Visualization Techniques for the Gyrokinetic Tokamak Simulation Code

PPPL PRINCETON PLASMA PHYSICS LABORATORY

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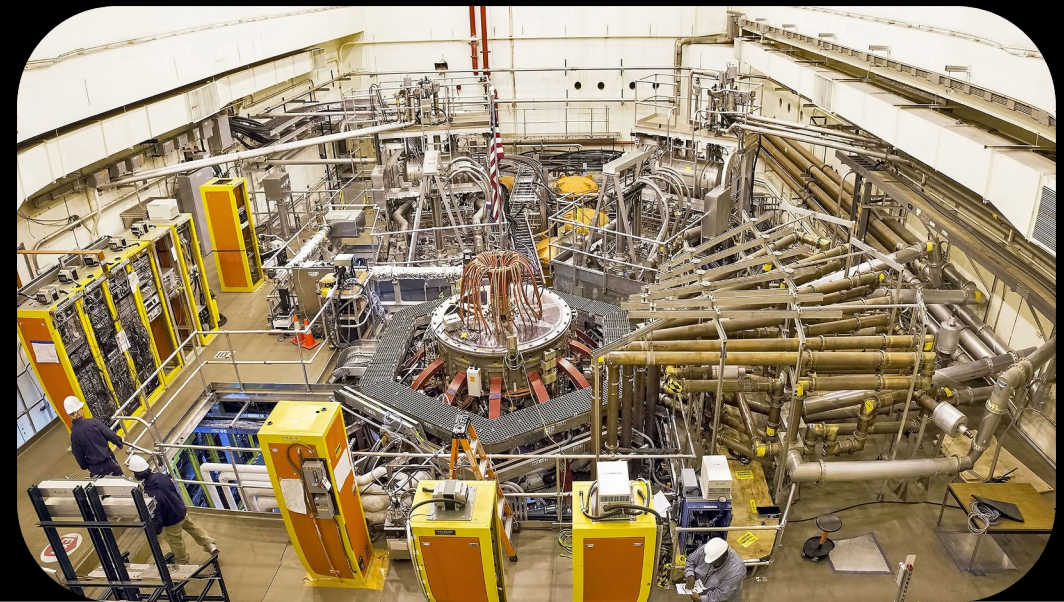

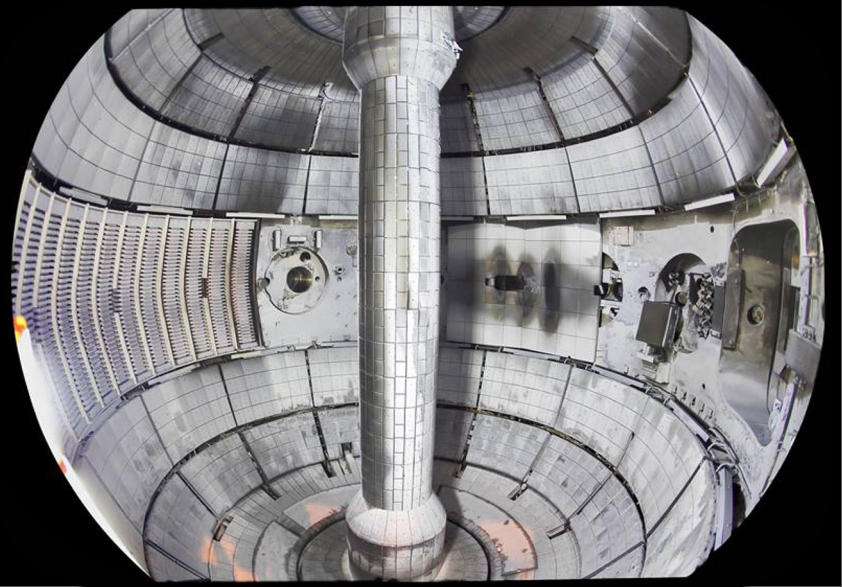

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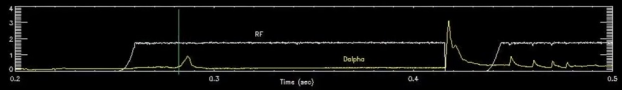

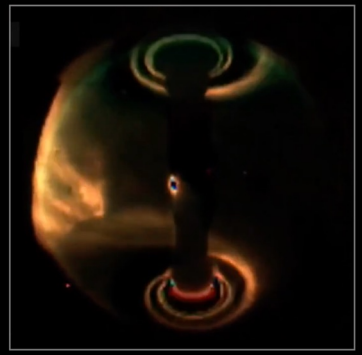

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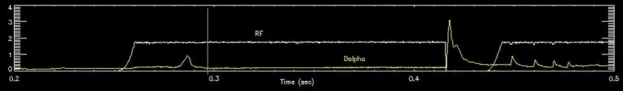

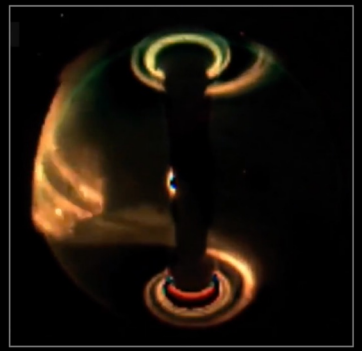

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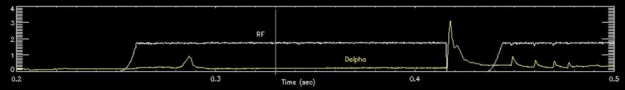

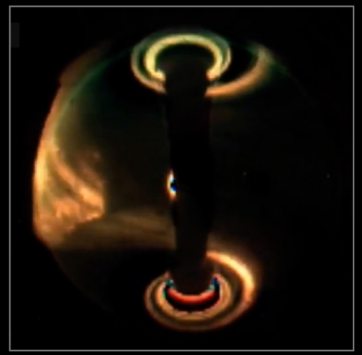

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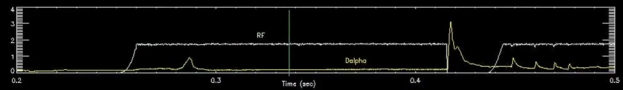


Fast camera at 4 time steps

Lithium – Green spectrum.

High Harmonic Radio Frequency heats tiles in spiral pattern.

Fast waves along magnetic field lines in front of RF antenna.

GTS - Gyrokinetic Tokamak Simulation

Weixing Wang - Physics of Plasmas, 13, 2006. Active development.

Time dependent datasets of plasma microturbulence. Short time scale.

Intrinsic rotation - clockwise & counter-clockwise ← Collisionless Trapped Electron Mode CTEM. Generalized geometry, non-circular cross section.

20B particles.

400M grid points around torus.

Large Capability Runs

50,000 time steps computed. 1,000 time steps written to files.

TB output.

100,000 cores, 48 hours at NERSC.

1,000 cores, 24 hours on stellar.princeton.edu

Capacity

GTS File Output

32 planes typical, 1 plane per file:

Compute Grid file - mesh topology based on magnetic flux surfaces.

Density, Temperature, Phi files - all time steps

Fortran writes

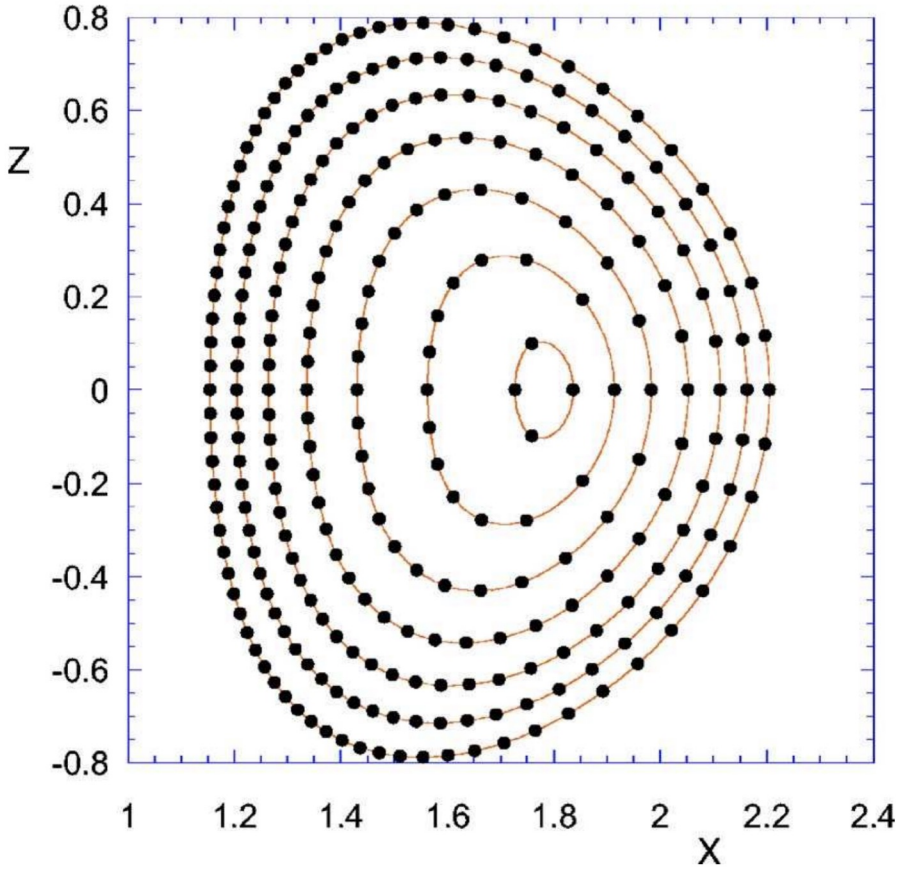
1. Poloidal Plane Visualization

Each ring has a different number of points!

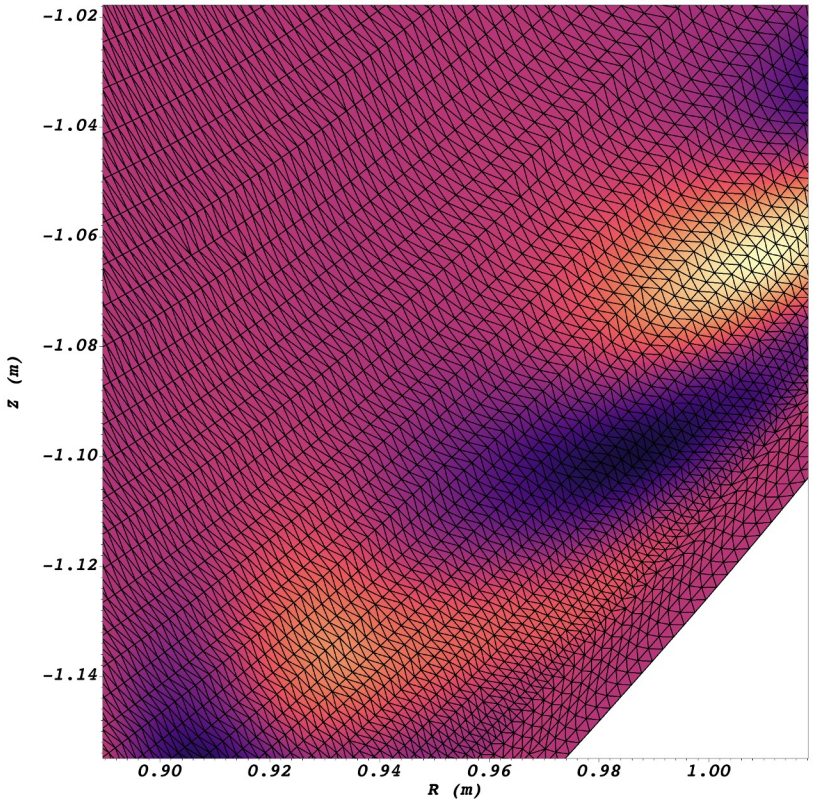
Points are non-uniformly spaced.

Constant over time. *f(x,y,t)*

100 rings → 500,000 points / plane



Delauney Triangularization Between Pairs of Rings



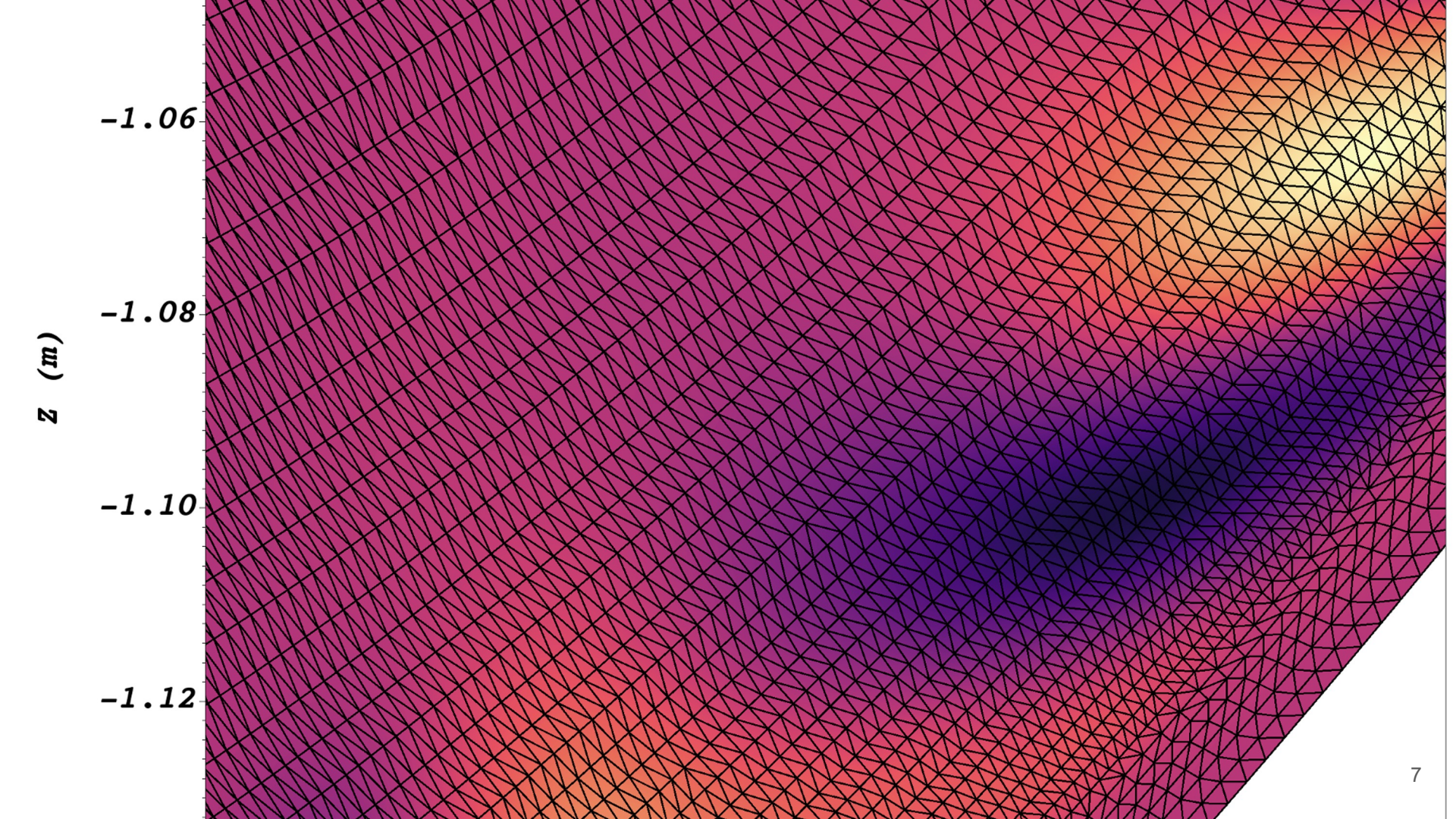
Utilize concentric ring structure.

Apply Delauney to each pair of rings.

Mask off empty inner ring.

Improves mesh compared to using all vertices in 1 triangulation.

Vertex density → Small triangles → Good color interpolation across high resolution pixels. Eliminates long, skinny triangles.


-1.06
-1.08
-1.10
-1.12
z (m)

GUI workflow

Histogram guides selection of data range & color Bar preview.

Save image per time step.

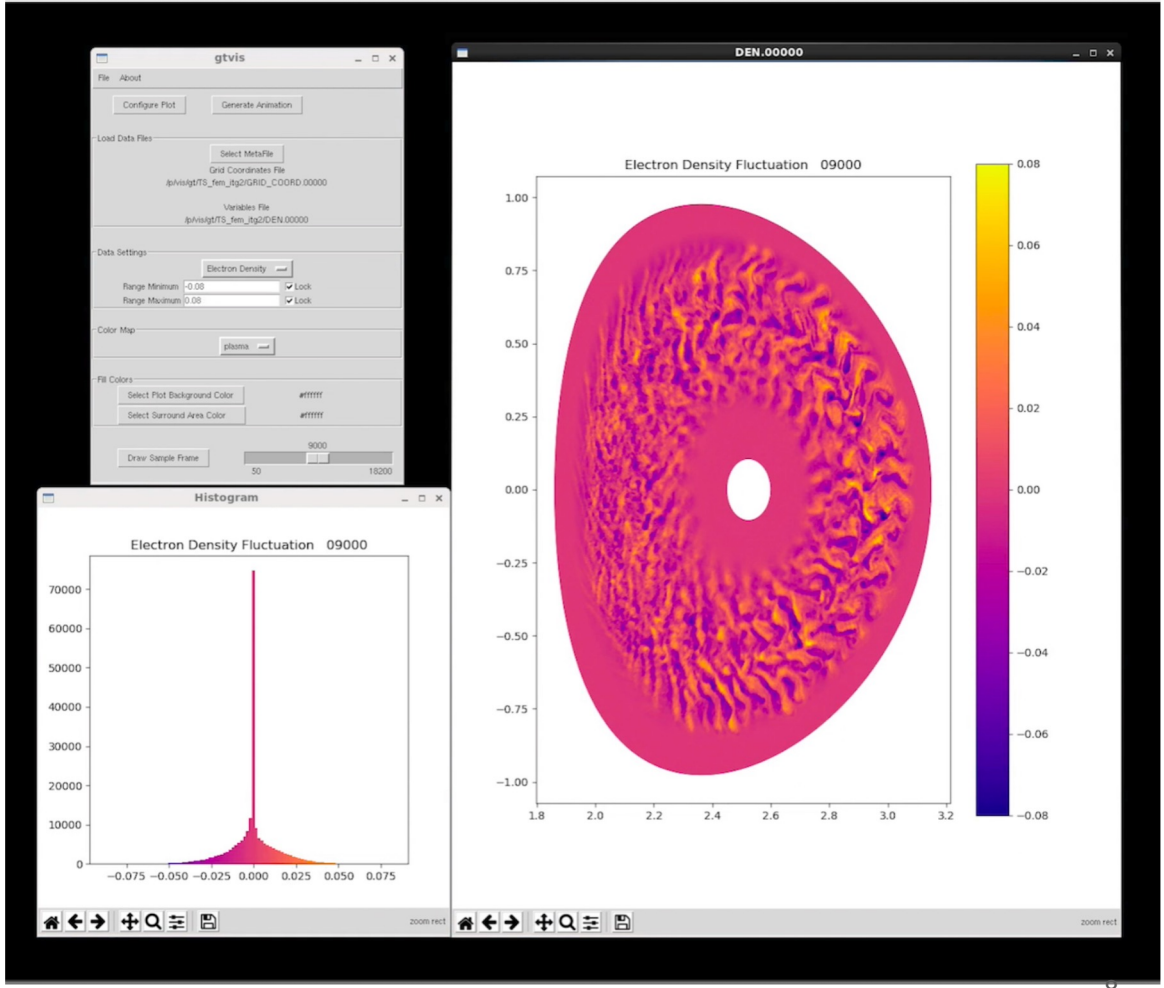
20 MB movie, considerably smaller than remote data TB.

900 lines of Python, Tkinter GUI.

Preview any time step.

Global min/max.

Command line option - batch.

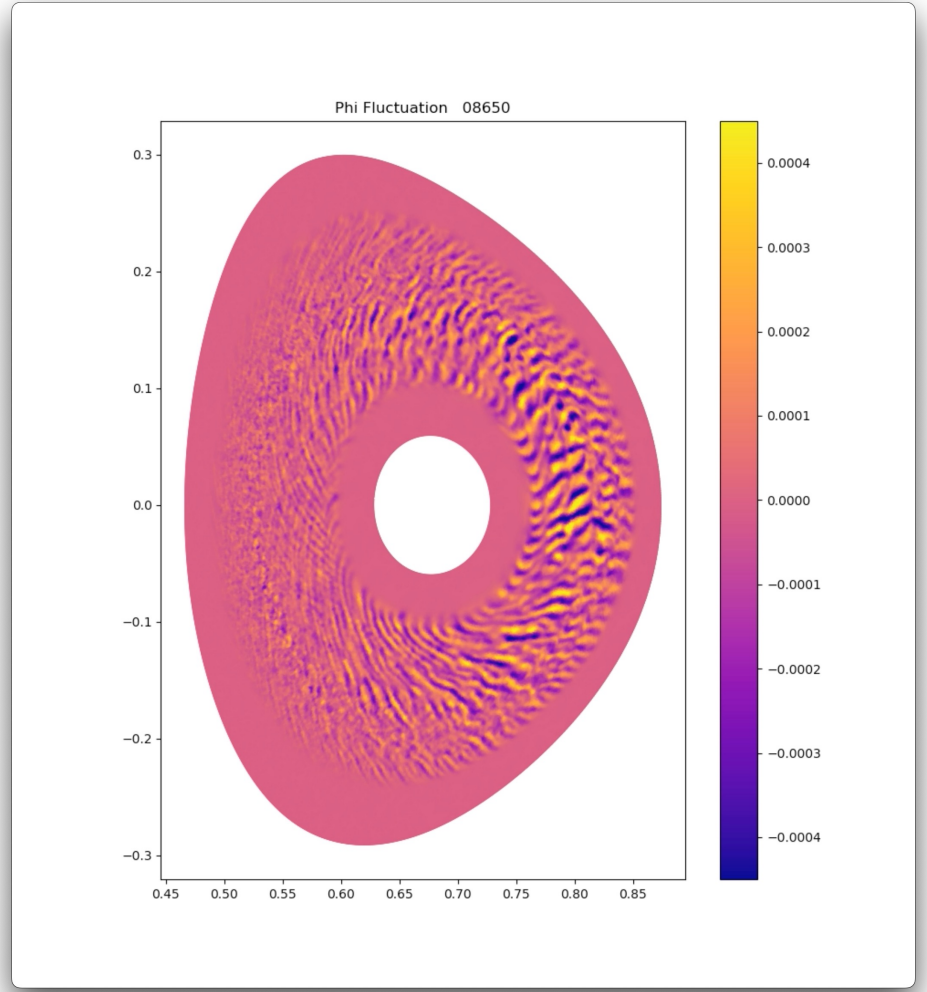


C-Mod Small Island Study

Weixing Wang

Clockwise & counter-clockwise rotation.

Micro-turbulence.



https://w3.pppl.gov/~efeibush/movies/Phi_00000.mp4

2. Flux Surface Models

Each poloidal plane has the same rings, but different vertices due to spiral magnetic field!

GTS provides index offset between planes.

GTS computes in Magnetic Coordinates - field lines are straight.

Saves data in Cartesian - field lines spiral.

High Resolution Surface Model

Follow field lines from plane to plane.

Definition points for interpolation along cubic spline.

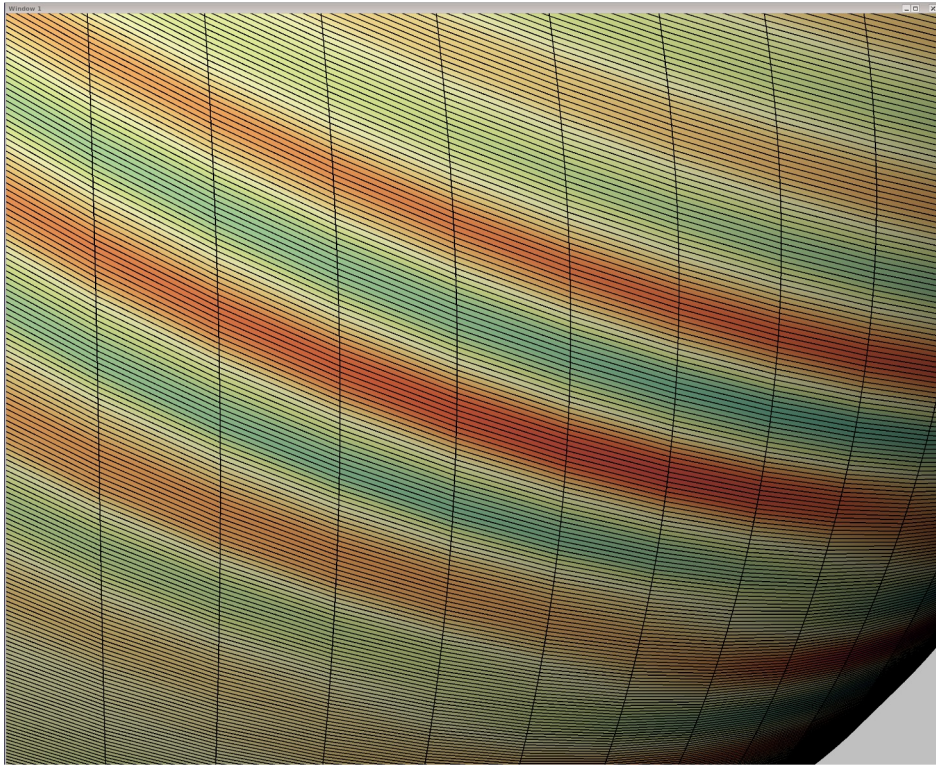
Interpolate geometry:

48 to 64 planes for smooth curvature to match 2K or 4K display resolution.

Interpolate variable for smooth shading.

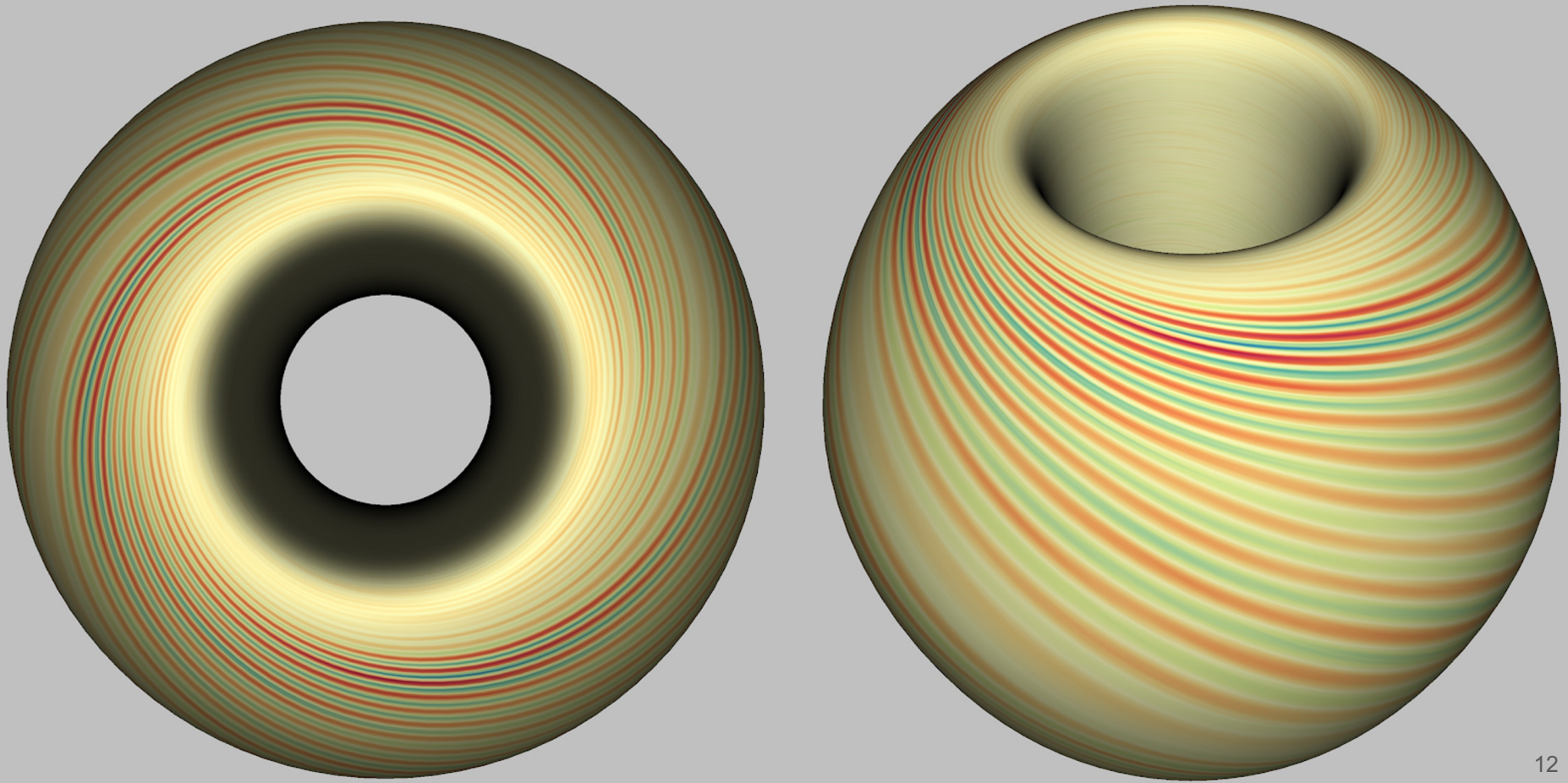
Compute surfaces in parallel per timestep.

Binary VTK files → VisIt & Paraview, script animation.



VTK 30 year anniversary!

Fluctuation of Electrostatic Potential - NSTX-U



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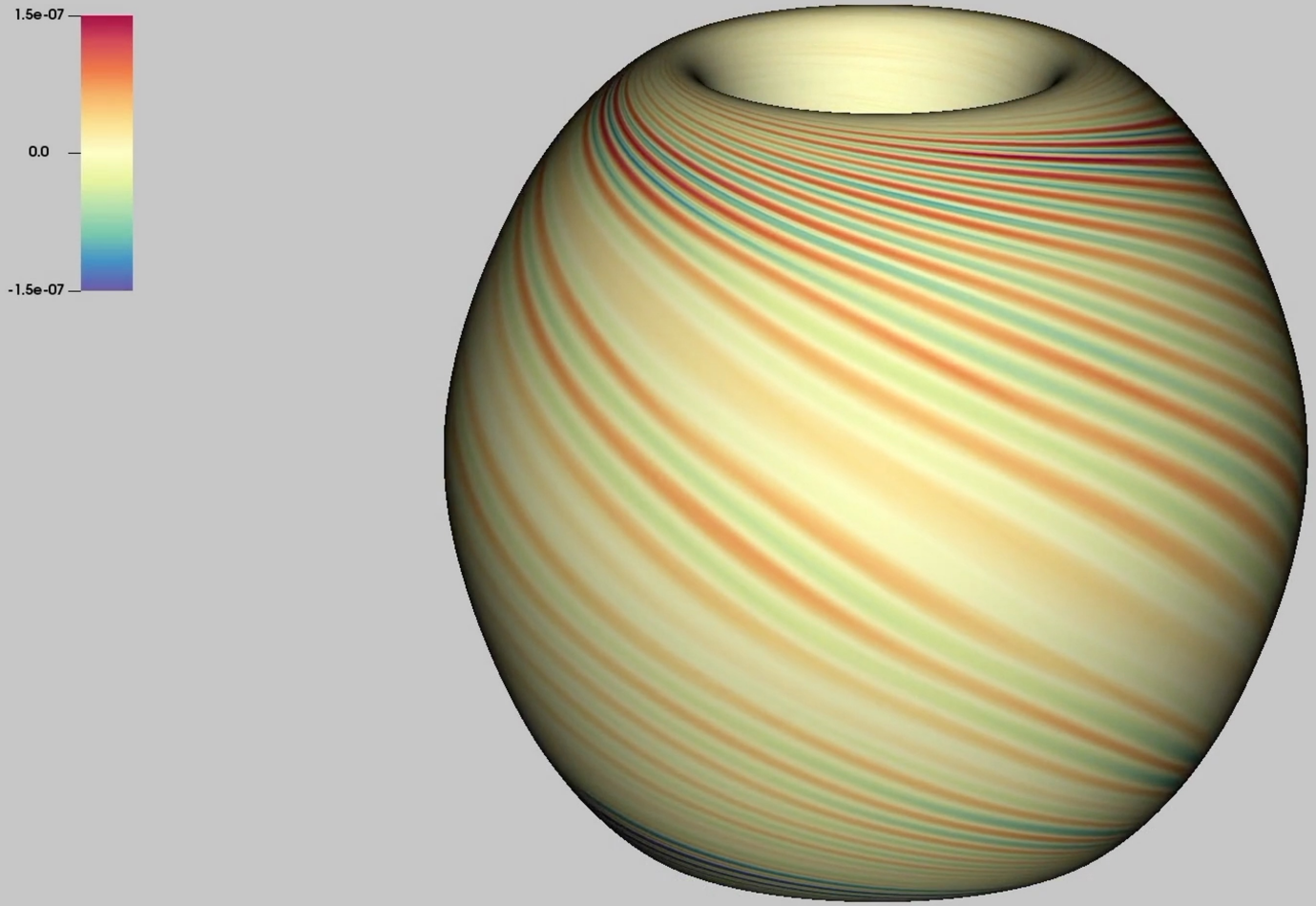


3. Solid Models *f(x,y,z,t)*

Continuous model of triangular prisms:

Poloidal & toroidal cutting planes.

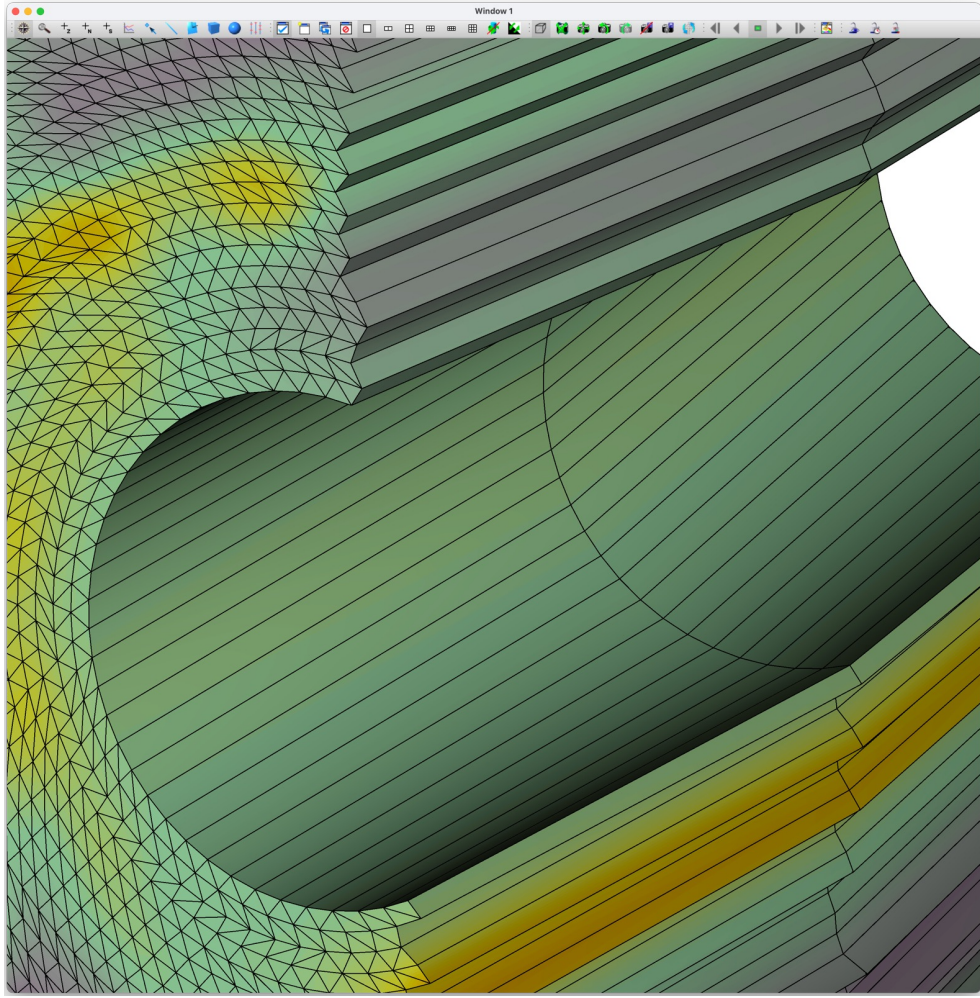
Isovolumes, flux tubes.

Python workflow - 1,200 lines of code

command line, config file.

Compute models in parallel for timesteps.

Binary VTK files → VisIt & Paraview.



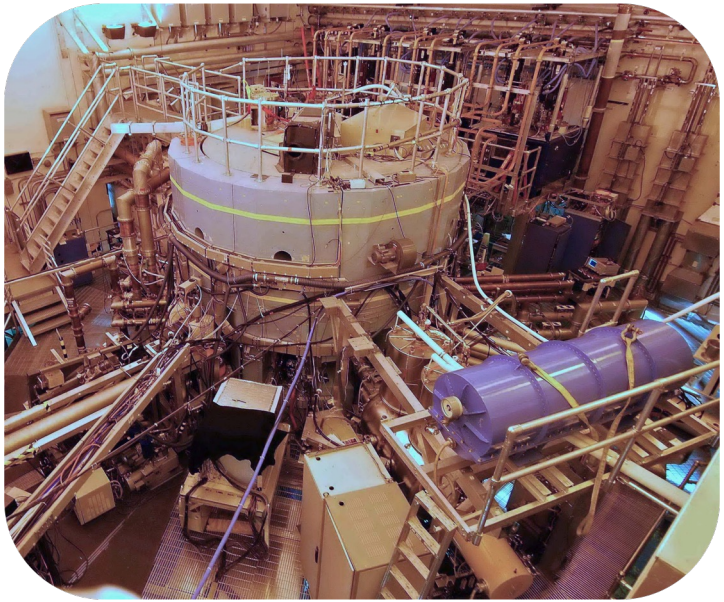
Geodesic Acoustic Mode

Global radial mode.

Can Reduce radial transport.

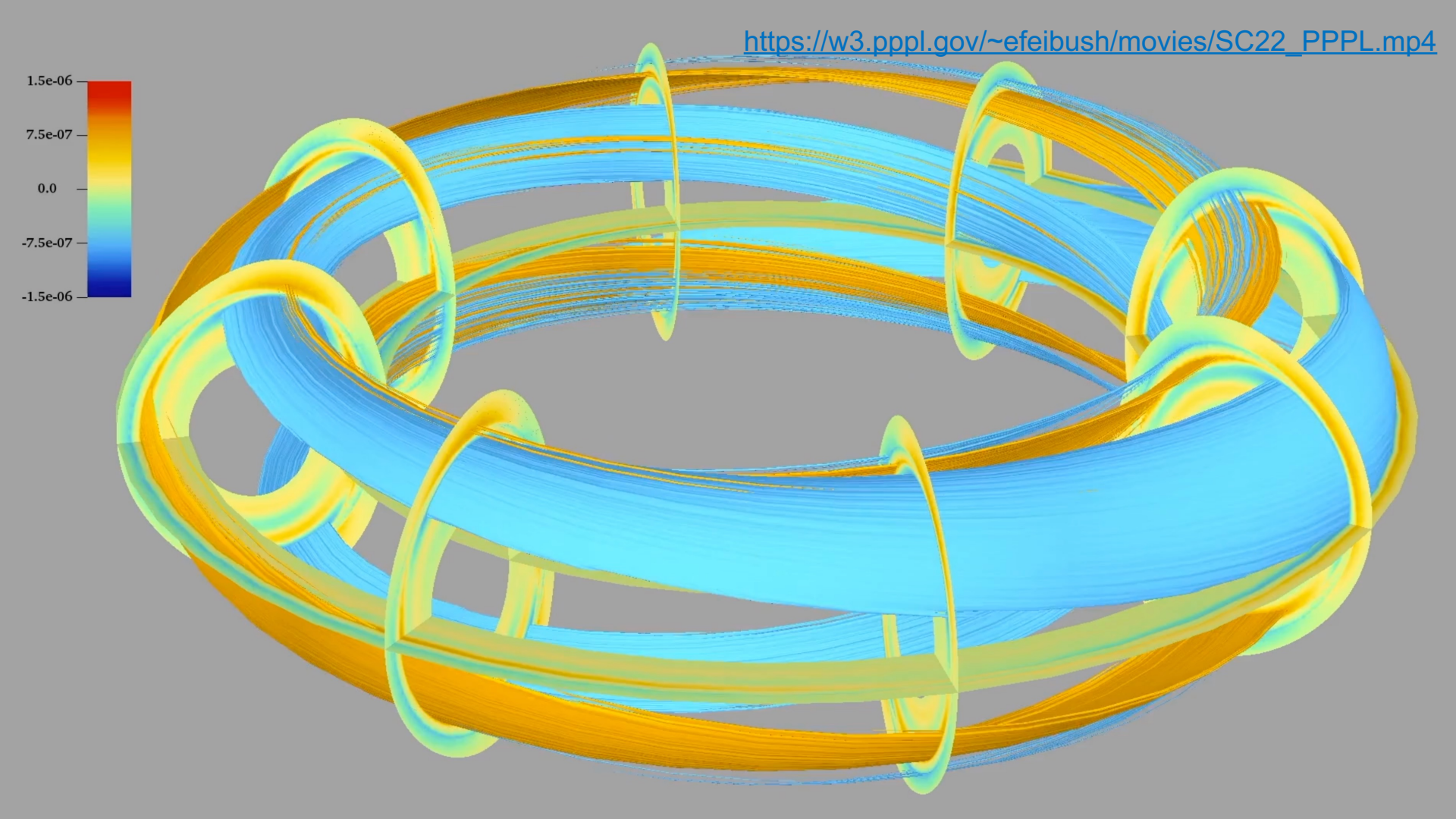
This simulation run is based on a particular shot.

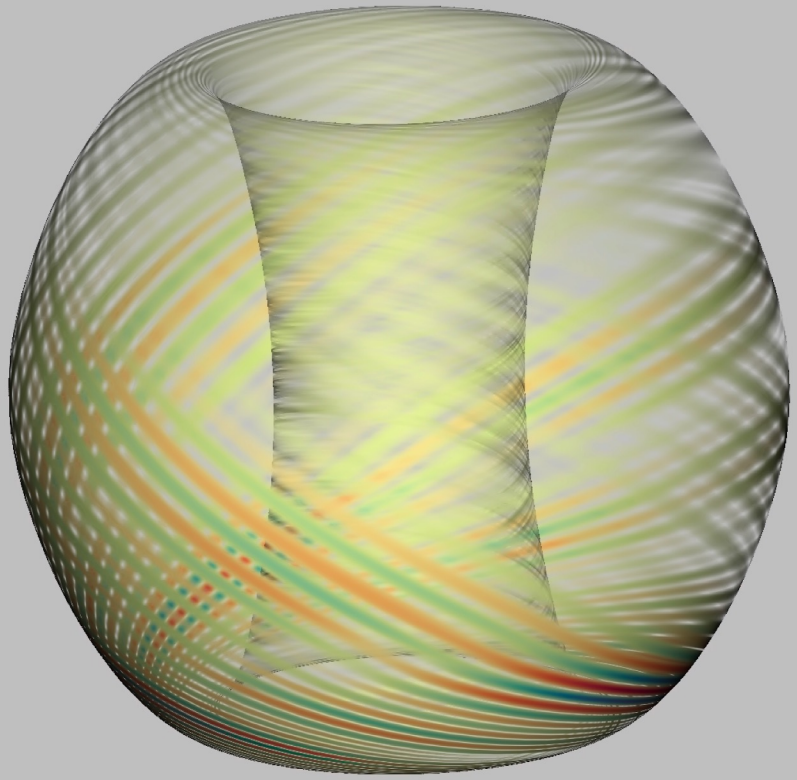
Computed & rendered on stellar.princeton.edu cluster.



Alcator
C-MOD

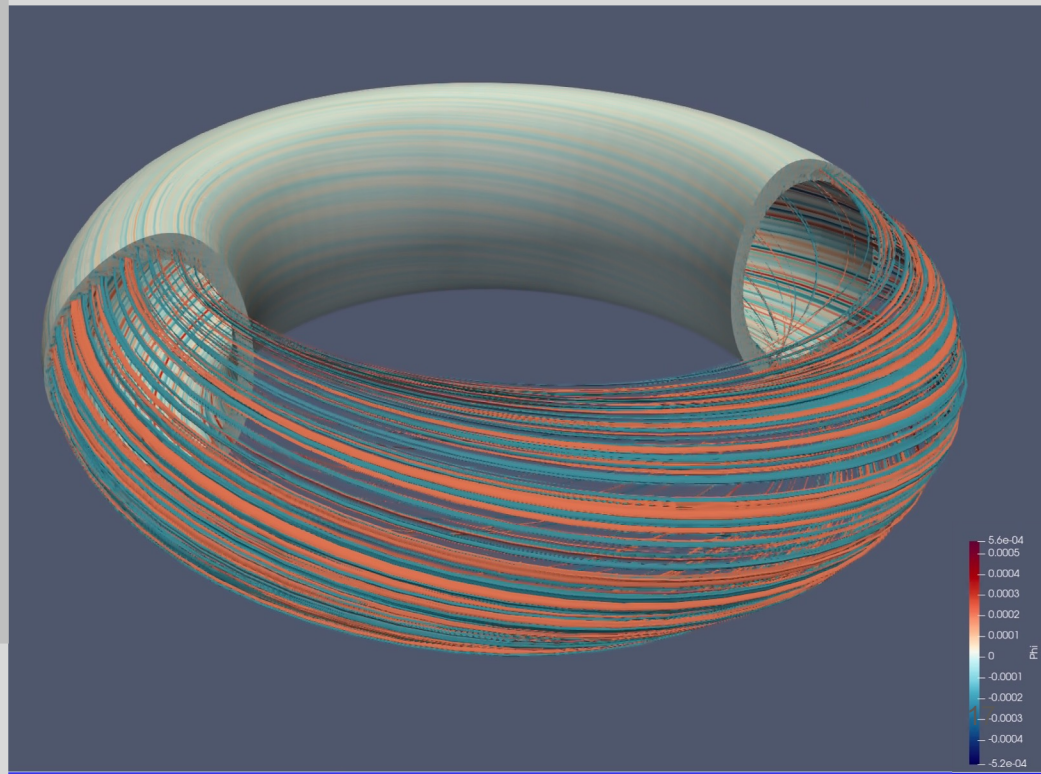
https://w3.pppl.gov/~efeibush/movies/SC22_PPPL.mp4





Surface with selective transparency in color map of low fluctuation.

Solid model of edge region with isovolumes of upper & lower quartiles.



4. Tokamak Digital Twin

Application of gyrokinetic visualization in context of comprehensive system simulation.

William Tang, IAEA Fusion Energy Conference 2023.

Visualization

Nvidia Omniverse + Paraview Connector

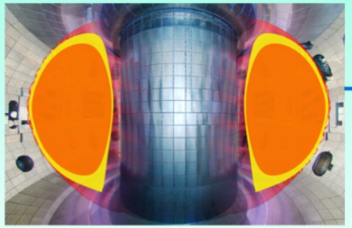
John Stone, Tom Gibbs

Architecture, Components, Proof-of-Concept stage.

DIII-D

Experiment & Engineering

Theory & Computation



DIII-D Fusion Experiment

Shot Data

Equilibrium Fit

Gyrokinetic Tokamak Simulation

ML Training

Model

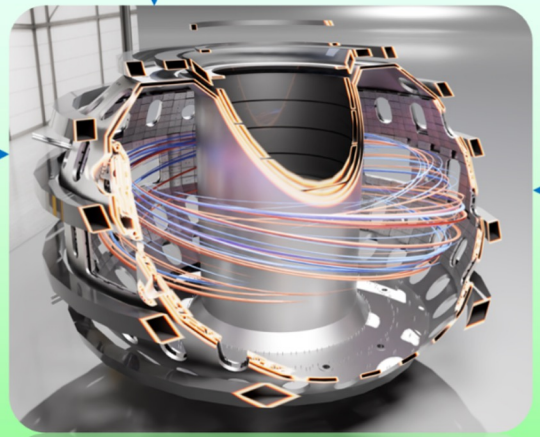
Surrogate Gyrokinetic Tokamak Simulation

CAD Model

Equilibrium Visualization

Visualization
Discovery
Communication

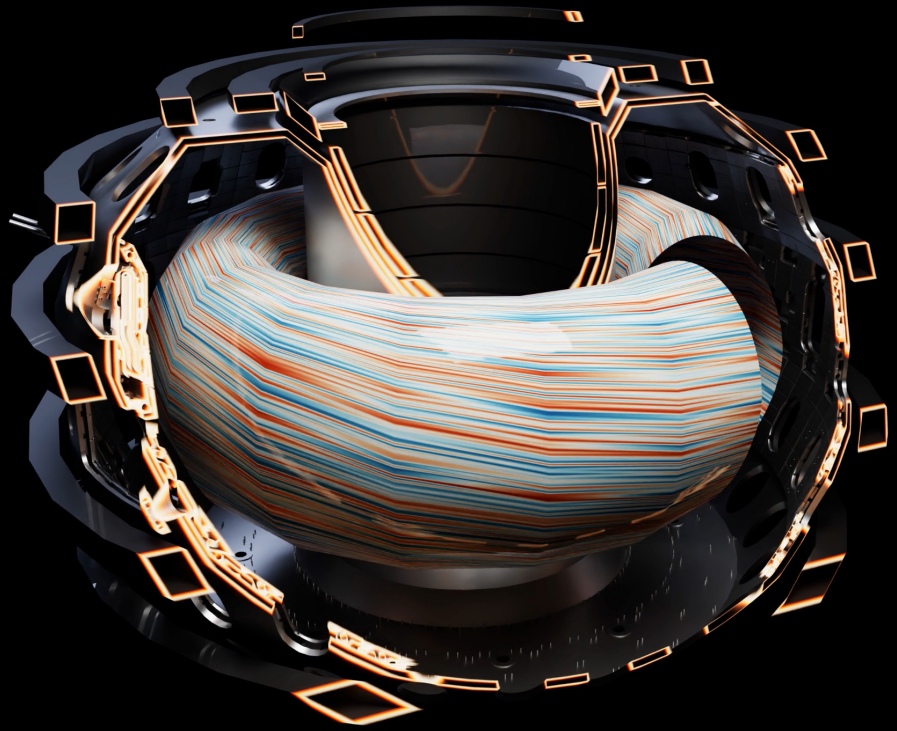
CAD Visualization



Omniverse Nucleus

Gyrokinetic Visualization

Paraview Connector



https://w3.pppl.gov/~efeibush/DigitalTwin/CADsurf.mp4

Tokamak Digital Twin

Integration of engineering CAD, experimentally-validated theory, computation, and advanced visualization. ML enables fast, realistic prediction of dynamic plasma instability properties.

Workflow

- CAD model of General Atomics DIII-D tokamak. Pre-processed to visualization format.
- Signal data acquired from 5,000 experimental shots on DIII-D.
- Calculate current profile, plasma shape, & magnetic field as input to GTS.
- Output used to train ML model - SGTC (surrogate), rapid prediction of linear stability & 2D mode structure.
- SGTC can run simultaneously with shot to predict kink mode. Provide feedback to plasma control system.

Visualization

Omniverse platform for interactive display of large 3-D models & simulations.

Displays entire mesh without data reduction. Highly realistic rendering on NVIDIA RTX GPU.

Related Simulations

GTC - Gyrokinetic Toroidal Code - Zhihong Lin, Xishou Wei

https://sun.ps.uci.edu/gtc/

XGC - X-Point Gyrokinetic Code - C.S. Chang

https://xgc.pppl.gov/html/general_info.html

References

Visualization of fieldlines & poloidal planes

D. Crawford, IEEE VIS '04.

G. Stantchev, IEEE Transactions on Plasma Science, 36, 2008.

Tokamak Digital Twin

W. Tang, IAEA Fusion Energy Conference 2023.

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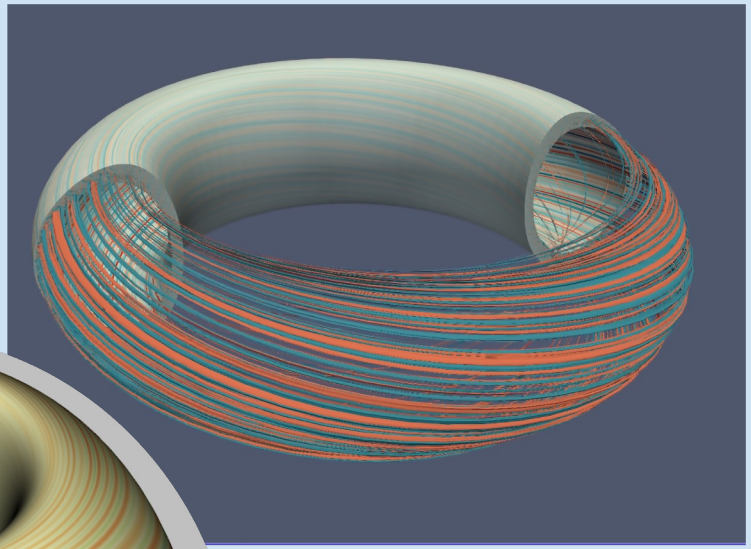

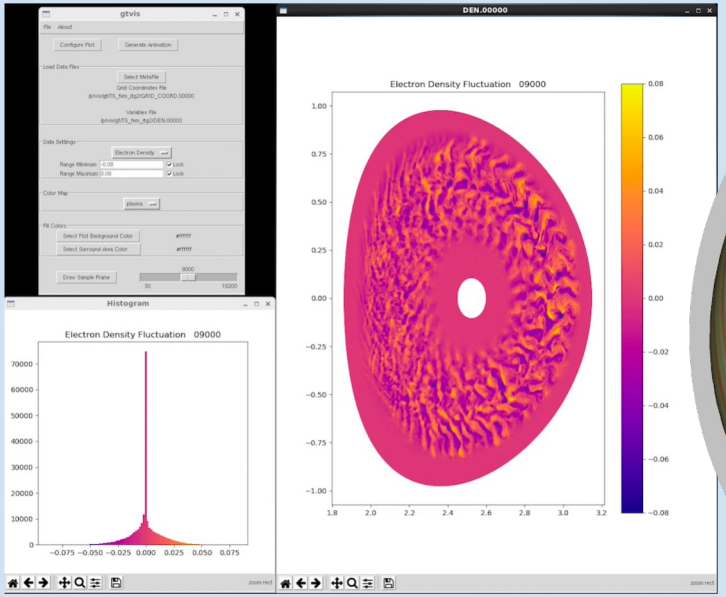

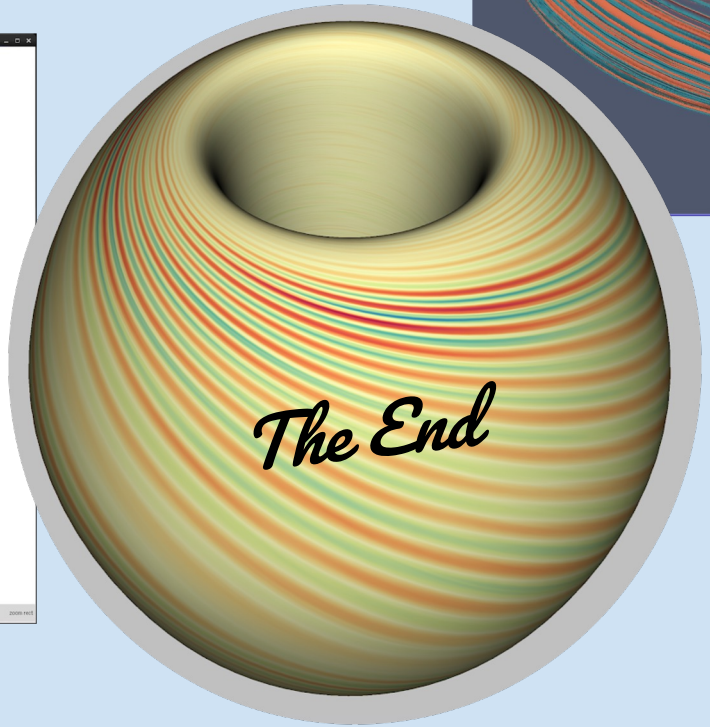

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