DESIREE: a unique cryogenic electrostatic storage ring for merged ion-beams studies

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In this proceedings I will describe the design of a new 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 for studies of interactions between cations and anions at low and well-defined centre-of-mass energies. I discuss the design of the DESIREE facility, highlighting some of the technical advantages of using purely electrostatic over magnetic elements, as well as the issues that have arisen during its development and construction. Finally, the advantages of this design are a boon to fundamental experimental studies and I finish by discussing an example of such potential research.

1 Introduction

One of the driving forces for the initial development of ion storage rings was from high-energy particle physics, and the size of these rings covers a wide range with circumferences ranging from tens to thousands of meters. In recent decades, these devices have also proven successful in addressing the needs of the atomic and molecular physics communities into low-energy processes. The majority of these devices are modeled after the LEAR device at CERN [17], in which magnetic elements such as dipole, quadrupole and higher multipole magnets are used to define and control the ion orbits in the device. Examples of such devices are CRYRING (Stockholm, Sweden [1]), ASTRID (Aarhus, Denmark [6]), TSR (Heidelberg, Germany [4]), TARN II (Tokyo, Japan [14]) and the newly constructed HIRFL-CSR (Lanzhou, China [19]).

Importantly, electrostatic elements are rarely used in these devices, and when they are 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. Using electrostatic elements clearly removes the problems associated with effects such as remanent fields and hysteresis in the magnets and the requirements for water cooling. Furthermore, magnets are expensive, big and heavy, but 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 needing to change the settings of the ion-optical elements. Another important advantage, especially related to the general direction of research in atomic and molecular physics, is that an electrostatic device can store heavy ions in low charge states, something 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 a large role in the experimental uncertainties [16]. Finally, also from a purely scientific perspective, the lack of magnetic fields also plays a
role in studied of 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], and through Zajfman and Schmidt and their co-workers through their developments of linear electrostatic ion traps for storage of fast ion beams [20, 12]. Since its construction, several other such devices have been built based on ELISA’s design, [15, 3], while construction on several larger electrostatic storage devices is also under way [18, 21, 10, 5, 2]. Two of these represent significant advances on ELISA since they will operate at cryogenic temperatures: the first, CSR, is under construction in Heidelberg, Germany, and has a design similar to the “traditional” magnetic storage rings listed earlier, especially it’s sister ring TSR which is located in the same laboratory [21]. The second, which is the facility presented in these proceedings, is under construction at Stockholm University, adds a unique twist to 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 [10, 5, 2]. 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 are fully open and the whole “storage volume” is enclosed in a double-walled vacuum vessel. This has many advantages from an 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 baseplate, 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.

2 Technical Design

The cryogenic environment, open construction, and the double ring structure all make DESIREE truly unique, though also a considerable technical challenge. In the following section, I will briefly discuss some of the technical highlights of DESIREE.

2.1 Rings and Injectors

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. Each of the rings has two 160° cylindrical bends and four 10° parallel-plate deflectors, where the two 10° deflectors located on either end of the merger section are common for each ring. This immediately means that only ions with opposite charge can be stored in the two rings at the same time. Figure 1 shows a technical schematic of the heart of the DESIREE facility. As can be seen in Fig. 1, the lower ring (ring 2) has a somewhat different layout compared to the upper ring (ring 1). Ring 2 can store ions with different energy or charge compared to the ring 1 and the bending angle will therefore differ from 10° in the two common deflectors. To compensate for this effect, and to make the ion beams collinear in the merging region, additional deflector plates are added to the second ring. Four quadrupole doublets, for focusing of the beams, and a few smaller deflectors for minor corrections of the beam position are located in each of the rings. Ion-injection into the two rings is achieved by rapid switching of the relevant 10° deflectors.

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 [16], 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. All of these ion sources are 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.

2.1.1 Mechanical Design

The two rings are housed in a common double-walled vacuum chamber, where the outer chamber is constructed of steel. The external dimensions of the outermost chamber are approximately 5.0 m x 2.0 m x 0.7 m. In order to stand the pressure difference the outer vessel is reinforced by an external framework of I-beams on all sides. The inner chamber, for technical reasons, is made from aluminium. All optical elements and detectors are mounted directly on the bottom of this chamber. The inner chamber is stand-off from the outer chamber via thin-walled stainless steel tubes. Separating the two vessels is a copper thermal screen and several layers of super insulation are placed between this screen and the outer chamber. All components, such as pumps, the cryogenerators, and the electrical feedthroughs are mounted on the bottom of the vessels. This facilitates access to the two vessels from the top. After initial baking and testing, DESIREE will normally be operated over a range of cryogenic temperatures.

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. These connections are made with
heavy-duty copper braids to give the best thermal conductivity and to isolate from vibrations. The total heat load on the thermal screen and the inner vessel is estimated to be 60 W and 3 W, respectively, where the main contribution to the heat load on the inner vessel is from blackbody radiation from the screen. If this low heat load can be realized, the final temperature of the inner vessel and the rings should be around 5 K. At cryogenic temperatures the inner vessel will be pumped by the cold walls of the chamber. It is expected that the main contribution to the background pressure will be H₂, which will be reduced by Ti sublimation pumps. After the initial baking at ≈ 400 K of the aluminium vessel, a pressure of 1×10⁻¹⁰ 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.

3 Test System

During the initial development of the project, it became quickly clear 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 was necessary to answer such fundamental issues as: the cryogenic properties of the detectors which will be used in DESIREE, and the vacuum and cryogenic properties of the different materials which will be used in its construction. In each of these cases, data often proved to hard to find or was even unknown. Furthermore, questions such as the optimum way to mount the cryogenerators, laser windows, as well as the operation of hitherto standard components such as vacuum gaskets, all needed to be investigated.

The test chamber constructed to address these issues was built as a cryostat with an inner and outer chamber and a copper screen in between, and figure 2 shows a schematic of the test chamber. This chamber then represents a copy of the DESIREE device, though certain differences are worth mentioning here. Although the inner chamber is still made from aluminium, the outer chamber is made from stainless steel. Furthermore, no super insulation is used in the test chamber. In order to minimize the heat conductance between the two vessels, the inner chamber rests only on three thin walled stainless steel tubes located at the bottom of the outer chamber. The test chamber is pumped with two turbo pumps, one for each chamber. Furthermore, the inner chamber can also be pumped by a Ti sublimation pump. The system is equipped with a residual gas analyzer (RGA) for analysis of the background gas.

All components which connect with the inner vessel, such as turbo pumps, pressure gauges, the RGA and all the electrical feedthroughs are mounted on the bottom of the outer vessel. The turbo pump and RGA are interfaced with the inner chamber via thin walled bellows with cooled baffles in order to minimize the heat load on the inner chamber. All flanges on the inner chamber are sealed with only Helicoflex gaskets while standard Viton o-rings are used on the outer chamber where the vacuum requirements are not that high. Cryogenic cooling is achieved by the same type of two-stage cryogenerator that will be used on DESIREE, with a specified cooling capacity of 35 W at 50 K on the first stage and 1.5 W at 4.2 K on the second stage. The first stage is connected to the copper screen and the second to the bottom of the aluminium vessel via a flexible copper braid.

In order to test the cooling, temperature sensors are mounted on the aluminium chamber and the screen. Prior to mounting the cryogenerator, tests were performed to verify its specified cooling power and to measure cooling power at temperatures where it is not specified. The results agreed with the those stated by the manufacturer. During these tests the aluminium chamber bottom reached 9 K while the second stage of the cryogenerator was at 4.5 K. From
the cooling power test it can be concluded that the total heat load on the aluminium chamber is 1.5 W. The somewhat higher temperature observed at the inner vessel is due to the limited thermal conductivity of the flexible copper braid.

As mentioned, 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 [11], 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 [12], was placed inside the inner vacuum chamber. A pulse of ions were 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, $\text{He}^- (1s2s2p \ {}^4P_{5/2})$, 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 2p electron by 300 K blackbody radiation photons emitted from the surrounding vacuum chamber. In performing this experiment in a suitable cryogenic environment, in practice under 80 K, this effect is eliminated. The results from these tests gave the most accurate measurement for the lifetime of these ions [9], as well as providing valuable information on the ion-beam storage lifetimes as a function of the residual gas pressure in the chamber [8].
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. The most unique feature is the merging region, and so I 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.

One of the most successful applications of CRYRING and other similar-sized heavy-ion storage rings over the last decades has been the investigation into reaction of molecular ions with a free electron [16]. Here we consider the mutual neutralisation between small molecular cations and anions, which is related to the molecular recombination in the following way. 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 recombination and cation/anion mutual neutralisation. One of the primary motivations for the studies at CRYRING of dissociative recombination for astrophysically abundant cations (e.g. H$_2^+$ (HD$^+$), H$_3^+$, OH$^+$, H$_3$O$^+$, CO$^+$, HCO$^+$, CH$_4^+$, CH$_3^+$, and CH$_5^+$ [16] 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. 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 mutual neutralisation in the ion chemistry is more important than dissociative recombination and the possibility offered by DESIREE to study these processes highly relevant to this field [13].

Current Status

The inner and outer vacuum chambers have been machined and fully assembled and are currently undergoing leak testing, including all of the feed-throughs and pumping/injection/optical ports. The copper screen has also been made as have all of the electrostatic/dynamic elements that will be located inside the main double walled chamber - these have also been electrically tested. The 25-keV 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 completion of the leak testing of the inner chamber, followed by testing the cryogenic cooling of the whole inner and outer chamber, with all elements in place, as well as a full electrical test.

References

[1] K. Abrahamsson, G. Andler, L. Bagge, E. Beebe, P. Carlé, H. Danared, S. Egnell, K. Ehrnstrén, M. Engström, C.J. Herrlander, J. Hilke, J. Jeansson, A. Källberg, S. Leontein, L. Liljeby, A. Nilsson, A. Paal, K.-G. Rensfelt, U. Rosengård, A. Simonsson, A. Soltan, J. Starker, M. af Ugglas, and A. Filevich. Cryring a synchrotron, cooler and storage ring. Nucl. Instrum. Methods Phys. Res., Sect. B, 79:269, 1993.

[2] H. Danared, L. Liljeby, G. Andler, L. Bagge, M. Blom, A. Källberg, S. Leontein, P. Löfgren, A. Paal, K.-G. Rensfelt, A. Simonsson, H. T. Schmidt, H. Cederquist, M. Larsson, S. Rosén,
and K. Schmidt. Desiree - a double electrostatic storage ring for merged-beam experiments. *AIP Conf. Proc.*, 821:465, 2006.

[3] S. Jinno, T. Takao, Y. Omata, A. Satou, H. Tanuma, T. Azuma, H. Shiromaru, K. Okuno, N. Kobayashi, and I. Watanabe. Tnu electrostatic ion storage ring designed for operation at liquid nitrogen temperature. *Nucl. Instr. Methods Phys. Res. A*, 532:477, 2004.

[4] D. Krämer, G. Bisoffi, M. Blum, A. Friedrich, Ch. Geyer, B. Holzer, H. W. Heyng, D. Habs, E. Jaeschke, M. Jung, W. Ott, R. E. Pollock, R. Repnow, F. Schmitt, and M. Steck. One year of operation at the heidelberg tsr. *Nucl. Instrum. Methods Phys. Res. A*, 287:268, 1989.

[5] P. Löfgren, G. Andler, L. Bagge, M. Blom, H. Danared, A. Källberg, S. Leontein, L. Liljeby, A. Paål, K.-G. Rensfelt, A. Simonsson, H. Cederquist, M. Larsson, S. Rosén, H. T. Schmidt, and K. Schmidt. Design of the double electrostatic storage ring, desiree. In *Proc. EPAC 2006*, page 252, 2006.

[6] S. P. Møller. Astrid-a storage ring for ions and electrons. In L. Lizama and J. Chew, editors, *Conference Record of the 1991 IEEE Particle Accelerator Conference*, page 2811. New York, IEEE, 1991.

[7] S. P. Møller. Elisa, an electrostatic storage ring for atomic physics. *Nucl. Instrum. Methods Phys. Res. A*, 394:281, 1997.

[8] P. Reinhed, A. Orbán, S. Rosén, R. D. Thomas, I. Kashperka, H. A. B. Johansson, D. Misra, A. Fardi, L. Brännholm, M. Björkhage, H. Cederquist, and H. T. Schmidt. Cryogenic kev ion-beam storage in conetrap - a tool for ion-temperature control. *Nucl. Instrum. Methods Phys. Res. A*, 621:83, 2010.

[9] P. Reinhed, A. Orbán, J. Werner, S. Rosén, R. D. Thomas, I. Kashperka, H. A. B. Johansson, D. Misra, L. Brännholm, M. Björkhage, H. Cederquist, and H. T. Schmidt. Precision lifetime measurements of he$^-$ in a cryogenic electrostatic ion-beam trap. *Phys. Rev. Lett.*, 103:213002, 2009.

[10] K.-G. Rensfelt, G. Andler, L. Bagge, M. Blom, H. Danared, A. Källberg, S. Leontein, L. Liljeby, P. Löfgren, A. Paål, A. Simonsson, Ö. Skeppstedt, H. T. Schmidt, H. Cederquist, M. Larsson, and K. Schmidt. Desiree - a double electrostatic storage ring. In *Proc. EPAC 2004*, page 1425, 2004.

[11] S. Rosén, H. T. Schmidt, P. Reinhed, D. Fischer, R. D. Thomas, H. Cederquist, L. Liljeby, L. Bagge, S. Leontein, and M. Blom. Operating a triple stack microchannel plate-phosphor assembly for single particle counting in the 12-300 k temperature range. *Rev. Sci. Instrum.*, 78:113301, 2007.

[12] H. T. Schmidt, H. Cederquist, J. Jensen, and A. Fardi. Conetrap: A compact electrostatic ion trap. *Nucl. Instrum. Methods Phys. Res. B*, 173:523, 2001.

[13] H. T. Schmidt, H. A. B. Johansson, R. D. Thomas, W. D. Geppert, N. Haag, P. Reinhed, S. Rosén, M. Larsson, H. Danared, K.-G. Rensfelt, L. Liljeby, L. Bagge, M. Björkhage, M. Blom, P. Löfgren, A. Källberg, A. Simonsson, A. Paål, H. Zettergren, and H. Cederquist. Desiree as a new tool for interstellar ion chemistry. *Int. J. Astrobiol.*, 7:205, 2008.
[14] T. Tanabe, K. Noda, T. Honma, M. Kodaira, K. Chida, T. Watanabe, A. Noda, S. Watanabe, A. Mizobuchi, M. Yoshizawa, T. Katayama, H. Muto, and A. Ando. Electron cooling experiments at ins. *Nucl. Instrum. Methods Phys. Res., Sect. A*, 307:7, 1991.

[15] T. Tanabe, K. Noda, M. Saito, S. Lee, Y. Ito, and H. Takagi. Resonant neutral-particle emission in collisions of electrons with peptide ions in a storage ring. *Phys. Rev. Lett.*, 90:193201, 2003.

[16] R. D. Thomas. When electrons meet molecular ions and what happens next: Dissociative recombination from interstellar clouds to internal combustion engines. *Mass. Spec. Rev.*, 27:485, 2008.

[17] T. Walcher. Experiments at the low-energy antiproton ring (lear). *Annual Review of Nuclear and Particle Science*, 38(1):67–95, 1988.

[18] C.P. Welsch, J. Ullrich, C. Gläßner, A. Schempp, R. Dörner, and H. Schmidt-Böcking. Fire-the frankfurt ion storage experiments. *Nucl. Instr. Methods Phys. Res. A*, 527:284, 2004.

[19] J. W. Xia, W. L. Zhan, B. W. Wei, Y. J. Yuan, M. T. Song, W. Z. Zhang, X. D. Yang, P. Yuan, D. Q. Gao, H. W. Zhao, X. T. Yang, G. Q. Xiao, K. T. Man, J. R. Dang, X. H. Cai, Y. F. Wang, J. Y. Tang, W. M. Qiao, Y. N. Rao, Y. He, L. Z. Mao, and Z. Z. Zhou. The heavy ion cooler-storage-ring project (hirfl-csr) at lanzhou. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 488:11, 2002.

[20] D. Zajfman, O. Heber, L. Vejby-Christensen, I. Ben-Itzhak, M. Rappaport, R. Fishman, and M. Dahan. Electrostatic bottle for long-time storage of fast ion beams. *Phys. Rev. A*, 55:R1577, 1997.

[21] D. Zajfman, A. Wolf, D. Schwalm, D. A. Orlov, M. Grieser, R. von Hahn, C. P. Welsch, J. R. Crespo Lopez-Urrutia, C. D. Schröter, X. Urbain, and J. Ullrich. The cryogenic storage ring project at heidelberg. *J. Phys.: Conf. Ser.*, 4:296, 2005.