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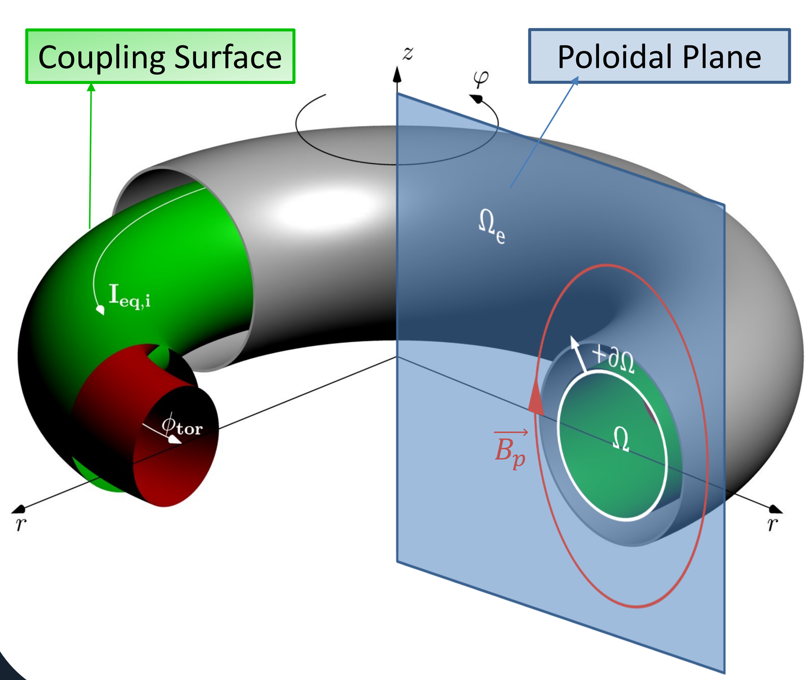
## Tutor: Prof. Fabio Villone

## XXXIV Cycle - II year presentation

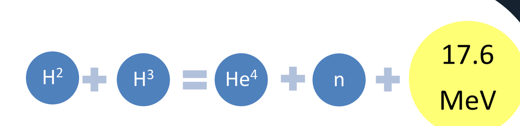
# Electromagnetic Interaction of Fusion Plasmas and Conducting Structures




The raising request of energy and the growing threats of climate change require a deep renewal of the actual oil-dominated energy market. Wind and solar electric energy generation are valid alternatives, although they lack in predictability, requiring serious renovation of the electrical power system. In this context, the large availability of deuterium in sea-water, the intrinsic lack of $CO_2$ and toxic emissions of a fusion power plant, besides its structural safety make Fusion Energy a valid candidate for the **future base-load energy**.

Probably the most promising fusion device technology is the **tokamak** (toroidal kamera magnetic konfinement). A plasma is essentialy a strongly ionized gas. As simple picture, we can think that a charged particle free to move in a uniform magnetic field just spirals around a magnetic field line. Bending magnetic field lines in a torus-shape we can keep the gas far from solid structures, allowing to increase the temperature, even higher than what in the sun core, an essential requirement to trigger fusion reactions of hydrogen isotopes.

During my PhD, we are studying the key-points related to the **interaction of a tokamak fusion plasma with surrounding structures**: *eddy currents, electromagnetic forces* and *heat loads* on the structures surrounding the plasma, besides the key-aspects of the *plasma-wall interface* on macroscopic plasma evolution.

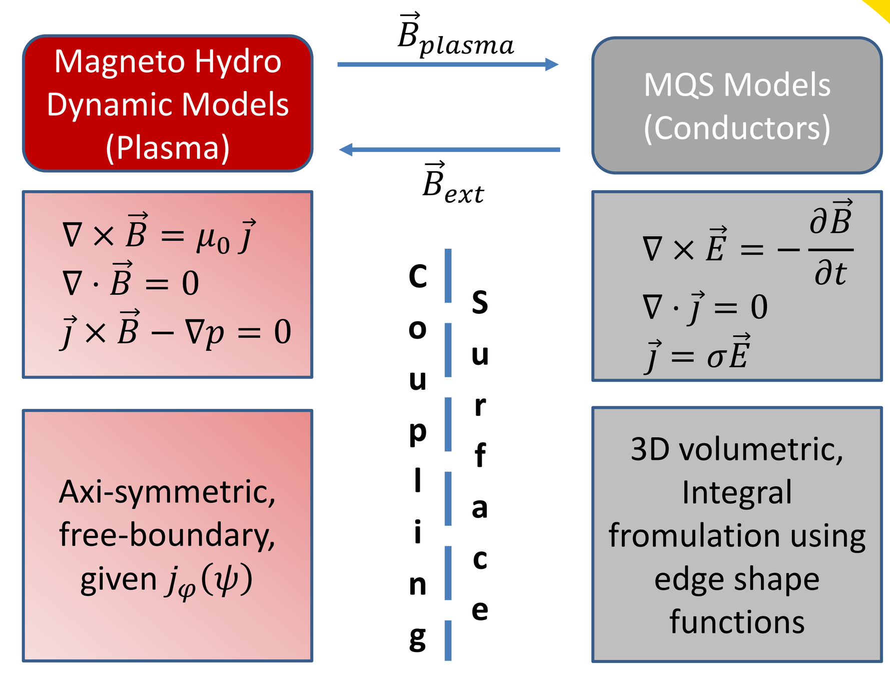


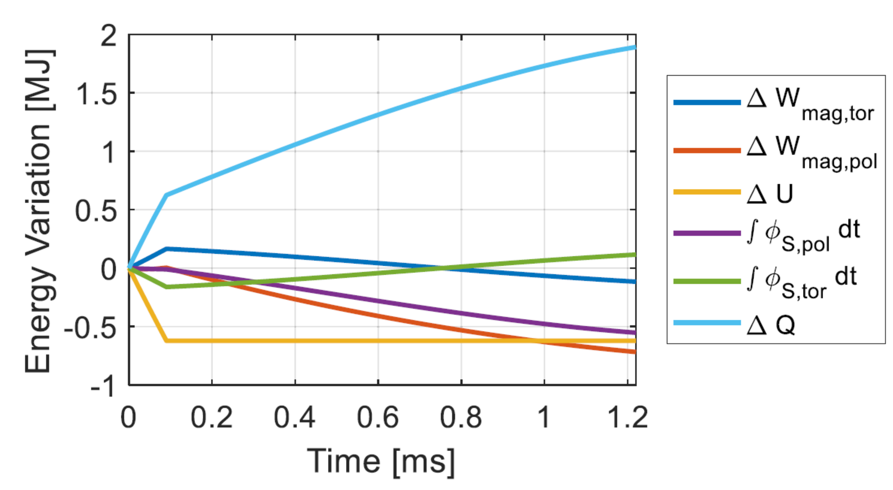

| Fuel | MJ/kg |
|---|---|
| D-D | 78 $10^6$ |
| D-T | 338 $10^6$ |
| $CH_4$ | 40 |

| Example: JET M18-33 | |
|---|---|
| $I_p$ | 2 MA |
| $B_{tor}$ | 2 T |
| $F_z$ | $100\ tons$ |
| $T_e$ | $17 \cdot 10^6\ K$ |

In present experiments, nominal **toroidal currents** in tokamak devices are **in the MA range**, with **toroidal magnetic fields up to 5 T**. The eddy currents generated in solid structures due to plasma transients are themselves responsible for changes in the magnetic field which keeps the plasma in mechanical equilibrium, resulting in a tight coupling between eddy currents and plasma currents and motion. In ***Magneto-Hydro-Dynamics*** the plasma is essentially thought as a conducting fluid, which moves under the action of pressure gradient and Lorentz force.

Hard-to-predict fast plasma transients, often called ***disruptions***, may generate eddy currents in the surrounding Vacuum Vessel large enough to be responsible for large ***electromagnetic forces***. These pose serious limits to the operation and design of tokamak devices. We explored this point both theoretically, by comparison of analytical and numerical models for circular high-aspect-ratio geometries [1], and for application to the design of the future tokamak device COMPASS-U [2-3]. A particular focus was dedicated to the role of net poloidal currents in Vessel structure, as generally under-estimated.




$$\Delta Q_{CQ} \simeq -\frac{1}{2}\Delta\left(L_{fw}J^2\right) - \int_{t_1}^{t_2} L_w J \frac{\mathrm{d}J_w}{\mathrm{d}t}\mathrm{d}t$$

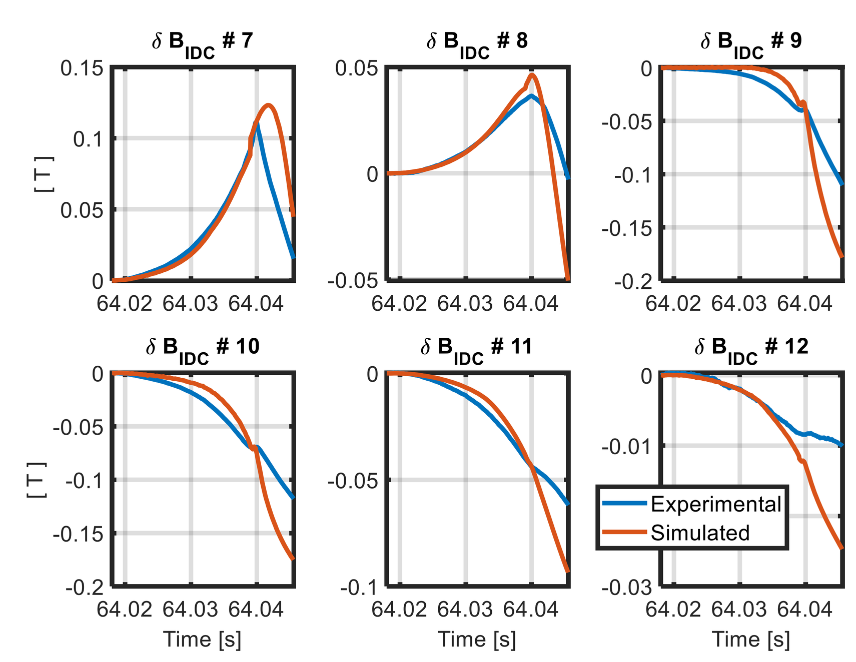
$$L_w = \mu_0 R_w \left[\ln\frac{8R_w}{b_w} - 2\right]$$

$$L_{fw} = \mu_0 R_w \left[\ln\frac{8R_w}{b} - 2 + \frac{\ell_i}{2}\right]$$

A further serious threat for the integrity of fusion devices concerns the severe localized heat fluxes which may permanently damage the *first wall* and *plasma facing components*. An overall understanding of the energy balance in the vacuum chamber of a tokamak device is often masked from the great variety of models necessary to describe the different physical phenomena to be studied. In [4] we proposed and integrated approach, which has the great advantage of making possible **integral estimates of plasma losses from evolutionary equilibrium models**.

This allowed to use and extend tools used during the first year. The main energy sinks are essentialy *magnetic energy* and *thermal energy*, while the kinetic energy is usually negligible. The variation of toroidal magnetic energy is found to be almost perfectly compensated from the portion $\boldsymbol{E_{pol}} \times \boldsymbol{H_{tor}}$ of the Poynting vector flux for the typical values of toroidal magnetic field. During the *Thermal Quench* the dissipated heat is essentially related to variations of the thermal energy. During the *Current Quench* the plasma converts poloidal magnetic energy into dissipated heat. The actual amount of energy available for conversion depends on the duration of the Current Quench respect to the typical electromagnetic time constants, $\tau_{0,w} = \mu_0 \sigma b_w d_w [\ln(8R_w/b_w) - 2]$ for a circular cross section high-aspect-ratio tokamak. In these hypothesis novel analytical formulas were developed in order to estimate plasma losses as function of plasma global parameters.

Real disruption mitigation systems are implemented in many tokamak devices in view of the ITER design. The effect of ***Shattered Pellet Injection*** is promising and was tested during the M18-33 **experimental campaign on JET**. Work is ongoing to interpret the experimental results in the framework of evolutionary equilibrium modelling, testing simulated measurements against real ones and setting different plasma pressure and current profiles in simulation.




The solid surfaces are really sinks for charged particles and sources of neutrals. A sound understanding of the fusion plasma macroscopic evolution when the plasma is touching the first wall may require to include a neutral gas within the model. We decided to explore this modelling possibility in the framework of ***Non-Equilibrium Thermodynamics***. We treat the gas as a multi-component fluid of charged and neutral particles immersed in a magnetic field. The framework allows to integrate *Saha Equation* within the model, and the spatial symmetry constraints allow to clearly distinguish isotropic effects from the Hall effect and the reduced conductivity across magnetic field lines. The ***kinetic energy of diffusion*** is normally discarded from modelling. Within this framework preliminary studies indicate that this is not always possible. In particular the *kinetic energy of diffusion* might reveal helpful for the understanding of the energy exchange mechanisms between *thermal plasma* and *runaway electrons*. This point is still under investigation.

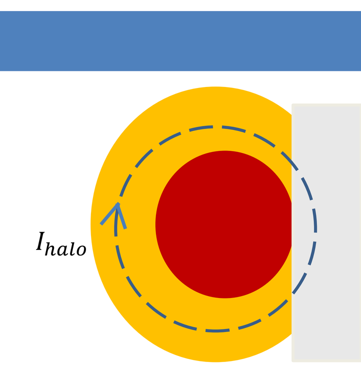
**References**


[1] Isernia et al., Plasma Physics and Controlled Fusion, Vol. 61(11), 2019 DOI
[2] Yanovskiy et al., Fusion Engineering and Design, Vol. 146, 2019, DOI
[3] Yanovskiy et al., IAEA Technical Meeting on Disruptions and their Mitigation, 2020, URL
[4] Isernia et al., Plasma Physics and Controlled Fusion, Vol. 62(9), 2020, DOI



INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES – Ph.D. Vadim Yanovskiy: COMPASS experiments and COMPASS-U design.
CCFE – M18-33: Disruption Mitigation with SPI; T17-13: Disruption and Runaways
Prof. V. D. Pustovitov: MHD analytical models
PPPL – Prof. S. Jardin: M3DC1 – CARIDDI coupling
JOREK TEAM – Prof. M. Hoelzl, Ph.D. J. Artola-Such: JOREK – CARIDDI coupling
Oak Ridge National Laboratory – Ph.D. M. Cianciosa: VMEC – CARIDDI coupling


We are far from a self-consistent modelling of the plasma-surface interface, due to the great variety of chemical and physical phenomena occurring. We want to address this point in a macroscopic framework at least capturing the key phenomena and aspects. In particular we are interested in the estimation and analysis of «*halo currents*» exchanged between plasma and solid structures. Firstly, we will study the plasma-solid interface by the means of Thermodynamic approaches. On a more operative level, we will advance the coupling of three-dimensional extend-MHD codes, such as JOREK or M3D-C1, with the 3D eddy current code CARIDDI. Some preliminary studies are already ongoing by collaborations with the relevant laboratories. A fully volumetric 3D coupled model has never been implemented in the literature, and it would be greatly helpful especially in the study of *halo currents.*



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