Continuous Caesiation System. Implementation and Safety Features.

180th Machine Protection Panel Meeting (Injector topics): Continuous Cesiation at LINAC4

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Introduction.

Identification of Cs heaters and sensors.
Implementation details.

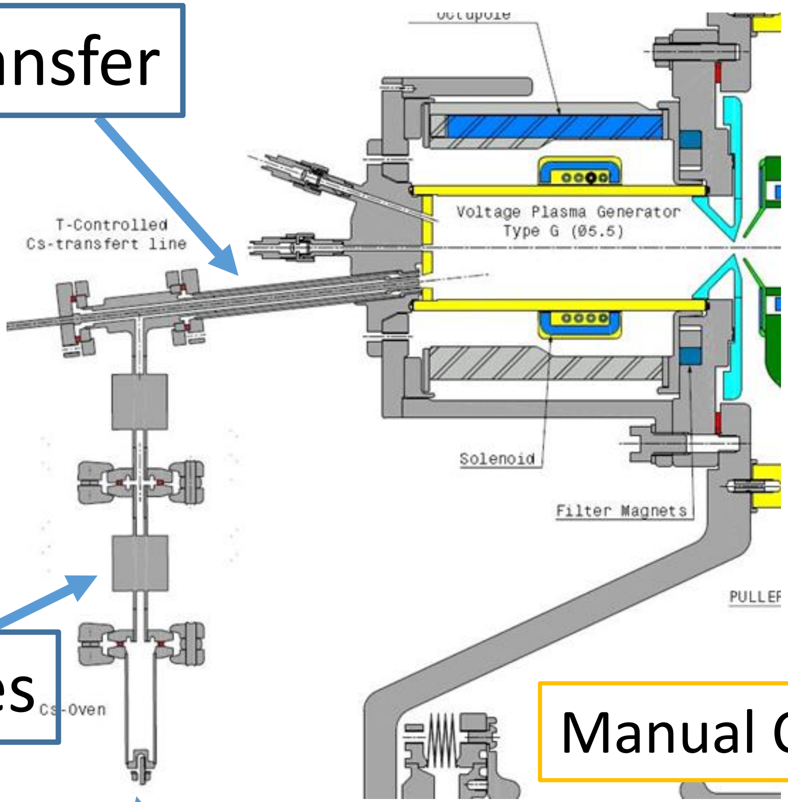
Heating modes and switching between them.

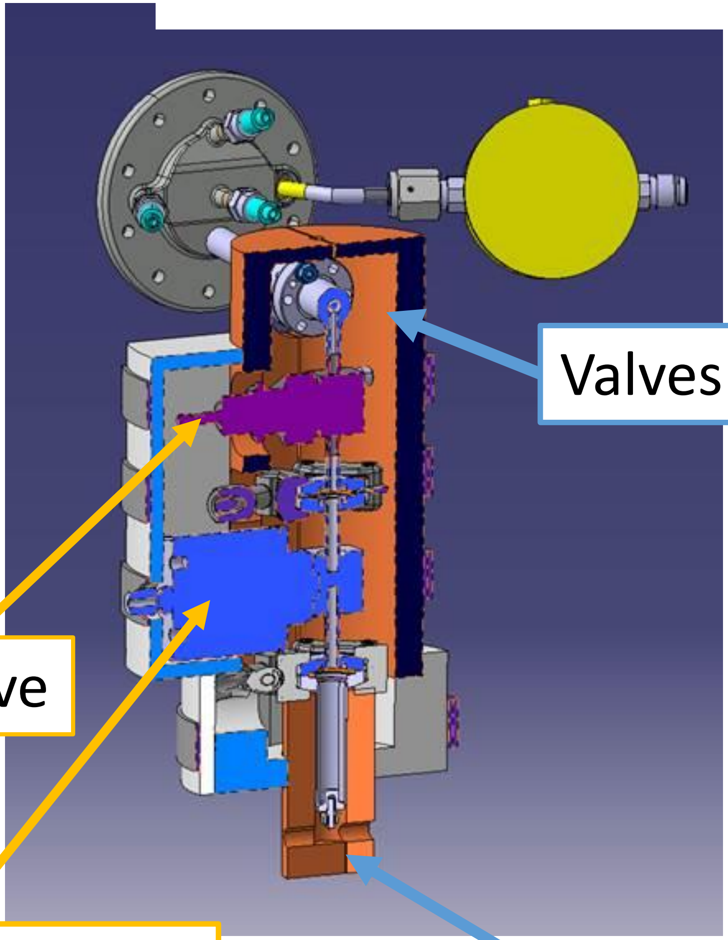
Detailed description of design.
Fault/failure modes, detection, reaction and mitigation.

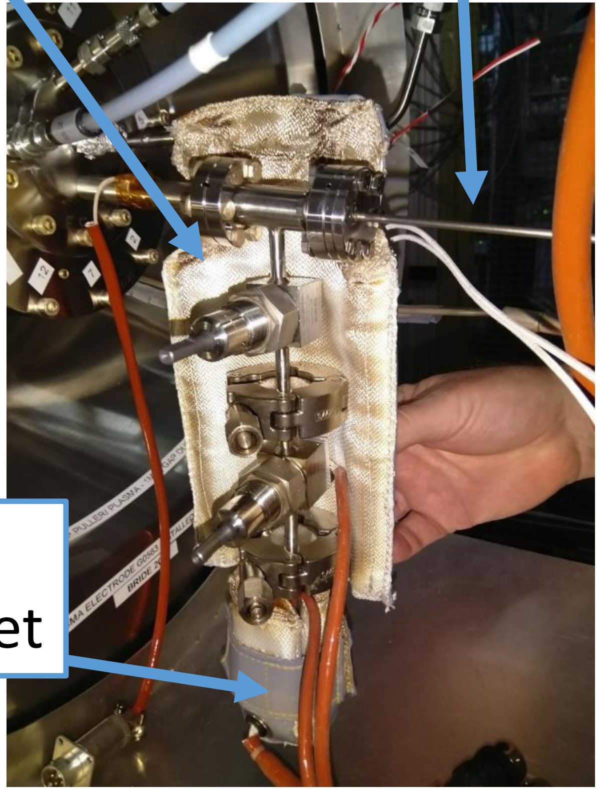
Reliability results so far.
Normal operation.

Summary

Valve and heater identification







Temperature sensor positions

Implementation.

Siemens standard S7-300 series PLC.

- Proven reliability in CERN ion sources.
- Spares readily available.

Programmed in the high level SCL (Pascal) language.

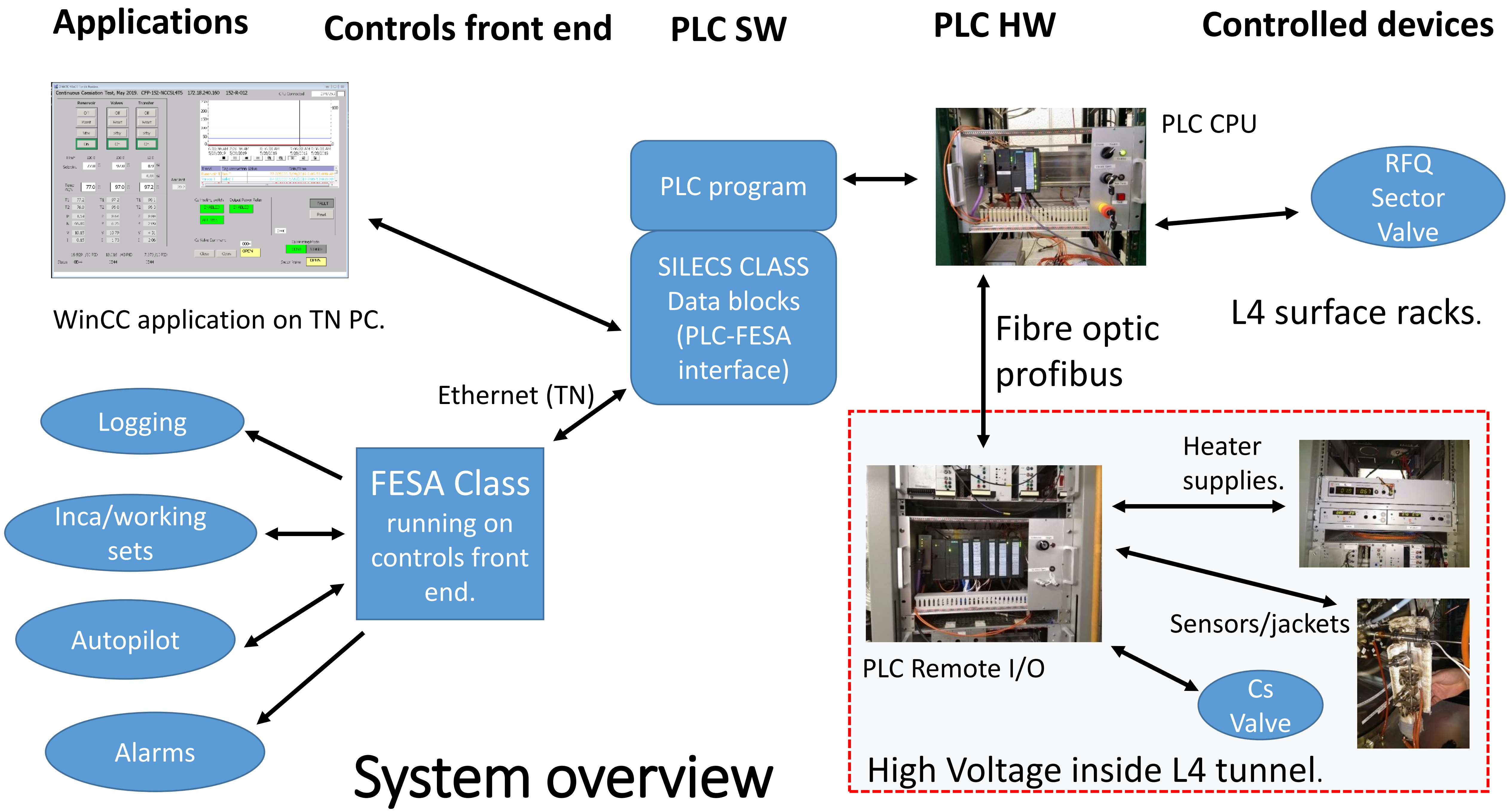
- Easier to maintain.

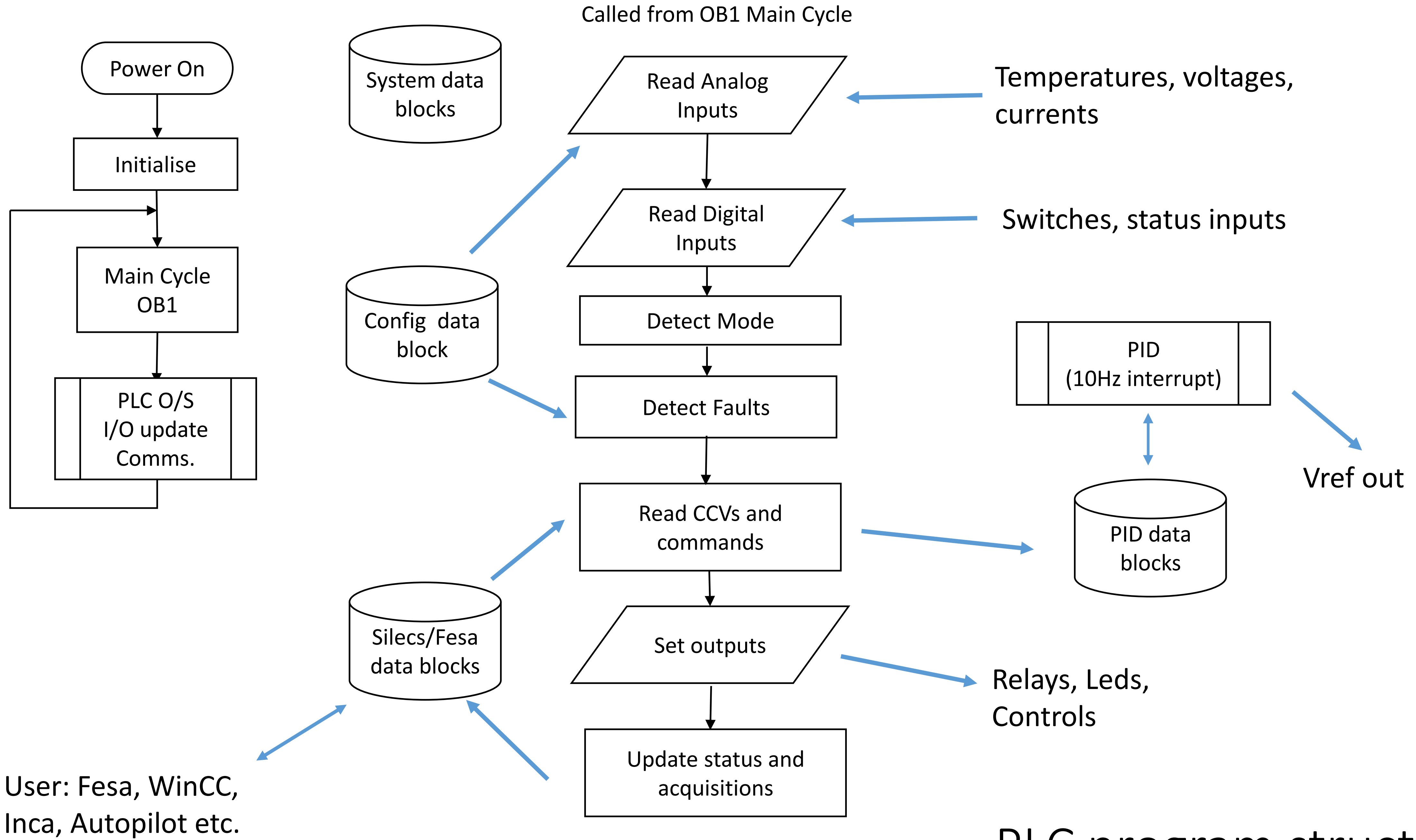
Individual voltage controlled DC power supplies for each heated element.

- Maximum flexibility per heated element.
- Maximum current individually limited to that necessary to reach max temperature.
- Facilitates monitoring of performance.

SILECS framework to provide interface to FESA.

- CERN supported, used extensively on our ion sources and test stands.


Applications
Controls front end
PLC SW
PLC HW
Controlled devices
WinCC application on TN PC.
PLC program
SILECS CLASS Data blocks (PLC-FESA interface)
PLC CPU
RFQ Sector Valve
L4 surface racks.
Fibre optic profibus
Ethernet (TN)
Logging
Inca/working sets
Autopilot
Alarms
FESA Class running on controls front end.
Heater supplies.
Sensors/jackets
PLC Remote I/O
Cs Valve
High Voltage inside L4 tunnel.
System overview



PLC program structure

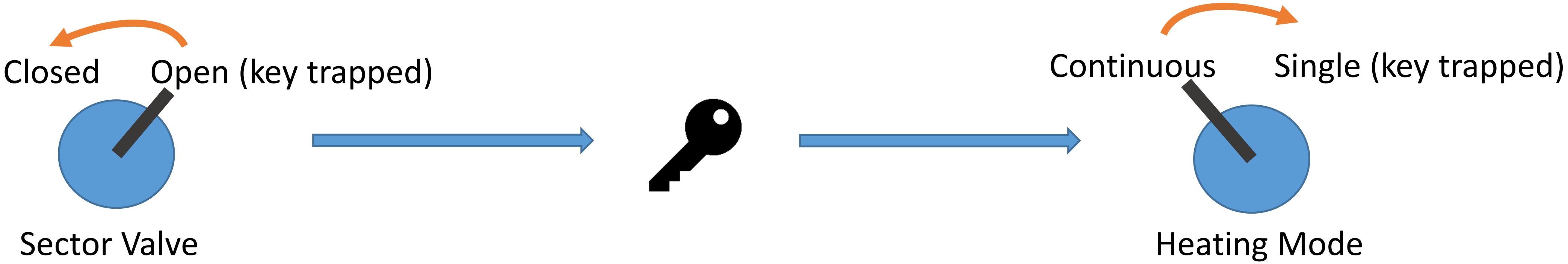
Caesiation modes.

Characteristic \ Mode	Single	Continuous
Reservoir temperature	High, up to 140°C	Low, 60 - 80°C
Duration	~2 hours + 1-2hr cool down	Continuous
Periodicity	~ Once per month	Continuous
Sector valve RFQ	Closed	Open
Cs valve	Opened for ~1-2 hours.	Always open.
Beam availability	Stopped for several hours/month	Fully available
Stability (e/H)	Varies (1 to 10)	Constant (~1)
Stored Cs in reservoir	Typ. 2g	Typ. 2g
ASSUMPTIONS	**Safe at high reservoir temperatures while sector valve is closed.**	**Safe if reservoir temperature is kept below 80°C while sector valve is open.**

Caesiation mode switching.

From continuous (low temperature) to single shot (high temperature) and back.

A single key must be transferred from surface CPU to tunnel I/O chassis.



Surface CPU

Failsafe mode switching.

An open sector valve excludes ‘Single shot’ mode (high temperature).

Single shot mode excludes open sector valve.

Tunnel IO

Switching between modes.

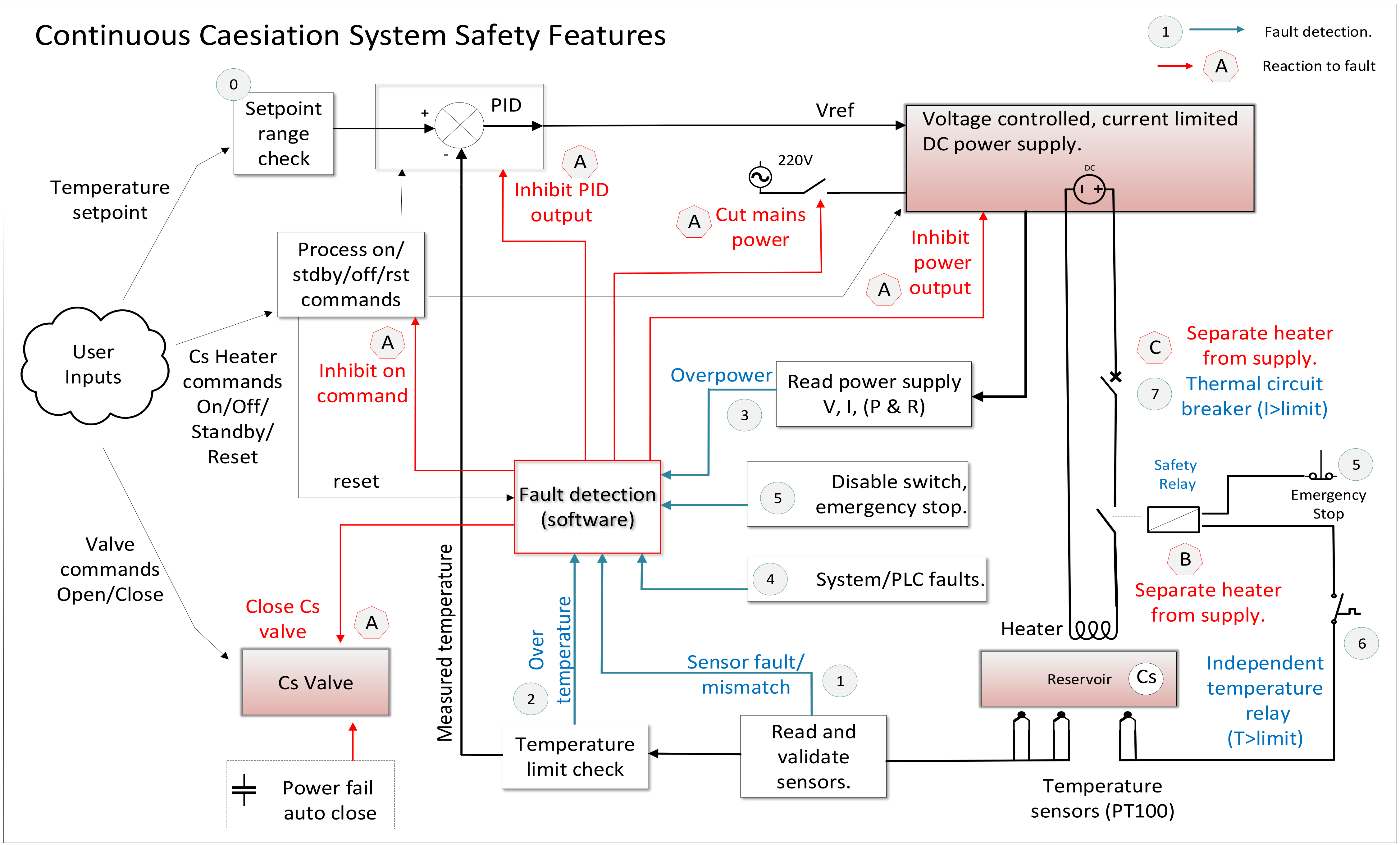
CCV Temperature limits for each mode.

CCV limits for single shot are only applied if sector valve status is confirmed closed.

Mode:	Continuous			Single shot		
	CCV (Max)	T limit (SW)	Secondary (HW) T limit	CCV (Max)	T limit (SW)	Secondary (HW) T limit
Reservoir	80	83	85	140	143	-
Valves	100	106	-	170	176	-
Transfer line	100	106	-	170	176	-

Switching back to continuous mode from single mode.

- Reverse of the key switch procedure.
- Operator must open sector valve via PVSS Vacuum application.
- If T > CCV (max continuous) heaters will shutdown at switchover.
- If CCV > CCV(max continuous) it will reset to 0.0 at switchover.


Continuous Caesiation System Safety Features
1
Fault detection.
A
Reaction to fault
0
Setpoint range check
PID
+
-
Vref
Voltage controlled, current limited DC power supply.
DC
220V
A
Inhibit PID output
A
Cut mains power
Inhibit power output
A
Temperature setpoint
Process on/ stdby/off/rst commands
User Inputs
Cs Heater commands On/Off/ Standby/ Reset
A
Inhibit on command
C
Separate heater from supply.
7
Thermal circuit breaker (I>limit)
Overpower
Read power supply V, I, (P & R)
3
reset
Fault detection (software)
Disable switch, emergency stop.
5
Safety Relay
5
Emergency Stop
B
Separate heater from supply.
4
System/PLC faults.
Valve commands Open/Close
Close Cs valve
A
Measured temperature
Over temperature
2
Heater
6
Cs Valve
Sensor fault/ mismatch
1
Reservoir
Cs
Independent temperature relay (T>limit)
Temperature limit check
Read and validate sensors.
Power fail auto close
Temperature sensors (PT100)

Fault conditions and detection/mitigation.

Fault mode	Fault type	Main reaction	Backup reaction
1	Sensor fault	A	B
2	Over temperature	A	B
3	Over power	A	BC
4	System faults	A	BC
5	User actions	A	B
6	Secondary over temp	B	A
7	Over current	C	B

Reaction A to fault (Software detected)	Reactions B & C to fault (Hardware detected)
Cut mains to heater PSU	Separate heater from power supply
Inhibit heater power supply	
Reset PID output to 0	
Force Off command/ block On	
Close Cs Valve	

Any single fault detected on any subsystem (reservoir, valve or transfer heater) will shutdown all heater subsystems and close the Cs valve.

Fault 1. Sensor fault.

Sensor type: PT100 (2 wire, connected to PLC via 4 wires).

Averaged reading of two sensors per measurement site.

Risk: A false sensor reading could cause the PID to deliver more power and exceed safe temperature.

Reaction to detected fault is to shutdown power and close Cs valve (Reaction A).

Failure mode	Primary Detection	Mitigation	Tested
Open circuit	Software function (FC20)	Independent T relay (6-B)	✓
Short circuit	(FC20)	(6-B)	✓
False reading <0°C	(FC20)	(6-B)	-0.1 ✓
False reading >250°C	(FC20)	(6-B)	250.1, (Res 155.1) ✓
Mismatch >5°C	(FC20)	(6-B)	5.1 ✓

Testing method: Substitute each sensor individually with a PT100 simulator, disconnect sensor, short out sensor.

Fault 2: Over temperature.

Possible causes include: PID regulation overshoots, external heat source, general failure of power supply or control software.

Reaction to fault: Shutdown power and close Cs valve (A)

Failure mode	Primary Detection	Mitigation	Tested
Reservoir > (CCV max +3°C)	Software function (FC13)	Independent T relay (6-B)	83.0 ✓
Valve block > (CCV max +6°C)	(FC13)	Independent T relay (6-B)	106.1 (inertia to 107.1) ✓
Transfer line > (CCV max +6°C)	(FC13)	Independent T relay (6-B)	106.1 (inertia to 107.1) ✓

Testing method: Heater to local control, max power. Monitor temperature until switch off.

Fault 3: Over power

Possible causes: PID regulation failure, power supply remote interface failure or power supply fault.

Reaction to fault: Shutdown power (A)

V and I read from power supply, P (& R) calculated and tested against limit.

Heater circuit	PID max power (nominal)	Primary detection (Software power limit)	Mitigation	Tested
Reservoir	4W	Software (FC13) 5.0W	Circuit breaker (7C) (250mA) and T relay (6B)	
Valve block	92W	Software (FC13) 100.0W	7C (4.0A) and 6B	
Transfer line	17W	Software (FC13) 20.0W	7C (3.0A) and 6B	

Testing method: Heater to local control, increase power until shutdown.

Fault 4: System and PLC faults.

Some fault scenarios unrelated to the heating process.

Detection is the PLC operating system or default behaviour of PLC.

Failure mode	Reaction	Primary Detection	Mitigation	Tested
CPU stop, crash.	Shutdown (A)	Default I/O module reaction.	Independent T relay (6-B)	✓
CPU power cut.	Shutdown (A)	Default I/O module reaction.	(6-B)	✓
Remote I/O power cut.	Shutdown (A)	Software function (OB86, OB122)	(6-B)	✓
Fibre optic link break.	Shutdown (A)	Software function (OB86, OB87)	(6-B)	✓
Ethernet link loss.		PLC continues to run, not considered unsafe.	AUL, disable switch.	✓

Fault 5: User controls

Enable/disable switch

- When disable is selected, the output shuts down (A) and remote commands are ignored.

Emergency stop

- When presses, system is shutdown as for enable/disable and in addition the power output relay (B) is also opened.
- Emergency stop is transmitted to tunnel via independent fibre optic cable to control a relay within the remote I/O chassis.

Fault 6: Independent temperature relay.

- To provide redundancy in over temperature detection (reservoir).
- Independent hardware modules and sensor (PT100).
- Independent 24V power supply.
- Safety relay contacts separate all heaters from power sources via reaction (B), at same time reaction (A) is triggered.
- Fail safe: Contacts open if power fails. Reset required.

Heater circuit	T Limit	Mitigation	Tested
Reservoir	85.0°C	Circuit breaker (7C) (250mA)	85.4 (inertia 86.1 after 2 mins) ✓

Testing method: Heater to local control, full power (4W) until relay trips.

Fault 7. Independent overcurrent protection.

Fault scenario:

- Power supply remote control and PLC control function fails.
- Power supply delivers its maximum power for the given load resistance.

Thermal circuit breaker in power output reacts to over current to separate the heater from the power supply (reaction C).

	Reservoir	Valves	Transfer
R nominal/Ohms	80	6.3	2.1
I max (normal PID)	0.225A	3.8A	2.85A
Chosen thermal circuit breaker rating	0.25A	4A	3A
Normal P max	4W	92W	17W
Chosen software limits for P max	5W	100W	20W
Power supply fault scenario:			
Max possible output for the given load i.e. 30V OR 5A.			
Max current	0.375A	4.8A	5A
Max Power	11.25W	142W	52.5W
% power overload	281	154	308
CCB reaction time	31s	381s	21s
Equiv time at full power (overload % x reaction time)	87s	586s (10 min)	65s
Typical T rise at full power for this time.	5.3°C	38.6°C	1.1°C

Testing method: Bench test in lab with DC supply to theoretical max current and time circuit breaker reaction.

User / Installation faults.

Fault 0: User input error.

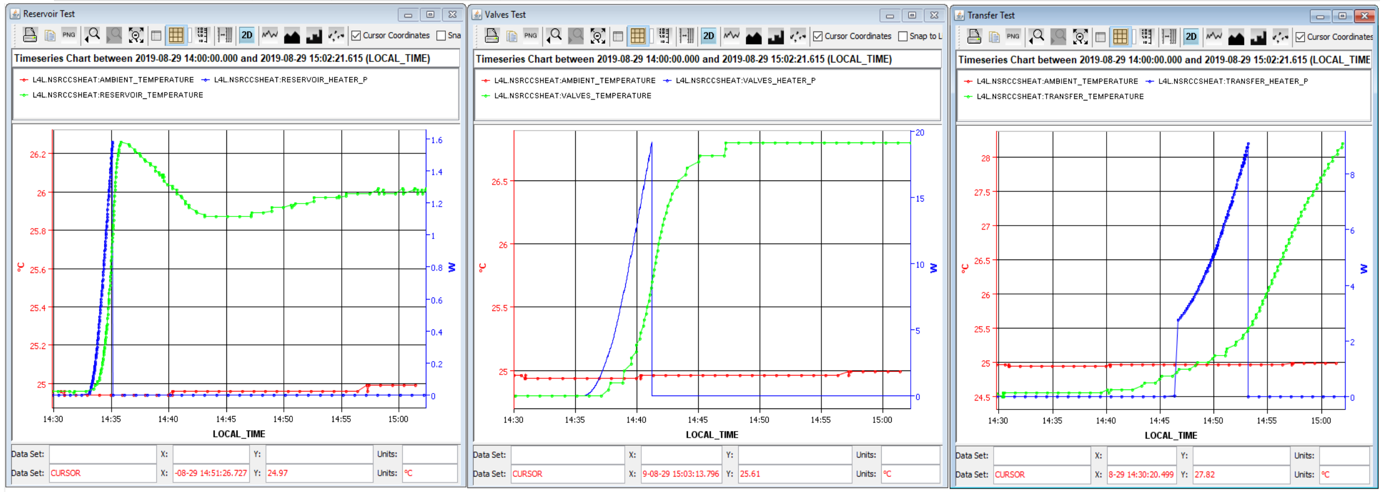
- CCV is tested against limits in both FESA class and PLC (software function FC22). It is ignored if out of limits and last good value retained.

Preventing installation errors.

- All connectors to heaters and sensors are different. Mismatch impossible.
- 220V to power supplies, phase on different pins, no heater power if mismatched.
- Heater supply remote control/power connectors, output power is on different pins so no power reaches heater if mismatched.
- Post install test of each heater/sensor individually to verify sensors correctly placed.

Annual checklist test of all safety features.

- Before yearly start-up.
- After any repair or modification.



Power / temperature response tests.

Reliability, EMC.

Two units built, ‘152’ test stand and ‘400’ Linac 4 machine.

Electrically noisy environment, HT 45kV sparks, pulsed 50kW RF.

All inputs protected with ‘transorb’ voltage spike suppressors, mains power is filtered.

152 unit - Test Stand installed May 2019.

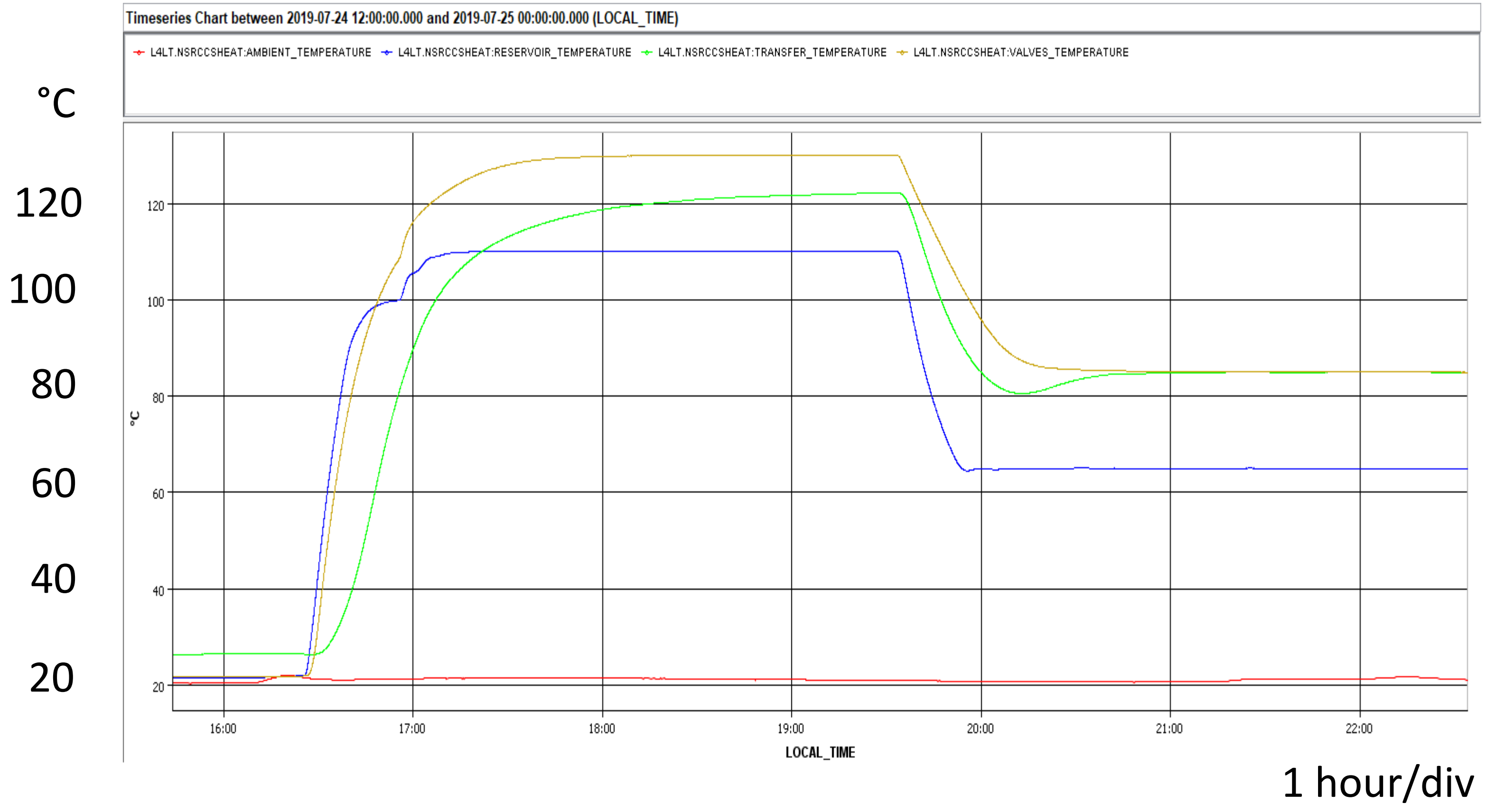
- Test run in continuous mode for 5 weeks.
- Since then 3 months general use (continuous and single shot).
- No component failures.
- Several hundred einzel lens trips/sparks, ~30 source HT and RF sparks/trips.
- No CPU interruptions.

400 unit - Linac 4 Installed end July 2019.

- Two ‘single shot’ caesiations performed otherwise in monitoring mode (heaters disabled).
- Approx. 20 HT sparks/trips.
- Following HT spark, 1 PT100 failure (short circuit), system detected and shutdown as designed.
- No CPU interruptions.

WinCC control application.

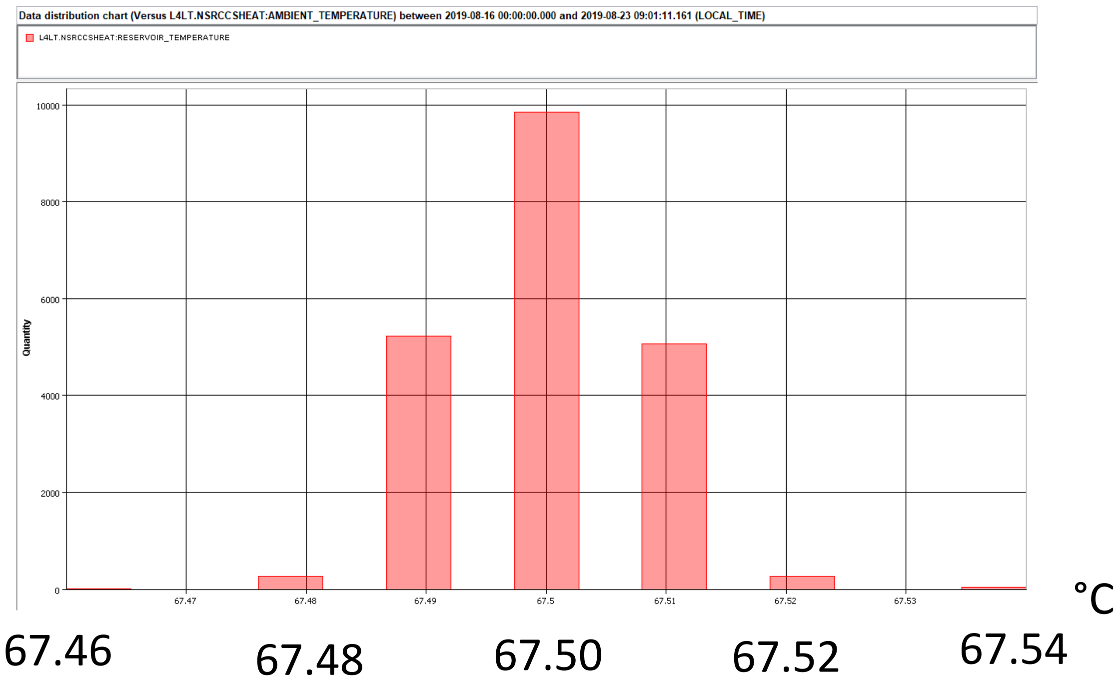
Single shot caesiation then switch to continuous.

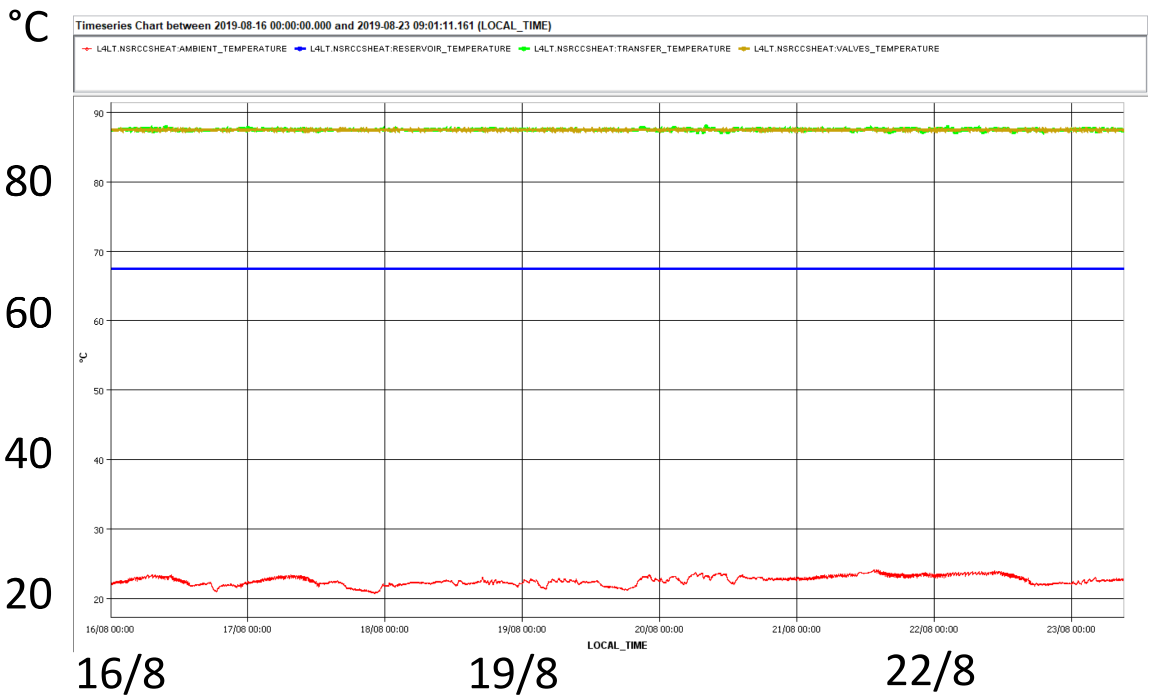


Test stand 24/7/2019.

Red: Ambient, Blue: Reservoir, Yellow: Transfer, Green: Valves

Test stand 1 week continuous mode.





Red: Ambient, Blue: Reservoir,
Yellow: Valves, Green: Transfer

Reservoir stability, test stand 7 days (16/08 – 23/08)
Set point 67.5°C.
~500,000 temperature measurements
(filtered by Timber).

	Values Count	MIN Value	MAX Value	AVG Value	Standard Deviation
AMBIENT_TEMPERATURE	25269	20.7	24.1	22.6	0.641
RESERVOIR_TEMPERATURE	20724	67.46	67.54	67.5	0.007947
VALVES_TEMPERATURE	29185	87.45	87.55	87.5	0.03241
TRANSFER_TEMPERATURE	14625	87	88.1	87.5	0.115

Summary.

- System allows both single shot high temperature, and continuous low temperature operation.

- Safety in single shot mode is assured by forcing (and verifying) closure of the sector valve before single shot mode can be enabled.

- Safety in continuous mode is assured by limiting the maximum reservoir temperature to a safe level.
  - Achieved with multiple modes of fault detection and redundancy in over-temperature detection.
  - Redundancy in fault reaction to remove power to heaters and shutoff Cs flow.

- Test system has functioned reliably during 4 months operation in both modes and has been effective in maintaining a low e/H ratio in continuous mode.