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Introduction

A tenuous, cool plasma called the halo shields the core plasma in a tandem mirror from neutral gas and impurities. The neutral particles are ionized and then pumped by the halo to the end tanks of the device, since flow of plasma along field lines is much faster than radial flow. Plasma reaching the end tank walls recombines, and the resulting neutral gas is vacuum pumped. The basic geometry of the MINIMARS halo is shown in Fig. 1. For halo modeling purposes, the core plasma and cold gas regions shown there may be treated as single radial zones leading to halo source and sink terms. The halo itself is differentiated into two major radial zones: halo scraper and halo dump. The halo scraper zone is defined by the radial distance required for the ion end plugging potential to drop to the central cell value, and thus have no effect on axial confinement; this distance is typically a "sloshing" plug ion Larmor diameter. The outer edge of the halo dump zone is defined by the last central cell flux tube to pass through the choke coil. This paper will summarize the halo model that has been developed for MINIMARS and the methodology used in implementing that model as a computer code.

The halo model discussed here has evolved from earlier tandem mirror halo modeling work [1-5]. However, a considerably more sophisticated model is required for MINIMARS. In part, this is because the use of thermal barrier drift pumping leads to a strong radial gradient in the heat fluxes to the end tanks. Thus, the computer code uses multiple zones, both axially and radially, for the halo scraper and halo dump regions. These are shown schematically in Fig. 2. The octupole end cell has only a small effect on the azimuthal symmetry of the flux tubes in the halo regions, so a two-dimensional model suffices. The number of radial zones is allowed to vary, depending on the accuracy required, e.g. parametric studies or reference point definition. The four axial zones are defined as the regions where significant changes in source and sink terms are expected to occur; they are the central cell, transition, mantle, and end tank.

An important consideration for the halo computer code was that it be flexible, in order to incorporate new features of MINIMARS or developments in experiments and theory. Thus, structured, modular, top-down programming techniques were used throughout [6]. This lead to the program organization diagrammed in Fig. 3. The various modules shown there are largely self-explanatory. The heart of the code is contained in the box labeled "Single Zone Equations", where the source and sink terms given by individual modules (subroutines) are combined into three equations for each zone: plasma particle balance, electron power balance, and ion power balance.

Halo modeling difficulties result primarily from the intrinsically nonlocal character of charge exchange, the complexity of plasma-wall interactions, and the geometric dependence of halo heating by alpha particles. Table 1 summarizes the areas which must be

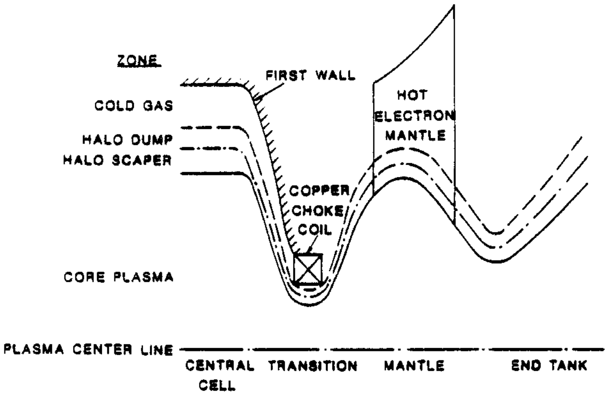

Fig. 1. Basic geometry of the MINIMARS halo. Figure is not to scale.

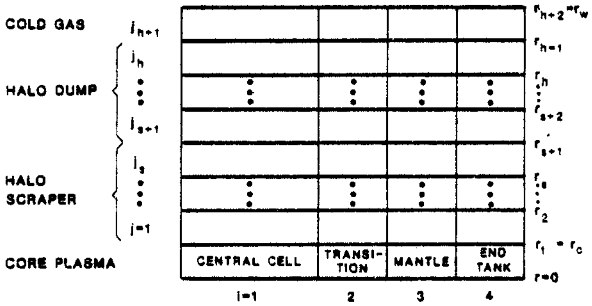

Fig. 2. Halo model zone structure.

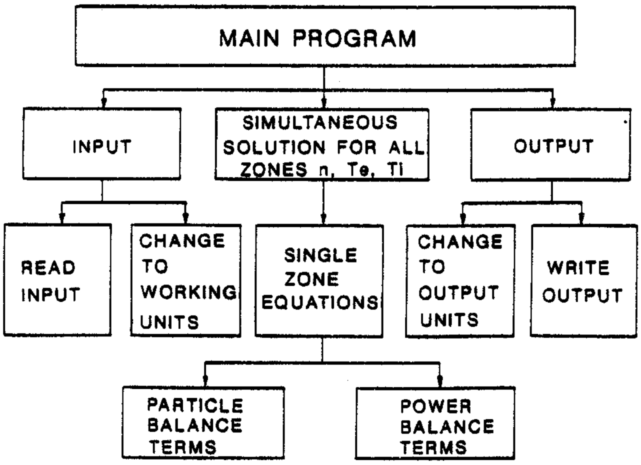

Fig. 3. Structure of the halo computer code.

Table 1. Halo Modeling Areas

Flux mapping
Alpha particle heating of the halo
Plasma/radial wall interactions
Neutral gas attenuation
Reionization of charge-exchanged neutrals
Particle and energy end loss
Radial particle and energy transport
Neutral gas flow and vacuum pumping
Plasma/end wall interactions and recycling
Mantle interaction with the halo

modeled for the MINIMARS halo. The remainder of this paper will discuss the models to be used in each area.

Flux Mapping

The inner and outer radii of the flux tubes defining the zones shown in Fig. 2 vary along the axis due to changes in the magnitude of the magnetic field. Conservation of magnetic flux,

$$\int_0^r dr\, rB(r) = \text{constant} \qquad (1)$$

where $B(r) \approx B_{vac}(r)\sqrt{1 - B(r)}$ is the plasma magnetic field, allows the mapping of flux tubes. An effective length for each axial zone may then be defined by

$$L_{eff} \equiv \frac{\int_{-L}^{L} dz\, r^2(z)}{2\, r_0^2} \qquad (2)$$

where L is the central cell half-length, r_0 is the radius at the midplane of the flux tube, and r(z) is given by Eq. (1).

Alpha Particle Heating of the Halo

Alpha particles whose orbits intersect the halo transfer energy to halo electrons through collisional drag. The energy transfer rate depends, to zeroth order, on the relative thermal equilibration times for alpha particles in the halo and in the core plasma. These equilibration times are proportional to the respective $n/T_e^{3/2}$ values and the fraction of the orbit intersecting the halo. The analysis is further complicated by modifications to alpha particle Larmor orbits as the alphas slow down.

For the simple case of unmodified Larmor orbits, the alpha energy transfer problem reduces to a straightforward geometric calculation. A constant density and temperature halo using a slab model was treated in Refs. [1], [2], and [5]. The generalization of the Ref. [5] model to multiple zones will be one option in the MINIMARS halo code. The more sophisticated approach of following alpha particle slowing down orbits was taken in Refs. [4], again for a constant density and temperature halo. This approach will be modified for multiple zones and will be an alternative option in the MINIMARS halo code.

Neutral Gas Effects and Radial Wall Interaction

Perhaps the most difficult problem in modeling tenuous plasmas in contact with material surfaces is that of dealing with cold gas effects. There are three causes for this: (1) the multitude of species and charge states involved, (2) the intrinsically nonlocal character of charge exchange transport, and (3) the lack of a comprehensive plasma-wall interaction data base. The first difficulty leads to complicated problems requiring intensive numerical calculations with results that are difficult to simplify or scale. The second implies that global solutions are needed and that local solutions have limited usefulness. The third, partially arising from the first two, results in largely unknown source terms, especially for impurities.

Fortunately, a number of computer codes for plasma-wall interactions exist. The SPUDNUT code [7] has been chosen for use in MINIMARS halo modeling. SPUDNUT was designed to treat neutral transport in slab geometry, including wall effects. The code gives gas ionization rates and energy transfer rates between gas and the halo for discrete radial zones in a single axial zone. SPUDNUT has been modified for use as a subroutine in the MINIMARS halo code. The code will iterate over the four axial zones, using SPUDNUT to generate neutral particle parameters and a separate subroutine to generate halo parameters.

Particle and Energy End Loss

End loss is a relatively well-characterized area [8], due to the large data base for simple mirror machines. There are two types of terms: (1) convection terms, which are important for both ions and electrons and (2) conduction terms, which are large only for electrons. One option in the MINIMARS halo code will be to use the model described below. A more sophisticated model, whose application to MINIMARS is being assessed, has recently appeared [9].

There are two regimes for ion end loss, somewhat arbitrarily delineated into collisional and collisionless by the ratio of ion-ion scattering time, $\tau_\perp$, to bounce time, $\tau_\parallel$. For $\tau_\perp < \tau_\parallel$, the halo is called collisional. For both the halo scraper and halo dump zones, a simple flow time may be used:

$$\tau_{flow} \approx \frac{R_c L_c/2}{(2T_i/\pi m_i)^{1/2}} . \qquad (3)$$

For $\tau_\parallel < \tau_\perp$, the halo is called collisionless. In the halo dump zone, where no ion end plugging occurs, end loss is that of a standard mirror machine,

$$\tau_{scat} \approx \tau_{ii} \ln R_c \qquad (4)$$

where the ion-ion scattering time is

$$\tau_{ii} \approx 4.9 \times 10^5 \frac{T^{3/2}}{n} . \qquad (5)$$

For the halo scraper zone, the ion end loss rate depends on the ratio of ion confining electrostatic potential, Φ_i, to ion temperature, and is given by the Pastukhov formula [9] for ions:

$$(n\tau)_{pas} = \frac{1.3 \times 10^4}{Z_i} \frac{G_i}{I_i} \left[\frac{m_i}{m_e}\right]^{1/2} T_i^{1/2} \Phi_i \exp\left[\frac{\Phi_i}{T_i}\right] \quad (6)$$

where Φ_i is a function of radius, G_i/I_i is on the order of one, and $Z_i \approx 1/2$.

Electron end loss is also given by the Pastukhov formula with the appropriate confining potential. Electron thermal conduction is given by the standard formula for the heat flux, Q [11]:

$$Q \approx \kappa_{\parallel} \nabla_{\parallel} T_e \; . \quad (7)$$

Radial Particle and Energy Transport

Since MINIMARS is essentially axisymmetric out to the outer edge of the halo, classical radial transport applies for most of the halo. The radial diffusion coefficient is well-established in this case:

$$D_r = \nu_c \rho_i^2 \quad (8)$$

where ν_i is the collisional scattering rate and ρ_i is the gyroradius.

An unknown effect is that of thermal barrier drift pumping. Thus, radial transport in the thermal barrier region will be parameterized in the computer code.

Neutral Gas Flow, End Wall Interaction, and Vacuum Pumping

The physics model of the halo plasma must include the flow of gas from surfaces, since the main purpose of the halo is to intercept this gas and prevent it from reaching the core plasma. Most of the gas is formed at the halo dumps in the ends of the machine, but some is produced near the choke coils where part of the neutron shielding serves to limit the radial extent of the halo. Models based on the work of Refs. [3] and [4] will be used to reach a reasonable estimate for these effects. In those studies, the three basic processes that determine the halo parameters were treated separately.

The first of these effects is the flow of the halo plasma along a magnetic flux tube. In this part of the model, the high recycling rate was included as a source at the ends of the halo. The second effect, the recycling at the ends, was calculated for assumed plasma parameters. Because the dimensions of the halo are much larger than the mean free paths for either molecules or for Franck-Condon neutrals, the recycling is approximately a one-dimensional problem there. The third effect is the vacuum pumping by the halo along its length, and the shielding of the core plasma from gas and impurities released at the walls.

The assumption that these three effects can be analyzed separately is probably good everywhere except near the limiters. This fact should allow the combining of separate existing codes. However, in order to produce the high halo density that is needed in MINIMARS, the recycling at the ends must be great enough to reduce the Mach number to near zero everywhere in the halo. This appears to be required in order to limit the power consumption, and to produce an acceptable heat load on the collector plates when the halo density is high. These near-stagnant conditions may require a new fluid code to properly treat flow.

Halo/Mantle Interaction

Two effects of the mantle electrons are involved here: (1) Heating of the halo plasma and (2) Creation of a thermal barrier.

Heating by mantle electrons is straightforward and may be scaled from standard formulas [11]. Creation of a thermal barrier, which has a major impact on electron thermal energy convection to the ends of the device, is more difficult to assess, since details of the mantle parameters await the outcome of a Fokker-Planck computer code analysis. For the purpose at hand, thermal barrier creation will be parameterized in the MINIMARS halo code.

Status of the Computer Code

The modules for input/output and for solving the required simultaneous equations have been written. A BASIC version of the flux mapping module exists, and modification for FORTRAN will not be difficult. Work on the alpha particle heating module is in progress, with a FORTRAN version available from Ref. [5] for the unperturbed orbit case and a BASIC version available from Refs. [4] for the slowing down orbit case, both for constant density and temperature halos. Conversion of SPUDNUT into a subroutine of the needed form is almost finished; present effort is aimed at including molecular gas effects. End loss modules will be taken from those used for Ref. [5], with a new but simple module written for the electron thermal conduction term. A preliminary version of the axial gas flow module exists in BASIC. The modules required for halo/mantle interaction are essentially written.

Thus, the major remaining computer code modeling work for the MINIMARS halo will be in the alpha particle heating and neutral gas flow areas. There then remains, of course, the task of defining MINIMARS halo parameters using this code.

Summary

The MINIMARS halo modeling effort has concentrated on extending previous tandem mirror halo work into a much more sophisticated model. In particular, alpha particle and neutral gas effect modeling will be greatly improved. Also, radial and axial profiles are now calculated in more detail. A computer code based on the new model is in the development stage, with an expected early transition into a debugging phase and, finally, into parameter definition.

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