CONCEPTUAL DESIGN OF THE FUSION ENERGY EXPERIMENT (FENYX)

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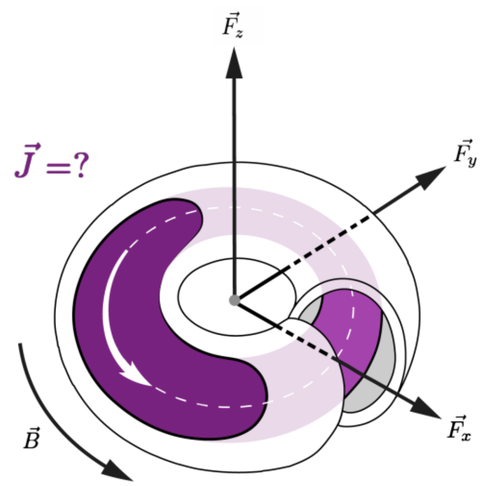
Abstract. In 1996, when the danger of sideways forces was first recognised, the operational window of the JET tokamak was significantly restricted. Limits were placed on the maximum magnetic field and plasma current to prevent potential damage to the vacuum vessel. Despite extensive research efforts, predictions for the sideways force on the ITER wall remain highly uncertain, ranging from 2.4 to 60 MN [1–8]. The upper estimate exceeds the design margin of 48 MN and, if confirmed, could necessitate a reduction in ITER's target operational parameters, potentially compromising its scientific objectives. To address this issue, the ITPA community launched the dedicated joint experiment MDC-25 in 2018. While substantial progress has been made, recent findings [6, 8] 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. The findings will inform the design of vacuum vessels and plasma facing components for future tokamaks. By advancing disruption physics, FENYX will contribute to the development of fusion energy as a sustainable power source, accelerating progress towards commercial fusion reactors.



$$F_i = \int_{wall} (\vec{J} \times \vec{B}) \cdot \vec{e_i}\, dV$$

Fig. 1. Vertical, $\boldsymbol{F_z}$ 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 deep purple region highlights the 'wet' zone, where plasma-wall contact occurs. The uncertainty in the magnitude and direction of the plasma-wall current, ***J****, leads to a 25-fold variation in predictions for the sideways force on the tokamak wall.*

1. INTRODUCTION

During disruptions, the plasma comes into contact with nearby conducting structures, commonly referred to as the 'wall.' This interaction induces eddies and also redirects part of the plasma current into the wall, producing significant electromagnetic forces. While the mechanisms governing the total vertical force are well understood, the origin and behavior of the total horizontal, or 'sideways' force on the wall remain elusive, posing a critical gap in our understanding [1–8], see Fig.1. The sideways force is generated primarily by the electric currents shared by plasma and wall: halo [1, 9, 10], allegedly Hiro [2] and ATEC currents [3]. Unlike tokamaks, where the above effects are highly coupled, the linear device FENYX will provide a controlled and simplified experimental environment that will allow precise measurement of halo, Hiro, and ATEC currents independently. By enabling reproducible parametric studies across a wide range of plasma and wall parameters, the new device will generate data that is applicable to ITER and future reactors, surpassing the scope and precision of any previous experimental setup.

2. LINEAR PLASMA DEVICE FOR STUDYING PLASMA-WALL CURRENTS DURING A KINK

The main components of the FENYX device are illustrated in Fig. 2. A pulse forming network (1) powers an array of seven plasma guns (2) and biases the plasma to a segmented anode (5), driving plasma current of up to 2 kA.

The magnetic field produced by the coil (7) stabilises the plasma (3); however, when the current exceeds the Kruskal-Shafranov limit [11], an external ideal kink instability develops. A conducting shell (4) slows the instability from approximately 1 μs to 50–150 μs, enabling measurements at a sampling rate of 2 MHz. The FENYX plasma operates in pulsed mode with a duration of 5 ms. The linear device utilises plasma gun technology [12] to generate hydrogen plasma current channels with high current density (~1 MA/m^2), achieving electron densities and temperatures in the range of $n_e = 1 - 3 \times 10^{19}\ m^{-3}$ and $T_e = 10 - 20$ eV. These parameters are particularly relevant for ITER following the thermal quench [7]. The plasma column radius and length are 5 and 50 cm, respectively. For experiments on halo and Hiro currents, which require triggering a kink mode, the magnetic field is limited by 130 G, whereas the setup for ATEC studies will feature the field of up to 1 T.

3. THE VALIDITY OF THREE THEORIES PREDICTING THE LARGEST SIDEWAYS FORCES

Source & Sink [1], WTKM [2] and ATEC [3] theories – will be tested by verifying the main assumptions behind each model. In particular, the setup shown in Figs. 3 will reveal the global pattern of wall-current and its dynamics during a kink instability. The anode, segmented poloidally into four parts, will enable the identification of the fundamental harmonic (m/n=1/1) of Hiro current, see Fig. 2. Finally, a specialised set of biased tiles will be installed at the edge of plasma column, to study ATEC currents and their dependence on plasma and wall parameters. The results will allow to refine predictions of the sideways forces for ITER and BEST.

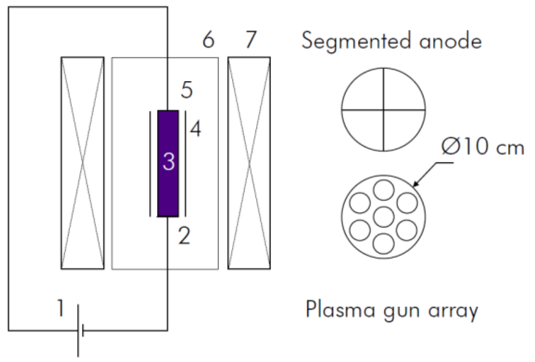


Fig. 2. Cross section of the FENYX device with the main elements: (1) pulse forming network, (2) plasma gun array, (3) plasma column, (4) conducing shell, (5) segmented anode, (6) stainless steel vacuum vessel and (7) magnet coil.

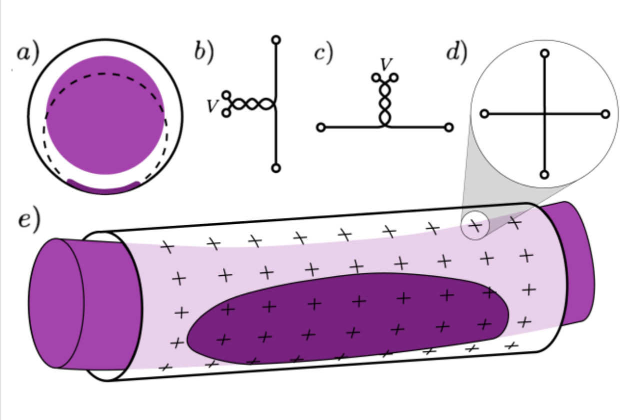


Fig. 3. FENYX setup for studying the wall-current patterns: (a) poloidal cross-section, (b), (c) and (d) two single and one double wall-current probes [13], (e) kinking plasma touching the conducting shell, with related eddy and halo currents monitored by an array of wall-current probes 2x8x8=128 in total.

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