International Workshop on the Frontiers of Modern Plasma Physics

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Q-Machine Plasmas Yielding New Experimental Methodologies of Sheared-Flow and Nano-Quantum Physics

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The Q machine has been used since the 1960s (~1958): Ion acoustic, electron plasma, ion cyclotron, drift, … waves and instabilities, nonlinear phenomena such as double layers, …. in magnetized plasmas
⇒ Modification to sheared-flow physics study

Contact Ionization

Work function of solid and ionization potential of atom.

Innovative transformation of Q machines into the contribution to nano physics & chemistry fields since 1995.
1. Q-Machine Modification
   Corresponding to Sheared-Flow Plasma Physics Study
Both the ion and electron emitters are concentrically segmented.
Superposition of $B_{||}$ and $B_{\perp}$ Flow Velocity Shears
Superposition of K and Cs Ion Flow Velocity Shears

Electron Emitter
Determine space potential ⇒ $E \times B$ flow velocity
Control of perpendicular flow velocity shear

Ion Emitter
Determine ion flow energy parallel to B
Control of parallel flow velocity shear

Potassium ion flow shear

Cesium ion flow shear

Effect of hybrid ions

Superposition

Plasma Fusion Res. 3 (2008) S1011
Superposition of $B_{\parallel}$ and $B_{\perp}$ Flow Velocity Shears (Drift Wave)

Normalized fluctuation amplitude at $r = -1.0$ cm (shear region).

Superposition of K and Cs Ion Flow Velocity Shears (Drift Wave)
Electron Temperature Gradient Instabilities in Magnetized Plasmas
**Temperature Gradient Driven Modes in Magnetically Confined Plasmas**

**Ion Temperature Gradient (ITG) Modes**
- ITG modes are the most plausible candidate for the anomaly of ion channel thermal transport.
- EXB sheared flow suppression effects on ITG modes are identified [1,2].

**Electron Temperature Gradient (ETG) Modes**
- ETG modes are also the plausible candidate for the electron transport properties of tokamak devices [3].
- ETG modes are difficult to be stabilized by EXB shear.

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Why ETG Mode is Important?

• Experimental observation expresses that the low frequency instability is driven by ETG and nonlinear effects of ETG modes generate significant electron transport.

• The growth rate of ETG mode is about 20 times larger than that of short wave length ITG mode.

• It is an important issue to reduce the electron thermal transport observed in magnetically confined fusion devices.

• Therefore it is necessary to examine the role of ETG driven mode in a linear machine so that the result would be applicable in tokamak plasmas.
ITG mode


ETG mode

Stabilization by ExB shear

Where, $\eta_{e,i} = \frac{d\ln T_{e,i}}{d\ln n_{e,i}}$ = electron, ion temperature gradient, and $V_{E}$ is the ExB shear velocity.
To produce and control electron temperature gradient (ETG) using a thermionic electron superimposed electron cyclotron resonance (ECR) plasma and applying voltages to two different sized mesh grids and finally to examine the stabilization of ETG mode by E X B sheared suppression in a linear machine.

• In laboratory experiments, several techniques have been applied to the control of the electron temperature[4-6], but it is difficult to realize spatially different electron temperatures at a localized area.

Objective

EXPERIMENTAL APPARATUS

![Experimental Apparatus Diagram]

- **ECR Plasma**
- **Grid 1**
- **Grid 2**
- **Electron Emitter**
- **μ Wave**
- **Source Region**
- **Experimental Region**
- **B_{ECR} = 0.24 T**

*Graph showing the magnetic field profile along the Z (cm) axis.*
Electron emitter (W hot plate)

Construction of mesh grids

Deformation of density and temperature profiles from source to experimental region due to mesh grids

Grid bias: additional discharge generates low $T_e$ electron

Supply of thermionic low $T_e$ electrons from electron emitter (EE)

Thermionic electrons superimposed (SI)

Electron emitter (W hot plate)

Grid 1

Grid 2

High $T_e$ electrons in ECR plasma

$\frac{30}{60} \times 170$ mesh/inch

$\frac{30}{60} \times 170$ mesh/inch
By applying different voltages to the electrodes 1, 2, and 3, radial profiles of plasma potentials can be changed and as a result, E X B shear is generated in the central region.
Formation and Control of ETG in thermionic electron superimposed ECR plasmas by changing $v_{g2}$

$v_{g1} = \text{floating potential}$

- $v_{g2} = -5\text{V}$: No ETG is formed
- $v_{g2} = -10\text{V}$: Small ETG is formed
- $v_{g2} = -50\text{V}$: ETG becomes large
2. Innovative Transformation of Q Machine Corresponding to Nano Physics & Chemistry Study
Electron-based electronics & Information technology

Atom

Electron

Charge (Semiconductor)

Spin (Magnetic materials)

Exploiting both the two

Semiconductor spintronics

Endofullerene-based nanoelectronics

Pseudo atom (Atom encapsulated fullerene)

● Endohedral metallofullerene
  Charge transfer
  Single molecular orientation switching
  High efficiency solar cell
  High-temperature superconductivity

Fe

ferromagnetic

Magnetic semiconductor

● Gaseous atom encapsulated fullerene
  (H, He, F, N, ⋯)

N

Long spin lifetime
Sharp resonance

Quantum computer
(Atomic nitrogen encapsulated fullerene)
Generation of Alkali-Fullerene Plasma

Low-Temperature Alkali Plasma

Alkali Oven

A\(^+\) = Li\(^+\), Na\(^+\), K\(^+\), Cs\(^+\)

Electron Attachment

Alkali-Fullerene Plasma

\(B\)

Magnetic Field

\(\phi_{\text{ap}}\)

Slightly Positive Bias

Positive-Negative Ions Interaction

Phys. Plasmas 1 (1994) 3480

Pair $C_{60}$-Ion and H-Ion Plasmas

### Periodic Table

#### Alkali-Metals

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#### Halogens

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<tr>
<td>I</td>
<td>Iodine</td>
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<tr>
<td>Xe</td>
<td>Xenon</td>
<td>54</td>
<td>131.29</td>
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</table>
Alkali-Halogen (Cs⁺ – I⁻) Plasma Generation

Salt: KCl, CsCl, CsI,

(10,10)

From the home page of Maruyama Lab, Univ. Tokyo
http://www.photon.t.u-tokyo.ac.jp/index-j.html
Carbon Nanotube Properties

Tube electric properties drastically change from metal to semiconductor by slight differences of their structure (without any impurity doping).
There are 3 basic types of nanotubes:

- **SWNT:** single-walled nanotube
- **DWNT:** double-walled nanotube
- **MWNT:** multi-walled nanotube

**Diameter:** ~ nm
**Length:** < nm ~ μm ~ mm

Nanoscopic plasma process

Ion Injection via Plasma

End-Cap Modification (Open and Close) with Plasma

Diffusion Plasma CVD Growth

Electron Temperature

One-Dimensional Nanoelectronics Device with Individually-Vertically-Aligned SWNTs (Diode, Superconductor, Magnetic semiconductor, Illuminant, ...)
Freestanding growth of individual SWNTs on a flat substrate

From these results (SEM, TEM, Raman)

- Dgs : 20, 70 mm,
- \( P_{RF} \) : 40 W,
- \( T_{pro} \) : 60, 180 sec,
- \( T_{sub} \) : 700, 750°C

Freestanding-individual SWNTs have been successfully produced on a silicon-based flat substrate due to plasma-sheath effect !!

Unique photoluminescence features in freestanding SWNTs

The continuous equation for PL intensity is found to hold in the time trance of isolated and bundled tubes.

$\frac{\partial S(t)_{(6,5)}}{\partial t} + \frac{\partial S(t)_{bundle}}{\partial t} = 0$

Exciton energies transfer from isolated to bundled tubes caused the PL brightening.

3. Inner Nano – Space Control of Carbon Nanotubes Based on Fundamental Plasma Physics

“Charge and Spin of Electrons are expected to be effectively exploited”
Formation of Atom / Molecule Encapsulated Single- and Double-Walled Carbon Nanotubes Using Different-Polarity Ion Plasmas

Positive ions

- Li^+ 1.5 Å
- Ca^{2+} 2 Å
- Cs^+ 3.3 Å
- Li@C_{60}^+ 7.1 Å

Negative ions

- Cl^- 3.6 Å
- I^- 4.4 Å
- C_{60}^- 7.1 Å

Ionic Liquid^+ ~5 Å ± 10 Å

Ionic Liquid^- ~5 Å ± 20 Å (× 0.1)

13.6 Å

40 Å
Plasma Experimental Method

Stationary Operation

Positive bias is applied
$0 \text{ V} < \phi_{ap} < 50 \text{ V}$

$\phi_p$ : positive ion
$\phi_{ap}$ : negative ion

Dispersive Application

Pulsed Operation

Compound Formation inside SWNT/DWNT

$\phi_{ap}$

$t (\text{sec})$

Positive Ion

Negative Ion

Junction Formation inside SWNT/DWNT

$\phi_{ap}$

$t (\text{min})$

Positive Ion

Negative Ion

SWNTs/DWNTs

-300 V < $\phi_{ap}$ < 0 V
 TEM Images of Atoms and Molecules Encapsulated SWNTs / DWNTs

**SWNTs**

- C_{60}@SWNTs
- C_6@SWNTs
- Li@SWNTs
- DNA@SWNTs

**DWNTs**

- DWNTs
- C_{60}@DWNTs
- C_8@DWNTs

References:

TEM Images of Pristine and Various Fullerenes Encapsulated SWNTs

Pristine SWNT  C_{60}@SWNT  C_{70}@SWNT  C_{84}@SWNT  C_{59} N@SWNT

Scale bar: 2 nm
Electronic Structure inside Atom Encapsulated SWNT

Z-contrast image

Bright field STEM image

Empty

Encapsulated


Theoretical calculation!

STS / STM Result

Cs unfilled

Cs filled

Collaboration with Y. Kuk’ group

4. Electromagnetic Properties of Atom/Molecule Encapsulated Carbon Nanotubes
4.1 Control of Semiconducting Properties of Single-Walled Carbon Nanotubes
Field-Effect Transistors (FETs) Based on SWNT

A schematic of SWNT-FET

An AFM image of SWNT-FET

Pristine SWNT

Cₙ@SWNT (n = 60, 70, 84)

C₅₉,N@SWNT

I₃Dₜ - V₃G characteristics
(V₃DS = 1 V, in vacuum, at 297 K)


p- and n-type transport properties appear.
Dependence of Ion Dose on Electrical Characteristics of Cs@SWNTs

Transport Properties of Cs@SWNT
(In Vacuum, Room Temp., $V_{DS} = 1$ V)

<table>
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<th>Time</th>
<th>Dose</th>
<th>p-type</th>
<th>n-type</th>
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<tr>
<td>15 min</td>
<td>2.2×10^4 /nm²</td>
<td>-22.2 V</td>
<td></td>
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<tr>
<td>30 min</td>
<td>4.3×10^4 /nm²</td>
<td>-29.6 V</td>
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<tr>
<td>45 min</td>
<td>6.5×10^4 /nm²</td>
<td>-35.6 V</td>
<td></td>
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<tr>
<td>60 min</td>
<td>8.6×10^4 /nm²</td>
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</table>

- As the amount of dosed Cs increases, the threshold for $p$-type shifts left.
- After 60 min Cs irradiation Cs@SWNT shows completely $n$-type behavior.

Electronic structure of SWNT can be controlled by adjusting an amount of dosed Cs atoms.

**Dependence of Ion Dose on Electrical Characteristics of I@SWNT**

**Transport Properties of I@SWNT (In Vacuum, Room Temp.)**

- **30 min**
  - $V_{DS}=500$ mV
  - $I_{DS}$ (nA) vs. $V_G$ (V)
  - $-20$ V

- **60 min**
  - $V_{DS}=100$ mV
  - $I_{DS}$ (nA) vs. $V_G$ (V)
  - $-10$ V

- **120 min**
  - $V_{DS}=100$ mV
  - $I_{DS}$ (nA) vs. $V_G$ (V)
  - $+10$ V

- **240 min**
  - $V_{DS}=100$ mV
  - $I_{DS}$ (nA) vs. $V_G$ (V)
  - $+60$ V

**Enhanced p-type**

- As the amount of dosed I increases, the threshold for p-type shifts right.
- After 240 min I irradiation I@SWNT shows a clear enhanced p-type behavior with threshold at 60 V.

4.2 Formation of Nano $pn$ Junctions by Controlling Different-Polarity Ion Plasmas
Controlled Formation of Nano pn Junctions [(Cs/C60)@SWNT]

Positive bias is applied

\[ 0 \text{ V} < \phi_{ap} < 50 \text{ V} \]

Negative bias is applied

\[ -300 \text{ V} < \phi_{ap} < 0 \text{ V} \]

Pulsed Operation

\[ \phi_{ap} \]

Negative Ion

Positive Ion

0

5 nm

C60

Cs
Using Alkali-Halogen (Cs⁺ - I⁻) Plasma

Nano pn Junction

Alkali-Halide Plasma

Magnetic Filter

Alkali-Metals

Halogens
Nano pn Junction Formed by (Cs/I) @ DWNT

For ideal diode measured at $V_G = -40$ V

$$I_{DS} = I_S \left(e^{\frac{qV_{DS}}{nK_BT}} - 1\right)$$

$I_S = 10^{-12}$ A; $n = 1.5; T = 300$ K
Nano pn Junction with stable rectifying behavior of (Cs/I)@DWNT and (Cs/I)@SWNT in air

Output characteristics keep stable even in air, indicating p-n junction in SWNTs & DWNTs with high-performance can be fabricated by hetero-atoms or -molecules encapsulation.
4.3 Coulomb Oscillation Characteristics of Encapsulated Carbon Nanotube — Quantum Dot Formation —
The energy level is quantized in a quantum dot. Current through only when the quantum energy level matches with the fermi energy of drain electrode. The static energy level in quantum dot can be controlled by externally applied $V_G$ ($V_{DS}$ : constant).

Current through only when the quantum energy level matches with the fermi energy of drain electrode.

The quantum dot size can be estimated with the Coulomb oscillation:

$$C_g = \frac{e}{\Delta V_G} \approx \frac{2\pi \varepsilon_0 L}{\ln(2L/d)}$$

$L$: Dot size, $d$: SWNT diameter.

Investigate the effect of alkali-atom encapsulation on SWNTs.

Fig.: Quantum dot and Coulomb oscillation formed by a single dot.
Coulomb Oscillations Observed in Encapsulated Nanotubes

Quantum dots formed in nanotubes due to foreign materials encapsulation.
### Summary

Historical evolutions over 50 years of Q-machine plasma researches are reviewed, where a special emphasis is placed on experimental methodologies of sheared-flow and nano-quantum physics.

Following the drift-wave studies on superposition effects of parallel and perpendicular flow velocity shears and hybrid ions flow velocity shears, an experiment on electron temperature gradient (ETG) instabilities is started, where the large ETG is successfully generated with the radial density profile kept uniform using thermionic electron superimposed ECR plasma.

The innovative transformation of Q machine plasmas for nano physics and chemistry studies has been performed in order to create novel nano-structures and new functional nano-materials by controlling inner nano-spaces of fullerenes and carbon nanotubes.
Welcome to Fukuoka, Japan
A Step toward Creating Novelty Fields in the Future
Plasma Science & Technology Age

ISGLP2008
International Interdisciplinary-Symposium
on Gaseous and Liquid Plasmas

September 5-6, 2008
Hotel Crescent
Tohoku University
Akiu / Sendai, Japan

http://www.plasma.ecei.tohoku.ac.jp/ISGLP/
International Interdisciplinary-Symposium on Gaseous and Liquid Plasmas (ISGLP2008)

September 5-6, 2008
Tohoku University / Sendai, Japan

Calendar of Events

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<td>First announcement and call for papers</td>
<td>March 2008</td>
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<tr>
<td>One-page abstract deadline</td>
<td>May 2008</td>
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<td>Second announcement</td>
<td>June 2008</td>
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<td>Four-page papers deadline for a proceedings volume</td>
<td>August 2008</td>
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<td>Final announcement/program</td>
<td>August 2008</td>
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http://www.plasma.ecei.tohoku.ac.jp/ISGLP/

Satellite Meeting of International Congress on Plasma Physics (ICPP2008)

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