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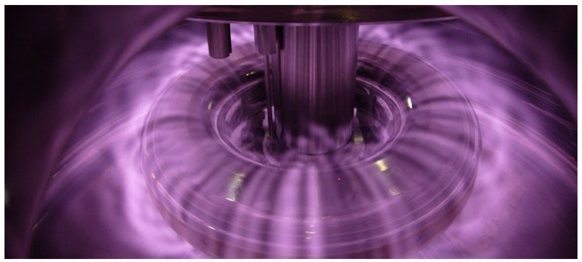
新領域創成科学研究科
GRADUATE SCHOOL OF FRONTIER SCIENCES
THE UNIVERSITY OF TOKYO

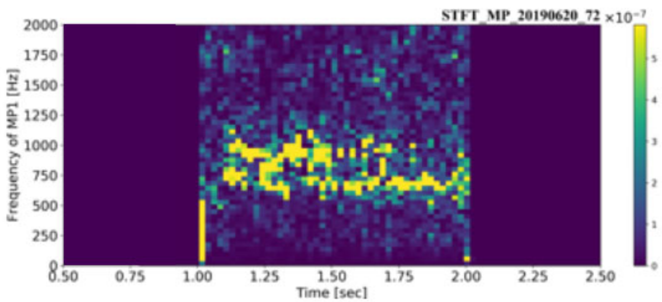
Spontaneous chirping whistler excitation in RT-1

Haru Saitoh, GSFS U. Tokyo, Japan

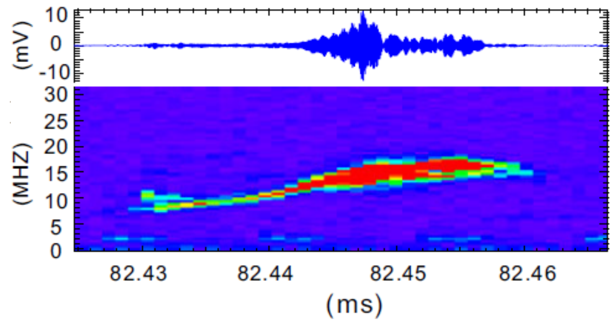
1. Introduction; Levitated dipole or artificial magnetosphere
2. RT-1 Levitated dipole
3. Spontaneous excitation fluctuations in hot electron plasma
4. Summary



Plasma in RT-1 Levitated dipole



Low freq. ~KHz: inward diffusion



10-100 MHz: whistler/chorus

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

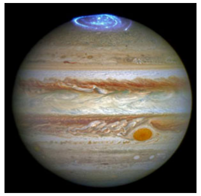
1. Introduction: Plasma experiments in levitated dipole

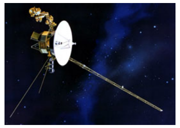
- Levitated dipole : high-β plasma investigation for advanced fusion

1987 Hasegawa, Comm Plasma Phys. Contr. Fusion

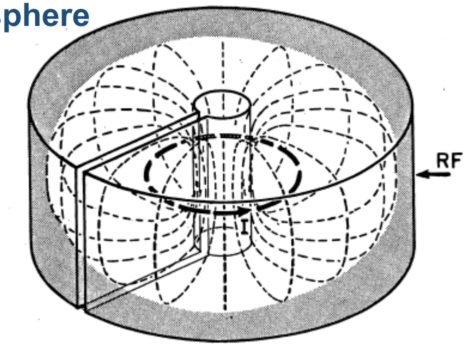
"Dipole Fusion" inspired by plasma in Jovian magnetosphere

β>100%

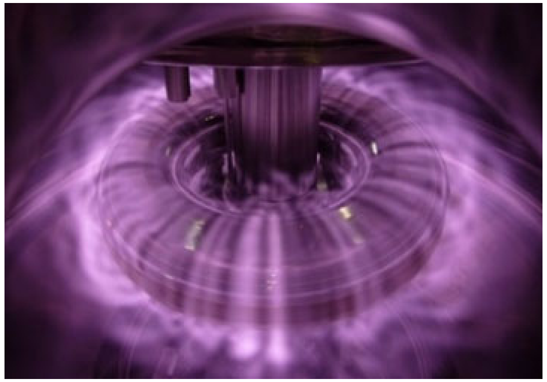




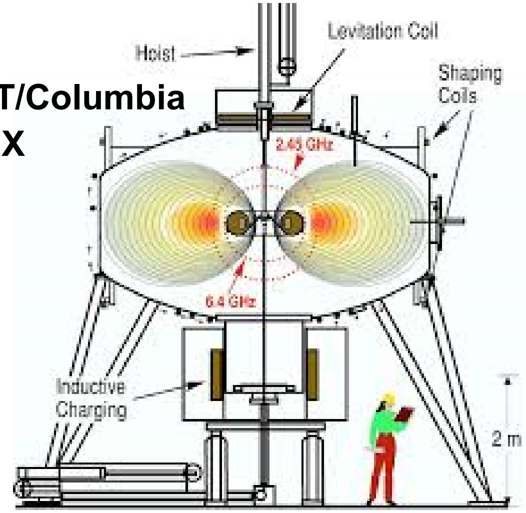
Globally equivalent to magneto-sphere



RT-1 of U. Tokyo



MIT/Columbia LDX

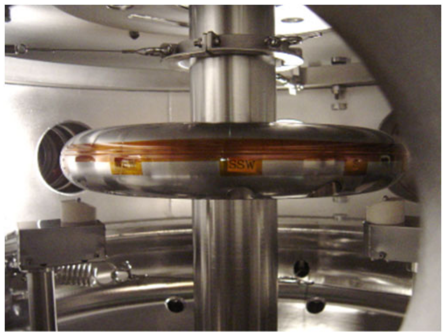


D-T ⇒ D-D, D-^{3}He Advanced Fusion

Levitated Dipole with SC coil

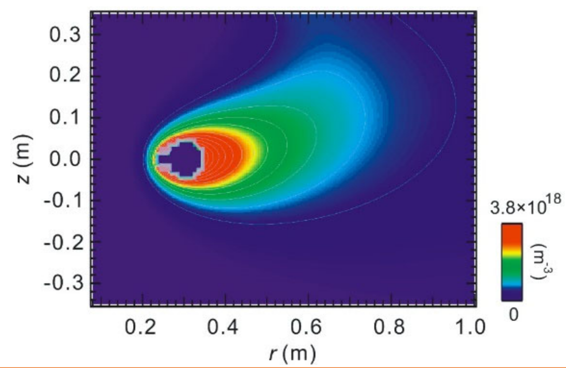
2006 Yoshida+ Plasma Fusion Res.
2010 Boxer+ Nature Phys.

High-Tc SC technologies



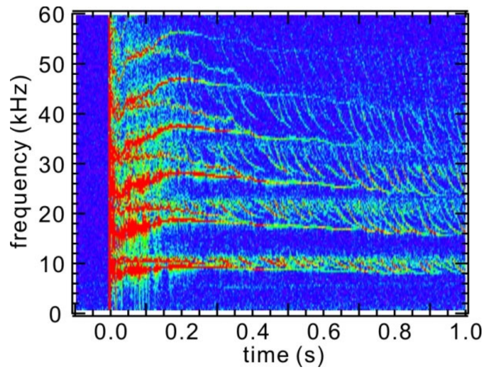
- Fusion/Geospace physics

Wave particle interaction, relaxation



- NNP and antimatters

Charged particle trap application



2013 Ogawa, Mito, Yanagi+ Teion Kogaku

2022 Kenmochi, Nishiura+ NF

2010 Yoshida+ PRL; 2020 Stoneking+ JPP

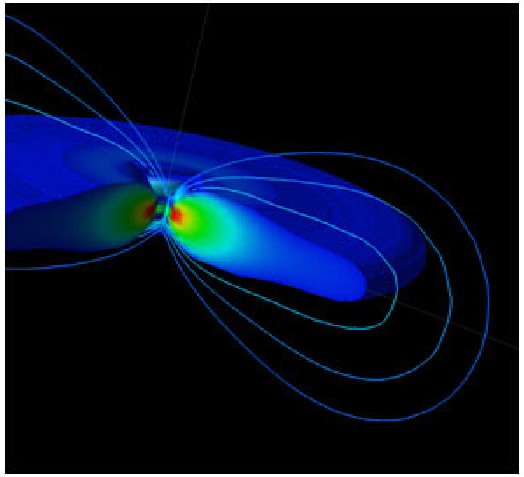
Plasma confinement in levitated dipole

- Dipole: strongly inhomogeneous field
  - Self-organization of peaked structure, inward "diffusion"
  - globally equivalent to magnetospheres; diverse common phenomena

2016 Yoshida+ Adv. Phys.

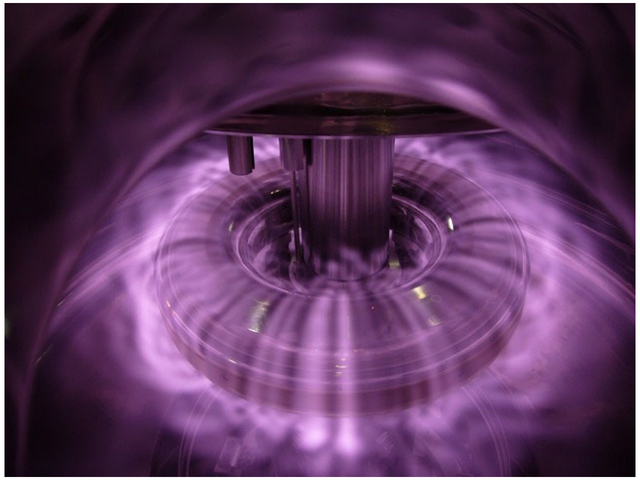
- Common/similar phenomena and mechanisms in space and laboratory

Magnetosphere (Jupiter)

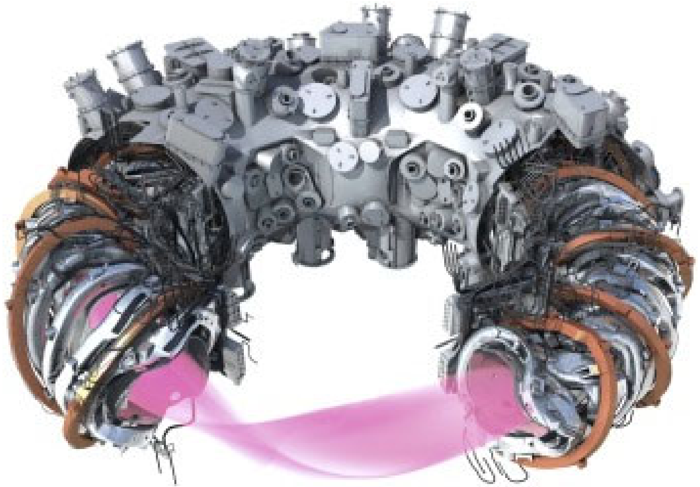


2005 Shiraishi & Yoshida PFR

Rt-1 levitated dipole

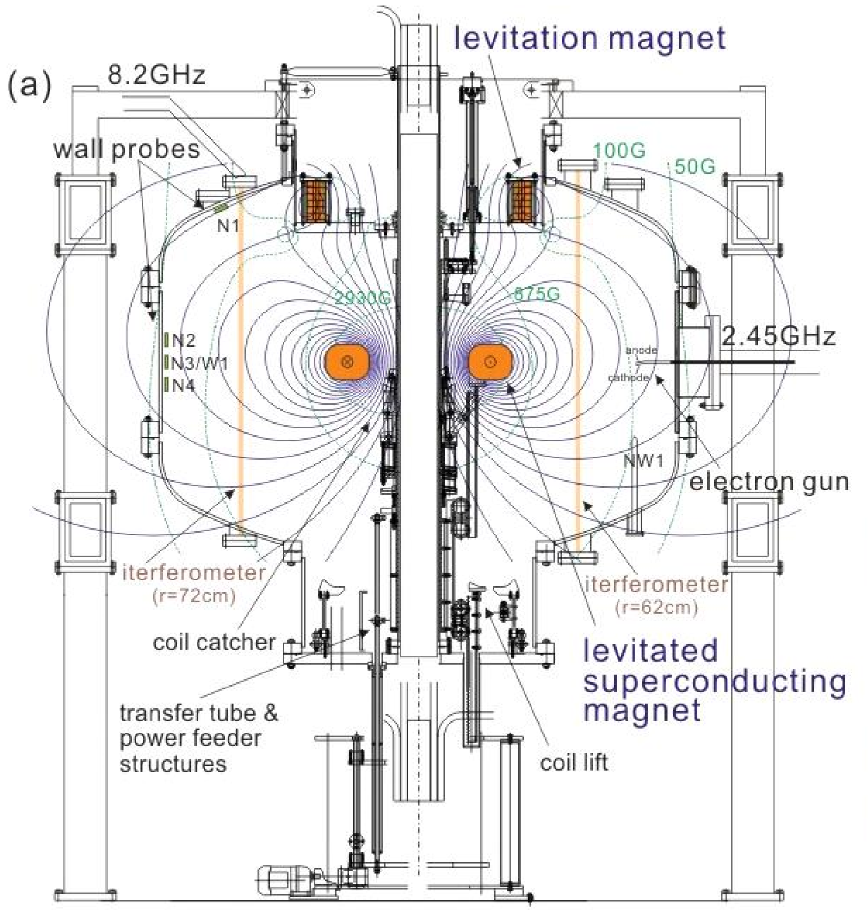


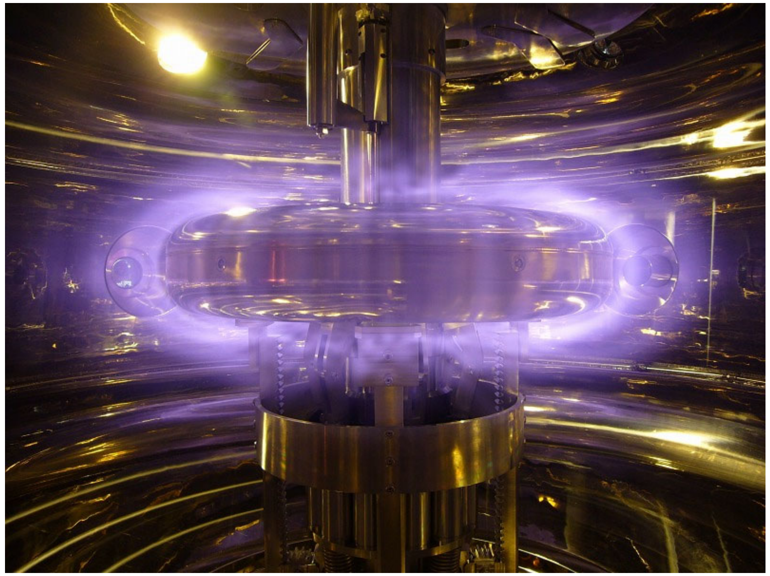
Fusion plasma (7X)



- Comparison between different magnetic configurations
- Non-linear wave evolution; chorus mode emission, TAE, etc.

2. RT-1 Levitated Dipole generated by SC dipole field coil



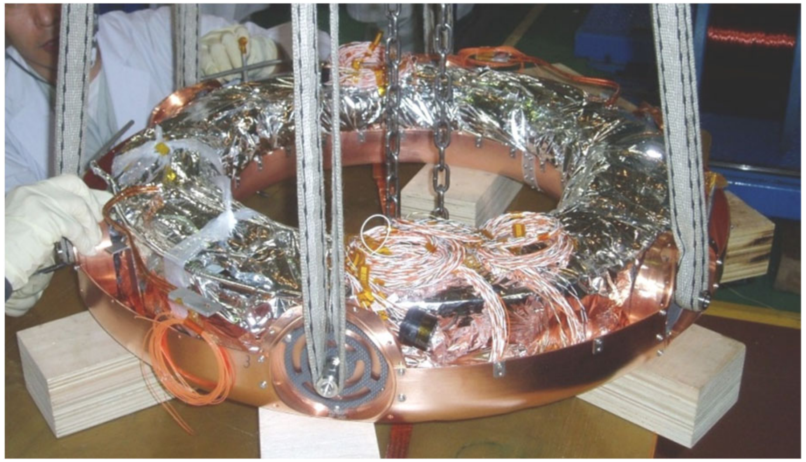


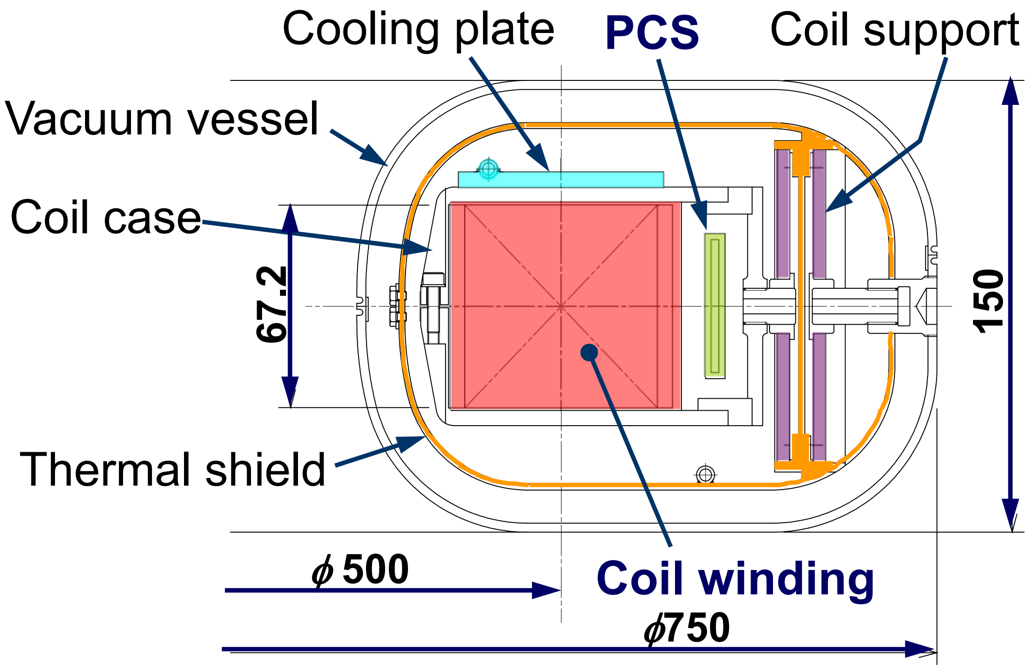
- Hi-Tc SC（Bi-2223）coil is magnetically levitated by feedback control
- ECH with 2.45/8.2GHz microwaves, ICH
- Diagnostics: magnetic and electrostatic probes, Thomson scattering, spectroscopy, x-ray, etc.

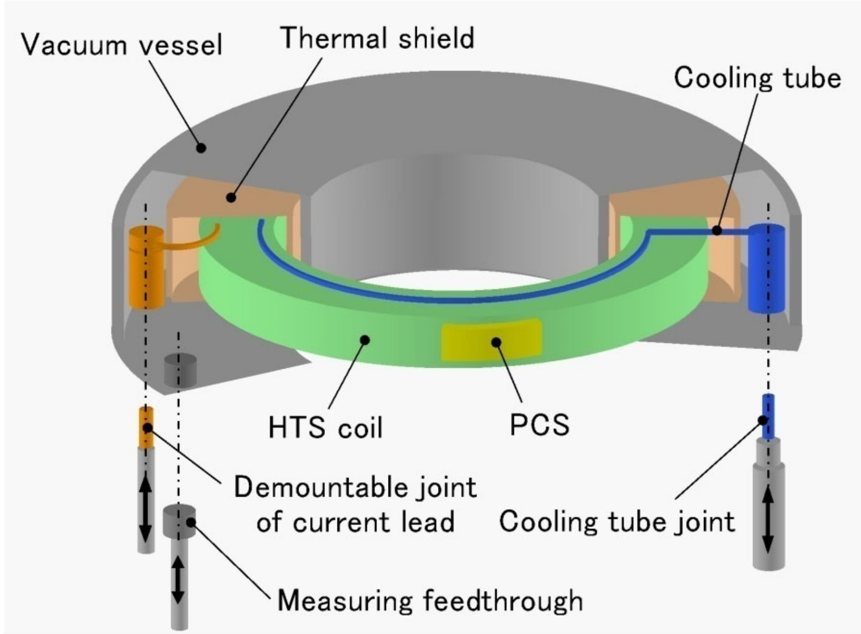
- High-beta (~100%) plasma, by electron cyclotron heating
- Self-organization and wave particle interaction in plasmas towards advanced fusion, as common physics in space plasmas

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

Inside the SC coil winding: levitation without cooling





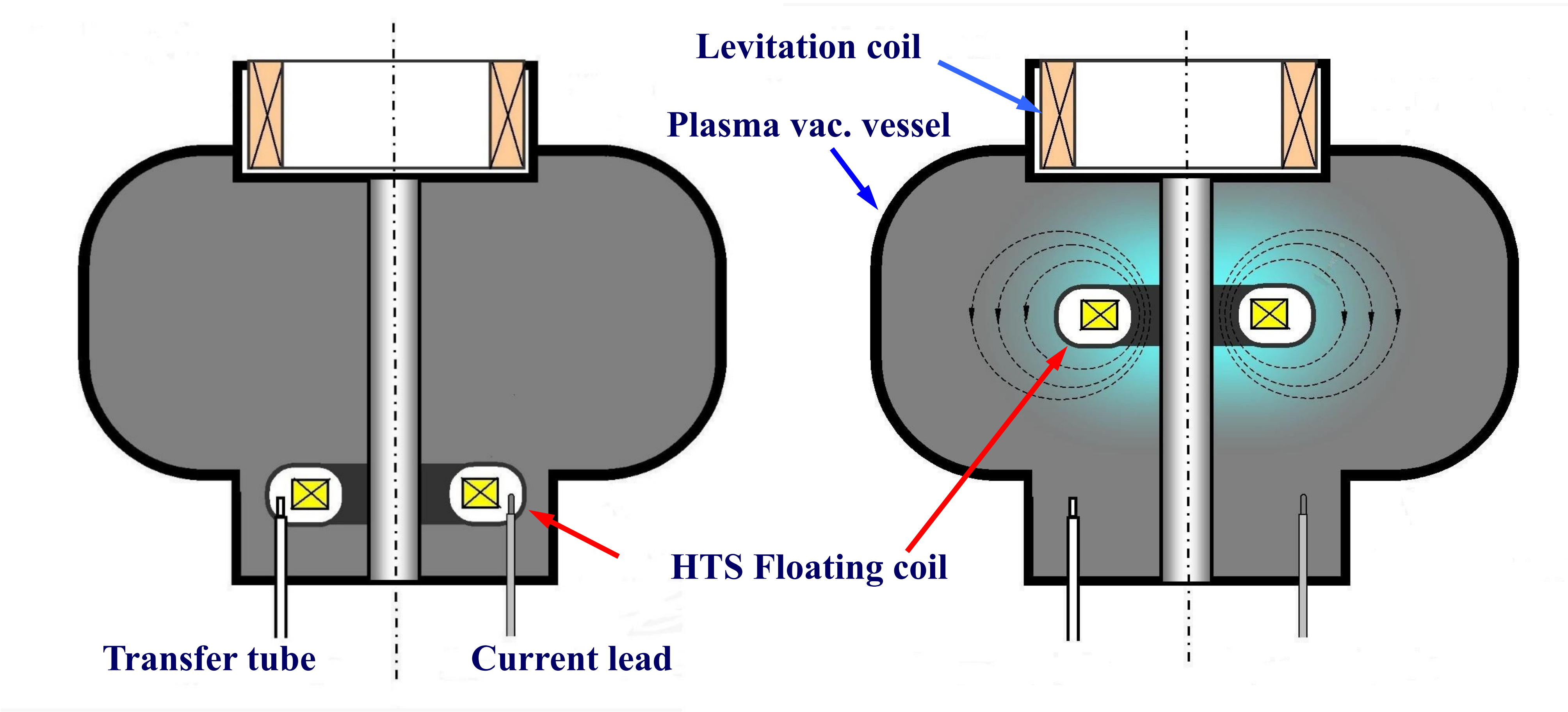


Main Parameters of the Floating HTS Coil

Winding method		Single pancake
Stack number of pancakes		12
Dimension	Major diameter	ϕ 500 mm
	Hight	67.2 mm
Operating temperature		20~30 K
Magnetomotive force		250 kA
Operating current		115.6 A
Inductance		3.3 H
Stored energy		22 kJ

- Bi-2223 high-Tc SC coil (PCS: YBCO), m=120kg, heat input <1W
- More than 6 hours of persistent current without cooling/monitoring

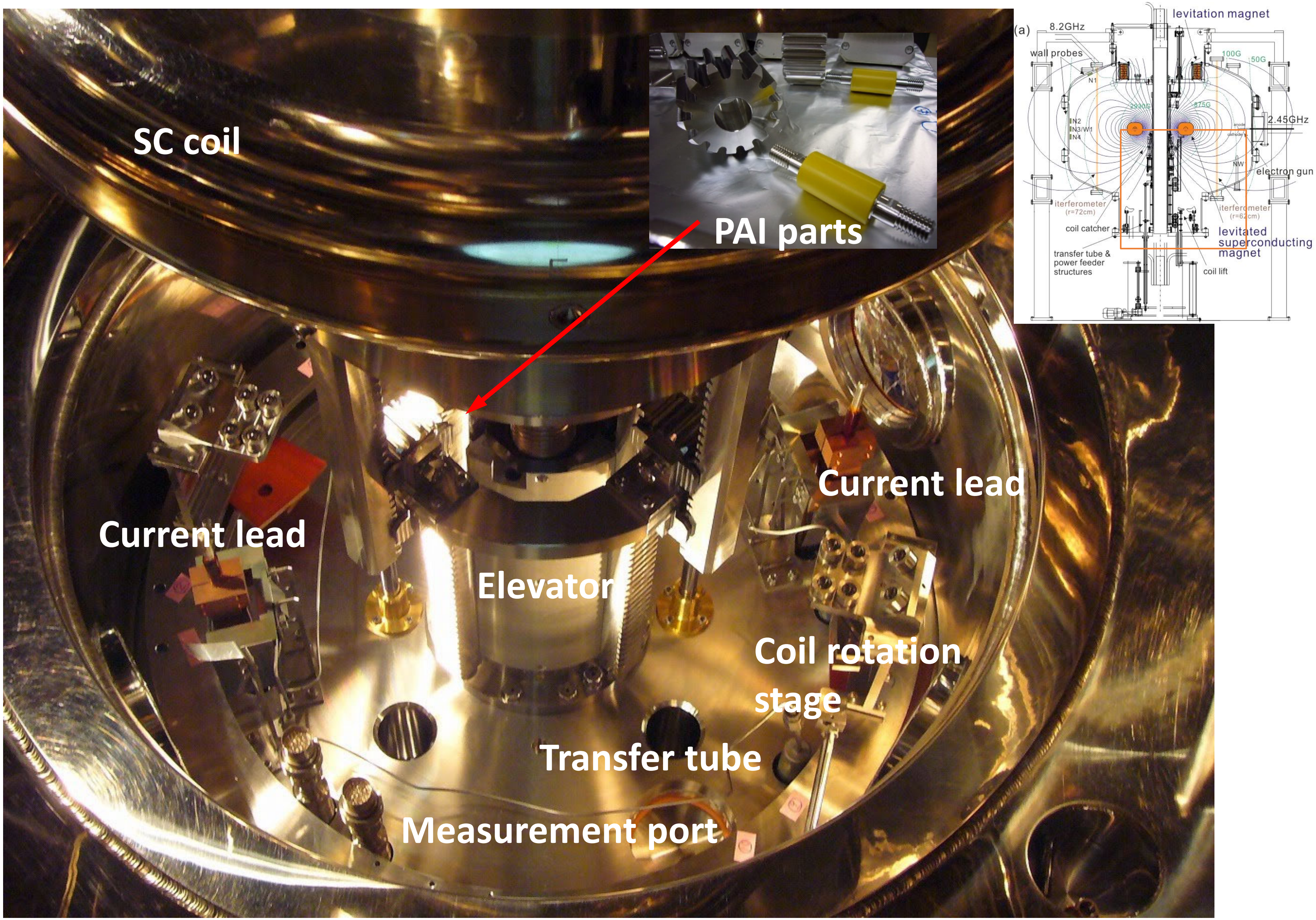
Operation procedures for the SC coil of RT-1



Cooling to 20K (He gas circulation) and excitation of persistent current of 116A at maintenance position

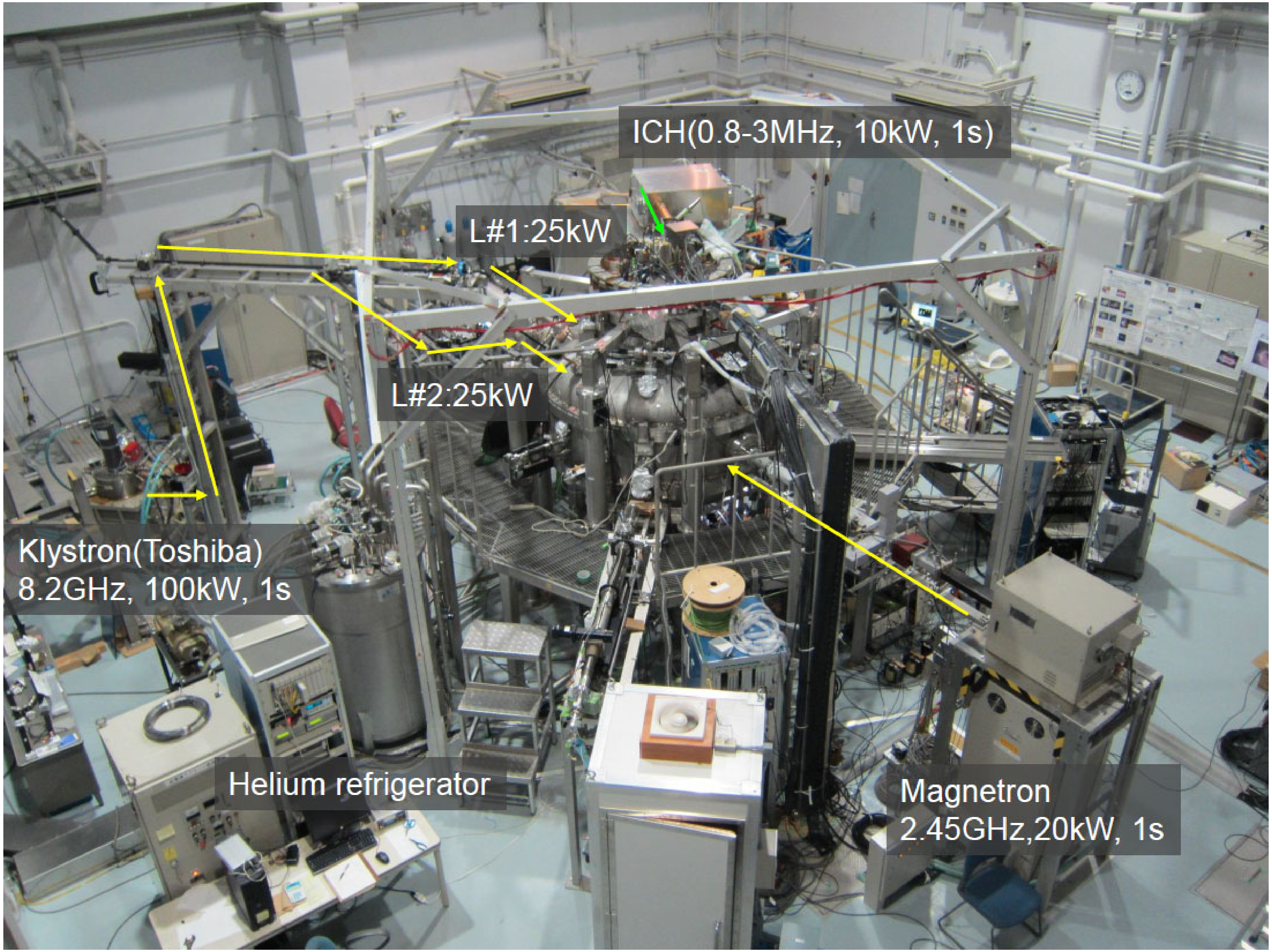
Lift up to the experiment position and levitation, plasma experiments before coil warm up (30K)

Inside the vacuum chamber of RT-1



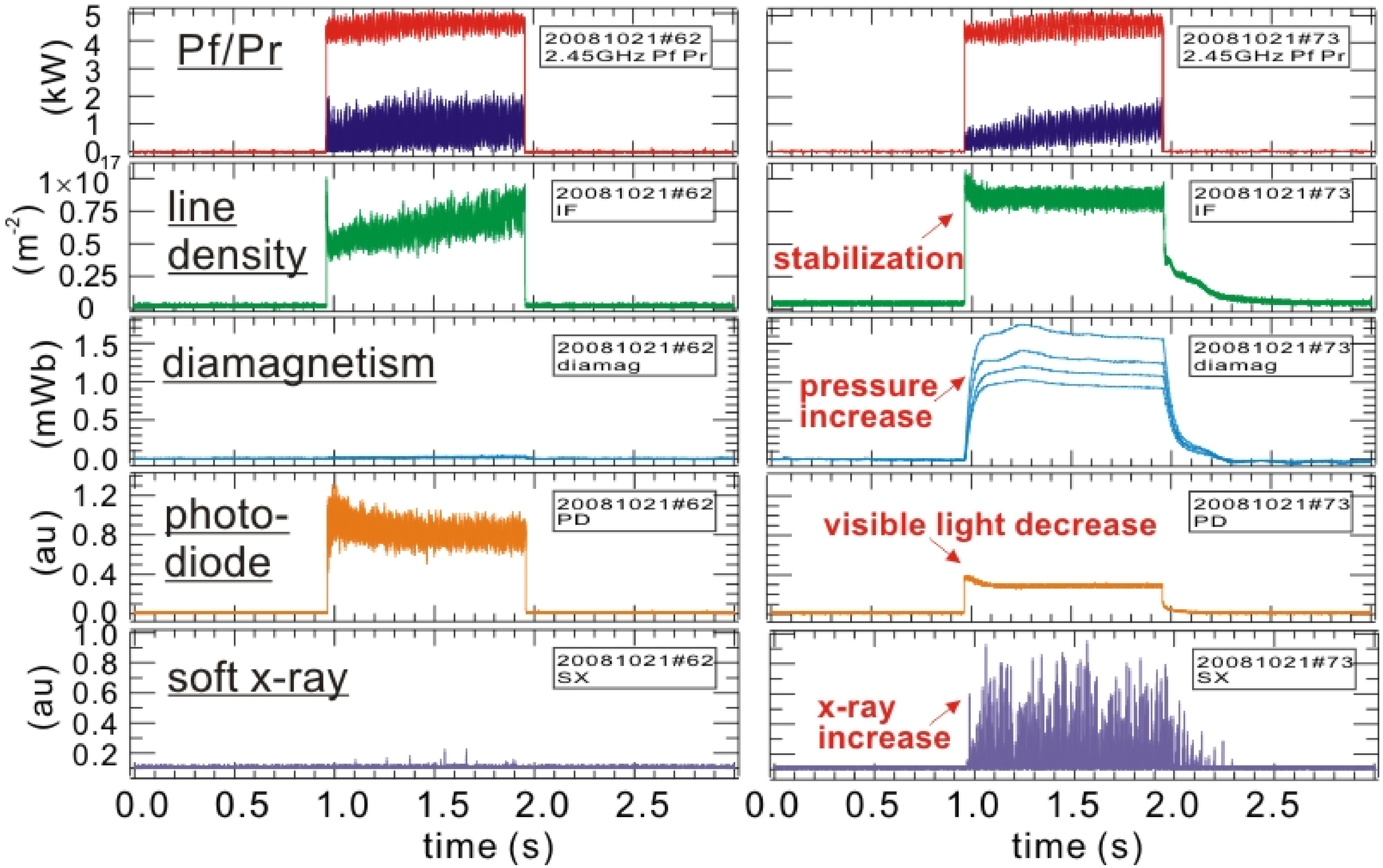
Overview of the RT-1 experimental hall

M. Nishiura



3. Spontaneous excitation fluctuations in hot electron plasma

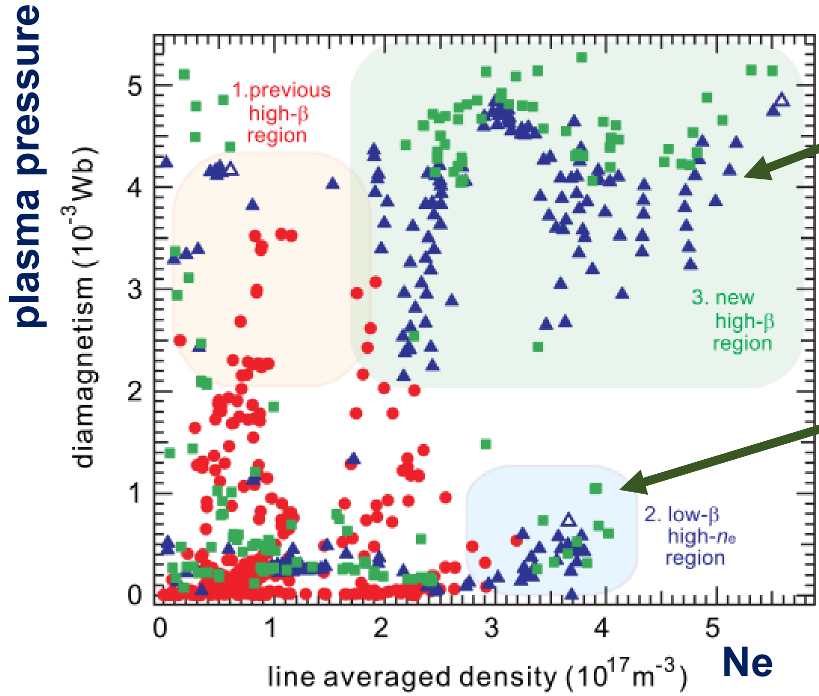
In the first series of plasma experiment, plasmas were generated by ECH with 2.45GHz and 8.2GHz microwaves

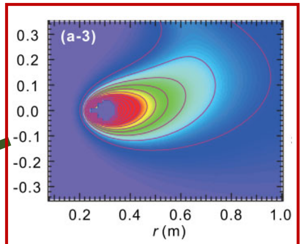


Waveforms of ECH plasma in RT-1 with (a) P_{H2}=4.5×10^{-2}Pa (b) 1.3×10^{-3}Pa.

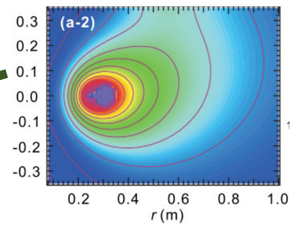
Operation range of RT-1 and comparison with space plasma

2015 Nishiura+ NF, 2017 Nishiura+ NF

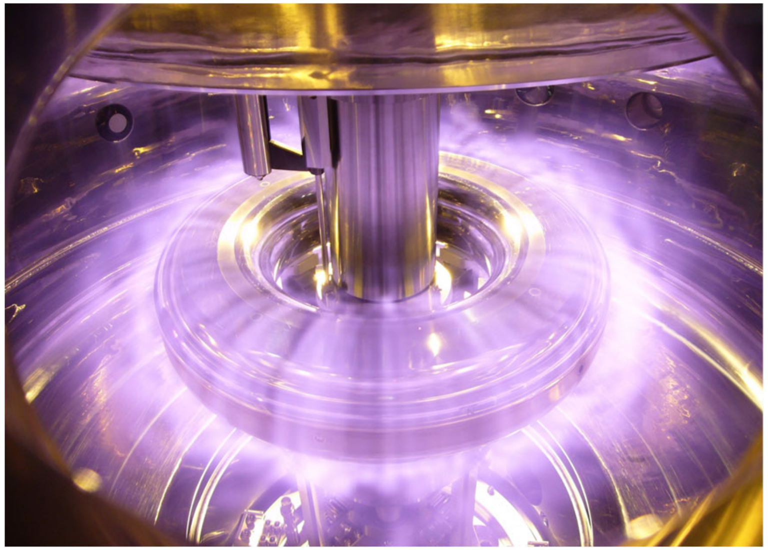


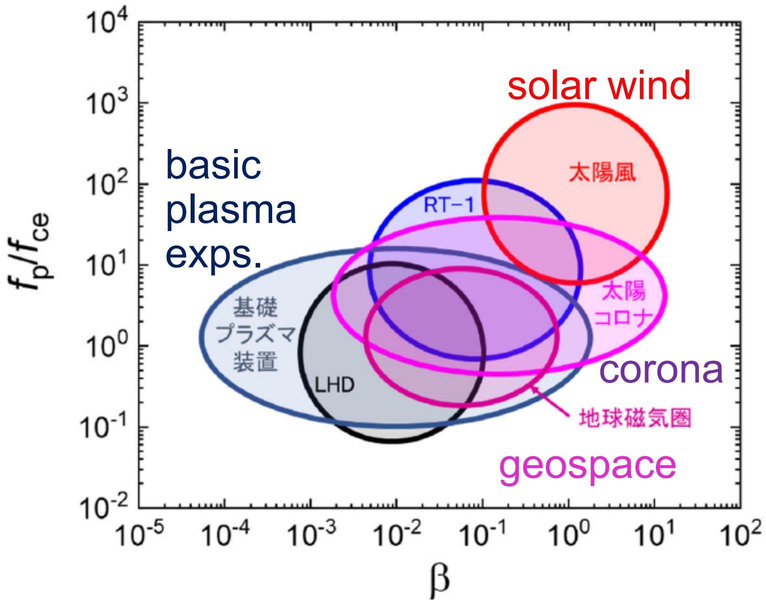


High-β state



Low-β state





- Optimized operation realized
  - Local β ~ 100%, Ne ~ 10^{17} m^{-3}
  - ~1s discharge (set by ECH)
  - Hot electron (>~keV) plasma
- Comparison with space plasmas

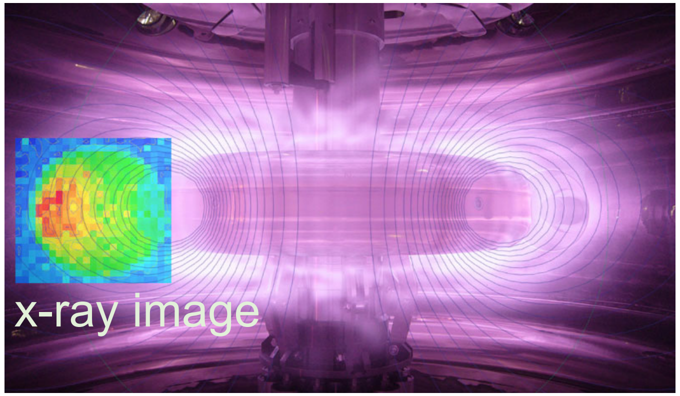
  high Ne, strong B, but several similarities

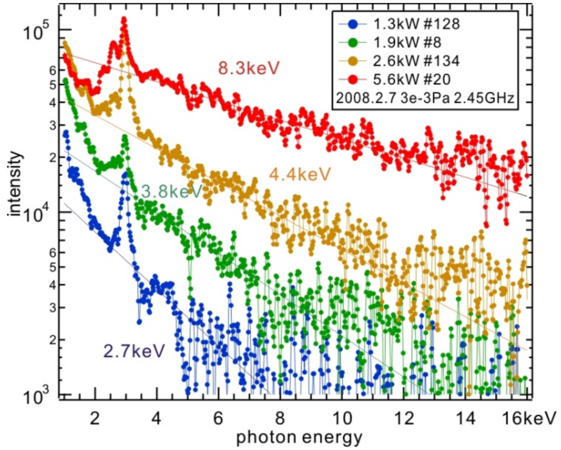
2021 Kato&Nagaoka, J. Plasma Fusion Res. (in Jpn.)

Hot-electron high-β plasma with temperature anisotropy

2015 Kawazura+ PoP.

- ECH and inward diffusion create electron temperature anisotropy





X-ray emission from hot electrons of plasmas

Temperature anisotropy (perp>para) by ECH as well as by inward transport

2014 Furukawa PoP
2021 Aihaba

➡ Micro-instabilities caused by phase space anisotropy

Common wave-particle interaction in fusion and space plasmas

- Whistler mode excitation for electrons with Tperp>Tpara

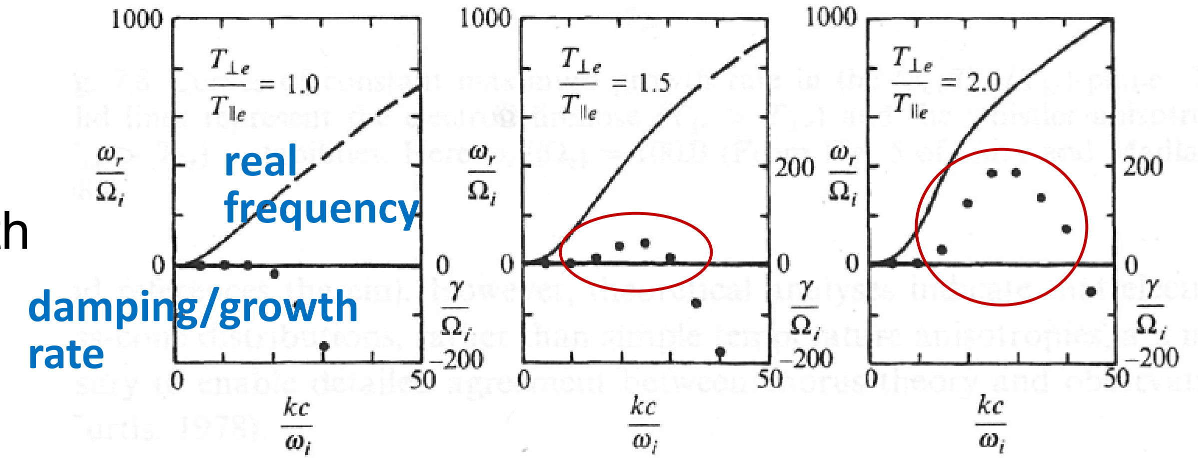
Dispersion relation of R wave

$$\omega_r \simeq k^2c^2\frac{\Omega_p}{\omega_p^2}\left[1+\left(\frac{T_{\perp e}}{T_{\parallel e}}-1\right)\frac{\beta_e}{2}\right]$$

Linear condition for instability growth

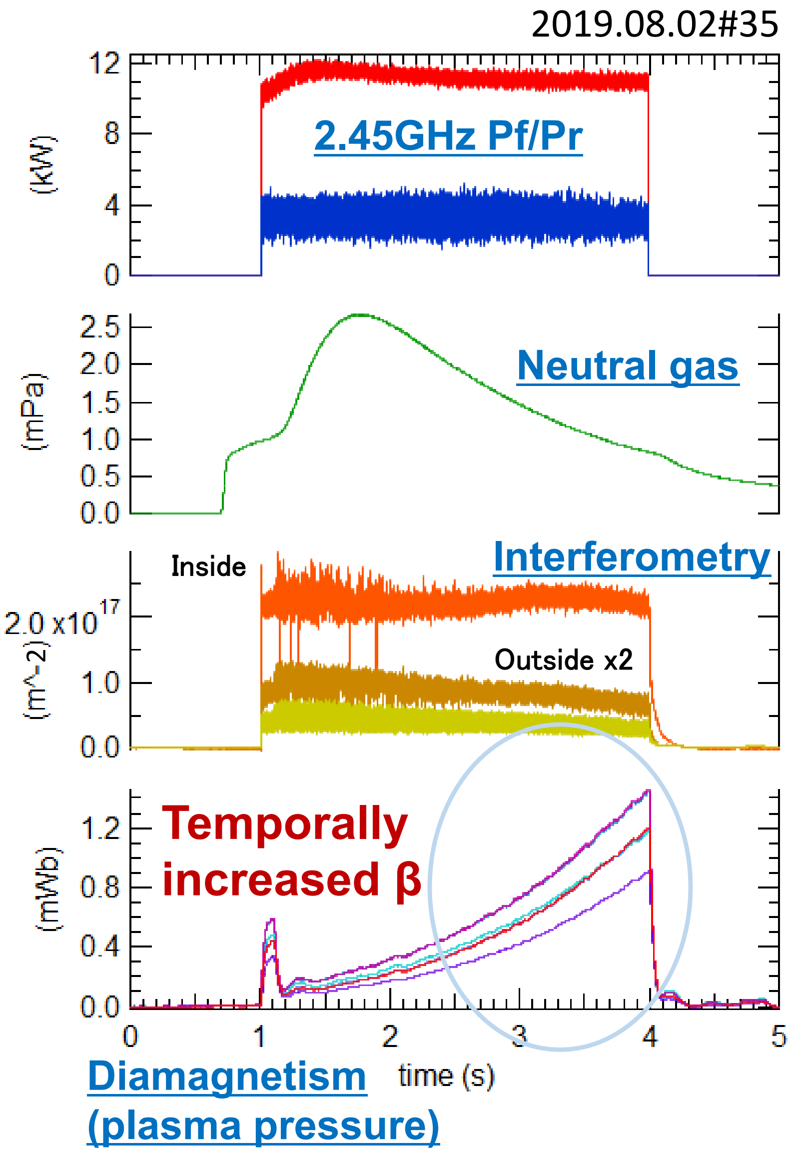
$$\frac{T_{\perp e}}{T_{\parallel e}}-1>\frac{1}{|\Omega_e|/\omega_r-1}$$

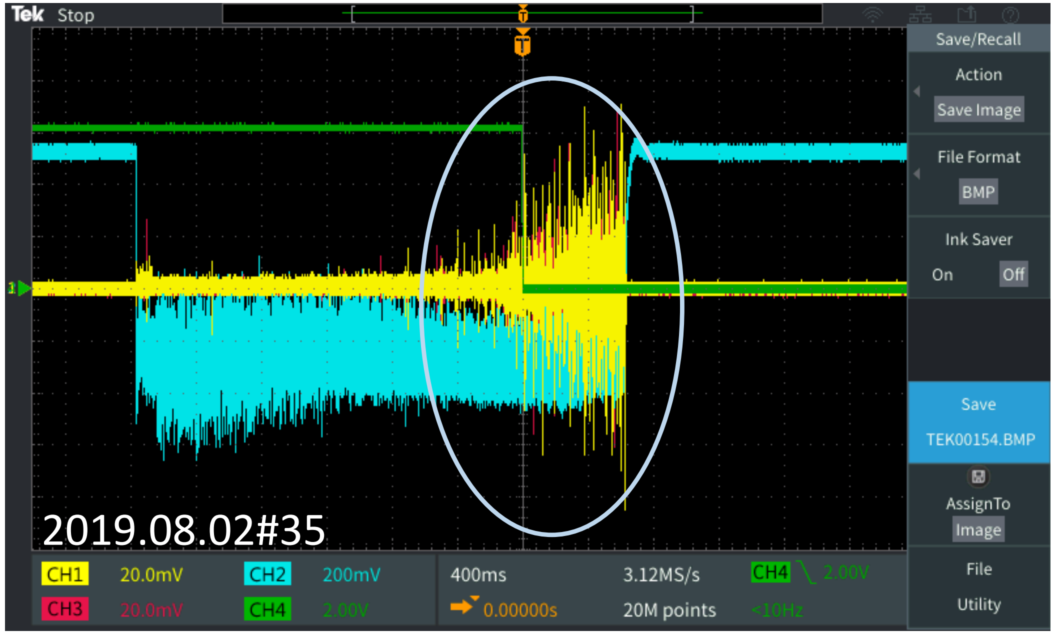
1966 Kennel Petschek



Detection of electromagnetic activities for high-β plasma

Magnetic activities above MHz range appears only for high-β state with hot electrons generated by ECH



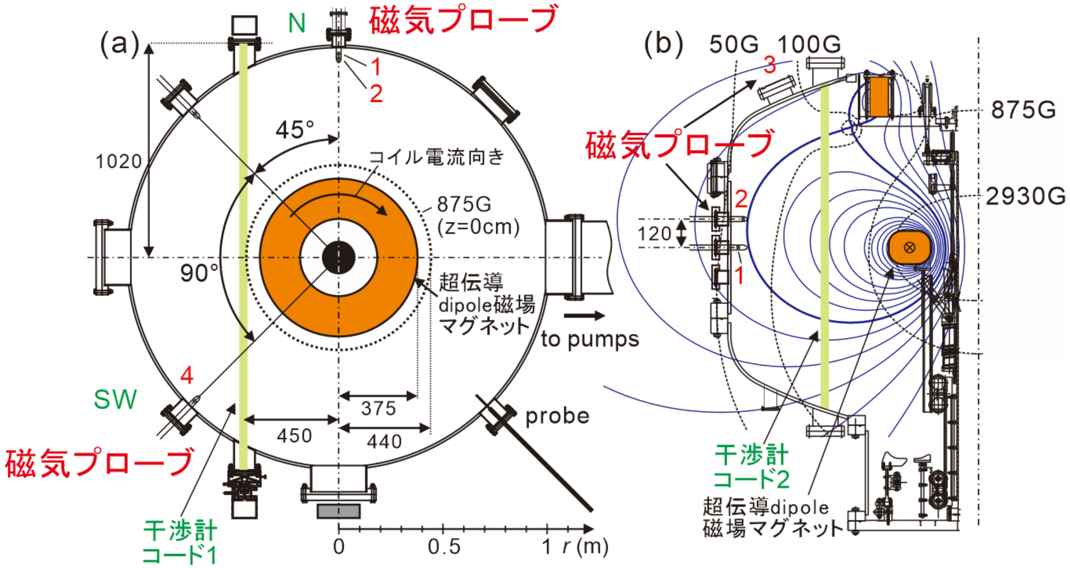


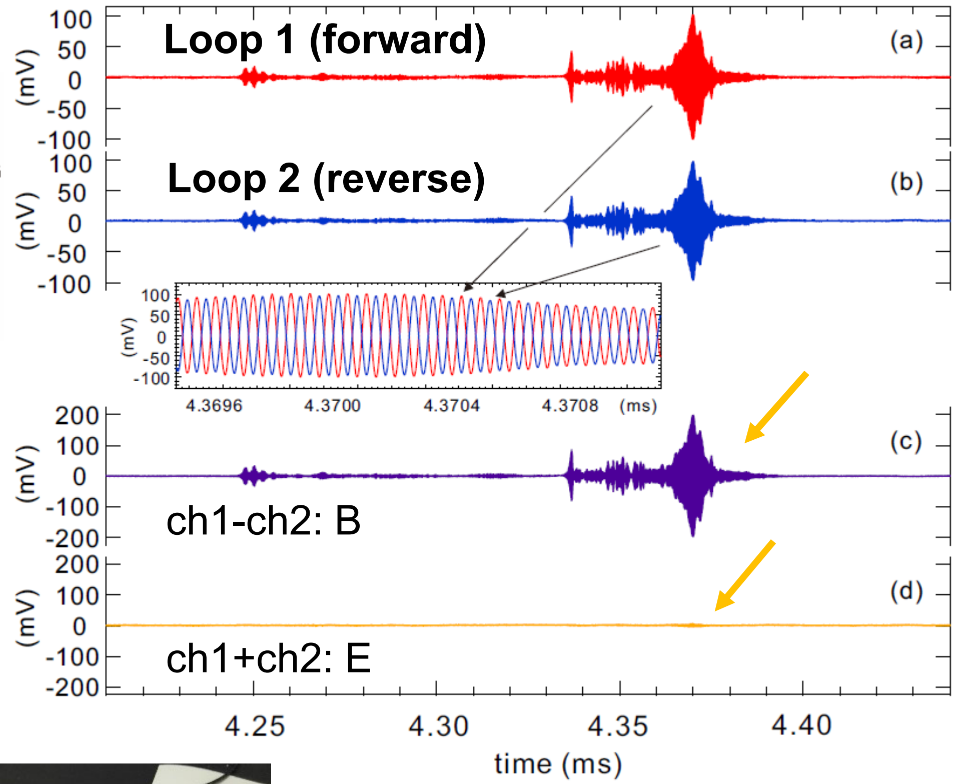
ch1: Bdot probe 1, ch2: Interferometer, ch3: Bdot probe 2

- Control to change plasma pressure while keeping input power and density for 3 s
- Plasma pressure is sustained by increased hot electrons with temperature anistropy

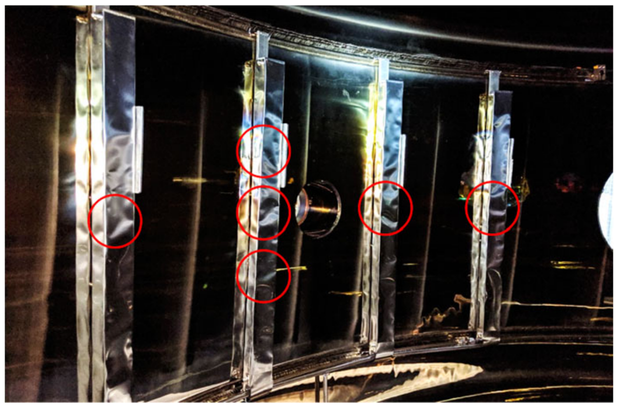
Intermittent excitation

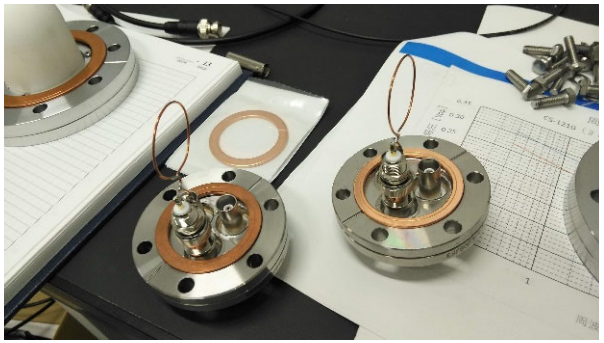
Bdot probes

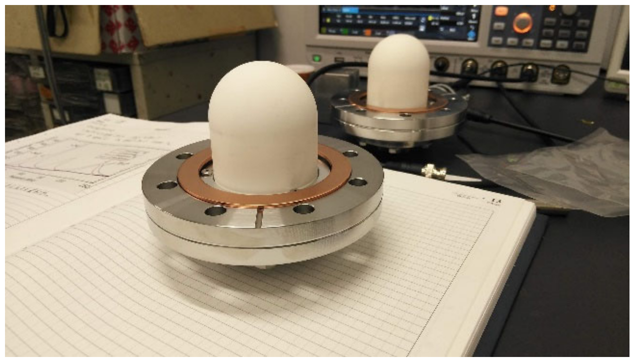




Interferometry

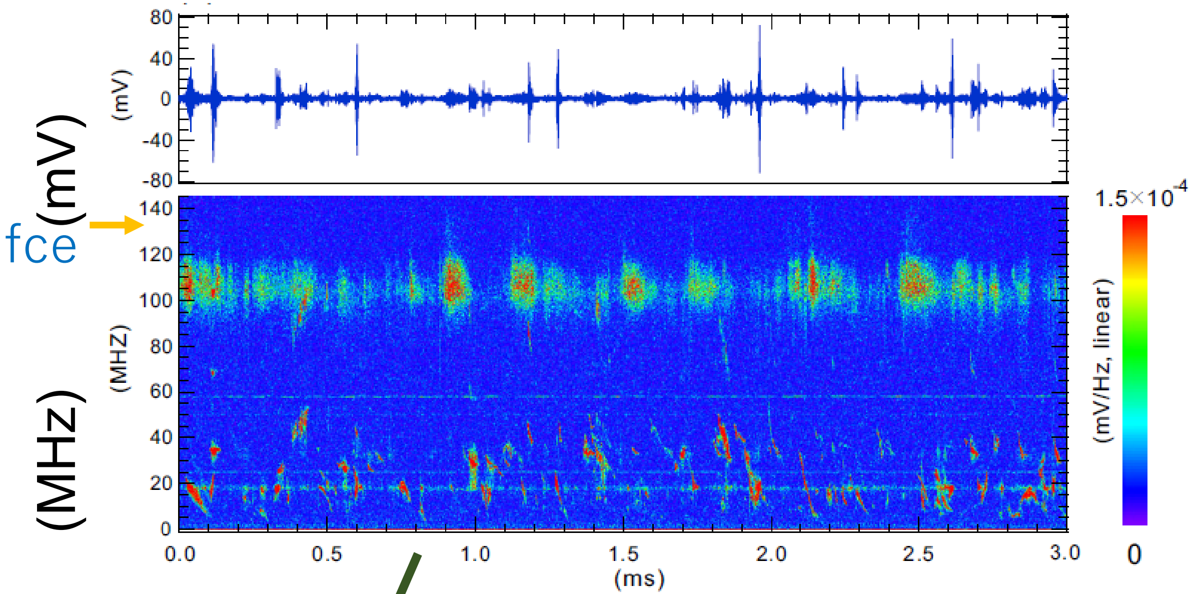




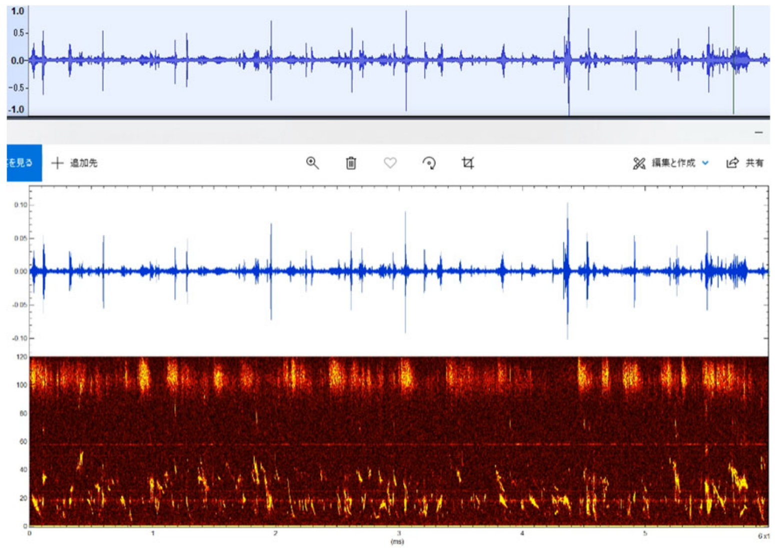


- Coherent magnetic and weak electrostatic components

Intermittent nature of magnetic and electrostatic fluctuations

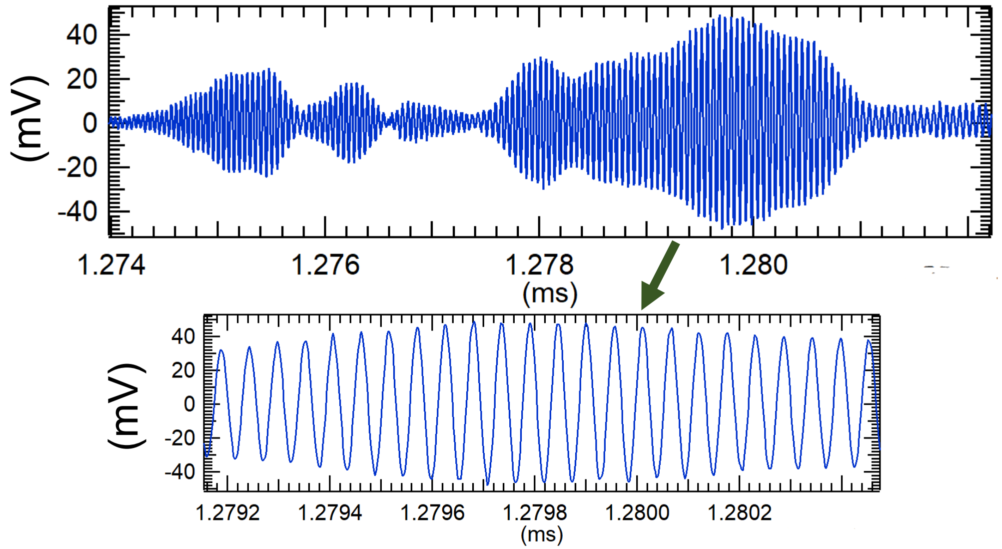


(sound) 1/10000 slow play

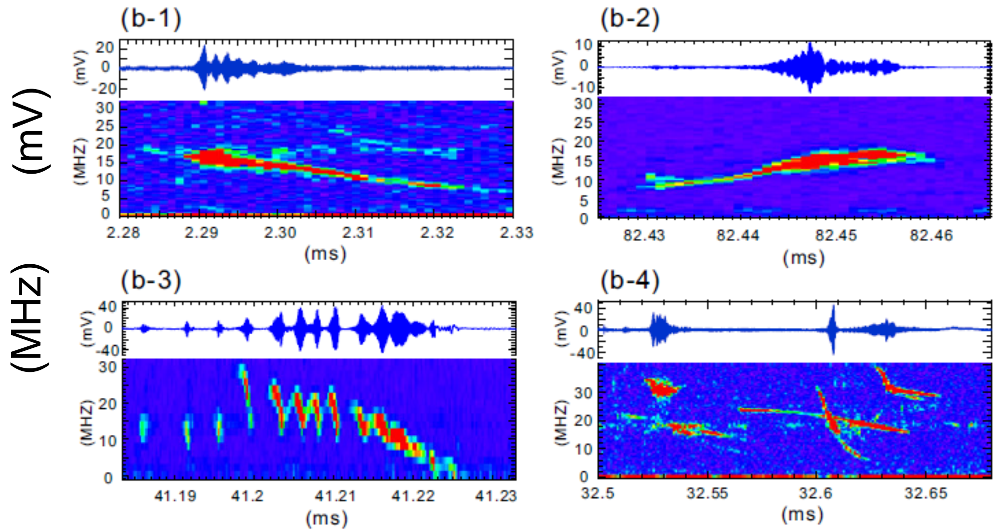


0.1fce~0.4fce (strong) and ~0.6fce (weak): B, ~fce: E

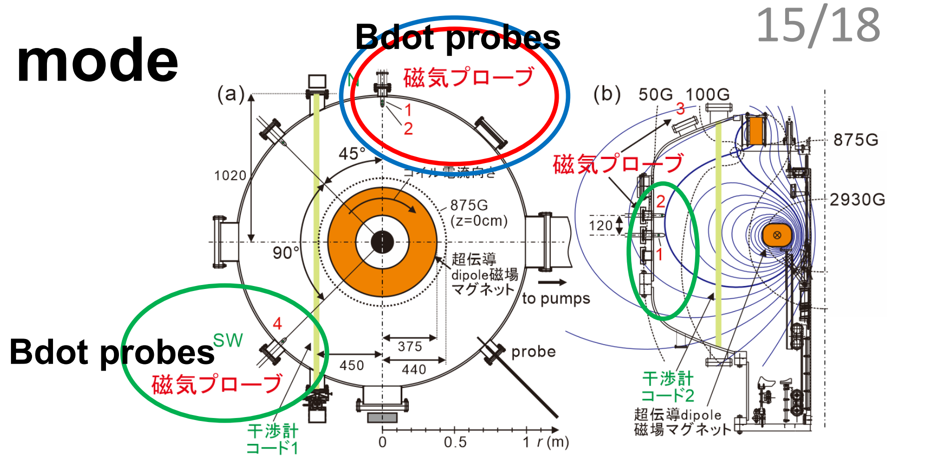
Each event is envelop of coherent waves



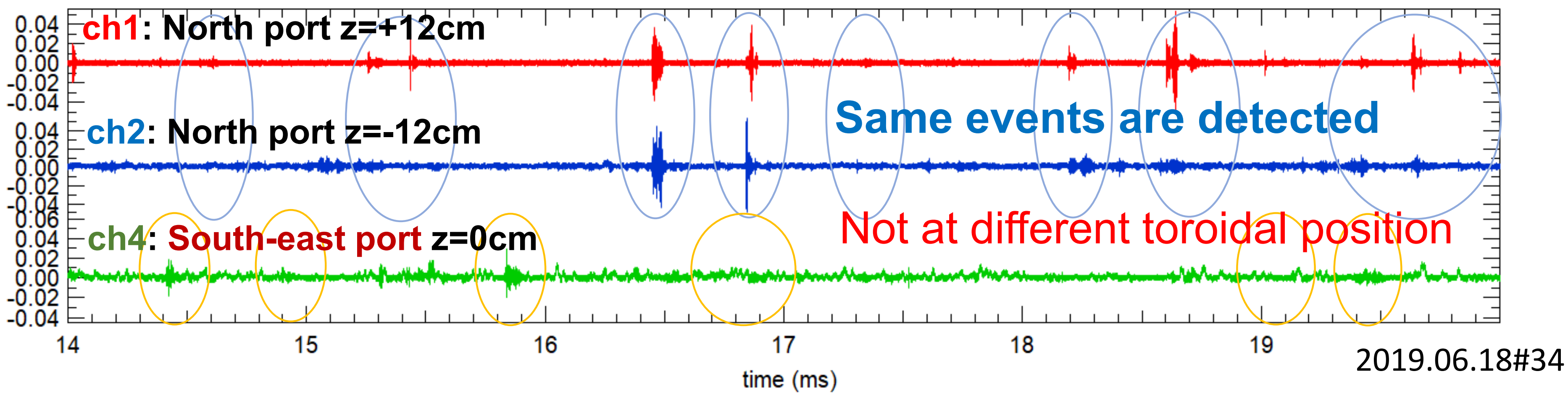
Up and don chip and more

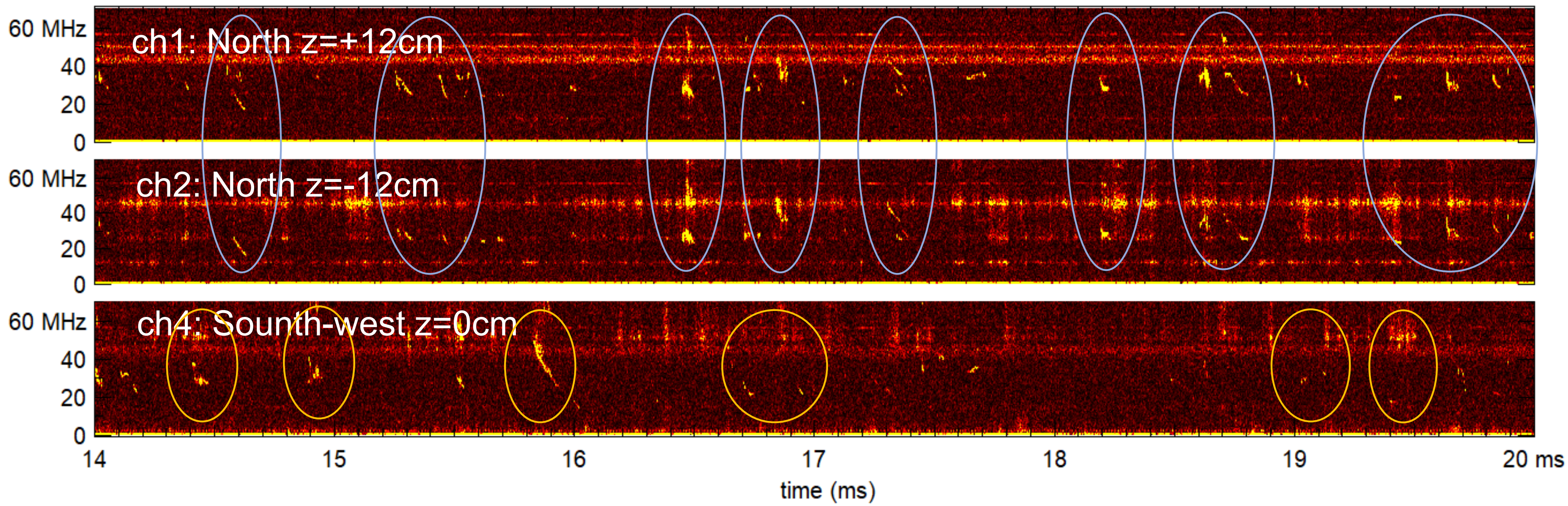


Toroidally localized nature of the wave mode (propagation direction)



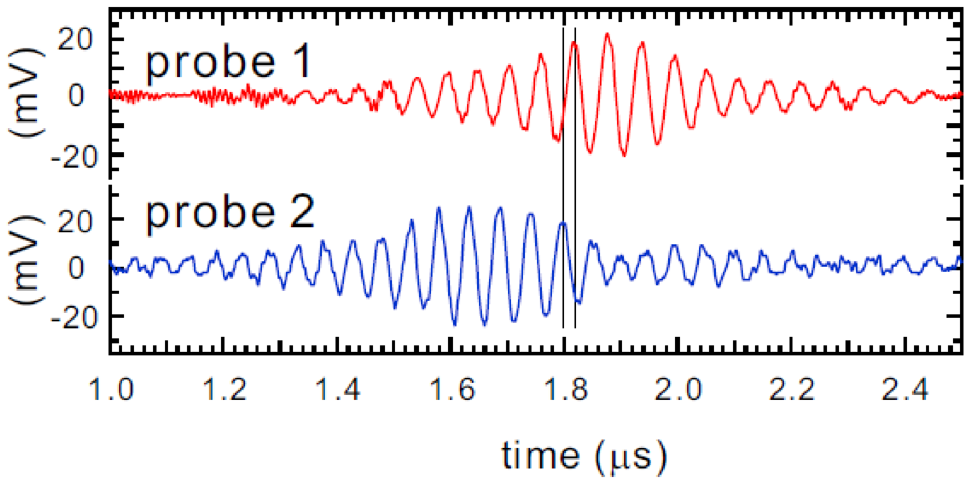
Measurements at different positions shows the waves propagates along field lines



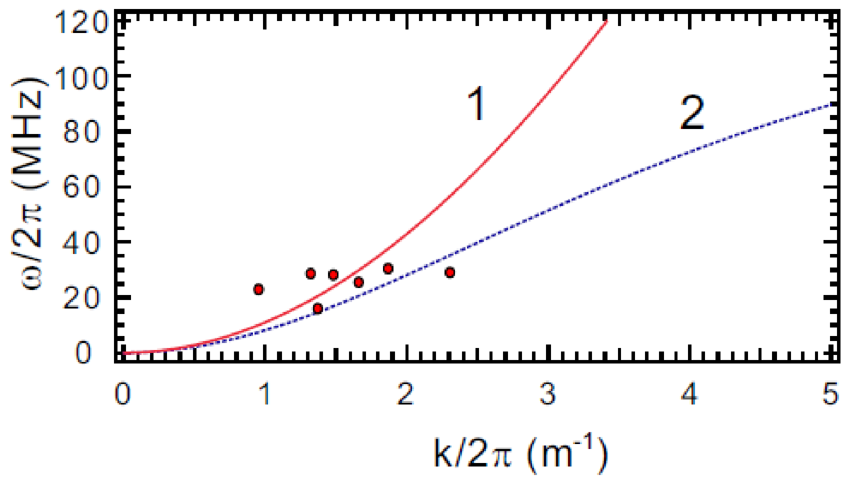


Comparison with the characteristics of whistler wave

- Dispersion relation (preliminary)



For parameters of 1. edge and
2. averaged over confinement region



  - Consistent with dispersion relation of whistler along field lines
  - Multiple (more than 2) probe measurements is strange: wave direction?

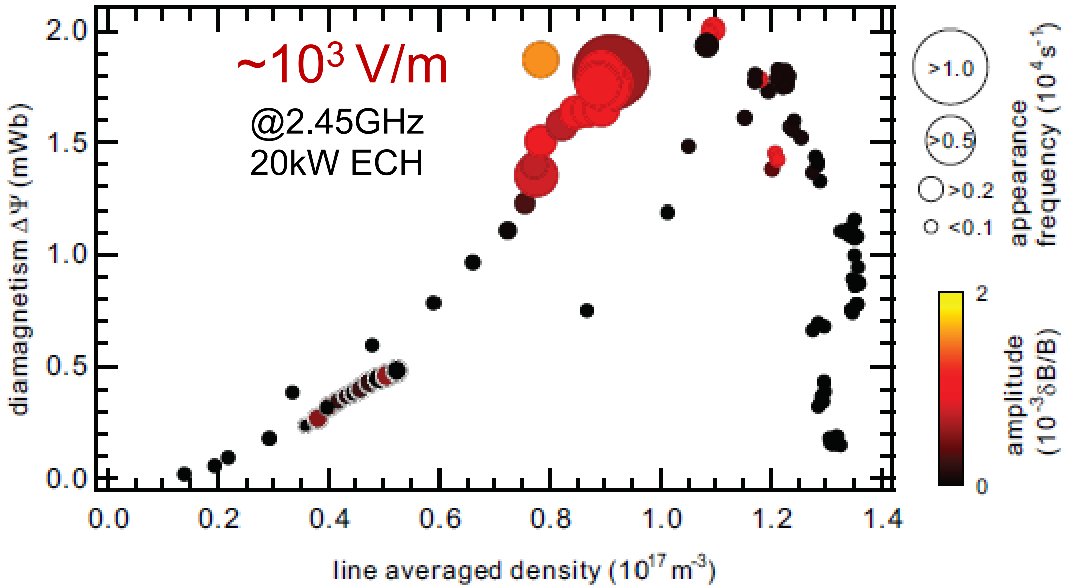
- Anisotropy estimated from the upper limit of active frequency range

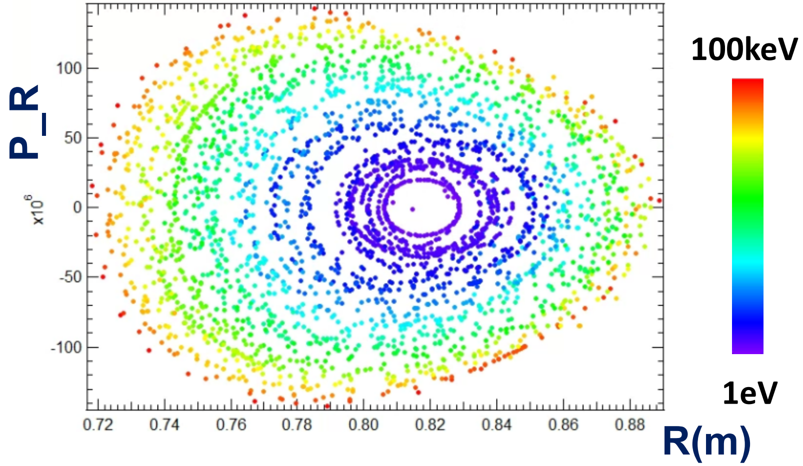
$$f < f_{\rm ce} A/(A+1)$$

$$A = T_{\perp}/T_{\parallel} - 1 = 0.7$$

  - Linear analysis（1966 Kennel Petschek）
  - Rather moderate anisotropy that is fairly consistent with Grad-Shafranov analysis

Possibility of heating and chaotic orbit caused by R wave



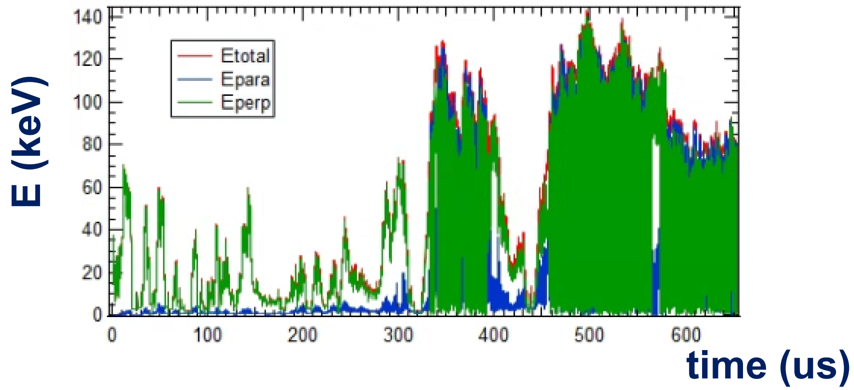


Poincaré plot of electron orbit (initial 100us)

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

1990 Murakami, Sato, Hasegawa, PoF; 2016 Saitoh+ PRE

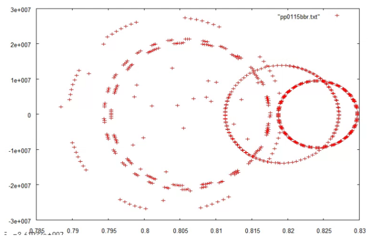
Non-integrable chaotic behavior even in a symmetric geometry, caused by the coupling Between different periodic motions



- Efficient heating and chaotic orbit of electrons

Test particle simulation with R wave of 2×10^4 V/m is applied to electron

Initially 10eV (dot, periodic) electron Is heated to show chaotic behavior



- Efficient heating and particle loss are possible with R wave

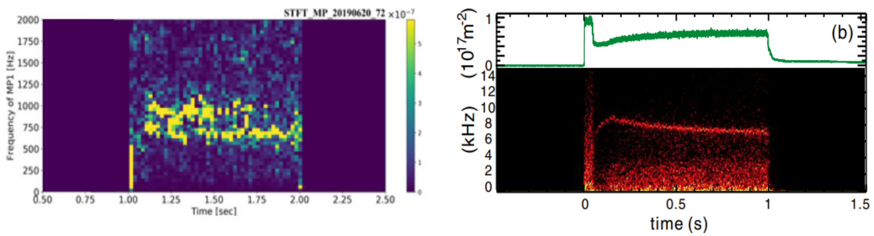
4. Summary

- In RT-1 Levitated dipole, spontaneous excitation of whistler mode（$\sim f_{ce}$）was observed , in addition to low frequency fluctuations mode（$\sim f_{toroidal}$）.

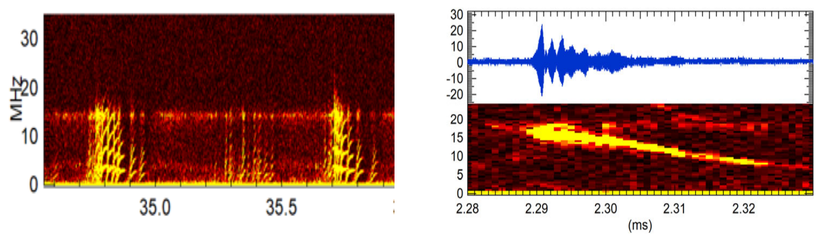
- In hot-electron high-β plasmas, the fluctuation activity is active at $f \sim 0.1\text{-}0.4 f_{ce}$, $0.6\text{-}0.8 f_{ce}$ (B, chirping), $\sim f_{ce}$ (E, broad).

- Coherent magnetic mode propagates along field lines.

Low frequency fluctuations ~kHz



Chirping modes <~ 100MHz



- Future works: Propagation direction, source location, linear to non-linear transition process, acceleration of electrons, etc.

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