Application of a two-phases hybrid model to atom transport in ITER simulations

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Motivation :

- Modelling of edge plasma through fluid plasma solver (like SolEdge2D [1]) coupled to kinetic Monte Carlo code for neutrals (like Eirene [2]).
- In most of the simulation domain Knudsen number $Kn \equiv m.f.p./L$ for neutrals much larger than one, but may not be true near divertor targets in detached regime due to high plasma density ($10^{20} - 10^{21}\ m^{-3}$) and low temperature (below $5eV$)
- Neutrals undergo high number of charge-exchange and elastic collisions before getting ionized, so Monte Carlo codes inefficient/inaccurate
- Hybrid kinetic-fluid model for neutrals could improve performances of edge plasma codes

Hybrid model for Soledge2D:

✓ Based on [1]: atom vdf f split into a kinetic part f_k and a fluid part f_F, such that $f=f_F+f_K$

$$\frac{\partial f_{K,F}}{\partial t} + \vec{v}\cdot\vec{\nabla} f_{K,F} = S_{iz}^{K,F} + S_{rc}^{K,F} + S_{cx}^{K,F} + S_{mol}^{K,F} \pm S_{F\to K} \pm S_{K\to F}$$

✓ Transition processes between kinetic and fluid phases introduced – evaporation & condensation

$S_{F\to K} = -\nu_{evap} f_F$ $\quad S_{K\to F} = -\nu_{cond} f_K$ At this point: choice of rates is arbitrary

✓ Aim : condensation >> evaporation in highly collisionality regions (HCRs), i.e. f ~ f_F~ Maxw., evaporation >> condensation in LCRs

✓ Next step : collisionnal closure for moments of f_F with the idea that f_F/f_K<<1 in regions where the later is not valid.
Here two moments assuming $T_n = T_i$ in the HCRs – capture momentum exchanges

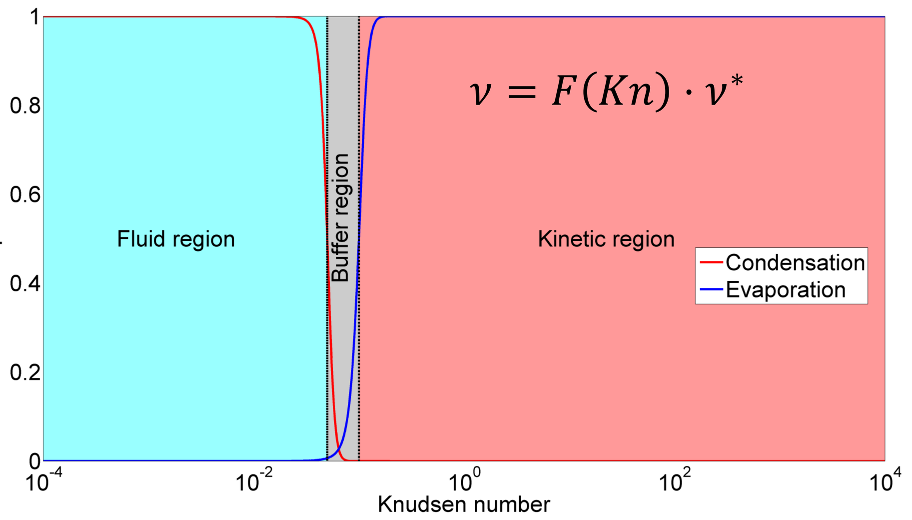
$$\frac{\partial n_F}{\partial t} + \vec{\nabla}\cdot(n_F\vec{u}_F) = S_{iz,n}^F + S_{rc,n}^F + S_{evap,n}^F + S_{cond,n}^F$$

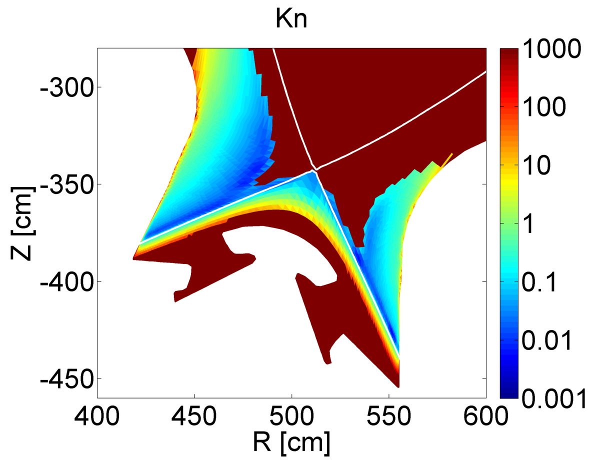
$$\frac{\partial n_F\vec{u}_F}{\partial t} + \vec{\nabla}\cdot\left(n_F\vec{u}_F\vec{u}_F + \frac{p_F}{m}I\right) = \vec{S}_{iz,mom}^F + \vec{S}_{rc,mom}^F + \vec{S}_{cx,mom}^F + \vec{S}_{evap,mom}^F + \vec{S}_{cond,mom}^F$$

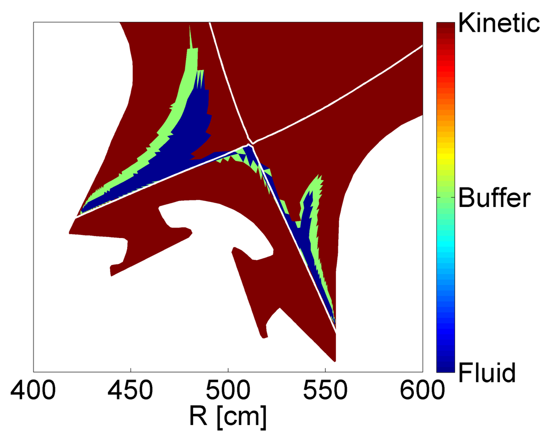
f_F is *assumed* purely Maxwellian (appears *explicitely* in the equation for f_K + f_K=f-f_F – positive definiteness of f_K ?)

✓ Fluid breakdown parameter → local gradient length Knudsen number $Kn = \frac{\lambda}{L} = \frac{v_{th}/(n_i\langle\sigma v\rangle_{cx})}{\max(\nabla_\parallel n_e, \nabla_\perp n_e)/n_e}$

✓ Kn can be small in regions with no plasma or not dominated by cx → kinetic zone forced where $n_e = n_i \le n_{min}$ and/or $\frac{\langle\sigma v\rangle_{cx}}{\langle\sigma v\rangle_{iz}} \le min$







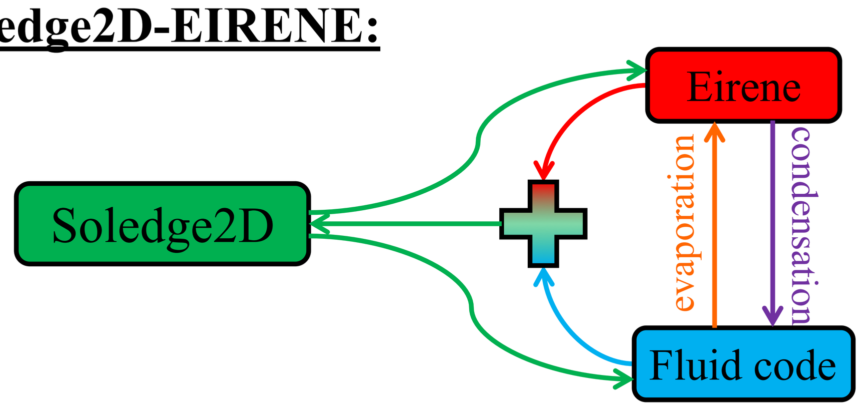
✓ MC slow because of cx → make condensation more probable than cx in fluid areas $\nu_{cond}^* = M\cdot n_i\langle\sigma v\rangle_{cx}$ with $M \gg 1$ (here $\nu_{evap}^* = \nu_{cond}^*$)

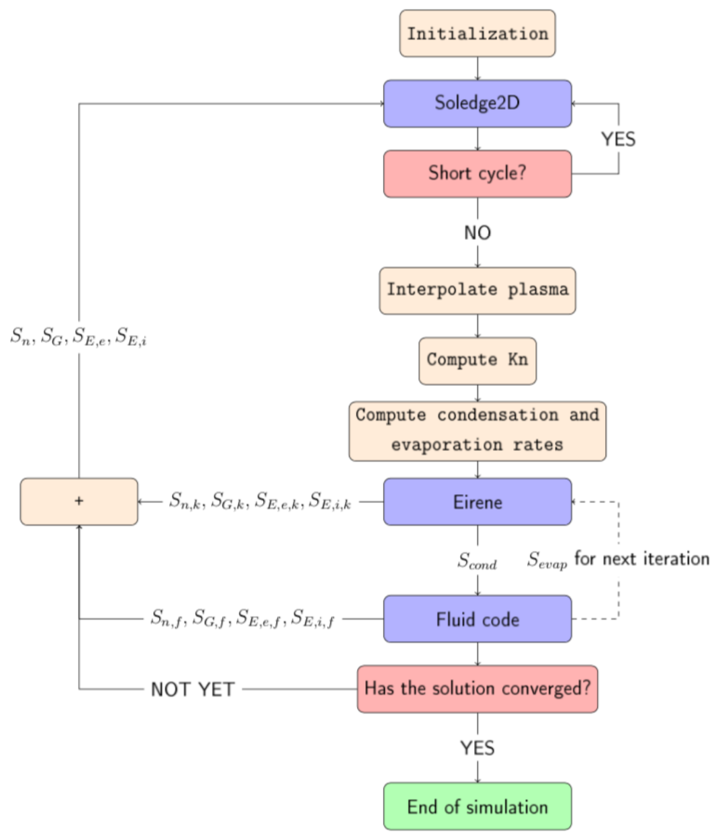
✓ fluid approximation valid for $Kn \ll 1$, so the shape of the factor F(Kn) determines whether mesh region is fluid or kinetic

So essentially this approach amounts to a spatially hybrid model with a dynamic boundary between fluid and kinetic domain, enforced by an immersed boundary technique similar to the penalization scheme implemented in Soledge2D.

✓ boundary conditions discussed in the literature (analysis ongoing). Buffer region added to prevent "fluid/kinetic" oscillations.

Implementation in Soledge2D-EIRENE:





✓ Specifically developped fluid code based on HDG scheme, on the same grid as EIRENE [4]

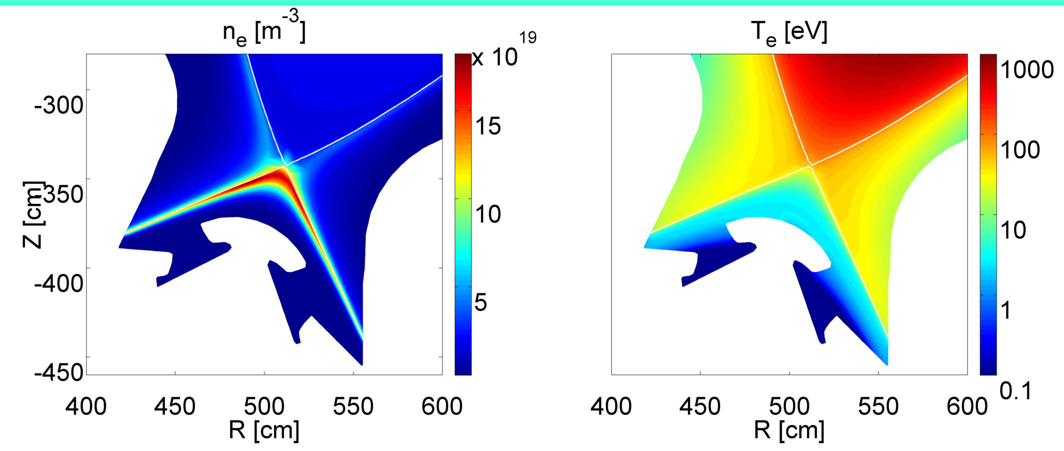
✓ Absorbing BC for fluid atoms at the wall, recycled as kinetic atoms/mol.
$\Gamma_{F\to K} = R\Gamma_F^- = R\int_- f_{Max}(\vec{u}_F, T_F)\vec{v}_F\cdot\hat{n}d\vec{v}_F$

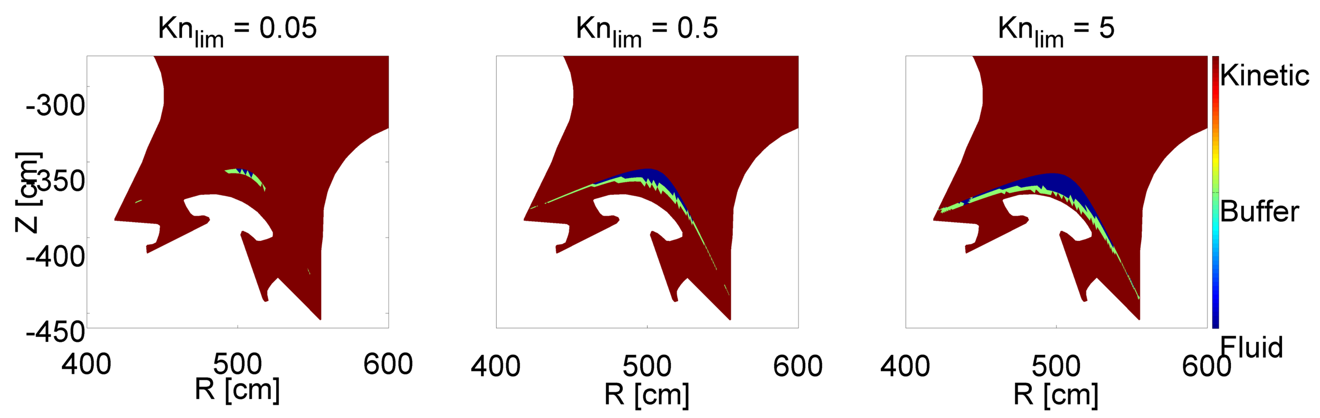
✓ Molecules treated kinetically (hybrid may be needed too because of elastic collisions !)

✓ Condensation implemented as an extra CX process with background fluid atoms

Hybrid simulations: comparison with fully kinetic case

ITER test case (P. Tamain et al., and Refs. [5])
Pure H, $P_{SOL} = 20MW$, self-consistent core density BC
$D = 0.3m^2/s$, $\chi_e = \chi_i = 1m^2/s$
Be wall $R = 1$
1 pump below dome with $R = 0.9928$
2 puffs (top) with same rate $5.65\cdot 10^{21}e^-/s$

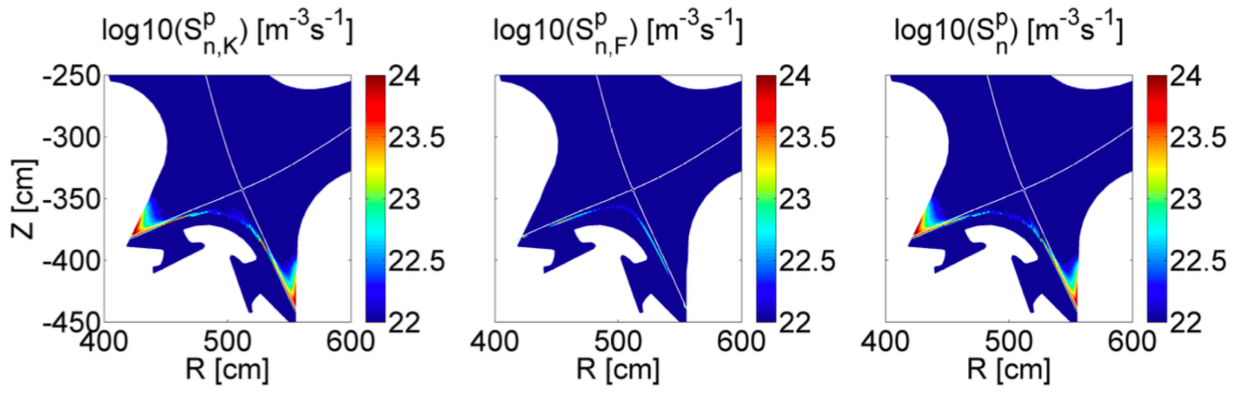




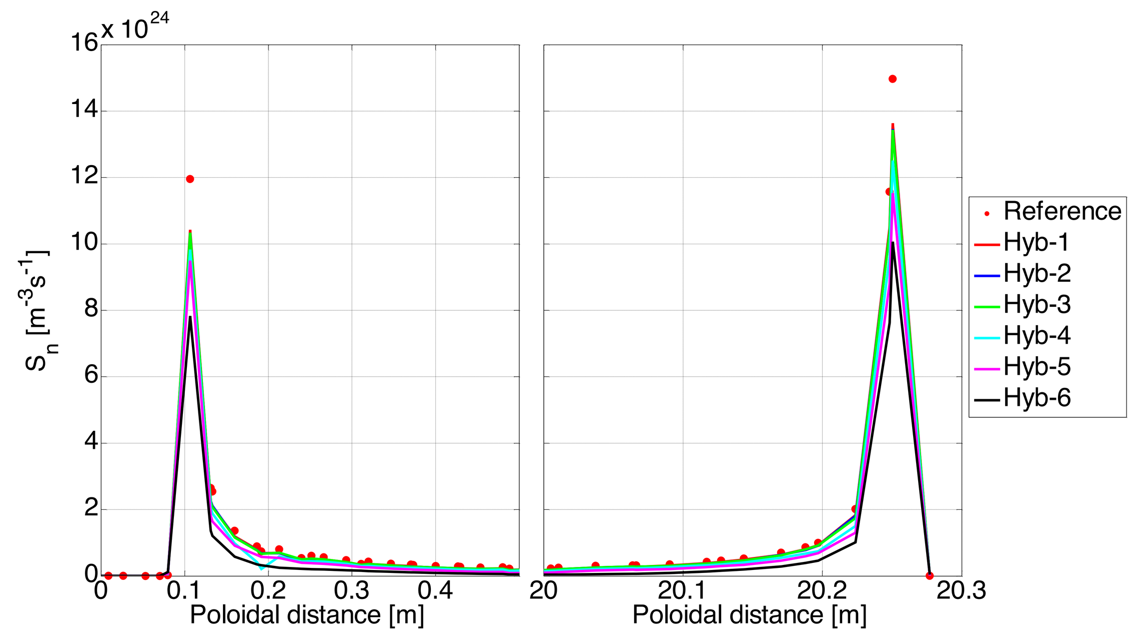
	Eirene	Fluid code	Kn_{lim}
Reference	✓	×	×
Hyb-1	✓	✓	0.01
Hyb-2	✓	✓	0.05
Hyb-3	✓	✓	0.1
Hyb-4	✓	✓	0.5
Hyb-5	✓	✓	1.
Hyb-6	✓	✓	5.

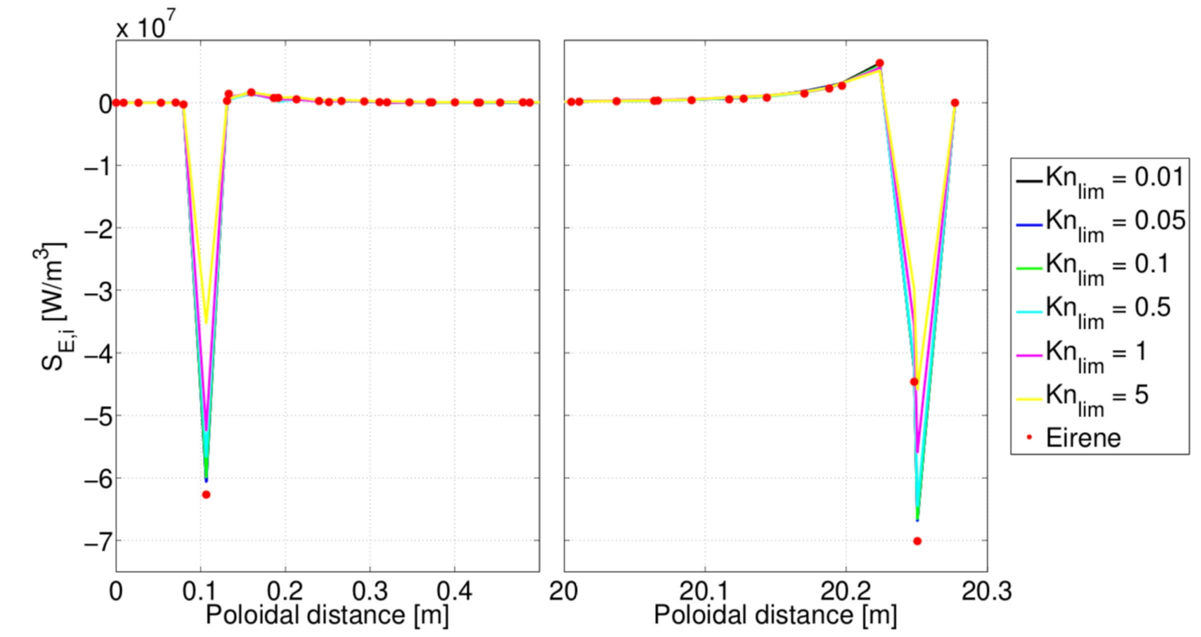
Total plasma sources = kinetic sources + fluid sources

Code package converged with the hybrid model

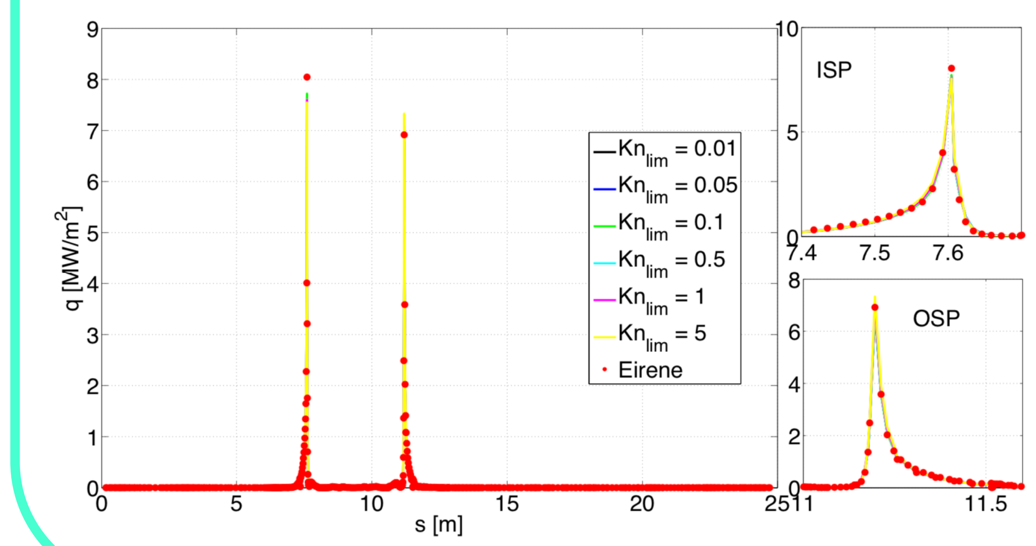


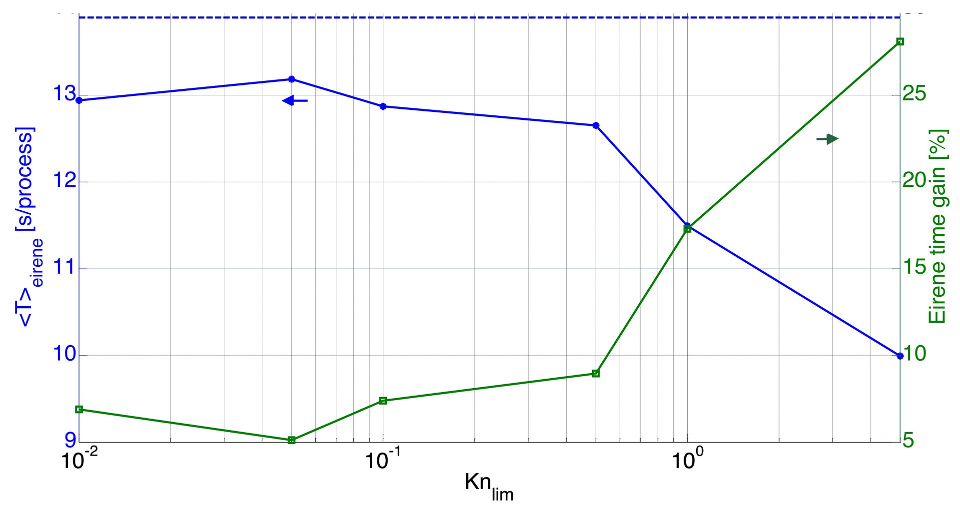
S_{Ei} approximated due to $T_F = T_i$ assumption → possible error introduced in ion energy equation in fluid areas. Here not critical but likely to be case dependent … would be made more robust with an energy equation for neutrals





BUT negligible impact on the target profiles





reduction of 5 ÷ 30% average time for Eirene vs reference
(note that the case considered is not troublesome when using EIRENE alone & that the neutral fluid code is not parallelized yet)

Conclusions:

- ✓ The method initially proposed by Karney&Stotler can be seen as the implementation of a spatially hybrid scheme. Complementary with macro/micro approach developed by Horsten et al.
- ✓ First results encouraging but robustness with model parameters need to be investigated further.
- ✓ Could be seen as a convergence accelerator (subsequent fine tuning with kinetic only allowing one to assess modeling errors related to the hybrid model)

References :

[1] H. Bufferand et al, Nuclear Fusion 55, 053025 (2015)
[2] D. Reiter et al, Fusion Science and Techn. 47, 172 (2005)
[3] C.F.F. Karney et al,Contrib. Plasma Phys.38 1/2, 319(1998)
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[5] M. Valentinuzzi NME (2019), Phd Thesis

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