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Lumped Circuit Model for Eddy Currents in Tokamak Passive Structures

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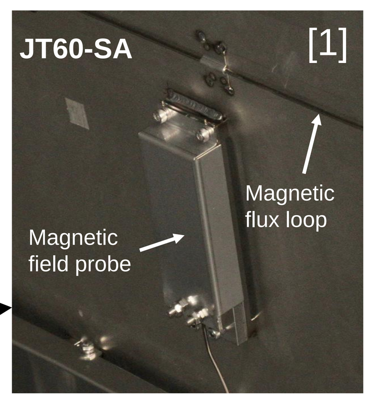
1 Introduction

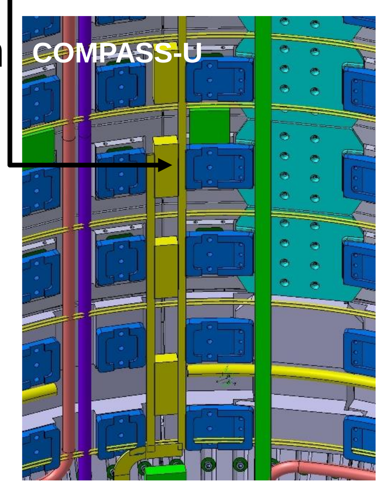
- Measurements of **local magnetic fields** and **magnetic fluxes** in tokamak → plasma control feedback + equilibrium reconstruction.
- Magnetic sensors:
  - Installed on vacuum vessel or other conductive surface
  - Protected by complex geometry metal elements

→ Changes in magnetic signal affected by **eddy currents** induced in the vicinity.

→ Necessary to evaluate this effect for plasma control.

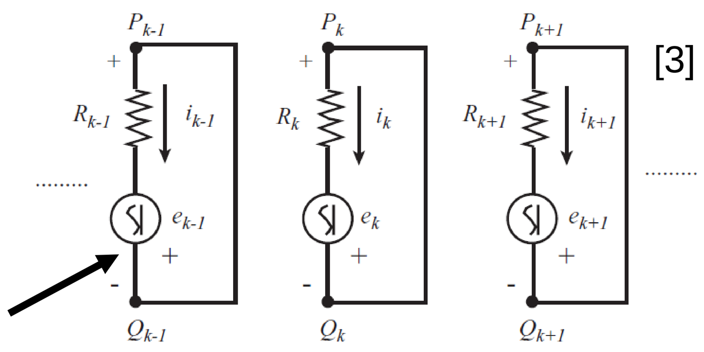
In this work:
- Ready-to-use model based on **lumped circuit approach** is presented and compared to a more sophisticated Ansys model.
- Provided an example of the model use in **assessment of magnetic sensor positions** in COMPASS-U.





2 Lumped circuit eddy model

- Tokamak plasma equilibrium – toroidally symmetric → so are **fields** and **eddy currents**.
- For non-axisymmetric effects see our paper [2].
- **Vacuum vessel (VV)** → approximated by **series of toroidal filaments**. These are **coupled** to **plasma**, **tokamak PF coils** and **to each other**.
- Method well described in [3], popular in tokamak community [3-6]. First degree ODE.
- Drawback – PF coils and plasma current are **assumed** not to be affected by eddy currents.



Lumped circuit model

$$\mathbf{Ri} + \frac{\mathrm{d}}{\mathrm{d}t}(\mathbf{Mi} + \mathbf{M_E i_E}) = \mathbf{u}$$

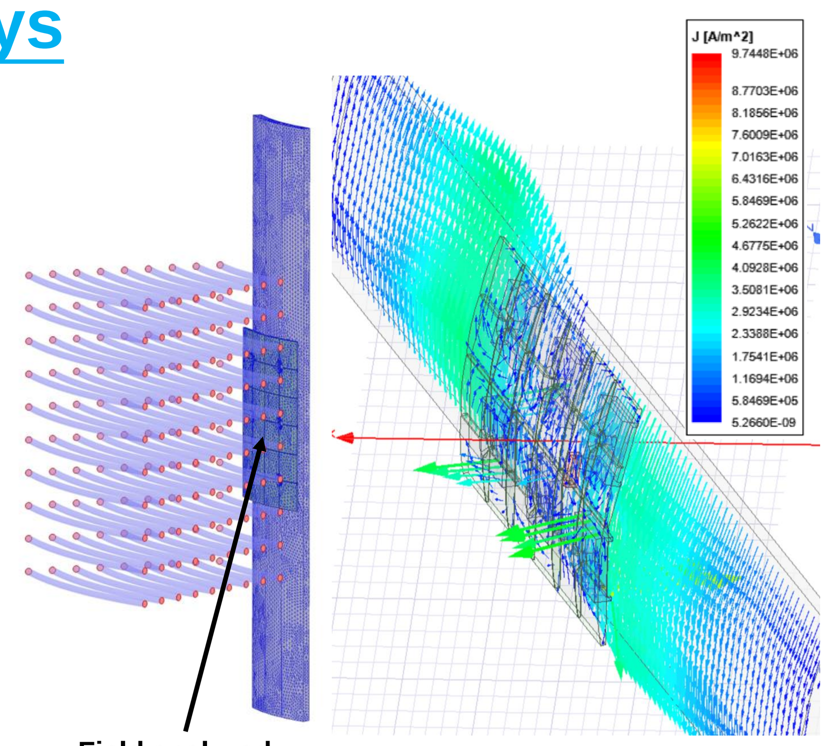
Diagonal resistivity; Known plasma and PF coil currents; =0 for toroidally conductive; Sought eddy current; Filament self- and mutual inductance matrix; Mutual inductance between filaments and plasma or PF coils

3 Model validation with Ansys

Ansys Maxwell software – finite element analysis – 3D calculation of eddy currents in fusion devices [7] (mechanical forces).

3.1 Vacuum vessel model

- **VV** – 1/16 periodic **cylindrical segment**. In this work effect of 3D PFC elements is neglected.
- **Plasma** – 9x10 filaments of independent currents – represented COMPASS-U discharge 6409 I_{plasma} flat-top phase.
- Investigated **vertical and radial shift** of whole plasma column **at 2 cm/ms** speed.



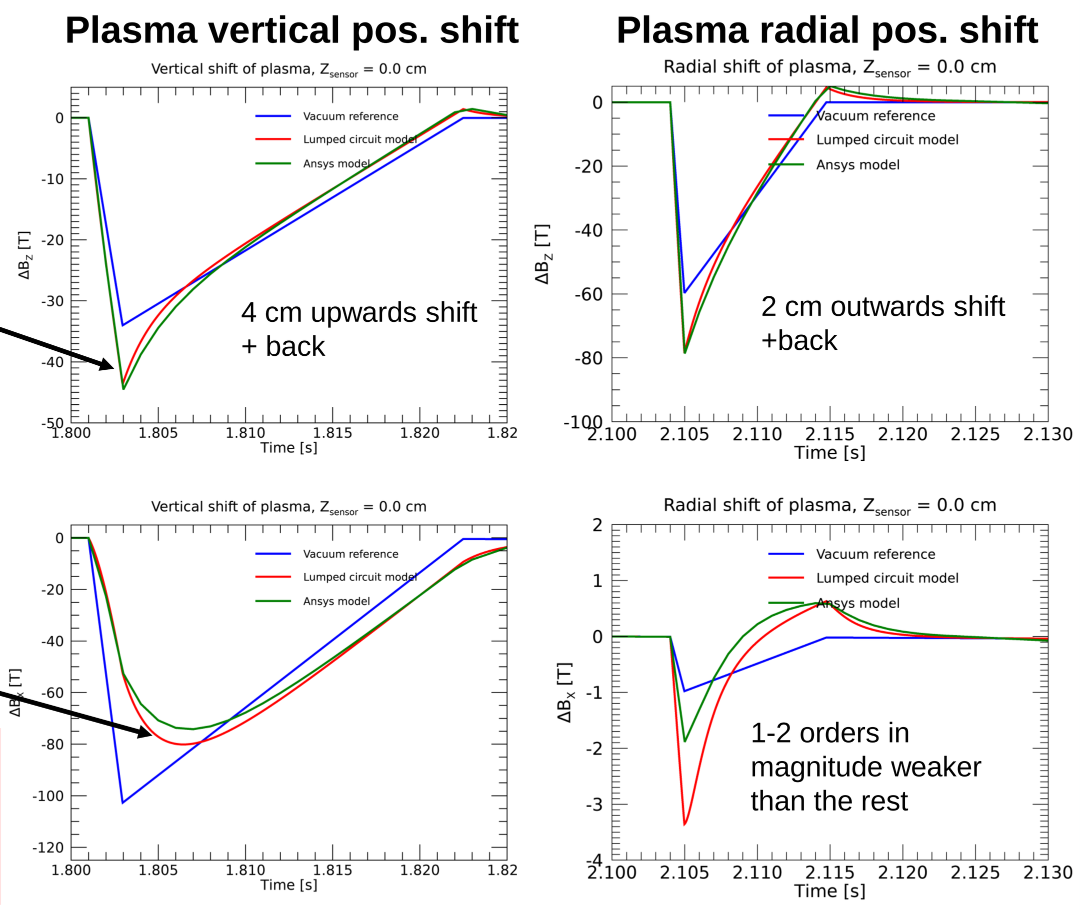
Field analyzed in this position

Eddy currents induced by vertical plasma shift (Ansys simulation)

Vertical field component B_Z:
- Good agreement between lumped circuit and Ansys.
- Amplified by eddy currents.

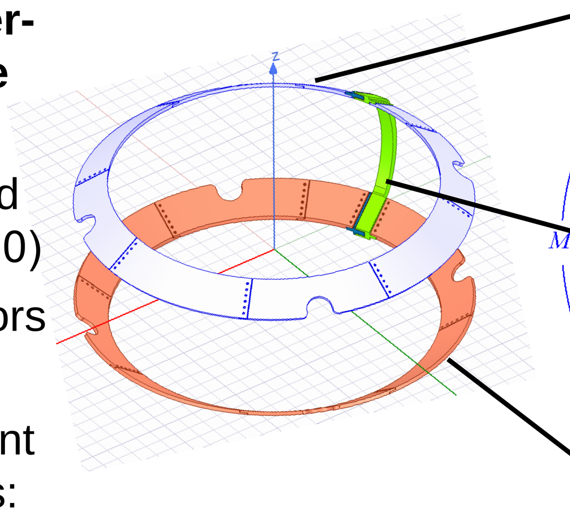
Normal field component B_X:
- Non-negligible only for vertical plasma movement. Good model agreement.
- Attenuated by eddy currents.

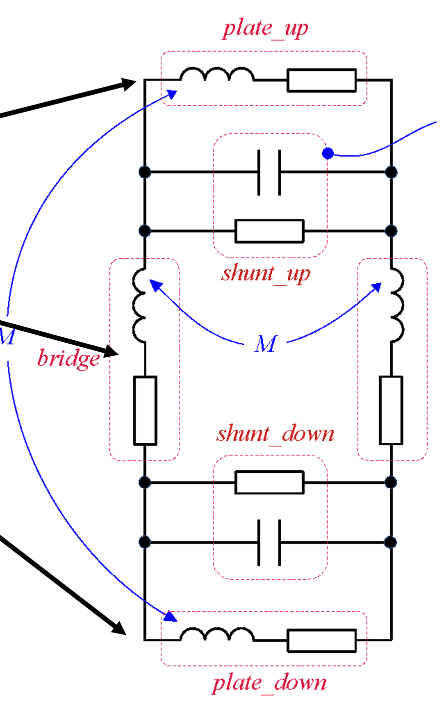
Agreement between lumped circuit model and Ansys for **toroidally symmetric structures**.

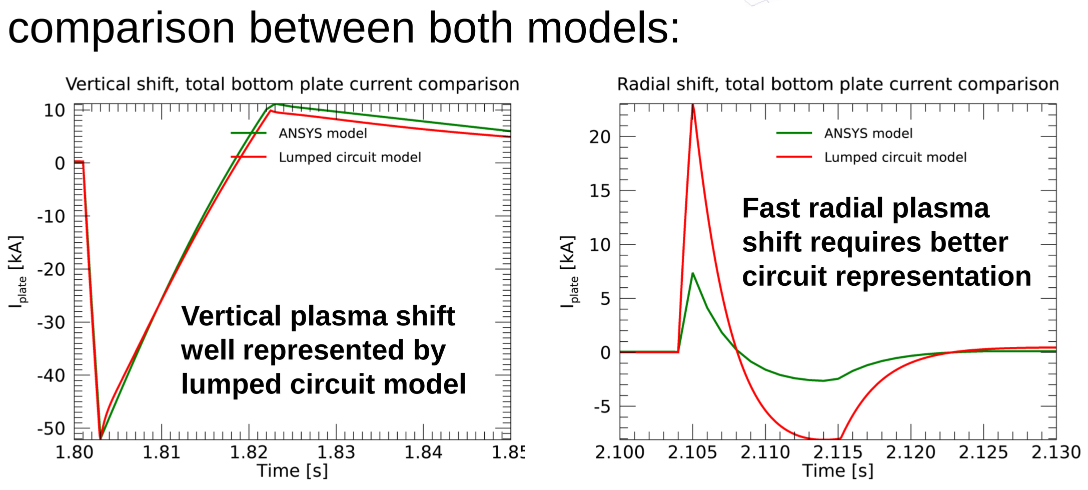


3.2 Plasma stabilizing plate model

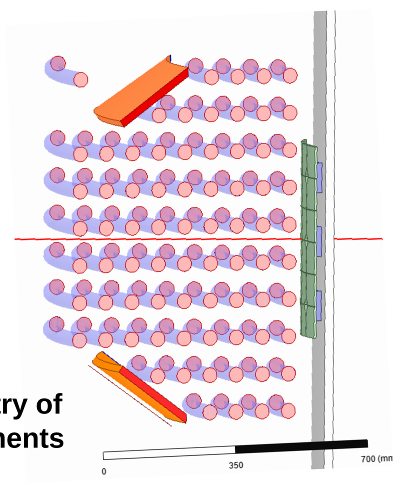
- COMPASS-U will feature **counter-wound plasma stabilizing plate** structure.
- Coupled current circuit introduced into the model (equivalent to **u** ≠ 0)
- Bridge included as well. Capacitors only present in the Ansys model
- Validation – total plate eddy current comparison between both models:







Lumped circuit model of PSP **describes vertical plasma position shifts well**. Fast **radial shifts insufficiently** described with the present circuit.

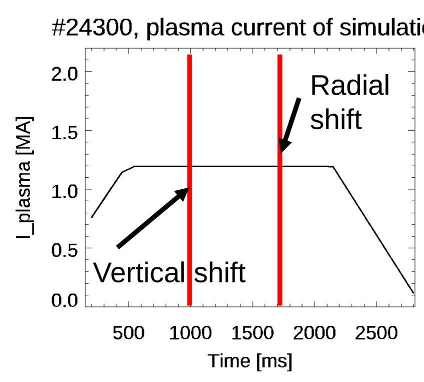


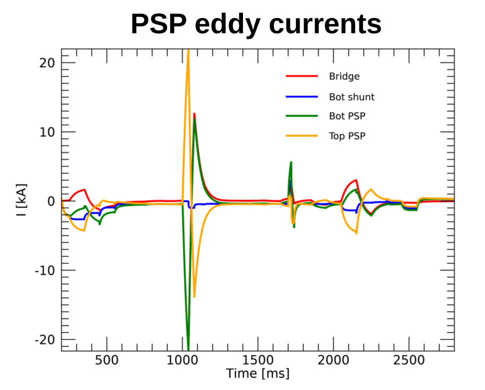
Relative geometry of VV, plasma filaments and the PSP

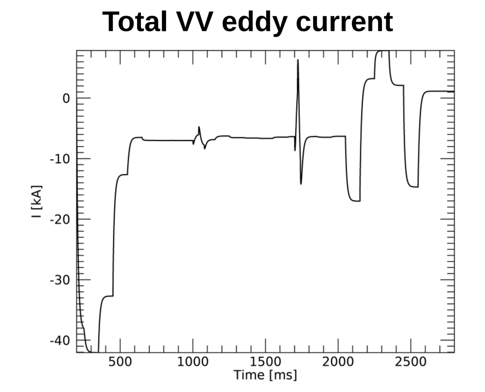
4 Interpretation of tokamak magnetic sensor signal

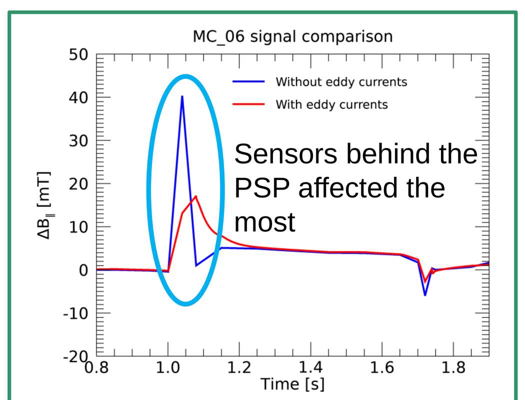
4.1 Regular conditions

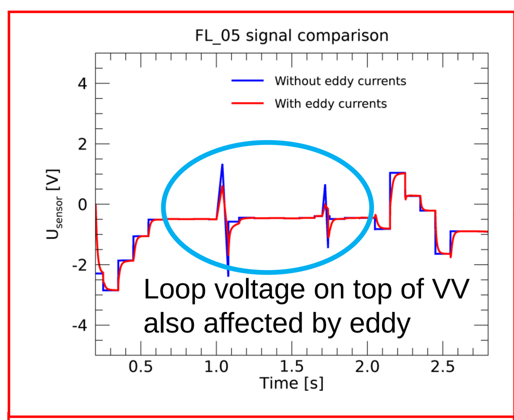
- Effect of eddy currents on magnetic sensor signals evaluated for **#24300** typical COMPASS-U shot.
- I_{plasma} flat-top phase enriched by 0.2 cm/ms shifts in plasma position.
- Comparison of signal vacuum reference to **signals affected by eddy currents.**
- Local magnetic fields and local toroidal loop voltage.

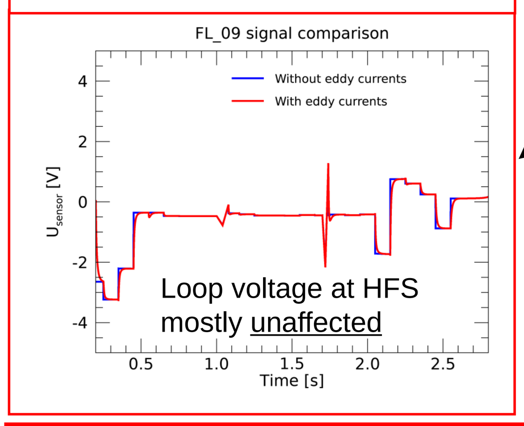


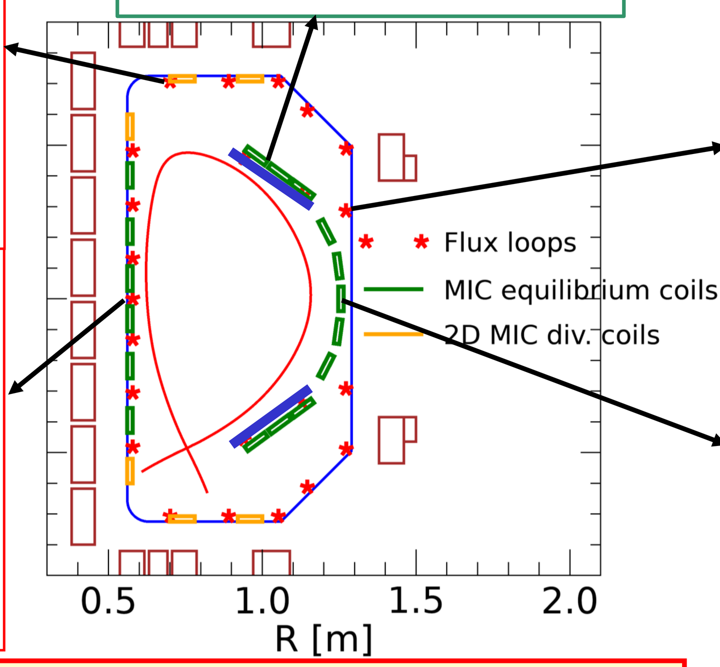


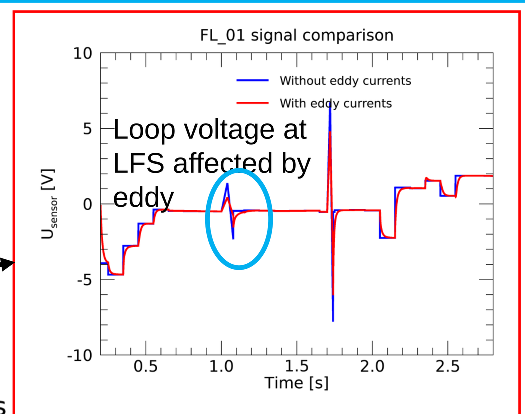


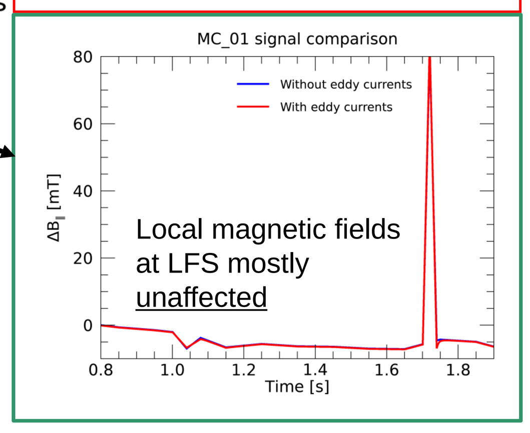












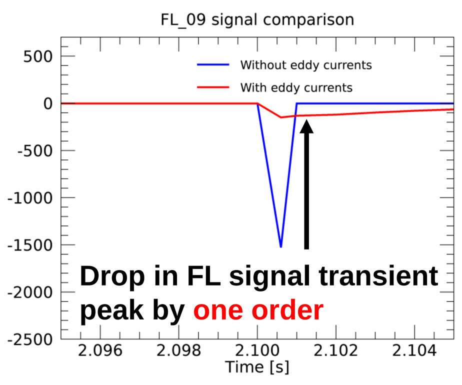
- Eddy current shielding across sensor arrays → lumped circuit model necessary for equilibrium reconstruction.
- Optimal sensors for **fast plasma feedback** – HFS flux loops and LFS magnetic coils.

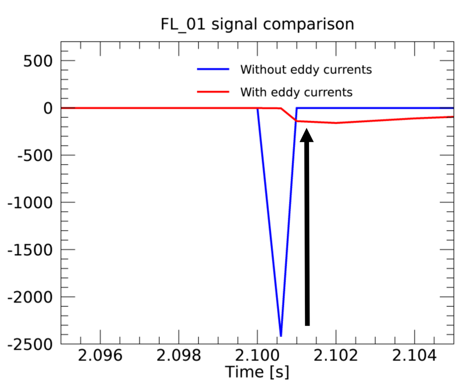
4.2 Disruption voltages

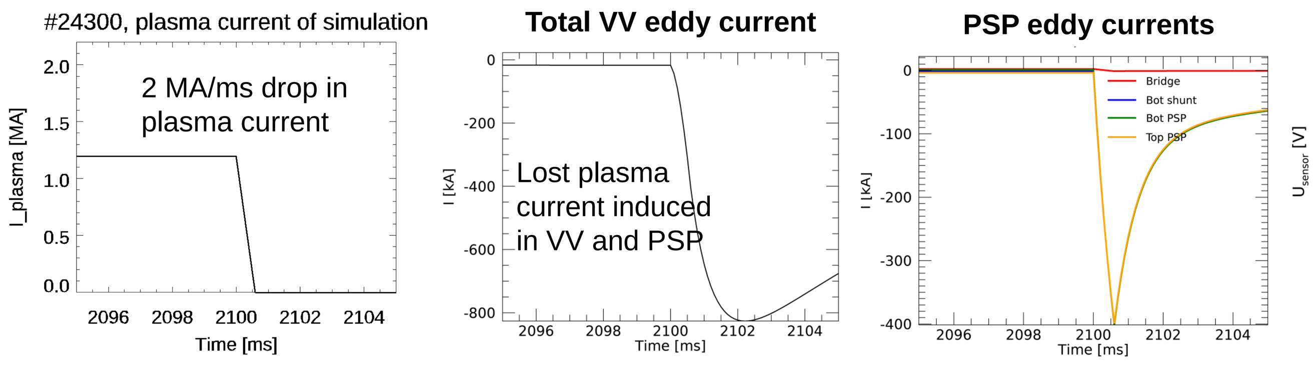
- Discharge duration – rapid disappearance of ~1-2 MA

→ ~10^0 kV in flux loops →not acceptable for wire ins. material.

Lumped circuit model predicts ~10^{-1} kV peaks only, thanks to the eddy current attenuation.
→ Acceptable for wiring.







5 Summary

- Eddy currents induced in tokamak conducting structures can significantly affect magnetic field and flux measurements in their vicinity.
- Lumped circuit model performs well to quantify this effect – validated by Ansys model in this work. However, calculation of currents that force themselves across shunt resistors of PSP need although improvement in PSP circuit representation.
- Model shows that the least affected sensors by axisymmetric eddy current attenuation are LFS midplane coils and HFS flux loops → optimal choice of sensors for fast feedback plasma control algorithms.

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