COMMISSIONING OF THE HEIDELBERG CRYOGENIC TRAP FOR FAST ION BEAMS (CTF)

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Abstract

We report on the present state of commissioning of the cryogenic electrostatic trap for fast ion beams (CTF) at the Max-Planck-Institut für Kernphysik in Heidelberg. The device has recently passed a cryogenic test, during which the trap was cooled down by 1.8 K superfluid helium. No leaks of the helium supply system were observed, the temperature below 10 K was reached, and the required position stability of the trap electrodes was confirmed over the investigated temperature range.

INTRODUCTION

At the Max-Planck-Institut für Kernphysik, a cryogenic storage ring CSR [1] is currently being developed. As storage times of several minutes are envisioned for heavy molecular ions of up to 300 keV, extremely high vacua of 10^{-11} mbar at room temperature (RT) and 10^{-15} mbar at cryogenic temperature (10^{-13} mbar RT equivalent) must be achieved. To this end the vacuum system will be baked to 320 °C and then cooled below 10 K (2 K in some locations). As these extreme operating conditions severely restrict the choice of materials and pose a considerable technological challenge, the CTF has been constructed as a prototype and is presently undergoing commissioning.

THE CTF

The CTF (Fig. 1) consists of an inner (experimental) vacuum chamber, which is suspended on 24 inconel wires from an outer (insulation) vacuum chamber, to reduce heat load by thermal conduction. At the center of the experimental chamber, an electrostatic ion beam trap [2] is installed, to which additional vacuum chambers are connected by CF and COF flanges. These contain ion gauges, a bakeable cryo pump [3] and a cross piece where particle detectors can be mounted and which leads out of the cryostat to a pump stand consisting of a gate-valve separated oil-free piston pump backing a 500 ls^{-1} turbomolecular pump, and an ion getter pump. The insulation vacuum is pumped by two 300 ls^{-1} turbomolecular pumps backed by an oil-free piston pump, and two simple cryo pumps (mesh envelopes filled with zeolite granules) attached to the cold helium supply pipes.

The trap consists of two electrostatic mirrors (Fig. 2) with six ring electrodes of 40 mm aperture each, between which an ion beam of up to 20 keV can be stored. The beam is focused by an electrostatic lens attached to the front of each mirror. The electrodes of the mirror unit are mounted within an aluminium cage and are aligned on three ceramic rods by precision bores and sapphire spacer rings. The position and inclination of the mirrors are adjusted by moving the vacuum chambers they are mounted in, with a precision of 0.1 mm and 2 mrad, respectively, by turnbuckles or adjustable end pieces integrated into the wires. To avoid movement of the mirror electrodes between room temperature and cryogenic operation, great care was taken to compensate the thermal expansion of wires and vacuum chambers. As
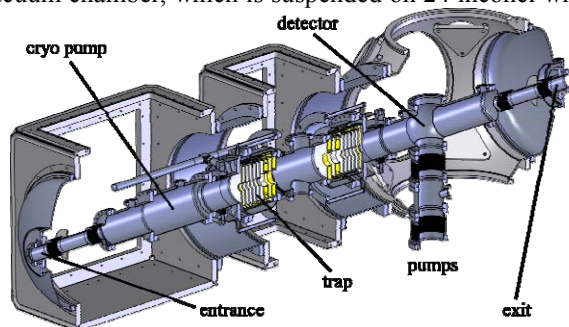

Figure 1: Cross-section of the CTF: Inside an outer vacuum chamber, the cold inner chamber is suspended on wires (not shown). The inner chamber consists of the trap, a cryo pump, a detector chamber and two entrance/exit chambers. A bellow in the middle of the trap chamber allows adjusting the mirror electrode units separately. In the detector chamber there is a connection to the pumping station outside of the cryostat. The outer vacuum chamber is approx. 3.5 m long, its average diameter is ~0.8 m.
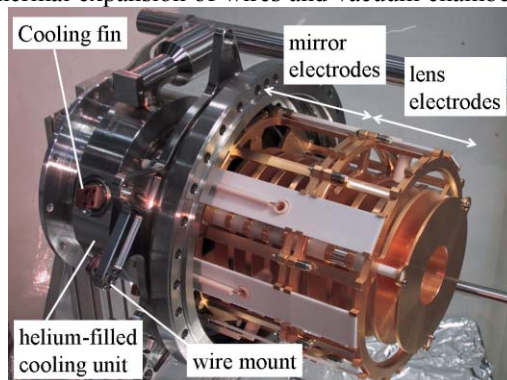

Figure 2: Photograph of a section of the trap chamber containing an electrostatic mirror unit. On the left side of the picture one of the ring-shaped cooling units can be seen together with the pipes by which liquid helium is supplied (bottom) and evaporated gas is pumped away (top). To the left of the open flange a mount point for the wire suspension is also visible.

far as permitted by the outer vacuum chamber, the mount points of the wires to the inner chambers were selected such that the thermal expansion of wires and chamber cancels. Springs were incorporated into 16 of the wire mount points on the outer chamber to relieve residual tension on the wires. The remaining eight mount points are distributed symmetrically with respect to all three planes of mirror symmetry of the suspension system and have no springs. This causes an (unimportant) 1-2 mm movement of the chambers along the beam axis when temperature changes, but allows better fixation of the lateral chamber position and inclination.

To obtain ultra high vacuum of 10^{-11} mbar at room temperature (RT), the inner vacuum system will be baked to about 320 °C [3] by coaxial electric heating wires wrapped around the chamber walls. The temperature above 300 C is required to activate non-evaporative getter strips (NEG ST707) attached to the inside chamber walls. Additional pumping facility includes a cryo pump and the pump stand described above. In cryogenic mode of operation, hydrogen is no longer pumped by the NEG strips. Instead, cryo-pumping of hydrogen on the inside of the stainless steel chamber walls will take over below 2 K, so that pressures in the 10^{-15} mbar range are expected [3]. To bring a sizeable proportion of the trap to this temperature, the inner vacuum chambers in two places form part of ring-shaped cooling units [1] filled with superfluid helium of 1.8 K. Cooling fins incorporated in these units as well as in an smaller unit in the middle of the CTF are attached to strips of high-purity 99.997% copper to distribute cooling power to remote parts of the device. The cold helium is supplied from the CSR closed-cycle cryogenic refrigerator [1], which provides 21 W of cooling power at 1.8 K, and 600 W at 60 K for cooling two concentric aluminium radiation shields by a separate helium circuit. The outer shield is surrounded by vacuum multilayer insulation (MLI) to further reduce heat input by radiation. This MLI is made from alternating layers (40 in total) of aluminium foil and glass fibre fleece and can withstand temperatures of 240 °C occurring during baking. The shields are also equipped with a water cooling system to reduce their temperature below 100 °C, which allows the use of MLI made from aluminized Mylar foil, which is preferred for the CSR because of cost reasons.

Another item which required particular attention was the system of supply pipes for the cold helium. To minimize leakage of superfluid helium into the insulation vacuum, all but five pipe joints (out of approx. 100) were welded instead of using flanges or fittings. Because the pipes operate at relatively high pressure under cryogenic conditions, we have examined a large fraction of all pipe joints with extensive x-ray, pressure and helium leak tests. We have investigated electron beam and tungsten-inert-gas (TIG) welding, as well as an orbital welding robot. As many as 20% of the joints made with electron-beam welding exhibited serious defects in x-ray tests (although all were mechanically sound and showed helium leak rates below 10^{-9} mbarls^{-1}). TIG welding produced a much

lesser defect rate (5-10%), with many defects being either uncritical, or obvious without an x-ray test. Orbital welding yielded a still lower proportion of defects, all of which were already diagnosed by the welding robot itself, so that no additional defects were found by x-raying at all. For this reason, we have decided to make orbital welding the method of choice for both the CTF and CSR, and to use TIG welding for those joints where the robot could not be mounted for space reasons. Electron beam welding is still used for the inner vacuum chambers, since these are designed so that liquid helium and the experimental vacuum are separated by a continuous piece of steel.

TEST RESULTS

The CTF was recently subjected to a first cryogenic test. To simplify operation of the device, the middle piece of the inner vacuum chamber was not installed so that experimental and isolation vacuum were not separated. The apparatus was cooled down at first by passing cold helium gas of several bar pressure through the entire pipe system. When the returning gas reached 4.5 K, the circuit for cooling the inner vacuum chamber was supplied with liquid helium, while the evaporating gas was pumped away so that an absolute pressure of 16 mbar was maintained in this pipe circuit. The circuit for the shield supply was still operated under pressure of 1.3 bar. The speed of cooling was limited initially to 3 Kh^{-1} by the poor heat conduction along the stainless steel walls of the inner vacuum chambers and hence by the maximum permissible temperature gradients along its components. Below 100 K cooling speed was increased twofold as the heat conductance of copper strips connecting remote parts of the vacuum system to the cooling units improved.

The temperature of the inner vacuum chamber and the radiation shields was monitored by 45 platinum resistance sensors (Pt-1000), which are reliable above 30 K, and by three rhodium-iron resistance sensors (Rh-Fe) and five silicon diode sensors (Si) for lower temperature measurements. Because the high temperatures during baking prevent us from using standard material like indium or cryogenic grease for improving thermal connections, it is in general difficult to establish a precise temperature measurement in the CTF. Since the dominant problem is the thermal contact of sensors and leads at the low temperature end, the readouts of the Pt-1000 and the Rh-Fe sensors may deviate upwards from the true temperature. The problem is less pronounced for the Si sensors, which must be removed for baking and were hence mounted using Apiezon-N grease.

At the end of the test, the radiation shields had approximately reached a steady state with average temperatures of 43 K and 83 K. Although this is very close to their respective design temperatures, the spread over different locations of the shields was considerable. Especially the lids of access hatches exhibited temperatures of up to 100 K, while locations with exceptionally good connection to the helium pipes were at 10 K. This is mostly due to the already mentioned difficulty of making a good thermal connection between

two metal parts, and to the limited thermal conductance of the aluminium shields.

The temperatures on the inner vacuum chamber were also almost constant at the end of the test, and with observed temperatures between 3 K and 30K depending on location, the spread was much smaller than for the radiation shields. Fig. 2 gives an overview of the final temperatures measured on the inner vacuum chamber. Temperature was highest near the two exits of the vacuum system (Rh-Fe 2 and Si 1 and 4 in Fig. 3), which is explained by infrared radiation entering from their RT ends, as well as by heat conduction along the beam pipe (although this incorporates two sets of bellows to reduce conduction, while the section between the bellows is also connected to the 40K shields). The effectiveness of using copper strips to cool remote places can be seen from the measurements obtained with sensors Si 1 and Si 4. In this case, a copper strip is connected to a DN150 CF flange of the cold chamber near Si 1 resulting in a temperature of 8.4 K, while opposite side of the flange where Si 4 is mounted is only cooled by conduction along the stainless steel, resulting in a temperature higher by 6.4 K. The lowest temperatures measured on the inner chamber were 3.1 K on the central cooling unit, and 5.1 K on a copper strip attached to a fin of one of the ring-shaped cooling unit. Both temperatures were measured with silicon diode sensors. Although we believe these to give the most precise information of all sensors, it is very likely that the temperatures at the cooling units were still lower: Both the freshly supplied liquid helium and the evaporated helium gas pumped from the return pipe had temperatures of 1.8 K, obtained from an independent and reliable measurement outside of the CTF. Considering that the heat input on the inner vacuum chamber is very small and cooling power comparatively large, there is no reason why the cooling units and an adjacent region of the inner vacuum chamber should not have been at the same temperature.
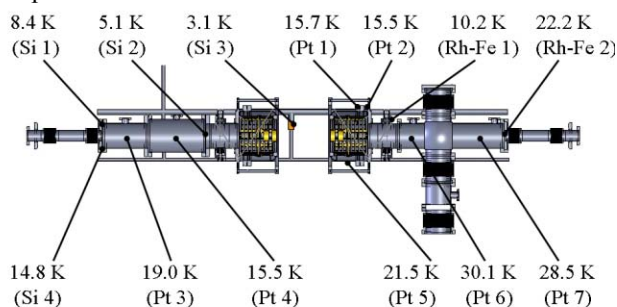

Figure 3: Final temperatures of the inner chambers measured during the cryogenic test. The sensor type is indicated below the respective temperatures: Pt: platinum resistance; Rh-Fe: rhodium-iron resistance; Si: silicon diode.

During this test, the position of alignment targets placed into the holes of the mirror electrodes was monitored closely. Between room temperature and cryogenic operation, a small movement of the targets was recorded. It corresponds to a common lateral shift of both mirrors

by 0.2 mm, and individual tilt angles of 0.8 mrad and 1.5 mrad, respectively. While this small change is in itself an achievement, considering the covered range of temperatures of almost 300 K, numeric modelling has also shown that it somewhat affects the acceptance of the trap, but is far from preventing the storage of ions. The temperature induced shift is most likely caused by the fact that while the mirror chambers are essentially kept in place by the suspension, the helium pipes shrink by approx. 3 mm between the two points where they are attached to the vacuum chambers. In the present design this is not fully compensated by the bellows integrated into all pipes in the middle plane of the apparatus, and it could account for most of the observed movement.

CONCLUSIONS AND OUTLOOK

We have constructed a cryogenic ion beam trap and successfully performed a first cooling test where we have obtained the design temperature of below 10 K in the trap. This also showed that the connection of remote trap parts to the cooling units could still be improved. In addition, only a small change of alignment in the electrostatic trap mirrors was found. Although it is not critical to operation of the CTF, we will continue to investigate this issue as it may affect the design of the CSR.

Since the conclusion of the test, additional copper connections to the cooling units have been mounted to the experimental vacuum chambers to increase cooling speed, and the Rh-Fe sensors have been mounted differently to improve the quality of measurement. The central section of the experimental vacuum system, which contains two sets of beam position pick-up or kicker electrodes and one ring electrode [4] has also been mounted.

An injection beamline with a penning ion source has also been set up. It will be used over the next weeks to test the storage of Ar^+ ions at different energies and temperatures. From the decay of the stored ion beam with time at different temperatures, in combination with measurements of the residual gas composition, we aim at deducing the density of residual gas molecules at the lowest possible temperatures, which is expected to elude the detection threshold of any ion gauge.

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