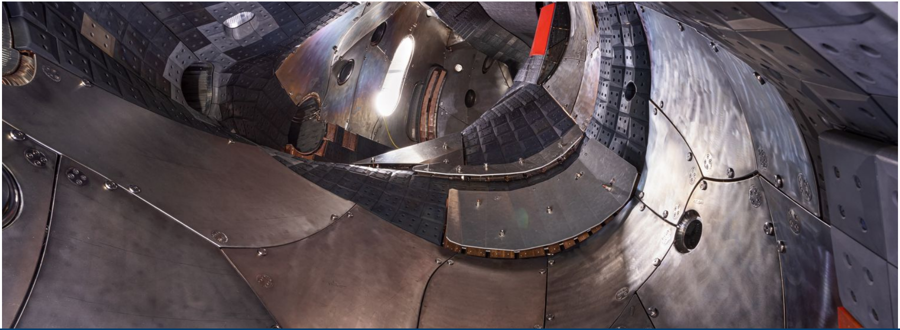

OBSERVATION OF TEM IN W7-X

February 26, 2024 | A. Krämer-Flecken | IEK-4

OUTLINE

Motivation and Diagnostic Aspects

Observation of QC-modes

From QC-modes to TEMs

QC-modes/TEMs in different magnetic configurations

Conclusions

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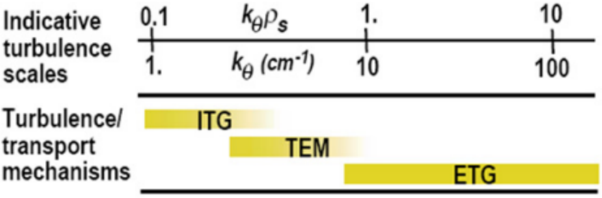
TRANSPORT IN FUSION DEVICES

- Two types of radial transport
  1. Neoclassical transport
  2. Anomalous transport
- Low wave number instabilities
  1. Ion Temp. Grad. driven transport
  2. Trapped Elect. Modes transport
- TEMs created by resonance between trapped elect. and waves
- Rotating in electron diamagn. drift direction
- Wave numbers: $2\,\mathrm{cm}^{-1}$ to $10\,\mathrm{cm}^{-1}$



X. Garbet, C. R. Physique 7 (2006)

TRAPPED ELECTRON MODES

Trapped Electron Modes (TEMs)

DTEMs

- Dissipative TEMs
- Requires strong ∇T
- Needs large collisionallity
- Important transport mechanism in the plasma edge

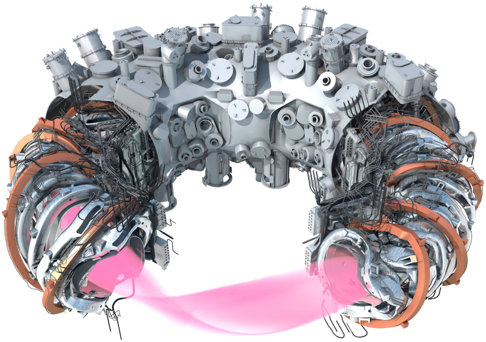
CTEMs

- Collisionless TEMs
- Observed in the plasma core
- Needs $T_e \geq T_i$
- Contributes to particle thermal diffusivity
- Observed in tokamaks (ASDEX, DIII-D, Tore Supra ...)

The rest of the presentation deals with CTEMs in W7-X

Jianying Lang, Yang Chen, and Scott E. Parker; DOI: 10.1063/1.2771141

THE STELLARATOR W7-X



- Variable plasma cross section
- Mean radius 5.5 m
- Minor radius 0.52 m
- Plasma volume $V \approx 30\,m^3$

- Stellarator with 5-fold symmetry
- Magnetic configuration defined by:
  - Current in nonplanar coils
  - Current in planar coils

Magnetic configuration defined by 3 letter code

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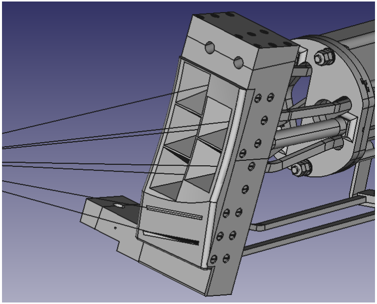
THE CORRELATION REFLECTOMETER

- Installed in the bean plane
- Poloidally spaced antennae
- Localized measurement:

$$f_{ref} \sim \sqrt{\frac{n_e\, e^2}{\epsilon_0\, m_e}}$$

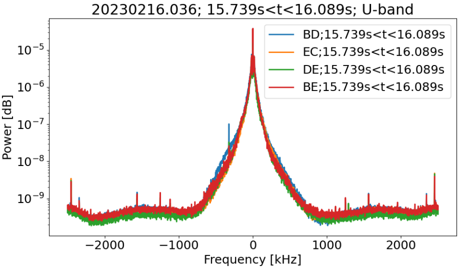
- Probing $0.6 \times 10^{19}\,\mathrm{m}^{-3}$ to $4.5 \times 10^{19}\,\mathrm{m}^{-3}$
- Measurement of pol. velocity
- and turbulence properties
- Continuous frequency hopping every 10 ms by 0.5 GHz
- Each single scan lasts for 370 ms

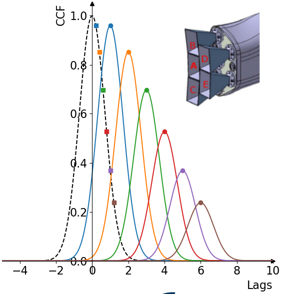


MEASURED QUANTITIES

- Measurement of frequency spectra
- Probing different poloidal separation
- Deduce poloidal structure from PSD, CPSD, Coherence

- Estimation of delays from CCF
- Delays estimated for selected frequency intervals and ...
- different poloidal distances
- Velocities from elliptical model





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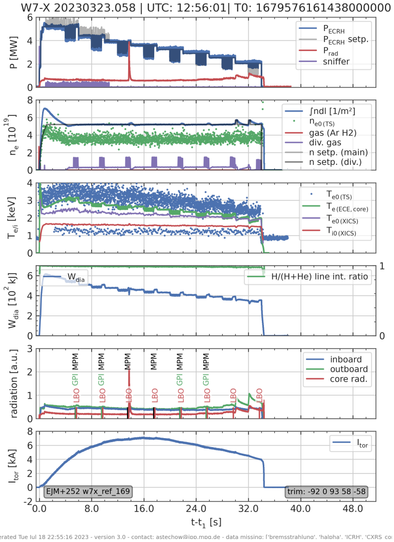
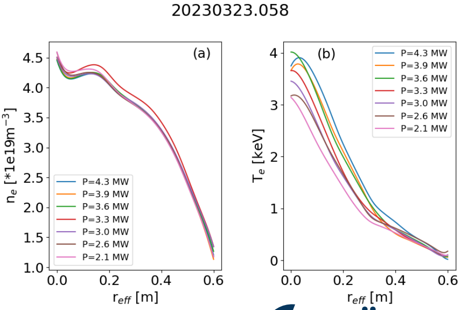
STANDARD CONFIGURATION



- Power Scan from 5 MW to 2 MW
- Power modulation in each step
- Constant density of $5 \times 10^{19}\,\mathrm{m}^{-3}$
- $T_e, \nabla T_e$ decreases with power,
- but, T_i nearly constant



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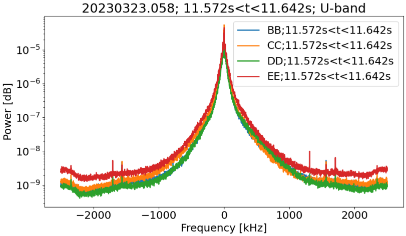
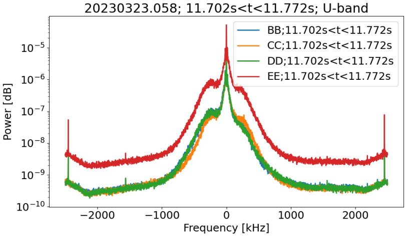
PSD ANALYSIS

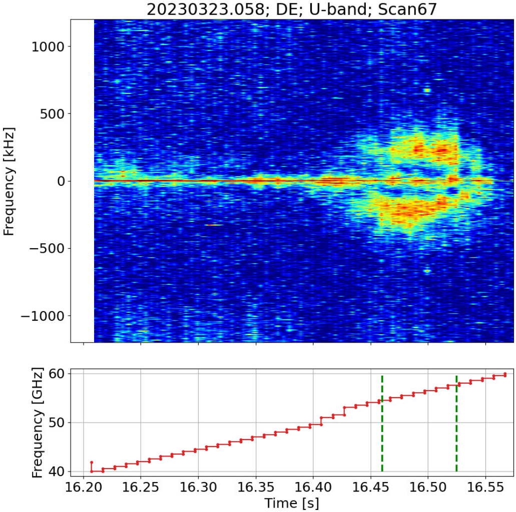


- PSD in the plasma edge
- Density interval: 2.63 m^{-3} to 3.04 m^{-3}
- Exponential decay – no structures



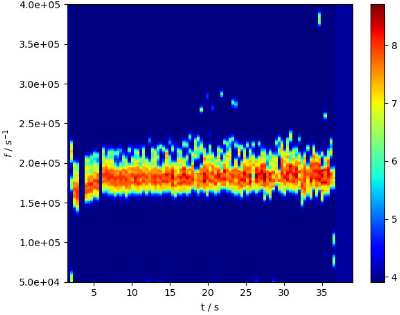
- PSD in the plasma core
- Density interval: 3.69 m^{-3} to 4.18 m^{-3}
- Broad structure detected

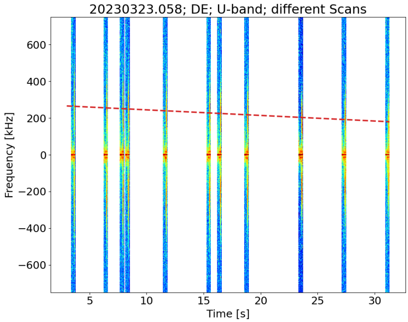
INVESTIGATION OF COHERENCE SPECTRA



- One Scan of PCR at $P = 3.6\,\mathrm{MW}$
- Coherence reduces background
- Broad modes observed in the plasma core
- These modes are quasi coherent
- FWHM of QC-mode similar to f_c

COMPARISON WITH MIRNOV COILS





- Constant frequency $f_c \approx 180\,\text{kHz}$
- Increase of f_c with decrease of n_e

- f_c decreases with power
- Ranges from 250 kHz to 180 kHz

QC-modes have no magnetic component

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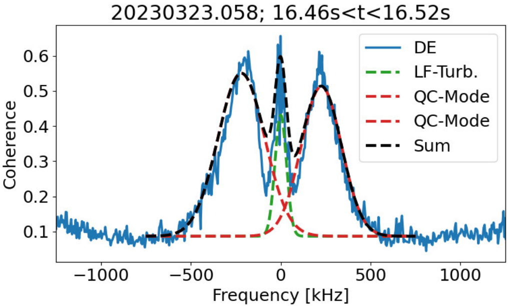
COHERENCE SPECTRA

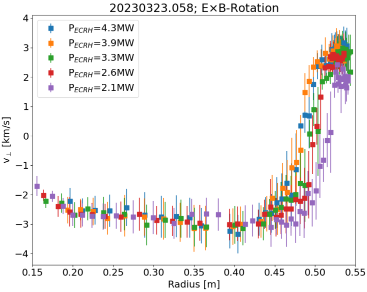


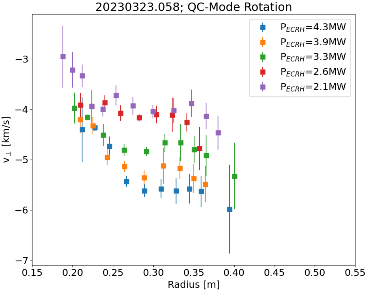
- Decomposition of coherence spectrum in Gaussian components:
  - LF turbulence −110 kHz to 110 kHz
  - QC-modes: 140 kHz to 450 kHz & −450 kHz to −140 kHz
- Good agreement with measured spectra

Use different frequency ranges to calculate poloidal velocities

E×B AND QC-MODE VELOCITIES

- Estimation of $E \times B$-rotation for 5 kHz to 110 kHz
- Estimation of $v_\perp = v_{E\times B} + v_{QC}$ for 140 kHz to 450 kHz





- Constant $v_{E\times B}$ in the core
- Independent of P_{ECRH}

- Variation of $v_\perp$ with P_{ECRH}
- For all cases: $|v_\perp| > |v_{E\times B}|$

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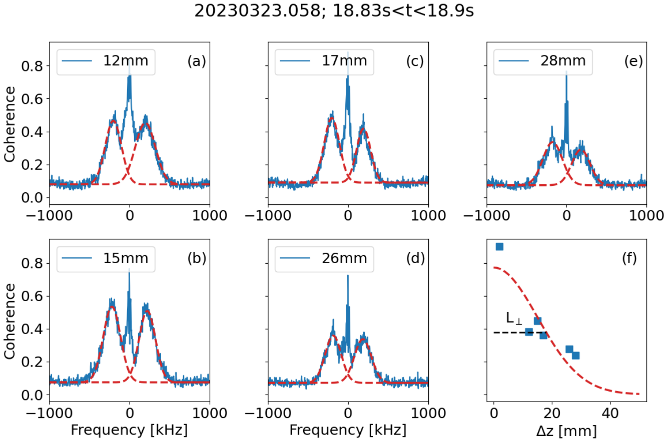
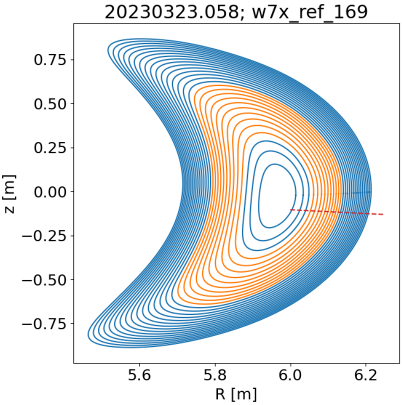
POLOIDAL SIZE OF QC-MODES

- Poloidal size of TEMs ($L_\perp$) is assumed to be 6 mm to 30 mm
- PCR probes different poloidal distances; Used to estimate of $L_\perp$



Estimated $L_\perp = 18$ mm; Agrees with TEMs

MODE NUMBER ESTIMATION



- QC-mode observation
- LoS of PCR

- Estimated mode number as:

$$m = \frac{s\, f_{QC}}{v_\perp}$$

- Circumference s ranges from 1.57 m to 2.74 m
- For all power steps:
  - Mean mode numbers: 101 ± 5
  - Mean $L_\perp$: 21 mm±1 mm
  - Corresponding $k_\perp$: $2.95\,\mathrm{cm}^{-1} \pm 0.14\,\mathrm{cm}^{-1}$
- Values are in agreement with TEM nature of QC-modes

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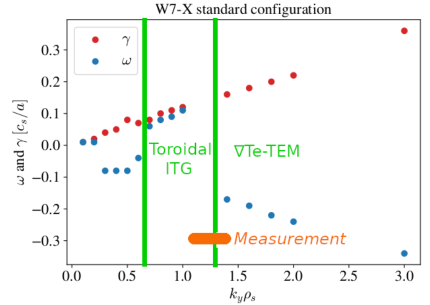
LINEAR GYRO KINETIC CALCULATIONS

Last check the for TEMs: $k_{\perp}\rho^{*} \geq 1$ and compare with gyro kinetic calculations

- Estimated T_e at $r_{eff} = 0.28\,\mathrm{m}$ for all power steps
- Calculate range of $k_{\perp}\rho^{*}$: 1.06 to 1.37
- Linear gyro kinetic calculation support TEMs for this range
- TEMs are ∇T_e driven



Strong evidence that QC-modes have TEM nature and driven by ∇T_e

OUTLINE

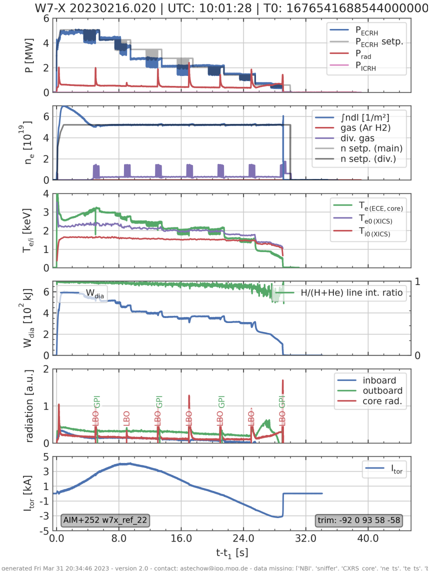
EFFECT OF MIRROR RATIO

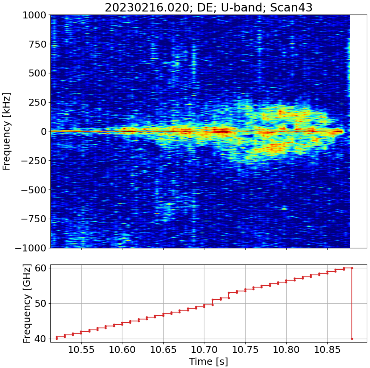
- TEMs depend on the interplay of trapped electrons with waves
- Influence of mirror properties on the observed QC-mode is expected
- Characterize the mirror by the mirror ratio *mr*:

$$mr(r=0) = \frac{B_{ax}(\phi = 0^o) - B_{ax}(\phi = 36^o)}{B_{ax}(\phi = 0^o) + B_{ax}(\phi = 36^o)}$$

- Standard configuration has a mirror ratio of $mr = 0.044$
- Try to investigate the extreme cases low mirror (AIM) and high mirror (KKM)

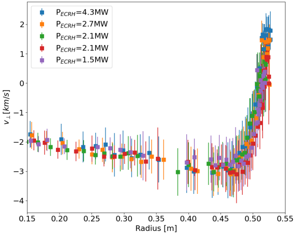
LOW MIRROR CONFIGURATION (AIM)

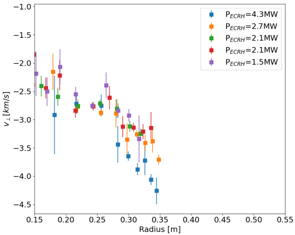


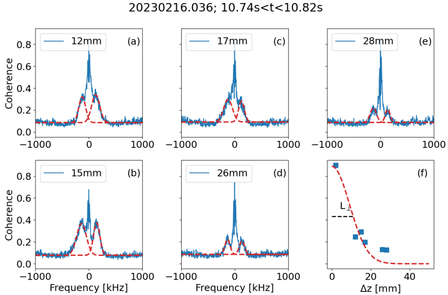


- Low mirror configuration
- QC-modes in the core
- ranges from 90 kHz to 170 kHz

RESULTS FROM LOW MIRROR







- QC-mode rotation in e^- drift direction
- Poloidal size $L_\perp = 12\,\text{mm}$
- Similar mode number as in EJM
- Yields $k_\perp \rho^* \approx 1$

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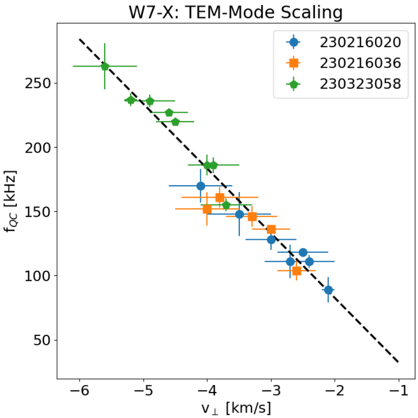
FREQUENCY SCALING OF TEMS

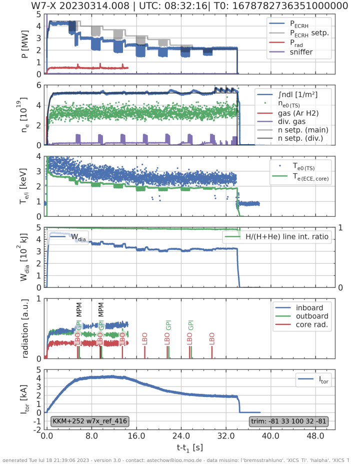


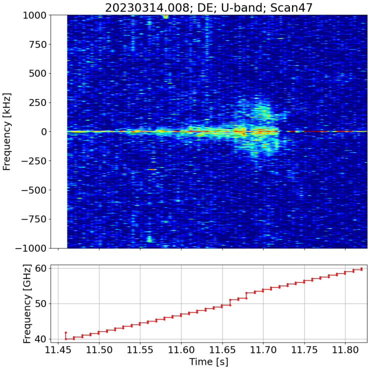
- Linear relation between frequency and rotation
- $E \times B$-rotation in all programs similar
- Scaling depends on mode number and $L_\perp$:

$$f_{QC} \propto \frac{m}{L_\perp} v_\perp$$

- QC-modes in standard & low mirror conf. have TEM nature

HIGH MIRROR CONFIGURATION (KKM)

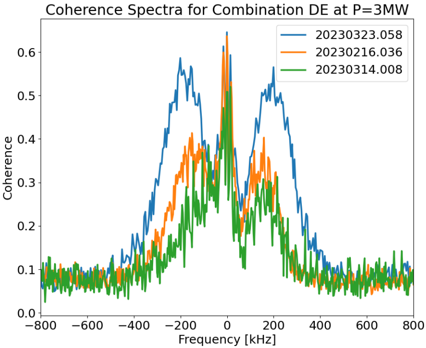




- Power scan as in EJM & AIM
- No/weak QC-mode in KKM

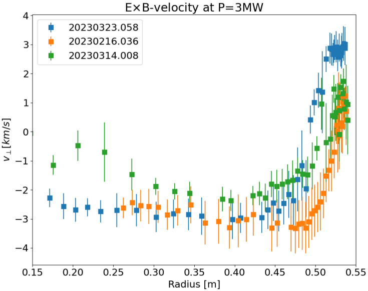
Weak QC-modes observed in KKM

COHERENCE AND MIRROR RATIOS



- QC-mode pronounced in EJM
- Nice QC-modes in low mirror
- Weak QC-modes in high mirror

- Small radial interval for QC-modes in KKM
- Similar E×B-velocity in observed



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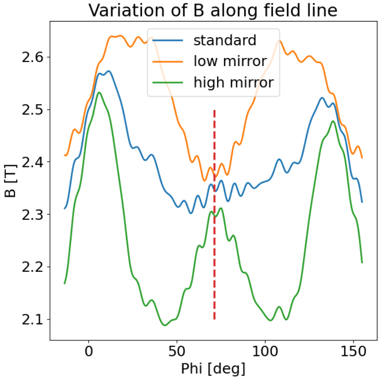
MIRROR CONDITION FOR AIM, EJM & KKM



Position of PCR at $\Phi = 71.1^{\circ}$
Radial position $r_{eff} = 0.28\,\mathrm{m}$

- Conditions for trapped electron in EJM, AIM & KKM
- PCR location in minimum *B* for EJM & AIM
- KKM: PCR located in a maximum
- Explains absence of TEMs in KKM for PCR
- PCR in a bad position to detect QC-modes
- Does not exclude TEMs in general in KKM

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CONCLUSIONS

Conclusions

- QC-modes observed in the plasma core of W7-X
- Velocity of the modes is in electron diamagn. drift direction
- Poloidal structure length in agreement with TEMs
- QC-mode frequency scales with power and ∇T_e, respectively
- $k_\perp \rho^* \geq 1$ supports TEM nature of QC-modes
- Linear qyro kinetic calculation support ∇T_e driven TEMs

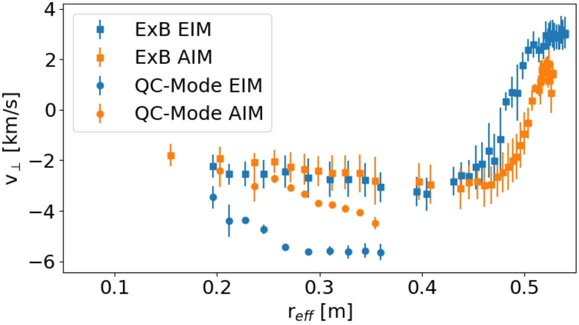
Thanks for attention

Thanks to contributing colleagues:

D. Carralero, P. Costello, T. Estrada, G. Fuchert, J. Geiger, S. Heuraux, A. Knieps, M. Maragkoudakis, J.H.E. Proll, K. Rahbarnia, R. Sabot, L. Salazar, H. Thomsen, G. Weir, T. Windisch, H.M. Xiang

Backup Slides

$E \times B$-ROTATION FOR DIFFERENT CONFIGS.



- $E \times B$-rotation in EJM & AIM at similar power level
- Difference in the QC-mode rotation
- Decrease in QC-mode rotation results in decreased frequency for AIM

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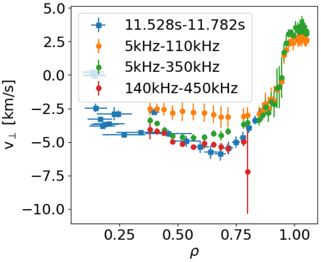
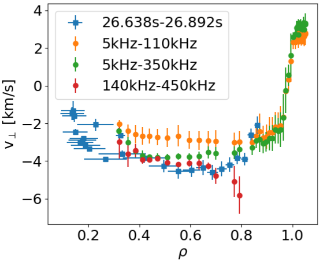
COMPARISON PCR VERSUS DR





- Power level $P_{ECRH} = 3.9\,\text{MW}$
- DR (blue circles) agree with PCR outside $r_{eff} > 0.8\,\text{m}$
- DR agrees well QC-mode frequency interval
- For 5 kHz to 110 kHz no agreement
- Indicates that DR measures QC-mode rotation dominantly
- Same result for $P_{ECRH} = 2.6\,\text{MW}$

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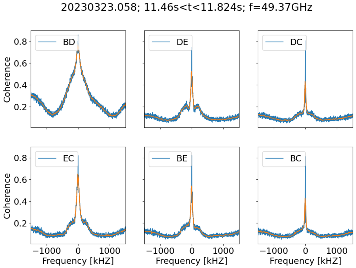
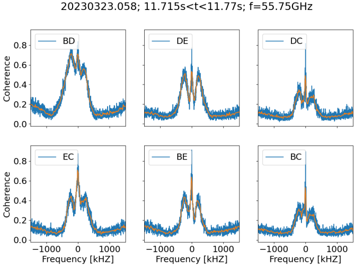
EFFECT OF LINE INTEGRATION



- Coherence spectra reduce noise, already
- Spectra for one full scan
- QC-mode nearly not visible



- Coherence spectra for interval with QC-mode
- QC-mode clearly visible in all spectra