1. Purpose of Experiments

Include immediate goal of the experiments, scientific importance and/or programatic relevance. Refer to any relevant program milestones.

In low-density ohmically heated plasmas, the global energy confinement time appears to increase linearly with density, known as “Alcator scaling” [1]. The “neo-Alcator scaling,” describing the results of twelve facilities, is given by (MKS units with confinement time in ms) [2]

$$\tau_{E}^{\text{neo Alc}} = 192 \tilde{n}_{e20} R^{2.04} a^{1.04} \kappa^{0.5}.$$ 

Another version had an explicit $nq$ dependence [3],

$$\tau_{E}^{\text{neo Alc}} = 70 \tilde{n}_{e20} q R^{2} a^{0.5} \kappa^{0.5}.$$ 

On the other hand, density does not enter the dimensionless $\delta f$ gyrokinetic-Maxwell equations, except through the collision frequency (suggesting the role of trapped electrons). The purpose of this experiment is to determine whether the plasma energy confinement time really does increase linearly with density, or only appears to. Strong variations in
$T_i/T_e$, collision frequency, $Z_{\text{eff}}$ and profile shape accompany the change in density are observed and would produce a qualitatively consistent variation of $\tau_E$ if TEM or ITG/TEM modes dominate the electron thermal transport. Increased density profile peaking at low densities could also vary turbulent transport consistently when the trapped electron drive is significant.

These experiments will use mode conversion electron heating to directly heat bulk thermal electrons, decoupling $T_i/T_e$ and electron collision frequency from changes in density, to obtain separate scalings with each parameter. This will provide new information along several axes.

Through detailed transport analysis, gyrokinetic simulations, and comparisons with fluctuation measurements using synthetic diagnostics \[4\], we expect this work to clarify the physics mechanisms underlying neo-Alcator scaling, which is on the surface a surprising result. Further, this regime is dominated by electron channel heating and transport, which remains poorly understood relative to ion channel transport. Studies of electron thermal transport in C-Mod, DIII-D, and NSTX are a focus of the newly funded SciDAC Center for the Study of Plasma Microturbulence, in which the author is the MIT PI.

Gyrokinetic simulations using the codes GS2 and GYRO, as well as flux-driven gyrokinetic transport simulations, will be carried out and directly compared with measured and inferred transport, fluctuations, and profiles. Validation of gyrokinetic codes against experiments has become a high priority activity in the U.S. fusion program. This work also contributes directly to the 2012 Joint Research Target: Conduct experiments on major fusion facilities leading toward improved understanding of core transport and enhanced capability to predict core temperature and density profiles. In FY 2012, FES will assess the level of agreement between predictions from theoretical and computational transport models and the available experimental measurements of core profiles, fluxes and fluctuations. The research is expected to exploit the diagnostic capabilities of the facilities (Alcator C-Mod, DIII-D, NSTX) along with their abilities to run in both unique and overlapping regimes. The work will emphasize simultaneous comparison of model predictions with experimental energy, particle and impurity transport levels and fluctuations in various regimes, including those regimes with significant excitation of electron modes. The results achieved will be used to improve confidence in transport models used for extrapolations to planned ITER operation. (draft)

**REVISIONS 9/6/11**

This proposal was presented at the C-Mod 2011 Ideas Forum, submitted 2/4/11, and presented and discussed at the weekly Turbulence Users Group meeting on 2/15/11. The most important revision is the addition of ICRF hydrogen minority heating. We have made the following revisions, as detailed below.
1. Purpose of Experiments

The goals of this MP are to understand the physics of electron transport in the neo-Alcator scaling regime, and to understand the mechanisms for the apparent density scaling.

We have included MP653 in the following proposals as a key part of our work:

SciDAC Center for the Study of Plasma Microturbulence (funded)
MIT PSFC Theory Group three year grant renewal (under review).

INCITE proposal: Validation Studies of Multiscale Plasma Turbulence (under review).

In the original proposal, dated 2/4/11, we suggested the density change induced toroidal flow reversals could occur at the transition from neo-Alcator scaling to saturated ohmic confinement (LOC to SOC transition), and that this could alter the interpretation (but did not seem likely). On 2/8/11 John Rice presented results at the weekly C-Mod meeting showing that in fact the flow reversals occur at the LOC to SOC transition. He used data from the same MP571 run day, conducted by M. Porkolab, as shown in our Fig. 1. In the seven months since this MP was submitted, these results have been published [5]. I was not given the opportunity to be a coauthor on this important paper, so for the sake of preserving originality, I wish to point out that it also contains a figure very similar to Figure 1 of this MP, with a similar aim.

The fact that the flow reversals occur at the confinement transition may be related to a change of the dominant instability from TEM to ITG, consistent with previous (qualitative) published work on the LOC to SOC transition. The dominance of TEM turbulence in the neo-Alcator regime would be consistent with the observed scalings, as we originally suggested.

Given the above, we should observe flow reversals at constant density, while heating electrons. If we begin at a density just above the transition, raising $T_e$ could change the dominant instability from ITG to TEM, resulting in a flow reversal. We have modified the run plan slightly to include this test.

Finally, ICRF mode conversion heating can drive significant flows that could mask flow reversals. In addition, while TORIC simulations of modulated mode conversion heating match heat deposition profiles measured from a break in slope analysis of $T_e$ reasonably well, a large discrepancy between simulations and PCI measurements of mode converted wave intensity exists.

The effect of ion dilution has been recently discussed by Dorris & Porkolab. Ion dilution is generally a stabilizing effect in gyrokinetic simulations. It is very important to understand the plasma composition to make quantitative comparisons with gyrokinetic simulations. On the other hand, dilution would yield a trend in the wrong direction to explain neo-Alcator scaling, given that $Z_{\text{eff}}$ decreases as density increases, while confinement improves. Nathan Howard has developed a technique for constraining the dilution which we plan to use in our analysis.
The issue of dilution by the 8-15% $^3$He needed for mode conversion heating has also been raised. We can write down qualitative expressions for the scaling of the linear growth rate with charge, mass, and dilution. In the case of heavy impurities which do not play a significant role in the dynamics, dilution is the main effect and is stabilizing. In the case of lighter impurities such as $^3$He, which have $Z > 1$, the net effect could be moderately destabilizing. Prior to conducting the experiment, we will carry out gyrokinetic simulations to investigate this effect.

For these reasons, we have added additional scans using ICRH minority heating.

To accommodate the minority ICRH comparison, we have added a third run-day. To reduce run-time, the 7.9T day could be sacrificed at the cost of having sawteeth within 40% of the minor radius, which impact the analysis. If extra run time is available, we would consider adding a day with lower hybrid heating.

Finally, because of the possibility that one or two chords of ECE fluctuation measurements may be available, and because ongoing studies by M. Porkolab and students are related, we have added Anne White and M. Porkolab to the author list.

end REVISIONS 9/6/11

2. Background

Discuss Physics basis of the proposed research, Prior results at Alcator or elsewhere, and any related work being carried out separately

This experiment builds on previous mini-proposals 400a, 571 and 602, which were focused on electron thermal transport (for a recent review of electron loss dominated experiments and simulation, see Ref. [6]. MP400a was an ohmic density scan intended to reproduce neo-Alcator scaling with fluctuation measurements, with the intent of using low density as a way to obtain an electron loss dominated regime with $T_e > T_i$. MP571 was a similar ohmically heated density scan with improved diagnostic coverage, while MP602 was a study of fluctuations and electron particle and thermal transport in ITB’s controlled by on-axis heating (with emphasis on TEM turbulence).

Figure 1 shows the results of data mined from the Lin/Porkolab 1091215 run for MP571, with TRANSP runs kindly provided by J. Dorris. This scan was chosen primarily because it has inverted HIREX Sr. $T_i$ data (the neutron $T_i$ data is subject to an uncertain $Z_{\text{eff}}$). The upper left frame shows the energy confinement time (from both EFIT and from TRANSP) increases linearly with line integrated density. However, several other important variables also show strong linear variation. The parameter $T_e/T_i$ decreases by a factor of two over the scan, while the electron collision frequency increases nearly a factor of five. Both parameters are well-known in drift-wave linear stability theory, and have also been emphasized in recent nonlinear gyrofluid and gyrokinetic work. The transport is expected to have a gyro-Bohm scaling $\chi \propto T_i^{3/2}$. However, as shown, $T_i$ remains relatively constant, so the important parameter becomes $T_e/T_i$. The effects of both $\nu_e R/v_{\text{thi}}$ and $T_e/T_i$ on toroidal ITG/TEM turbulent transport are qualitatively consistent with the observed increase in $\tau_E$. The trend in $T_e/T_i$ is opposite that for ETG dominated transport, but in that case, $T_e^{3/2}$ would enter through gyroBohm scaling, producing a consistent trend.
In addition, the parameter $Z_{\text{eff}}$ varies inversely with density, which would produce a weaker, opposite variation for ITG/TEM transport. In essence, neo-Alcator scaling could be an artifact of the strong variations in $T_e/T_i$ and/or $\nu_e R/v_{thi}$ with density, assuming ion-scale ITG/TEM turbulence dominates.

The present study is intended to complement ongoing validation efforts by M. Porkolab and J. Dorris (MP571, and Refs. [7, 8]). Some of their work focuses on comparisons of GYRO and TGLF codes with C-Mod ohmically heated density scan experiments, and the possible influence of the electron parallel drift velocity associated with the ohmic current. They found good consistency between GYRO simulated fluctuation levels due to ITG turbulence in the saturated ohmic confinement and H-Mode regimes. However, they found GYRO underestimated electron thermal transport while overestimating ion thermal transport at low densities, where the global confinement time increases with density [7, 8]. To the extent we are aware, their current work focuses on further analysis of this apparent discrepancy. We aim to avoid duplication of any effort having a defined scope and presently underway, and will coordinate where possible with such efforts. If successful, we plan one or more publications emphasizing the above mechanisms for neo-Alcator scaling rather than validation per se.
3. Approach

Describe the methodology to be employed; explain the rationale for the choice of parameters, etc. Describe the analysis techniques to be employed in interpreting the data, if applicable. If the approach is standard or otherwise self-evident, this section may be absorbed into the Experimental Plan.

This experiment will use mode conversion heating of electrons to decouple density, $T_e/T_i$, and collision frequency. Mode conversion ICRF heating [9] is ideal because it heats bulk electrons directly and instantaneously via Landau damping of Ion Bernstein waves. This allows us to directly measure the radial power deposition profile by observing the rate of $T_e$ rise from well-resolved fast ECE measurements during RF or sawtooth modulation. This will remove a significant uncertainty from the analysis, particularly for flux-driven simulations, which depend on the accuracy of the power deposition profile. Second, mode conversion heating does not produce fast particles that would need to be accounted for in the gyrokinetic simulations or in the plasma stored energy. Third, demonstrated mode conversion heating scenarios [9] provide on-axis heating at each of our desired magnetic fields, 7.9 T / 80 MHz and 5.4 T / 50 MHz. Finally, mode conversion heating is effective over a wide range of densities, and the required $^3$He fraction is independent of density.

Three scans will be performed (see Fig. 2):

Scan 1: vary density and collisionality at constant $T_e/T_i$

Scan 2: vary $T_e/T_i$ and collisionality at constant density

Scan 3: vary density without auxiliary heating

The results will yield separate scalings of $\tau_E$ with density, $T_e/T_i$, and normalized collision frequency.

Figure 2. Proposed scans. Gray: Scan (1); Orange: Scan (2).
Power Requirements and H-Mode Threshold

Next, we turn to estimating the power requirements for these scans. As a rough estimate, we find the following relation holds for the scan shown in Fig. 1:

\[ n_{el20}(T_{e0} + T_{i0}) \simeq (\mu \kappa a/V_p) (P_{oh} + P_{aux}) \tau_E \]

where \( \mu \kappa a/V_p = 0.06 \) if temperatures are in keV, powers are in MW, and the confinement time \( \tau_E \) is in ms. The power \( P_{aux} \) required to maintain constant \( T_e/T_i \), while density varies over the same range, is given approximately by

\[ 0.6(2.7 + 1.3) = 0.06 (1.2 + P_{aux})(10) \]

if we assume \( \tau_E = 10 \) ms, corresponding to the lowest density. This yields \( P_{aux} < 2.3 \) MW. This would drop to 1.16 MW if \( \tau_E = 20 \) ms. Scan (2) requires raising \( T_{a0} \) by \( \sim 1 \) keV at \( n_{el20} \sim 0.4 \), where \( \tau_E \sim 15 \) ms, which would require \( P_{aux} < 0.6 \) MW. The ohmic heating power remains close to 1.2 MW throughout the scan, so the total heating power would be

\[ P_{oh} + P_{aux} < 2.36 \text{ MW} \]

for all scans, assuming \( \tau_E = 20 \text{ ms} \) at the highest density for Scan (1).

The ohmic H-mode threshold scaling is approximately \( P_{th}^{LH}/(B_T n_{e20}) \sim 0.03 \text{ MW m}^{-3} \text{ T}^{-1} \). However, it is to our advantage that \( P_{th}^{LH} \) is higher at low densities [10]. At 5.3 T 0.8 MA with \( n_{e20} \sim 1.0 \), the threshold is \( P_{th}^{LH} \sim 2.7 \text{ MW} \), but at higher densities, \( n_{e20} \sim 1.5 \), the threshold is \( P_{th}^{LH} \sim 1.7 \text{ MW} \). Accordingly, we expect little difficulty staying out of H-mode as we add heating power, even for a lower single null configuration. This holds true particularly for 7.9 T operation. If H-mode onset becomes an issue, we have the option of using unfavorable drift (upper single null), in addition to limiting on the inner wall.

Sawteeth

Sawteeth often complicate transport analysis and the comparison with gyrokinetic simulations. Because the profile measurements other than ECE \( T_e \) generally do not resolve sawteeth, the profiles are often averaged over the sawtooth period. One way to reduce the impact of sawteeth is to move the inversion radius as close to the magnetic axis as possible, so that the size of the sawtooth heat pulse is minimized. Operation at high toroidal field and reduced plasma current raises the edge safety factor, and moves the \( q = 1 \) radius inward. We have performed a database search of all ohmic discharges at high magnetic field and low current, covering 20,000 shots from 1998 onward. We did not find any cases without sawteeth in the ohmic phase. Selecting a handful of discharges representing a range of \( q_{95} \) from 3 to 10, we have plotted the normalized midplane minor radius of the EFIT \( q = 1 \) surface. We note this is somewhat artificial from EFIT, and we plan to update this plot with actual inversion radius data. The plot merely reflects the fact that \( q_0 \sim 1 \) and therefore the \( q = 1 \) radius decreases with \( q_{95} \). We have also shown the sawtooth period from ECE data, and the peak-to-peak relative amplitude of sawteeth from ECE.
data in Fig. 3. The $q = 1$ normalized midplane minor radius correlates well with $q_{95}$, as does the sawtooth period, while the sawtooth relative amplitude shows little correlation with $q_{95}$. The MP571 point at 5.4 T, 1.0 MA is the leftmost, lowest $q_{95} \sim 3$, having a sawtooth radius almost 40% of the cross-section. Apparently we can reduce the impact of sawteeth significantly by raising $B_T$ and/or lowering $I_p$ to reach $q_{95} > 7$, reducing the sawtooth radius to 12-15% of the cross-section, with less improvement beyond this. For the discharges considered, $q_{95} = 0.64 B_T(T)/I_p(MA)$.

![Graphs showing EFIT $q = 1$ surface $r_{mid}/a$, sawtooth period, and sawtooth relative amplitude vs. EFIT $q_{95}$](image)

**Figure 3.** EFIT $q = 1$ surface $r_{mid}/a$, sawtooth period, and sawtooth relative amplitude vs. EFIT $q_{95}$
Scenarios

We will perform the scans at two magnetic fields (and therefore with two RF frequencies).

The first scenario will be at 5.4 T, 500 kA and 1 MA, $q_{95}=6.9$ and 3.45. This field provides excellent ECE coverage to determine the heating profile. The first run day will utilize minority ICRF heating. The second scenario will use 7.9 T, 500 kA and 1 MA, $q_{95}=10$ and 5. Mode conversion heating is approximately on-axis at 80 MHz in this scenario, requiring no frequency changes. Further, the H-mode threshold is higher than at 5.4 T.

Mode conversion heating is on-axis at 50 MHz at 5.4 T (requiring the J-port RF antenna frequency to be changed from 80 MHz to 50 MHz). We will modulate the RF power to allow measurement of the $T_e(r)$ rate of rise from mode conversion heating. The lower current will not be a problem for mode conversion heating, as we are not relying on a minority ion tail, and are not particularly concerned about fast ion confinement.

<table>
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<th>$B_T$ (T)</th>
<th>$I_p$ (MA)</th>
<th>$q_{95}$</th>
<th>$\tau_{q=1}^{mid}$ (EFIT)</th>
<th>$\frac{\Delta T_e}{T_{e0}}$ (m/s)</th>
<th>$\tau_{saw}$ (ms)</th>
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Table 1. Sawtooth data used to make Fig. 3.
4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

Toroidal Field: 5.4, 7.9 T
Plasma Current: 1.0 MA, 0.5 MA
Working gas species: D2 with 15-20% $^3$He
Density: Flat top $n_{l04} \sim 0.2$ to $1.0 \times 10^{20}$ m$^{-3}$
Boronization: two nights prior, very important to reduce $Z_{eff}$ at low densities
Equilibrium configuration (if possible, refer to database equilibria): 1101119022, 1091215028, 1030604032

4.2 Auxiliary Systems

RF Power, pulse length, phasing: separate days: 1.5 MW 50 MHz, 1.5 MW 80 MHz, 180 deg. phasing
Pellet Injection (species):
Impurity blow-off injection: yes
Diagnostic Neutral Beam: yes
Special gas puffing: $^3$He for mode conversion heating (110 - 180 ms puff); 40 ms Ar puffs; D2 NINJA puffs for GPI and CXRS
Cyropump: yes
Non-axisymmetric Coils (Connections,Current):
Other:

4.3 Diagnostics

List required diagnostics, and any special setup or configuration, e.g. non-standard digitization rate.

ECE full radial coverage (GPC or FRC for mode conversion heating core power deposition).
CECE as available
MSE
HIREX Sr. full profile coverage
CXRS (both NINJA and DNB systems, core and edge).
PCI without mask (may reconsider).
GPI, edge thermocouples.
Reflectometry
Mirnovs
Fast TCI (desired)
Soft and Hard Xrays
Thomson scattering, core and edge
VB for \( Z_{\text{eff}} \)
XTOMO
Bolometers, AXUV
ZEUS coverage
Fast Ion Charge Exchange
Active MHD QC mode antenna in passive detection mode

We will have useful MSE measurements at densities up to \( n_{\text{el20}} < 0.6 \), which will aid the interpretation in the event magnetic shear varies. The ECE profile coverage will not be as good at 7.9 T as it is as 5.4 T. PCI will be set up with the mask and with heterodyning to simultaneously measure RF and turbulence. We will also use Fast Ion Charge Exchange to monitor RF for comparison with TORIC. The LH reflectometer could be useful for either edge fluctuations or edge density. We would like to have ZEUS monitoring to watch for impurity injections from the RF antenna. Edge turbulence diagnostics play a crucial role in discriminating core turbulence from edge turbulence in PCI. At low current, the effectiveness of the PCI mask will be reduced. The CECE diagnostic is beginning to produce data and should be functioning.

5. Experimental Plan
(revised 1/11/12) Both sections must be filled in.

5.1 Run sequence plan
Specify total number of runs required, and any special requirements, such as consecutive days, no Monday runs, extended run period (10 hours maximum), etc.

This experiment supports JRT2012.

This revised plan addresses the EPC recommendation from 9/7/11:

“prioritize shot plan probably more than can be done for each day, consider higher (than 0.35 MA) operation”

We have reduced the number of good shots required for each day to \( \sim 20 \). In addition, we have prioritized the run days to account for the available J-port power and likelihood of an RF frequency change.
As we pointed out in the original version of this MP a year ago, an apparent density scaling can only arise through collisionality or other “hidden variables” which correlate with density. According to recent multi-machine studies by Rice and others, the rotation reversal and LOC-SOC transition appears to scale with electron collisionality, \( \nu_\ast \propto qR Z_{\text{eff}} n_e T_e^2 \), and appears to occur for \( \nu_\ast \sim 0.4 \). This experiment will clarify the role of collisionality in the LOC regime and separate the effects of \( T_e/T_i \) and density from collisionality. It will also investigate the effect of electron heating and associated transitions from ITG to TEM regimes \([11, 4]\) on rotation reversals. The \( q \) dependence has motivated us to keep the same current at higher magnetic field, increasing \( q_{95} \) by 50%, instead of maintaining constant \( q \). This should change both the slope of the LOC scaling curve and the LOC-SOC transition density by 50%. A brief foray into 1.0 MA at these toroidal fields will further expand this space.

Three run days are planned:

Day 1: 5.4 T, 80 MHz, 500 kA H-minority ICRH
Day 2: 7.9 T, 78 MHz, 500 kA He3 Mode Conversion ICRH, extended run day
Day 3: 5.4 T, 50 MHz, 500 kA He3 Mode Conversion ICRH

Three scans will be performed (see Fig. 2):

Scan 1: vary density and collisionality at constant \( T_e/T_i \)
Scan 2: vary \( T_e/T_i \) and collisionality at constant density
Scan 3: vary density without auxiliary heating

The results will yield separate scalings of \( \tau_E \) with density, \( T_e/T_i \), and normalized collision frequency.

Establish operation at 5.4 T, 500 kA, \( n_{e\text{el}20} = 0.4 \). Perform Scan 3 (ohmic density scan) before we use RF and introduce more impurities into the machine. Scan through LOC (linear ohmic confinement) to SOC (saturated ohmic confinement) transition. Near the transition, perform a density ramp to find the flow reversal density.

We will then add heating at \( n_{e\text{el}20} = 0.4 \). Following optimization of the RF, we will carry out Scan 2 (RF power scan at constant density). To prepare for Scan 1 (density scan at constant \( T_e/T_i \)), we will use the data from Scan 3 (ohmic density scan) together with a discharge at higher density, which ramps the RF power on successive modulation pulses. Observing the value of \( T_e/T_i \) at \( n_{e\text{el}20} = 0.2 \), and the power required to reach this same value of \( T_e/T_i \) at \( n_{e\text{el}20} = 1.0 \), we will interpolate to find the power required to maintain this value of \( T_e/T_i \) at each density. We will then carry out Scan 1 (constant \( T_e/T_i \)) and optimize the RF power at each density if needed.

We may choose to have the PCI mask on and rotated for full cross-section viewing. In the event rotation reversals are observed, the we could rotate the mask and repeat. This is our only means of identifying the mode propagation direction.

The 7.9 T run day will proceed in the same way and in the same sequence, but some scans may have to be reduced depending on the number of available shots.

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5.2 Shot sequence plan

For each run day, give detailed specification for proposed shot sequence: number of shots at each condition, specific parameters and auxiliary systems requirements, etc. Include contingency plans, if appropriate.

Day 1 (5.4 T, 80 MHz H-minority ICRH)

Shot counts given below include “good” shots only.

1) Begin with 1101119022 (USN) or 1091215028 (LSN), but at 500 kA, density \( n_{el} = 0.4 \times 10^{20} \, \text{m}^{-2} \). Add 40 ms Ar puff. (2 shots)

2) Lower density to \( n_{el20}=0.2 \) and observe temperatures. \( T_e/T_i \) at this density will be the target \( T_e/T_i \) for the scan. Locked modes may occur and will be used for HIREXSr calibration. (2 shots)

3) If locked modes have not occurred, take a locked mode shot for HIREXSr. (1 shot)

4) Complete Scan 3: scan density \( n_{el20} = 0.3, 0.4, 0.6, 0.8, 1.0 \) without RF power. (5 shots)

5) Ramp density to nail down LOC-SOC transition via rotation reversal. (1 shot)

6) Once established, begin Scan 2: RF power scan at \( n_{el20}=0.4 \). Increase RF power on successive shots: 0.4, 0.6, 0.8, 1.0, 1.6 MW. If impurity influx becomes problematic, may need to increase density and/or current. (5 shots)

RF Pulsetrain 80 ms on / 20 ms off, with DNB 40 ms on / 60 ms off, delayed 20 ms relative to RF, as shown below in Fig. 4. This timing allows a 20 ms CXRS background frame before and after the 40 ms integration time, while RF is on. Overall RF start time TBD. Observe heating profile via ECE rise, and adjust \( B_T \) for on-axis heating if needed.

![Figure 4. RF and DNB timing.](image)

7) With target density \( n_{el20} = 1.0 \), ramp RF power (with modulation) on successive modulation pulses, starting at 0.6 MW, and increasing in 0.2 MW increments. Watch for rotation reversals and spectral changes in PCI (expected). (1 shot)

Observe power required to reach the target \( T_e/T_i \) attained earlier in the ohmic case at \( n_{el20}=0.2 \). Look for rotation reversals (not expected: we are starting below
LOC-SOC transition, and further decreasing collisionality). Linearly interpolate between $n_{el20} = 0.2$ and $nel20 = 1.0$ to determine power required at each density to maintain constant $T_e/T_i$.

8) Perform Scan 1: Scan density and RF power (using the powers obtained by interpolation above), with density values $n_{el20} = 0.4$, 0.6, 0.8. Adjust powers if needed to accommodate changes in energy confinement time. (3 shots)

**Total Day 1: 20 good shots**

If time remains on Day 1:

1) Fill in remaining density values in Scan 1: $n_{el20} = 0.2$, 0.5, 1.2 (3 shots)
2) Fill in remaining powers in Scan 2: 0.2, 1.2, 1.4 MW (3 shots)
3) If rotation reversals are observed during RF power scans, increase current to 1.0 MA and repeat power scans. This will make a connection with Lower Hybrid rotation reversals, which change direction as current increases. (2 shots)

Contingency: We expect to have trouble with runaways and locked modes at the lowest densities, and also with impurities during RF. However, MP571 was successful in attaining very low densities without RF.

We will monitor x-rays and ECE for evidence of runaways. If the low densities become a problem, we may have to move the RF power scan to $n_{el20}=0.6$, and use the $T_e/T_i$ from $n_{el20}=0.3$ as the reference low density point. We will move to coarser scans if delays are encountered. We chose to boronize two nights before to avoid losing time to RF conditioning, but this could be problematic.

**Day 2 (7.9 T, 78 MHz, Mode Conversion ICRF)**

Begin with 1030604032, but at 500 kA, 7.9 T, density $n_{el} = 0.4 \times 10^{20}$ m$^{-2}$. Add 40 ms Ar puff. Proceed with essentially the same plan as for Day 1. Going to 7.9 T at constant $q$ should shift the wavelength spectrum to slightly longer wavelengths, keeping $k_y\rho_i$ const. The toroidal velocity will be stronger in the counter-current direction at larger toroidal field.

In addition, the $^3$He puff may need to be reduced to maintain 10-15% $^3$He concentration at lower densities.

1) Begin with 1101119022 (USN) or 1091215028 (LSN), but at 500 kA, density $n_{el} = 0.4 \times 10^{20}$ m$^{-2}$. Add 40 ms Ar puff. (2 shots)
2) Lower density to $n_{el20}=0.2$ and observe temperatures. $T_e/T_i$ at this density will be the target $T_e/T_i$ for the scan. Locked modes may occur and will be used for HIREXSr calibration. (2 shots)
3) If locked modes have not occurred, take a locked mode shot for HIREXSr. (1 shot)
4) Complete Scan 3: scan density $n_{el20} = 0.3$, 0.4, 0.6, 0.8, 1.0 without RF power. (5 shots)
5) Ramp density to nail down LOC-SOC transition via rotation reversal. (1 shot)
6) Return density to \( n_{\text{el}20} = 0.4 \). Add 110 to 180 ms \(^3\text{He}\) puff and modulated ICRH mode conversion heating (timing TBD based on results). (3 shots)

7) Once established, begin Scan 2: RF power scan at \( n_{\text{el}20} = 0.4 \). Increase RF power on successive shots: 0.4, 0.6, 0.8, 1.0, 1.6 MW. If impurity influx becomes problematic, may need to increase density and/or current. (5 shots)

8) With target density \( n_{\text{el}20} = 1.0 \), ramp RF power (with modulation) on successive modulation pulses, starting at 0.6 MW, and increasing in 0.2 MW increments, up to 2.0 MW. Watch for rotation reversals (expected). (1 shots)

   Observe power required to reach the target \( T_e/T_i \) attained earlier in the ohmic case at \( n_{\text{el}20} = 0.2 \). Look for rotation reversals (not expected). Linearly interpolate between \( n_{\text{el}20} = 0.2 \) and \( n_{\text{el}20} = 1.0 \) to determine power required at each density to maintain constant \( T_e/T_i \).

9) Perform Scan 1: Scan density and RF power (using the powers obtained by interpolation above), with density values \( n_{\text{el}20} = 0.4, 0.6, 0.8 \). Adjust powers if needed to accommodate changes in energy confinement time. (3 shots)

Total Day 2: **23 good shots**

If time remains on Day 2:

1) Fill in remaining density values in Scan 1: \( n_{\text{el}20} = 0.3, 0.5, 1.2 \) (3 shots)

2) Fill in remaining powers in Scan 2: 0.2, 1.2, 1.4 MW (3 shots)

3) If rotation reversals are observed during RF power scans, increase current to 1.0 MA and repeat power scans. This will make a connection with Lower Hybrid rotation reversals, which change direction as current increases. (2 shots)

**Day 3 (5.4 T, 50 MHz Mode Conversion ICRH - J port \( \leq 1.6 \text{ MW} \))**

This run day will closely follow Day 2. However, data for Scan 3 (ohmic density scan) will already be in hand from Day 1 at 5.4 T. We use the shots remaining at the end of the day to fill in any missing density values in Scan 3.

Scan 3 will be replace by an extended RF power scan at \( n_{\text{el}20} = 1.0 \).

1) Begin with 1101119022 (USN) or 1091215028 (LSN), but at 500 kA, density \( n_{\text{el}} = 0.4 \times 10^{20} \text{ m}^{-2} \). Add 40 ms Ar puff. (2 shots)

2) Lower density to \( n_{\text{el}20} = 0.2 \) and observe temperatures. \( T_e/T_i \) at this density will be the target \( T_e/T_i \) for the scan. Locked modes may occur and will be used for HIREXSr calibration. (2 shots)

3) If locked modes have not occurred, take a locked mode shot for HIREXSr. (1 shot)

4) Return density to \( n_{\text{el}20} = 0.4 \). Add 110 to 180 ms \(^3\text{He}\) puff and modulated ICRH mode conversion heating (timing TBD based on results). (3 shots)

5) Once established, begin Scan 2: RF power scan at \( n_{\text{el}20} = 0.4 \). Increase RF power on successive shots: 0.4, 0.6, 0.8, 1.0, 1.6 MW. If impurity influx becomes problematic, may need to increase density and/or current. (5 shots)
6) With target density \( n_{e120} = 1.0 \), ramp RF power (with modulation) on successive modulation pulses, starting at 0.6 MW, and increasing in 0.2 MW increments, up to 2.0 MW. Watch for rotation reversals (expected). (1 shots)

Observe power required to reach the target \( T_e/T_i \) attained earlier in the ohmic case at \( n_{e120} = 0.2 \). Look for rotation reversals (not expected). Linearly interpolate between \( n_{e120} = 0.2 \) and \( n_{e120} = 1.0 \) to determine power required at each density to maintain constant \( T_e/T_i \).

7) Perform Scan 1: Scan density and RF power (using the powers obtained by interpolation above), with density values \( n_{e120} = 0.4, 0.6, 0.8 \). Adjust powers if needed to accommodate changes in energy confinement time. (3 shots)

8) With target density \( n_{e120} = 1.4 \), ramp RF power (with modulation) on successive modulation pulses, starting at 0.6 MW, and increasing in 0.2 MW increments. Watch for rotation reversals and spectral changes in PCI (expected). (2 shots)

Total Day 3: 19 good shots

If time remains on Day 3:
1) Fill in remaining density values in Scan 1: \( n_{e120} = 0.3, 0.5, 1.2 \) (3 shots)
2) Fill in remaining powers in Scan 2: 0.2, 1.2, 1.4 MW (3 shots)
3) If rotation reversals are observed during RF power scans, increase current to 1.0 MA and repeat power scans. This will make a connection with Lower Hybrid rotation reversals, which change direction as current increases. (2 shots)

6. Anticipated Results (original 2/4/11 version)

Discuss possible experimental outcomes and implications. Indicate if the program may be expected to lead to publications, milestone completions, improved operating techniques, etc. Indicate if the experiments are intended to contribute to a joint research effort, or an external database.

This experiment supports JRT 2012.

The main results will be separate scalings of the global energy confinement time with density, \( T_e/T_i \), and normalized collision frequency. These scalings will test our hypothesis that the observed linear scaling with density is a possible artifact of the strong variations in \( T_e/T_i \) and electron collision frequency.

The experiments will be compared directly with gyrokinetic simulations, including fluctuation measurements from PCI and fast TCI, where available, with attention paid to edge fluctuations from GPI, reflectometry, Mirnov coils, and LH antenna reflectometer, where available.

One possible complication may arise from the intrinsic rotation, which increases with plasma stored energy, and also reverses at some critical density. This critical density appears at first glance to be above the density at which saturated ohmic confinement is obtained. However, if the rotation reverses near the “knee” in the \( \tau_E \) vs. density curve, and the \( E \times B \) shearing rate is comparable to the maximum linear growth rate, then an alternative interpretation arises. We believe this will not be the case, however. The mode conversion flow drive [12] may also complicate the interpretation, but only if the shearing
rate is significant. The driven toroidal flow is slightly reduced at higher magnetic field. In any case, the measured toroidal velocity can be used to obtain the radial electric field, which will then be included in the gyrokinetic simulations if significant.
7. References

Include references both to external and internal literature or communications which bear on this proposal. See Section 2.


