Abstract

Experiments to elucidate the nature of electron thermal transport have been conducted in DIII-D plasmas using modulated off-axis electron-cyclotron heating (ECH). Density fluctuations were measured using beam-emission spectroscopy, microwave reflectometry, and far-infrared scattering. Simulations of the experiment are performed with the gyrokinetic and gyrofluid flux-tube codes GS2[1] and GRYFFIN,[2] respectively. Comparisons of experiment and simulation results for the fluctuations (amplitude, k-spectra, etc.) and transport fluxes (ion and electron) will be presented for both time-averaged and modulated quantities.

[1] F. Jenko, W. Dorland, M. Kotschenreuther, and B. N. Rogers, Phys. Plasmas 7, 1904 (2000) and refs. therein.

[2] W. Dorland and G. W. Hammett, Phys. Fluids B 5, 812 (1993); M. A. Beer and G. W. Hammett, Phys. Plasmas 3, 4046 (1996).

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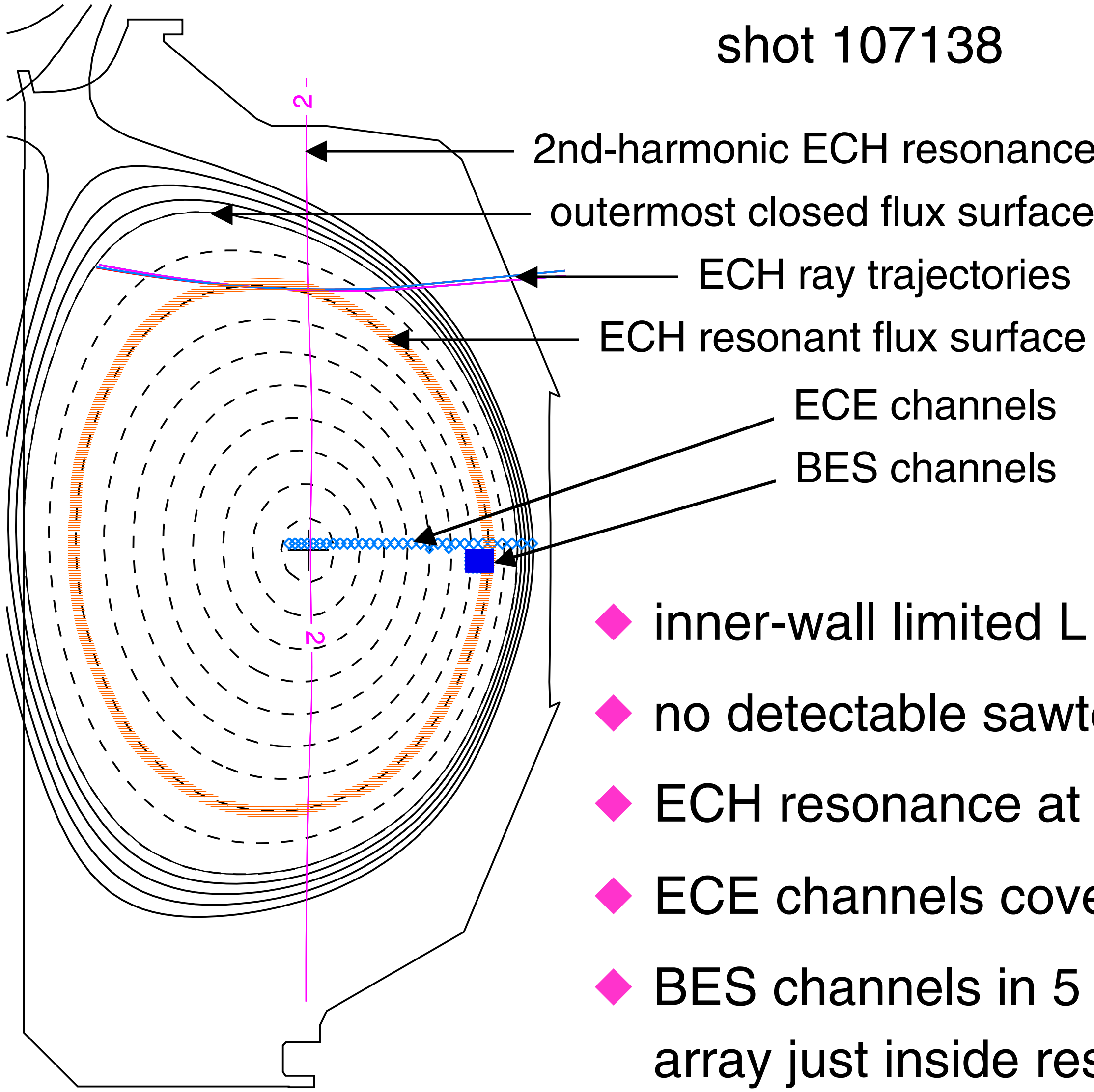
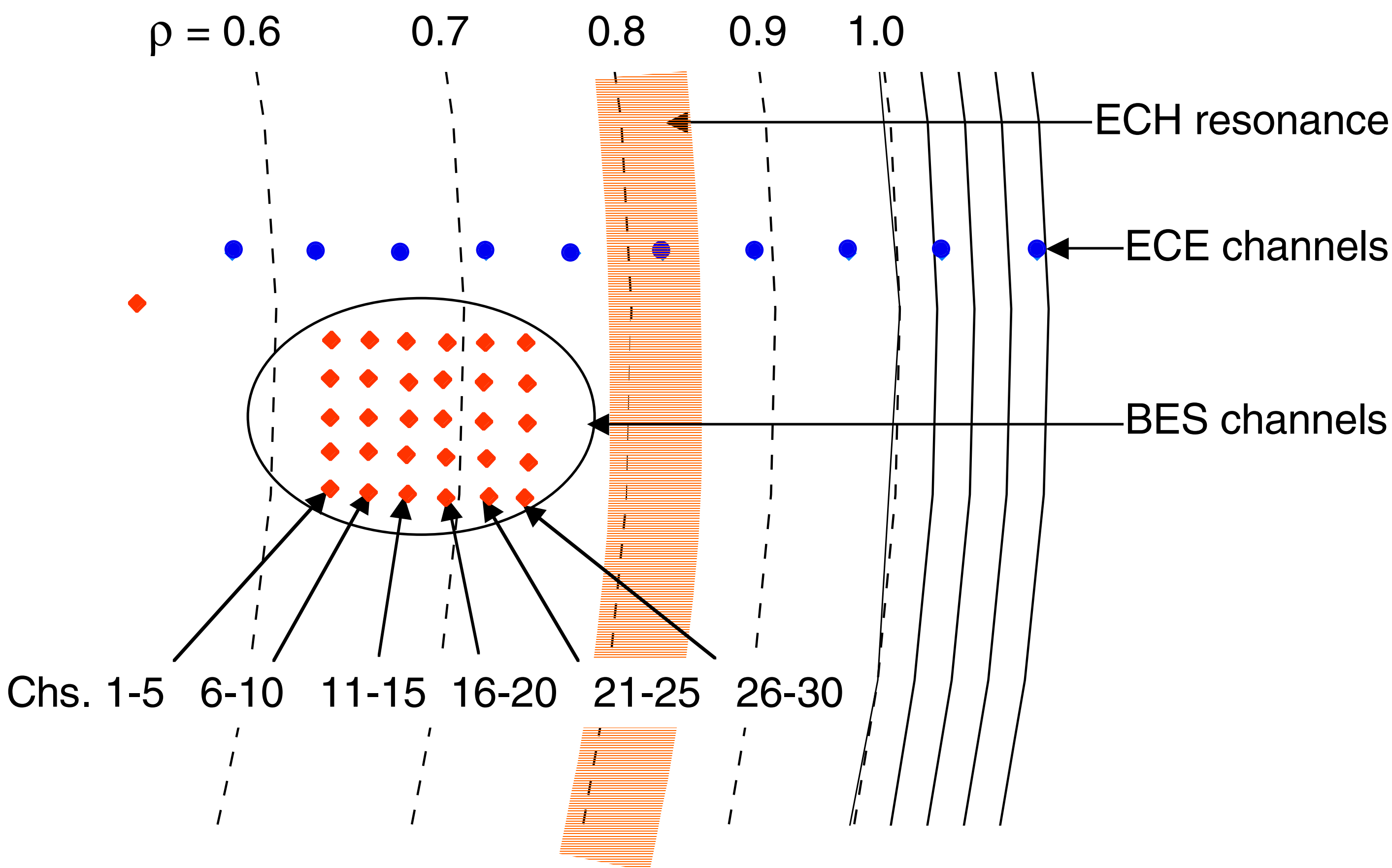
Experimental Setup



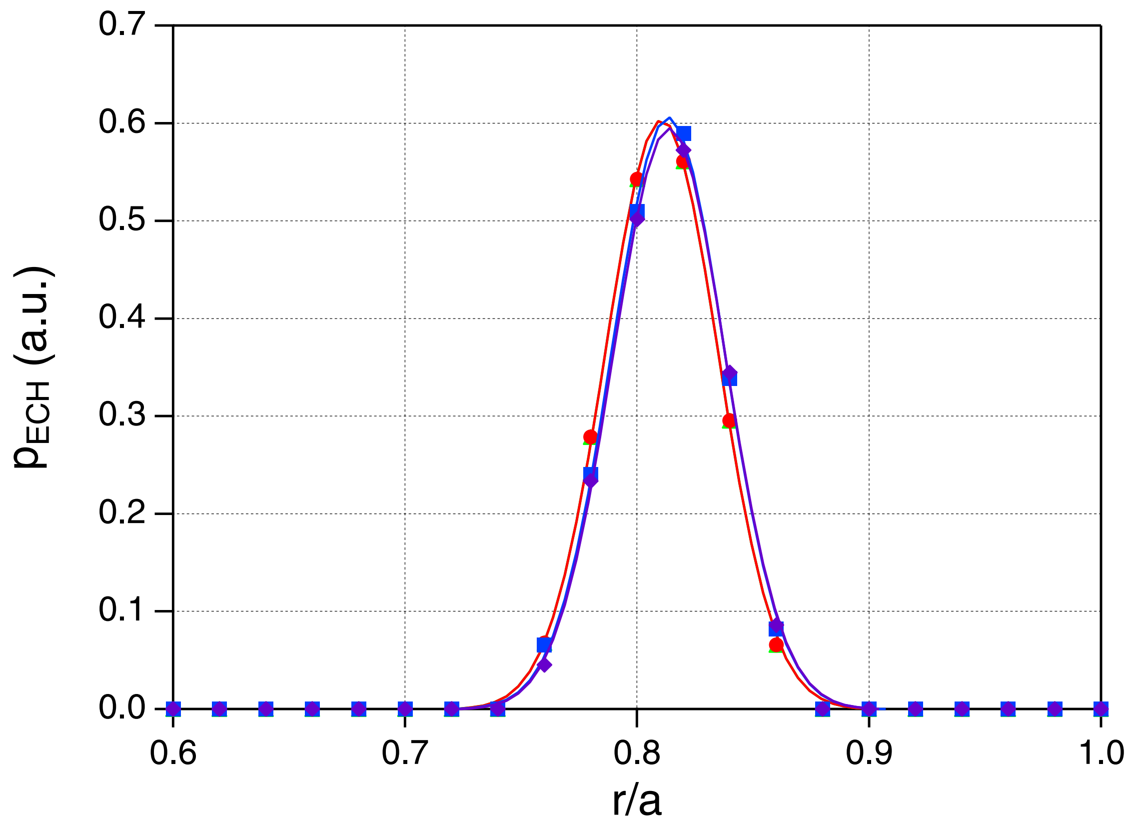
- inner-wall limited L mode (no ELMs)
- no detectable sawteeth, MHD
- ECH resonance at $r/a \approx 0.815$
- ECE channels cover entire minor radius
- BES channels in 5 (vertical) x 6 (radial) array just inside resonance radius.

Experimental Setup (close-up)



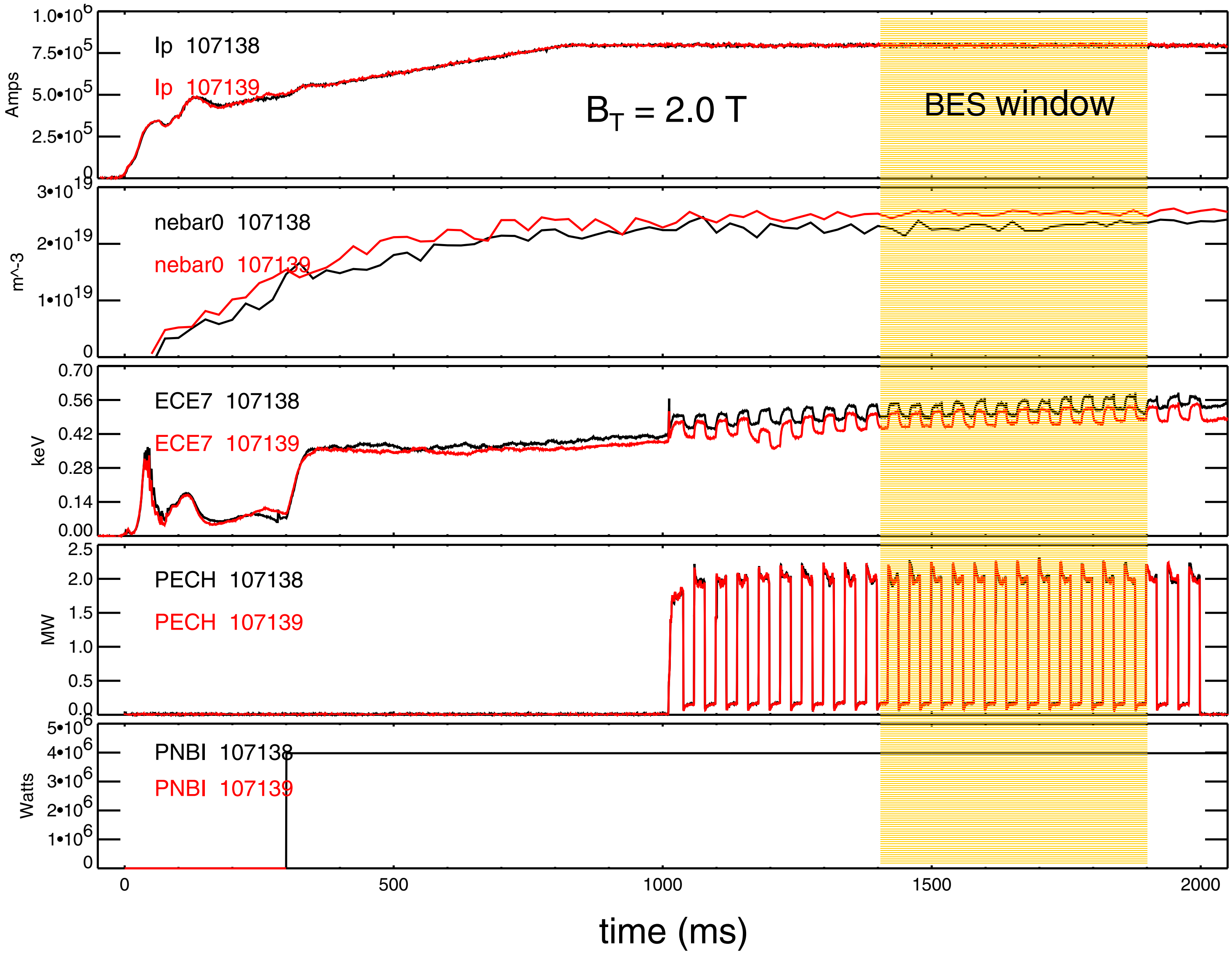
- Six poloidal arrays of five channels each, all separated by ~ 1 cm
- All interior to ECH resonance radius

ECH Deposition



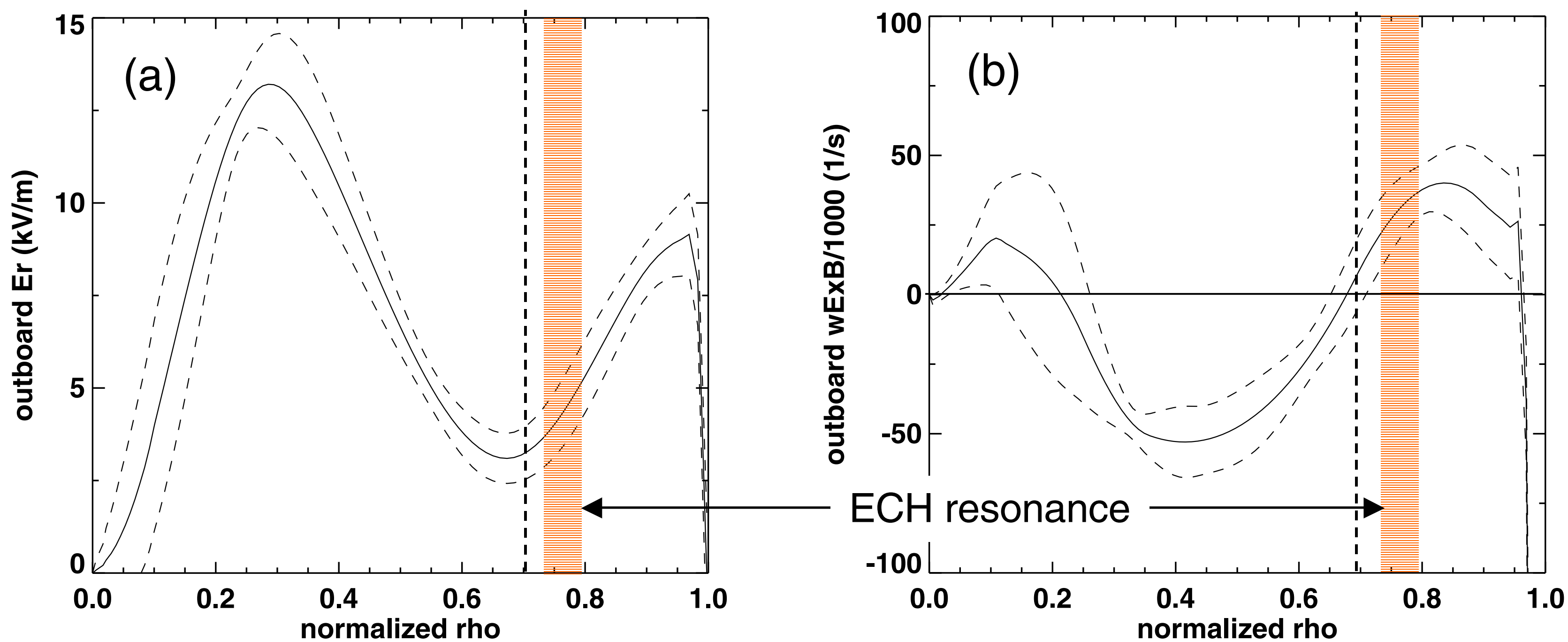
- Resonance peaks at $r/a \approx 0.815$, FWHM/$a \approx 0.057$.
- Power launched (time-averaged) ≈ 1.33 MW
- Peak power ≈ 2.55 MW

Discharge Waveforms



E_r and ω_{ExB}

Shot 107139 (r_{res}/a = 0.76)

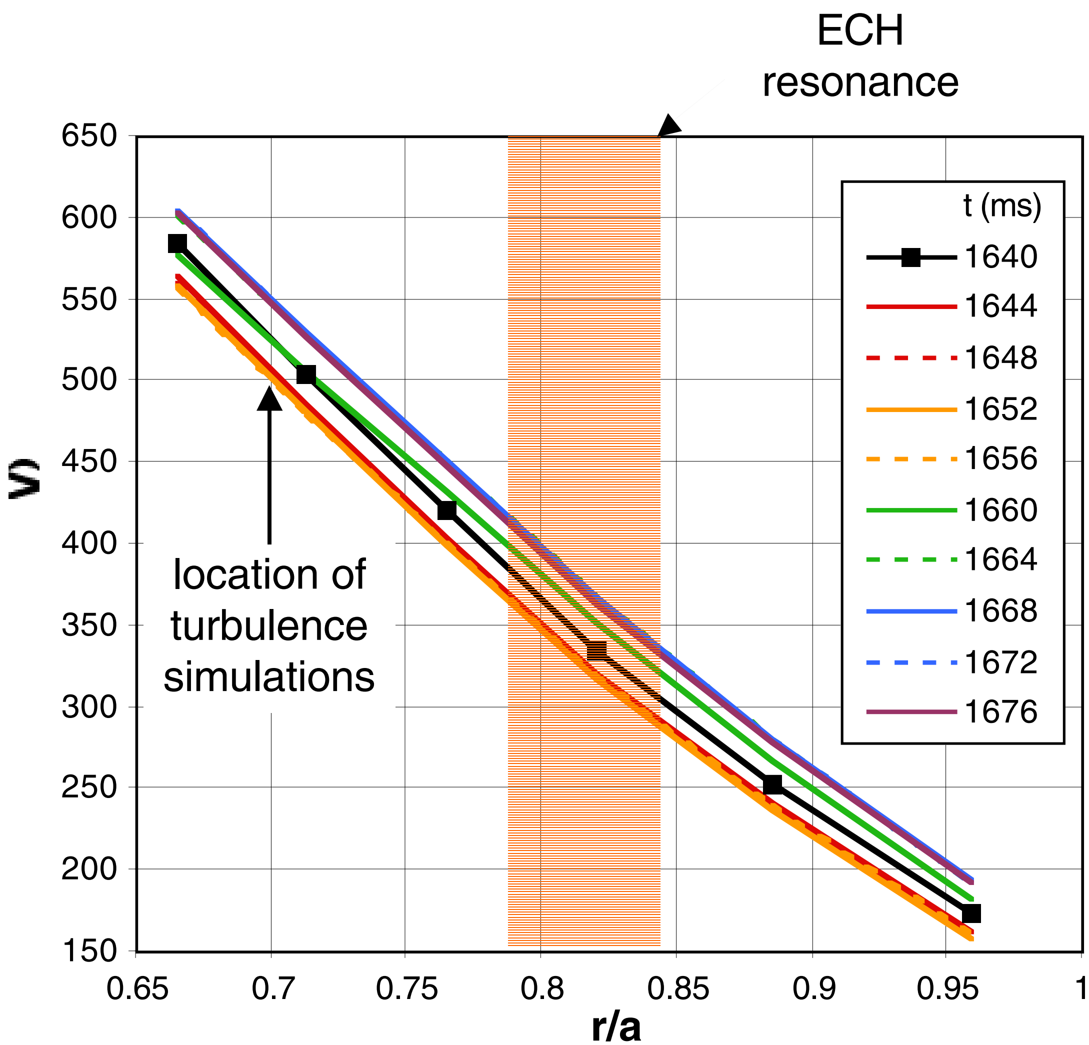


At r/a = 0.70: $E_r \approx$ 3.2 ± 0.7 kV/m, $\omega_{E\times B} \approx$ 7.9 ± 13 krad/s.

$\upsilon_{ExB} \equiv E_r/B_T \approx$ 2.0 ± 0.4 m/s.

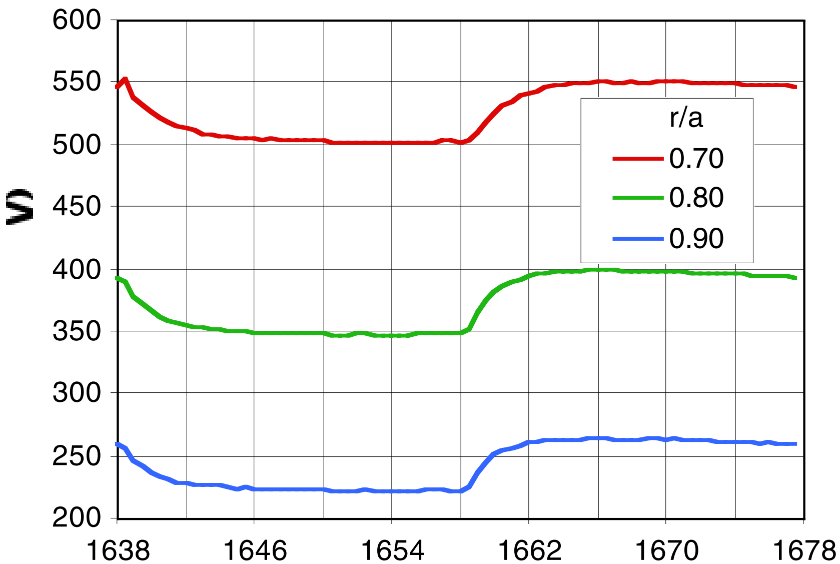
➡ Because resonance is farther out ($r/a \approx$ 0.815), values may be somewhat different for shot 107138.

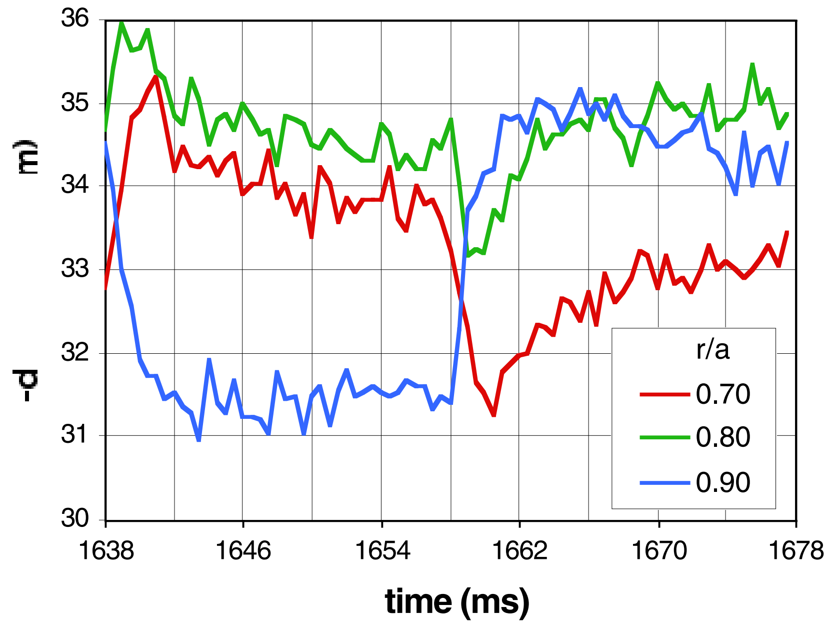
T_e Profiles During ECH

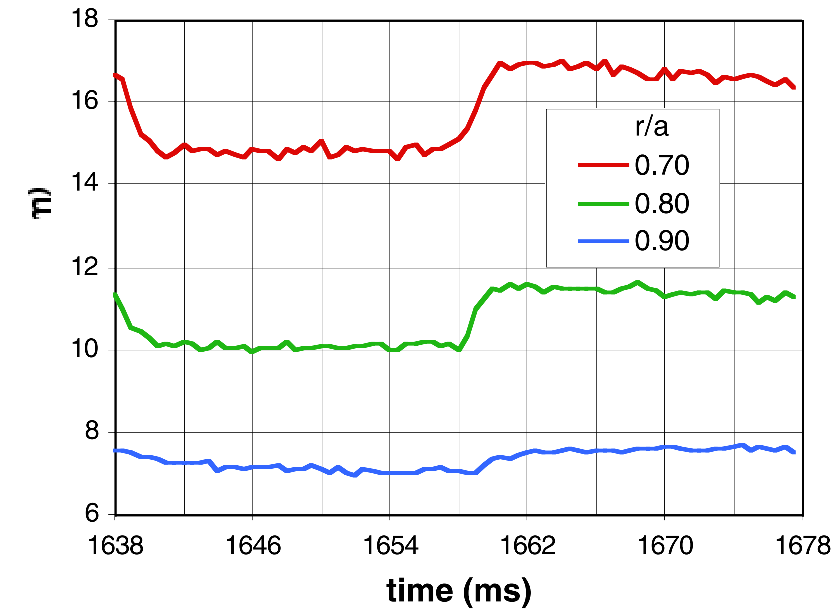


- T_e data from ECE heterodyne radio-meter
- Data de-trended and boxcar-averaged over 17 ECH periods starting at 1298 ms

T_e(R,t) During Modulated ECH



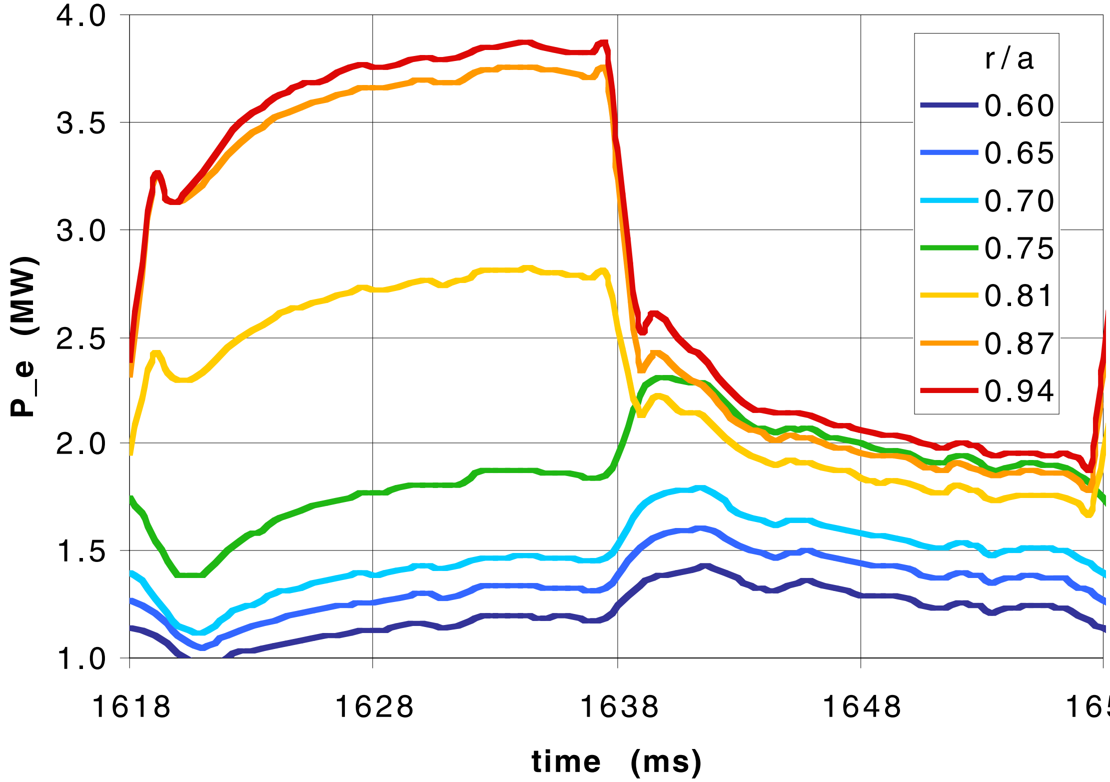




- T_e profile quickly equilibrates.
- $|dT_e/dR|$ drops at ECH turn-on inside resonance radius r/a = 0.81, remains ~ const. *at* resonance radius, increases outside.
- L_{Te} increases during ECH pulse.

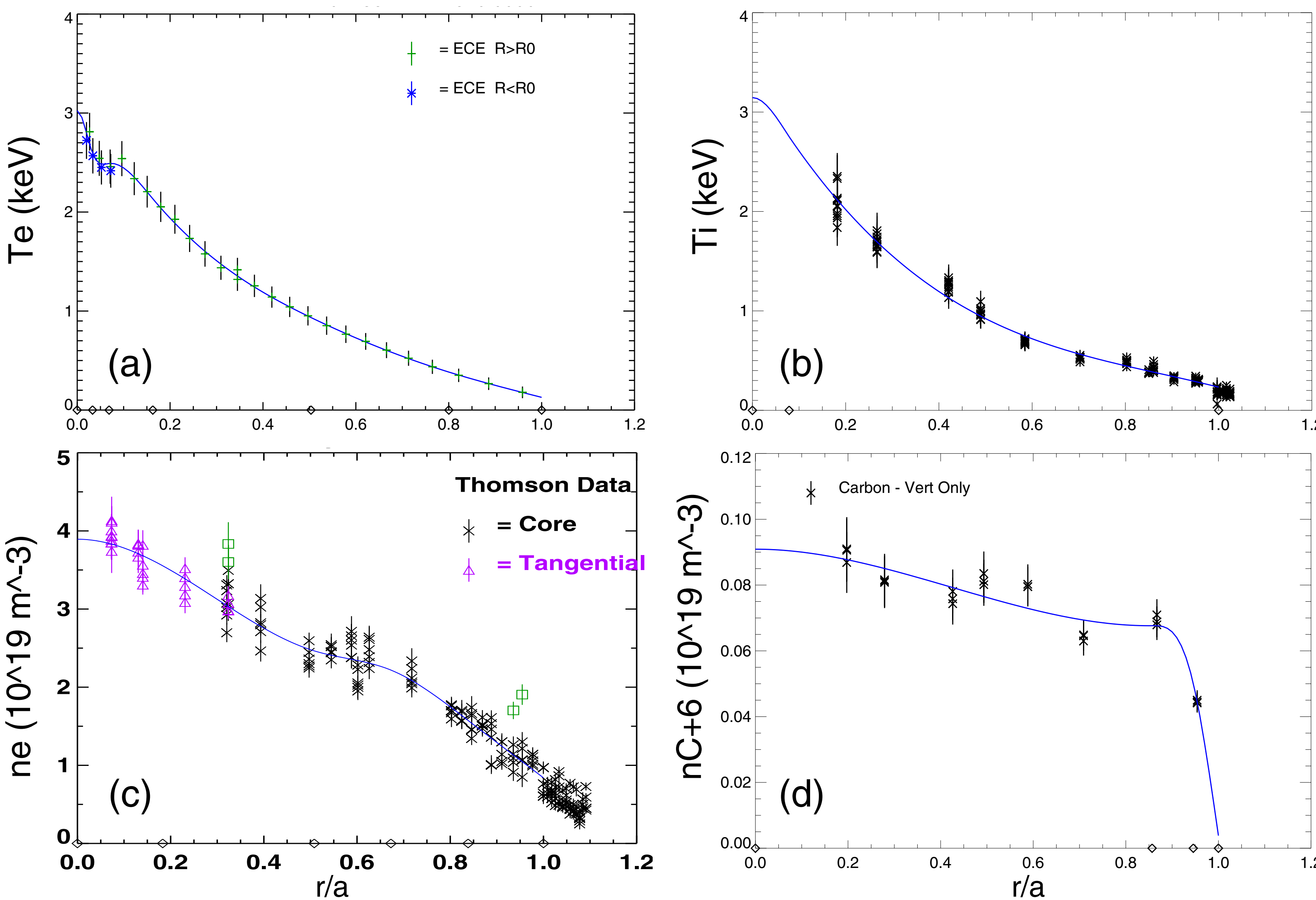
Electron Power Flux

Time-averages from ONETWO analysis,
Modulations from electron energy equation (2 MW peak into electrons):



- Power flux in phase with ECH at or outside resonance radius
- Power flux out of phase with ECH inside resonance radius (only transiently)

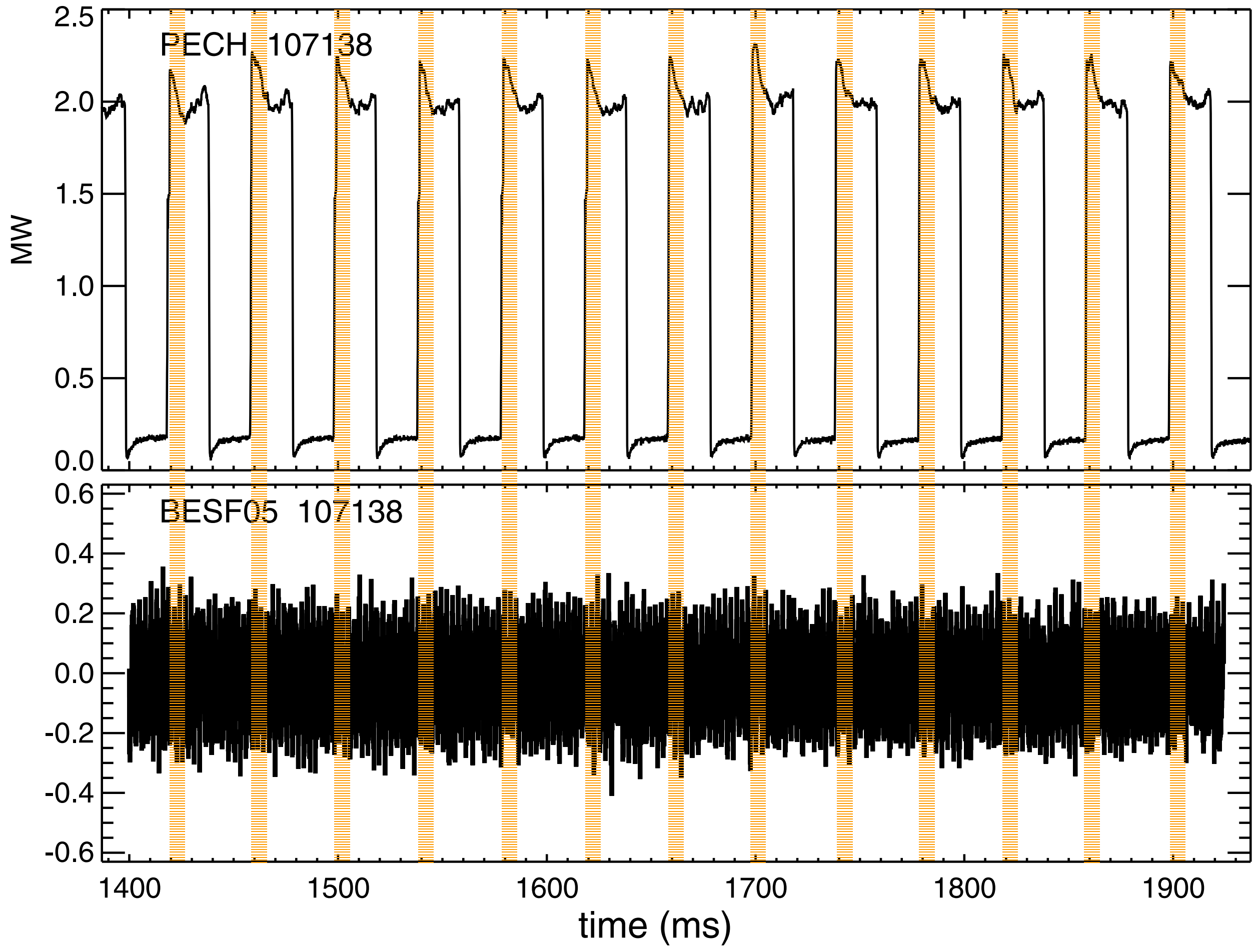
Plasma Profiles (averaged 1620-1660 ms)



Fluctuation Analysis

- Discharge in near steady state (except for ECH modulation) $\Rightarrow$ improved statistics by "boxcar averaging" (see next slide).
- 512 ms total window $\Rightarrow$ 12 modulation periods
- Digitization at 1 MHz, 8 ms intervals $\Rightarrow$ 96 k samples per data set
- Time dependence of fluctuations determined by moving the boxcar function in time.
- Frequency range of analysis: 50 - 300 kHz
- Cross powers between poloidally adjacent channels used to enhance S/N.

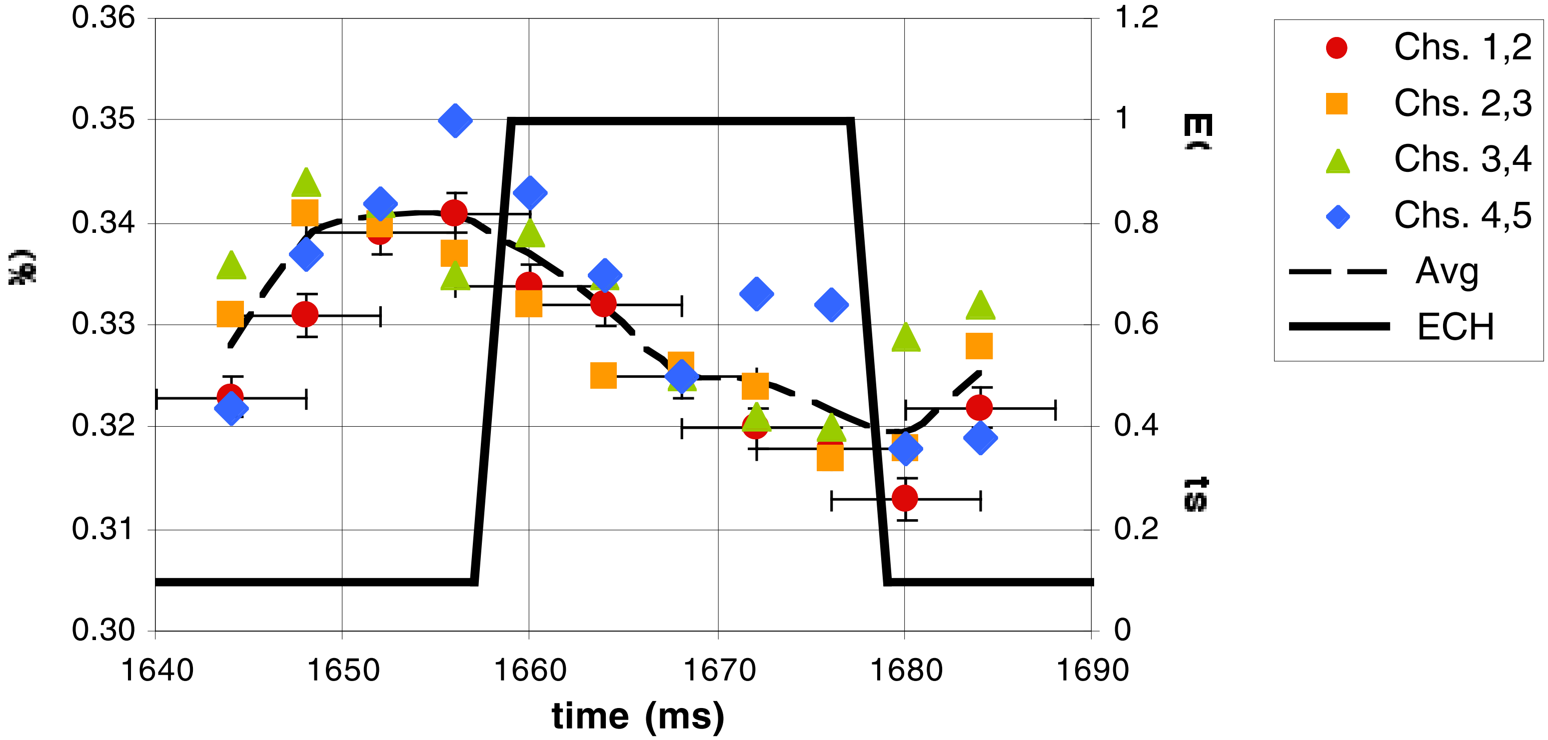
“Boxcar Averaging”



- Fluctuation data from 8-ms intervals separated by modulation period (40 ms) are grouped together.

Fluctuation Level at Inner Poloidal Array

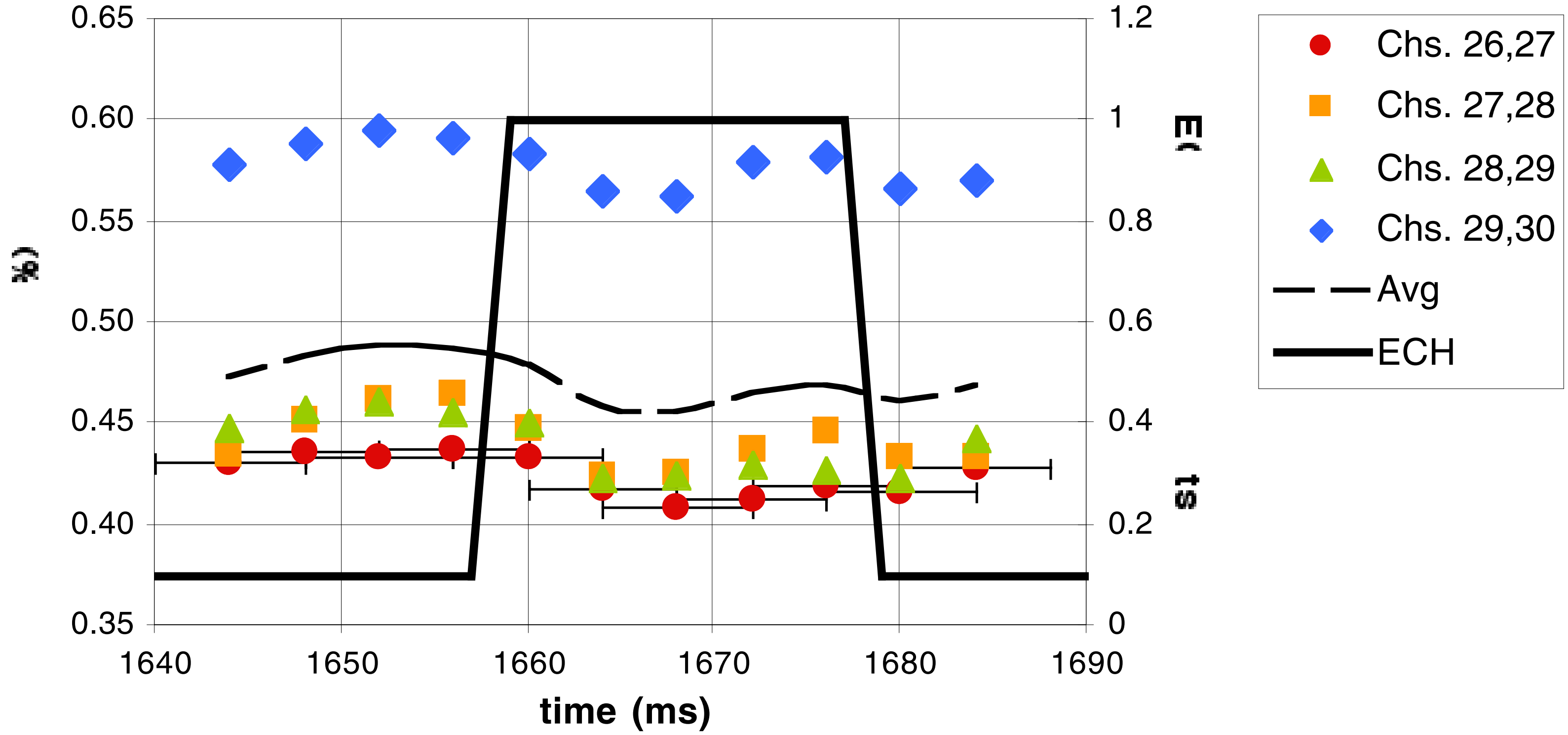
$(r/a \approx 0.63)$



- Fluctuation level lags ECH by ~ $5\pi/4$ (leads by ~ $3\pi/4$).
- Anomaly in channels 4,5 at 1672,1676 ms. ??

Fluctuation Level at Outer Poloidal Array

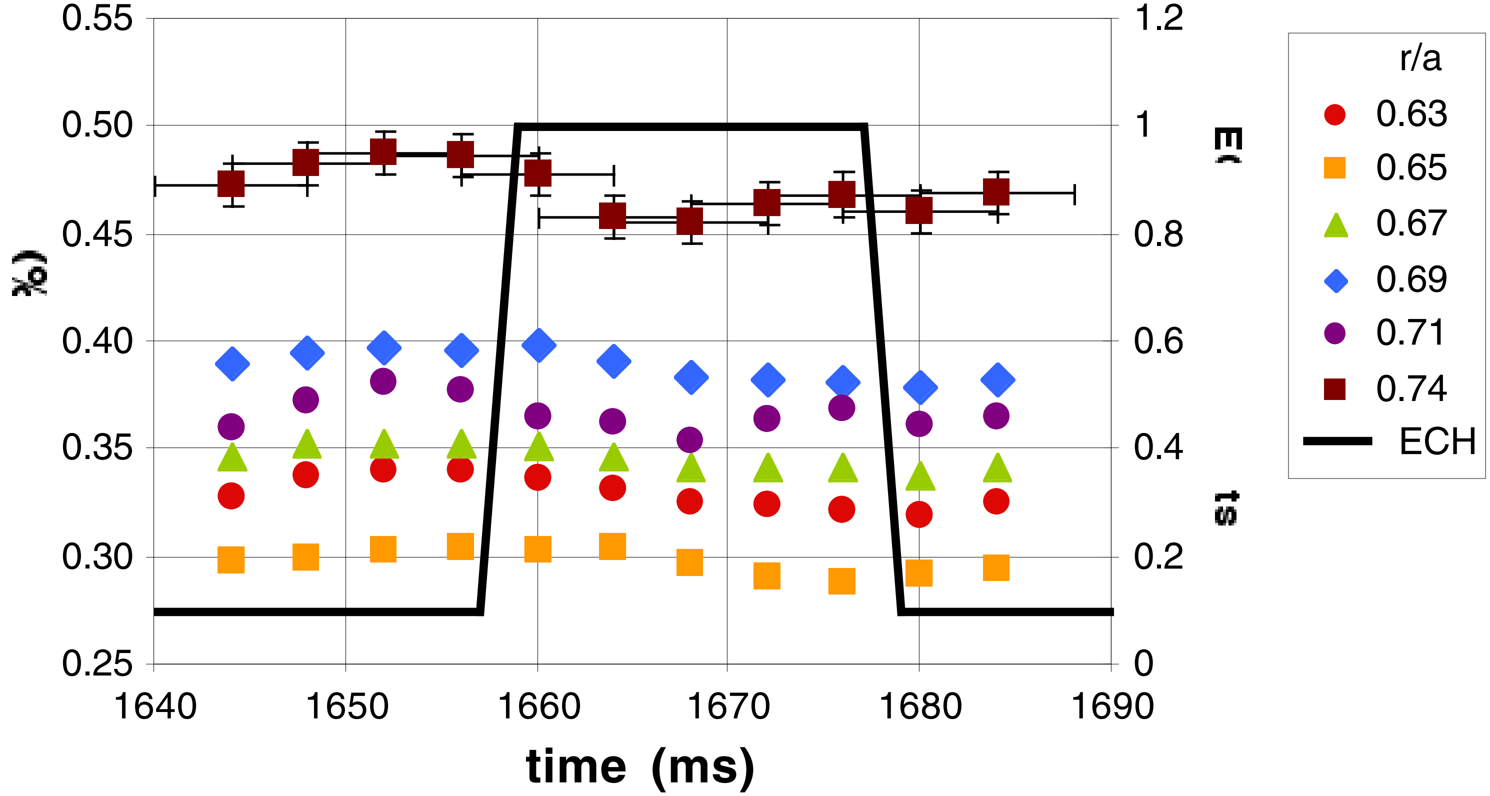
($r/a \approx 0.74$)



- Similar phase relationship as for inner array except for anomalies at 1672,1676 ms. Real??
- Larger fluctuation level on channels 29, 30 due to alignment of view and B-field.

Fluctuation Levels

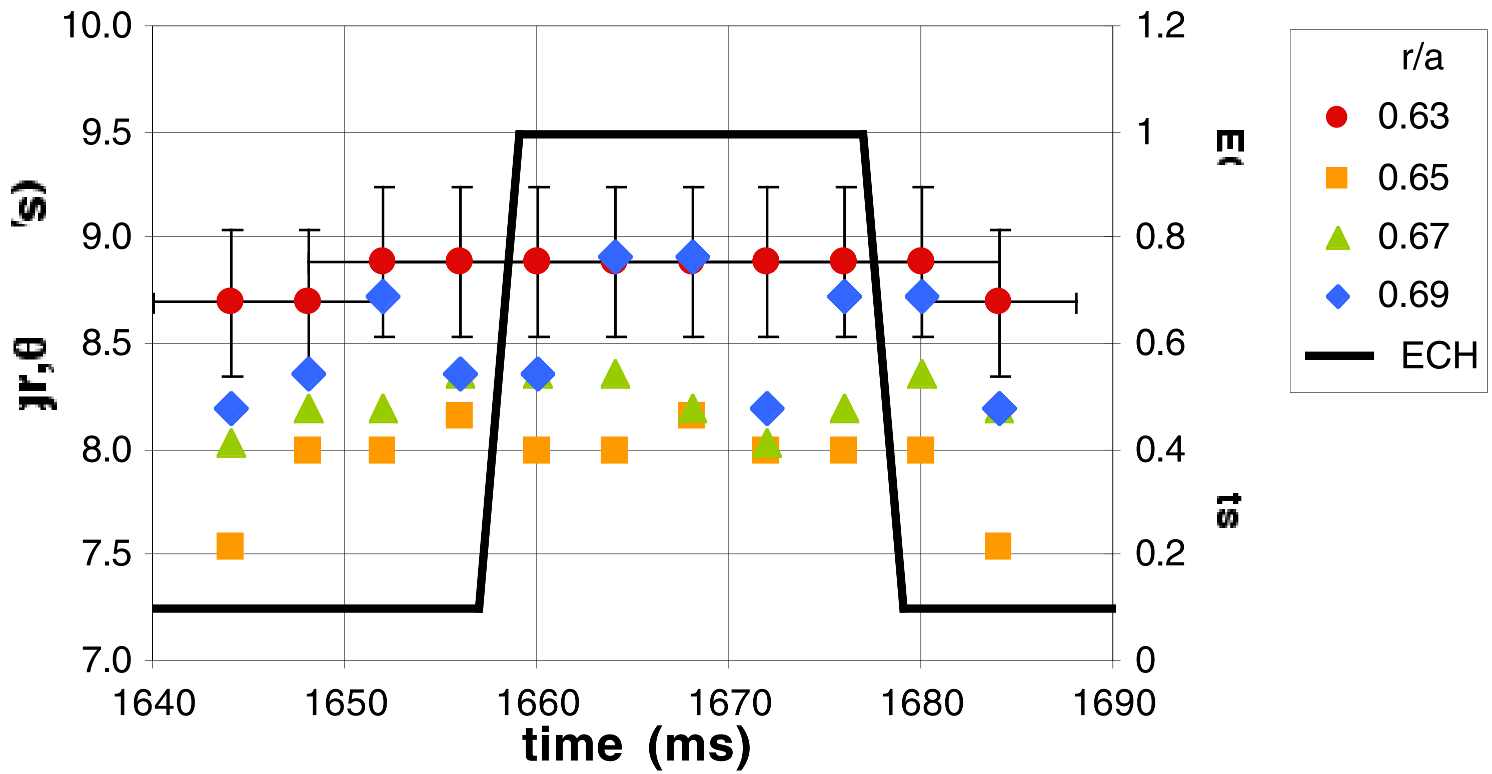
Average over poloidal pairs:



- Fluctuation level inside resonance layer decreases during ECH.
- Near resonance layer, level starts to rise again at ~ 1670 ms. ??

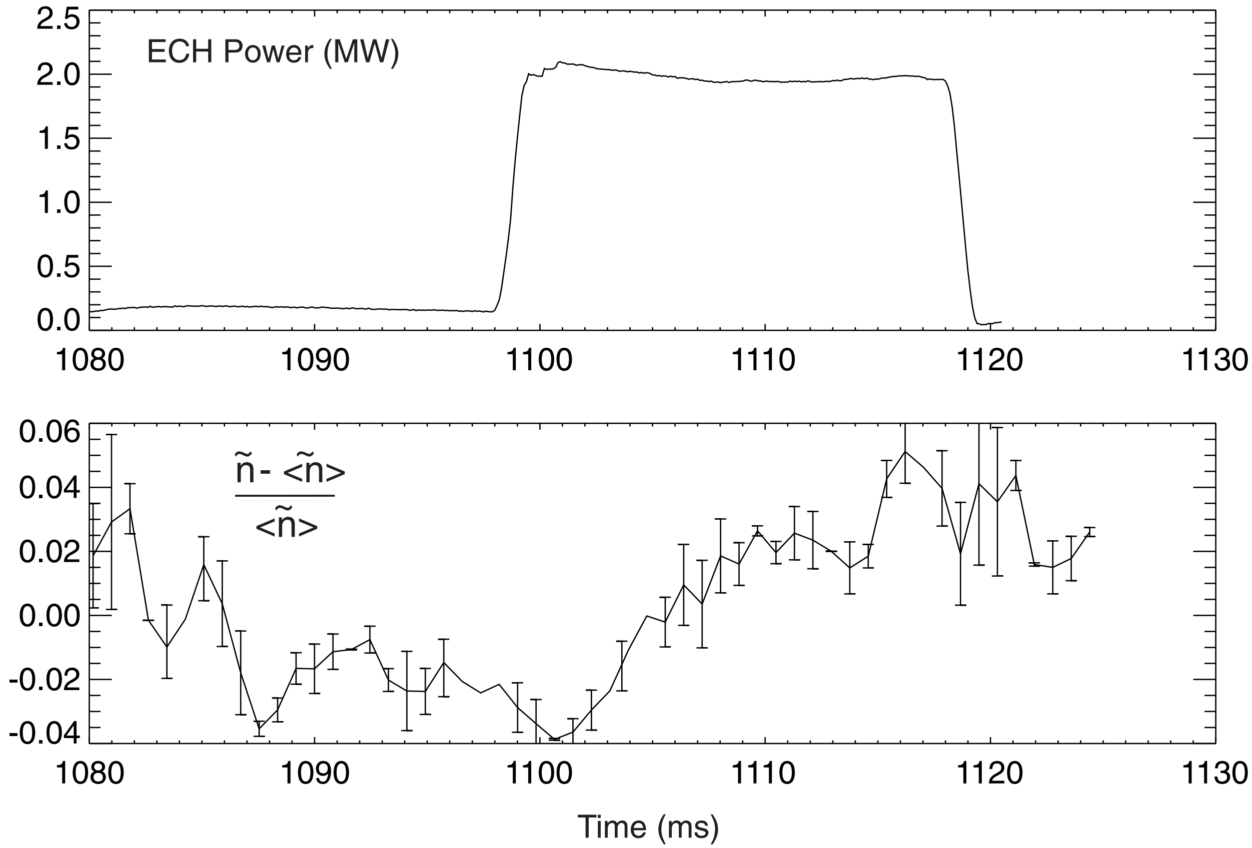
Poloidal Group Velocity

From time-delay correlations between upper and lower channels of each poloidal array:



- No clear modulation of the phase velocity.

FIR Scattering Results



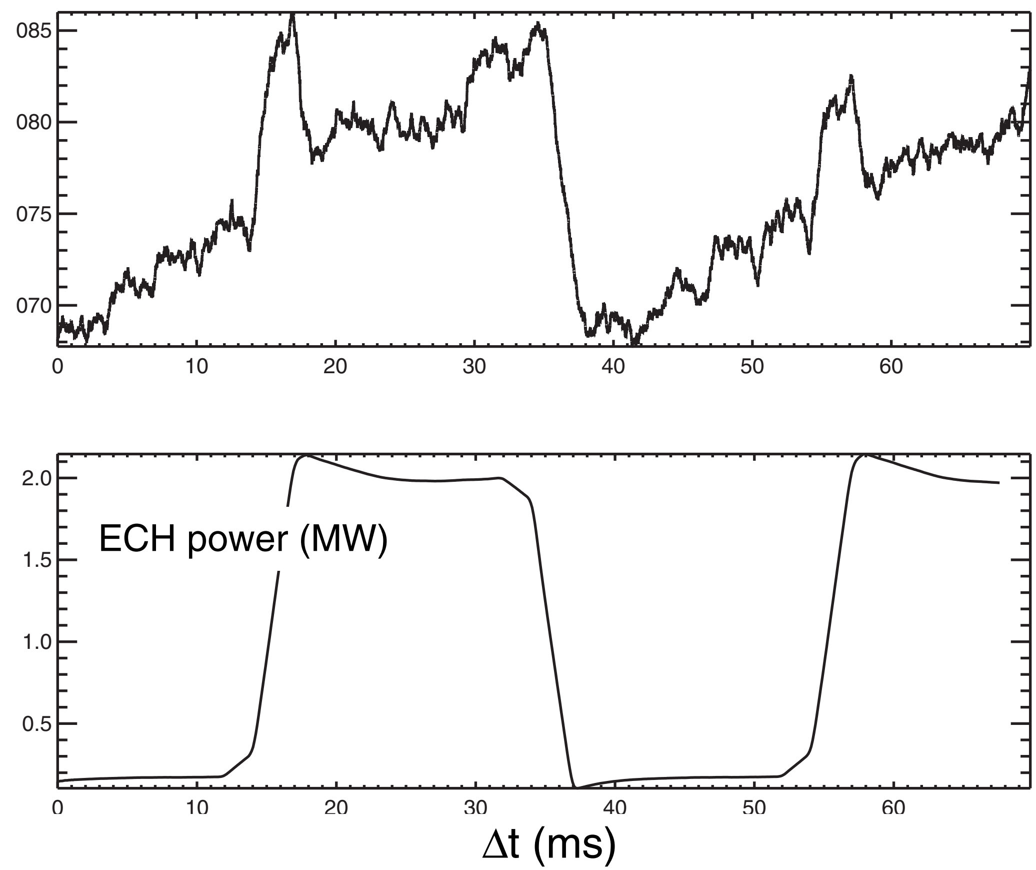
$k_\theta = 1\ \mathrm{cm}^{-1} \Rightarrow$ chord-average along midplane

boxcar-averaged from 1080 to 1480 ms, 10 kHz < f < 1.7 MHz

- Fluctuation level “in phase” with ECH waveform.

Reflectometry Results

$\rho \approx 0.9$



RMS fluctuation level boxcar-averaged from 1200 to 1600 ms

- Fluctuation level “in phase” with ECH waveform.

Turbulence Simulations

- Simulations with GS2 gyrokinetic code and GRYFFIN gyrofluid code include:
  - flux-tube geometry
  - linear and **nonlinear** cases (with $\boldsymbol{E} \times \boldsymbol{B}$ nonlinearity)
  - full magnetic geometry from EFIT equilibrium
  - trapped electrons (& passing electrons in GS2)
  - one impurity species (C^{+6})
  - $\boldsymbol{E} \times \boldsymbol{B}$ background flow shear **not** included
- Input parameters characteristic of plasma profiles at $r/a \approx 0.7$ are varied within their error bars to seek agreement with experiment averaged over an ECH period 1620-1660 ms.
- Sensitivities of turbulence levels and transport fluxes to changes in T_e corresponding to observed modulation are then determined. Measured profiles at different times are treated as steady state in the nonlinear simulations.

Turbulence Simulations (cont.)

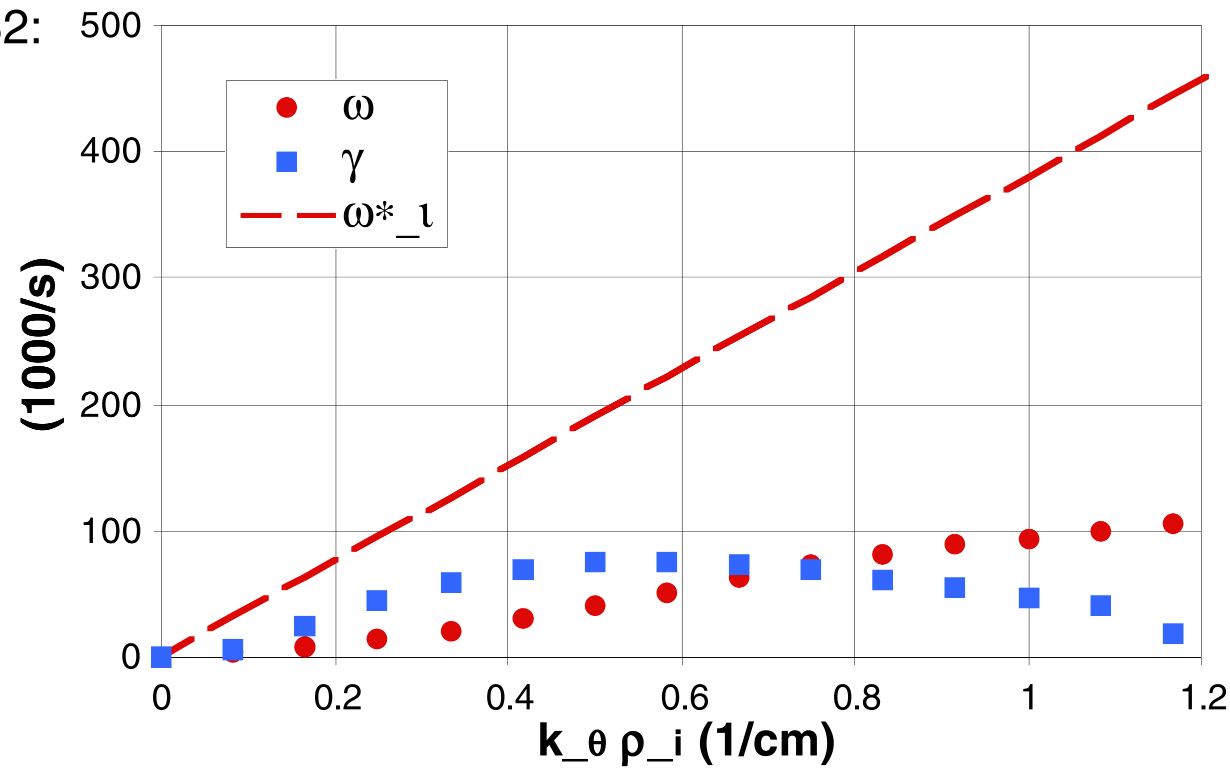
- Absence of background $\boldsymbol{E} \times \boldsymbol{B}$ shear in code requires translation of results toward marginal stability using standard rule of thumb [4]:
  - γ_{max}, fluxes, and $(\tilde{n}/n)^2$ are reduced by roughly the factor $(1 - \omega_{E\times B}/\gamma_{max})$ where [5]

$$\omega_{E\times B} = \frac{(RB_\theta)^2}{B}\frac{\partial}{\partial\psi}\left(\frac{E_r}{RB_\theta}\right)$$

[4] R. E. Waltz, R. L. Dewar, and X. Garbet, Phys. Plasmas **5**, 1784 (1998).
[5] T. S. Hahm and K. H. Burrell, Phys. Plasmas **2**, 1648 (1995).

Linear Results at r/a = 0.70

From GS2:



- $\gamma > 0$ and peaks at $k_\theta \rho_i \approx 0.6$ with $\gamma_{max} \approx 7.6 \times 10^4$ s^{-1}
  - $\gamma_{max} >> \omega_{E \times B}$ so we will ignore flow shear effects at $r/a = 0.7$.
- Modes propagate at < 0.3 $v_i^* \approx$ 0.10 - 0.17 km/s.
- Gryffin gives similar results.

Nonlinear Simulation Results at r/a = 0.70

In the following tables,

$P_e, P_i \equiv$ electron and ion power fluxes through flux surface at $r/a = 0.7$.

$\hat{s} \equiv \rho/q\ (dq/d\rho)$

$\upsilon_\theta \equiv$ poloidal velocity of fluctuations

yellow: time-average, green: perturbations to T_e (20%) and L_{Te} (24%)

General observations:

- P_e, P_i, and $\tilde{n}/n$ increase as R/L_{Ti} increases or $\hat{s}$ decreases.
- P_e is most sensitive to $\hat{s}$; P_i is most sensitive to R/L_{Ti}.
- $\tilde{n}/n$ is generally less sensitive.
- Serious discrepancies between simulated and measured υ_θ
  - Propagation is much faster than predicted, OR
  - Error in measured $\boldsymbol{E}\times\boldsymbol{B}$ velocity E_r/B_T which is subtracted from the measured values.

Nonlinear GS2 Results at r/a = 0.70

<table>
<tr><th></th><th></th><th colspan="9">GS2</th><th>Exp</th></tr>
<tr><td rowspan="6">INPUT</td><td>$\hat{s}$</td><td>1.32</td><td colspan="8">1.65</td><td>1.29 ± 0.55</td></tr>
<tr><td>R/L_{ne}</td><td colspan="2">3.80</td><td>4.56</td><td colspan="6">3.80</td><td>3.8 ± 0.8</td></tr>
<tr><td>R/L_{C6}</td><td colspan="3">0.90</td><td colspan="6">0.00</td><td>0.9 ± 0.9</td></tr>
<tr><td>R/L_{Ti}</td><td colspan="4">5.20</td><td colspan="4">5.77</td><td>6.15</td><td>4.4 ±1.8</td></tr>
<tr><td>R/L_{Te}</td><td colspan="6">8.34</td><td>6.34</td><td>6.95</td><td>8.34</td><td>8.34 ± 0.20</td></tr>
<tr><td>T_e/T_i</td><td colspan="5">0.95</td><td>1.14</td><td>1.14</td><td colspan="2">0.95</td><td>0.95 ± 0.05</td></tr>
<tr><td rowspan="5">OUTPUT</td><td>P_i (MW)</td><td>1.39</td><td>1.26</td><td>1.26</td><td>1.32</td><td>1.59</td><td>1.61</td><td>2.13</td><td>2.12</td><td>1.77</td><td>1.54</td></tr>
<tr><td>P_e (MW)</td><td>2.07</td><td>1.72</td><td>2.00</td><td>1.63</td><td>1.67</td><td>2.07</td><td>1.86</td><td>1.68</td><td>1.66</td><td>1.67</td></tr>
<tr><td>$\tilde{n}/n$ (%)</td><td>1.03</td><td>1.01</td><td>1.10</td><td>1.02</td><td>1.12</td><td>1.02</td><td>1.22</td><td>1.29</td><td>1.08</td><td>0.91</td></tr>
<tr><td>$\bar{k}_\theta \rho_i$</td><td></td><td></td><td></td><td></td><td>0.33</td><td>--</td><td>--</td><td>--</td><td></td><td>0.29</td></tr>
<tr><td>υ_θ (km/s)</td><td></td><td></td><td></td><td></td><td>0.1-0.17</td><td>--</td><td>--</td><td>--</td><td></td><td>7.4 ±1.6</td></tr>
</table>

Nonlinear GS2 Results at r/a = 0.70 (cont.)

- Time-average quantities (except υ_θ) agree well with experiment (yellow).
- With increase in T_e from time-average case (blue)
  - $\tilde{n}/n$ decreases, as in experiment
  - P_e increases, contrary to experiment
- With decrease in R/L_{te} from time-average case (green)
  - $\tilde{n}/n$ increases, contrary to experiment (and intuition!)
  - P_e is constant, as in experiment
- With simultaneous increase in T_e and decrease in R/L_{te} (in proportion to experiment)
  - $\tilde{n}/n$ increases, contrary to experiment
  - P_e increases, contrary to experiment

Nonlinear GRYFFIN Results at r/a = 0.70

		Gryffin						Exp
INPUT	EFIT	107138					107139	-
	q	2.75					3.66	3.2 ± 0.5
	$\hat{s}$	0.93		1.87		0.74		1.29 ± 0.55
	R/L_{Ti}	4.3		6.15				4.4 ± 1.8
	R/L_{Te}	5.75	7.18		6.46	7.18		8.34 ± 0.2
	T_e/T_i	1.05			0.95			0.95 ± 0.05
OUTPUT	P_i (MW)	1.01	1.03	1.52	1.50	1.48	1.88	1.54
	P_e (MW)	0.98	1.39	0.87	0.70	0.76	1.42	1.67
	$\tilde{n}/n$ (%)	1.44	1.45	1.75	1.54	1.55	1.57	0.91
	$\bar{k}_\theta \rho_i$			0.35	0.35	0.40	0.40	0.29
	v_θ (km/s)					< 0.17		7.4 ±1.6

- Not optimized (Crays decommissioned, code not yet adapted for IBM)
- $\tilde{n}/n$ consistently too large (hard to rectify).

Summary/Conclusions

- Fluctuation levels from BES interior to ECH resonance radius are out of phase with ECH and T_e.
  - Consistent with drop in $|dT_e/dR|$, increase in L_{Te} during ECH pulse
- Fluctuations from edge ($\rho \approx 0.9$) reflectometer channel and FIR-scattering at low k (chord-averaged) are *in phase* with ECH and T_e.
  - Consistent with rise in $|dT_e/dR|$ *outside* ECH resonance radius during ECH pulse ($\tilde{n}$ peaks near plasma edge)
- GS2 simulations are consistent with time-averaged measured power fluxes and turbulence characteristics (except poloidal velocity?)
- GS2 simulations are *inconsistent* with ECH modulation of fluctuation level and electron power flux.
- GRYFFIN simulations not optimized, but yield excessively high fluctuation levels.

Future Work

- Examine discrepancy between experiment and simulation in poloidal propagation velocity of turbulence.
  - Explore uncertainties in E_r inferences, *I.e.*, measurements of poloidal impurity velocity.
- Examine effects of modulations of profiles other than T_e (*e.g.*, T_i) on simulated power fluxes and fluctuation parameters.
- Repeat experiment with BES views just *outside* resonance layer.
- Examine uniqueness of solutions.
- Perform experiment/simulation comparisons on other discharges with different parameters, *e.g.*, with $E_r \approx 0$, $T_e/T_i << 1$, *etc*.
- Run GYRO (J. Candy, *et al.*, invited talk UI2.002, Fri. morning)
  - Includes background $\boldsymbol{E}\times\boldsymbol{B}$ shear flow
  - Allows profile variation within simulation domain