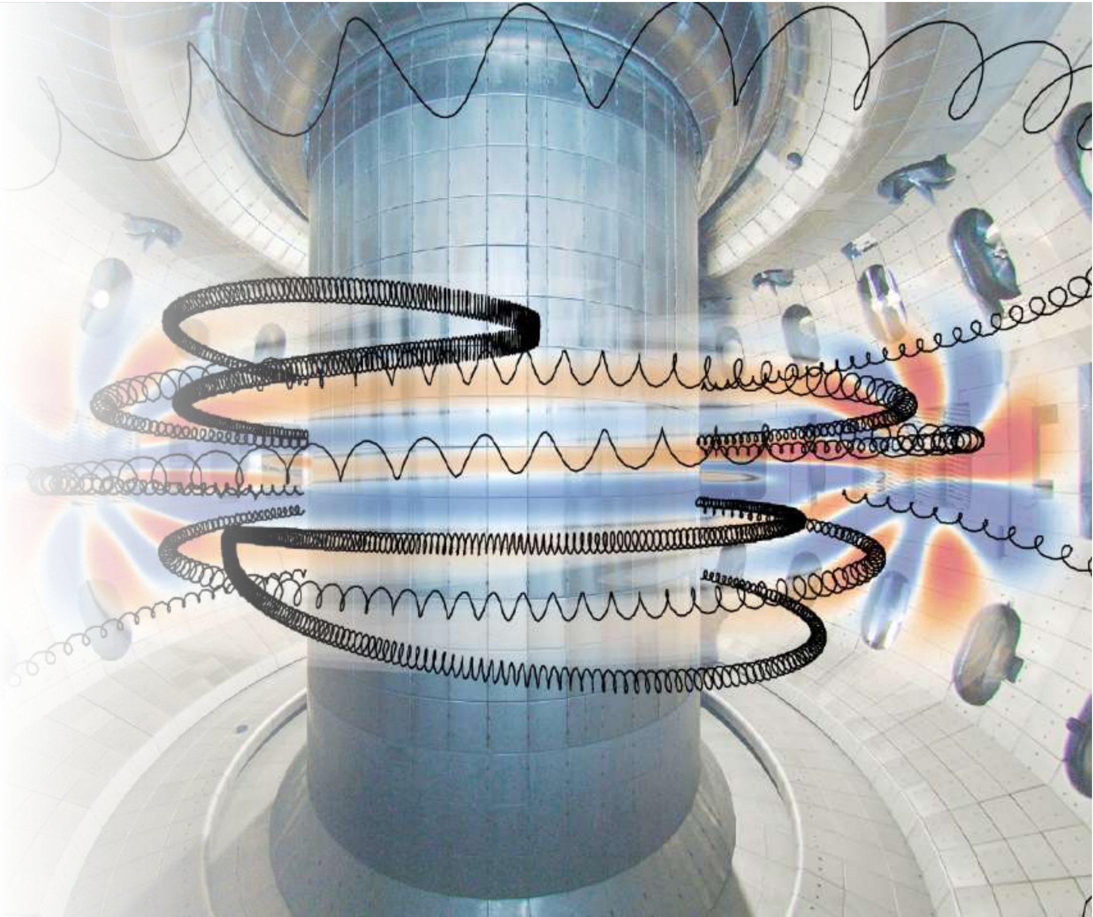
"Diagnostics Associated With Redistribution of Confined EPs and the Causes"

M.A. Van Zeeland[1]

Contributions by: M. Austin, J. Chen, C. Collins, X. Du, W. Heidbrink, G. McKee, C. Muscatello, M. Salewski, S. Sharapov

[1]*General Atomics, PO Box 85608, San Diego, CA, USA*



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Motivation

- **20+ years ago many DIII-D experiments showed indications of significant fast ion transport – primarily neutron deficit**
  - Could not be explained with few modes observed by magnetic diagnostics at edge
  - Heidbrink was ready to quit EP physics!

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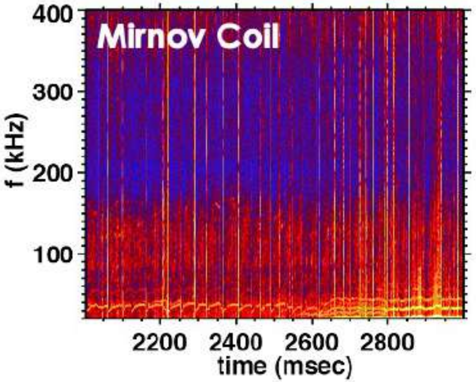

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- ***Enter new diagnostic advances!***
  - New core fluctuation measurements revealed wealth of relatively low amplitude core modes
  - New core fast ion diagnostics began making phase space resolved measurements of large-scale transport
- **Eventually, simulations confirmed measured modes and were able to resolve overlap of resonances leading to transport**
- **Talk is about tools and techniques that enabled understanding and *that you can use today***

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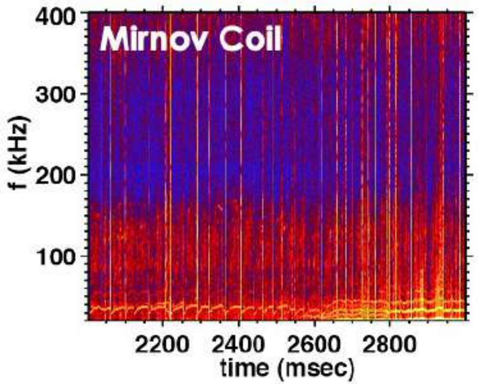
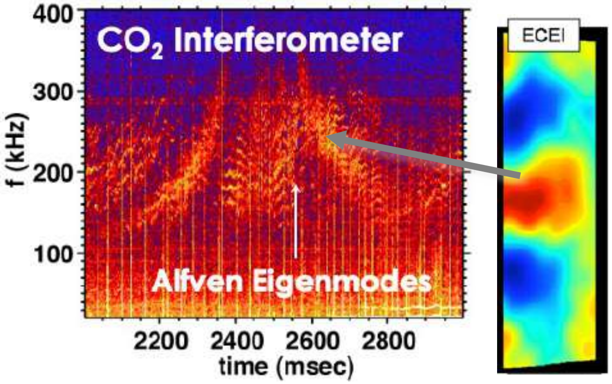


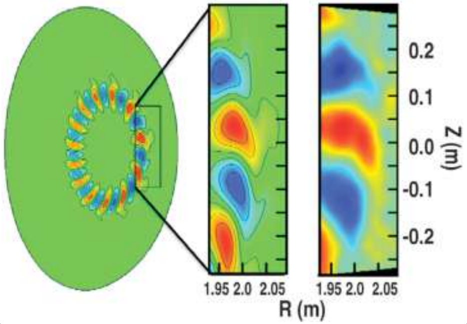
After



D. Pace et.al., Physics Today, October 2015

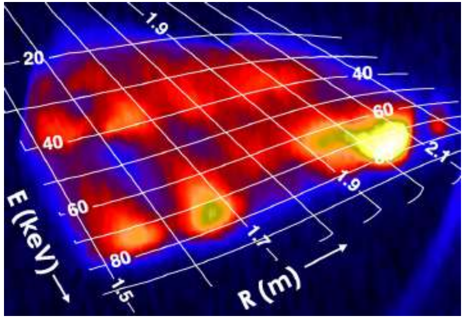
Outline

Measurement of Instabilities



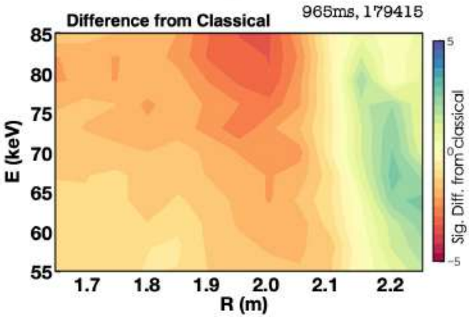
- Perturbed quantities
- Spectral analysis and pulling small signals out of noise
- Fluctuation diagnostics (Interf., Polarimetry, ECE, BES, Reflectometry, SXR)

Measurement of Confined Fast Ions



- DD Beam-Plasma neutrons
- Neutral Particle Analyzers (NPA, INPA)
- Equilibrium pressure

Measurement of Instability Impact



- Abrupt events / relative measurements
- Quantitative / absolute measurements
- Example putting it all together

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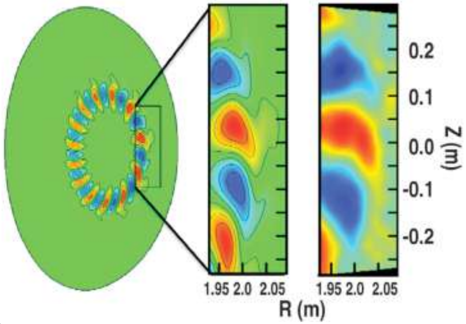

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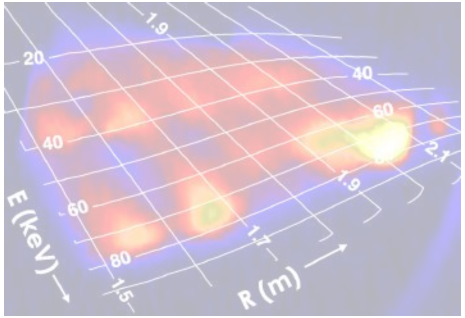

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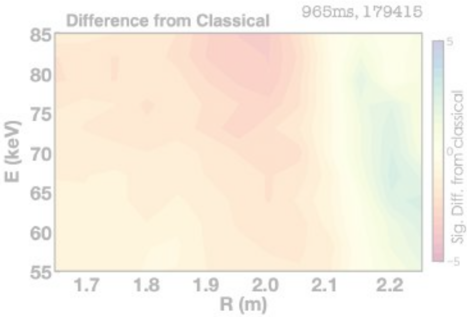

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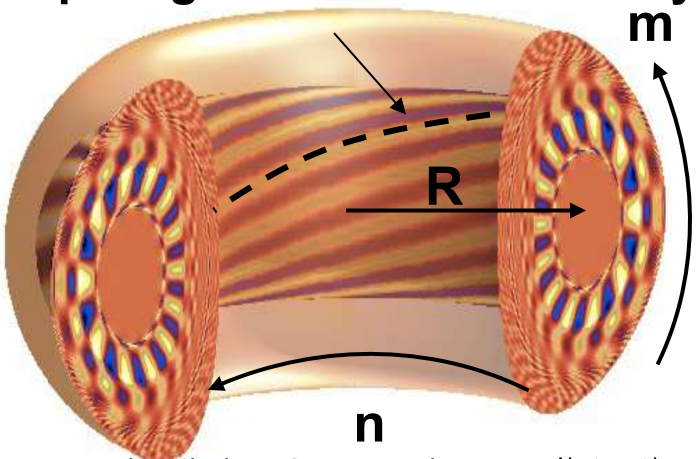
Most of the Discussion Focuses on Measurements of Alfvén Eigenmodes (AEs) and Impact

- **AEs are normal modes of the plasma (*many more details by Sharapov*)**
- **Physical properties are determined by the internal structure of the magnetic field (q, B) and thermal plasma profiles (n_e,n_i,T_e,T_i)**
- **Not observed unless excited by energetic particles (neutral beam ions) or antennas**
- ***Things we wish we could measure***
  - Frequency
  - Localization
  - m,n
  - Amplitude δB, δE
  - Polarization
  - And evolution of all these quantities

q: magnetic field line helicity



Periodicity Constraint ~ $e^{i(n\phi - m\theta)}$
- *n=toroidal mode number*
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In principle, work here applies to any range of perturbations

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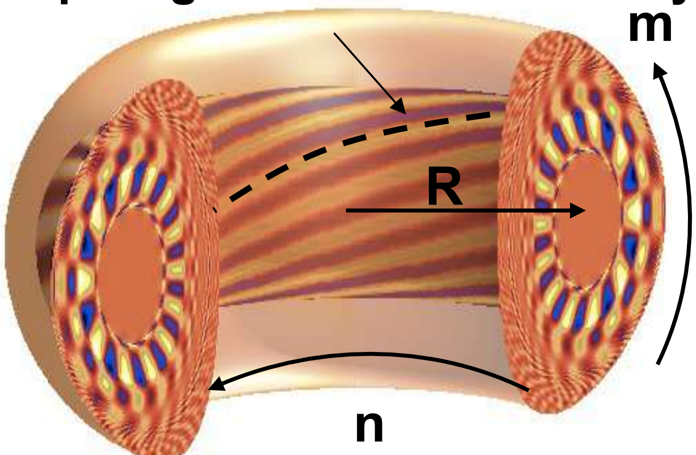

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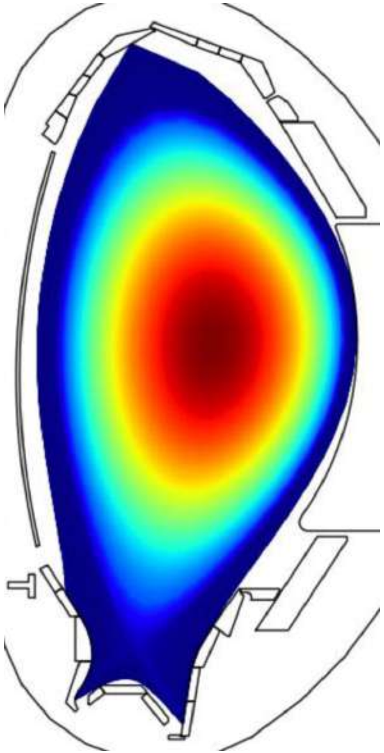
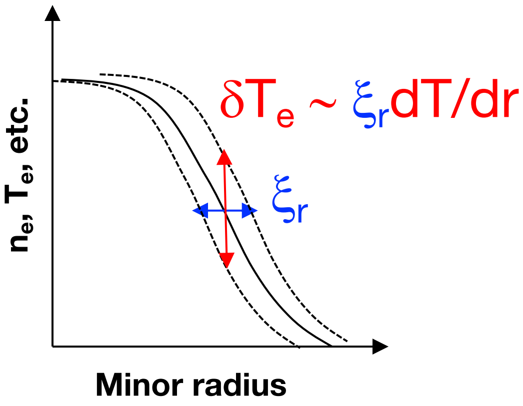
Primary Quantities Measured in Core are Perturbed Temperature and Density – Not Perturbed Field





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- **Localized measurements see fluctuating quantites proportional to gradient**

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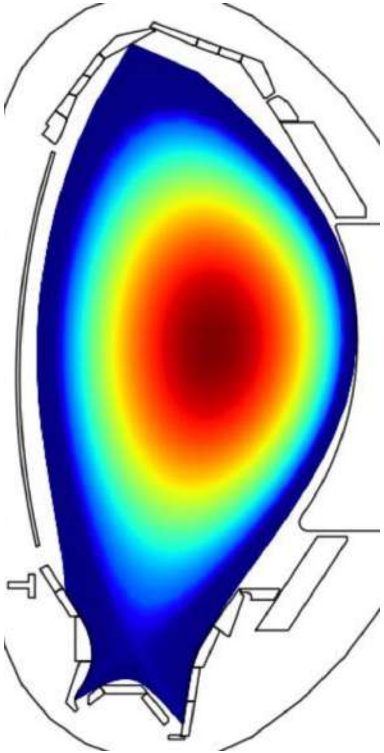

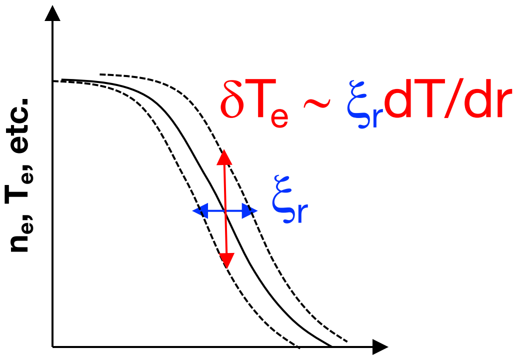

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- Localized measurements see fluctuating quantites proportional to gradient
- Perturbed kinetic profiles have displacement and compressional contributions

Electron Density

$$\frac{\delta n_e}{n_e} = -\nabla \cdot \xi - \xi \cdot \frac{\nabla n_e}{n_e}$$

Electron Temperature

$$\frac{\delta T_e}{T_e} = -(\gamma - 1)\nabla \cdot \xi - \xi \cdot \frac{\nabla T_e}{T_e}$$

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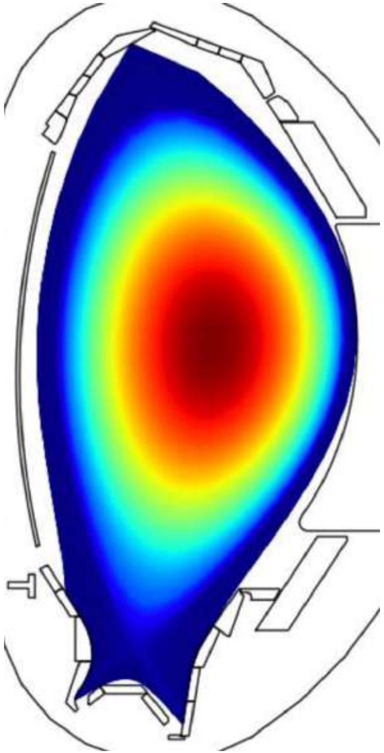

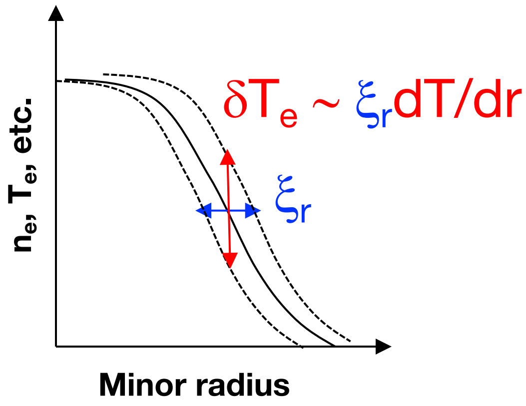

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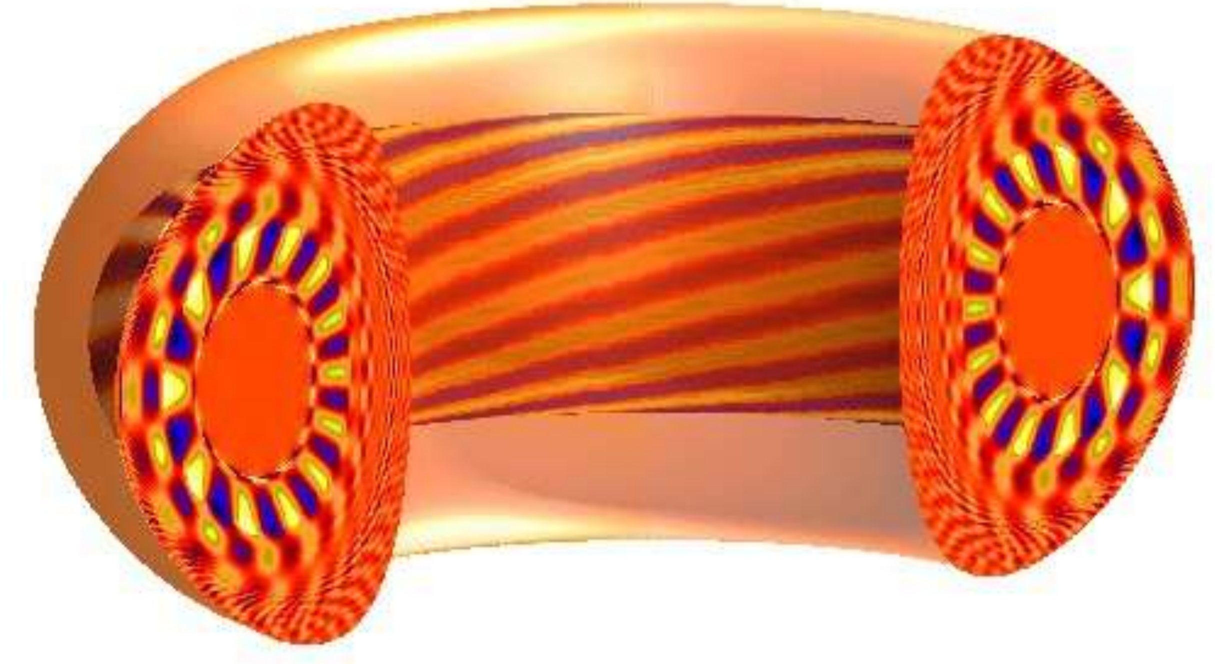
For shear waves, compressional term is small but not always the case for other instabilities – also need some gradient

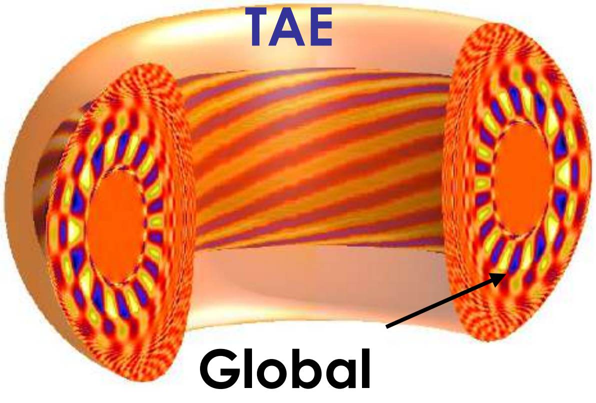
Perturbed Quantities Have Complex 3D Structures

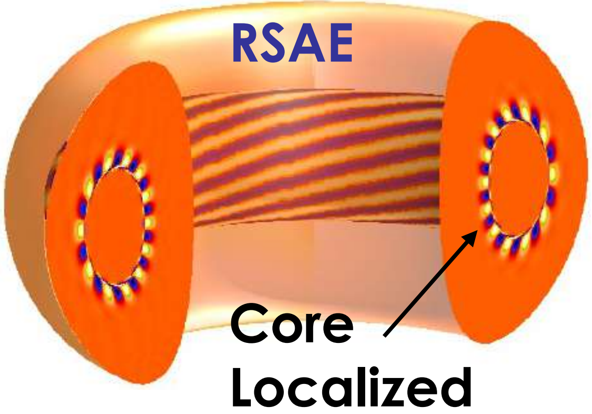
TAE Temperature Perturbation



- Combination of multiple poloidal mode numbers, radial structure and n, leads to complex 3-D structure
- Rotates past fixed diagnostics in time

Different Modes Have Different Localizations with Different Implications for Impact on Fast Ion Profile



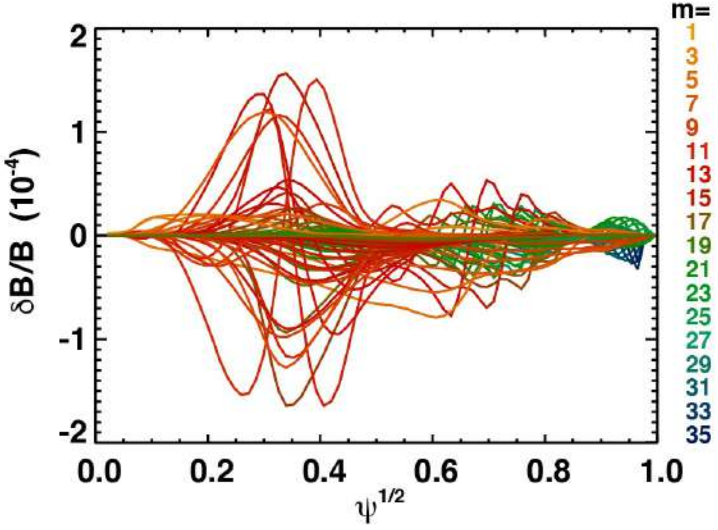


- **Sergei covered in detail**
- **Obvious implication is that larger scale modes can potentially transport particles further across plasma**
- **Key to assessing impact is measurements of mode localization**

Even Very Low Level Fluctuations Can Cause Large EP Transport….

- **AEs with peak δB/B~10^{-4} are typical**
  - Still can cause large scale transport
- **What does that mean?…Means low signal levels!!**
  - **Typically δT/T & δn/n < 1%**

This set of AEs caused 50% reduction in central fast ion density δB/B < $2x10^{-4}$



W.W. Heidbrink, et. al., PRL 99, 245002 (2007)
R.B. White,et.al., Phys. Plasmas 17, 056107 (2010)

Fortunately, Many of the Instabilities We Focus on are Coherent Oscillations and Several Analysis Techniques Exist to Extract Key Information

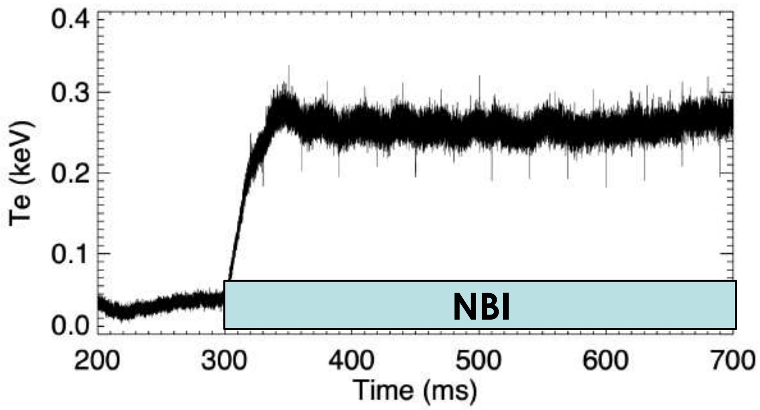
$X_1(\omega) = FFT[x_1(t)]$ $X_2(\omega) = FFT[x_2(t)]$	Complex FFT of time series $x_1(t)$ and $x_2(t)$
$C_{12}(\omega) = \langle X_1(\omega) X_2^*(\omega) \rangle$	Cross Spectrum
$P_{12}(\omega) = \lvert C_{12}(\omega) \rvert = [C_{12}(\omega) C_{12}^*(\omega)]^{1/2}$	Cross Power
$\Theta_{12}(\omega) = tan^{-1}[Imag.[C_{12}(\omega)]/Re.[C_{12}(\omega)]]$	Cross Phase Spectrum
$n(\omega) = \Theta_{12}(\omega)/\Delta\phi_{12}$	Toroidal mode number spectrum from probes separated by $\Delta\phi$
$\gamma_{12}(\omega) = \dfrac{P_{12}(\omega)}{[P_{11}(\omega) P_{22}(\omega)]^{1/2}}$	Coherence Spectrum
$\gamma_{95\%} = \tanh\,[1.96/\sqrt{2M-2}]$	95% Confidence Level

< > indicates smoothing over M frequency elements

1. J.R. Ferron and E.J. Strait, RSI, **63**, 10, (1992)

2. Bendat and Piersol, ”Random Data Analysis and Measurement Procedures”, Wiley, 2000

FFT Is the Starting Point For Extracting Information About Small Amplitude Modes From Our Noisy Signals



- **EP driven instabilities are typically not obvious in raw data**

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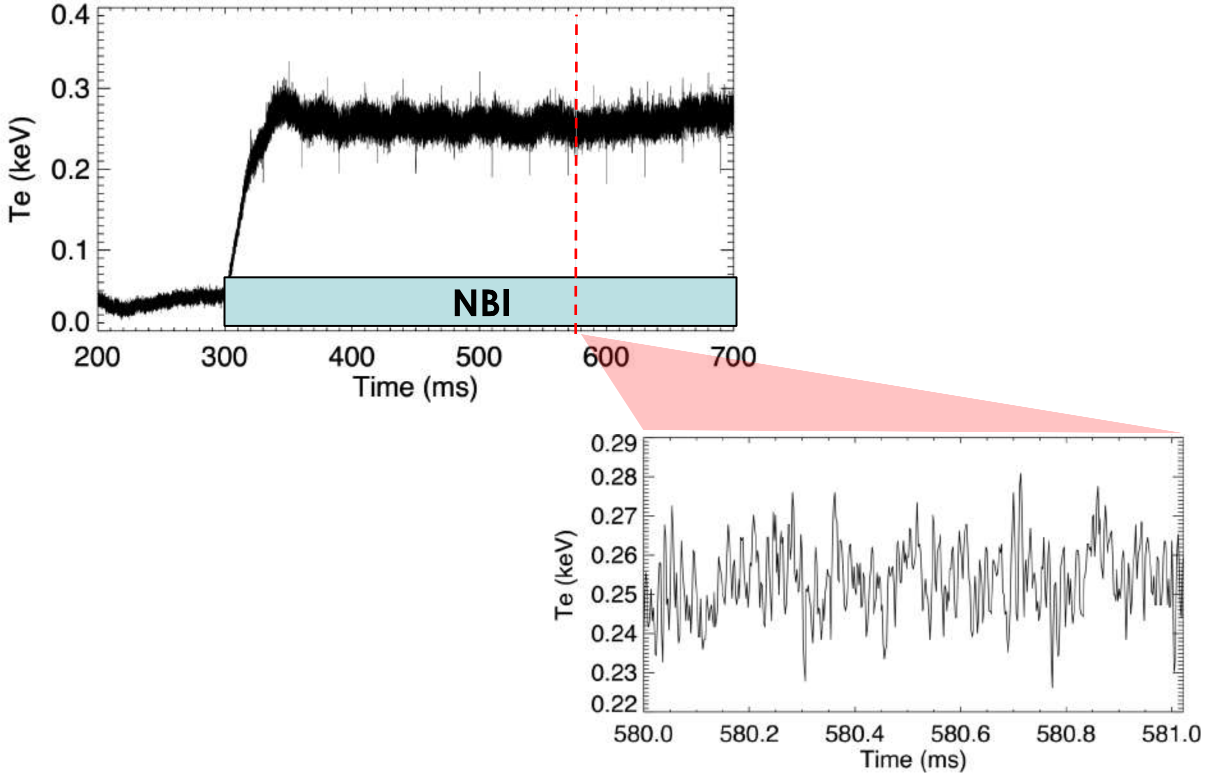

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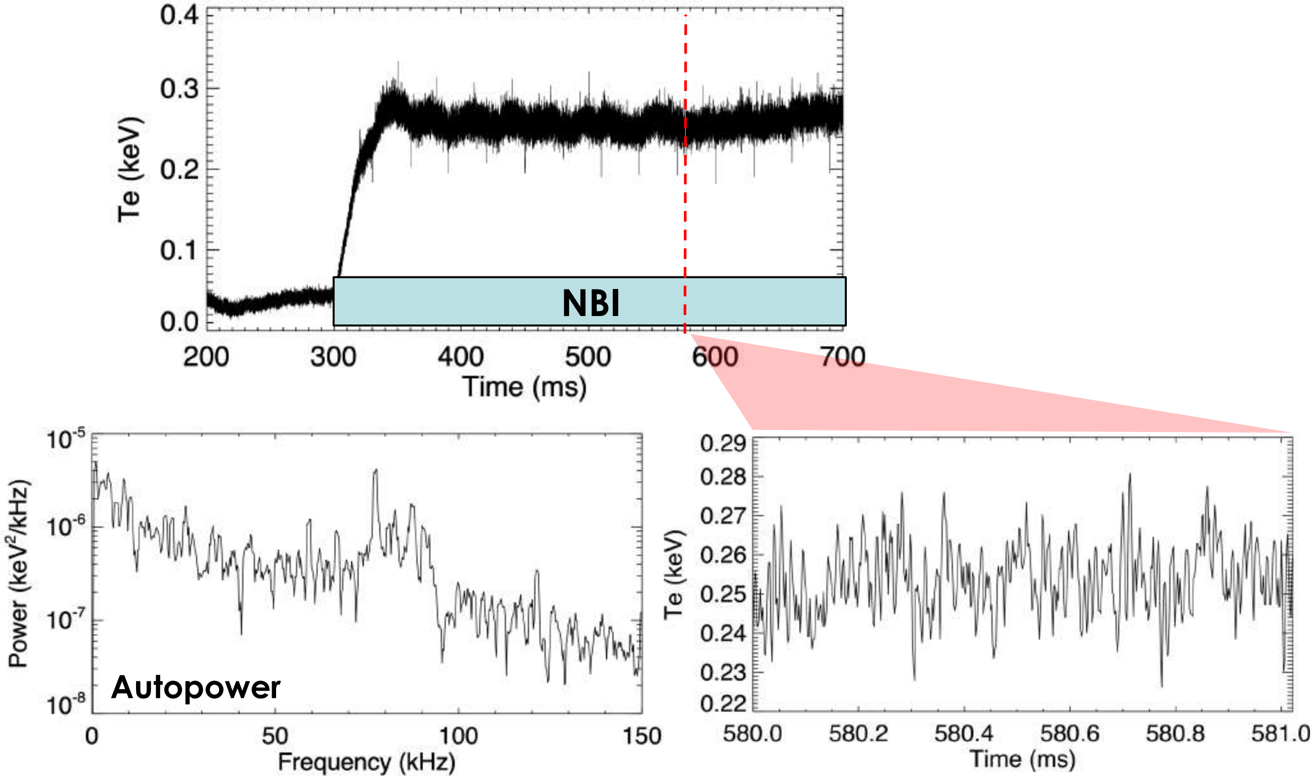

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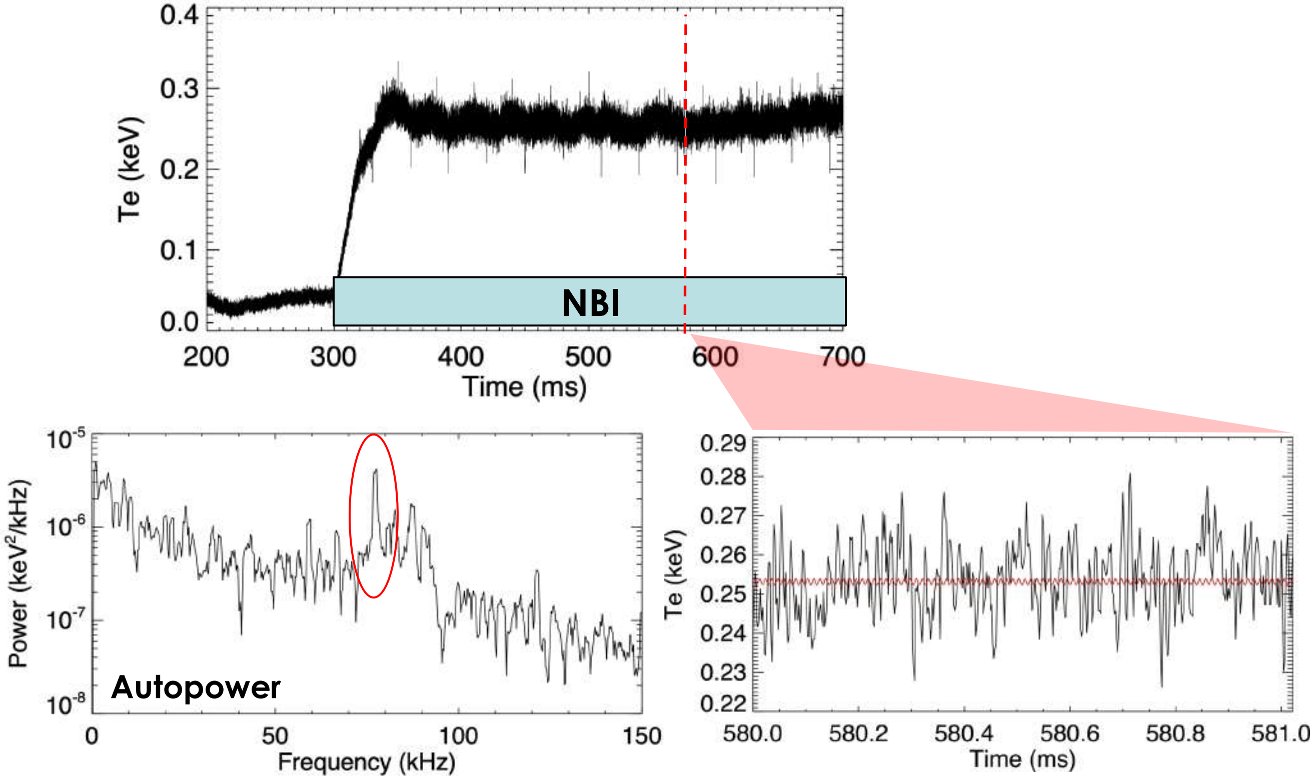

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  - Large bit depth digitizers are essential

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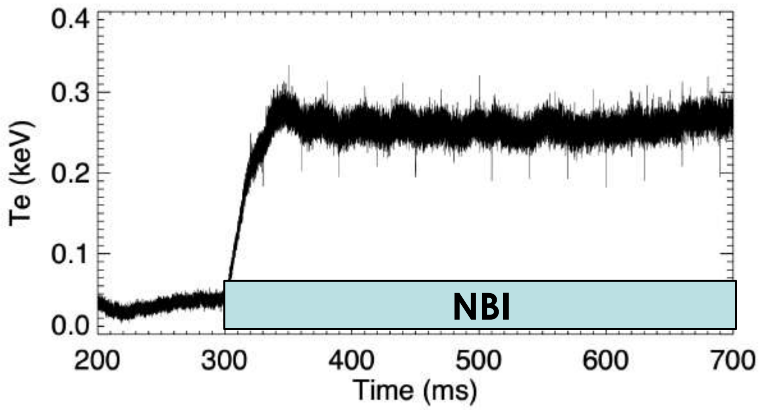

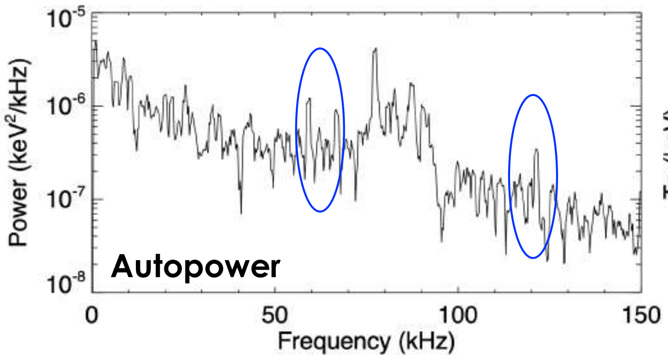

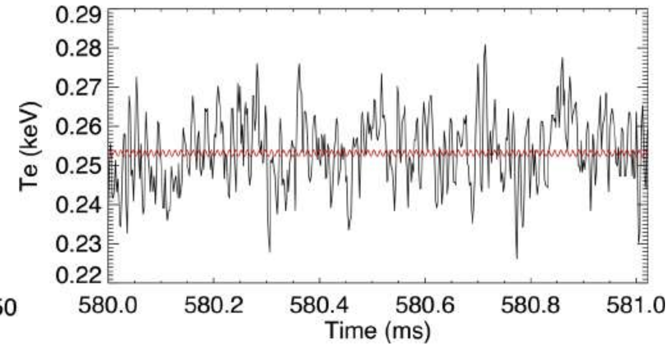

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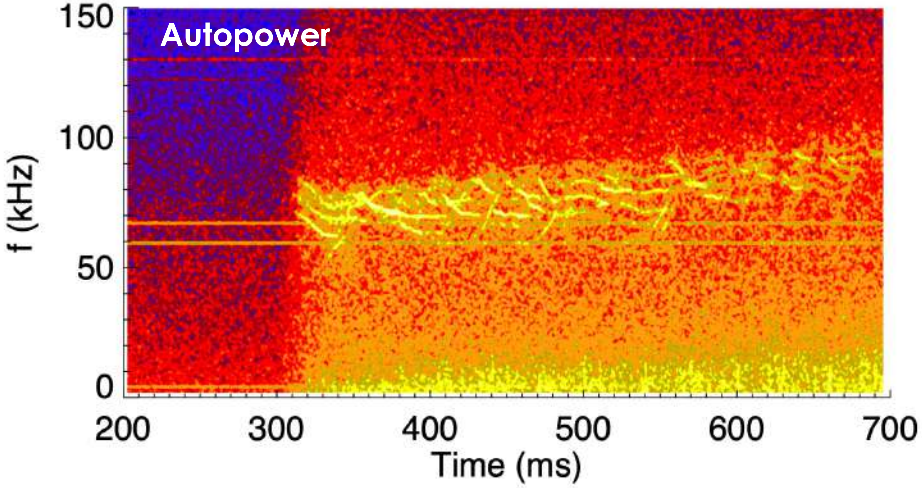
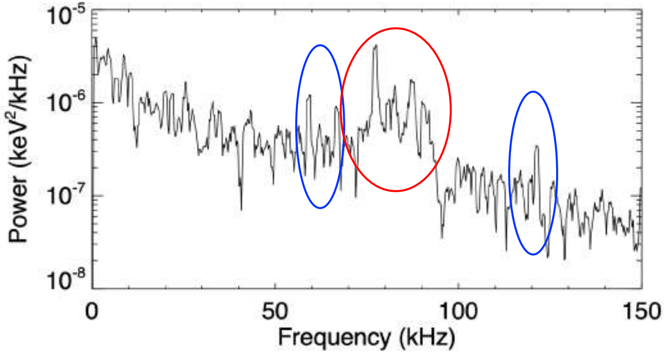
  - Large bit depth digitizers are essential
- Are these modes?

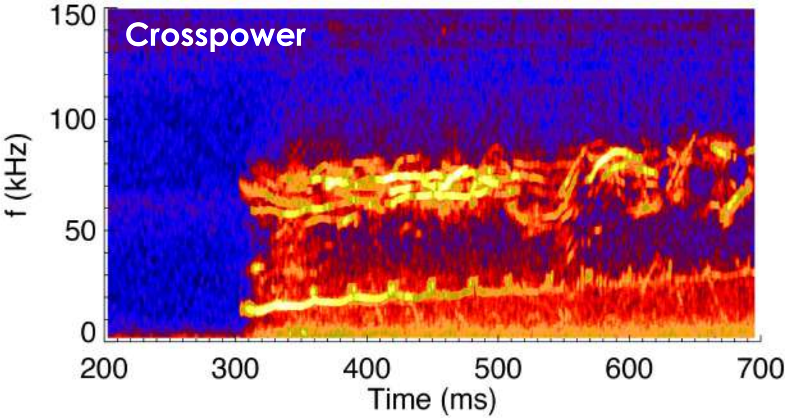
Windowing Is Key To Understanding Mode Evolution and Differentiating Noise From Real Signals





- **Windowed FFT or Spectrogram is constructed from series of small subsets of data**
  - Overlapping of windows smooths out evolution
- **Modes are clearly evolving with discharge**
- **Fixed frequency bands are typical of noise/pickup**

Multiple Probes Allow More Complex Analysis and Additional Information



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  - Example shows crosspower of two toroidally separated magnetic pickup loops

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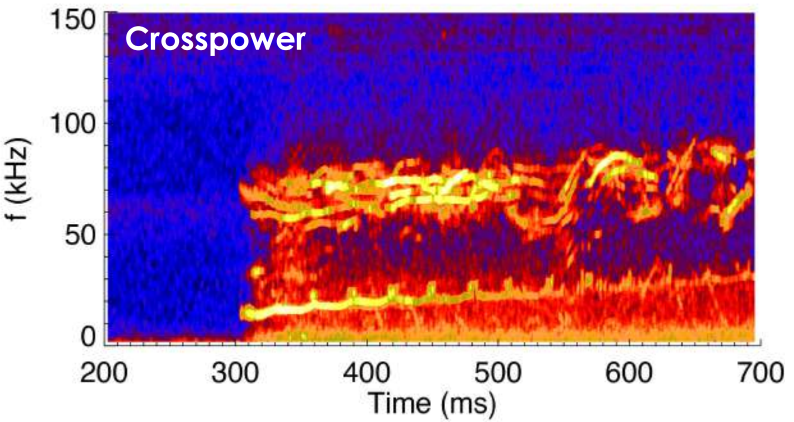
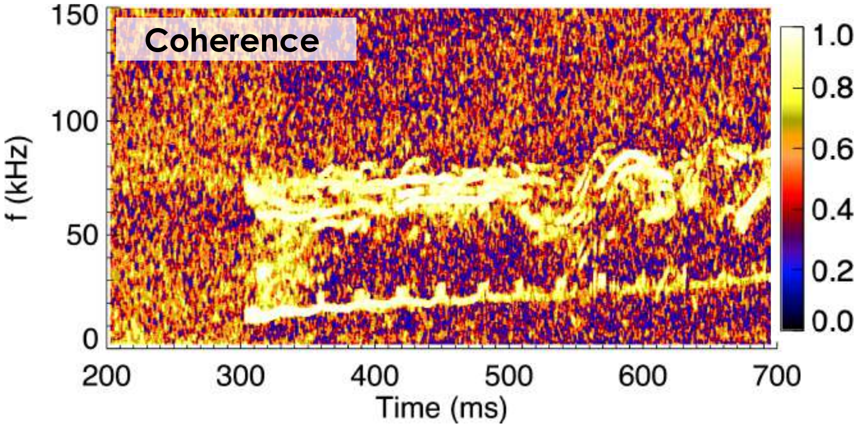
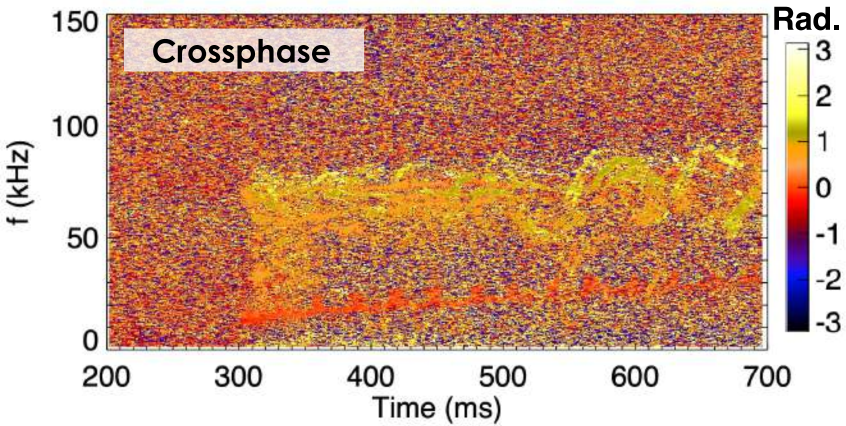




- **Crosspower between two probes combines features present in both spectra and often reduces noise contribution**
  - Example shows crosspower of two toroidally separated magnetic pickup loops
- **Coherence is a normalized crosspower (0-1) and very useful in finding coherent mode activity without a-priori knowing amplitude cutoff**
  - Linear correlation of two signals vs. frequency
  - Examples to follow

Multiple Probes Also Allow Phase Information To Be Extracted



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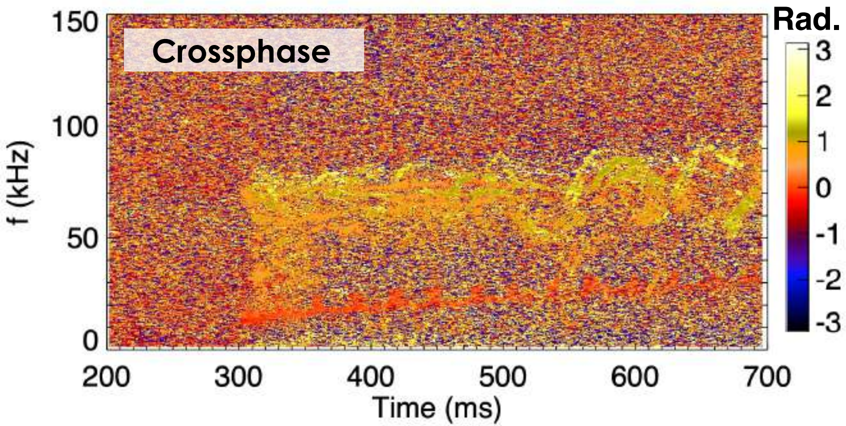

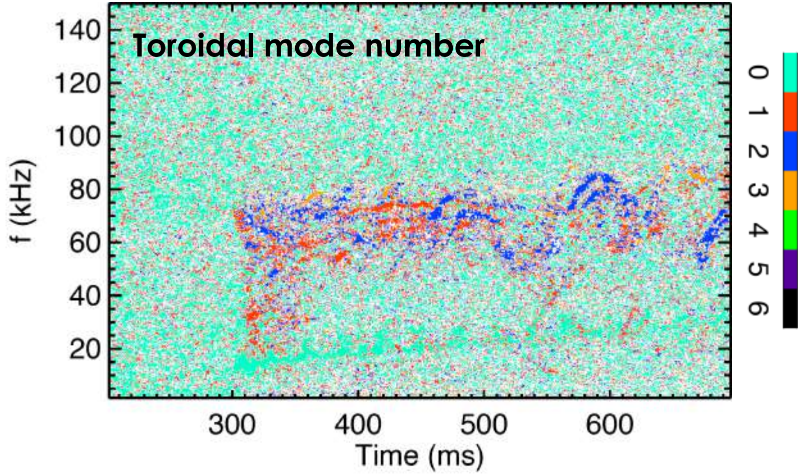

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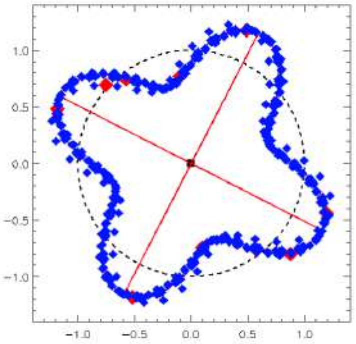
  - $n_{tor} \sim \delta$phase / toroidal separation
  - n_{tor} constrained to be integers



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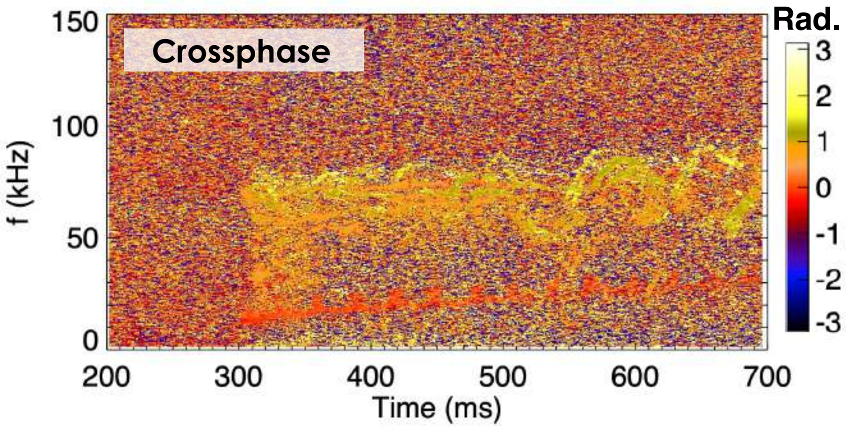

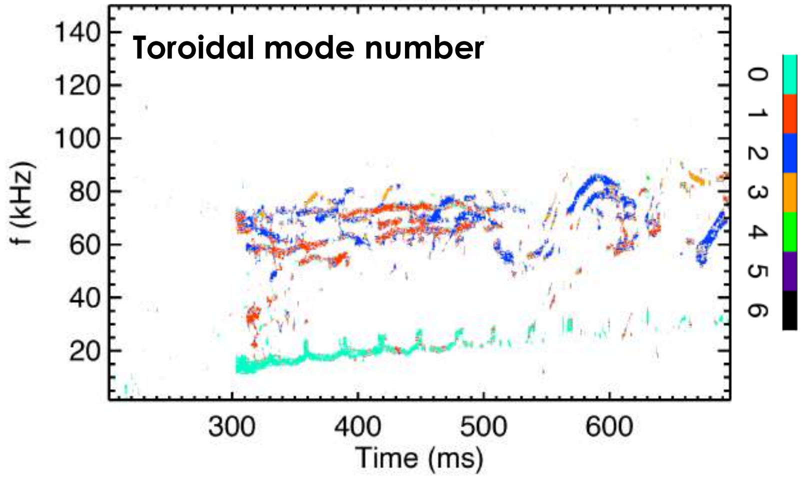

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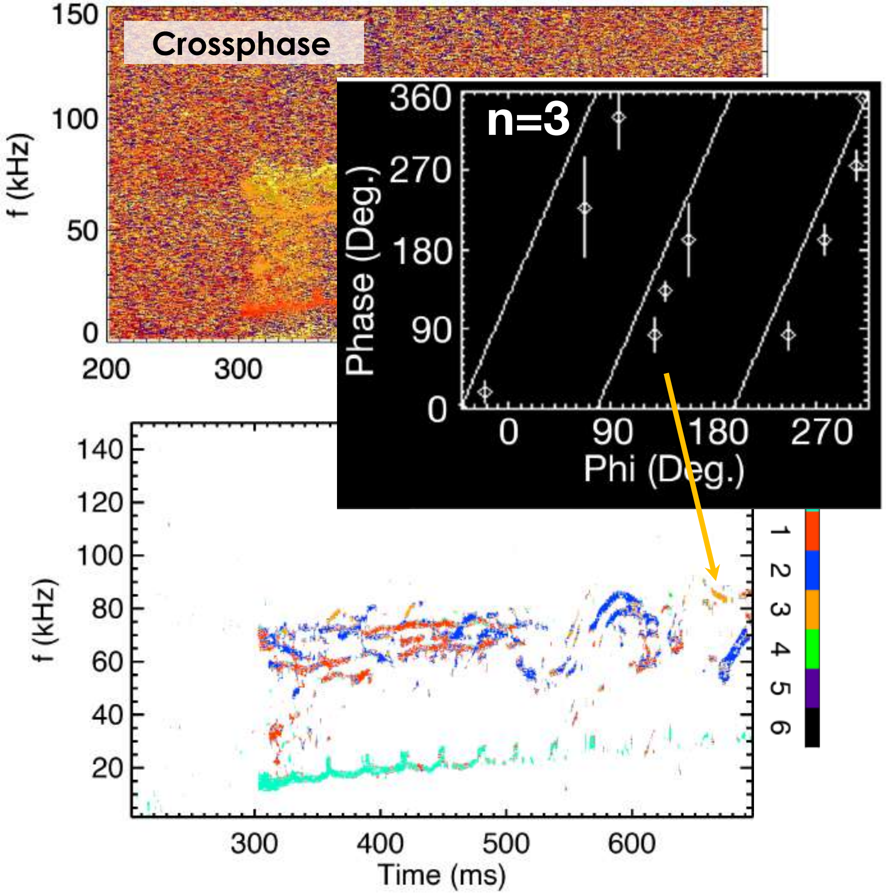

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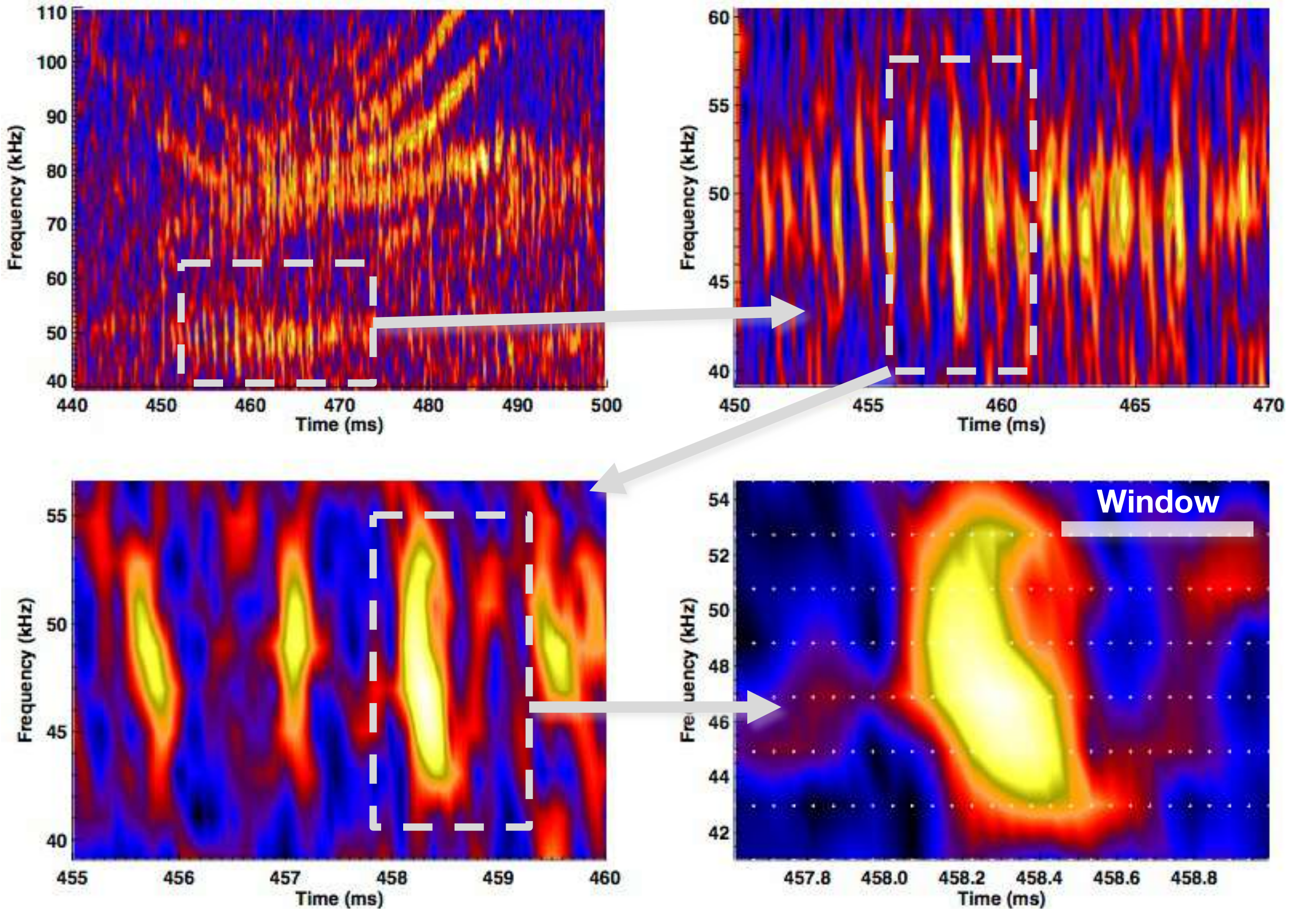
- **Using more toroidal probes allows fitting of the phase vs. toroidal angle**

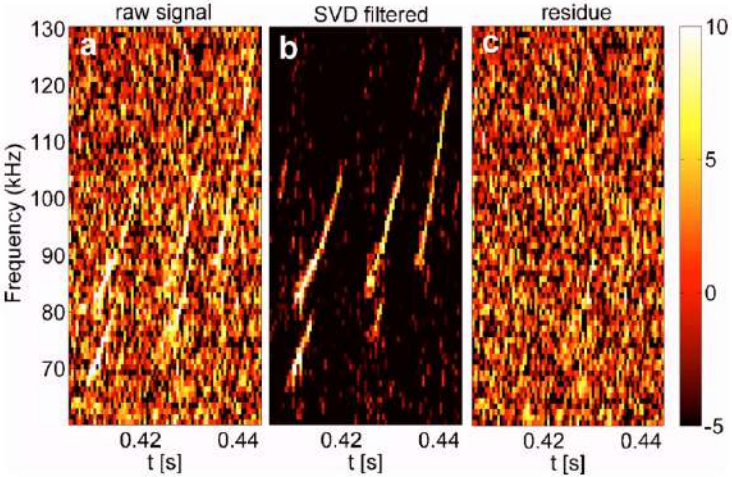
Instability Evolution Can be So Rapid and Duration Short, that Choice of Window Properties are Critical



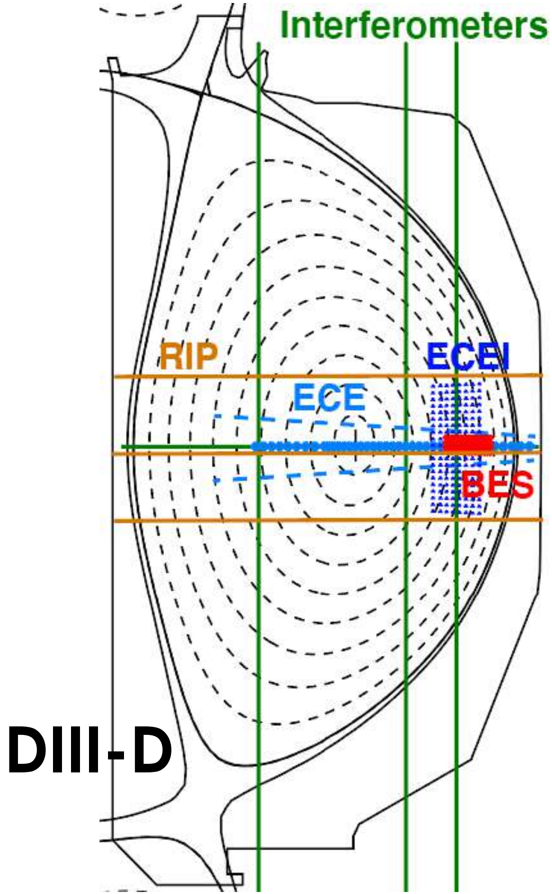
- **Sampling rate (f_{samp}) picks highest frequency (Nyquist Frequency=$f_{samp}/2$)**
- **Window duration picks lowest resolvable frequency (f_{samp}/N) and averaging interval**
- **Window overlap helps resolve short changes**
- **No fixed rules**
  - Parameters often chosen to visualize desired info

Many other techniques exist as well

- **Singular Value Decomposition (SVD)**
  - C Nardone, *PPCF*, 34 1447, 1992
  - I. Classen, et.al. RSI, 81, 10D929, 2010
- **Wavelets**
  - C. Mitchell, et.al., Gophys. Res. Letters, 28, 5, 923-926, (2001)
  - Cheng, et.al. PoP, 24, 092516 (2017)
  - M. Farge and K. Schneider, JPP, 81, 6, (2015)
- **Machine Learning**
  - A. Bustos et al., PPCF, 63, 095001 (2021).
  - V. Škvára et al., FST, 76, 962– 971 (2020).
  - B. J. Q. Woods et al., IEEE Transactions on Plasma Science 48, 71–81 (2020).
  - S. Haskey et al., Computer Physics Commun. 185, 1669–1680 (2014).
  - A. Jalalvand et. al. Nucl. Fusion 62 026007 (2022)
  - A. Garcia et.al. International Joint Conference on Neural Networks (IJCNN), 2023



Multiple Core Fluctuation Diagnostics are Able To Provide Data on Different Aspects of EP Instabilities



Magnetic Pickup Coils (δB at wall)

Interferometers (line-integrated, δne)

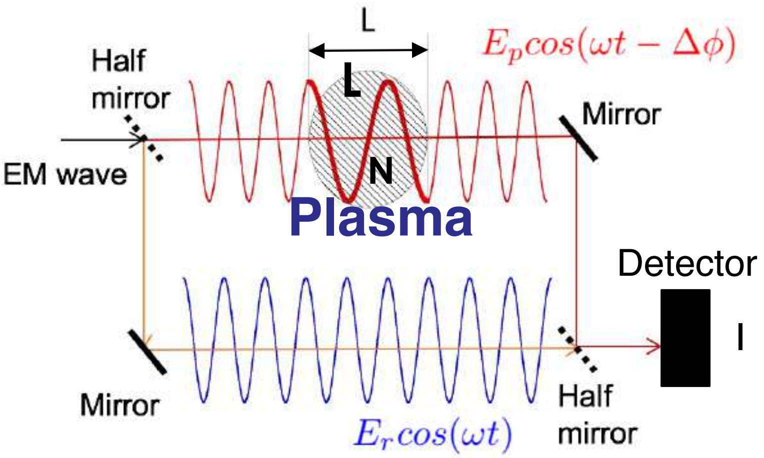
Combined Interferometry and Polarimetry (RIP) (line-integrated, δB + δne)

ECE - Electron Cyclotron Emission Radiometer and ECEI (local, δTe)

BES - Beam Emission Spectroscopy (local, δne)

Reflectometer (local, δne)

Interferometers Measure a Phase Shift Proportional to Line-Integrated Density



$$I \propto \overline{\left\{E_r \cos(\omega t - \Delta\phi) + E_p \cos \omega t\right\}^2}$$
$$= E_r^2/2 + E_p^2/2 + E_r E_p \cos\Delta\phi$$
$$(I_p) \qquad (I_R) \qquad (2\sqrt{I_R I_P})$$

$$\Delta\phi = \phi_r - \phi_p$$
$$= \frac{2\pi}{\lambda}\int(1-N)dL$$

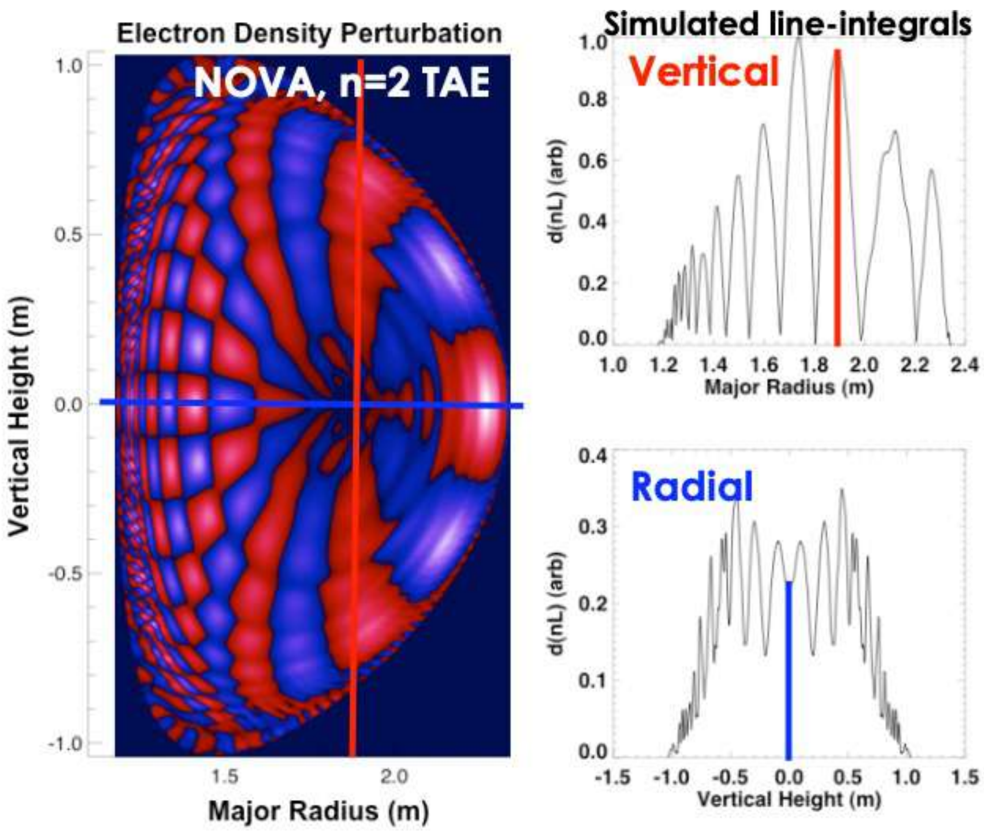
Plasma-Induced Phase Shift

$$= r_e \lambda \int n_e dL$$

- **Interferometer – inteferes two waves to make precise measurements of the relative change in phase**
  - Many different configurations (Mach-Zehnder, Michelson, etc.)
- **Change in optical path length between probe and reference leg result in change in intensity (phase)**
- ***Plasma phase shift is proportional to line-integrated electron-density and wavelength***
  - *Refraction typically limits wavelengths to mid or far infrared (10.59 micron CO2 laser typical) in fusion plasmas*
- **Many techniques for phase determination**
  - Most precise interferes two slightly different frequency waves = heterodyne detection

r_e=2.82x10^{-15} rad-m

Interferometry is Proving to be an Extremely Sensitive AE diagnostic

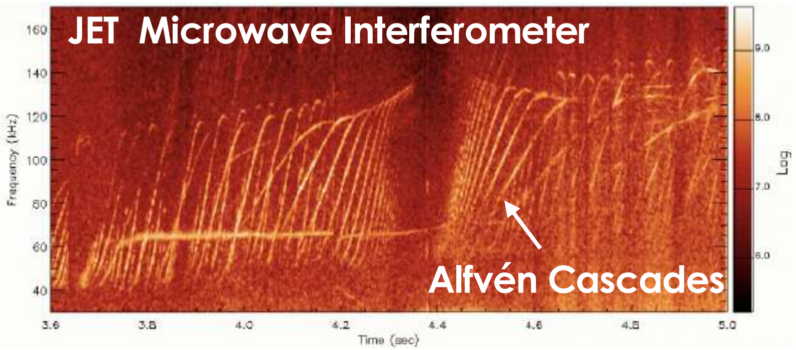


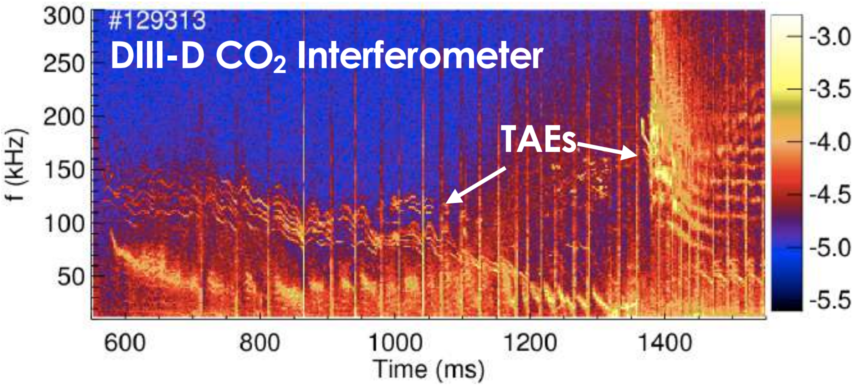
- **Interferometry measures the line-integrated AE density perturbation**

$$\delta\phi = r_e \lambda \int \delta n_e \, dL$$

Interferometry is Proving to be an Extremely Sensitive AE diagnostic

Sharapov S E et al 2004 Phys. Rev. Lett. 93 165001-1



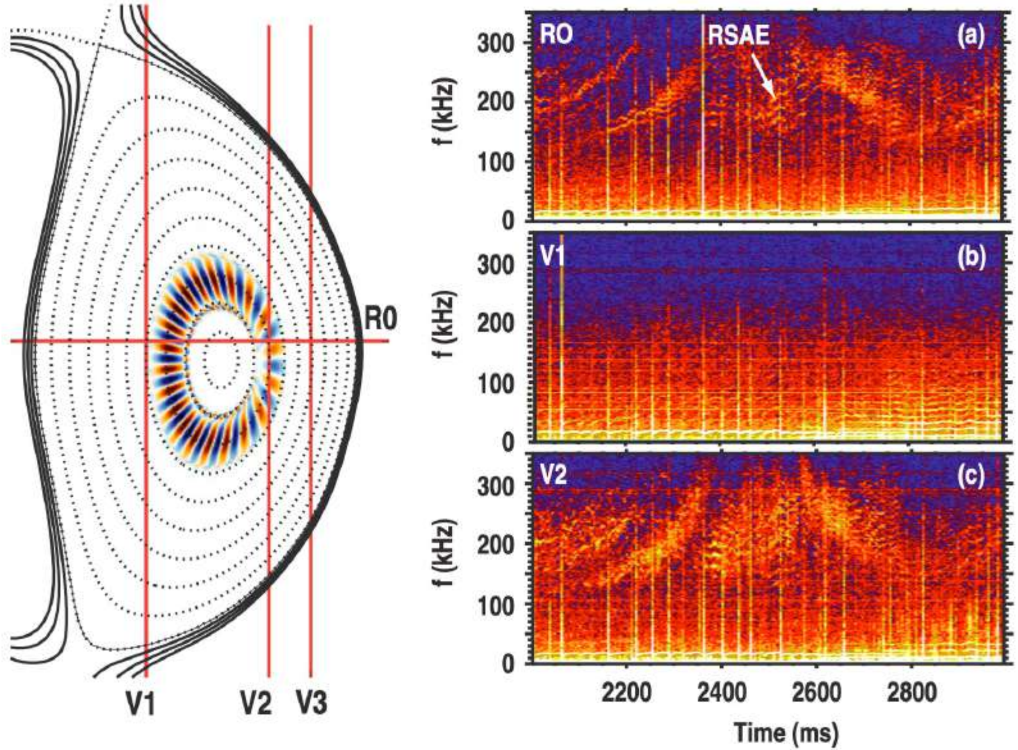


- **Interferometry measures the line-integrated AE density perturbation**

$$\delta\phi = r_e \lambda \int \delta n_e \, dL$$

- **Very sensitive($\delta nL/nL \sim 10^{-5}$), large bandwidth capability, and typically capable of running in all plasma conditions**
- **Provides an excellent global view of long wavelength fluctuations**
- **Extrapolates favorably to ITER**
  - Same noise floor but larger line-integrated densities

Interferometry Can Provide Rudimentary Mode Localization



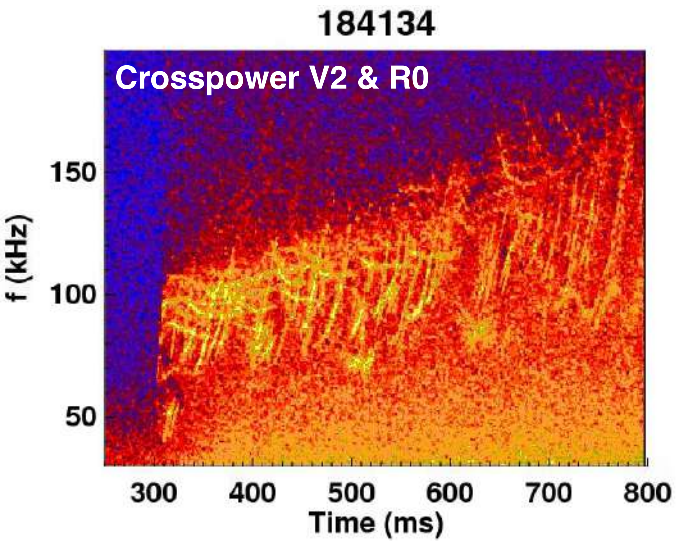
MA Van Zeeland, et.al., NF, 46 (2006) S880–S887

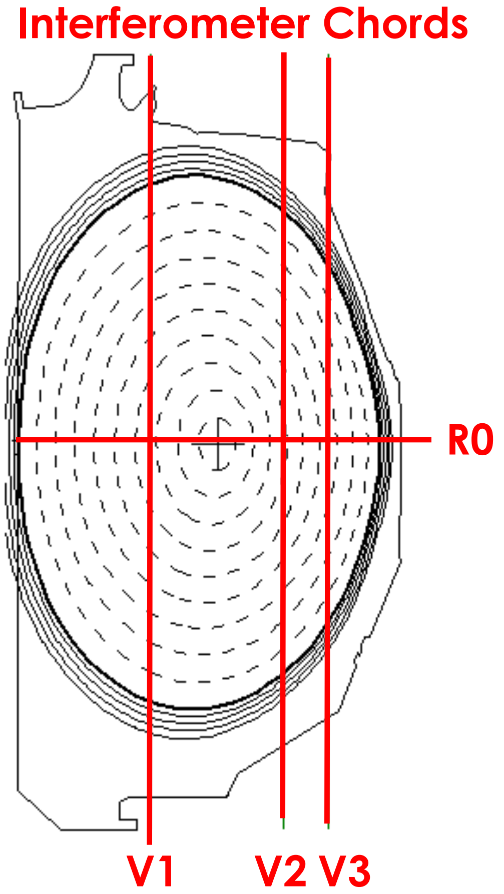
- **Tangency radii constrain minimum minor radius of mode**
  - Can also tell if a mode is peaked on high-field side or low-field side (Balooning, anti-ballooning), etc.
- **Higher density arrays with spatial coverage also have been employed[1,2,3]**
  - Some of first AE structure measurements were made with interferometry[3]

1. Imaging Interf. - K. Tanaka et.al., RSI, 72, 1089–1093 (2001)
2. PCI - M. Porkolab, et.al., IEEE Trans. on Plasma Science 34(2):229 - 234 (2006)
3. T.E. Evans, PRL 1984

Multiple Interferometer Chords Can Be Used To Identify Approximate Amplitude of Coherent Global Mode Activity

- **Typically use crosspower of V2 and R0 interferometers to get global picture of mode activity**
- **Coherence of V2&R0 and V2&V3 identifies coherent modes**
  - RSAEs show up better on R0 and V2
  - TAEs better on V2 and V3





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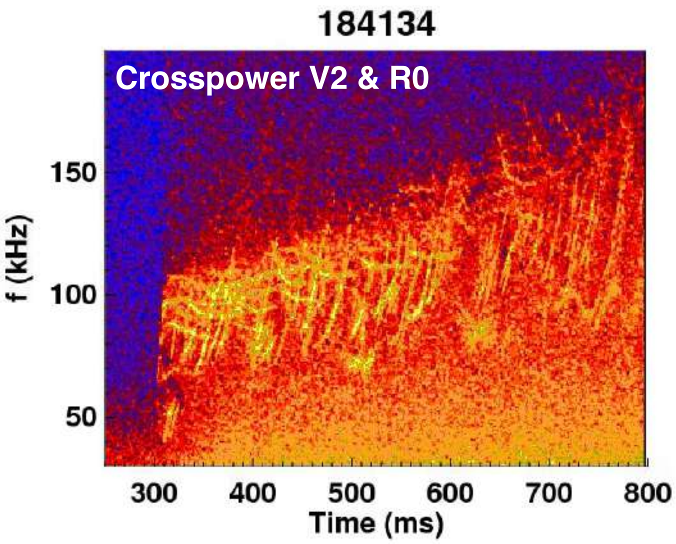
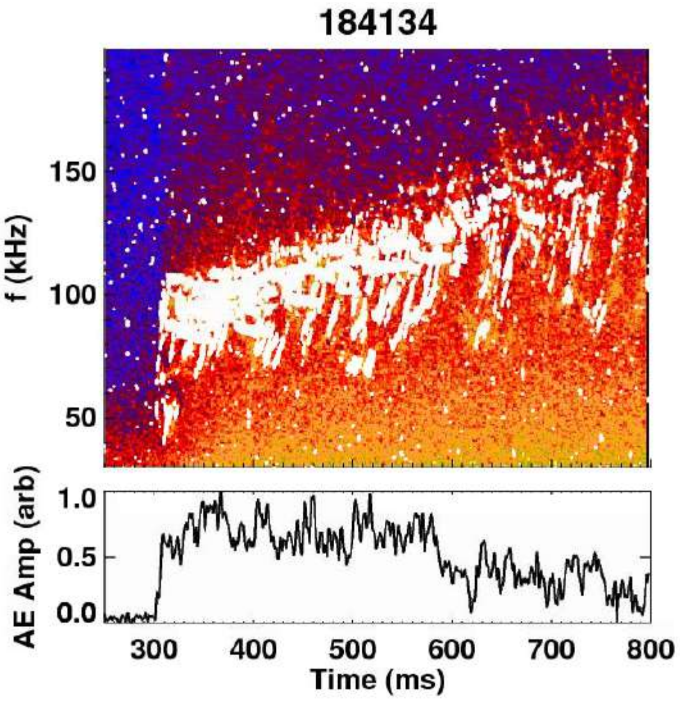
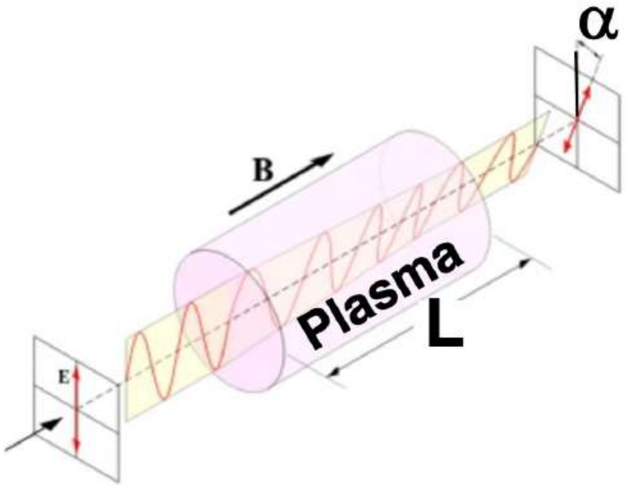
- **Coherence of V2&R0 and V2&V3 identifies coherent modes**
  - RSAEs show up better on R0 and V2
  - TAEs better on V2 and V3
- **"AE Amplitude" is integrated crosspower where coherence is high**





Polarimeters Can Be Used To Measure Faraday Rotation



Faraday Rotation

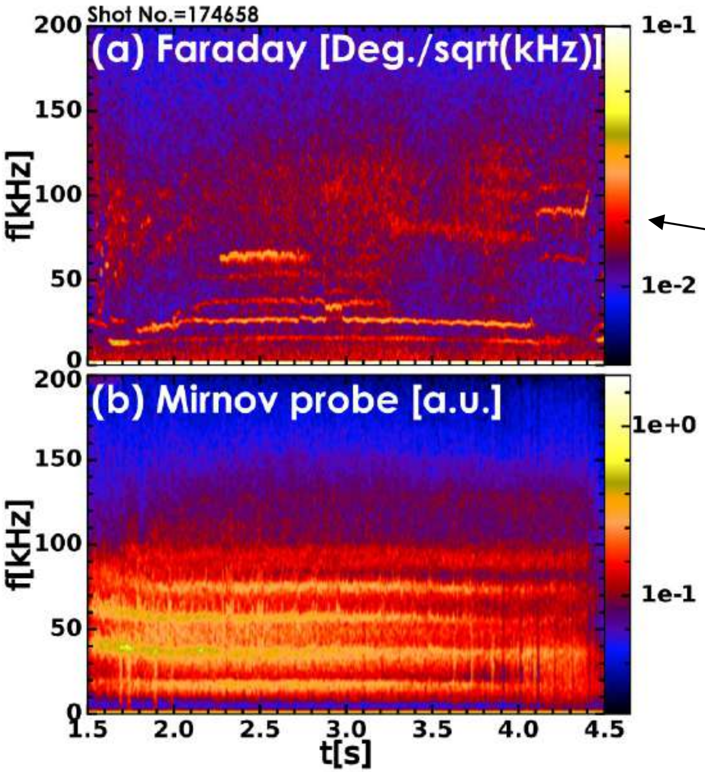
$$\alpha = C_p \lambda^2 \int n_e \vec{B} \cdot d\vec{L}$$

$$C_p = 2.62 \times 10^{-13}\ \mathrm{rad/T}$$

$$\omega >> \omega_{pe}\ \&\ \omega >> \omega_{ce}$$

- **Linearly polarized electromagnetic wave propagating along magnetic field in plasma will see plane of polarization rotated**
- **Effect is due to difference in RH and LH index of refraction = "Faraday Rotation"**
- **Can be used to measure electron density or magnetic field if one or other is known**
- **Typically probed with lasers or high frequency microwaves**
  - Fairly small effect (example, for L=1m, $n_e = 1\text{x}10^{20} m^{-3}$, $B_{||}$=1 T, λ=10.59 μm -> α~0.17 Degrees)

Polarimeter Faraday Rotation Measurements Provide Instability Induced Magnetic and Density Fluctuations



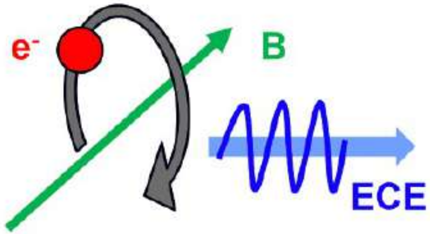
- **For instability studies gives information about density and magnetic field fluctuations**

$$\delta\alpha = C_p \lambda^2 \left[\int \delta n_e B_{||}\, dL + \int n_e \delta B_{||}\, dL \right]$$

  - Example shows midplane radial view = no $B_{||}$ so purely $n_e\delta B$
- **When combined with interferometry, potential to isolate magnetic and density perturbation components**
- **For fluctuations, typically require <1THz sources**
- ***One of only diagnostics that can provide core magnetic fluctuation information at relevant frequencies***

J. Chen, et.al. Rev. Sci. Instrum. 89, 10B101 (2018)

Electron Cyclotron Emission (ECE) Diagnostics Provide Localized Measure of Electron Temperature



$$P = kT_e \cdot \Delta f$$

- **Emitted power at cyclotron harmonics proportional to electron temperature**

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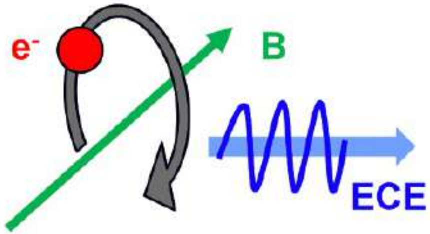

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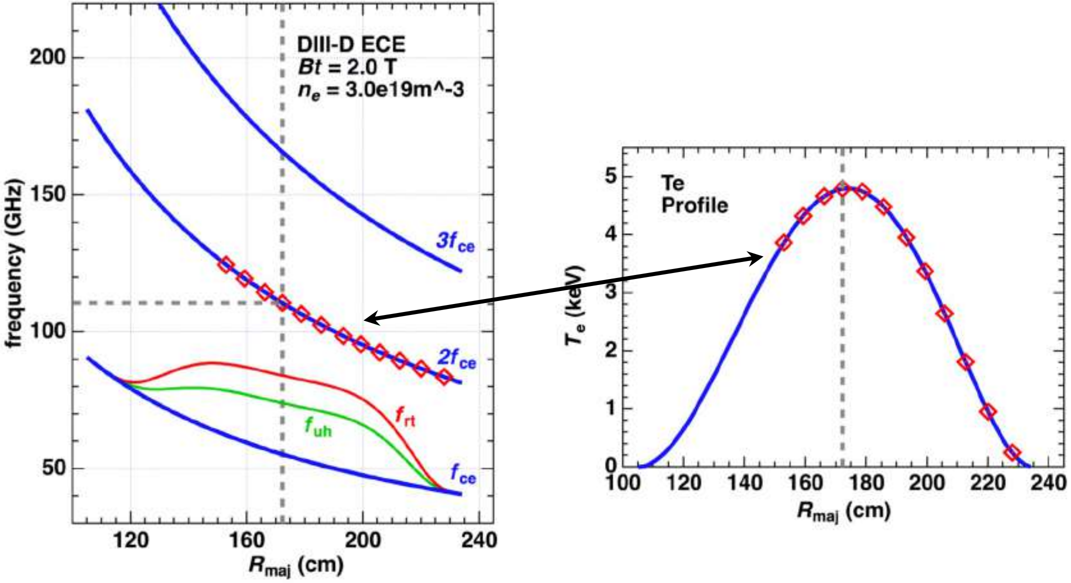
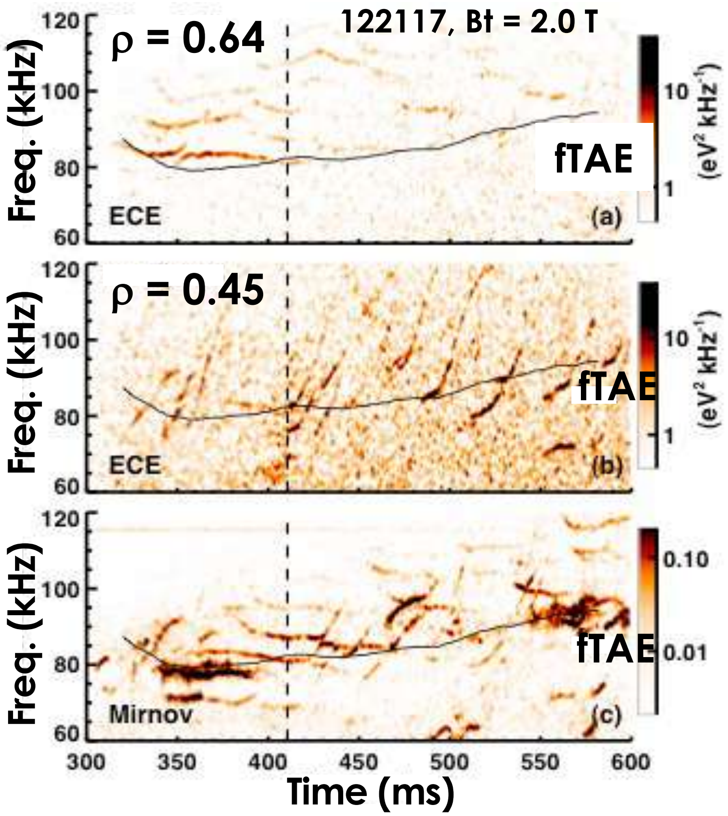


- **Emitted power at cyclotron harmonics proportional to electron temperature**
- **In tokamaks B~1/R so radius maps to cyclotron frequency**
- **Monitoring emitted power in frequency band Δf vs. frequency gives T_e(Radius)**
  - Emitted power in narrow band is small

kT_e = 1 keV & Δf = 1 GHz, <u>P = 160 nW</u>

- ***Large bandwidth measurements with very sensitive detectors and large bit depth digitizers can yield δTe(Radius)***

ECE Channels at Different Locations Can See Very Different Mode Activity



ECE measures local δTe at multiple locations along midplane

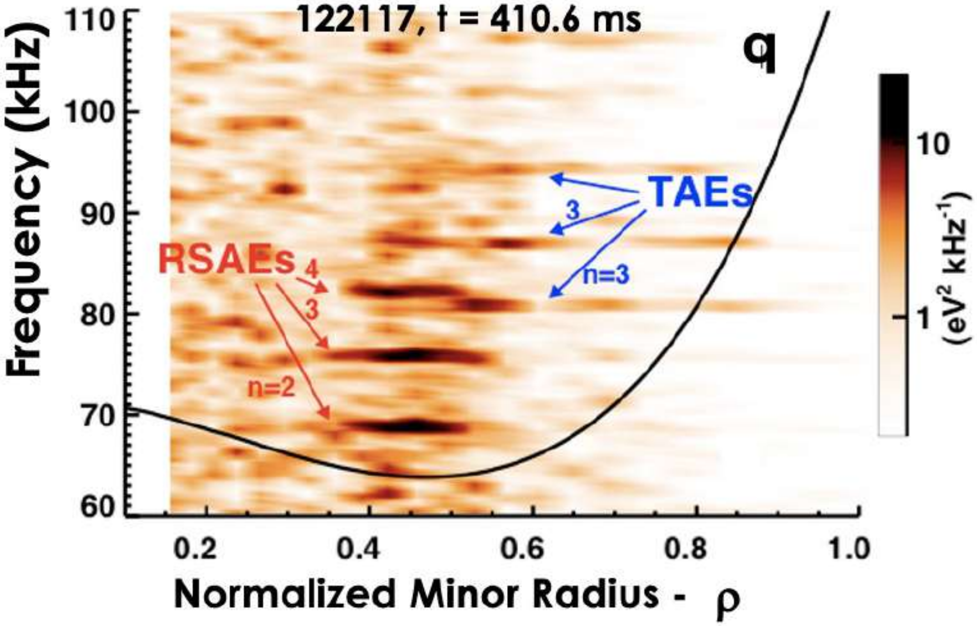
Outer radii ECE channels see mostly TAE

Inner radii ECE channels see RSAE

Mirnov (δ*B*) coil sees a combination of both RSAE and TAE

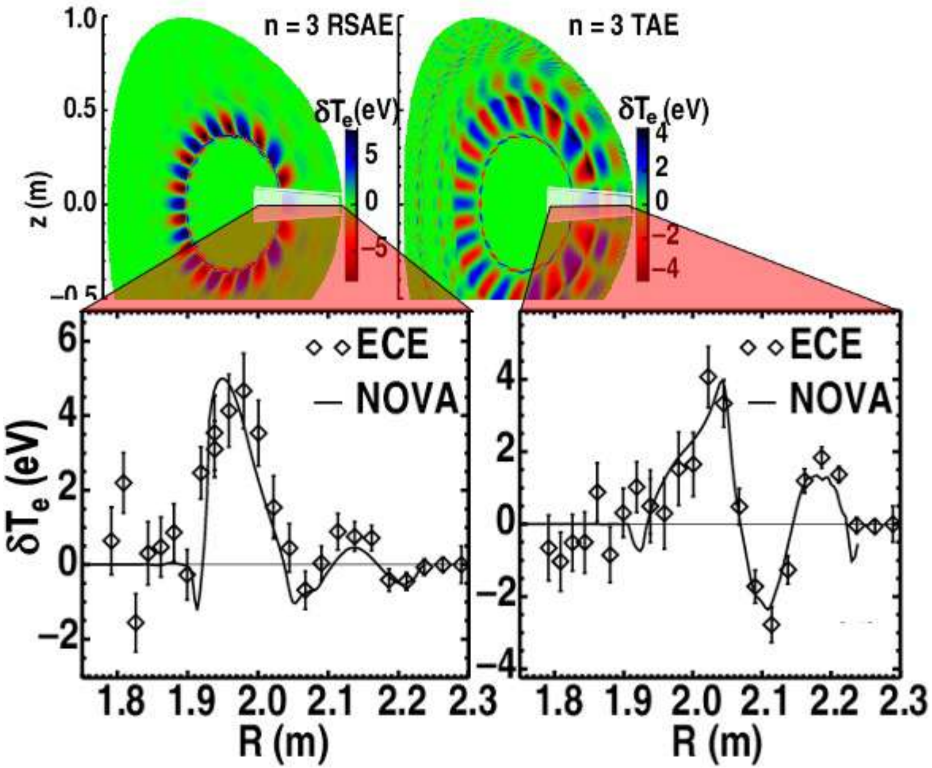
Analysis of Many ECE Channels Reveals AE Structure

Radial profile of ECE radiometer power spectra at a fixed time



- RSAEs are peaked near q-min as expected
- TAEs are more global and extend to the edge

Structure of Individual Modes Can be Extracted and Compared to Modeling



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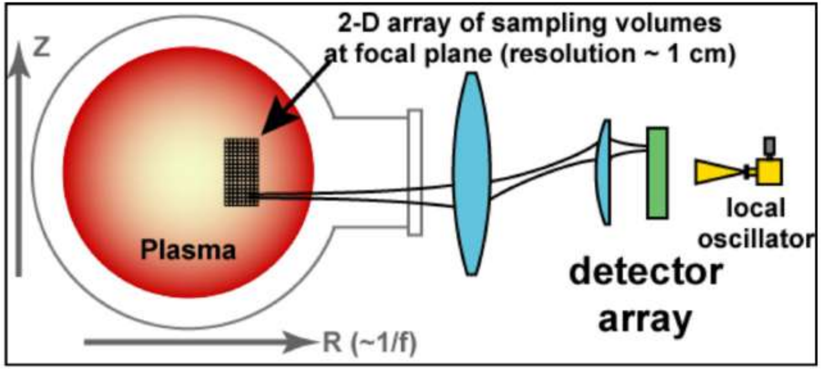
M.A. Van Zeeland, et.al., PRL 97, 135001 (2006)

ECE Has Even Been Extended to 2D = ECE Imaging (ECEI)



I.G.J. Classen, TEXTOR, 2006

- **Essentially a multi-chord radiometer measurement with large shared optics**
- **Typical patterns are 8 radial x 20 vert. = 160 channels and multiple arrays**

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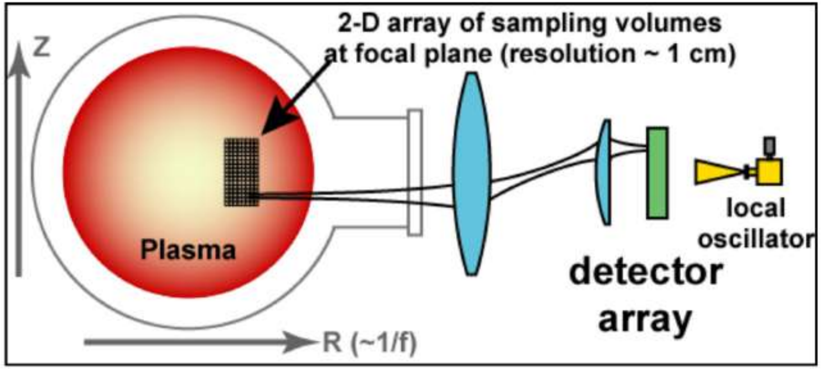

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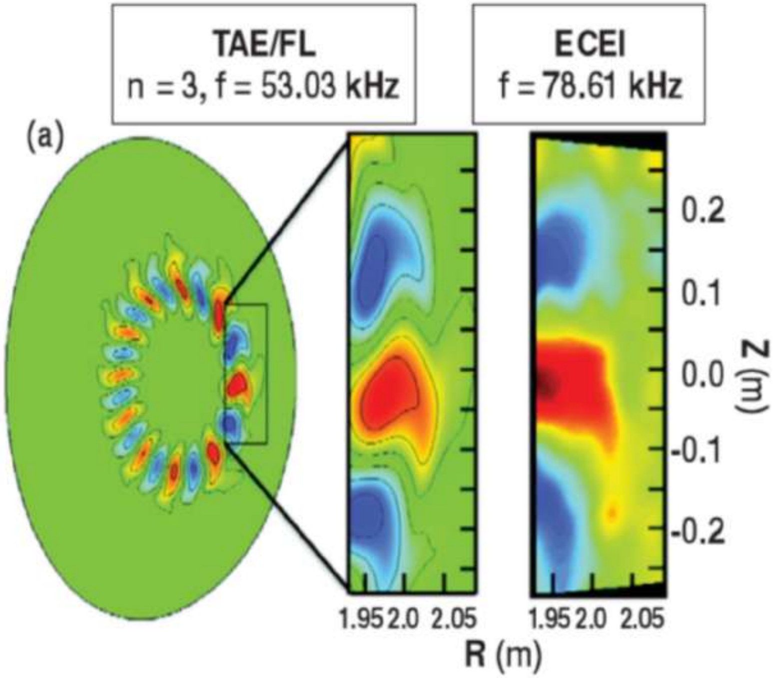
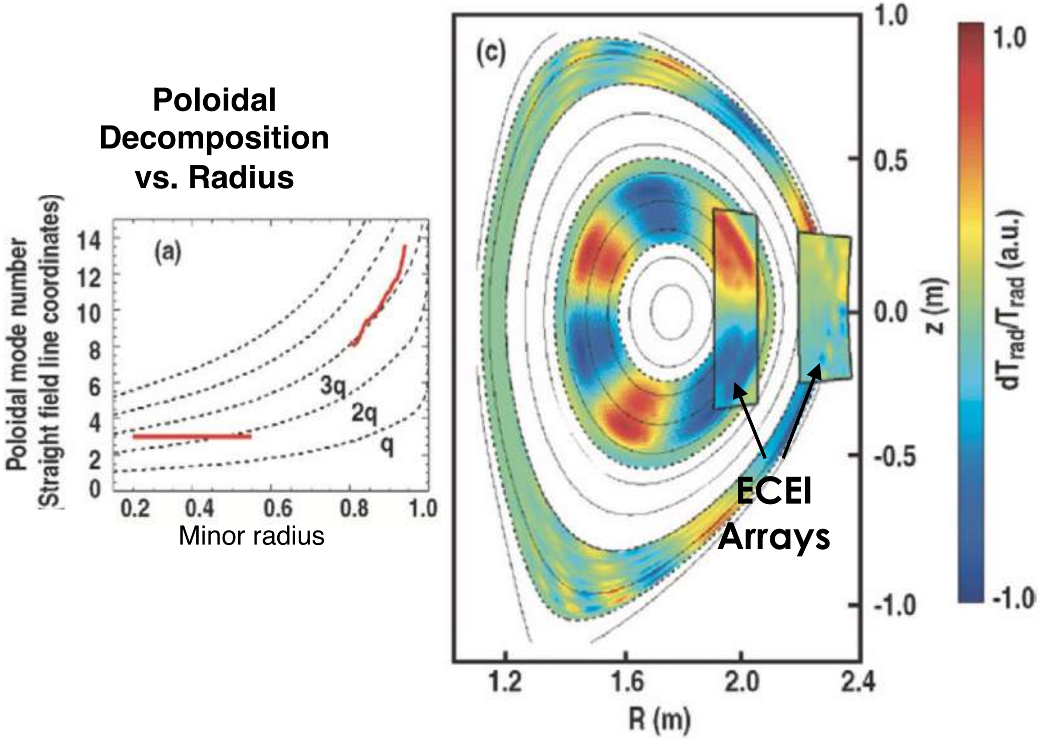
- **Essentially a multi-chord radiometer measurement with large shared optics**
- **Typical patterns are 8 radial x 20 vert. = 160 channels and multiple arrays**
- ***Able to resolve 2D features of Alfven Eigenmodes with MHz bandwidth!***

TAEs imaged with ECE-I system



B. Tobias, PRL 2011

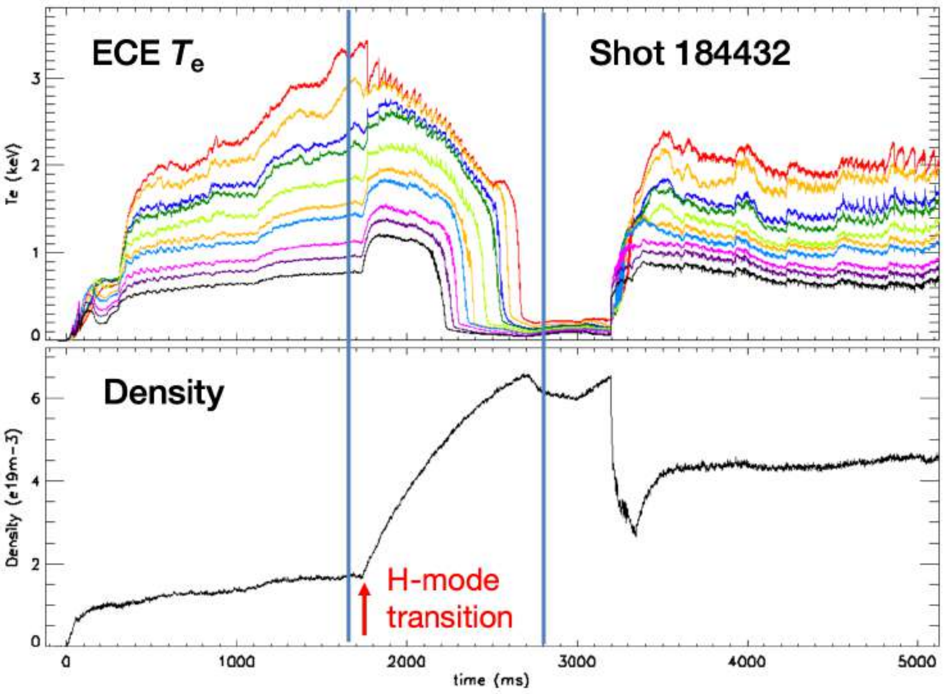
2D Measurements Allow Poloidal Decomposition



B.J. Tobias, et.al., PPCF **55** (2013) 095006

- **Similar procedure as discussed for n_{tor} from magnetics**
- **Decomposition carried out vs. minor radius**
  - Gives effective m_{pol} vs. radius
  - Key for validation
- **Multiple arrays of limited extent combined with poloidal decomposition → mode reconstruction over almost entire plasma cross section**

ECE is Extremely Powerful for Fluctuation Measurements but Some Issues Exist



- **ECE Radation can be cutoff at higher densities**

Courtesy M. Austin

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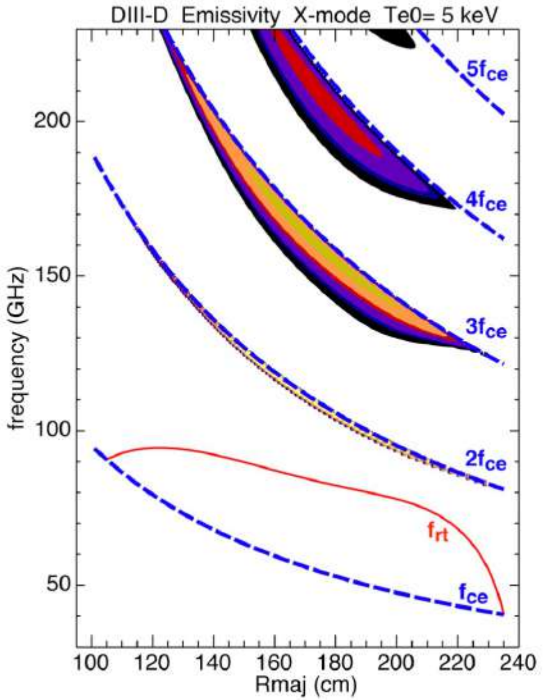
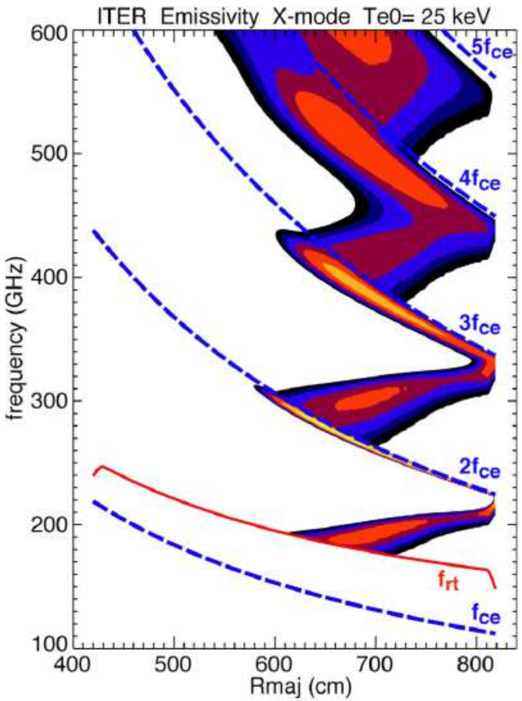




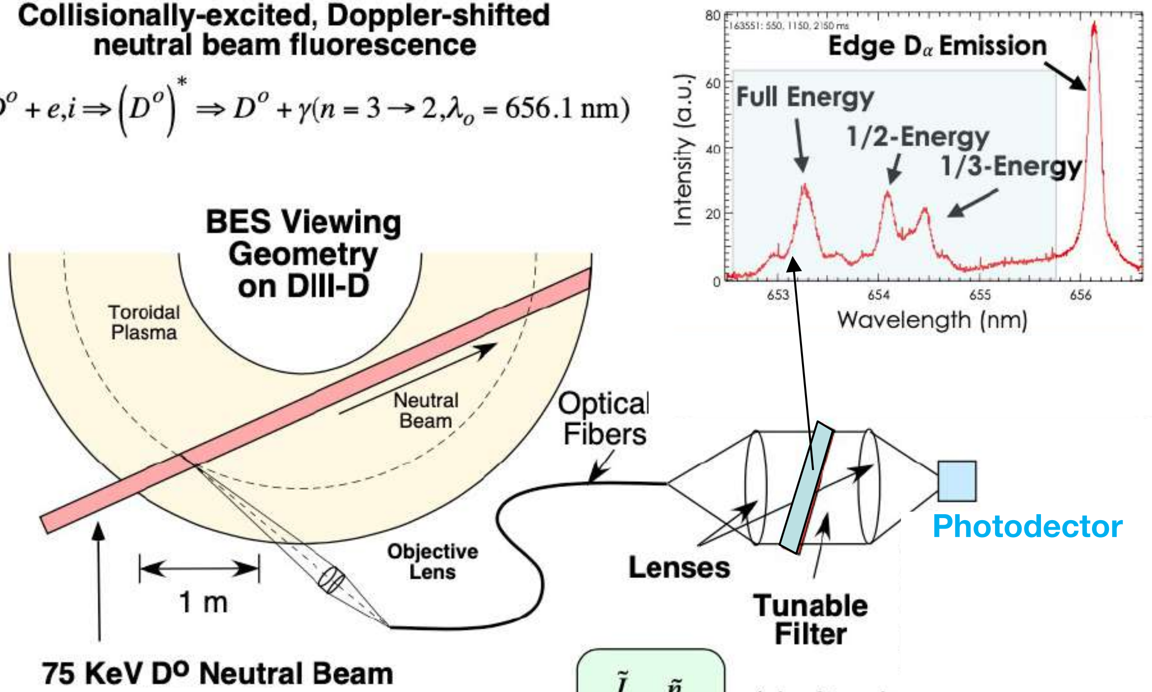
- **ECE Radiation can be cutoff at higher densities**
- **In higher temperature plasmas, relativistic broadening is a concern**
  - Broadened emission region ruins spatial resolution
  - Downshifted absorption from higher harmonics blocks emission from HFS

Courtesy M. Austin

Beam Emission Spectroscopy (BES) Measures Fluctuations in Beam D-alpha to Give Local Density Fluctuation Amplitude

Collisionally-excited, Doppler-shifted neutral beam fluorescence

$$D^o + e,i \Rightarrow \left(D^o\right)^* \Rightarrow D^o + \gamma(n = 3 \rightarrow 2, \lambda_o = 656.1 \text{ nm})$$

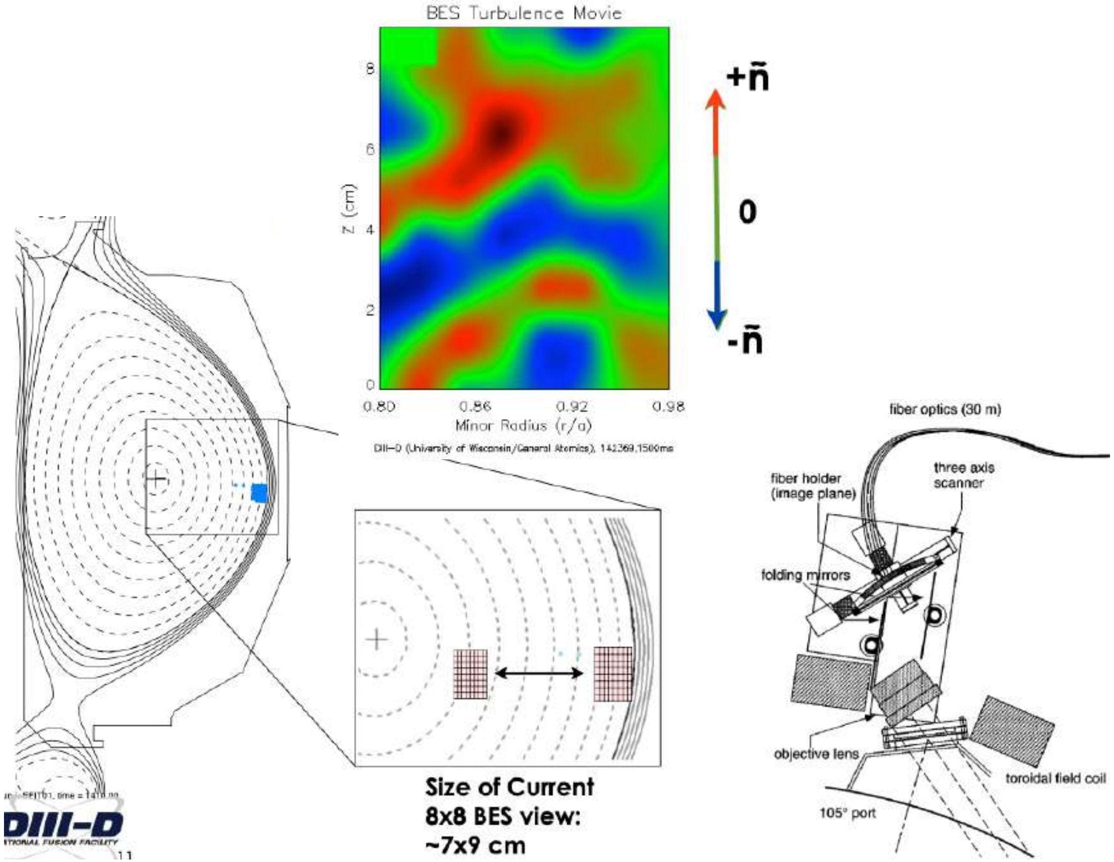


$$\frac{\tilde{I}}{I} \propto \frac{\tilde{n}}{n}$$

- **Active diagnostic – requires injected neutral source**
- **Injected neutrals are excited by plasma and emit D-alpha**
  - Emission proportional to density dI/I ~ dn/n
- **Measurement localized to sightline intersection with beam**
- **Poor signal at high density because of beam attenuation**
- **~100s kHz bandwidth**

R.J. Fonck et al., Rev. Sci. Instrum. 61, 3487 (1990)
G. McKee et al., Rev. Sci. Instrum. 70, 913 (1999)

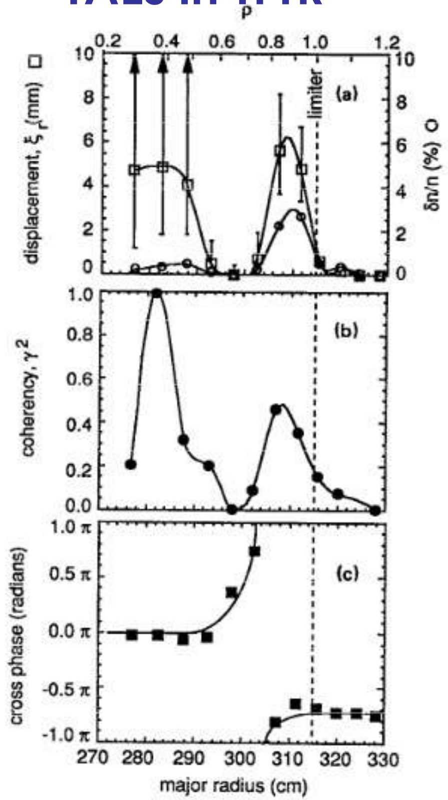
Array of BES Detectors / Fibers Used to Build up 1D and 2D Images of Fluctuations



- **Motorized fiber array moves fibers in image plane of fixed lens to change location in plasma**

BES Instrumental in Measurements of Both EP driven Instabilities and Turbulence

TAEs in TFTR



- **Some of first measurements made of TAEs carried out with BES**

Durst, et.al., Phys. Fluids B, 4, 3707–3712 (1992)

BES Instrumental in Measurements of Both EP driven Instabilities and Turbulence

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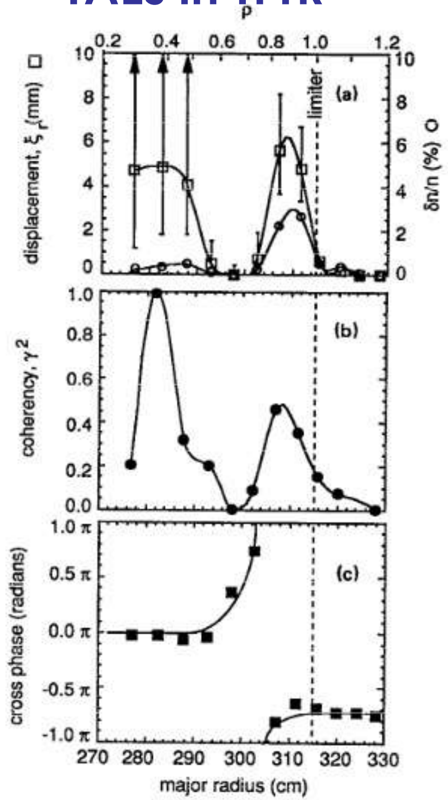
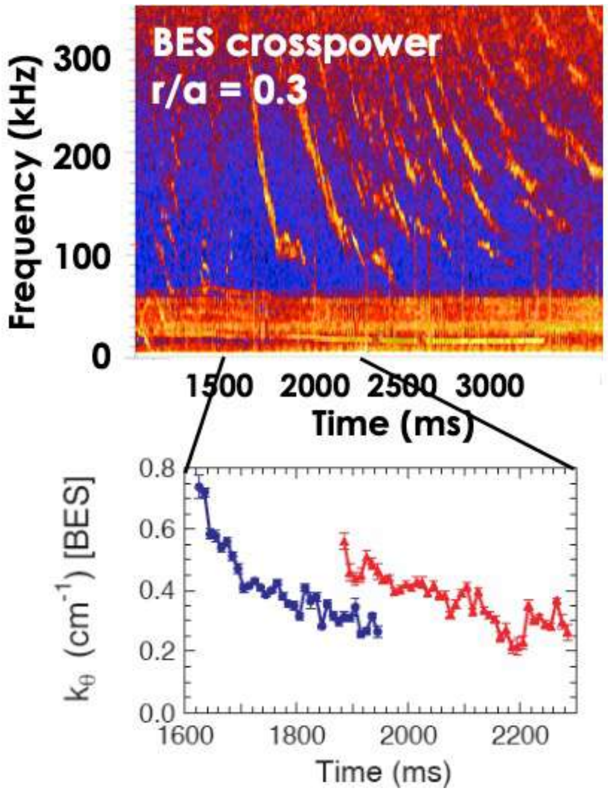
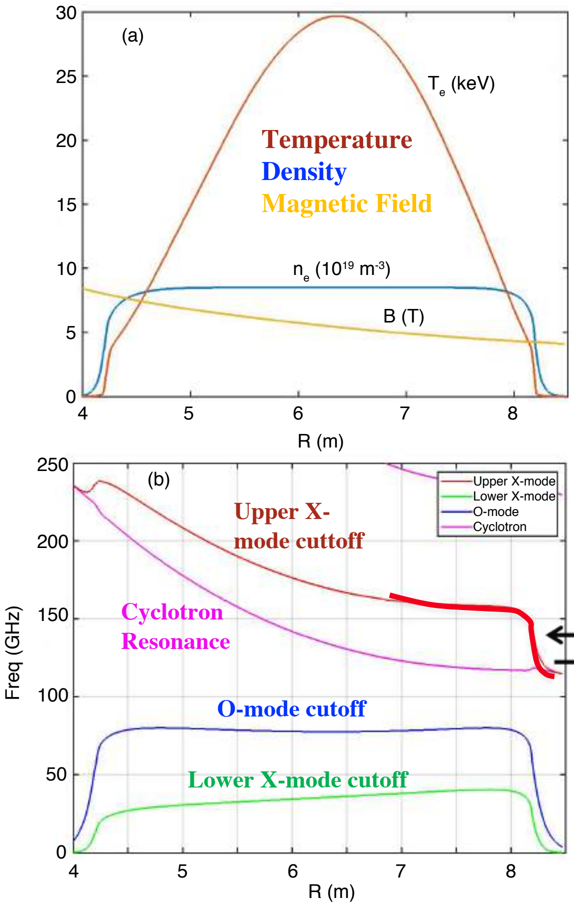




- Some of first measurements made of TAEs carried out with BES
- 2D array gives measurements of $k_{poloidal}$

Durst, et.al., Phys. Fluids B, 4, 3707–3712 (1992) R. Nazikian, et.al, PRL 96, 105006 (2006)

Reflectometry Can Provide Localized Measurements of Electron Density



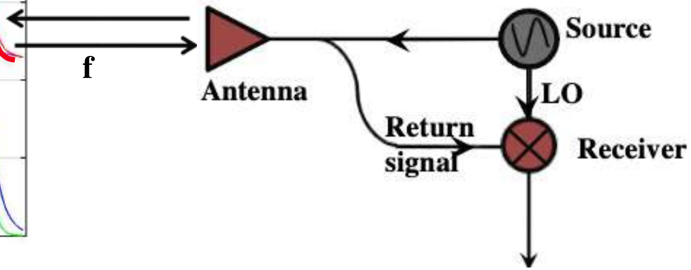
- **Cutoff (reflection) layers depend on density, magnetic field and microwave frequency**
  - 1-to-1 correspondence between density and frequency

$$\omega_{O-mode} = \omega_p = \left(\frac{n_e e^2}{m_e \epsilon_o}\right)^{1/2}$$

$$\omega_{upper-x} = \frac{1}{2}\left[\omega_c + \left(\omega_c^2 + 4\omega_p^2\right)^{1/2}\right]$$

$$\omega_{lower-x} = \frac{1}{2}\left[-\omega_c + \left(\omega_c^2 + 4\omega_p^2\right)^{1/2}\right] \qquad \omega_c = eB/m_e$$

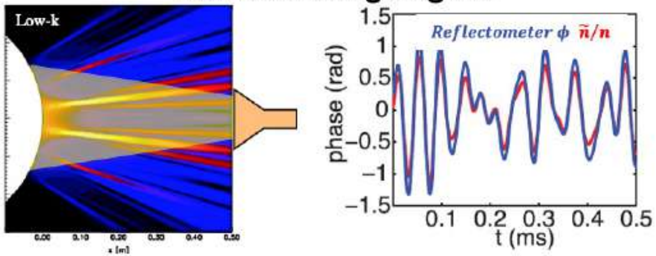
- **By launching known frequency/polarization and measuring time delay (phase), location of corresponding cutoff in plasma can be determined**
- **Launching multiple frequencies allows spatial profile of cutoff (and density) in plasma to be reconstructed**
  - *Similarly can be used for density fluctuation measurements*



For Long Wavelength Fluctuations Like AEs, Reflectometry Provides Localized Measurements of Density Fluctuations

- **A fluctuating density profile ($\tilde{n}/n$) modulates the reflectometer phase ϕ**
- **In the low-scattering regime (e.g. low-k), the reflectometer phase front is modulated like the density fluctuation[1]**
  - **Reflectometer ϕ is highly correlated with $\tilde{n}/n$**

Low-Scattering Regime



1. X. Ren, et al., RSI **85**, 11D863 (2014)

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- **Has been used extensively for measurements of AEs and other long wavelength instabilities[2,3]**

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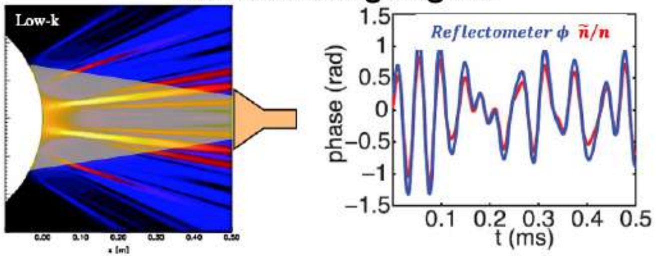
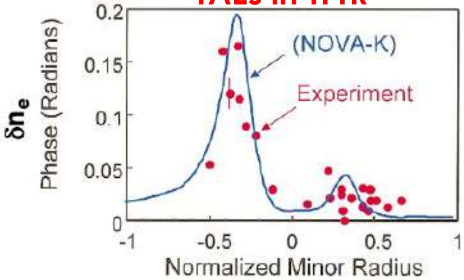
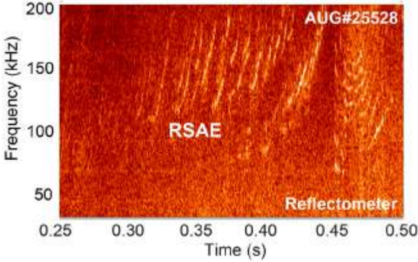


TAEs in TFTR



RSAEs in AUG



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3. M. Garcia-Munoz, et al., NF **51** 103013 (2011)

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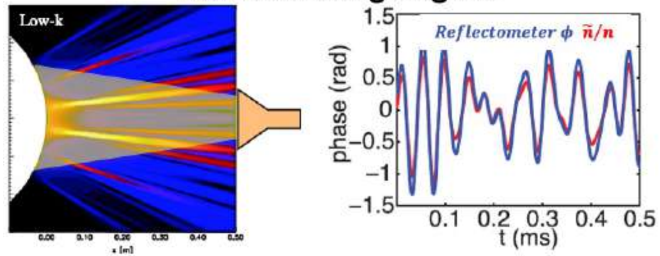
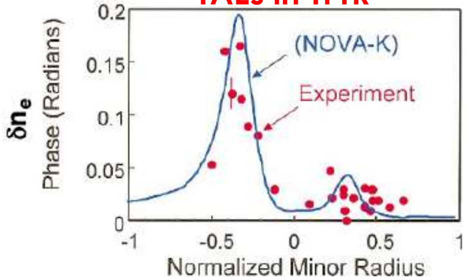
- **Has been used extensively for measurements of AEs and other long wavelength instabilities[2,3]**
- **For shorter wavelength instabilities, interference effects become an issue and interpretation is difficult[1]**

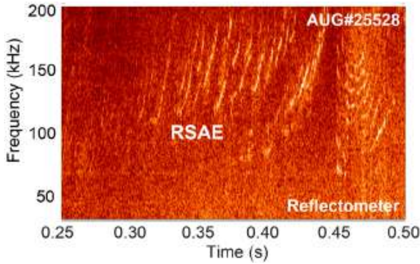
Low-Scattering Regime



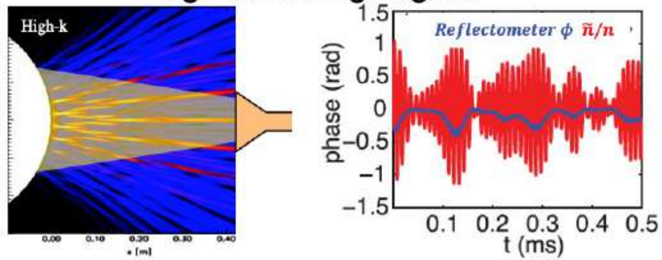
TAEs in TFTR



RSAEs in AUG



High-Scattering Regime



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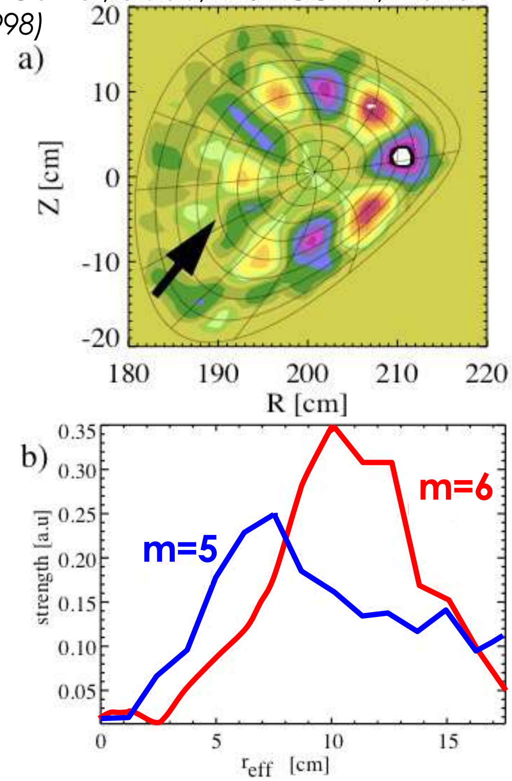
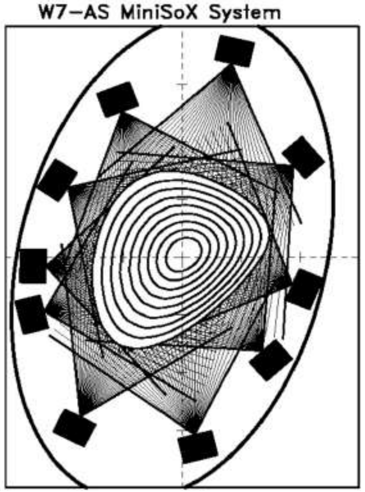
3. M. Garcia-Munoz, et al., NF **51** 103013 (2011)

Some of the Most Detailed TAE Measurements to Date Have Been Made in a Stellerator (W7-AS)

- **TAEs modulate the Soft X-Ray (SXR) emissivity**
  - Continuum radiation - function of n_e, Z, T_e
- **Eigenmode is obtained through SXR tomographic reconstruction of fluctuating component**
  - 10 Cameras, 320 viewing chords
  - 200 kHz bandwidth
- **Clear identification of the two dominant poloidal harmonics present (m=5,6)**
  - Up to m=9 was identified unambiguously with this system

C. Gorner, et. al. , *EPS - CCFPP, Praha (1998)*





Weller, 94

QUIZ ON DIAGNOSTICS

- **For which of these can the measurement localization depend critically on magnetic field?**
  1. Interferometer
  2. BES
  3. ECE
  4. SXR
  5. Reflectometer & ECE

QUIZ ON DIAGNOSTICS

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  1. Interferometer
  2. BES
  3. ECE
  4. SXR
  5. Reflectometer & ECE

- **Which of these diagnostics can have issues at high density**
  1. BES
  2. ECE
  3. Interferometer
  4. All of the above

QUIZ ON DIAGNOSTICS

- **For which of these can the measurement localization depend critically on magnetic field?**
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  3. ECE
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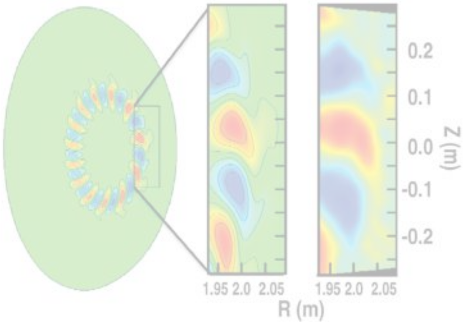
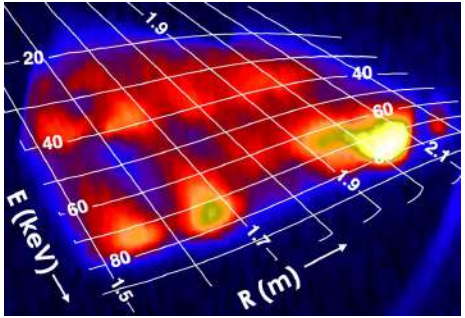
Outline

Measurement of Instabilities



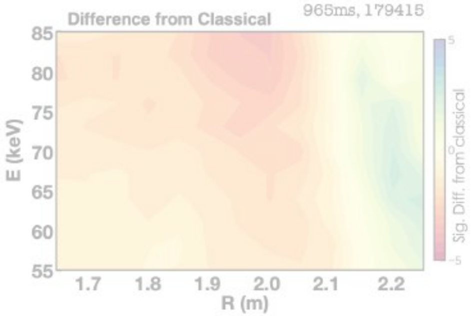
- Perturbed quantities
- Spectral analysis and pulling small signals out of noise
- Fluctuation diagnostics (Interf., Polarimetry, ECE, BES, Reflectometry, SXR)

Measurement of Confined Fast Ions



- **DD Beam-Plasma neutrons**
- **Neutral Particle Analyzers (NPA, INPA)**
- **Equilibrium pressure**

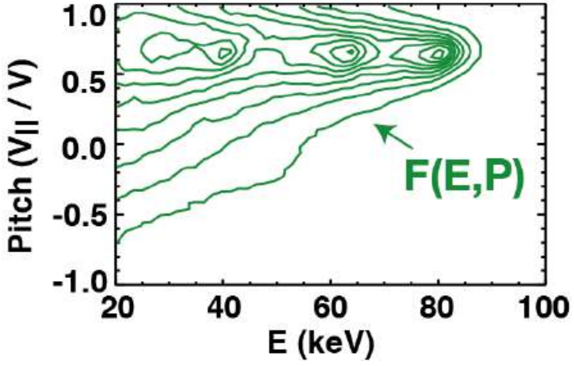
Measurement of Instability Impact



- Abrupt events / relative measurements
- Quantitative / absolute measurements
- Example putting it all together

Detailed Measurements of EP Profile and Interaction With Instabilities is Critical for Understanding Physics

80kV Beam Ion Dist. Function



- *EP Distribution functions can be complicated and typically are not Maxwellian*
- **Phase space sensitivy and coverage of phase space important consideration when selecting EP diagnostics**

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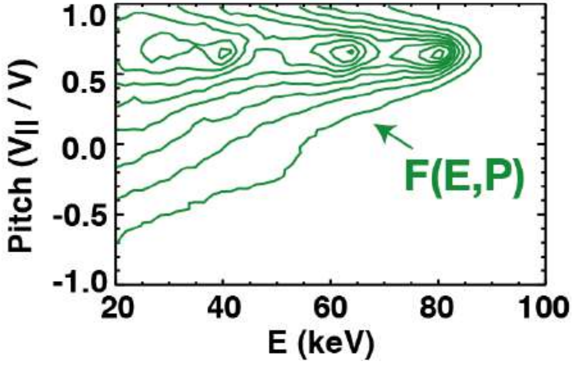
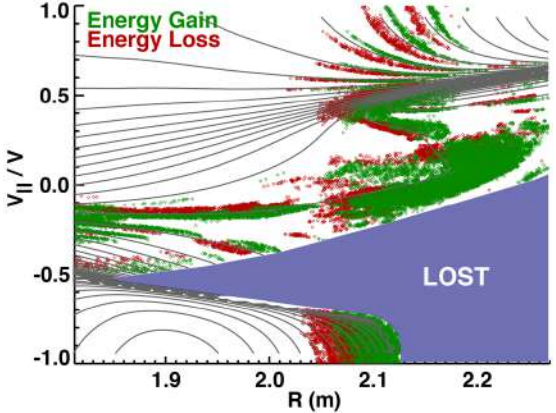


Fast Ion Resonances and Energy Exchange with an Alfven Eigenmode

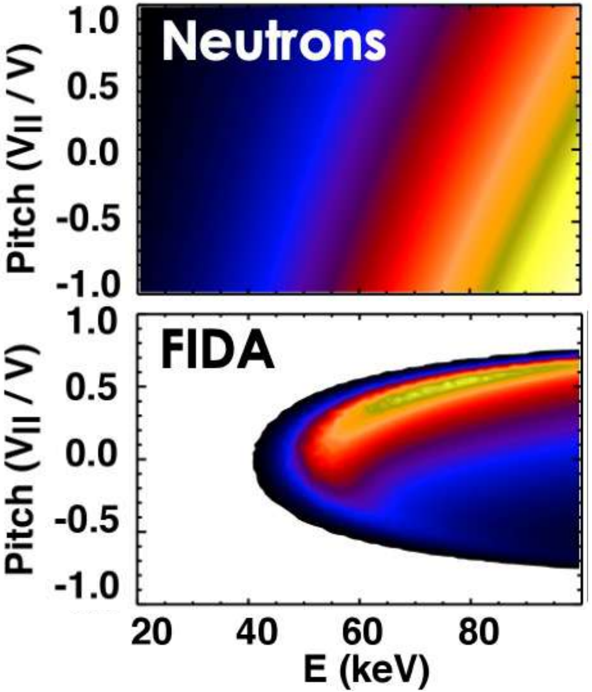


- *EP Distribution functions can be complicated and typically are not Maxwellian*

- **Phase space sensitivy and coverage of phase space important consideration when selecting EP diagnostics**
  - wave-particle interaction often happens through localized resonances

Most EP Diagnostics Integrate Over Large Regions of Phase Space

Weight Functions



Convolution W*F

$$S = \int\int\int\int (W * F)dE\ dp\ dR\ dz.$$

- **Examples show phase space weight functions for:**
  - Neutron measurement
  - Doppler shifted fast ion **Dα** light (FIDA)
- **Weight functions like these are great for global view of EP confinement**

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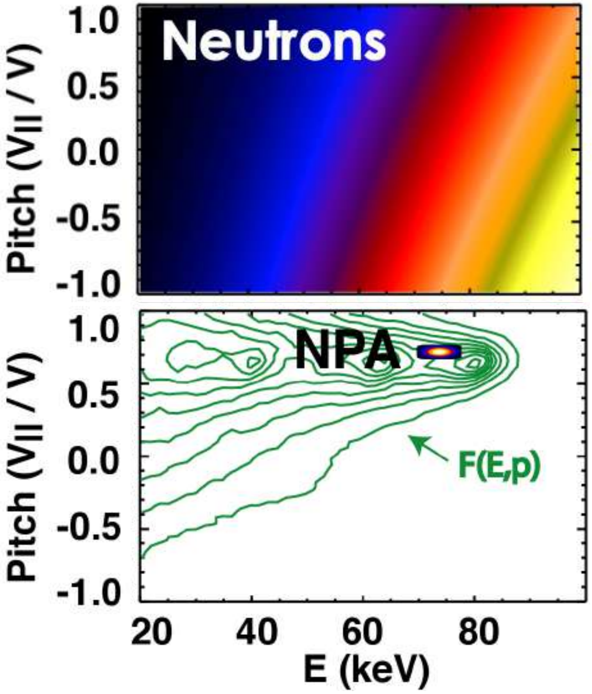

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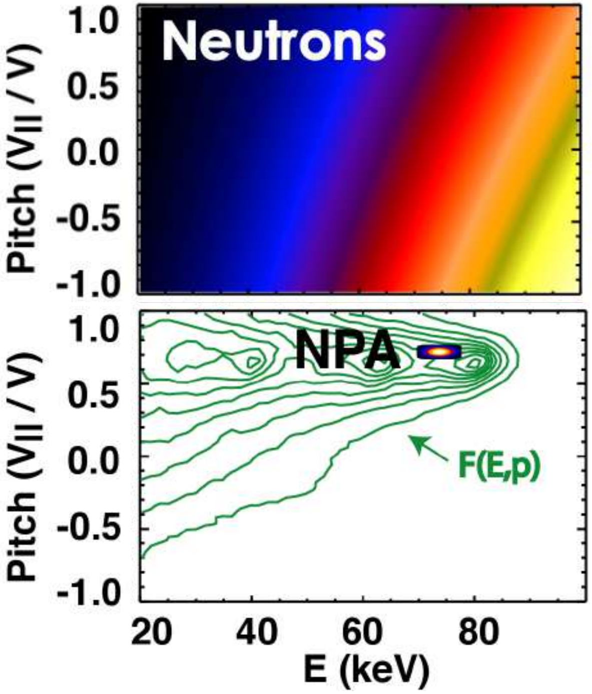

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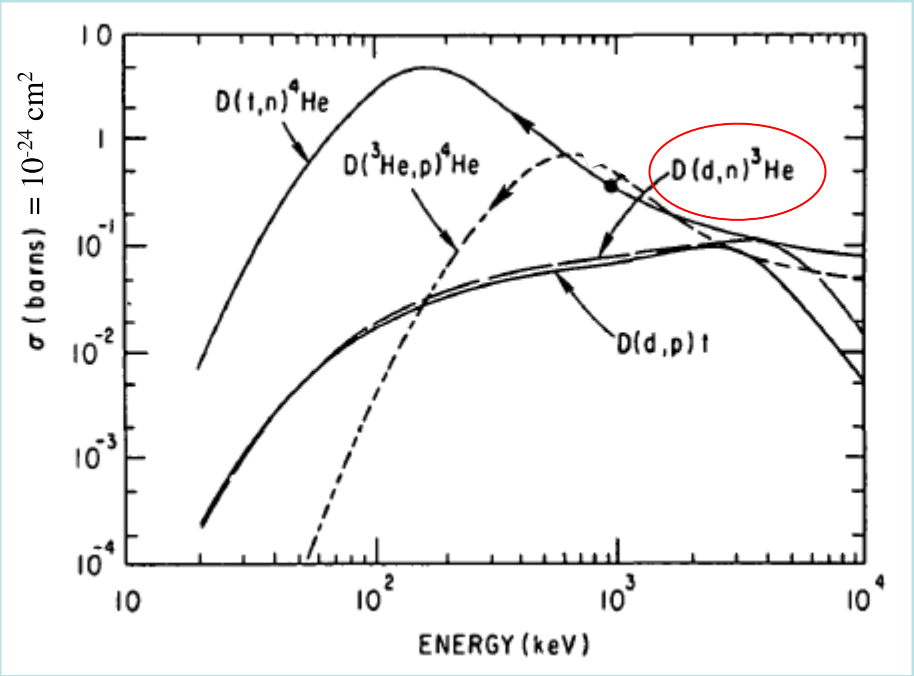
- **Best set is combination of broad phase space (FIDA, neutrons, pressure, etc.) complemented by localized phase space (NPA, INPA) measurements to get at details of phase space interaction**
  - Must ensure localized measurements probe populated region of phase space!

Fusion Reactions Require High Energies and Can Be Used for EP Diagnostics

- **D + T → n + 4He is written T(D,n)4He in nuclear physics notation**
- **All cross sections increase rapidly with energy → highest energy ions create most of the reactions**
- **Discussion here focuses on measurements of D+D generated 2.5 MeV neutrons in beam heated plasmas**

D + D → **2.5 MeV n** + 0.8 MeV ^{3}He
→ 3.0 MeV p + 1.0 MeV T

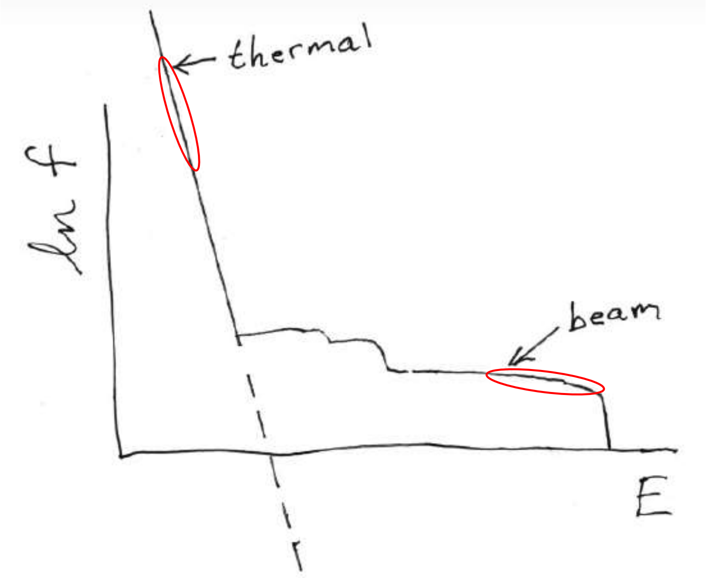


Heidbrink, Nucl. Fusion 23 (1983) 917

For Beam-Plasma Reactions, the Beam Velocity Governs the Reaction Rate

$$\langle \sigma v \rangle = \int \int \sigma |\mathbf{v}_1 - \mathbf{v}_2| f_1(\mathbf{v}_1) f_2(\mathbf{v}_2)\, d\mathbf{v}_1\, d\mathbf{v}_2 \qquad (2)$$

- **For D-D reactions, often artificially divide the distribution function into a thermal and fast beam population.**
  - Can have: **beam-plasma**, beam-beam, thermonuclear
- **Beam-plasma reactivity depends primarily on the beam velocity with some (relatively weak) dependence on Ti & thermal drift velocity**



This implies that

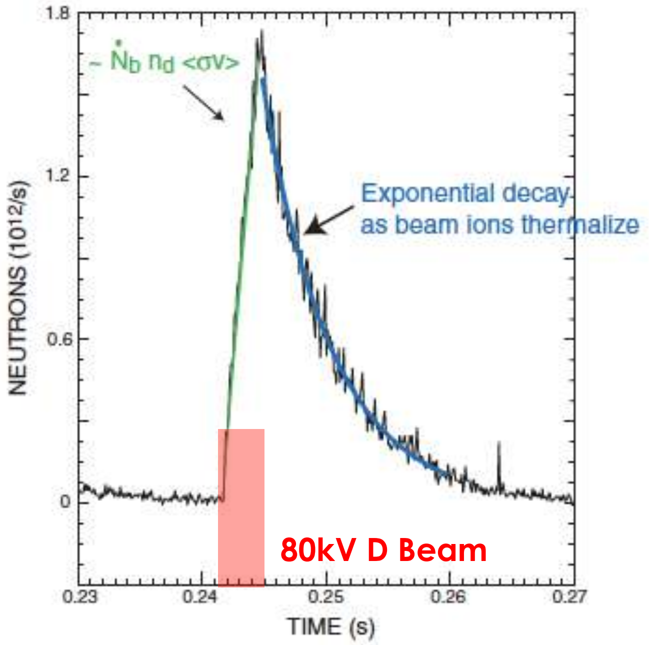
$$S_{beam-plasma} \propto N_1 \bar{n}_2 \langle \sigma v \rangle_{beam-plasma}$$

where N_1 is the number of beam ions.

- ***When beam-thermal reactions predominate, the reaction rate is proportional to the number of fast ions = confined fast ion diagnostic***

Neutron Measurements During Beam Blips Can Yield Beam Fueling Rate and Confinement

- Inject beam pulse that is short compared to the thermalization time (a “beam blip”)
- Use to measure the rate beam ions are injected if n_D known
- Decay gives measure of thermalization or confinement time of beam ions (cross section weighting makes decay faster than slowing down time)
- Combined with modeling neutron emission can yield powerful measurement of beam ion confinement



Heidbrink, Nucl. Fusion 43 (2003) 883

Heidbrink, Nucl. Fusion 28 (1988) 1897

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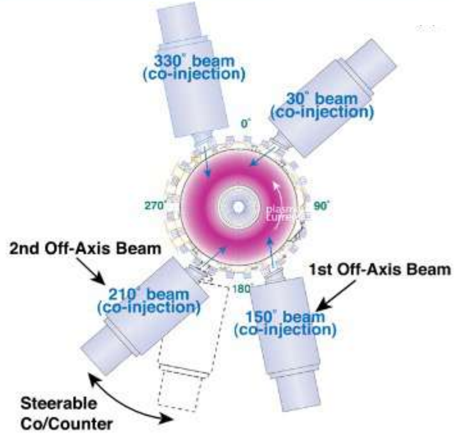
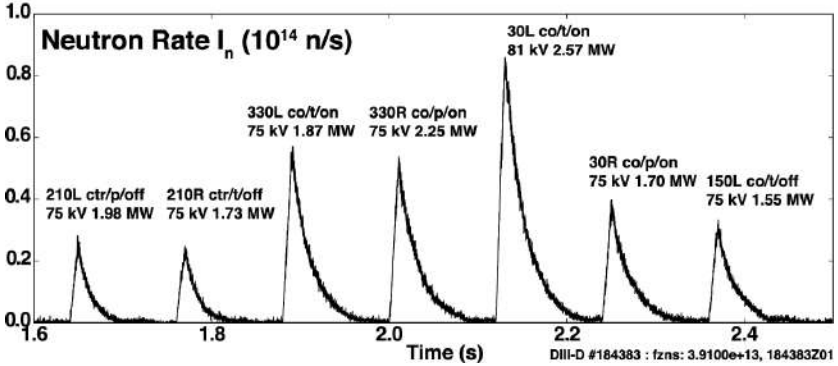
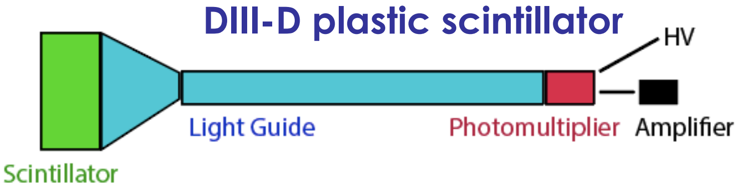
  - Particularly useful for making relative comparisons
- **Other examples follow in next section**

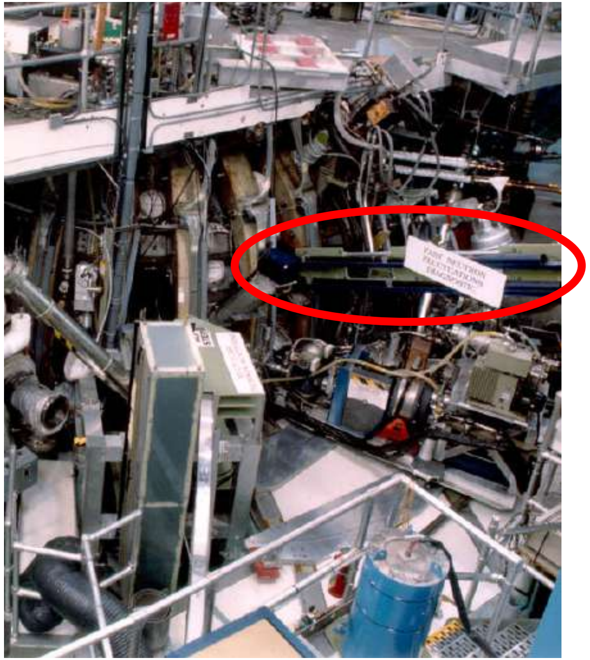




B. Grierson, et.al., NF, 61 (2021) 116049

Neutron Emission Diagnostics Can Span a Range of Complexity





- **Simple scintillator based measurement can give relative measure of total neutron emission**

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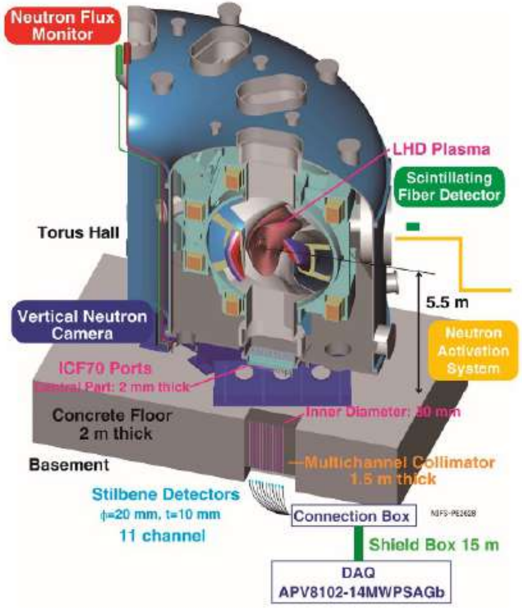

Ogawa, NF 59 (2019) 076017

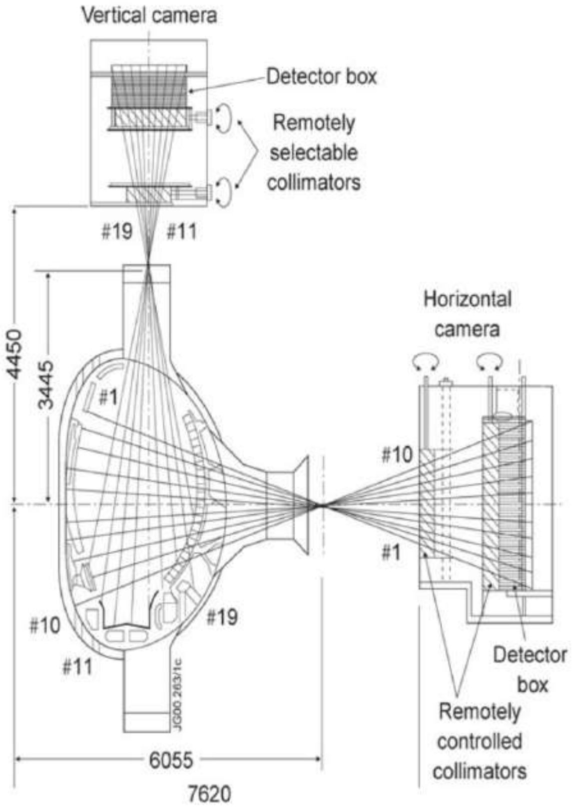

Fig. 13. Schematic view of JET neutron profile monitor.

Sasao, FST, 53 (2008) 604

- **Simple scintillator based measurement can give relative measure of total neutron emission**
- **Massive neutron cameras can yield spatially resolved neutron emissivity profile and measure of confined beam ion profile**

NPA Diagnostics Probe the Ion Distribution By Detecting Neutrals Escaping the Plasma After Charge-Exchange Reactions

- **Charge exchange reaction occurs when an ion collides with neutrals in the plasma**
  - Neutrals from injected neutral beams = active
  - Other neutrals = passive

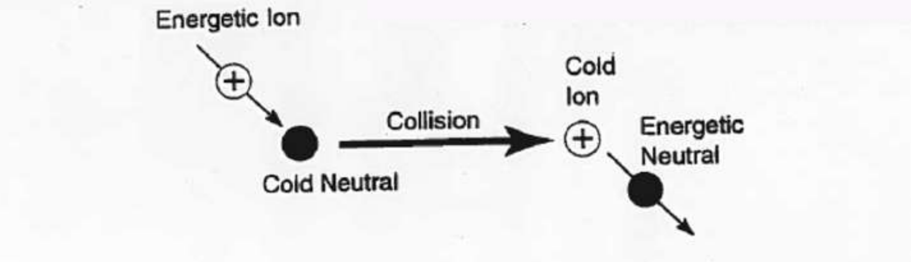

Figure 10.7. Charge-exchange process in which an energetic ion takes an electron from a cold neutral, thereby becoming an energetic neutral. A time just before the charge-exchange collision is shown to the left of the thick black arrow; a time just after the collision is shown to the right.

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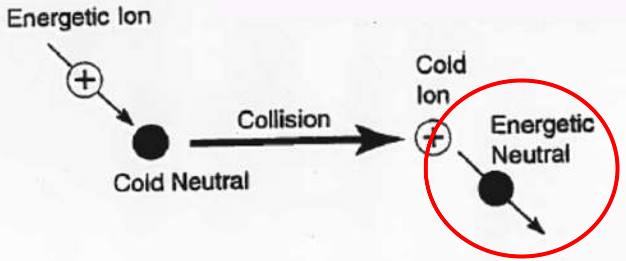
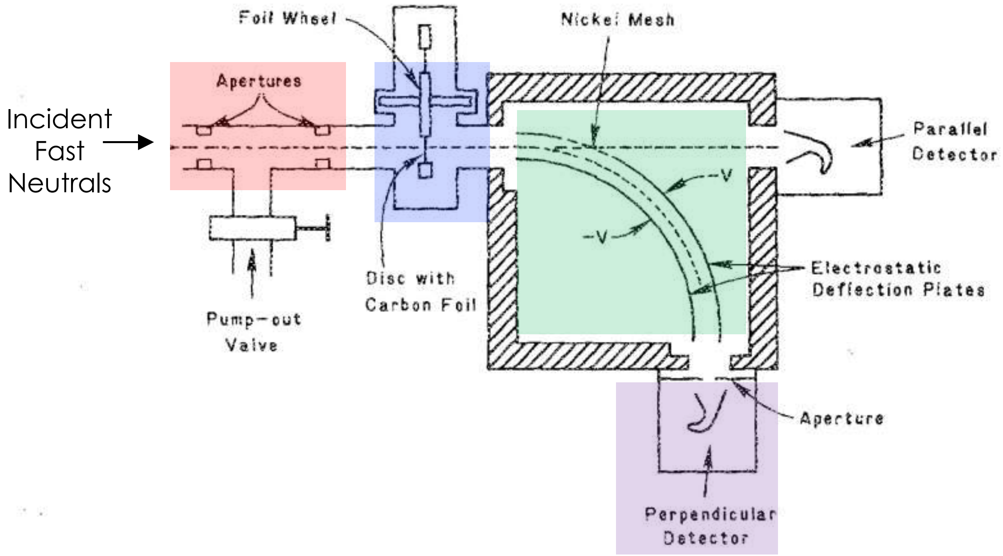


Figure 10.7. Charge-exchange process in which an energetic ion takes an electron from a cold neutral, thereby becoming an energetic neutral. A time just before the charge-exchange collision is shown to the left of the thick black arrow; a time just after the collision is shown to the right.

- **Energetic neutral can escape plasma and be detected ("Neutral Particle Analysis")**
  - Escaping neutral flux → density and energy of ions with the velocity vector and localization defined by the collection sightlines
- **NPAs measured Ti in the '60s, e.g., Afrosimov, Sov. Phys. Tech. Phys. 5 (1961) 1378 and are now routinely employed to probe fast ions**

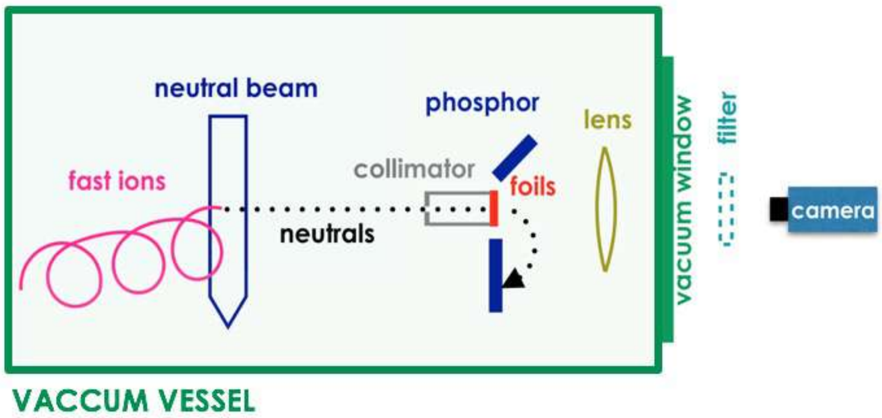
A Variety of Neutral Particle Analyzer Designs Exist



P. Beiersdorfer, RSI, 58, 11, 1987
INPA Review: S.S. Medley, et.al., RSI. 79, 011101 (2008)

- **Common features include:**
  - some type of collimation (to limit the line-of-sight through the plasma)
  - Stripping agent to reionize neutral particle (foil, gas)
  - Energy / mass selection mechanism (Electrostatic, Magnetic, E||B)
  - Detection (Channel plates, scintillators, diodes, etc.)
- **Can include multiple sightlines but bulky and typically provides relatively few channels**

The Imaging Neutral Particle Analyzer (INPA) is Inspired by Scintillator Based Fast Ion Loss Detectors (FILD) and a Traditional NPA



- **Escaping neutrals**
  - Stripped by a foil
  - Strike a phosphor
  - Imaged with a Camera or PMT

X.D. Du, et.al. Nucl. Fusion, 58, 082006 (2018)
M.A. Van Zeeland et al 2019 JINST 14 C09027

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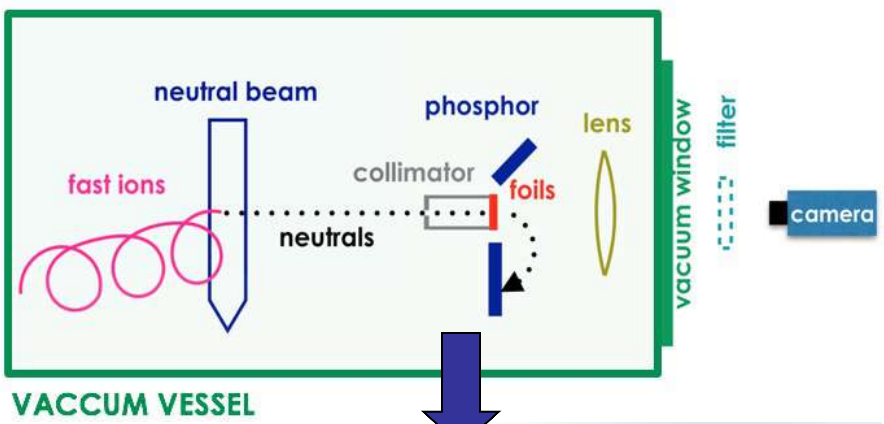

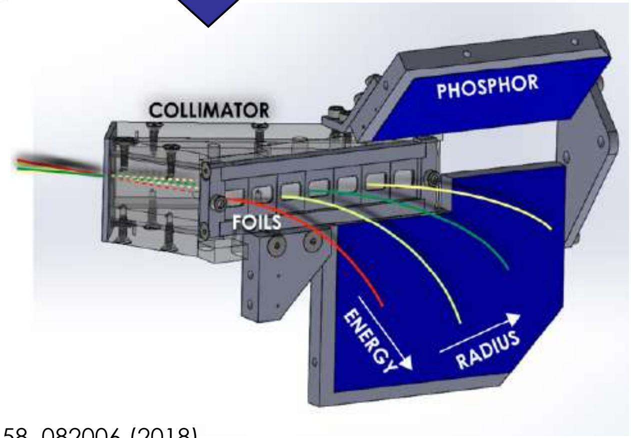

- **Escaping neutrals**
  - Stripped by a foil
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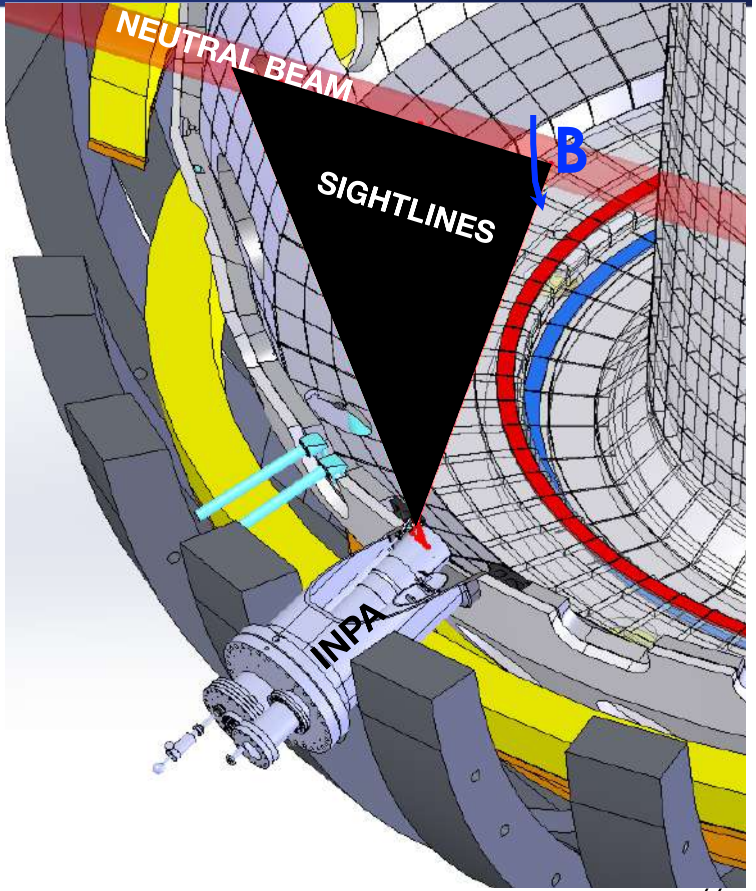
- **INPA provides an energy and radially resolved image**
  - Gyroradius -> energy
  - Line of sight -> Radius
  - Local fast ion distribution function at a given range of pitch
- **Leverages best parts of traditional NPA and FILD**
  - Localized velocity space measurements
  - Light emission vs current
  - Low noise

X.D. Du, et.al. Nucl. Fusion, 58, 082006 (2018)
M.A. Van Zeeland et al 2019 JINST 14 C09027

INPA is Installed Inside the Vacuum Vessel for a Broad Radial View

- **INPA views can span large range of vessel but must intersect a diagnostic beam (active)**
  - To achieve desired views, the system is in vacuum vessel, close to plasma
  - Probed pitch ($v_{//}/v$) determined by sightline intersection with beam
    - Critical that this overlaps with a populated region of phase space!



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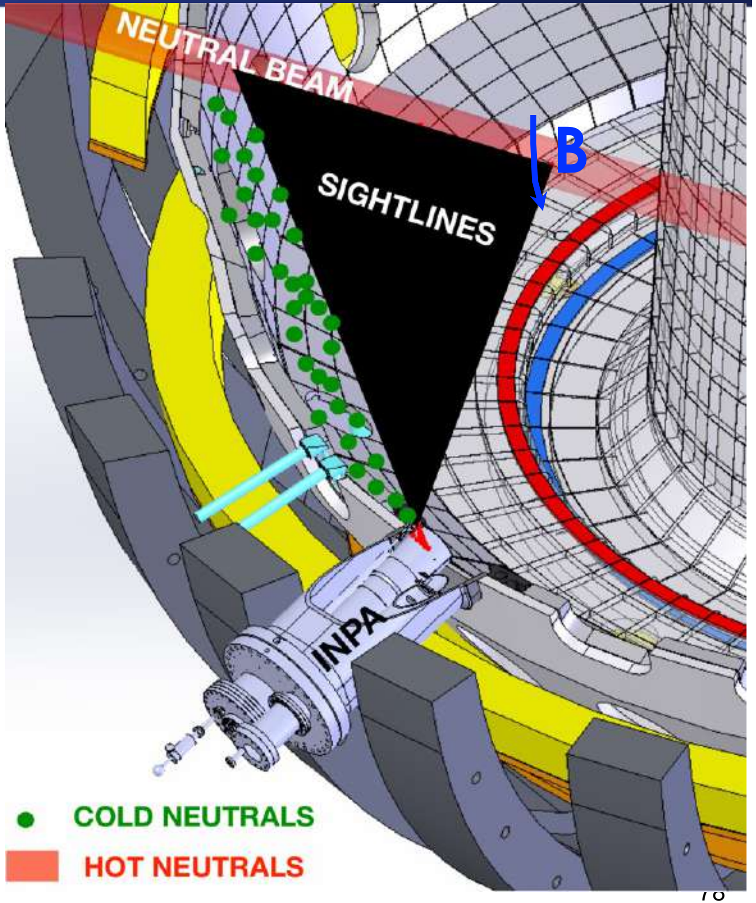
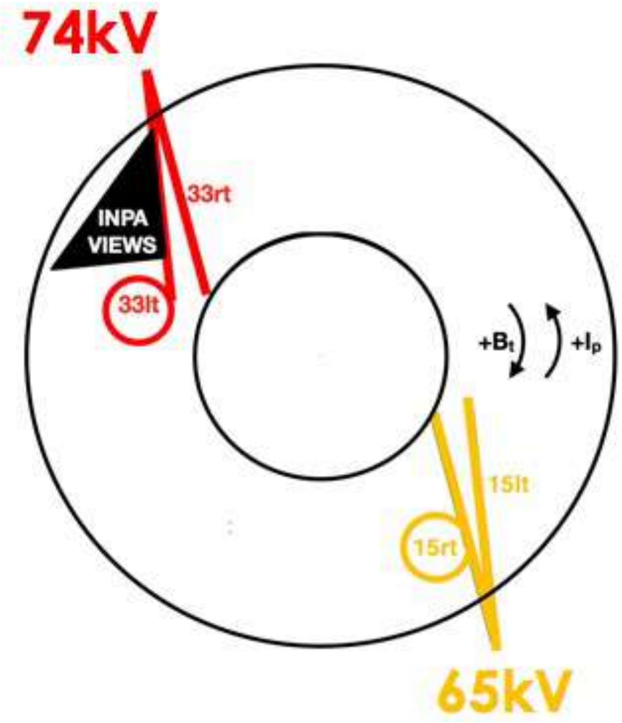
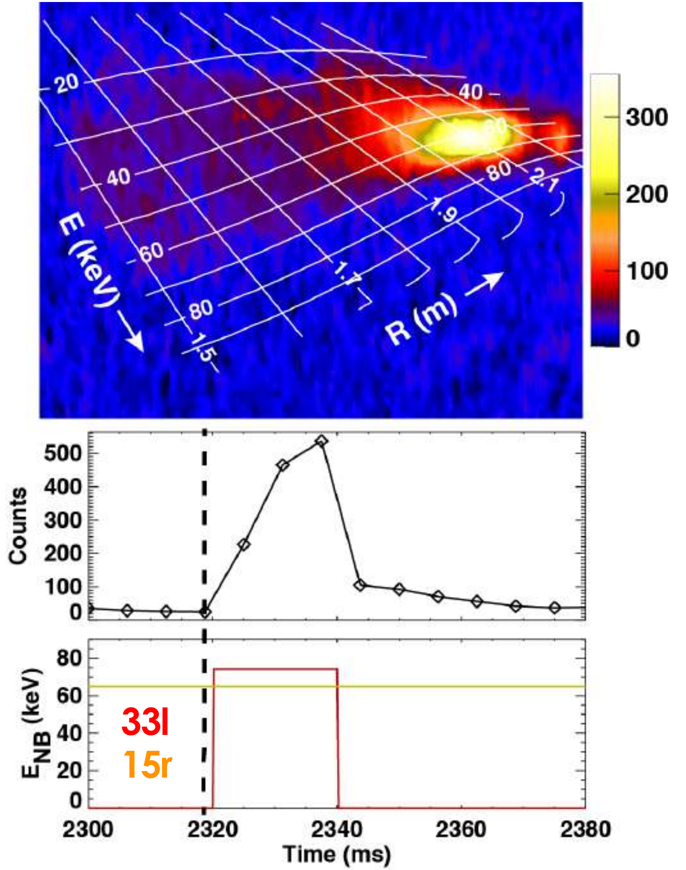
- **Passive emission can also come from edge regions but heavily weighted towards closest**
  - Can be separated from active emission by modulating the active beam on/off



Time Evolution of INPA Signal During Single Beam Blip Shows Many Key Features of Phase Space Dynamics

- **Passive emission visible from 65 keV beam**





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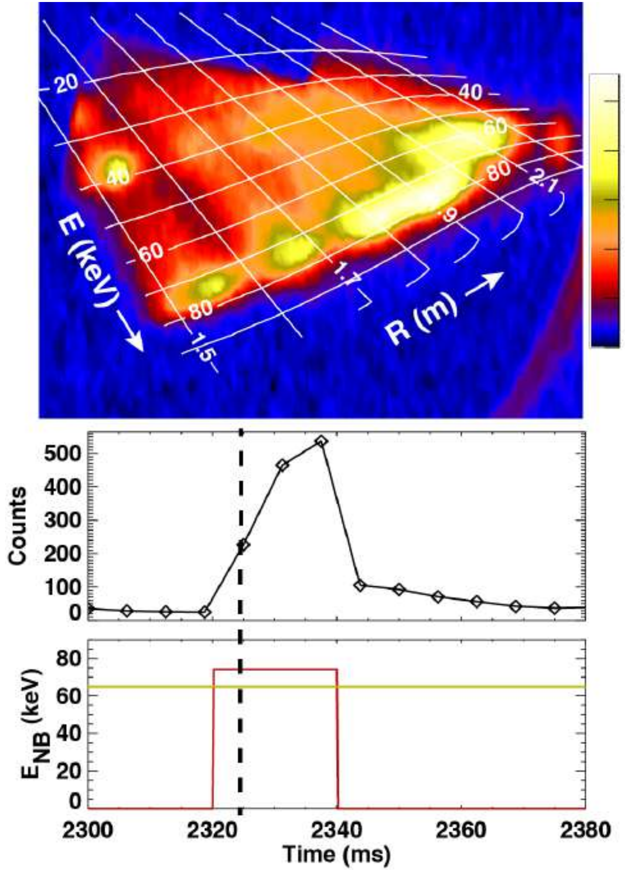
  - Active measurement of confined 65kV beam ions
  - Increasing signal to 74 kV due to fueling by active beam



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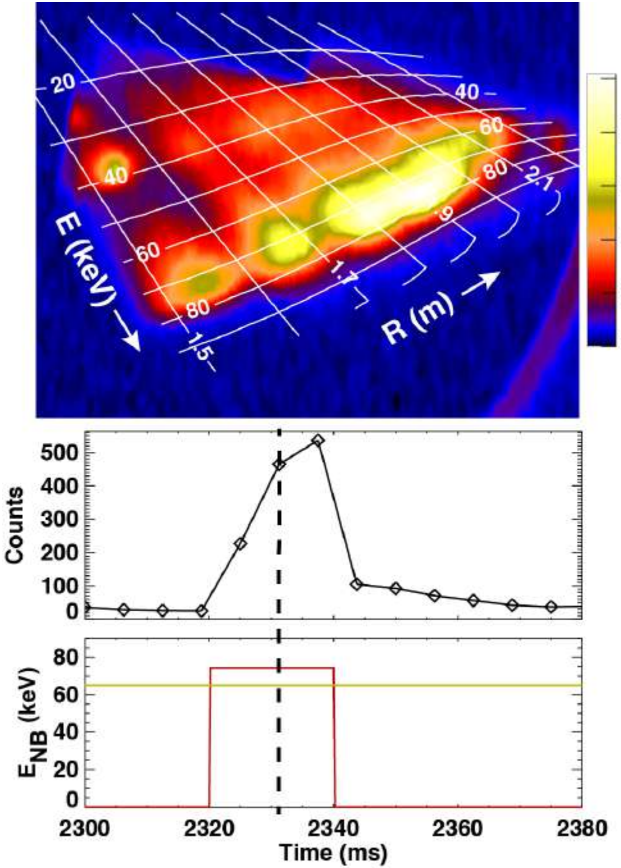

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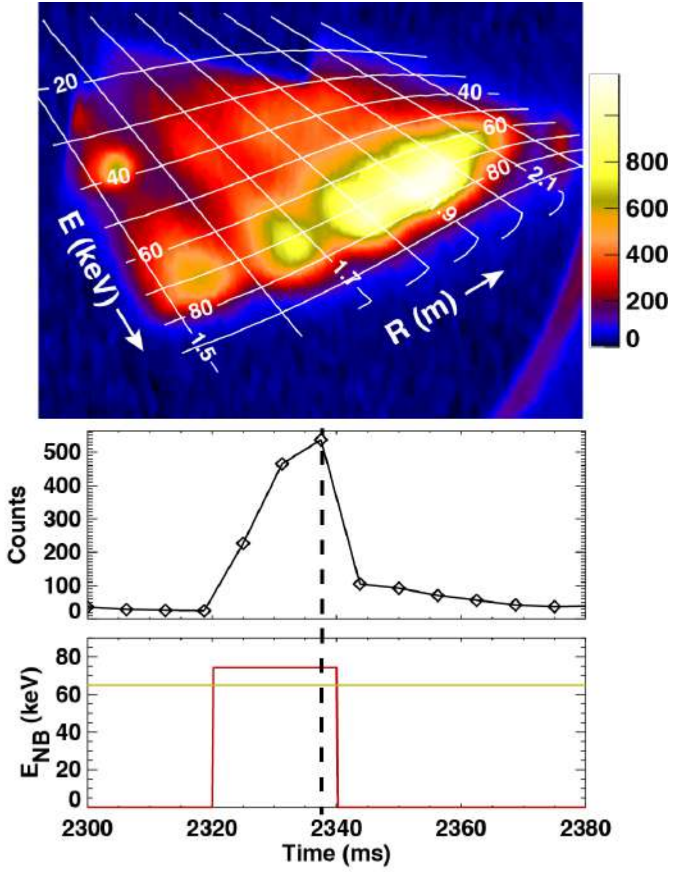

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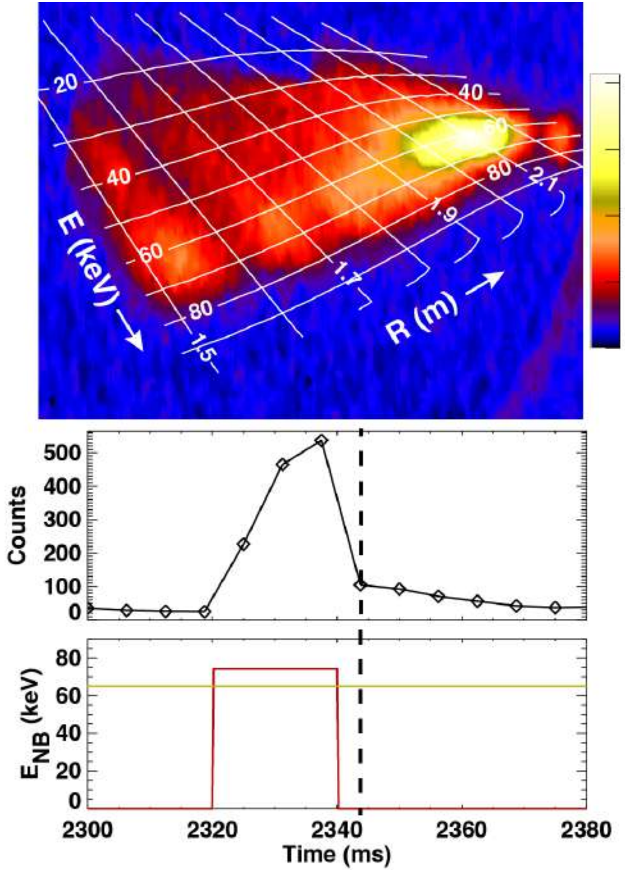

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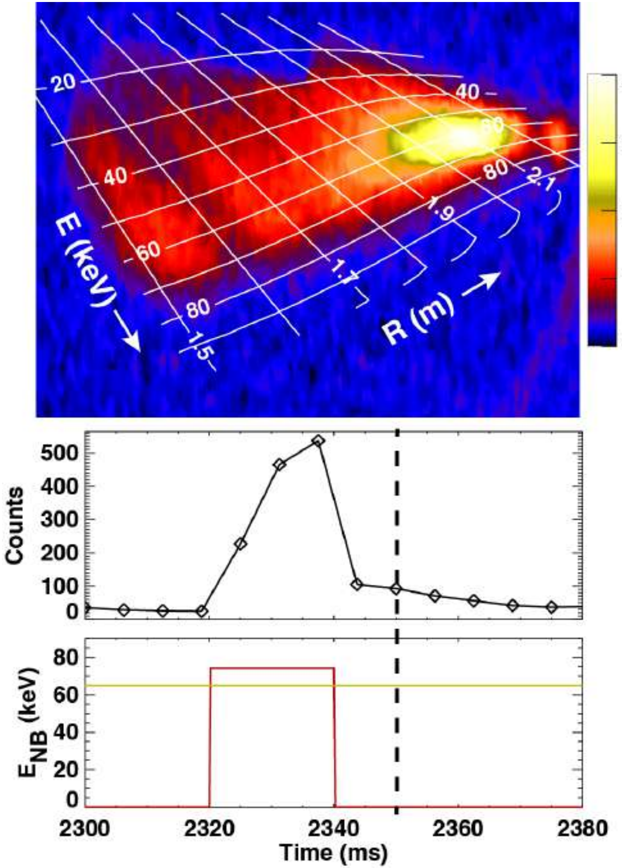

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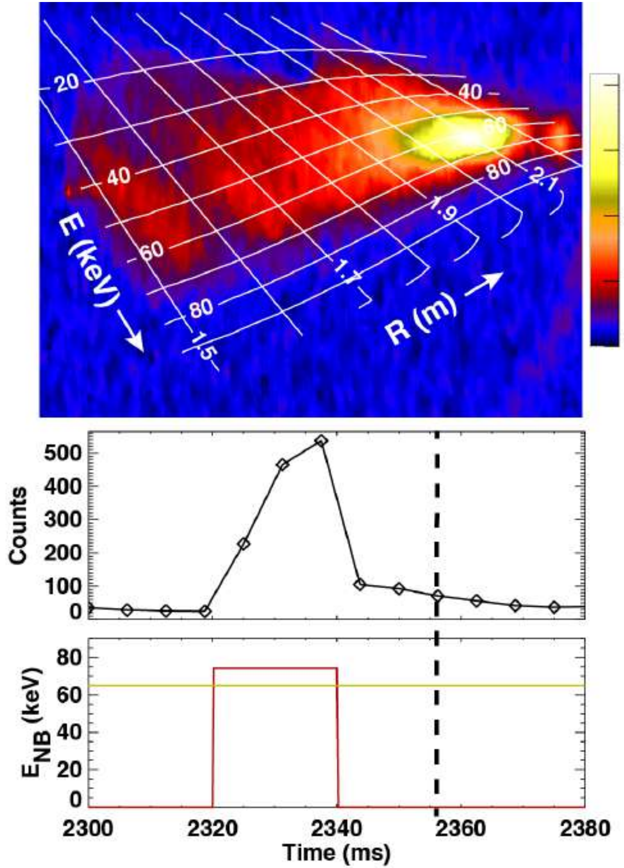

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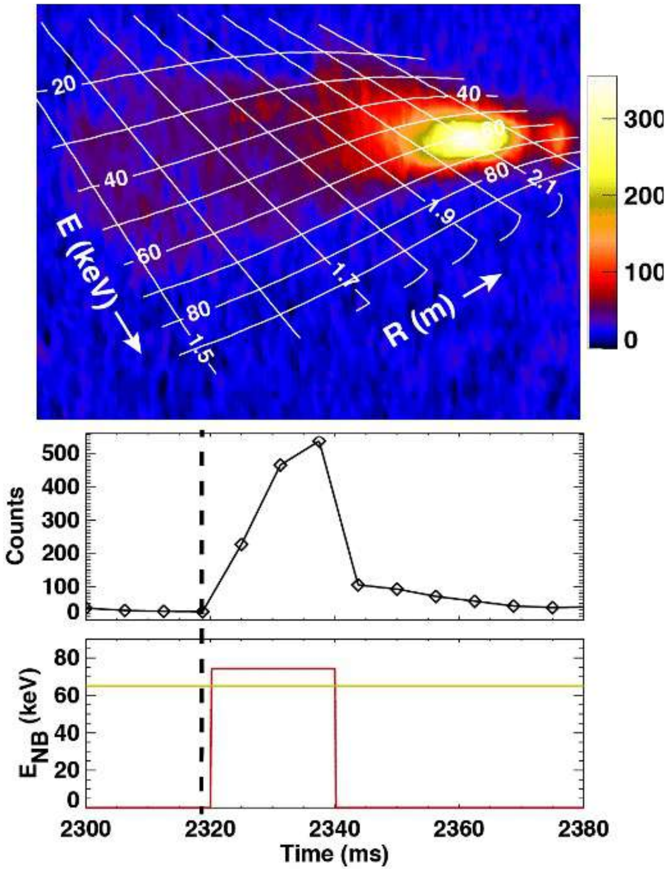
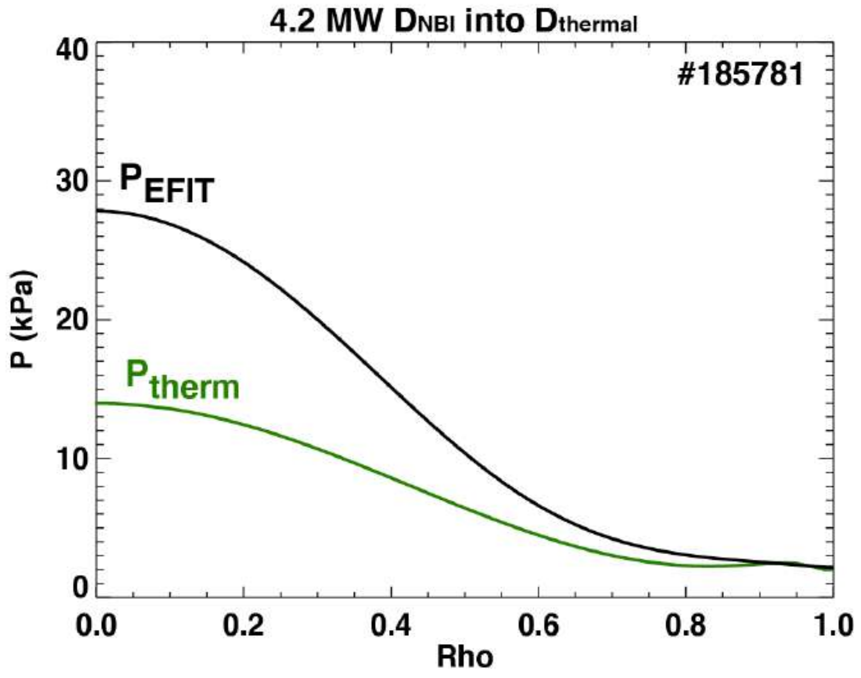


MSE Constrained Equilibrium Reconstructions Can Be Used to Obtain Approximate Fast Ion profiles and Transport



- **Motional Stark Effect diagnostic measures pitch angle and helps constrain magnetic axis location**
- **Total pressure profile obtained from equilibrium reconstruction**
  - Core pressure constraint can be used: Typically thermal + classical fast ion pressure with large error bars
- **Thermal pressure is known from core kinetic profile diagnostics**

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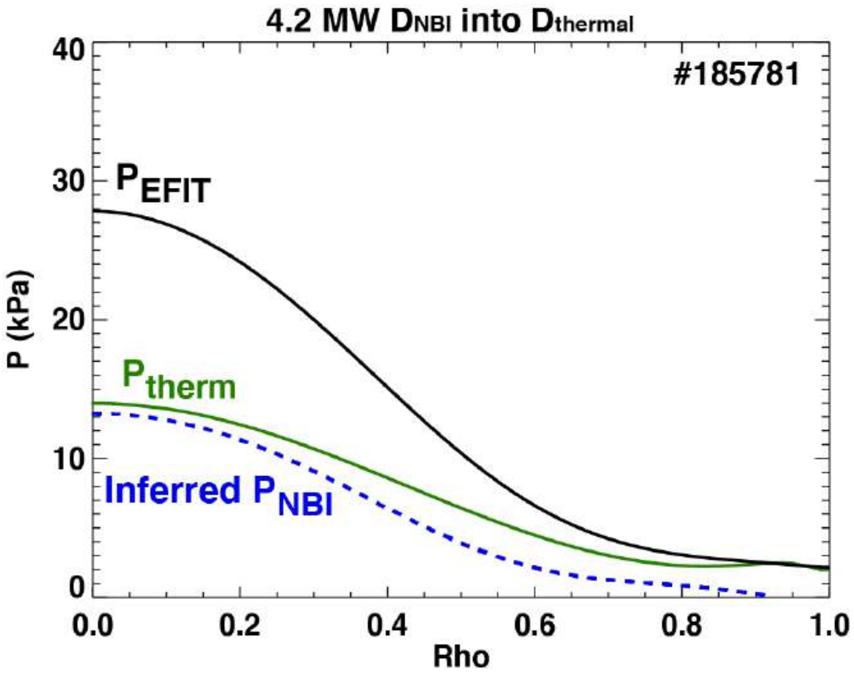

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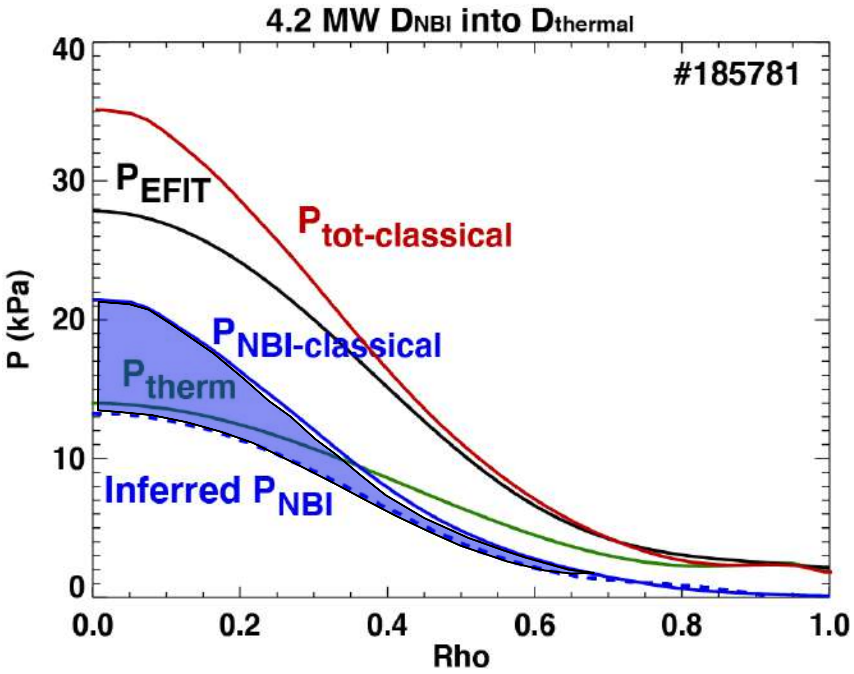

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- **Inferred deficit is difference from classiscal**

Advantage – simple, can be easily compared to simulation

QUIZ ON EP DIAGNOSTICS

- **Which of these EP diagnostic techniques can have issues as the device gets larger?**
  1. DD Neutrons
  2. NPAs
  3. EP pressure from equilibrium pressure

QUIZ ON EP DIAGNOSTICS

- **Which of these EP diagnostic techniques can have issues as the device gets larger?**
  1. DD Neutrons
  2. NPAs
  3. EP pressure from equilibrium pressure

- **Which of these diagnostic techniques can have issues at high density?**
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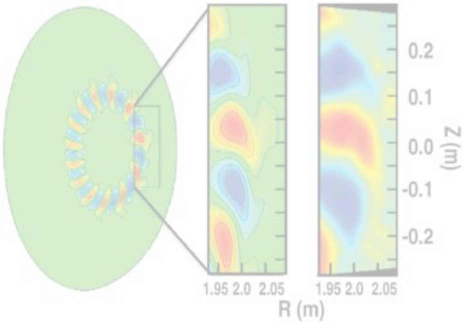
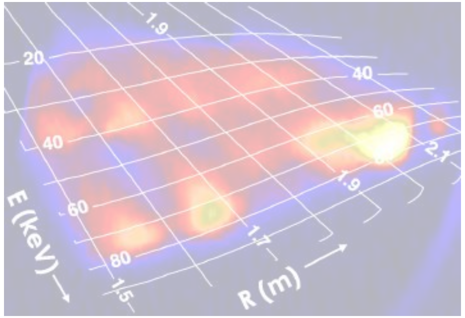
Outline

Measurement of Instabilities



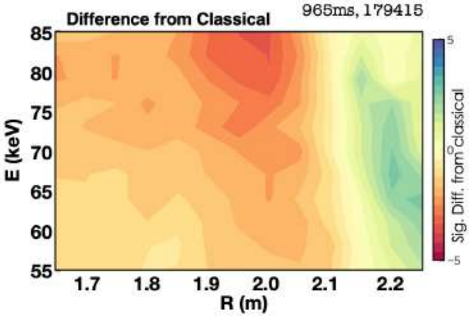
- Perturbed quantities
- Spectral analysis and pulling small signals out of noise
- Fluctuation diagnostics (Interf., Polarimetry, ECE, BES, Reflectometry, SXR)

Measurement of Confined Fast Ions



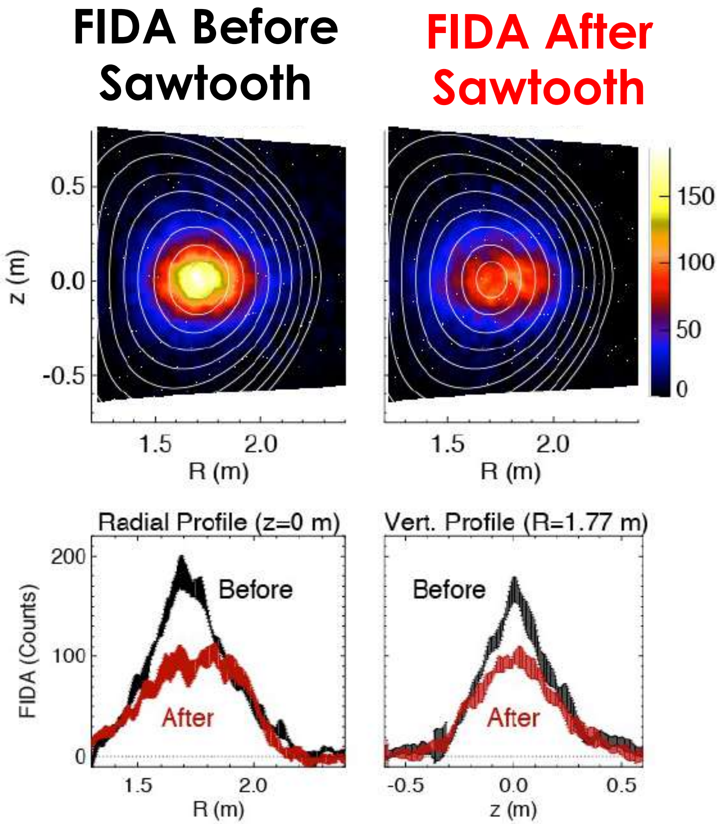
- DD Beam-Plasma neutrons
- Neutral Particle Analyzers (NPA, INPA)
- Equilibrium pressure

Measurement of Instability Impact



- **Abrupt events / relative measurements**
- **Quantitative / absolute measurements**
- **Example putting it all together**

Impulsive / Abrupt Events Can Yield Clear and Obvious Measure of Instability Induced Transport



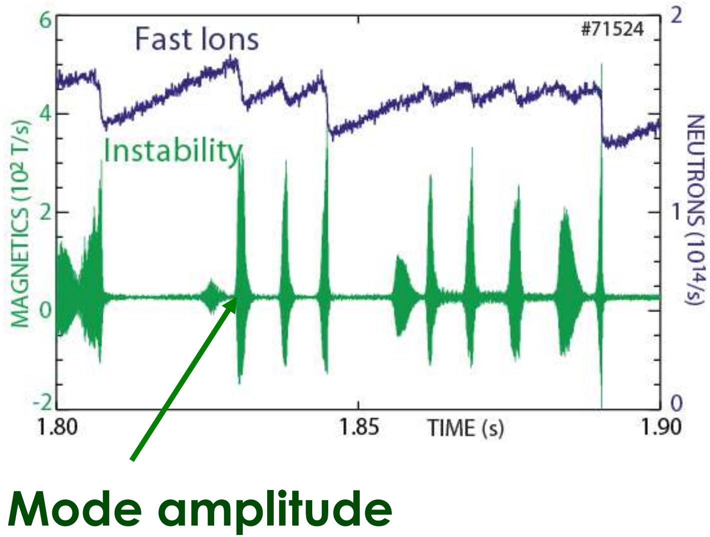
Several examples:

- **Sawteeth**
  - Drop in central FIDA emission and flattening of fast ion profile

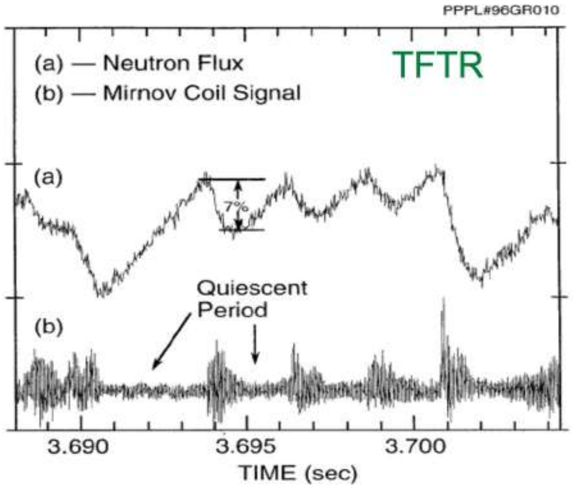
M.A. Van Zeeland, et.al., 50 (2010) 084002

Impulsive / Abrupt Events Can Yield Clear and Obvious Measure of Instability Induced Transport

Large drops in neutron emission at each burst of AE activity caused by rapid transport of beam ions



HH Duong et.al., Nucl. Fusion, 33, 749 (1993)

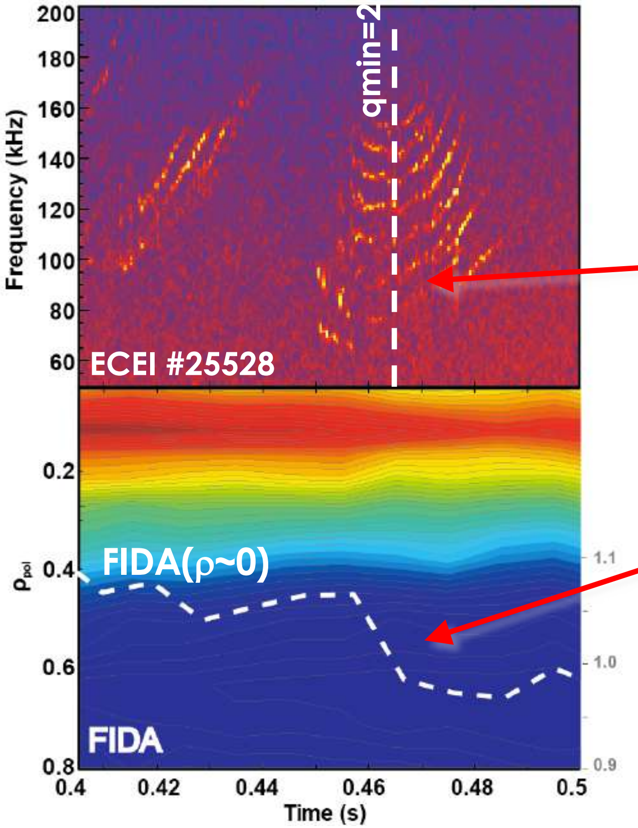


K.L. Wong, PPCF, 41 R1 1999

Several examples:

- **Sawteeth**
  - Drop in central FIDA emission and flattening of fast ion profile
- **Bursting modes (TAEs, Fishbones, etc.)**
  - Drops in neutron emission due to fast ion loss or transport

ASDEX Upgrade FIDA System Measures a Drop in Central Fast Ion Population as q_{min} Passes Through an Integer



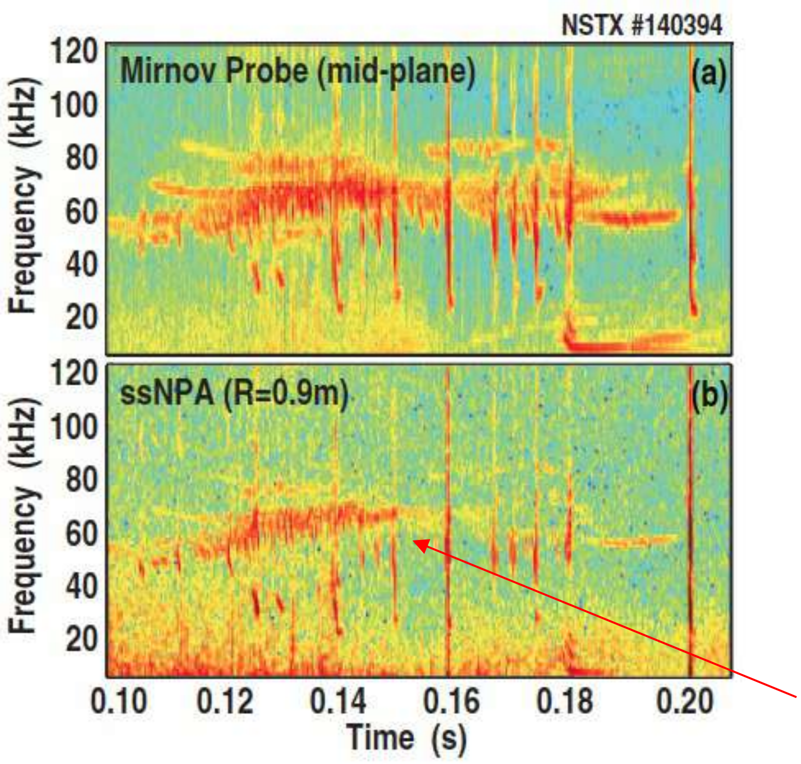
- **At qmin=2 crossing, several RSAEs are excited by 60kV beams**
- **Rapid drop in central fast ion density corresponding to peak in RSAE amplitude**

M. Garcia-Munoz, et.al. NF 51 (2011) 103013

Max-Planck-Institut für Plasmaphysik

ASDEX Upgrade

Coherent Fluctuations in Fast Ion Signals are Another Way to Quantify Impact of Instabilities



- **Example shows fluctuations in solid-state NPA signal at EP driven instability frequencies**
  - Correlated with magnetics
- **Can clearly resolve which modes are causing transport as well as amplitude of fluctuation**

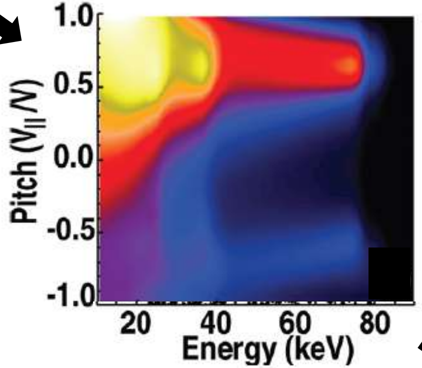
Coherent fluctuations in fast ion density (in small region of phase space)

Y. Zhu, et.al., Rev. Sci. Instrum. 83, 10D304 (2012)

Often, To Quantitatively Assess Impact of Modes on Fast Ion Profile, Modeling of Classical Expectation Is Required

Measured equil., kinetic profiles & heating waveforms

TRANSP/NUBEAM calculates EP distribution



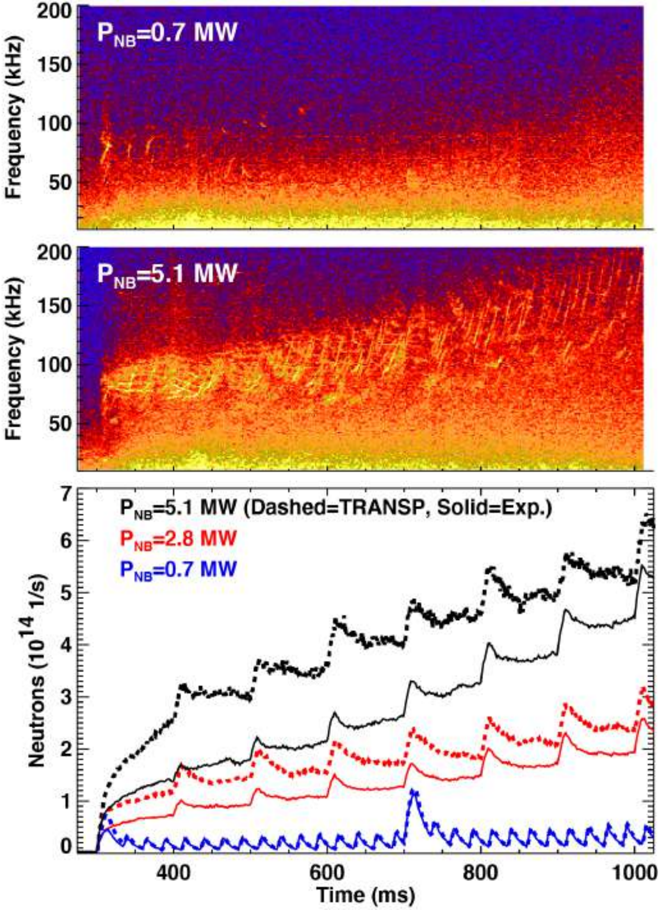
Synthetic EP diagnostics / Diagnostic simulation codes[3,4]

Predicted EP diagnostic signals

- **TRANSP/NUBEAM[1,2], etc. calculation of classical fast ion distribution function**
  - Takes measured kinetic profiles and heating waveforms
  - Assumes fast ion profile evolves purely under influence of scattering, CXR, etc. (NO MHD)
  - Gives expected distribution function, fusion products, etc.
  - Can be processed with **synthetic diagnostics** for comparison to EP measurements
  - Can also be run w/ some type of diffusivity to quantify transport

1. TRANSP: Poli F., et.al. 2018 Transp (Computer Software) (https://dx.doi.org/ 10.11578/dc.20180627.4)
2. NUBEAM: A. Pankin, et.al., Comp. Phys. Commun. 159 (2004) 157–184
3. FIDASIM: WW Heidbrink et al., Commun. Comput. Phys., 10 (2011)
4. INPASIM: X. Du, et.al., NF 58 (2018) 082006

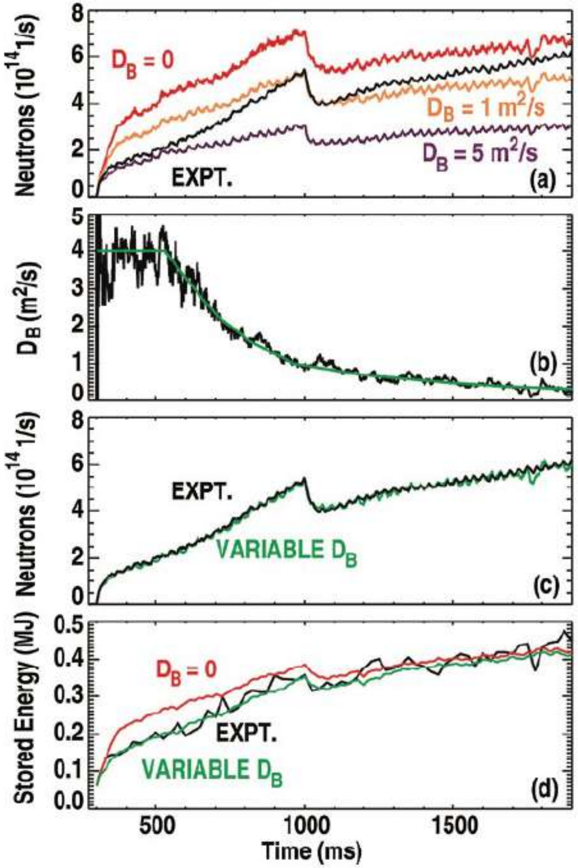
Example Shows Neutron Deficit Relative to Classical Calculations as AE Amplitude Increases



- **Low beam power (0.7MW) - few AEs**
  - Measured neutrons match classical TRANSP calculations
- **High beam power (5.1MW) - multiple AEs**
  - Up to 50% deficit relative to classical
  - Beam ions are being transported out of plasma or to lower T_e/n_D

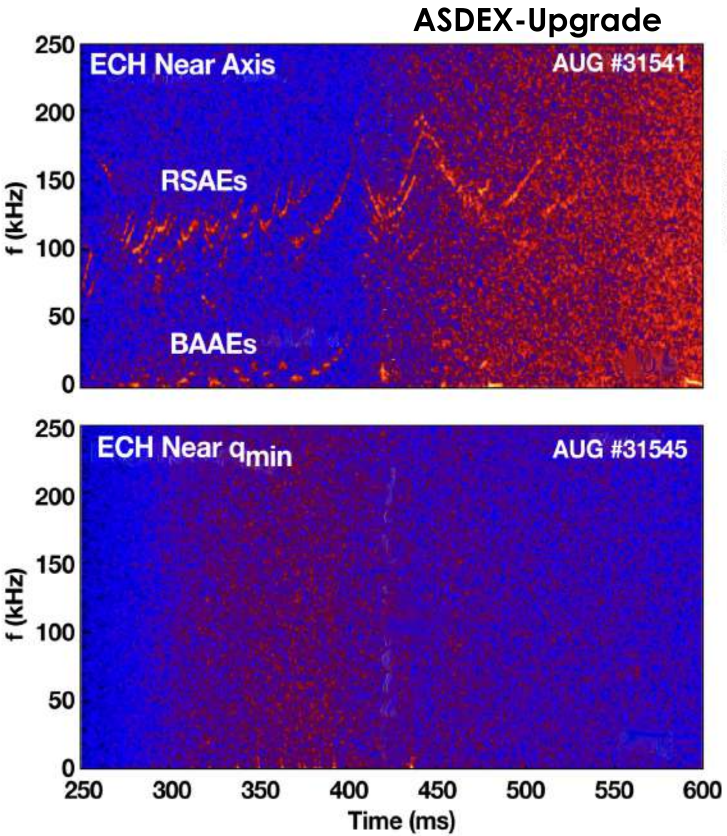
M.A. Van Zeeland, et.al., PoP, 18, 056114 (2011)

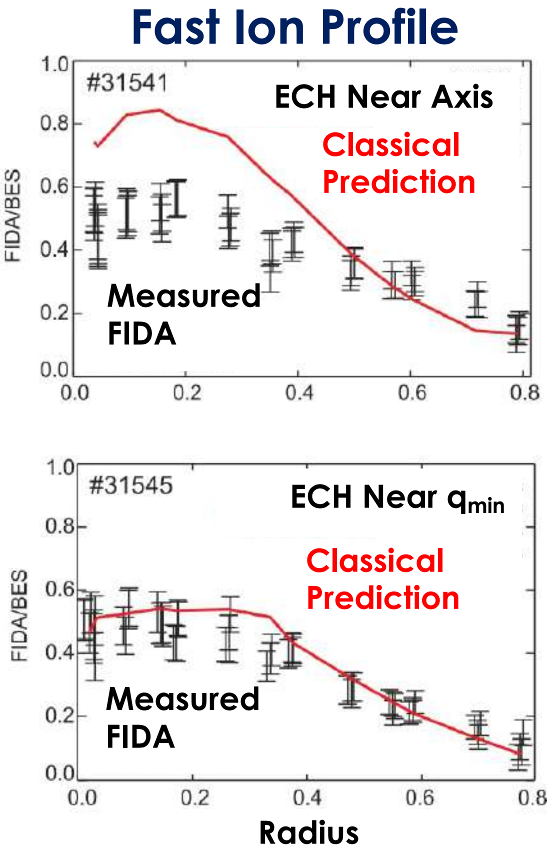
Approximate Diffusivity from AEs Can Be Inferred



- **TRANSP and other codes can be run with an assumed ad-hoc fast ion diffusivity (D_B)**
  - Can be spatially, energy, pitch angle dependent
- **By adjusting diffusivity to match masured neutron rate, an effective diffusivity can be inferred**
- **In example, stored energy from equilibrium reconstructions also matches prediction with diffusivity**
  - Deficit from classical case is due to reduction in EP pressure

Similar Comparisons of Fast Ion Transport Can Be Made Using More Complex Fast Ion Diagnostics

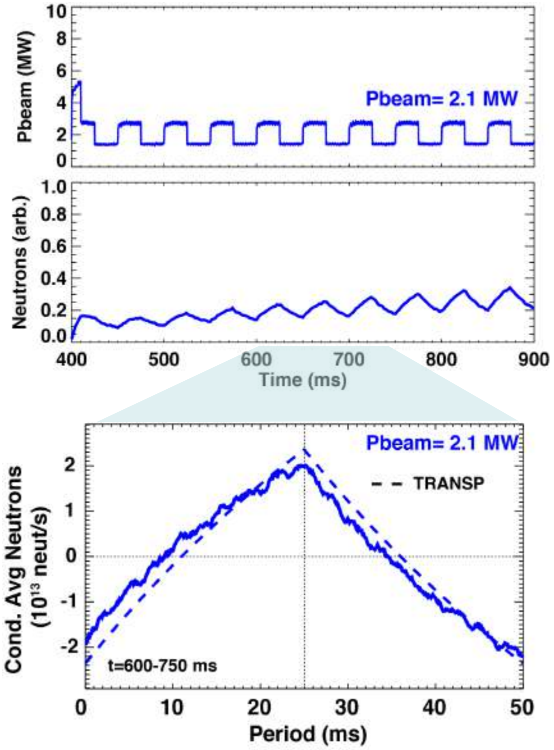


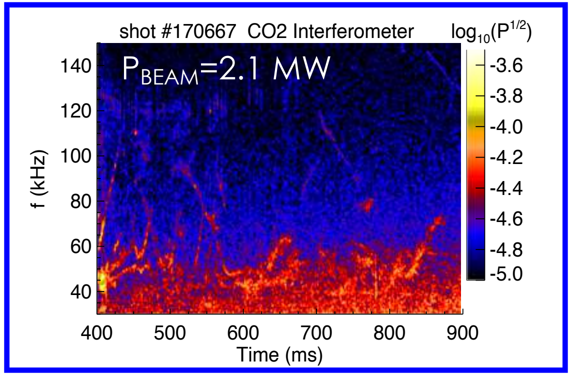


- **In this ASDEX-Upgrade example, two cases with and without AEs are compared to predicted FIDA profiles**
- **ECH near q_{min} resulted in:**
  - *NO AE activity*
  - *Classical fast ion confinement*
- **ECH near *axis* resulted in:**
  - *Strong AE activity*
  - *~35% central fast ion deficit!*
- **This is forward modeling**
  - Alternatively, can compare local distribution using tomography as Mirko discussed

S. Sharapov, et.al., PPCF 60 (2018) 014026

Beam Modulation Technique Can be Used to Infer AE Induced Fast Ion Transport





- **Technique looks at response of fast ion diagnostics to modulated beam[1,2]**
- **For low AE levels, measured waveform agrees with classical modeling**

1. Heidbrink et. al., NF 56 (2016)
2. C. Collins et. al., PRL 116 (2016)

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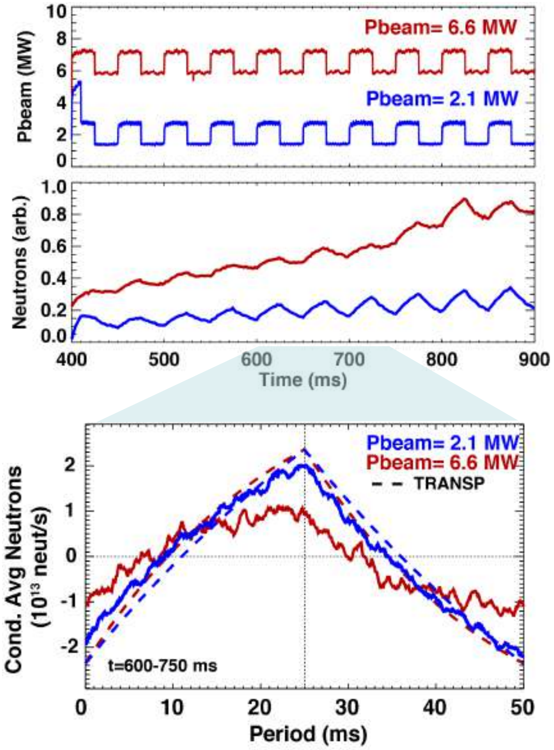
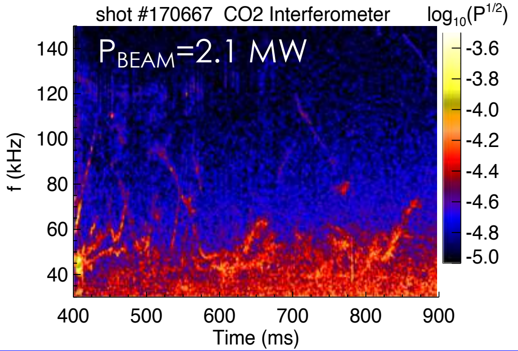
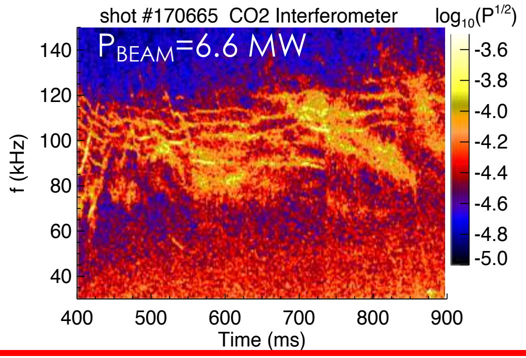






- **Technique looks at response of fast ion diagnostics to modulated beam[1,2]**
- **For low AE levels, measured waveform agrees with classical modeling**
- **Fast ion transport causes distortion of waveform**
- **From deviation can determine AE induced transport levels**

1. Heidbrink et. al., NF 56 (2016)
2. C. Collins et. al., PRL 116 (2016)

Transport Levels are Quantified Through Particle Balance

Measured time derivative of fast-ion signal, such as FIDA, Neutron, INPA

$$\frac{\partial \tilde{n}}{\partial t} = \tilde{S} - \frac{\tilde{n}}{\tau} - \nabla \cdot \tilde{\Gamma}$$

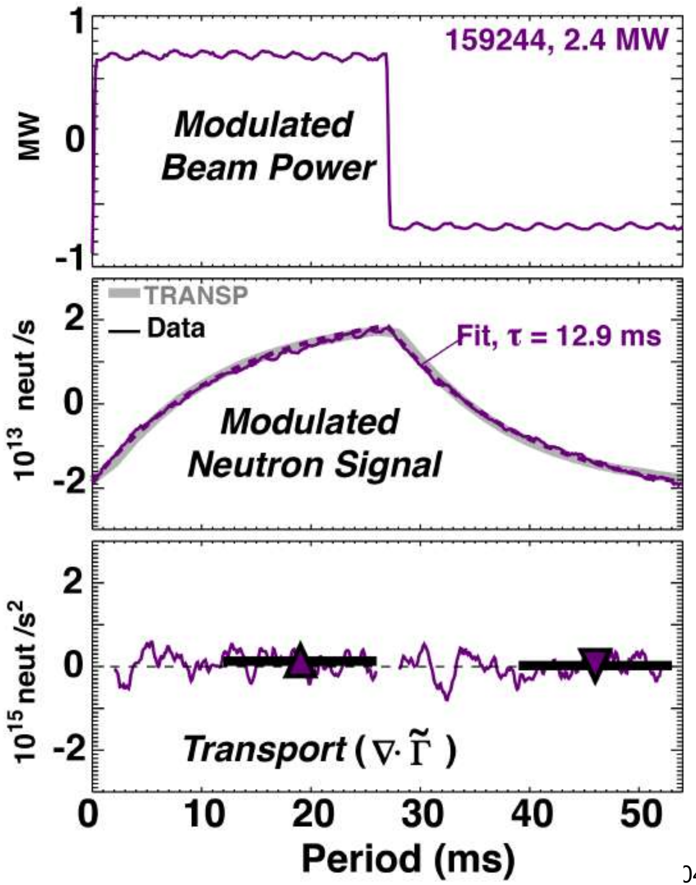
source (modulated beam)

Sink term (modulated particles thermalize)

Divergence of Flux (transport) due to interaction with AEs

$$\tilde{n} = \int\int\int \tilde{f}(\mathrm{E}, \mathrm{p}, \mathbf{x}) W(\mathrm{E}, \mathrm{p}, \mathbf{x}) d\mathrm{E} d\mathrm{p} d\mathbf{x}$$

NPAs weight the local phase space → Transport at local phase space



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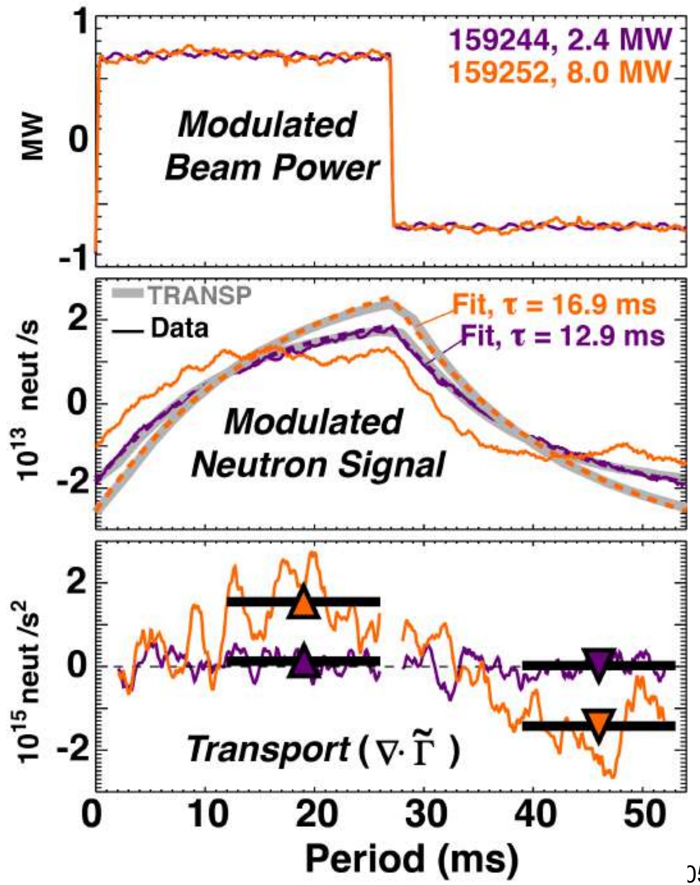
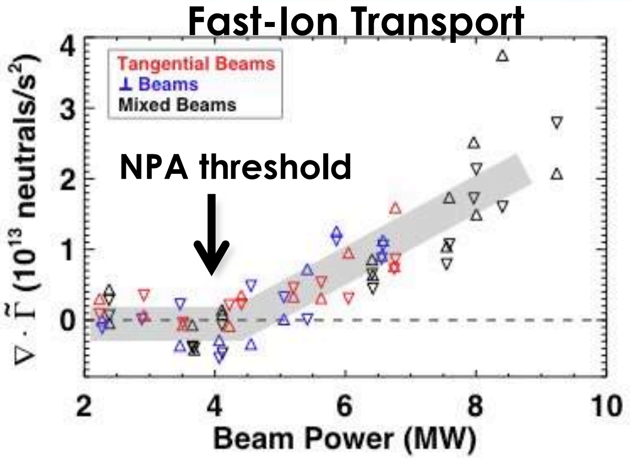
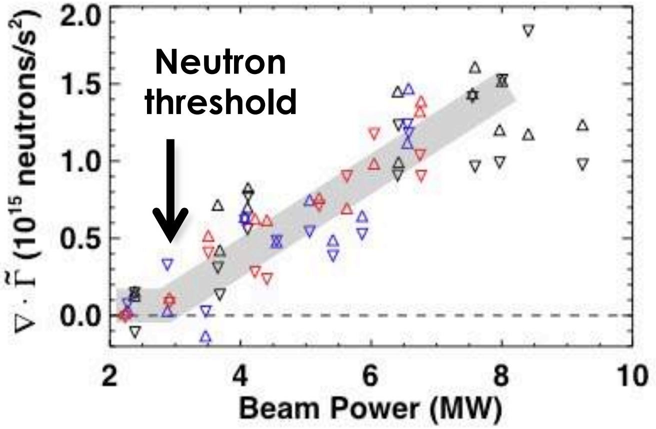


Technique Has Been Used to Show Variation in Threshold for Transport Between Various Fast-ion Diagnostics as Well as Scaling With Drive





- **Fast ion transport shows clear threshold in Beam Power (AE drive)**
- **Threshold depends on diagnostic**
  - A result of phase space sensitivity of each diagnostic

C.S. Collins et al 2017 NF 57 086005

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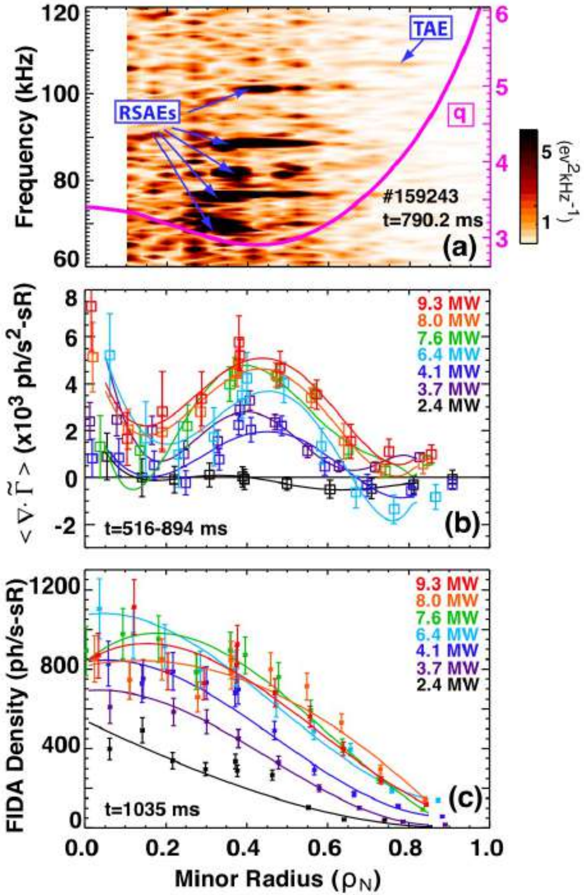
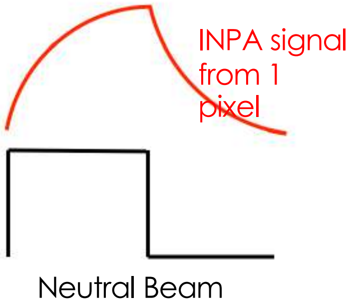


- **Fast ion transport shows clear threshold in Beam Power (AE drive)**
- **Threshold depends on diagnostic**
  - A result of phase space sensitivity of each diagnostic
- **Rapid increase in transport results in saturation of fast ion profile**

C.S. Collins et al 2017 NF 57 086005
C.S. Collins et. al., PRL 116 (2016)

Phase Space Resolved EP Transport is Obtained Using The INPA Combined With A Simplified Version of the Beam Modulation Technique

AT CERTAIN LOCAL PHASE SPACE (1 pixel of the INPA)



- **Modulate a neutral beam that populates the INPA interrogated phase space**

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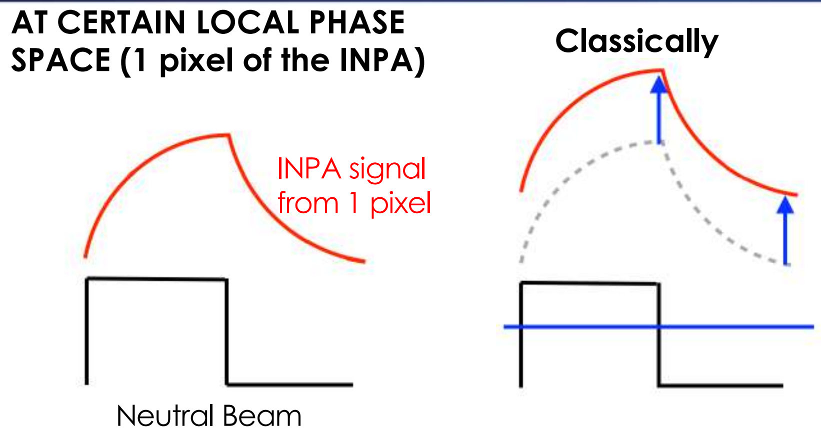
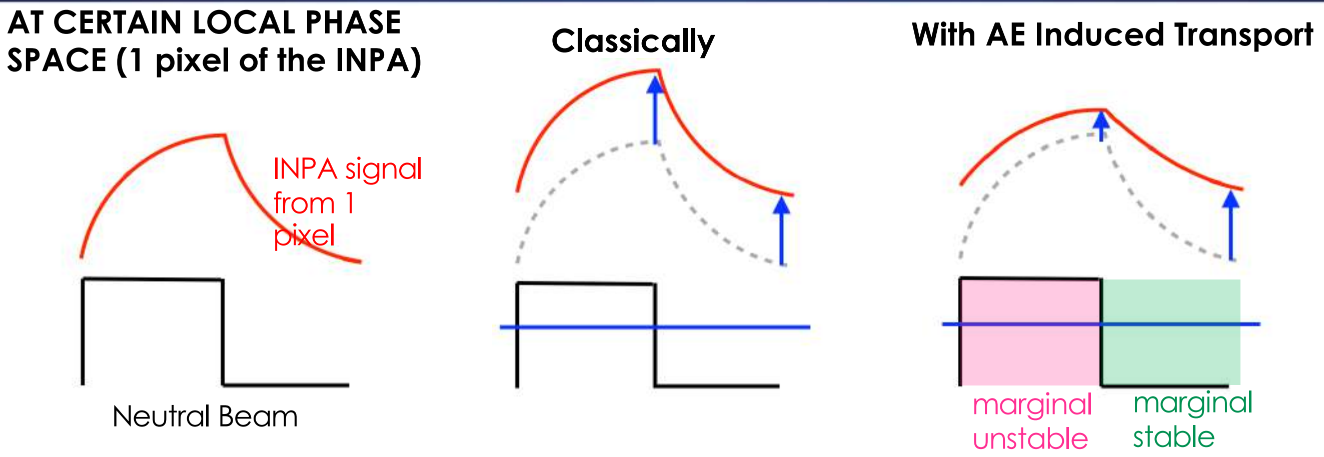


- **Modulate a neutral beam that populates the INPA interrogated phase space**
- **In next discharge, add a steady beam that populates same phase space.**
- **If plasma is away from an AE stability boundary,**
  - Modulated INPA signal will shift upward, based on the power of the steady beam

Phase Space Resolved EP Transport is Obtained Using The INPA Combined With A Simplified Version of the Beam Modulation Technique



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- **If the plasma is close to AE marginal stability boundary,**
  - AEs are destabilized during the on-period; stabilized during the off-period
  - Reduced increase reflects transport of fast ions from probed region phase space

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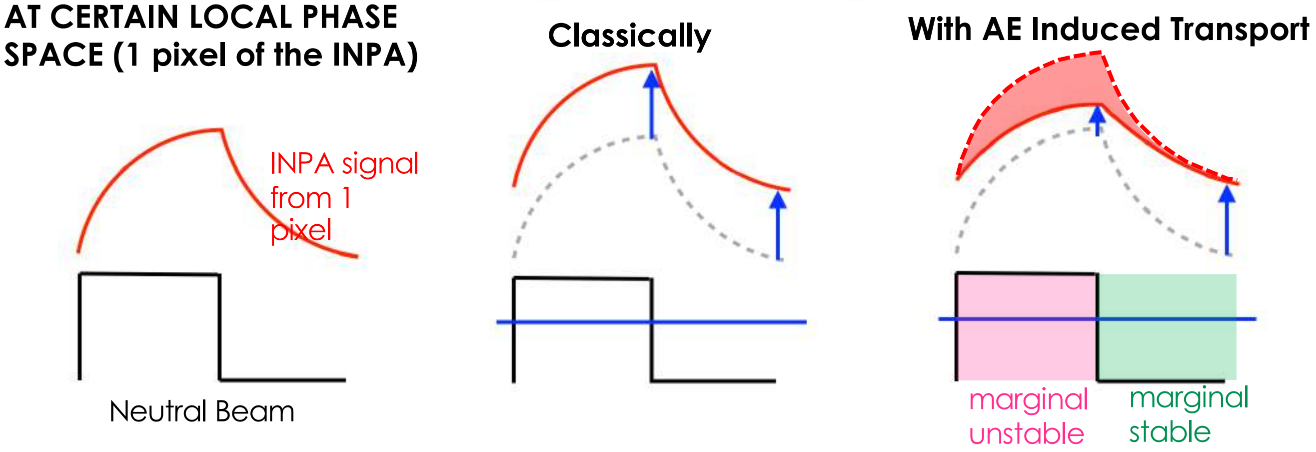

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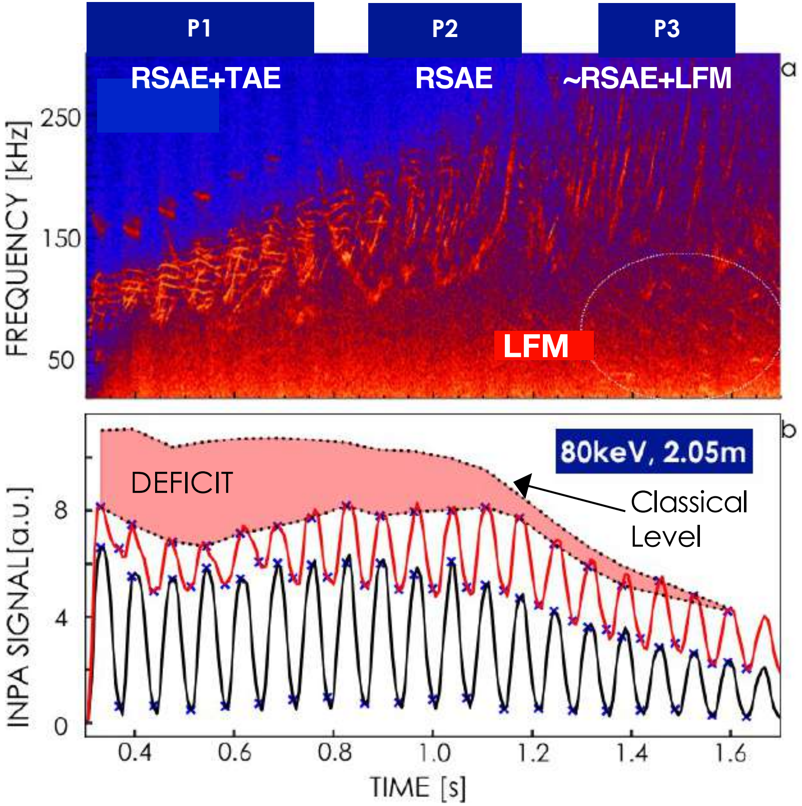
- **If the plasma is close to AE marginal stability boundary,**
  - AEs are destabilized during the on-period; stabilized during the off-period
  - Reduced increase reflects transport of fast ions from probed region phase space -> ***The difference is the measured fast ion transport***

Phase Space Behavior Can Largely Deviate From Classical Predictions When AEs Are Destabilized

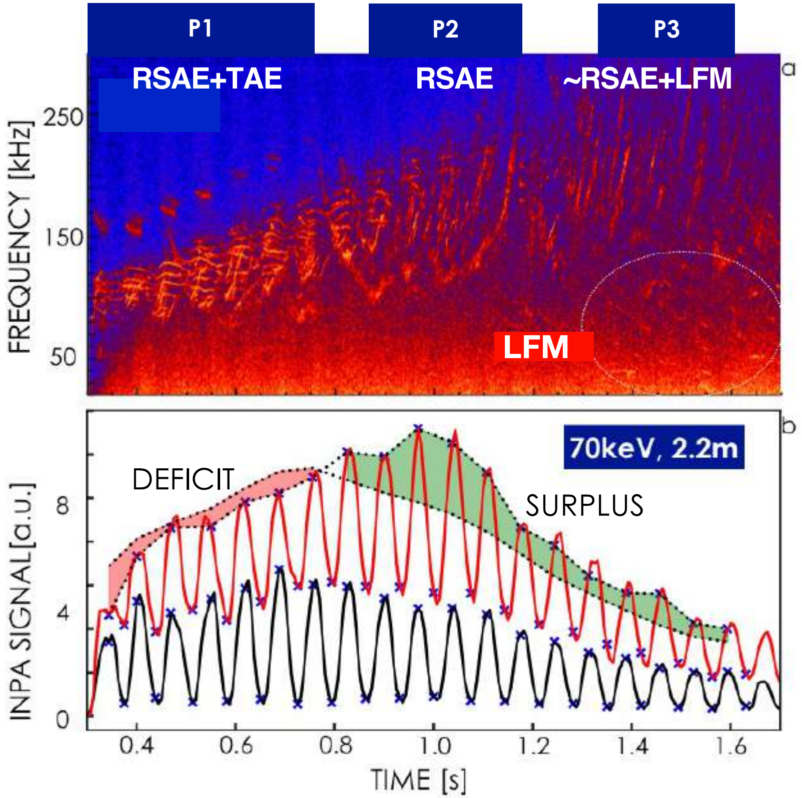


At 80kV and R=2.05m

- **P1: During the RSAE & TAE dominant phase**
  - Large transport at inj. energy
  - 80% signal from the steady beam missing
- **P2: RSAE dominant phase with weakened TAE**
  - Reduced transport at injection energy
  - 50% signal from the steady beam missing
- **P3: LFM dominant phase with weakened RSAE**
  - Reaches classical

X.D. Du et al 2023 Nucl. Fusion 63 046020

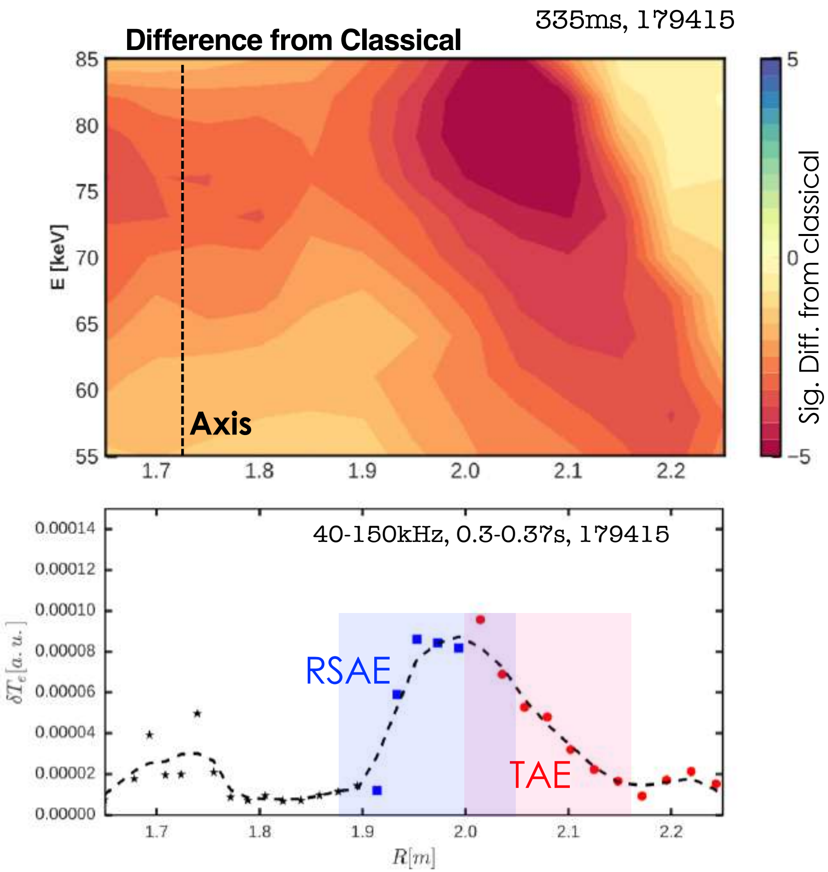
The Inferred Fast Ion Transport Can Vary Significantly Depending On The Interrogated Region of Velocity Space



At 70kV and R=2.2m

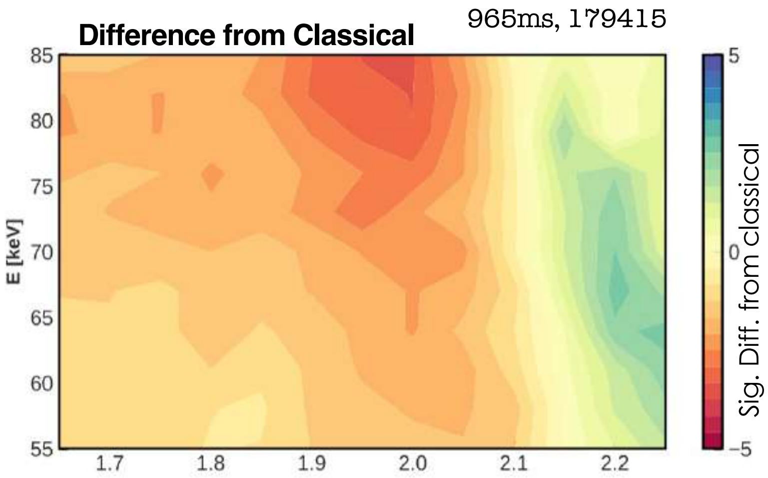
- **P1: During the RSAE & TAE dominant phase**
  - Small deficit at 70kV and R=2.2m
- **P2: RSAE dominant phase with weakened TAE**
  - *Signal exceeds the classical expectations*
- **P3: LFM dominant phase with weakened RSAE**
  - Nearly classical

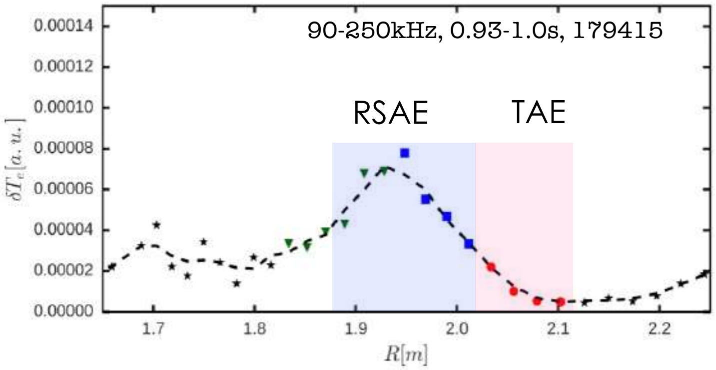
A Phase Space Map Of The Fast Ion Transport at 10^4 Different Points Due To Different Modes Can Be Obtained



- **The plasma is dominated by a combination of RSAE and TAE**
  - RSAE, R~1.9 - 2.0m
  - TAE, R~2.05 - 2.1m
  - TAE and RSAE overlap at

Evolution Of The Phase Space Transport Map Is Consistent With The Change In AE Activity

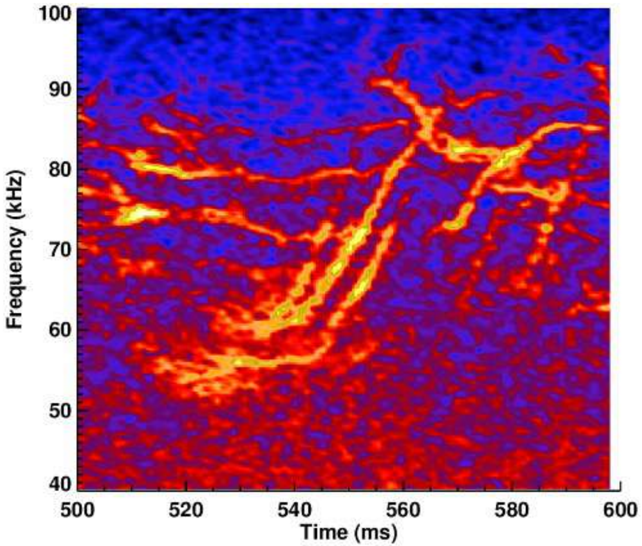




- **The plasma is dominated by the RSAE**
  - TAE amplitude is reduced
- **The transport region moves inward with q_{min}**
  - Significant transport aligns with the RSAE locations
- **A portion of phase space outside R~2.1m now exceeds classical levels**
  - Clear redistribution in phase space is observed
- **The transport in the plasma core R~1.7m is reduced**

Now, An Example of Putting It Together….

ECE and ECEI Data Combined With FILD Are Used to Identify Primary Modes



- **Many RSAEs and TAEs observed by ECE and other diagnostics**

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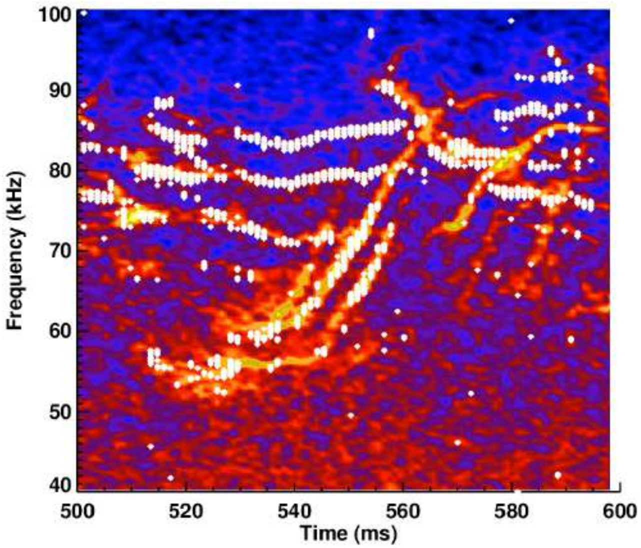

- **Many RSAEs and TAEs observed by ECE and other diagnostics**
- **White points represent modes with significant coherence between several adjacent ECE channels and FILD (*these are the modes that cause fast ion loss*)**

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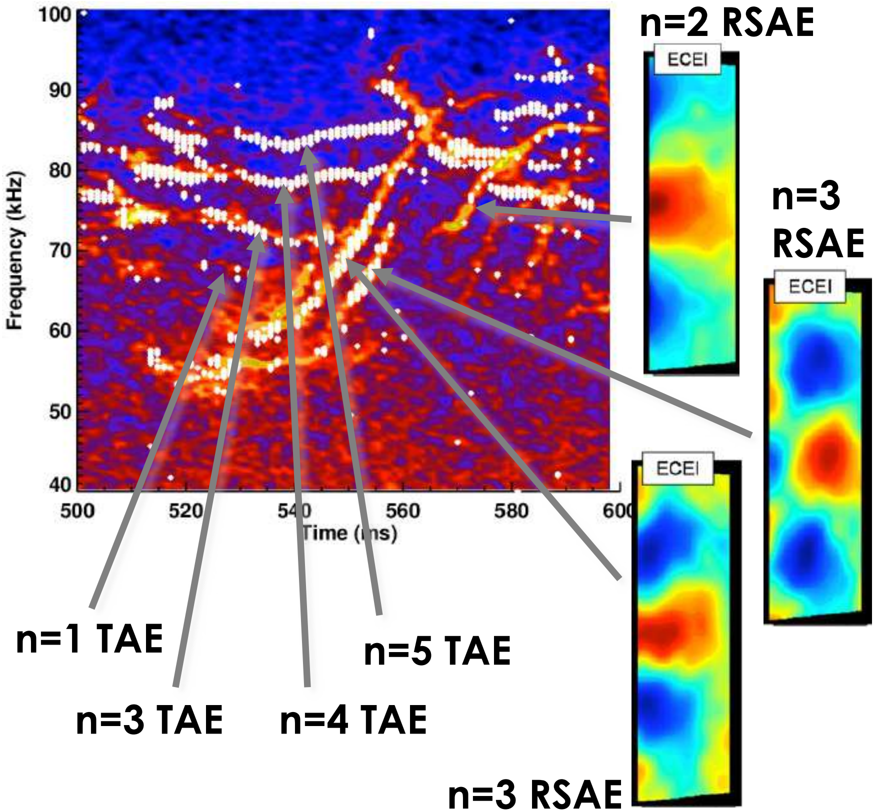
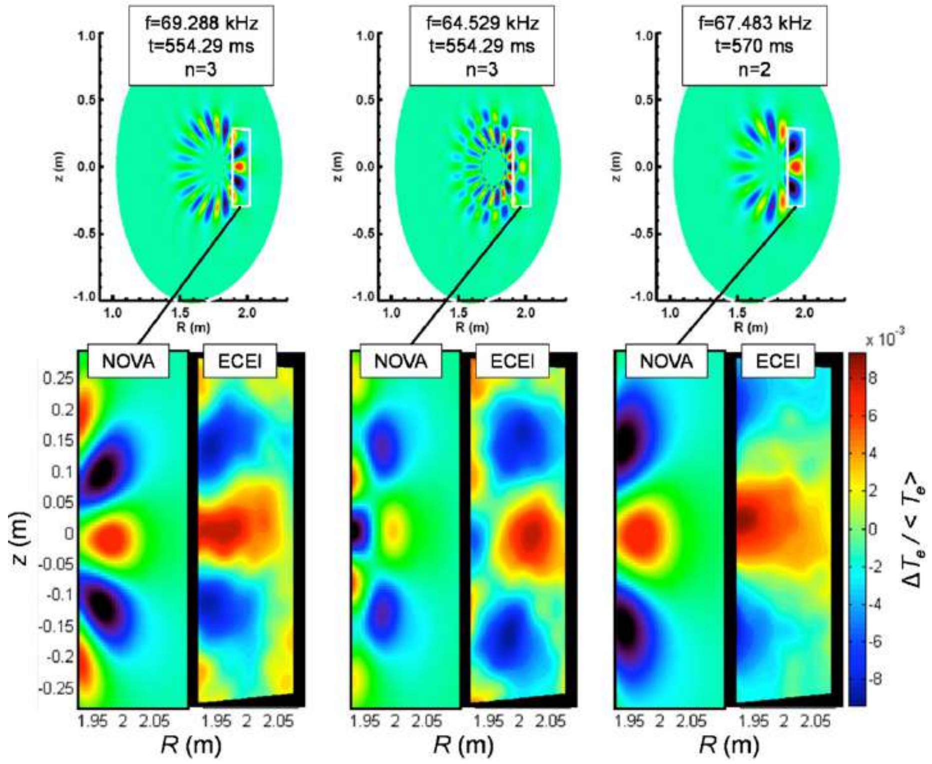


- Many RSAEs and TAEs observed by ECE and other diagnostics
- White points represent modes with significant coherence between several adjacent ECE channels and FILD (*these are the modes that cause fast ion loss*)
- *n* is determined from magnetics and ECEI/BES give *m*

NOVA* Calculated Eigenmodes are Selected Based on Mode Type and Match to ECE and ECEI Data

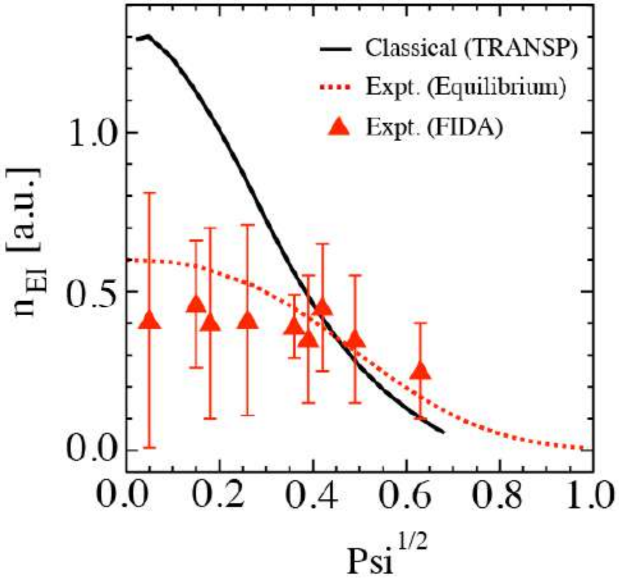


- **NOVA* solves for linear ideal MHD eigenmodes using experimentally measured profiles**
- **δT_e is used to determine experimental amplitude**

*Cheng CZ, *Phys. Rep.* **211**, 1 (1992)
B.J. Tobias, et.al., PRL

Simple Modeling Reproduced Measured EP Transport

~Fast Ion Density



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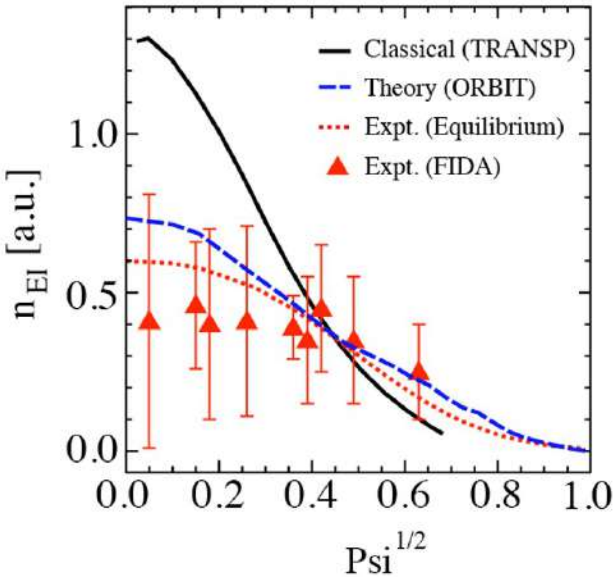

*R.B. White,et.al., Phys. Plasmas 17, 056107 (2010)

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- **Orbit following was carried out in presence of:**
  - NOVA calculated eigenmodes with amplitudes from ECE and ECEI
  - Scattering / drag
  - Fueling
- **Simulations were able to resove the measured flattening of the fast ion profile!**
  - Cause was resonance overlap of multiple small amplitude modes

Simple Modeling Reproduced Measured EP Transport

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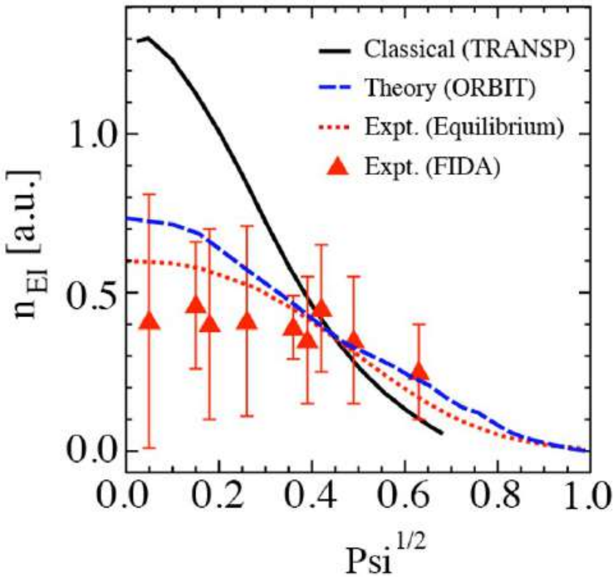

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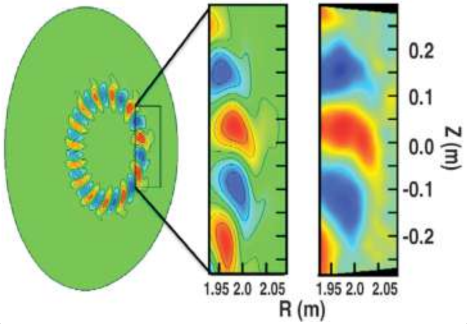
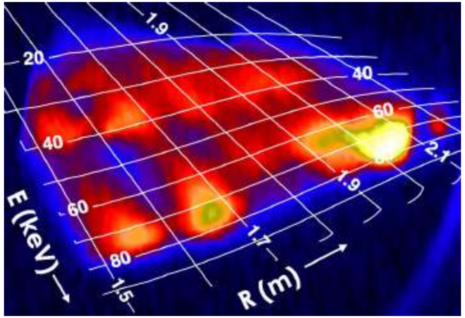
The End

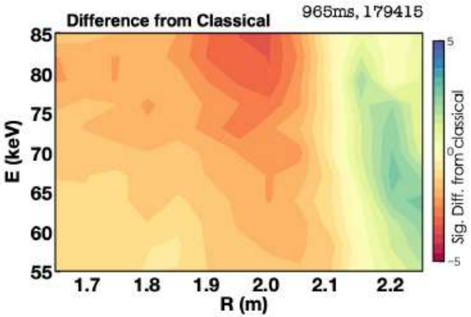
Measurement of Instabilities



Measurement of Confined Fast Ions



Measurement of Instability Impact



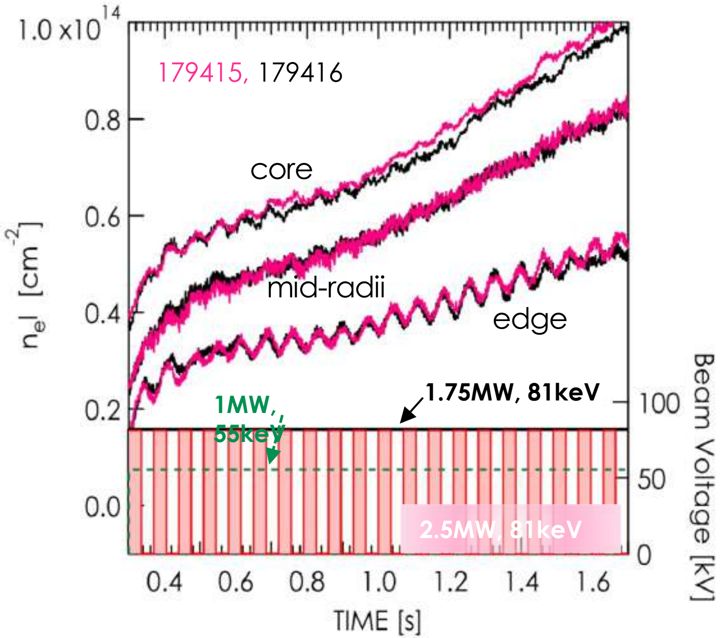
- Perturbed quantities
- Spectral analysis and pulling small signals out of noise
- Fluctuation diagnostics (Interf., Polarimetry, ECE, BES, Reflectometry, SXR)

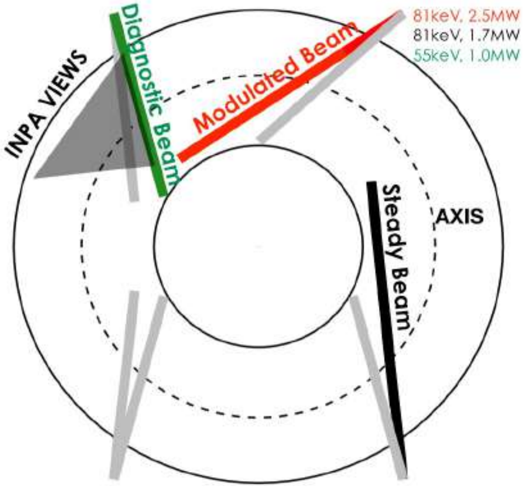
- DD Beam-Plasma neutrons
- Neutral Particle Analyzers (NPA, INPA)
- Equilibrium pressure

- Abrupt events / relative measurements
- Quantitative / absolute measurements
- Example putting it all together

EXTRA

A Well-Matched Density Profile In Low-Power And High-Power Discharges Is Important For Simplified Interpretation of This Beam Modulation Experiment

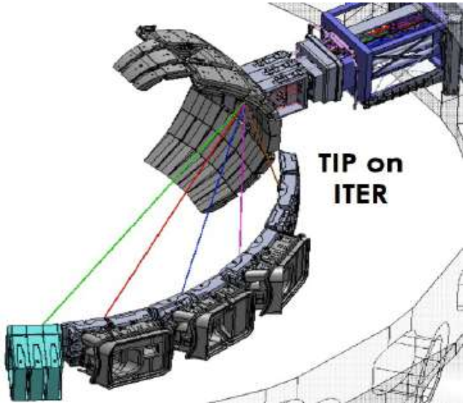


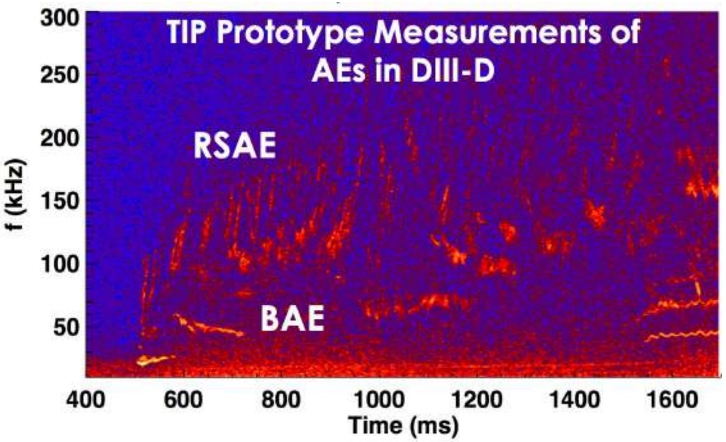


- **Low power, 1MW 55kV Diagnostic beam (provides neutrals for charge exchange) held steady**
  - It does not populate the interrogated phase space of the INPA
- **Modulated beam and *Steady beam* populate the same phase space**
  - Modulated beam: 2.5MW, 81keV
  - Steady beam: 1.7MW, 81keV
- **Density profile well matched from 0.3s to 1.7s – *Critical, otherwise slowing down doesn't match***

ITER Interferometer Prototype Shows Diagnostic Should Be Sensitive Monitor of Core Instabilities

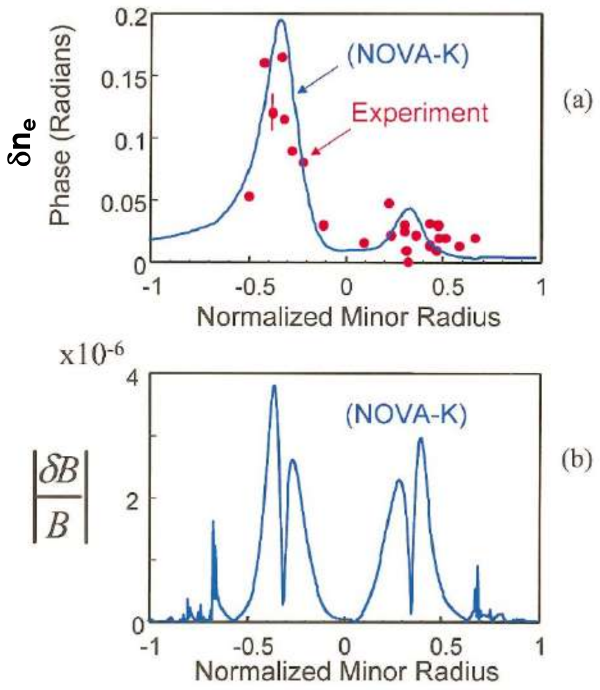
- **Toroidal Interferometer Polarimeter (TIP)**
  - ~500kHz bandwidth, 5 tangential chords spanning midplane
  - Prototype shows encouraging results on DIII-D. Likely can detect AEs with $\delta n/n \sim 10^{-5}$+
  - Will work independent of magnetic field, density, etc.





M.A. Van Zeeland, et.al., RSI, 89, 10B102 (2018)

Primary Quantities Measured in Core are Perturbed Temperature and Density



$$\frac{\delta\rho}{\rho} = -\nabla\cdot\xi - \xi\cdot\frac{\nabla\rho}{\rho} \cong \left(\frac{-2\hat{\mathbf{R}}}{R} + \frac{\hat{\mathbf{n}}}{L_\rho}\right)\cdot\xi,$$

- **Perturbed field leads to field line and flux surface displacement (ξ)**
- **Localized measurements see fluctuating quantites proportional to gradient**
- **Perturbed kinetic profiles have displacement and compressional contributions**

Electron Density

$$\frac{\delta n_e}{n_e} = -\nabla\cdot\xi - \xi\cdot\frac{\nabla n_e}{n_e}$$

Electron Temperature

$$\frac{\delta T_e}{T_e} = -(\gamma-1)\nabla\cdot\xi - \xi\cdot\frac{\nabla T_e}{T_e}$$

- **Relative contribution of each depends on mode properties and structure**
  - Can make a cylindrical mode appear anti-balloning