# High Performance Tokamak Microturbulence Visualization With AVS/Express

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## Abstract

*This research is part of the Numerical Tokamak Turbulence Project, a national consortium of efforts to create predictive numerical simulations of plasma turbulence in tokamak fusion experiments. This particular work represents efforts to create high performance, interactive visualizations of simulations using a gyro-fluid closure in a flux-tube with magnetic field line following coordinates.*

## 1. Introduction

The tokamak magnetic field geometry is challenging to visualize. In field line following coordinates the integral curves of the field appear as straight lines. This allows the use of a fast Fourier transform (FFT) technique for time advancement, a distinct computational advantage.

Two issues complicate solving the gyro-fluid moment equations in a tokamak with FFTs. First, enforcing (parallel) periodicity of the solutions in field-line following coordinates is non-trivial. Second, the equations do not fully diagonalize in either ***x***-space or ***k***-space.

Methods have been developed to cope with both of these difficulties in the time advancement scheme. The result retains an overall computing efficiency characteristic of applications of spectral methods to other computational fluid dynamics systems. [Hammett, et al, 1994]

The solutions based on these methods are a set of gyro-fluid moment fields. These fields each have the form of a 2-D set of Fourier amplitudes for each of a set of locations along a magnetic field. Since the tokamak is essentially an axisymmetric system, any magnetic field-line can be used to define a flux-surface by a suitable rotation about the axis of symmetry. The inverse transform of each Fourier spectrum is then a representation of the moment field on a surface whose normal is locally parallel to the magnetic field.

## 2. Previous Work

### *2.1 Parallel Ray Casting*

Our early work focussed on simplified tokamak field geometry: concentric circular flux-surfaces, typical of circular tokamaks operating at low plasma pressure. In these studies, we used ray casting to visualize simulation results. Specifying the surfaces on which the moment fields were to be presented, the intersections with these surfaces of straight line rays, one ray per pixel, were computed and an interpolant of the field at each intersection was used to color the pixel. With nested concentric circular flux-surfaces, the ray casting technique was relatively simple, fast and fully (computationally) parallelizable. High resolution view dependent images could be generated in real time (~1 frame/sec) with software rendering on large parallel computers.[Waltz, et al, 1994]

### *2.2 AVS/CAVE Parallel Flow Visualizer*

In subsequent work, reusing much of the same software and techniques, we built a parallel flow visualizer. This application used the computing power of a large parallel computer as a data generator to drive the rendering hardware of a multiple graphics-pipeline **SGI** in a **CAVE** multiple screen virtual reality environment. [Kerbel, et al, 1996] The flow data was generated on the fly by integrating the time dependent 3D flow fields. Initial condition schemas were supplied by user gestures in the **CAVE** with the help of the **AVS** visual development environment. **AVS** provided a convenient mechanism for generating the control structures for the data generator and also served as a previewing apparatus for parameter selection. This mode of operation was necessary in order to decouple the fast local rendering response of the virtual reality environment, determined by the response to the tracker positions, from the much slower response of the data generator to parameter changes. Controlling the the data generator involved sending *control* data via sockets and receiving back flow data updates to schedule for the render traversals. The application was fully interactive and staged at multiple levels.

### 2.3 AVS/Express Volren Volume Rendering

The experience of these early developments as well as improvements in graphics hardware led us next to build a volume renderer **AVS** module based on the volume texture mapping technique pioneered by Cabral [Cabral, et al, 1994]. Texture mapping is a technique that replaces per-vertex color lookup with per-vertex mapping from a specifiable space of colors. With hardware support, pixel-fill proceeds at nearly the same rate in both cases. The advantage is that one may specify the color interpolation independently of the vertices at little or no price in performance. Without textures, one needs finer (more costly) geometry to resolve finer image patterns. With textures one simply uses the finer image pattern as a texture and leaves the geometry coarse.

We reused the earlier ray casting code to extract image sets with which to construct volume textures. The extraction process was interactive only in the sense that the **AVS** previewer facilitated the data selection (e.g. with navigation interactors). The view dependent volume rendering was interactive owing to the use of hardware accelerated volume texture mapping and texture look-up tables for color and transparency adjustment. [Kerbel, et al, 1995] These two applications were run separately, the extractor generating input for the volume renderer.

## 3. Current Work

### 3.1 Geometry Generalization

We were led by this previous work to develop a technique that would be flexible and interactive with respect to the underlying magnetic geometry. The idea was to harness graphics hardware to do what we had done analytically through ray casting, and to do this with more generality. We wanted to relax the constraint of concentric circular flux-surfaces in favor of geometry characteristic of more realistic tokamak equilibria.

In practice, these equilibria are generally computed by solving the Grad-Shafranov equation, an elliptical partial differential equation representing magnetohydrodynamic force balance. Our ray casting technique was impractical with such a complex geometry, known only numerically. As a further consideration, the meshes natural to the tokamak gyro-fluid computation are typically sheared across flux-surfaces and stretched in the direction along the magnetic field. As a result, polygons whose vertices correspond to neighboring nodes on the computational mesh generate a particularly inefficient tessellation for rendering magnetic flux-surfaces in the lab coordinate frame.

We wanted a mapping of the fluid moment field solutions onto an independently specifiable manifold (geometry) which would be continuously adjustable and rendered fast enough for interactive inspection by researchers. We anticipated that such a mapping, once computed, could be reused to view time dependent data, thus amortizing the cost of its generation.

### 3.2 Volume Texture Mapping

Recognizing the periodicity implicit in the spectral flux-tube analysis, we felt there was great advantage to be gained adapting the 3D texture mapping technique used for the volume rendering work to this more general application. With the correct 3D tiling, only one flux tube texture would be required to map any manifold we might choose.

In the volume rendering application one defines for each frame a set of equally spaced viewing planes normal to the current viewing direction. Subdividing each of these planes into a triangle strip, computing 3D texture coordinates for each vertex and rendering the associated texture patches back to front with alpha blending creates a wide range of volume rendering effects, depending on the choice of alpha mapping one associates with the data. The method is fast because the textures are rasterized in hardware and the number of polygons is just a few times the number of viewing planes, typically fewer than 1000. Modern graphics rendering hardware is capable of rendering $>10^6$ polygons per second per $1K, so the overall performance is determined by the rate at which textures can be blended and applied, the rasterization or pixel-fill rate.

Our adaptation of the 3D texture mapping technique was to specify the fluid moments as textures in the natural (field-line following) coordinates of the physics computation and compute the associated texture coordinates for an efficient tessellation of a manifold based on the Grad-Shafranov equilibrium. This approach has a number of advantages.

First, for flux-tube calculations, the mesh necessary to resolve the turbulence is typically much finer than one to resolve the structure of the equilibrium. Thus a coarse tessellation of the equilibrium appears quite smooth relative to the structure typical of the fluid moment solutions. One ends up with a high resolution representation of the moment solutions rendered on a set of surfaces, including flux-surfaces and various cross sections, which can be accurately specified with a relatively small number of polygons. Since the number of polygons is small and the rasterization is done with texture hardware, the resulting scene can be manipulated at high frame rates. Furthermore, the solution set can be made to evolve in time simply by preloading a set of textures and resetting a texture pointer for each time slice.

### 3.3 The Equilibrium

The mathematical model we have used to study tokamak gyro-fluid microturbulence is essentially a local approximation. We compute a statistical characterization of the turbulence in the neighborhood of a flux-surface. For

this reason, the equilibrium specification we use, after Miller [Miller, et al, 1998], includes only linear variations in quantities describing force balance in the neighborhood of a flux-surface.

The Miller model provides a wide range of realistic local tokamak equilibria parameterized by 9 parameters including magnetic helicity and shear, flux-surface triangularity and elongation and their derivatives, Shafranov shift and aspect ratio. An example of the field lines associated with a typical equilibrium is shown in Figure 1. The great advantage of this model for us is that it avoids having to solve a 2D elliptic PDE.

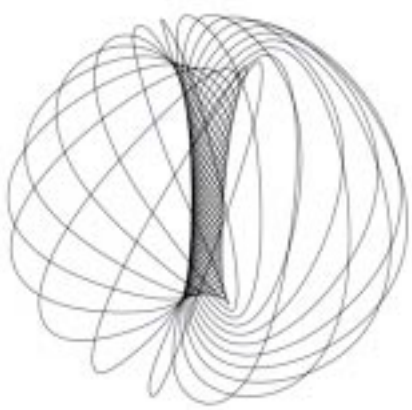

**Figure 1 : Magnetic field lines on a flux surface associated with a tokamak equilibrium.** Field lines on neighboring flux surfaces are related to these through magnetohydrodynamic force balance.

### *3.4 AVS/Express Field Construction*

Once standard **AVS/Express** field objects are populated with coordinates and the coordinates have been associated with texture coordinates, tesselations associated with surface extraction operations applied to the field object will automatically become associated with corresponding texture coordinates, all computed internally by **AVS/Express**. This rather subtle point is a remarkable virtue of **AVS/Express** as a visual development environment. Populating field objects such that the fastest surface extraction operators produce optimal tessellations pays off royally in performance. For our case, using the computational coordinates and the computed moment fields directly for populating an **AVS/Express** field object and then using an isosurface extraction operator to produce a visualization results in a truly unacceptable product. A hammer is a fine tool for a nail, but a poor one for a screw.

### *3.5 3D Flux-tube Tiling*

The spectral representation for the moments in the coordinates transverse to the magnetic field generate naturally periodic solutions in those coordinates. Thus wrapping (periodically continuing) the map in the transverse dimensions gives a naturally continuous tiling in those dimensions. The tiling itself is discontinuous in the direction parallel to the magnetic field and special care is necessary to generate a texture and a mapping that appear continuous in that direction. The texture must map into itself relative to its transverse texture coordinates after one parallel texture coordinate cycle as the magnetic field maps into itself over one poloidal circuit. Each field line rotates in the toroidal sense at $q$ times the rate it rotates in the poloidal sense. This quantity $q$ varies from one flux surface to another producing a shear in the magnetic field.

The Miller model generates a single poloidal circuit for a magnetic field-line on each of a set of neighboring flux-surfaces. Using toroidal axisymmetry, an appropriate toroidal rotation of points on the field-line can be used to generate a tessellation of any flux-surface in the domain. This toroidal rotation provides the (cyclic) registration with respect to one of the texture coordinates. A second texture coordinate is provided by the radial coordinate, which also serves as the flux-surface index. The third texture coordinate maps to the arclength along the poloidal circuit of a magnetic field-line.

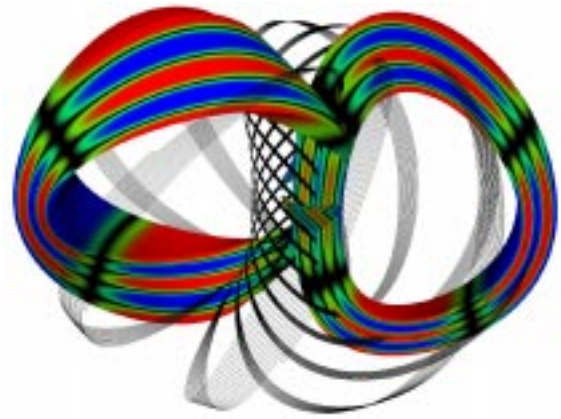

**Figure 2: Two alternative 3D flux tube tilings.** The simulation uses field line following coordinates in a flux tube, shown on the left. Tesselations associated directly with these coordinates are inefficient, requiring many polygons to appear smooth. The shape on the right is more efficient. The mapping between these two coordinate systems is represented as the texture coordinates.

### *3.6 Optimal Tessellations*

An optimal tessellation of a smooth surface for our purposes is one that gives the best impression of smoothness using the fewest polygons. In the general case, this may not be perfectly quantifiable, but in this case it's a good bet that the best choice involves regular tessellations of circles about the axis of symmetry as edges. The simulation uses field line following coordinates in a flux tube like the one shown on the left in Figure 2. Tessellations associated directly with these coordinates are inefficient, requiring many polygons to appear smooth, especially where the field lines are highly curved. The shape on the right in Figure 2 is constructed from orthogonal slices of a mesh in conventional toroidal coordinates. This construction is more efficient, requiring fewer polygons to appear smooth. The mapping between these two coordinate systems is represented to **AVS/Express** through the texture coordinates.

Using the Miller model we generated a poloidal cross section of the mesh then rotated it about the axis of symmetry to populate the coordinates of an **AVS/Express** field. From this field we extracted a variety of textured manifolds conveniently and efficiently. To complete the preparation, we populated the texture coordinates for the vertices of the mesh using the method outlined above.

Figures 3 and 4 show close-up views of the 3D tiling at the parallel ends of the flux tube. The two ends of the flux tube do not align with one another because of the rotational transform of the magnetic field. Accounting for this in the texture coordinate mapping leaves a weak discontinuity remaining at the parallel boundary owing to the finite number of modes retained in the simulation. Figures 4, 5 and 6 use textures constructed from data obtained from a **GRYFFIN** simulation. They show the electrostatic potential for ion temperature gradient gyro-fluid microturbulence in a tokamak. The toroidal fundamental mode number, $n_0$, is an adjustable parameter inversely proportional to $\rho/a$, the ratio of the ion gyro-radius to the minor radius of the tokamak. Parameter $n_0$ appears in the visualizations as the number of 3D flux-tube tiles necessary to fill the toroidal annulus. The theory takes $\rho/a$ to be small and is insensitive to its value. Thus, all else being equal, as $n_0$ is increased, the *picture* should become more representative of experiment. Figure 6 shows the same simulation data using $n_0$ values of (left to right) 7, 14 and 21.

### *3.7 Remote Hardware Acceleration*

In recent versions of **AVS/Express** the volume texture hardware acceleration technique works well remotely only between some **X**Servers with certain local hardware configurations, for small textures. Early in the development reported here, we realized this could be an important issue for some users, especially for large textures and remote **X**Servers without onboard texture hardware. The reasons for this are beyond the scope of this paper. To address this issue we developed enhancements to the core **OpenGL** renderer used by **AVS/Express** incorporating Kilgard's **GLR** [Kilgard] thus enabling remote access to performance gains realized using a central graphics server with volume texture hardware acceleration capability.

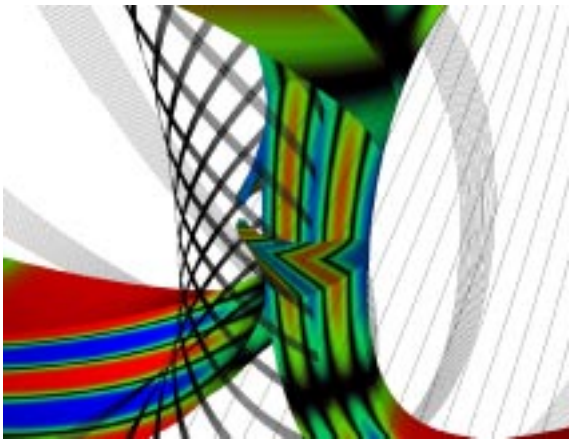

**Figure 3: The 3D flux tube tiling is discontinuous in the direction parallel to the magnetic field.** Special care is necessary to generate a texture and a mapping that appear continuous in that direction. The data here is legislated.

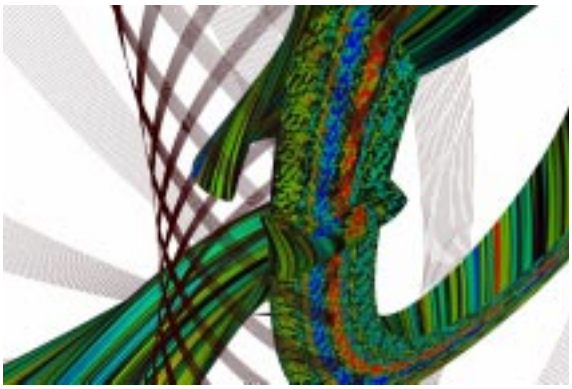

**Figure 4: Structure of the gyrofluid solution at the flux tube parallel boundary.** The texture shows a discontinuity due to limited parallel resolution in the simulation.

## 4. Summary

We have developed a set of high performance tools based on the **AVS/Express** visual development environment designed for visualizing the results of tokamak gyro-fluid microturbulence simulations.

The tools can be used in a variety ways to generate interactive 3D representations of noncircular, finite aspect ratio, local Grad-Shafranov equilibria. The fluid turbulence is visualized by specifying an equilibrium interactively, generating surfaces associated with that equilibrium and mapping local values of the fluid moment fields onto those surfaces using a volume texture technique.

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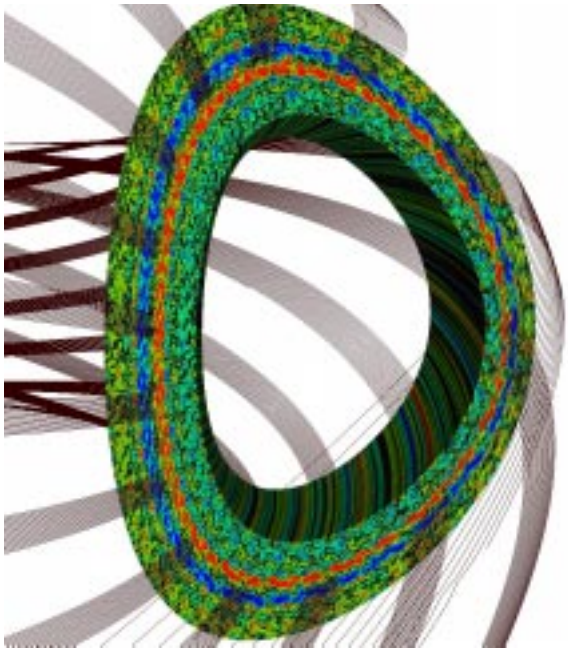

**Figure 5: Tokamak Gyrofluid Microturbulence:** The electrostatic potential for ion temperature gradient gyrofluid microturbulence in a tokamak.

**Kilgard,** M.J. *GLR, an OpenGL render server facility*, **URL:** http://reality.gi.com/opengl/glr/glr.html.

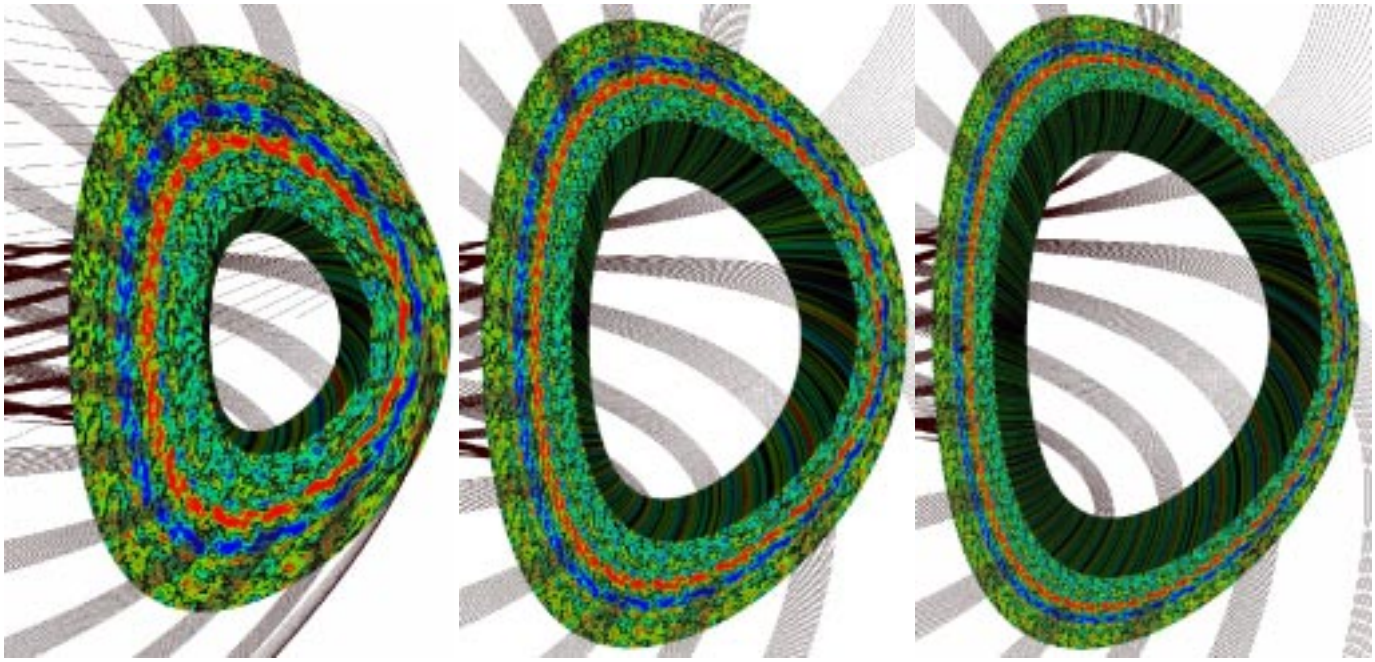

**Figure 6**

**Tokamak Gyrofluid Microturbulence:** The electrostatic potential for ion temperature gradient gyrofluid microturbulence in a tokamak. The tiling periodicity or toroidal fundamental mode number $n_0$ for each is (left to right) 7,14 and 21. This adjustable parameter is inversely proportional to **ρ/a,** the ratio of the ion gyro-radius to the minor radius of the tokamak. The theory on which the simulation is based takes **ρ/a** to be small. Thus, all else being equal, as $n_0$ is increased, the scale of the turbulence becomes finer and the picture becomes more representative of experiment