OV/4-3Ra: Overview of SST-1 Upgrade & Recent Experiments in SST-1

OV/4-3Rb: Overview of Recent Experimental Results from Aditya Tokamak

Presented by:

Subrata Pradhan

Institute for Plasma Research

India

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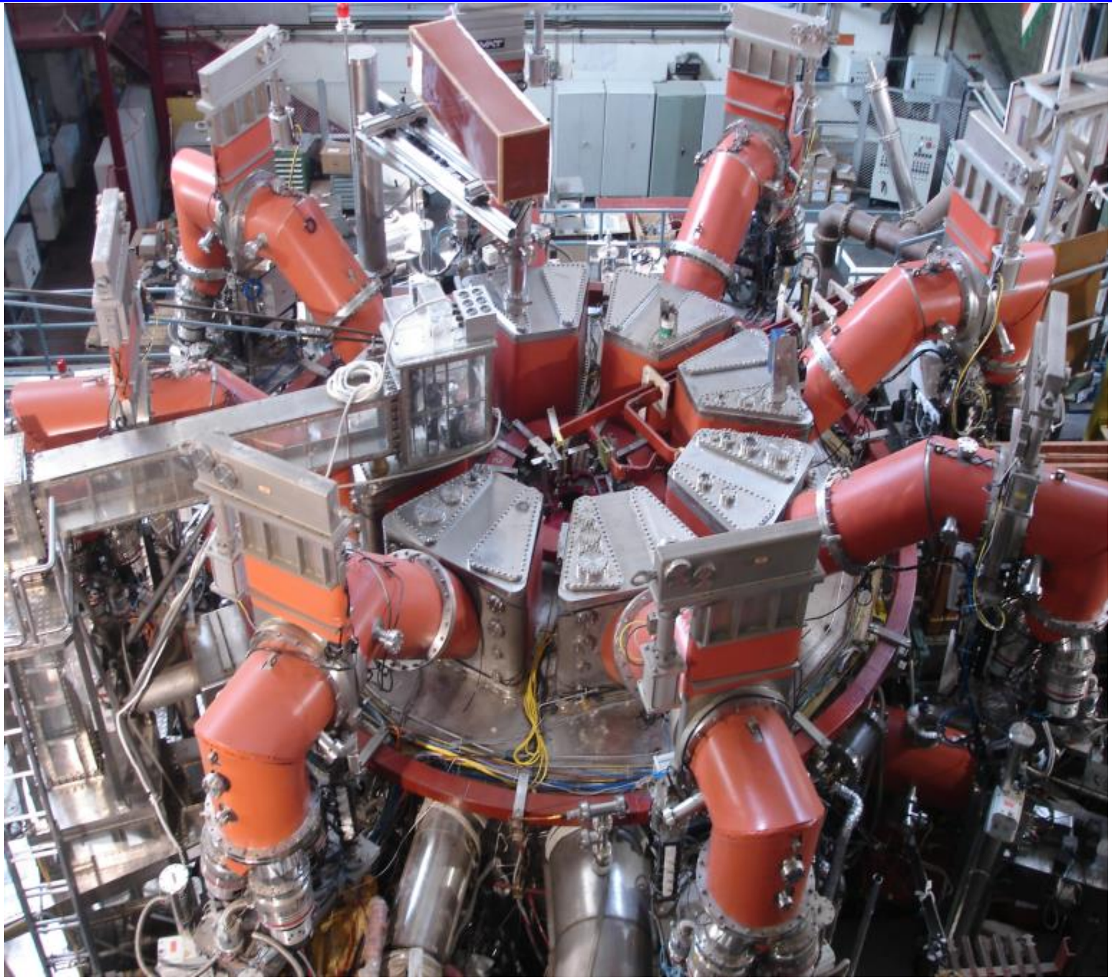
Contributors: OV4-3Ra:

<u>S. Pradhan</u>, Z. Khan, V. L. Tanna, U. Prasad, Y. Paravastu, D. C. Raval, H. Masand, Aveg Kumar, J. R. Dhongde, S. Jana, B. Kakati, K. B. Patel, M. K. Bhandarkar, B. K. Shukla, D. Ghosh, H. S. Patel, T. J. Parekh, I. A. Mansuri, K. R. Dhanani, A. Varadharajulu, Y. S. Khristi, P. Biswas, C. N. Gupta, S. George, P. Semwal, D. K. Sharma, H. K. Gulati, K. Mahajan, B. R. Praghi, M. Banaudha, A. R. Makwana, H. H. Chudasma, M. Kumar, R. Manchanda, Y. S. Joisa, K. Asudani, S. N. Pandya, S. K. Pathak, S. Banerjee, P. J. Patel, P. Santra, F. S. Pathan, P. K. Chauhan, M. S. Khan, P. L. Thankey, A. Parkash A, P. N. Panchal, R. N. Panchal, R. J. Patel, G. I. Mahsuria, D. P. Sonara, K. M. Patel, S. P. Jayaswal, M. Sharma, J. C. Patel, P. Varmora, G. L. N. Srikanth, D. R. Christian, A. Garg, N. Bairagi, G. R. Babu, A. G. Panchal, M. M. Vora, A. K. Singh, R. Sharma, H. D. Nimavat, P. R. Shah, G. Purwar, T. Y. Raval, A. L. Sharma, A. Ojha, S. Kumar, N. K. Ramaiya, V. Siju, M. V. Gopalakrishna, A. Kumar, P. K. Sharma, P. K. Atrey, S.V. Kulkarni, K. K. Ambulkar, P. R. Parmar, A. L. Thakur, J. V. Raval, S. Purohit, P. K. Mishra, A. N. Adhiya, U. C. Nagora, J. Thomas, V. K. Chaudhari, K. G. Patel, S. Dalakoti, C. G. Virani, S. Gupta, Ajay Kumar, B. Chaudhari, R. Kaur, R. Srinivasan, A. N. Sharma, K. J. Doshi , D. Raju, D. H. Kanabar, R. Jha, A. Das, D. Bora & SST-1 Team

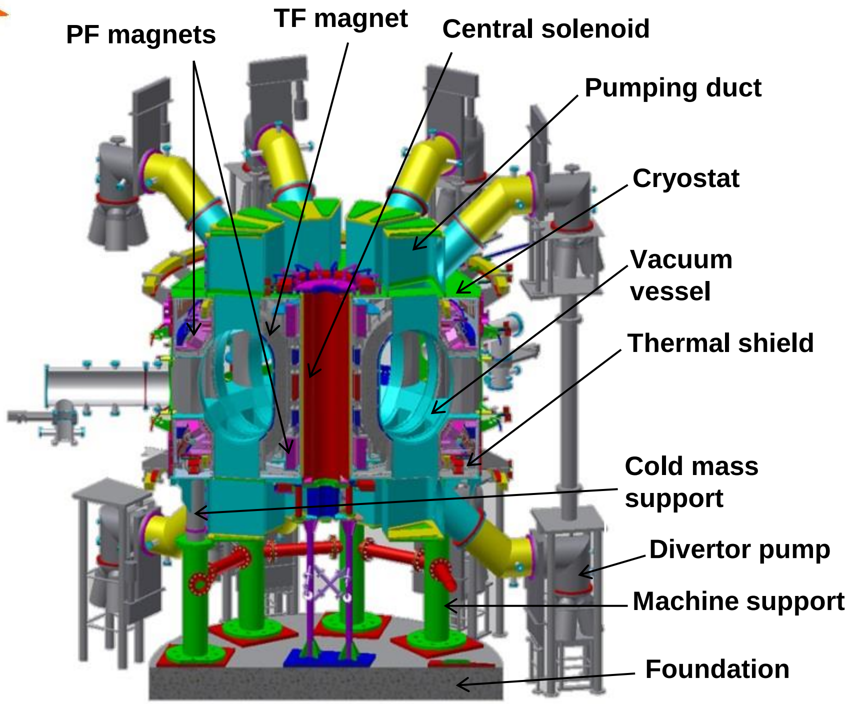
Contributors: OV4-3Rb:

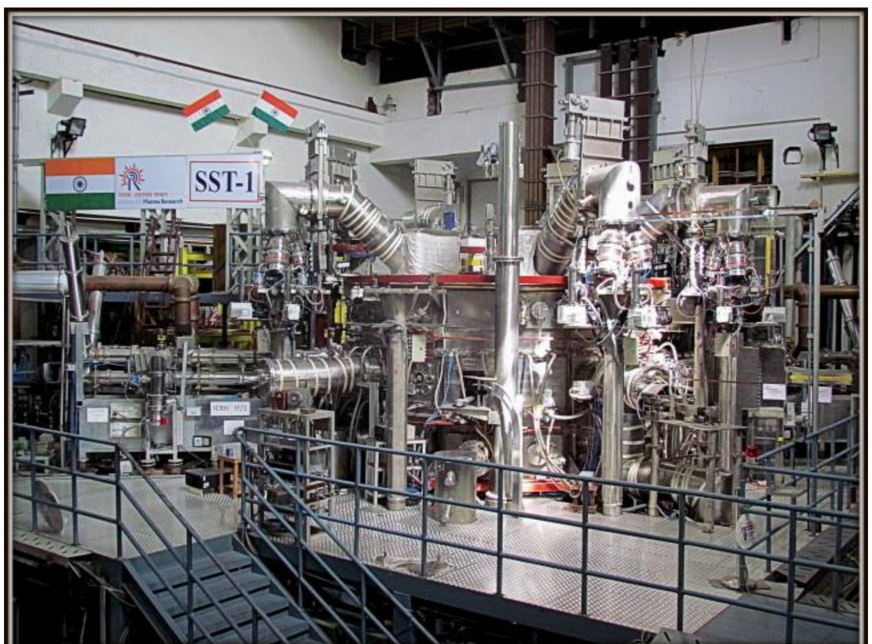
<u>R. L. Tanna</u>, J. Ghosh, P. K. Chattopadhyay, Harshita Raj, Sharvil Patel, P. Dhyani, C.N. Gupta, K.A. Jadeja, K.M. Patel, S.B. Bhatt, V.K. Panchal, N.C. Patel, Chhaya Chavda, Praveenlal E.V, K.S. Shah, M.N. Makawana, S.K. Jha, M.V. Gopalkrishana, K. Tahiliani, Deepak Sangwan, D. Raju, Umesh Nagora, S.K. Pathak, P. K. Atrey, S. Purohit, J. Raval, Y. S. Joisa, C.V.S. Rao, M. B. Chowdhuri, S. Banerjee, N. Ramaiya, R. Manchanda, J. Thomas, Ajai Kumar, Kumar Ajay, P. K. Sharma, S.V. Kulkarni, K. Sathyanarayana, B.K. Shukla, Amita Das, R. Jha, Y.C. Saxena, A. Sen, P.K. Kaw, D. Bora and the ADITYA Team.

OV/4-3Ra: Overview of SST-1 Upgrade & Recent Experiments in SST-1



- **Up-gradation in SST-1 since 2014 (PFC)**
- **Recent Experiments in PFC equipped SST-1 & Future plans**

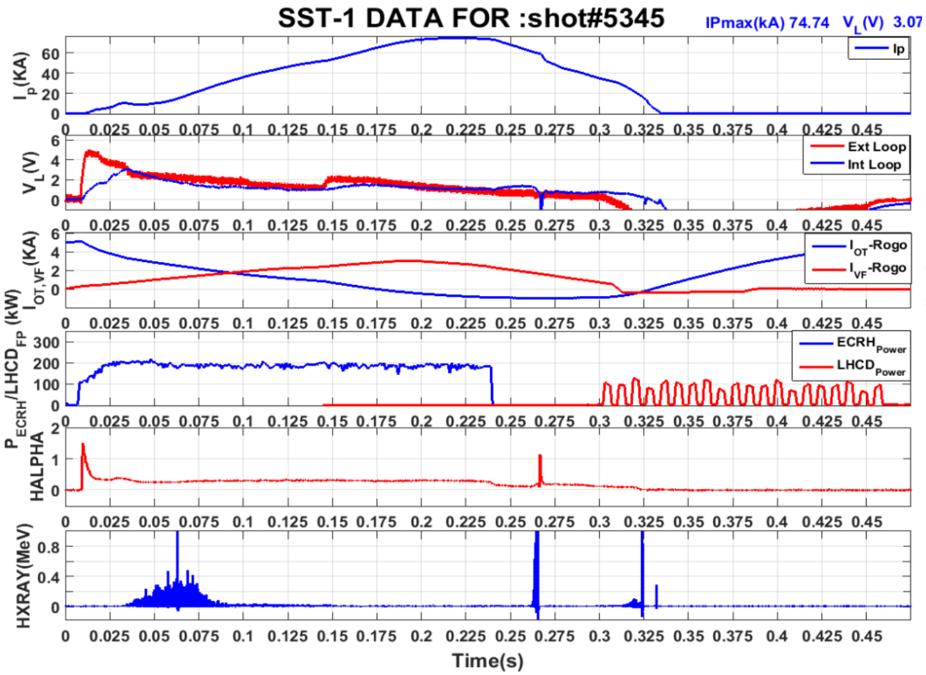


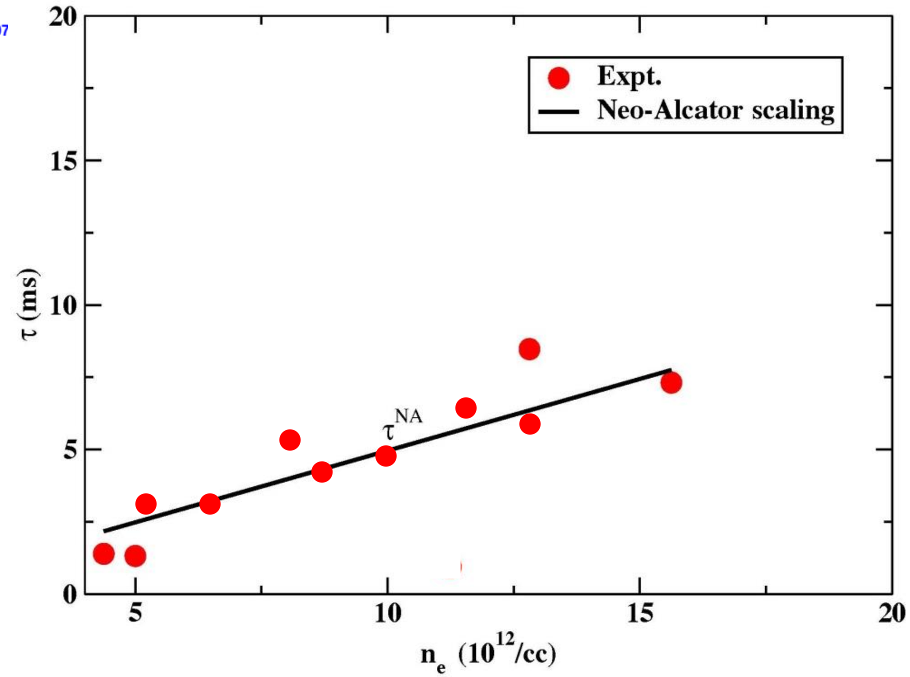


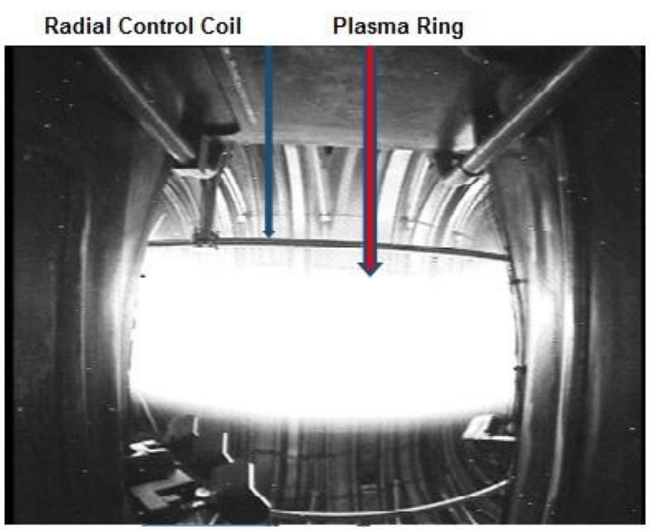
Parameters	Values
Major radius	1.1 m
Minor radius	0.2 m
SS surface area of VV	75 m^2
Exposed surface area of PFC	40 m^2
Plasma species	Hydrogen
Volume enclosed by PFC	16 m^3
Ultimate vacuum in VV	~1.0×10^{-8} mbar
Operating pressure range	5.0×10^{-5} mbar (max)
Steady State Heat Flux (First wall Comp.)	
Main Baffle	0.25 MW/m2
In / Outboard	0.25 MW/m2
Passive Stabilizer	
In / Outboard	0.6 MW/m2
Divertor Plate	
In / Outboard	1.0 MW/m2
Poloidal Limiter	

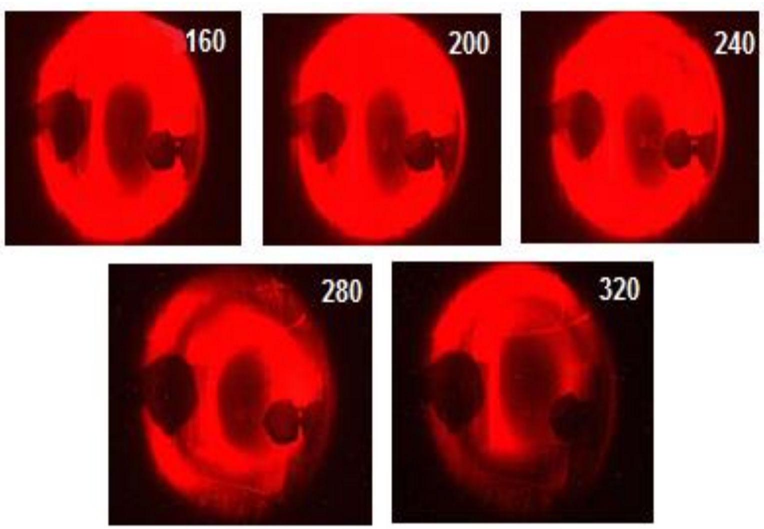
SST-1 up-gradation (phase-1): Assembly & installation of Plasma Facing Components

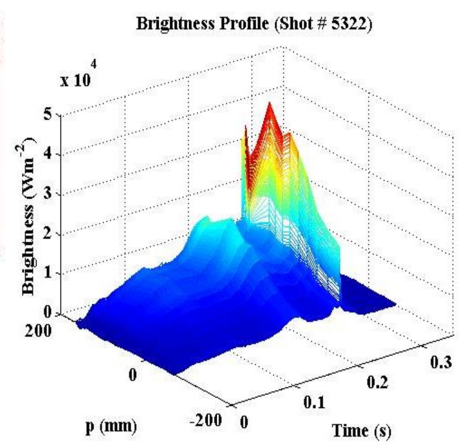
Typical SST-1 discharges (prior to PFC)





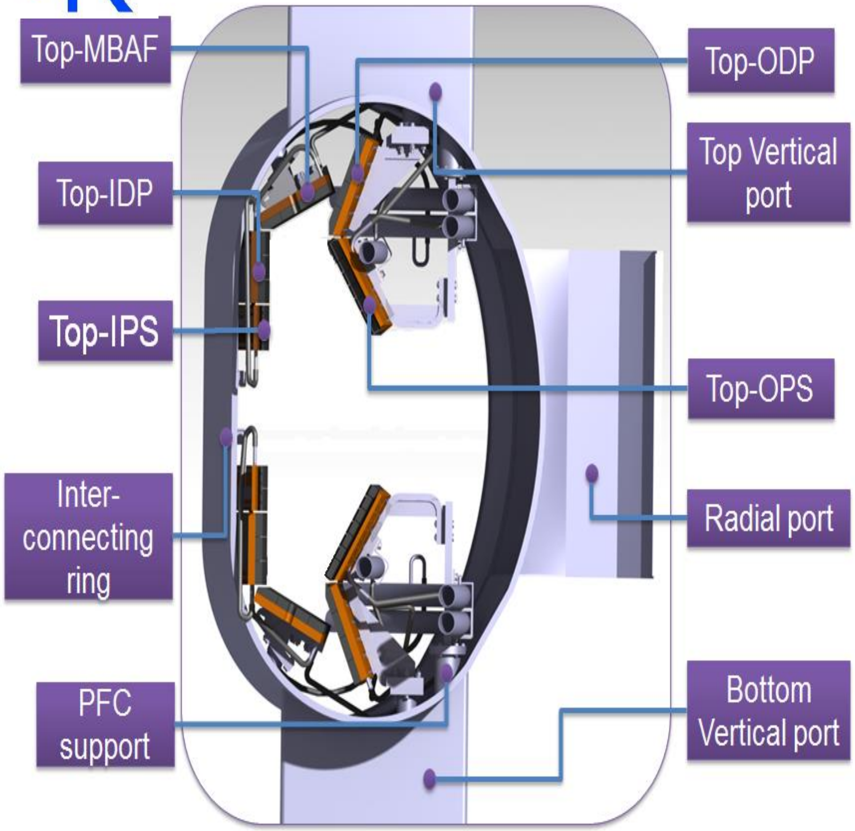


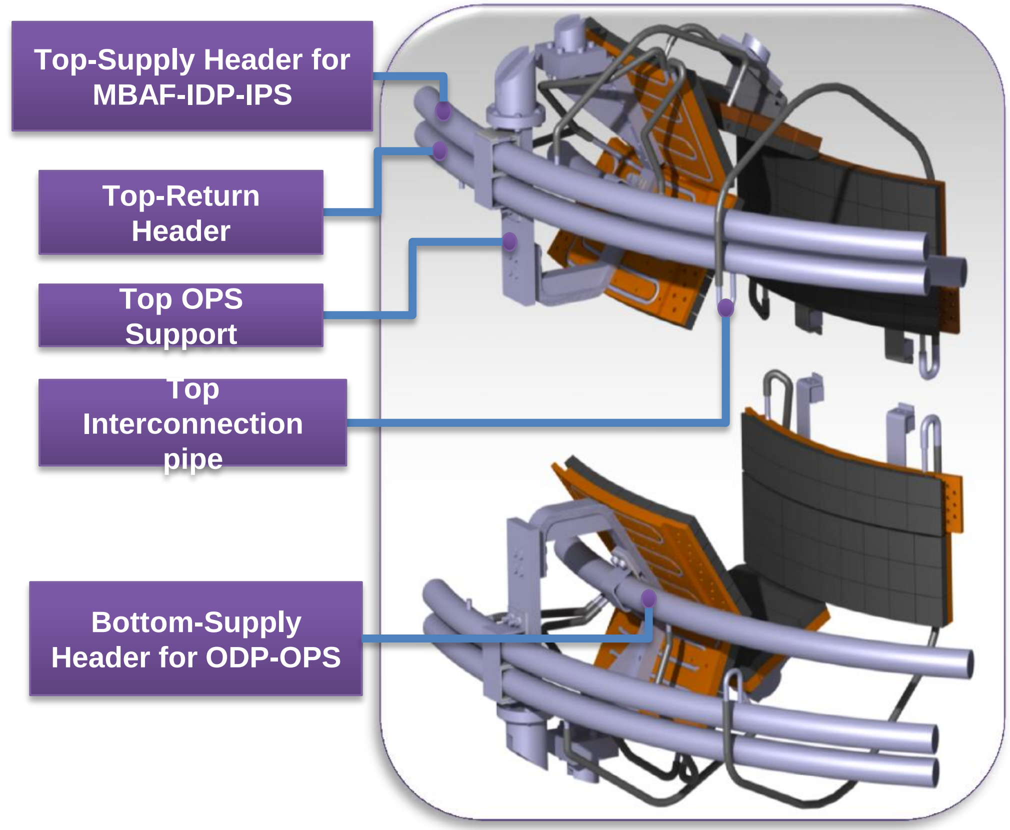


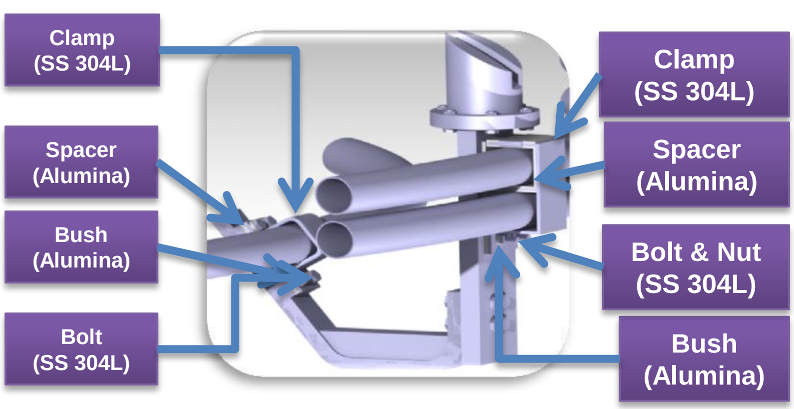


NF 55 (2015)

Up-gradation: Plasma Facing Components in SST-1



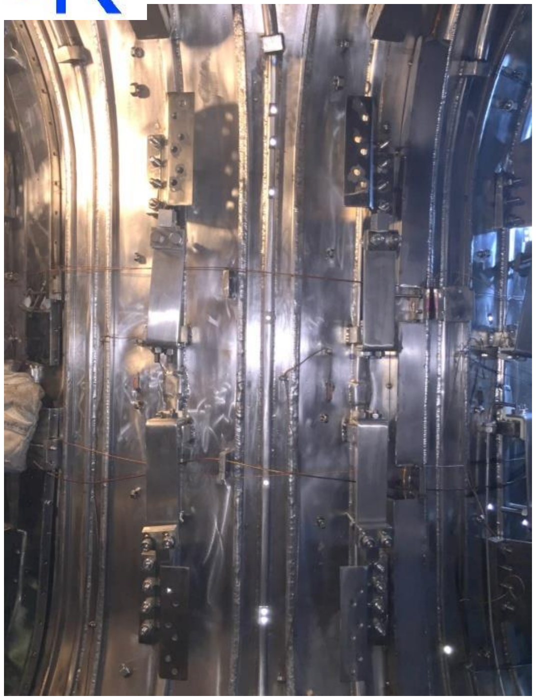


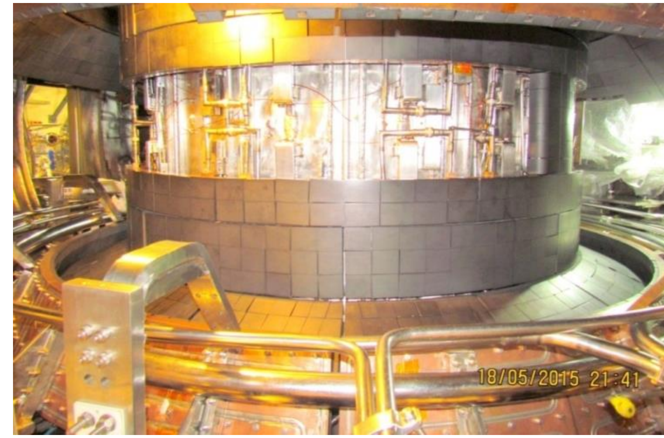


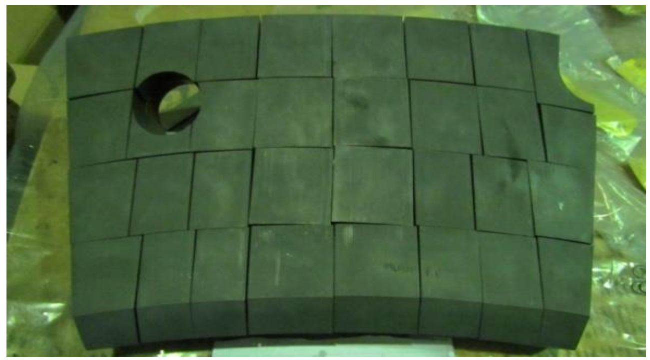
PFC Module
Inboard Divertor Plate (IDP): 480 Nos. of GT, 32 Nos of Inconel supports
Outboard Divertor Plate (ODP): 1024 Nos. of GT, 32 Nos of Inconel support
Inboard Passive Stabilizer (IPS): 256 Nos. of GT, 32 Nos of Inconel support
Outboard Passive Stabilizer (OPS): 960 Nos of GT, 16 Nos of Inconel support
Main Baffle (MBAF): 1024 Nos. of GT, 32 Nos of Inconel support
Isolation requirements: 1MΩ isolation across support location of IPS and OPS

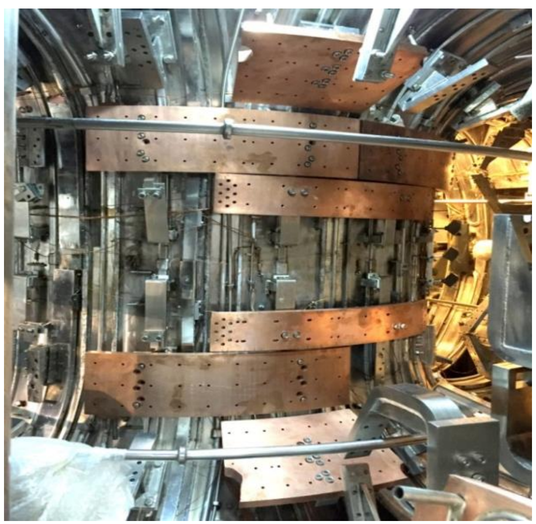
Poster: Oct 20: EX/P5-33: Raval

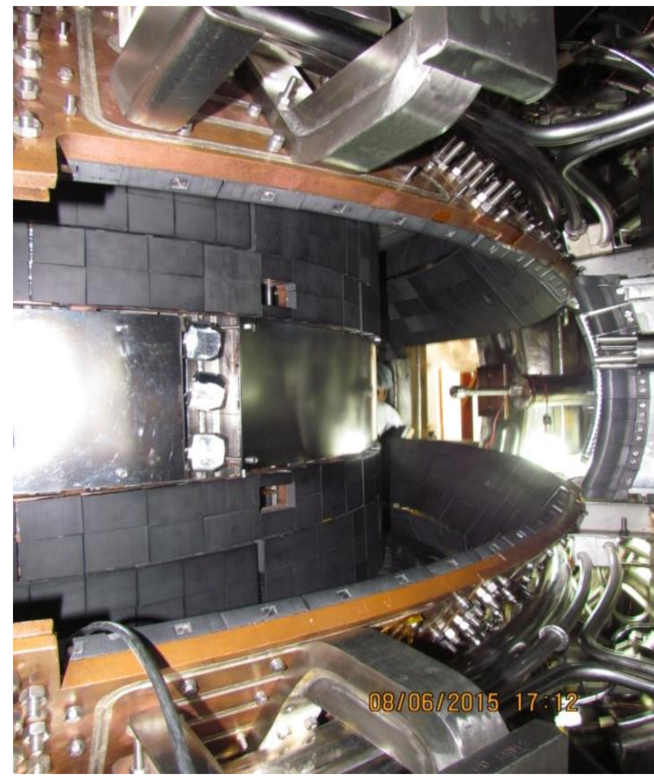
Assembly of PFC in SST-1



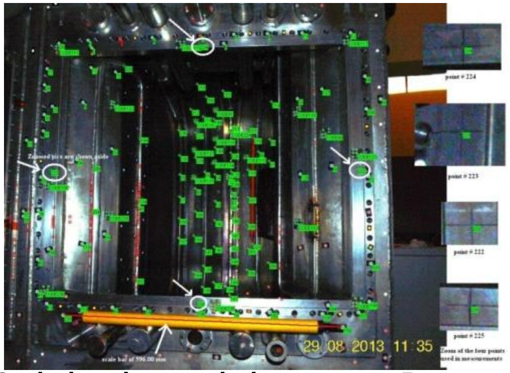




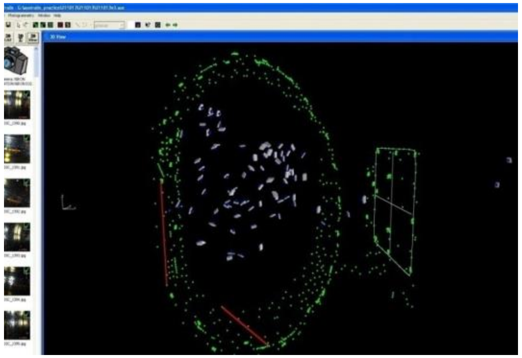




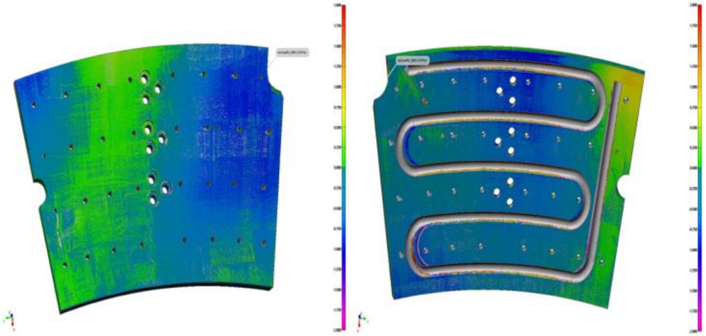
Qualification and Prototyping of PFC in SST-1



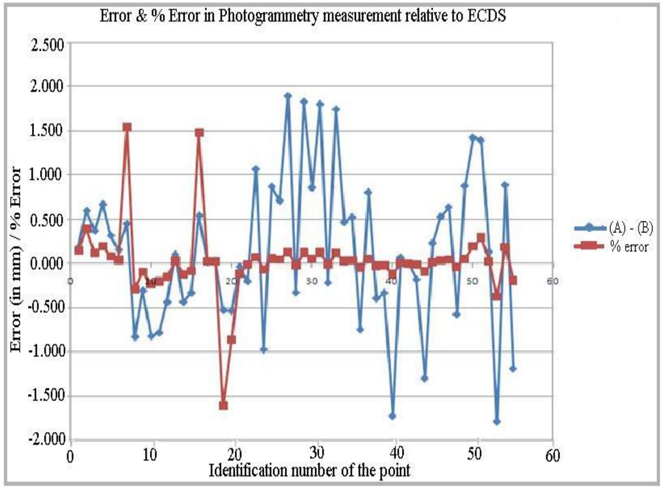
Coded and un-coded targets on Prototype vacuum vessel



Co-ordinates created in Software

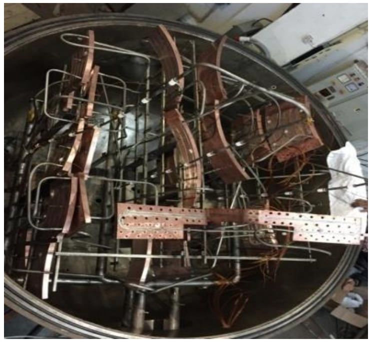


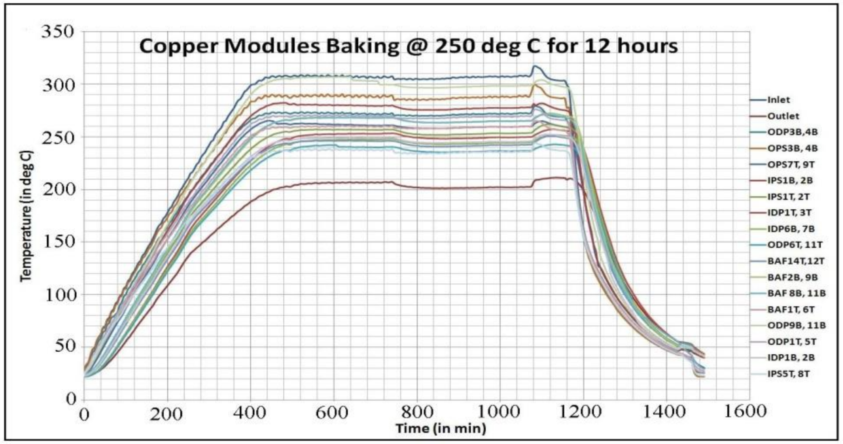
3D CATIA model is superimposed on the scanned surface of actual fabricated components to detect fabrication deviation



Measurement Validation relative to ECDS

Assembly on SST-1 Prototype

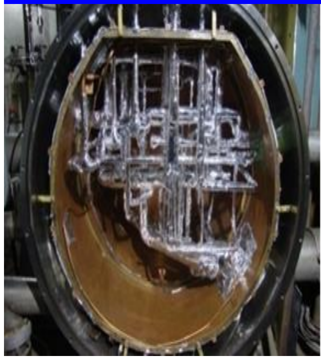




Baking of PFC in excess of 250 C for qualification and hydraulic scheme validation

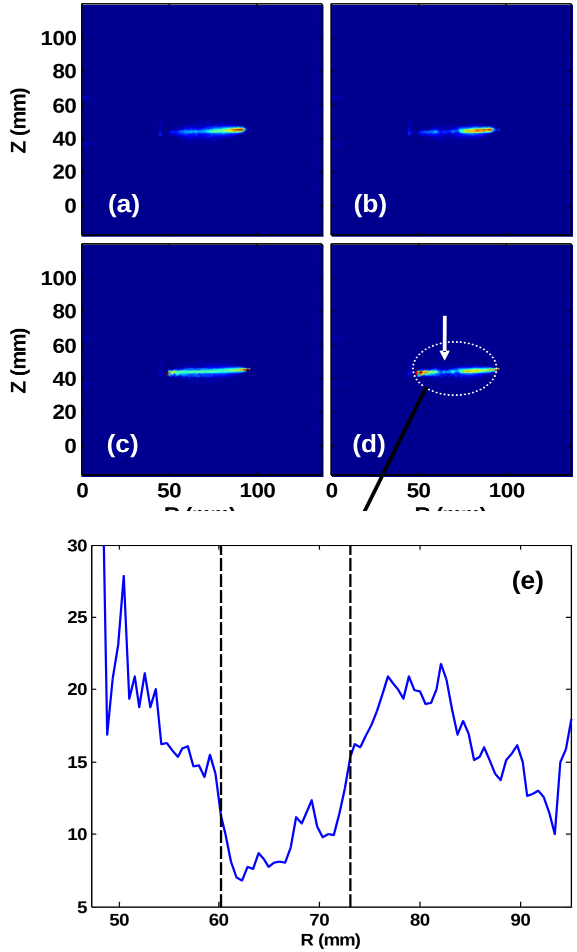
- Assembly (combination of Photogrammetric & ECDS) : 0.5 mm for 500 mm and 1.9 mm for 1600 mm of length.
- All PFC copper alloy back validated to: 7 bar and in > 270 C.
- Tolerances achieved in assembly of PFC is ~ ±5mm.
- Isolation > 1 MΩ

Integrated Flow Diustribution System



Modification in the flow distribution system towards flow uniformity

Super Sonic Molecular Beam Injection (SMBI)



Fast Imaging Exp.

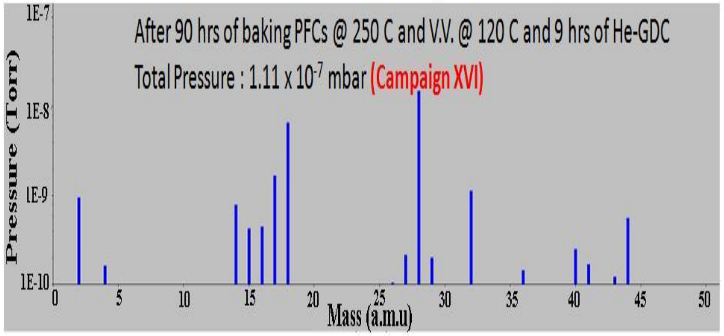
- **~1.2 degree divergence with a laser beam and with fast imaging.**

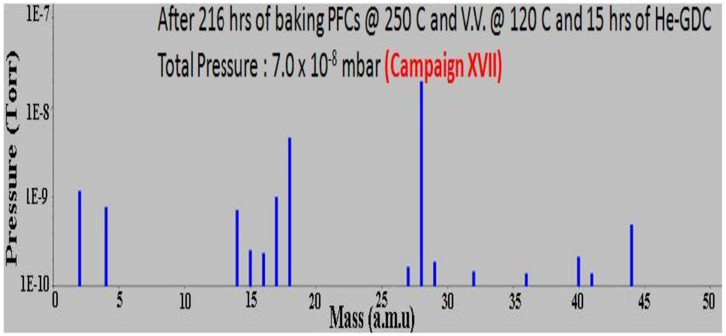
Fast Reciprocating Probe System (FRPS)

- **Scanning length: R=1.250 m to 1.352 m.**
- **Probe velocity: 1m/s**
- **Stroke : 20 mm.**

Preparations towards physics Experiments

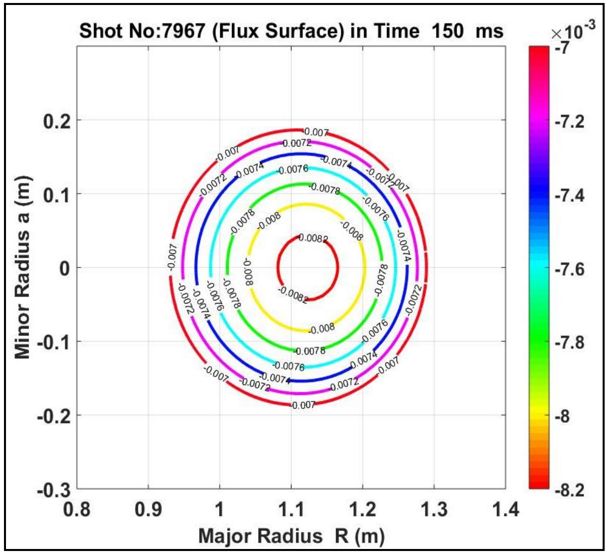
Helium GDC results



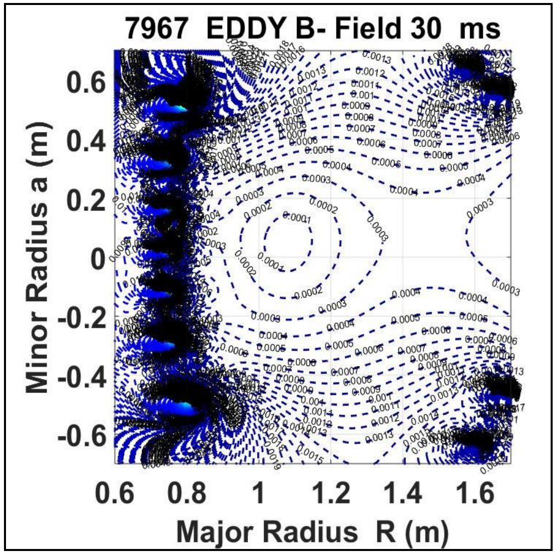


	Total pressure (mbar)	*2*	*18*	*28*	*32*	*44*
Before backing	1.2 E-6	1E-9	3E-7	5E-8	9E-9	2E-8
After GDC	7E-8	1E-9	3E-9	1E-8	3E-10	5E-10

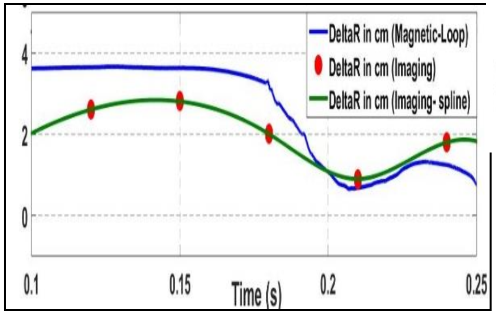
Flux surfaces



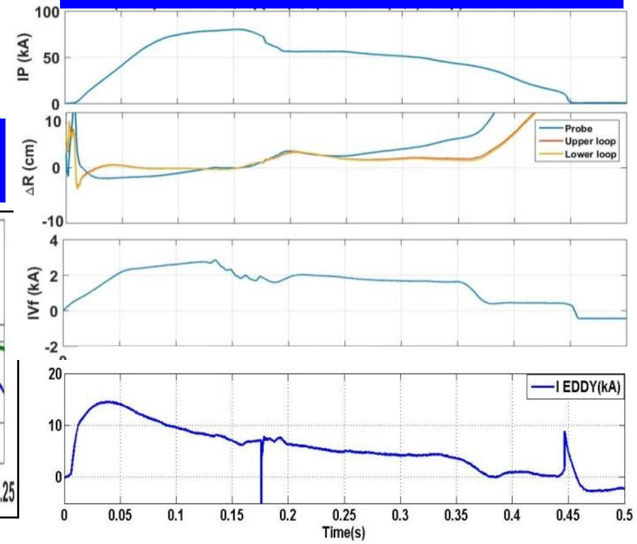
Eddy field lines



Comparison with imaging diagnostics Shot# 7916

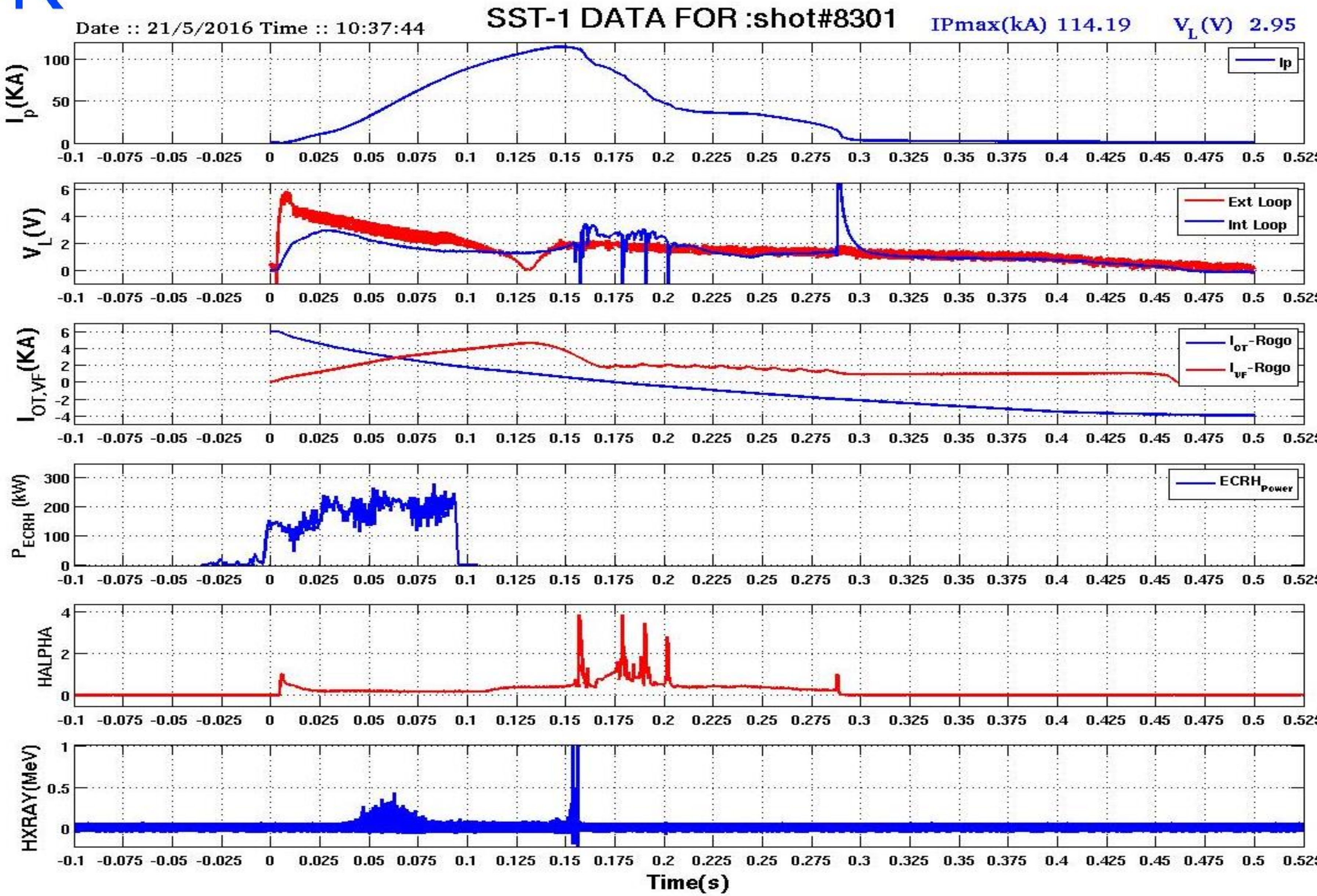


Plasma shifts & Eddy current

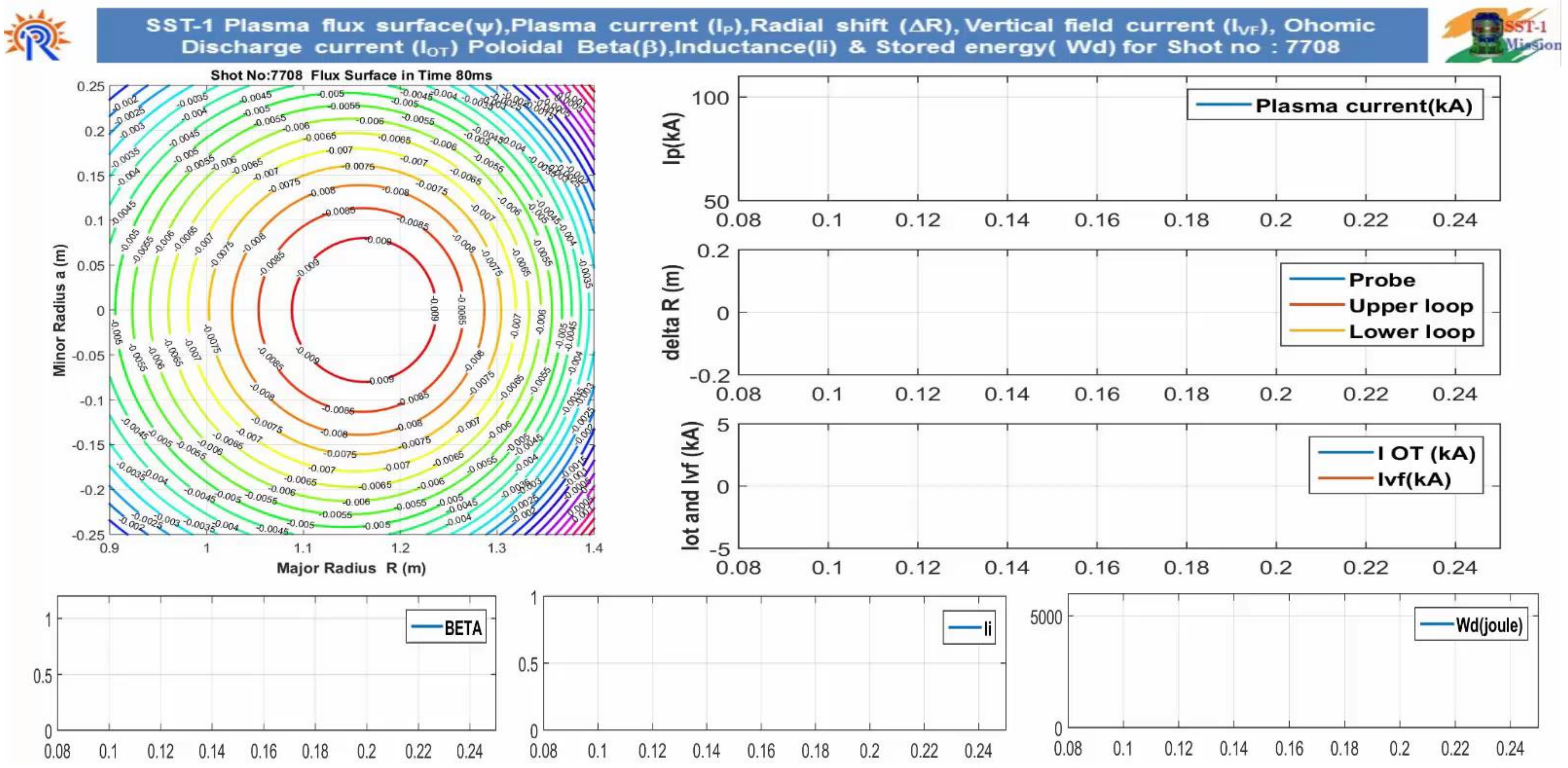


S. Jana , S Pradhan, et. al , Fusion engineering and design (2016).
S. Jana, S. Pradhan, et al, "Magnetic flux surfaces and Radial Shafranov shifts in SST-1 Tokamak Plasma." (Fusion Engineering and Design, 2016).

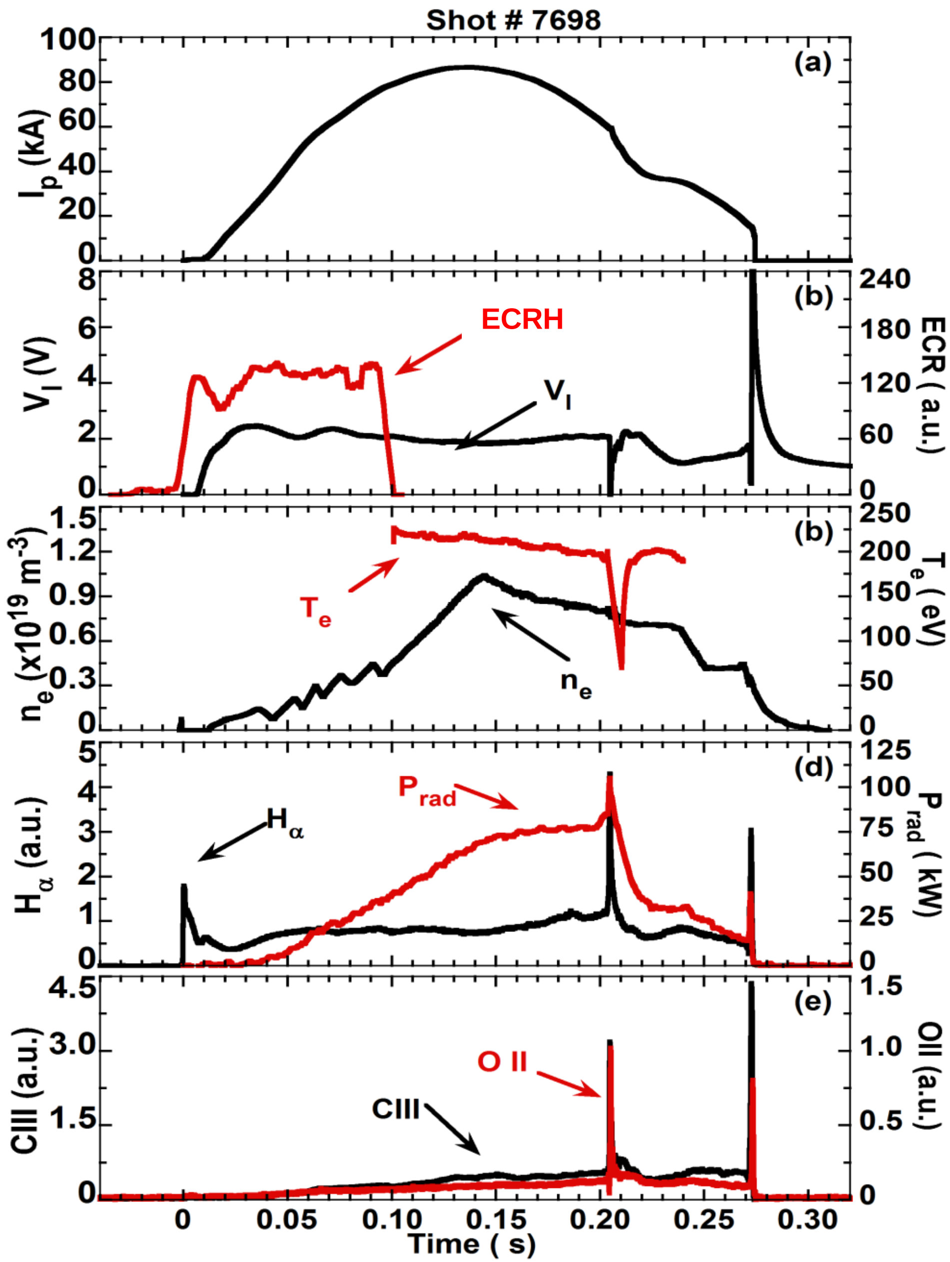
Typical Shot# 8301 in SST-1

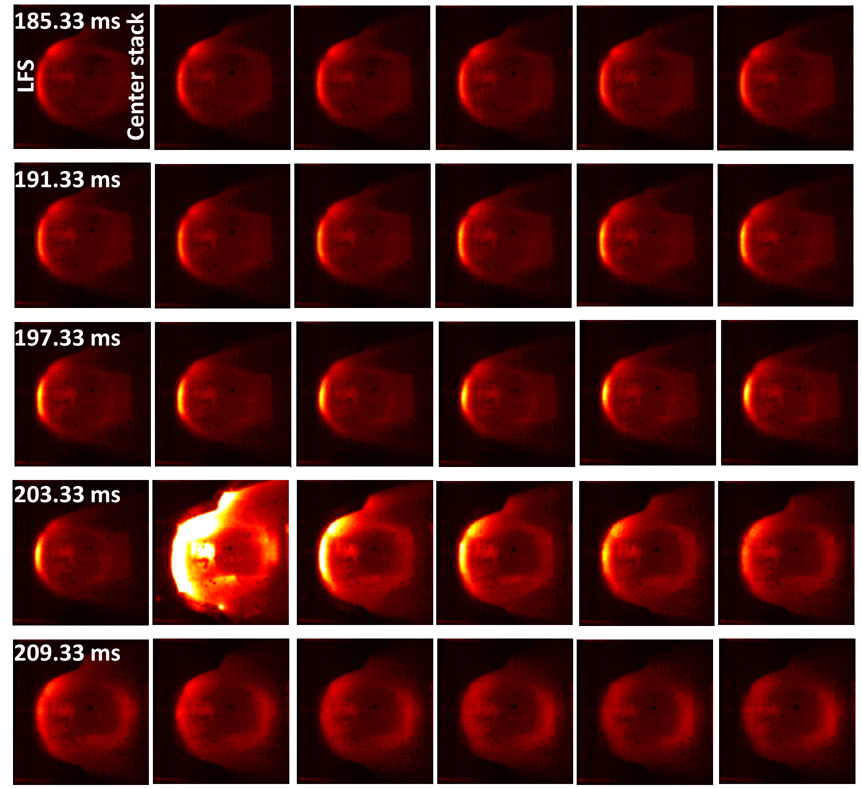


Typical plasma evolution



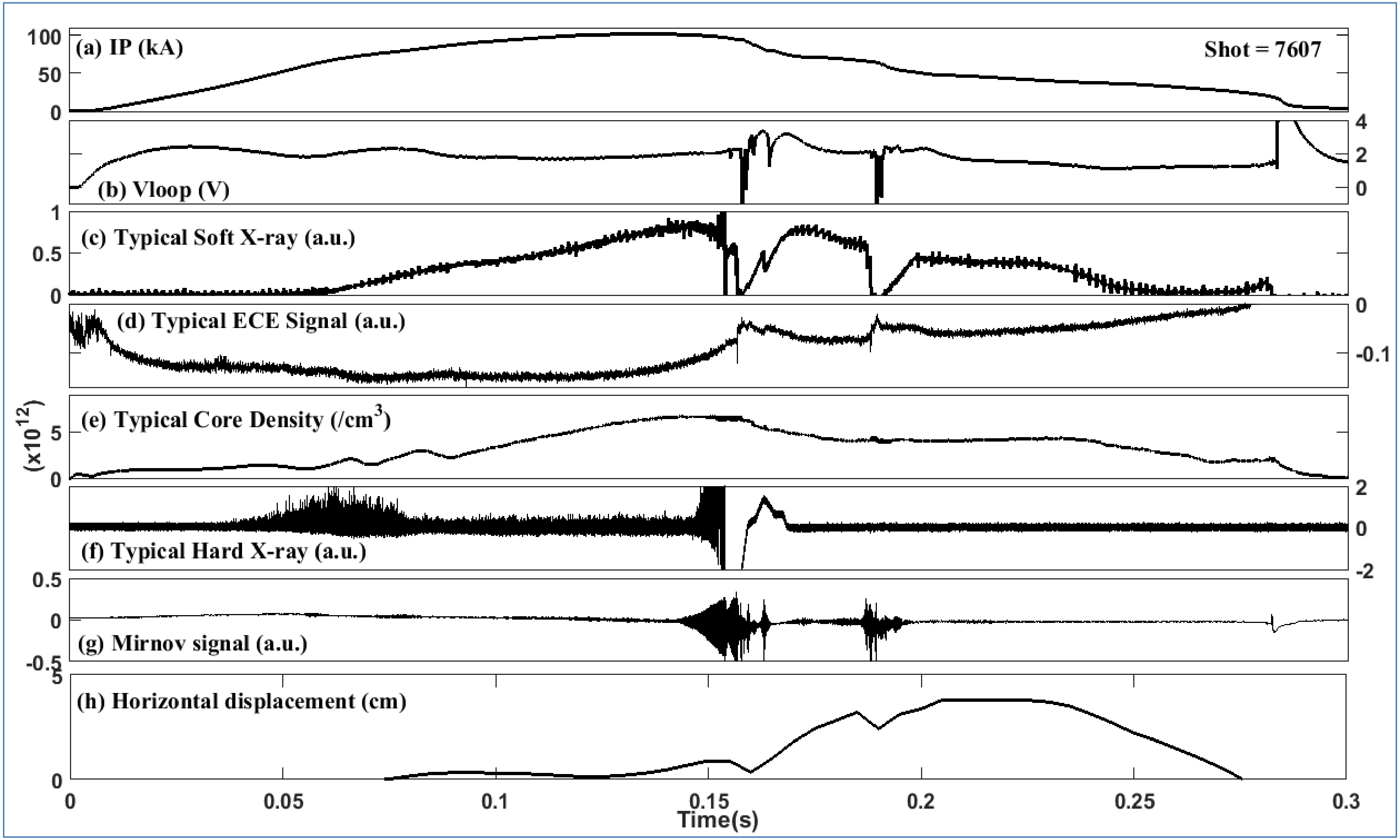
Diagnostics results for typical Shot# 7698 in SST-1





Shot # 7698; Fast images acquired from a tangential line of sight at 3 kHz rate are shown at every ms. Gradual shift of the plasma column towards the low field side (LFS) and subsequent enhanced interaction with the LFS limiter can be seen at ~204.33 ms. Plasma column regains the full permissible column width thereafter. Images run left to right and top to bottom

MHD Characteristics in SST-1 plasma



- Poster- EX/P5-30 - 'MHD Phenomena and Disruption Characteristics in SST-1 Early Plasma ', J. Dhongde, M. Bhandarkar, S. Pradhan et.al , FEC 2016

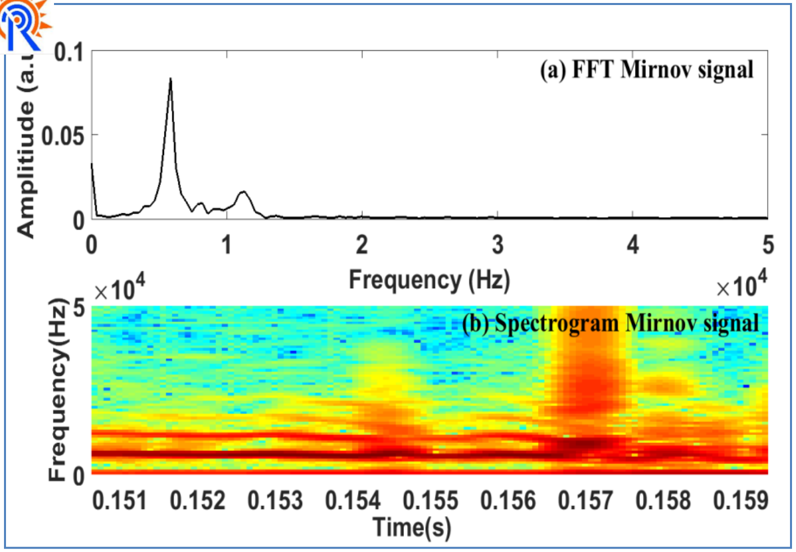


Fig. (a) Fourier transformation of Mirnov signal,
(b) Time-Frequency spectrum of Mirnov signal

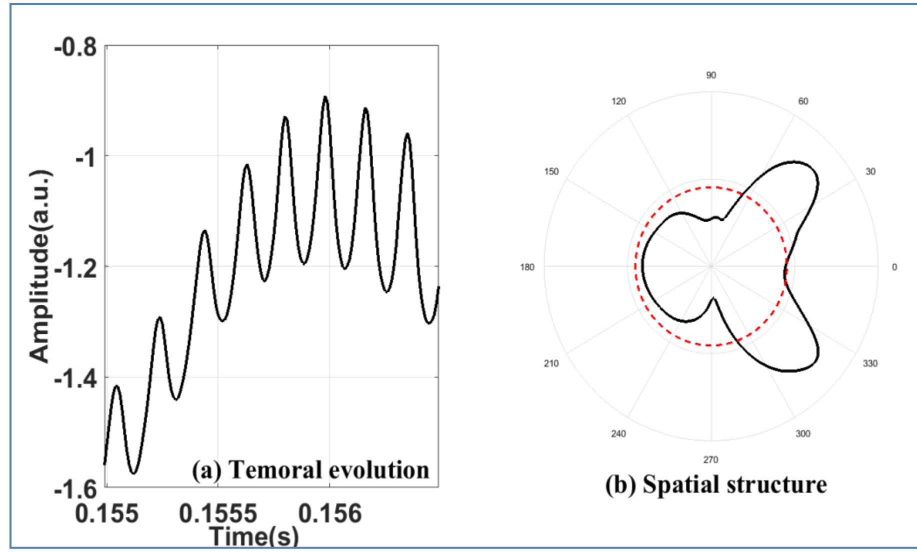


Fig. (a) Temporal evolution (b) Spatial structure m=2 mode

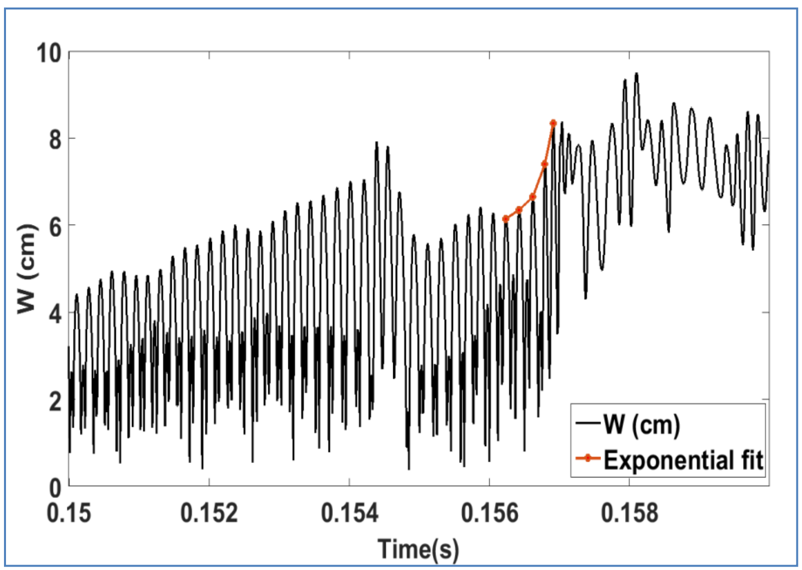
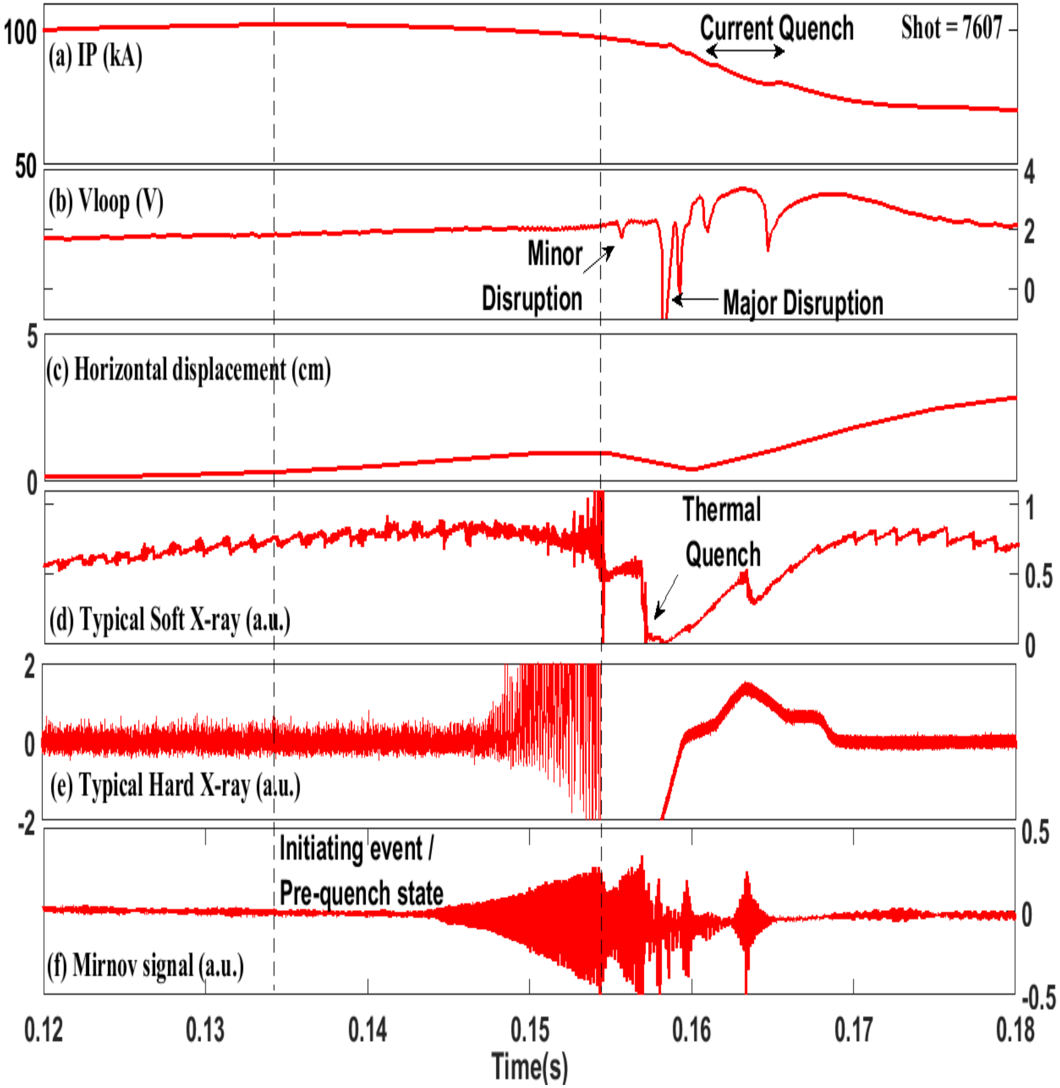


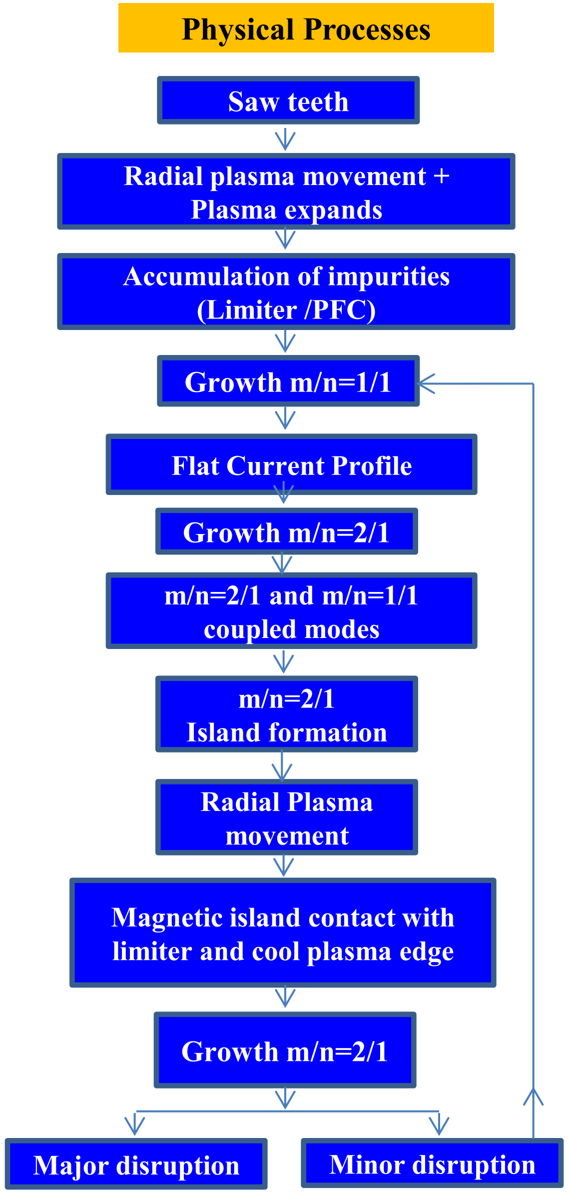
Fig. (a) Calculated W (Island width) with exponential fit (red) during interval 156-157ms

- Dominant mode frequency associated with tearing mode ~ 5.9kHz .
- Tearing mode: m=2, n=1
- Ideal time scale (τ_A)= 0.7µs , Resistive diffusion time (τ_R)= 0.2654s, Resistive time scale (τ_S)= 1586µs and Time scale for non linear growth of mode (τg) ~ 670µs
- Island width (W) saturates at disruption ~ 8 cm
- Estimated growth rate ~ 450 s^{-1} (during time interval 156-157ms)

-Poster- EX/P5-30 - 'MHD Phenomena and Disruption Characteristics in SST-1 Early Plasma ', J. Dhongde, M. Bhandarkar, S. Pradhan et.al , FEC 2016
-Study of MHD activities in SST-1 Plasma', J. Dhongde, M. Bhandarkar, S. Pradhan et.al , Fusion Engineering and Design 108 (2016) 77-80

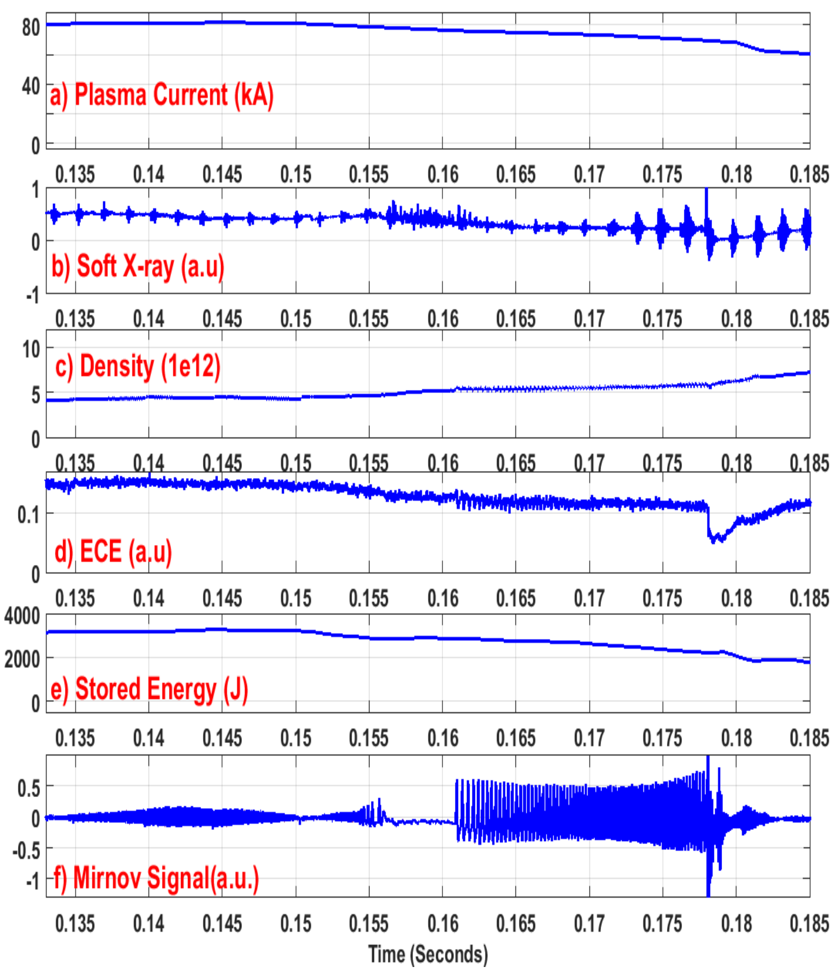
Disruption scenario different phases



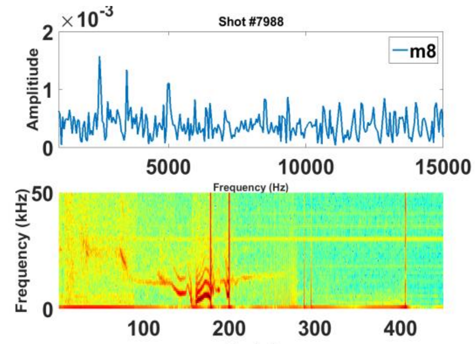


- Poster- EX/P5-30 - 'MHD Phenomena and Disruption Characteristics in SST-1 Early Plasma ', J. Dhongde, M. Bhandarkar, S. Pradhan et.al , FEC 2016

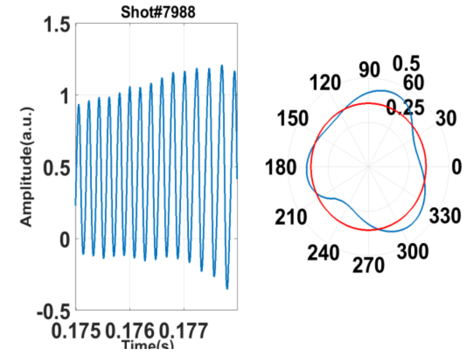
Mode Locking observations at higher density discharge : shot#7988



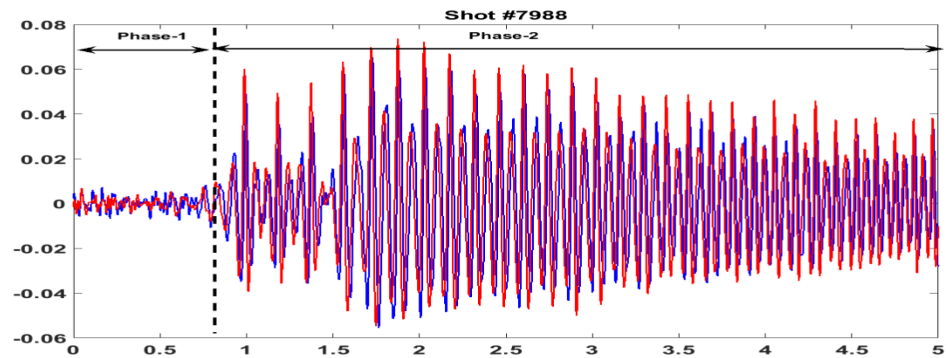
shot#7988, I_p=81.64 kA & line-average electron density (heterodyne) 1x10^{19} m^{-3}. Plasma Stored energy, ECE and density undergo changes during lock mode duration (162-178ms) and major disruption occurs there after.



FFT and Wavelet spectrogram of Mirnov signal for the resolved frequency



SVD shows predominantly m=3 (poloidal) during mode locking duration



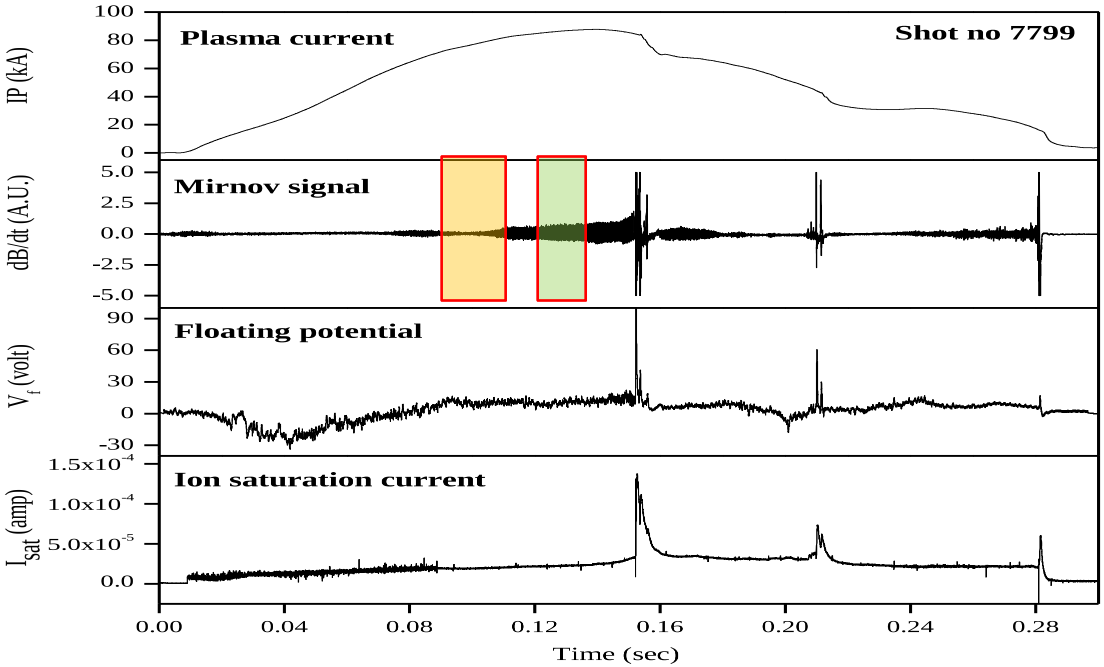
Rotational frequency slows down gradually from 4.34 kHz to ~3.03 kHz during mode locking as shown in phase-1 & 2

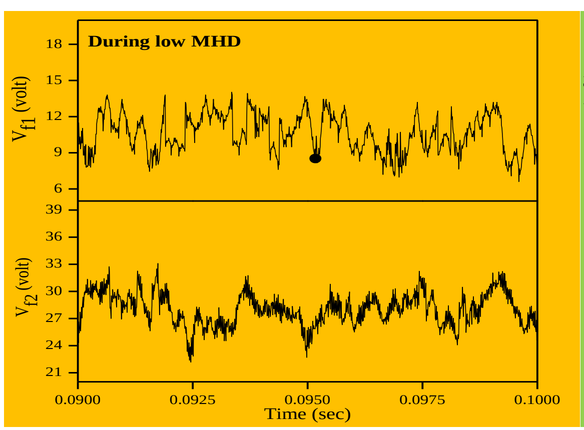
Tokamak	T_{e0} *(eV)*	B_t *(T)*	R_0 *(m)*	*a (m)*	f_{De} *(kHz) Calculated*	$f_{exprimental}$ *(kHz)*
COMPASS-C *	~ 600	1.1	0.56	0.18	~ 15	~ 13
DIII-D *	~ 920	1.3	1.67	0.67	~ 1.7	~ 1.6
HL-1M*	~ 700	2.1	1.02	0.26	~ 3.2	~ 3.1
SST-1 (shot#7988)	~ 280#	1.5	1.1	0.2	~ 4.6#	~ 4.34

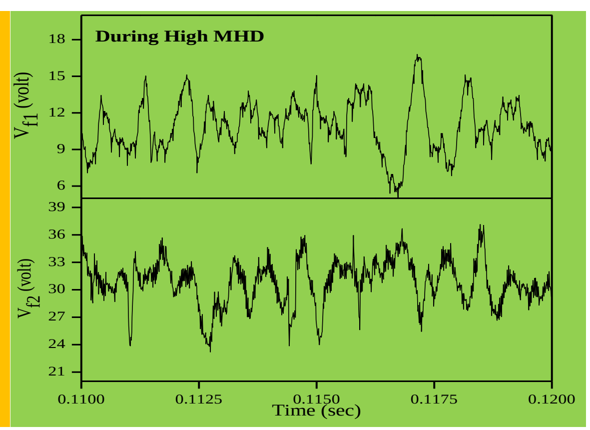
Comparison with other contemporary devices

Poster EX/P5-31, FEC 2016: Bhandarkar

Fluctuation induced Edge Transport

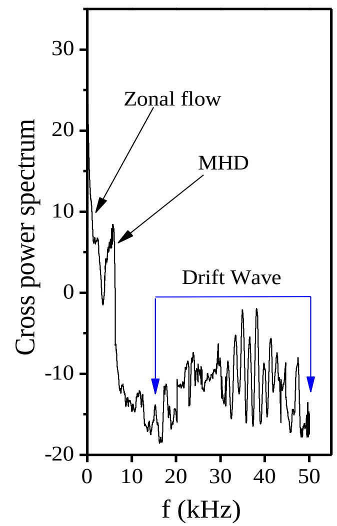


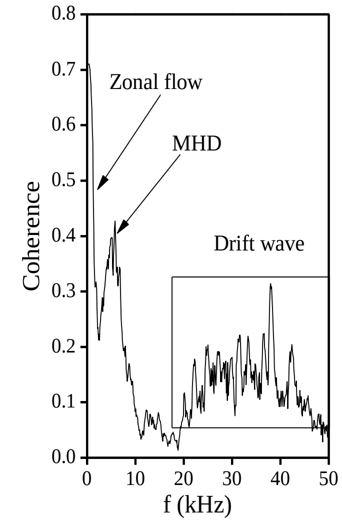




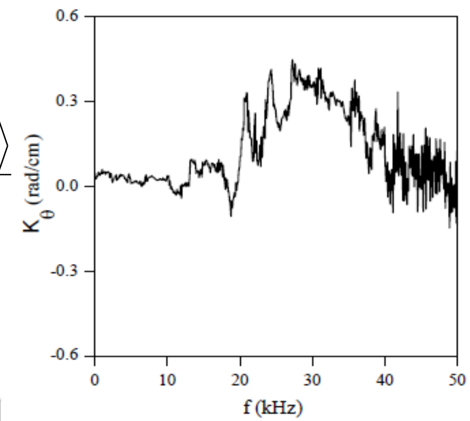
Magnetic fluctuation increasing floating potential and ion saturation current indicating an anomalous particle transport during the high MHD activities.

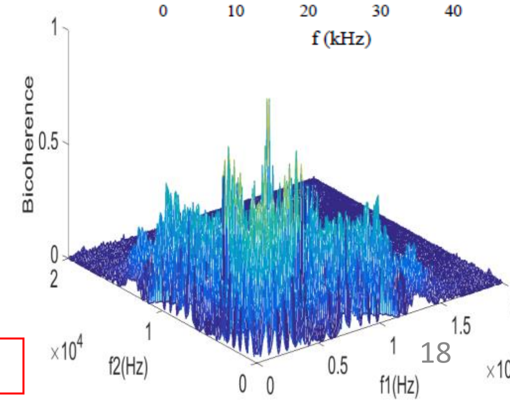
Zonal flow, Drift waves





$$k_\theta(f) = \frac{\langle \theta_{xy}(f) \rangle}{\Delta_\theta}$$





FED (2016)

Summary

- First Wall components have been successfully integrated in SST-1.
- SST-1, equipped with First Wall now is an `experimental superconducting Tokamak'
- ECH pre-ionization assisted SST-1 ohmic standard typical plasma parameters are > 110 kA at 1.5 T (q=2.6), T_e~ 200-250eV, n_e~10^{19}.
- Standard disruption phenomena with pre-cursers, MHD activities, NTM modes, Mode locking etc have been observed & characterized.
- Interesting electrostatic and magnetostatic fluctuation induced turbulence have been observed including signatures of zonal flow and drift waves in SST-1 edge plasma.
- SST-1 plans for plasma with improved densities and temperatures in multi-second durations in future with active control and LHCD.

OV4-3Rb: Overview of Recent Experimental results of 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 – 1.25 T

Peak loop voltage: 20 V

Fuel Gas: Hydrogen

Operating Pressure: 0.8–1.0x10^{-4} torr

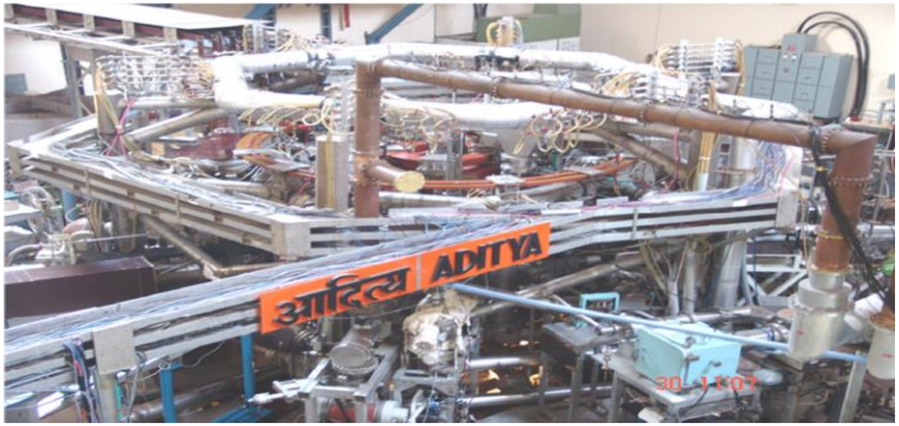
Vessel Volume: 2.0 m^3

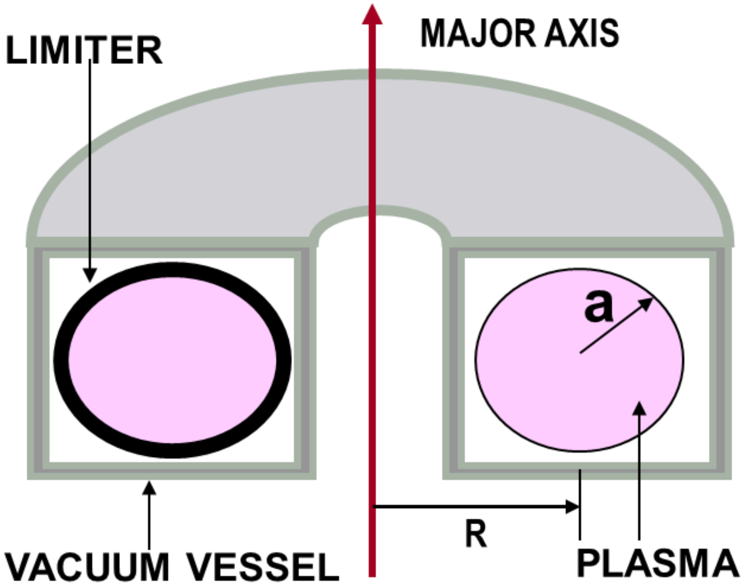
Surface Area: 20 m^2

Pumping System:

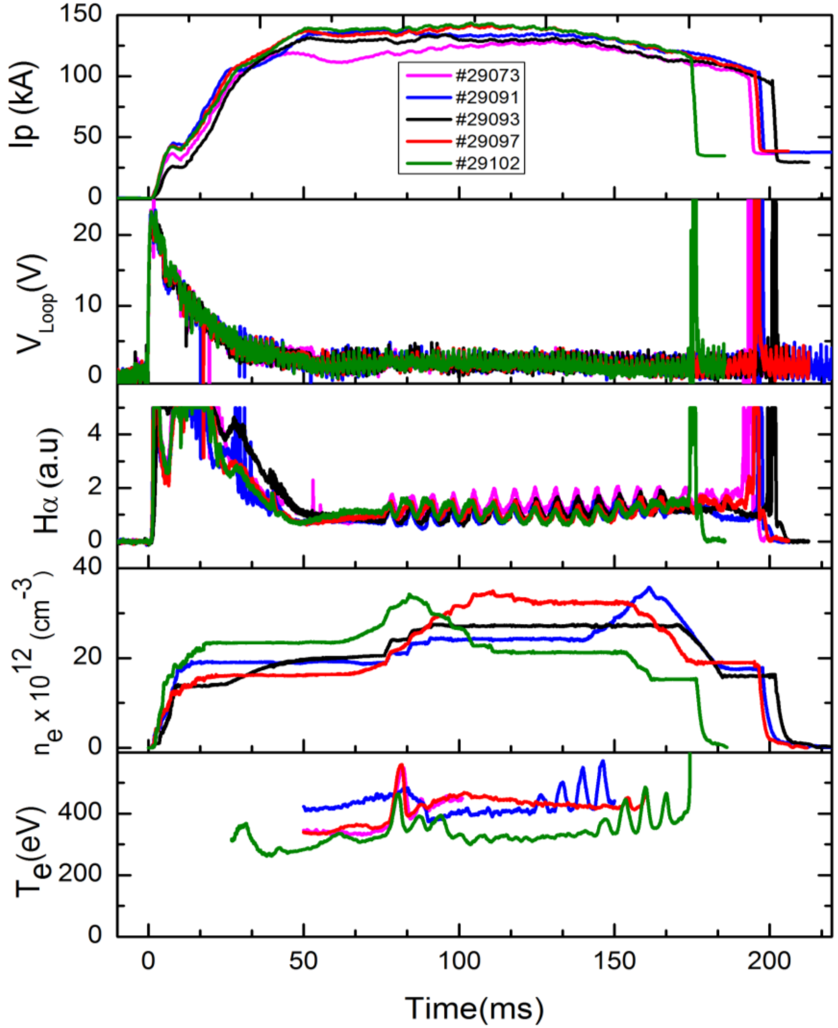
2 TMPs (2000 l/s each),
2 Cryopump (3500 l/s)

Base Pressure ~ 3.0 x 10^{-8} torr

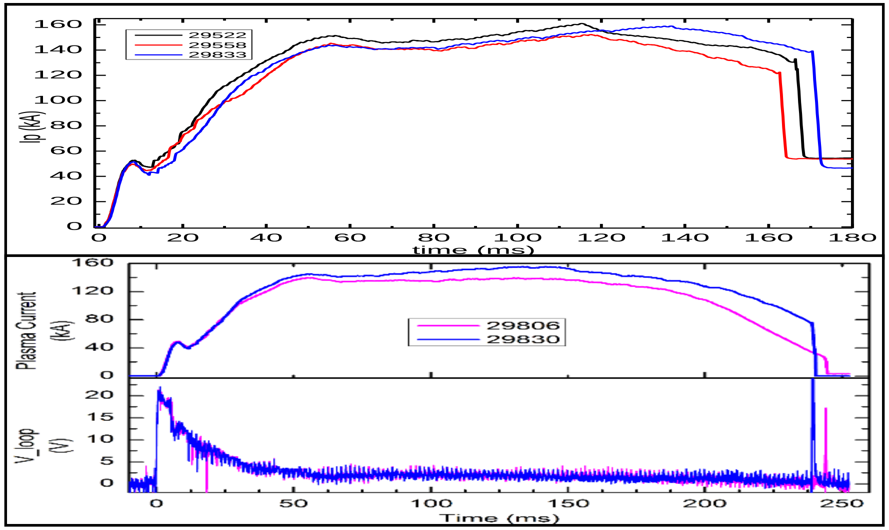




Machine preparation- High current long pulse Shots



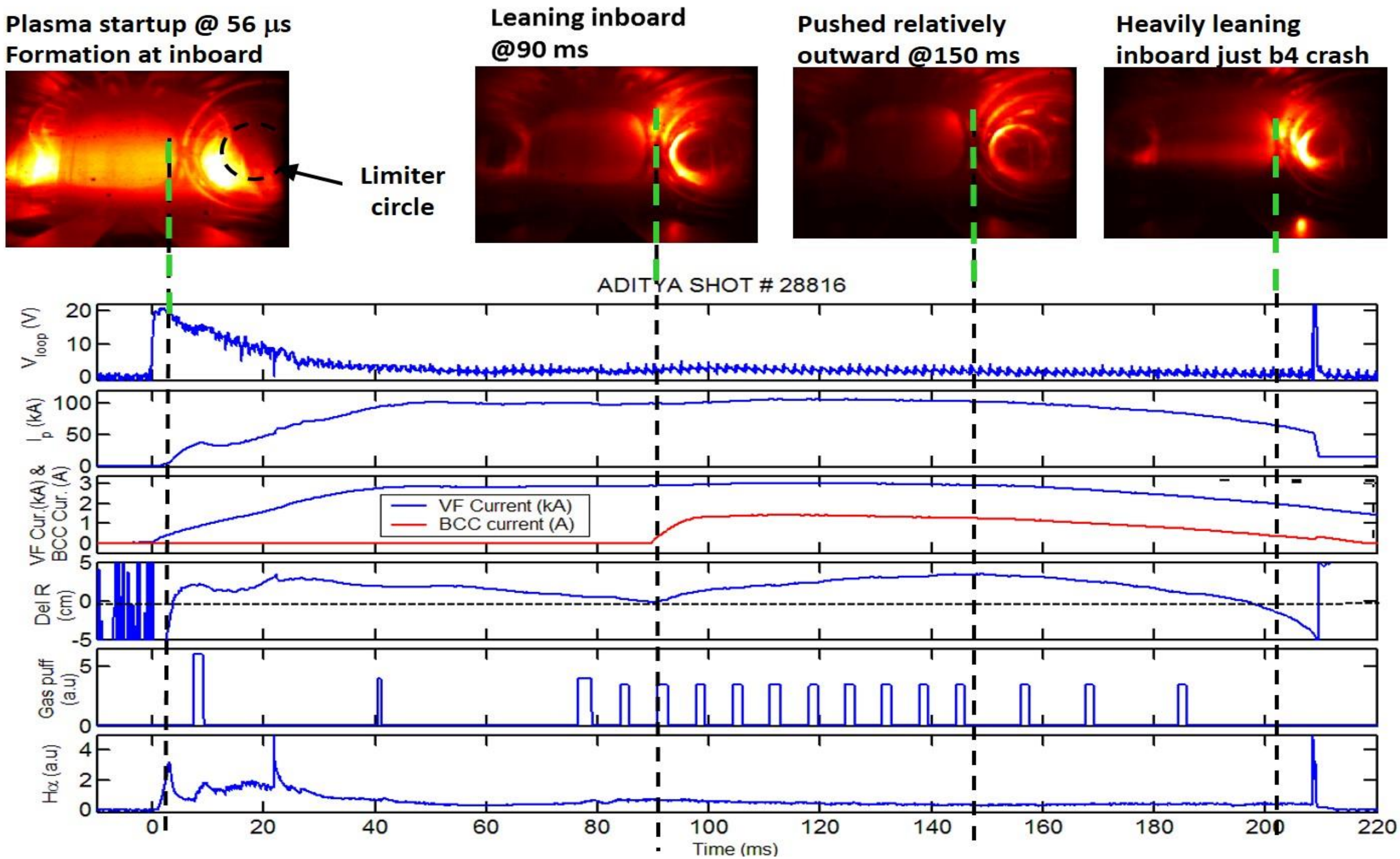
Typical discharges of ADITYA tokamak



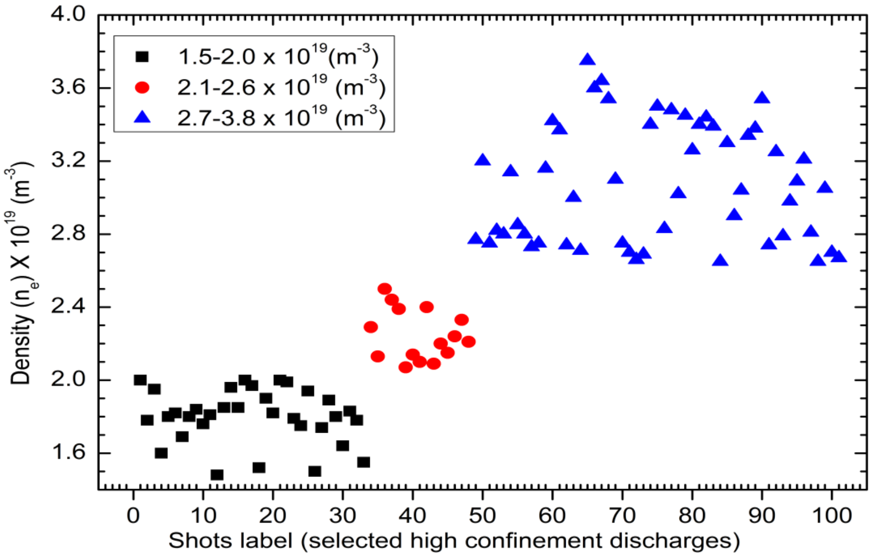
- Max I_P (kA) **~ 160 kA**
- Max duration **~ 250 ms**
- Max flattop duration ~ **144 ms**
- Min. avg. loop voltage ~ **1.6 V**
- Max n_e ~ **6.0 x 10^{19} m^{-3}**
- Max T_e ~ **700 eV**

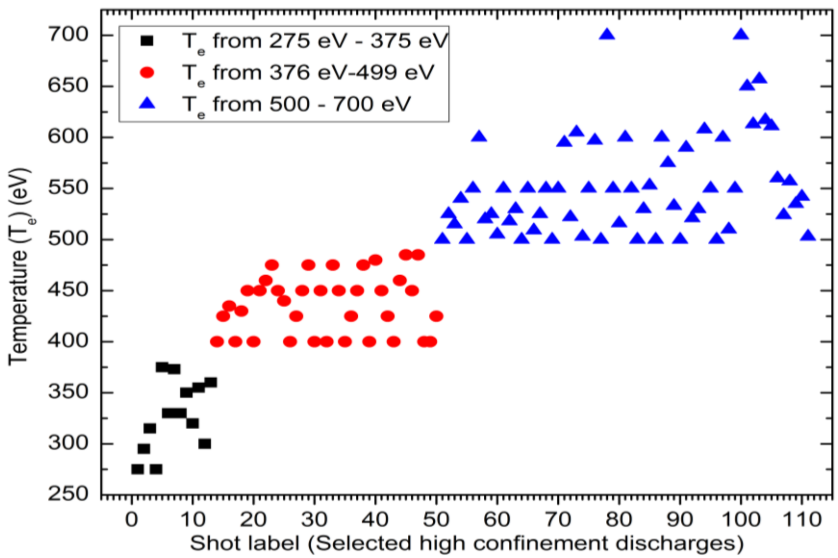
Plasma Evolution, Position Control

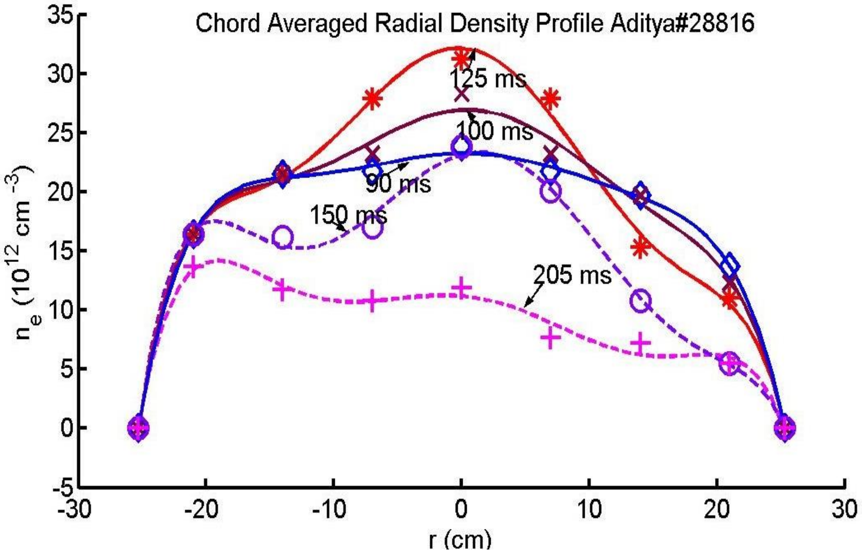
ADITYA long pulse; Shot # 28816

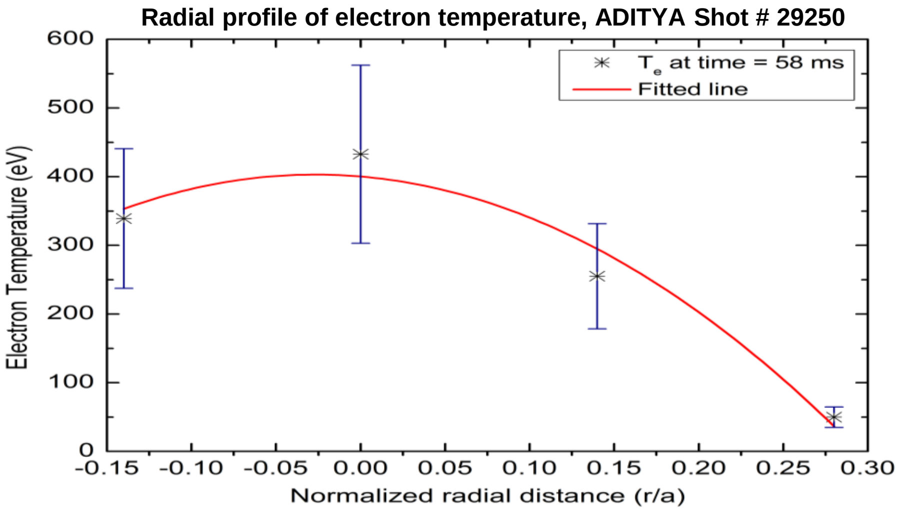


Density and Temperature Data







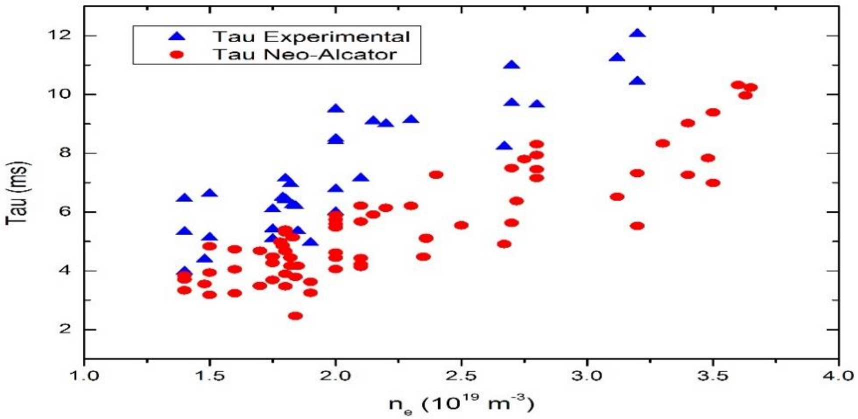


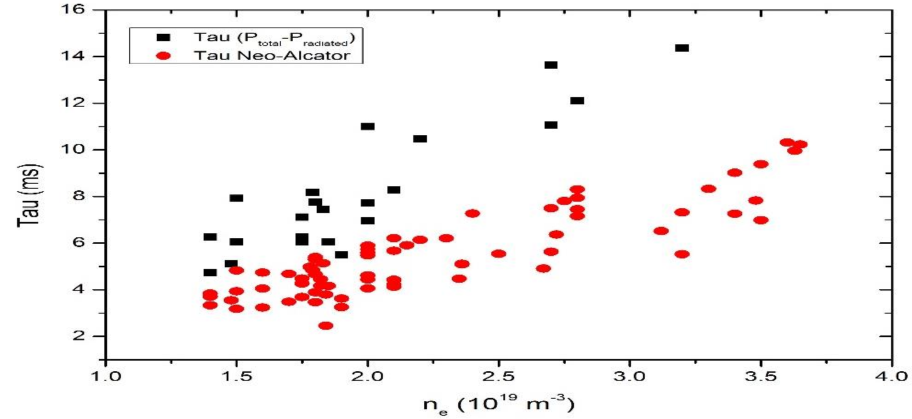
Energy Confinement Time (τ_E)

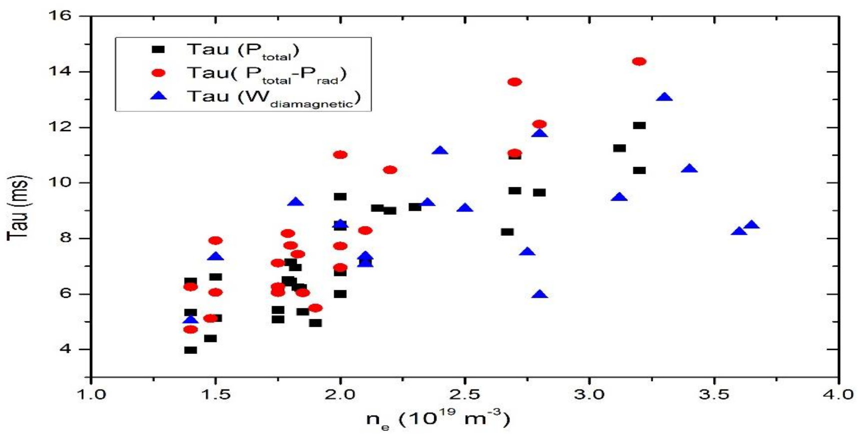
Experiment Vs Neo-ALCATOR Scaling

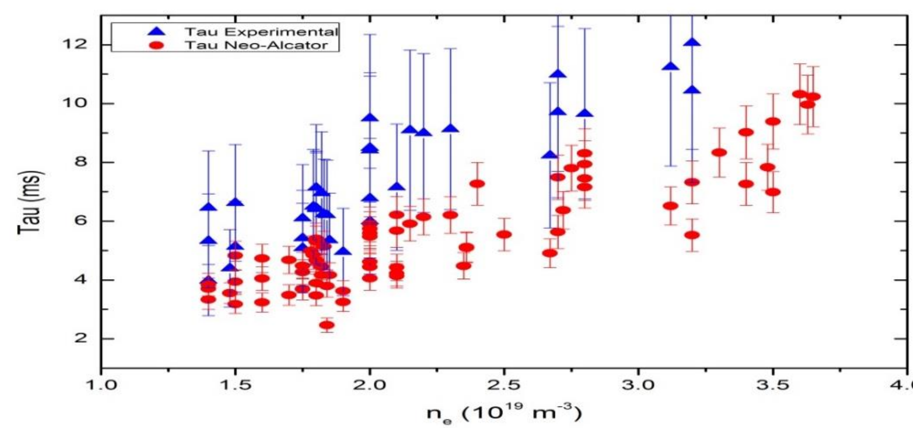
Neo-ALCATOR Scaling: $\tau_E = 7 \, X \, 10^{-2} \, n_e \left(10^{20} \, m^{-3}\right) a \, R^2 \, q_{eff} (Sec)$

$$\tau_E = \frac{\frac{3}{2}\left(n_e T_e + n_i T_i\right) * V}{I_P V_L} \qquad \tau_E = \frac{\frac{3}{2}\left(n_e T_e + n_i T_i\right) * V}{I_P V_L - P_{rad}} \qquad \tau_E = \frac{W_p}{\left(P_{total} - dW_p/dt\right)}$$



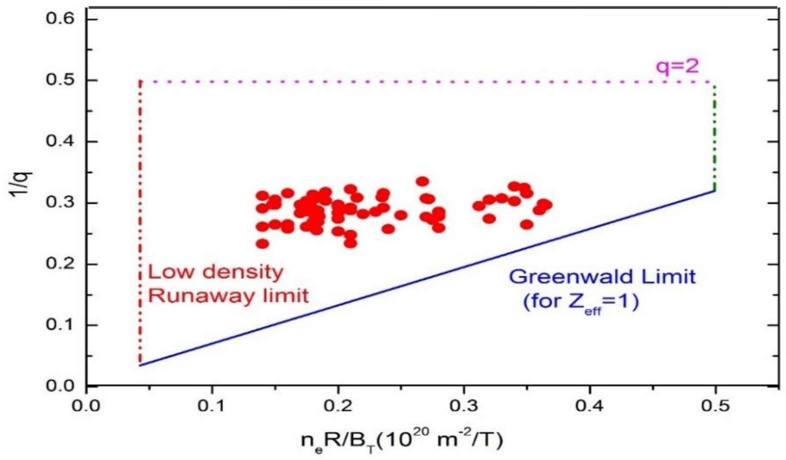






ADITYA Operation Regime

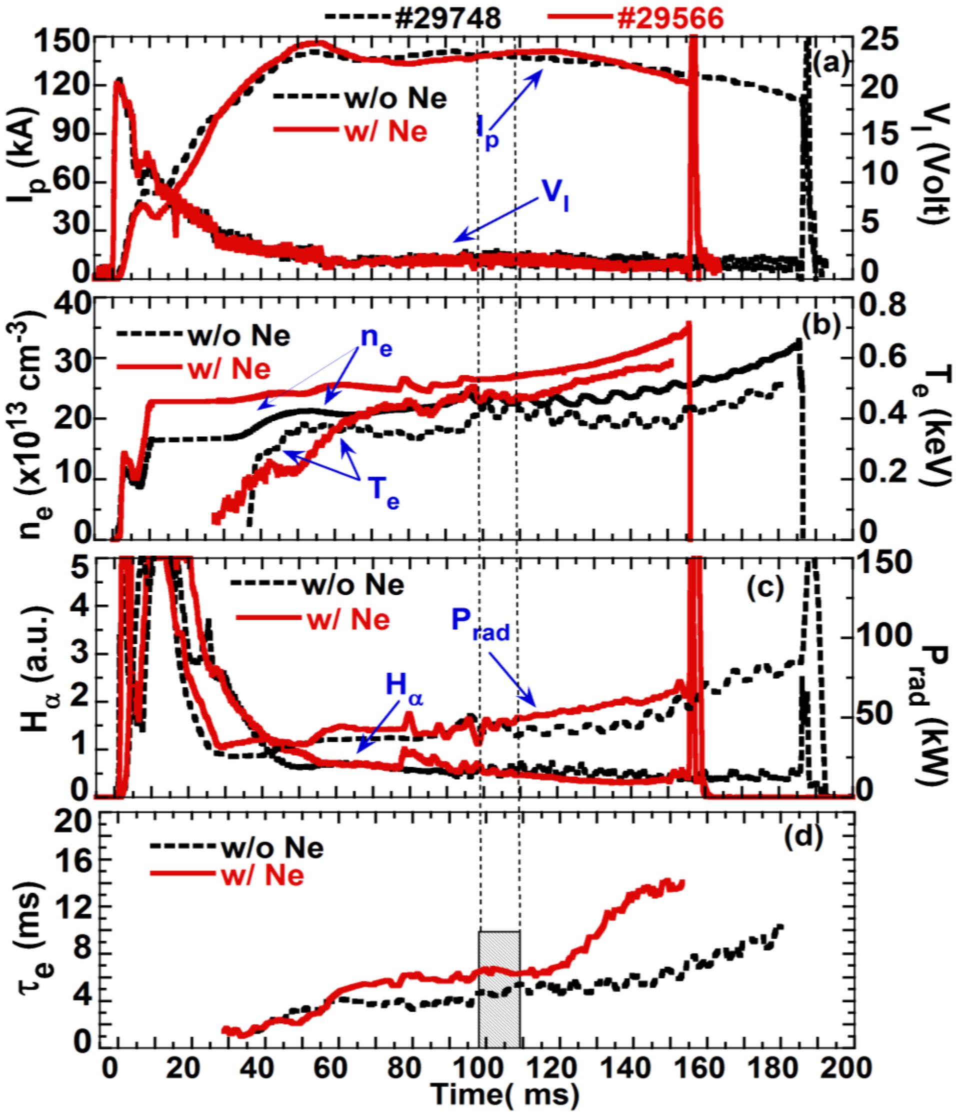
- The operating space is restricted by several limitations among which the plasma performance has to be optimized.
- At a given plasma current there exist a lower and an upper density limit. The lower density limit leads to the generation of a runaway electrons.
- The upper density limit, i.e. Greenwald limit ($n_G = {}^{I_p}/_{\pi a^2}$) (n: $10^{20}/m^3$, I_P: MA, a: m), for a given plasma current for circular machines.
- Similarly, for a given density, an upper limit to the plasma current is set by the MHD kink instability.



We have attained density quite close to this Greenwald limit in ADITYA with efficient gas fueling, lithium wall conditioning and radial plasma position control.

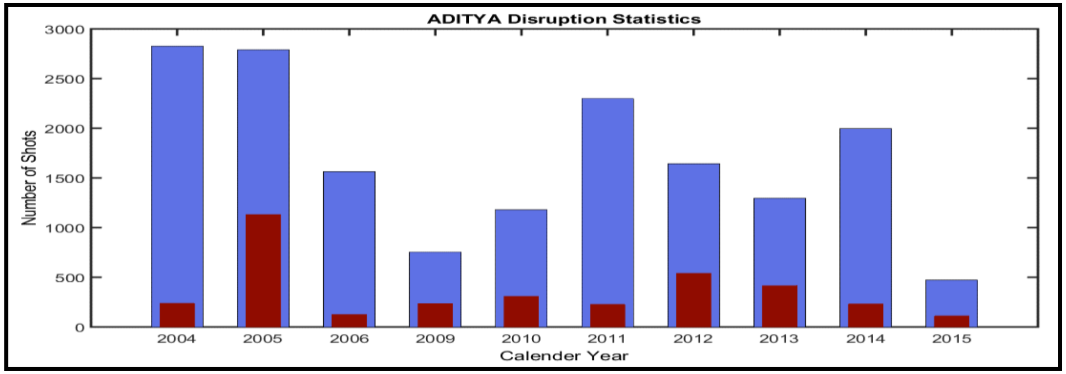
Probable reason for τ_E higher than Neo-Alcator scaling: LITHIUMIZATION

Neon gas puff assisted RI Mode Experiment



- The Fig. shows that the density (n_e), temperature (T_e) and radiated power (P_{rad}) increases after the application of neon gas puff from 98 ms to 108 ms as depicted by shaded rectangle.
- Simultaneous decrease in Hα signal and increase in n_e indicates better particle confinement after the neon gas puff.
- The energy confinement time (τ_E) was improved by a factor of 2 from 6.5 to 13 ms as shown in Fig. (d) and the transition in τ_E happens at 117 ms.
- It is believed that improved confinement in the RI mode is mostly based on the reduction of growth characteristics of the toroidal ion temperature gradient (ITG) mode due to the increase of Z_{eff} and also because of the suppression of turbulence due to increase of E x B shear rotation in the impurity injected plasma. ***(Tokar M.Z., et al., "Confinement mechanisms in the radiatively improved mode", Plasma Phy. Cont. Fusion 41 (1999))***

Analysis of Disruption (ITER relevant)



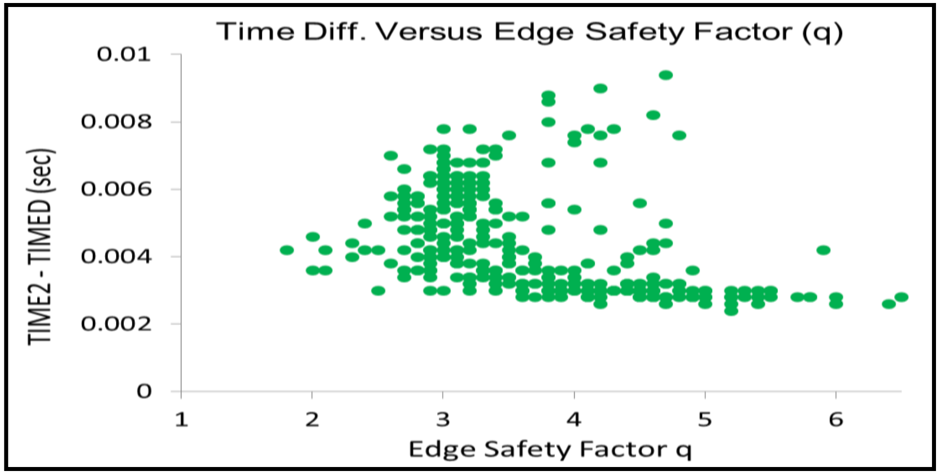
Nature of Plasma Current for ADITYA Disruptive Discharges

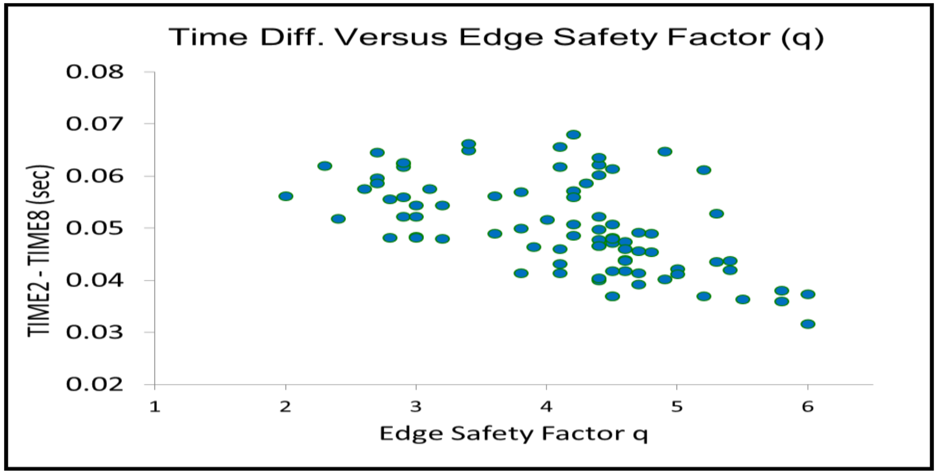
Sr. No.	World Tokamak	Disruptivity
1	ADITYA	21% (5% deliberate disruptions)
2	ASDEX	31.5% (overall)
3	ASDEX – U	5-8% (At 80% of the β, Greenwald limit)
4	COMPASS	49%
5	TCV	38% (15% deliberate disruptions.)
6	JET	26% (general disruptivity before 1993), 17% (after major shutdown of 1993-1994), 6% (2005-2007).
7	DIII-D	30%(overall)

Schuller F.C. et al 1995 "Disruptions in tokamaks", J. Plasma Physics and Controlled Fusion 37 A135-A162

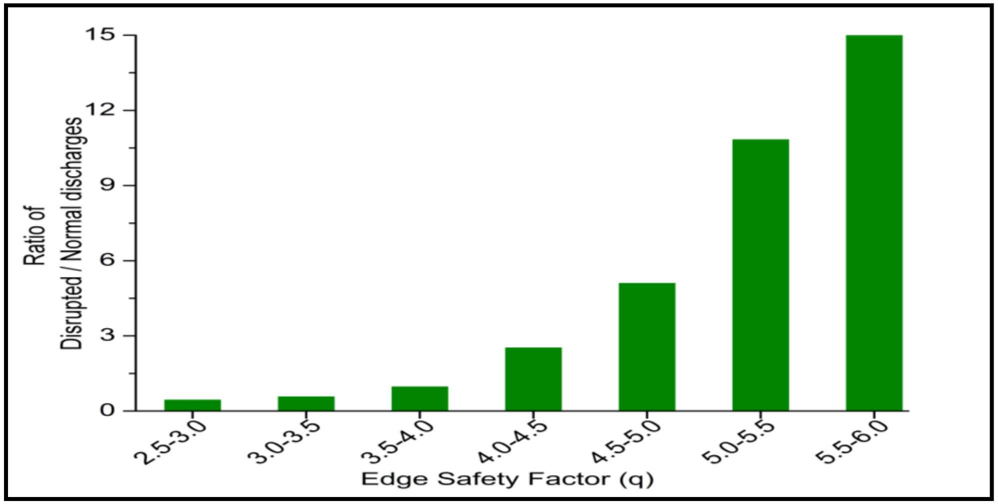
- ❖ 17000 ADITYA discharges from last ten years has been analyzed.
- ❖ Discharges disrupted in I_P flattop are considered.
- ❖ Averaged over all discharges in collection, the total disruptivity is found to be ~ 21% augmented with 5% deliberate disruptions for experiment and research purpose.
- ❖ The lowest disruptivity found in the year 2004 (8.4%), 2006 (8.18%), 2011 (9.87%) and in the year 2014 (11.6%). The highest disruptivity found in the year 2005 (40.6%) mainly due to equilibrium control problems.

Current Quench Time Vs Edge Safety Factor (q)





Current quench time DECREASES with increase in qedge



High qedge discharges are more prone to Disruptions.

This may be due to higher growth of MHD islands and their overlaps in high q_{edge} discharges. (Details in overview poster)

SUMMARY

- ✓ Repeatable plasma discharges of maximum plasma current ~ 160 kA and discharge duration of ~250 ms has been obtained for the first time in the ADITYA.
- ✓ The peak electron density $n_e(0) \sim 6 \times 10^{19}$ m^{-3} and the max. electron temperature (Te) ~700 eV have been achieved in these discharges.
- ✓ Energy confinement times (τ_e) experimental compared with Neo-Alcator scaling showed, experimental confinement time almost ≈ 1.5 times higher than that predicted by neo- ALCATOR scaling.
- ✓ The Hugill plot for ADITYA operating parameters space showed that densities quite close to the Greenwald limit has been achieved.
- ✓ Neon gas puff assisted radiative improved confinement mode has been observed in ADITYA. The energy confinement time improved by a factor of ~2 in discharges with Neon gas puff.
- ✓ The current quench time is found to be inversely proportional to q_{edge}, which is due to higher growth of MHD islands in high q_{edge} discharges.
- ✓ Recently, ADITYA tokamak operated with limiter configuration has been upgraded into a state-of-art machine with divertor operation. First plasma operation in ADITYA-Upgrade will be initiated in near future.

Thank you