FASTRAN: An Efficient Transport Solver for Tokamak Plasma

by
J.M. Park
ORNL

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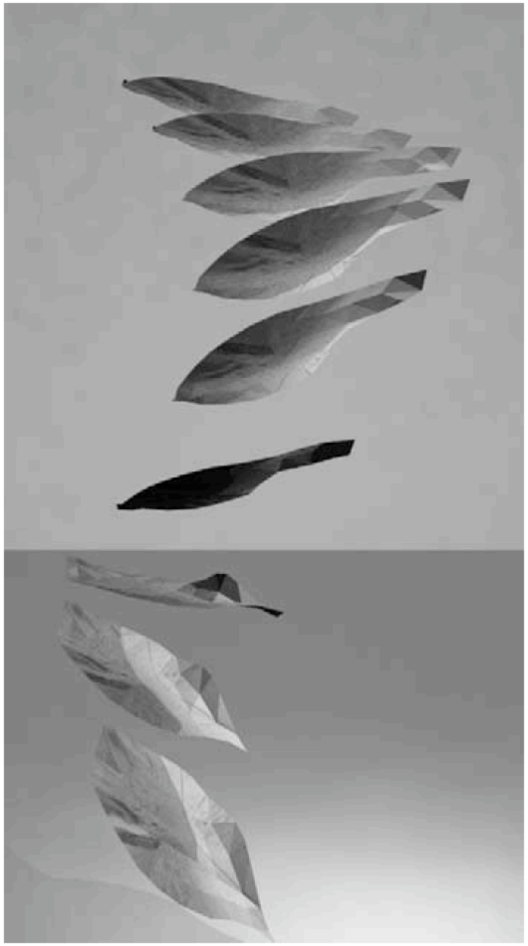
Oak Ridge National Laboratory

Simulation of Falling Leaf: *Cool!!!!!*

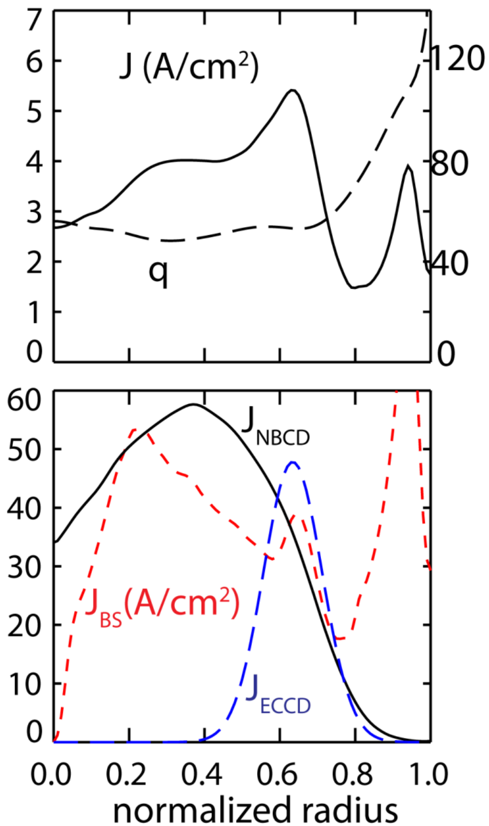
- **FASTRAN (FASt TRANsport):**
  - A modular 1.5-D transport code
  - Solve efficiently Te, Ti, rotation, density and poloidal flux evolution with stiff transport models such as TGLF, GLF23, MMM, …
  - Employ numerical scheme (Interpolated Differential Operator) used in fluid simulation of falling leaf, post-it, …
  - Solve not only physics variable but also its derivative
  - Smaller number of grid (only 5!!!) can be used with high accuracy (4^{th} order scheme)



FASTRAN Has Been Used Extensively for DIII-D, ITER, …

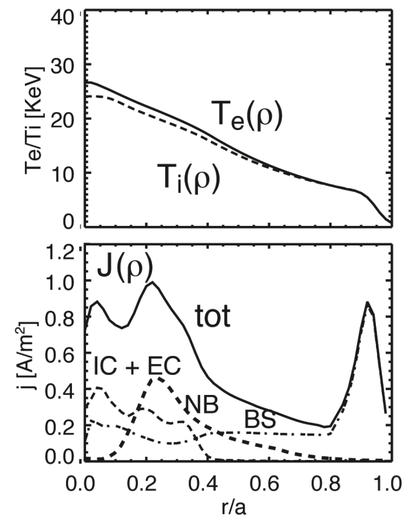
- **Guide DIII-D H/CD upgrade**

High $q_{min}>2$, $\beta_N=5$ Scenario



Ferron, APS2012 Invited
Park, APS2013 Invited

- **ITER Prediction**

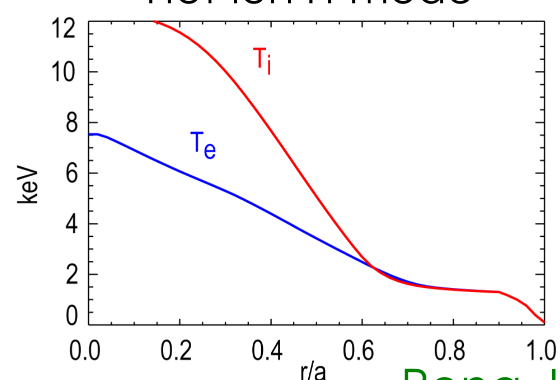


P_{NB}	33 MW
P_{FW}	20 MW
P_{EC}	20 MW
B_T	5.3 T
I_p	9.0 MA
q_{95}	5.0
N_{GW}	0.91
f_{BS}	57%
f_{NB}	20%
f_{FW}	3.6% (50%CD)
f_{EC}	6.0%
f_{NI}	87%
Q_{fus}	4.6
H_{98y2}	1.4
V_{loop}	5.7 mV
β_N	2.9

Murakami, NF2011

- **FNSF-ST Design Study**

Hot-ion H-mode



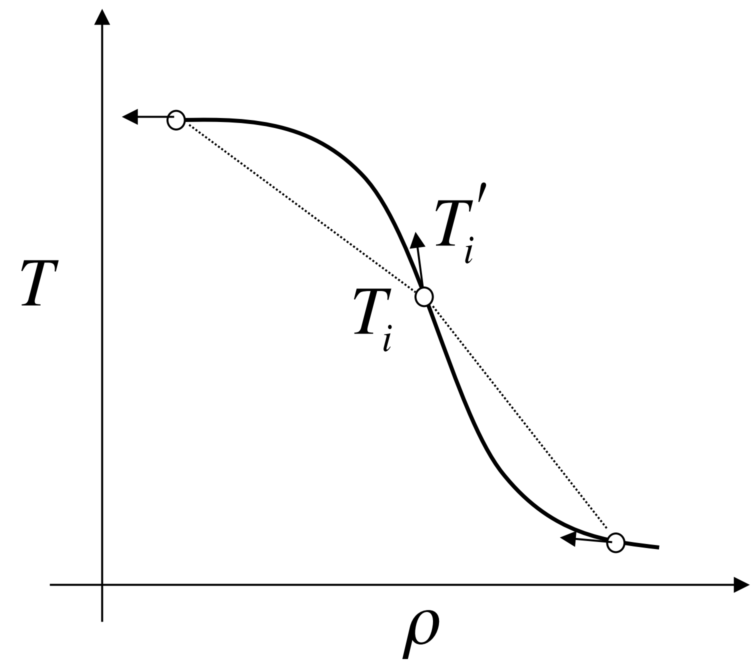
Peng, IAEA2010

FASTRAN is Fast

- **Example: TGLF simulation for DIII-D Steady-State Discharge**

Solve Not Only Physical Variable But Also its Gradient

- **Assume interpolation function to be an approximate solution of the governing equation**
- **Interpolation functions constructed by both the value & its gradient**
- **Use additional equation derived by taking derivative of the original equation**



T. Aoki, *Interpolated Differential Operator (IDO) scheme for solving partial differential equations*. Comput. Phys. Commun. **102** 132 (1997)

Example: $\chi d^2T/d\rho^2 = S$

- **5^{th} order Hermite Interpolation Function for ρ-Δρ<=ρ<=ρ-Δρ**

$$T(\rho) = a\rho^5 + b\rho^4 + c\rho^3 + d\rho^2 + T_i'\rho + T_i$$

- **Matching conditions determine a, b, c, and d**

$$T(-\Delta\rho) = T_{i-1} \qquad T(\Delta\rho) = T_{i+1} \qquad T'(-\Delta\rho) = T'_{i-1} \qquad T'(\Delta\rho) = T'_{i+1}$$

- **Higher order derivative**

$$T_i'' \equiv \left.\frac{\partial^2 T}{\partial\rho^2}\right|_i = \frac{2}{\Delta\rho^2}\left(T_{i+1} - 2T_i + T_{i-1}\right) - \frac{1}{2\Delta\rho}\left(T'_{i+1} - T'_{i-1}\right)$$

$$T_i''' \equiv \left.\frac{\partial^3 T}{\partial\rho^3}\right|_i = \frac{15}{2\Delta\rho^3}\left(T_{i+1} - T_{i-1}\right) - \frac{3}{2\Delta\rho^2}\left(T'_{i+1} + 8T_i' + T'_{i-1}\right)$$

- **Discretization of equation**

$$\chi_i T_i'' = S_i \quad \Rightarrow \quad \chi_i\left[\frac{2}{\Delta\rho^2}\left(T_{i+1} - 2T_i + T_{i-1}\right) - \frac{1}{2\Delta\rho}\left(T'_{i+1} - T'_{i-1}\right)\right] = S_i$$

- **Additional equation**

$$\chi_i T_i''' = S_i' \quad \Rightarrow \quad \chi_i\left[\frac{15}{2\Delta\rho^3}\left(T_{i+1} - T_{i-1}\right) - \frac{3}{2\Delta\rho^2}\left(T'_{i+1} + 8T_i' + T'_{i-1}\right)\right] = S_i'$$

"Simplest" Time Stepping & Nonlinear Relaxation

- **Implicit Backward Euler**

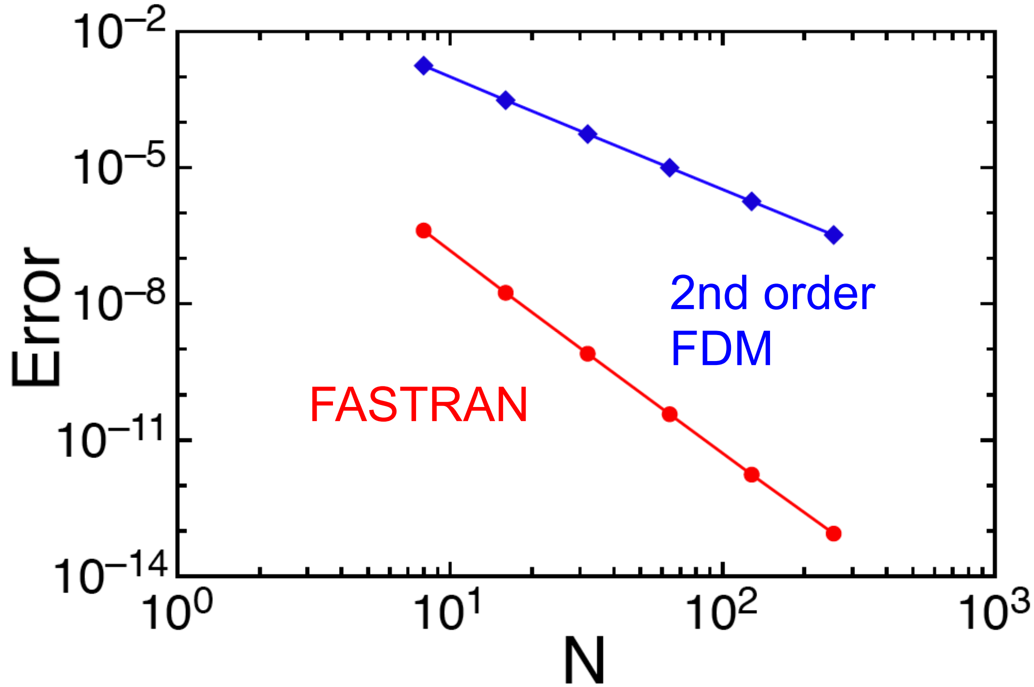
$$\left.\frac{\partial T}{\partial t}\right|_i = \frac{T_i - T_{i0}}{\Delta t} \qquad \left.\frac{\partial T'}{\partial t}\right|_i = \frac{T_i' - T_{i0}'}{\Delta t}$$

- **Picard iteration with under-relxation**

$$\chi_i = \chi_i\left(T_i, T_i', \ldots\right)$$

$$\chi_i^{n+1} = \alpha \chi_i^n + (1-\alpha)\chi_i^{n-1}$$

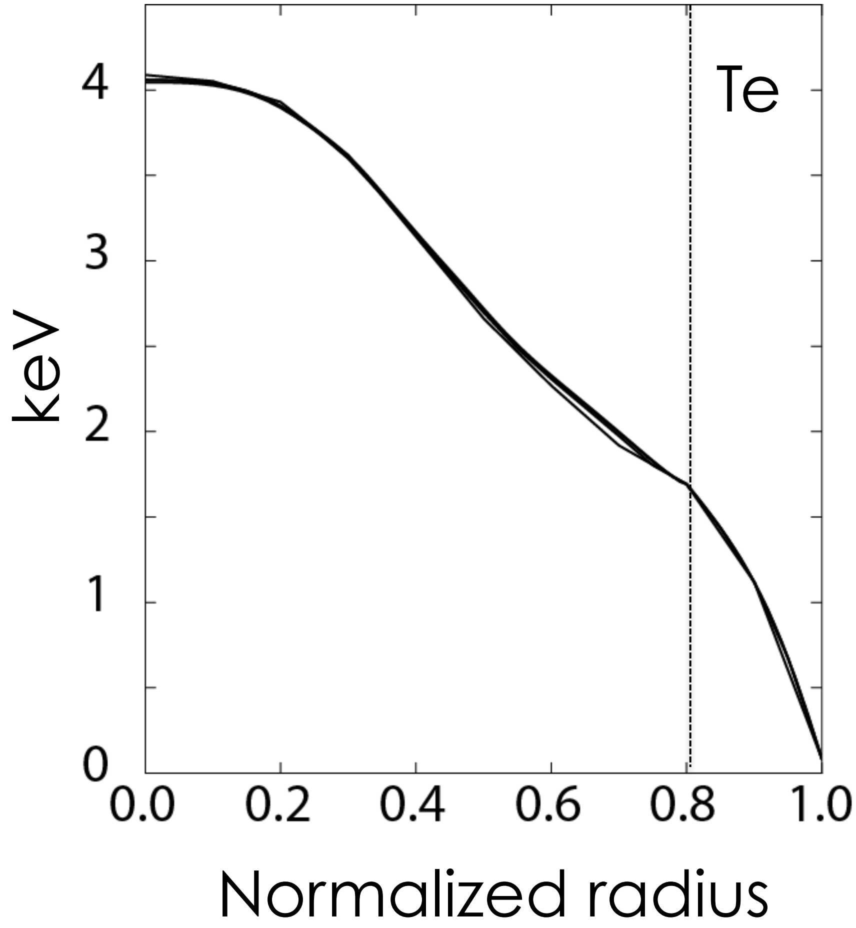
4^{th} Order Accurate in Space

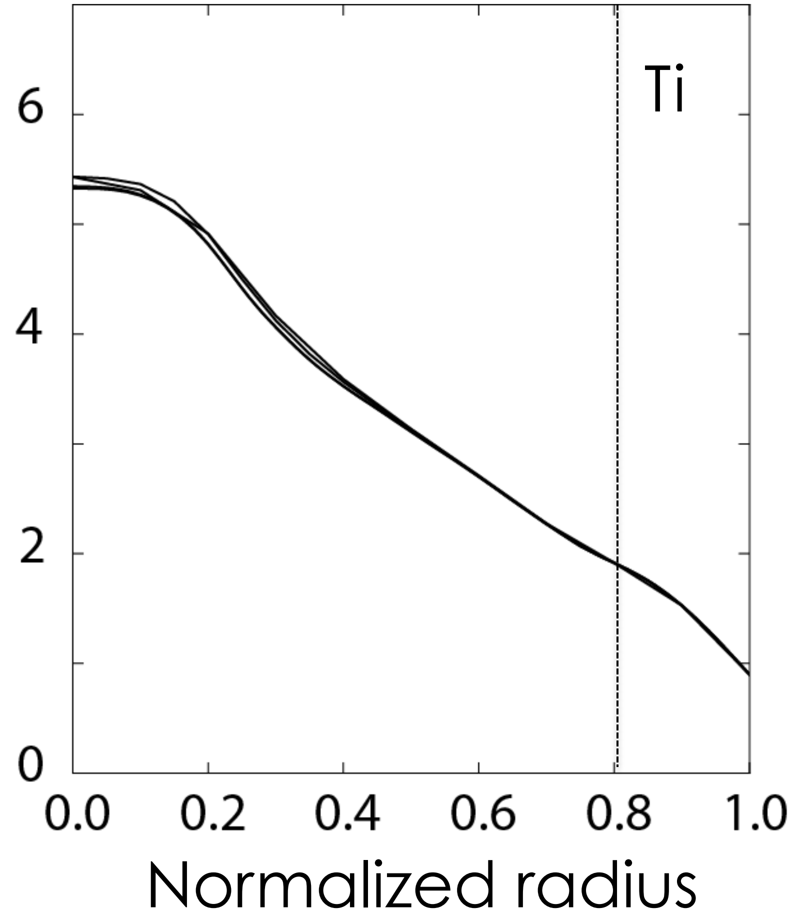


- **Model Equation** $n\frac{\partial T}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left(r(-K\frac{\partial T}{\partial r}+\alpha rT)\right)=S$
- **Analytic Solution** $T(r,\infty)=\exp\left(\frac{\alpha}{2K}\right)\left(T_a\exp\left(-\frac{\alpha}{2K}\right)+\frac{S}{2K}\int_r^a t\exp\left(-\frac{\alpha}{2K}t^2\right)dt\right)$

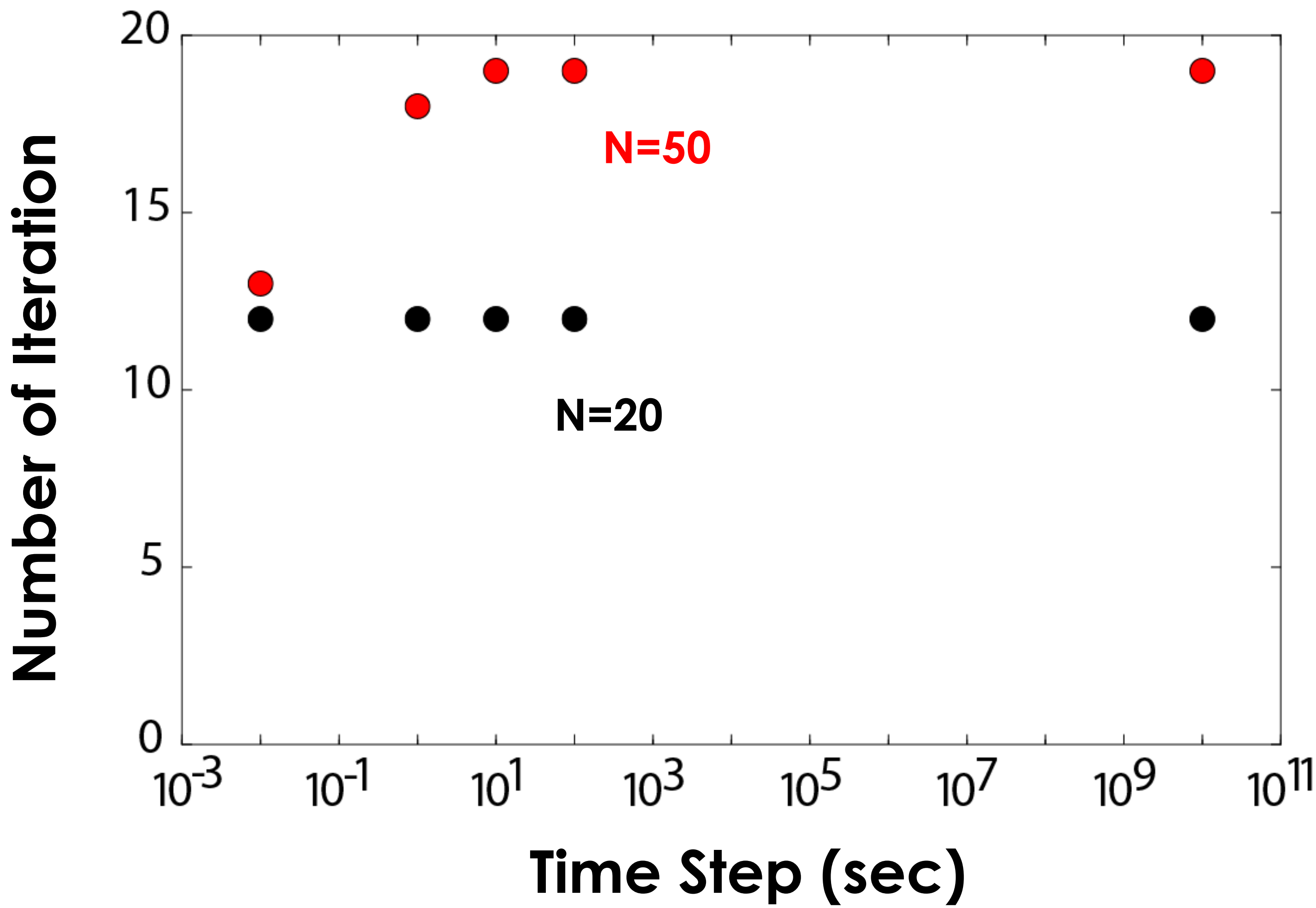
Converge Rapidly with Number of Grid

- **DIII-D Steady-State discharge, TGLF, BC at ρ=0.8**
- **N = 10, 20, 50, 100**





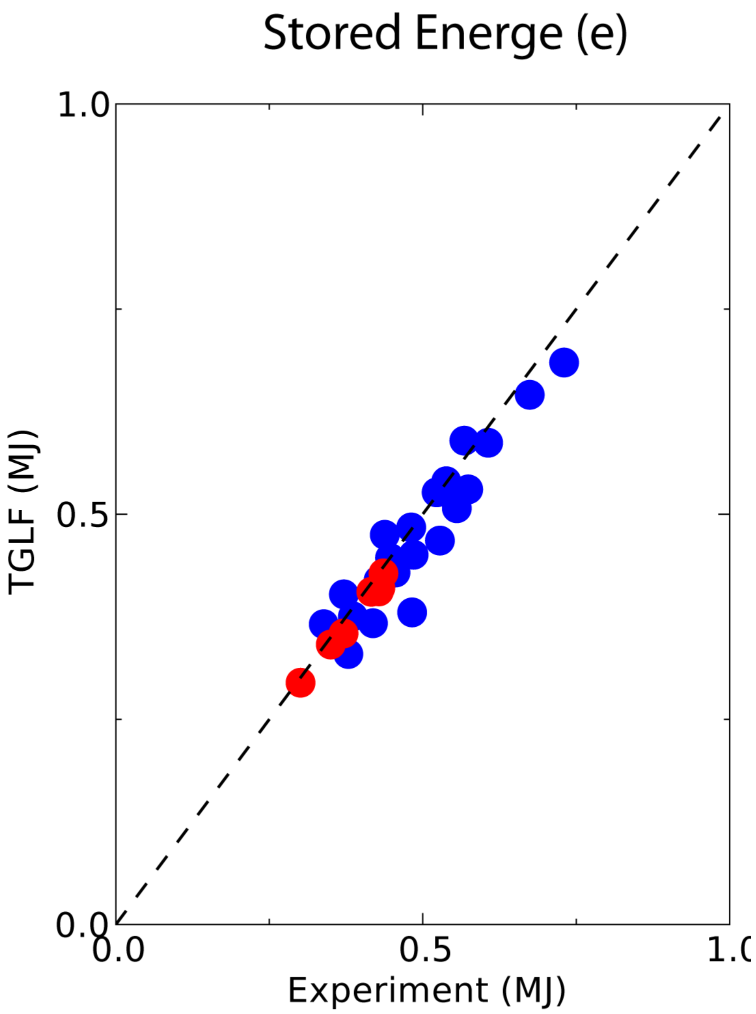
Number of Iteration Stays ~Constant with Time Step



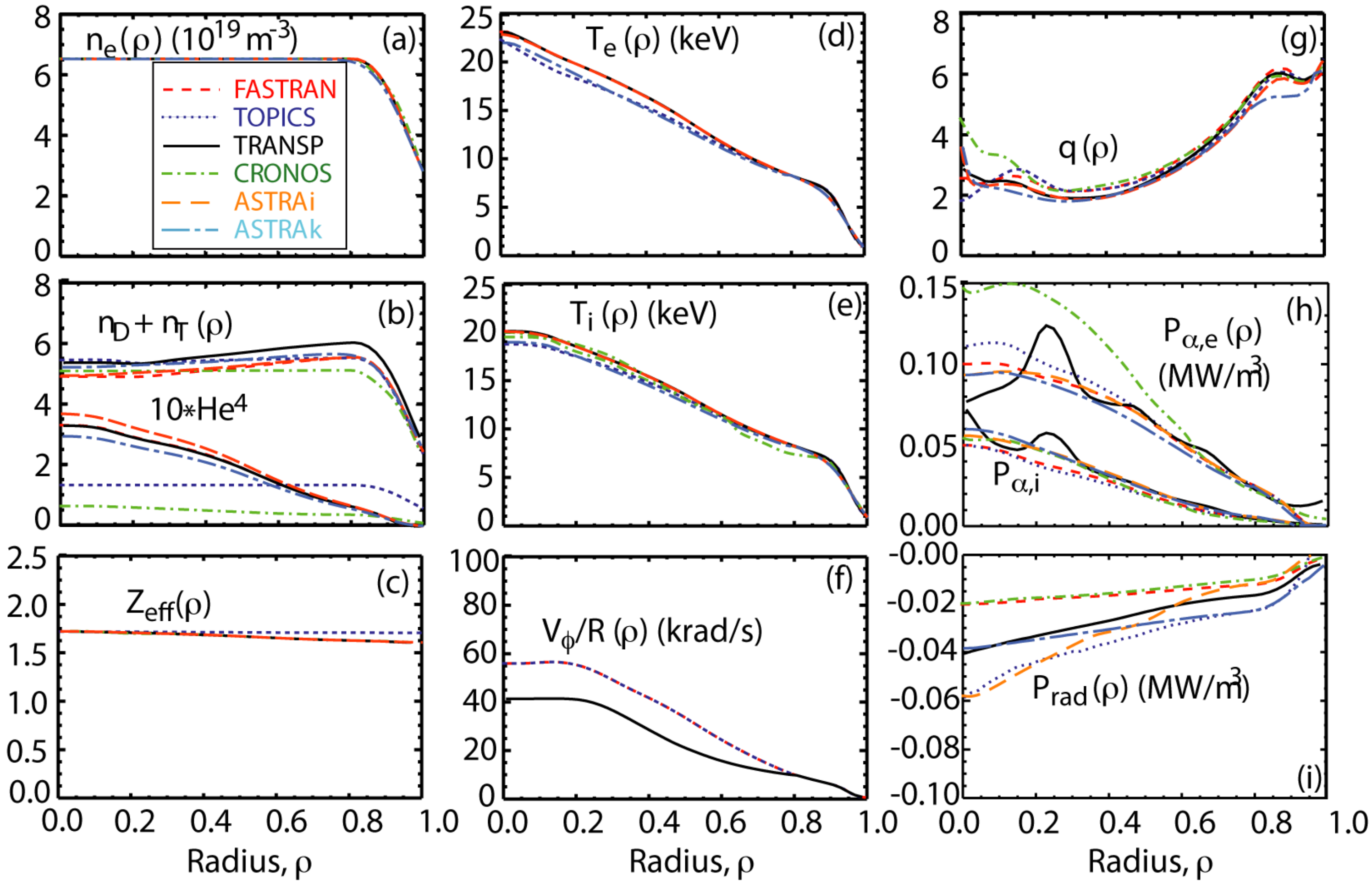
Robust Convergence in Wide Range of Condition

- **21 DIII-D high beta discharges**
- **Steady-state solution**

Iteration	N=20	50	100
Min	6	7	9
Max	16	21	24



Benchmarked Well with Major 1.5-D Transport Codes



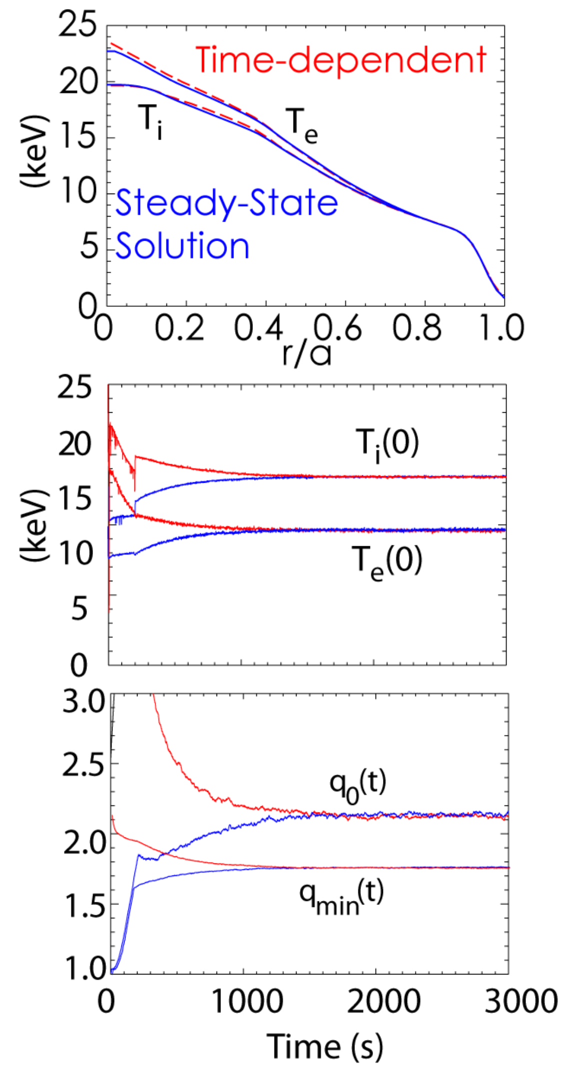
- **ITPA-IOS Joint Modeling: ITER SS Scenario Code-Code Benchmark**

Murakami, NF2011

Main Application: Iterative Solution Procedure to Develop Target High β Steady State Scenario

- **Efficient/robust iterative method to find a stationary solution (d/dt=0) of core transport**
  - Self-consistent with heating/current drive, equilibrium, and stability
  - Fully relaxed final state including inductive drive
- **Well benchmarked with time-dependent simulation**
  - Highly nonlinear system but no bifurcation observed so far
  - Requires a few iterations equivalent to less than10 time steps
- **Simulate realistic DIII-D configuration**
  - Used for DIII-D to show how H/CD upgrade tools enable research

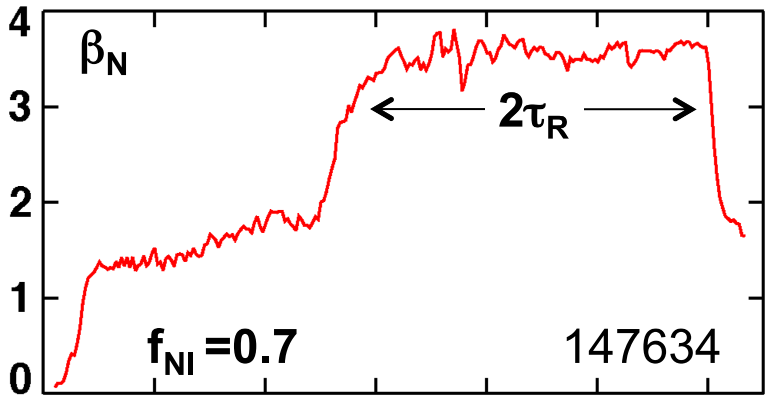
Example of ITER simulation

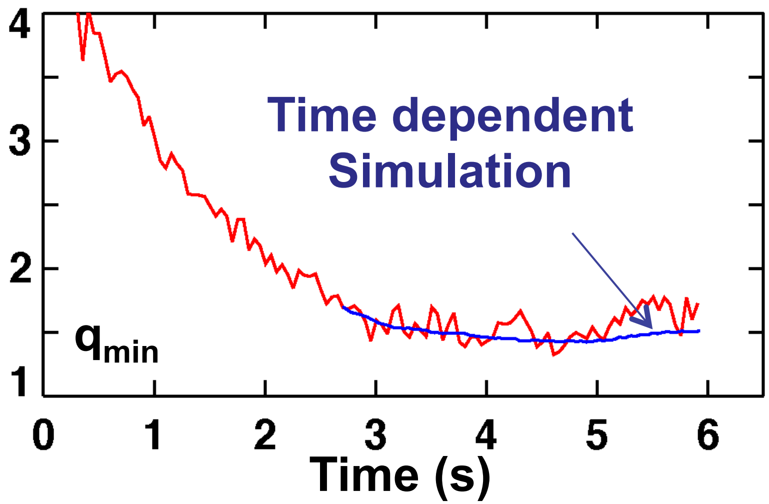


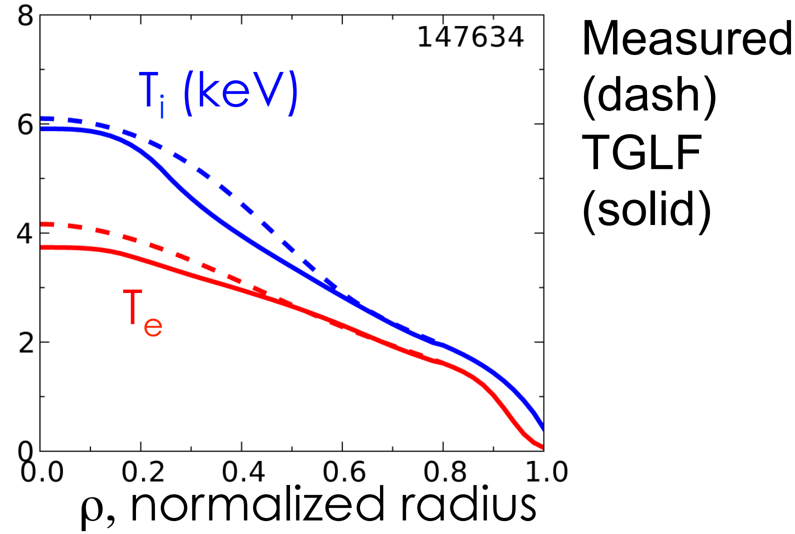
084-13/JMP/jy

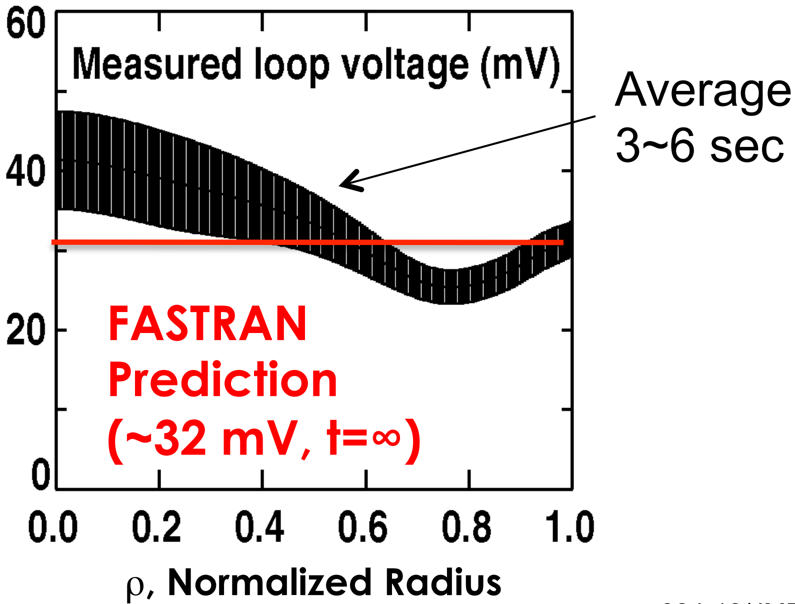
FASTRAN Steady State Solution Procedure Reproduces Most Key Features of DIII-D High β Discharges in Stationary Condition

- **Stationary discharge sustained by off-axis NBI**









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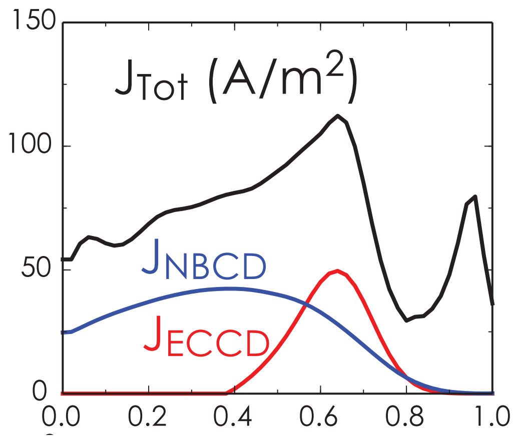
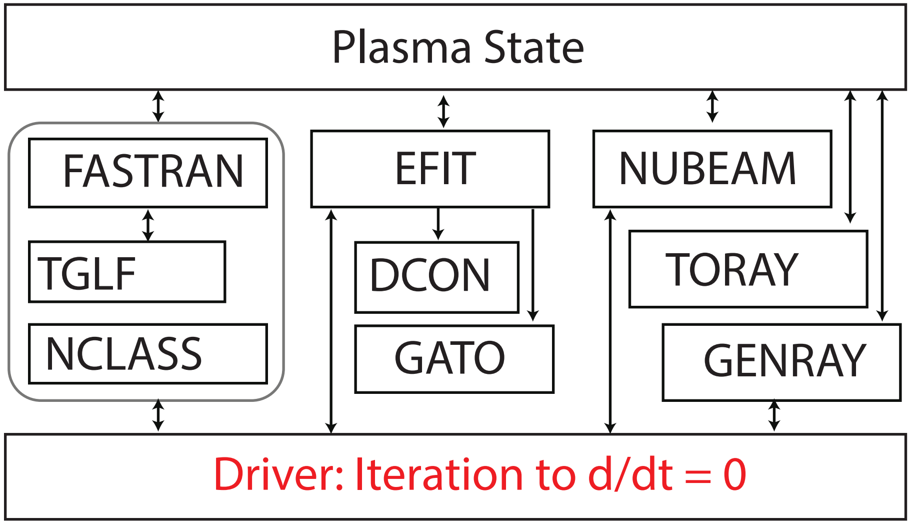
FASTRAN Being Used as a Transport Component of IPS, Providing Extended/Flexible HPC 1.5D Integrated Modeling

- **DIII-D SS scenario at β_N=5**

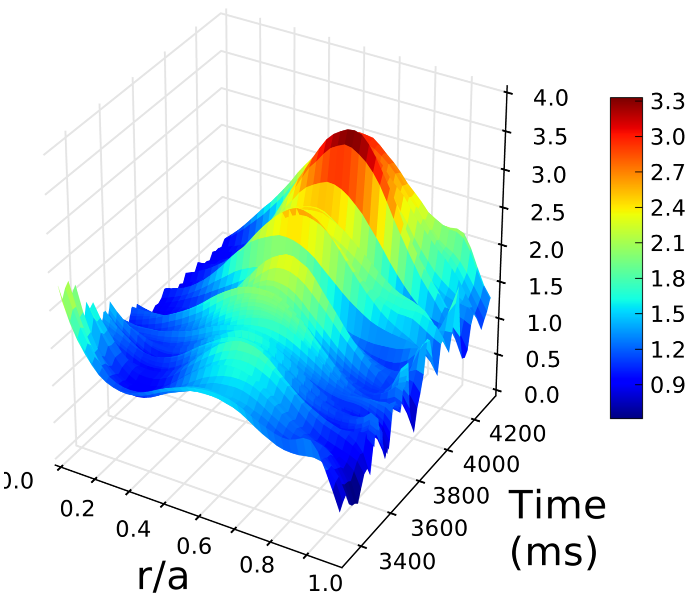


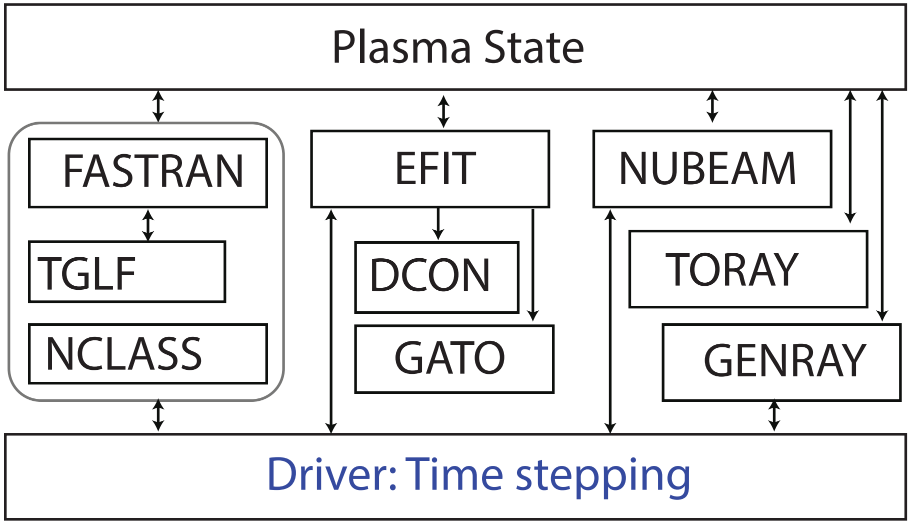


- **Framework/component architecture, using existing codes & file-based communication**
- **Accelerate repeated cycle of modeling, experimental validation, and scenario design/development**
- **Allow easy plug-in/out new codes identified important for optimization**

FASTRAN Being Used as a Transport Component of IPS, Providing Extended/Flexible HPC 1.5D Integrated Modeling

- **Power balance diffusivity for DIII-D high li discharge**





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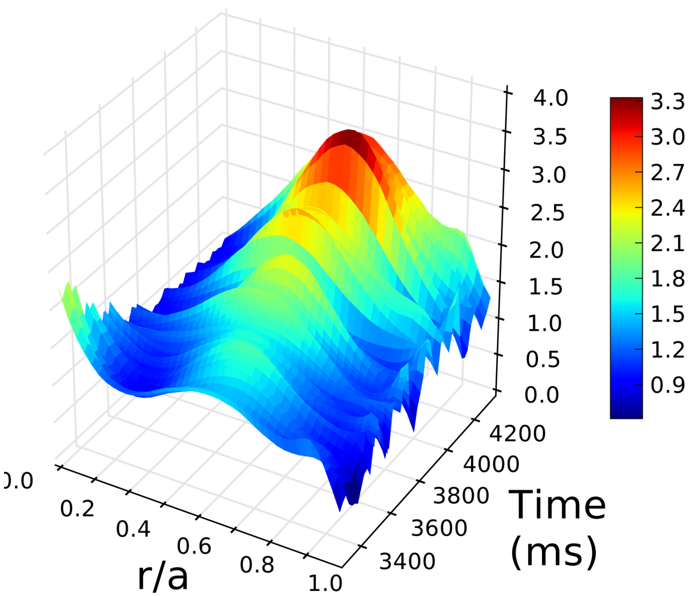

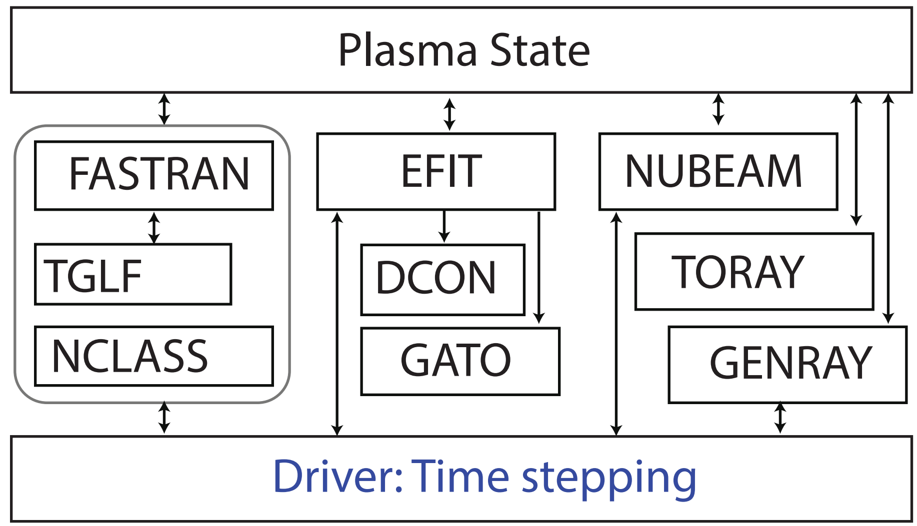

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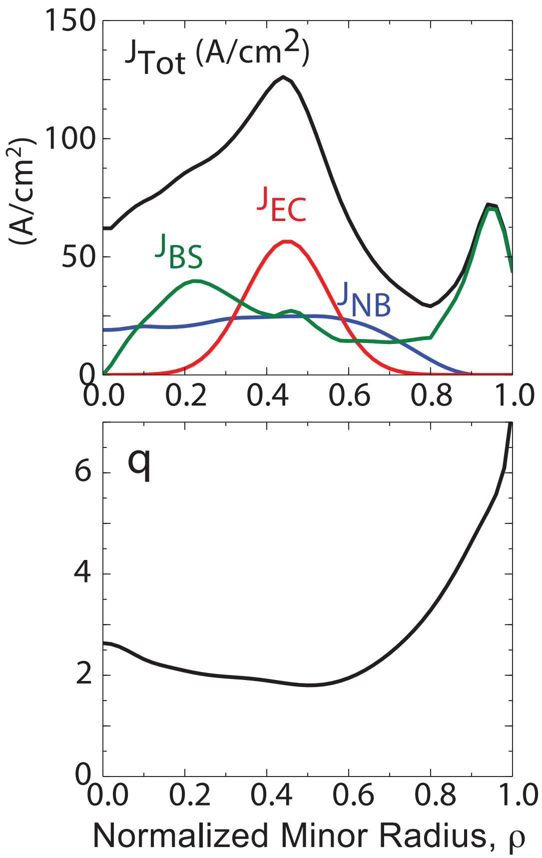
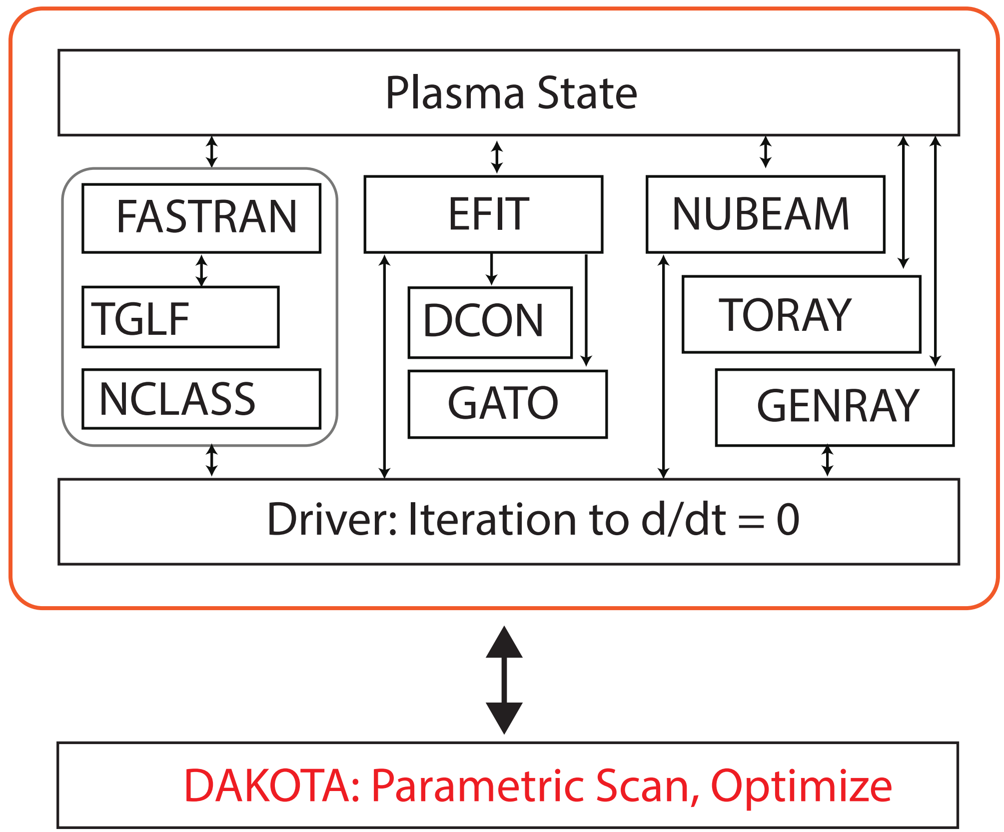
GLF23, MMM, CDBM, Coppi-Tang, ESC, TOQ, ELITE, BALOO, TORIC, AORSA, CQLF3D, ...

DAKOTA-enabled FASTRAN/IPS Optimizes DIII-D Steady-State Scenarios to Guide H/CD Upgrade

- **Low rotation SS scenario with balance beam**



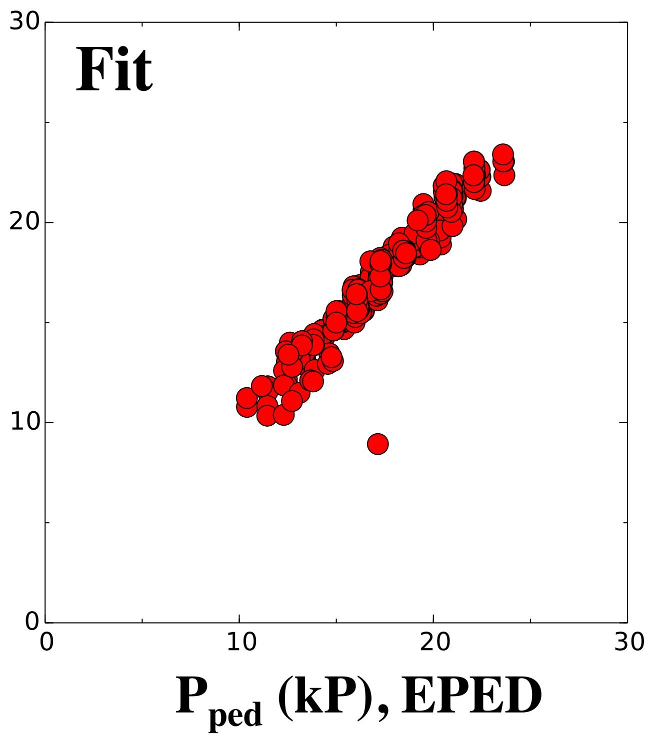
FASTRAN/IPS Integrated Modeling

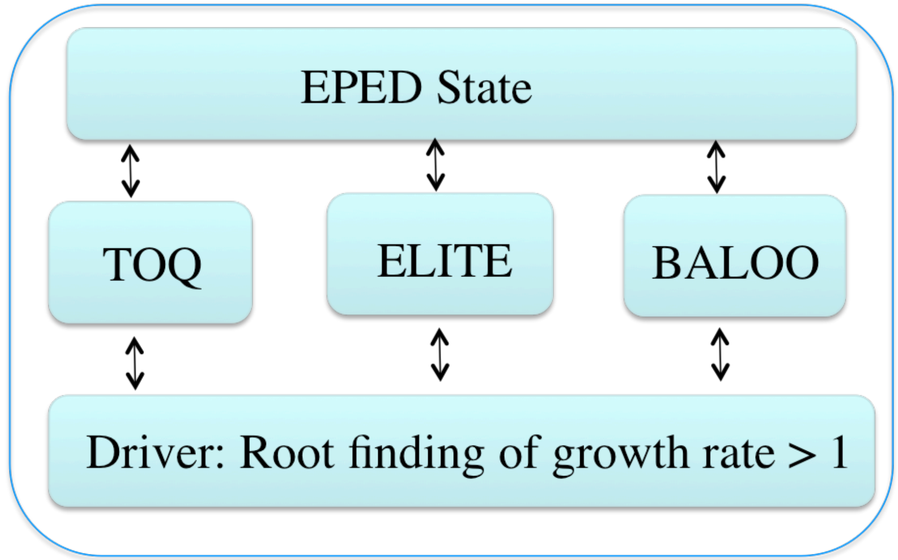


⇒ **Systematic scan of ~1000 simulations (0.1M CPU hours) found self-consistent β_N~5 scenario, guiding DIII-D H/CD upgrade**

EPED Workflow Built Upon IPS Provides FASTRAN Boundary Condition: Self-consistent Core-Edge Modeling

Regression for 500 EPED results for DIII-D SS scenario





- **Original EPED is a composite component that has been upgraded to a modular IPS-EPED Workflow**
- **IPS-EPED runs in parallel, 480 TOQ + 400 BALOO + 700 ELITE runs**
  - Fast enough for core-edge coupling
  - 2 minutes using ~700 CPUs at NERSC
- **Verified successfully against standalone idl-EPED**

Summary

- **FASTRAN is Fast**

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- **FASTRAN is Fast**
- **How about plugin FASTRAN to TRANSP …. ?**