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MFTF-B OPERATING IN THE HIGH NEUTRON WALL LOADING MODE

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MODELING AND OPTIMIZATION OF A TEST-CELL UPGRADE FOR MFTF-B OPERATING
IN THE HIGH NEUTRON WALL LOADING MODE*

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ABSTRACT

Models of the plasma particle and power balances in a tandem mirror with a high-field test-cell insert in the central cell have been used to calculate operating points for test-cell upgrades of the MFTF-B configuration. The code results have been benchmarked against the proposal plasma parameters for the MFTF- α +T configuration operating in the high neutron wall loading mode. Some parametric studies have been done. Using the results from these parametrics an optimized set of operating parameters for an MFTF- α +T-like configuration with a test-cell which will accommodate two 1.5 m long blanket test modules has been generated. This operating point has the same test-cell neutron wall loading as the original configuration and lower input powers to other systems in the device. The neutral beam power per unit blanket module length is also somewhat reduced in the optimized case.

INTRODUCTION

This paper will describe recent work concerning physics modeling of the MFTF- α +T device in the high wall loading (high- Γ) mode of operation. The parameters for this mode, as originally proposed, can be found in Ref. 1. For the present studies, new models of the particle and energy balances in tandem mirrors with MARS-type end cell configurations and high-field beam-driven inserts in the central cell have been incorporated in the TMRBAR tandem mirror physics code.² These models, which reflect a better understanding of MFTF- α +T plasma physics since the original proposal,

have been used to obtain a new set of baseline parameters for the high- Γ operating mode. In addition, some trade studies have been done and a partially optimized set of operating parameters has been obtained. Finally, plasma physics issues characteristic of high-field test-cell operation of a tandem mirror device have been raised and the need for future work in several areas identified.

DESCRIPTION OF THE PHYSICS MODEL

The goal of the high- Γ operating mode is to achieve high neutron wall loading on the blanket test module in the test-cell. To accomplish this the density in the test-cell is increased by more than a factor of two over the density of the central cell Maxwellian plasma by injecting large currents of neutral beam particles into the test-cell. In steady state, the trapped particle current from these beams must eventually scatter out of the test-cell mirror confinement and provide a particle source for the central cell particle population. Finally, this current must escape the device either through neoclassical transport (usually small), radial losses induced by the drift pumping system, or axial (Pastukhov) end losses. To keep the required pumping currents for the drift pump coils as low as possible, the axial confinement is significantly decreased in high- Γ mode by reducing the electrostatic potential in the plug region. Thus, the particle current is removed axially rather than radially.

The finite plasma pressure in the bad curvature regions of the test-cell during high- Γ operation requires that the central cell be operated at lower beta to satisfy the MHD stability criteria. At fixed anchor beta these stability criteria set an upper limit on the total pressure weighted normal curvature in the central cell region. When a finite beta test-cell is introduced, MHD requires that the pressure in the central cell be decreased whenever the pressure in the test-cell is increased. The stability boundary for the base-line

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configuration, giving beta in the central cell as function of beta in the test-cell for fixed anchor beta, has been generated.³ Beta values for this study were chosen to lie near the marginal stability boundary to optimize performance.

The physics models describing test-cell operation which have been developed for this study focus on the energy and particle balances for the hot mirror trapped particles in the test-cell.⁴ A Logan-Rensink plug model⁵ for neutral beam injection into a mirror trap with a potential is used to obtain the test-cell average ion energy, average loss energy, and particle confinement time. The hot ion density is obtained from the test-cell beta input to the model. In addition, particle and energy transfer between the HOT component in the test-cell and the mirror trapped population in the central cell (HOT*) has been included as well as particle and energy flow between both of these populations and the Maxwellian background. A crude model of energy transfer by particle convection in velocity space has been used. A modified Logan-Rensink model is used to calculate the average energy of the mirror trapped population in the central cell. Multi-region Fokker-Planck⁶ calculations have been used to calibrate the Logan-Rensink models for configurations like MFTF- α +T. Detailed descriptions of the models are given in Ref. 4.

BASELINE PARAMETERS

The plasma physics models used in this study incorporate several improvements in the understanding of MFTF- α +T high-T mode physics (primarily in the end cell physics) compared with the models employed in Ref. 1. As a result, the physics parameters for a baseline device with approximately the same dimensions and other physical characteristics as in the reference case may be different from the reference values. Comparison of the reference physics values and the current results, for the reference design, serves to benchmark the new models.

The critical parameters for test-cell, central cell, and end cell performance and those fundamental parameters which are significantly different between the previous work and present results will be compared below. The differences can be explained in terms of the improvements in the physics understanding that have occurred between the two studies. Before proceeding to a parameter-by-parameter comparison of the two studies, some frequently used terminology will be presented. Each of the following terms concerns an aspect of the MFTF- α +T physics which has changed between the original study and the present work. A more complete list is given in Ref. 7.

g and H Factors

Improved calibration of the Futch-LoDestro trapping formulas⁸ in the transition regions against Fokker-Planck code results indicates that g (ratio of [passing + trapped] density to passing density) must be greater than or equal to two for transition region resistance to two-stream instabilities and that the functional dependence of the formulas may not be accurate for $g < 2.0$. In addition, these results indicate that H (correction factor for non-square well magnetic field shape) may be related to g by a scaling law.

Cutoff

Improved mapping formulas to calculate the passing density at cardinal points in the end cell regions include a cutoff in particle energy, which depends on the electrostatic confining potential ϕ_c , above which particles cannot exist in the end cells. For low potentials relative to the central cell temperature, as in MFTF- α +T, these formulas produce lower passing densities in the end cell regions.

Calibrated (nT)

Recent calibration of the confinement parameters (nT) for the hot mirror trapped particles in the test-cell from multi-region Fokker-Planck code results indicate that the Logan-Rensink plug model may underestimate the confinement by 50%. A correction coefficient has been used in the present study.

COLD Ion Drag

The energy balances for the HOT and HOT* particles have been modified to include drag of these ions on the COLD Maxwellian ions in the central cell and test-cell regions. For the low background ion temperatures in MFTF- α +T, this term may be comparable to drag on electrons.

Finally, it should be noted that the present model includes a loss channel from the HOT* particles due to pitch angle scattering out of the central cell mirror trap at energies above the electrostatic confining potential. When this occurs, the HOT* particle is lost rapidly from the device (one axial transit time). In the previous calculations it was assumed that all of the test-cell beam particles which were trapped eventually fueled the COLD Maxwellian population in the central cell. Since some of the HOT* particles leak out in the new model, the need for supplemental fueling of the COLD population, by a pellet injection system or low energy neutral beam, may be indicated by the present model when it was not shown in Ref. 1.

Benchmark Cases

To benchmark the code models, plasma parameters for MFTF-Q+T operating in the high-I mode were generated and compared with the values from Ref. 1. For this comparison, the following physical dimensions and machine parameters are held constant in the test-cell, central cell, and end cell regions: (1) mirror-to-mirror and plasma effective lengths; (2) peak and midplane on axis magnetic field values; (3) peak and volume averaged plasma beta values; and (4) the plasma radius at the various cardinal points used in the models. In addition, the central cell Maxwellian ion temperature, test-cell trapped current from the neutral beam injectors, and end cell axial (Pastukhov) confinement parameter ($n\tau$) for the central cell ions have been fixed to the reference values.

Comparison of the parameters in Ref. 1 with those in Table 1 shows that the current model benchmarks quite well against the reference results provided that the injection energy in the test-cell is increased from 60 keV (average) to 83.2 keV. This result is consistent with the inclusion of COLD ion drag terms in the energy balances for the HOT ion populations in the present calculations. At balance, this added power to the test-cell ($P_{NB, TRAP} = 15.8$ MW compared with 11.4 MW in Ref. 1) results in a higher density and average energy of the HOT mirror trapped population and, therefore, a higher test-cell fusion power and wall loading. At fixed test-cell and central cell beta the increased HOT ion pressure in the test-cell produces a lower electron and HOT* pressure there (and in the central cell) primarily through lower electron temperature. The present results also indicate that particle balance of the COLD central cell ion population requires 32.8 A of supplemental fueling current from a pellet injector or low energy neutral beam system in the central cell. This is consistent with 71.3 A of Pastukhov end loss of HOT* ions from the central cell (not considered in the reference model) combined with the reduction of transition region trapping current from 97 A to 55 A.

Other parameters of the device that are somewhat different in the present study are the end cell passing densities and some of the end cell species energies. The passing densities for ions are lower in all of the end cell regions in the present study due to the cutoff which has been taken into account in the passing density formulas. As a result, for constant beta, the average energies of either the hot ions or hot electrons will increase so that the pressure is the same as in the reference study. In the anchor the hot ion average energy is up to 1.18 MeV (from 0.4 MeV) and in the barrier region the hot electron energy is up to 1.46 MeV (from 0.475 MeV). The required ECRH

Table 1. Baseline parameters for MFTF-Q+T High-I mode from present models.

DT Test Cell	
n_{hot}	$5.08 \times 10^{14} \text{ cm}^{-3}$
E_{HOT}	41.8 keV
T_{ec}	6.36 keV
ϕ_e	46.8 kV
ϕ_c	23.4 kV
$(n\tau)_{LOCAL}$	$2.76 \times 10^{13} \text{ cm}^{-3}/s$
$\Delta\phi_{TC}$	8.3 kV
$\beta_{TC} (PEAK)$	0.46
$P_{FUS, TC}$	14.6 MW
r_p	15.0 cm
r_{WALL}	27.0 cm
Γ_{TC}	2.46 MW/m^2
$I_{NB, TRAP}/I_{NB}$	190 A/217 A
$P_{NB, TRAP}/P_{NB}$	15.8 MW/18.1 MW
E_{INJ}	83.2 keV
θ_{INJ}	75°
Central Cell	
n_c	$1.49 \times 10^{14} \text{ cm}^{-3}$
n_{ec}	$1.67 \times 10^{14} \text{ cm}^{-3}$
n_{HOT*}	$1.73 \times 10^{13} \text{ cm}^{-3}$
T_c	15.0 keV
T_{ec}	6.36 keV
E_H	36.2 keV
ϕ_{ic}	31.7 kV
ϕ_{ec}	38.5 kV
$\beta_c (PEAK)$	0.60
r_c	26.1 cm
P_{FUS}	6.11 MW
$I_{c, PAST}$	93.7 A
$I_{HOT*, PAST}$	71.3 A
$I_{FUEL, COLD}$	32.8 A
Anchor	
$n_{PASS, ANC}$	$2.49 \times 10^{12} \text{ cm}^{-3}$
$n_{HOT, ANC}$	$1.07 \times 10^{13} \text{ cm}^{-3}$
$E_{HOT, ANC}$	1181 keV
P_{ICRH}	0.583 MW (TOTAL)
Transition	
I_{TRAP}	55 A
I_{Heo}	0.83 A
ϕ_t	21.3 kV
$n_{PASS, t}$	$3.58 \times 10^{12} \text{ cm}^{-3}$
δ_{DT}	1.62
n_{DT}	1.31
Plug/Barrier	
$n_{PASS(b)}$	$1.39 \times 10^{12} \text{ cm}^{-3}$
$n(b)$	$5.02 \times 10^{12} \text{ cm}^{-3}$
$P_{ECRH, b}$	1.56 MW (TOTAL
$P_{ECRH, a}$	0.06 MW TRAPPED)

power in the plug and the required ICRH power in the anchor are lower in the present study because the major contributions to these powers vary as $n^2 E^{-3/2}$ where n is the appropriate particle density and E is the average energy. The required ECRH power in the barrier is

higher in the present study because, for high hot electron energies, the dominant term in this power is due to synchrotron radiation which increases as nE^2 .

Another area showing some differences is in the transition region where the trapping current (that current which the drift pump coils must pump out of the device) is down to 55 A (from 97 A). The present study uses an H-factor which is 4 times greater than the reference calculation, which would tend to increase the trapping current. However, since this current is proportional to the square of the passing density in the transition region, the effect of the cutoff is to produce lower trapping current.

OPTIMIZATION OF TEST-CELL PERFORMANCE

The goal in this section will be to present attractive options for MFTF- α -T configurations having improved performance over the baseline configuration, and the tradeoffs involved in choosing those options. The design goals and constraints which have been adopted at this stage of the optimization process are:

- (1) require high wall loading in the test-cell region over the length of two blanket test modules (including shielding and coolant piping) each of which is the length of the baseline MFTF- α -T test module; (2) obtain test cell wall loading in the range $1.8 \leq \Gamma_{TC} < 2.5 \text{ MW/m}^2$ for effective blanket testing; and (3) minimize neutral beam injection power and current to the test-cell for average injection energy $E_{INJ} \leq 95 \text{ keV}$. The maximum injection energy is set by projections of the achievable high power neutral beam technology in the MFTF- α -T time frame.

Expansion of the test-cell to accommodate two blanket test modules is desirable for two reasons. First, two different blanket concepts could be tested simultaneously in the same environment and their performance directly compared. Second, the scattered neutron flux in the blankets is significantly increased when out-scattering is minimized by increasing the number of test modules.

The physics constraints of MHD stability for the central cell and test-cell (beta limits), microstability of the plug sloshing ions (peak-to-midplane sloshing density ratio > 2.0), and mirror confinement of the sloshing ions must also be satisfied. All of the results to follow satisfy the requirements of the up-to-date physics understanding of MFTF- α -T as described in Sec. 3.

Parametrics

Several variables characterizing the test-cell region have been chosen for parametrics. In general, variation of one aspect of the device requires some variation in at least one

other part of the device to obtain an operating point (i.e., a solution to the plasma balance equations). Typically there are several choices for the supplemental variables in each parametric. The implications of the particular choices which have been made for this study will be described below.

As an example of the parametric studies, test-cell performance as a function of the neutral beam current is shown in Fig. 1. These cases were obtained by varying the COLD ion temperature at fixed plasma beta throughout the device and, therefore, represent the effect of changing density and plasma confinement parameters (through electron temperature) on the test-cell performance. The trend in this parametric is consistent with expectations based on scaling arguments; higher test-cell wall loading is obtained at higher beam power. In addition, to achieve high wall loading, the beam power should come in the form of many sources at lower injection energy. At $\Gamma_{TC} = 2.0$, the beam energy is $E_{INJ} = 92.6 \text{ keV}$ compared with $E_{INJ} = 99.4 \text{ keV}$ at $\Gamma_{TC} = 1.5$. Optimization of a given design requires balancing the cost and access limitations of a large number of beam-lines at lower energy against fewer beamlines at higher energies.

Fig. 1. Test cell wall loading and beam power as functions of beam injection current. ($\beta_{TC} = 0.40$, $\beta_C = 0.49$).

The shape of the curves in Fig. 1 can be understood from scaling arguments. The injection energy remained nearly constant at $E_{INJ} \approx 95 \text{ keV}$ (within 5%) for this parametric so that the beam power is proportional to the injected current. Neutron wall loading scales as $\Gamma_{TC} \propto n_H^2 \langle \sigma v(E_H) \rangle r_{TC}$ where n_H and E_H are the HOT density and average energy, respectively, and r_{TC} is the test-cell plasma radius. The injection current required for test-cell particle balance scales as $I_{NB, TC} \propto n_H^2 V_{TC}/(nT)$ where

V_{TC} is the test-cell volume and $(n\tau)$ is the HOT ion confinement parameter. The wall loading can then be written in terms of the injection current as $\Gamma = I \langle v(E_H) \rangle (n\tau)$ for constant plasma dimensions. The confinement parameter scales with $T_{ec}^{3/2}$ and $E_{INJ}^{3/2}$ where T_{ec} is the electron temperature. The wall loading would be proportional to the injection current if the electron and HOT ion temperatures could be held constant. However, ion particle balance for the device requires that as the injection current increases the end cell ion losses must also increase. The radial pumping in the transition scales as $n_{pass,t}^2 T_c^{3/2}$ for fixed g value where $n_{pass,t}$ is the passing density in the transition region (mapped from the central cell density). The axial (Pastukhov) losses scale as $n_c^2/(n\tau)_A$ where n_c and $(n\tau)_A$ are the central cell density and axial confinement parameter, respectively. With $(n\tau)_A$ and the central cell beta fixed in this parametric, the ion temperature must decrease as the injection current increases so that the loss rates will increase (the densities increase and the confinement decreases as the temperature decreases). Decreasing ion temperature produces decreasing T_{ec} and E_H , and therefore decreasing $\langle v \rangle$ and $(n\tau)$, so that the increase in wall loading with injection current is slower than linear. In other words, as the beam current is increased the ion temperature must decrease to let the particles out of the machine [for fixed beta and $(n\tau)_A$]. This produces a fall-off in $\langle v \rangle$ and $(n\tau)$ with $I_{NB,TC}$ and thereby a slower than linear increase in Γ_{TC} with $I_{NB,TC}$.

Optimization

Parameters from partially optimized cases for MFTF-Q-T with two blanket test modules in the test-cell are given in Table 2. The injection energy E_{INJ} , neutral beam power $P_{NB,TC}$, and neutral beam current $I_{NB,TC}$ to the test-cell are constant within 5%. The test-cell wall loading increases by 27% from $\Gamma_{TC} = 1.92$ to $\Gamma_{TC} = 2.44 \text{ MW/m}^2$ as the COLD ion temperature and beta values are increased. In addition, the trapping current (drift pump required current), cold fueling current (pellet injector requirement), and ECRH power at the potential peak (point a) all decrease as the wall loading increases. This indicates more efficient use of the end cell plasma to sustain the test-cell. The ECRH power at the barrier (point b) increases 8% (80 kW) over this range of ion temperatures. The final case at $T_c = 17 \text{ keV}$ requires central cell and test-cell beta values which are very near the stability boundary given by MHD analysis of this configuration.

Comparing the performance of Case 4 with the parameters in Table 1 for the original configuration shows that the same test-cell wall loading is achieved and the required ECRH and ICRH powers in the end cell are lower in Case 4. In addition, the neutral beam power per unit test-

Table 2. Partially optimized parameter sets for MFTF-Q-T with a 6.0 m test-cell.

Parameter	Case 1	Case 2	Case 3	Case 4
$\Gamma_{TC} \text{ (MW/m}^2\text{)}$	1.92	2.13	2.27	2.44
$P_{NB,TC} \text{ (MW)}$	24.9	25.4	25.7	26.1
$I_{NB,TC} \text{ (A)}$	266	268	278	277
$E_{INJ} \text{ (keV)}$	93.5	94.6	92.3	94.2
$I_{TRAP} \text{ (A)}$	12.7	9.98	8.01	6.45
$I_{FUEL,c} \text{ (A)}$	107	100.4	90.9	88.0
$P_{ECRH} \text{ (MW)}$	0.676	0.600	0.550	0.490
$P_{ECRH,A} \text{ (MW)}$	0.022	0.019	0.017	0.014
$P_{ECRH,B} \text{ (MW)}$	0.92	0.94	0.97	1.00
$T_c \text{ (keV)}$	14.0	15.0	16.0	17.0
$T_{ec} \text{ (keV)}$	5.63	5.90	6.07	6.34
β_c	0.49	0.52	0.55	0.58
β_{TC}	0.40	0.43	0.45	0.48

cell effective length is 6.21 MW/m^2 in Case 4 compared with 6.46 MW/m^2 in the original configuration. The increased average energy of the beams results in more efficient use of the beam power. The Case 4 requirements which increase over the original configuration are the beam current, $I_{NB,TC} = 277 \text{ A}$ delivered compared with 217 A and the cold fueling current (pellet injector requirement), $I_{FUEL,c} = 88.0 \text{ A}$ compared with 32.8 A . Note, however, that the beam current per unit test-cell length, important for access considerations, is down to 46 A/m from 62 A/m in the reference designs. Finally, note that the transition region in the original case requires a low value of $g = 1.62$ (i.e., the fraction of passing particles, g^{-1} , is high). This is marginally within the range ($g < 2.0$) for two stream instabilities and inaccuracies in the trapping current formulas. Case 4 operates with $g = 2.3$ in the transition which is above this threshold.

CONCLUSIONS

The modeling and optimization of MFTF-Q-T high- Γ operation have been re-examined using the original proposal of this device as a starting point. The improvements in the physics understanding of this type of tandem mirror facility which have occurred in the interim between these studies have been incorporated in the current study.

Benchmarking the results of the present study against the original parameters shows that similar physics parameters are achieved for the same test-cell trapped beam current, provided that the beam average injection energy is increased from 60 keV to 83.2 keV . This increase is consistent with the inclusion of hot ion drag on the cold ion species in the hot ion energy balances in the present study. In addition, the need for supplemental fueling of the central

cell Maxwellian population is indicated by the present model. This is consistent with the direct axial loss of the hot mirror trapped population occupying the central cell, which has been included in the present model. Other differences between the results of the two studies can be traced to improvements in the physics understanding of the device as described in Sec. 3.

Partial optimization of MFTF- α +T in the high- Γ operating mode has been done subject to the constraints that: (1) the test-cell should be long enough to accommodate two blanket test modules, (2) the test-cell neutron wall loading over the length of the blanket modules be in the range $1.8 \leq \Gamma \leq 2.5 \text{ MW/m}^2$ for effective blanket testing, and (3) the average injection energy of the neutral beam particles into the test-cell be held to $E_{INJ} < 95 \text{ keV}$. Given these constraints, a partially optimized set of operating parameters was found which features $\Gamma_{TC} = 2.44 \text{ MW/m}^2$ over a 4.2 m test-cell plasma effective length (for blanket testing) with test-cell neutral beam power, $P_{NB,TC} = 26.1 \text{ MW}$, current $I_{NB,TC} = 277 \text{ A}$ (delivered) and average injection energy $E_{INJ} = 94.2 \text{ keV}$. This set of parameters represents some improvement in the beam power per unit test-cell effective length and has lower requirements on the other systems of the tandem mirror central cell and end cell compared with the benchmark parameters for the reference design (Table 1). An exception to this is the higher required cold fueling current in the central cell ($I_{FUEL,c} = 88.0 \text{ A}$ compared with 32.8 A). Further optimization may be possible using the present models and will be an area for future work. Other areas for future work include better calibration of the Logan-Rensink models for the hot components over a range of background ion density, electron temperature, and injection energy and improvement of the charge-exchange models for the beams injected into the test-cell region.

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