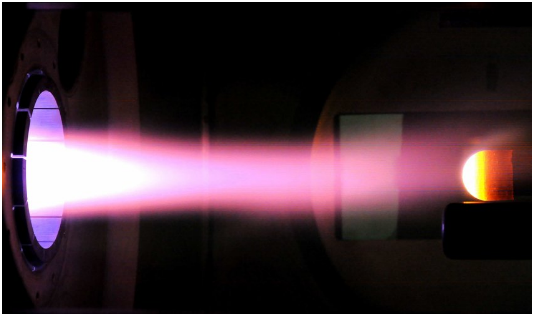
Development of a high-order solver for inductively coupled plasma



Corthouts Nicolas, Hillewaert Koen, May Georg, Magin Thierry

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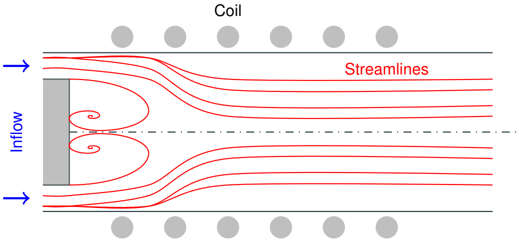
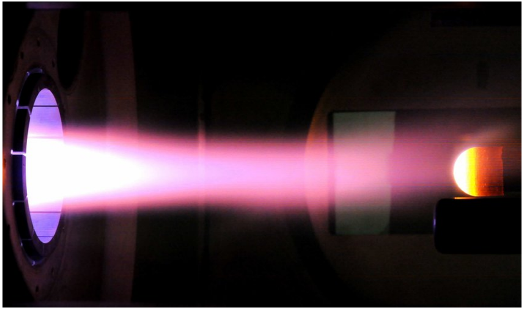
Context of research



Torch

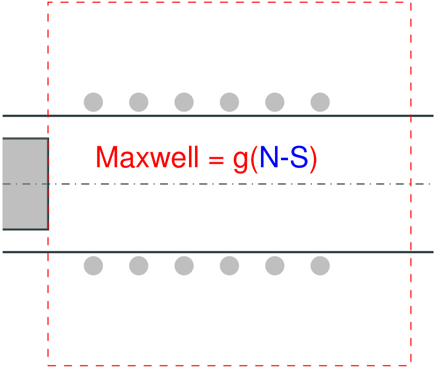


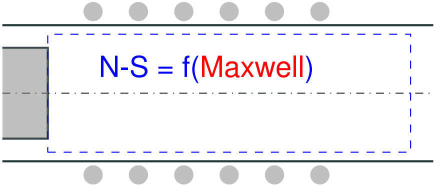
Test chamber

$$Re \sim 100 \quad Ma \sim 0.001 \quad \rho \simeq \rho(T).$$

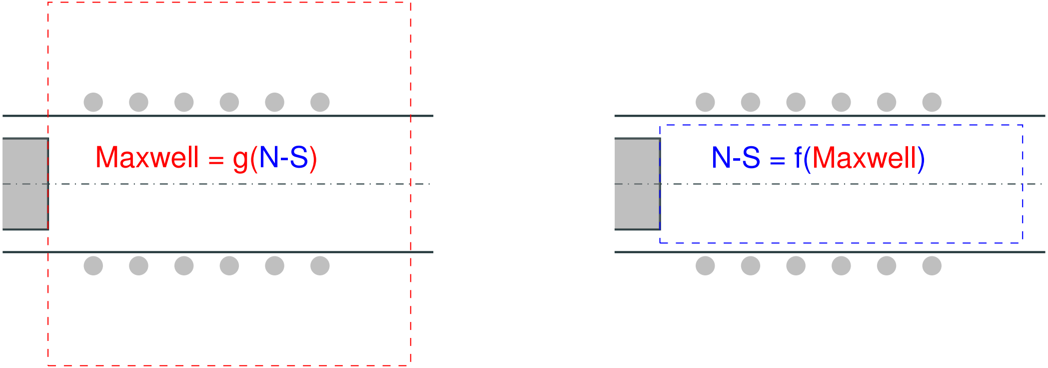
Goal: Simulation of **complex physics** with **less constraints on the mesh** + instabilities.

ICP: segregated approach of previous solvers





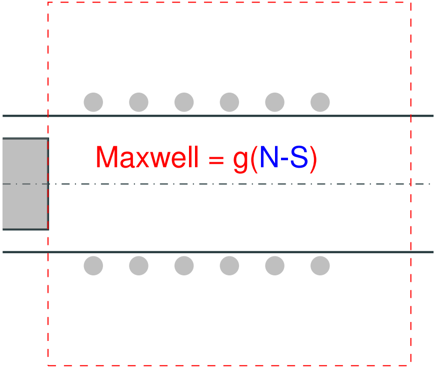
ICP: segregated approach of previous solvers

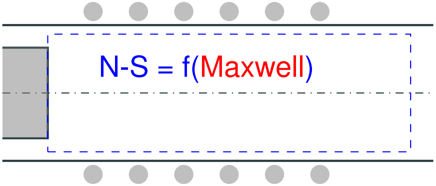


Pros

- It works (see Magin, 2004).
- Allows to freeze the electric field in unsteady simulations.

ICP: segregated approach of previous solvers





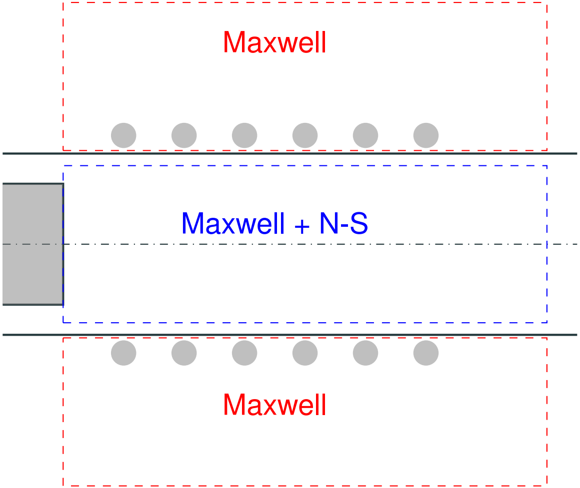
Pros

- It works (see Magin, 2004).
- Allows to freeze the electric field in unsteady simulations.

Cons

- Convergence can be hard to achieve (O(1000) iterations with COOLFluiD).

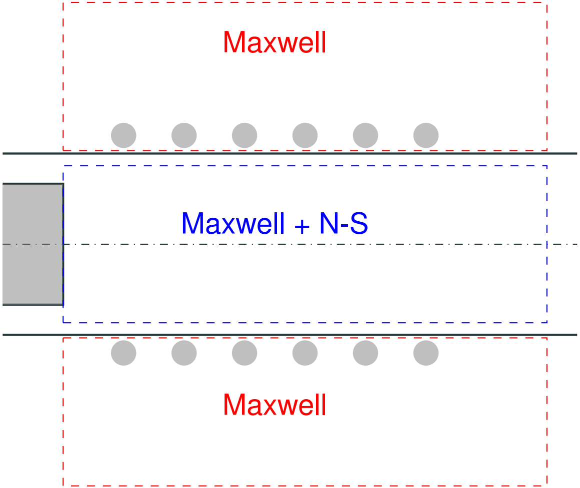
A multi-domain solver



Two approaches

- MONOLITHIC: system solved as a whole.
- COUPLED: two solvers that exchange interface data.

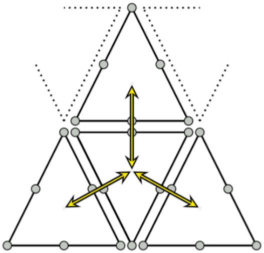
A multi-domain solver



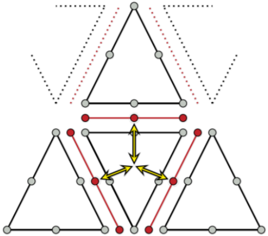
Two approaches

- **MONOLITHIC: system solved as a whole.**
- COUPLED: two solvers that exchange interface data.

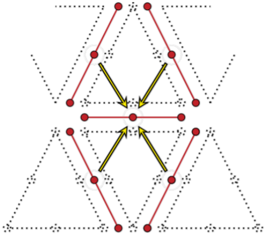
The numerical method: HDG



Classic DG.



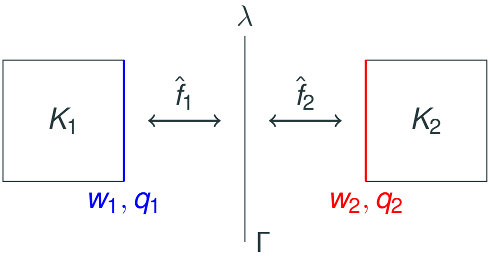
HDG: traces.



HDG: elements as transmitters.

1. **Local systems** of element size solved directly.
2. **A global system** smaller than the global DG system.

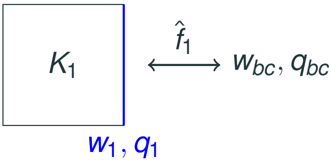
Multi-domain HDG



Weak Conservativity

$$\int_{\Gamma} \left[\hat{f}_1(w_1, q_1, n_1) + \hat{f}_2(w_2, q_2, n_2) \right] \mu dS = 0.$$

Multi-domain HDG



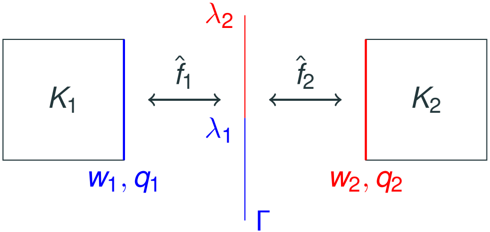
Weak Conservativity

$$\int_\Gamma \left[\hat{f}_1(w_1, q_1, n_1) + \hat{f}_2(w_2, q_2, n_2)\right] \mu dS = 0.$$

Weak imposition of BC

$$\hat{f}_1 = \hat{f}_1(w_1, q_1, w_{bc}, q_{bc})$$

Multi-domain HDG



Weak Conservativity

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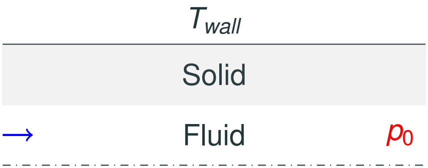
Weak imposition of BC

$$\hat{f}_1 = \hat{f}_1(w_1, q_1, w_{bc}, q_{bc})$$

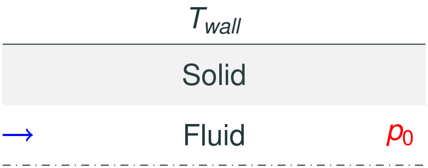
Weak Kinematic Conditions

$$\int_\Gamma \mathcal{F}(\lambda_1, \lambda_2) \mu dS = 0$$

Application: Conjugate heat transfer



Application: Conjugate heat transfer



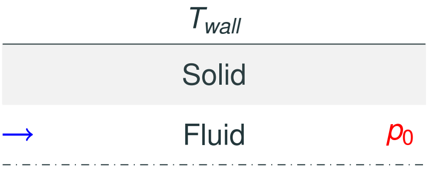
Interface conditions

$$T^f = T^s$$

$$k_f \nabla T^f = k_s \nabla T^s$$

$\mu(T), k(T)$ + axisymm.

Application: Conjugate heat transfer



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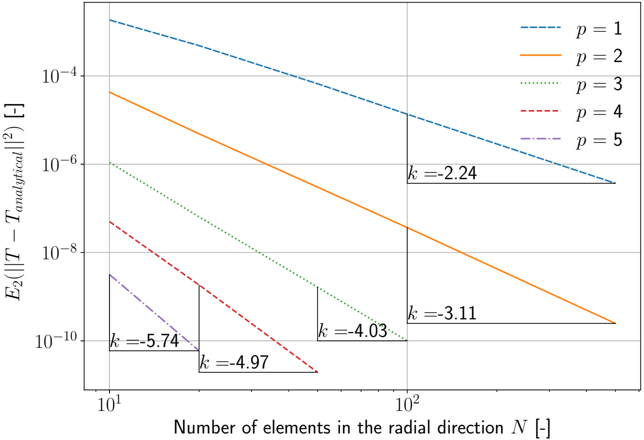
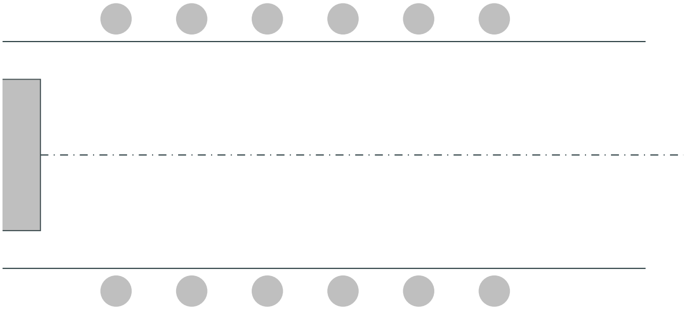


ICP: many challenges



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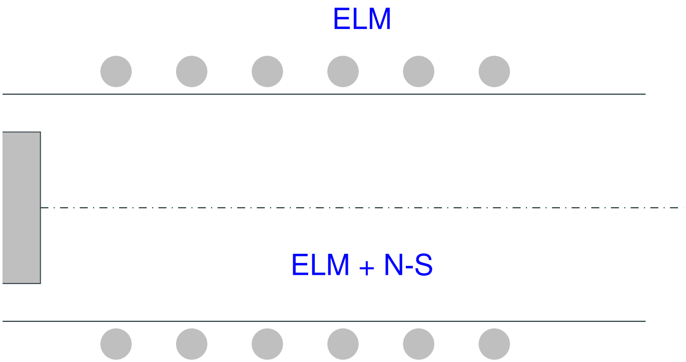

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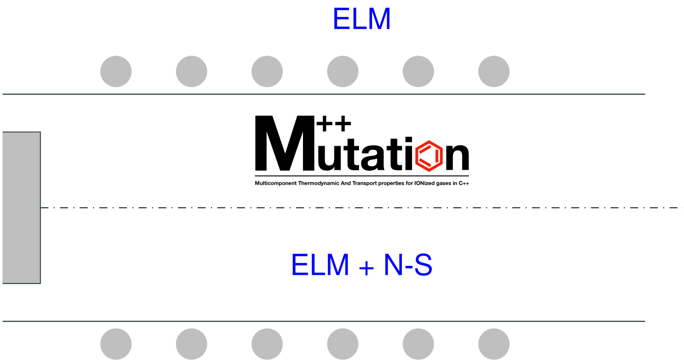

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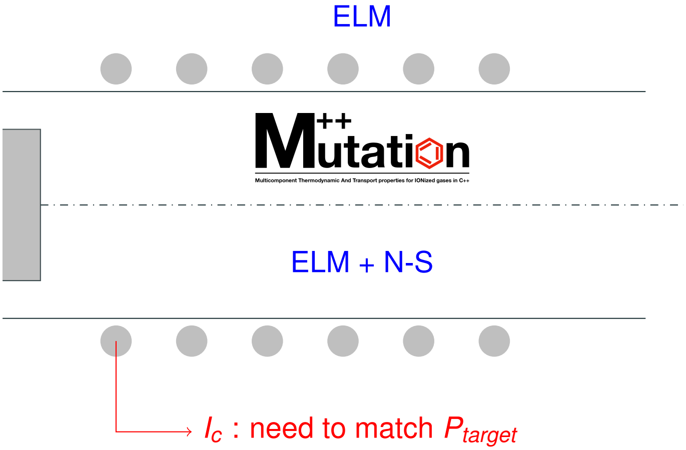
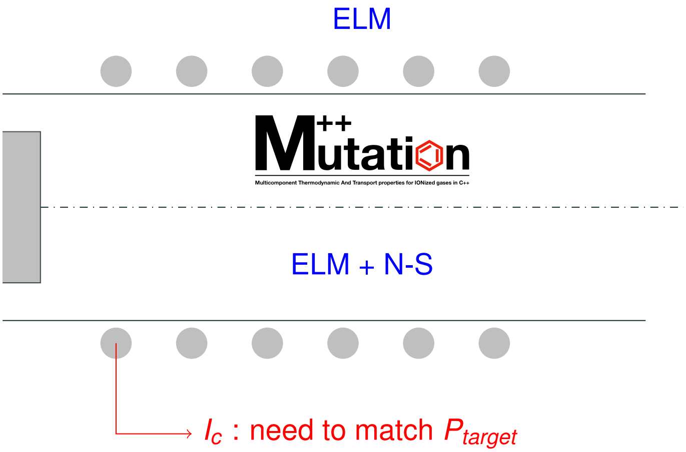


ICP: many challenges

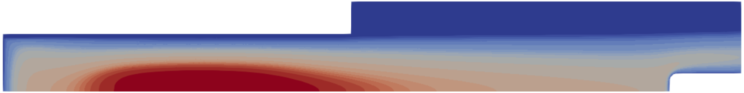


AUSM numerical flux + low-mach preconditioning (Magin 2004) and Damped Newton-Raphson method.

Application to ICP: Qualitative results

Application to ICP: Qualitative results

Temperature profile

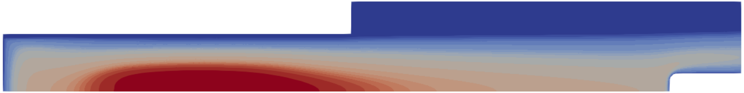


$T_{min} = 350$ K

$T_{max} = 11000$ K

Application to ICP: Qualitative results

Temperature profile



$T_{min} = 350$ K
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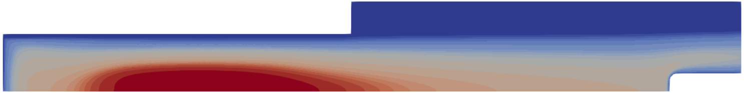
Electric field profile

$E_{min} = 0$ V
$E_{max} = 3650$ V

Application to ICP: Qualitative results

Temperature profile



$T_{min} = 350$ K
$T_{max} = 11000$ K

Electric field profile

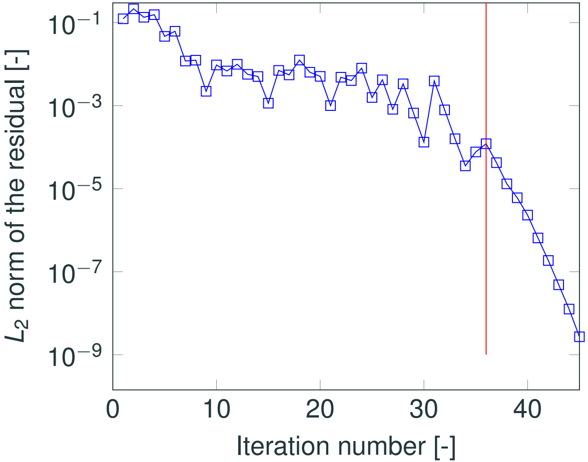
$E_{min} = 0$ V
$E_{max} = 3650$ V

Power dissipated in the facility

$P_{min} = 0$ W/m^3
$P_{max} = 10^{11}$ W/m^3

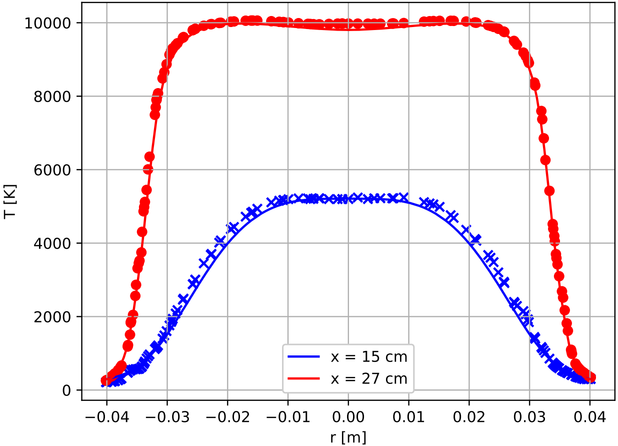
Convergence history

- Damped inexact Newton-Raphson + GMRES(50)-ILU.
- Current adaptation to match dissipated power.



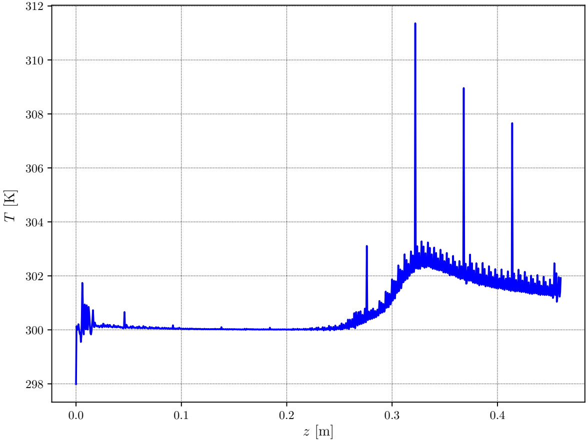
Application to ICP: quantitative results for the mini-torch

Comparison with results of previous ICP code (AUSM flux, $p = 2$, swirl = 45°).



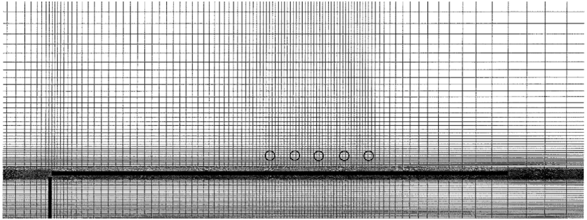
Application to ICP: oscillations near the wall

Temperature oscillations in the near wall region.

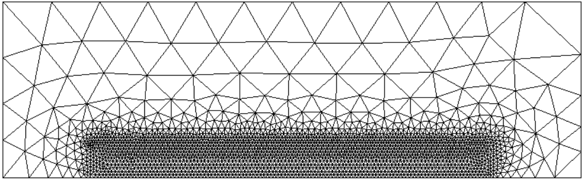


ICP: mesh comparison

FV mesh



ICP mesh



Conclusions and future work

- A versatile tool has been implemented in the HDG code.
- Works on unstructured mesh.
- High-order ICP simulations are now possible.
- Possibility of extending to various physical situation.
- High order methods are prone to oscillations. We are working on them.

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Hybridized Discontinuous Galerkin Method for Multiphysics Problems: Application to Inductively Coupled Plasmas

Nicolas Corthouts, Koen Hillewaert, Georg May and Thierry Magin

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Abstract:

This paper presents one of the first high-order simulations of inductively coupled plasma (ICP). First, a multi-domain solver using a variant of discontinuous Galerkin method, called the hybridized discontinuous Galerkin method, is developed. This multi-domain solver is verified on an analytical conjugate heat transfer problem, showing that the order

Orlando, FL

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