Experimental characterization of AC discharges transition in ISTTOK

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contributions from:

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Typical parameters

- Major radius 0.46 m
- Minor radius 0.085 m
- Plasma current = 4-8 kA
- Toroidal field < 0.45 – 0.6 T
- Discharge duration ~ 1 s (AC), 35 ms (DC)
- Plasma density = 3-5x10^{18} m^3
- Electron temperature (center) ~ 30 - 120 eV
- Toroidal flux swing = 0.25 Vs
- Energy confinement time ~ 0.3 - 0.4 ms
Goal

- Increase current of AC discharges
- Develop efficient plasma Control
- Increase time exposition and deposition power on test PFCs
Diagnostic techniques used in ISTTOK
(for the present experiments)

Magnetic and Electric Probes
Optical (photodiode)
Hard X-ray
Interferometer
Heavy Ion Beam Diagnostic (HIBD)
Actuators

- Programmable V/H magnetic field coils (wave form)
- Plasma V/H position real time FB control (electric probes)
- Plasma V position real time FB control (HIBD)
- Real time FB control for plasma current (IGBT)
- Real time Gas puff
- Edge Biasing Electrode (+)
ISTTOK AC operation

Fast acquisition and control:
Telecommunications Computing Architecture (ATCA)

Multi-Platform Real-Time Framework (MARTe)
Outline

• ISTTOK AC operation
  – Plasma AC current and density evolution

• The Heavy Ion Beam Diagnostic
  – Principles
  – Pressure like profiles
  – Poloidal magnetic field measurements

• Biasing electrode experiments (DC)
  – Plasma confinement improvement experiments

• AC operation experiments under electrode biasing
  – Density increase (@ I_p=0)
  – Gas puff experiments
  – Runaway electrons
  – H/V external fields

• Conclusions and future work
ISTTOK AC operation: $I_p = 4 \text{ kA}$
ISTTOK AC operation: \( I_p = 4 \, kA \)

\[ \Delta T_{AC} \sim 3 \, ms \]

\[ (\tau_c \sim 0.3 - 0.4 \, ms) \]

\[ \bar{n} \, (I_p = 0) \sim 1 \times 10^{18} \, \text{part./cm}^3 \]
The Heavy Ion Beam Diagnostic (HIBD)
(development work in progress)

Can perform simultaneous local measurements of absolute profiles (up to several mm and few µs):
- Electron density
- Electron temperature
- Plasma poloidal field
- Plasma potential
Based: Multiple Cell Array Detector

Measurements for configuration 12x1 cells

Pressure like: $I_{cell} \propto r(n)\sigma_{eff.}[T_e(r)]$

Integral poloidal field force: $\Delta z_{pri}$
Retrieval of plasma parameters
Pressure like profiles
retrieving the correct $n \sigma$ values

(ne=6.5e18; Te=130 eV)

$m=1; \ r=2.5 \ cm$
$f=67 \ kHz$
(mod. 6.7 \ kHz)

$10 \times 10 \ cm$

Current in central cell

nsigma sample volume's profile
input ----- retrieved——

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m=1 (r=0.025 m; 80 kHz)
m=2 (r=0.045 m; 120 kHz)
(ne=6.5e19; Te=1keV)

10 x 10 cm
$m=1 \ (r=0.025 \text{ m}; \ 80 \text{ kHz})$ ;

$m=2 \ (r=0.045 \text{ m}; \ 120 \text{ kHz})$
Experimental measurements MHD activity

HIBD L=#7 spectra (pulsed beam)

Correlation of cell no. 7 with all the Mirnov coils

Correlation of cell no. 2 with all the other cells

Even mode

no profile filtered around 65 kHz

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Island location (even mode)
Two similar discharges were used (due to limited number of ADCs)

Profile flattening (T1→T4)
Edge electrode biasing experiments: DC discharges
Turbulent transport is modified in a fast time scale (~10us)

The $n_e\sigma_{\text{eff}}(T_e)$ builds up in a slower time scale (~150us)

$n_e\sigma_{\text{eff}}(T_e)$ reaches its maximum almost 1 ms after the biasing
AC discharges: biasing electrode experiments
Typical parameters of AC discharge:

\[ \text{EB} = 0 \text{V} \]

- Current feedback control (4 kA)
- Density does not vanish during AC transition
- Symmetric \( V_{\text{loop}} \) for AC (±) cycles
‘pressure’ profile during failed transition: EB=0 V

Check the profiles in detail
Nsigma @ transition: EB=0 V

White line – interferometer
Background - HI BD

Quiescent plasma phase (0.7 ms) lasts longer than confinement time (<0.4 ms)

nsigma peaked profiles
nsigma hollow profiles: Loss of temperature
Density remains at top level up to 0.3 ms after current starts to decay.

The plasma temperature drops within that period.

Plasma pressure forms a hollow profile within that period.
Positive bias at 120V during 2 ms in each positive current semi-cycle (applied 2ms before transition)

Density increases:
- before transition
- @ $I_p=0$

Use of EB can help to increase the plasma density during quiescent plasma phase $\rightarrow$ facilitates AC transition?
Collection of experiments during failed negative transitions

- Plasma confinement time is not affected by biasing
- Bias induces a density increase at $I_p=0$
- No improvement on the success rate of negative semi-cycle
Several causes can be proposed for the failing of semi-cycles:

- Impurity contribution and neutral gas pressure
- Formation of fast electrons (drift)
- Existence of runaway electrons
- Offset of the plasma column (vertical and horizontal fields)

Investigation on the possible influence of these parameters for partially successful discharges at 4 kA under electrode biasing of 120 V
Evolution of chamber background pressure after shutdown

Requires several days of discharge cleaning to bring background pressure to operating values
Evolution of chamber background pressure during normal operation

The background pressure always recovers to the same value between shots

Good conditioned chamber!
Impurity contribution and neutral gas
Pressure (puff)

Systematic sharp increase of plasma temperature with number of AC cycles

No impurity accumulation

\[ \bar{n} \]

\[ \sigma \]

visible
Impurity contribution and neutral gas pressure (gas puff)

Runaway electron (x-ray signal) seems not reduced by gas puff

This could be due to the lowering of plasma density and possible presence of hollow temperature profiles (it is noticeable a correlation between x-ray and plasma density:

less plasma density $\rightarrow$ more x-rays

On the other hand, increasing gas puff seems to help to obtain more successful full AC cycles

Wider gaps between gas puffs $\rightarrow$ larger x-ray signal events (in lower and higher density semi-cycles)
In using data from interferometer and HIBD the role of plasma vertical shift is not so important.

In this shot the horizontal shift is relatively low.
The broader x-ray signal may imply a larger runaway plasma fraction.

The runaway gradually drifts to the wall.

After runaway vanishes the plasma density and temperature increases.

The fast x-ray pulse rise and decay indicates a very localized runaway beam (drift to the wall).

The fast vanishing of the runaway beam induces a transient plasma pressure increase.

This could be attributed to the conversion of runaway beam magnetic energy into a residual plasma current increase.
Runaway influence on discharge ramp-up

Runaway during pressure build-up → possible compromise on plasma discharge performance

Transition +/-
Ramp-up of plasma pressure presents oscillations synchronized with runaway formation

Transition -/+:
Ramp-up of plasma pressure presents smoother evolution without runaway formation

BE current
X-ray

Ip
$\bar{n}$
drift electrons signature:
Non-successful AC transition

@ 50.4 ms during ramp-up

- Relatively large transient visible emission
- Residual plasma current
- Residual plasma density

- Residual nsigma detection
- Signature of vertically shifted electron density

Electrons seem to drift to the vertical part of the vessel (in agreement with expected drift direction due to gradB)
The role of external V/H magnetic fields

#40035: plasma column has an offset of -17 mm vertically but almost all semi-cycles were successful.

#40237: plasma column is nearly centred but many semi-cycles have failed.

#40493: the plasma column swings up and down of the centered position depending on the plasma current direction maintaining some successful AC transitions.

If the plasma fully forms the V/H fields tuning does not influence the progress of the AC discharge (within practical limits).

And what about during burn-through and ramp-up phases - critical phases?
• During discharge the primary current follows the plasma current
• Without plasma discharge the iron core saturates towards the end of the semi-cycle
• During saturation the primary coils current increases and also the ‘free air’ magnetic field
The primary beam position (in the toroidal direction) is proportional to the total plasma current.

When there is plasma the beam position follows by enlarge the plasma current.

When there is no plasma the beam position follows the ‘free air’ magnetic generated by the primary coils.
Plasma current during the AC transition

As observed for when there is no plasma:
The effect of H/V field is negligible in the primary beam position.

During discharge the beam toroidal position is by increase determined by the plasma current.
Plasma current during the AC transition

Beam toroidal shift accuracy = +/- 280 A
sensitivity = 0.25 mm/KA

- The beam position follows the change of plasma current
- Near the point of current inversion the beam position stays frozen for 0.4 ms
- During this time the plasma current changes by 800 A
- The beam position follows the change of plasma current but with a different evolution than above
- During initial stable current phase (111-114 ms) the plasma pressure and density are still evolving
- During this phase the beam position evolves indicating a current density profile change (flat profiles generate larger shifts for the same plasma current)
Two opposite plasma currents inducing a low beam toroidal shift

\[ +0.7 \text{ kA} - 0.5 \text{ kA} = 0.2 \text{ kA (net)} \]

\[ \Delta z = -0.1 \text{ mm} \]

- The presence of 2 counter current channels during Ip transition has been measured in the CT-6B tokamak.

- The results from ISTTOK show a freeze of the HIBD toroidal beam shift for 0.4 ms during current inversion (it could be compatible with the formation of two counter current channels).

- As for the -/+ transition the beam shift seems to indicate a plasma current evolution from flat to peak profile.
• During AC operation it is observed that a quiescent plasma is maintained for up to 0.8 ms after the unsuccessful AC transition, which is longer than ISTTOK confinement time (0.3-0.4 ms).
• Electrode biasing experiments have demonstrated that it is possible to increase the plasma density during the AC transition (when $I_p = 0$) roughly from 30%-40% above the non-biased cases.
• The increase of density via EB did not translate into a higher success rate of full AC cycles.
• We observe that the use of bias electrode to increase the density at the AC transition causes a reduction of the electron temperature leading to the production of runaway electrons that show an interplay with plasma pressure.
• The presence of runaway electrons was detected during plasma pressure build-up phase and showed to influence the plasma evolution.
• The presence of a drift-electrons-like population was also detected in some particular shots.
• Gas puff in controlled doses can help to increase the number of AC semi-cycles: what dose? n? T?
• The current evolution during AC transition was measured by HIBD and indicated some non-linear features that could be compatible with the presence of a double counter current.
• Current density profile changes from flat to peaked could justify the observed changes on HIBD beam position @ constant $I_p$.

The experimental data available may be used to support the development of a first order predictive model that could integrate the observed results and inform on the interplays between different plasma parameters.
Three phases of the AC transition that can be proposed:

1. Transition from full to null current, from when Vloop swings to Ip=0
2. Quiescent plasma and ramp-up
3. Burn-through and full plasma development

1. – Treat like a disruption? What kind?
   • how does the plasma evolve while the flux swings direction?
     • Up to when during the transition there is equilibria?
       • Two counter currents formation?

2. – Treat like could plasma? (neutral population?)
   • What keeps the quiescent plasma?
   • What external control parameters are important for the good ramp-up of plasma current?
   • What are the optimal quiescent density an temperature for successful plasma ramp-up?

3. Treat like a partial evolving plasma with important runaway population
   • What is the role of runaways and how to mitigate their presence or effects on plasma development
     • What is the role of fast electrons?

ETC,


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