DEPARTMENT OF ATOMIC ENERGY, GOVERNMENT OF INDIA

INSTITUTE FOR PLASMA RESEARCH, GANDHINAGAR, INDIA

# Overview of Recent Experimental Results from the ADITYA-U Tokamak

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***On behalf of the ADITYA-U Research Team***

# Outline of the Talk

**ADITYA TOKAMAK**
**Limiter Machine**

**Dismantled April 2015**

**Construction Dec 2016**

**ADITYA-U TOKAMAK**
**Divertor Machine**
**(Operational December 2016)**

**Preliminary results presented in FEC 2018**

## Part I: ADITYA Upgrade (ADITYA-U) Operations:

- ✓ Plasma Parameters Enhancement in Circular Plasmas
- ✓ Deuterium Plasma Operation
- ✓ 42 GHz ECR Two Pulses Operation
- ✓ Shaped Plasmas Operation

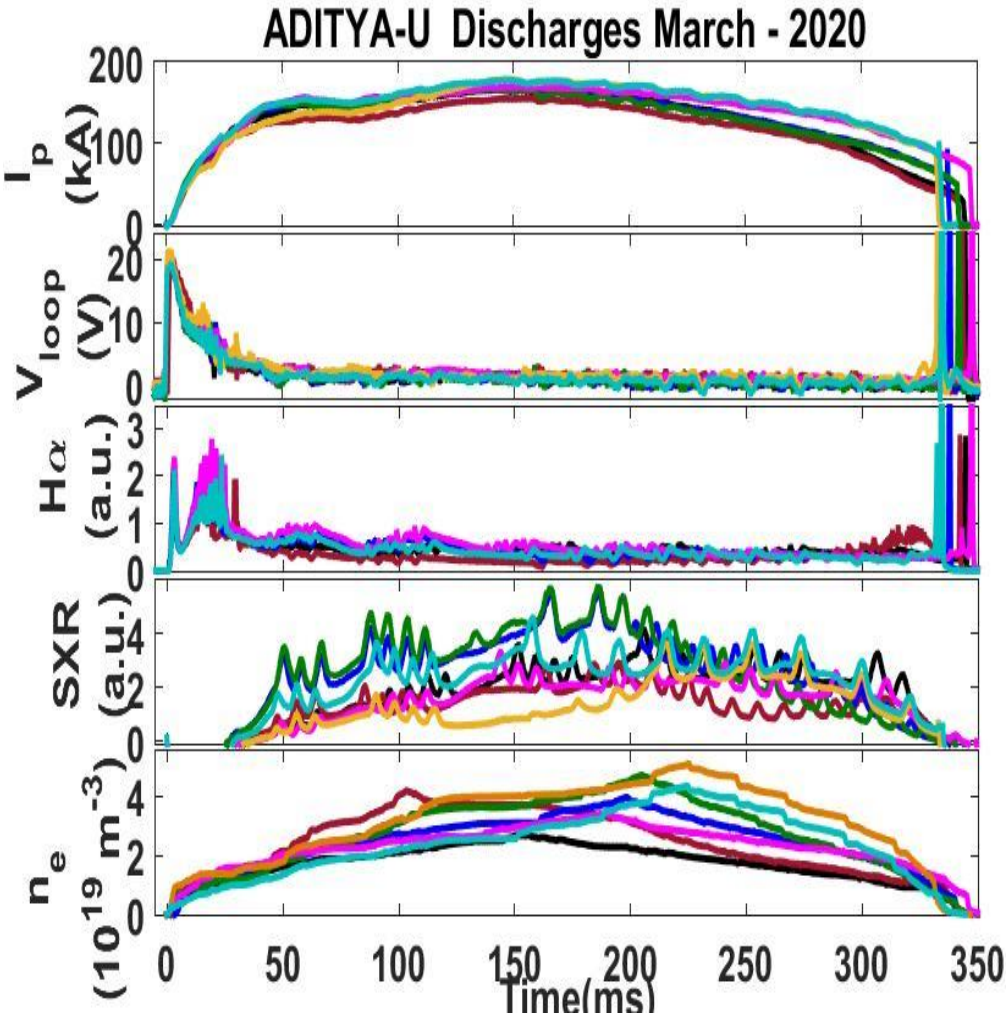
## Part II: Experiments in ADITYA-U Tokamak

- ✓ Inductively driven Pellet Injection for Disruption mitigation
- ✓ Drift Tearing Mode rotation studies through Electrode Biasing
- ✓ Gas-puff induced Cold Pulse Propagation Studies
- ✓ Neon Impurity Seeding Studies
- ✓ Summary

# Introduction to ADITYA-U Tokamak

- ✓ A mid-size tokamak with Divertor Configuration (single & double null)
- ✓ Major Aim: Shaped plasma operation and experiments on runaways, disruption etc.

| Machine and Plasma Parameters | |
|---|---|
| Major radius (R) | 0.75 m |
| Minor radius (a) | 0.25 m |
| Plasma Shape | Circular / Shaped |
| Toroidal Field | 1.3 - 1.5 T |
| Plasma Current | 150 - 213 kA ± 10 % |
| Plasma Duration | ~300 - 400 ms |
| Electron Density | 3 - 5 x $10^{19}$ $m^{-3}$ ±10% |
| Electron Temp. | 250 – 500 eV ± 30% |
| Ion Temp. | ~ 150 eV |
| Elongation | Shaping Attempted! |
| Triangularity | Shaping Attempted! |



# Wall Conditioning Experiments

Graphite content increased in ADITYA-U
--- Toroidal Belt Limiter
--- Divertor Plates etc.

**Optimized the Vessel cleaning and Coatings**

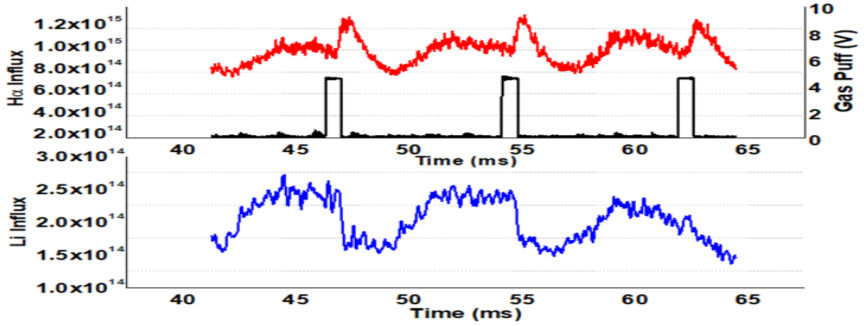
Vessel Cleaning using GDC ---

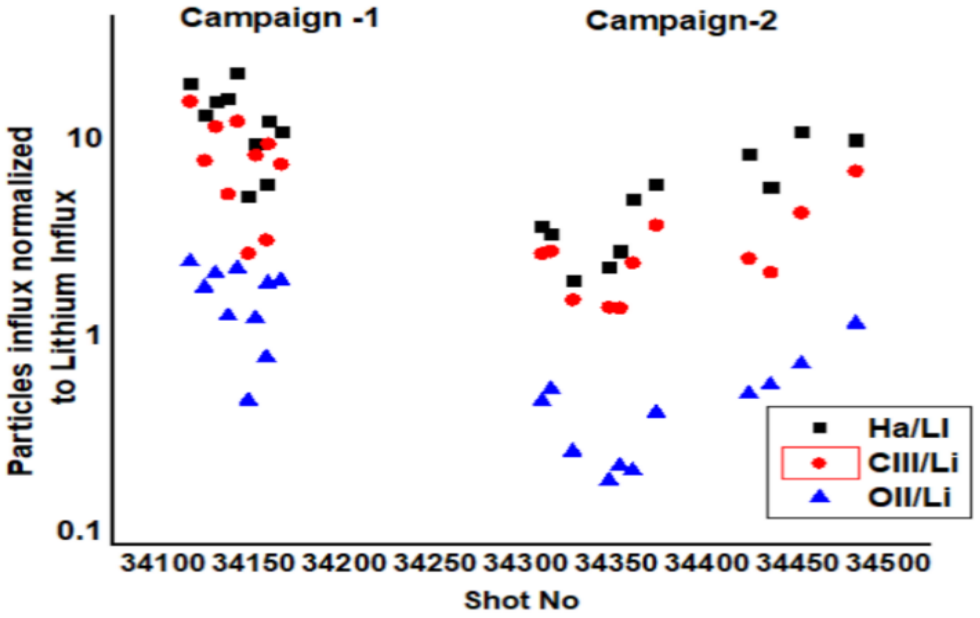
(1) Ar + H2 Mixture for Carbon removal

(2) He for Hydrogen Removal

(3) Pulsed GDC for low gas load on walls

Wall coating --- Lithiumization
✓ Li-rod sputtering
✓ Li-Evaporator --- Works better
✓ Controlled Fuel Injection

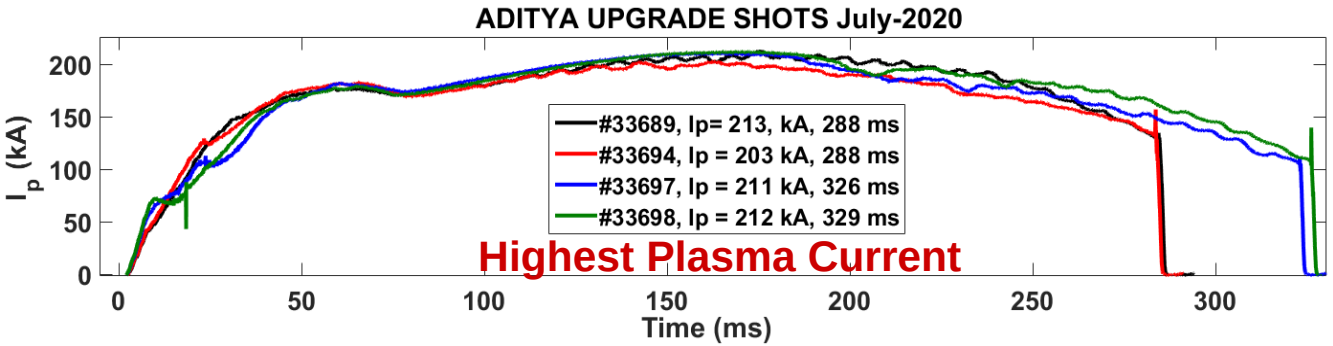


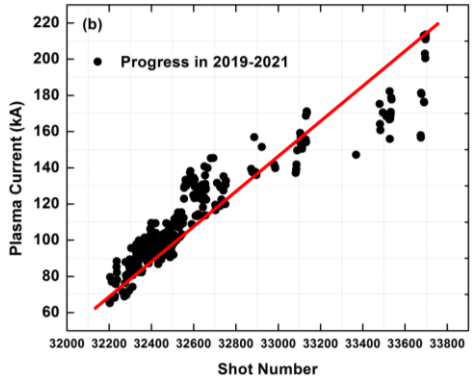




*[Poster by K.A. Jadeja et al, EX/P4, #1210]*

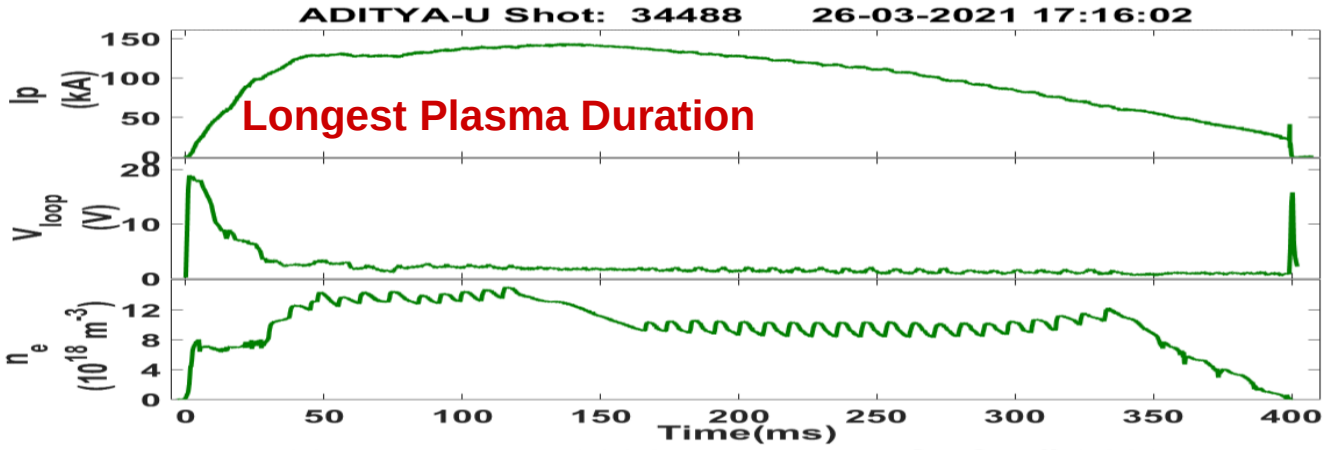
# Discharge Parameters

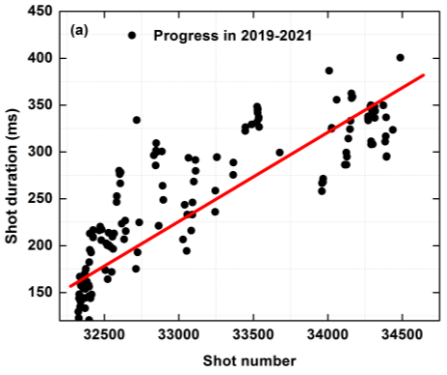
## Circular Plasma Operation with Toroidal Graphite Limiter



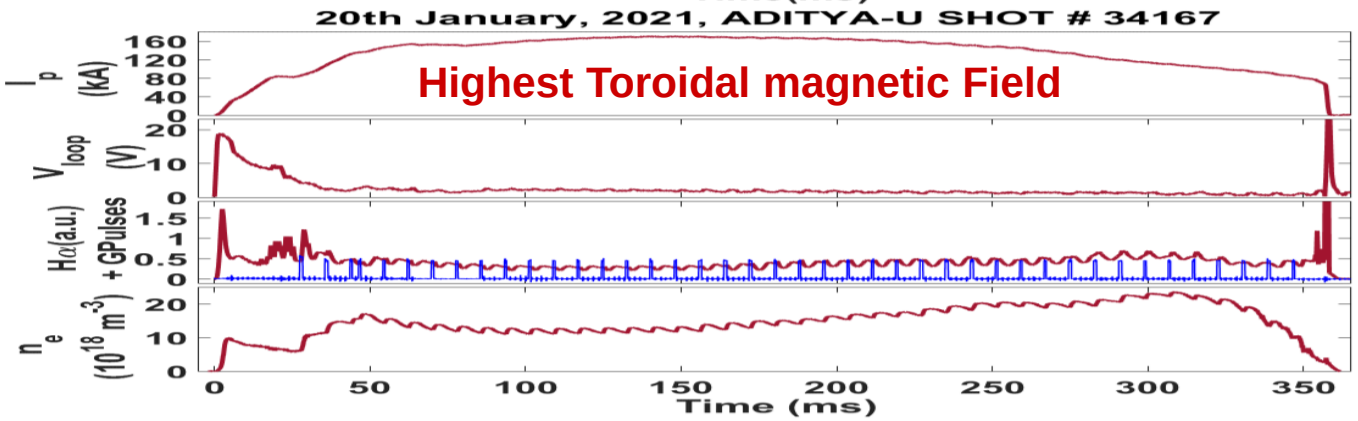




**Max. Plasma Current ~210 kA**



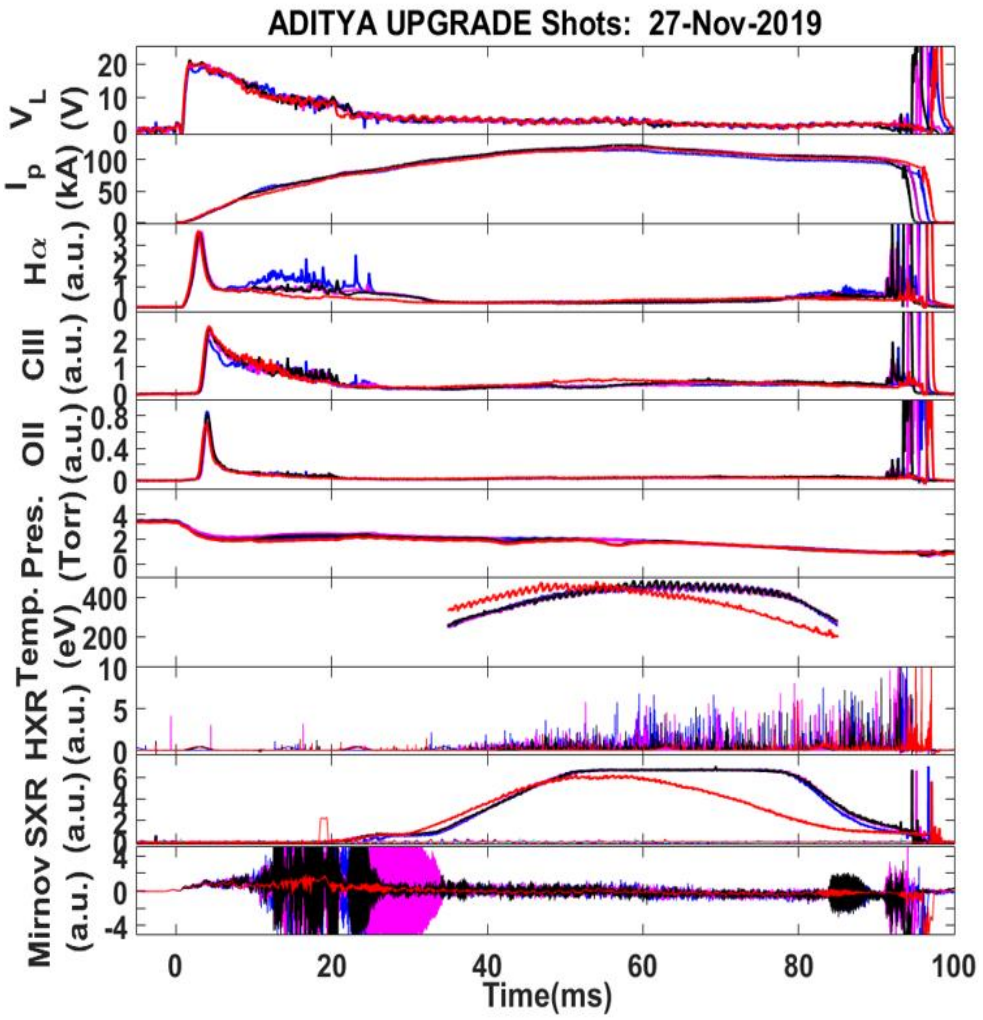

**Max. Plasma duration ~400 ms**




**Max. Toroidal Field ~ 1.5 T**

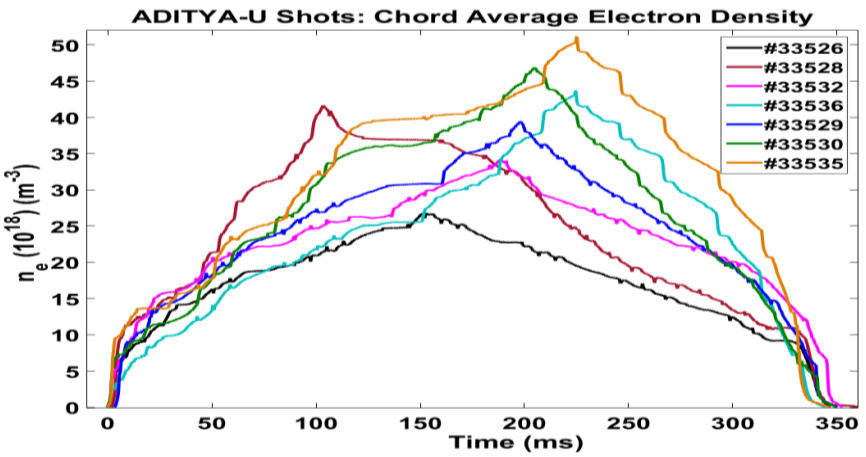
# Discharge Parameters

## Electron Temperature

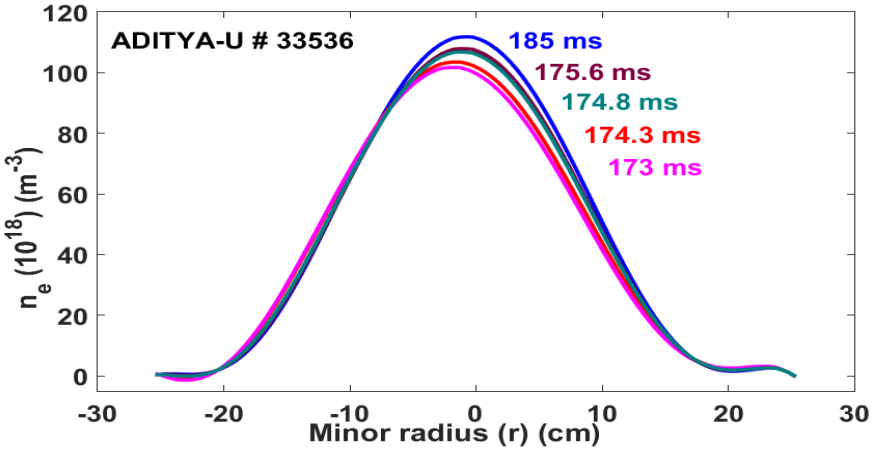



***Max. Electron Temperature ~ 500 eV***

## Time evolution: electron density



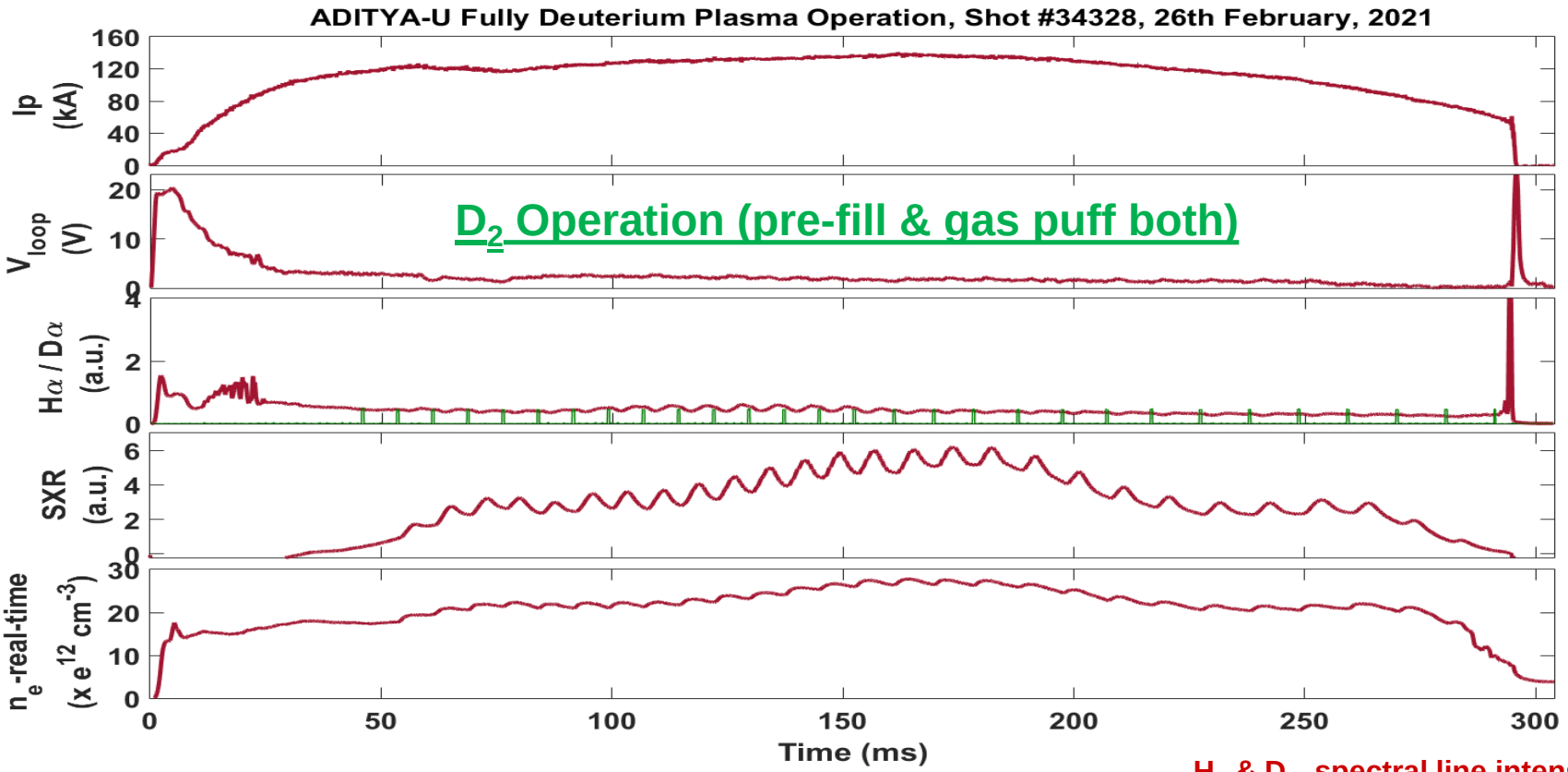

## Radial density Profile




***Chord averaged Electron density ($n_e$) ~ 6 x $10^{19}$ $m^{-3}$***

# Deuterium Plasmas in ADITYA-U

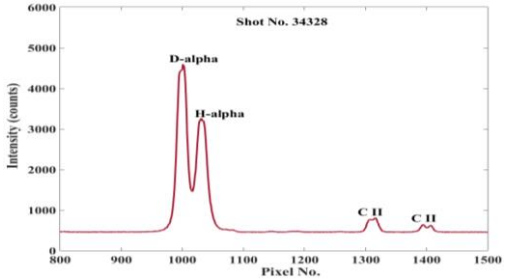
✓ Aim to achieve improved confinement through isotope effect.




✓ Ip ~ 140 - 150 kA, t ~300 – 350 ms, chord average real-time ne ~ 3 - 3.5 x 10^19 m-3 at toroidal field ~1.28 T

✓ Observed Confinement Improvement ~ factor of 2

$H_\alpha$ & $D_\alpha$ spectral line intensity



# 42 GHz ECR Two Pulse Operation in ADITYA-U

**Microwave Source (Gyrotron):**

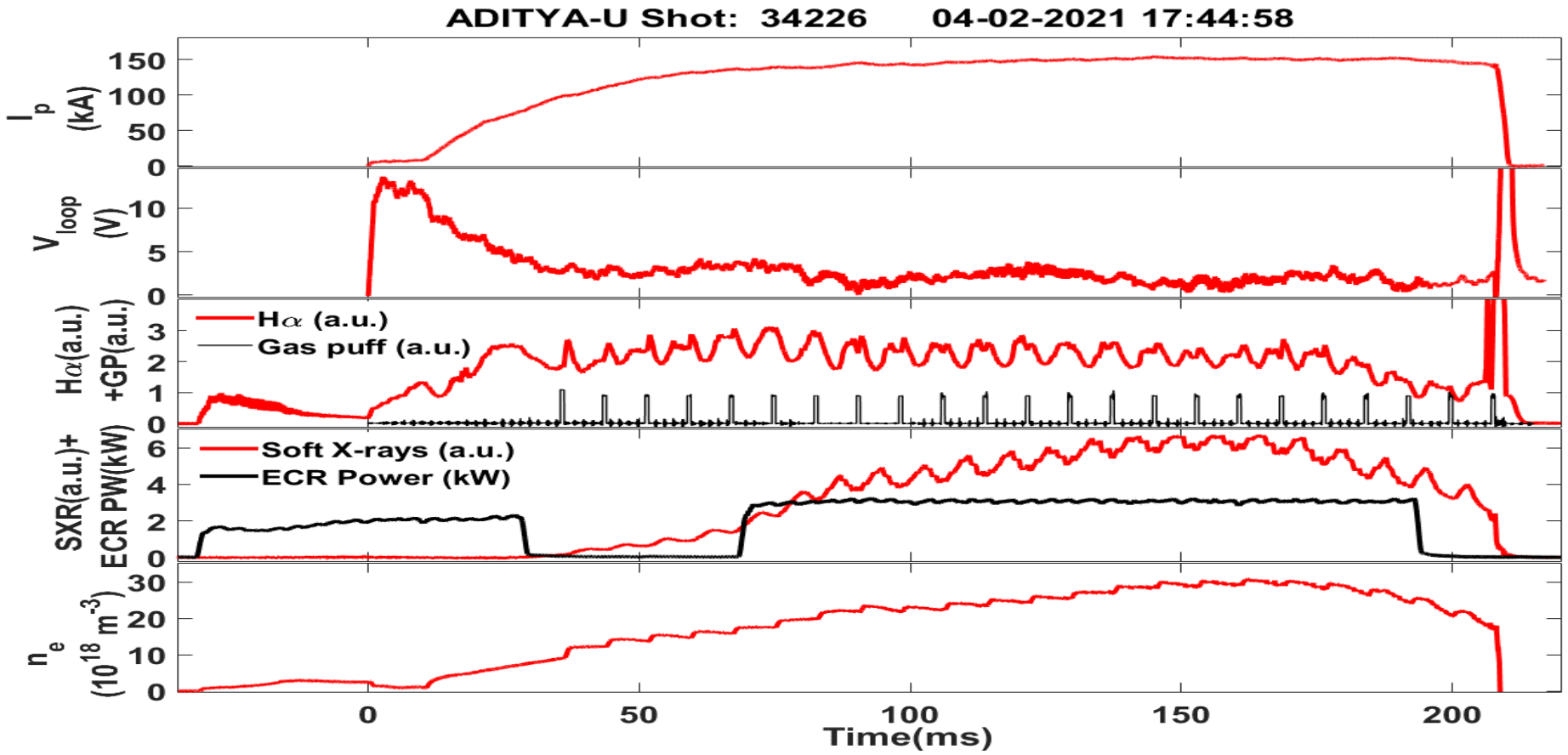
- **Frequency : 42GHz, Power : 500 kW, Pulse duration : 500ms**
- **Transmission Line: Approximately 75meter long transmission line is used to launch power from SST- hall to ADITYA-U tokamak.**
- **Transmission line consists of 63.5mm ID corrugated waveguide, bends, polarizer, DC breaks & bellows.**
- **System is directly connected to tokamak using BN window and UHV gate valve**


**ECRH System in ADITYA-U tokamak**

**42GHz Gyrotron System**

# 42 GHz ECR Two Pulse Operation in ADITYA-U

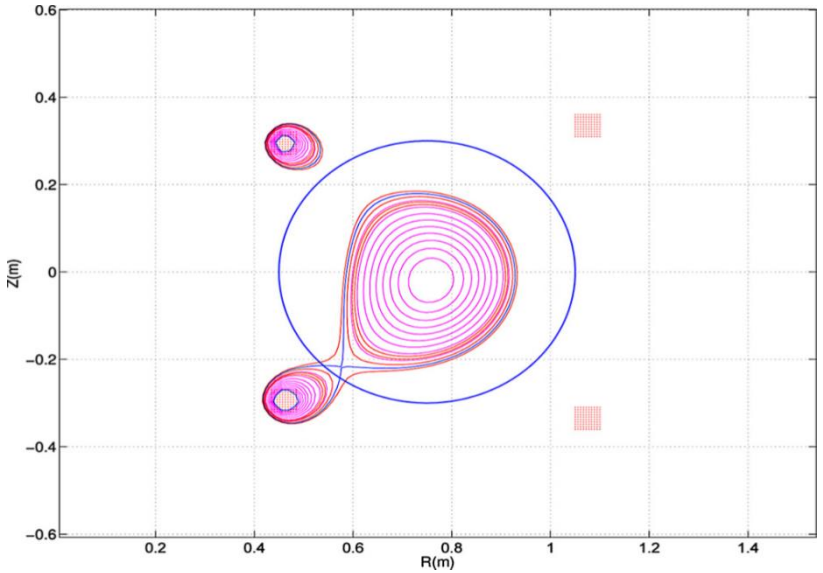
**One pulse for low loop voltage start-up & second for heating simultaneously in a single discharge**



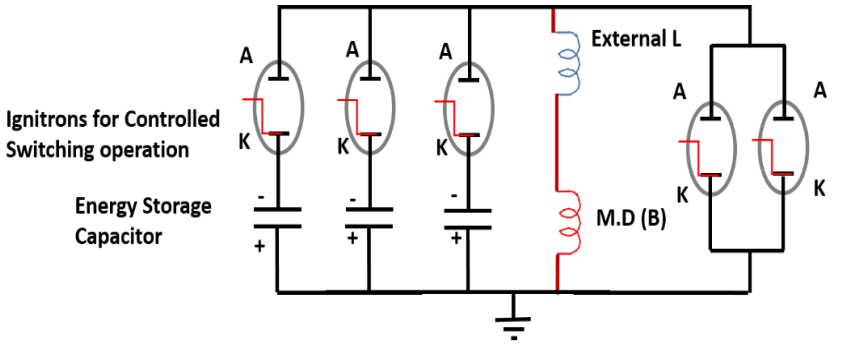

- ✓ **Increase in SXRs with saw-tooth activities during 2nd pulse correlates with rise in $T_e$**
- ✓ **Chord averaged $n_e$ ~3.2 x $10^{19}$ $m^{-3}$ ; Signature of confinement improvement**

# Preliminary Shaped Plasma Operation in ADITYA-U

## ADITYA-U Divertor Operation Simulations: IPR-EQ code simulations

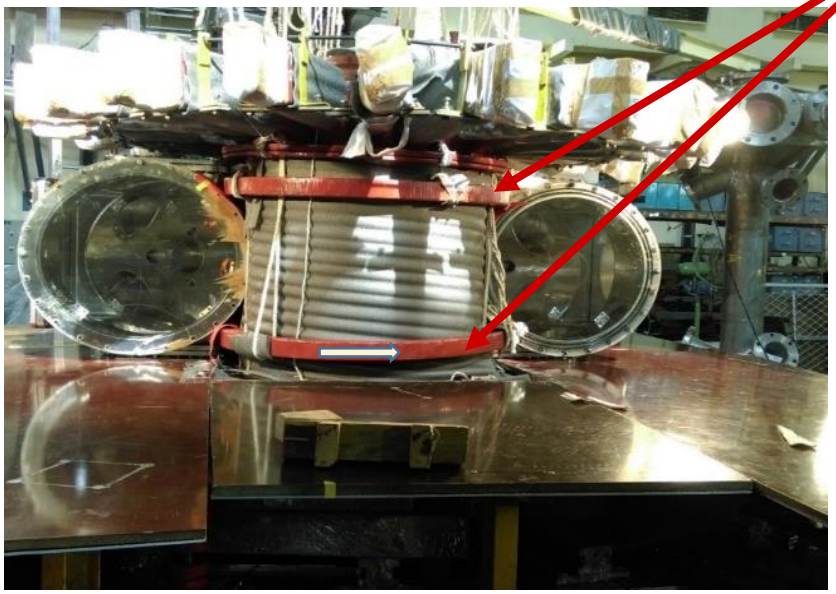


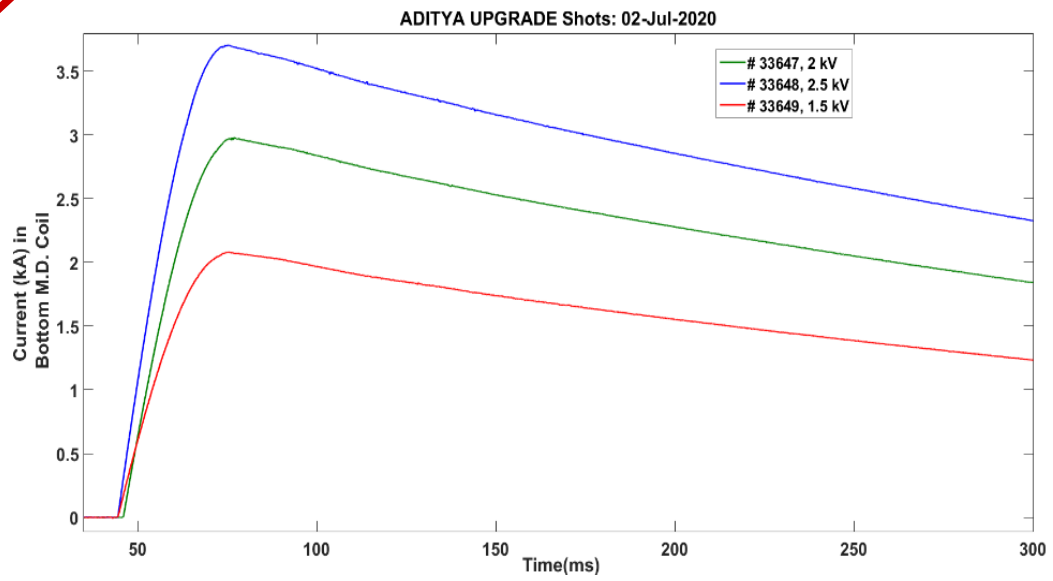

### L, C, R Combination:



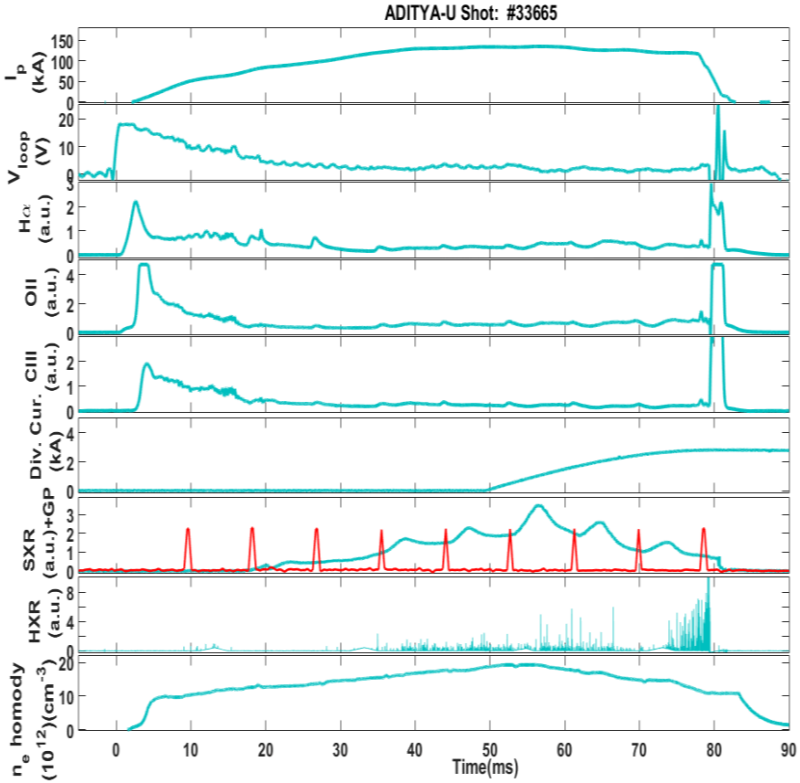

Pair of main Divertor Coil

Capacitance= 30 mH
M.D(B)= 63 µH, 1 mΩ
External L = 12 mH, 60 mΩ

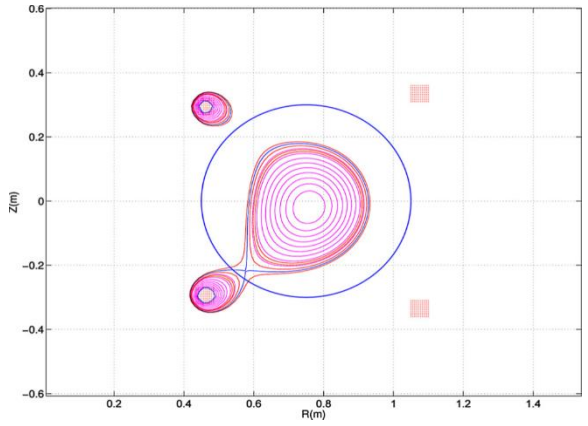


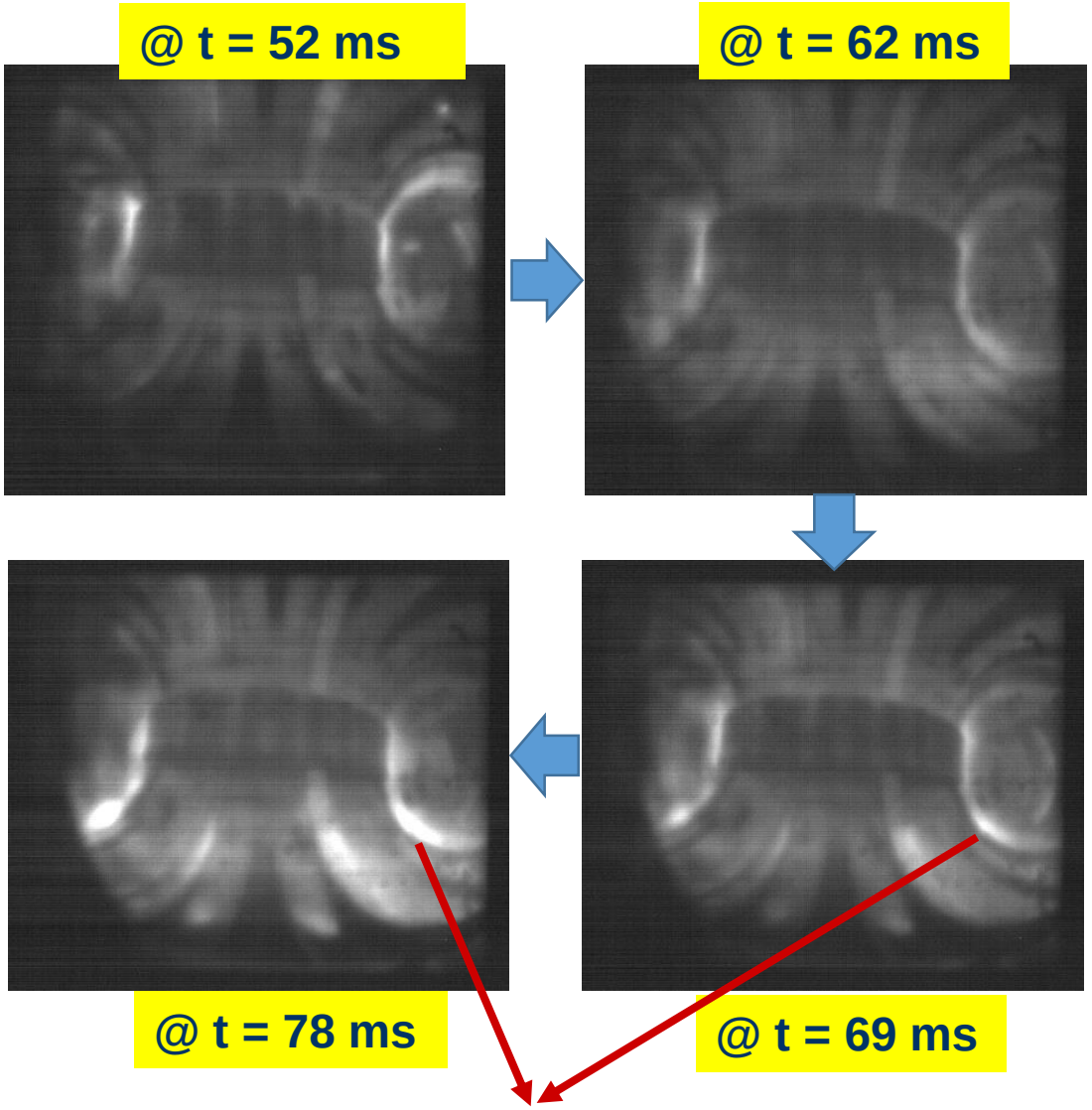


# Shaped Plasma Operation in ADITYA-U




*IPR-EQ code simulations*

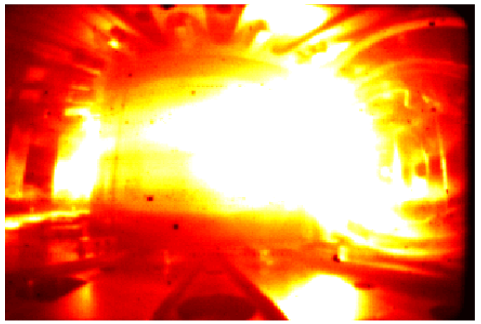


# Inductively driven Pellet Injection in ADITYA-U

**Disruptions in Tokamaks:**

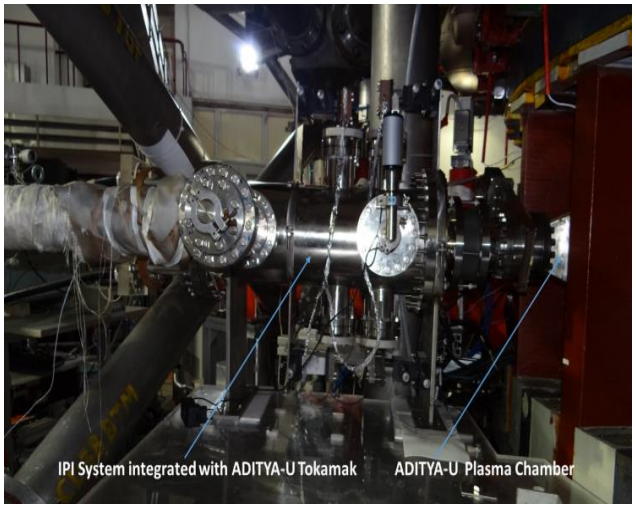
- An abrupt termination of a tokamak discharge
- Sudden loss of plasma stored energies
- The force and heat loads damage the plasma facing components (PFCs)



Mitigation: → Existing technique: Massive Gas injection

→ Problems: Slow penetration to the core of the plasma, Massive loads on pumps

→ **Remedy: Fast injection of solid particles**



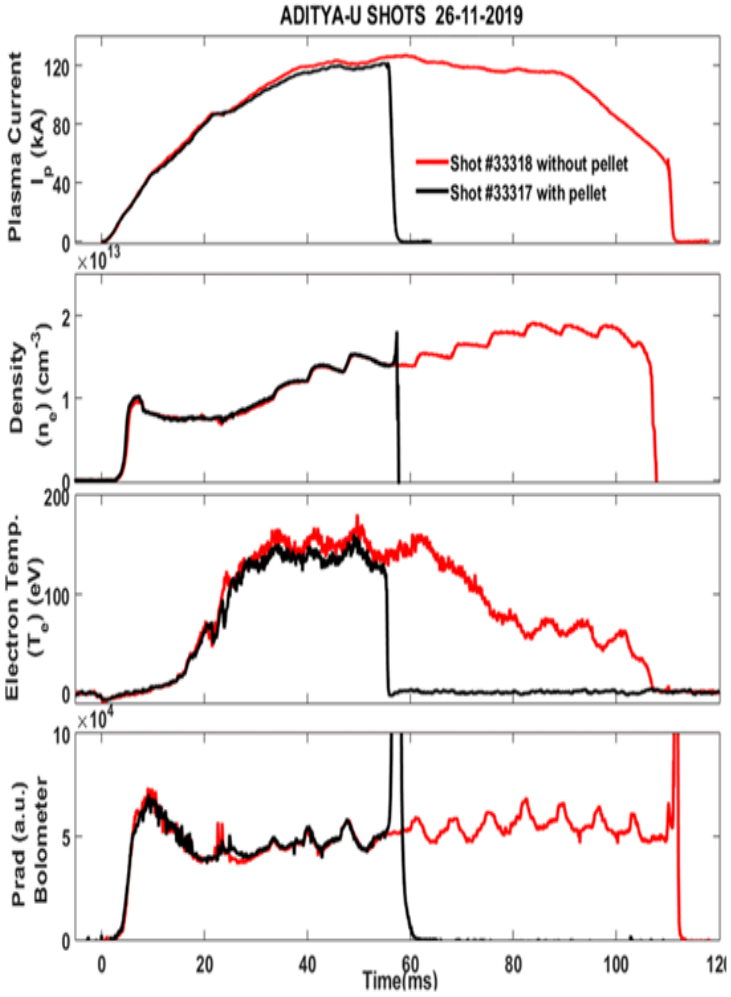

***Designed, Installed and Operated Successfully In ADITYA-U Tokamak***

- ✓ Particles injected using a high-speed pellet injector
- ✓ Pellets reached hot plasma core in few milliseconds
- ✓ Radiated away its thermal energy, causing a rapid quench of plasma current.

***Collaborative effort between IPR and BARC, Visakhapatnam, India***

# Pellet Injection Experiment in ADITYA-U

An Inductively-Driven Pellet accelerator and Injector used to fire particles into ADITYA-U tokamak
Significant development towards disruption control




**Injected Particles: Lithium Titanate / Carbonate**

**Particle size ~ 50 micron**

**Particle velocity ~ 200 m/s**

**Particles reached ADITYA-U core in ~ 4 ms**

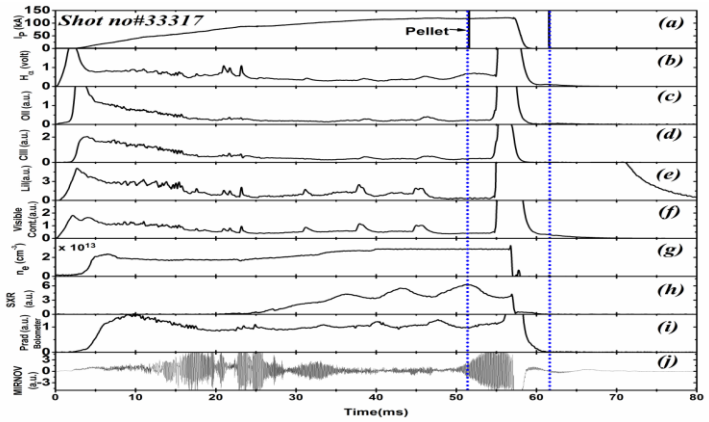
**Amount injected ~ 50 – 200 mg**

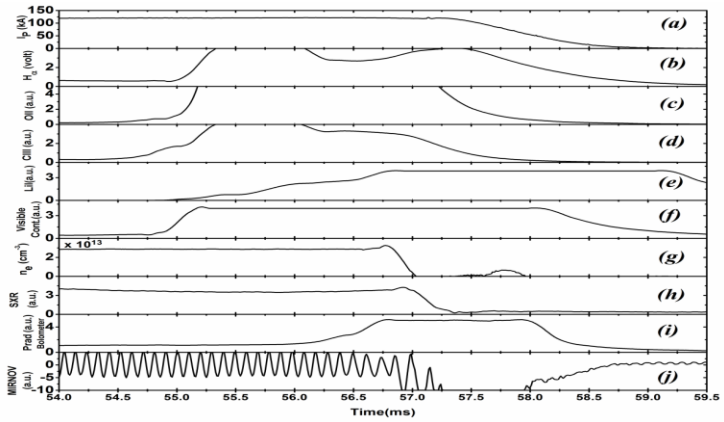
**Particle Injected causes fast Disruption of Plasma Current**
**(Red Curve: No Injection)**
**(Black Curve: With injection)**

**Density, temperature terminate very rapidly due to increased radiation after the injection**

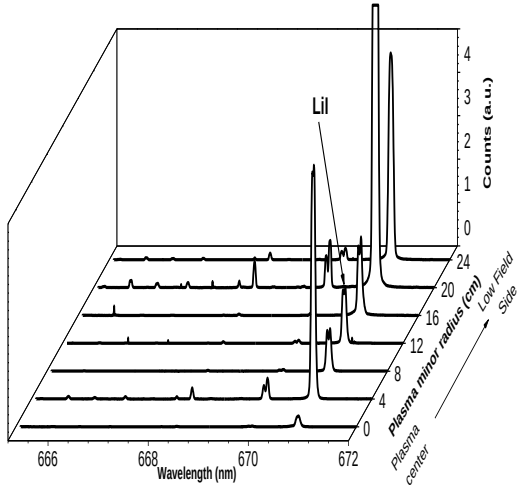
*[Poster by J. Ghosh et al, EX/P4, #1290]*

# Plasma Parameters with Particle Injection



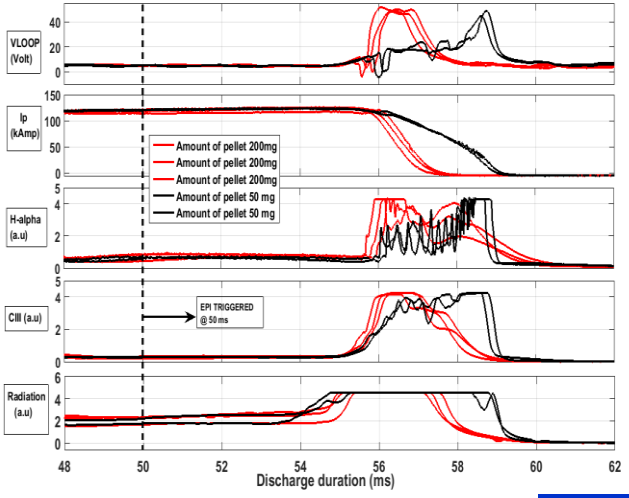



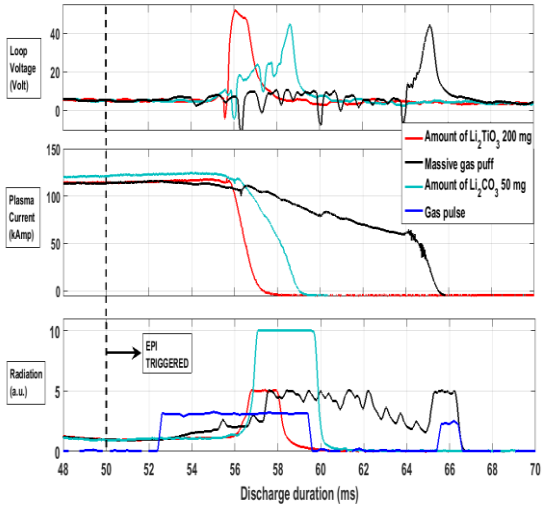

## Radiation leads to Disruption




High Li Density near the plasma center

Plasma Current Fall rate control with different amount of pellet dust



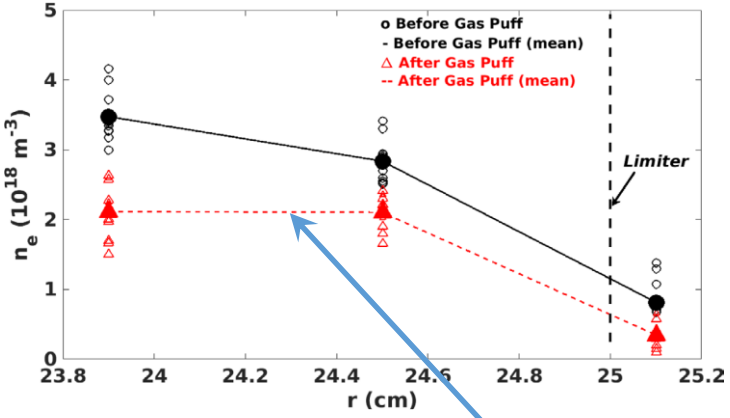

Faster decay than Massive Gas-puff

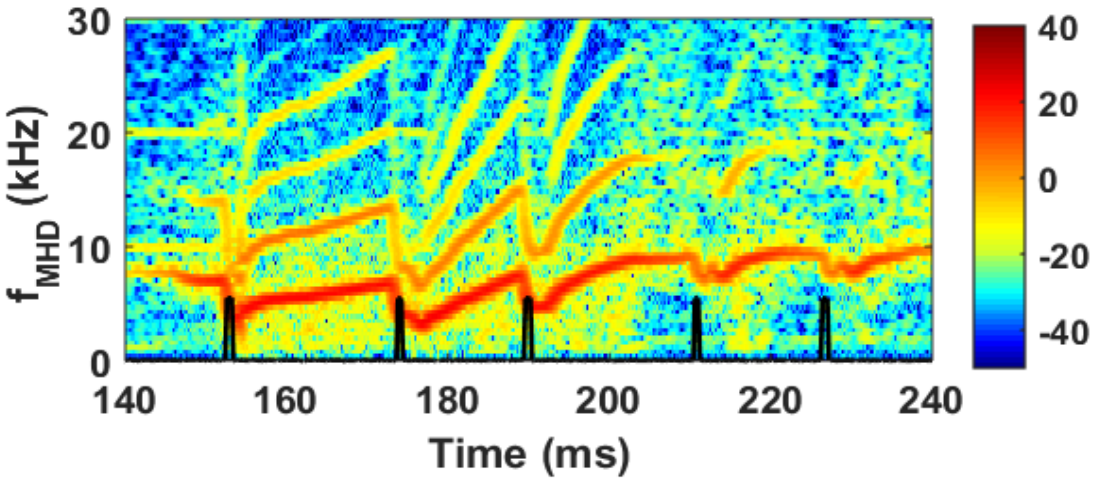


*[Poster by N. Yadava et al, EX/P4, #1291]*

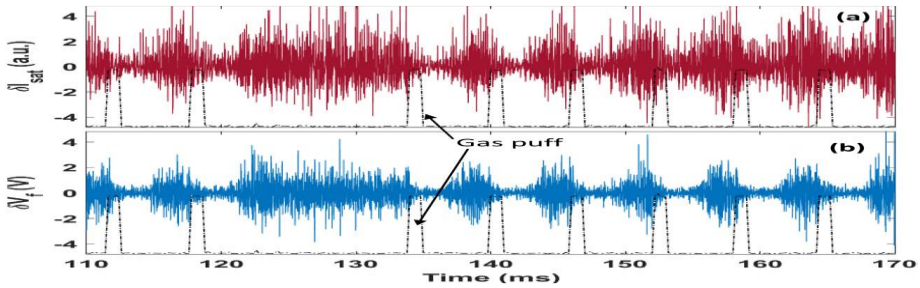
# Drift tearing modes rotation studies in ADITYA-U

**DTM rotates in Electron Diamagnetic Direction in ADITYA-U are controlled by controlling drifts**




$$\omega^* = \frac{k_y T_e}{e\,B\,L_n}$$




Gas puff → $T_e$ ↓ → Reduces the edge temperature

$L_n$ ↑ → Increases the density scale length

Gas puffs decreases $\omega^*$ → **Decreases the mode rotation**

***[Harshita Raj, Tanmay, et al, Nucl. Fusion, 60, 2020]***

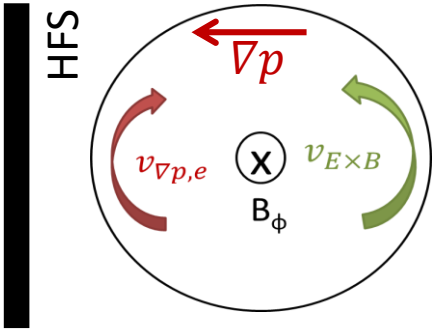
# Drift tearing modes rotation studies in ADITYA-U

## Plasma Rotation rotating the Drift Tearing Modes (DTMs)

**For ADITYA-U Geometry and Field Configuration**

- $\overrightarrow{v_{MHD}} = (v_{E\times B} - v_{\nabla p})\hat{\theta}$
- $\overrightarrow{v_{E\times B}} = \frac{\overrightarrow{E_r}\times\overrightarrow{B_\varphi}}{B^2}$; $\overrightarrow{v_{\nabla p}} = -\frac{\overrightarrow{\nabla p}\times\overrightarrow{B_\varphi}}{nqB^2}$

**Mode rotation depends on plasma rotation**

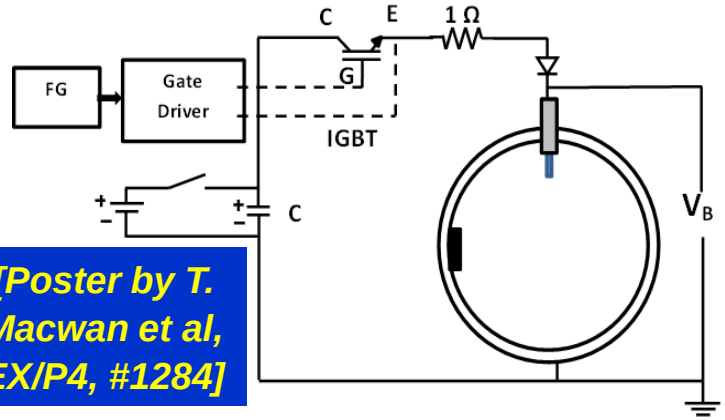



**Experimentally demonstrated background plasma rotates the DTMs**

-modified plasma rotation using biased electrode

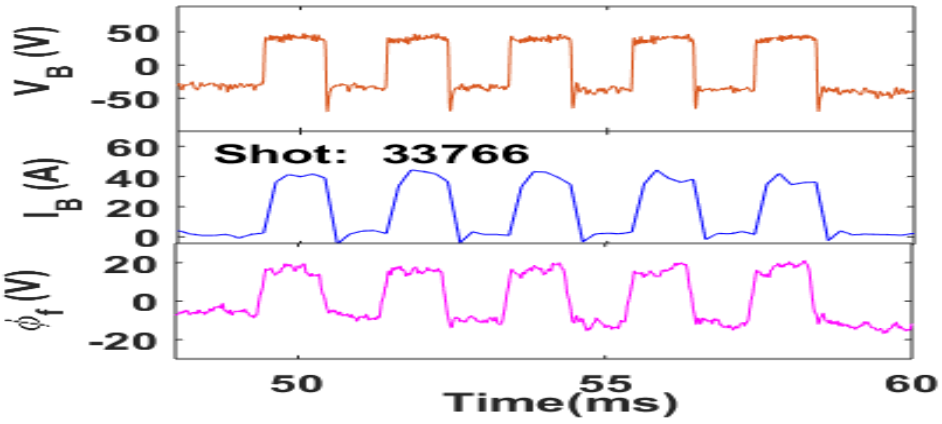
$$\overrightarrow{v_{E\times B}} = \frac{\overrightarrow{E_r}\times\overrightarrow{B_\varphi}}{B^2}$$

### Bias Circuit




*[Poster by T. Macwan et al, EX/P4, #1284]*

### Multiple Bias Pulses in Plasma



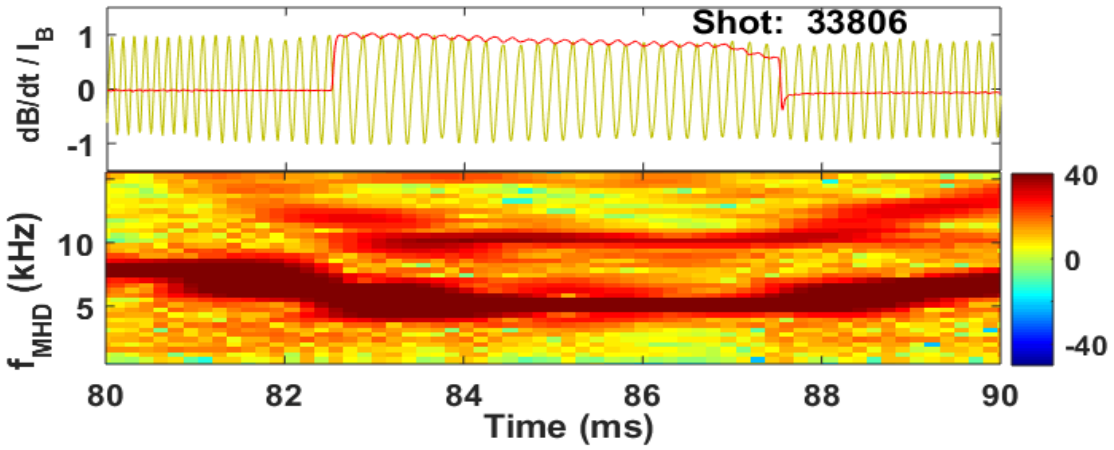

*[Tanmay, et al, Submitted to Nucl. Fusion]*

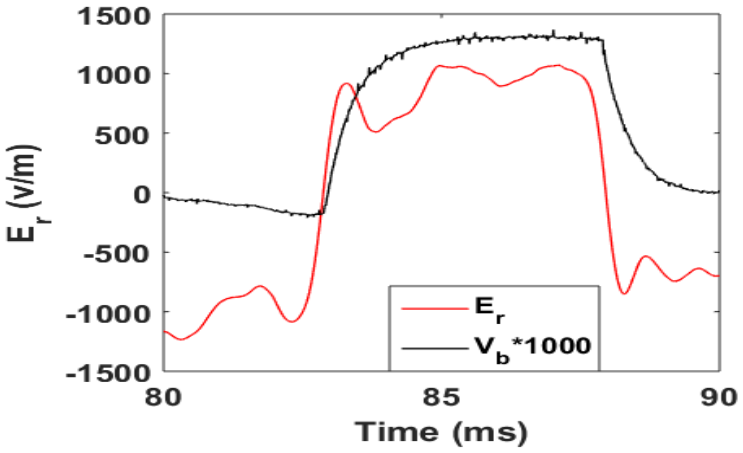
# Positive Bias: Rotating Plasma in Ion Diamagnetic Direction

**Positive Bias: Rotating plasma in Ion Diamagnetic Direction [Opp. to DTM rotation]**

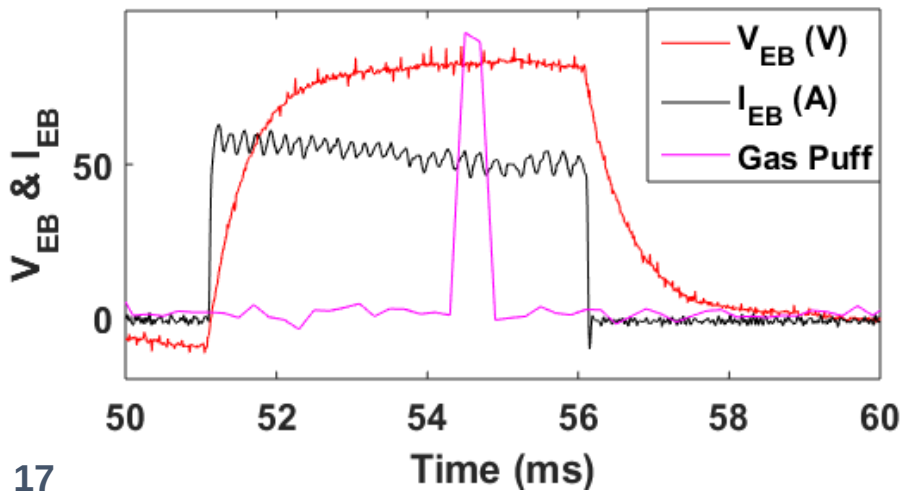
**DTM Rotation Frequency Decreases by ~ 2-3 kHz after biasing**

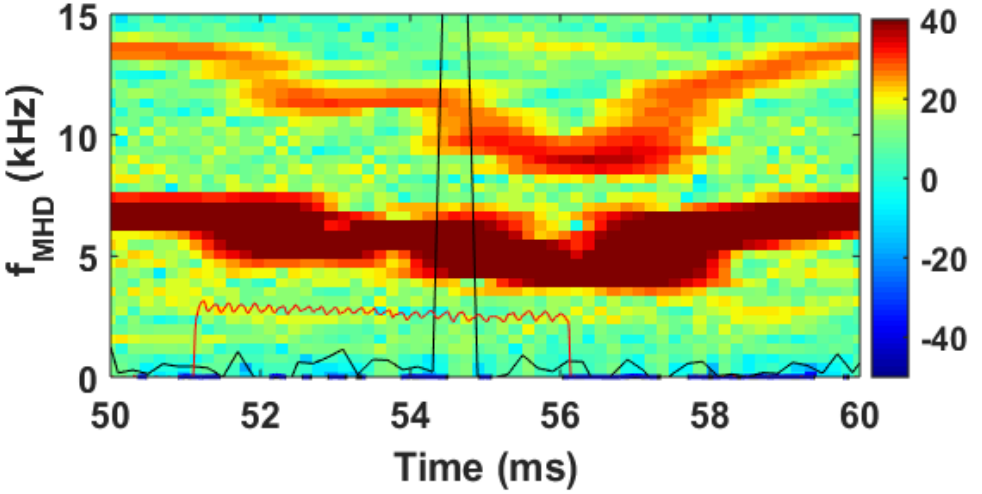
**$E_r$ ~ 2 kV/m; $\Delta v \sim E_r/B_\varphi$ ~ 2.3 km/s; Δf ~ 2 kHz as observed**



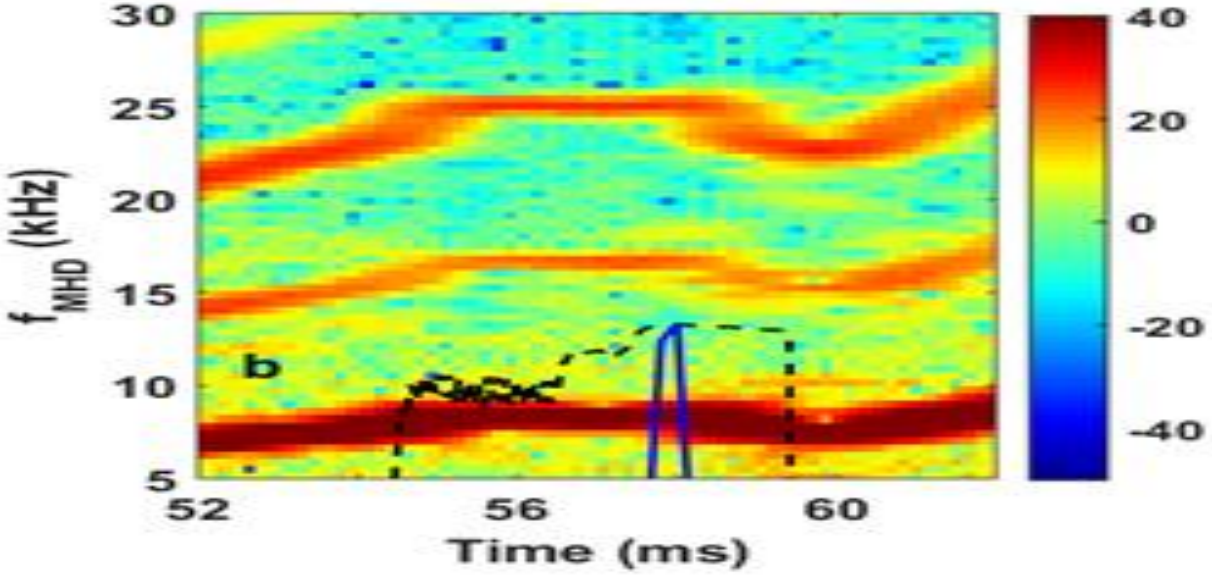



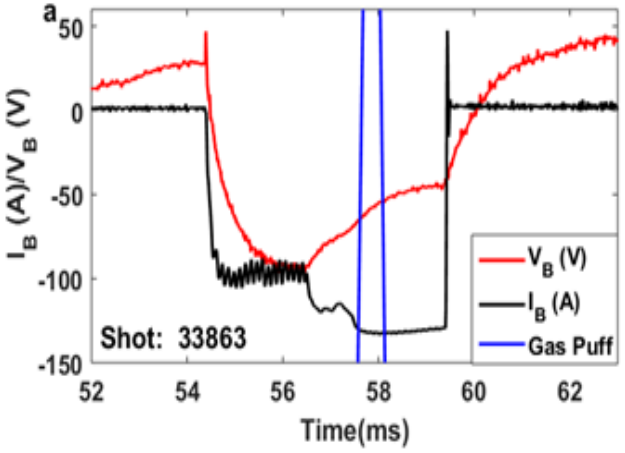

## Positive Bias with gas puff: Both decreasing the DTM rotation



# Negative Bias: Plasma rotation in e⁻ diamagnetic direction




**DTM Rotation Frequency Increases by ~ 1 – 2 kHz after biasing and reduced after gas-puff**

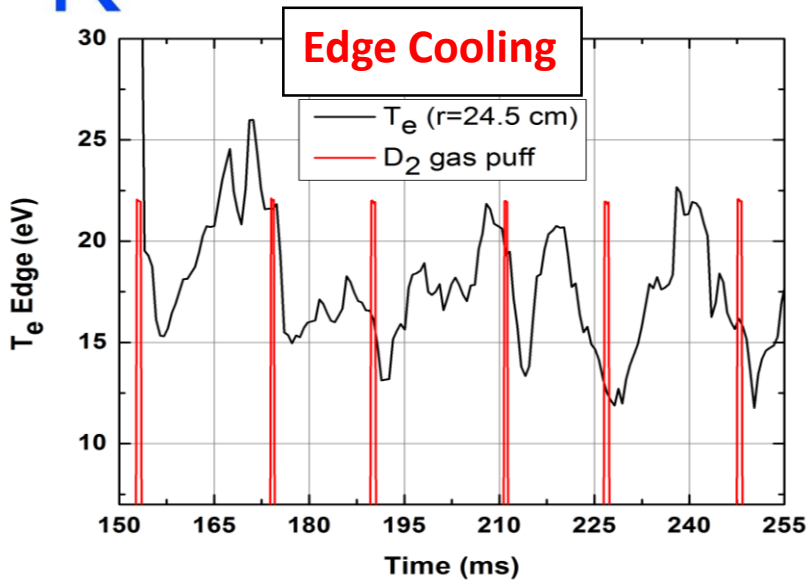
## Important Findings:

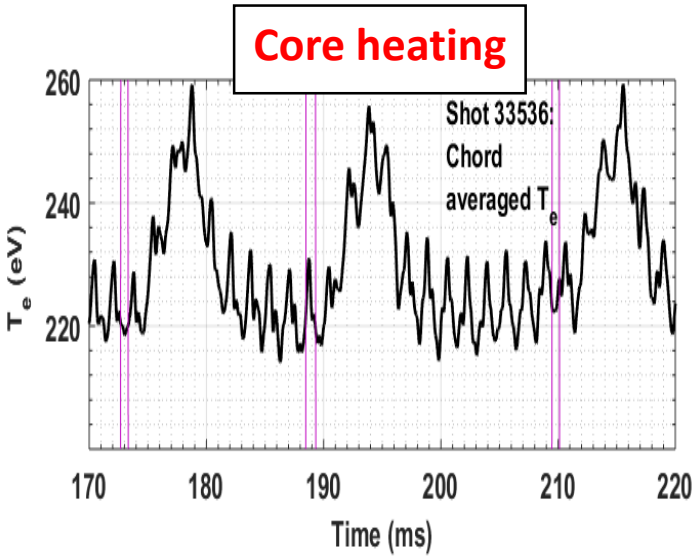
**Plasma rotation influence the DTM rotation**

**Insight: Bias Polarity dependency of improved confinement**

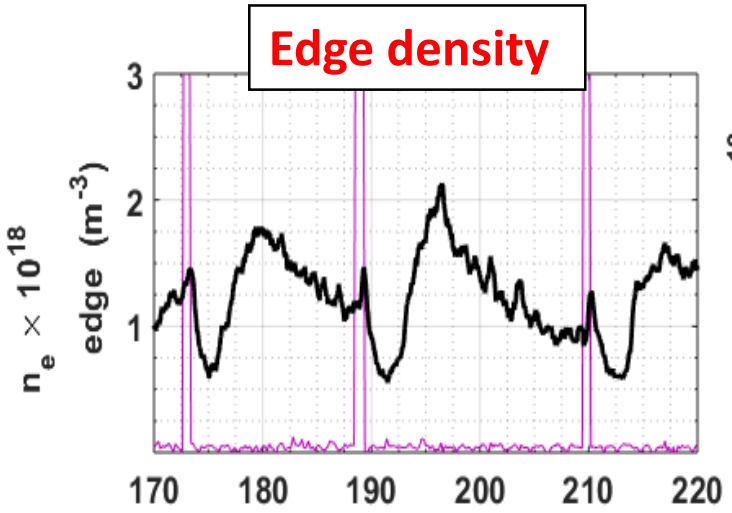
***Tanmay, et al, Submitted to Nucl. Fusion***

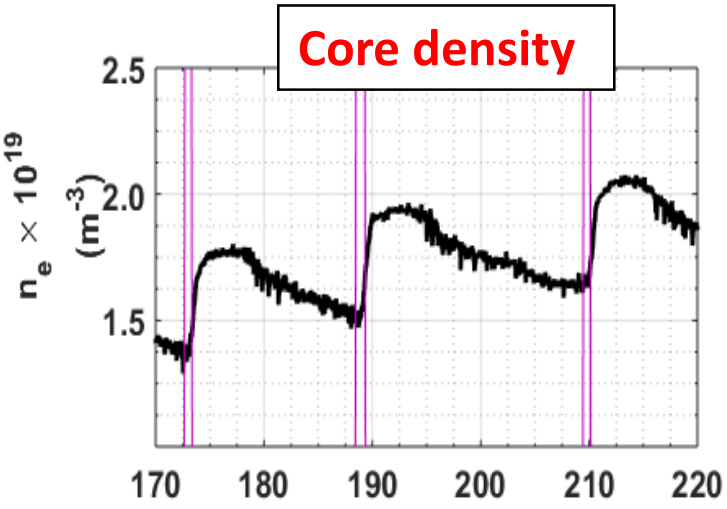
# Cold Pulse Experiments in ADITYA-U




**With Gas Puff--- Core $T_e$ increases in ~ 2 ms! Edge $T_e$ decreases in same time**

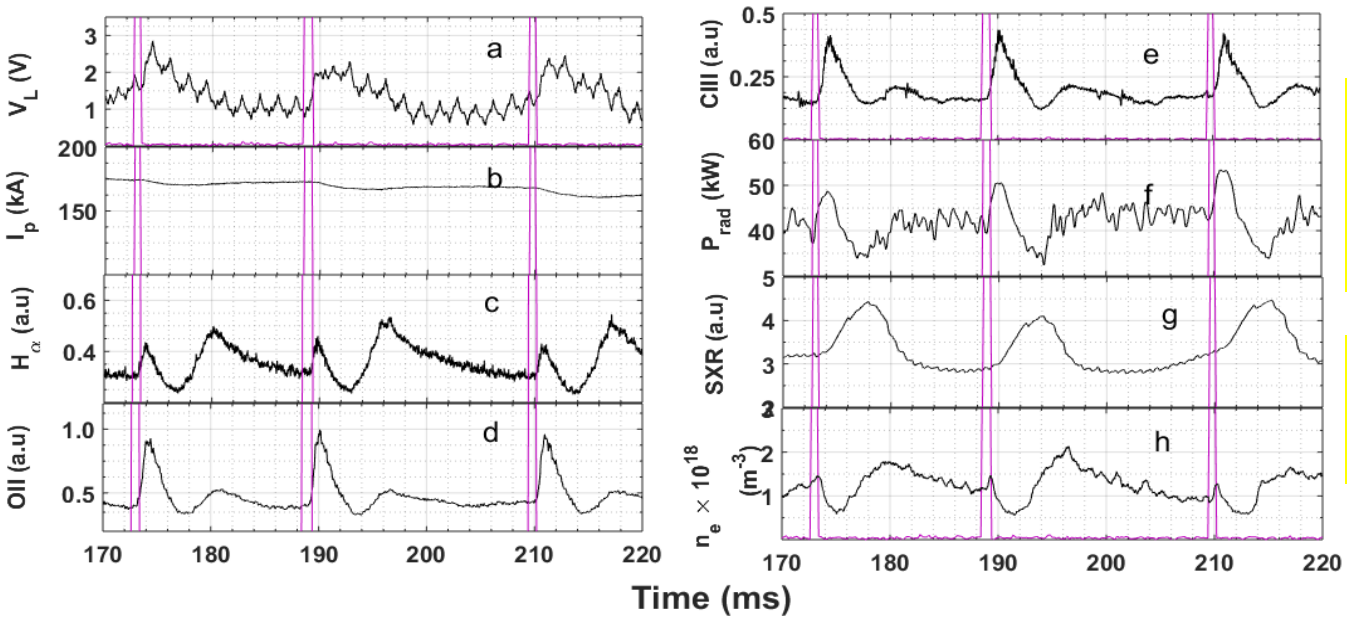



**Density increase much larger than the injected neutrals increases in ~ 1 ms!**

**Density is the first to react during a cold-pulse injection**
**Core-temperature increase: consequence of density Variation**

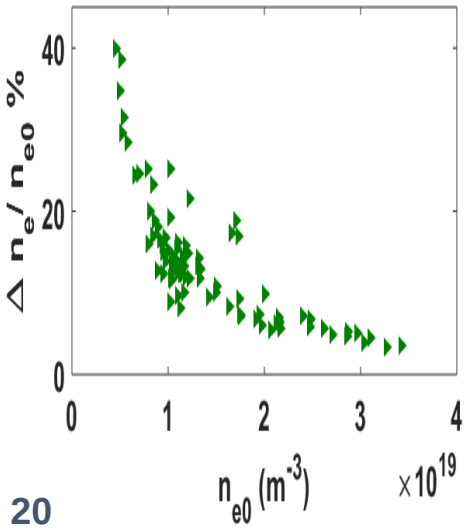
# Cold Pulse Experiments in ADITYA-U



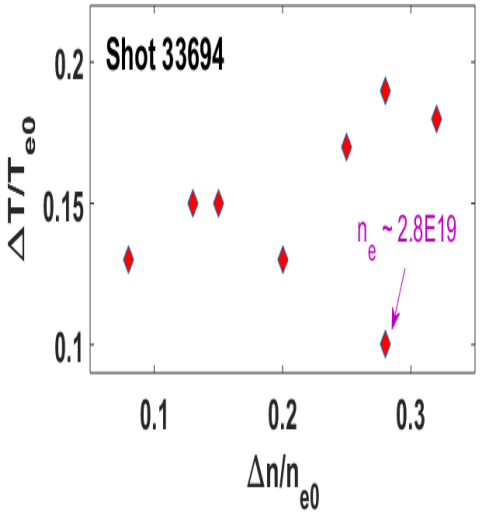

Variation in Plasma parameter with gas injection

Edge Fluctuation also suppressed

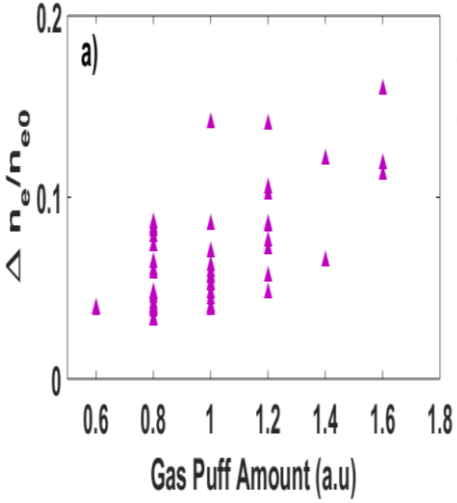
**Density Threshold Exists**



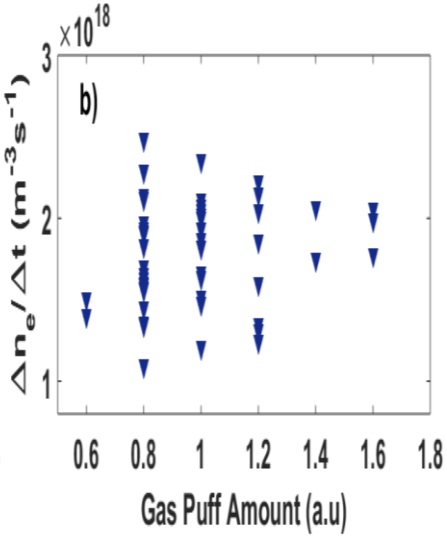

**Increase in $T_e \propto \Delta n_e$**




**$dn_e/n_{e0}$ increase with gas puff**

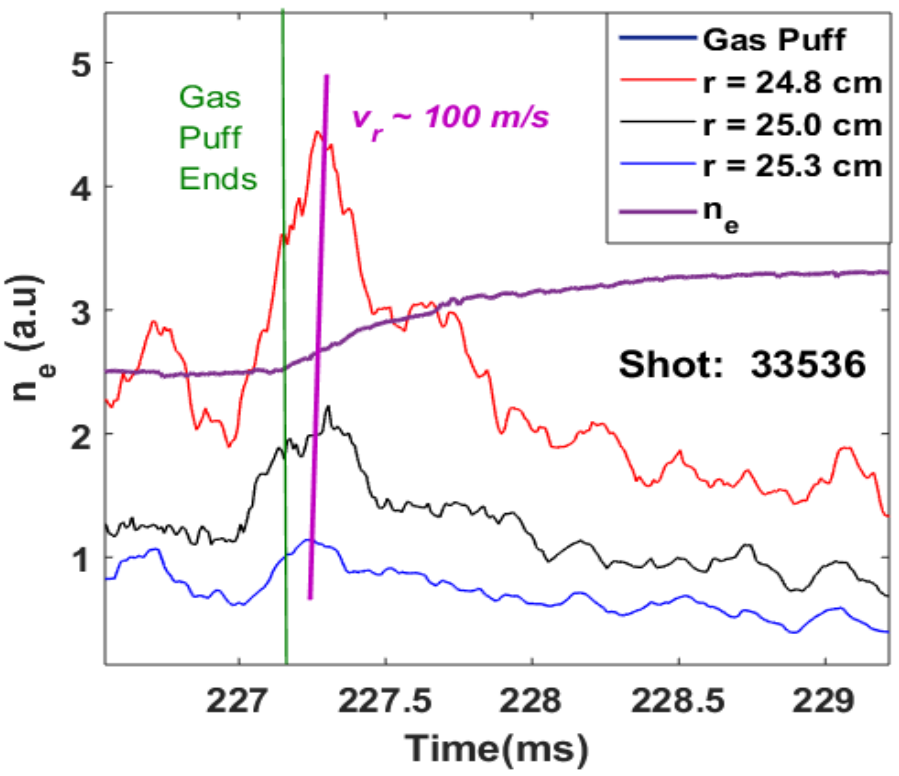



**dn/dt same with gas puff**

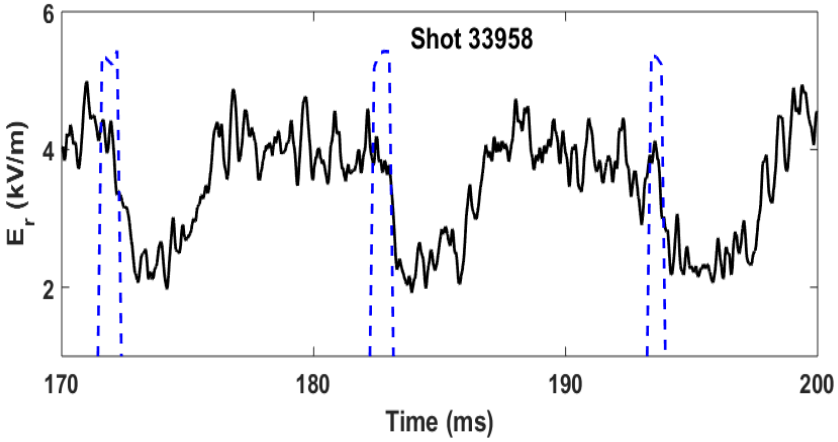


# Rapid Density Propagation

Density Peak Velocity in the Edge ~***100 m/s*** With Gas Injection




Positive Radial Electric Field Reduces With Gas Injection




***Density Rise:***
***Reduced ion-orbit Loss***
***(Decrease in + $E_r$)***
***Increase in Ware Pinch***
***(increase in Loop Voltage)***

**Pinch: most plausible reason for sharp density rise**

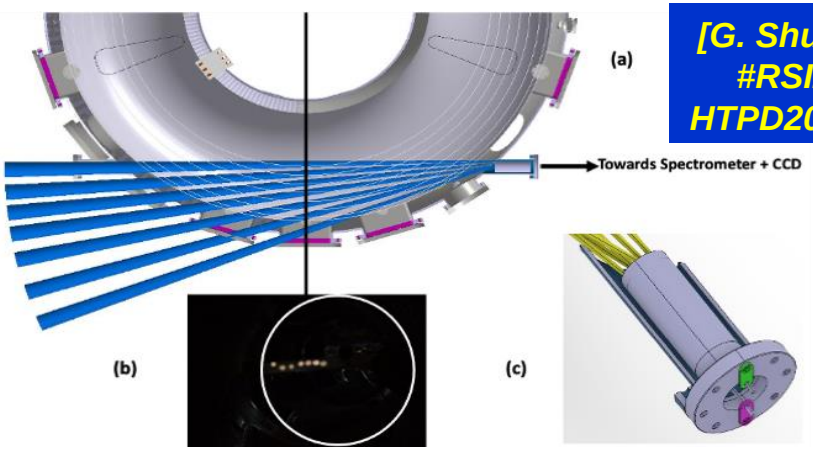
# Impurity toroidal / poloidal rotations in ADITYA-U

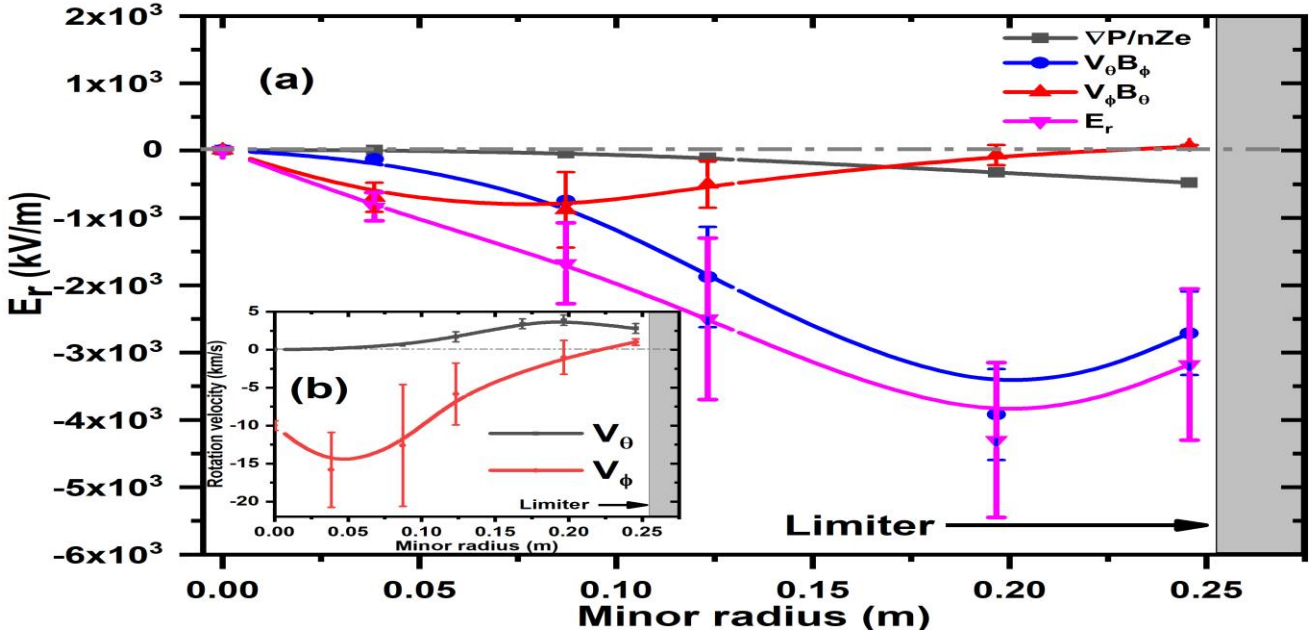
Doppler-shifted passive charge exchange line emission of $C^{5+}$ at 529 nm

**A toroidal rotation velocity of ~ 15 km/s in the core with almost negligible edge toroidal rotation**

**A Poloidal rotation velocity of ~ 5 km/s**

*[G. Shukla et al, #RSI21-CF-HTPD20-00144R]*

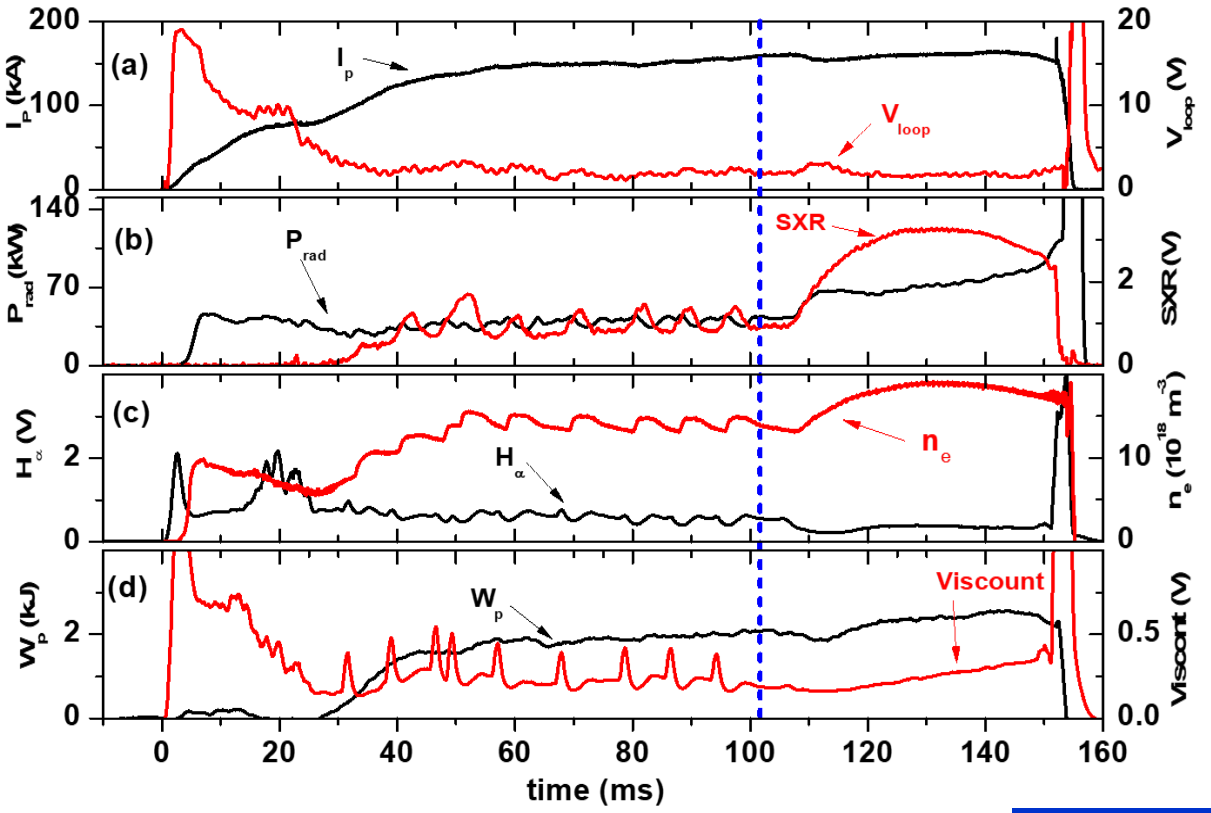


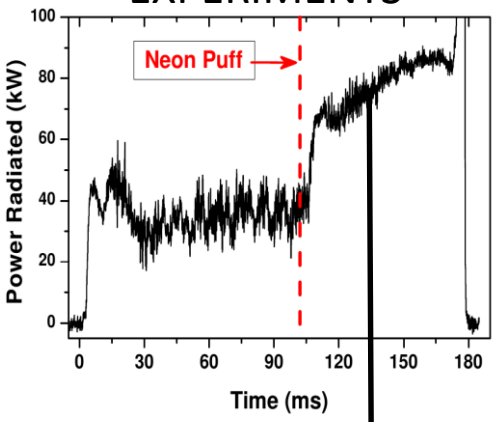

**A max. radial electric field ~ 4.5 kV/m is estimated at ~ 0.20 m of minor radius**

# Neon Impurity Seeding Experiment in ADITYA-U

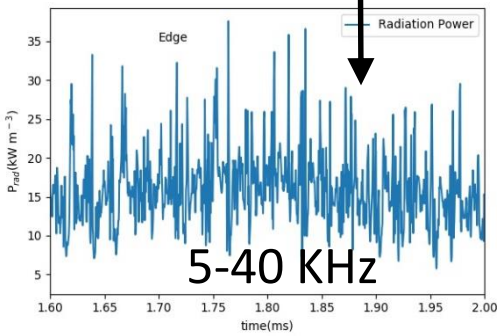
Ne puffed during Ip flattop with different electron densities and at different $B_\phi$




EXPERIMENTS




BOUT++ 2D Simulation




*[Poster by M. Chowdhuri et al, EX/P4, #1271]*

*[Poster by N. Bisai et al, TH/P8-4, ]*

After Ne Puff:

**--- Radiative Power Loss increased by ~ 60 - 70 %**

**--- Particle Recycling Reduced by ~ 70 %**

**--- Confinement Improvement by a factor of ~ 1.5**

# SUMMARY

- ✓ Plasma Parameters in ADITYA-U: $I_P$ ~ 210 kA, duration ~ 400 ms, chord-averaged $n_e$ ~ 3 - 6 x $10^{19}$ $m^{-3}$, $T_e$ ~500 eV, W ~3 kJ, Max. $B_\phi$ ~1.5 T
- ✓ Optimization of Vessel Cleaning and Lithiumization with novel techniques
- ✓ Shaped and Deuterium plasmas in ADITYA-U
- ✓ Development, installation and operation of an Inductively Driven Particle Injector in ADITYA-U for disruption mitigation studies.
- ✓ Low loop voltage start-up and heating with two pulse 42 GHz ECR application in a single discharge executed for the first time in ADITYA-U.
- ✓ Mode rotation frequency of DTM controlled by controlling background plasma poloidal rotation using Electrode Biasing.
- ✓ The experiments show Cold-pulse propagation is a local phenomena.
- ✓ Radial electric field estimated from toroidal and poloidal rotation measured.
- ✓ Ne puff impurity seeding in ADITYA-U at varied $B_\phi$ to study toroidal rotation and R-I modes

# Thank you!

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

## Posters from ADITYA-U:

*[Poster by K.A. Jadeja et al, EX/P4, #1210]*

*[Poster by N. Bisai et al, TH/P8, #1251]*

*[Poster by S. Dutta et al, TH/P1, #1255]*

*[Poster by M. Chowdhuri et al, EX/P4, #1271]*

*[Poster by R. Manchanda et al, OV/P, #1282]*

*[Talk by I. Bandyopadhyay, TH/7, #1263]*

*[Poster by T. Macwan et al, EX/P4, #1284]*

*[Poster by S. Aich et al, EX/P4, #1323]*

*[Poster by J. Ghosh et al, EX/P4, #1290]*

*[Poster by N. Yadava et al, EX/P4, #1291]*