Numerical modeling of plasma actuators and application to flow control

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ONERA
THE FRENCH AEROSPACE LAB

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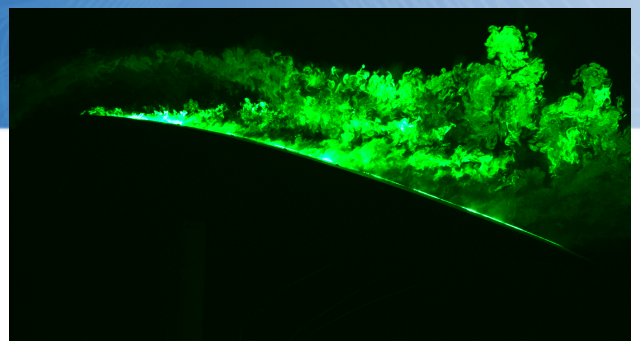
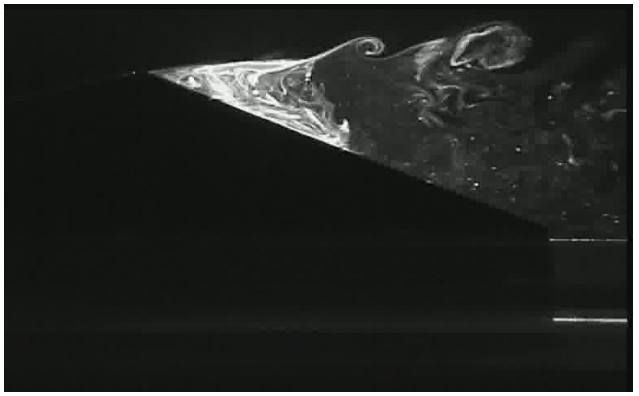
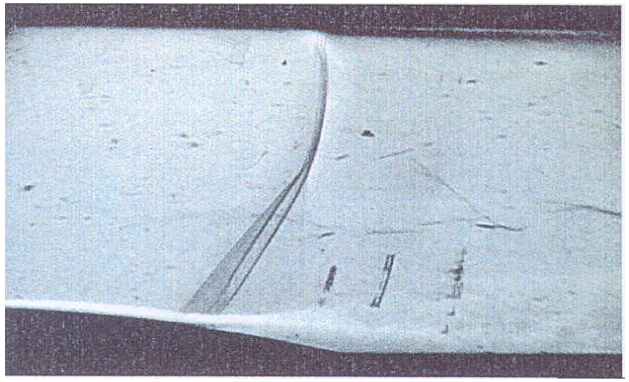
Motivations and last works



- Possibility of generating a gas flow with an electric discharge: Electro Hydrodynamic effect
- Research of EHD effects to modify aerodynamic profile:
  - Control the laminar-turbulent transition (*Shcherbakov (Russia), Colver (USA), Opaits (Russia))*
  - Reduce the drag (*Kazakov (Russia*), Kuo Bivolaru, Knight
  - Stabilize the flow (*Roth (USA), Moreau (France), Corke (USA))*
- Others applications :
  - Magnetohydrodynamic control of hypersonic flows
  - Electromagnetic absorbers



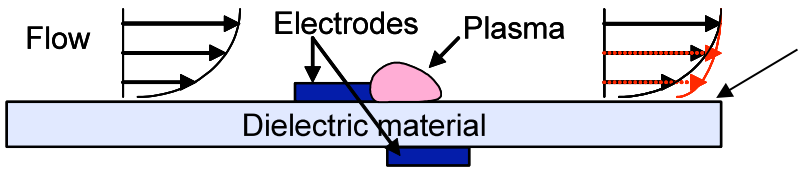


Outline

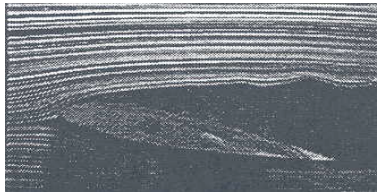
- Motivations
- Surfaces discharges modeling: Corona, Dielectric barrier
- Arc actuator : plasma synthetic jet
- Laser induced plasma for supersonic flow drag reduction
- Conclusion

Surface plasmas Actuator

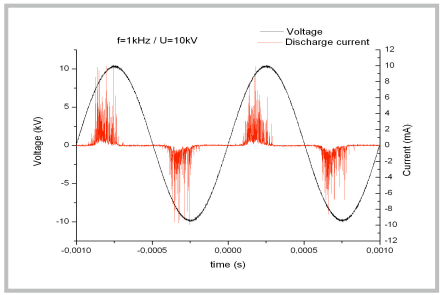
Dielectric Barrier Discharge (DBD)

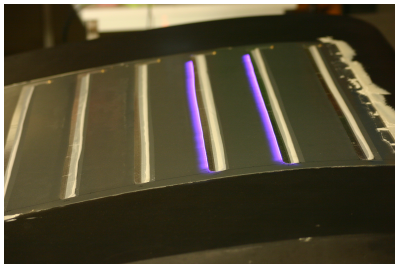


ionic wind
close to the wall

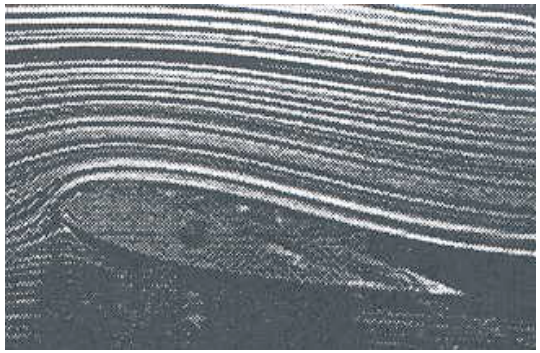


U: 20 – 30 kV
I: 10 à 20mA
f : 500 à 2000 Hz



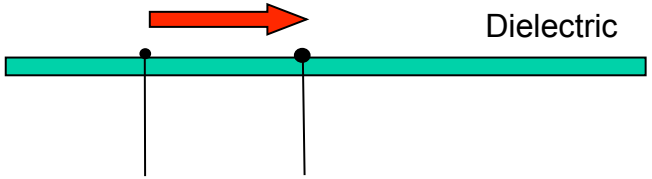


Plasma off



→ *alternating power supply*

Corona Discharge (DC)



Plasma on

U ionic wind up to 8m/s

→ *Continue power supply*

Plasma/flow modelling

- **Non equilibrium plasma (Te~1eV,T+=T_-=Tgas)**
- **Mass conservation with Ohm's law**
- **Simplified air kinetic modeling**
- **Interaction with electrode and dielectric : electronic secondary emission, surface charging**

Global fluid momentum:

$$\rho\left(\frac{\partial U^i}{\partial t} + U^j \frac{\partial U^i}{\partial x^j}\right) = -\frac{\partial P}{\partial x^i} + \mu \frac{\partial^2 U^i}{\partial x^j \partial x^j} + F$$

Specie densities:

$$\left(\frac{\partial n_k}{\partial t} + \frac{\partial n_k U_k^i}{\partial x^i}\right) = \dot{\omega}_k$$

Ions velocity:

$$U^i_{k \neq e^-} = U^i \pm \mu_k E^i$$

Electrons velocity:

$$U^i_e = U^i - \mu_e E^i + \frac{D_e}{n_e}\frac{\partial n_e}{\partial x^i}$$

Electric field:

$$\frac{\partial E^i}{\partial x^i} = \frac{\rho_{ch}}{\varepsilon_0} + \frac{\sigma_S}{\varepsilon_0}\delta$$

→ Time scale from ps to to ms

ONERA

Plasma/flow modelling

Air kinetic : ionization, attachment, recombination,…

Reactions	Reactants	Products	Effects
Ionisation	N_2, e^- O_2, e^-	N_2^+, e^-, e^- O_2^+, e^-, e^-	Electron avalanche
Photoionisation	N_2, h^ν O_2, h^ν	N_2^+, e^- O_2^+, e^-	Electron avalanche
Electronic attachment	O_2, e	O_2^-	Negative ions formation
Recombination	N_2^+, e^- O_2^+, e^- O_2^+, O_2^- N_2^+, O_2^-	N_2 O_2 O_2, O_2 N_2, O_2	Charged particles losses
Excitation	O_2, e	O_2^*	
Electronic detachment	O_2^-, O_2^*	O_2, O_2, e^-	Electron formation
Quenching	O_2, O_2^*	O_2, O_2	

Only non neutral region of the discharge are active (sheath or drift zones)=> EHD force depends on the local charge space

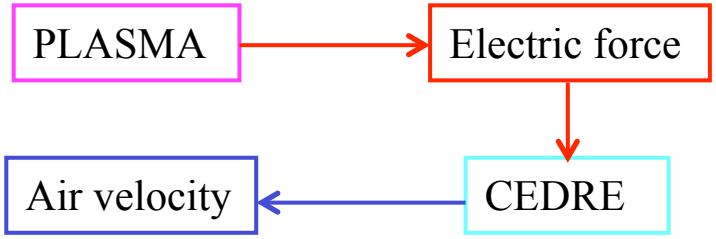
$$F \approx (n_+ - n_-)eE$$

Corona and DBD are similar:
They generate a EHD force significant in the non neutral region
The flow induced is called ionic wind

Numerical modelling of surfaces discharges

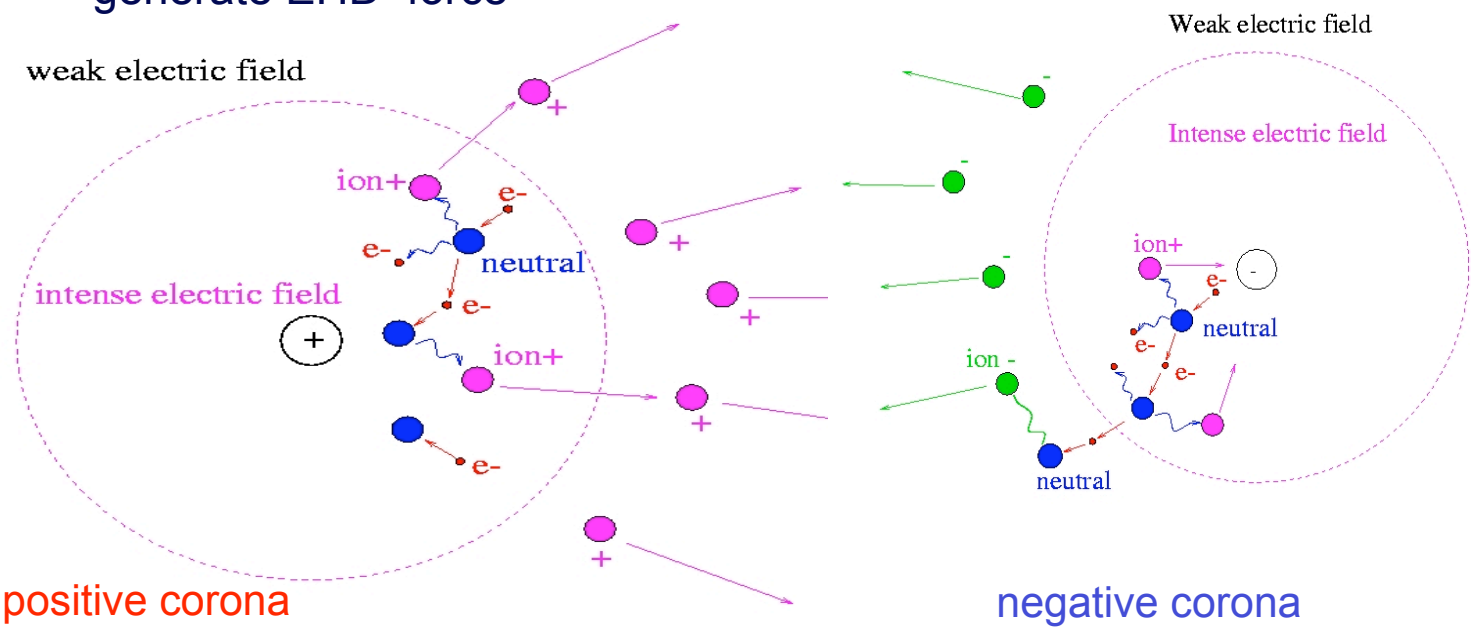
- **Plasma Solver**
  - Simplified air plasma kinetic model (derive diffusion model)
  - Explicit finite volume method for species discretization,
  - Time integration by a 2-steps Runge-Kutta method,
  - Flux corrected method MUSCL,
  - PCG algorithm for electric field calculation.

- **Plasma - Aerodynamics: 1 way coupling model**
  - Time scale of discharge 10^{-6} s < Time scale of aerodynamics 10^{-3} s
  - Aerodynamics code:
    - CEDRE (NS solver, ONERA code for fluid mechanics)
  - Way of chaining the two codes:



Corona
discharge scenario

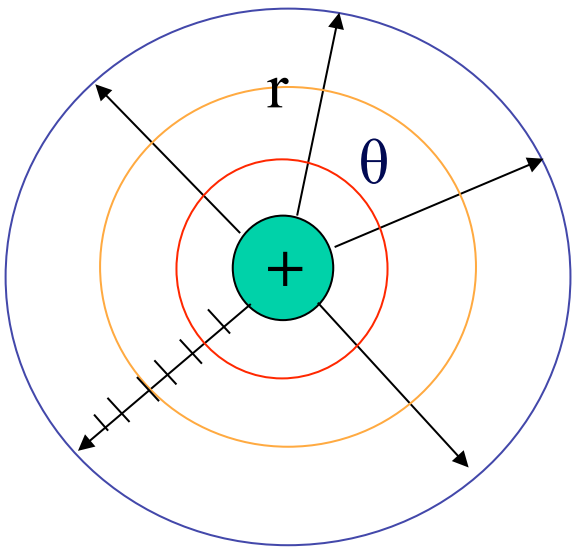
- **How they work**
  - Large electric field :
    - Cathode : electrons avalanche ⇒ attachment ⇒ion-
    - Anode : electrons avalanche ⇒ ionization ⇒ion+
  - ions drift to the electrodes =>exchange momentum to neutral=>generate EHD force
  - Secondary electrons emission occurs at cathode=> e attach to neutral => ions- => generate EHD force



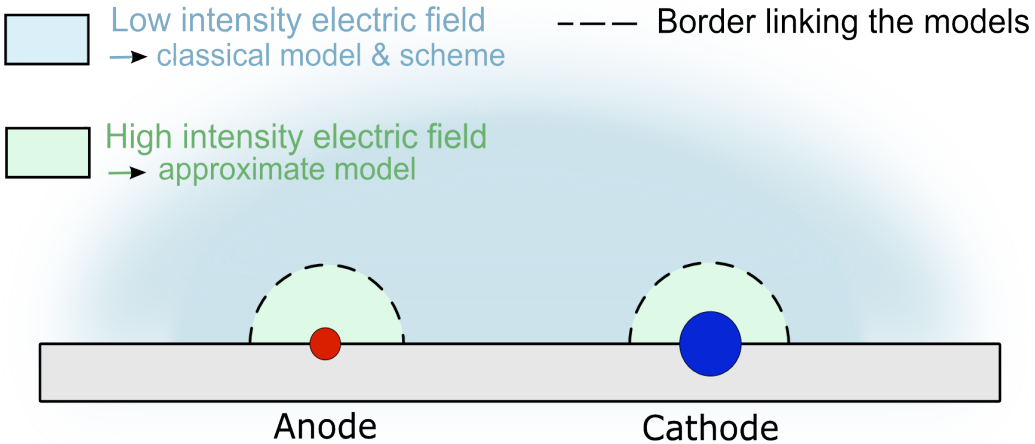
Corona
Numerical modelling : a domain decomposition method

Dealing with the multiscale aspects :

- Electric field is a radial function close to the stressed electrode
- Fine mesh is required in the intense field region -> use of local radial mesh is useful
- Asymptotic expansion ->reduce the CPU in the anode region
- Intermediate region is computed with the full model and is coupled with electrode region with appropriate B.C.



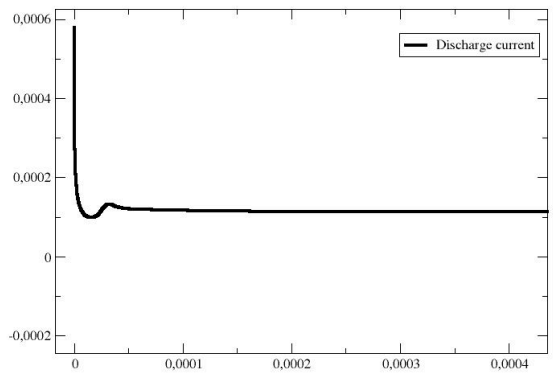
Region of the positive corona



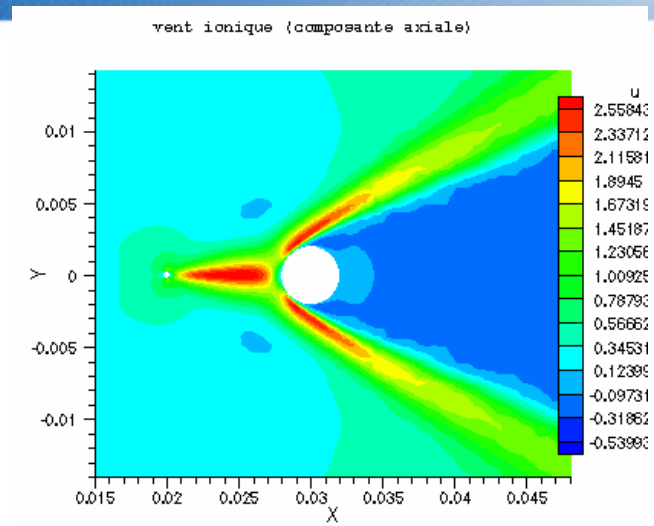
Extension of the method to any electrode shape: tip plane, …

Math. Comp. Mod: Seimandi, Rogier, Dufour (2009)

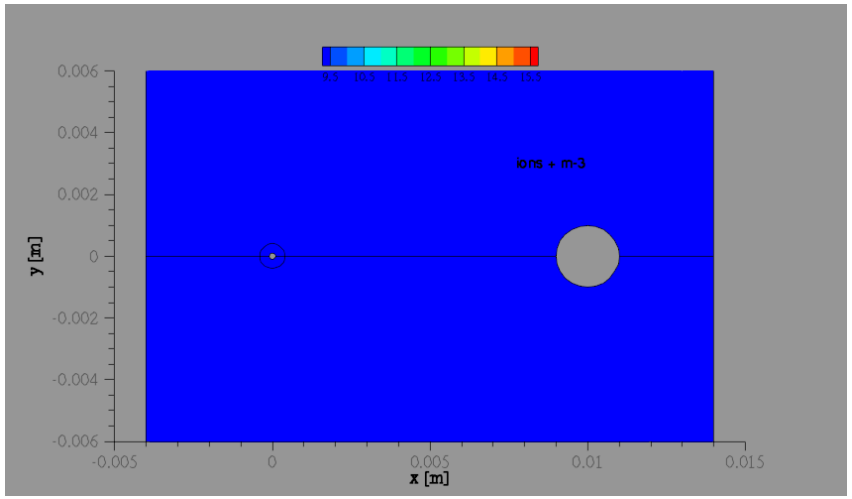
Corona discharges:
13kV, 1cm, r-anode=0.1mm, r-cathode=1mm (Bérard & all)



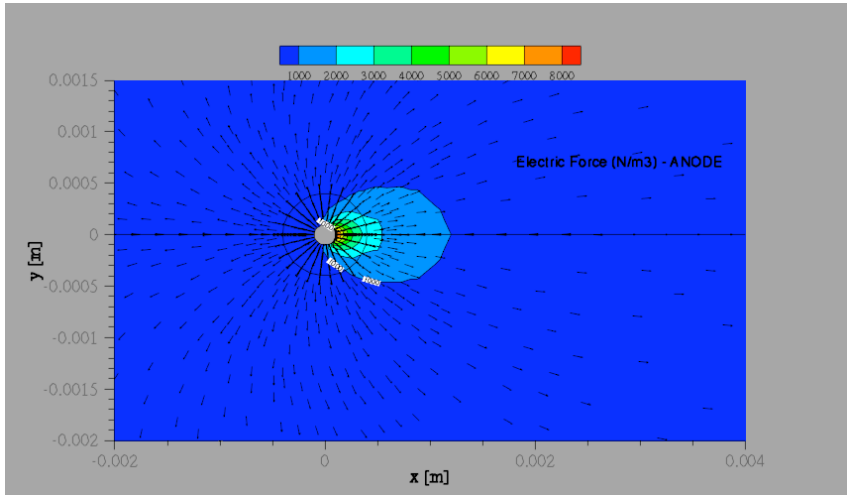
Current discharge



Ionic wind calculated with CEDRE



Isocontours :Ions +



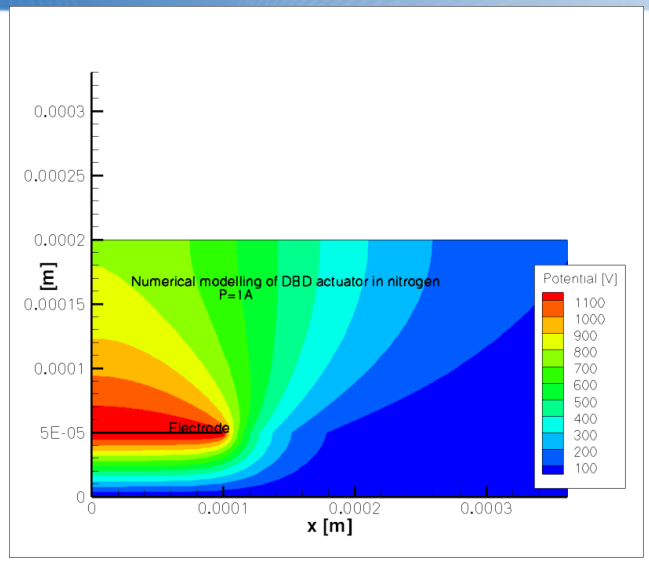
Isocontours :force

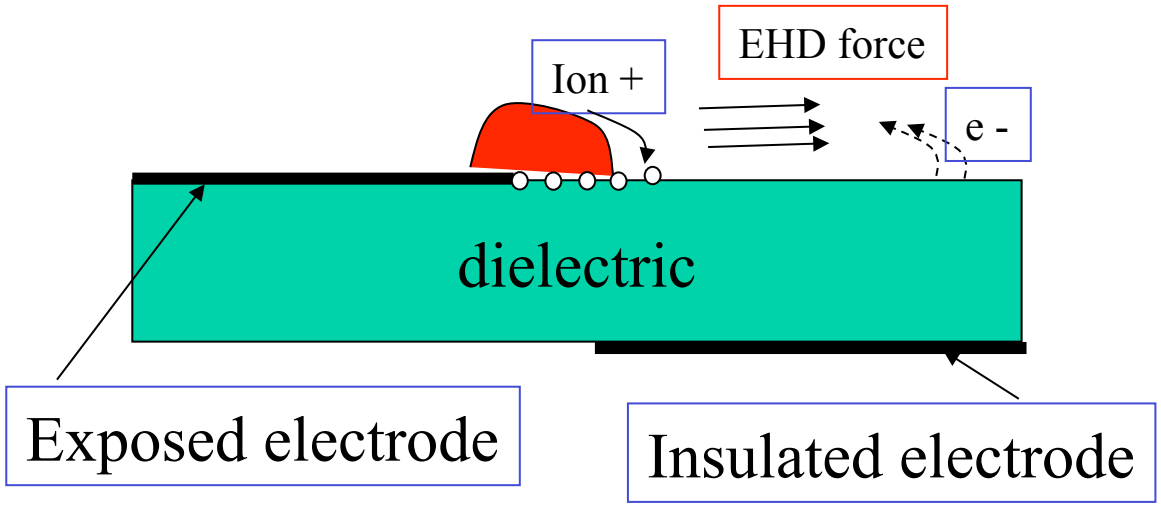
20% relative error with PIV measurements

DBD : mechanism of the discharge (for constant voltage)

discharge scenario (Boeuf,Pitchford 2005)

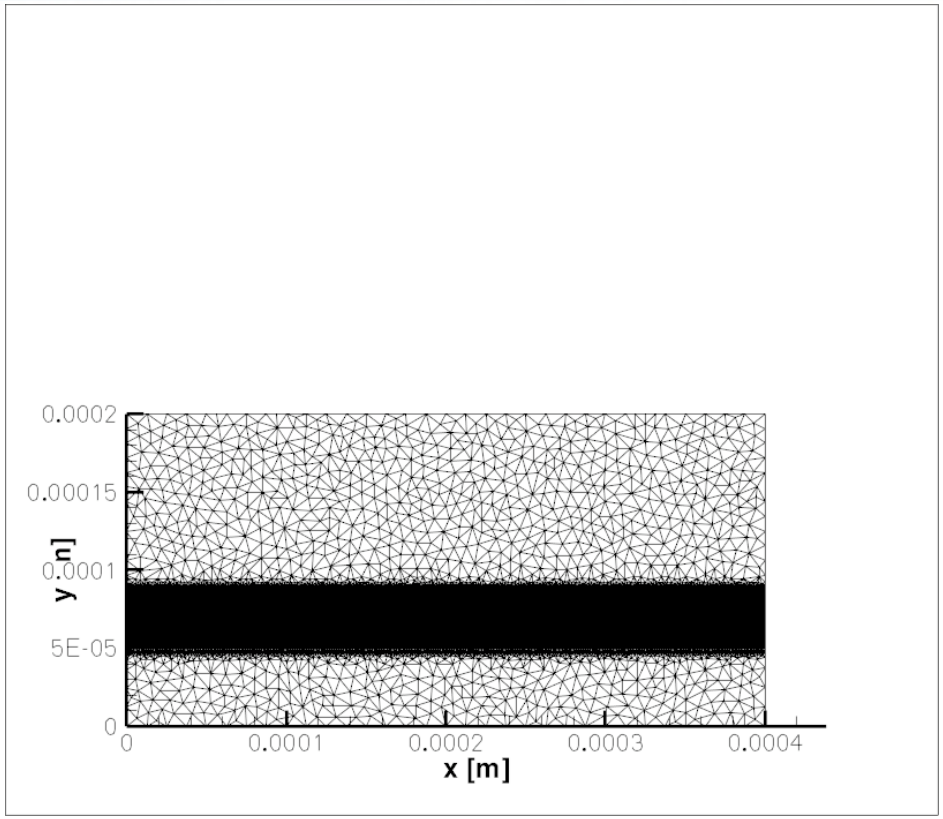
- **Large electric field=>breakdown**
- **Secondary electrons emission occurs Ions+ move to the dielectric and charge the surface**
- **Charge surface change the potential near the plasma**
- **A positive space charge sheath is created ahead the plasma => large parallel EHD force**



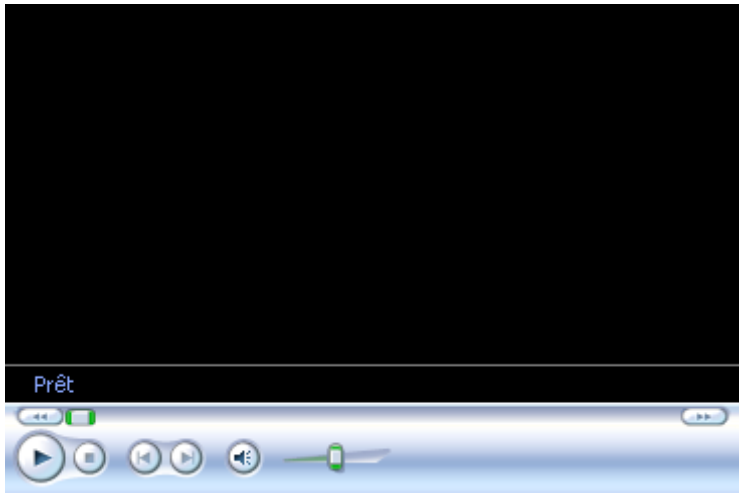


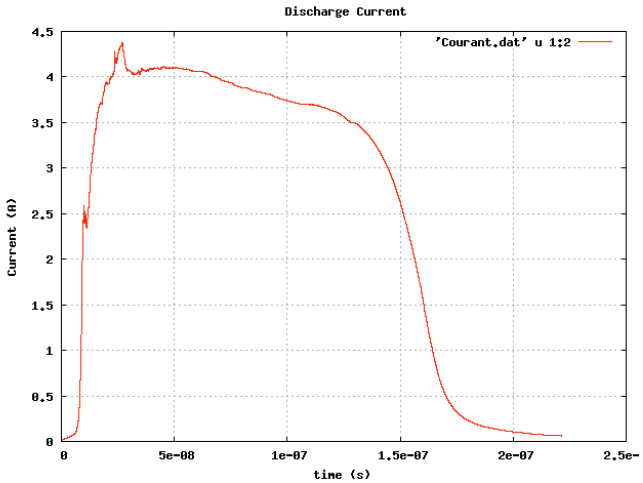
DBD : Numerical modelling

- **High multiscale problem**
  - **Mesh size ~µm / characteristic length ~0.5mm**
  - **Step time ~ 0.1ps / time 100 ns**
- **Improvements of numerical methods**
  - **Local time stepping (T.Unfer, J.P Boeuf, F. Rogier and F. Thivet, JCP 2009)**



Numerical modelling of DBD results in nitrogen V=1.2kV

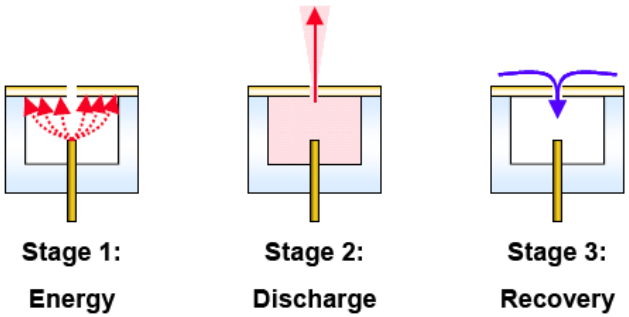


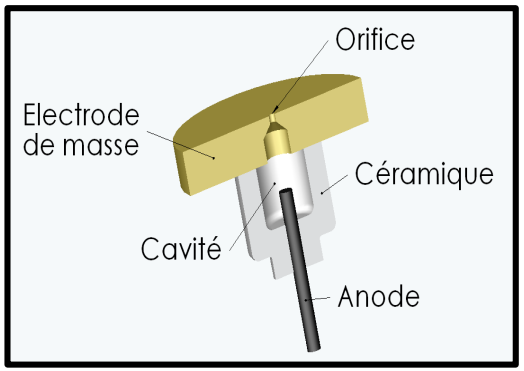


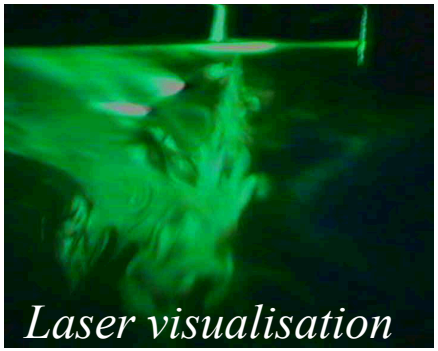
Arc Plasma Actuators

Synthetic Jet by Plasma (PSJ):

Concept of John Hopkins University







Characteristic values :

Geometrical :

- orifice ~0.5 mm
- volume ~8 mm^3

Electrical

- Voltage: 3 to 5000 Volts
- Current: 100 to 250 A

V up to 250m/s (T=1200K)
f up to 2000 Hertz

Modelling objectives

- ***Fine experimental measurements are difficult to perform:***
  - Hot wire : large temperature at the exhaust (>1000K) ?
  - PIV : Difficulty to measure the velocity at the core (shear flow)
  - Spectroscopy : Complexity of air spectrum
  - No measurement inside the cavity (small size)

- ***Available experimental results:***
  - Front jet velocity (ONERA), PIV measurements (J Hopkins)
  - Medium temperature of the arc (LAPLACE)
  - Electrical measurements (LAPLACE)

- ***Numerical modelling:***
  - helps to understand which mechanism of energy transfer are important
  - provides accurate information in areas where no measurements is possible
  - gives trends of actuators performances / geometry, voltage, frequency...

ONERA

Modelling arc actuator

Thermodynamical approach

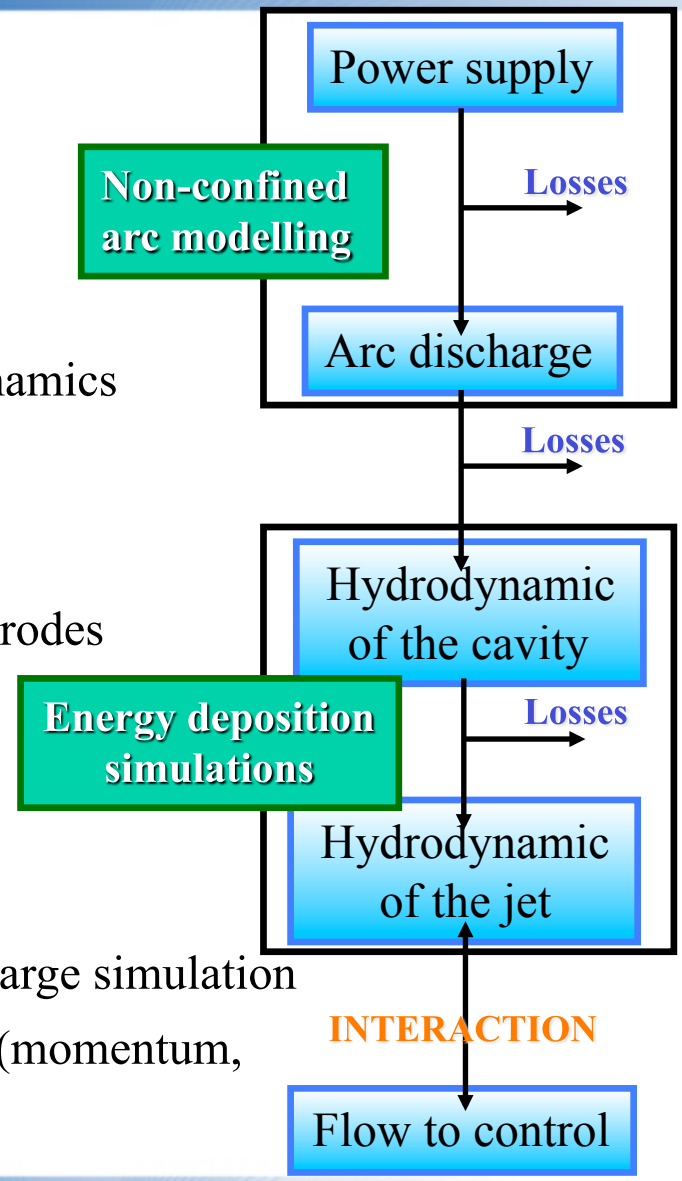
- Energy deposition profiles
- Localization of the energy deposition
- **Real gas effects**
- Modelling the interaction of the arc with the fluid dynamics

Understanding the discharge development

- Non-confined geometries (2D axisymmetric)
- Better understanding of the interactions with the electrodes
- Taking into account radiative transfers
- **Coupling with the external electrical circuit**

Providing realistic inputs for CFD simulations

- Energy deposition models based on detailed arc discharge simulation
- Boundary conditions CFD simulating the JSP effects (momentum, energy, etc.)



Arc modelling

Model description :

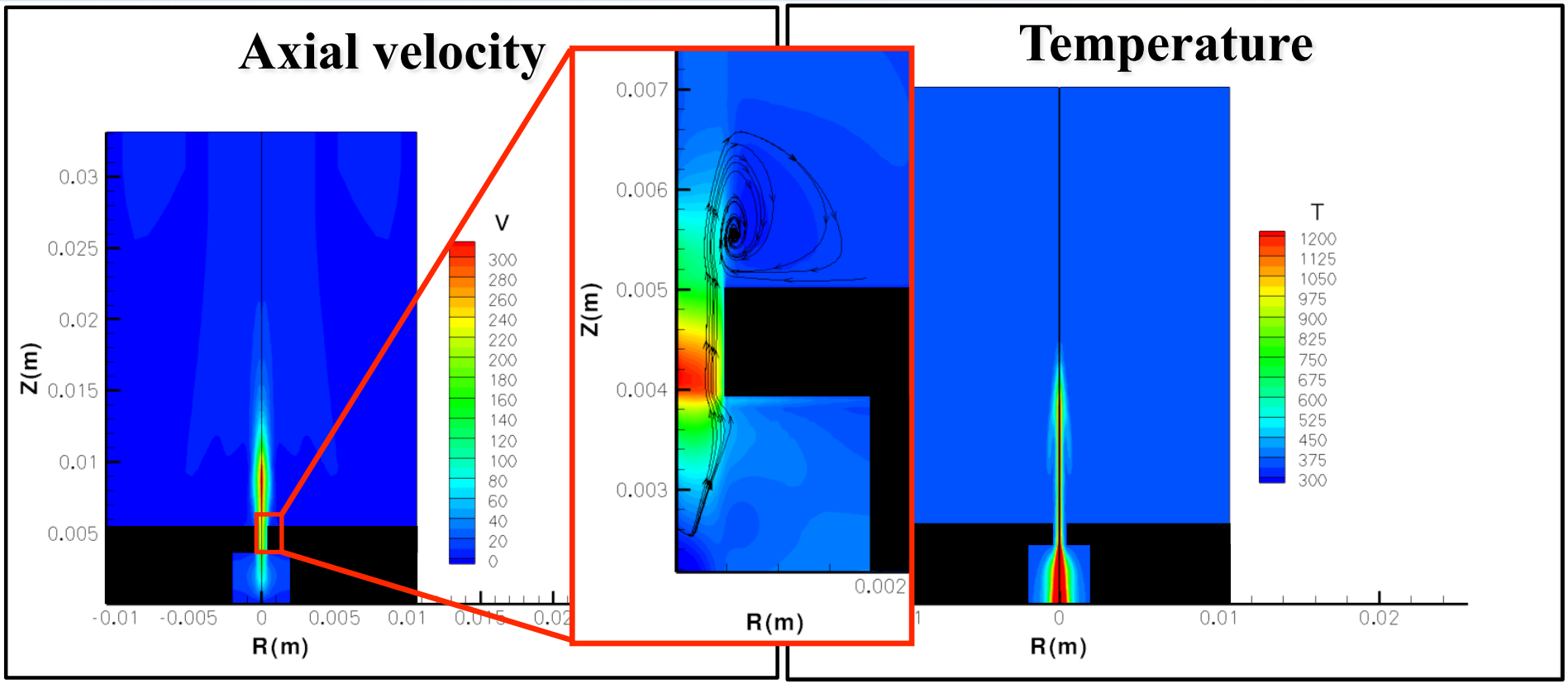
• Main assumptions : LTE, Euler equations, Real gas law=>electric conductivity of the plasma depending on the temperature (d'Angola & all)

• The initial condition is given by a Gaussian temperature law describing the arc state in the first microseconds.

• Coupling with an external electrical circuit : Electric field computed according to the current conservation law, Joule effect obtained through an equivalent resistance, sheath voltage drops reduce the electric field.

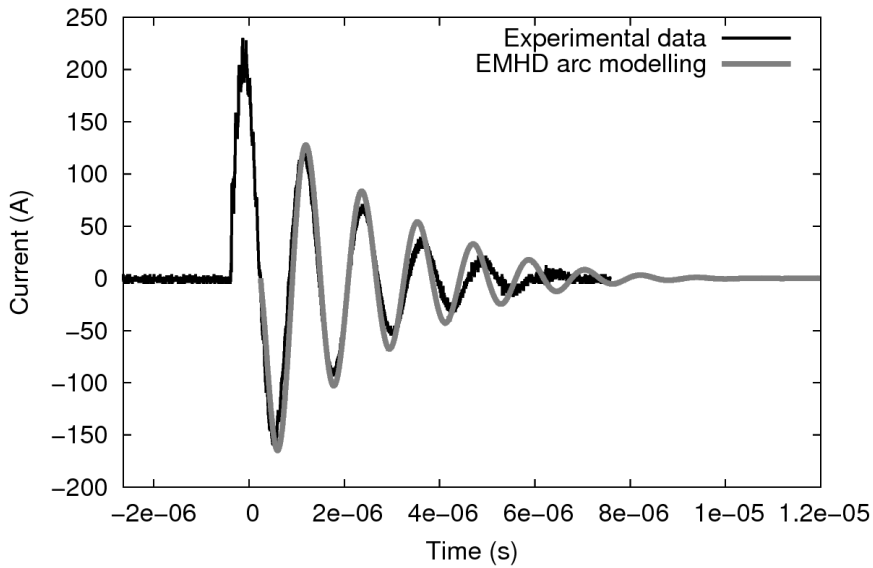
• Radiative transfer modelling (Gleizes *et al*.)

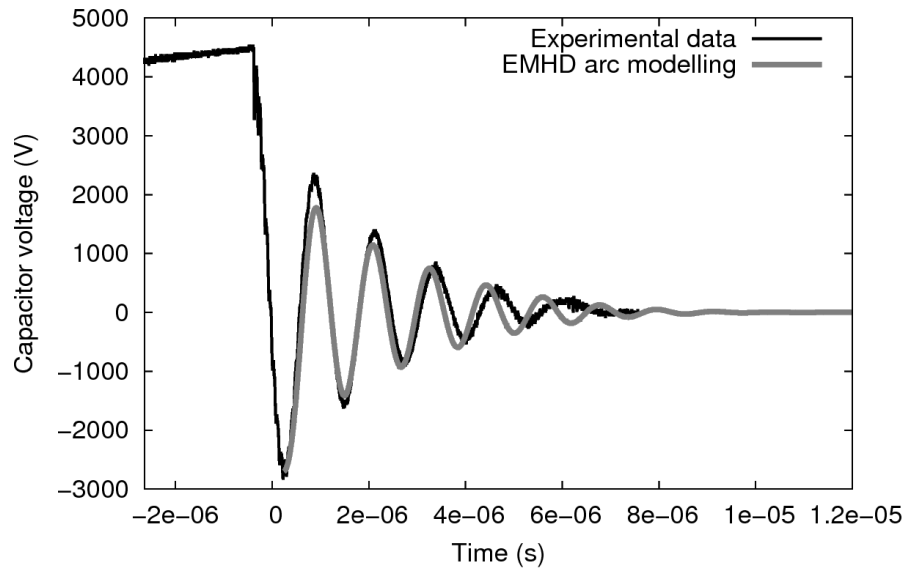
Thermodynamical Approach – Localized energy deposition



- Important front jet velocity (up to **250 m.s^{-1}**)
- Temperature of the arc region remains large, but increases also at the exhaust (jet temperature about **1,200 K**) : the ejected gas is hot.
- **Pressure reflexions** at the walls generate velocity oscillations – although the JSP nozzle is not represented.

Discharge development
- Comparisons with electrical experimental values





- **Good reprensation of the real power supply** thanks to the coupling of the arc with the simplified RLC circuit.

- When the arc resistance becomes important (after 3.5 µs), the model deviates slightly from the experimental data in frequency and in amplitude.

Conclusions

Two simulations have been performed

• ***by an energy deposition modelling inside JSP cavity*** (localization and real gas law)

⇒Provides **quantitative information** on the jet characteristics: mass flow rate, thermal flux, impulsion,..

⇒ Provides **qualitative information**: hot jet, pressure oscillations and long thermal diffusion characteristic time

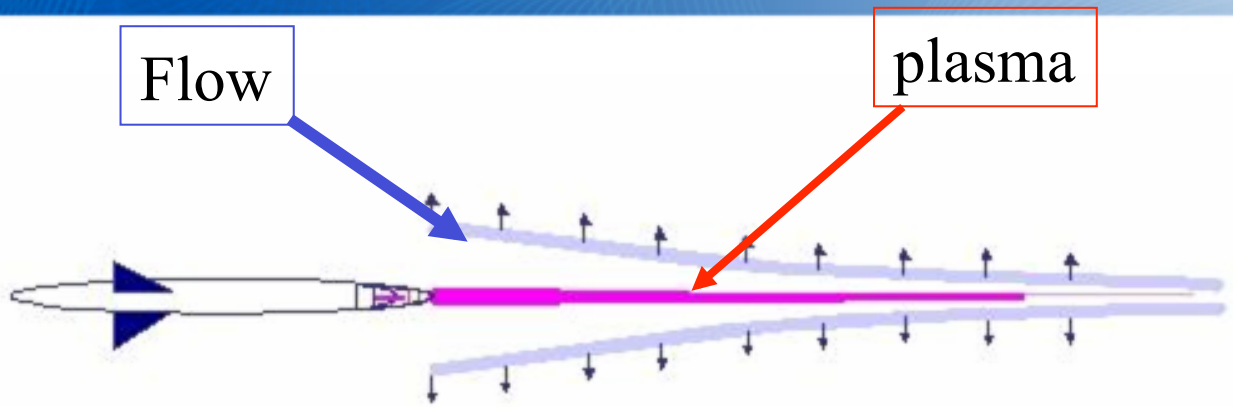
• ***Detailed model of the arc development:***

⇒Electric sheaths and radiative transfer play an important role in the energy dissipation mechanism

⇒Natural convection inside the cavity, long arc thermal diffusion times

⇒ Numerical results compare well with experiments (discharge current, voltage)

Numerical Modelling of supersonic flow actuated by laser-induced plasma



Experiments have shown that in presence of a structural aerodynamic spike, the bow shock past a body is modified and the drag is significantly reduced. The studied device aims to replace the structural spike by a virtual one created by a laser induced plasma.

The objective is to produce a low- pressure channel ahead of the body in order to increase the penetration of the body in air. .

Numerical Modelling

Plasma/flow modelling:

- **Plasma quasineutral**
- **Ambipolar diffusion**
- **Ionisation and two and three body recombination**
- **Thermodynamical non equilibrium with gas**

$$\begin{cases} \partial_t n_e + \nabla.(n_e v_e) = S_e^{Mass} \\ v_e = v - D_a \dfrac{\nabla n_e}{n_e} \\ \partial_t p_e + \nabla.(\dfrac{5}{3} p_e v_e) - \nabla.(\dfrac{2}{3} \lambda_e \nabla T_e) = \dfrac{2}{3} S_e^{NRJ} \end{cases}$$

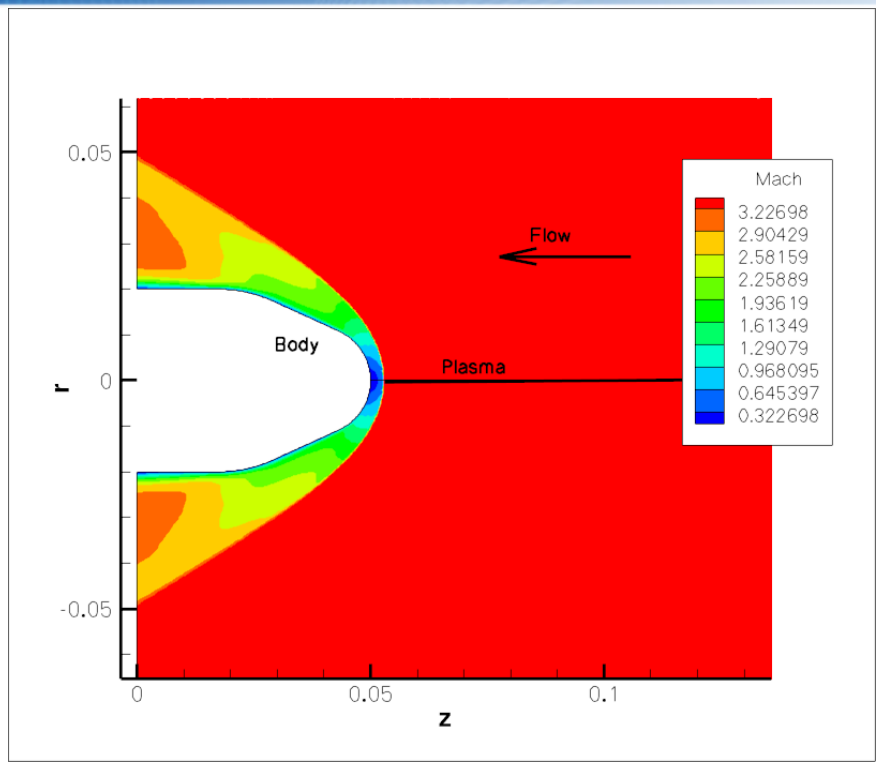
$$\Updownarrow$$

$$\begin{cases} \partial_t n + \nabla.(nv) = 0 \\ \partial_t nv + \nabla.(nv \times v) + \nabla p = S^{Mov} \\ \partial_t p + \nabla.(\dfrac{7}{5} pv) = \dfrac{2}{5} S^{NRJ} \end{cases}$$

ONERA

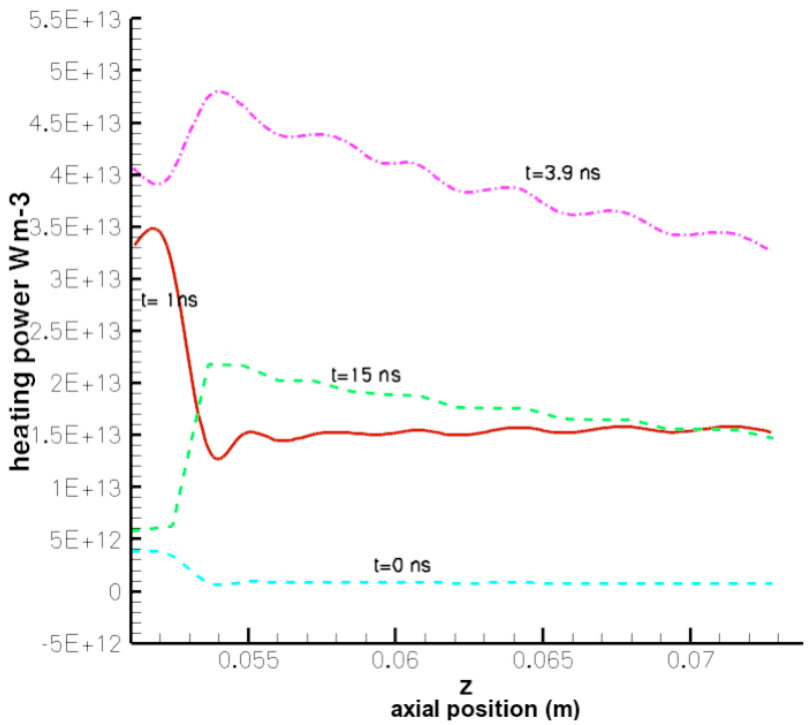
Numerical Modelling
initialisation

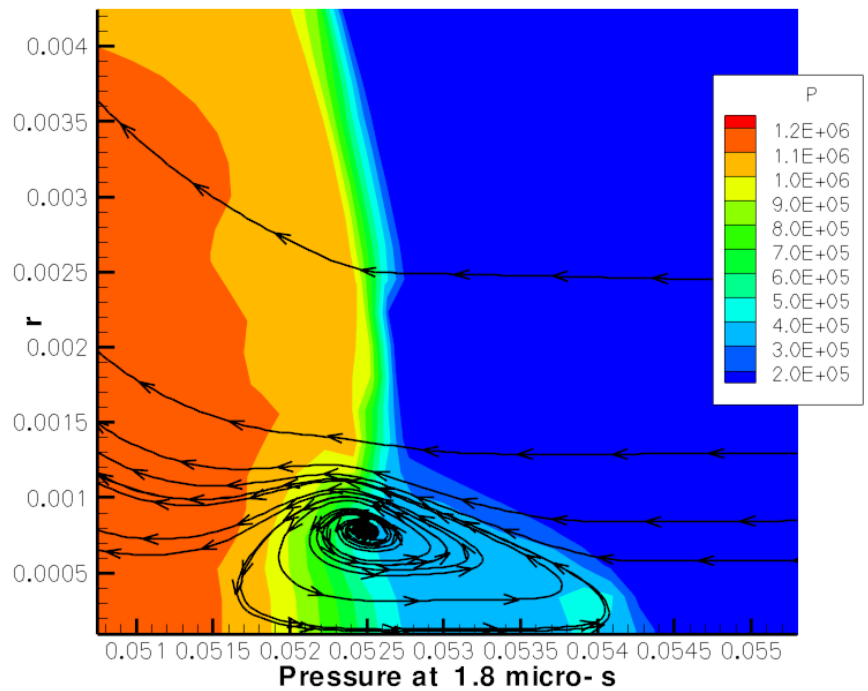
Parameter	***Value***
Mach	3,54
Freestream pressure	200000 Pa
Freestream temperature	300 K
Plasma column elongation	0.25 m
Plasma column radius	200 µ-m



Initial plasma characteristics is coherent with the femtolaser data input.

Numerical Modelling
Results

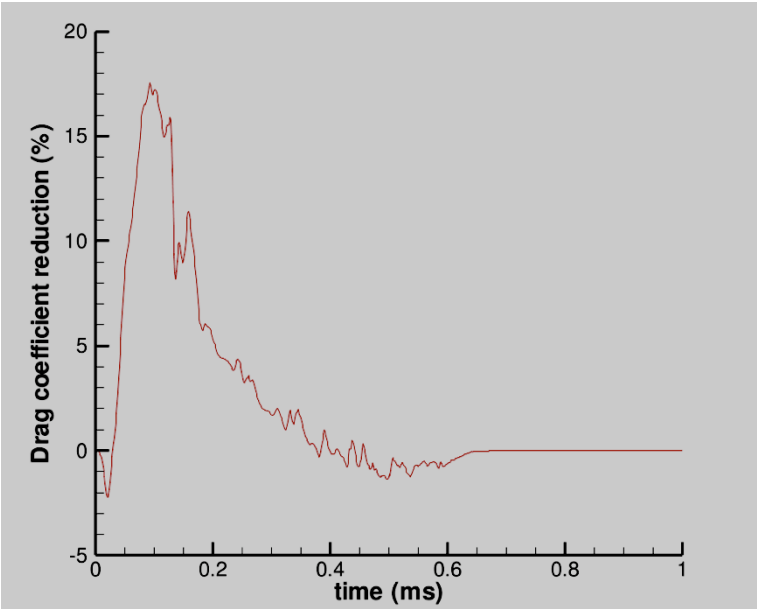


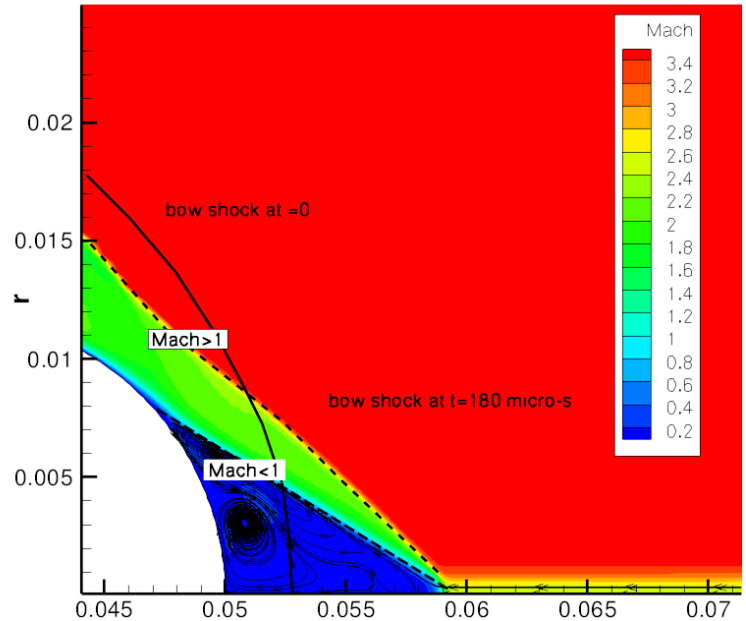


At t=0ns, t=1ns and t=3.7 ns heating power is high downstream the shock wave
Three body recombination frequency increases inducing a transfer of a significant part of plasma energy to the flow in this region

=> recombination reactions play a major role

Numerical Modelling
Results





- Toroidal vortices appear in the region of low density
- The bow shock moves upstream
- T his configuration corresponds to a maximum enhancement of the drag reduction coefficient (about 18 %, at t = 0.5 ms): the global pressure exerted from the flow to the body is reduced by the change of the flow structure.
- After t=0.5ms, the drag reduction coefficient falls corresponding to a relaxation step toward the initial state

Conclusion

Action of surfaces discharges on aerodynamics

- in qualitative agreement with experimental results,
- transfer of momentum between charged and neutral particles,
- a good representation thanks to 2D simulation but stramersare=> 3D is necessary
- large CPU=> need to improve existing numerical methods

Plasma synthetic jet

- modeling provide qualitative results
- explain the energy balance
- arc modeling has to be improved (vaporization and melting)

Laser induced plasma actuator

- Results show a significant effect of the plasma downstream leading to an 18% reduction of the drag coefficient
- plasma has to be modeled carefully