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Conceptual Design of Reciprocating Probes and Material-Testing Manipulator for Tokamak COMPASS Upgrade

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Abstract: Three new in-vessel manipulators are designed and built for the new COMPASS Upgrade tokamak with uniquely high vessel temperature (250-500 °C) and heat flux density (perpendicular to divertor surface $q_\perp \sim 80$ MW/m^2 and $q_\parallel \sim$ GW/m^2 at separatrix), which challenges the edge plasma diagnostics. Here we show their detailed engineering designs supported by heat conduction and mechanical models.

Deep reciprocation of electrostatic probes near the separatrix should be possible by optimizing older concepts in a) the head and probe geometry, b) strongly increasing the deceleration up to 100× gravity by springs and strengthening the manipulator mechanical structure. One reciprocates close to the region of edge plasma influx (the outer midplane), the other at the plasma sink (between the outer divertor strike point and X-point), for studying the plasma divertor (impurity-seeded) detachment and liquid metal vapor transport. Both probe heads are equipped with a set of ball-pen and Langmuir probes, measuring reliably extremely fast (10^{-6} s) and local (1 mm) plasma potential, density, electron temperature and heat flux and even ion temperature with 10^{-5} s resolution.

The divertor manipulator (without reciprocation) will place various material test targets at the outer divertor. Unique will be its capability to increase 15× the surface heat flux with respect to the surrounding tungsten tiles just by controllable surface inclination of the test targets. We plan to test liquid metal targets where such inclined surface was found critical to achieve the desired mode with lithium vapor shielding. Even in the conservative expected performance of COMPASS Upgrade, we predict to reach and survive the EU DEMO relevant heat fluxes.

Keywords: Plasma diagnostics - probes, Nuclear instruments and methods for hot plasma diagnostics, Overall mechanics design

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Contents

1 Introduction

COMPASS Upgrade (COMPASS-U) will be a mid-size tokamak capable of generating fusion relevant plasma and containing it by high magnetic field (up to 5 T) configuration surrounded by uniquely high vessel temperatures 250-500 °C. Consequently, high density ($\sim 10^{20}$ m^{-3}) thermonuclear plasma will cause extreme heat stress on divertor surface reaching $q_\perp \sim 80$ MW/m^2 [8] and enormous heat flux density $q_\parallel \sim$ GW/m^2 at last closed flux surface (LCFS) in a discharge 2 s long. Such parameters of plasma equilibrium can be reached with the help of copper coils cooled in cryostat to the temperature of liquid nitrogen and 8 MW of plasma heating.

As the new opportunities for research evolves also the need for proper diagnostic and semi-automatic manipulator system is important. This lead to the re-design of an unfinished set of two independent fast reciprocating manipulators (signed as HRCP and XRCP) and to the design of one completely new slow & precise divertor tile manipulator (DivMat) capable of transporting heat-resistant materials (in between discharge) onto the divertor outer strike point.

Both pneumatic reciprocating manipulators will be equipped with a set of ball-pen (BPP) and Lanqmuir probes (LP). Combined set of BPPs and LPs is able to measure extremely fast (1 MHz [4]) & locally plasma potential, plasma density, electron temperature without sweeping and heat flux density [3]. Even fast measurement 10^{-5} s of ion temperature can be obtained when sweeping the BPP [4]. LP as one of the primary tools to study boundary plasma physics in experimental fusion reactors are in a direct contact with the plasma, hence in order to provide safe measurement in deep Scrape-Off Layer (SOL), fast reciprocation in/out is necessary. In later stages of COMPASS-U, exponentially increasing heat flux of decay length of <1 mm is expected in region close to LCFS [5]. Therefore, an inaccuracy in the relative position of the probe to the plasma of the order of the decay length (1 mm) yields $\approx 3\times$ higher heat flux on the probe. Such harsh conditions could quickly lead to melting of the probe or (even before the melting) to thermionic electron emission, which makes the measurement uncertain.

The paper is focused both on the engineering design of each manipulator and on the research & ideas, which were made in order to reciprocate as deep as possible and to have as much universal tile manipulator as possible.

2 Reciprocating Manipulators

Both HRCP and XRCP consist of similar mechanisms that allow mounted probes to protrude every $\sim 10^{-1}$ s into plasma and if needed (figure 1a), retract outside of the tokamak, seal the vacuum, review probe heads (figure 1b) or shift the whole manipulator along its short rails and remove probe heads (figure 1c).

HRCP will scan low-field side midplane region, see figure 1d. How close to LCFS will depend on implementation of secondary mechanisms (described below) allowing probes to measure SOL turbulence transport and physics in high density plasma. XRCP will measure plasma properties in divertor region, between X-point and outer strike-point, or can poloidally extend HRCP resolution in scenarios with vertically inverted plasma. Its further usability lies in support of experiments with prototype tiles on DivMat, especially on liquid metal experiments, where it is almost directly (toroidally moved, see figure 1e) in contact with evaporated impurities from the tested tiles.

2.1 Design Review

The long (≈ 2.5 m) slow movement is conducted by servomotors rotating long screw pole that causes the movement of reciprocating system with probes and expansion/detraction of long vacuum bellow. Probe heads are pushed by a long heat-resistant stainless steel rod, filled with Mineral Insulated Cables sustaining high temperatures of vacuum chamber, in secondary support tube with the help of three sliding plates. After reaching the parking position ≈ 15 cm outside LCFS, manipulators wait for a discharge to reciprocate. Filling up 2×2 pistons for each manipulator with helium gas, probes reach velocity of 2.5 m/s and retract with deceleration of ≈ 100 m/s^2 (for a 3 kg probe head). Piston filling can be adjusted, for example, to obtain more data at one significant position, where conditions are not so demanding. Commonly to all pneumatic systems, this maximum speed is limited by the friction of both the moving components and the helium gas.

At the same time, the probes must withstand double-exponential heat flux density profile of decay lengths λ_q^{near}, λ_q^{far} in radial direction r outside LCFS [5]

$$q_{\parallel}(r) = q_{\parallel}^{\text{LCFS}} \frac{R_q \exp(-r/\lambda_q^{\text{near}}) + \exp(-r/\lambda_q^{\text{far}})}{1 + R_q} \text{ reaches at LCFS} \sim \text{GW/m}^2, \tag{2.1}$$

where R_q is the ratio of *near* and *far* exponential decays of parallel heat flux at LCFS. In order to measure more deep in the plasma, improvements are described below and can be additionally implemented to the design.

2.2 Real-Time Depth Control

The decision was made that for safe and deep protrusion into plasma it is essential to check heat deposited on the probe in real time. The first reciprocation of each plasma discharge will be safe and shallow. Total heat Q deposited on the probe during its movement can be retrieved directly from the

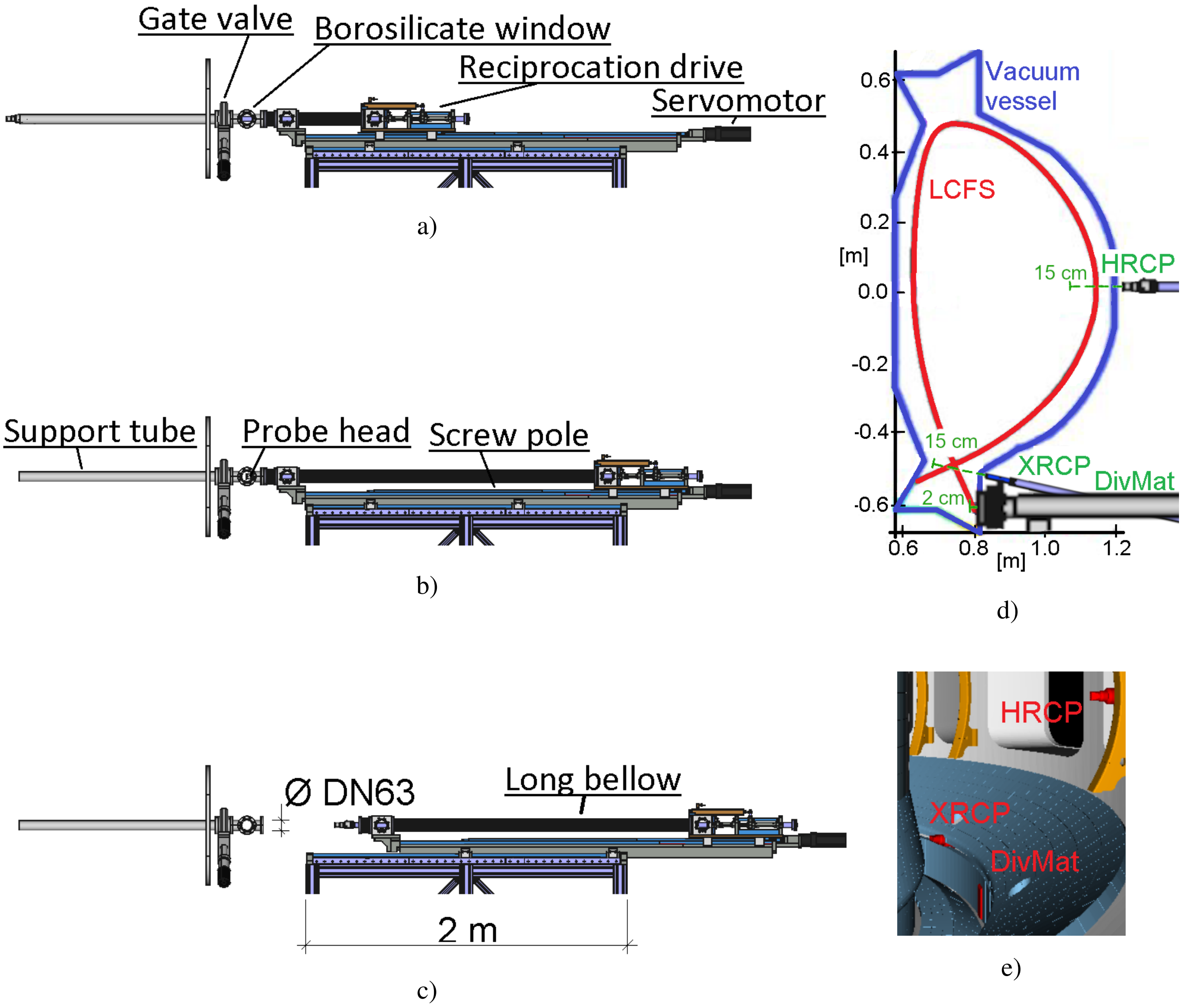


Figure 1: Schematic view on HRCP manipulator (XRCP and DivMat works on the same principle) in its three stages of operation. a) The probe waits in the parking position for a discharge followed by several reciprocations. b) Probe in the diagnostic window (possible check also between individual discharges). c) Manipulator ready to disassemble the probe. d) Poloidal cut showing the protrusion of all manipulators. e) Visible light camera view into the chamber.

ion saturation current $I_{\mathrm{sat}} = I_{\text{-}300\mathrm{V}}/(1 - \exp([-300 - V_{\mathrm{fl}}]/T_{\mathrm{e}}))$ (from corrected current measured at probe biased to -300 V, such correction is important during numerous instability events, such as periodic Edge Localized Modes (ELMs), when $\phi - 3T_{\mathrm{e}}$ drops below ≈ -200 V) and electron temperature $T_{\mathrm{e}} = (\phi_{\mathrm{BPP}} - V_{\mathrm{fl}})/2.2$ [3] as

$$Q = \int_{\mathrm{reciprocation}} \gamma \cdot \frac{I_{\mathrm{sat}}(t)}{A} \cdot T_{\mathrm{e}}(t) dt, \tag{2.2}$$

where A is the effective area of the probe and γ is the sheath heat flux transmission coefficient.

Since the profile of incoming heat flux can be approximated as exponential (with decay length λ_{q} obtained from scaling laws [6, 7] and later calibrated for each mode), let us shift each plunge depth by a distance Δr as

$$\Delta r = \lambda_q \log\left(\frac{P_{\mathrm{prev}}}{P_{\mathrm{next}}} \cdot \frac{Q_{\mathrm{opt}}}{Q}\right) + \Delta d_{\mathrm{LCFS}}, \tag{2.3}$$

where P_{prev}, P_{next} is the external plasma heating power during *previous* and *next* plunge. Δd_{LCFS} is the shift of LCFS position compared to previous plunge and obtained from real-time magnetic reconstruction EFIT. Even though EFIT has a large systematic error ($\approx$ 1 cm), relative shift Δd_{LCFS} can be calculated with sub-millimeter accuracy. Q_{opt} means an "optimum received heat" and will be determined by trial and error practise in different operation regimes (L-mode, H-mode, ELMy H-mode, ...), so that the surface probe temperature will be kept under its melting point throughout the whole discharge. Servomotor of the slow movement (5-7 mm/s) is sufficiently fast to rearrange the starting position of the fast reciprocation by Δr ($\sim 0.5 - 1$ mm) during every of 10 to 20 plunges for a 2 s long discharge.

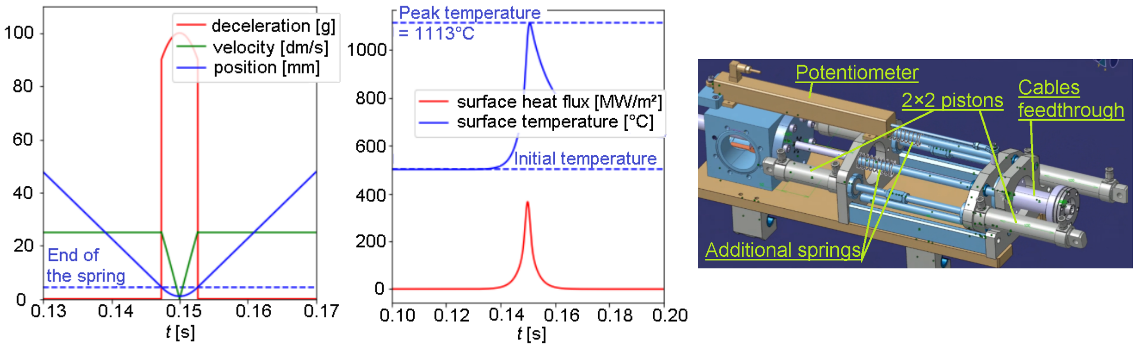
2.3 Accelerating the Reciprocation

Since total amount of deposited heat increases with time spent in plasma, it is desirable to reciprocate as fast as possible. This can be achieved by increasing both the deceleration in plasma and the maximum velocity of the movement (which is reached within several centimeters for common pneumatic systems). 1D heat equation simulation has been created in order to demonstrate the situation.

We noticed the same behavior as seen on the Linear Servomotor Probe Drive System on Alcator C-Mod tokamak [9]. The extremely variable heat flux density profile eq. (2.1) causes the heat supplied to the probe after reaching the maximum velocity to be negligible compared to the heat it receives during its turn around phase. Knowing that, we were able to propose improvements to the existing design of the "slow" deceleration profile caused purely by increasing He gas pressure in pistons. As shown in figure 2c, by adding a set of pre-loaded mechanical springs to the end of the reciprocation mechanism, we acquired merely constant profile of deceleration (up to 100 g, the stress limit for 3 kg of moving mass for our manipulator) causing probe to safely regain its maximum velocity few times faster than in original setup. By doing so, we are able to keep surface temperature T_{max} of graphite head under 1200 °C even when protruded 1 mm outside of LCFS, see figure 2b where the heat flux perpendicular to the surface reaches 400 MW/m^2.

2.4 Passive Radiation Cooling

Typically, reciprocations are so fast and discharge is so short (compared to time needed for energy recovery in between discharges) that probes can take advantage of inertial cooling, i.e., only a thin surface layer is heated and total gained heat during whole discharge is negligible to the total probe heat capacity (< 20 reciprocations on COMPASS-U causes temperature rise of $\sim$ 1 °C if distributed along the whole probe mass), so the sudden temperature rise can be quickly ($\sim \alpha_C l^2_{\mathrm{head\&probe}} = 10^2$ s, where α_C stands for thermal diffusivity of carbon composite) cooled down by its surroundings. But on COMPASS-U (and future fusion reactors) vacuum vessel will be heated even up to 500 °C, which limits self-cooling of the probe head to this temperature. Therefore, a system of passive radiation cooling is further developed, cooling the pre-discharge head temperature down by 340 °C (the entire temperature profile at figure 2b drops down by 340 °C).



a) b) c)

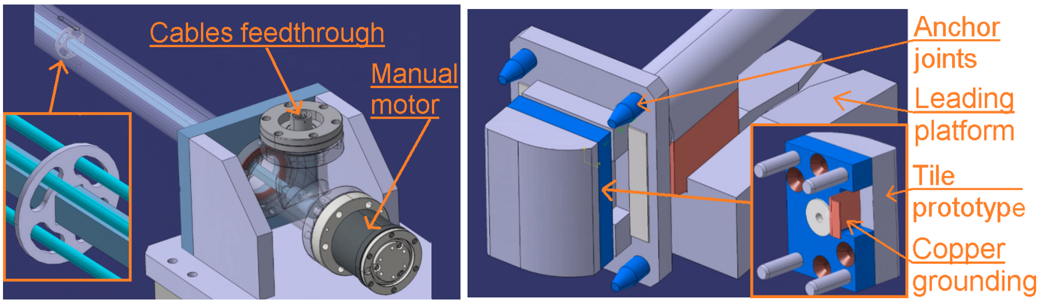
Figure 2: a), b) Simulated time evolution of one reciprocation for $a_{\max}$ = 100 g (981 m/s^2), $v_{\max}$ = 2.5 m/s protruding 1 mm outside of LCFS in SOL with parameters $\lambda_q^{\text{near, far}}$ = {0.7; 7.0} mm [6, 7] and R_q = 4 [5]. c) The fast reciprocation pneumatic system of 2×2 pistons and two springs of total strength 90 N/mm.

Assuming a simple model of cylindrical graphite probe head coated by tungsten, heated differently from both sides and cooled down by its thermal radiation into surrounding cooler. Vacuum vessel at T_{vessel} = 500 °C shines only to the front face of the head, resulting in heat influx P_{front} = 5 W. Stainless steel outer support tube isolated by Multi-Layer Insulation causes the heating of the head from behind P_{behind} = 4 W. Due to only 1 W difference between P_{front} and P_{behind}, correction to the temperature gradient in the head is negligible thanks to its high heat conductivity. Total heat influx $P_{\text{front}} + P_{\text{behind}}$ can be radiated from the head, hence cooling it down to temperature of 160 °C, by the help of surrounding radiation absorber at temperature of 20 °C. Radiation absorber could be a metal tube (emissivity ε = 0.2 is sufficient) winded around the head in its parking position (behind the first wall of COMPASS-U) and cooled down by the outer cooling system connected via additional tubing through the same vacuum vessel port as the manipulator uses.

3 Material-Testing Manipulator

Unlike two previous manipulators, DivMat is made from scratch, but it keeps the same simple design of slow & long rotational screw pole with servomotor attached to a set of manually manipulated rails. The reciprocating mechanism has been replaced by an additional rod (with square cross section in order to stop its own rotation) that connects the tile holder with manual rotational magnetic mechanism at the beginning of vacuum bellow, see figure 3a. This rod causes the tile to be additionally positioned up to 2 cm with 1 mm precision with respect to the alignment of the tiles in divertor region.

Tile attached to the holder at the end of manipulator slowly reaches the leading platform just behind the vessel, which guides it to four corner joints serving as the main anchor fixing the tile in one exact position. A copper plate leads from the tile holder to the manipulator, see figure 3b. Electric current, induced during discharge by numerous instability events, is conducted by this plate to the manipulator grounding. Such conductor minimizes $\boldsymbol{j}\times\boldsymbol{B}$ force, which could mean serious damage to the manipulator and surroundings.



a) b)

Figure 3: a) The beginning of the precise movement rod with moment magnetic feedthrough. b) Detail of the tile holder in parking position, showing the specially shaped tile for experiments (not only) on liquid metals.

Precise and rigid anchor of the tile is necessary since at later operational phases of COMPASS-U with complete tungsten divertor heat flux at divertor tiles could reach even $q_\perp$ = 80 MW/m^2 in stable H-mode [8]. Such high heat load is limiting even for estimated ∼ 10^2 – 10^3 ms long discharges for most of materials. On the other hand, it provides a worldwide opportunity to further investigate priority tasks for ITER with tungsten melting [10] and pre-damaged material testing [11], or plasma deposition into gaps in between plasma facing components [1] (carried out in inner-wall limited discharges on COMPASS with two follow-up experiments performed in divertor of AUG and WEST). Experiment on liquid metals on COMPASS tokamak in 2019 [2, 7] was relevant thanks to the simple shape of a quarter of a cylinder of the tile used there, see figure 3b. This particular shape allowed to vary angle of impact with protrusion to plasma, which can also be ensured on DivMat by the manually operated rod of precise movement. By doing so, DEMO relevant fluxes ($q_\perp$ = 160 MW/m^2 [8]) are achievable on the inclined tile surface even with long lasting (> 2 s) low power H-mode COMPASS-U conditions at $q_\perp$ = 10 MW/m^2 on the surrounding divertor tiles.

4 Conclusion

Set of three independent manipulators is designed for the upcoming new COMPASS-Upgrade tokamak. It consists of two fast reciprocating manipulators, horizontal HRCP scanning the midplane region and XRCP scanning the region responsible for plasma detachment. Both of them can be equipped with a set of additional springs allowing them to safely protrude 1 mm outside of LCFS in a dense (∼ 10^{20} m^{-3}) thermonuclear deuterium plasma. If additional pre-cooling system is accepted or in low power long lasting (>2 s) scenarios in L-mode, manipulators are capable of protruding even inside LCFS. The third material testing manipulator (DivMat) is without the ability to reciprocate but can fix the prototype tile (designed by DEMO engineers) in exact position ranging up to 2 cm deeper than surrounding divertor tiles.

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