Journal of Physics: Conference Series 185 (2009) 012013

# **Storage Modes in a Low Energy Charged Particle Storage Ring for Atomic and Molecular Experiments**

P Hammond<sup>1</sup>, T J Reddish<sup>2</sup>, A J Alderman<sup>1</sup>, D R Tessier<sup>2</sup> and F H Read<sup>3</sup>

<sup>1</sup> School of Physics, CAMSP, University of Western Australia, Perth WA6009, Australia

<sup>2</sup> Department of Physics, University of Windsor, Windsor N9B 3P4, Canada

<sup>3</sup> School of Physics & Astronomy, University of Manchester, Manchester M13 9PL, UK.

E-mail: hammond@physics.uwa.edu.au

Abstract. Specific storage modes have been identified and explored both experimentally and computationally for a new type of low energy charged particle storage ring for use in Atomic & Molecular Physics experiments [Tessier *et al*, *Phys. Rev. Lett.*, **99**, 253201, (2007)]. These modes offer the possibility of storing monoenergetic charged particle beams injected into the ring. Alternatively, some of the storage modes identified may be appropriate for energy filtering a stored charged particle beam within the ring. The ring is entirely electrostatic and has been shown experimentally to be capable of storing low energy electrons with storage lifetimes in the region 50 microseconds (~150 orbits) that are vacuum pressure limited. The ring is constructed from two 180° hemispherical deflector analyzers which are interconnected by two identical cylindrical lens stacks. Each lens stack is primarily controlled by 3 voltages. The storage modes observed occur at specific combinations of these voltages and are consistent with a multiple orbit charged particle optics model of the apparatus explored using both a matrix approach and trajectory integration in a 3 dimensional electrostatic model.

#### 1. Introduction

Historically charged particle storage rings have been achieved using magnetic lenses with the development goal to reach ever higher kinetic energies for the particles circulating in the ring as exemplified by cyclotrons, synchrotrons and tokomak's. Electrostatic storage systems have been a much later development and are typically used for low kinetic energy charged particles [1].

The design aim for the electrostatic charged particle storage system to be described here has been not only to achieve passive storage of charged particles, but also provide flexible setting of the kinetic energy and energy filtering of the stored beam to facilitate collision studies in atomic and molecular physics. Essential to achieving these aims is a charged particle optics model in which the predicted design performance closely matches the observed behaviour of the storage ring. This article briefly

The 8th Asian International Seminar on Atomic and Molecular Physics	IOP Publishing
Journal of Physics: Conference Series 185 (2009) 012013	doi:10.1088/1742-6596/185/1/012013

describes the progress made in developing and exploring the charged particle optics for an electrostatic storage ring which has already been demonstrated to achieve, when used for electrons, storage times in excess of 150  $\mu$ s [2].

## 2. Apparatus

The apparatus is shown schematically in figure 1. It consists of two electrostatic hemispherical deflector analysers (HDA's) interconnected by two identical cylindrical lens systems. In the present apparatus these consist of a field free region located midway between the HDA's and separated from the HDA's by a cylindrically symmetric three element lens. Electrons are introduced into the race-track shaped ring using an external pulsed electron beam injected through HDA 2 while the voltages of the analyzer hemispheres are both briefly held at voltage  $V_1$ . Lens 4 transfers the electrons into the source region held at a voltage  $V_3$ . During the ~200 ns time period taken by the clockwise traveling electrons to transit around the ring to reach the entrance of HDA 2, the voltages of HDA 2 are rapidly slewed to match the voltages of HDA 1 and allow electrons to return to Lens 4 and re-enter the source region. In the usage of the apparatus to be described here, the source and target regions are held at the same voltage  $V_2$ . The orbit length for a median electron trajectory around the complete storage ring is 0.64 m, with typical orbit times of ~330 ns for electron kinetic energies averaging 20 eV [2].

In the target region electrons in the stored beam are crossed with a gas jet aligned normal to the beam. A channel electron multiplier views the centre of the target region and detects scattered electrons. The yield of scattered electrons is recorded as a function of time from the electron injection pulse using a time to amplitude convertor with output pulse heights analysed using a computer based pulse height analyzer.



**Figure 1.** Schematic layout of the low-energy charged particle storage ring configured for electrons.

### 3. Charged Particle Optics

A charged particle trajectory from the source region passes through three optical components in the transit of one half-orbit of the ring to reach the target region. In the absence of aberrations, each of these components has a unique transfer matrix;  $m_1$  for Lens 1,  $m_h$  for HDA 1 and  $m_2$  for Lens 2 to give an overall source to target region transfer matrix of  $M_{st} = m_2 m_h m_1$ . In terms of characteristic lengths associated with thick lenses:

$$M_{st} = \frac{1}{f_1 f_2} \begin{pmatrix} f_1 f_2 - 2K_1 K_2 & 2K_1 (f_1 f_2 - K_1 K_2) \\ -2K_2 & f_1 f_2 - 2K_1 K_2 \end{pmatrix}$$
(1)

where  $K_1 = P - F_1$ ,  $K_2 = Q - F_2$  and focal lengths  $f_1$ ,  $f_2$  and mid-focal lengths  $F_1$ ,  $F_2$  of Lens 1. The position of the source and the entrance of HDA 1 with respect to the reference plane of Lens 1 are given by *P* and *Q* respectively and are not necessarily the positions of conjugate objects and images. In the specific spatial and voltage geometry under consideration here, the target region is held at the same voltage  $V_3$  as the source region, and the voltages on HDA 1 are the same as HDA 2, Hence in voltage terms Lens 2 is equivalent to Lens 1 but traversed in the opposite direction and the focal lengths of the two lenses are interrelated. This enables  $m_2$  to be expressed in terms of Lens 1 focal properties.

The transit from the target region back to the source region is, in terms of transfer optics, the same as that from source to target since Lens 3 is equivalent to Lens 1 and Lens 4 is equivalent to Lens 2. Hence  $M_{st}$  is the transfer matrix for each half orbit of the system.  $M_{st}$  can be viewed as a phase space rotation matrix which, for particular numbers of half-orbits H causes  $(M_{st})^H$  to rotate phase space through an angle  $\pi$  (in which case trajectories map onto the same trajectory coordinates after 2H half orbits) or through an angle  $2\pi$  (in which case the same coordinates are achieved after H half-orbits). This leads to a general expression for the relationship between focal and mid-focal lengths which needs to be satisfied to achieve stable orbits:

$$\frac{K_1 K_2}{f_1 f_2} = \sin^2 \left(\frac{m\pi}{2H}\right) \tag{2}$$

where *m* is an integer and 0 < m < H [3].

Specific focal and mid-focal lengths of three element electrostatic lenses are set by specific voltage ratios  $V_3/V_1$  and  $V_2/V_1$ . In the present apparatus the voltages  $V_1$  and  $V_3$  are selected to achieve particular pass energies in the HDA's and collision energy in the target region, respectively. It is therefore  $V_2$  which can be adjusted to vary the focal properties of the lenses to enable equation 2 to be satisfied for a particular m/H ratio. To test equation 2 we have used the parameterisation of focal lengths given by Harting and Read [4] to deduce the mapping from  $V_2$  to m/H for specific  $V_3/V_1$  values.



**Figure 2.** The trajectory coordinates (r, r') in the source and target regions for  $V_3/V_1 = 1$  and  $V_2$  voltages derived from the parameterised focal length data [4] and predicted to produce (H,m) modes (a) (2,1)  $V_2 = 92.2$  V (b) (3,1)  $V_2 = 80.1$  V (c) (4,1)  $V_2 = 74.3$  V

In figure 2 are shown the trajectory coordinates (r, r') in the source and target regions resulting from using the focal and mid-focal lengths in a matrix model for 120 half orbits at the  $V_2$  values predicted to achieve specific (H,m) modes in equation 2, namely (2,1), (3,1) and (4,1). When m is odd it is expected phase space will rotate through  $\pi$  after H half-orbits and result in 2H phase space "dots" as seen in figure 2. A trajectory integration model using CPO3D [5], in which the apparatus is modelled and which implicitly includes the effects of aberrations, reproduces figure 2 phase space diagrams using  $V_2$  voltages within 3% of those calculated to satisfy equation 2.

#### 4. Experimental Results and Discussion

Experimental results from the storage ring for  $V_3/V_1 = 1$  are shown in figure 3. The logarithmic yield of scattered electrons from the target region is plotted as a function of storage time and applied voltage  $V_2$  (recorded in 2 V increments). (*H*,*m*) modes of low *H* and m = 1 and 2 are marked on the figure at the predicted voltages from equation 2. Observed structures lie approximately 2 V above the predicted

values. Very little yield is observed for voltages above 100 V; the reasons for this are unclear. The observation of reduced storage time near the (5,2) mode may be indicative of instability arising from HDA aberrations for even-*m* modes. Some evidence for this behaviour has been observed in the trajectory integration modelling, and to a lesser extent in an aberration modified matrix model.



Figure 3. The yield of scattered electrons from the target region as a function of storage time and applied lens voltage  $V_2$  for  $V_3/V_1 = 1$ . The yield scale is logarithmic and a maximum at zero  $\mu$ s. The deduced (*H*,*m*) mode voltages from equation 2 using the parameterized focal length data [4] are indicated.

## 5. Conclusions

A transfer optics model of a 4 lens electrostatic storage ring for low energy charged particles has been developed. Specific lens voltage ranges are predicted to achieve storage. Excellent agreement is achieved between experimentally observed electron storage and the model developed. The experimental results and theoretical modeling suggest HDA aberrations cause instability in specific regions of lens voltage.

## Acknowledgements

Financial support from The Royal Society, The Australian Research Council and the Canadian Funds: CFI, OIT and NSERC are gratefully acknowledged.

## References

- [1] Andersen L H, Hebner O, Zajfman D 2004 J. Phys. B. 37 R57
- [2] Tessier D R, Niu Y, Seccombe D P, Reddish T J, Alderman A J, Birdsey B G, Read F H, and Hammond P 2007 *Phys. Rev. Lett.* **99** 253201
- [3] Hammond P, Reddish T J, Alderman A J, Tessier D R and Read F H in preparation
- [4] Harting E and Read F H 1976 *Electrostatic Lenses* Elsevier, Amsterdam
- [5] CPO Programs, available on the Web site <u>http://www.electronoptics.com/</u>