TCV intrinsic torque in balanced NBI experiment

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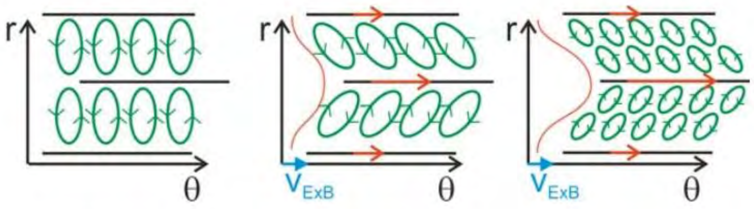
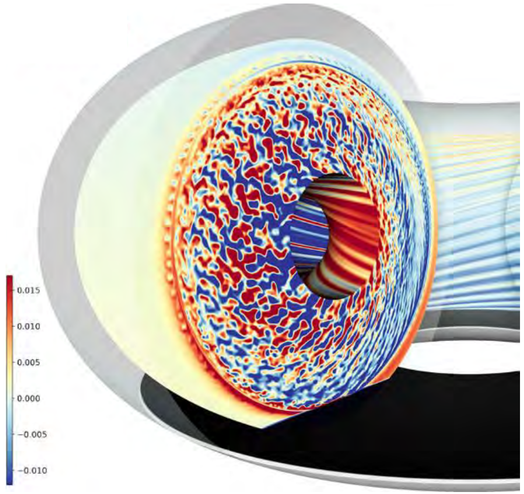
Benefits of toroidal rotation

- Plasma stabilisation against MHD events such as NTMs and RWMs that can lead to a disruption
- Stabilisation against turbulence leading to improved plasma performance
  - Turbulent eddies tilt and become radially narrower reducing transport

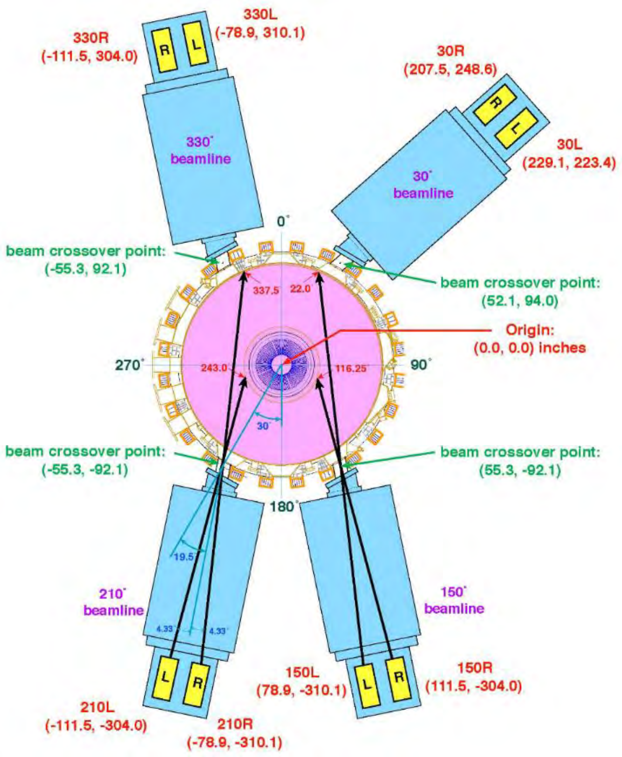




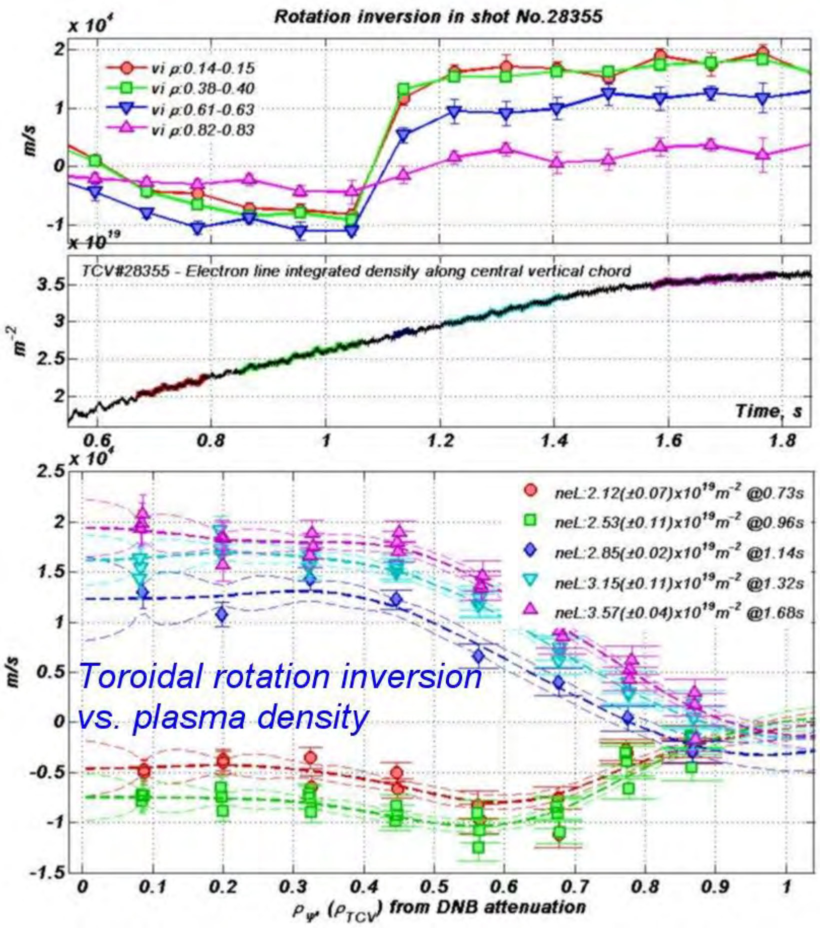
External rotation drive

- Neutral Beams inject energetic particles into the tokamak which heats and spins up the plasma and also contributes to fuelling of the plasma
- DIII-D tokamak (San Diego, USA) has a versatile setup with co- and counter current directed injectors capable of generating strong rotation
- ITER beams and those envisioned for FPP scale are still great for heating but much less efficient in delivering torque (100 keV➔1 MeV)

DIII-D NBI system



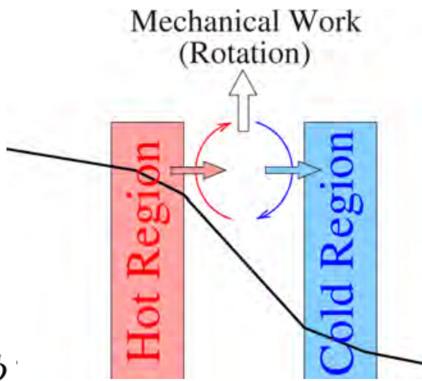
Plasma rotation reversal at TCV



- Plasma rotation and even spontaneous direction changes have been observed in **Ohmic** plasmas on many tokamaks, including JET
- Rotation predictions for larger devices are challenging as experiments are far from burning plasma regime
  - Balanced NBI experiments can help

What is intrinsic torque $-\nabla \cdot \langle n \rangle \Pi^{\mathrm{R}}_{\mathrm{r},\phi}$?

- A part of turbulence generated Reynolds stress
  - The part that can not be assigned neither as diffusive nor as convective flux



ES momentum flux (drift wave turbulence)

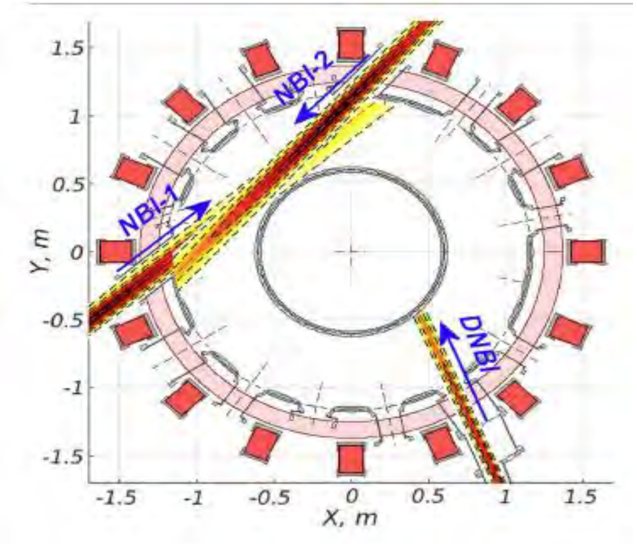
$$\Pi_{r,\phi} = \langle n \rangle \boxed{\langle \widetilde{v}_r \widetilde{v}_\phi \rangle} + \langle \widetilde{v}_r \widetilde{n} \rangle \langle v_\phi \rangle + \langle \widetilde{n} \widetilde{v}_r \widetilde{v}_\phi \rangle$$

$$\Rightarrow \quad \langle \widetilde{v}_r \widetilde{v}_\phi \rangle = \underbrace{-\chi_\phi \frac{\partial \langle v_\phi \rangle}{\partial r}}_{\text{Diffusion}} + \underbrace{V \langle v_\phi \rangle}_{\text{Convection}} + \underbrace{\Pi^{\mathrm{R}}_{r,\phi}}_{\text{Residual stress}}$$

- Self-generated by the plasma itself
- It can accelerate plasma from rest

Intrinsic torque using balanced NBI

- Null toroidal rotation[1] using the TCV new counter-current NBI capability to study the intrinsic torque



$$\underbrace{\frac{\partial L_\phi}{\partial t}}_{\approx 0} - \nabla \cdot \left(\chi_\varphi \underbrace{\frac{\partial L_\phi}{\partial \rho}}_{\approx 0} - \underbrace{V_c L_\phi}_{\approx 0} \right) = \tau_{NBI} + \tau_{int}$$

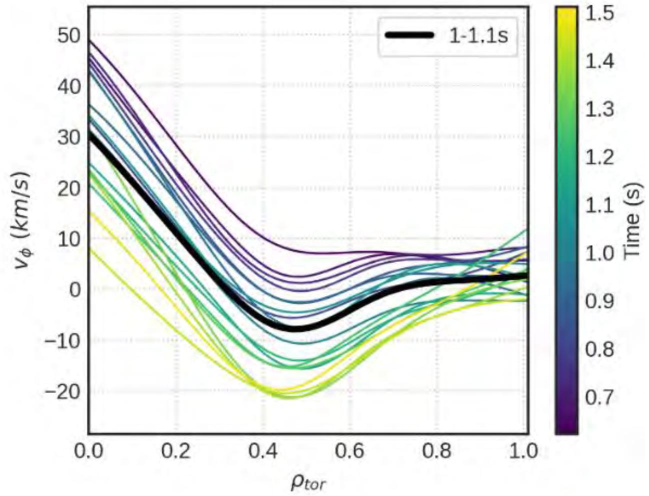
$$L_\phi = \langle m_i n_i R v_\varphi \rangle$$

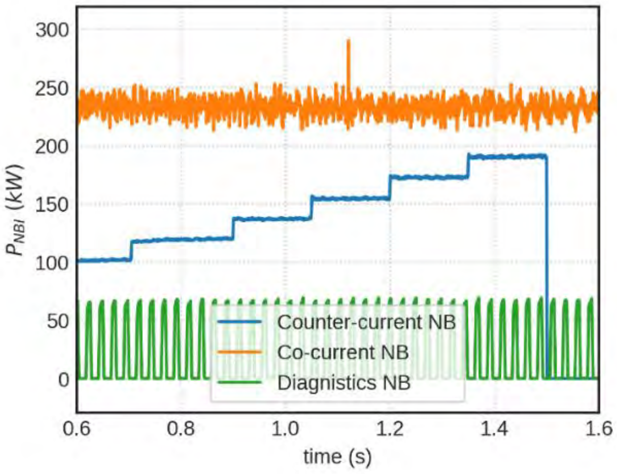
1) Make estimates for TCV plasmas
2) Tokamak size scaling for extrapolation

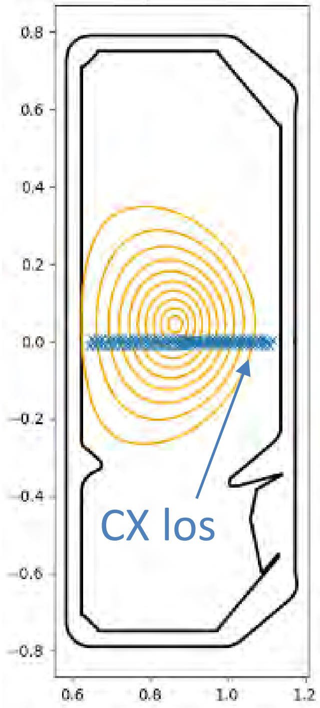
[1] Solomon, NF, 2011

#78931 experiment with NBI steps

- Minimum rotation searched by stepping up counter current NBI while keeping co-current constant
- Average rotation hits null level, but
  - Do local rotation and rotation gradient generate significant momentum fluxes?

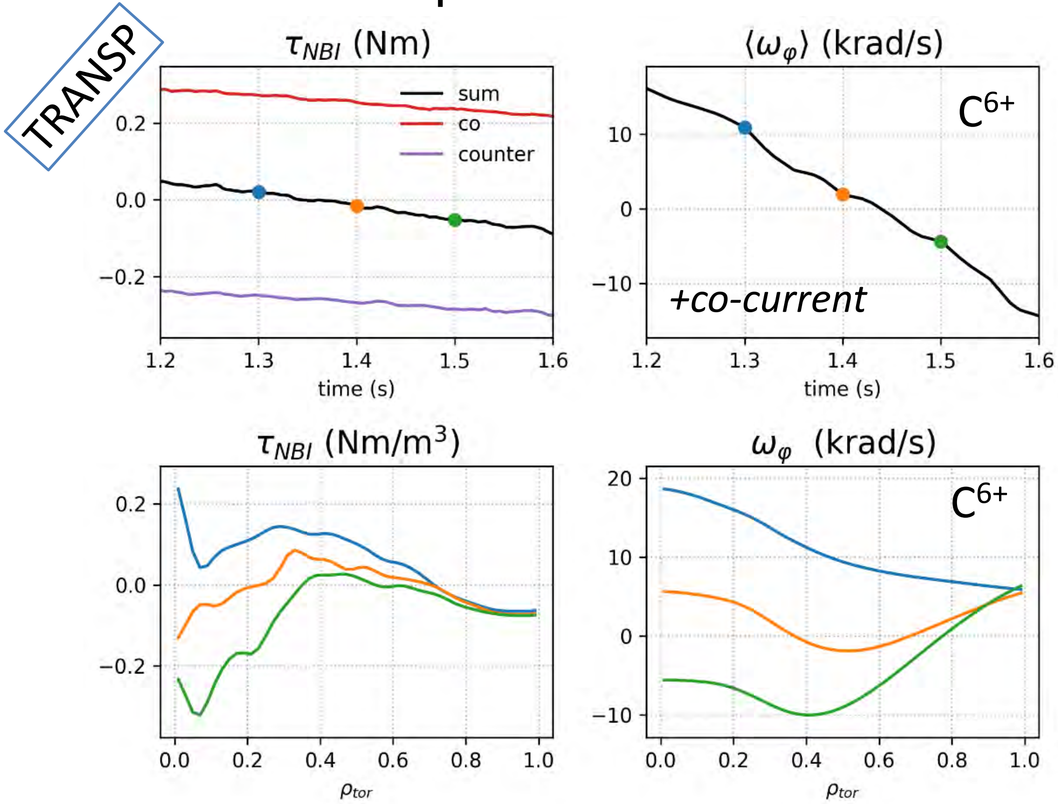




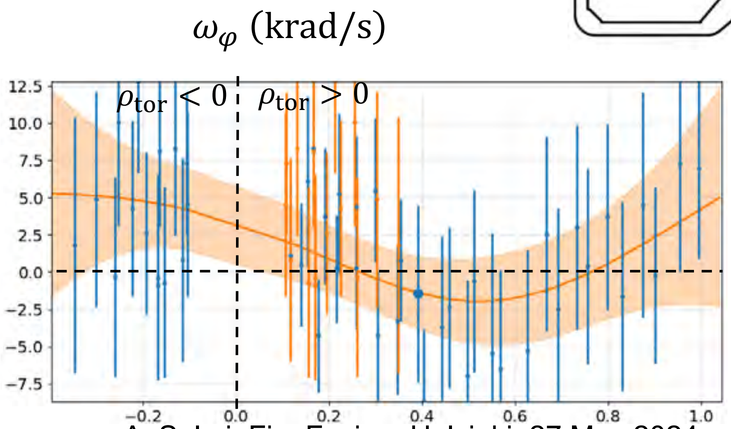


#80324 NBI torque ramp

- Rotation smallest with ~0 total torque suggesting a small intrinsic torque



- Upper single null
- HFS and LFS data agree within error bars



Estimating transport fluxes

- Momentum equation (=ASTRA w/o NC or $\frac{\partial B}{\partial t}$ terms*)

$$\frac{\partial}{\partial t}(V' mnRu_{\parallel}) - \frac{\partial}{\partial \rho}\left[V'\langle(\nabla\rho)^2\rangle mnR\left(\chi_{\varphi}\frac{\partial u_{\parallel}}{\partial \rho} - V_c u_{\parallel}\right)\right] = V'S \qquad u_{\parallel} = \frac{\langle U_{\parallel} B\rangle}{B_0}$$

$$\chi_{\varphi} = (4.8\,\epsilon + 0.2)\,\chi_i \text{ and}$$

$$V_c = -\frac{\chi_{\varphi}}{R}\,(0.5\,R/L_{n_e} + 0.44\,s)$$

from Zimmermann, PoP'24

- Steady state solution: $u_{\parallel} = e^{-\alpha(\rho)}\left(\int_0^{\rho} B(x)e^{\alpha(x)}dx + C\right)$

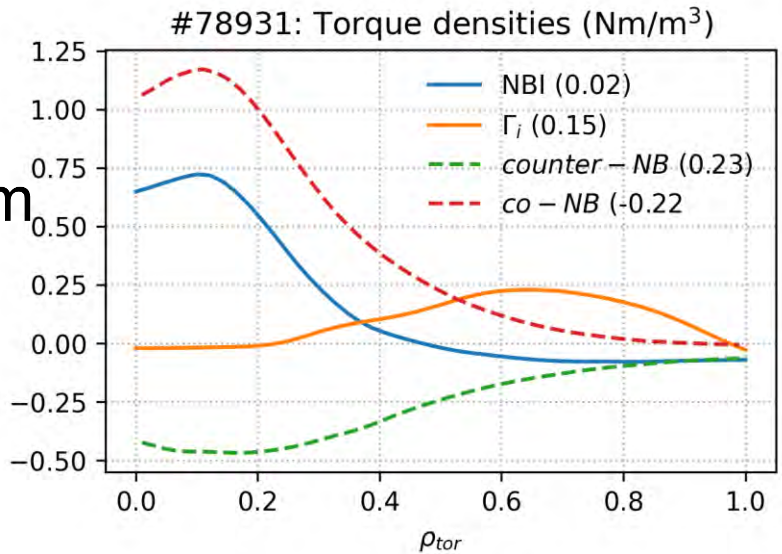
* E. Fable ASTRA-7.0 *Addendum with changes and new features* (IPP report) Feb 2012

Torque from particle flux τ_{Γ_i}

$$\frac{1}{V'}\frac{\partial}{\partial\rho}\left(V'\langle R^2(m\Gamma_\mathrm{i}\omega_\varphi + \Pi_\varphi)\rangle\right) = \tau_\varphi$$

- For magnitude comparison against NBI we can move the ‘particle flux torque’ term on the right hand side

$$\int \tau_\varphi dv \Rightarrow \int \tau_\varphi dv - V'\langle R^2\rangle m\Gamma_\mathrm{i}\omega_\phi$$



- Particle flux *drags* the momentum
- Magnitude scales with rotation and can be significant if there is rotation with small NBI torque

Intrinsic torque τ_{int}

- For perfectly nulled rotation intrinsic torque τ_{int} will simply be the negative of the NBI torque [Solomon]

$$\tau_{int} = -\tau_{NBI}$$

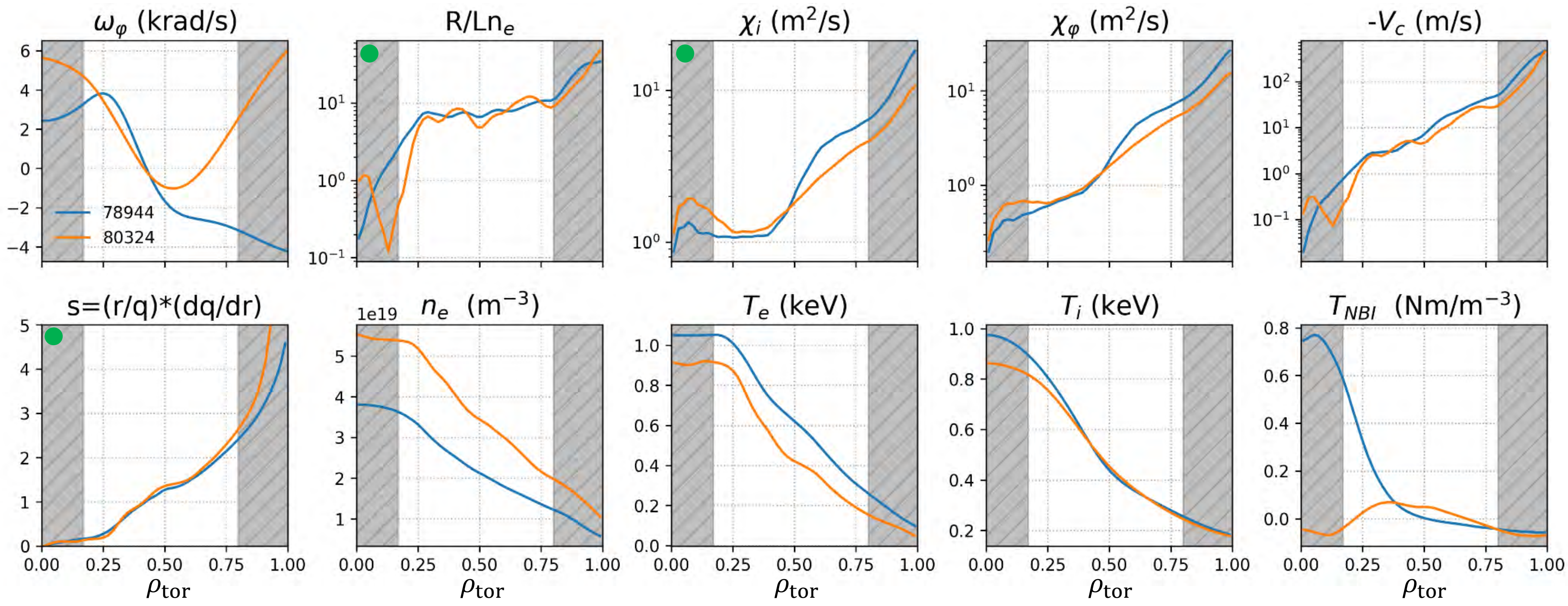
- When transport driven fluxes can not be neglected τ_{int} can still be solved through

$$\int_0^v \tau_{int} dv = -mnRV'\langle(\nabla\rho)^2\rangle\left(\chi_\varphi \frac{\partial u_\parallel}{\partial\rho} - V_c u_\parallel\right) - \int_0^v (\tau_{NBI} + \tau_{\Gamma_i}) dv$$

Profile comparison

- R/L_{n_e} becomes large especially outside $\rho > 0.8$
  - Not in the valid range for the simple model of χ_φ and V_c
- Rotation measurements miss the magnetic axis

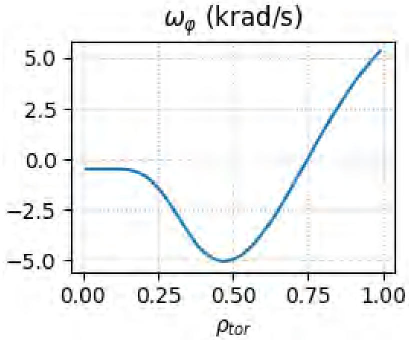
● Input (+ϵ) for χ_φ and V_c

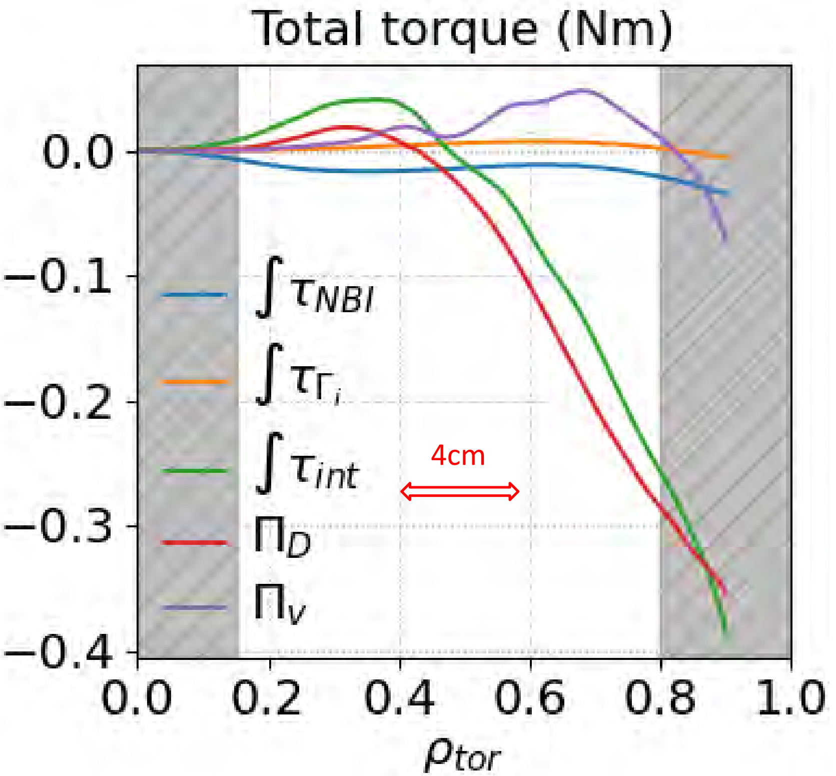


Steady-state momentum balance

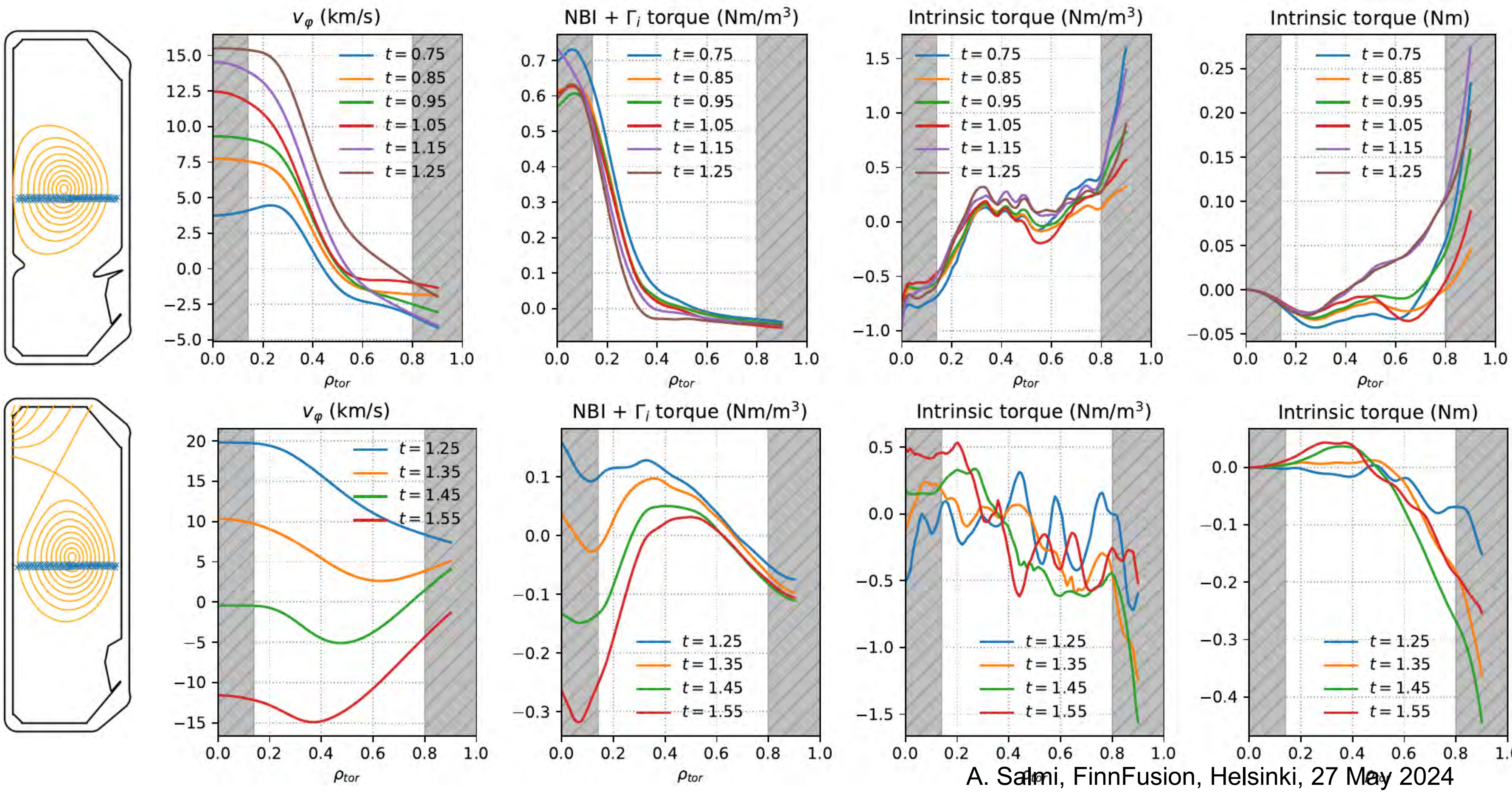
- To compare the various terms we plot all in torque units (Nm)
  - One NB unit equals ~0.2-0.4 Nm

$$-mnRV'\langle(\nabla\rho)^2\rangle\chi_\varphi \frac{\partial u_\parallel}{\partial \rho}$$
$$+ mnRV'\langle(\nabla\rho)^2\rangle V_c u_\parallel$$
$$-\int_0^v \tau_{int} dv$$
$$-\int_0^v \tau_{NBI} dv$$
$$-\int_0^v \tau_{\Gamma_i} dv$$
$$= 0$$





Intrinsic torque near the low rotation



Further optimisations planned

- Improve estimates of Π_φ or χ_φ, V_c
  - TGLF, QLK, TCV specific, …
- Improve experiments for even smaller rotation and rotation gradients
  - Co/counter NBI power / voltage optimisation
- Improve measurements
  - Slower ramps for longer averaging times
- Use main ion rotation instead of C^{6+}
  - NCLASS, NEO,…?

Summary

- TCV rotation is ~nulled with ~balanced NB torque
- The analysis approach presented here accounts for the transport and can be used also for non-zero rotation
- Rotation gradient can have large effect even in ~null rotation TCV plasmas
  - small minor radius ➔ large gradient ➔ large diffusive flux
- Uncertainties in ‘known’ quantities leads to spurious contributions to intrinsic torque
  - v_{tor}, ∇v_{tor}, Z_{eff}, τ_{NBI}, Γ_i, ∇T_i and L_{n_e}
- Experiments with physics scans scheduled for week ~44