BEAM AND PUMP CURRENTS FOR A MARS ANCHOR

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ABSTRACT

The MARS anchor has been modelled and analyzed with a numerical bounce-average Fokker-Planck treatment. The interactions between the various ion classes (passing, spanning and trapped) are treated in detail. Consistent solutions have been obtained for the complete asymmetric anchor. For baseline MARS parameters, 5.7 MW per end must be delivered by the anchor neutral beams, and 6.5 A per end must be pumped to maintain the sloshing ion axial density profiles.

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1. Introduction

A tandem mirror in the MARS (Mirror Advanced Reactor Study) configuration consists of four identifiably different regions (Fig. 1): center cell, axicell, transition section and yin-yang anchor. Each of these regions is characterized by a class of trapped ions which are spatially isolated from each other. There are also classes of ions that span two or more of the major regions. For MARS parameters, there are four such spanning classes: center cell-axicell, transition-anchor, axicell-transition-anchor, and the center cell-axicell-transition-anchor, also known as the passing ions. The distribution functions in each major trapping region are interrelated through the intermediary action of these spanning ion classes.

The different spanning classes occupy characteristic regions of velocity space. The three spanning classes which extend into the anchor can be seen in Fig. 2, which shows their velocity space boundaries at the 6 Tesla mirror between the anchor and transition section.

The anchor configuration in the MARS design is chosen to simultaneously satisfy several constraints. The magnetic field is designed to provide MHD stability by providing a sufficient region of positive curvature. The ion loss-cone in the center cell midplane velocity space is plugged by maintaining a large potential peak in the outboard side of the anchor (at a) (see Fig. 1), and a potential well at the anchor midplane (at b) allows center-cell and plugging electrons to be thermally insulated from each other. In this way, the latter, so-called warm electrons, can be heated by ECRH to enhance the electrostatic potential. The barrier is formed by a low ion density at b where hot, mirror-trapped electrons are also located. The higher ion density needed at a is furnished by sloshing ions, i.e., ions are injected normal to the field at a or a' (see Fig. 1), thereby peaking the ion density away from the midplane.

Collisional scattering of ions which span the anchor as well as of sloshing ions will tend to fill in the ion density at b, thereby spoiling the thermal barrier. These trapped ions must be removed by some form of pumping, e.g., with charge-exchange off a neutral beam or with rf magnetic fields. To compute the required pumping current and sloshing-ion current, it is necessary to solve the Fokker-Planck equation for ions. A powerful tool for this is the bounce-average code developed at LLNL.¹ The manner in which this code is applied to the present problem is described in the next section.

Additional constraints are imposed on the distribution functions by the requirements for microstability. Experimental results have indicated that drift cyclotron loss-cone (DCLC) modes can be stabilized by a small population of warm plasma. In addition, to eliminate the free energy available to drive the Alfvén ion cyclotron (AIC) instability, a constraint is imposed on the ion temperature anisotropy. We do not address these stability problems in detail; however, the distribution functions obtained could be used to check for stability.

2. Solution Strategy

The anchor analysis is considerably simplified by imposing reasonable constraints at the outset. As in M. Rensink's analysis of the MFTF-B Anchor,² the vacuum magnetic field is obtained from an EFFI^{3,4} run and the beta-reduced field is calculated using $B = B_v \sqrt{1-\beta}$. The potential profile is fixed and modeled as piecewise quadratic in the magnetic field, i.e.,

$$\begin{aligned}\phi &= \phi_a - (\phi_a - \phi_0) \left(\frac{\psi_a - \psi}{\psi_a - 1} \right)^2, & 1 \leq \psi \leq \psi_a \\ &= \phi_a - (\phi_a - \phi_m) \left(\frac{\psi - \psi_a}{\psi_m - \psi_a} \right)^2, & \psi_a \leq \psi \leq \psi_m\end{aligned}$$

where⁵:

ϕ_0 $\equiv$ anchor mid-plane potential = 21 kV.

ϕ_a $\equiv$ the potential at the peak for the outboard side = 333 kV.

= the potential at the injection point for the inboard side = 144 kV.

ϕ_m = the mirror point potentials.

= 0.0 kV for the outboard side.

= 152 kV for the inboard side.

ψ_a = the ratio of the magnetic field at the potential peak to the magnetic field at the midplane.

= 1.84 for the outboard side.

= 3.14 for the inboard side.

ψ_m = magnetic field ratio at the mirrors = 4.677.

The magnetic field and potential profiles in the anchor region are shown in Fig. 3.

The class of ions which pass from the center cell and reflect off the potential peak, for practical purposes, have their distribution function and axial density profile effectively specified by their collisional equilibration to a loss-cone Maxwellian in the center cell. It is further hypothesized at this point that the distribution function of the class of ions which spans the anchor and the transition section is determined by collisional interaction in the transition section alone. The argument for this hypothesis relies on the

larger number of particles with which these ions experience Coulombic collisions in the transition section as compared to in the anchor. A solution for the transition section using the bounce-averaged Fokker-Planck code can thus be used to obtain the distribution of the transition-anchor and axicell-transition-anchor spanning ion classes. A contour plot of one such solution showing the boundaries of the passing and spanning classes and their distribution functions at the anchor inboard mirror can be seen in Fig. 2.

Knowing the transition-anchor spanning ion distribution function, we can use it as the boundary condition on the anchor distribution function for the Fokker-Planck equation. Consideration of Fig. 2 shows that we can model f at the mirror by the function

$$f \sim e^{-a(v_{||} - v_{||0})^2} e^{-bv_{\perp}^2}$$

where a , b and $v_{||0}$ are adjustable constants. It is also found that the density of spanning ions at the anchor midplane is only slightly less than the total density of warm ions assumed by Campbell in his computation of MARS parameters.⁵ Thus, pumping to be supplied in the anchor must hold the anchor-midplane ion density to a low value.

In its present form, the bounce-average code assumes symmetry in θ and ϕ in performing the bounce averaging. However, it is possible to specify boundaries for losses or between spanning and trapped particles from θ and ϕ profiles which are not symmetric. We can therefore use the outer half profiles for the bounce-averaging and center-cell, axicell and inner mirror potentials and magnetic fields to determine the passing-spanning and spanning-trapped boundaries. Potentials and magnetic fields for a typical set of MARS parameters are given in Table I.

The presence of the sloshing ion beam at point a (see Fig. 1) also contributes to the asymmetry of the problem. Ions injected perpendicular to the field line at point a' will reflect at the conjugate point a found from conservation of energy and magnetic moment. We can insert an equivalent beam at point a with energy $475 - (\phi_a - \phi_{a'}) = 286$ keV. The pumping term is modeled as $-vf$, where v is taken as constant over a range of z near the anchor midplane. Effective pump and beam ranges are shown in Fig. 3.

The calculations reported here were carried out for a single set of MARS parameters. Some of the plasma quantities needed for these calculations are collected in Table 2. The normalization constant in the spanning-ion density is adjusted to match the trapped density of $6.25 \times 10^{12} \text{ cm}^{-3}$ while the passing central-cell density at point b is $3.57 \times 10^{12} \text{ cm}^{-3}$. The pumping and sloshing-ion beam currents are then adjusted to yield the total midplane and peak densities, $1.69 \times 10^{13} \text{ cm}^{-3}$ and $2.35 \times 10^{13} \text{ cm}^{-3}$, respectively.

The bounce-average code only yields line average currents which must be averaged over the plasma radius. Following the assumptions of the MARS point-model code we find its cross-sectional area of the anchor from

$$A_A = \pi r_c^2 B_c \sqrt{1 - \bar{B}_c/B_b} \sqrt{1 - \bar{B}_b} \\ = 1.22 \times 10^4 \text{ cm}^2$$

where a cubic density profile has been assumed in computing the mean plasma $\bar{B}$. Since ion scattering scales as n^2 , we must also multiply the results by the factor 9/20 to get the final total current per end.

3. Results and Discussion

The results for several pump profiles and spanning particle treatments are tabulated in Table 3. Cases 4 and 5 include no transition spanning ions and we see that the pumping and beam currents are much reduced over the corresponding value with transition spanning ions. The presence of these ions enhances the scattering rates, thus causing higher loss rates of ions out the end as well as higher diffusion of ions into the low $v_{\perp}$, $v_{\parallel}$ region where they must be pumped. Pumping over 8 m (case 3) is clearly inferior to pumping only over 3 m (case 1), since the former removes sloshing ions, thus requiring higher beam current. The pump currents listed in Table 3 include only pumping of anchor trapped ions, i.e., those above the boundary indicated by numerals "1" and "2" in Fig. 5a. The present MARS design calls for rf induced drift pumping of ions and will also induce losses of passing and spanning ions. For cases 1-3 these losses amount to 9.9, 8.6 and 7.6 A/end, respectively. Such losses are far below several hundred amperes of losses which occur because of pumping in the transition section.

For the parameters of these calculations the point-model code predicts a beam power of 3.1 MW/end, closer to the value without scattering from spanning ions. For this case alone, the power should be scaled up by a factor 1.83.

The axial density profile for the baseline case 1 is shown in Fig. 4, while the distribution function at the anchor midplane is given in Figs. 5a and 5c. Useful for analysis of stability are the parallel and perpendicular distribution functions as defined by

$$f_{\parallel} \equiv 2\pi \int dv_{\perp} v_{\perp} f(v_{\parallel}, v_{\perp})$$

$$f_{\perp} \equiv \int dv_{\parallel} f(v_{\parallel}, v_{\perp})$$

These are plotted in Fig. 6.

The midplane distribution $f_{\perp}$ (Fig. 6) has positive slope for $2 \times 10^8 < v_{\perp} < 4 \times 10^8$ cm/s. It does not meet one simple criterion for micro-stability, namely that $df_{\perp}/dv_{\perp} < 0$ everywhere. However, the warm plasma can stabilize the most severe mode (drift-cyclotron loss-cone) if its temperature and density are large enough. We have not tested this distribution function for stability, but can obtain an indication by applying the results for the MFTF-B anchor.⁶ These results show that the ratio of warm to sloshing ion

densities and energies must fall within a certain range for stability. From examination of Fig. 6, we find that there is more than enough warm plasma, but that its temperature is too low, leading to two-component instabilities. However, it has been found that unstable distributions such as this will relax to a marginally stable state, i.e., enough rf-induced diffusion will take place to heat the warm ions sufficiently to achieve stability. Some additional beam current must then be supplied to make up for the concomitant rf-induced loss of sloshing ions.

This analysis considered only deuterium and electrons. The inclusion of tritium further alters the picture of the spanning and passing ion classes. In velocity space, the passing region for tritium extends over both the passing and spanning regions for deuterium. Though this may affect the spanning class distribution functions, the tools for this analysis do not yet exist. The alpha particle classes have the same velocity space boundaries as deuterium.

The code can also be used to analyze the anchor as if the profile for the bounce average were that of the inboard side of the anchor. The outboard magnetic field and potential are used to construct the loss boundary (curve 2 in Fig. 5b). The pumping frequency ν is taken the same as found in the solution of the "outer" problem and the beam current at point a' is adjusted to maintain the total midplane density of $1.69 \times 10^{13} \text{ cm}^{-3}$. The solution for the distribution function is shown in Fig. 5b. The required beam current of 12A/end (Table 3) is essentially identical to the value obtained from the outboard analysis. The distribution functions at the anchor midplane obtained from the inboard and the outboard analysis are very similar (compare Figs. 5a and 5b). In addition, the sloshing ion density peak, at point a' ($3.2 \times 10^{13} \text{ cm}^{-3}$) follows closely the simple relation⁷

$$\frac{n_i(a')}{n_i(b)} = \left(\frac{B(a')}{B_b} \right)^{1.2} \frac{E_{inj}^{a'} + \delta\phi_{a'}}{E_{inj}^{a'}}$$

where $\delta\phi_a$ is the potential difference from b to a' (Fig. 1). 12 A/end can thus be taken with confidence as the required anchor injection current for this set of MARS parameters.

References

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TABLE 1

MARS POTENTIALS AND MAGNETIC FIELDS⁵

<u>ϕ (kV)</u>	<u>B-Reduced B(T)</u>	
198	2.574	Center Cell
198	21.000	Axicell Mirror
233	7.668	Axicell Midplane
182	24.000	Axicell Mirror
170	11.8	Pump Beam Location
106	1.981	Transition Section
152	6.000	Inner Mirror
144	4.027	Injection Point a' (475 keV Ions)
21	1.283	Anchor Midplane
333	2.359	Point a
0	6.000	Outer Mirror

TABLE 2
MARS PLASMA PROPERTIES (17 June 1982)

<u>Central Cell</u>	
Ion Temperature, T_{ic}	35 keV
Electron Temperature, T_{ec}	28 keV
Electron density, n_{ec}	$4.22 \times 10^{14} \text{ cm}^{-3}$
Plasma radius, r_c	42.0 cm
Plasma β	0.70

<u>Anchor</u>	
Passing midplane density, $n_p(b)$	$3.57 \times 10^{12} \text{ cm}^{-3}$
Trapped midplane density, $n_t(b)$	$6.25 \times 10^{12} \text{ cm}^{-3}$
Total midplane density $n_i(b)$	$1.69 \times 10^{13} \text{ cm}^{-3}$
Peak sloshing ion density, $n_{ih}(a)$	$2.35 \times 10^{13} \text{ cm}^{-3}$
Plasma β at midplane	0.65

TABLE 3

MARS REQUIRED CURRENTS

Case	Pumping	Passing Ions	Anchor-Transition Spanning Ions	Pump Current	Beam Current	Power
1	-150 to 150 cm	Maxwellian	From Transition Calculation	6.5 A/end	12.1 (outboard) A/end 12.0 (inboard)	5.7 MW/end
2	-50 to +50 cm	"	"	6.2	11.8	5.6
3	-400 to +400 cm (uniform)	"	"	8.1	14.7	7.0
4	-150 to +150 cm (uniform)	None	None	2.1	4.1	1.9
5	-150 to +150 cm (uniform)	Maxwellian	None	3.7	7.4	3.5

*All cases except 1 considered only the outboard half of the anchor.

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