Report to DOE on
Refueling of Phaedrus

by

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I. Perspective on the Development of Refueling Ideas for Phaedrus

When the Phaedrus proposal was submitted we had only briefly examined the question of end plug refueling. The main thrust of the proposal dealt with the use of RF to heat the end plugs and the question of the effect of ICRF on confinement made it necessary to carry out detailed calculations to demonstrate the viability of ICRF. We were able to show that ICRF was indeed compatible with mirror confinement and, in fact, could be used to reduce the neutral beam energy required to sustain the ion temperature in an end plug. We applied the then new idea of RF diffusion in mirrors to the problem of stream refueling of end plugs. This idea was presented in the original written Phaedrus proposal. RF trapping of a streaming plasma is a relatively inefficient process due to the fact that only plasma near the loss cone boundary can be diffused into the trapped region of velocity space. The untrapped plasma stream causes an undesirable cooling load on the plasma. Since the proposal, more refined treatments of RF diffusion including Yushmanov trapping in the end plug of central cell electrostatically confined plasmas have been done by Kesner. The application of this work will be reviewed in the report.

During the time that transpired between the submission of the written document and the oral presentation, we began to look at low energy neutral beams. This work was undertaken in part due to Baldwin's concerns that the stream currents used in the proposal to refuel the plugs were not compatible with reasonable electron temperatures in a tandem mirror. Furthermore, the stream currents required were not consistent with maintaining the desired density ratio between the central cell and end plug. After further

discussions among Conrad, Kesner and Post at the University of Wisconsin and Logan at Lawrence Livermore Laboratory, we began looking into low energy neutral beams as a refueling source. In our oral presentation of the Phaedrus experiment, we proposed refueling by low energy neutral beams and presented a modified budget to reflect the development costs. It was planned that beam sources, beam lines and power supplies would be developed over the two-year Phaedrus construction schedule. The refueling beams would then be built and installed during the third year. Details of the low energy neutral beam refueling calculations will be presented in this report.

II. Possible Refueling Methods

B. Plug Refueling by Trapping of the Central Cell Stream

1. Introduction

The application of RF to tandem mirror plugs may serve as a method for partial plug refueling. This possibility was discussed in Ref. 1 and we will now discuss its implications for the Phaedrus experiment. The basic idea is as follows.

In a tandem mirror, some of the confined central cell ions can go as far as the midplane of the plugs before being reflected by the electrostatic barrier. If the RF wave particle resonance zone is located on the central cell side of the plug midplane, these central cell ions will pick up perpendicular energy on each pass through the resonance zone. If an ion can get sufficient perpendicular energy in this way, it would become trapped in the plug and thereby serve to fuel the plug. The perpendicular energy required for an ion to become trapped in this fashion is equal to the velocity space hole for the plug trapped ions, about 100 eV for Phaedrus. Since it can be shown² that the maximum energy that an ion can pick up in one pass through the resonance zone is less than this value, the process described above becomes one of diffusion whereby a central cell confined ion will gain perpendicular energy during many bounce periods. Between passes through the resonance zones located in the plugs these ions will however pitch angle scatter and thereby transfer this energy gained from the perpendicular to the parallel direction. If these ions gain sufficient parallel energy in this way they can escape the system. The envisioned process is therefore a

competition between RF heating at the plug and pitch angle scattering at the central cell.

Two additional points should be made. In order for RF trapping to take place the ambipolar potential must peak at the plug midplane while the particle wave resonance zone must be located on the central cell side of the midplane. If RF trapping were the sole plug fueling mechanism, the plug density, and therefore the ambipolar potential, would peak at the resonance zone location. In this case, RF trapping could not take place because an ion would not feel the RF until it had already essentially escaped over the ambipolar barrier. For this reason it is necessary to have an additional fueling source such as neutral beams, which creates a density maximum at the plug midplane.

Furthermore, for RF to serve to refuel the plugs it is necessary that ions in the vicinity of the resonance zone be capable of being "Yushmanov" trapped, that is, trapped between the electrostatic potential barrier at the plug midplane and the inner magnetic mirror. This can be best understood with the aid of Fig. 1. The parallel energy of an ion can be expressed as

$$W_{||} = \epsilon - (\mu B + \frac{e}{m} \phi) = \epsilon - \psi$$

For μ the adiabatic invariant ($1/2 v_{\perp}^2 / B$), ϵ the total particle energy and ϕ the electrostatic potential. ψ is a pseudo-potential defined as $\psi = \mu B + \frac{e}{m} \phi$. For a small μ the pseudo-potential resembles the potential ϕ and the resulting case, shown in Fig. 1C, represents a central cell ion that enters the plug. If the ion gains perpendicular energy within the plug (due to interaction with RF) μ increases and this will create the

Fig. 1

situation pictured in Fig. 1D, that of a Yushmanov trapped ion. A further increase in μ produces trapping as seen in Fig. 1E. For Yushmanov trapping to take place, however, requires that the ambipolar potential be peaked with respect to the magnetic field variation. Since the ion distribution function determines the potential profile as well as the self-consistent magnetic field, a self-consistent treatment of RF trapping should be done. A peaked ambipolar potential is known to result from perpendicular beam injection.

In the following sections we will estimate the fraction of ions leaving the central cell that we may expect to trap in the plugs. We will see that although this fraction is insufficient to fuel the plugs without an additional ion source (such as neutral beams) it may provide a significant aid in plug refueling.

2. RF Trapping Efficiency

The Phaedrus experiment has been designed so that the stream leaving the central cell is sufficient for plug DCLC stabilization. This criterion determines that we need about 10 Amperes of central cell loss flowing through each plug. If the plugs turn out to be more stable to the DCLC instability than expected, we would be able to lower the central cell density, thereby increasing central cell confinement and the stream might be as low as ~ 5 Amperes. (Added stability could result from the presence of the central cell plasma in the plug or a stabilization of the DCLC by the ion cyclotron waves we are generating.)

The neutral beam system that we are developing will deliver about 50 to 100 Amperes per plug of 4 to 6 keV neutrals which would create a 1 to 2 Amperes ion plug source. Since the RF trapped ions enter the device

near the loss cone hole energy (~ 200 eV) and are thereby less well confined than the neutral beam injected ions, we would expect that a trapping rate of about one Ampere would be needed to significantly increase the plasma density. This represents $\sim 10\%$ of the central stream.

To estimate the trapping fraction of the central cell stream we refer to Ref. 1. Here we show that for a RF diffusion coefficient that is independent of velocity and for parallel diffusion caused by ion-ion collisions in the central cell we may solve a velocity space diffusion equation for the distribution function f :

$$\frac{\partial f}{\partial t} = D_{||} \frac{\partial^2 f}{\partial v_{||}^2} + D_{RF} \frac{\partial^2 f}{\partial v_{\perp}^2} + S. \quad (1)$$

The fraction (F_T) of flux that crosses the confinement boundary in velocity space so as to become trapped in the plug can be estimated¹ to be

$$F_T = \frac{4}{\pi} \sum_{m=1}^{\infty} \frac{(-1)^{m+1}}{(2m-1)} \exp \left[-\pi (V_T/V_L) (m - .5) \sqrt{D_{||}/D_{RF}} \right] \quad (2)$$

with $V_T/V_L = \left[\chi_n / (1 - \chi_n) (B_m/B - 1) \right]^{1/2}$

with $\chi_n = \phi/\phi_c$, the ambipolar potential at the resonance location normalized to the peak potential the plug midplane ($\chi_n = 0$ at the central cell).

It is clear that the trapped fraction (F_T) is a function of the ratio of RF to collisional diffusion coefficients ($D_{RF}/D_{||}$) and the location of the resonance plane (which enters through χ_n). Figure 2 is a plot of the fraction trapped vs. the RF to collisional diffusion coefficient ratio.

Fig. 2

A simple estimate of the RF diffusion coefficient can be made by noting that for a velocity independent diffusion coefficient the power deposited in a plasma of volume V_p is proportional to the diffusion coefficient.

$$P_{RF} = \int_0^{\infty} 2\pi V_{\perp} dV_{\perp} \left(\frac{1}{2} m V_{\perp}^2 \right) \frac{1}{V_{\perp}} \frac{\partial}{\partial V_{\perp}} V_{\perp} D_{RF} \frac{\partial f}{\partial V_{\perp}} = 2m D_{RF} n_p V_p \quad (3)$$

For Phaedrus

$$D_{RF} = \frac{P_{RF}}{2m n_p V_p} = 1.3 \times 10^{27} \frac{P_{RF}(W)}{n_p (cm^{-3})}$$

n_p is the mean plug density at the resonance zone location.

For the case of 10 kW of power deposited into a plug volume of 2.3 liters and density of $2.5 \times 10^{12} cm^{-3}$, $D_{RF} = 5.2 \times 10^{18} cm^2/sec^3$. The central cell RF diffusion coefficient will be smaller by the ratio of central cell to plug length $L_c/L_p \sim 2.5$. The process that competes with the RF diffusion is pitch angle scattering in the central cell. This will tend to isotropize the RF heated ions, which have gained perpendicular energy.

The characteristic diffusion coefficient for this process may be estimated to be $\langle (\Delta W_{\perp})^2 \rangle$ where we shall use the diffusion coefficients of Spitzer³.

For $T_e = 12$ eV, $n_c = 2 \times 10^{12}$, $\phi_c = 100$ eV, we find $\langle (\Delta W_{\perp})^2 \rangle \approx 1.0 \times 10^{18} (cm^2/sec^3)$ and therefore $D_{RF}/D_c \approx 2$. From Eq. 2 with $\chi = 0.8$, $B/B_0 = 1.1$, we find about 7% or 0.7 Amps of central cell ion stream would be trapped in the plugs. If the electron or central cell ion temperature were to increase the trapping fraction could increase further. In a more accurate calculation of D_{RF} in

Ref. 2 we find excellent agreement with the above estimate.

This result then indicates that we may obtain a significant RF trapping of the central cell ions in the plug. Again, a self-consistent treatment of the problem must be made to demonstrate the existence of a Yushmanov region in velocity space.

If it is desired to trap a higher fraction of ions or if the potential distribution does not allow for Yushmanov trapping, we could consider a periodic heating of the plugs at high power levels. If an ion gains enough energy on one pass through the resonance zone it would become trapped in the plugs without the need for the intermediate Yushmanov trapped state. This process is also independent of a competing central cell isotropization. The necessary wave field levels for one pass trapping are presently being evaluated².

It should be stated that we view this process as an interesting area for experimentation and one whose understanding may be necessary to an understanding of RF heated tandem mirror behavior. It is not, however, central to the use of RF for plug heating and we feel that the experiment should not depend on it for steady state operation.

II. Possible Methods

C. Neutral Beam Refueling

The neutral beams for Phaedrus must sustain the end plug plasma density at a constant value of approximately $5 \times 10^{12} \text{ cm}^{-3}$ or higher for a period of time greater than several central cell confinement times. In order to determine the neutral beam current and energy required to refuel, we consider the end plug plasma production rate

$$\frac{dn}{dt} = \frac{I_n \langle \sigma v \rangle_i 2af}{e v_b V} - \frac{n}{\tau} \quad (4)$$

where I is the neutral beam current, v_b is the beam velocity, n is the end plug density, $\langle \sigma v \rangle_i$ is the total ionization rate coefficient (predominantly due to electrons for the energies of interest here), a is the plasma radius, f is a geometrical factor related to the beam and plasma density profiles, and V is the end plug volume. The particle loss rate τ^{-1} is given by

$$\frac{1}{\tau} = \frac{1}{\tau_{ii}} + \frac{1}{\tau_{\text{drag}}} + \frac{1}{\tau_{\text{cx}}} + \frac{1}{\tau_{\text{anom}}} \quad (5)$$

where τ_{ii}^{-1} is the ion-ion scattering rate into the loss cone, τ_{drag}^{-1} is the rate at which hot ions enter the loss cone due to slowing down on electrons, τ_{cx}^{-1} is the ion loss rate due to charge exchange on cold background gas, and τ_{anom}^{-1} is the anomalous loss rate associated with non-classical processes. We will ignore the fueling contribution due to charge exchange of the neutral beam particles with stream ions. This process could contribute to the fueling rate by perhaps 10 - 20%. The results we quote here thus represent a lower limit for

the fueling.

For the beam energies of interest here the dominant ionization mechanism is electron impact ionization so for $T_e = 50$ eV, $\langle \sigma v \rangle_i \approx 3 \times 10^{-8} \text{ cm}^3/\text{sec}$, independent of beam energy. The plasma production rate (first term in Eq. 4) is therefore proportional to $E_b^{-1/2}$, favoring lower energy beams due to their greater transit time through the target. However, at higher energies the beam divergence decreases by $E_b^{1/2}$ and so the axial plasma extent would decrease in approximately this dependence. The resulting smaller plasma volume means an increase in local density. Furthermore, the ion loss rate decreases with beam energy, in particular the loss rate (τ_{ii}^{-1}) due to ion-ion scattering varies as $\tau_{ii}^{-1} \propto E_b^{-3/2}$. Considering these factors there will be an optimum beam energy for which the steady state density obtained from Eq. 4 will be a maximum.

Before proceeding with estimates of the refueling current, we consider first the allowable range of injected beam energy. A lower limit on the beam energy is set by the requirement that the one-third energy component of the beam be in the confined region of velocity space. This requires $E_b > E_{bmin} \approx 3\phi_a \approx 17 T_e \approx 0.9 \text{ keV}$ if we take $T_e = 50$ eV and assume that the plug ambipolar potential ϕ_a relative to ground is roughly 5.5 times T_e .

An upper limit for the beam injection energy is set by limits on the plug beta and on the ratio of beam-particle gyroradius to plug radius. The latter condition requires that the plasma radius (a) be larger than the gyroradius ρ_i of a full energy beam particle evaluated at the plug midplane. If we require $a/\rho_i \geq 2$ (note that 2XIIB operates⁴ with a/ρ_i as small as 1.6), then for $B_0 = 4 \text{ kG}$ and $a = 7 \text{ cm}$, we must keep $E_b \leq 9 \text{ keV}$. However, if we

assume that the average plug ion energy before RF heating is approximately equal to the average beam energy, then in order to keep $a/\rho_i \geq 2$ subject to a doubling of T_i by RF heating we must keep $E_b \leq 6$ keV. This assumes that the average beam energy $\bar{E}_b$ is about 0.75 times the peak beam energy because of the half and third energy components of the beam. The plasma beta for the case of 6 keV injection into a plasma with $n = 1 \times 10^{13} \text{ cm}^{-3}$ and $T_i = 9$ keV (twice the average beam energy after RF heating) is $\beta_i = 8\pi n k T_i / B^2 = 0.2$. The 2XIIB experiment has operated successfully⁴ with beta above $\beta = 0.5$.

In order to estimate the refueling current, we solve a coupled set of rate equations (similar to Eq. 4 with $\frac{dn}{dt} = 0$), one for each of the beam components (full, one-half, and one-third energy). The resulting equations constitute Logan's approximation⁵ of solutions obtained with the Hybrid II Fokker-Planck code. We include the effect of the beam and plasma density profiles and obtain the axially averaged radial density profile. We treat the charge exchange loss rate τ_{cx}^{-1} as a parameter, guided by experimental results from 2XIIB, and assume that τ_{anom}^{-1} is negligible.

An approximate estimate of the source profile $J(x,z)$ is made for a gaussian beam given by

$$J = J_0 \exp[-(z^2/z_c^2 + x^2/x_c^2)]$$

for x_c, z_c the beam half width in the vertical and axial directions (see Fig. 3). The ion source would then have the profile

$$S = c \left(\frac{I}{e} \right) n e^{-x^2/x_c^2}$$

with

$$c = \frac{u}{\sqrt{\pi}} \frac{\langle \sigma v \rangle}{x_c^2 v_b}$$

and v_b the beam velocity. This source will spread out on its respective drift surfaces. To find the source as a function of radius consider injection at the mirror midplane. Since drift surfaces are circular we want to average the source at a radius (r), and within a width δr (see Fig. 3b). This will then give

$$S_A = \frac{1}{2\pi r \delta r} 4 \int_0^{\pi/2} S_0 e^{-x^2/x_c^2} (r \delta r) d\theta \quad (6)$$

Setting $x = r \cos \theta$ then gives

$$\begin{aligned} J(r) &= \frac{2S_0}{\pi} \int_0^{\pi/2} \exp\left(-\frac{r^2}{x_c^2} \cos^2 \theta\right) d\theta \\ &= S_0 e^{-\xi} I_0(\xi) \quad \text{with } \xi = \frac{r^2}{2x_c^2} \end{aligned} \quad (6a)$$

with I_0 the modified Bessel function of zero order.

Typical radial density profiles for several cases are shown in Figs. 4 - 6. In Fig. 4 we have assumed a source extraction current density of 0.375 A/cm^2 , which is roughly 70% of that typically obtained in Berkeley type sources. Operation of the sources at this current density should be easily attainable and results in 78 A of neutrals on target per end plug from two sources.

BEAM FOOTPRINT

FIG 3a

FIG 3b

Fig. 4

Fig. 5

Fig.6

With careful grid design it should be possible to extract at a current density of 0.45 A/cm^2 to obtain 94 A of neutrals on target. The improved fueling for this case is shown in Figs. 5 and 6. It should be noted that the density profiles in Figs. 4-6 are those which are predicted to be obtained in the absence of RF heating. The fueling should be significantly improved when the RF is applied due to the decreased collisionality and an increase in neutral beam ionization resulting from higher T_e .

The extracted species composition for these calculations is assumed to be 75% H^+ , 15% H_2^+ and 10% H_3^+ so the neutral beam composition on target is $0.75I_0 \text{ H}^0$ at E_b , $0.3I_0 \text{ H}^0$ at $E_b/2$ and $0.3I_0 \text{ H}^0$ at $E_b/3$ for an average beam energy of $0.73 E_b$ and a total (all species) equivalent neutral current of $1.35I_0$ on target. The above results indicate that depending on the charge exchange time and beam energy, approximately 60 to 90 A of equivalent neutral current are required to sustain a peak plasma density near $1 \times 10^{13} \text{ cm}^{-3}$. For the sake of comparison we note that 2XIIB scaling⁴ indicates that a plasma density of $1.5 \times 10^{13} \text{ cm}^{-3}$ in deuterium can be maintained with 80 A of neutral beam current at $E_b \approx 4 \text{ keV}$. With regard to the charge exchange times assumed we note that 2XIIB obtains charge exchange times ranging from 1 - 3 msec depending on the product of beam current times injection time. It is claimed⁴ that the charge exchange times observed on 2XIIB are limited by gas build up from the neutral beam drift tanks which do not have liquid nitrogen cooled titanium gettering. It is reasonable to assume that with LN_2 cooled gettered liners in the beam lines, Phaedrus should achieve charge exchange times at least as long as 2XIIB and probably better.

Neutral beam parameters for Phaedrus are shown in Table I. Four

Table I. Neutral Beam Parameters

Current Density	0.375 A/cm ²
Grid Transparency	0.60
Extractor Area	200 cm ²
Extracted Ion Current per Source	45 A
Neutral Current on Target per Source	39 A
Total Neutral Current per Plug (Two Sources)	78 A
Extraction Energy	4 - 6 keV
Beam Divergence at 6 keV (Half Angles to 1/e Points)	
Parallel to Slots	0.9°
Perpendicular to Slots	3.3°
Distance from Extractor Grids to Target	200 cm

neutral beam sources, two per end plug are required.

With regard to possible improvements of the refueling system we will consider the incorporation of magnesium curtains⁶ at the apertures of beam line drift and dump tanks to reduce thermal gas flux into the confinement region. We will also explore the possibility of using an H_3^+ source to increase the effective fueling current. Finally, we note that the fueling would be substantially improved by operating with deuterium. For fixed neutral beam current, the steady state density which can be maintained in deuterium is roughly twice that in hydrogen due to the smaller collision frequency in D^+ .

III. Physics Objectives for Phaedrus

In order to study central cell confinement, experimental operation will be required for a confinement time thereby necessitating plug refueling. We shall return to the question of central cell confinement studies shortly.

The Phaedrus experiment should also be viewed in the context of its role in the Mirror Fusion Program; more specifically, its impact on the TMX and MFTF experiments at Livermore. Both of these experiments use high energy neutral beams for both heating and fueling of the end plugs. Since the extraction voltage for the MFTF beams is 80 kV, the maximum overall Q for MFTF operated as a tandem (MFTF-B) is limited to 0.1. If 200 keV negative ion beams were developed and used on MFTF-B, a central cell Q of 1.2 would be possible with an overall $Q = 0.7$. This would be an impressive achievement. Although we have not carried out calculations on MFTF-B with RF, it is not unreasonable to expect that Q could be significantly enhanced by using RF to double the end plug ion temperature and thereby increase the central cell confining electrostatic potential. Thus the main near term application of RF will be the heating of beam driven systems. As physics objectives we will want to study the effect on $n\tau$ as the plug ion energy content is increased by ICRF. The ion energy increase will cause an increase in T_e and therefore, ϕ_c , the ambipolar potential which confines central cell ions. One would want to measure the central cell $n\tau$ as a function of the increase in plug ion temperature. Such experiments require quasi steady state operation, i.e., experiment times longer than particle confinement times. Operation in quasi steady state will be required to carefully evaluate the

amount of RF trapping of central cell plasma that can be achieved.

The study of a number of other important tandem mirror physics questions is dependent on steady state operation. One such question is the ion energy limit that results from superadiabaticity. Superadiabaticity is known to impose an upper limit on the ion energy that can be achieved through the use of RF heating by a monochromatic wave. We are presently studying this question with respect to its applicability to Phaedrus. Relevant measurements would clearly require plug confinement several plug particle confinement times.

The heating of end plugs with RF will necessarily also result in the flow of some power to the central cell. This is because for plug heating a wave-particle resonance point will also exist in the central cell. The amount of power that goes to the central cell is dependent on the location of the resonance zones and on the type of wave launched. We have found² that for typical Phaedrus parameters slow wave plug heating could have the effect of doubling the central cell ion temperature. For the fast wave at the second harmonic of the plug cyclotron frequency this effect is much smaller. Recently Rognlien and Cutler⁷ have examined the effect of finite mean free path on central cell confinement and found a significant increase in confinement due to collisionality. The central cell RF heating is thereby desirable since it provides a method for increasing the stream to the end plug as is needed for DCLC stability.

Another experimental objective will be to do direct RF heating of the central cell as a method of increasing the ion temperature there. This would allow a measure of the effect of central cell temperature on confinement and to observe whether collisional processes dominate confinement or

additional radial loss mechanisms are observed, as in Ogra III at Kurchatov. It is quite likely, given the history of plasma confinement, that some anomalous radial transport will be present.

The Phaedrus central cell energy density is sufficiently low that Langmuir and magnetic probes may be used to complement μ -wave scattering. Thus we will be able to study the fluctuation spectrum in detail. Since the central cell will be able to operate from $\beta < m_e/m_i$ up to $\beta \sim 0.5$. We will cover the transition from a pure electrostatic spectrum to an electromagnetic domain. Up to the present, very little work has been done which adequately covers this β domain. This is not only important for better understanding of tandem mirror physics but is also important for magnetic confinement in general. It should be noted that fluctuations by themselves do not necessarily imply diffusion. This has been clearly observed in the Levitated Octupole⁸ and in PLT⁹. Thus it is absolutely necessary to have good confinement time measurements as in the above experiments.

For these reasons we feel strongly that quasi steady state operation is desirable for Phaedrus. This implies refueling of the end plugs for several central cell confinement times.

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