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Chaos of energetic positron orbit in a dipole magnetic field configuration

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Conservation and violation of adiabatic invariants for particles in dipole magnetic field, the case of high-energy e+

- Particle orbit in a dipole field basically consists of three periodic motions, making three adiabatic invariants as actions

- Adiabatic invariants are not always const.

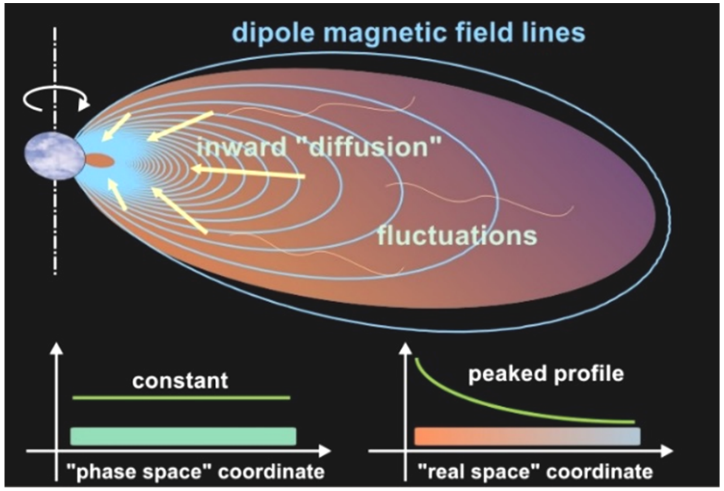
  ex) slow fluctuations break Ψ conservation, while conserving μ and J, causing radial transport and acceleration of particles

- Collective behavior of particles under such constraint makes macroscopic self-organization of plasmas

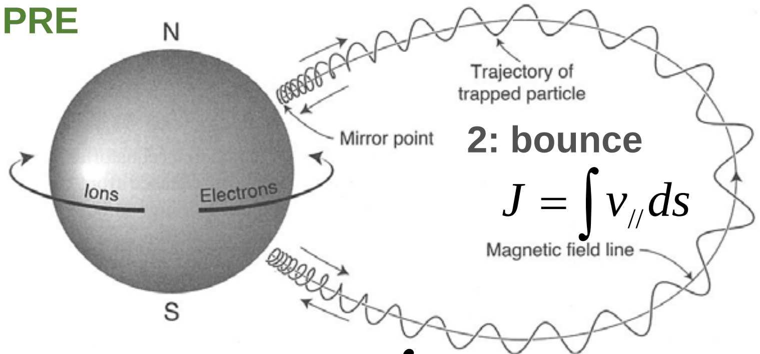
  2015 Yoshida Mahajan, Prog. Theor. Exp. Phys.
  2019 Nishiura+ NF, 2015 Kawazura+ PoP, 2017 Sato+ PRE

- Breakdown of adiabaticity and orbit chaos appear even without fluctuations or asymmetry of the system:

  High-energy positrons in dipole field



1: gyration $\mu = v_\perp^2 / B$



2: bounce $J = \int v_{//} ds$

3: toroidal drift $\Phi = \int BdS \sim P_\theta$

Non-linear term in *H* of e+, due to coupling between motion modes, violates the adiabaticity, making system non-integrable

- When the three adiabatic invariants are conserved, the Hamiltonian is

$$H = \mu\omega_c + J\omega_b + \Psi\omega_d$$

$\omega_c, \omega_b, \omega_d$:
gyro, bounce, drift frequencies

- According to Arnold-Liouville theorem, this system is integrable, particles are trapped on periodic orbits in a dipole field

Number of first integral (independent conserved quantity) > degree of freedom

- Non-linear term violates the adiabaticity of μ, J, and Ψ, through the effects of fluctuations, asymmetry, orbit mode coupling, etc.

$$H = \mu\omega_c + J\omega_b + \Psi\omega_d + \boxed{N_c}$$

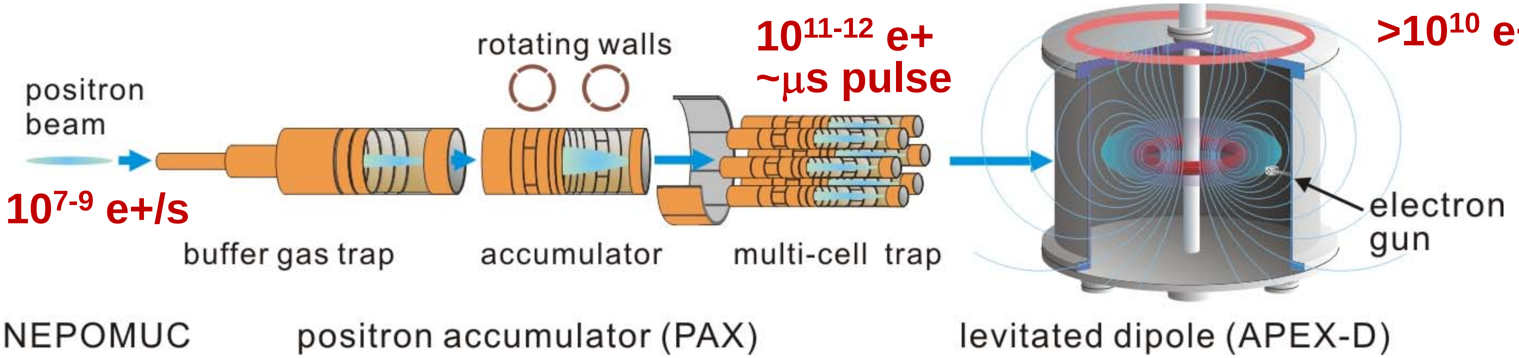
1990 Murakami, Sato, Hasegawa, PoF

- For high energy positrons, gyro and bounce motions easily couple, which means there are only two constants of motion, *H* and $P_\theta \sim \Psi$ (axisymmetry)

→ **We numerically and experimentally investigate the chaotic behavior of positrons from Na-22 isotope in a dipole field**

Chaotic motion of high-energy positrons is also applicable to scientific application: electron-positron plasmas

- APEX collaboration plans to create and study electron-positron plasmas

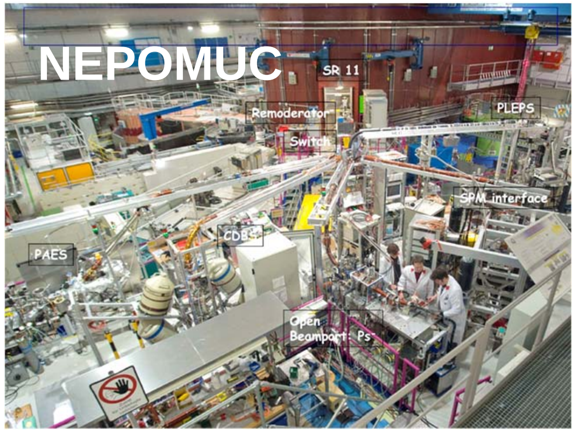


unique wave/stability properties as pair-plasmas

2012 Pedersen+, New J. Phys.
2015 Saitoh+ New J. Phys.

- Available positron beam is not very strong; efficient injection are essentially important

- Use of chaotic long orbit of high-energy positrons, together with intense Na-22 source can be alternative method



Chaotic long orbit of positrons is attractive

2002 Nakashima+ PRE

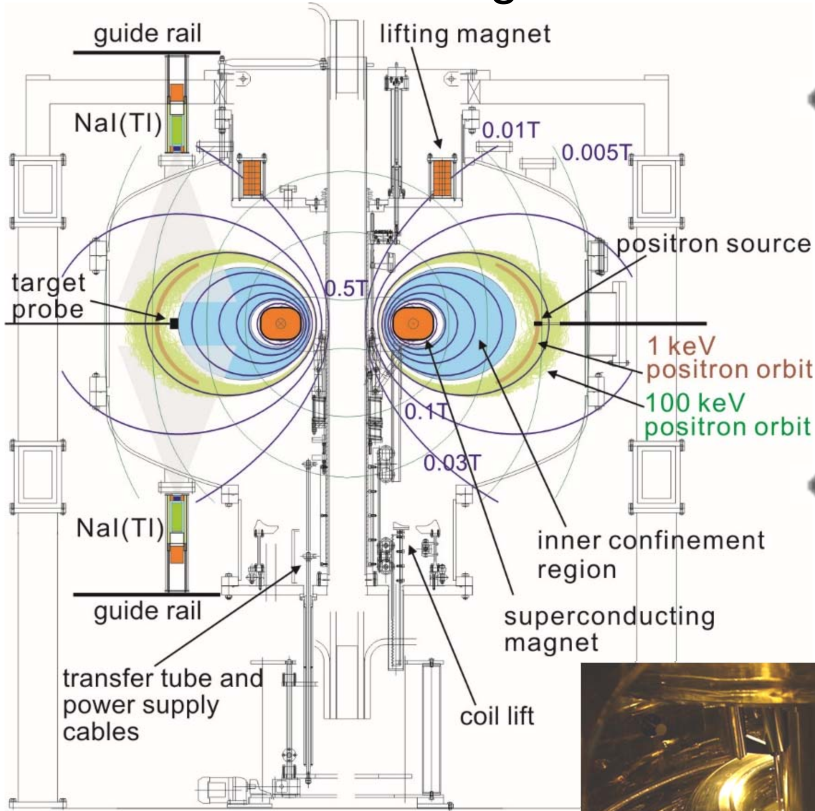
Reactor (FRM-II) based e+ source

2012 Hugenschmidt+, New J. Phys.

Orbit and adiabatic invariant properties of positrons are investigated in the dipole configuration of RT1

- Positrons are injected from a Na-22 source located at the edge of the confinement region of RT1

2016 Saitoh+, PRE



RT1 (Ring Trap 1), super-conducting levitated dipole of Uni. Tokyo, Japan

2006 Yoshida+ PFR, 2010 Yoshida+ PRL

- In a dipole field generated by a ring current of 250kA (R=0.25m), orbit is calculated by numerically integrating

$$\frac{d}{dt}(\gamma m \mathbf{v}) = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

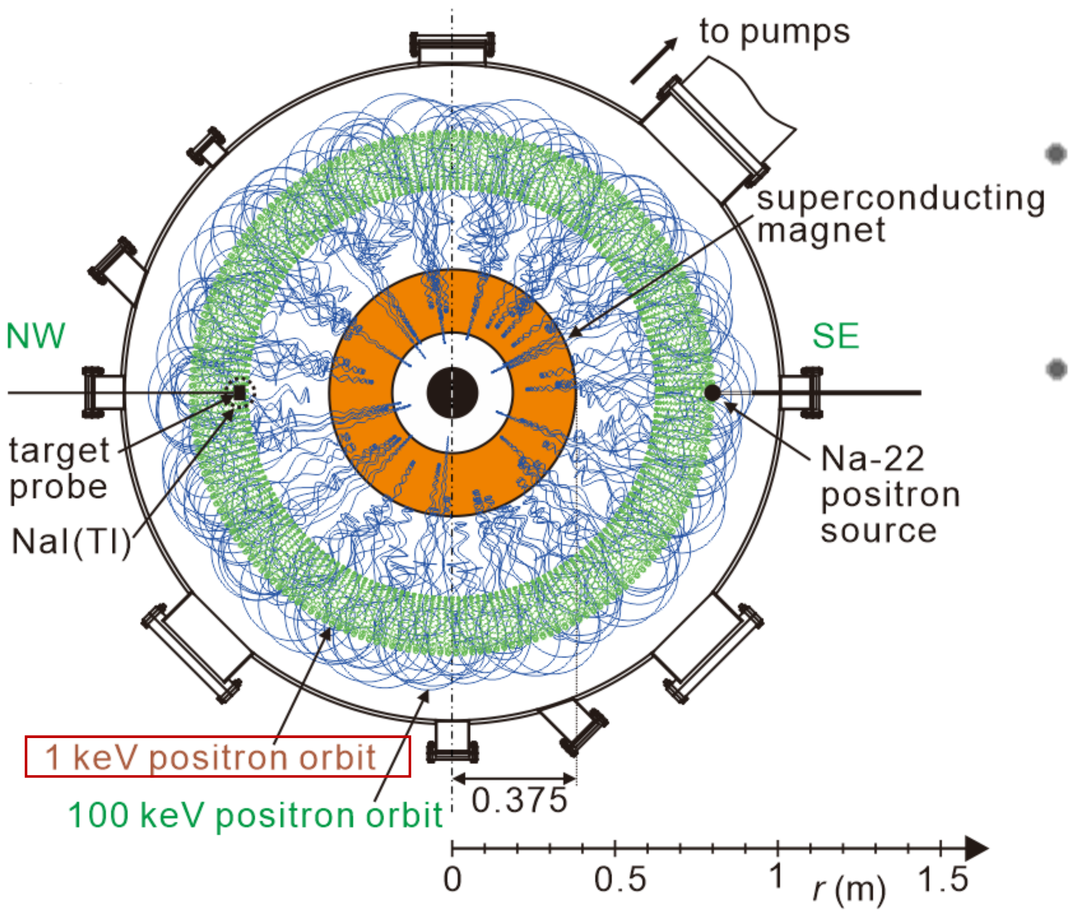
- Relativistic adiabatic invariants:

$$\mu = \int \gamma v_\perp dl = \int \frac{\gamma^2 v_\perp^2}{B} dt$$

$$J = \int \gamma v_\parallel ds$$

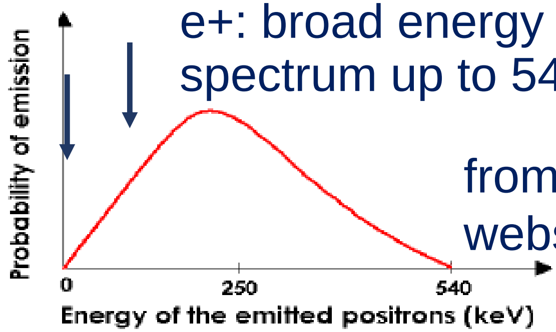
$$\Psi = \int \mathbf{B} \cdot d\mathbf{S}$$

Regular (low energy) and non-regular (high energy) orbits according to kinetic energy of e+



Top view of RT1, including typical orbits of positrons injected from Na-22 source

- Particle motion consists of gyro + bounce + toroidal drift
- Toroidal motion is realized by the curvature and grad-B drift
- Orbit properties are different according to particle energy
  - 1keV: periodic, return to Na-22 source after one circulation
  - 100keV: non-periodic motion

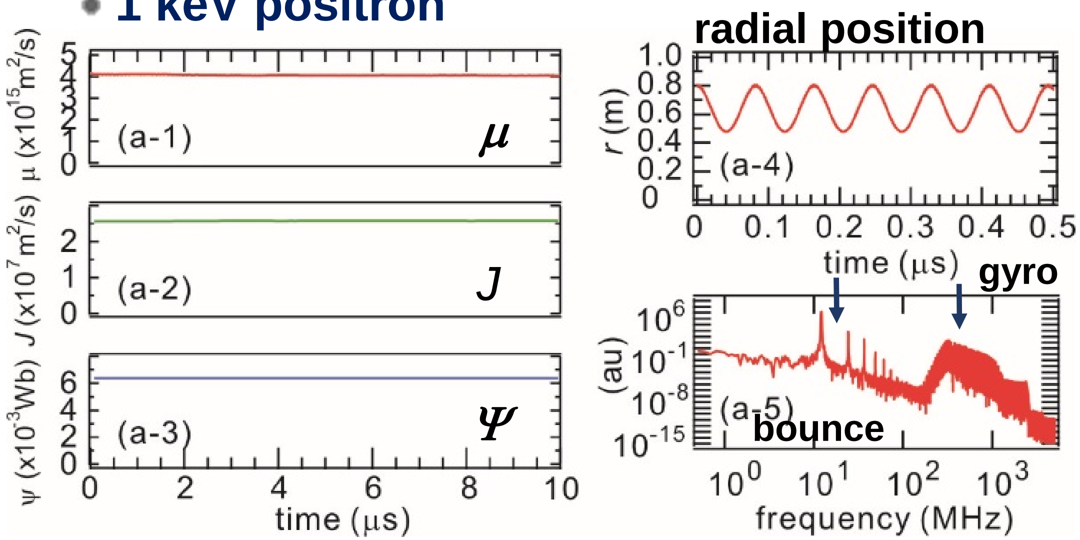


e+: broad energy spectrum up to 543 keV

from: ETHZ website

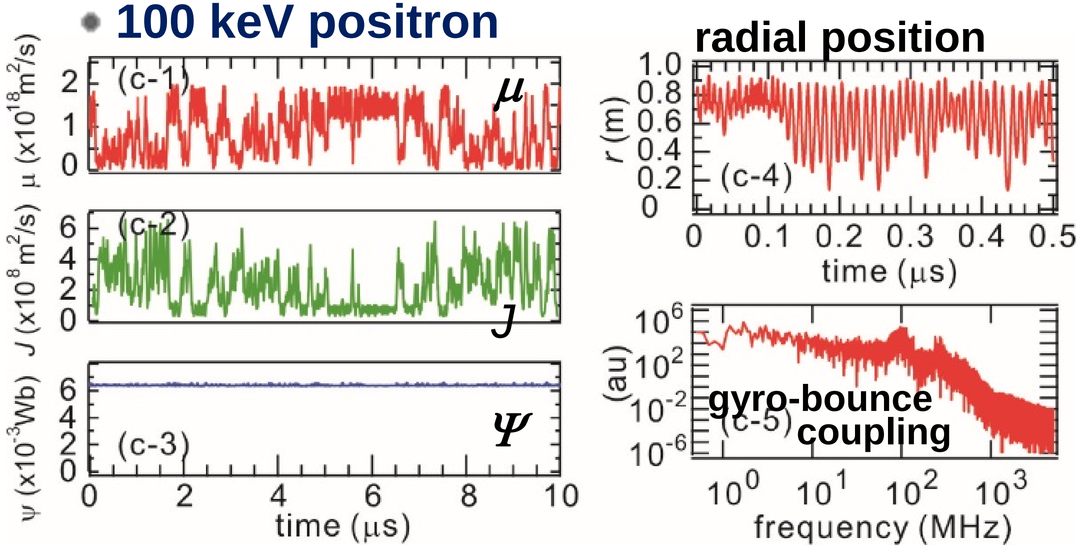
Mode coupling between gyro and bounce motions breaks The conservation of μ and J, making chaotic behavior

- **1 keV positron**



- μ and J are conserved for 1 keV positron
- motion is periodic
- gyro and bounce motions are separated

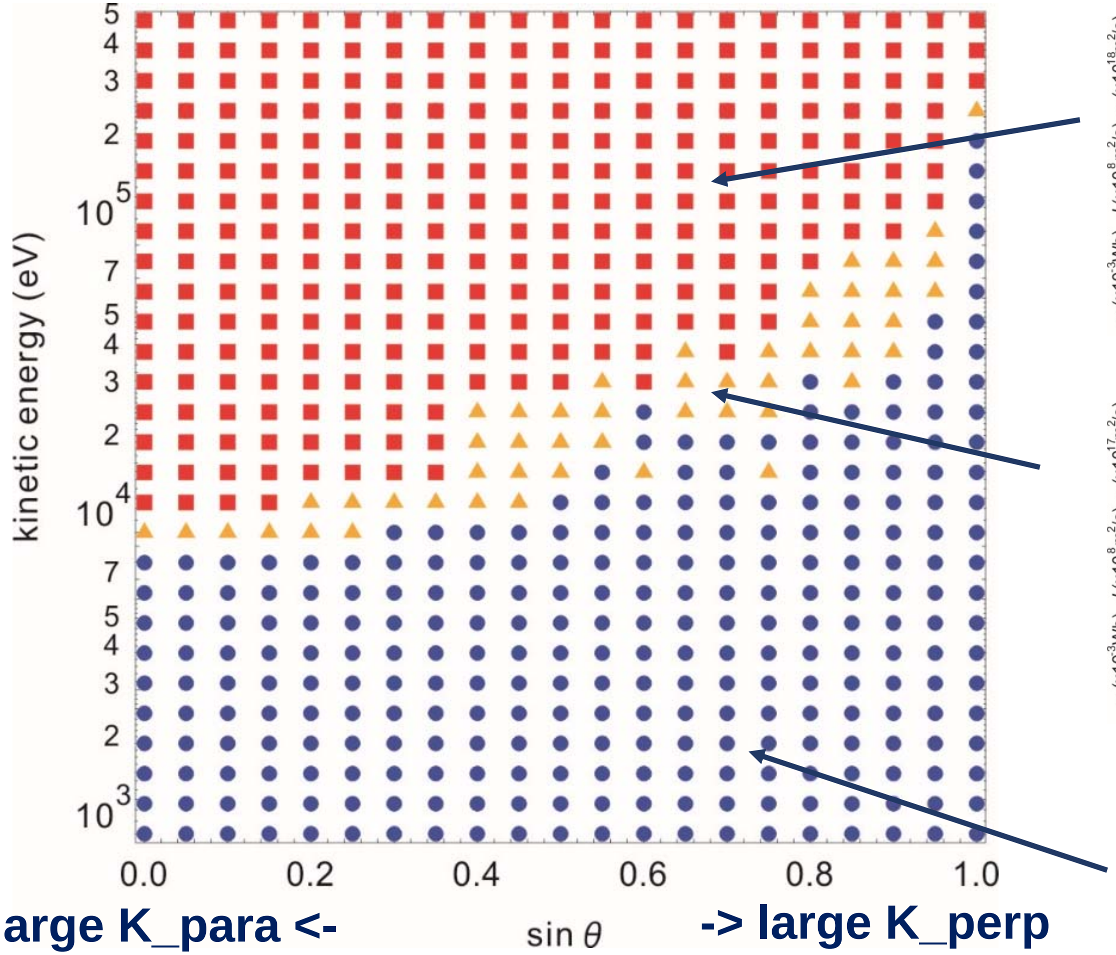
- **100 keV positron**



- μ and J are not conserved for 100 keV positron
- motion is non-periodic
- gyro and bounce motions are overlapped

Ψ is always conserved due to the asymmetry

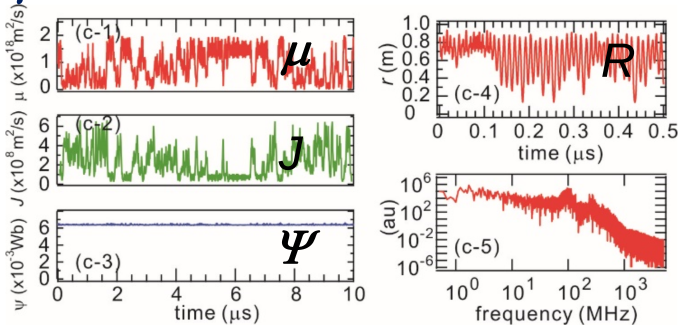
Conservation map for μ and J shows dependence on both kinetic energy and pitch angle of particle



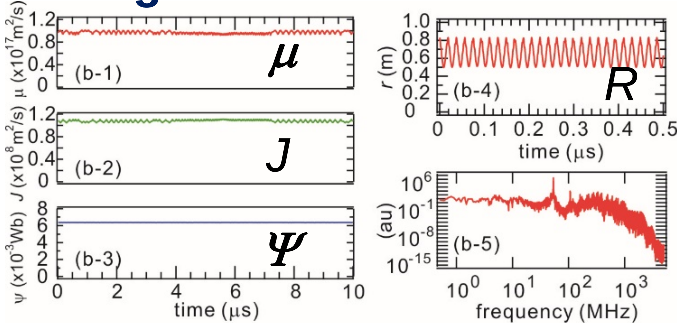
large K_para <- **-> large K_perp**

Conservation map of μ and J for different particle energy and pitch angle

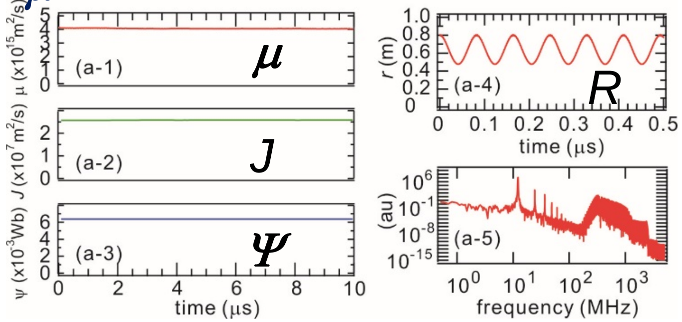
μ and J are NOT conserved



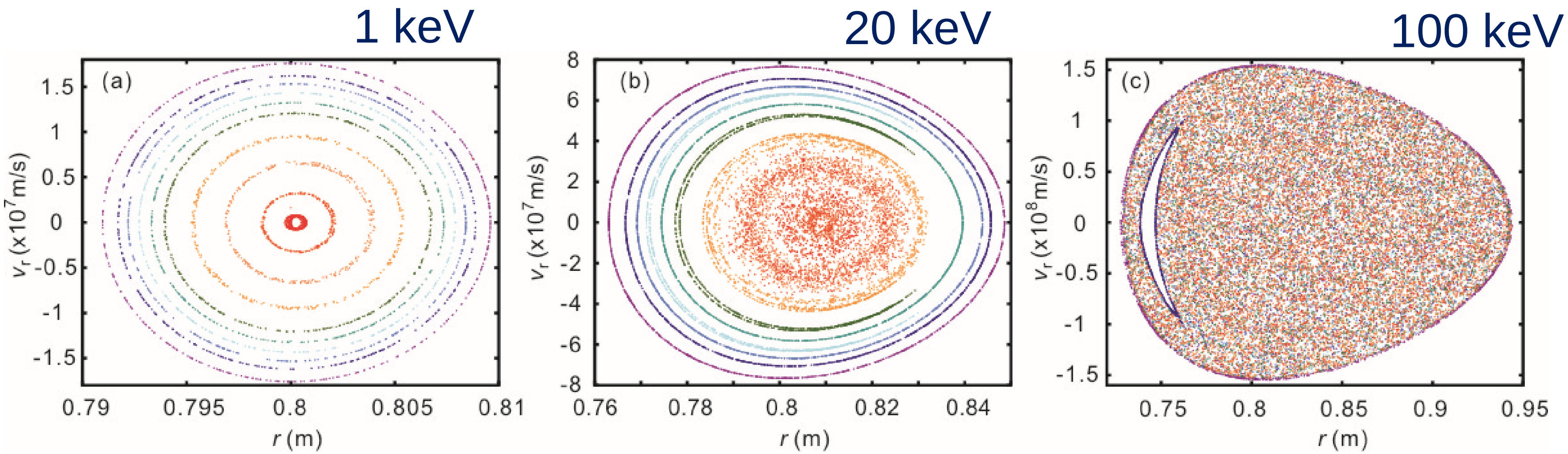
marginal



μ and J are conserved



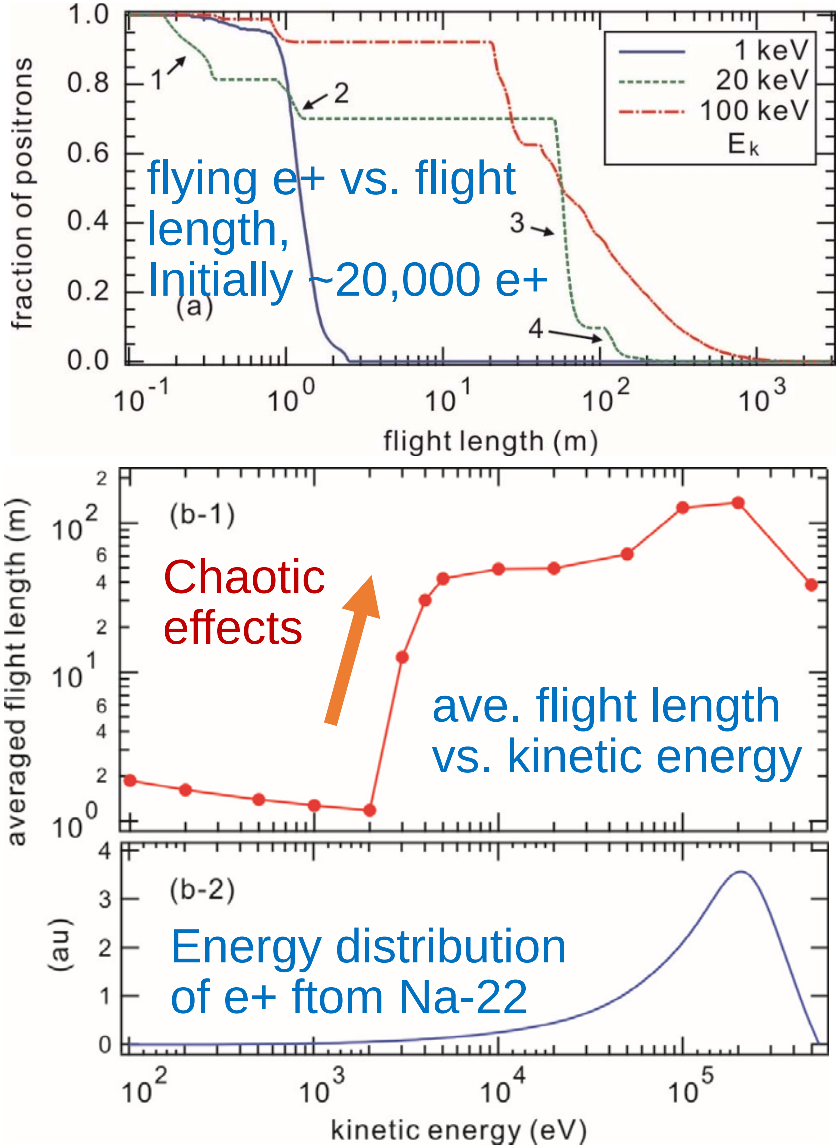
Breakdown of the first and second invariants results in the chaotic motion of high-energy positrons



Poincaré plot of orbit in the phase space for different pitch angles for positrons of kinetic energy 1, 20, and 100 keV

- Considerable ratio of positrons from Na-22 source exhibits chaos in the geometry of the RT1 levitated dipole
- Such particles may have long orbit (i.e., long trapping time) in RT1 before annihilation by recombination at the source

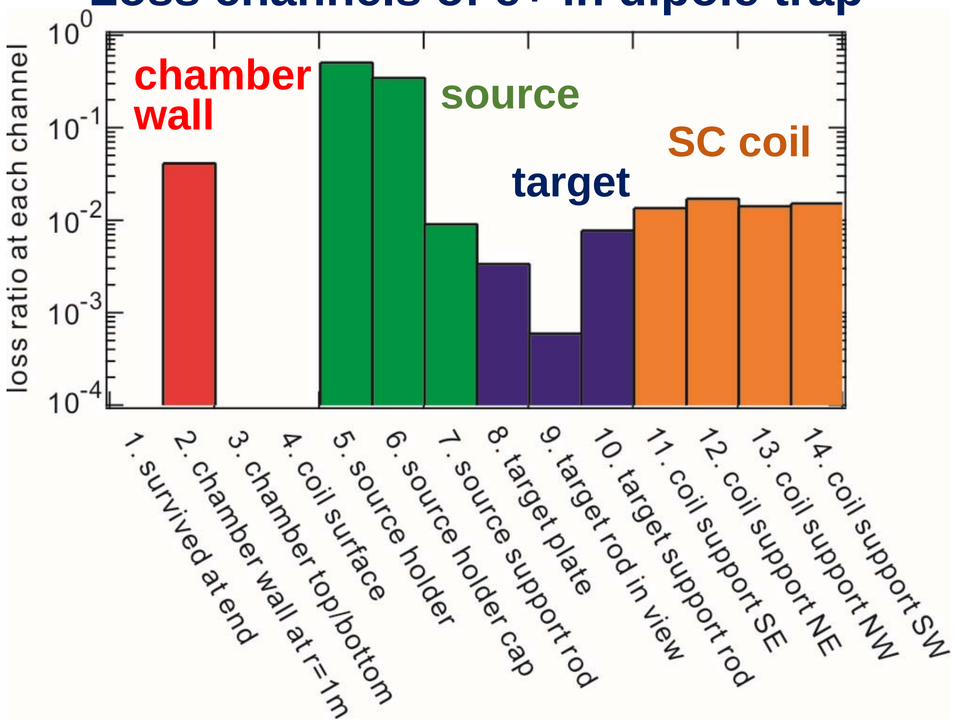
Effects of chaos: Positrons with non-integrable chaotic trajectories have considerably long orbit before annihilation



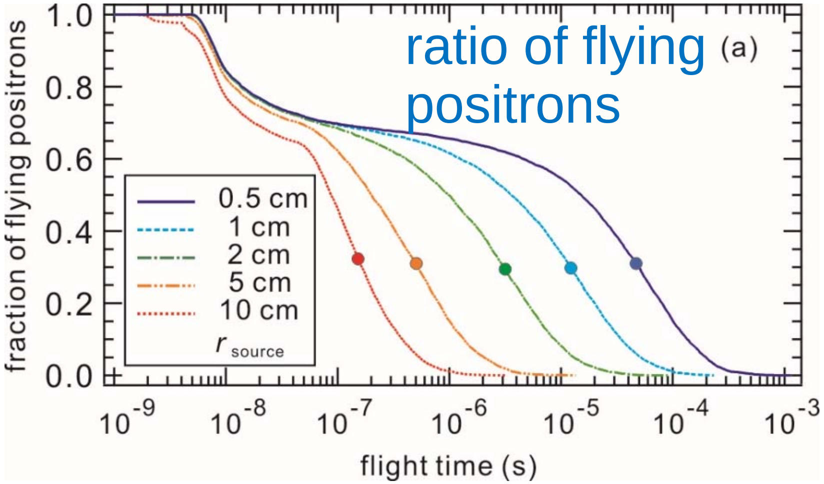
Flight length of single particle:

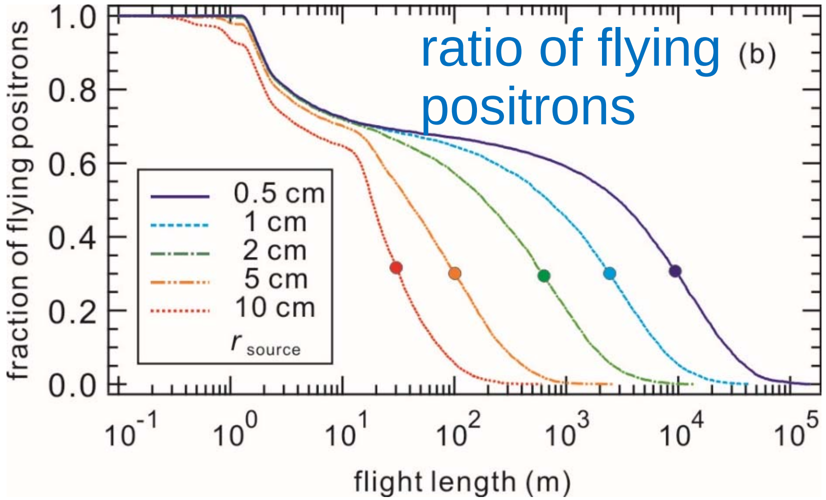
- e+ in periodic motions return to source just after single gyro/bounce motion
- positrons with chaotic orbits make multiple toroidal circulation with longer flight time

Loss channels of e+ in dipole trap



By minimizing the source size, thin torus e+ cloud is steadily generated, to be transported into strong field region





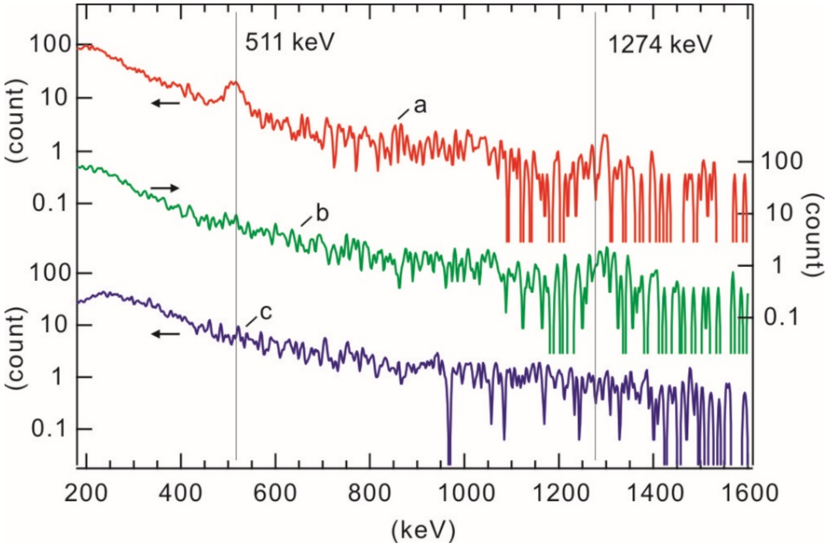
Flight time and length reflecting energy distribution:

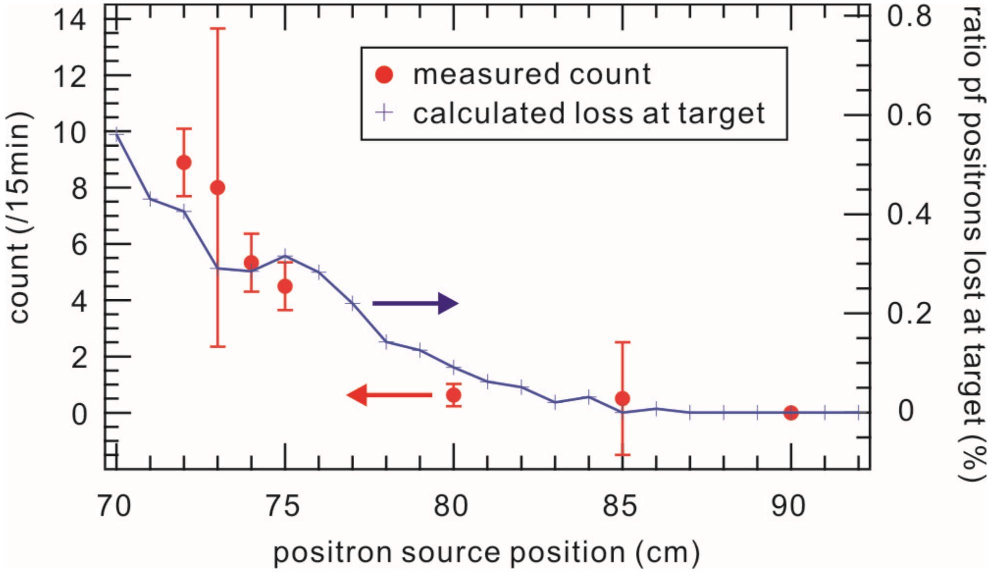
$$\frac{dN_1}{dt} = \int \Gamma dS - \frac{N_1}{\tau}$$

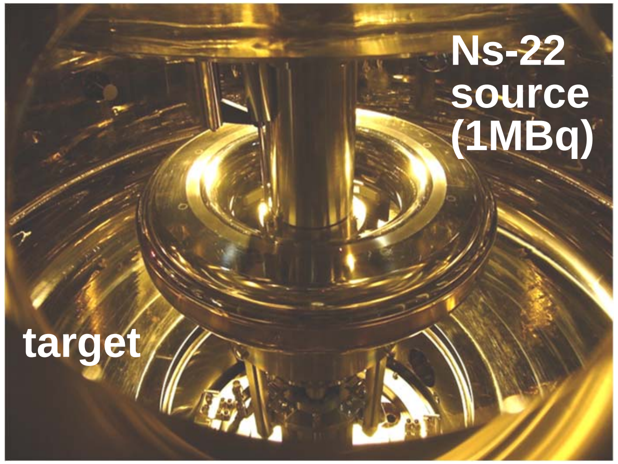
particle balance inside the hollow cloud

- Na-22 source size (r_{source}) limits the flight time
- with a source of $r_{source} = 0.5$cm (-> averaged flight time: 50 μs) and100 mCi (3.7 GBq), a hollow could of ~1×10^4 positrons are steadily generated
- if 1% of e+ from the source are transported inward by rotating wall, and assuming 1000 s trapping time, $N_1 \sim 10^{10}$ is expected in strong field region

Experiments at RT1 show fairly good agreement with numerical analysis, indicating the validity of chaos effects







- Positrons injected from a 1 MBq (27 μCi) Na-22 source at the edge confinement region
- Target probe at the opposite side detect e+ by coincidence measurements of 511 keV γs
- Orbit calculations including the chaotic effects well reproduced the experimental results

Summary

- Non-linear behavior of high-energy positrons in a dipole field was investigated both numerically and experimentally.

- In a typical levitated dipole field experiment, such as RT-1, it was shown that considerable ratio of high-energy positrons from radioactive sources have non-integrable chaotic and long orbits.

- These particles make multiple toroidal precessions forming a hollow toroidal cloud, which may be applied for the formation of dense positron cloud in a strong magnetic field region.

- Experiments with a small Na-22 source in RT-1 demonstrated the existence of long-lived positrons in the dipole field, showing a good agreement with numerical orbit analysis.

- Such chaos effects would do exist and play some role for high-energy protons and electrons in magnetospheres.