

CONCEPTUAL DESIGN OF THE FUSION ENERGY EXPERIMENT

鳳 FENYX 凰

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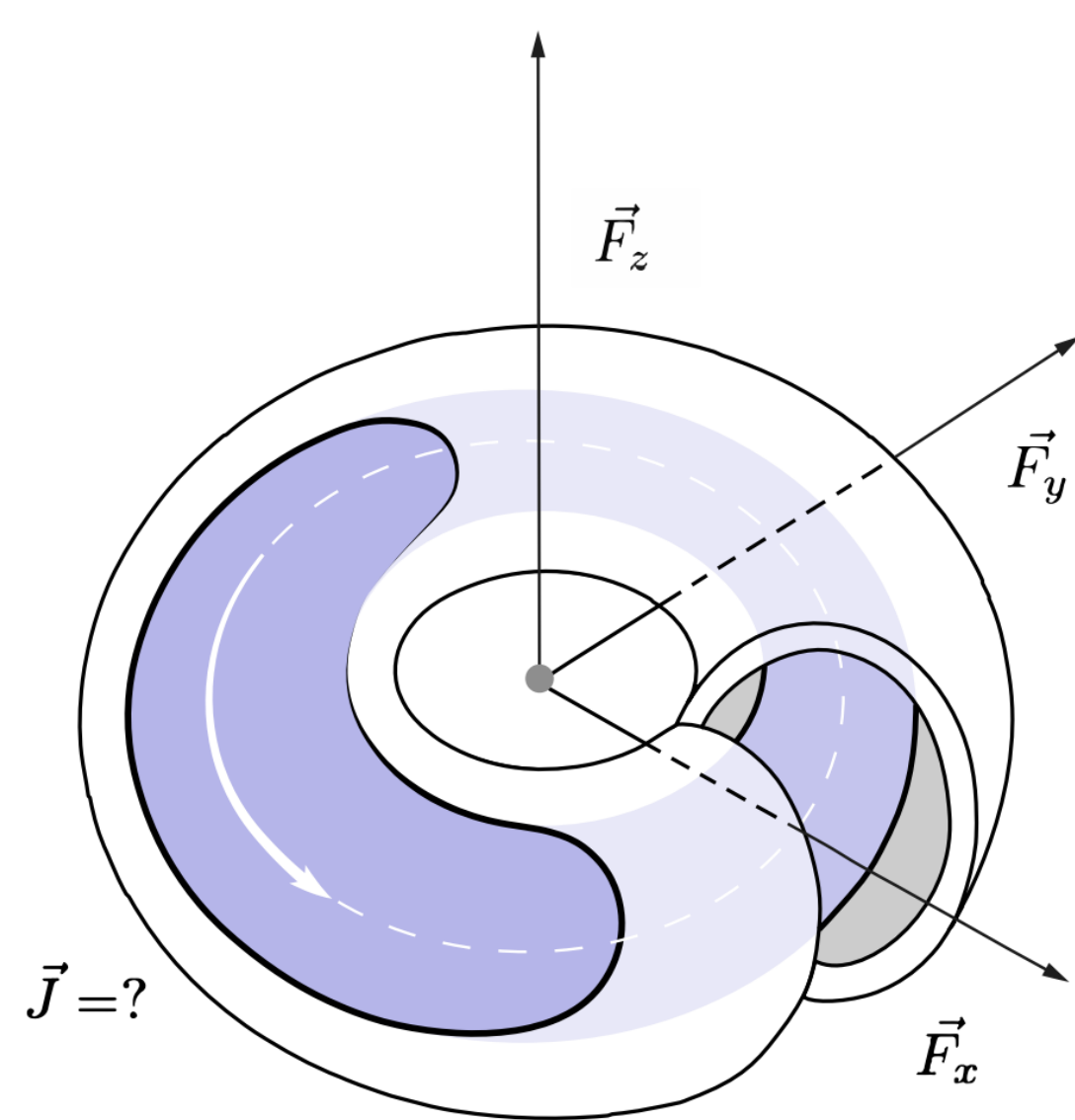
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WHAT, WHERE, AND WHEN?

- **What?** – We propose a new **linear device** FENYX specifically designed to study **plasma-wall currents** during **kink instability**.
- **Why?** – Uncertainty in plasma-wall currents dynamics leads to large uncertainties in the magnitude of the sideways forces on the tokamak wall during plasma disruptions. For example, **predictions for the sideways force on the ITER wall vary from 2.4 to 60 MN** with the upper estimate exceeding the design margin of 48 MN. This problem is recognised as a **critical priority for ITER** and is addressed by the dedicated joint experiment ITPA MDC25 (AUG, COMPASS, DIII-D, JET, JT-60SA, RFX-mod, TCV).
- **Where?** – At **Consorzio RFX, Padua, Italy**. The proposed design leverages the existing equipment, infrastructure and expertise. Moreover, the new linear device will operate in synergy with **RFX-mod2** [see poster #3070 by L. Marrelli], one of the few machines capable of measuring the sideways force directly using magnetic diagnostics only [Abate 2023 & 2025].
- **When?** – **July 2025**: first experiments began on a smaller device, the **Halo Machine**. Results from Halo Machine experiments support the design and commissioning of **FENYX**.
- **Expected outcome** – The findings will help **define the upper limits of disruption forces** for ITER, BEST, DEMO, CFETR, and other new tokamaks.

PLASMA-WALL CURRENTS AND DISRUPTION FORCES



$$F_i \equiv \int_{wall} (\vec{J} \times \vec{B}) \cdot \vec{e}_i dV$$

FIG. 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, J** , leads to a 25-fold variation in predictions for the sideways force on the tokamak wall.

THREE THEORIES OF SIDEWAYS FORCES AND RELATED CURRENTS: HALO, HIRO & ATEC

- 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 [Mironov & Pustovitov 2017].
- All **three theories predicting large sideways forces**—such as **Source & Sink** [Riccardo et al. 2000] Wall Touching Kink Mode (**WTKM**) [Zakharov 2008] and Asymmetrical Toroidal Eddy Current (**ATEC**) [Rocella 2016] models—are associated with different types of plasma-wall currents: halo, Hiro and ATEC, respectively.
- **HALO**: 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.
- **HIRO**: The term Hiro refers to a hypothetical plasma surface current at the plasma-wall interface [Zakharov 2008]. Numerical simulations with the NIMROD code 'support the possibility of reproducing WTKM physics' [Sovinec & Bunkers 2019], 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 [Xiong et al. 2015]. Nevertheless, some theoretical studies have questioned the very existence of Hiro currents [Pustovitov 2022].
- **ATEC model** [Rocella 2016] suggests that the sideways force is generated by eddy currents in the vacuum vessel, with particular emphasis on their deviation through the plasma, which short-circuits adjacent tiles. To test this hypothesis, a series of dedicated experiments were carried out on the COMPASS tokamak [Hron 2022]. The results provided qualitative support for the theoretical predictions, but quantitative extrapolation to ITER requires new experiments, preferably in a highly reproducible and controlled environment that allows systematic scans over different plasma and tile parameters.

NEW LINEAR PLASMA DEVICE

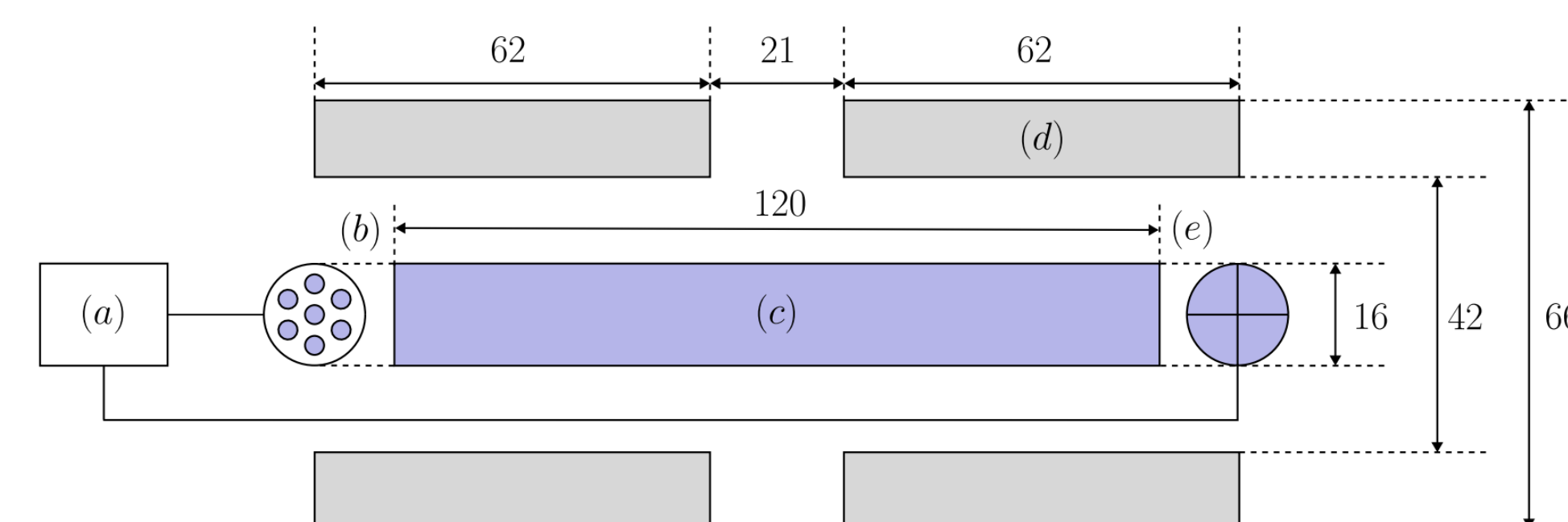


FIG. 2. Schematic of the linear pinch experiment: (a) pulse forming network, (b) plasma gun array, (c) plasma column, (d) magnetic coils, and (e) segmented anode. All dimensions are in centimeters.

- **Main plasma parameters**. Maximum plasma current: 2.1 kA. Maximum magnetic field: 1 T. Electron temperature 3 eV, density up to 5×10^{20} . Current density up to 30 A/cm². These parameters are particularly relevant for ITER conditions following a thermal quench.
- FENYX will provide a **controlled environment** for isolating and studying plasma-wall interaction phenomena.
- Unlike tokamaks, where key effects are strongly coupled, 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 and materials, FENYX will be the first linear plasma device dedicated to investigating plasma-wall currents in the presence of kink modes.

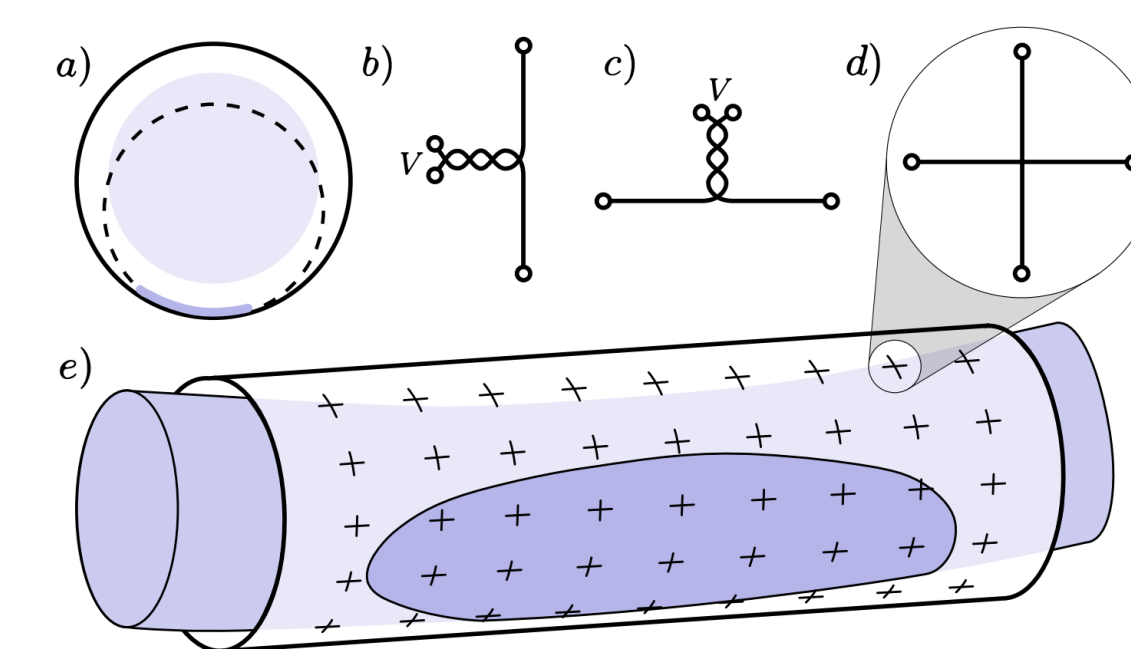


FIG. 3. Configuration for studying the wall-current patterns: (a) poloidal cross-section, (b), (c) and (d) two single and one double wall-current probes, (e) kinking plasma in contact with the conducting shell, with related eddy and halo currents monitored by an array of probes.

- Halo currents 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, thereby revealing the global pattern of wall currents and their dynamics during a kink instability. 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.

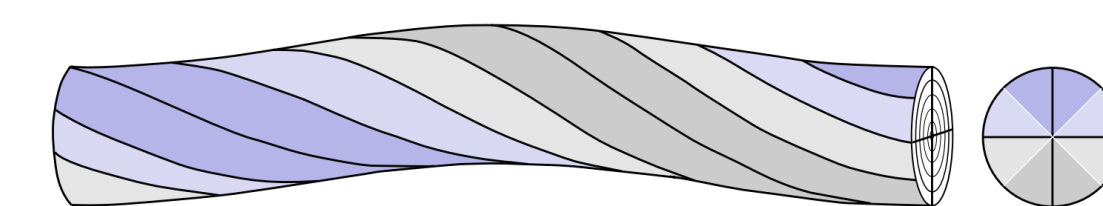


FIG. 4. Configuration for measuring **Hiro currents**. The plasma column, distorted by the kink mode, generates surface currents of opposite polarity. The anode, poloidally segmented in 4 parts, allows the fundamental harmonic of the Hiro currents to be resolved. The plasma surface current represents the ideal plasma response to an external kink. According to the **Wall Touching Kink Mode (WTKM) model**, the plasma surface current in contact with the wall (Hiro current) exhibits specific properties [5]. For instance, it has been argued that the Hiro current breaks down the boundary sheath and is therefore not limited by the ion saturation current, unlike the halo current.

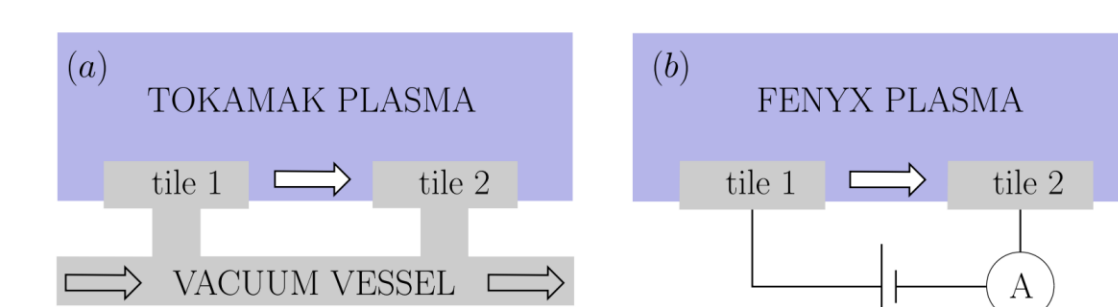


FIG. 5. **ATEC current** flowing between adjacent tiles 'wetted' by plasma in a tokamak (a), and in the FENYX device, where tiles are artificially biased to replicate the potentials naturally occurring in tokamaks during plasma disruptions (b). The current flowing between the tiles will be measured for different applied voltage, plasma density, the inter-tile gap and tile geometry.

HALO MACHINE

In support of the FENYX design activities, a series of experiments is being performed on a small linear plasma device, the Halo Machine.