SPATIALLY LOCALIZED mm-WAVE BACKSCATTERING MEASUREMENTS OF HIGH-k TURBULENCE IN THE DIII–D TOKAMAK

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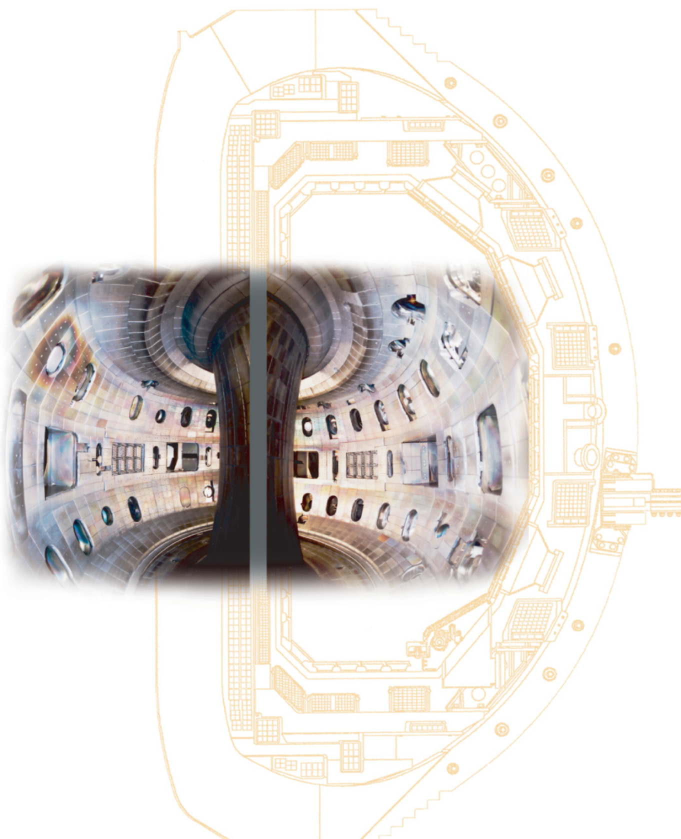

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Motivation

Electron thermal transport in fusion plasmas remains anomalous

Understanding this "scientific challenge" is important. Validating transport predictions would provide confidence extrapolating to "next-step" devices.

Potential causes of anomalous electron transport

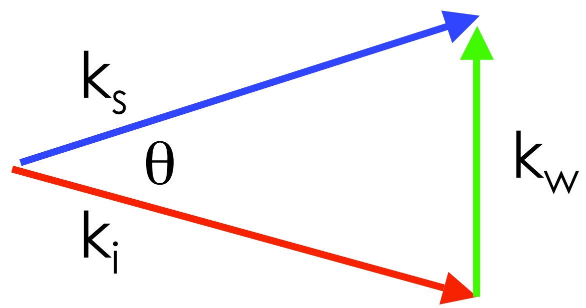
- **Low/Intermediate - k turbulence. e.g. ITG, TEM, etc.**
- **Magnetic turbulence**
- **Short-wavelength turbulence. ETG modes originate at large wavenumbers but may exist over a broad wavenumber range (10-100 cm^{-1}) and are predicted to drive electron transport**

Microwave backscattering is able to probe ETG scale turbulence on DIII-D and is well-suited to ITER and other fusion devices

Collective Scattering Principles

<u>Momentum Matching and Energy Conservation Require:</u>

$\boxed{\underline{k}_i + \underline{k}_w = \underline{k}_s}$ $\boxed{\omega_i + \omega_w = \omega_s}$



Where: k_i = Incident wavevector

k_s = Scattered wavevector

k_w = Probed wavevector

For $|k_i| \approx |k_s|$:

Bragg Eqn.

$$k_w = 2k_i \sin(\theta/2)$$

$$\Delta k = 2/w_o$$

Where: θ = Scattering angle

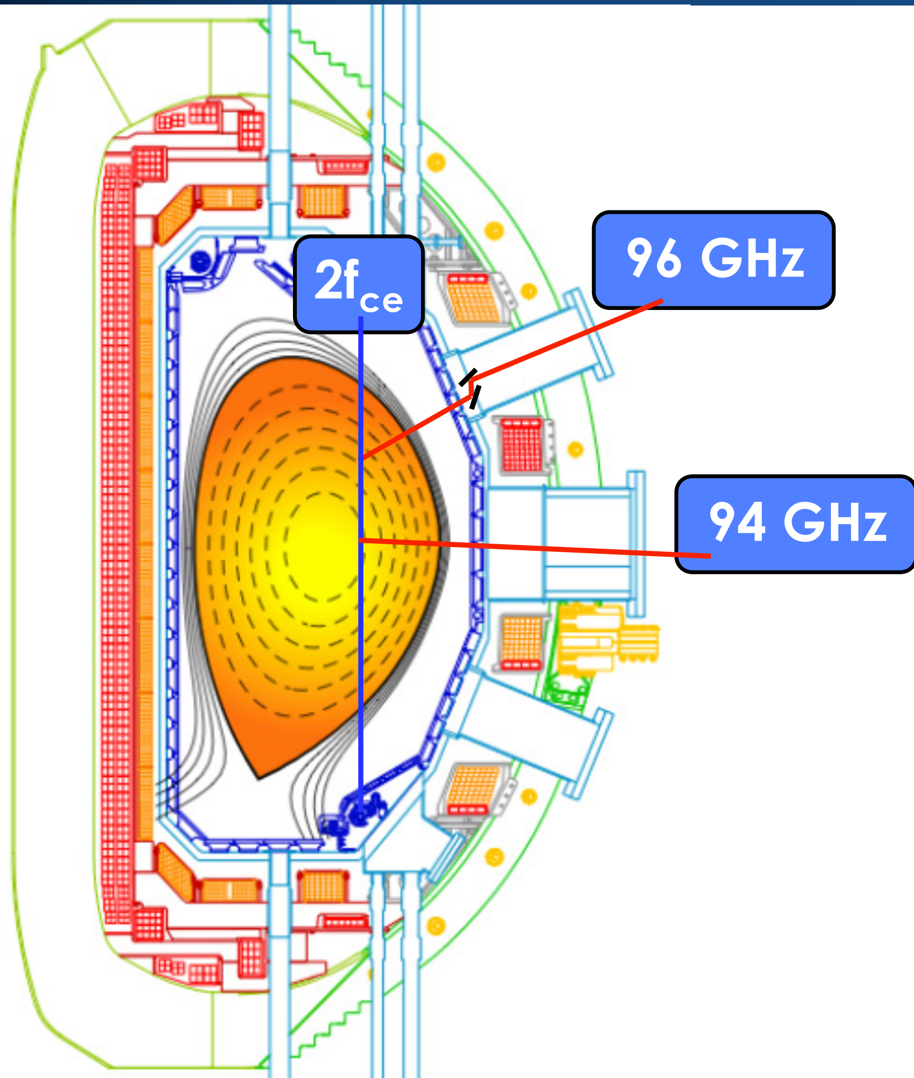
w_o = Incident beam waist

Δk = k-resolution for forward scattering

Backscattering means $\theta \sim 180°$ $k_w \approx 2k_i$, and $\Delta k << 2/w_o$.

We use: $k_i = 20$ cm^{-1} **giving** $k_w \approx 40$ cm^{-1} , $\Delta k < 1$ cm^{-1}

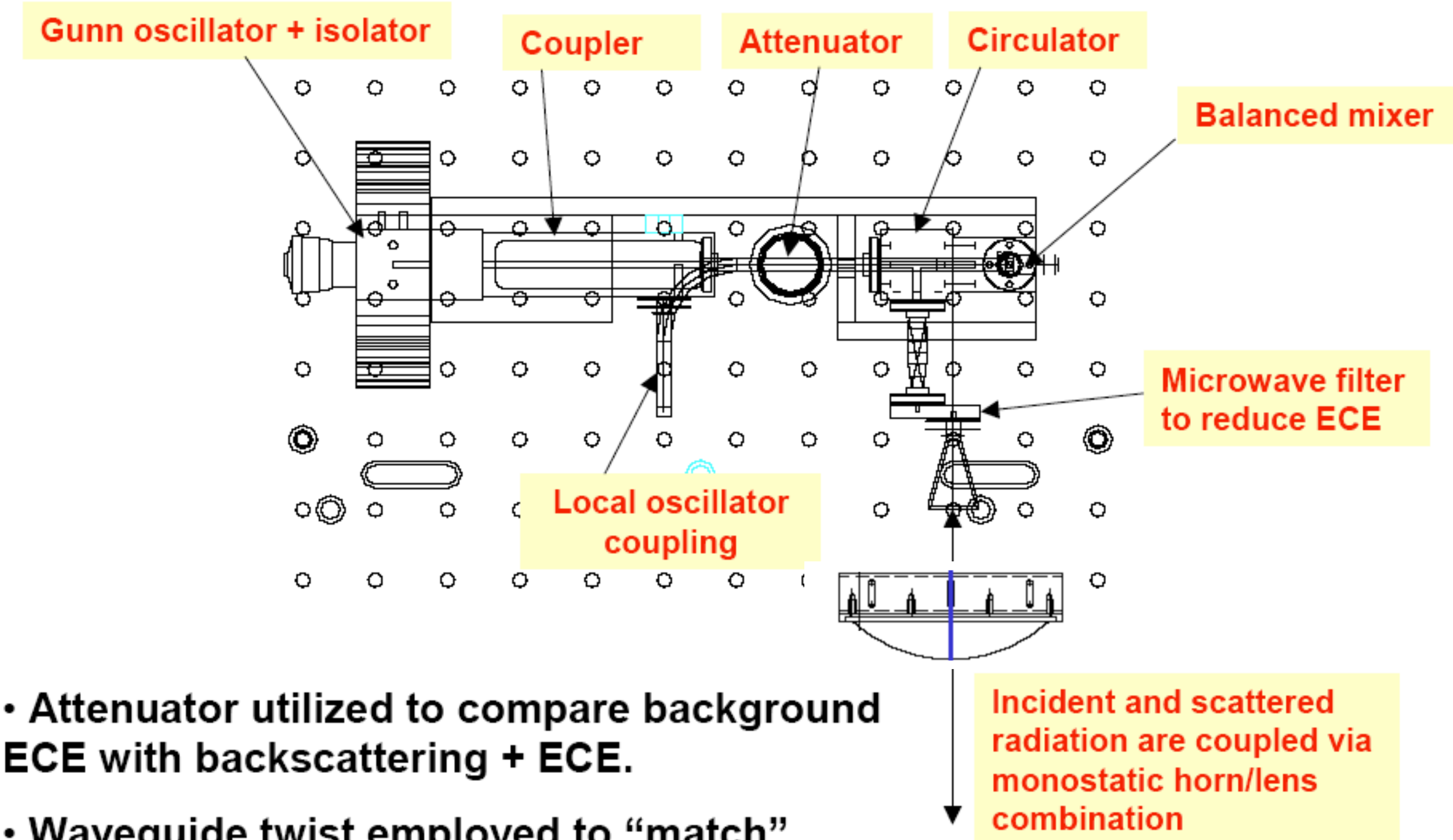
96 GHz Launch and $2f_{ce}$ Layer Beam Dump



The $2f_{ce}$ layer is used as a beam dump for the incident beam as well as forward scattered radiation allowing us to clearly identify backscattering from turbulent high-k fluctuations

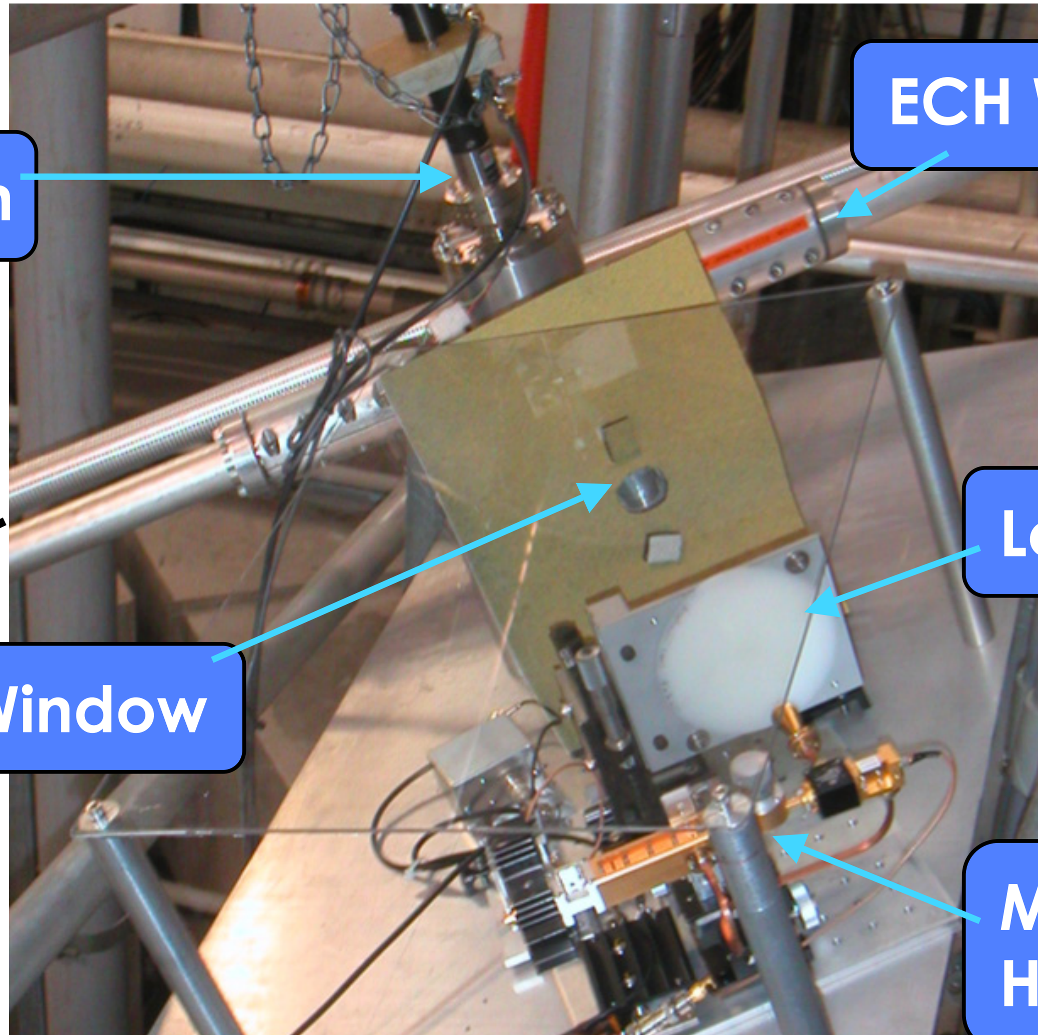
Two backscattering systems are installed on DIII-D. One at an upper port utilizing a steerable ECH launcher and one on the midplane.

Microwave Hardware



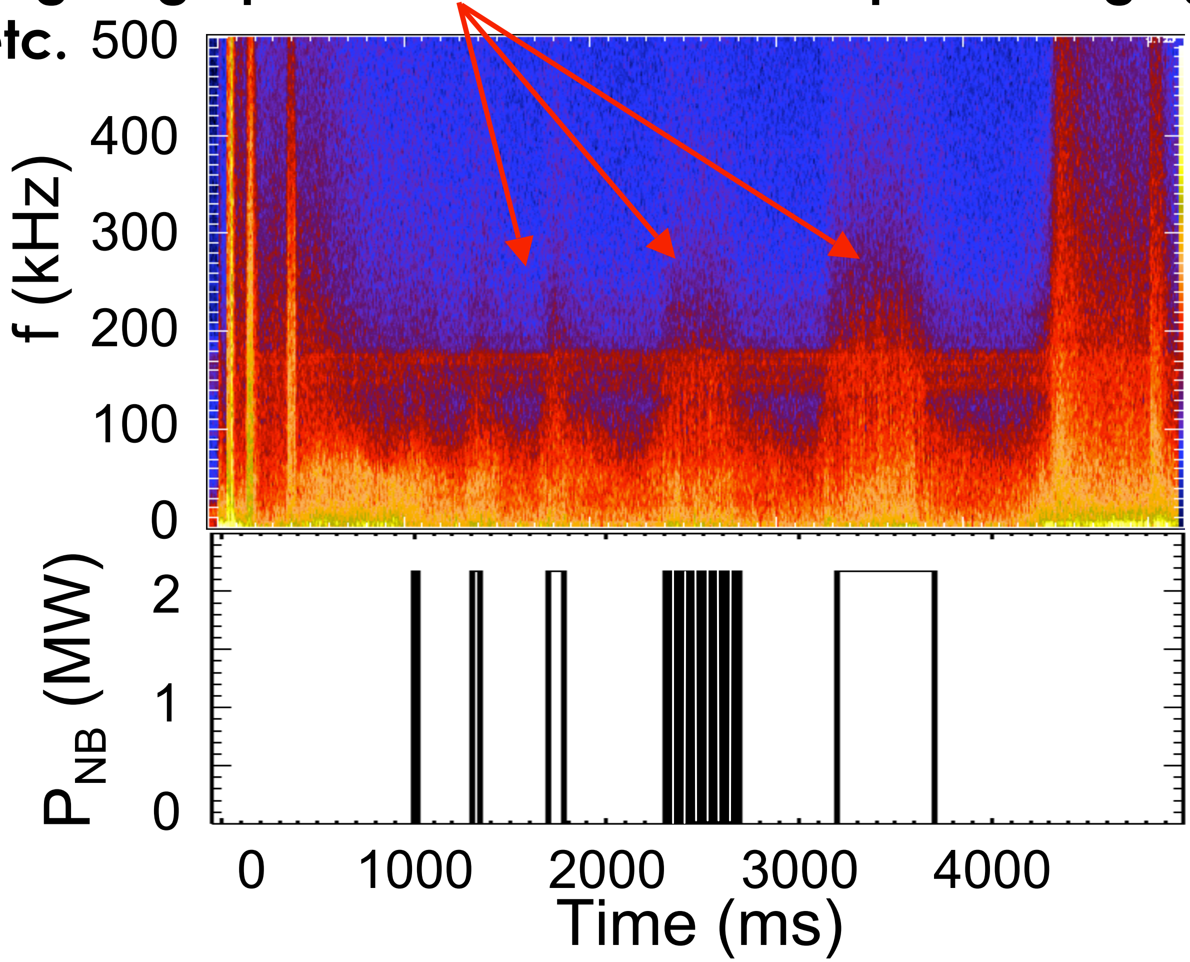
- Attenuator utilized to compare background ECE with backscattering + ECE.
- Waveguide twist employed to "match" polarization to edge magnetic field.

Installed System



Scattered Radiation is Observable Above ECE Background and Behaves Qualitatively as Expected

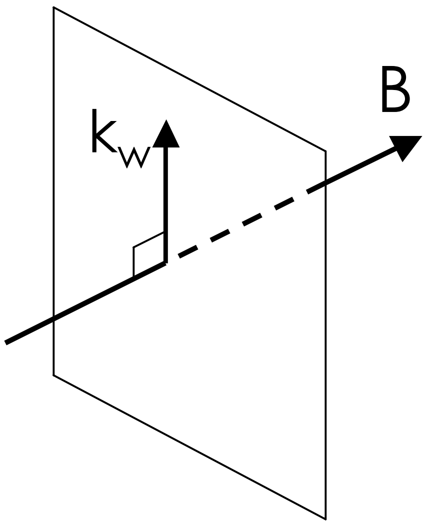
Intermittent bursts are due to increasingly larger avgerage power neutral beam "blips" changing profiles etc.

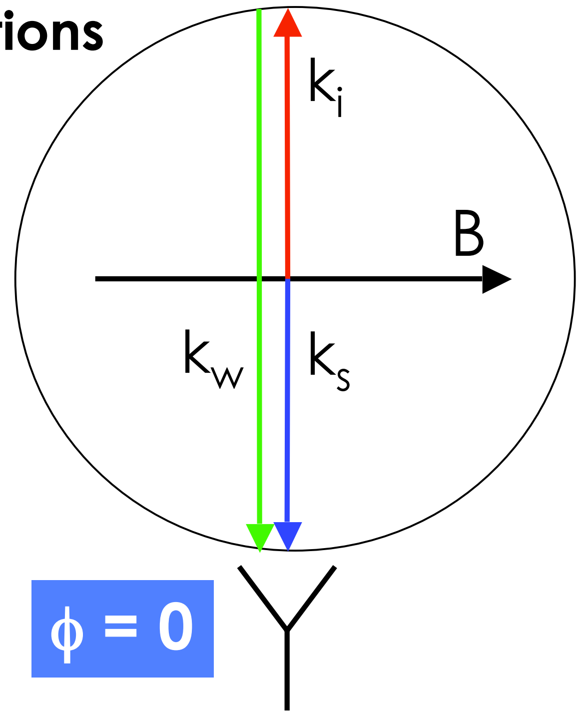


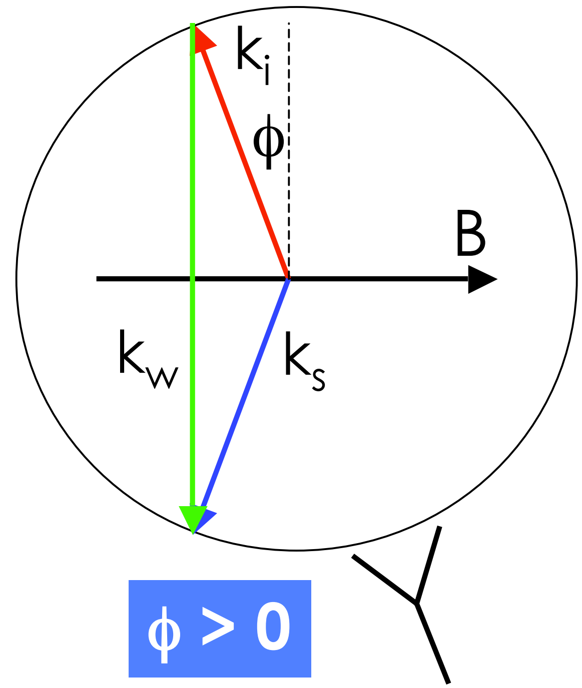
Backscattered power is approximately an order of magnitude above ECE (Electron Cyclotron Emission)

Field Line Pitch Angle Strongly Affects Scattering Measurements

For the turbulent fluctuations being considered, $\lambda_{||}$ is large, $\underline{k_w} \perp \underline{B}$



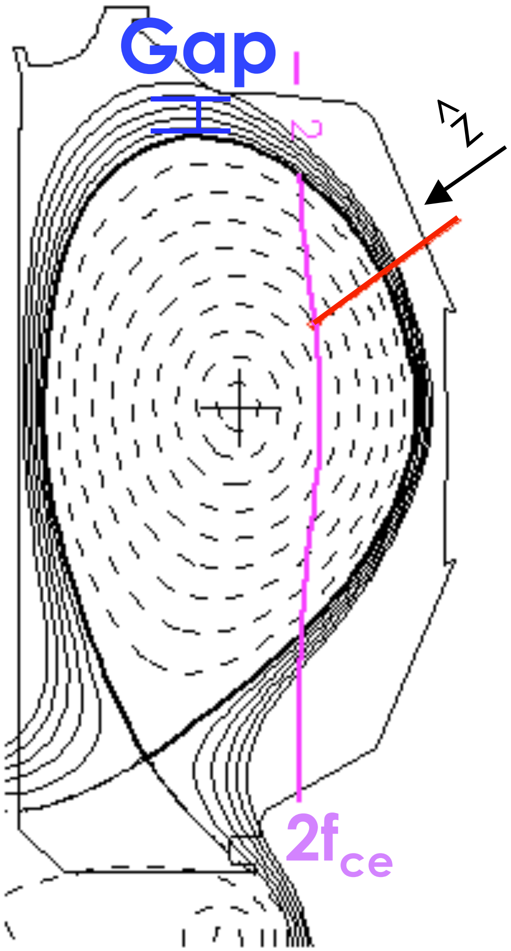




Received scattered power will decrease as ϕ increases, where ϕ is the angle between k_i and the plane normal to B. In general, ϕ is a function of position (z) along the incident ray path.

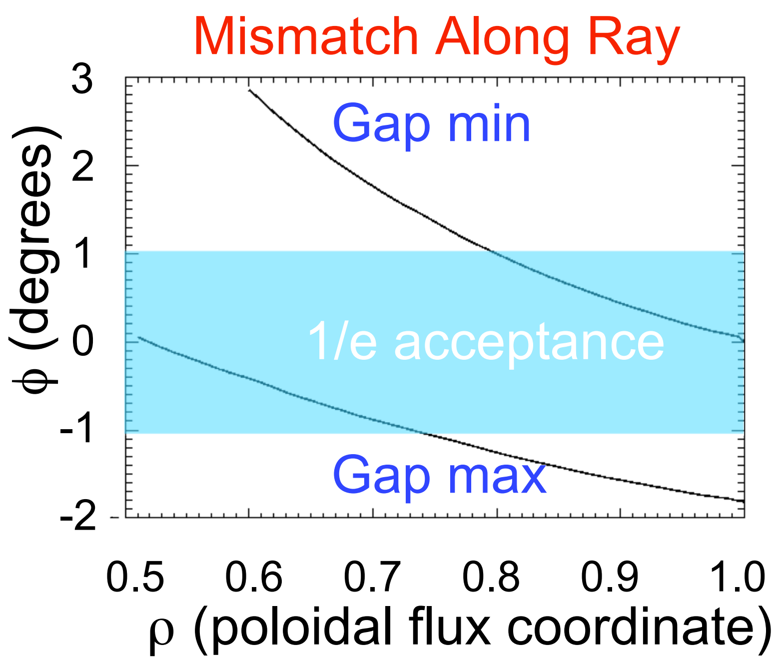
$$\boxed{P_{scatt}(t) = f\left(k_o, \tilde{n}(z,t), \phi(z,t)\right)}$$

The Pitch Angle Helps Obtain Better Fluctuation Localization / Plasma Jog

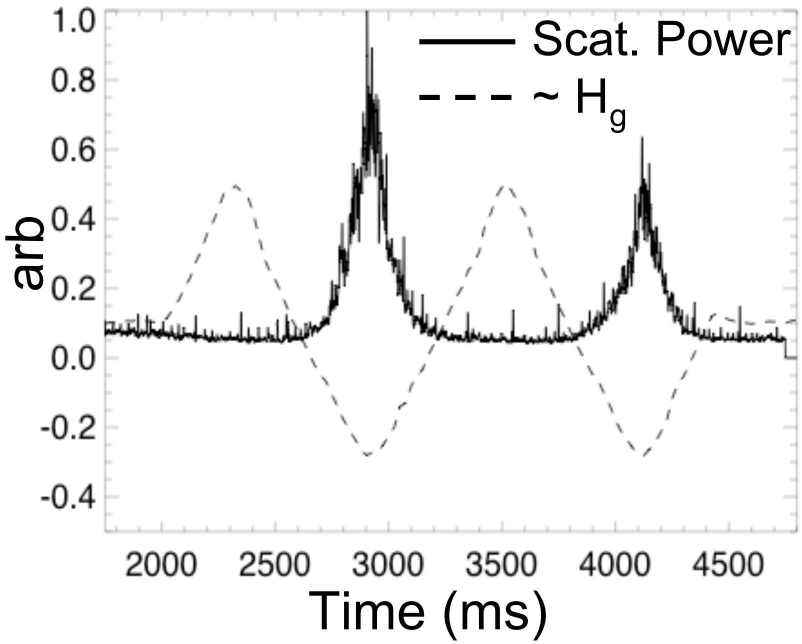


EFIT Equilibrium Reconstruction

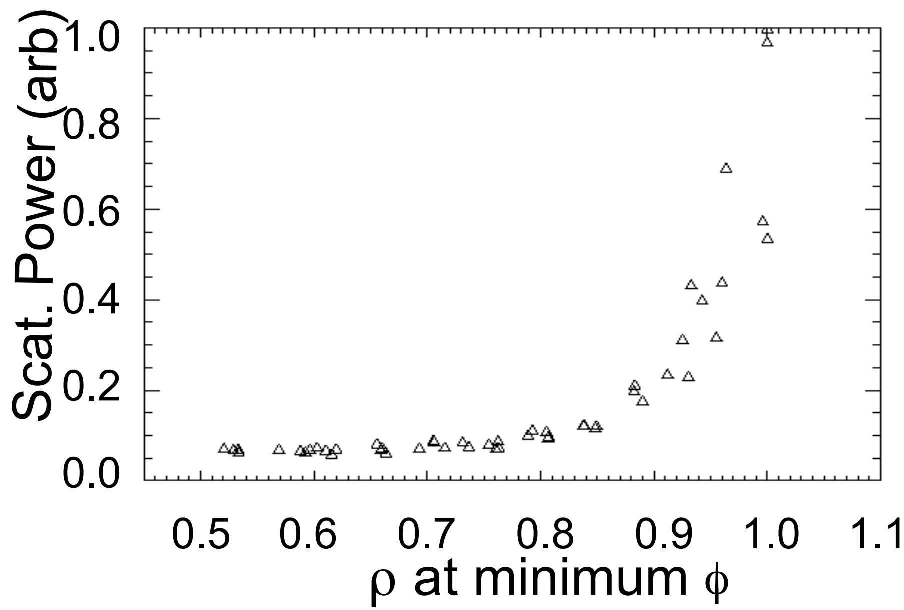
In general, ϕ is a function of position along the ray, $\phi(z)$. A rigid body shift of the plasma is carried out in order to continuously vary $\phi(z)$. At Gap min, matching occurs at outer radii while at Gap max, matching occurs at inner radii.



Rigid Body Shift Leads to a Varying P_{scatt}



As the plasma is translated up/down we change our "viewing" location. The resultant temporal evolution of the scattered power is a convolution of the instrument function w/ ñ(z) .



Based on where the best matching is at the time of peak power, we can qualitatively estimate where ñ(ρ) peaks.

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The Resultant $P_{scatt}(t)$ is a Convolution of Mismatch Angle and Fluctuation Distribution Along Ray

The scattered power is related to the fluctuation distribution along the ray path according to:

$$P_{scatt}(t) \propto \left[\int \tilde{n}(z,t)\exp\left(-\left(k_o a_o \sin\left(\phi(z,t)\right)\right)^2\right)\cos\left(2k_o z\left(\cos\left(\phi(z,t)\right)-1\right)\right)dz\right]^2 *$$

- $P_{scatt}(t)$ is a measured quantity, and $\phi(z,t)$ is available from EFIT (Equilibrium Reconstruction)

- If we approximate ñ as ñ(ρ) in the region considered, it can be extrapolated onto ray-path and ñ(ρ) can be de-convolved from $P_{scatt}(t)$

- In order to do the de-convolution many methods were investigated, however, a Genetic Algorithm was settled upon due to its relative insensitivity to local minima.

* Derived from R.E. Slusher and C.M. Surko, Phys. Fluids **23**, 472 (1980)

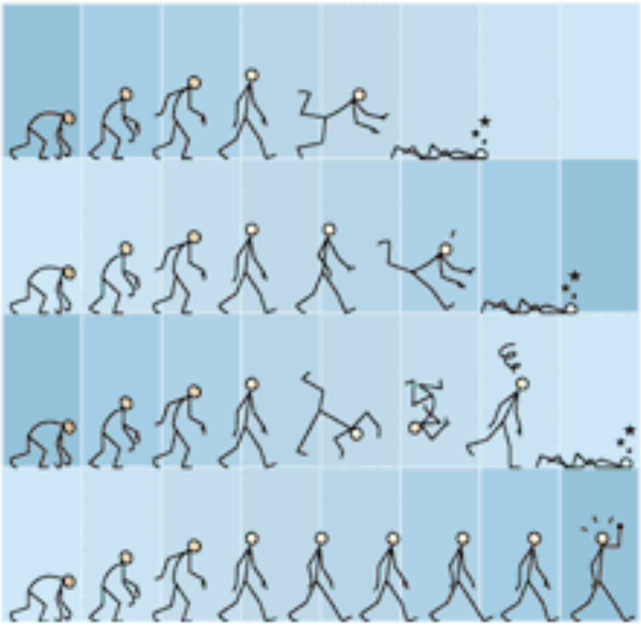
What is a Genetic Algorithm?

GAs (Genetic Algorithms) are a class of algorithms inspired by the mechanisms of genetics which can be applied to global optimization or many such problems in which there is a defined "fitness" or measure of performance.

Examples of GA Applications

GAs have been used in a variety of fields, from Plasma Physics to Hollywood animation

- **Stellerator magnet design**
- **Evolutionary Modeling**
- **Neural Network Optimization**
- **DNA analysis**
- **Electronic circuit design**
- **Animation**



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A Trivial Example: Try to Guess $\underline{O} = [1,3,5,7]$

1. Create a population of *N* guess vectors (chromosomes): $\underline{G}_i$, $i = 1 \ldots N$
2. Evaluate the "Fitness" (*F*) of each guess: $F_i^{-1} = \sum_j \left(O_j - G_{ji}\right)^2$

3. "Breed" the population to create a new population of N individuals, where partners are randomly selected but with a probability (P_i) in proportion to their fitness:
$$P_i = F_i \Big/ \sum_i F_i$$
4. The "Offspring" are formed by randomly taking components (genes) of $\underline{G}_i$ from each "parent".**
5. For each offspring, randomly (but with a low probability of occurrence) "mutate" a component of $\underline{G}_i$ to a new value.
6. Go to Step 2 and Repeat until some individuals fulfill requirements on *F*

A Genetic Algorithm for Deconvolving $\tilde{n}(\rho)$

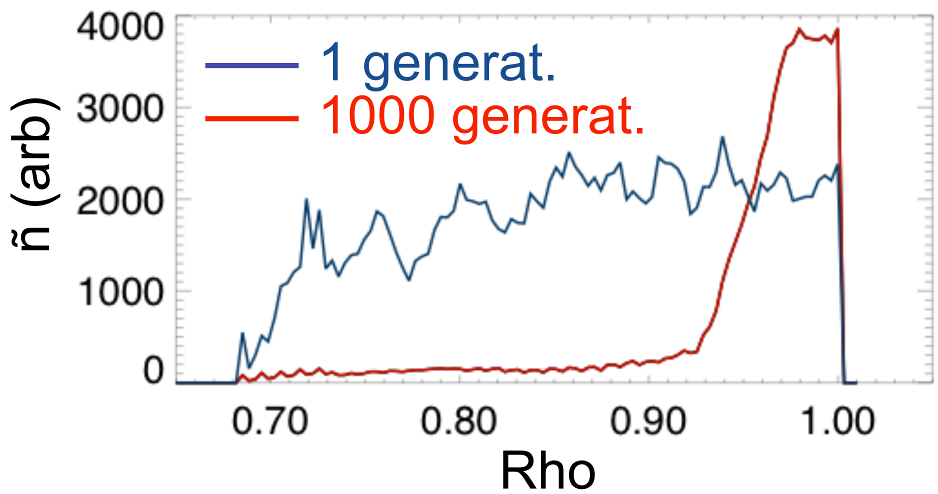
1. Create a N (typically 1000) member population of $\tilde{n}_i(\rho)$ evaluated at M (typically 100) fixed ρ values.
2. Using $\phi(z,t)$ calculated from EFIT and each $\tilde{n}_i(\rho)$, interpolate onto ray path and perform P_{scatt} integral at each timestep of jog, generating $P_{scatt}(t)$.

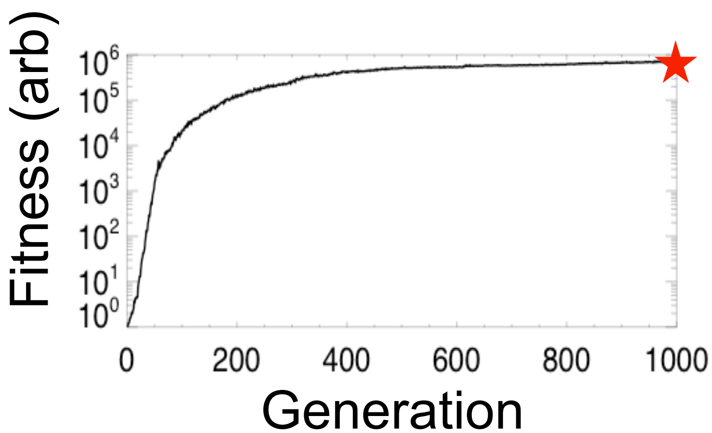
$$P_{scatt}(t) \;\; \alpha \;\; \left[\int \tilde{n}(z,t) \exp\left(-\left(k_o a_o \sin(\phi(z,t)) \right)^2 \right) \cos\left(2 k_o z \left(\cos(\phi(z,t)) - 1 \right) \right) dz \right]^2$$

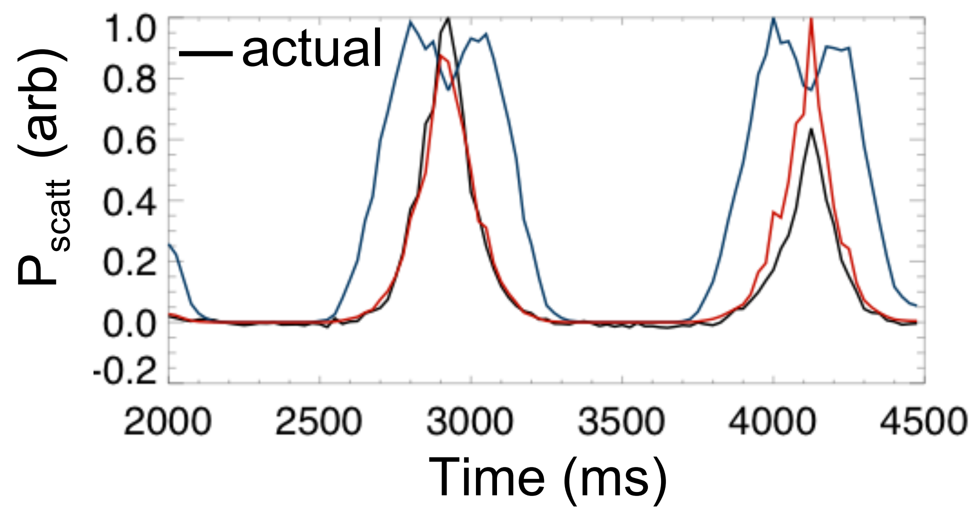
3. Evaluate fitness (F_i) by least-square comparison of $P_{scatt}(t)$ to actual $P_{meas}(t)$.
4. Breed and evolve $\tilde{n}_i(\rho)$ until $P_{scatt}(t) \approx P_{meas}(t)$.

Genetic Algorithm Results - Theoretical $P_{scatt}(t)$ and $\tilde{n}(\rho)$

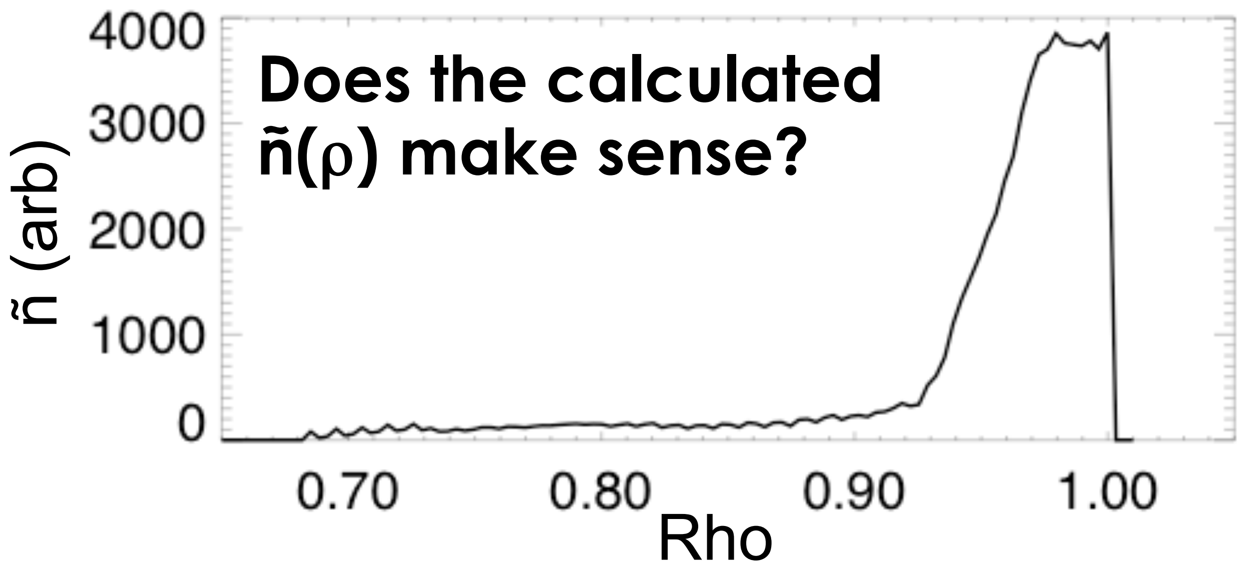
As the population evolves, $\tilde{n}(\rho)$ is found to peak outside of $\rho > 0.9$. The *avg. of the top 5 members from Generation 1 and 1000* are shown to convey the evolution of $P_{scatt}(t)$ as $\tilde{n}(\rho)$ is changed. Beyond 1000 generations, the fitness increases very little and the $\tilde{n}(\rho)$ profile no longer continues to change.







Genetic Algorithm Results (cont.) - final $\tilde{n}(\rho)$ shows strong localization at ρ > 0.9



1. Consistent with B_t scan that localized the turbulence to $\rho > 0.75$
2. Consistent with simple plot shown of $P_{meas}(t)$ vs. Position of best matching.
3. This is the region in which the gradients are the largest, i.e. T_e & n_e.
4. Preliminary GKS calculations show largest growth rates near the outer radii.

Conclusions and Future Work

- Two mm-wave backscattering systems have been installed on DIII-D that are capable of observing turbulence in the range of k = 30-40 cm^{-1} such as that expected of ETG (Electron Temperature Gradient) modes.
- First measurements of the spatial distribution of ETG scale turbulence have been obtained
- The radial distribution of 30-40 cm^{-1} turbulence has been observed to be highly peaked at $\rho > 0.9$ in an Ohmic L-mode plasma

Future work will include comparison to stability code predictions, extensions of this method to other plasma shapes as well as H-mode plasmas, and several hardware upgrades.