MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

ASDEX Upgrade

Drift wave nature of the Weakly Coherent Mode on ASDEX Upgrade

M Herschel[1,2,3], T Happel[2], D Wendler[1,2], M Griener[2], J Kalis[1,2], P Manz[4], U Stroth[1,2], The ASDEX Upgrade Team[a]

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I-mode: Improved energy confinement mode

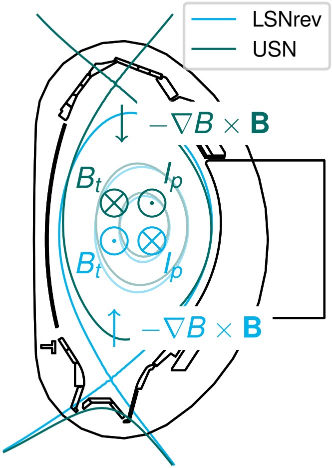
ELM-free confinement regime

“Recipe” for I-mode:

- Strong enough heating
- Unfavorable magnetic configuration

Configurations at ASDEX Upgrade:

- LSNrev: Lower Single Null with reversed I_p, B_t
- USN: Upper Single Null



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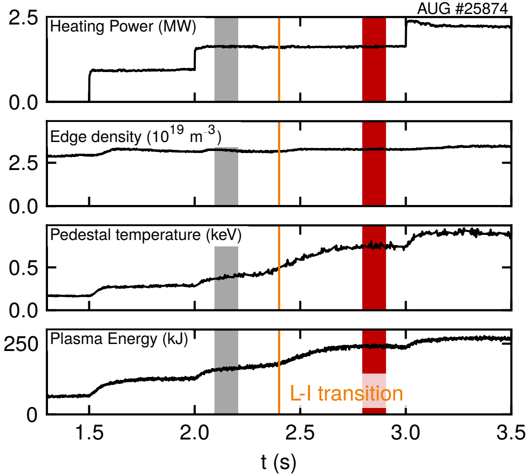

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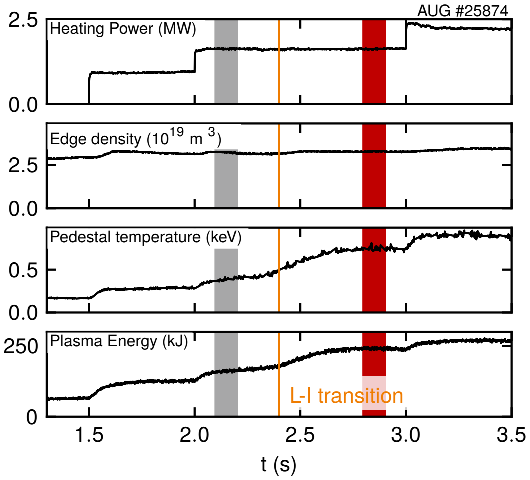

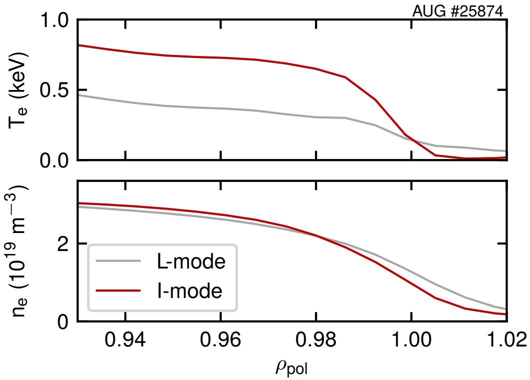

Pedestal only in temperature

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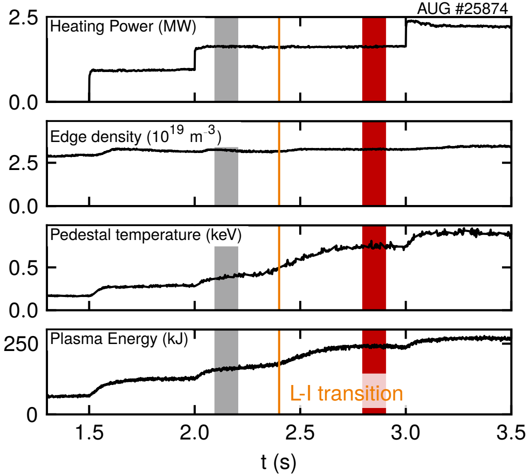
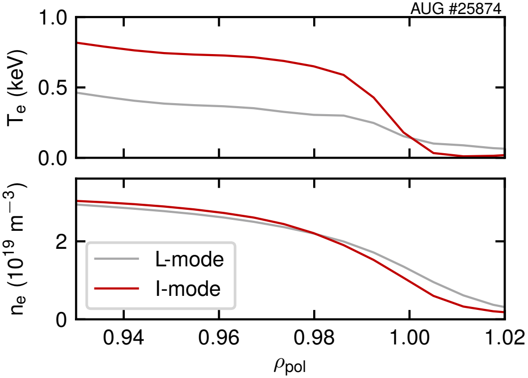




Pedestal only in temperature

Unusual, unlike other regimes

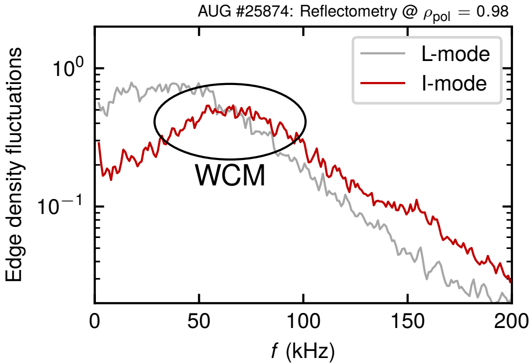
Weakly Coherent Mode

- Reduction in low frequency turbulence
- Appearance of weakly coherent mode (WCM)

WCM often suspected to cause unusual edge transport in I-mode

Origin of the WCM?

WCM responsible for I-mode?



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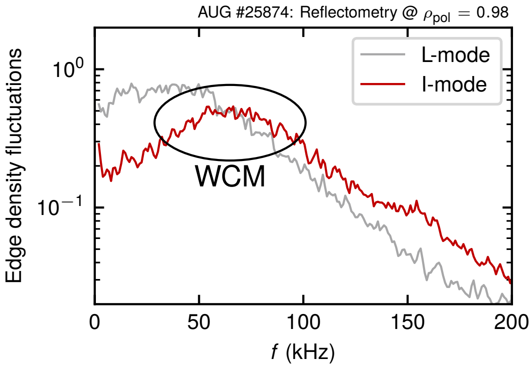

Underlying instability?

Instability	Drive	Propagation	Scale	$\alpha_{\phi,\tilde{p}}$
IPM	$J_{\|\|}$	n.p.	$k_\theta \rho_s \ll 0.1$	
(I-R)BM	∇p	n.p.	$k_\theta \rho_s < 0.1$	$\pi/2$
KBM	$\nabla T_{e,i}$	i dia.	$k_\theta \rho_s \sim 0.1$	$\pi/2$
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[Manz 2018 Habil.]

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$\Rightarrow$ Look at phase velocity: $v_{\text{lab,WCM}} = v_{E\times B} + v_{\text{ph,WCM}}$

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$\Rightarrow$ Look at phase velocity: $\underbrace{v_{\text{lab,WCM}}}_{\text{Helium Beam @ } 0.5\,\text{cm}^{-1}} = \underbrace{v_{E\times B}}_{\text{Doppler @ } 10\,\text{cm}^{-1}} + v_{\text{ph,WCM}}$

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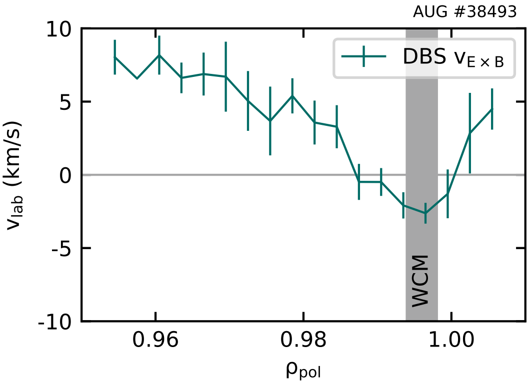
Velocity profiles

- Experimentally:

$$v_{\text{phase}} = v_{\text{lab,WCM}} - v_{E\times B}$$



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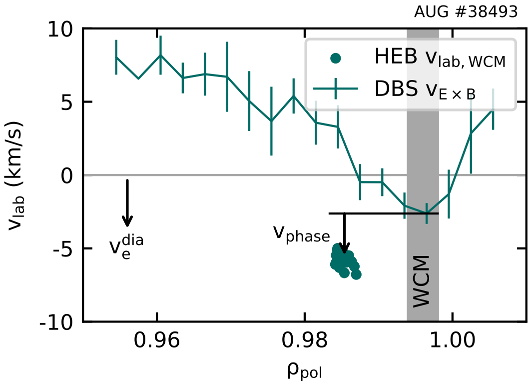

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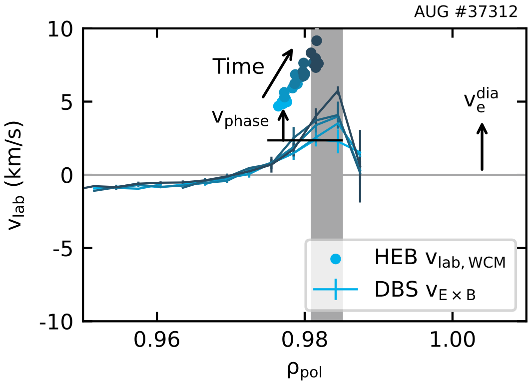
- Found in USN and LSNrev



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Remaining instabilities "drift-wave-like", as in simulations

Liu et al 2016 Phys. Plasmas 23 120703
Manz et al 2020 Nucl. Fusion 60 096011
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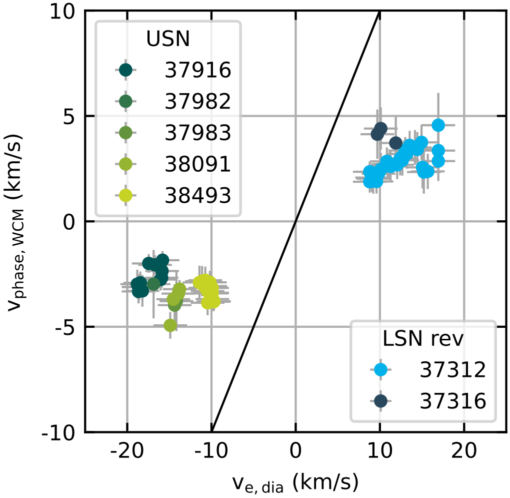

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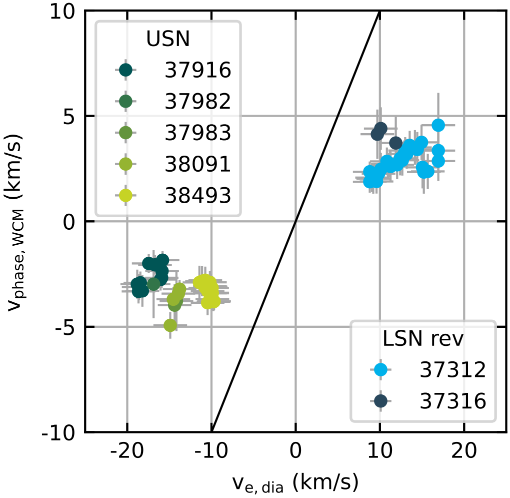
But: theory can help us!



Excursion: our current understanding of I-mode

Unfavorable
∇B-drift

Strong heating

Manz et al 2020 Nucl. Fusion

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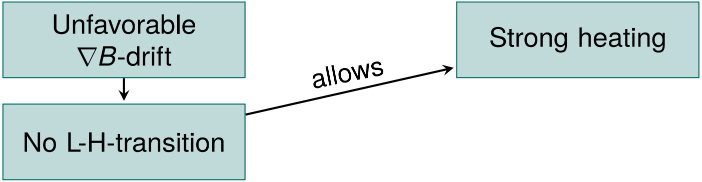

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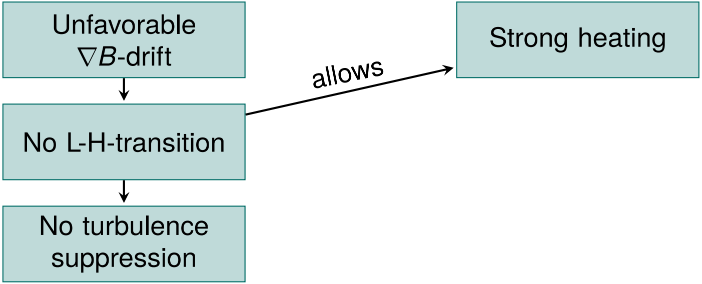

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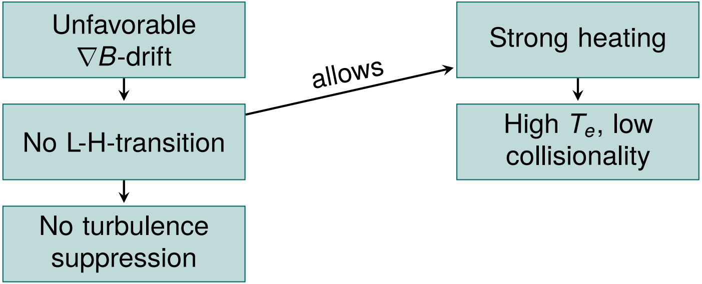

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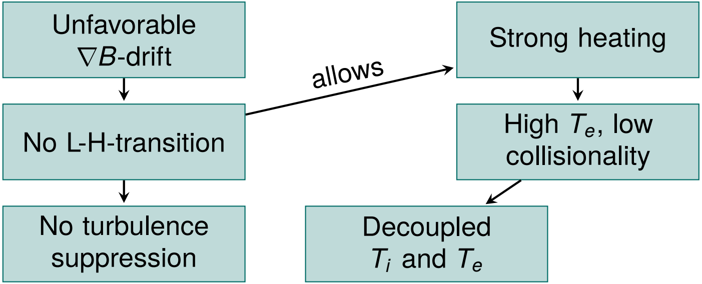

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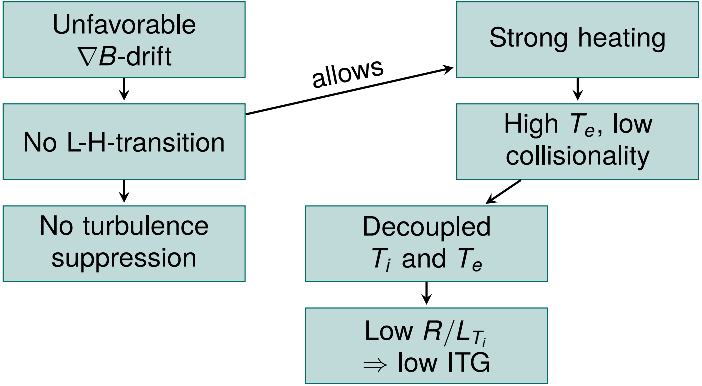

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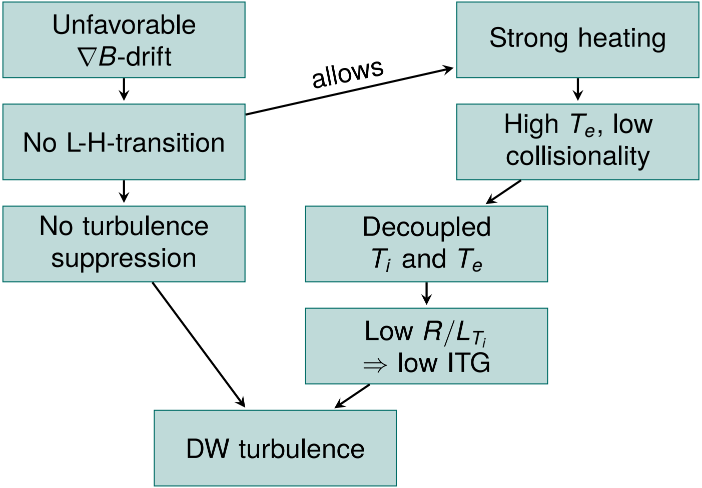

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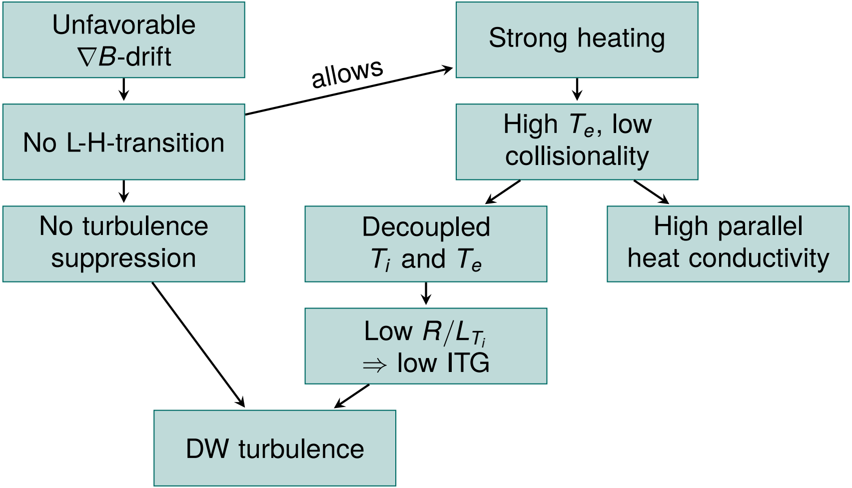

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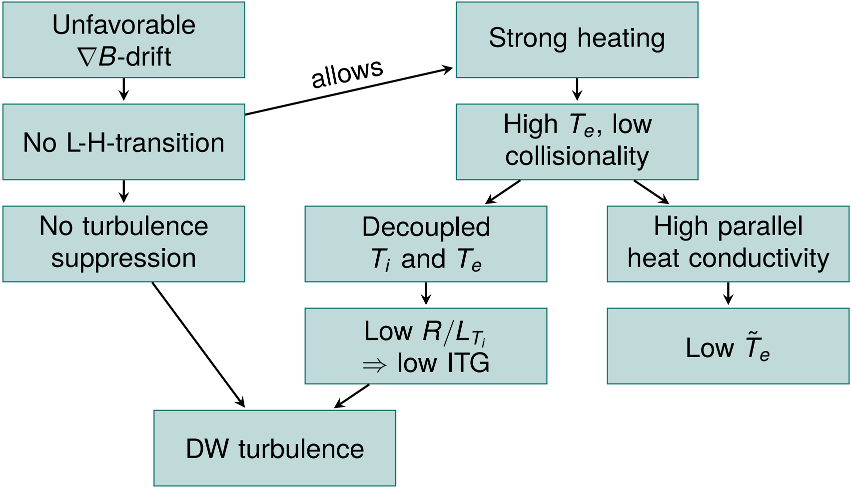

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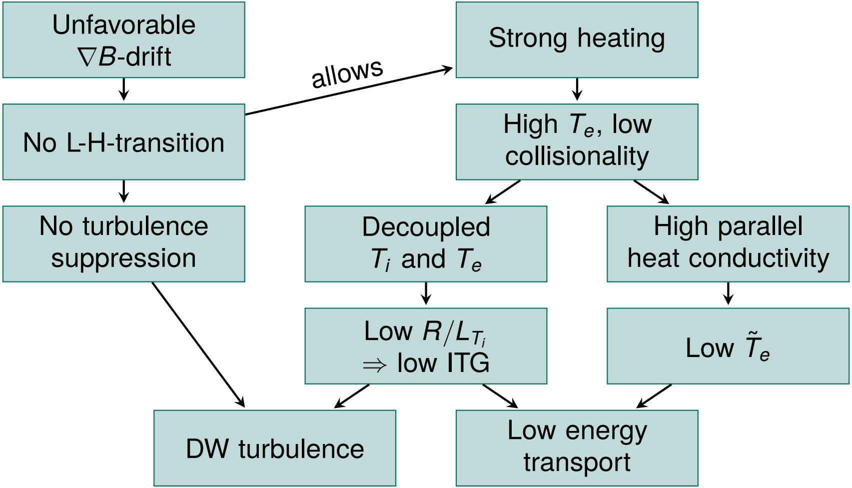

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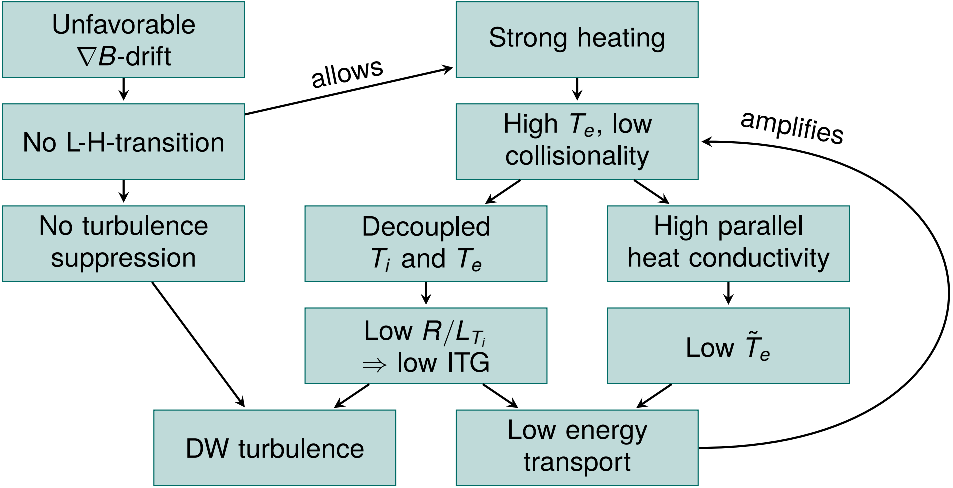

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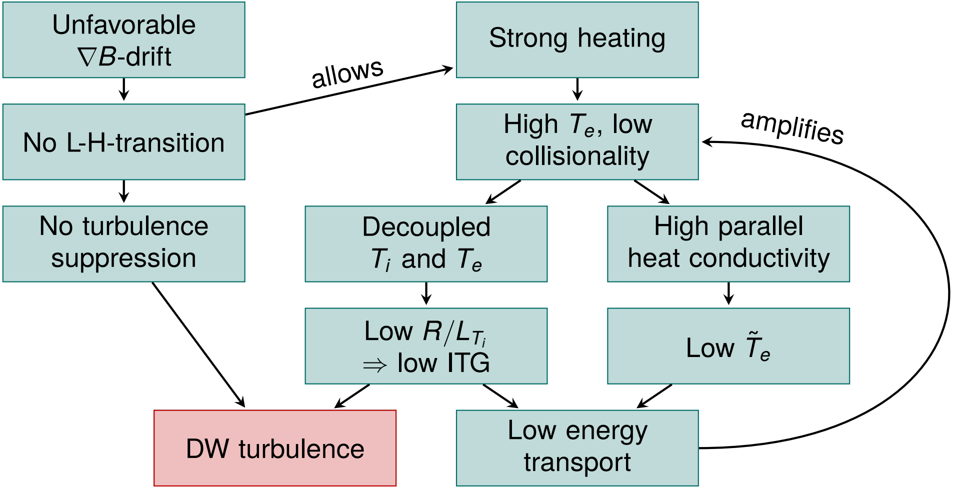

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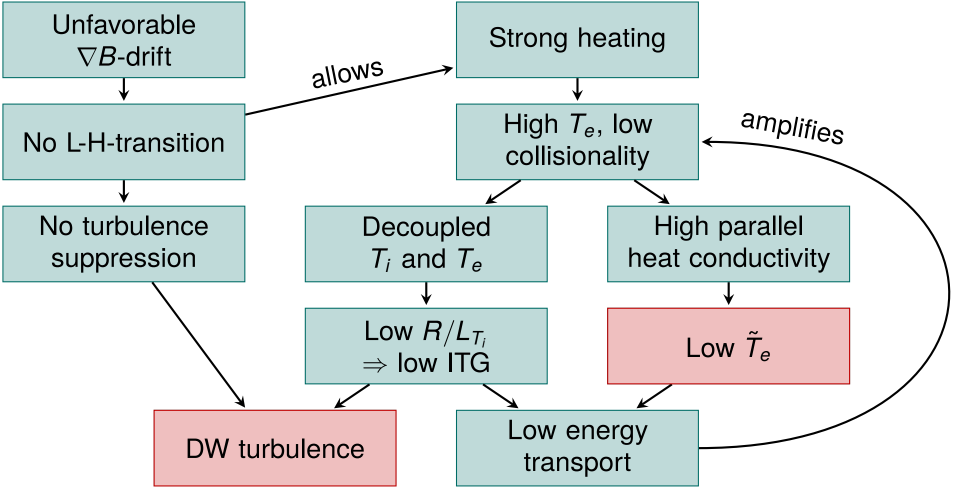

Manz et al 2020 Nucl. Fusion

Impact of temperature fluctuations

- Boltzmann's law in drift wave theory:

$$\frac{e\tilde{\Phi}}{T_e} = \frac{\tilde{n}}{n_0} + \frac{\tilde{T}_e}{T_{e,0}}$$

- Drift wave phase velocity:

$$v_{\mathrm{ph,DW}} = \frac{T_e}{eB}\left(\frac{1}{L_n} + \frac{1}{L_T}\right)$$

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Negligible temperature fluctuations decrease v_{ph}

Comparison to experimental phase velocity II

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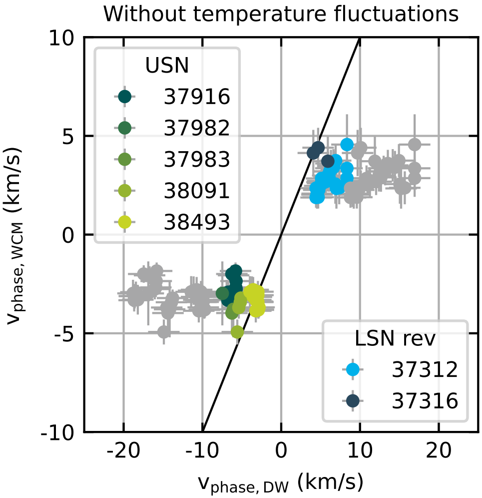

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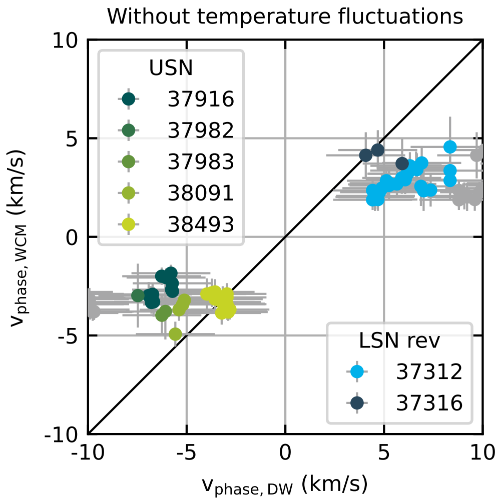

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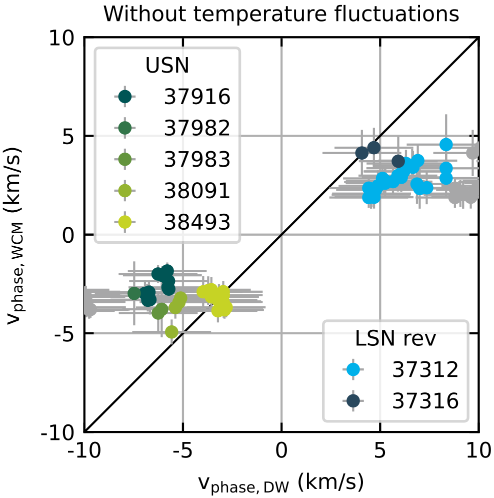
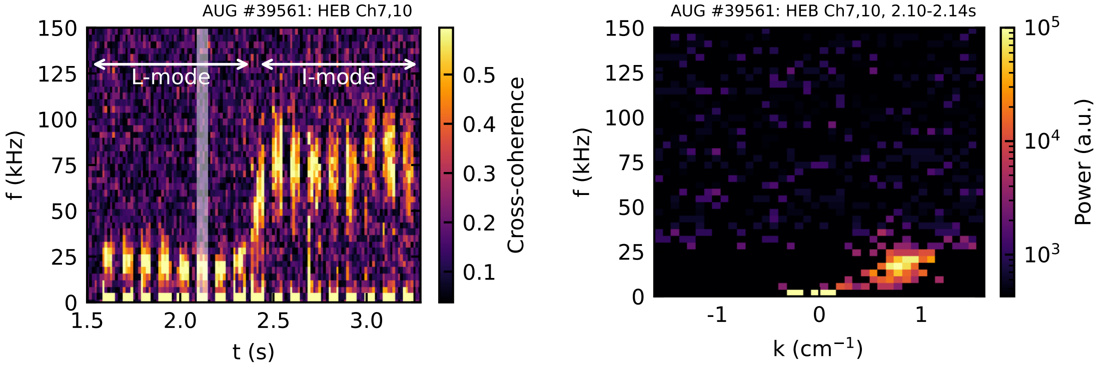
Various uncertainties:

- Instability type (DW, TEM, MTM)
- Cross-phases $\alpha_{\phi,\tilde{n}}$ and $\alpha_{\phi,\tilde{T}_e}$
- v_{phase} in Doppler



Our current understanding of WCM



L-mode WCM visible in coherence diagnostic

Happel et al 2019 NME
Bielajew et al 2022 Phys. Plasmas

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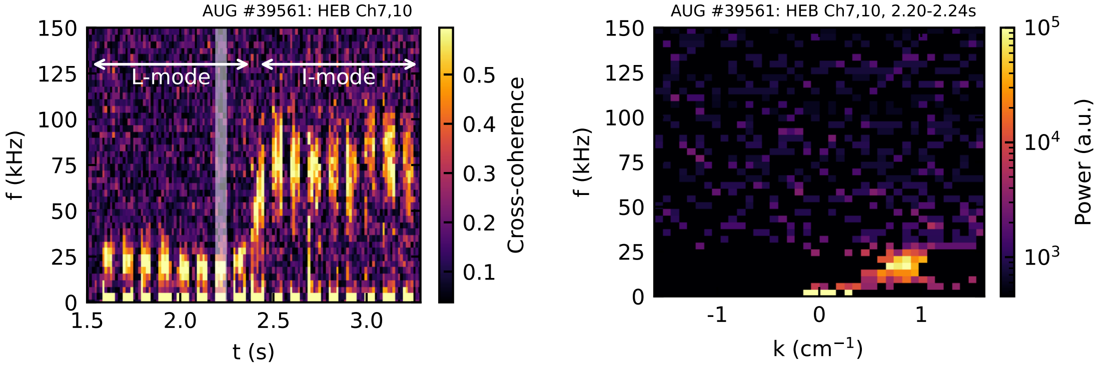

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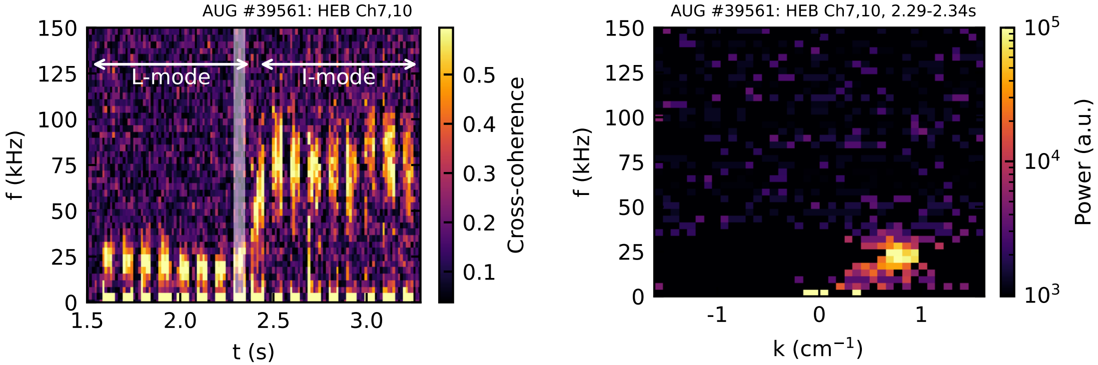

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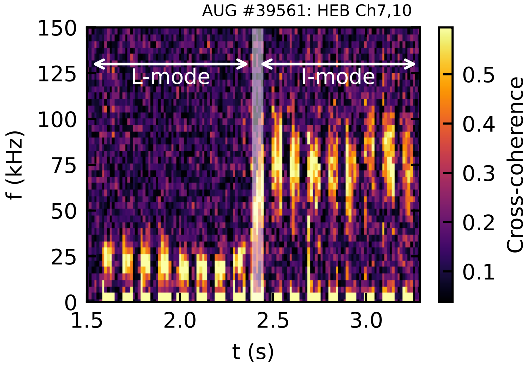

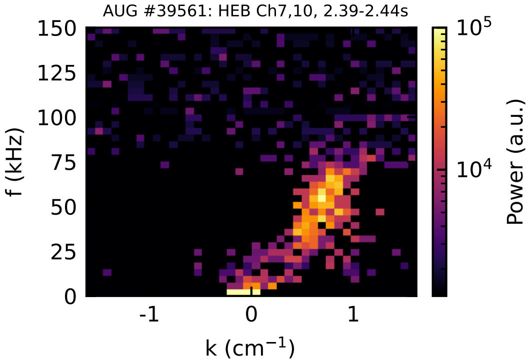

L-mode WCM visible in coherence diagnostic

Happel et al 2019 NME
Bielajew et al 2022 Phys. Plasmas

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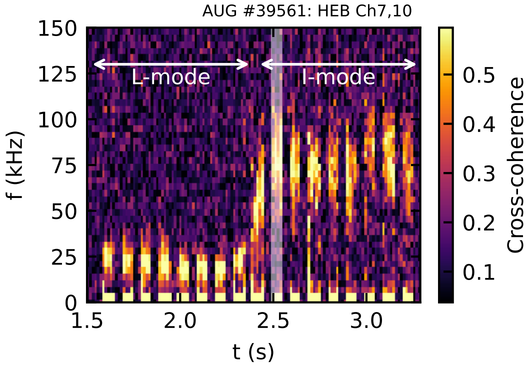

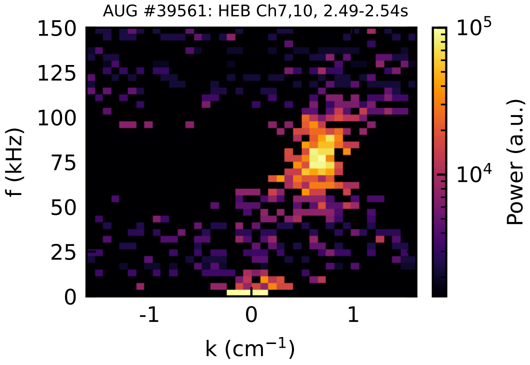

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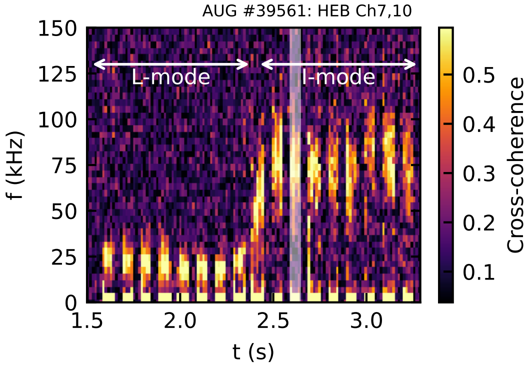

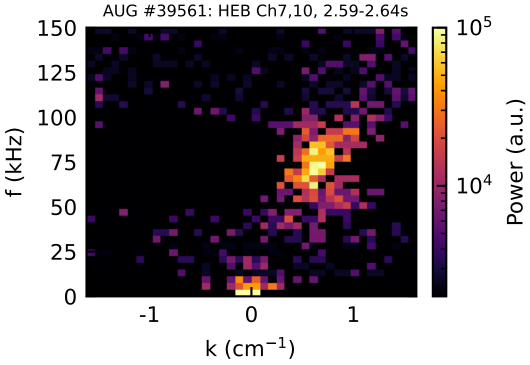

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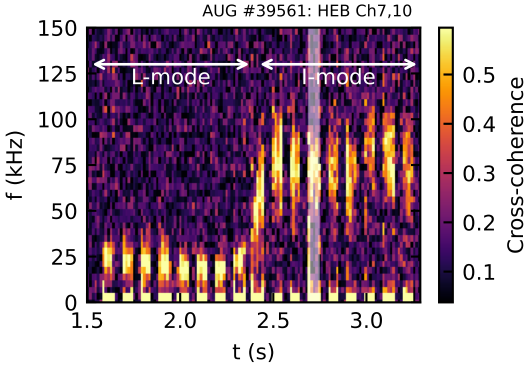

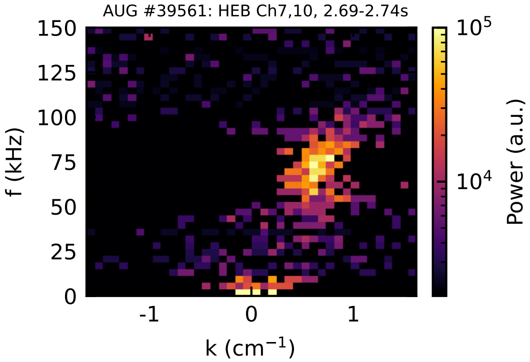

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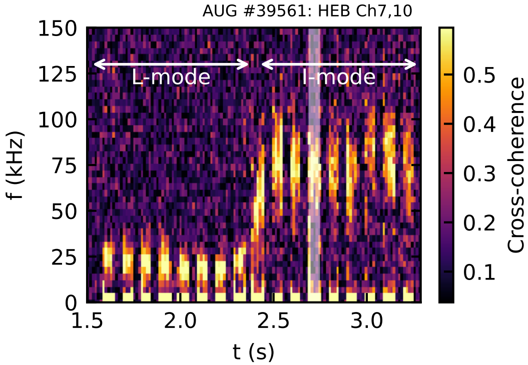

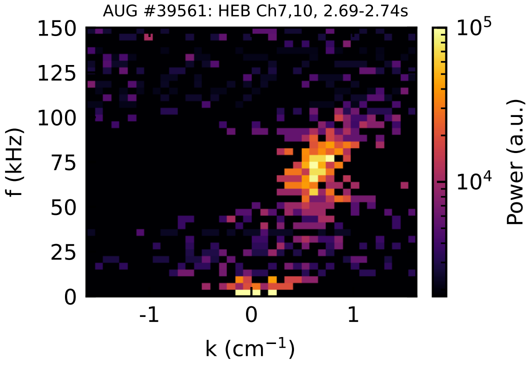

$$\underbrace{f_{\mathrm{WCM}}}_{\nearrow \text{ at L-I-transition}} = \frac{1}{2\pi} \underbrace{k_{\mathrm{WCM}}}_{\searrow} \left(\underbrace{v_{E\times B}}_{\nearrow} + \underbrace{v_{\mathrm{ph,WCM}}}_{\nearrow} \right)$$

Prediction for WCM frequency

- Only I-mode plasma considered (yet)
- Use fixed k_{WCM} to estimate f_{WCM}:

$$f_{\mathrm{WCM}} = \frac{1}{2\pi} k_{\mathrm{WCM}} \underbrace{\left(v_{E\times B} + v_{\mathrm{ph,\,DW}}\right)}_{v_{\mathrm{lab,\,DW}}}$$

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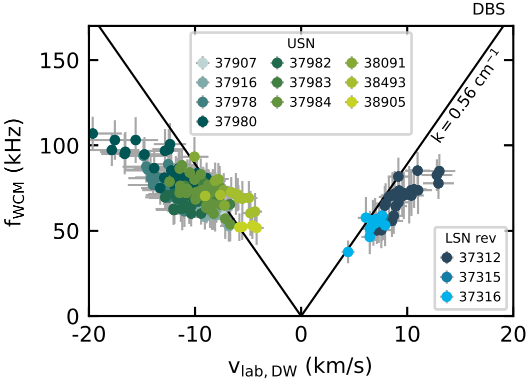
- Predicts f_{WCM} in most cases



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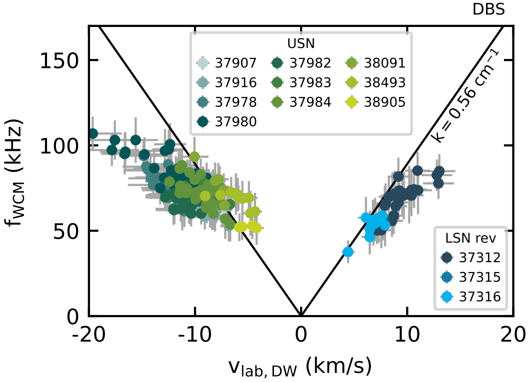
- Predicts f_{WCM} in most cases
- L-I-transition: future work



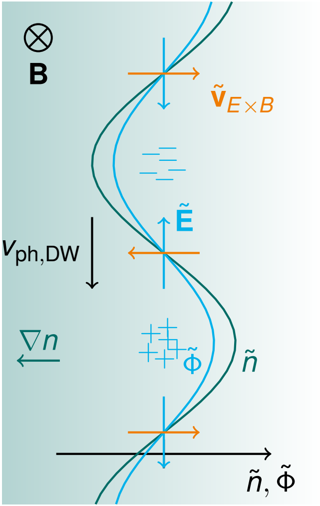
Summary

- WCM matches drift wave with low $\tilde{T}_e$
- Consistent with current understanding of I-mode
- WCM appears in I-mode due to acceleration in lab frame
- Transport caused by WCM not directly measured

Outlook:

- Hopefully measurements with Langmuir probes
- Simulations with GRILLIX
- Comparison with C-Mod data envisioned

Ideal drift wave



- For simplest drift wave: ∇n, $\mathbf{B}$, $\tilde{n}$
- Electrons react fast to density perturbation:

$$\frac{\tilde{n}}{n_0} = \frac{e\tilde{\Phi}}{T_e}$$

- Cross-phase between $\tilde{n}$ and $\tilde{\Phi}$ zero
- Electric and magnetic field $\Rightarrow \mathbf{v}_{E\times B}$
- Perturbation propagates:

$$v_{\mathrm{ph,DW}} = \frac{T_e}{eL_nB}$$

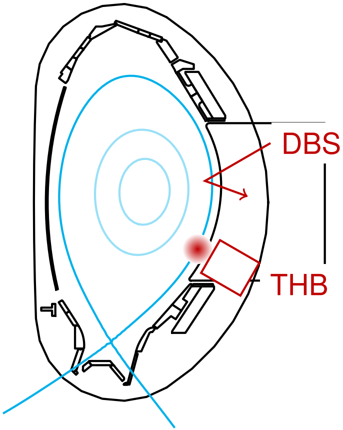
Diagnostics

Edge diagnostics used here:

- Thermal Helium Beam (THB)
- Doppler Back-Scattering (DBS)

Procedure (not covered here):

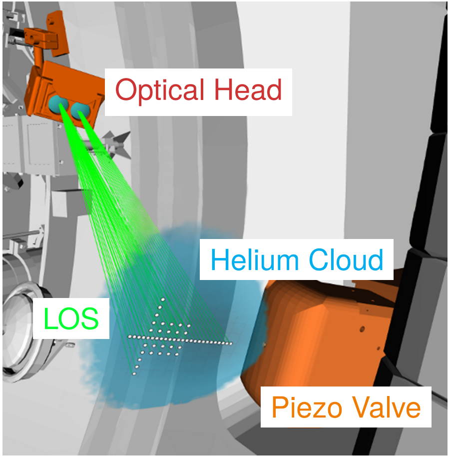
- Setup up database of I-mode shots
- Automatically scan diagnostics for WCM
- Filter database to remove noisy data



Diagnostics: Thermal Helium Beam

- Spectroscopic diagnostic
- Small cloud of helium puffed
- Measure line radiation at many lines-of-sight
- Cross-coherence
  $\Rightarrow f_{\text{WCM}}, k_{\text{WCM}}$
  $\Rightarrow v_{\text{lab,WCM}}$
- Measures at WCM scales ($k_{\text{WCM}} \approx 0.5\,\text{cm}^{-1}$):

$$v_{\text{lab,WCM}} = v_{E\times B} + \underbrace{v_{\text{ph}}(k_{\text{WCM}})}_{v_{\text{ph, WCM}}}$$

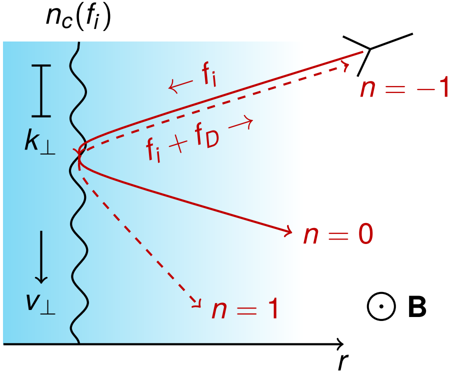


Diagnostics: Doppler Back-Scattering

- Microwave beam scatters at turbulence
- Signal returns Doppler-shifted
- Measures at small scales ($k_\perp \approx 10\,\mathrm{cm}^{-1}$):

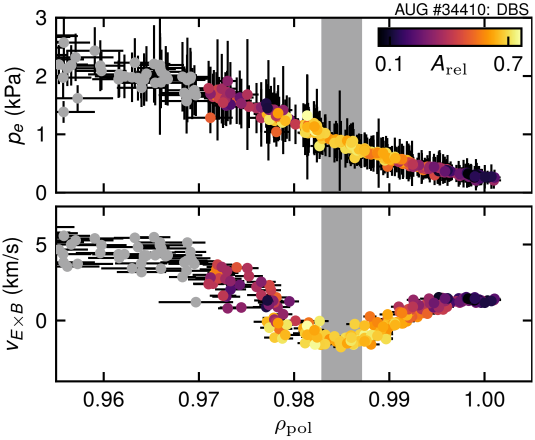
$$v_\perp = v_{E\times B} + \underbrace{v_{\mathrm{ph}}(k_\perp)}_{=0 \text{ at } k_\perp}$$

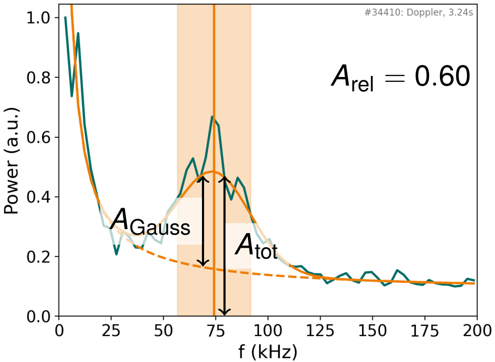
- Incident frequency can be hopped $\Rightarrow$ Radial scan
- Indirectly picks up f_{WCM}



$k_\perp$ given by Bragg's law

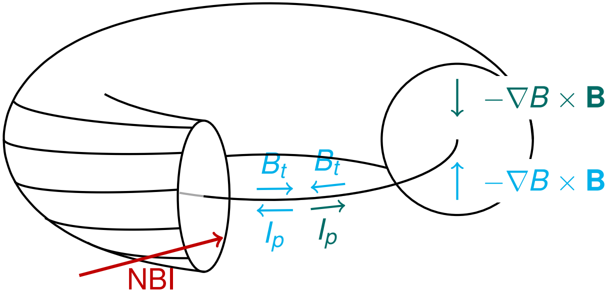
Experimental approach: Mode localization

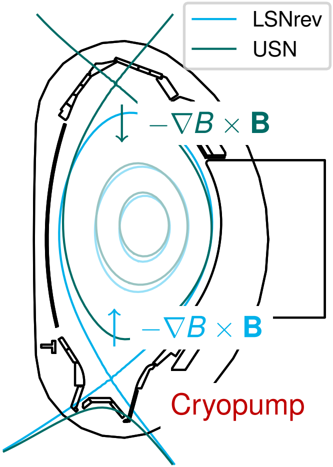




$$A_{\mathrm{rel}} = A_{\mathrm{Gauss}}/A_{\mathrm{tot}}$$

I-mode: Magnetic configurations

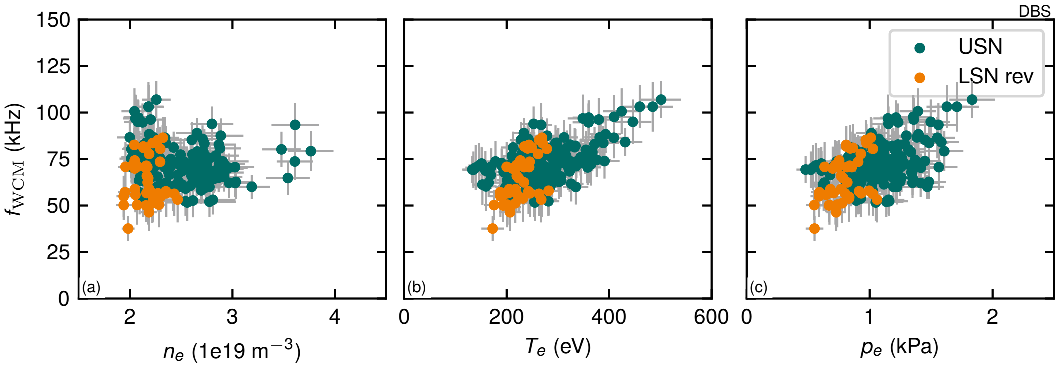




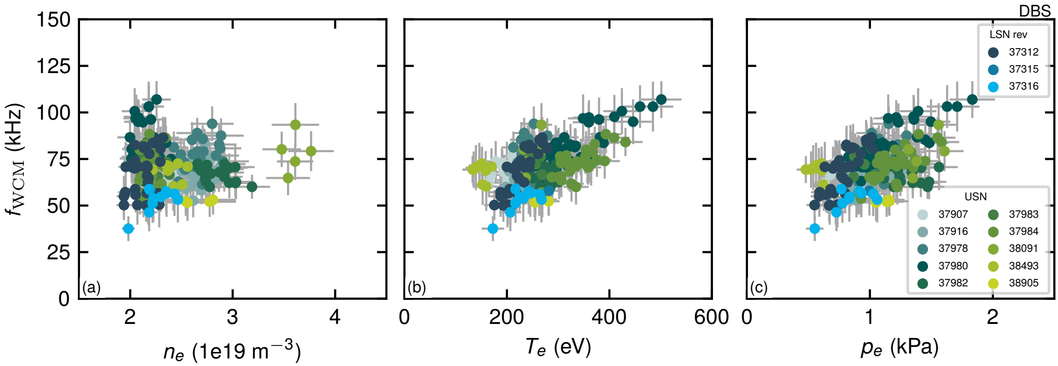
Configurations used for I-mode: USN and LSNrev

Main differences: NBI and divertor pumping

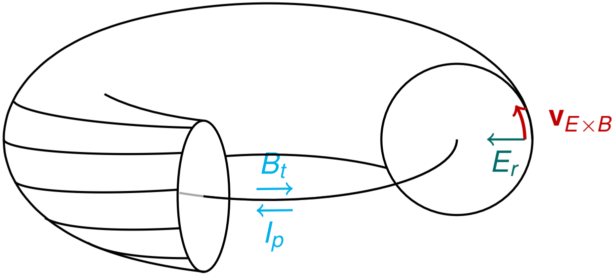
WCM frequency scaling

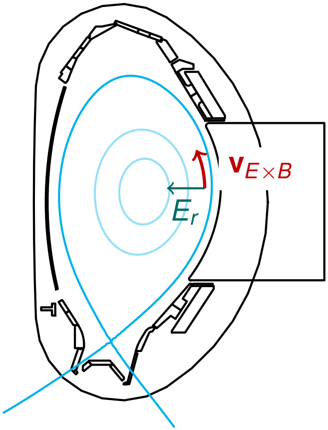


WCM frequency scaling



Plasma velocity





Complicated radial electric field E_r

Plasma rotates with $v_{E\times B} = \frac{\mathbf{E}\times\mathbf{B}}{B^2}$

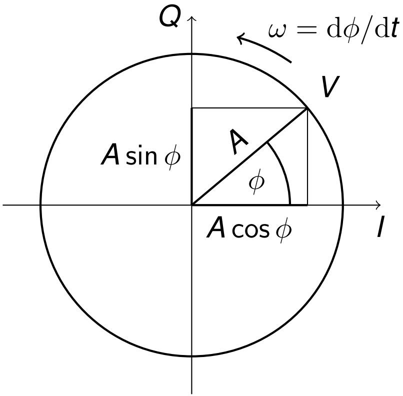
$\Rightarrow$ “Plasma frame”

Heterodyne signal detection

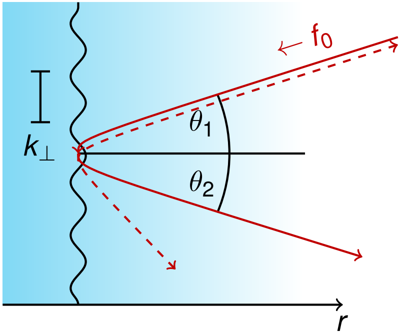
- Mix signal with reference and with 90° phase-shifted reference
- Down-conversion to remove emitted frequency ω_0
- Phase and amplitude of reflected wave detected
- Complex values obtained

$$V = A\cos\phi + i\,A\sin\phi = A\,e^{i\phi}$$

- WCM strongest in spectrum of $\mathrm{d}\phi/\mathrm{d}t$

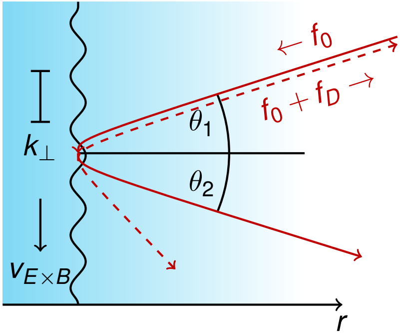


Doppler Back-Scattering (DBS)



- Microwave scattering at specific turbulence scale $k_\perp$

Doppler Back-Scattering (DBS)

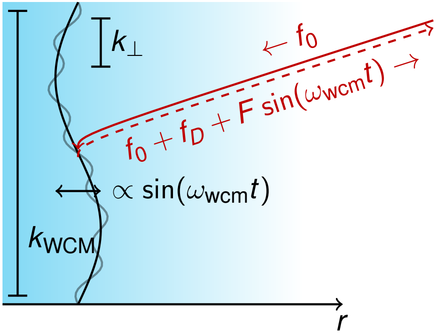


- Microwave scattering at specific turbulence scale $k_\perp$
- Outgoing beam Doppler shifted

$$f_D = v_{E\times B} \cdot k_\perp / 2\pi$$

- Measure plasma velocity $v_{E\times B}$

Doppler Back-Scattering (DBS)



- Microwave scattering at specific turbulence scale $k_\perp$
- Outgoing beam Doppler shifted

$$f_D = v_{E\times B}\cdot k_\perp/2\pi$$

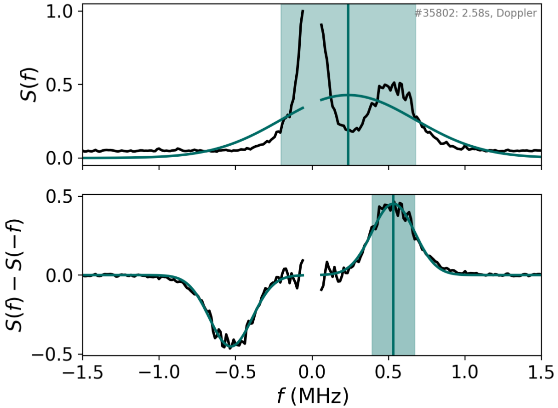
- Measure plasma velocity $v_{E\times B}$
- Indirectly picks up f_{WCM}, but cannot measure $v_{lab,WCM}$

Doppler Reflectometry

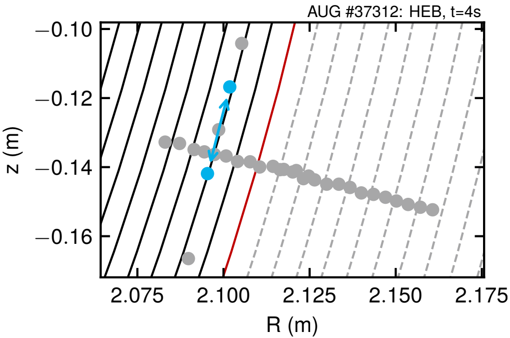
Fitting the Doppler shift f_D:

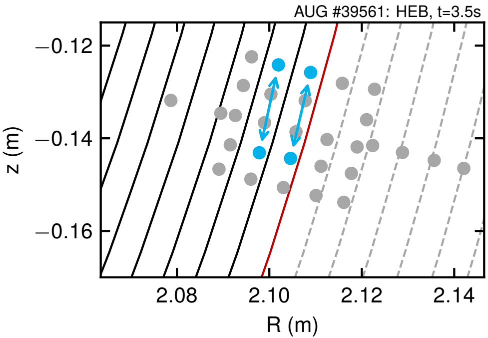
- Simple case: Gaussian peak
- Sometimes a strong 0th-order reflection present
- Use asymmetric part of the spectrum in these cases
- Use empiric criteria to detect failed fits

Does not always work automated, requires manual adjustments



THB: LOS setup





Helium Beam

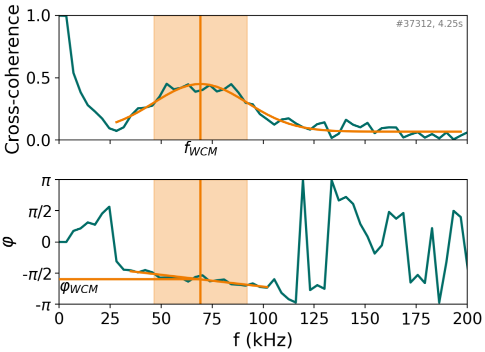
- Single channel relatively noisy
- Use multiple lines of sight for correlation
- Cross-correlation yields both coherence and phase
- Phase can be used to get k_{wcm}

$$k_{\text{wcm}} = \varphi_{\text{wcm}}/d$$

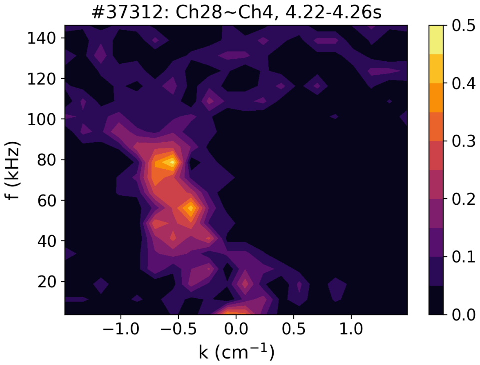
with distance d between LOS

- Calculate v_{wcm} with

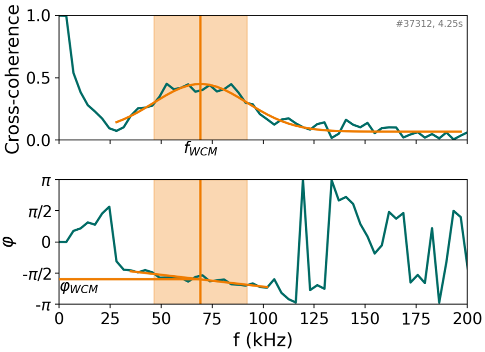
$$v_{\text{wcm}} = 2\pi f_{\text{wcm}}/k_{\text{wcm}}$$



Helium Beam

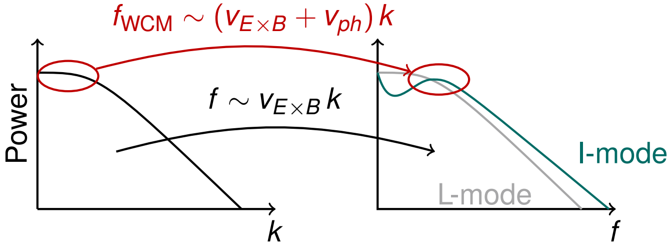


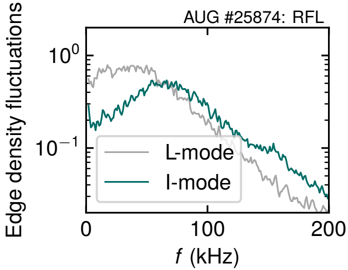
#37312: Ch28~Ch4, 4.22-4.26s
f (kHz)
k (cm^{-1})
140
120
100
80
60
40
20
−1.0
−0.5
0.0
0.5
1.0
0.5
0.4
0.3
0.2
0.1
0.0



Cross-coherence
#37312, 4.25s
1.0
0.5
0.0
f_{WCM}
φ
π
$\pi/2$
0
$-\pi/2$
$-\pi$
φ_{WCM}
0
25
50
75
100
125
150
175
200
f (kHz)

Discussion





k-spectrum could be the same in L- and I-mode

Phase velocity shifts WCM in f-spectrum