Nature of intrinsic toroidal rotation in Ohmically heated discharges of ADITYA-U tokamak measured using Passive Charge eXchange spectroscopy

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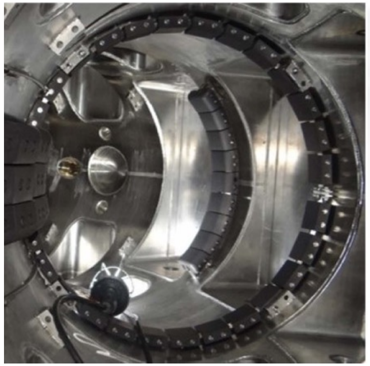
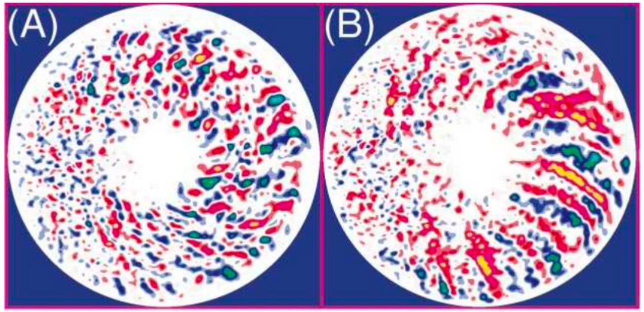


Plasma rotation

- Plasma confinement in a tokamak is limited by the transport of energy and particles.
- Radial transport takes place from hot plasma core to cooler plasma edge.
- A large part of the transport is driven turbulence.
- A good understanding on magnetic instabilities is necessary to know how to avoid them.
- Plasma rotation has been known to have beneficial effects on both stability and confinement.

Importance of Plasma rotation

- Plasma rotation plays a crucial role in achieving improved confinement and stability by suppressing turbulence and magneto-hydrodynamic instabilities[1].
- A relation between sheared radial electric field and poloidal rotation is found to suppress edge fluctuations and is found to be related to L-H transition[2].
- The study of intrinsic rotation is important since external momentum on future large fusion devices like ITER will not be sufficient to drive large plasma volume.
- The underlying mechanisms of intrinsic rotation are still not known.



A simulation of turbulence with (A) sheared flow and (B) without sheared flow.
Turbulent cells in case of sheared flow (A) are smaller, indicating reduction a reduction in overall transport[3]

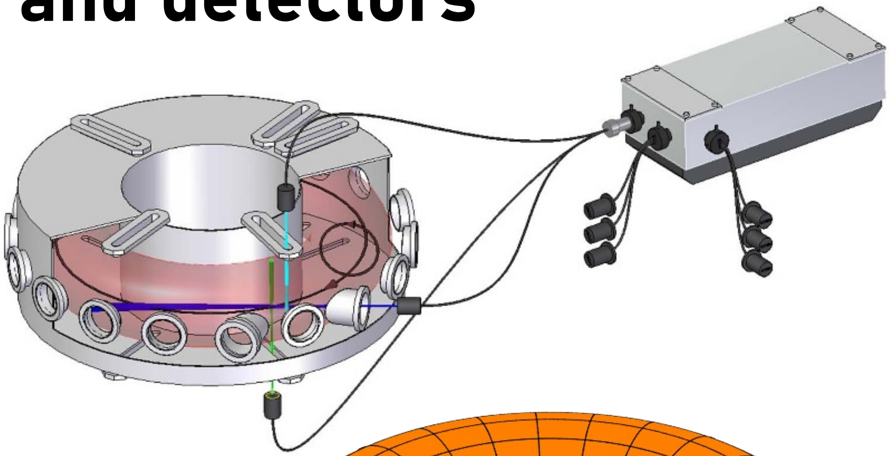
[1] Stoltfuz-Dueck, T., 'Transport driven toroidal rotation in the tokamak edge', *Physical Review Letters 108*, 065002, 2012.
[2] Groebner, R.J., Burrell, K.H., Seraydarian, R.P., 'Role of edge radial electric field and poloidal rotation in L-H transition', *Physical Review Letters 64,* 25, 1990.
[3] Lin, Z., Hahm, T.S., Lee, W.D., *et al.*, 'Turbulent transport reduction by zonal flows: Massively parallel simulations ', Science 281, 1998.

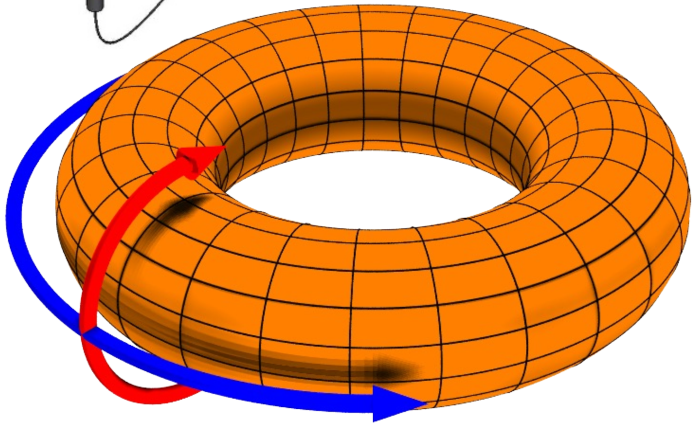
Tokamak	Diagnostic	Impurity	Toroidal Velocity	Nos of points	Heating	
ALCATOR - C Mod	X-ray CXRS	Ar^{17+} (3.7 Angstrom) B^{5+} (494.467 nm)	60 km/s 50 km/s	>8	NBI	Energy bifurcation related to rotation reversal, n_e fluctuation
ASDEX - U	CXRS	B^{5+} (494.467 nm) C^{5+} (529.059 nm)	100 km/s	5 16	NBI NBI	Rotation reversal with deep SOC, and increased collisionality
DIII – D	CXRS	C^{5+} (529.059 nm)	150 km/s	>10	NBI &ECRH	Role of ITG gradient
JET	X-ray CXRS	Ar^{6+} (nm) C^{5+} (529.059 nm)	30 km/s 300 km/s	< 12	NBI &ICRH	Role of ∇P_i in U_T
JT - 60 U	CXRS	C^{5+} (529.059 nm)	300 km/s	15	NBI	Role of ∇P_i in U_T
J – TEXT	X-ray PCX	Ar^{17+} (3.7 Angstrom) C (227.09;464.7;529 nm)	25 km/s	>5	Ohmic	Role of n_e on U_T
KSTAR	X-ray CXRS	Ar^{17+} (3.7 Angstrom) C^{5+} (529.059 nm)	50 km/s	>8	NBI, ICRH &ECRH	Rotation reversal with ECH and NLT
TCV	CXRS	C^{5+} (529.059 nm)	50 km/s	40	ECRH	Rotation reversal with high n_e, presence of C_ϕ to sustain U_T
TCABR	PCX	C^{5+} (529.059 nm)	30 km/s	6	Ohmic	Edge rotation effect on GP location
TEXTOR	CXRS	C^{5+} (529.059 nm)	100 km/s	10	NBI	Role of ICRH, ECRH as source,

Plasma rotation using Doppler shift spectroscopy

Components of visible spectroscopy include optics, spectrometer and detectors

- Optical lenses and fibers are commercially available.
- A spectrometer with a custom fiber mount along with low noise and a fast detector is installed to capture photoemission.





Poloidal direction shown by red arrow
Toroidal direction shown by blue arrow

Image from: Severo, J.H.F., Canal,G.P., Ronchi, G.,et al, 'Overview of plasma rotation studies on TCABR tokamak', Plasma Phys. Cont. Fusion 63, 0795001, 2021.
Image courtesy: Made in POV-Ray by Dave Burke 2006 obtained from Wikipedia

Measurement of plasma velocity by utilizing photoemission from the impurity ions

- One can see a Doppler shifted and broadened Gaussian.

$$V = \frac{d\lambda \, . c}{\lambda \, . \cos\theta}$$

$$\frac{d\lambda}{\lambda} = 2.43 \text{ x } 10^{-3} \sqrt{\frac{T}{m}}$$

- Few neutrals are present in the tokamak core.
- Neutral are also injected externally by Neutral Beam Injection.

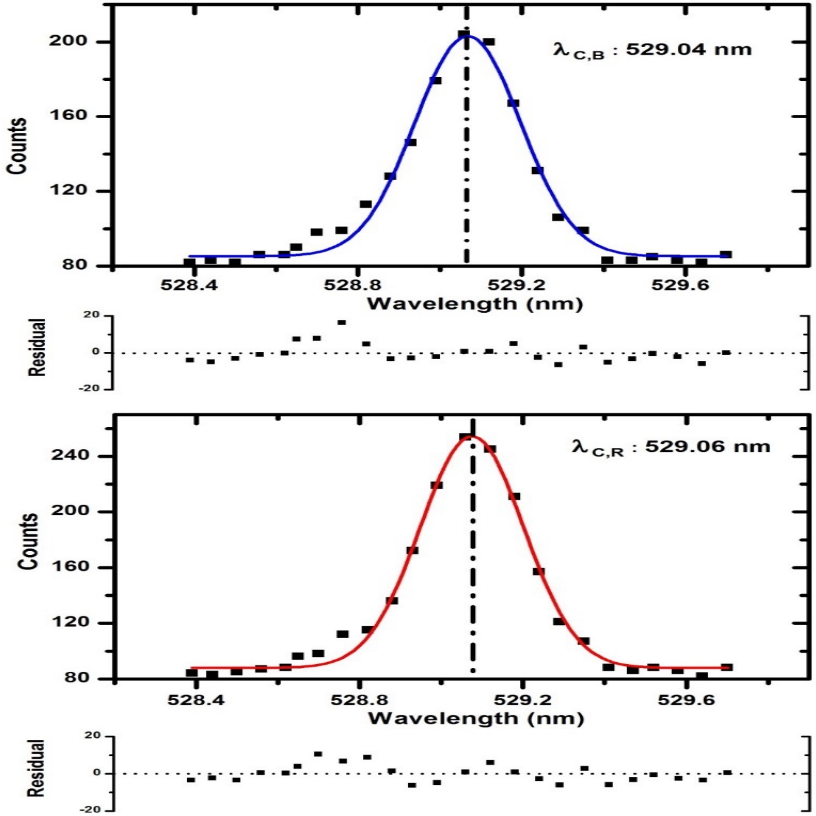
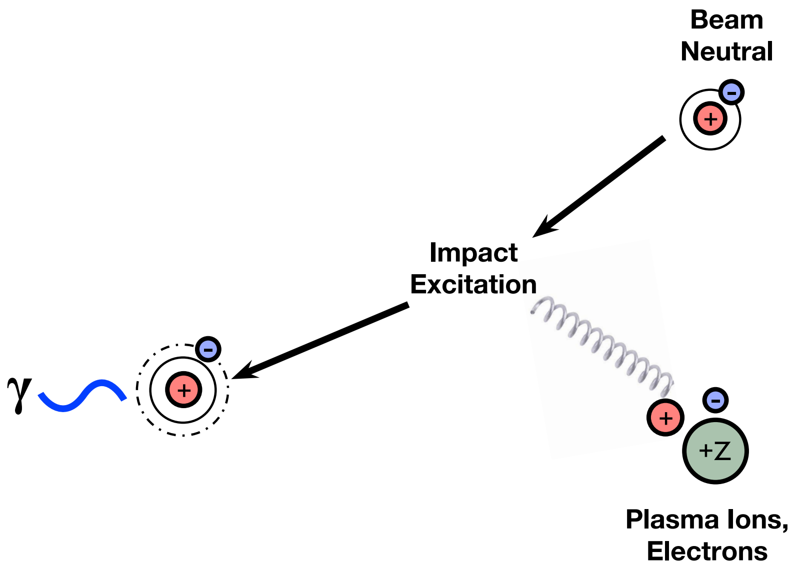


Image from: Shukla, G., Shah, K., Chowdhuri, M.B., *et al*, 'Observation of toroidal rotation reversal in ADITYA-U tokamak', Nuclear Fusion, 59(110), 106049, 2019.

Measurement of plasma velocity by utilizing photoemission from the impurity ions

- For charge exchange reaction, the ions must receive an electron.
- The neutrals coming from neutral beam generally provide this required electron leading the receiving ion into excited state

$$H + C^{6+} \rightarrow H^{+} + C^{5+}$$



Measurement of plasma velocity by utilizing photoemission from the impurity ions

Principle of measurement

- For ADITYA-U tokamak, carbon is chosen for the study because it remains the main impurity due to the graphite toroidal-belt and poloidal limiter.
- The high-resolution spectroscopy diagnostic for the measurement of plasma rotation will capture PCX line emission of C^{5+} ion at 529.01 nm.

$$E = Q_{cx} n_e n_{C^{5+}} + Q_{rec} n_e n_{C^{6+}} + Q_{cx} n_n n_{C^{6+}}$$

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Electron impact excitation

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Recombination

Measurement of plasma velocity by utilizing photoemission from the impurity ions

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Electron impact excitation

Charge Exchange

$$E = Q_{cx} n_e n_{C^{5+}} + Q_{rec} n_e n_{C^{6+}} + Q_{cx} n_n n_{C^{6+}}$$

Recombination

Measurement of plasma velocity by utilizing photoemission from the impurity ions

Principle of measurement

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Electron impact excitation — Charge Exchange — Recombination

$$E = Q_{cx} n_e n_{C^{5+}} + Q_{rec} n_e n_{C^{6+}} + Q_{cx} n_n n_{C^{6+}}$$

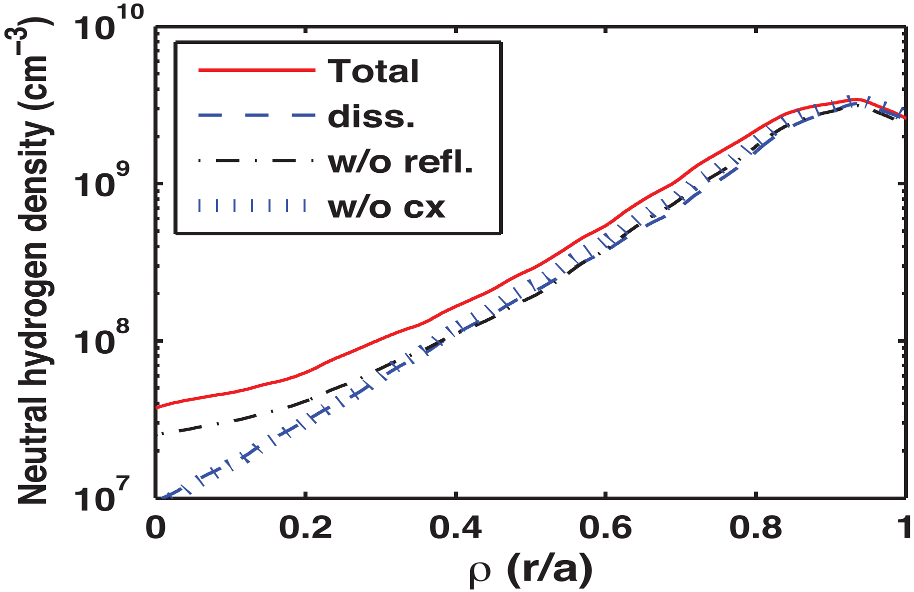
- **The last term is of importance to us, $\mathbf{Q_{cx} n_n n_{C^{6+}}}$, this term is the thermal charge exchange occurring due to neutrals $\mathbf{n_n}$ present in plasma along with $\mathbf{n_{C^{6+}}}$ impurity density.**

Passive Charge eXchange (PCX) spectroscopy on ADITYA-U tokamak

Passive emission using simulated neutral and impurity density profile for ADITYA-U tokamak

The passive charge exchange line intensity, $\boldsymbol{I_{pcx}}$, of the spectral line:

$$I_{pcx} = \frac{1}{4\pi}\sum n_c(r)n_{neu}(r)\langle\sigma v\rangle_{pcx}$$



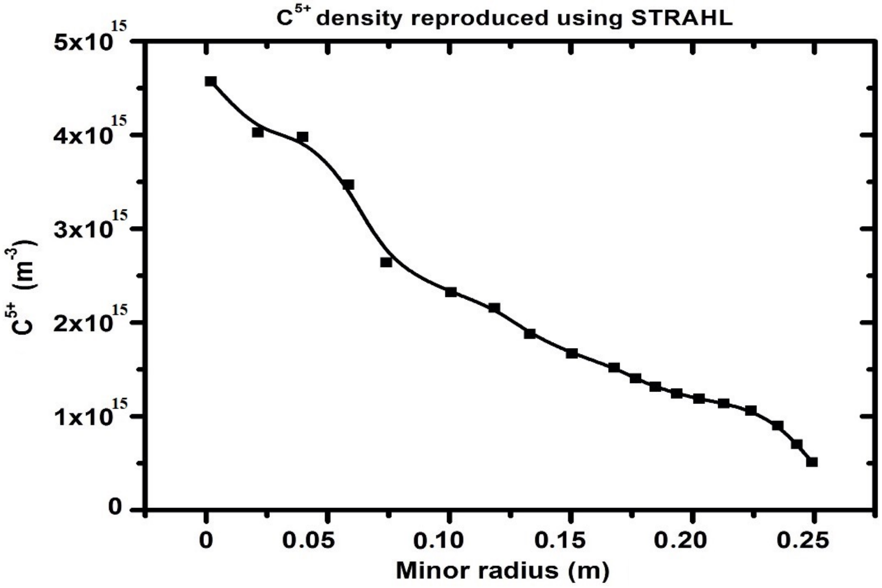


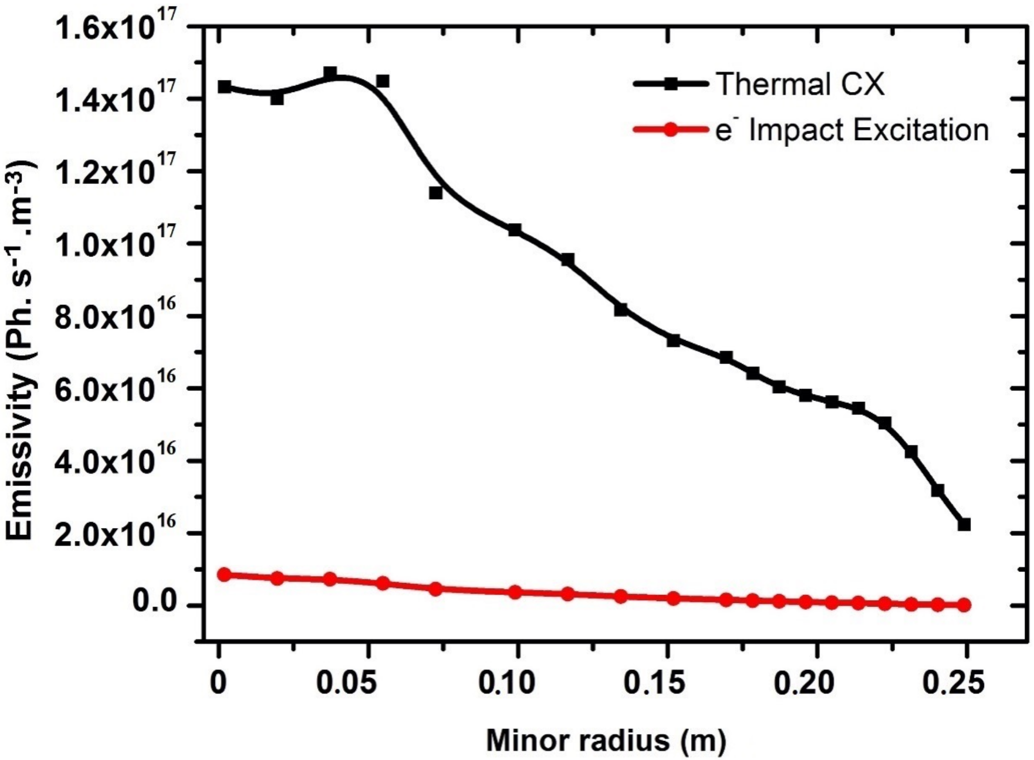
Image from: Dey, R., Ghosh, J., Chowdhuri, M.B., *et al.*, 'Investigation of neutral particle dynamics in Aditya tokamak plasma with DEGAS2 code', *Nuclear Fusion* 57, 086003, 2017.

Passive emission using simulated neutral and impurity density profile for ADITYA-U tokamak

- The passive charge exchange line intensity, $\boldsymbol{I_{pcx}}$, of the spectral line:

$$I_{pcx} = \frac{1}{4\pi}\sum n_c(r) n_{neu}(r) \langle \sigma v \rangle_{pcx}$$

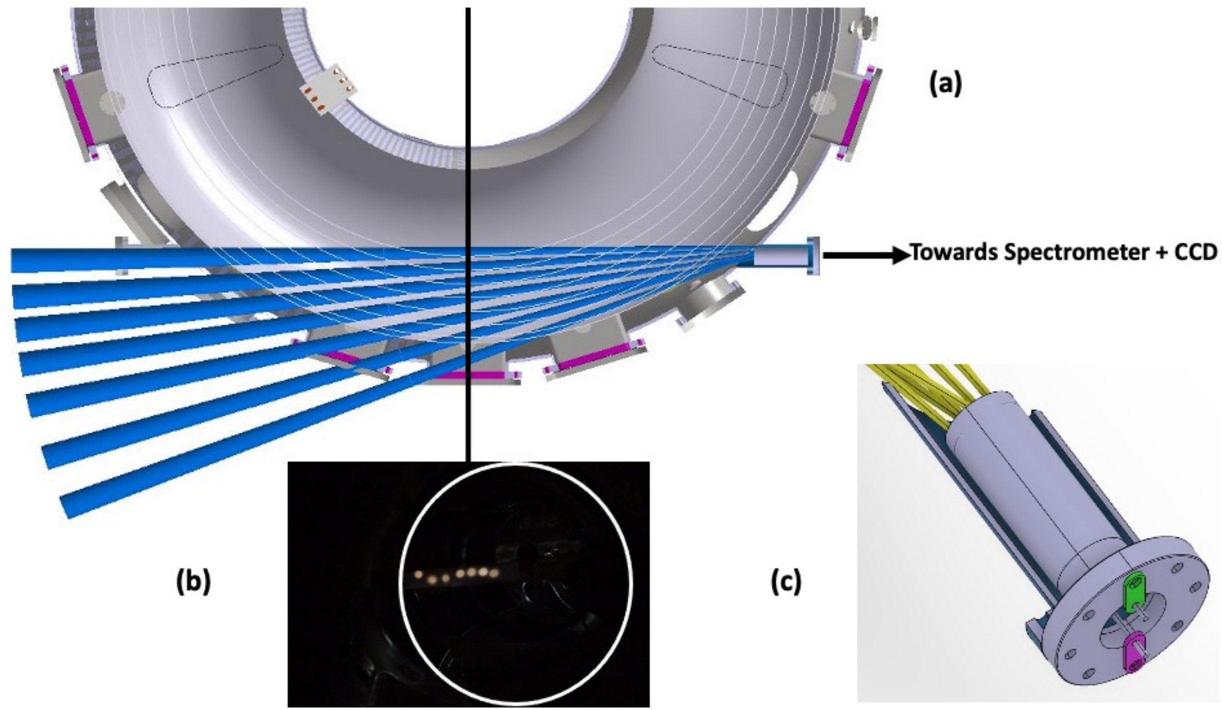
- e-impact excitation is less than 10% in the edge region[4].



[4] Shukla, G., Chowdhuri, M.B., Shah, K., *et al.*, 'Plasma rotation measurement using UV and visible spectroscopy on ADITYA-U tokamak', *Review of Scientific Instruments* 89, 10D132, 2018.

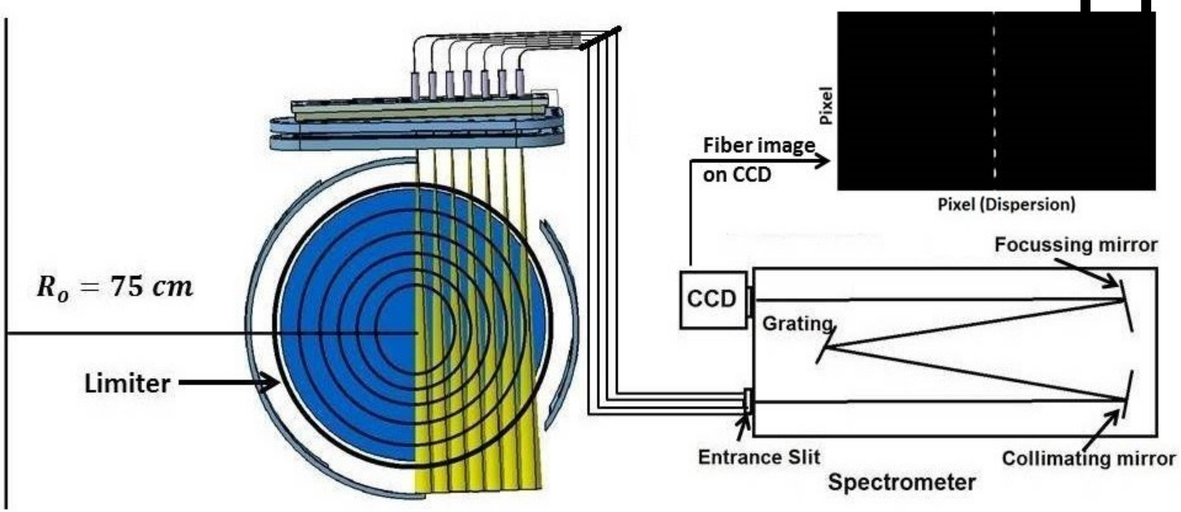
Collection optics of visible PCX spectroscopy on ADITYA-U consists of a re-entrant viewport for toroidal velocity measurement

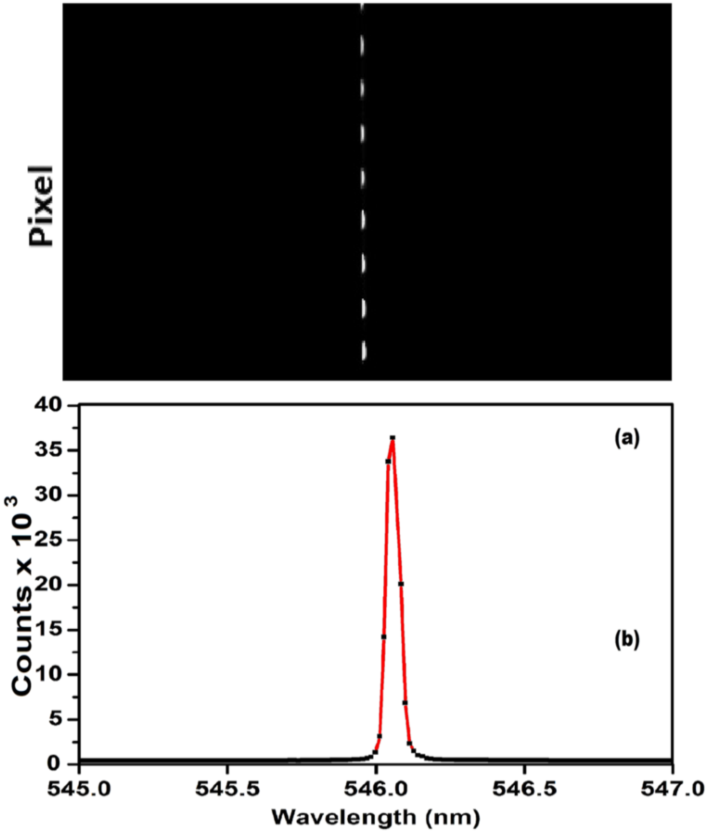
- Upgraded set up was installed in 2019.
- Total **<u>7 lines of sights</u>** cover plasma minor radius.
- Increase the radial coverage upto **<u>0.24 m of plasma minor radius</u>**[5].



[5] Shukla, G., Shah, K., Chowdhuri, M., *et al.* 'Impurity toroidal rotation profile measurement using upgraded high resolution visible spectroscopic diagnostic on ADITYA-U tokamak', *Review of Scientific Instruments*, 92, 063517, 2021.

Collection optics for poloidal velocity measurement is installed on top port

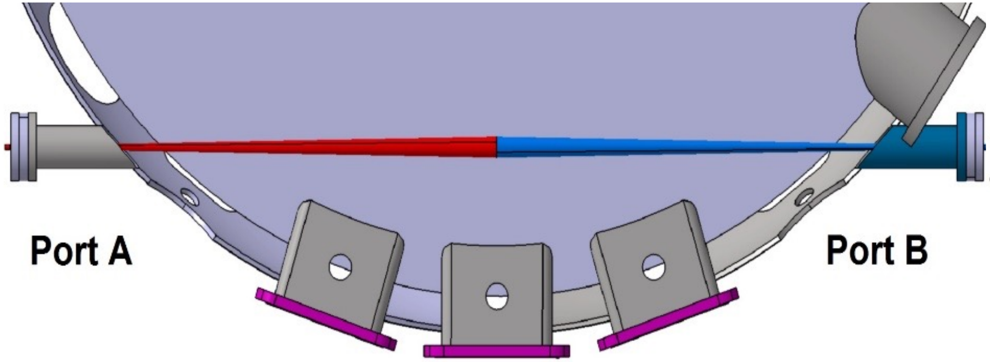




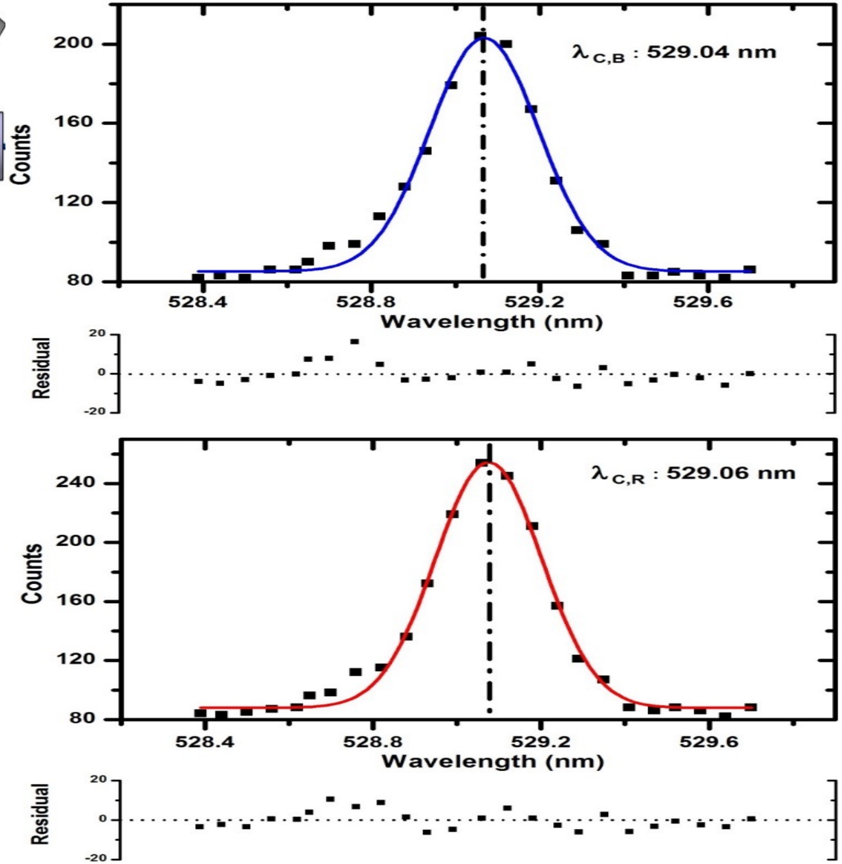
- Poloidal rotation is measured using C^{2+} line emission at **464.74 nm**.
- **Four LoSs** cover the plasma **minor radius from 0.115m to 0.215m**[6].
- Dispersion of the system is **0.01446 nm/px**

[6] Shukla, G., Chowdhuri, M., Shah, K., *et al,* 'Poloidal Rotation and Edge Ion Temperature Measurements Using Spectroscopy Diagnostic on Aditya-U' Tokamak. Atoms, 7(3), 93, 2019.

Important aspect of Doppler shift measurement is unshifted wavelength



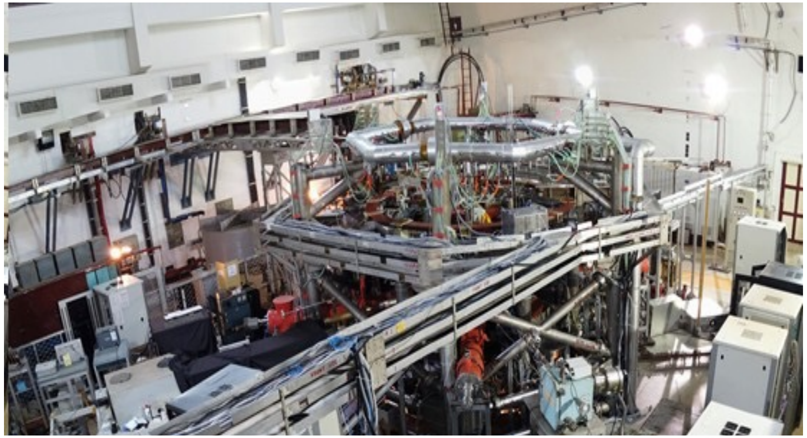
- Both the **LoSs** look at the same radial location
- Red and blue-shifted spectral lines are observed simultaneously.
- The average gives the unshifted reference wavelength[7].

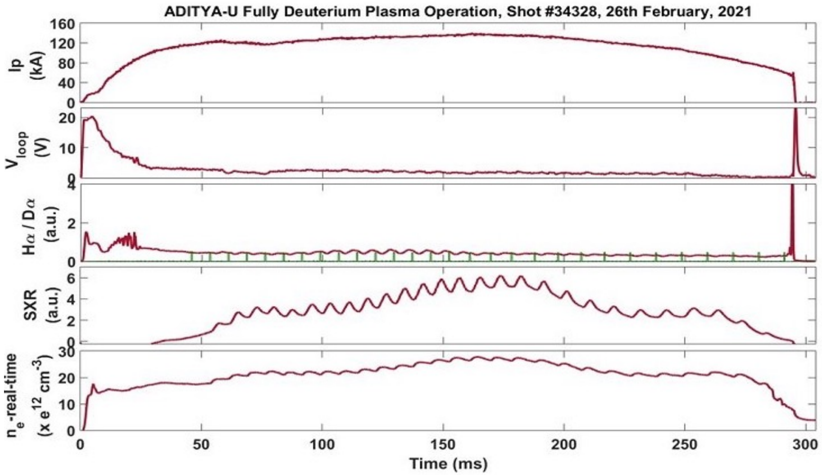


[7] Shukla, G., Shah, K., Chowdhuri, M.B., *et al*, 'Observation of toroidal rotation reversal in ADITYA-U tokamak', Nuclear Fusion, 59(110), 106049, 2019.

Identification of the nature of Intrinsic plasma rotation on ADITYA-U tokamak

ADITYA tokamak





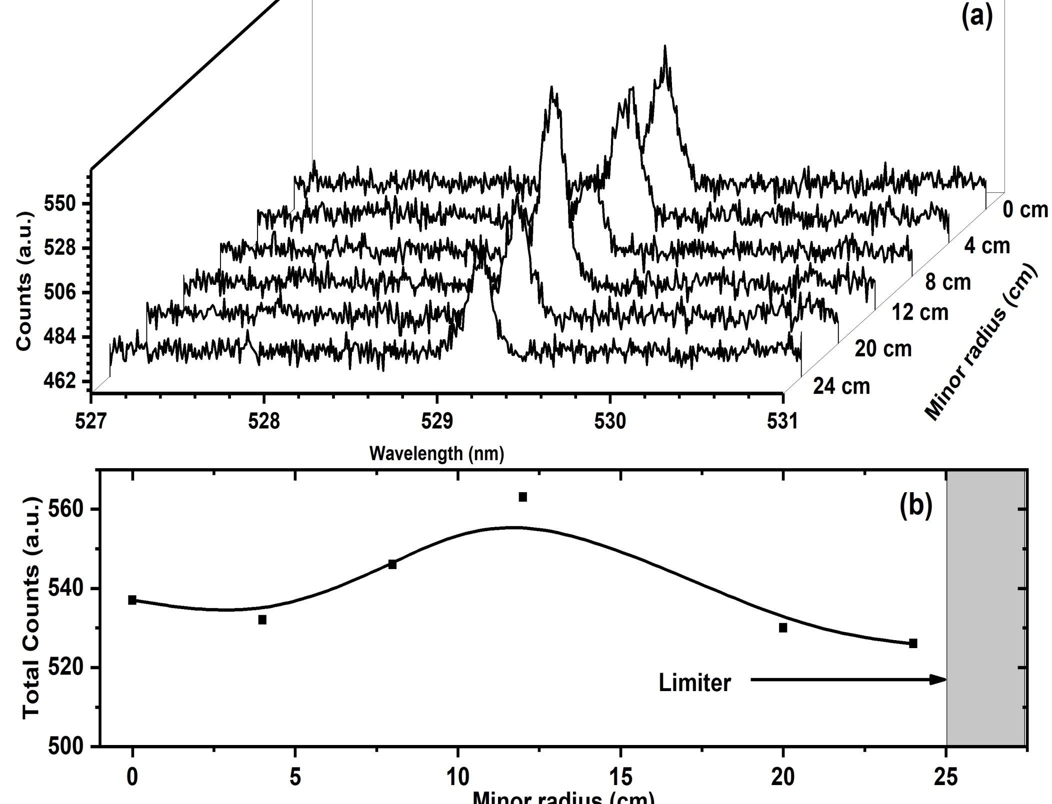
Main plasma parameters	ADITYA-U Tokamak
Major radius, Minor radius	0.75 m, 0.25 m resp.
Electron density	$1 - 4 \times 10^{19}$ m^{-3}
Electron temperature	400-700 eV
Toroidal Magnetic field	0.75-1.5 T
Plasma current	~150 kA
Plasma duration	~200 ms (repeatable)

- ADITYA[8] is a medium size tokamak located at IPR, India.
- The maximum toroidal field is = 1.2 T and has 20 TF coils
- During experiments, Hydrogen Plasma is produced
- ICRH heating of 20 - 40 MHz and 200 kW
- ECRH heating of 28 GHz and 200 kW
- Gas puffing of Ne, Ar impurities
- ADITYA is now upgraded to ADITYA-U[9] and is operational since winter 2017

[8] Tanna, R. L., et al., 'Overview of recent experimental results from the Aditya tokamak', Nuclear Fusion, 57, 102008, 2017.
[9] Ghosh, J., et al.,' Upgrade of ADITYA Tokamak with Limiter Configuration to ADITYA Upgrade Tokamak with Divertor Configuration', 26th IAEA-FEC proceedings, 2016.

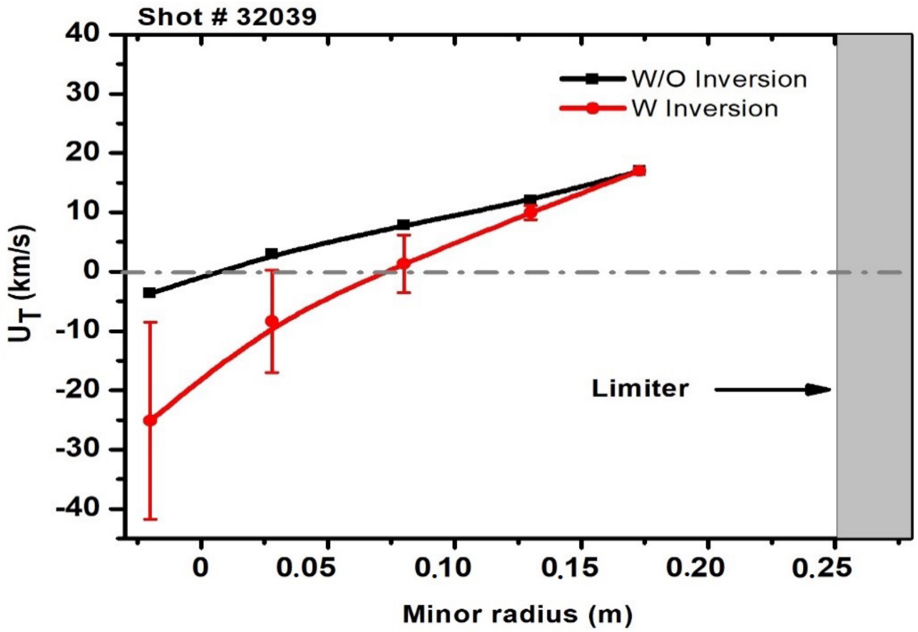
Space resolved spectra of the measured C^{5+} impurity passive charge exchange line emission

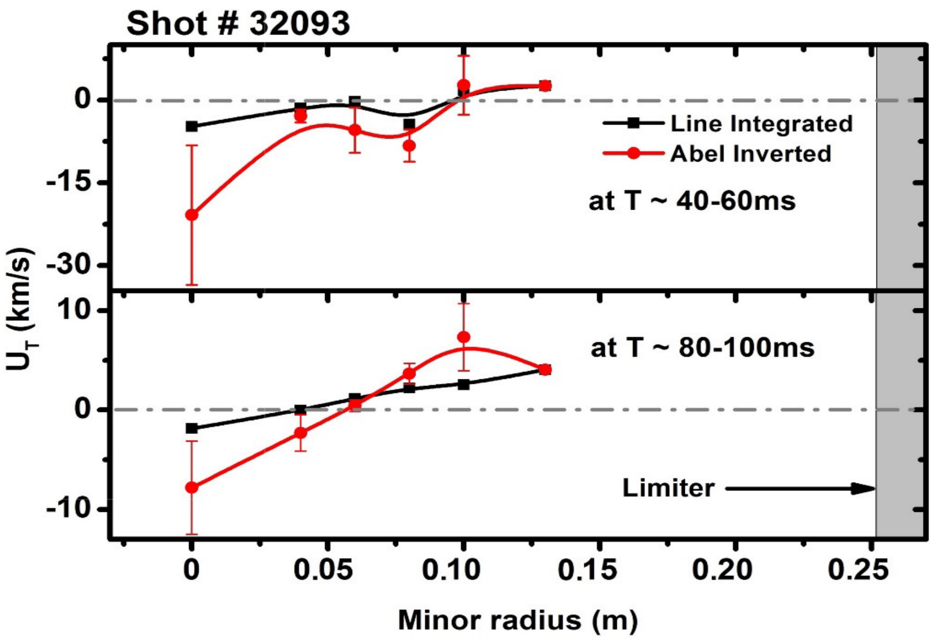
- (a) Space resolved spectrum of C^{5+} corresponding to various LoSs covering plasma radius from <u>**~ 0 cm to 24 cm**</u> of plasma radius,
- (b) total counts for each **LoS** and spline fitted line on data points[10].



[10] Shukla, G., Shah, K., Chowdhuri, M., *et al.*, 'Impurity toroidal rotation profile measurement using upgraded high resolution visible spectroscopic diagnostic on ADITYA-U tokamak', *Review of Scientific Instruments*, 92, 063517, 2021.

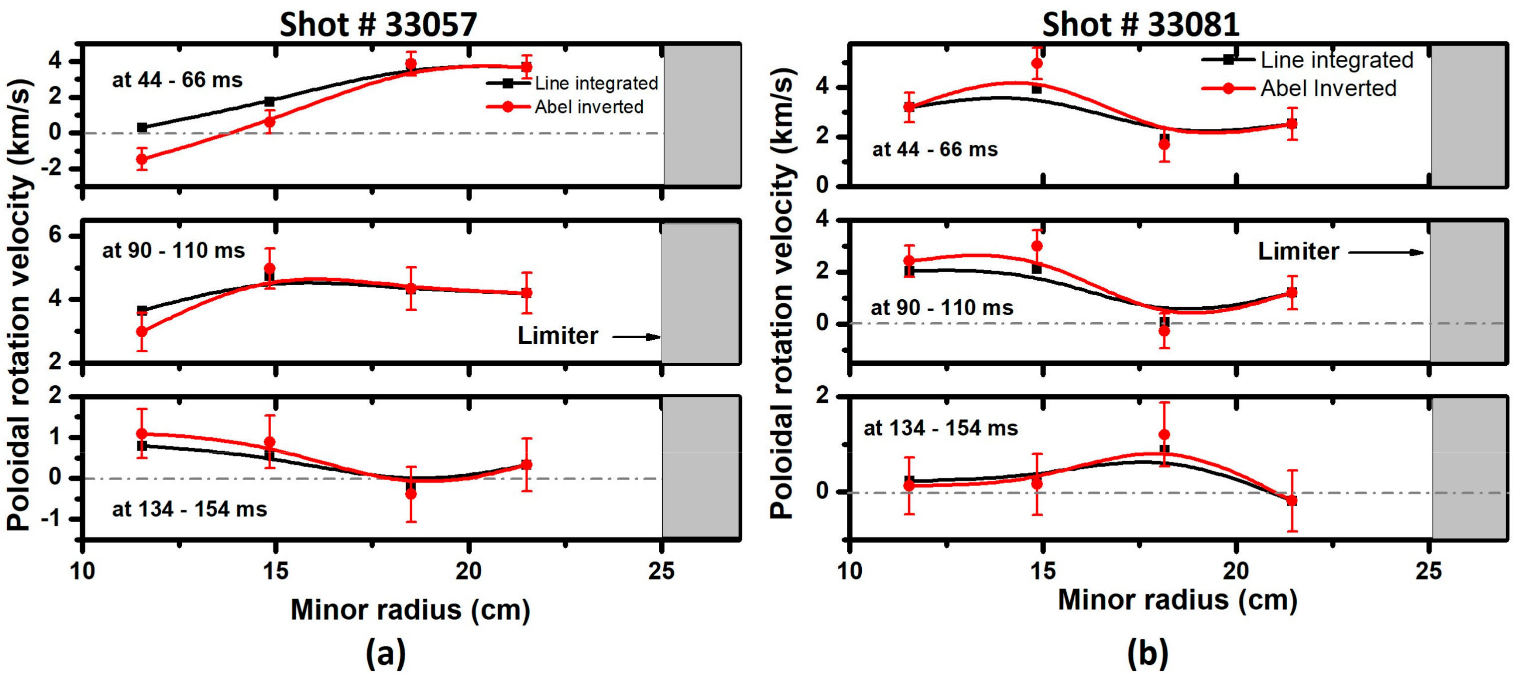
Toroidal rotation on ADITYA-U shows counter-current rotation in core





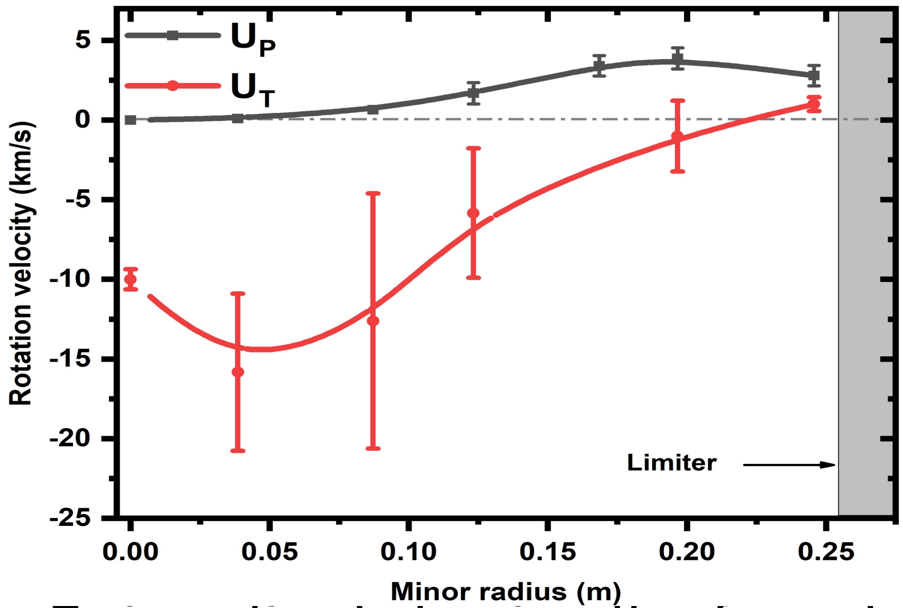
- The maximum **line averaged electron density** during the discharge is **$\sim 1.5 - 2 \times 10^{19} m^{-3}$**.
- The **direction of rotation** is similar to those reported from other tokamaks.

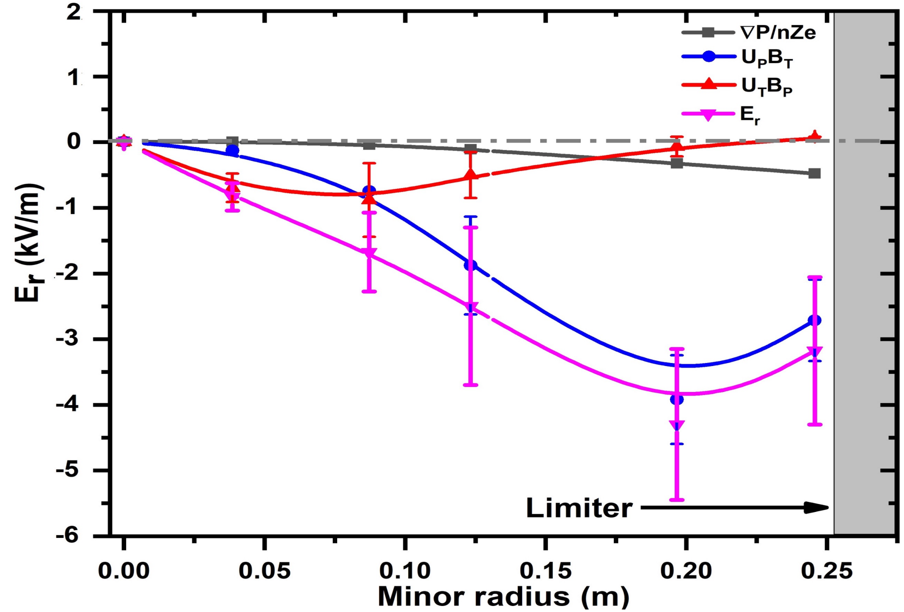
Spatial profile of carbon ion poloidal rotation velocity along with error bars for Aditya-U tokamak



- Radial profile of the carbon ion poloidal rotation velocity (km/s) along with the error bars for Aditya-U tokamak.
- Maximum poloidal velocity of **<u>~ 2.5 km/s</u>** is measured near edge region.

Estimation of Radial electric field from measured rotation velocities





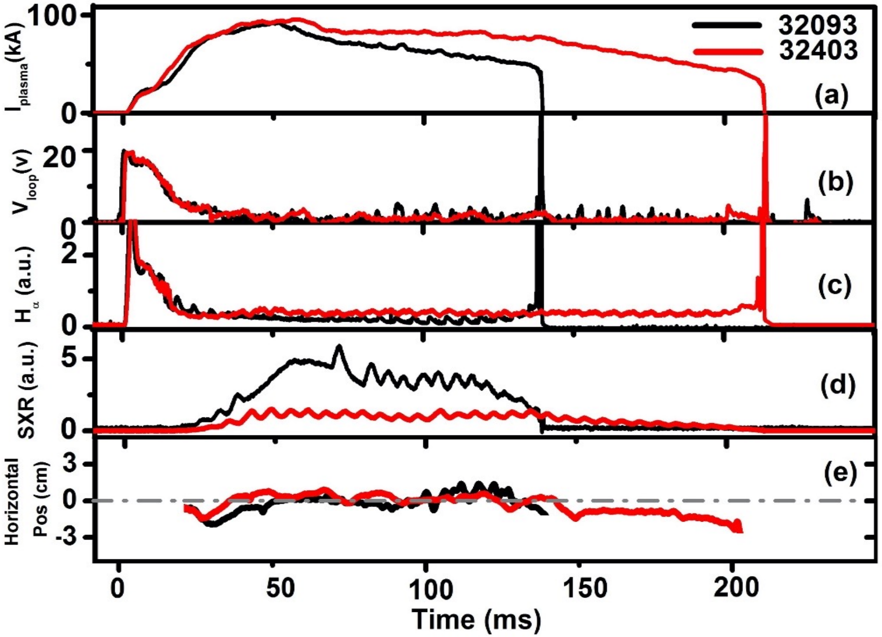
- E_r is estimated using the force balance equation, the poloidal velocity measurement is also required.

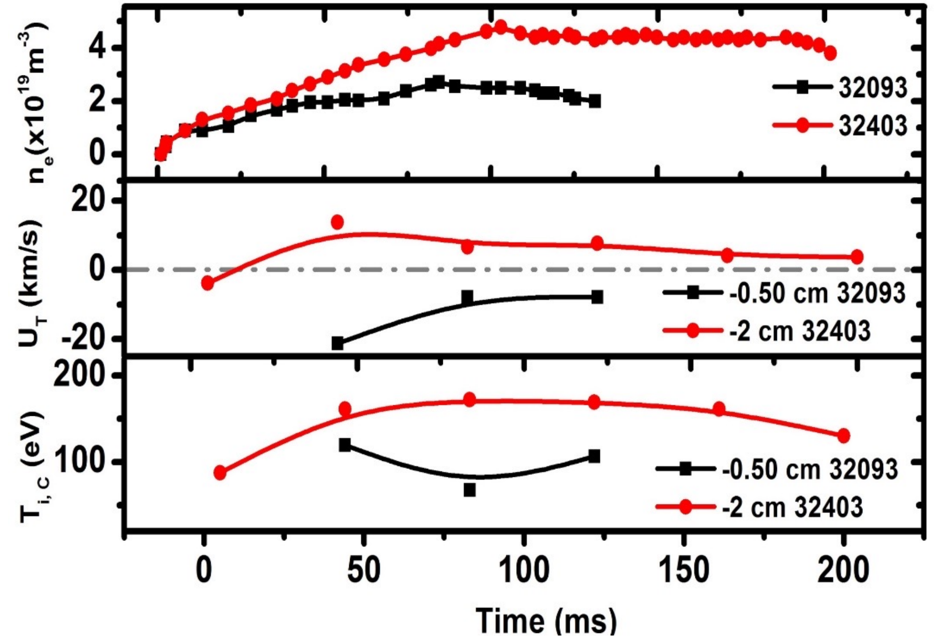
$$E_r = \frac{\nabla P}{nZe} + V_\varphi B_\theta - V_\theta B_\varphi$$

- The value of **radial electric field** is maximum at ~ 0.20 m with **~ 4.5 kV/m**[11].

[11] Shukla, G., Shah, K., Chowdhuri, M., *et al*. 'Impurity toroidal rotation profile measurement using upgraded high resolution visible spectroscopic diagnostic on ADITYA-U tokamak', *Review of Scientific Instruments*, 92, 063517, 2021.

Toroidal rotation in high density Ohmic discharges show change in direction from CO to CTR

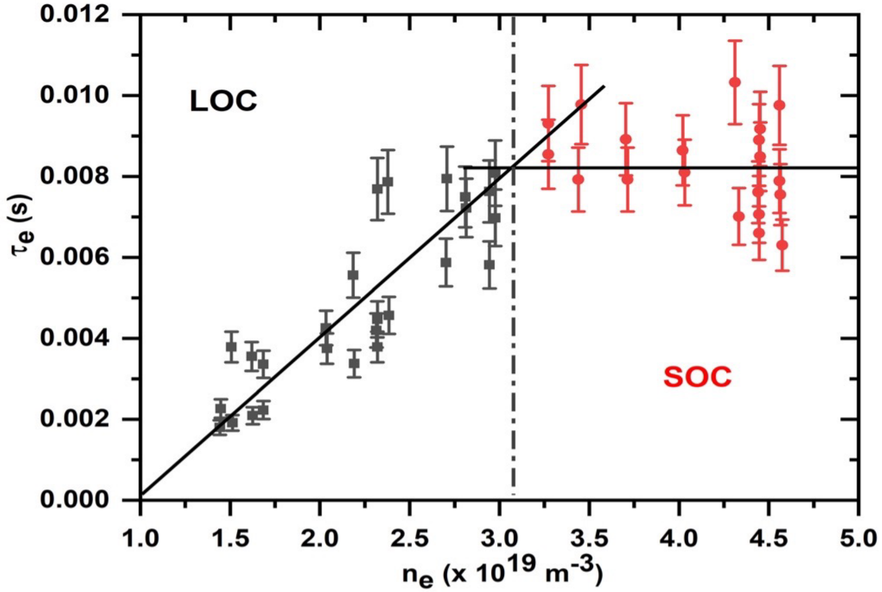


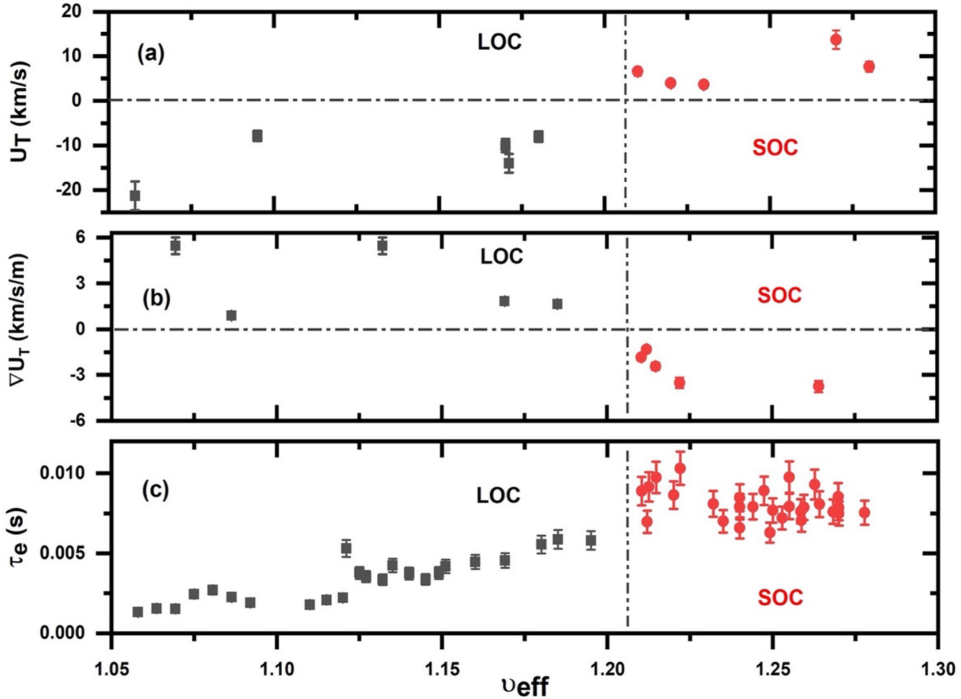


Core rotation velocity	**- 20 km/s**	$2.5\ x\ 10^{19} m^{-3}$
Core rotation velocity	**15 km/s**	$4.5\ x\ 10^{19} m^{-3}$

Image from: Shukla, G., Shah, K., Chowdhuri, M.B., *et al*, 'Observation of toroidal rotation reversal in ADITYA-U tokamak', Nuclear Fusion, 59(110), 106049, 2019.

Rotation reversal and change in confinement regime alongwith collisionality on ADITY—U



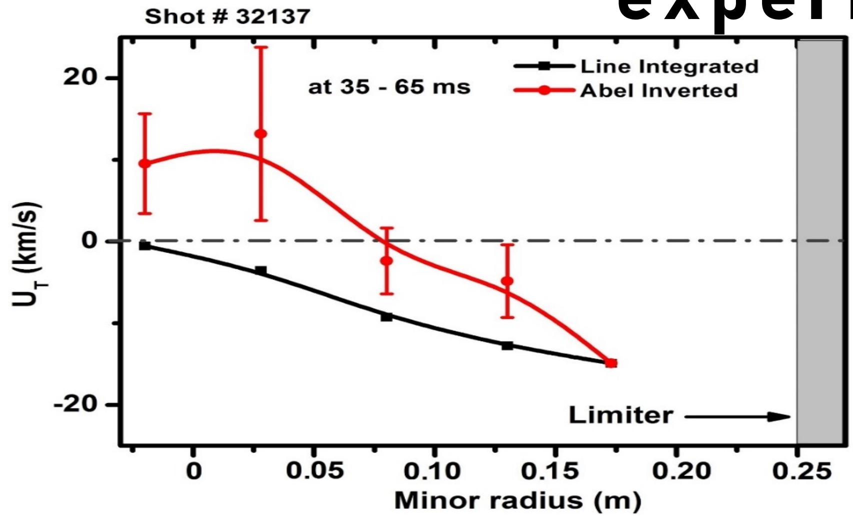


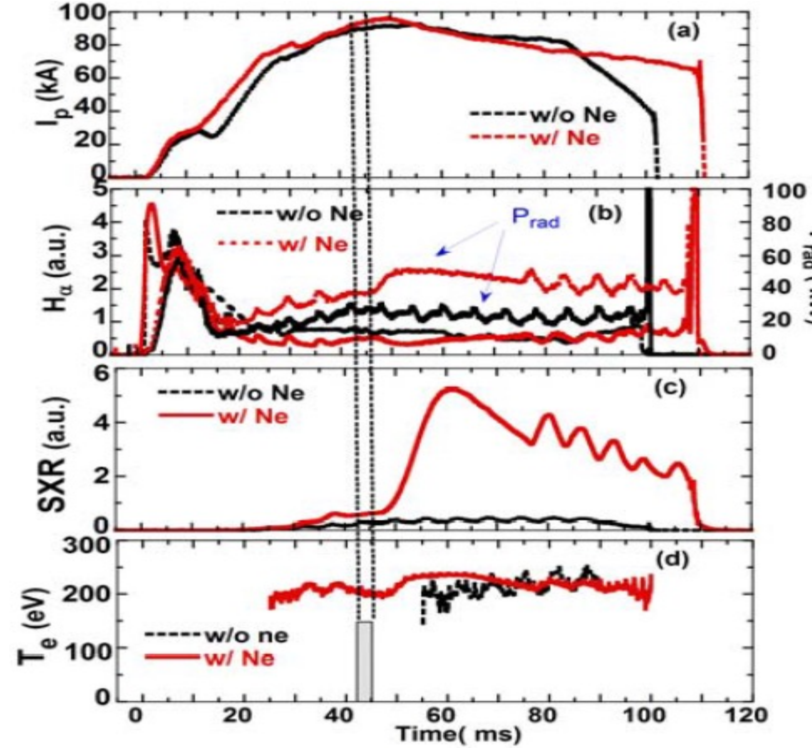
- A possible change in the confinement regime beyond critical density of ~ 3 x 10^{19} m^{-3} in ADITYA-U tokamak.

- Central toroidal rotation velocity as a function of effective collisionality given by

$$\nu_{eff} = 0.1\ R\ Z_{eff} n_e / T_e^2$$

Investigating nature of rotation by altering plasma density during Ne GPI for IOC experiments





Ne GPI → SXR ↑ Rise in n_e, T_e

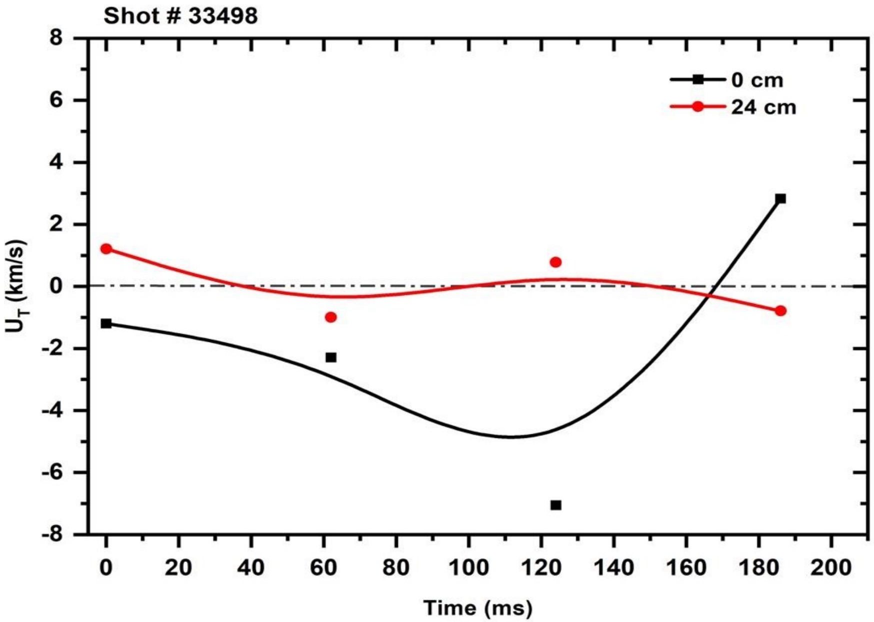
↓

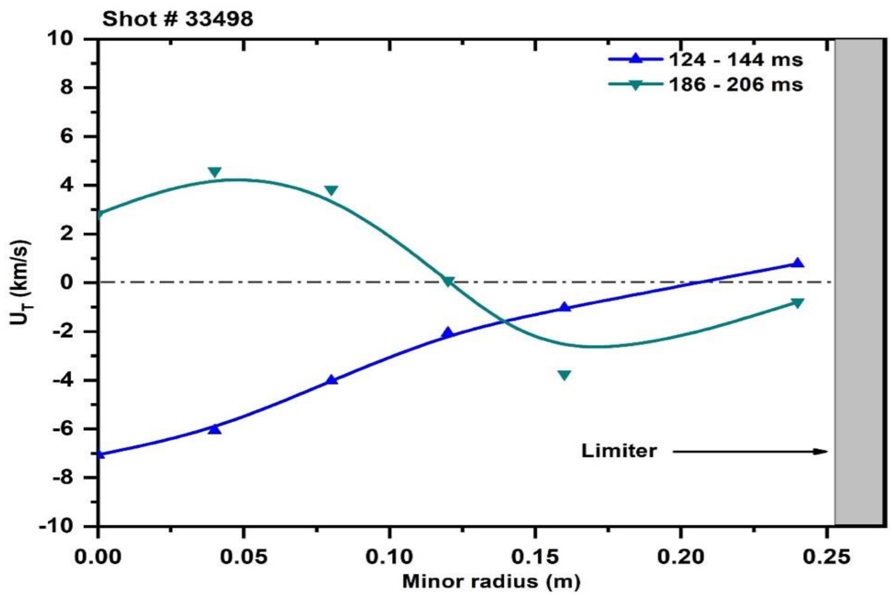
I_{sat} (A) ↑ Rise in $n_{e,\ edge}$

Image from: Shukla, G., Shah, K., Chowdhuri, M.B., *et al*, 'Observation of toroidal rotation reversal in ADITYA-U tokamak', Nuclear Fusion, 59(110), 106049, 2019.

Image from" Chowdhuri, M.B., Ghosh, J, *et al.*, 'Neon seeded radiative improved mode in ADITYA-U tokamak', IAEA-FEC, 2018.

U_T profile in ADITYA-U shows opposite direction in both edge and core velocities





- Core plasma and edge plasma rotation are in **opposite directions**.
- Rotation reversal can be explained by residual stress.
- Role of edge dynamics is investigated.

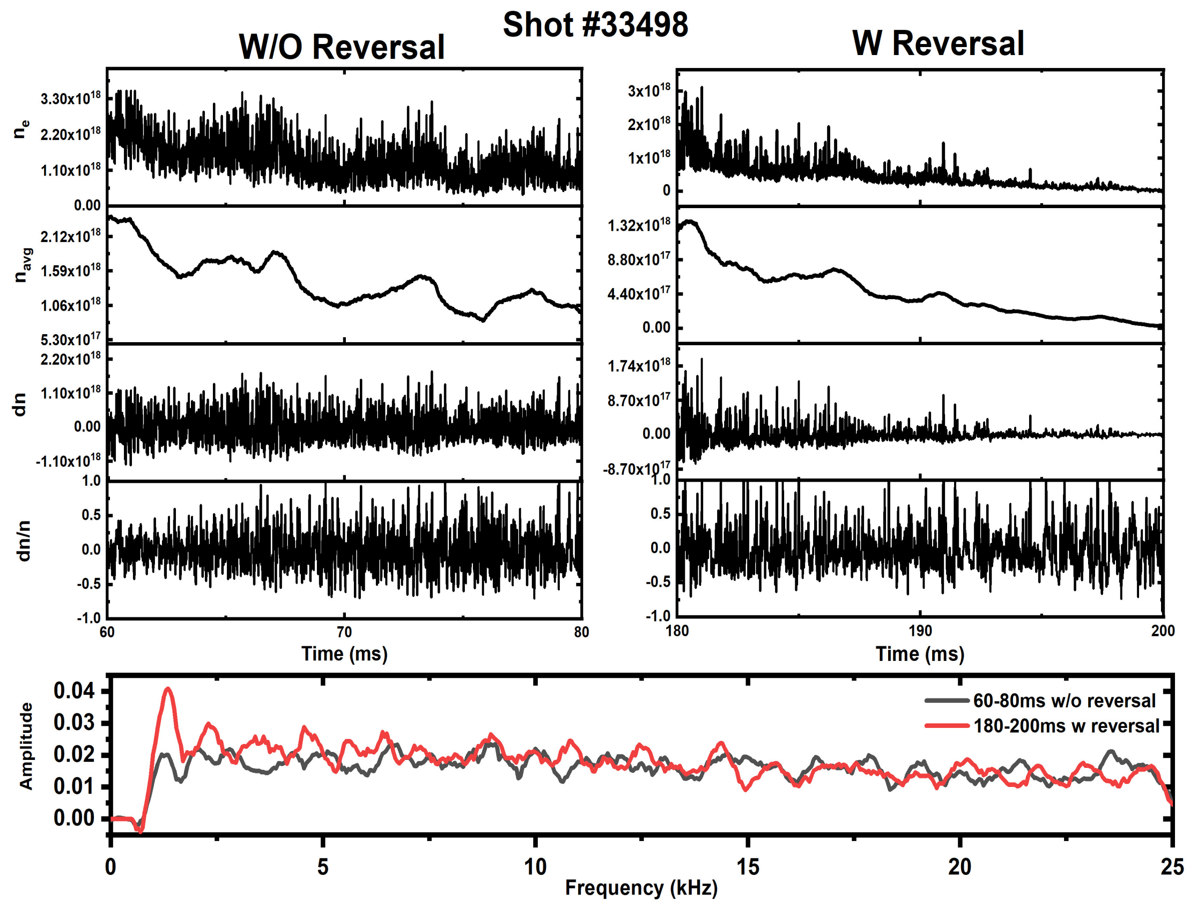
Rotation profile seems to be influenced by edge plasma parameters

- Since fluctuation induced, residual stress is known to play role in plasma rotation, we turn our attention to examine residual stress, for this radial toroidal momentum transport equation is given as.

$$\Gamma_{\emptyset}(r) = -\chi_{\emptyset}\frac{\partial u_{\emptyset}}{\partial r} + V_{\emptyset}u_{\emptyset} + C_{\emptyset}v_{th}$$

Edge parameters are investigated to establish possible momentum source

- The **residual stress** can be understood as momentum flux which is **driven by gradient of plasma density, temperature, and pressure etc**.
- **No change in the frequency amplitude spectrum**.



Rotation profile seems to be influenced by edge plasma parameters

- Since fluctuation induced, residual stress is known to play role in plasma rotation.
- Here $C_{\emptyset}$ is estimated by assuming a constant momentum diffusivity over plasma minor radius and by neglecting convective term,
- $C_{\emptyset}$ is estimated as

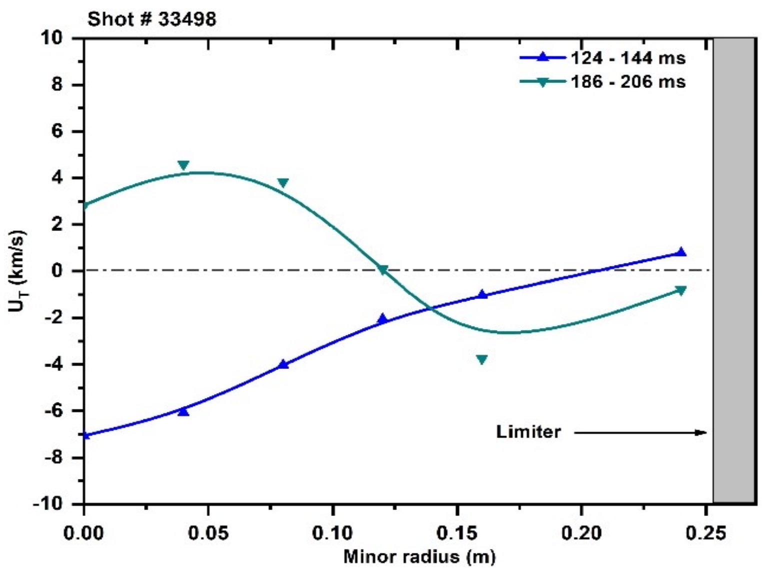
$$C_{\emptyset} = \frac{1}{v_{th}} \nabla u_{\emptyset} \chi_{\emptyset}.$$

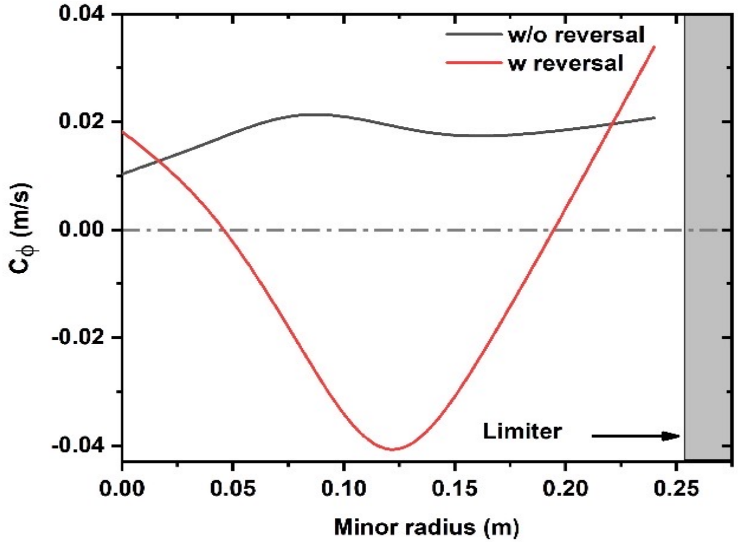
Convective term

$$\Gamma_{\emptyset}(r) = -\chi_{\emptyset} \frac{\partial u_{\emptyset}}{\partial r} + V_{\emptyset} u_{\emptyset} + C_{\emptyset} v_{th}$$

Diffusion term

Rotation reversals show gradient in residual stress from edge to core region

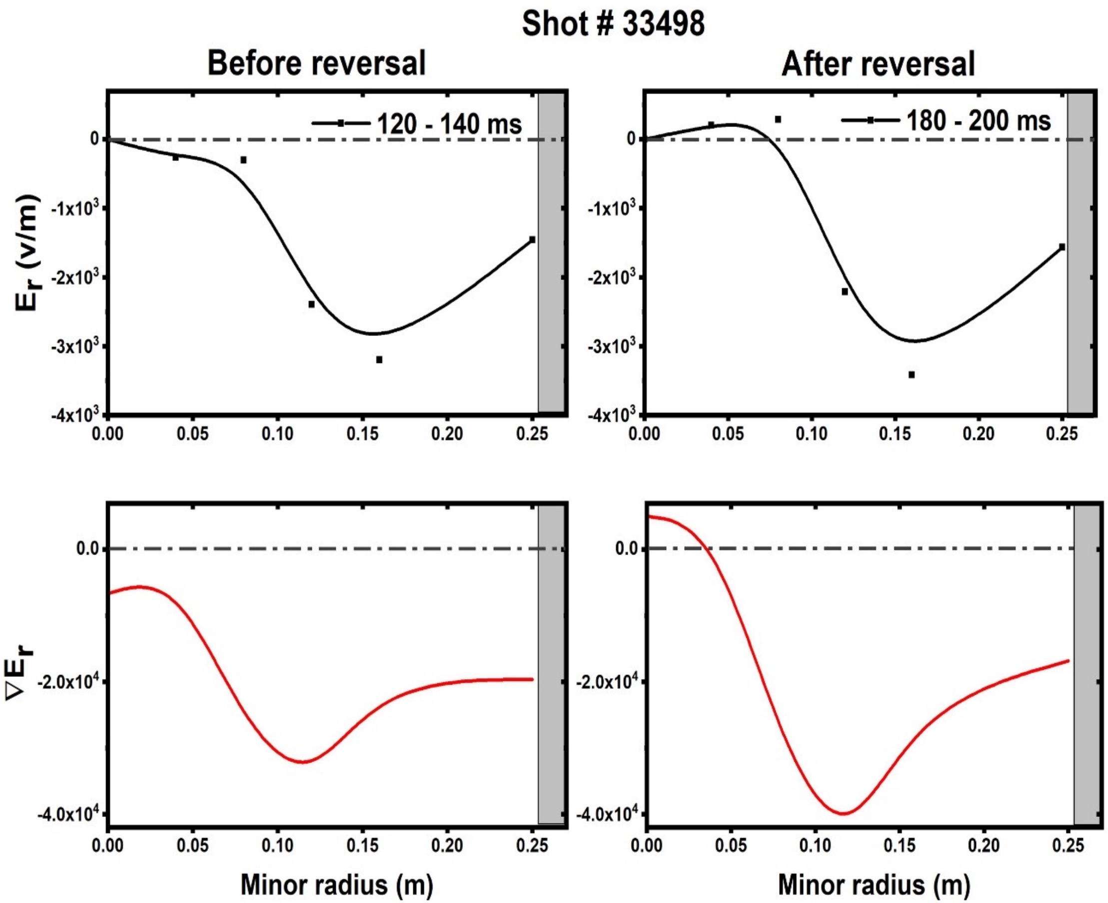




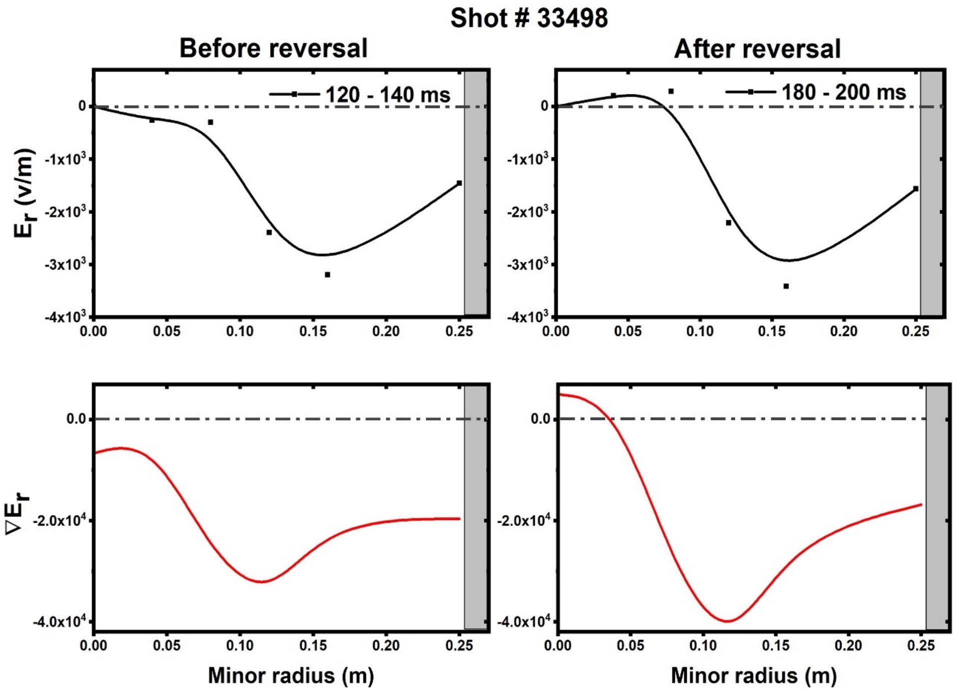
- Toroidal rotation profile show opposite direction rotation towards the edge.
- Profile of $\mathbf{C}_{\Phi}$, residual stress generated by assuming $\chi_{\phi} = 1.2\ \mathrm{m}^2/s$.
- The $\mathbf{C}_{\phi}$ profile is relatively flat compared case of rotation reversal.

Rotation reversals is accompanied by shear in radial electric field

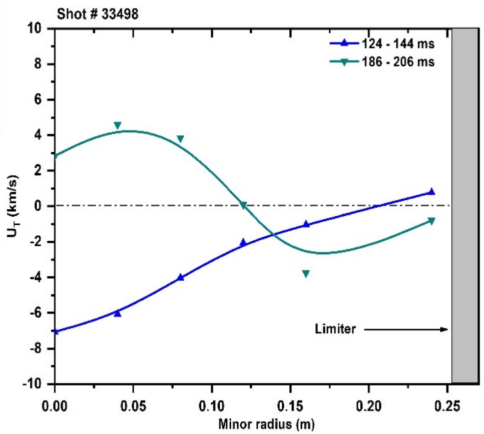
- A shear in radial electric field is present in region ~ 0.15m towards plasma edge whereas its **gradient is relatively constant before reversal** towards the edge region.
- The shear in radial electric field when correlated with C_ϕ radial profile **may justify change in C_ϕ along plasma minor radius**.

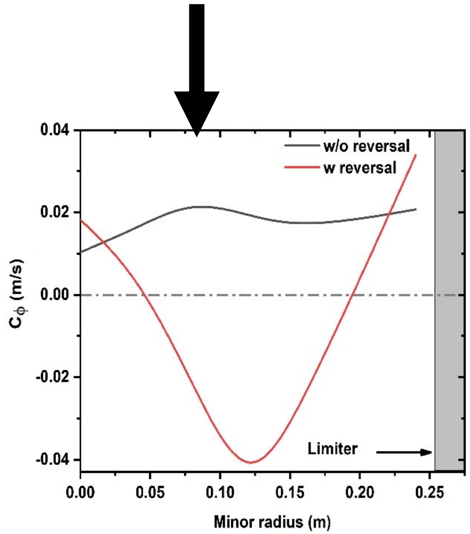


Rotation reversals is accompanied by shear in radial electric field



- A sheared radial electric field is observed in case of rotation reversal.
- Change in C_Φ during reversal.





- Shear in E_r may lead to E x B shear.
- E x B shear maybe responsible for rotation reversal.

To conclude

- **Intrinsic toroidal rotation** is found to be **~ 25 km/s** with core rotation in **counter current direction** in typical discharges of ADITYA-U tokamak.
- The edge **poloidal rotation** in typical discharges of ADITYA-U tokamak is observed to be **~ 4 km/s**.
- The E_r in the mid radius section has been found to be **~ 5 kV/m**.
- Toroidal **rotation reversal** has been triggered by increasing the **plasma density**.
- Transition in **confinement regime** and collisionality is observed with threshold **density of rotation reversal**.

- Incase of ADITYA-U tokamak **no change in fluctuation** of ion saturation current is measured by Langmuir probe.
- Estimation of **radial electric field** from toroidal and poloidal rotation velocities show a **sharp gradient** in the core and towards edge region.
- ∇E_r corresponds with a **gradient in residual stress** term during rotation reversal.
- The presence of radial electric field shear indicates a **sheared E x B rotation** which could possible be **linked with rotation reversal** in ADITYA-U tokamak.

An important conclusion is to have identified role of **radial electric field shear in toroidal rotation reversal** in ADITYA-U tokamak.

Thank you

Nature of intrinsic toroidal rotation in Ohmically heated discharges of ADITYA-U tokamak measured using Passive Charge eXchange spectroscopy

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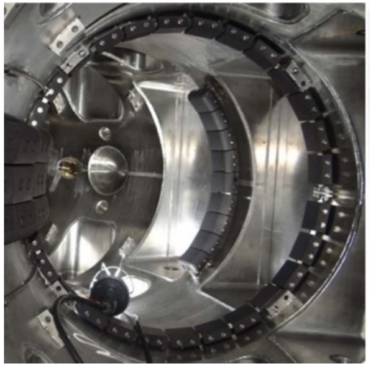

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