	N	N	Y	N	N	N	Y	N		Y	N	N	N																
16	N	PS_COMPRESSOR	VENTING	CMP_11	Y	Y	N	N	N	N	N	N	N	N	N		Y	Y	N																
17	Y	PS_COMPRESSOR	VENTED	CMP_12	Y	Y	N	N	N	N	N	N	N	N	N	N		Y	Y																
18	N	PS_COMPRESSOR	PURGING	CMP_13	Y	Y	N	N	N	N	N	N	N	N	N	N	Y		N																
19	Y	PS_COMPRESSOR	OPEN_FOR_ACCESS	CMP_14	N	N	N	N	N	N	N	N	N	N	N	N	Y	N																	
20	Y	OPCPA	SEALED_STANDBY	OPA_0																	Y	N	N	Y	N	N	N	N	N	N	Y	Y	N	N	
21	N	OPCPA	ROUGHING_SOFT	OPA_1																Y		Y	N	N	N	N	N	N	N	N	Y	N	N	N	
22	N	OPCPA	ROUGHING_FULL	OPA_2																Y	N		Y	N	N	N	N	N	N	N	Y	N	N	N	
23	N	OPCPA	ROUGH_VACUUM_READY	OPA_3																Y	N	N		Y	N	N	N	N	N	N	Y	N	N	N	
24	N	OPCPA	TMP_ACCELERATION	OPA_4																N	N	N	N		Y	N	Y	Y	N	Y	N	N	N	N	
25	N	OPCPA	HV_PUMPING	OPA_5																N	N	N	N	N		Y	Y	Y	N	Y	N	N	N	N	
26	N	OPCPA	HV_READY	OPA_6																N	N	N	N	N	N		Y	Y	N	Y	N	N	N	N	
27	N	OPCPA	CLEANING	OPA_7																N	N	N	N	N	Y	N		Y	N	Y	N	N	N	N	
28	N	OPCPA	P_SLOWDOWN_STANDBY	OPA_8																N	N	N	N	Y	N	N	N		Y	Y	N	N	N	N	
29	N	OPCPA	INJECT_AIR	OPA_9																Y	N	N	N	N	N	N	N	N		N	N	N	N	N	

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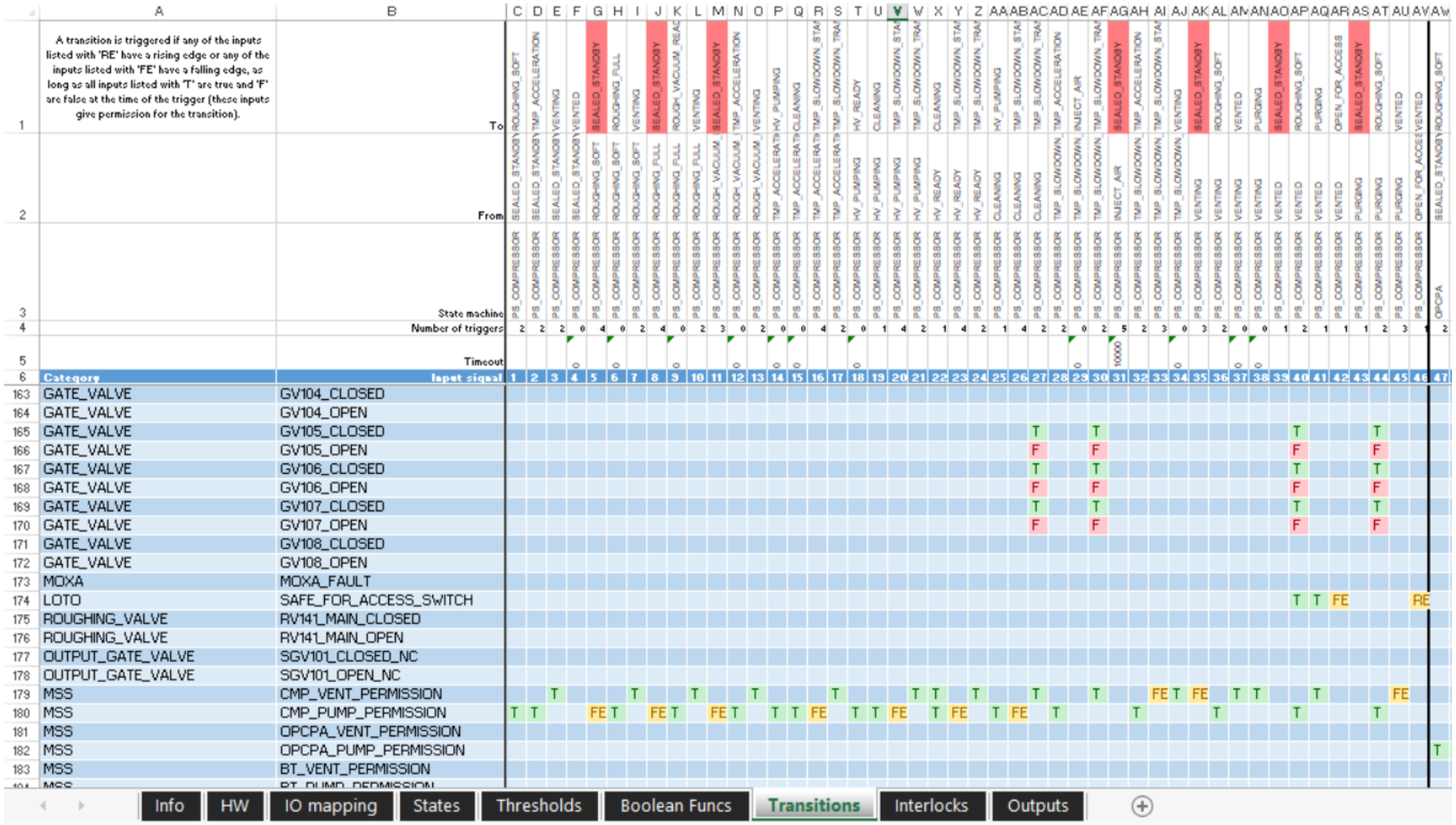
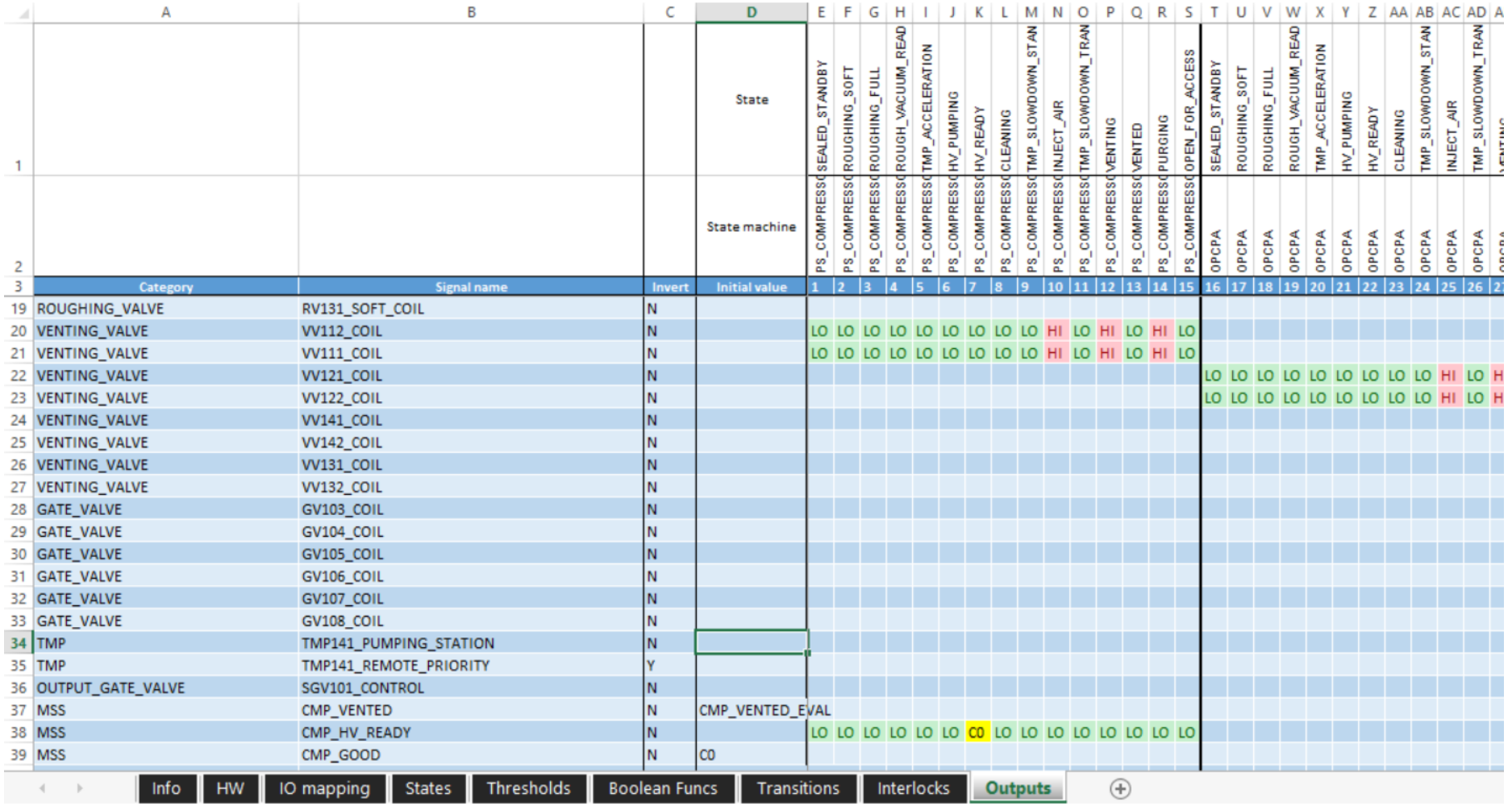
Description in a spreadsheet

Triggers & permissions



Description in a spreadsheet

Outputs



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD
1				State	SEALED_STANDBY	ROUGHING_SOFT	ROUGHING_FULL	ROUGH_VACUUM_READ	TMP_ACCELERATION	HV_PUMPING	HV_READY	CLEANING	TMP_SLOWDOWN_STAN	INJECT_AIR	TMP_SLOWDOWN_TRAN	VENTING	VENTED	PURGING	OPEN_FOR_ACCESS	SEALED_STANDBY	ROUGHING_SOFT	ROUGHING_FULL	ROUGH_VACUUM_READ	TMP_ACCELERATION	HV_PUMPING	HV_READY	CLEANING	TMP_SLOWDOWN_STAN	INJECT_AIR	TMP_SLOWDOWN_TRAN
2				State machine	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	PS_COMPRESSO	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA	OPCPA
3	Category	Signal name	Invert	Initial value	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
19	ROUGHING_VALVE	RV131_SOFT_COIL	N																											
20	VENTING_VALVE	VV112_COIL	N		LO	LO	LO	LO	LO	LO	LO	LO	LO	HI	LO	HI	LO	HI	LO											
21	VENTING_VALVE	VV111_COIL	N		LO	LO	LO	LO	LO	LO	LO	LO	LO	HI	LO	HI	LO	HI	LO											
22	VENTING_VALVE	VV121_COIL	N																	LO	LO	LO	LO	LO	LO	LO	LO	LO	HI	LO
23	VENTING_VALVE	VV122_COIL	N																	LO	LO	LO	LO	LO	LO	LO	LO	LO	HI	LO
24	VENTING_VALVE	VV141_COIL	N																											
25	VENTING_VALVE	VV142_COIL	N																											
26	VENTING_VALVE	VV131_COIL	N																											
27	VENTING_VALVE	VV132_COIL	N																											
28	GATE_VALVE	GV103_COIL	N																											
29	GATE_VALVE	GV104_COIL	N																											
30	GATE_VALVE	GV105_COIL	N																											
31	GATE_VALVE	GV106_COIL	N																											
32	GATE_VALVE	GV107_COIL	N																											
33	GATE_VALVE	GV108_COIL	N																											
34	TMP	TMP141_PUMPING_STATION	N																											
35	TMP	TMP141_REMOTE_PRIORITY	Y																											
36	OUTPUT_GATE_VALVE	SGV101_CONTROL	N																											
37	MSS	CMP_VENTED	N	CMP_VENTED_EVAL																										
38	MSS	CMP_HV_READY	N		LO	LO	LO	LO	LO	LO	C0	LO	LO	LO	LO	LO	LO	LO	LO											
39	MSS	CMP_GOOD	N	C0																										

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Code generators

Full description in spreadsheet – can we program systems only by changes in Excel?

Yes, we can! (although some people don't believe that)

LabVIEW parser to extract data from Excel to LabVIEW dictionary or JSON

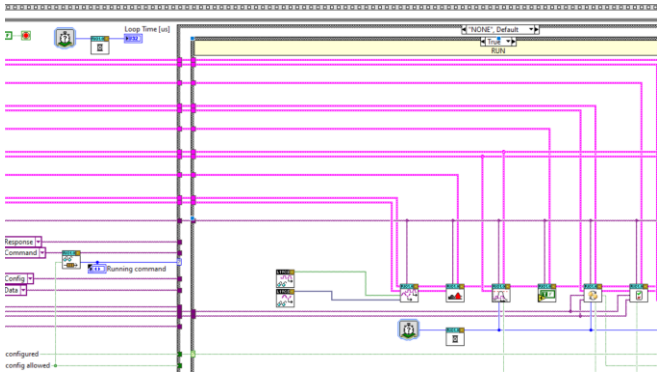
System description passed to scripters developed for each application type

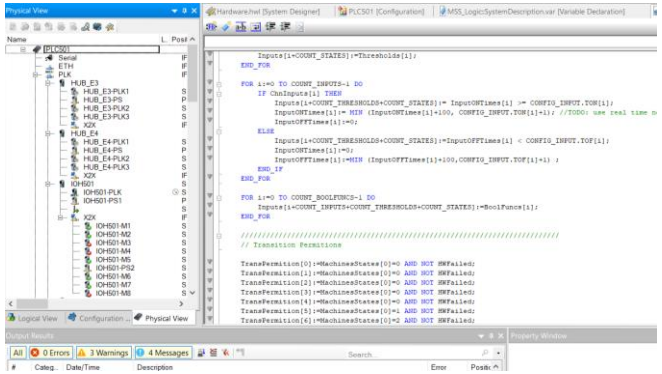
Unified simulation and diagnostics tools

Code generators

Pilz scripter
- Generates “hardcoded” ST code
- PAS4000 API used to create ready-to-build project
- Verified for safety-rated applications

LabVIEW FPGA scripter
- FPGA runs spreadsheet interpreter
- System description stored in RAMs
- Generated RAM and IO definitions
- Configuration changes – only RAM contents -> no recompilation





B&R scipter
- Generates XML files to create ready-to-build project
- Partially “hardcoded” ST code
- Dynamic version under development

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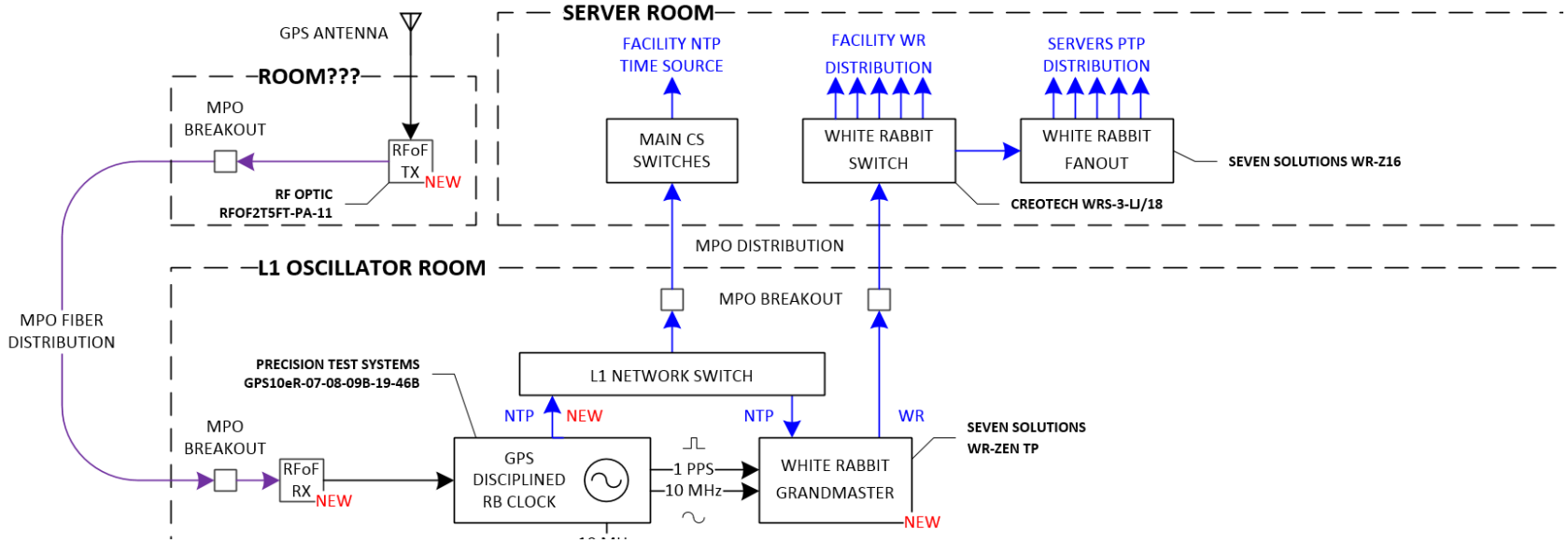
Timing system



GPS – timestamp + 1 pulse per second

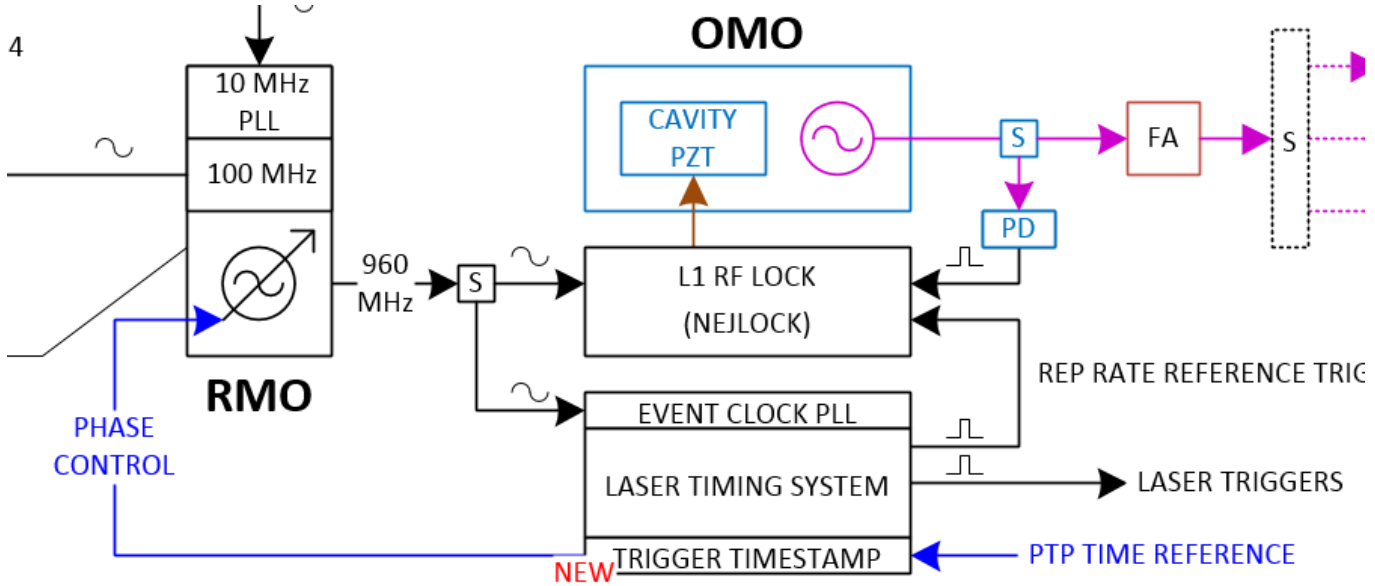
Rb clock as GPS receiver

-> 1 PPS, 10 MHz, NTP timestamp to White Rabbit grandmaster

White Rabbit distributed through facility to synchronize all lasers and experiments

Timestamping not too difficult, we know when an event (shot) occurs, highest rep rate 1 kHz

Timing system



Seed laser – usually 80 MHz Ti:Sapphire optical oscillator

RF oscillator + feedback loop to compensate for frequency drift in optical cavity

ETS generates 1 kHz trigger signals -> pulse picking in Pockels cells -> 1 kHz laser

1 kHz trigger distributed through beamline

Data visualization

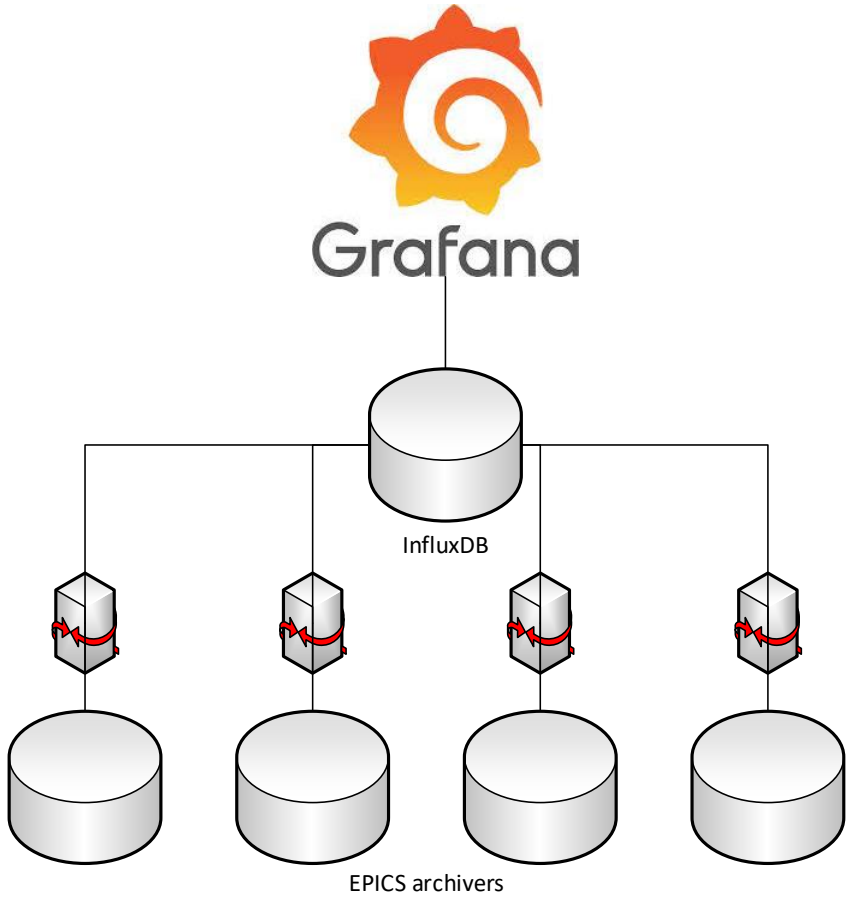
Direct access to controls confined to integration layers – only in control rooms

Operators require data even in offices or even remotely

Grafana – easy to setup dashboards for PV visualization

Alarm notifications – SMS gateway, Cisco Webex…

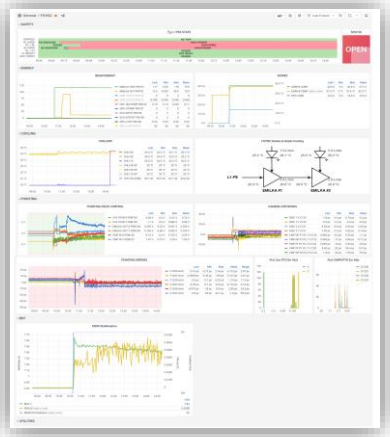
InfluxDB – “archiver cache”; polls PVs, time series kept for 30 days



Data visualization

L1-E1 dashboards pre-campaign

L1-E1 dashboards 1 week later



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Thank you

Karel Majer

karel.majer@eli-beams.eu

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