Overview of Recent Experimental results from the ADITYA Upgrade Tokamak

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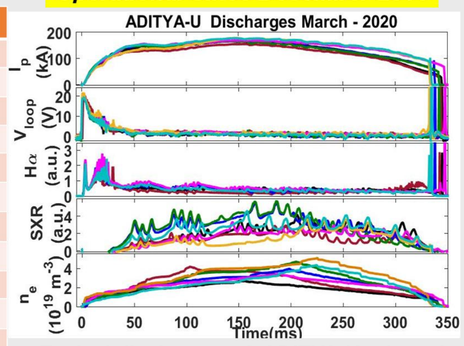
OV/4

Introduction to ADITYA Upgrade Tokamak

- ✓ 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

Operational Since December-2016

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.	~ 140 eV
Elongation	Shaping Attempted!
Triangularity	Shaping Attempted!

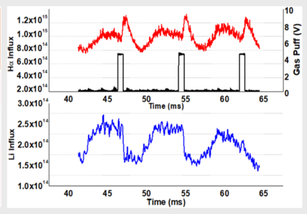


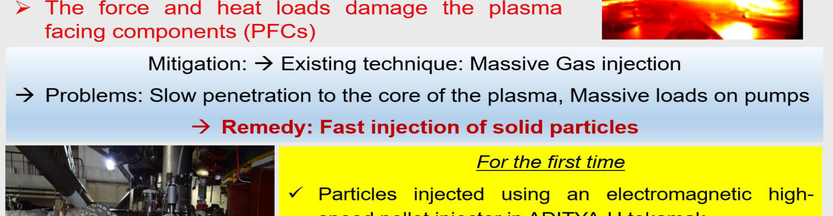
Typical discharges of ADITYA-U tokamak

Machine Preparation (Wall Conditioning)

- ✓ Lithium wall conditioning with Li-rod sputtering and Li-Evaporator.
- ✓ Continuous and Pulsed GDC with H_2,He, Ar-H_2 mixture.
- ✓ Controlled Fuel Injection

Shot No.	Type of Li-H Coating	Li particle influx to plasma at Ip flattop	H_α particle Influx to plasma at Ip flattop	H_α/Li	Reservoir Pressure (Bar)
34311	Fresh Li rod 120 C + H-GDC 2 h	8.1 x 10^{13}	2.6 x 10^{14}	3.3	2.2
34348	Li-Evaporator 600 C + H-GDC 2 h (D-Plasma)	8.0 x 10^{13}	3.4 x 10^{14}	4.3	2.2
34149	Li-Evaporator 500 C & H-GDC 2 h + 2nd Day only He P-GDC (10 min) + 3/4 h H-GDC	6.8 x 10^{13}	1.8 x 10^{14}	2.6	0.8

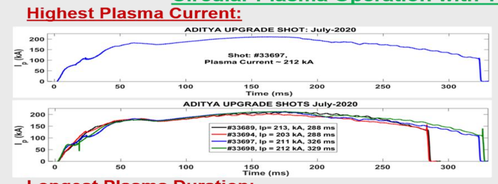




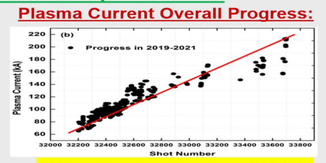
Operation Highlights: Plasma Current & Duration

Circular Plasma Operation with Toroidal Graphite Limiter

Highest Plasma Current:

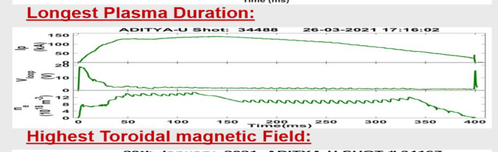


Plasma Current Overall Progress:

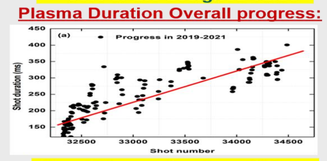


Max. Plasma Current ~213 kA ~ 85% of the designed value

Longest Plasma Duration:

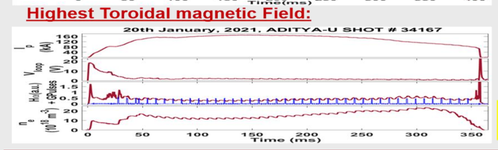


Plasma Duration Overall progress:



Max. Plasma duration ~400 ms ~ 90% of the designed value

Highest Toroidal magnetic Field:

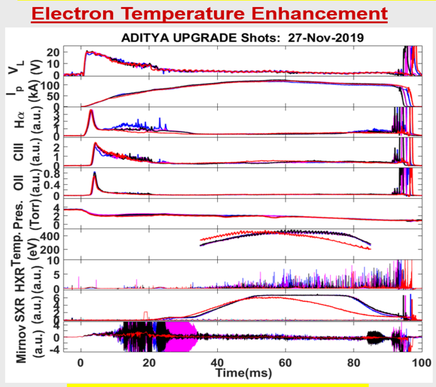


Max. Toroidal Field operated ~ 1.5 T, ~ 100% of the designed value

Operation Highlights: Density & Temperature

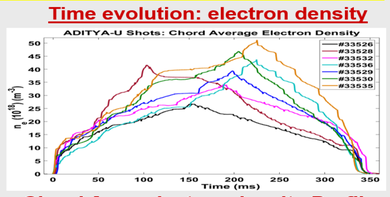
Enhance performance due to lithium coating through lithium titanate pellet injection

Electron Temperature Enhancement

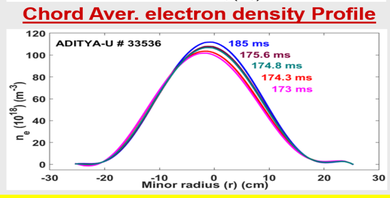


Max. Electron Temperature ~ 500 eV, ~ 100% of the Goal

Time evolution: electron density



Chord Aver. electron density Profile

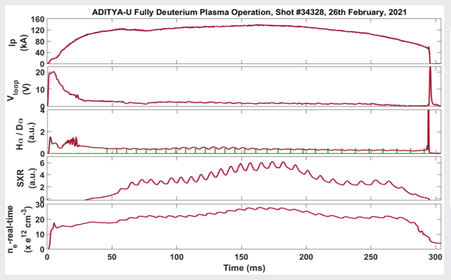


Chord averaged Electron density (n_e) ~ 6 x 10^{19} m^{-3}, ~ 100% of the Goal

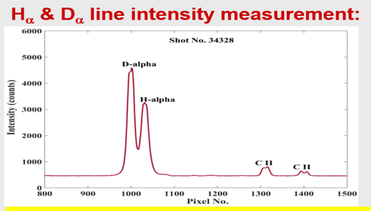
First Deuterium Plasma Experiment

- ✓ Major milestones towards the realization of the thermo-nuclear fusion reaction
- ✓ Aim to achieve improved confinement through isotope effect.

Circular toroidal limiter Plasma with wholly D_2 Operation (pre-fill & gas puff both)



H_α & D_α line intensity measurement:



H_α @656.23 nm, D_α @656.11 nm measured with 1 m focal length visible spectrometer with CCD detector

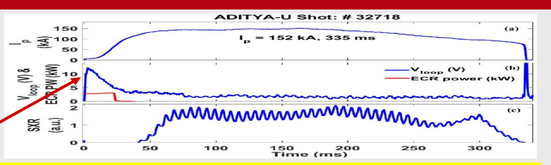
- ✓ DD neutron flux measurement, Berthold make LB 6411 neutron dose rate probe used
- ✓ Obtained D plasma discharges with parameters: Ip ~ 140 - 150 kA, t ~300 – 350 ms, chord average real-time ne ~ 3 - 3.5 x 10^19 m-3 at toroidal field ~1.28 T
- ✓ Improved confinement observed in these discharges.

42 GHz ECR Two Pulses Operation

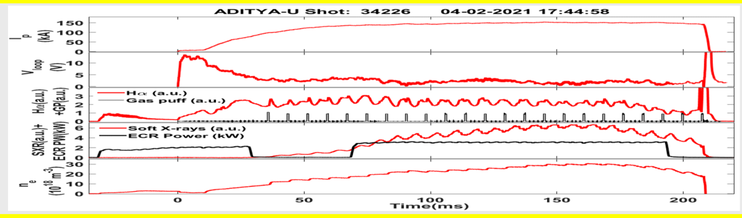
EC pulse launched ~39 ms prior to the start of the loop voltage and remains in overlap for ~20 ms during loop voltage phase.

Peak V_{loop} ~ 20 V w/o ECRH

Peak V_{loop} ~ 12 V with ECRH



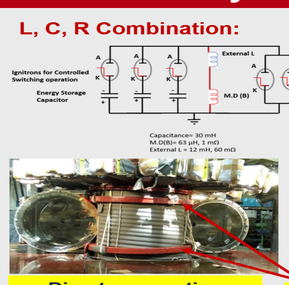
Novel concept of 42 GHz ECR assisted two pulse operation (one for low loop voltage start-up & second for heating) simultaneously in a single discharge

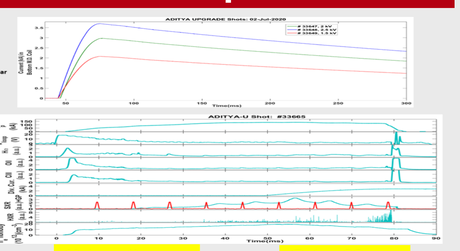


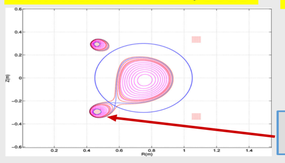
- ✓ Increase in SXRs with saw-tooth activities during 2nd pulse correlates with rise in T_e
- ✓ Chord averaged n_e boost up ~3.2 x 10^{19} m^{-3} shows confinement improvement

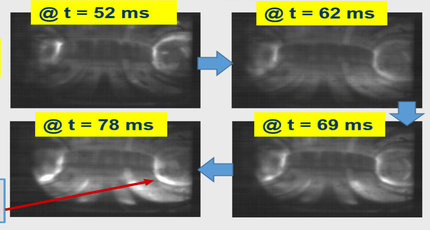
Preliminary Shaped Plasma Experiments

L, C, R Combination:









Inductively driven Pellet Injection Experiment

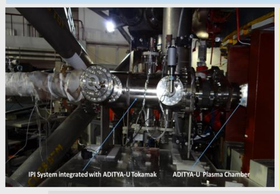
Disruptions in Tokamaks:

- ➢ 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**



For the first time

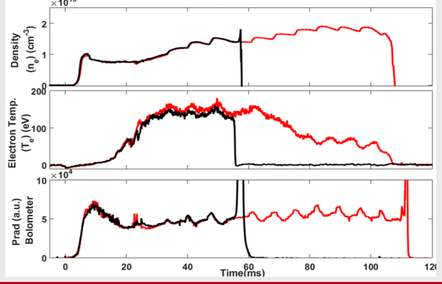
- ✓ Particles injected using an electromagnetic high-speed pellet injector in ADITYA-U tokamak.
- ✓ Pellets reached hot plasma core in a few milliseconds.
- ✓ Radiated away its thermal energy, causing a rapid quench of plasma current.

Collaborative effort between IPR and BARC, Visakhapatnam, India

Pellet Injection Experiment in ADITYA-U

First time an electromagnetic pellet injector used to fire the pellets into the tokomak

Significant development towards ITER disruption control



Lithium Titanate particles injected during plasma current flat-top

Particle size ~ 50 micron

Velocity of particles ~ 200 m/sec (reaching ADITYA-U core in ~ 1.25 ms)

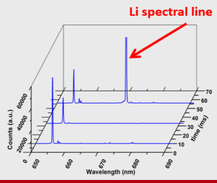
Particle injection causes fast Disruption of plasma current

(Red curve: No injection)

(Black Curve: With Injection)

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

Spectra of Li: signature of Lithium-Titanate Injection



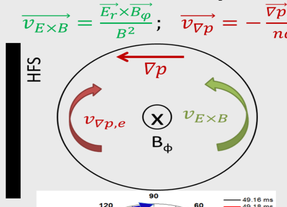
Background: Drift tearing modes rotation studies

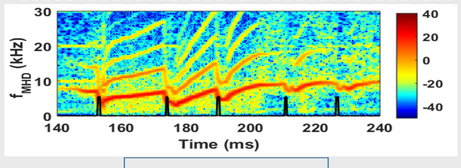
Plasma Rotation rotating the Drift Tearing Modes (DTMs)

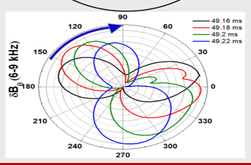
In the high diamagnetic-drift frequency regime, drift mode couple to tearing modes, known as drift-tearing modes

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

Previous Study: 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 Increases the density scale length hence decreases the mode rotation

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

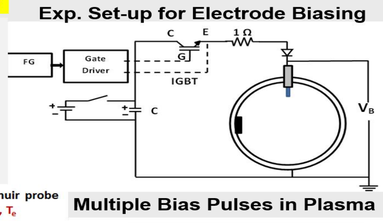
Electrode Biasing Set-up for rotation studies

Experimentally demonstrated background plasma rotates the DTMs

-modified plasma rotation using biased electrode

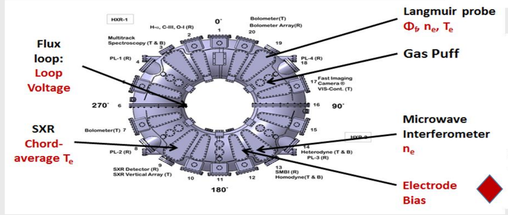
$$\overrightarrow{v_{E\times B}} = \frac{\overrightarrow{E_r}\times\overrightarrow{B_\varphi}}{B^2}$$

Exp. Set-up for Electrode Biasing

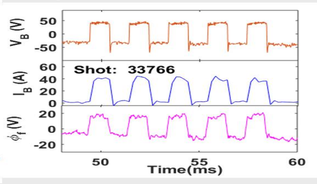


Development:

- ❑ A new edge electrode bias set up installed
- ❑ 30 mF, +/- 900 V capacitor based power supply
- ❑ IGBT as a switch
- ❑ Can operate up to 20 kHz
- ❑ Electrode: Tungsten, 8 mm diameter
- ❑ Electrode placed at r = 22.5 cm
- ❑ Exposed length: 1.5 cm



Multiple Bias Pulses in Plasma



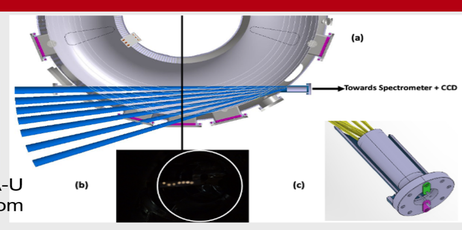
Toroidal & Poloidal Plasma Rotation measurements

Impurity ion toroidal rotation velocity is upgraded to cover complete minor radius towards low field side (LFS)

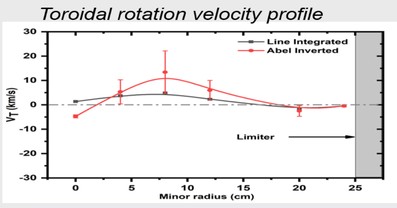
A toroidal rotation velocity of ~ 5 km/s in the core with almost negligible edge toroidal rotation has been observed

Poloidal rotation measured on ADITYA-U

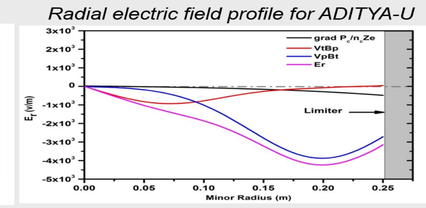
Radial electric field E_r is estimated from both the measurements.



Toroidal rotation velocity profile



Radial electric field profile for ADITYA-U



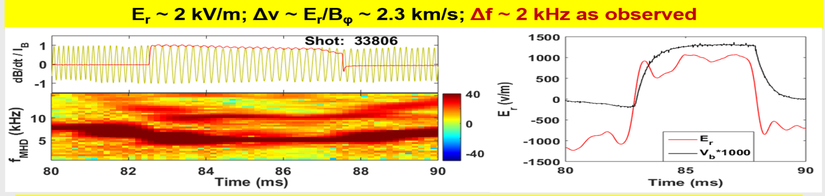
A max. radial electric field ~ 4/5 kV/m is estimated at ~ 0.20 m of minor radius

Positive Bias: rotating plasma in ion diamagnetic direction

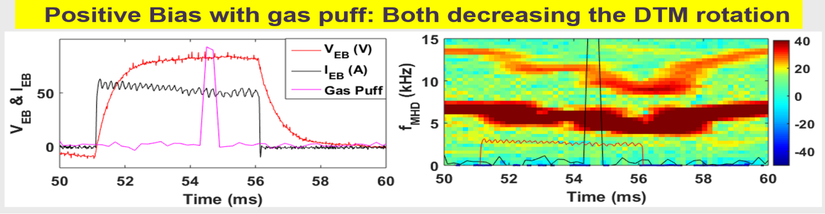
Positive Bias: Rotating plasma in Ion Diamagnetic Direction [Opp. to DTM rotation]

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

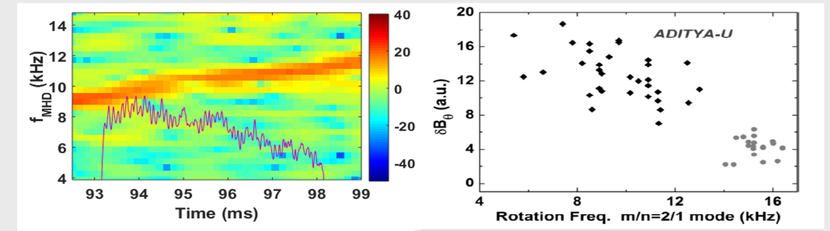
E_r ~ 2 kV/m; Δv ~ E_r/B_φ ~ 2.3 km/s; Δf ~ 2 kHz as observed



Positive Bias with gas puff: Both decreasing the DTM rotation



Negative Bias: rotating plasma in electron diamagnetic direction



DTM Rotation Frequency Increases by ~ 1 – 2 kHz after biasing;

Amplitude of DTM decreases with the increase in rotation frequency[1]

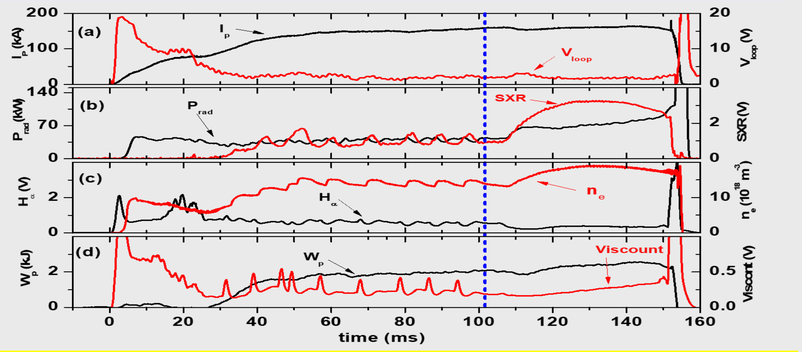
Important Findings:

Plasma rotation influence the DTM rotation

Clarifies Bias Polarity dependency of improved confinement

Neon Impurity Seeding Experiments in ADITYA-U

Ne puffed during Ip flattop with different electron densities and at different B_ϕ



Particle recycling reduces to 70% after the Ne puff.

Radiative power loss P_{rad} increase from 43 to 71 kW, which is ~ 27% of Ohmic i/p power

Leads to the improve plasma energy confinement to 9 ms from 6.5 ms

Summary

- ✓ ADITYA-U operations endeavours towards the demonstration of plasma parameters close to the design parameters of circular plasma operations in graphite toroidal belt limiter configuration.
- ✓ Achieved plasma parameters are: I_P ~ 213 kA, duration ~ 400 ms, chord averaged density (n_e) ~ 3 - 6 x 10^{19} m^{-3}, electron Temp.(T_e) ~ 250 - 500 eV, W ~3 kJ, Max. B_ϕ ~1.5 T (~100% of the design parameter), q ~ 4.
- ✓ Significant plasma performance enhancement is subject to various wall conditioning techniques such as lithium gettering, pulse GDC with He-H_2, Ar-H_2 gas mixture along with robust control of real-time horizontal position.
- ✓ First attempts to produce shaped plasmas by energizing the divertor coil using a Cap-bank. Formation of strike point confirmed through CCD camera, matches quite well with simulation results obtained from code IPREQ.
- ✓ Obtained full deuterium discharges in ADITYA-U, one of the major milestones towards realization of thermo-nuclear fusion reaction. Observed confinement improvement through isotopes effect.
- ✓ Demonstrated for the first time, a novel technique of Inductively driven pellet injector (EPI) in ADITYA-U for disruption mitigation studies, very much relevant for resolving key challenges for fusion devices such as ITER.
- ✓ Novel concept of 42 GHz ECR assisted two pulse operation (one for low loop voltage start-up & second for heating) simultaneously in a single shot executed for the first time. Plasma performance improved considerably.
- ✓ The rotation frequency of the 2/1 drift tearing mode has been controlled by controlling background plasma poloidal rotation using Electrode Biasing experiment in ADITYA-U.
- ✓ Spatial profile of carbon impurity ion toroidal rotation velocity is measured using upgraded high resolution spectroscopic diagnostic installed on ADITYA-U and radial electric field is estimated.
- ✓ Ne puff impurity seeding experiment performed at varied toroidal field to study toroidal rotation & R-I modes. Improved confinement seems to be related to suppression of turbulence due to increase of ExB shear rotation.

28th IAEA Fusion Energy Conference (FEC-2020), 10-15 May, 2021, Virtual.