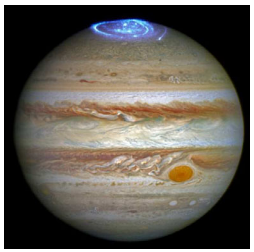
AAPPS-DPP2023 Nagoya

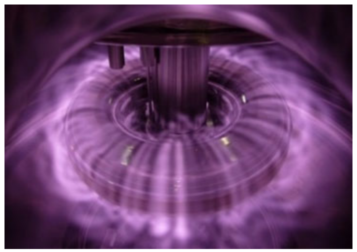
Injection and trapping of pulsed positrons in dipole magnetic field toward pair-plasma creation

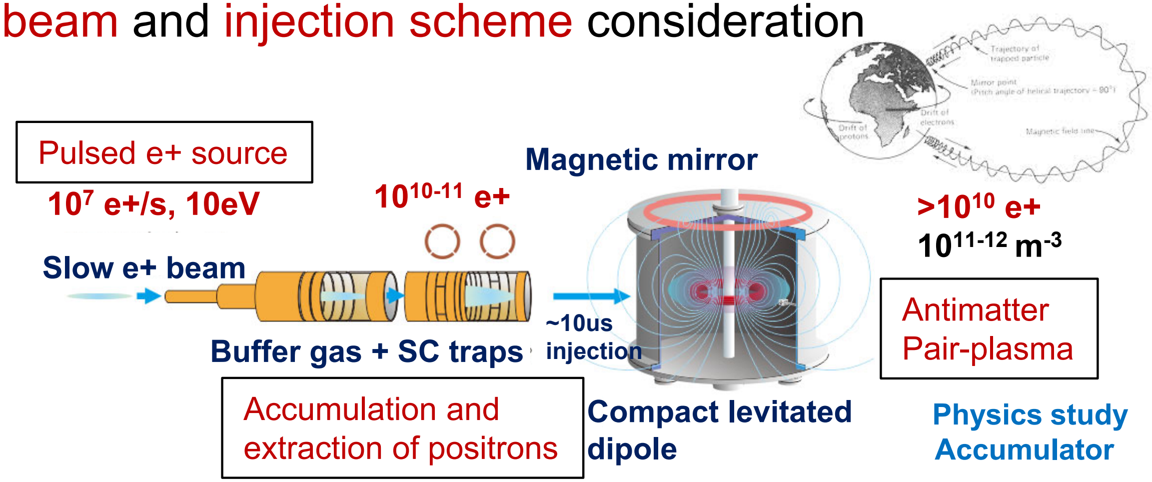
H. Saitoh[1,2], J. von der Linden[3], A. Deller[3], H. Higaki[4], K. Michishio[5], T. Hori[5], N. Oshima[5], S. Nissl[3], E. V. Stenson[3]

[1] Department of Advanced Energy, The University of Tokyo
[2] National Institute for Fusion Science
[3] Max Planck Institute for Plasma Physics
[4] Division of Advanced Science and Engineering, Hiroshima University
[5] National Institute of Advanced Industrial Science and Technology

1. Introduction; ***artificial magnetosphere*** for application to laboratory plasma experiments
2. Plan for the creation and study of magnetically-confined **electron-positron plasma**
3. Progress of ring trap experiment generated by a levitated superconducting magnet
4. Injection experiment with pulsed e+ beam and injection scheme consideration
5. Summary and future work







Introduction: Magnetosphere for laboratory experiments

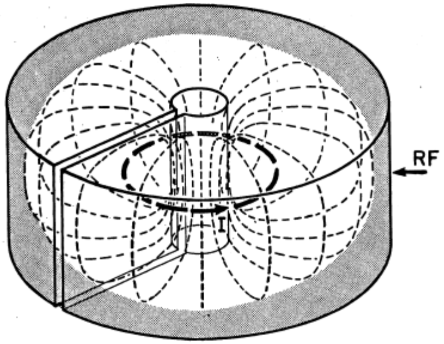
Scientific applications of *artificial magnetosphere*

1987 Hasegawa, Comm Plasma Phys. Contr. Fusion

Among various properties, excellent confinement is very attractive

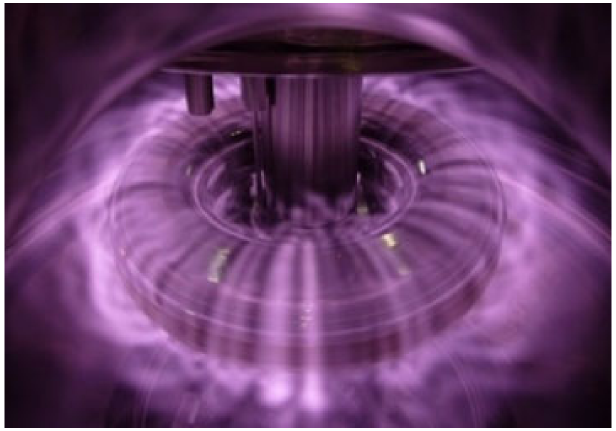
"Dipole Fusion" by Hasegawa



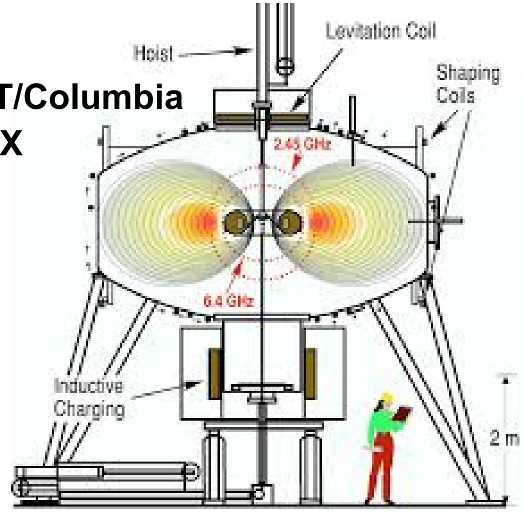


D-T ⇒ D-D, D-^{3}He etc.

RT-1 of U. Tokyo



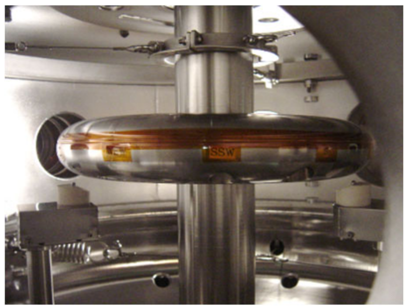
MIT/Columbia LDX



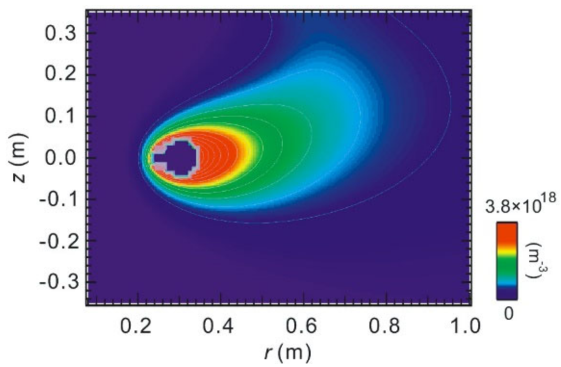
Levitated dipoles with SC coils

2006 Yoshida+ Plasma Fusion Res.
2010 Boxer+ Nature Phys.

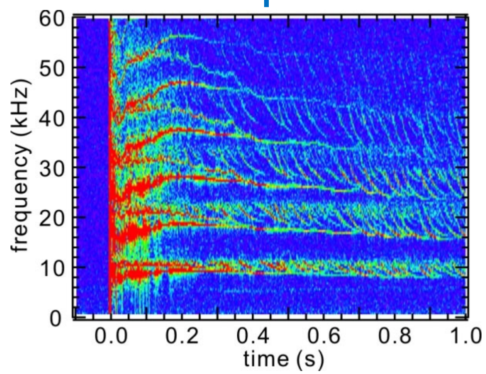
- High-Tc SC technology
- high-beta plasma for advanced fusion concept
- non-neutral plasmas and antimatter plasmas



2013 Ogawa, Mito, Yanagi+ 低温工学



2022 Kenmochi, Nishiura+ Nuclear Fusion

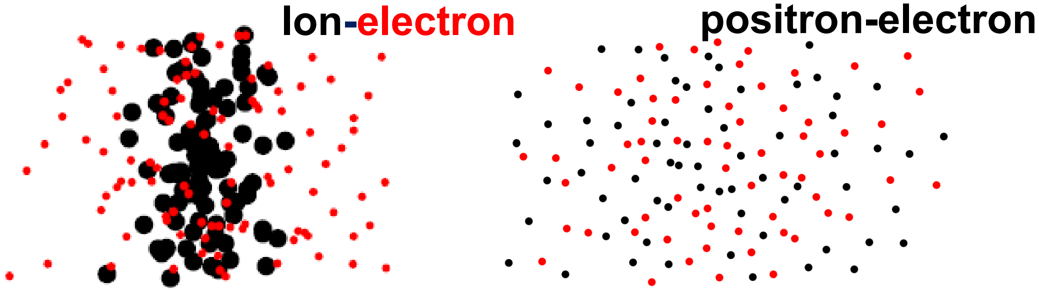


2010 Yoshida+ Phys. Rev. Lett.

Laboratory electron-positron plasmas as one of frontiers in plasma fusion research

- Matter-antimatter pair-plasma
  - Unique wave and stability properties as pair-plasma（$m_{e+}=m_{e-}$）

    ➡ Experimentally unknown
    （as **basic plasma physics**）



  - e+/e- plasma is common in space environment

    ➡ Structure formation, instabilities, etc. around astrophysical objects

  - Required large number of positrons is useful

    ➡ **Positronium**（atom-like e+/e-）Bose-Einstein condensation, Coherent **g-ray laser**, toward **more complex antimatters**

- Anti-hydrogen plasmas

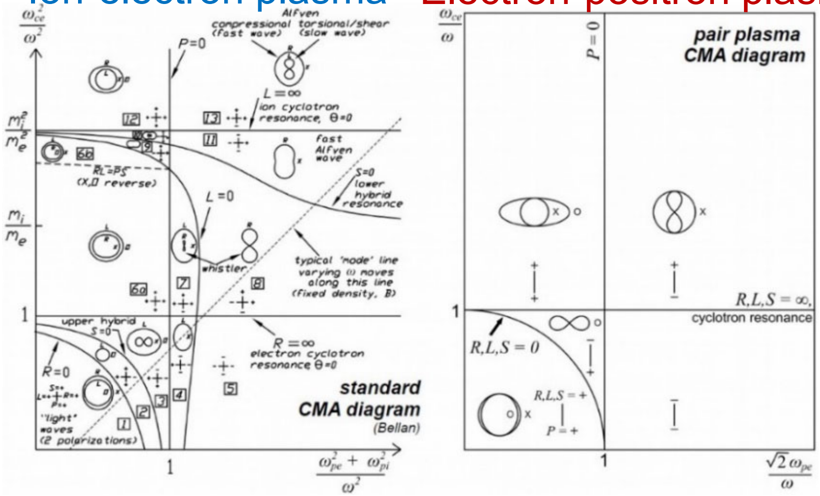
  ➡ **CPT symmetry**, **gravity of antimatters**, **physical constants**

Status of electron-positron plasma studies

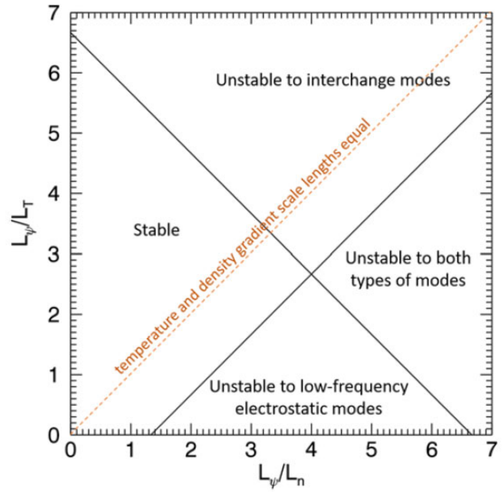
Theoretical ad numerical progress

- Degenerated dispersion relation
- Robust stable state prediction

Ion-electron plasma Electron-positron plasma



Wave modes are simplified in pair-plasmas.
No Faraday rotation, etc.



Stability against temperature/density gradient

1978 Tsytovich&Wharton, Comm. Plasma Phys. Cntr. Fusion*
2014 Helander, Phys. Rev. Lett.**; 2017 Stenson, J. Plasma Phys.

- Stabilities, shock, structures of space plasmas

Works of "e-/e+ plasma" > 4000
（Web of Science 2022）

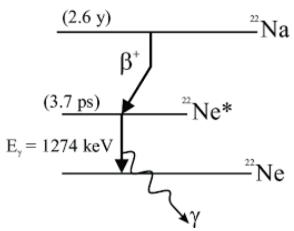
Experimental works

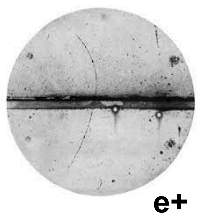
- pair-ion（c60+-C60-）plasma — 2003 Oohara&Hatakeyama PRL
- hydrogen pair plasma（negative ion） — 2017 Oohara+ PoP
- electron-positron plasmas
  - **Mirror** — 2020 Higaki+ App. Phys. Exp.
  - **Dipole, Helical** — 2020 Stoneking+ J. Plasma Phys.

So why challenging to experimentally create e+/e- plasmas?

- In order to satisfy plasma conditions,
  - to accumulate at least 10^9 positrons, and further,
  - simultaneous trapping with electrons is needed

- Antimatter

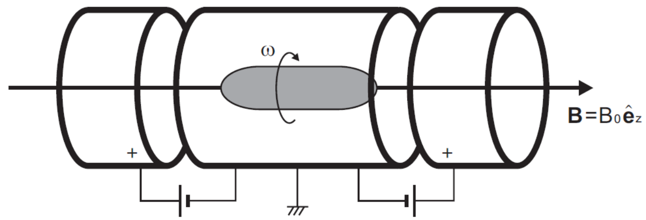




Slow positron source with isotope: up to ~10^6 e+/s

Intense source and injection methods

- Plasma (non-neutral)



Linear trap for single-component plasma

Trapping of pair-plasma methods

- Recent breakthroughs in these areas

1. Stable confinement of plasma with arbitrary non-neutrality in levitated dipole

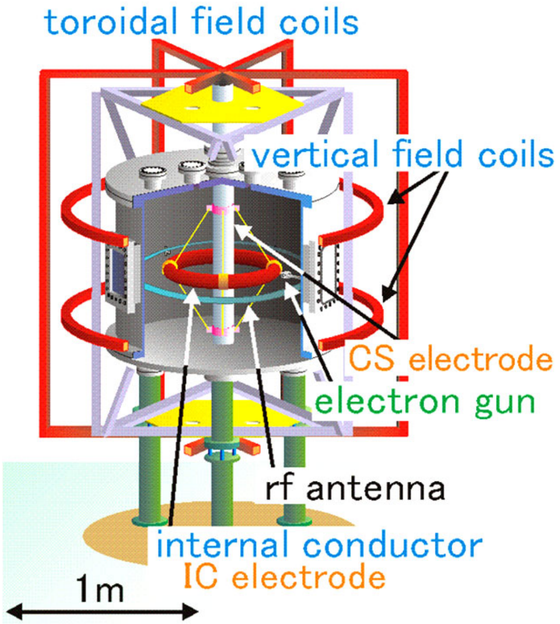
   1987 Hasegawa Comm. Plasma Phys. Cnt. Fusion, 2004 Saitoh+ Phys. Rev. Lett., 2010 Yoshida, Saitoh+ Phys. Rev. Lett.

2. Progress in positron technologies, injection and accumulation in dipole

   2015 Saitoh+ New J. Phys., 2018 Stenson+ Phys. Rev. Lett., 2018 Horn-Stanja+ Phys. Rev. Lett.

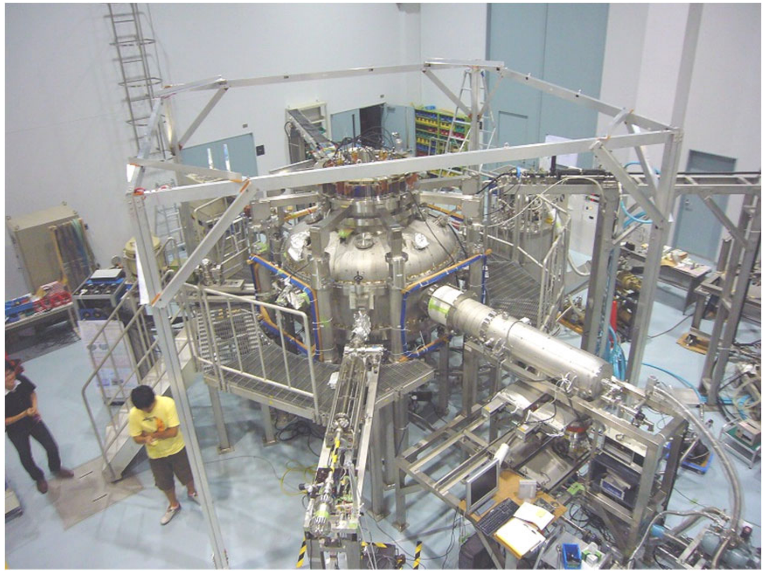
➡ e+/e- plasma realization in levitated dipole with intense e+ source

Levitated dipole (Ring Trap) for fusion plasma studies

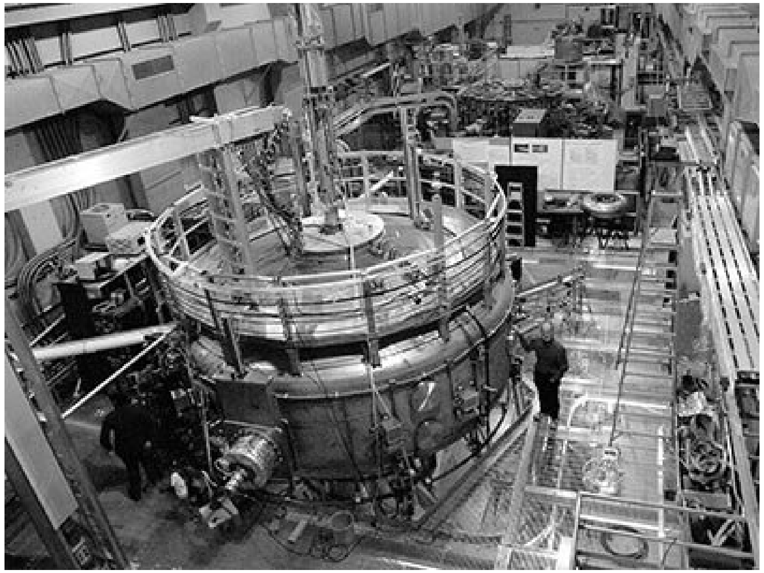


- Proto-RT: normal-conducting dipole
- Levitated dipoles in Japan and USA, motivated by advanced fusion concept
- Theoretical work on high-beta flowing plasma
- Progress of superconducting technology

1987 A. Hasegawa, Comm. Plasma Phys. Ctr. Fusion **11**, 147.
2013 Z. Yoshida+, Plasma Phys. Control. Fusion **55**, 014018.

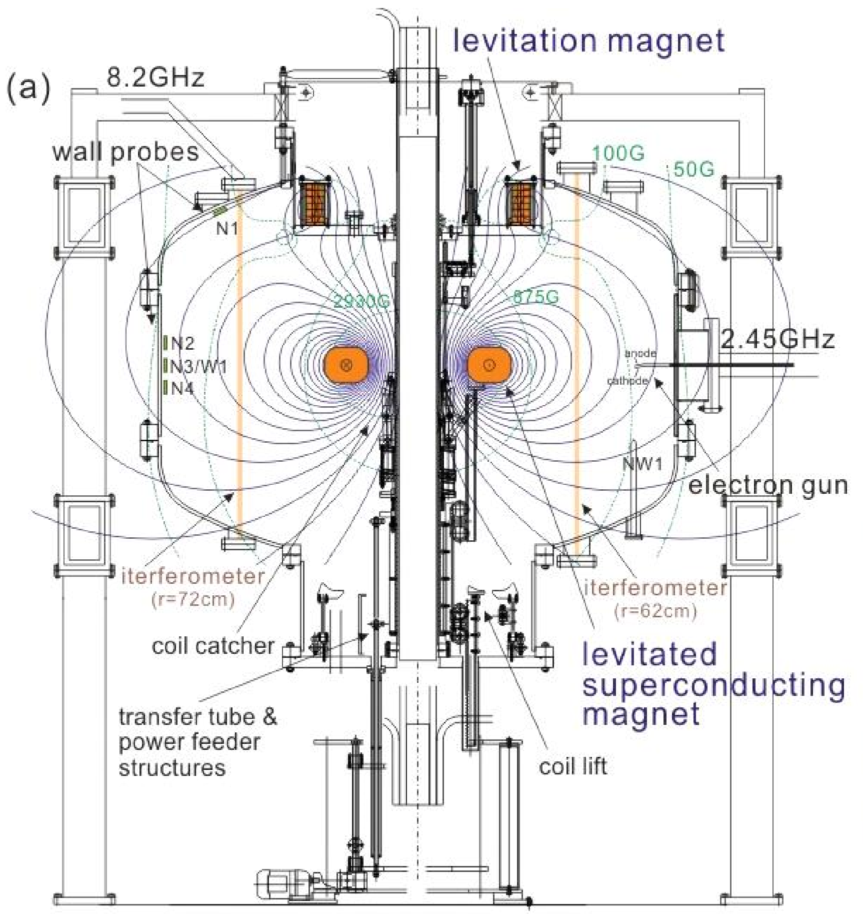


Tokyo: RT-1（Proto-RT->Mini-RT->…）
2010 Z. Yoshida+, Phys. Rev. Lett. **88**, 095001.



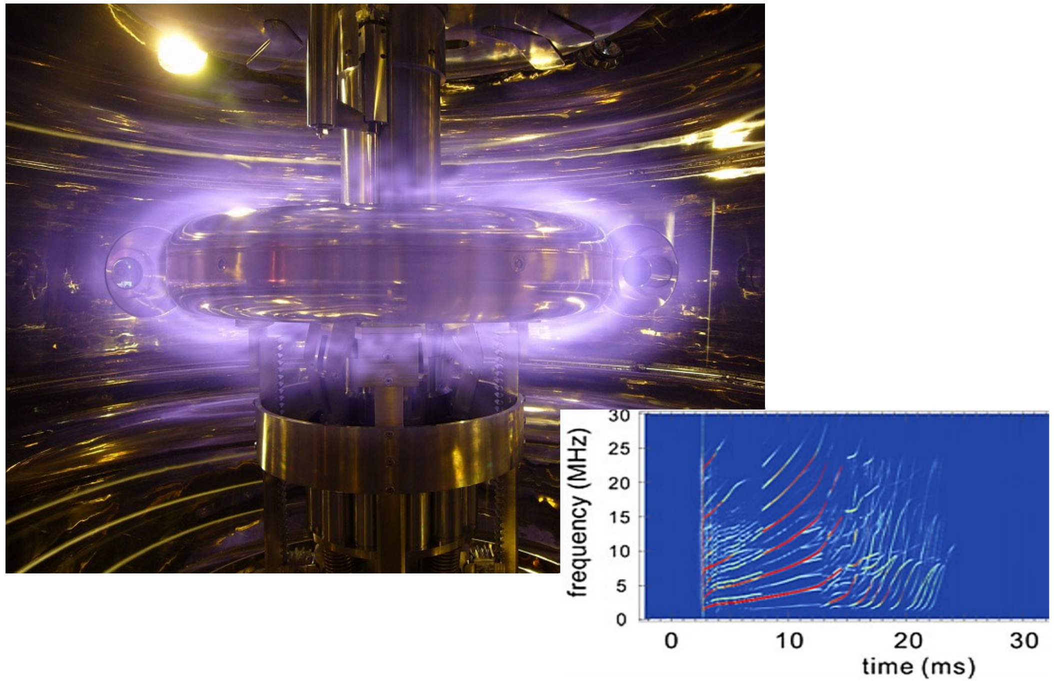
MIT/Columbia: Levitated Dipole eXperiment
2010 A.C. Boxer+, Nature Phys. **6**, 207.

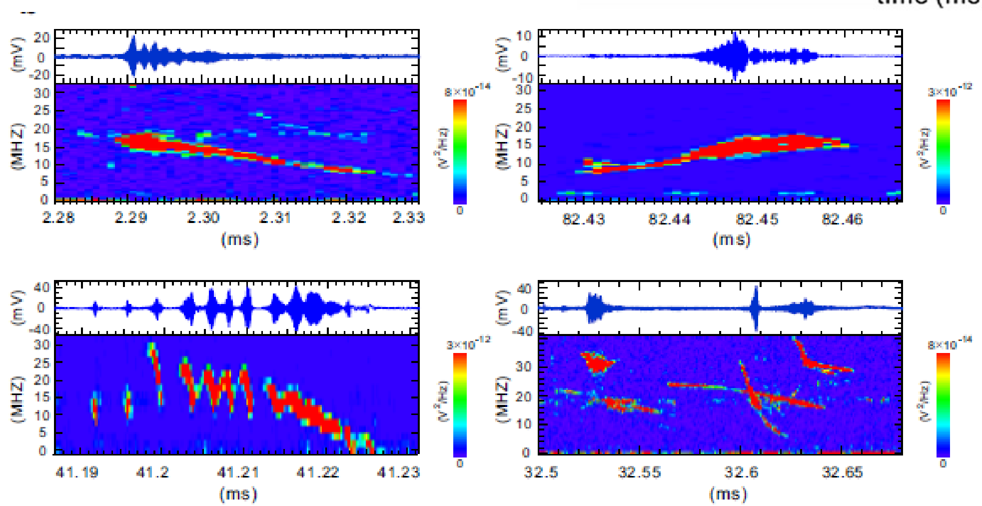
RT-1 Levitated dipole with high-temperature SC coil



- Hi-Tc SC（Bi-2223）coil is magnetically levitated by feedback control

- ECH with 2.45/8.2GHz microwaves, creating hot-electron high-beta plasmas





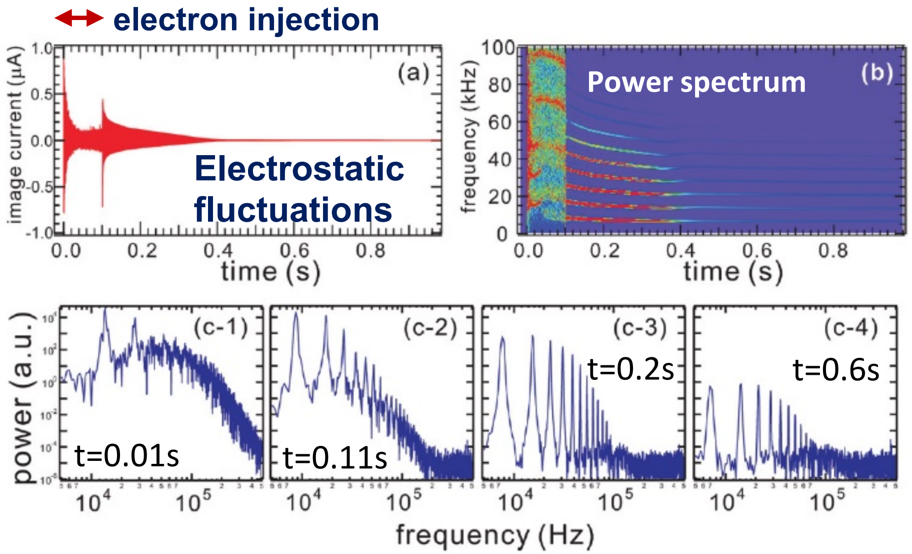
- Several fluctuation activities including those similar to whistler mode chorus emission

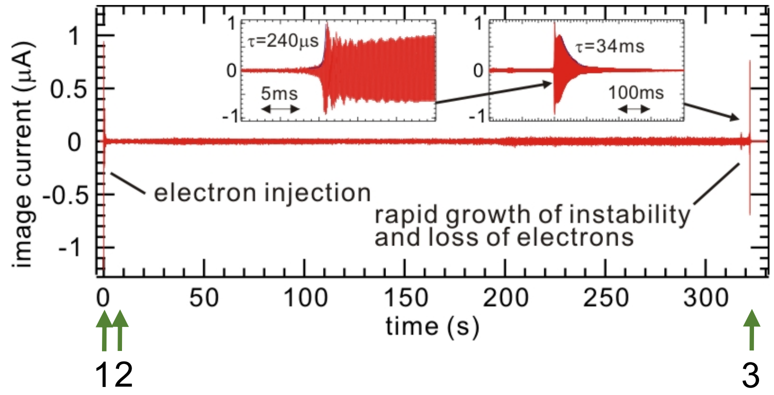
2006 Yoshida+ PFR; 2016 Yoshida+ Adv. Phys.; 2019 Nishiura+ NF; 2022 Kenmochi+ NF

Trapping of non-neutral plasmas in levitated dipole

Toroidal pure electron plasmas confined for >300 s in RT-1

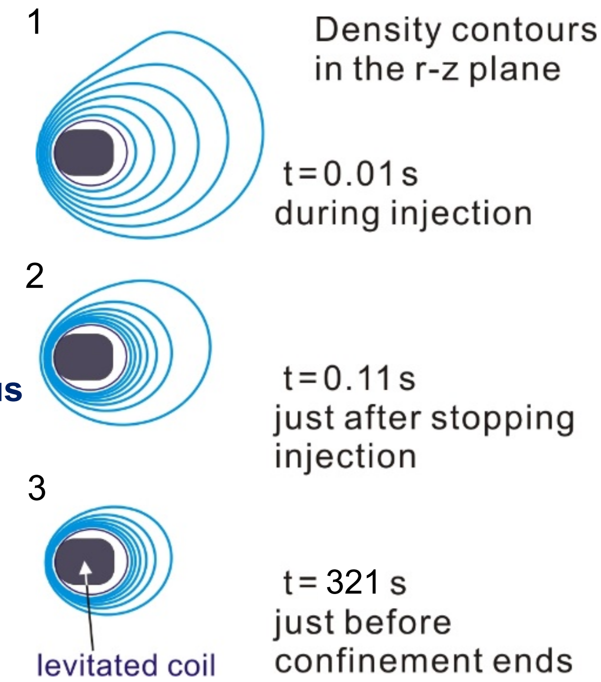
Pure magnetic (without E) toroidal system for particle trapping





Selective decay of turbulence and spontaneous creation of stable vortex structure that lasts for more than 300s.

2004 Saitoh+ Phys. Rev. Lett.
2010 Saitoh+ Phys. Plasmas



Structure formation in strongly inhomogeneous dipole is understood as a kind of diffusion

2018 Sato&Yoshida Phys. Rev. E

In principle, positrons can be simultaneously trapped in the same geometry of levitated dipole

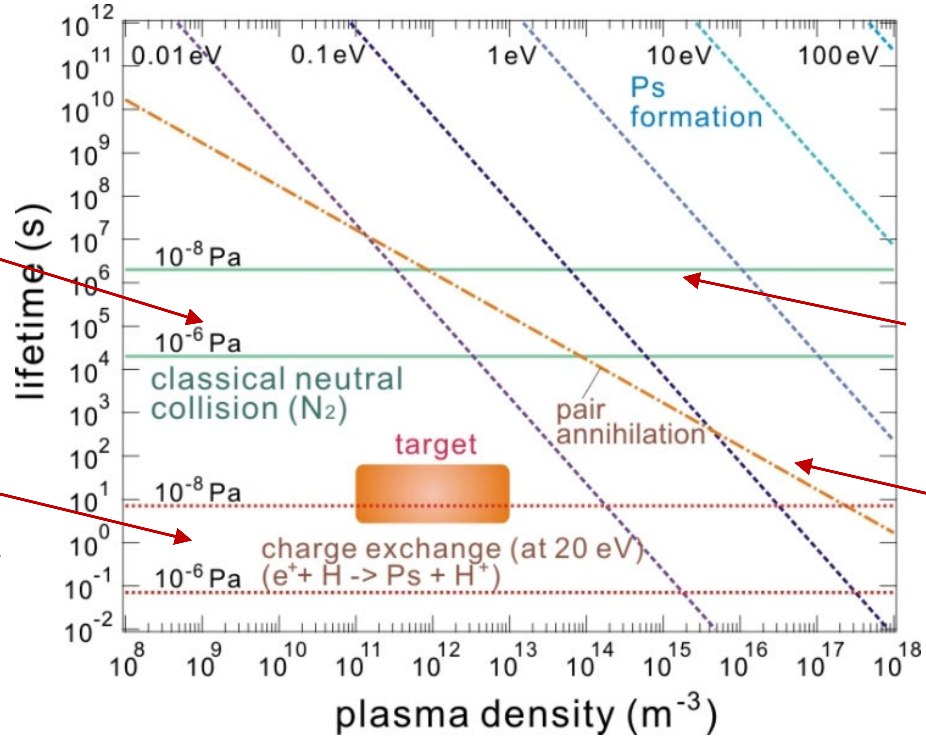
Feasibility of electron-positron plasma experiments

- **target: $n_{e+/e-}$ >~$10^{11\text{-}12}$ m^{-3}, T_e~1eV**

Debye length λ_D~2cm < exp. size,
collective phenomena as plasmas

Classical collisions with neutrals can be negligible at UHV environment

Charge exchange with hydrogen atoms may set the lifetime.
The cross section has a peak around 20eV



Positronium (Ps) formation
Effective only in extremely low temperature (<10meV) conditions

Pair-annihilation
Negligible at low density operation region

Life time of positrons and electron-positrons set by various processes

Expected lifetime, set by charge exchange, Ps formation, and pair-annihilation, is much longer that the time scales of plasma phenomena

Overall plan of the pair-plasma experiment

Linac-based e+ source at AIST

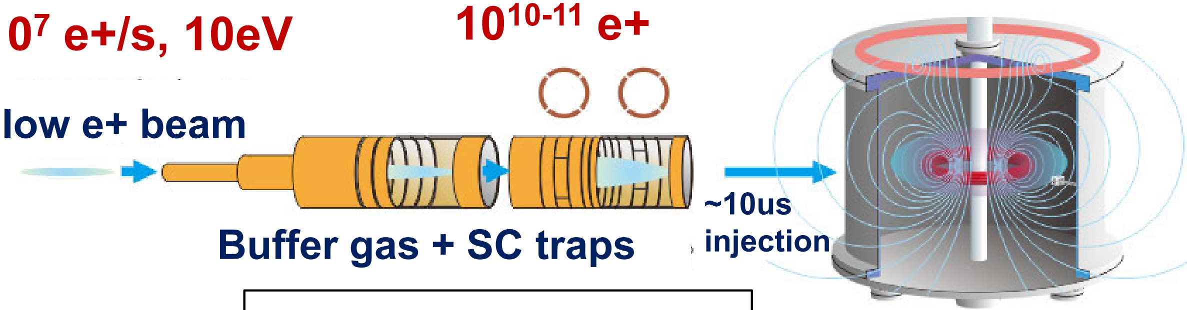
2020 Higaki Michichio+ Appl. Phys. Exp.

Pulsed e+ source

10^7 e+/s, 10eV

Slow e+ beam

$10^{10\text{-}11}$ e+



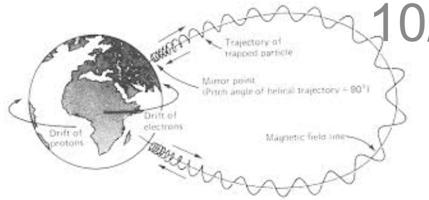
Buffer gas + SC traps

~10us injection

Accumulation and extraction of positrons

2020 Higaki+ App. Phys. Exp.

Magnetic mirror



>10^{10} e+

$10^{11\text{-}12}$ m^{-3}

Antimatter Pair-plasma

Compact levitated dipole

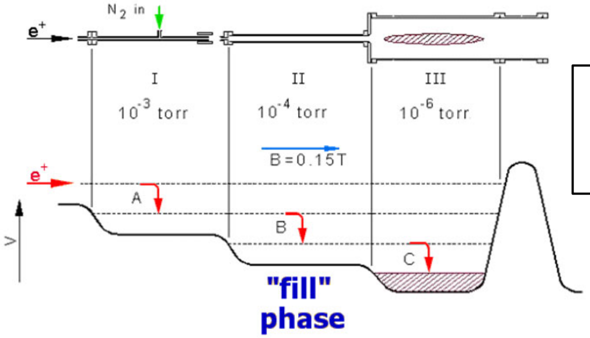
2006 Yoshida+, PFR

Physics study

Accumulator

- Trap and extraction of many e+s

Separation of injection and trapping phases



SC trap enhance e+ number

2020 Higaki Michichio+ Appl. Phys. Exp.

Inelastic collision and efficient deceleration

Collaboration with e+ groups at UCSD and IPP/TUM/U. Greifswald

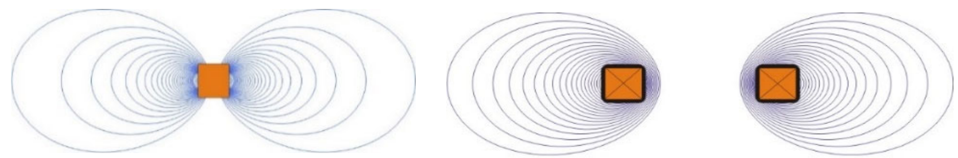
*2015 Danielson, Dubin, Greaves, Surko, Rev. Mod. Phys.

- Pair-plasma in artificial magnetosphere

Simultaneous trapping of e+ and e-

Dipole development

Fast pulse injection



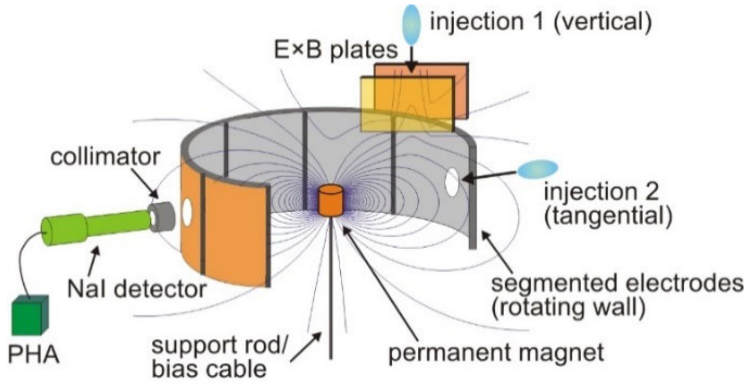
- Prototype dipole with permanent magnet
- Artificial magneto-sphere with SC dipole

- Theoretical approach

Waves and stabilities

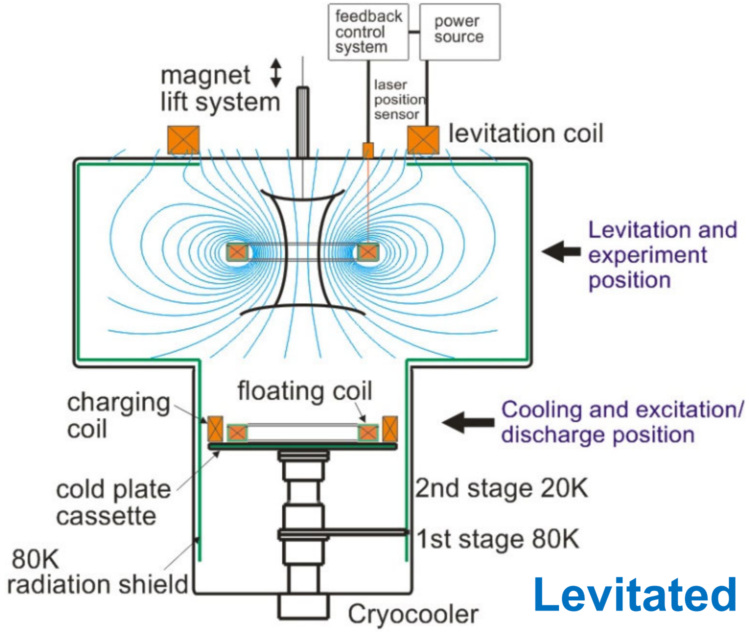
Self-organizaiton

Development steps toward pair-plasma and today's topics



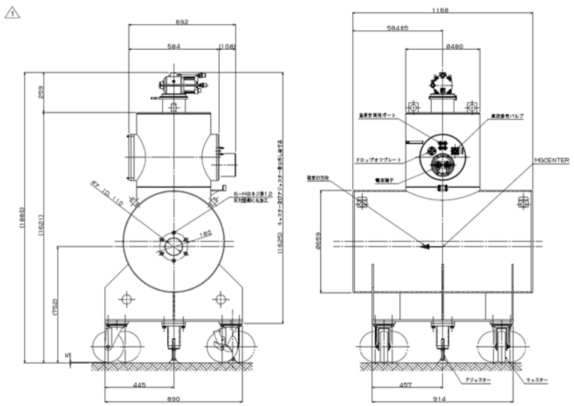
Prototype dipole with permanent magnet

- **drift injection (100% efficiency)**
- **positron trapping (~1s): 1000 e+ so far**
- **experiment with buffer gas trap: 1e5 e+ numerical orbit analysis of their dynamics**

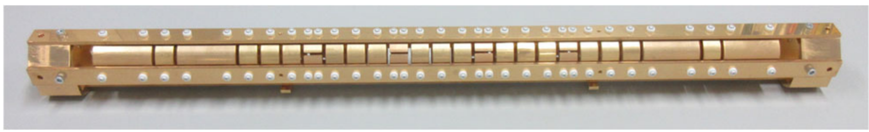


Levitated SC dipole

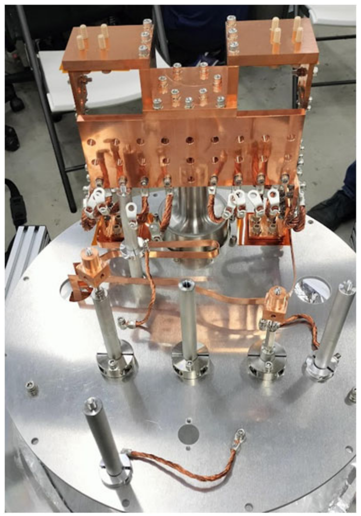
- **simultaneous trapping of e+ and e-**
- **SC coils and levitation system**
- **new injection scheme is needed**

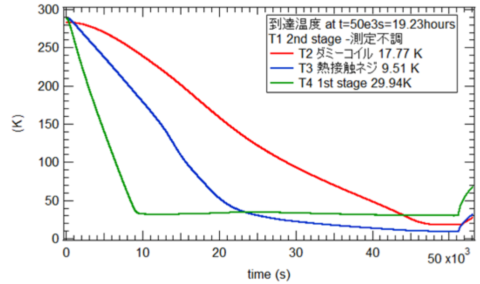


- **60cm homogeneous B region**



Linear e+ accumulator with 5T magnet





- **cooling without He gas**
- **design of compact levitated dipole**

Injection experiment of e+ into permanent magnet dipole @AIST

J. von der Linden, A. Deller+, to be published

- Permanent magnet dipole operated at Linac-based slow e+ with buffer gas trap

  x100 increase of positron number as before

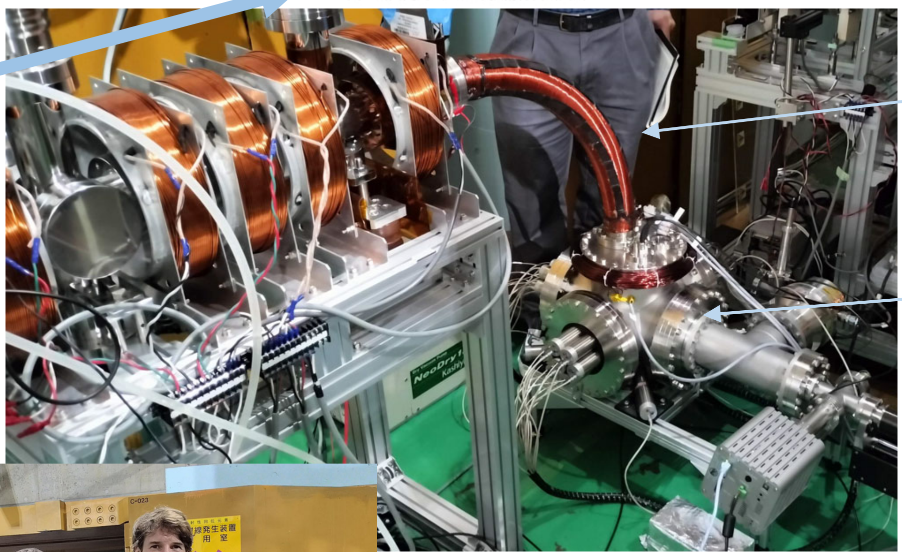
~10^5 e+ are injected and trapped

- **short pulse -> toroidal cloud**
- **spatial profiles?**
- **effects of neutral collisions**

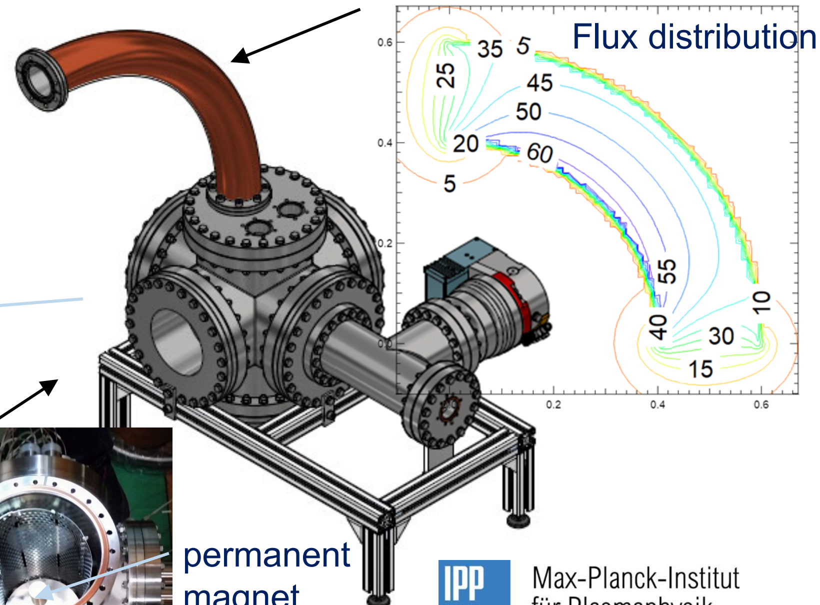
- Guiding field(+ steering coil) + ExB drift injection

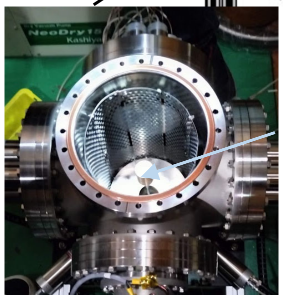
AIST 国立研究開発法人 産業技術総合研究所 広島大学

e+



Beam transfer B~50 Gauss





permanent magnet

Dipole trap

IPP Max-Planck-Institut für Plasmaphysik

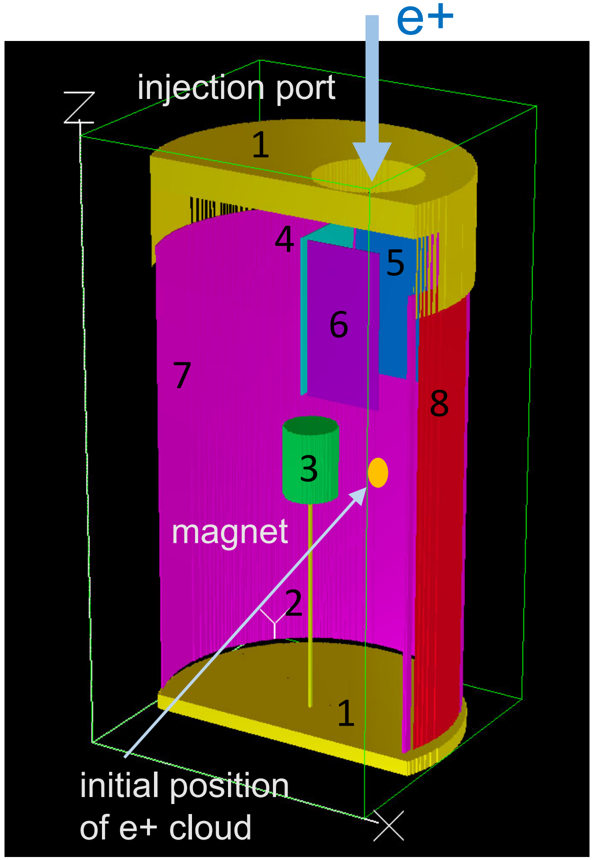
2023-Injection Exp.

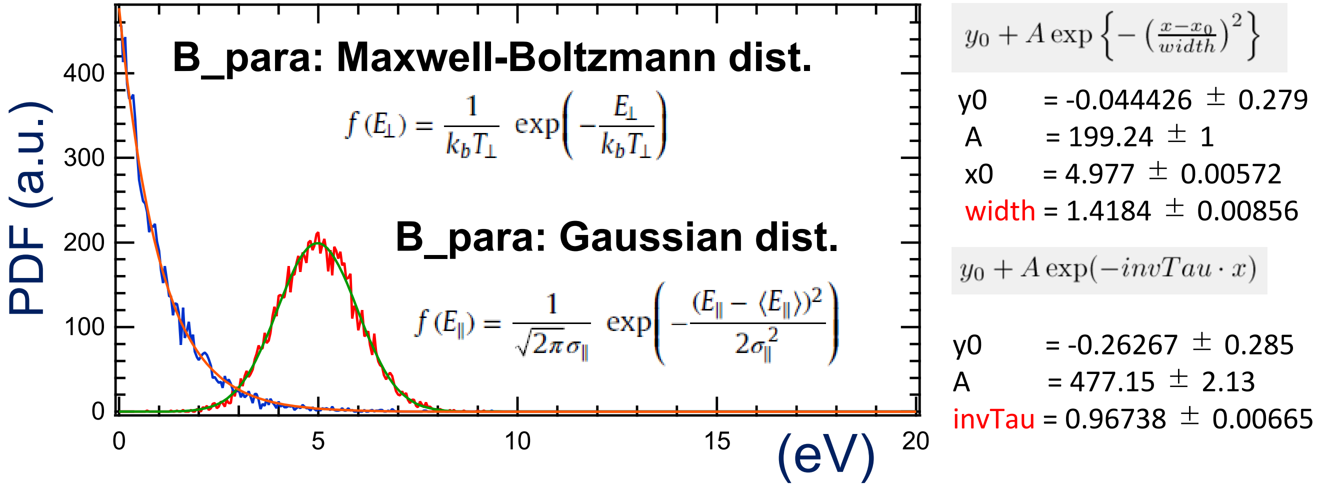
Dynamics of many positrons in dipole after injection

In this study, we mainly numerically analyze the orbit

Orbit of many positrons in permanent magnet dipole

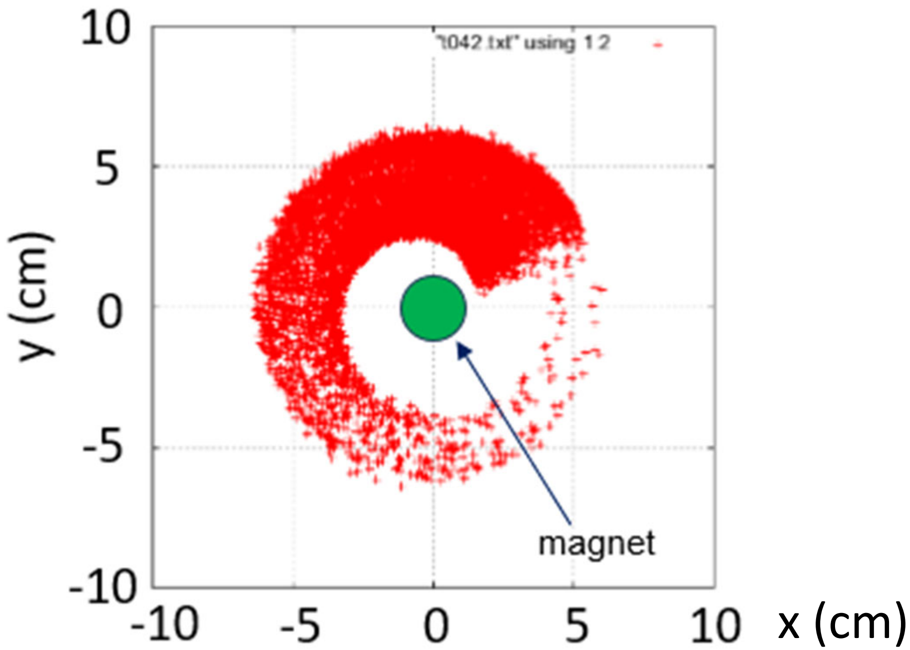
- Orbit trace in electromagnetic fields generated by injection electrodes
- Analysis with realistic spatial and temperature spreads





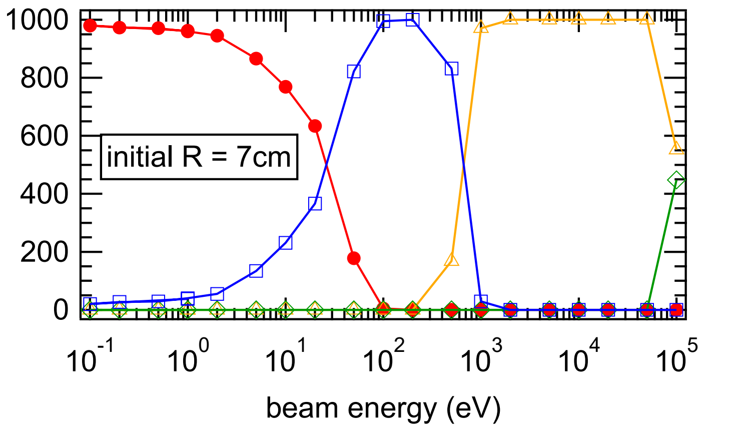
Integration with Boris method for particles starting from equator of the trap

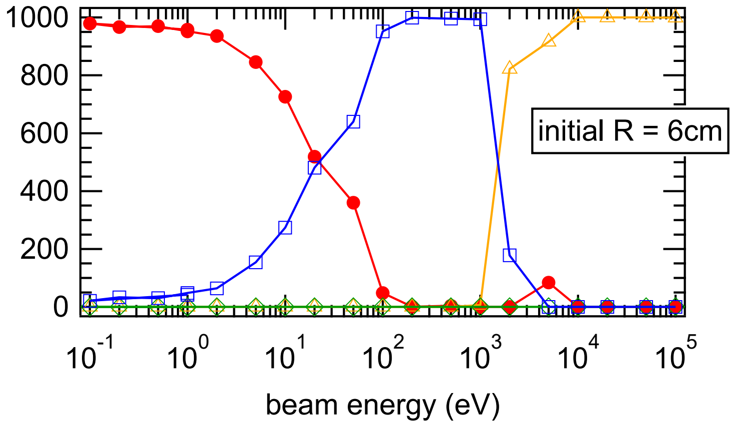
Homogeneous e+ could is formed due to toroidal drift of finite temperature

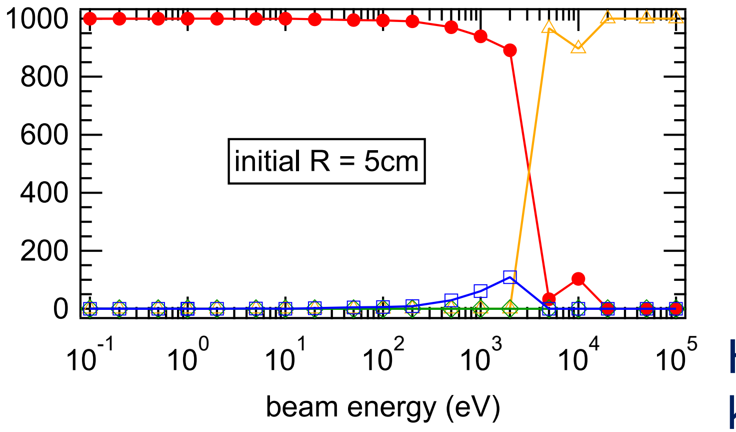


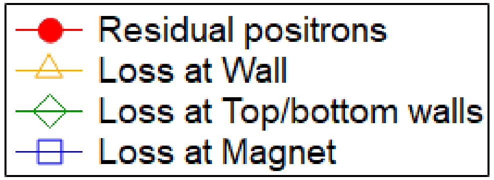
Typical orbits（top view, for 200us）

Trapping ability and loss channel for various energy e+ (0.6T magnet)



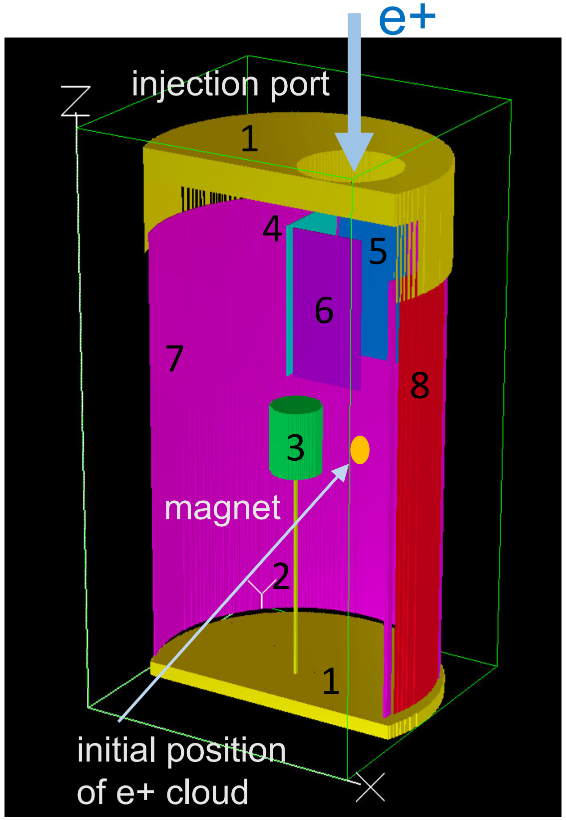


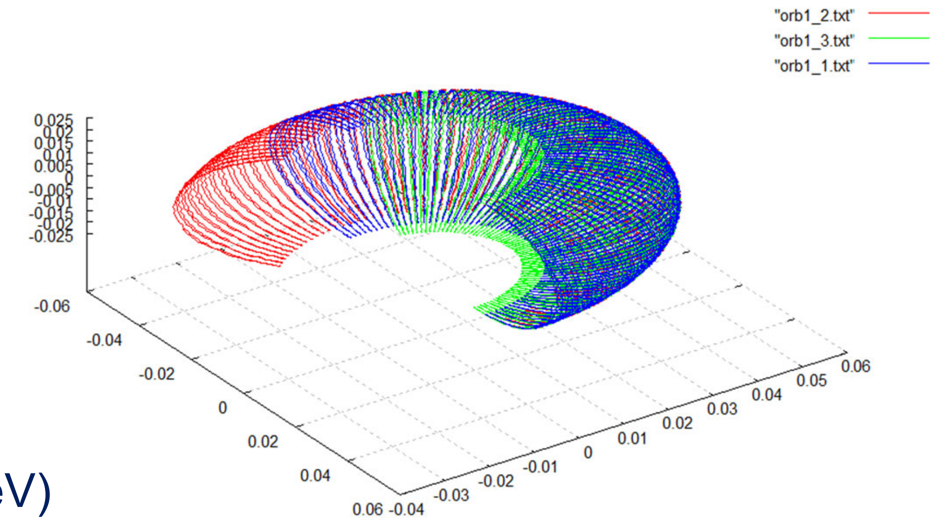




General tendency:

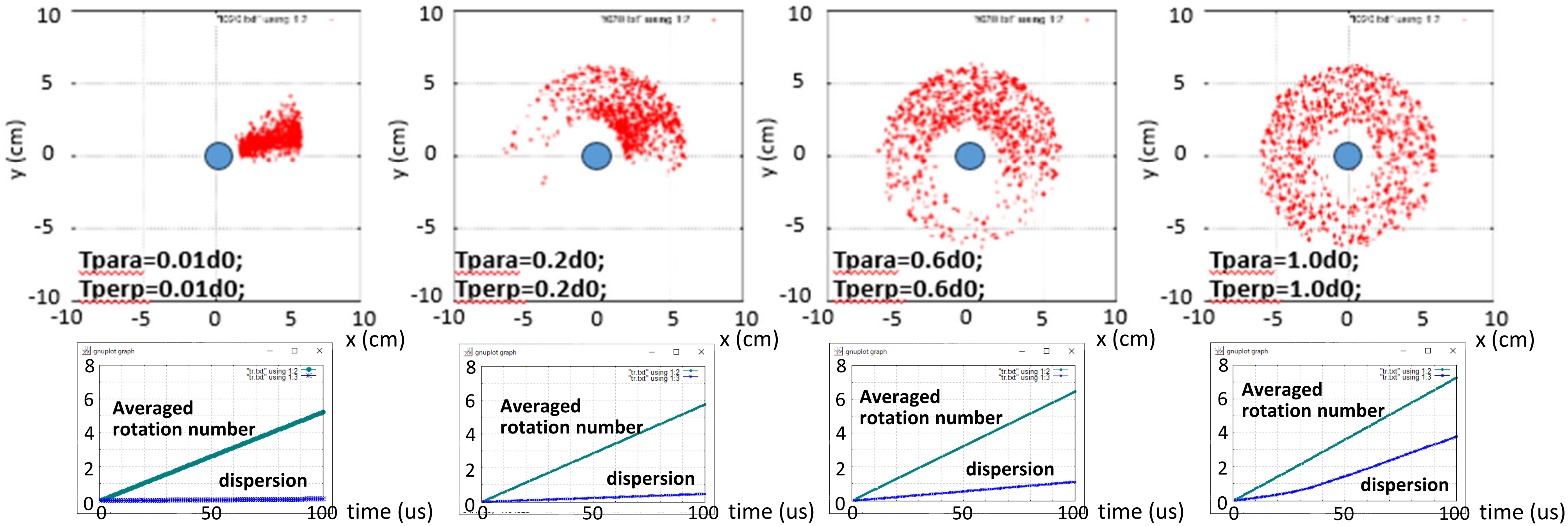
- ~10eV e+s are injected into trapping orbit (red).
- Loss on magnet (blue) is dominant for higher energy
- Further higher energy e+s are lost on chamber wall (yellow).

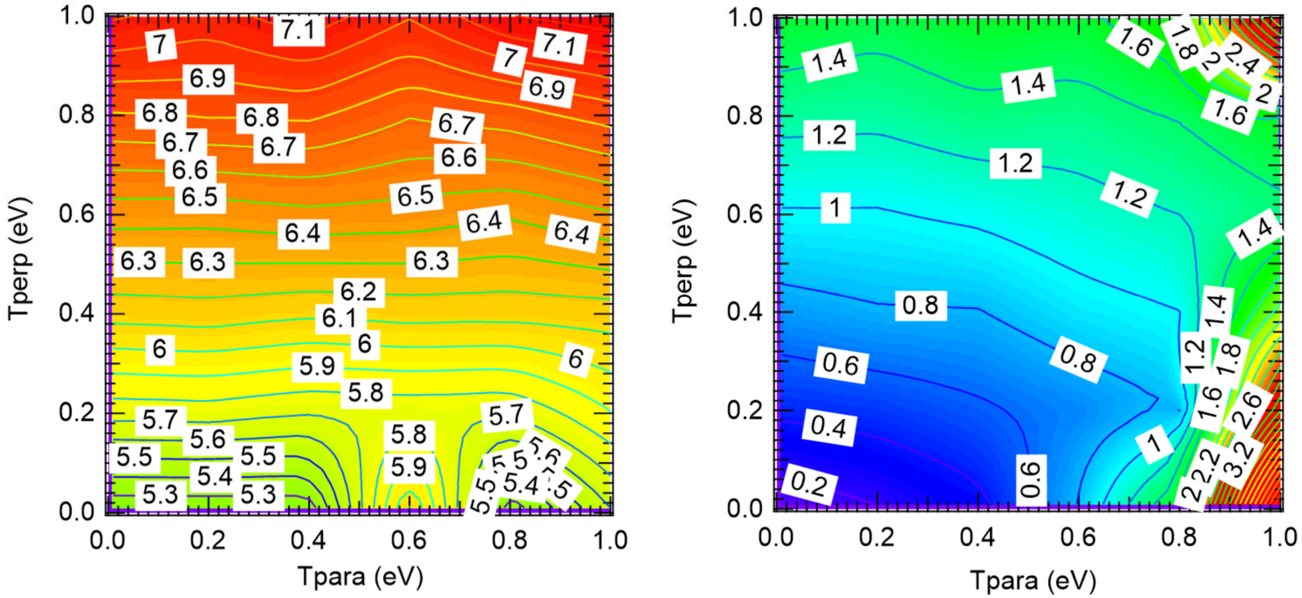




Horizontal axis : kinetic energy (eV)

Typical time required for the formation of toroidally homogeneous e+ cloud is much shorter than typical trapping time

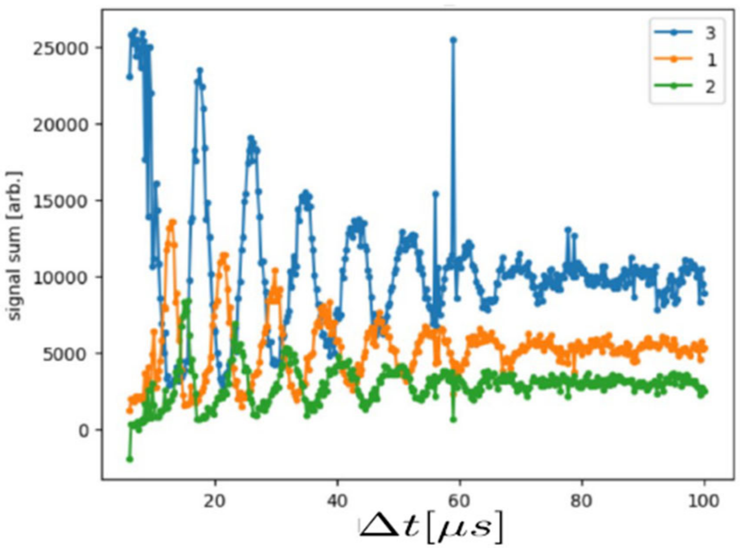




For realistic temperature of ~eV, toroidally homogeneous state is realized in ~100us

(Left) toroidal rotation number and (right) its dispersion after flight of 100us

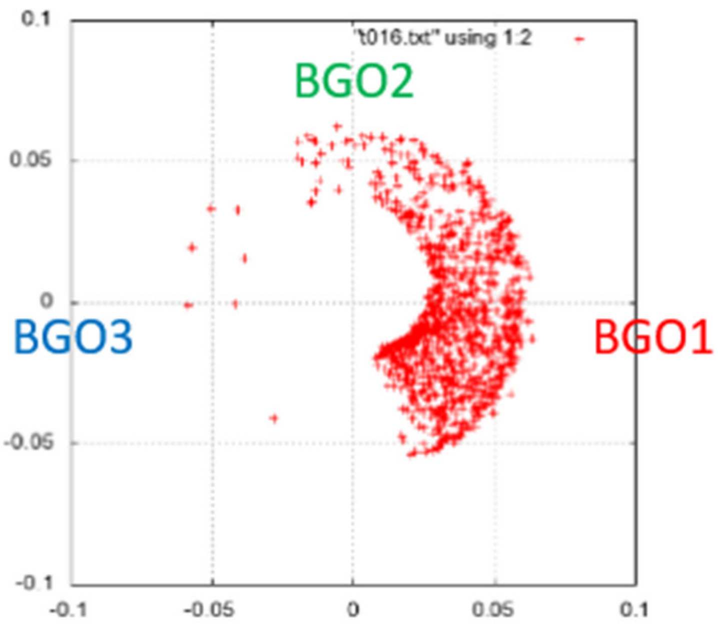
Comparison with measurements with annihilation gamma-rays



Annihilation gamma observation by BGO1-3（Experiment）

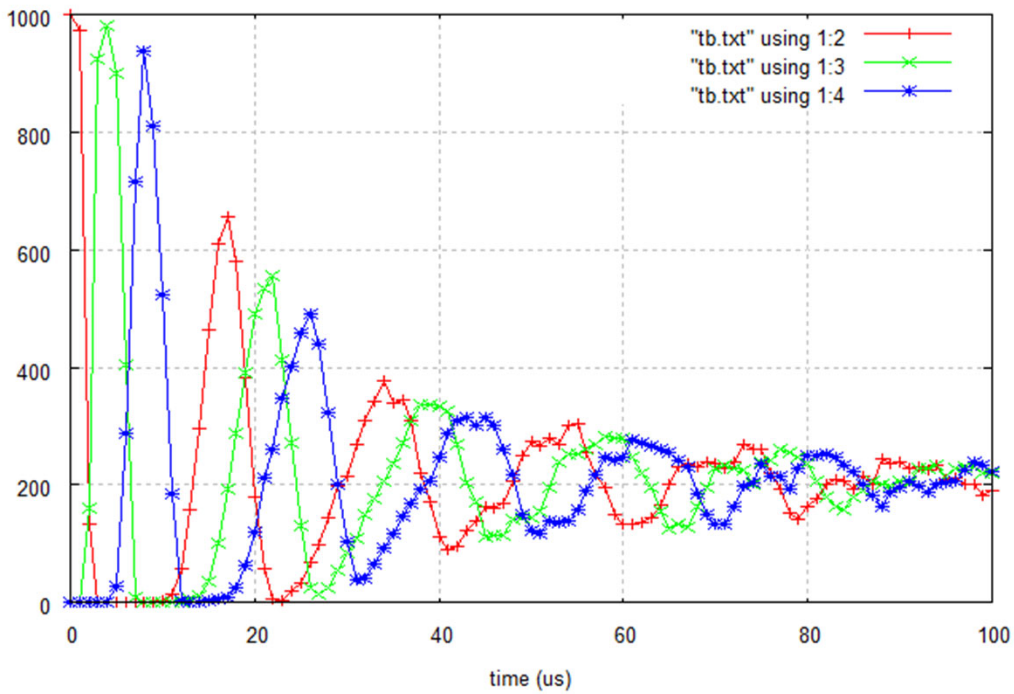
Oscillating signals with slow decay of amplitude are observed, as bunched e+s become toroidally homogeneous state

J. von der Linden, A. Deller+, to be published



Numerical estimate of gamma-ray counts

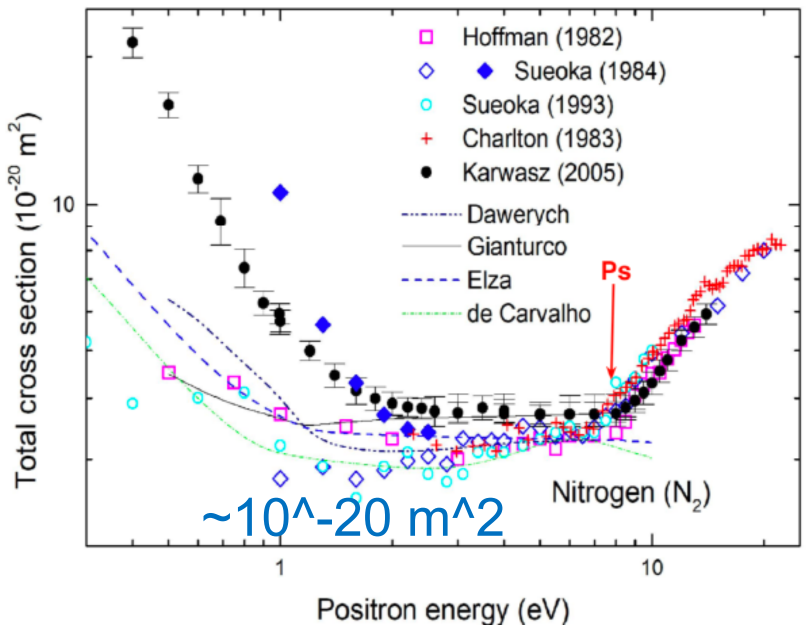
which reproduce the gamma-ray observations

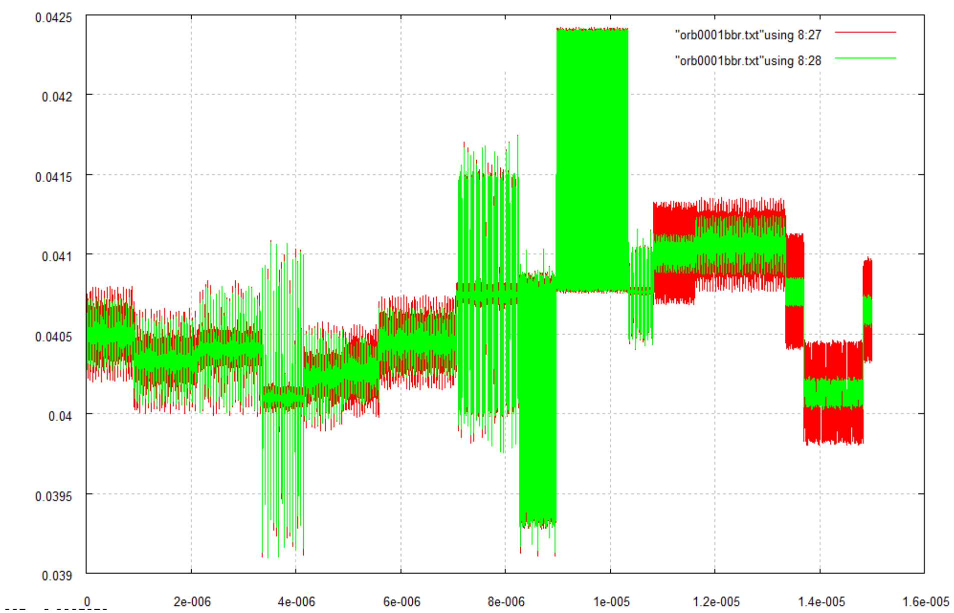


Trapping time estimate of e+s including neutral collision effects

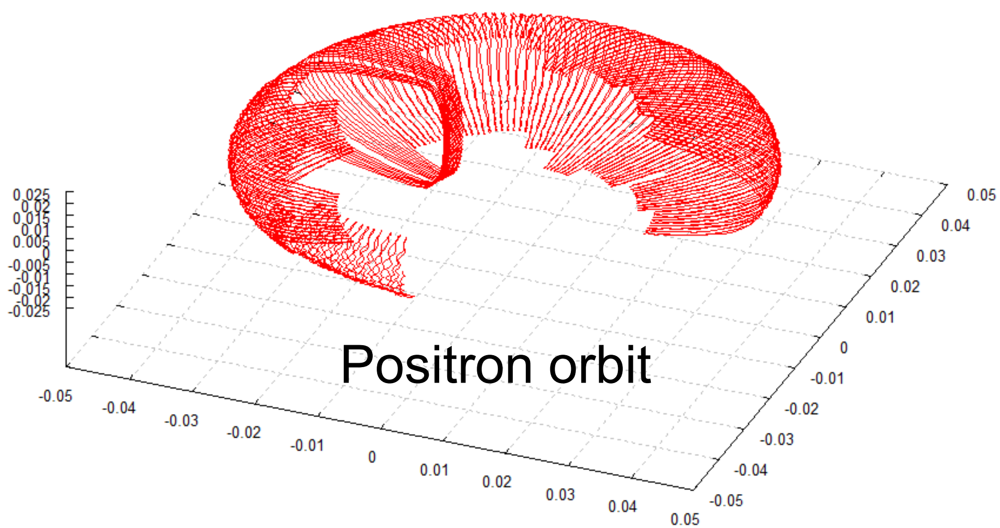
- Erratic collisions are dominant for low energy at~10^-6Pa, mean collision frequency ~10^-1s
- Collisions with random time interval was included in the orbit calculations
- Direction changes randomly, while keeping kinetic energy

2021 Carelli+

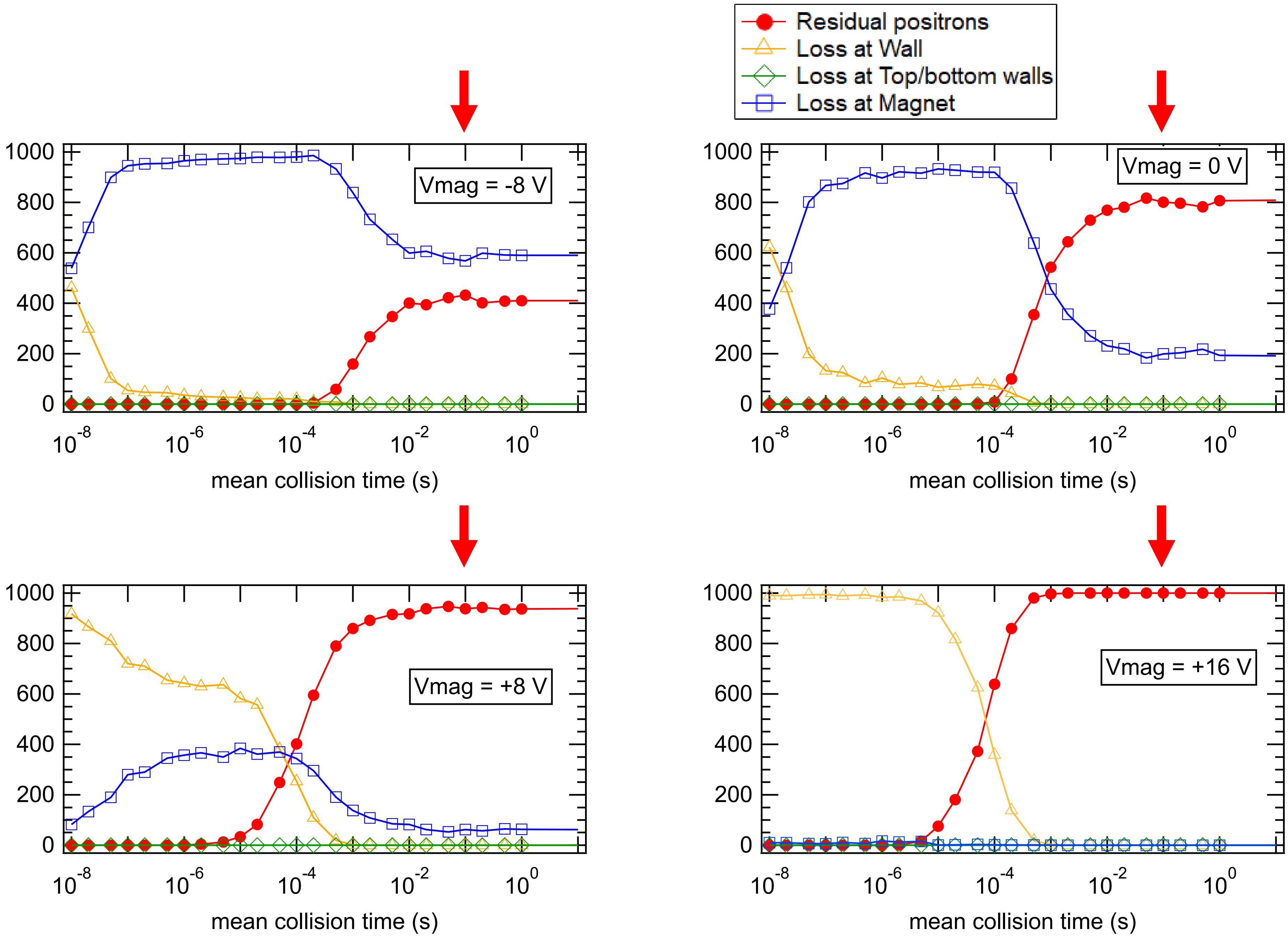




Temporal behavior of Radial position of e+

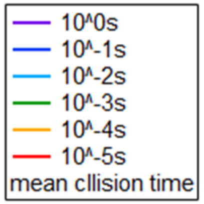


Effects of neutral collisions (remaining ratio of after 10ms trapping)

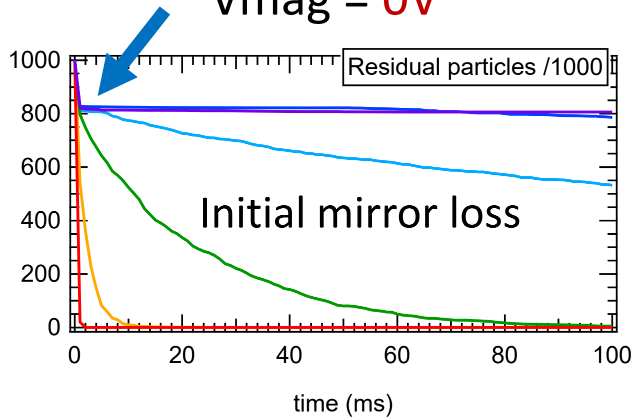


At 10^-6Pa, neutral effect at t~10ms are negligile

Towards longer-time confinement



Vmag = 0V

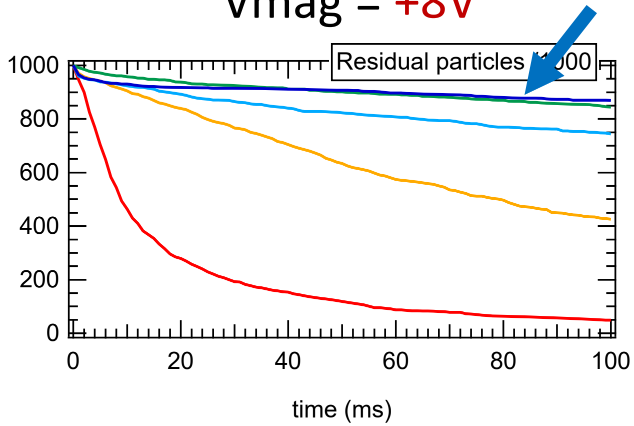


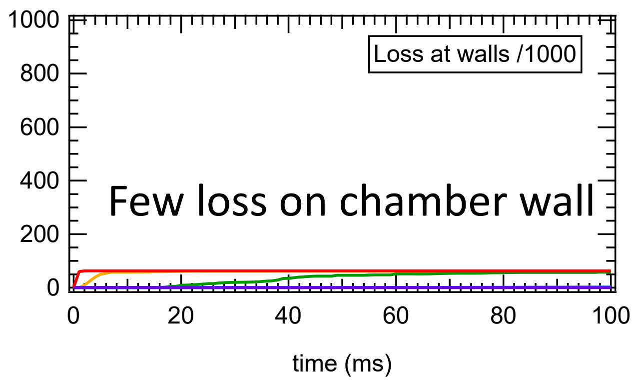
Remaining particles

By positively biasing the magnet, initial loss is reduced

However, slow loss due to error electric fields may limit longer trapping time

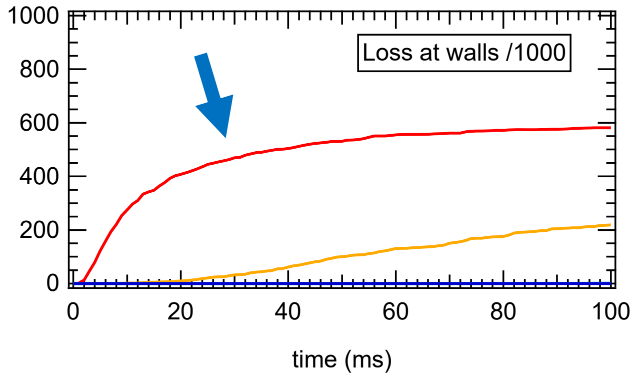
Vmag = +8V

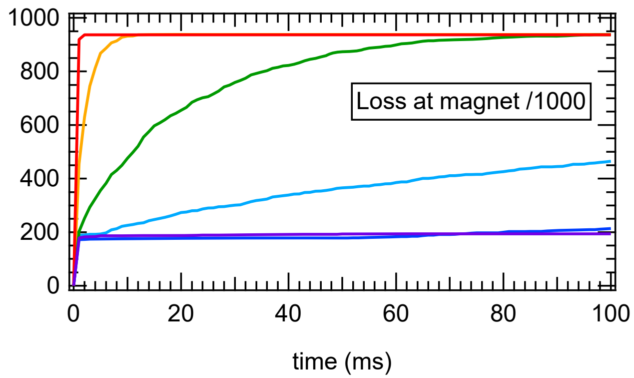




Loss to chamber wall

Problematic only when the Magnet is positively biased and neutral collisions are frequent (right)

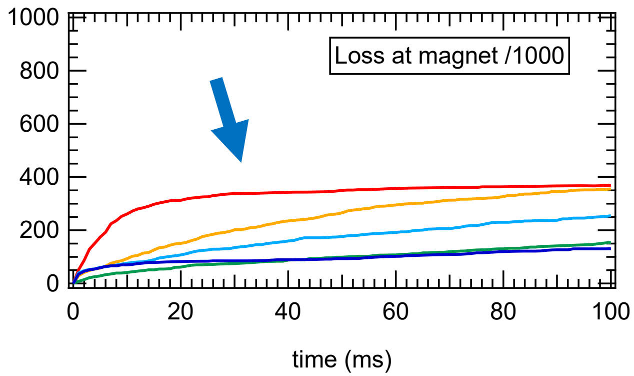




Loss to the magnet

Main loss channel when the magnet is not biased (left)

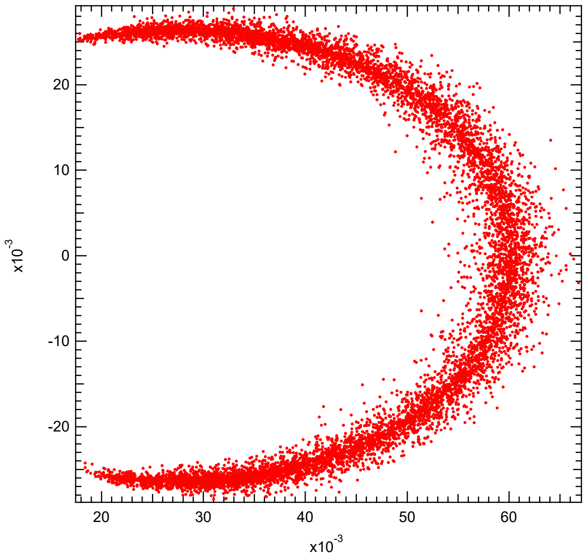
Some particles are lost due to inward diffusion of particles

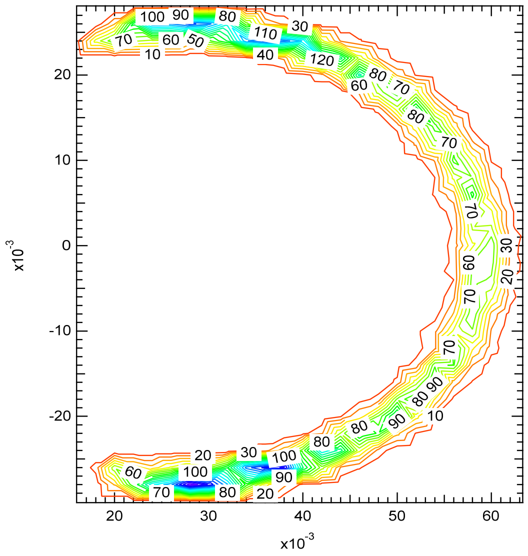


Up to several 100ms of trapping would be expected in the present configuration

Trapping orbit and Debye length of positron cloud

While toroidally homogeneous,
RZ distribution is rather
localized





0: 2342 // number of bin with no e+
1-9: 104 particle number: 320
10<: 155 particle number: 9679
20<: 117 particle number: 9141
30<: 103 particle number: 8806
40<: 93 particle number: 8468
total particle number: 10k

Center of distribution R=0.0430851

96.79% of particles are inside the contours in right figure, cross section is
S = 6.2e-4 (m^2)

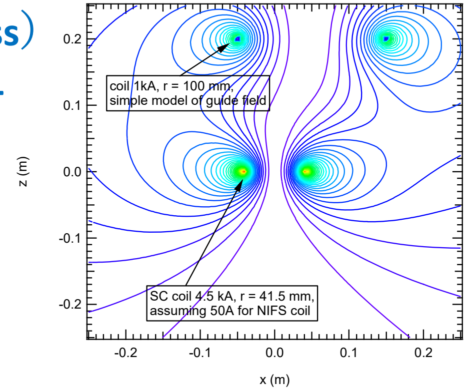
Volume is
V = 2piRS = 1.675e-4 (m^3)

Debye length 7439*sqrt(Te/n) ~ m
Is still large compared with device size

Off-set injection is not suitable for levitated dipole

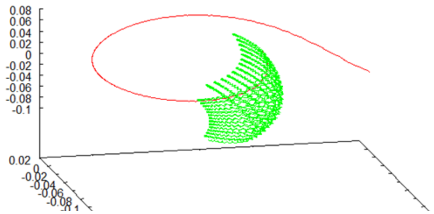
- On coil levitation,
  - stable levitation is not realized due to error fields
  - theoretically, dummy injection port (only B) is useful

Geomagnetic field （<1Gauss） needs compensation in RT-1

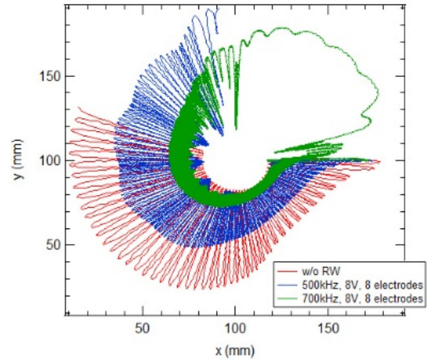


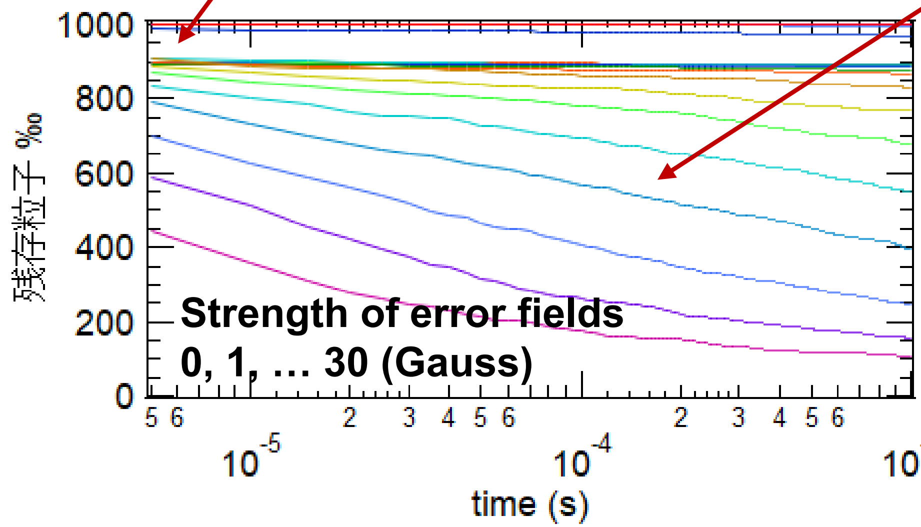
- On confinement properties of trap
  - error field due to injection port is unacceptable

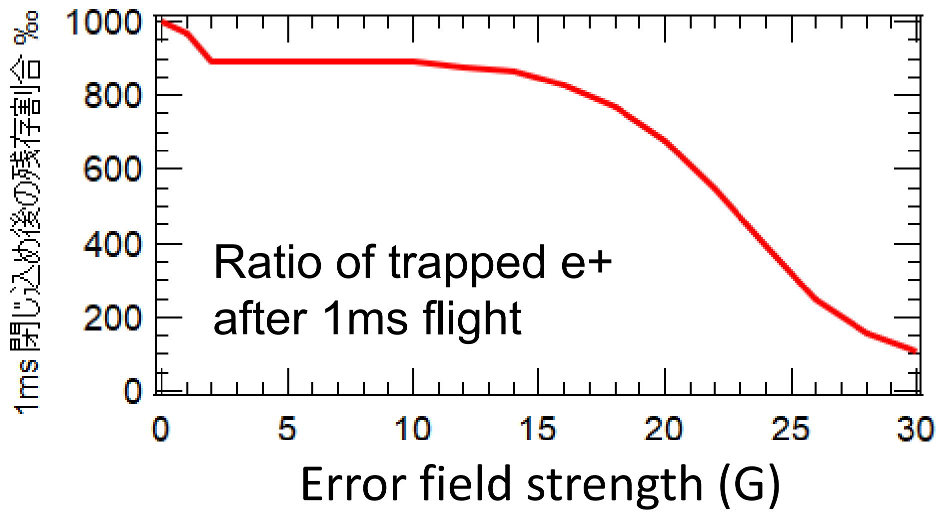
Injection into toroidal rotation orbit is not successful for some particles



Loss at chamber wall due to orbit expansion





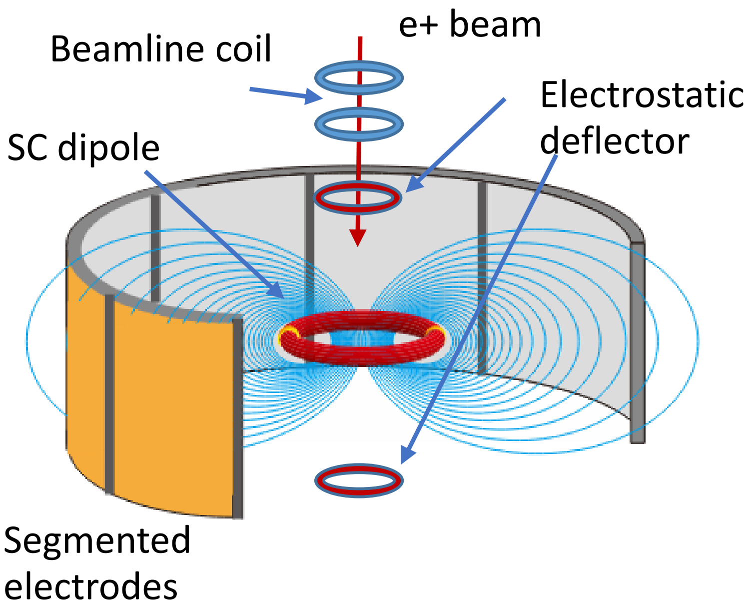


- ~Gauss error reduce trapping time

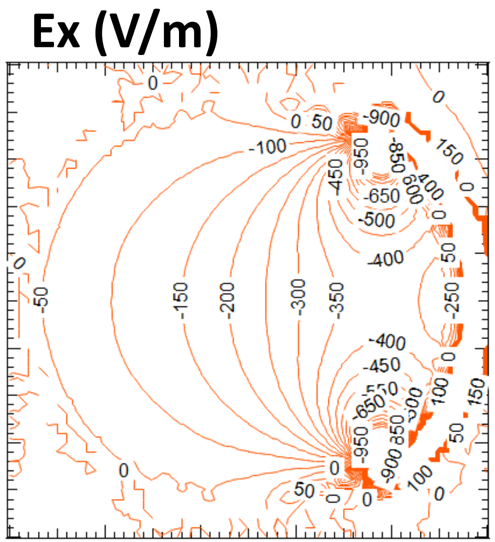
Another injection method is needed

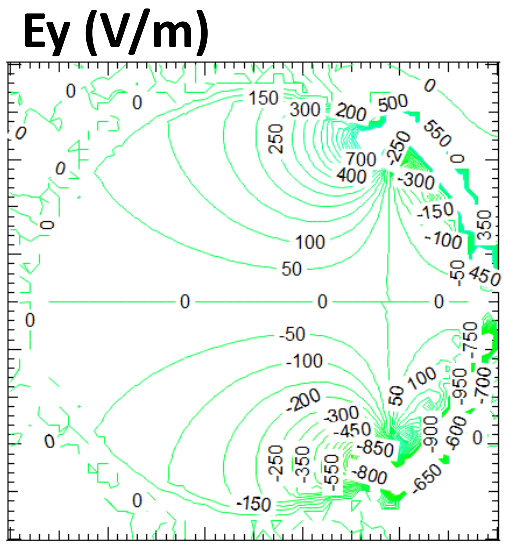
On-axis injection with symmetric B and asymmetric E

- Suitable injection method for levitated dipole
  - Injection beamline and coils are coaxially aligned
  - ExB drift injection by means of biased segmented electrodes



Segmented electrodes in prototype dipole



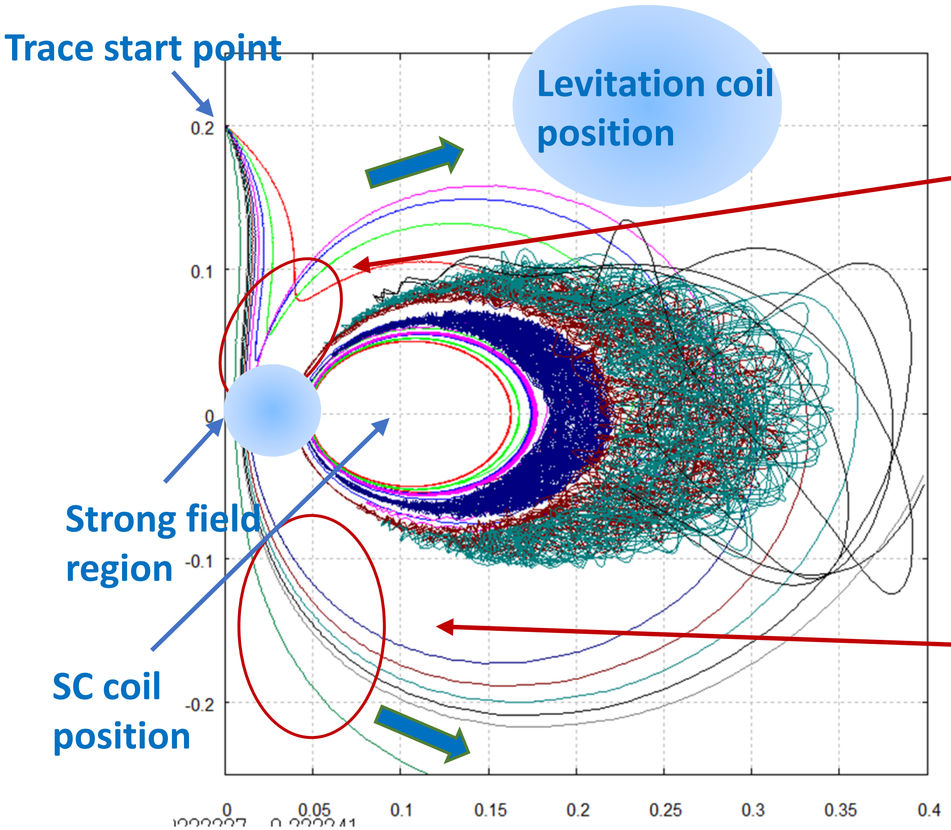


Ex (para) and Ey (perp) created by Segmented electrodes of diameter 60cm, top view of the experiment.

➡ Injection orbit analysis with realistic (<=100V) bias voltage of the electrodes

Successful injection route examples

- Injection scenario with keeping magnetic field symmetry
  - Looks promising for levitated dipole, compared with off-axis injection
  - Injection efficiency for many particles can be challenging



Typical two injection orbits for Vpara=3eV, Vperp=1eV positron

1. Northbound injection:
   Large bias and fast drift above equator, mirror reflection into trap region

   Similar to previous permanent magnetic dipole experiment

2. Southbound injection:
   Relatively weak bias without reflection

   Levitation coil does not perturb this orbit

Summary and future work

- Creation and experimental understanding of electron-positron plasma is one of near future challenges of levitated dipole project.
- Parallel development of compact levitated dipole, 5T linear trap, injection and trapping schemes are underway.
- Injection of 10^5 e+ into permanent magnet dipole and their dynamics: formation of toroidal homogeneous state, long trapping, inward diffusion
- Future works: Accumulation of many (10^9) e+ (2024) and simultaneous trapping with e- (2025), towards wave and stability experiments