FERMILAB'S CENTRAL HELIUM LIQUEFIER CAPACITY UPGRADE

M. G. Geynisman and J. N. Makara

Fermi National Accelerator Laboratory*
Batavia, Illinois, 60510, USA

ABSTRACT

Fermilab's Tevatron Superconducting Accelerator has begun operations of colliding beams of protons and antiprotons at 980 GeV. This has been accomplished by lowering the operating temperature of the Tevatron magnet system from 4.5K to 3.6K using cold compressors on the two-phase portion of the system. The heat of compression by the cold compressors produces a greater liquid helium demand from the Central Helium Liquefier (CHL). Various upgrades have been completed or are in progress to provide sufficient capacity and redundancy for the liquid helium supply. The maximum allowable pressure of the helium system has been raised from 1.31 MPa to 1.65 MPa, thus providing a measured 18% liquefaction capacity increase for same compressors flow. One of four reciprocating helium compressors has been modified for four-stage operations, thus providing 33% increased capacity and more reliable operations. Together with capacity control of individual compressors, the available choice of operation of two 3-stage and two 4-stage compressors will provide the flexibility to operate the Central Helium Liquefier system at the most economical power consumption relative to the liquid helium demand by the accelerator cryogenic system.

INTRODUCTION

The original CHL system was built in 1979 and consisted of the helium reliquefier plant with one 4000 liters/hour helium coldbox (Coldbox-1) and two 530 g/s 3-stage reciprocating compressors (A and B) [1]. Over the years of operations, general upgrades were made to improve the reliability and availability of the system, including an addition of two more helium compressors (C and D) and the second coldbox (Coldbox-2) [2, 3]. In the 1990s Tevatron accelerator system was upgraded for 1 TeV operation using cold

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compressors on the magnet system allowing lower temperature operations at 3.6K [4]. Tevatron testing in 1997 showed that the net effect on the cryogenic system operating at 8.5 psia required CHL liquefaction capacity up to 185 g/s. At the time, compressors A, B, C were configured as 3-stage machines with maximum output of 550 g/s. Compressor D was configured as a 4-stage machine with maximum output of 730 g/s. Compressors discharge was limited at 1.31 MPa with pressure ratings of the coded vessels in the oil removal system. Therefore, the combined compressors flow to the coldbox had to be kept above 1550 g/s with three compressors on-line to the coldbox in order in order to keep production above 185 g/s. Both requirements, the pressure below 1.31 MPa and high flow, resulted in increased electrical power and precool liquid nitrogen consumption, as well as reduced availability of off-line compressors.

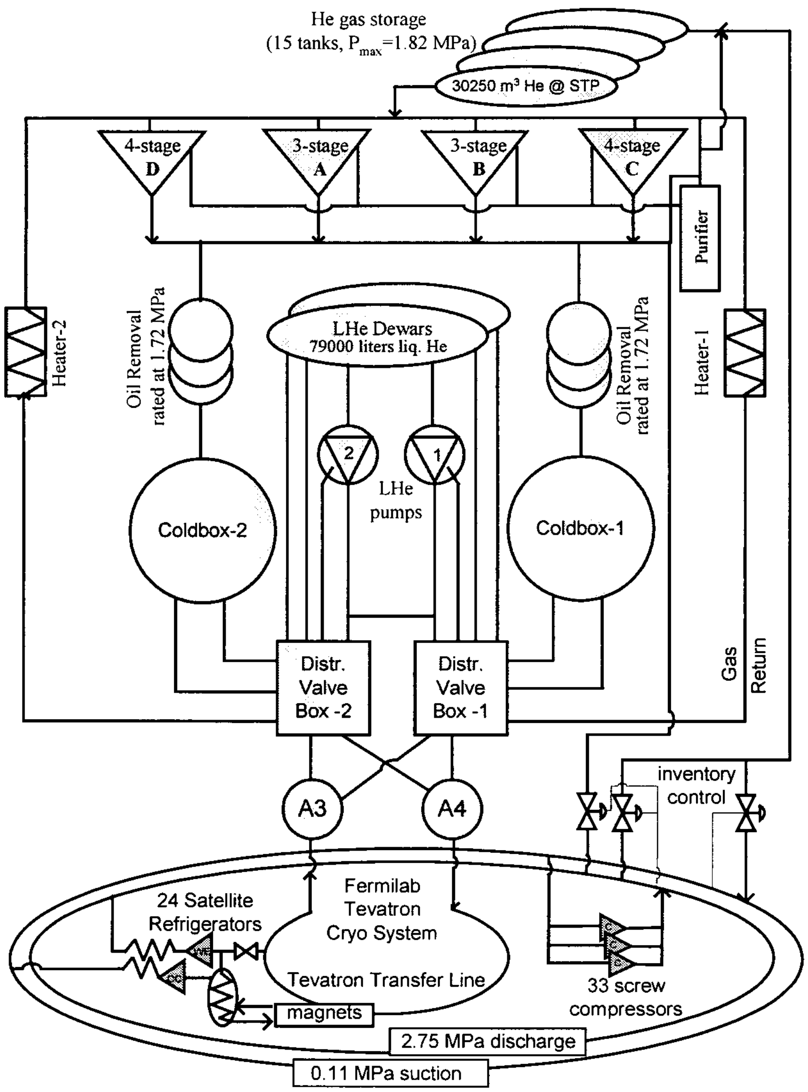

FIGURE 1. CHL Layout. As of June 2001, CHL consists of four parallel reciprocating compressors rated at 6.4 MW total power at 1.65 MPa and two independent cold boxes rated each at up to 216 g/s (equivalent of 6225 liter/hour @ STP) of supercritical helium at 0.33 MPa and 4.8K with LN_2 precool.

The mathematical model of the helium liquefier was developed to understand the limits of the plant capacity [5]. Those simulations, together with discussions with Dr. Hans Quack of Dresden Technical University, showed that raising the coldbox pressure from 1.31 MPa to 1.65 MPa would result in 16.7% increase of liquefaction capacity. That would be enough to operate two on-line compressors instead of three, which would drastically reduce the power consumption. CHL conducted a series of tests using coldbox-2 and the available compressors to confirm simulation results. As the results confirmed the simulations, the decision was made to upgrade the helium system for 1.65 MPa and to modify compressor C to be a 4-stage machine. The modifications were completed in March 2001. The present CHL layout is shown on FIG 1.

EXPERIMENTAL DATA

The first capacity measurement test was conducted in June 2000. The measurements were done for two (2) on-line compressors. The compressors were the 3-stage machines. The compressors discharge pressure was varied from 150 psia to 225 psia at almost constant flow rate of ~1100 g/s. The constant flow rate for the reciprocating compressors was maintained by closing the kickback valve, thus only small variations due to suction gas density were introduced into the test. In November 2000 CHL repeated the test with two (2) on-line compressors. This time it was the 3-stage and the 4-stage compressor. The compressors discharge pressure was varied from 174 psia to 235 psia at almost constant flow rate of ~1320 g/s. The results of the tests are in TABLE 1. Additionally, an earlier test was conducted in May 1997 with three compressors on line to the coldbox-II routing its production to the Tevatron transfer line. The test resulted in record 216 g/s liquefaction capacity at 1.21 MPa inlet pressure and 1790 g/s inlet flow to the coldbox. The results of the tests match the results of the simulations. FIG 2 shows one of the snapshots of the coldbox-2 thermodynamics during the testing. Both, inlet flow and pressure to the coldbox can be varied to change the coldbox production.

TABLE 1. Results of the CHL liquefaction capacity measurements.

Calculated data:						
Design pressure	MPa	n/a	1.207	1.358	1.551	1.655
Production increase (calculated)*	%	n/a	100.0	107.1	114.0	116.7
Test data (06-12/13-2000):						
Test pressure	MPa	*1.034**	1.207	1.365	1.551	
Measured capacity	g/s	*115.0*	124.0	134.0	142.0	
Compressors' flow	g/s	*1130.0*	1140.0	1110.0	1110.0	
Normalized measured capacity	g/s	*116.0*	124.0	137.6	145.8	
Production	%	*93.6*	100.0	111.0	117.6	
Coldbox inlet pressure	MPa	*0.999*	1.172	1.331	1.524	
Measured compressors' power	MW	*2.48*	2.62	2.78	2.91	
Power	%	*94.7*	100.0	106.1	111.1	
** data is not used for analysis*						
Test data (11-07-2000):						
Test pressure	MPa		1.200	1.379	1.538	1.620
Measured capacity	g/s		159.0	168.0	179.0	185.0
Compressors' flow	g/s		1320.0	1310.0	1300.0	1300.0
Normalized measured capacity	g/s		159.0	169.3	181.8	187.8
Production	%		100.0	106.5	114.3	118.1
Coldbox inlet pressure	MPa		1.200	1.351	1.517	1.517
Measured compressors' power	MW		2.94	3.09	3.19	3.28
Power	%		100.0	105.1	108.5	111.6

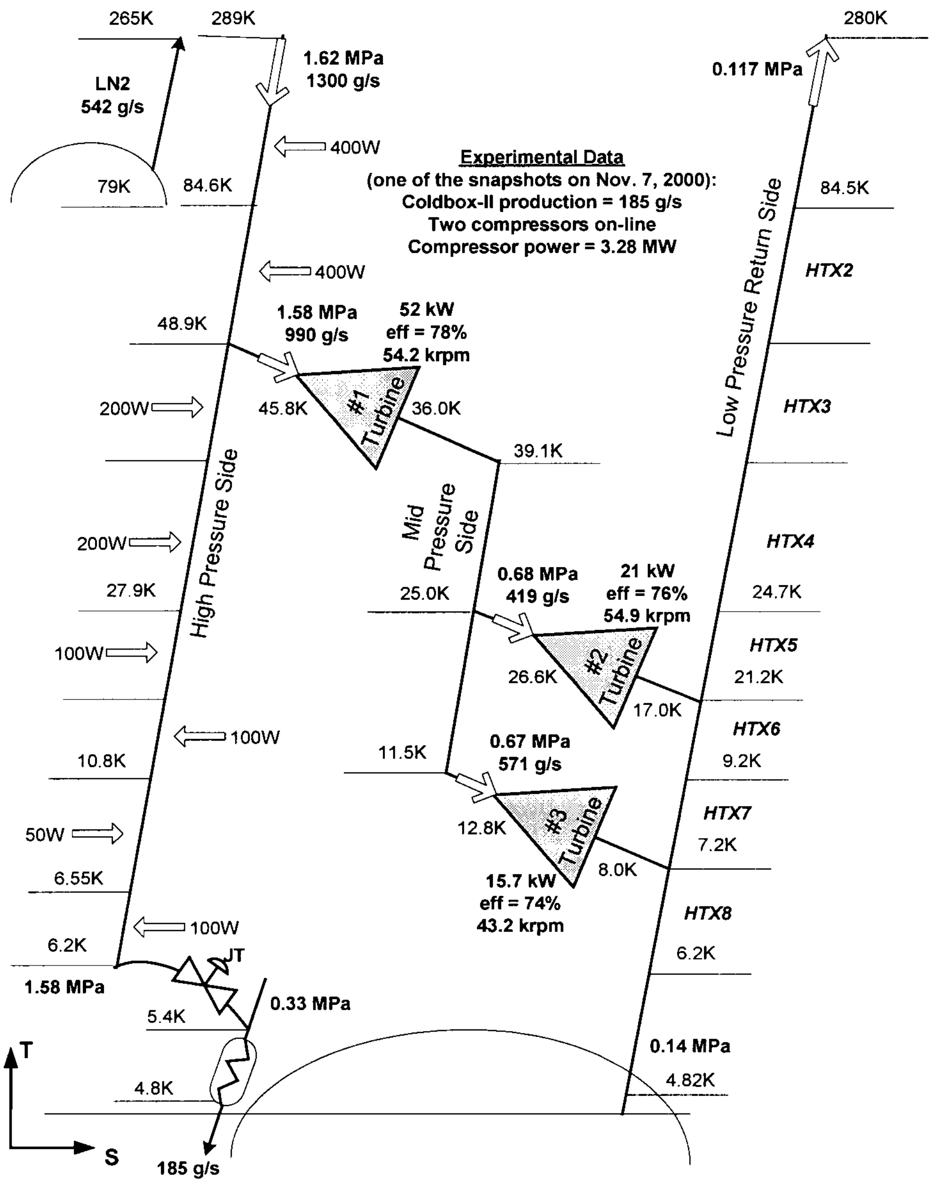

FIGURE 2. Coldbox-2 experimental data showing liquefaction capacity of 185 g/s at 0.33 MPa and 4.8K.

The test results confirmed the calculations. The coldbox liquefaction capacity was linearly increasing with the coldbox inlet pressure. FIG 3 shows the relative capacity increase due to increase of the inlet pressure. It shows 17.6 % increase of capacity (1130 g/s compressor flow at 225-psia) and 18.1% (1330 g/s compressor flow at 235-psia) compare to 16% increase for the calculated data (1500 g/s compressor flow at 240-psia).

Plotting the normalized results of the experimental data for 1130 g/s and 1310 g/s inlet flows, as shown on FIG 4, display a similarity between the linear fits "capacity vs. pressure" for these two data sets.

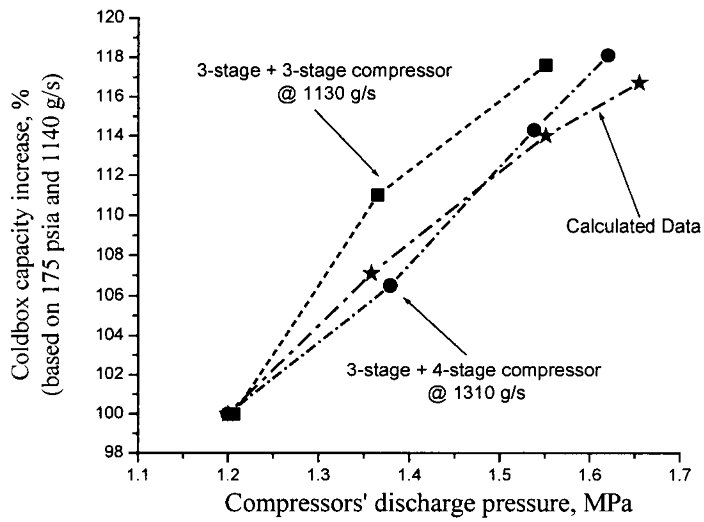

FIGURE 3. Coldbox-2 liquefaction capacity increase (%) due to increase of inlet pressure.

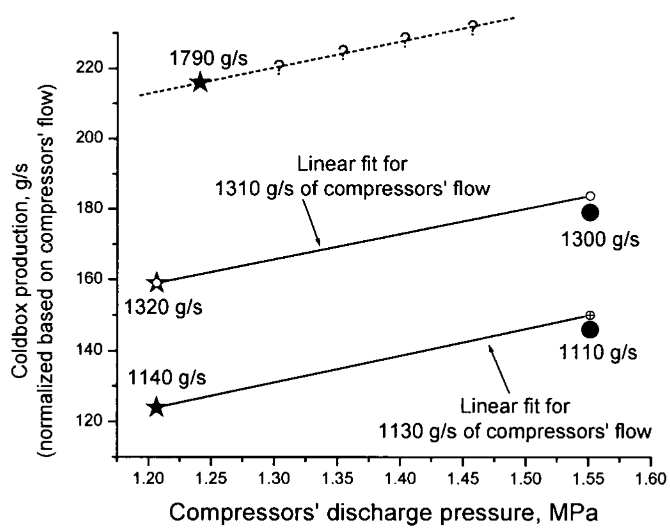

FIGURE 4. CHL Coldbox-2 liquefaction capacity versus inlet pressure and flow.

The plots on FIG 3 and FIG 4 show that the data point for 1790 g/s compressors flow is far above the data sets for 1130 g/s and 1310 g/s. It is unreasonable to assume that the coldbox production at higher compressor flow would keep increasing linearly. The limiting factors for the production increase are the midline pressure, the speeds of the turboexpanders and the capacity of the oil system used for removing the work in the turboexpanders. At the same time, we do not pursue an objective to achieve the highest possible production, but rather an objective to achieve a required capacity with minimum compressor flow. That would result in saving electric power and liquid nitrogen for the helium precool.

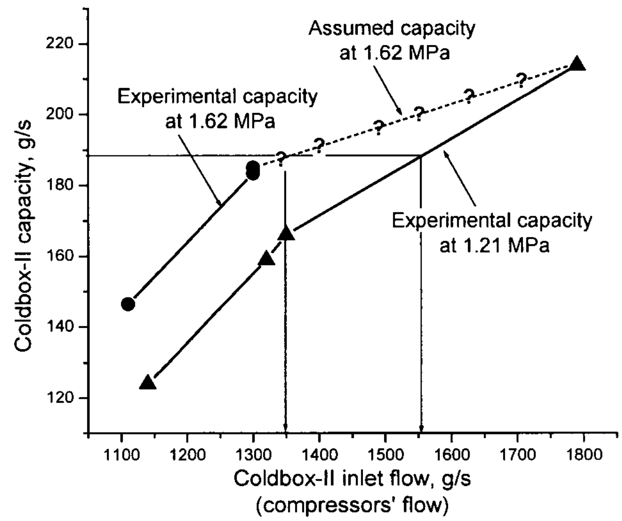

FIGURE 5. CHL Coldbox-2 liquefaction capacity versus inlet flow at 1.62 MPa compressor discharge pressure. The experimental data shows that the CHL liquefaction capacity can be achieved with less then 1350 g/s compressor flow.

The experimental data for the operating range of coldbox-2 flow show that the coldbox capacity varies linearly with inlet flow for each given discharge pressure. Then we can connect several experimentally known points for 1.21 MPa and for 1.62 MPa discharge pressure, and build a graph describing coldbox-2 capacity versus the inlet flow as shown on FIG 5 above. The "?" line connecting known points @ 1300 g/s and 1790 g/s is a hypothetical capacity of the coldbox at 1.62 MPa. It is built with assumption that the coldbox production at higher compressor flow would not keep increasing linearly due to design limitations. The experimental data shown in TABLE 1 and FIG 5 show that the required capacity can be achieved with less then 1350 g/s compressors flow at 1.62 MPa discharge pressure. Therefore, we can conclude that CHL can operate one 3-stage compressor and one 4-stage compressor in order to support Fermilab Physics Run 2b. That would provide up to 6300 MW-hr in annual electricity savings.

DISCUSSION OF CONTROL STRATEGY FOR POWER SAVINGS

CHL operates reciprocating compressors on-line to the coldbox by controlling the compressors discharge pressure with the "kickback" valves. As the coldbox production is tuned up, or down matching the demand from the Tevatron, the kickback valve controls the coldbox inlet pressure. The helium flow to the coldbox varies. That results in variations in nitrogen precool flow (5/2 ratio). It is conceivable to conserve nitrogen by minimizing the helium flow to the coldbox. Therefore, the control strategy should be to minimize the discharge pressure and flow while matching the Tevatron demand for liquid helium supply. As we operate two compressors, instead of three, thus achieving a significant incremental power saving, we have to note that the increase of the compressors discharge pressure results in certain increase in the consumed electrical power. That increase was previously calculated within a range from 10% (Dr. H. Quack) to 14.5% (CHL). In fact, the test results show that the consumed electrical power is anticipated to increase less then 12% when raising the pressure from 1.2 MPa to 1.62 MPa as shown on FIG 6 below.

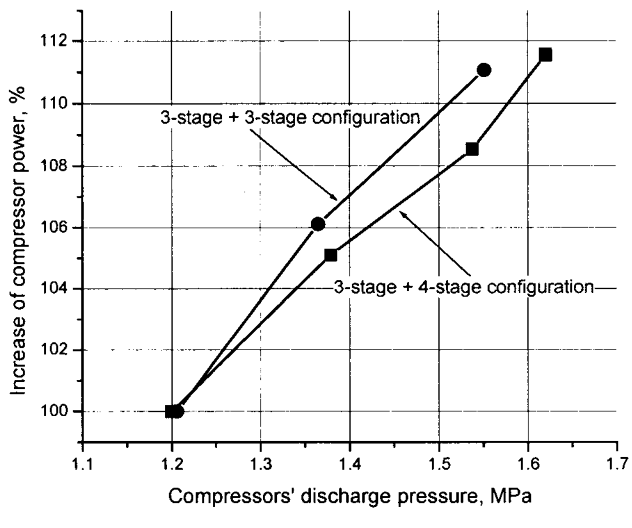

FIGURE 6. Compressors power versus compressors discharge pressure.

The proper way of regulating the flow is to unload the 1st stage of one of the operating compressors, thus reducing the flow through the compressor. The test was performed for the 4-stage compressor to see the capability of flow capacity control using the 1st stage loading valve. The compressor was loaded to 1.1 MPa discharge pressure. Then the 1st stage loading valve, a 6-inch butterfly valve, was opened in increments and the compressor was allowed to stabilize. The measured power consumption indicated a reduction of 23% at 33% compressor flow reduction as shown below on FIG 7. It is important to realize that keeping the discharge pressure constant and regulating the flow to the coldbox with compressors kickback valve(s) is non-economical.

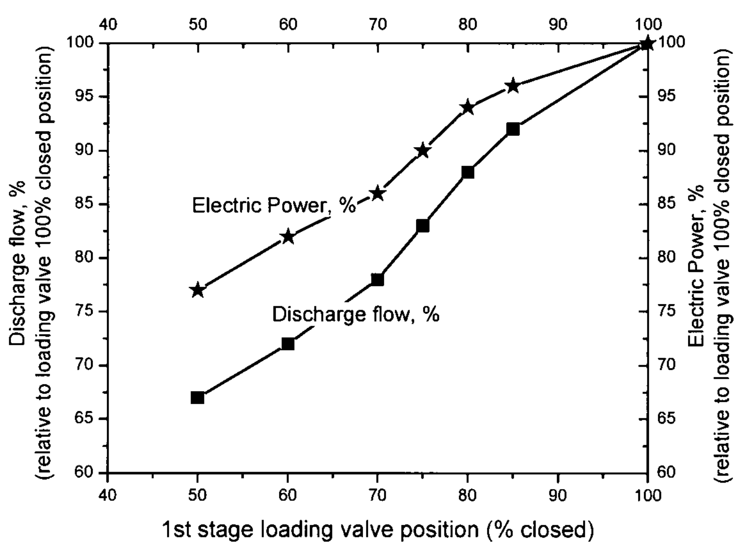

FIGURE 7. Compressors power versus compressors discharge pressure.

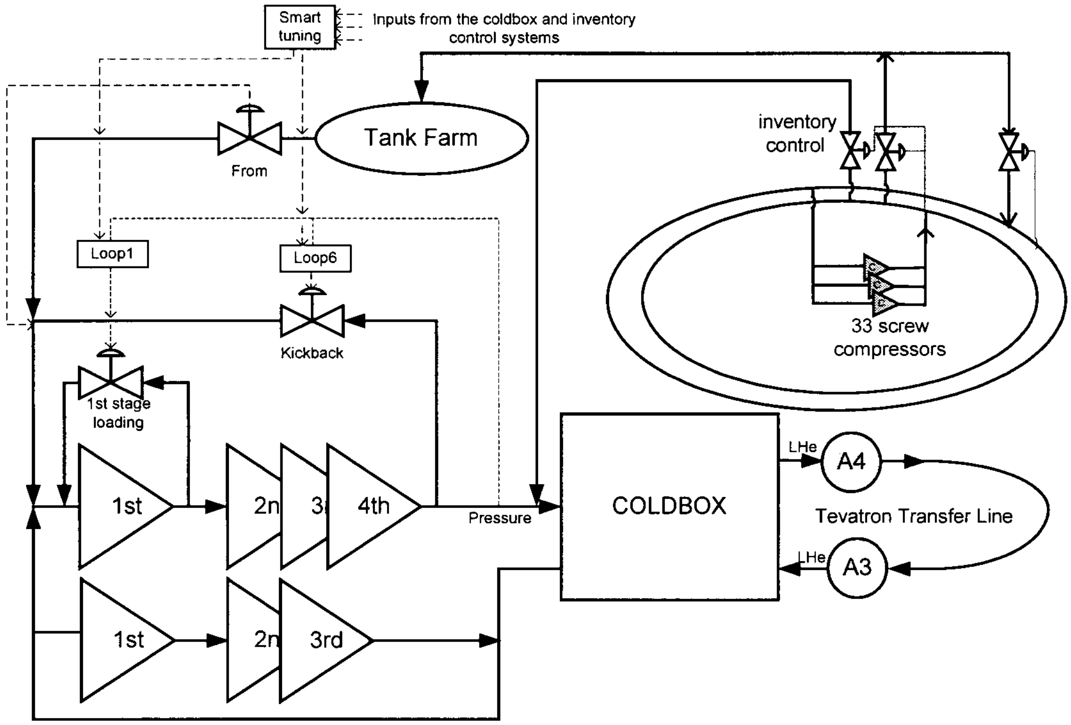

FIGURE 8. Control strategy for the CHL compressors-coldbox setup

The simplified control schematic is shown on FIG 8. For maximum coldbox production the compressor(s) kickback valve should be set to regulate at 1.65 MPa and the 1st stage loading valve should be set to at 1.62 MPa. If the coldbox capacity needs to be reduced, then the setpoints for the 1st stage loading valve and the kickback valve have to be lowered synchronously while keeping predetermined differential between them. That would reduce the compressors flow with closed kickback valve, consequently stabilizing the coldbox at lower inlet flow and pressure. The limiting factors for this strategy are the pressure ratios and discharge temperature distribution through the compression stages. Unloading of the 1st stage results in higher discharge temperatures in the downstream stages, thus this mode of operation may be limited for 4-stage compressors only, or for fall-to-spring seasons.

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