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電子陽電子プラズマ生成のための小型ダイポール磁場トラップの開発状況

Development status of a compact superconducting levitated dipole trap for electron-positron plasma formation

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1. Unique properties of pair-plasmas and their experimental investigation

Unique research subjects in plasma physics

Because of the mass symmetry, pair-plasmas are predicted to exhibit unique properties, which are fundamentally different from conventional ion-electron plasmas. Examples of such difference include remarkable wave propagation and stability properties, enhanced soliton behavior, the lack of Faraday rotation, and strong nonlinear Landau damping effects.

1978 Tsytovich Wharton, Comm. Plasma Phys. Ctr. Fusion **4**, 91.

Pair plasma with electron-positron system

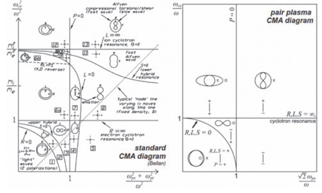
Experiments with light-mass particles enables investigation on wave and instabilities ranging from low to very high frequencies, which are not yet investigated in the ion systems.

2005 Oohara Hatakeyama PRL **95**, 175003.

Insight into astrophysics and scientific applications

Electron-positron plasmas are believed to exist ubiquitously in the environments of high-energy density astrophysicak objects, such as pulsar magnetospheres and active galaxies. Also, realization of a large number of stored positrons and stable confinement of plasmas at any non-neutrality is a basis for the formation of a large number of positronium (Ps) atoms and their Bose Einstein condensation (BEC), development of an intense γ-ray source, efficient antihydrogen atom production, and formation of antihydrogen plasma and further complicated matter-antimatter plasmas.

from: 2017 Stenson+



CMA diagrams for usual (ion-electron) and symmetric (electron-positron pair) plasmas

2017 Stenson+ J. Plasma Phys. **83**, 59580106.
2014 Helander PRL **113**, 135003.
2019 Horn-Stanja+ J. Plasma Phys. **85**, 905850302.

A lot of theoretical and numerical works, but very few experimental approaches so far

- theory: waves, instabilities, gyrokinetics
- experiment: linear traps including mirror, laser

2017 Higaki+ New J. Phys. **19**, 023016. 2015 Sarri+ Nat. Comm. **6**, 6747.

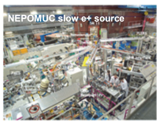
Experimentally, what are challenging?

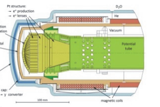
- Simultaneous trapping of high-density positrons and electrons as a plasma
- Very intense slow positron source is required

2. The PAX/APEX project with NEPOMUC, FRM-II

2012 Pedersen+ New J. Phys. **14**, 035010. 2012 Hugenschmidt New. J. Phys. **14**, 055027.

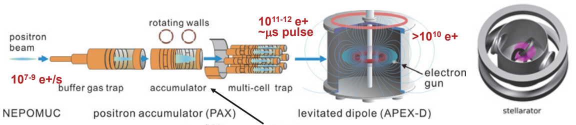
NEPOMUC: World's strongest slow positron facility

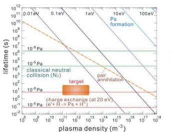




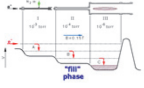
~10^9 /s at 1 keV, ~10^7 /s at 5 eV, DC
cf) ^{22}Na: ~10^6 /s, liniac: ~10^7 /s

Magnetic confinement of pair plasmas in toroidal configurations





Lifetimes of e+ and e+/e- clouds determined by various processes



- buffer-gas based accumulator

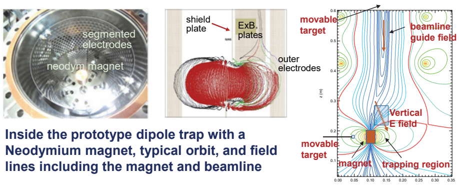
2015 Danielson+ Rev. Mod. Phys. **87**, 247.
2004 Surko Greaves Phys. Plasmas **11**, 2333.

- toroidal confinement geometry for pair-plasmas
- Minimum target: n_e >~10^{11}m^{-3} and T_e~1eV, which realizes realistic Debye length of λ_D< 2cm

3. e+ experiments with prototype dipole

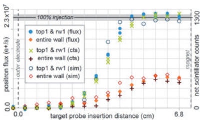
Injection and trapping of positrons in a toroidal geometry

- For injection, efficient transport is need across closed field lines
- Long and stable trapping properties are also essential
- These experiments were done with permanent magnet trap



Inside the prototype dipole trap with a Neodymium magnet, typical orbit, and field lines including the magnet and beamline

Loss-less injection and fairly long trapping of positrons



Ratio of positron number reaching the target probe after injection

2018 Stenson+ PRL **121**, 235005.

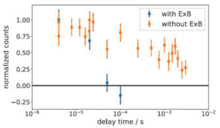
Drift injection scheme into dipole

- drift injection across separatrix
- beamline ~ 5mT << magnet ~ 0.6T

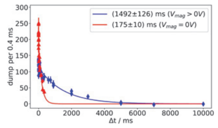
ExB drift by perpendicular electric fields*

Trapping time improvement

- gating ExB plate bias: τ ~ 0.1ms ➡ ~ 10ms
- gating other electrodes: ➡ τ ~ 100ms
- biasing the magnet (+) : ➡ τ ~ 1s



Trapping time with and without gating the ExB plate voltages



Trapping with positively biasing and grounding the magnet

2018 Horn-Stanja+ PRL **121**, 235003.

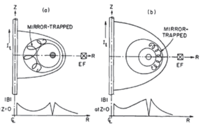
4. Toward HTS dipole trap for pair-plasmas

How can we create symmetric closed field lines?

Permanent magnet dipole	Levitated SC dipole
field lines intersect the magnet	closed field lines
confinement along field lines was done by electric fields and mirror trapping	positrons and electrons fly on magnetic field lines without any perturbation

For simultaneous trapping of positrons and electrons as plasmas, we need closed field lines / magnetic surfaces, which are realized by a magnetically levitated superconducting coil (or stellarator).

Previous "internal conductor" experiments and levitated dipole



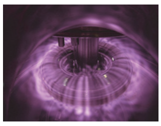
Dates back to works in 1960s

- One of milestones in fusion plasm studies
- Concept of Min-B, overcoming Bohm diffusion

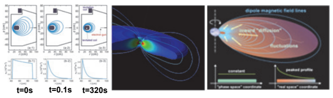
1973 Yoshikawa Nucl. Fusion **13**, 15.

Recent renewed interest

- Unique stability against steep pressure gradient
- Relaxation of flowing high-β plasmas



RT1, example of levitated dipole



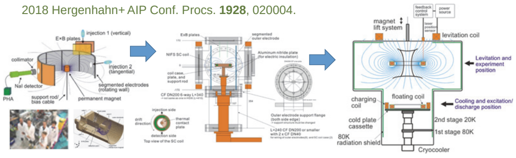
Recent experiments at RT-1 and LDX showed fluctuation-induced inward diffusion and excellent confinement properties of plasmas

2010 Yoshida+ PRL **104**, 235004.

5. Overall plan of the compact SC dipole

Step-by-step development of compact levitated dipole

2018 Hergenhahn+ AIP Conf. Procs. **1928**, 020004.



Permanent magnet trap　Supported SC trap (2019-)　Levitated SC trap (2020-)

Basic concepts and differences from previous experiments

- Compact confinement region is needed (plasma condition)
- This means that previous coil cooling and magnetic excitation methods, used in Mini-RT and RT-1 is not realistic to implement
- Direct (i.e., without using fluid circulation in the coil) cooling and inductive excitation of the F coil are planned schemes

Tentative parameters vs previous experiments

- Compact HTS coil winding with Bi-2223 tape for dipole field
- Magnetic levitation of the coil by feedback control

	RT-1	LDX	APEX-D
SC tape	Bi-2223	Nb3Sn	Bi or ReBCO
Rcoil	250 mm	300 mm	75 mm
current	116 A	1820 A	100 A
turn	2160 turns	714 turns	300 turns
total current	250 kA	1400 kA	30 kA
operation temperature	20-30 K	4 K	20-50 K
coil weight	110 kg	580 kg	2 kg
cooling method	He gas	He	thermal contact
excitation method	direct (PCS)	induction	induction
thermal shield	coil	coil (He)	chamber

Parameters and comparison with other experiments

RT-1, Uni Tokyo, Japan

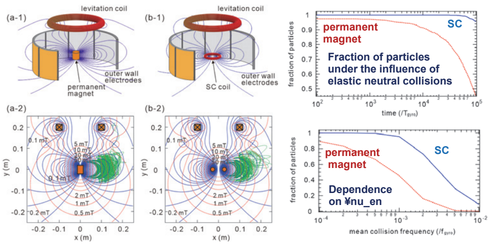
LDX, MIT/Columbia, USA

2010 Boxer+, Nature Phys. **6**, 207.

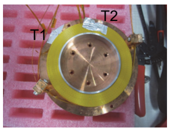
6. Development work on the compact HTS dipole experiment

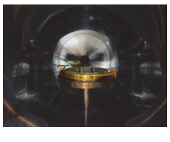
Expected Trapping enhancement in the SC geometry

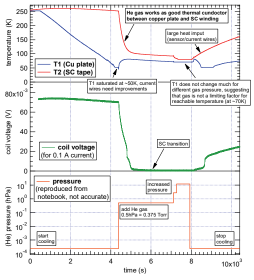
- End loss is suppressed by replacing permanent magnet with SC coil



Enhanced thermal contact and cooling with filling fluid



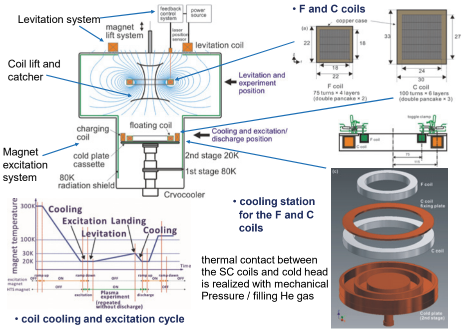




2018 Stoneking+ AIP Conf. Procs. **1928**, 020015.

Each of the device components and operation scheme

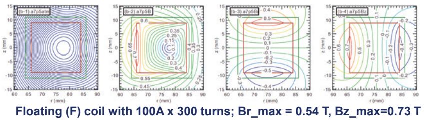
one of plans as of 2018



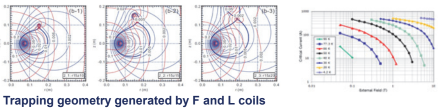
- F and C coils
- cooling station for the F and C coils

thermal contact between the SC coils and cold head is realized with mechanical Pressure / filling He gas

- coil cooling and excitation cycle



Floating (F) coil with 100A x 300 turns; Br_max = 0.54 T, Bz_max=0.73 T

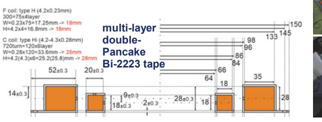


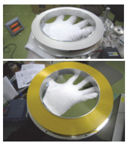
Trapping geometry generated by F and L coils

Based on NIFS collaboration program with IPP

"F" and "C" HTS coils and impregnation

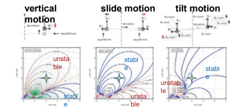
- Dimensions of floating and excitation coils



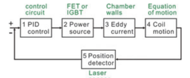


- HTS coil winding and impregnation test at U. Tokyo

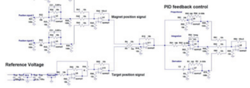
- Feedback-controlled levitation of test magnet



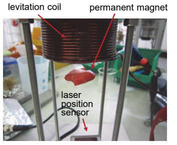
Coil configuration can be chosen so that only one-dimensional vertical motion needs feedback-control



Transfer-function analysis on the feedback-controlled stabilization of vertical motion



PID feedback-control circuit design



Permanent magnet levitation

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