Princeton Plasma Physics Laboratory

NSTX Experimental Proposal

Title: Title	**Investigation of long-wavelength turbulence in the core of NSTX plasmas**	
XP-439	**Revision:**	Effective Date: *(Ref. OP-AD-97)* Expiration Date: *(2 yrs. unless otherwise stipulated)*

PROPOSAL APPROVALS

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Responsible Division: Experimental Research Operations	

Chit Review Board (designated by Run Coordinator)

MINOR MODIFICATIONS (Approved by Experimental Research Operations)

NSTX EXPERIMENTAL PROPOSAL

Title: Investigation of long-wavelength turbulence in the core of NSTX plasmas

1.0 Overview of planned experiment

The primary goal of the proposed experiment is to characterize long wavelength turbulence (especially the radial correlation length via reflectometry) in the *core* of NSTX plasmas and make direct comparisons with predictions from gyro-kinetic codes, as well as with measured confinement properties. ***It should be noted that, to date, there have been virtually NO core turbulence measurements in ST plasmas.*** The experiment should be viewed as a ground-breaking investigation that will provide the first insight into the nature of turbulence in the core of an ST plasma.

It is planned to sequentially study single-beam NBI L-mode, H-mode and RF-only plasmas. (Note: due to constraints imposed by existing density profiles, it will probably not be possible to probe the core of high power NBI discharges using reflectometry.) However, the above-proposed plasmas have widely ranging ExB flows, Te/Ti ratios and confinement properties. Note that in RF plasmas $T_e > T_i$, whereas in NBI $T_e < T_i$. It is expected that ion transport in NBI plasmas will be superior to that in RF-only plasmas due to larger ExB flow and a higher Ti/Te ratio. Gyro-kinetic linear stability analysis of existing NSTX data suggests that long wavelength growth rates (ITG, TEM) in NSTX are small. It has often been suggested that long wavelength turbulence may be strongly suppressed or be “intrinsically stable” in NSTX (e.g. 12th International Toki Conference, PAC 2004) and that short wavelength ETG modes are dominant and likely responsible for observed electron transport properties. It should be noted that preliminary evidence suggests that long wavelength turbulence does in fact exist at large levels in the edge of single beam L-mode plasmas and in the core of low beta Ohmic NSTX plasmas. The goals are to characterize this turbulence in the core of a variety of NSTX operating regimes, make direct comparison with gyro-kinetic code predictions and identify the role in confinement.

The experiment focuses on long wavelength turbulence in the core NSTX plasma. Short wavelength turbulence associated with ETG modes is not investigated at this time. The radial correlation length of long wavelength core turbulence will be measured in single beam NBI L-mode, the period following an L-H modes transition and RF only plasmas. As shown in Figure 1 *previous* correlation length measurements in the ***far edge*** of NBI NSTX plasmas showed a strong dependence on *local* magnetic field strength or gyroradius. Turbulent correlation length is thought to be the step-size on which diffusive transport occurs and so should be an indicator of confinement properties. These edge observations were consistent with neon penetration measurements, which showed less penetration to the core at larger magnetic fields. However, there was no evidence of a significant change in stored energy (or ion temperature) with magnetic field. This further motivates correlation measurements deeper into the core plasma. In addition to extending these correlation length measurements to the core plasma, it is also hoped to simultaneously monitor local density fluctuation levels and measure frequency spectra (which will provide a local indicator of ExB flow) via quadrature reflectometry. In addition, line-integrated information will be obtained via sensitive 1 mm-wave interferometry as well as the existing Fire-Tip system.

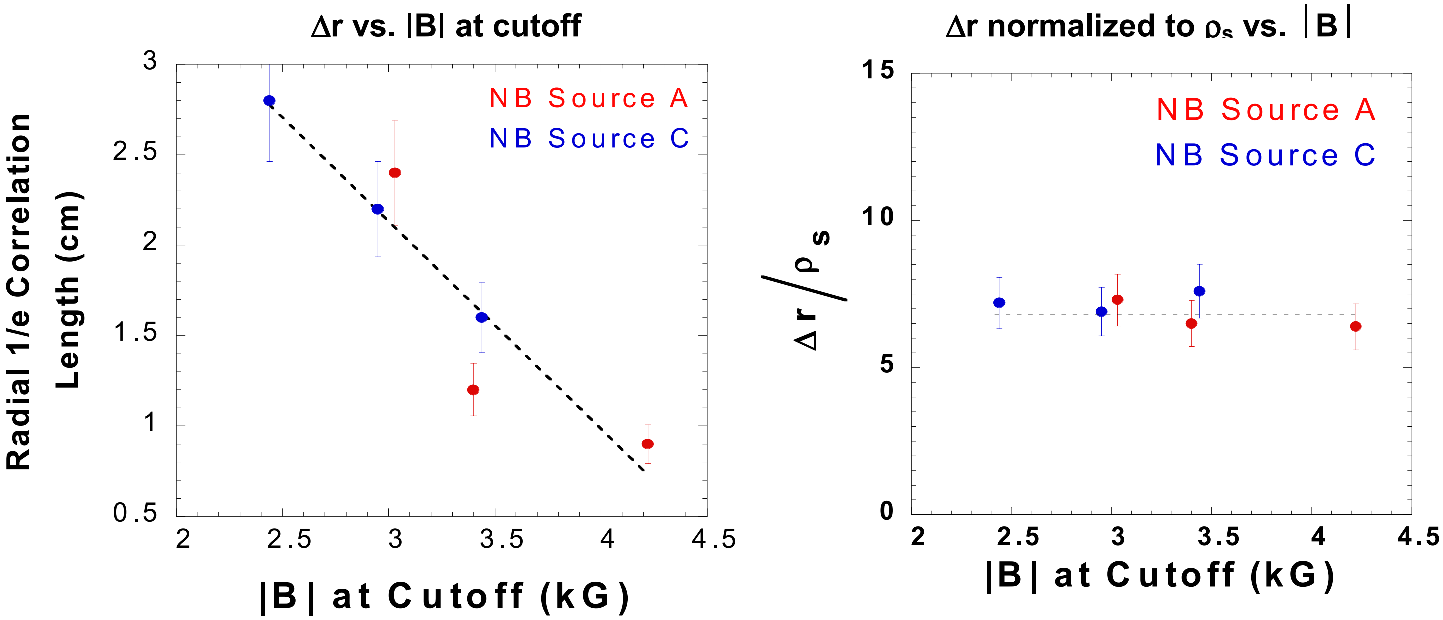


Figure 1. *Measured correlation length in NSTX NBI plasmas as a function of local magnetic field during a constant q scan (i.e. Ip/B_T constant). In these scan the central toroidal field was varied from 3.5 to 6 kG. Note that when the correlation length was normalized to the gyro-radius the vale as constant vs field.*

For comparison with theory, extensive profile information will be necessary including density, ion/electron temperature, Zeff, toroidal and poloidal flows (to determine Er) and, of course, q profile. Magnetic and electric field shear can have a large impact on modeling calculations for long wavelength ITG-like modes. It is important we understand the limitations of our estimates of these parameters (especially ion temperatrure and q profile). Many factors influence fluctuation level and spectra of long wavelength turbulence in NSTX. This, combined with fact that not all required profiles are likely to be known accurately on NSTX at this time, means that the ***primary goal of this XP*** will be on characterizing (for the first time) long wavelength turbulence in the core of NSTX plasmas. In addition, the information gained would be correlated with the observed confinement properties. A secondary, longer-term (but very important) goal will be detailed comparison of measured turbulent correlation lengths with those predicted via nonlinear gyrokinetic simulation. The measurement of turbulent correlation length and autocorrelation time (in plasma reference frame) allows (in principle) a local diffusion coefficient to be estimated. More importantly, it also allows a rather direct way of comparing with gyro-kinetic code predictions and studying the dependence on parametric scaling (e.g. gyro-radius). This will form the long-term focus of this research - a direct comparison of experimentally determined correlation lengths with gyro-kinetic predictions and transport properties over a broad range of plasma conditions.

2. Theoretical/ empirical justification

As mentioned above, theoretically it has been suggested that long wavelength ITG turbulence plays a secondary role in the transport properties of NSTX discharges. The paper by Rewoldt et al. (PoP 1996) suggested that linear growth rates reduce dramatically for both the trapped electron eta-i mode (low beta considered) and kinetic ballooning mode (high beta considered) as aspect ratio is reduced : see Figure 2 below.

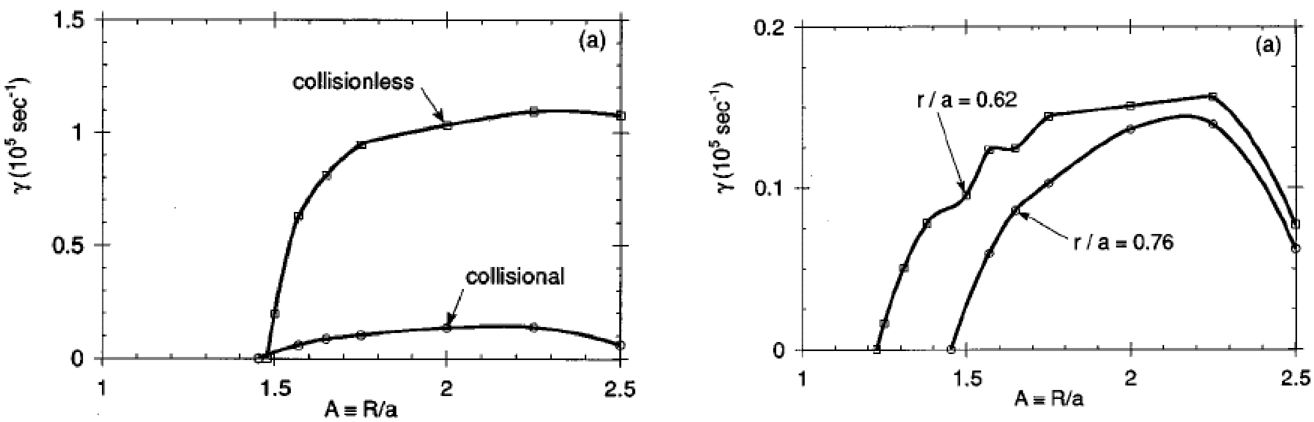


Figure 2. *Growth rate vs A for the electrostatic toroidal drift mode (or trapped electron eta-i mode). $k_\theta \rho_i = 0.46$. (a) comparison of collisional vs collisionless. (b) growth rates at two different radial locations.*

This result was thought to be primarily due to the reduction in bad curvature available to drive the modes as aspect ratio reduced. Note that this effect reduces as you penetrate deeper in to the core plasma. i.e. the effect of aspect ratio would be much weaker at r/a =0.5.

It has also been suggested that if beta-normal is kept fixed then there is very little effect of aspect ratio alone on growth rates of microinstabilities, especially ITG. This is described in the Nuclear Fusion paper by Kotschenreuther et al (40 (3Y), 677, 2000) where the following statement is made

> *" There is no substantial difference in the magnitude of the maximum growth rates and the Dm between A = 3 and A = 1.4 for modes with $k_\theta \rho_i < 1$, or in the extent of the minor radius over which the instability is present. We find this result is typical when one compares cases, which are at a comparable fraction of the ideal MHD β limit. Previous comparisons of kinetic drift instabilities at different aspect ratios have not related beta in this way"*

Therefore, it appears that the indication that growth rates for ITG modes are very similar in different aspect ratio devices operating at the same beta-normal suggests that any "intrinsic stability" for such modes in an ST is based on some alternative reasoning. Possibilities include the role of ExB sheared stabilization in an ST vs a higher aspect ratio tokamak, as well as effects resulting from the gradient in beta and/or the details of actual profile data.

Gyro-kinetic calculations by Bourdelle et al using actual EFIT and profile data from NSTX have indicated that growth rates for short wavelength ETG modes far exceed those for ITG and TEM modes, especially in the core (see Figure 3 below from presentation by Bourdelle at TTF for a 9% beta NBI discharge). In fact, it is often indicated that ITG is fully stabilized in the core. The calculations also indicate that the estimated ExB shear flow suppression can be significant for long ITG wavelengths but less important for the short wavelength ETG turbulence. Bourdelle et al have also indicated that growth rates for both ITG and ETG scale length turbulence are very sensitive to the electron to ion temperature ratio, as shown below in Figure 4. As can be seen, when the "real-value" of Ti/Te is taken for a beam-heated NSTX plasma, the growth rate for ETG modes increased, whereas that for ITG modes reduced significantly (in fact the mode appears to have been completely stabilized). Note that when the temperature ratio is reversed ITG modes are destabilized and ETG stabilized!

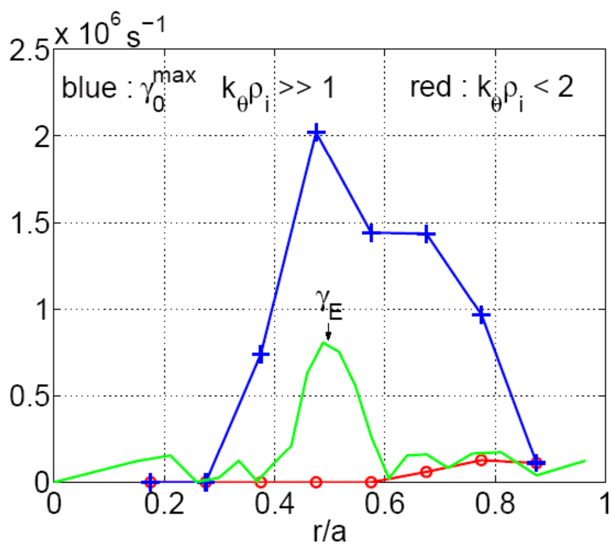


Figure 3 *Linear growth rates for long and short wavelength turbulence in mderate beta (9%) NBI NSTX discharge (104001 at t = 280ms.) Green indicates estimated ExB shearing rate. From Bourdelle et al TTF 2001.*

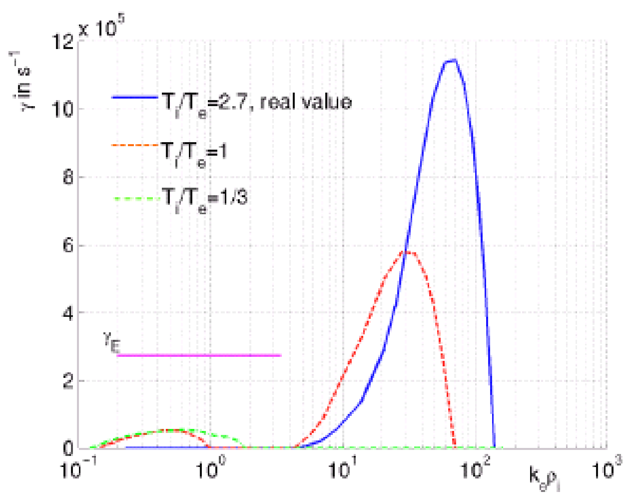


Figure 4 *Linear growth rates for long and short wavelength turbulence for different ion to electron temperature ratios. From Bourdelle et al*

More recently, a paper by Bourdelle et al (PoP 10(7), 2003) indicates that, in the core of high beta ST plasmas, the high ***gradient in beta*** can be a primary source of stabilization and not simply aspect ratio. This is shown below in Figure 5.

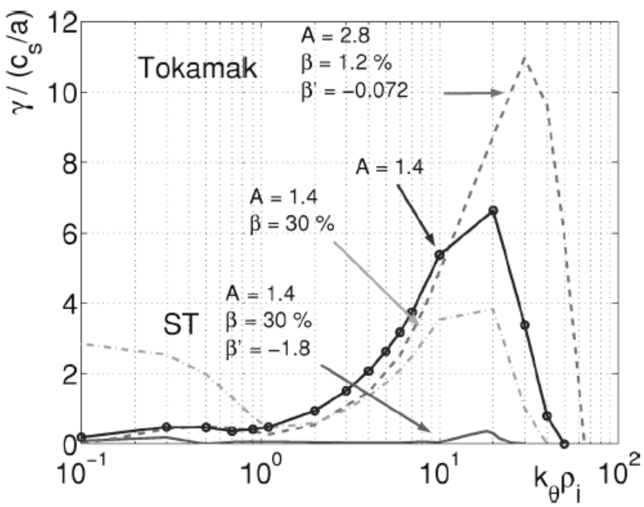


FIG. 7. Spectrum of normalized growth rates. a is the minor radius, $c_s = \sqrt{T/m_D}$, $\rho_s = \sqrt{T m_D}/(eB)$. Dashed line: $A=2.8$, $\beta=1.2\%$, $\beta' = -0.072$; solid line with dots: $A=1.4$, $\beta=1.2\%$, $\beta' = -0.072$; dashed and dotted line: $A=1.4$, $\beta=30\%$, $\beta' = -0.072$; solid line: $A=1.4$, $\beta=30\%$, $\beta' = -1.8$.

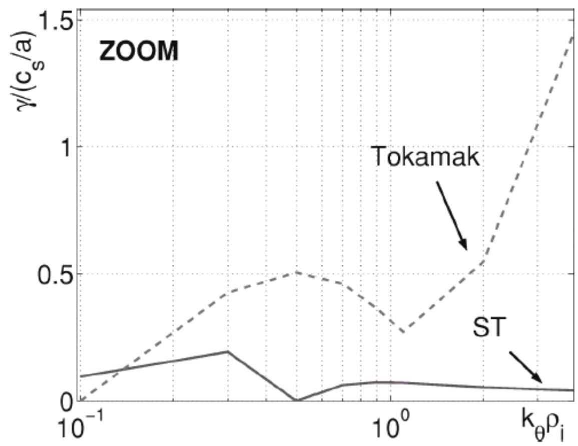


FIG. 8. Enlargement of Fig. 7 in the low $k_\theta \rho_i$ zone for the tokamak-like case, dashed line, and the ST-like case, solid line.

Figure 5 *Linear growth rates for long and short wavelength turbulence for plasma conditions where β and β' are artificially varied to indicate their respective roles in ST and tokamak plasmas..*
From Bourdelle et al PoP 10 (7) 2887 2003

This effect appears to significantly reduce growth rates for ***both*** ITG and ETG modes. A comparison with a higher aspect ratio, lower beta tokamak indicates that growth rates are significantly reduced for both long and short wavelength turbulent modes – everything is predicted to be better in a high beta gradient ST ! However, it should be noted that the β' values used in the calculations have not yet been achieved.

In summary, growth rates for microinstabilities in STs are predicted to depend on a wide range of parameters including electron to ion temperature ratios, ExB flow shear, magnetic shear, temperature and density gradients, beta, beta-prime, aspect ratio, etc. Gyrokinetic analysis indicates that growth rates for long wavelength ITG-like turbulence are much lower than for shorter wavelength ETG-like modes. In addition, ExB shear flow suppression is generally predicted to be effective for ITG-like modes in NBI heated plasmas while ineffective to significantly affect the shortest wavelength ETG modes. It appears that the most significant parameters affecting long wavelength turbulence in an ST are the level of ExB sheared flow, the Ti/Te ratio and the value of beta-prime. For the purposes of the current XP it is hoped that profile data will be sufficiently accurate that nonlinear gyrokinetic calculations can be utilized effectively to predict measured correlation lengths and associated transport. The current lack of detailed q profile information may be an obstacle. However, MSE is now operational and even 2 points might provide a significant constraint to EFIT. It should also be noted that GS2 currently does not contain all of the necessary physics and that GYRO will probably be the preferred vehicle for comparison.

3. Specific Goals of the Proposed Experiment

Based on the above analysis, combined with reflectometry constraints set by the typical density profile shapes (we need a somewhat peaked profile to access the core) at the highest betas, it appears that the focus should be to study plasmas with large variations in ExB flow and the Ti/Ti ratio The expected outputs from the experiment are as follows listed in order of increasing difficulty:

(1) For the first time, characteristics of long wavelength turbulence in the core of an ST plasma will be documented.

e.g. the turbulent correlation length spatial profile will be determined in single beam NBI heated plasmas: turbulence levels will also be estimated and the relative ExB flows measured locally will be compared. The period following an L-H mode transition would also be studied. Plans call for future piggy back observations in RF heated plasmas.

(2) The experimental turbulence data will be compared with gyro-kinetic linear growth rate calculations, which will be contrasted with ExB shear flow suppression rates. These should be quite different in the core of RF and NBI heated plasmas.

(3) A direct comparison of measured turbulent correlation lengths with those predicted using non-linear gyrokinetic calculations will be made.

This will primarily require analysis using the GYRO code since GS2 does not include the effects of diamagnetic shear, ExB shear, strong toroidal rotation, etc. Scaling (of both experiment and theory) with magnetic field strength (gyro-radius) would be pursued as a priority.

This work will produce the first quantitative information regarding long wavelength turbulence in the core of ST plasmas while also allowing direct comparison with theoretical predictions.

3. Experimental run plan

Due to the shot limitations on a single day (~30), it has been decided to focus during the XP on single-beam NBI LSN plasmas. Some effort will also be directed towards the study of the period following an L-H transition. Reflectometry access to peaked density RF-only plasmas is excellent and so it is felt that data could likely be obtained on a "piggy-back" basis for RF plasmas.

The plasma requirements are listed below. They are driven by plasma measurement accessibility and optimization.

Table1

Requirement	Reason/motivation
Peak electron density ~2.5 10^{13} cm^{-3}.	maximize spatial coverage

“Peaked” rather than “flat” profiles	to allow accessibility for reflectometry
Maintain approximate profile shape when changing B field etc.- **control fueling**	to ensure measurement region overlaps under different operating conditions
Minimize temporal density evolution during current flat top	ensures measurement is at an approximately fixed location (measurement takes ~20ms)
Minimize MHD activity	eliminates interference in correlation analysis.

The broad experimental plan is described below: a detailed shot plan follows.

(1) Establish stable single beam, LSN (minimal MHD) plasma with desired electron density profile. **Base plasma on discharge 112814.**

(2) Employ 60 kV beam for heating thereby maximizing momentum input and minimizing energy coupling.

(3) Use 80kV, 10ms beam blips for ion temperature/rotation measurement.

(4) Later in discharge utilize 30ms blips and observe spin-up, spin-down turbulence spectra and access to H-mode.

(5) Measure correlation lengths from edge to core plasma

- also attempt to measure fixed reflectometer phase fluctuations: estimate density fluctuation levels
- monitor line-integrated density fluctuation levels via 1 mm interferometry and FireTip

(6) Vary the magnetic field while keeping edge q constant (ρ^* scan)

i.e. change gyroradius while keeping q approximately constant

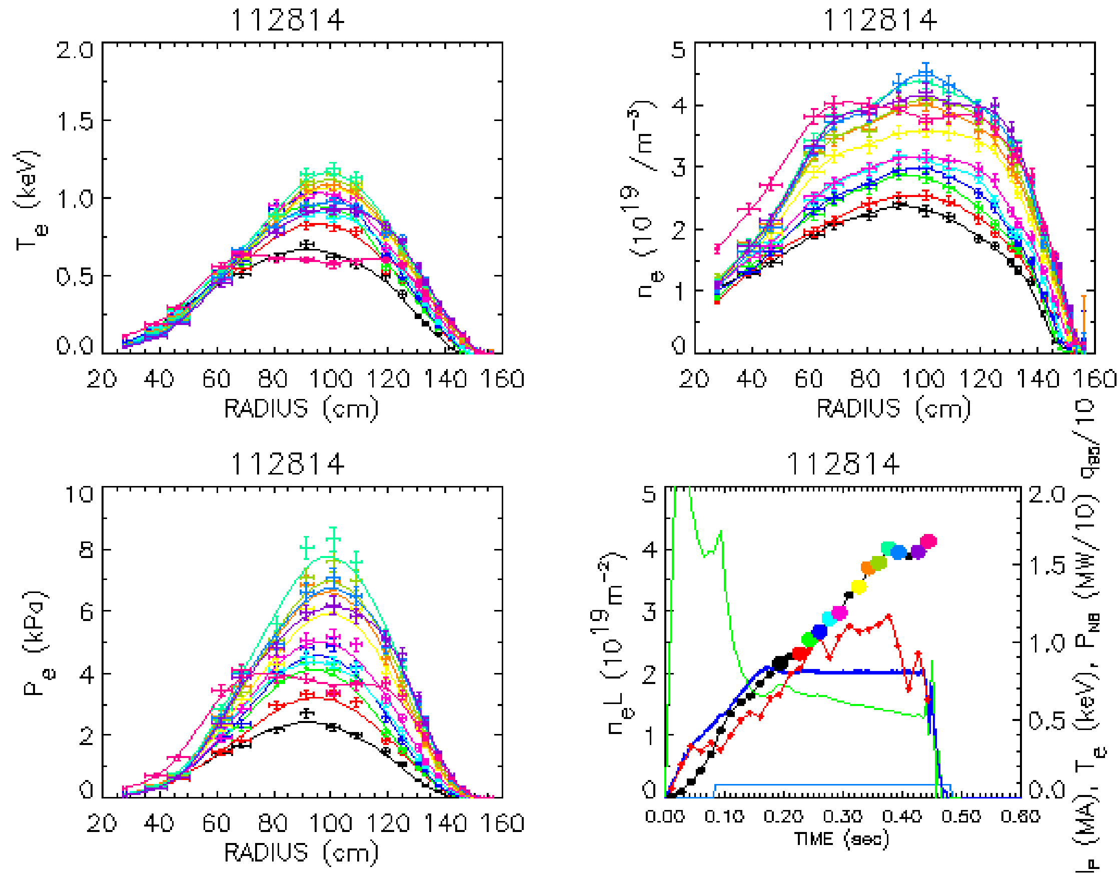
3 different fields and plasma currents would be utilized

(7) Vary magnetic field while keeping plasma current fixed. This varies the gyroradius *and* edge q and may allow the roles of gyroradius and q to be separated. This approach also connects well to previous edge correlation length data (see Figure 1)

(8) On a separate day or in “piggy-back” mode investigate RF-only plasmas. Density profiles are usually peaked and ideally suited for reflectometry accessibility.

(9) It should be noted that recently developed Ohmic H mode plasmas also look suitable for investigation in both the Ohmic and H-mode phase. Again it may be possible to probe such plasmas in a ”piggy-back” mode.

As mentioned above it is planned to utilize a modified version of recent LSN single beam discharges (#112814). Details regarding shot 112814 are shown below.



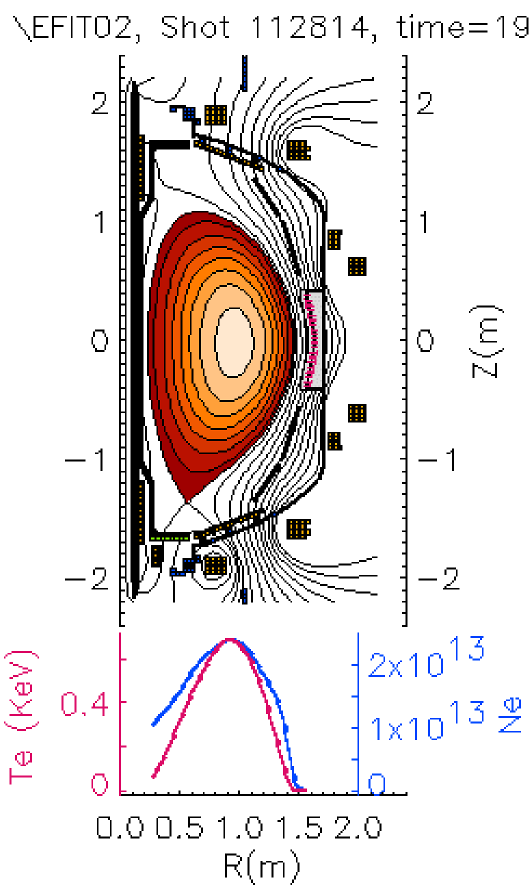


Figure 6 *Illustration of selected plasma configuration based on recent discharge development - shot #112814. This single beam LSN plasma has excellent plasma density profile evolution, long pulse, and minimal MHD activity.*

Shot Plan

LSN, single, 60kV heating beam Based on discharge 112814

 # Shots

Tune density to ~2.5 10^{13} cm^{-3} at 200ms : B_T = 4.5 kG, Ip ~0.85 MA. **60kV heating beam C**. 6
Start 60kV beam at ~80ms as in shot # 112814.
If, after 4 shots, experience difficulty at 0.85 MA drop to 0.8 MA
80kV, beam blips. Start with a **10ms** blip (**Beam B)** at 225ms, 325ms, then **40ms** at 375ms.
Integrate over first 10ms for Ti and rotation.
Longer beam blip used to study spin up via CHERs. Turbulence spectrum monitored for spin-up and spin-down
Monitor longer blip for potential H-mode transition. Potentially increase pulse duration of 40ms blip.

Once target plasma established, perform a magnetic field (ρ* scan) by changing Ip & B_T while keeping **Ip/B_T constant i.e. edge q approximately constant.**
Changes gyroradius at constant edge q
3 toroidal fields(3.2, 3.75 and 4.5 kG)
3 equivalent currents (0.6, 0.71 & 0.85MA)
Need to obtain at least 2 good shots for each combination 6-12

Fix Ip = 0.7 MA, change toroidal field (3.2 & 4.5 kG only – 3.75 kG obtained above)
Need to obtain at least 2 good shot for each combination
This changes gyro radius *and* edge q
May need to switch beams at lower B field 4-8

NOTE: During Ip/B_T scan it will likely be necessary to modify gas fueling in order to maintain similar density profile evolution.

Fix Ip = 0,7 MA, B_T = 3.75kG. 60kV main heating beam.
Add 80kV, ~100ms "blip" beam at 225ms – transition to full **H-mode.** 4

Repeat above for Ip = 0.85MA, B_T = 4.5kG. 60kV main heating beam
Second 80kV, ~100ms beam "blip" at 225ms – transition to **H-mode**. 4

Shot total 24-34

Decision points

(1) If difficulty experienced with high current discharge, lower current after 4 shots.
(2) If oversubscribed drop constant Ip scan. Keep ρ* scan at all costs.
(3) As last resort, go to fewer conditions in ρ* scans.
(4) NBI L mode has higher priority than H-mode.

4. Required machine, NBI, RF, CHI and diagnostic capabilities

Some plasma development planned based on shot **112814**. Attempt to establish plasma utilizing **lower** gas fueling. Require 60kV NBI for heating and 80kV beam blips for diagnosis. CHERS, Thomson are essential. MSE important. Correlation and fixed frequency reflectometers are essential. mm-wave interferometer and Fire-Tip important. All edge and core turbulence diagnostics highly desirable.

7 min GDC for reproducible low density L mode operation

Highly desirable – fresh boronization

5. Planned analysis

Analysis will involve

(1) Reflectometry correlation analysis to recover turbulent correlation length and hopefully local density fluctuations level.

Requires accurate knowledge of density profile.

(2) Linear stability calculations (GS2) to generate profiles of growth rate for long wavelength electrostatic modes and ExB shearing rates.

Requires accurate profile information for input to the code including EFIT, q-profile, temperature and density profiles, Zeff profile, etc.

(3) Non-linear gyro-kinetic calculations (using GYRO and perhaps GS2) to determine local turbulent correlation lengths.

Also requires accurate profile information for input to the code including EFIT, q-profile, ion and electron temperature profiles, density profiles, Zeff profile, etc.

6. Planned publication of results

These results will likely be published in PRL and PoP since they will be the first turbulence results from the core of an ST plasma. Ideally PRL would probably require some definitive statement regarding relationship with transport properties. On a longer timescale detailed comparison with nonlinear gyrokinetic predictions should be possible which would lead to further publications.

PHYSICS OPERATIONS REQUEST

Title: Investigation of long-wavelength turbulence in the core of NSTX plasmas
Use shot # 112814 as prototype L mode discharge. **XP-439**

Machine conditions (specify ranges as appropriate)

I_{TF} (kA): ______ Flattop start/stop (s): _____/_____

I_P (MA): **0.55-0.85MA** Flattop start/stop (s): **150ms/600ms**

Configuration: **Inner Wall / Lower Single Null / Upper SN / Double Null**

X

Outer gap (m): _____, Inner gap (m): **0**

Elongation κ: _____, Triangularity δ: _____

Z position (m): **0.00**

Gas Species: **D** Injector: **Midplane / Inner wall / Lower Dome**

X

NBI - Species: D, Sources: A/B/C, Voltage (kV): 80/80/60, Duration (s):BU/.01-0.1/1

ICRF – Power (0 MW): Phasing: Heating / CD, Duration (s): _____

CHI: Off

Either: List previous shot numbers for setup: **112814**

Or: Sketch the desired time profiles, including inner and outer gaps, κ, δ, heating, fuelling, etc. as appropriate. Accurately label the sketch with times and values.

Diagnostic	Need	Desire	Instructions
Bolometer – tangential array		X	
Bolometer array - divertor			
CHERS	X		
Divertor fast camera			
Dust detector			
EBW radiometers			
Edge deposition monitor			
Edge pressure gauges			
Edge rotation spectroscopy		X	
Fast lost ion probes - IFLIP			
Fast lost ion probes - SFLIP			
Filtered 1D cameras			
Filterscopes	X		
FIReTIP		X	
Gas puff imaging		X	
Infrared cameras			
Interferometer - 1 mm		X	
Langmuir probe array			
Magnetics - Diamagnetism	X		
Magnetics - Flux loops	X		
Magnetics - Locked modes	X		
Magnetics - Pickup coils	X		
Magnetics - Rogowski coils	X		
Magnetics - RWM sensors	X		
Mirnov coils – high frequency	X		
Mirnov coils – poloidal array	X		
Mirnov coils – toroidal array	X		
MSE		X	
Neutral particle analyzer		X	
Neutron measurements			
Plasma TV			
Reciprocating probe		X	
Reflectometer – core	X		
Reflectometer - SOL		X	
RF antenna camera			
RF antenna probe			
SPRED		X	
Thomson scattering	X		
Ultrasoft X-ray arrays		X	
Visible bremsstrahlung det.	X		
Visible spectrometers (VIPS)			
X-ray crystal spectrometer - H			
X-ray crystal spectrometer - V			
X-ray PIXCS (GEM) camera			
X-ray pinhole camera			
X-ray TG spectrometer			