Novel Approaches for Mitigating Plasma Disruptions and Runaway Electrons in Tokamak ADITYA

by

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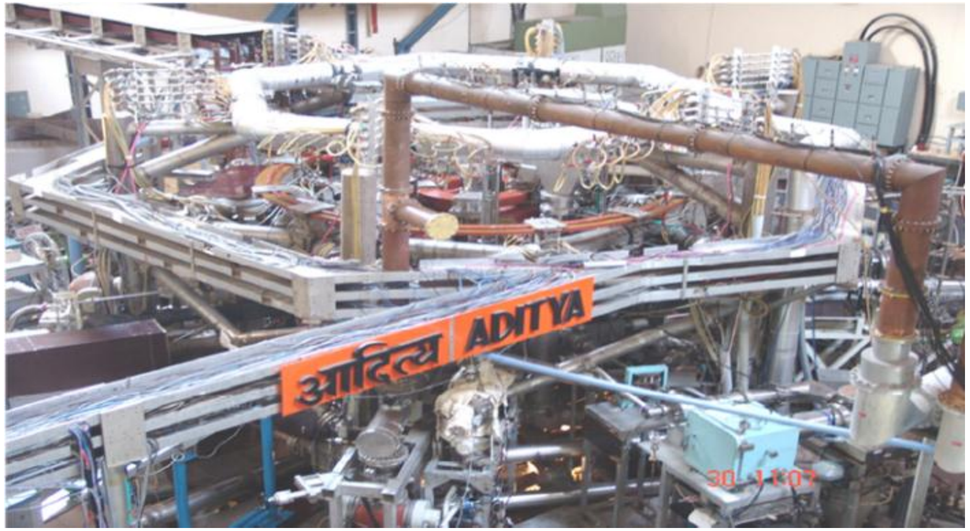
(Contribution from ADITYA Team)



Introduction and Outline

Disruptions in Tokamaks:

- An abrupt termination of a tokamak discharge
- Leading to the sudden loss of plasma stored energies
- The force and heat loads, induced by disruption, damages the machine walls, support structure and in-vessel components

Runaway Electrons (RE) in Tokamaks:

- Electrons that run away in velocity space due to driving force, eE, which overcomes the collisional drag force
- RE generation with higher energies of several tens of MeV is expected during major disruptions in ITER
- When locally deposited these REs can damage the first wall components

Introduction and Outline

Disruptions must be avoided
and
Runaway electrons should be mitigated

Both these topics of utmost importance to bigger Tokamak have been addressed in ADITYA using new techniques

The talk is organized as follows:

- ✓ Novel approaches towards disruption mitigation in ADITYA tokamak
- ✓ Runaway electrons mitigation in ADITYA tokamak
- ✓ Summary

ADITYA Tokamak

Aditya tokamak is a mid-sized air-core tokamak

Machine Parameters:

Major Radius: **0.75 m**

Minor Radius: **0.25 m**

Toroidal field: **0.75 – 1.1 T**

Peak loop voltage: **20 V**

Circular Plasma with circular poloidal limiter

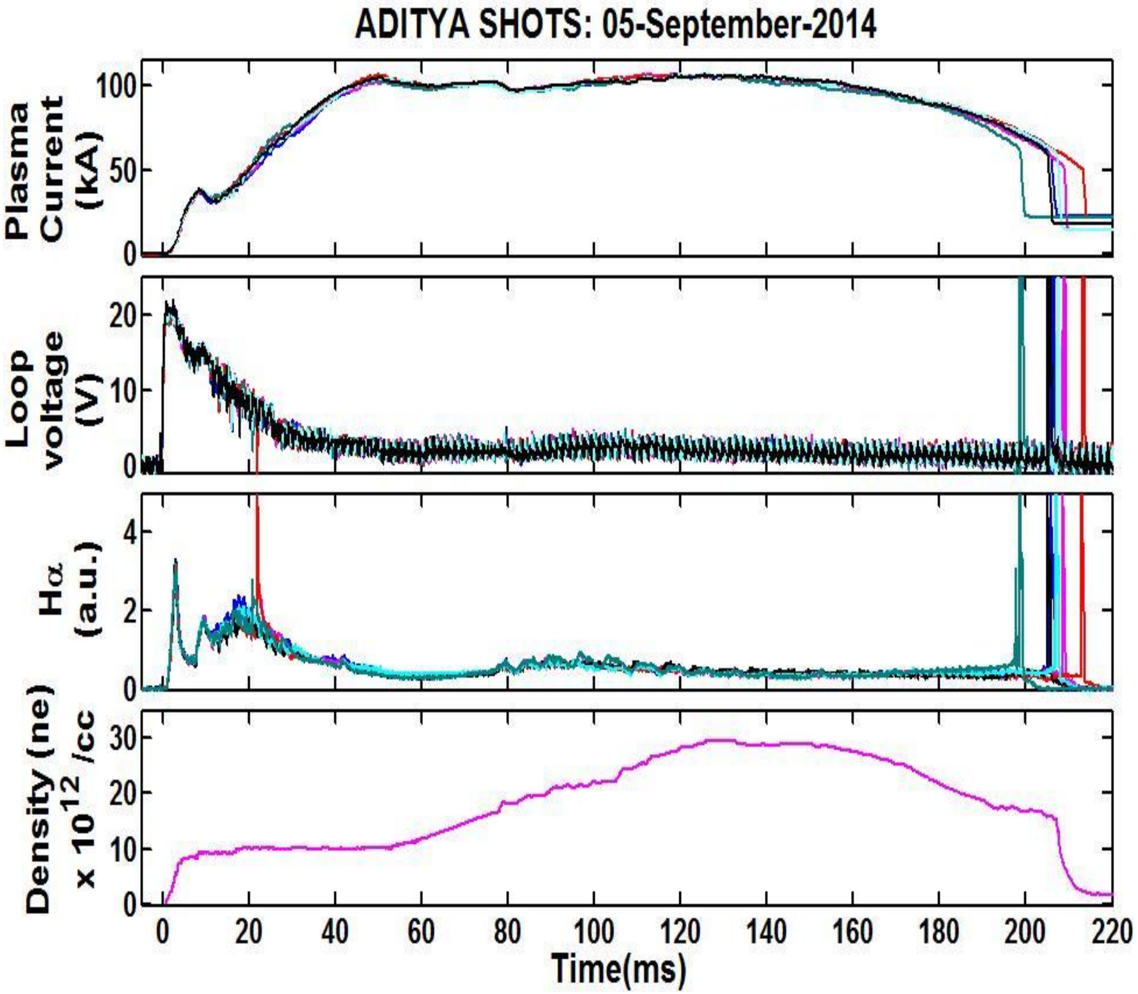
Plasma Parameters:

I_P ~ **70 – 110 kA**

$\overline{n_e}$ ~ **$1 – 3 \times 10^{19}$ m^{-3}**

Te ~ **300 – 600 eV**

Duration ~ **70 – 200 ms**



Typical discharges of ADITYA tokamak

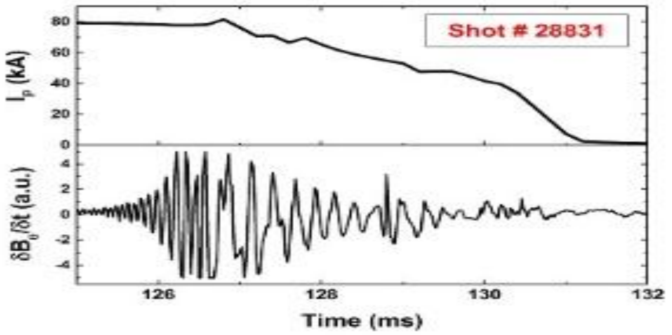
Disruptions in ADITYA

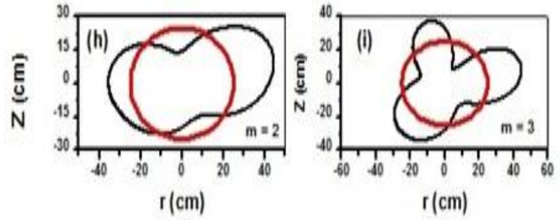
‡ Majority (> 95 %) of disruptions in Aditya show

- ➢ MHD growth prior to disruptions
- ➢ (Identified as m/n = 2/1, 3/1 resistive tearing modes)
- ➢ Cessation of mode rotations and locking
- ➢ Growth of neighbouring chains of islands lead to loss of confinement
- ➢ Total termination of plasma current

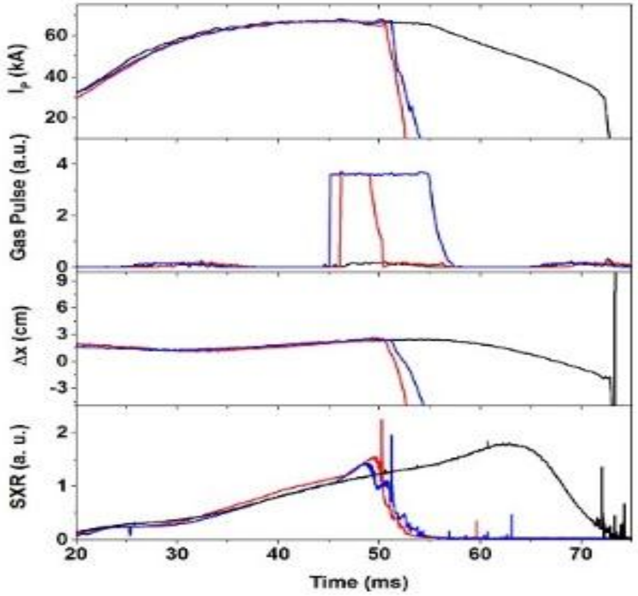
‡ Disruption can be induced by controlled gas puffing

- ➢ Edge cooling leading to generation of resistive tearing modes
- ➢ Causing Disruptions





Deliberate disruption by Gas puffing



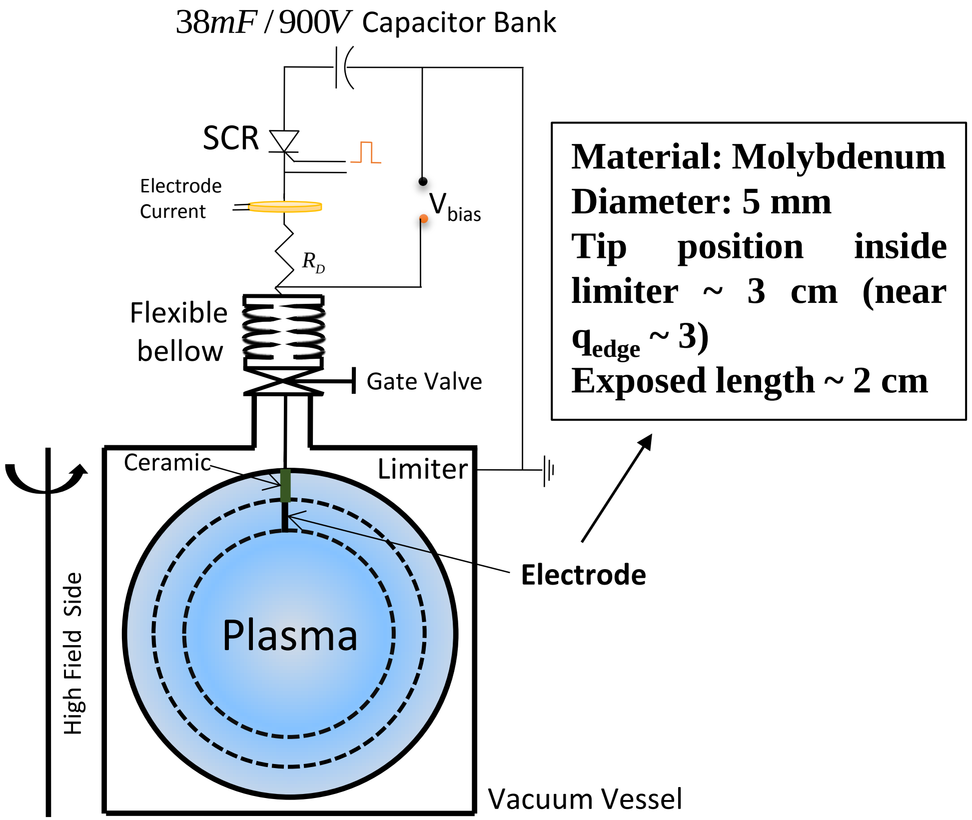
Disruption Mitigation by Biased Electrode

Biased Electrodes induces sheared radial electric fields

Generation of sheared poloidal rotations in edge region

Sheared rotations are known to suppress the MHD fluctuation

Experimental Set-up



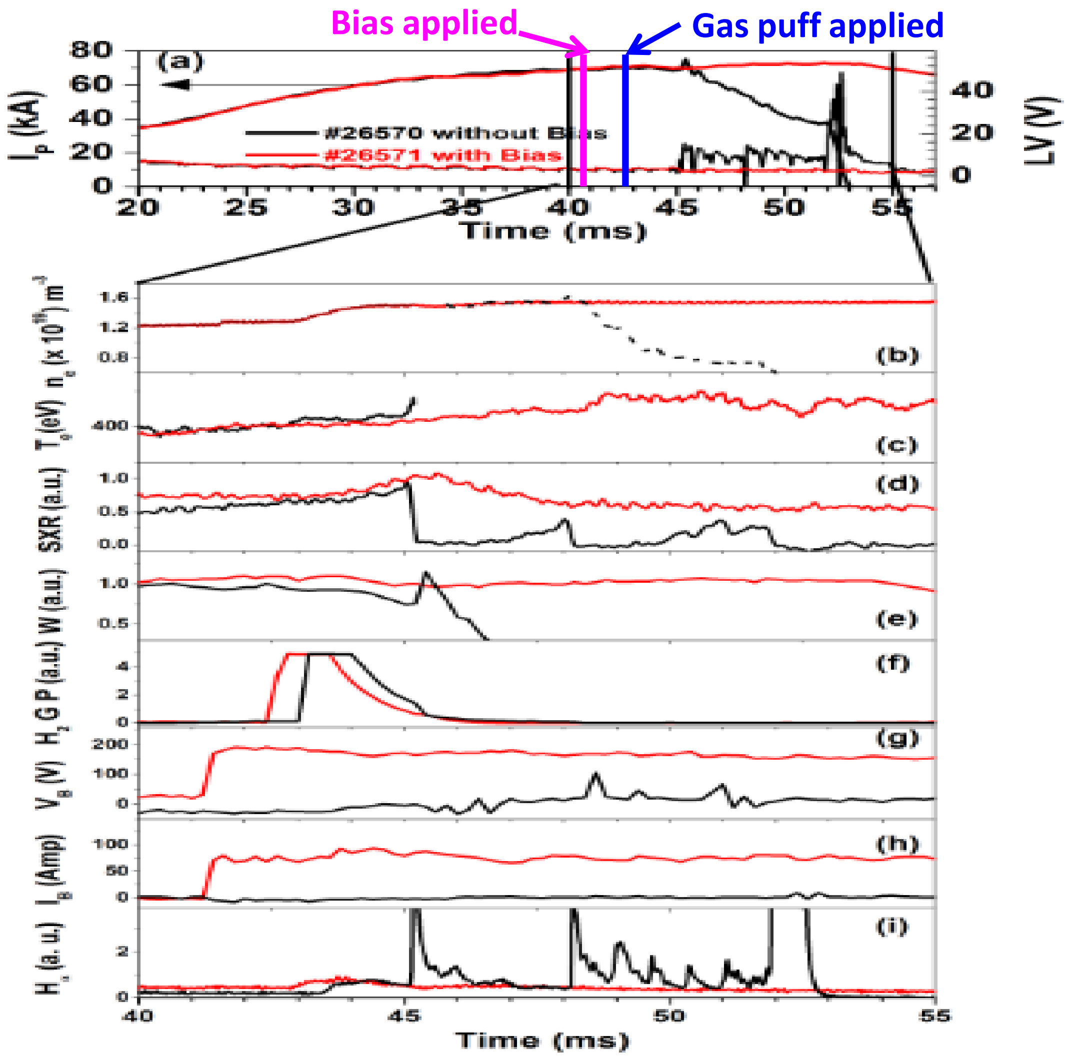
Material: Molybdenum
Diameter: 5 mm
Tip position inside limiter ~ 3 cm (near q_{edge} ~ 3)
Exposed length ~ 2 cm

Hence, MHD generated disruptions in Aditya tokamak are targeted with sheared rotation induced by biased electrode

Disruption Mitigation by Biased Electrode

Disrupted Shot # 26570 without bias – in Black

Disruption avoided in Shot # 26571 with bias (~190V) – in Red


Bias applied

Gas puff applied

By applying bias voltage

Current quench avoided
Plasma current sustained

Density Restored

Temperature Restored

SXR emission Restored

Stored energy Restored

Gas Puff Pulse

Bias Voltage

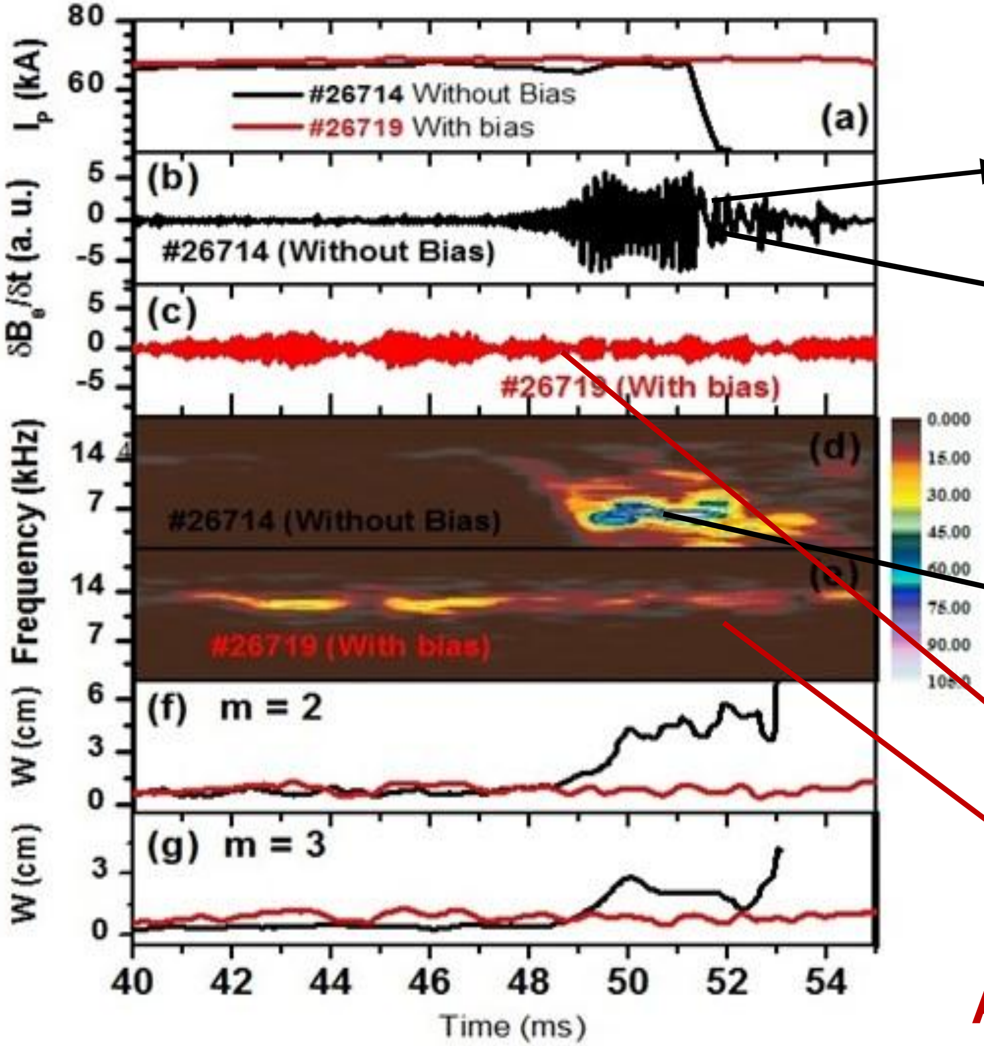
Bias Current

DISRUPTION AVOIDED!!!

Disruption Mitigation by Biased Electrode

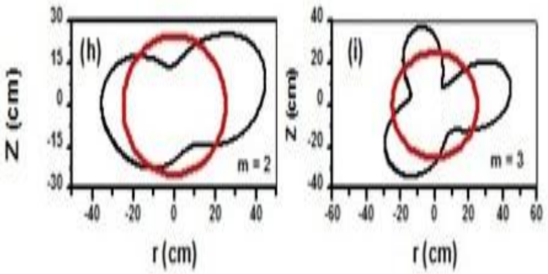
Shot # 26714 without bias – Disrupted (Black)

Shot # 26719 with bias (~ 220V) - Disruption avoided (Red)



With Gas puffing at t ~ 42 ms

MHD Oscillations increases with gas puff in Disruptive discharge



Growth of m/n = 2/1, 3/1 modes

Mode rotation ceases

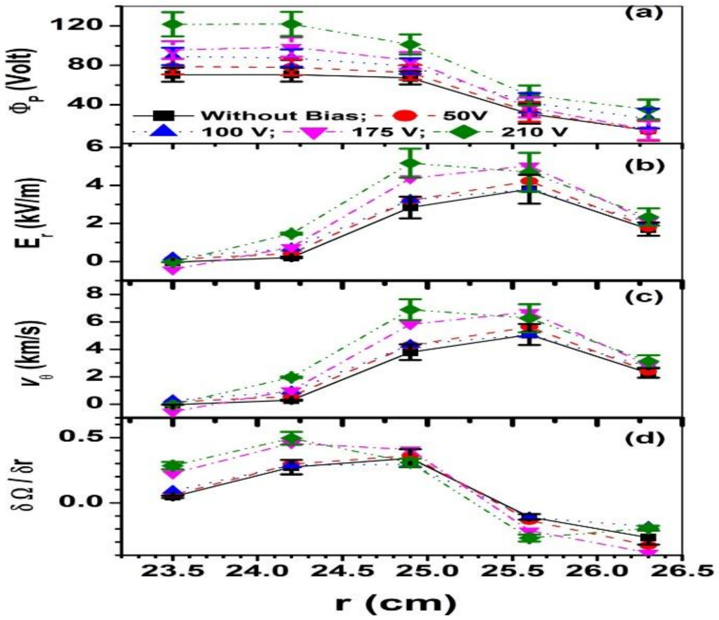
With Application of bias at t ~ 41 ms

Modes do NOT grow

Mode rotation continues

And Disruption does NOT occur !!!

Disruption Mitigation by Biased Electrode



<u>With Application of bias voltage</u>

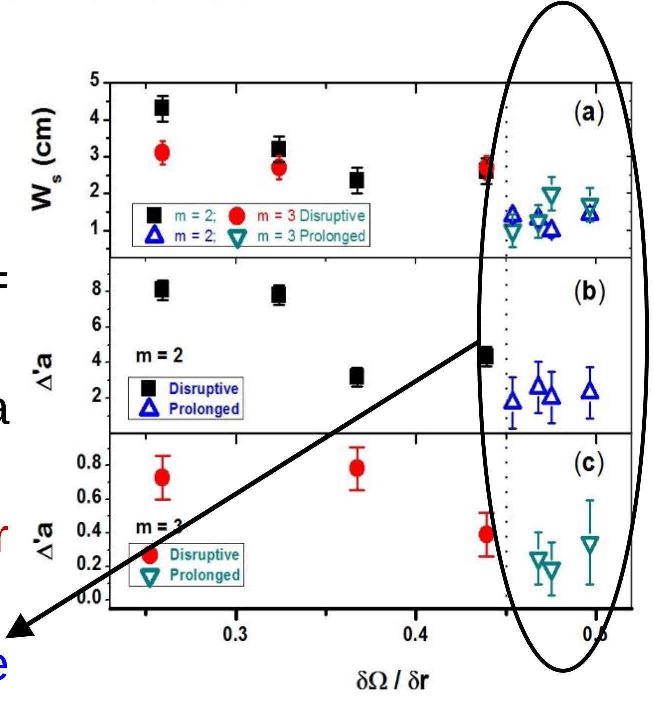
Plasma Potential profile gets modified and Radial Electric field E_r and its shear increases

Leading to

increase in $\boldsymbol{E_r \times B_\Phi}$ rotation and its shear

<u>As the bias voltage is increased</u>

- Increased poloidal flow shear stabilizes both m/n = 2/1, 3/1 modes
- Saturated island width and stability index Δ'a decreases slowly with increase in poloidal flow shear
- For bias voltage ≥ 180 Volts, the flow shear $(\delta\Omega/\delta r \geq 0.45)$ ≥ magnetic shear
- TM generated due to gas puff are stabilized and the Disruptions caused by these modes are mitigated

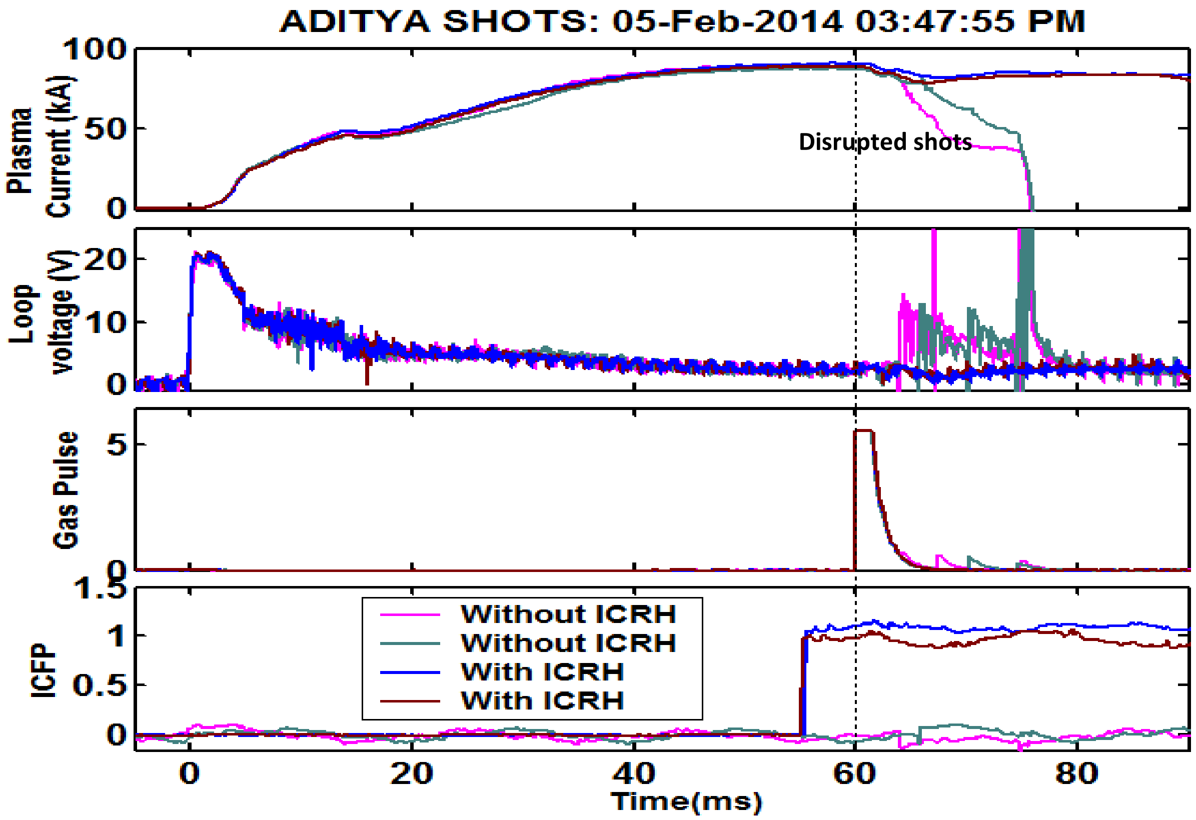


(More details in Poster # EX/P7-17)

Disruption Mitigation by ICRH Power

A biased electrode cannot be put in the edge region of a reactor grade tokamak

Disruptions induced by hydrogen gas puffing are successfully mitigated by applying ICRH power through a fast wave antenna



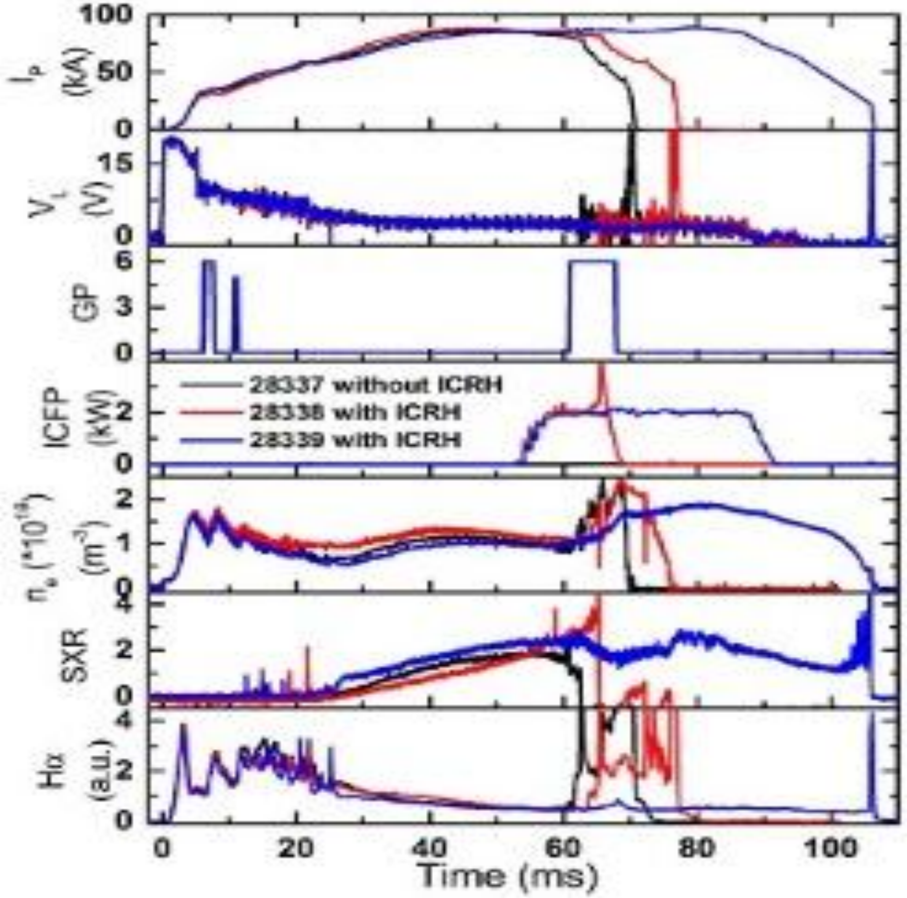
Pre-Programmed ICRH power for disruption mitigation

Current quench avoided
Plasma current sustained

Power Injected
~ 50 to 70 kW
5 ms prior to gas puff injection

DISRUPTION AVOIDED!!!

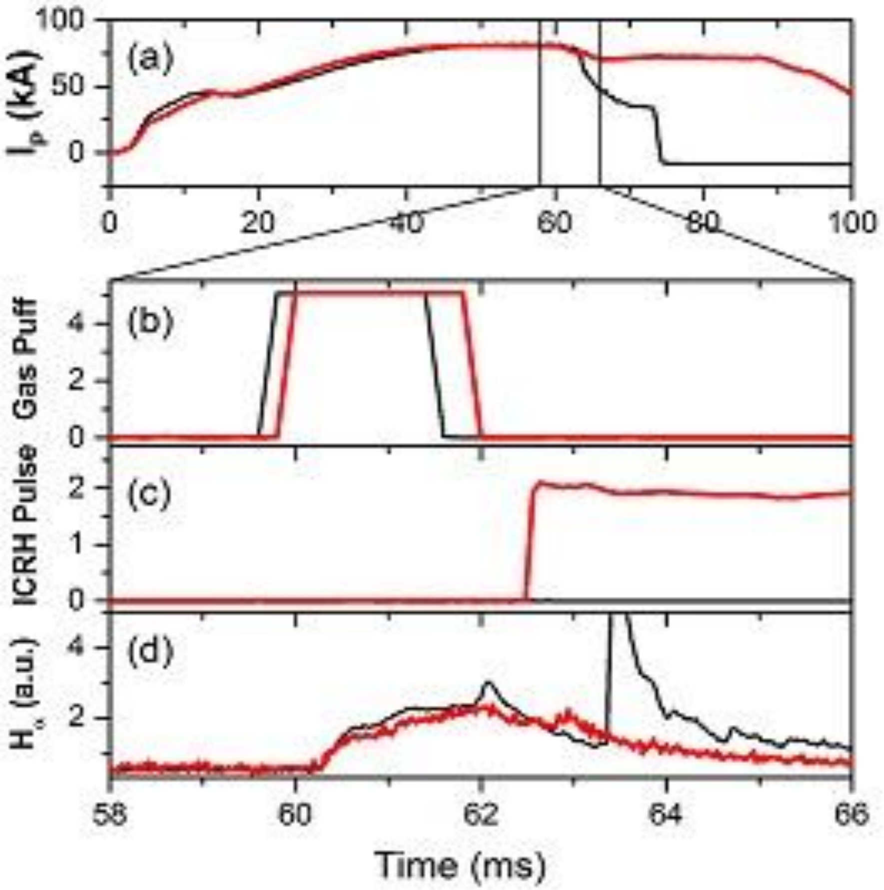
Disruption Mitigation by ICRH Power



Similar to bias experiments

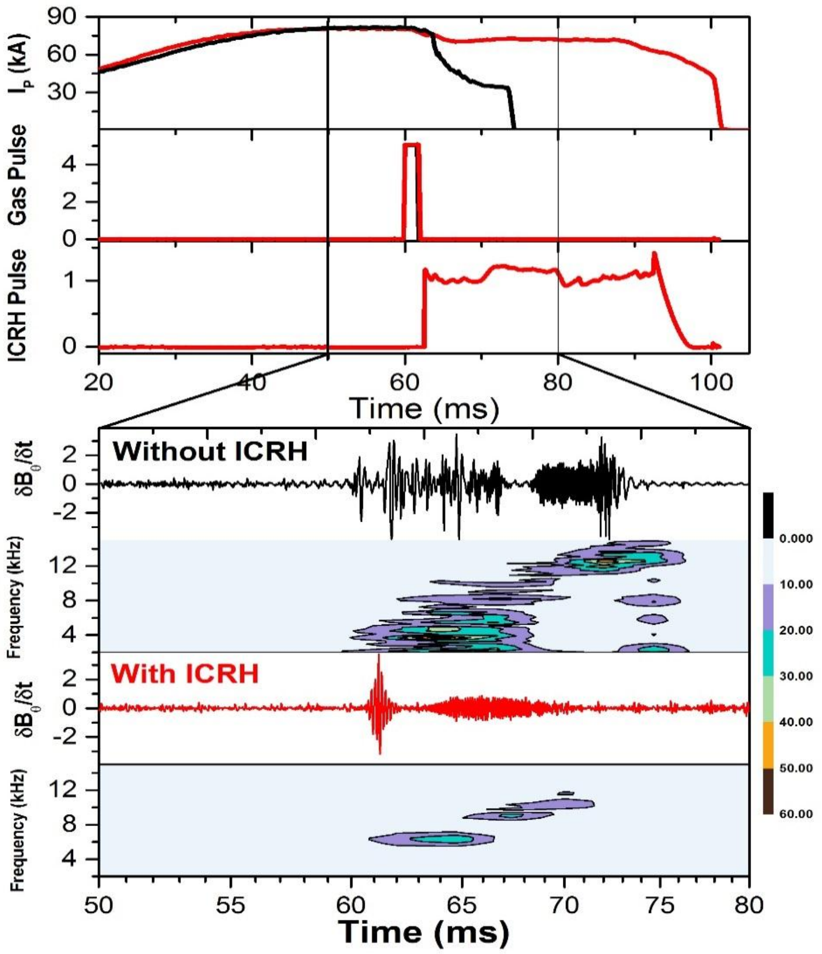
- ✓ **The plasma density is restored**
- ✓ **Temperature is restored**
- ✓ **disruption avoided with ICR pulse**

Disruption Mitigation in Real time



Gas-puff induced H_α intensity increase is used as a precursor for triggering the ICR pulse.

Disruption Mitigation by ICRH Power



Radial Electric Field measurements in presence of ICR pulse is underway

Further Analysis Show

- ➢ The MHD activity induced by gas puff gets reduced with ICRH pulse.
- ➢ The disruption avoidance is observed with ~50 to 70 kW of ICR power
- ➢ Increasing the power > 70 kW does not lead to disruption avoidance

Possible Cause

- ➢ The disruption avoidance does not seem to be due to heating near the Islands. ICR Heating required power > 100 kW
- ➢ ICR induced radial electric field generating a shear rotation and subsequent avoidance of disruption as in case of biasing may be a possibility

(More details in Poster # EX/P7-17)

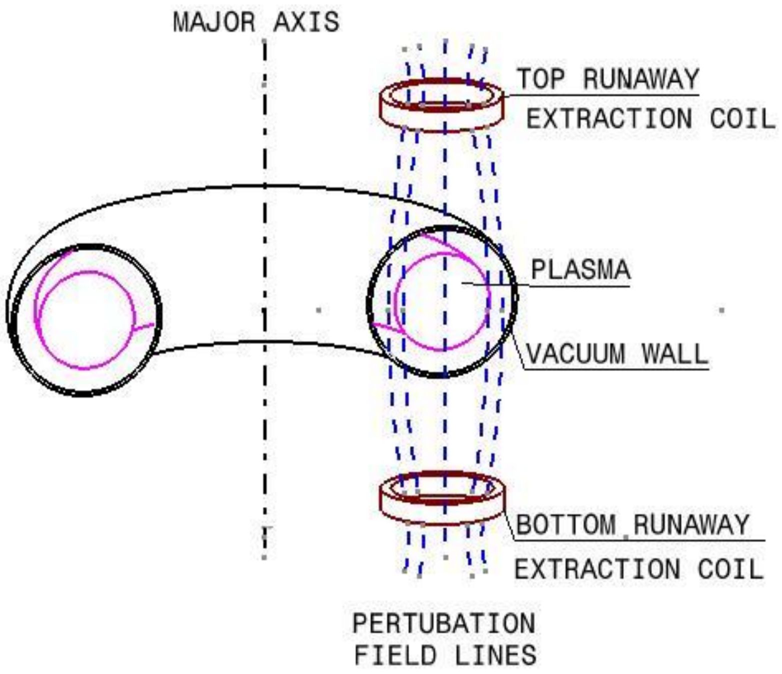
Runaway Electrons Mitigation

Mitigation techniques used in other tokamaks:

‡ injection of high pressure gas jet through the nozzle or fast valves

‡ Resonant magnetic perturbation (RMP) for runaway losses through magnetic fluctuation

In Aditya tokamak, Localized Vertical Magnetic field (LVF) perturbation technique is successfully attempted to mitigate REs



LVF setup

- Application of a short localized vertical field perturbation of 150 to 260 Gauss
- The perturbation causes no disruption of the thermal component of the plasma
- The perturbation leads to a radial diffusion

$$D_{\perp} \approx \left[\left(B_p/B\right)L\right]^2 v_{\parallel}/2\pi R$$

$v_{\parallel}$ → particle velocity along magnetic field, B

B_p→ perturbation magnetic field

L→ Scale length of the perturbation field gradient

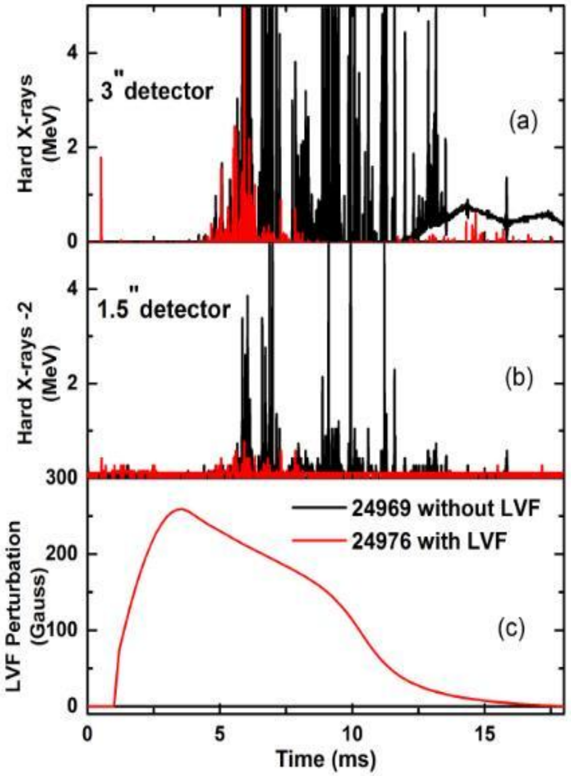
As $D_{\perp} \propto v_{\parallel}$ the runaway particle diffusion must be larger than the thermal particle diffusion by at least a factor of $\frac{v_{\parallel r}}{v_{\parallel th}}$

Hence REs can be extracted without disturbing the thermal plasma

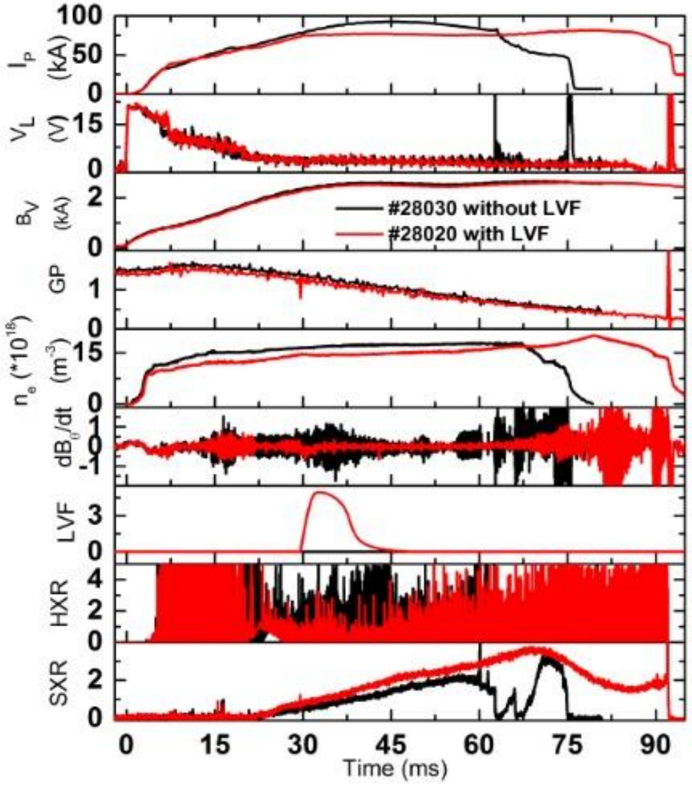
RE Extraction by LVF Perturbation

RE mitigation with application of LVF in different phases of plasma current

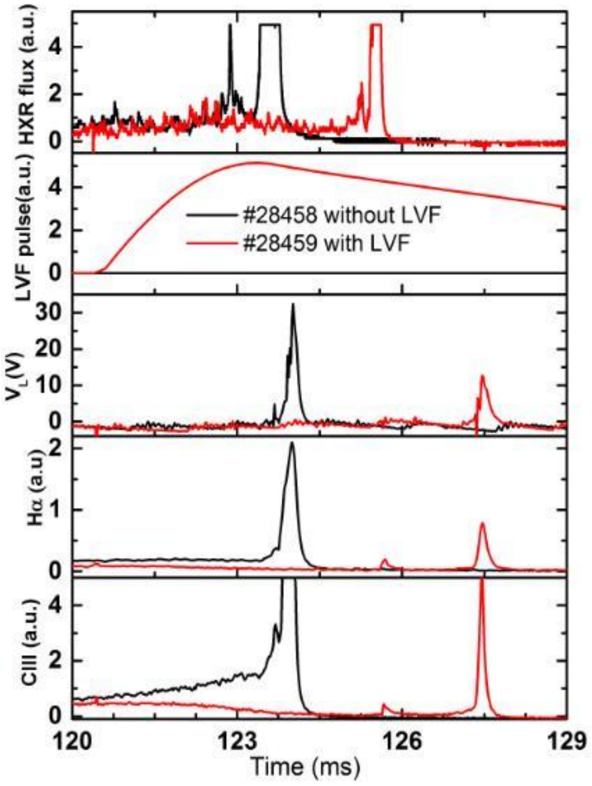
Breakdown phase



Current ramp up phase



Disruption phase



Results:

- ➢ Significant reduction (~ 5 times) in initial RE population
- ➢ Reduction in REs during current ramp up and disruption phases
- ➢ Runaway current contribution in main current reduced and the discharge parameters are also improved

Conclusions

- ✓ Disruptions, induced by hydrogen gas puffing are successfully mitigated using biased electrode and ICR pulse techniques
- ✓ Both methods show identical characteristics such as MHD activity suppression leading to disruption avoidance.
- ✓ Biasing voltage ~ 180 – 250 V and ICR power of 50 – 70 kW required for disruption avoidance
- ✓ Induced poloidal rotation shear > magnetic shear with biasing stabilizes the resistive tearing modes leading to disruption avoidance
- ✓ ICR induced radial electric field may be inducing sheared poloidal rotation leading to disruption avoidance
- ✓ The runaway electrons (RE) are mitigated using local vertical field perturbation
- ✓ The REs are mitigated during plasma current startup, plasma current flattop and discharge termination phases

Thank you!

The ADITYA Team:

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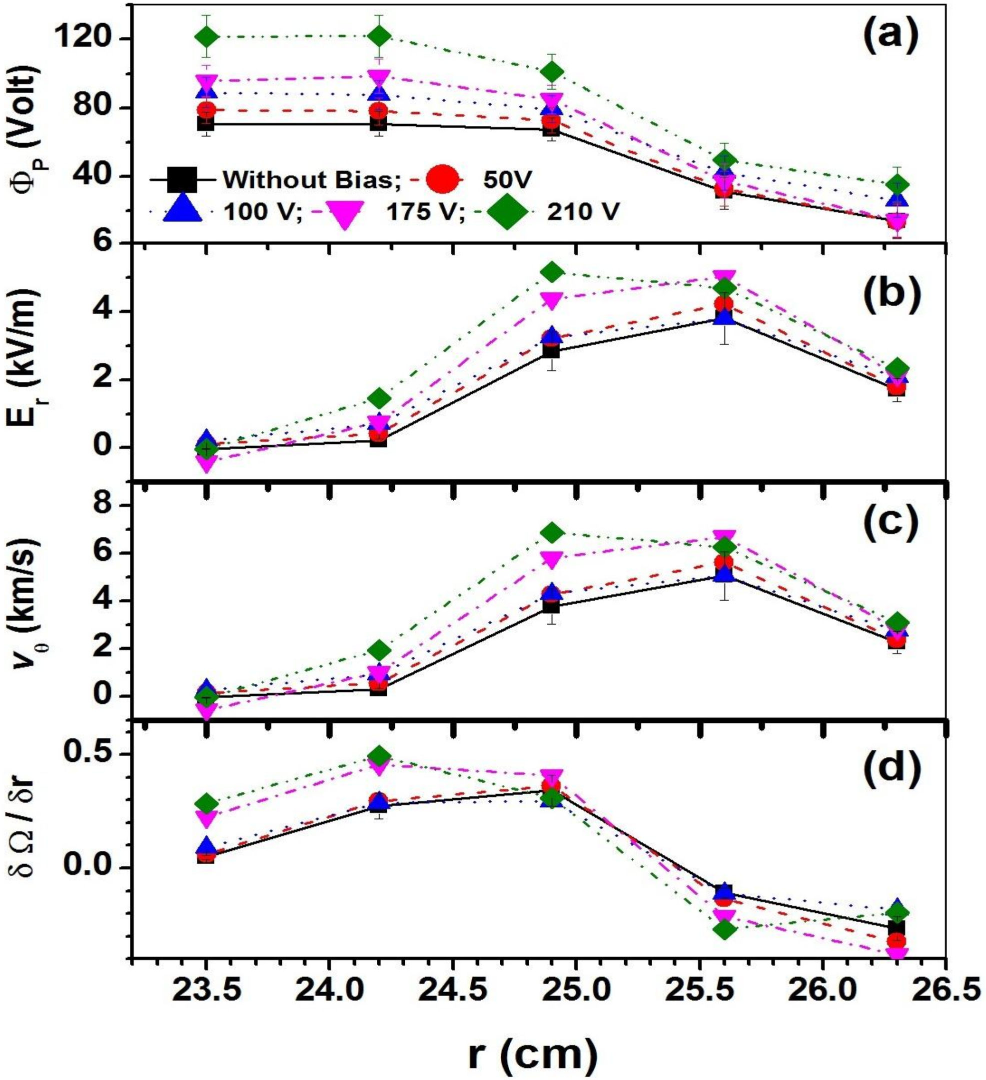
Back up slides

Plasma Poloidal Rotation with and without biasing



Radial profiles of

(a) plasma potential $\Phi_P = \Phi_f + 3k_B T_e$

(b) radial electric field $E_r = -d\Phi_P / dr$

(c) poloidal flow velocity E_r / B_ϕ

(d) normalised poloidal flow Shear

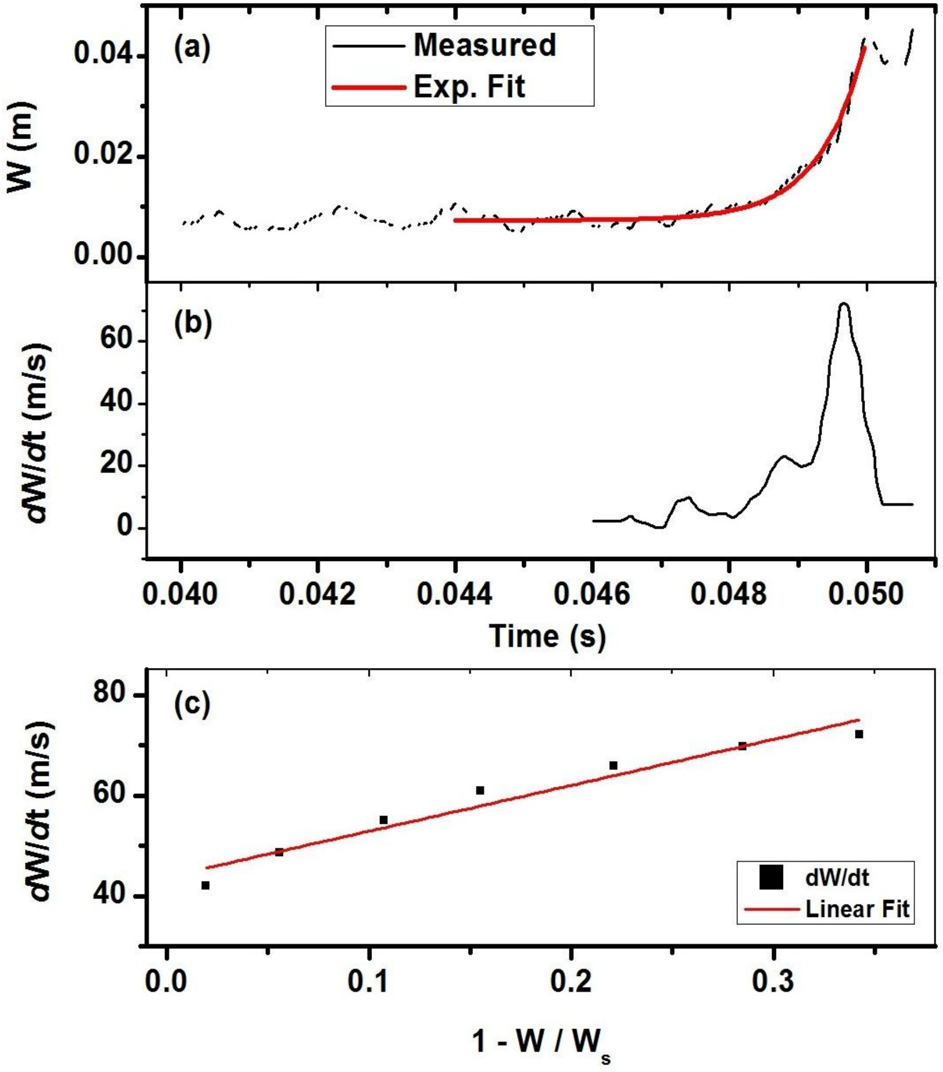
$$\delta\Omega / \delta r = a\left(\frac{d}{dr}\left(\frac{E_r}{B_\phi}\right)\right) / v_{A\theta}$$

$$v_{A\theta} = B_\theta / \sqrt{\mu_0 m_i n_i}$$

$E_r \times B_\phi$ rotation (in ion-diamagnetic drift direction) of plasma at r ~ 24 cm increases from ~ 3.5 km/s (without bias) to ~ 7.0 km/s (with +210 V bias)

Increased Poloidal Flow Shear with Bias

Stability index (Δ') calculation from Mirnov Coil Measurements



Using $$\gamma \approx 0.55\tau_R^{-3/5}\tau_A^{-2/5}(\Delta' a)^{4/5}\left(\frac{a}{R}n\frac{aq'}{q}\right)^{2/5}$$

$\tau_R = \mu_0 r_s^2 / \eta$ is resistive diffusion time

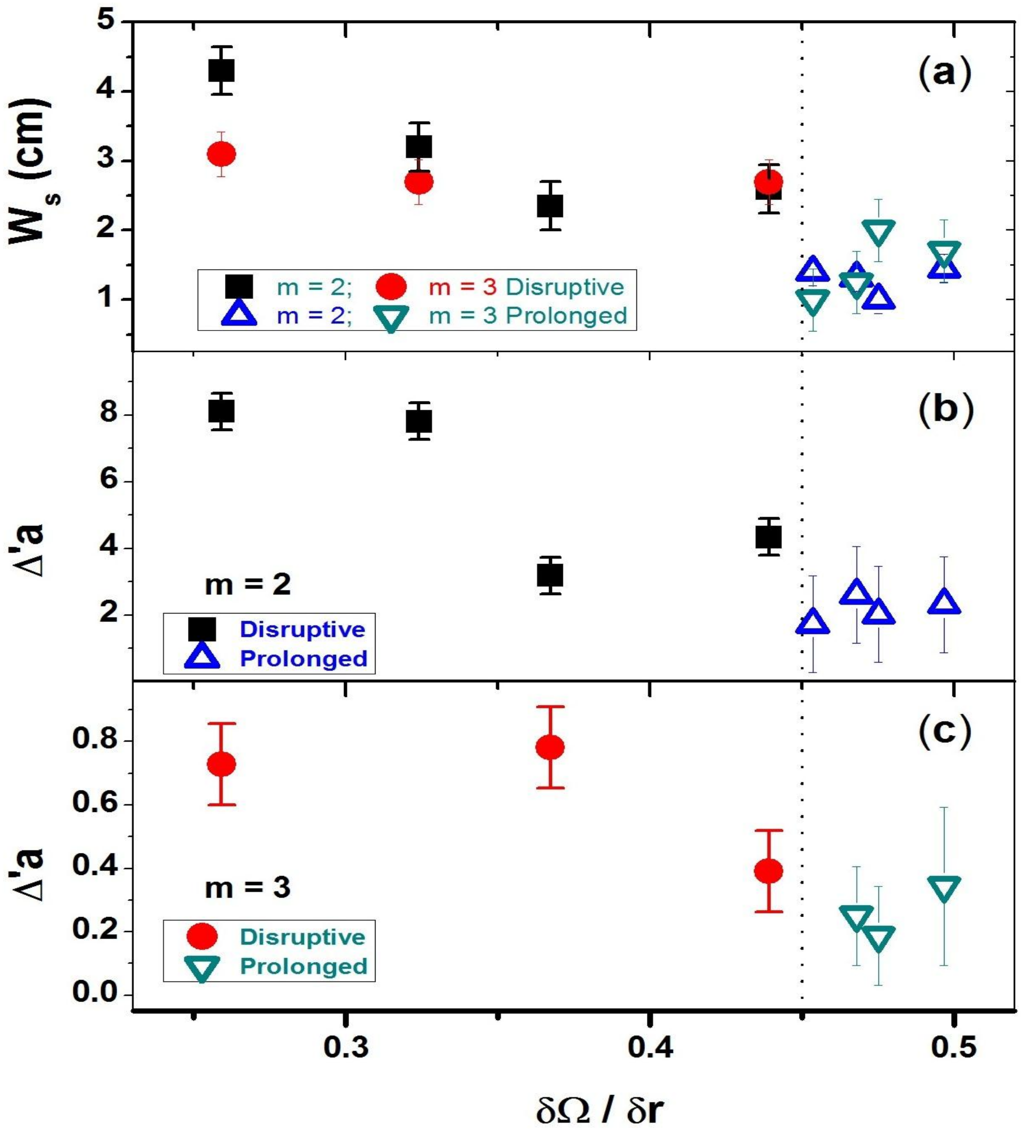
τ_A Alfven transit time

Using Rutherford equation:

$$\frac{dW}{dt} = 1.66\Delta'\frac{\eta}{\mu_0}\left[1 - \frac{W}{W_S}\right]$$

W_S is saturation island width

η is Spitzer resistivity



Variation of saturation island width (W_S)
and (Δ'a) as a function of poloidal flow
shear for m = 2 and m = 3 modes.

Disruptions Avoided for

$$\delta\Omega / \delta r \; > 0.45$$

When
Ratio of Flow Shear to Magnetic Shear

$$|G' / F'| \; \approx \; 1$$