Lower hybrid current drive in conditions of an unbridgeable spectral gap by toroidal refraction

Y. Peysson, D. Mazon, J.-F. Artaud, A. Ekedahl, L Delpech, J. Hillairet, T. Hoang, X. L. Zou, X. Y. Bai, Y. P. Zhang, et al.

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DE LA RECHERCHE À L'INDUSTRIE

Lower Hybrid current drive in conditions of an unbridgeable spectral gap by toroidal refraction

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Outline

- The spectral gap problem
- Kinematics of the LH wave
- Current drive calculations
- Conclusion

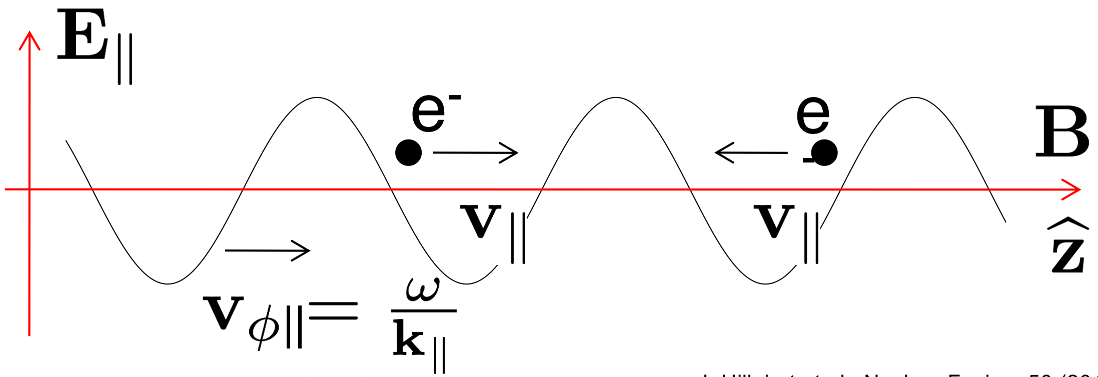
The spectral gap problem

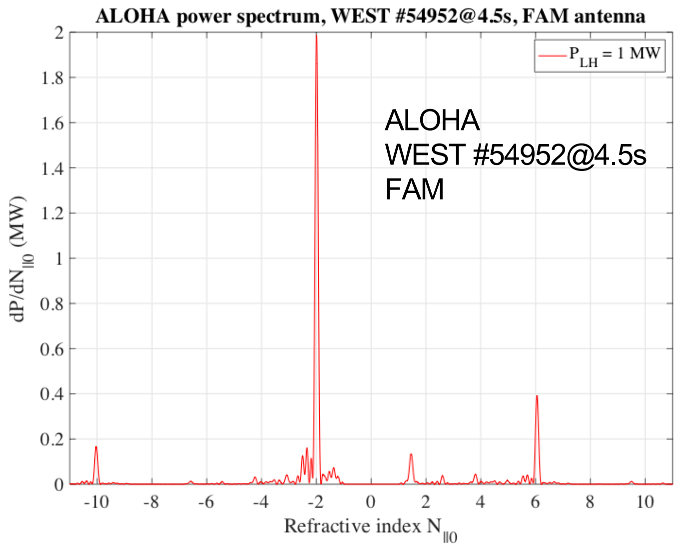
- The spectral gap problem is the consequence of minimizing the recycling RF power for driving a toroidal current in tokamak plasmas (Fisch's theory)

- Direct push parallel to local magnetic field B $\left(v_{\parallel} \gg v_{te}\right)$:

$$\frac{\Delta J_{\parallel}}{\Delta P} \sim \frac{1}{v_{\parallel}\nu_{coll}\left(v_{\parallel}\right)} \quad + \quad \nu_{coll}\left(v_{\parallel}\right) \sim \frac{n}{v_{\parallel}^{3}} \quad \rightarrow \quad \boxed{\frac{\Delta J_{\parallel}}{\Delta P} \sim \frac{v_{\parallel}^{2}}{n}}$$

- Longitudinal kinetic resonance : $\boxed{v_{\parallel} = v_{\phi\parallel} = \frac{c}{N_{\parallel}}}$



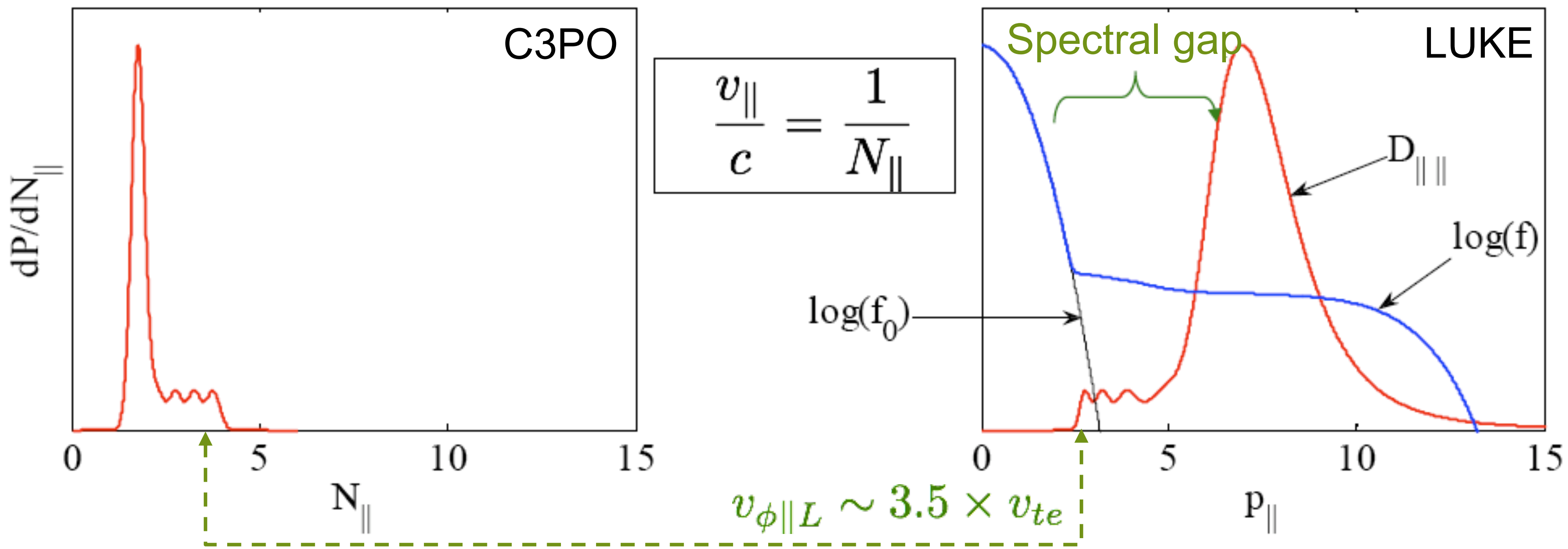


N.J. Fisch, Rev. Mod. Phys., 59 (1987) 175

J. Hillairet et al., Nuclear Fusion, 50 (2010) 125010

The spectral gap problem

- For typical tokamak plasmas : T_{Te} = (1 – 10 keV), $v_{Te}/c \approx$ (0.04 – 0.14)
- $N_{\|}$ ($5 \times v_{Te}$) ≈ (1.4 – 4.5) $\rightarrow$ *$E_{c\|}$ ($5 \times v_{Te}$) ≈ (10 – 200) keV*
- ***Problem**: there is no electron at these kinetic energies with a Maxwellian distribution function → the plasma almost transparent to the RF wave*



Y. Peysson et al., Plasma Phys. Control. Fusion, 54 (2012) 045003

Y. Peysson and J. Decker, Fusion Science and Technology, 65 (2014) 22–42.

The spectral gap problem

- Linear theory of the LH wave → strong absorption when

$$N_{\parallel L} = c/v_{\phi\parallel L} \simeq 6.5/\sqrt{T_e\,[keV]}$$

- Excited power spectrum (main lobe) : $N_{\parallel 0} = c/v_{\phi\parallel 0}$

- **Spectral gap** : $\boxed{\delta_{N_{\parallel 0}} = \left(N_{\parallel L}^{\min} - N_{\parallel 0}\right)/N_{\parallel 0}}$

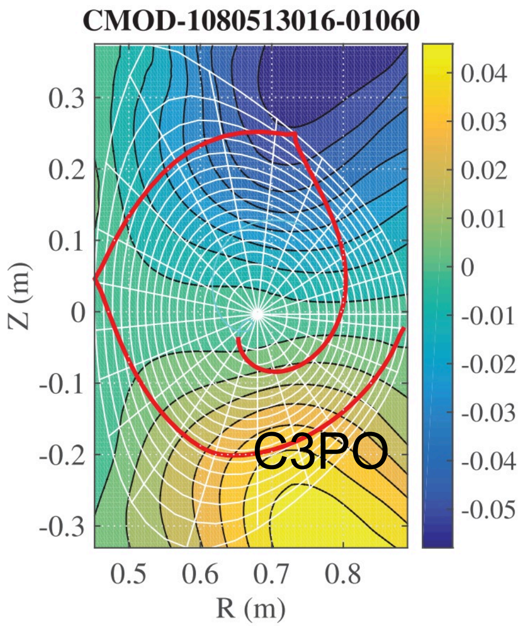
    - *Small gap* $\delta_{N_{\parallel 0}} < 1$ *(ITER)*

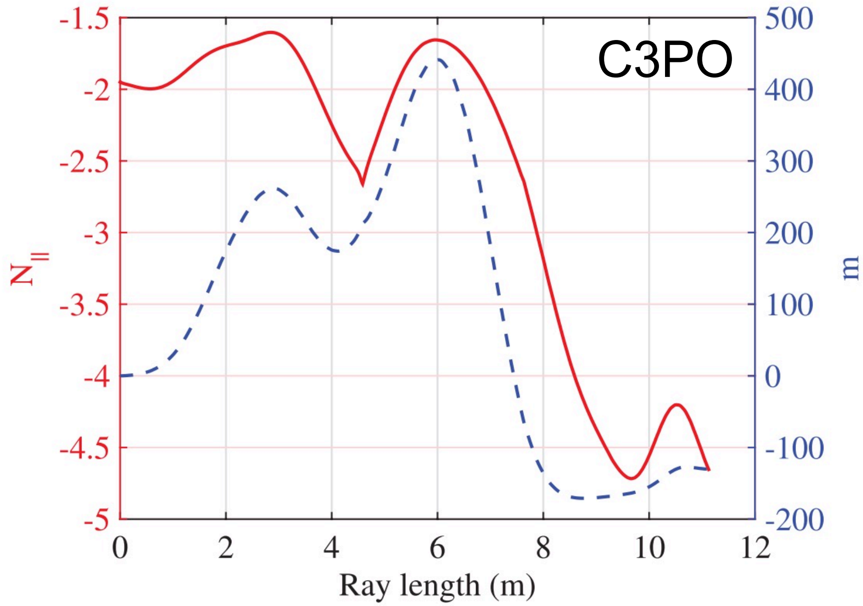
    - *Very large gap* $\delta_{N_{\parallel 0}} \gg 1$ *(all existing tokamaks)*

Y. Peysson, et al. EPJ Web of Conferences, 157 (2017) 02007

The spectral gap problem

- Main mechanism considered so far to bridge the spectral gap → *toroidal refraction (WKB approximation* → wave propagation described by ray-tracing)



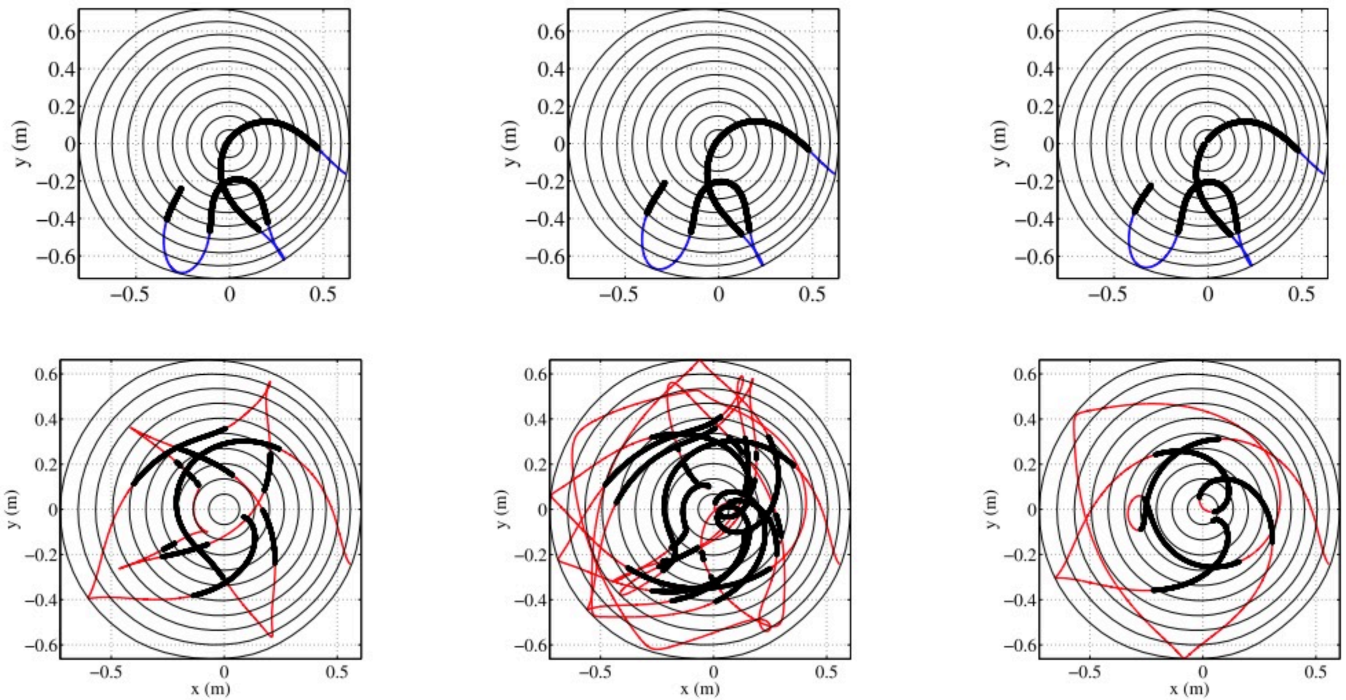


- When $\delta_{N_{\|0}} \gg 1$, wave absorption is weak, multipass absorption takes place leading to chaotic ray dynamics : high sensitivity to toroidal MHD equilibrium, launching conditions, numerics,… In this case, a wavefront cannot be defined because neighboring rays have diverged before full absorption → WKB approximation fails and ray tracing is not valid → *full-wave calculation (TORLH, ELECTRE)*

Y. Peysson, et al., Plasma Phys. Control. Fusion, 58 (2016) 044008

The spectral gap problem

C3PO



Tore Supra #45525

Tore Supra #45155

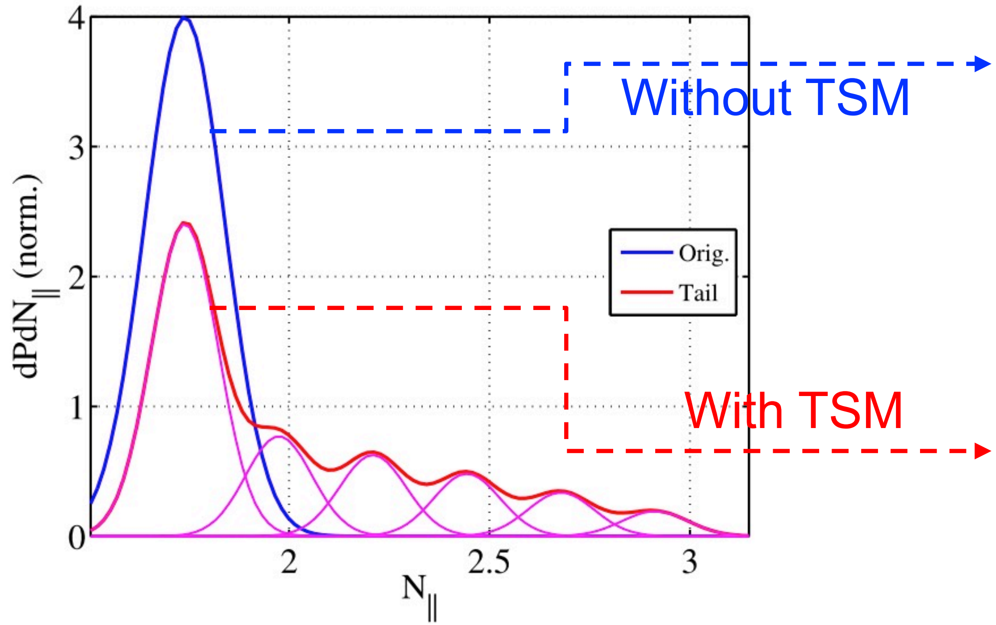
- The large numerical sensitivity of ray dynamics (trajectory, spectral upshift,…) impacts LH wave absorption, leading to poor agreement with observations (HXR,…).

- **Conversely, experimental observations are systematically robust and reproducible** → *Something is missing in the wave modeling*.

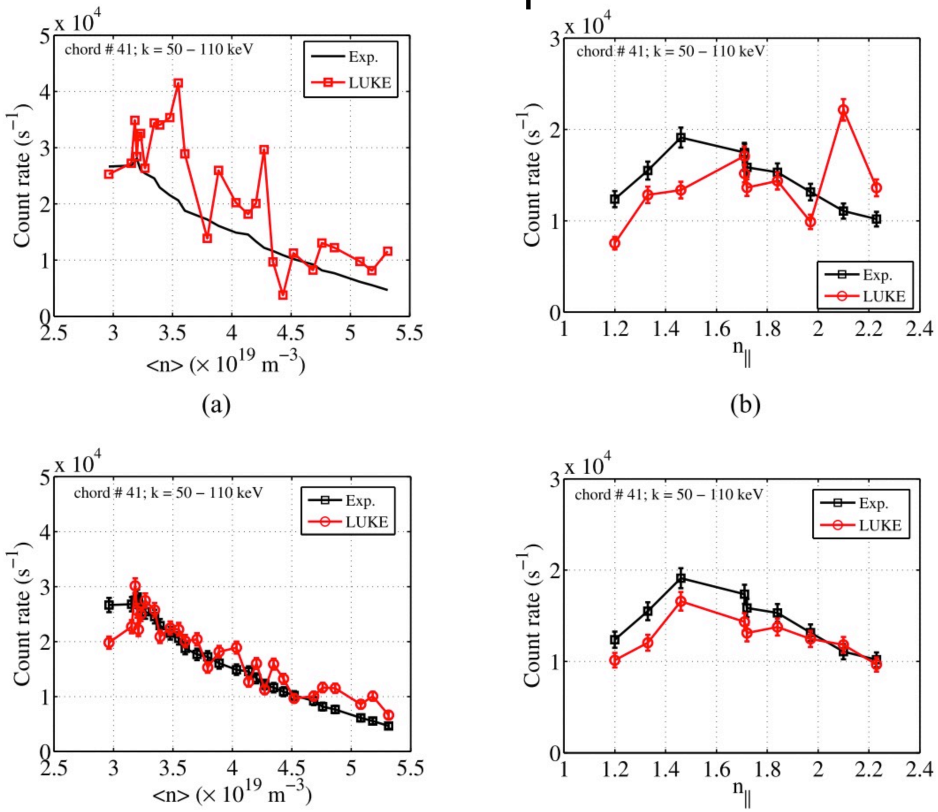
J. Decker, Y. Peysson, et al. Phys. Plasmas, 21 (2014) 092504

The spectral gap problem

Following full-wave simulations of full LHCD in TRIAM-1M characterized all by a huge spectral gap because of the very large aspect ratio (ELECTRE), its was suggested that the spectral gap is already filled when the LH wave penetrates the core plasma through the separatrix → ***tail spectral gap model (TSM)***



Tore Supra

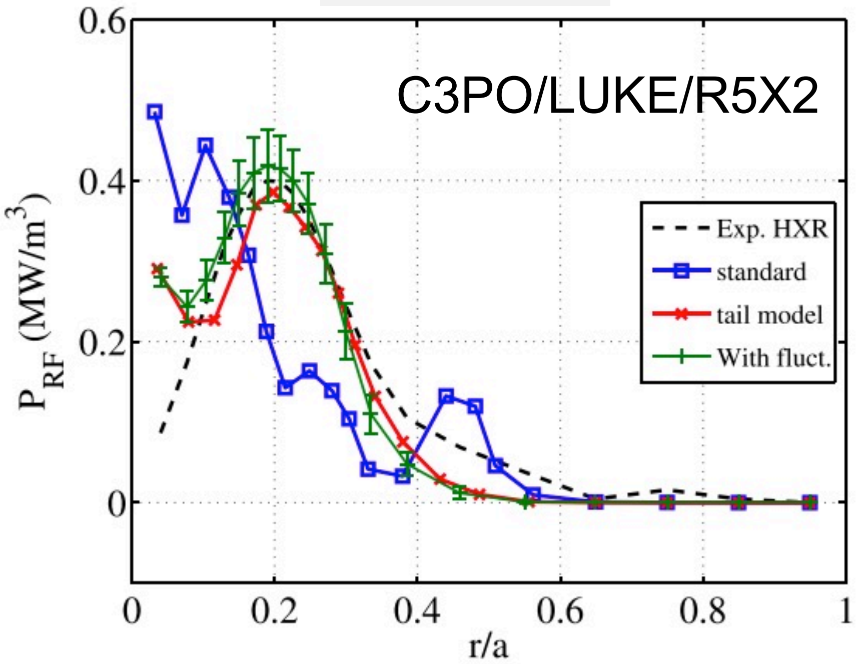


J. Decker, Y. Peysson, et al. Phys. Plasmas, 21 (2014) 092504

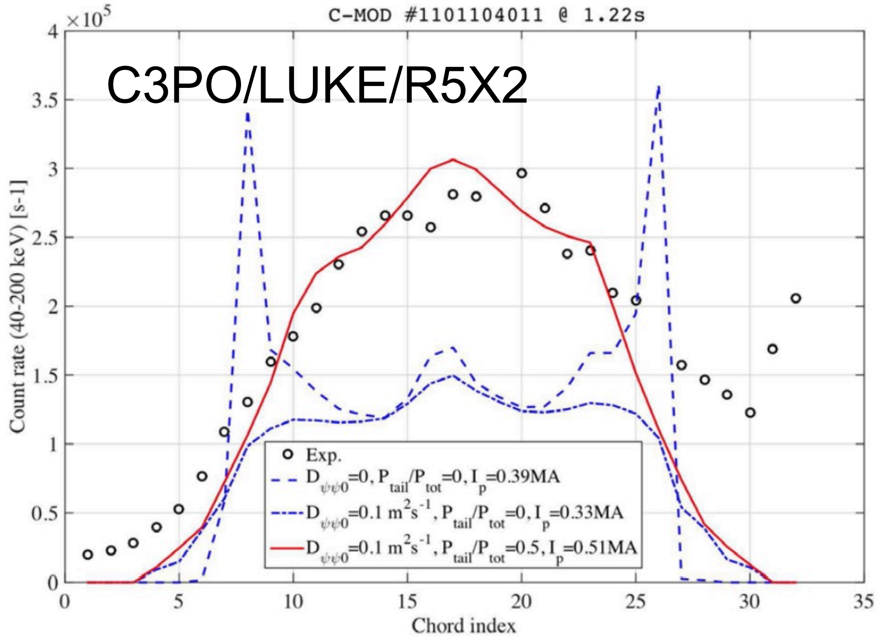
Y. Peysson, et al., Nucl. Fusion, 38 (1998) 939

The spectral gap problem

Tore Supra



Alcator C-Mod



- Tail spectral model greatly improves quantitative agreement with FEB observations
- In all studied regimes, *the spectral gap may be simultaneously bridged by TSM and the toroidal upshift.*

Find plasma conditions where toroidal upshift cannot bridge the spectral gap
→ very large aspect ratio tokamaks TRIAM-1M, WEST, HL-2A

J. Decker, Y. Peysson, et al. Phys. Plasmas, 21 (2014) 092504

Y. Peysson, et al., Plasma Phys. Control. Fusion, 58 (2016) 044008

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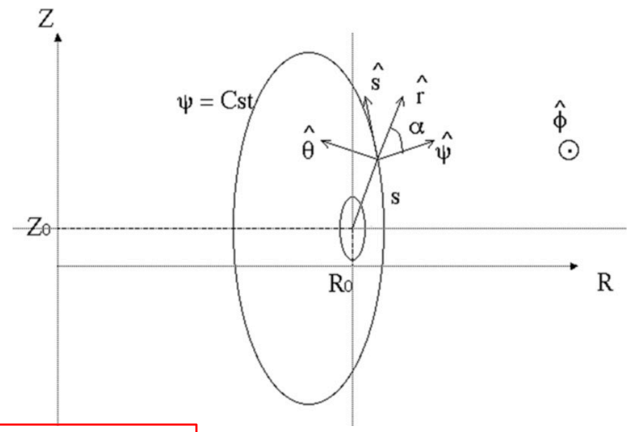
Kinematics of the LH wave

- Boundaries of the spectral domain into which the LH wave characterized by $N_{\|0}$ propagates are determined by the condition :



$$\boxed{k_\psi = 0} \qquad \text{with} \qquad k_\psi = \mathbf{k} \cdot \hat{\psi}$$

- Boundaries are solutions of the equation

$$\boxed{N^2_{\perp,\pm}\left(N_\|\right) - \left(\frac{N_\| - \left(\mathcal{T}/\mathcal{T}_0\right)\left(\Upsilon_0/\Upsilon\right) N_{\|0}}{\mathcal{P}\cos\alpha}\right)^2 - \frac{\Upsilon_0^2}{\Upsilon^2}\frac{N^2_{\|0}}{\mathcal{T}_0^2} + N^2_\| = 0}$$

where $\pm$ stands for slow or fast wave branches.

- $N^2_{\perp,\pm}$ is determined from the dispersion relation $\mathcal{D}\left(\mathbf{k},\omega\right) = 0$ (cold plasma approx.)

$$\Upsilon = R/R_p \qquad \mathcal{P}\left[\mathcal{T}\right] = B_p\left[B_T\right]/B \qquad R\left(\psi,\theta\right) = R_p + r\left(\psi,\theta\right)\cos\theta$$

Y. Peysson, et al., Plasma Phys. Control. Fusion, 58 (2016) 044008

Kinematics of the LH wave

- In the electrostatic limit, $N_\perp^2 = -\left(P/S\right) N_\parallel^2$, neglecting second order terms in $\mathcal{P}$

$$\left(\overline{\omega}_{pe}^2 \mathcal{P}^2 \cos^2\alpha - 1\right) N_\parallel^2 + 2\left(\mathcal{T}/\mathcal{T}_0\right)\left(\Upsilon_0/\Upsilon\right) N_{\parallel 0} N_\parallel - \left(\left(\mathcal{T}/\mathcal{T}_0\right)\left(\Upsilon_0/\Upsilon\right)\right)^2 N_{\parallel 0}^2 = 0$$

- Propagation domain has two boundaries if : $\boxed{\overline{\omega}_{pe} \mathcal{P} \left|\cos\alpha\right| > 1}$
- Since $\mathcal{P} \simeq \left(1+\kappa^2\right) \mathcal{A}^{-1} / \left(2q\right)$, a scaling may be deduced to identify plasmas with large spectral gaps

$$\boxed{\gamma_{KAM}^{cyl} = 5.68 \frac{I_P\left[MA\right] \sqrt{n_{e0}\left[10^{+19} m^{-3}\right]}}{f_{LH}\left[GHz\right] a_p\left[m\right] B_{T0}\left[T\right]}}$$

- If $\boxed{\gamma_{KAM}^{cyl} \ll 1}$, the propagation domain is bounded (two boundaries), otherwise it is open and in principle $N_{||}$ may grows up indefinitely.

F. Paoletti et al., Nucl. Fusion, 34 1994 (771)

Peysson, Y, et al., J. Fus. Energy 39 (2020) 270

Kinematics of the LH wave

Tokamak	Discharge	Aspect ratio	γ_{KAM} (cyl.)
TRIAM-1M	-	7.5	0.059
WEST	#54952	5.6	0.44 [0.37]
WEST	#55539	5.6	1.26
HL-2A	#35261	5.0	0.43
Tore Supra	#32299	3.4	0.9
Alcator C-Mod	#1101104011	3.1	1.5
ITER	Scenario IV	3.1	3.2

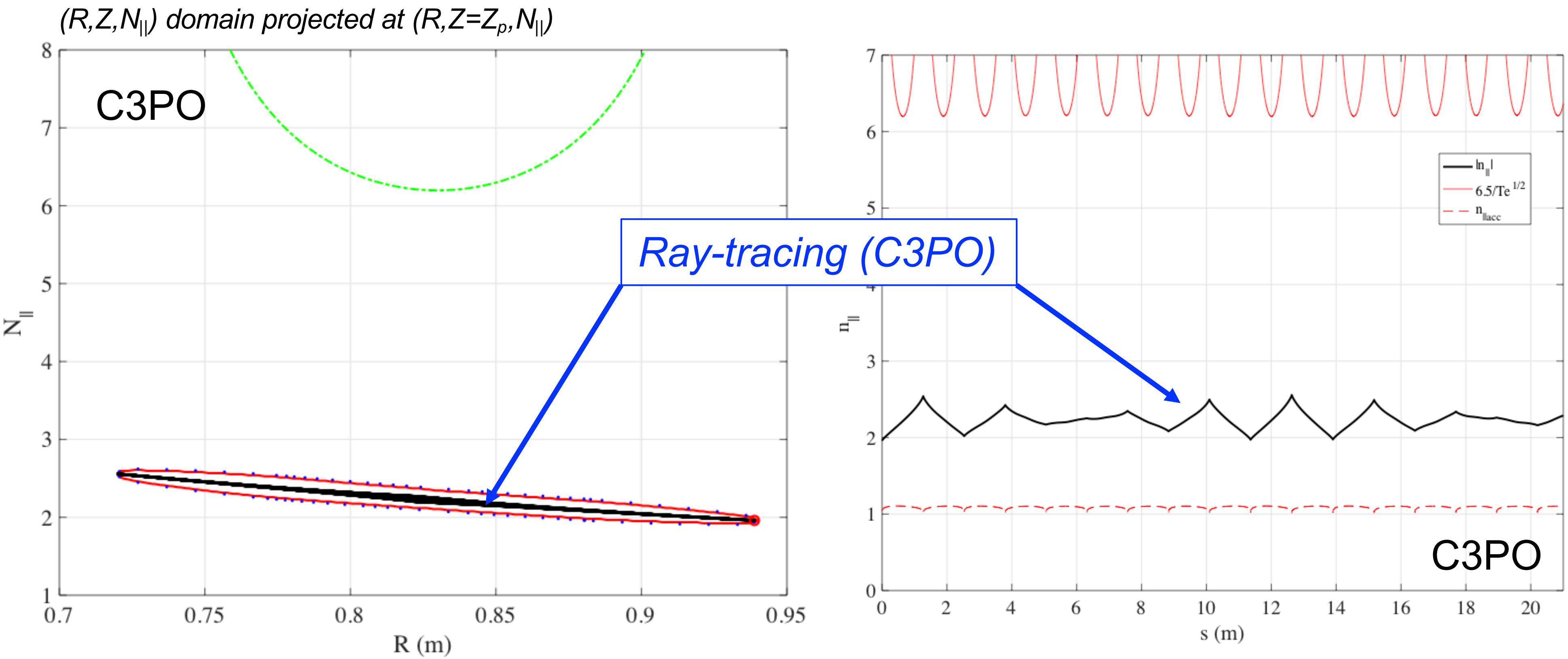
- **Spectral gap that are unbridgeable by toroidal upshift** corresponds to the condition γ_{KAM} (cyl.) << 1, with the additional condition :

$$\boxed{N_{\parallel 0} \ll \frac{6.5}{\left(1+\gamma_{KAM}^{cyl}\right)\sqrt{\max\left(T_e\left[keV\right]\right)}}}$$

Peysson, Y, et al., J. Fus. Energy 39 (2020) 270

Kinematics of the LH wave

TRIAM-1M



V_{loop} = 0V, I_p = 27 kA

$P_{LH} \approx$ 23 kW, f_{LH} = 2.45 GHz

$T_{e0} \approx$ 1.1 keV, B_{T0} = 5.0 T

$$\bar{n}_e \simeq 1.7 \times 10^{+18}\, m^{-3}$$

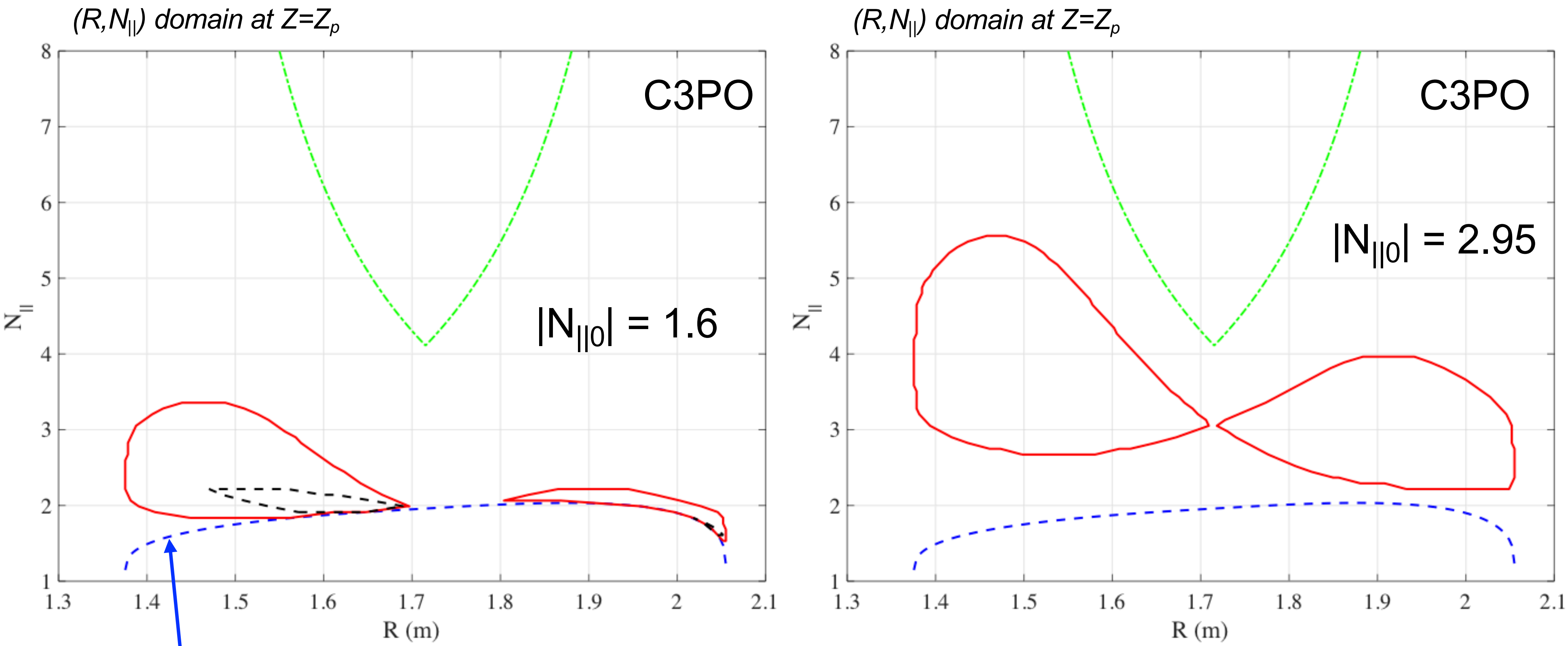
S. Moriyama, et al., Nucl. Fusion, 30 (1990) 47

Peysson, Y, et al., J. Fus. Energy 39 (2020) 270

H. Zushi, et al., Nucl. Fusion, 43 (2003) 1600

Kinematics of the LH wave

HL-2A, #35261



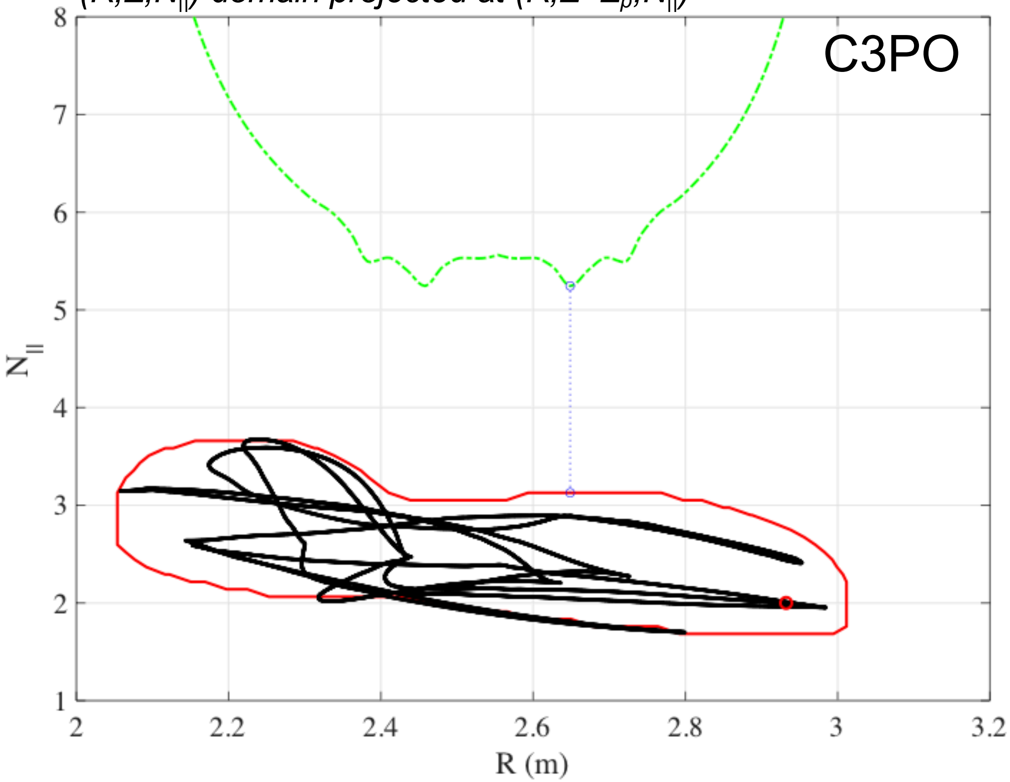
Stix-Golant accessibility

$V_{loop} \approx$ 0V, I_p = 127 kA
$P_{LH} \approx$ 0.8 MW, f_{LH} = 3.7 GHz
$T_{e0} \approx$ 2.5 keV, B_{T0} = 1.3 T
$\bar{n}_e \simeq 7.5 \times 10^{+18}\, m^{-3}$

Peysson, Y, *et al., J. Fus. Energy 39 (2020) 270*
Y. Liu, et al., Nucl. Fusion, 45 (2005) S239

Kinematics of the LH wave

WEST #54952@4.5s



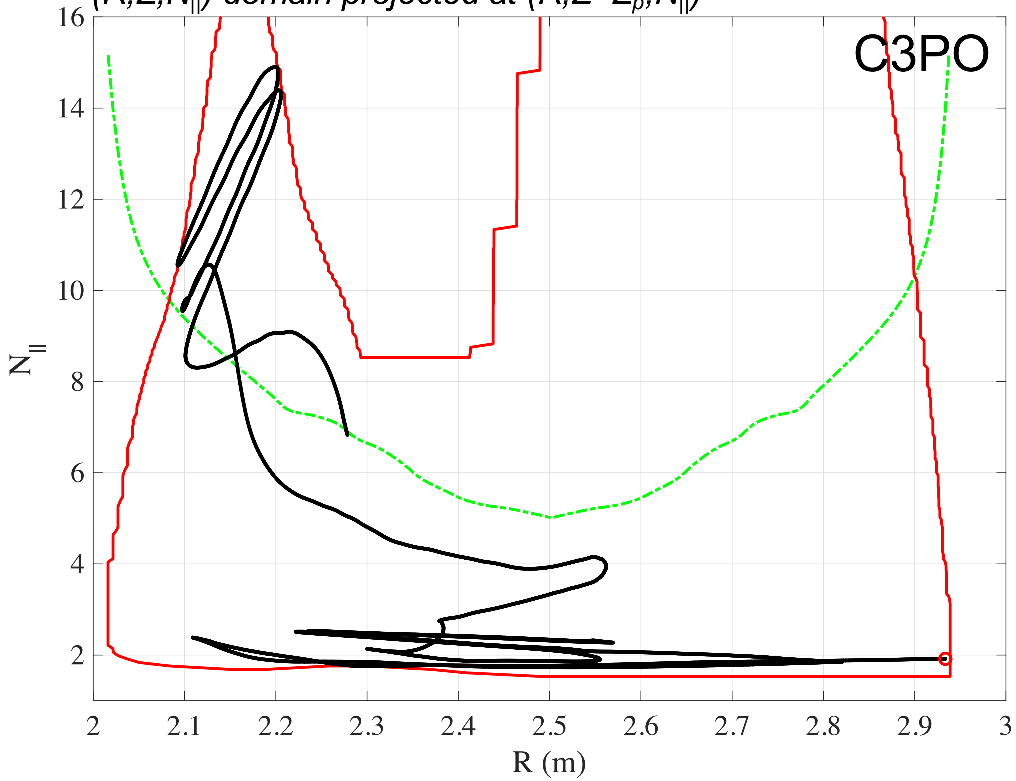
$V_{loop} \approx$ 0V, I_p = 300 kA, $P_{LH} \approx$ 1 MW

$T_{e0} \approx$ 1.5 keV, B_{T0} = 3.57 T, f_{LH} = 3.7 GHz

$$\bar{n}_e \simeq 1.7 \times 10^{+19}\, m^{-3}$$

C. Bourdelle, et al.,Nucl. Fusion, 55 (2015) 063017

WEST #55539@9.93s



$V_{loop} \neq$ 0V, I_p = 530 kA , $P_{LH} \approx$ 4.8 MW

$T_{e0} \approx$ 1.7 keV, B_{T0} = 3.57 T, f_{LH} = 3.7 GHz

$$\bar{n}_e \simeq 4.6 \times 10^{+19}\, m^{-3}$$

Peysson, Y, et al., J. Fus. Energy 39 (2020) 270

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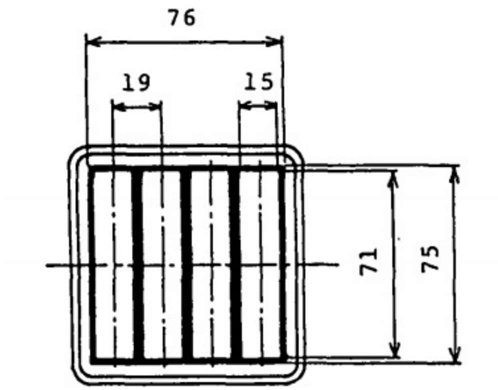
Current drive calculations : TRIAM-1M

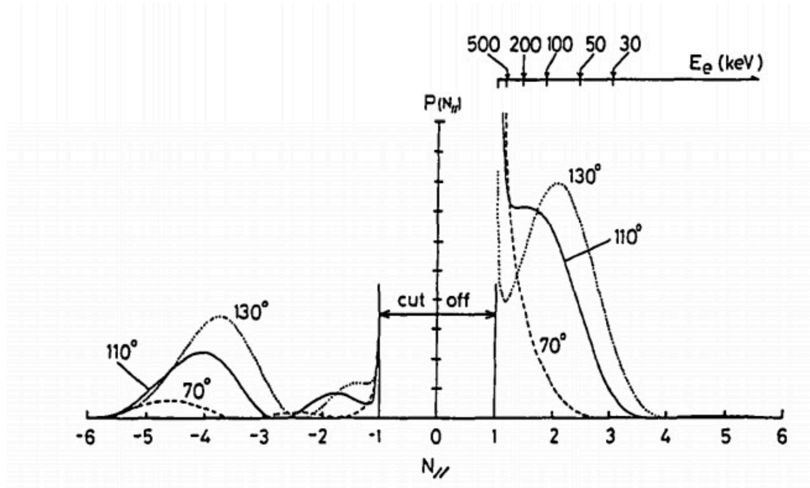
- Plasma parameters and LH launching conditions have been rebuilt from detailed available publications.

- LH wave is coupled by a grill : Brambilla's theory is used to link waveguide phasing with the excited power spectrum.

$$N_{\parallel 0} = \frac{30}{f_{LH}\Delta_w}\frac{\Delta\phi}{2\pi}$$

$$\Delta N_{\parallel 0} = \frac{c}{f_{LH} N_{\parallel 0} L_w}$$



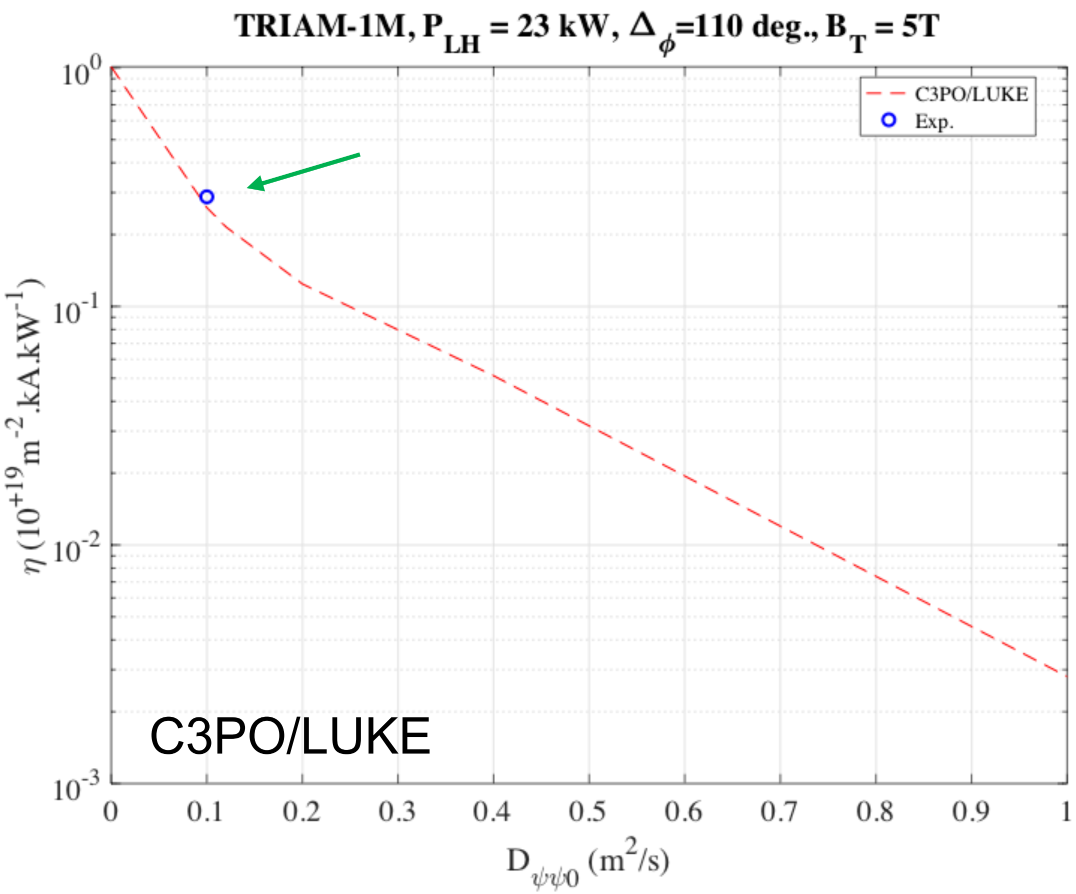


- **Without TSM, zero LH current and HXR is predicted, while full current drive is well sustain during several minutes**

S. Moriyama, et al., Nucl. Fusion, 30 (1990) 47

G. Tonon, Plasma Phys. Control. Fusion, 26 (1984) 145

Current drive calculations : TRIAM-1M



- Too much LH current is predicted with $N_{\|0}$ =1.91.
- Anomalous radial transport may be significant in small size tokamak.
- $D_{\psi\psi 0}$ = 0.1 m^2.s^{-1} + $v_{\|}$ dependency above 3.5v_{th} is estimated to recover the LH current drive efficiency for Δ_φ=110 deg (consistent with transport studies in many tokamaks)
- $\tau_c > \tau_D$ for E_c > 30 keV

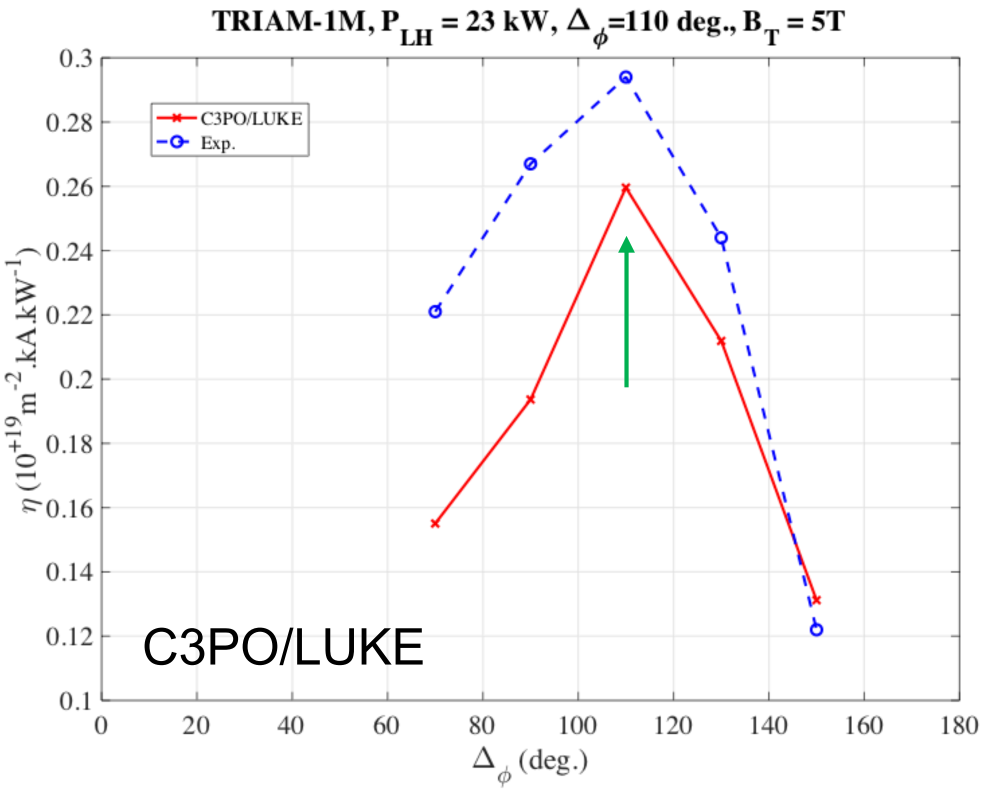
Y. Peysson and J. Decker, Fusion Science and Technology, 65 (2014) 22–42.

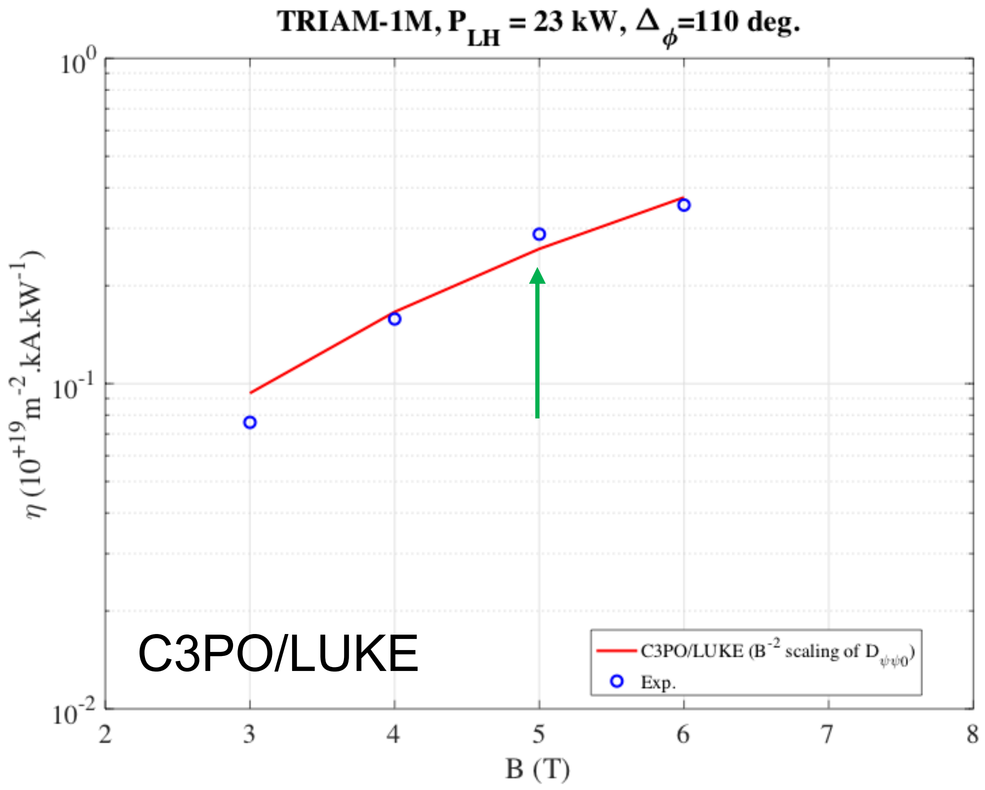
Y. Peysson et al., Plasma Phys. Control. Fusion, 54 (2012) 045003

Peysson, Y, et al., J. Fus. Energy 39 (2020) 270

Y. Peysson, Plasma Phys. Control. Fusion, 35 (1993) B253

Current drive calculations : TRIAM-1M



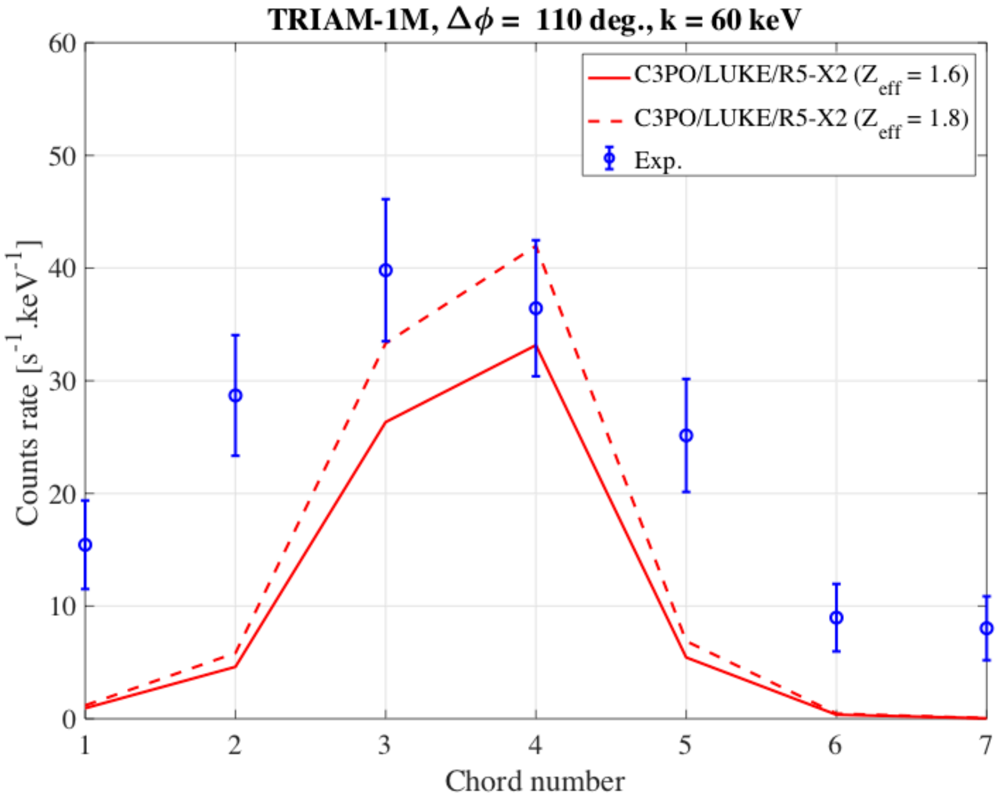


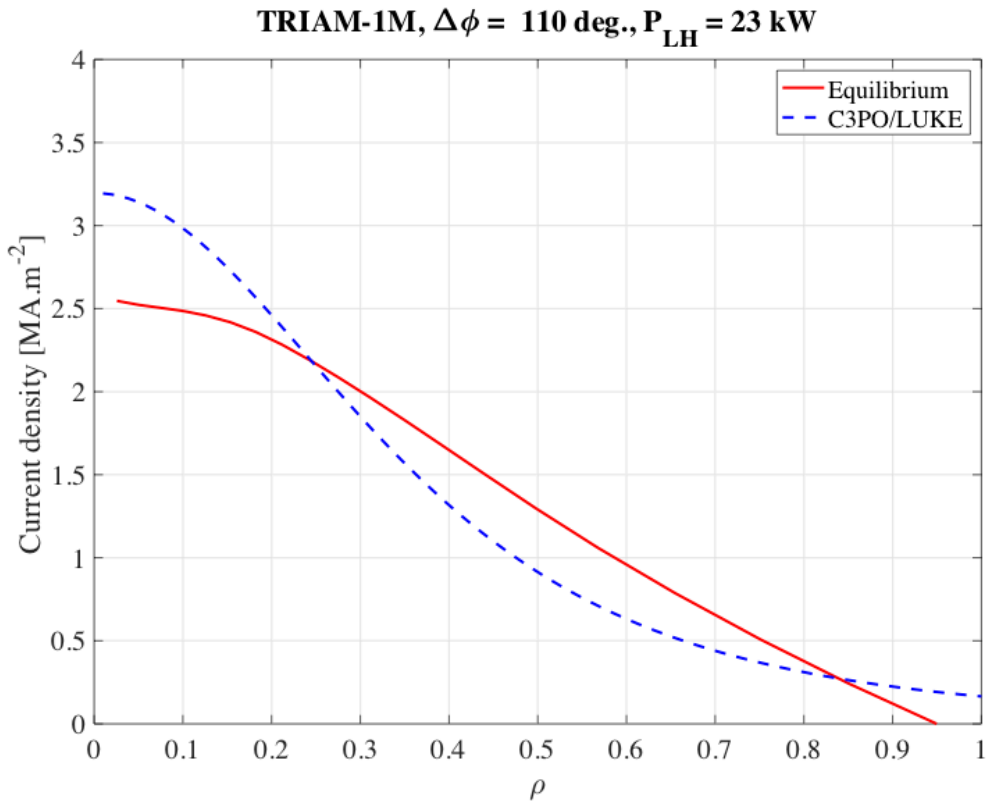
green arrow : reference discharge

Gyro-Bohm B^{-2} scaling of the anomalous radial transport.

Peysson, Y, et al., J. Fus. Energy 39 (2020) 270

Current drive calculations : TRIAM-1M





Similar current density profiles → consistent with steady-state regime

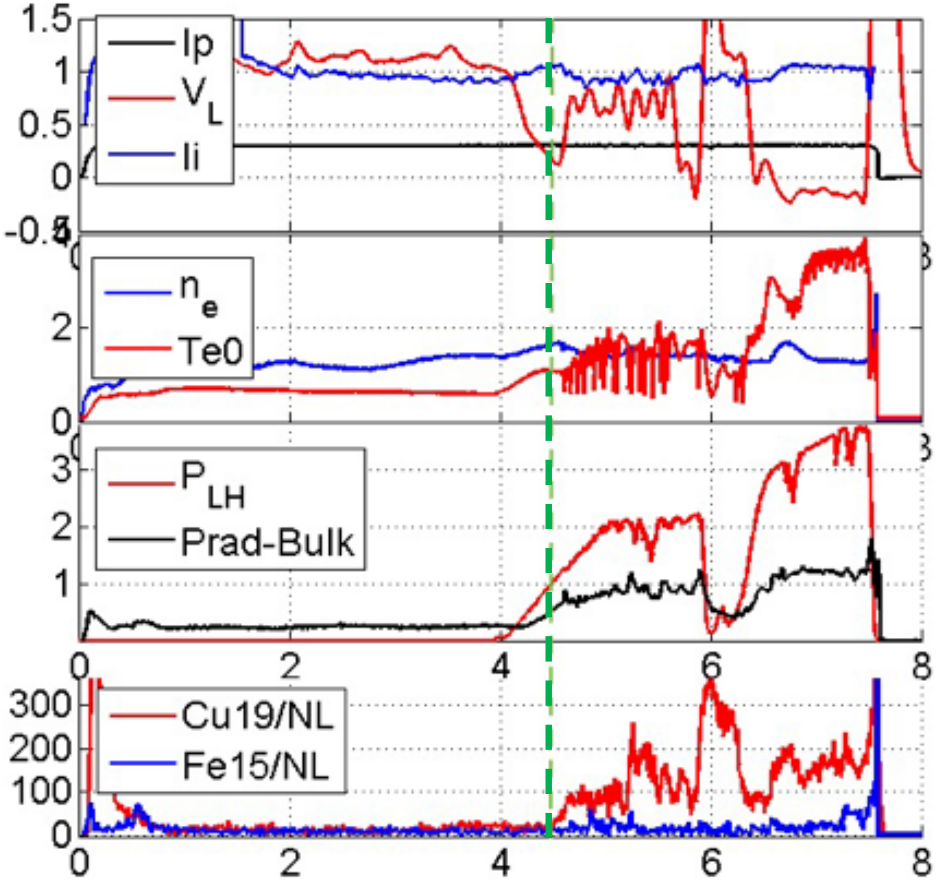
Peysson, Y, et al., J. Fus. Energy 39 (2020) 270

Y. Peysson and J. Decker, Phys. Plasmas, 15 (2008) 092509

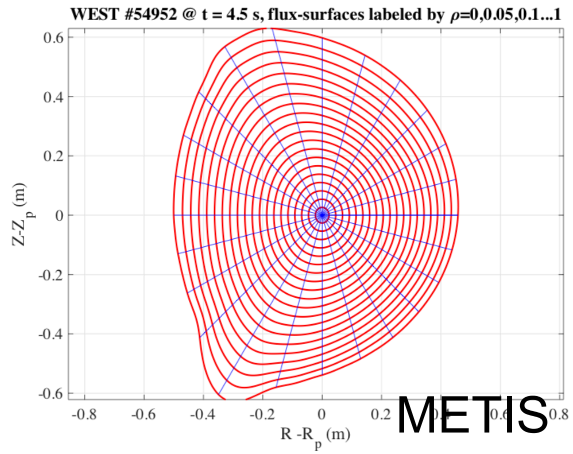
Y. Peysson and J. Decker, Fusion Science and Technology, 65 (2014) 22–42.

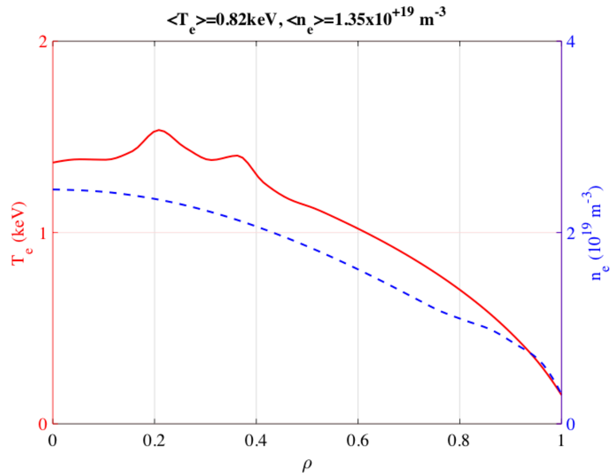
Current drive calculations : WEST #54952@4.5s

- *WEST discharge #54952 has been identified by the scaling in the database.*
- P_{LH} = 1MW coupled to the plasma by the FAM multijunction alone at t = 4.5 s.
- Small flat T_{e0} plateau when V_{loop} ≈ 0V before large MHD activity.
- No heavy metallic impurities at t = 4.5 s.



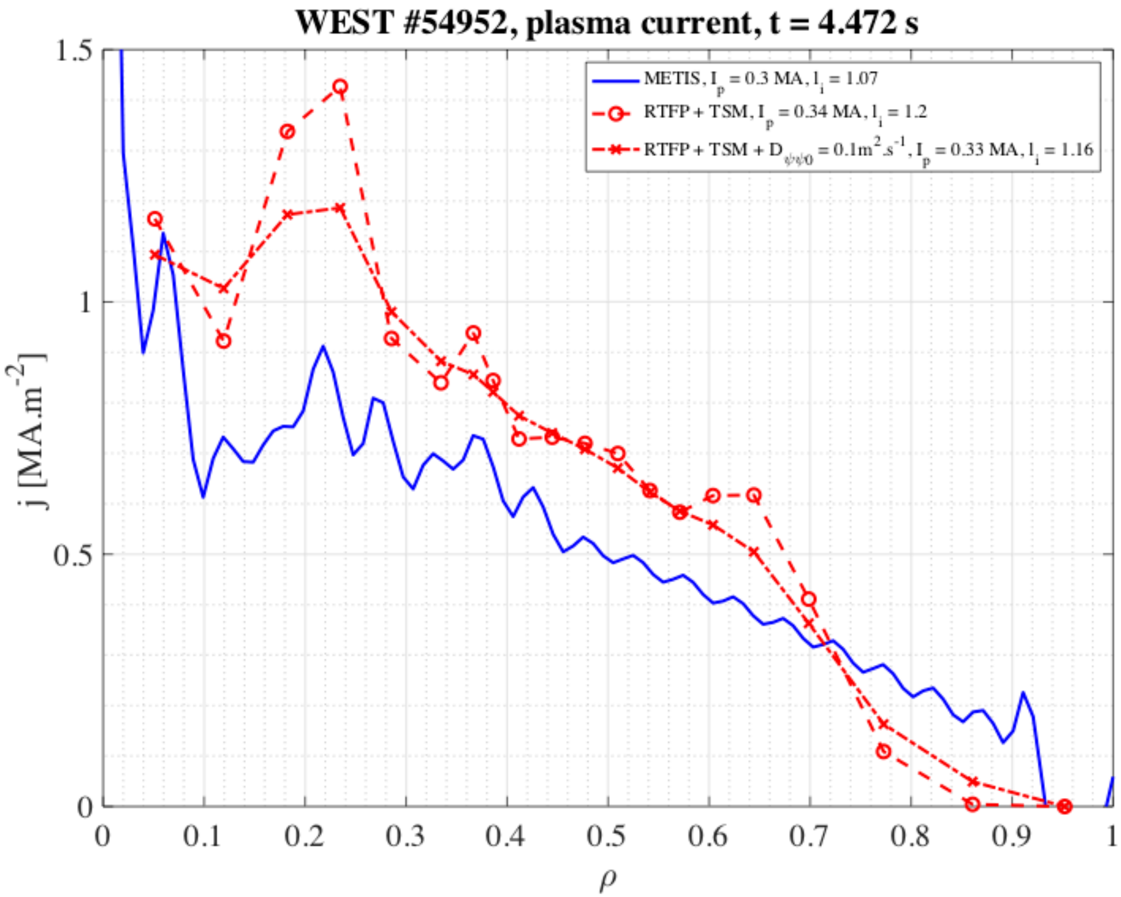
J.F. Artaud, et al., Nuc. Fusion, 58 (2018) 105001





Peysson, Y, et al., J. Fus. Energy 39 (2020) 270

Current drive calculations : WEST #54952@4.5s



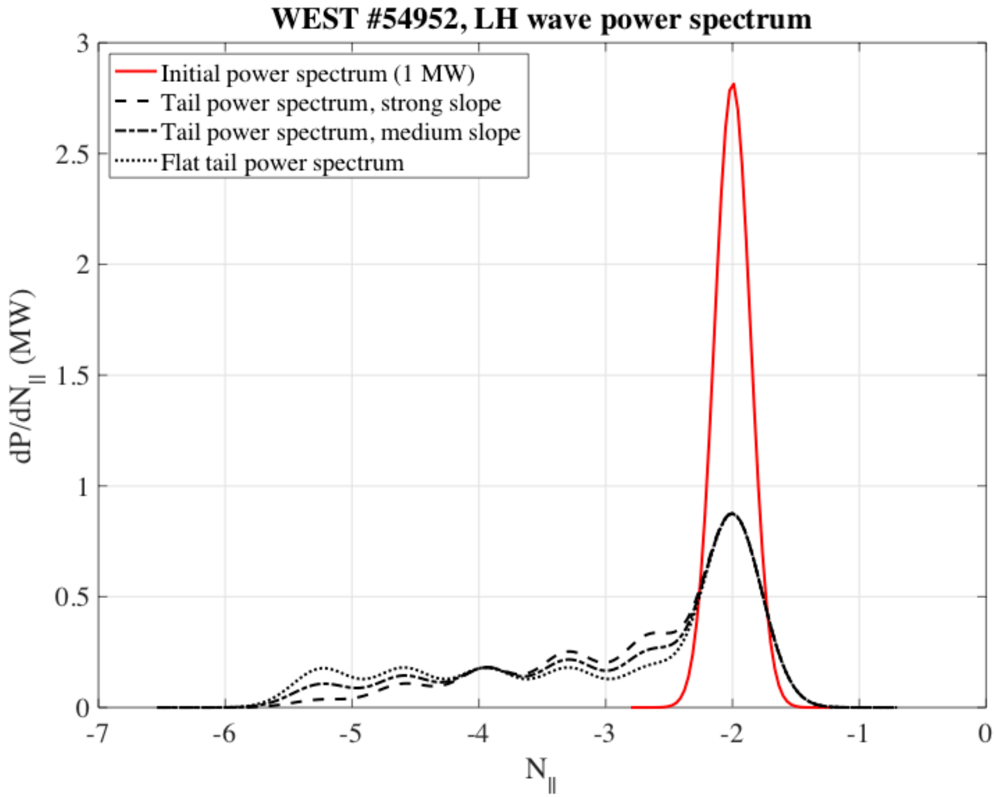
- METIS and ALOHA/C3PO/LUKE + TSM gives consistent current density profiles
- Anomalous radial fast electron radial transport has a weak effect → Coulomb collisions predominate
- Internal inductance is consistently retrieved

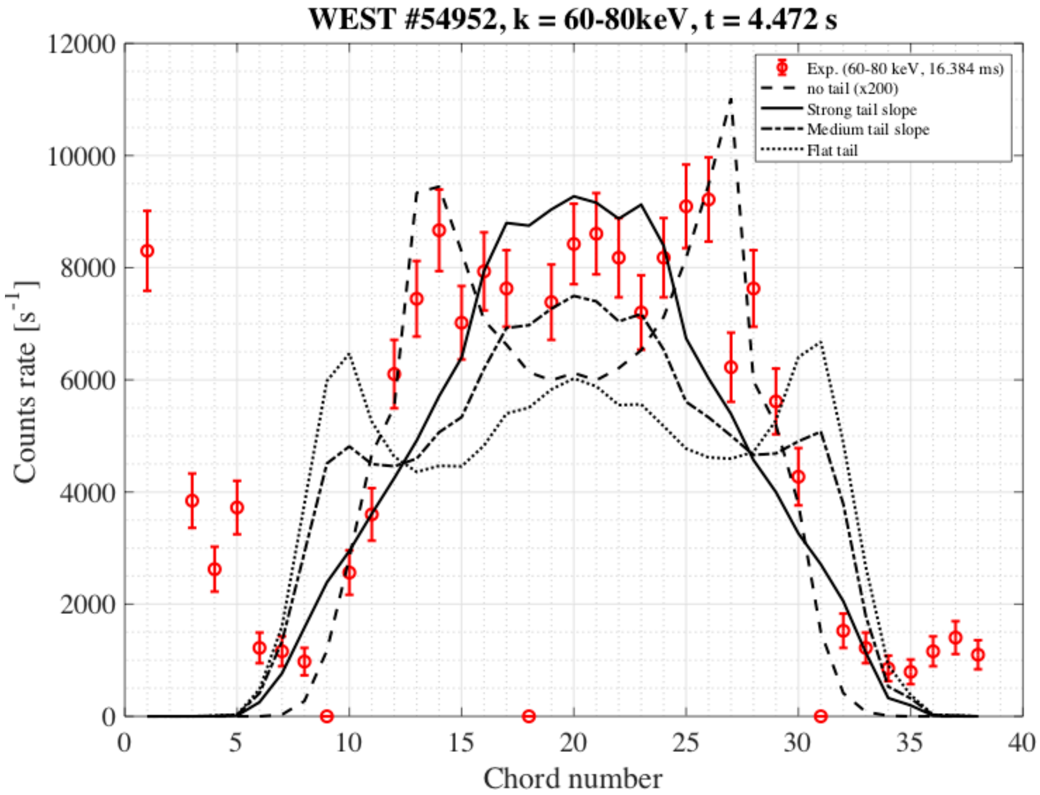
Peysson, Y, et al., J. Fus. Energy 39 (2020) 270

J.F. Artaud, et al., Nuc. Fusion, 58 (2018) 105001

Y. Peysson and J. Decker, Fusion Science and Technology, 65 (2014) 22–42.

Current drive calculations : WEST #54952@4.5s





No HXR signal without TSM

Y. Peysson and J. Decker, Phys. Plasmas, 15 (2008) 092509

Peysson, Y, et al., J. Fus. Energy 39 (2020) 270

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Conclusion

- High aspect ratio tokamaks have the potential to access easily to **LH regimes where the spectral gap cannot be bridged by toroidal refraction**.

- An **original scaling** has been derived to identify plasmas for which the LH propagation domain is strongly bounded (used successfully for WEST)

- Unbridgeable spectral gap regimes are unique opportunities to investigate the possibility that the power spectrum is already broad before the LH wave enters into the plasma (Tail Spectral Model, TSM)

- All aspects of the TRIAM-1M full LH current experiments have been well reproduced by C3PO/LUKE/R5-X2 codes, clearly indicating that TSM is a critical ingredient in the LH modeling.

- Similar results have been obtained for a discharge of WEST tokamak for which the spectral gap cannot be bridged by toroidal upshift. Quantitative agreement is found for FEB, I_{LH} and l_i. HXR line-integrated profile is nevertheless slightly too peaked.

Conclusion

- The spectral broadening has been so far interpreted as the consequence of fast spectral fluctuations with respect to the collision time.

- The fact that TSM must be used whatever the type of LH antenna (grill, PAM, FAM) may indicate that this broadening mechanism is universal and dominant even over the usual toroidal refraction when the latter becomes significant.

- *The TSM may be an artefact to by-pass intrinsic limitations of the rf diffusion operator that is used in most Fokker-Planck calculations, which is derived for a plane-wave.*

- Extended analysis of full LHCD discharges for which the spectral gap is unbridgeable may deeply contribute to understand LH wave physics and explore its full potential for fusion reactor : current profile control, interactions with runaway electrons,…

Peysson, Y, et al., J. Fus. Energy 39 (2020) 270

This work has been partially funded by National Science Centre, Poland (NCN) grant HARMONIA 10 no. 2018/30/M/ST2/00799. We thank the PLGrid project for computational resources on the Prometheus cluster.