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Deconfinement of runaway electrons by local vertical magnetic field perturbation

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Runaway electrons (REs) [1], having energies up to several MeV, get generated under certain plasma conditions such as disruptions or high-power heating, pose significant risks to reliable tokamak operations to small scale tokamaks and severe damage to reactor components, particularly in large-scale devices like ITER and DEMO. Therefore, the deconfinement and suppression of REs are critical for the sustainable operation of tokamaks and fusion reactors. Among various mitigation techniques developed to manage REs, including massive gas injection (MGI), shattered pellet injection (SPI), and gas puffing, the active magnetic field control techniques such as resonant magnetic perturbation (RMP) and local vertical magnetic field (LVF) perturbations assisted deconfinement methods have more versatile benefits over the others.

Though RMPs have been applied in several tokamaks achieving varying levels of success, they have shown limited efficacy in larger devices such as ITER. On the other hand LVF assisted RE deconfinement experiments are only conducted in VERSATOR-I [2] and ADITYA [3] tokamak with no detailed numerical modelling supporting these experimental findings of successfully deconfining the REs in those plasma operations. This article focuses on mitigating the dangers posed by runaway electrons (REs) in tokamaks using local vertical field (LVF) perturbations and thereby exploring the capabilities of the technique by numerically modelling such experiments conducted in ADITYA tokamak.

In the LVF assisted RE deconfinement experiments conducted in ADITYA tokamak a pair of up-down symmetric LVF coil in Helmholtz-like configuration, as shown in figure 1, is used to produce LVF perturbation of 150 to 260 G at the major radius R_0 = 75 cm of the tokamak. In the experiment, a significant reduction (about five times) in HXRs was observed in the initial phase of discharges in which the LVF perturbation was applied (shot #24976, 5–10 ms) compared with the case when LVF was not applied (shot #24969), as shown in figure 2. This means that the REs are extracted from the plasma before gaining higher energies without affecting the thermal component of the plasma in typical ADITYA discharges. Without the LVF, HXR emission continues for longer during the breakdown and current ramp-up phases. However, HXR emission ceases once the LVF is applied.

To this end, the pre-existing PARTICLE [4] code has been extended to the relativistic full-orbit-following code PARTICLE-3D (P3D) [5] integrated with the magnetic field calculation code EFFI and plasma equilibrium field calculation code IPREQ to include the required fields for modelling particle dynamics in general; which is then used to numerically model LVF perturbation-assisted RE deconfinement experiments conducted in the ADITYA tokamak.

Figure 3 shows P3D simulated RE drift orbits along with the originating plasma equilibrium surface for different energies and velocity direction. The co- and counter-passing RE orbits follow different paths for the same energy; the co-passing orbit shrinks the orbit volume on the inboard side while the counter-passing orbit does the opposite, i.e. it expands on the inboard side. Also, it is observable that with higher energy, their shrinkage or expansion is higher as per the velocity direction. The P3D code has been tested by studying the physical phenomenon of relativistic energy and momentum conservation along with accurately capturing the Banana orbit topology, a strikingly complex phenomenon exclusive to the magnetic field topology of the tokamak. Details of these studies are presented in Ref.[5].

P3D simulations suggest that for both positive and negative cases the perturbation field breaks the symmetry of the drift orbits obtained for the no LVF case. In the case of negative LVF confinement zone shrinkage takes out the REs in the outer plasma region towards the edge of the plasma, while in the positive LVF case the drift orbit topology is strikingly different from that of the negative LVF case. The expansion of the confinement zone for positive LVF, shrinking of the confinement zone for negative LVF and, for both cases, merging and bunching of the drift orbits for 3 MeV REs in the inboard side of the plasma region are clearly observable from the poloidal view of the Poincaré section plots in figure 4.

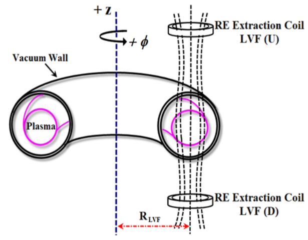


Figure 1. Schematic of the Helmholtz-like LVF coil configuration used for RE deconfinement in ADITYA, illustrating the placement and structure of the LVF coils, which generate the required magnetic perturbations for RE suppression

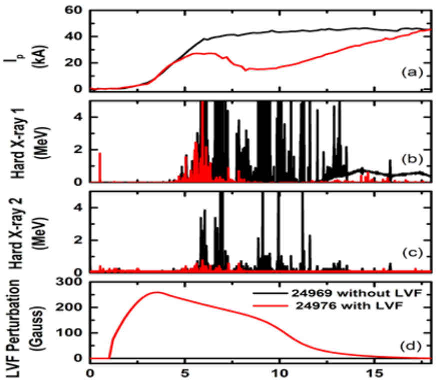


Figure 2. Comparison of ADITYA plasma discharges with and without LVF perturbation, showing the temporal evolution of the hard x-ray (HXR) signal, which is used as an indicator of RE presence. The figure demonstrates a significant reduction in REs when LVF perturbation is applied

Detailed analysis of P3D simulation studies with multiple REs, provided a deeper understanding of RE deconfinement mechanisms, revealing that the direction and magnitude and configuration of the LVF perturbation as shown in figure 5 plays a critical role in RE suppression. A threshold magnitude of the perturbation field was identified, which varied depending on the energy of the REs. For higher-energy REs, a stronger LVF perturbation was required for deconfinement, while lower-energy REs could be deconfined with lower perturbation magnitudes.

Simulation results presented in figure 6, for RE loss fraction studies (achieved deconfinement up to 90% of REs in different phases of plasma operation) were consistent with experimental observations from ADITYA tokamak, where RE suppression was achieved through LVF perturbations. The study also reveals a strong correlation between the safety factor (q) profile at the plasma edge and the effectiveness of RE deconfinement. REs originating from the plasma edge (ψ_N > 0.7) being more prone to be lost with LVF perturbations, depending on the q-profile and the direction of the perturbation.

Different simulation results require specific run configurations; for instance, Figure 6 illustrates the outcome of six separate simulations, each utilizing 120 cores with a wall-time of approximately 3 hours per run. These were executed as PBS array jobs using the Intel-2020 compiler (ifort) along with its runtime libraries and built-in subroutines.

In conclusion, this study [5] demonstrates the effectiveness of LVF perturbation as a technique for RE deconfinement in tokamaks. Using the PARTICLE-3D code, the research shows that a properly directed LVF perturbation can achieve significant RE suppression, closely aligning with experimental results from the ADITYA tokamak. These findings suggest that LVF perturbation, particularly when combined with other mitigation methods, could serve as a viable solution for RE suppression in larger tokamaks like ITER.

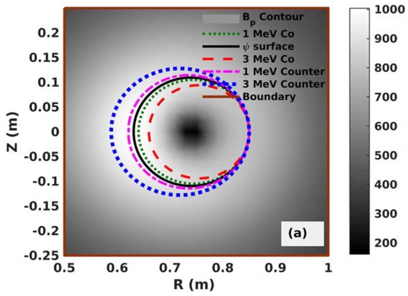


Figure 3. 2D drift orbits of REs with different energies (1 and 3 MeV) under various configurations (co-passing and counter-passing), illustrating how REs deviate from their original trajectories under the influence of drifts experienced by those REs

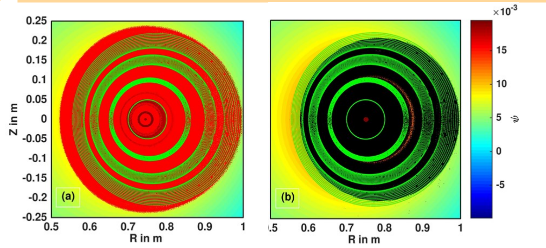


Figure 4. 2D Poloidal view of Poincaré section plot of drift orbits for 3 MeV co-passing REs with (a) positive LVF (red) and no LVF (green) and (b) negative LVF (black) and no LVF (green). The LVF perturbation generated by 4.3 kA of current in the LVF coils (50 turns) is shown for both positive and negative configurations. The figure reveals how LVF perturbations alter the confinement zone of the REs, leading to deconfinement.

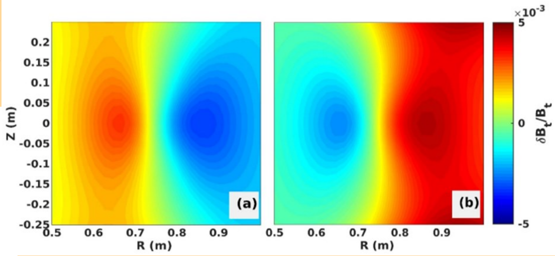


Figure 5. Configuration of total magnetic field perturbation δBt/Bt on the ϕ = 0 plane for (a) a negative LVF perturbation of 4.3 kA and (b) a positive LVF perturbation of 4.3 kA .

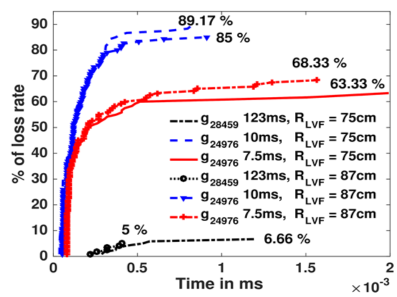


Figure 6. Loss fraction study of 3 MeV REs with negative LVF perturbation generated by 4.3 kA current with two different RLVF positions and for three different plasma equilibria: shot 24976 at 7.5 ms, shot 24976 at 10 ms and shot 28459 at 123 ms.

References:

[1] Lehnen M. et al 2015 J. Nucl. Mater. 463 39
[2] Stone D.S. and Richards B. 1978 Phys. Fluids 21 149–50
[3] Tanna R.L. et al 2015 Nucl. Fusion 55 063010
[4] Dutta S et al 2019 Plasma Sci. Technol. 21 105101
[5] Someswar Dutta et al 2024 Nucl. Fusion 64 096027

Quick Guide to Boosting I/O Performance in HPC Workflows

In High-Performance Computing (HPC), optimizing computation is only part of the equation—data transfer and I/O (Input/Output) can often be the hidden bottleneck in workflows. For data-intensive tasks like large simulations or machine learning, slow I/O can cause significant delays. Fortunately, there are practical ways to improve I/O performance, making workflows faster and more efficient. This guide provides essential strategies for users to manage data handling and I/O effectively in HPC environments.

1. CHOOSE EFFICIENT FILE FORMATS

Formats: HDF5, netCDF

Using efficient file formats like **HDF5** and **netCDF** can improve data handling speed. These formats support parallel I/O and enable high-speed data access for large datasets. Install them in user's environment (e.g., via Spack or modules), and structure the data to take advantage of compression and efficient read/write operations.

2. ENABLE PARALLEL I/O FOR HIGH THROUGHPUT

Libraries: MPI-IO, Parallel HDF5, Parallel netCDF

Parallel I/O distributes read/write tasks across multiple nodes, which can significantly speed up data-heavy applications. If the application uses MPI, consider using **MPI-IO** or parallel versions of **HDF5** and **netCDF**. By enabling these, the program can perform multiple I/O operations concurrently, reducing waiting time.

```
import h5py
from mpi4py import MPI

comm = MPI.COMM_WORLD
with h5py.File("data.h5", "w", driver="mpio", comm=comm) as f:
  f.create_dataset("dataset", data=[...]) # Parallel I/O enabled
```

3. PROFILE I/O PERFORMANCE TO FIND BOTTLENECKS

Profiling tools provide insights into I/O performance, helping identify bottlenecks. This helps pinpoint areas for improvement.

4. ORGANIZE AND CHUNK DATA FOR FASTER ACCESS

Efficient data layout and chunking are key to reducing I/O time. Store data in sequential chunks (e.g., by time or spatial coordinates) to improve access patterns. HDF5 and netCDF support built-in chunking options, allowing to divide data into manageable pieces for faster reading and writing.

5. COMPRESS DATA TO SAVE SPACE AND TRANSFER TIME

Tools: HDF5 Compression, Gzip, pigz

Compressing data reduces storage space and speeds up transfers, which is useful when dealing with large datasets. In **HDF5**, enable internal compression; for other files, use external tools like **Gzip**. Smaller data size means quicker I/O operations and reduced storage needs.

```
gzip large_data_file.txt # Compress a file to reduce size
```

6. USE EFFICIENT TRANSFER TOOLS FOR MOVING DATA

Tools: Rsync, SCP

For transferring files across nodes or storage systems, use optimized tools like **Rsync** (for incremental updates). These tools handle large files more efficiently than basic copy commands.

```
rsync -avz large_file user@remote:/destination
```

7. MONITOR STORAGE TO AVOID I/O DISRUPTIONS

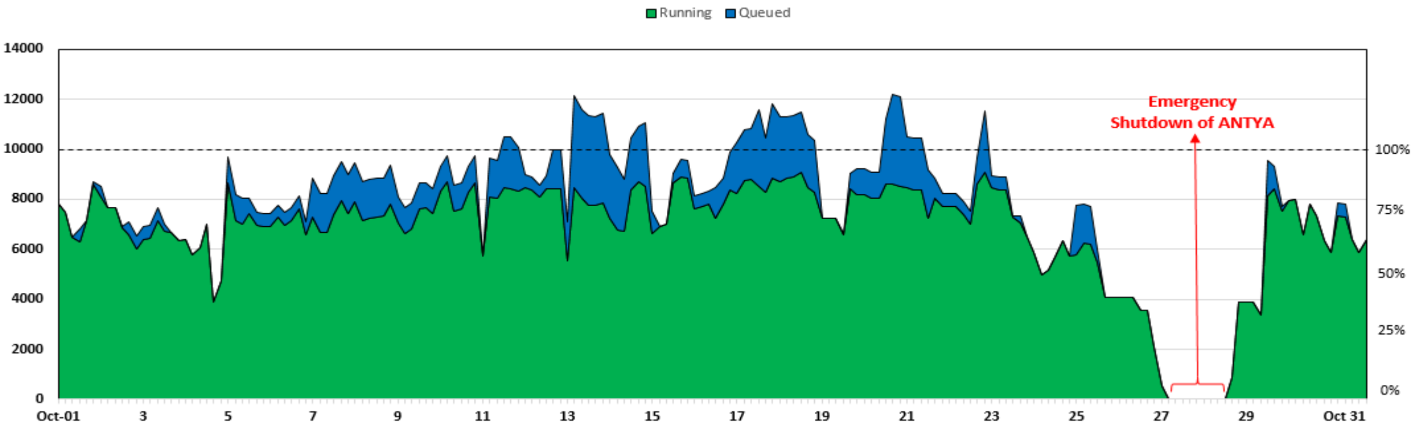
Regularly check storage usage to avoid hitting quota limits, which can disrupt jobs. Use below mentioned command to monitor disk space and clean up unnecessary files to maintain smooth I/O operations.

```
du -h --max-depth=1 /directory_name        # Check directory sizes
mmlsquota --block-size auto                # Monitor quota usage
```

By applying these simple strategies, users can optimize data transfer and I/O performance in HPC environments. Efficient file formats, parallel I/O, data organization, compression, and proper transfer tools collectively minimize I/O bottlenecks, helping users get the most out of HPC resources. Small improvements in I/O management can lead to significant gains in performance, keeping workflows fast and efficient.

ANTYA Utilization: OCTOBER 2024

ANTYA Daily Observed Workload



Other Recent Work on HPC

Integrated experiment control system for Inverse Mirror Plasma Experimental Device (IMPED)	Jigneshkumar Jagjivandas Patel
Effect of Reversed Magnetic Shear in ADITYA-U Tokamak	Gopal Krishna M
Numerical study of two phase liquid nitrogen flow in square tube with varying heat flux	Arvind Kumar Tomar
Particle-in-cell simulation of electron acceleration from thin foils by tightly focused few-cycle Gaussian laser beam	Mrityunjay Kundu
Transformer-Based Deep Learning Model to Predict Disruptions at ADITYA-U	Rameshkumar Babubhai Joshi
Simulations of Collective Excitations in Strongly Coupled Media	Prince Kumar
Driven Ion Acoustic BGK Mode	Chingangbam Amudon
3D Simulation and Measurement of Magnetic Field in Aditya –U Tokamak	Ananya Kundu
Simulations of low frequency whistler mode waves in space and laboratory plasmas	Devendra Sharma
Detection and compensation of error field in ADITYA-U tokamak	Rohit Kumar
Neutral Gas Puff Transport Modeling Using DEGAS-2 Code	Ruchi Varshney
Plasma transport study with 3D shaped first wall for limiter start -up phase of ITER	Arzoo Malwal
Off-target gradient-driven flows in inboard limited Aditya-U Plasmas	Arzoo Malwal
Quasi-Longitudinal Whistlers in the Lower Hybrid Regime	Gayatri Bhayyaji Barsagade
Study of Collisionless Heating using particle in cell method in Capacitively Coupled Plasma (CCP) discharge	Rishabh Singh
Tritium-Titanium Target Degradation Studies Using SDTrimSP Simulations & Experimental Validation Using 14 MeV Neutron Generator at IPR	Varun Vijay Savadi

ANTYA UPDATES AND NEWS

1. New Packages/ Applications Installed

=> New modules have been installed in ANTYA

1) Quantum Espresso
module load qe/7.2

2) Smilei
module load smilei

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

ANTYA HPC USERS' STATISTICS— OCTOBER 2024

Total Successful Jobs~ 928

♦ **Top Users** (Cumulative Resources)

- **CPU Cores** — **Amit Singh**
- **GPU Cards** — **Shishir Biswas**
- **Walltime** — **Amit Singh**
- **Jobs** — **Someswar Dutta**

Acknowledgement

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