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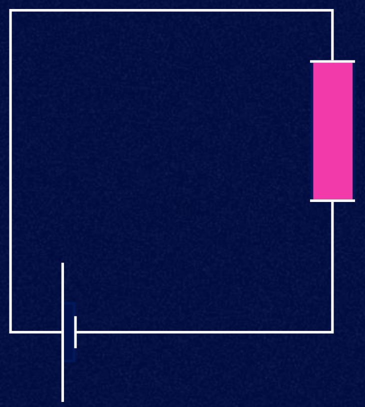


PRELIMINARY DESIGN OF HALO MACHINE

V. YANOVSKIY[1], D. ABATE[2], G. BECATTI[3], R. CAVAZZANA[2], L. CORDARO[2], B. MOMO[2], A. PIMAZZONI[2], A. PODOLNIK[1], M. SIRAGUSA[2], S. SPAGNOLO[2], D. TSKHAKAYA[1], F. VILLONE[4] AND M. ZUIN[2]

[1]IPP PRAHA
[2]CONSORZIO RFX, PADOVA
[3]INSTITUTE OF SPACE SYSTEMS, STUTTGART
[4]CONSORZIO CREATE, NAPOLI

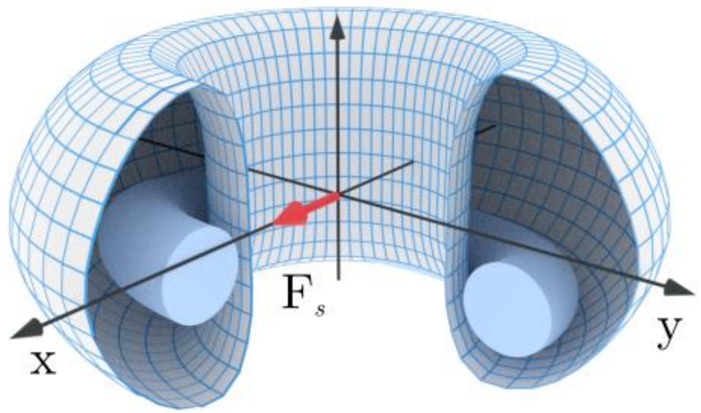
MINISTRY OF EDUCATION, YOUTH AND SPORTS

3rd IAEA TM on Plasma Disruption and their Mitigation, 3 – 6 September 2024, ITER

- Challenges of the ITPA Joint Experiment MDC25 on sideways forces and how
- the Halo Machine can resolve them, including testing of the models predicting the largest forces for ITER:

  - Source & Sink by V. Riccardo, 2000
  - WTKM by L. Zakharov, 2008
  - ATEC by R. Roccella, 2016

SIDEWAYS FORCE ON THE WALL

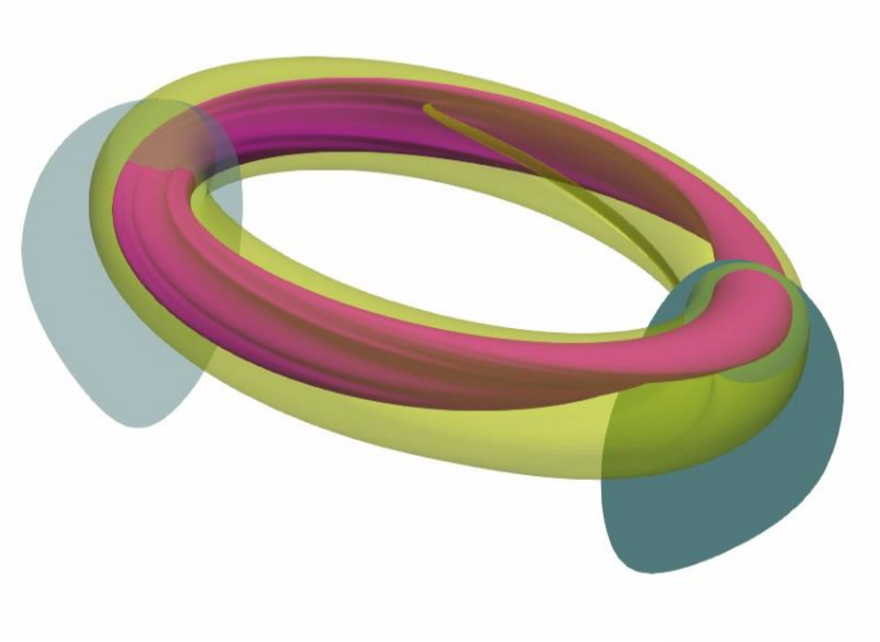


MOTIVATION

- Uncertainty in the magnitude of sideways force for ITER.
- Predictions vary greatly, up to a factor of 25.
- The upper estimate exceeds the design margin.

Current numerical studies to address the issue

- JOREK [1, 2] and coupled JOREK-CARIDDI [3] codes are currently being updated to resolve the uncertainty regarding the sideways force.



[1] M. Hoelzl et al Nucl. Fusion 61 n.6 (2021).
[2] F J Artola et al Plasma Phys. Control. Fusion 66 055015 (2024).
[3] N. Isernia et al Phys. Plasmas 30 113901 (2023).

Last year, we learned how to measure the total force with high temporal resolution

- In 2015, V. D. Pustovitov proposed to evaluate the force DIRECTLY using MAGNETIC diagnostics ONLY.

  V. D. Pustovitov, Nucl. Fusion 55 113032 (2015).

- In 2023, we implemented the new technique on COMPASS [1] and RFX-mod [2]

  [1] V. V. Yanovskiy, A. Iaiunese et al., O2.104, 49th EPS (2023).

  [2] D. Abate et al., Nucl. Fusion **63** 126025 (2023).

- However, we could measure only the total force. To extrapolate results to ITER, we would need to distinguish between different effects generating the force.

5 EFFECTS GENERATING THE FORCE

- Wall asymmetry (Yanovskiy 2022)

The effect is well understood and can be modelled on CarMa0NL code.

- Kink mode (Mironov & Pustovitov 2017)

The model is currently being tested on the RFX-mod data.

- Halo , Hiro & ATEC currents (Riccardo 2000, Zakharov 2008, Roccella 2016)

The models predict large forces and, therefore, have to be tested.

ATEC current measurements on COMPASS

- Throughout 2018 – 2020, ITER Organization conducted dedicated experiments to measure the ATEC currents.
- Special set of tiles have been installed on COMPASS and the currents have been measured indeed as predicted by ATEC.
- It was concluded that to study the effect further a dedicated linear device is necessary.

M. Hron et al., *Overview of the COMPASS results*, Nucl. Fusion 62 042021 (2022).
E. Matveeva, *Studies of plasma disruptions in the COMPASS tokamak*, PhD Thesis (2022).

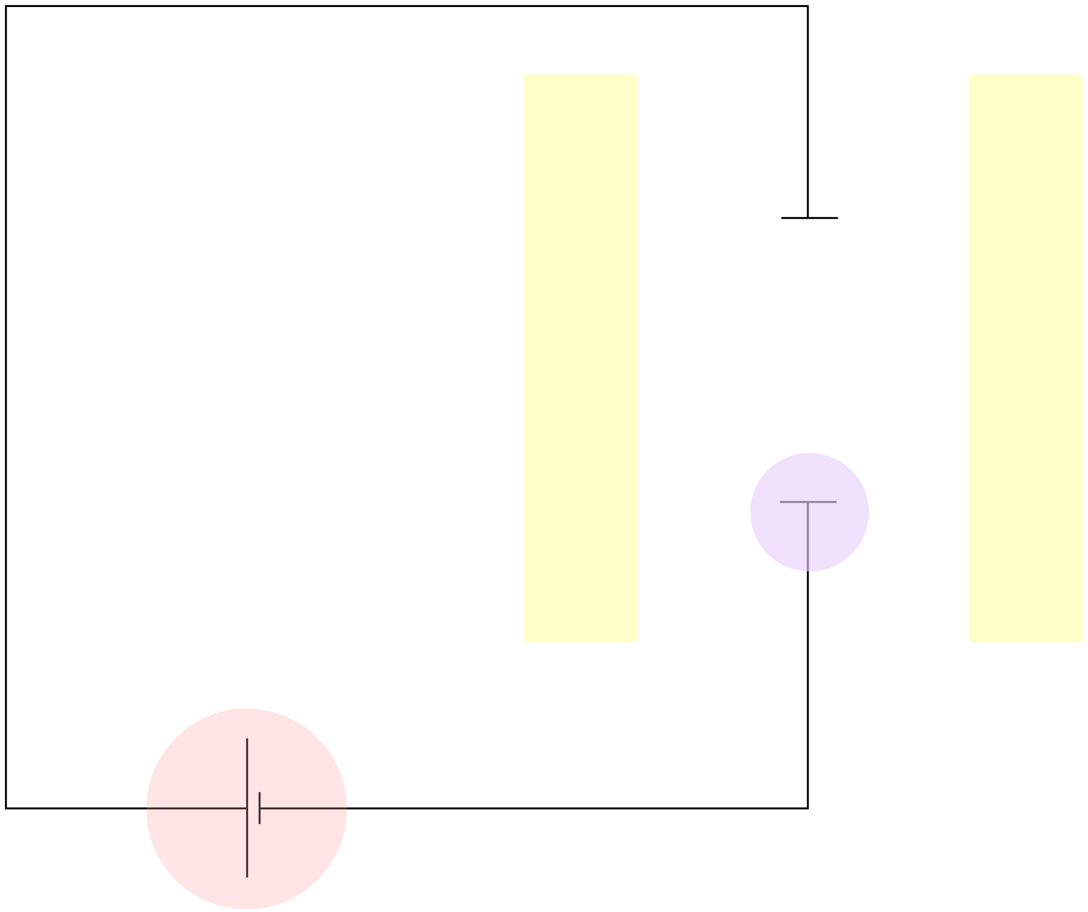
THREE THEORIES AND ONE EXPERIMENT

- The largest sideways forces are related to the halo (hiro) current,
- as predicted by the theories of Riccardo, Zakharov and Roccella.
- All three theories can be tested in the Halo Machine.

2000	2008	2016	2024
S&S	WTKM	ATEC	
V. Riccardo	L. Zakharov	R. Roccella	Halo Machine

Design is driven by the equipment already available

- A cathode 0.5 kA, 30 V
- A magnetic coil (up to 1 T)
- A power supply 5 kA, 150 V



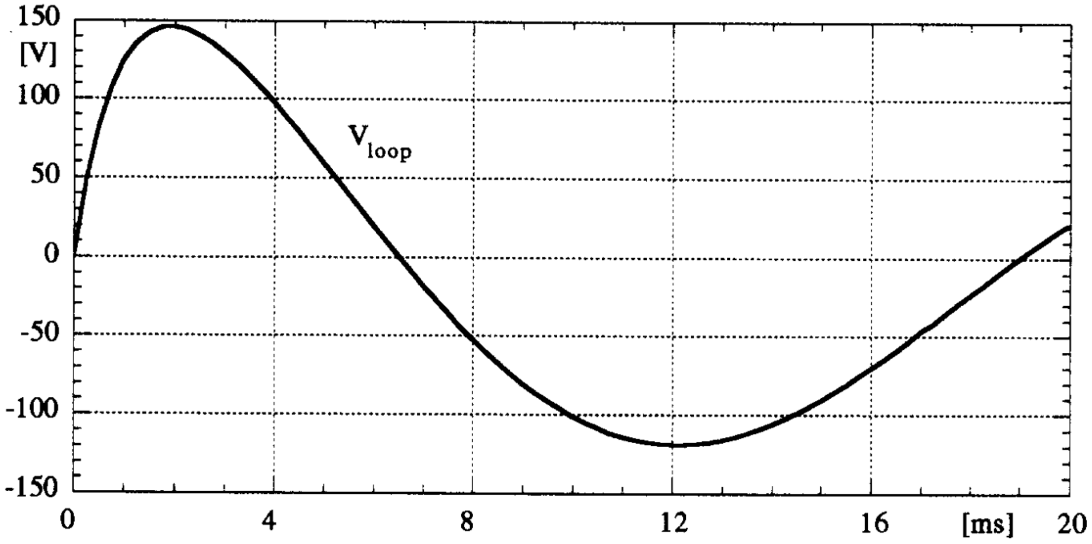
100 KW POWER SUPPLY

The Pulse Discharge Cleaner (PDC)

Plasma current: 5 kA

Voltage: 150 V

Voltage duration (at 30 V) : >10 ms

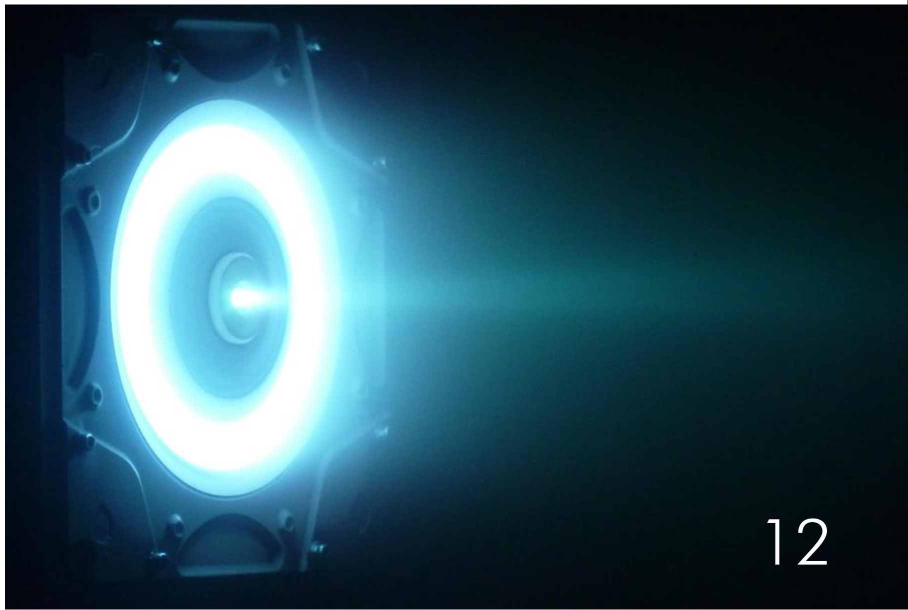


A. Maschio et al., "The Power Supply of RFX", Fusion Engineering and Design **25** 401-424 (1995).

LaB_6 hollow cathode, 1 pc

- Plasma current 500 A
- Discharge voltage 30 V
- Plasma column radius 3 cm
- Electron temperature 10 eV
- Plasma density 10^{19} m^{-3}
- Designed at NASA for Hall thrusters

G. Becatti and D.M. Goebel. "500-A LaB6 hollow cathode for high power electric thrusters." *Vacuum* **198** 110895 (2022).



MAGNETIC COILS

- Magnetic field: 1 T
- Inner diameter: 42 cm
- Outer diameter: 66 cm
- Length: 62 cm
- Number of coils available: 8

Halo/Hiro/ATEC currents and the Halo Machine

- Halo:

Source & sink model by V. Riccardo

Nucl. Fusion **40** 1805 (2000).

- Hiro:

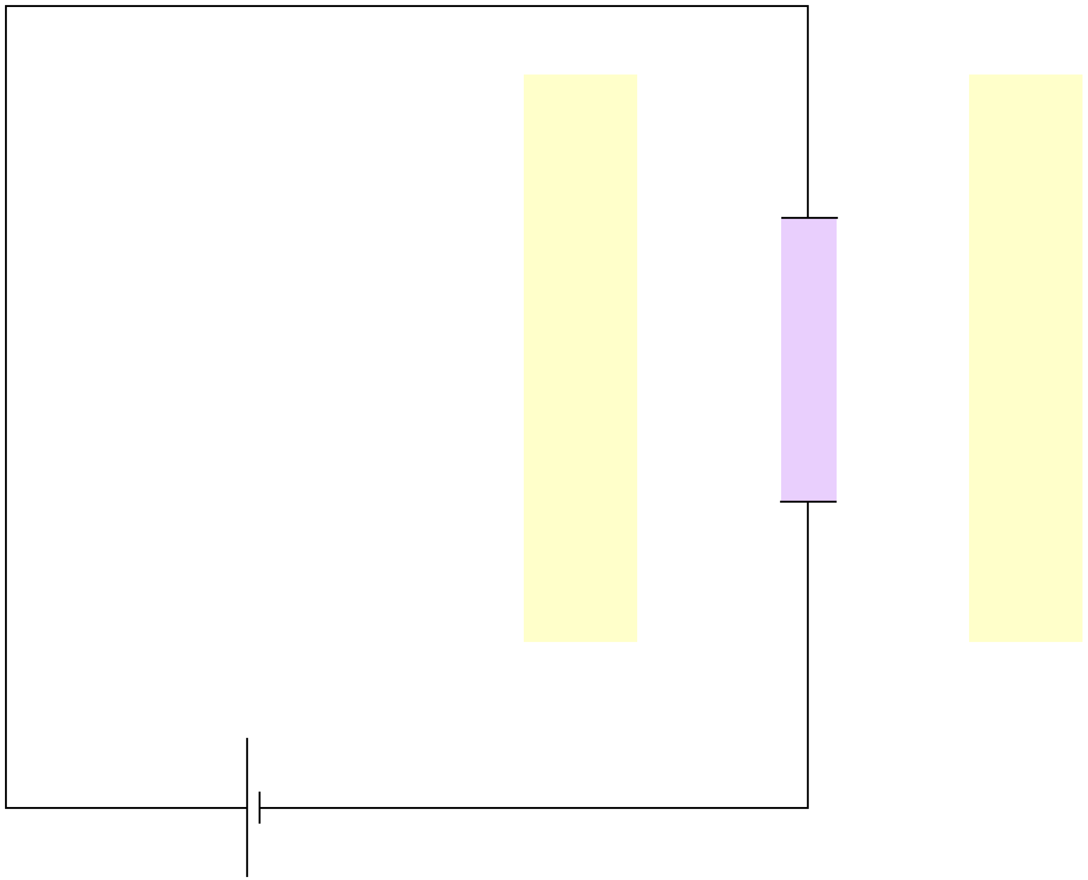
WTKM model by L. E. Zakharov

Phys. Plasmas **15** 062507 (2008).

- ATEC

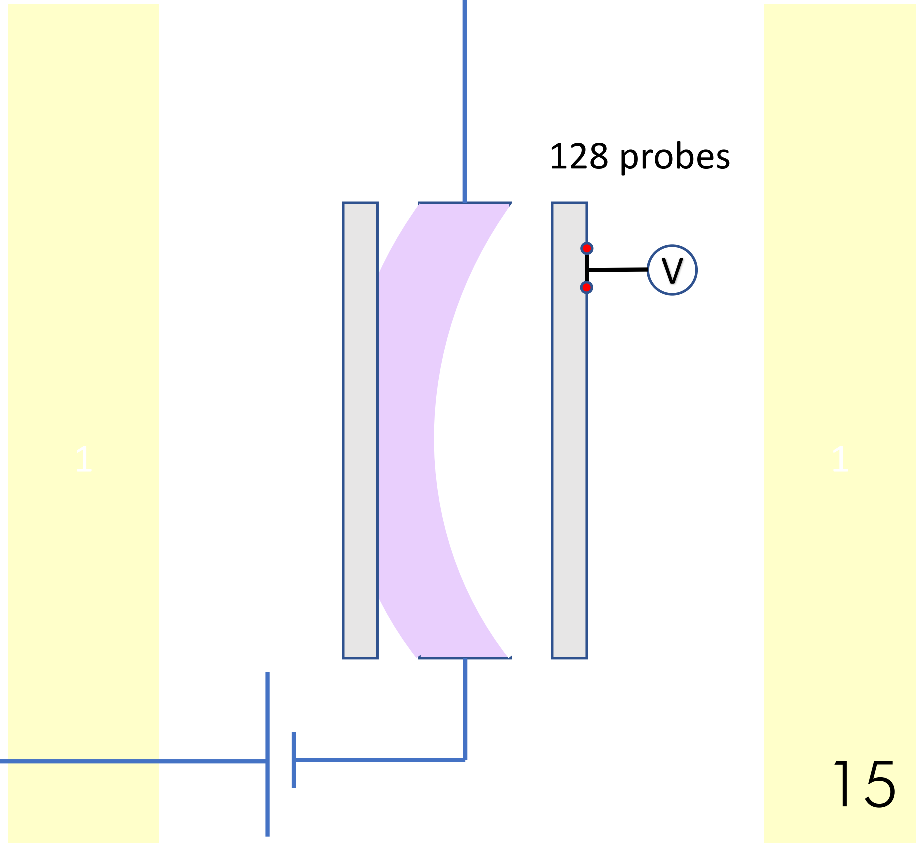
ATEC model by R. Roccella

Nucl. Fusion **56** 106010 (2016).



Testing source & sink model in the Halo Machine

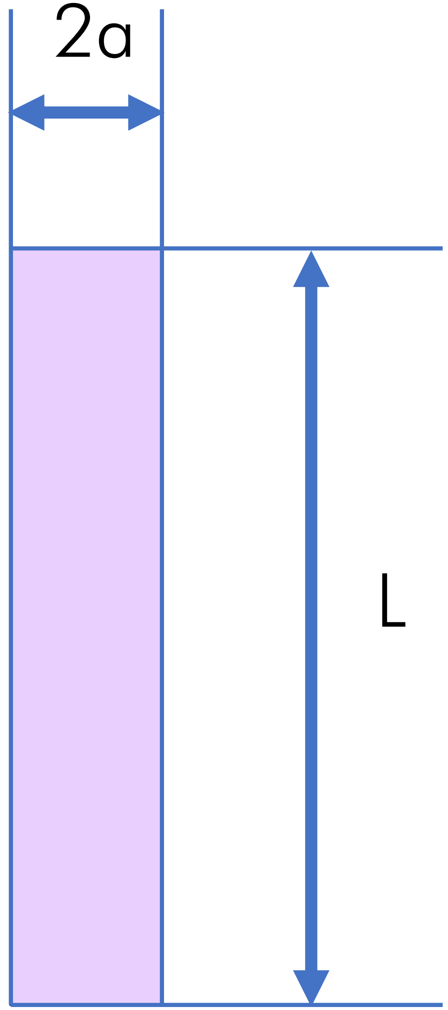
- Plasma column is immersed in a weak magnetic field (~50 Gauss), then an instability is triggered.
- Plasma kink interacts with a nearby conducting shell.
- Eddy and halo currents in the shell are measured by an array of probes.



Kruskal-Shafranov limit for a line tied pinch

$$\mu_0 I_{KS} = 4\pi^2 a^2 B_z / L$$

- For a=3 cm, I_{max}=500 A and L=0.3 m (half-length of the coil) the kink condition is at Bz<50 Gauss.



Time scales (Alfvénic, conducting shell and resistive plasma)

$$\tau_A = a\sqrt{\mu_0 \rho}/B_z \qquad \tau_w = \mu_0 r_w d_w / \eta_w \qquad \tau_R = \mu_0 a^2/\eta_{pl}$$

For hydrogen plasma with a=3 cm, B_z=50 Gauss, $n_e=10^{19}$ m^{-3}, T_e=10 eV and a stainless steel conducting-shell with radius r_w=1.1a and thickness d_w=1 mm:

$$\tau_A \approx 0.3\mu s \qquad \tau_w \approx 30\mu s \qquad \tau_R \approx 100\mu s$$

Since $\tau_w << \tau_R$

the ideal plasma effects should prevail over the resistive plasma effects.

Riccardo model and the current pattern in the wall

- Predictions of the Riccardo model are related to a specific halo current pattern in the wall.
- Hiro current model suggests different current direction and distribution.
- The Halo Machine will study wall currents in detail.

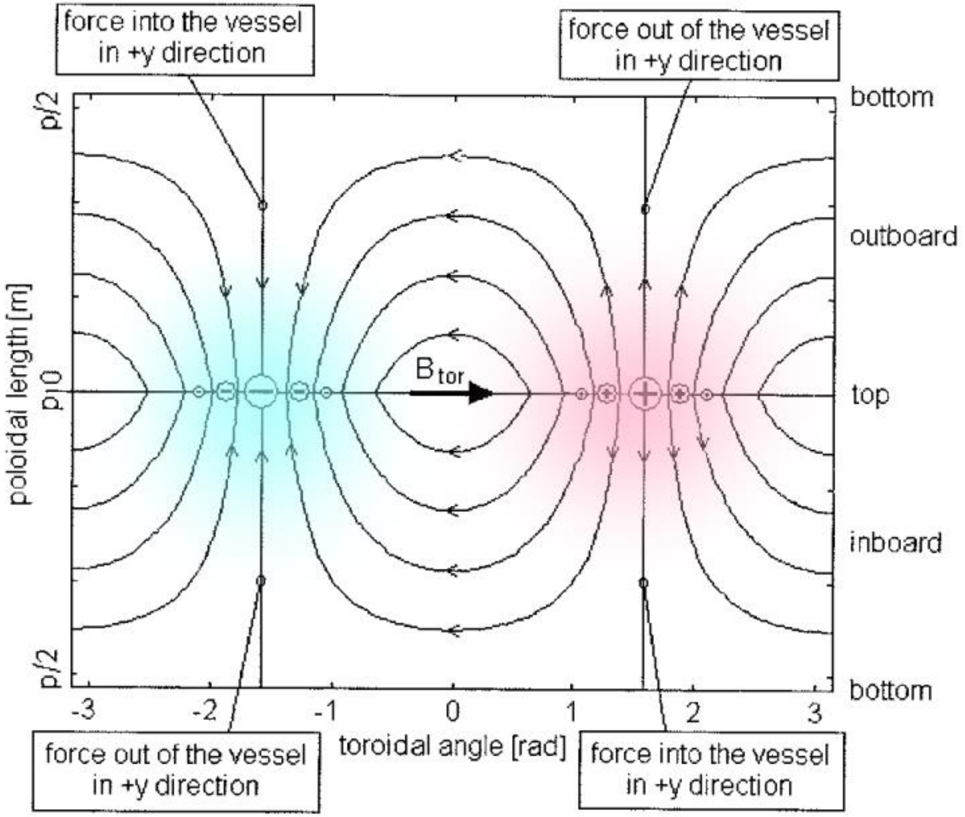


Figure 4. Vessel asymmetric current pattern with the source/sink symbolized at the top of the vessel.

New wall-current probes

$$v_{CD} = \int_{\gamma_{AB}} \eta \mathbf{J} \cdot \hat{\mathbf{t}} \, dl$$

- New probes measure the total wall current (eddy + halo).
- Dedigned by Consorzio CREATE.
- Tested at the University of Cassino.

*F. Villone et al., "Design and experimental validation of an eddy currents probe", *44th EPS Conference on Plasma Physics (Belfast, Northern Ireland)*, P1.106 (2017)

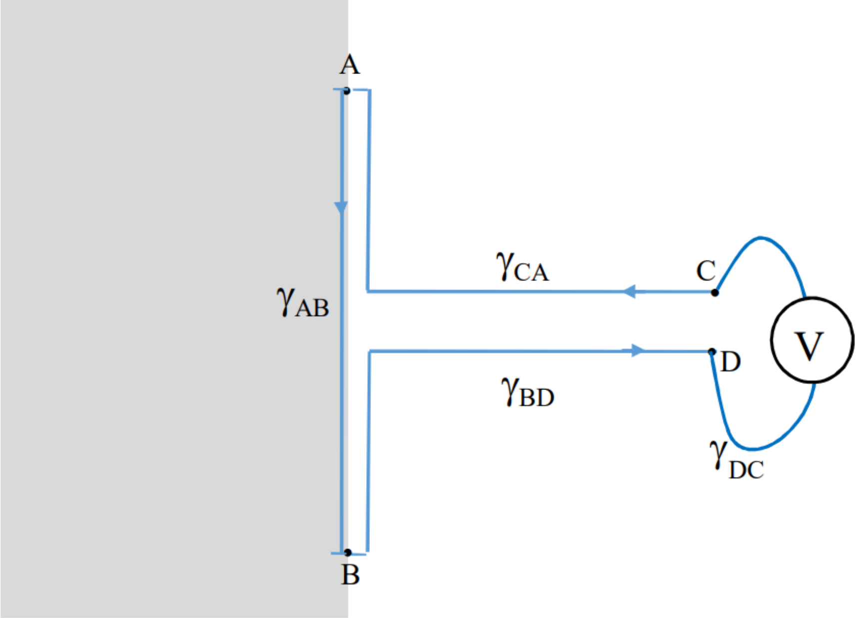
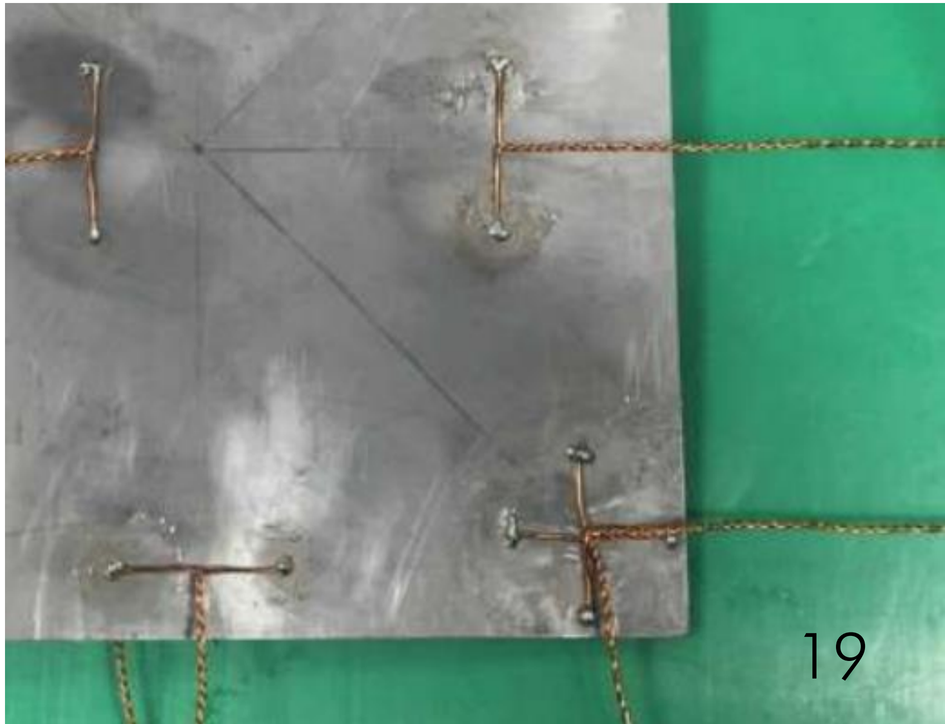
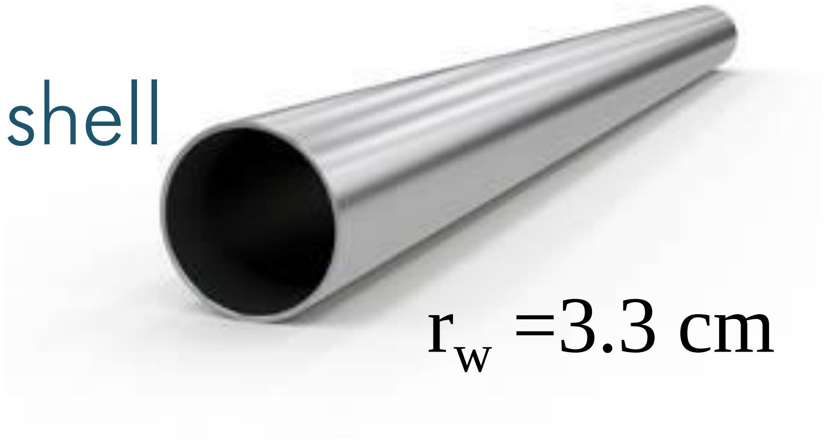


Fig. 1. Layout of the proposed probe



8x8x2=128 wall-current probes cover the shell

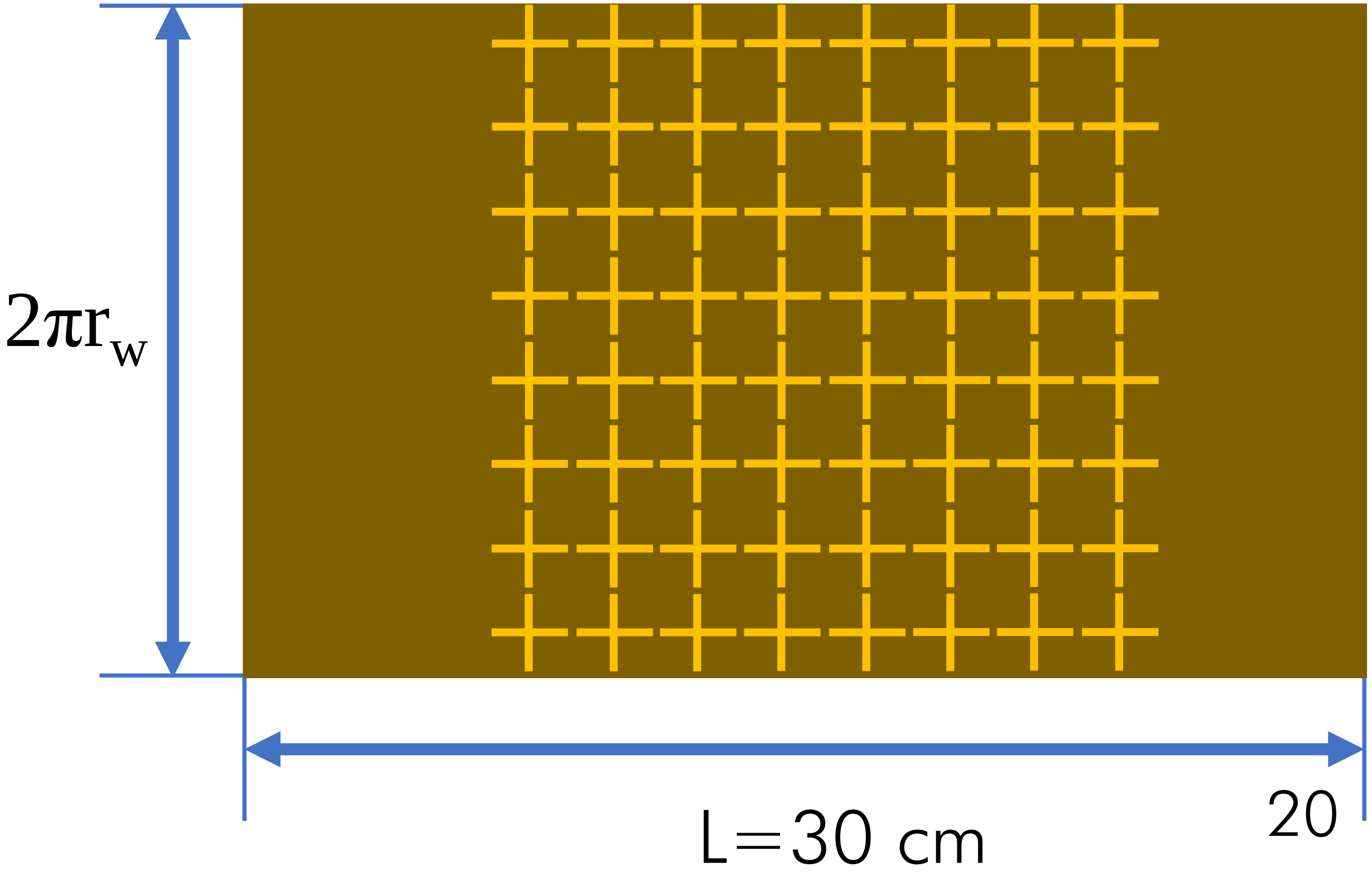


- Each cross represents two probes: one for poloidal and one for longitudinal wall current.
- Expected current density

Halo: 0.2 MA/m^2 (cf. 1 MA/m^2 on ITER)

Eddy: 0.2 MA/m^2 (cf. 1 MA/m^2 on ITER)

- This diagnostic will provide detailed spatial distribution of the wall current (eddy+halo).



Current patterns in the wall: model vs. experiment

- Current patterns measured on the Halo Machine will be compared with the patterns considered by the Riccardo model.
- Then, conclusions about the sideways force will be derived.

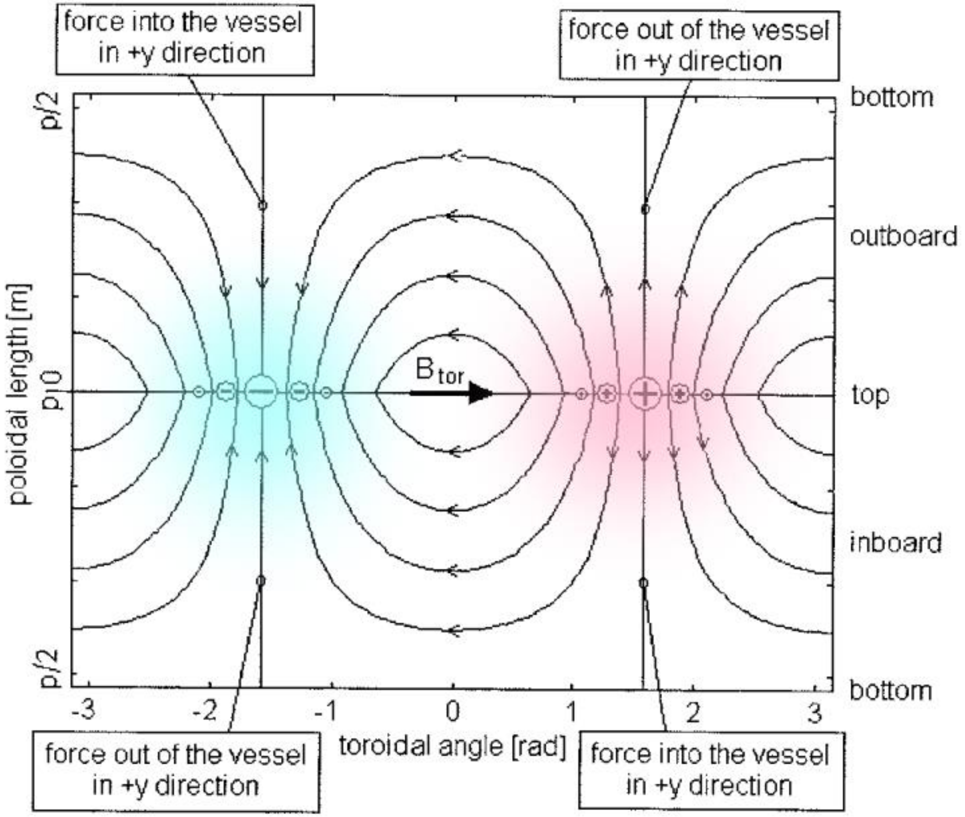
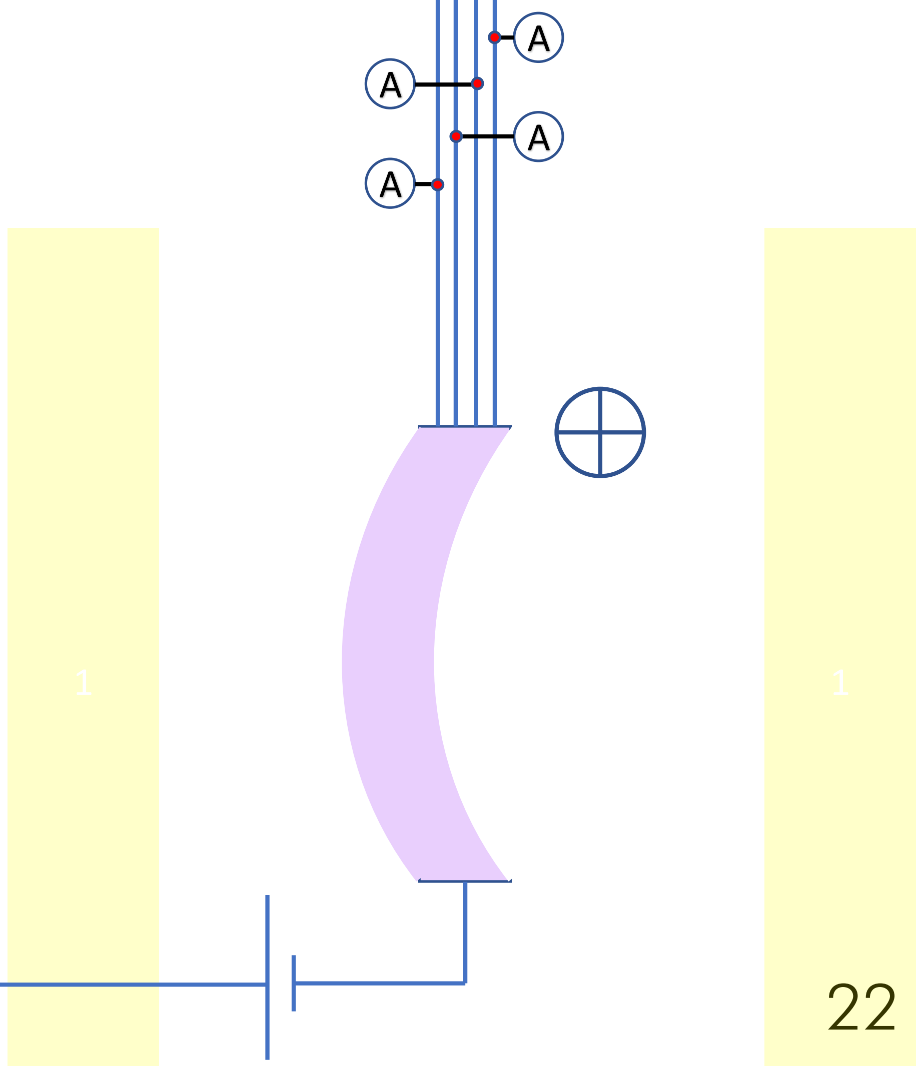


Figure 4. Vessel asymmetric current pattern with the source/sink symbolized at the top of the vessel.

Measuring Hiro currents on the Halo Machine

- Plasma column is immersed in a weak magnetic field (~50 Gauss), then an instability is triggered.
- An anode is divided in 4 segments.
- The current in each segment is measured by a Rogowski coil.



Hiro vs. Halo currents

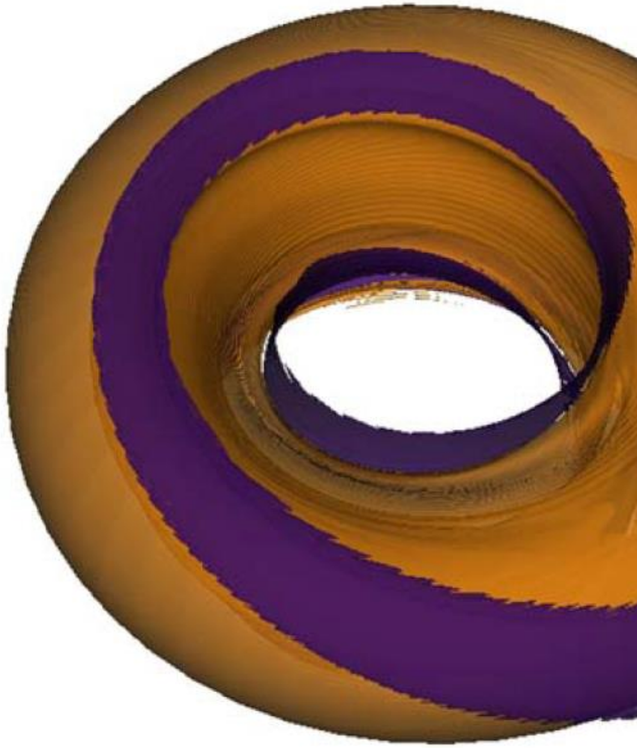
TABLE I. Currents shared between a plasma and the wall during disruptions.

	Hiro currents	Evans currents:	Halo currents:
1	Both result from magnetic flux conservation.		Derived from questionable use of equilibrium reconstruction. No strong reason for existence.
2	Driven by instability acting as current generator.	Driven by instability acting as voltage generator.	Assumed to be driven by a residual voltage outside the last closed magnetic surface.
3	Highly concentrated at the plasma edge.		Diffused in space with open field lines.
4	Big in amplitude, proportional to plasma deformation.		Limited by the ion saturation current.
5	Absolutely necessary to slow down the instability.	Force-free, little, if any, effect on stabilization.	Secondary, if any, effect on stabilization.
6	**Opposite to I_{pl}.**	**Same direction as I_{pl}.**	**Same direction as I_{pl}.**
7	Consistent with toroidal asymmetry in JET VDEs.		Ruled out as a reason of toroidal asymmetry.

*from L. Zakharov et al Phys. Plasmas 19, 055703 (2012).

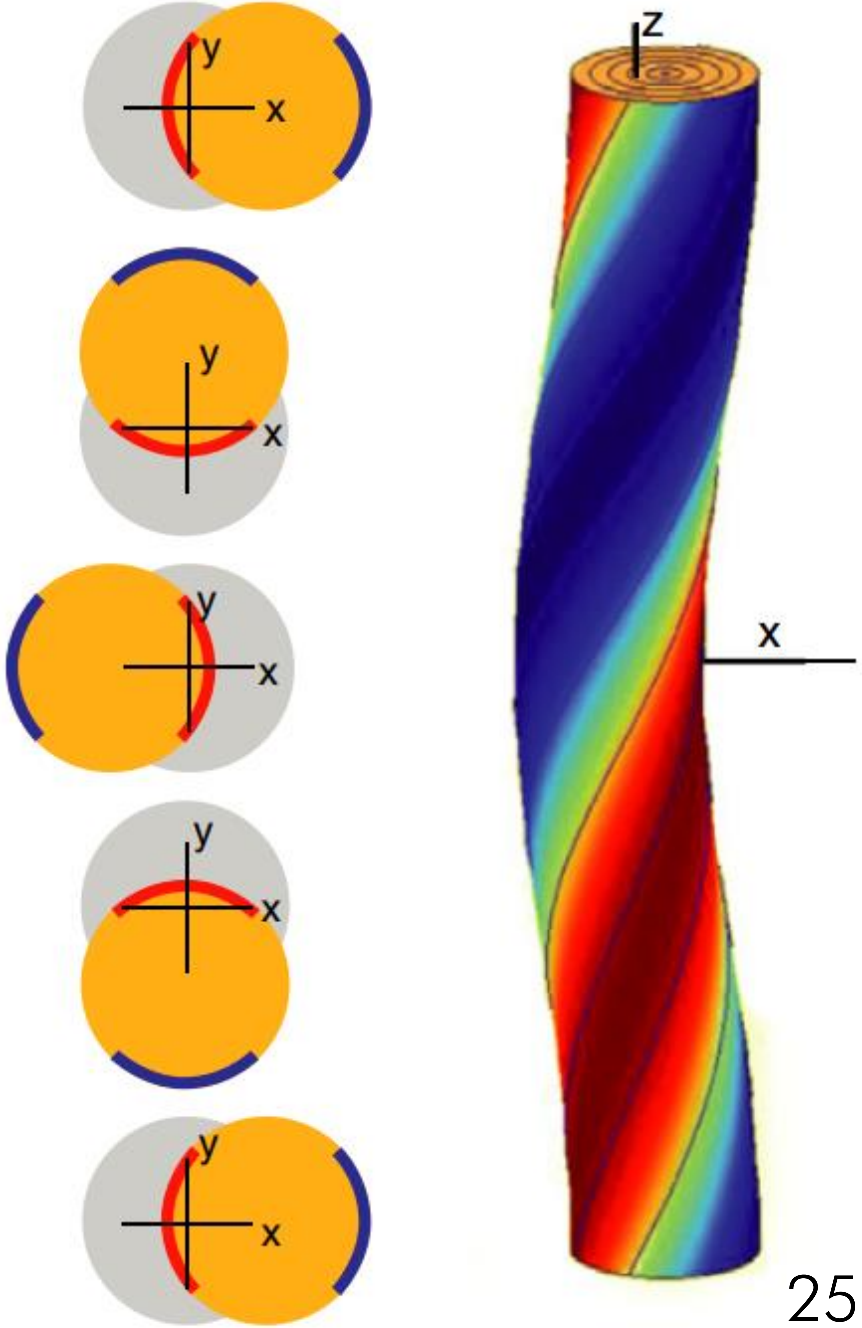
Wall-Touching Kink Mode (WTKM) model: pro et contra

- [Hao Xiong et al., *PoP* **22** 060702 (2015)]: "Hiro currents with direction opposite to the plasma currents have been observed, confirming the sign prediction by the WTKM theory"
- [C. R. Sovinec and K. J. Bunkers, *PPCF* **61** 024003 (2019)]: "results of NIMROD simulations support the possibility of reproducing WTKM physics".
- [V. D. Pustovitov, *Phys. Plasmas* **29** 062509 (2022)]: "WTKM model is incompatible with the fundamental requirement F_pl=0 for the integral force on the plasma".
- The Halo Machine can test the WTKM model and resolve the uncertainty.



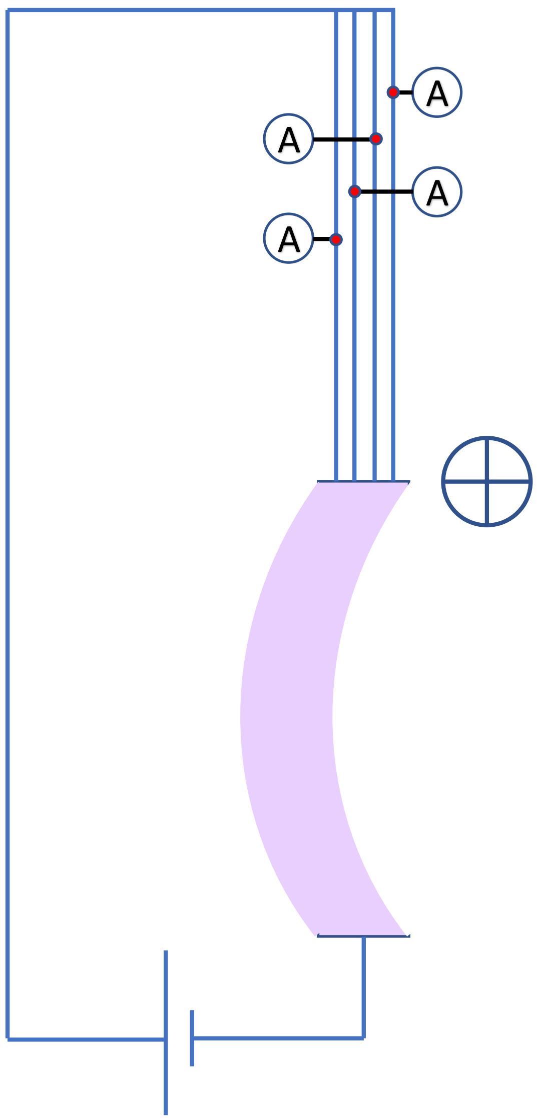
Hiro current

- Hiro current is a surface current that is a plasma reaction on kink instability.
- Poloidal harmonic of Hiro current is m=1.
- It would be useful to measure Hiro current before and after the plasma-wall contact…



Segmented anode

- An anode divided in 4 pieces can distinguish m=1 harmonic of the Hiro current.
- Predicted Hiro current is large – 25 A per segment (20% of pre-disruption current – 125 A per segment).
- Plasma column displacement can be measured, so the dependence of Hiro current on the plasma deformation can be verified, both, before and after the plasma-wall contact.



Conducting shell

- Conducting shell slows down the ideal instability so we can perform the measurements (at 2 MHz sampling rate).

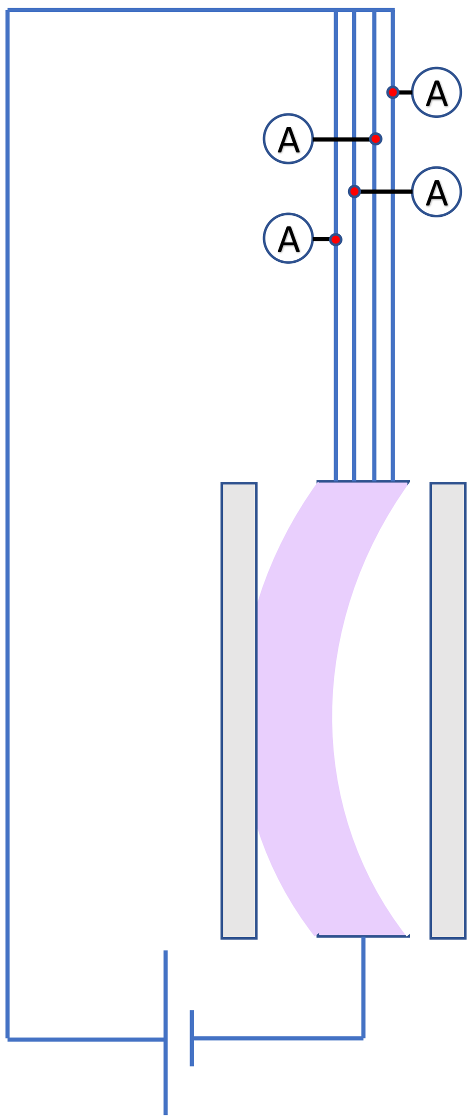
$$\tau_A \approx 0.3\mu s \quad \Longrightarrow \quad \tau_w \approx 30\mu s$$

- At the same time, the ideal plasma effects prevail over the resistive plasma effects, since $\tau_w << \tau_R$, where $\tau_R \approx 100\mu s$

$$\tau_A = a\sqrt{\mu_0 \rho}/B_z$$

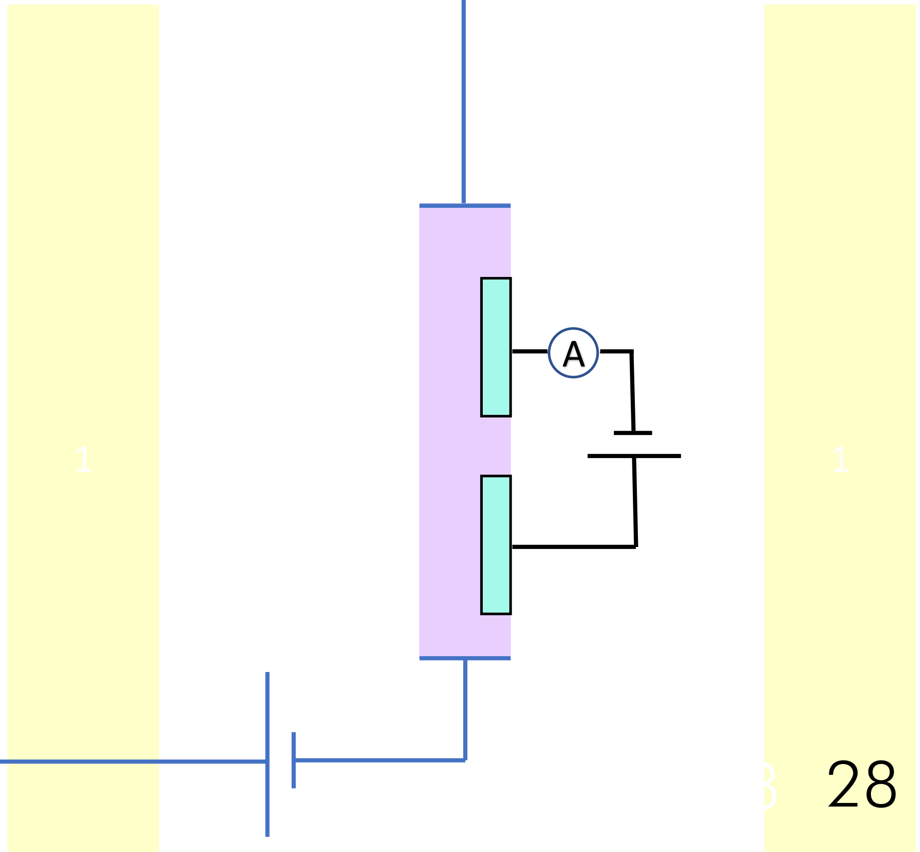
$$\tau_w = \mu_0 r_w d_w / \eta_w$$

$$\tau_R = \mu_0 a^2 / \eta_{pl}$$



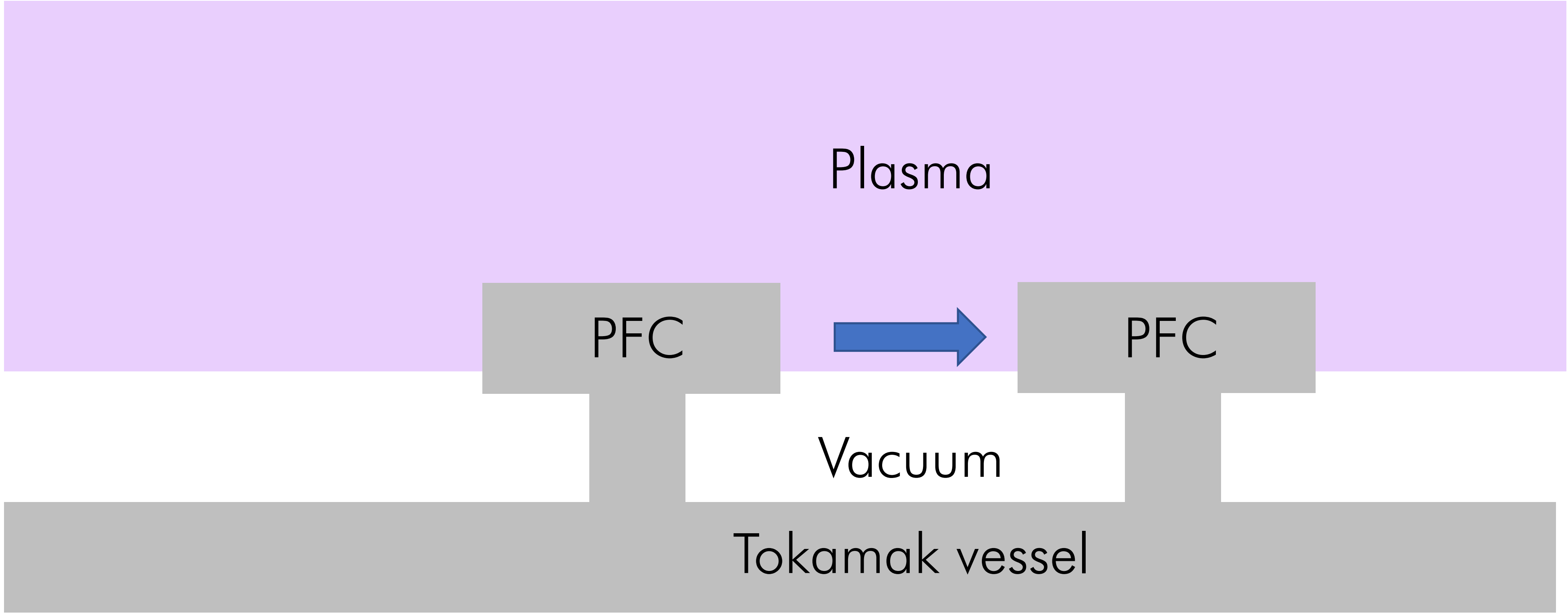
Measuring halo currents in the gap between tiles (ATEC)

- Plasma column is immersed in a strong magnetic field (1 T), and is kept stable.
- The current is measured between two biased tiles inserted in the plasma column.
- Plasma parameters are measured in the gap.



ATEC model

- Main assumption: during a VDE, halo current can flow in the gap between adjacent PFCs.
- The Halo Machine will test this assumption.



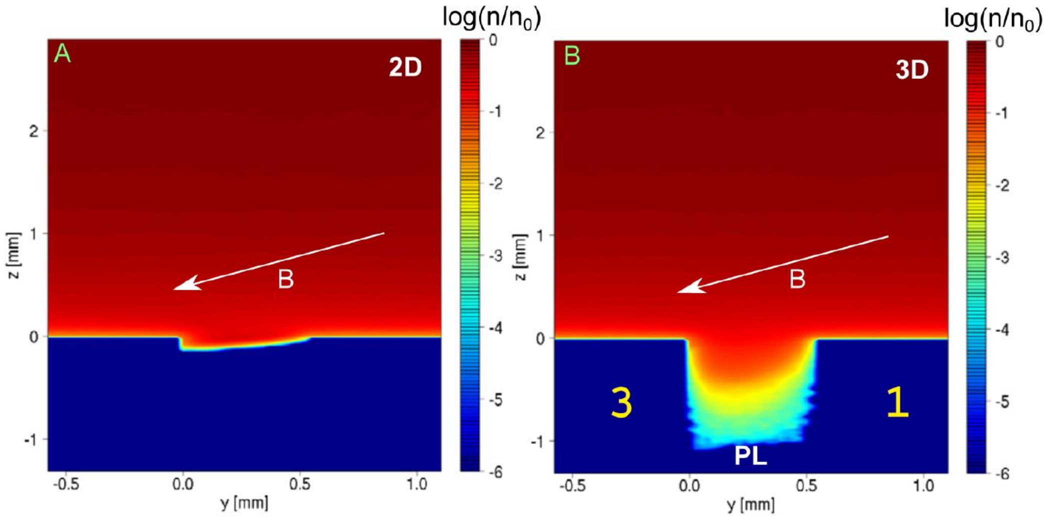
Plasma in the gap modelled with SPICE3 code

- 3D PIC simulations on SPICE3 code [1] show that the plasma temperature and density in the gap can be large enough to allow for halo current.

- The halo current is limited by the ion saturation current [2]:

$$j_i^{max} = q_e n_e c_s$$

- Hence, it is prohibited at low plasma density or temperature.



- Electron density in the gap, 2D vs 3D.

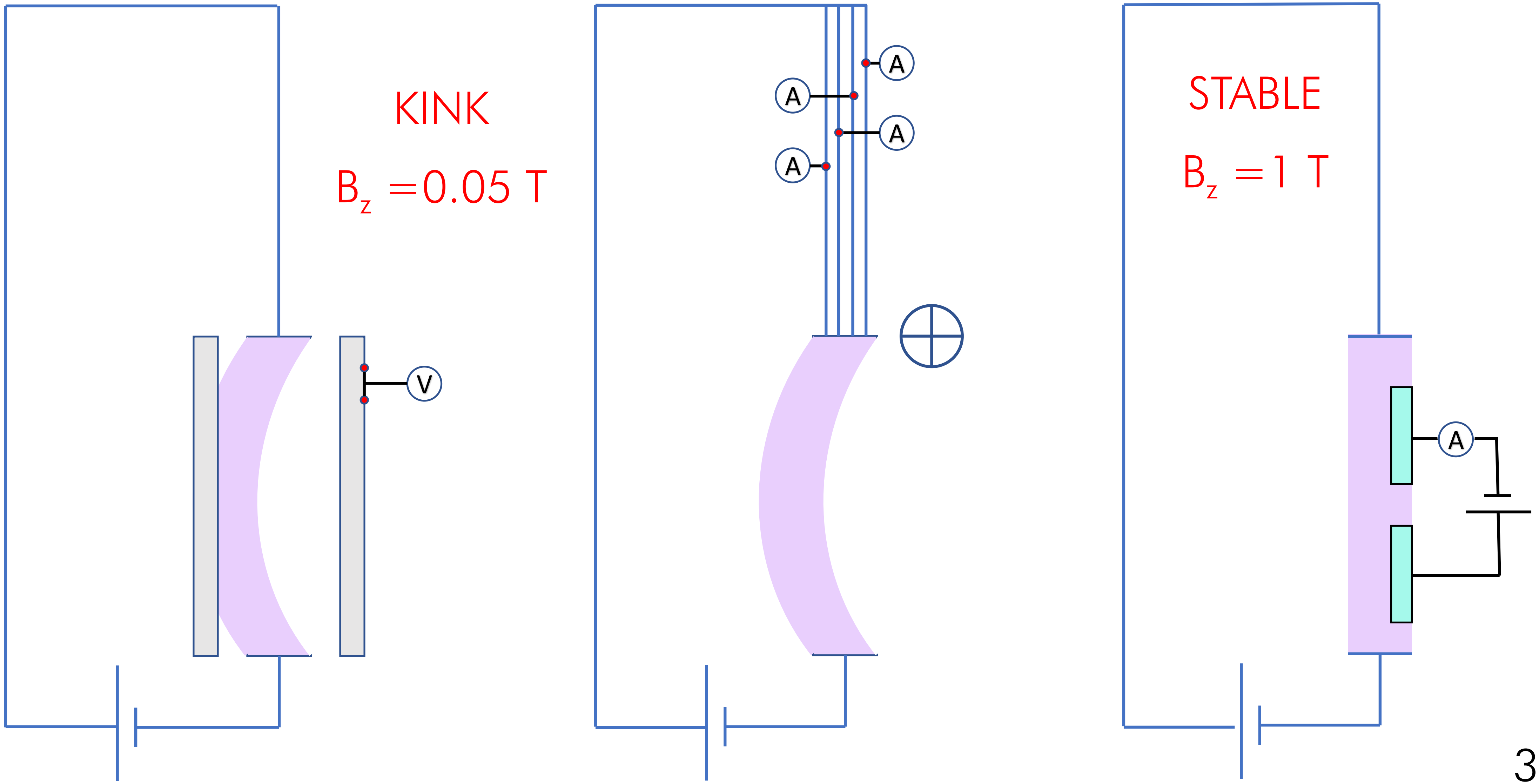
[1] M. Komm et al., *Plasma Phys. Control. Fusion* **55** 025006 (2013).
[2] J. Adamek et al., Nucl. Fusion **62** 086034 (2022).

ITER post-TQ vs. Halo Machine

- The particle density and the ion temperature are larger on ITER.
- The electron temperatures and the magnetic fields are comparable.
- The electron/ion Larmor radii are comparable too.

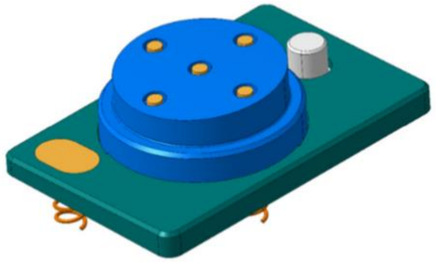
	ITER Post-TQ @ PFCs	Halo Machine
n, 10^19 m^{-3}	10 – 100	1
T_i, eV	5 – 30	1
T_e, eV	5 – 30	10
B, T	1 – 5	1
r_e, mm	0.001 – 0.013	0.008
r_i, mm	0.05 – 0.50	0.10

S&S, 2025 | Hiro, 2026 | ATEC, 2027



Available and missing hardware

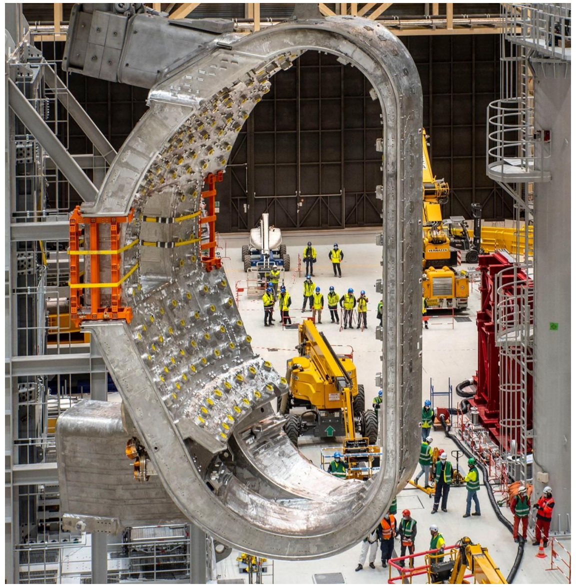
- A cathode, a magnetic coil and the power supplies for them.
- Langmuir probes (T_e, n_e, plasma potential).



- A vacuum vessel and a vacuum system.
- Control and data acquisition systems.
- A conducting shell with wall-current probes.
- A segmented anode.

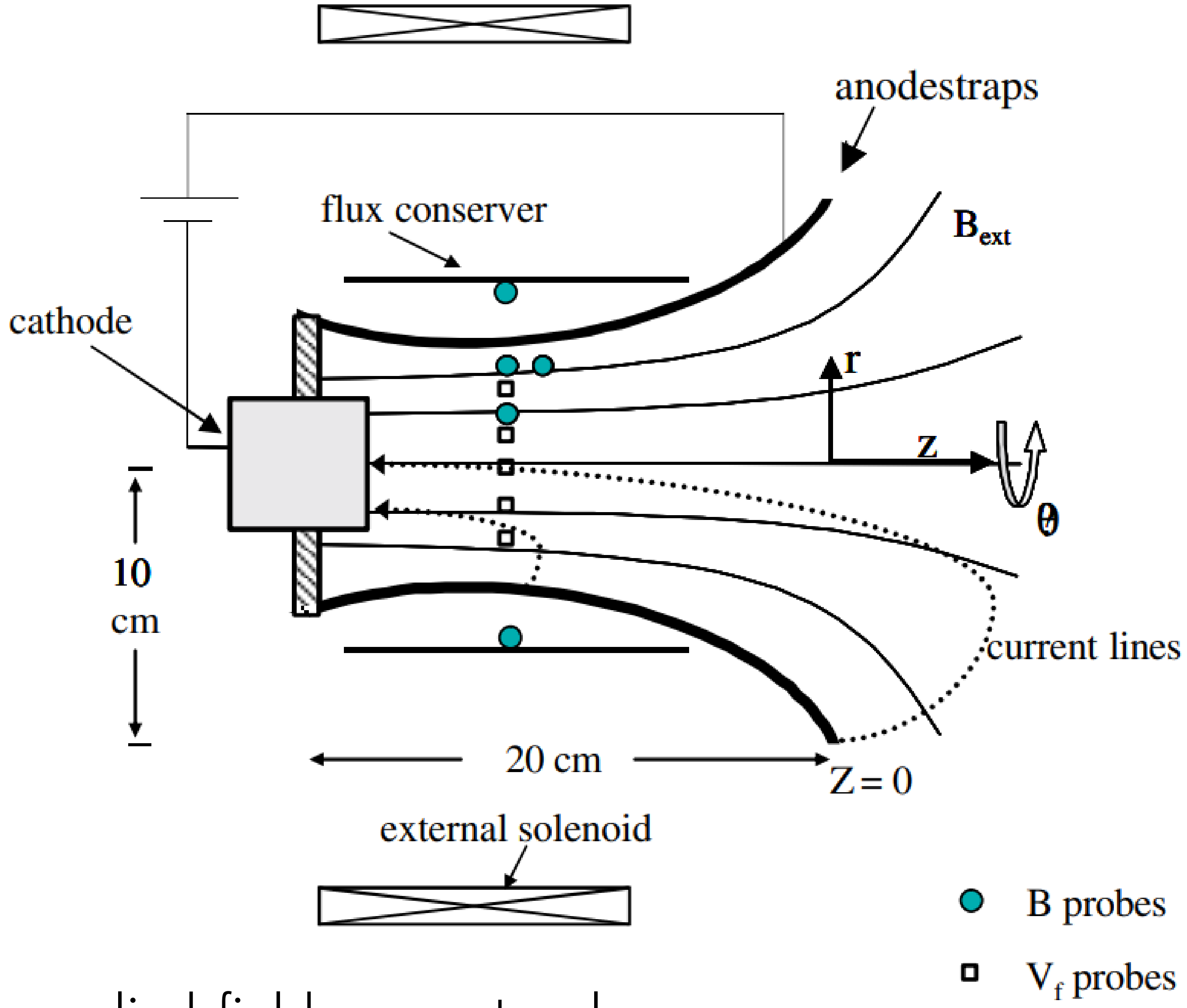
*S. Spagnolo et al., “First wall Electrostatic probes for RFX-mod2”, RFXmod2_TN_064

Halo Machine is a small but important piece in resolving the puzzle of sideways forces on ITER



KINK MODES AND PLASMA PROPULSION

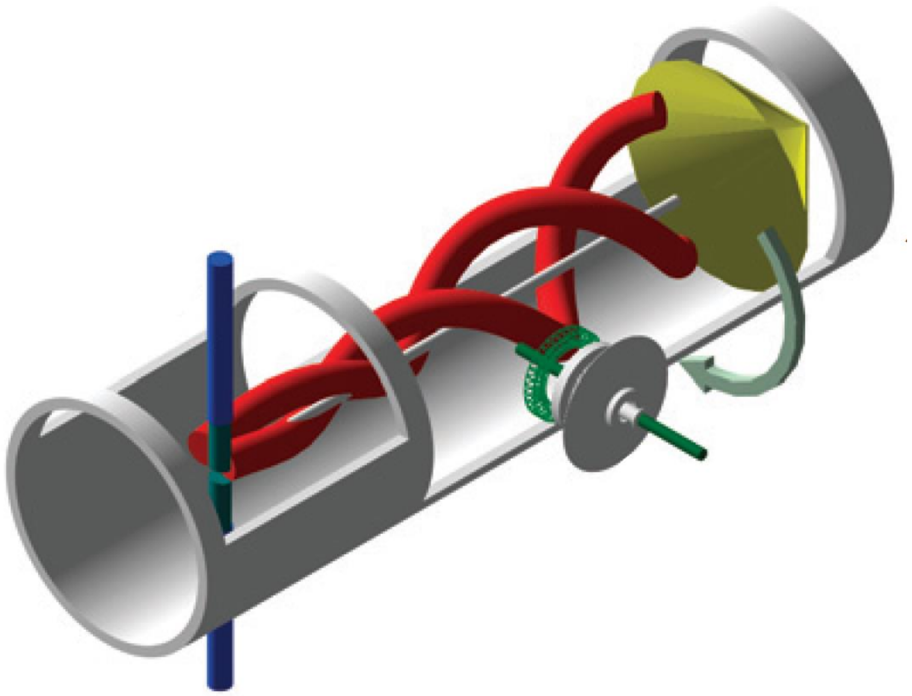
- Performance of magneto-dynamic-plasma thrusters is limited by onset of rotational kink modes*.
- Halo machine will investigate this issue at a new parameter space (up to 1 T).



Zuin, M., et al. "Kink instability in applied-field magneto-plasma-dynamic thrusters." *Phys. Rev. Lett.* **92** (2004) 225003.

Halo Machine and Magnetic Reconnection

- The same device can be used for studies of magnetic reconnection in a configuration similar to the Reconnection Scaling Experiment (RSX) from Los Alamos.



*T. P. Intrator et al., *Nature Phys.* **5**, 521–526 (2009).

- A new linear plasma device has been proposed to test
  - Source & Sink
  - WTKM and
  - ATEC models

- The results obtained on the Halo Machine will contribute at resolving the uncertainty regarding the sideways forces on ITER.

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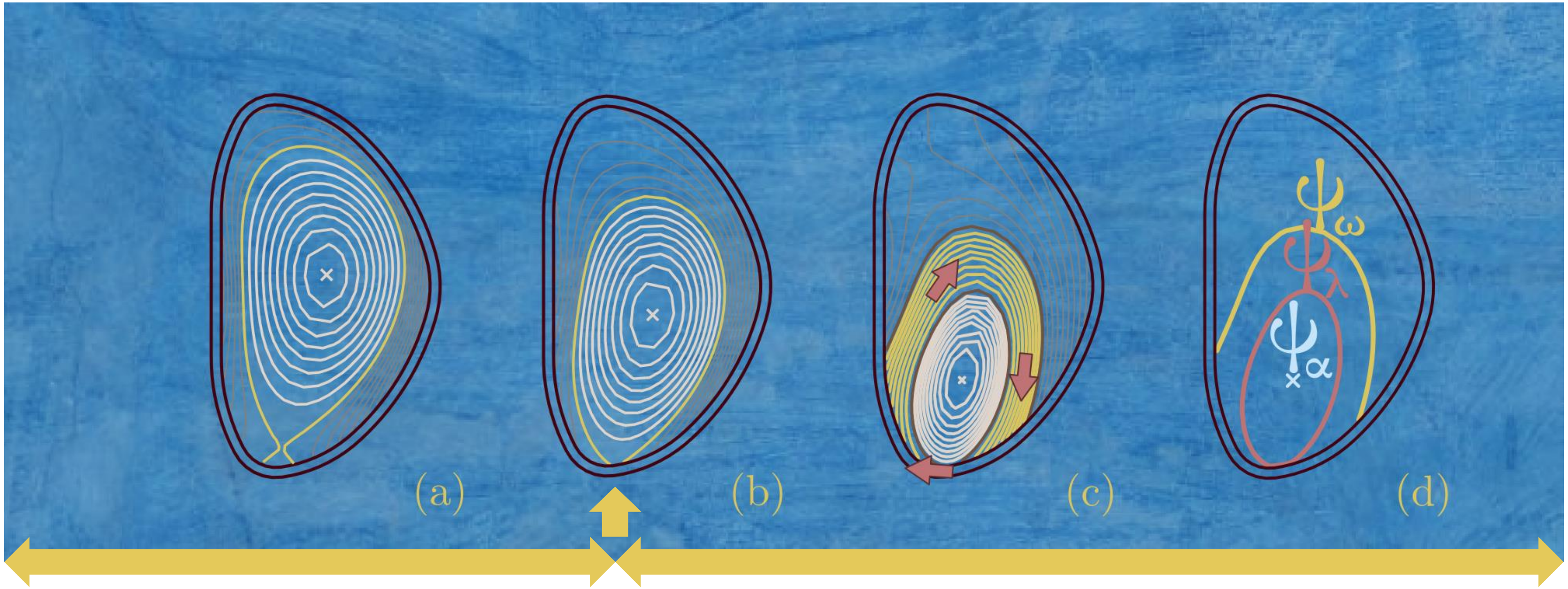
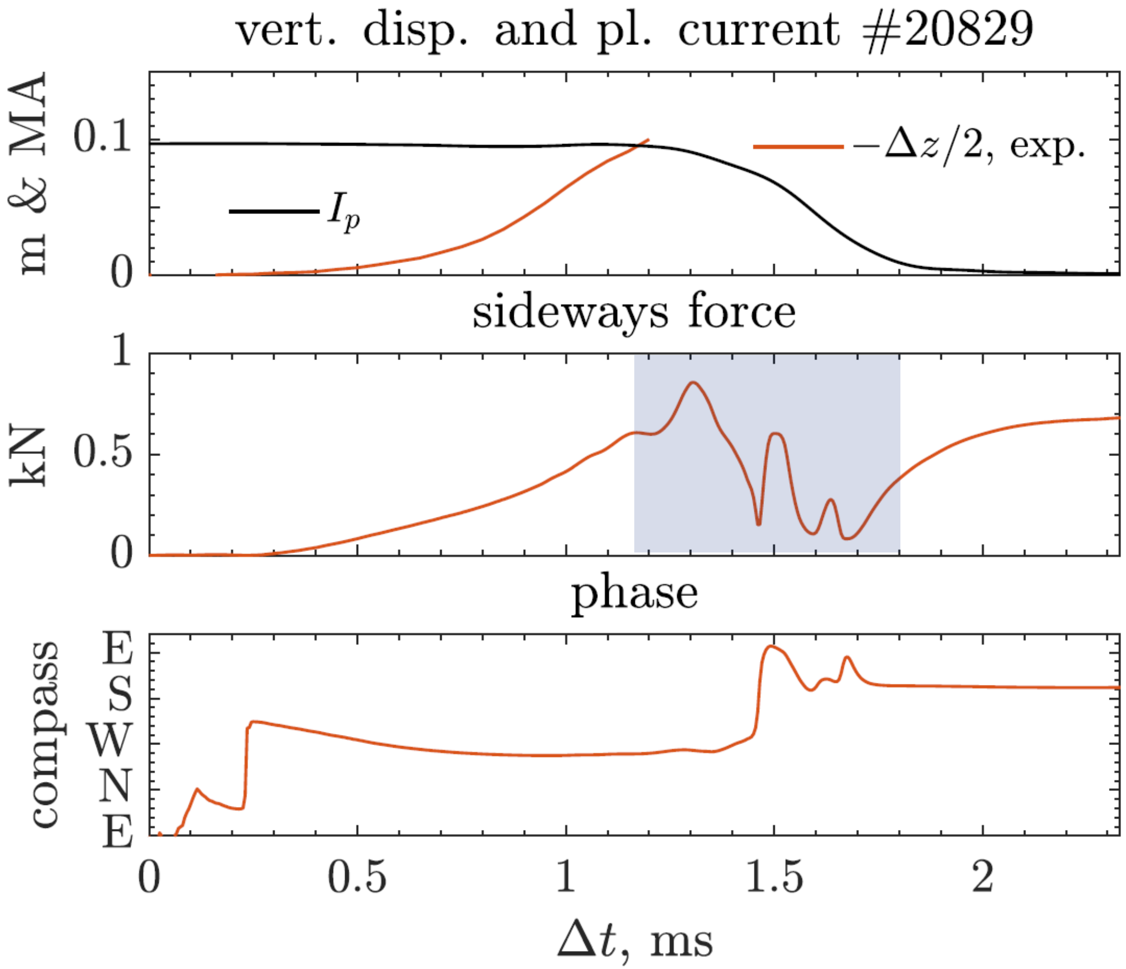
AN EXAMPLE FROM COMPASS



The total sideways force measured on COMPASS

- Before the plasma-wall contact the only contribution into the force is the wall asymmetry.
- After the plasma-wall contact other effects (kink, halo, Hiro, ATEC) can contribute too.



*V. Yanovskiy, A. Iaiunese et al., Magnetic measurements of disruption forces on COMPASS, 49th EPS (2023).

Kink instabilities on different devices

- Halo Machine is a flexible facility to study kink instabilities for various applications.
- It can operate at magnetic field up to 1T.
- The plasma column length can be increased from the present 0.3 m to 5 m.

	PHASMA	RSX	ReWM/RWM	LAPD	Caltech	Halo Machine
n_e (10^{19} m^{-3})	5	0.9	4 – 25	0.1	10	1
T_e (eV)	5	12	2 – 10	4	12	10
B_z (Gauss)	375	120	270 – 600	660	800	50 – 10.000
Length (m)	1-1.7	0.92	1.2	11	0.25	0.3 – 5
Radius (cm)	2	2	6 – 9	2.5	5	3
Bias current (A)	500	320	5.000	75	100.000	500

*Peiyun Shi et al. "Alfvénic modes excited by the kink instability in PHASMA." Physics of Plasmas 28.3 (2021).