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Conceptual design of the Halo Machine

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Abstract

In 1996, when the danger of sideways forces was first recognised, the operational window of the JET tokamak was significantly restricted. Limits were placed on the maximum magnetic field and plasma current to prevent excessive stresses on the vacuum vessel. Despite three decades of research, predictions for the sideways force on the ITER wall remain highly uncertain, ranging from 2 to 60 MN with the upper estimate exceeding the design value of 48 MN, which would result in operational restrictions (operation with $I_\mathrm{p} < 15$ MA potentially affecting ITER's ultimate fusion performance). To address this issue, the ITPA community launched the dedicated joint experiment MDC-25 in 2018. While substantial progress has been made, recent findings highlight the need for complementary studies on a specialised linear device to investigate plasma–wall currents, key contributors to sideways forces. Here, we propose the first linear device specifically designed to investigate plasma–wall interactions in the presence of kink modes, with the aim of resolving uncertainties related to plasma–wall currents and associated sideways forces. It is expected that the findings obtained with the new device will guide the design of vacuum vessels and plasma facing components for future tokamaks.

Keywords: tokamaks, disruptions, halo currents, sideways forces

(Some figures may appear in colour only in the online journal)

1. Introduction

During plasma disruptions in tokamaks, plasma facing components (PFCs) and the vacuum vessel (commonly referred to as the 'wall') are subjected to strong electromagnetic forces. While the mechanisms governing the total vertical force F_z are relatively [1] well understood, the origin and behaviour of the total horizontal (or 'sideways') force on the wall (F_x, F_y) remain elusive, posing a critical gap in our knowledge [2–10] see figure 1. By definition, the force is

$$F_i \equiv \int_{\mathrm{wall}} \left(\vec{J} \times \vec{B}\right) \cdot \vec{e_i}\, \mathrm{d}V, \tag{1}$$

where $\vec{J}$ is the current density in the wall, $\vec{B}$ the magnetic field, and $\vec{e_i}$ the unit vector in a given direction, with the integration performed over the wall volume.

Some models suggest that the sideways force is generated by the electric current shared by plasma and wall, which is known in literature under different names, such as halo [2–4, 11–15], Hiro [5, 16–18] and ATEC currents [6, 19, 20].

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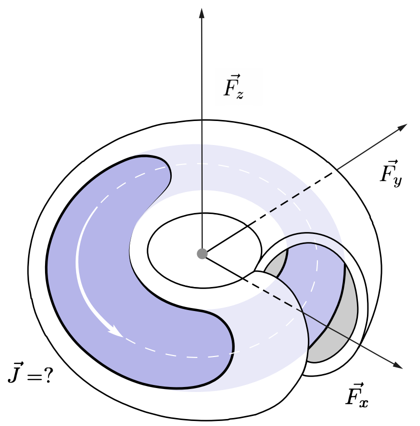

Figure 1. Vertical, F_z, and sideways force (F_x, F_y) on the tokamak vacuum vessel during a plasma disruption with a significant kink mode (tilt and shift of the plasma ring). The coloured region highlights the 'wet' zone, where plasma–wall contact occurs. The uncertainty in the magnitude and direction of the wall current, $\vec{J}$, leads to a 25-fold variation in predictions for the sideways force on the tokamak vacuum vessel.

This variety of terms reflects the complexity of plasma–wall interaction during disruptions and the absence of a universally accepted theory. The current density $\vec{J}$ encompasses the eddy (Foucault) currents, which can generate forces even in the absence of plasma–wall contact [7, 8].

Uncertainty in the magnitude and distribution of plasma–wall currents results in a 25-fold variation in predictions for the sideways force on the tokamak wall. Consequently, the magnitude of the sideways force for ITER remains highly uncertain, with estimates ranging from 2 MN [7] to 60 MN [16] and even 70 MN [21]. Notably, the upper estimates exceeds the design value of 48 MN [12], which would imply operation at $I_\mathrm{p} < 15$ MA and a potential risk for the project not to achieve its targeted fusion performance. Given the intrinsic limitations of studying plasma–wall currents in tokamaks, we propose to investigate their fundamental characteristics in a dedicated linear plasma device as described in this paper.

The sideways force on the tokamak wall can be estimated from the vessel motion or measured directly using magnetic diagnostics. The latter is a more precise method with higher temporal resolution, but so far it has been implemented exclusively on the COMPASS [22] and RFX-mod devices [23, 24]. The former was the sole option until 2023. It allows calculation of the sideways impulse only, requiring additional assumptions to estimate the force. Both mechanical and magnetic approaches provide the total sideways force. However, to distinguish between the different effects contributing to force generation, plasma–wall currents must also be measured.

2. Plasma-wall currents and the related sideways force on the tokamak wall

In 1996, during a disruption, the 300-tonne vacuum vessel of the JET tokamak shifted 7 mm sideways [3]. Today, three decades later, the origin of the sideways force remains poorly understood. What is clear, however, is that this force is associated with the 1/1 external kink mode, corresponding to a tilt and shift of the entire plasma ring. Yet, the force generated by the kink mode alone prior to plasma–wall contact is estimated to be relatively small [7, 8]. In contrast, all theories predicting large sideways forces–such as Source & Sink [4], wall touching kink mode (WTKM) [5] and asymmetrical toroidal eddy current (ATEC) [6] models–are associated with different types of plasma–wall currents: halo, Hiro and ATEC, respectively.

The ITER vacuum vessel has been designed based on estimates of sideways forces obtained using the Source & Sink model [12], which assumes a static distribution of halo current, unaffected by the presence of eddy currents. While this assumption is reasonable for the JET tokamak, where the characteristic wall time, τ_w, is much shorter than the typical disruption duration ($\tau_\mathrm{w} \ll \tau_\mathrm{CQ}$), it may not hold for larger machines. In ITER, for instance, $\tau_\mathrm{w} \geq \tau_\mathrm{CQ}$, making the influence of eddy currents a critical factor. Although halo currents have been routinely measured during disruptions on nearly all operational tokamaks for decades, these measurements are inherently fragmented and localised, which has so far prevented detailed studies of the interplay between halo and eddy currents in the presence of a kink mode.

The term Hiro refers to the plasma surface current at the plasma–wall interface [5, 16]. Numerical simulations with the NIMROD code 'support the possibility of reproducing WTKM physics' [17], and experiments on the EAST tokamak in 2015 confirmed the theoretically predicted polarity of the Hiro current, which is opposite to that of the halo current [18]. Nevertheless, some theoretical studies have questioned the very existence of Hiro currents [9]. To address this and other uncertainties related to sideways forces, the ITPA community launched a dedicated joint experiment (JEX MDC25), initiated in 2018 and continuing until presently. In particular, several experimental campaigns on COMPASS have been dedicated to the studies of Hiro and ATEC currents [19, 20].

The ATEC model [6] suggests that the sideways force is generated by eddy currents in the vacuum vessel, with particular emphasis on the current flowing through the edge plasma, which short-circuits adjacent PFCs (toroidally connected among them only through the vacuum vessel). For example, in the case of locked asymmetric VDE, the maximum sideways force on the ITER vacuum vessel due to the ATEC current alone can reach up to 28 MN [25]. In addition, ATEC currents may induce significant local electromagnetic loads on individual plasma-facing components (PFCs) [26]. These considerations motivated a series of dedicated experiments that were carried out on the COMPASS tokamak [19, 20]. While the results provided partial support for the theoretical predictions, a reliable extrapolation to ITER requires new experiments, preferably in a highly reproducible and controlled environment that allows systematic scans over different plasma and tile parameters.

Although based on completely different physical mechanisms, all three models [4–6] predict forces of the same order of magnitude for both JET and ITER. Each theory relies on

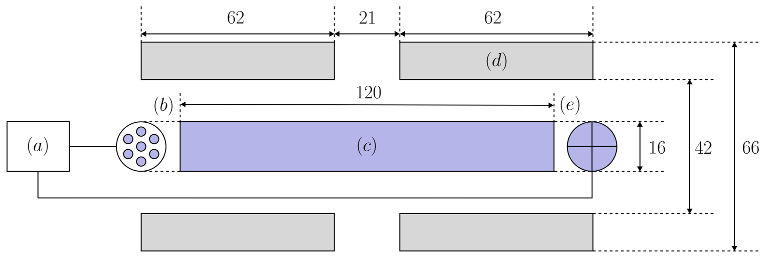

Figure 2. Schematic of the line-tied pinch experiment: (*a*) pulse forming network, (*b*) plasma gun array, (*c*) plasma column, (*d*) magnetic coils, and (*e*) segmented anode. All dimensions are in centimeters.

specific assumptions about plasma–wall currents in the presence of a kink mode. In this paper, we introduce a new linear plasma device designed to test these assumptions by studying halo, Hiro, and ATEC currents.

3. Linear device as a support platform for tokamak disruption studies

Halo Machine (HM) will provide a controlled environment for isolating and studying plasma–wall interaction phenomena. Unlike tokamaks, where key effects are strongly coupled [20], the linear device allows independent measurement of halo, Hiro, and ATEC currents, enabling the disentanglement of overlapping mechanisms and supporting the development of predictive models. Designed for reproducible parametric studies across a wide range of plasma conditions, HM will be the first linear plasma device dedicated to investigating plasma–wall currents in the presence of kink modes.

Despite many advantages of a linear device, only the tokamak environment can provide definitive insights into wall-current dynamics and the associated sideways forces. HM is therefore conceived as a complementary platform for designing tokamak experiments in which individual effects can be isolated. In addition, it will serve as a test bed for specialised tiles developed to measure halo, Hiro, and ATEC currents in tokamaks.

In contrast to most tokamaks, COMPASS [19] and RFX-mod [27], both equipped with comprehensive sets of magnetic diagnostics located outside the vacuum vessel [28], enabled direct magnetic measurements of the total sideways force, providing improved accuracy relative to the traditional mechanical approach [22–24]. In addition, several other devices—KTX [29], RFX-mod2 [30], JT-60SA [31] and ITER [32]—are equipped with a sufficient number of magnetic sensors on the outer side of the vacuum vessel to allow direct measurements of the total sideways force. Future studies of plasma–wall currents on the proposed linear apparatus, combined with dedicated experiments on the machines listed above, are expected to support the validation and refinement of sideways force models for ITER.

4. HM description and rationale for its parameters

The main components of the HM device are shown in figure 2. A pulse-forming network (*a*) powers an array of seven plasma guns (*b*) and biases the plasma towards a segmented anode (*e*), driving currents of up to 2.1 kA. The field generated by magnetic coils (*d*) stabilises the plasma column (*c*). However, once the current exceeds the Kruskal–Shafranov limit, an external kink instability develops.

In many respects, the design follows the Rotating Wall Machine (RoWM) previously operated at the University of Wisconsin-Madison [33]. For example, the device employs the same plasma gun technology to generate hydrogen plasma with an electron temperature of $T_\mathrm{e} \approx 3$ eV and a density in the range $n = (1-5)\times 10^{20}$ m^{-3}. The resulting current density can reach up to $j \approx 40$ A cm^{-2}. The corresponding ion saturation current density varies in the range, $j^+_\mathrm{sat} = 0.5\, enc_\mathrm{s} \approx 15-75$ A cm^{-2}, where $c_\mathrm{s} \approx \sqrt{kT_\mathrm{e}/m_\mathrm{i}}$ is the sound speed, neglecting the contribution from the ion temperature since $T_\mathrm{i}/T_\mathrm{e} << 1$. These parameters are particularly relevant for ITER conditions following a thermal quench [34].

To observe plasma surface currents (and the associated Hiro currents), ideal plasma behaviour must dominate over resistive effects. This condition requires the characteristic growth time $\tau_A = a\sqrt{\mu_0\rho}/B_z \sim 1$ μs of kink modes to be much shorter than the resistive plasma time $\tau_R = \mu_0 a^2/\eta_\mathrm{pl}$. Here, a is the plasma column radius, μ_0 the vacuum magnetic permeability, ρ the plasma mass density, B_z the axial magnetic field, and η_pl the Spitzer resistivity. For $T_\mathrm{e} = 3$ eV one obtains $\eta_\mathrm{pl} \approx 0.1$ mΩ·m. With $a = 8$ cm, this gives $\tau_R \approx 0.1$ ms, which indeed satisfies the required condition $\tau_R \gg \tau_A$.

For a line-tied pinch, the Kruskal–Shafranov condition defines the threshold current (or equivalently the axial magnetic field) for the onset of the kink instability as $B_z^\mathrm{KS} = \mu_0 IL/(4\pi^2 a^2)$, where I is the total plasma current and L the pinch length [35]. To avoid excitation of the sausage ($m = 0$) mode, the Taylor criterion for a skin screw pinch, $L/a > \sqrt{2}\pi$, must also be satisfied at the onset of the kink mode. In addition, individual flux ropes from the plasma guns must merge to form a single plasma column; in the RoWM this was observed at a distance of $z \approx 36$ cm from the source [36]. For consistency with RoWM, we chose the plasma column length as

$L = 120$ cm. For $I = 2.1$ kA, $a = 8$ cm, and $L = 120$ cm, the critical magnetic field is $B_z^{KS} \approx 130$ G.

While some experiments will require triggering a kink mode, others will be conducted with a stable plasma at magnetic fields of up to 1 T. This is of particular interest in the context of the ATEC current, as described in the following chapter. The HM plasma operates in pulsed mode with a duration of 5 ms. The shot repetition rate is limited by the parameters of the pulse-forming network, allowing approximately one shot per minute. For experiments at high magnetic fields, the air-cooled magnetic coil may further constrain the repetition rate; for example, only one shot every 10 minutes is feasible when operating at 1 T.

5. Device configurations for studying different wall-currents

To investigate halo, Hiro, and ATEC currents, the device can be configured in multiple ways, enabling controlled studies of different plasma–wall interaction scenarios. Each configuration is designed to test the key assumptions underlying the Source & Sink, WTKM, and ATEC models of sideways forces.

5.1. Halo current and source & sink model

Halo currents [2, 14, 15] are relatively well understood; however, the global-scale interaction between halo and eddy currents in the tokamak wall during a kink instability remains poorly characterised. In particular, it is unclear whether these currents predominantly cancel each other or combine to amplify the net effect.

Whereas only local measurements of eddy and halo currents are available in tokamaks, a linear plasma device enables complete coverage of the conducting shell surrounding the plasma column by an array of probes [37], thereby revealing the global pattern of wall currents and their dynamics during a kink instability (see figure 3). The shell will be instrumented with $2 \times 8 \times 8 = 128$ probes. Each probe consists of a pair of copper wires welded to the shell, and the measured voltage is directly related to the current density between the two contacts. For example, for a current density of ~ 30 A cm^{-2}, a 6 cm long probe produces a signal of about 13 mV.

A conducting shell slows the instability growth from the Alfvén timescale $\tau_A \sim 1$ μs to the resistive-wall timescale $\tau_w = \mu_0 r_w d_w / \eta_w \sim 0.1$ ms, thereby allowing measurements at a sampling rate of 2 MHz. Here, r_w, d_w, and η_w are the radius, thickness, and resistivity of the shell, respectively. To provide a stabilising effect, the wall must be sufficiently close to the plasma; for instance, achieving $\tau_w = 0.1$ ms requires a stainless-steel shell with radius $r_w = 1.1a \approx 9$ cm and thickness $d_w = 1$ mm.

Mode rotation may interfere with measurements; however, it can be suppressed by applying an external error field of a few gauss [38]. This error field will also be used to generate highly reproducible shots, with the plasma locked to the wall at a consistent angle. A fast camera aligned along the main axis will be used to estimate the plasma column displacement.

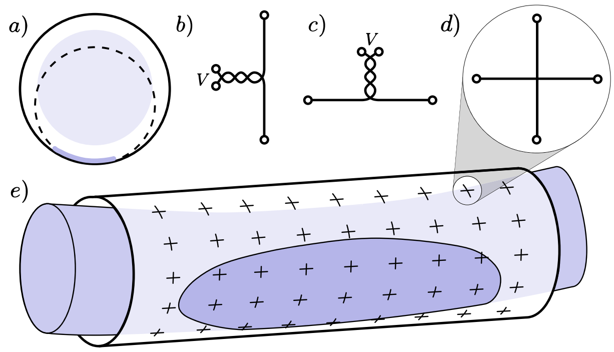

Figure 3. Configuration for studying the wall-current patterns: (*a*) poloidal cross-section, (*b*)–(*d*) two single and one double wall-current probes [37], (*e*) kinking plasma in contact with the conducting shell, with related eddy and halo currents monitored by an array of probes.

The measured wall current represents the sum of eddy and halo currents, with the latter inferred through appropriate modelling and data analysis.

The observed eddy-halo-kink interaction will be compared with that assumed in the Sink & Source model of sideways forces, and its predictions will be refined if necessary.

We stress, however, that HM is not intended to reproduce the full disruption physics of a tokamak. In particular, processes relevant to halo-current evolution during vertical displacement events (VDEs), such as toroidal flux compression and current quench [11], lie beyond the scope of a linear device. Instead, HM is designed to investigate plasma–wall current closure and its coupling to kink perturbations under controlled conditions. This approach targets a key aspect that remains difficult to access experimentally in tokamaks: the spatial structure and interplay of halo and eddy currents.

5.2. Hiro current and WTKM model

The Hiro current is introduced within the Wall Touching Kink Mode (WTKM) model. However, [9] showed that the WTKM model is incompatible with the fundamental requirement that the integral force on the plasma be nearly zero. Motivated by this finding, we designed an experiment to independently verify previous observations of the Hiro current [18].

WTKM model suggests that the Hiro current breaks down the boundary sheath and is therefore not limited by the ion saturation current, unlike the halo current. Instead, the Hiro current density, i_{11}^{surf}, is expected to scale with the kink amplitude ξ_{11} as $i_{11}^{surf} = 4\pi B_z \xi_{11} \sin(\theta)/(\mu_0 L)$ [16], where θ denotes the poloidal angle around the main axis of the linear device. This scaling indicates that, for $\xi_{11} = 0.1a$ and $a = 8$ cm, the Hiro current flowing towards the anode is $I_{surf} = 8\pi a \xi_{11} B_z/(\mu_0 L) \approx 140$ A. This corresponds to approximately 7% of the total plasma current, a level that should be readily detectable. The Hiro current flowing in the opposite direction is expected to have the same magnitude. An anode divided into four segments, as shown in figure 4, with currents measured in each segment, will be used to resolve the fundamental harmonic of the Hiro current. The plasma displacement will be

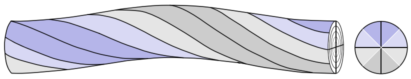

Figure 4. Configuration for measuring Hiro currents. According to [5], the kink mode induces surface currents of opposite polarity on the plasma column. The anode, segmented into four poloidal sections, allows the fundamental harmonic of the Hiro currents to be resolved.

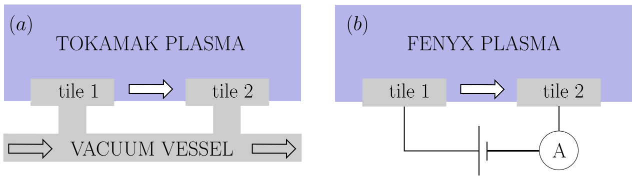

Figure 5. ATEC current flowing between adjacent tiles 'wetted' by plasma in a tokamak (*a*), and in the HM device (*b*), where tiles are artificially biased to replicate the potentials naturally occurring in tokamaks during plasma disruptions.

measured using an array of magnetic probes, as well as a fast camera aligned along the main axis.

According to [16], the Hiro current can generate sideways forces of up to 60 MN on the ITER wall, which significantly exceeds the design limit of 48 MN. To test this claim, the proposed experiments will investigate the Hiro current in detail and refine the predictions for the resulting sideways forces.

5.3. ATEC model and related current

During disruptions, rapid variations in magnetic flux induce large eddy currents in the tokamak vacuum vessel. The ATEC model proposes that, when PFCs are wetted by plasma-for example, during a VDE–a fraction of the vessel eddy current is diverted through the plasma between adjacent tiles [6], as shown in figure 5(*a*). This diverted current (the ATEC current) together with the consequent modification of the global current distribution in the vessel, can give rise to substantial sideways forces proportional to its magnitude. It is therefore essential to investigate how the ATEC current depends on plasma density and temperature, as well as on the material properties and geometrical configuration of the tiles.

To mimic a tokamak setting, two electrically biased tiles will be installed at the plasma edge, see figure 5(*b*). The current flowing between the tiles will be measured for different applied voltage, plasma density, the inter-tile gap. Notably, both HM conditions (ion temperature $T_\mathrm{i} = 1$ eV, magnetic field $B = 1$ T) and ITER post–thermal quench conditions ($T_\mathrm{i} = 10$ eV, $B = 5$ T) yield the same ion Larmor radius of approximately 0.1 mm, which remains significantly smaller than the 20 mm gap between ITER blanket modules. The dependence of the ATEC current on the magnetic field strength and its angle relative to the tiles will also be investigated, providing insight into the role of these parameters.

6. Astrophysical plasmas and space propulsion

With minor modifications, the proposed device can be employed for studies of astrophysical plasmas and magnetic reconnection [39]. Moreover, it provides opportunities to investigate the stability limits of magneto-plasma-dynamic (MPD) thrusters [40]. In particular, future experiments will assess whether a segmented anode can serve as an effective tool for the active control of MHD instabilities.

7. Discussion and conclusions

This paper presents a proposed linear plasma device designed to complement tokamak disruption studies, providing a controlled platform to investigate plasma–wall currents and to address long-standing uncertainties regarding the upper limits of sideways forces, with direct relevance for ITER.

A natural question is whether the better understanding of plasma–wall currents and related sideways forces could be achieved simply by upgrading diagnostics on existing tokamaks. Such upgrades are indeed essential, and in several cases already underway [29, 30]. Nevertheless, even with improved diagnostics, tokamak experiments remain constrained by limited access to PFCs, partial coverage of wall-current diagnostics around the conducting structures, restricted flexibility in geometry, and shot-to-shot variations in disruption conditions. By contrast, HM is intended to provide complete diagnostic coverage of the conducting shell, highly reproducible discharges, and systematic scans of plasma density, magnetic field, biasing and tile geometry. These capabilities make it possible to separate mechanisms that are difficult to disentangle in tokamaks, while the resulting understanding can then be used to optimise dedicated measurements on tokamak devices.

Recent works [1, 41, 42] have shown that an increase in halo current does not lead to an increase in the total vertical force. If a similar result were to be demonstrated for the sideways force, it would rule out the Source & Sink model. Moreover, if the amplitudes of Hiro and ATEC currents were also shown to be much smaller than expected, this would imply that the maximum sideways force is determined solely by the kink mode contribution [7, 8]. For instance, the conservative estimate for the rotating kink in ITER is 17 MN, which is significantly lower than the design value of 48 MN [8]. Such a result would also relax the design requirements for future tokamaks. Conversely, if all three theories predicting large sideways forces [4–6] were confirmed, the question would arise as to whether their effects could superimpose, and what strategies could be developed to mitigate them.

The present design is driven by the equipment currently available at Consorzio RFX in Padua. However, following suitable upgrades, the proposed experiments could also be conducted at the Keda linear magnetized plasma device in Hefei [43]. In both cases, the proximity of the RFX-mod2 [30] and KTX [29] devices, both equipped for halo-current and force measurements, would facilitate complementary experiments in toroidal geometry.

Finally, we note that plasma–wall currents and the associated sideways forces are also expected to be relevant for the Burning Plasma Experimental Superconducting Tokamak (BEST), the China Fusion Engineering Test Reactor (CFETR) [44], and the China Fusion Engineering Demo Reactor (CFEDR) [45].

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