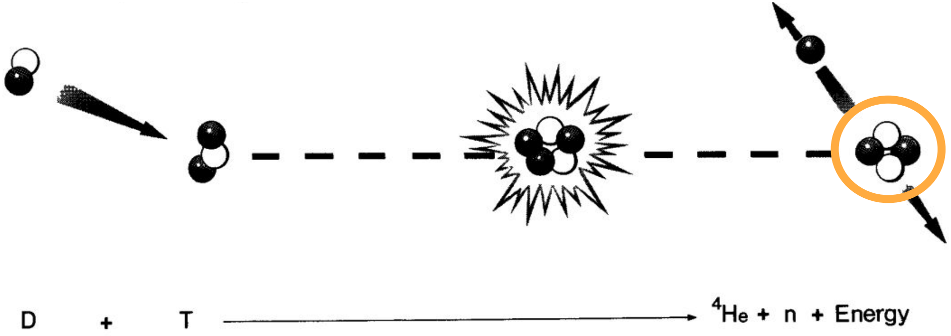
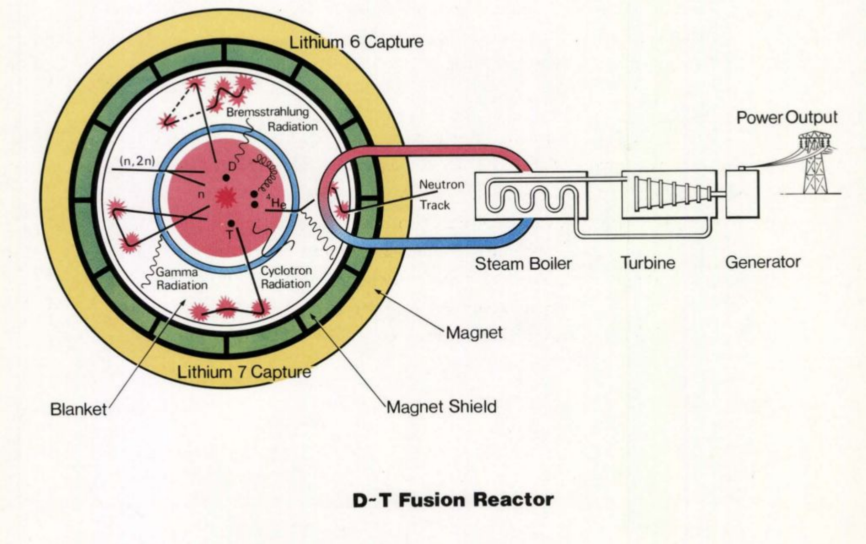
Study of the phase difference between turbulent density and electrostatic potential fluctuations in the TJ-II stellarator

Kaitlyn Yanna[1], Juan Arturo Alonso[2], Carlos Hidalgo[2], Oleksandr Kozachek[2], Oleksandr Chmyga[2], Jose Luis de Pablos[2], Anne White[1]

1: Massachusetts Institute of Technology (MIT), 2: Laboratorio Nacional de Fusión - CIEMAT

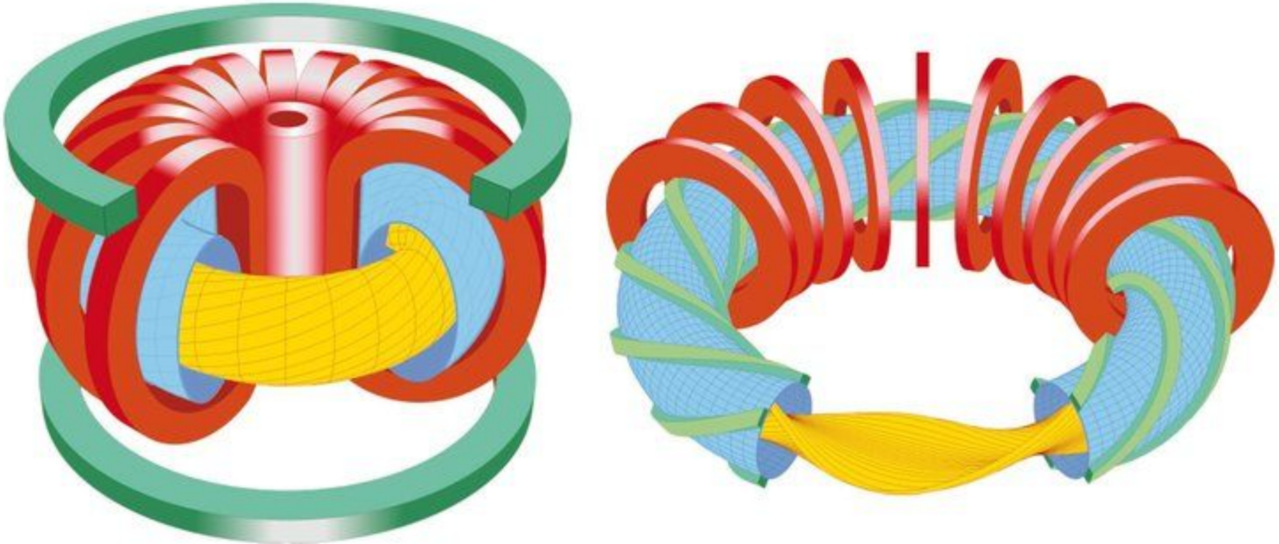
Background: Fusion





- The more alpha particles that remain confined, the more energy they give to other particles, causing more reactions, generating more neutrons
- The better the confinement, the more energy is generated
- Particles are confined to the field lines
- However, pressure gradients cause turbulence, which causes cross field transport of particles
- Fusion devices rely on generating a rotational transform for plasma confinement.

Tokamak v. Stellarator

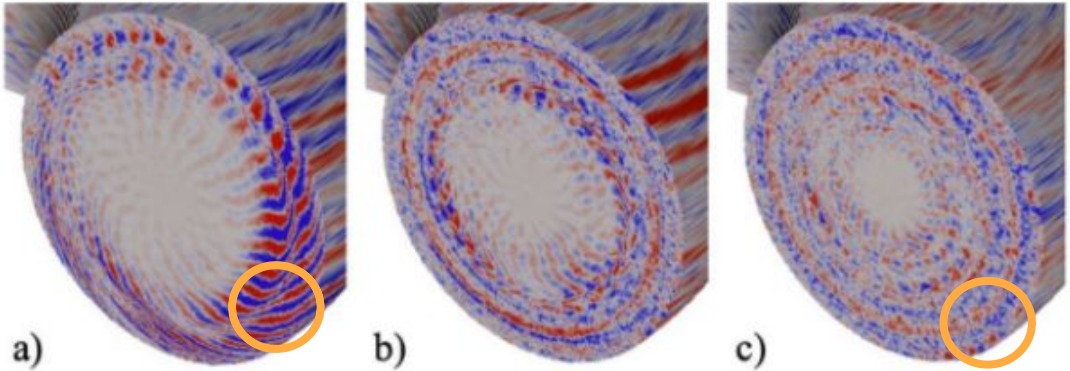


Confinement relies on the additional external magnetic coils for confinement, instead of a driven plasma current. All toroidal confinement configurations need three B field pieces for confinement: B toroidal, B poloidal, and B vertical. Both tokamaks and stellarator use external coils for Bt and Bv

- Tokamak makes Bp with the Ohmic coil driven current via a transformer mechanism
- Turbulence tends to dominate transport

- Stellarator makes Bp with external coils
- Configurations: torsatron, heliotron, heliac, etc
- Neoclassical theory tends to dominate in stellarators

Turbulence is an important transportation mechanism in tokamaks & stellarators

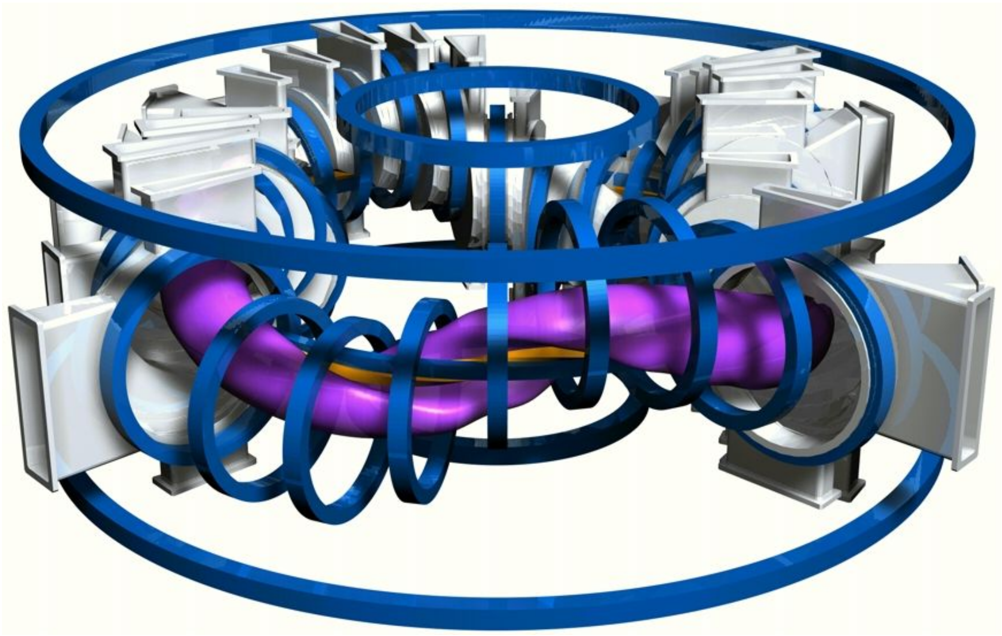


- Fusion plasmas have steep gradients and are far from thermodynamic equilibrium
- Turbulence arises from the plasma trying to achieve thermodynamic equilibrium and correct these gradients
- Neither classical transport theory nor neoclassical transport theory are sufficient to explain experimental observations*
- Previous research has shown that when the neoclassical transport theory takes into account the particle flux driven by fluctuations of the density and electrostatic potential - specifically when the density is lagging** - the disagreement between the theory and experiment vanishes

*Boudewijn https://doi.org/10.1088/978-0-7503-4856-0 **Thienpondt et al. 2023 Phys. Rev. Research 5 L022053

TJ-II is a well-diagnosed stellarator for studying turbulence

- Heliac four-period stellarator
- R = 1.5 m, a ~ 0.22, B = 0.95 T
- Heated by electron cyclotron resonance heating (ECRH) and neutral beam injection (NBI) - and sometimes a combination of the two
- Various diagnostics, including but not limited to Thomson scattering, Doppler reflectometer, Langmuir probes, and heavy-ion-beam probes (HIBP)



Diagnostic Description: HIBP

- Inject heavy ions, such as Cs+, with a known energy into the plasma in the form of a primary beam
- These ions collide with electrons at an ionization point (also called the sample volume) and are deflected
- The difference between the injection and detection energy is proportional to the electric potential at the sample volume (Figure 1A).
- In TJ-II Cs+ at 130 kV is injected with 400 km/s. This velocity corresponds to crossing the vacuum vessel in 2 microseconds

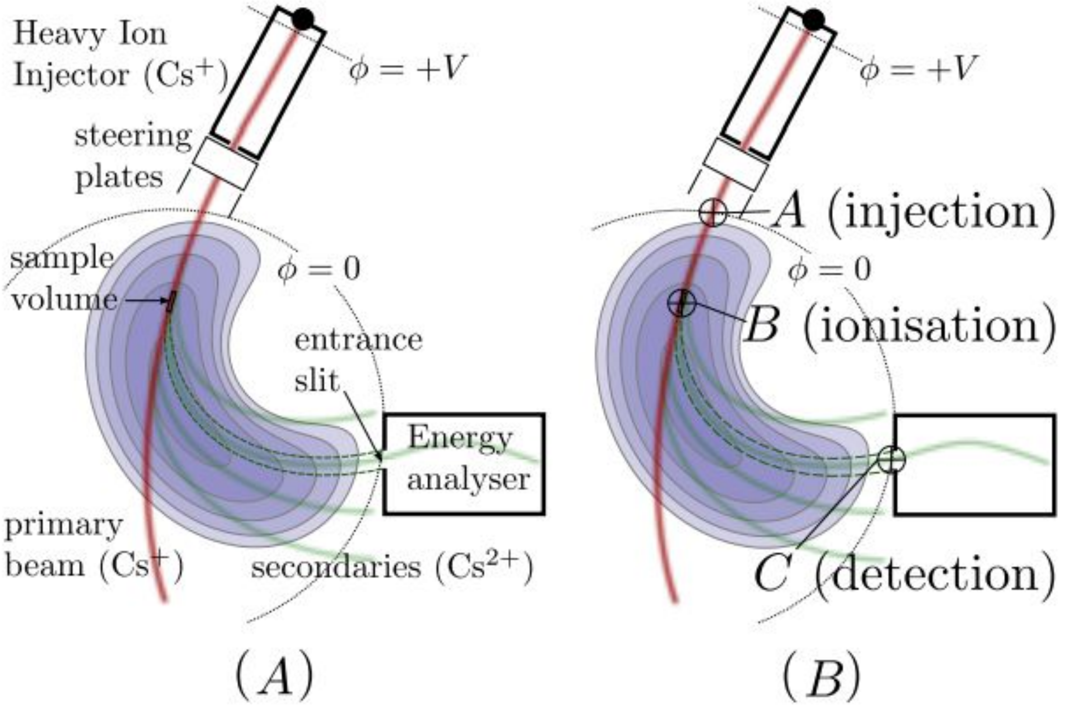


Figure 1: General principle of HIBP

Open Questions

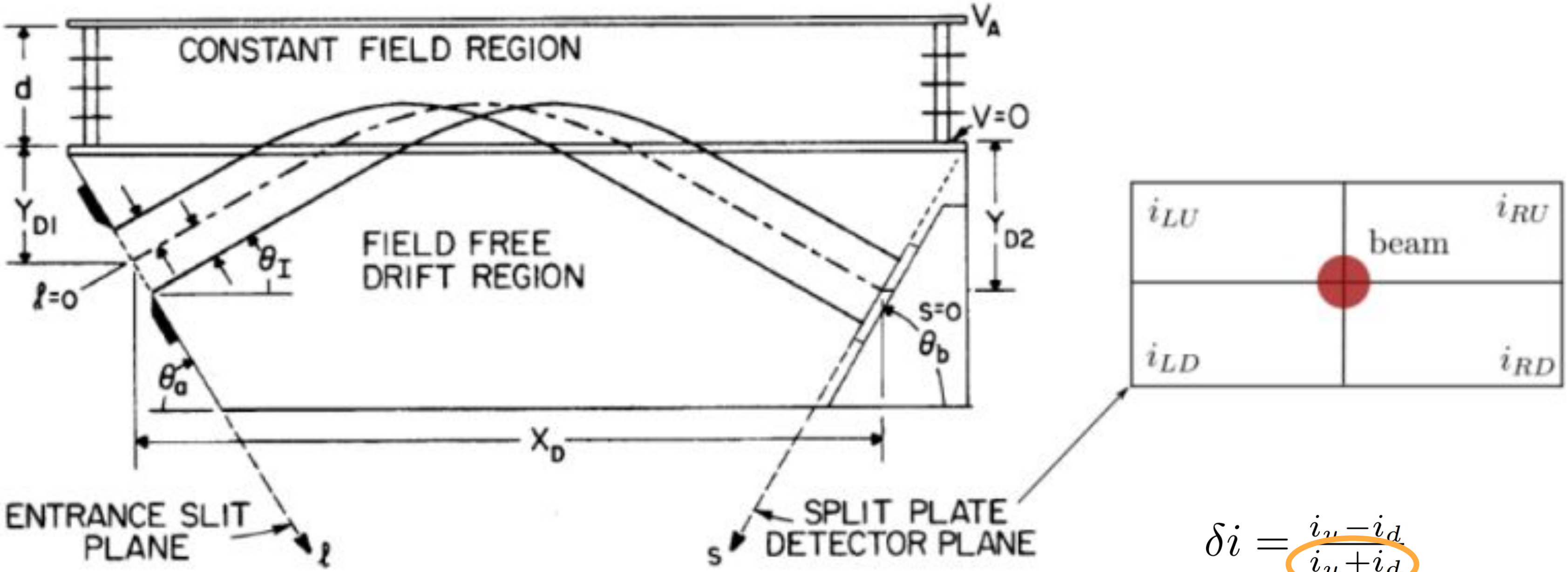
1. Can we characterize the phase difference between the electrostatic potential and density fluctuations?

2. Up to what frequency are we able to do this characterization?

Research Plan

- A systematic scan of HIBP relative positions and pellet injections was conducted, where the relative position of HIBPs and 2 sample volumes were changed in an ordered, purposeful way
- One probe was kept stationary while the other probed different radial positions to determine any long range correlations, if any
- Transient changes in the electron density gradient were investigated
- The raw data was processed to prevent noise in calculating the coherence and phase difference (more detail later)

Analysis Description: Proca-Green & MATLAB



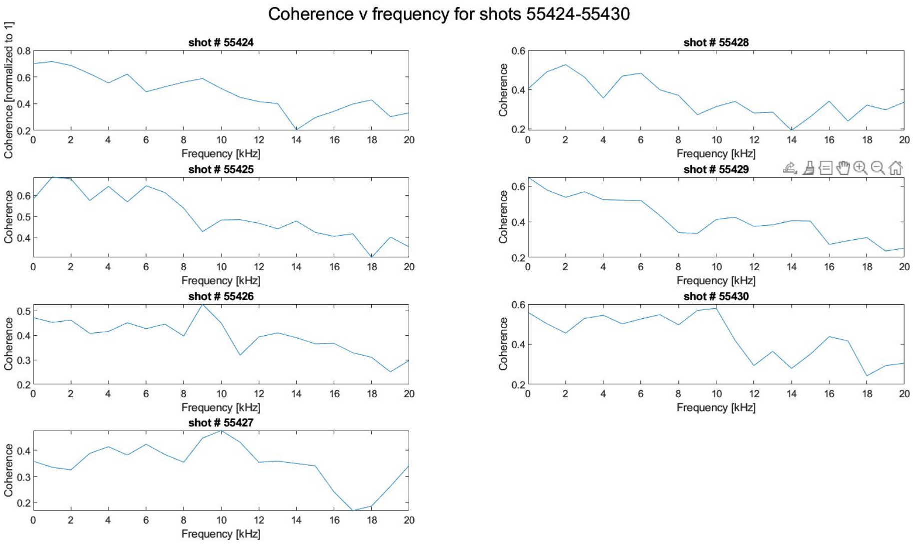
$$\delta i = \frac{i_u - i_d}{\underbrace{i_u + i_d}_{I^T}}$$

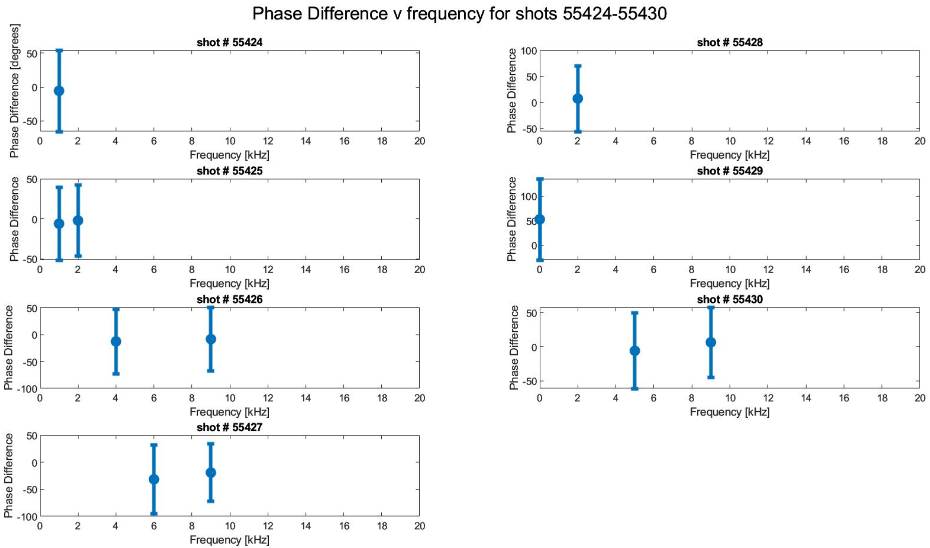
- Density and electrostatic potential was modeled in MATLAB
- Data was acquired from the Proca-Green energy analyzer’s four different signals and calculated δi and I_total, which are proportional to the electrostatic potential and density respectively. The Proca-Green energy analyser works via beam deflection in a constant electric field, where the electric field is a function of the beam’s energy
- The electric field is proportional to δi; I_total can be calculated from δi

Sample of Analysis

- The model used takes the raw data, smooths it, and subtracts the smoothed data from the raw data to perform a high pass filter
- The high passed data is then put into MATLAB's `mscohere` to calculate the coherence per frequency.
- The high passed data is chopped into sections and then the fast fourier transform (FFT) is taken. An average over the sections is performed
- This sectioning was done to improve data quality
  - Prevent noise
  - Further smooth the data
  - Reduce the size of the data set
- The frequencies are computed via associating the frequencies to their FFT coefficients

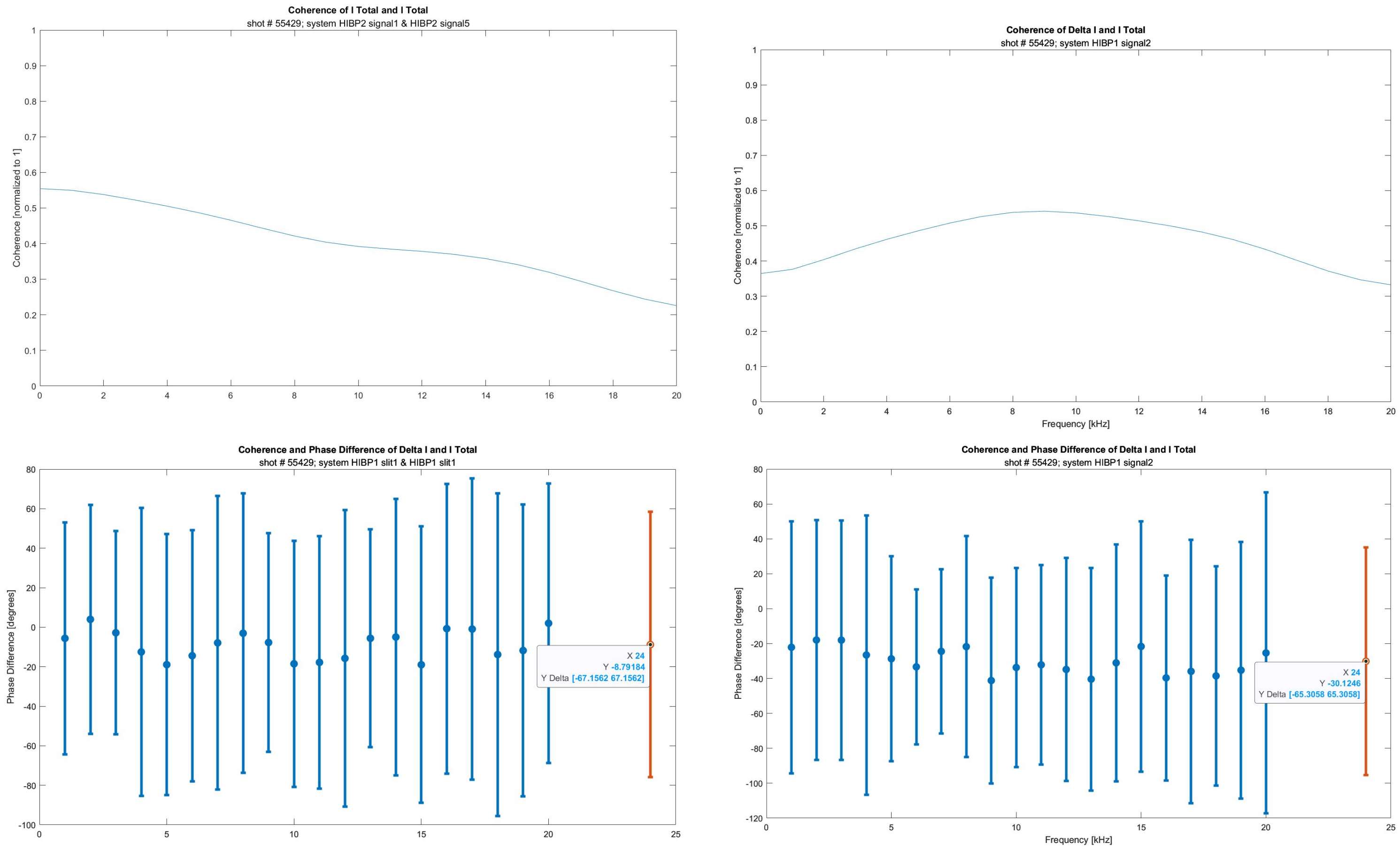
Coherence is semi-reproducible at specific low frequencies





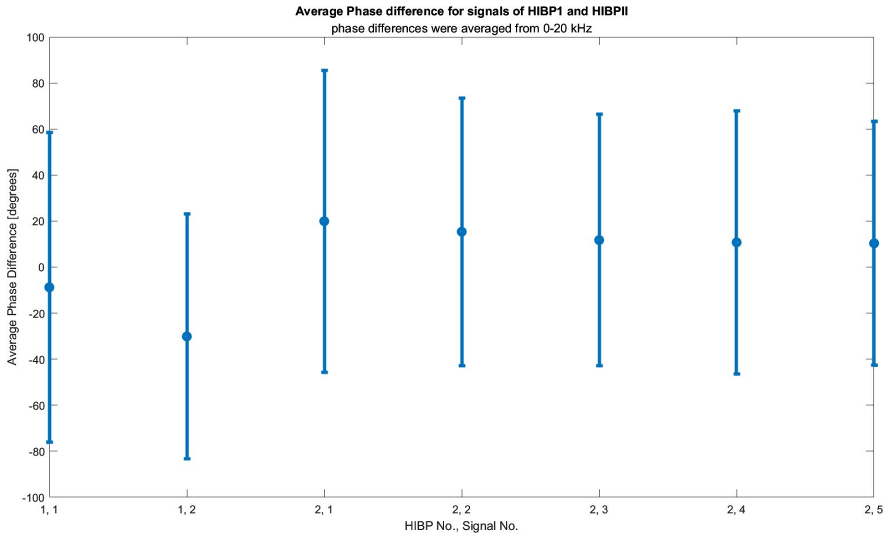
- Phase difference is displayed for frequencies that are relatively peaked
- Due to the large standard deviation, the phase difference is not observable

Phase difference is ~negative

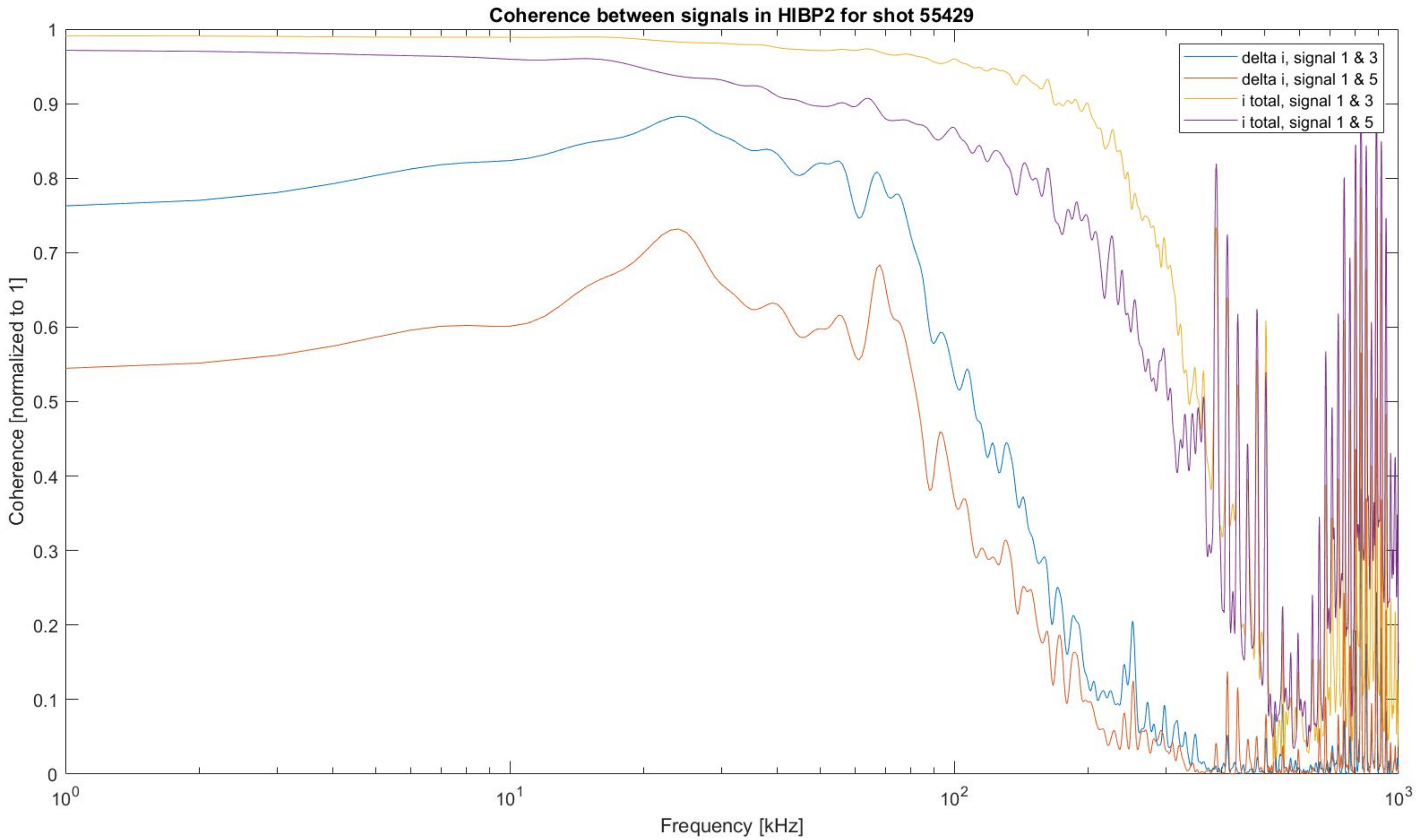


Average Phase difference up to 20 kHz

HIBP No., Signal No.	Average phase difference	Standard deviation
1, 1	-8.7918	67.1562
1, 2	-30.1246	53.1252
2, 1	19.9335	65.5414
2, 2	15.3544	58.1209
2, 3	11.7323	54.6579
2, 4	10.7322	57.2034
2, 5	10.3215	52.9529



Coherence falls below 0.4 at ~80 kHz



Frequencies greater than this cut off limit should not be analyzed, $f_{Nyquist} = 1000$

Summary

- Background: Fusion
- Tokamak v. Stellarator
- Turbulence is an important transportation mechanism in tokamaks & stellarators
- TJ-II is a well-diagnosed stellarator for studying turbulence
- Diagnostic Description: HIBP
- Open Questions
- Research Plan
- Analysis Description: Proca-Green & MATLAB
- Sample of Analysis
- Coherence is semi-reproducible at specific low frequencies
- Phase difference is roughly 0, regardless of coherence
- Average Phase difference up to 20 kHz
- Coherence falls below 0.4 at ~80 kHz

Discussion

- Expected to see a negative phase difference, instead saw a negative phase difference for HIBPI and a positive phase difference for HIBPII
  - Previous research indicates that "inward particle flux contributions occur when the density fluctuations lag behind on the potential fluctuations (negative values of the phase difference)*"
  - Data has not reached the maturity required to calculate the phase difference due to the large standard deviations
  - If phase difference was 0, it'd be measuring was in phase fluctuations, meaning that the turbulent mode at low frequencies is not driving transport (Boltzmann electron was not driving transport)
- How high in frequency is the data not dominated by noise?
  - After 80 kHz, the coherence between signals 1 & 5 goes below 0.4
  - Up to around 60 kHz, the coherence between signals 1 & 5 begins to drop
  - Up to around 20 kHz is when all of the coherences are stable (no significant fluctuation in coherence)
  - Since these frequencies are below the Nyquist frequency (1000 kHz), the perturbations in coherence are likely due to the machinery (i.e. amplifier) or turbulence

*Thienpondt et al. 2023 Phys. Rev. Research 5 L022053

Future Work

- Future experimental campaigns to improve data accuracy

- Calculate the phase difference differently:
    - Spectral density as a function of k and omega

- STEP validation project

- Designed an ECE diagnostic for SPARC
- Conducted research on the degradation of plasma facing mirrors used in ECE

Background:

In fusion plasmas, two isotopes of hydrogen fuse together to give an alpha particle and a neutron. Ideally, the alpha particle stays in the plasma (confined) and maintains the reaction. The more alpha particles that remain confined, the more energy they give to other particles, causing more reactions, generating more neutrons. Ideally, the neutron escapes the plasma and collides with the blanket module that covers the inside of the device. In doing so, the neutron transfers its energy to the blanket, producing heat that generates electricity via turbines. Thus, the better the confinement, the more energy is generated. In a sufficiently strong magnetic field, charged particles will rotate around the field lines in a helical pattern. In this way, the particles are confined to the field lines. However, particles drift from these field lines due to the electromagnetic field with a certain velocity (drift velocity), causing turbulence. Since this velocity is independent of the mass and charge of the particle, electrons and ions will drift at the same velocity. Additionally, small fluctuations in the magnetic field cause particle drift. Two modes of confinement exist: low and high confinement (L-mode and H-mode respectively). H-mode was only available after the 1980's when researchers at ASDEX saw that confinement was rapidly improved. The benefit of H-mode instead of L-mode is that there is less turbulent transport and power degradation. This transition occurs above a certain power and H-mode is around two times better at confinement than L-mode. The exact mechanism of this transition is not well understood. Fusion devices rely on generating a rotational transform for plasma confinement.

Motivation

In fusion plasmas steep gradients (in fact, some of the steepest in the universe [6]) give rise to instabilities. It is important to note that plasmas are far from thermodynamic equilibrium as some analytical methods are only technically viable for systems in such a state. Turbulence arises from the plasma trying to achieve thermodynamic equilibrium and correct these gradients; turbulence works against maintaining a fusion plasma in the laboratory. Additionally, turbulence accounts for the nonlinear interaction between the electromagnetic field and the motion of the particles it confines. Moreover, when the plasma is heated, losses occur. Transport is the name given to losses due to convection and conduction. Classical transport theory accounts for diffusion due to particles experiencing Coulomb interactions, moving from one field line to another. Compared to classical transport theory, neoclassical transport theory takes into account trapped particles (caused by the magnetic field's geometry) and particle drifts (caused by the electric fields induced by the steep gradients). However, neoclassical transport assumes thermodynamic equilibrium and no turbulence. In neglecting turbulence, neoclassical transport neglects a significant portion of the total transport. Traditionally, neoclassical transport has hindered stellarator performance [5]. Additionally, there is a discrepancy between neoclassical theory and experiments. Previous research has shown that when the neoclassical transport theory takes into account the particle flux driven by fluctuations of the density and electrostatic potential - specifically when the density is lagging - the disagreement between the theory and experiment vanishes [5].

Motivation cont.: Analysis of Turbulence in Fusion Plasmas by Boudewijn van Milligen

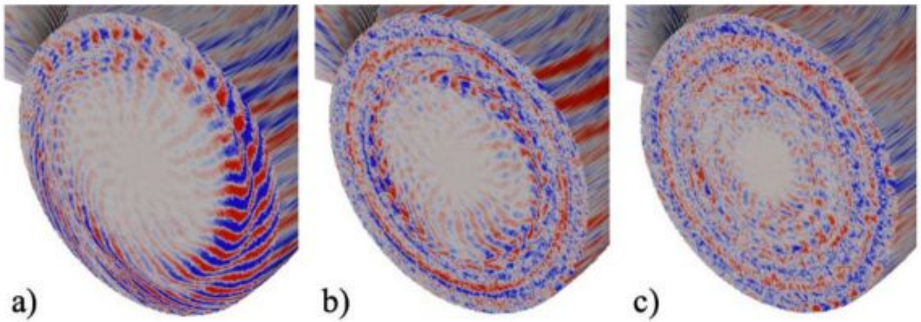


Figure 1.5. Poloidal cross sections of potential fluctuations in a nonlinear global turbulence simulation. (a) Close to the start of the simulation, radially connected structures ('streamers') dominate the system. (b) Zonal flows, spontaneously generated from the ambient turbulence in this strongly magnetised system, rupture the streamers. (c) In the final state, the radial extension of the turbulent structures is strongly reduced [18].

Motivation cont:

Fusion plasmas have steep gradients. These steep gradients give rise to instabilities. Plasmas are far from thermodynamic equilibrium. Turbulence arises from the plasma frying to correct these gradients (and return to thermodynamic equilibrium), thus working against maintaining a fusion plasma. Turbulence accounts for the nonlinear interaction between the electromagnetic field and the motion of the particles it confines. When the plasma is heated, losses occur. Transport is the name given to losses due to convection and conduction. Classical transport theory accounts for diffusion due to particles experiencing Coulomb interactions, moving from one field line to another. Compared to classical transport theory, neoclassical transport theory takes into account trapped particles (caused by the magnetic field's geometry) and particle drifts (caused by the electric fields induced by the steep gradients). However, neoclassical transport assumes thermodynamic equilibrium and no turbulence. In neglecting turbulence, neoclassical transport neglects a significant portion of the total transport. Traditionally, neoclassical transport has hindered stellarator performance. Additionally, there is a discrepancy between neoclassical theory and experiments. Previous research has shown that when the neoclassical transport theory takes into account the particle flux driven by fluctuations of the density and electrostatic potential - specifically when the density is lagging - the disagreement between the theory and experiment vanishes.

Diagnostic Description

$$\mathcal{H}(x,p,t) = \frac{1}{2m}(p - qA)^2 + q = \frac{1}{2}mv^2 + q = E_k + E_p$$

$$\mathcal{H} = \int_{t_A}^{t_B} \frac{d\mathcal{H}}{dt}\, dt = \int_{t_A}^{t_B} \frac{\partial \mathcal{H}}{\partial t}\, dt$$

$$\Delta\mathcal{H}(A \to B) = q\int_{t_A}^{t_B} \frac{\partial \phi}{\partial t}\, dt - q\int_{t_A}^{t_B} \frac{\partial A}{\partial t}\, dt = q\Omega_{AB}$$

$$\Delta\mathcal{H}(B \to C) = (q+e)\Omega_{BC}.$$

$$\Delta\mathcal{H}(A \to C) = q\Omega_{AB} + e\phi(B) + (q+e)\Omega_{BC}$$

$$e\phi(B) = \mathcal{H}_C - \mathcal{H}_A - (q\Omega_{AB} + (q+e)\Omega_{BC})$$

$\phi(A) = \phi(C) = 0$ and $\Omega \approx 0$

$$e\phi(B) = E_{k,C} - E_{k,A}$$

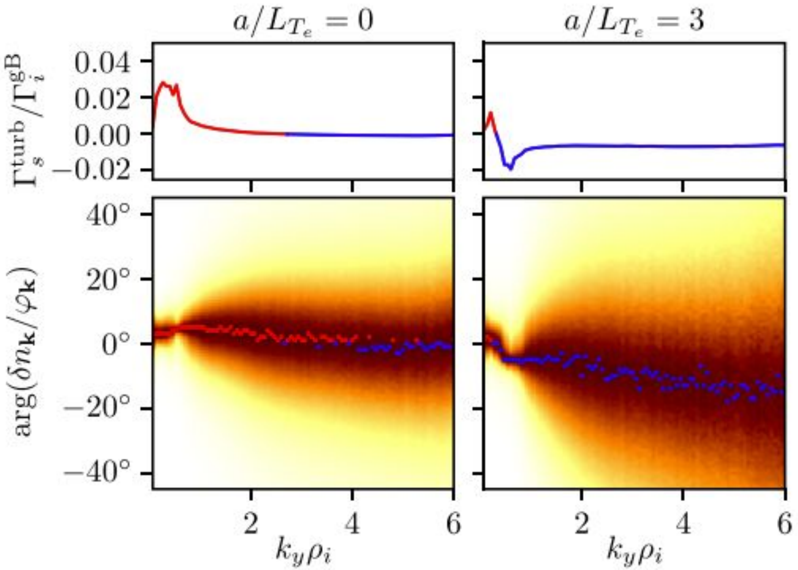
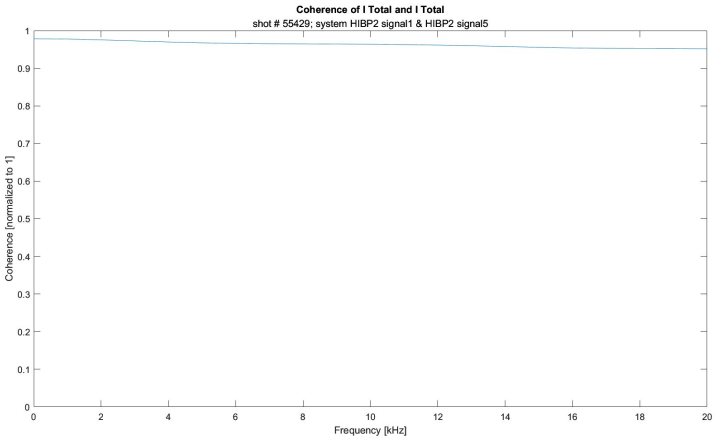
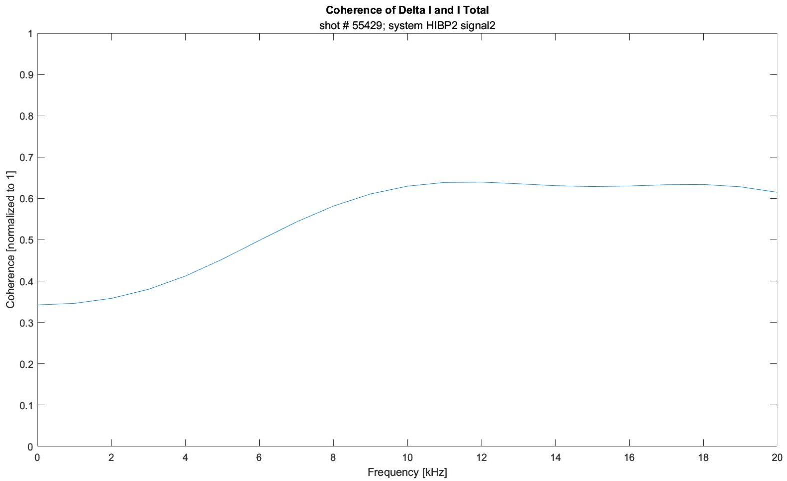
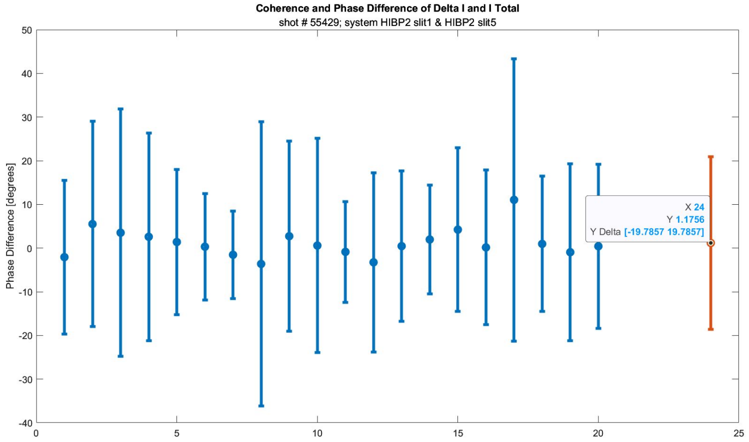
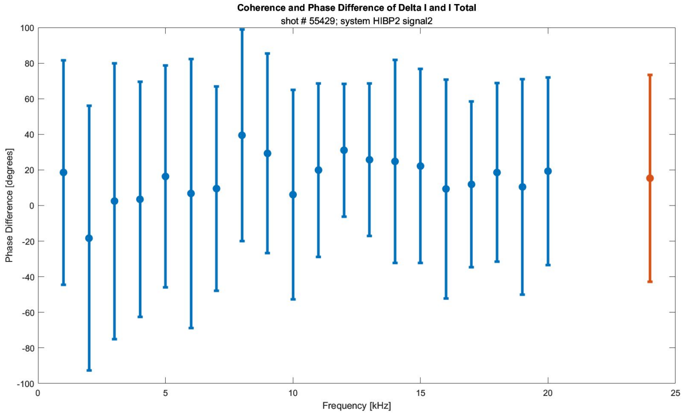


FIG. 3. Spectra of the particle flux (top) and phase difference between the density ($\delta n_{\mathbf{k}}$) and electrostatic potential ($\varphi_{\mathbf{k}}$) fluctuations (bottom), with $a/L_{T_e} = 0$ (left) and $a/L_{T_e} = 3$ (right). The dominant phase difference for each $k_y\rho_i$ is denoted by a dot. Positive values are highlighted in red, and negative values are in blue.


Coherence of I Total and I Total
shot # 55429; system HIBP2 signal1 & HIBP2 signal5
Coherence [normalized to 1]
Frequency [kHz]


Coherence of Delta I and I Total
shot # 55429; system HIBP2 signal2
Coherence [normalized to 1]
Frequency [kHz]


Coherence and Phase Difference of Delta I and I Total
shot # 55429; system HIBP2 slit1 & HIBP2 slit5
Phase Difference [degrees]
X 24
Y 1.1756
Y Delta [-19.7857 19.7857]


Coherence and Phase Difference of Delta I and I Total
shot # 55429; system HIBP2 signal2
Phase Difference [degrees]
Frequency [kHz]