Understanding the Physical Processes Prevailing in the Edge Plasma Region of ADITYA-U Tokamak using Spectroscopic Measurements

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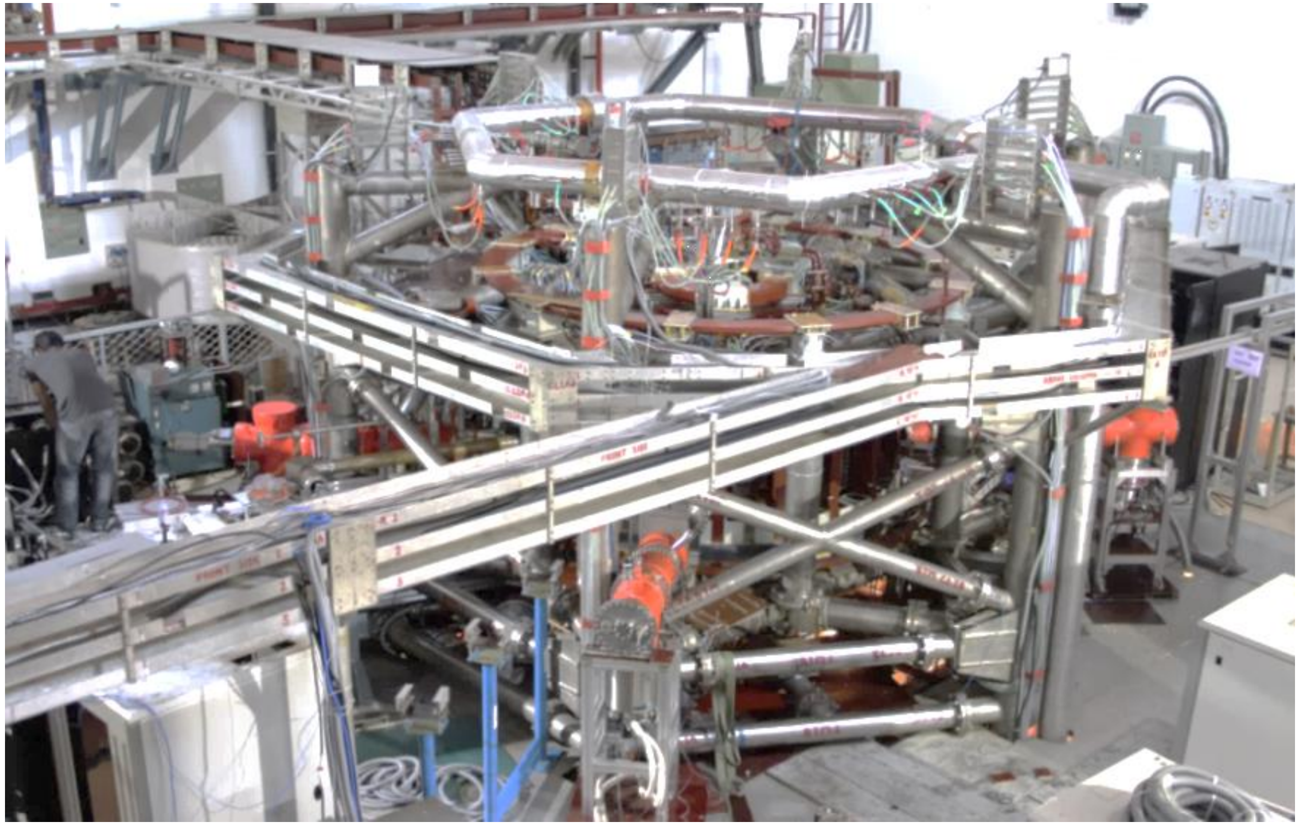

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Importance of neutral and impurity

Impurities and fuel-recycling in Tokamaks are important areas of present day thermonuclear research

Necessity: cleaner Core-plasma and impurity-aided radiative edge-plasma

Plasma-wall interaction

Fuel neutrals

Mainly H / D / T

Affecting:

Retention / Recycling [3]
Fueling efficiency
Plasma density control
H-mode pedestal formation etc.

Plasma facing components (PFC) act as:

Major Source

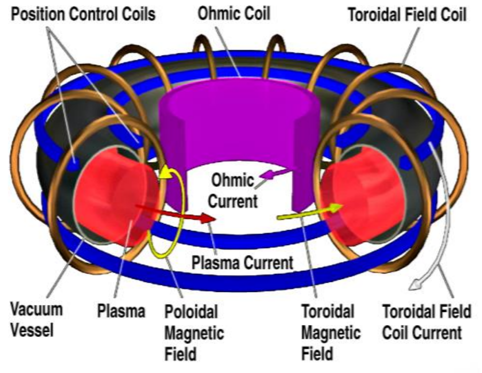
Except for seeded ones (Ne, Ar, N, etc. diagnostic and other heat-mitigation purposes!!)

Non-fuel ions

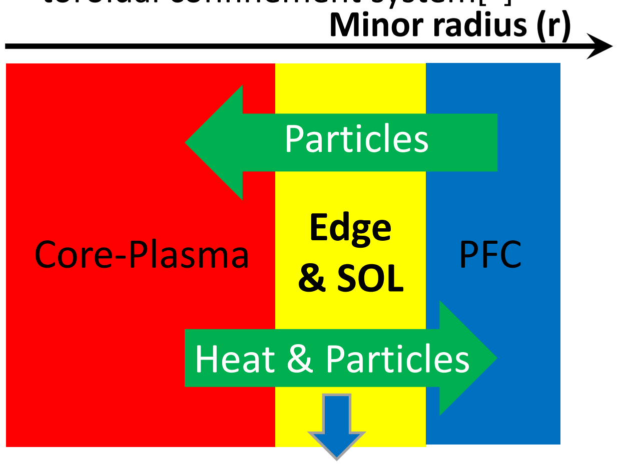
C, O, Fe, Mo, W, Li, Be, B etc.

Causing:

Fuel dilution
Radiation losses [2]
Low Z: edge/SOL
Medium high Z: Core
Power loss from core plasma etc.



The tokamak: most advanced toroidal confinement system[1]

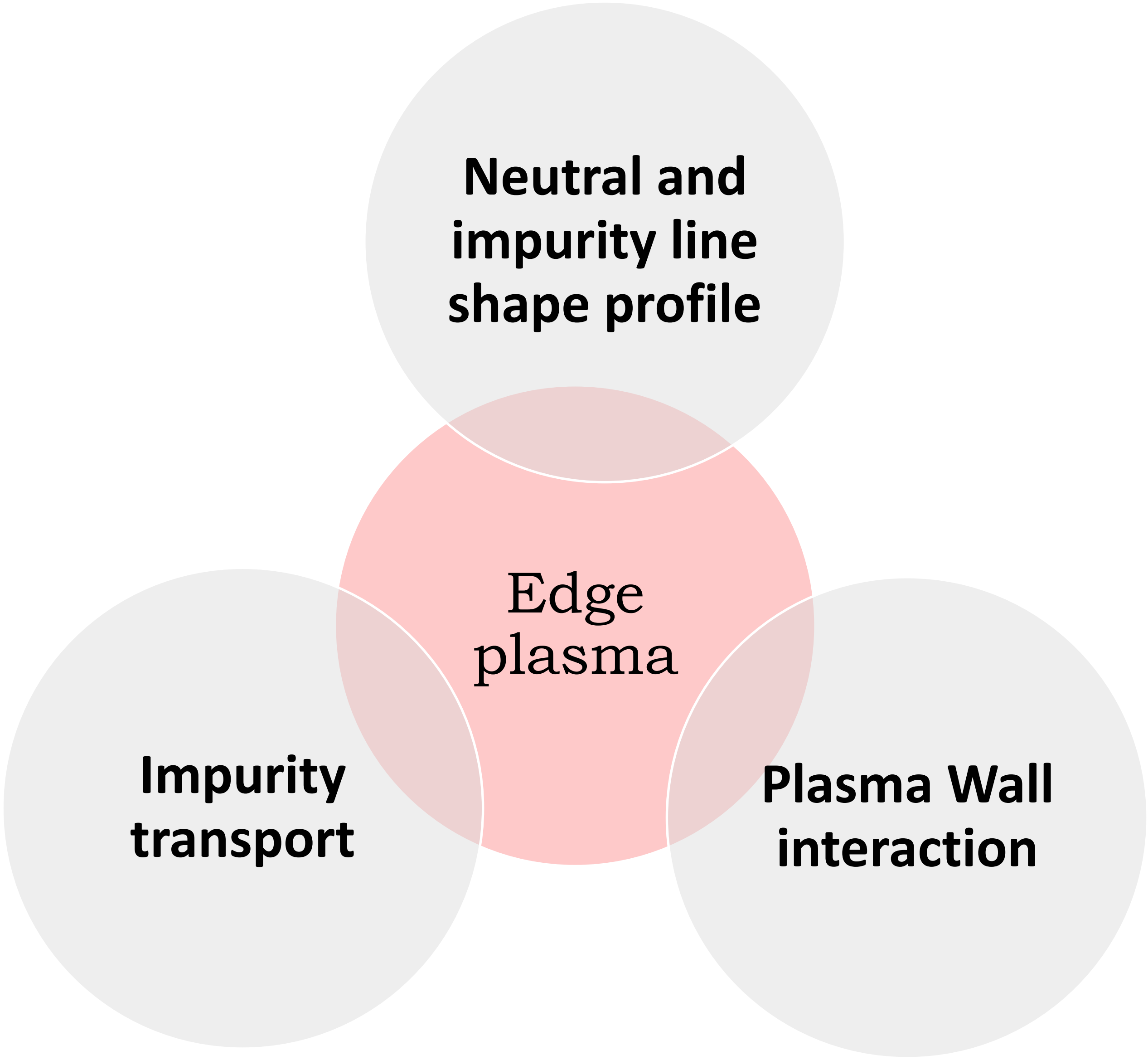


EDGE and SOL Plasma isolates the Core and PFCs

IMPORTANT TO UNDERSTAND NEUTRAL AND IMPURITY BEHAVIOR IN THE TOKAMAK PLASMAS!!

*[2] G M McCracken 1987 Plasma Phys. Control. Fusion **29** 1273*
*[3] Ehrenberg, J., et al. 1989. Journal of Nuclear Materials, **162**, pp.63-79.*

Outline



Neutral and impurity line shape profile

- Neutral, ion corrected temperature measurement (Zeeman broadening)
- Poloidal asymmetry in neutral temperatures
- Self-absorption in tokamak plasma

Plasma Wall interaction

- Recycling and particle influxes estimations
    - Different surface
    - Different wall-conditioning
- Molecular contribution in particle recycling

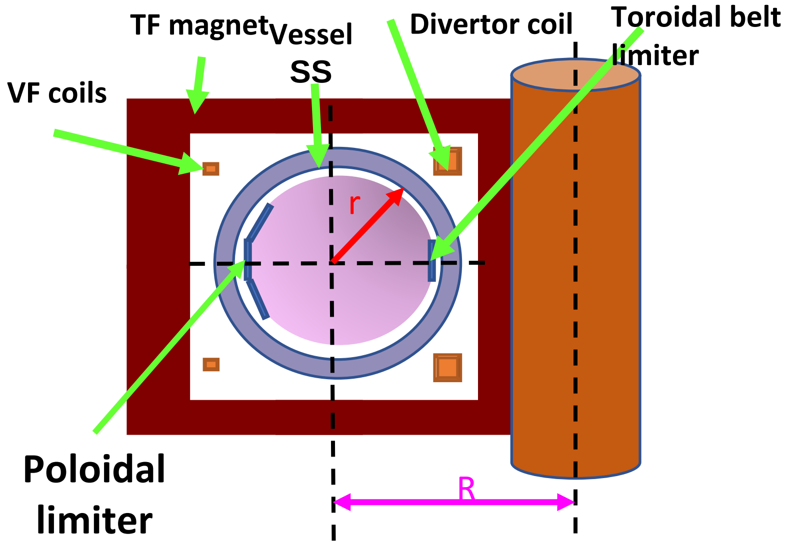
Impurity transport

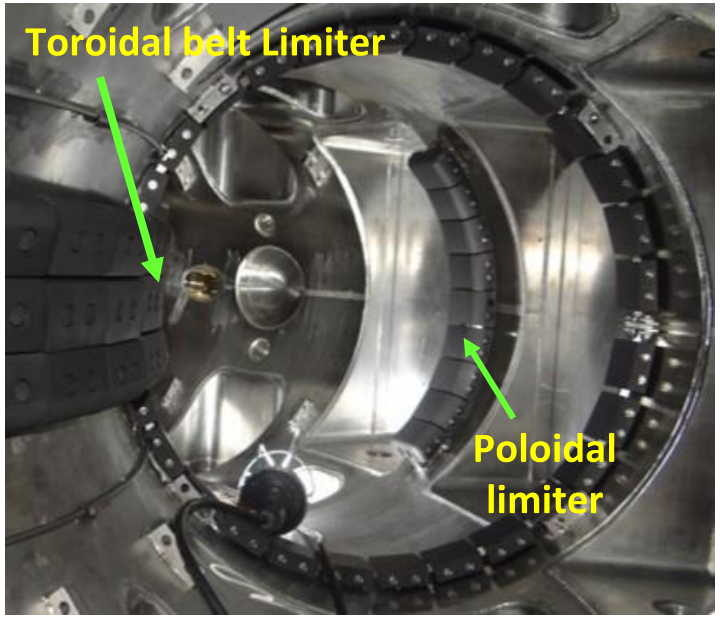
- Mass dependency of Diffusivity for Aditya-U tokamak

Divertor plasma

In the divertor region the MOLECULAR contribution is highly dominated-Characterization technique required

Experimental Device: ADITYA-U tokamak





Base Vacuum: 5 x 10^{-9} torr
Pre-fill: 1 - 4 x 10^{-4} torr
Basic parameters
Plasma current : 70-200 kA
Duration : 100-350 ms

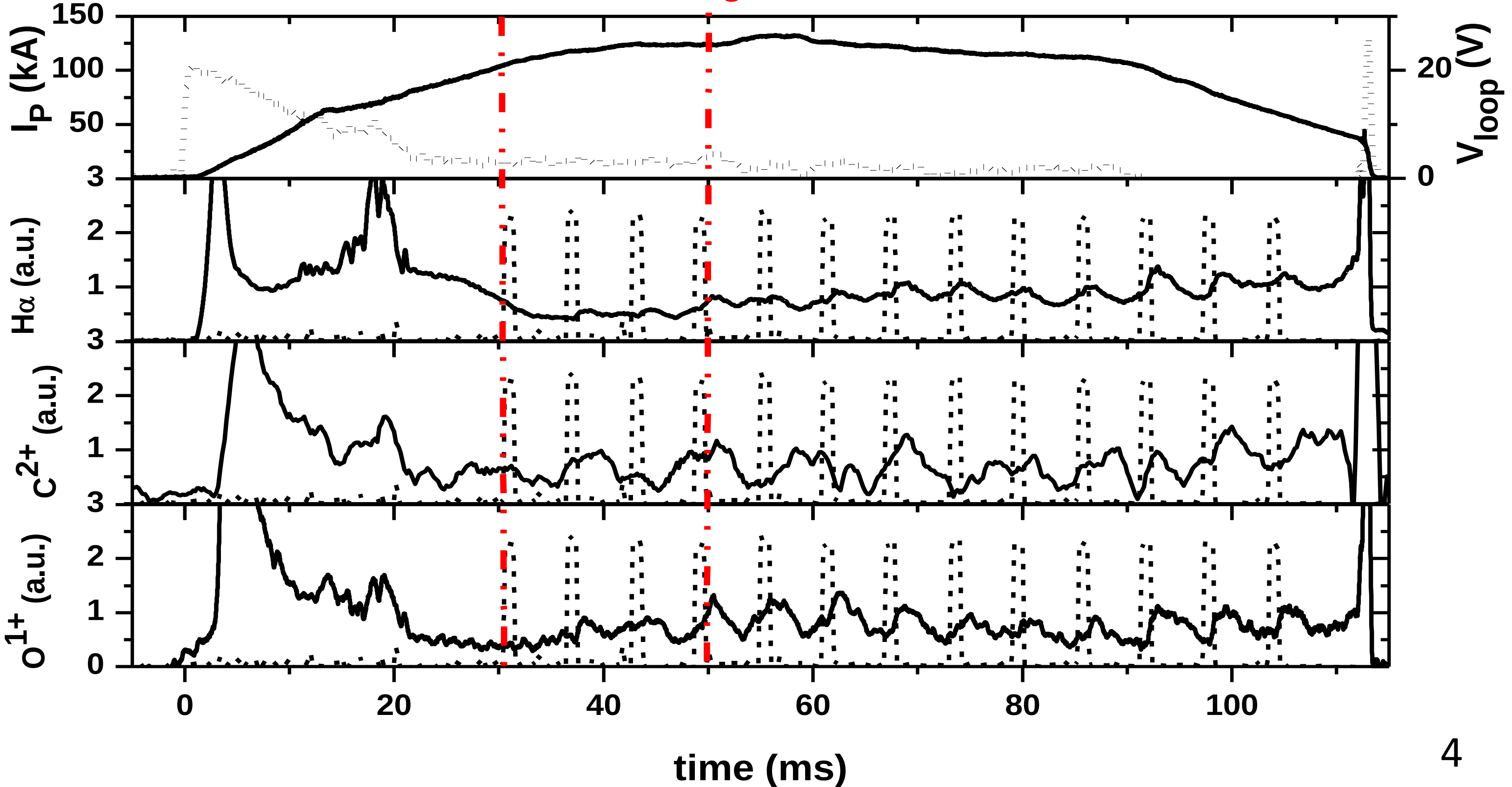
Edge & SOL:

$$n_e = 0.7 - 5 \times 10^{12}\ cm^{-3}$$
$$T_e = 8 - 20\ eV$$

$R_0 = 75\ cm$,
$a = 25$ cm
$B_T = 0.75 - 1.5\ T$

Wall material:
Stainless Steel
Limiter material:
Graphite

ADITYA-U Discharge shot no #33015

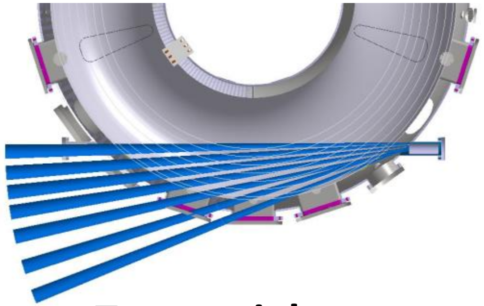


Diagnostic installed and used

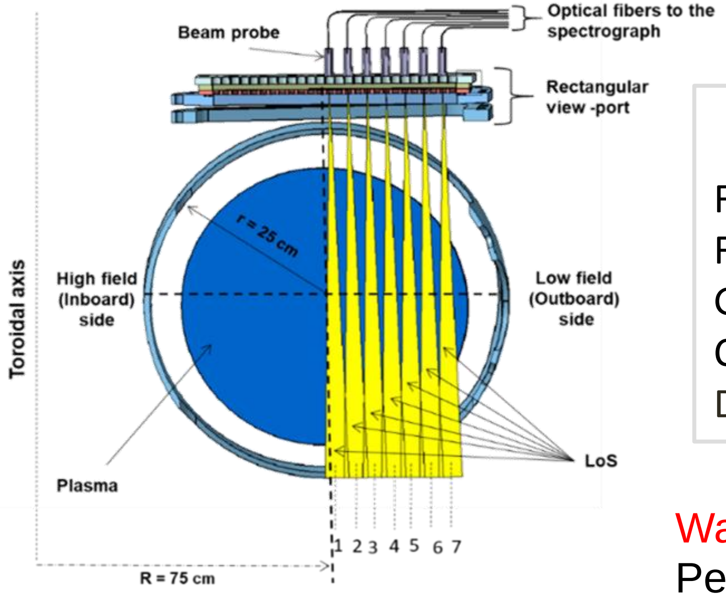
Light (visible region) from the tokamak is mainly collected using optical fibres with collimated lenses

Fibre + collimated Lens define a Line-of-Sight (LoS)

Total 50 vertical (top + bottom)
8 tangential and 15 radial
LoSs are available



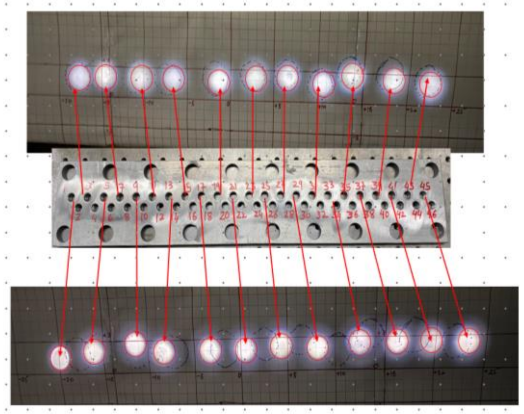
Tangential



Vertical

A large rectangular based on double V groove O-ring technique viewport developed

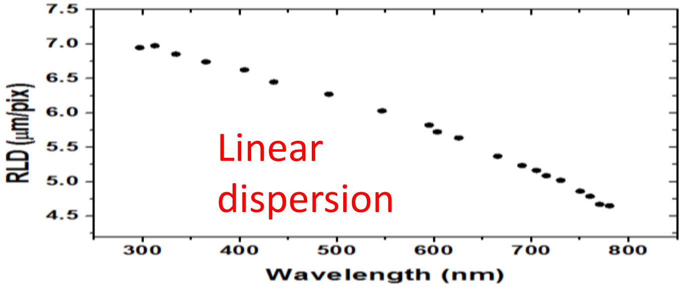
Space resolution at midplane
~ 1.5 cm (2.4) with
0.4 (1) mm core dia fibers



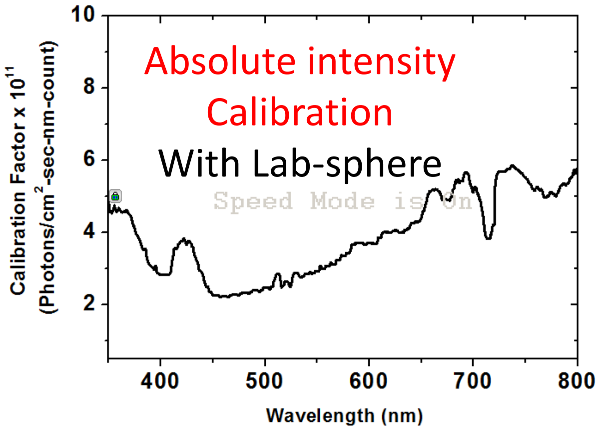
Two Spectrometer- CCD systems

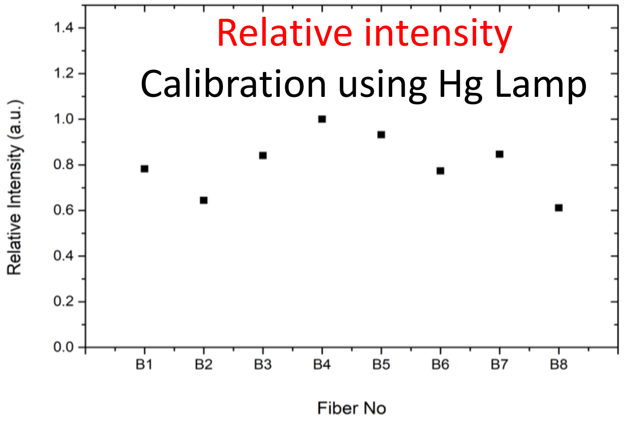
Focal Length: 1 m / 0.5 m
F-number: *f/8.7* / *f/6.5*
Grating: 1800 / 1200 grooves/mm
CCD: 2048 x 512 pixels (13.5 µm) / 1024 x 256 pixels (26 µm)
Dispersion: 0.0055 / 0.0433 nm / pixel

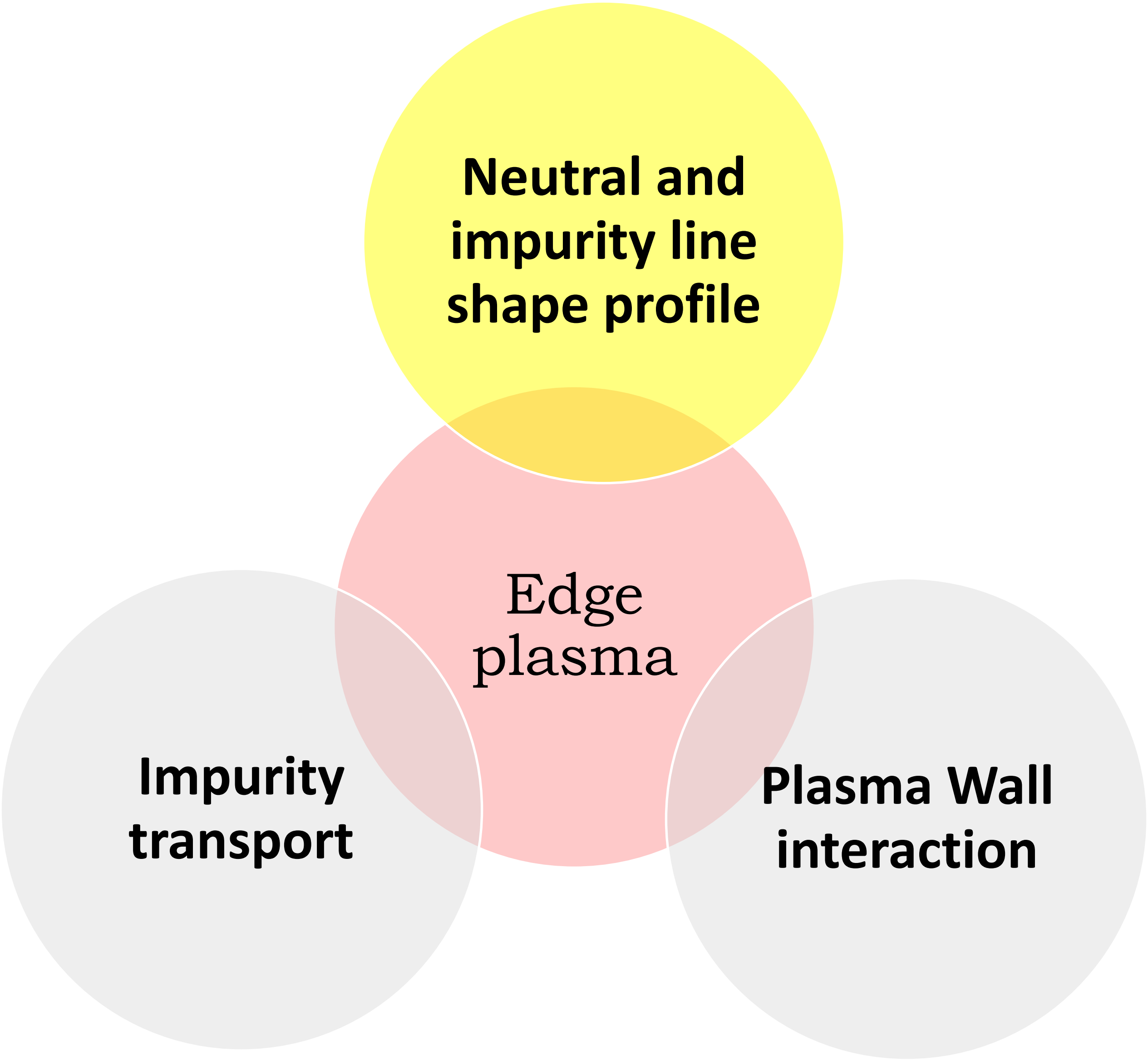
Wavelength Calibration
Pen-ray sources



Intensity Calibration
Using Lab-sphere (Absolute) and white-light source (Relative)







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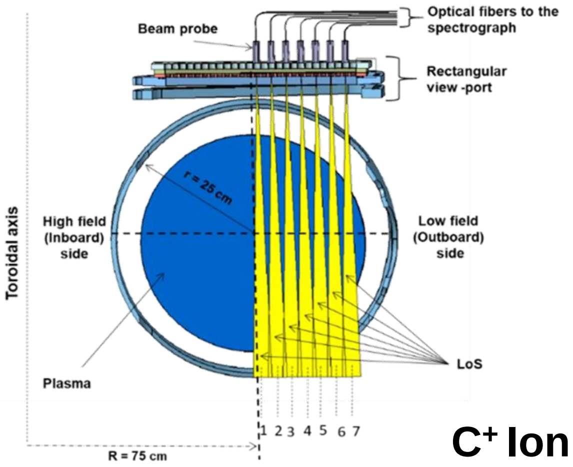
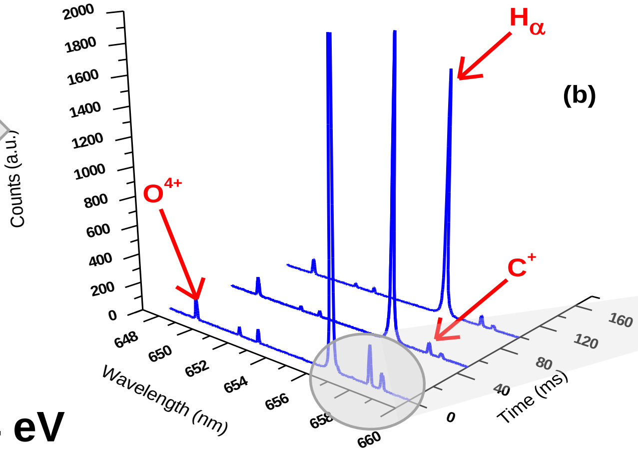
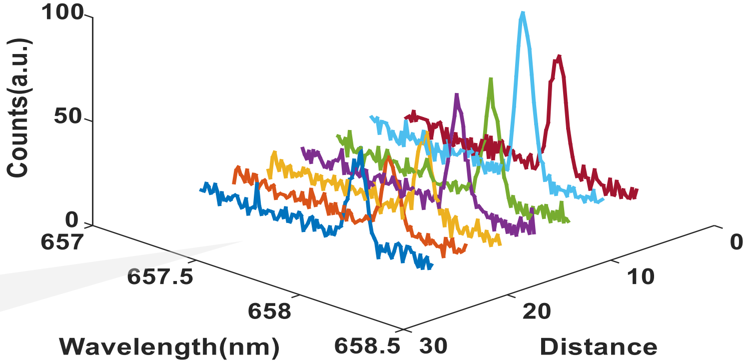
Anomaly in carbon ion temperature



C^+: $^2S_{1/2}$ - $^3P_{3/4}$

At 657.8 nm



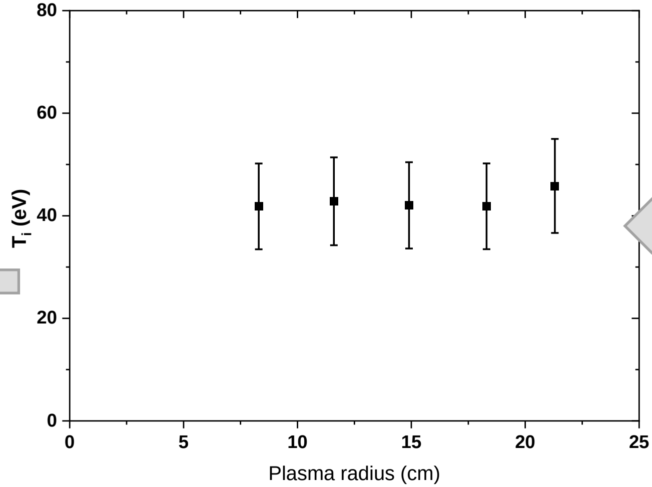


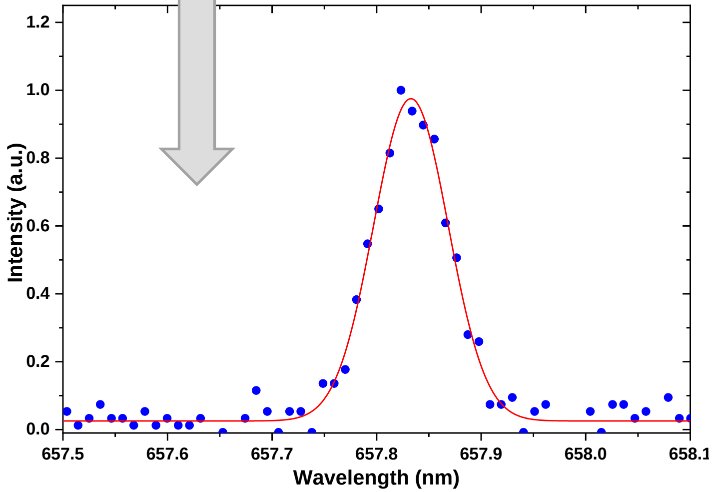
C^+ Ionization potential : 24 eV

NOT considering Zeeman effect

Ion temperature from Doppler Broadening:

$$\Delta\lambda = 7.715 \ X \ 10^{-5}\lambda\left(\frac{T\ (eV)}{m\ (u)}\right)^{1/2}$$





Deduced Edge Ion Temperature
~ 40 eV

Electron Temperature
(Langmuir probes) ~ 8 – 10 eV

Anomalous C^+ ion Temperature?
Or
Measurements Error?

Emission from Magnetic field environment:
Zeeman Effect should be considered!!!

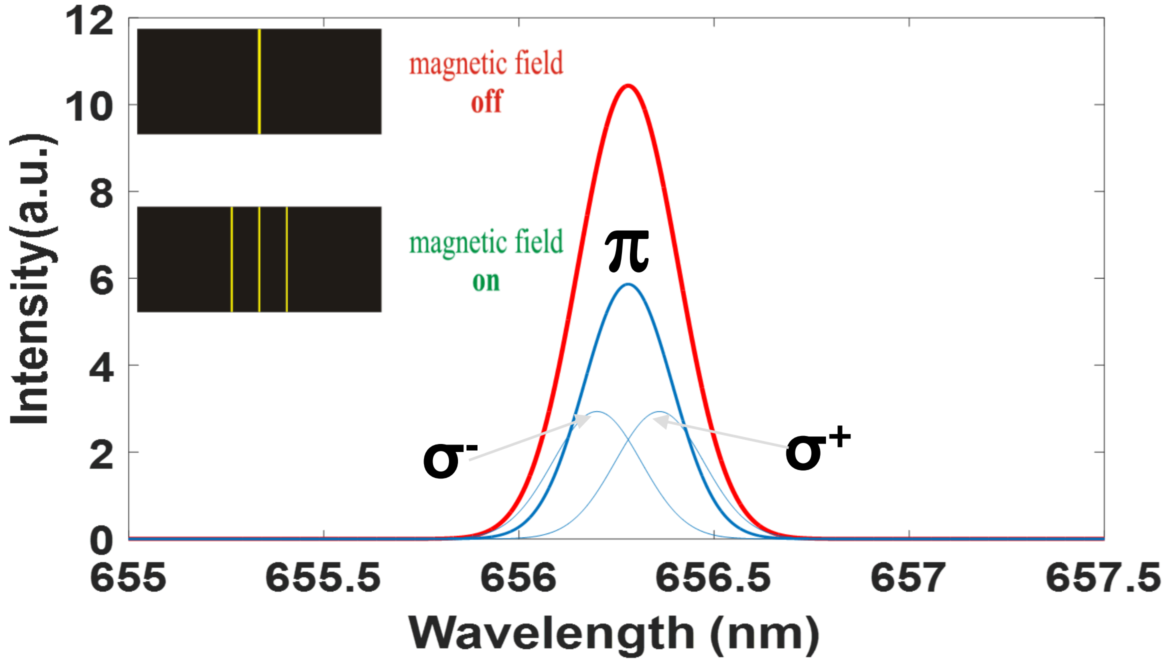
They add up to increase the width of the spectral Line

Measurement of ion temperature

The Line-shape of any spectral line radiation is influenced by

- Doppler broadening
- Natural broadening (~ 10^{-4} °a)
- PRESSURE BROADENING (high density)
- STARK BROADENING (high density)
- Broadening due to Zeeman effect
- Instrumental broadening
- Self-absorption

In presence of Magnetic field
B $\neq$ 0, Zeeman Effect



The Line-shape of any spectral line radiation from tokamak is mainly influenced by

DOPPLER BROADENING

BROADENING DUE TO ZEEMAN EFFECT

As energy level split, many transitions having different wavelengths appear

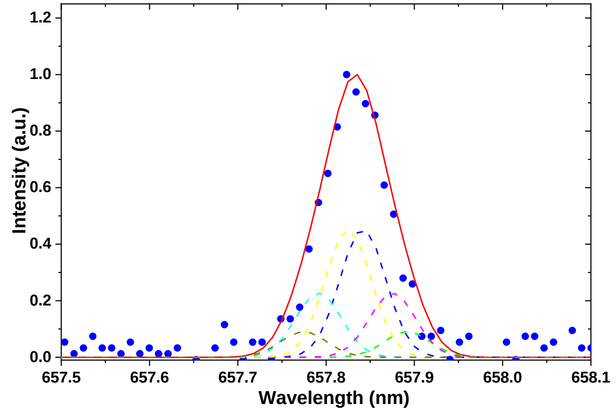
They add up to increase the width of the spectral Line

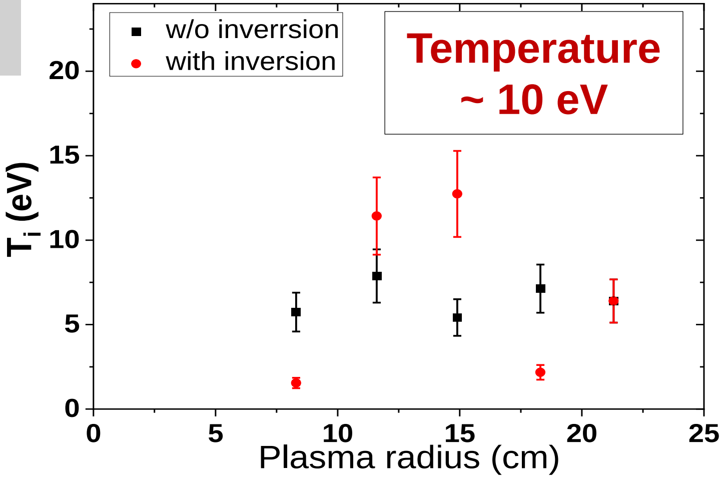
WHAT ARE THE CONSEQUENCES?

Resolving anomaly present in ion temperature estimation

Species	Observed Wavelength (nm)	Zeeman components
C^{1+}	657.8	6
O^{4+}	650.02	21
H_{α}	656.28	48

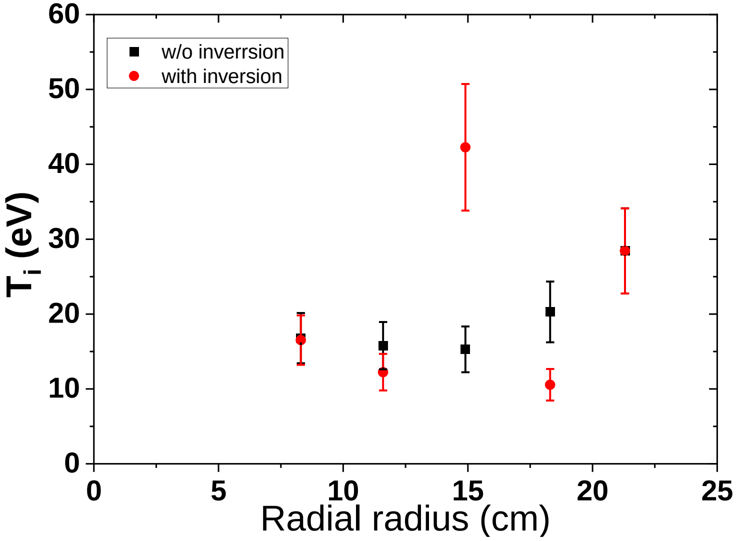
Carbon ion temperature





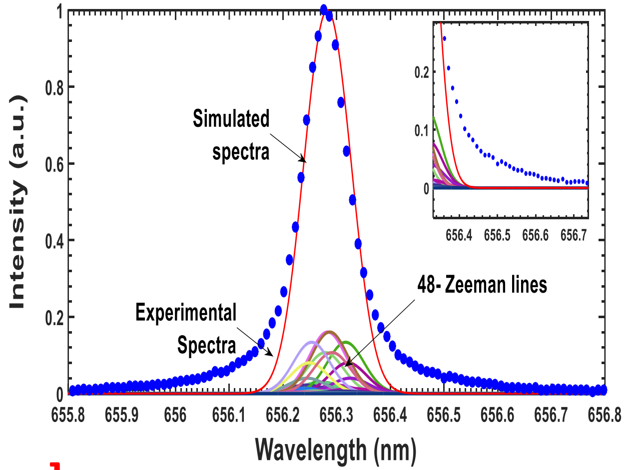
$B_T = 1.32$ T
($B_T \sim 1/R$)

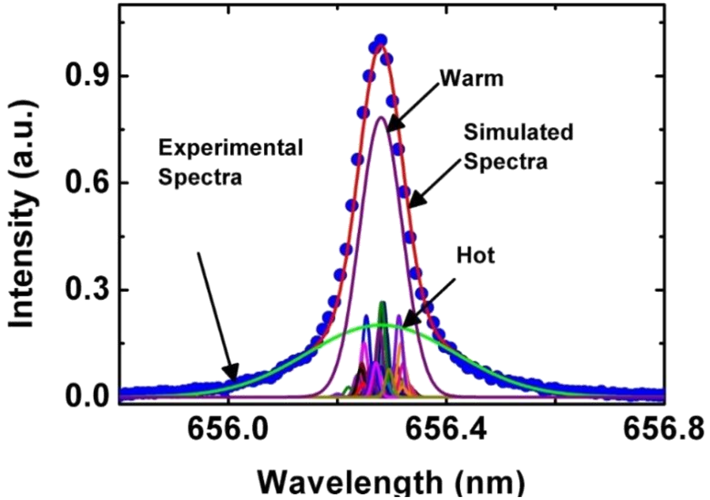
Oxygen ion temperature



Considering Zeeman Effect, Ion temperature C^{1+} ≈ Electron temperature in the Edge region of ADITYA

Hydrogen neutral Zeeman incorporated spectral line shape profile





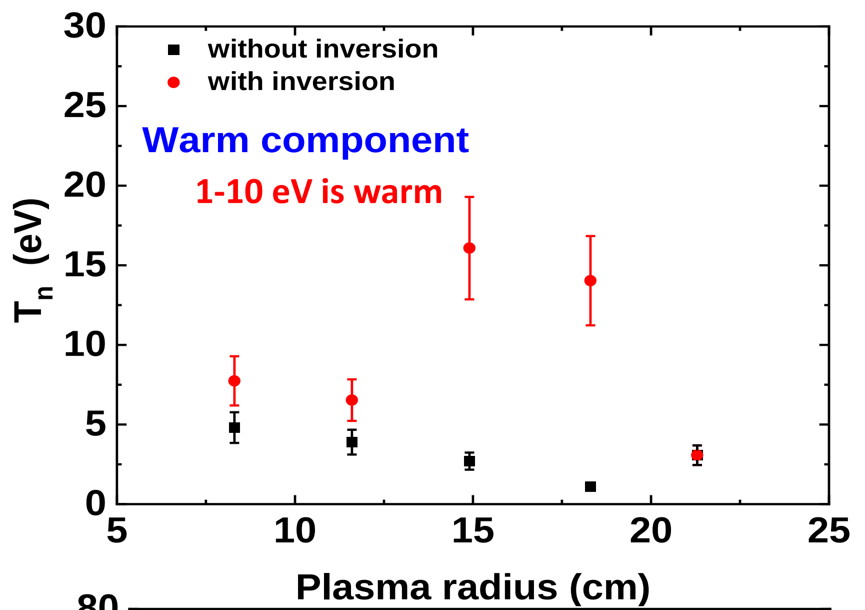
Warm component of hydrogen
Franck-condon dissociation

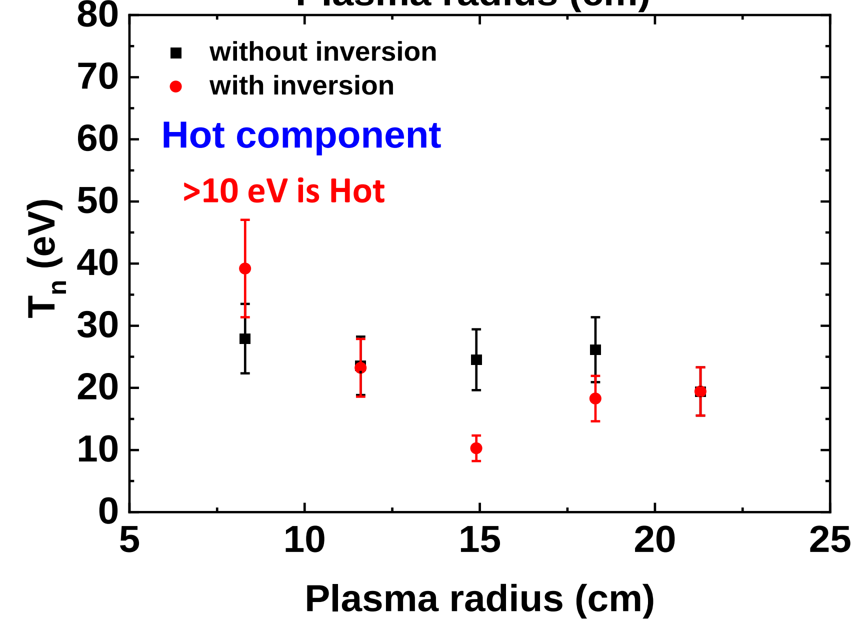
Hot Component of hydrogen
Charge-exchange process

[manuscript submitted to internal review]

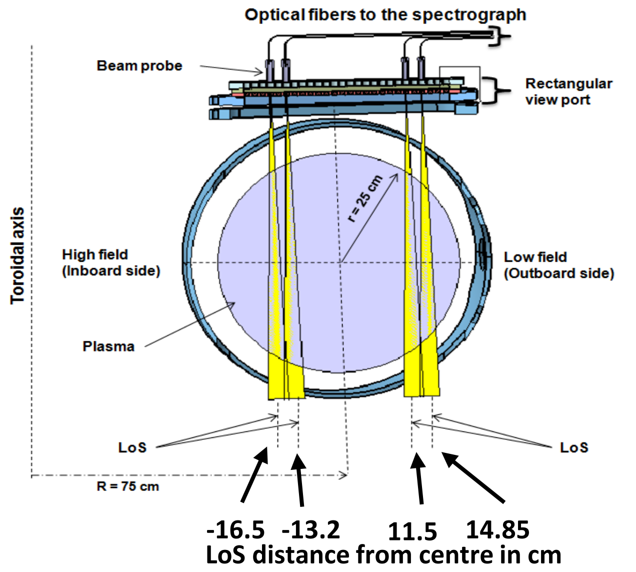
H_α neutral temperature

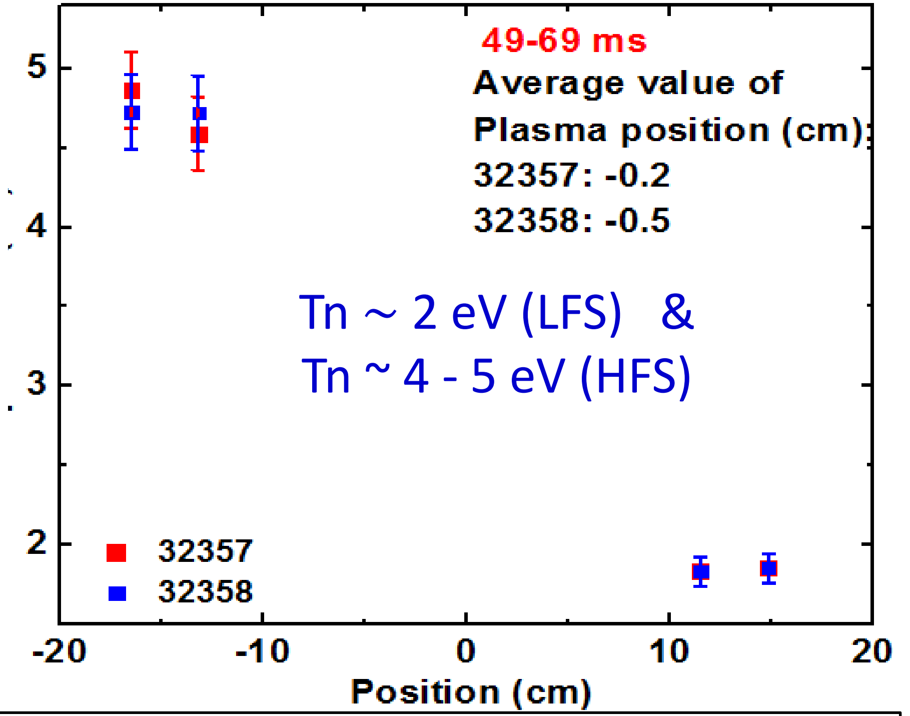
H_α neutral temperature and their radial profiles





Poloidal asymmetry in H_α neutral temperature





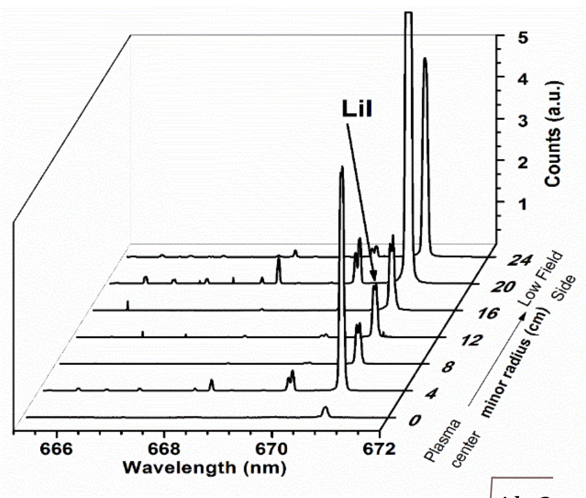
HFS having higher temperature
compared to LFS

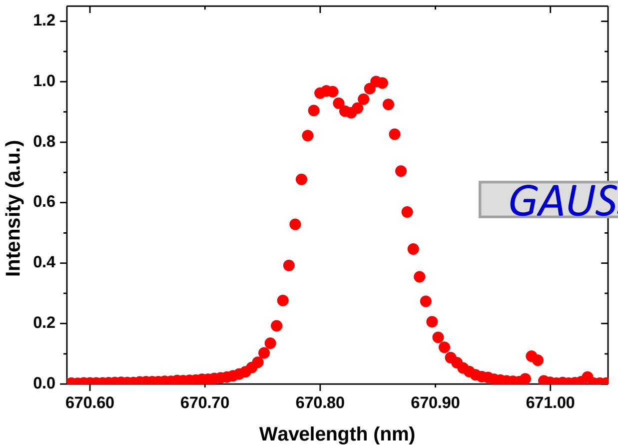
Poloidal asymmetry in neutral temperatures observed for the first time

Neutrals seem to be heated through charge exchange with ions.
JET and Alcator C-Mod tokamaks, ion temperature asymmetries observed. [7-9]

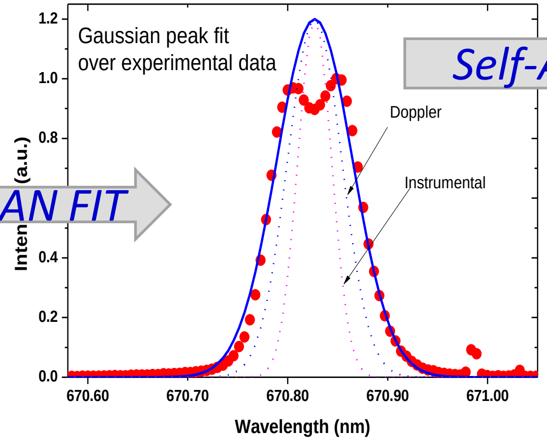
[5] Nandini Yadava , et al., Atoms 7, no. 3 (2019): 87.
[6] Nandini Yadava et al 2019 Nucl. Fusion 59 106003
[7] Chen H. And Hawkes N.C. Et al., plasmas Phys. Plasmas 7 4567
[8] Churchill R.M., et al., Nucl. Fusion 53 122002
[9] Marr K.D et al.,Control. Fusion 52 055010

Measurement of Li-self absorption during Li_2TiO_3 pellet experiments

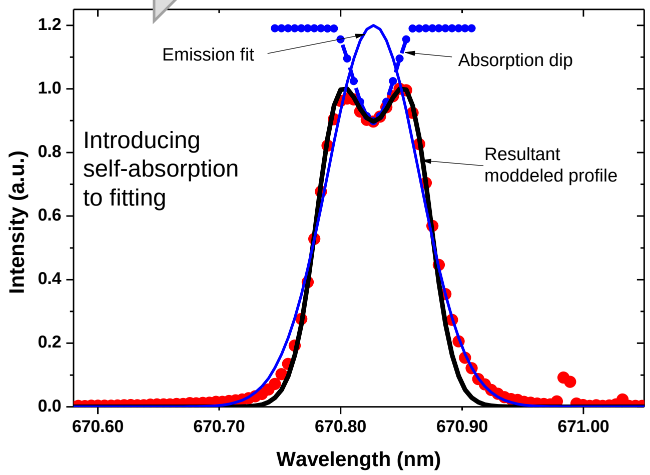




GAUSSIAN FIT



Self-Absorption



$$f(\lambda) = \sqrt{\frac{4ln2}{\pi}}\frac{1}{\Delta\lambda_{FWHM}}e^{\left[-4ln2\left(\frac{\lambda-\lambda_0}{\Delta\lambda_{FWHM}}\right)^2\right]}$$

$FWHM_{Ins}$ 0.04 nm, $FWHM_D$ ~ 0.069 nm, $FWHM_m$ ~ 0.089 nm.

When absorption dip is considered: FWHM ~ 0.06039 nm, width

opacity parameter τ = 1.55.

Absorption coefficient κ = Opacity $\tau \times$ Depth of LoS l

Scarce Literature!

self-absorption

in Lithium spectral line has been observed with pellet experiment

$$\kappa(0) = n_{LI}\frac{\lambda}{c}\frac{fe^2}{4\,\epsilon_0 m_e}\sqrt{\frac{\mu m_p}{2\pi kT_g}}$$

Li Density

n_{Li} ~ 2 ×10^{16} cm^{-3}

Inclusion of absorption in Line Shape Simulations Self-absorption in Lithium line shape measurement

[FEC2020 proceedings]

[manuscript ready, submitting soon]

Power loss

$P_{loss} = n_e n_{LI} L_{LI}$

at $n_e = 1.2 \times 10^{13}\ cm^{-3}$

$P_{loss} = 148\ kW$ & $P_{in} = 260\ kW$

Oscillation strength $f = 0.248$

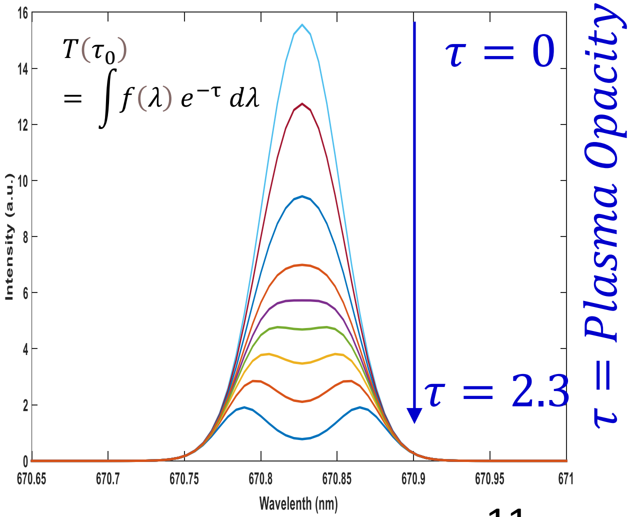
$kT_g = 0.025\ eV$

$\kappa(0) = 0.25\ at\ l = 6\ cm$

All other has standard values

More than 60% of power is radiated due to the pellet

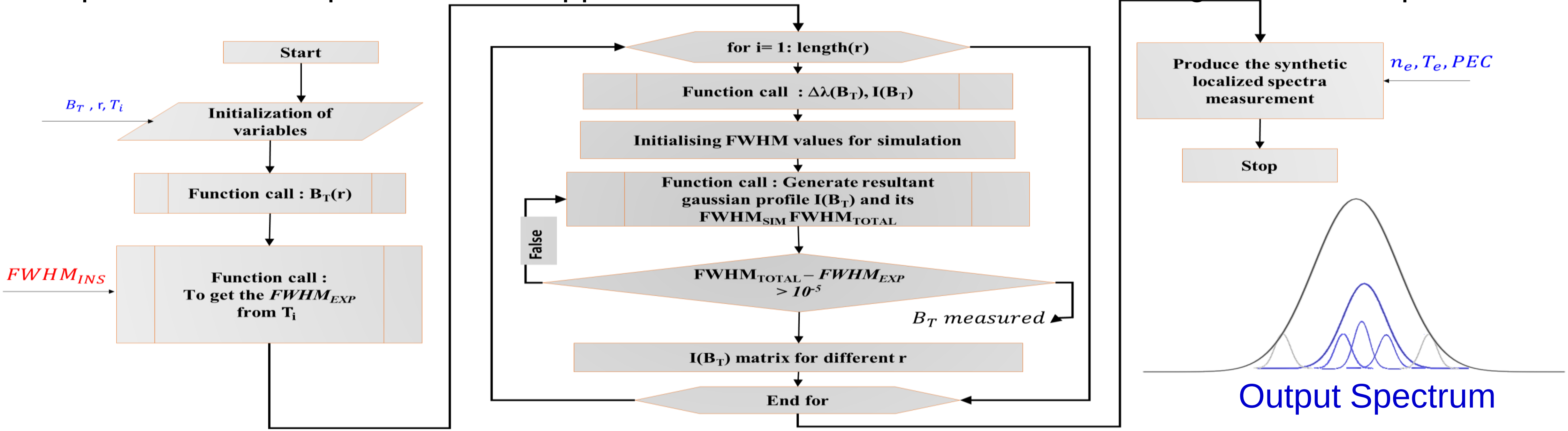
Resulting sudden disruption



Generalized code for the modelling of a spectrum shape profile from any LoS

A code has been developed, which outputs the spectra from any LoS

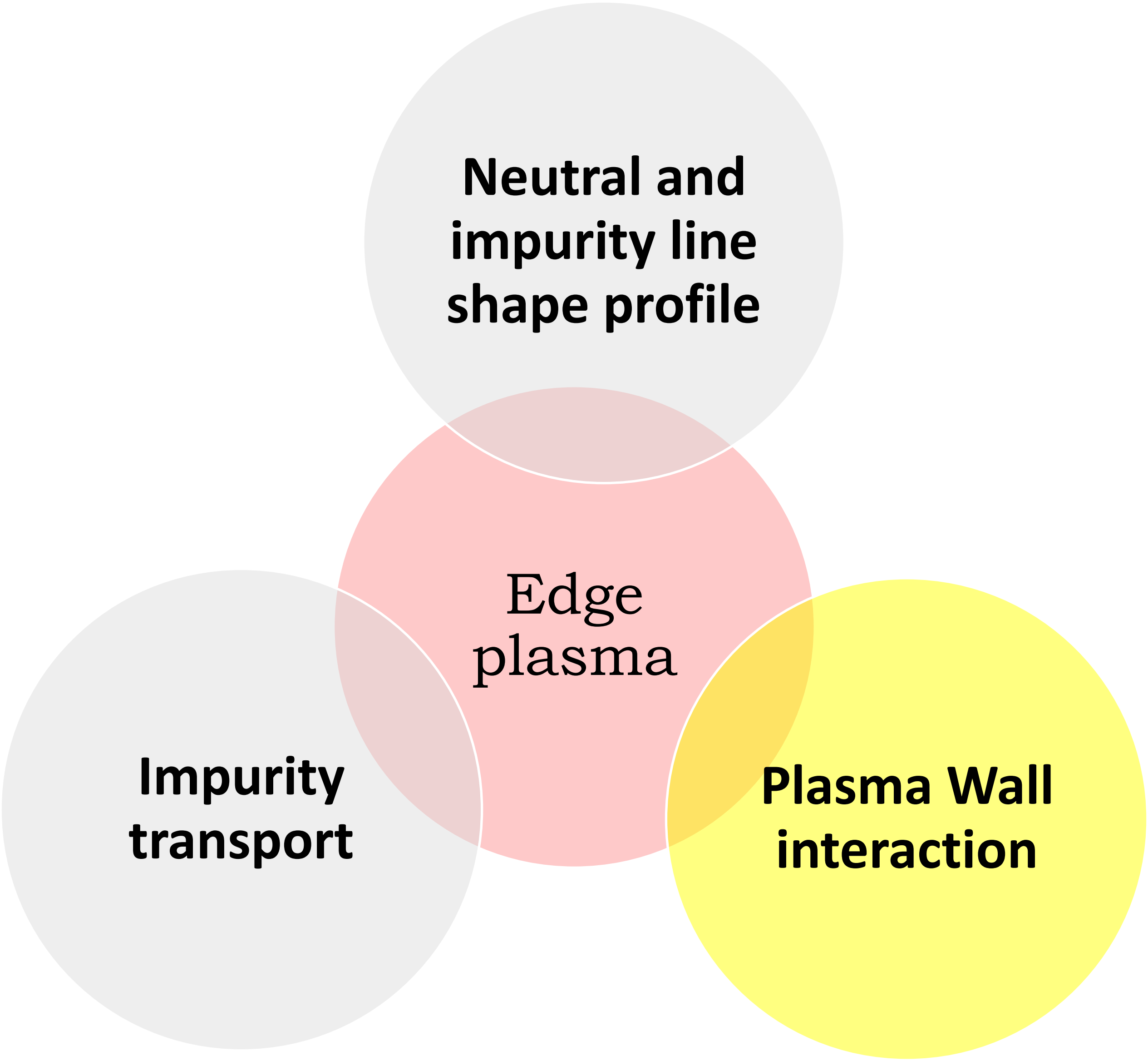
Spectral Line Shape includes: Doppler + Instrumental + Zeeman broadening + Self-absorption



Measured parameter	Inputs to the code
Neutral/Ion temperature	Experimentally measured spectra , Radial locations, B_{T0}
Magnetic field Value	Experimental spectra, Radial location, Ion/Neutral Temperature
Predicting the spectra	Species, Magnetic field, Radial locations, Ion/Neutral temperature, FWHM –instrumental, n_e, T_e

This incorporates almost all the broadening mechanisms present in Aditya-U tokamak

[manuscript under preparation, FED]



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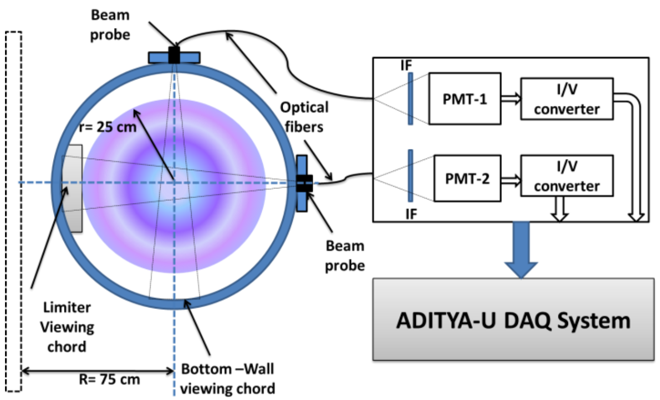
Investigation of improved particle confinement with recycling

Limiter, Divertor plate, PFC/Wall all take part in fuel-specie recycling in tokamaks: Knowledge of recycled fuel-neutrals are important.: Overall Density control, Fueling, Fuel retention

Limiter and Wall recycling is studied in ADITYA-U using spectroscopic techniques [7]



Recycling:

$$R = \frac{outflow(particles\ to\ the\ wall)}{influx\ (particles\ to\ the\ plasma)}$$

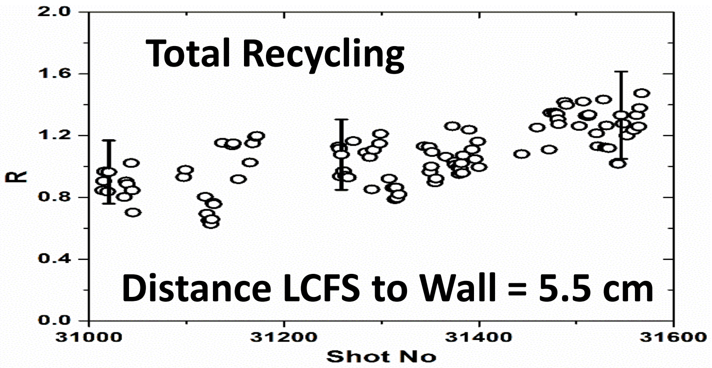
Particle confinement time

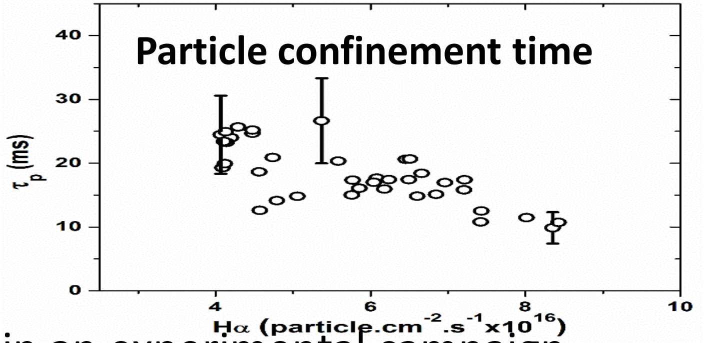
$$\tau_p = (N/\Phi)$$

N : total fuel particle content

Φ is the total outflux of the fuel ions

ADITYA-U Results





Influx measurement

$$\Gamma_{particle} = 4\pi\ (S/XB)\ I_{abs}$$

S effective ionization rate coefficient
X effective excitation rate coefficients
B is the branching ratio of observed spectral
I_{abs} is absolute intensity

Outflux measurement:

$$\Gamma_{out} = < n_e v_r >$$

n_e and v_r : DC components of electron density and the radial drift velocity

– Recycling increases progressively in an experimental campaign

– In the beginning of any campaign:

Limiter + Wall acts a sink

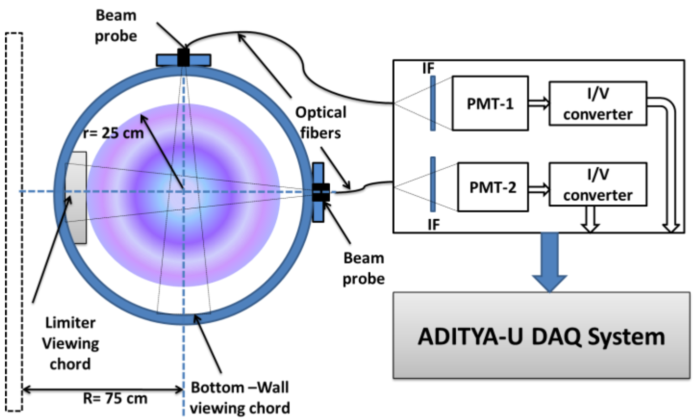
Slowly it starts acting as a source [as the wall getting saturated through Plasma Wall Interaction (PWI)]

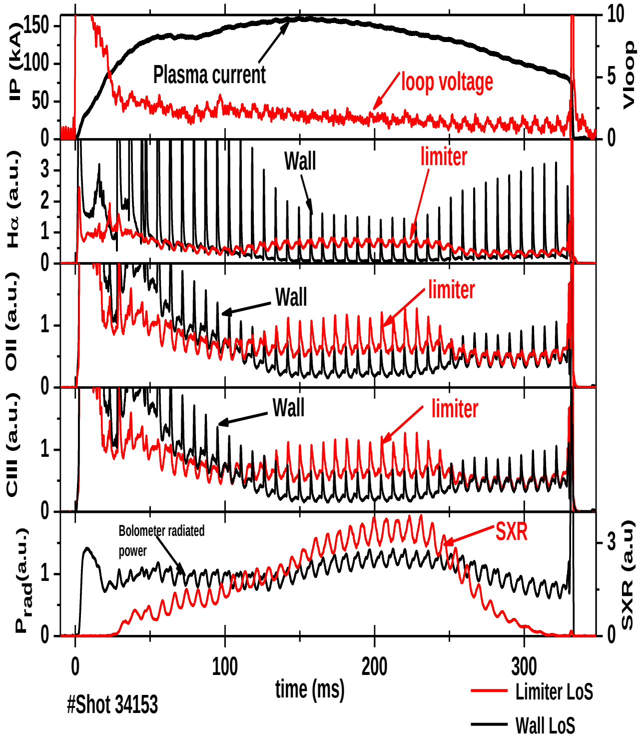
– Particle confinement times decreases with increase in hydrogen influx → Better confinement with lower recycling.

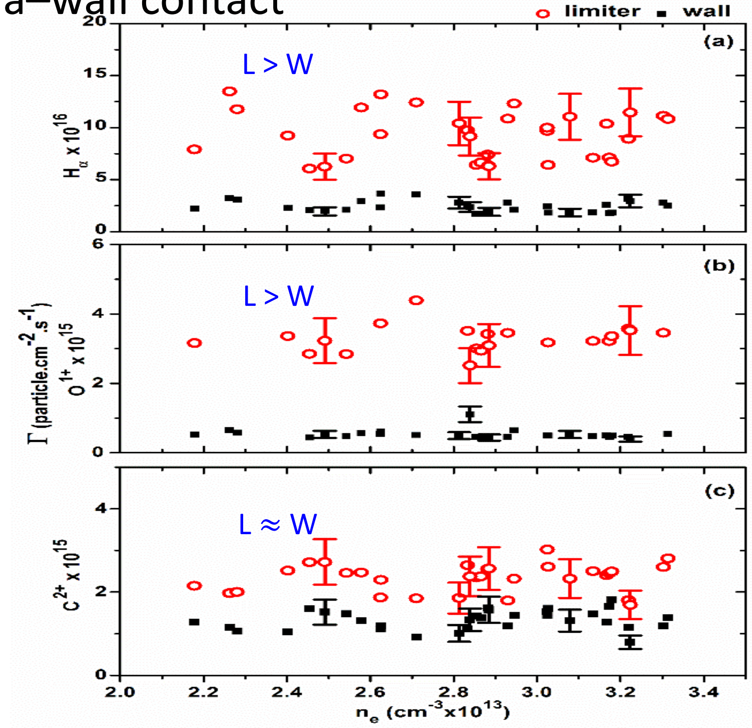
[10] Yadava, N., 2021. Plasma and Fusion Research, 16, pp.2402055-2402055.

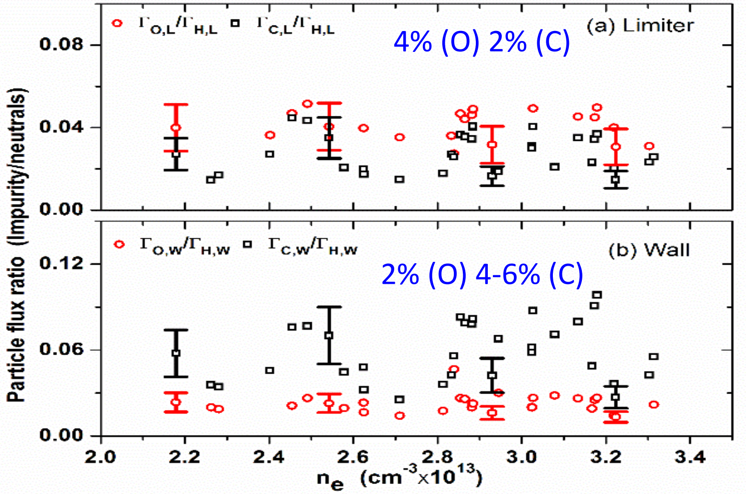
Impurity and neutral behaviour from various first wall components

Limiter / Diverter: Minimizing plasma–wall contact









Species	*Total influx per sec from limiter*	*Total influx per sec from wall*
H 656.28 nm	1.83×10^{21}	1.28×10^{21}
O^{1+} 441.2 nm	5.50×10^{19}	2.70×10^{19}
C^{2+} 464.7 nm	3.80×10^{19}	9.00×10^{19}

Lim : 2 m^2 ,
Wall : 5.4 m^2

ADITYA-U: [7]

Wall – Stainless Steel (SS)

Limiter – Graphite

Distance LCFS to Wall = 5.5 cm

With GDC only

- Oxygen and Hydrogen influx

  Limiter > wall

  Due to the higher plasma particle out-flux on the limiter!!

- Carbon influx

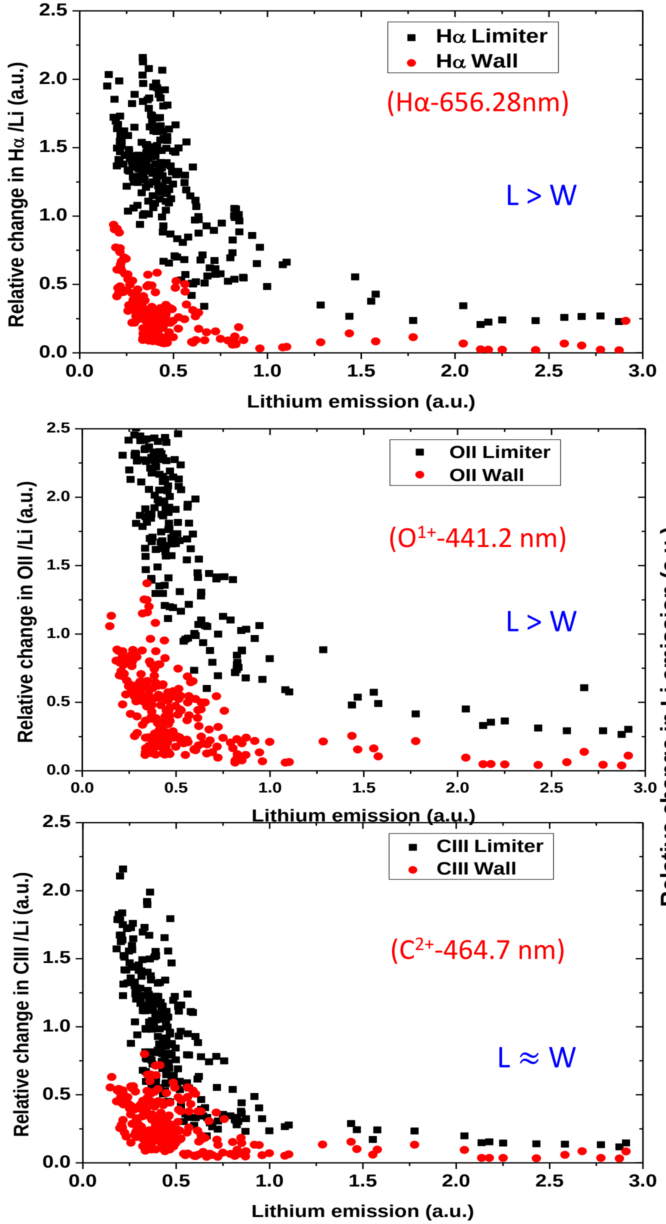
  Limiter < wall

  Due to the Carbon coating on the wall during a discharge!!

[11] Yadava, N., 2021. Plasma and Fusion Research, 16, pp.2402055-2402055.

Impurity and neutral behaviour with different cleaning techniques

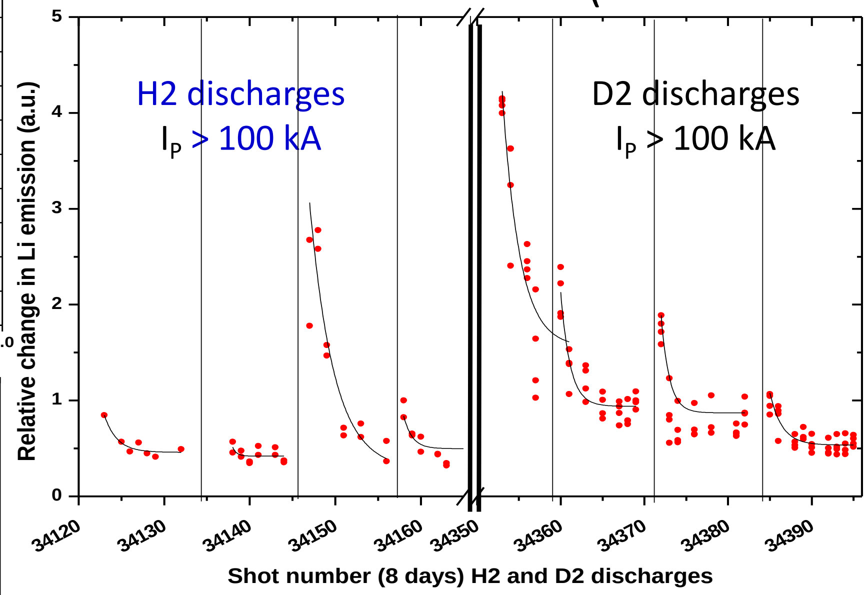
Relative emission data



Significant reduction in fuel and impurity recycling with Li coating

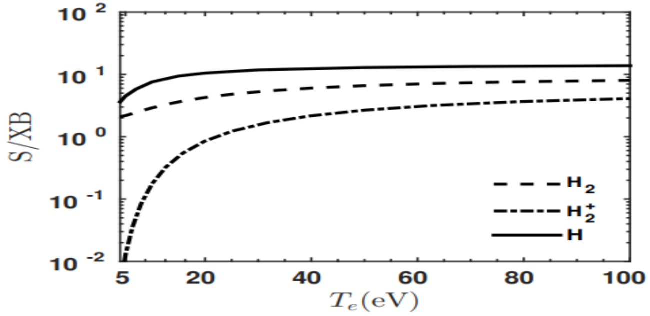
Reduction in emission	Hα-656.28nm	O^{1+}-441.2 nm	C^{2+}-464.7 nm
Limiter	60 %	83 %	50 %
Wall	30 %	50 %	50 %

Lithium emission (Li I : 670.8 nm)



Data taken (5 ms) during 40-60 ms of plasma current flat-top [8]

Molecular contribution in influx estimation



Effective flux at 7 eV

Atomic : $4.09 \times 10^{16}\ cm^{-2}s^{-1}$

Atomic + Molecular: $3.88 \times 10^{16}\ cm^{-2}s^{-1}$

With GDC+Lithiumization:

- Oxygen and Hydrogen influx

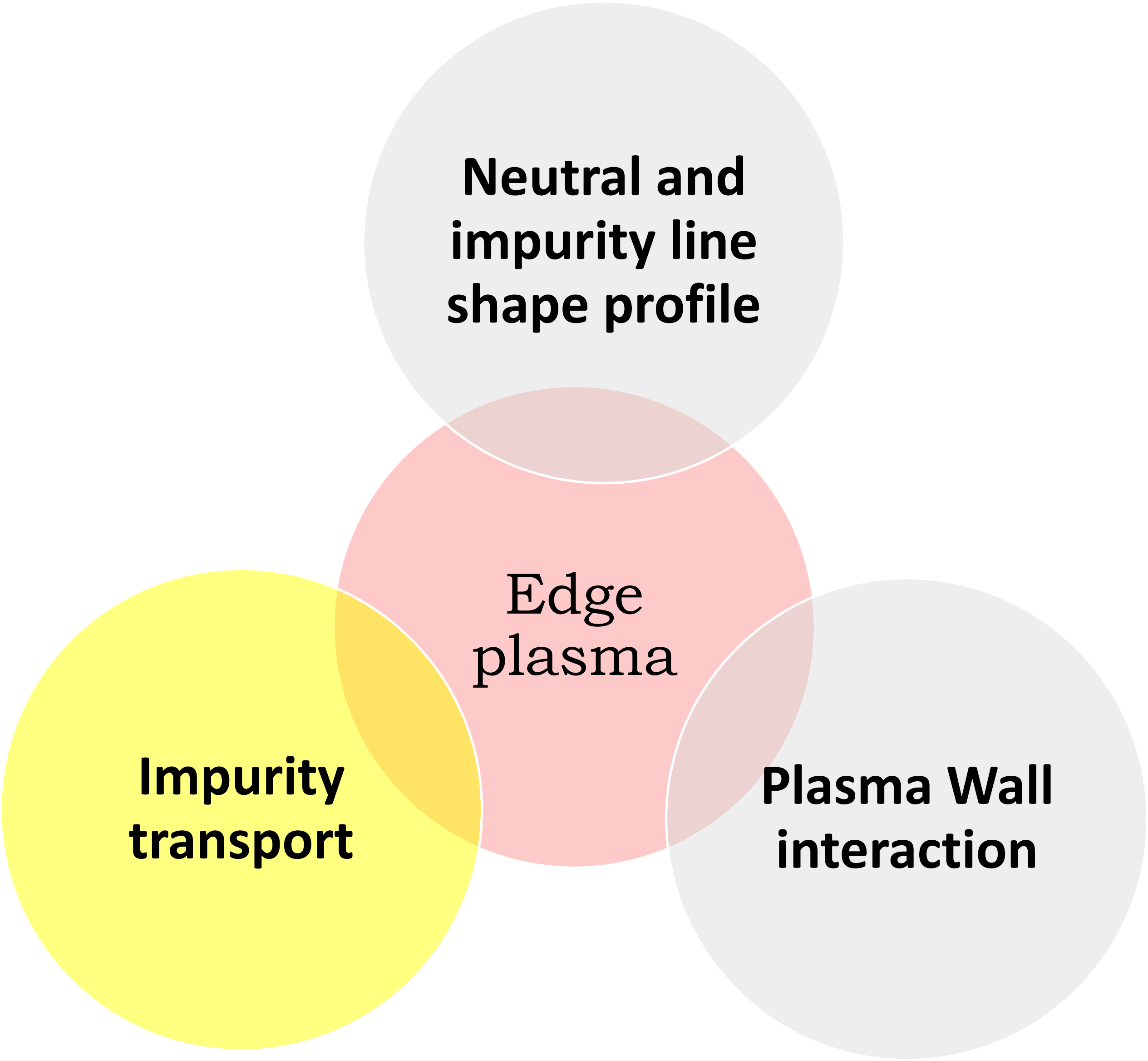
  Limiter < wall

  Due to the reduced plasma particle out-flux on the limiter!!

- Carbon influx

  Limiter < wall

[12] K.A. Jadeja, J. Ghosh, N. Yadava et al. et al 2022 Nucl. Fusion 62 016003 [12] Quantification of molecular contribution in particle influx estimation using S/XB calculations of Hα emission in tokamaks, R. Dey, N. Yadava, M.B. Chowdhuri et al. (under review in Atoms)



Neutral and impurity line shape profile

- Neutral, ion corrected temperature measurement (Zeeman broadening)
- Poloidal asymmetry in neutral temperatures
- Self-absorption in tokamak plasma

Plasma Wall interaction

- Recycling and particle influxes estimations
  - Different surface
  - Different wall-conditioning
- Molecular contribution in particle recycling

Impurity transport

- Mass dependency of Diffusivity for Aditya-U tokamak

Divertor plasma

In the divertor region the MOLECULAR contribution is highly dominated-Characterization technique required

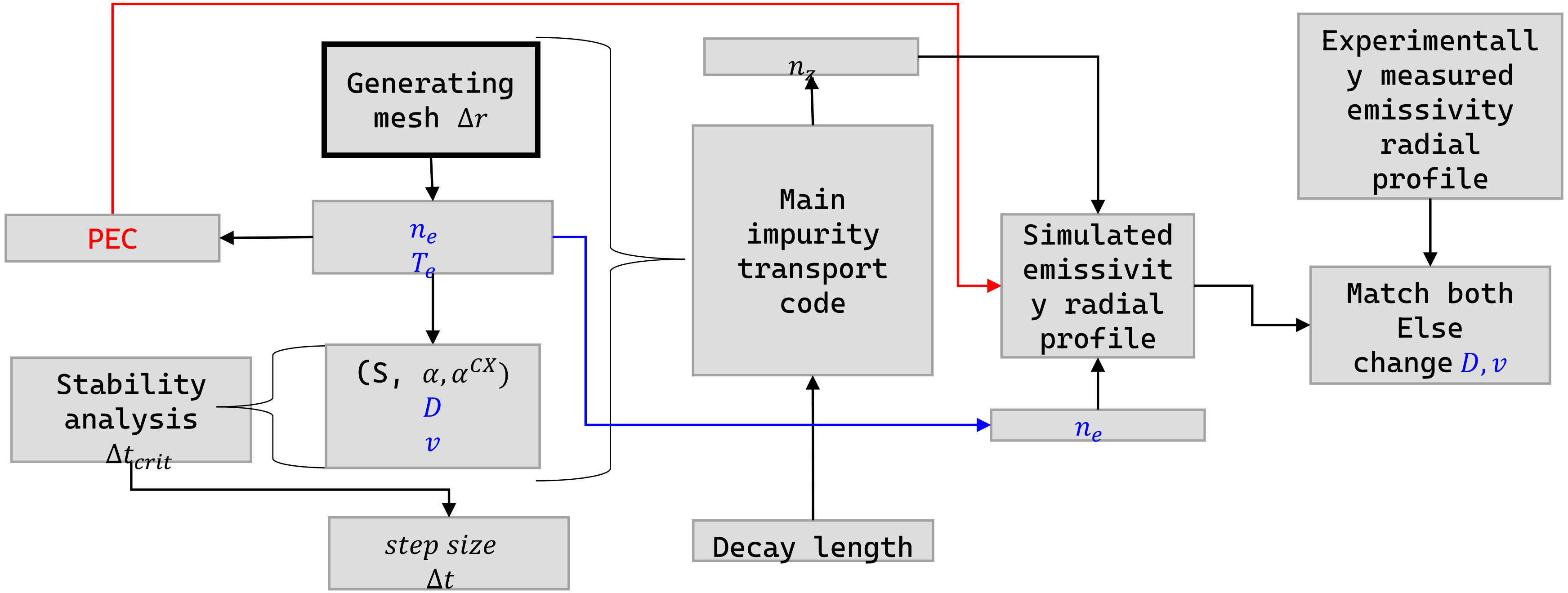
Impurity transport by indigenously developed code

Where the impurities travel to inside the plasma: effecting the Edge and Core plasma?

By solving the Radial Impurity Transport Equation for each charge state

$$\frac{\partial n_Z(r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r \left(D(r)\frac{\partial n_Z(r,t)}{\partial r} - v(r)\, n_Z(r,t) \right) + Q_Z(r,t)$$

$Q_z(r,t)$ is the source term which includes ionization, recombination and charge exchange reaction processes.



Part of my studies

- Introduced separate modules for:

Carbon, Neon, Argon, Iron impurities

- Modules for speedup run time
- Mass dependency studies
- GUI upgradation initialize

Indigenously developed impurity transport code used semi - implicit numerical method* [13]

– Diffusion is considered as IMPLICIT and drift velocity term is EXPLICIT.

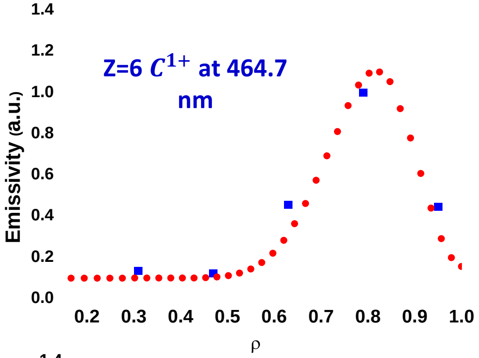
– Source term is treated for both IMPLICIT and EXPLICIT.

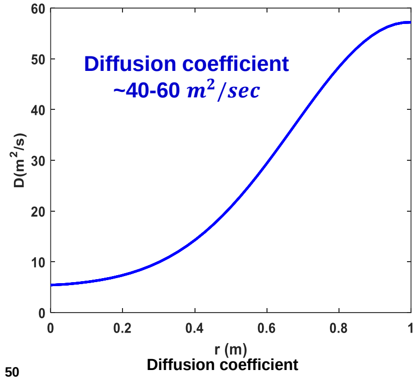
The code is benchmarked with STRAHL through oxygen impurity transport study

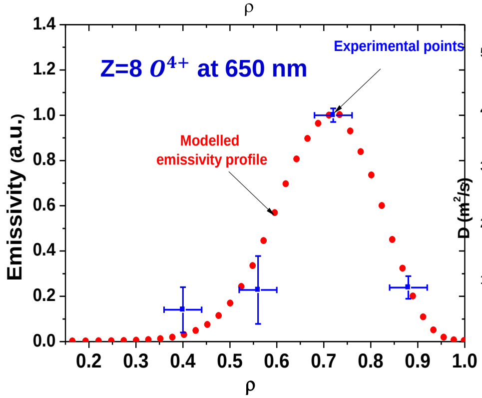
[13] Bhattacharya, A., Ghosh, J., Chowdhuri, M.B. and Munshi, P., 2020. Physics of Plasmas, 27(2), p.023303.

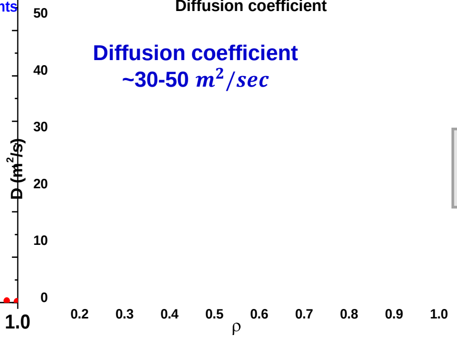
Study of mass dependency of diffusivity

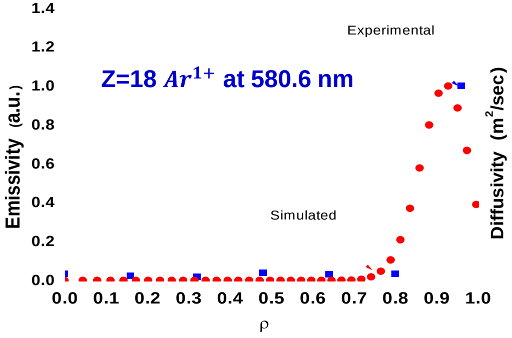
The code is used for different impurity species!

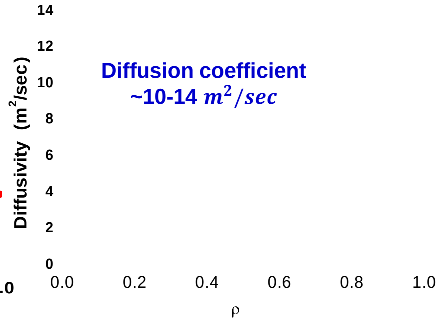


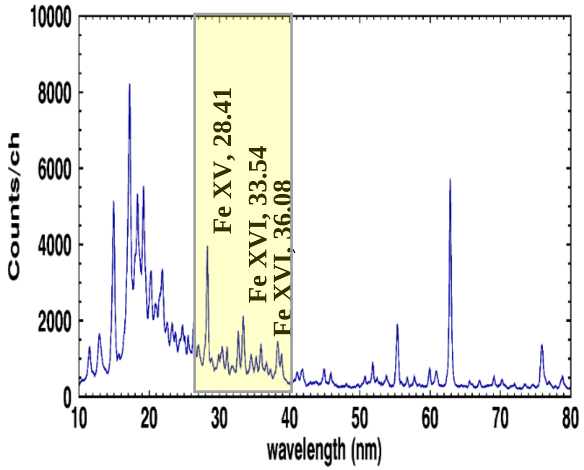




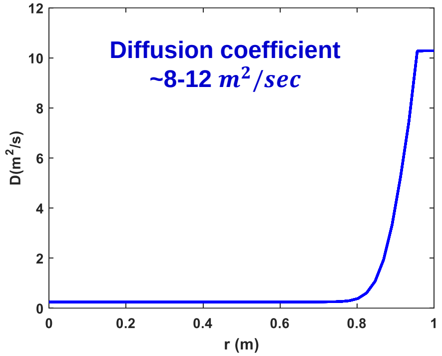








Observed iron impurity in VUV range of the EM spectrum



To understand iron impurity behaviour in Aditya-U tokamak. The ratio of emissivity of different iron lines has been taken from experimentally measured data and the same has matched with the simulated emissivity

Emissivity ratios (nm)	Exp. Ratio	Simu. Ratio
28.4/33.5	1.19	1.14
33.3/36.0	2.00	1.96

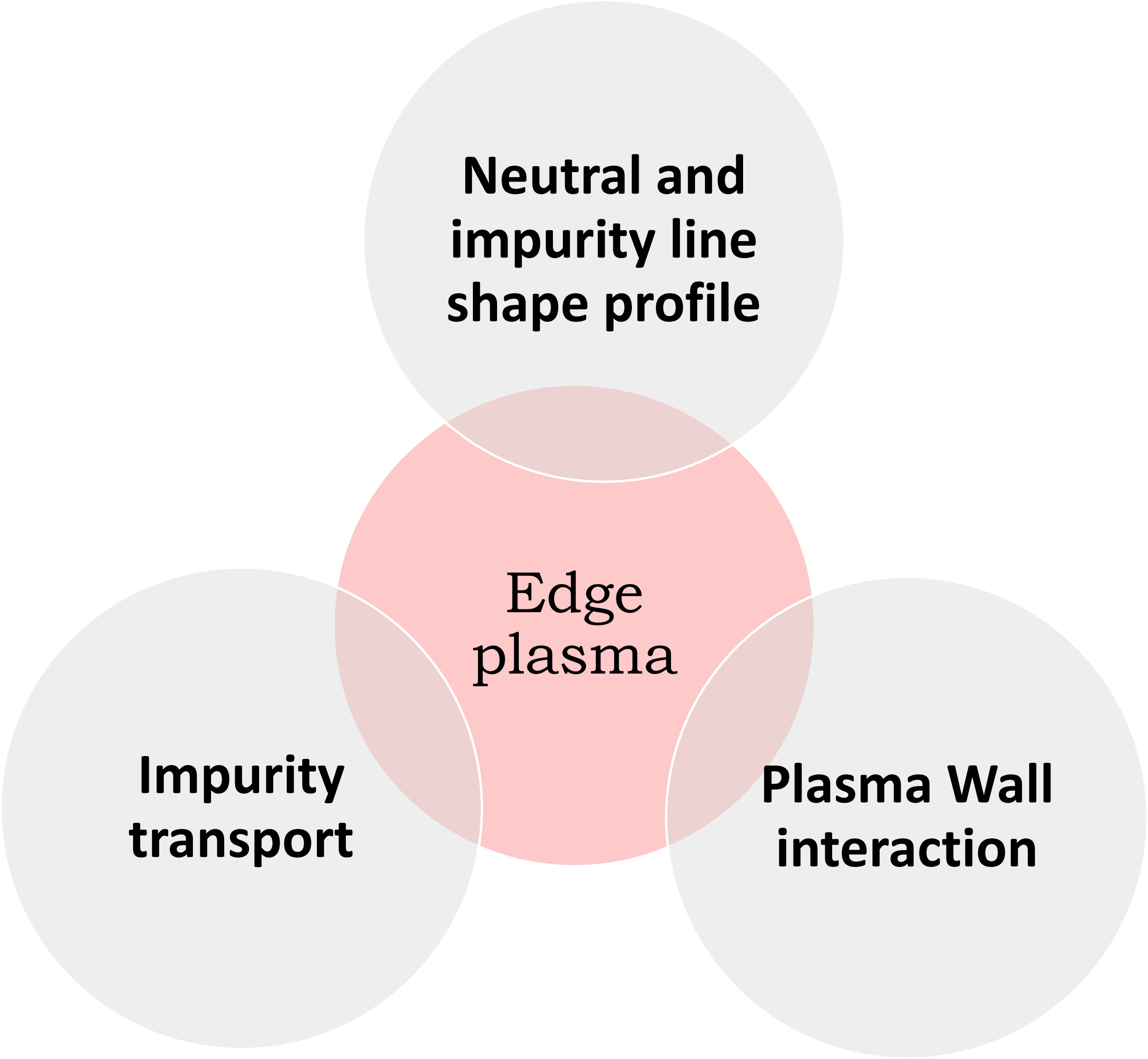
Mass dependency

Increasing Z

Impurity Z number	Diffusivity (m²/sec)
Carbon Z=6	40-60
Oxygen Z=8	30-50
Neon Z=10	15-20
Argon Z=18	10-14
Iron Z=26	8-12

Decreasing D

The study of Mass Dependency of Diffusion Coefficient deduced. (manuscript under preparation)



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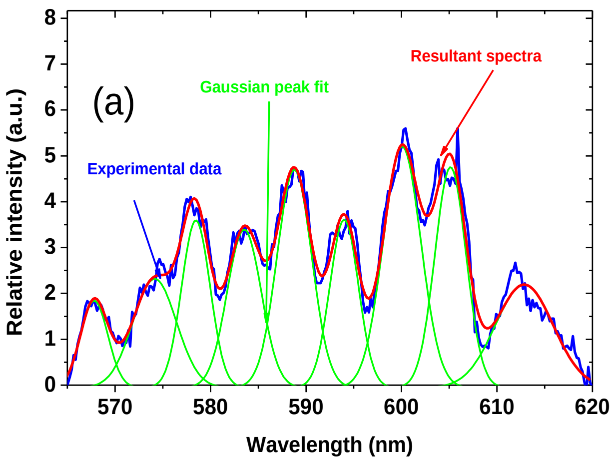
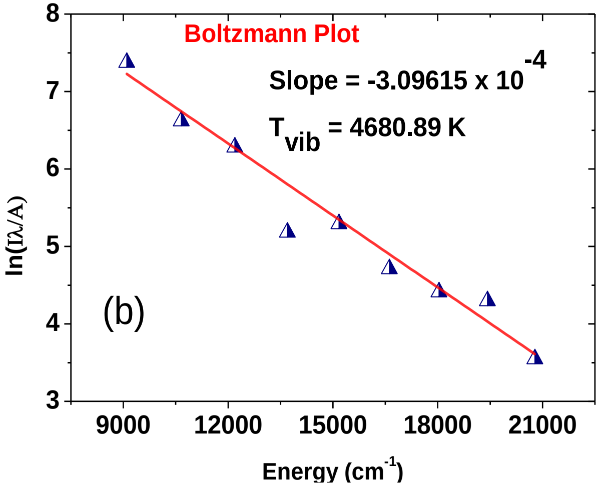
Development of technique to study divertor like plasmas

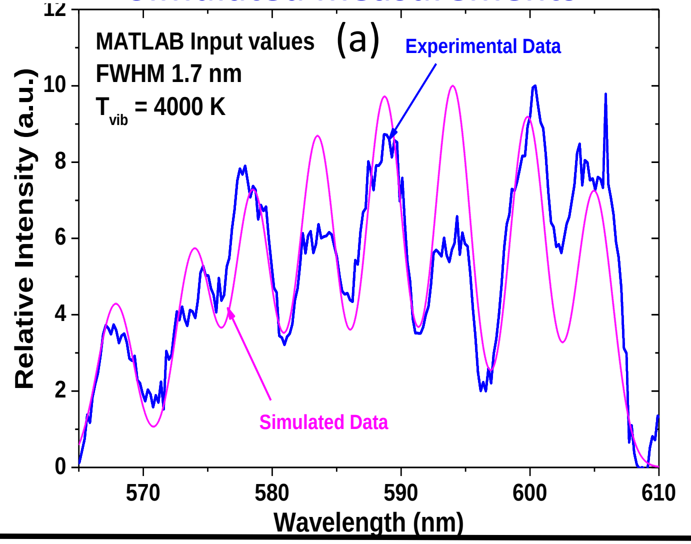
Vibrational Temperature Estimation of Nitrogen Molecules in Radio-Frequency (RF) Produced Plasma using Boltzmann-plot method

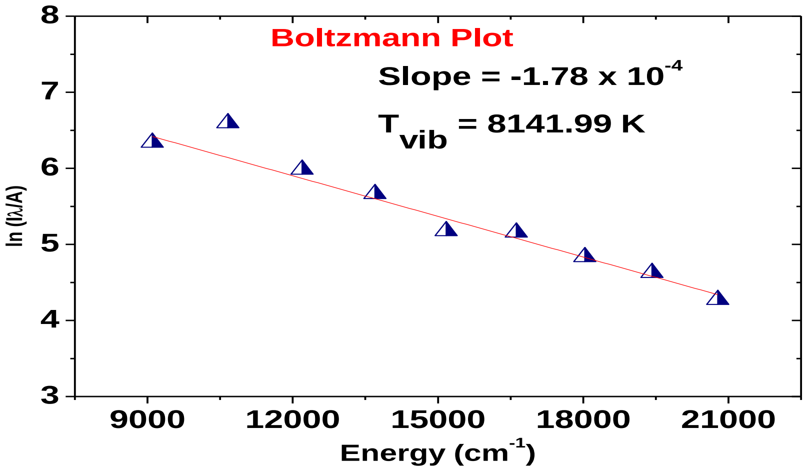
Experimental measurement





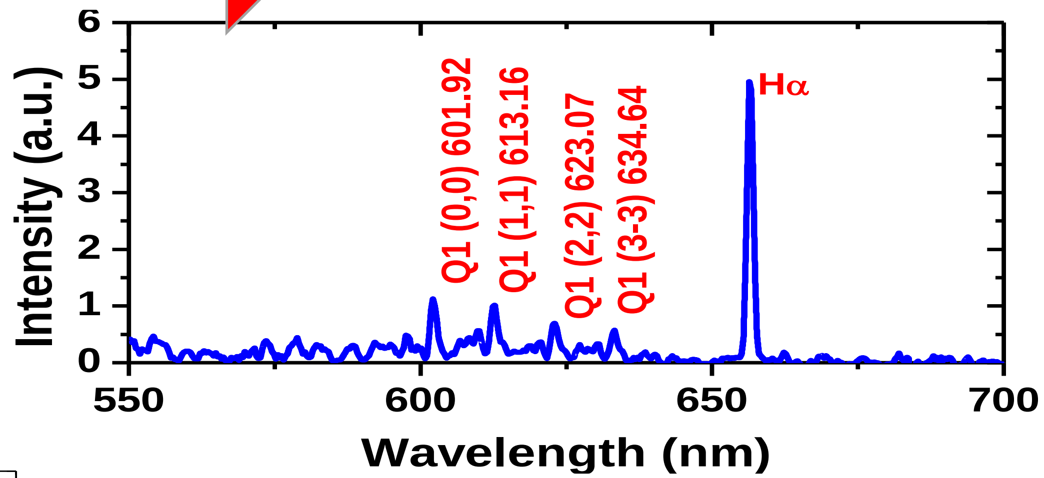
Simulated measurements

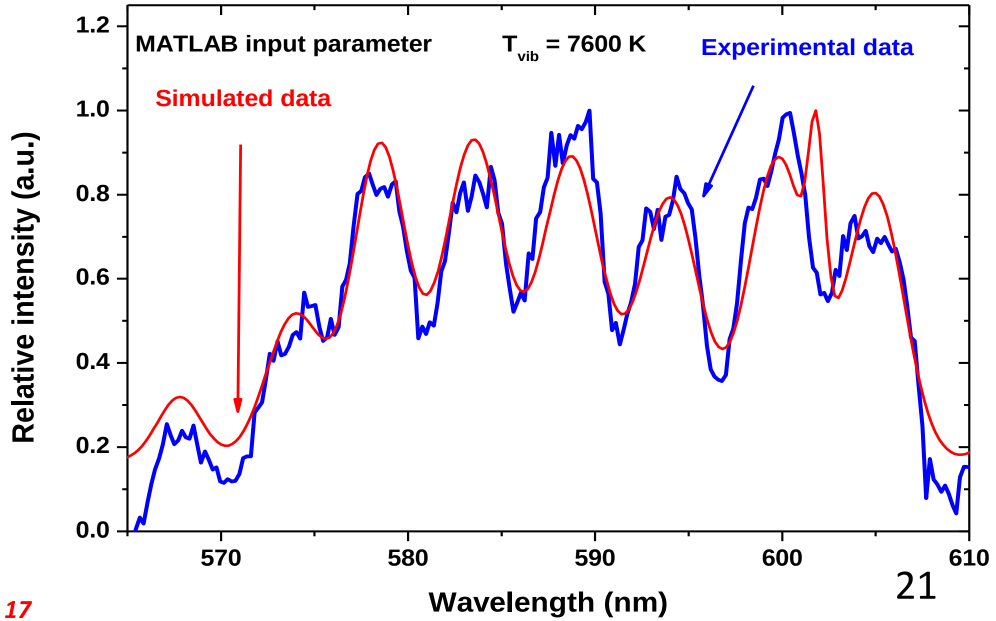




Fulcher band correction

- H_2 Fulcher band is corrupting the N_2 molecular bands
- Affecting the temperature measurement





Plasma gas temperature measured with different nitrogen molecular bands.
Temperature observed to be ~7800 K

[13] Vibrational Temperature Estimation of Nitrogen Molecules in Radio-Frequency (RF) Produced Plasma, N. Yadava et al., PFR, Volume 17

Conclusion

- An integrated code for simulating the spectral line-shape profiles of Hα and impurity ions along any chord. This code incorporates different broadening mechanism (Doppler, Zeeman, Instrumental and opacity).

- Using the code

  Correct values of neutral and impurity-ion temperatures are deduced.

  Observed poloidal asymmetry in fuel-neutral temperatures in ADITYA-U tokamak.

  Found out the existence of two temperature components (warm < 10 eV and hot > 10 eV) hydrogen atom

- Plasma opacity during *self-absorption* of Lithium emission has been estimated.

- Investigation of Influx of hydrogen, oxygen and carbon from limiter and wall in ADITYA-U tokamak.

In absence of wall coating:	Oxygen and Hydrogen influx: Limiter > wall, Carbon influx: Limiter < wall
In presence of wall coating (Lithium):	Oxygen and Hydrogen influx: Limiter < wall, Carbon influx: Limiter < wall

$$lower\ recycling \rightarrow Better\ confinement \rightarrow higher\ temperature$$

- Study of mass dependency of transport coefficients revealed diffusion coefficient reduces with impurity mass.
- Using molecular bands of N_2 and CN molecules the gas temperature is derived to be ~ 5000-8000 K. LabView based application developed for gas temperature measurement.

THANK YOU FOR YOUR KIND ATTENTION!

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- Dr. Ankur Pandya (Nirma University), Dr. Ashoke De (IIT-Kanpur), Dr. Sripathi Punchithaya K. (NIE-Mysuru)
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