Analysis Tools for Turbulence Studies at Alcator C-Mod

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Suite of analysis tools written in IDL is being developed to support turbulence studies at C-Mod

• **New GUI for higher-order spectral analysis to study 3-wave coupling**
  • Presently optimized for Gas Puff Imaging (GPI) data
  • Quick visual analysis of time history, Easy selection of different GPI channels
  • Choice of bispectrum normalizations
  • Preliminary use of bicoherence widget shows possible coupling during I-Mode, but not during H-mode and L-Mode. More analysis is needed.

• **New routines for in-between shot calculation of plasma cut-offs, resonances and optical depth**
  • Utilizes automatic $n_e$ and $T_e$ FITS routine developed by D. Ernst
  • Writes save files to user directory for ease in future analysis/plotting
  • Allows for easy tracking of reflectometer measurement locations in time

• **Adaptation of spectral analysis tool, INSPECT, for C-mod**
  • Capability to use identical data analysis routines at DIII-D and C-Mod benefits validation studies and supports joint experiments

• **User-friendly interface for ray-tracing tool, GENRAY**
  • Is under development and will implement in-between shot profile analysis for automated ray-tracing analysis
Data from fluctuation diagnostics and turbulence simulations can be analyzed with same analysis tools

Gas Puff Imaging (GPI)

Correlation reflectometer


Synthetic diagnostics and gyrokinetic codes
User-friendly spectral analysis tools are already available at C-Mod
- FFT-based autopower spectrum (W_FLUCT, M. Greenwald)
- Autopower spectrum is a linear spectral analysis technique

Higher order spectral analysis techniques are needed to better characterize the fluctuating signal, study nonlinear processes

New FFT based bicoherence GUI to study 3-wave coupling has been developed, called GPIW3, and run with IDL gpiw3.pro

- Allows for study of three-wave coupling in Gas Puff Imaging (GPI) data
- User-friendly interface has been implemented
- Preliminary analysis of H-Mode and I-Mode transitions has begun
• Cross-section of Alcator C-Mod with a representative LSN magnetic equilibrium and the GPI viewing-array

• 2-D GPI array has 9x10 views covering 4 cm x 4cm area. Data from this array of views is used for bicoherence calculations.

• Diagnostic gas puff enters from a nozzle mounted in the low-field-side limiter, ~ 2.5 cm below the height of the magnetic axis.

• GPI measures $D_\alpha$ emission from diagnostic gas puff, $D_\alpha \sim n_0 \times f(n_e, T_e)$. DEGAS-2 modeling shows typical $D_\alpha$ response to be $\sim n_e^{0.7} \times T_e^{0.3}$.

• Fluctuations in $D_\alpha$ emission are NOT fluctuations in $n_0$

• $D_\alpha$ fluctuations are measured edge, in region of closed flux surfaces, inside separatrix (shown in red) and also in region of open field lines, in scrape off layer (SOL)
Biocherence is used to detect phase coupling between three waves

- The bispectrum in frequency space is defined as

\[ B(f_1, f_2) = \langle \phi(f_1) \phi(f_2) \phi^*(f_3) \rangle \]

- The bicoherence is defined as

\[ b^2(f_1, f_2) = \frac{|B(f_1, f_2)|^2}{\langle |\phi(f_1)\phi(f_2)|^2 \rangle \langle |\phi(f_3)|^2 \rangle} \]

- \( \phi(f) \) is the Fourier transform of the time signal at the mode frequency, \( f \).

- The modes obey the three wave coupling rules \( f_1 + f_2 = f_3 \) or \( f_1 - f_2 = f_3 \) and the bicoherence picks out the presence of phase coupling where the three modes maintain a phase relationship \( \phi_1 + \phi_2 = \phi_3 \) or \( \phi_1 - \phi_2 = \phi_3 \).
To illustrate bicoherence, consider test signal that is superposition of four sine waves

• The waves obey the three wave coupling rules for frequency:
  \( f_1 = 220 \text{ kHz} \) and \( f_2 = 375 \text{ kHz} \), and \( f_3 = f_1 + f_2 \) and \( f_4 = f_2 - f_1 \)

• The power spectrum cannot distinguish between coupled phase relationships:
  \( \phi_1 + \phi_2 = \phi_3 \) and \( \phi_4 - \phi_2 = \phi_1 \)

And random, or non-coupled, phase relationships:
  \( \phi_1 + \phi_2 \neq \phi_3 \) and \( \phi_4 - \phi_2 \neq \phi_1 \)
Bicoherence is high when the four sine waves are phase coupled

- The waves obey the three wave coupling rules for frequency:
  \[ f_1 = 220 \text{ kHz} \] and \[ f_2 = 375 \text{ kHz} \], and \[ f_3 = f_1 + f_2 \] and \[ f_4 = f_2 - f_1 \]

- In case on left, the waves are given phase relationships:
  \[ \phi_1 + \phi_2 = \phi_3 \] and \[ \phi_4 - \phi_2 = \phi_1 \]

- In case on right, the waves are given random phase relationships:
  \[ \phi_1 + \phi_2 \neq \phi_3 \] and \[ \phi_4 - \phi_2 \neq \phi_1 \]
New Bicoherence GUI allows for rapid analysis of 3-Wave Coupling using GPI data

C. Burns and S. Shehata, 52nd APS-DPP
Chicago, IL 2010
I-Mode confinement regime characterized by pedestal in temperature, but not density

High energy confinement, matching H-mode scalings ($H_{98y_2}=1$)

Electron and impurity confinement remain near L-mode levels

Typically ELM-free

High frequency, $f \sim 250$ kHz, weakly coherent magnetic/density fluctuation feature in edge, $r/a \sim 0.9$
I-Mode, to H-mode to L-mode transitions are analyzed using bicoherence widget
I-Mode, H-mode and L-mode confinement regimes are demarcated by changes in edge fluctuations.

Reflectometer data (A. Dominguez, TP9.00066, Thursday am)

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Chicago, IL 2010
Bicoherence of GPI signals indicates existence of quadratic phase coupling during I-Mode

• Coupling is present in multiple frequency bands

• Strongest coupling is between fluctuations at 200 kHz and low frequency fluctuations near 20-30 kHz

Peak in squared bicoherence, \( b^2 \), at the bifrequency \( (f_1, f_2) \) is interpreted as proportion of energy at \( f_1 + f_2 \) that is quadratically phase coupled to the components at \( f_1 \) and \( f_2 \)

Preliminary analysis shows evidence of nonlinear coupling \( (b^2 > 0.5) \) during I-Mode

GPI [7, 5]: \( R = 91 \) cm, \( z = 3.3 \) cm below midplane

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Chicago, IL 2010
Bicoherence widget allows for quick visual analysis of data to determine if time history is stationary. Nonstationary time series can result in artifacts or false positives in the bicoherence.
No coupling is seen during H-Mode and L-Mode

• No coupling is observed in H-Mode or L-Mode

H-Mode: 1100204015, t = 1.12-1.18 sec, GPI [7, 5]: R = 91 cm, z = 3.3 cm below midplane
In-between shot profile analysis supports study of turbulence with mm-wave diagnostics

• In between shot profile analysis with FITS (D. Ernst) and QUICKFITS tools (Y. Ma) is being used for calculation of plasma cutoffs, resonance and optical depth

• Automatic in between shot profile analysis supports ray-tracing with GENRAY code: used for interpretation of reflectometry, scattering and ECE measurements

• In-between shot profile analysis will also allow for in-between shot power balance analysis and linear stability analysis (TGLF at C-Mod – see Y. Ma TP9.00059, Thursday am)
In-between shot analysis of characteristic frequencies using CHARFREQ IDL routines

- CHARFREQ routines
  - In-between shot calculations of plasma cut-offs, resonance and optical depth
  - Utilizes automatic $n_e$ and $T_e$ FITS routine developed by D. Ernst

Allow for easy visualization of reflectometer and ECE measurement locations
In-between shot analysis of characteristic frequencies using CHARFREQ IDL routines

**CHARFREQ routines**

- Allow for easy tracking of O-Mode and X-mode reflectometer measurement locations in time
- Aid in interpretation of edge fluctuations across confinement transitions

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In-between shot analysis of characteristic frequencies using CHARFREQ IDL routines

- CHARFREQ routines
  - Allow for easy tracking of optical depth for ECE in edge
  - Optical depth vs. Time at $R = 0.88\ m$
  - Density and $T_e$ vs. Time at $R = 0.88\ m$
  - Aid in interpretation of edge fluctuations across confinement transitions

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Adaptation of IDL-based INSPECT analysis widget allows for advanced spectral analysis at C-Mod

Edge fluctuations in I-mode at C-Mod monitored in cross-power spectrum of adjacent fast edge ECE signals from UT Austin 32-channel radiometer

- INSPECT (T. Rhodes UCLA) developed for fluctuation analysis, used at DIII-D
- INSPECT is being adapted for use at Alcator C-Mod
- Beneficial for cross-machine comparisons of turbulence measurements and validation efforts
  - Identical analysis can be applied to variety of diagnostics at both DIII-D and C-Mod
- Calculations of
  - Cross-power
  - Coherency
  - Cross-Phase

Test version
/home/whitea/inspect/inspect_fast_frcece.pro

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Future Work

• **GPIW3** GUI for higher-order spectral analysis to study 3-wave coupling
  • Add colorbar to output image, add low power correction option
  • Output option for .eps file
  • Add Biphase and Cross-Bispectrum analysis
  • Add in capability to read data from reflectometer and radiometer
  • **Adapt for use with DIII-D turbulence data**

• **CHARFREQ** routines for *in-between shot* calculation of plasma cut-offs, resonances and optical depth
  • Update to use also automatic $n_e$ and $T_e$ QUICKFITS routine (Y. Ma)
  • Allow user to overplot optical depth and cut-offs from two shots
  • **Couple with** in-between shot power balance analysis code (e.g. TRANSP or ONETWO), and linear stability analysis with TGLF

• **Adaptation of INSPECT for C-mod**
  • Incorporate CHARFREQ into INSPECT at C-Mod
  • **Drop down menu for plotting reference time series is needed**

• **GENRAY** code run on workstations to allow for in-between shot ray-tracing analysis


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