NUMERICAL SIMULATION
OF MULTIPOLE CONFINEMENT (Examples)

by

J. R. Patau and J. C. Sprott

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ABSTRACT

Some examples of numerical simulations of multipole confinement, generated by program SIMULT, are presented and discussed. Where possible, comparisons with experimental results are made. The agreement between the calculations and the plasma parameters from experiments, is surprisingly good in spite of the approximations inherent in a zero-dimensional calculation.

1"Numerical Simulation of Multipole Confinement," J. R. Patau and J. C. Sprott, PLP 556. This PLP is an expanded version of the examples portion of a talk given at the Philadelphia APS meeting on 2 Nov. 73. See PLP 556 for the first part of that talk.
This PLP demonstrates usage of program SIMULT discussed in detail in PLP 556. Examples 1a, 2, 4 and 5 were shown at the Philadelphia APS meeting in November 1973. All cases are for neutral H₂ background.

The excitation energy loss term (PE3 in SIMULT) used in calculating these results is different from the one in PLP 556. PE3 was changed to the new version after the calculations discussed here were done; in this paper, PE3 is given by

\[
\text{PE3} = 10.44T_e^{1.085}\exp(5.912T_e^{-1.08}) - 1.036.
\]

However, the new PE3 would make little difference in these results.

The first two examples simulate the PSL octupole with supports, and show results of two simulations differing only in the microwave input power. For both examples, background pressure is 10⁻⁶ Torr, magnetic field is 1 Kgauss maximum and plasma is an ECRH plasma, formed by 2.45 GHz CW microwaves. Example 1a is for 100 W microwaves, while 1b is for .5 W.

For 1a, the 100 W input power initially all goes into heating the low density \(10^6/\text{cm}^3\) electrons, which get quite hot (80 eV) and become quite efficient at ionizing the neutrals. This ionization raises the charged particle density and thus lowers the heating rate per particle, shown by the rapidly decreasing electron temperature.

Until just after peak field, particle loss is mainly to obstacles. Then, when the field starts to decay, field decay becomes the dominant particle loss mechanism, and the density drops. For most of the run, the main electron energy loss is to neutral excitation.
Ion temperature rises like the density as the ions are heated by electron-ion collisions. At late times, field decay particle loss is the dominant ion energy loss. The high \( T_i \) spike at very late times in both examples a and b are not physical - they result from failure of the numerical method when the magnetic field gets too low.

In example b, the power input is lowered to 0.5 W. The resulting density and temperature profiles change noticeably. Again, we see the electron temperature spike - but this time it is much lower, indicating that most electrons are cooler than the neutral ionization threshold energy, so that little ionization occurs. As a result, the density builds steadily to a maximum at late times, when field decay again dominates the particle loss.

The \( T_e \) spike at early times has been experimentally observed.

Example 2 is an extension of examples a and b. Here we plot ion saturation current to a 0.5 cm\(^2\) Langmuir probe versus CW microwave power, for the PSL octupole operated supported. Background pressure is \( 10^{-6} \) Torr \( H_2 \). The lower solid curve is computer prediction; the individual points are the corresponding experimental results.\(^2\) The upper curve is for the levitated case. Agreement is very good between experiment and simulation.

This graph can be understood in terms of examples a and b. For the conditions described here, ion saturation current measured primarily the density. For high powers, the density peaks near max field and is quite large; for low powers \( T_e \) is too low to cause much ionization and the density peaks very late, when the field decay starts to dominate particle loss. Neutral excitation dominates the electron
energy losses; excitation and obstacle losses combine to almost cancel out the electron energy gain due to microwaves.

The upper curve for the levitated case is in general agreement with observation. With levitation, a steady state is never reached and the density continues to build up until a large particle loss, due to field decay, results. Again the primary electron energy loss is to neutral excitation, and the knee around 1 Watt reflects the strong temperature dependence of the ionization rate.

Example 3 gives the predicted maximum ion saturation current to a Langmuir probe on the small octupole versus CW microwave power for four different neutral pressures: 1, 2, 5 and $10 \times 10^{-5}$ Torr. This time the simulations are carried out to find the maximum power levels at which plasma is produced. The cutoff in each case is very sharp - for instance the $10^{-4}$ Torr case goes from much plasma to no plasma by increasing power by 10 W.

The same comments for case 2 apply to this graph. However near the upper cutoffs the density doesn't rise as fast as the saturation current - the hot electrons determine the value of $J^+$. Above the cutoff power levels, runaway electrons occur which cause breakdown of the program method.

Example 4 shows experiment$^3$ (circles) and prediction (solid curve), for the time evolution of ion saturation current in a gun injected plasma in the small octupole. $J$ is in arbitrary units; theory was normalized to experiment at about 750 µsec after injection. Computer prediction is that obstacle loss is the dominant loss for both particles and energy. The experimental initial fast drop is probably from turbulence left over from the injection process. The experimental drop at late times comes
from densities being measured by a probe on the separatrix, and as the field decays, the density peak moves towards the wall so that the measured density is lower than the average density.

Example 5 shows $T_e$ versus time for the two milliseconds after gun injection for the same case as example 4. There is a noticeable difference between the experimental points$^4$ (x) and the solid curve prediction. However, this discrepancy probably occurs for several reasons:

1. $T_e$ can vary considerably in space,
2. Impurities aren't treated in our program,
3. Treatment of low energy excitation losses is still not perfect.

Again, obstacle loss dominates both particle and electron energy loss.

Example 6 shows charges particle density as a function of time, this time for a pulsed ECRH plasma. Time is measured from the start of the pulse. Experimental measurements$^4$ are by microwave perturbation (0's) and time integrated particle loss flux to hoops, walls and obstacles (x's). Again there is good agreement between prediction and experiment.

Particle losses are dominated by obstacle loss until near the break around 3 ms, when field decay dominates. These processes also account for energy losses.
REFERENCES

For a description of the computer program used to generate these examples, see:

1 J. R. Patau and J. C. Sprott, PLP 556.

2 J. C. Sprott, Phys. Fluids 14, 1795 (1971). See Fig. 5.


4 J. C. Sprott, Phys. Fluids 13, 1626 (1970). Example 5 - see Fig. 7 - curve labeled GUN - 10^{-6} TORR. Example 6 - see Fig. 6.
MULTIPOLe SIMULATION

DENSITY - 10^6/cm^3

SAT CUR - MA/cm²

TEMPERATURE - ev

POWER - WATTS

MAG FIELD - KGAUSS

ION SAT CUR

100.0

TIME

5.0 x 10^-2

T_E

100.0

TIME

5.0 x 10^-2

NEUT DENS

ELEC DENS

10.0

TIME

5.0 x 10^-2
Example 2

ECRH - PRODUCED PLASMA
LARGE OCTUPOLE

\[ p = 1 \times 10^{-6} \text{ TORR} \]

○ = EXPERIMENT
(WITH SUPPORTS)

Computer prediction
- Levitated

Computer prediction
- Supported
Ex. 3
ECRH - PRODUCED PLASMA
SMALL U.W. OCTOPOL
PLASMA SIMULATION ONLY

PEAK ION SATURATION CURRENT (mA/cm²)

C.W. MICROWAVE POWER (Watts)
GUN INJECTION
SMALL OCTUPOLE
p = 1 \times 10^{-6} \text{ TORR}

ION SATURATION CURRENT (ARB. UNITS)

TIME (msec)

TIME AFTER INJECTION

EXAMPLE 4
ECRH - PRODUCED PLASMA
SMALL OCTUPOLE

- MICROWAVE PERTURBATION
- PARTICLE LOSS

\[ p = 1 \times 10^{-4} \text{ TORR} \]

\[ \bar{n}(t) \]

TIME (msec)

EXAMPLE 6