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

The purpose of these experiments is to characterize the necessary parameters to obtain I-mode (a.k.a. enhanced L-mode) while documenting I-mode plasma characteristics and optimizing I-mode towards its application in Alcator C-Mod for high confinement at low density. The experiment will focus on expanding the available I-mode operating space by exploring the effects of shaping, density, $q_{95}$, and $I_p$ with a goal of obtaining basic scaling relationships for further use on C-Mod and possible exploration on other devices. A plausible goal is obtaining record plasma stored energy in C-Mod, possibly without the requirement of a fresh boronization.

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

Previous work on C-Mod began exploring intriguing results of enhanced confinement in discharges with the ion grad-B drift pointed away from the active divertor (see MP 539 of Lipschultz, et al). These I-modes (or enhanced L-mode) feature energy confinement above that expected for L-mode, yet do not have any sudden transition in energy confinement and/or density as associated with H-mode. The lack of density buildup, presumably due to the lack of a strong edge particle transport barrier, is particularly important for C-Mod where non-boronized H-modes are plagued by rapid impurity and radiation buildup following an H-mode transition. The three key identifying features of the I-mode are a) significantly improved confinement over L-mode, reaching $H_{98} \sim 1$ in some cases, b) minimal density increase, and c) the appearance of a high-n (12-14) edge oscillation which is between 100 and 400 kHz, with frequency features significantly broader than QC oscillations associated with EDA.
A critical, but poorly understood, feature of the I-mode is H-mode avoidance. The I-modes are found at high RF power, typically at RF heating levels just below the H-mode threshold. The runs of 1080416 (USN) and 1070726 (LSN, reversed B) have provided us with important starting observations of the H-mode threshold with ion grad-B drift away from the active divertor which we now discuss.

Previous research on DIII-D with unfavorable ion grad-B drift and/or double-null configurations [Carlstrom] found that $P_{L\rightarrow H}$ did not exhibit a strong density or B dependence, unlike the near linear dependences on n and B with favorable ion grad-B drift. This lack of a strong density dependence was confirmed in C-Mod at 800 kA. Discharges with matched shapes (two cases of matched elongation and triangularity) had the same LH threshold over the available density range (Tables 1 and 2). This result is consistent with previous C-Mod experiments [Hubbard] which found weak density dependence in this density range. The B sensitivity was not tested since these discharges were restricted to 5.4-5.6 T. However, in contradiction to the usual LH threshold scaling, a very strong dependence on $I_p$ (or $1/q_{95}$ since B was nearly constant) was found in the I-mode scans, with $P_{LH}$ doubling stepping from 0.8 MA ($q_{95}$~4.6) to 1.35 MA ($q_{95}$~2.9) as shown in Figs. 1-2. Indeed, at high current / low $q_{95}$ this makes H-mode barely accessible with available RF heating on C-Mod (so we may want LH in heating phase available for the experiments). Carlstrom et al (and other DIII-D experience) showed that shaping and X-point clearance were important for H-mode avoidance near DN. The C-Mod experiments show that increased elongation and/or decreased X-point clearance produced modest but measurable increases in $P_{LH}$ at 800 kA (Fig. 1). However a limitation of this data set is that because the focus was primarily on moving the X-point, the triangularity monotonically decreased unintentionally with elongation (Fig. 3); therefore the independent effects of elongation, triangularity and X-point clearance are not clear. Nevertheless a variety of regression fits (for 800 kA shots only) always show that $P_{LH}$ increases with elongation, triangularity and moving the X-point close to the wall. The shaping sensitivity at high $I_p$ / low $q_{95}$ is unexplored.

We now discuss density control. I-mode density was varied by changing the ohmic target density and using the upper divertor cryopump in the USN shots (1080416). It is interesting to note that there is a measurable, but slow, density and decrease with the I-mode using cryopumping (Fig. 4) since the I-mode density was above the target density. The density pumpout and lack of impurity accumulation leads to extremely low radiated power ~ 0.25 MW with ~3 MW of input heating, resulting in a 750 eV pedestal (Fig. 4). Note that following the H-mode onset of this 800 kA shot, the density and impurity radiation rapidly build up, indicative of transient ELM-free H-modes found without boronization rather than EDA H-mode. This raises the intriguing possibility that stationary high confinement can be obtained in I-mode with a “bare” Mo wall. However due to the exploration of the H-mode threshold, most of these shots feature RF power ramps and we have not truly tested the stationary nature of I-mode for density, impurity radiation and confinement.

Not surprisingly, the I-mode confinement does not exactly follow L-mode scaling, nor H-mode scaling. In Fig. 4 the H98 factor increases throughout the I-mode until the H-mode
transition. I-mode energy confinement is compared to H98 scaling in Fig. 5. The high current / high RF power exhibit a higher H98 (H98 ~1), indicating the power-law for the heating degradation from H-mode is too ‘pessimistic’ in I-mode. Tables 1 and 2 show that the energy confinement has either increased with decreased density (Table 1) or has a null effect with density (Table 2), also in contradiction to H-mode scaling where $\tau_e \sim n^{0.5}$.

An interesting question is how I-mode fits into the peeling-ballooning stability model shown by ELITE [Burrell], especially given its weak density gradient and hence low edge current through bootstrap.

![Table](image)

<table>
<thead>
<tr>
<th>Shot.time</th>
<th>$n_{20}$</th>
<th>$\delta$</th>
<th>$\kappa$</th>
<th>$P_{\text{heat, or LH}}$ (MW)</th>
<th>W (kJ)</th>
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<td>1.63</td>
<td>2.93</td>
<td>68</td>
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</table>

Table 1  Comparison of matched USN 0.8 MA, modest elongation enhanced L-mode shots at different densities just prior to the LH transition.

![Table](image)

<table>
<thead>
<tr>
<th>Shot.time</th>
<th>$n_{20}$</th>
<th>$\delta$</th>
<th>$\kappa$</th>
<th>$P_{\text{heat, or LH}}$ (MW)</th>
<th>W (kJ)</th>
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<td>3.4</td>
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</table>

Table 2  Comparison of matched USN 0.8 MA, high elongation enhanced L-mode shots at different densities just prior to the LH transition.

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.

The experimental approach is relatively straightforward. We will build on the success of the previous I-mode experiments with an emphasis towards better characterizing and ‘filling out’ the available operating space for I-mode, and in a sense, pushing the I-mode towards its ultimate possible performance in C-Mod. This contrasts to the existing MP 539 which will emphasize detailed pedestal diagnosis of a few I-mode conditions (although of course this MP will provide an opportunity for more I-mode diagnosis). The goals of this exploration are to:

- Provide, if possible, a larger RF heating gap between I-mode and H-mode to better assure stationary I-mode (e.g. that a sawtooth crash does not trigger H-mode)
- Push density and pedestal collisionality down to the minimum value, possibly to the ITER pedestal $\nu^* \sim 0.08$ level or below.
- Maximize absolute plasma performance of stored energy and I-mode’s H98.

Experiments will all be in clockwise $B_t$ USN to exploit cryopumping for scanning and controlling density. The necessity of avoiding melting of the upper divertor tiles at the cryo entrance (Fig. 6) will limit upper triangularity to above $\delta \sim 0.6$; since $P_{\text{LH}}$ increased (weakly) with triangularity this seems like a reasonable compromise compared to un-
pumped LSN. (There are hints of better transient I-mode confinement in LSN, reverse-Bt which will be assessed in MP 539). Access to lower density is particularly important since it appears that the quasi-coherent edge oscillation associated with I-mode exists only at low collisionality. For example impurity injection events terminated the mode (#1080416028) and I-mode was not seen with line averaged density above $1.8 \times 10^{20}$ m$^{-3}$. (For this reason the use of O-mode edge correlation reflectometry for diagnosing the I-mode fluctuation is prohibited, since this requires a local density in the edge of $\sim 1.5 \times 10^{20}$).

RF power will be scanned in discrete steps from below and through the estimated H-mode threshold, rather than with continuous power ramps. The steps will be $\sim 250$ ms in duration; this assures $dW/dt \to 0$ and allows for better documentation of the stationary plasma performance, but still allows for 4 different powers to be examined in each shot (RF duration $\sim 1$ s). Also at constant RF power we can assess whether the H-mode state (if triggered) would be EDA or ELM-free.

We will scan the important global parameters: $I_p$, $B_t$, $q_{95}$ and density. This is motivated primarily by the surprising observation that $I_p/q_{95}$ appears to have the biggest effect on the threshold, but the inter-dependencies of this need to be sorted out. Density does not seem to be critical to the H-mode threshold, but the I-mode and associated QC, appear to prefer low collisionality. The first day of the experiment will feature these scans at a fixed shape (Circle 1 of Fig. 3) which was used in the 2008 run. The reference shot #1080416015 was at 0.8 MA.

The dual purpose of the $B_t$ scans is to separate the $I_p$ vs. $q_{95}$ dependencies, and to check the B dependence on the threshold ($P_{LH}$ is linear with $B$ in favorable grad-B drift). We begin with Step 1 a magnetic field scan from 5.0 to 5.8 T, which keeps ICRF viable without frequency changes, fixing $I_p$ at 0.8 MA. This will also provide the opportunity to assure that we are obtaining similar results to last year. The power threshold was $\sim 2.7$ MW in 2008 for this configuration at 5.4 T (H98 $\sim 0.9$ in I-mode).

Step 2 is a scan of $I_p$ at fixed $q_{95}$ to separate those dependencies. This is a necessarily limited scan because of the B scan to keep $q_{95}$ fixed. Estimated RF powers are given but may need to be adjusted during the experiment.

Step 3 is a larger $I_p/q_{95}$ scan at fixed density, with a relatively fine spacing in $I_p$. The $NL04 = 0.8e20$ was chosen based on the experience in the 2008 campaign that the I-mode was seen at lower density, yet this value of target density should be available (with cryopumping) over this large range of $I_p$. For example at $I_p=1.35$ MA a target density of $NL04=0.9e20$ still had active gas fuelling in the ohmic phase. The listed RF power scans are based on estimates that the power threshold increases linearly with $I_p$, but these may need adjustments during the experiment.

Step 4 is a density scan at the highest $I_p = 1.35$ MA. It is uncertain if the lowest densities will be achievable, even with cryopumping, since the natural plasma density will be high at this current. The purpose of pushing to higher densities is to document the density /
collisionality limit of the I-mode. The RF power steps are fixed, but may need to be adjusted if H-mode thresholds are found to vary in this wider density scan.

Step 5 is a similar density scan as Step 4, but at lower Ip.

Steps 1-5 constitute the scoping of I-mode dependences on Ip, q95, B and density.

DAY 2
With Ip, q, B and density dependencies explored in the first day at essentially fixed shape, for the second day we’ll start to explore dependence on shaping. Shaping is important to avoiding H-mode and optimizing performance. This pushes the experiment to eventually maximize simultaneously elongation and triangularity (Circle 4 in Fig. 3). Elongation has a positive effect on H-mode avoidance and at fixed q95 confinement increases ~κ^{2-3} (mostly due to access to higher I_p). Higher average triangularity is known to have a beneficial effect on pedestal stability (e.g. ELITE calculations in [Burrell] for QH mode on DIII-D).

The sequence of Steps 6-9 follows the Circles of Fig. 3 in order to properly “fill out” the shaping space and break the correlation between elongation and triangularity in the 2008 experiments. The initial shape development is done at 1 MA for each of the cases in order to high current disruptions if we hit the VDE limit. At each shape (Steps 6-9) we do a two-step density scan at 1 MA. The first density is 0.8e20 in order to match the scans of Day 1. The second density is set at the lowest target density available, based on the Day 1 experiments. Going up in density is probably not interesting. The third case increases Ip to 1.35 MA (decreases q95 to 2.9) at the standard 0.8e20 NL04 density in order to provide a crude check on the current dependence at each shape.

Finally, with the results of the scoping in-hand, we explore shots where we attempt to hold the I-mode stationary for the duration of the RF heating. This is an important feature that we have not yet explored. A concern is that relatively small excursions in power (e.g. a sawtooth crash) will inadvertently trigger H-mode. Also density / impurity control may not be stationary. While the exact conditions will certainly be affected by the scoping studies, there are two conditions that are desirable to study:

1) A demonstration ITER-like discharge: stationary, ELM-free, q95 ~ 3, B ~ 5.4 T, H98 ≥ 1, pedestal v*~ 0.08, β_N ~ 1.5.
2) An AT target suitable for LH current drive which would feature higher q95 > 4 and β_e with the lowest possible density.

Each of these conditions will feature small scans in target density in order to optimize steady I-Mode robustness and/or performance.

4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

Toroidal Field: 5.0 – 5.8 T (clockwise)
Plasma Current: 0.8 – 1.4 MA
Working Gas Species: D2
Density: Target NL04 densities from 0.3 to 1 \(10^{20}\)
Boronization Requested (if yes, specify whether overnight or between-shot, how recently needed, and any special conditions.): NO
Equilibrium configuration (if possible, refer to database equilibria): USN, forward Bt, 1080416015

4.2 Auxiliary Systems

ICRF Power, pulse length, phasing: > 5 MW, up to 1 s
LHCD Power, pulse length, phasing: If available, heating phasing.
Pellet Injection (species): No
Impurity blow-off injection: No
Diagnostic Neutral Beam: Yes, highest possible beam current
Special gas puffing: Argon available during discharge
Cryopump: Yes
Non-axisymmetric Coils (Connections, Current): Normal A-coil configuration
Other:

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

Edge and core TS (edge alignment as 1080416015)
ECE with tuning varied to assure Te at top of pedestal with varying Bt
CXRS /w DNB for Er, rotation and T_i in pedestal
Fluctuation diagnostics: PCI, reflectometer, magnetics
Impurity monitoring: McPherson

5. Experimental Plan
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.

Two day run plan.

Day 1: Ip, q95, B and density scoping.

Day 2: Shaping scoping. Steady-state tests.

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:
1. **B scan**  
   3 shots  
   Reference shape: #1080416015, Ip=0.8 MA, NL04 target = 0.8e20.  
   250 ms P$_{rf}$ steps: 2.5, 2.6, 2.7, 2.8  
   Scan B:  
   a) 5.4 T (q95 ~ 4.66)  
   b) 5.8 T (q95 ~ 5.0)  
   c) 5.0 T (q95 ~ 4.3)  

2. **Ip scan at fixed q95 and density**  
   3 shots  
   Reference shape: #1080416015, q95 ~ 4.3, NL04 target = 0.8e20  
   a) Ip = 0.85 MA, B = 5.31 T, 250 ms P$_{rf}$ steps: 2.6, 2.7, 2.8, 2.9  
   b) Ip = 0.9 MA, B = 5.63 T, 250 ms P$_{rf}$ steps: 2.7, 2.8, 2.9, 3.0  
   c) Ip = 0.95 MA, B = 5.94 T, 250 ms P$_{rf}$ steps: 2.8, 2.9, 3.0, 3.1  

3. **Ip and q95 scan at fixed B and density**  
   5 shots  
   Reference shape: #1080416015, NL04 target = 0.8e20, Bt = 5.63 T  
   a) Ip = 0.8 MA, q95 ~ 4.8, 250 ms P$_{rf}$ steps: 2.5, 2.6, 2.7, 2.8  
   b) Ip = 1.0 MA, q95 ~ 3.9, 250 ms P$_{rf}$ steps: 3.1, 3.2, 3.3, 3.4  
   c) Ip = 1.15 MA, q95 ~ 3.36, 250 ms P$_{rf}$ steps: 3.4, 3.6, 3.8, 4.0  
   d) Ip = 1.25 MA, q95 ~ 3.1, 250 ms P$_{rf}$ steps: 3.9, 4.1, 4.3, 4.5  
   e) Ip = 1.35 MA, q95 ~ 2.9, 250 ms P$_{rf}$ steps: 4.3, 4.6, 4.9, 5.2  

4. **Density scan at high Ip / low q95**  
   3e forms part of scan  
   Reference shape: #1080416015, NL04 = 1.3e20, Bt = 5.63 T  
   6 shots  
   a) NL04 = 1.3e20, P$_{rf}$ steps: 4.3, 4.6, 4.9, 5.2  
   b) NL04 = 1.1e20, P$_{rf}$ steps: 4.3, 4.6, 4.9, 5.2  
   c) NL04 = 0.9e20, P$_{rf}$ steps: 4.3, 4.6, 4.9, 5.2  
   d) NL04 = 0.7e20, P$_{rf}$ steps: 4.3, 4.6, 4.9, 5.2  
   e) NL04 = 0.6e20, P$_{rf}$ steps: 4.3, 4.6, 4.9, 5.2 (if possible)  
   f) NL04 = 0.5e20, P$_{rf}$ steps: 4.3, 4.6, 4.9, 5.2 (if possible)  

5. **Density scan at low Ip / high q95**  
   3b forms part of scan  
   Reference shape: #1080416015, Ip = 1.0 MA, Bt = 5.63 T  
   6 shots  
   a) NL04 = 0.3e20, P$_{rf}$ steps: 3.1, 3.2, 3.3, 3.4 (or lowest density achievable)  
   b) NL04 = 0.4e20, P$_{rf}$ steps: 3.1, 3.2, 3.3, 3.4  
   c) NL04 = 0.5e20, P$_{rf}$ steps: 3.1, 3.2, 3.3, 3.4  
   d) NL04 = 0.6e20, P$_{rf}$ steps: 3.1, 3.2, 3.3, 3.4  
   e) NL04 = 0.7e20, P$_{rf}$ steps: 3.1, 3.2, 3.3, 3.4  
   f) NL04 = 1e20, P$_{rf}$ steps: 3.1, 3.2, 3.3, 3.4  

**Day 2**  

6. **Increase κ to ~1.7, same triangularity ~ 0.6 as Day 1**  
   (Circle 2 Fig. 3)  
   3 shots  
   a) Ip = 1 MA, Bt = 5.63 T, q95 ~ 3.9, NL04 = 0.8e20, P$_{rf}$ steps: 3.1, 3.2, 3.3, 3.4  
   b) Ip = 1 MA, Bt = 5.63 T, q95 ~ 3.9, NL04 = 0.5e20 (or lowest possible), P$_{rf}$ steps: 3.1, 3.2, 3.3, 3.4  
   c) Ip = 1.35 MA, Bt = 5.63 T, q95 ~ 2.9, NL04 = 0.8e20, P$_{rf}$ steps: 4.3, 4.6, 4.9, 5.2  

7. **Increase κ to ~1.8 (or max.), same triangularity ~ 0.6 as Day 1**  
   (Circle 3 Fig. 3)  
   3 shots  
   a) Ip = 1 MA, Bt = 5.63 T, q95 ~ 3.9, NL04 = 0.8e20, P$_{rf}$ steps: 3.1, 3.2, 3.3, 3.4  
   b) Ip = 1 MA, Bt = 5.63 T, q95 ~ 3.9, NL04 = 0.5e20 (or lowest possible), P$_{rf}$ steps: 3.1, 3.2, 3.3, 3.4
c) \( I_p = 1.35 \, \text{MA}, \quad B_t = 5.63 \, \text{T}, \quad q_{95} \sim 2.9, \quad NL04 = 0.8e20, \quad P_{\text{rf}} \text{ steps: } 4.3, 4.6, 4.9, 5.2 \)

8. Keep \( \kappa \) at \( \sim 1.8 \) (or max.), increase triangularity to 0.8 (Circle 4 Fig. 3) **3 shots**
   a) \( I_p = 1 \, \text{MA}, \quad B_t = 5.63 \, \text{T}, \quad q_{95} \sim 3.9, \quad NL04 = 0.8e20, \quad P_{\text{rf}} \text{ steps: } 3.1, 3.2, 3.3, 3.4 \)
   b) \( I_p = 1 \, \text{MA}, \quad B_t = 5.63 \, \text{T}, \quad q_{95} \sim 3.9, \quad NL04 = 0.5e20 \text{ (or lowest possible)}, \quad P_{\text{rf}} \text{ steps: } 3.1, 3.2, 3.3, 3.4 \)
   c) \( I_p = 1.35 \, \text{MA}, \quad B_t = 5.63 \, \text{T}, \quad q_{95} \sim 2.9, \quad NL04 = 0.8e20, \quad P_{\text{rf}} \text{ steps: } 4.3, 4.6, 4.9, 5.2 \)

9. Reduce \( \kappa \) to \( \sim 1.7 \) (or max.), keep triangularity at 0.8 (Circle 5 Fig. 3) **3 shots**
   a) \( I_p = 1 \, \text{MA}, \quad B_t = 5.63 \, \text{T}, \quad q_{95} \sim 3.9, \quad NL04 = 0.8e20, \quad P_{\text{rf}} \text{ steps: } 3.1, 3.2, 3.3, 3.4 \)
   b) \( I_p = 1 \, \text{MA}, \quad B_t = 5.63 \, \text{T}, \quad q_{95} \sim 3.9, \quad NL04 = 0.5e20 \text{ (or lowest possible)}, \quad P_{\text{rf}} \text{ steps: } 3.1, 3.2, 3.3, 3.4 \)
   c) \( I_p = 1.35 \, \text{MA}, \quad B_t = 5.63 \, \text{T}, \quad q_{95} \sim 2.9, \quad NL04 = 0.8e20, \quad P_{\text{rf}} \text{ steps: } 4.3, 4.6, 4.9, 5.2 \)

10. Steady demonstration shot Type #1: “ITER q=3” **4 shots**
    \( B_t = 5.4 \, \text{T}, \quad q_{95} \sim 3, \quad \text{shape: TBD} \)
    Variables (influenced on parameter scan results of 2-4).
    - target density: NL04 \sim 0.5-0.7 to reduce pedestal collisionality to ITER target 0.08
    - RF: constant through shot, \sim 4.5 - 5 MW

11. Steady demonstration shot Type #2: Low collisionality AT / LH target **4 shots**
    \( B_t = \text{TBD}, \quad q_{95} \sim 4, \quad \text{shape: TBD} \)
    Variables (influenced on parameter scan results of 2-4).
    - target density: minimum possible NL04 \sim 0.5-0.7
    - RF: constant through shot, \sim 3.5 - 4 MW

### 6. Anticipated Results

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, an ITER request, or an external database.

Successful completion of the MP should lead to publication of I-mode results in a leading general fusion journal such as Nuclear Fusion. Demonstration of an ELM-free, high confinement, stationary plasma at ITER dimensionless parameters with a high-Z first wall should be of high interest to ITER. It is possible that the scoping study will suggest the study of I-mode on other devices.

For C-Mod, the I-mode could open up important target plasmas for AT research and high-performance without boronization.

### 7. References

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


Fig. 1 LH threshold power versus elongation for previous I-mode campaigns.
Fig. 2 LH threshold power versus X-point clearance (in m)
Fig. 3 Elongation vs. triangularity for I-mode shots of 1070726 and 1080416 (blue squares). The yellow circles represent shapes to be used for the experiment.
Fig. 4 Example traces for I-mode with scanning RF power with USN cryopumping. I-mode occurs just before H transitions at \( \sim 1.2 \) s with H\(98\sim 0.85\), decrease in radiated power and high pedestal Te > 700 eV. Shaping: \( \kappa \sim 1.65 \), \( \delta \sim 0.5 \)
Fig. 5 Energy confinement of I-mode compared to H98 H-mode scaling law.
Fig. 6 Example equilibrium with TS points overlaid