Low-Z impurity particle transport and intrinsic rotation studies using the new CXRS capabilities at ASDEX Upgrade

R. M. McDermott[1], A. Lebschy[1,2], C. Bruhn[1,2], C. Angioni[1], R. Dux[1], I. Erofeev[1], E. Fable[1], B. Geiger[1], W. Hornsby[1], A. Kappatou[1], P. Manas[1], D. Prisiazhniuk[1,2], T. Pütterich[1], U. Stroth[1,2], E. Viezzer[3] and the ASDEX Upgrade Team

[1]Max-Planck-Institut für Plasmaphysik, Garching, Germany
[2]Technische Universität München, Garching, Germany
[3]Dept. of Atomic, Molecular and Nuclear Physics, University of Seville

Monday, January 8, 2018, PPPL, Princeton, NJ, USA

HELMHOLTZ GEMEINSCHAFT

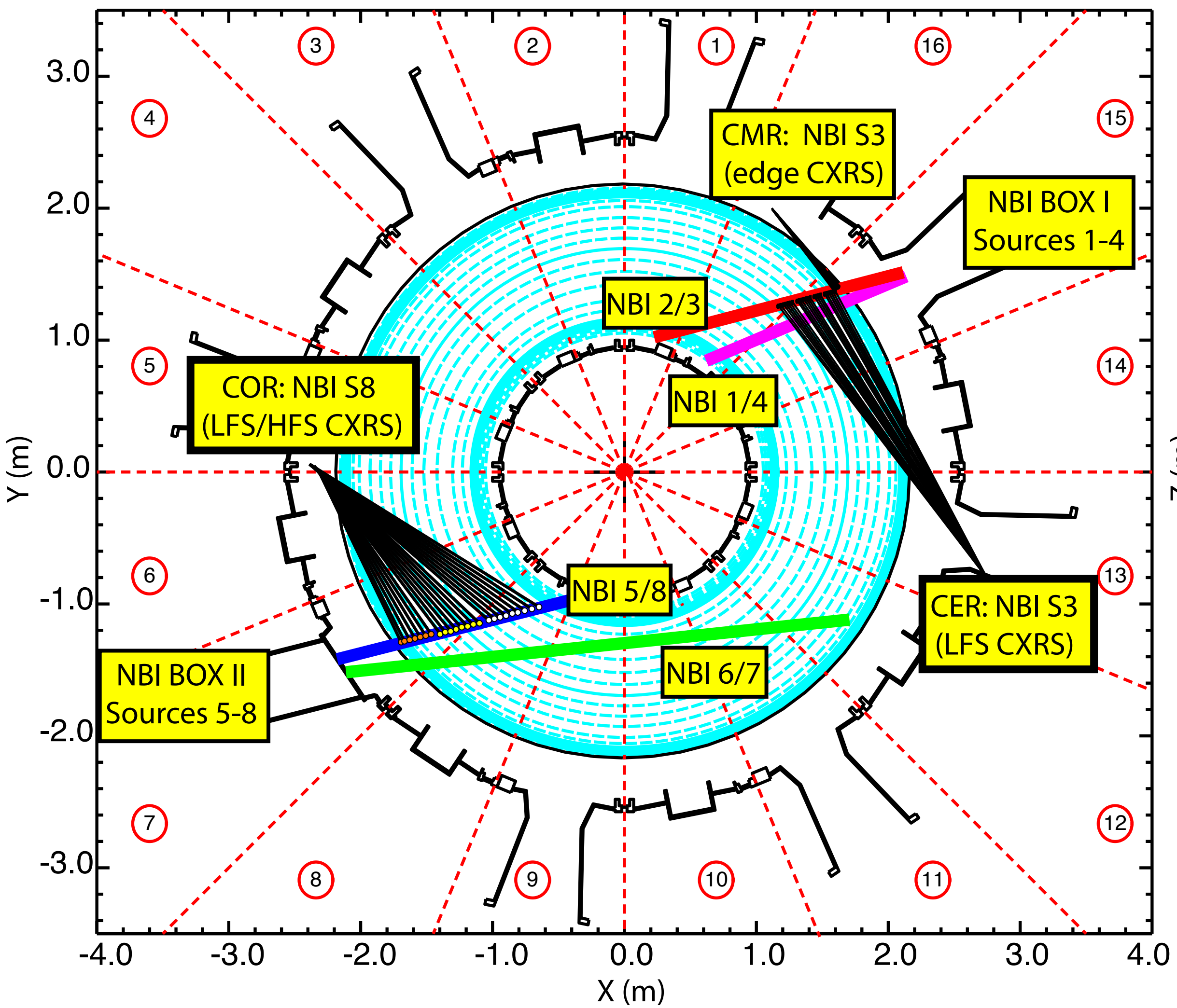
Overview

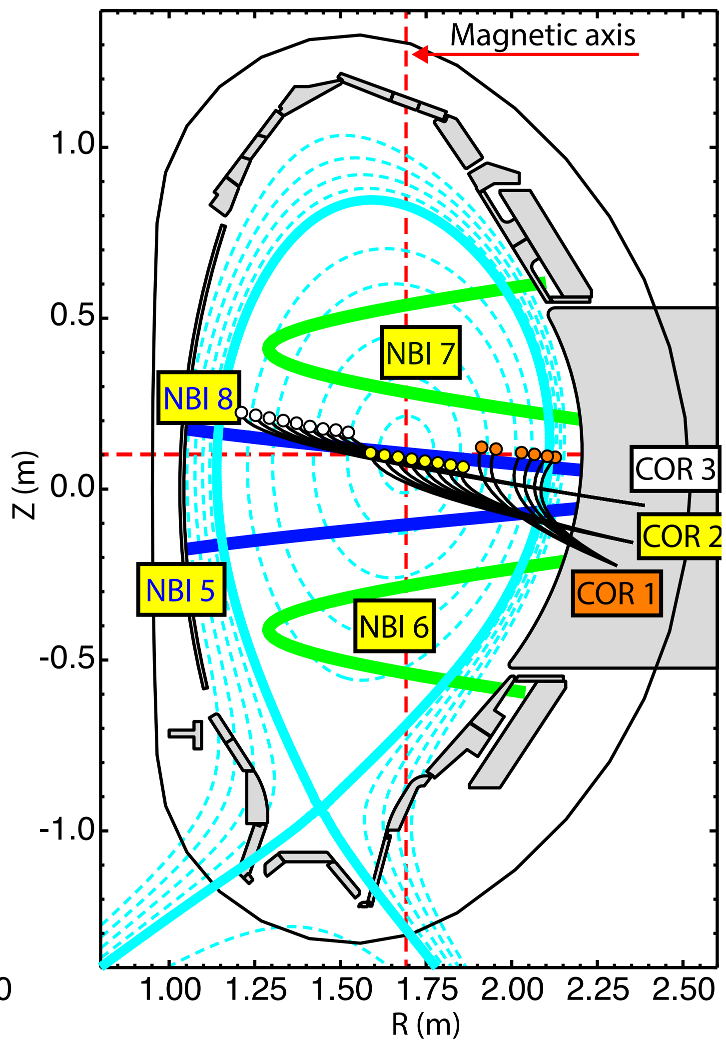
- CXRS diagnostics at ASDEX Upgrade
  - System capabilities & routine operation
  - Measurement of core impurity poloidal rotation
- Rotation studies
  - Database of impurity poloidal rotation
  - Measurements across the LOC-SOC
- Impurity particle transport studies
  - New method for determining B transport coefficients
  - Initial data and comparisons to theory

Overview

- CXRS diagnostics at ASDEX Upgrade
  - System capabilities & routine operation
  - Measurement of core impurity poloidal rotation
- Rotation studies
  - Database of impurity poloidal rotation
  - Measurements across the LOC-SOC
- Impurity particle transport studies
  - New method for determining B transport coefficients
  - Initial data and comparisons to theory

Full coverage CXRS at AUG





McDermott RSI 2017

Full coverage CXRS at AUG

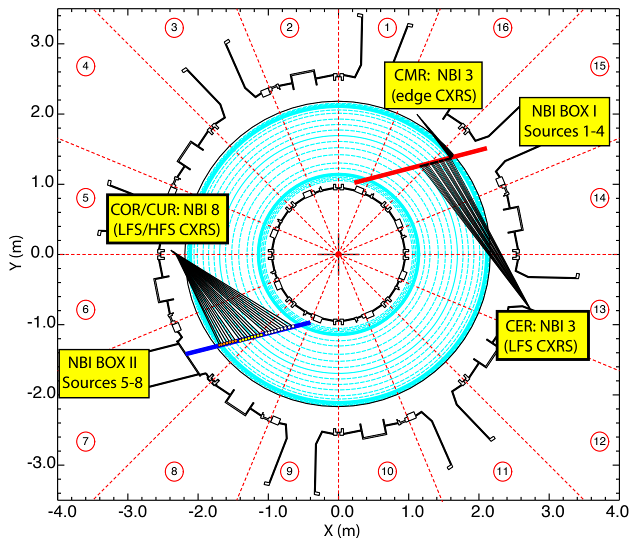
	# LOS	T_{int}>	Δr (cm)	λ	
CAR: LFS core φ	24	4ms	1.5	He	NBI Box I
CCR: LFS core φ	24	4ms	1.5	C	NBI Box I
CER: LFS core φ	24	3.5ms	1.5	B (flex.)	NBI Box I (workhorse)
CHR: LFS core φ	8	10ms	1.5	N (flex.)	NBI Box I
CMR: LFS edge φ	24	1.9ms	0.3	B (flex.)	NBI Box I (workhorse)
CPR: LFS edge θ	24	1.9ms	0.5	B (flex.)	NBI Box I
COR: L/HFS core φ	24	2.5ms	0.75	B (flex.)	NBI Box II (New 2014)
CUR: L/HFS core φ	24	2.5ms	0.75	B (flex.)	NBI Box II (New 2014)

Standard operation with 8 CXRS systems

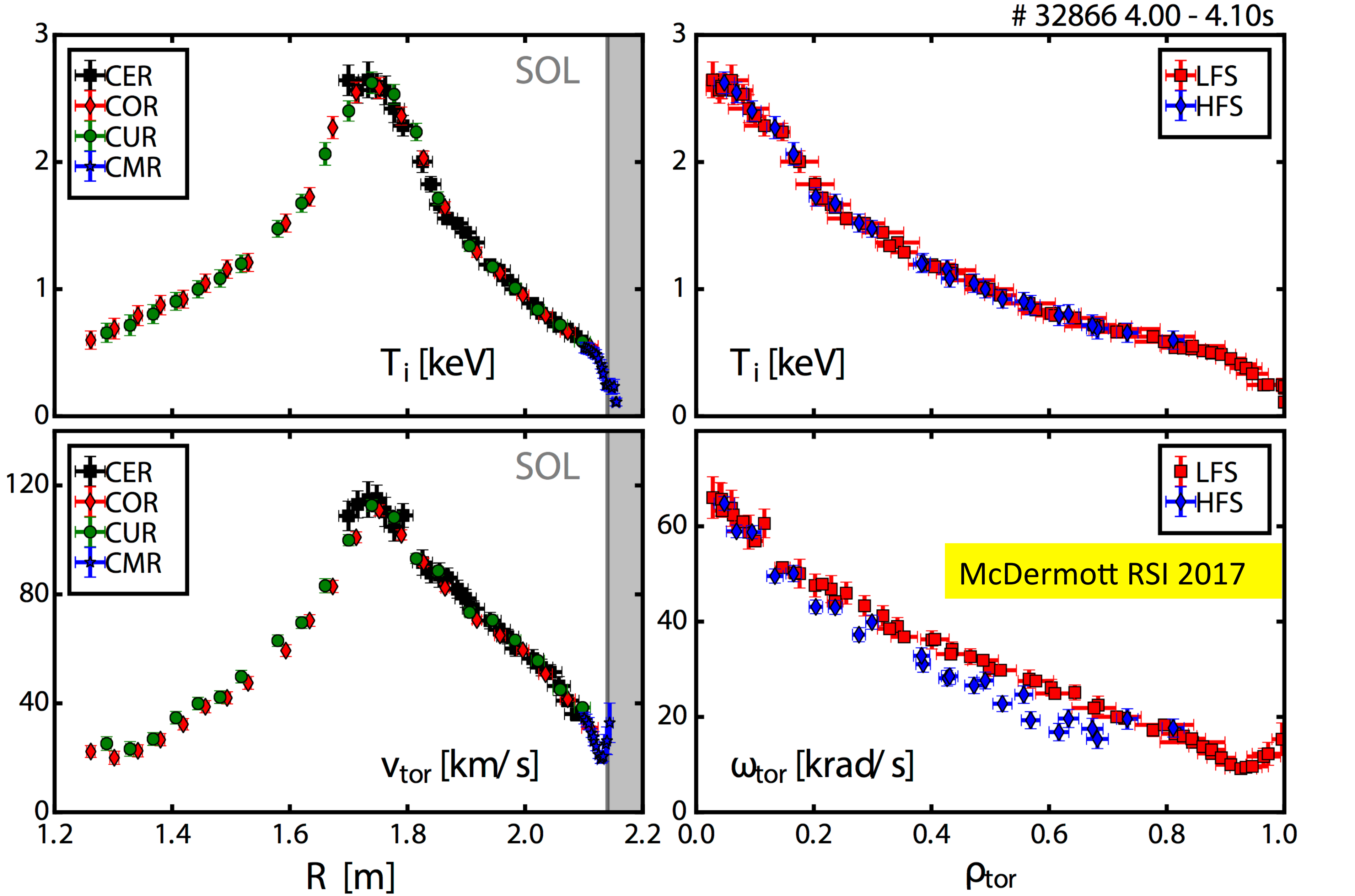
- 10ms core, 2ms edge
- Very detailed profiles!

Non-Standard operation

- Fast pedestal system (CNR) ~ 50µs
- HFS gas puff toroidal and poloidal pedestal systems



Full coverage CXRS at AUG



Poloidal Rotation Measurements

- Direct CXRS measurement using poloidal LOS
  - Works well in edge, but not in core
- Indirect measurement technique → Use poloidal asymmetry in toroidal rotation to infer poloidal rotation

$$\vec{u}_0 = \hat{\omega} R \vec{e}_\phi + \hat{u} \vec{B} \quad \begin{cases} u_\phi = \hat{\omega} R + \hat{u} B_\phi \\ u_\theta = \hat{u} B_\theta \end{cases}$$

Hinton & Hazeltine, Rev. Mod. Phys 1976
Bortolon, NF 2013

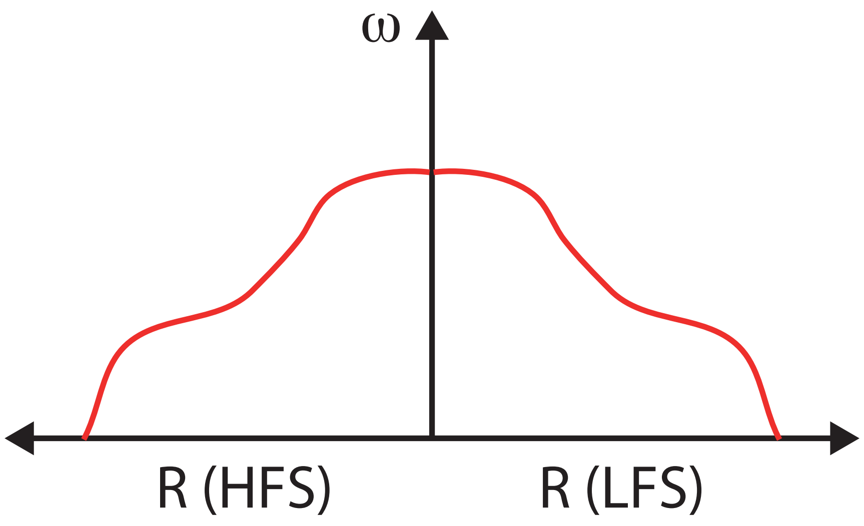
Poloidal Rotation Measurements

- Direct CXRS measurement using poloidal LOS
  - Works well in edge, but not in core
- Indirect measurement technique → Use poloidal asymmetry in toroidal rotation to infer poloidal rotation

$$\vec{u}_0 = \hat{\omega} \mathrm{R} \vec{\mathrm{e}}_\phi + \hat{u}\vec{B} \begin{cases} u_\phi = \hat{\omega} R + \hat{u} B_\phi \\ u_\theta = \hat{u} B_\theta \end{cases}$$

Hinton & Hazeltine, Rev. Mod. Phys 1976
Bortolon, NF 2013

- If zero poloidal velocity
  - Flow → solid body rotation
  - Expect to measure **SAME ω** at all points on a flux surface



Poloidal Rotation Measurements

- Direct CXRS measurement using poloidal LOS
  - Works well in edge, but not in core
- Indirect measurement technique → Use poloidal asymmetry in toroidal rotation to infer poloidal rotation

$$\vec{u}_0 = \hat{\omega} R \vec{e}_\phi + \hat{u} \vec{B} \begin{cases} u_\phi = \hat{\omega} R + \hat{u} B_\phi \\ u_\theta = \hat{u} B_\theta \end{cases}$$

Hinton & Hazeltine, Rev. Mod. Phys 1976
Bortolon, NF 2013

1) PDX: Brau NF 1983
2) TCV: Bortolon NF 2013
3) DIII-D Chrystal RSI 2014

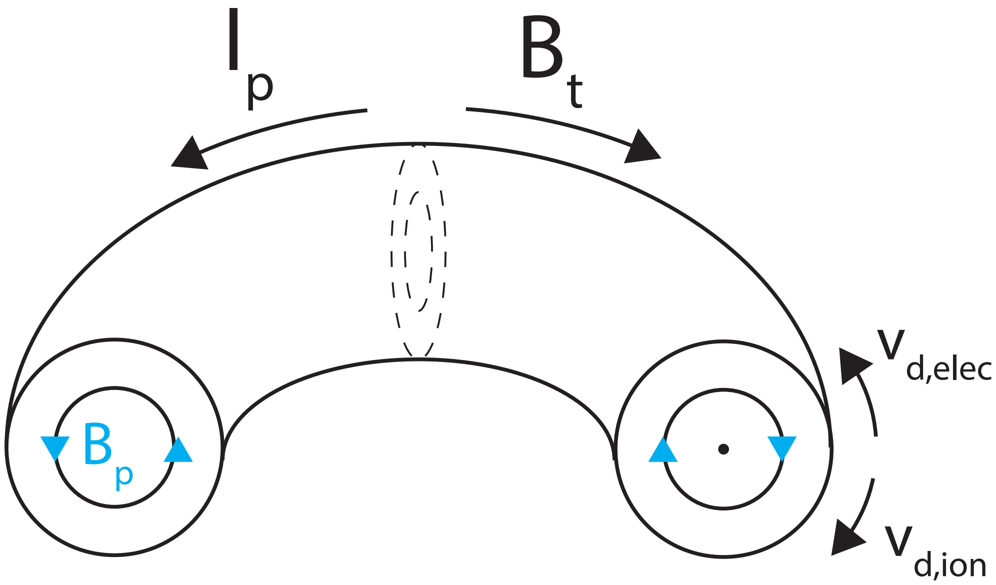
- If there is polodial velocity:
  - HFS and LFS "measured" ω **not constant on flux surface**
  - Expect to see different rotation frequencies

$$\frac{u_{\phi,LFS}}{R_{LFS}} = \hat{\omega} + \hat{u} \frac{B_{\phi LFS}}{R_{LFS}}$$

$$\frac{u_{\phi,HFS}}{R_{HFS}} = \hat{\omega} + \hat{u} \frac{B_{\phi HFS}}{R_{HFS}}$$

Which way does the asymmetry go?

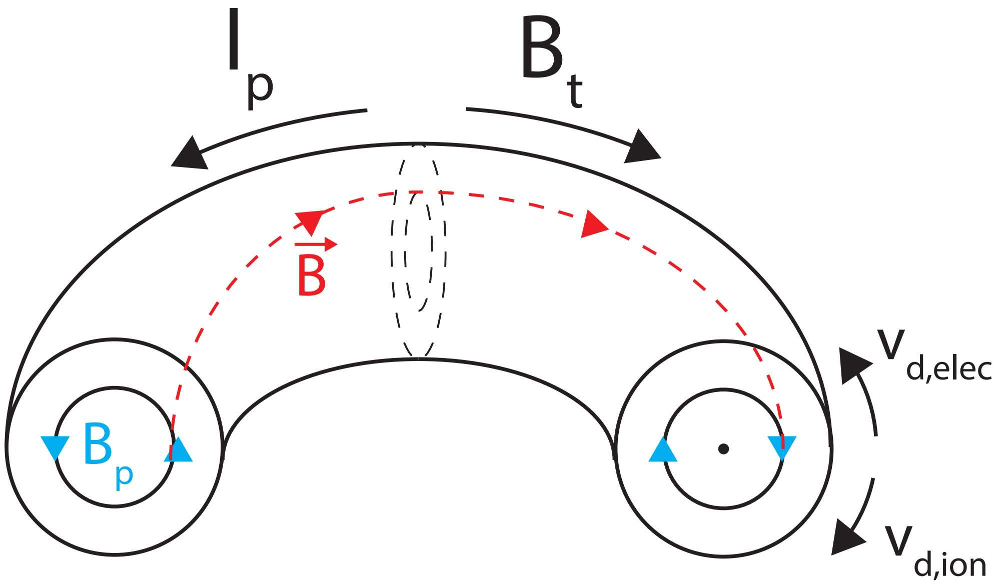
ASDEX Upgrade magnetic geometry



- Define:
  - Positive v_φ in co-I_p direction
  - Negative v_φ in cntr-I_p direction

Which way does the asymmetry go?

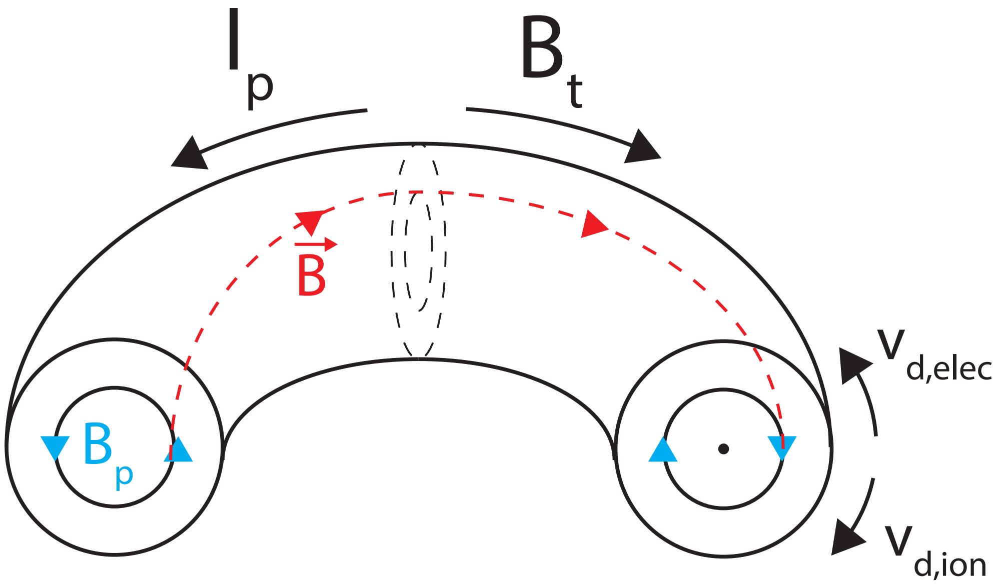
ASDEX Upgrade magnetic geometry

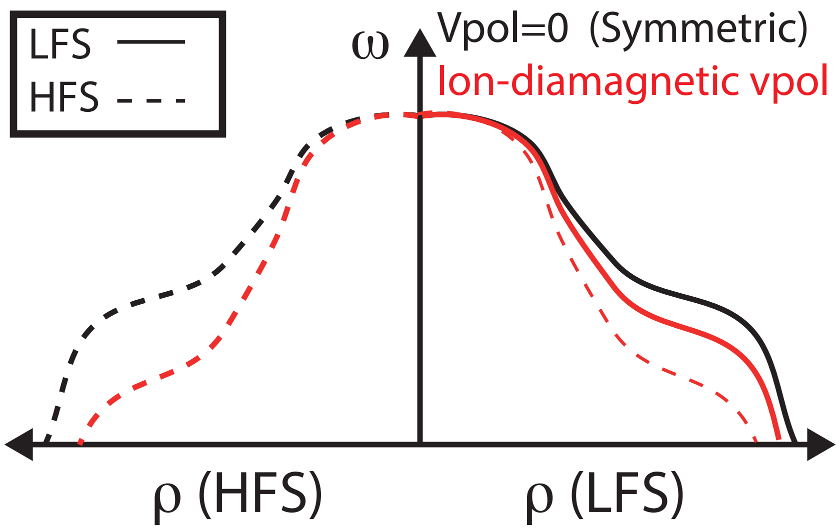


- Define:
  - Positive v_φ in co-I_p direction
  - Negative v_φ in cntr-I_p direction
- Assume flow parallel to B
  - Ion diamagnetic v_θ
  - Reduces measured toroidal flow on both LFS and HFS
  - But reduced the HFS more!

Which way does the asymmetry go?

ASDEX Upgrade magnetic geometry





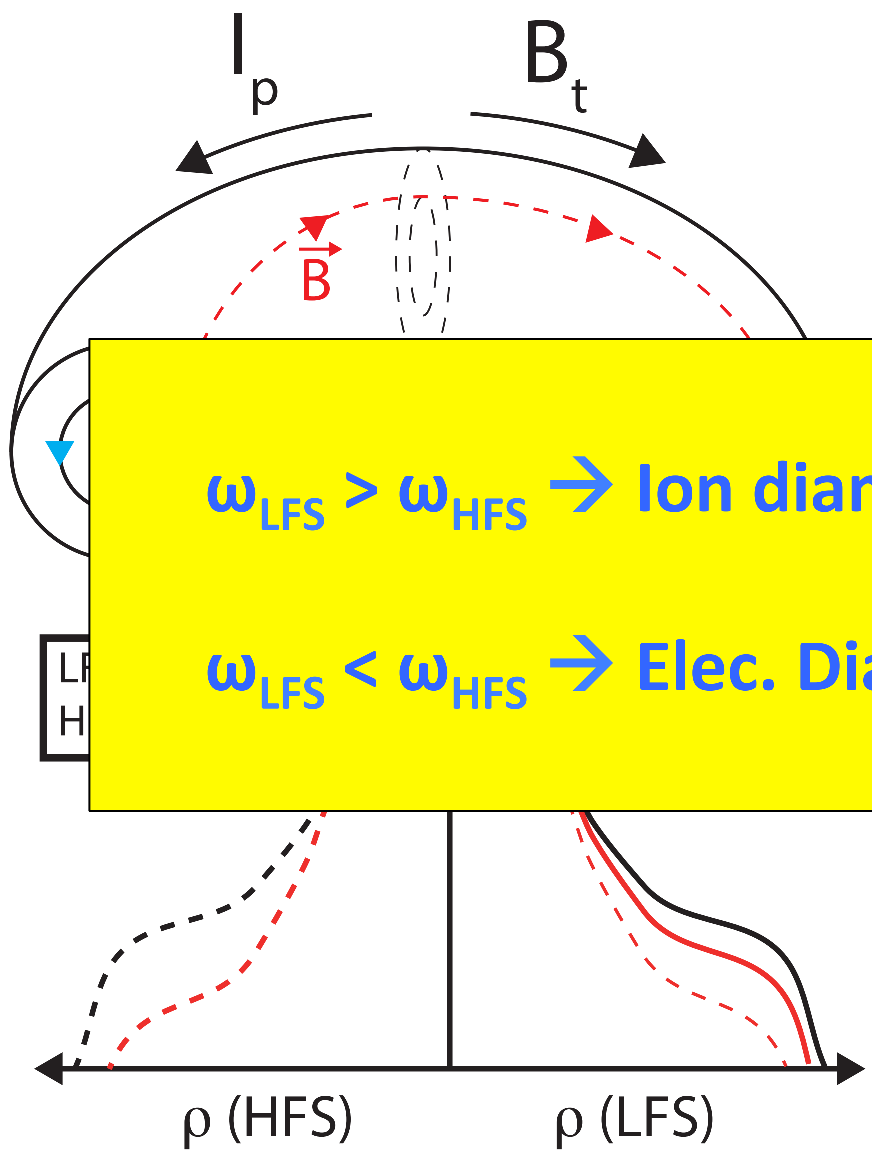
- Define:
  - Positive v_φ in co-I_p direction
  - Negative v_φ in cntr-I_p direction
- Assume flow parallel to B
  - Ion diamagnetic v_θ
  - Reduces measured toroidal flow on both LFS and HFS
  - But reduced the HFS more!

$$\frac{u_{\phi,LFS}}{R_{LFS}} = \hat{\omega} + \hat{u}\frac{B_{\phi LFS}}{R_{LFS}}$$

$$\frac{u_{\phi,HFS}}{R_{HFS}} = \hat{\omega} + \hat{u}\frac{B_{\phi HFS}}{R_{HFS}}$$

Which way does the asymmetry go?

ASDEX Upgrade magnetic geometry



- Define:
  - Positive v_φ in co-I_p direction
  - Negative v_φ in cntr-I_p direction
- Assume flow parallel to B
  - Ion diamagnetic v_θ

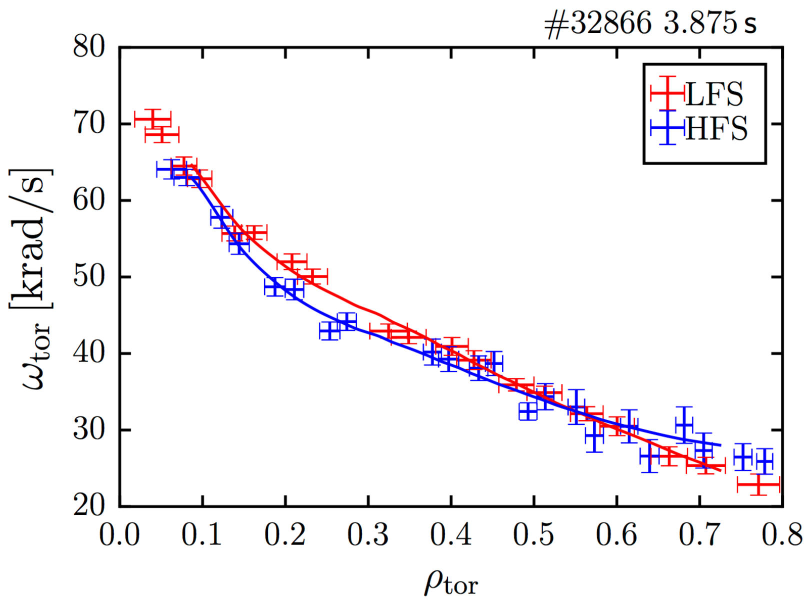
idal
FS
ore!

$$\frac{u_{\phi,HFS}}{R_{HFS}} = \hat{\omega} + \hat{u}\frac{B_{\phi HFS}}{R_{HFS}}$$

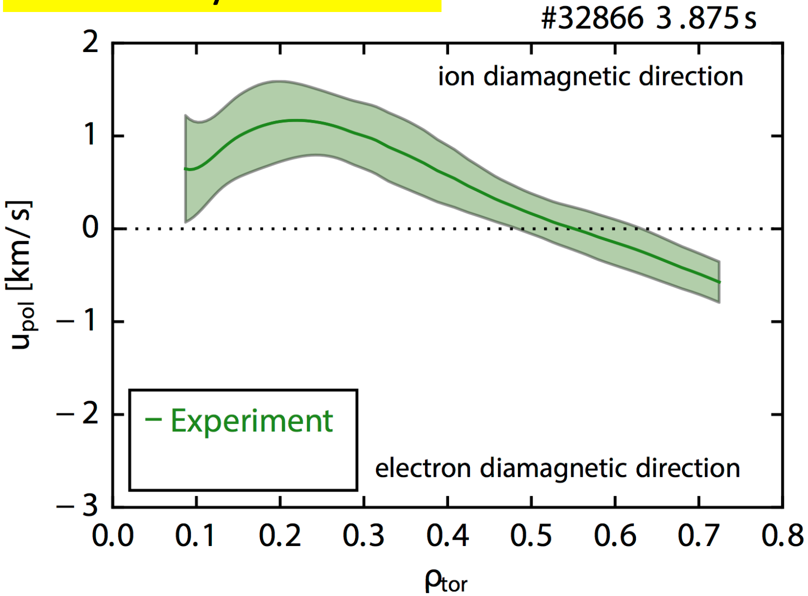
$\omega_{LFS} > \omega_{HFS}$ → Ion diamagnetic poloidal flow

$\omega_{LFS} < \omega_{HFS}$ → Elec. Diamagnetic poloidal flow

Core v_θ ion diamagnetic directed

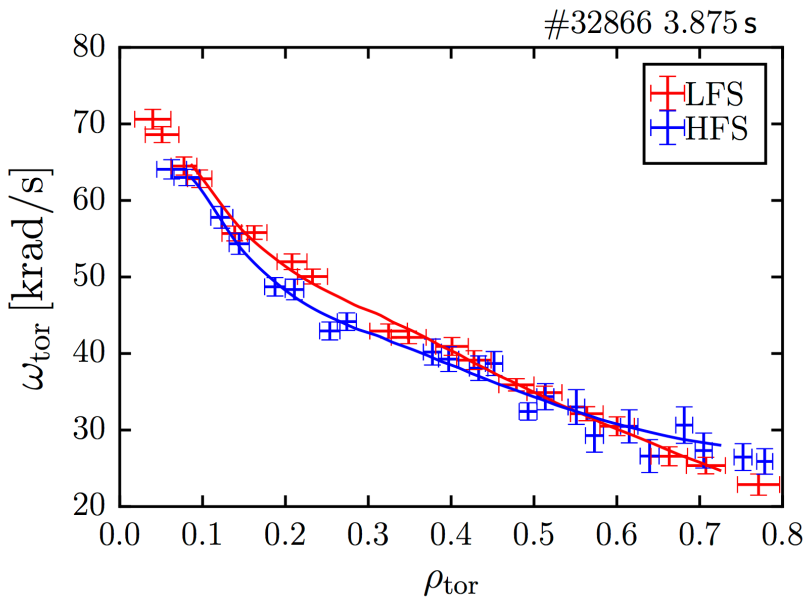


A. Lebschy APS 2017

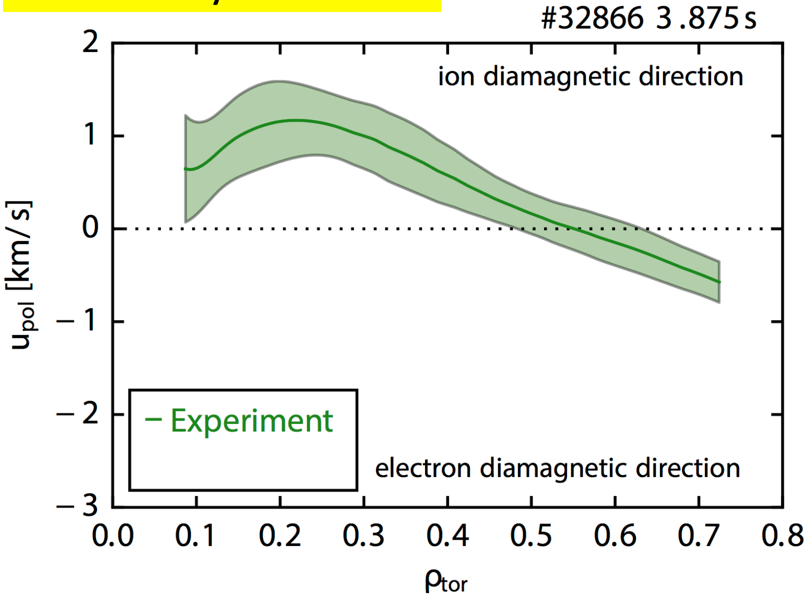


- "Cross-over" → change in sign of $v_{\theta,B}$
  - Ion directed in the core
  - Electron directed in the edge

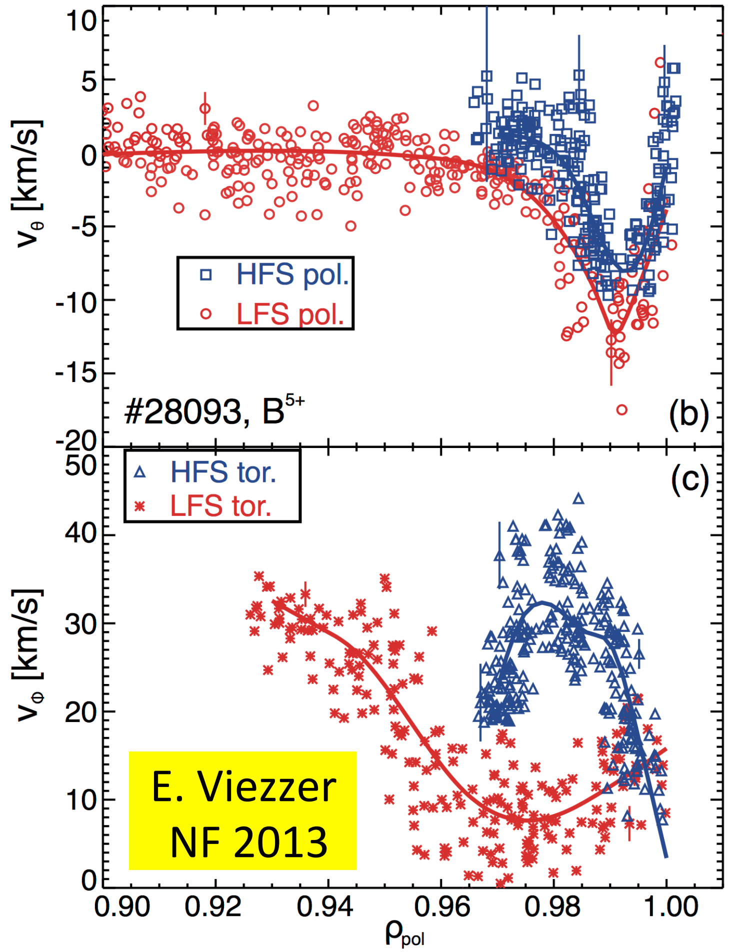
Core v_θ ion diamagnetic directed



A. Lebschy APS 2017

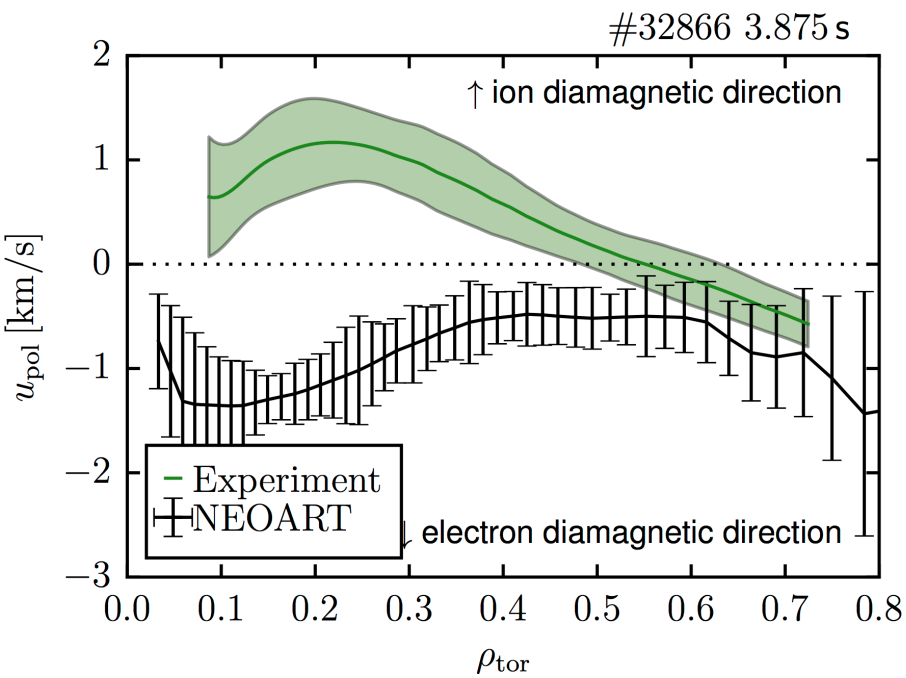


- "Cross-over" → change in sign of v_θ
  - Ion directed in the core
  - Electron directed in the edge
- Comparison w/ edge measurements



Rotation not neoclassical

- In core of AUG ion-diamagnetic impurity poloidal rotation routinely observed
  - Neoclassical calculations: NEO, NCLASS, NEOART



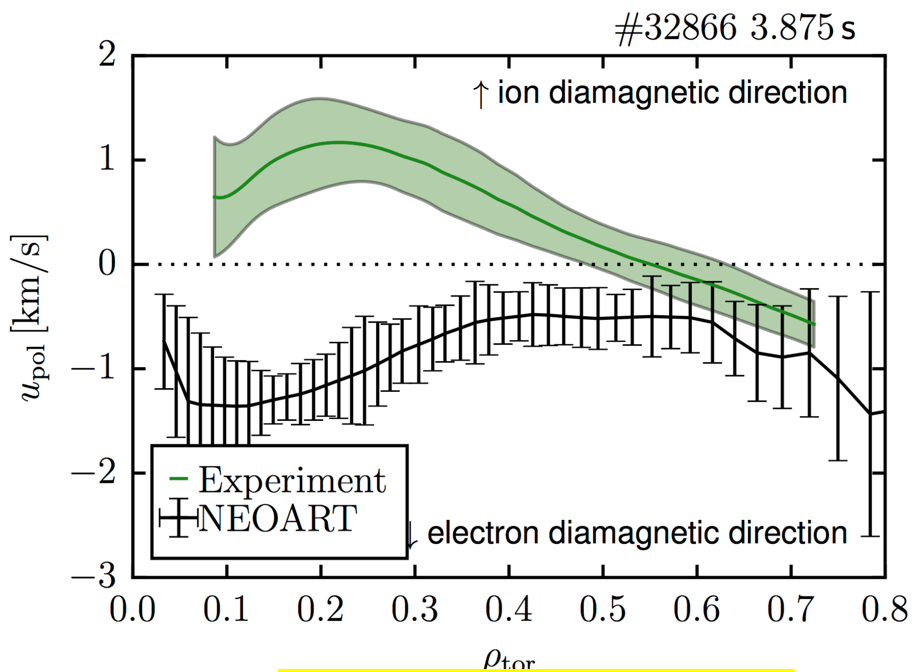
A. Lebschy, APS 2017 & t.b.s. PoP 2018

Overview

- CXRS diagnostics at ASDEX Upgrade
  - System capabilities & routine operation
  - Measurement of core impurity poloidal rotation
- Rotation studies
  - Database of impurity poloidal rotation
  - Measurements across the LOC-SOC
- Impurity particle transport studies
  - New method for determining B transport coefficients
  - Initial data and comparisons to theory

Rotation not neoclassical

- In core of AUG ion-diamagnetic impurity poloidal rotation routinely observed
  - Neoclassical calculations: NEO, NCLASS, NEOART
  - Turbulent (other?) drive stronger than viscous damping?



A. Lebschy, APS 2017
&
t.b.s PoP 2018

<u>AUG Core (B) poloidal rotation database</u>

- Good data on HFS and LFS:
  - Recent boronization
  - low to moderate n_e<6e19 m^{-3}
- Edge region w/ imp. density asymmetry excluded

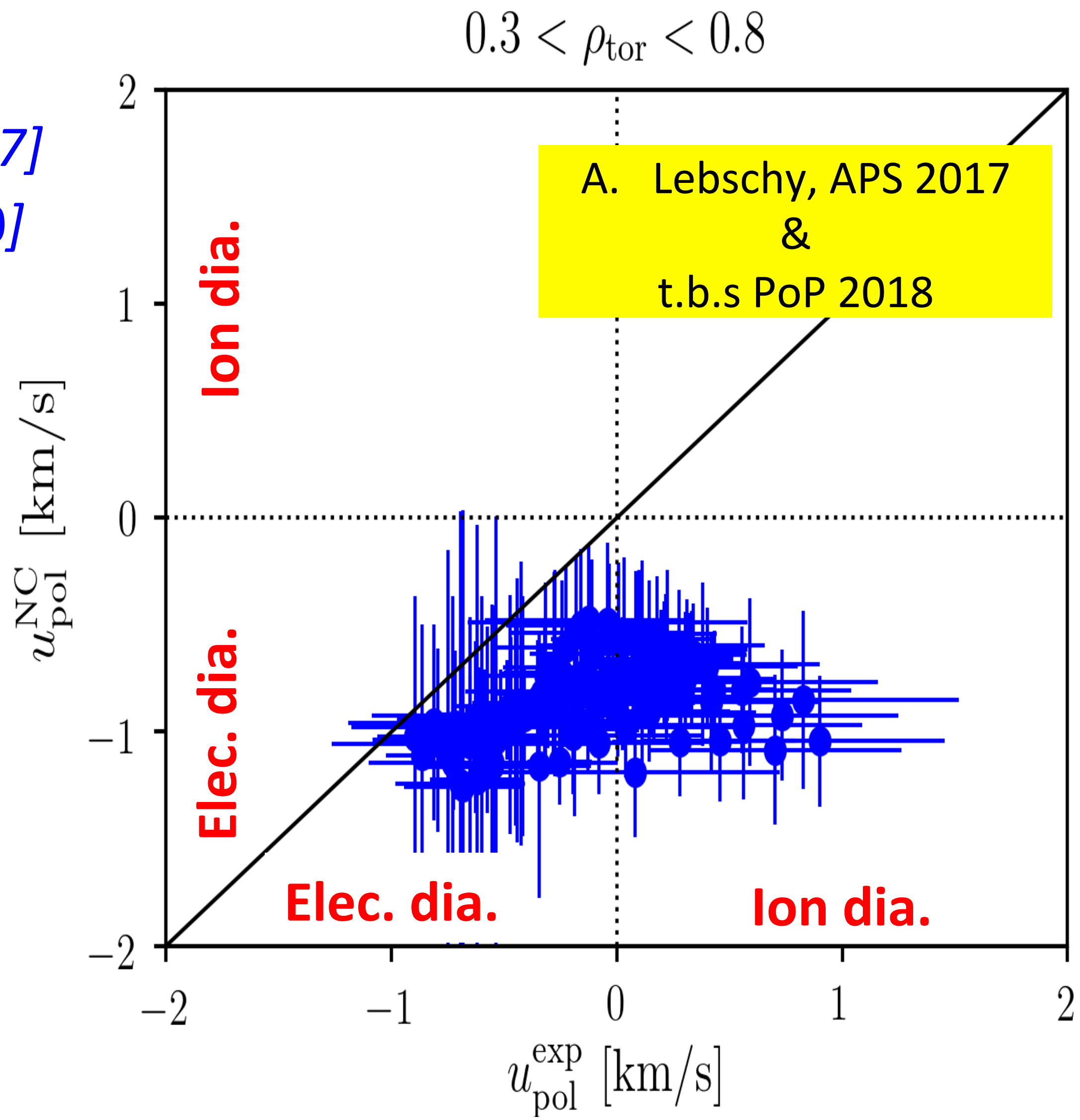
Database:	Parameter range:
• 15 discharges	• υ_i^*: 0.15 – 3.4
• 62 time intervals	• R/L_{Ti}: 2-10
• 400 entries	• R/L_{ne}: 0-6

H-mode database: non-NC B pol. rotation

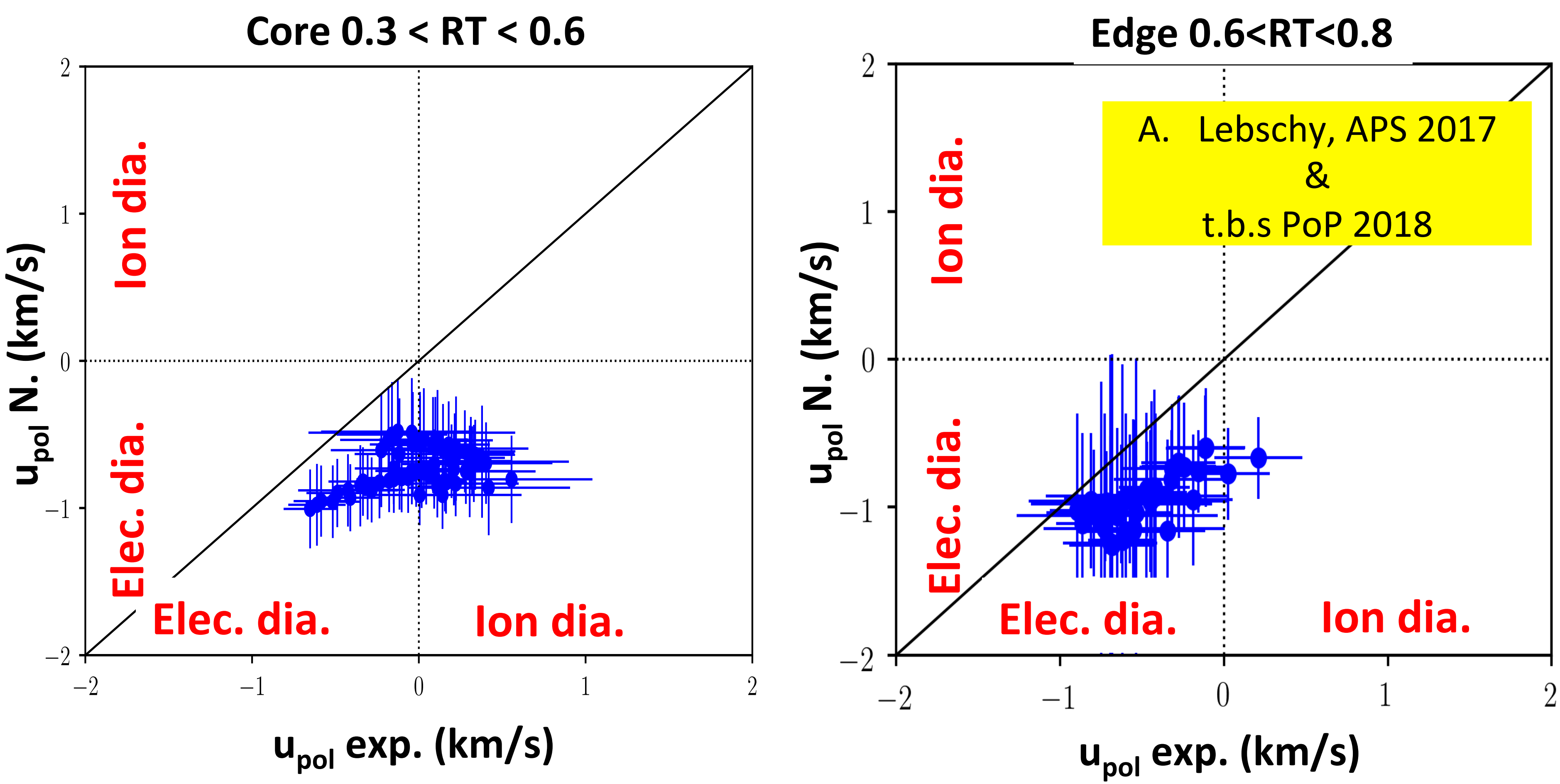
- NC u_{pol} calculated w/:
  - NCLASS *[Houlberg PoP 1997]*
  - NEOART [Peeters PoP 2000]
  - NEO *[*Belli PPCF 2008*]*

- Data points significantly shifted in ion diamagnetic direction

- Only small variations in neoclassical u_{pol}



Ion dia. shift in both core & edge



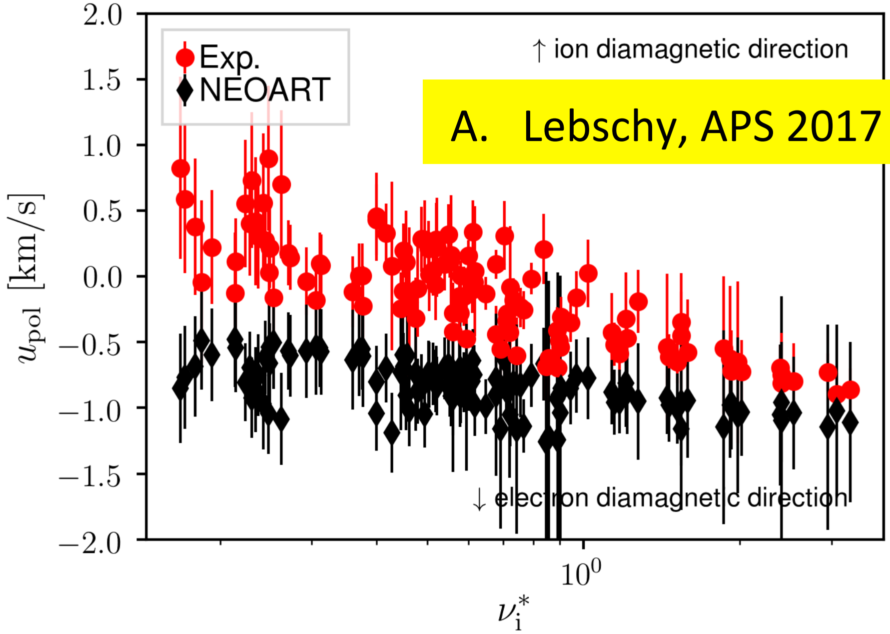
- Substantial number of points with opposite drift direction

- Slight shift in ion dia. direction
- same trend as NC predictions

u_{pol} scales with collisionality

- NC u_{pol} scales with R/L_{Ti} & R/L_{ne}
  - No clear correlations with either
  - R/L_{Ti} & R/L_{ne} strongly correlated
  - Expansion of database – future work
- Difference in NC and exp. boron u_{pol} increases at low υ*

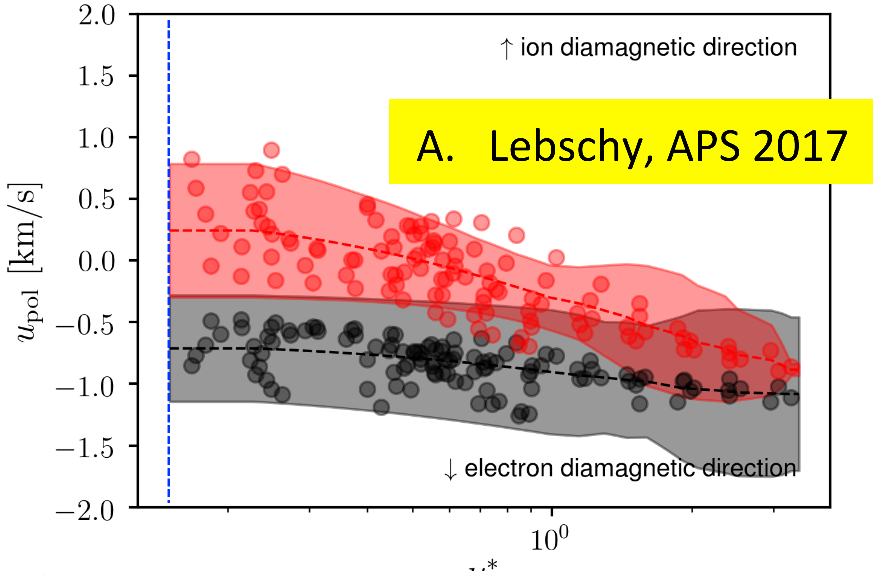
0.3<RT<0.8

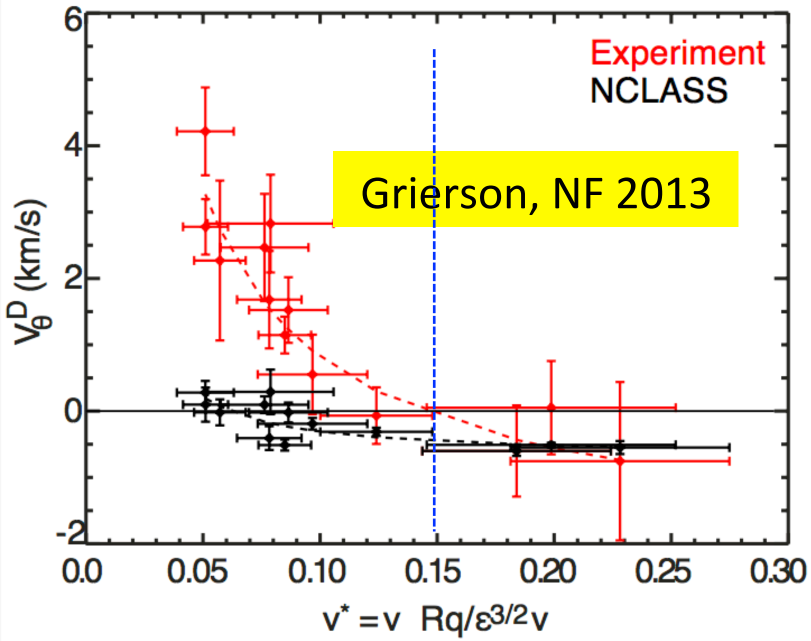


A. Lebschy, APS 2017

u_{pol} scales with collisionality

- NC u_{pol} scales with R/L_{Ti} & R/L_{ne}
  - No clear correlations with either
  - R/L_{Ti} & R/L_{ne} strongly correlated
  - Expansion of database – future work
- Difference in NC and exp. boron u_{pol} increases at low υ^*
- DIII-D <u>main ion</u> u_{pol} deviates from NC at low collisionality
- AUG "low υ_i^*" much higher than DIII-D "low υ_i^*"
  - Additional hidden parameters
  - Future work: expansion of database for wider range of υ_i^* at "single r "
  - Main ion measurements at AUG



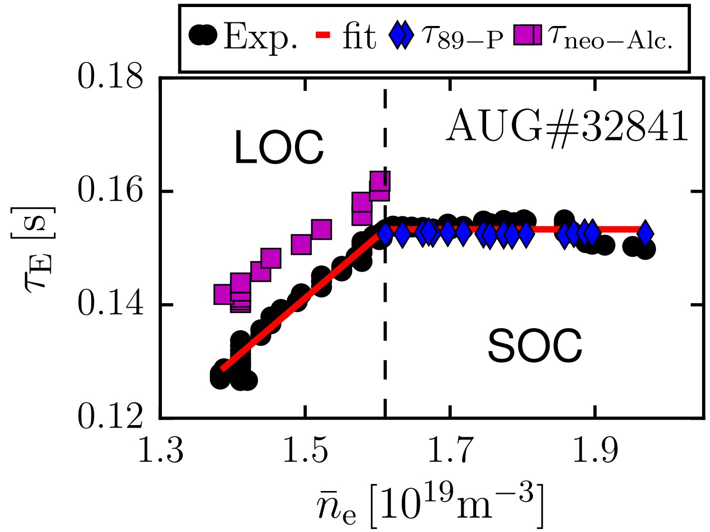


Overview

- CXRS diagnostics at ASDEX Upgrade
  - System capabilities & routine operation
  - Measurement of core impurity poloidal rotation
- Rotation studies
  - Database of impurity poloidal rotation
  - Measurements across the LOC-SOC
- Impurity particle transport studies
  - New method for determining B transport coefficients
  - Initial data and comparisons to theory

Transport changes in LOC-SOC

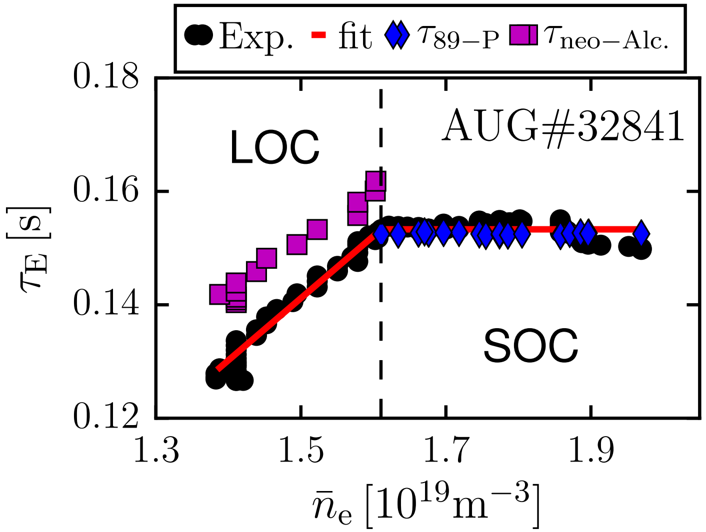
- Energy, particle, and momentum transport change in ohmic plasmas with increasing n_e
  - τ_E increases linearly until critical n_e, above which it saturates [1]
  - n_e shows non-monotonic behavior [2]
  - Intrinsic v_φ flips sign [3], twice [4]



[1] Murakami PRL1979, Ejima, NF 1981 , …
[2] Fable 2010, Angioni 2012
[3] Bortolon 2006, Duval 2007, Rice 2012
[4] Angioni 2011, McDermott 2011

Transport changes in LOC-SOC

- Energy, particle, and momentum transport change in ohmic plasmas with increasing n_e
  - τ_E increases linearly until critical n_e, above which it saturates [1]
  - n_e shows non-monotonic behavior [2]
  - Intrinsic v_φ flips sign [3], twice [4]



- Changes historically attributed, directly or indirectly, to changes in plasma turbulence → TEM-ITG
  - Transition present, but not needed to explain energy transport changes — I. Erofeev NF 2017
  - TEM-ITG needed to explain electron particle transport [2]
  - Direct detection of turbulence changes difficult — Arnichand, NF/PPCF 2014/2016

[1] Murakami PRL1979, Ejima, NF 1981 , …
[2] Fable 2010, Angioni 2012
[3] Bortolon 2006, Duval 2007, Rice 2012
[4] Angioni 2011, McDermott 2011

Attempt to infer v_{ph} with NC v_θ failed

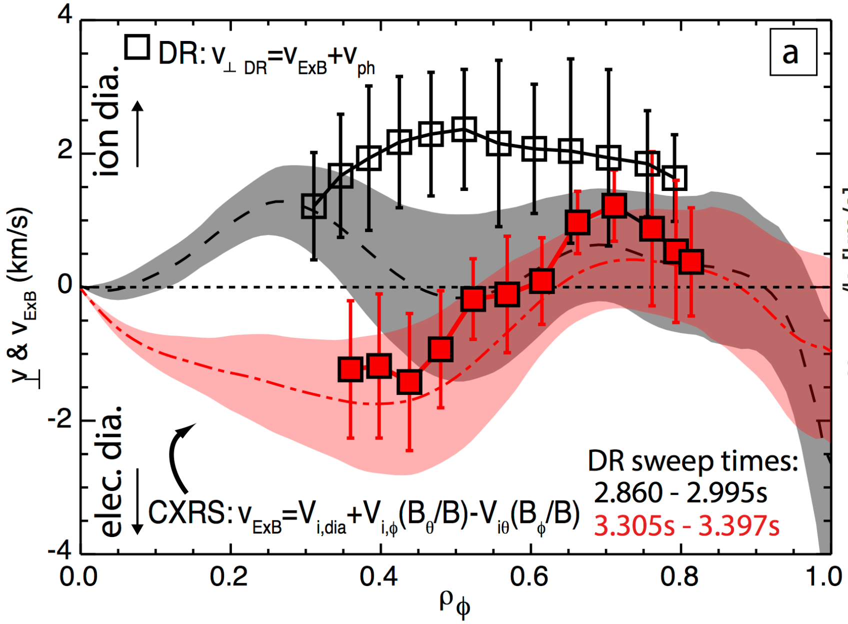
- v_{ph} indicative of “type”: TEM/ITG rotate in elec./ion direction
  - Reflectometry measures: $v_{perp} = v_{ExB}+v_{ph}$
  - Independent measure of v_{ExB} yields information on v_{ph}

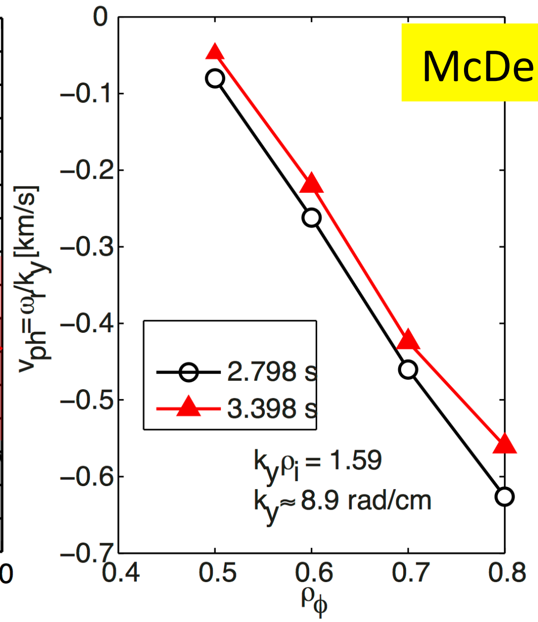
Attempt to infer v_{ph} with NC v_θ failed

- v_{ph} indicative of "type": TEM/ITG rotate in elec./ion direction
  - Reflectometry measures: $v_{perp} = v_{ExB} + v_{ph}$
  - Independent measure of v_{ExB} yields information on v_{ph}
    - 2014: v_{ExB} from radial force balance eqn. w/ CXRS v_φ & **NC v_θ**

Attempt to infer v_{ph} with NC v_θ failed

- v_{ph} indicative of "type": TEM/ITG rotate in elec./ion direction
  - Reflectometry measures: $v_{perp} = v_{ExB}+v_{ph}$
  - Independent measure of v_{ExB} yields information on v_{ph}
    - 2014: v_{ExB} from radial force balance eqn. w/ CXRS v_φ & NC v_θ



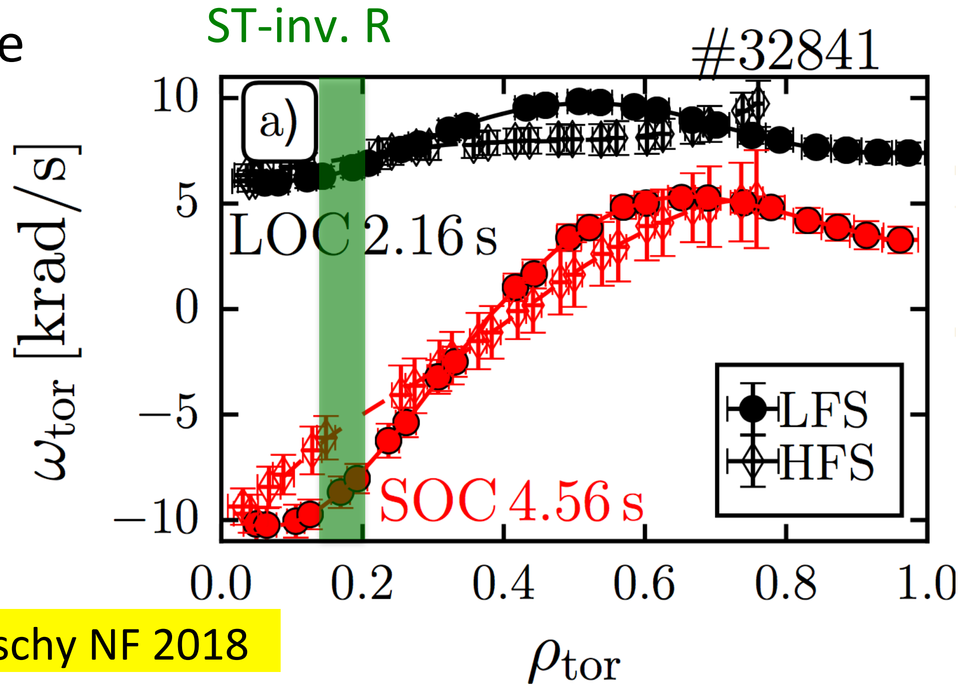


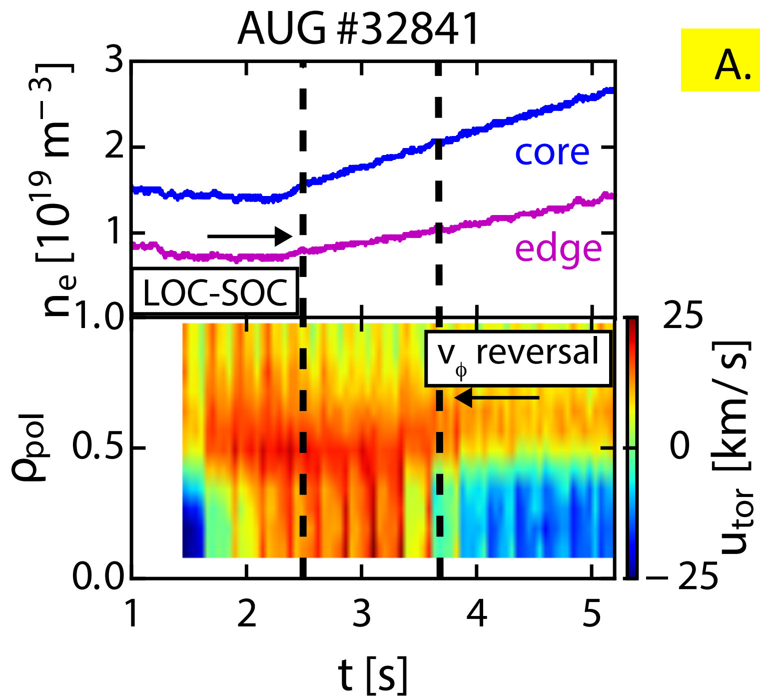
McDermott NF 2014

- Comparison in LOC indicated v_{ph}=~2km/s (ion-directed)!
  - Too big and 'wrong' direction!
  - 'Necessary' changes for 'reasonable' v_{ph} outside error bars → Non NC v_θ?

New CXRS provides higher quality data

- New CXRS diagnostics more sensitive
  - Smaller error bars
- v_φ reversal after LOC-SOC

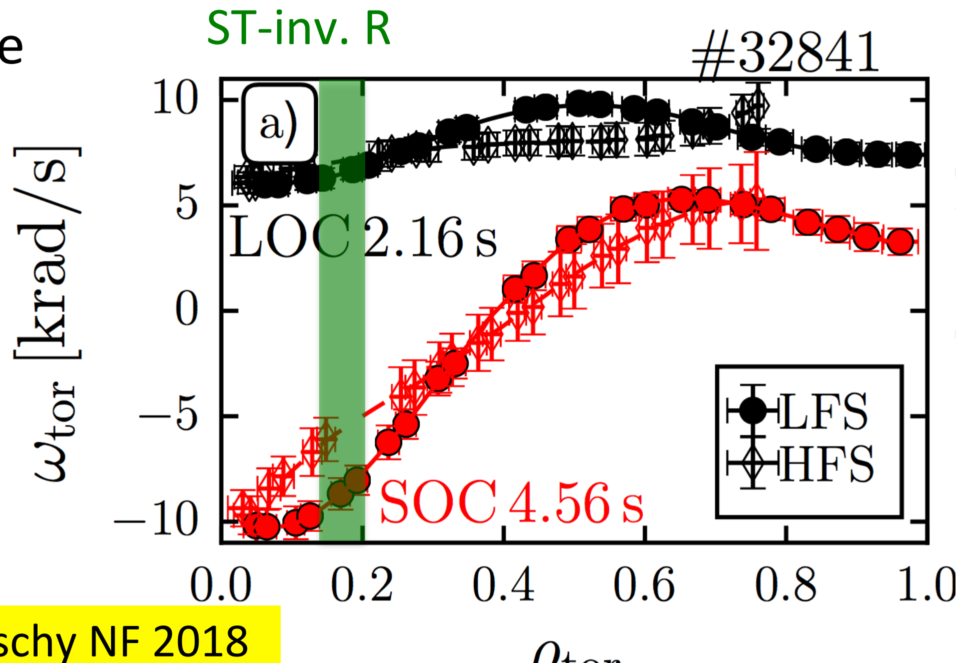


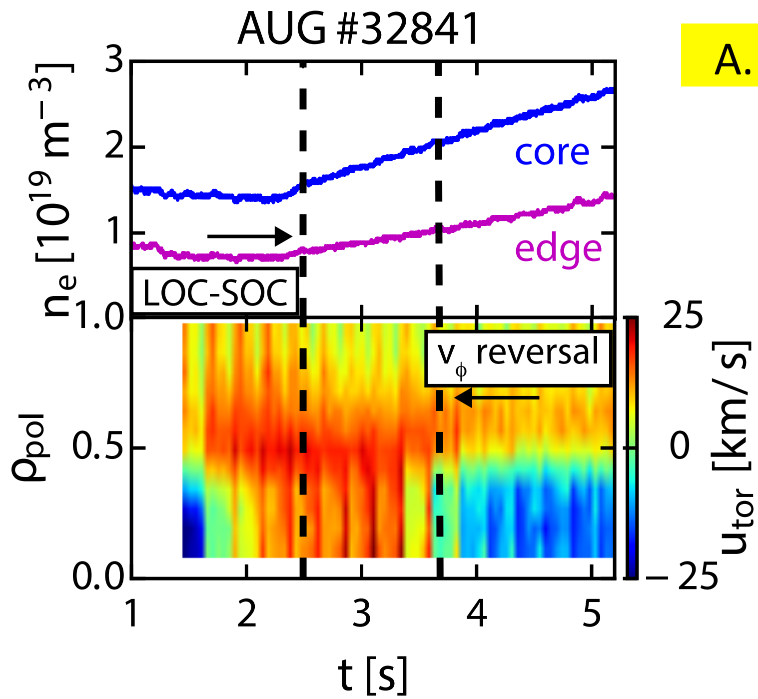


A. Lebschy NF 2018

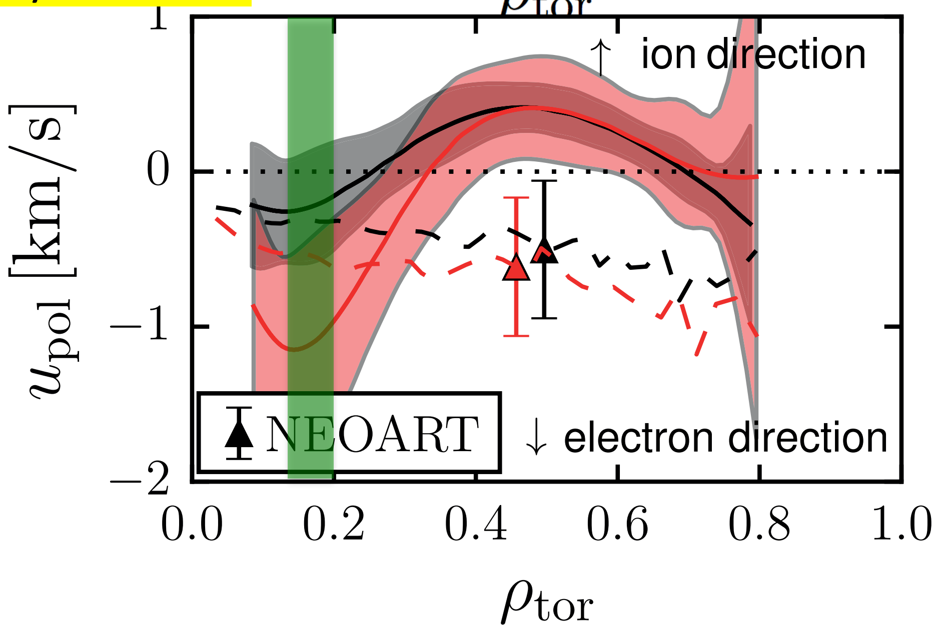
B pol. rotation not NC at mid-radius

- New CXRS diagnostics more sensitive
  - Smaller error bars
- v_φ reversal after LOC-SOC
- $v_{\theta,B}$ constant at both transitions
- Non-NC $v_{\theta,B}$ at mid-radius
  - More ion-directed by >1km/s!



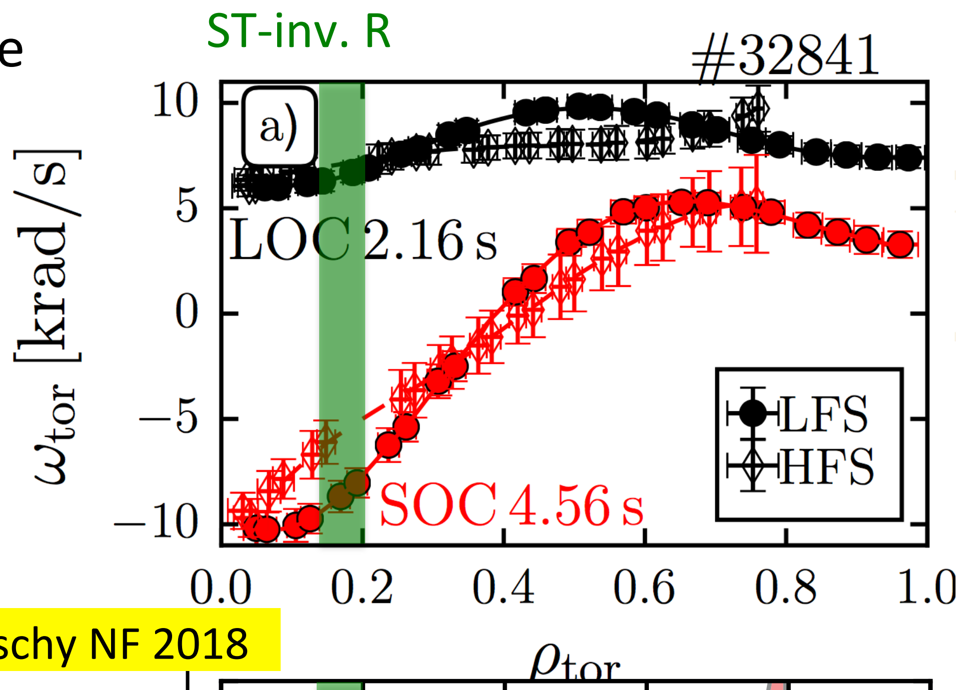


A. Lebschy NF 2018

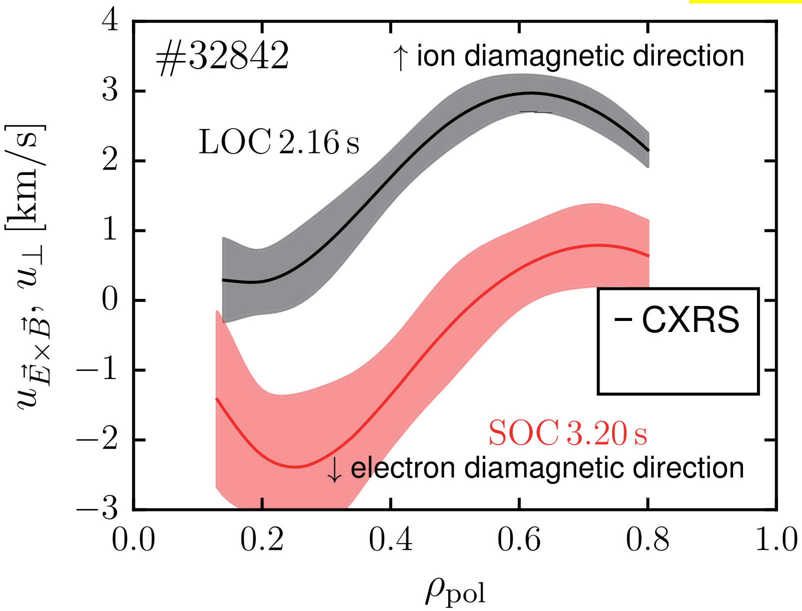


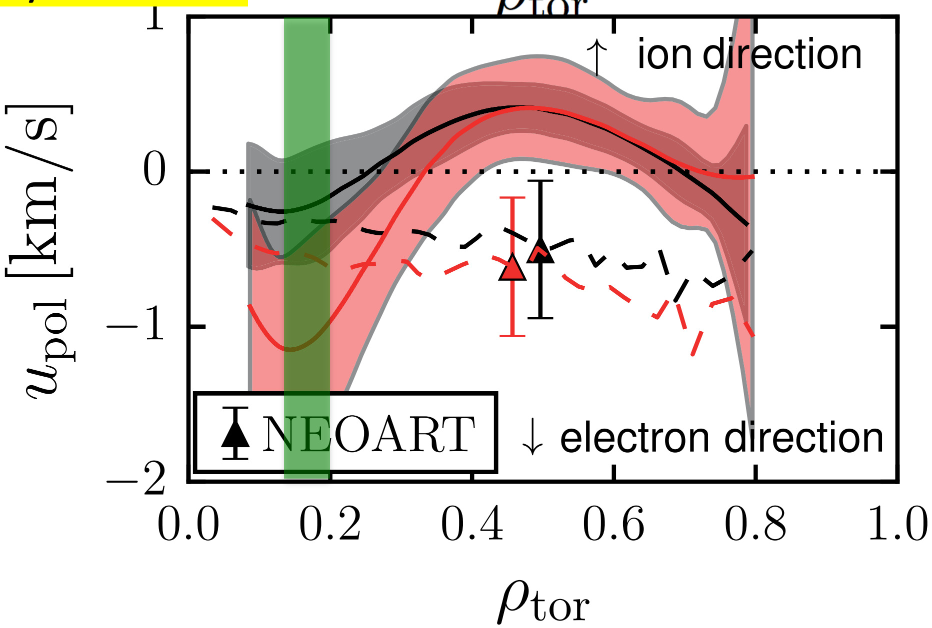
B pol. rotation not NC at mid-radius

- New CXRS diagnostics more sensitive
  - Smaller error bars
- v_φ reversal after LOC-SOC
- $v_{\theta,B}$ constant at both transitions
- Non-NC $v_{\theta,B}$ at mid-radius
  - More ion-directed by >1km/s!
- v_{ExB} determined to ~0.5km/s



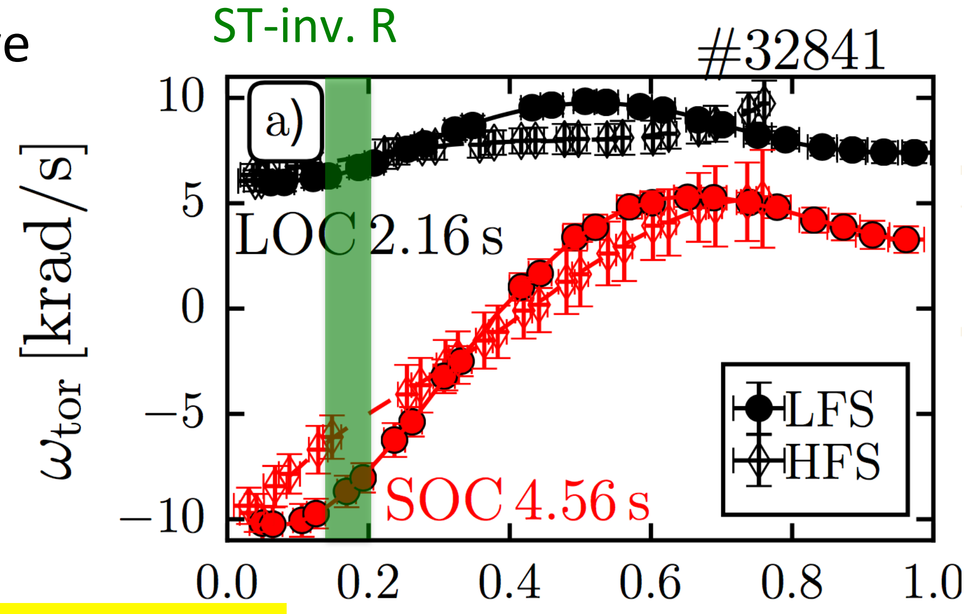
A. Lebschy NF 2018



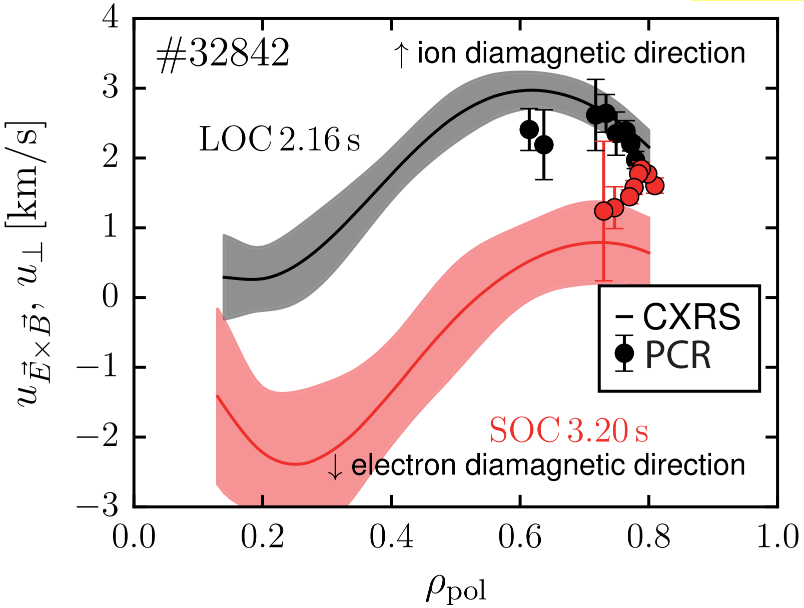


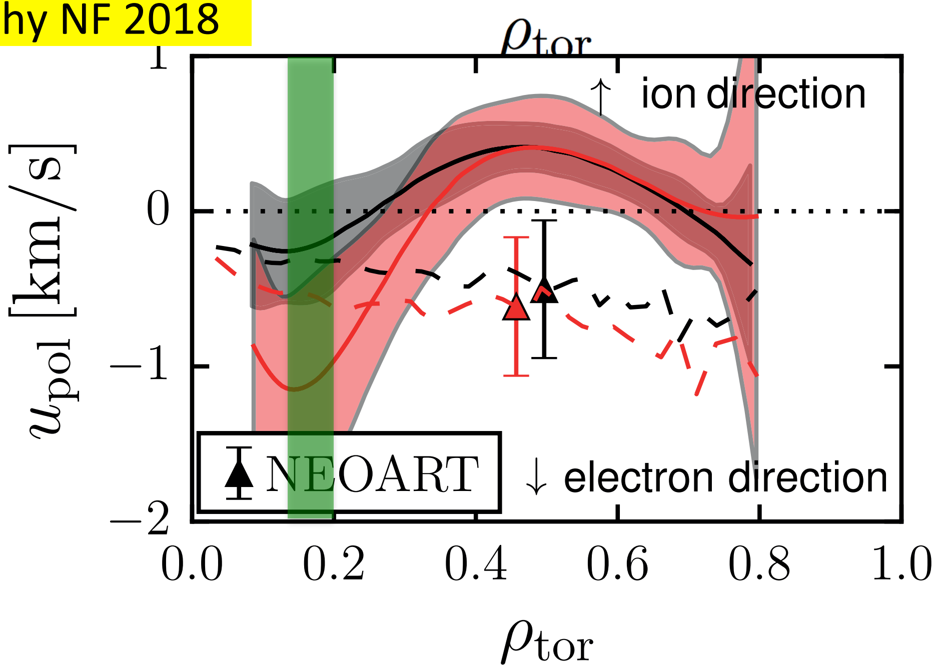
Core v_{ExB} now very well determined

- New CXRS diagnostics more sensitive
  - Smaller error bars
- v_{φ} reversal after LOC-SOC
- $v_{\theta,B}$ constant at both transitions
- Non-NC $v_{\theta,B}$ at mid-radius
  - More ion-directed by >1km/s!
- v_{ExB} determined to ~0.5km/s



A. Lebschy NF 2018

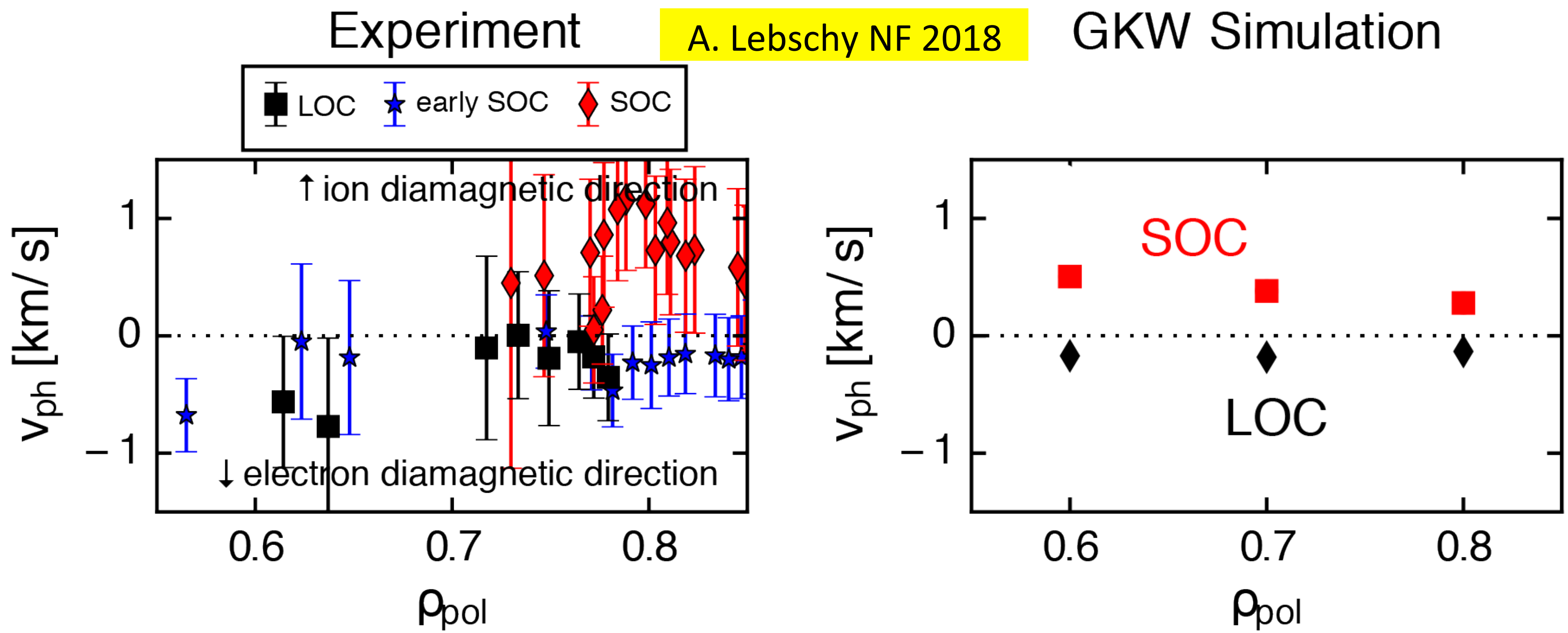




Edge TEM-ITG transition after LOC-SOC

- Data obtained from 2 LOC-SOC transitions and comparison between reflectometry and CXRS data
- Change in edge v_{ph} from elec. to ion direction after LOC-SOC (in SOC)
- Qualitatively consistent with GKW simulation predictions
  - Strongly sensitive to Zeff

A. Lebschy NF 2018

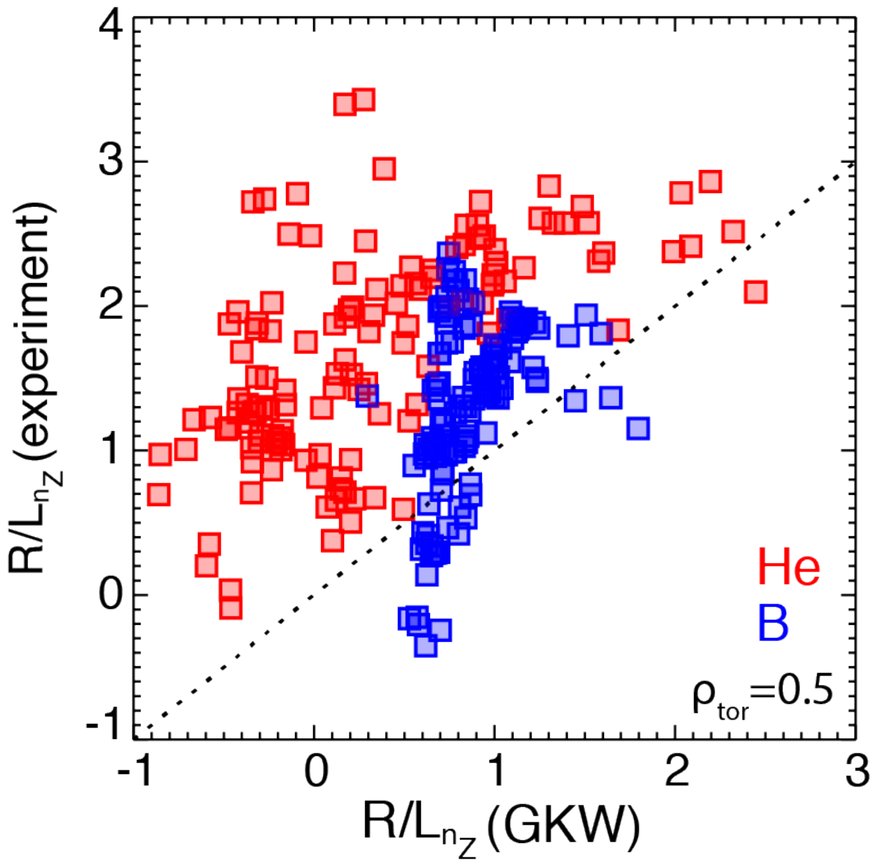


Overview

- CXRS diagnostics at ASDEX Upgrade
  - System capabilities & routine operation
  - Measurement of core impurity poloidal rotation
- Rotation studies
  - Database of impurity poloidal rotation
  - Measurements across the LOC-SOC
- Impurity particle transport studies
  - New method for determining B transport coefficients
  - Initial data and comparisons to theory

GK+NC unable to predict low-Z R/L_{nZ}

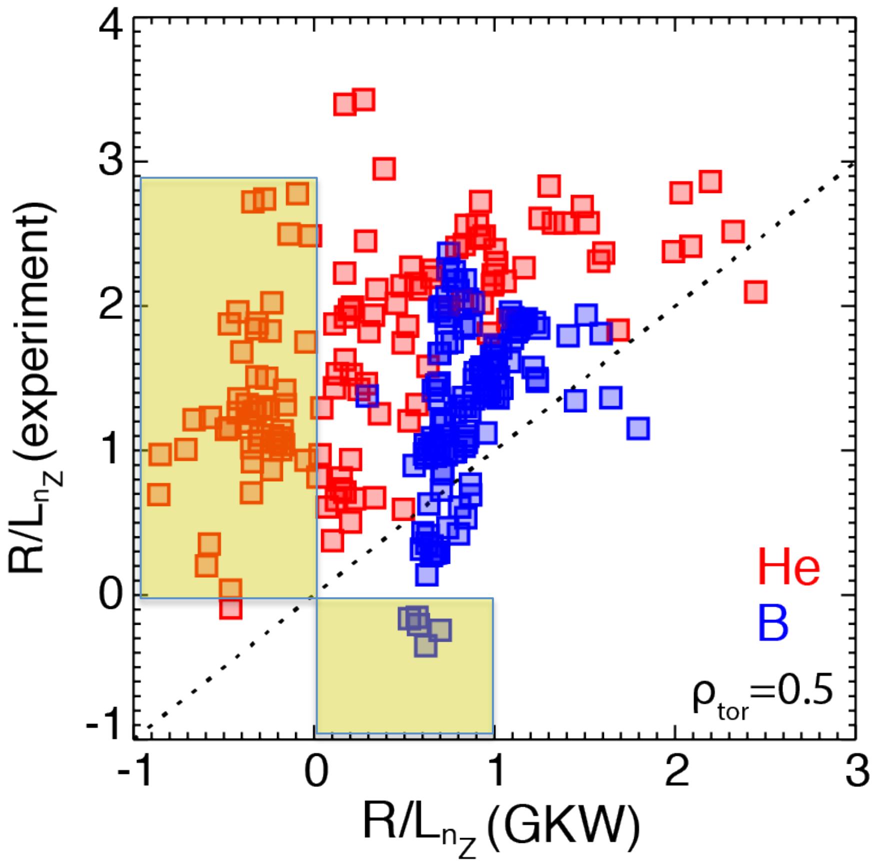
- Database of He and B density profiles constructed over wide parameter space:
  - R/L_{ne} ~ 0-4
  - R/L_{Ti} ~ 3-7
  - u' ~ -0.15-1.1
  - $v_{eff} = v_{ei}/(c_s/R)$~ 0.3-1.9
- Theory unable to capture experimental observations
  - He profiles systematically under-predicted



Thesis Work Dr. A. Kappatou, t.b.s NF 2018

GK+NC unable to predict low-Z R/L_{nZ}

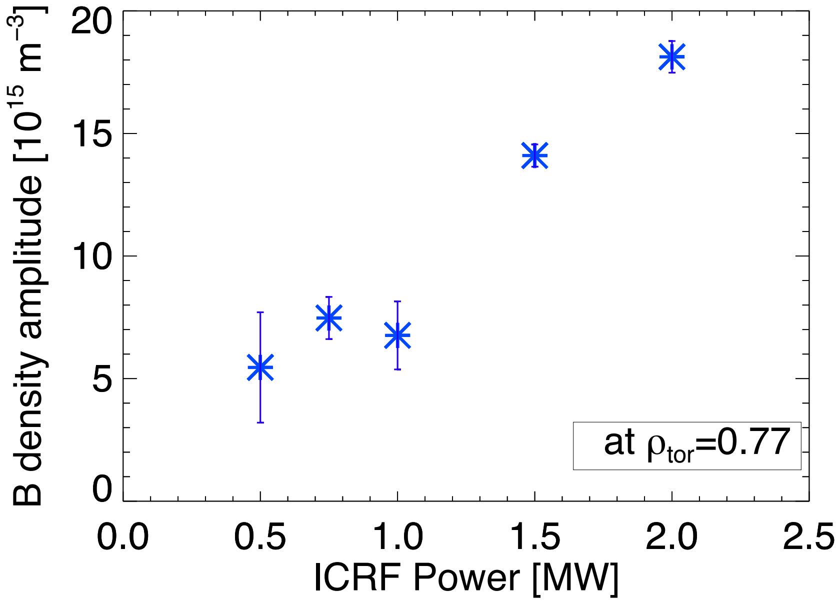
- Database of He and B density profiles constructed over wide parameter space:
  - R/L_{ne} ~ 0-4
  - R/L_{T_i} ~ 3-7
  - u' ~ -0.15-1.1
  - $\nu_{eff} = \nu_{ei}/(c_s/R)$~ 0.3-1.9
- Theory unable to capture experimental observations
  - He profiles systematically under-predicted
  - Regions of opposite sign indicate "v" incorrect
    - Does not mean "D" is right

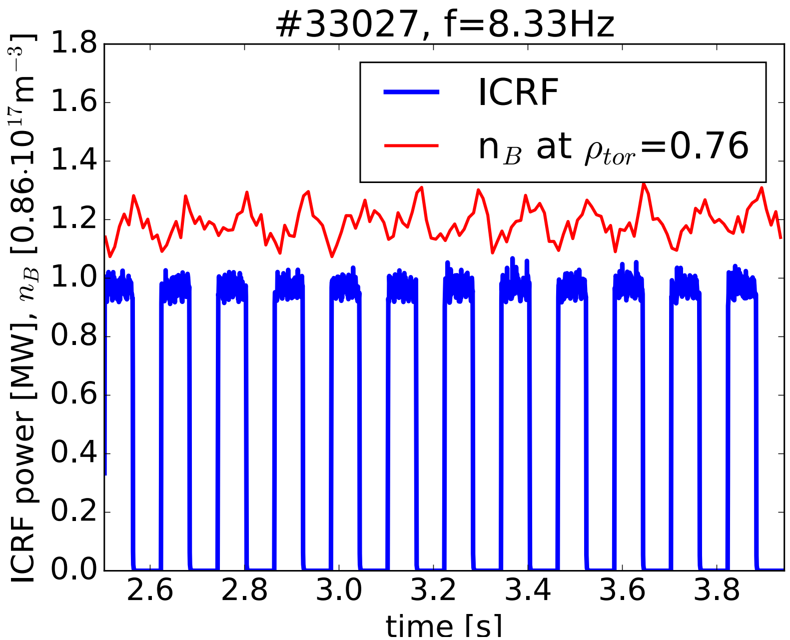


Thesis Work Dr. A. Kappatou, t.b.s NF 2018

ICRF power increases n_B in plasma

- After boronization (~2 weeks) application of ICRF increases n_B
- B increases first at edge & propagates inward → SOL source
  - 36MHz, H-minority ICRF
  - W and B-coated antennas
  - $\Delta n_B \sim P_{ICRF}$
  - No B increase for either steady state or modulated ECRH
  - P_{ICRF}<1MW + f_{mod} > 8Hz
    - stable background conditions
    - ~10-15% n_B perturbation at edge

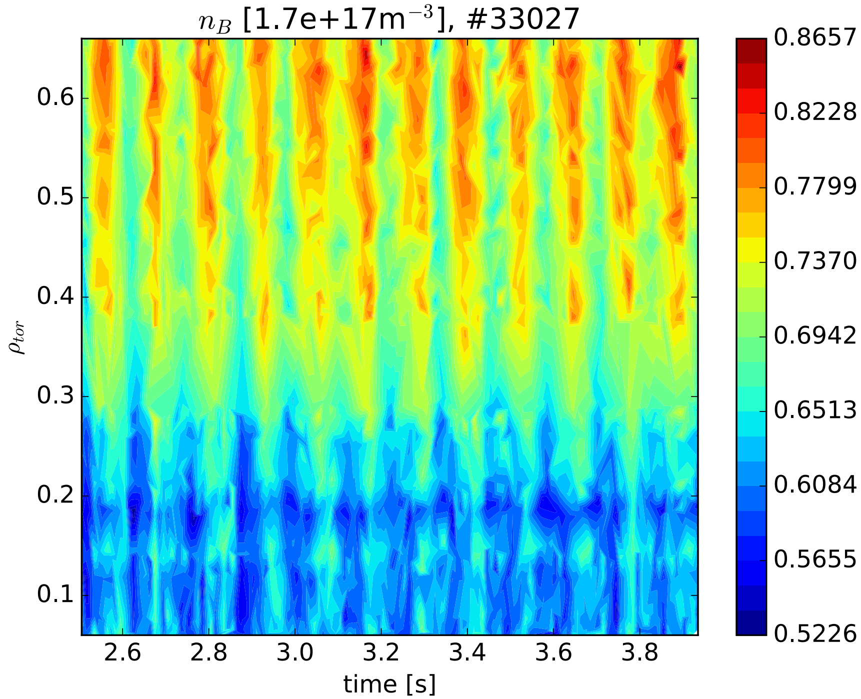




Thesis Work C. Bruhn, PPCF in preparation

n_B signal clear and sinusoidal

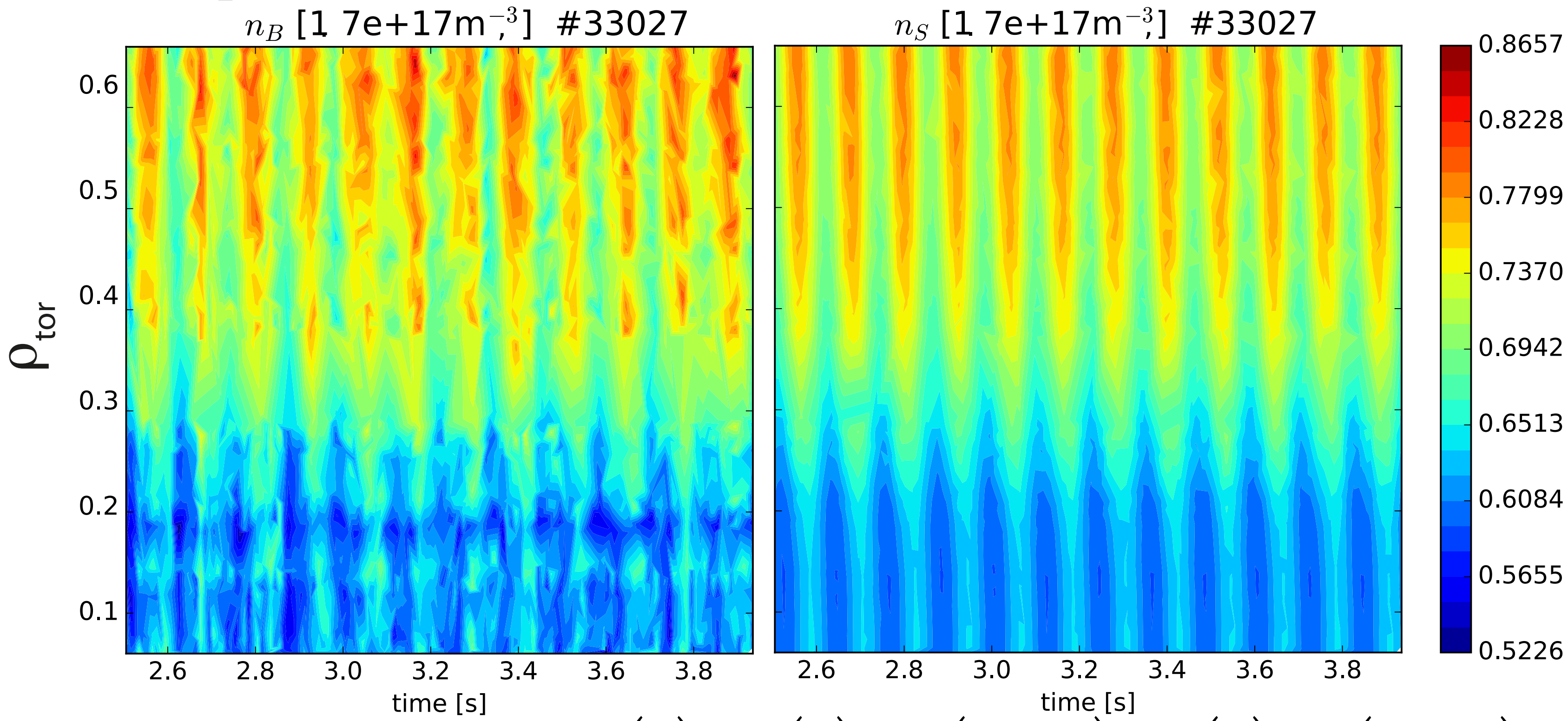
- 8-10Hz symmetric modulation
- Up to 10% n_B perturbation at pedestal top
- 2-4% in plasma center
- n_B measured w/ 10ms & 16-40 radial locations on LFS
- Data fits VERY well to sine + cosine ansatz



- Model n_B: $$n_{B\_\mathrm{mod}} = n_0(r) + a(r)\cos(2\pi f t) + b(r)\sin(2\pi f t)$$
- Minimize: $$\min_{D,v} \frac{1}{2}\left\| n_{B\_\mathrm{mod.}} - n_{B\_meas.} \right\|^2$$
- Such that: $$\frac{\partial n_{B\_\mathrm{mod}}(r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r \left(D(r) \frac{\partial n_{B\_\mathrm{mod}}(r,t)}{\partial r} - v(r) n_{B\_\mathrm{mod}}(r,t) \right)$$

Thesis Work C. Bruhn, PPCF in preparation

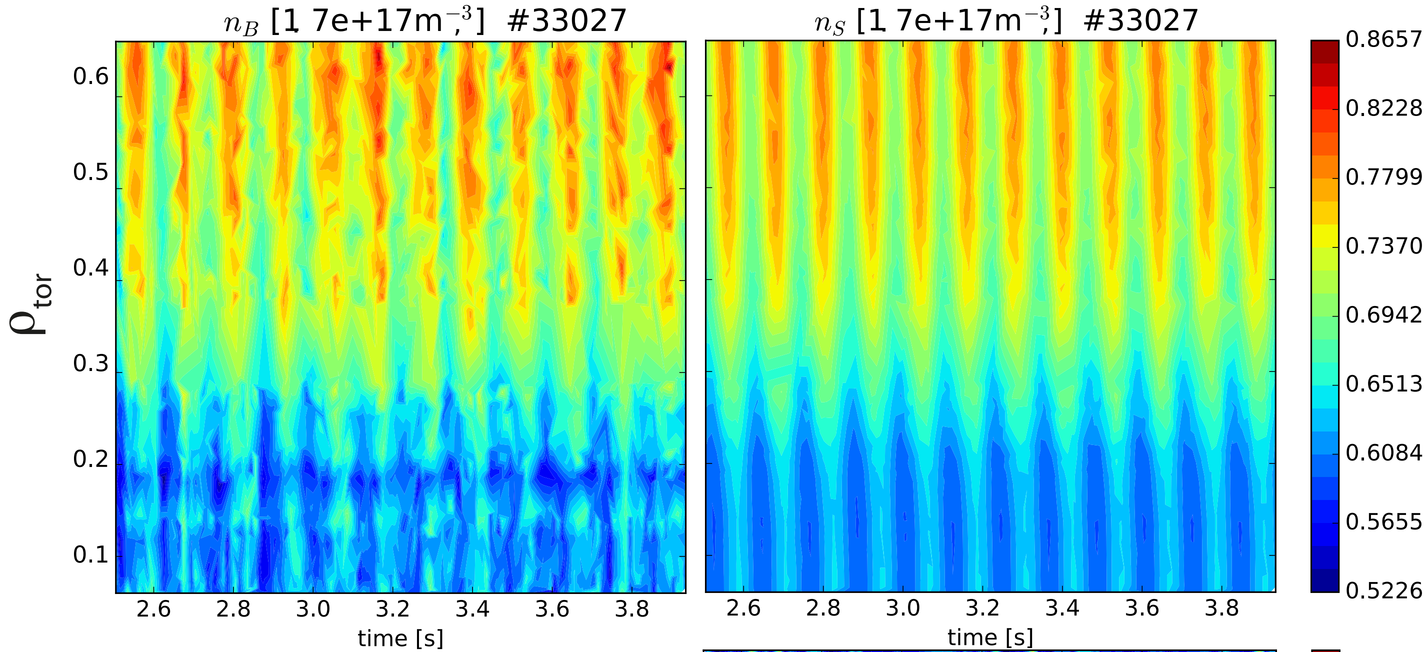
n_B signal clear and sinusoidal



- Model n_B: $$n_{B\_\mathrm{mod}} = n_0(r) + a(r)\cos(2\pi f t) + b(r)\sin(2\pi f t)$$
- Minimize: $$\min_{D,v} \frac{1}{2}\left\| n_{B\_\mathrm{mod.}} - n_{B\_meas.} \right\|^2$$
- Such that: $$\frac{\partial n_{B\_\mathrm{mod}}(r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r\left(D(r)\frac{\partial n_{B\_\mathrm{mod}}(r,t)}{\partial r} - v(r) n_{B\_\mathrm{mod}}(r,t) \right)$$

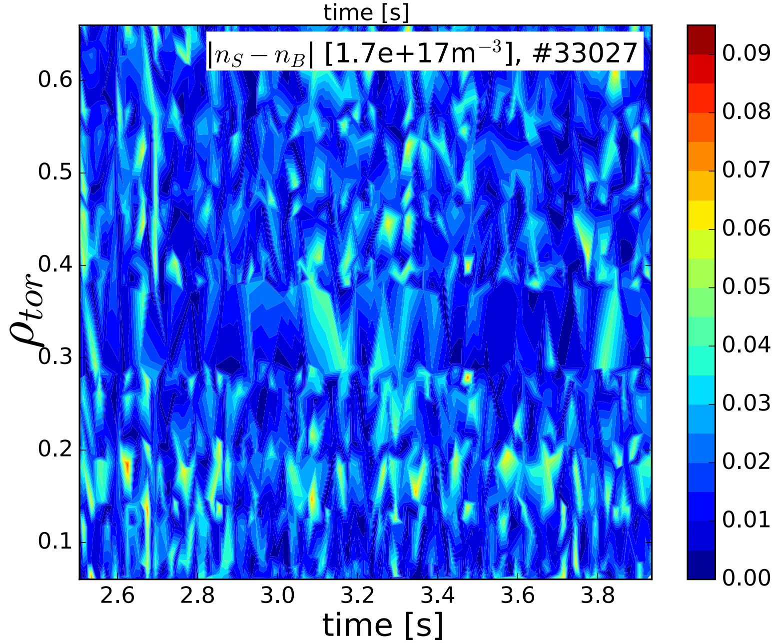
Thesis Work C. Bruhn, PPCF in preparation

n_B signal clear and sinusoidal



$$n_{B\_mod} = n_0(r) + a(r)\cos(2\pi f t) + b(r)\sin(2\pi f t)$$

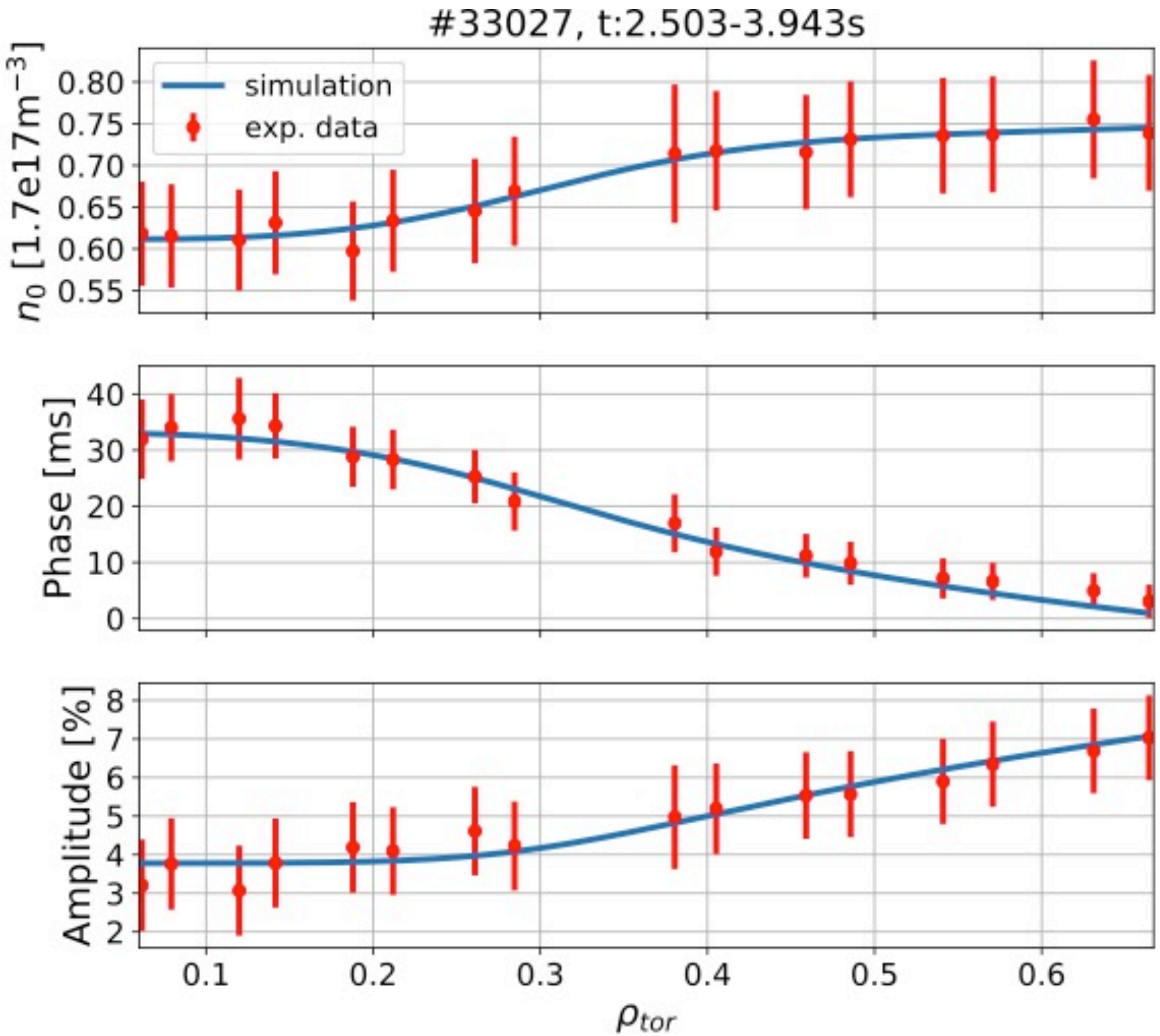
- Residuals ~3-5%
- FFT of residuals indicates ansatz characterizes the data well
  - No remaining freq. peaks



Thesis Work C. Bruhn, PPCF in preparation

Experimental data well reproduced

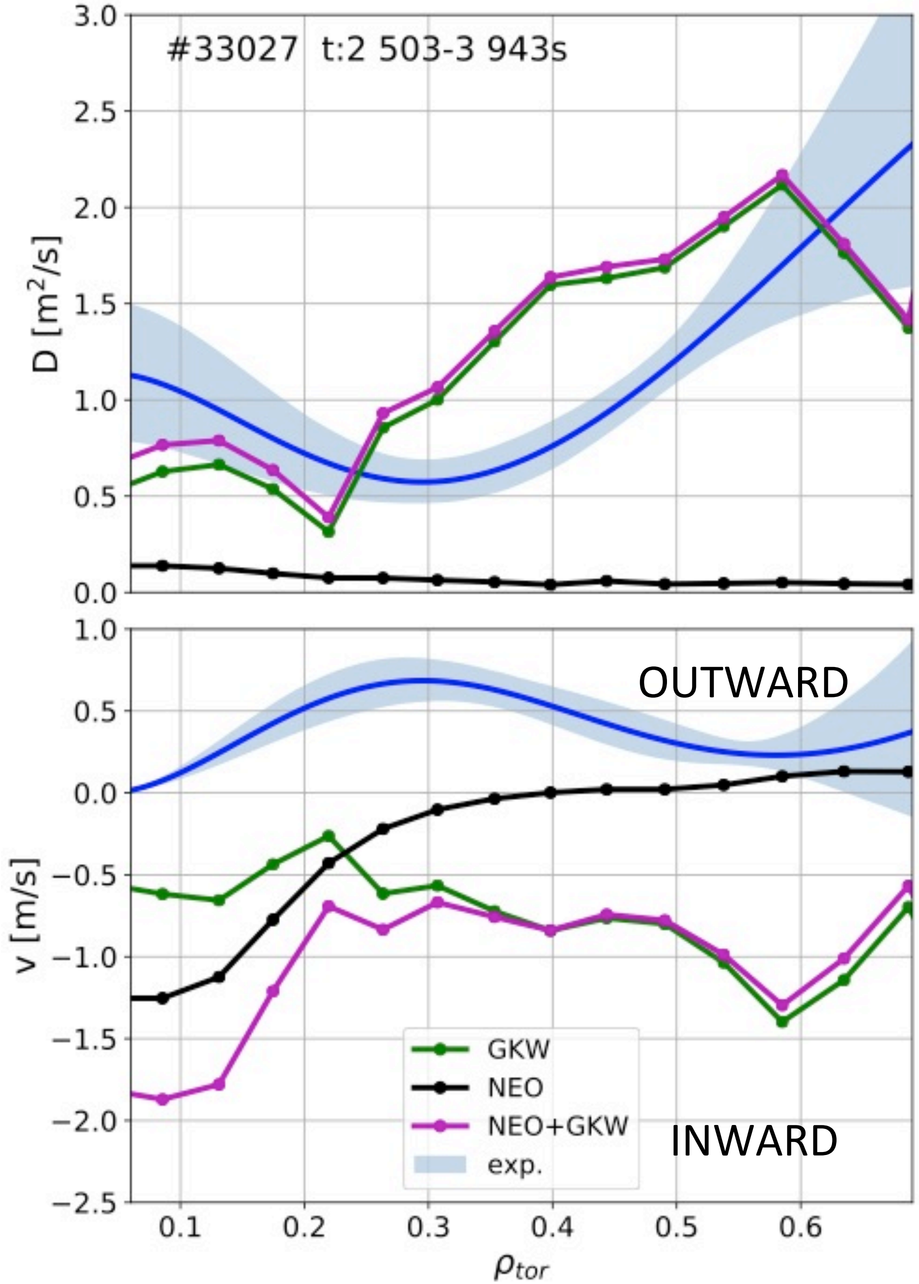
- Steady state, phase and amplitude from simulation reproduce experiment well
- Analysis also benchmarked against STRAHL



Thesis Work C. Bruhn, PPCF in preparation

Predicted convection is a problem

- Neoclassical transport coefficients (NEO) 10x too small
- GKW QL correct order of magnitude and qualitatively very similar diffusion coefficients
- GKW convective velocity predicted wronged way (inward instead of outward)!
    - Missing outward flux, too strong inward flux?
- Next steps: database approach covering achievable variation in dimensionless parameters



Thesis Work C. Bruhn, PPCF in preparation

Summary and Conclusions

- CXRS systems at ASDEX Upgrade upgraded (McDermott, RSI 2017)
  - Routinely provide full profiles of T_i, V_φ, and n_Z from 4 (up to 6) impurity species
  - Provide very high quality v_θ and v_{ExB} profiles in the plasma core

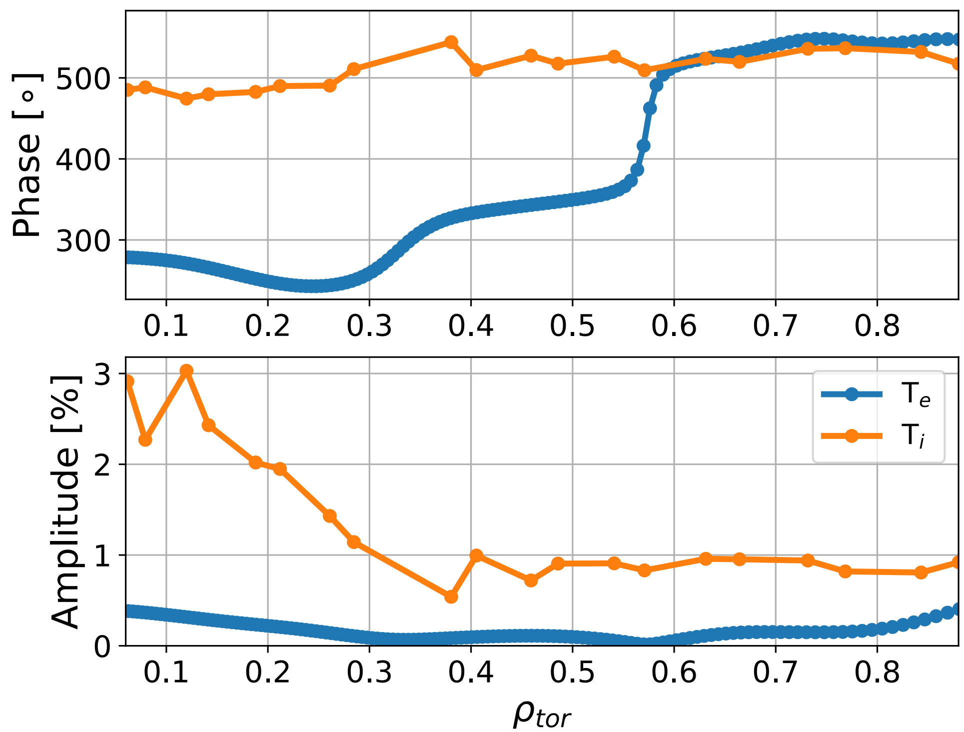
- Core $v_{\theta,B}$ routinely measured in the ion-dia. direction (A. Lebschy, NF 2018)
  - Non NC, indicates a strong unaccounted for turbulent (or other?) drive
  - Correct $v_{\theta,B}$ important for correctly determining core ExB velocity

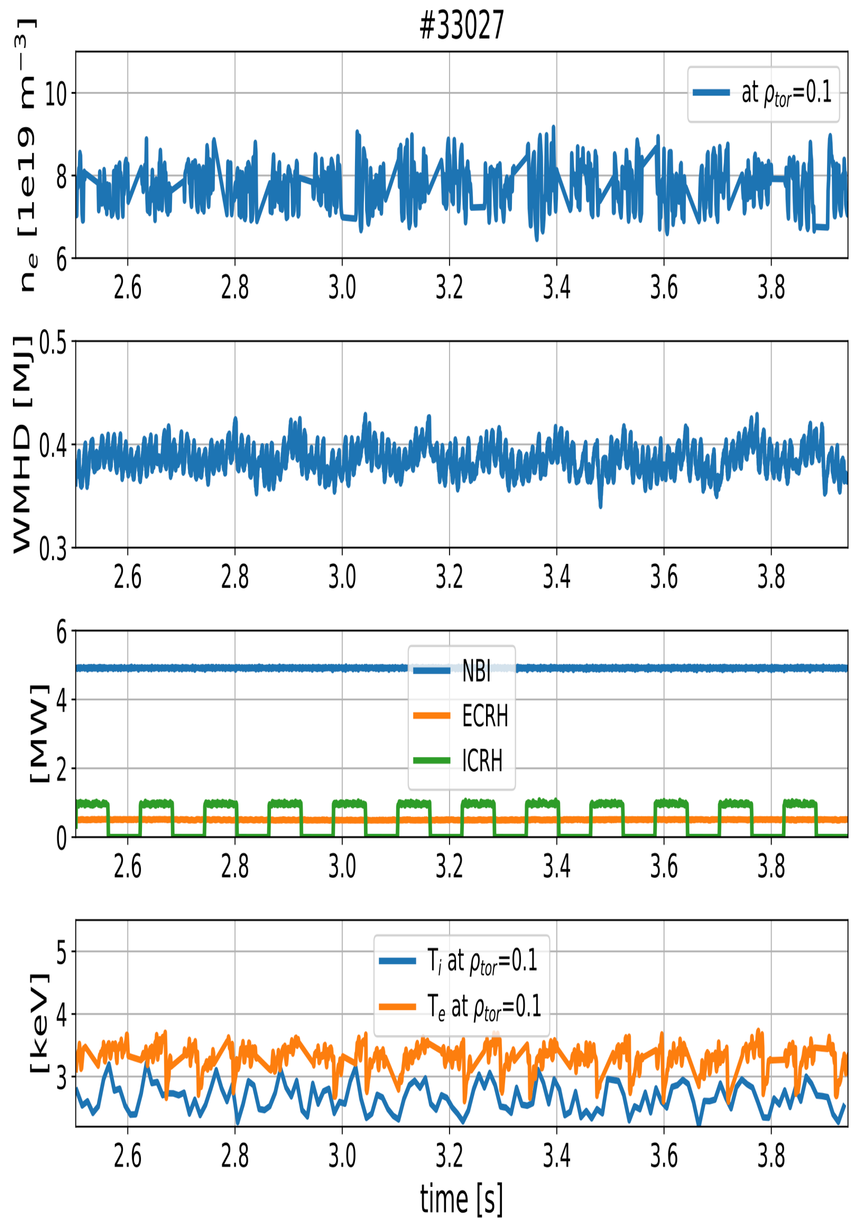
- Comparison of v_{ExB} & "$v_{ExB}+v_{ph}$" yield v_{ph} (A.Lebschy, NF 2018)
  - In SOC regime: change of v_{ph} toward the ion direction at edge

- New modulation method to separate D & v (C. Bruhn, PPCF, 2018 in preparation)
  - Applicable (and has ben applied) over wide range of plasma parameters
  - NC insufficient to explain observed transport
  - GKW D of correct order of magnitude and qualitatively similar shape
  - Predicted convective velocity goes the wrong way

Minimal perturbation from P_{ICRF} modulation

- No modulation visible on n_e & T_e
- W_{MHD} perturbation from T_I at ICRF deposition location (<3%)
- Steady conditions for transport analysis for RT> 0.25





Thesis Work C. Bruhn, PPCF in preparation