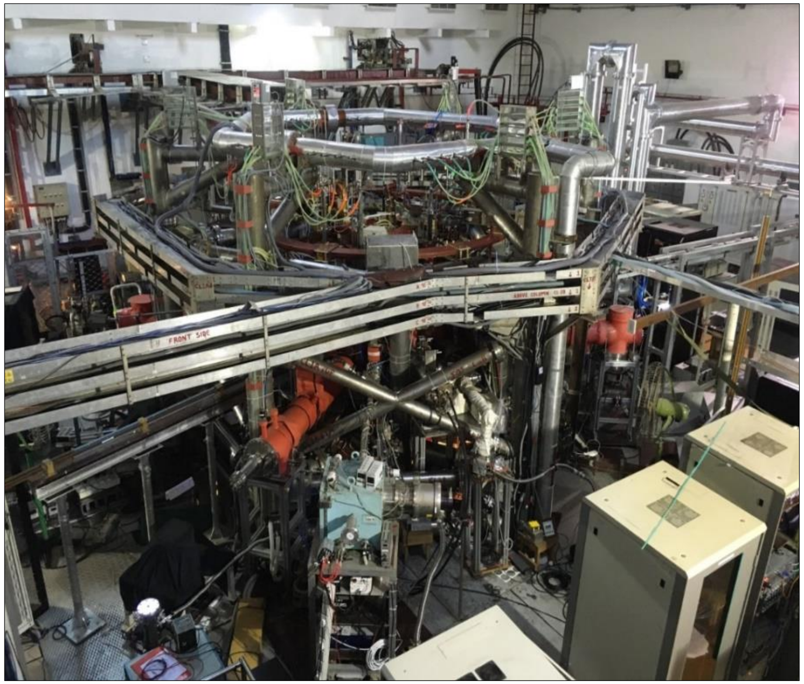
Characterization of argon impurity transport and measurement of toroidal plasma rotation using spectroscopic techniques in Aditya-U Ohmic plasma

Kajal Shah*

Aditya-U Tokamak



***Pandit Deendayal Energy University (PDEU), Gandhinagar, Gujarat, India**

***Institute for Plasma Research (IPR), Bhat, Gandhinagar, Gujarat India**

Seminar talk at Princeton Plasma Physics Laboratory, Princeton, USA

27.04.2022

Outline

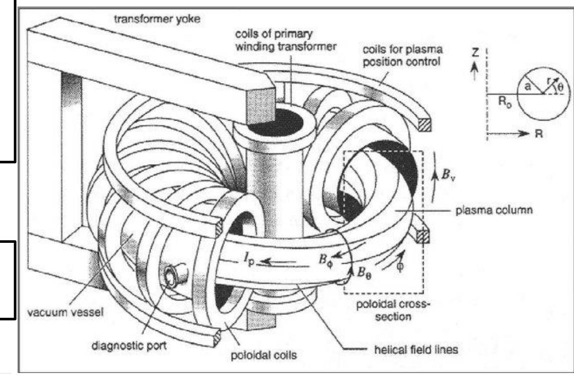
- Introduction
  - Importance of Impurity transport and intrinsic rotation in tokamak (ITER relevance, major challenges)
  - Aditya-U tokamak - good candidate for the above studies.
- Development of tangential X-ray Crystal Spectrometer (XCS)
  - Basics of crystal spectroscopy
  - Spectrometer parameters - design and fabrication of the system
  - Testing of the entire system in lab and alignment
- Characterization of argon impurity transport in ohmic discharges
  - Turbulent transport behaviour of argon
  - Input XCS
- Results of plasma rotation in ohmic discharges
  - Rotation direction, rotation reversal, isotopic effect on rotation
  - Input for XCS
- Summary

Importance of plasma rotation in a Tokamak

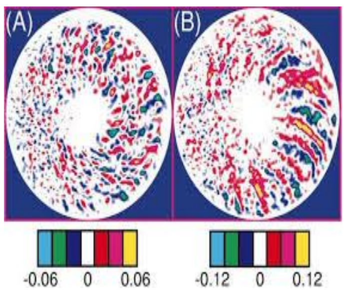
<u>A fusion relevant tokamak plasma must fulfill:</u>

- High energy and particle confinement (Lawson criterion).
- The confinement must also be stable. (Instability control).
- Impurity optimization.

The tokamak: most advanced toroidal confinement system



A fast rotating plasma helps in achieving the above through…

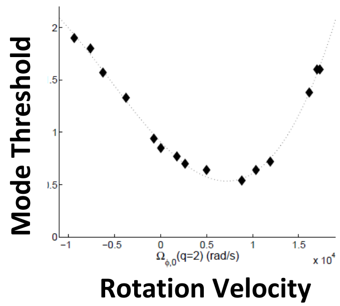


Turbulence suppression

⬇

Confinement Improvement

+

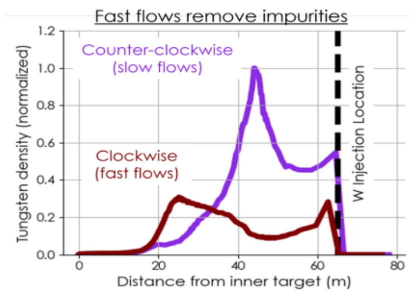


High threshold for tearing modes & RWMs

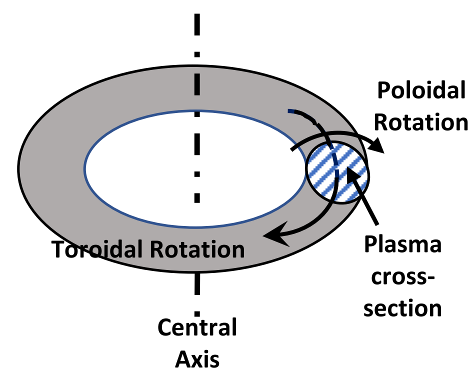
⬇

Better Stability

+



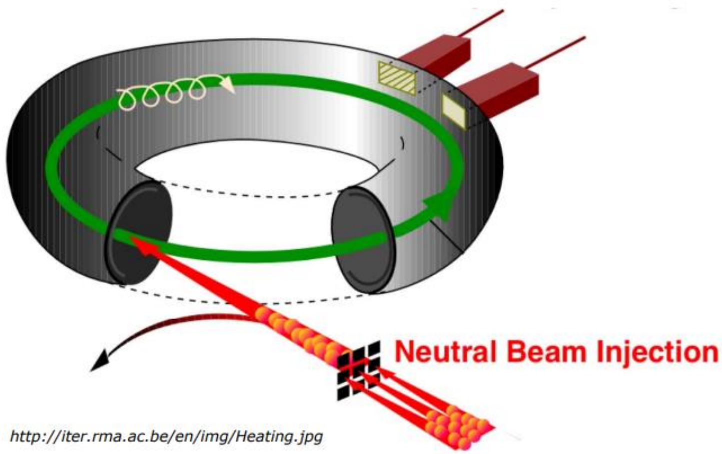
Fast flows facilitate Impurity Removal



PC: https://pure.tue.nl/ws/files/2338508/200612332.pdf, Shawn Zamperini, UT-Knoxville.

How a large plasma rotation can be driven?

Importance of plasma rotation in a Tokamak



The original and most studied external rotation drive method is from Neutral Beam Injection

Limitations of NBI:

- large machine sizes,
- high densities and
- the limitations of beam current

may limit usage of this drive mechanism in future reactor-grade devices

Intrinsic (spontaneous) plasma rotation without external momentum input will be beneficial for achieving more economical reactor operation

Intrinsic plasma rotation has been widely observed in tokamaks

✓ However, the Intrinsic (spontaneous) plasma rotation are not well understood

✓ Reliable models are under development for predicting intrinsic rotation in large fusion devices

✓ LOC-SOC plasmas show rich phenomenology and will be useful to asses

- Mechanisms of rotation reversal
- Effect of turbulence on rotations
- MHD effect
- Coupling of core-edge physics

Why study impurity transport in tokamak?

Efficient fusion reactors should have clean plasma: We do not want Impurities!

Because:

Radiate energy (energy confinement time $\tau_e\downarrow$)

Impurity accumulation in the core Dilute the fuel (N↓)

At the same time: We do want Impurities! Because:

To radiate energy at plasma periphery to reduce the heat flux on PFCs

Impurity (Nitrogen etc.) seeding helps in confinement improvement

Impurities (Ar, Ne etc.) required for Diagnostics

Hence knowledge of impurity behaviour in tokamak is essential!

- How the seeded or wall and PFC generated impurity transport to tokamak interior?
- In case of seeding and diagnostic, the appropriate injection quantities?
- How they affect the plasma rotation?
- How their transport depend on their charge and mass? etc.

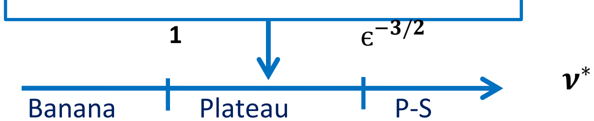
No single model describes the behaviour of all relevant impurities

Classical transport (purely collisional)

Neoclassical transport (toroidal geometry)

Turbulent/ anomalous transport

$$D_{CL} = \rho_e^{\,2}\ \nu_e$$

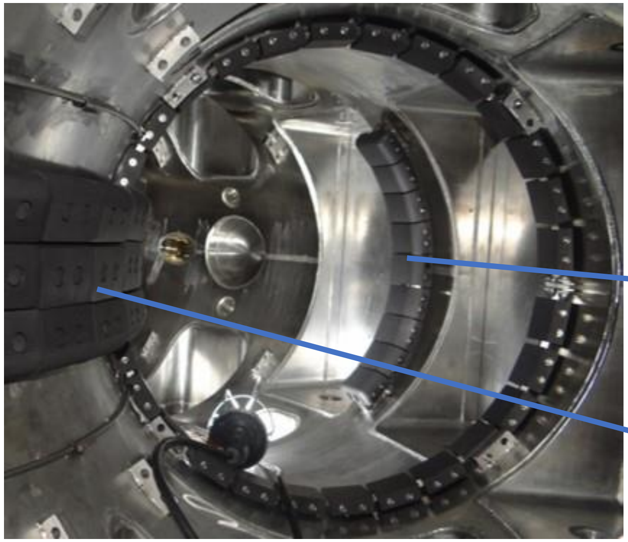


$$\nu^* = \frac{\nu_{iz} qR}{v_{th,z}\epsilon^{-3/2}}$$

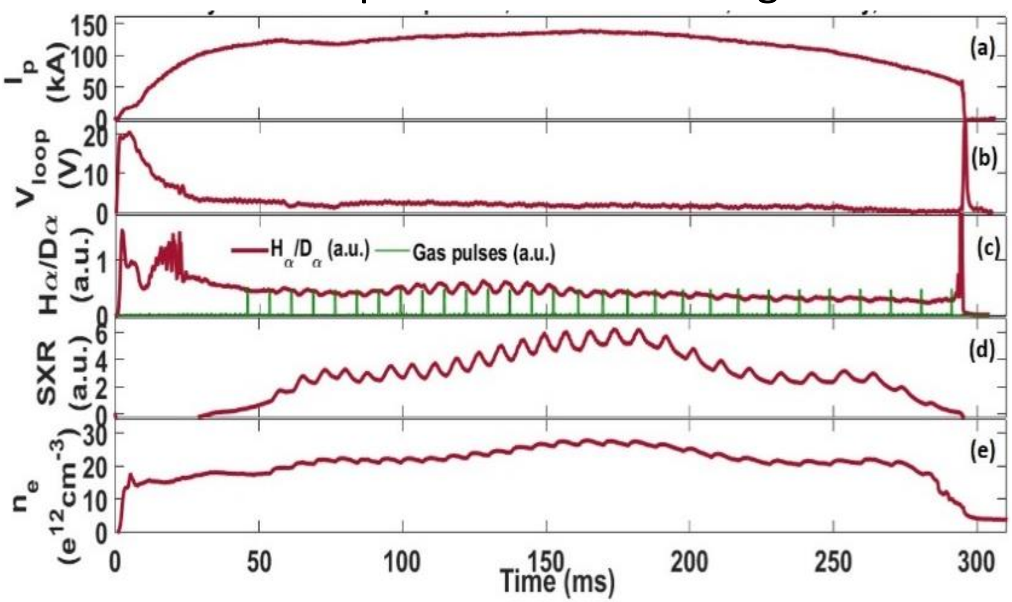
D m^2/s

Rotation and Impurity studies in Aditya-U Tokamak

Machine and Plasma Parameters	
Major radius (R)	0.75 m
Minor radius (a)	0.25 m
Plasma Shape	Circular / Shaped
Toroidal Field	1.1 - 1.5 T
Plasma Current	200 kA ± 10 %
Plasma Duration	~ 0.2 - 0.4 s
Electron Density (CA)	1.0 - 4.0 x 10^{19} m^{-3} ±10%
Electron Temp.	250 eV – 700 eV ± 30%
Ion Temp.	~ 150 eV
Fuel Gas	H_2 and D_2
Impurities	O, C, Li, He, Ne, Ar, Fe



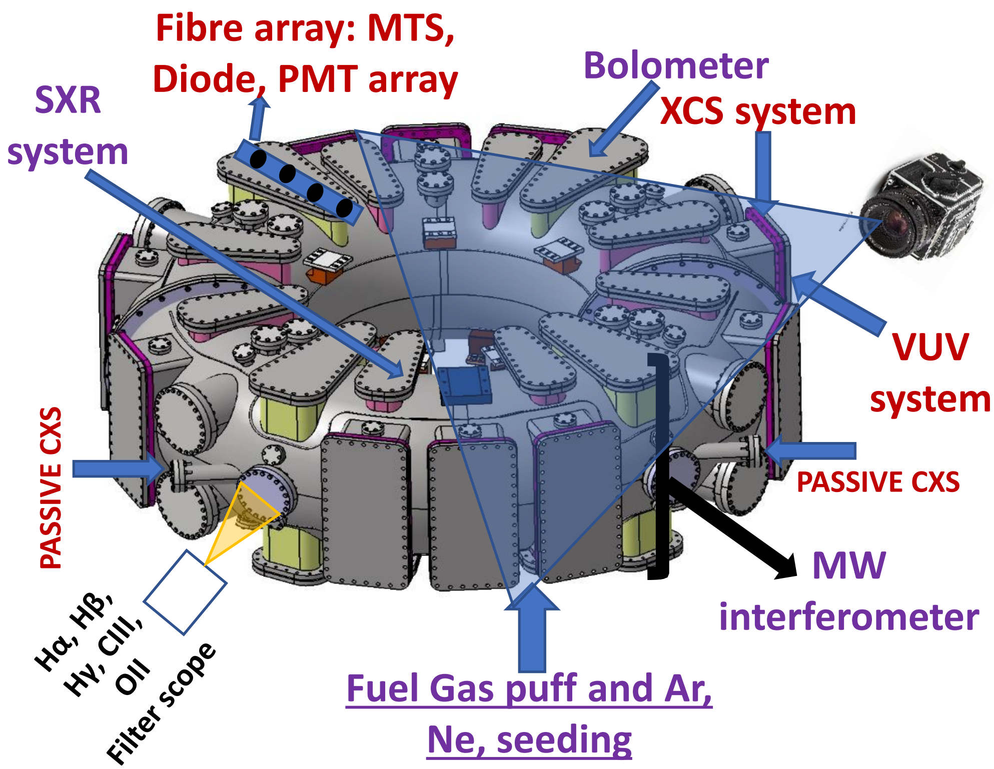
Representative Discharge

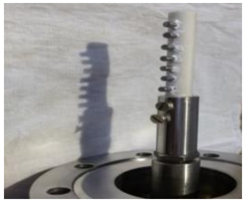


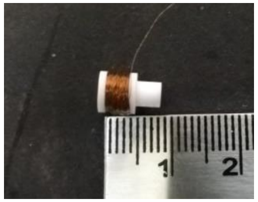
In this presentation: Results from Circular Plasmas with Toroidal Limiter Only

Rotation and Impurity studies in Aditya-U Tokamak

Equipped with adequate diagnostics

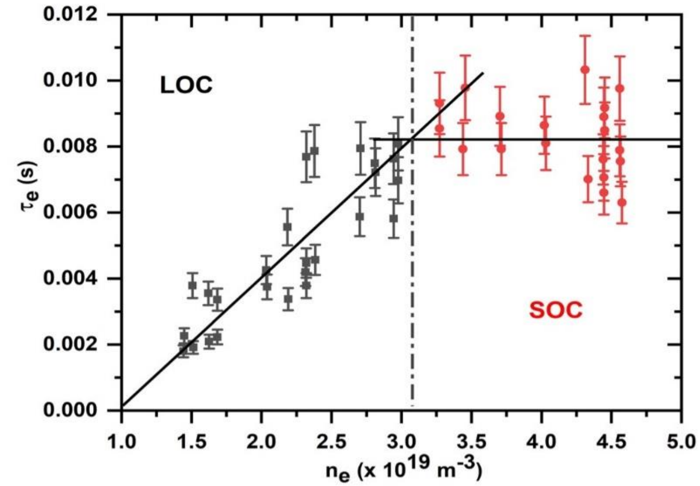




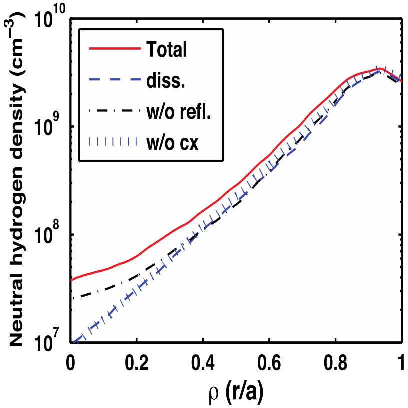


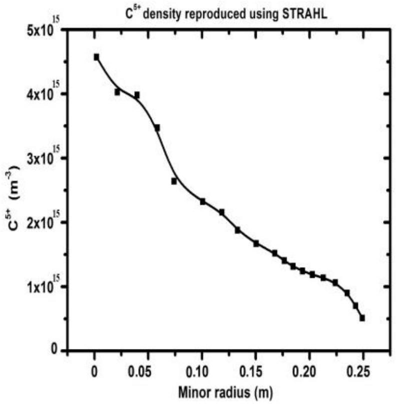
Langmuir (single, triple) and Magnetic Probe arrays at several locations

Discharges in LOC – SOC Regimes



simultaneous observation of Ar^{16+} (X-ray) and C^{5+} (Visible CX) possible from plasma core





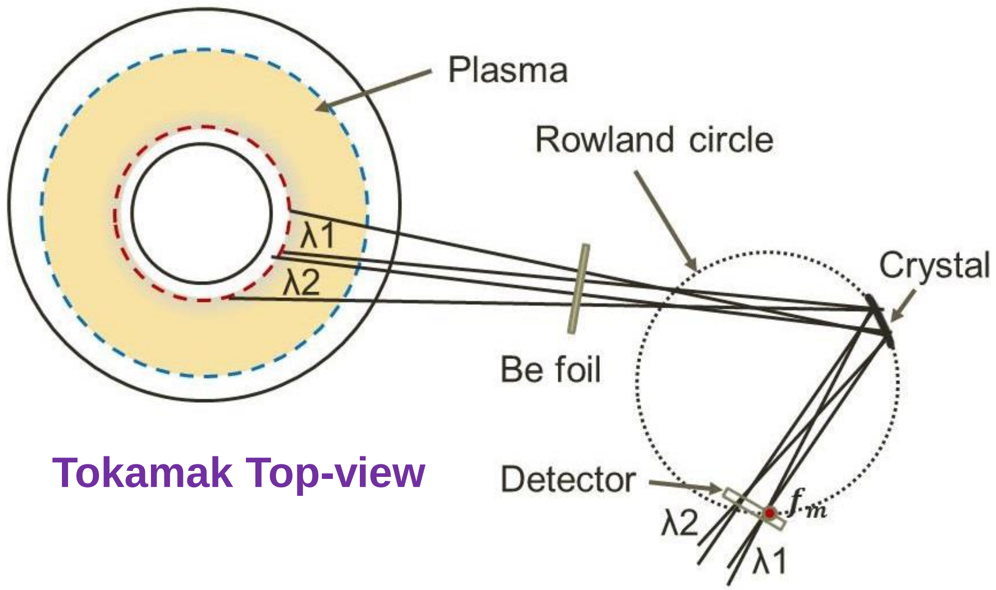
In this presentation: Results from Circular Plasmas with Toroidal Limiter Only

Development of Tangential X-ray Crystal Spectrometer (XCS) to measure toroidal rotation and ion temperature in ADITYA-U

- ✓ First XCS on Indian tokamaks
- ✓ Designed, fabricated and installed from scratch
- ✓ A great learning experience

XCS for ADITYA-U

Typical XCS schematic used in Tokamak

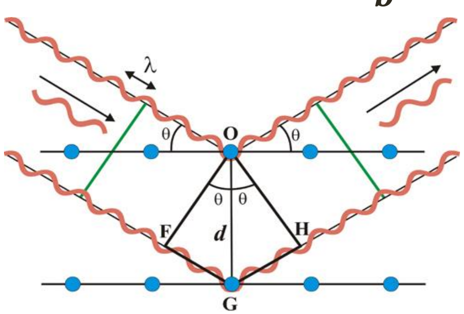


Tokamak Top-view

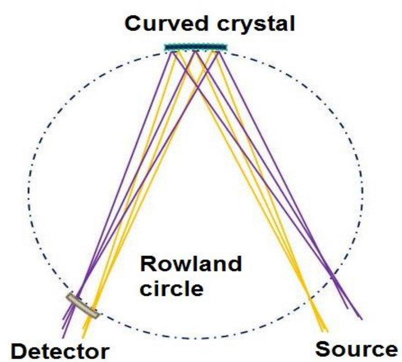
Based on:

Bragg Diffraction

$$n\lambda = 2\, d\, sin\theta_b$$



Curved Crystal



Curved-Crystal enhances focussing properties

Major Considerations

– For single chord measurement

Cylindrical Crystal

- Crystal radius of curvature (R_c) = diameter of the Rowland circle

Choice of Crystal

- Ar or Ne line emission

Factors affecting resolving power of XCS

- Crystal rocking curve
- Johann error
- pixel width of detector
- Arrangement of the detector plane

Crystal Parameters

- Crystal size –length (l_c),height (h_c)
- 2d spacing, R_c, Bragg angle (θ_b)

Line of sight

- Angle between LoS and Magnetic axis

XCS for ADITYA-U

Design Flow Chart

$$n\lambda = 2\, d \sin\theta_b$$

$$f_m = R_c \sin\theta_b$$

Selection of line emission

Depends on T_e
Aditya-U
(300-500 eV)
He-like neon:
13.4474 Å,
He-like argon:
3.9494 Å

Choice of crystal,
Cylindrical- single chord
Spherical-space resolved

Cylindrical- single chord
θ_b, R_c, $2d$ length, height,
rocking curve

Optimize R_c

Higher R_c
Lesser Johann error
Better linear dispersion
focussing distance f_m ↑
engineering limit
Allowed f_m: 0.5-0.6m
Allowed R_c (0.79-0.9m)

Optimize crystal size

Lesser l_c
Lesser Johann error
But **throughput** ↓
Higher h_c
throughput ↑

Optimize θ_b

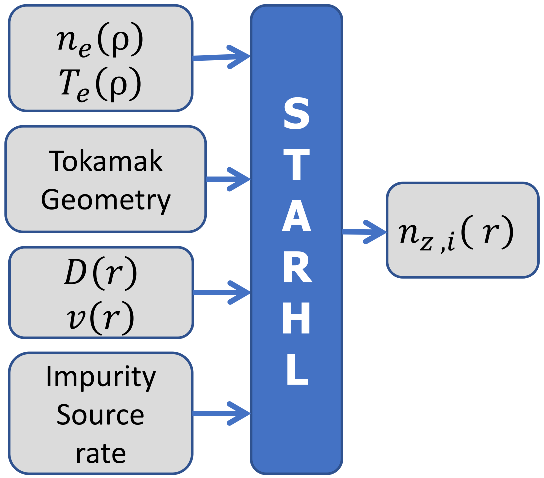
Larger θ_b
Lesser Johann error but
Allowed θ_b (38° to 45°) due to limited space around the port

Linear Dispersion: $\frac{d\lambda}{dx} = \frac{2d}{R_c \tan\theta_b}$;

$\Delta x_j = \frac{l_c^2 \cos\theta_b}{8R_c}$ (Δx_j Johann error)

XCS for ADITYA-U

Selection of line emission

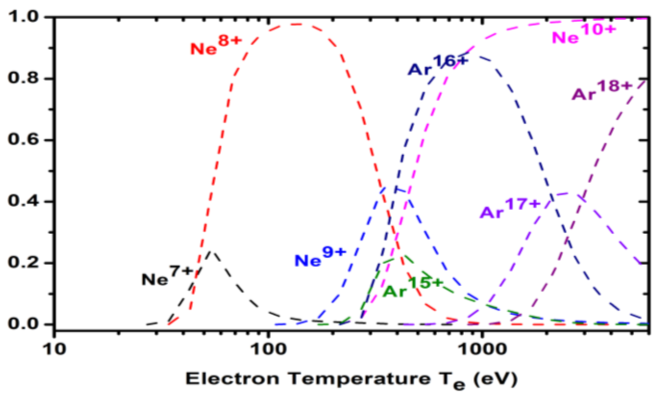


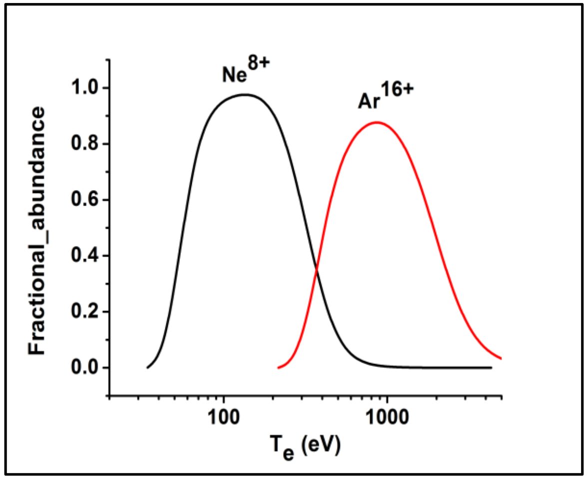
Estimating emissivity of He-like neon and He-like argon from coronal equilibrium using STRAHL code

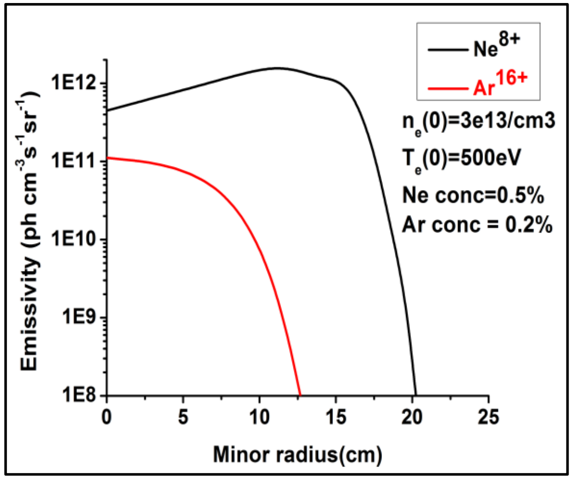
$$\varepsilon_{z,i,j}(r) = n_{z,i}(r) * n_e(r) * PEC_{z,i,j}(r)$$

(PEC from ADAS)

$n_{z,i}(r)$= fractional abundance * % of impurity * n_e(r)







Both He-like neon and He-like argon are possible

XCS for ADITYA-U

Choice of Crystal

He like Ne, Ne^{8+} at 13.4474 Å

Suitable crystals:

1. Mica (200), 2d spacing:19.84 Å, θ_b~42°
   - natural crystal- imperfections
   - Poor resolving power (λ/Δλ)~1800 - Not available
2. TIAP (100), 2d spacing: 25.9 Å,θ_b~31°
   - Engineering limitation due to θ_b
3. KAP (100), 2d spacing: 26.63 Å, θ_b~30°
   - Engineering limitation due to θ_b

He like Ar, Ar^{16+} at 3.9494 Å

Suitable crystal:

1. Quartz (11$\bar{2}$0), 2d spacing: 4.913 Å, θ_b~53.5°
   - Extensively used, high (λ/Δλ)
   - Engineering limitation due to θ_b

2. Silicon (111), 2d spacing: 6.271 Å,
   - **Selected for study**
   - **Bragg angle:**
   - **$\theta_{b,w}$ = 39.03°for w line at 3.9494Å**
   - **$\theta_{b,z}$ =39.56° for z line at 3.9944 Å**

He-like Argon is chosen!

X-RAY DATA BOOKLET- Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720

XCS for ADITYA-U

Silicon (111), 2d spacing: 6.271 Å, θ_b~39˚ is selected for the measurements

He-like argon lines to be captured:

Resonance line:

(w): $1s^2\,{}^1S_0$ - 1s2p $^2P_1$ at 3.9494 Å

Satellite lines:

(x) $1s^2\,{}^1S_0$ - 1s2p $^3P_2$ at 3.9661 Å

(y) $1s^2\,{}^1S_0$ - 1s2p $^3P_1$ at 3.9695 Å

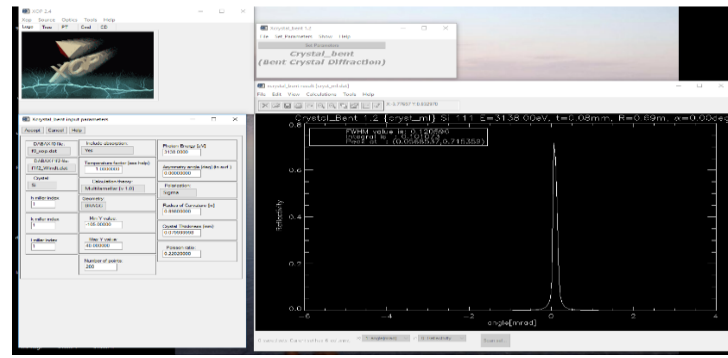
(z) $1s^2\,{}^1S_0$ - 1s2p $^3S_1$ at 3.9944 Å

$\theta_{b,w}$= 39.03˚for w line, $\theta_{b,z}$=39.56˚ for z line

Average Design parameter:

$\theta_{b,avg}$= 39.3˚, λ_{avg}=3.9719 Å

Estimation of Resolving Power due to crystal rocking curve



Rocking curve of Silicon (111) crystal obtained using XOP code

$\Delta\theta$ = 0.101 *mrad*

$$\frac{\lambda}{\Delta\lambda} = \frac{\tan\theta_b}{\Delta\theta}$$

Crystal	$\frac{\lambda}{\Delta\lambda}$ (resolving power)	Min. measurable Temperature
Silicon (111)	~7000 (rocking curve)	~130 eV

$$\Delta\lambda = \lambda \times 2.43 \times 10^{-3}\sqrt{\frac{T}{m}}$$

XCS for ADITYA-U

Johann error further limits the resolution

R due to	$\Delta\theta$	$\frac{\lambda}{\Delta\lambda}$	Min. measurable Temp	Number of pixels on CCD (500 eV corresponds to ~ 6 pixels)
Rocking curve	$\Delta\theta$= 0.101mrad (XOP code)	~7000	~130 eV	~3 pixels
Johann error $\boldsymbol{\Delta x_j = \frac{l_c^2 \cos\theta}{8R_c}}$ **=172µm**	$\Delta\theta = \frac{\Delta x_j}{R_c \sin\theta}$ =3.017x 10^{-4}	**~2700**	~ 921 eV	~8 pixels
		~ 4800	~**280 eV** (masking the crystal: $\boldsymbol{l_c}$**= 30 mm**)	~4 pixels
Pixel width	$\boldsymbol{\Delta x_p}$**=20 µm**; since $\Delta x_p << \Delta x_j$ hence error due to pixel width neglected			

The reciprocal Linear Dispersion: 0.170 mÅ / pixel
(with R_c = 0.9 m)
This corresponds to velocity resolution ~ 29 km/s per pixel shift

$$\left[v = \frac{\Delta\lambda_{shift} * c}{\lambda \cos\theta}\right]$$

XCS for ADITYA-U: Final Design Parameters

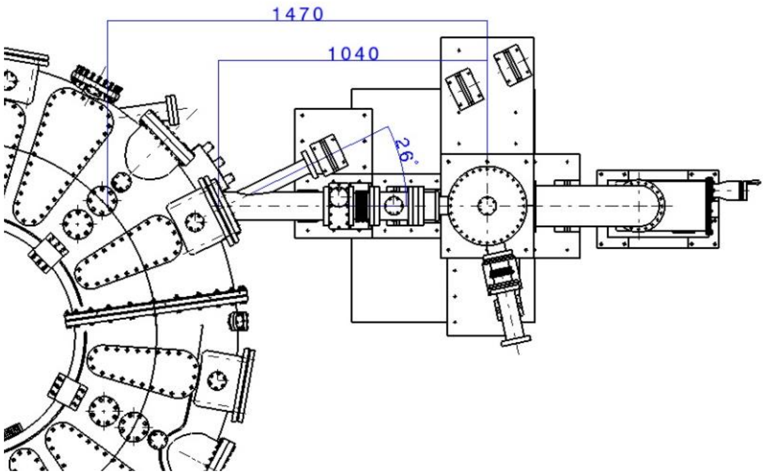
Silicon (111) crystal parameters	
2d spacing	6.271 Å
Crystal radius of curvature $\boldsymbol{R_c}$	0.9 m
Length ($\boldsymbol{l_c}$)	40 mm
height ($\boldsymbol{h_c}$)	50 mm
Bragg angle $\boldsymbol{\theta_{b,avg}}$	39.3°

CCD parameters – PIXIS-XO 400B	
Overall size	26.8 mm x 8 mm
pixels	1340 x 400
pixel size	20 x 20 μm^2
Max. Readout rate	2 MHz/pixel
Readout time	1 ms
Typical time resolution	10 - 20 ms

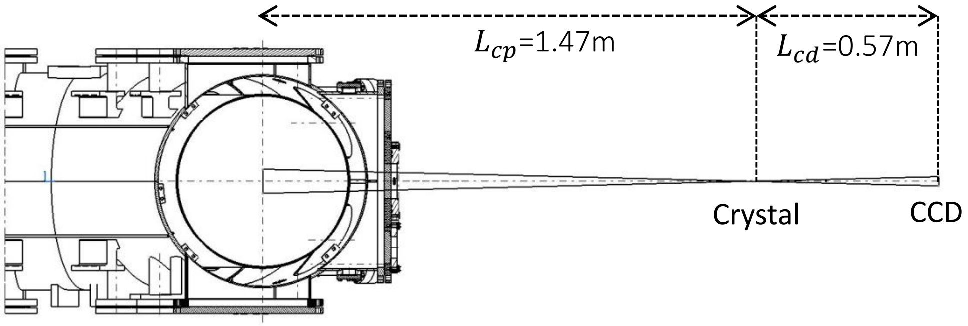
Instrument parameters	
Crystal to plasma distance ($\boldsymbol{L_{cp}}$)	1.47 m
Crystal to detector distance ($\boldsymbol{L_{cd}}$)	0.57 m
Demagnification of plasma on detector	0.38
Observable core plasma size (length x height)	70 x 21 (mm^2)
Linear dispersion	8.512 mÅ/mm
Resolution on CCD	0.172 mÅ/pixel
Wavelength coverage on CCD	230 mÅ
Tangential angle for rotation measurement	26°

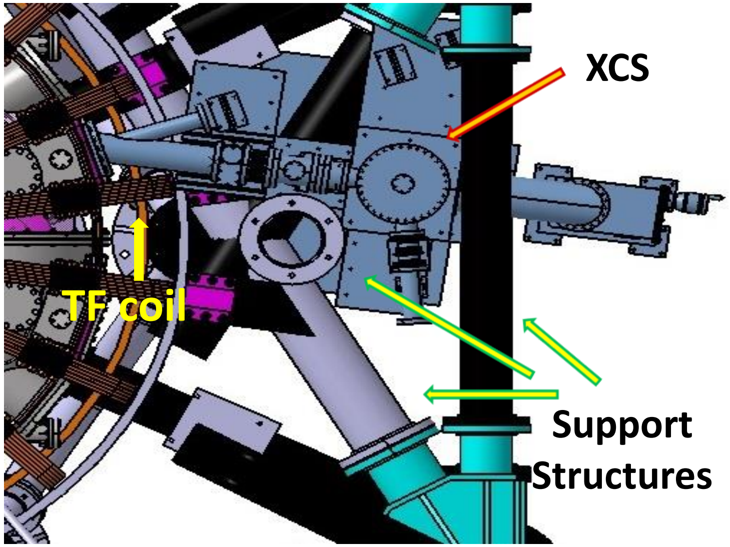
XCS for ADITYA-U

Top view



Side view

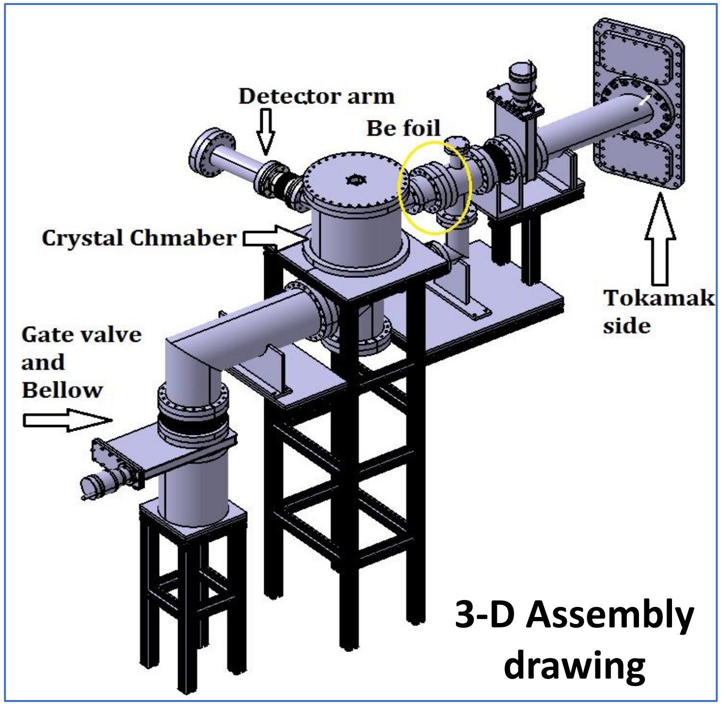




- L_{cp} (Crystal to plasma distance) = 1.47 m
- L_{cd}: Crystal to detector distance = 0.57 m
- Observable plasma area
  ~ 7 cm (l) x 2 cm (h)
- Maximum Tangential injection = 26°
  (~ 44%measurable component of v_{tor})

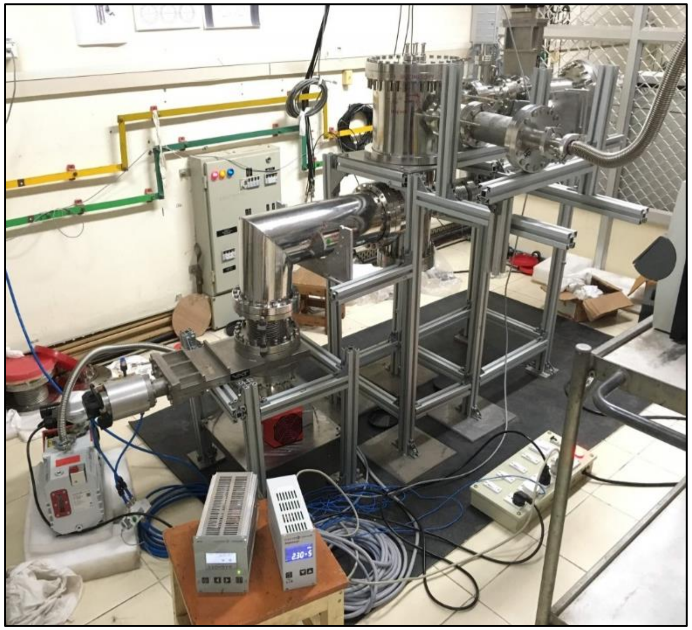
XCS for ADITYA-U

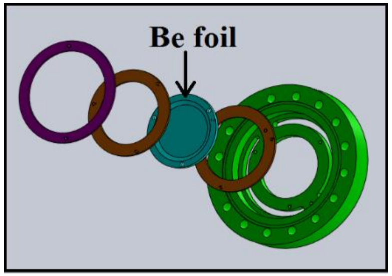
Assembly and Testing

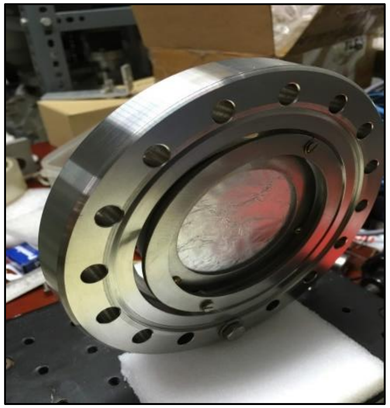


3-D Assembly drawing

Assembled XCS in Lab







Flange with Be foil

1) Leak testing of all system components:
   Leak rate achieved: ~ 10^-8 mbar l/s
   No welding joint issues- critical for UHV
2) Baking test of the main beam line
   Baked at ~ 165 ˚C
3) Beryllium foil holder
   (50 µm thickness, 50 mm diameter)
   Tested for differential pressures

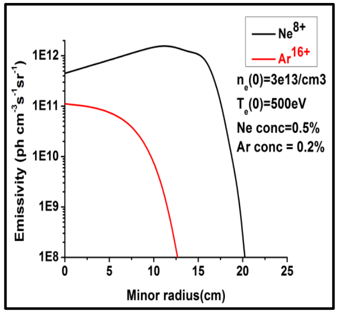
System on Machine: First Results soon.....

XCS for ADITYA-U

For realising the velocity and temperatures measurements with XCS using Ar^{16+} ---- Few questions still remained to be answered:

- Is Ar^{16+} available in sufficient quantity in ADITYA-U core?
- How much quantity of Ar needs to puffed?
- How the Ar transport to ADITYA-U core?
- Does ADITYA-U core-plasma rotate toroidally with sufficient velocity?
- Can the core-plasma rotation be measured with another diagnostics and used for calibrating the crystal spectrometer?

Earlier calculations based on assumed quantities



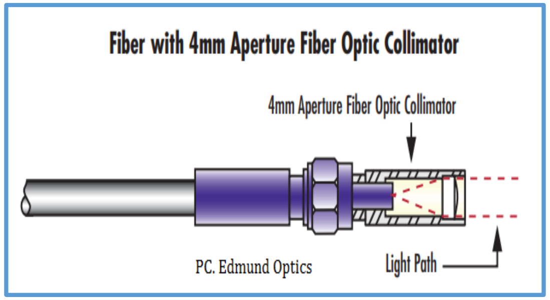
Scarce Literature on Ar transport

Plasma rotation measurements and Argon impurity transport studies in Ohmic discharges of ADITYA-U using passive spectroscopy

- Answers above questions regarding XCS
- Increases the knowledge base of Ar impurity transport in tokamaks
- Increases the knowledge base on plasma rotation

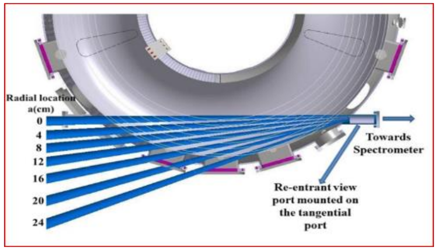
Set-up: Passive Visible Spectroscopy in ADITYA-U

Collection Optics: Light collection from Tokamak



Collimators:
Aperture: 4mm
Focal length: 10 mm
Fiber core dia: 400 µm
Fiber NA: 0.22

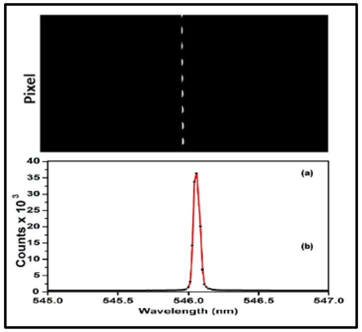
Seven LoSs covering the entire plasma radius



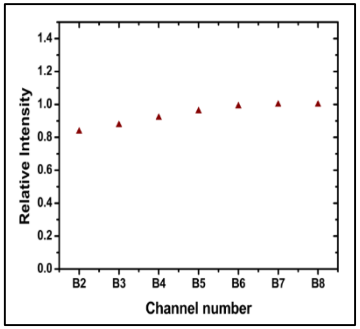
Two Spectrometer- CCD systems

Focal Length: 1 m / 0.5 m
F-number: *f/8.7* / *f/15*
Grating: 1800 / 600 grooves/mm
CCD: 2048 x 512 pixels (13.5 µm) / 1024 x 256 pixels (26 µm)
Dispersion: 0.00749 / 0.0433 nm / pixel

Instrumental function

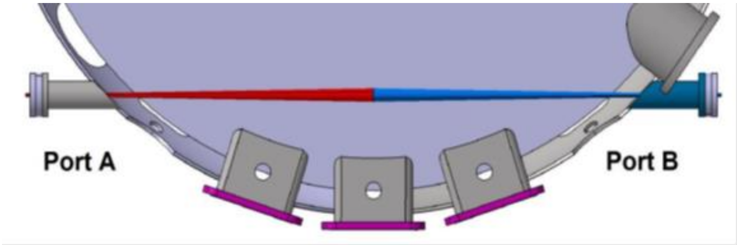


Relative intensity



Wavelength Calibration

(1) Pen-ray sources
(2) Perpendicular view measurements
(3) Parallel View measurements from both sides



Intensity Calibration

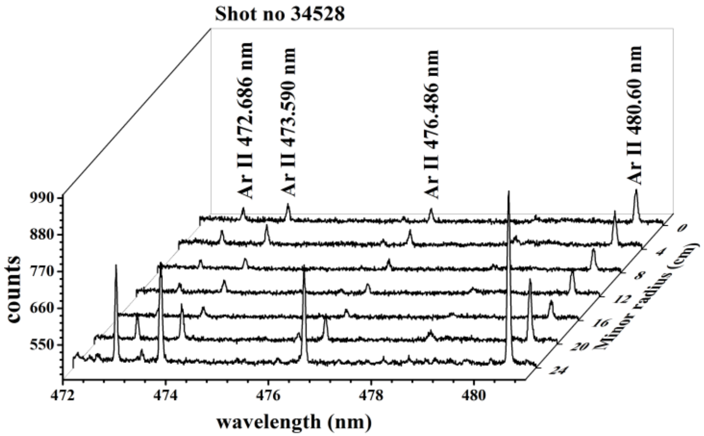
Using Lab-sphere and white-light source

CSTM-URS-600

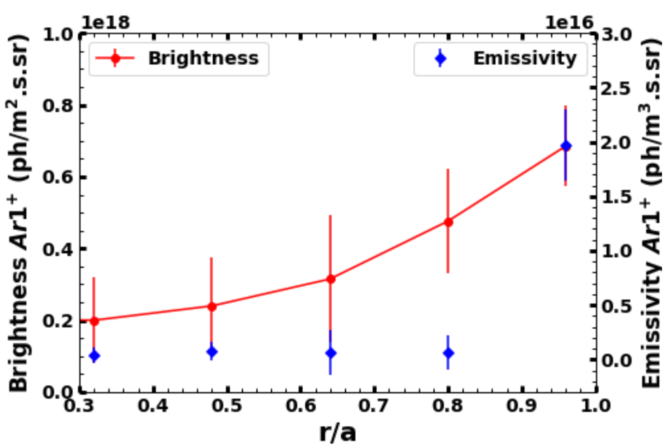
G. Shukla, M. B. Chowdhuri, K. Shah. et al ., RSI. 89, 10D132 (2018)
G. Shukla, M. B. Chowdhuri, K. Shah. et al ., RSI. 92, 063517 (2021)

Passive Visible Spectroscopy in ADITYA-U

Argon Transport studies using Spectral Line intensities

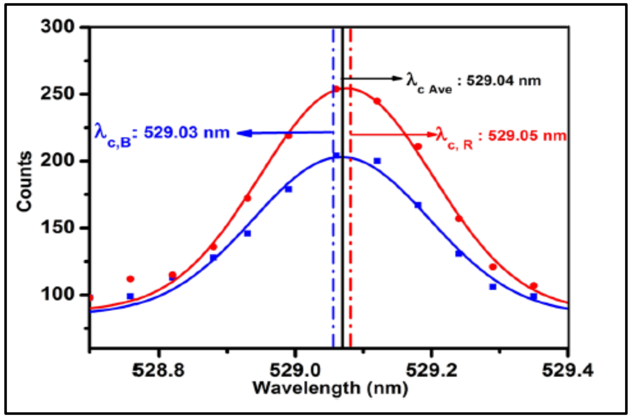


Radial Brightness profile is converted into radial Emissivity profile using Abel-like Matrix inversion technique
(R. Bell, Rev. Sci. Instrum. 66 (1) January 1995)



Toroidal rotation velocity is estimated using Doppler shift measurements

Spectral emission of passive charge exchange line, C^{5+} at 529.05 nm (n 8 → 7)



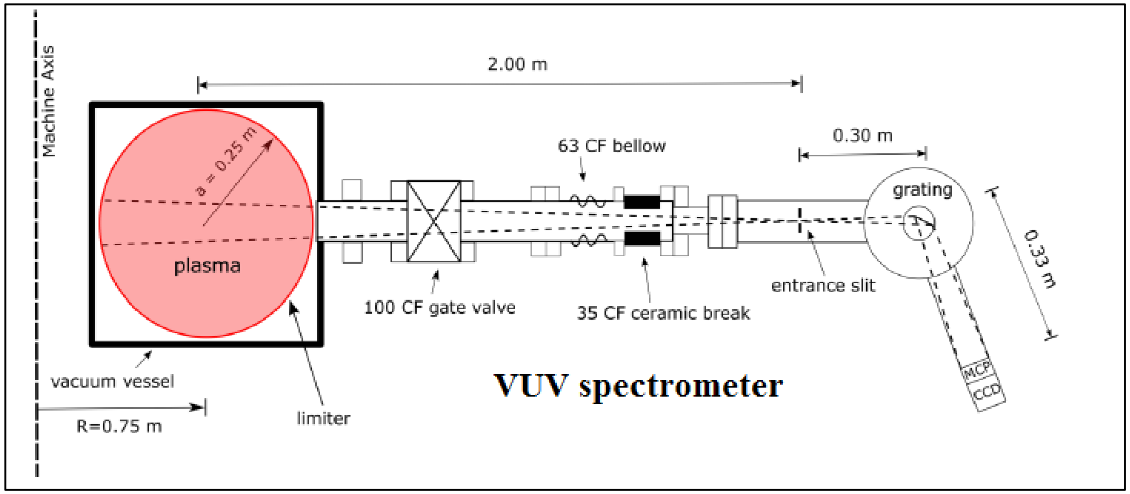
$$v = \frac{\Delta\lambda_{shift} * c}{\lambda \cos\theta}$$

Velocity resolution: 4.27 km/s per pixel shift

Radial profile of Toroidal rotation (v_{tor}) profile obtained by inverting the chord-averaged velocity measurements
(Shi et al. Rev. Sci. Instrum. 83, 10D717 (2012))

Set-up: VUV Spectroscopy in ADITYA-U

VUV spectrometer in ADITYA-U



Three Gratings: 290, 450, 2105 grooves/mm

Wavelength range:

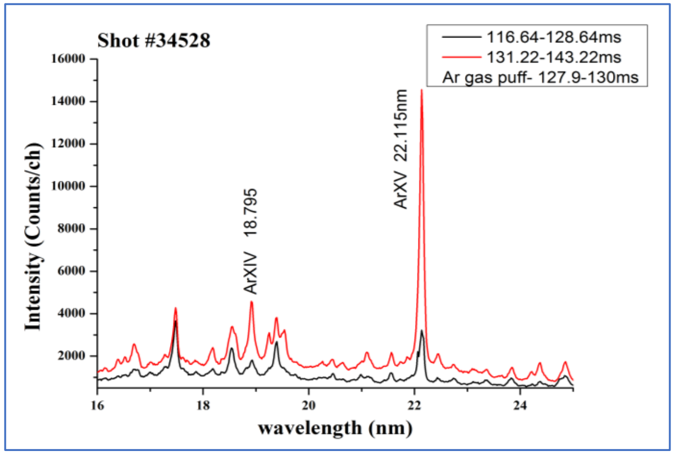
- Grating 290 : $15 < \lambda < 170$ nm
- Grating 450 : $10 < \lambda < 110$ nm
- Grating 2105 : $9.5 < \lambda < 32$ nm

Entrance slit: 10-250 μm, (30 μm for present study)

Reciprocal linear dispersion respectively:
0.122 nm/pixel / 0.0813 nm/pixel / 0.020 nm/pixel

CCD: 1340/255 pixels and Pixel size: 20 μm

Used for Measurement of Ar^{13+} and Ar^{14+} VUV line emissions



Observed Ar^{13+} and Ar^{14+} transitions
Ar^{13+} at 18.796 nm ($2s^2 2p\ ^2P_{1.5}$ - $2s2p^2\ ^2P_{1.5}$)
Ar^{14+} at 22.115 nm ($1s^2 2s^2\ ^1S_0$ - $1s^2 2s2p\ ^1P_1$)

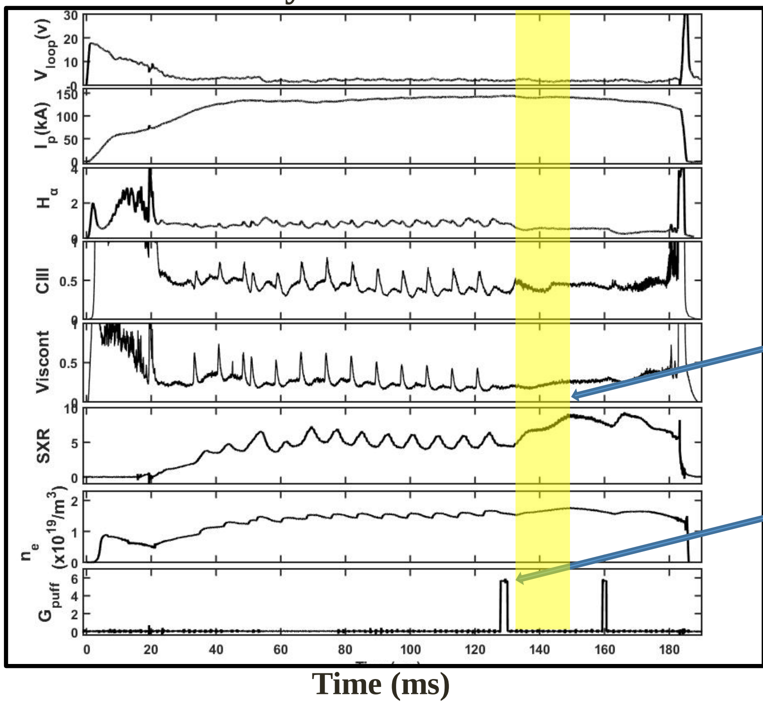
Line integrated measurements
Experimental Ratio of the brightness of the Lines:

$$\frac{I_{Ar^{13+}}}{I_{Ar^{14+}}}$$

used for estimating the radial profile of Ar emission

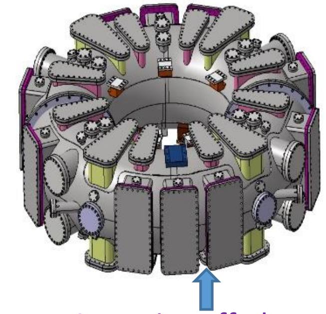
Argon Transport in ADITYA-U

Aditya-U Shot #34528



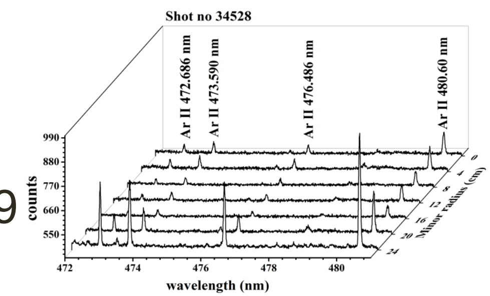
Argon source rate
$\sim 5 - 6 \text{ x } 10^{18}/s$

Measurement time window ~ 20 ms

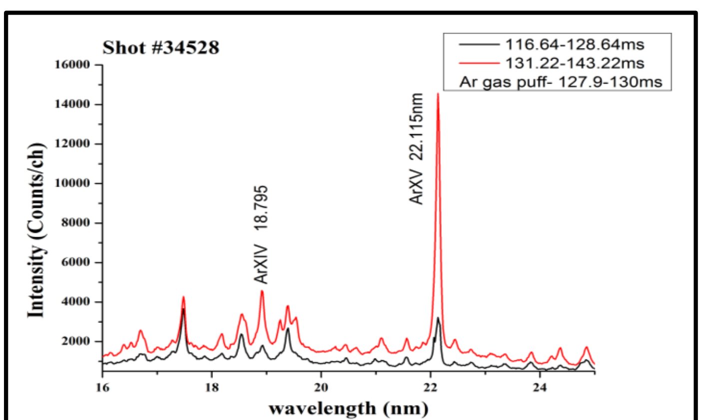


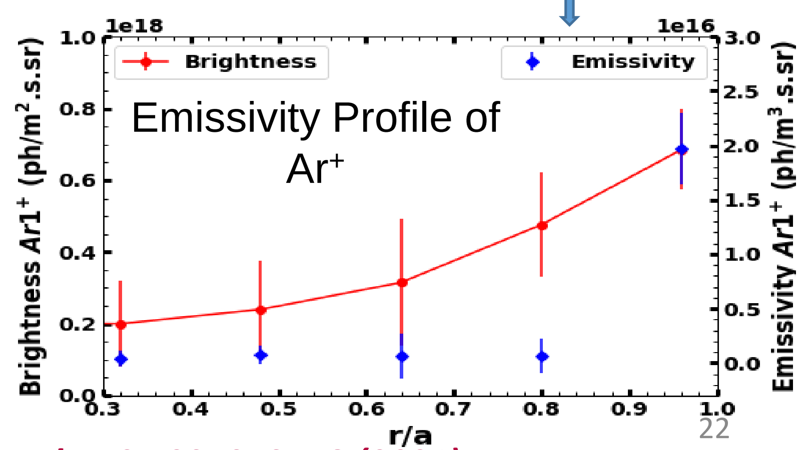
Argon is puffed from bottom port

Observed Ar^{1+} spectral lines in the visible region 472.68 nm, 437.59 nm, 476.48 nm,480.60 nm



Simultaneously observed the Ar^{13+} at 18.796 nm and Ar^{14+} at 22.115 nm



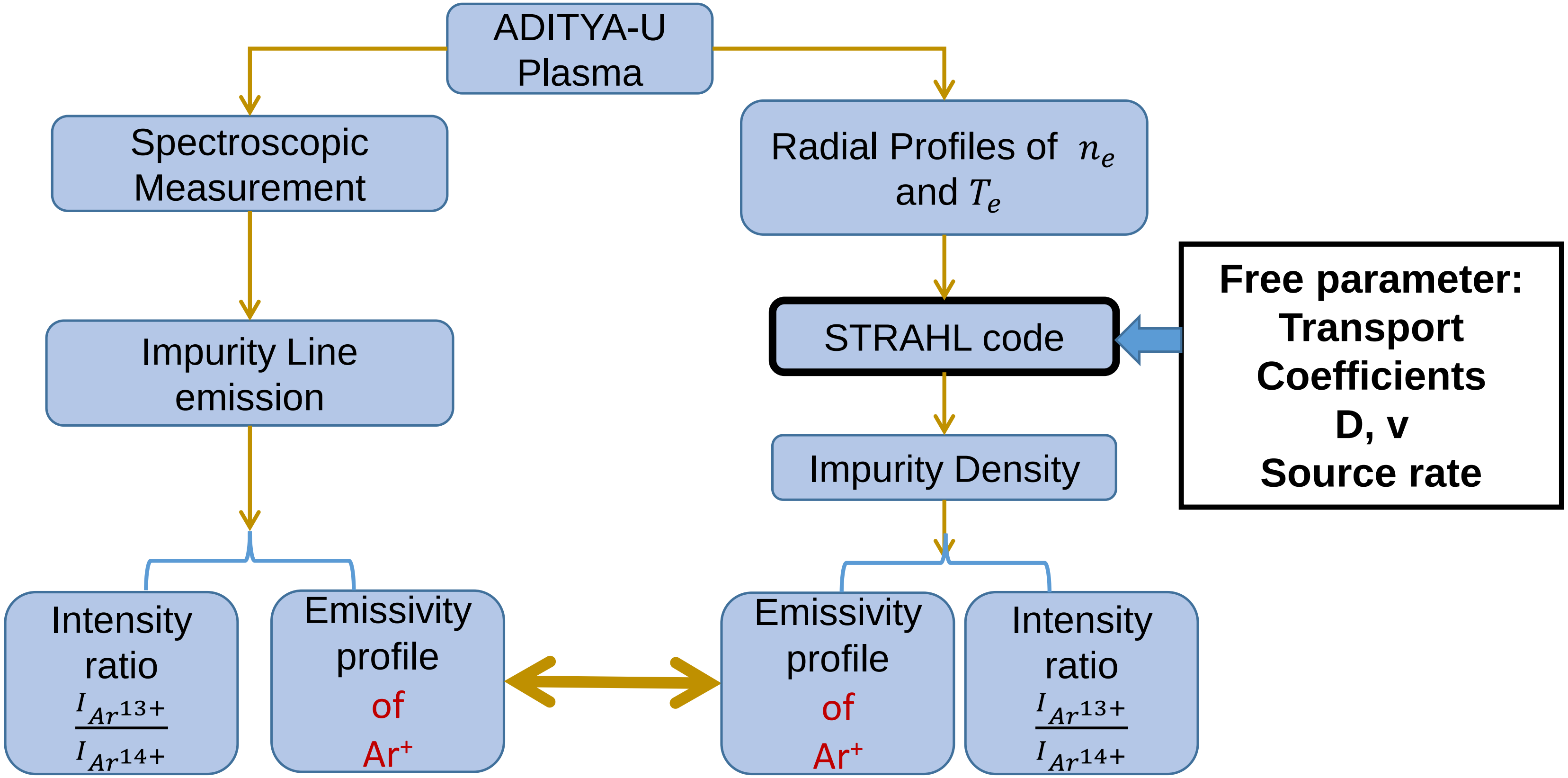


Kajal Shah et al., RSI. 92, 053548 (2021).

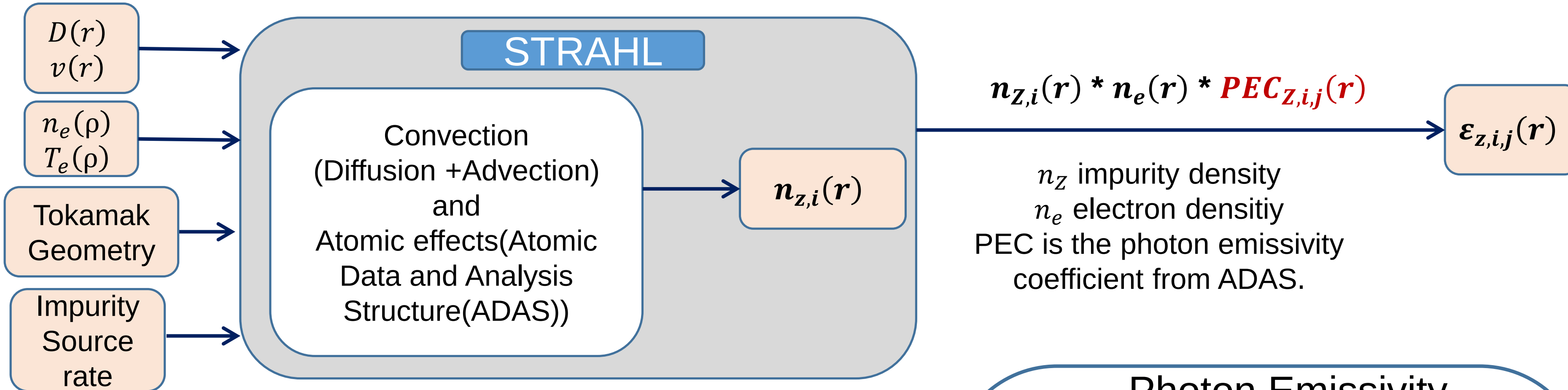
Argon Transport in ADITYA-U

After obtaining the emissivity profile of Ar^+ line and the intensity ratio of Ar^{13+} at 18.796 nm and Ar^{14+} at 22.115 nm spectral line

The Argon transport coefficients are obtained by comparing the measured emissivity and line ratio with the those simulated with STRAHL code



Argon Transport in ADITYA-U



n_Z impurity density
n_e electron densitiy
PEC is the photon emissivity coefficient from ADAS.

STRAHL solves radial continuity equation for each ionization stage given in 1D Geometry.

$$\frac{\partial n_Z}{\partial_t} = \frac{1}{r}\frac{\partial}{\partial_r} r \left(D \frac{\partial n_Z}{\partial_r} - v^* n_z \right) + Q_Z$$

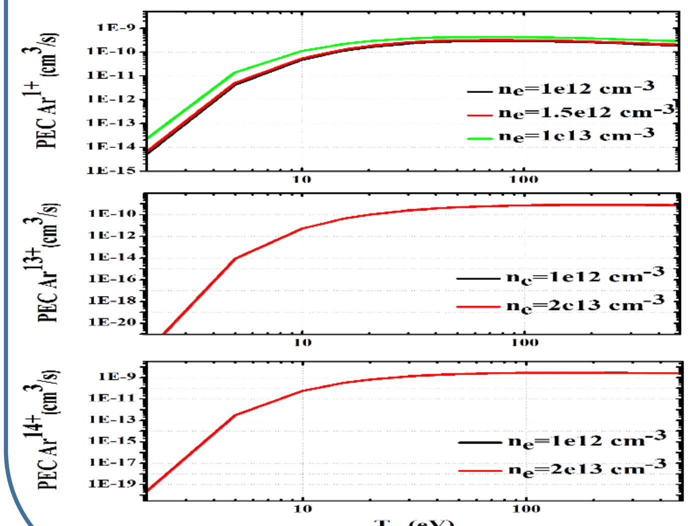
D - diffusion coefficient,
v - convective flow inside plasma

Q_Z is source or sink term

Q_Z =-$(n_e S_Z + n_e \alpha_Z + n_H C_Z) n_Z + n_e S_{Z-1} n_{Z-1} + (n_e \alpha_{Z+1} + n_H C_{Z+1}) n_{Z+1}$

S , α , C are rate coefficients for ionization, recombination (radiative and di-electronic) and charge exchange(CX) recombination respectively.

Photon Emissivity Coefficients are generated using NIST and ADAS databases

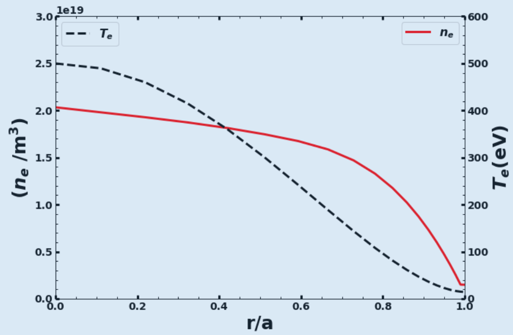


R. Dux,2005 Impurity Transport in Tokamak Plasmas IPP10/27,Garching. Behringer K. 1987 JET-R(87)08, JET Joint Undertaking, Culham.

Argon Transport in ADITYA-U

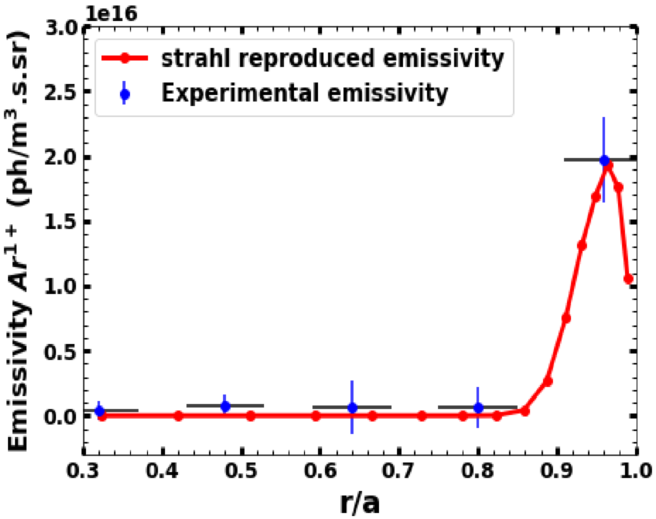
Using:

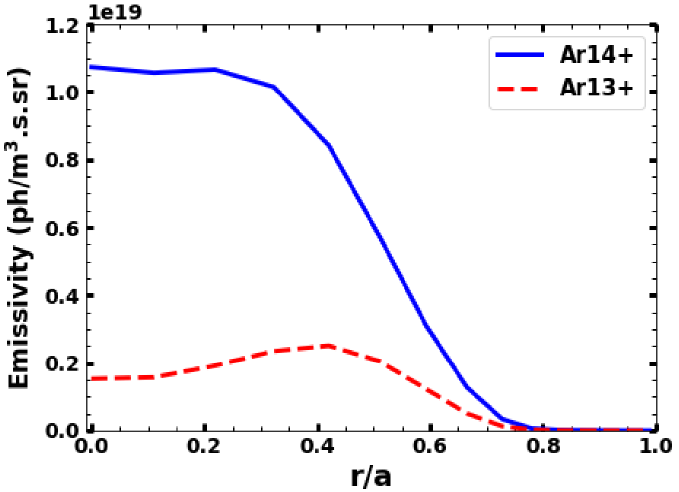
Radial Profile of Density and Temperature



+ Argon source rate: $\sim 5 - 6 \text{ x } 10^{18}/s$

From best fit of Ar^{1+}profile in the edge and ($I_{Ar^{13+}}/I_{Ar^{14+}}$) line ratio in the core





$\frac{I_{Ar^{13+}}}{I_{Ar^{14+}}} = 0.230$ (experimental)

$\frac{I_{Ar^{13+}}}{I_{Ar^{14+}}} = 0.234$ (simulated)

Diffusivity:

~ 8 – 12 m^2/s in the edge

~ 0.3 - 0.4 m^2/s in the core

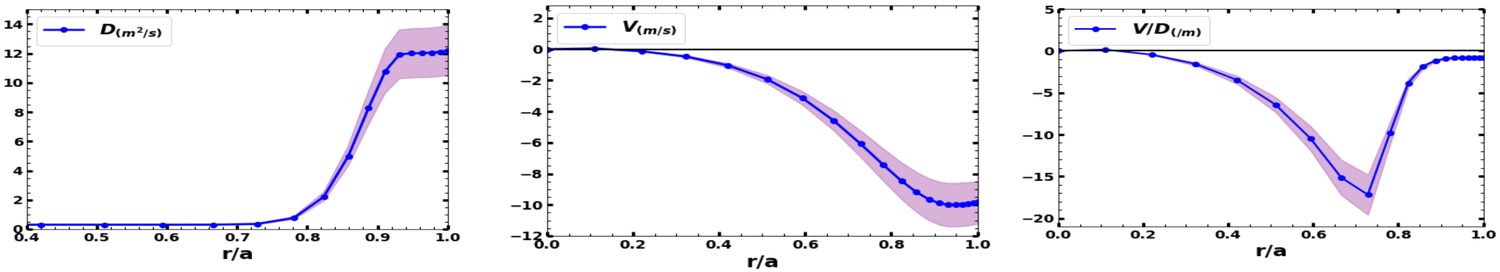
Convective velocity:

~ - 10 m/s in edge

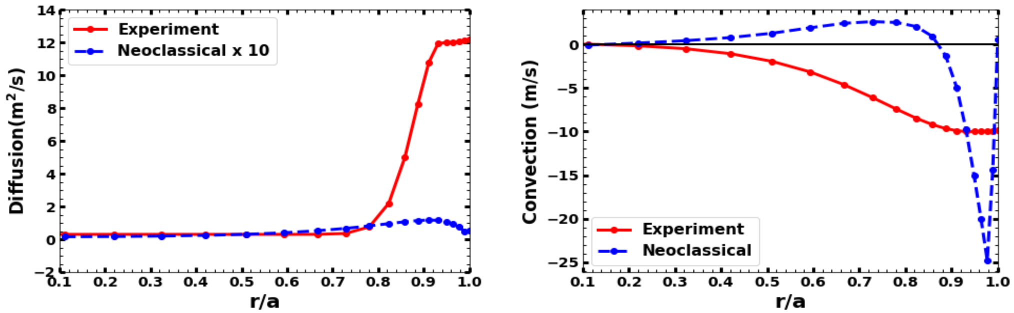
~ - 0.7 m/s in core

Argon Transport in ADITYA-U

Measured profiles of diffusion and convection



Comparison- Neoclassical and Measured diffusion and convection



Argon transport is above Neoclassical values in edge and core of ADITYA-U !

Transport in edge region seems to be influenced by fluctuations

$$D_{ITG} \sim \frac{c_s \rho_s^{\,2}}{(L_p R)^{1/2}} \left(\frac{q^4 R}{L_p}\right)^{1/4} \sim 13\ m^2/s$$

c_s: ion sound speed, ρ_s: ion Larmor radius, R: major radius
q: edge safety factor, L_p: pressure scale length

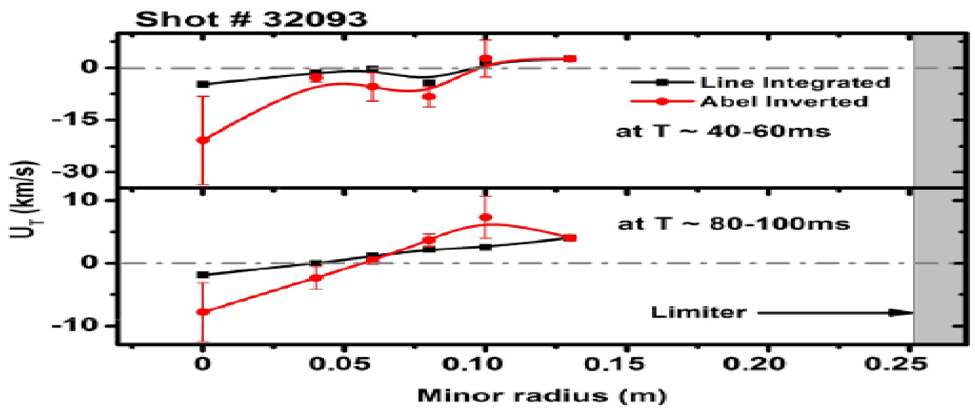
c_s	8.66 x $10^3 m/s$
ρ_s	3.83 mm
R	0.75 m
q	3.45
L_p	0.011m

Transport in core region is under investigation!

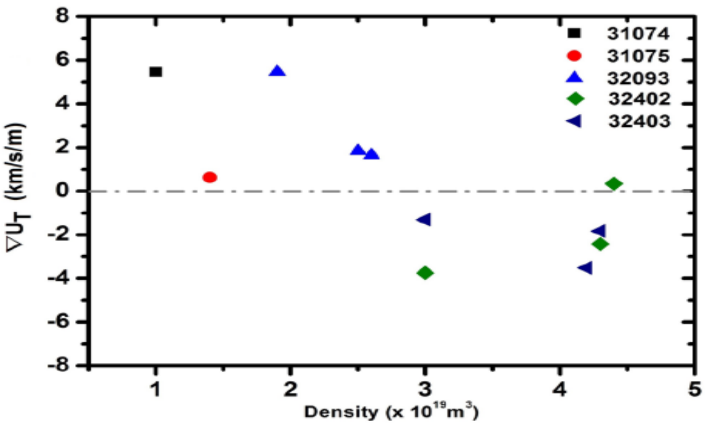
Toroidal Rotation in Aditya-U Tokamak

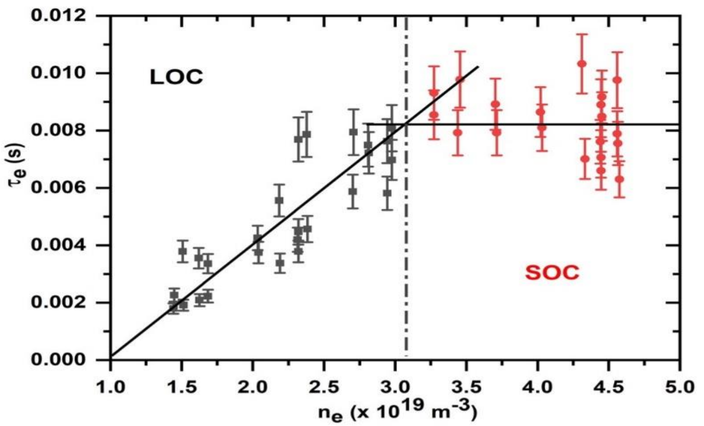
From the Doppler shift of passive charge exchange line of C5+ at 529 nm

Intrinsic toroidal rotation $\boldsymbol{v_{\phi} \sim -20\frac{km}{s}}$ in counter-current direction in low density Ohmic discharges of ADITYA-U



Direction of toroidal rotation reverses to co-current direction in high density Ohmic discharges (SOC regime) [Density threshold ~ $2.8 \text{ x}10^{19}\ m^{-3}$]

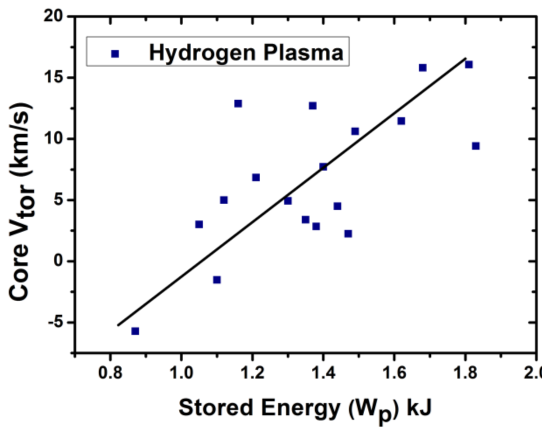


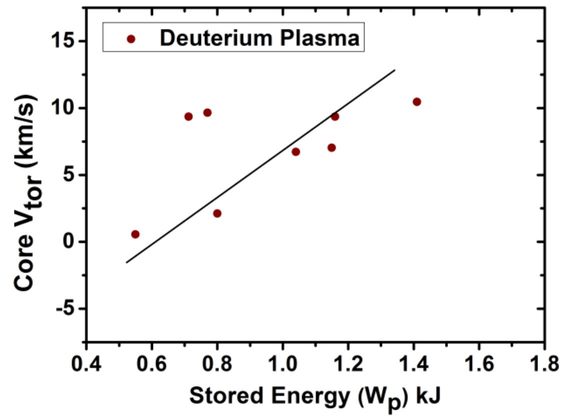


G. Shukla, K. Shah. et al ., Nucl. Fusion 59 (2019) 106049

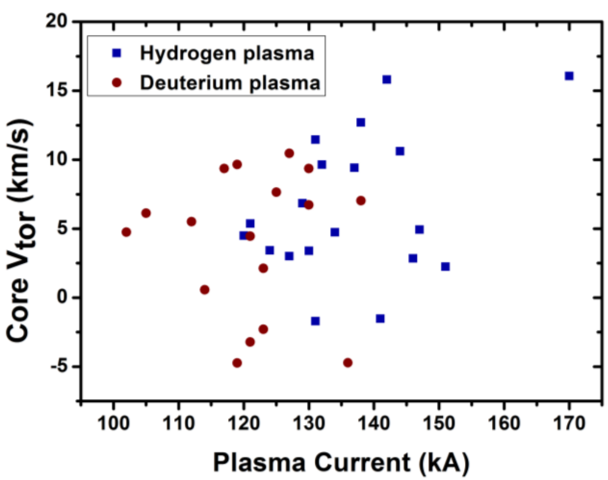
Toroidal Rotation in Aditya-U Tokamak

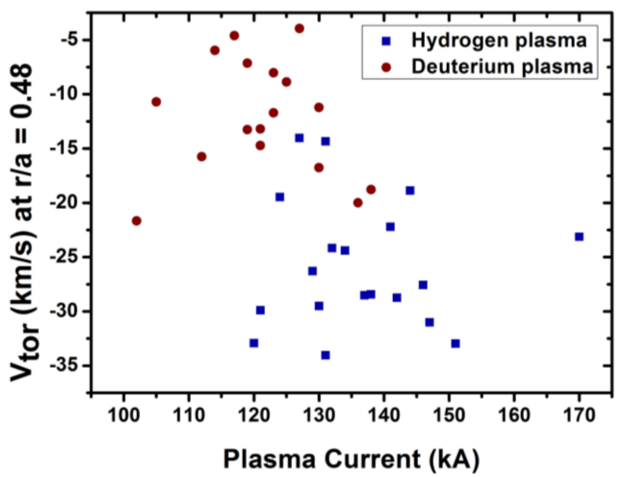
The core rotation increases with stored energy

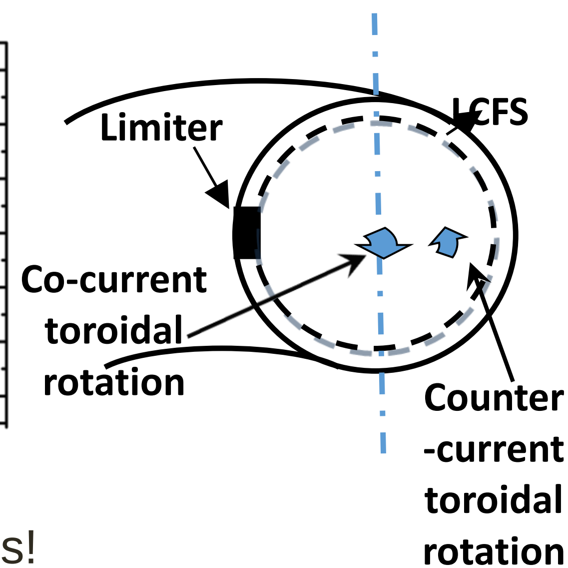




The core and mid-radius rotation velocity increases in opposite directions with plasma current





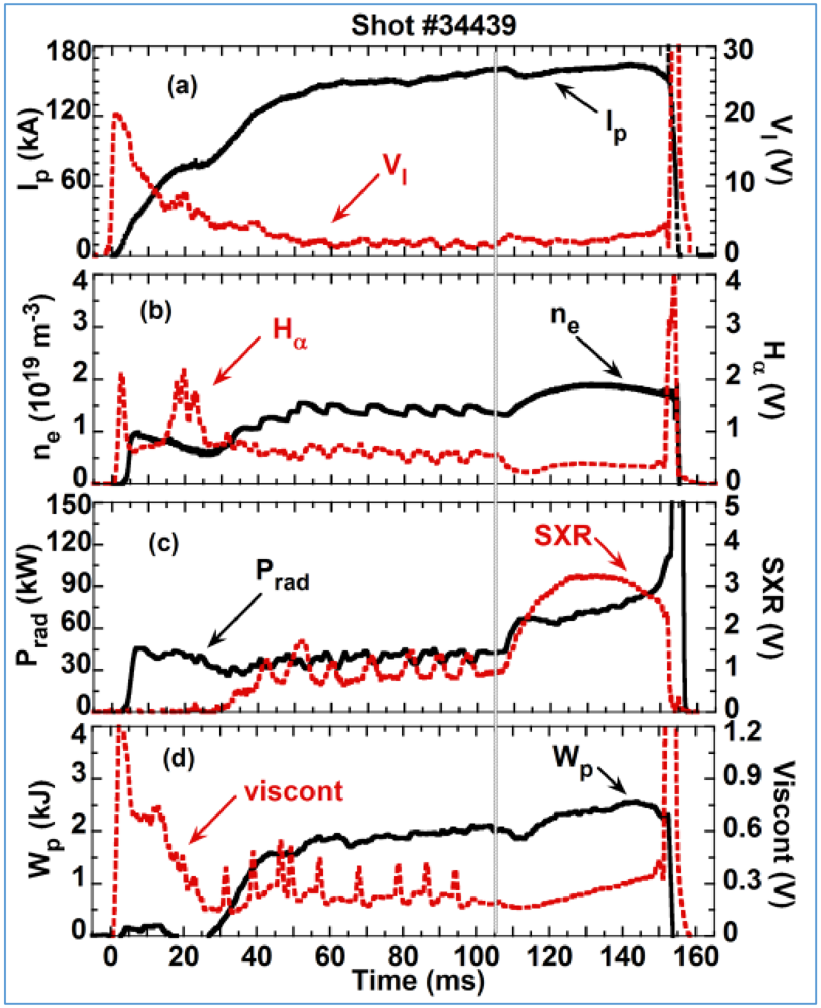


Hence, rotation shear increases in high current discharges!

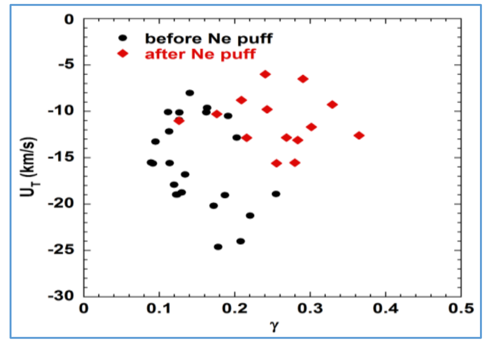
K. Shah et al., manuscript in progress

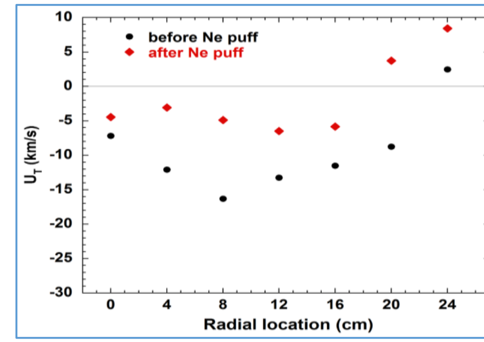
Toroidal Rotation in Aditya-U Tokamak

Intrinsic toroidal rotation values can be modified using neon injection

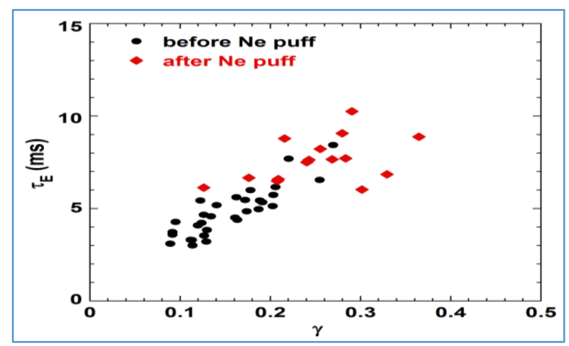


Counter-Current rotation values decreases with neon injection





Energy confinement time increases with neon injection



Density threshold for rotation reversal can be lowered using Ne puff

M. B. Chowdhuri, K. Shah et al., manuscript in progress

Outcome from visible and VUV spectroscopy

From Argon transport studies:

Input to XCS:

- Estimated Ar^{16+} density in core plasma of ADITYA-U ~ (4 x 10^{15}/ m^3)
- Ar^{16+}density (~ 4 x 10^{15}/m^3) corresponds to Ar^{16+} emissivity ~ (8x10^{14}/ $\mathrm{m}^3 s\ sr$)
- Assuming ~ 50% overall losses in the spectrometer, this corresponds to intensity ~ 10^4 counts on CCD

Physics Study:

- Argon transport is found to exceed the non-neoclassical value both in plasma edge and core. Argon transport in the edge seems to be influenced by fluctuations (ITG).

From Rotation studies:

Input to XCS:

- Intrinsic toroidal plasma rotation (~ 20 km/s) is observed in ADITYA-U, hence measurements are possible with the designed XCS system
- Simultaneous measurement with PCX and XCS will be useful in wavelength calibration of XCS.

Physics Study:

- Advantage with ADITYA-U: Passive charge exchange line of C^{5+} available from core. Reversal of rotation direction is observed in high density plasmas
- Variations in rotation magnitudes has been observed using Ne puff.
- Controlled variation of intrinsic toroidal rotation by changing fuel gas, varying the plasma current as well as neon puffing will help in consolidating rotation measurements using XCS.

Summary

– Design, development, fabrication, installation of first Tangential X-ray Crystal Spectrometer (XCS) for an Indian tokamak (Aditya-U)

– Intrinsic plasma toroidal rotation and ion (electron) – temperature will be obtained by measuring the He-like Ar^{16+} spectral line emission at 0.39494 nm using the XCS system.

– To optimize the Argon injection for sufficient presence of Ar^{16+} from the core-plasma, detailed argon transport study is carried out.

– Ar^{1+} line emission in the visible range using a visible spectrometer and Ar^{13+} and Ar^{14+}spectral emissions in VUV range using a VUV spectrometer are measured.

– Measured emissions are compared with those simulated using STRAHL code to obtain the diffusivity and convective velocity of argon in ADITYA-U.

– Argon transport is found to exceed the neoclassical value both in plasma edge and core. Argon transport in the edge seems to be influenced by fluctuations (ITG).

– Intrinsic plasma toroidal rotation ~ 20 km/s measured using the passive charge exchange line of C^{5+} (529 nm) using Doppler shift measurements in visible region.

– Reversal of rotation direction is observed in high density plasmas and variations in rotation magnitudes has been observed using Ne puff.

– Intrinsic toroidal rotation increase with stored energy and its radial shear has been found to be increasing with plasma current.

– Simultaneous measurement with PCX and XCS will be useful in wavelength calibration of XCS.

Acknowledgements

I sincerely thank all my collaborators…

- **Prof. Joydeep Ghosh and** Aditya-U operation and diagnostic team, IPR
- **Dr. Malay Bikas Chowdhuri** and Spectroscopy division, IPR
- **Dr. Balamurali Krishna Mayya K** (PDEU)
- Drafting and workshop division, IPR.
- Special Thanks to **Dr. Luis Delgado (PPPL), Dr. Novimir Pablant (PPPL), Prof. Shigeru Morita (NIFS), Dr. Sang Gon Lee (NFRI)**
- The work done is partially supported by the Department of Atomic Energy-Board of Research in Nuclear Sciences (DAE-BRNS) funded Project No. 2931.

“Alone we can do so little; together we can do so much…”

— Helen Keller