C/ORNL00-0585

CRADA Final Report
for
CRADA Number ORNL00-0585

THE DESIGN OF AN RF ANTENNA FOR A LARGE-BORE, HIGH POWER, STEADY STATE PLASMA PROCESSING CHAMBER FOR MATERIAL SEPARATION

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Prepared by the
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managed by
UT-Battelle, LLC
for the
U.S. Department of Energy
Under contract DE-AC05-00OR22725

Abstract

The purpose of this Cooperative Research and Development Agreement (CRADA) between UT-Battelle, LLC, (Contractor), and Archimedes Technology Group, (Participant) is to evaluate the design of an RF antenna for a large-bore, high power, steady state plasma processing chamber for material separation. Criteria for optimization will be to maximize the power deposition in the plasma while operating at acceptable voltages and currents in the antenna structure.

Objectives

The project objectives are to evaluate the design of an RF antenna for a large-bore, high power, steady state plasma processing chamber for material separation. Criteria for optimization will be to maximize the power deposition in the plasma while operating at acceptable voltages and currents in the antenna structure.

Benefits to the Funding DOE Office's Mission

Archimedes Technology provided a conceptual design of the RF system that ORNL as the basis for its detailed design and analysis of the RF antenna. Archimedes was responsible for the design of the tuning and matching equipment and the phase control circuitry for the antenna. The design of these systems is heavily dependent on the characteristic electrical parameters that were generated as part of the ORNL design and analysis effort. Expected currents and voltages were calculated by ORNL and used by Archimedes Technology to engineer the power delivery and control systems. This iterative procedure will give ORNL valuable feedback on the predictive nature of our codes and enable us to extend them where they may be lacking. This will have a direct benefit to our Plasma Separation Project, our helicon plasma source for mini-RFTF, and our VASIMIR space propulsion system for NASA.

Technical Discussion of Work Performed

Configuration Selection

ORNL analyzed the base antenna configuration (two arrays of four full turn loops) with the EMIR code. Initial modeling used f = 10 MHz and plasma densities as high as 5e18 m^{-3} in oxygen; subsequent efforts concentrated on lower frequency operation. Figure 1 shows RF power deposition for 5 MHz operation for plasma densities of 1.25 and 2.5e19 m^{-3}. It soon became apparent that power absorption by electric fields parallel to the axial magnetic field in the device ($E_{||}$) causes plasma density peaks close to the antenna, leading to hollow plasmas. The EMIR code in its present form was not capable of accurately calculating the $E_{||}$ effects. A decision was made to employ codes with more complete RF/plasma physics capabilities, at the expense of using somewhat idealized antenna/plasma geometry. RANT3D, a 3D Fourier-mode antenna code was used to calculate the electromagnetic fields created by the antennas in the presence of plasma. GLOSI, a 1D infinite slab, warm plasma model, was used to calculate the plasma response to the wave excitation of the antennas. Fig. 2 shows the cylindrical geometry of the device represented by poloidally periodic antenna structure in RANT3D.

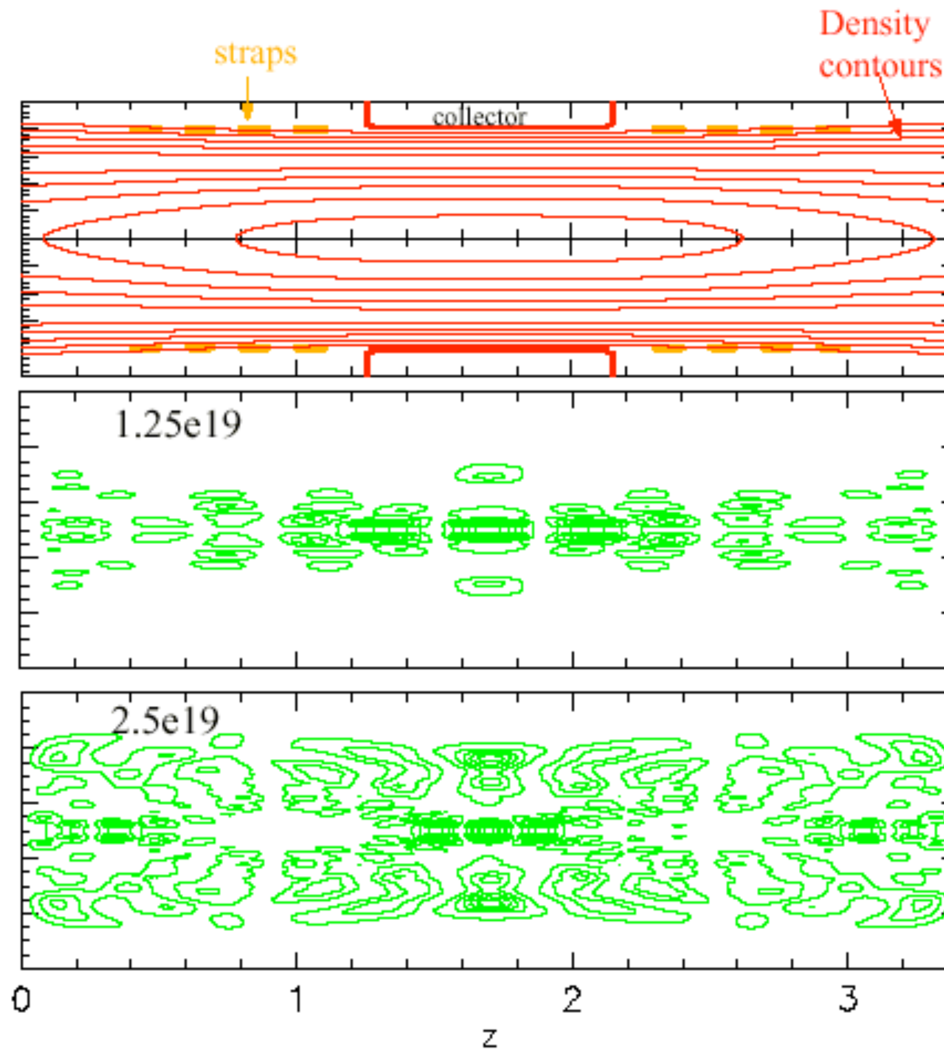

Fig. 1 EMIR power deposition calculations for 0ππ0-0ππ0 phasing, 5 MHz operation, and a parabolic density profile. Penetration may not be this good when $E_{\parallel}$ is properly accounted for.

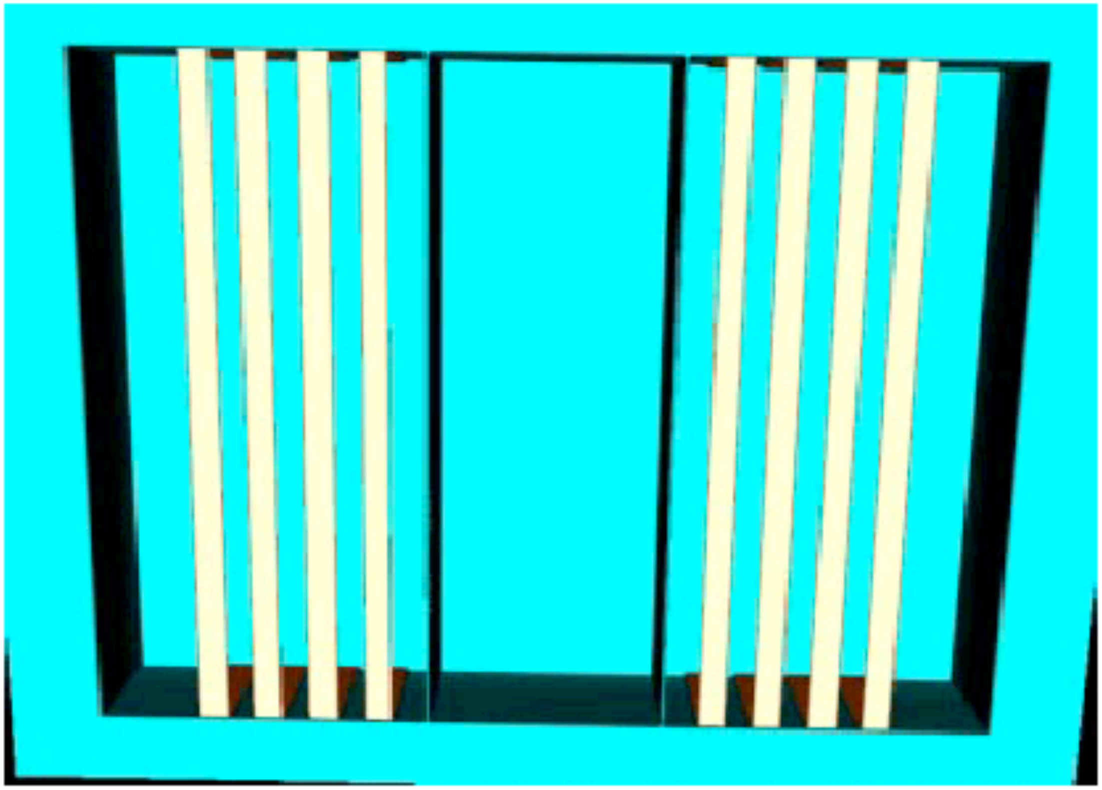

Fig. 2. RANT3D geometry showing four antenna straps on either side of collector region.

Design Evolution

The axial wave number of the launched antenna spectrum, $k_{||}$, was found to have a pronounced effect on the $E_{||}$ power absorption. The antenna spacing and phasing was adjusted to optimize the $k_{||}$ spectrum. Higher $k_{||}$ gave greater wave penetration toward the axis of the device, although too high a $k_{||}$ led to wave cutoff and poor plasma loading. Figure 3 shows that higher parallel mode numbers (wave numbers) penetrate further toward the center but the magnitude of the power deposition is lower (lower plasma loading). The power penetrates even less at the higher plasma density of Fig. 4.

Figure 5 shows the assumed density profile used in the GLOSI calculations. This density profile has a lower hybrid resonance layer close to the antenna surface, where slow waves can be converted to fast waves, which peaks up $E_{||}$. This can lead to large damping for non-zero poloidal mode numbers. Normally for fusion antennas, the collisionality is low, the density is low, and the density gradient is really steep, so there is not too much power going in at the LH resonance. Here the collisionality is high because of the neutrals, and the density gradient is pretty shallow, presumably because of the ponderomotive force.

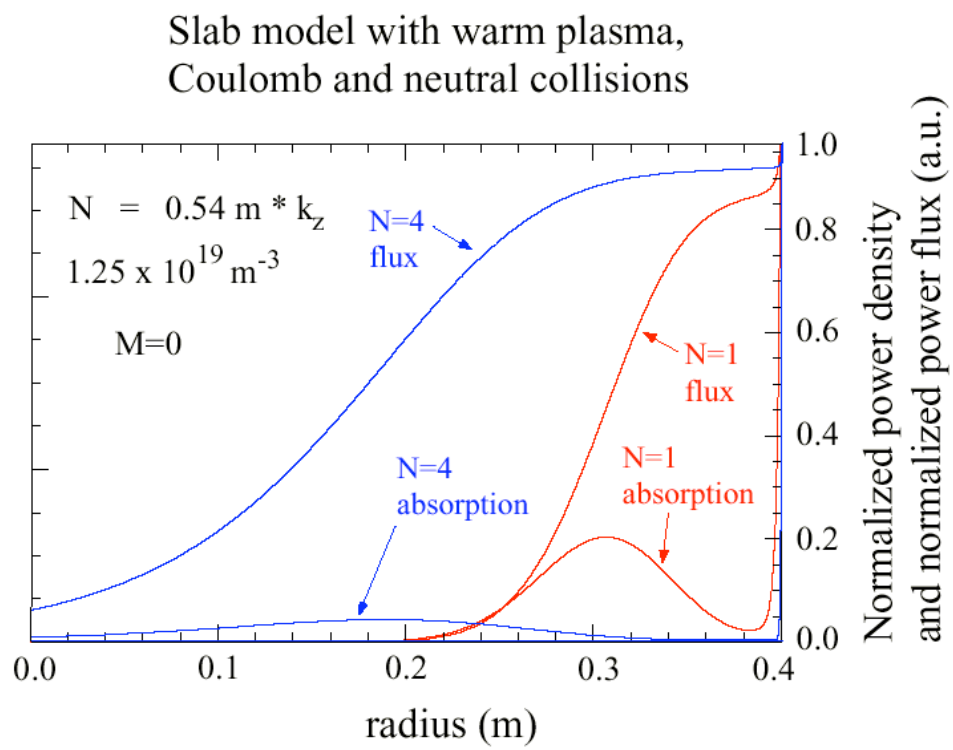

Fig. 3. Power penetration at low density as a function of parallel mode number.

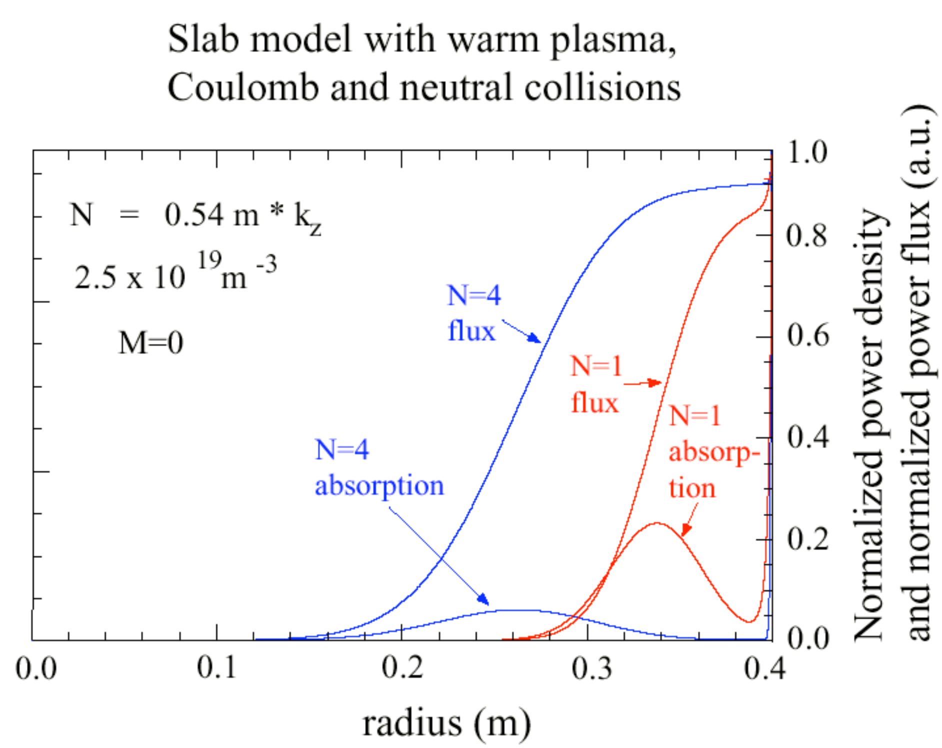

Fig. 4. Power penetration at high density as a function of parallel mode number.

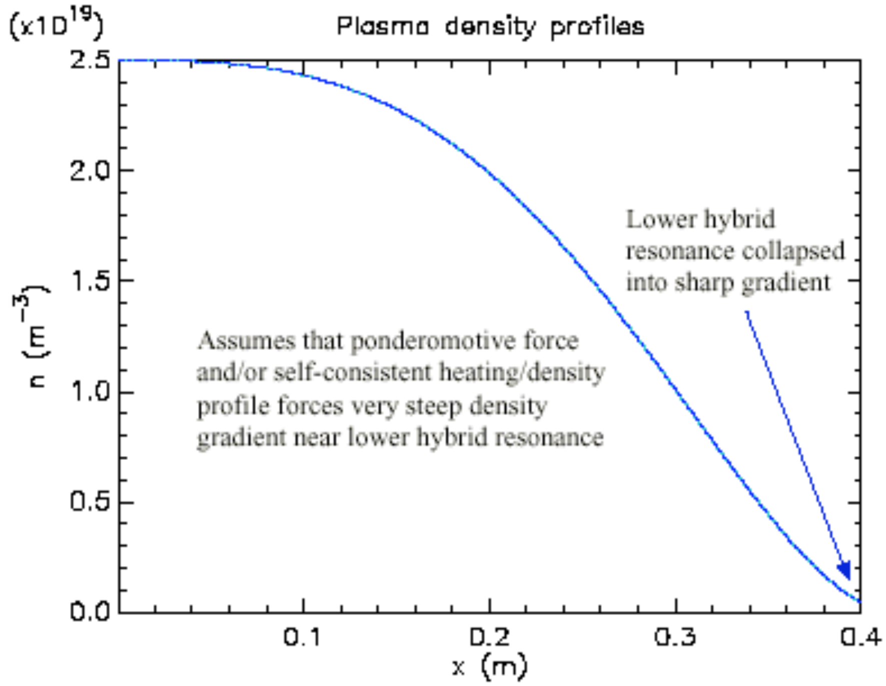

Fig. 5. Assumed density profile for calculations.

GLOSI results shown in Fig. 6 calculate that the edge absorption for the M = 1 (poloidal mode number) can be as high as 25%, compared to only 6% for the M = 0 mode. While there are assumptions contained in the density profile that might not hold true, the recommendation was to not use the dual half-turn antennas that were contemplated as an alternative antenna design, since these may lead to slow wave excitation and power losses to the edge plasma.

The anticipated plasma loading tended to decrease as the geometry was adjusted to avoid power deposition problems. The final baseline geometry gave average loading values of 3-7 ohms for the low-density cases and 5-8 ohms for the high-density cases.

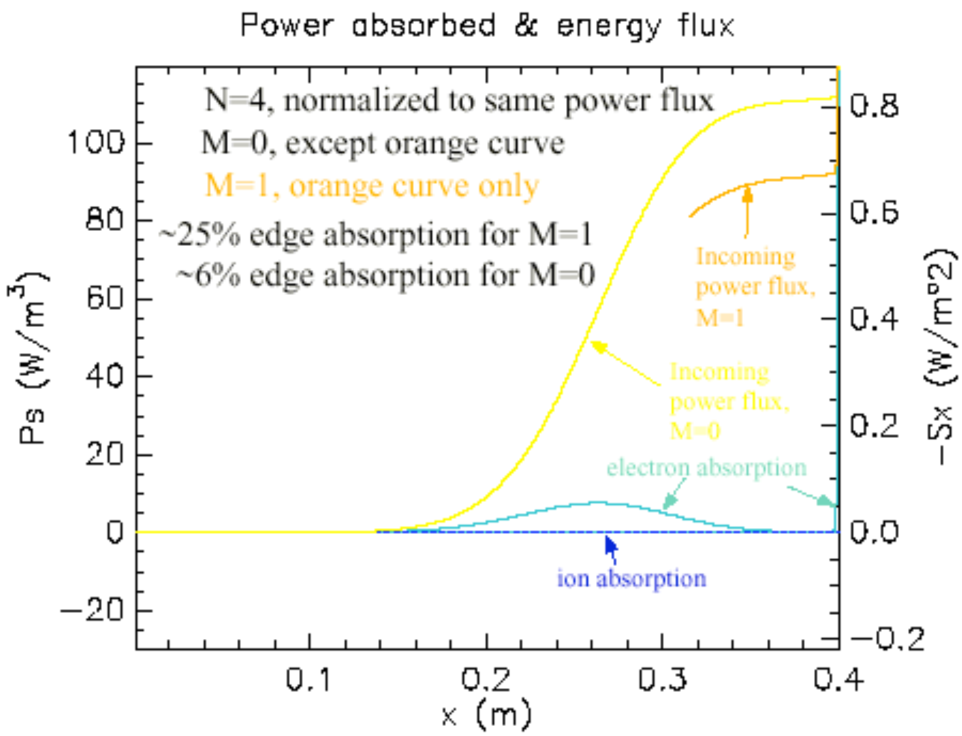

Fig. 6. Power absorption profiles indicate less edge absorption for m = 0 poloidal modes.

Antenna Design

The electrical characteristics of the straps were calculated with a 2D magnetostatic code. This code self-consistently solves for the current distribution to give accurate inductance matrices for the strap array *in vacuum*. As the plasma evolves from low density at start up to high density at full operation, the inductance matrix will change from its vacuum values. This change was calculated with the GLOSI/RANT3D plasma codes.

The first issue was to determine how well the two approaches agreed with each other in vacuum. The 2D magnetostatic code used thin current straps (6-mm thickness) to approximate the infinitely thin current sheets employed by RANT3D. The comparison of the 4x4 inductance matrices is shown below (coupling is sufficiently small across the central collector region that the four loops on either side of the collector can be considered independently). The diagonal terms are the self-inductances and the off-diagonals are the mutual inductances.

L' calculated by GLOSI/RANT3D in vacuum ($\times 10^{-7}$ H/m)

5.793	1.770	0.670	0.232
1.770	5.870	1.770	0.578
0.670	1.770	5.781	1.515
0.232	0.578	1.515	5.118

L' calculated by 2D magnetostatic code in vacuum (x10^{-7} H/m)

5.286	1.699	0.693	0.255
1.698	5.301	1.669	0.594
0.694	1.664	5.206	1.430
0.257	0.596	1.430	4.644

This exercise demonstrated that the inductances calculated by RANT3D were in reasonable agreement with those calculated for more realistic geometry, in the limit of very thin strap cross section. The inductance values calculated for a 25-mm strap were 7-10% lower than those for a 6-mm strap.

The presence of plasma reduces the strap impedance by 30% at low densities and up to 45% at high densities. The plasma loading calculated by RANT3D for 5 MHz operation gives peak voltages of 8.6 kV on the strap for a total of 5 MW delivered to the plasma at densities of 2.5x10^{19} m^{-3}. The same voltages give total powers of 4.2 MW at 1.25x10^{19} m^{-3} and 2.9 MW at 2.5x10^{18} m^{-3}.

Remaining Issues

A continuing concern during this design exercise was possibility of sustaining arcs between the straps connected by field lines. Staggering the straps at different radial locations was found to have minor effects on operation, and may therefore offer an attractive approach for avoiding parallel breakdown.

Sustained arcs between the straps and the plasma due to the relatively high pressure in the region were a related concern. Experiments at ORNL suggested that voltage holding would be severely degraded in such an environment.

Inventions

None.

Commercialization Possibilities

Plans for Future Collaborations

None at this time.

Conclusions

Power deposition profiles were calculated for the antenna geometry proposed by Archimedes Technology Group, Inc. The proper phasing for good RF wave penetration under the specified plasma densities was identified. The issue of antenna arcing at low voltage in the presence of a high background neutral pressure was identified.