Overview of Operation and Experiments in the ADITYA Upgrade Tokamak

Rakesh L. Tanna

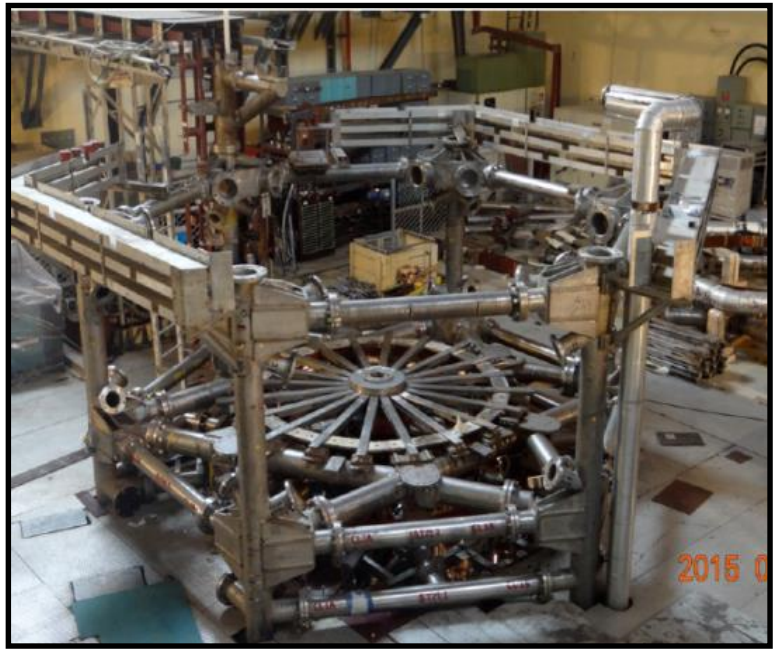
Institute for Plasma Research, India

On behalf of the ADITYA-U Research Team

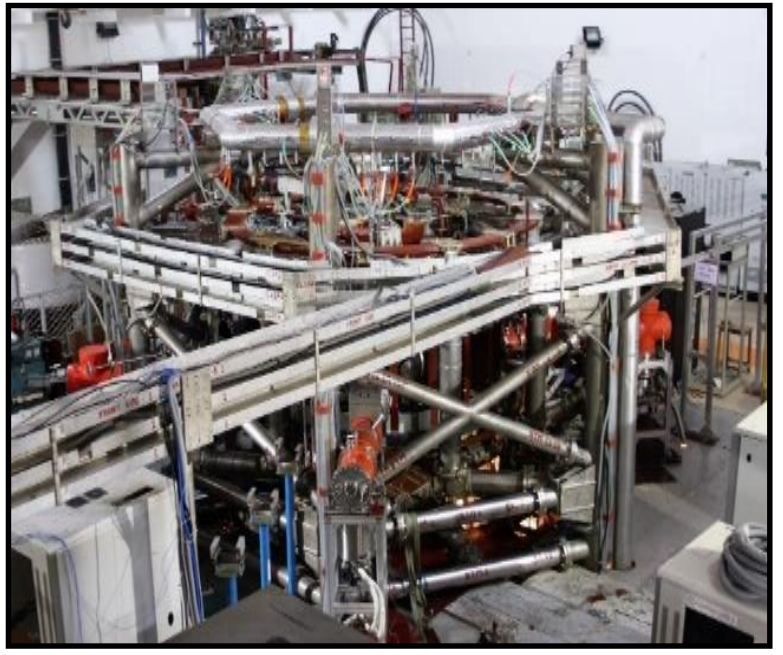
ADITYA Upgrade Tokamak

The Aim:

- ✓ A small/mid-size tokamak with Divertor Configuration (single & double null)
- ✓ To carry out experiments relevant for Bigger Machines (runaways, disruption etc.)
- ✓ Easier access and Smaller duty cycle



ADITYA Dismantled

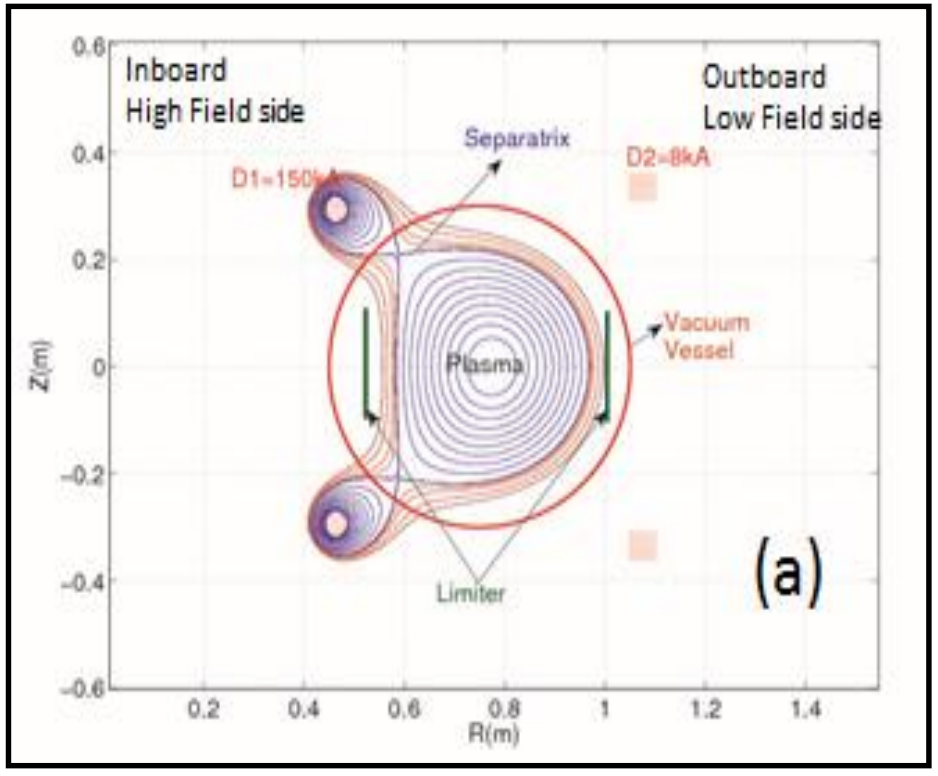


ADITYA-U Operation started –Dec'16

Major radius (R)	**0.75 m**
Minor radius (a)	**0.25 m**
Plasma Shape	**Circular / Shaped**
Toroidal Field	**1.5 T**
Plasma Current	**150 - 250 kA**

Transforming ADITYA to ADITYA-U Tokamak

Divertor coil locations identified using Plasma equilibrium reconstruction with equilibrium code IPREQ



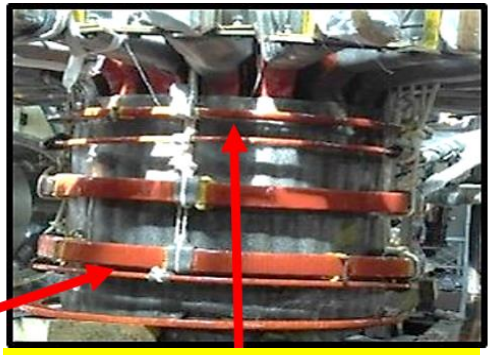
New Inclusions in ADITYA – U Tokamak

1. New Vessel with circular cross-section

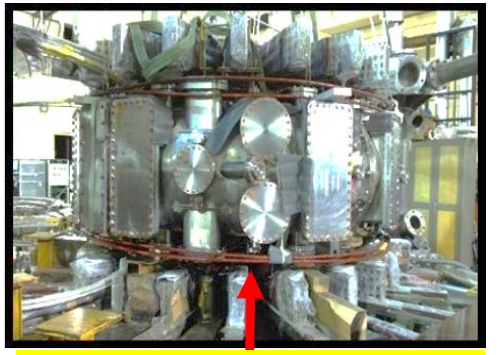
Major Radius: 0.75 m
Minor Radius: 0.3 m
Volume ~ 1.6 m^3
Number of Ports: 114
Material: Stainless Steel

2. Three sets of divertor coils

Main Divertor Coil (Inner)

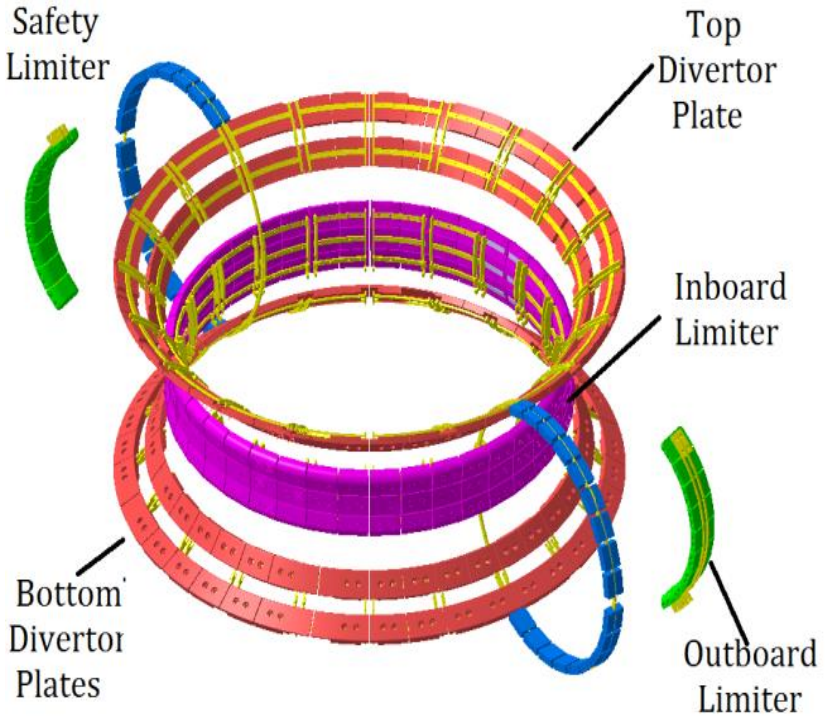


Aux. Divertor Coil (Inner)



Outer Divertor Coil

New Inclusions in ADITYA – U Tokamak (Continued)



Isometric view of Limiter and Divertor

Plasma Facing Components

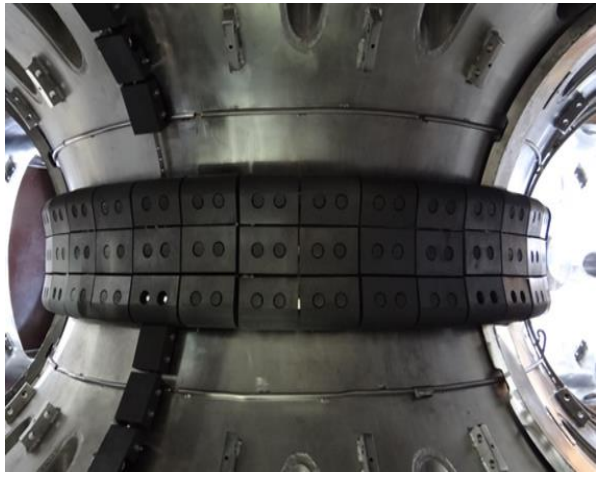
High purity graphite IG-430 tiles

High field side toroidal limiter with small poloidal extent

Two Partial Poloidal Limiters on low field side

Diverter Plates: To be installed in the machine in the phase III of the operation.

Toroidal belt Limiter



Safety and poloidal ring Limiter

New Inclusions in ADITYA – U Tokamak (Continued)

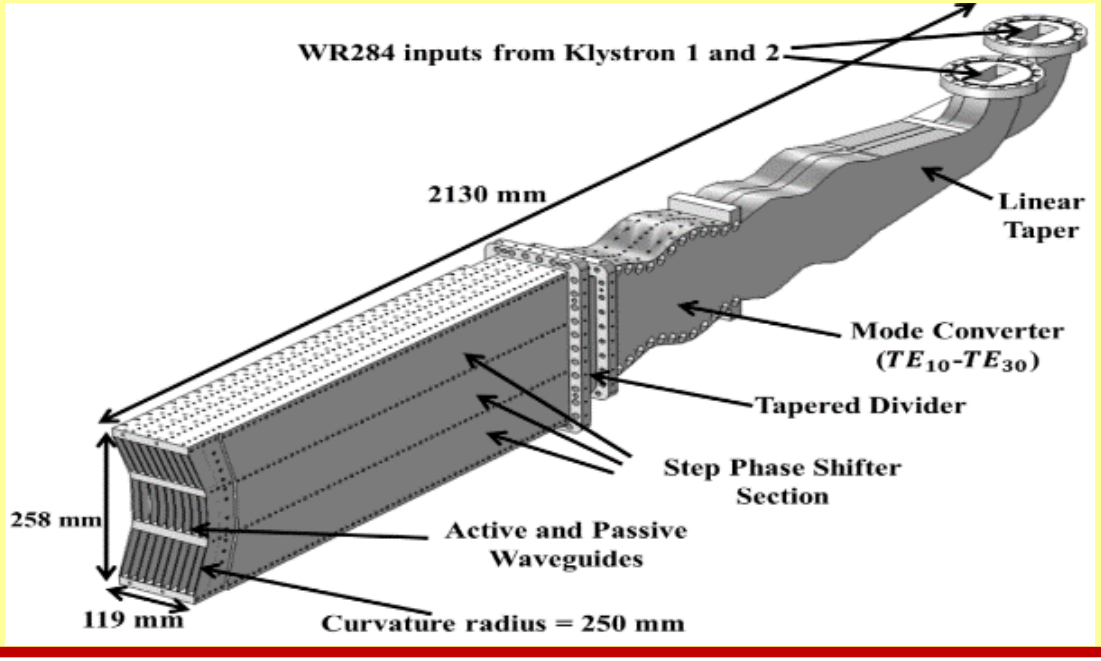
42 GHz ECRH system for Aditya-U (Operational)

Microwave Source (Gyrotron); Frequency: 42GHz; Power : 500 kW

The system is directly connected to tokamak using a BN window and UHV gate valve

LHCD System for ADITYA-U

Passive Active Multijunction (PAM) launcher (to be installed)



ICRH system for ADITYA-U (to be installed)

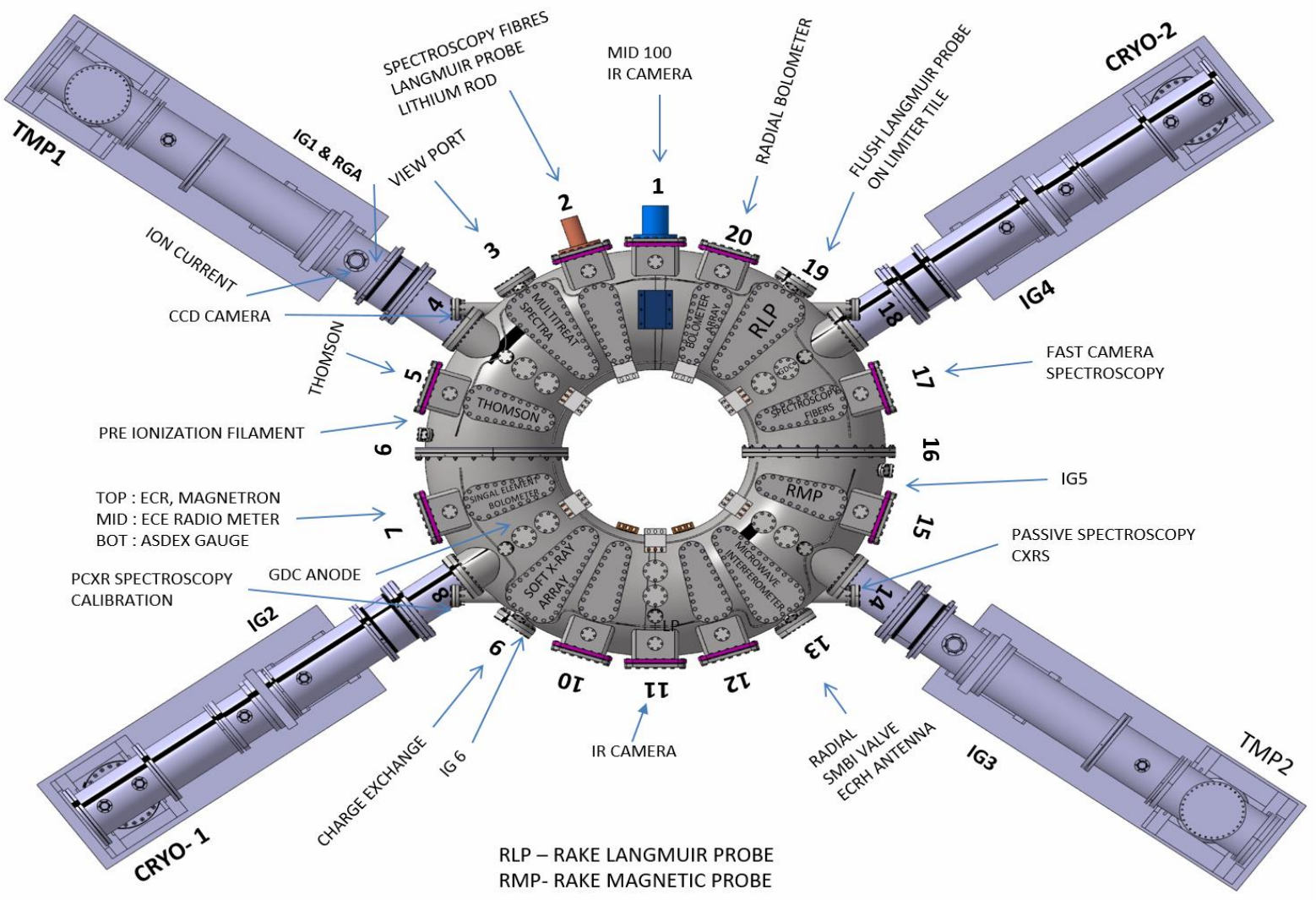
Frequency: 20 -30 MHZ; Power: 500 kW; 2 Strap Antenna

PAM Parameters	Values
Frequency	3.7 GHz
Maximum power	250 kW
Number of modules in the toroidal / poloidal directions	2 / 3

[Poster by Yogesh Jain et al, FIP/P3-53]

New Inclusions in ADITYA – U Tokamak (Continued)

Diagnostics Installed



Magnetic Probes ~ 70

Langmuir Probes ~ 60

Spectroscopy:

Visible, VUV, IR, Imaging: 2

Soft X-ray Arrays: 2

Hard X-ray detectors: 3

Microwave:

Interferometer: 6 channel

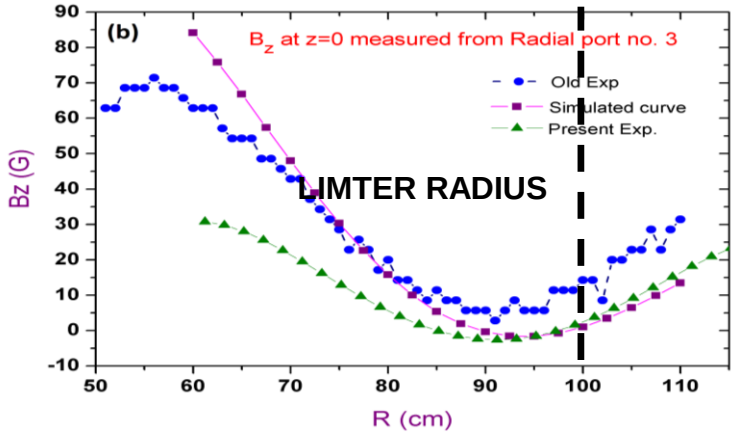
Reflectometer: 1 Channel

Bolometer: 2 Arrays

ECE: 12 channel

[Suman Aich et al, EX/P4-31]

Operation Preparation before 1st Plasma in ADITYA – U



Error Field

$$\frac{B_{err}}{B_T} \sim 5 - 7 \times 10^{-4}$$

(nearly ½ to 1/3 of the error-field values prevailing in ADITYA)

Wall Conditioning

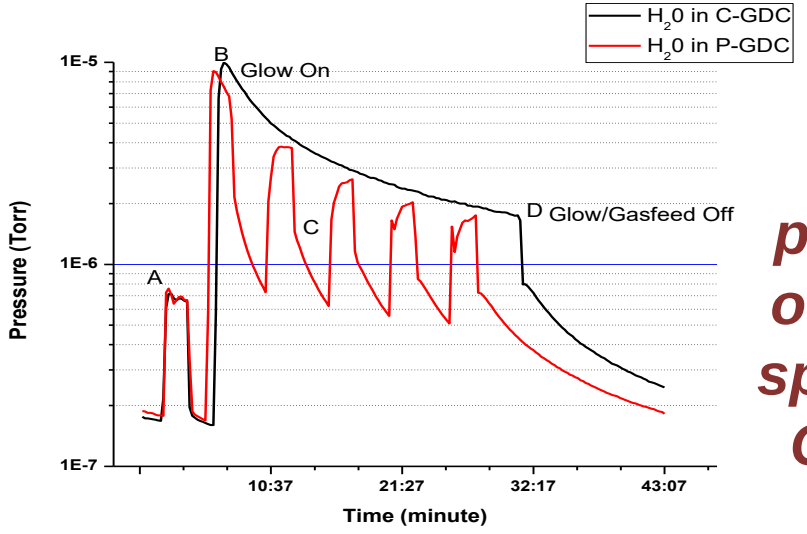
Novel (pulsed) H_2 GDC for long hours

Periodic discharges + ECR plasma

Vessel Baking~130^0 C

Reduced Retention of Hydrogen in Limiters using Pulsed-GDC

[Poster by K.A. Jadeja et al, FIP/P3-64]

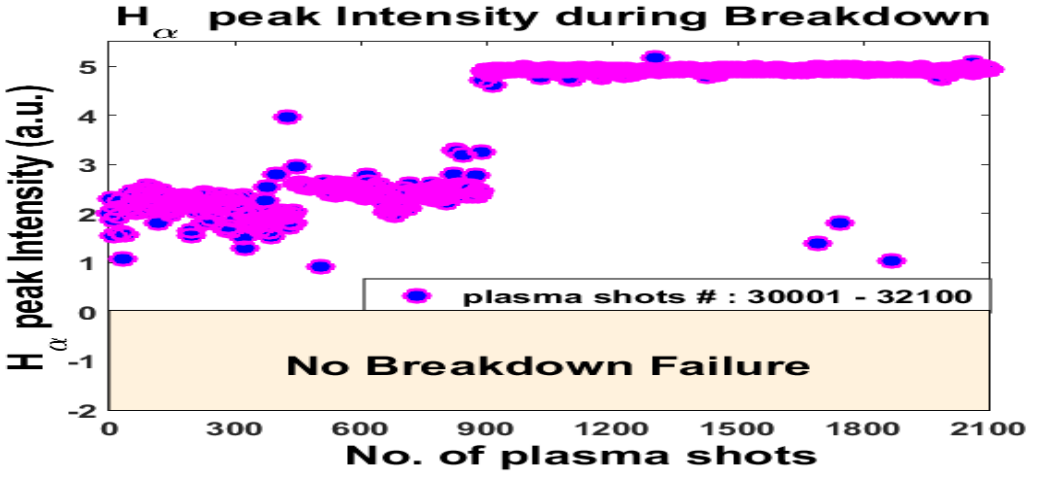


Significant reduction in partial pressure of various mass species (H_2, H_2O, CO, N_2 and O_2)

Removal of water vapour by P-GDC and C-GDC

RESULTS

Base pressure ~ 9 x 10^{-9} Torr

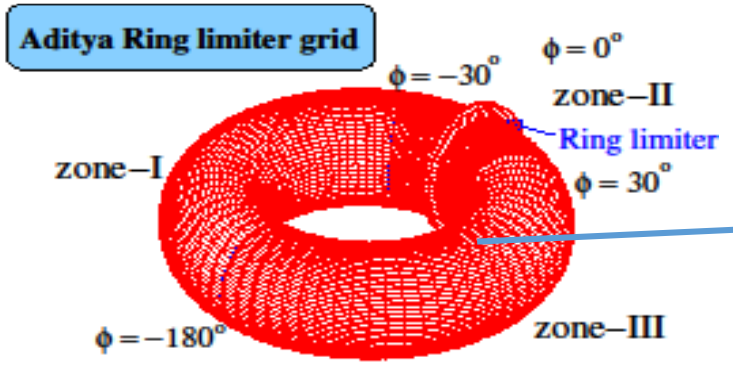


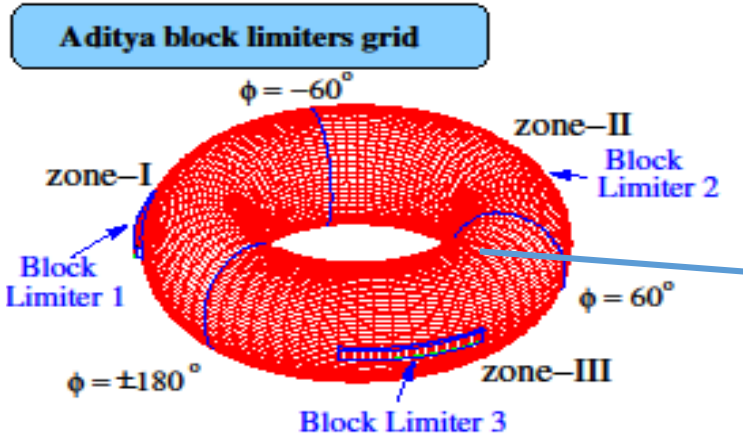
Breakdown obtained in every discharge without a single failure

Comparison of Recycling fluxes in ADITYA and ADITYA-U

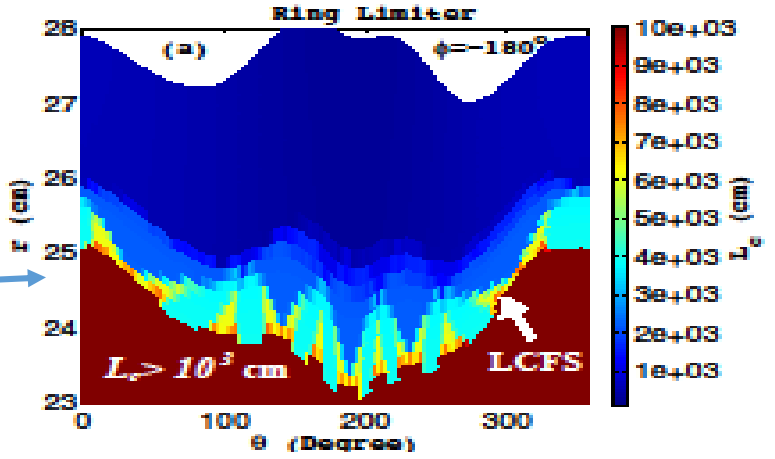
3D Simulation using EMC3-EIRENE Model

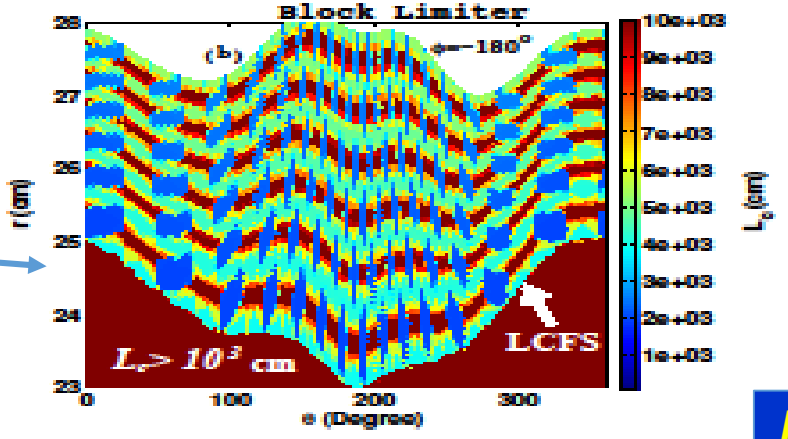
3D Grids for Ring Limiter and 3 Symmetric Block Limiters





Connection length (L_C) in SOL



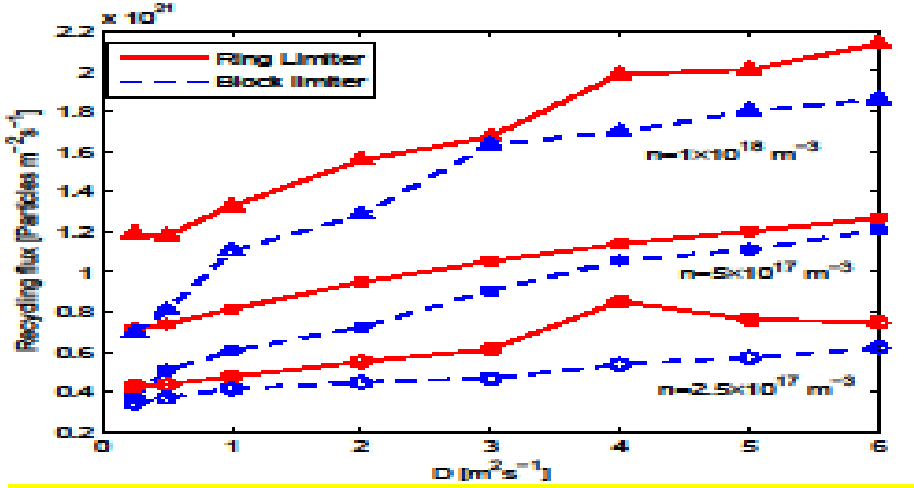


[Sahoo et al, Phys. Plasmas, 24, 082505 (2017)]

Recycling flux

ADITYA (Poloidal ring limiter) : HIGH

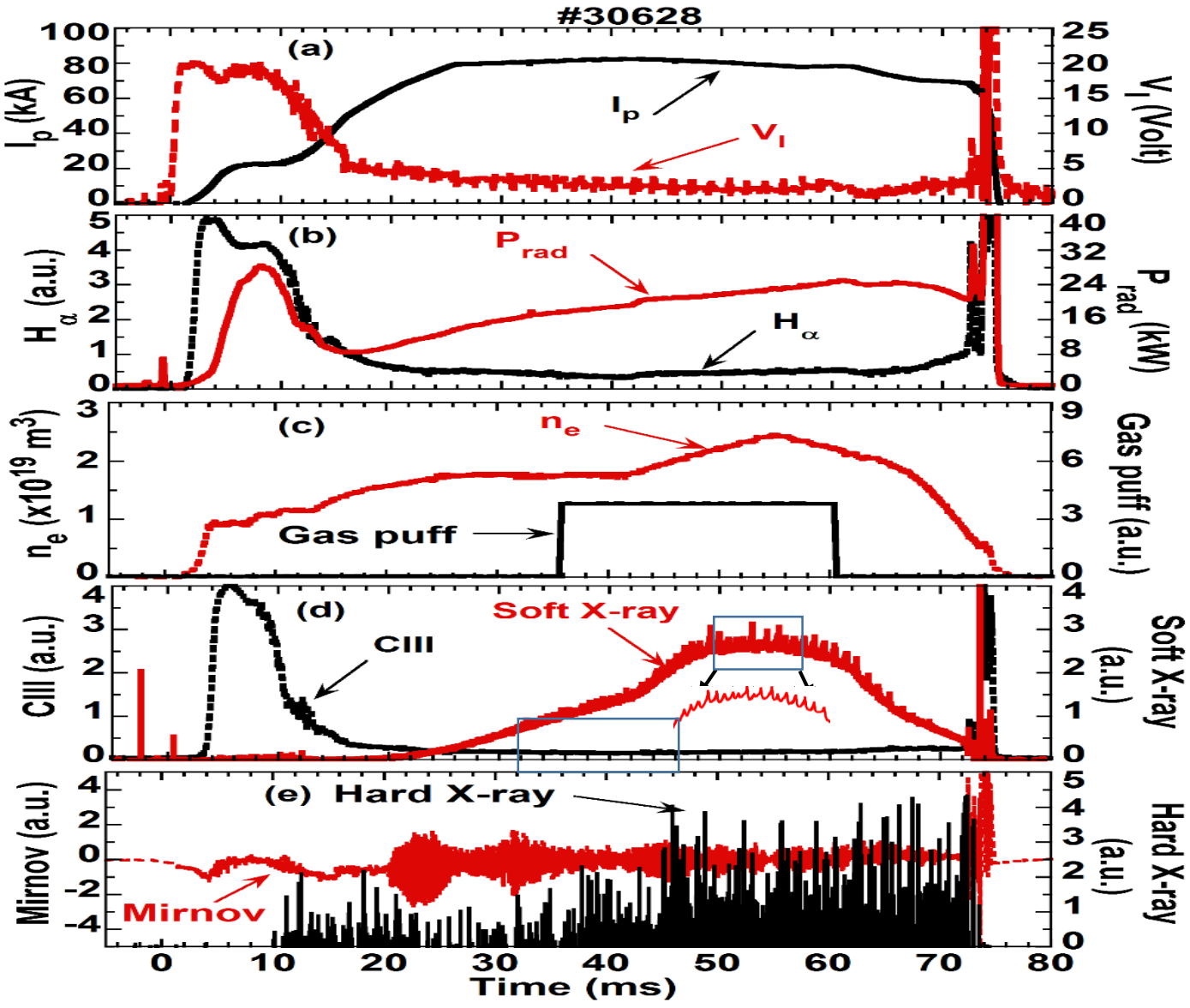
ADITYA-U (Toroidal Belt Limiter) : LOW



LOW RECYCLING OBSERVED in ADITYA-U DISCHARGES

[Poster by B. Sahoo et al, TH/P7-9]
[Poster by D. Sharma et al, TH/P7-6]

Typical Initial Discharges of ADITYA-U



Circular Plasma OPERATION with Toroidal belt limiter STARTED in : Dec. 2016

Plasma Current ~ 80 – 90 kA

Discharge Duration ~ 70 – 80 ms

Chord averaged density ~ 2.5 x 10^{19} m^{-3}

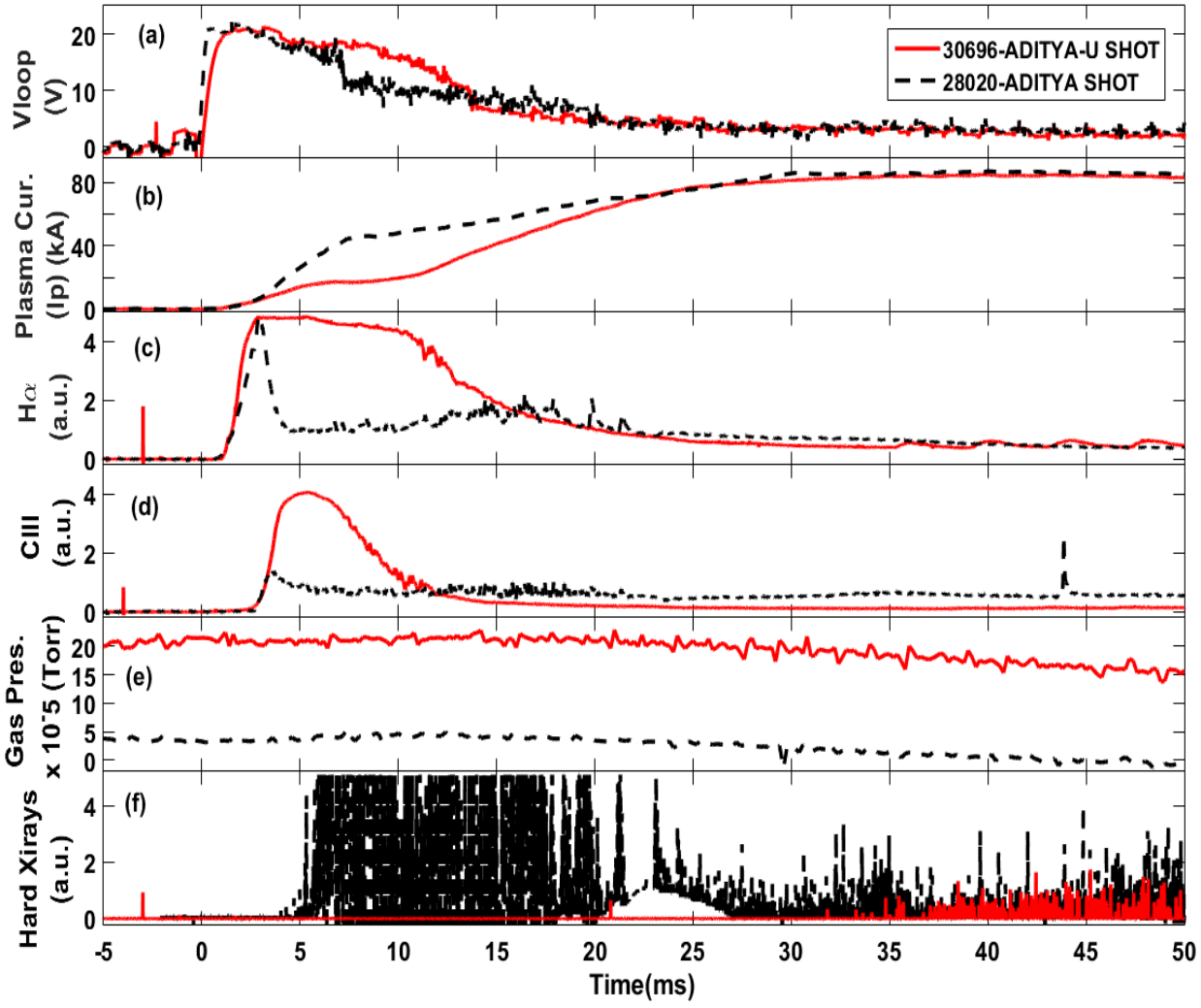
Electron Temperature ~ 250 eV

[R.L. Tanna et al, 2018 Plasma Sci. Technol. 20 074002]

Comparison of Discharge initiation in ADITYA and ADITYA-U

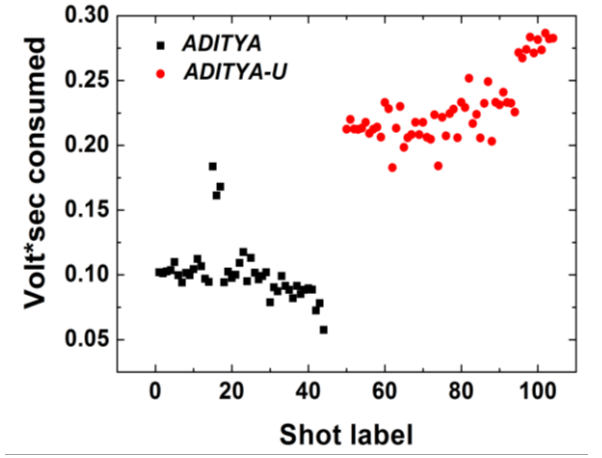
ADITYA (poloidal ring limiter)
ADITYA-U (toroidal ring limiter)

Due to increased graphite surface area in ADITYA-U (~5 times)



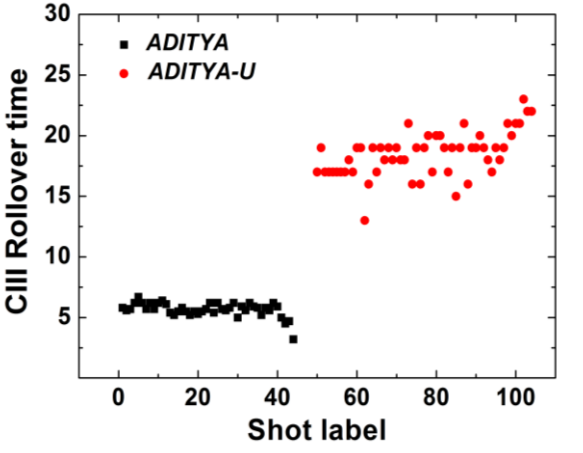
More (Twice) Volt-sec required for Burn-through in ADITYA-U

Initial current rise rate reduces by half in ADITYA-U



Carbon roll over time increases by factor of 2 in ADITYA-U

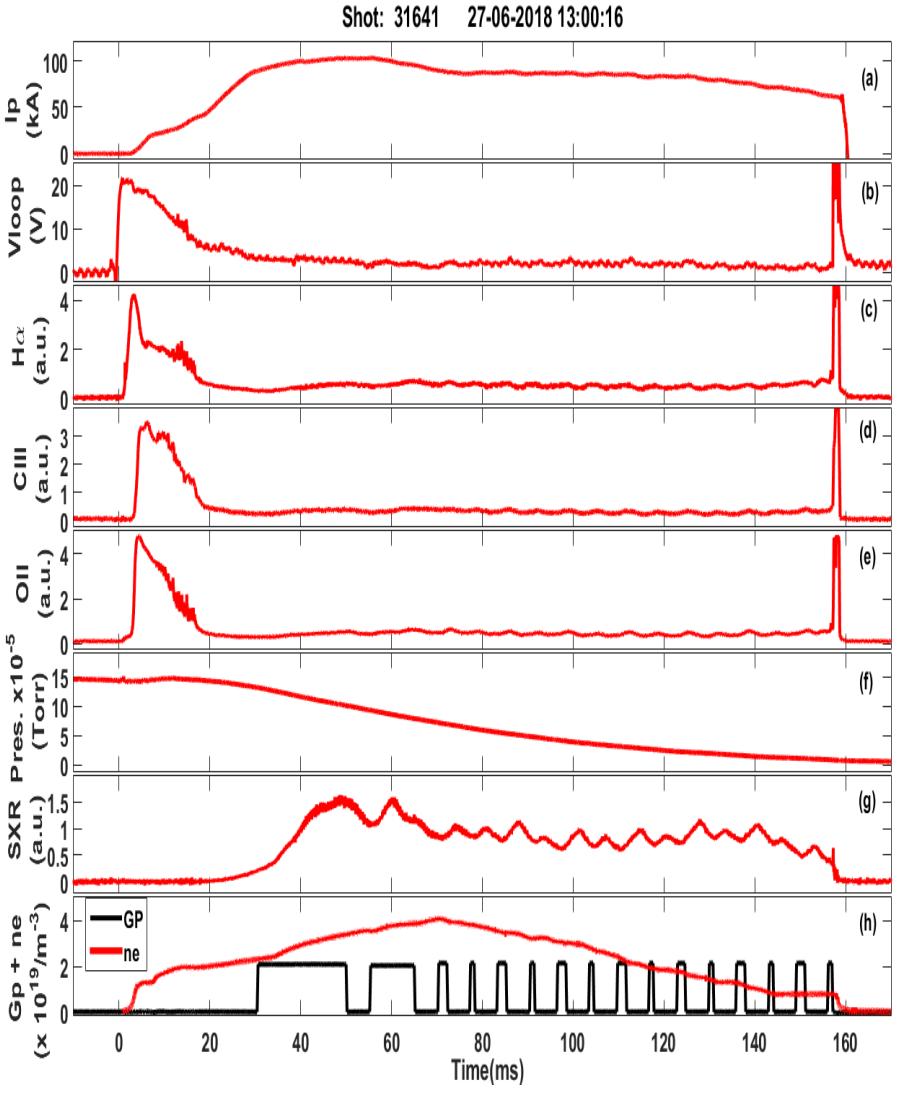
High fill-pressure is required in ADITYA-U

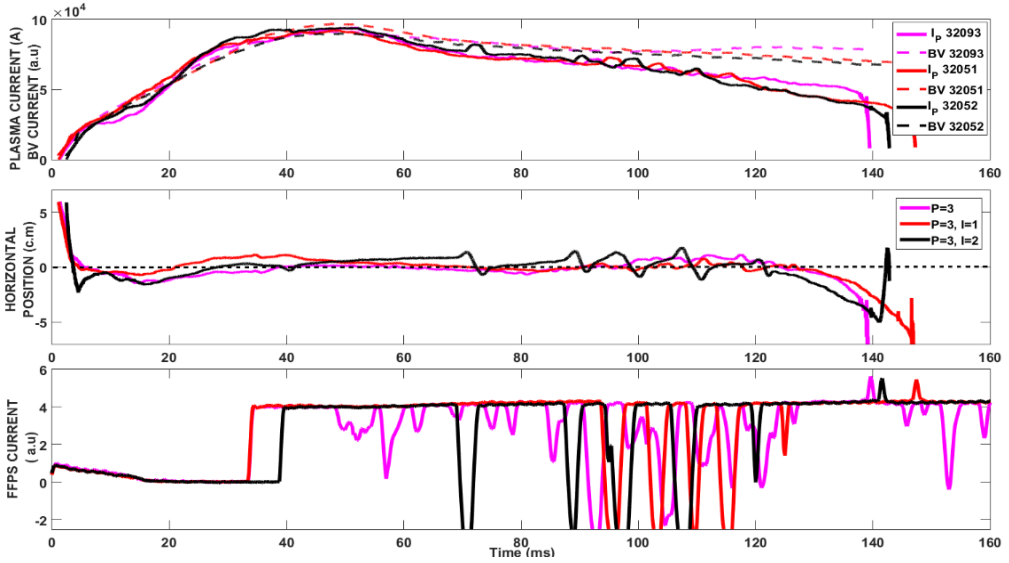


Break-down generated Runaway electron eliminated in ADITYA-U

Regular Discharges of ADITYA-U

ADITYA -U Discharge # 31641

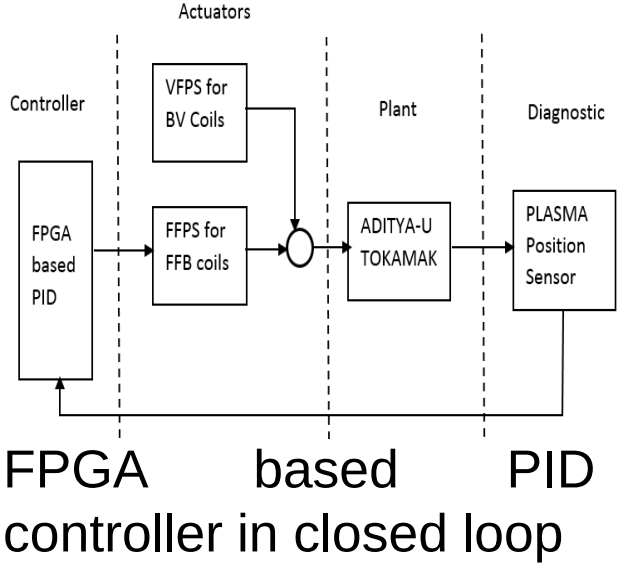




Plasma Shape	Circular
Toroidal Field	1.35 T
Plasma Current	~ 100 – 135 kA
Plasma Duration	~ 150 - 190 ms
Electron Density	1 - 4.0 x 10^{19} m^{-3}
Electron Temp.	350 eV ± 30%
Ion Temp	140 eV ± 30%

PLASMA CONTROL INCLUDES

1. Real Time Plasma Position Control



FPGA based PID controller in closed loop

[Poster by R. Kumar et al, FIP/P3-58]

2. Auto Gas-feed Control

Experiments in ADITYA Upgrade Tokamak

Runaway Electrons:

✓ Generation, Transport, Mitigation using SMBI and Gas-puff etc.

MHD studies:

✓ Modulation of Frequencies of MHD modes using multiple periodic gas puffs

✓ Presence and Absence of Harmonics of MHD modes

Radiative Improved Modes using Neon gas puff:

Current Filaments during Disruptions:

Neutral Particle Penetration:

✓ Radial profiles of Neutrals

Experiments in ADITYA Upgrade Tokamak

Runaway Electrons:

✓ Generation, Transport, Mitigation using SMBI and Gas-puff etc.

MHD studies:

✓ Modulation of Frequencies of MHD modes using multiple periodic gas puffs

✓ Presence and Absence of Harmonics of MHD modes

Radiative Improved Modes using Ne gas puff:

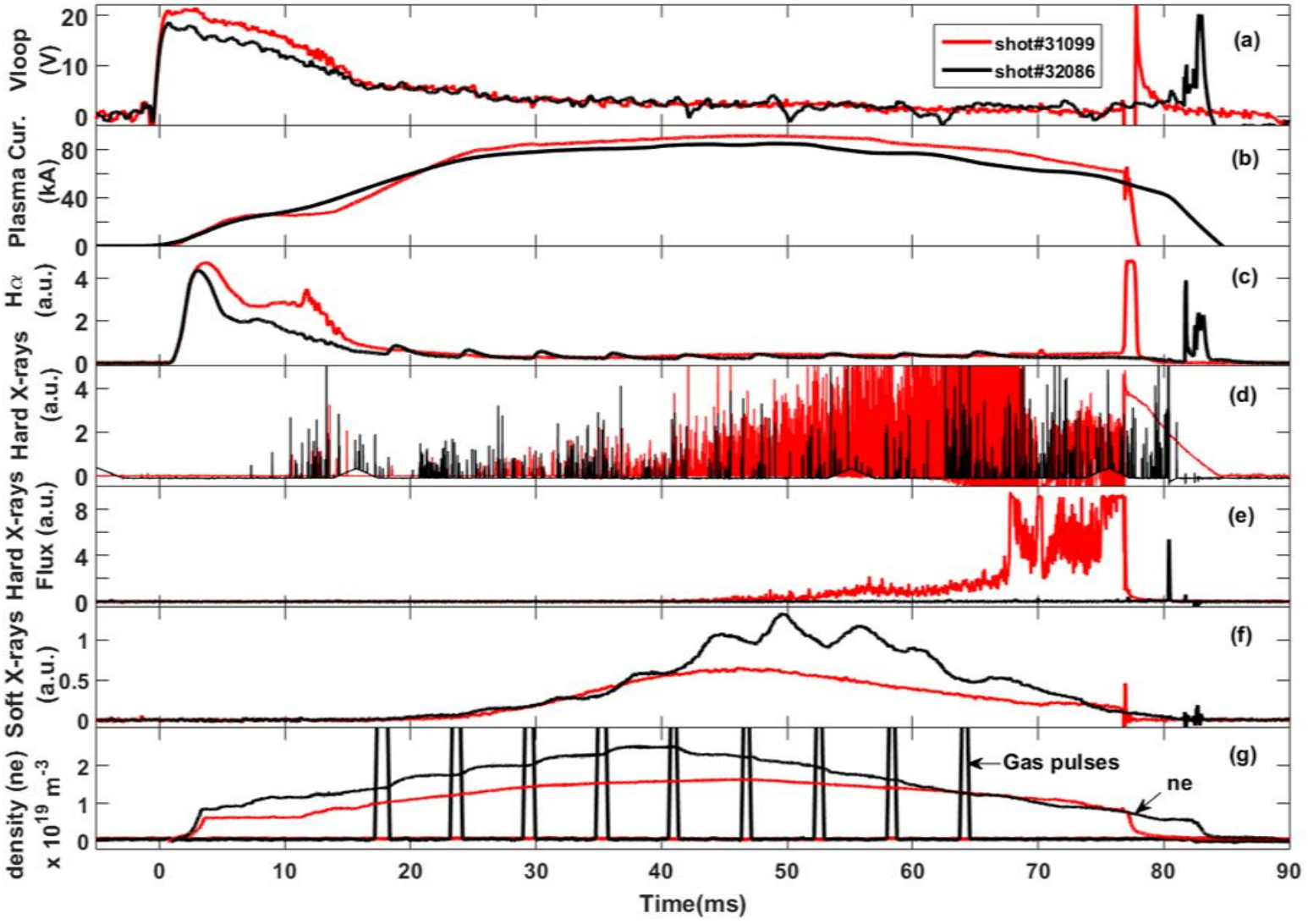
Current Filaments during Disruptions:

Neutral Particle Penetration:

✓ Radial profiles of Neutrals

Operational control over RE content in ADITYA-U

ADITYA-U discharges (#31099, Black) and (#32086, Red)



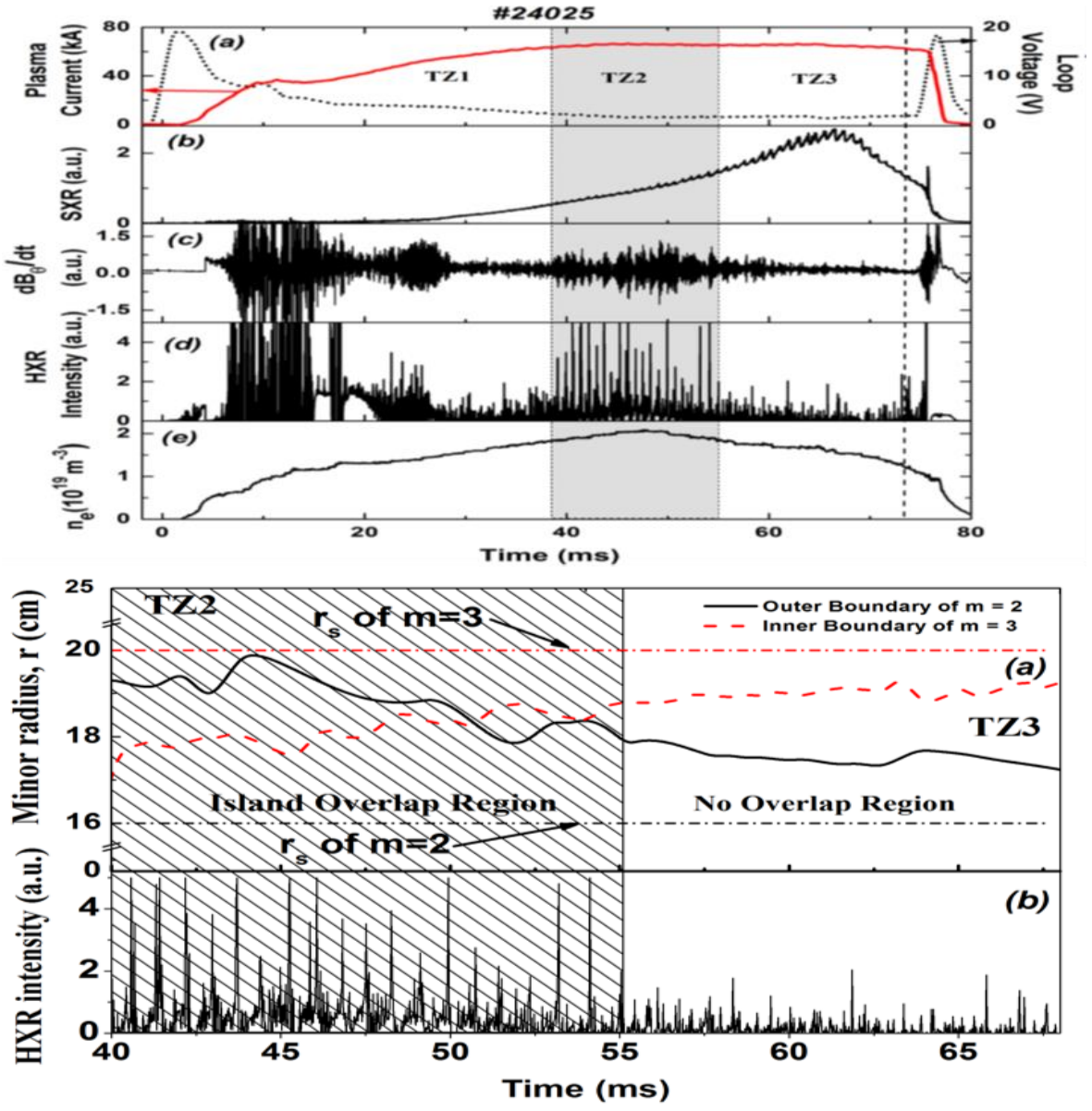
Discharges with and without REs

Significant RE flux when the Chord averaged density < 1.5 x 10^{19} m^{-3} (RED)

Significant reduction in RE flux when the Chord averaged density > 2.0 x 10^{19} m^{-3} (BLACK)

✓ Limiter hard X-Rays detected using NaI (3 inch diameter) lead shielded scintillator detector

Sawteeth generated REs and their transport



Correlated HXR bursts with each sawteeth crash

suggests that sawtooth crash generates REs

$E_{swc} \sim 20\ V\ m^{-1} > E_D \sim 16\ V\ m^{-1}$

Induced electric field due to sawtooth crash > critical electric field required for thermal electrons to runway.

Overlap of m = 2 and m = 3 islands facilitates faster RE loss

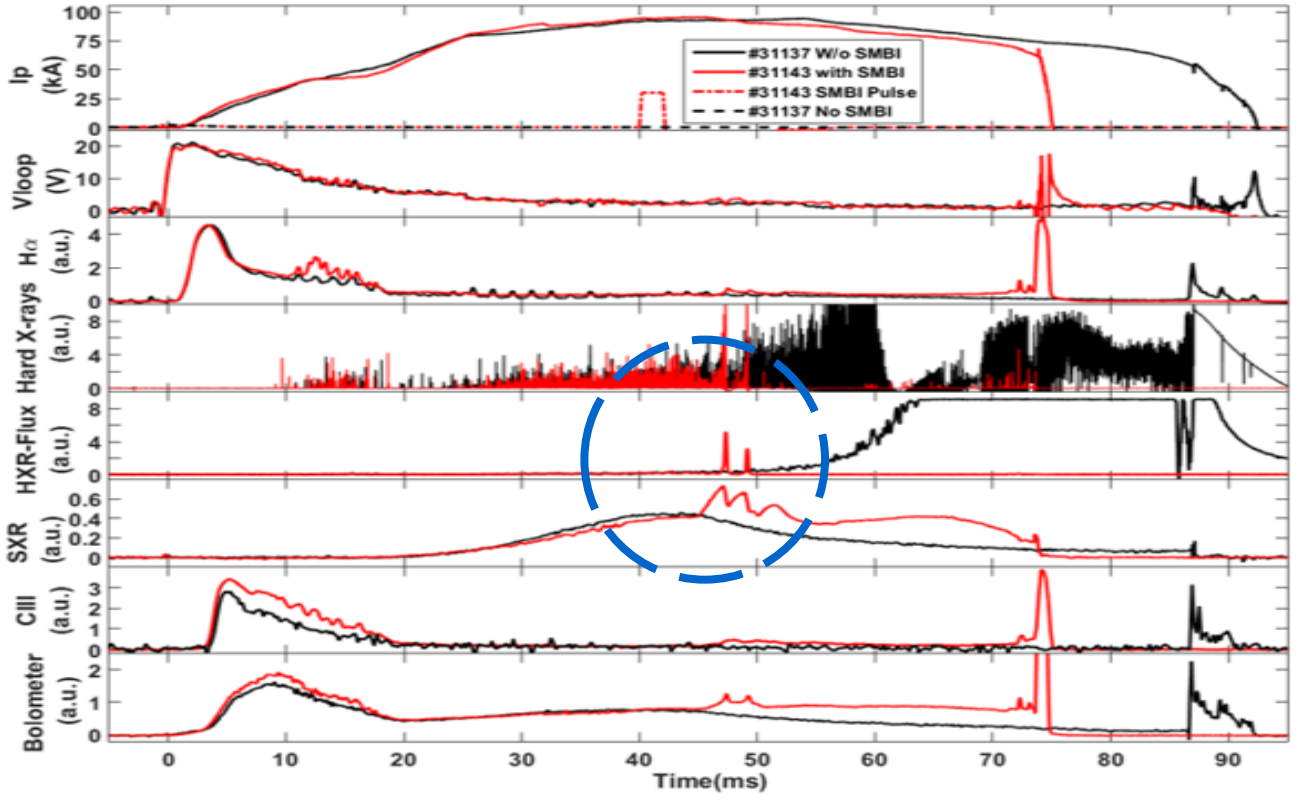
Islands with good surfaces in between delay the RE loss.

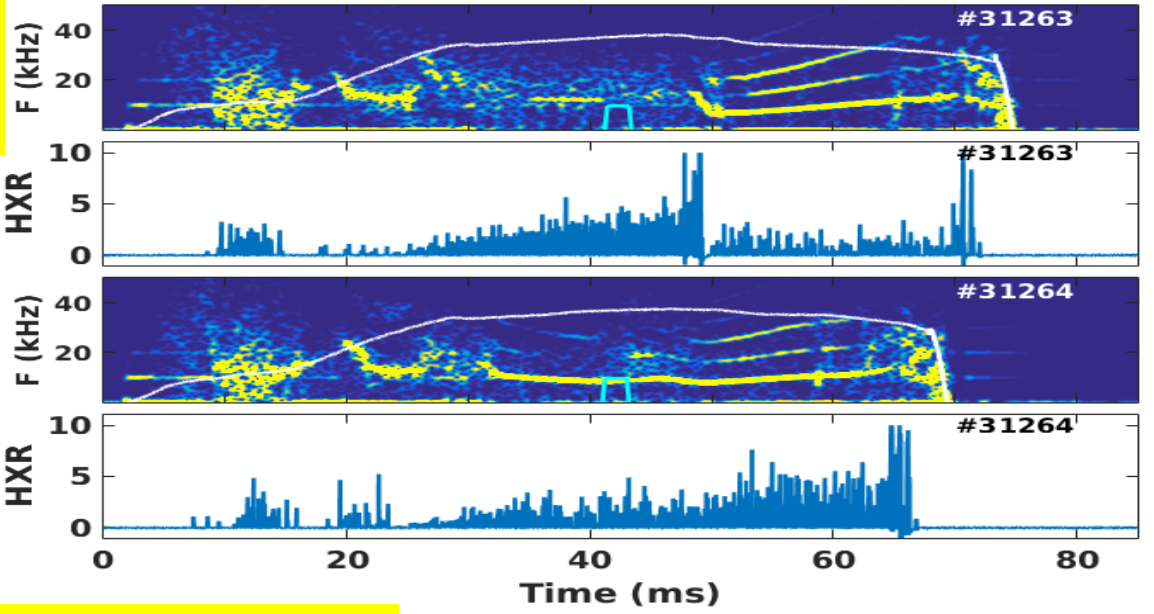
[Harshita Raj et al 2018 Nucl. Fusion 58 076004]

Runaway Electrons mitigation by SMBI in ADITYA-U

✓ *To enable deep neutral penetration inside the plasma*

✓ *A Laval nozzle of throat diameter 0.25 mm*





Strong correlation between ⟹ **MHD mode rotation frequency and RE reduction**

Higher the Reduction in mode rotation ⟹ **More RE flux extraction**

Interestingly, very little dependence on MHD amplitude

Significant reduction in the RE population

~5% decrease in Ip seen following the SMBI pulse

[Poster by S. Banerjee et al, EX /P4-4]

Experiments in ADITYA Upgrade Tokamak

Runaway Electrons:

✓ Generation, Transport, Mitigation using SMBI and Gas-puff etc.

MHD studies:

✓ Modulation of Frequencies of MHD modes using multiple periodic gas puffs

✓ Presence and Absence of Harmonics of MHD modes

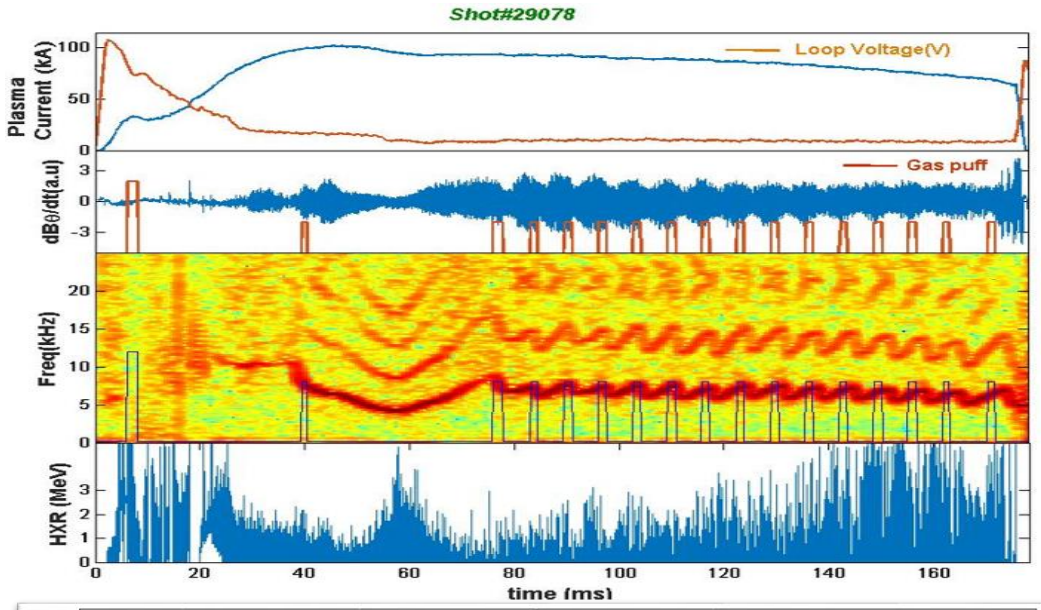
Radiative Improved Modes using Ne gas puff:

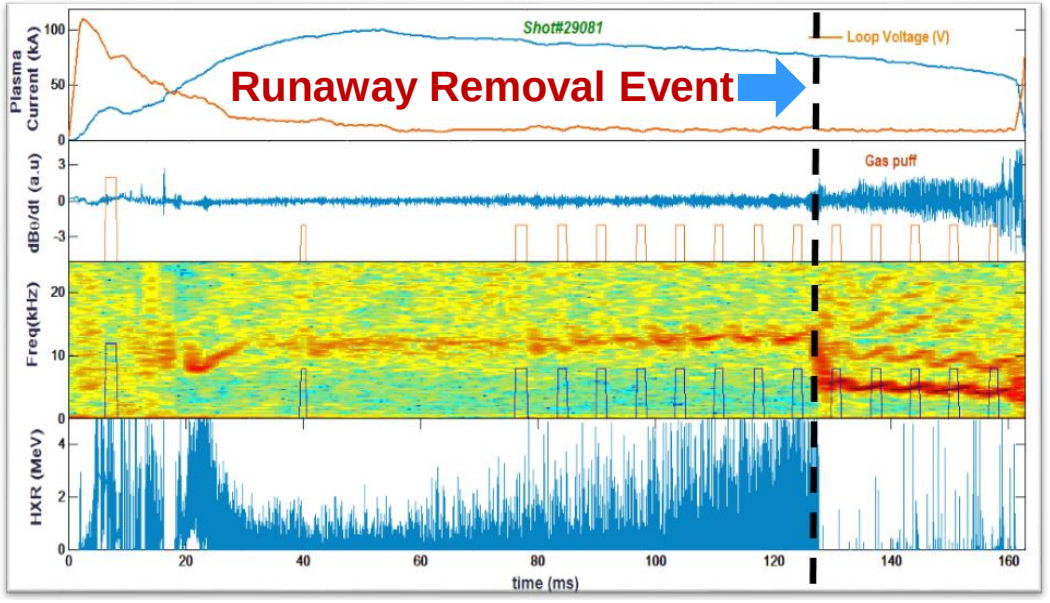
Current Filaments during Disruptions:

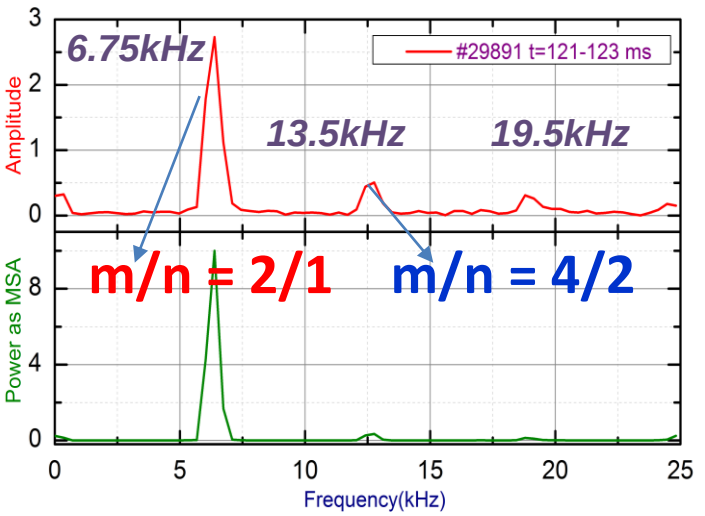
Neutral Particle Penetration:

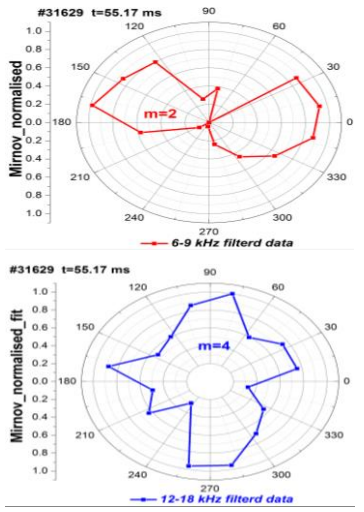
✓ Radial profiles of Neutrals

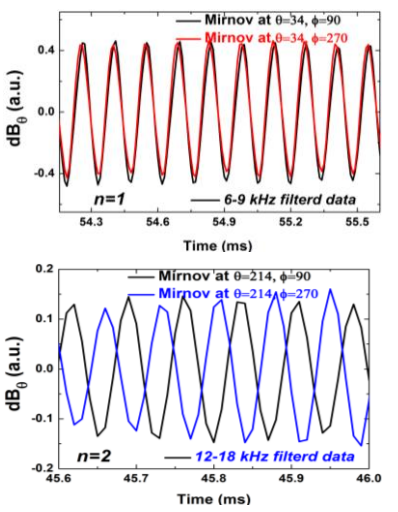
Multiple Harmonics of Drift-Tearing Modes











Integer multiple of Fundamental 2/1 mode frequency

POLOIDAL MIRNOVS (16)

TOROIDAL MIRNOVS (2) 180^0 Apart

Further Investigation revealed

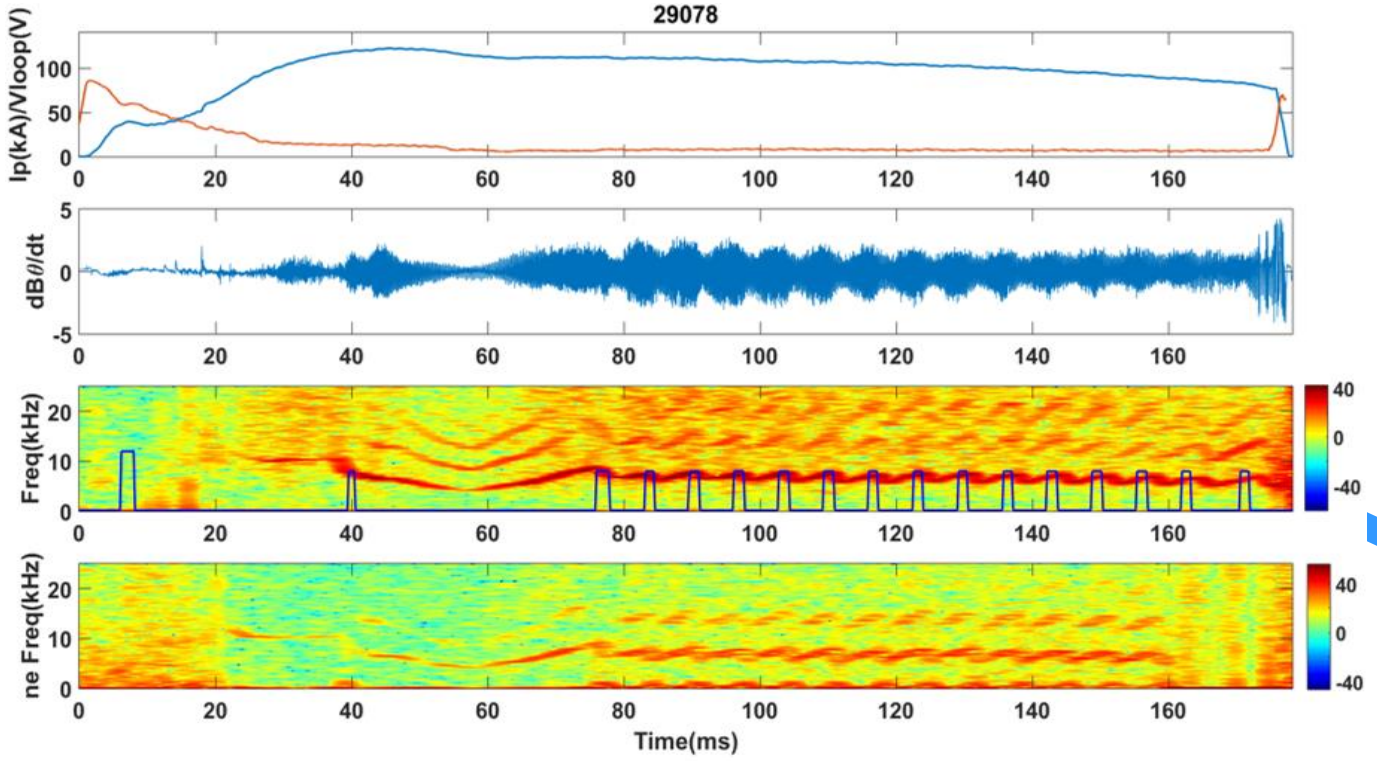
LOW RE content HARMONICS

HIGH RE content NO HARMONICS

Current Profile / Radial Electric Field modification due to sudden RE loss may be the cause

[Talk by Harshita Raj, EX/11-1]

Controlling MHD Mode Rotation frequency by Periodic Gas Puffs



MHD mode rotation frequency

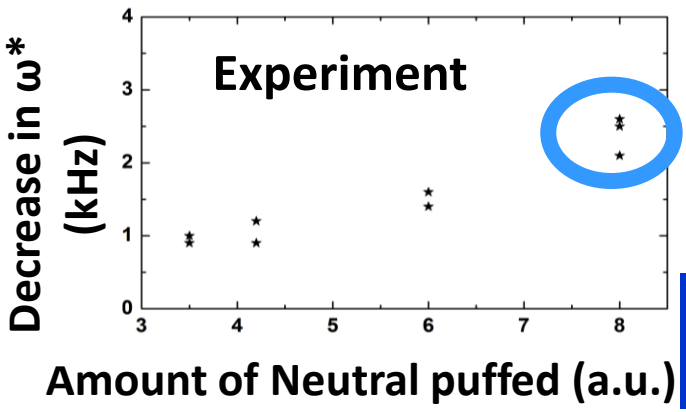
$$\omega^* = k_y T_e / e B L_n$$

Application of gas-puff in the edge leads to….

$T_e \downarrow$ $L_n \uparrow$ $\omega^* \downarrow$

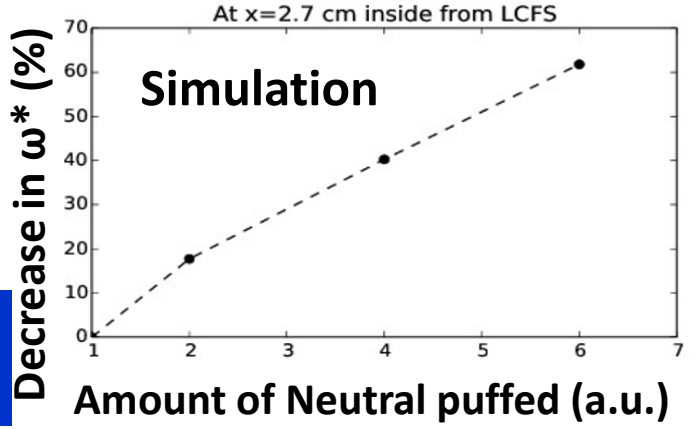
Decrease in MHD mode rotation frequency

Application of periodic gas-puffs lead to periodic reduction in MHD mode rotation frequency



40 - 50 % reduction with ~ 1×10^{18} nos. of particles

Poster by N. Bisai et al, TH/P6-23]



Simulating the ω* variation with neutral injection in the edge using BOUT++ code

Confirms the decrease in ω* with neutral gas injection

Experiments in ADITYA Upgrade Tokamak

Runaway Electrons:

✓ Generation, Transport, Mitigation using SMBI and Gas-puff etc.

MHD studies:

✓ Modulation of Frequencies of MHD modes using multiple periodic gas puffs

✓ Presence and Absence of Harmonics of MHD modes

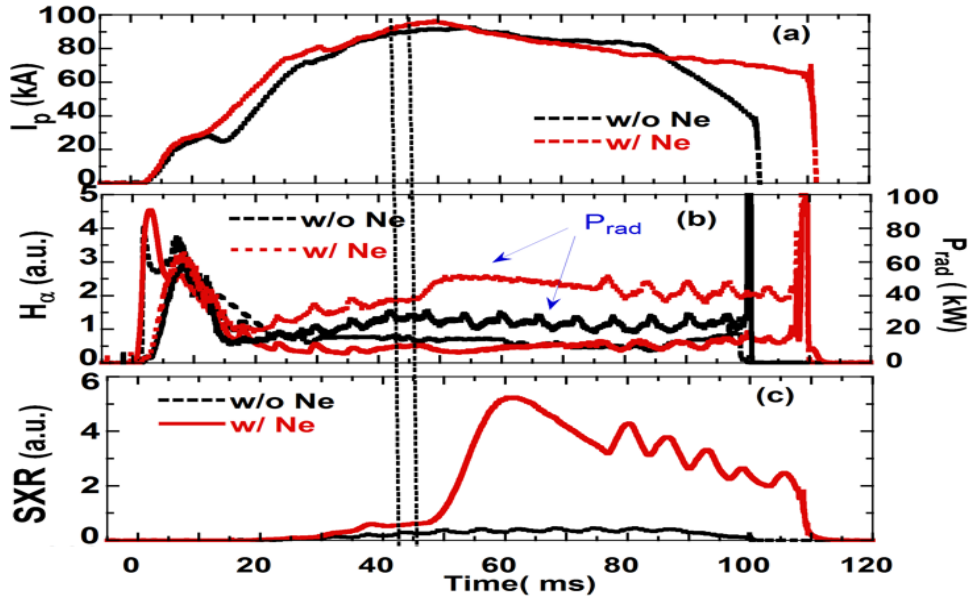
Radiative Improved Modes using Ne gas puff:

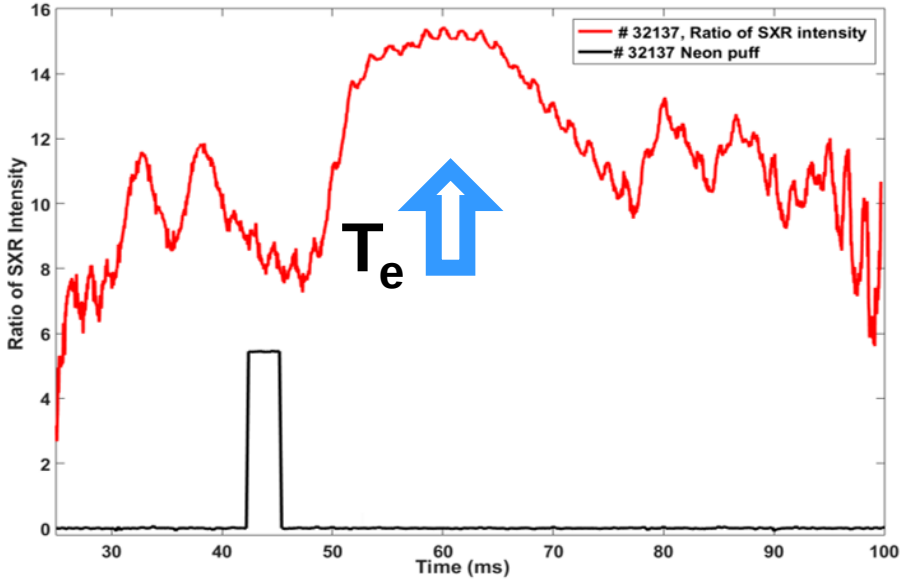
Current Filaments during Disruptions:

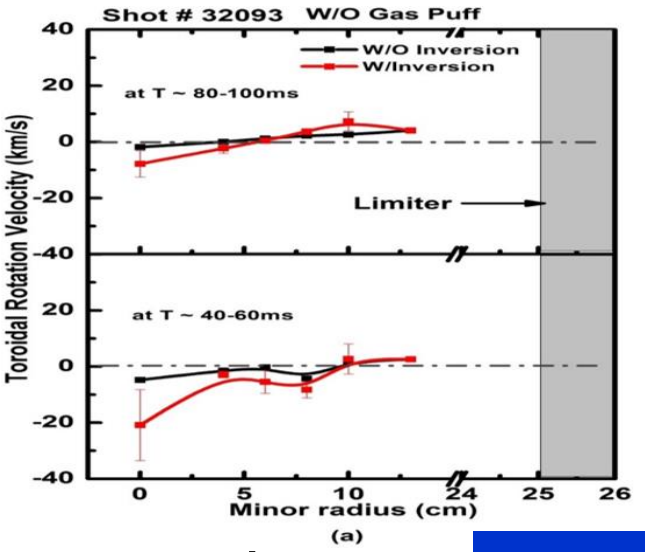
Neutral Particle Penetration:

✓ Radial profiles of Neutrals

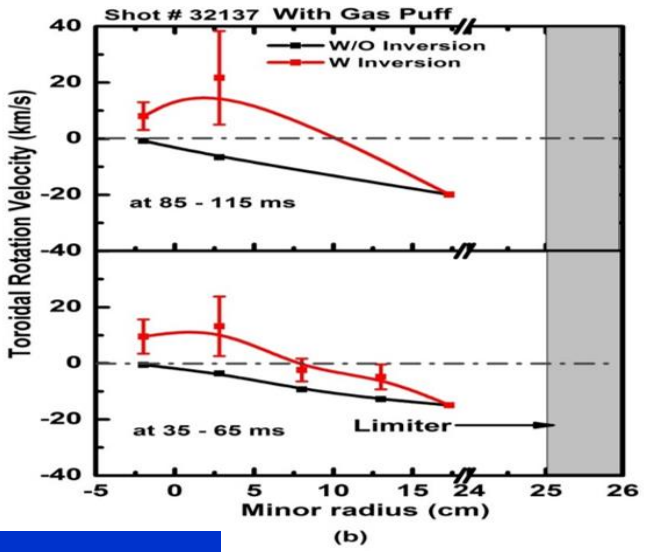
Radiative Improved Modes in ADITYA-U







V_Φ w/o Neon (Counter)



V_Φ w/o Neon (Counter)

[Poster by G. Shukla, EX/ P4-10]

APPROPRIATE AMOUNT OF Ne PUFF LEADS TO

Increase in core temperature and density; Signature of Improved Confinement *[Poster by M.B. Chowdhuri EX /P4-5]*

Most Interestingly the ***direction of toroidal core plasma rotation reverses from Counter-current to Co-current direction***

Transition at lower edge radiation (~50 %) in ADITYA-U compared to other tokamaks. (Under investigation)

Experiments in ADITYA Upgrade Tokamak

Runaway Electrons:

✓ Generation, Transport, Mitigation using SMBI and Gas-puff etc.

MHD studies:

✓ Modulation of Frequencies of MHD modes using multiple periodic gas puffs

✓ Presence and Absence of Harmonics of MHD modes

Radiative Improved Modes using Ne gas puff:

Current Filaments during Disruptions:

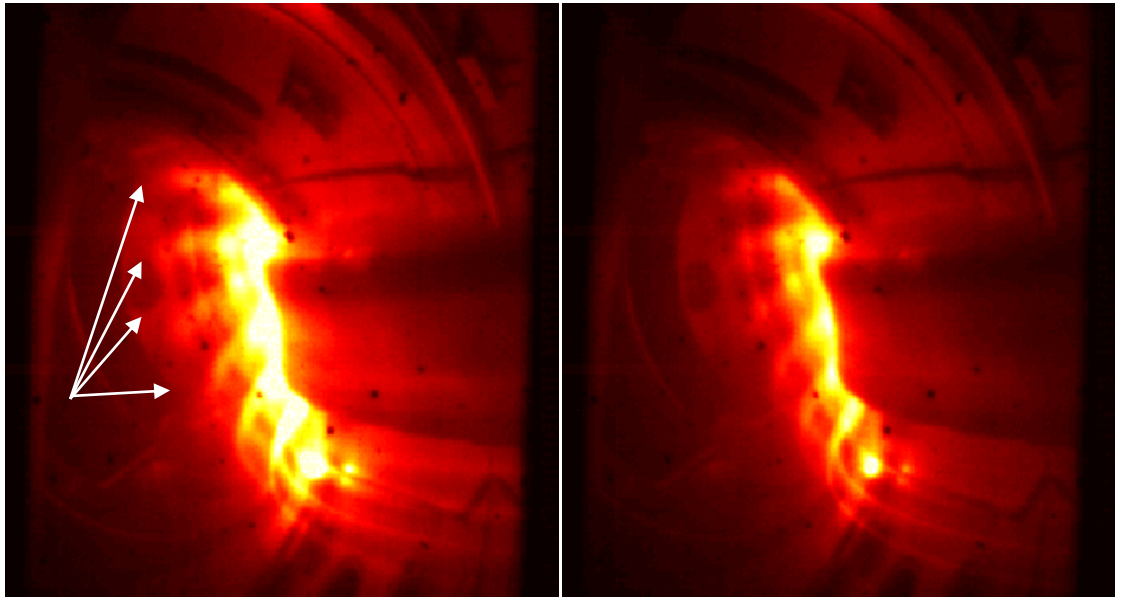
Neutral Particle Penetration:

✓ Radial profiles of Neutrals

Thick filaments during plasma disruption in ADITYA-U

Large number of filaments during Disruption

[Banerjee et al. POP 24 102513 2017]



Fast camera images of shot #30878

Estimation of Number of Filaments

Interchange turbulence in the edge region of tokamak

Poloidal wave number k_y of the mode with highest growth rate is given by:

$$k_{y0} = \left(\frac{\sigma}{D + \nu} \right)^{1/4}$$

With reduced σ *(conductivity)* and sharply increased *D (diffusivity)*,

k_{y0} will be smaller during the quench phase, leading to observation of several filaments

Theory conforms well with experimentally observed number of filaments

[Poster by S. Banerjee et al, EX /P4-4]

Experiments in ADITYA-U

Runaway Electrons:

✓ Generation, Transport, Mitigation using SMBI and Gas-puff etc.

MHD studies:

✓ Modulation of Frequencies of MHD modes using multiple periodic gas puffs
✓ Presence and Absence of Harmonics of MHD modes

Radiative Improved Modes using Ne gas puff:

Current Filaments during Disruptions:

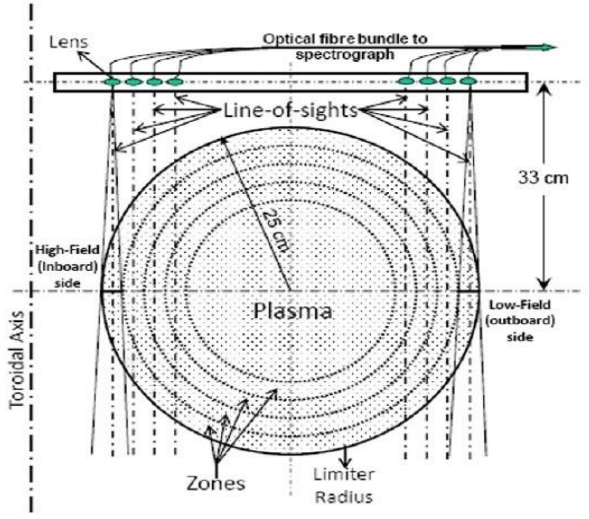
Neutral Particle Penetration:

✓ Radial profiles of Neutrals

Neutral particle penetration using DEGAS2 code

ADITYA and ADITYA -U limiter geometry

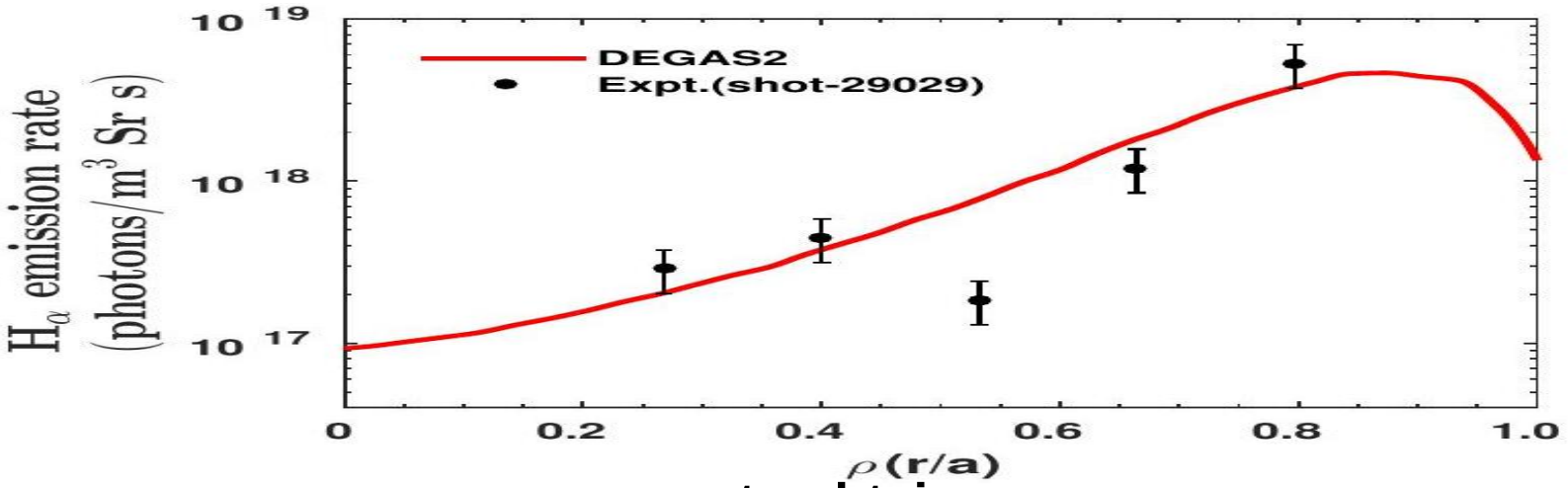
Set-up for measurements of H_α emission profile



Neutral H density ~ 250 times lower at the core than at edge

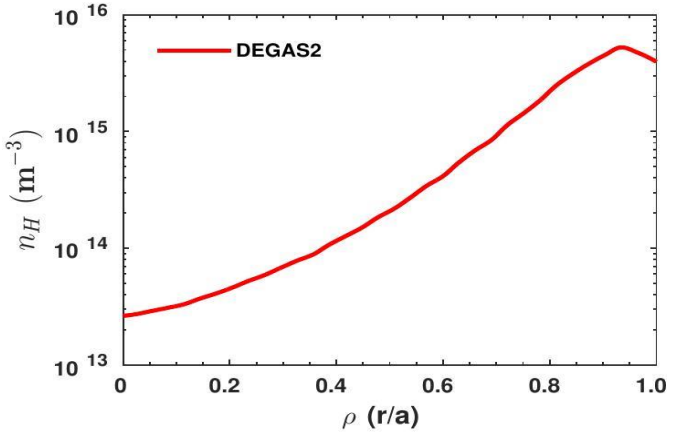
[Poster by Ritu Dey et. al. TH /P8-5]

Measured and Simulated H_α emissivity profiles are matched….

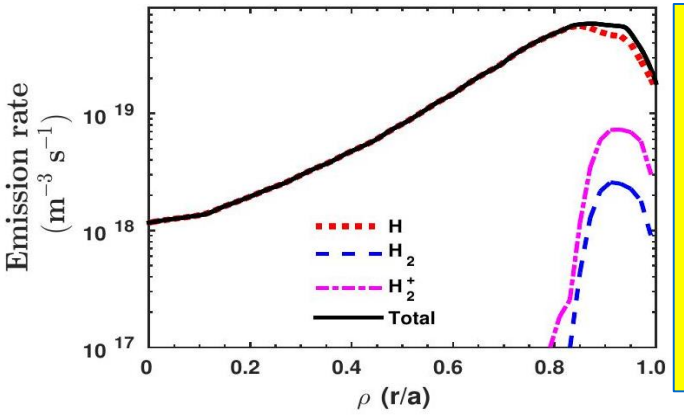


…to obtain

Radial Profile of Neutrals



Atomic and Molecular contribution in H_α emission



Molecules and molecular ions contribute only at the edge region (~4 cm) within limiter

SUMMARY

ADITYA-U tokamak:

- ✓ **The ADITYA-U tokamak is operational from December 2016.**
- ✓ **Upgradation include a new vessel, divertor coils, toroidal limiters etc.**
- ✓ **Improved Error fields facilitates breakdown in more than 2000 discharges without a single failure. Successful development and implementation of real time position control.**
- ✓ **Achieved wider pressure window and significant reduction in runaway electrons (REs)**

Experiments carried out in ADITYA-U:

- ✓ ***Presence of multiple harmonics of drift tearing mode seems to be related to the presence and absence of REs.***
- ✓ ***A novel technique of controlling MHD rotation frequency by varying ω* using periodic gas puffs.***
- ✓ ***Significant reduction of REs by application of SMBI. The reduction depends upon the rotation frequency variation due to SMBI***
- ✓ ***Radiative improved modes with Neon gas injection with ~50 % of edge radiated power. The core toroidal rotation changes sign after the Ne puff.***

Shape Plasma Experiments will commence soon

Thank you!

Acknowledgement: I would like to thank all the Co-authors and contributors from ADITYA –U Team.

Posters from ADITYA-U:

[Poster by Yogesh Jain et al, FIP/P3-53]

[Poster by Suman Aich et al, EX/P4-31]

[Poster by K.A. Jadeja et al, FIP/P3-64]

[Poster by B. Sahoo et al, TH/P7-9]
[Poster by D. Sharma et al, TH/P7-6]

[Poster by R. Kumar et al, FIP/P3-58]

[Poster by S. Banerjee et al, EX/P4-4]

[Talk by Harshita Raj, EX/11-1]

[B. Sahoo et al, Phys. Plasmas, 24, 082505 (2017)]

[R.L. Tanna et al, 2018 Plasma Sci. Technol. 20 074002]

[Harshita Raj et al 2018 Nucl. Fusion 58 076004]

[S. Banerjee et al. POP 24 102513 2017]

[Poster by N. Bisai et al, TH/P6-23]

[Poster by M.B. Chowdhuri EX /P4-5]

[Poster by G. Shukla, EX/ P4-10]

[Poster by Ritu Dey et. al. TH /P8-5]