Edge plasma studies on the COMPASS Tokamak


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• Originally operated in UKAEA Culham in 1992-2001,
• Re-Installed in Prague in 2006-2011, put into scientific exploitation in 2012
• ITER-like geometry with a single-null-divertor (H, D)
  (10x smaller)
• Scientific program (and diagnostics) is focused on the edge, SOL and divertor plasma

New NBI system (2 x 370 kW) enabling co and balanced injection

Major radius  0.56 m
Minor radius  0.2 m
We operate currently
• Toroidal magnetic field \( \text{up to} \, 1.38 \, \text{T} \)
• Plasma current \( \text{up to} \, 350 \, \text{kA} \)
• Discharge duration \( \text{up to} \, 0.4 \, \text{s} \)
• Central electron temperature \( \text{up to} \, 1.3 \, \text{keV} \)
• Central electron density \( \text{up to} \, 2 \times 10^{20} \, \text{m}^{-3} \)
• Central ion temperature \( \text{up to} \, 1.2 \, \text{keV} \) (at NBI heating)

Standard discharge regimes
• Standard ohmic regime
• Ohmic H mode (ELMy and ELM-free)
• L mode (NBI heating)
• NBI assisted H mode

Sometimes
Low density shots (runaway electrons studies), Resonant Magnetic Perturbations (mitigation of ELMs), ITER relevant shots (circular plasma, mimicking of the central solenoid misallignement, ...
Example - ELMy H-mode

Plasma current - ~ 300kA

Line average density ~ 4-5 x 10^{19} m^{-3}

Loop voltage ~ 1 – 2 V

D_α emission, HXR emission
Radial Profiles by HR Thomson scattering

#6358 $P_{\text{NBI}} = 515$ kW

- **Black symbols** – L mode
- **Blue symbols** – H mode

- Formation of pedestals on $T_e$ and $n_e$ are clearly visible
- Electron heating after LH transition
- Electron density increase as well
COMPASS is relatively well diagnosed

**Magnetics (400 sensors)**
- Loop voltage, plasma current, plasma position, EFIT reconstruction, several arrays of Mirnov coils

**Microwaves** - interferometer (4 mm), reflectometer (collaboration with ISTTOK)

**Spectroscopy**
- Temporal evolution selected spectral lines - $D_\alpha$, impurities (C, He, ..)
- Several fast cameras (visible, infrared)
- HR Thomson scattering core + edge – radial profiles of the electron temperature and density, 52 spatial channels, temporal resolution 17 ms
- 6 Arrays of AXUV-based fast bolometers
- 3 arrays SXR detectors

**Neutral particle Analyzer** – ion temperature with temporal resolution of ~200 $\mu$s

**Lithium beam diagnostics** - temporal evolution radial profiles of plasma density at the edge of the plasma column

**Others**
- ECE emission, spectrometers (VUV, visible, near IR), HXR&neutron detectors

... and

**Electric Probes** – subject of my talk
What is required to understand edge plasma physics?

**Edge plasma** plays a decisive role in global plasma confinement in tokamaks and electric probes are almost ideal tool to study underlying physics.

It is evident that understanding of edge plasma physics requires simultaneous measurements of:

Plasma parameters such as the plasma density, temperatures, plasma potential with a good spatial and **temporal resolution** (turbulence, ..), and plasma **flows** in poloidal (and toroidal) direction.

Practical solution used in all tokamaks => **electric (Langmuir) probes** - almost ideal tool to diagnose the edge plasma with sufficient spatial (up to ~1-2 mm) and temporal resolution (<< 1 ms)

Magnetic probes should sometime accompany electric probes to study electromagnetic features (turbulence, quasi-coherent modes GAMs – talk of A Melnikov yesterday, …

Drawback – probes always perturb plasma, therefore non perturbing diagnostics also used in tokamaks:

- Fast cameras to visualize the density fluctuations (2D)
- Beam emission spectroscopy (2D)
- Microwave reflectometry
- Heavy Ion Beam Probe (see talk of A Melnikov)
- Gas puff imaging (2D)
COMPASS vessel

Vessel INCONEL

Belt limiter
Graphite tiles
Inertial cooling only

64 Diagnostic ports

Divertor
Graphite tiles - inertial cooling only
First wall elements (made of graphite) and D shape plasma cross section

- Protecting limiters
- Last closed magnetic surface (or separatrix)
- Scrape off layer (SOL)

Edge plasma is strongly poloidally asymmetric => probes located at as many poloidal angles as possible are required (constrains – number of diagnostic ports)
Special measures have to be taken, if the probe is used to measure plasma parameters in proximity or even inside the separatrix:

- Probe head must stay in plasma as short as possible. Only solution – probe head is fixed to a reciprocating manipulator.

Typical duration of a single plunge – 150 ms

- Probe head must be sufficiently robust to survive high heat loads.

Probes to diagnose plasma
Just in the scrape off layer can stay at fixed position (and move on shot to shot basis)

Arrays of Langmuir probes embedded in the divertor tiles
Advanced electric probes are exploited on COMPASS. Some of them were designed and tested on the CASTOR tokamak in a broad international collaboration.

They could be utilized on other small devices with magnetic confinement and might be of interest of RUSFD community.

In particular,

- Ball pen probe (*our invention*)
- Tunnel probe (*in collaboration with CEA Cadarache*)
- Langmuir probe arrays (*in collaboration with Bulgaria*)
- Retarding field analyzer (*in collaboration with AUG*)
- ExB analyzer (*in collaboration with AUG*)
- U probe (*in collaboration with RFX Padova*)
What is the Ball Pen Probe?

A novel probe for direct measurement of plasma potential in magnetized plasmas - designed and tested on the CASTOR tokamak ~15 years ago. Exploited on many tokamaks and its proper operation proved since that time (COMPASS, ASDEX-U, MAST, ISTTOK, IR-T1, .....)

Relation between floating and plasma potential

\[
V_{fl} = \Phi - T_e \cdot \ln\left(\frac{j_{sat}^- \cdot A_e(h)}{j_{sat}^+ \cdot A_i(h)}\right);
\]

\[
\frac{j_{sat}^- \cdot A_e(h)}{j_{sat}^+ \cdot A_i(h)} = 1 \implies V_{fl} = \Phi
\]

Ai – collection area for ion flux
Ae – collection area for electron flux

We exploited the Ball Pen probe routinely, but we did not know the mechanism why electrons penetrate to the retracted collector.


Electron and ion trajectories in BPP from PIC simulations
Direct measurements of the plasma potential $\Phi$

L mode

ELMy H mode

Huge spikes of plasma potential Associated with ELMs!!
Direct measurements of the radial electric field $E = -\nabla \Phi$

Shear of the radial electric field $\Rightarrow v_{pol} = E_{radial} \times B_{toroidal}$
$\Rightarrow$ Impact to edge plasma turbulence
BPP in pedestal region

- Probe head penetrates inside the separatrix (into pedestal region)
- Highly sheared radial electric field is formed in proximity of the separatrix after transition to H mode
- Note different character of potential fluctuations inside and outside the separatrix

Array of magnetic probes $\Rightarrow$ cross-coherence with electric probes is possible

The BPP probe directly localizes quasi-coherent modes (GAMs) in the pedestal region

A Melnikov, 12th ITPA energetic particle physics TG meeting (2014)
Fast measurement of the electron temperature by combined Ball Pen and Langmuir Probes

\[ V_{fl} = \Phi - \alpha T_e \Rightarrow T_e = \frac{(\Phi - V_{fl})}{\alpha} \]

\( \alpha = 2.2 \) for Deuterium plasmas – confirmed by TS

Ball Pen probe for the GOLEM tokamak

BPP at low magnetic field?

Langmuir probe  BPP

Collector retracted by 4.2 mm
Coefficient $\alpha$ - Hydrogen plasma GOLEM

\[ \alpha = \frac{V_{fl}^{BPP} - V_{fl}^{LP}}{T_e} \]

Electron temperature and the floating potential - measured by swept Langmuir tip

$\Rightarrow$ appears to be independent on the magnetic field

Coefficient $\alpha$ remains almost constant $\sim 3.8$ at magnetic fields from 0.3 to 0.5 T

However, it increases significantly for $B < 0.3$ T

??????
Radial profile of $q_{||} \sim T_e I_{sat}$ measured by horizontal reciprocating manipulator (equipped by BPP+LP) at outer midplane.

Decay length of the parallel heat flux of the inter-ELMy SOL plasma is significantly shorter than that of the ELMs (by a factor 2-3)
• Parallel heat flux: \( q_{//} = n \cdot T_e \cdot c_s \cdot \gamma \)

• The electron temperature is measured by BPP and toroidally separated Langmuir probe with temporal resolution 0.2 \( \mu s \).

Filamentary structure of a single ELM is observed with sub-microsecond temporal resolution

The parallel heat flux during filaments up to 50-70 MW/m\(^2\) is observed at the outer midplane
A strong coherence at $f \sim 25$-$35$ kHz, radially localized inward from velocity shear layer, is observed

$\Rightarrow$ strong long range correlation (both $V_{fl}$ and $V_{BPP}$)

Furthermore, a strong magnetic component is also observed in D-shape plasmas with $n \approx 0$, $m \neq 2$

Candidate mode for GAMs is identified

Both reciprocating manipulators are inserted simultaneously into plasma
Reciprocating probe head, driven by electromagnetic force ($J \times B_{tor}$), is equipped by two Tunnel probes => fast simultaneous measurements of the electron temperature, ion saturation current, and parallel Mach number at the same magnetic surface.
Numerical simulations (PIC) shown that the ratio of ion saturation currents on the tunnel and the back plate is a strong function of electron temperature. Tested on CASTOR - routinely exploited on Tore Supra. Now commissioned for COMPASS and WEST tokamaks. Electron temperature is measured without collecting any single electron!!
Tunnel探针——一个CASTOR的结果
39 Langmuir probes spaced poloidally by 5 mm

IV characteristics are measured with the temporal resolution 1 ms, or
Ion saturation current/floating potential is recorded with sampling frequency 2 MHz

see talk of Tsviatko Popov
New array of Langmuir and Ball Pen Probes in the divertor tiles (design)

Goal:
plasma parameters in the divertor with a high spatial and temporal resolution

Two toroidally separated arrays of 55 Ball Pen Probes
Spatial resolution 3 mm
Different location with respect to LPs – to avoid shadowing

Two toroidally separated arrays of 55 Langmuir probes
Spatial resolution 3 mm
Combined local measurements of electric and magnetic properties of filaments are important tools to improve our understanding of the filaments. U-Probe consists of two identical towers spaced poloidally by 40 mm (made of boron nitride).

3D magnetic coils

Radial rake of 6 Langmuir probes

1. U probe is fixed below midplane
2. Movable on shot to shot basis
ELMs are characterized by a complex electromagnetic filamentary structure

- Positive peak of parallel current density, $J_{tor}$ is accompanied by negative secondary $J_{tor}$ peaks $\Rightarrow$ a nearly zero time integral of the $J_{tor}$ is associated to the current filament

Filamentary feature is confirmed by the closed patterns of $\delta B_{pol}$ and $\delta B_{rad}$ fluctuations in the cross-field plane.
- Existing measurements show that Ti in SOL is 2x – 10x higher than Te
- Ti is rarely measured at high temporal resolution
- Ions transport majority of heat flux

**Objective**

- Develop diagnostics for fast measurements of Ti (>= 100 kHz)
- Measure Ti evolution during ELMs
- Measure Ti fluctuations in SOL (L-mode)

**Zeff**

- TZM fixation bolts
- Peak insulation
- Molybdenum grid
- Lower BN holder
- Dural washer
- Stainless steel rods
- Graphite housing
- Tungsten slit plate
- Brass nuts
- Dural washer
- Upper BN holder
- Peak spacers
- Copper electrodes
- PCB with collector array
- Peak grip for the PCB
- Vessel probe interface

Compatible with COMPASS and AUG reciprocating manipulators
Results indicate that there are two ion populations in SOL with different temperatures. Ratio of the populations depend on density. Could be low Ti ions from recycling/fueling and high Ti transported from LCFS? Needs more experimental verification on both COMPASS and AUG.
Survey of probe diagnostics on COMPASS

- Langmuir and Ball Pen Probes on reciprocating manipulators to measure radial profiles of plasma potential and the electron temperature with a high temporal resolution at two poloidal angles (midplane and the top of the torus).

- Array of Langmuir and Ball Pen Probes embedded in divertor tiles to measure plasma parameters with a high spatial and temporal resolution at two toroidal positions.

- Probe heads equipped by tunnel probes to measure radial profiles of Te and parallel Mach numbers.

- U probe to measure current filaments in SOL.

- ExB analyzer for fast measurement of the ion temperature in SOL - comparison COMPASS and AUG (in progress).

- Retarding Field Analyser to measure the ion temperature.
• Edge plasma is an important region in tokamaks – confinement, transport barriers, turbulence, quasi-coherent modes, transient phenomena, ….

• Edge plasma diagnostics with a good spatial and temporal resolution are required to understand the underlying physics.

• Electric probes (arrays) accompanied by magnetic sensors are extremely useful tools for that purpose.

• The COMPASS tokamak is now well equipped with several probe systems, and interesting results are already achieved. More data are expected in future.