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Commissioning of the Cryogenic Plant for the Cryogenic Storage Ring (CSR) at Heidelberg

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At the Max-Planck-Institute for Nuclear Physics in Heidelberg a next generation electrostatic storage ring for low velocity atomic and molecular ion beams is under construction. In contrast to existing electrostatic storage rings, the Cryogenic Storage Ring CSR will be cooled down to temperatures below 2 K. Thus acting as a large cryopump it will provide long storage times and, in addition, open a new field of quantum state controlled molecular physics due to a low heat radiation background from space-like environment.
A concept for cooling the storage ring has been developed and is presently tested by means of a linear trap as a prototype with a length of 1/10 of the planned ring. A commercial refrigerator with 21 W at 2 K has been successfully commissioned and was connected to the prototype. This paper presents the status of the cryogenic plant after the commissioning and one year of operation.

INTRODUCTION

With a main focus on atomic and molecular quantum physics the interaction between molecules and electrons is investigated at the Test Storage Ring TSR, a magnetic storage ring with 55 m circumference, at the Max-Planck-Institut für Kernphysik in Heidelberg [1]. The experiments showed a strong dependence of the measured cross section on the quantum state of the target molecules. To enable new experiments in well defined quantum states, a wall temperature seen by the ions or molecules below 10 K is required. Therefore a cryogenic storage ring CSR has been designed. A vacuum of at least 10^{-13} mbar is required to achieve storage times allowing the above-mentioned experiments. Due to a very low velocity and a broad range of the ions of interest the storage ring has to be built as an electrostatic one. Internal optical elements often restrict the available local pumping speed considering the molecular conductances in the system. Therefore, integrated pumps, realized by the cold chamber walls, are chosen for efficient vacuum pumping. However, the desired vacuum pressure can only be achieved by efficient pumping of hydrogen, the remaining residual gas component at pressures lower than 10^{-11} mbar. For this purpose the chamber walls will be cooled down at strategic positions to 2 K and if possible even below 1.8 K. In 2005 a cooling and vacuum concept was developed [2,3], based on a commercial helium refrigerator. A schematic drawing of the CSR is presented in Figure 1 showing the 35 m circumference ring with four straight sections. Three of these sections are reserved for experiments, one is for diagnostics purposes. The corner sections consist of 6^o, 39^o, 39^o, and 6^o electrostatic deflectors. The ring itself will be built in an onion skin principle with the innermost shell as the cold chamber for the experimental vacuum, followed by two thermal shields and the outer chamber for the insulation vacuum at 10^{-7}mbar.

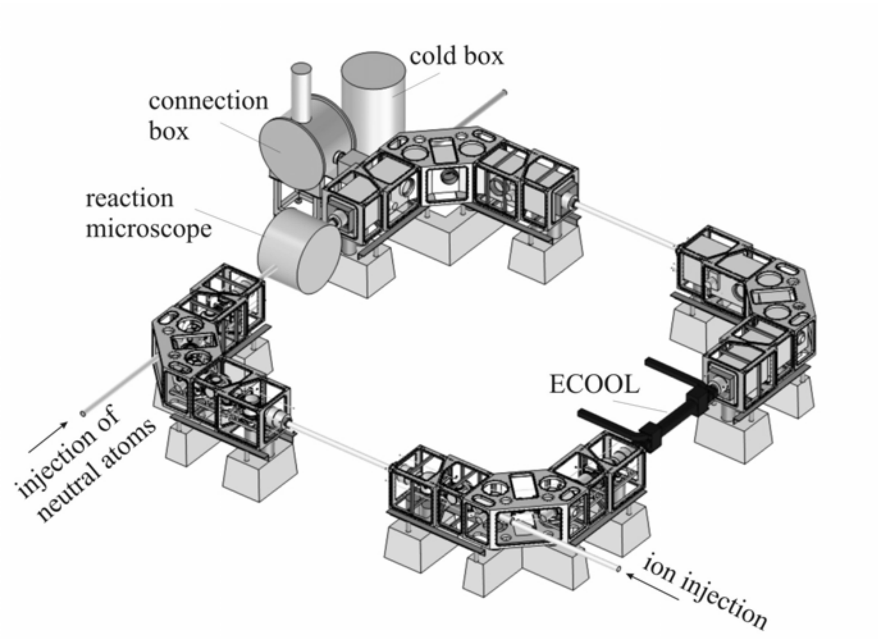

Figure 1 Overview of the Cryogenic Storage Ring CSR.

CRYOGENICS

The cryogenic concept for the CSR was already discussed in [2] and [4]. It consists of a 2 K helium distribution line and a 2 K evaporation return line to cool the experimental chambers. A 4.5 K helium line for cooling the thermal shields wraps around the ring three times warming up to 80 K at the return line to the connection box. The use of liquid nitrogen for precooling of the cold box was optionally prepared.

Refrigerator realization

A Linde LR140 refrigeration system consisting of the standard cold box, the specially designed connection box, pump and compressor, as well as the cold tubing was ordered at the end of 2005. Delivery and acceptance took place mid 2007. In comparison to the former TCF20-system, Linde introduced various modifications in the LR140. Mainly, next generation turbines [5] increasing the cooling efficiency were used and a standardized concept for the cold box based on the former TCF50 diameter was adopted. In addition the cold box is now equipped with an internal dewar to deliver liquid helium directly to the connection box. In addition we agreed to use a dry helium pump instead of the standard Breox sealed oil pump for achieving the 32 mbar for 2 K and 16 mbar for 1.8 K. The pump, compressor and gas management system were delivered in a turnkey container, whereas the warm tubing had to be supplied by the customer. The safety interlock for the turbines is realized in hardware instead of software solution by the SPS control system.

The connection box (diameter 1.6 m, height about 5 m) is the key component in this system. Helium at 1.5 bar from the cold box is delivered to the shield and to the distribution line in the connection box. In the distribution line the helium is precooled by the return stream of the pumped gas before it is expanded and delivered to the ring. Pumping to 16 mbar brings the temperature to 1.8 K. In the return line the 1.8 K evaporated helium supports the shield circuit and the turbines of the cold box by cooling room temperature helium down by virtue of two additional heat exchangers in the box. During the cool-down careful balancing of the bypass valves has been shown to be necessary for smooth operation.

Acceptance test and 1 year of operation

Table 1 summarizes the specifications of the refrigerator to be demonstrated as acceptance test. Behind the connection box a heating module was installed with two heaters allowing heat loads of up to 1600 W for the shield and 60 W for the superfluid circuit. For precise load control the delivered switched power supplies had to be replaced by linear regulated units.

Table 1 Specified requirements for the refrigerator

	case A	case B	case C
	with LN_2	with LN_2	without LN_2
Cooling power below 1.8 K		13 W	10 W
Cooling power below 2.0 K	21 W		
Shield cooling power with input below 5 K and exit below 80 K	560 W	560 W	400 W

A liquid level meter is used to keep a stable liquid level in the main dewar during the measurement of the cooling power. This level is adjustable to the level expected in the storage ring. Already during the acceptance test the refrigerator cooled down completely in automatic mode. The only required operator intervention is starting the helium pump at 4.5 K. The design values for the cooling powers (cases A and B) could be demonstrated without use of liquid nitrogen and with the helium pump at a reduced speed.

After the successful completion of the acceptance tests an extended period was invested to tune and optimize the refrigerator as well as to try to measure the achievable cooling powers. While the shield circuit was kept stable at a power-level of 600 W, the load on the superfluid system was increased slowly. Various instabilities of the refrigerator with oscillatory behaviour of the complete system were encountered; however by changing integration times of several control circuits those problems could be overcome. No universal set of control parameters was found and some empirical settings will be necessary for future tests with different loads. In Table 2 the measured cooling capacities are summarized.

Table 2 Achieved final values after one year of operation

Temperatures	1.8 K	2 K
Guaranteed power	13 W	21 W
Achieved power	20 W	27 W

It should be noted that these capacities are only limited by the helium pump and not by the capacity of the refrigerator itself, thus additional cooling capacity can be activated by increasing the pumping speed.

The 4th shield

The CSR should be operated preferably in the cryogenic mode. However, ion storage operation was demanded at all wall temperatures. Consequently, even with the inner walls at room temperature a vacuum of 10^{-11} mbar has to be achieved.

As the internal NEG getter pumps do not pump some important residual gas components, additional cryopumps [3] with bakeable absorber materials will be necessary. Although a closed cycle helium refrigerator system could be used, an alternative design exists using the connection box for feeding cryopumps only. Therefore an additional cooling circuit with two additional regulating valves was added to the connection box, delivering 4 K liquid helium to the cryopump heads independent from the operating condition of the main ring

Safety aspects

The safety requirements of the refrigerator system have to cope with a considerably larger liquid mass in the storage ring. Two worst scenarios were considered: a) loss of the insulation vacuum and b) breaking of the helium lines. The helium tubes are designed for a maximum pressure of 20 bar with opening of safety valves or burst disks at 17 bar. So after opening the safety valve at 17 bar, the pressure at all positions in the tubes must stay below 20 bar.

The overall length of the shield circuit is 120 m, looping around the ring three times with increasing diameter of the tube with temperature. The first loop (40 m) consists of a superinsulated tube whereas the remaining others are not shielded. In the connection box a safety valve is placed in the shield input line. Simulations have shown that an additional valve in the 80 K return line is required to limit the pressures to below 20 bar.

The 2 K circuit consists of the distribution line, the evaporation line and the connections to the chambers, with a total helium mass of about 10 kg. Simulations show that the pressure remains below 20 bar without any additional valve, using the available safety valve at the connection box with a diameter of DN 40 and calculated 654 g/s gas flow capacity.

COOLING OF THE PROTOTYPE

To test the layout of the beam control components under cryogenic conditions together with the cooling scheme and the heat loads and temperature distribution, a 4 m long linear prototype was built and connected to the refrigerator [6]. For in-situ measurements of the extremely high vacua envisaged, the prototype is equipped with an electrostatic ion beam trap and by measuring the storage time of externally injected ions the pressure can be calculated.

At the beginning of May 2008 first cooling tests were performed on the prototype. We started with the refrigerator in automatic mode, limiting the difference between the helium input and return lines to 40 K. However, as the cool-down proceeded too fast, generating excessively high temperature gradients in the components, we switched in these tests to manual operation of the refrigerator. To reduce the cooling power in the beginning, we ran the turbines at a lower speed by throttling the valve of the turbine entrance. Thus, less room temperature helium had to be added to the cold box exit. At this first cool-down the experimental and insulation vacua were not yet separated. Therefore, the main goals were checks of the performance of the complete system, which was found to be very satisfactory, and the mechanical stability of the trap alignment during the cool-down, which was also demonstrated successfully [6]. The inner chamber was cooled down by passing superfluid helium through the innermost cooling leads, with 1.8 K achieved at the return line from the prototype. Probes at the inner vacuum chambers indicated their cool down at a mean temperature of 10 K. The inner and outer shields were at mean temperatures of 40 and 80 K, respectively. In both cases there were still remarkable temperature deviations.

THE CSR

In parallel to the development, assembly and testing of the prototype, the mechanical design of the CSR has continued, adopting experiences gained in all phases of the prototype construction. The main difference between the prototype and the CSR will be the support of the cold chamber and the electrostatic electrodes. While in the prototype the electrodes are fixed to the chambers that are suspended by wires, the CSR will instead use rigid, low-heat-conduction stems (Figure 2). It will be realized such that the electrodes are completely decoupled mechanically from the cold chambers by bellows and intermediate thermal anchors will reduce their final heat input into the cold chamber. The stem consists of a G10 structure followed by a meander stainless steel form and two connections to the electrodes allowing independent electrode rotation.

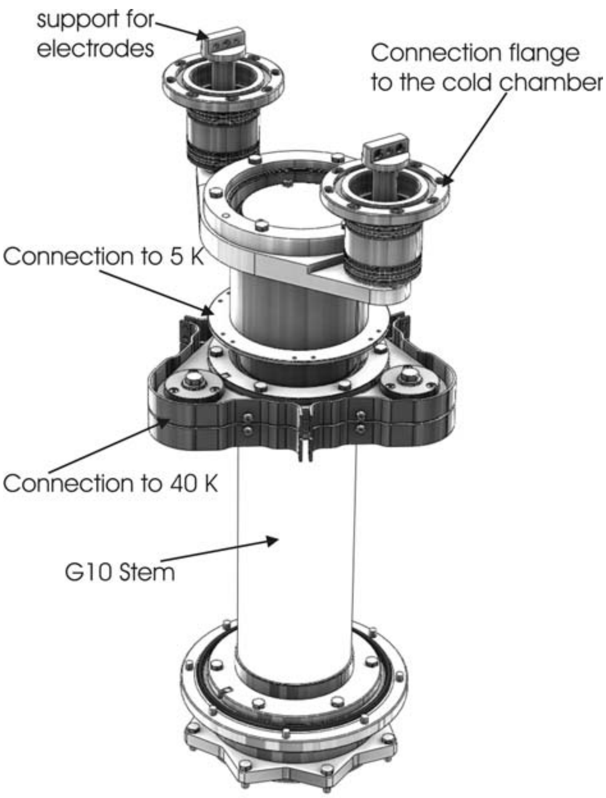

Figure 2 Design drawing of a stem for the electrodes

The calculated heat transfer to the 2 K chamber by all 24 stems of the storage ring is about 1.5 W, about 1 W coming from the rigid connection to the electrodes and the remainder coming from the bellows.

OUTLOOK

For completing the prototype tests, ions will be trapped in a cold environment to determine the achievable vacuum in the complex setup. For this purpose the prototype is now equipped with an ion injection system and several ion diagnostics elements. In addition, the temperature sensors controlling the automatic mode of the refrigerator have been repositioned and some thermal interconnections between different parts of the prototype were optimized, aiming at a fully automatic operation in the next cool-down process.

The next major milestone in the construction of the CSR is the assembly and test of a complete quarter of the storage ring, which will be separately connected to the refrigerator for extended mechanical and thermal stability tests.

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