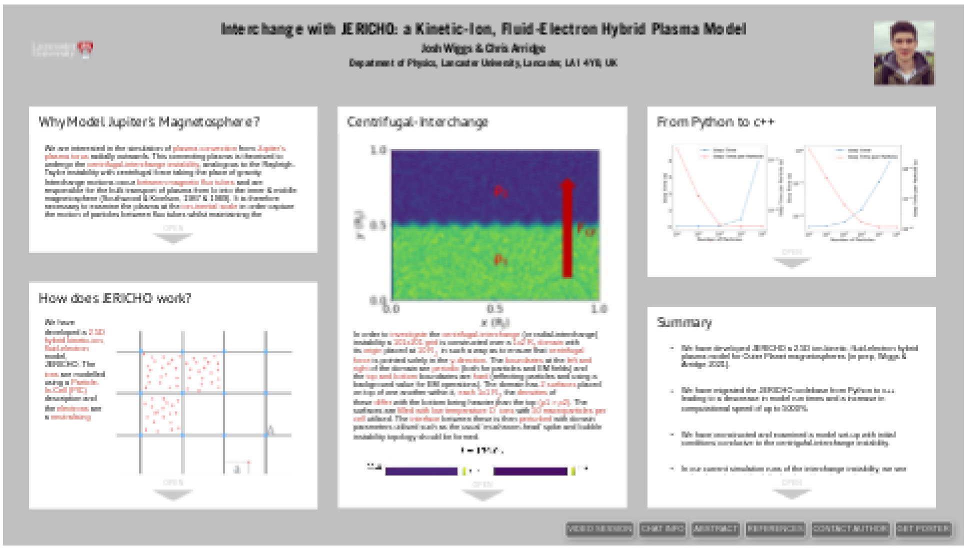
Interchange with JERICHO: a Kinetic-Ion, Fluid-Electron Hybrid Plasma Model



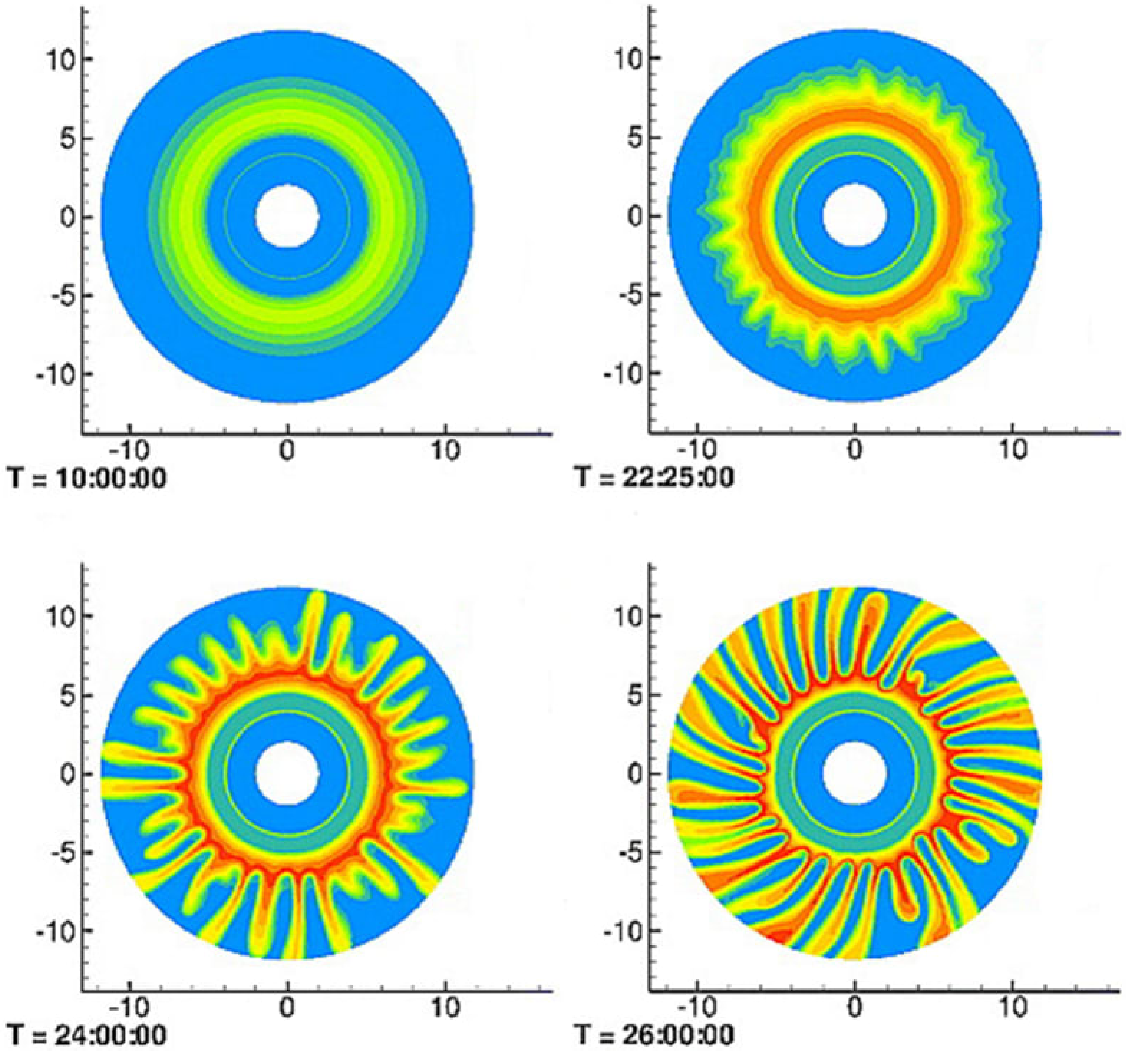
Josh Wiggs & Chris Arridge

Department of Physics, Lancaster University, Lancaster, LA1 4YB, UK

PRESENTED AT:

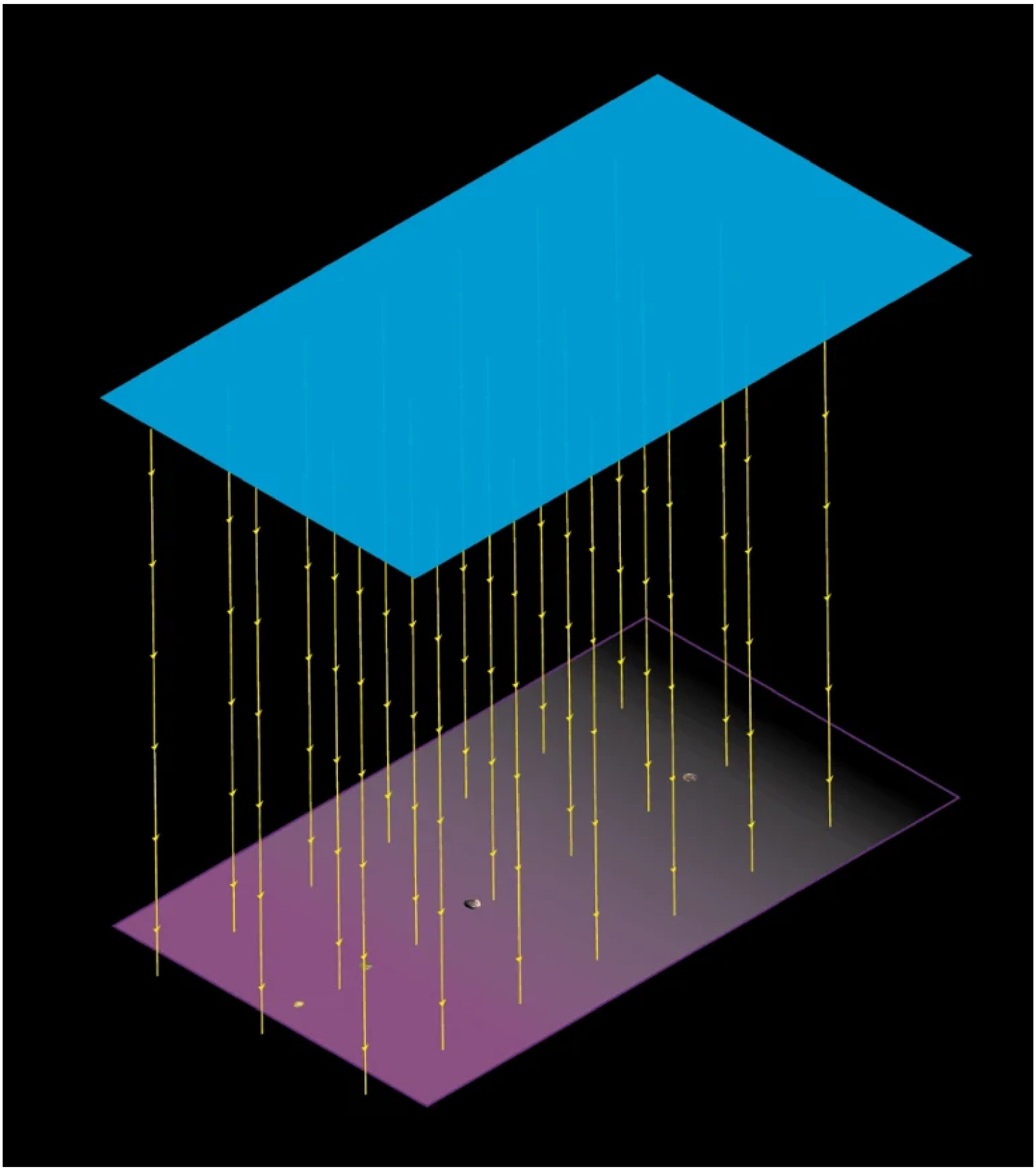
WHY MODEL JUPITER'S MAGNETOSPHERE?

We are interested in the simulation of plasma convection from Jupiter’s plasma torus radially outwards. This convecting plasma is theorised to undergo the centrifugal-interchange instability, analogous to the Rayleigh-Taylor instability with centrifugal force taking the place of gravity. Interchange motions occur between magnetic flux tubes and are responsible for the bulk transport of plasma from Io into the inner & middle magnetosphere (Southwood & Kivelson, 1987 & 1989). It is therefore necessary to examine the plasma at the ion-inertial scale in order capture the motion of particles between flux tubes whilst maintaining the computational capacity to resolve length scales on the order of the planetary radii. Current state-of-the-art models predicts transport will break-out into interchange fingers (Yang+ 1994, Liu+ 2010), but this has recently been disputed (Vasyliunas, 2019).



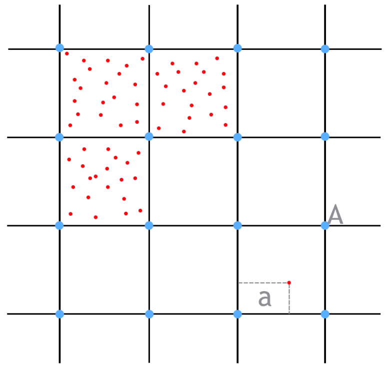
Liu+ 2010

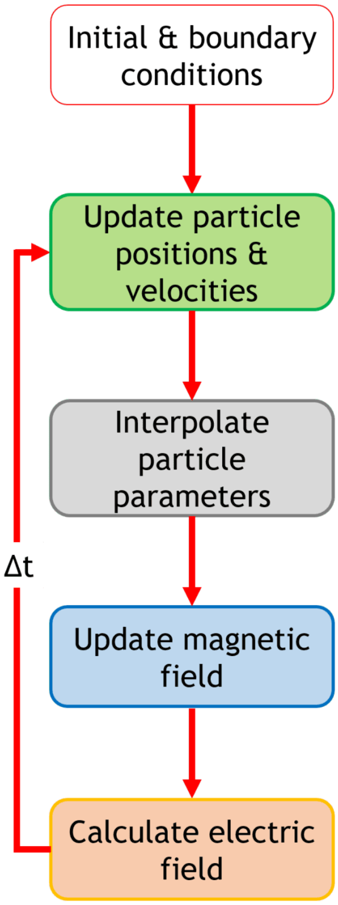
JERICHO (Jovian magnEtospheRIC ion kinetic fluid electron Hybrid plasma mOdel) is a 2.5D kinetic ion, fluid electron hybrid plasma model (Wiggs & Arridge, in prep) with codebases in both Python and c++. It has been developed with the aim of analysing radial outflows and magnetic flux transport from Io’s torus into the middle magnetosphere over time scales comparable to the Jovian day. JERICHO currently reproduces a 2D magnetosphere which will be coupled to the Ionosphere with orthogonal field lines, this will allow insights into interchange ion motions.



HOW DOES JERICHO WORK?

We have developed a 2.5D hybrid kinetic-ion, fluid-electron model, JERICHO. The ions are modelled using a Particle-In-Cell (PIC) description and the electrons are a neutralising magnetohydrodynamic (MHD) fluid (Winske+ 2003, Bagdonat 2004). A Cartesian grid is overlaid across the simulation region on the vertex's of which the electromagnetic (EM) fields are calculated. The model is advanced through time numerically, with the magnetic field being obtained with a modified MacCormack Predictor-Corrector scheme in order to minimise numerical instabilities allowing larger time steps.





Ions are pushed numerically considering the Electromagnetic, Coriolis and Centrifugal forces

$$\frac{d\underline{v}}{dt} = \frac{q}{m}(\underline{E} + \underline{v}\times\underline{B}) - 2\underline{\Omega}\times\underline{v} - \underline{\Omega}\times(\underline{\Omega}\times\underline{r})$$

$$\frac{d\underline{r}}{dt} = \underline{v}$$

$$\rho_c = \sum_p W(\underline{x}_p, q_p)$$

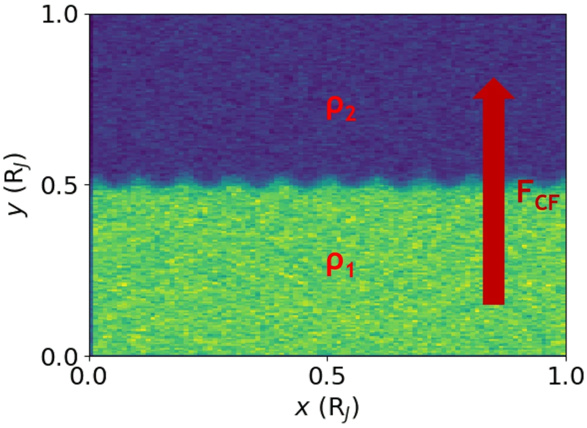
Parameters are obtained from ion distributions using first-order interpolation onto the EM field grid vertices

$$\frac{\partial \underline{B}}{\partial t} = -(\nabla\times\underline{E})$$

The magnetic field is updated using Faraday's Law and the electric field using the MHD momentum equation for massless electrons

$$\underline{E} = -\frac{1}{\rho_c}\nabla\cdot\underline{\underline{p}}_e - \left[\underline{U}_i\times\underline{B} - \frac{1}{\mu_0\rho_c}(\nabla\times\underline{B})\times\underline{B}\right]$$

CENTRIFUGAL-INTERCHANGE

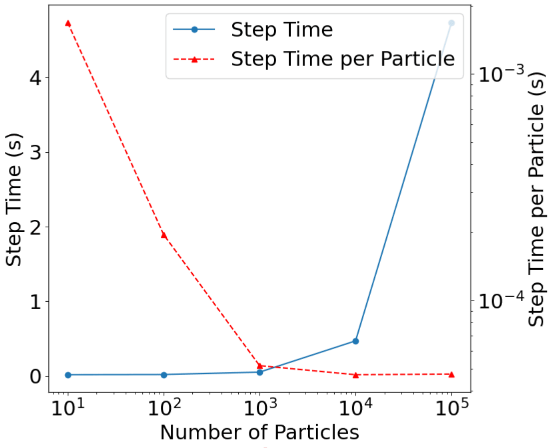


In order to investigate the centrifugal-interchange (or radial-interchange) instability a 101x201 grid is constructed over a 1x2 R_J domain with its origin placed at 10 R_J in such a way as to ensure that centrifugal force is pointed solely in the y-direction. The boundaries at the left and right of the domain are periodic (both for particles and EM fields) and the top and bottom boundaries are hard (reflecting particles and using a background value for EM operations). The domain has 2 surfaces placed on top of one another within it, each 1x1 R_J, the densities of these differ with the bottom being heavier than the top ($\rho 1 > \rho 2$). The surfaces are filled with low temperature O^+ ions with 50 macroparticles per cell utilised. The interface between these is then perturbed with domain parameters utilised such as the usual 'mushroom-head' spike and bubble instability topology should be formed.

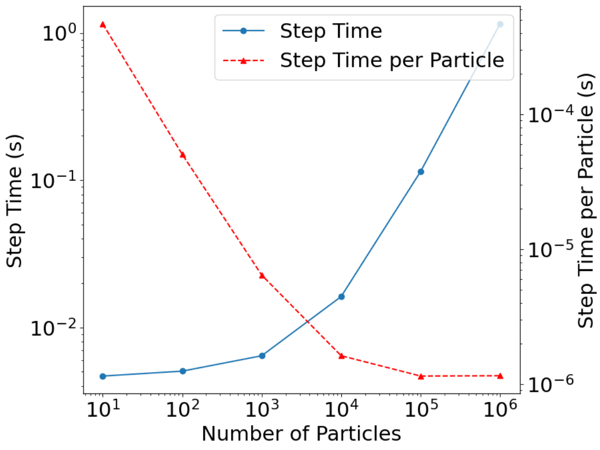
[VIDEO] https://res.cloudinary.com/amuze-interactive/image/upload/f_auto,q_auto/v1639404769/agu-fm2021/f0-f5-57-a8-9d-cb-19-aa-ca-7c-b5-29-c1-7f-db-30/image/rt_test_server_hi_res_lower_dt_fbkixv.mp4

Analysing the evolution of the perturbed interface in the time series the spikes can be seen to begin to form. However, the stage where the 'mushroom-head' structures are clearly reproduced is not reached. We will increase the temporal end point of simulation runs in order to capture the full breadth of instability dynamics.

FROM PYTHON TO C++



Python



C++

A series of performance tests on the Python and c++ versions of JERICHO were carried out on a 10x10m surface with a 51x51 grid. It can be seen that as the number of particles increases then the step time per particle decreases linearly up to a critical value. This value is where the particle operations dominate the run time. The critical value is reached at 47μs in the Python version and 1.1μs in the c++ version.

SUMMARY

- We have developed JERICHO a 2.5D ion-kinetic, fluid-electron hybrid plasma model for Outer Planet magnetospheres (in prep, Wiggs & Arridge 2021).

- We have migrated the JERICHO codebase from Python to c++ leading to a descrease in model run times and a increase in computational speed of up to 5000%.

- We have cronstructed and examined a model set-up with initial conditions conducive to the centrigufal-interchange instability.

- In our current simulation runs of the interchange instability, we see spikes form but not the fully developed 'mushroom head' structures, therefore we need to increase run length.

ABSTRACT

Plasma in the Jovian magnetosphere is removed from Io's torus mainly via ejection as energetic neutrals and by bulk transport into sink regions in the outer magnetosphere. The physical process generally considered to be responsible for bulk transport is the centrifugal-interchange instability, analogous to the Rayleigh-Taylor instability, but with centrifugal force replacing gravity. This mechanism allows magnetic flux tubes containing hot, tenuous plasma to exchange places with tubes containing cool, dense plasma, moving material from the inner to outer magnetosphere whilst returning magnetic flux to the inner magnetosphere. In order to examine the transport we have developed a full hybrid kinetic-ion, fluid-electron plasma model in 2.5-dimensions, JERICHO. The technique of hybrid modelling allows for probing of plasma motions from the scale of planetary-radii down to the ion-inertial length scale, considering constituent ion species kinetically as charged particles and forming the electrons into a single magnetised fluid continuum. This allows for insights into particle motions on spatial scales below the size of the magnetic flux tubes. Results from this model will allow for the examination of bulk transport on spatial scales not currently accessible with state-of-the-art models, improving understanding of mechanisms responsible for moving particles between flux tubes and from the inner to the outer magnetosphere. In this presentation we will analysis the latest results from the model as well as examining the process of coupling the simulated magnetosphere to a Jovian ionosphere.

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