Towards the use of AI for predicting and controlling transport and losses of energetic particles in fusion plasmas

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Energetic particles → Ubiquitous in fusion plasmas

Three sources of energetic particles (ions) in fusion plasmas

→ RF heating (ICRH): perpendicular heating up to MeV

→ Neutral Beam Injection (NBI): tangential or perpendicular injection

→ Fusion plasma in future reactors

$$D + T \longrightarrow \alpha + \mathrm{n}$$

Deuterium (D) and Tritium (T) at 10keV ↔ Thermal plasma (E_{th})

Alpha particle (α) at 3.5 MeV, isotropic, slowing-down on e^-

Neutron (n) at 14.1 MeV

α particles must remain sufficiently well confined to transfer their energy to the thermal plasma via Coulomb collisions → Self-sustained reaction

Energetic particles → A major challenge for fusion

EP are not described by a Maxwellian distribution function (positive gradients in phase-space)

→ Instabilities can be triggered via a wave-particle interaction

→ EP transport and losses enhanced

Fusion plasma: steep profiles of density and temperature

→ Micro-turbulence

→ Limit thermal confinement

Instabilities ↔ Energetic Particles ↔ Micro-turbulence

Importance of prediction & control of α particle confinement in the presence of MHD instabilities and micro-turbulence

KAMITEP project funded by A*Midex 2015-2018

Main results presented at FRFCM Colloquium in 2016 and 2018

Gyro-kinetic simulations of MeV ions → Improved confinement

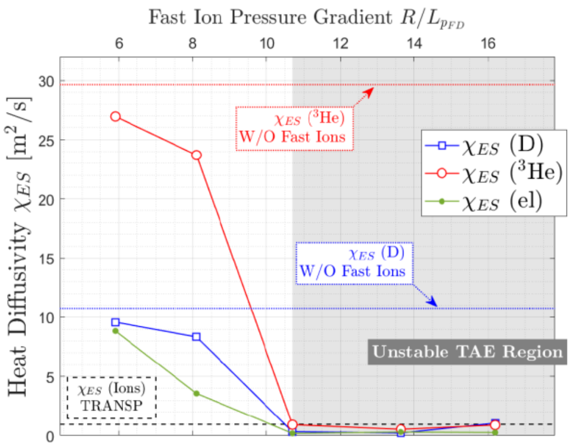
Improved thermal confinement in experiments in JET with 3-ion heating scheme [Y. Kazakov Nat. Phys. 2017]

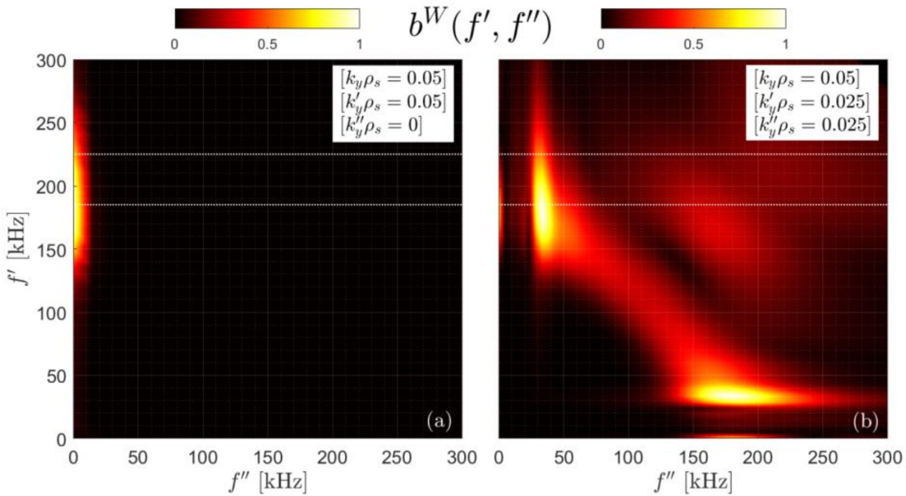
Modelling with GENE code in agreement with the observations

Nonlinear coupling TAE-ZFs-low freq modes → Turbulence suppression

S. Mazzi *et al* 2022 *Nat. Phys.* (in press)

S. Mazzi *et al* 2022 *PPCF* (in preparation)





GPU particle tracing → Increased statistics for particle transport

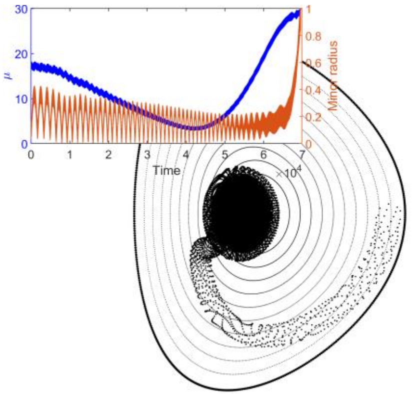
Need to analyse in detail the transport and losses of α particles → development of a new accelerated particle tracing code in collaboration with IDRIS.

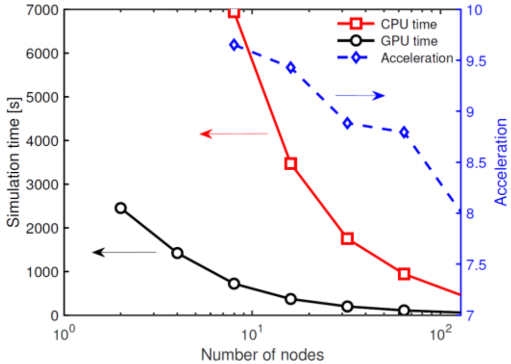
TAPAS, for **T**oroidal **A**ccelerated **PA**rticle **S**imulator [D. Zarzoso *et al* 2022 *PPCF*]

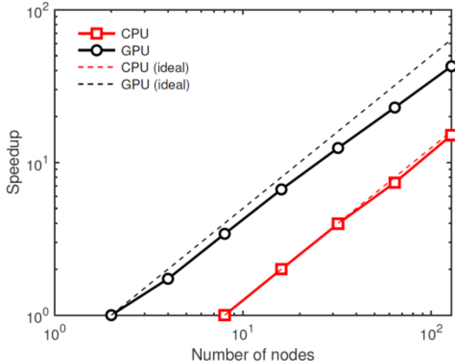
- Three possibilities: guiding-centre (with and w/o gyro-average) and full-orbit
- With arbitrary 3D electro-magnetic perturbations in arbitrary magnetic equilibrium
- Parallelised using MPI-OpenACC on CPU and GPU → Acceleration up to 9.5x

Observation of non-diffusive transport of α particles in the presence of tearing modes.

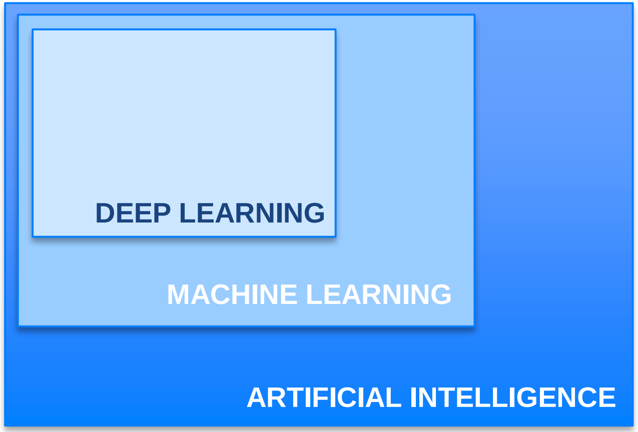
In-depth analysis of fusion-born α particles in JET-like tokamak → Dataset of 2000+ simulations to analyse transport and loss patterns

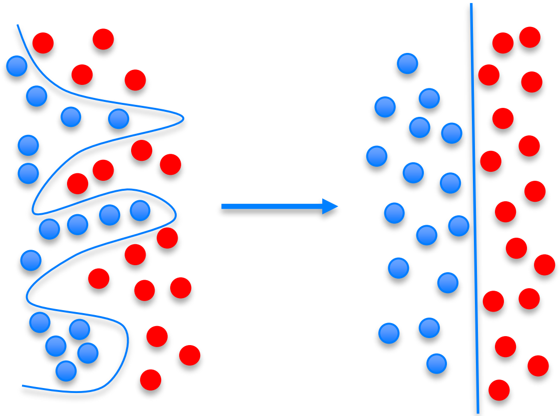






What Artificial Intelligence can provide





- **Can computers be made to think?** How to automate intellectual tasks usually performed by humans.
  - Symbolic AI → handcraft a sufficient number of explicit rules (1940-1950). Good start but not enough…
- **Can computers learn from data?** How can a computer program its own codes.
  - Machine learning → Find statistical structure by training on data (1990s).
  - **The *deep* in deep learning** computers can learn complex concepts building them out of simpler ones → Flatten boundaries to facilitate decisions

AI for three main physics applications

INSTABILITIES: detect them, classify them and eventually avoid them

TRANSPORT: obtain reduced models, predict chaotic trajectories

LOSSES: predict losses, link the losses to the core activity and infer global properties from localised measurements

IEA CNRS-CIEMAT-Seville → **Co-funded ISFIN-ITER PhD Enrique ZAPATA**

Application to ~9000 TJ-II discharges

S. Mazzi and D. Zarzoso 2022 *Complex Systems* (in press)

ANR JCJC 2022-2025 →
- → **Internship Matisse LANZARONE** (TAPAS full-orbit)
- → **Postdoct Homam BETAR** (α particles in stellarators)
- → **PhD recruitment in progress** (turbulent EP transport)

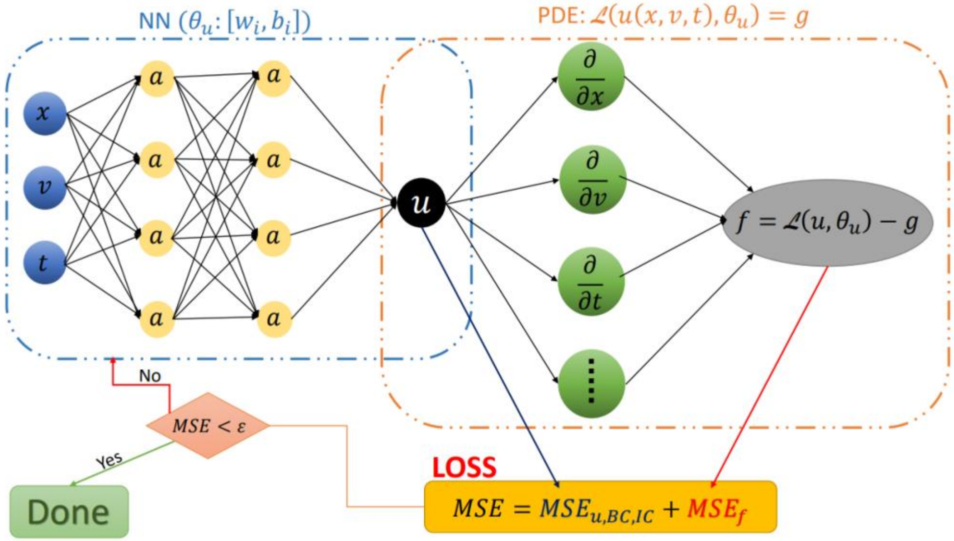
PACA Region PhD funding → **recruitment in progress** (Probabilistic description of rare events)

AI for three main numerical applications

Accelerate HPC codes **Rationalize storage** **Verification of solution**

PhD CEA Jai KUMAR → Towards exascale gyro-kineticc simulations of fusion plasmas

Development of Deep Neural Networks augmented by Physics information (PiNN) to optimize the storage and verify the solution of gyro-kinetic simulations



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Solution of the wave-particle resonance with a mesh-free method

Applied to any PDE (Quasi-neutrality equation) J. Kumar *et al* 2022 in preparation