Modeling a Plasma Disruption in Magnetically Confined Fusion

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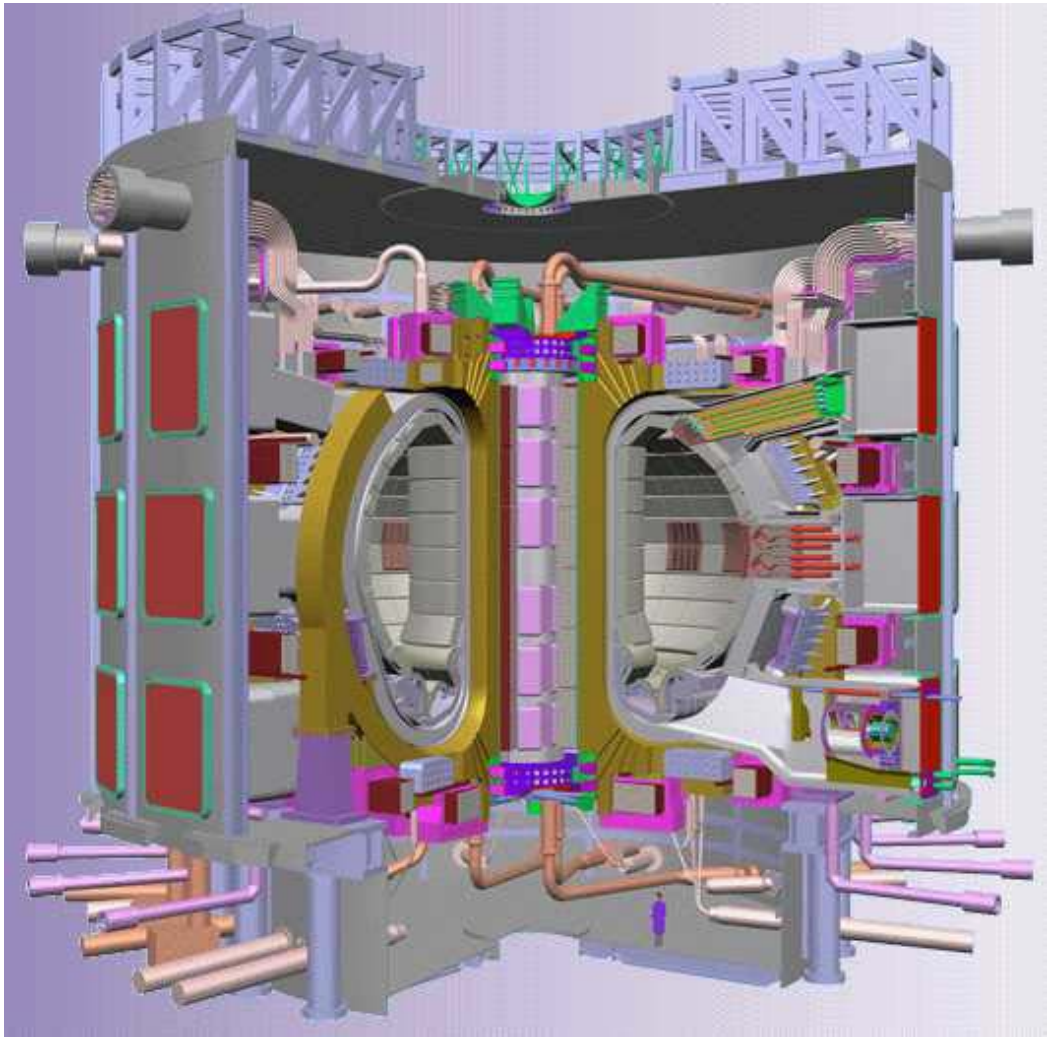
Outline

- ITER Background
- Sandia's Role: The Blanket
- My Role: Representing a Plasma for Electromagnetic Analysis

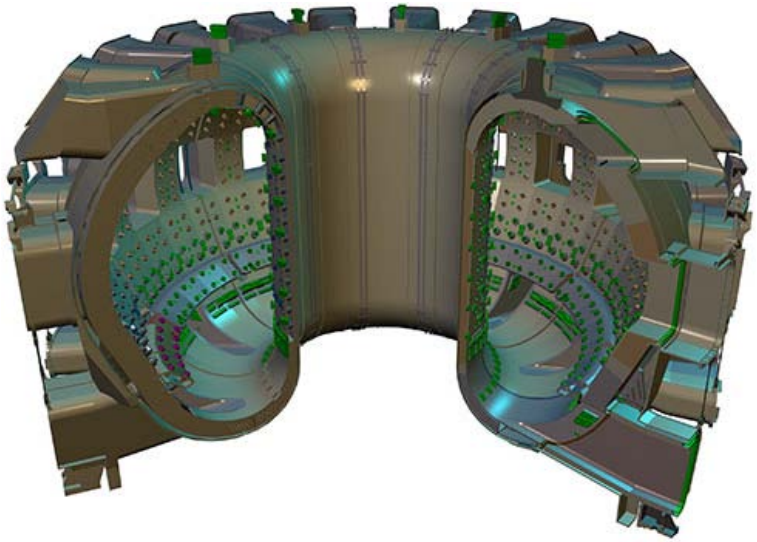
What is ITER?

- An international experimental reactor to achieve a burning plasma
- Magnetic Confinement Fusion
- Tokamak Reactor

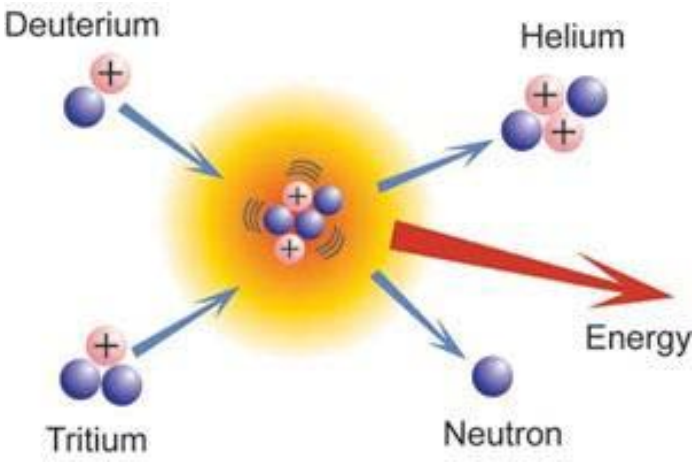


Interesting Facts and Figures

- ITER will be the first fusion reactor to achieve a burning plasma, the goal is 500 MW of output for 50 MW of input
- The plasma will reach temperatures of 150 million °C, ten times hotter than the core of the sun
- The tokomak will weigh 23,000 tons, approximately the weight of three Eiffel Towers
- The ITER tokomak will be the largest tokomak ever at 840 m^3



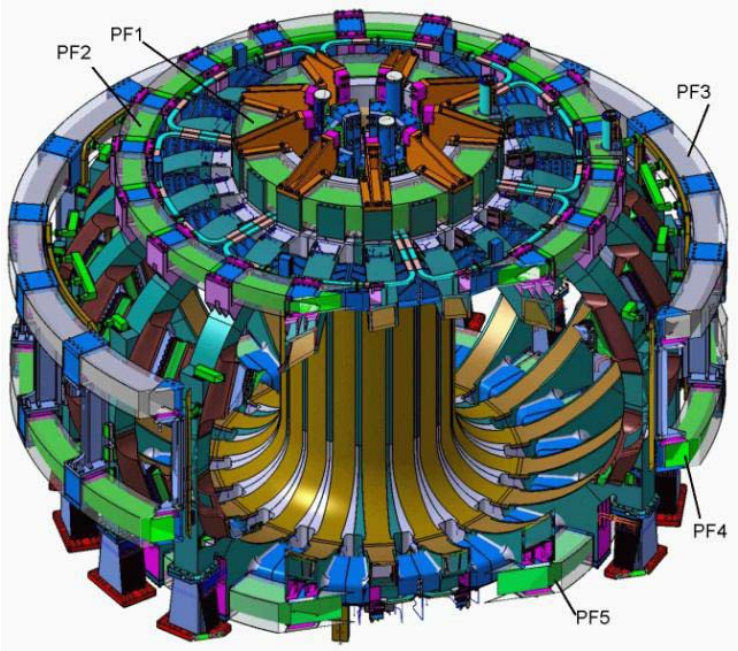
Fusion

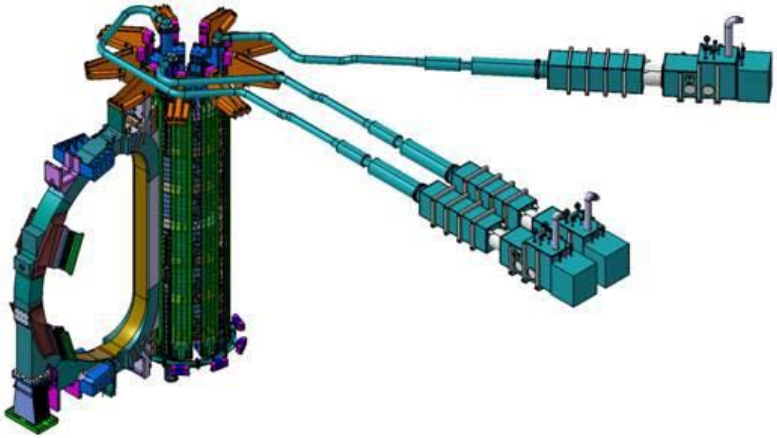


- Controlled fusion has three requirements to get net energy
  - Confinement (High Density)
  - High Temperature
  - Stability (Long Duration)
- Inertial Confinement Fusion
  - A pulse of energy heats a fuel pellet to extremely high temperature and density, but the reaction time is much less than a second
- Magnetic Confinement Fusion
  - Magnets stabilize plasma so that a lower density is required
  - ITER will have reactions that last 400-500 seconds

Magnetic Confinement - Tokamak

- Plasma held in a toroidal shape by huge superconducting magnets
- Toroidal Field Coils confine the plasma
- Poloidal Field Coils shape and control the plasma
- Central Solenoid induces the plasma current
  - It will be the largest and highest field solenoid in the world at 13 T

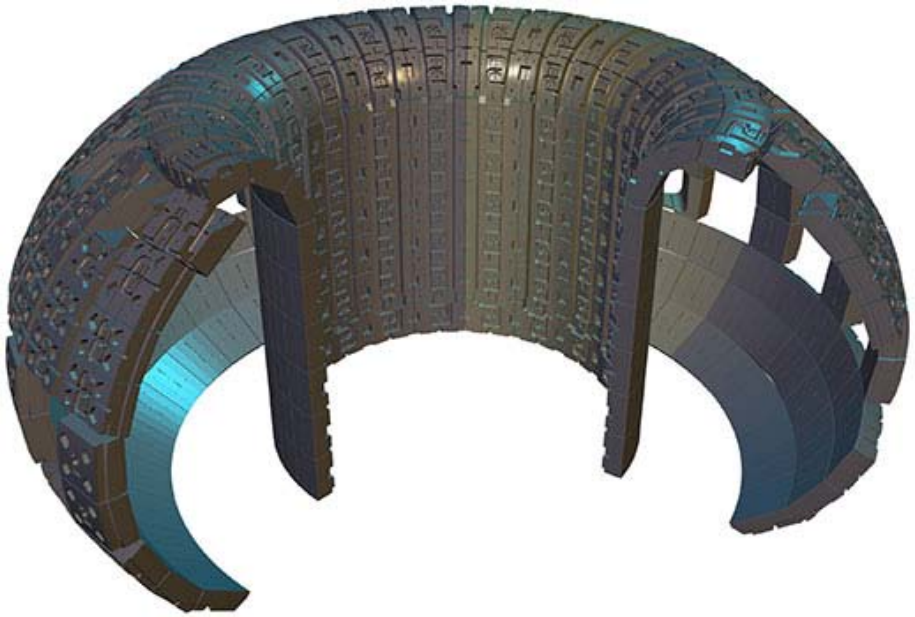




Sandia's Role: The Blanket

The Blanket

- First Wall (Be, CuCrZr, and Stainless Steel)
  - Faces the plasma
  - Dissipates Plasma Heat Flux
  - Water Cooled
- Shield Modules (Stainless Steel)
  - Neutron Shielding
  - Water Cooled



The Blanket

- Truly an extreme environment
- Subject to:
  - Extreme Temperatures
  - Neutron Bombardment
  - Eddy Currents
- Some blanket modules are being designed here at Sandia
- This design involves analysis of:
  - Neutronics
  - Heat Flow
  - Thermal Stress Analysis
  - Electromagnetics / Eddy Currents
  - Stress Analysis

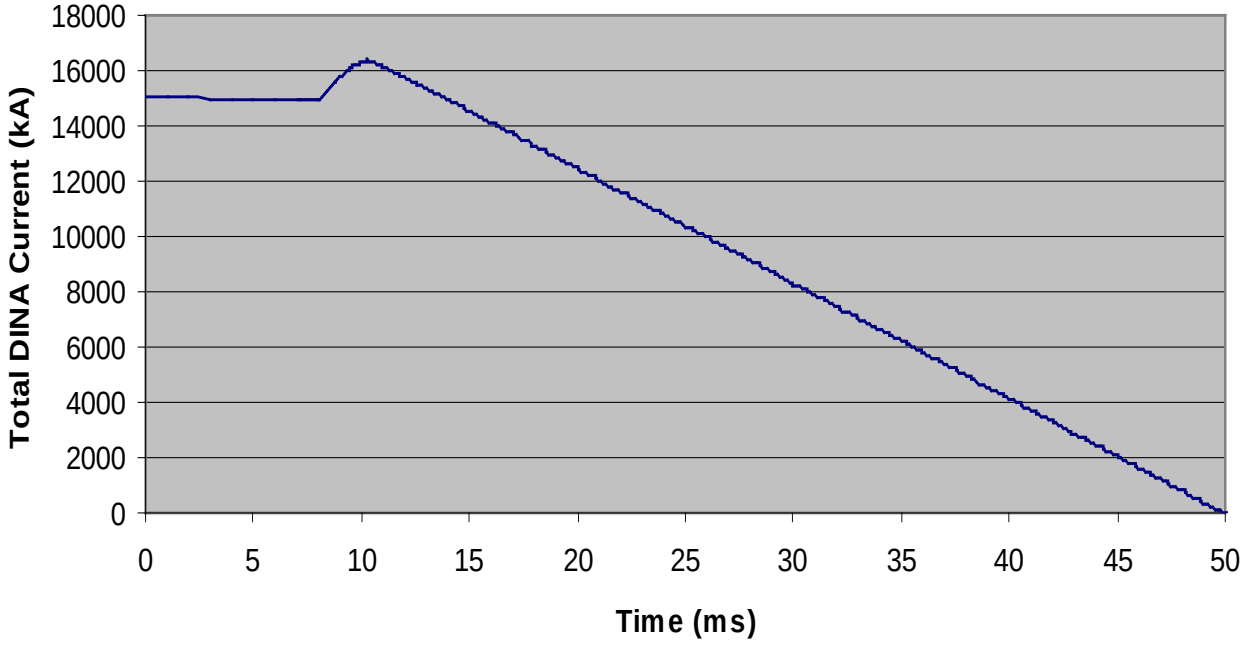
Electromagnetic Analysis

- Impurities in the plasma can cause disruption events
- Decay of current in disruption events causes eddy currents
- Large forces result from these eddy currents because of the strong magnetic fields
- The shield modules must be designed with slits to reduce the eddy currents

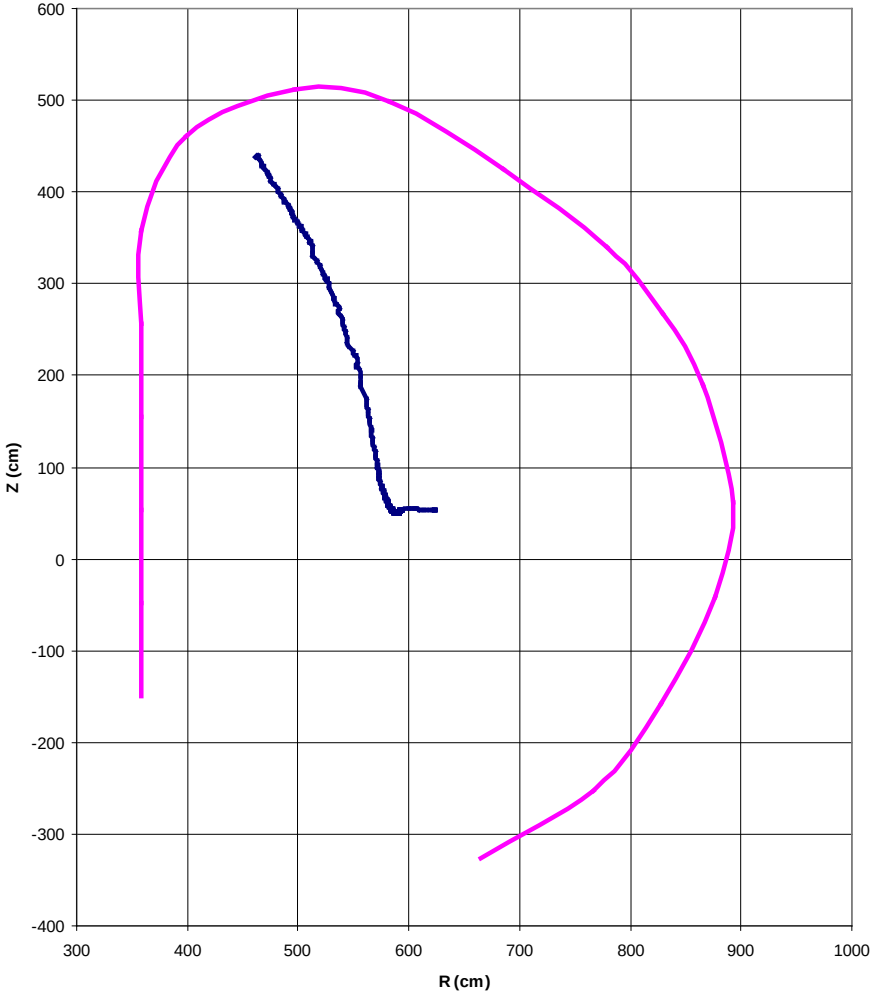
$$\vec{F} = \vec{J} \times \vec{B}$$

Disruption Events

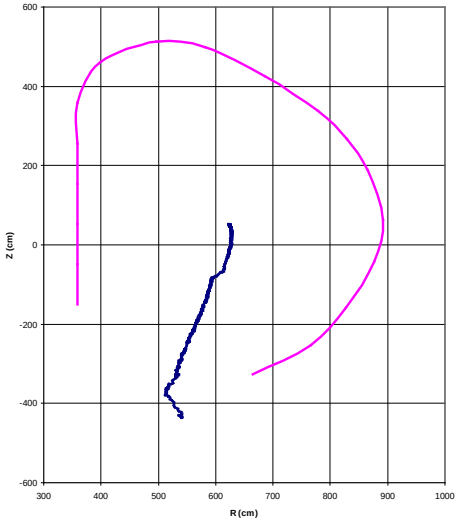
- Types of Disruption
  - Major Disruption Linear: causes the plasma to shift upwards and the plasma current to linearly decay
  - Major Disruption Exponential: the plasma current to exponentially decay
  - Vertical Disruption Event: a slower disruption event that can shift the plasma up or down and causes the plasma current to linearly or exponentially decay



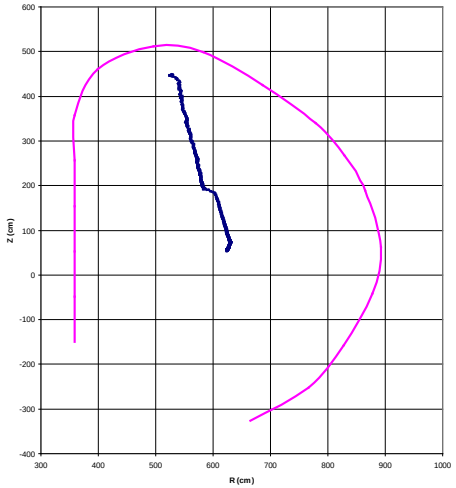
Disruption Events



Major Disruption

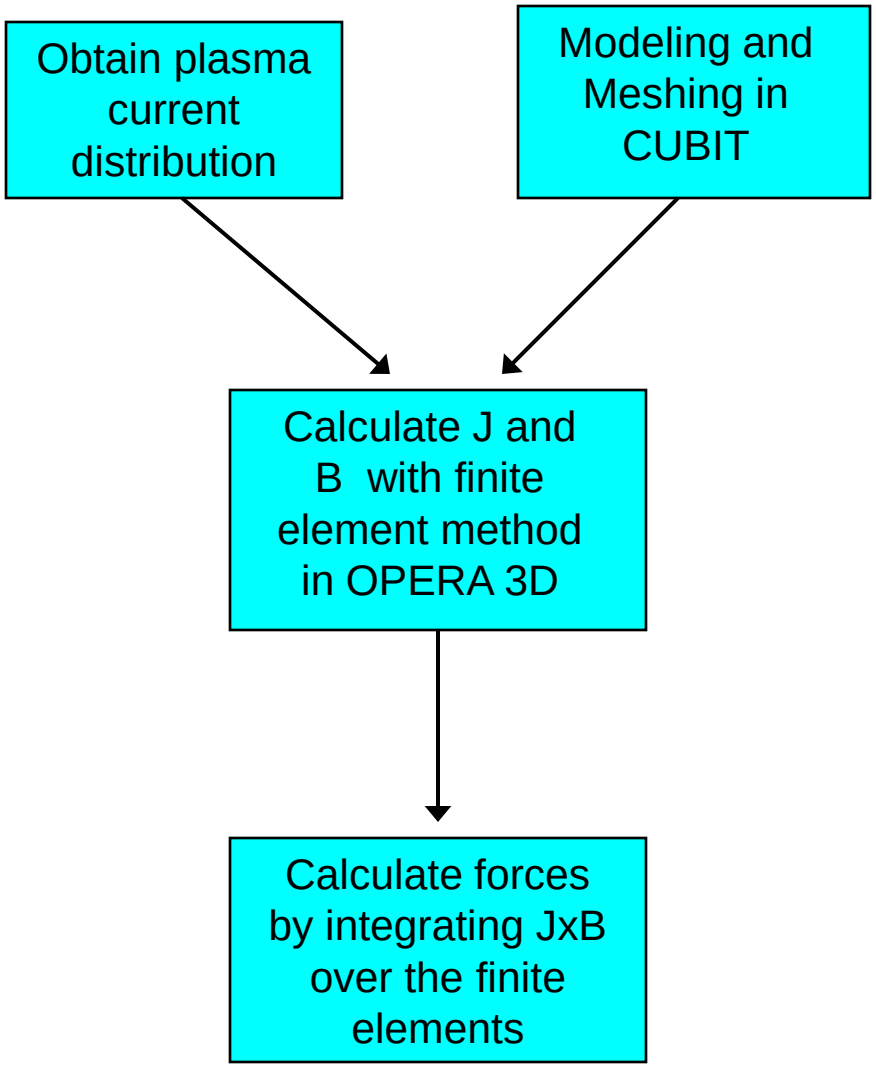


VDE Down

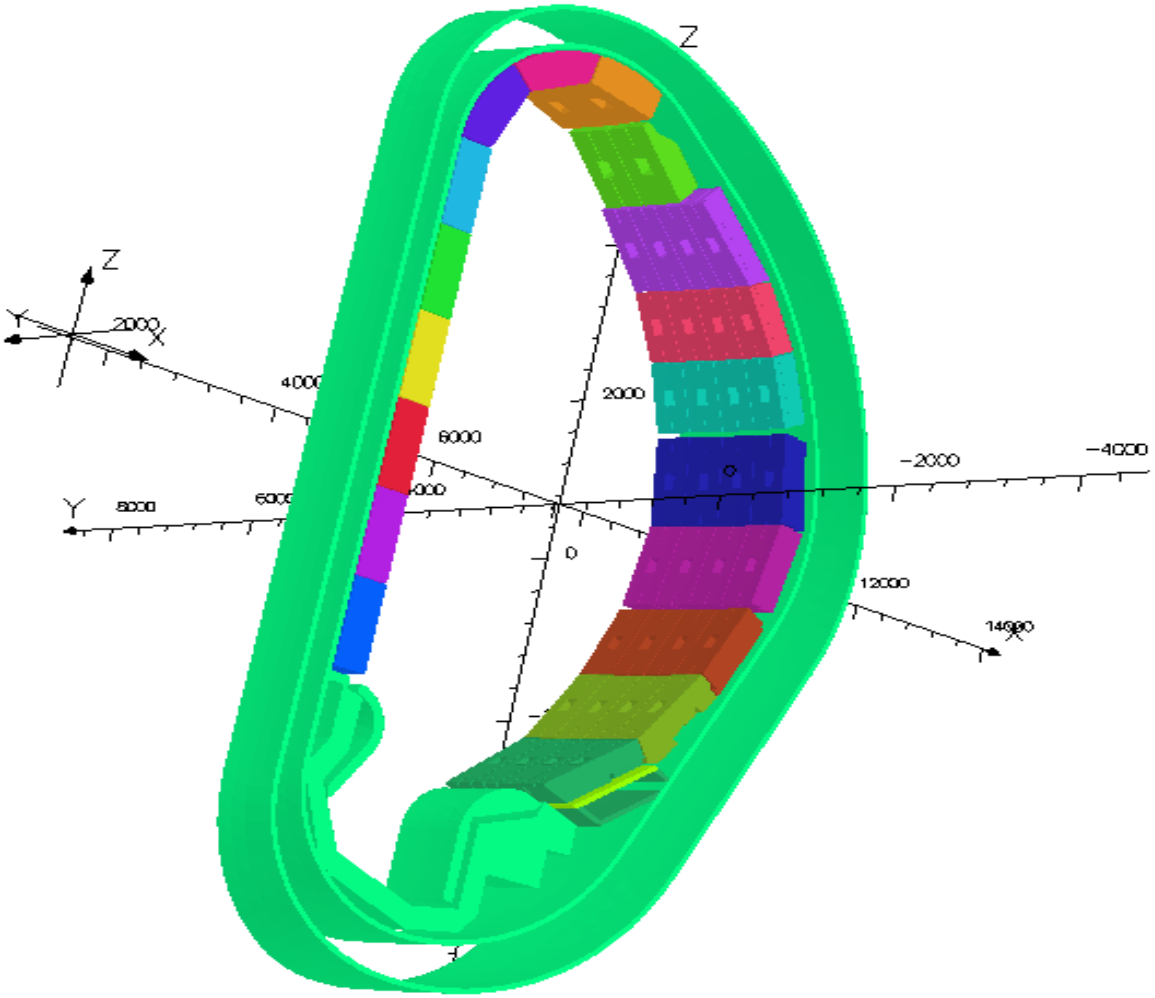


VDE Up

Electromagnetic Analysis



All 18 Shield Modules, Divertor, and Vacuum Vessel



Vector Fields
software for electromagnetic design

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My Role: Modeling a Plasma Disruption for Electromagnetic Analysis

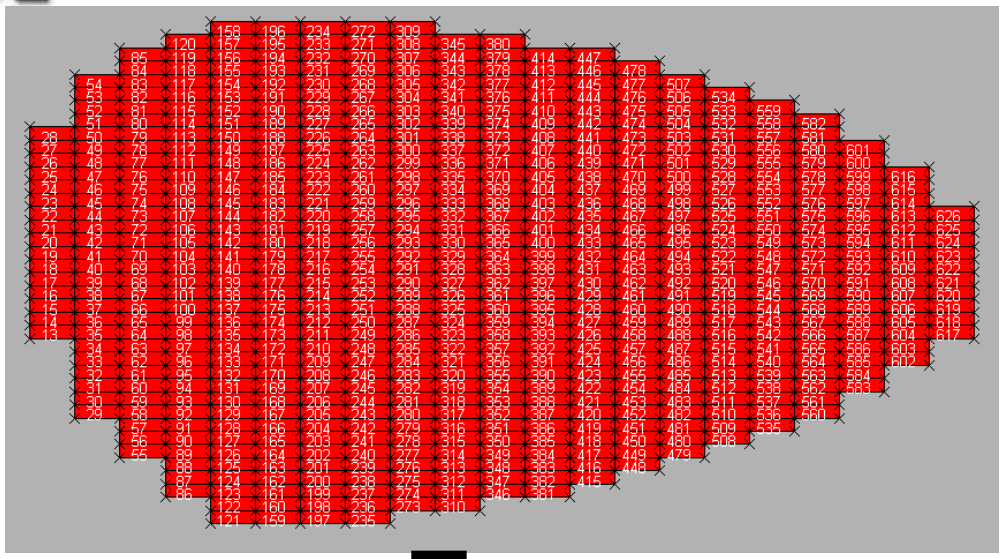
Modeling a Plasma Disruption

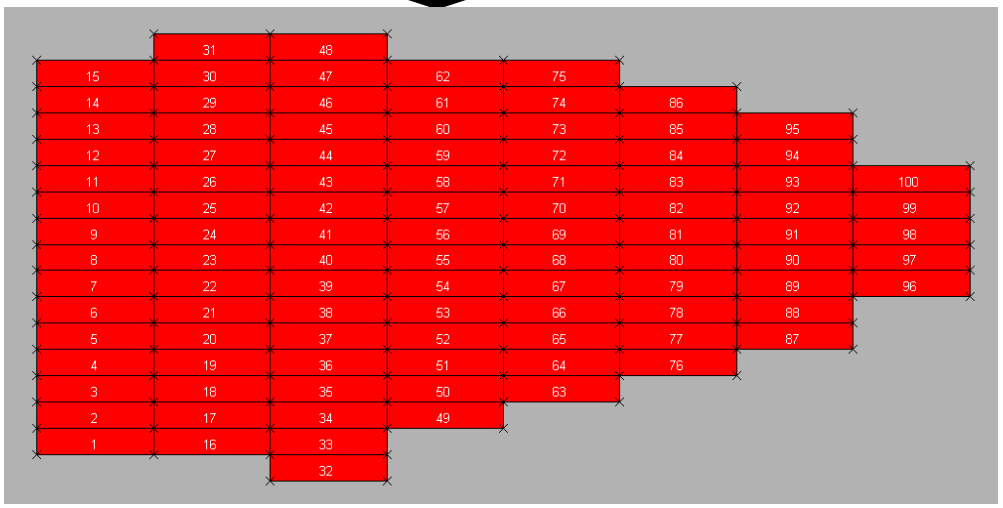
- DINA Simulation
  - Russian plasma physics code for modeling plasma disruptions
  - Contains an array of toroidal conductors that represent the plasma
  - Their number, location, and current all change in time
  - DINA conductors have infinitesimal area
- In OPERA
  - Location and number of conducting filaments cannot change in time
  - Filaments must have finite area
  - An approximation must be used to represent DINA simulation in order to do transient analysis
  - Transient analysis is necessary because eddy currents are a transient phenomenon

My Role in the Project

- Evaluate the current approximation used to model the DINA simulation
- If possible, find a better approximation to model the DINA simulation
- Current Approximation
  - A sum of DINA current is taken over 100 fixed grid regions
  - This current is divided by the area of the region to get a current density which can be used to drive a filament in OPERA
  - The result is a fixed array of 100 current filaments each with a current that varies in time

Current Approximation



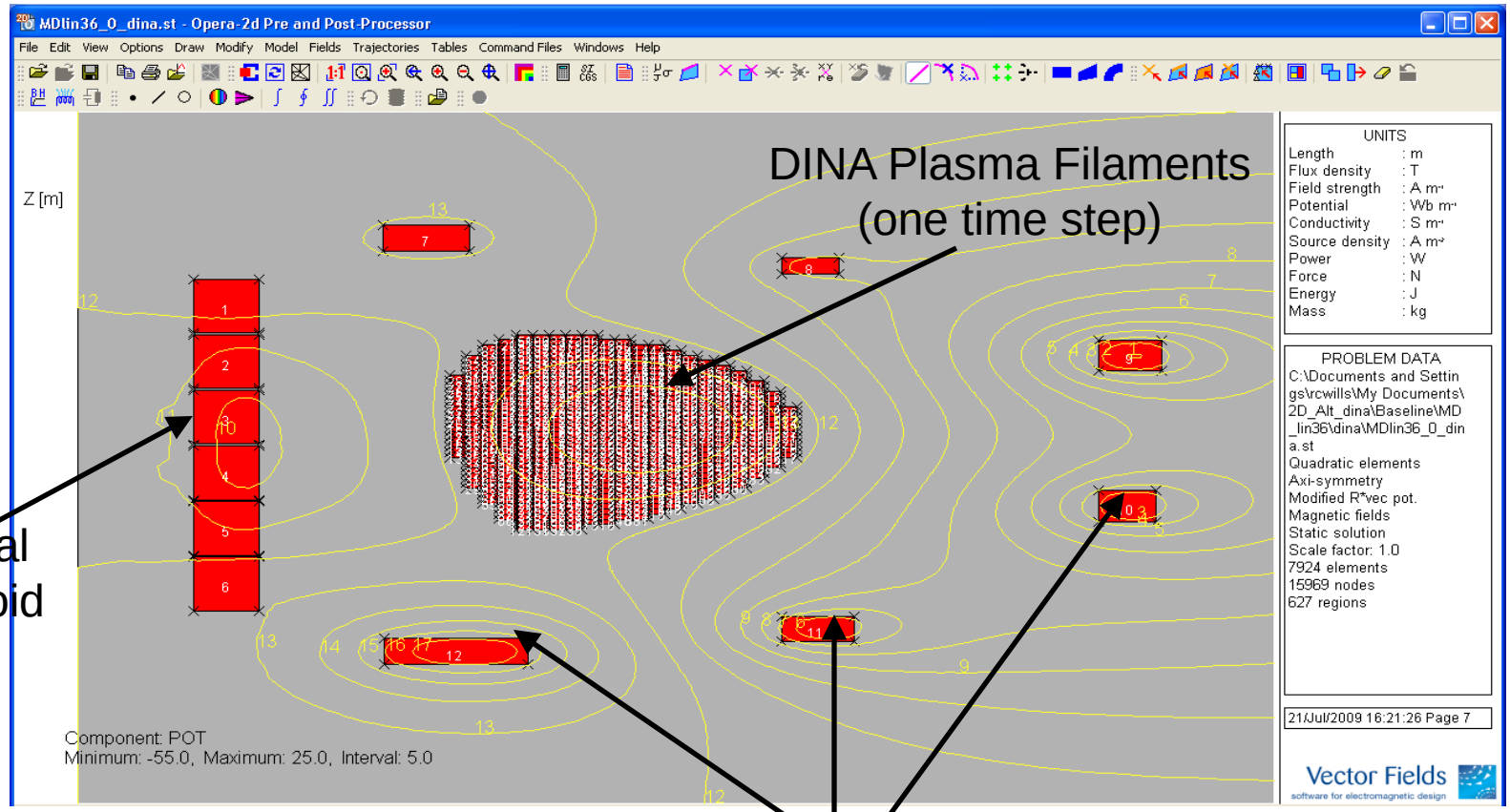


- **DINA Simulation**
  - **Because locations of filaments vary with time, this can only be put into OPERA for a single time step.**
  - **Cannot be solved transiently**

- **100 Fixed Filament Grid Approximation**
  - **Locations are fixed, only current varies in time**
  - **Allows transient solutions**

My Tools: OPERA 2D

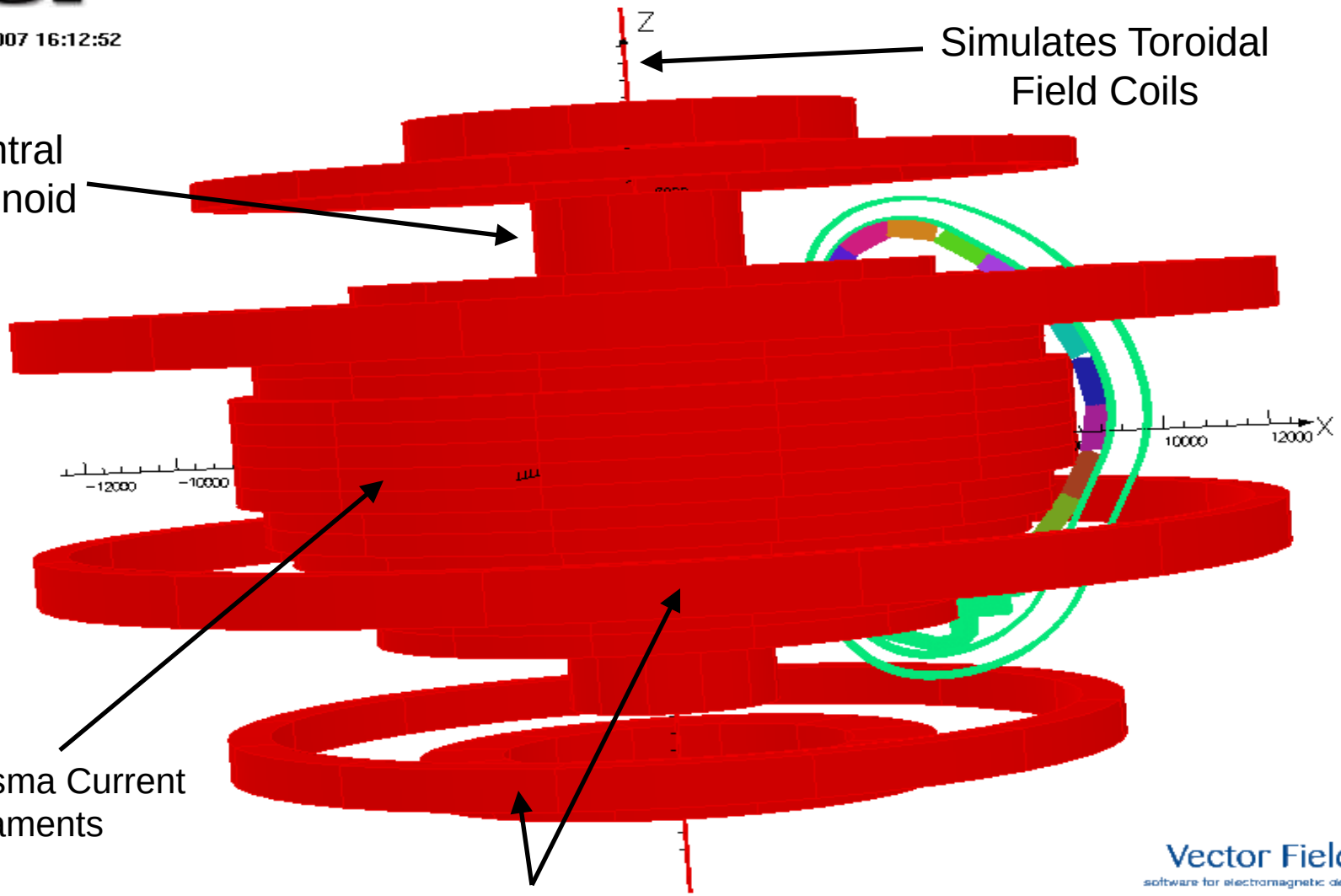
- Commercial code for 2D electromagnetic analysis
- Can obtain B field, but OPERA 3D is needed to calculate Eddy Current, J



Central Solenoid

Poloidal Field Coils

Opera 3D



Simulates Toroidal Field Coils

Central Solenoid

100 Plasma Current Filaments

Poloidal Field Coils

Vector Fields
software for electromagnetic design

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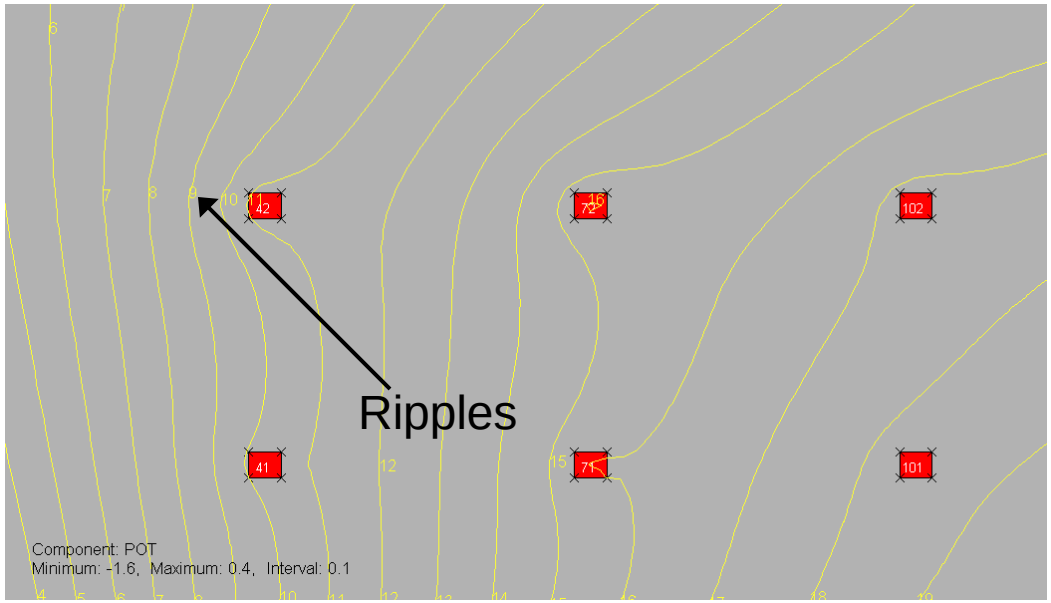
Which grid is best?

- The 100 filament grid that had been used so far was put together quickly
- Not necessarily the best approximation

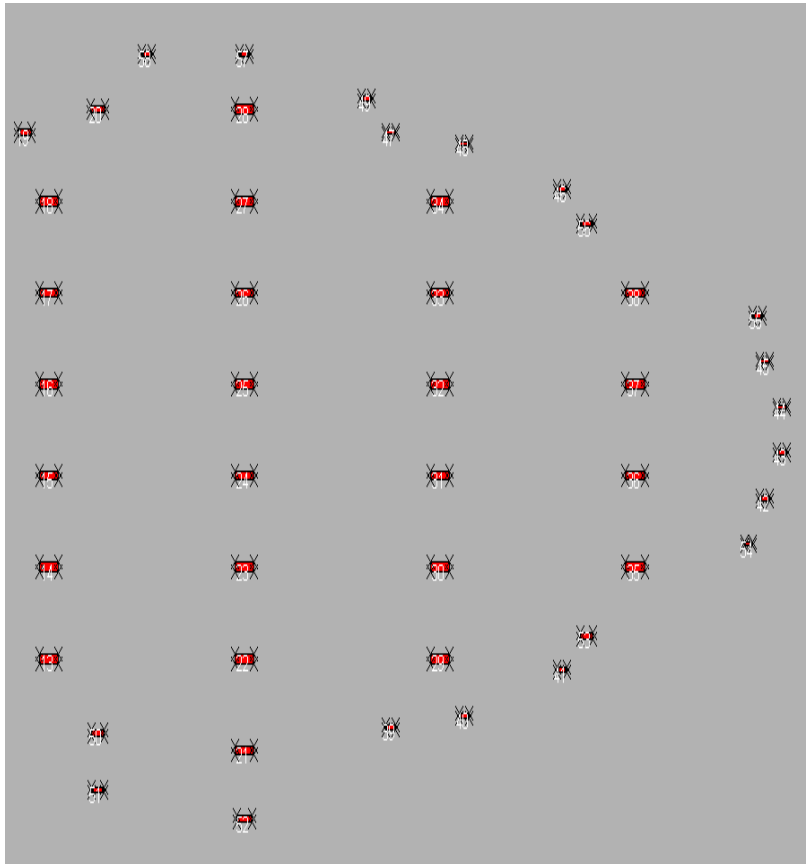
Which grid is best?

- Adding more filaments would better model the spatial distribution of current in the DINA simulation
- More filaments caused problems because some filaments were too close to the points where the field is measured
- The filaments cause ripples in the field

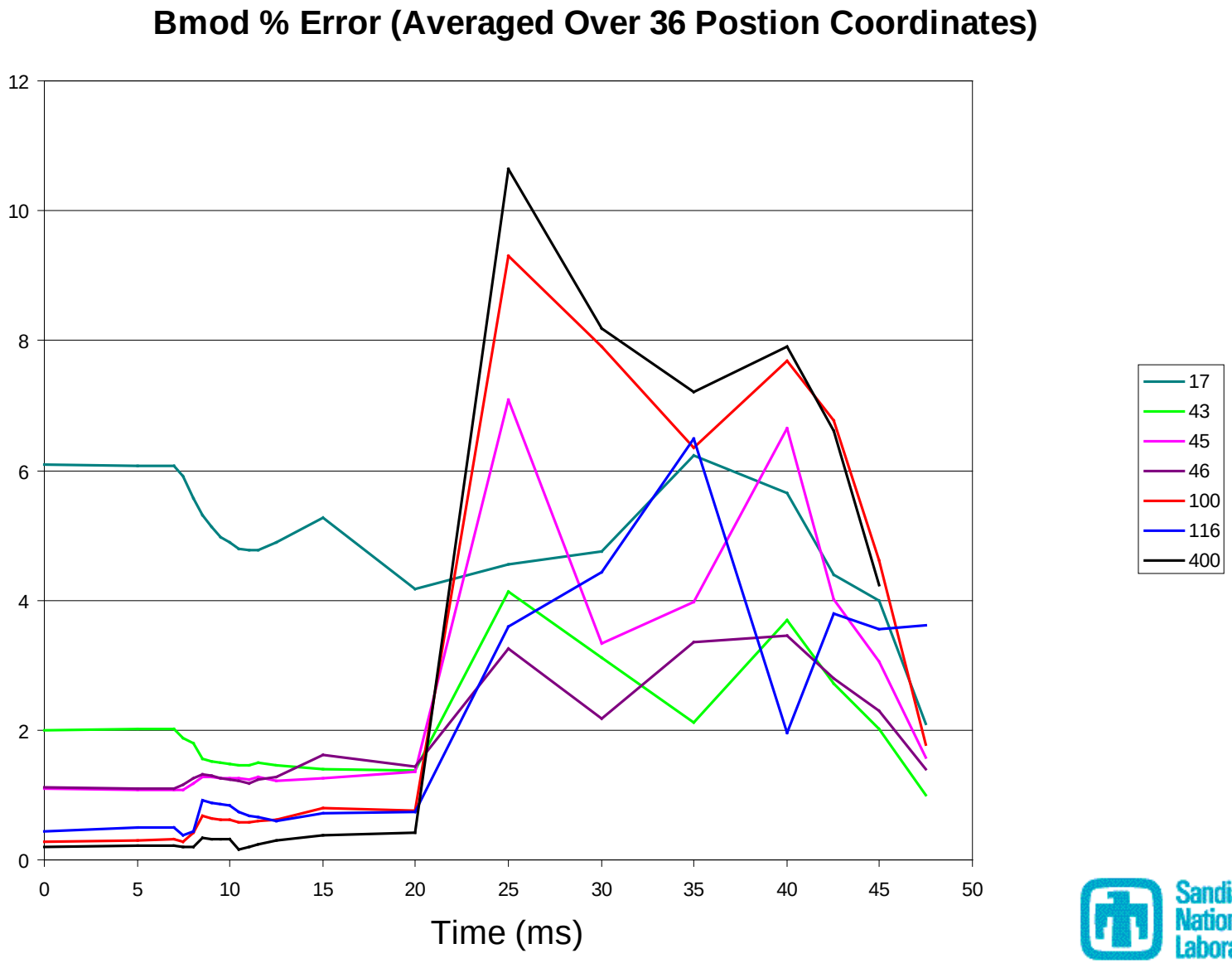


Which grid is best?

- Since adding filaments increased error the possibility of subtracting filaments was explored
- Less filaments is advantageous because it means quicker runtime
- Irregular size and shape were used to keep the filaments far enough from the points of interest

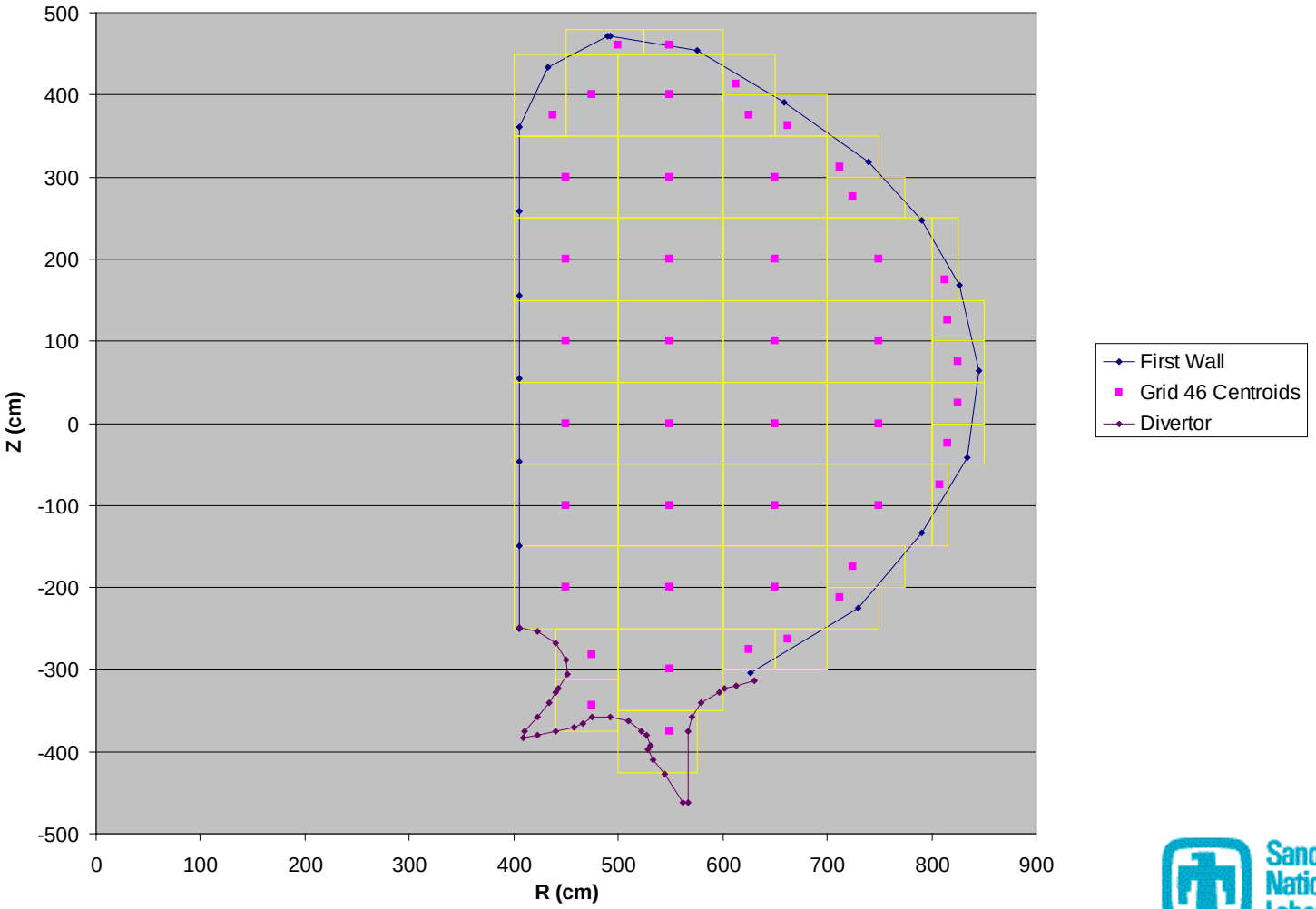


Accuracy vs. Number of Grid Filaments



Which grid is best?

- **Most accurate grid so far is a 46 filament grid with irregularly shaped filaments to better fit inside the first wall.**

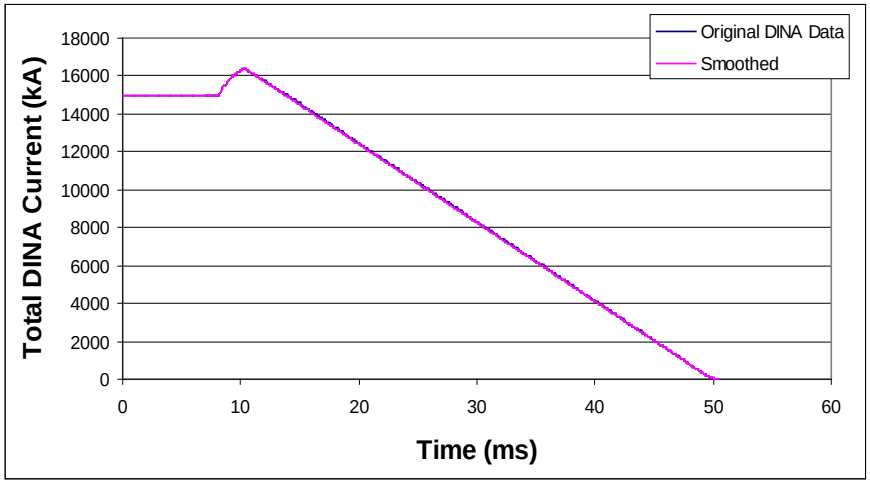


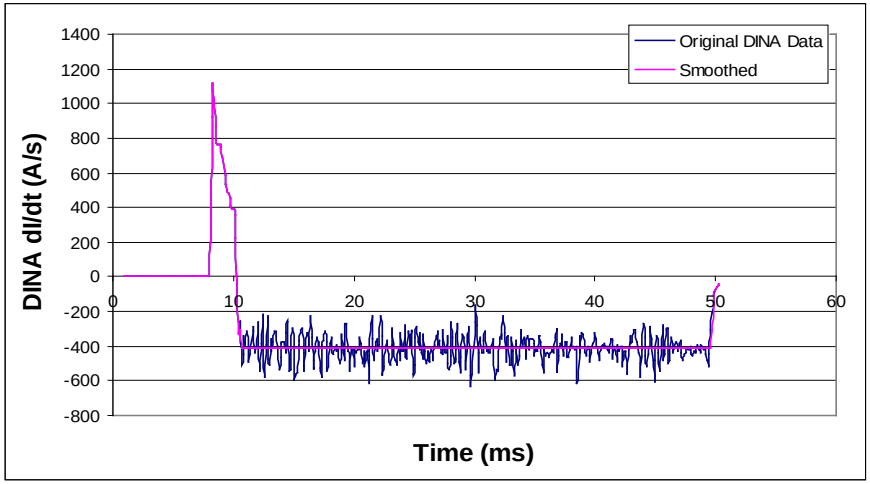
Smoothing DINA Simulation

- The DINA simulation is not perfect
- There is noise in the time variation of the plasma current
- There is noise in the spatial distribution of current because the DINA simulation uses a finite number of current filaments
- A better approximation might be obtained if these effects are investigated

Temporal Smoothing

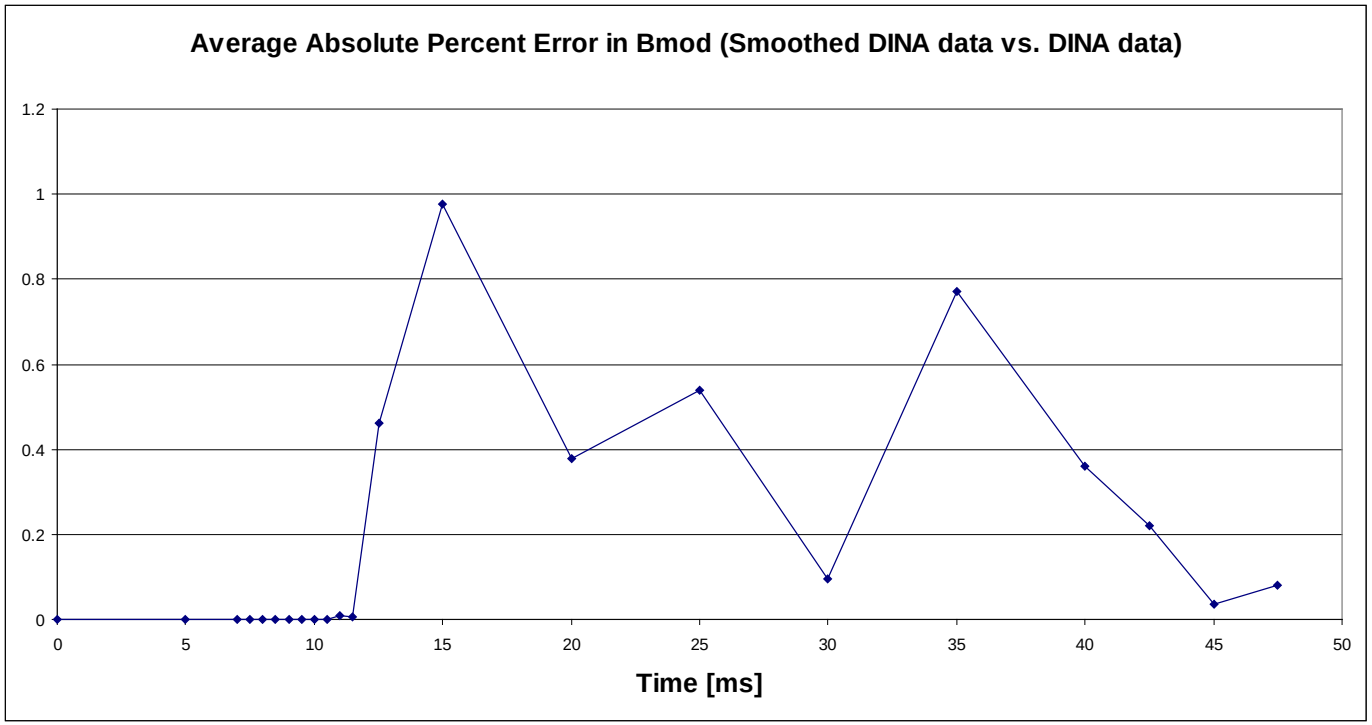
- **The total DINA current was noisy as it varied in time**
- **This was smoothed by normalizing to a smoothed current variation**





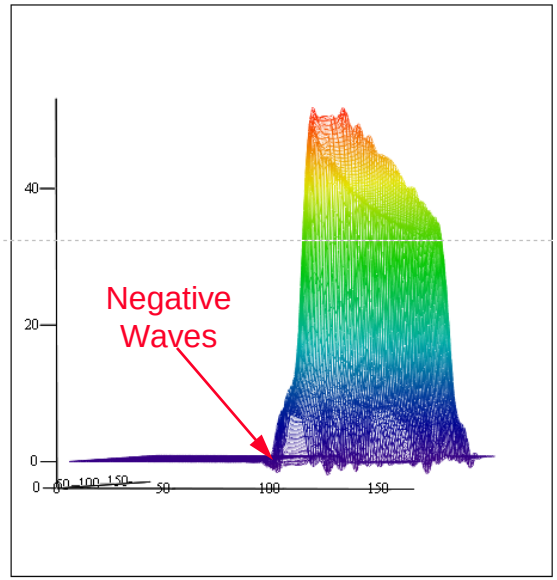
Temporal Smoothing

- The effect of the smoothing had a negligible effect on the accuracy so the raw data is still used

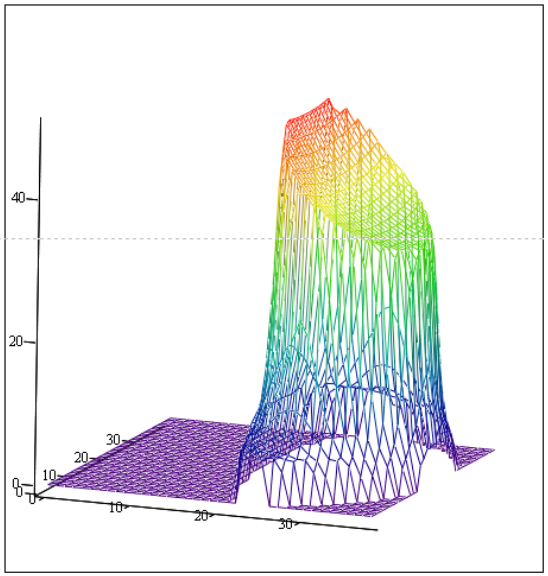


Spatial Smoothing: Interpolation

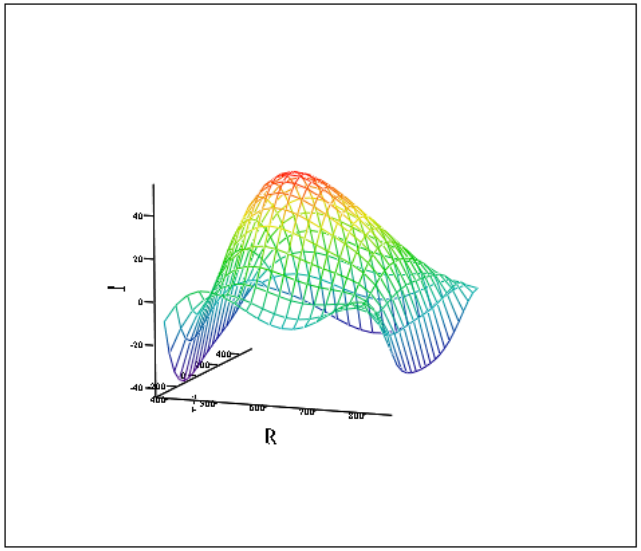
- **Interpolating over current to assign a value of current density to the grid filament**
- **Linear interpolation works better than cubic spline interpolation because the cubic spline would introduce nonphysical negative waves of numeric noise**
- **Regression was not useful at all for fitting the sharp edges of the current distribution**



Cubic Spline Interpolation



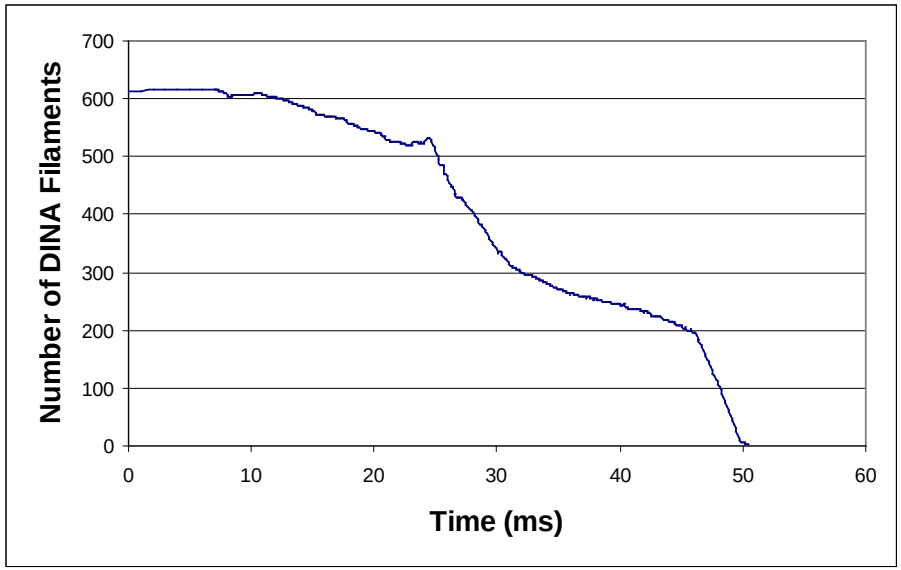
Linear Interpolation



5th Order Polynomial Regression

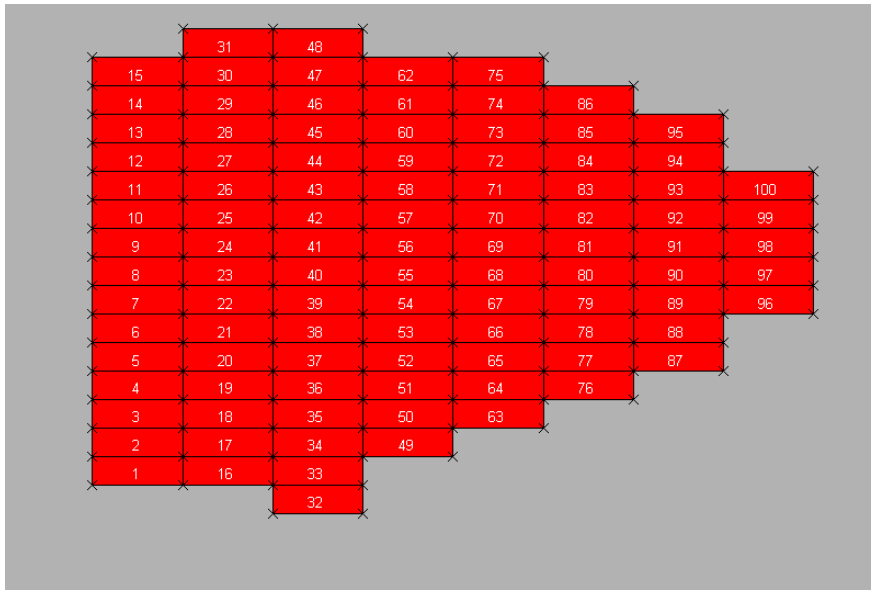
Problems with Interpolation

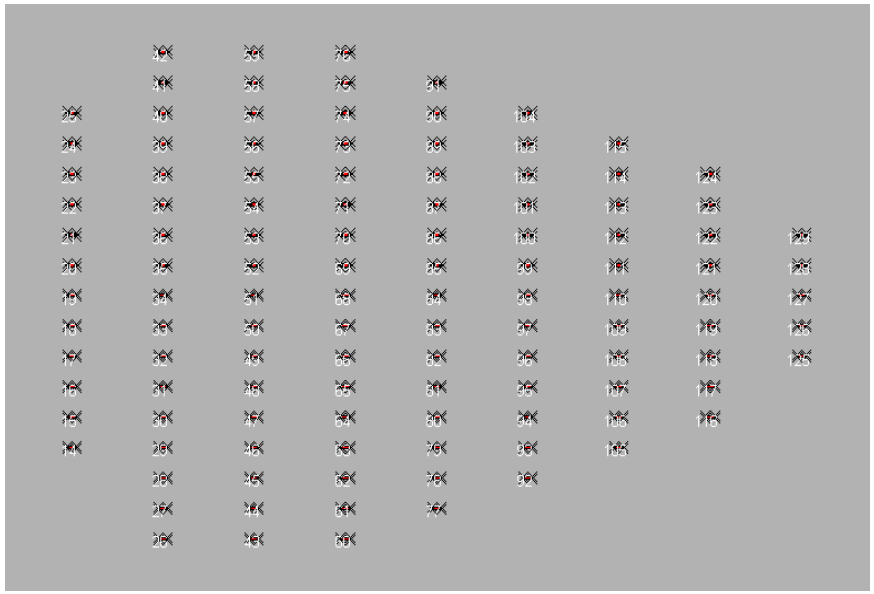
- It is impossible to keep the number of grid filaments equal to the number of DINA filaments
- Extrapolating over same current distribution
- There will be a discrepancy between the total current of the DINA filaments and the grid filaments
- This discrepancy must be fixed by multiplication by a corrective constant adding numeric noise



Space Filling vs. Small Filaments

- Two ways of putting filaments into Opera have been used
- The space filling method (on left) puts the filament in the entire area it summed over
- The small filament method (on right) sums over the whole area, but then modifies J so that a filament with smaller area can be used



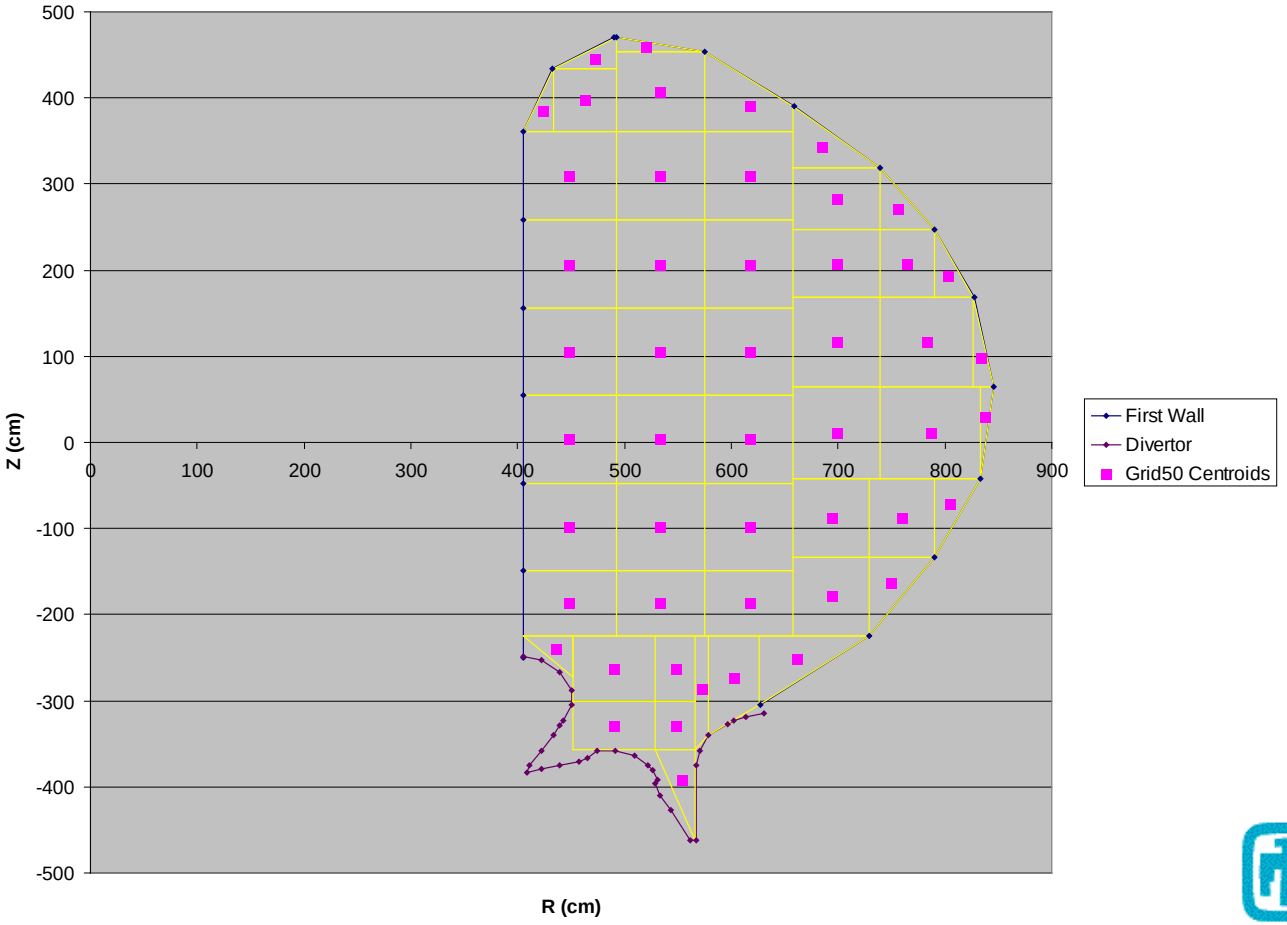


Space Filling vs. Small Filaments

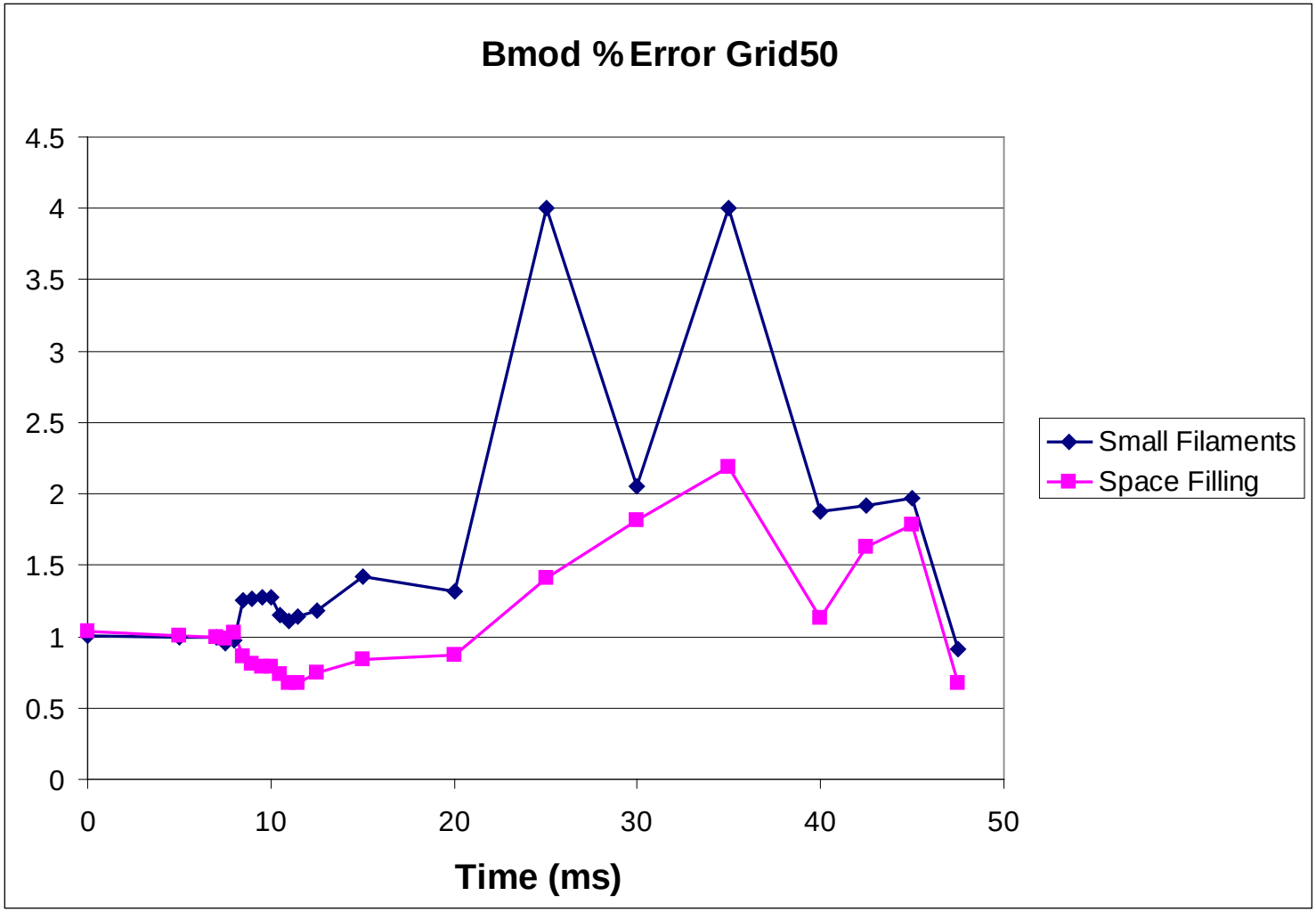
- The space filling method had problems because it is hard to make filaments that sum over the whole area without overlapping with the first wall
- Space filling method has advantage of not creating ripples in the field, so the filaments can be much closer to the points of interest and better model the spatial distribution of current

Space Filling vs. Small Filaments

- To better fit to inside of first wall with space filling filaments a new grid with triangular and trapezoidal filaments was created

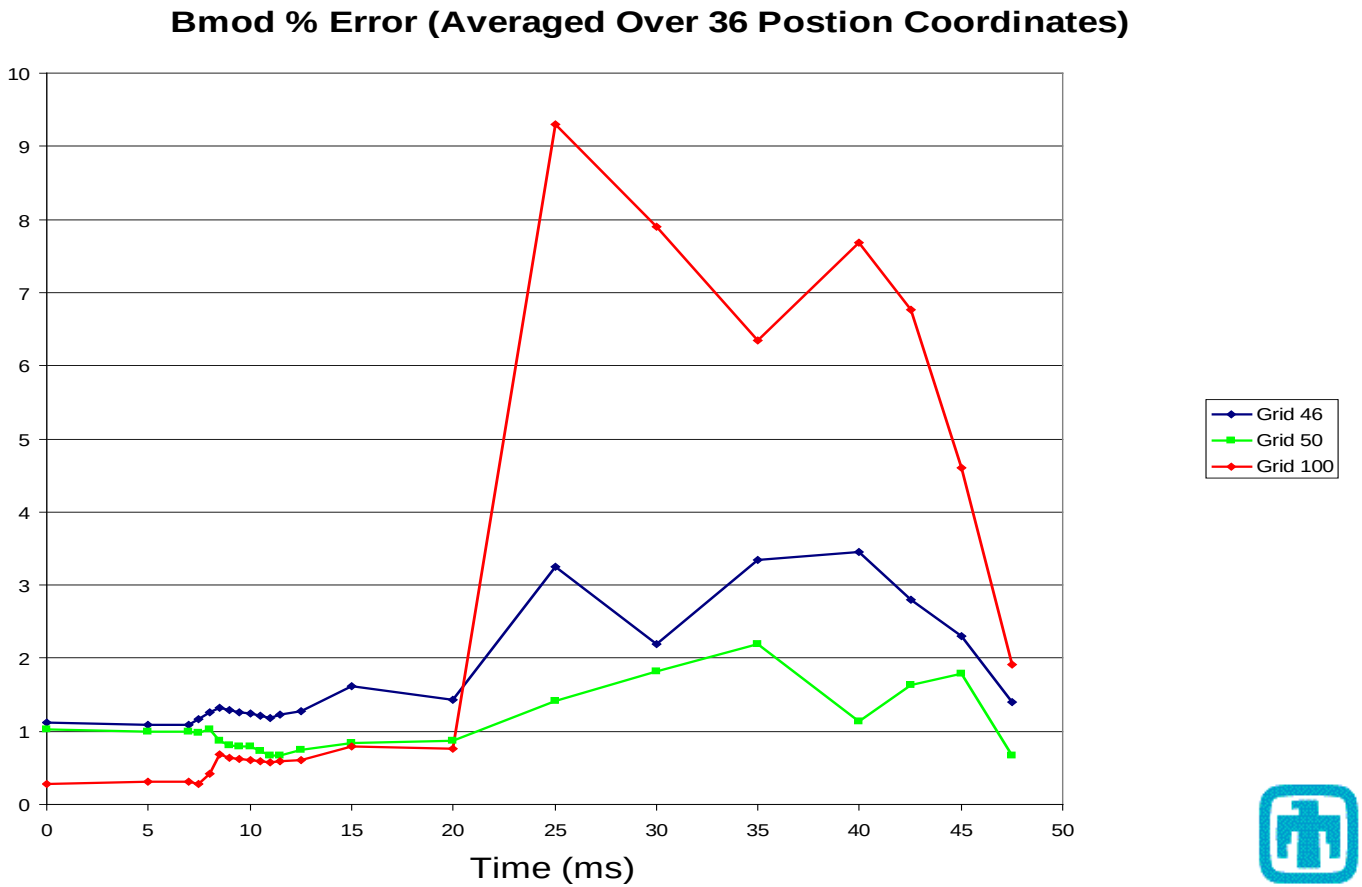


Space Filling vs. Small Filaments



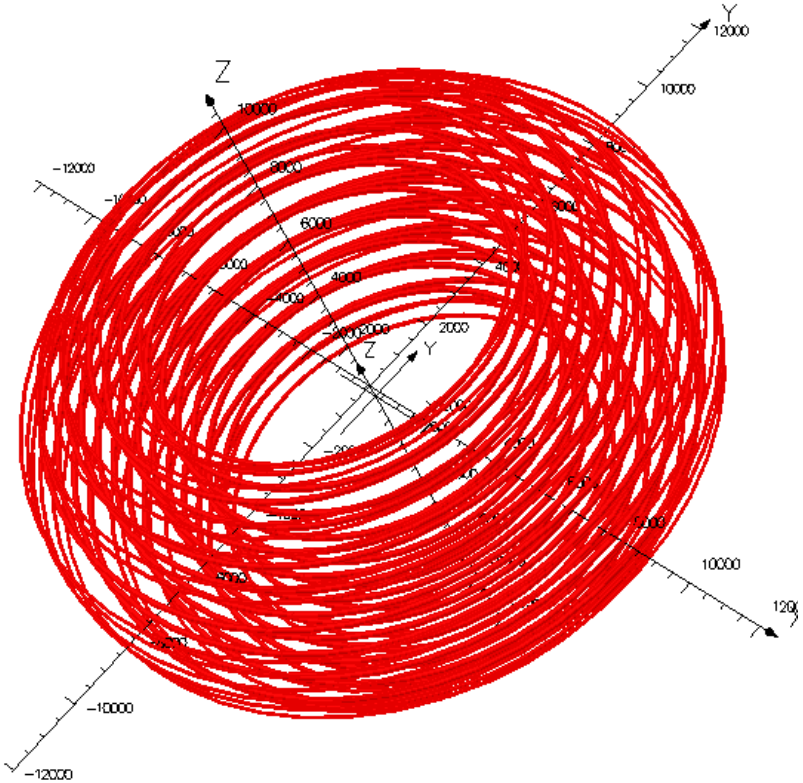
Choosing an Approximation Method

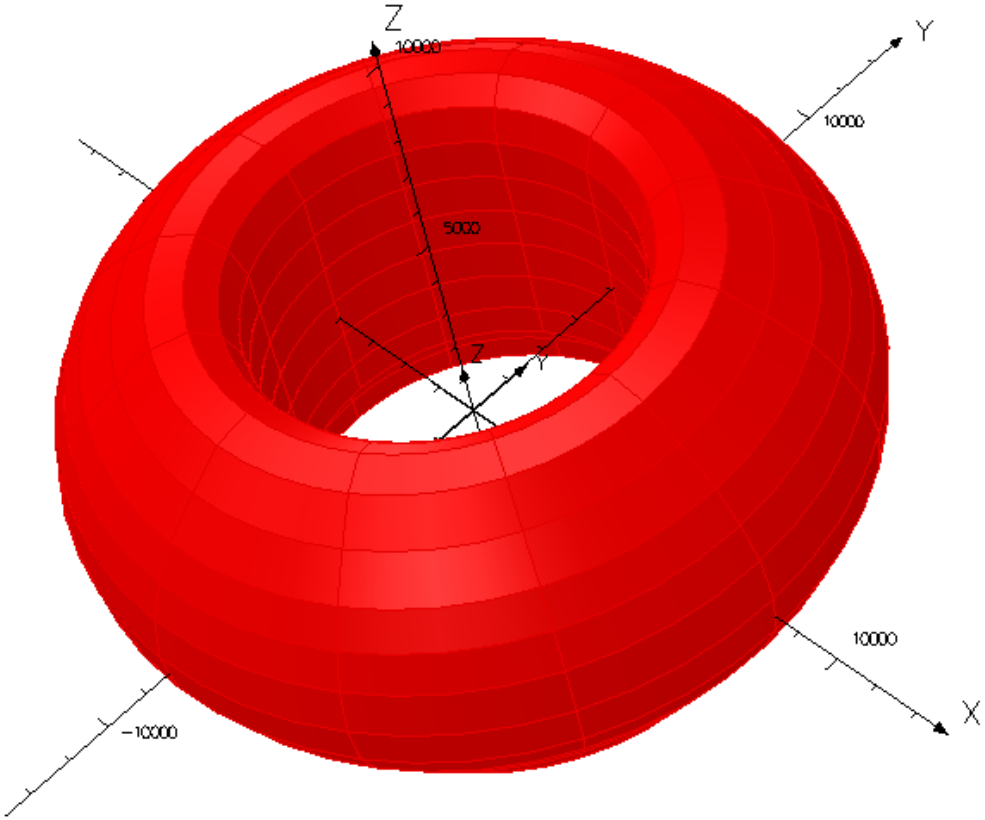
- 46 filament grid with small filaments
- 50 filament grid with space filling filaments
- Both have been found to increase the accuracy in field calculation in 2D



Choosing an Approximation Method

- **Now they will be analyzed in 3D to see if they have a significant effect on the force calculation**





Results

- Now we have data showing the accuracy of our methods.
  - This is important in an international project because there are some people that doubt your methods.
  - This is also necessary for quality control
- All electromagnetic analysis can now run quicker because we are using a grid with less filaments