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INSIDE THIS ISSUE
(4 Pages)

Topic	Page No.
Research Highlight Numerical Simulation Of An Expanding Magnetic Field Plasma Thruster: A Comparative Study For Argon, Xenon and Iodine Fuel Gases	1
HPC Article Introduction to CUDA Libraries	3
ANTYA Utilization: JUNE 2024	4
ANTYA HPC Users' Statistics — JUNE 2024	4
Other Recent Work on HPC	4

GAṆANAM (गणनम्)

HIGH PERFORMANCE *COMPUTING* NEWSLETTER

INSTITUTE FOR PLASMA RESEARCH, INDIA

Numerical Simulation Of An Expanding Magnetic Field Plasma Thruster: A Comparative Study For Argon, Xenon and Iodine Fuel Gases

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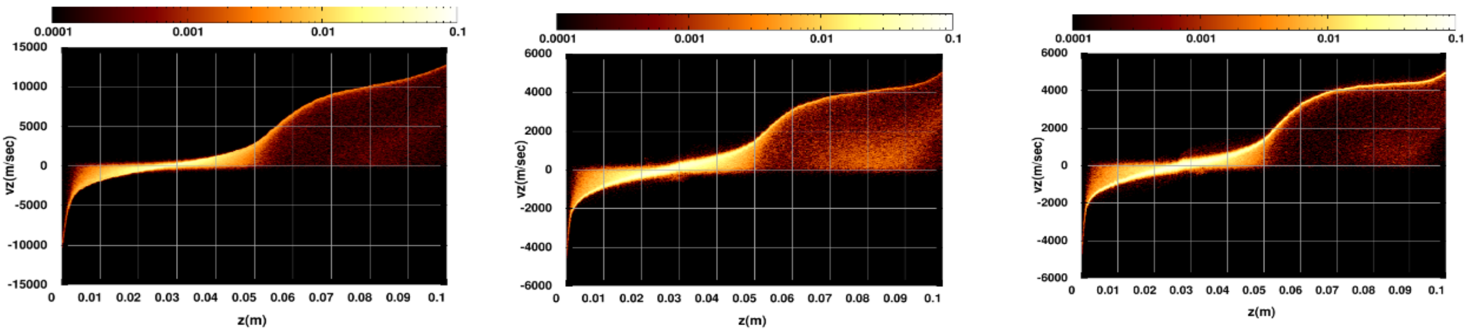
Chemical propulsion engines are commonly used to lift off the spacecraft and once the spacecraft is out of the Earth's gravity, one switches to the electric propulsion engine due to low thrust requirement. In a chemical propulsion engine, hot gas exhaust velocities are in the range of 3-4 Km/sec and specific impulse is generally less than 500 seconds. An electric propulsion device has specific impulse in the range of 1500-20000 seconds which helps to reduce the overall spacecraft mass for a mission and results in an overall into mission cost reduction[1]. Gridded ion plasma thruster and Hall plasma thruster are established technologies and they are successfully deployed in several space missions for orbit correction and deep space mission[1]. In these devices, continuous erosion of electrode material due to energetic charged particles bombardment, compromises the mission longevity. An electrode-less plasma thruster or Helicon plasma thruster (HPT) is regarded as a viable alternate to overcome the issue of electrode material erosion[2].

In a HPT device, most commonly used fuel gas is xenon. It is non-hazardous, non-reactive and stored in high pressure tanks during the operation. However, Xenon is not easily available in nature and it is extracted from liquefied air which makes it costlier . In the past, Mercury and Cesium were used as fuel due to high mass and low ionization energy but they are toxics and highly reactive. In recent times, iodine is considered as a very promising candidate and a good alternate of xenon for HPT fueling and several numerical simulation and laboratory experiments have been performed worldwide[3]. Iodine is easily available in nature and it is found both in atomic and molecular form. Iodine does not have any storage issue and during HPT operation, solid iodine is vaporised by sublimation and used as a fuel. As iodine is known to be relatively reactive, it is expected that proper precautions are taken during operation. Szabo et al experimentally demonstrated that Hall effect thruster with iodine vapor as a fuel shows similar performance as xenon fuel[3]. These Authors have measured thrust, efficiency and specific impulse using both xenon and iodine fuel. Grondein et al used iodine as fuel instead of xenon for gridded ion thruster and show that overall performance is similar for both fuels. They have shown that below a certain propellant mass flow rate (1.3mg/sec), iodine shows higher efficiency than xenon[4]. Bellomo et al demonstrated 0.6mN thrust and 600 sec specific impulse for REGULAS a complete propulsion device using the iodine fuel [5]. Dmytro Rafalskyi et al reported an in-orbit demonstration of an iodine plasma thruster. They have shown that using an iodine fueled plasma thruster, one can achieve more efficiency in comparison to xenon plasm thruster. They have performed small satellite maneuvering and confirmed using satellite tracking system[6]. However, in numerical simulation and laboratory experiments Ar is used most commonly as a fuel to cut down simulation cost and experiment cost, respectively.

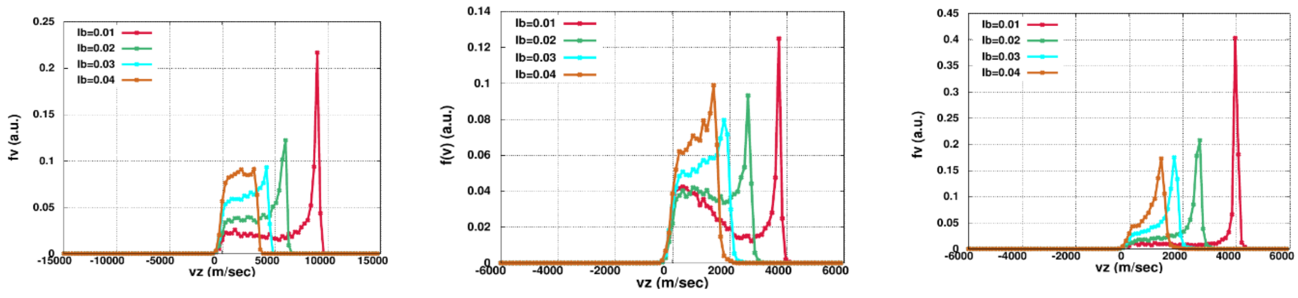
In the current work, in our numerical simulations, we have used argon, xenon and iodine as a fuel gas and compared the net thrust generation. We compare here, net particle flow and directed beam velocity in plasma expansion region for different gases with different magnetic field gradient in the plasma expansion region.

Fig.1 shows the ion velocity distribution function for different magnetic field gradient in the plasma expansion region. Here we have sampled the ion velocity distribution around z = 0.07m. For Ar case, maximum directed beam velocity is around 9000 m/sec for magnetic field gradient length *lb* = 0.01. Apart from clear signature of directed ion beam , it is observed that ion-neutral elastic and charge exchange collisions causes a broadened ion velocity distribution function. As we increase the *lb*, directed ion beam velocity is found to decrease in the plasma expansion region and for *lb* = 0.04, distribution function shows a shifted Maxwellian kind behavior. For xenon and iodine plasma case, maximum ion beam velocity is around 4000 m/sec. Here also while increasing the *lb* value, directed ion beam velocity amplitude decrease and for *lb* = 0.04 case



(a) Argon: Ion Phase Space **(b) Xenon: Ion Phase Space** **(c) Iodine: Ion Phase Space**

Figure 1: At the end of simulation time, ion phase space plot for argon, xenon and iodine where neutral fuel gas pressure is fixed at 1.23 mTorr. Here we have shown *lb* = 0.01 case.



(a) Argon (b) Xenon (c) Iodine

Figure 2: Ion velocity distribution function at z = 0.07m for argon, xenon and iodine, where fuel gas neutral pressure is fixed at 1.23 mT orr. A directed ion beam having velocity around 9km/s for argon plasma, around 4km/s for xenon and iodine plasma case are observed.

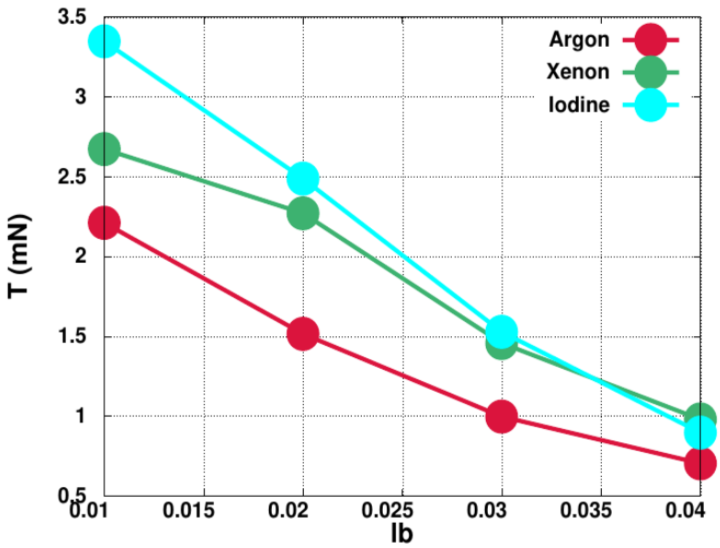


Figure 3: Net plasma thrust profile with different magnetic field divergence for argon, xenon and iodine fuels.

ion velocity distribution is near Maxwellian.

Fig.3 shows the net thrust generation for argon, xenon and iodine having different magnetic field divergence rate in the plasma expansion region. The net ion thrust has been measured at axial location z = 0.07m for magnetic nozzle configuration. Thrust measurement diagnostic is, $T = \dot{m}v_{exh}$, where $\dot{m}$ (ion flow rate × Fuel atomic mass) represents the ion mass flow rate and v_{exh} (see Fig.2) refers ion exhaust velocity. In an expanding magnetic plasma thruster, radial electron pressure is converted in an axial momentum flux and the electron temperature is reduced in the axial direction by losing their internal energy while ions get accelerated. The plasma is adiabatic in the diverging section of a magnetic nozzle, so any energy lost by the electrons must be transferred to the ions via the electric field. Total force over a bounded plasma system of magnetic nozzle is the sum of the static electron pressure force exerted on the axial boundary, Lorentz force onto a magnetic nozzle (para axial approximation for one dimensional case) and force causes by bulk electric field which arises due to sudden plasma expansion[7]. For *Ib* = 0.01 case which have largest magnetic field gradient, shows maximum thrust generation and it reduces with increasing *Ib* values. Here, low *Ib* values shows significant change in the net thrust generation for different fuel gases. Iodine shows 1.5 times jump in the thrust while compare with Ar for identical input parameters which is basically due to higher atomic mass[8-11].

The total time for simulation is 25 microseconds with a time step of 3.8e-11, with 192 PIC particles per cell and 512 grids. This is in-house-developed PIC code, parallelized using OpenAcc. The simulation is performed on a single GPU card in ANTYA.

References:

1. Goebel, D. M. & Katz, I. 2008 Fundamentals of Electric Propulsion: Ion and Hall Thrusters. Hoboken, New Jersey: John Wiley and Sons, Inc.
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3. James J. Szabo, Bruce Pote, Surjeet Paintal and Michael Robin 2011 Journal of Propulsion and Power 28(4).
4. Nicolas Bellomo, Mirko Magarotto, Marco Manente and Fabio Trezzolani 2021 CEAS Space Journal 14(1)
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6. Rafalskyi, D., Martnez, J.M., Habl, L. et al 2021 Nature 599, 411415.
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8. V. Saini, S. K. Pandey, P. Trivedi & R. Ganesh 2018 Physics of Plasmas 25, 092107.
9. V. Saini & R. Ganesh 2020 Physics of Plasmas 27, 093505.
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11. V. Saini & R. Ganesh 2024 ,Journal of Plasma Physics (June 2024,accepted).

Introduction to CUDA Libraries

NVIDIA provides a rich set of CUDA APIs and libraries that are readily available for integration into user-defined algorithms and applications. In this series, we will examine a C++ program that leverages NVIDIA's cuFFT library to execute a 3D complex-to-complex Fast Fourier Transform (FFT) using cuFFT on a dataset of complex numbers. Below, we provide a concise explanation of the CUDA calls and libraries featured in the code snippet. The complete source code can be accessed here.

```
##Cuda Initialization

CUFFT_CALL(cufftCreate(&plan));

## Configuring the plan, specifying the dimensions, data layout, transform type, batch size

CUFFT_CALL(cufftPlanMany(&plan, fft.size(), fft.data(), nullptr, 1,
                         fft[0] * fft[1] * fft[2],            // *inembed, istride, idist
                         nullptr, 1, fft[0] * fft[1] * fft[2], // *onembed, ostride, odist
                         CUFFT_C2C, batch_size));

## to perform asynchronous data
CUDA_RT_CALL(cudaStreamCreateWithFlags(&stream, cudaStreamNonBlocking));

## transfers and FFT computations
CUFFT_CALL(cufftSetStream(plan, stream));

## Allocate Memory
CUDA_RT_CALL(cudaMalloc(reinterpret_cast<void **>(&d_data),
                        sizeof(data_type) * data.size()));

## Transfer data from CPU to GPU
CUDA_RT_CALL(cudaMemcpyAsync(d_data, data.data(),
                        sizeof(data_type) * data.size(), cudaMemcpyHostToDevice, stream));

## Forward FFT – Time to Freq.
CUFFT_CALL(cufftExecC2C(plan, d_data, d_data, CUFFT_FORWARD));
## Backward FFT – Freq. to Time
CUFFT_CALL(cufftExecC2C(plan, d_data, d_data, CUFFT_INVERSE));

## Transfer data from GPU to CPU
CUDA_RT_CALL(cudaMemcpyAsync(data.data(), d_data, sizeof(data_type) * data.size(),
                        cudaMemcpyDeviceToHost, stream));

## Wait till Streams are Complete
CUDA_RT_CALL(cudaStreamSynchronize(stream));

## Freeing Resources ##
CUDA_RT_CALL(cudaFree(d_data))
CUFFT_CALL(cufftDestroy(plan));
CUDA_RT_CALL(cudaStreamDestroy(stream));
CUDA_RT_CALL(cudaDeviceReset());
```

Parameters

Build and run the example above as,

```
$ module load cuda10.2/toolkit/10.2.89
$ mkdir build
$ cd build
$ cmake ..
$ make

$ ./3d_c2c_example
```

Fascinating Insight: The algorithm's time complexity is O(nlogn). Interested readers intrigued by the algorithm's performance characteristics, can investigate the specific portion of the algorithm that consumes the most time

Input	Output
(base) [agraj@gn15 bin]$ ./3d_c2c_example Input array: 0.000000 + 0.000000j 1.000000 + -1.000000j 2.000000 + -2.000000j 3.000000 + -3.000000j 4.000000 + -4.000000j 5.000000 + -5.000000j 6.000000 + -6.000000j 7.000000 + -7.000000j 8.000000 + -8.000000j 9.000000 + -9.000000j 10.000000 + -10.000000j 11.000000 + -11.000000j 12.000000 + -12.000000j 13.000000 + -13.000000j 14.000000 + -14.000000j 15.000000 + -15.000000j	Output array: 0.000000 + 0.000000j 8.000000 + -8.000000j 16.000000 + -16.000000j 24.000000 + -24.000000j 32.000000 + -32.000000j 40.000000 + -40.000000j 48.000000 + -48.000000j 56.000000 + -56.000000j 64.000000 + -64.000000j 72.000000 + -72.000000j 80.000000 + -80.000000j 88.000000 + -88.000000j 96.000000 + -96.000000j 104.000000 + -104.000000j 112.000000 + -112.000000j 120.000000 + -120.000000j

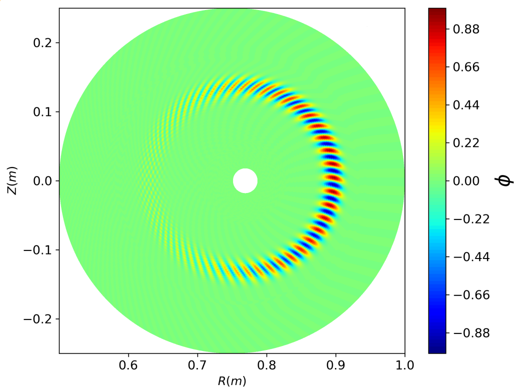
ANTYA UPDATES AND NEWS

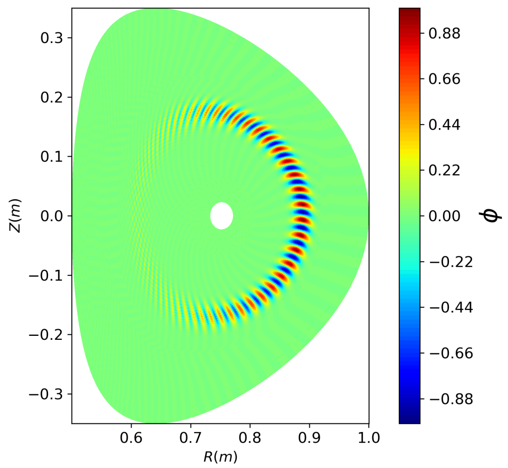
1. New Packages/ Applications Installed

>> openmpi-singu/4.0.1
This module is compiled using singularity, to bind MPI environment into singularity containers.

To check the list of available modules
$ module avail –l

HPC PICTURE OF THE MONTH



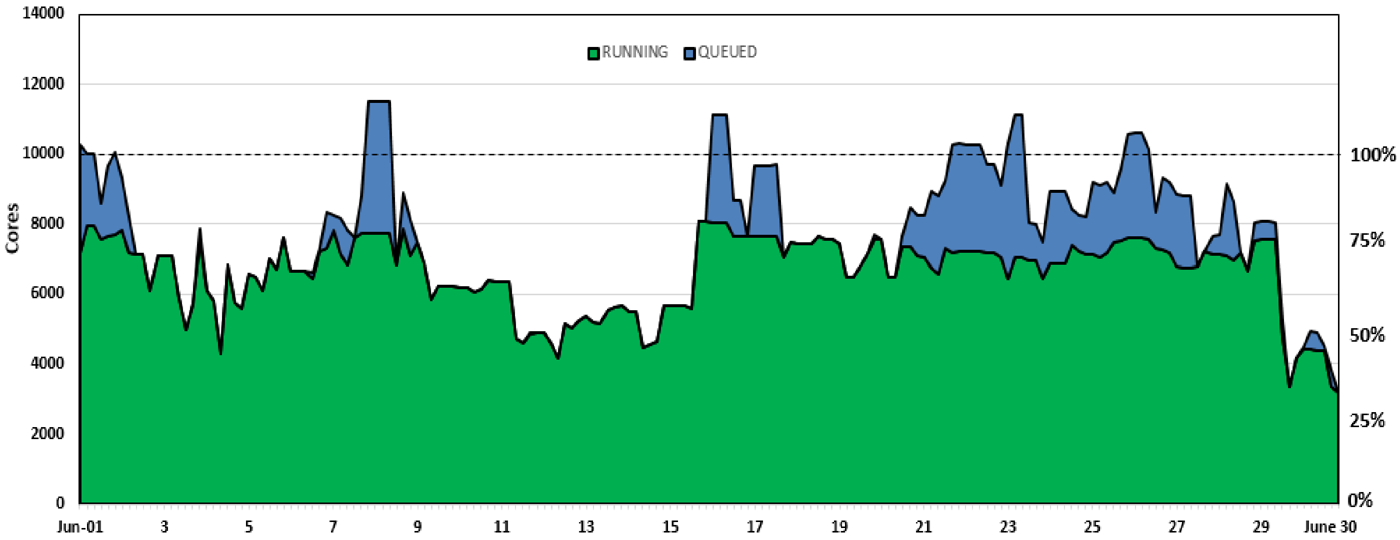


Pic Credit: Amit Singh

Linear Poloidal mode structures of the electrostatic potential in the (R, Z) plane for ITG-TEM simulations for the circular (elongation=1.0) and shaped (elongation=1.4) equilibrium of ADITYA-U for toroidal mode number n = 25. Mode structures are plotted here at the final time of simulation

ANTYA Utilization: JUNE 2024

ANTYA Daily Observed Workload



Other Recent Work on HPC

The Role of Helical and Non-Helical Drives on the evolution	Shishir Biswas
Efficient Data-driven Simulation of Microwave Interaction With Complex Plasma Profiles	Dr. Pratik Ghosh
Design and Investigation of View-Dump for Vertical Electron Cyclotron Emission (V-ECE) Receiver System	Prabhakar Tripathi
Excitations of Cylindrical and Spherical Pinned Solitons in a Flowing Dusty Plasma Medium: Experimental and Simulation Studies	Prasanta Amat
Spontaneous Convective Patterns in a Dusty Plasma	Ankit Dhaka
Applicability of BCA using SDTrimSP in Fusion Science & Technology Areas	Varun Vijay Savadi
Subcritical turbulence at large aspect ratios in 3D Yukawa	Suruj Jyoti Kalita
Engineering Design of a Prototype Center Stack Toroidal Field Coil for Spherical Tokamak	Aditya Kumar Verma
Influence of Fluid Helicity on Turbulent Dynamo Action	Shishir Biswas
Simple fluid approach for the nonlinear excitations in Yukawa fluids	Prince Kumar
Ion temperature gradient effects on plasma blob formation	Nirmal K. Bisai
Comparison of Unmitigated and Mitigated Disruptions with Tungsten and Beryllium wall in ITER	Trivesh Kant

ANTYA HPC USERS' STATISTICS— JUNE 2024

Total Successful Jobs~ 1464

♦ **Top Users** (Cumulative Resources)

- **CPU Cores** Amit Singh
- **GPU Cards** Anjan Paul
- **Walltime** Amit Singh
- **Jobs** Arzoo Malwal

Acknowledgement

The HPC Team, Computer Division IPR, would like to thank all Contributors for the current issue of *GAṆANAM*.

On Demand Online Tutorial Session on HPC Environment for New Users Available
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