Stable operation of cryogenic system at 2K during the RF or magnet power variations

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Abstract. In the last 40 years several large laboratories, e.g. CERN, DESY, TJNAF, constructed the accelerators with large number of superconducting (sc) cavities or sc magnets operating at 2 or 4 K temperature levels. The sc cavity operation requires more stringent ranges of pressure variation than ones of sc magnets. In comparison to small testing benches or single cavities modules, for large accelerators a complicated controlling of refrigerator and cryogenic system is required. In the present paper, a review of controlling principles and loops, typically applied for the controlling of liquid helium (LHe) level and pressure for large accelerators is presented. Other possible control loops, e.g. cascade control or multivariable feed-forward (or with feed-forward option), are discussed. Activities related to the commissioning of control loops and some supporting measurements are mentioned. Experimental data on investigation of gas/liquid thermal equilibrium are also presented.

1. Introduction

Future large linear accelerators with superconducting (sc) cavities will need cryomodules capable to accelerate beams to higher energies. E.g. by doubling accelerating fields for cryomodules, the overall linac length could be substantially reduced. So costs reduction could be also achieved, which significantly facilitates starting of large projects like International Linear Collider (ILC). In many cases, one of limitations is an available cryogenic power, i.e. either total heat loads, which limits the power capacity of refrigerators or heat flux densities in cavities, which limit maximal RF power till a quench occurs. To overcome cryogenic limitations, it is possible either to increase the cavity quality factors $Q_0$ or by using other cooling schemes, e.g. with sub-cooled superfluid helium. In both of these cases, the cryomodule parameters will be changed, although the pressure stability requirements will be tougher, see Table 1 for some cavity related cryogenic parameters of accelerators with sc cavities.

In the present paper, review of controlling principles and loops for liquid helium level and pressure is given. Several options, e.g. cascade controlling, multivariable feed-forward (or feed-back) are also discussed. Experimental data showing the thermal equilibration between gaseous and liquid helium in ILC/XFEL/TESLA-style cryomodule are also shown.

XFEL cryogenic scheme is taken as one of the examples for the following reasons: i) it has many similarities to the ILC, ii) it is the most recent accelerator taken in operation and iii) it has several unique designs, like 2K box with very flexible operation options and cascade pressure control in linac [1, 2].
In order to fulfill the stringed parameters of pressure stabilities, see Table 1, the relative sophisticated control loops must be applied. These requirements are given by two main reasons:

a) Radiofrequency (RF) tuning system of single cavities must set the cavities on resonance and as a consequence, the allowable pressure range variation (relative and absolute) is very limited in comparison to the system with sc magnets. Additionally, cavity operation at pulse or continuous (CW) mode and typical feed forward compensation for the beam will also lead to different requirements on pressure stability. This is the main difference to the operation of sc magnets at accelerators or fusion facilities, where dynamic heat load is present during ramping up/down, while requirements to the pressure stability are less stringent.

b) For the operation at subatmospheric pressures and large mass flows the application of cold compressor (CC) is foreseen for large accelerators. In this case the stable GHe flow and pressure must be present at the inlet of the first stage of CC in order to avoid possible CC trips.

As a consequence, electrical heaters in the helium bath could be also used to compensate sudden dynamic heat load changes, which are induced by RF load changes.

For the large accelerators with sc cavities operated at 2K temperature level, there are practically no alternative to the application of CC due to two main reasons: i) without CC, number of warm compressors will be enormous, and ii) the sizes of heat exchangers for helium flow with sub-atmospheric pressure will be very large. It is worth to note that several different operation schemes, e.g. helium gas compression to 1 bar(a) or to some intermediate pressure, are possible and careful overall optimization of refrigerator design is required, see [3] for more detailed discussion.

In the present paper, the cryogenic control of accelerator for steady-state operation modes and shortly for large RF variation, e.g. during cavity quench or RF switching on/off, is discussed. Several control loops with different choices of control parameters are mentioned. The RF heat load compensation scheme (shorty – compensation scheme), for more details see [4], could be also applied as part of the feed-forward option for one of the control loops.

In the first part, a short listing of instrumentation as well as measuring sensors related to the control loops is presented. Several optional control loops with corresponding sensors are also discussed in this part. In the next part, we concentrate on several control loops, and some support measurements are also shown there.
2. Instrumentation and control loop choices

The JT and cool-down/warm up valves as well as temperature, pressure and liquid helium (LHe) level meters, heaters are located at the ends of the group of modules, (also called as “strings”), i.e. at String Connection Boxes, Feed-/End Boxes, e.g. XFEL [4-7], FLASH, ILC accelerators, or at each single cryomodule, e.g. LEP [8-9], CEBAF [10], SNS [11], ESS, LCLS-II [12]. As an example of “string” concept, the ILC/XFEL/FLASH accelerators could be chosen [1-2, 4-7]. Figure 1 shows the very simplified scheme of accelerator, where one main sub-cooling (also named as “JT”) heat exchanger (HE) is foreseen for several cryomodules. It is also possible to install HE in each cryomodules, similar to SNS accelerator. There is only one JT- and cool-down valve per string or cryomodule (LCLS-II), and all other instrumentation is mainly located at both string sides or to some extent in cryomodules. Valves and pressure transmitters at both sides of the JT-heat exchanger are typically installed. For better flow regulation or adjustment of pressure at the inlet of CC, two control valves for fine or coarse flow regulation could be installed inside the refrigerator cold box at the inlet of CC (only one is shown in Figure 1) as well as pressure transmitters for different operation ranges.

It is worth to particular stress that for the discussion in this chapter, only general cases are considered, which are not related to any presently constructed accelerator.

For the stable CC operation, it is necessary to keep GHe flow and pressure (+/- 1% relative) at the constant value, however, assuming that CCs will operate at the (quasi-) constant rotational speeds (this assumption is taken for the further discussion), than one of these parameters (i.e. flow or pressure) can be neglected, because they are directly related. It is worth to note that sudden variation of rotational speed could cause helium pressure variation or shock wave propagation, which negatively influences sc cavity operation. As pressure measurement is simpler in comparison to the flow, only pressure transmitters will be further considered (we also note that the Coriolis flow meters are typically not installed in the lines between cryomodules and CC inlet due to space limitation, as well as non-negligible pressure drop, though it is possible to install them after CC or other process lines). The second parameter to be controlled is LHe level. As control elements, the JT-valves, heaters and valves before and after JT-heat exchanger could be used. Therefore, three cases are possible:

a) LHe level is controlled by JT-valve and pressure in linac – by valve V1 before JT-heat exchanger (or after by valve V6), while heaters are not used for active regulation (“classical scheme”). This scheme works perfectly, if instead of CC (which is “kinetic” pump) constant volumetric pumps, e.g. roots or mechanical, are applied. With CC operational, in case of active regulation of pressure
upstream of V1, i.e. in linac (e.g. P3 or P9), there will be non-negligible variation of pressure (and as consequence GHe flow) downstream, i.e. at inlet of CC, which could lead to CC trip. However, it is still possible to apply this optional scheme by using the fact that two valves, V1 and V6 are installed in series and JT-heat exchanger (JT-HE) is used as “thermal buffer”, which could smooth pressure variations at CC inlet to some extent. One of the solution (somehow similar to cascade control) could be to use V1 for pressure regulation before JT-HE (PIC2, this regulation loop should be slow), and V6 for fast pressure regulation before CC, (PIC#16, see Figure 1) and hopefully that pressure in linac stays within allowable ranges. The second possibility is to apply the true cascade control, i.e. pressure to be regulated is measured by P13 (or P9) transmitter (“slow loop”), analyzed by controller, and is supplied as a set value for “fast loop” controller (PIC16), which is operating the valve V6 and measuring pressure directly before CC.

b) JT-valve is kept at fixed position, LHe level is regulated by heaters and pressure is by valve V1 or V6 (or both). Actually, this case is very similar to the previous one with one exception that LHe level regulation with heater is typically more challenging that the one with JT-valve due to the larger time constant (or sometimes called response time) of electrical heaters.

c) JT-valve is regulating the LHe level, and heater – the pressure, while keeping the valves V1 and V6 at some fixed values, i.e. flow impedance between linac and CC is kept constant. This scheme is less often used, because it is more difficult to find appropriate PID parameters in order to have the stable operation point. This can be justified by the fact that we have two systems with integral behaviours, i) LHe level, and ii) pressure. The case of pressure is not so obvious from the first notice, but this could be explained as following: if one makes the linearization around operating point, i.e. at steady-state, the GHe flow inside the system through JT-valves is equal to the GHe flow to the CC (and for this approximation, we neglect LHe variation). Thus any variation of heating power (RF or heater) will lead to evaporation (or condensation) of helium and as consequence of the pressure increase (or decrease), so, system could be described by isochoric process and behaves as “storage”, i.e. storing energy (and as consequence – pressure varies according to the “stored” energy). From the classical control technology, the system, which has two integrating behaviours needs special attention, because it could be as stable as well as unstable, so finding the stable regions of PID parameters is in any case a very time-consuming activity but could be also principally not possible [13]. It is worth to note that through this scheme was seldom used, the cryogenic system at JLab successfully explored it for the operation of CEBAF accelerator and tested at other facilities, see next chapter.

It is also possible to locate the JT-HE inside the single cryomodules, e.g. SNS accelerator [11]. In this case, the controlling principles are similar to the above mentioned though pressure variations in single cryomodule will have smaller influences on others due to thermal and hydrodynamic impedances of these heat exchangers.

It is worth to note that first tests of control loops were performed in 70ies, when first cryostats with s.c. cavities operating at 4 and 1.8 K temperature level were built [14-15]. The main reasons of investigations were to find parameters for sufficiently stable pressure operation inside the cryostat with sc cavities as well as not to disturb a stable operation of refrigerator. Operation at subatmospheric pressures was achieved by applying the pumps operating at ambient temperatures, while keeping the total helium mass flow from refrigerator at constant value. Operation at 4K temperature level for single standing cryostats was similar, i.e. 4K return flow was warmed up and supplied to a recovery line.

Due to increasing number of sc cavities, the cryogenic groups at Argonne National Laboratory (ATLAS project) and CERN (LEP project) had to resupply the 4K return flow to the refrigerator low pressure line, otherwise the liquefaction load could be too high. Two solutions were applied:

a) Buffer tank(s) at ANAL [16]: Installation of several large 1 m³ LHe tanks allowed smoothing of pressure variations in return line to the refrigerators. Different controlling schemes were successfully applied, including e.g. LHe control or pressure control with heaters. It is worth to note that this cryogenic system was mainly developed based on available refrigerators from
CTI/HPS/KPS/PSI company, and additional cryomodules were added, while trying to modify the cryogenic system in such way that single down-time of refrigerator will have negligible effect on the whole system.

b) Without buffer tanks at CERN (LEP project): application of buffer tanks was not possible due to increased number of cryomodules with sc cavities as well as due to space limitations inside the tunnel. Different controlling schemes were tested on “small”, 1.5 and 6 kW refrigerators, which were later successfully applied to 12 (18) kW ones [8-9].

3. Design options

3.1 Pressure control loop with heater

Before one starts detailed discussion of the pressure controlling loop with electrical heater, it is worth to mention that this scheme was already applied with remarkable success (+/- 0.1 mbar pressure stability over several month period) by cryogenic group of Jefferson Laboratory at CEBAF for old and new refrigerators [10], SNS [11] and will be also applied at FRIB [18] and probable for LCLS-II [19].

Although one can note a “large” number of cryogenic systems mentioned above where this controlling scheme has applied or going to be used for the controlling, all these cases are different due to various types of cryomodules, i.e. at CEBAF - the “old” as well as “Renascence”, see Table 1, at SNS – other type, at FRIB – typical cryomodules for heavy ion accelerators, and for LCLS-II – the TESLA-style one; and therefore special attention must be paid to the details, otherwise the control system with two integral behaviours could be designed unstable.

It is worth to stress that although the PID control algorithms are still sufficiently for many practical cases; in some cases more complicated controlling schemes should be applied in order to obtain sufficiently good results. During this conference [12], Fermilab cryogenic group also showed that combination of PID, Fuzzy, Predictive and Adaptive algorithms in some cases give significantly better results than simple PID one. So, with application of new algorithms, it was possible to reach design parameters. And last but not the least, sufficient time must be planned for the commissioning of new or “old”, i.e. PID, algorithms.

The design of controlling loops including the controller structure is first discussed. Multivariable controlling loop has to be considered, i.e. “control actuators” at XFEL – 9 JT valves, 18 heaters, V1 and V6 valves, and controlling parameters – LHe levels (18 positions), pressure as well as acceleration field ($E_{acc}$) in each module (96 in total). For LCLS-II/ILC these numbers per string are of similar order. To solve the system with such numerous inputs and outputs variables is very challenging tasks, which require very elaborate knowledge in the field of system identification with emphasis on cryogenics as well as experimental time [13]. Moreover, for most of the cryogenic systems, where multivariable feedback control was used [17], linearization around operating point was applied, i.e. cryogenic system was very stable, which allowed linearization (sometimes also including with time-delays) and further improvements of control stabilities due to multivariable control, feed-forward, etc. were around 5-15 %. In practice, first the cryogenic system had to be commissioned and only after that the “fine-tuning” based on multivariable control was applied [17]. For that reasons, the multivariable feed-back control for the first commissioning and initial operation of any accelerator is not considered, though for the future, it would be possible to apply.

Further simplification will be to consider LHe level control loops in each string or single cryomodules as independent ones and to apply PID settings to each of them. The measurements at Cryogenic Test Module Bench (CMTB), DESY, showed that depending on the operating point, it is possible to describe this system as pure integral or sometimes integral with time delays (10-150 s). The reason for appearing of the time delay is still unclear, though we consider that it could be related to the hysteresis operation of JT-valve or slight LHe overfilling or emptying of 2-phase tube.
The first measurements of pressure regulation with heaters were performed at CMTB, see Figure 2, where pressure evolution for different averaged heating power levels, i.e. 20, 40, 60 W, as well as with and without range limitation of JT-valve, are shown. The PID parameters of LHe level and pressure regulation loops were kept constant. It was possible to find PID parameters for operation at the acceptable pressure range for single module, though the following challenges were noticed:

- The range of pressure variation depends on the time constant of electrical heaters (large time constant of heaters at this facility was related to a relative weak thermal contact between heater cartridge and stainless steel tube, in which the heater cartridge was inserted. The stainless steel tube was welded into LHe vessel and was always in contact with LHe). For the given heating powers 20-60 W, the time constant is ca. 300–400 s but starts to increase up to 1200 s for smaller values of heating power [4]. It was possible to find stable operation range for the smaller values of heating power; however pressure variation range was larger, i.e. out of ±0.3 mbar range.

- LHe level and pressure control loops are coupled, i.e. variation of flash gas from the JT-valve leads to variation of the pressure, which also force the pressure regulation loop to react more aggressive, which leads to positive feed-back and pressure further increases, see Figure 2, when no limitation on JT-valve was applied. One solution is to limit operation range of JT-valve around operation point for a couple of percents. Another one would be to slow down the PID parameter of LHe control loop, though this was not applied due to limitation on available measurement time.

- In comparison to other controlling schemes, see chapter 2 for more detailed discussion, the system is very sensitive to the heat load disturbances. We added some additional heat load by electrical heater or by supplying 4.5 K gas to the 2 K volume and noticed that system run over acceptable pressure ranges and it needs long time, typically several hours, till system stabilizes again.

Though it could be the case that at steady-state conditions without disturbances, the pressure will stay within the ranges, for the case of heat load changing due to large variation of heat powers, e.g. switching on/off of RF power or cavity quench, the pressure will not be within the expected range for a quite substantial time period. Therefore, it would be necessary to compensate the effect of the heat variation by using of other heaters. Fortunately, it would possible to reduce influence of the RF power variation, if one is able to precisely estimate it, see discussion below. According to the classical
control technology it implies that we have again multivariable feed-back control: input parameters are acceleration field $E_{acc}$ in each module (or string of 12 modules), as well as pressure, and outputs are heaters for pressure control and RF heat load compensation. However, for the simplicity of control loop operation and system overview, it would be very advantageous to have a single (also called “separated”) loop operation. It is possible to realize, if one considers the RF operation as classical “disturbance”, which is predictable in time, and also measurable. This is classical feed-forward option applied at control technology. This scheme is identical to the one at JLAB applied for the “old” as well as new “Renascence” cryomodules [10, 11] or at LEP [5, 6], though several challenges have to be mastered for the TESLA-style accelerators: i) other type of cryomodule, ii) accelerator lengths are substantially longer, and iii) diverse operation modes, e.g. short-, long pulses, (quasi-) continuous wave (CW) operation.

It is worth also to note that challenges on achieving the pressure stability for the LCLS-II cryomodule, which is quite similar to ILC/XFEL/TESLA-style but operated with much higher heat loads, was also noted by cryogenic group at Fermi laboratory [12]. Due to combination of PID, fuzzy, predictive, adaptive control algorithms; it was possible to achieve pressure stability at required level.

One of the important questions was whether helium gas and liquid phases at TESLA-style cryomodule will be at thermal equilibrium for the time scale important for controlling, i.e. tens of seconds up to couple of minutes. Two types of the representative measurements were performed at DESY by supplying: i) either the heating pulse into LHe, see Figure 3, or ii) 4.5 K GHe injection into 2.0 K system, see Figure 4.

![Figure 3: Pressure variation inside the module due to natural warming up and applied heating pulse](image1)

![Figure 4: Pressure variation inside the module due to natural warming up and supplied GHe at 4.5 K temperature level](image2)

During the measurements, the module was isolated, i.e. helium supply and return flows were stopped and natural warming-up of cryomodule occurred. The heater operation, see Figure 3, showed that even for the case of film boiling regime, the gas and liquid phase were in thermal equilibrium and pressure increase was smooth as during the heating pulse as well as after switching off of heater. For the case, if “overheated” GHe was supplied into the system, see Figure 4, the G- and LHe phases reached thermal equilibration within the time of 0-200 s, which is also sufficient for the controlling purposes.

The importance of time constant of gas/liquid thermal equilibration can be shown on the following example. Amount of stored LHe inside the cryomodules for the same GHe flow to CC is the largest for CEBAF and smallest for TESLA-style (SNS and “Renascence” cryomodules have somehow middle values), see Table 1. Practically it means that variation of gas pressure gives noticeable variation of LHe temperature for TESLA-style cryomodules, but practically no influence over extended time period on CEBAF ones, e.g. it is possible to fill CEBAF cavity with 1 bar GHe and not to see a significant temperature change on LHe over couple of hours. So, for CEBAF, it is possible to adjust the mass flow to CC according to the expected RF heat load and over that time cavity temperature is not significantly changed. Thus, the pressure control loop with heater is set for low dynamics response and is effectively “decoupled” from control loop of CC. For that reason, case of
LHe level control with JT-valve and pressure with heaters is relative easily applicable for CABAF cryomodules and it is important to have measured the working map of CCs in order to be able to operate them in wide mass flow ranges. For the case of TESLA cavities, pressure must be actively controlled, which could lead to limitation of time response of CCs. Therefore, it is important to consider all possibilities of pressure control for TESLA-style cryomodules, e.g. additional by-pass loop like it is realized at XFEL, as well as to have complete working field of CCs.

In order to test pressure controlling loop over the system with extended length, the measurements at FLASH accelerator, which represents around half of XFEL string, were successfully performed [4].

3.2 RF power compensation with heaters (Feed-forward option)

For the successful application of the feed-forward option, it is necessary to be able to predict the cryogenic heat load based on the applied RF power. One of the possibilities is to use data from the continuous wave (CW) measurements of each cavity at the vertical cryostats and to scale it down using duty factor (portion of time, when RF is operated) for each particular mode, e.g. for short, long, very long pulses, or (quasi-) CW operation.

Another method is to estimate the averaged value of the quality factor \( Q_0 \) for the single cryomodule with 8 cavities. For example, the measurement uncertainties of heat load measurements at XFEL cryomodules were estimated as ±30% (2σ), which are largely dominated by statistical error [20]. Uncertainties of heat load measurements of single cavities for CW mode are of the similar order of magnitude, which are related to the measurement of cavity quality factor \( Q_0 \). Additionally, there are uncertainties due to recalculation of the CW data of single cavities into pulse ones for each cryomodule, i.e. during the test of cryomodule, all cavities are simultaneously powered to different values of \( E_{\text{acc}} \) and then averaged value is used, so some cavities are at higher another ones at lower values. So, the quadratic fit formula (\( Q_{\text{heat}} \) versus \( E_{\text{acc}} \)) for single cryomodule could be applied.

Another method to estimate the heat load is to measure the heat load versus \( E_{\text{acc}} \) in situ. Though direct heat load measurement of single cryomodule in XFEL tunnel with warm flow meters will not be possible due to very small heat load per single cryomodule, the heat load per one string (12 modules) or probably 4 modules (one RF station) could be feasible. For cross-checking of this method, the measurements at FLASH were performed [4], i.e. heat loads versus total \( E_{\text{acc}} \) field of 6 cryomodules (up to 1.2 GeV) was fitted with quadratic formula. Results were very promising though total uncertainties are within ±(30-40)% (2σ) relative to the fit curve.

Another interesting method, which was successfully applied at XFEL accelerator, is to use the RF power from klystrons (one klystron per 4 cryomodules) and to scale RF cryogenic heat load according to the duty factor of cavities. In this case, total number of measurement channels is reduced (and RF power is measured at room temperature!), which simplifies measurement system and improves its reliability.

4. Examples of commissioning procedures of LHe and pressure control loops

The commissioning of control loops depends on available infrastructure and cryogenic system design as well as foreseen controlling schemes. For that reason, it is difficult to discuss controlling procedure for each specific case without detailed knowledge of the system. Nevertheless, we tried to write some general guidelines for the commissioning and more details on system identifications could be found in [13].

a) LHe level: the JT-valves are most convenient way to regulate the LHe level due to advantages of negligible time constant (also sometimes called response time) in comparison to the one of heater. However, at the beginning, when the RF heat load is not known (or has to be measured), the LHe level control with heater leads to the advantages that total heat load on the system could be measured. By increasing the RF power and decreasing the power of electrical heaters, the RF heat load could be estimated. Other challenges could be related to specific design of each cryogenic system, e.g. operation XFEL string, which is two times longer than the one at FLASH or operation of ILC string which is even larger than XFEL one. Some trials would be necessary for
the choosing the most convenient LHe level meter, either one located at around JT-valve (which has advantage of negligible dead-time) or another one located at other string end or cryomodule end, e.g. at LCLS-II. Additionally, it is necessary to measure low and high operation points of LHe level as for cryogenics as well as for RF interlock system.

b) Pressure: commissioning of pressure control loop with heater should be done for two cases: i) steady-state operation with typically stringent requirements on pressure stability, and ii) RF power variation, e.g. during RF switching on/off or cavity quench. Challenges are also related to the fact that the hydrodynamic impedances of return transfer line from cryostat to refrigerator as well as low pressure refrigerator return line influence the setting parameters of control loops, see e.g. work done at CERN [6]. So, finding operation ranges of valves in return lines as well as of JT-valve (pressure and LHe control loops are strongly coupled by flash gas) is quite challenging and time-consuming. In some cases, the author was able to find first initial parameters (“zero-approximation”) in the following way: i) setting the control system in “classical” scheme, i.e. heater at required power, LHe level is controlled by JT-valve and pressure by the valve in return line (this valve will be used for impedance adjusting), ii) noting the averaged values of valves and heaters (it is not absolutely necessary that system will reach perfect steady-state or pressure stability), and iii) fixing the pressure regulating valve at averaged value, setting the pressure control loop by heater, and applying the high and low limits on JT-valve in order to avoid large influence of flash gas on pressure regulating loop (these high and low limits could be cancelled after some experience is gained).

c) Feed Forward: it is possible to estimate the heating load from measurements of single cavities or cryomodules, see previous chapter for more discussion. In many cases, the in-situ measurements, e.g. by “compensation” scheme (RF power is increased and power from heaters is decreased while trying to keep total flow at constant value) or by direct measurement, e.g. with warm pumps, are feasible. In the first case one should be able to keep the total flow at the constant value and limitation in the second case is that flow capacity of warm pumps.

Recent results on XFEL accelerator operation showed that pressure could be controlled by CC and in order to have good possibility to control the pressure, the mass flow through CCs should be kept at constant value [1-2, 21-22]. The constant mass flow is achieved by re-supply of helium from outlets of CCs. JT-valves are used for the LHe level control. RF heat load compensation with heater, i.e. adjusting of heater power according to actual RF power, is helpful for the reduction of heat load disturbances due to RF operation. It is also possible to apply cascaded regulation for pressure, i.e. pressure in linac is measured by “slow” controlling system, which further supplies this value as set one for the “fast” loop, which is regulating the pressure at CC inlet.

5. Conclusion
In the present paper, the several possibilities to choose the control loops are presented.

For the pressure regulation the control loop with heater operation or cascade control are considered. The classical feed-forward could be also applied, i.e. some heaters must be reserved for compensation of the RF power.

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