Low Frequency Instability in the Levitated Dipole Experiment

Jay Kesner, A. Boxer, J. Ellsworth, I. Karim
MIT
D.T. Garnier, A. Hansen, M.E. Mauel, E.E. Ortiz
Columbia University

Columbia University

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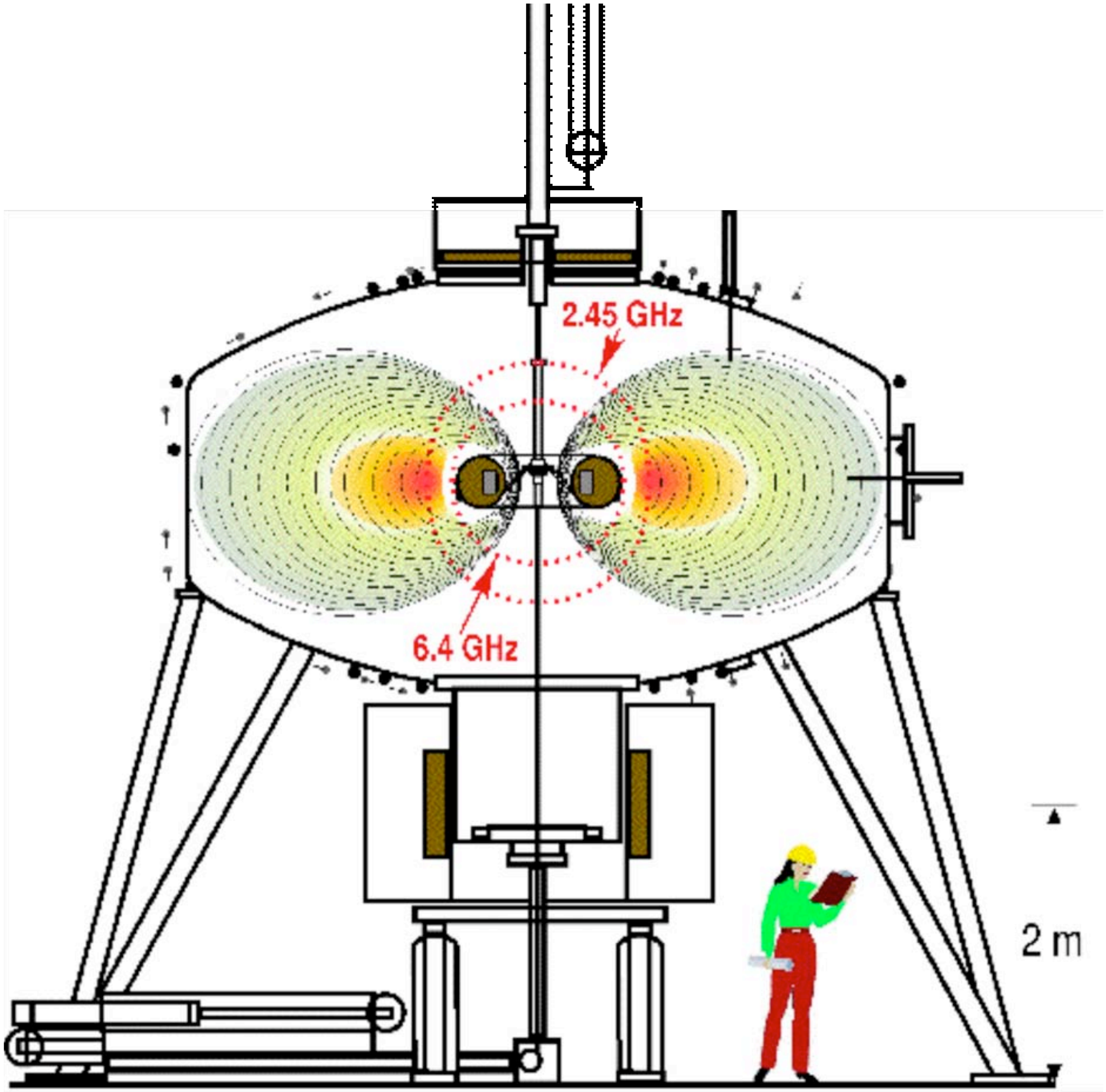
Plasma that is heated by ECRH can be subject to instability that feeds on the free energy of either the hot component or the thermal plasma component. Confinement in a closed field line system such as a levitated dipole imposes particular restrictions on collective effects; notably the plasma compressibility will play an important stabilizing role. Theoretical considerations of thermal plasma driven instability indicate the possibility of MHD-like behavior of the background plasma, including convective cells, drift frequency (entropy mode) fluctuations and ECRH-accessibility related "breather" modes. In experiments in LDX (in the supported mode of operation) we create a two- component plasma in which a thermal species contains most of the density and an energetic electron species contains most of the plasma stored energy. In addition to high frequency fluctuations reported elsewhere [Garnier et al, PoP (2005)] we observe low frequency fluctuations that presumably are driven by the thermal species. The observed frequencies include modes in the kHz and 100 Hz range. A variation of the frequency spectrum with neutral gas pressure indicates a dependence on the imposed plasma profiles and possibly on the relative temperature and density gradients.

LDX Experiment Cross-Section

- Superconducting dipole magnet $I_c > 1$ MA
- Large 5 m diameter vacuum vessel
- Expansive diagnostic access
- Dipole supported by three thin spokes
- Two ECRH heating frequencies provide up to 5 kW power



The Levitated Dipole Experiment (LDX)

ECRH sustains hot electron and thermal species

- $n \sim n_{eb}$: n_e dominated by background thermal plasma
  - Can be unstable to low frequency modes: $\omega \sim \omega_d \sim \omega_*$
  - Can be unstable to MHD
- $\beta \sim \beta_{eh}$: Beta is dominated by hot electrons
  - Stability of hot electron species requires background density
  - Can be unstable to high frequency modes: $\omega \sim \omega_{dh}$

In future levitated high density experiments thermal species will dominate both β and n_e

ECRH: EBT and Dipole

- Similar to EBT (bumpy torus):
  - MHD-like background mode and kinetic hot electron interchange can be present.
  - EBT symbiosis: Background stabilized by diamagnetic well of hot electrons. Hot electron stability requires $n_{eh}/n_b < N_{crit} \sim 0.2$
    - EBS was “long-thin” mirror, I.e. no significant compressibility
- Dipole: background plasma stability does not require hot electrons
  - MHD mode stabilized by compressibility
  - MHD instability leads to convective motion of background
    - tends to create $n_{core}/n_{edge} \sim V_{edge}/V_{core}$ & $p_{core}/p_{edge} \sim (V_{edge}/V_{core})^{\gamma}$, i.e. to centrally peaked n_b & p.
  - LDX shaping (Helmholtz) coils permit variation of V_{edge}/V_{core}

Properties of hot and thermal species

- Hot electron species: E_{eh}>50KeV
  - Hot electron interchange mode: f ~ 1-100 MHz
    - Free energy of hot electron density gradient
  - Loss cone modes: unstable whistler modes: f >2 GHz
    - Hot electron loss cone and anisotropy
- Background plasma: Te, Ti ~10-50 eV
  - MHD-like modes; f ~ 20-100 kHz
    - Background plasma pressure gradient
  - Drift frequency (entropy) modes: f ~1-5 KHz
    - Background plasma density and temperature gradients
- ECRH accessibility oscillations: f~50-200 Hz

Some theoretical results: Maxwellian Plasma

Bad Curvature region (between pressure peak & vacuum vessel)

- MHD: stable to interchange when $\delta(pV^{\gamma})>0$, $V=\oint dl/B$
  $p_{core}/p_{edge}<(V_{edge}/V_{core})^{\gamma}\sim 10^3$: want large vacuum chamber
  - MHD equilibrium from field bending and not grad-B term -> $\beta\sim 1$
  - Unstable interchange modes evolve into convective cells
- Ballooning modes stable when interchange stable
- Weak resistive mode at high β ($\gamma\sim\gamma_{res}$ but no $\gamma\sim\gamma_{res}^{1/3}\gamma_A^{1/3}$ mode)
- Drift frequency modes: electrostatic “entropy” mode
  - unstable when $\eta< 2/3$

- Good curvature region (between floating coil and pressure peak)
  - Entropy mode can be unstable when grad(n_e)<0

Summary of Collective Modes in Dipole

- Hot electron driven modes
  - Hot electron interchange (HEI): $\omega \sim \omega_{dh}$, f~1-50 MHz

    Ref: Garnier et al., to be published in PoP 2006.
  - Whistler (loss cone) modes; $\omega \sim \omega_{ce}$, f~1-30 GHz
- Background plasma driven
  - Entropy mode: $\omega \sim \omega_{*b}$, $\omega \sim \omega_{db}$, f~1-10 KHz
  - Background MHD: $\gamma \sim \gamma_{MHD\text{-}b}$, f~50-100 KHz

    [Krasheninnikova, Catto, PoP **12** (2005) 32101].
    - Non-linear development can form convective cells

    [Pastukhov and Chudin, Plasma Physics Reports **27** (2001) 907.]
- ECRH "breather mode" possible
  - Over-dense cutoff of heating: f~L^2/D, f~100-300 Hz
  - Would prevent large density grad and raise η

Stability of background plasma gives us information on thermal plasma dipole confinement

LDX Parameters in high-β Regime

ECH creates a hot electron component within a background plasma.

Hot Electron Plasma

- Density: $n_{eh} << n_{eb}$
- Temperature: $T_{eh} >> T_{eb}$
  - Hot electron energy > 50 keV, ω_{dh}~1-10 MHz
- Pressure
  - Core 200 Pa.
  - $\beta_{max} \sim 20\%$
- Confinement
  - Stored energy ~ 200 J, "τ_E" ~ 50 msec.

Background Plasma

- Density
  - Core: $\langle nl \rangle / L \sim 1\text{-}5 \times 10^{16}\ m^{-3}$
    - n_{cutoff}(2.45 GHz)= 7.6e16 m^{-3} @ R_0=0.78 m
    - n_{cutoff}(6.4 GHz) = 5.2e17 m^{-3} @ R_0=0.60 m
  - Edge density 1-2 x $10^{16}\ m^{-3}$
- Temperature:
  - Edge temperature ~10-20 eV, ω_{*d} ~1-10 KHz
- Pressure
  - Edge 0.01 Pa

$P_{Core}/P_{edge} \sim 10000$

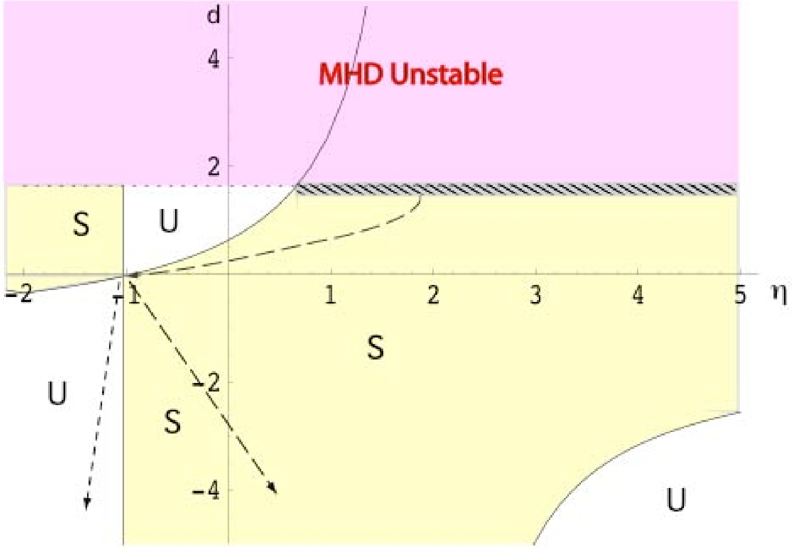
Plasma can be unstable to drift frequency mode

- Entropy mode is a drift frequency, flute mode.

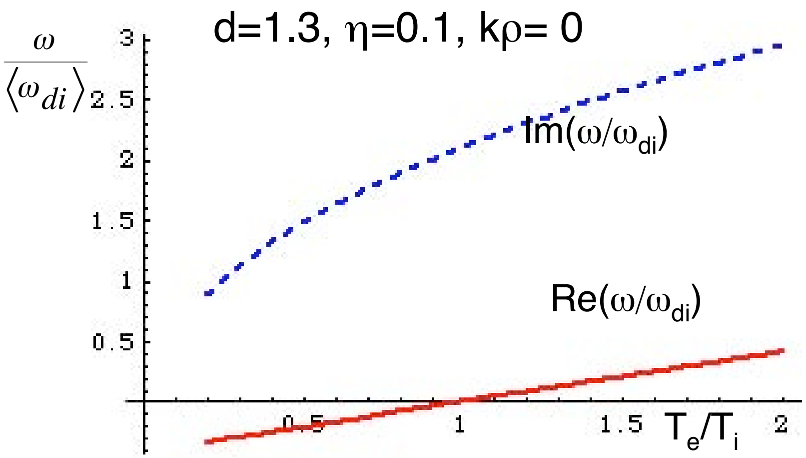
  Dispersion Relation:

$$\hat{\omega}^2\left(\frac{d\ln p}{d\ln V}+\frac{5}{3}\right)+\frac{5\hat{\omega}}{3}\left(\frac{T_e}{T_i}-1\right)\left(\frac{d\ln p/d\ln V}{1+\eta}+1\right)+\frac{5}{9}\frac{T_e}{T_i}\left(\frac{d\ln p}{d\ln V}\frac{3\eta-7}{\eta+1}-5\right)=0$$

$$\hat{\omega}=\omega/\langle\omega_{di}\rangle,\quad d=-\frac{d\ln p}{d\ln V}=(1+\eta)\frac{\omega_{*i}}{\langle\omega_{di}\rangle},\quad \eta=\frac{d\ln T}{d\ln n}$$



Real frequency is introduced for $T_e \neq T_i$



Properties of entropy mode

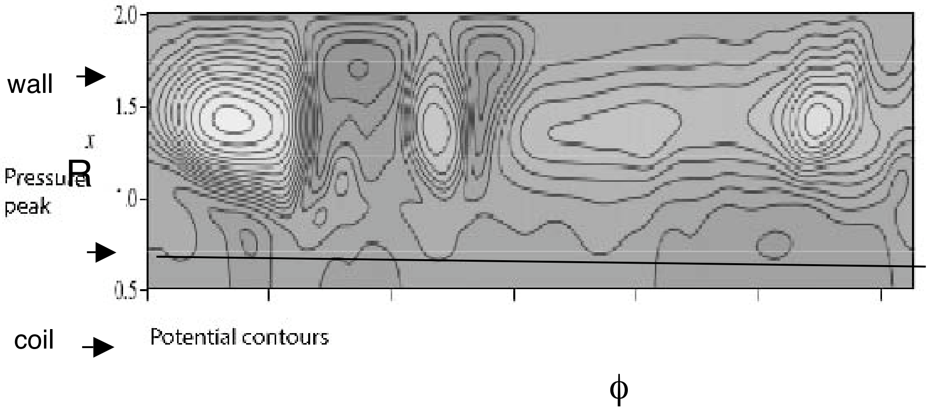
- Frequency $\omega \sim \omega_{*i} \sim \omega_{di}$
  - ω increases with ∇n_e and T_{ib}
  - Plasma beyond pressure peak stable for $\eta > 2/3$
  - Stable at $d=5/3$, $\eta=2/3$
    - Instability will move plasma towards marginal $d=5/3$, $\eta=2/3$, i.e. tends to steepen density gradient
- Stability in good curvature region depends on sign of ∇n_e
- Mode appears at both high and low collisionality [2]
- Electrostatic “entropy” mode persists at high β [3]
- But linear theory is not always predictive of real plasmas

Some references:

1. Kesner, PoP **7**, (2000) 3837.
2. Kesner, Hastie, Phys Plasma **9**, (2002), 4414
3. Simakov, Catto et al, PoP **9**, (2002), 201

Convective Cells in Dipole

- Convective cells can form in closed-field-line topology.
  - Field lines charge up -> $\psi - \phi$ convective flows (r-z in z-pinch)
  - 2-D nonlinear cascade leads to large scale vortices
  - Cells circulate particles between core and edge
    - No energy flow when pV^{γ}=constant, (i.e. $p' = p'_{crit}$).
    - When $p' > p'_{crit}$ cells get non-local energy transport. Stiff limit: only sufficient energy transport to maintain $p' \gtrsim p'_{crit}$.
  - Non-linear calculations use reduced MHD (Pastukhov et al) or PIC (Tonge, Dawson et al) in hard core z-pinch



Reduced MHD: Pastukhov, Chudin, Pl Physics 27 (2001) 907.

PIC: Tonge, Leboeuf, Huang, Dawson, 10 Phys Pl. (2003) 3475.

Low frequency turbulence (f< 6 KHz) sometimes seen

- Often not observed
- On 5/13/05 had well conditioned vacuum chamber
    - Well defined modes (f~3-5 kHz) observed for 4e-7< p_0<1e-6 torr
    - Turbulent spectrum (f~1-3 KHz) observed for 1e-6< p_0<4e-6 torr
  - Gas control experiments
    - Gas off: mode frequency rises and mode weakens.
    - Gas puff: mode frequency drops and forms broad low frequency spectrum

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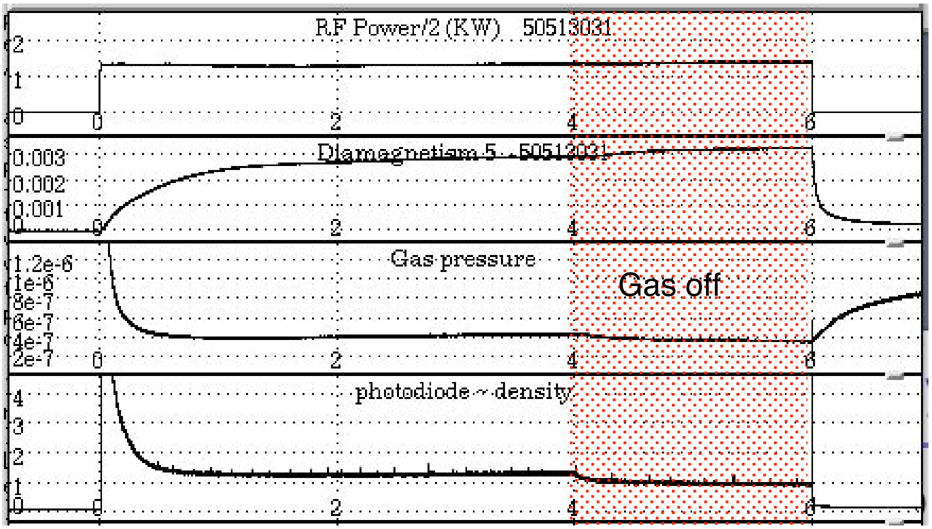

2005

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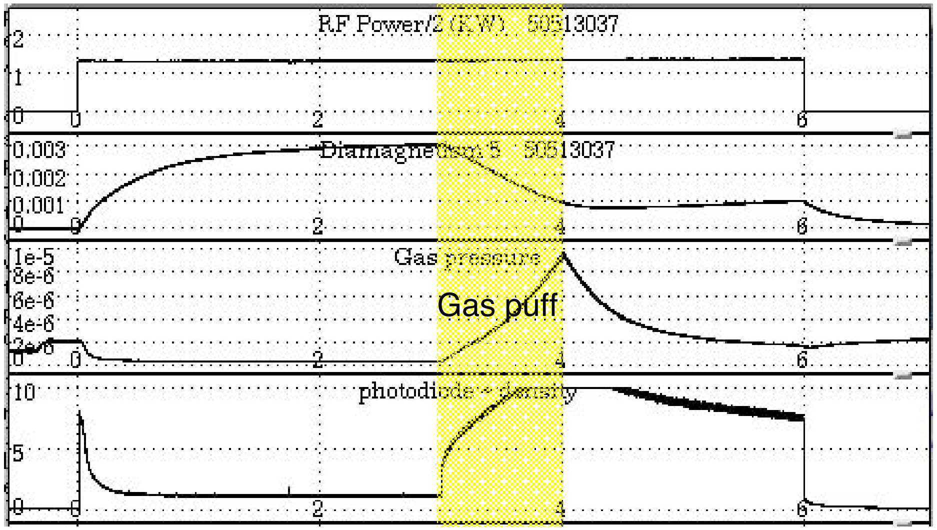
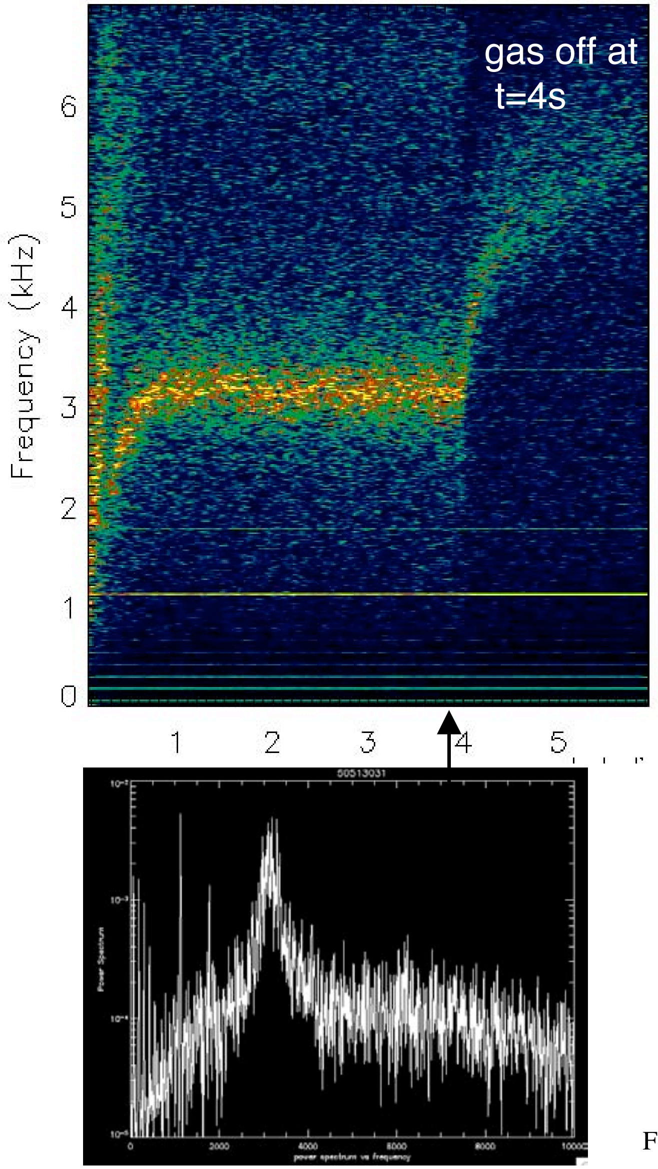
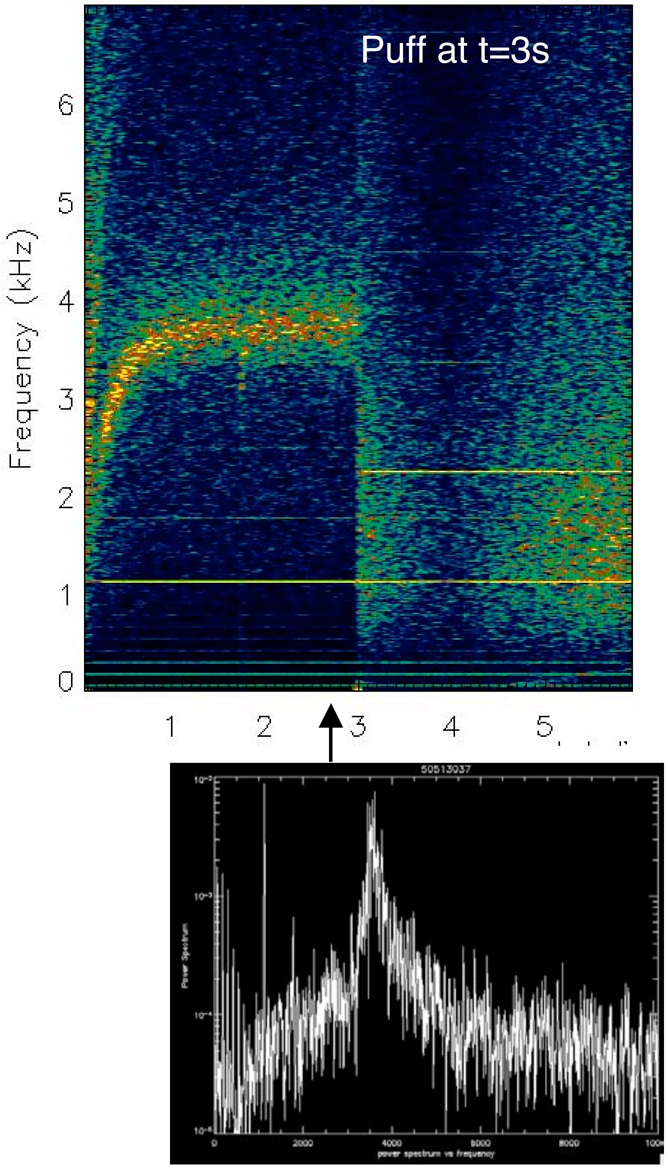


5/13/05: low base pressure in chamber

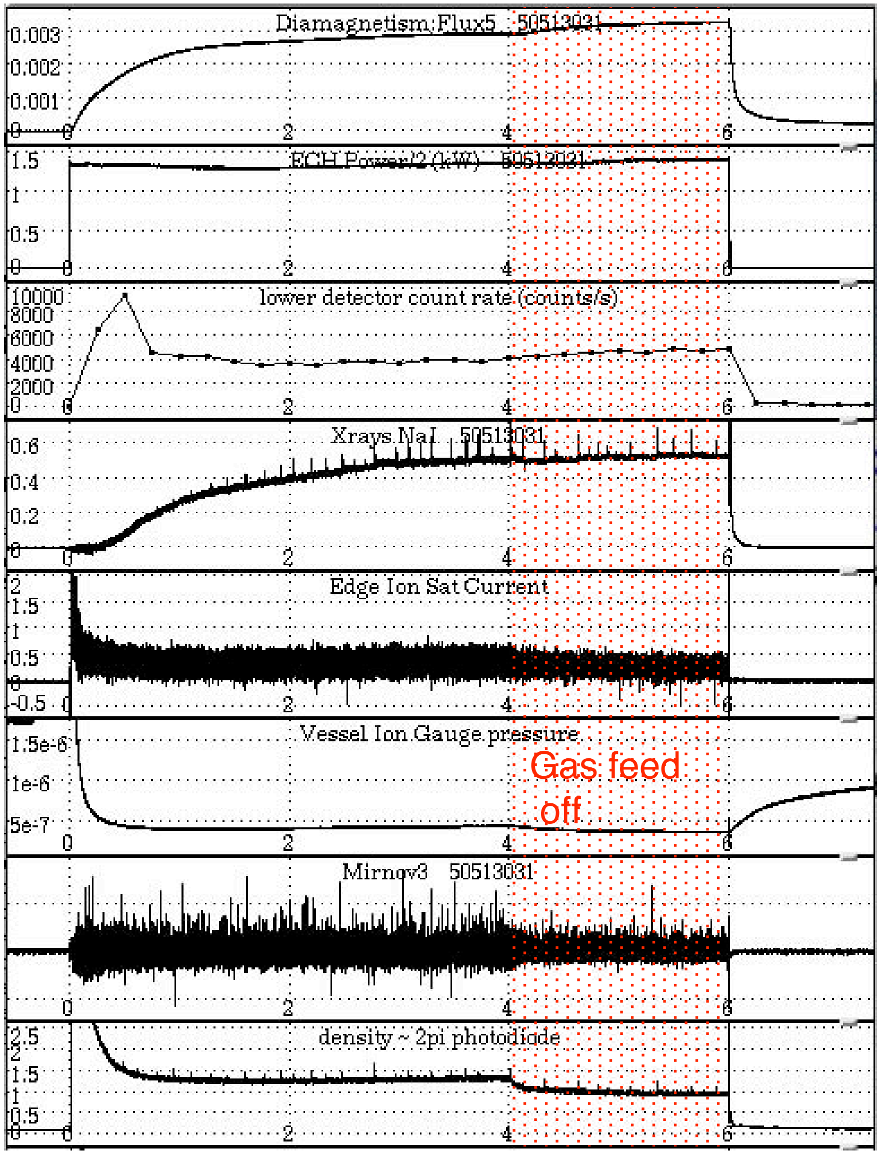
50513031 higher base pressure
p_0(t< 4s)=4.4e-7 torr.

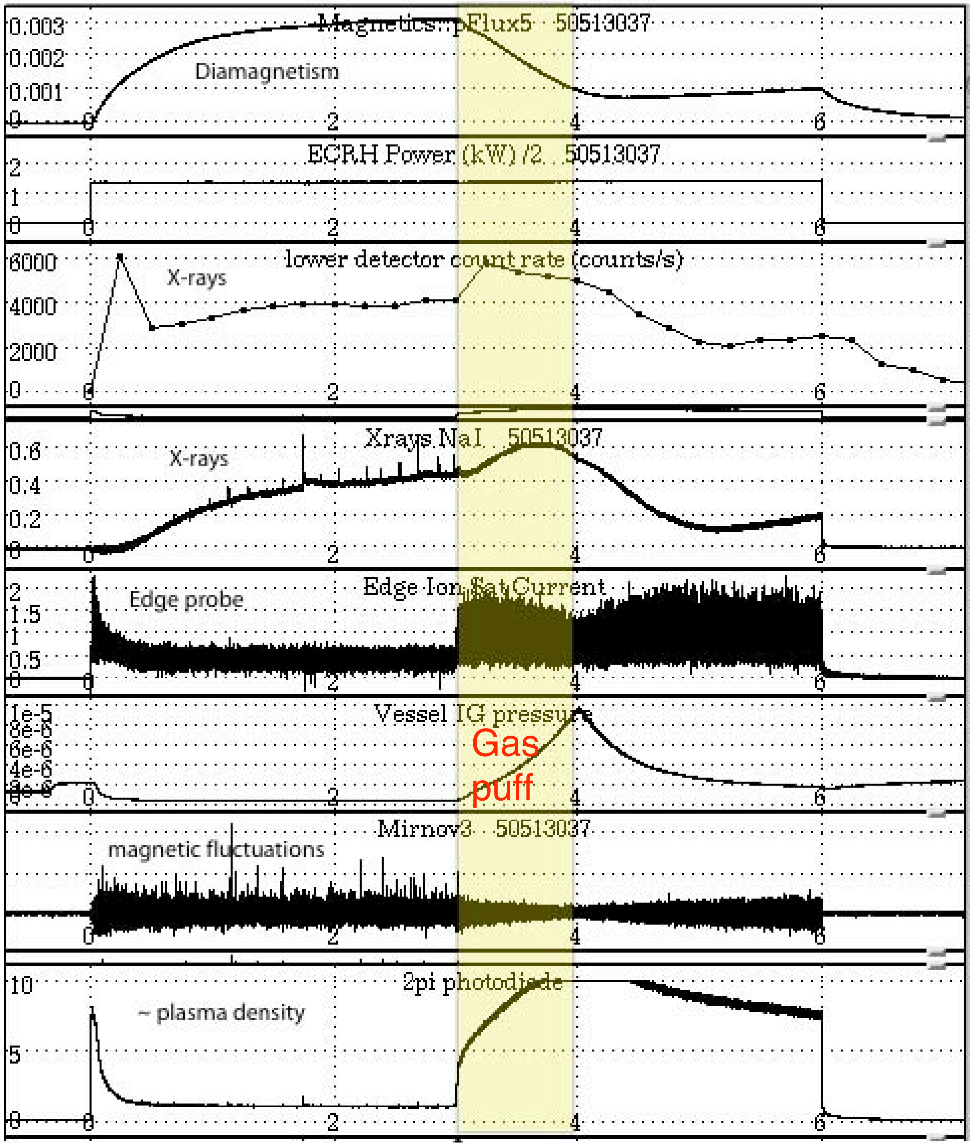


50513037 lower base pressure
p_0(t< 3s)=3.9e-7 torr.



Compare Discharges 50513031and 037





Compare two discharges from 5/13/05

- 50513031
- p_0(t<4s)=4.4e-7 torr, Turbulence (τ_{cor}~12 μs) & *f*=3.2 kHz
- gas off at t=4 s raises *f* and weakens mode
  - → β rises (from pFlux5: diamagnetism)
  - → n_{eb} falls (from photodiode)

- 50513037
- p_0(t<3s)=3.9e-7 torr, Turbulence & *f*=3.75 kHz
- gas puff at t=3 s lowers *f*.
- Density rises factor 3 on both core interferometer and edge probe
  - ➢ Indicates increase in η=dlnT/dln

☹ No measure of rotation frequency. Is observed frequency affected by doppler shift of rotating plasma?

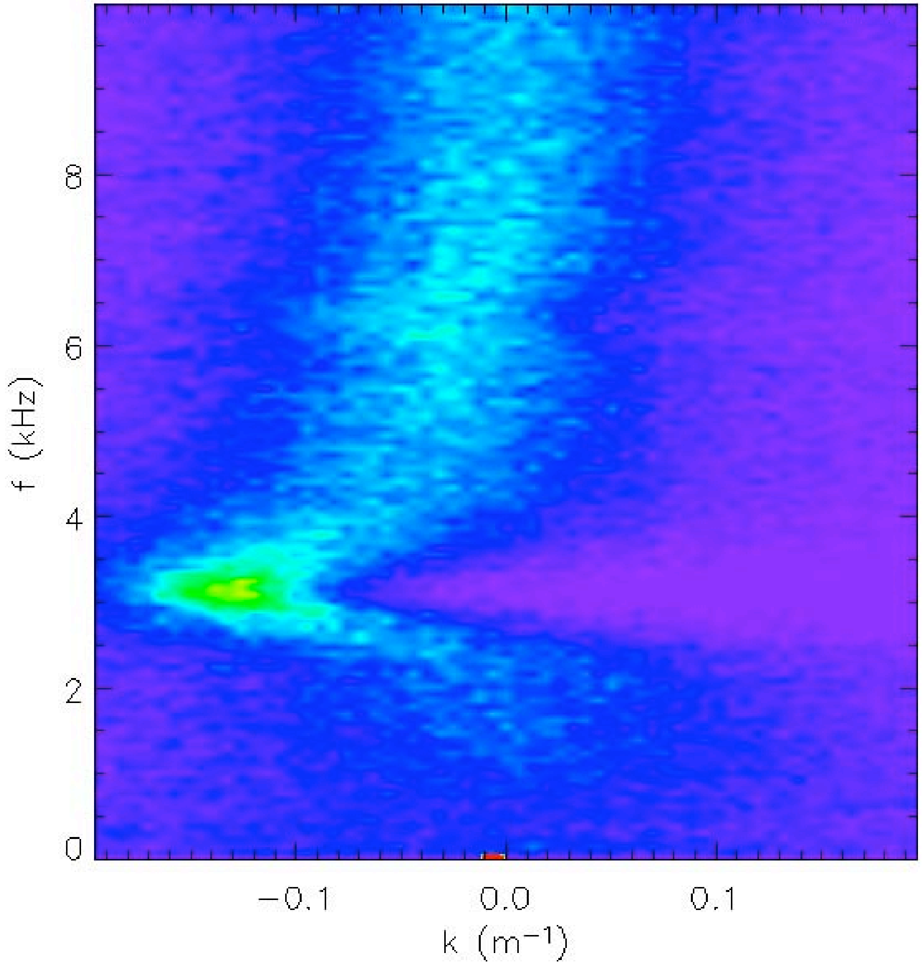
☹ No measure of $k_\perp$ spectrum as yet

Two point spectral density, Mirnov coils

Spectral density identifies $k_\perp$ for observed frequencies

Ref: Beall, Kim, Powers, J App Phys 6 (82) 3933.

50513031



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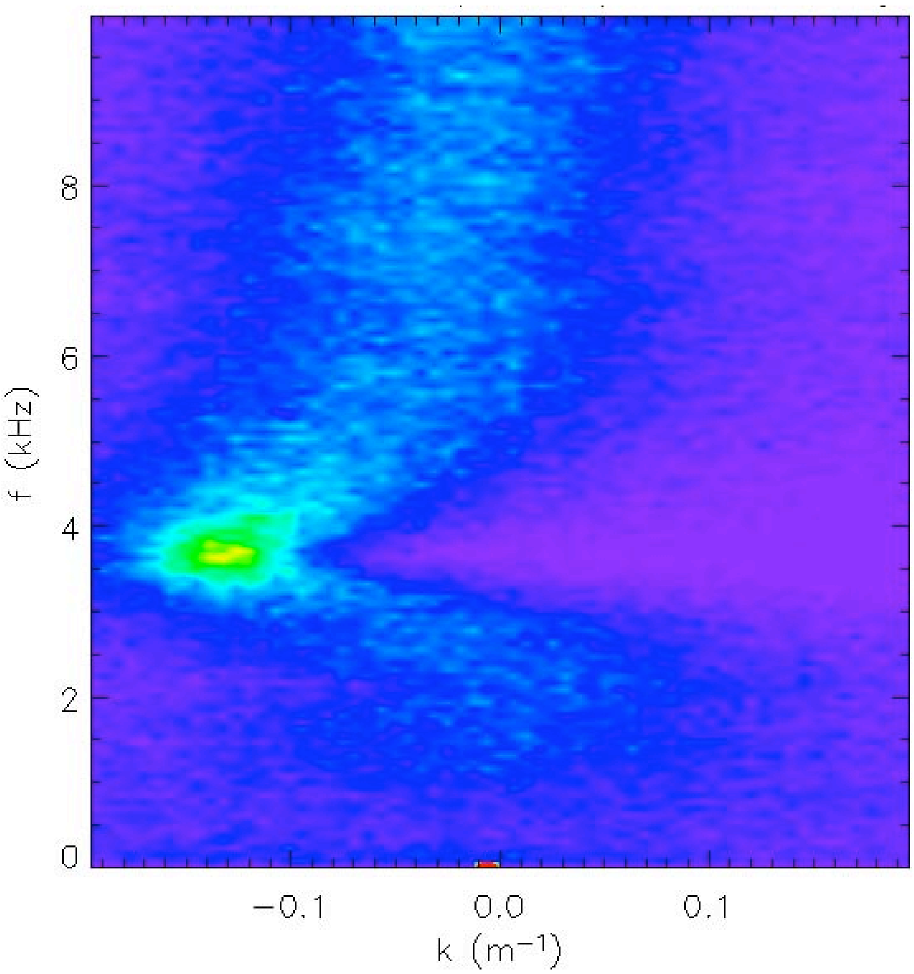
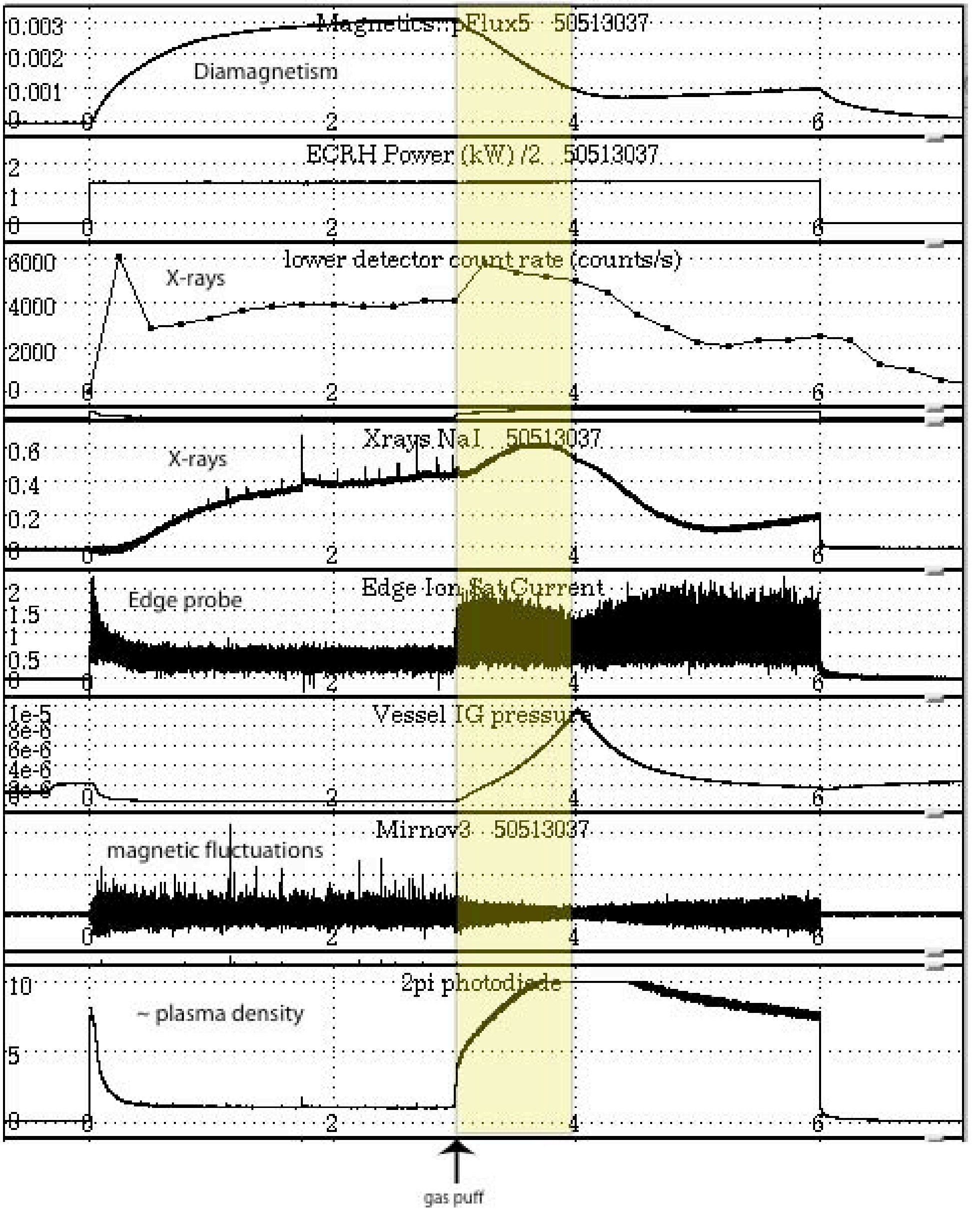


Discharge 50513037: gas puff at t=3 s

- Gas puff at t=3 s leads to:
  - ➔ fast rise in n_{eb}
  - ➔ Slow fall in β (& n_{eh}) due to increased pitch angle scatter
- Density rises factor 3 on both core interferometer and edge probe
  - ➔ Indicates increase in η=dlnT/dln
- In future levitated operation will eliminate pitch angle scatter loss. Gas puffing should provide dense plasmas



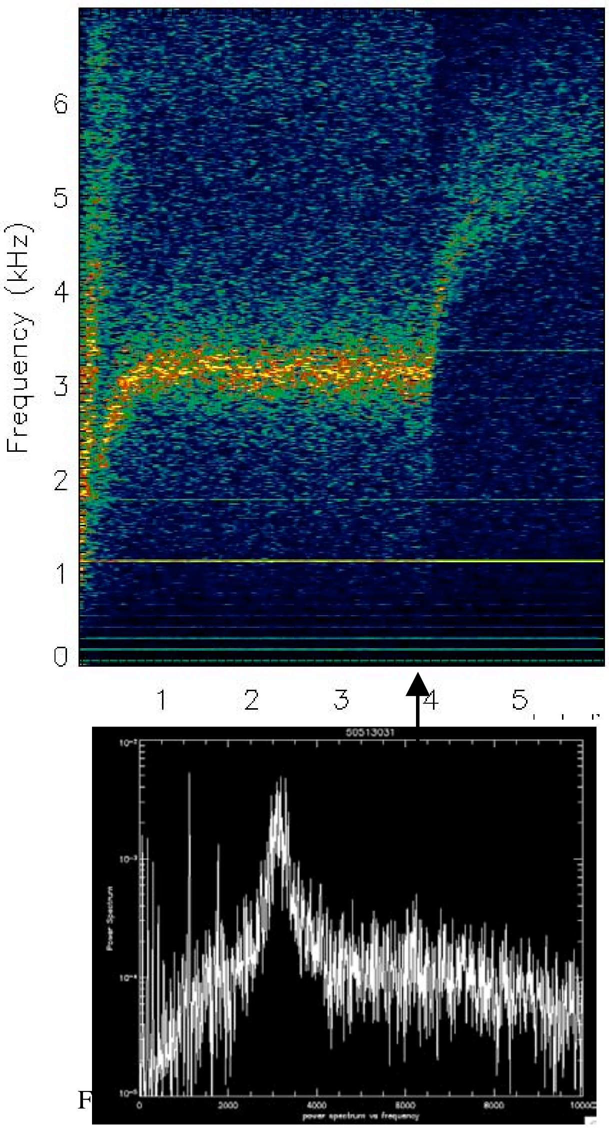
Entropy mode ? mode frequency rises with ω_*

Edge gas fueling will decrease T_i and increase edge fueling relative to central fueling (from recycle off f-coil). Lower P_{0edge} -> higher ∇n_e

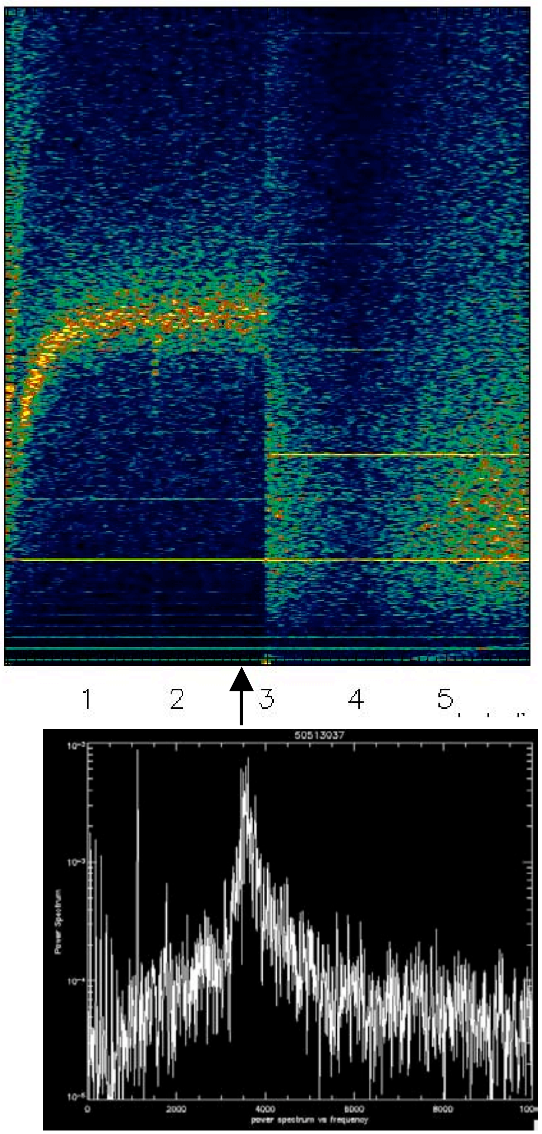
$p_{0\text{-}31} < p_{0\text{-}37}$

- From interferometer ($<n_e l>$) and edge probe observe higher neutral pressure
  -> lower $\omega_{*i} \propto T_i \nabla n_i / n_i$ & $\omega_{di} \propto T_i$
- 50513031:
  - $p_0(t<4s)$=4.4e-7 torr, f=3.1 kHz
  - gas off at t=4 s raises f.
- 50513037:
  - $p_0(t<3s)$=3.9e-7 torr, f=3.75 kHz
  - gas puff at t=3 s lowers f.
  - Gas puff will also raise η and can stabilize entropy mode (3 < t <5s).

50513031 high base pressure
$p_0(t=4s)$=4.4e-7 torr
gas off at t=4s



50513037 lower base pressure
$p_0(t=3s)$=3.9e-7 torr
puff at t=3s



Gas puff experiment

- Gas puff at t=3 s can raise η and stabilize mode.

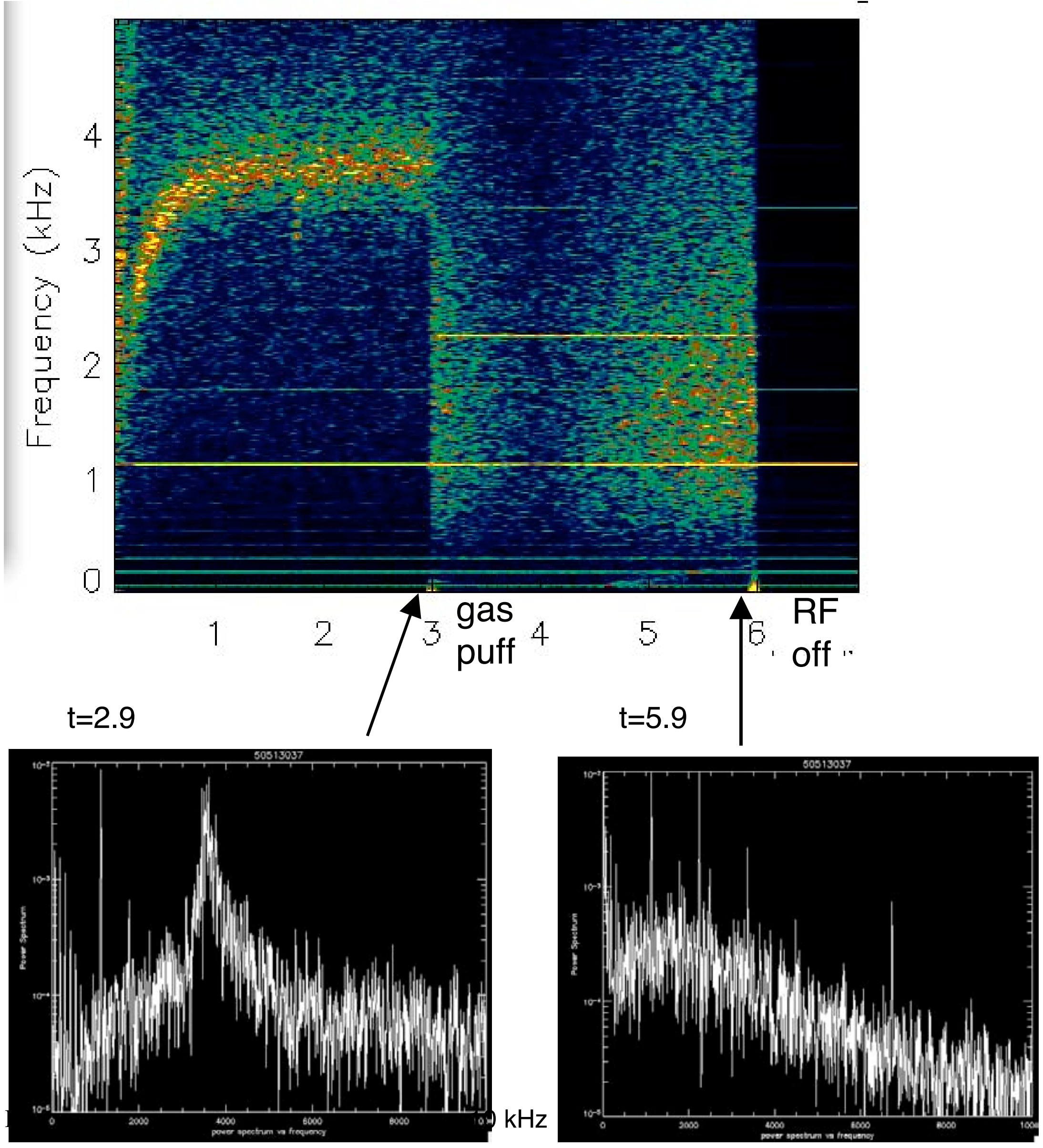
  Instability absent at t~4s

  - Theory requires $\eta > 2/3$ for stability for entropy mode

- At later time (t > 5 s) broadband fluctuations appear with 1< f < 3 KHz (at higher density)

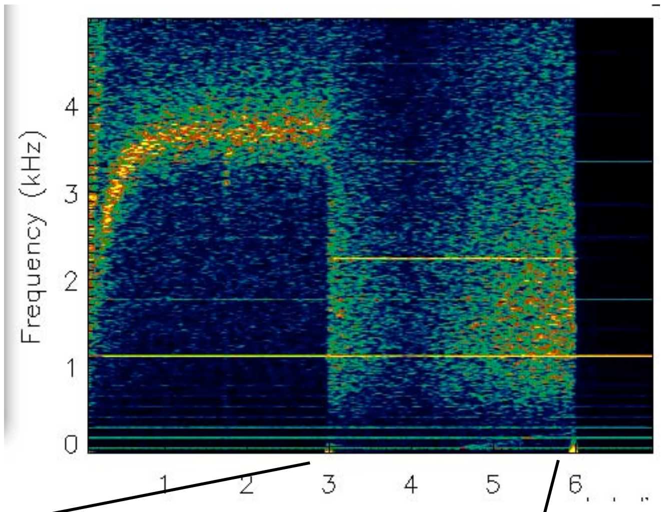
- During afterglow (t > 6 s) background plasma reduced, profiles relax and mode disappears.

Photodiode-9 (50513037)

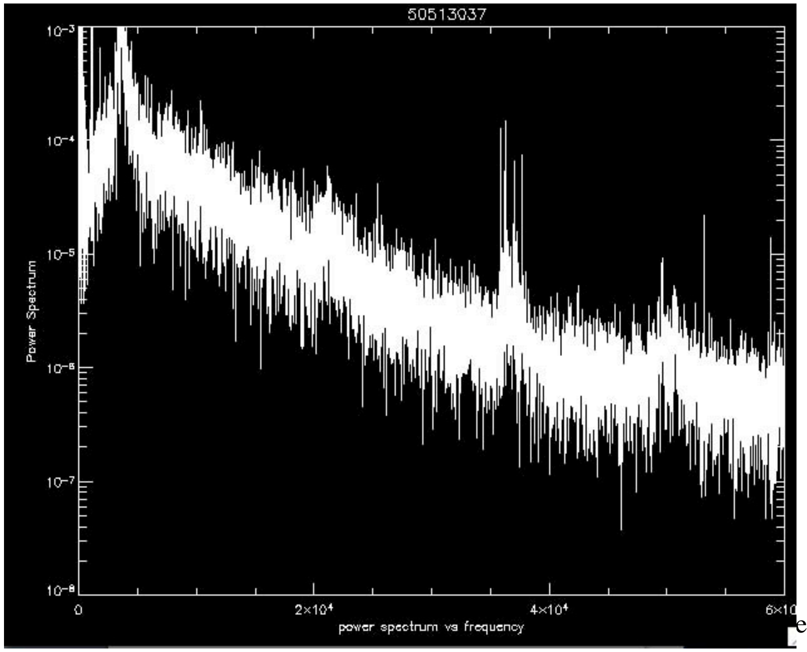


Power Spectra for 1-10 kHz shows f^{-3} falloff

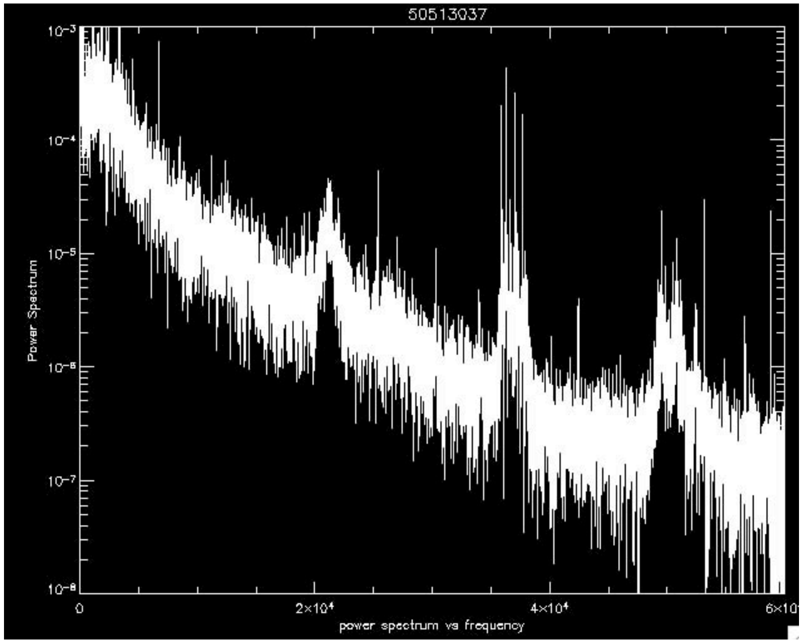
- Power spectrum $P_I \propto f^{-a}$, a~3
- High frequency features may be background MHD



Power spectrum: t=2.9 s



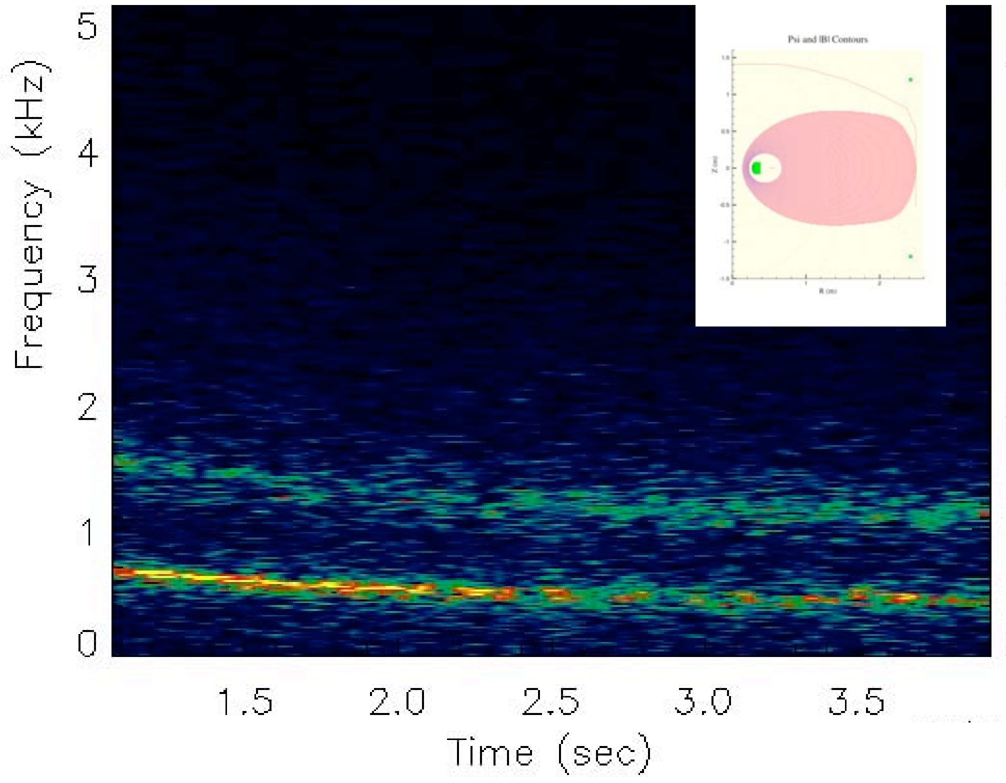
t=5.9s



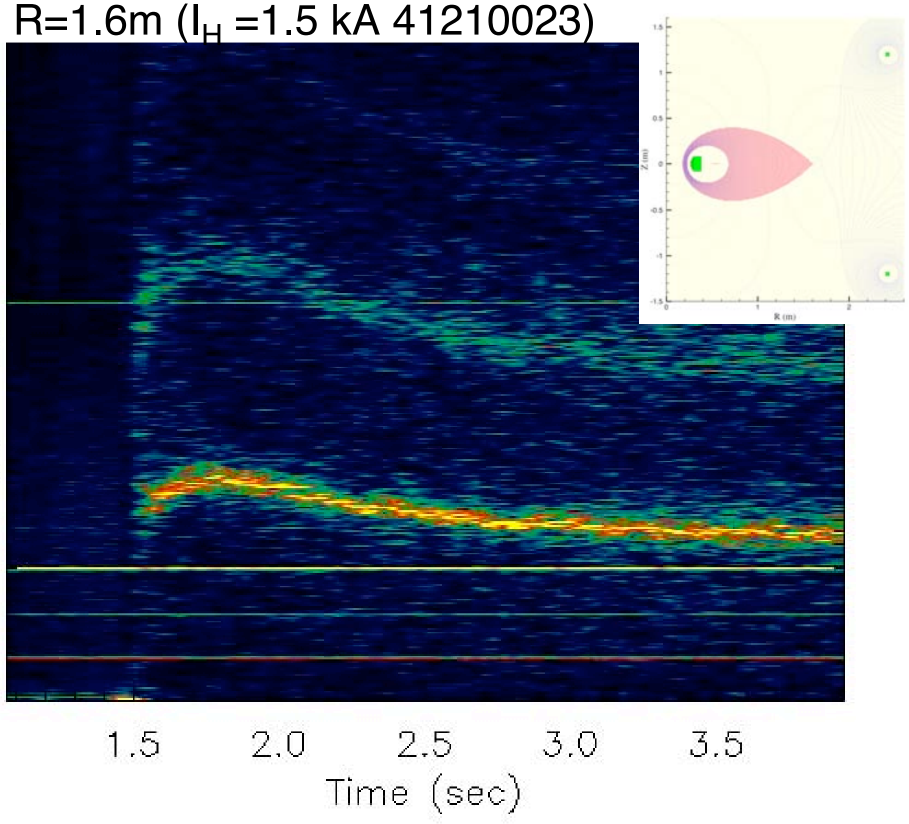
During shaping experiment frequency falls. May indicate flattening of density profile (higher ω_*)

- Helmholtz coils create separatrix and reduce plasma size
  - Diverted plasma may have reduced density gradient and $\omega \propto \omega_{*i} \propto T_i \nabla n_i / n_i$
- Frequency appears to be dependent on plasma size
  - Frequency higher in smaller plasma with larger gradients
- Mode not present when for I_H=0 in these discharges.
- Observed at edge (probes) & core (Mirnov coils, photodiode array)

R=2.5m (I_H =0.25 kA 41210025)



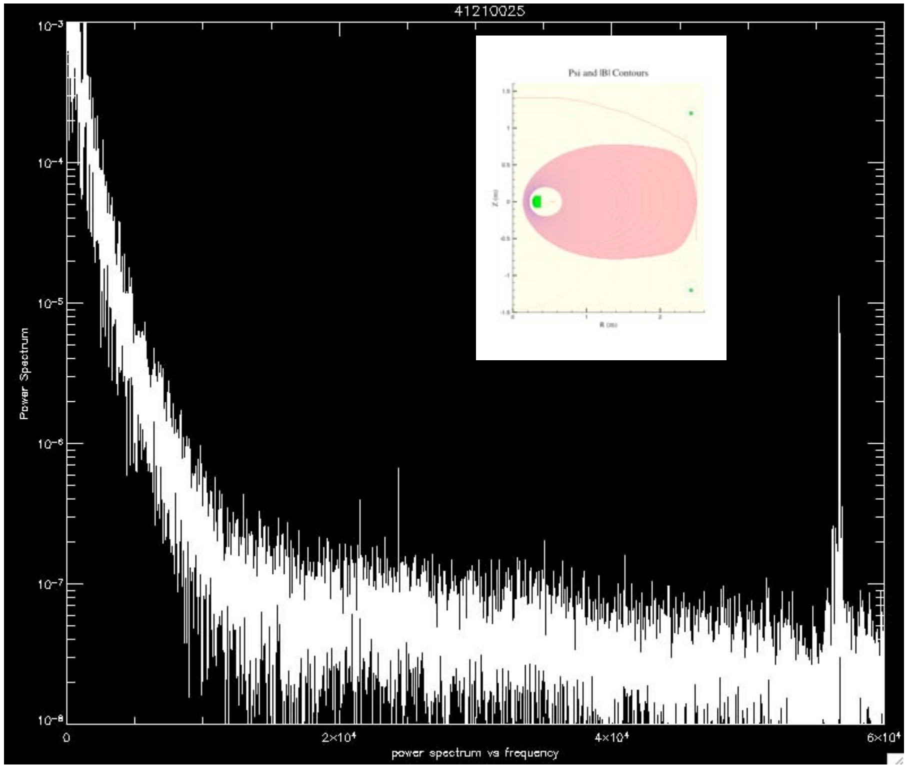
R=1.6m (I_H =1.5 kA 41210023)



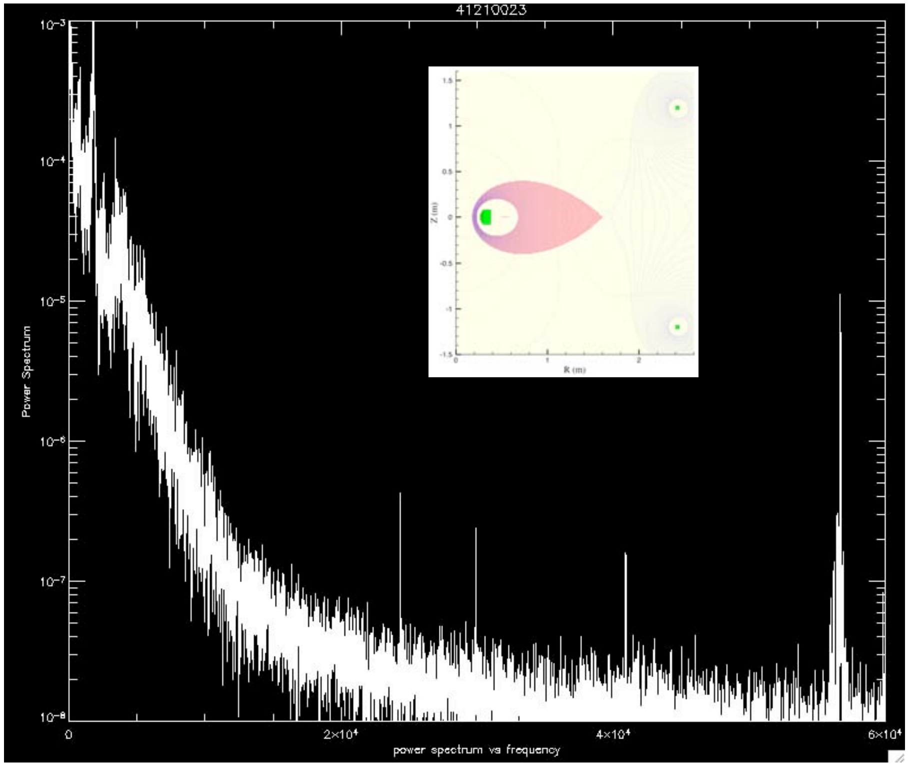
Plasma shaping experiments: 55 MHZ MHD mode appears

- 55 KHz “MHD” mode appears for both large and smaller plasma size. Seen on photodiode array
- Power spectrum of low frequency spectra similar for small and large plasmas: $d\ln P_I/df \approx -3$

R=2.5m (I_H =0.25 kA 41210025)



R=1.6m (I_H =1.5 kA 41210023)

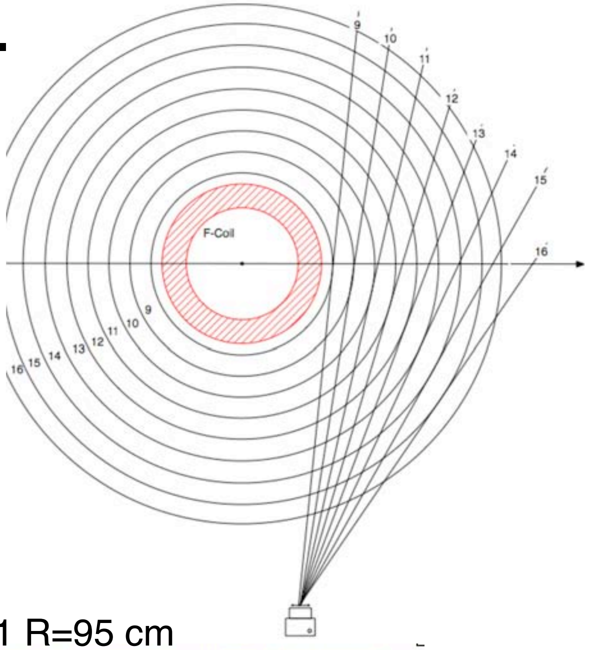


Unresolved issues

- Doppler shift from plasma rotation not yet measured
- Wave number, $k_\perp$, spectrum not measured

ECRH accessibility mode ?

- 220 Hz mode peaked at 6.4 resonance.
  - Localized to core. Closeness to-coil increases frequency of density feedback
- 100 Hz mode peaked at 2.45 resonance
- Both modes weaken for single frequency heating
  - Indicates interaction of RF diffusion with density profile.

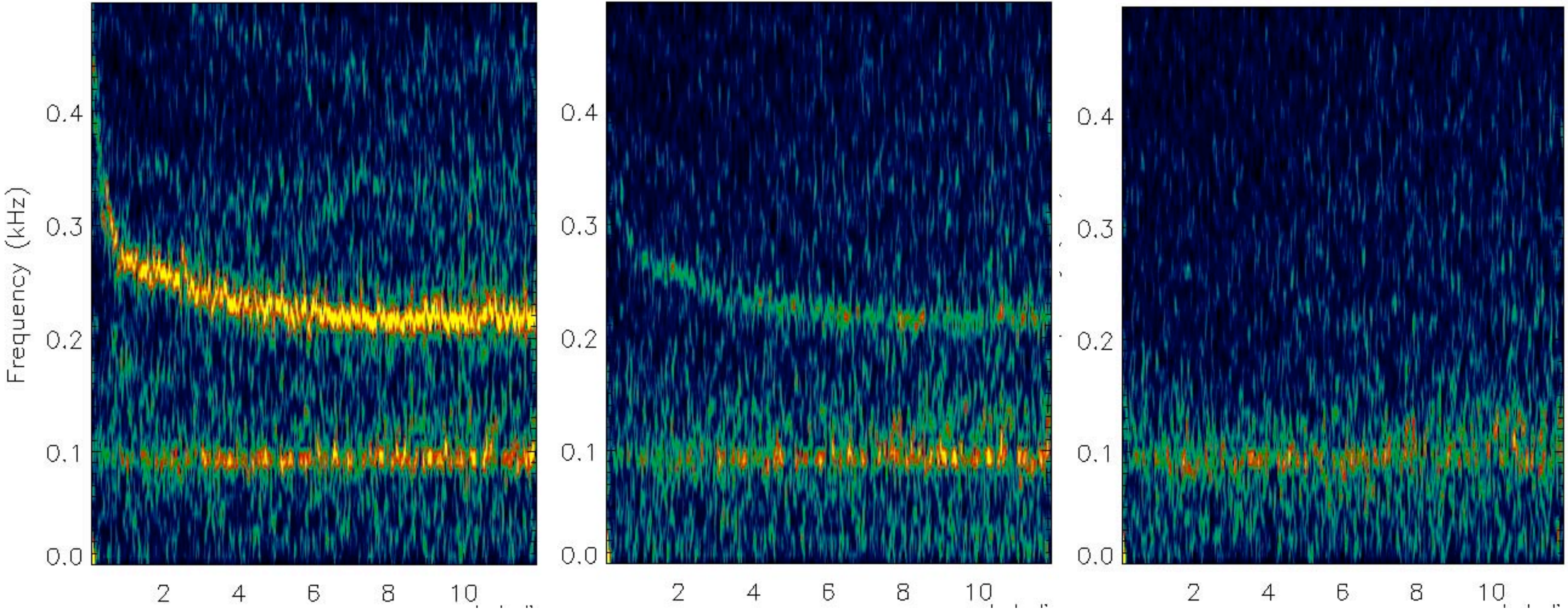


Collimated photodiode: Shot 50701009

view # 9, R=65 cm

#10, R=80 cm

#11 R=95 cm



Conclusions: thermal LDX plasma

- ECRF heated plasmas yield valuable information on background (thermal) plasma
  - Low frequency turbulence can be present
    - May evolve from entropy mode. Need info on $k_\perp$
  - MHD activity can be present, presumably forming convective cells
    - 2-D structures not yet measured
- At higher density background plasma more strongly coupled to thermal plasma

LDX Parameters in “High beta” Regime

- Density: $n_{eh} << n_{eb}$
  - Core line average density 1-5 x 10^{16} m^{-3}
  - Edge density 1-2 x 10^{16} m^{-3}
    - n_{cutoff}(2.45 GHz)= 7.6e16 m^{-3} @ R_0=0.78 m
    - n_{cutoff}(6.4 GHz) = 5.2e17 m^{-3} @ R_0=0.60 m
- Temperature: $T_{eh} >> T_{eb}$
  - Hot-electron energy > 50 keV, ω_{dh}~1-10 MHz
  - Edge temperature ~10-20 eV, ω_{*b} ~1-10 KHz
- Pressure
  - Edge 0.01 Pa, Core 200 Pa. --> Ratio ~ 10000
  - Beta (local maximum) ~ 20%
- Confinement
  - Stored energy ~ 200 J, “τ_E” ~ 50 msec.