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3D CFD Analysis of the NBI Ion Source Back Plate

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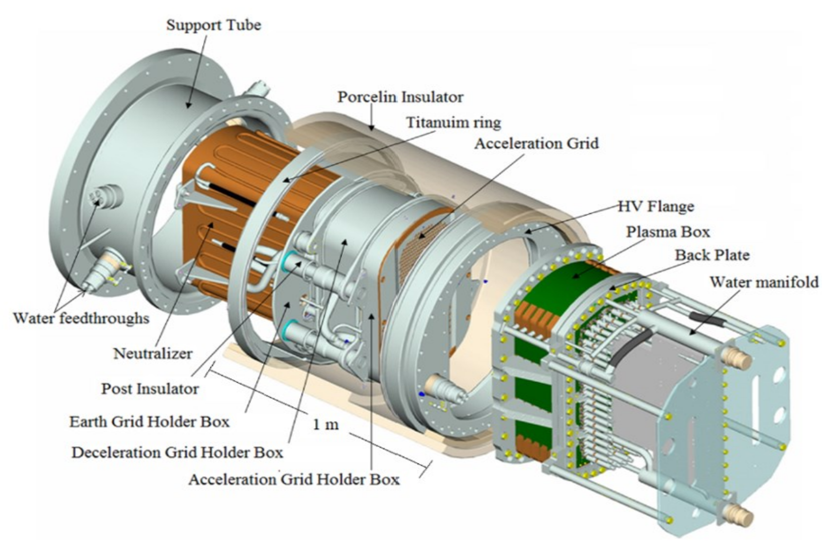

Fig. 1 NBI ion source [3]

Neutral Beam Injection (NBI) is a well-established technique for Tokamak plasma heating and current drive [1, 2]. The Steady State Superconducting Tokamak-1 (SST-1) has a provision of a positive ion-based NBI (PNBI) system, which can produce a neutral hydrogen beam power of 1.7 MW at 55 keV [3]. The ion source is the heart of the NBI system as shown in Fig. 1.

The back plate (BP) is an important component of the NBI ion source. It has several functions in the ion source operation e.g. it provides vacuum integrity to the plasma chamber, holds permanent magnets in position which are required for plasma confinement, provides gas to the plasma source, and also acts as a heat removal component. The BP consists of 3 components e.g. SS304L Magnet Positioning Plate, SS304L Magnet Cover Plate, and OFE Copper Cooling Plate. Fig.2 depicts the 3D CAD model of BP. Inlet water flows into the inlet manifold, which splits into two sub-manifolds: one with an inner diameter (ID) of 20.9 mm, supplying water to 35 cooling channels in the OFE copper plate, and the other with an ID of 15.8 mm, delivering water to the outer 8 cooling channels as shown in Fig.3. This study presents a 3D Computational Fluid Dynamics (CFD) analysis of the actual sized back plate using ANSYS 2021R1. The analysis is conducted under a steady heat load of 2.5 MW/m² applied to the Oxygen Free Electronic (OFE) copper cooling plate. Cooling water is supplied through the inlet header of the back plate at a mass flow rate of 1 kg/s and a temperature of 34°C. The results provide the surface temperature distribution of the OFE copper cooling plate, showing a maximum temperature of 174°C and an average temperature of 122°C. These findings show good agreement with the High Heat Flux Test (HHFT) experimental results [4].

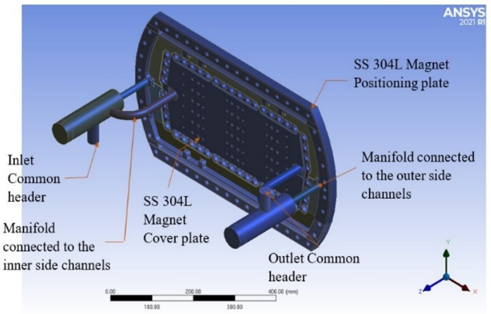

Fig. 2 Three-dimensional CAD model of actual sized Back Plate [6].

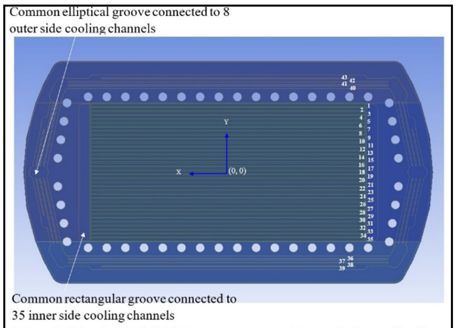

Fig. 3 Model of OFE copper cooling plate with the position of 43 (35 are at the inner side and 8 are at the outer side) cooling channels [6].

The present 3D CFD model is simulated using a pressure-based solver, as previous studies [5] have shown that this solver is particularly effective for addressing incompressible fluid flow problems. The momentum, turbulence, and energy equations are discretized implicitly using the second-order upwind method. The solution is obtained iteratively, employing the Semi-Implicit Method for Pressure-velocity Linked Equation (SIMPLE) algorithm. The convergence criterion for the simulation is set to 1 × 10^{-4}. The entire simulation is conducted on the ANTYA cluster (16-core CPU) with visualization mode, which significantly reduces the simulation time. A single simulation run on the ANTYA cluster takes 45 minutes, whereas it would take 3 to 4 hours on a typical single-core CPU system. This facility is available in the Institute for Plasma Research (IPR).

3D computational fluid dynamics analysis of PINI ion source back plate under high heat flux conditions The CFD analysis results [6] for the actual 3D model of the Back Plate are obtained through multiple iterations. Fig. 4a displays the contour plot of water velocity distribution at the mid-plane of the cooling channels. The average water velocities for the 35 inner channels are shown at different locations (Planes A, B, and C) in Fig. 4b, revealing a non-uniform distribution. This is consistent with the velocity distribution observed in the contour plot in Fig. 4a. The maximum velocity of 14.2 m/s is observed in cooling channel no. 17, while the minimum velocity of 4.1 m/s is found in the channels no. 6 and 30. Higher velocities are seen in the middle region (channels no. 10 to 26) due to their closeness to the inlet header and lower hydraulic resistance. In contrast, velocities in channels no. 1 to 9 and no. 27 to 35, located away from the common inlet manifold, are lower due to higher hydraulic resistance. It is observed that velocity increases from 4.1 m/s to 6.8 m/s in channels 6 to 2 and from 4.1 m/s to 6.9 m/s in channels 30 to 34 on both sides of the inlet water header (Fig. 4b). It then decreases slightly from 6.8 m/s to 6.5 m/s in channels 2 to 1 and from 6.9 m/s to 6.6 m/s in channels 34 to 35 due to the inertia effect.

This is an interesting finding of the inertia effect has been confirmed by simulating the result of the velocity distribution considering the air as fluid (shown in Fig. 5). This shows that velocity decreased from channel no. 17 to channel no. 1 and 35 as shown in Fig. 5. Fig. 6 shows the results of the ANSYS-simulated temperature distribution over the surface of the OFE copper cooling plate.

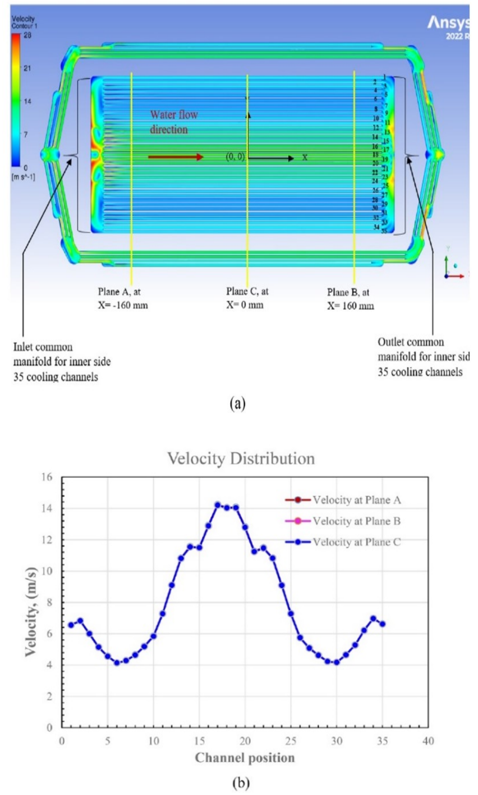

Fig. 4 (a) Contour plot of velocity distribution (b) Plot of average velocity distribution at the plane A, B, and C with water as fluid [6].

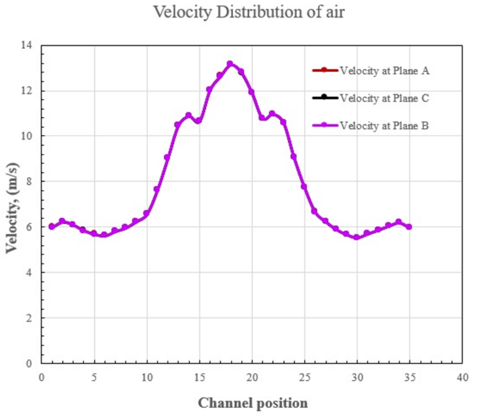

Fig. 5 Plot of average velocity distribution at the plane A, B, and C with air as fluid.

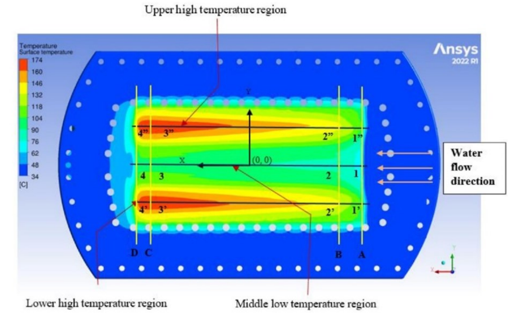

Fig. 6 Results of surface temperature distribution over OFE copper plate surface using 3D CFD BP model [6].

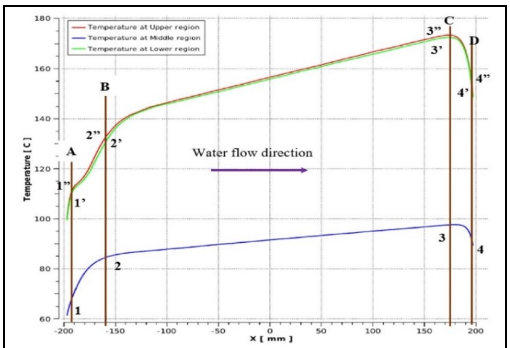

Fig. 7 Temperature profile on the OFE copper surface along the water flow direction [6].

The surface temperature distribution is divided into three regions: (i) the Upper region (channels 1–9, as shown in Fig. 3) exhibits a maximum surface temperature of 174°C, (ii) the Middle region (channels 10–26) shows a maximum temperature of 97°C, and (iii) the Lower region (channels 27–35) reaches a maximum temperature of 172°C. The temperature variations are due to non-uniform velocity distribution and thermal resistance within the non-uniform cross-section of the channels. CFD analysis indicates that the average surface temperature of the OFE copper cooling plate is 122°C.

Fig. 7 illustrates the quantitative results of the spatial temperature profile (along the X direction) across three distinct temperature regions: lower (green curve), middle (blue curve), and upper (red curve). It is observed that the surface temperature of the OFE copper cooling plate gradually increases towards the outlet in all three regions. This is attributed to the rise in water temperature along the channels, as the bulk water temperature increases with flow advance towards the outlet. It is also observed that the OFE copper-water interface temperature is 162°C, which is below the boiling point (171°C at 8.2 bar), confirming the absence of nucleate boiling.

The HHFT experiment [4] is conducted on the Back Plate (BP) with an incident heat flux of 2.5 MW/m² using a 200 kW electron beam over an interface area of 400 × 200 mm² on the OFE copper cooling plate, at the IPR, High-Temperature Technology Division (HTTD). Cooling water is supplied at a mass flow rate of 1 kg/s and an inlet temperature of 34°C, flowing through CNC-machined cooling channels (Fig. 3) of the OFE copper plate. Infrared (IR) measurement shows that there are three temperature regions: Upper high-temperature region, Middle low-temperature region, and Lower high-temperature region respectively due to non-uniform water velocity distribution caused by non-uniform cross-section of the cooling channels and manifolds. The IR measurement shows the maximum surface temperature at upper, middle, and lower regions are 173°C, 114°C and 162°C respectively.

In conclusion, the CFD analysis reveals that the maximum surface temperature variations between the CFD and IR results for the upper region, middle region, and lower region are 0.57 %, 14.91 %, and 6.17 % respectively. These variations arise from factors such as surface roughness, emissivity, and the IR camera's viewing angle, which are not considered in the CFD analysis. The study effectively explains the three temperature regions observed in IR measurements during high heat flux tests and demonstrates good agreement with IR camera results. It is also concluded that the surface temperature distribution is directly correlated with the non-uniform velocity distribution inside the cooling channels along with the inertia effect. Additionally, CFD analysis confirms that there is no nucleate boiling in the cooling channels of the OFE copper plate. This CFD analysis results show that the NBI ion source back plate can be used for long pulse operation.

References:

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Fundamental HPC Technologies for Optimized Performance

HPC users often struggle with optimizing their workflows due to the rapid evolution of technologies. Understanding and effectively utilizing the latest tools can significantly enhance performance, efficiency, and scalability. This article will guide users through essential HPC technologies, offering insights into their applications, best practices, etc. By following these practices for compilers, libraries, job schedulers, GPU acceleration, and monitoring tools, users can significantly improve their workflows.

A) Choosing the Right Compiler for HPC Applications

Compilers play a crucial role in optimizing HPC workloads. Different compilers optimize code differently, impacting overall HPC application performance.

- **Intel Compiler/Intel oneAPI**: Best for Intel-based architectures, offers auto-vectorization.
- **GCC**: Open-source and widely supported.
- **Nvidia HPC SDK**: Designed for GPU-accelerated applications, supports CUDA and OpenACC.

Best Practices:

- Use compiler flags like -O3 for better optimizations.
- Test with different compilers to determine the best fit.

B) Libraries for Performance Optimization

Users often rely on libraries to speed up their computations instead of writing everything from scratch. Using optimized libraries eliminates the need to write custom code for common mathematical operation

- **MPI (Message Passing Interface)**: For parallel computing across multiple nodes.
- **OpenMP:** Enables multithreading on shared-memory systems.
- **PnetCDF and HDF5**: Efficient I/O handling for large-scale data.

Best Practices:

- Implement hybrid programming with MPI + OpenMP for better resource utilization.

C) Job Scheduling with PBS

Efficient job management ensures faster execution and better cluster utilization.

- **PBS Scheduler**: Common in many HPC environments, allows job arrays and dependencies.

Best Practices:

- Request only necessary resources (ncpus, mem, walltime) to avoid wastage.
- Use job dependencies (afterok) to automate multi-stage workflows.

D) GPU Acceleration and CUDA Optimization

HPC workloads benefit significantly from GPU acceleration.

- **CUDA**: NVIDIA’s parallel computing framework.

Best Practices:

- Use CUDA streams and memory optimizations to maximize GPU performance.

E) Monitoring and Debugging HPC Jobs

Understanding job performance can help identify inefficiencies.

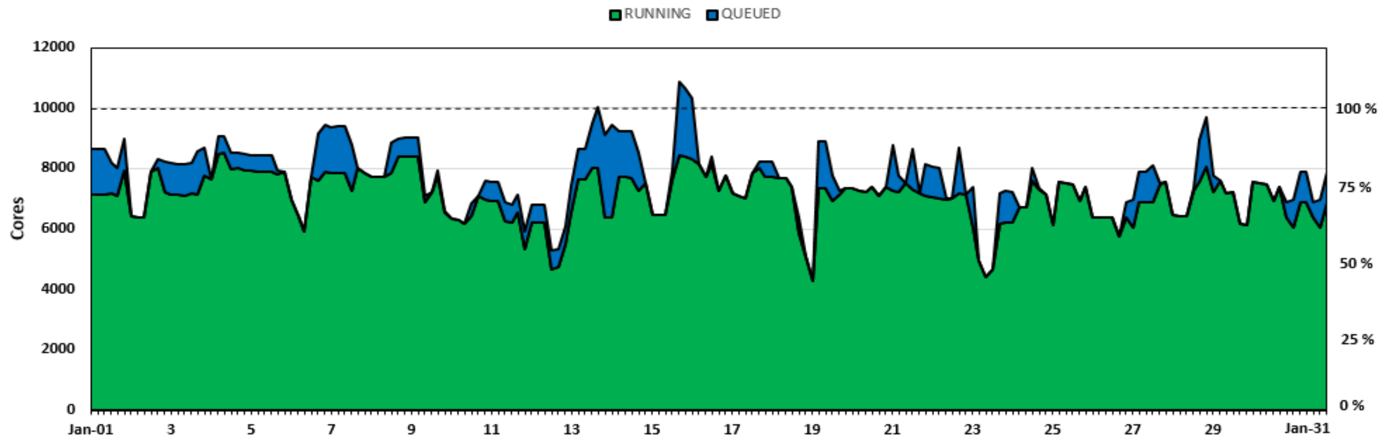
- **qstat**: Monitor job status in PBS and Slurm.
- **Intel VTune, NVIDIA Nsight**: Profile CPU and GPU usage.

Best Practices:

- Analyze logs (stderr, stdout) for failed jobs.

ANTYA Utilization: January 2025

ANTYA Daily Observed Workload



Other Recent Work on HPC

Study on the Reduction of Air Drag in the Presence of Dielectric Barrier Discharge Plasma	**Jugal Chowdhury**
Design and analysis of Solid Breeder Blankets for Indian future fusion reactors	**Deepak Sharma**
Design and Experimental validation of Pattern and Frequency Reconfigurable Central Plasma Antenna Array	**Manisha Jha**
HTS magnet development activities for the Indian fusion programme	**Upendra Prasad**
R&D activities carried out for cryopumping to provide customized needs for Fusion Research	**Samiran Mukherjee**
Design and Analysis of Heat Extraction and Power Conversion Systems for a Gross Electricity Producing Fusion Pilot Plant	**Dr. Piyush Prajapati**

ANTYA UPDATES AND NEWS

1. New Packages/ Applications Installed

=> New modules have been installed in ANTYA

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

ANTYA HPC USERS' STATISTICS— JANUARY 2025

Total Successful Jobs~ 936

♦ **Top Users** (Cumulative Resources)

● CPU Cores	**Amit Singh**
● GPU Cards	**Suruj Kalita**
● 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*.

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