Introduction of "Plasma Apparatus" Unit 3: Creation and investigation of Antimatter Plasmas

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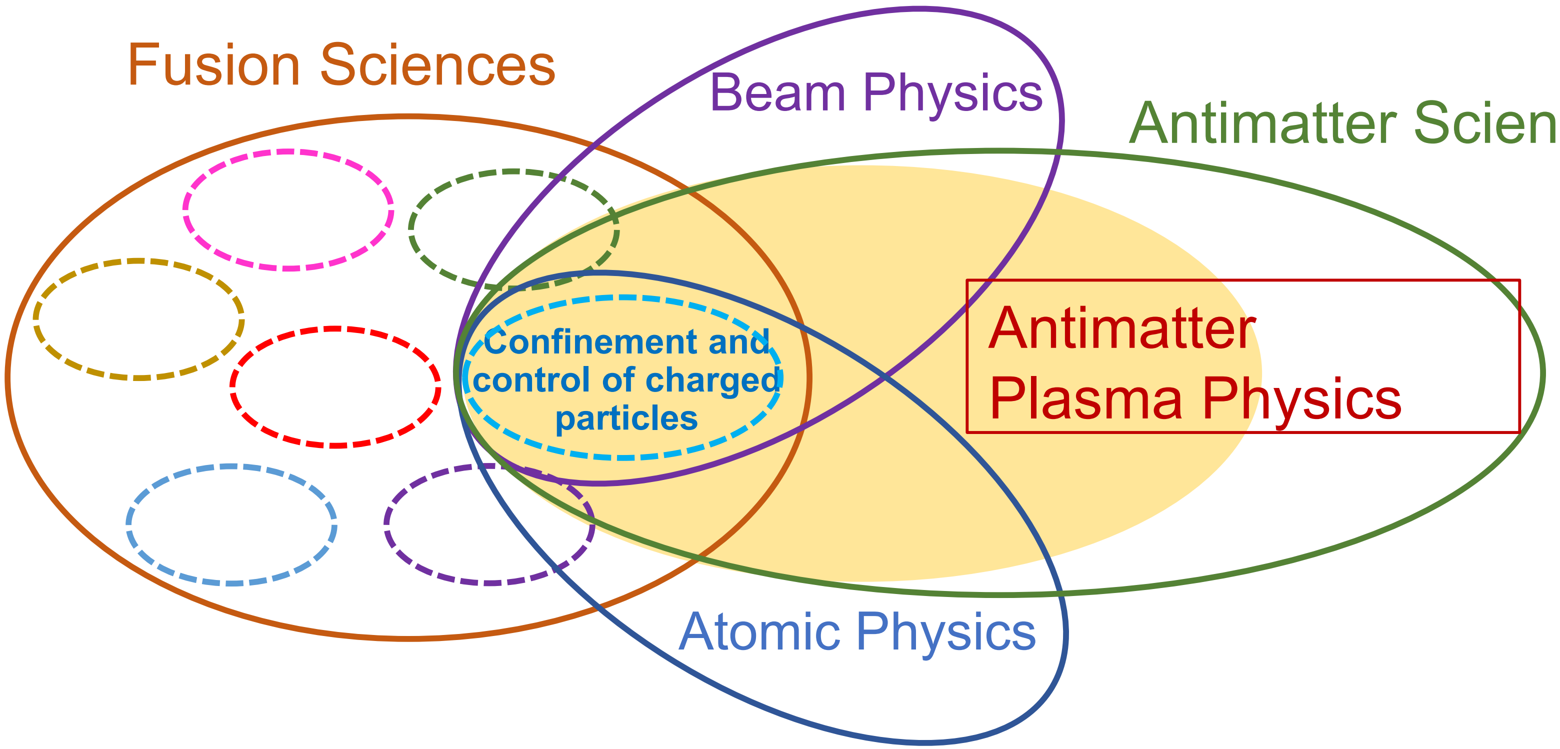
"Antimatter plasma" project in Plasma Apparatus unit

- Plasma Apparatus on Confinement and control of charged particles
  - One of central topics in plasma fusion sciences
  - Fundamental technologies and research subjects in many areas

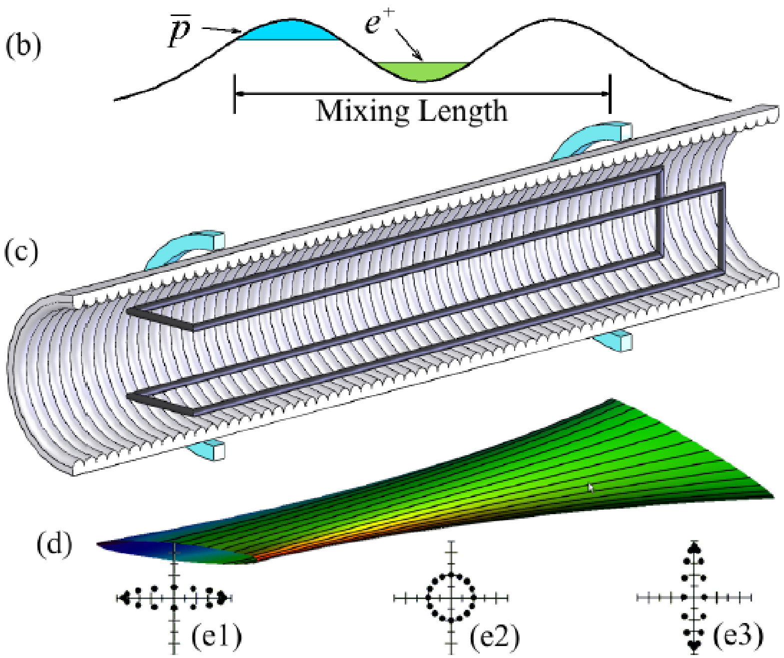


Creation of interdisciplinary research field, *antimatter plasma physics**

* 2022 Higaki+ (electron-positron plasmas), Kuroda+ (anti-hydrogen), Nagata+ (positronium), J. Plasma Fusion Res. (in Japanese).

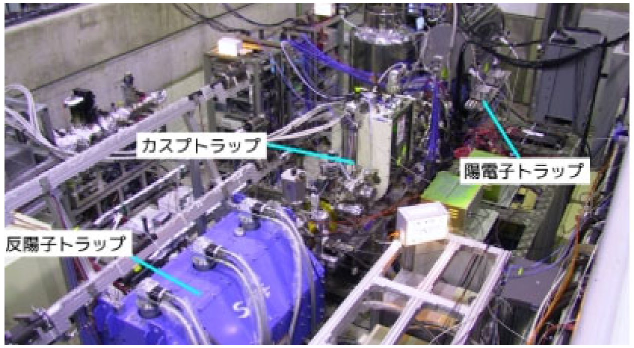
Antimatter studies realized by technologies of fusion sciences

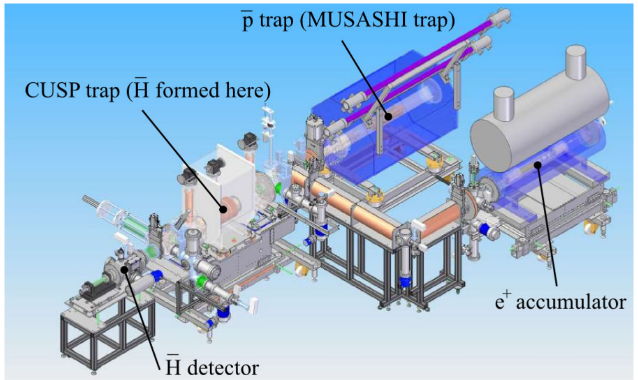
- Scientific application of *plasma apparatus* technology
  - "Confinement difficulties" are common issues in many areas
  - Knowledges in fusion science can open new physics studies
  - Collaboration with recent progress in antimatter sciences



2005 Fajans+, PRL

Antihydrogen formation and non-neutral plasma confinement（ALPHA,ATRAP）



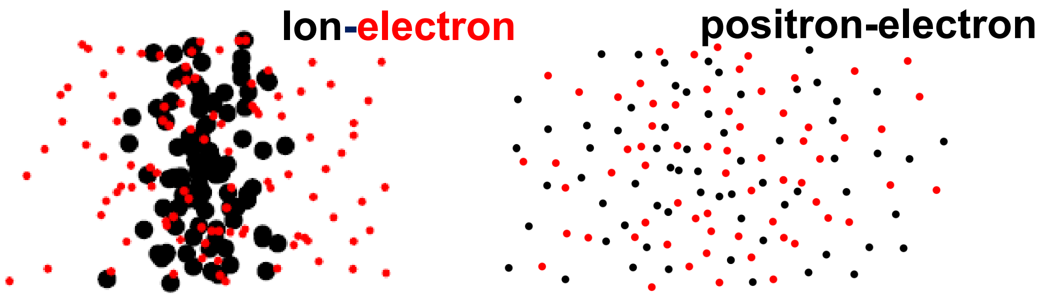


Cusp magnetic field trap to anti-hydrogen formation (ASACUSA)

Electron-positron plasma as primary research target

- 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

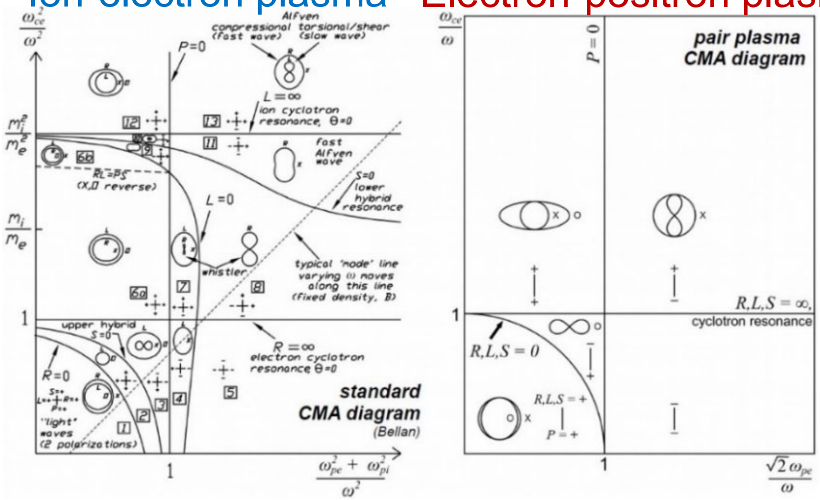
➡ **CPT symmetry**, **gravity of antimatters**, **physical constants**

State of the art of electron-positron plasma studies

Theoretical ad numerical progress

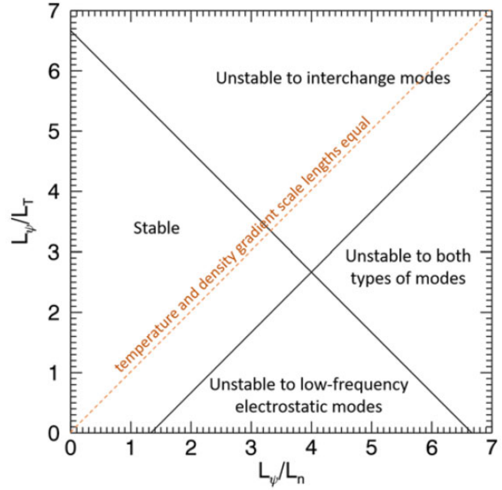
- Degenerated dispersion relation

Ion-electron plasma Electron-positron plasma



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

- Robust stable state prediction



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.

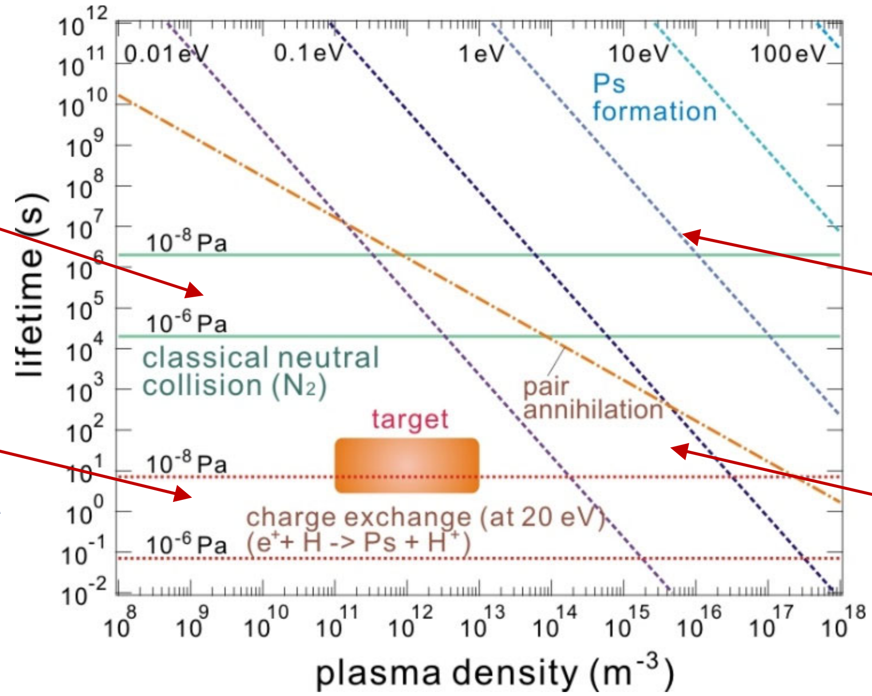
Feasibility of electron-positron plasma experiments

- **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

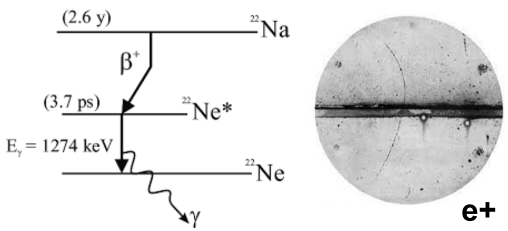
Life times of positrons and electron-positrons set by various processes

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

So why difficult to create e+/e- plasmas?

- In order to satisfy plasma conditions,
  - to accumulate more than 10^9 positrons, and further
  - simultaneous trapping with electrons are needed

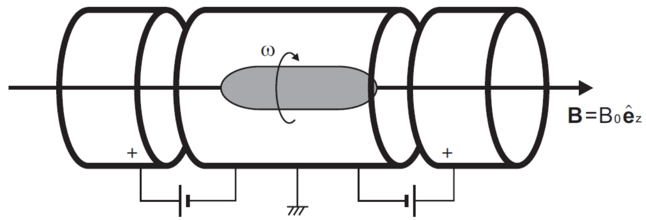
- Antimatter



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

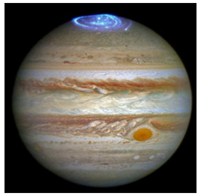
Trapping configuration for electron-positron plasmas

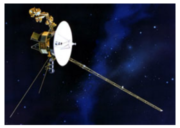
Plasma studies in *artificial magnetosphere*

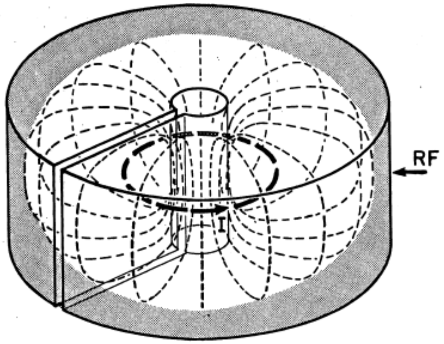
1987 Hasegawa, Comm Plasma Phys. Contr. Fusion

Globally equivalent to magnetospheres, generated by SC ring magnet

"Dipole Fusion" by Hasegawa

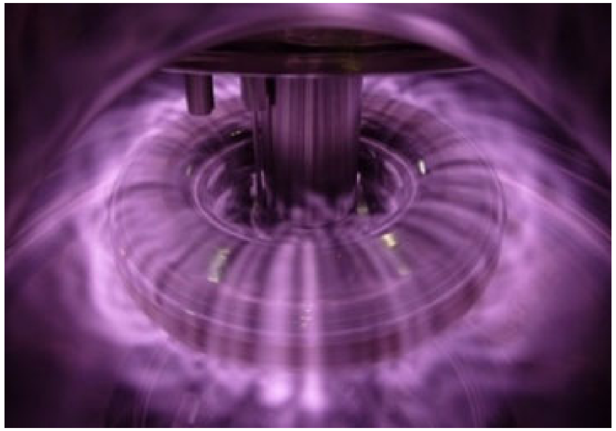




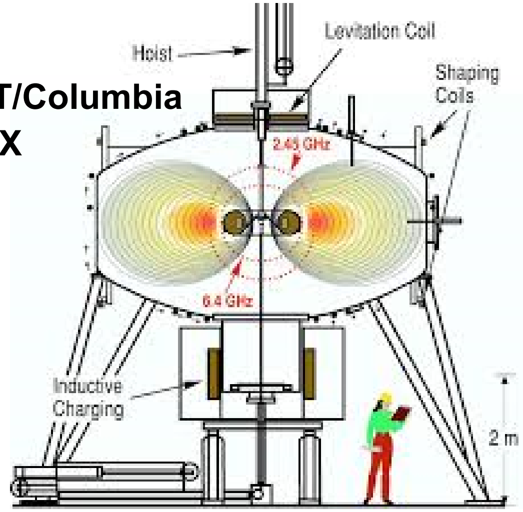


D-T ⇒ D-D, D-^{3}He etc.

RT-1 of U. Tokyo



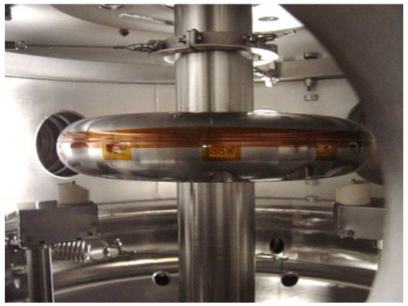
MIT/Columbia LDX

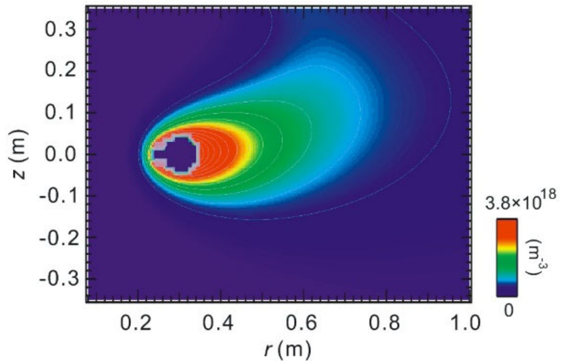


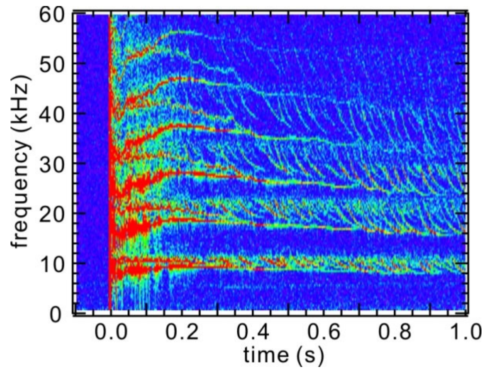
Levitated dipoles with SC coils

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

- High-Tc SC technology
- high-beta plasma
- non-neutral plasmas







2013 Ogawa, Mito, Yanagi+ 低温工学

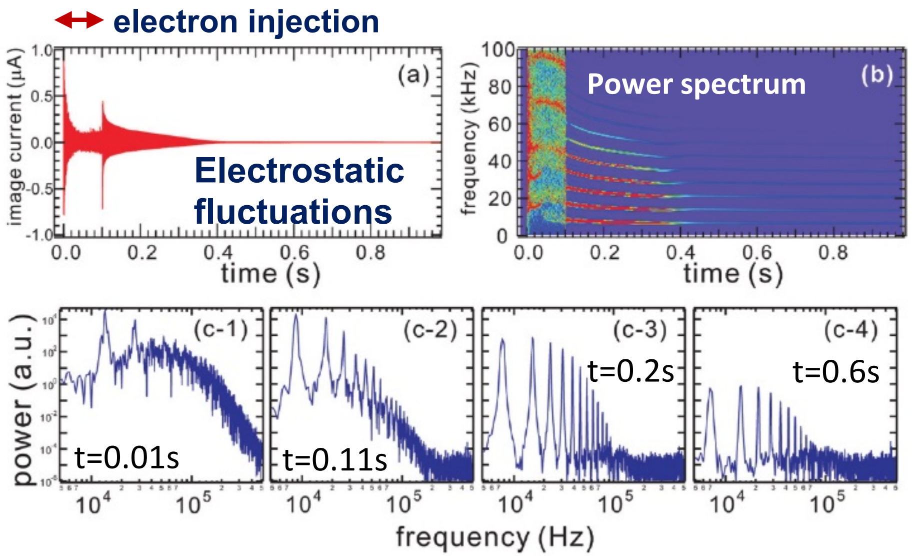
2022 Kenmochi, Nishiura+ Nuclear Fusion

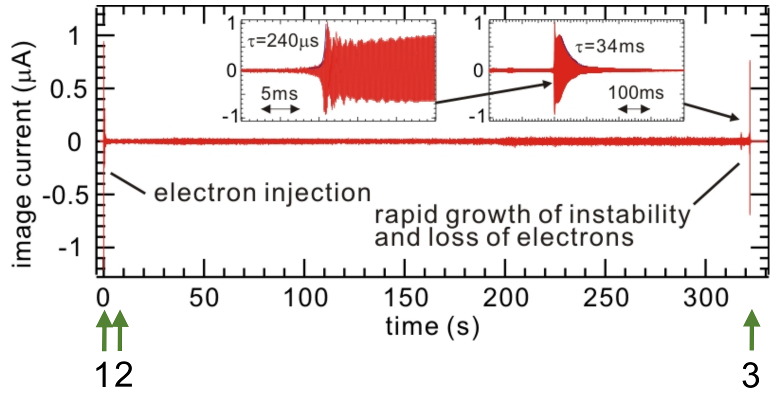
2010 Yoshida+ Phys. Rev. Lett.

Trapping of non-neutral plasmas in levitated dipole

Pure electron plasmas confined for >300 s in RT-1

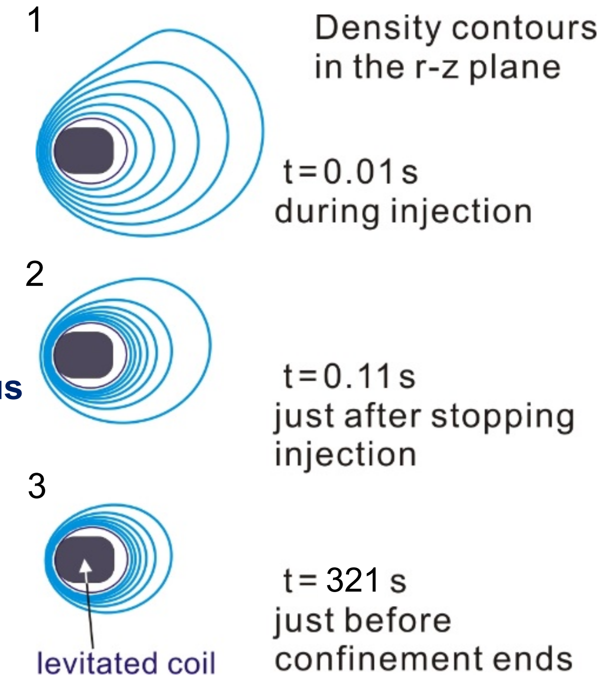
Pure magnetic (without E) toroidal system for particle trapping





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 are simultaneously in a same geometry of levitated dipole

Goal of Antimatter Group of the Plasma Apparatus unit

Creation and investigation of "antimatter plasma physics"

- By combining Pulsed slow e+ beam and Compact levitated dipole, create plasma state (Ne~10^{11-12} m^{-3}, Te<~1eV) of electron-positrons

Linac + buffer gas trap
Large number of e+ trapping

\+

Injection into dipole and
Simultaneous trap with e-

→ Pair-plasma creation

- Experimental study of collective phenomena of antimatter plasmas by

1. Emergence of collective phenomena of e-/e+ system as plasmas and investigation of degenerated dispersion relation and wave properties

2. Transport control and creation of plasmas with steep density gradient, in relation to stability of pair-plasmas that decide the plasma structure

3. Effects of instabilities on the transport and loss of pair-plasmas

Further application of large number of positrons to antimatter plasma physics

Overall plan of the pair-plasma experiment

Linac-based e+ source at AIST

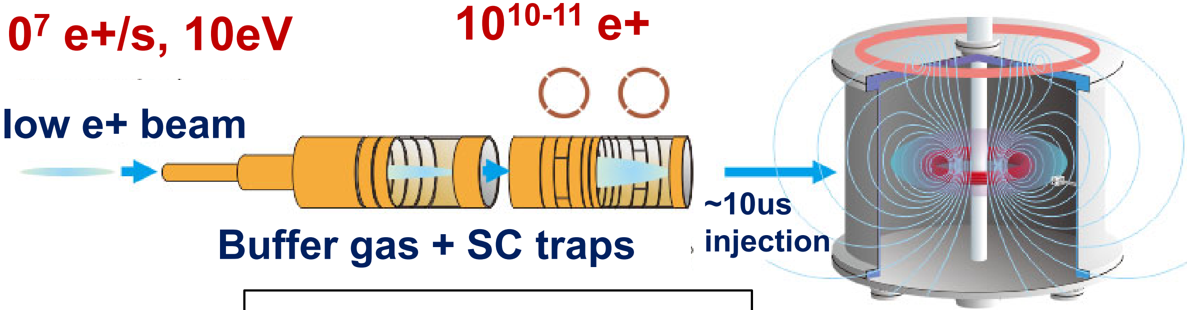
2020 Higaki Michichio+ Appl. Phys. Exp.

Pulsed e+ source

10^7 e+/s, 10eV

Slow e+ beam

10^{10-11} e+

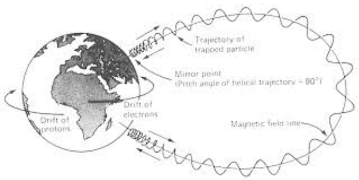


Buffer gas + SC traps

~10us injection

Accumulation and extraction of positrons

2020 Higaki+ App. Phys. Exp.



Magnetic mirror

>10^{10} e+

10^{11-12} m^{-3}

Antimatter Pair-plasma

Compact levitated dipole

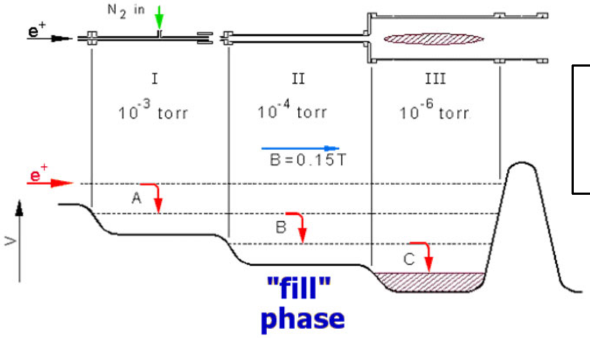
2006 Yoshida+, PFR

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.

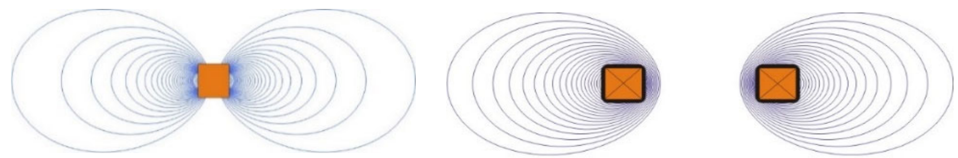
Inelastic collision and efficient deceleration

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

- 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

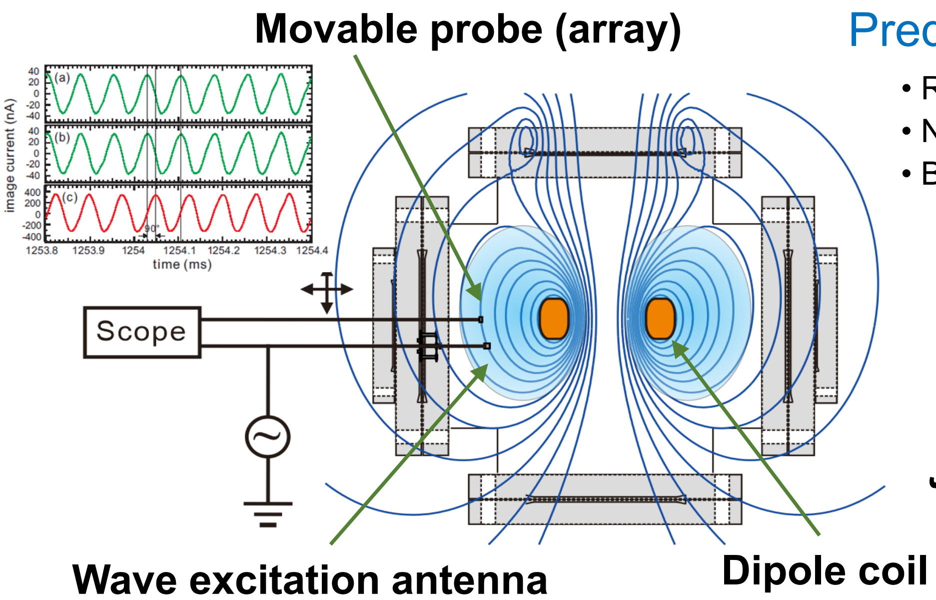
- Theoretical approach

Waves and stabilities | Self-organizaiton

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

Wave propagation properties and control of radial profile

- Collective phenomena as plasmas and study of dispersion relation

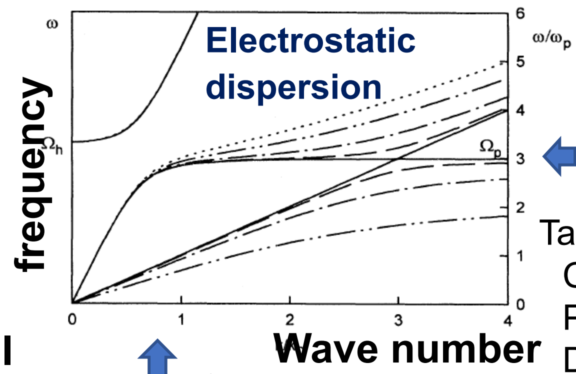


Wave experiments with pair-plasma in levitated dipole

Predicted modes including backward waves

- R and L waves are degenerated
- No helicon and whistler branches
- Backward wave (phase/group speed opposite)

1995 Zank Phys. Rev. E



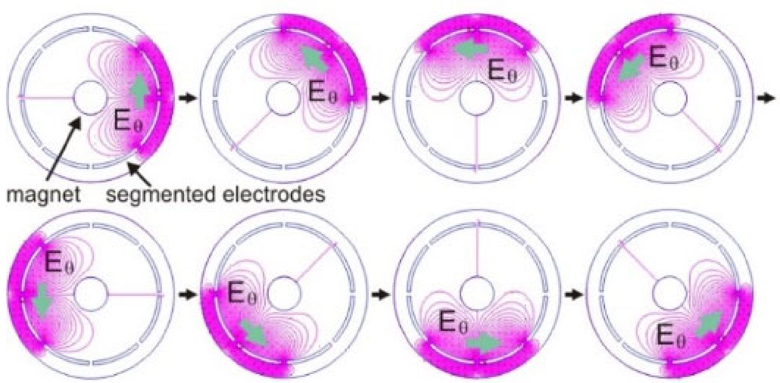
λ=<~cm

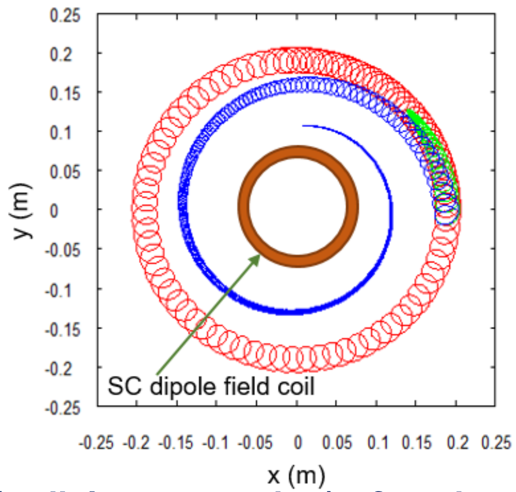
Many modes have realistic (measurable) parameters

f_p=2.8 MHz

Target B=0.01T, N_e=10^{11} m^{-3}
Cyclotron freq. f_{ce} = 280MHz
Plasma freq. f_p = 2.8 MHz
Debye klength L_d = 2.3 cm

- Detection of fluctuation modes with segmented electrodes





Rotating wall electric fields and typical motion (radial compression) of positrons

- Fluctuation mode number
- Find new mode

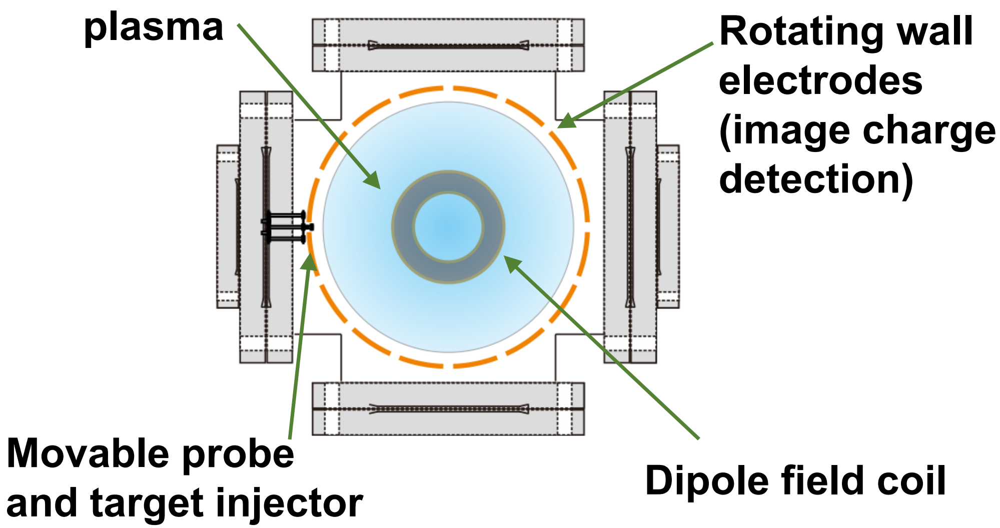
Global mode in the toroidal geometry, instabilities

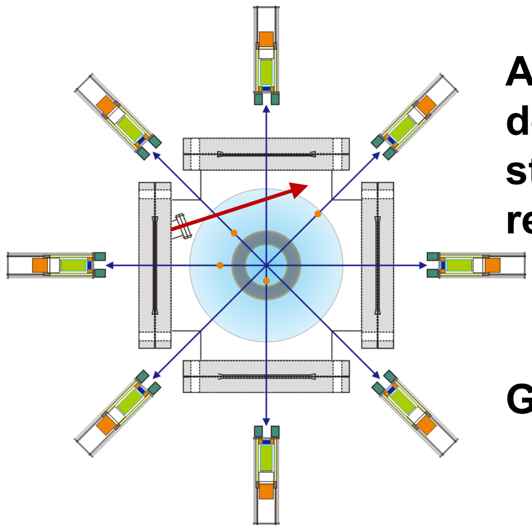
- Mode coupling effects

Classical/turbulent transport properties

Stabilities and structure formation studies

- Self-organization state of pair plasma in dipole field





- Image charges at segmented electrodes
  - Applicable to non-neutral state plasmas
  - Single-component plasmas
  - Diagnostics for pair-plasma formation process

- Use of 511 keV annihilation signal
  - Pair annihilation with residual neutral
  - Target is used for a probe
  - Tomographic density reconstruction

- Density gradient limit is different from conventional plasma?
- Instability decides the density gradient?

Pair plasma related physics research with e+/e- system

Summary of "antimatter plasma physics" activity

- Plasma conditions for electron-positron system is challenging
  - Accumulation of more than 10^9 cold positrons
  - Simultaneous trapping with electrons with same number

- We solve these issues by fusion science-based Plasma Apparatus methods; Injection of intense pulsed positron beam into compact levitated dipole to realize plasma state with electrons, Ne~$10^{11\text{-}12}$ m^{-3}, Te<~1eV

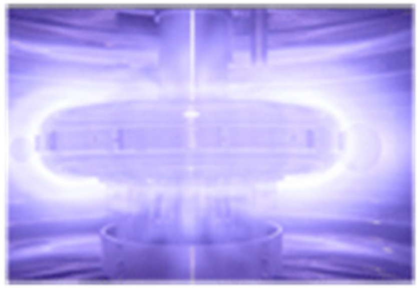
Linac + buffer gas trap
Large number of e+ trapping

+

Injection into dipole and
Simultaneous trap with e-

→ Pair-plasma creation

2020
Higaki Michichio+
Appl. Phys. Exp.



2006
Yoshida+,
PFR

- Comparison with other approaches（mirror, hydrogen）, application to more complex antimatter plasmas and physics research

2017 Oohara+ PoP   2020 Higaki+ App. Phys. Exp.