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CRYOGENIC SUPPLY AND BOIL-OFF REMOVAL FOR A LHE CRYOPUMP IN A 4 BAR SF$_6$ INSULATED 1 MV ACCELERATOR

Hans-Dieter Falter +), Wolfgang Obert ++)

Abstract

Accelerated clusters of the hydrogen isotopes have been considered for plasma heating and fueling. With a 1 MV high power cluster injector, insulated by 4 bar SF$_6$, particle currents up to 100 A equiv. are presently under development. The cluster beam is produced at high voltage potential with a gas efficiency ≈5 %. To pump the corresponding gas load of about 250 mbarl/s a LHe cryopump is installed within the high voltage terminal. The paper describes the supply and boil-off system of the cryopump. The cryogenic storage at high voltage potential, rated for a many hours operation, is supplied by means of a 30 cm i.d. lock through the 4 bar SF$_6$. The boil-off gas is transferred to ground potential during high voltage operation by a voltage controlled polyamid tubing of 19 m in length. This allows a transfer rate of 1.5 l/s even at gas pressures down to 500 mbar. In addition an emergency transfer line can be used having a transfer rate of 300 l/s, activated only with high voltage switched off. Experiments, where the heat load is buffered by the pressure rise of the cryogenic liquids are also described and discussed.

1. Introduction

A high power injector of hydrogen cluster ions, rated for 1 MV and 120 kW is in operation at the Karlsruhe Nuclear Research Center 1). Accelerated cluster ions are of interest for refueling of present day tokamaks with divertor 2) as well as for the production of negative hydrogen ions by charge exchange on a cesium target 3).

The cluster injector is insulated by 4 bar SF$_6$. The cluster ions, produced at high voltage potential, are accelerated to ground potential. By producing cluster beams with intensities of $6\cdot10^{20}$ atoms/s (particle current of 100 A$_0$) a gas load of 250 mbarl/s (21 mgr/s) has to be pumped at high voltage potential while the pressure in the acceleration gap must be kept below 10^{-5} mbar.

The pumping of the gas load is done by a cryopump fitted in the high voltage terminal. Pumps normally installed there work in a closed cycle without exhaust to atmosphere 4)5)6). In our case the high gas flow calls for a LHe cryopump. As a refrigerator of 5 watts at 4 K was not compatible with our accelerator design we installed a cryopump cooled by a 50 ℓ LHe bath at high voltage. For filling the containers a lock is installed. A d.c. transfer line and an emergency line with high conductance serve for removing the gas boiled-off during operation.

2. Description of the cryogenic system

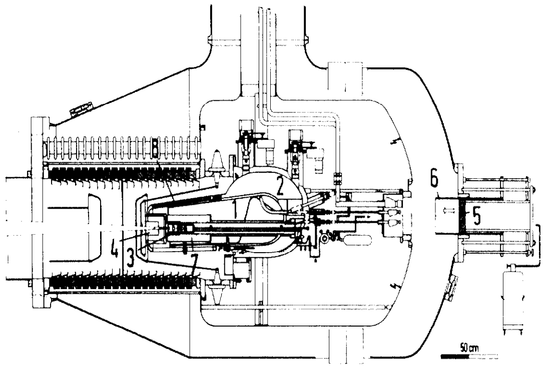

Fig. 1: Sectional view of the beam tank showing the beam producing system with the LHe (1) and LN$_2$ (2) container, the cluster beam source with nozzle and skimmers (3) and the ionizer (4), the lock with tube (6) and back plate (5) and the inner (7) and outer (8) cryogenic surfaces.

The cryopump, described elsewhere 7), is integrated in the cluster beam producing system installed within the acceleration tube as reentrant system (Fig. 1). The uncondensed part of the nozzle flow (≈95 %) is directly pumped by an unbaffled cryosurface (7) enclosing the nozzle and the skimmers (3). The highly directed condensed part, called cluster beam, is transferred to high vacuum by means of two skimmers.

The gas load of the ionizer (4) and of the acceleration tube are pumped by shielded cryogenic surface with a pumping speed of 1,500 l/s (ionizer) and 10,000 l/s (tube). Both values are for hydrogen gas. The cryogenic surfaces are cooled by a cryogenic bath of LHe. The LN$_2$ shield of the cryogenic surfaces and of the LHe container is cooled by a bath with a volume of 90 l. This large storage allows for a long time of operation without supply. A heat influx of 30 kJ increases the pressure in the LHe container only by 1 bar. The containers can be pressurized up to 5 bar. They are connected to the SF$_6$ insulating gas by means of a safety valve.

Fig. 2 shows the cryogenic system in front of the acceleration tube.

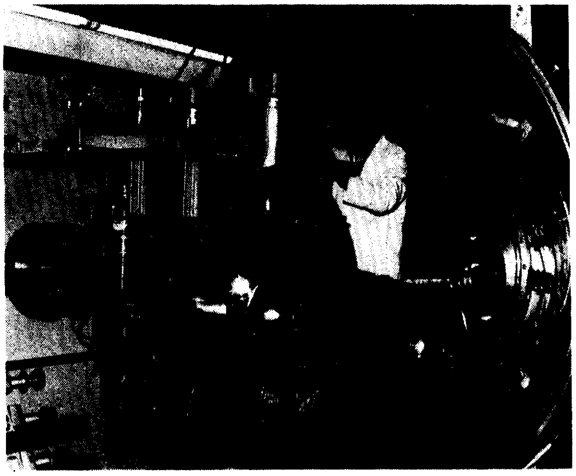

Fig. 2: Hydrogen cluster ion beam source with the baffled outer cryopump in front of the acceleration tube. The outer cryopump directly faces the tube.

+) Kernforschungszentrum Karlsruhe, IKVT, Karlsruhe

++) The JET Project Abingdon Oxfordshire, UK

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3. Cryogenic supply and boil-off removal

The cluster injector consists of three separate tanks connected by a coaxial 1 MV line (Fig. 3). The cryogenic containers are housed in the beam tank. The boiled-off gases are transferred to the atmosphere in the supply tank.

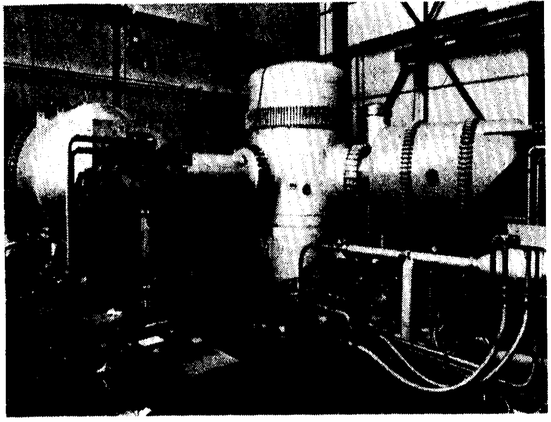

Fig. 3: 1 MV cluster ion accelerator. The three tanks contain (from left to right) the beam source and the acceleration tube, the power supplies and the boil-off transfer lines of the beam source, and the high voltage generator.

Supply of the cryogenic liquids

A lock mounted on the beam tank (Fig. 1) allows to supply the cryogenic vessels without depressurizing the SF_6 atmosphere. The tube of the lock is moved towards the beam source. Then, after expanding the gas between tube and back plate, the back plate is removed, opening a port with 30 cm i.d. to the cryogenic system. After filling the cryogenic vessels the back plate is reinstalled, the tube removed, and high voltage can be applied.

Buffered operation of the gas removal

In this operation mode the cryogenic liquids are cooled by pumping down the cooling baths through the high conductance transfer line in the supply tank (Fig. 4).

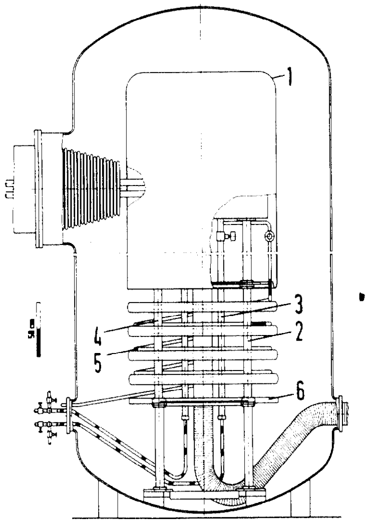

Fig. 4: Sectional view of the supply tank showing the high voltage terminal (1), the insulating column structure (2), the emergency line for N_2 removal (3), the emergency line for He removal (4), the d.c. gas line (5) and the base plate (6) at ground potential.

Then the cryogenic containers are shut off, the transfer line is floated by 4 bar SF_6, and the cluster ion accelerator can be operated, until the temperature (and the vapor pressure) exceeds an upper limit due to the warming up of the cryogenic liquid. To raise the temperature of the LHe from 3.4 to 4.2 K the internal energy of the liquid and of the vapor in the closed system of 50 l must be increased by 10 - 15 kJ, depending on the level of the cryogenic liquid (Fig. 5). The corresponding values of the LN_2 system with a volume of 90 l are in the range of 1,100 - 1,600 kJ when the temperature is raised from 77 - 91 K. The level of the LN_2 must be kept high enough in order to prevent an imperfect shielding of the LHe system. The loss of cryogenic liquid by one operation period (warming up and subsequent cooling by pumping) is indicated in Fig. 5 by a pair of arrows. The right one gives the volume at the low temperature at the beginning of the cycle, the left one gives that at the end of the cycle. This estimate neglects effects of boiling, foaming etc..

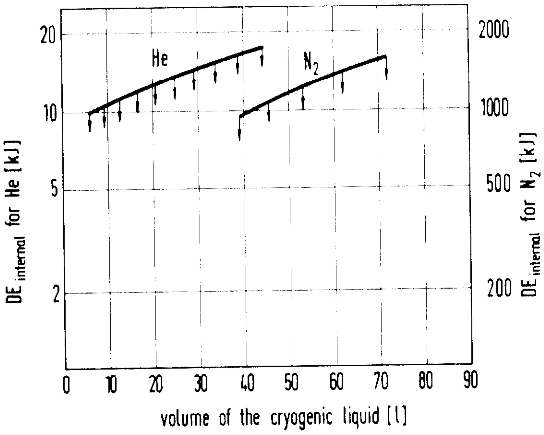

Fig. 5: Difference of the internal energies $DE_{internal}$ between 3.4 and 4.2 K for He (77 and 91 K for N_2) for a closed system of 50 l (90 l for N_2).

In our case, where the heat influx to the LHe can be as high as 7 watts, operation periods up to 35 minutes can be expected if temperature stratification is avoided. The do this, rings of highly pure aluminium are installed in the cryogenic containers.

Operation with continuous gas removal

The dielectric strength of helium at room temperature is smaller than that of SF_6 at the same pressure by more than one order of magnitude [8]. To get rid of a large compressor in the high voltage terminal, we tried to transport the helium gas through a 19 m polyamid tubing wound to a spiral and installed in the insulating column structure of the supply tank. The gradient in the tubing is controlled by a resistor chain of 230 resistors installed inside the tubing. The helium gas directly contacts this resistor chain. To measure the breakdown voltage or the tracking voltage of this tubing the internal helium pressure was reduced down to 200 mbar at an applied voltage of 500 kV. As shown by Fig. 6 the current in the chain has a noise of about 0.01/μA. A discharge with a low resistance along one resistor would increase the current in the chain by about 2 μA. In the case of Fig. 6 the pressure in the tubing increased at a rate of 3 mbar/minute due to a leak to the external SF_6. The conductance of the tubing allows to transport 5 m^3/h of helium gas at room tem-

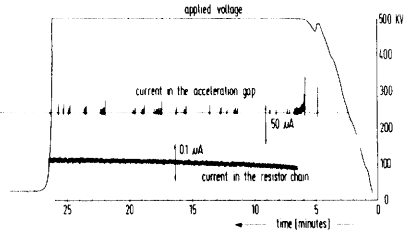

Fig. 6: Current in the resistor chain and in the acceleration gap during high voltage operation. He pressure was 200 mbar. Small discharges are seen in the acceleration gap but not in the current in the tubing.

perature with a pressure drop of 400 mbar in the transfer line. Owing to the excellent electrical properties of the tubing the pump for the helium gas could be installed outside the SF_6 pressure tanks. Normally the pressure in the LHe container is in the range of 600 - 1000 mbar. Up to now we work with voltages in the range of 500 kV. No flashovers are observed and no tracks are visible in the tubing after an operation time of 50 - 100 h. Fig. 7 shows the column structure of the supply tank and the transfer lines installed there.

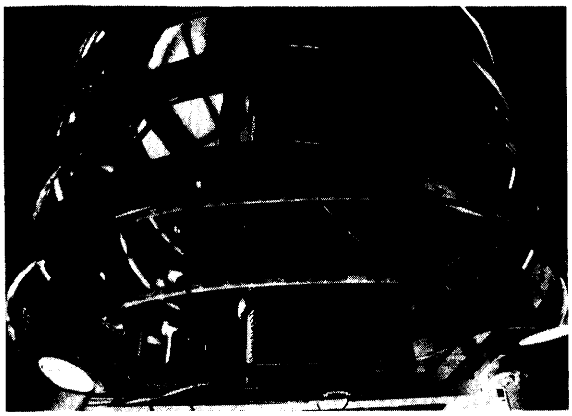

Fig. 7: Photograph of the transfer lines installed in the column structure of the supply tank.

Safety aspects

As already mentioned, a heat influx of 30 kJ to the LHe or 1,000 kJ to the LN_2 can be tolerated owing to the large volume of the cryogenic containers without causing a dangerous increase in pressure. If the pressure exceeds an upper limit (1 bar for He, 2.5 bar for N_2) the high voltage is shut off automatically and the high conductance line is opened, offering an additional transfer rate of up to 1 m^3/s. If the pressure in the cryogenic containers exceeds the pressure of the insulating SF_6 the boil-off gas is released into the SF_6 by means of safety valves.

4. Performance of the system

To supply the cryogenic liquids the high voltage has to be shut off for about 1 hour. In buffered operation the LHe warms up within 20 - 30 minutes. The following pump down lasts 5 - 10 minutes. As seen by Tab. 1 the loss of cryogenic liquid is considerably above the values of Fig. 5. It is assumed, that this high loss is caused by a violent boiling due to the pumping of the saturated vapor. Stratification is practically avoided by the installation of the aluminium rings. In a comparable cryosystem without these rings we observed an increase in pressure from 350 to 1000 mbar in 12 minutes in contrast to 75 minutes estimated for warming up the LHe system. The continuous gas removal, works at voltages of 500 kV with an internal pressure of 200 mbar. To increase the high voltage up to 1 MV we confidently expect, that the He pressure in the tubing must not be raised above 1 bar. Thus, even at higher voltages, it should be possible to work without or if really necessary with a small compressor in the high voltage terminal.

By testing the beam source outside the accelerator structure we find a heat influx of 1.8 watts. With this evaporation rate the cryogenic storage is sufficient for 20 hours of operation and the buffered operation would allow periods of 90 - 150 minutes. Up to now the high evaporation rate mostly observed in the accelerator is not understood.

Tab. 1: Typical operation periods with a buffered gas removal.

time of operation	23		21		22		14		13
pumping time		6,5		7,5		8		3	

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