THE DEVELOPMENT OF AN ELECTROSTATIC CHARGED-PARTICLE ORBIT RECYCLING SYSTEM

D.R. Tessier[A], Y. Niu[A], D.P. Seccombe[A], T.J. Reddish[A], A.J. Alderman[B], B. Birdsey[B], P. Hammond[B] and F.H. Read[C]

[A] Department of Physics, University of Windsor, Windsor, Ontario N9B 3P4, Canada

[B] School of Physics, University of Western Australia, Crawley WA 6009, Australia

[C] School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK

Abstract

The progress in the development of a completely new type of electron spectrometer, an Electron Recycling System (ERS) is described, in which low energy electrons are passively stored in a desktop sized ring. The design of the system is likely to enable the storage of any type of charged particles, including positrons, polarized electrons, and positive & negative ions. Preliminary results will be presented which demonstrate electron storage with lifetimes ~ 9.3 μs corresponding to ~ 30 orbits. The orbital path for the electrons is 0.65 m long and defined through the application of design voltages to two series of cylindrical lenses inserted between two identical hemispherical deflector analysers. The ERS design concept exploits the very low scattering cross sections in electron-molecule collisions, where the majority of electrons do not interact with the target. Unscattered electrons are collected and passed back through the ERS for another collision opportunity in the interaction region - i.e. they are "recycled" so that each electron generated in the electron source may undertake multiple passes through the interaction region.

Keywords: storage ring, electrostatic trap, spectrometer, electron, positron, ions

Introduction

The trapping of charged particles in laboratory scale instruments has been primarily achieved in recirculating systems defined through magnetic fields, such as the fine beam tube now used in teaching laboratories for the measurement of *e/m* for electrons, through to cyclotron-type storage rings introduced by Lawrence in the late 1920's (Lawrence 1939). Storage rings based on electrostatic trapping have been far less explored. A recent development of such a ring is the ion storage ring ELISA (Møller 1997). Linear electrostatic traps, in which charged particles oscillate back and forth along the same path, have also been successfully introduced (Paul 1990, Dahan *et al* 1998).

The present system was originally intended as an electron storage ring of desktop size based on passive electrostatic orbit definition, but the design is applicable to any type of charged particle. The Electron Recycling System (ERS) was conceived as a high energy resolution electron source/spectrometer that was meant to overcome the delicate nature and low current yield of previous high energy resolution electron sources (Gopalan 2003). In typical scattering experiments, each electron in the source beam has a very low probability of scattering from the target of interest, meaning that a very small fraction of the low current in such sources has an opportunity to excite the process of interest. In the ERS, unscattered electrons are collected, passed around the ERS ring, and re-routed through the interaction region for more collision opportunities – they are literally recycled so that each electron stored in the ERS may pass through the interaction region many times and have many opportunities to scatter from the target.

For example, a single electron in a recycling orbit with an orbit time of ~300 ns and retained in the system for 1 s, would be equivalent to a "beam current" in the interaction region of ~0.5 pA. Hence 1000 recycling electrons stored in the ERS would be equivalent to ~0.5 nA – a typical current in a single pass electron spectrometer passing 3×10^9 electrons s^{-1}. The ratio of source strengths required for a recycling system in comparison to a single pass system is proportional to the number of recycling orbits that can be achieved, and hence the achievement of long storage times is crucial.

The first successfully stored beam in the prototype Electron Recycling System is reported in this article with a preliminary analysis of its performance.

Materials and Methods

The passive electrostatic orbit recycling system for electrons is shown schematically in figure 1. Consider electrons leaving the source towards the right in the figure. They are accelerated and focused by an electrostatic lens onto the entrance of a hemispherical deflector analyser. Here the electric field between the hemispheres bends

the trajectories of electrons with kinetic energy similar to the pass energy of the analyser around to the exit plane. Electrons leaving the analyser pass through a second electrostatic lens and are focused into the interaction region. For the initial tests no gas jet is present in the interaction region, and electrons pass through a third lens which focuses onto the entrance of the second hemispherical deflector analyser where again electron trajectories are bent onto the exit plane. A fourth lens refocuses the electrons back into the source region, from where the whole orbiting process is repeated. Although the geometrical configuration is "race-track" in shape, the potentials around the ERS vary such that it is better described as a "rollercoaster" from the perspective of electron energy. The apparatus is housed in an UHV vacuum system currently operating at a base pressure of 10^{-7} mbar. Magnetic fields are minimised using mu-metal shielding and Helmholtz coils to < 2 mGauss.

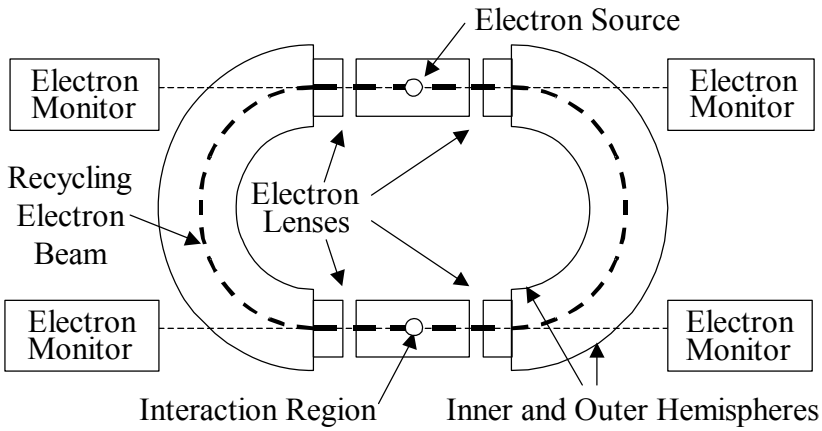

Figure 1. Schematic of the charged particle recycling system for electrons.

At present, electrons are injected into the ERS by scattering a high current, pulsed electron gun of temporal width ~150 ns from a 4 mm diameter wire loop in the source region as shown in figure 2. Low energy secondary electrons are produced on the wire loop and extracted by pulsing the voltage applied to both the wire loop and the surrounding cylinder synchronously with the pulsing of the incident electron beam. Following this pulse, all electrode elements in the source return to their normal voltages, producing a nominally field-free region in the source. If the source region was not modified in this way during the flight-time of the initial electron pulse, electrons on re-entrant trajectories would be forced to impact the ring on their return.

Scattered electron signal from the interaction region is detected using a particle counting channel electron multiplier (CEM). Timing spectra are recorded using a Time to Amplitude Converter (TAC) with start and stop signals provided by the CEM and the electron gun driving pulse.

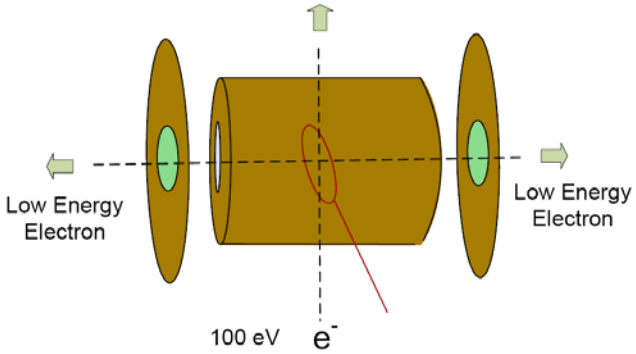

Figure 2. The pulsed, low-energy secondary electron source produced from ~100 eV electron impact on the tungsten wire loop.

The design of the charged particle optics has been achieved through the combined use of formal matrix representations of electron beam transport through the optical system and a three dimensional model of the ERS in the CPO3D simulation program (CPO3D). This software solves Laplace's equation using a charge density representation for electrodes from which trajectory integrations are performed. A number of advantages are achieved through this process. The matrix representation of the optics is rather "ideal" and for trajectories that may explore the voltage space many thousands of times this may not necessarily model "reality", due to the existence of higher order aberrations. Predictions from this matrix model were tested in the numerical model, which intrinsically includes aberrations in the optical performance of lenses and hemispherical deflector analysers. However the

tracing of many orbits in a numerical model is very time consuming and may also suffer from the build up of numerical calculation inaccuracies. It was for these reasons that both the matrix and numerical approaches were used in an interlinked manner, with the expectation that consistency between the approaches would accurately describe the prototype "real" ERS constructed to excellent mechanical tolerances.

Results and Discussion

The matrix approach to the design of the charged particle optics suggests passive stability can be achieved with a number of different voltage sets applied to the lenses. A simple example of this is shown in figure 3 where a voltage set for the optics to produce a particular charged particle storage mode are used in the CPO-3D numerical model to trace the trajectories for an orbit. In this example, 4 trajectories are launched from the source and tracked around the ERS. After one orbit, the returning trajectories produce an inverted image of the object in the source region. If the trajectories were tracked for a second orbit, the resulting image in the source region would map back onto the original object - a good representation of a stable orbit. Extensive simulations show that electrons with well specified ranges of initial momentum at the source can undergo stable recycling for an arbitrary length of time.

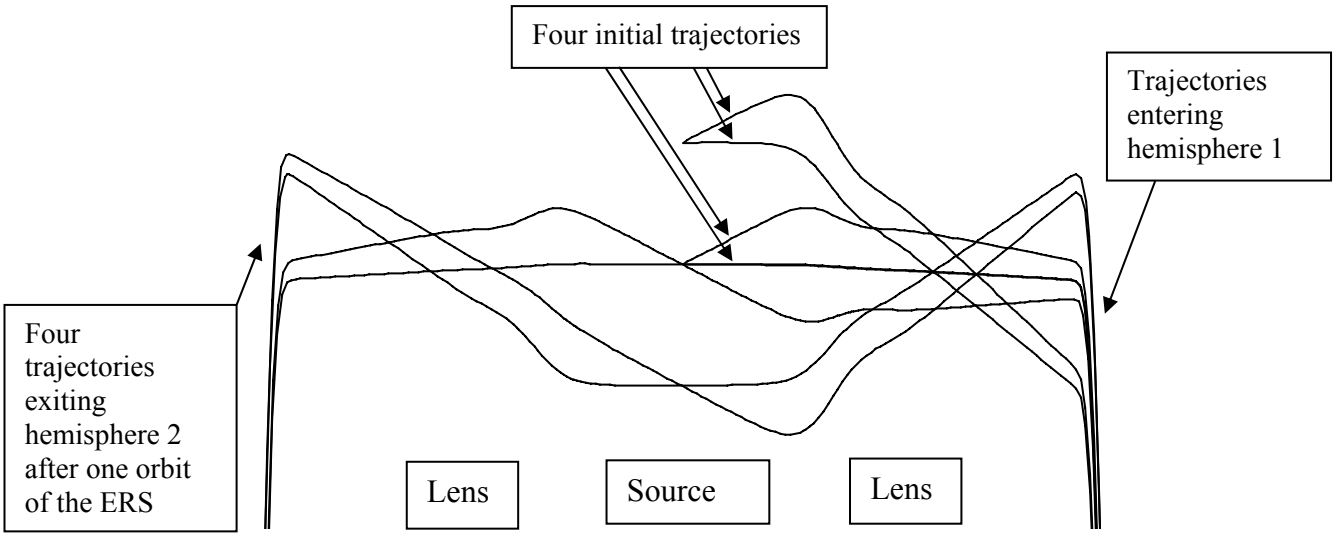

Figure 3. The focusing properties of the ERS for 4 paraxial trajectories in the source lens stack tracked over 1.3 orbits and showing an inverted image of the initial object after one orbit. The scale is magnified in the vertical direction.

The design optics for storage have been implemented in the prototype ERS. Tuning the spectrometer into storage is a complex and challenging process which primarily iterates the system into the matching of the actual pass energies of the two hemispherical analysers (rather than the matching of the applied voltages). This process requires the use of the 4 electron monitors shown in figure 1 with various combinations of the two hemispherical deflector analysers being set to passing or not-passing electrons.

A measurement of the electron scattering rate from the background gas and defining apertures in the interaction region as a function of elapsed time from the injection pulse is presented in figure 4 and demonstrates the achievement of passive electron storage. The peak at ~0.3μs represents the electron pulse from the wire loop traversing half an orbit. Subsequent peaks in yield are separated by one orbit and the recycling passage of the electron pulse can be tracked out to greater than 18 μs flight time, corresponding to ~38m flight distance.

Preliminary analysis of the signal profile shown in figure 4 indicates an orbit time of ~310 ns around the orbit of length 0.65 m. The source and interaction region voltages are ~10 V and the nominal pass energy of the two hemispherical deflection analysers was 10 eV. Two lifetime components can be discerned in the decrease of the peak amplitude as a function storage time. In approximately the first 5 orbits the storage lifetime is ~190 ns whereas longer term storage has a lifetime of ~9.3 μs. The experimental results also show a distinct variation in the full width at half maximum of the peaks as a function of orbit time as shown in figure 5. There is a decrease in the width of the peaks over approximately the first five orbits with the minimum width reached being ~37 ns. Following this the peak widths increase in an approximately linear manner.

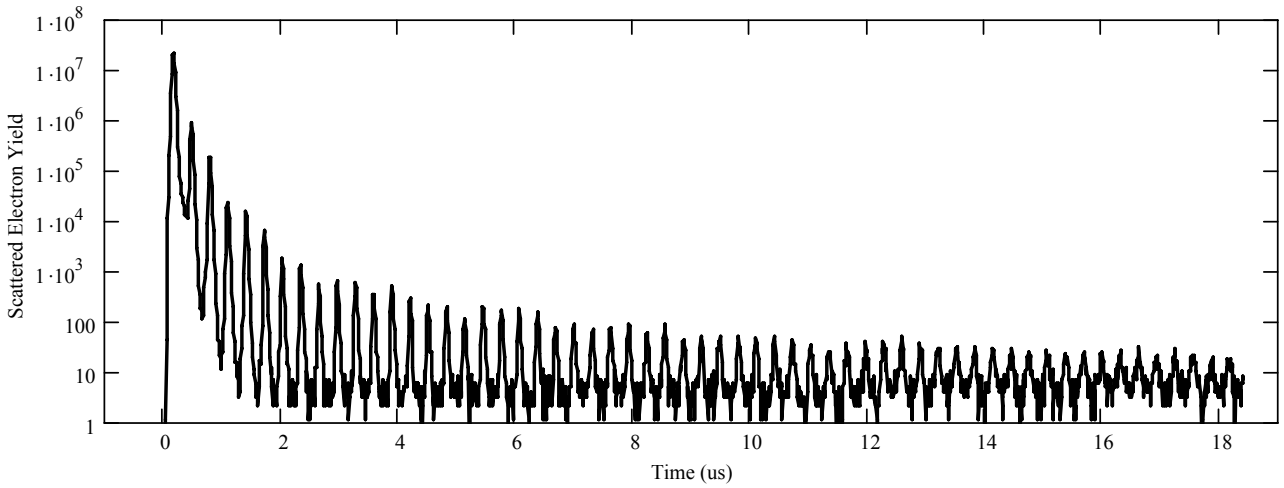

Figure 4. The scattered electron signal from the background gas and defining apertures in the interaction region. The peak at ~0.3 μs represents one half of an orbit. Subsequent peaks in yield are separated by one orbit.

Further numerical modeling of the ERS is being undertaken to explore the experimental observations. Preliminary results from this modeling suggest that the observed amplitude decrease in the first 5 orbits is much more rapid than expected and that the experimental widths are considerably narrower, and more slowly increasing in width with storage time than expected.

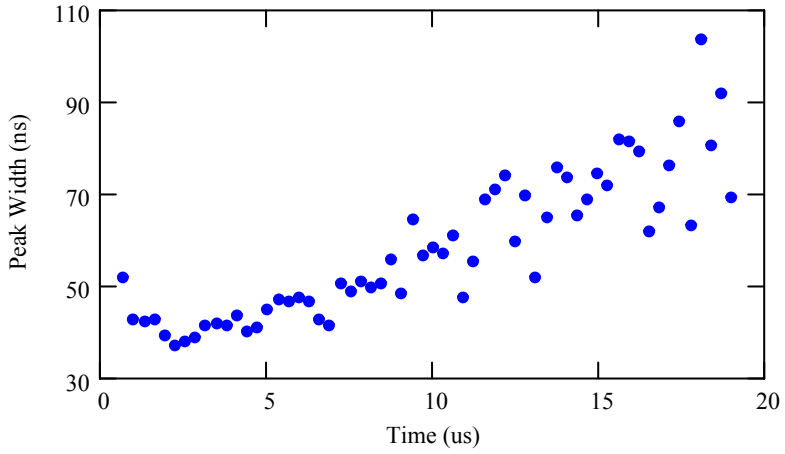

Figure 5. The widths (FWHM) of the stored electron signal as a function of storage time.

Conclusion

The storage of electrons in a passive electrostatic desk top sized ring has been demonstrated with a storage lifetime of ~9.3 μs.

Acknowledgements

Financial support from The Paul Instrument Fund of the UK Royal Society, the Australian Research Council Linkage Infrastructure Fund (LE0238631) and the Canadian funding agencies CFI, OIT and NSERC.

References

CPO3D programs, available from www.electronoptics.com
Dahen M. *et al* (1998) *Rev. Sci. Instrum.* **69**, 76-83
Gopalan A. *et al* (2003) *Eur.Phys.J.D* **22**, 17-29
Paul W. (1990), *Reviews of Modern Physics* **62**, 3
Lawrence E.O. (1939) *Nobel Prize Lectures*, http://nobelprize.org/physics/laureates/1939/index.html
Møller S.P.(1997), *Nucl. Inst. Meth. A* **394**, 281