TP9-67

Initial Results on Positron Confinement in a Magnetospheric Configuration

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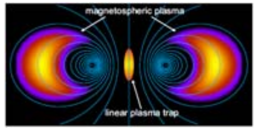
- Ring Trap 1 (RT-1)[*1] is a magnetospheric experiment generated by a levitated dipole field magnet.
- Studies on toroidal non-neutral plasmas have been conducted in RT-1[*2].
- Toroidal geometries can confine plasmas with arbitrary non-neutrality, potentially applicable to antimatter plasmas including electron-positron plasma.
- RT-1 has succeeded to stably trap toroidal pure electron plasma[*3]: Spontaneous inward diffusion, self-organization of rigid rotating state, confinement time t > 300s.
- The next goal of RT-1 is the formation and confinement of toroidal pure positron plasma.
- We have started positron injection experiment in RT-1 with a small 1MBq Na-22 source.
- Preliminary experiment suggests that energetic positrons have closed trajectories in RT-1.
- Positron injection method using external rotating electric field is under consideration.

1. Z. Yoshida *et al.*, Plasma Fusion Res. **1**, 008 (2006); Y. Ogawa *et al.*, Plasma Fusion Res. **4**, 020 (2009).
2. Z. Yoshida *et al.*, in *Non-Neutral Plasma Physics III* (1999); H. Saitoh *et al.*, Phys. Rev. Lett. **92**, 255005 (2004).
3. Z. Yoshida *et al.*, Phys. Rev. Lett. **104**, 235004 (2010); H. Saitoh *et al.*, Phys. Plasmas **17**, 112111 (2010).

Toroidal non-neutral plasmas

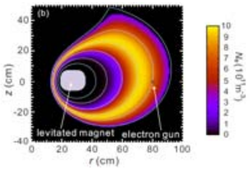
- **Toroidal configuration enables confinement of plasmas with arbitrary non-neutrality**
  - In contrast to linear traps, use no plugging electric fields
  - Applicable to high energy charged particles, independent of their electric signs and charges
  - Creation of antimatter plasmas, such as positron plasma and electron-positron plasma is one of challenging tasks to be realized in toroidal configurations



Magnetospheric plasma confinement

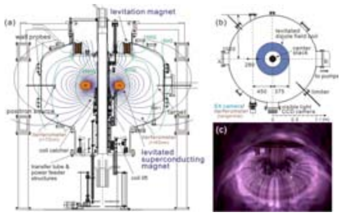
- **Magnetospheric configuration realizes axisymmetric stable toroidal confinement**
  - Confinement magnetic field is generated by a combination of dipole field coils
  - Axisymmetric system: conservation of canonical angular momentum or 3rd adiabatic invariant
    $P_\theta = mrv_\theta + qrA_\theta \sim qrA_\theta = const.$ $K = \int P_\theta ds \sim q\Phi = const.$
  - Orbit deviation from initial magnetic surface is smaller than poloidal Larmor radius $d \le \left| mr\dot{\theta}/qB_p \right|$

- **Particles must be injected across closed magnetic surfaces**


Electron density distribution in RT-1

  - Effective inward transport and kinetic energy increase have been demonstrated in RT-1 by using pure electron plasma
  - Cross field penetration and energization of charged particles: Common process observed in planetary magnetospheres
  - Fluctuations with time scales faster than or comparable to toroidal rotation period can violate K and P_θ; Orbit of particles can deviate from the initial magnetic surfaces
  - If the first invariant $\mu = m_e v_\perp^2/2B$ and the second invariant $J = \int m_e v_\parallel dl$ are conserved in this period, kinetic energies of particles transported to strong field regions increase

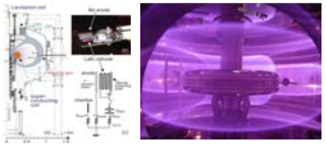
RT-1: Magnetoshperic configuration for various plasmas


Cross section of RT-1 and ECH plasma in RT-1

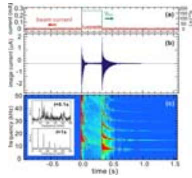
- **Field generated by a levitated dipole magnet**
  - High-T_c Magnet with Bi-2223 (T_c=110K) tape 250kAT (116A × 2160turns), 112kg
  - Magnet is levitated and operated for more than 6 hours without external cooling, resulting drastic reduction of perturbations to plasmas
- **Research subjects of RT-1**
  - Toroidal non-neutral plasma including antimatters 300s confinement, rigid-rotating state, inward diffusion
  - High-β ECH plasma suitable for advanced fusion 70% local β, τ~0.5s (hot electron), peaked profiles

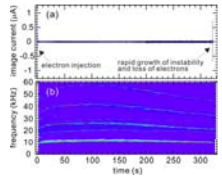
- Self-organization of various plasma structures -

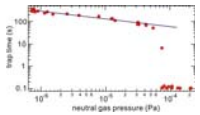
Stable confinement of toroidal pure electron plasma


Electron gun and visualized magnetic surface

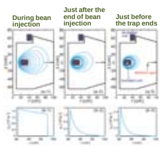
- **Stable confinement of toroidal non-neutral plasma was demonstrated by using electrons**
  - Antiparticles of positrons, equivalent test for basic properties
- **Electrons are successfully injected, and plasma is stabilized after the formation phase**
  - Electrons are injected into static dipole magnetic field with V_{acc}~200V from electron gun at edge region
  - After turbulent-like phase, plasma relaxes to a quiescent state with strongly peaked frequency spectrum
  - Confinement time exceeds 300s

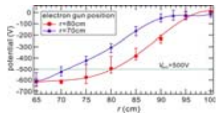

Formation and stabilization phase


Long term confinement


Trap time *vs* neutral gas pressure

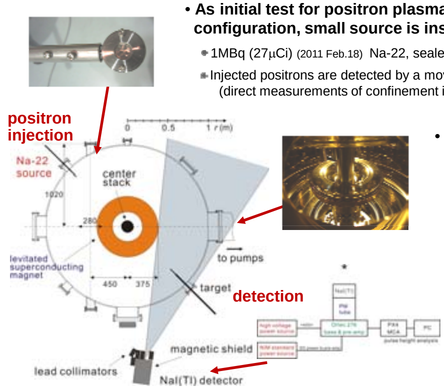
- **Plasma structures are consistent with predicted inward diffusion**
  - Confinement region moves to strong field region, peaked density profiles are spontaneously self-organized.
  - Space potential is close to V_{acc} near the gun and exceeds V_{acc} in strong field region: suggesting the conservations of μ and J.


Estimated density profiles


Radial space potential profiles

Installation of positron source and detectors

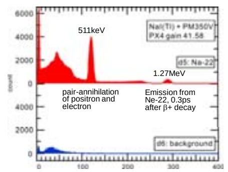
- **As initial test for positron plasma in toroidal magnetospheric configuration, small source is installed.**
  - 1MBq (27μCi) (2011 Feb.18) Na-22, sealed with 5μm-thick titanium foil
  - Injected positrons are detected by a movable target probe and NaI(Tl) scintillator (direct measurements of confinement is not conducted at present)

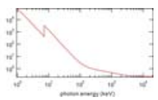


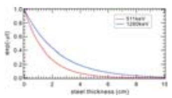
Experimental setup for positron injection and detection

- **High energy positrons are injected into RT-1**
  - β+ decay at Na-22 source, positron formation and 1.28MeV γ (from Ne-22)
  - Positrons are injected without using moderators; energy profile peak at ~100keV
  - Some low energy positrons return to the source and holder structures
  - Some positrons have long orbit lengths, injected into confinement region
  - Two 511keV γ-ray is generated when a positron hits target or chamber wall and is annihilated with an electron

- **Annihilation γ-ray detection with target and scintillator**
  - Positron beam orbit is estimated by using movable target and detecting γ-rays when positrons annihilated on the target
  - NaI(Tl) scintillator :φ25mm with 500μm-thick aluminum foil housing
  - Detection efficiency of 511keV γ-ray is calculated to be 8.9%
  - Transmittance of 1cm thick steel is 49%, γ-rays can be measured from outside of the RT-1 chamber

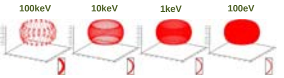

Photon energy distribution with and without Na-22


linear attenuation coefficient of iron

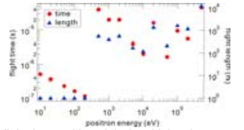

Transmittance of γ-ray photon

511keV γ-ray:
6.16 cps at distance of 1m (4.91x10^{-4} sr)
Test on 2011 Aug.1: Na-22 0.89MBq
511keV positrons arriving at the detector: 34.7 cps

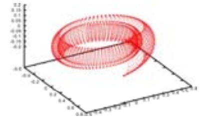
Positron orbit in dipole field

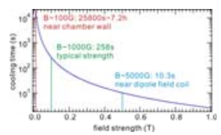

Typical orbits of positron in RT-1

- **Closed orbits of high energy positrons without deceleration in the magnetospheric configuration**
  - In static fields, dipole configuration can stably trap charged particles even at higher energies
  - Positrons survives before returning to the source; orbit length is set by the positron source size
  - In the present setup in RT-1, typical positron rotates in the toroidal direction 50 times (orbit length ~1km) before annihilation
  - If positron orbits are modified and transported inward from the source, long confinement and formation of plasma are expected


Flight time and length before hitting the source

- **Application of (rotating) electric field can violate μ and J conservations, resulting inward diffusion of positrons**
  - By applying high frequency electric field in azimuthal direction, positrons undergo radial drift motion, resulting inward diffusion
  - Once transported inward, Na-22 source do not disturb the positron orbits
  - Most effective radial transport is realized just for "trapped" particles, further optimization is require

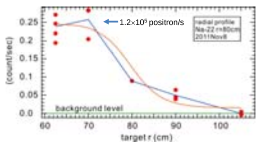

10keV positron orbit with E_θ=10kV/m


1/e cooling time due to synchrotron radiation

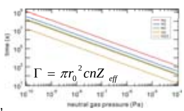
- **Effective cooling of positrons are expected during the long orbital motions**
  - To confine positrons as plasma, low temperature state is required
  - After transported to strong field region, positrons are cooled by the synchrotron radiation
  - Cooling time calculated by the Larmor formula: 1/e cooling time is 260s at B=1000G, 10s at B=5000G

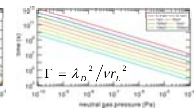
Preliminary results and confinement time estimation

- **Survival rate of positrons from source to target: 13%**
  - Positrons travelled from the source to the target are detected; 1count corresponds to 4.9×10^5 positron loss at the target
  - Positron number emitted from the Na-22 source is 8.9×10^5 /s
  - Assuming that all travelling positrons are lost at the target, 13.4% of the emitted positrons arrived at the target
  - Approximately 120000 positrons /s are successfully injected into the travelling trajectories using 1MBq (27μCi) source


511keV γ-ray count in variation of target position

- **Supply and loss balance of positrons**
  - In a steady state, positron supply is balanced by target loss, annihilation with neutral gas, and loss by transport across magnetic surfaces
    $$\frac{dN}{dt} = S - L_{target} - L_{annihilate} - L_{transport}$$
  - At base pressure of RT-1, 8×10^{-7} Pa (N_2 dominant), annihilation time is 2.1×10^5 s and effects of neutral gas are negligible

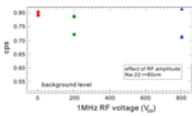

$\Gamma = \pi r_0^2 cnZ_{eff}$
Annihilation with remaining neutrals


$\Gamma = \lambda_D^2/\nu r_L^2$
Classical diffusion with neutral collisions

  - By detaching the source and positron orbits in some way, drastically longer confinement time is expected
  - Application of rotating wall and fast-moving source are possible solutions for this purpose
  - Using the observed confinement time of electron plasma, τ~300s, confinement region volume V~0.2m^3, steady state positron number and density are estimated to be 3.6×10^7 and 1.8×10^8 m^{-3}: Debye length 0.5m at 1eV

Future tasks

- **Application of RF for radial inward transport of positrons**
  - Preliminary RF application test does not significantly change the γ-ray detection level observed at the target
  - New electrode design and further RF optimization are under consideration


RF application on the source


Coincidence measurement

- **Accurate position detection of positron annihilation**
  - Coincidence measurement system of 511keV γ-ray will be installed
  - It will be used for the detection of annihilation point in the entire region of chamber and target