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MERGED-BEAMS TOOLS FOR THE STUDY OF ULTRA-COLD REACTIONS

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В статье кратко описывается новая установка для сохранения ионов, которая в настоящее время строится в Стокгольмском университете, Швеция. Эта установка использует только электростатические фокусирующие и отклоняющие элементы и позволяет сохранять ионные пучки противоположных зарядов, находящиеся в экстремально высоком вакууме и при криогенных условиях, в отдельных «кольцах» и затем объединять их на общем прямом участке. Этот аппарат для Экспериментов на Двойном Электростатическом Ионном Кольце (Double ElectroStatic Ion Ring ExpEriment (DESIREE)) позволяет изучать взаимодействие между катионами и анионами при низких и точно определённых энергиях в системе центра масс. Статья завершается обсуждением примера такого потенциально возможного исследования. Полный технический обзор этой установки недавно был опубликован [1].

Ключевые слова: *кольцевой накопитель, катионы, анионы, реакции в объединённых пучках, криогенные температуры, реакции взаимной нейтрализации.*

Here we will briefly describe a new ion storage device currently under construction at Stockholm University, Sweden. This device uses purely electrostatic focussing and deflection elements and allows ion beams of opposite charge to be confined under extreme high vacuum and cryogenic conditions in separate “rings” and then merged over a common straight section. This Double ElectroStatic Ion Ring ExpEriment (DESIREE) apparatus allows studies of interactions between cations and anions at low and well-defined centre-of-mass energies, and we will finish the paper by discussing an example of such potential research. A complete technical review of this facility has been recently published [1].

Keywords: *Storage ring, cations, anions, merged beams reactions, cryogenic temperatures, mutual neutralisation reactions.*

Introduction

One driving force for initial development of ion storage rings was taken from high-energy particle physics. In recent decades these devices have also proven to be successful in addressing the needs of the atomic and molecular physics communities into low-energy processes. Many such devices are modeled after LEAR [2] at CERN, in which magnetic elements such as dipole, quadrupole and higher multipole magnets are used to define and control the ion orbits in the device, and examples of such devices are CRYRING [3] (Stockholm, Sweden), ASTRID [4] (Aarhus, Denmark), and TSR [5] (Heidelberg, Germany).

Electrostatic elements are rarely used in these devices: when they are used it is primarily for electrostatic septa for the injection/extraction of ions. This aspect is relevant when it comes to comparing devices based on electrostatic storage as opposed to magnetic storage. The use of electrostatic elements clearly removes the problems associated with the effects such as remanent fields and hysteresis in the magnets and the requirements for water cooling. Magnets are also expensive, big and heavy, while with electrostatic elements a compact and less expensive solution can be realized. The fact that all elements are electrostatic means that, for an injector on a given potential, the mass and charge of the injected ions can be changed without need to change the settings of the ion-optical elements. Another advantage is that an electrostatic device can store heavy ions in low charge states, an issue which is often a problem in magnetic rings where the maximum mass of the stored ions is limited by the bending power of the magnets, and this plays an important role in the experimental uncertainties [6]. Finally, from a purely scientific perspective, the lack of magnetic fields also plays a role in studies fundamental physics since such fields can give rise to mixing and transitions between quantum states in the ions being stored in the device.

These advantages were realised through the pioneering work of Møller in Aarhus, Denmark, with the construction of the purely electrostatic storage ting ELISA [7]. The DESIREE facility adds a unique twist to this storage-ring design: it consists of two separate storage rings with a common section in which, for example, the interaction between oppositely charged ions can be studied in a merged beams configuration [1]. The unique position of the DESIREE facility is further highlighted through its design. Instead of the usual approach, in which the two rings would be mounted in separate beam pipes, the ion optics for the whole device is fully open and the whole "storage volume" is enclosed in a double-walled vacuum vessel. This has many advantages if one takes into account experimental perspective: it is easier to create extreme high vacuum conditions, leading to longer storage times; and since all the ion-optical elements are mounted on a common base-plate, which then also serves as the floor for the inner vacuum chamber, everything thermally shrinks together during cooling, allowing the inner vessel to be cryogenically cooled to approximately 10 Kelvin through the use of cryogenerators without significantly affecting the environment. Figure 0.1 shows a schematic overview of the DESIREE facility.

1 The DESIREE facility

The DESIREE facility consists of two high-voltage ion source platforms, one at 100 kV and the other at 25 kV, which service the two storage rings and the common straight merging section that are located in the common vacuum vessel. The main DESIREE vessel consists of a double-walled chamber, i. e., two separate vacuum vessels with the one placed inside the other and separated with a thermal screen. The outer box is constructed entirely of steel plates which are welded together, and has external dimensions of 4.7 m × 2.5 m × 0.7 m. For mainly thermal-conduction reasons the inner chamber is constructed from plates of an aluminium alloy which are welded together.

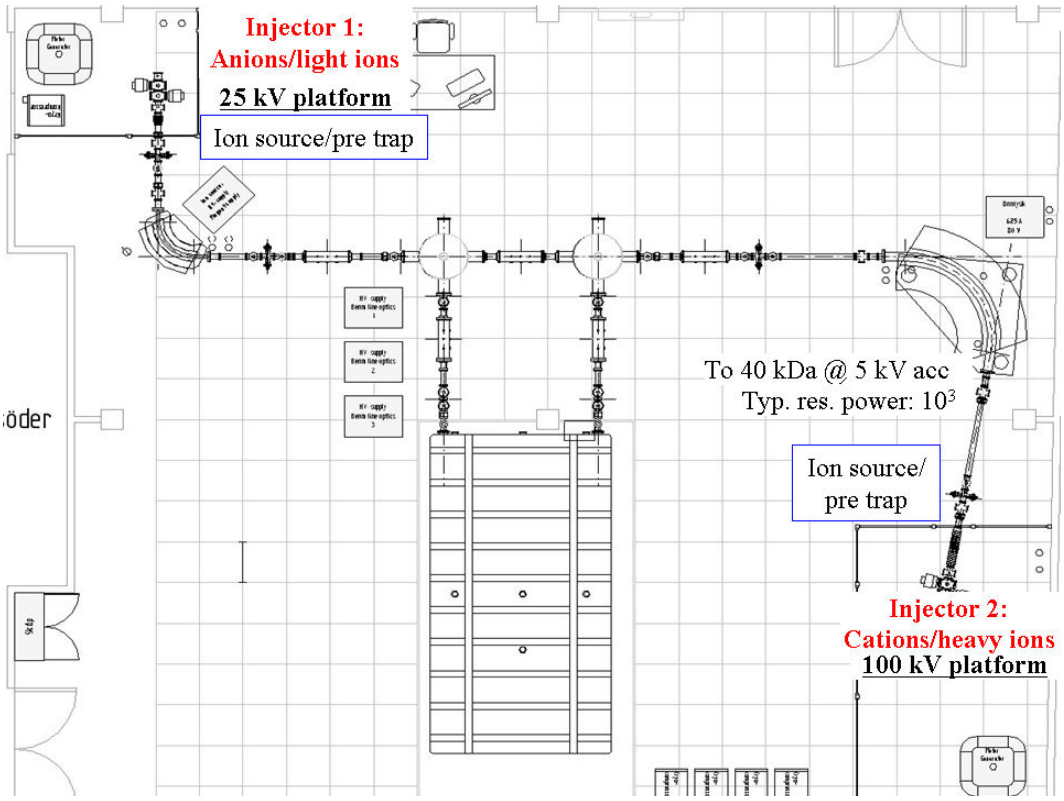

Figure 0.1 – Overview of the DESIREE facility: the two ion source platforms, injection beam-lines, and the main vacuum chamber

The particular alloy used in the final construction was chosen because it can be machined, and both its thermal properties are known, and its heat conductivity is sufficiently good, over the whole temperature range from 400 K down to a few Kelvins. The physical dimensions of the inner chamber are 4.4 m × 2.4 m × 0.2 m. All ion-optical elements and detectors are carefully mounted directly on the bottom of this chamber. Access to all components for their mounting is through the top of the chamber via a removable lid. The lid and the bottom plate, together with nearly all of the ports into the inner chamber, such as pump-ports, feedthroughs etc., are made vacuum-tight with AstraSeal gaskets. Separating the two vessels is a thermal screen which, for its excellent thermal conductivity, is constructed from copper sheets and 30 layers of Mylar super-insulation, which are placed directly on the outside of the copper screen.

During cryogenic operation, the inner chamber will be cooled with four cryogenerators (Sumitomo RDK-415D) where the first stage of each cryogenerator is connected to the thermal screen and the second stage to the bottom of the inner chamber. The total heat load on the thermal screen and the inner vessel is estimated to be 60 W and 3 W, respectively. If this low heat load can be realized the final temperature of the inner vessel and the rings should be about 5 K. At cryogenic temperatures the inner vessel will be pumped by the cold walls of the chamber. The main contribution to the background pressure will be H_2, which will be reduced by Ti sublimation pumps. After the initial baking at ~400 K of the aluminium vessel, a pressure of $1\text{x}10^{-10}$ mbar is expected to be reached at room temperature. The outer chamber, whose main purpose is to thermally insulate the inner vessel, will be pumped with turbo pumps. All feedthroughs and pump-ports located on the inner chamber are sealed with a combination of Helicoflex and Astraseal gaskets while those through the outer chamber are sealed with standard Viton gaskets.

Figure 1.1 shows a rough scheme of the ion-optical layout of the inner chamber: the heart of the DESIREE facility:

Each ring is ~8.8 m in circumference and has two 160° cylindrical deflectors and four 10° parallel-plate horizontal deflectors, where the two 10° deflectors on both ends of the merging section (MR) are common to the both rings. Only ions with opposite charge can be stored if both rings are operated at the same time though either ring can be operated independently with ions of any charge. R2 has a somewhat different layout compared to R1, and can store ions with different energy [and charge] compared to R1. Hence the bending angle will differ from 10° in the two common deflectors. To compensate, and to make the ion beams collinear in the merging region, additional deflector plates are added to the second ring.

In addition to the "traditional" filament and cold-cathode ion sources which have been used to create the singly charged atomic and molecular ions studied in molecular storage rings such as CRYRING [6], the platforms have been designed to accommodate a suite of different ion sources ranging from an expansion source for producing rotationally cold molecular ions, an electrospray source for creating biomolecules and large molecular cluster ions, and a sputter source for generating negative ions [6]. Each of these ion sources is available, having been either purchased or constructed in-house, and are currently undergoing testing on a dedicated ion-source experimental platform – though this is beyond the scope of these proceedings.

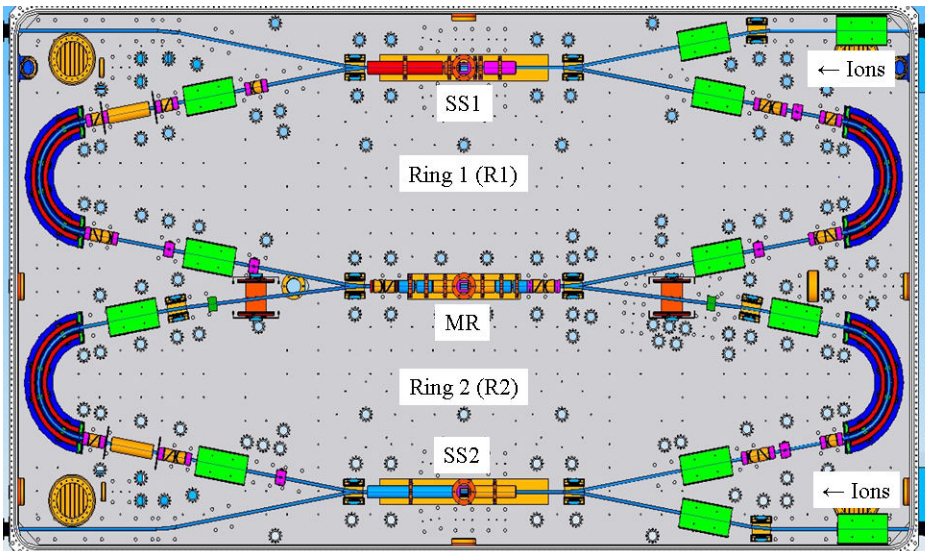

Figure 1.1 – A rough scheme of the heart of the DESIREE facility showing: the two rings, the two straight sections in each ring (SS1, SS2) and the common straight section – the merging section MR

2 The test system

It became quickly clear during the initial development of the project that in order to meet the technical challenge of designing a complex system like DESIREE a smaller test and training system needed to be constructed. This chamber was built as a cryostat, with an inner and outer chamber and a copper screen in between, and represented an almost exact copy of the design for DESIREE. One of the important tasks for this chamber was to test the cryogenic properties of the different kinds of detectors that were planned for use in DESIREE. One such family of detectors are microchannel-plate based detectors (MCPs), in which these plates are coupled to different types of anode depending on the purpose of the detector. Both resistive- and phosphor screen-anodes have been tested, and the results from the MCP-phosphor screen anode have been reported [8], and showed that these detectors successfully operate under cryogenic conditions.

One of the most significant scientific highlights to come out of these investigations arose from the placing of an electrostatic ion trap in the test chamber, i.e, to mimic the ion-storage properties of DESIREE. Here, a linear ion-trap, ConeTrap [9], was placed inside the inner vacuum chamber. A pulse of ions was injected into the trap, which was then closed, and the lifetime of the ions in the trap studied as function of their storage time. The ions chosen for this particular test were the metastable helium anion, $He^-(1s2s2p\ ^4P_{5/2})$, with the motivation that results from earlier lifetime measurements were limited in the accuracy of systematic effects due to the photo-detachment of the loosely bound 2*p* electron by 300 K blackbody radiation photons emitted from the surrounding vacuum chamber. In the course of this experiment in a suitable cryogenic environment, in practice less than 80 K, this effect is eliminated. The results from these tests gave the most accurate measurement for the lifetime of these ions [10], as well as providing valuable information on the ion-beam storage lifetimes as a function of the residual gas pressure in the chamber [11].

3 Proposed experiments

DESIREE has been planned and constructed so that any given experiment can be undertaken in either of the two rings or a single experiment can utilise both rings. Examples of such experiments are discussed in the recently published technical paper [1]. The most unique feature is the merging region, and so we briefly discuss an example of the type of experiment which now can be undertaken at DESIREE and which otherwise have proven extremely difficult or impossible. The possibility to perform merged-beams experiments with positive and negative ions that are stored and cooled to low temperatures by temperature equilibrium with the surroundings is the most clearly unique feature of DESIREE.

Here we consider the mutual neutralisation between small molecular cations and anions. The formation of polyatomic ions in the interstellar medium is considered to be through chemistry involving ionized species. The degree of ionization in the interstellar clouds is determined by a balance between ionization through cosmic and stellar radiation and neutralisation processes. In the gas phase two such neutralisation processes exist: Electron-cation dissociative recombination (DR) and cation/anion mutual neutralisation (MN). One of the primary motivations for the studies at CRYRING of DR for astrophysically abundant cations (ref [6] and references therein) has been the role of this process in interstellar chemistry in regions where the negative charge is primarily in the form of free electrons. One of the most recent observations in the interstellar medium has been that of long carbon-chain anions [12]. If present in the amounts required to explain the observed absorption, it is possible that in these regions negative charge is more often in the form of anions than free electrons. In such an environment the role of MN in the ion chemistry is more important than DR and the possibility offered by DESIREE to study these processes highly relevant to this field. For the simplest such MN reaction, $H^+ + H^-$, high-level fully quantum calculations have recently been published [13] and allow benchmarking for the planned experimental studies, and suggestions for how this reaction could be measured in DESIREE are presented in the technical review [1].

4 Current Status

Both the inner and outer vacuum chambers, as well as the copper screen, have been machined and fully assembled, as have all of the electrostatic/dynamic elements that will be located inside the main vacuum vessel. The 25-kV platform has also been constructed and assembled, as have all parts for both the injection beam lines and their associated ion optics. The next stages include transfer the inner chamber into the copper shield, attachment of the super-insulation layers, and completion of the leak testing of the whole chamber, followed by testing both the cryogenic cooling an electrical testing of the whole inner and outer chamber, with all elements in place.

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