Cryogenic Functional Analysis:

Process control for the RF Cavity system

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Summary

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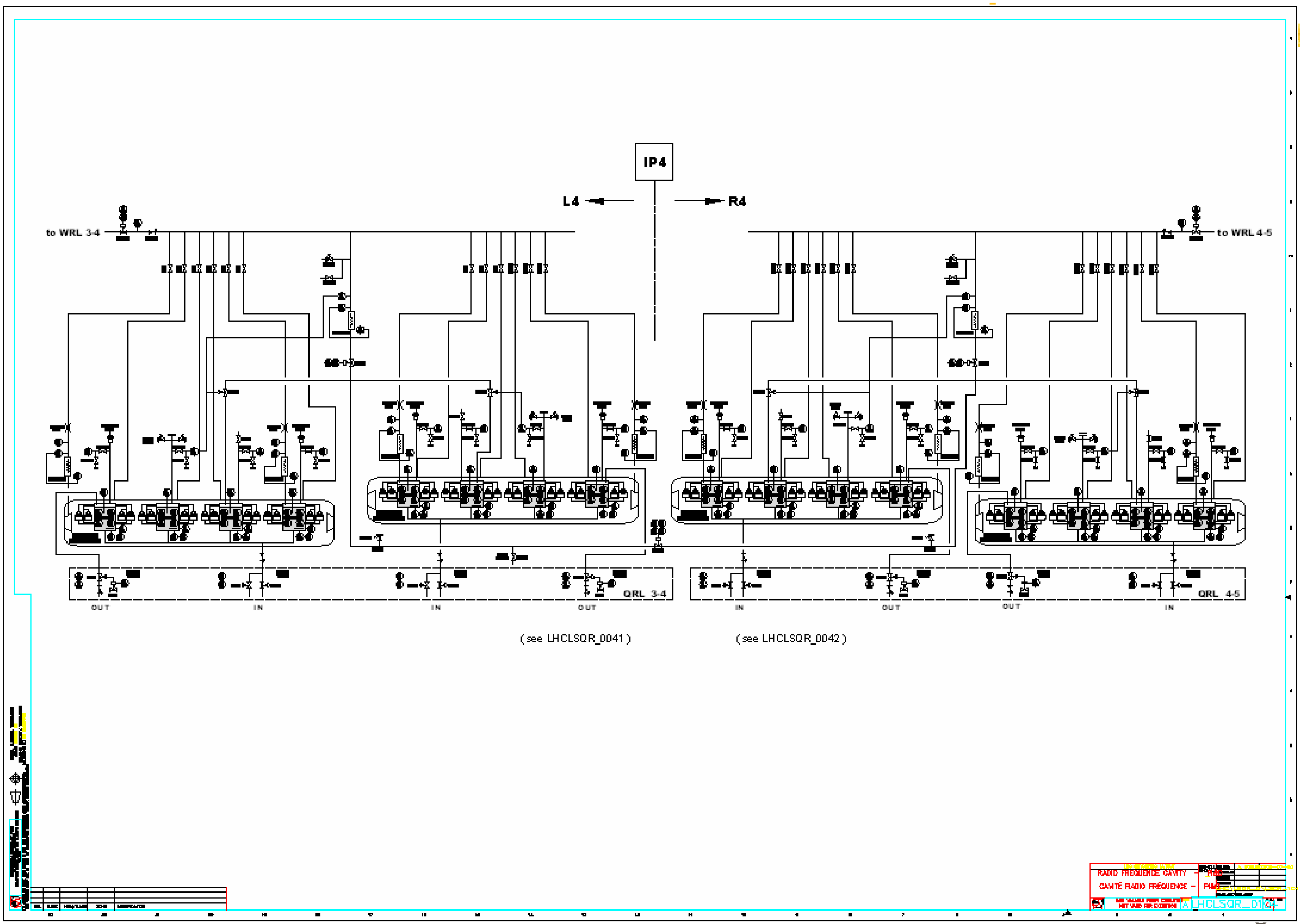
1) Flow scheme



2) Flow distribution

- The virtual flowmeter is a software tool used to obviate the absence of real flowmeter all along the cryogenic distribution line or at the outlet of the current leads. By means of simple computations it will be possible to have an indirect measurement of the helium flow passing through a valve. The virtual flowmeter has been already successfully tested and used during the String 2 operations and during the first 8-1 QRL sector cool-down giving information on the process flow with about 15% accuracy for cryogenic valves with measured Kv; for the warm valves of the current leads an accuracy of about 30 % can be expected;

- The virtual flowmeter will ensure that during cooldown the cryogenic power is correctly distributed to allow a homogenous cooling of the whole sector. During nominal operation the virtual flowmeter will verify that the overall cryogenic power demand from the tunnel cryogenic system is compatible with the cryogenic power produced at the refrigerators level; the refrigerators cryogenic power availability will be communicated to the tunnel cryogenic system via two flags called “increase capacity” and “decrease capacity”. Additional virtual flowmeters would be available on other control loops such as the current leads temperature control loop as diagnostics to infer the mass flow rate and identify or solve possible clogging problem in the cooling circuits.

Virtual flowmeter regulation

- First step: repartition of the total available flow wrt the thermal capacity or the subsystem volume

$$\begin{cases} \dot{m}_i = \dot{m}_{tot} \cdot \dfrac{M_i C_i}{\sum_i M_i C_i} & \text{if } T \geq 5K \\ 770\, g/s \leq \dot{m}_{tot} \leq 150\, g/s & \end{cases}$$

$$\dot{m}_i' = \dot{m}_{tot} \cdot \frac{V_i}{V_{tot}} \qquad \text{if } T < 5K$$

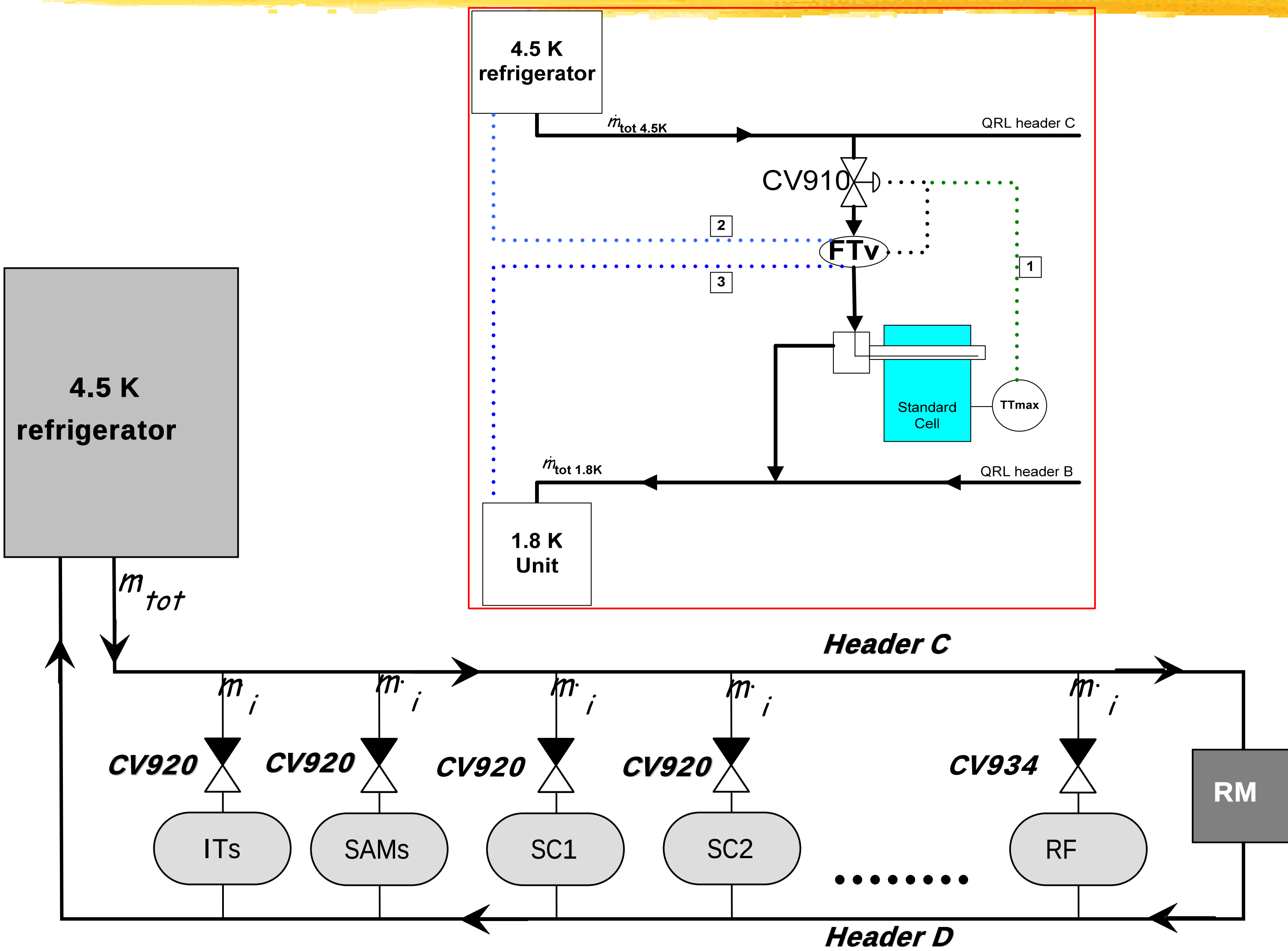
$\dot{m}_{tot}$ = total mass flow supplied by 4.5K Refr.
$\dot{m}_i$ = system mass flow
M_i = system mass
C_i = specific heat capacity
V = system volume

- Second step: tune the ST wrt the sub-system cool-down speed

$$\dot{m}_i = \dot{m}_{tot} \cdot \frac{M_i C_i f_i}{\sum_i M_i C_i f_i}$$

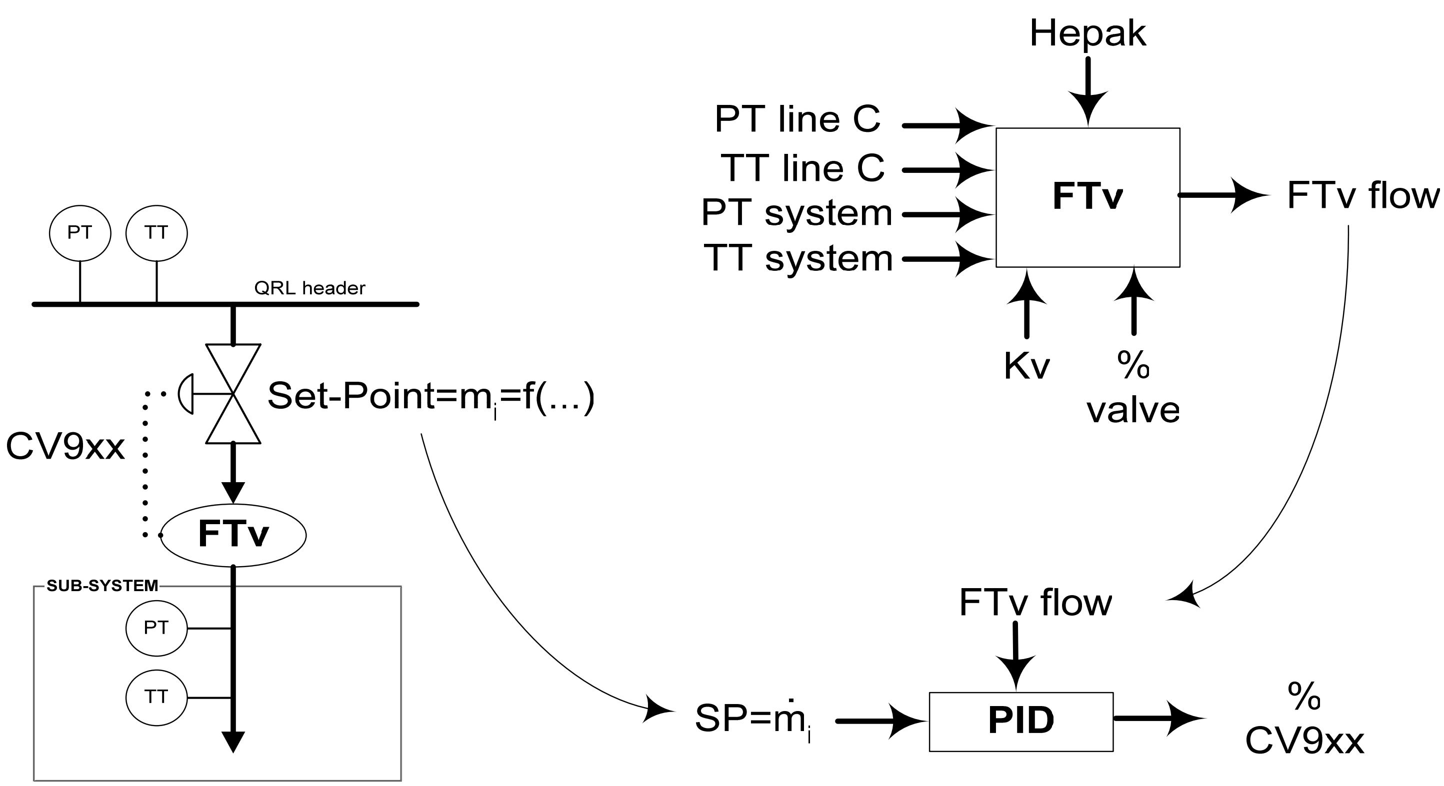
f_i = distribution factor $\qquad f_i = \dfrac{T_{out\,i}}{\overline{T}_{out}}$

PFD for flow distribution and control



Virtual flowmeter regulation

1. Virtual measurement of helium flow (FTv);
2. Set-point computing (formulas);
3. PID adjustment.



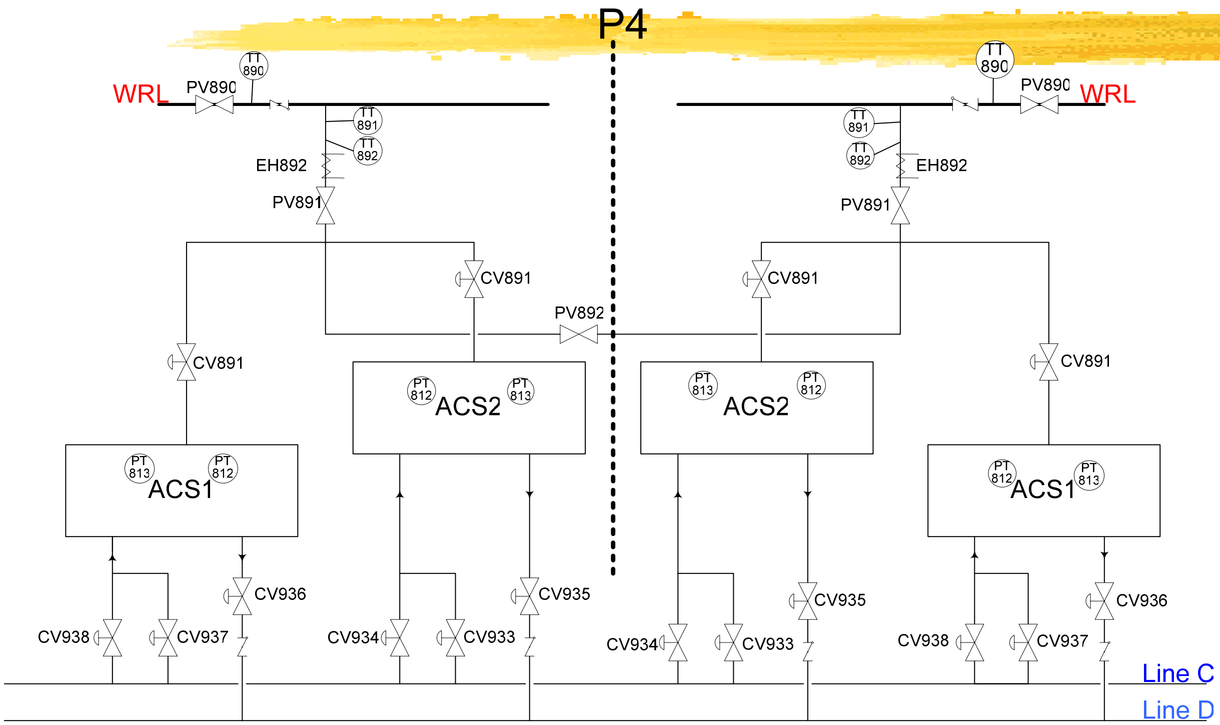
3. Sensors break down

- Special programming of the cryogenic control system will take care of sensors break-down.
- If a sensor is clearly out of order (e.g. open circuit, short circuit or value outside the range) a flag will be set in order to send an operator alarm and either set in manual (with fix or zero value of the corresponding actuators) the affected control loop or try to recover the input data from other sensors or a computation of it.
- This is particularly important for the definition of the cryo authorization for powering and cryo request for discharge signals that require a high level of robustness but also immunity to sensor breakdown.

4) Cryogenic phases:

- Cool-down 300 K - 4.5 K
- Filling
- Normal Operation
- Powering
- Emptying
- Warm-up 4.5 K – 300 K
- Cold Floating (75 K)

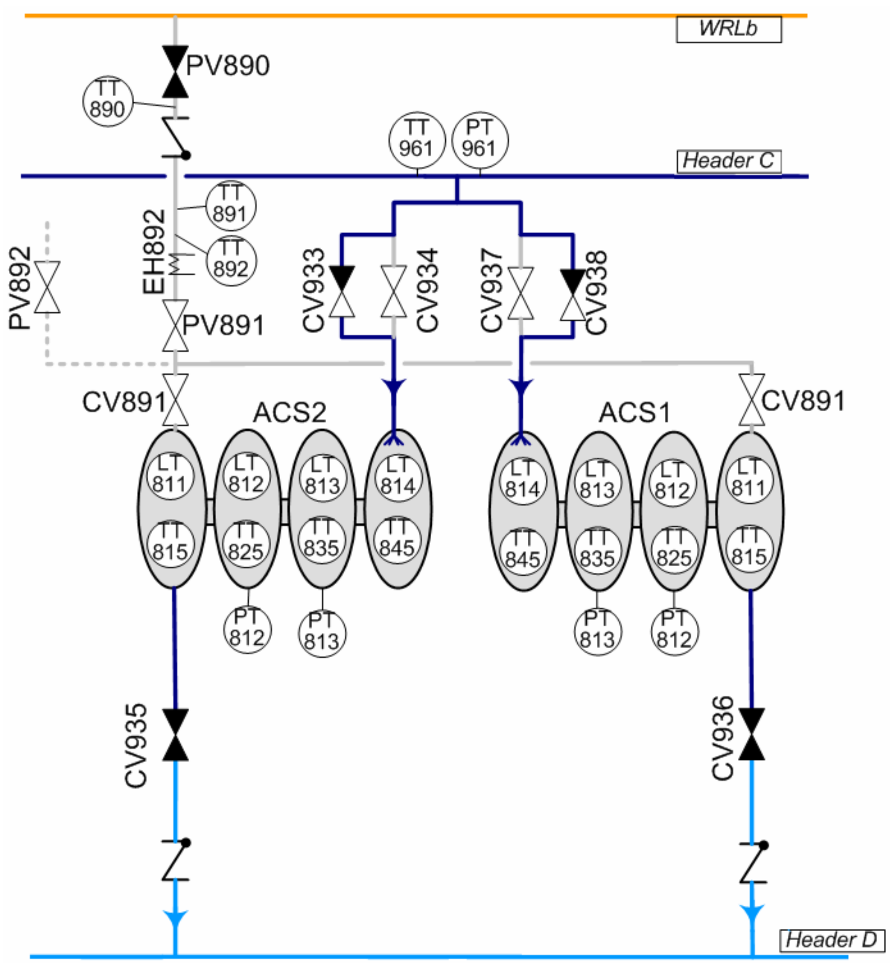
Valid for all phases (300-4.5 K once below 1.7 bar)



Connection to the WRL used to recover static losses in the modules when the normal exit to the line D of the QRL has to be closed due to pressure exceeding the 1.7 bar limit for the RF modules

CV891	IF PT812/13>1.5bar and (CV935/36>95% or <5%) REGULATION on the minimum output calculated by these 2 regulators: -PT=1.35bar ; -TT891=285K else closed
PV891_L4	OPEN IF PT812/13_L4>1.5bar and (CV935/36_L4>95% or <5%) and TT891_L4>270K or IF PT812/13_R4>1.5bar and (CV935/36_R4>95% or <5%) and TT891_R4<270K else CLOSE
PV891_R4	OPEN IF PT812/13_R4>1.5bar and (CV935/36_R4>95% or <5%) and TT891_R4>270K or IF PT812/13_L4>1.5bar and (CV935/36_L4>95% or <5%) and TT891_L4<270K else CLOSE
PV892	OPEN IF PT812/13_L4>1.5bar and (CV935/36_L4>95% or <5%) and TT891_L4<270K or IF IF PT812/13_R4>1.5bar and (CV935/36_R4>95% or <5%) and TT891_R4<270K
PV890	OPEN
EH892	REGULATION on TT892=300K

Cool-down 300 K - 4.5K

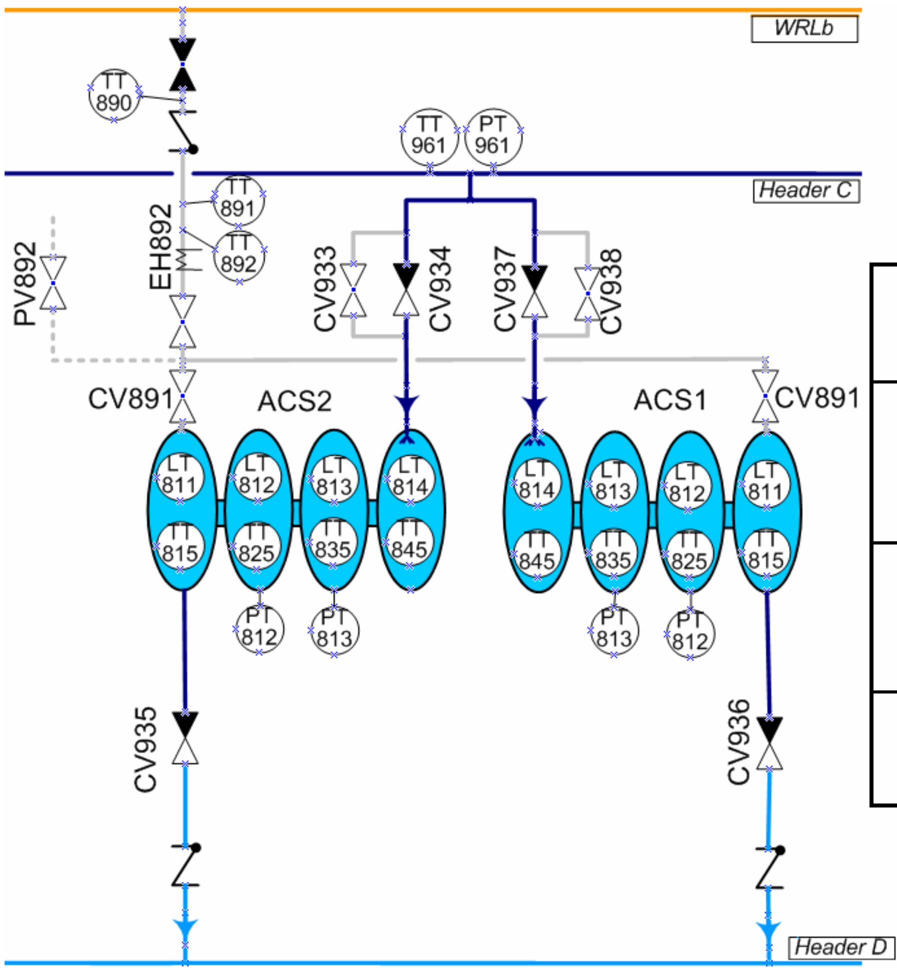


The cool-down of cavities begins only when:

- Vacuum RF Ok
- Cryo unaible
- Pressure in line D is below 1.7 bar, it corresponds to a temperature of 70 K for the magnets.

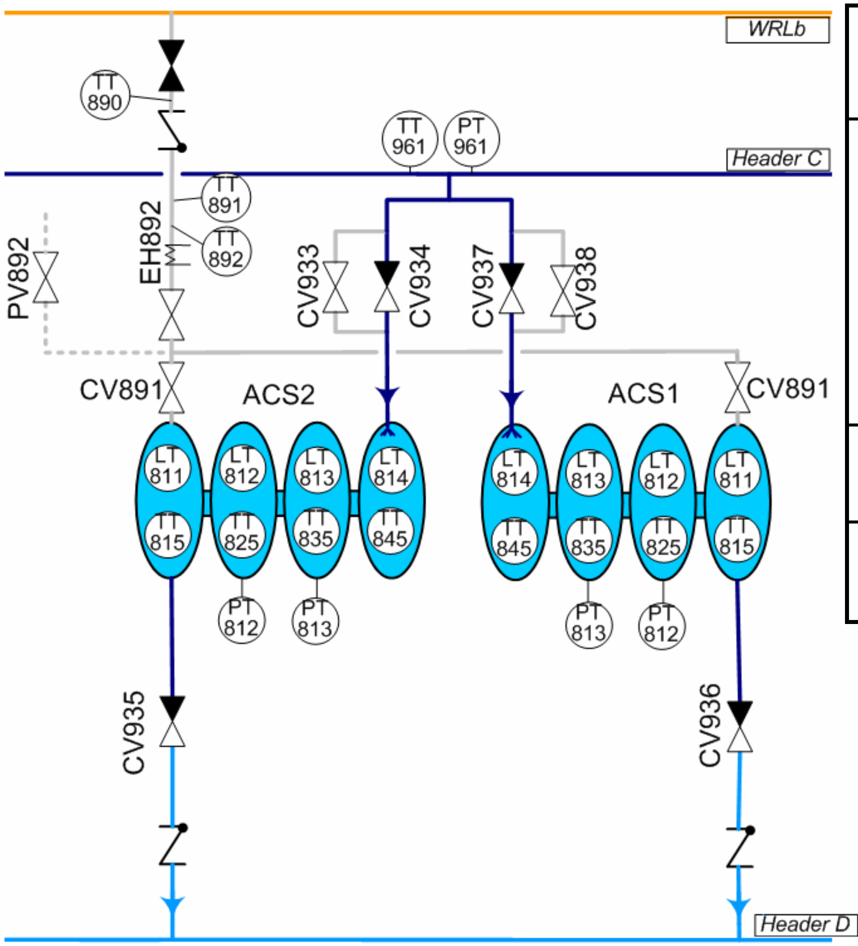
CV934, CV937	REGULATION FTV(Cp, $M_{AVLB\ 4.5K}$) FROM PT991<2BAR
CV933, CV938	OPEN @ 10% WHEN TT846<10K
CV935, CV936	OPEN @ 100% FROM PT991<2BAR
EH811, EH812, EH813, EH814	OFF

Filling



CV933, CV938	CLOSED
CV934, CV937	REGULATION FTV(V,$M_{AVLB\ 4.5K}$) UNTIL LT≥50% THEN REGULATION on minLT=60%
CV935, CV936	REGULATION ON PT=1.35bar
EH811, EH812, EH813, EH814	OFF

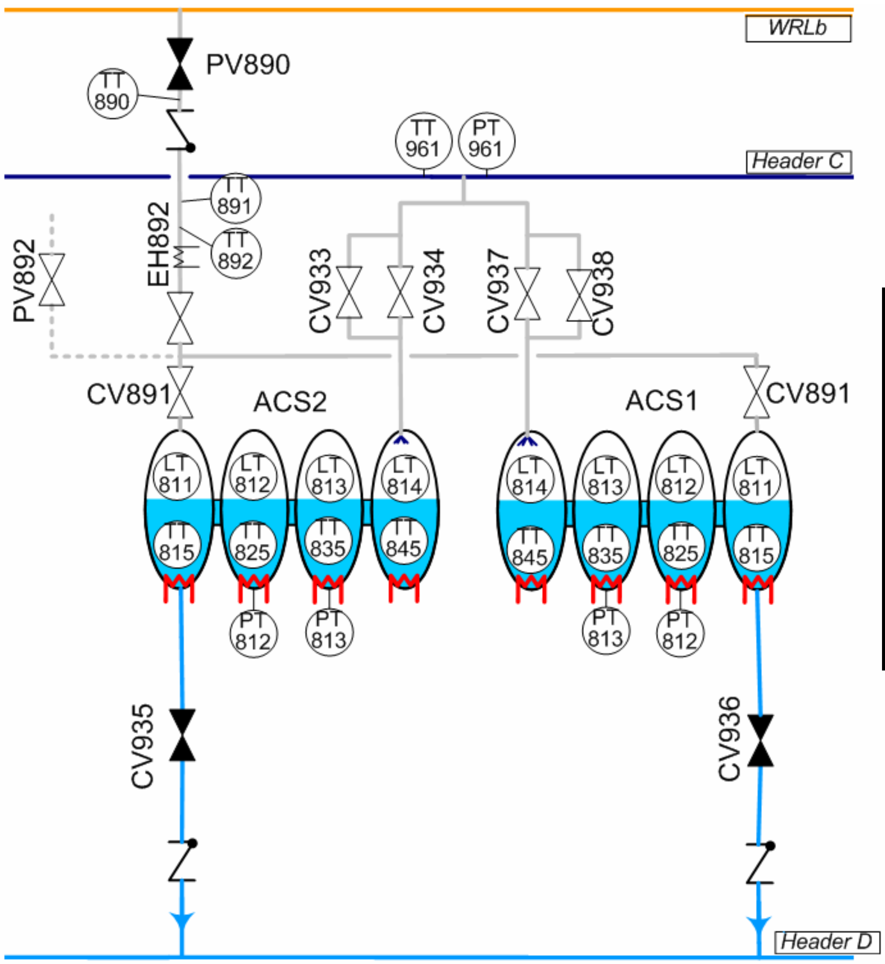
Normal Operation and Powering



CV933, CV938	REGULATION ON minLT=60% IF CV933/37>95% ELSE CLOSED
CV934, CV937	IF (Decrease Capacity ON) REGULATION on the minimum calculated output of these 2 regulators: -minLT=60% -FTV(Q,M_{TOT}4.5K) ELSE REGULATION on minLT=60%
CV935, CV936	REGULATION ON PT=1.35bar
EH811, EH812, EH813, EH814	OFF

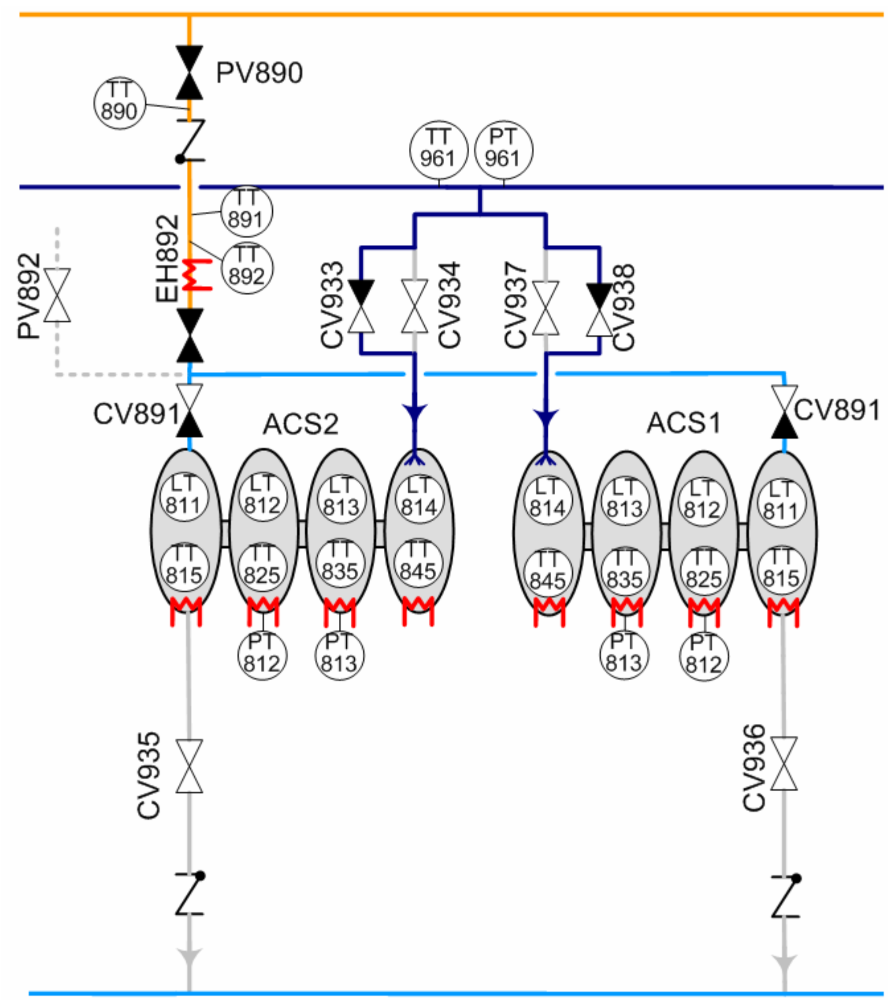
EH could be used to have constant opening of valve controlling heater power with beam current to obtain constant heat load.

Emptying



CV933, CV938	CLOSED
CV934, CV937	CLOSED
CV935, CV936	REGULATION ON PT=1.35bar
EH811, EH812, EH813, EH814	ON @ EHi

Warm-up 4.5 K – 300 K



CV933, CV938	REGULATION FTV(Cp,$M_{TOT\ 4.5K}$)
CV934, CV937	CLOSED
CV935, CV936	CLOSED
EH811, EH812, EH813, EH814	REGULATION on TT815/25/35/45=310K
CV891	OPEN @ 100%
PV891_L4	OPEN IF TT891_L4>270K or IF TT891_R4<270K else CLOSE
PV891_R4	OPEN IF TT891_R4>270K or IF TT891_L4<270K else CLOSE

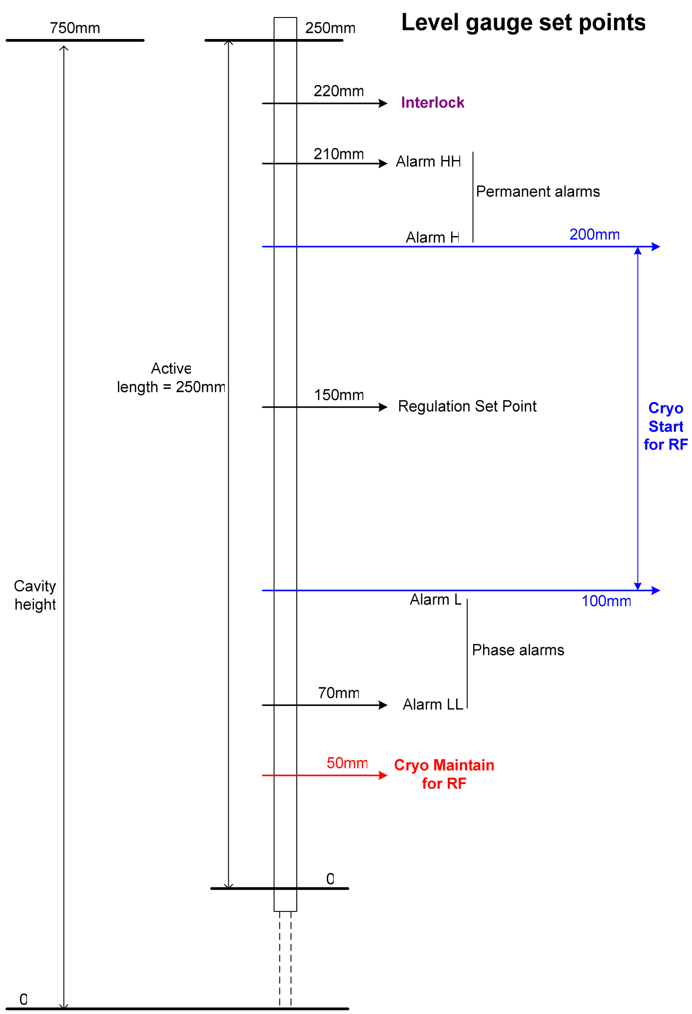
? Cold Floating (75 K) ?

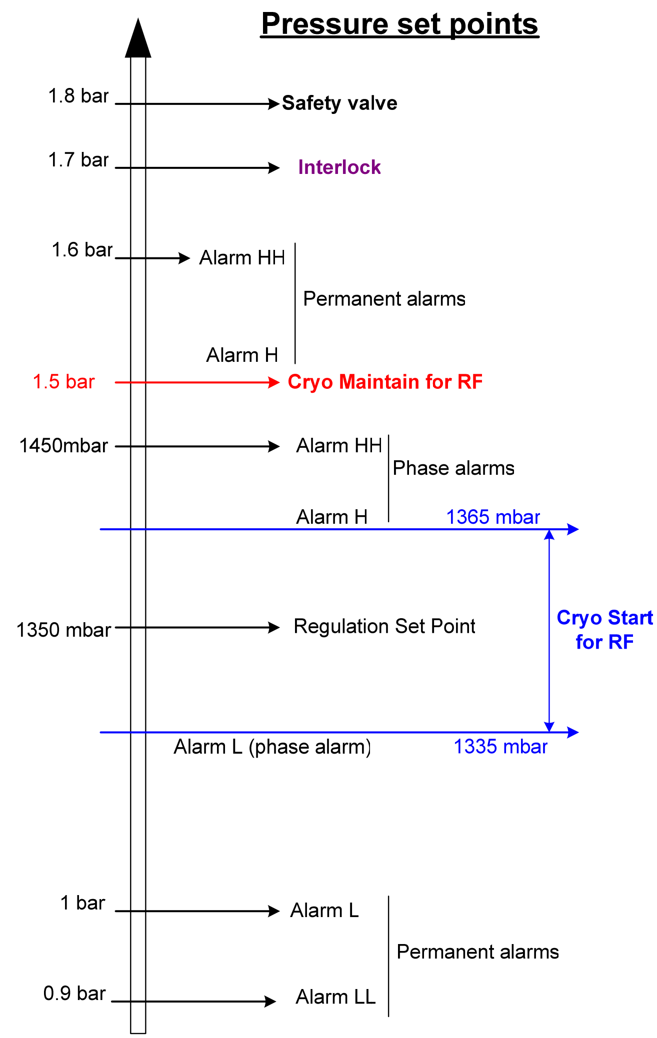
- Do the cavities need to be maintained at 75K during the shut down?

  - No shielding circuit ➔ different than others systems (magnets, DFB..)
  - Otherwise requires flow via line C return D

➔ This phase is not necessary for RF Cavities

5) Level and pressure set points





6) Interlocks

- The interlocks are software mechanisms that prevent the process both in automatic or manual mode to perform actions that would take the system out of its safe operating range and would therefore generate an alarm.
- Interlocks are valid in all cryogenic phases

Interlock objective	Sensor	> or <	Threshold LIMIT	Statement
Pressure limitation in Cavity	PT812/ 813	>	1.7bar	Close CV934/37, CV933/38
Level limitation in Cavity	LT811/ 12/ 13/ 14	>	88% (220mm)	Close CV934/37, CV933/38
Limit pressure in line D	PT991	>	1.5bar	Close CV935/ 936
Temperature limitation in WRL	TT891_L4 and TT891_R4	<	270K	Close CV891
Temperature limitation in WRL	TT890	<	200K	Close PV890
Protection of the heater	TT815/25/35/45	>	323K	OFF EH811/ 12/ 13/ 14
Protection of LT	PT812/ 813	<	0.5bar	OFF LT811/ 12/ 13/ 14
	TT811/ 21/ 31/ 41	>	50K	
Vacuum in Cavity	Vac.RF	=	NOT OK	CLOSE CV934/37, CV933/38, CV935/ 936

7) Alarms

PERMANENT ALARMS

Alarm objective	Sensor	> or <	alarm H	alarm HH
Temperature limitation in WRL	TT890	<	210 K	205 K
Temperature limitation in WRL	TT891	<	280 K	275 K
Pressure limitation in Cavity	PT812/ 813	<	1bar	0.9bar
		>	1.55 bar	1.6 bar
Level limitation in Cavity	LT811/ 12/ 13/ 14	>	80%(200mm LT)	84% (210mm LT)
Temperature limitation in Cavity	maxTT8x1/x2/x3/x4 with x=1 or 2 or 3 or 4	>	310K	320K

ALARMS: Normal Operation

Alarm objective	Sensor	> or <	alarm H	alarm HH
Level limitation in Cavity	LT811/12/13/14	<	40%(100mm LT)	28%(70mm LT)
Pressure limitation in Cavity	PT812/13	>	1365mbar	1450mbar
		<	1335mbar	/

8) Cryo Start / Cryo Maintain

THE CRYO NOMINAL FOR START POWERING (Cryo Start):

- ☒ RF OK
  - Liquid helium level in RF cavities between threshold: (40% = 100mm - 80% = 200mm)
  - Pressure between 1335 mbar and 1365 mbar
  - Vacuum RF Ok
  - Cryo enable
  - Cryoplant Ok for Powering
  - Ethernet communication Ok

THE CRYO ACCEPTABLE FOR MAINTAIN POWERING (Cryo Maintain) :

- ☒ To have a Cryo for RF request to Stop the condition must stay active more than 30 seconds
  - Liquid helium level in RF cavities below threshold (20%=50mm)
  - Pressure above 1.5 bar

HOW CRYO OPERATORS WILL VERIFY CONTROL RF