Nuclear Instruments and Methods in Physics Research A 736 (2014) 118–123

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Evidences for isochronous behavior in electron and ion storage for a low energy electrostatic storage ring

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ARTICLE INFO

Article history:
Received 14 May 2013
Received in revised form
1 October 2013
Accepted 24 October 2013
Available online 29 October 2013

Keywords:
Isochronous
Storage ring
Electrostatic
Mass spectrometry

ABSTRACT

The temporal width of a stored bunch of low energy (~30 eV) electrons circulating in desk-top sized passive electrostatic storage ring has been observed to be unchanging with orbit number. The storage ring has been operated with a range of asymmetric voltages for both stored electron and ion bunches with a particular focus on controllably probing the edges of stable storage regions to explore variations in the temporal widths as a function of storage time. For electron storage an operating condition is identified in which the temporal width approaches a constant value after a period of increase – isochronous behavior. Measurements using stored ions indicate similar behavior can be achieved. Possible mechanisms for the observed behavior are discussed.

1. Introduction

Electrostatic Storage Devices (ESDs) continue to be developed in order to confine charged particles for a multitude of purposes within the atomic and molecular physics community [1]. In contrast to localized atom, ion, and molecular traps, charged particles can be confined in an ESD by forcing them to either oscillate along a linear path [2,3] or to traverse a closed loop within a storage ring [4–6]. Long-term stable storage of charged particles is a highly desirable feature in either geometry. Even more sought-after for pulsed injection devices is stable storage that minimizes losses and the spreading, in either time or energy, of the stored particle 'bunch'. Identification of operating potentials for an ESD that enables such storage requires the behavior of stored particles within the ESD be well characterized [7,8]. Stored bunches of particles can be characterized using a variety of related parameters that include: energy width, temporal width, spatial width and current density. These characteristics depend both on the properties of the charged particle source, the initial injection conditions and the evolution of the bunch in time and energy as it performs multiple, passes through the components of the storage device. In this work the bunch temporal width evolution is examined as a function of storage time for both stored electrons or ions within a passive desk-top sized (circumference of 65 cm) electrostatic storage ring for low energy particles (<30 eV) [5]. In particular, we explore how this behavior changes if the voltage configuration of the system is altered. The storage ring can be tuned so that the bunch width is independent of orbit number. Identification of this mode of operation is particularly advantageous if the system is to be used as a mass spectrometer [9–11].

2. Experimental setup

A low energy race-track shaped electrostatic storage ring capable of storing charged particles has been designed, built and tested using electrons [5]. This 'Electron Recycling Spectrometer' (ERS) is composed of two 180° hemispherical deflector analyzers (HDAs) connected by two mechanically identical cylindrical lens stacks as illustrated schematically in Fig. 1. Each lens stack consists of two 3-element lenses separated by a field free region. In the experiments described here the field free regions are held at the same voltage. Thus one lens is before the entrance and one after the exit of each HDA and used to accelerate/decelerate and control the trajectory of the charged particles [8]. When used to store electrons the base pressure is $\sim 2\times10^{-7}$ mbar and for ions is $\sim 2\times10^{-6}$ mbar. The ring is designed to store charged particles at energies <30 eV. With appropriate voltage supplies the ring could be used at higher energies, though the current optical design may restrict the upper limit if energy dispersion in at least one of the HDAs is required.

Long term electron storage of the form shown in Fig. 2 has been observed using a range of different lens and HDA potentials. For a given voltage applied to the field-free regions in the central sections of the two lens stacks, and pass energies E_{HDA1} and E_{HDA2},

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http://dx.doi.org/10.1016/j.nima.2013.10.059

storage is established by varying the potentials of the middle lens element in the four 3-element lenses. These voltages are varied in pairs, with the middle element voltages of the lenses closest to HDA 1 and HDA 2 being $V_{2,1}$ and $V_{2,2}$, respectively. In normal operation for electron storage, an ~35 ns wide (FWHM) bunch is injected into the ring through HDA 1 after it has been pulsed 'off' to create a field free region. Once the injected bunch has entered HDA 2, HDA 1 is pulsed back 'on' so allowing electrons to orbit the ring multiple times. For detection of the stored particles, the bunch is extracted through the opposite side of HDA 1 by sending a second 'off' pulse at a user-defined delay. The bunch then exits the ring and is detected by a channel electron multiplier (CEM) located along the optical axis of the lens stack beneath HDA 1. The bunch of stored electrons is then viewed every orbit by sequentially changing the delay between the injection and detection pulses applied to HDA 1. Each peak shown in Fig. 2 represents the accumulation of the number of detected electrons over $\sim 4 \times 10^5$ injection cycles. By computationally increasing the delay, the peaks are probed in succession until a complete spectrum is generated (*See on-line animation*, Video S1).

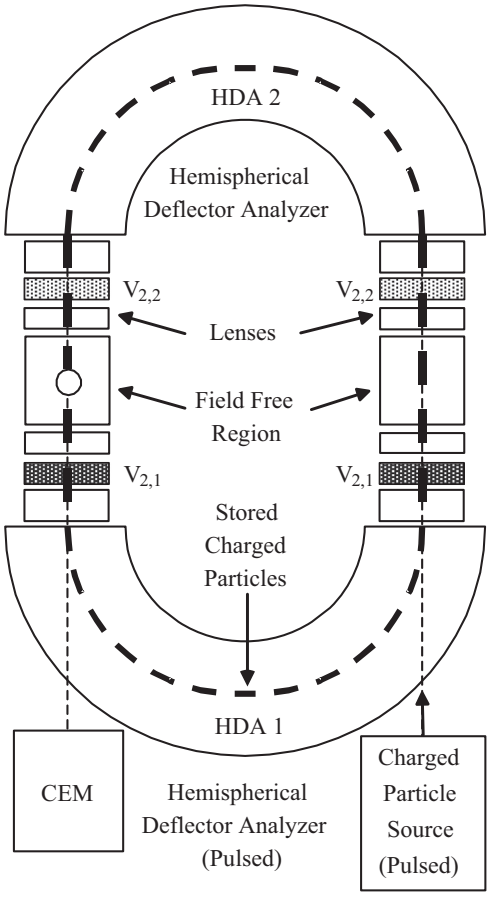

Fig. 1. A schematic diagram of the storage ring layout. The $V_{2,i}$ lens elements are varied over a range of potentials to locate and explore regions of stable storage.

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.nima.2013.10.059.

The temporal width of the electron bunch, as a function of orbit number, is determined by a Gaussian least squares fit to each peak. The bunch width typically broadens over time due to (a) the initial energy spread in the injected bunch and (b) the different electron paths taken around the ring. No evidence of space charge effects within the bunch, which could result in change in pulse width, has been observed within the ERS. All data presented in this study have been recorded using asymmetric operating conditions in which the pass energy E_{HDA1} was significantly larger than E_{HDA2}. In this way HDA 1 acts more like a mirror and HDA 2 as an energy dispersive prism. The voltages of the middle lens element $V_{2,i}$ in the 3-element lenses before the entrance and exit of each HDA, respectively, were set to the same value. Therefore the changes in operating conditions could be defined by changes in the *pairs* of $V_{2,i}$ voltages associated with each HDA. To examine regions of storage in the system, time spectra of the type shown in Fig. 2 are measured as a function of the $V_{2,i}$ potentials. Using these spectra, contour plots can be created that display stored yield as a function of both time and $V_{2,i}$ potentials to reveal regions of stable storage. Use of this type of contour plot is discussed in Sections 3.2 and 3.3.

3. Results & discussion

3.1. Isochronous electron storage

Storage time and bunch temporal width variations are observed to occur as a function of the $V_{2,1}$ and $V_{2,2}$ potentials. Fig. 3 shows the two distinctly different behaviors for two different $V_{2,1}$ lens potentials for the same $V_{2,2}$ potential. Typically for the most stable storage conditions (i.e. the minimum long term losses), the peak width steadily increases with storage time, as in Fig. 3 curve (a). As identified by Zajfman and collaborators [7], the peak width variation in the *dispersive* mode is described by

$$W_n = \sqrt{W_o^2 + n^2 \Delta T^2} \tag{1}$$

where W_n is the peak width at the n^{th} orbit, W_o is the initial peak width and is a property of the source, and ΔT is the time spread per orbit.

We have found that the rate of peak width change decreases dramatically when the $V_{2,1}$ potential is slightly (≤ 1 V, or ~2% of $V_{2,1}$) de-tuned from that with the highest count rate, as shown in Fig. 3 curve (b). The peak widths become essentially constant

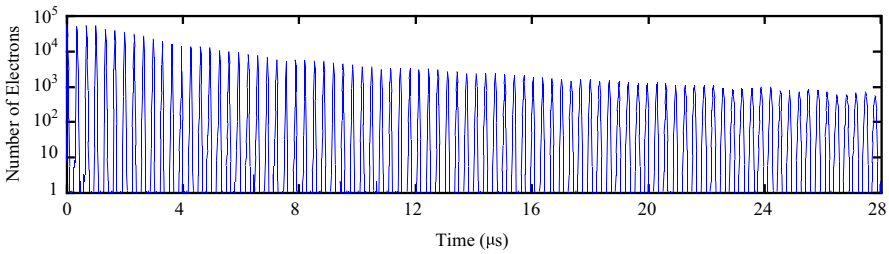

Fig. 2. Typical spectrum showing the integrated number of electrons detected as a function of storage time for $\sim 4 \times 10^5$ injection cycles/peak with asymmetric operating conditions (i.e. $E_{HDA1} = 18$ eV and $E_{HDA2} = 6$ eV). The storage time on the *x*-axis is referenced from the detection time of the center of the first measured peak, not from the injection pulse, and the *y*-axis is a log scale of electron yield. The decay in peak height is due to inevitable loss mechanisms, with the main limiting factor being residual gas scattering.