A backup compressor system for the ESS Accelerator Cryoplant

P Arnold [1*], E Asensi [1], J Cardoso [1], W Hees [1], P Nilsson [1], J Zhang [1], H Stuckenberg [2]
[1] ESS ERIC, Lund, SE-22100, Sweden
[2] Aerzener Maschinenfabrik GmbH Germany

[*] Email: philipp.arnold@ess.eu

Abstract. The European Spallation Source (ESS) is a neutron-scattering facility being built with extensive international collaboration in Lund, Sweden. An essential part of the project is the linear 2.0 GeV proton accelerator (linac). Its superconducting part is cooled by means of a dedicated 2 K refrigerator, the Accelerator Cryoplant (ACCP). 2 K are achieved with three serial turbo compressors and a warm sub-atmospheric screw compressor. The ACCP operates in a four-pressure process with three warm oil-flooded screw compressors providing these pressures, one of them with sub-atmospheric suction pressure. Every single one of these three compressors is a single point of failure for the entire ESS operation. Even worse, periodic maintenance on the high pressure (HP) machine would not be possible without warming up the plant and with it the superconducting linac. It has therefore been decided to implement a backup compressor (BC) that can replace any of the existing warm compressors. The paper summarizes all project phases from initial decision to conceptual design, specification, procurement, execution, installation, commissioning and acceptance testing. Particularly mechanical and controls integration challenges are described in more detail as also lessons learnt and planned improvements.

1. Introduction

The process design of the ESS cryogenic system has been introduced in [1] and the process design of the ACCP, cooling the superconducting linac (SCL) in [2]. The ACCP operates in a four-pressure-process, consisting of high pressure (HP), medium pressure (MP), low pressure (LP) and sub-atmospheric pressure (SP) as illustrated in the simplified process flow diagram in Figure 1.

The SP compressor has the capability to replace the LP compressor. However, no hot spare is available for the SP compressor due to the absence of a helium guard on other stages, nor for the HP compressor due to its high motor power. Originally, redundancy of compressors was not specified in the 2014 cryoplant requirements. The process design of the system provided an opportunity to evaluate availability and redundancy options. Following the contract signing with Linde in 2015, multiple configurations were assessed, including the replacement of only the HP compressor, the simultaneous replacement of HP and SP compressors, and configurations with or without additional bulk oil removal system (BOS) and final oil removal system (FORS). Budgetary constraints led ESS to forgo these options, instead opting to prepare the necessary piping, flanges, space, and utility connections for a future backup compressor. This decision was made to facilitate later integration without disrupting the existing warm compressor system (WCS) too much.

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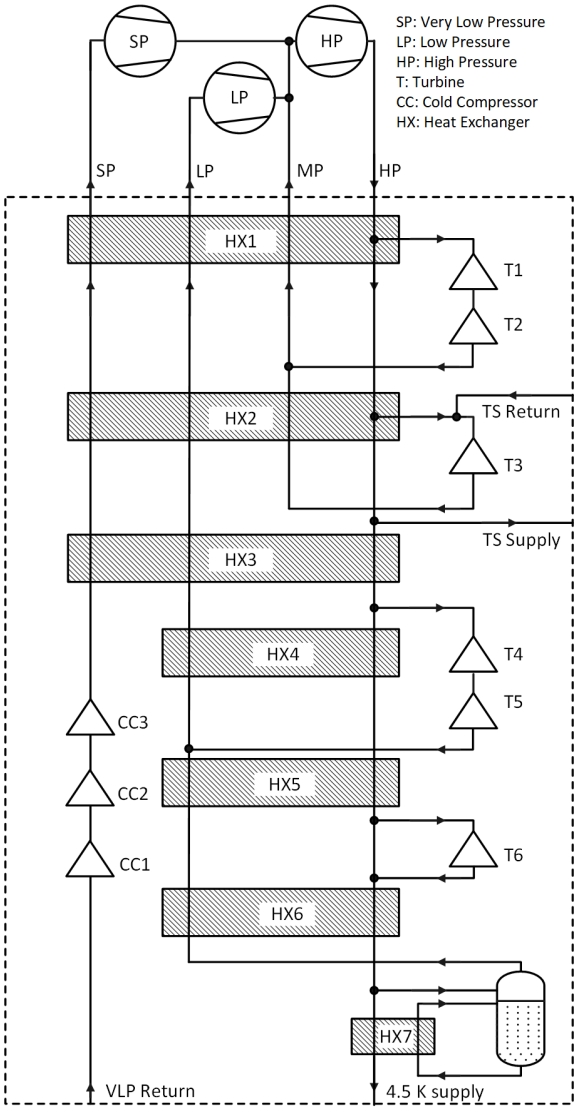


Figure 1. Simplified process flow diagram of the ESS Accelerator Cryoplant (ACCP) as shown in [1].

There is only one single warm compressor for every pressure step. All three machines are very similar with the same skid frame size and the same screwblock size.

They are, however, not identical. The compressors have different internal vi due to different design pressure ratios. There are 600 kW motors and variable frequency drives (VFD) for the LP and SP compressor while the HP compressor has 1600 kW motor power and no VFD.

Furthermore, there is a helium guard for the SP compressor for all sections that are exposed to sub-atmospheric pressure.

SP and LP compressor share one oil skid which has the same size as the oil skid of the HP compressor which has its own.

Between 2017 and 2018, the ACCP WCS was installed, commissioned, and subsequently underwent final acceptance testing in 2019 [3]. This was followed by the commissioning of the coldbox and the final acceptance testing of the complete ACCP in 2020. As part of the ESS project re-baselining in 2021, driven partially by the global pandemic, schedule and budget constraints were revised, allowing a renewed focus on the ACCP backup compressor.

Meanwhile operation experience and evolving requirements of the SCL provided further insight.

Running the ACCP in a "40 K mode" by operating only the HP compressor, while the SP and LP compressors remain inactive, is possible but proved to be not really useful for the SCL.

Operating both HP and LP compressors while the SP compressor was inactive, or alternatively running the HP and SP (as LP) compressors with the LP compressor offline, allowed the ACCP to maintain the SCL at 4 K while preserving liquid helium inventory. While useful during planned downtimes, this configuration is insufficient when superconducting radiofrequency (SRF) activities such as cavity conditioning or beam operations are scheduled.

Re-establishing steady-state conditions requires more time than anticipated. First, the WCS and gas management haved to be stabilized, followed by the coldbox, and finally, the SCL. Even without considering repair times, merely recovering from an operational trip proves time-intensive. Within approximately one hour of cooling loss, the liquid helium level in most spoke cryomodules deplete. In subsequent hours, depletion extends to the elliptical cryomodules, particularly when the thermal shield is also lost. The impact of cryogenic downtime consequently extends way beyond cryogenics alone, affecting SRF, in extreme cases even cavity detuning and beam vacuum conditions. Additionally, operational health and safety (OHS) constraints access

permissions to the accelerator tunnel during transients above 80 K. These factors significantly complicate system operation across multiple teams.

2. Conceptual design and specification

ESS decided to implement a backup compressor (BC) that can replace any of the existing warm compressors.

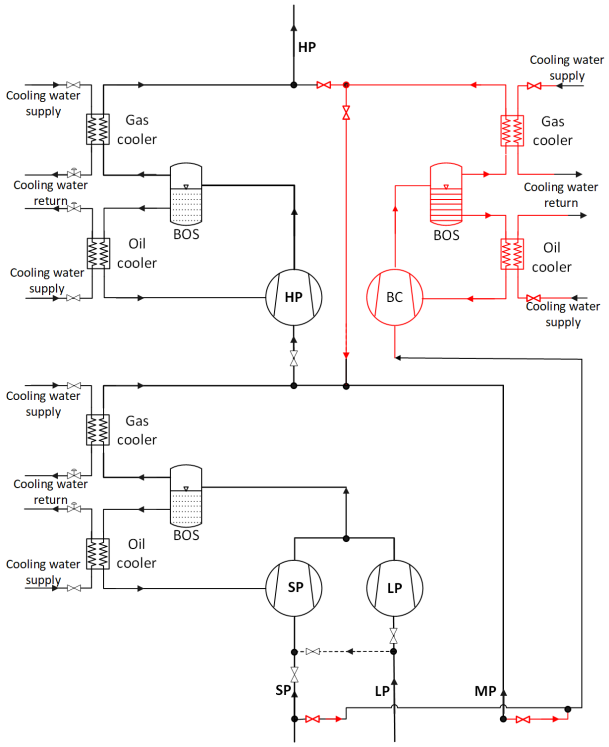


Figure 2. Conceptual design of the original WCS (black) and new scope (red).

In 2021 the integration strategy for the ACCP backup compressor system was defined and budgetary considerations were assessed. The backup compressor system was essentially meant to be a repeat of the HP compressor and oil skid but with helium guards on all connections to the suction side. Additional shut-off valves, piping, cabling, installation, process and controls integration would be done by ESS. A 1600 kW motor was supplied by ESS from the original spares inventory.

The conceptual design of the ACCP WCS is shown in Figure 2. Note that the backup compressor can be fed from either SP or MP but not from LP directly. In case the LP compressor is down, the SP compressor can take over the LP service and the BC can take over the SP. The reason is that at maximum capacity the LP compressor needs to run above 50 Hz which the BC cannot do, lacking a VFD.

The backup compressor system was essentially meant to be a repeat of the HP compressor and oil skid but with helium guards on all connections to the suction side.

The technical specifications were finalized in 2022, eventually leading to an order placement with Aerzener Maschinenfabrik GmbH, the original supplier of the ACCP WCS in November 2022. Table 1 shows the duty specification of the new compression skid.

Table 1. Specified performance parameters.

Parameters	HP max	SP max	SP min	LP max
Inlet pressure	4.05 bara	0.6 bara	0.3 bara	1.05 bara
Inlet temperature	313 K	300 K	300 K	300 K
Outlet pressure after cooler	20.5 bara	4.25 bara	3.5 bara	3.1 bara
Outlet temperature after cooler	313 K	313 K	313 K	313 K
Mass flow	735 g/s	114 g/s	65 g/s	TBD

The residual oil content after the bulk oil removal stage, upstream the original final oil removal, was set to lower than 10 ppm which is tighter than the original WCS performance but allows for some margin.

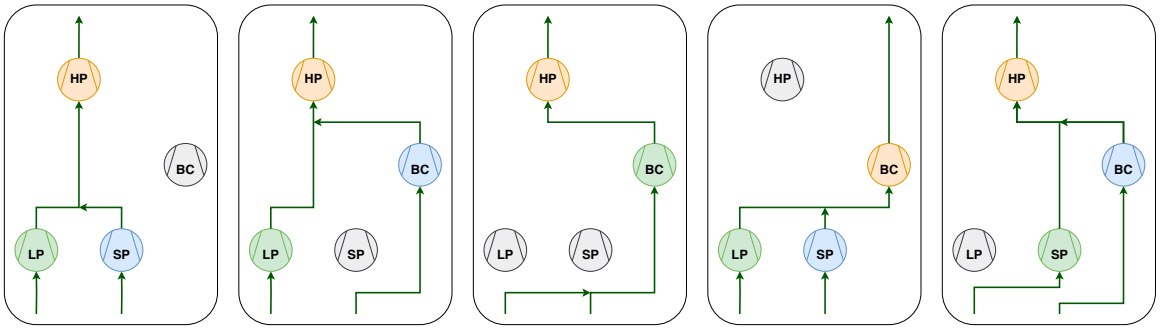
3. Controls integration

Modifications were made to the interlocks and startup conditions for the existing systems to ensure correct valve positioning, necessitating a valve matrix for all possible operational modes. Additional limit switches were installed on a number of existing shutoff valves to provide for safe interlocks. The method of determining running conditions was altered from direct machine readback to function-based readback, meaning that, for instance, the LP compressor now required verification that the HP function was running, regardless of whether the HP or backup compressor was in operation.

The SP suction pressure control was updated, taking into account that the BC has no VFD. A split-range controller uses a combination of VFD and MP-SP bypass valve opening to control the suction pressure, however only the bypass valve when the BC operated as SP.

The operator interface (OPI) was updated substantially to accommodate mode selections for the backup compressor integration. Figure 3 illustrates the different mode selections.

Simultaneously with the backup compressor project, a new communications PLC was introduced, representing a substantial change to the ACCP control system to overcome a number of issues on controls maintainability and upgradability [4]. This allowed a much better integration of the Aerzen BC control system to EPICS but added complexity during project execution.



BC off | SP off, BC as SP | SP and LP off, BC as LP | HP off, BC as HP | LP off, SP as LP, BC as SP

Figure 3. OPI pictograms for selecting operation modes for integration of Backup Compressor.

4. Design, project execution and installation

At contract signature the project duration until installation and commissioning was predicted with 2.5 years which was in line with the overall ESS schedule and our goal to integrate the backup compressor before cooldown of our SCL. Aerzen opted for a revised design integrating the compressor and oil skids into a single unit, illustrated in Figure 4, as opposed to separate skids. A notable deviation from the previous design was the adoption of a vertical bulk oil removal vessel instead of a horizontal one. This necessitated an upward discharge pipe connection rather than

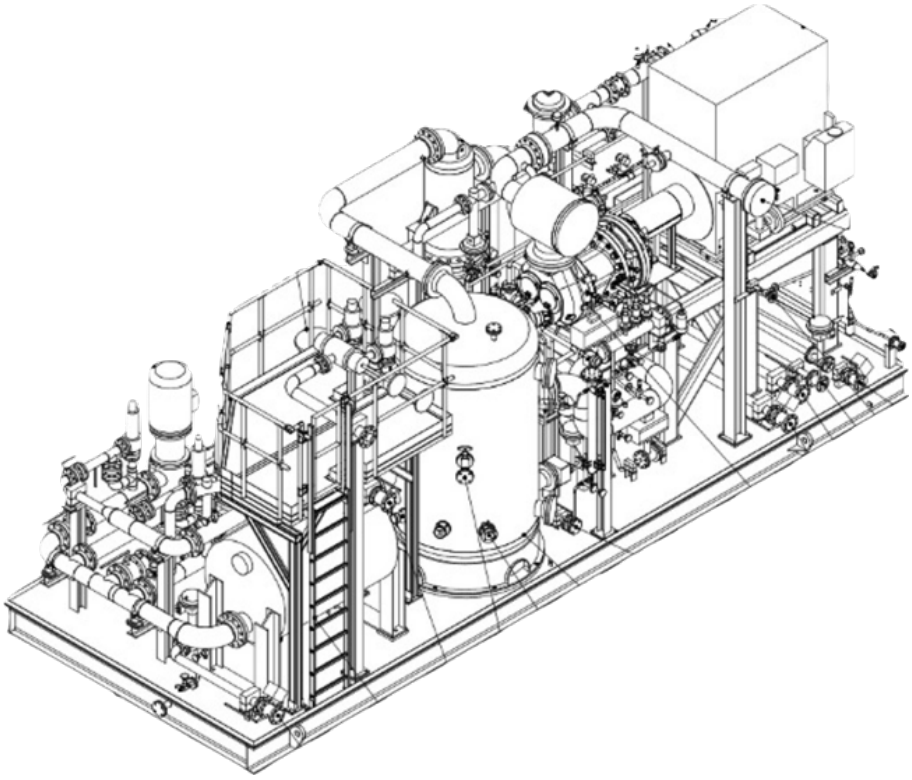


Figure 4. General arrangement of BCP skid by Aerzen GmbH.

the preferred slightly downward slope. Despite initial concerns, the new configuration demonstrated effective oil removal without obvious drawbacks.

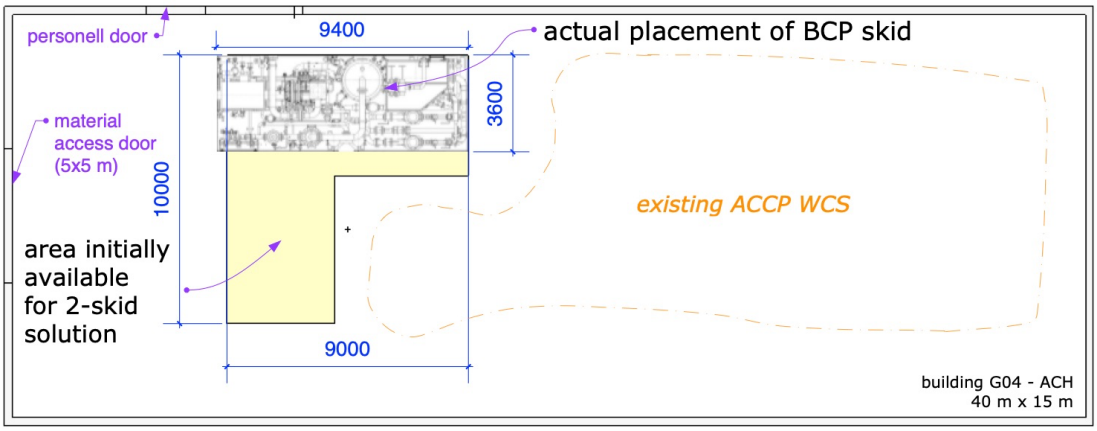


Figure 5. General arrangement of the BCP skid by Aerzen GmbH

This modification provided economic advantages and freed up space in the compressor hall for future expansions, see Figure 5.

Another design modification altered the slide valve control range from the previously reliable 20%-80% to a new range of 40%-85% for the backup compressor, permitting finer control in the more relevant higher range.

Access to the main safety valves (SVs) for periodic checks needed to be improved through a change order. Factory acceptance tests (FAT) were planned for the bare compressor alone and for the whole integrated skid, with air instead of helium. Due to issues with a wrong selection of the magnetic coupling for the oil pump motors the second FAT needed to be postponed. Other transport and sub-supplier delays added a few weeks to installation readiness.

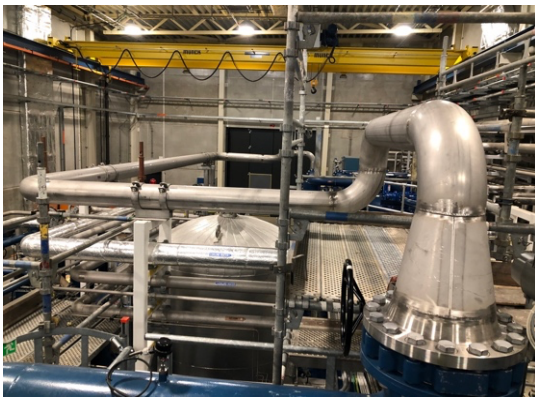


Figure 6. DN300-DN200 reducer of PN25 piping from BC outlet to HP inlet, resulting in PED class 3

Several integration challenges arose during installation at ESS. We faced problems with substantially delayed delivery of two large shut-off valves. Interconnecting piping design took longer than expected, pushing the installation start closer to our deadline. Combining the high pressure discharge of the BC (PN25) with the big diameter at the inlet of the HP (DN300) and the isolation valve on the big diameter side of the reduction piece (which was already in the ESS spares inventory) resulted in class 3 piping according PED which requiring design approval by a notified body. The respective isometric is displayed in Figure 6. This was flagged too late and resulted in large additional schedule delays.

Transport and lifting the compressor block in place, connecting all piping, cabling and wiring went considerably smooth. But pressure testing could not start until receipt of permission from the notified body which was at this point scrutinising the entire piping, design, material and documentation. The schedule slip was not possible to recover anymore and we were about to hit the SCL cooldown deadline.

5. Commissioning and acceptance testing

Preparation for commissioning included shutting down the entire system, draining the cooling water and refilling. Thorough leak checking, motor alignment and rotation check, oil filling, system pumping and purging, updating controls and network connections along with loop checks were part of the pre-commissioning. Leak testing revealed that the helium guard connection of the compressor inlet valve was not tight due to mismatching O-ring grooves, a design flaw that needs time to fix involving taking down a large pipe section, buying a new flange, cutting, rewelding, pressure testing and re-installation. In view of our schedule pressure ESS decided to leave the inlet connection unguarded and repair at a later occasion.

The hot commissioning started and was soon ready for acceptance testing. Initial tests of the backup compressor in SP mode confirmed satisfactory performance. We operated the compressor in a loop with the HP compressor, oil removal and bypass at the GMP, monitoring the impurity level on our gas analyser. Unfortuntely it became quickly clear that there was too much impurity intake via the switched off helium guard at the inlet, so the compressor could for the moment not be qualified to operate in SP mode.

Testing of the compressor in HP mode began successfully but had to be interrupted due to high vibration in the oil injection manifold resulting in an oil pipe rupture. It underlined the importance of our specified “100-hour test” since the rupture occurred not in the beginning or during commissioning but after more than 40 hours at maximum load. Prompt response from Aerzen and ESS personnel that was on site as it happened prevented further damage. An in-situ

repair of the manifold was tried but another test aborted due to the remaining high vibrations. The oil manifold required a re-design to minimize vibration while the SCL was cooled down successfully with the existing WCS without backup compressor [5].

The next opportunity occurred during a planned two-week machine stop in February 2025. With the coldbox and linac in operation, any off-nominal operation of the WCS is disruptive and needs meticulous planning. To allow the BC to start up and operate we need to

1. reduce the liquid levels levels in the CMs
2. switch off the cold compressors and transition from 2K to 4K
3. switch off the turbines and the coldbox
4. switch off SP, LP and HP compressor in this order

Due to more activities in the shutdown weeks, we started with a large controls and network update. Then the backup compressor was started up as HP. The system stabilized, the LP and SP compressors could be switched on. Subsequently the coldbox was reconnected, turbines started, SCL reconnected, CMs filled again and 2K pumpdown started. We had planned this to take two days before we needed to ramp up in order to bring the backup compressor to maximum performance condition for the 100-hour acceptance test. Therefore, we increased test heater powers and predominantly created virtual liquefaction load with a cooldown/warmup valve, carefully monitoring the plant conditions to keep the SCL stable while increasing the load command of the BC slide valve to match the SAT conditions.

We experienced another hick-up due to an instrument air outage at the coldbox during the maintenance stop. That taken aside the operation was a success, the backup compressor passed the SAT as HP compressor and is operating since as our HP compressor until the next planned shutdown.

6. Outlook and near-term improvements

In a longer shutdown in summer 2025 the SCL is warmed up again to allow for installation of six additional high beta CMs, boosting the possible beam power from 2 to 3 MW. At this opportunity a number of improvements on the backup compressor are planned.

The helium guard issues on the compressor inlet valve is being addressed, permitting a repeated SAT of the compressor in SP mode and also in LP mode that was skipped earlier due to schedule constraints.

Releasing pressure in the inlet connection was found to be cumbersome, requiring venting via the compressor skid's discharge side to prevent backflow of oily MP gas into the SP side of the coldbox. A check valve at the discharge side prevents backfilling, posing additional challenges when transitioning between operational modes. This is being addressed by additional small piping and hand valves, permitting easy pressure equalisation on the compressor suction side in any operation mode. The design is released, material procured and installation planned.

The BC bulk oil removal is slightly better performing like the old HP compressor but not as good as specified. The coalescer cartridges shall be swapped to different ones for even better oil removal. Also, several oil leaks have shown up that need to be tightened when the system is stopped and pressureless.

A substantial shortcoming of the current setup of the plant controls is that a seamless switchover between HP and BC (operating as HP) is not yet possible. The control logic was not clear and ready to be tested in time but such operation is absolutely essential for stable operation with the SCL.

In the long run we think about an additional final ORS and efforts to reduce vibrations at neuralgic points.

7. Summary and first operation experience

To ensure consistently high availability and long-term reliability of the cryogenic system, a minimum of warm compressor redundancy is paramount. There will always be unforeseen and unavoidable shut-downs, the effects of which can be mitigated by redundant machinery.

Integrating such a large new scope into an existing system is challenging and the efforts must not be underestimated, particularly with respect to controls integration.

It is very important to not only focus on the new scope of the backup compressor, but also on the impact these changes have on the existing machine and on the changes necessary there. Even when the WCS is operating in its initial configuration without the backup compressor, the mere addition of new interconnections between the different pressure levels requires the addition of a significant number of new interlocks for the existing machinery.

It is an advantage, not least financially, to have the same compressor model for all stages and to be able to have one multi-purpose machine to replace any of the other machines. However, attention must be paid to details so that the backup machine is fit for this purpose. Differing internal vi-s impact efficiency and, to some degree, performance but not in a critical way. Fully functional helium guarding is essential for sub-atmospheric service, as only one faulty connection out of many can cause leaks that are impossible to fix. It is important to foresee sufficiently many pump and purge connections and to place them correctly. Otherwise, quick switching of operation modes can be cumbersome.

Commissioning of (parts of) the compressor system is only reasonably possible with CBX switched off. Small changes and the associated testing are possible with CBX and SCL connected but require very detailed planning and evaluation of the consequences of potential mishaps.

During SAT, with remarkable timing, an oil leak at the LP/SP oil skid appeared. It turned out to be a fatigue rupture on the oil level gauge vessel. The gauge had to be switched off, dismounted and later repaired. Luckily, we could use the same vessel from the HP oil skid that was not in use, because the BC had just started running as HP. This happened while we could keep SCL under nominal conditions without interruption. Already during acceptance testing the BC has demonstrated its usefulness.

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