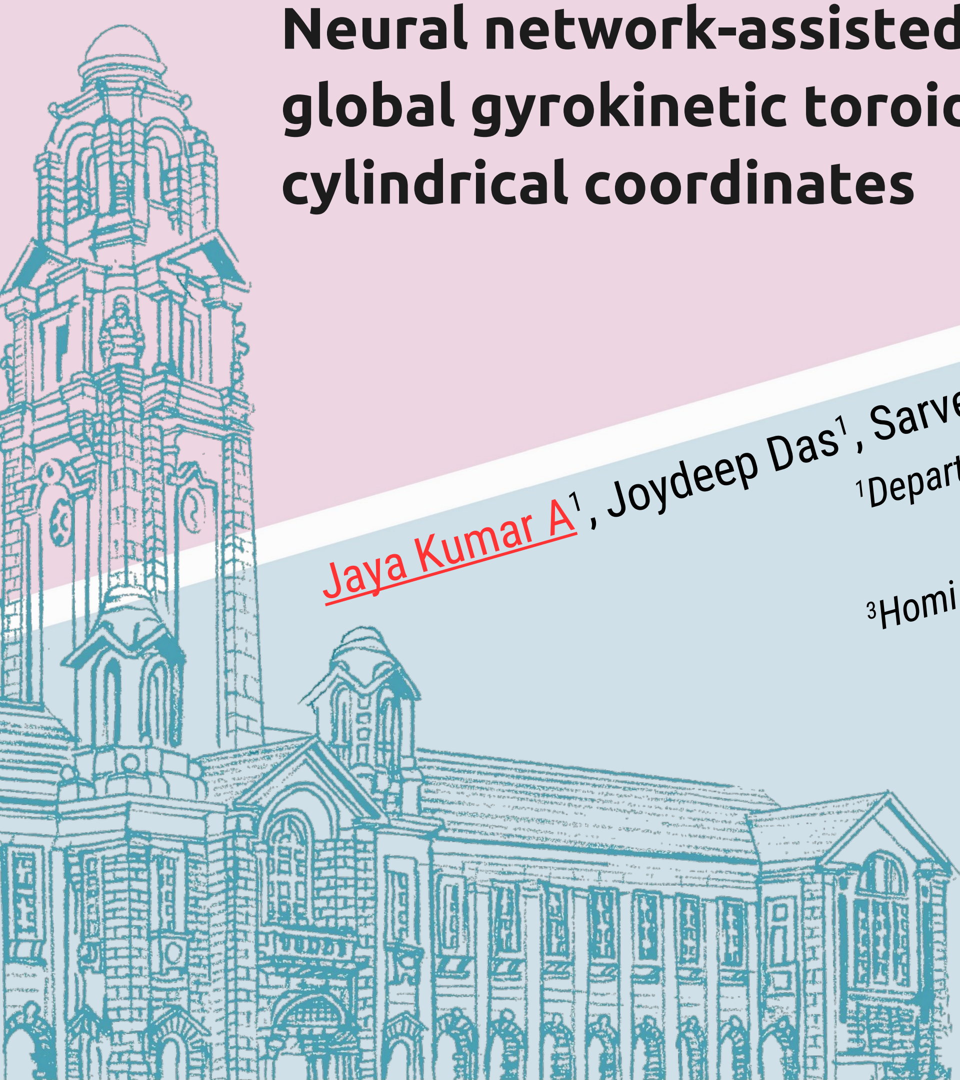
G2C3

Global Gyrokinetic
Code using Cylindrical Coordinates

Neural network-assisted electrostatic global gyrokinetic toroidal code using cylindrical coordinates

Jaya Kumar A[1], Joydeep Das[1], Sarveshwar Sharma[2], Abhijit Sen[2,3], Animesh Kuley[1]

[1]Department of Physics, Indian Institute of Science, Bangalore
[2]Institute for Plasma Research, Bhat, Gandhinagar
[3]Homi Bhabha National Institute, Anushaktinagar, Mumbai



ICTS

Apr 3, 2024

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Global **G**yrokinetic
Code using **C**ylindrical **C**oordinates

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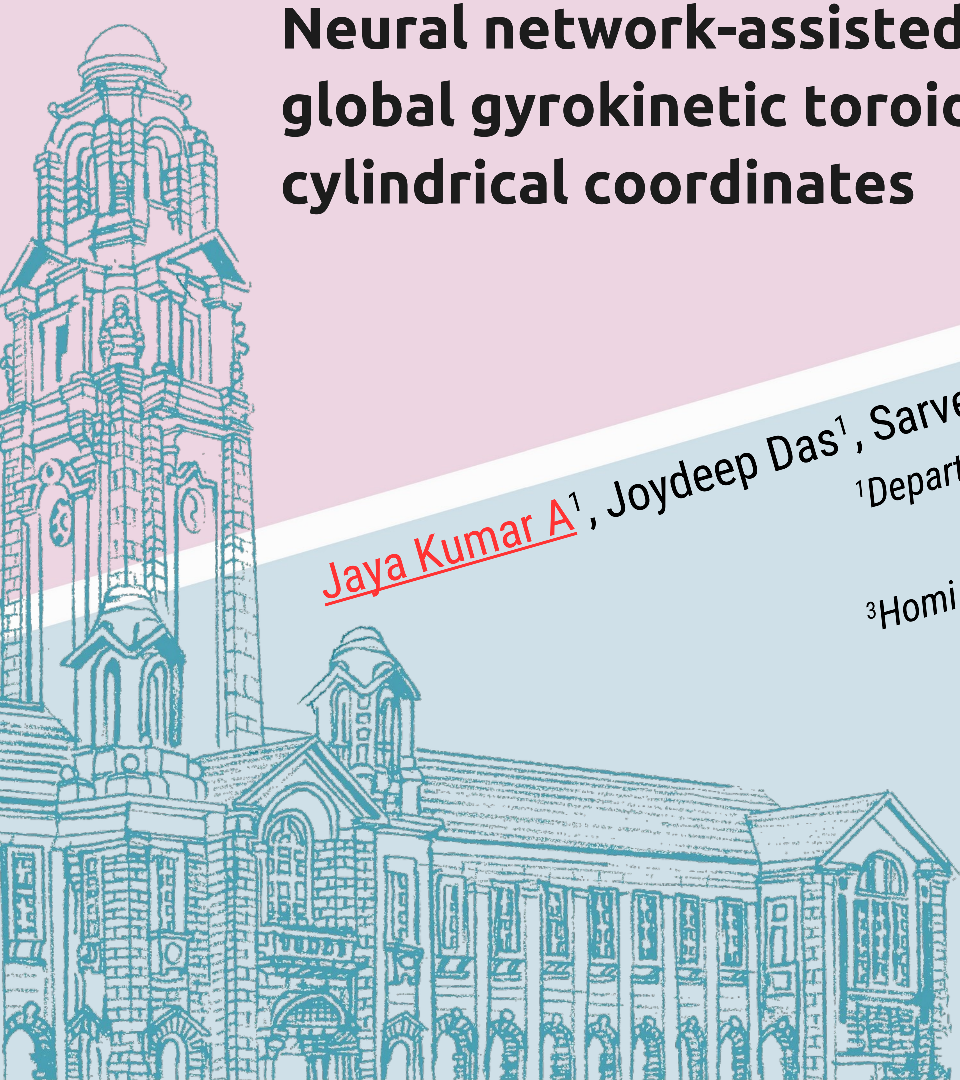
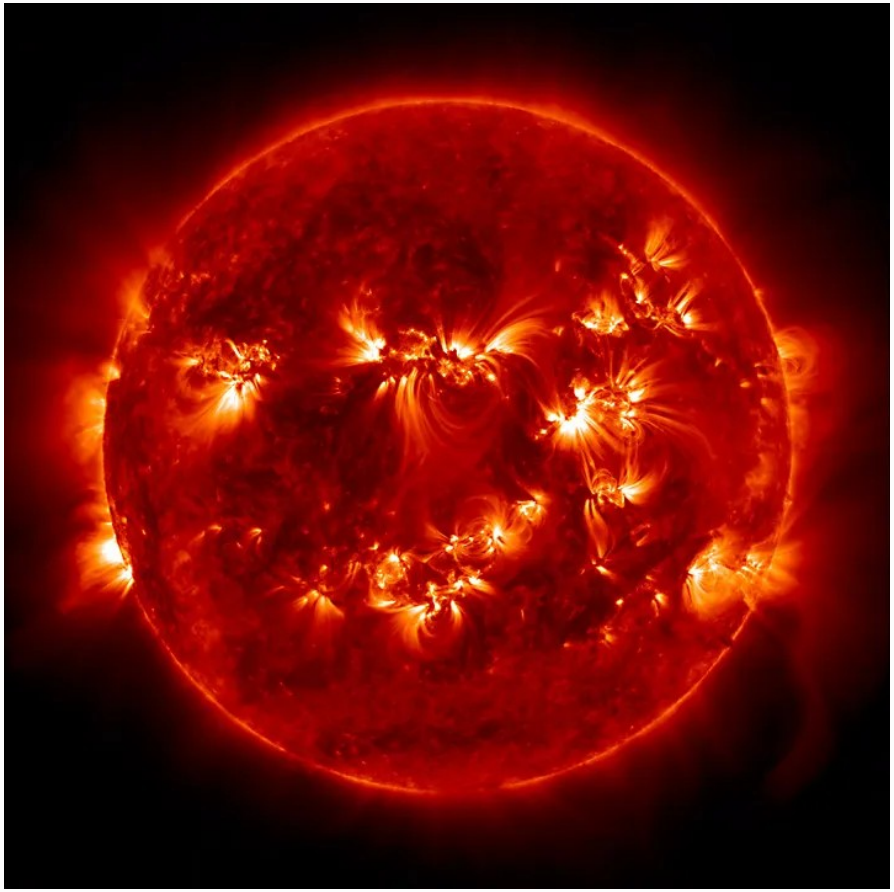
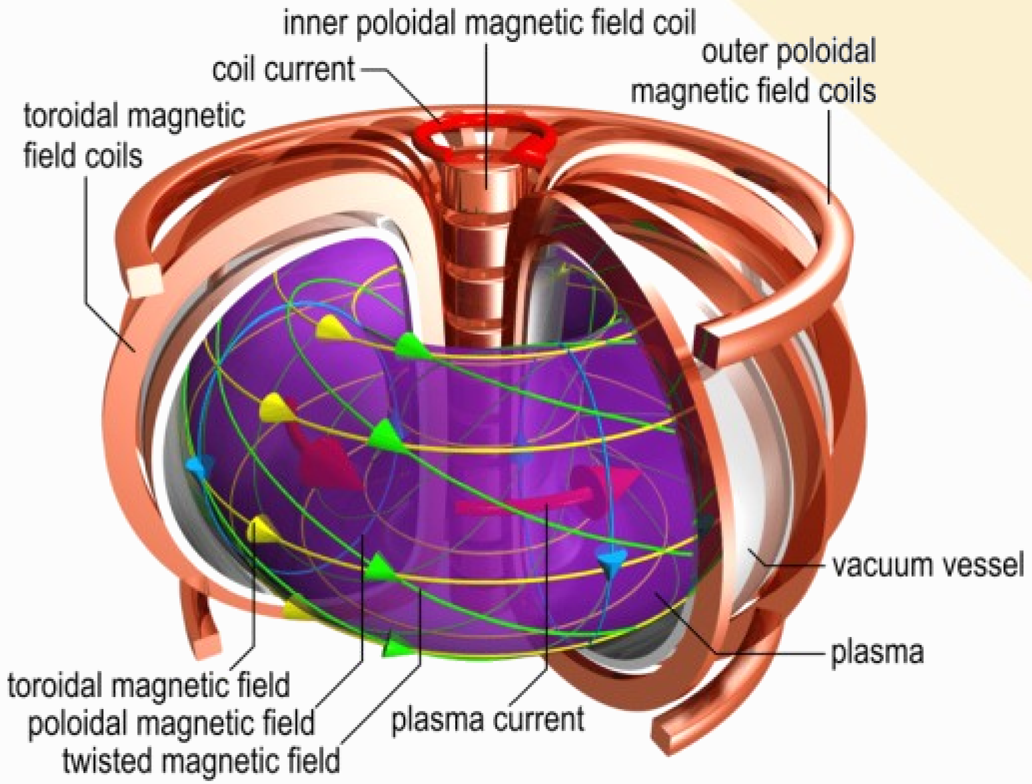


Apr 3, 2024

Nuclear Fusion Reactor





*J. H. E. Proll, Trapped-particle instabilities in quasi-isodynamic stellarators

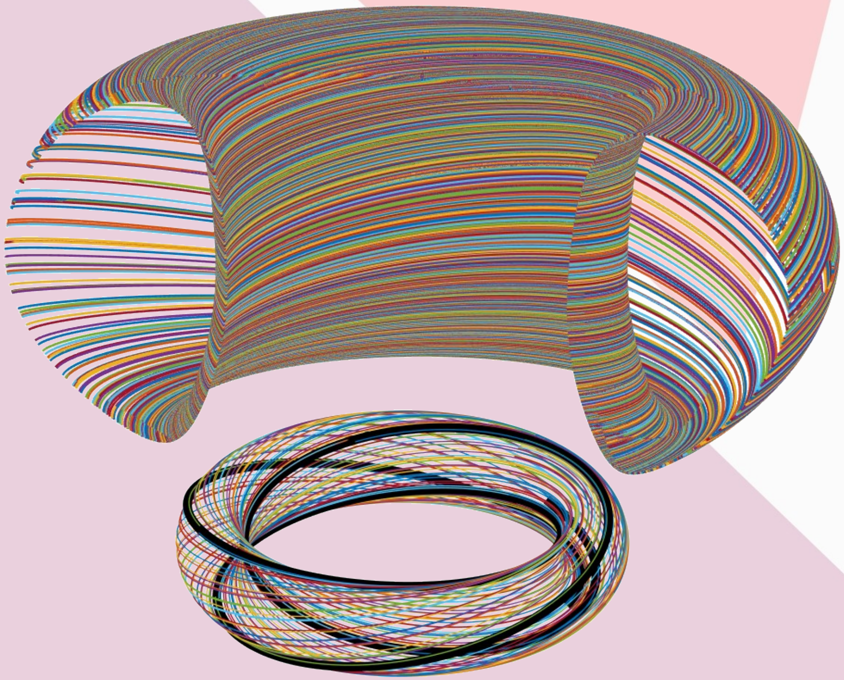
The only working nuclear fusion reactor in our solar system!

*Earth-orbiting Solar Dynamics Observatory (2015)

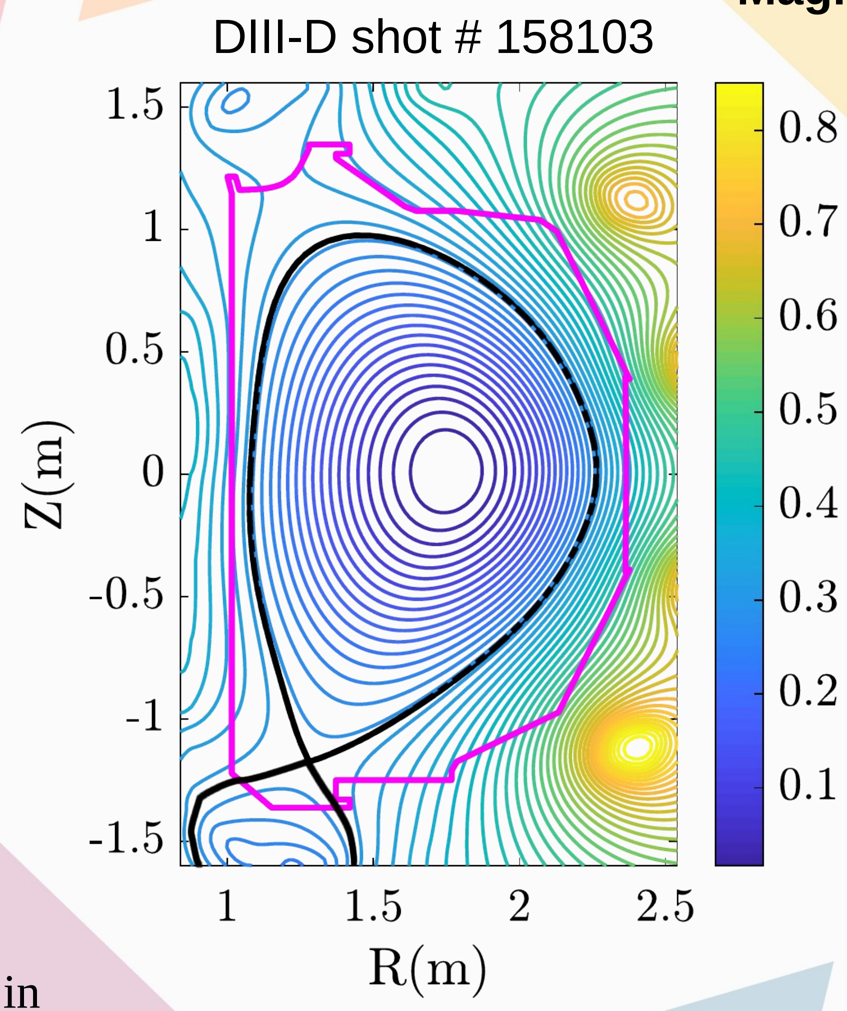
Tokamak
“Sun in a magnetic bottle”

Importance and objective

Magnetic field lines on a flux surface



Magnetic flux surface



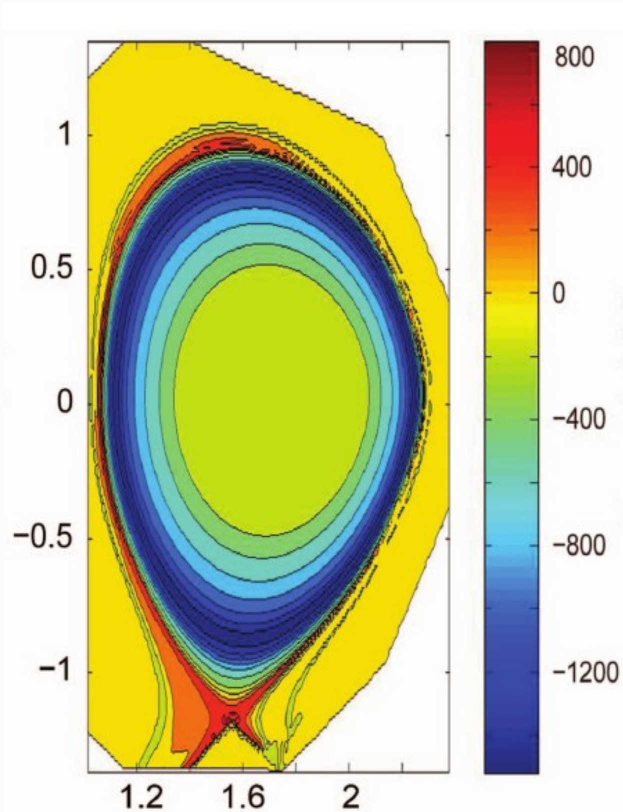
Explore the physics of microturbulent transport in the open flux surface region of tokamak (DIII-D, ADITYA-U).

Codes available:

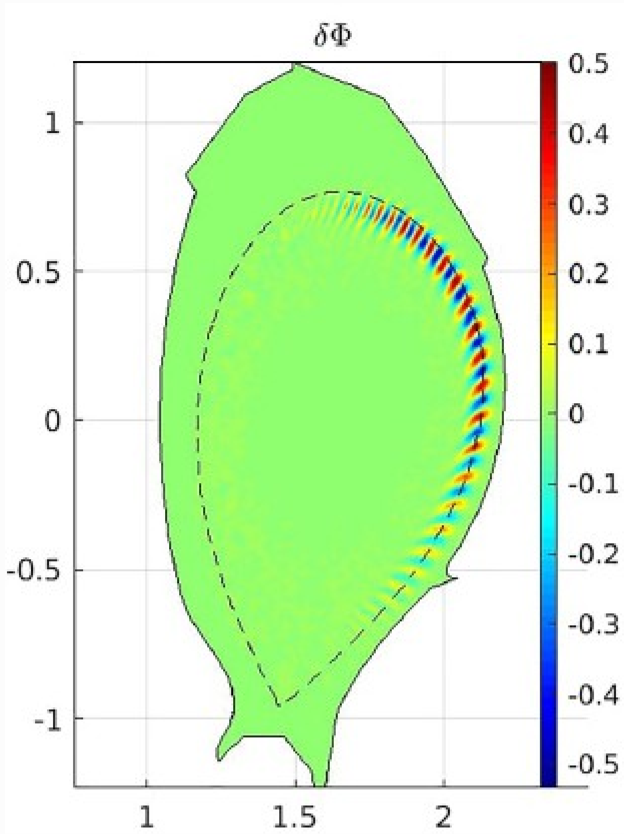
XGC (PPPL, USA), GENE-X, TRIMEG (Max-Planck, Germany)

G2C3

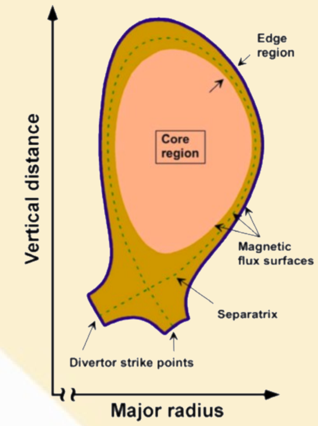
Importance and objective

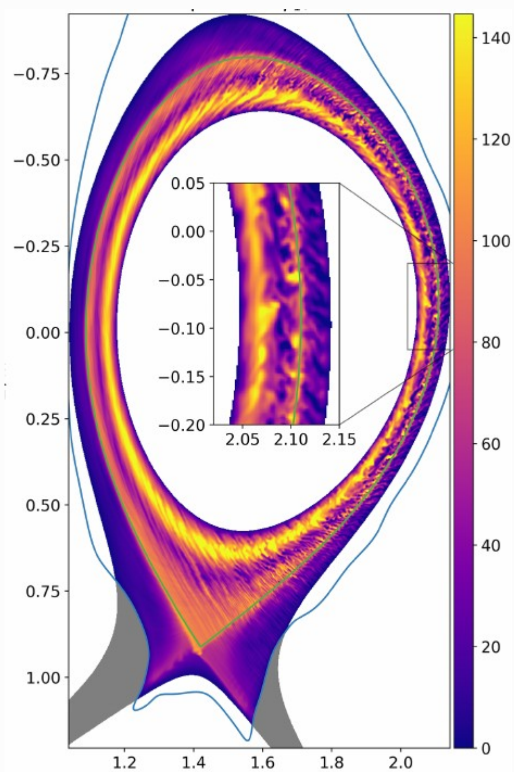


(XGC) C. S. Chang; S. Ku
Phys. Plasmas 15, 062510 (2008)



(TRIMEG) Z.X. Lu, et.al.
Plasmas 26, 122503 (2019)

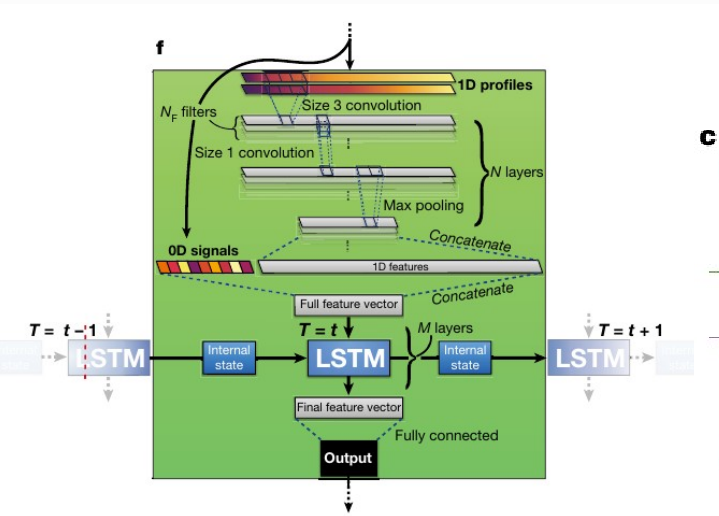




(GENE-X) D. Michels, et.al.
Phys. Plasmas 29, 032307 (2022)

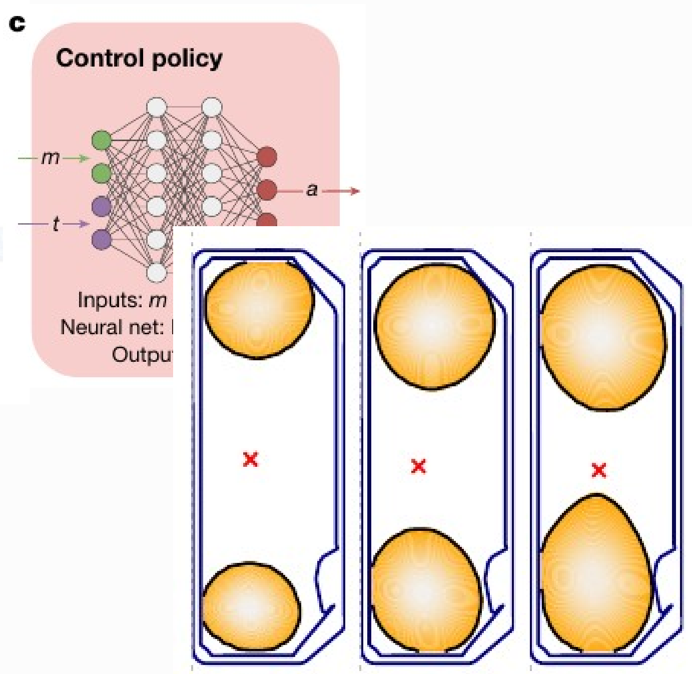
Electrostatic potential

ML in tokamak nuclear fusion research



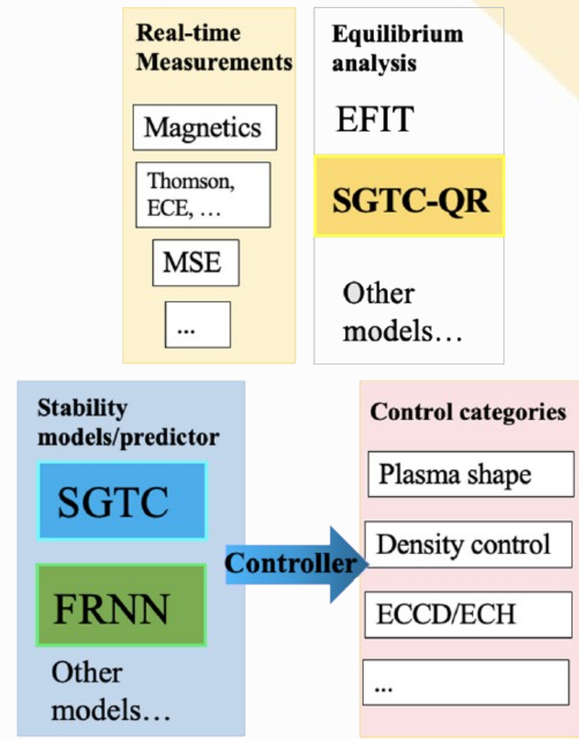
(DIII-D/JET) J.K. Harbeck, et.al. Nature, Vol 568, Apr 2019

Disruption-prediction



(TCV) J. Degrave, et.al. Nature, Vol 602, Feb 2022

Shape control

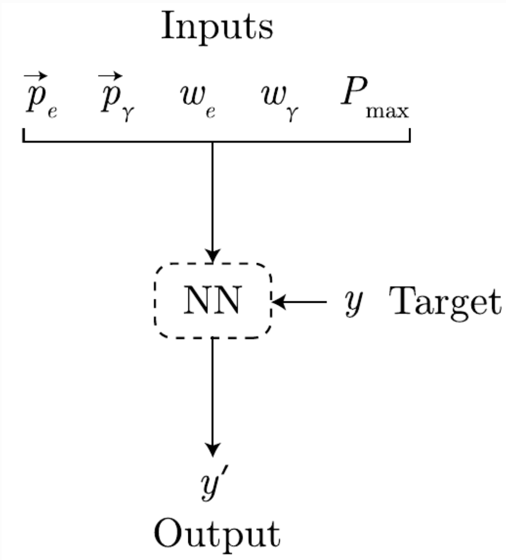


(DIII-D) X. Wei, et.al. Nucl. Fusion 63, 2023

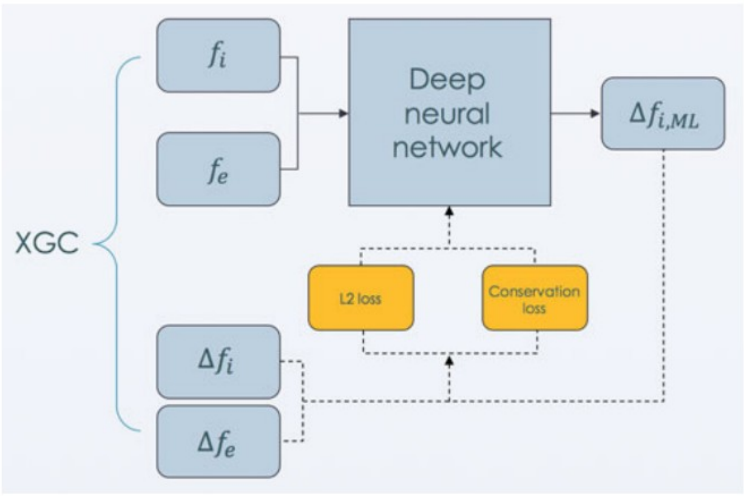
Profile reconstruction

Experimental data-driven

ML in plasma simulations

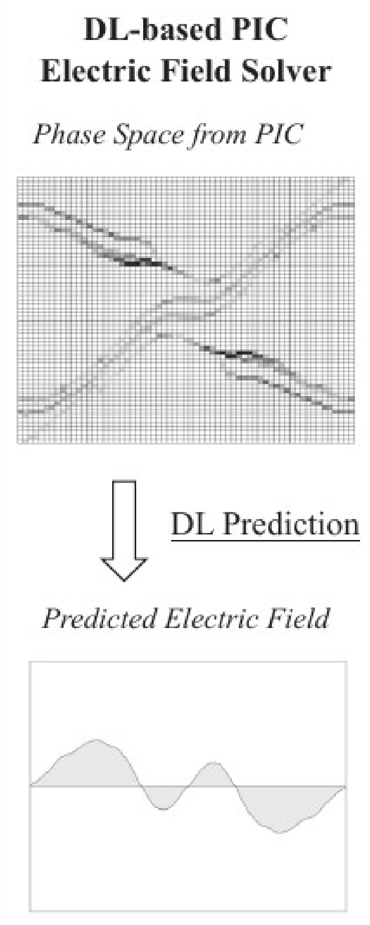


(OSIRIS) C.Badiali, et.al.
J. Plasma Phys. (2022), vol. 88



(XGC) M.A. Miller, et.al.
J. Plasma Phys. (2021), vol. 87

ML-based
Collision operator



(PIC) X. Aguilar, et.al.
IEEE International Conference on Cluster Computing, (2021)

Simulation data-driven

Reduced/Surrogate model

ML-based
Electric solver

Collisionless
Kinetic theory

The Vlasov–Maxwell system of equations

$$\frac{\partial f_e}{\partial t} + \mathbf{v}_e \cdot \nabla f_e - e\left(\mathbf{E} + \frac{\mathbf{v_e}}{c} \times \mathbf{B}\right) \cdot \frac{\partial f_e}{\partial \mathbf{p}} = 0$$

$$\frac{\partial f_i}{\partial t} + \mathbf{v}_i \cdot \nabla f_i + Z_i e\left(\mathbf{E} + \frac{\mathbf{v_i}}{c} \times \mathbf{B}\right) \cdot \frac{\partial f_i}{\partial \mathbf{p}} = 0$$

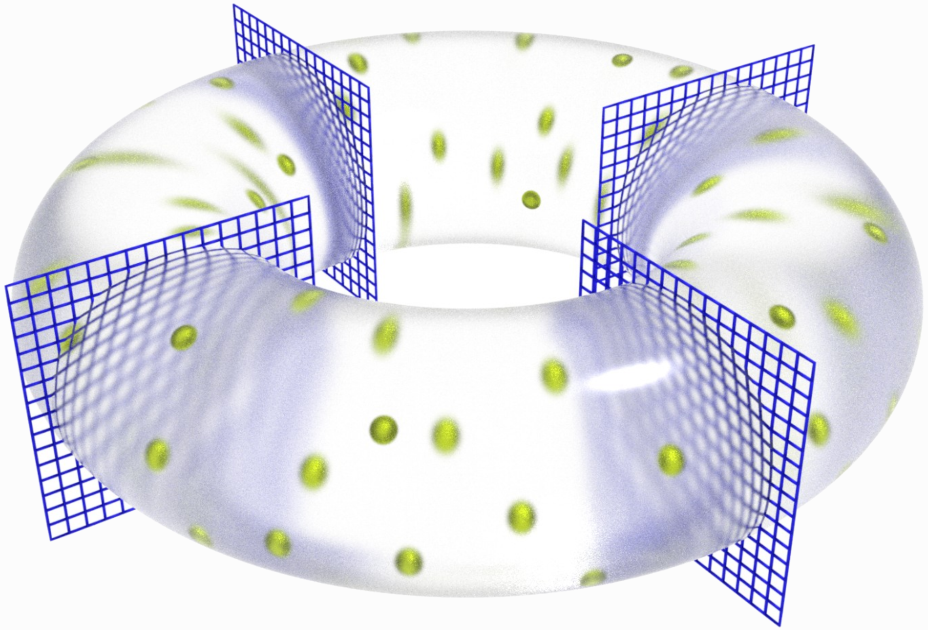
$$\nabla \times \mathbf{B} = \frac{4\pi \mathbf{j}}{c} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{E} = 4\pi\rho$$

$$\nabla \cdot \mathbf{B} = 0$$

Particle-in-cell



Collisionless Kinetic theory

The Vlasov–Maxwell system of equations

$$\frac{\partial f_e}{\partial t} + \mathbf{v}_e \cdot \nabla f_e - e\left(\mathbf{E} + \frac{\mathbf{v_e}}{c} \times \mathbf{B}\right) \cdot \frac{\partial f_e}{\partial \mathbf{p}} = 0$$

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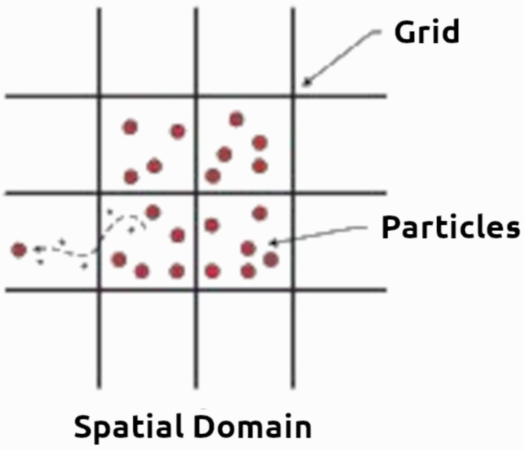
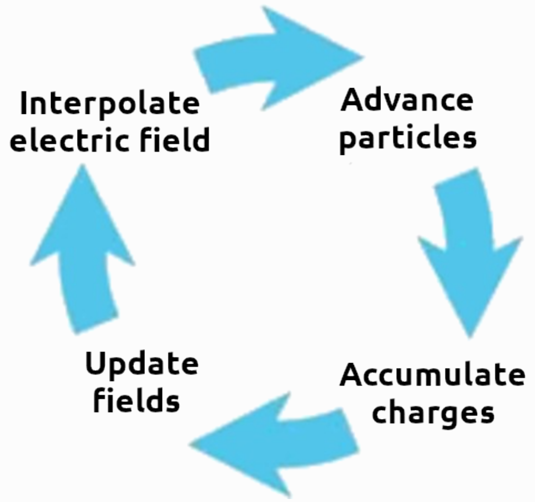


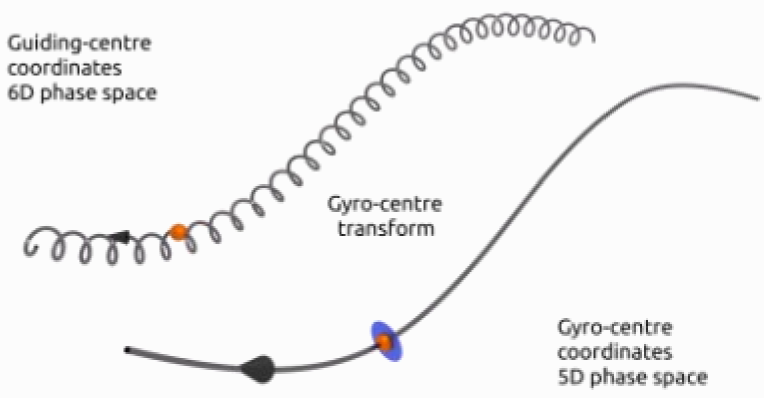


Gyro-kinetic theory in the presence of magnetic field

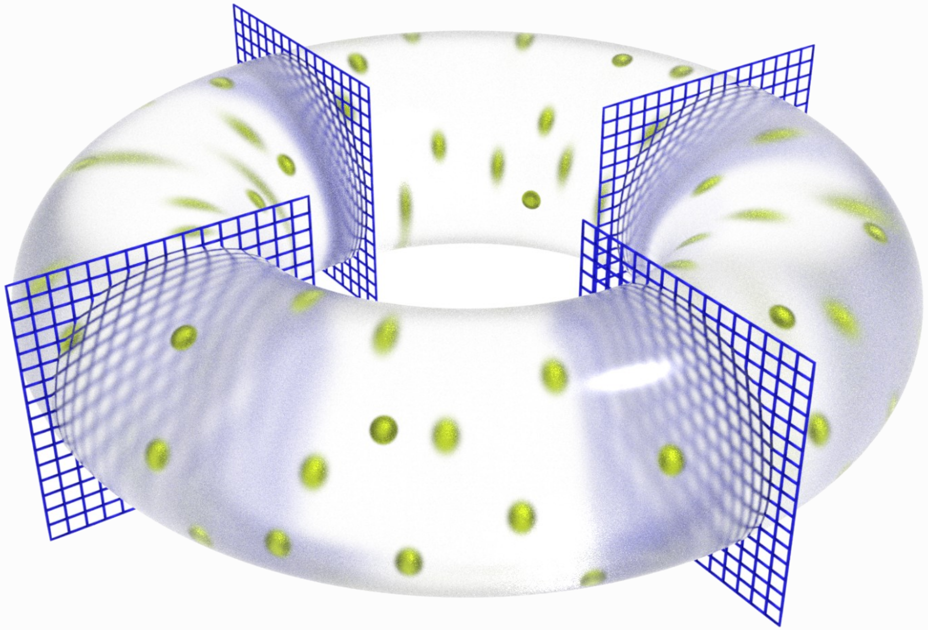
The Vlasov–Maxwell system of equations

The gyro-averaged evolution of phase-space density in five-dimensional phase space of $(R, \zeta, Z, v_{\|}, \mu)$, where $\mu = mv_{\perp}^2/2B$ is the magnetic moment, and $v_{\|}$ is the parallel velocity for the particle, is given by

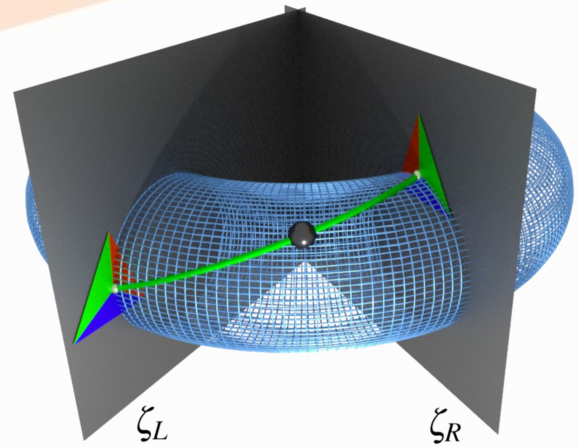
$$\frac{d}{dt} f_i = \frac{\partial f_i}{\partial t} + \dot{\vec{\mathbf{X}}} \cdot \nabla f_i + \dot{v}_{\|} \frac{\partial f_i}{\partial v_{\|}} = 0$$

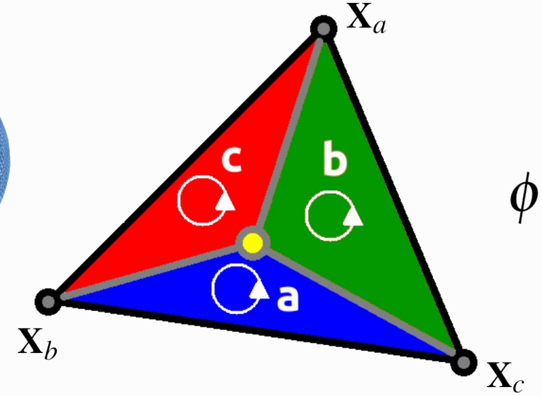


Particle-in-cell

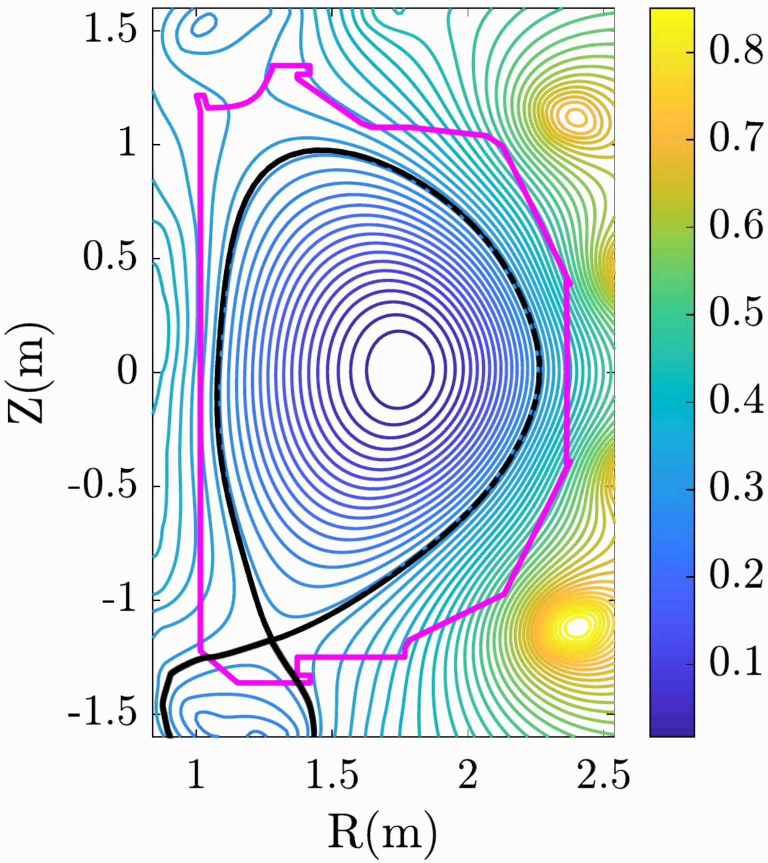


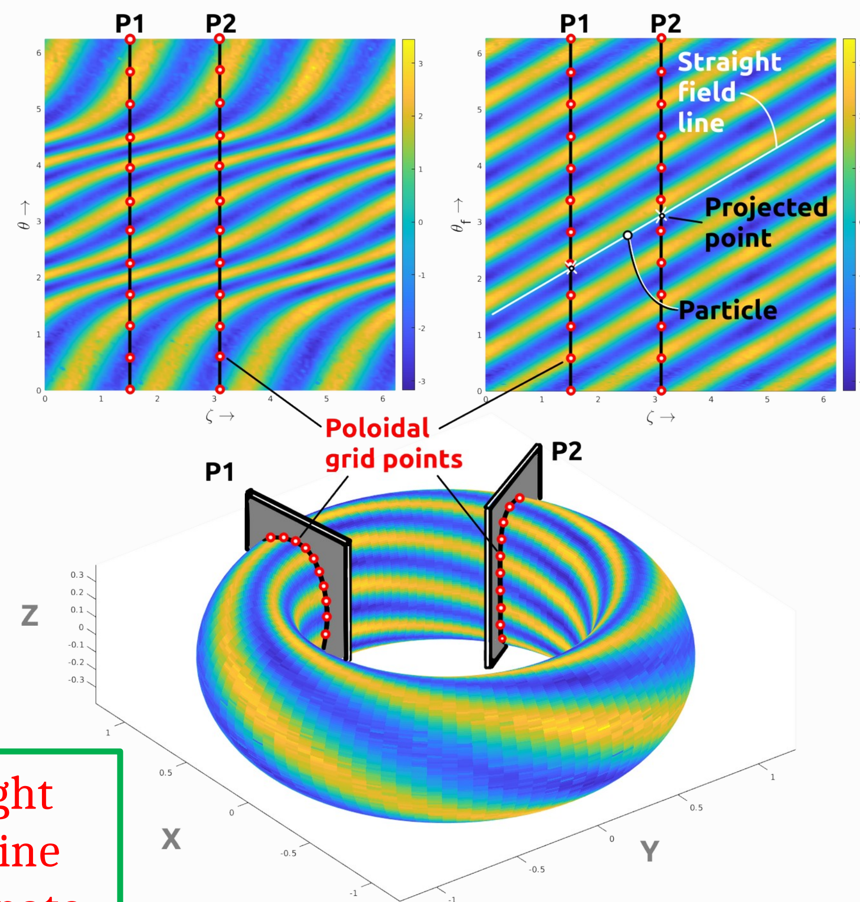
Gather-Scatter operations for field and charges





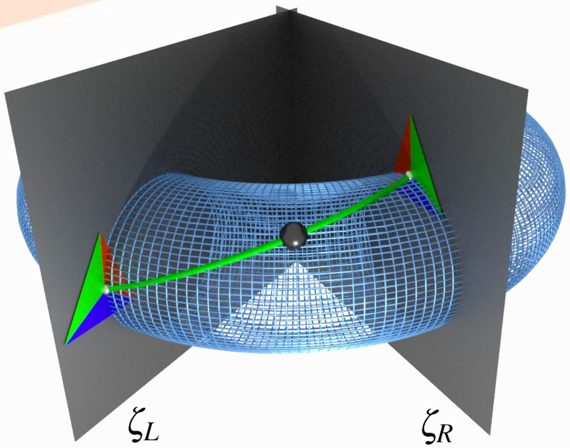
$$\phi(\mathbf{x}) = \left(\frac{a\,\phi_a + b\,\phi_b + c\,\phi_c}{a+b+c} \right)$$

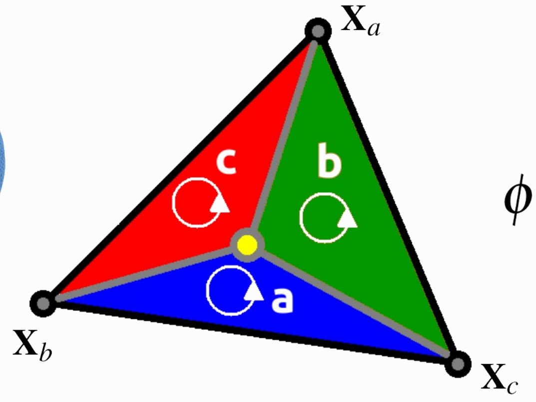




Straight field line coordinate

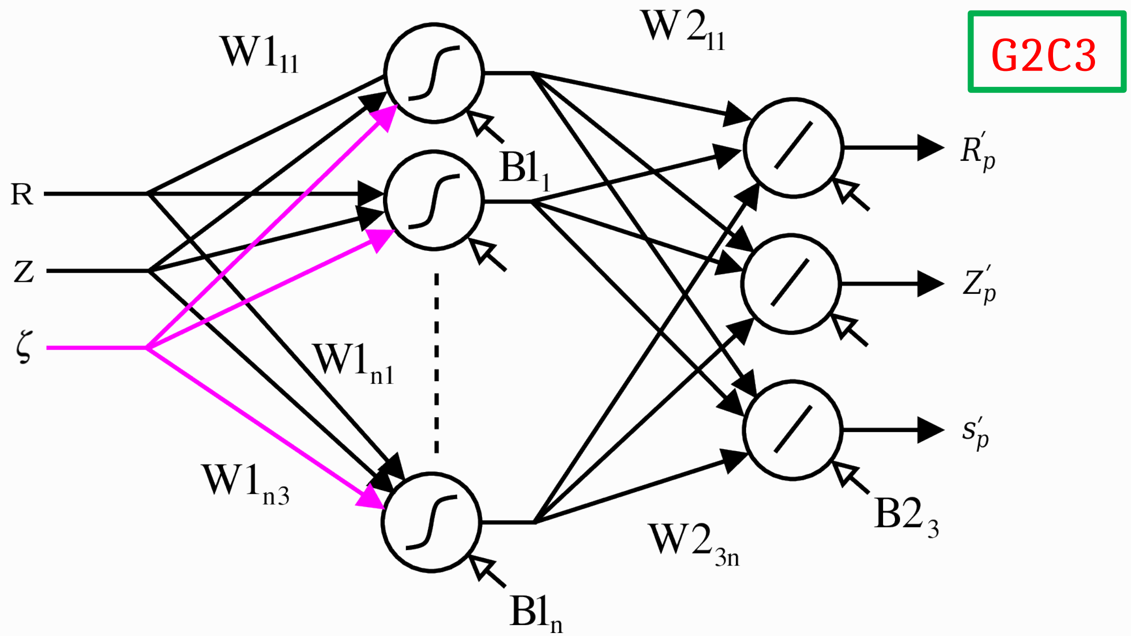
Gather-Scatter operations for field and charges

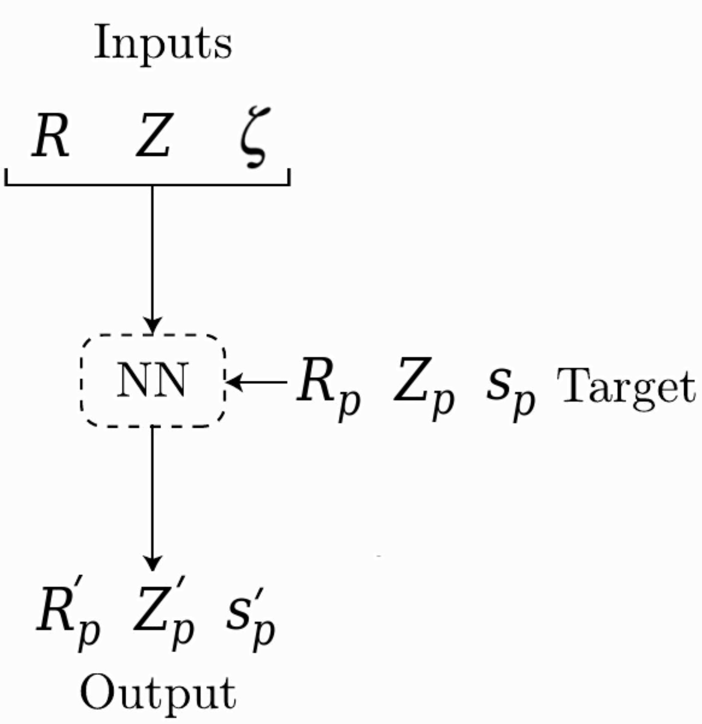




$$\phi(\mathbf{x}) = \left(\frac{a\,\phi_a + b\,\phi_b + c\,\phi_c}{a + b + c} \right)$$

Neural network as a universal approximator





Kolmogorov–Arnold representation theorem

In real analysis and approximation theory, the Kolmogorov-Arnold representation theorem (or superposition theorem) states that every multivariate continuous function can be represented as a superposition of the two-argument addition and continuous functions of one variable. It solved a more constrained, yet more general form of Hilbert's thirteenth problem.

The works of Vladimir Arnold and Andrey Kolmogorov established that if f is a multivariate continuous function, then f can be written as a finite composition of continuous functions of a single variable and the binary operation of addition. More specifically,

$$f(\mathbf{x}) = f(x_1, \ldots, x_n) = \sum_{q=0}^{2n} \Phi_q \left(\sum_{p=1}^{n} \phi_{q,p}(x_p) \right)$$

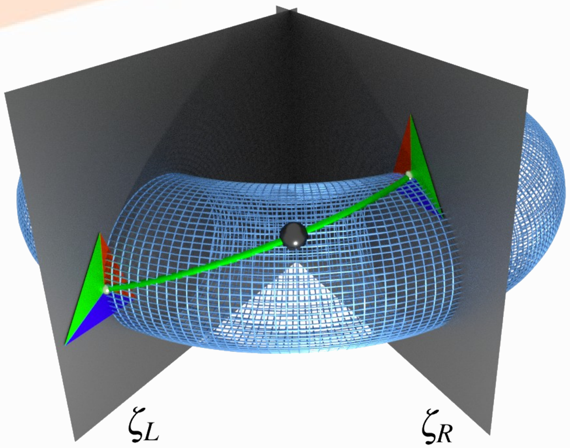
“Universal approximation theorems”

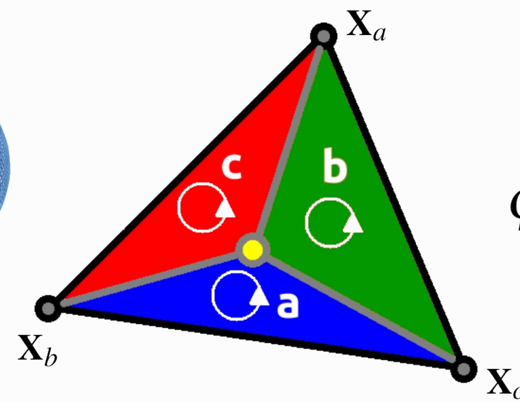
WIKIPEDIA
The Free Encyclopedia

Andrey Kolmogorov, "On the representation of continuous functions of several variables by superpositions of continuous functions of a smaller number of variables", Proceedings of the USSR Academy of Sciences, 108 (1956), pp. 179–182; English translation: Amer. Math. Soc. Transl., 17 (1961), pp. 369–373.

Vladimir Arnold, "On functions of three variables", Proceedings of the USSR Academy of Sciences, 114 (1957), pp. 679–681; English translation: Amer. Math. Soc. Transl., 28 (1963), pp. 51–54.

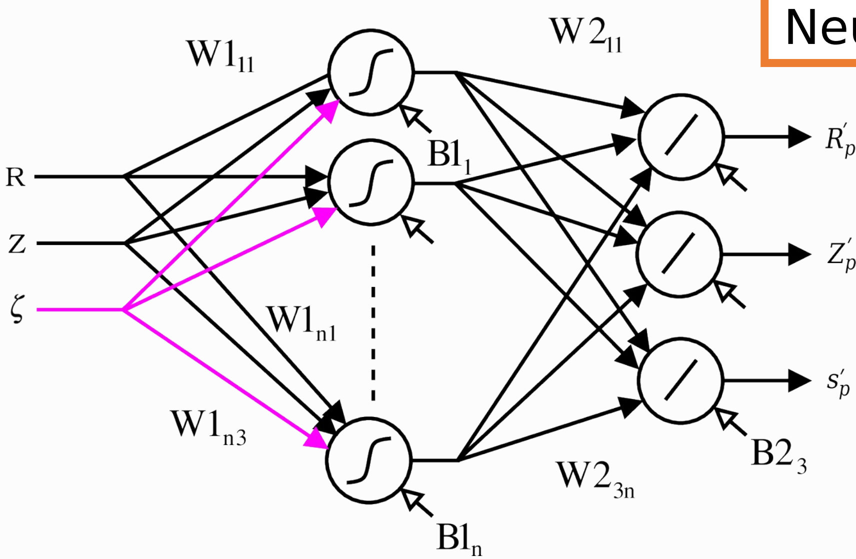
Gather-Scatter operations for field and charges



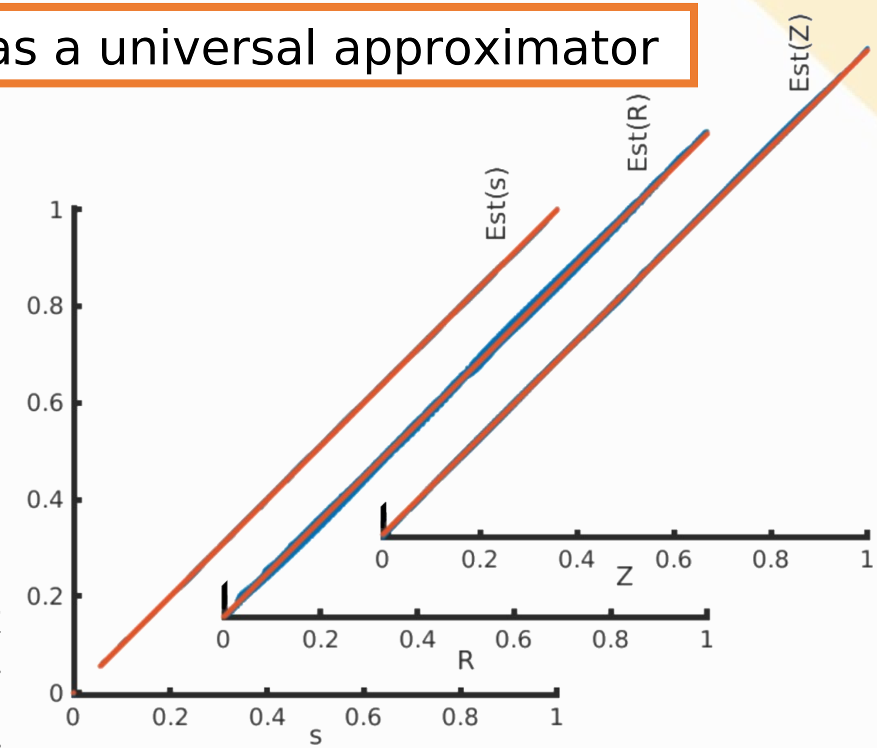


$$\phi(\mathbf{x}) = \left(\frac{a\,\phi_a + b\,\phi_b + c\,\phi_c}{a+b+c} \right)$$

Neural network as a universal approximator



G2C3



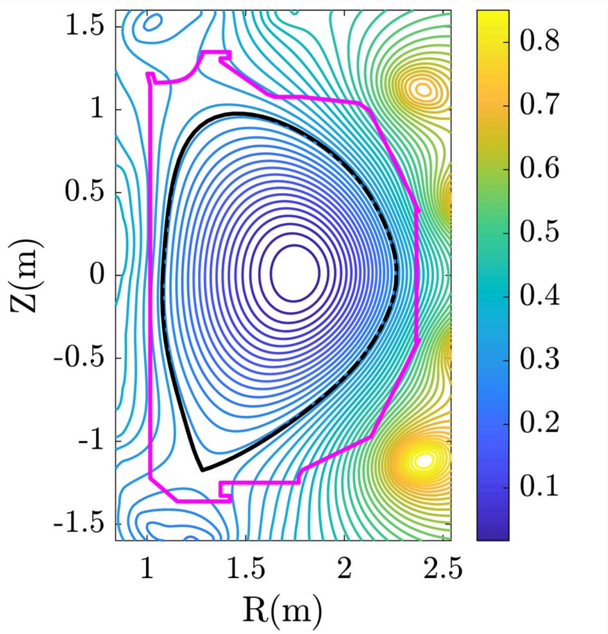
Estimation Error

Comparison of the trained neural network output against the target values. Left lower panel shows the relation for δs, center panel for δR, and the right panel shows δZ. Notice that a error free map corresponds to a 45^0 straight line.

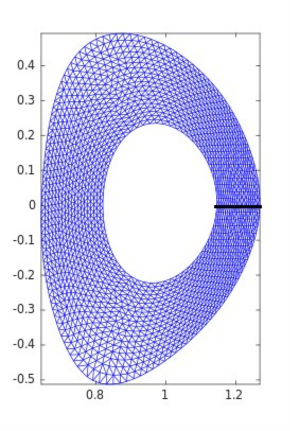
Ion Temperature Gradient (ITG) mode

Benchmarking ITG mode in DIII-D [*Shot # 158103*]:
(Linear-, Adiabatic electron-, gyrokinetic ion-, Electrostatic- case)

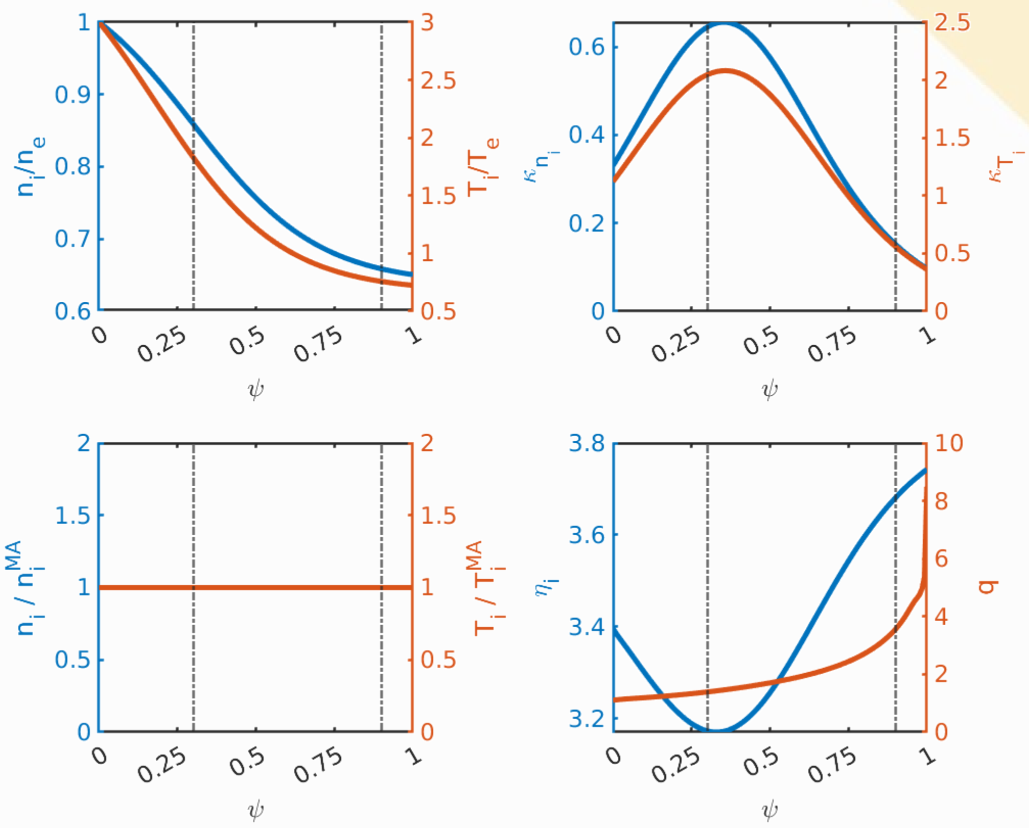
Flux function



Simulation grid

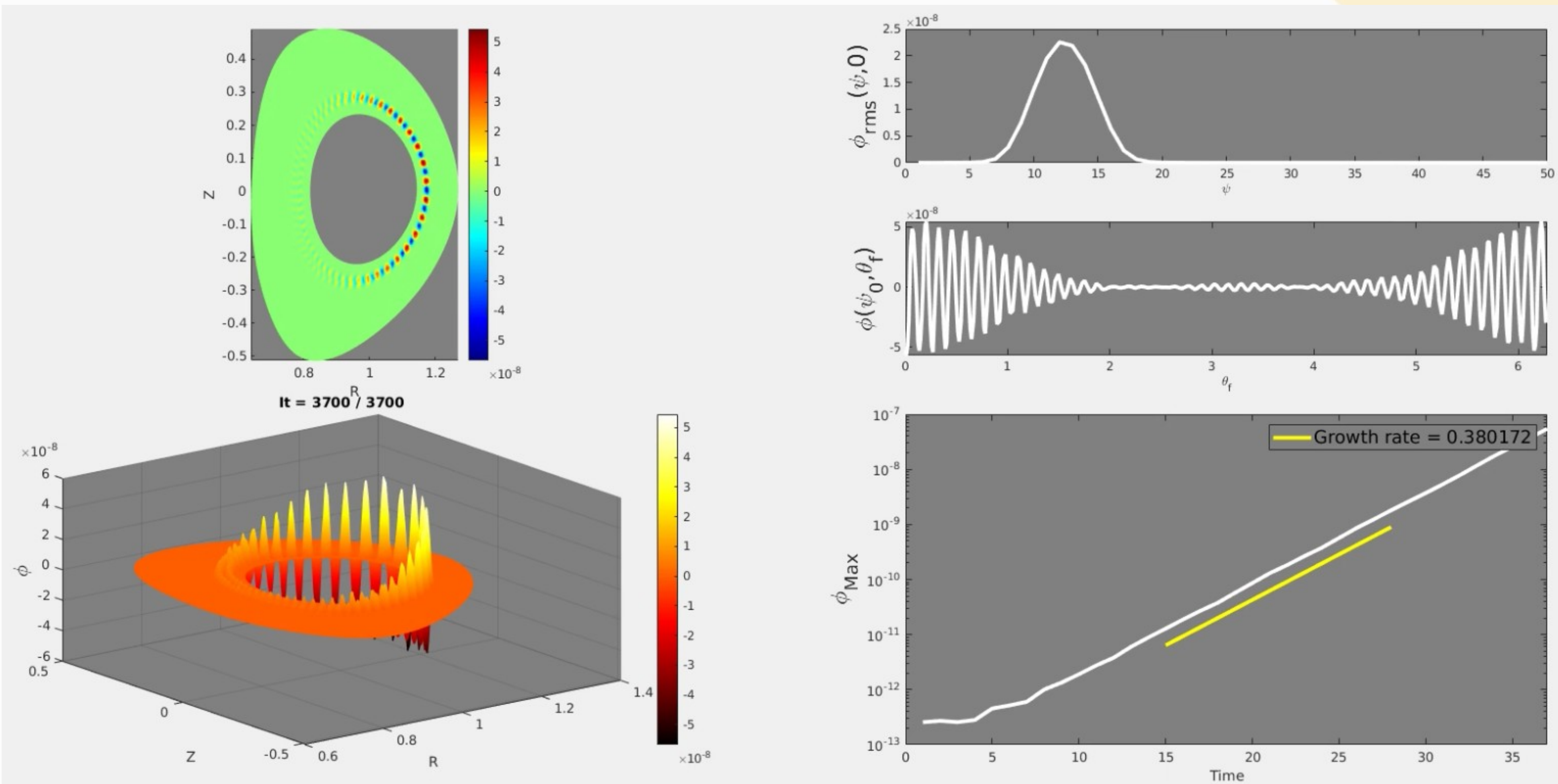


Temperature and density (cyclone) profiles:



Verification of Linear ITG mode in the core region of DIII-D tokamak

Electric potential

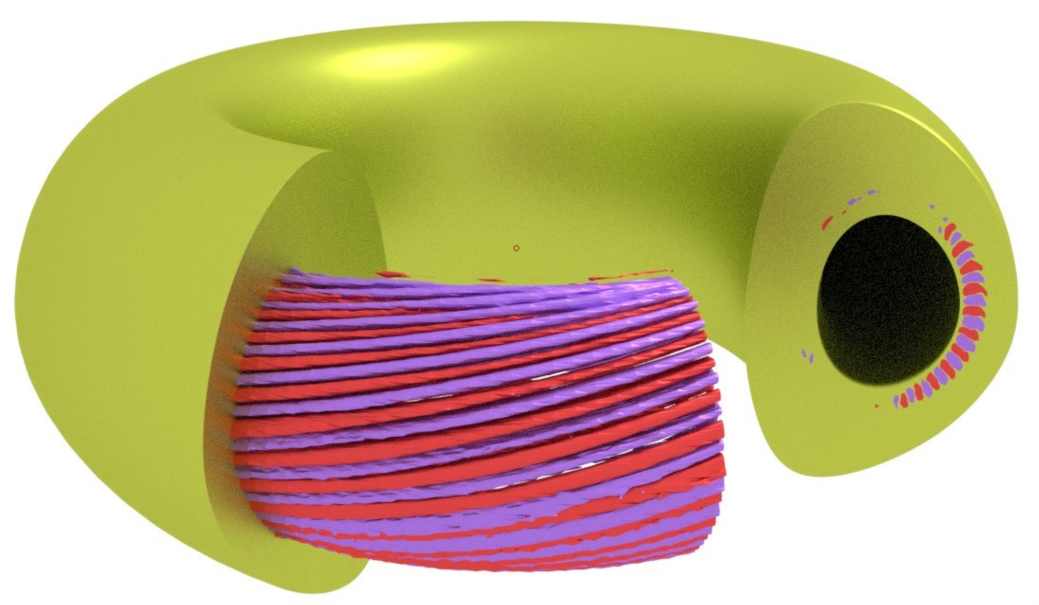


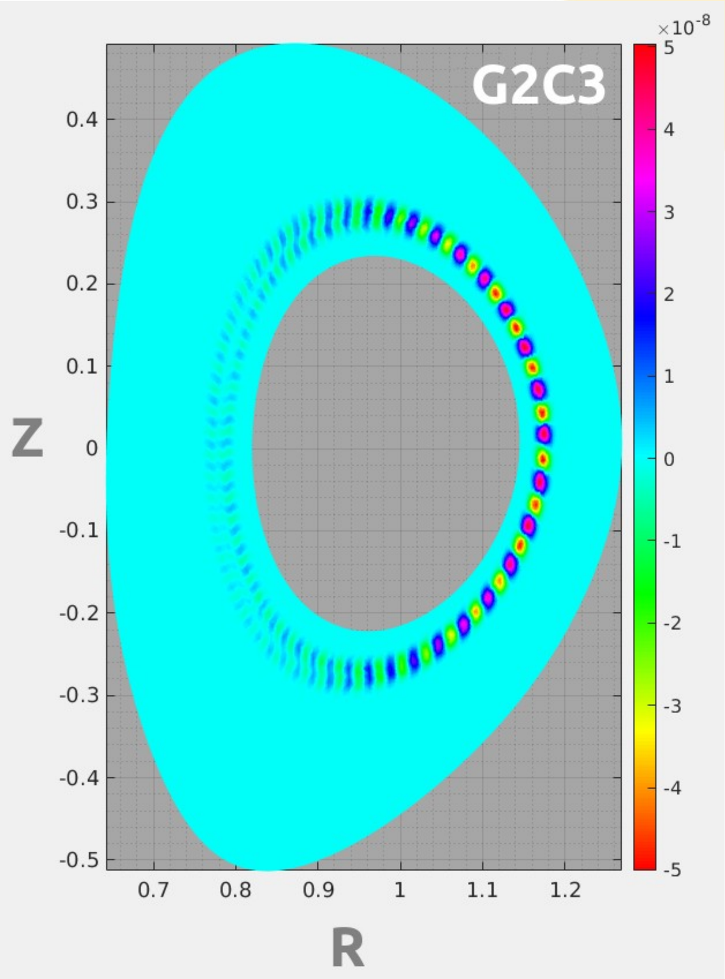
Verification of Linear ITG mode in the core region of DIII-D tokamak

Electric potential

2D View

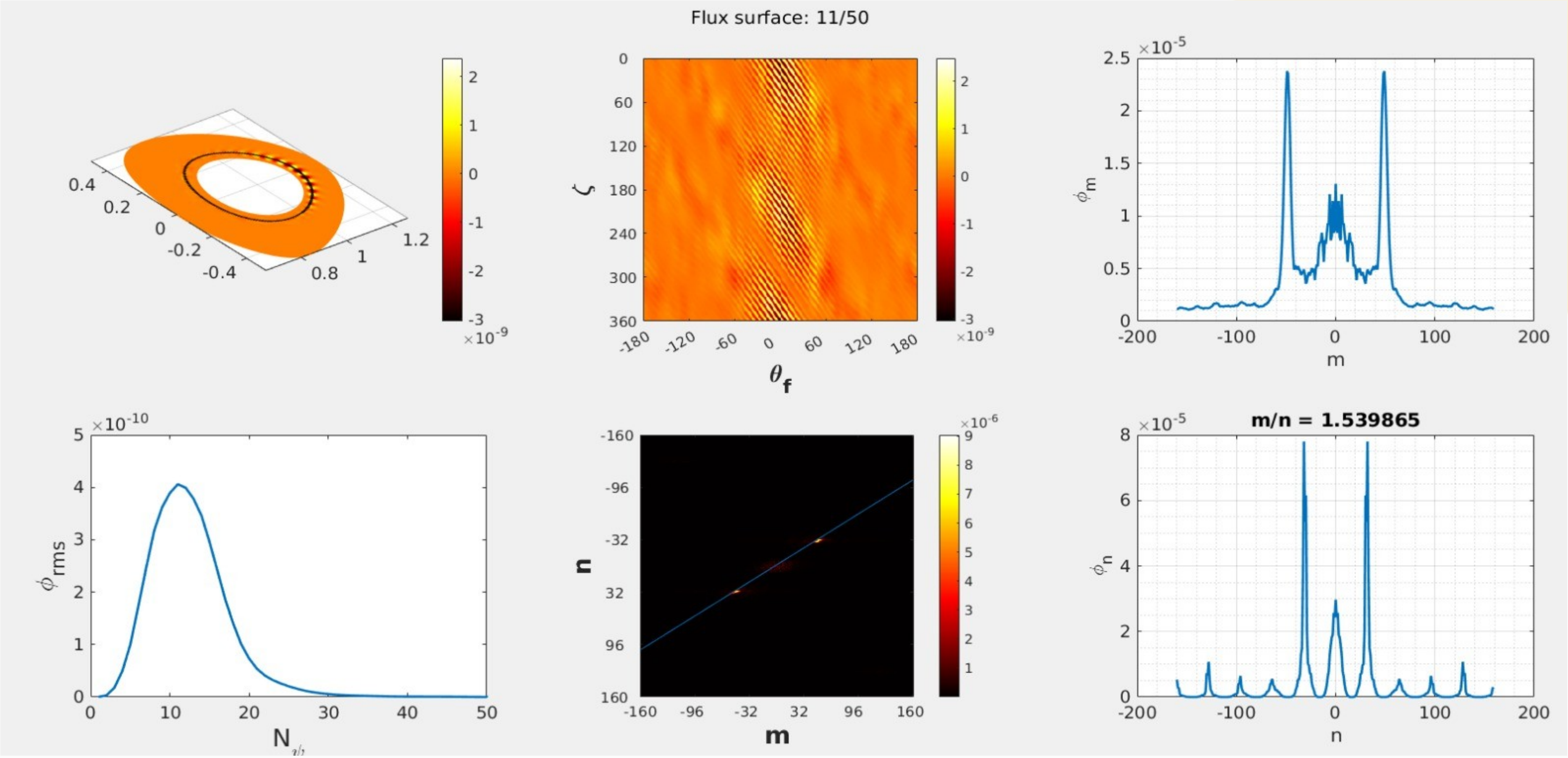
3D View





Mode Analysis

Electric potential



Capabilities of G2C3

❑ G2C3 is a global code currently under development at IISc Bangalore.

The G2C3 code has the following features:

- ❖ G2C3 is a first principle particle-in-cell (PIC) code based on cylindrical coordinates
- ❖ Global approach for plasma and background magnetic geometry, obtained from axisymmetric ideal MHD equilibria computed with EFIT and IPREQ code.
- ❖ Both gyrokinetic (5D for low-frequency micro-turbulence) and fully kinetic (6D for high-frequency modes) particle integrators.
- ❖ Field-aligned particle grid interpolation for axisymmetric mesh in cylindrical coordinates.
- ❖ G2C3 has MPI parallelization with particle decomposition.
- ❖ Poisson solver using PETSc library.
- ❖ Neural Network for particle locating, gathering scattering operation.
- ❖ Microturbulence: Gyrokinetic thermal ion and adiabatic electron.

Thank you for your attention.