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Chaos of Energetic Positron Orbit in a Dipole Magnetic Field Configuration

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In a Hamiltonian system of n degrees of freedom, the system is integrable when it has (n-1) first integrals (independent conserved quantities) in addition to the Hamiltonian. An integrable system implies non-chaotic periodic orbit in the phase space. In a dipole magnetic field, a charged particle may have three adiabatic invariants as actions for associated periodic motions. They are magnetic moment μ for gyromotion, longitudinal invariant J for vertical bounce motion, and magnetic flux Φ for toroidal precession motion, in the order of time scales. Here the toroidal drift of a particle is realized by the curvature and grad-B drift in the dipole field. When these adiabatic invariants are well conserved, particle motion in the dipole field is integrable and periodic. This is of course not always the case especially in a real system. When magnetized particles feel slow fluctuation, for example, the conservation of Φ is easily destroyed. In a strongly inhomogeneous dipole magnetic field, such slow fluctuation is a driving force to generate the so-called up-hill diffusion, which is a widely observed important self-organization mechanism of plasmas in planetary and artificial magnetospheres [1,2].

Another example of the breakdown of adiabatic invariants in a dipole field is found for high-energy charged particles even without applying fluctuating or stochastic fields [3]. In this study, we investigate the chaotic orbit of high-energy positrons emitted from a ^{22}Na isotope source in the geometry of RT-1 [4], a superconducting levitated dipole experiment [1,2]. Because the β+ decay emits electron neutrinos in addition to positrons, positrons from isotopes have broad energy spectrum. When a particle has a large enough kinetic energy so that its gyroradius is comparable to the mirror bounce length, there is a coupling between the gyro and bounce motions. This means that it is difficult to separate these two motions in the particle orbit. In this case, both μ and J are no longer conserved, while their temporal evolution shows strong correlation. Because the canonical angular momentum, which agrees with Φ in the limit of strong magnetization, is the only first integral in addition to the Hamiltonian, this system is non-integrable. High energy positrons supplied from a radioisotope source in a dipole field are thus expected to exhibit chaotic long trajectories in the trapping geometry. Experimentally, such chaotic long orbit of positrons is attractive because it is potentially applicable to novel injection and trapping schemes of charged particles in a toroidal geometry [5,6].

We consider a ^{22}Na source placed at the edge confinement region of RT-1. The energy spectrum of positrons from ^{22}Na has a peak at approximately 200 keV with an end point maximum energy of 543 keV. With this kinetic energy range and the parameters of RT-1, considerable ratio of emitted positrons shows meandering motion caused by the coupling of the gyro and bounce motions. In the present geometry, kinetic energy of approximately 10 keV is a threshold value needed for a positron to have chaotic orbit. In addition to the kinetic energy, pitch angle of the particle in the magnetic field is an important parameter to decide the temporal evolution of μ and J. There is a tendency that conservation of μ and J is easily destroyed for particles with smaller pitch angles. This is because such particles feel stronger inhomogeneousity of the dipole field due to the longer mirror reflection path. Including these effects, more than 40% of positrons emitted from a ^{22}Na source exhibit chaotic motions in the dipole field configuration of RT-1. Figure 1 shows the Poincaré map of a 20keV positron in RT-1 injected with different pitch angles. While plots are on continuous lines for large pitch angle cases which indicate periodic motions, such torus structures are destroyed by decreasing the pitch angle, emerging the chaotic motions for smaller pitch angles. Orbit analysis including the effects of finite source size showed that these positrons have long orbit before the recombination after returning to the source. When the orbit is periodic, on the other hand, positrons return to the source and are lost after making just few periodic motions in a short time. In order to evaluate the validity of the chaotic orbit analysis, we conducted positron injection experiments at RT-1 with a small (1 MBq) ^{22}Na source using a coincidence measurement technique for 511 keV annihilation γ-rays. Measurements of the radial profile of the γ-ray count showed good agreement with the calculation results. Combination of the chaotic properties and application of the so-called rotating wall (RW) type electric field realizes efficient inward transport of positrons in the dipole field configuration.

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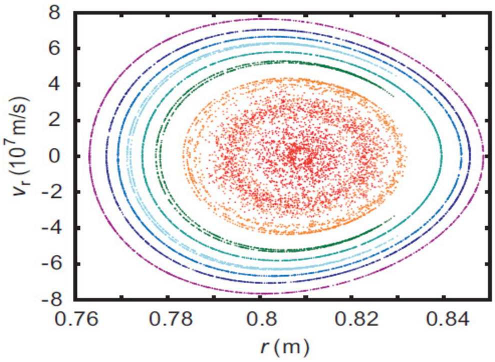

Fig.1 Poincaré map for the orbit of 10keV positrons flying in the dipole field of the RT-1 experiment for different injection pitch angles.