# Numerical simulation of the Pilot-PSI magnetized plasma jet

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## Pilot-PSI: experiment and modelling

In order to better understand the physics of the plasma-surface interaction in conditions relevant to the ITER divertor [1], Pilot-PSI, a linear magnetized plasma generator has been developed in the last few years. It aims at producing a high hydrogen ion flux in excess of $10^{23}$ particles $m^{-2}s^{-1}$ to a surface. It currently can operate with either Ar or $H_2$ working gas which flows into a cascaded arc plasma source at a pressure of 1-2 $\cdot 10^4$ Pa. Within the arc, a current in the range 30-100 A applies and the gas is weakly ionised there. The plasma thus produced expands from a divergent nozzle source into a cylindrical vacuum vessel 1 m long and 40 cm in diameter, which is continuously evacuated by booster pumps to maintain a constant vessel pressure of 4-200 Pa. Five surrounding coils can create a homogeneous coaxial magnetic field of 0.4 T inside the vessel for 2 minutes or even allow field strenghts of 0.8 T, 1.2 T and 1.6 T during few seconds. The externally applied field guides the collimated plasma beam to a specific target plate situated at the opposite end of the vessel [2]. In this work a first attempt to study this system is made, analyzing the hydrodynamic [3] and magnetohydrodynamic regimes for the neutral particles and charged ones respectively. The jet flow is then investigated numerically, solving the compressible hydrodynamic and MHD equations. The Versatile Advection Code [4] is used to solve these PDE systems of hyperbolic equations; the conservation laws are evolved temporally until the steady state is reached by the conservative, second order accurate Total Variation Diminishing Lax-Friedrichs scheme.

## 1D spherical and 2D axially symmetric results

Comparing 1D spherical and 2D cylindrical axially symmetric results, the well defined resulting free-jet flow shock structure is analyzed in the first region of the expansion.

As the entry conditions are slightly supersonic (Mach=1.01) a supersonic expansion of the neutral particle flow forms and the large pressure difference between the nozzle source and the

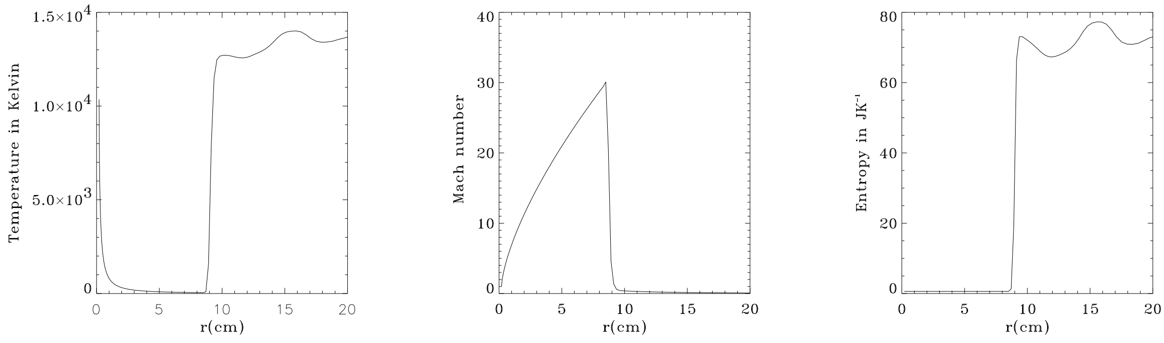


Figure 1: Temperature, Mach number and entropy profiles for a 1D spherical supersonic expansion into a vessel with background pressure $p_b$=30 Pa.

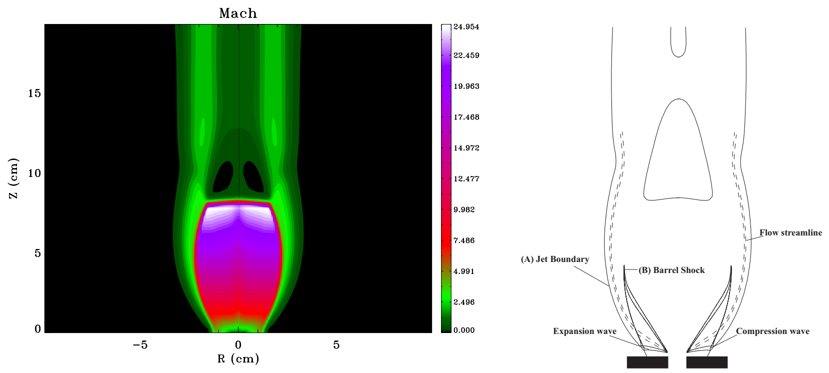


Figure 2: Computed distribution of Mach number for axisymmetric free-jet flow with with $p_b$=30 Pa (Left panel); (b)Analysis of the free-jet flow expansion using characteristic lines (Right panel).

vessel induces a shock transition to subsonic conditions. It's possible to distinguish three regions in the expansion (figure 1): a)in the first supersonic one the gas is accelerated and the temperature and density decrease, this supersonic flow is isentropic; b)across the shock the particles are decelerated and the density increases, as well as the temperature. The increased entropy marks this Mach disc region. Across it, the Mach number changes from super to subsonic values discontinuously; c)after the shock transition, the particles flow subsonically, the temperature and density increase only slightly in the further downstream flow. The entropy production in the flow up to the Mach disc is negligible compared with the entropy production across the Mach disc.

In figure 2 we show the distribution of the Mach number for the 2D cylindrical case. In order to understand the expansion process of the free jet, the characteristic lines C+ and C- [5] :

$$(dR/dZ) = tan(\theta \mp \mu), \quad (1)$$

have been calculated from the obtained stationary flow pattern. In figure 2 (Right panel) the complicated axisymmetric structure has been analyzed. As the gas leaves the nozzle, it expands and a rarefaction fan emanates from the nozzle orifice. These expansion waves (which we can recognize in the points from where the C- characteristic curves diverge) expand in the vessel and are reflected at the free-jet boundary (point (A)); as consequence, an intercepting shock (which can be recognized as the points where the reflected characteristic curves C+ converge) (point (B)) is formed in the interior of the jet by the reflected compression waves (i.e. C+ characteristics) which coalesce on the internal barrel shock. The barrel (intercepting) shock ends in a triple point Mach disc configuration, where it intersects the Mach disc. The presence of the walls of the vacuum vessel thus influences the free jet expansion pushing the gas toward the axis during the transient evolution to this steady state and a conical shape is then formed. The slightly curved Mach disc is the region where all the higher gradients reside : across this shock, in fact, the particles are decelerated suddenly to subsonic values. For the case of background pressure in the vessel of $p_b = 20$ Pa the neutral particles velocity decreases from $\sim$ 3150 m/s to $\sim$ 750 m/s, the number density increases from $4.27 \cdot 10^{19}$ particles/m$^3$ to $1.58 \cdot 10^{20}$ particles/m$^3$, as well as the temperature ranging from $\sim$ 40 K to 7750 K. The velocity of those particles crossing the barrel shock decreases but it remains supersonic. Beyond the Mach disc the fastest flow originates in an annular region from the gas deflected through the barrel shock. Only a few percent of all particles pass the Mach disc directly and become subsonic, while the highest percentage of neutral flow passes via the barrel shock.

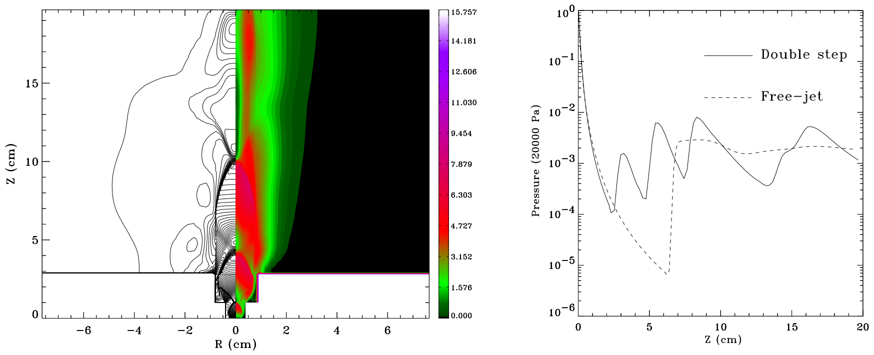


Figure 3: Logarithmic pressure and Mach number distributions for a double-step nozzle (Left panel) and comparison of the logarithmic pressure profiles for the free-jet case and double-step nozzle (Right panel).

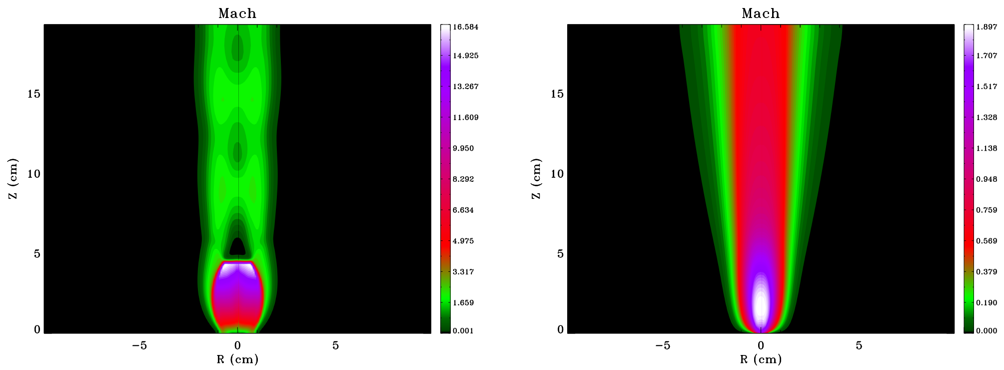


Figure 4: Transition from the hydrodynamic regime towards the MHD one : B=0.008 T (Left panel) and B=0.2 T (Right panel).

Furthermore the variations in the supersonic shock structure due to a geometric variation of the nozzle are studied. In this case (figure 3) there's an amplification of the usual expansion recompression process downstream of the nozzle exit, due to a more complicated wave structure containing multiple shock transitions. In fact the internal and oblique shocks create a recompression of the flow : the neutral gas undergoes a primary compression phase, followed by an expansion process which ends in a secondary recompression process and so on. The whole structure clearly induces a reduction of the cross-sectional area available and so doing in the flow the expansion-compression effects get amplified; the double-step nozzle clearly allows the flow to be more concentrated towards the axis of symmetry. From the 2D flow configuration we conclude that the general topology of the jet boundary converges towards the axis of symmetry; the radial components of the neutral flows are deflected by the nozzle and a more dense flux of particles is now present along the axis of symmetry.

**MHD regime**

A set of numerical simulations has been performed to investigate the gradual transition between the hydro regime and the MHD one. The strength of the axial magnetic field is controlled by varying the nozzle plasma beta, with fields ranging from B=0.008 Tesla to B=0.8 Tesla.

In figure 4 we show the cases of B=0.008 T and B=0.2 T : it's evident that the application of an increasing magnetic field gradually changes the expansion process and a confined plasma

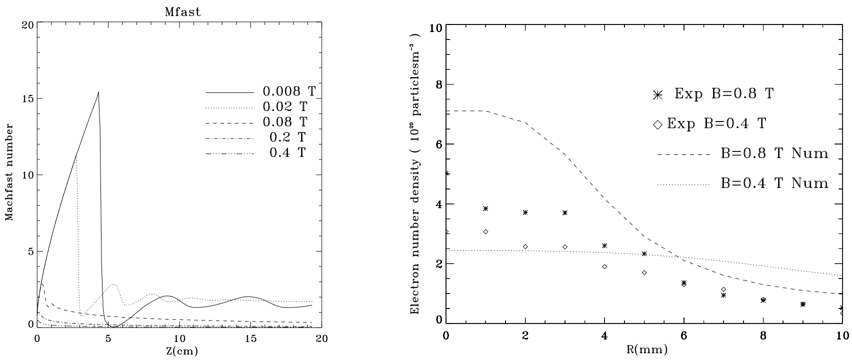


Figure 5: Machfast number (Left panel) and electron radial density at z=45 mm from the nozzle source (Right panel)

beam is formed gradually. With the application of high magnetic fields (B$\geq$ 0.2 T) a significant change in the flow structure can be noticed : in fact the typical hydrodynamical shock structure disappears above this value. The application of a magnetic field alters the inlet conditions as follows : in figure 5 (Left panel) we plot the fast Mach number for different values of the magnetic field and this shows the transition to a subfast magnetosonic inlet regime for high values of B. Therefore the Mach disc marking the fast magnetosonic shock at low fields doesn't exist anymore. In figure 5 (Right panel) we directly compare the electron radial density profile experimentally diagnosed by Thomson-Rayleigh scattering at 45 mm from the nozzle source and the computed ones (for B=0.4 T and B=0.8 T), showing a good agreement. The effect due to a magnetic confinement is evident : the electron density increases with the increase of the magnetic field. The axial densities at higher fields can be an order of magnitude higher beyond the nonmagnetized case.

## Acknowledgements

This work was performed as part of the research program of 'Stichting voor Fundamenteel Onderzoek der Materie' (FOM) with financial support from NWO, within the FOM program 75 on PSI-lab, an integrated laboratory on Plasma-Surface Interaction.

## References

[1] Pitcher C.S. and Stangeby P.C., Plasma Phys Control.Fusion **39**, 779 (1997)

[2] De Groot B. et al., Fusion Engineering and Design **74**, 155 (2005)

[3] Cinalli M. and Keppens R., Paper submitted to Journal of Physics D:Applied Physics (2006)

[4] Tóth G., Astrophys.Lett. & Comm. **34**, 245 (1996)

[5] Anderson, J. Modern Compressible Flow McGraw-Hill (2002)