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PROPOSED TANDEM MIRROR RESEARCH PROGRAM FOR FY87
PRESENTED TO THE
MFAC SUBCOMMITTEE ON MIRROR RESEARCH

JULY 8-9, 1986

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EXECUTIVE SUMMARY

1. We have re-examined the goal of $\sim 10^{13}$ cm^{-3} central-cell density with end-plugging and reconfirmed its importance as a test of thermal barrier end-plugging performance in either Tara or TMX-U. According to our present understanding and performance modeling, achievement of this density with available barrier pumping would require controlling radial transport to $\tau_\perp \geq 10$ ms and ion heating to $T_{\|i} \geq 400$ eV. Validation of our models is important for increased confidence in the projected performance of future devices.

2. We conclude that, when all factors are considered including the impact on other programs interlinked with LLNL in the present OFE budget, the lowest cost approach to have a fair chance to meet this goal is to extend Tara operation for the full FY87. Tara is a promising new facility that is just beginning to produce important results. Together with key support from LLNL and Phaedrus, the incremental cost for its full FY87 operation is $3.9 M (Case A).

3. Continuation of TMX-U operation in FY87, in addition to the full year of Tara operation, would greatly improve the chance of success. TMX-U has an established experience base and diagnostics well-suited to study plugging, and it has several new elements that are aimed at raising the plugged density. With an increase to the fusion budget by Congress, we recommend full year operation of TMX-U in addition to Tara in FY87, as represented at a minimum by Case C. This would provide the greatest chance for achieving the goal and provide a physics basis for continuing the mirror as a fusion option.

4. Continuation of the mirror program into FY88 and beyond would be based on an experimental program in TMX-U and Tara at a minimum budget level of $25M/yr, with restart of MFTF-B requiring an increase in the national fusion budget. The experimental program to be investigated by TMX-U and Tara would include improvement in the magnetic geometry (stability, beta limits, and transport), continued plug studies (longer pulse length,

impurities, drift pumping, and ECH efficiency), and transport studies (χ_e, fueling, and halo formation).

I. OVERVIEW AND PURPOSE

Demonstration of the practical realization of the thermal barrier tandem mirror end plug is at present incomplete. Although current experiments show plugging for low-to-moderate central-cell densities ($<3 \times 10^{12}$ cm^{-3}), strong plugging ($\tau_{||} >> 20$ ms) has failed for higher densities, although we observed related weaker plugging at higher densities. Steady progress in increasing this density is illustrated in Fig. 1. Reasons ascribed for loss of plugging (LOP) vary for different machines. They include barrier-filling in Gamma-10, related but less uniquely identified failure modes in TMX-U, and failure (with plugging) of the MHD anchor in Tara. Determining the important causes for LOP and the means for their avoidance warrants a continuation of mirror experiments through FY87 with a goal of reaching and holding thermal barrier plugging for central cell densities ~10^{13} cm^{-3}. This goal is consistent with past progress illustrated in Fig. 1. Success would be central to determining the value of the tandem mirror as a reactor concept.

In addition to axial plugging, the magnetic geometry is an important issue in the development of the tandem mirror reactor. The current tandem mirror program plan has pursued the two issues of plugging and magnetic geometry more-or-less in parallel. All current experiments have provided MHD stability by employing various average-minimum-B designs. TMX-U and MFTF-B have quadrupole plug cells, whereas in Gamma-10 and Tara the plug cell is axisymmetric and a minimum-B anchor cell is separate. Phaedrus can operate in a fully axisymmetric mode, stabilized by an RF ponderomotive force. The respective machines are illustrated in Figs. 2 and 3, and their important characteristics are given in Table 1. While quadrupole-plug designs were recognized as raising reactor issues regarding questions such as transport, beta-limits, and plug volume, they were adopted to allow focus on thermal barrier endplug physics with assured MHD stability. The designs combining symmetric plugs with average-minimum-B stability are intended to point the way to future improvements in the reactor concept. Other concept-improvement experiments have also been proposed to investigate geometries not relying at all on quadrupole cells.

The uncertainty regarding the causes for LOP and somewhat better performance in Gamma-10 than TMX-U have raised the concern that the geometry

Steady progress in increasing tandem mirror central cell density with thermal barrier plugging

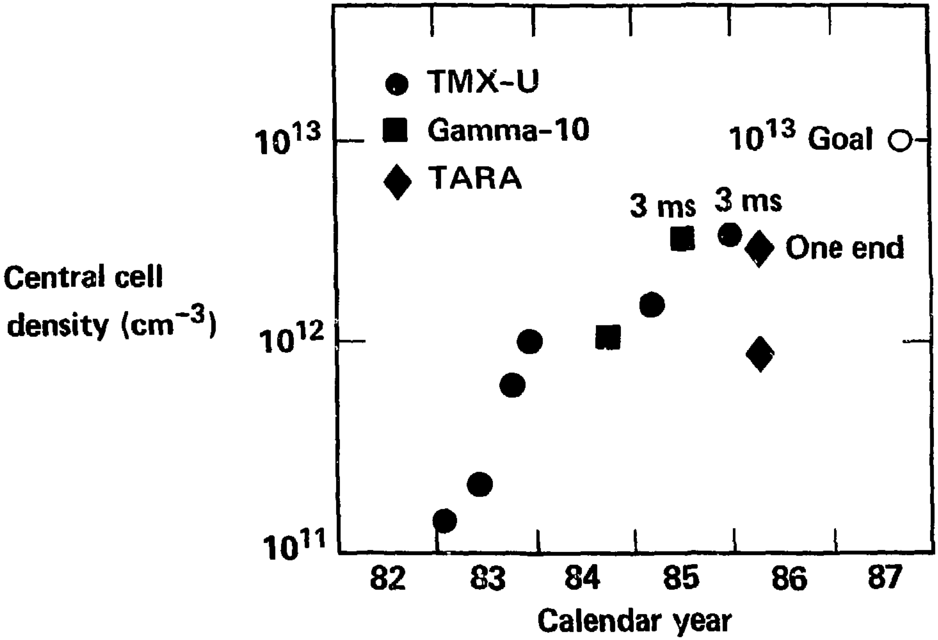


Figure 1.

Mirror Machines

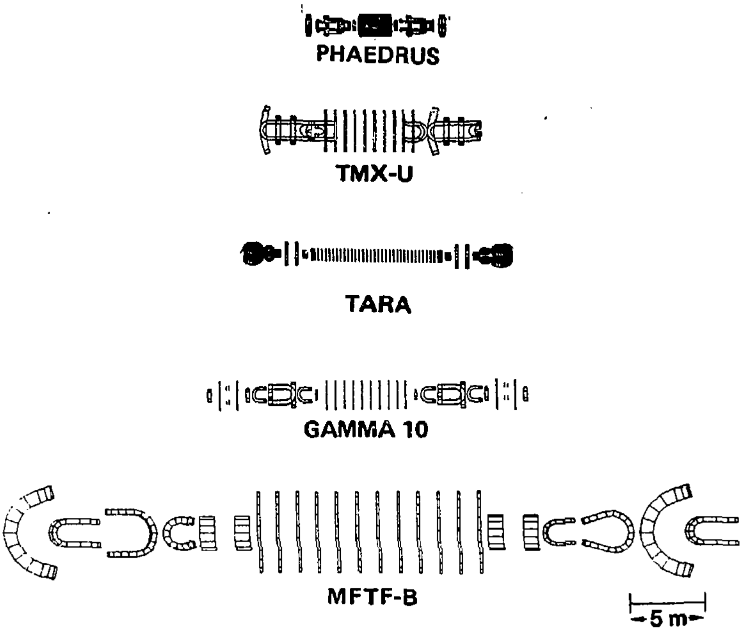


Figure 2.

Tandem mirror axial magnetic field profiles

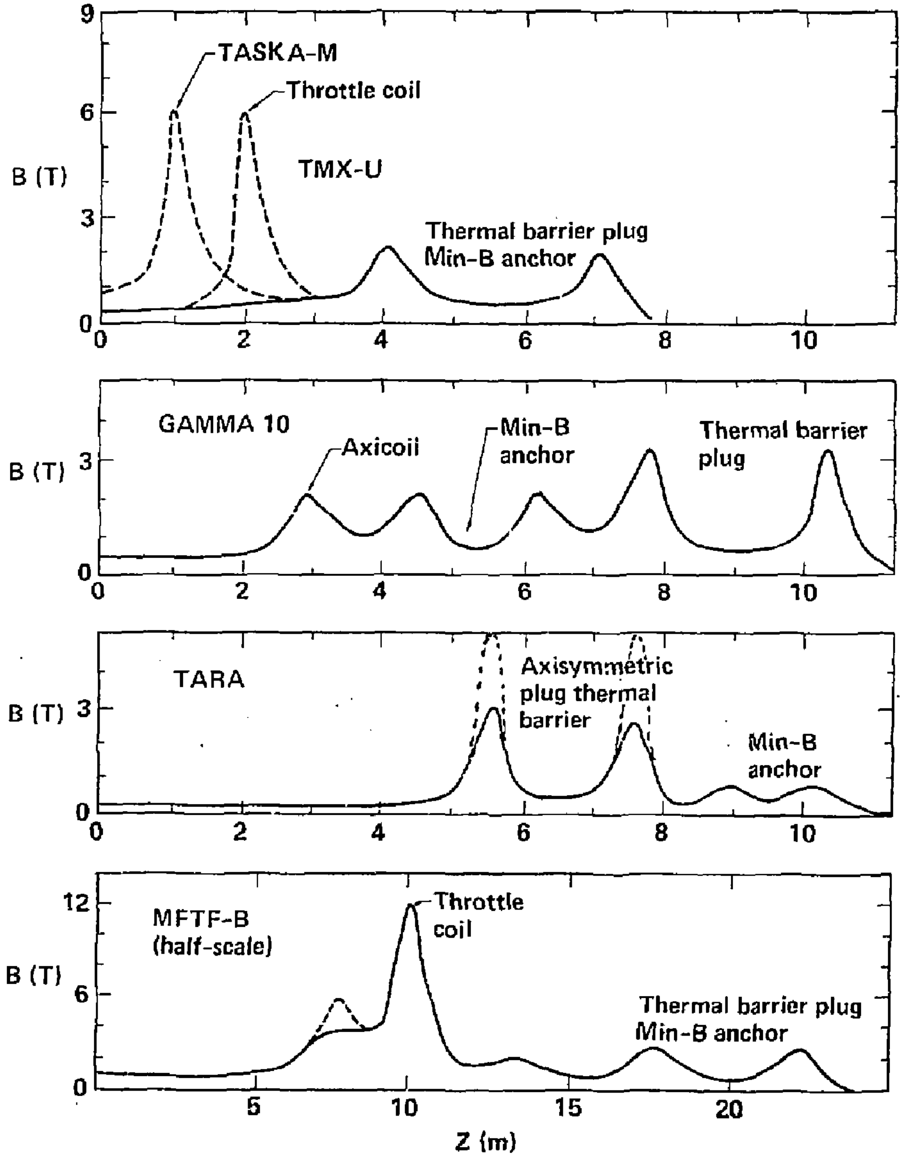


Figure 3.

Table 1. Machine operating levels of tandem mirror experiments: June 1986

Experiment	TMX-U	TARA	Phaedrus-B	GAMMA-10
Location	LLNL	MIT	U. of Wisc.	Japan
Beginning of thermal barrier operation	1983	1986	1986	1984
Central cell				
Radius (m)	0.25	0.22	0.2	0.2
Length (m)	8.0	10	3.0	15.0
Magnetic field (T)	0.3	0.2	0.06	0.4
ICH power (MW)	0.5	0.5	0.2	0.5
NBI power (MW)	1.7	-	-	-
Mirror ratio	7	15	8	8
End plug (each plug)				
Radius (m)	0.2	0.15	0.07	0.18
Length (m)	3.0	2.0	2.0	2.5
Magnetic field (T)	0.5	0.5	0.4	0.5
NBI power (MW)	1.0	0.8	-	0.6
ECH power, 28 GHz (MW)	0.4	0.4	0.02	0.3
ICH power (MW)	-	-	0.2	-
Mirror ratio	4	6	1.8	6
Anchor* (each anchor)				
ECH power (MW)	-	0.02	-	-
ICH power (MW)	-	0.4	-	(Coupling from central cell)
NBI power (MW)	-	-	-	0.7

---

*In TMX-U and Phaedrus-B MHD anchor is in minimum-B end plug.

of the plug may affect plugging characteristics. Example effects that could be playing a role are atomic physics in thin quadrupole fans (which are poorly shielded from the neutral gas environment) and enhanced energetic particle transport in the nonsymmetric fields. While there is no direct experimental evidence to support this concern, the question of geometry being a factor should be considered in assessing a program for concentrated study of LOP.

Tara and TMX-U are available for a program focussed on LOP, and each would present different advantages if continued in operation. Tara is a new and unique facility which represents a recent investment in DOE resources of $43M, one with high system reliability and fast turn-around capability, a substantial RF capability, a substantial and in some cases unique diagnostic system, and an up-to-date data and control system. All systems have been fully debugged over the past year. Its symmetric plugs, similar to those in Gamma-10, may prove to be superior for barrier formation owing to better shielding of the plug region. Tara has recently begun experiments with plugging in the thermal barrier mode and not yet shown LOP in the same way as TMX-U. The geometry is more susceptible to MHD instability; and in fact this has been observed with the onset of plugging. The stability problem is being addressed in parallel with plugging experiments. Three means for achieving stability are to be tested: the original hot-electron anchor, a recently proposed divertor-type stabilizing geometry, and RF ponderomotive stabilization (which has been demonstrated in Phaedrus). With successful stabilization, which should be achieved by this fall, Tara would be able to address the LOP problem in a symmetric geometry with the potential to be an improved reactor configuration.

TMX-U has been used to study thermal barrier plugging in quadrupole plugs for three years. This machine, therefore, has a broad experience base in vacuum, ECH, neutral beams, diagnostics and data analysis. The nonambipolar transport observed in early operation has been sharply reduced using floating end-wall plates, and the ambipolar transport has been measured to be small when the plasma is quiescent. This period of operation has also seen development of several diagnostics for studying details of hot-electron fractions, potentials internal to the plasma, and barrier-trapped distributions. Some of these have only recently become available, and their preliminary use in the Spring '86 run showed them capable of measuring important internal features of the plasma during double-ended plugging and into LOP (see Sec. II). In addition, there are new heating and fueling systems installed that may improve performance. These include an ECH system with increased pulse length and flexibility, a separate 18 GHz system, a feedback-controlled central cell gas feed under development, and improvements to keep the LN system liners cold overnight for improved end plug vacuum. The machine is, therefore, poised to make a careful physics study of the cause and cure of LOP.

Phaedrus has, in fact, already achieved plugging of a 10^{13} cm^{-3} central cell in the presence of a modified form of thermal barrier. While the technique used in Phaedrus does not appear to scale to reactor conditions, these results lend support to the prospects for achieving those conditions in TMX-U or TARA.

Calculations of the maximum, plugged central cell densities which could be achieved with plugging are about equal in TMX-U and Tara. Both can fuel and pump a central cell density of about 8×10^{12} cm^{-3}, of which about one-half is a thermal component extending into the plugs. Fueling in TMX-U at higher density uses low energy neutral beams. Beams for this purpose are presently in use, but so far have delivered only 60% of their rated current necessary for buildup. Fueling in Tara uses wall-reflux of charge exchange losses, a technique that might be employed in TMX-U. Achievement of above density parameters with plugging would represent a factor of 4 to 8 improvement over those obtained to date.

In the absence of additional funding over and above the OFE presidential budget case, Tara could not be able to demonstrate its full capabilities, nor could TMX-U be operated for a sufficiently long period to give assurance that the LOP problem will be resolved. As alternatives, we propose three budget cases, all of which permit Tara to operate for the full FY87 with varying amounts of TMX-U operation. This would hopefully allow Tara to address both MHD stability and its density dependence of plugging and in doing so to reach the goal of $\sim 10^{13}$ cm^{-3}. The three cases represent increasing cost and *increasing probability of determining* the cause of LOP and reaching the goal, according to how much operating time is permitted in TMX-U:

Case A. Tara runs throughout FY87 and TMX-U operation is terminated near the beginning of FY87.

Case B. Tara runs throughout FY87 and TMX-U operation is extended through March of 1987

Case C. Both Tara and TMX-U run throughout FY87.

All three cases include continuation of Phaedrus as a basic experiment in RF effects in tandem mirrors and as a test bed for alternative methods of enhancing plugging at 10^{13} cm^{-3} density. Phaedrus would support Tara in RF MHD stabilization techniques. Case B takes advantage of the greater diagnostic capability of TMX-U in assessing the cause and cure of LOP in parallel with Tara operation. Case C, which LLNL proposed to DOE subsequent to the review by MFAC Panel XVI, would permit TMX-U to operate the full FY87, thereby providing another machine with the opportunity to reach the goal of $\sim 10^{13}$ cm^{-3}. Milestones for these budget cases are presented in Sec. III with their financial and institutional implications in Sec. IV.

LLNL involvement with Tara and Phaedrus would vary with the program adopted. At the least, theory involvement would be increased. Supplying diagnostics and personnel to Tara would depend on the needs in TMX-U and would decrease with increased TMX-U operation. Exchanges with Gamma-10 would proceed, as is presently being planned, to include exchange of diagnostics and personnel. Again, details must await final determination of plans for TMX-U operation.

The proposed mirror program is aimed at understanding the thermal barrier and related potential formation along field lines, but it would also develop suitable startup techniques and increase understanding of many aspects of equilibrium and transport. Benefits from this understanding to the mirror program are clear, but results can also be expected to apply to aspects of confinement in other devices, e.g., confinement with or without thermal barriers in tokamak divertor plasmas, and the role of hot electrons in MHD modes. In addition, all three experiments are currently training graduate students (4 TMX-U, 6 Tara, and 15 Phaedrus).

Success in achieving the goal of $\sim 10^{13}$ cm^{-3} in either Tara or TMX-U would establish the physics basis for continuing the mirror program into FY88. This program would include broadening the tandem mirror data base using existing facilities with possible minor upgrades aimed at parameter improvements. It could also include preparation for MFTF-B operation with an increase in the national fusion budget, and it could open the way to international collaboration on the next generation of experiments.

In the following, Sec. II summarizes results obtained in TMX-U, Tara and Phaedrus since the time of the MFAC Panel XVI Review. Sec. III describes the proposed plans and milestones; and Sec. IV, the costs associated with the three different options.

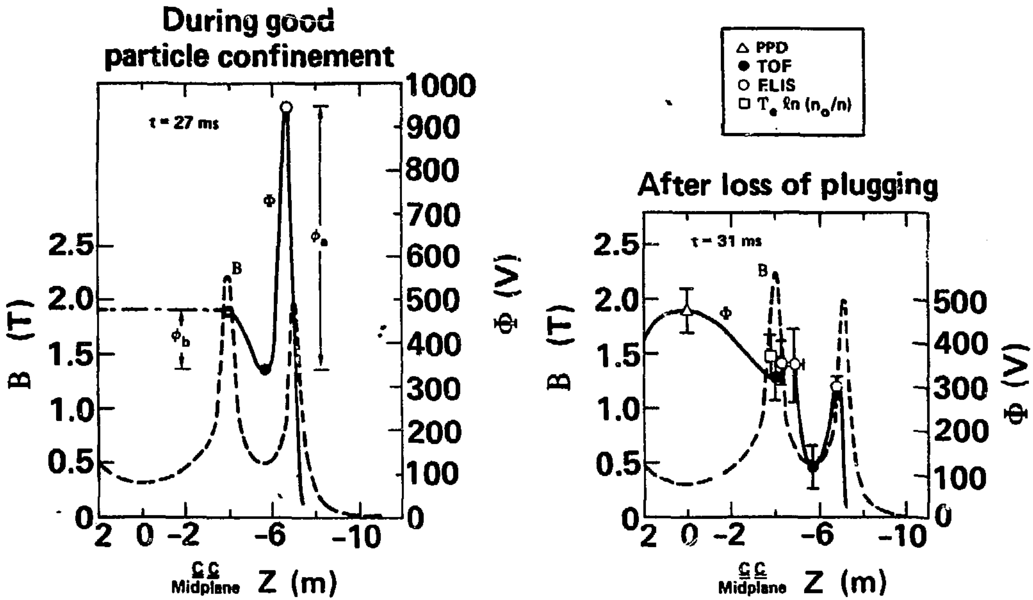
II. RESULTS SINCE THE MFAC PANEL XVI REVIEW

TMX-U RECENT PROGRESS

During the last TMX-U experimental run, which ended in March, 1986, we made significant progress in our ability to measure the axial potential profile. We now have several diagnostics in operation which provide sufficient information to permit us to determine the potential at several key axial locations, and hence to infer the axial potential profile in the machine. We have used these diagnostics to obtain the axial potential profile both during plugging, and after loss-of-plugging. The machine was operated in the standard thermal barrier configuration with sloshing beams, fundamental and second harmonic ECH, central cell ICH, and the potential control plates floated (10^4 Ω to ground). When the sloshing beams were turned on, the axial losses decreased and the radial transport did not increase, permitting the central cell density to rise rapidly. This led to a loss of plugging. The behavior of the potential profile throughout this operation is described in Appendix I, and summarized briefly here. These results, while very exciting, are preliminary and require additional experiments to expand the data base.

These initial results indicate that we have a thermal barrier configuration during the period with good total particle confinement. After the loss of plugging, the potential at the barrier remains lower than the inner mirror potential, but the potential at the outer sloshing ion turning point is less than the potential at the midplane of the central cell. The potential profiles measured with good total particle confinement and after the loss of plugging are shown in Fig. 4. The measured distribution function of ions confined in the thermal barrier is Maxwellian with the same temperature as the passing ions just before the loss of plugging whereas the distribution of the potentially confined ions has a lower apparent temperature than the passing ions during the period with good particle confinement. This suggests that collisional filling from the central cell is playing a role in the reduction of axial confinement. Earlier modeling indicated that ECH power limitations are also playing a role. Hence, we believe that our next experiments should examine both the effect of collisional filling and the effect of ECH on the axial potential profile. (TMX-U milestones 1 and 2 in section III.)

Measured axial potential profile for shot 18 on 13 March, 1986



During good particle confinement

After loss of plugging

Figure 4.

These initial results not only indicate that the diagnostics in TMX-U are capable of determining the axial potential profile, but they also indicate a possible mechanism for the loss of plugging. If early experiments on the next experimental cycle confirm the importance of collisional barrier filling, we must control the rate of rise of the central cell density to enable the central cell heating systems (ICH and beams) to heat the ions and hence control the barrier filling rate. We have examined these effects in the past, but the availability of the barrier-trapped ion distribution function permit a more effective experimental study. Direct measurements of the passing ion distribution permit more detailed control of the central cell heating and fueling rate to better match the collisional filling rate with the available pumping speed. This should permit achieving a higher central cell density for a given barrier density. Furthermore, an ability to better match the filling and pumping rates may permit operation with deeper thermal barriers than indicated in Fig. 4(a), thus permitting better utilization of the fundamental ECH power, and hence plugging at higher barrier densities.

TARA RECENT PROGRESS

At the time of the MFAC Mirror Review at LLNL, results from the central cell RF startup, neutral beam injection into the plug, and the first single ended plugging results were presented. Since that time, we have concentrated on improving energy confinement during startup, outside anchor stabilization studies, and thermal barrier formation. This has led to new progress towards thermal barrier operation summarized here.

With the installation of a new programmable gas control system, we were able to begin reducing gas feed after the initial breakdown. We have reduced the fueling from 40 Torrℓ/s used in previous experiments to 18 Torrℓ/s, with a trebling of the energy confinement time. The resultant plasma parameters are: $n_e = 2 \times 10^{12}$ cm^3, $Ti_{perp} = 400$ eV, and $T_e = \sim 60$ eV. The reduction in cx and increased T_e allows the production or a large central cell mirror trapped component equal to 30% of the total. This is particularly significant for increasing the central cell density during plugging by reduction of the plug stream. This also leads to improved electron core heating from the central cell ions.

This low fueling operation has also allowed us to study the outside anchor stabilization. During previous operation, the gas fueling level was high enough that the fluctuation level was low and the anchors did not significantly improve the energy confinement. At low fueling levels, when the anchors are terminated during the shot, abrupt loss of the central cell is observed. This has allowed us to measure the MHD and power limited operation of the central cell. Initial experiments suggest that the central cell beta limit follows an interchange criterion. Additional experiments are underway to evaluate the effective beta in the anchor from the hot electron contribution. Using a new 18 GHz, 15 kW ECH system fabricated for each anchor, we have produced up to 30% hot-electron beta. This beta can effectively contribute to central cell stability through coupling to the anchor core ion beta. These experiments will be completed in July '86.

The thermal barrier hot electron temperature should be on the order of 20-40 keV. Higher temperature produces excessive beta while lower temperature would use excessive power. We have produced thermal barrier electrons in this temperature range in experiments which also produce endloss reduction, starting from a plug stream density of 6×10^{11} cm^3. X-ray and diamagnetic measurements are underway to determine the hot electron fraction. However, the decay of the diamagnetic loop suggests that the fraction is appreciable and is observed to permit plugging at densities up to 1.8×10^{12} cm^3. The plugging takes place only after thermal barrier electrons have been generated. The same results are obtained with or without neutral beam injection. It is theoretically expected that neutral beam injected ions and associated barrier pumping will be required at the higher parameters projected in Tara. We have controlled the thermal barrier runaway electrons produced outside the main column using a scraper in the plug. This eliminates their absorption and beta contribution. Further experiments are aimed at determining the ECH bulk electron heating, plug temperature, and potential.

PHAEDRUS RECENT PROGRESS

A significant reduction in MHD fluctuation levels in experiments performed with central cell ICRF at 0.8 ω_{ci} has been achieved through the use of phased antennas. In central cell stand-alone mode, with no end cell ICRF, two dual half-turn antennas located 50 cm to either side of central cell midplane are excited at the same frequency, but with variable relative phasing. Previous experiments at 1.0 ω_{ci} have shown that fluctuation levels are strongly affected by relative antenna phasing for fixed excitation frequency. The results of experiments with 0.8 ω_{ci} excitation are shown in Fig. 5, which demonstrates that a factor of 4-5 range in MHD fluctuation levels can be achieved with a proper choice of phasing.

Experiments involving additional ICRF sources in the end cells have demonstrated strong single ended plugging. An end cell midplane dual half-turn antenna, resonant at the midplane ion cyclotron frequency, traps and heats the central cell loss stream. An additional dual half-turn antenna, located 20 cm inboard of end cell midplane, is excited at half the end cell midplane ion cyclotron frequency. This frequency is resonant only at magnetic beaches on either end of the central cell, near R = 1.5. Early experiments with only the west low frequency end cell source active resulted in strong single ended plugging. The best results obtained are displayed in Fig. 6, which shows the total ion endloss current on the four endloss analyzers nearest the machine axis. The end cell midplane sources are excited at 3 ms into the shot and the west low frequency source at 7 ms. A factor of 30-40 reduction in west endloss results. A partial failure of the west end cell midplane rf feedthrough has prevented full power double ended trials of the end cell low frequency oscillator system. In lower power double ended trails, operation of the low frequency sources routinely results in a factor of two increase in central cell diamagnetism and a 50 percent increase in central cell density due to the presence of magnetic beaches at the central cell--choke coil transitions. We have also observed a factor of three increase in the end cell electron temperature when the low frequency sources are excited.

Thermal barrier filling experiments have shown that a density dip in the inboard thermal barrier cell can be maintained without active pumping. Plug densities achieved are 2×10^{12} cm^{-3}; thermal barrier densities, 1×10^{12} cm^{-3}; with central cell densities of 4×10^{12} cm^{-3}. The passive pumping mechanism necessary to maintain this density dip has been found to pump ions radially but the exact cause is under investigation. The major filling mechanism of the thermal barrier region is the plug rf propagating

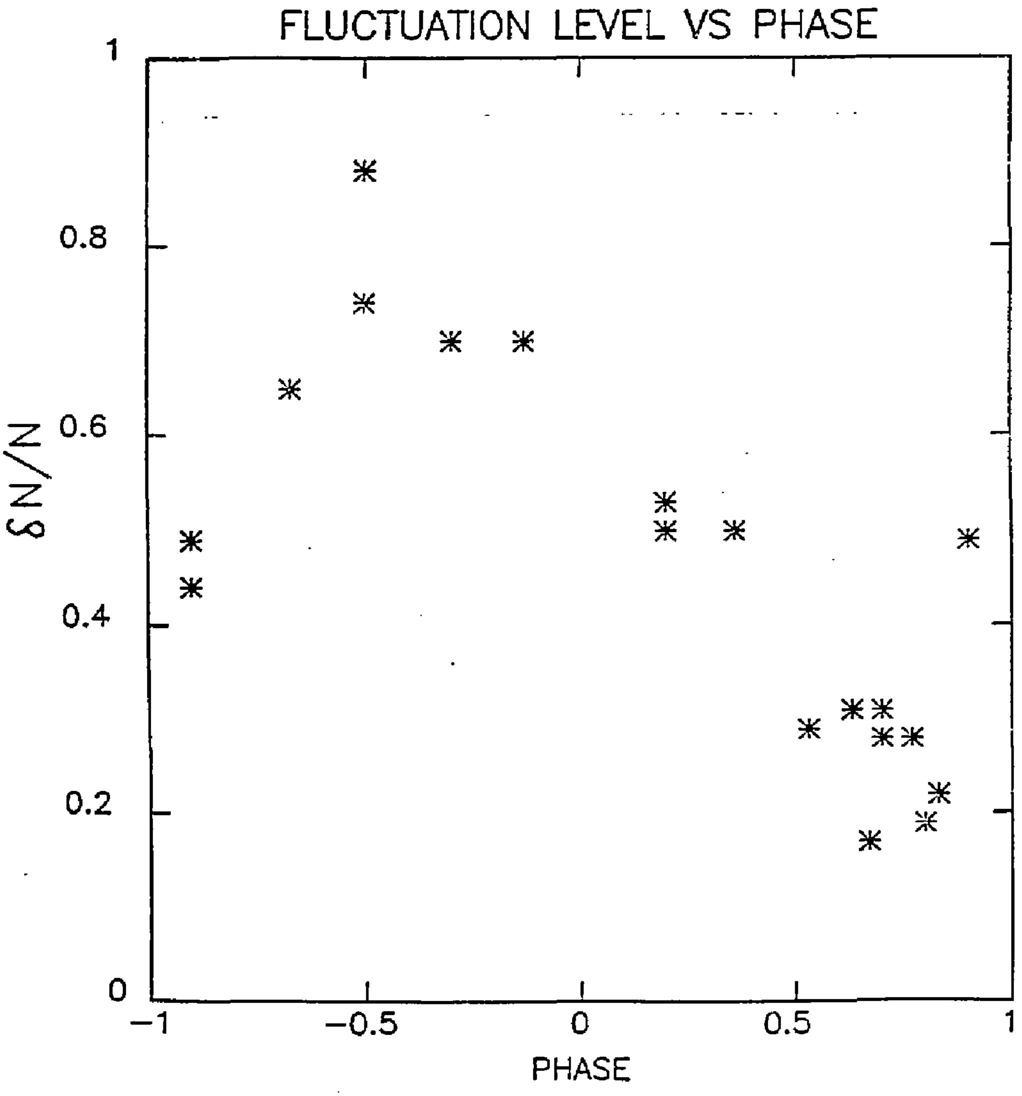


Figure 5. Amplitude of the 12 kHz MHD fluctuation level as a function of the relative antenna phasing, for $0.8\omega_{ci}$ excitation of the central cell antennas.

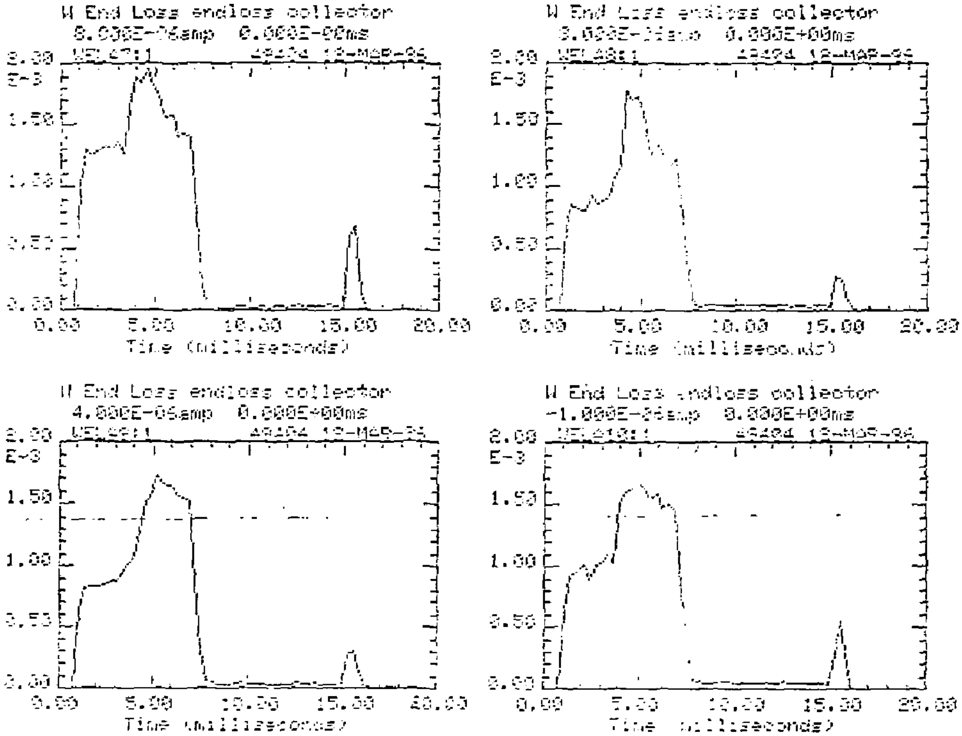


Figure 6. Total ion endloss signal on the central four endloss analyzers at the west end wall. The end cell heating/trapping sources are turned on at 3 msec, and the west end cell low frequency source is turned on at 7 msec.

into the thermal barrier region and trapping and heating streaming ions locally. This filling mechanism is independent of plug density increases. The passing ion density is lower due to the anisotropic velocity distribution of the rf heated central cell plasma. This reduces the Coulomb collisional filling to a minor role. The pumping of ions on the local thermal barrier limiters does not increase the local neutral pressure significantly. Neutrals do not dominate the filling process in the Phaedrus-B thermal barrier even when 10-12 amps of ions are intercepted by these limiters.

III. PROPOSED TANDEM MIRROR RESEARCH PROGRAM FOR FY87

Options

As described in Sec. I, both TMX-U and Tara offer good reasons for operating in FY87. With success, each could achieve the goal of a plugged central cell density of $\sim 10^{13}$ cm^{-3}. TMX-U has newly developed diagnostics well suited to address the questions of LOP and can address the LOP issue in a stable magnetic geometry. Tara is a new machine that has not yet been exploited, it has a geometry that with stabilization might be superior for barrier formation, and it has a configuration that projects to an attractive reactor. Being initially a lower budget facility, Tara requires a smaller increment to operate for the full FY87. Our minimum plan calls for full operation of Tara and Phaedrus. In addition, to increase the chance for success in meeting the plugging-density goal, we strongly recommend operation of TMX-U to take advantage of the experience base of that facility, its recently developed diagnostic capability, and new elements aimed at increasing the plugged density. The structure of the tandem mirror research plan and options is incorporated into the TMX-U milestone, with the termination of each funding case called out explicitly.

TMX-UPGRADE FY87 MILESTONES

OBJECTIVE: Physics investigation to establish thermal-barrier plugging with a central-cell density $\sim 10^{13}$ cm^{-3}.

Past experiments have attempted to reach a plugged central-cell density of 1×10^{13} cm^{-3} by varying the heating and fueling systems while we monitored the end loss current. Recently, new diagnostics to measure the plasma potential have become operational. The TMX-U plasma potential instrument set now includes the central-cell plasma potential diagnostic (PPD), the end-cell time of flight instrument (TOF), the two end-loss ion spectrometers (ELIS), and the four end-loss-ion analyzers (ELA) .

In addition to new diagnostics, there are several heating and fueling systems on TMX-U which are new and potentially important to achieving better performance. These include the long pulse (75 ms) ECH tubes, the inner 10kG

ECH system, the 18 GHz ECH system, the ability to aim the 5 kG ECH toward the central cell side of the barrier midplane, feedback-controlled central-cell gas feed (under development), and the ability to keep the liquid-nitrogen liner system continuously cold for several days.

The new diagnostics will be used to determine the axial potential profile during double ended plugging and during loss of plugging (Milestone 1). These measurements will help determine the order in which the experiments described in Milestone 2 are carried out. The results of these experiments should determine whether or not the heating and fueling systems presently on TMX-U are adequate to allow plugging at densities greater than 2×10^{12} cm^{-3}. If they are, we will need to control the rate of central cell density increase as outlined in Milestone 3. Once the beam target is adequate (Milestone 4) and the central-cell neutral-beam system output is sufficient (Milestone 5) then experiments to reach 10^{13} will be conducted (Milestone 6).*

We now list the six milestones which will mark our progress toward plugging at $\sim 10^{13}$ cm^{-3}. Particular emphasis is placed on Milestone 2 which deals with understanding the physics behind our present inability to sustain axial plugging at densities greater than 2×10^{12} cm^{-3}. Included with Milestone 2 is a table of the plasma parameters which we believe play a critical role in loss of plugging (LOP). We include a brief description of the experiments we feel are necessary to understand the role these parameters play (in LOP) and a list of the diagnostics and measurements which we will use. An overview of the resulting experimental program plan is presented in Fig. 7.

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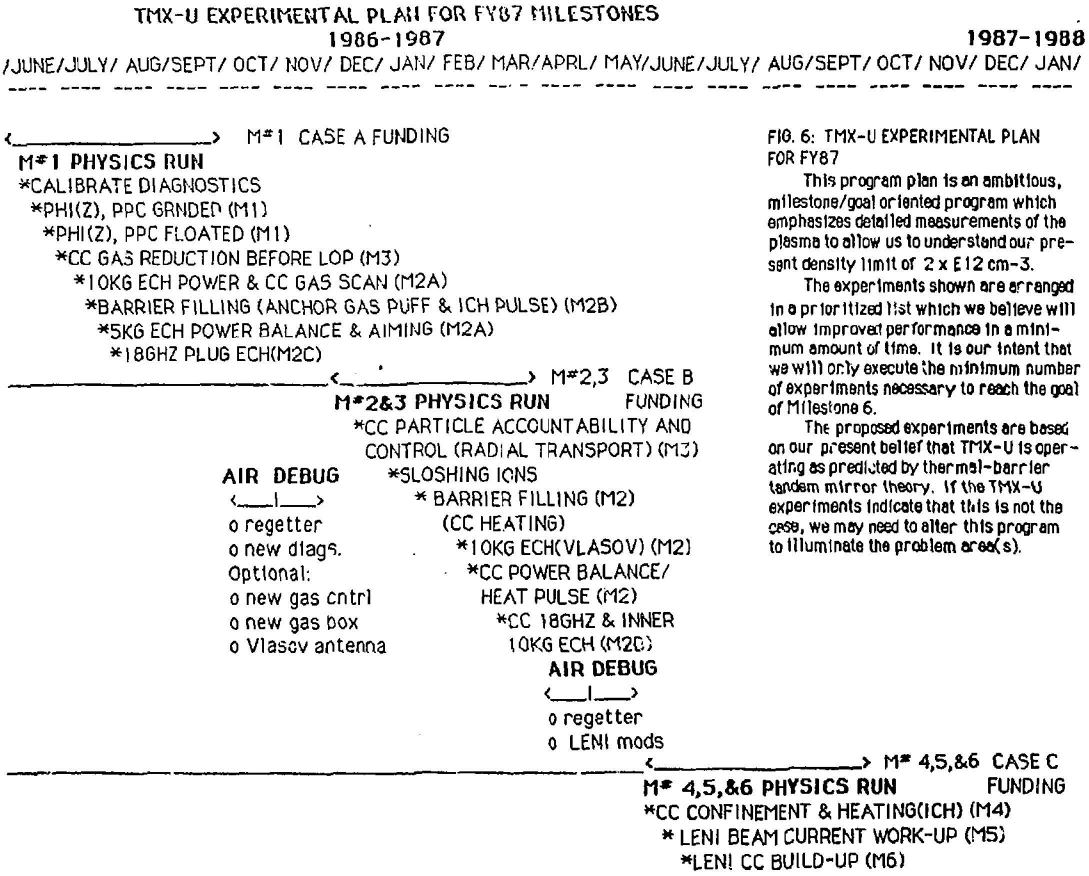
*This set of milestones (2-6) was based on the conventional picture of thermal-barrier potential confinement in a manner consistent with the TMX-U proposal and the models in the TREQ code. Nonconventional potential profiles will be recognizable from the data and may require some modification of the proposed experimental plan.

Figure 7.



TMX-U EXPERIMENTAL PLAN FOR FY87 MILESTONES

1986-1987

1987-1988

/JUNE/JULY/ AUG/SEPT/ OCT/ NOV/ DEC/ JAN/ FEB/ MAR/APRL/ MAY/JUNE/JULY/ AUG/SEPT/ OCT/ NOV/ DEC/ JAN/

<————————> M*1 CASE A FUNDING

M*1 PHYSICS RUN

*CALIBRATE DIAGNOSTICS
*PHI(Z), PPC GRNDED (M1)
*PHI(Z), PPC FLOATED (M1)
*CC GAS REDUCTION BEFORE LOP (M3)
*10KG ECH POWER & CC GAS SCAN (M2A)
*BARRIER FILLING (ANCHOR GAS PUFF & ICH PULSE) (M2B)
*5KG ECH POWER BALANCE & AIMING (M2A)
*18GHZ PLUG ECH(M2C)

————————————<————————> M*2,3 CASE B FUNDING

M*2&3 PHYSICS RUN

*CC PARTICLE ACCOUNTABILITY AND CONTROL (RADIAL TRANSPORT) (M3)
*SLOSHING IONS
* BARRIER FILLING (M2) (CC HEATING)
*10KG ECH(VLASOV) (M2)
*CC POWER BALANCE/ HEAT PULSE (M2)
*CC 18GHZ & INNER 10KG ECH (M2C)

AIR DEBUG

<——|——>

o regetter
o new diags.
Optional:
o new gas cntrl
o new gas box
o Vlasov antenna

AIR DEBUG

<——|——>

o regetter
o LENI mods

————————————<————————> M* 4,5,&6 CASE C FUNDING

M* 4,5,&6 PHYSICS RUN

*CC CONFINEMENT & HEATING(ICH) (M4)
* LENI BEAM CURRENT WORK-UP (M5)
*LENI CC BUILD-UP (M6)

FIG. 6: TMX-U EXPERIMENTAL PLAN FOR FY87

This program plan is an ambitious, milestone/goal oriented program which emphasizes detailed measurements of the plasma to allow us to understand our present density limit of 2 x E12 cm-3.

The experiments shown are arranged in a prioritized list which we believe will allow improved performance in a minimum amount of time. It is our intent that we will only execute the minimum number of experiments necessary to reach the goal of Milestone 6.

The proposed experiments are based on our present belief that TMX-U is operating as predicted by thermal-barrier tandem mirror theory. If the TMX-U experiments indicate that this is not the case, we may need to alter this program to illuminate the problem area(s).

Milestone 1. Determine the axial potential profile during double-ended plugging and during loss-of-plugging (September 1986).

This milestone is possible with the potential diagnostics: central cell plasma potential diagnostic, end loss ion spectrometers, end-cell time of flight instrument, and end loss analyzers.

--TERMINATION POINT FOR FUNDING CASE A--

At this point in the TMX-U experimental program we would be able to pass the following information to the TARA program:

A. Description of the axial potential profile in TMX-U before, during, and after loss of plugging.

B. Limited evaluation of the importance of barrier filling, hot electron fraction, and ECRH power at the plugging point on loss of plugging in TMX-U.

Milestone 2. Evaluate the role of critical plasma parameters in the reduction of potential confinement during loss-of-plugging (March 1987):

We believe that the following parameters play an important role in loss of plugging. The experiments in Fig. 7 were selected from Appendix II based on our appraisal of which experiments have the highest probability of illuminating the cause for LOP in the shortest possible time. Many of these experiments will yield data on more than one of the possible problem areas.

a. Hot electron fraction within the thermal barrier

b. Thermal barrier filling rate -

c. Sloshing ion axial-density profile and lifetime -

d. Central-cell electron temperature and power balance -

The relationship of the experiments in Fig. 7 to these parameters is shown in Appendix II where we outline the experiments according to the critical parameters which appear under Milestone 2 .

The experiments shown in Fig. 7 will also allow us to examine the effects of our heating and fueling systems on the plasma potential profile. This will not only allow us to increase our understanding of the role these systems play in plugging, but should also allow us to improve performance (i.e., maximum plugged density) as our understanding increases.

If the loss-of-plugging mechanism does not allow an improvement in central-cell performance with the heating and fueling hardware in place on TMX-U, we will determine what changes would be required and what implications these changes have to TMX-U, Tara, Phaedrus, GAMMA-10, and MFTF-B.

--TERMINATION WITH FUNDING CASE B--

At this point in the TMX-U experimental program we would be able to pass the following information to the Tara program.

A. Evaluation of the importance of barrier filling including an assesment of the relative importance of charge exchange in the plugs, scattering of the central cell passing ions, and anomalous processes.

B. Evaluation of the importance of hot electron fraction, including the importance of the beta shift of the ECRH resonance, the maximum rate at which the plug density can increase while maintaining a large hot electron fraction, and any limits to the achievable hot electron density in TMX-U.

C. Evaluation of the importance of ECRH power at the plugging point on loss of plugging, including the sensitivity to the 28 GHz ECH power (resonance at 10 kG) versus 18 GHz power (resonance at 6.4kG) -- related to changes in the sloshing ion turning point while plugged, and the maximum allowed sloshing ion density in TMX-U as a function of the plug ECH power.

D. Evaluation of the cause of the anomalous sloshing ion lifetime in TMX-U and its importance in plugging, in particular the role it plays in barrier pumping.

E. Limited analysis of the importance of controlling the build-up of the central cell density to maintain plugging.

Milestone 3. Control central-cell fueling and radial transport to control the rate of central cell density rise during plugging. Establish 30 ms plugging duration and total particle confinement time greater than 10 ms (March 1987).

Previous TMX-U experiments have indicated that when the radial losses are small, plugging the axial losses results in a rapid increase in the central cell density which in turn leads to LOP. During those experiments, we were able to control the non-ambipolar radial losses by electrically floating the Plasma Potential Control (PPC) plates on the end walls of TMX-U. We were able to minimize the ambipolar losses by tailoring the ICH power as a function of time (during the discharge) to "match" the plasma density. Our data base on controlling ambipolar losses, however, is small, so we may need experimental time to increase our ability to control ambipolar losses over a wider range of conditions.

We also believe that we may need to modify our present gas-feed control system by installing feedback control so that the central cell density rise is consistent with our existing ICH and ECH heating systems. Lastly, we are studying the desirability of installing a Tara style gas box to improve our gas fueling efficiency as is done in TARA and GAMMA 10.

Milestone 4. Demonstrate a central-cell beam-target plasma with sufficient confinement for central-cell low-energy neutral-injectors (LENI): $n = 4 \times 10^{12}$ cm^{-3}, total particle confinement time greater than 10 ms, duration of plugging greater than 30 ms (June 1987).

This milestone capitalizes on the results from Milestones 2 and 3 to increase the plugged central-cell density to a level adequate for LENI beam buildup to $\sim 10^{13}$ cm^{-3}.

Milestone 5. Increase low-energy-neutral-injector (LENI) current to permit reaching ~10^{13} cm^{-3}. (June 1987).

TREQ and analytical calculations predict buildup from the target plasma of Milestone 4 to a plugged central-cell density ~10^{13} cm^{-3} using 170 atom amps of LENI current at a mean beam energy of 1.3 kV. The present TMX-U LENI beam system (10 beams) delivers approximately 100 atom amps. An individual source operating on a test stand has delivered 17 atom amps. The work up and optimization of the LENI beams will proceed in parallel with the experiments on TMX-U as shown in Fig. 7.

Milestone 6. Use low-energy-neutral-injectors to increase central-cell plugged density to ~10^{13} cm^{-3} (September 1987).

TARA EXPERIMENTAL PLAN AND MILESTONES

We have re-examined the parameters which Tara can achieve. We find that Tara has the potential to produce parameters which exceed those in the original proposal when the mirror trapped central cell distribution is included. We have revised our goals in that light. The principal issue is whether the machine can be exercised fast enough to reach these goals in FY '87. We believe that realistically, more than one year may be required to complete the objectives as these goals are highly success oriented and do not allow for time to deal with unforeseen technical or physics problems. Given adequate time we can make a tandem mirror work at the desired performance level. The time to be allowed should be determined by how desirable it is to have a tandem mirror available as a reactor concept.

Our program is aimed at achieving plugged axicell confinement with high central cell density. We will focus our attention in three areas.

- Stability in plugged operation employing one of three stabilization schemes described below.
- Creation of halo plasma for increasing shielding of hot ions.
- Optimize plugging experiments for higher density and central cell parameters.

The program involves examining three stabilization schemes. In parallel, we will continue to develop thermal barrier physics, i.e., proper hot electron fraction, barrier pumping and plug potential formation. As soon as any of the stabilization schemes yield desired results, emphasis may change so as to take advantage of it and move more rapidly on plugging experiments.

The effort through Dec. '86 is directed towards exploring the compatibility of plugged operation with three stabilization schemes. The stabilization schemes are the outside anchor developed in the Tara proposal, magnetic limiter stabilization recently conceived of at MIT, and RF ponderomotive stabilization developed at UW. The outside anchor stabilization requires higher beta in plugged operation. The effective beta will be raised by generating a high beta hot electron component. As the core beta is produced by ICRF trapping of the stream, additional fueling from the transition is being perfected to maintain the anchor during plugged operation when central cell endloss is reduced. The results of the hot electron anchor will establish much of the physics of hot particle stabilization and will make contributions to other confinement concepts, notably tokamaks.

The Magnetic Limiter/Halo Generator concept is a significant new idea in tandem mirror design. The divertor is expected to stabilize $m = 1$ instabilities, characteristic of the MHD mode observed in Tara and to provide up to 1×10^{13} cm^2 of line density to shield the plug and central cell plasma from edge neutrals. It will thus improve stability and greatly improve the power balance by eliminating the transition and anchor plasma. Furthermore, the simplified coil set makes a significant improvement in the reactor configuration of a Tandem Mirror. Fabrication is underway and installation is planned for Aug. '86 with operation resuming in Sept. '86.

Ponderomotive stabilization has proved successful on Phaedrus. It is both desirable to try this method on a larger machine and if successful, could lead to more rapid progress on plugging in Tara. Experiments are planned for this July with additional experiments in December. This work will be done in collaboration with the Phaedrus group.

For Tara to establish high density, thermal barrier operation in FY '87, it must reach higher density than projected in the proposal. The new central cell configuration, developed since the proposal, permits Tara to achieve higher central cell density for the same thermal barrier pumping level as is given in the proposal. This is achieved by RF trapping to produce a central cell mirror trapped population. This mirror trapped population was not assumed in the initial design. Present operation without plugging has a central cell mirror peak to local well density ratio of 2-3. The gas box design incorporates charge exchange reflux and is able to fuel the axis at higher density than can be achieved by Franck-Condons. The maximum density at the central cell mirror peak which is consistent with thermal barrier pumping is 4×10^{12} cm^3. With a density ratio of 2 in plugged operation, Tara can achieve a peak central cell plugged density of $\sim 8 \times 10^{12}$ cm^3.

Plugging efforts will be pursued during the period of evaluation of stability concepts. We will thereafter focus on improving central cell parameters. This will require a continued effort in ICRF heating to limit barrier filling at high density and to maintain an equal mirror trapped ion component. A significant effort will be pursued in radial potential control and in limiting radial transport which might be introduced by the heating systems. We will use both the conventional plug ECH for potential generation as well as bounce resonance electron heating. Since power of the ICH transmitter is continuously adjustable, it may offer methods for initiating plugging on a slow time scale, making start up of plugged operation easier. The use of the HIBP together with endloss analyzers and potentially an LLNL ELIS to make plugging potential measurements will enhance understanding of thermal barrier plugging physics.

The margins that we have for achieving these overall goals are reasonable. Tara achieved plugging results of $n_e > 1 \times 10^{12}$ cm^3, similar to those obtained on Gamma-10, after only one month of plugging experiments. In order to improve these results on Gamma-10, the vacuum systems will be upgraded, rf power will be added to the central cell, and pump beams will be added, all over a period of three fiscal years. At the present time, Tara has all of these. In addition, the pressure in the Tara plug is an order of magnitude lower, the addition of a halo generator to Tara is a plus, Tara has 900 kW of rf for the central cell, and Tara has double the beam current of Gamma-10.

Milestone Summary Through FY '87 Based on a $7.5M Budget, as Elaborated in Fig. 8:

Milestone 1. Evaluate outside anchor stabilization in plugged operation.
Aug. '86

Stability in plugged operation requires that hot particle stabilization contribute to the effective anchor beta. Fueling of the anchor in plugged operation results from the transition outflow as opposed to the central cell stream in unplugged operation. These two effects will be established for outboard anchor stabilization of Tara.

Milestone 2. Complete installation and begin operation of the Magnetic Limiter. Sept. '86

The magnetic limiter and halo generator is in fabrication and will be installed during Aug. '86. It permits both purely axisymmetric stabilization and halo formation for charge exchange control at the low fueling levels of plugged operation. The method for stabilization removes the danger of trapped particle modes. Installation of the magnetic divertor is a significant machine modification and as such, may require several months to obtain good operating conditions and to learn how to operate with independent halo and core fueling and power balance.

Milestone 3. Evaluate the central cell stabilization by the Magnetic Limiter.
Nov. '86

This milestone is to establish the fundamental goal of stabilization with the magnetic limiter. The magnetic limiter allows separate control of the edge plasma and thus plays an additional important role in achieving higher density operation. Successful stabilization with the magnetic limiter will have impact beyond tandem mirrors, providing new methods for stabilization of the FRC, Spheromak and Drakon configurations.

Milestone 4. Begin plugging experiments with floating end plates for radial potential control. Jan. '87

Radial potential control has proven effective in improving operation of TMX-U and Gamma-10. Although potential control for transport in the central cell does not appear to be an issue, potential control will reduce rotational drive, leading to better stability. This milestone may be optional if adequate stability is achieved with grounded end plates.

Milestone 5. Assess the improvement in stability using floating end plates. March '87

The impact of potential control on the machine operation will be established.

Milestone 6. Continue scaling in plugged operation. April '87

At this time we will have evaluated the optimum method for stability in which to pursue plugged operation. We will continue to push up parameters in order to plug the central cell at the highest possible density. We will have available the detailed results from TMX-U in addition to Tara's, to formulate the best approach.

Milestone 7. Establish $n_e \sim 8 \times 10^{12}$ cm^3, $T_i = T_e = 400$ eV. Sept. '87

The goal will be to achieve the desired performance level by the end of FY '87. Successful achievement of this goal will naturally lead to improved parameters with emphasis on higher central cell beta in FY '88.

TARA TIMELINE JUNE 1986 - JANUARY 1987

	FISCAL YEAR 1986				FISCAL YEAR 1987			
	June	July	August	Sept.	Oct.	Nov.	Dec.	Jan.
Experimental Meas.	Anchor fuel requirements, X-ray TeH Stability w/wo hot elect. in anchor, ponderomotive stabilization			Re-establish high confinement mode then test Magnetic Limiter	Build-up NB and plug w/ Magnetic Limiter and Halo		Ponderomotive tests	Operate w/floating plates
Experimental Analysis	Establish: Hot fraction in barrier, limits, stability boundaries			Stability analysis for Magnetic Limiter		Analyze Ponderomotive Results		
Major Hardware Work			UP-TO-AIR Magnetic Limiter, general repairs				UP-TO-AIR Add floating end plates	
Major Milestones			1)Evaluate outside anchor	2)Operate Magnet. Limiter	3)Evaluate Stab. by Mag. Lim.			4)Begin exper.w/ floating plates
Tasks	* Anchor plugged startup * Anchor hot e * Plug ICH plugging		* Analysis * Diagnostic calibratn * Anchor RF * Diagnostic additions	* Halo fueling * Barrier buildup	* Plug with Halo and outside anchor * Plug NB buildup		* Stability with plugging	* Establish operation w/o floating plates

Figure 8.

TARA TIMELINE JANUARY 1987-OCTOBER 1987

FISCAL YEAR 1987

	Feb	Mar.	April	May	June	July	August	Sept.	Oct.
Experimental Meas.	Measure effects of end plates on confinement and stability		Raise cc density	Measure fuel. and confinement effects at higher density		HIBP radial scans	Optimize RF power and fueling for highest possible operating density		
Experimental Analysis	End plate effects		High density effects on plugging	Continue analysis of high dens. plugging		Relate cc phi profiles to plasma parameters confinement			
Major Hardware Work					UP-TO-AIR Maintenance and changes as needed				
Major Milestones	5)Assess floating end plates		6)Continue scaling in plugged operation				7)Establish n = 8E12/cm3 Ti = Te = 400eV		
Tasks	* Measure plugging effect on * Evaluate Halo conf. & power bal. * S.I. life-time, Halo benefits	* Evaluate stability in plugged operation	* Evaluate barrier pumping	* Optimize hot electron fraction		* Plug with ICH & ECH * Minimize heating effects on potential asymmetry			

Figure 8.

PHAEDRUS EXPERIMENTAL PLANS AND MILESTONES

The proposed milestones for Phaedrus have two goals. Half are devoted specifically toward optimizing rf ponderomotive stability for Tara-like parameters and half aim at strong axial plugging by taking advantage of thermal barriers.

The stability experiments are designed to provide an option in the event that MHD stable plasmas are not achieved with magnetic limiters. They involve investigations of ponderomotive stability at a frequency well above the ion cyclotron frequency produced by antennas similar to those on Tara and in raising Phaedrus parameters from the present $n = 10^{13}$ cm^{-3}, $T_e + T_e = 50$ eV to $T_e > 100$ eV, $T_i > 200$ eV.

Thermal barrier-like configurations have already been achieved in Phaedrus with μ-grad B pumping in an axisymmetric geometry and in Phaedrus with passive pumping in an axicell-to-quadrupole transition. Extensions of these configurations should allow us to achieve improved central cell parameters and to study generic rf issues such as ponderomotive effects on stability and transport, localized heating, and potential modifications in parameter regimes of interest to toroidal systems.

A funding level of $2.0 M is a flat budget with our current budget and would allow us to operate with a realistic level of supplies and expendables and to replace one technician and (on a temporary basis) one scientist, who have left the group.

PHAEDRUS MILESTONES

August 1986	1.	Evaluate rf stability using central cell ICRF at $\sim 4\omega_{ci}$ at $n \sim 1.0 \times 10^{13}$ cm^{-3}, $T_e \approx T_i \approx 50$ eV.
Sept. 1986	2.	Add plug ECH (14 GHz, 20 kW each plug) and determine bulk electron temperature increases.
Jan. 1987	3.	Using end cell ECH end plug and central cell ICRF achieve bulk electron temperatures >100 eV at central cell densities at $\geq 1.0 \times 10^{13}$ cm^{-3}.
April 1987	4.	Establish the scaling of passive thermal barrier pumping at central cell densities at $\sim 1.0 \times 10^{13}$ cm^{-3} and T_i between 30 and 200 eV.
June 1987	5.	Evaluate the basic physics issues of rf drift pumping. Carry out initial drift pumping studies using single pumping frequencies and measure the effect on the net trapping rate in the thermal barrier.
August 1987	6.	Determine the scaling of the ion plugging potential at $n \geq 1.0 \times 10^{13}$ cm^{-3} and $T_i > 100$ eV.
Nov. 1987	7.	Optimize rf stabilization by using phasing of two double-dual-half turn antennas to achieve $k_{\parallel}$ and m control.
Nov. 1987	8.	Establish the scaling of $\mu\nabla B$ pumping of thermal barriers at $n_c \sim 1.0 \times 10^{13}$ and T_i between 30 and 200 eV.

FUTURE TANDEM MIRROR PROGRAM

Success in achieving the plugging goal of ~10^{13} cm^{-3} accompanied by a validated theoretical understanding of the processes involved would be an important step in assessing the potential of the tandem mirror as a reactor. At that time the expected performances of MFTF-B and a tandem mirror reactor would be reevaluated, based on the theoretical picture emerging from the experimental results. Independent of the technical circumstances, proceeding with MFTF-B in FY88 would depend on an improvement in the fusion budget.

In any case, a strong program could be carried out in TMX-U and Tara in FY88 and beyond with the goals of broadening the mirror-physics data base and improving the reactor concept, pending a better budgetary climate. These physics studies would establish the full set of models used in the evaluation and design of future machines, and might also lead to improved confinement parameters with modest upgrades of either facility based on results in FY87. Examples of a FY88 physics investigation include

- Plug-physics studies to explore the density and other limits on sloshing-ion microstability and its dependence on the plug mirror ratio, the ECH absorption efficiency and profile control, hot-electron microstability, and thermal barrier drift pumping.

- Stability studies to explore limits due to beta, rotation, trapped particles, etc.

- Transport studies to explore particle and heat transport in a configuration lacking magnetic flux surfaces, effects of non-symmetric heating and fueling, scaling comparisons with theory of T, B, and n, and impurity accumulation and lifetime, especially in longer pulse operation.

Tara, particularly, is capable of longer pulse operation. An important part of these studies would be the further development of theoretical models used to scaled to future devices.

Examples of areas for concept improvement, suggested by the MINIMARS reactor study, include the magnetic geometry, heating techniques and their absorption efficiencies, barrier pumping techniques, and direct conversion techniques, all of which impact the reactor evaluation in a significant way. Even if MFTF-B were further delayed, a successful improvements program would continue to build the case for its restart.

Success in achieving the FY87 density goal in Tara's axisymmetric geometry would point toward modest upgrades of either Tara or TMX-U leading to improved performance. In either machine, these modifications would reduce the barrier-loss of central cell ions to approximately the level of Pastukhov axial loss. In Tara, the modification would be to increase the throttle coil field from 30 to 50 kG (requiring only power supplies) and add drift pumping. This would raise the central cell mirror ratio and (at constant temperature) permit a roughly 3 times higher thermal central cell density for the same barrier pumping. In TMX-U, by converting to an axisymmetric geometry with smaller end cells and using the high field throttle already fabricated, the $n\tau_E$ would potentially rise to the mid-10^{11} range. Similar modification of the MFTF-B facility in the same way would be straightforward, chiefly by rearranging slightly the equipment already installed or planned for the machine. The modification would lead to improvement factors of 4 to 8 in MFTF-B's potential $n\tau$ values.

On the other hand, if the FY88 fusion budget permits, success in the FY87 program could open the way directly to operation of MFTF-B, which is flexible enough to take advantage of results from either TMX-U or Tara. The current plan, calling first for a 0.5-sec operation in MFTF-B, would have as a goal $n\tau_E \sim 10^{12}$ cm^{-3} s, a reasonable step up from the $\sim 10^{11}$ value of Tara or TMX-U. The full capability of MFTF-B to reach $n\tau_E \sim 10^{13}$ cm^{-3} s could still follow in a later phase by adding the equipment necessary for 30 sec operation.

LLNL/Tara Cooperation and Support

LLNL would be able to lend support to an experimental program at Tara by both long and short term assignments to MIT and by data analysis, modeling and theory work done at LLNL. As an upper limit, we would expect 1-2 full time assignments to MIT, approximately 1-2 man-years of time at MIT distributed over visits of 2-4 weeks, and approximately 2-3 man-years of time spent at

LLNL. This level of support would vary, depending on the duration of TMX-U operation.

Experimental support would be chiefly in the area of diagnostics and the manpower to operate them. Example instruments would include an End Loss Ion Spectrometer (ELIS), an Extreme Ultraviolet (EUV) spectrometer, a Time of Flight (TOF) charge exchange analyzer, Germanium X-ray detectors, an H-alpha camera, and basic CAMAC equipment.

Problems that warrant theoretical attention as seen today include modeling using the TREQ rate code, Fokker-Planck codes, and Monte-Carlo codes studies of macrostability in the divertor-coil geometry or using ponderomotive stabilization, several aspects of ECH theory and modeling, and studies of ion microstability effects. While good work has been done in most of these areas by the small Tara theory group, LLNL brings a larger group capability having long experience in mirror problems and a wide variety of developed theoretical and computational tools.

Theory support would be valuable not only in understanding Tara itself, but also in projecting Tara results to MFTF-B and beyond. The performances of MFTF-B and reactors are projected on the basis of a set of physics models not yet fully validated by experiment. Successful plugging at higher density will mean either validating these models or replacing them with others. In the latter case, projections to future machines must be reevaluated.

Applied Plasma Physics Support

Since RF ponderomotive stabilization plays an important role in both Tara and Phaedrus in FY87, the SAI-Boulder group should continue its theory work in this area in collaboration with the experimental groups. The SAI group has developed substantial capability in this area and has been successfully collaborating with the Phaedrus group. In addition, SAI could contribute to stability analysis in the Tara limiter geometry and ponderomotive effects on trapped particle modes.

The APP mirror experiments continue to play an important role in developing new concepts and carrying out detailed experiments. For example, results from LAMEX were fundamental in the development of the magnetic-limiter stabilization concept at MIT. Constance has generated new data on hot electron equilibrium, heating and stability with applications to thermal barrier and hot particle stabilization concepts. We recommend the continuation of these types of experimental programs.

IV. BUDGETS AND INSTITUTIONAL IMPACT

As was stated in the Introduction, we shall consider the three budget cases shown in Table 2.

Case A.

Having adopted achieving ~10^{13}cm^{-3} density with thermal barrier end-plugging as the highest priority goal, we believe that the minimum-cost option to provide a fair chance to meet this goal is to extend TARA operation for the full FY'87 at an incremental cost of $3.0M. We also believe that the chances of succeeding on TARA would be substantially improved with the help of key experts and equipment from LLNL and additional technicians on Phaedrus, leading to a total incremental cost for this case of $3.9M as shown in Table 2.

Case B.

This case permits TARA to operate as in Case A but also extends TMX-U operation through mid-FY87 in order to utilize the greater diagnostic capability of TMX-U to understand and solve the LOP problem. The FY'87 funding for Case B in Table 2 provides 6 months operation plus termination costs.

Case C.

This case permits both TARA and TMX-U to operate for the full FY'87 and provides the largest probability for achieving the plugging goal.

Institutional Impact

The institutional impact at MIT and Wisconsin would be positive in all three cases, since the funding increments would avoid disruptive terminations of staff that must otherwise occur.

Table 2. Budgets for Mirror Program Options (in millions of $).

	Case A	Case B	Case C
Present OFE Budget			
TMX-U	2.0	2.0	2.0
TARA	4.5	4.5	4.5
Phaedrus	1.6	1.6	1.6
	8.1	8.1	8.1
Increments			
TMX-U	0*	8.0	13.0
TARA	3.0	3.0	3.0
LLNL support of MIT	0.5	0.3	0
Phaedrus	0.4	0.4	0.4
	3.9	11.7	16.4

*See Text

At LLNL, the impact has two facets, which are different for the three cases:

Impact on LLNL Manpower

The present OFE budget, and Case A also, calls for a major reduction in the LLNL staff at the end of FY'86 and makes no provision for experimental operating funds in FY'87. In particular, the $2M for TMX-U in Case A merely covers a portion of the physics staff that would bring the project to a close and analyze and document the final results. Actual operation of TMX-U would be terminated in September. Discussions have been held with OFE seeking ways to extend the operation of TMX-U two months into the fall in order to do a better job of preparing for the major fusion conference at Kyoto and making better use of the facility for Tara and the international mirror community before shutting it down. This additional operation would require operating funds of $1.25M per month over and above the Case A budget.

Case B, in which TMX-U operates part of the year, would defer the staff reduction problem by 6 months but ultimately require the same large staff reduction as Case A. Thus both Cases A and B would require a rebuilding of the operating staff if TMX-U were to be restarted in FY88.

Case C would continue the TMX-U staff for the full FY87, but at a reduced level (about 2/3) compared to FY86. It would provide the best position for continuing the mirror as a fusion option.

Impact on LLNL Commitments to Toroidal Program

1. FY87

LLNL has a strong commitment to mirror research and an institutional responsibility to put the large investment in MFTF-B to good use eventually. Thus, LLNL places high priority on continuing its leadership role in the mirror program if funding permits.

At the same time, in proposing to terminate mirror activity the OFE recognized strengths at LLNL that could contribute to the tokamak program and structured the FY87 budget accordingly, as shown in Table 3.

Table 3. LLNL FY87 budget - present OFE budget case (in millions of $).

	Total	Residual core staff funds included in the totals
<u>Mirror</u>		
MFTF-B	15	0
TMX-U	<u>2</u>	<u>2</u>
	17	2
<u>Toroidal</u>		
DIII Support	6	6
ETR	1.5	1.5
Beam Contracts	<u>7.3*</u>	<u>0</u>
	<u>14.8</u>	<u>7.5</u>
Totals	31.8	[illegible].5**

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* This item represents contract costs outstanding for a joint purchase of neutral beam sources for TFTR and DIII made through LLNL.

**For comparison, core staff funding in FY86 was approximately $21M.

In FY87, the primary LLNL obligation is to provide support for DIII at GA Technologies. Discussions are in progress to determine how best to provide this support, within the constraints of the LLNL budget shown in Table 3. This discussion applies both to the present circumstance in which the mirror program would be terminated and also to Case A in which Tara (but not TMX-U) would continue operation for the full FY87. As was noted above, this budget only provides funds for outstanding contractual obligations, a minimal maintenance staff to mothball MFTF-B, and a residual core staff - dominantly physicists - that is less than half of the FY86 level. In particular, no funds are provided for operating expenses or new equipment (e.g. ECH) deemed critical to the DIII program (a topic of ongoing discussion with OFE).

Turning to Cases B and C, in presenting Case C to OFE at its Spring program review, LLNL recommended that the staff support for a continued mirror effort be provided by the existing knowledgeable staff on TMX-U but with the understanding that other funds would be found to provide the support to DIII that would otherwise be provided by LLNL. The same recommendation applies to Case B. The OFE concurs in this view in light of the high priority it places on the DIII program. Thus, the incremental costs to extend TMX-U operation under Cases B and C should be regarded as a net increase in the combined LLNL-GA funding that would require additional funds from Congress or reprioritizing the overall OFE program.

2. FY'88

As was discussed in Section III, a possible outcome of continuation of the mirror program in FY'87 would be a decision to restart TMX-U in FY'88 (Cases A, B) or to continue its operation (Case C). On the other hand, a cooperative program on DIII and other toroidal activities at LLNL initiated in FY'87 would have a natural follow-on in FY'88. Moreover, LLNL finds itself in a unique position to contribute to the success of the CIT and ETR by applying to tokamaks a high power microwave heating technology developed at the Laboratory. A proposal to move Alcator C to Livermore in order to test this concept is currently under review. Since no FY'87 funds are provided for this experiment in the present OFE budget, any substantial financial impact of proceeding with it would probably be delayed to FY'88.

If OFE chose to do so, it could support both a mirror and a toroidal program at LLNL in FY'88 with no overall increase in LLNL funding relative to FY'87. Outstanding obligations for both MFTF-B and Beam Sources are fully paid under the present OFE budget for FY'87 (Table 3), and by FY'88 the cost to maintain MFTF-B in standby condition is only $2M if all contractual obligations are fully paid in FY'87 as provided in the plan. Then, in effect, a restart (or continuation) of TMX-U in FY'88 could be paid for from rolloff of MFTF-B mirror expenditures and a substantial toroidal effort could be funded by a continuation of the FY'87 toroidal program level in Table 3.

However, since neither MFAC nor the mirror community can foresee FY'88 budgetary conditions at this time, it seems best to resolve any conflict between mirror and toroidal activities in FY'88 in the future through normal OFE management procedures. The high priority that LLNL accords its responsibility to continue leadership of the mirror program has already been stated.

APPENDIX I. PRELIMINARY RESULTS OF THE TMX-U POTENTIAL MEASUREMENTS

During the last TMX-U experimental run, which ended in March, 1986, we made significant progress in our ability to measure the axial potential profile. We now have several diagnostics in operation which provide sufficient information to permit determination of the potential at several key axial locations, and hence to infer the axial potential profile in the machine. The initial results we have obtained with these diagnostics are very encouraging, but we require additional operation to gain confidence in our interpretation of these data.

These initial results indicate that we have a thermal barrier configuration during the period with good total particle confinement. After the loss of plugging, the potential at the barrier remains lower than the inner mirror potential, but the potential at the outer sloshing ion turning point is less than the potential at the midplane of the central cell. The measured distribution function of ions confined in the thermal barrier is Maxwellian with the same temperature as the passing ions just before the loss of plugging whereas the distribution of the potentially confined ions has a lower apparent temperature than the passing ions during the period with good particle confinement. This suggests that collisional filling from the central cell is playing a role in the reduction of axial confinement.

Earlier modeling indicated that ECH power limitations are also playing a role. Hence, we believe that our next experiments should examine both the effect of collisional filling and the effect of ECH on the axial potential profile. (TMX-U milestones 1 and 2 in section III.)

The information available from the diagnostics which provide the data necessary to measure the axial potential profile is summarized in Table I-1. The Plasma-Potential-Diagnostic (PPD) is a heavy-ion beam probe which determines the potential at the midplane of the central cell. The Time-of-Flight analyzer (TOF) is a charge-exchange analyzer which measures the distribution function of ions at the thermal barrier with kinetic energy in the range $50\ \text{eV} < E < 1500\ \text{eV}$, and with a pitch angle of 22.5°. Examination of this distribution function permits identification of phase space boundaries, which, in turn, determine the potential difference between the barrier and the inner mirror ($\delta\phi_b(t)$), and the potential difference between the barrier and the plug ($\delta\phi_{ab}(t)$). The End-Loss-Ion-Spectrometers (ELIS)

Table I-1. Potential-sensitive diagnostics on TMX-U.

Diagnostic	Location	Measurement	Limitations
PPD	Central cell midplane	$\phi(r,t)\|_z = 0$	$n_{ec} \geq 5 \times 10^{11}\ \mathrm{cm}^{-3}$
TOF	East plug midplane	$\delta\phi_b(t)$	$50\ \mathrm{eV} < E < 1500\ \mathrm{eV}$
	(West plug midplane)	$\delta\phi_{ab}(t)$	
ELIS	East end	ϕ_{max}	$j_{\|\|} > 0.3\ \mathrm{mA/cm}^2$
	West end	$\phi_{(\mathrm{inner\ mirror})}$	
		$B_{(\phi_{max})}$	
		$\phi_{(\mathrm{pump\ beam})}$	
ELA	East end	$\phi_{max}(r,t)$	$\phi_{max} < 1500\ \mathrm{V}$
	West end		

measure the energy spectrum of the ions which are lost axially. Detailed examination of this spectrum permit determination of the maximum potential in the plug region ($\phi_{max}(t)$), the magnetic field at the maximum potential ($B(\phi_{max} t)$), the potential at the inner mirror ($\phi_{inner\ mirror}(t)$), and the potential at the location of the pump beam footprint ($\phi_{pump\ beam}(t)$). Finally, the End-Loss Analyzers (ELA) are a set of four gridded analyzers which provide the energy spectrum of the end losses (ions or electrons). These devices can provide the maximum potential along a field line. Some of them are capable of being moved across the end-loss fan, hence they provide radial information.

We have used these diagnostics to obtain the axial potential profile both during the period with good total particle confinement, and after loss-of-plugging. The machine was operated in the standard thermal barrier configuration with sloshing beams, fundamental and second harmonic ECH, central cell ICH, and the potential control plates floated (10^4 Ω to ground). When the sloshing beams were turned on, the axial losses decreased, permitting the central cell density to rise rapidly. This led to a loss of plugging. The spectra measured on the TOF analyzer during the period with good particle confinement, just before loss-of-plugging, and just after loss-of-plugging are shown in Fig. I-1(a), I-1(b), and I-1(c) respectively. The corresponding potentials for plugged operation and just after loss-of-plugging are shown in Fig. I-2(a) and I-2(b). While plugged, the TOF spectrum consists of two Maxwellian populations; a low energy, barrier trapped species, and a higher energy passing ions species. The energy at which the spectrum transitions from one population to the other (250 eV in Fig. I-1(a)) determines the phase-space boundary between these populations, and hence is a measure of the potential difference between the inner mirror and the barrier, i.e. the thermal barrier depth. The relationship between the energy at which the break in the spectrum occurs and the potential difference is dependent on the viewing angle of the TOF analyzer and the mirror ratio between the inner mirror and the barrier. For TMX-U the break at 250 eV corresponds to a potential difference of 90 V. The lack of a break in the spectrum between 250 eV and 1000 eV indicates that the phase space boundary between the passing ions and the loss cone occurs above 1 keV. This permits a measure of the minimum ion confining potential. If the loss cone boundary occurred at 1 keV,

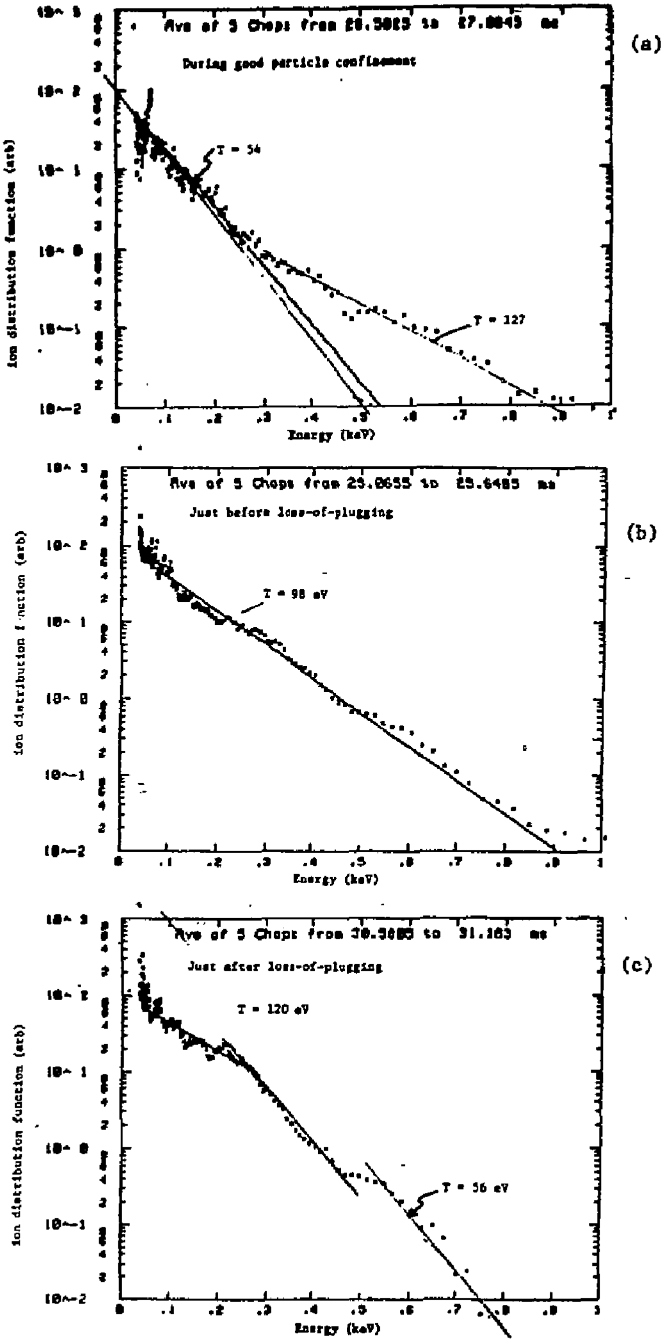

Fig. I-1. Time of Flight spectra measured with good total particle confinement (a), just before loss of plugging (b), and just after loss of plugging (c).

Measured axial potential profile for shot 18 on 13 March, 1986

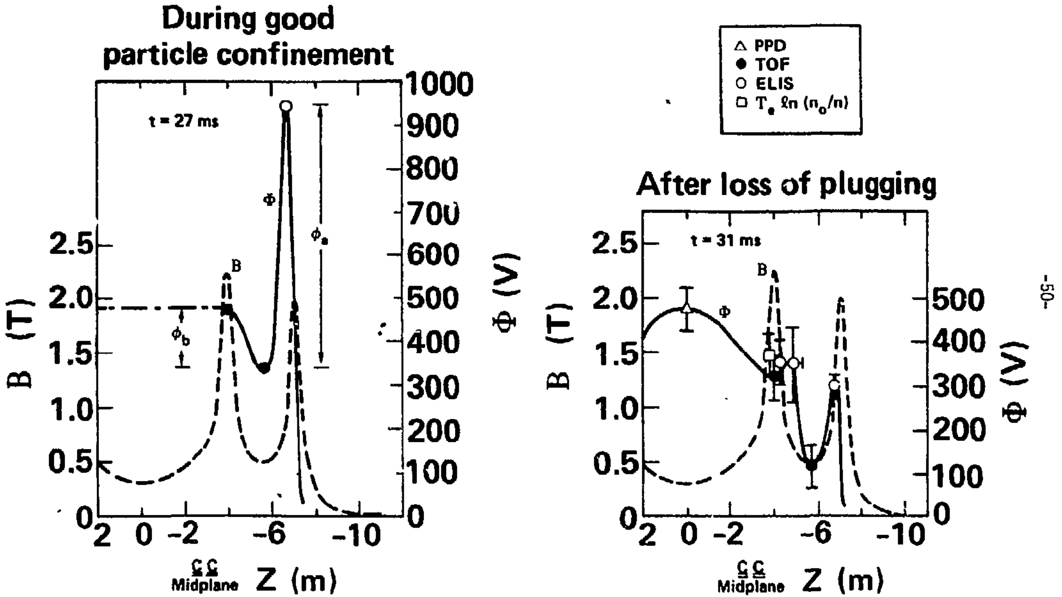

Figure 1-2.

the potential difference between the barrier and the plug would be 650 V as shown in Fig. I-2(a). The TOF spectrum just before loss of plugging (Fig. I-1(a)) indicates a single Maxwellian distribution, suggesting the barrier-trapped ions are in equilibrium with the passing ions, i.e. the barrier has filled in. Since there are no breaks in this spectrum, we are unable to determine either the thermal barrier depth or the ion confining potential. After the loss of plugging, the passing ions appear in the spectrum above 550 eV. The break in the spectrum at 550 eV is a measure of the potential difference between the inner mirror and the barrier. The ions confined in the barrier appear up to energies of 280 eV. The break at 280 eV is then a measure of the potential which confines these ions, i.e. the potential difference between the barrier and the outer potential maximum.

During plugging, the potential inferred from the data (Fig. I-2a) is qualitatively that which is expected in thermal barrier operation. The thermal barrier depth of 90 V is fairly small. The central cell electron temperature measured after the loss of plugging on the shot shown in Fig. I-1 was 115 eV. Although not measured at any other time on this shot, we typically find the electron temperature to be lower during plugging. Hence, it is reasonable to conclude that the thermal barrier depth is only $1 \leq \delta\phi_b/T_{ec} \leq 2$, i.e., a very shallow barrier. The potential difference between the inner mirror and the barrier is somewhat higher after the loss of plugging as is the temperature of the ions confined in the barrier. The ratio of the barrier depth to the temperature of the ions remains roughly constant, but is slightly higher during plugging. This is consistent with a weakly pumped barrier in which the barrier depth is only 1-2 times the confined ion temperature.

The ion confining potential is very large during the period with good axial confinement. As discussed above, the confining potential indicated in Fig. I-2(a) is a lower limit, reflecting the fact that we did not observe the phase space boundary on the TOF spectrum up to an ion energy of 1 keV. This high confining potential can be maintained if the fundamental ECH power is high enough that diffusion by the ECH dominates over collisional diffusion for the electrons confined in the plug. As the central cell density increases, the plug density also increases because of the weak barrier pumping. Hence, as the central cell density increases, collisional diffusion of the plug electrons becomes more important while ECH diffusion decreases for fixed ECH power. This would then lead to a loss of the ion confining potential as is seen in Fig. I-2(b). This model suggests that the loss of plugging arises from a combination of weak barrier ion pumping, and low ECH power.

We have modeled the ion distribution in the barrier using the multiregion Fokker-Planck code SMOKE. In this calculation we specify the passing ion density and temperature at the inner mirror, and calculate the barrier-trapped and sloshing ion densities and distribution functions consistent with the anchor gas pressure and sloshing beam current. We have also included an anomalous sloshing ion loss rate, which provides the barrier pumping. The result, for the distribution while plugged, is shown in Fig. I-3. The temperature of the passing ions is specified to be that obtained from the TOF spectrum shown in Fig. I-1(a), T_{ic} = 0.125 keV. We show the calculated TOF spectrum in Fig. I-3(b). This spectrum agrees well with the experimentally determined spectrum. The phase-space distribution function shown in Fig. I-3(a) indicates that the ion distribution is partially pumped. The calculated TOF spectrum for the condition extant just before loss-of-plugging is shown in Fig. I-4. In this case, the passing ion density is higher, and the passing ion temperature is slightly lower. As before, the calculated TOF spectrum (Fig. I-4(b)) agrees well with the measured one (Fig. I-1(a)). The phase-space distribution shown in Fig. I-4(a) indicates that the barrier trapped ions are nearly in equilibrium with the passing ions. This suggests that the pumping provided by the sloshing beams is ineffective against the collisional filling rate from the higher passing ion density.

These initial results not only indicate that the diagnostics in TMX-U are capable of determining the axial potential profile, but they also indicate a possible mechanism for the loss of plugging. If early experiments on the next experimental cycle confirm the importance of collisional barrier filling, we must control the rate of rise of the central cell density to enable the central cell heating systems (ICH and beams) to heat the ions and hence control the barrier filling rate. We have examined these effects in the past, but the availability of the barrier-trapped ion distribution function permit a more effective experimental study. Direct measurements of the passing ion distribution permit more detailed control of the central cell heating and fueling rate to better match the collisional filling rate with the available pumping speed. This should permit achieving a higher central cell density for a given barrier density. Furthermore, an ability to better match the filling

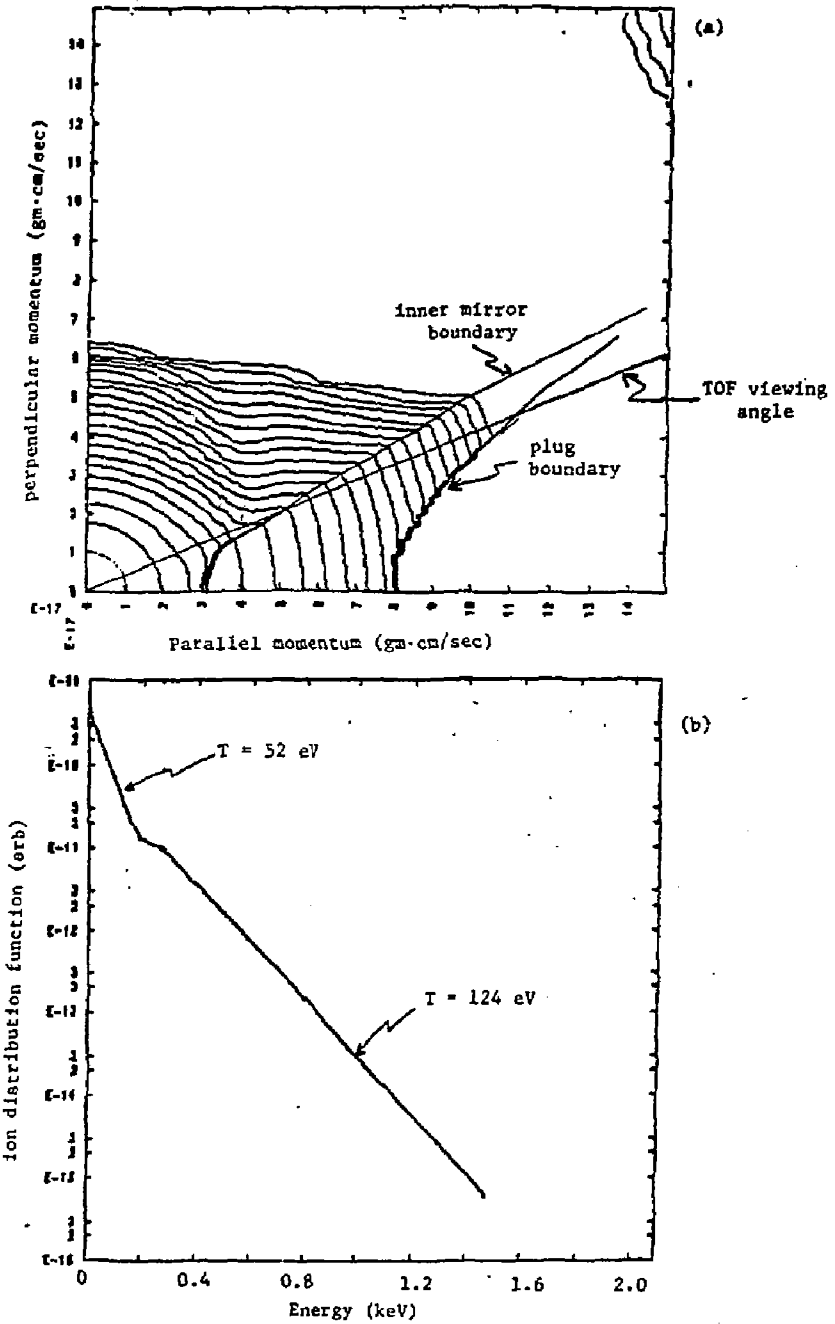

Fig. I-3 Fokker-Planck simulation of the time-of-flight spectrom measured during good total particle confinement. (a) Contour plot of the local distribution function at the barrier. (b) Ion distribution function along the time-of-flight viewing angle.

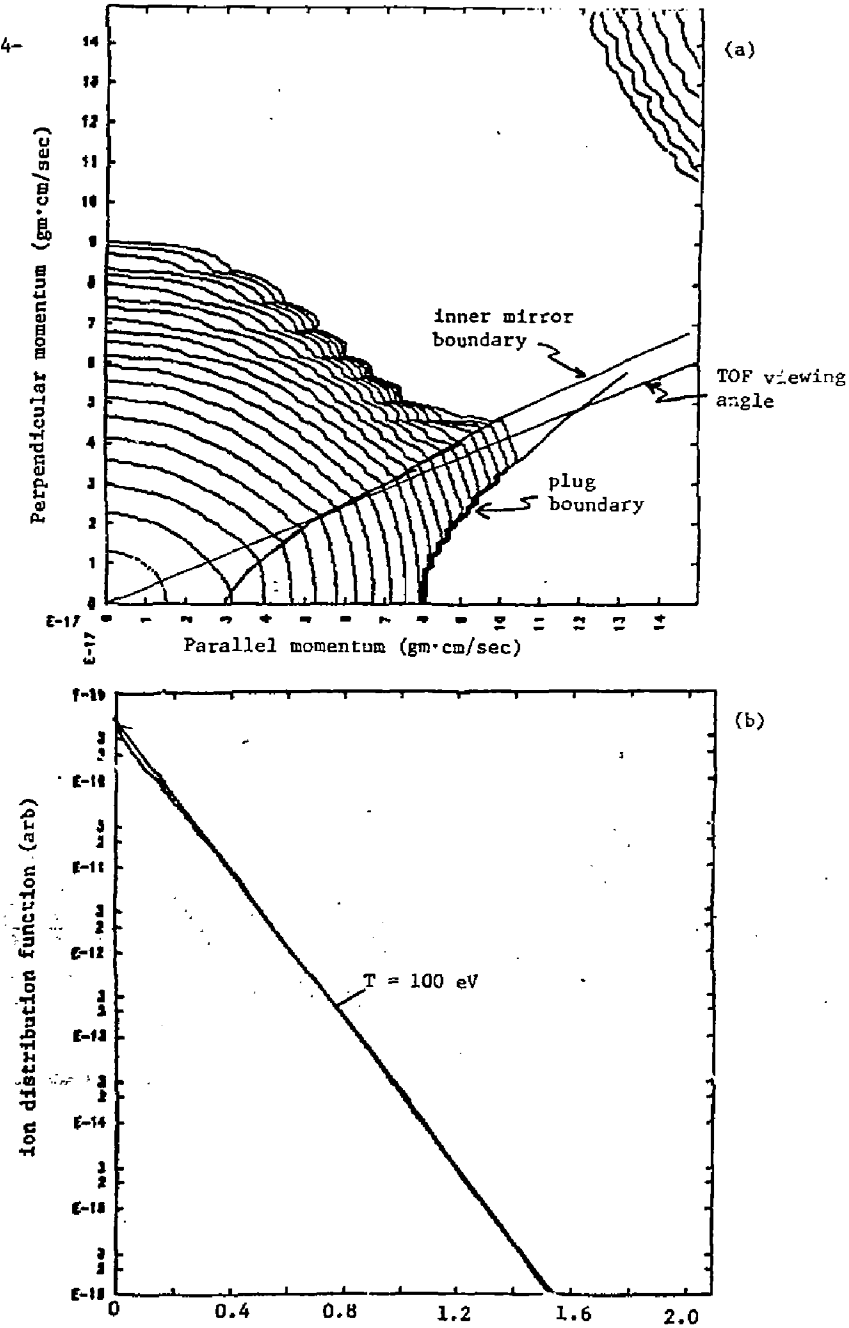

Fig. I-4. Fokker-Planck simulation of the time-of-flight spectrom measured just before loss of plugging. (a) Same as in Fig. I-3. (b) Same as in Fig. I-3.

and pumping rates may permit operation with deeper thermal barriers than indicated in Fig. I-2(a), thus permitting better utilization of the fundamental ECH power, and hence plugging at higher barrier densities.

APPENDIX II: OUTLINE OF TMX-U EXPERIMENTS FOR DETERMINING CAUSES OF LOP

We believe that the following physics issues are important to understanding the loss of plugging (LOP) phenomena in TMX-U. We expect that the majority of the experiments addressing these issues will be performed under plugged conditions, but allow that some investigations will require an initial period of experimentation without plugging before meaningful plugged experiments can be performed.

We also recognize our responsibilities to the graduate students (4) who are presently finishing their dissertations on TMX-U. Some of the experiments performed before September 31, 1986 will be dedicated to their needs.

We direct the reader to Fig. 7 of the milestone section of this report for the experimental program which will investigate the following physics issues under Milestone 2.

The following outline has the format:

I. Topic area
  A. Physics issue
    1. Classification of physics issue
      a. Detail of physics issue
        i. Experiment
          Date scheduled (See Fig. 7)

I. The fraction of mirror confined (hot) electrons at the barrier midplane is too small .

  A. The thermal barrier is filling with cold ions .
    1. The filling process is classical, i.e., collisional processes determine the filling rate.
      a. The central-cell passing ions are filling barrier.
        i. Modulate the passing ion density and temperature by modulating ICH power
          August 1986.
        ii. Scan the ICH power and the central cell gas feed to vary the inner mirror density and T_i.
          January 1987

        - b. Charge Exchange of the sloshing ions is filling the barrier.
            - i. Puff gas into the plug to vary the sloshing ion charge exchange rate.
              August 1986
            - ii. Measure the ionization rate at the plug midplane with an H-alpha camera
              August 1986
        - c. Impurities are accumulating in the barrier.
            - i. Monitor/inject impurities into barrier.
    - 2. The barrier filling rate is anomalous.
            - i. Reduce the central cell ICH power coupled into the plugs by changing the central cell magnetic field profile.
            - ii. Monitor plasma instabilities
- B. The hot electron fueling is insufficient to maintain a large fraction of hot electrons in the barrier.
    - 1. The large, plasma beta generated by the hot electrons shifts the cold plasma resonance magnetic field outside the ECH wave pattern.
            - i. Re-aim the 5kG (barrier) power towards a larger vacuum magnetic field
              September 1986
            - ii. Synchronize the magnetic field to the beta shift
    - 2. Either the 5 kG (barrier) or 10kG (plug) ECH power is insufficient.
        - a. The 10 kG power is absorbed on plasma edge and does not penetrate to plasma core.
            - i. Vary timing of 10 kG and 5 kG ECH and sloshing ion beams and monitor the radial profile of the X-Ray emission with the X-Ray camera.
            - ii. Modulate the 5 kG (barrier) and the 10 kG (plug) ECH to determine the relative importance of each in the formation of mirror confined electrons and cavity ECH fields.

  - b. The central cell density rises too quickly during plugging so that the available 5kG (barrier) ECH power can not create and heat hot electrons at the same rate.
    - i. Control the central cell fueling rate. Use feedback control of the central cell gas feed as necessary. July 1986 and January 1987
  - c. The central cell electron temperature (T_{ec}) is too low.
    - i. See section on T_{ec}
- 3. Based on potential measurements, the barrier is so deep that the central cell electrons can not reach either ECH resonance, so there is no source of hot electrons from the central cell
    - i. Puff gas into the plug and barrier regions to supply a source of cold electrons
      August 1986
    - ii. Vary aiming of 5kG ECH
      September 1986
    - iii. Create a second source of hot electrons on the central cell side of the plug using the inner, 10kG ECH system
    - iv. Modulate the 5 kG (barrier) and the 10 kG (plug) ECH to determine the relative importance of each in the formation of mirror confined electrons and cavity ECH fields.

II. Sloshing ion axial profile and lifetime

- A. Large potentials move sloshing ions away from a point so there is no density at the 10 kG ECH resonance
    - i. Use 18GHz heating in plugs
      September 1986
- B. The 10 kG ECH power (per unit sloshing ion) is too low
    - i. Scan 10kG ECH power and central cell gas
      August 1986
    - ii. Re-install Vlasov type ECH antennas
      Optional - October 1986

C. Sloshing ion density is too low because of anomalous losses
    i. Scan the sloshing ion beam current, both 40 and 47 degree beams
    January 1987
    ii. Monitor the sloshing ion lifetime versus the plug potential to determine if the sloshing ion orbit is being distorted by the DC electric fields in the plugs (makes sloshing ions more susceptible to charge exchange on background gas).
    iii. Monitor the plug instabilities, in particular look for the Post-Rosenbluth convective loss-cone mode near the outer sloshing ion turning point.

D. Sloshing ion density is low because of charge exchange
    i. Puff gas into the plugs
    August 1986

III. Loss of plugging occurs because T_{ec} is low. The available plug ECH power is not sufficient to heat electrons out of the plug potential peak as quickly as they collisionally scatter into the potential peak. This causes the plugging potential to be small

1. The low electron temperature can be explained by a classical power balance.
    i. Scan 10kG ECH power and central cell gas
    August 1986
    ii. Re-install Vlasov-type ECH antennas
    Optional - October 1986
    iii. While plugged, use the central cell neutral beams and/or the central-cell 18GHz to provide a heat pulse. Then measure/calculate the change in electron temperature.
    February 1987

2. Ambipolar losses cause a large electron heat loss.
    i. Monitor ionization rate and compare it to the measured axial and non-ambipolar radial loss rates. Adjust the machine operation to eliminate ambipolar losses (as done previously).

        - ii. Monitor MHD and trapped particle modes/look for fluctuation induced transport
    - 3. Radial electron energy transport is anomalously large.
        - i. Perform heat pulse experiment outlined above (III-1iii.).

          February 1987

IV. Non-conventional reasons for LOP

- 1. Inner potential peak required to reduce barrier filling
    - i. Re-aim 5kG ECH toward central cell side of plug midplane
- 2. Axial potential profile not as expected
    - i. Puff gas at outer sloshing ion turning point to create a source of cold electrons
    - ii. Vary the aiming of the 5kG (barrier)ECH
- 3. Plasma Instabilities
    - i. Trapped particle mode and/or MHD resulting from ineffective hot electron anchoring/stabilization
    - ii. Instability of the mirror confined (ICH or beams) central cell ions

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