ITEE Ph.D – Information Technology Electrical Engineering


# Isernia Nicola

## Tutor: Prof. Fabio Villone

XXXIV Cycle - I year presentation


# Electromagnetic Interaction of Fusion Plasmas with Conducting Structures


Università degli Studi di Napoli Federico II

# General Information

- M.Sc. In Electrical Engineering – Universitá degli Studi di Napoli Federico II
- Erasmus at *AAU, DK (project on Series Resonant Converters for DC Offshore Wind Power Plants)*
- Master Thesis on *Statistical Analysis of 3D effects of conducting structures on axisymmetric evolution of Fusion Plasmas*
- Post-graduate internship at IPP Prague in support of COMPASS-U design (June-July 2018)

- Athenaeum Fellowship
- Research Group:

**Electrical Engineering** Group

- Some Collaborations:

# Framework: Fusion Energy

A candidate for future base-load energy

- Large Availability of Deuterium and Lithium on earth
- Low envorinmental impact
- Intrinsic Safety

$$H^2 + H^3 = He^4 + n + 17.6\ \text{MeV}$$

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

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

***Engineering Open Problems:***

- *Electromagnetic Forces*
- *Heat Loads*
- *Plasma-Wall Interface*

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100 City Cars

SUN CORE

I Year

***Engineering Open Problems:***

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- *Heat Loads*
- *Plasma-Wall Interface*

# Plasma-Conductors Interaction

Framework

Magneto Hydro Dynamic Models (Plasma)

$\vec{B}_{plasma}$ →

← $\vec{B}_{ext}$

MQS Models (Conductors)

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \vec{v}_\alpha) = S_\alpha$$

$$m_\alpha n_\alpha \frac{D}{Dt} \vec{v}_\alpha + S_\alpha \vec{v}_\alpha =$$

$$= q_\alpha n_\alpha \left( \vec{E} + \vec{v}_\alpha \times \vec{B} \right) - \nabla \cdot \overleftrightarrow{\Pi}_\alpha - \sum_{\beta \neq \alpha} \vec{R}_{\alpha\beta}$$

[...]

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{j} = 0$$

$$\vec{j} = \sigma \vec{E}$$

# Plasma-Conductors Interaction

Our Problem

Magneto Hydro Dynamic Models (Plasma)

$\vec{B}_{plasma}$ →

← $\vec{B}_{ext}$

MQS Models (Conductors)

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \vec{v}_\alpha) = \cancel{S_\alpha}$$

$$m_\alpha n_\alpha \frac{D}{Dt}\vec{v}_\alpha + \cancel{S_\alpha}\vec{v}_\alpha =$$

$$= q_\alpha n_\alpha(\cancel{\vec{E}} + \vec{v}_\alpha \times \vec{B}) - \nabla \cdot \overleftrightarrow{\Pi}_\alpha - \sum_{\beta \neq \alpha} \cancel{\vec{R}_{\alpha\beta}}$$

[\cancel{...}]

No Ioniziation nor Recombination

Debye Shielding

$\nabla \cdot \overleftrightarrow{\Pi}_\alpha$ → $\nabla p_\alpha$

Compensation of Collisions between different species

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

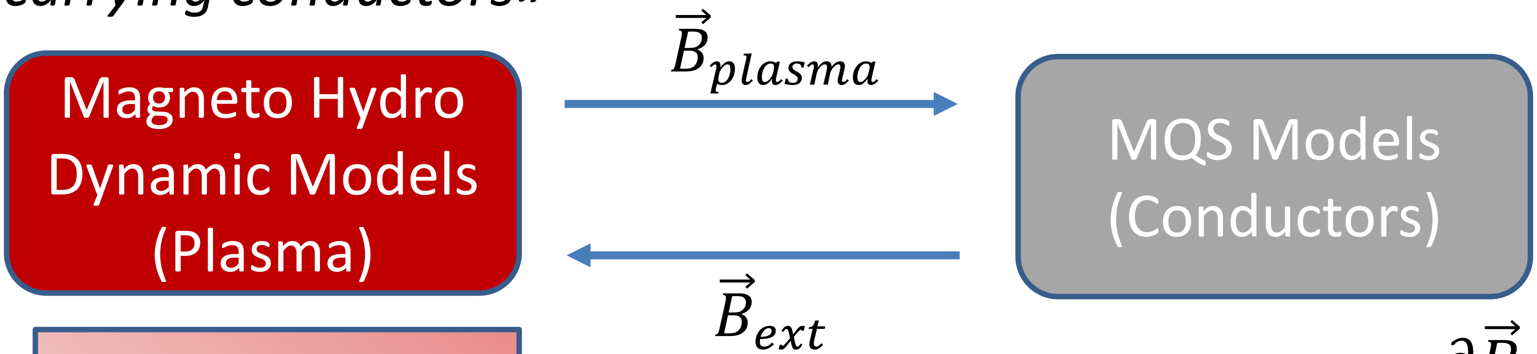
$$\nabla \cdot \vec{j} = 0$$

$$\vec{j} = \sigma \vec{E}$$

# Plasma-Conductors Interaction

## Our Problem

- *«Any bounded equilibrium plasma configuration with a magnetic field can exist only in presence of fixed current-carrying conductors»*[1]



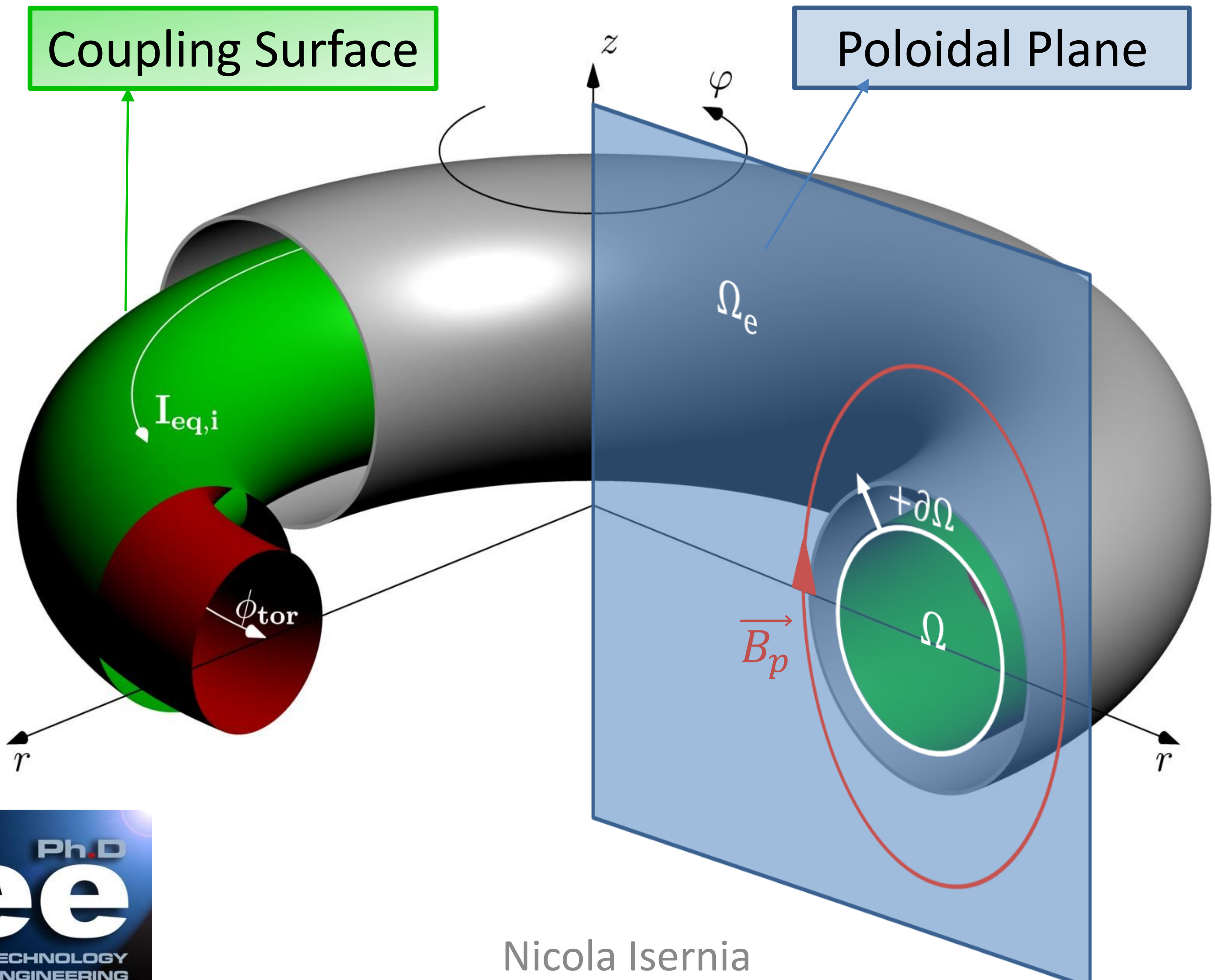

$$\nabla \times \vec{B} = \mu_0 \vec{j}$$
$$\nabla \cdot \vec{B} = 0$$
$$\vec{j} \times \vec{B} - \nabla p = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \cdot \vec{j} = 0$$
$$\vec{j} = \sigma \vec{E}$$

[1] V.D. Shafranov – Chapter 2 in *Reviews of Plasma Physics* Edited by M.A. Leontovich 1966

# Plasma-Conductors Interaction

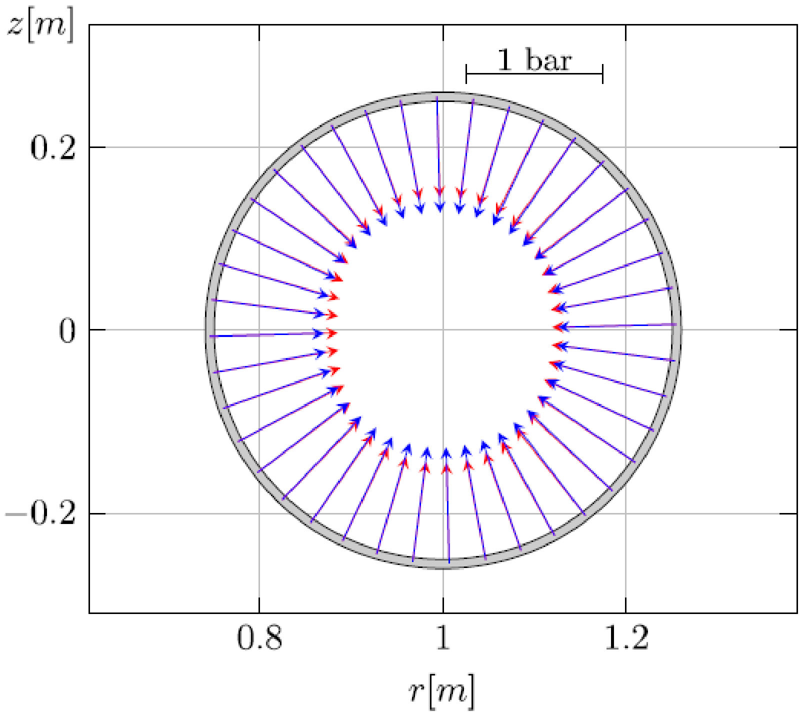
## Methodology




Nicola Isernia

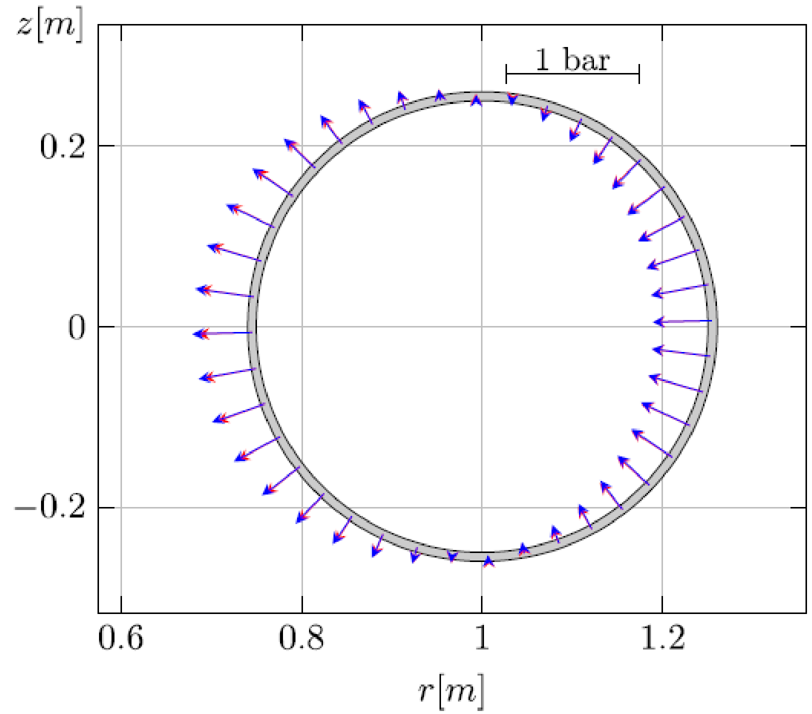
# Disruption Forces

Cross-Validation of Analytical and Numerical Models




| | Analytical | CarMa0NL |
|---|---|---|
| $\delta p_{m0}$ [bar] | −0.846 | −0.825 |
| $\delta p_{m1}$ [bar] | 0.015 | 0.001 |
| $F_r$ [kN] | −111.731 | −112.365 |

(a) with




| | Analytical | CarMa0NL |
|---|---|---|
| $\delta p^{\Psi}_{m0}$ [bar] | −0.000 | −0.005 |
| $\delta p^{\Psi}_{m1}$ [bar] | 0.440 | 0.417 |
| $F^{\Psi}_r$ [kN] | −217.250 | −212.389 |

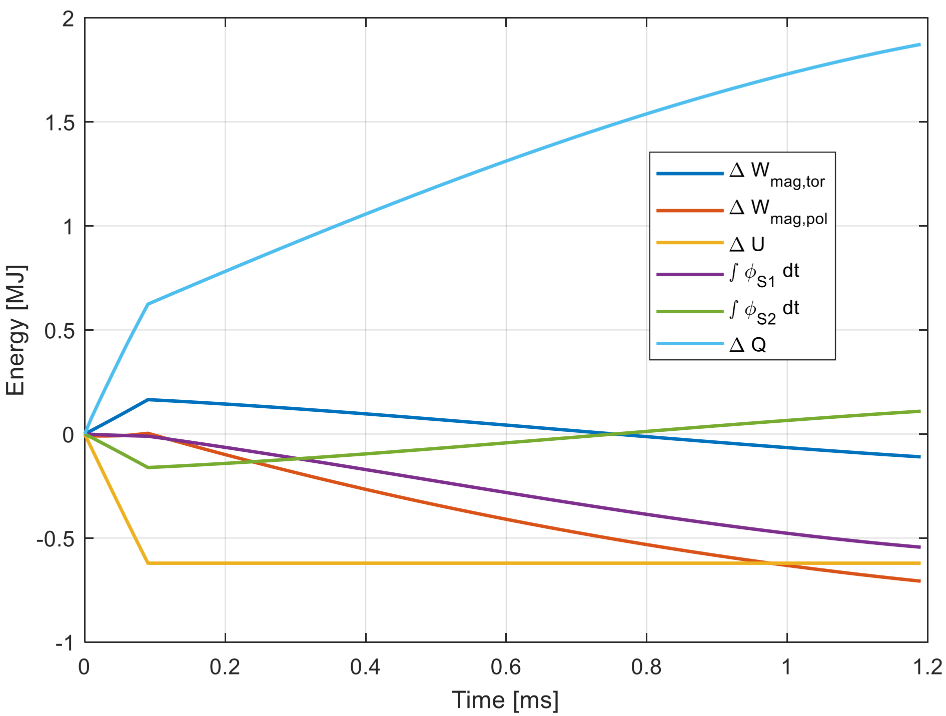
(b) without

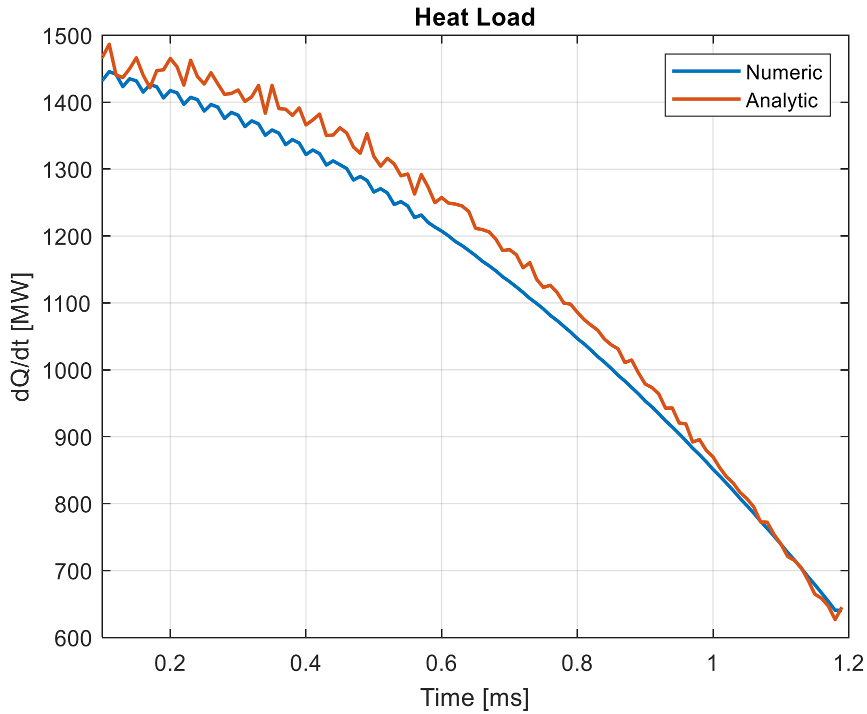
**Thermal Quench** 25% drop of kinetic pressure

[2]N. Isernia, et al, Plasma Physics and Controlled Fusion, Volume 61, Number 11, 2019.

# Overall Energy Balance

## First principle estimation of Plasma Losses

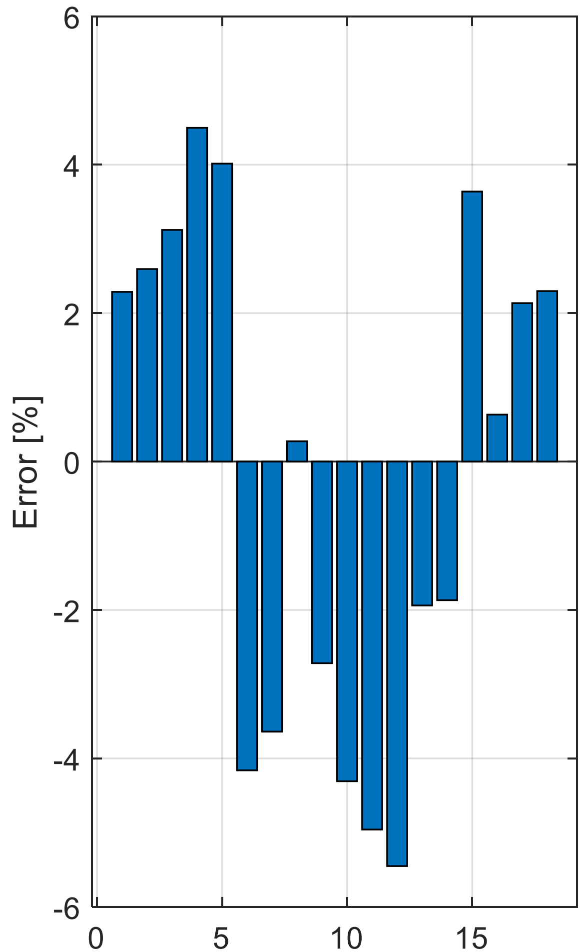


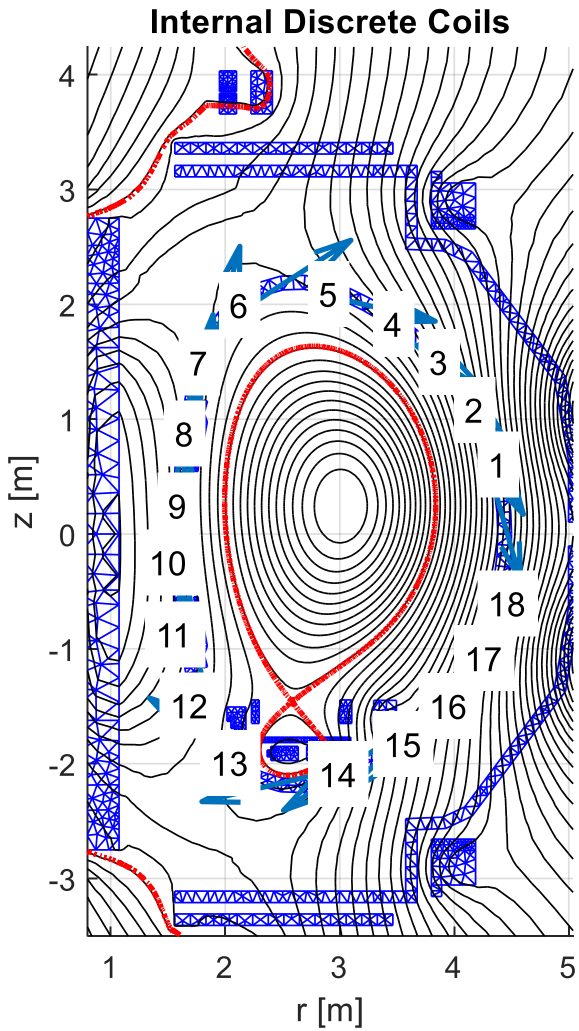




- **Compensation of Toroidal Magnetic Energy variation and $E_{tor} \times B_{pol}$ contribution to Poynting Flux for high $B_{\varphi}$**
- **Development of simplified analytical model for plasma losses**

[3]N. Isernia, et al, 46[th] Plasma Physics Conference of the European Physical Society, Milan, 2019

# Comparison of Experiment and Simulation for JET



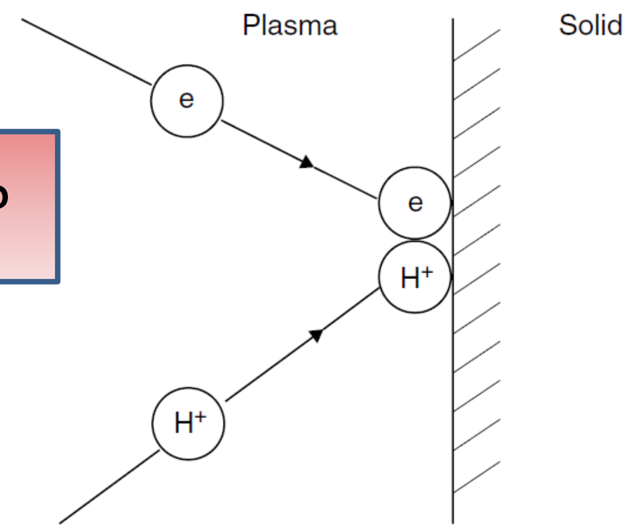

**Actual step**:
- Modelling JET Magnetic diagnostics in CarMa0NL
- Modelling of plasma equilibrium configuration fitting magnetic measurements

**Next steps**:
- Comparison of magnetic measurements for a whole simulated experiment
- Comparison of measurements at different toroidal locations

# What's next? Interface!

Magneto Hydro Dynamic Models (Plasma)

$$j_{n,pl} - j_{n,solid} = ?$$




$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \vec{v}_\alpha) = S_\alpha$$

$$m_\alpha n_\alpha \frac{D}{Dt}\vec{v}_\alpha + S_\alpha \vec{v}_\alpha =$$

$$= q_\alpha n_\alpha (\vec{E} + \vec{v}_\alpha \times \vec{B}) - \nabla \cdot \overleftrightarrow{\Pi}_\alpha - \sum_{\beta \neq \alpha} \vec{R}_{\alpha\beta}$$

[...]

Recombination?

Space Charge Layer?

$\nabla \cdot \overleftrightarrow{\Pi}_\alpha$ → ? → $\nabla p_\alpha$

Gas-Solid Potential Force?

# What’s next? Interface!

Magneto Hydro Dynamic Models (Plasma) → $(\vec{B}_{pl}, \vec{J}_{pl})$ → MQS Models (Conductors)

MQS Models (Conductors) → $(\vec{B}_{ext}, \vec{J}_{ext})$ → Magneto Hydro Dynamic Models (Plasma)

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \vec{v}_\alpha) = S_\alpha$$

$S_\alpha$ ← Recombination and Emission of particles?

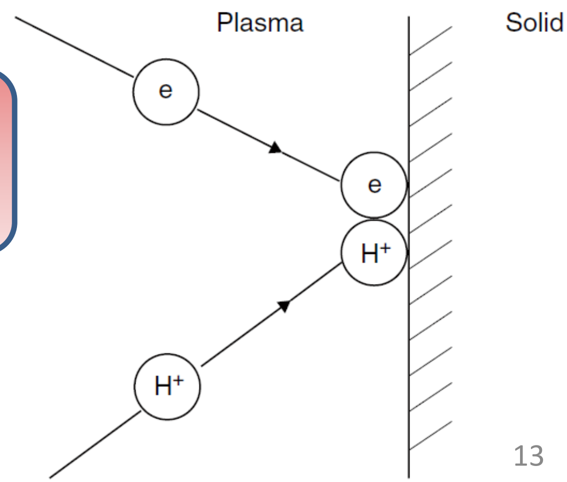
$$m_\alpha \frac{D}{Dt}(n_\alpha \vec{v}_\alpha) = q_\alpha n_\alpha \vec{v}_\alpha \times \vec{B} - \nabla \cdot \Pi_\alpha - \vec{R}_{\alpha\beta}$$

[...]

$\vec{R}_{\alpha\beta}$ ← Gas-solid force?

$\nabla \cdot \Pi_\alpha$ ← Isotropic at the interface?

$$j_{n,pl} - j_{n,solid} = ?$$



# Publications

- **Journal Papers**
  - V.V. Yanovskiy, N. Isernia, V.D. Pustovitov, F. Villone, D. Abate, P. Bettini, S.L. Chen, J. Havlicek, A. Herrmann, J. Hromadka, M. Hron, M. Imrisek, M. Komm, R. Paccagnella, R. Panek, G. Pautasso, S. Peruzzo, D. Sestak, M. Teschke, I. Zammuto, "*Comparison of approaches to the electromagnetic analysis of COMPASS-U vacuum vessel during fast transients*", Fusion Engineering and Design, Volume 146, Part B, 2019.
  - N. Isernia, V. D. Pustovitov, F. Villone,V. Yanovskiy, Cross-validation of analytical models for computation of disruption forces in tokamaks, Plasma Physics and Controlled Fusion, Volume 61, Number 11, 2019.
- **Conference Proceedings**
  - N. Isernia, V. Scalera, C. Serpico, F. Villone, "*Energy balance during disruptions*", 46th Plasma Physics Conference of the European Physical Society, Milan, 2019.
  - S. Chen, F. Villone, Y. Sun, B. Xiao, N. Isernia, G. Rubinacci, S. Ventre, "*Simulation of disruptions in EAST tokamak",* 46th Plasma Physics Conference of the European Physical Society, Milan, 2019
  - S. Jardin, F. Villone, C. Clauser, N. Ferraro, N. Isernia, G. Rubinacci, S. Ventre, "*ITER disruption simulations with realistic plasma and conductors modelling*", 46th Plasma Physics Conference of the European Physical Society, Milan, 2019
  - V. Yanovskiy, N. Isernia, V.D. Pustovitov, F. Villone, et al. "*Poloidal currents in COMPASS vacuum vessel during symmetrical disruptions: measurements using diamagnetic loop and comparison with CarMa0NL modelling*", 46$^{th}$ Plasma Physics Conference of the European Physical Society, Milan, 2019

# I Year Credits

| | Credits year 1 | | | | | | | | Credits year 2 | | | | | | | | Credits year 3 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Estimated | bimonth 1 | bimonth 2 | bimonth 3 | bimonth 4 | bimonth 5 | bimonth 6 | Summary | Estimated | bimonth 1 | bimonth 2 | bimonth 3 | bimonth 4 | bimonth 5 | bimonth 6 | Summary | Estimated | bimonth 1 | bimonth 2 | bimonth 3 | bimonth 4 | bimonth 5 | bimonth 6 | Summary | Total | Check |
| **Modules** | 23 | 9 | 9.4 | | 9 | | | 27 | 15 | | | | | | | 0 | 20 | | | | | | | 0 | 27 | 30-70 |
| **Seminars** | 7 | 0 | 0.6 | 0.7 | 1 | 0 | 3 | 5.3 | 3 | | | | | | | 0 | 5 | | | | | | | 0 | 5.3 | 10-30 |
| **Research** | 34 | 2 | 1 | 6.3 | 5 | 8 | 6 | 28 | 42 | | | | | | | 0 | 34 | | | | | | | 0 | 28 | 80-140 |
| | 64 | 11 | 11 | 7 | 15 | 8 | 9 | 61 | 60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 59 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 61 | 180 |

Thank you for your attention!

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# Backup Slides

# Plasma Conductors – Interaction

## CarMa0NL Numerical Coupling Scheme

### Coupling Strategy of Numerical Models

- Grad-Shafranov Equation ($\partial/\partial\varphi = 0$)

$$-r\nabla\cdot\left(\frac{\nabla\psi}{\mu_0 r^2}\right) = j_\varphi(\psi,r) = r\frac{d\,p}{d\psi} + \frac{2}{\mu_0}\frac{d\,f^2}{d\psi}$$

where:

$\psi = rA_\varphi;\;\; f = rB_\varphi;\;\; p =$ pressure

- Toroidal Current Parametrization

$$j_\varphi(\psi,r,\underline{w}) = h\left[\beta_0\frac{r}{R_0} + (1-\beta_0)\frac{R_0}{r}\right](1-\psi^{\alpha_m})^{\alpha_n}$$

- Galerkin FEM, 2nd order nodal basis function

$$A_{ij} = \int_\Omega \frac{\nabla\lambda_i\cdot\nabla\lambda_j}{r}dS;\quad g_i = \int_\Omega \mu_0 j_\varphi(\psi,r,\underline{w})\lambda_i dS$$

The $\widehat{hat}$ indicates boundary nodes of $\Omega$.

**Plasma** → 2D, non-linear, static

$$\underline{\underline{A}}\,\underline{\psi} = \left(\underline{I} - \underline{\underline{\hat{A}}}\,\underline{\underline{K}}\right)\underline{g}(\underline{\psi}) - \underline{\underline{\hat{A}}}\,\underline{\hat{\psi}}_e$$

Newton-Raphson Method

$$\left(\underline{\underline{R}} + \underline{\underline{L}}\frac{d}{dt}\right)\underline{I} + \underline{N}_{tor}\frac{d}{dt}\phi_{tor} + \underline{\underline{M}}\frac{d}{dt}\underline{I}_{eq} = \mathbf{0}$$

$$Q_{ie} = \frac{1}{2\pi}\int_{\gamma_{tor,i}} rA_\varphi\Big|_e d\ell$$

Toroidal average!

$$\underline{\hat{\psi}}_e = \underline{\hat{\psi}}_{act} + \underline{\underline{Q}}\,\underline{I}$$

Implicit Euler Scheme

$$\phi_{tor} = \int_\Omega (f/r)dS$$

$$\underline{I}_{eq} = \underline{\underline{S}}\,\underline{g}$$

$$M_{ei} = \int_{V_C} \boldsymbol{A}_{fil,i}\cdot\nabla\times\boldsymbol{N}_e dV$$

$$N_{tor,e} = \int_{V_C} \boldsymbol{A}_{pl}^{pol}\cdot\nabla\times\boldsymbol{N}_e dV$$

**Conductors** → 3D, linear, dynamic

- Integral $\boldsymbol{T}-\Omega$ formulation

$$\boldsymbol{j} = \nabla\times\boldsymbol{T} \text{ in } V_C$$

- Galerkin FEM with Edge Element basis functions:

$$\boldsymbol{T} = \sum_{e=1}^{N_{edge}} I_e\,\boldsymbol{N}_e$$

- 2-component gauge ↔ tree-cotree decomposition
- Additional d.o.f. due to multiple connected domain

***Physical idea of the degrees of freedom:***

$$\int_S \boldsymbol{j}\cdot\hat{\boldsymbol{n}}\,dS = \int_{+\partial S} \boldsymbol{T}\cdot\hat{\boldsymbol{t}}\,d\ell = \sum_{e\,\in\,+\partial S} I_e$$

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# Grad-Shafranov Equation

$$\nabla \times \vec{B} = \mu_0 \vec{j}$$
$$\nabla \cdot \vec{B} = 0$$

3

$$\vec{j} \times \vec{B} - \nabla p = 0$$

$$\psi = 2\pi r A_\varphi$$
$$I = \frac{2\pi r B_\varphi}{\mu_0}$$

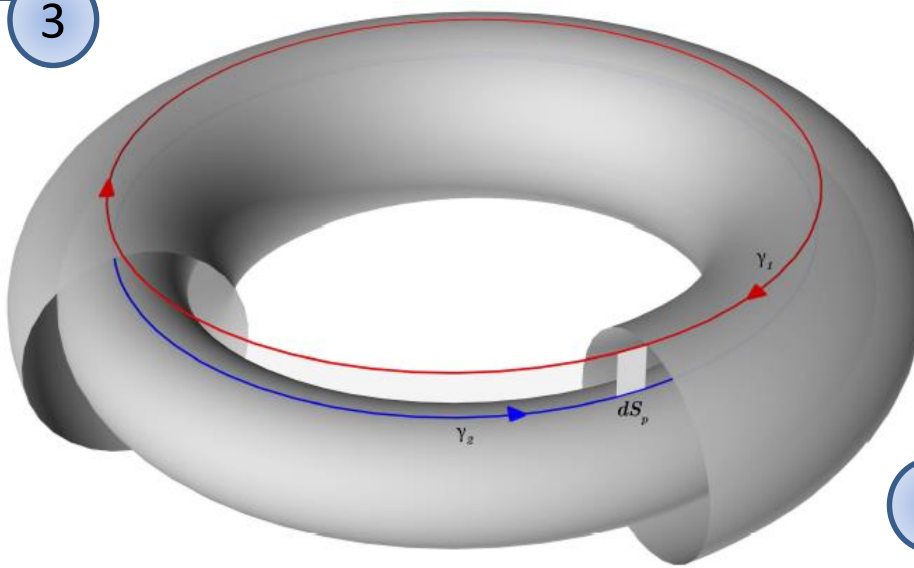
2

$$2\pi\vec{B} = \nabla\psi \times \nabla\varphi + \mu_0 I \nabla\varphi$$
$$2\pi\vec{j} = \nabla I \times \nabla\varphi - r^2\left(\nabla \cdot \frac{\nabla\psi}{\mu_0 r^2}\right)\nabla\varphi$$

$$\vec{B} \cdot \nabla p = 0$$
$$\vec{j} \cdot \nabla p = 0$$

1

$$p = p(\psi)$$
$$I = I(\psi)$$



1 2 3

$$-r\nabla \cdot \left(\frac{\nabla\psi}{2\pi\mu_0 r^2}\right) = 2\pi r\frac{dp}{d\psi} + \frac{\mu_0}{4\pi r}\frac{d}{d\psi}I^2$$