470-ICC/P8-02, 24th IAEA FEC, 12 October 2012, San Diego, USA.

Observation of Magnetic Fluctuations and Disruption of Magnetospheric Plasma in RT-1

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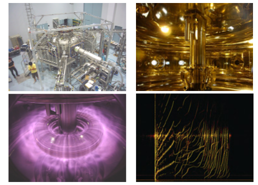
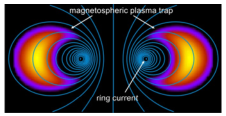
Abstract: The Ring Trap 1 (RT-1) device, a magnetospheric levitated dipole field configuration, has created high-β (local β~70%) hot electron plasma by using electron cyclotron resonance heating (ECH). When a very large population of energetic electrons is generated at low neutral gas operation, high frequency magnetic fluctuations are observed. When the fluctuations are strongly excited, disruptive rapid density loss were simultaneously observed especially in a decay phase after stopping the microwave injection. The fluctuations propagate in the toroidal electron diamagnetic drift direction and have no phase difference along field lines. The fluctuations are easily stabilized by decreasing the hot electron component below approximately 40%.



Magnetospheric dipole plasma confinement

- **Magnetospheric configuration enables high-β plasma confinement suitable for advanced fusion***

- Magnetospheric fusion concept was motivated by spacecraft observation of Jovian high-β (β>1) plasma
- In strongly inhomogeneous dipole field, MHD modes are stabilized by the effects of plasma compressibility



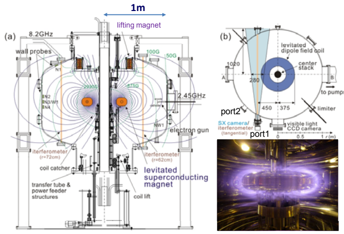
Magnetospheric plasma confinement

- Mechanism of high-β state is theoretically explained by the effects of hydrodynamic pressure of flow (Double Beltrami state)**
- Realization of ultra high β plasma confinement enables burning of advanced fusion fuels, such as D-D and D-^{3}He
- Self-organization of various structures as relaxed states of magnetospheric dipole plasmas (Hall effects, etc.)

*1987 Hasegawa, CPCF **11**, 147.
**2002 Yoshida, Mahajan PRL 88, 095001.

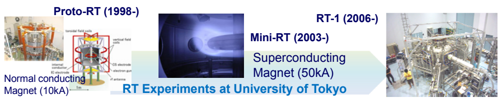
The Ring Trap 1 (RT-1) experiment

- **Magnetospheric configuration generated by a levitated superconducting dipole-field magnet***



Cross sections of RT-1 and generated ECH plasma

- Field generated by superconducting magnet and lifting magnet (pure poloidal field)
- Research topics are
  - Formation of high-β plasma suitable for burning advanced fuels
  - Confinement of non-neutral plasmas including antimatters

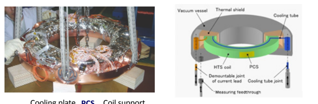


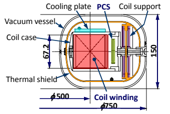
RT-1, Mini-RT (UT) and LDX, CTX (MIT/Columbia) are modern dipole field devices

*2010 Yoshida *et al.*, PRL **104**, 235004.

- **High-T_c superconductor (Bi-2223) enables 6 hours of magnet levitation operation without cooling***

- Magnetic dipole with 250kAT (116A)
- Magnetically levitated (total weight: 112kg)
- Bi-2223 high-temp. superconductor
- Operated between 20K and 30K





Main Parameters of the Floating HTS Coil

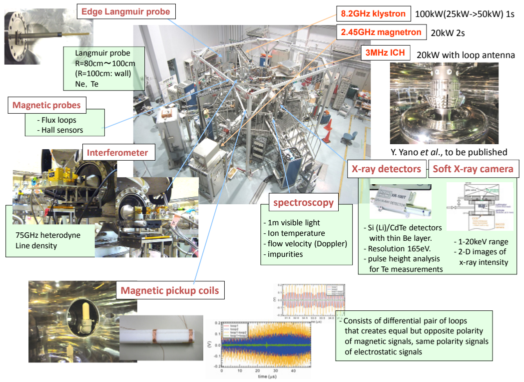
Winding method		Single pancake
Stack number of pancakes		12
Dimension	Major diameter	ϕ500 mm
	Hight	67.2 mm
Operating temperature		20~30 K
Magnetomotive force		250 kA
Operating current		115.6 A
Inductance		3.3 H
Stored energy		22 kJ

Structure of levitated superconducting magnet

*2009 Ogawa *et al.*, Plasma Fusion Res. **4**, 020.

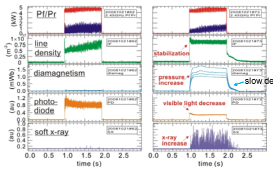
Heating and diagnostics systems in RT-1

- **Plasma is generated and heated by:**
  2.45 and 8.2GHz microwave ECH, ICH (3MHz 10kW) under construction
- **Diagnostic system consists of:**
  75GHz (4mm) interferometers, visible light spectroscopy, magnetic loops, Hall probes, magnetic pickup coils, Si(Li) and CdTe x-ray detectors, soft x-ray CCD camera, edge Langmuir probes

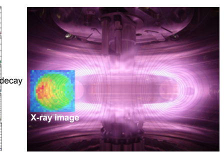


Formation of high-β hot electron plasma

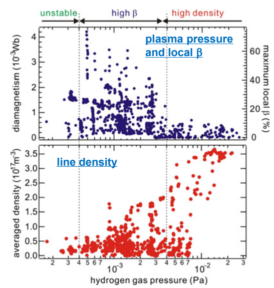
- **Stable high-β (local β~70%) state is realized by optimized operation conditions including neutral gas pressure**
  Hot electrons (~30keV when levitated, ~10keV when not levitated) are the main component of electrons. Ions are not heated and cold (~10eV).



Waveforms of low-β and high-β discharges



Visible light and x-ray image of plasma generated by ECH at 2.45GHz



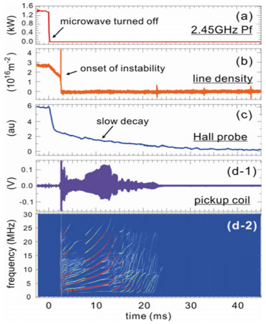
Parameters in variation of neutral gas pressure

- Discharge has three typical regimes according to neutral gas pressure P_n
- By reducing P_n, increase in plasma pressure and x-ray, and decrease in visible light are simultaneously observed
- Plasma pressure is mainly attributed to hot electrons generated by ECH
- X-ray measurements show electrons of ~30keV are the main component of plasma

*2011 Saitoh, Yoshida *et al.*, NF **51**, 063034.

Onset of disruptive magnetic fluctuations

- **Onset of fluctuations and destructive loss of plasma were observed especially in the decay phase***

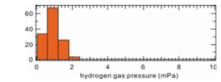


Onset of fluctuation in afterglow phase

- The plasma starts to decay after stopping microwave at t=0s (slow decay is due to hot electrons)
- When the hot electrons ratio is very high, magnetic fluctuations were observed in the decay phase
- Disruptive density loss following the growth of fluctuations
- Diamagnetic signals decay slower than the density signals, indicating remaining trapped hot electrons
- Frequency chirpings were repeatedly observed
- Similar fluctuations were observed during microwave injection at low P_n

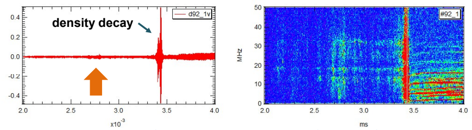
*2012 Saitoh, Yoshida *et al.*, PoP **19**, 064502.

- **Fluctuation onset and plasma loss appear at low P_n**
  - The disruptive fluctuations in the decay phase appear only when P_n is below ~2mPa
  - Strong correlation with the ratio of hot electrons



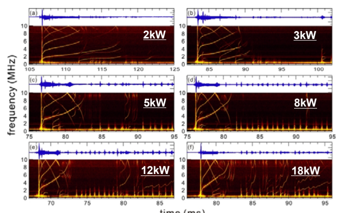
Frequency distribution of fluctuation onset

- **Prior to the destructive fluctuation growth and chirping, plasma has small fluctuations**



Pickup coil signal and its frequency power spectrum before and after the disruption

- **The chirping speed depends on plasma parameters**



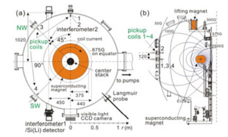
Fluctuation evolution in variation 2.45GHz RF power

- Higher RF input power results fast chirping
- Similar tendency is observed by changing P_n, fast chirp at low neutral gas pressure

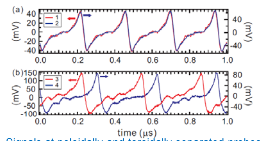
- **Comparison with typical frequencies and velocities**
  - For typical field strength of B=0.01-0.1T of the RT-1 device, electron cyclotron frequency f_{ce} = 280MHz-2.8GHz, ion cyclotron frequency f_{ci} = 150kHz-1.5MHz
  - For T_e=10keV, n_e=1 × 10^{15} m^{-3}, $\Lambda = n/n'$=0.1m (scale length), toroidal drift velocity ~mv^2/qRB = 4 × 10^5 - 4 × 10^6 m/s, diamagnetic drift velocity $k_B T_e / qB\Lambda$ = 1 × 10^6 - 1 × 10^7 m/s

Fluctuation characteristics

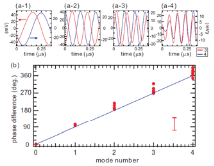
- **The fluctuation rotates in toroidal diamagnetic direction of electrons and has no phase difference along field lines**



Top view and poloidal cross section of RT-1

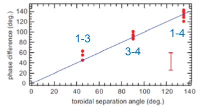


Signals at poloidally and toroidally separated probes



(a) k=1~4 components of probe signals 3 and 4, and (b) phase differences

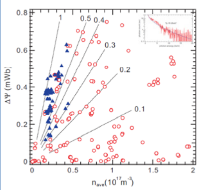
- Clear phase differences are observed at probes located at different toroidal positions
- No phase differences along field lines
- The fluctuation signals are a sum of each of frequency components $\sum_{k=1}^{n} A_k \cos(2\pi f_k t - \phi_k)$ where $f = f_k$ $(k = 1, 2, \ldots)$ and $f_k = k f_1$
- The phase differences of k=1 component indicate that possible mode numbers are $m = 1 \pm 8n$ where n is an integer



Phase differences of k=1 component

- If n≠0, discrete modes (m=9,18,27,36 for n=1) are selectively excited, which is physically quite improbable
- If n=0, phase velocity is in the electron diamagnetic drift direction

- **The disruptive fluctuations are stabilized by reducing the ratio of hot electron component**



Ratio of hot electrons when plasma is stable (circles) or not stable (triangles)

- Hot electron ratio was estimated by using the measured T_e and plasma pressure
- Strong magnetic fluctuations and disruptive loss were not observed when $\alpha \sim n_h/n_{ave}$ is below 30~50%
- Stabilizing condition for the high-frequency hot-electron interchange mode*

$$\frac{n_h}{n_c} < \left[1 - \left(\frac{1}{q} + \frac{\beta_c R}{2\Delta}\right)\right]^{1/2}$$

predicts that plasma is stable when α<~30%, implying kinetic or other effects

*1983 Berk *et al.*, Phys. Fluids **26**, 201.

Conclusion

- **When the population of hot electron component is large in dipole plasma, a burst of electromagnetic fluctuations and disruptive rapid density loss were observed.**
- **The fluctuations propagate in toroidal direction, which agrees with the electron diamagnetic drift direction. The fluctuation frequency is comparable to the toroidal drift frequency of the hot electrons.**
- **The fluctuations have sharp frequency peaks, suggesting that the fluctuation sources are spatially quite localized.**
- **The fluctuations are easily stabilized by reducing the ratio of hot electron component: When the ratio is below ~40%, disruptions do not appear even in the decay phase.**