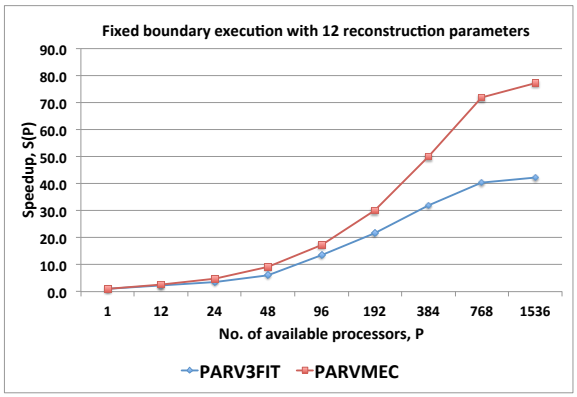
First Confirmation of Helical Core in DIII-D Tokamak

Achievement: Unprecedented high-speed, high-resolution plasma reconstruction runs of PARVMEC+V3FIT have **confirmed the existence of helical cores in DIII-D plasma for the first time** – only hypothesized until now.

Significance and Impact:

Research Details

- PARVMEC is the first scalable version of VMEC, the decades old de-facto plasma equilibrium solver used all over the world for fusion reactor design and data analysis.
- Lead developer: Sudip Seal (DCS Group, CSMD); Science lead: Steven Hirshman (FMNSD).
- Demonstrated PARVMEC speedup of over 100X; Has been integrated with the plasma reconstruction code, V3FIT (Custodian: Mark Cianciosa, FMNSD).



Plasma reconstruction using PARVMEC +V3FIT

Facility: DIII-D National Fusion Facility, OLCF and NERSC

PI and affiliation: Ezekial A. Unterberg, FMNSD, ORNL

Team: Sudip K. Seal, Mark R. Cianciosa, Steven P. Hirshman, Andreas Wingen, Robert S. Wilcox and Ezekial A. Unterberg

Publication(s):

- "*Parallel Reconstruction of Three Dimensional Magnetohydrodynamics Equilibria in Plasma Confinement Devices*", Sudip K. Seal, Mark R. Cianciosa, Steven P. Hirshman, Andreas Wingen, Robert S. Wilcox and Ezekial A. Unterberg, Bristol, UK, **ICPP (2017).**
- "*Helical Core Reconstruction of a DIII-D Hybrid Scenario Tokamak Discharge*", Mark R. Cianciosa, Andreas Wingen, Steven P. Hirshman, Sudip K. Seal, et.al., **Nuclear Fusion, Volume 57, Number 7 (2017).**
- "*Use of reconstructed 3D equilibria to determine onset conditions of helical cores in tokamaks for extrapolation to ITER*", Andreas Wingen, Robert S. Wilcox, Sudip K. Seal, Ezekial Unterberg, Mark Cianciosa, Luis Delgado-Aparicio, Steve Hirshman and L. Lao, **Nuclear Fusion (2017)**

Sponsor: LDRD/DOE (Office of Fusion Sciences)

Publication Overview:

Parallel Reconstruction of Three Dimensional Magnetohydrodynamics Equilibria in Plasma Confinement Devices

Fast, accurate three dimensional reconstructions of plasma equilibria, crucial for physics interpretation of fusion data generated within confinement devices like stellarators/ tokamaks, are computationally very expensive and routinely require days, even weeks, to complete using serial approaches. Here, we present a parallel implementation of the three-dimensional plasma reconstruction code, V3FIT. A formal analysis to identify the performance bottlenecks and

scalability limits of this new parallel implementation, which combines both task and data parallelism, is presented. The theoretical findings are supported by empirical performance results on several thousands of processor cores of a Cray XC30 supercomputer. Parallel V3FIT is shown to deliver over 40X speedup, enabling fusion scientists to carry out three dimensional plasma equilibrium reconstructions at unprecedented scales in only a few hours (instead of in days/weeks) for the first time.

Helical Core Reconstruction of a DIII-D Hybrid Scenario Tokamak Discharge
This paper presents the first fully 3-dimensional (3D) equilibrium reconstruction of a helical core in a tokamak device. Using a new parallel implementation of the Variational Moments Equilibrium Code (PARVMEC) coupled to V3FIT, 3D reconstructions can be performed at resolutions necessary to produce helical states in nominally axisymmetric tokamak equilibria. In a flux pumping experiment performed on DIII-D, an external $n = 1$ field was applied while a 3/2 neoclassical tearing mode was suppressed using ECCD. The externally applied field was rotated past a set of fixed diagnostics at a 20 Hz frequency. The modulation, observed to be strongest in the core SXR and MSE channels, indicates a localized rotating 3D structure locked in phase with the applied field. Signals from multiple time slices are converted to a virtual rotation of modeled diagnostics adding 3D signal information. Starting from an axisymmetric equilibrium reconstruction solution, the reconstructed broader current profile flattens the q-profile, resulting in an $m = 1$, $n = 1$ perturbation of the magnetic axis that is larger than the applied $n = 1$ deformation of the edge. Error propagation confirms that the displacement of the axis is much larger than the uncertainty in the axis position validating the helical equilibrium.

Use of reconstructed 3D equilibria to determine onset conditions of helical cores in tokamaks for extrapolation to ITER
The threshold for spontaneous symmetry breaking, which results in growth of m/n = 1/1 helical cores, in tokamaks is determined using VMEC. This model is based on a DIII-D hybrid discharge with helical core, and it predicts ITER (15MA scenario) to operate far in the helical core unstable regime. Helical cores can only exist in tokamak discharges with monotonic but low, or reversed q-shear and qmin □1 in the core. The helical core is a saturated internal kink mode [J.A. Wesson, PPCF 28, 243 (1986)]; its onset threshold is proportional to (dp/dρ)/Bt2 around q = 1. Below the threshold, applied 3-D fields can drive a helical core to finite size, as in DIII- D. Above it, a random 3-D kick causes a bifurcation form axisymmetry and excites a spontaneous helical core. Helical cores occur frequently in C-Mod due to impurities; modeling shows the axisymmetric equilibrium becomes unstable at the end of the current ramp up due to the slow current penetration and a resultant reversed shear q-profile, which lowers the threshold. Finally, a comparison of the helical core onset threshold for discharges from DIII-D, C-Mod and ITER confirms that while DIII-D is marginally stable, C-Mod and especially ITER are highly susceptible to helical core formation.