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Dynamic Modeling of Equilibrium in XGC Gyrokinetic Simulations of Pedestal Evolution

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Outline

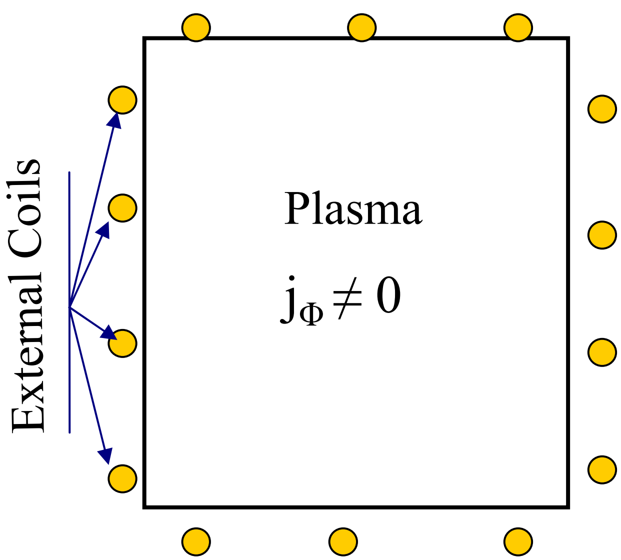
- Dynamic modeling of the equilibrium in the XGC edge gyrokinetic code is needed for
  - Advances in the gyro-kinetic modeling for longer physical times when equilibrium profiles change due to
    - Transition from L- to H-mode
    - H-mode pedestal build up
    - ELM crashes and H-mode pedestal recovery
  - Coupling of the XGC code with MHD instability codes such as M3D and NIMROD
- Effect of equilibrium changes in the XGC code
- New equilibrium solver in the XGC code
- TEQ equilibrium solver in the XGC code
- Summary

Grad-Shafranov Equation with Current Sources

- XGC edge gyrokinetic code is designed to use eqdsk files generated with the EFIT equilibrium code
- Bootstrap current density and plasma pressure computed by XGC depart over time from original EFIT equilibrium
  - Plasma pressure and parallel component of current density evolve

$$p = p_{\mathrm{EFIT}} + p_{\mathrm{XGC}} \qquad \langle \boldsymbol{J}\cdot\boldsymbol{B}\rangle = \langle \boldsymbol{J}\cdot\boldsymbol{B}\rangle_{\mathrm{EFIT}} + \langle \boldsymbol{J}\cdot\boldsymbol{B}\rangle_{\mathrm{XGC}}$$

- XGC code needs a module to solve the Grad-Shafranov equation with current source:



$$\Delta^{*}\psi = -\mu_0 \frac{dp}{d\psi}\left[R^2 - \frac{I^2}{\langle B^2\rangle}\right] - \mu_0 \frac{\langle \boldsymbol{J}\cdot\boldsymbol{B}\rangle}{\langle B^2\rangle} I$$

bootstrap current contribution

- Ideal boundary is located at infinity
  $\Rightarrow$ boundary values for poloidal flux must be provided at edge of computational domain

Solving GS Equation in the XGC code

- Boundary value poloidal flux can be represented in the form

$$\psi_{boundary} = \psi_{bounadry}^{coils} + \psi_{boundary}^{plasma}$$

  - $\psi_{bounadry}^{coils}$ is contribution from currents in external toroidal coils
    - remains fixed during numerical integration in XGC code
  - $\psi_{bounadry}^{plasma}$ is contribution from plasma currents
    - continuously changing until convergence
- The solution for the plasma poloidal flux is expressed through the Green's function

$$\psi_{boundary}^{plasma}(\vec{x}) = \int_{plasma} J_{\varphi}(\vec{x}')G(\vec{x},\vec{x}')d\vec{x}'$$

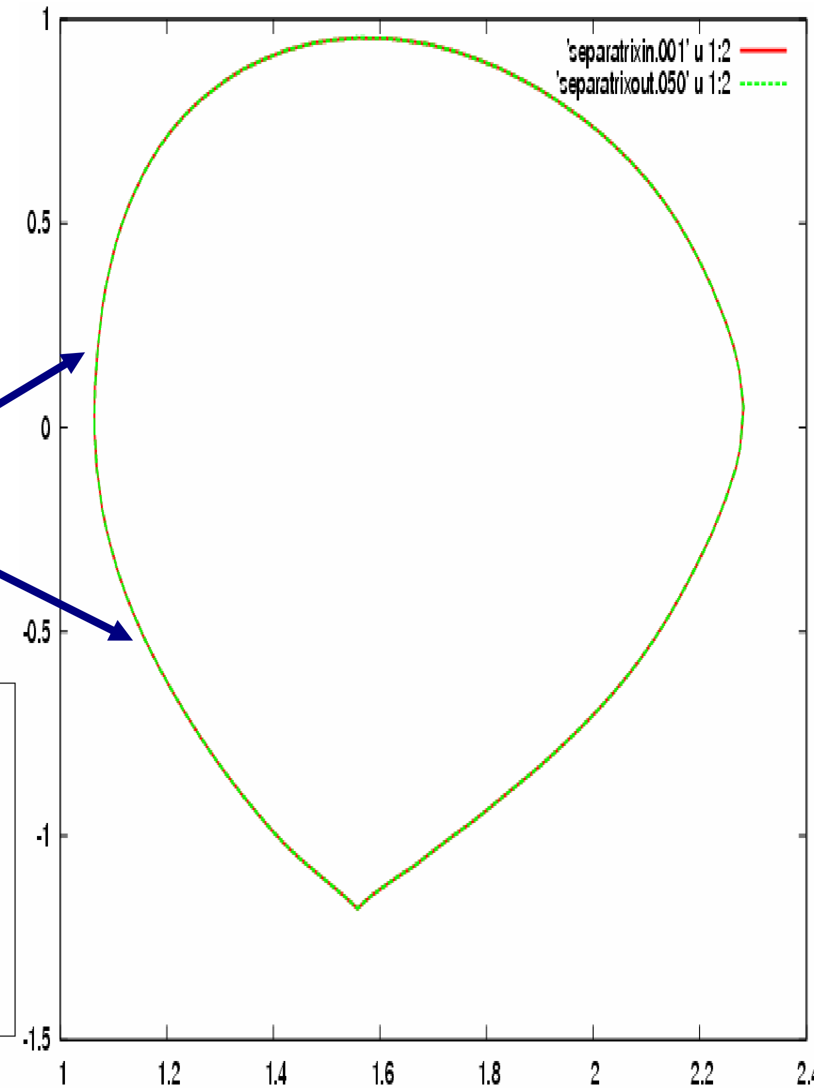
  - The Green's function can be considered as a vector potential due to an axisymmetric current source

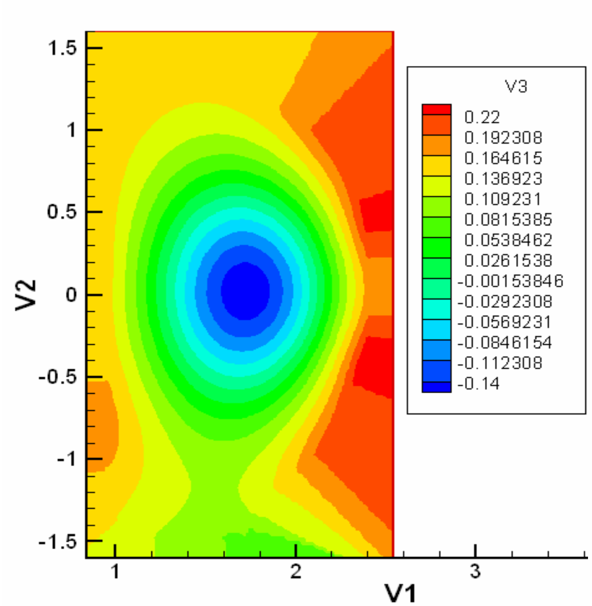
$$G(\vec{x},\vec{x}') = \frac{\mu_0\sqrt{RR'}}{2\pi k}\left[\left(2-k^2\right)K(k^2) - E(k^2)\right]$$

$$k^2 = \frac{4RR'}{\left[(R+R')^2 + (Z-Z')^2\right]}$$

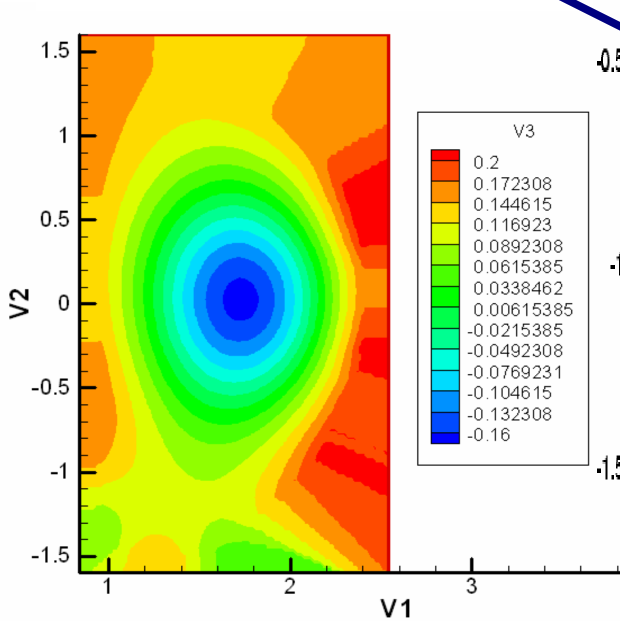
Verification of GS Solver in the XGC Code

- The solution of the GS equation is straightforward as long as $\psi_{bounadry}$ is defined
- A new equilibrium solver was developed for XGC code by S. Ko
- With fixed $\psi^{coils}_{bounadry}$, separatrix location does not change in time





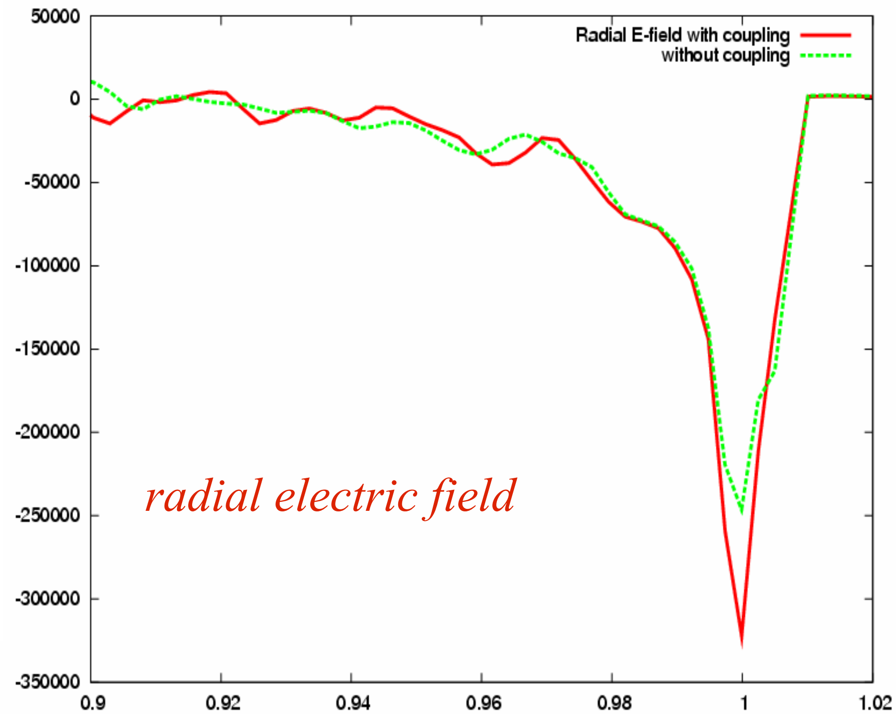
Initial poloidal flux

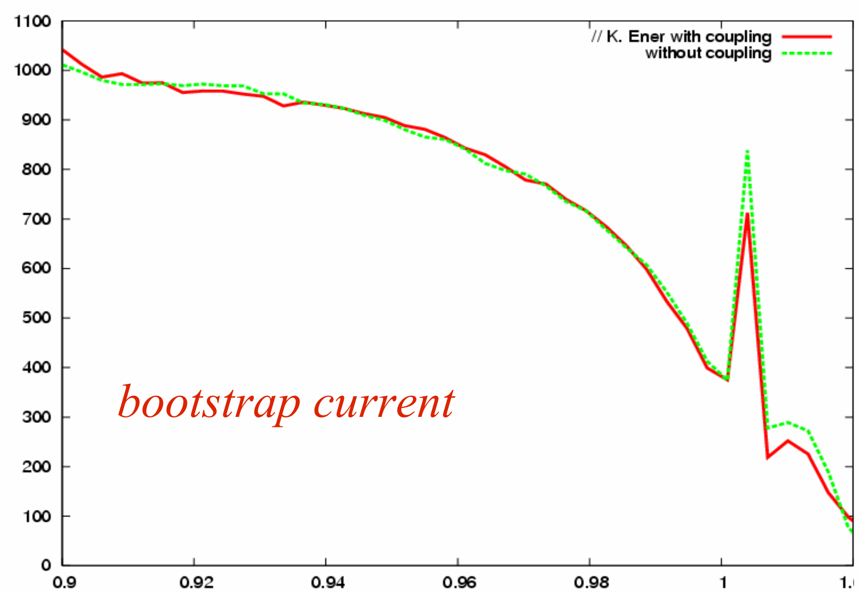


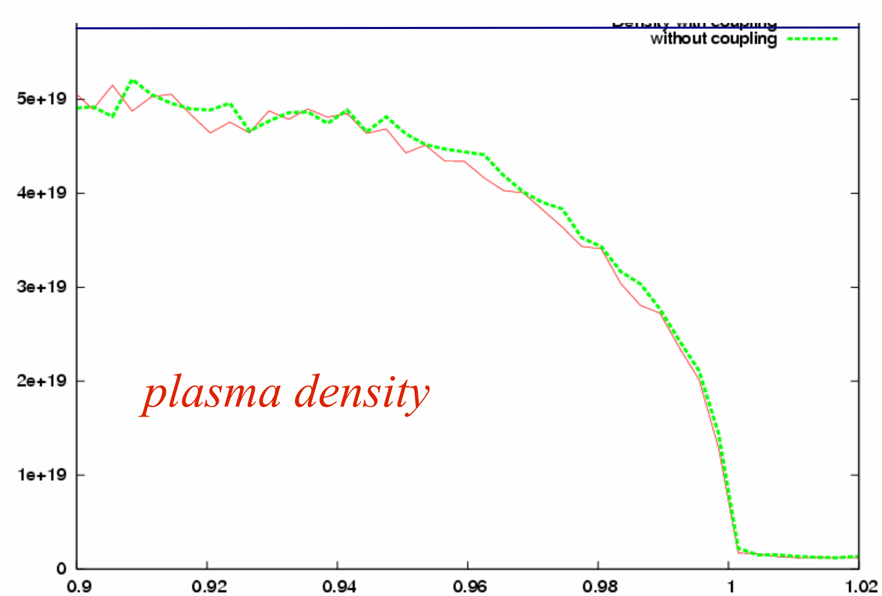
Poloidal flux after 50 equilibrium solver calls

XGC Results With and Without Equilibrium Solver

- XGC code with and w/o new equilibrium solver shows little difference in plasma profiles
- With the equilibrium solver
  - The radial electric field is somewhat lower near separtrix
  - The width of pedestal density is marginally wider
  - Bootstrap current is lower in SOL

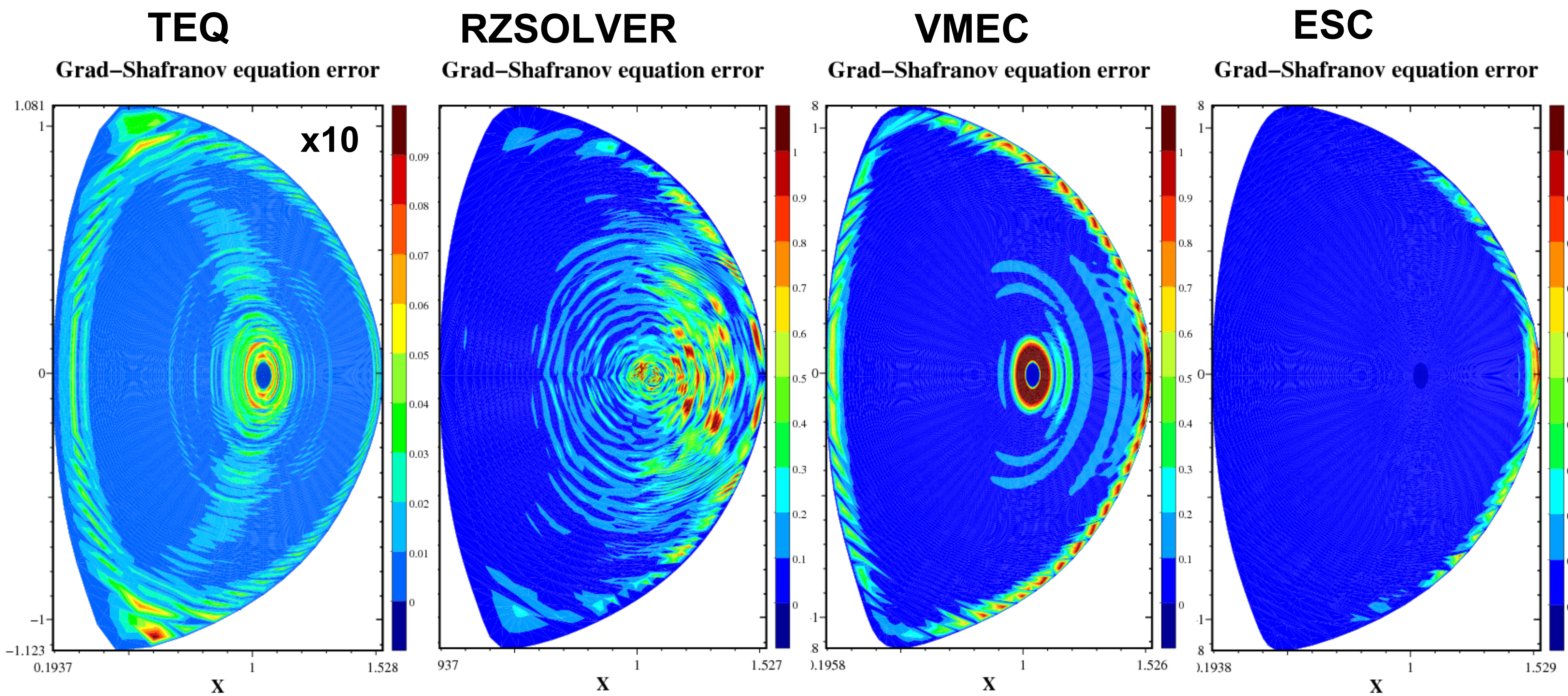






Equilibrium Solvers in NTCC module library

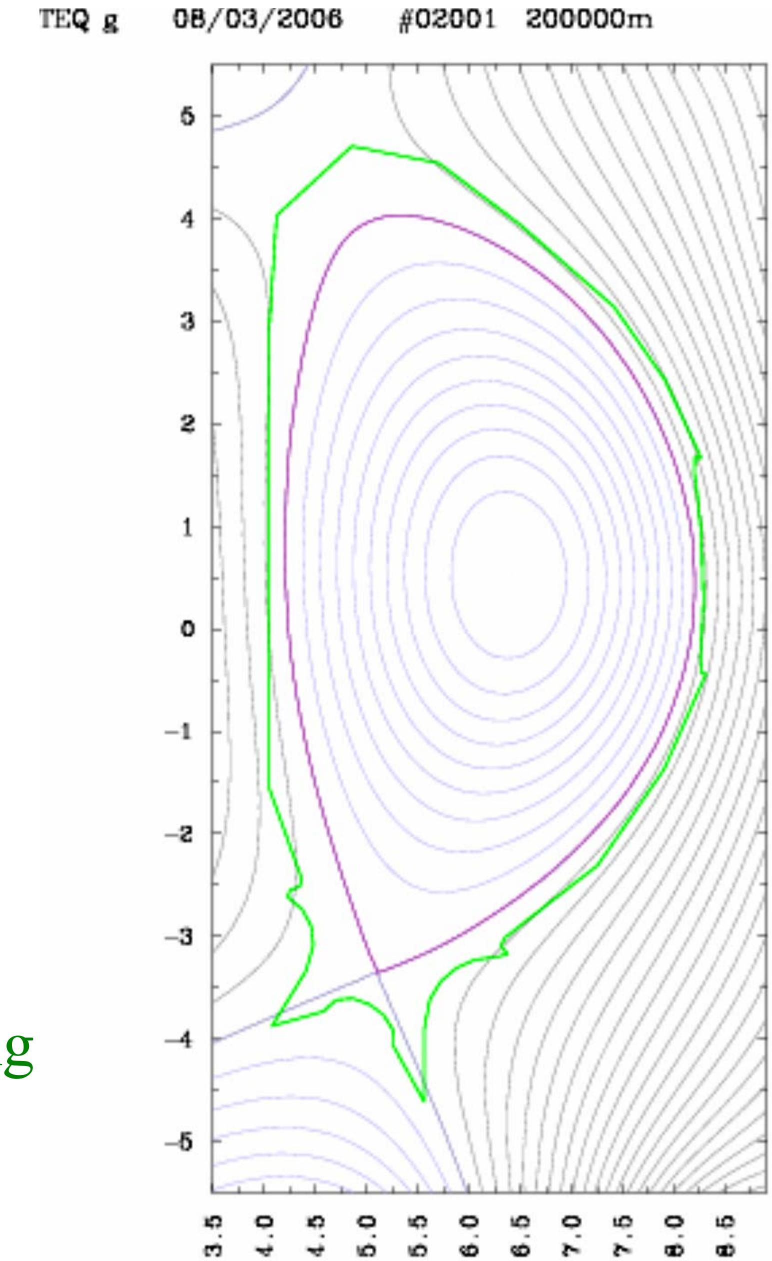
- Four different equilibrium solvers from NTCC module library (http://w3.pppl.gov/NTCC) has been recently compared in the PTRANSP code
  - It is found that the TEQ code produces the smallest residual error
- Equilibrium error contour plots shown for different solvers



From Rob André, APS-DPP 2006

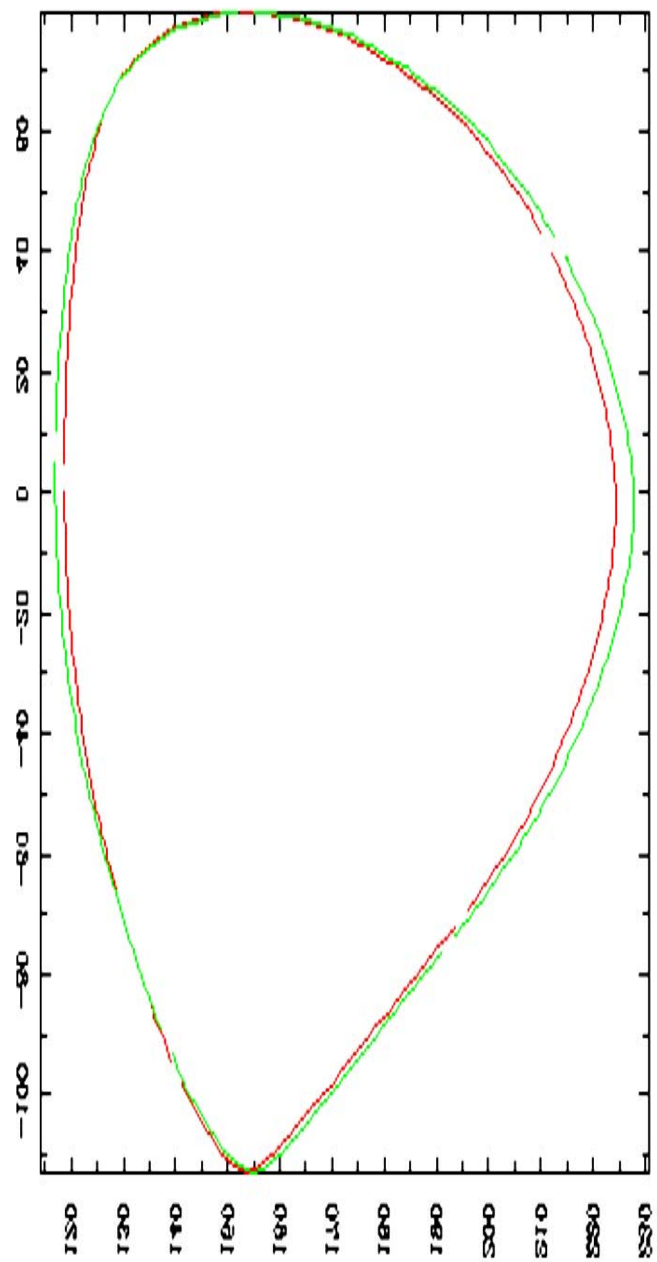
TEQ Equilibrium Solver

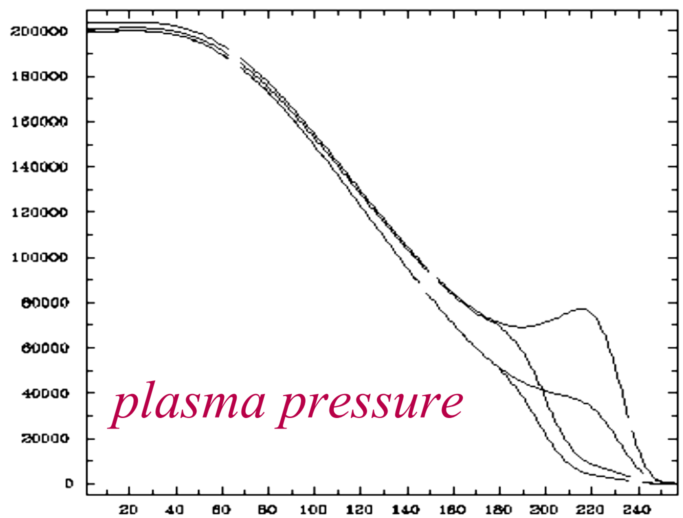
- **TEQ equilibrim code includes both direct (free boundary) and inverse (fixed boundary) equilibrium solvers**
  - TEQ was extracted from CORSICA code as an NTCC module
  - TEQ can be used both for prescribed boundary and free boundary equilibria
  - Parameterized pressure and current density profiles generated in a similar manner as with TOQ code
  - Free-boundary TEQ equilibrium solver applied to generate new equilibria, including scrape-off region, for use with non-ideal MHD NIMROD code
  - Example of equilibrium is shown for ITER

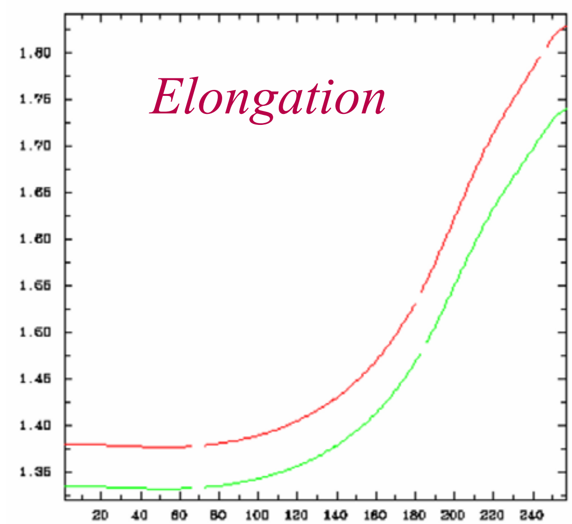


Generating New Equilibrium for XGC code

- Experimentally based equilibrium computed with EFIT code for the DIII-D discharge 113317 has been used as a starting point
- In order to verify effects of small equilibrium changes on the XGC results, a set of equilibria has been generated with the TEQ code
  - Plasma shape has been change to alter the elongation and current density profiles
  - The position of H-mode pedestal has been altered
  - q-profile was fixed

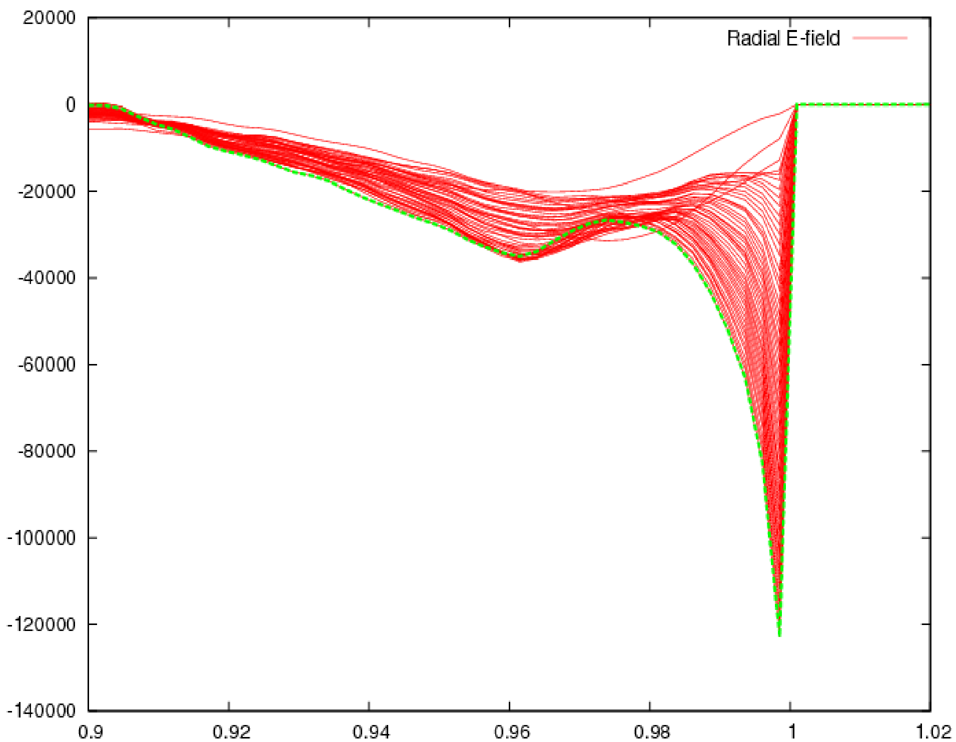


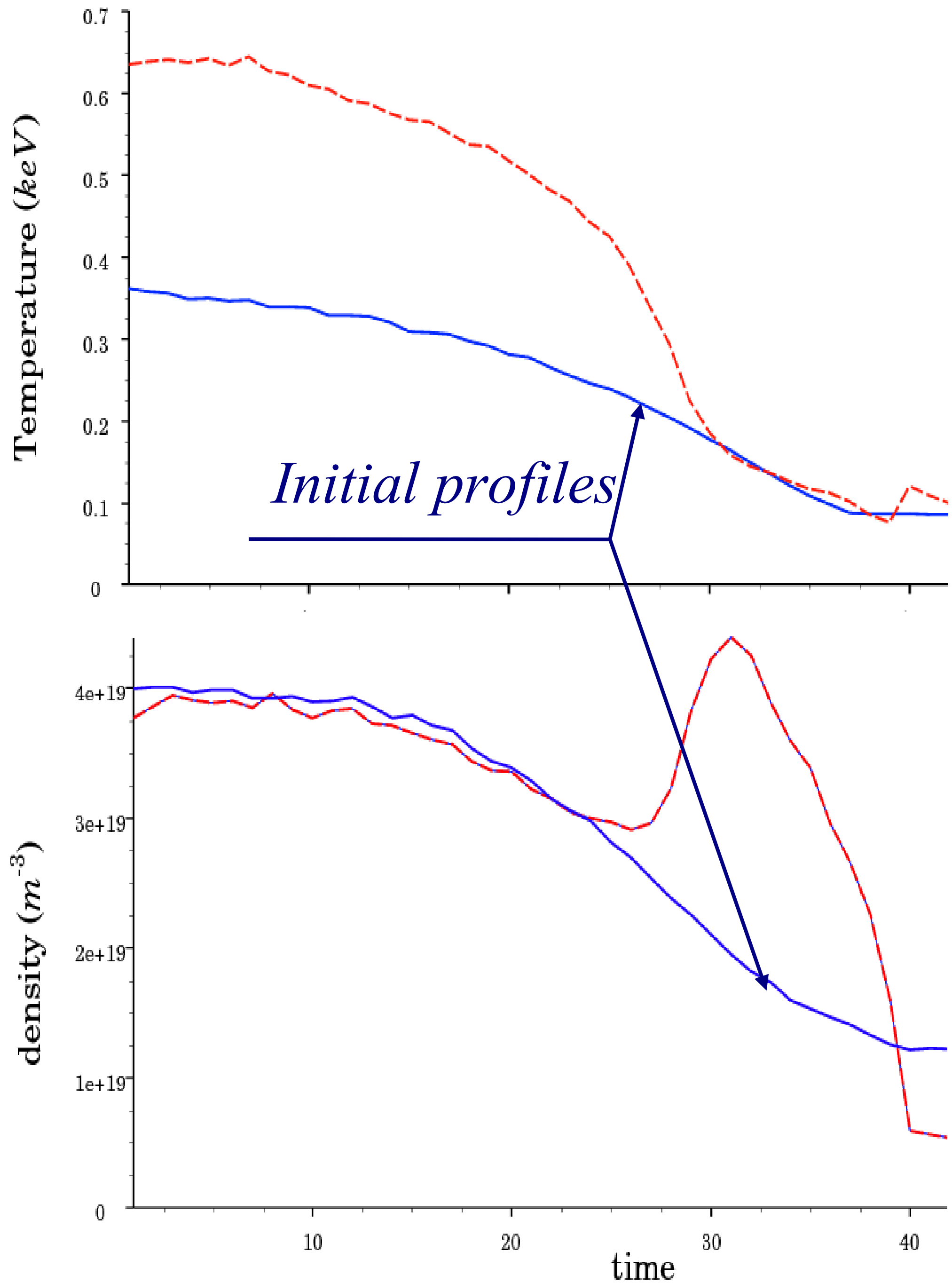




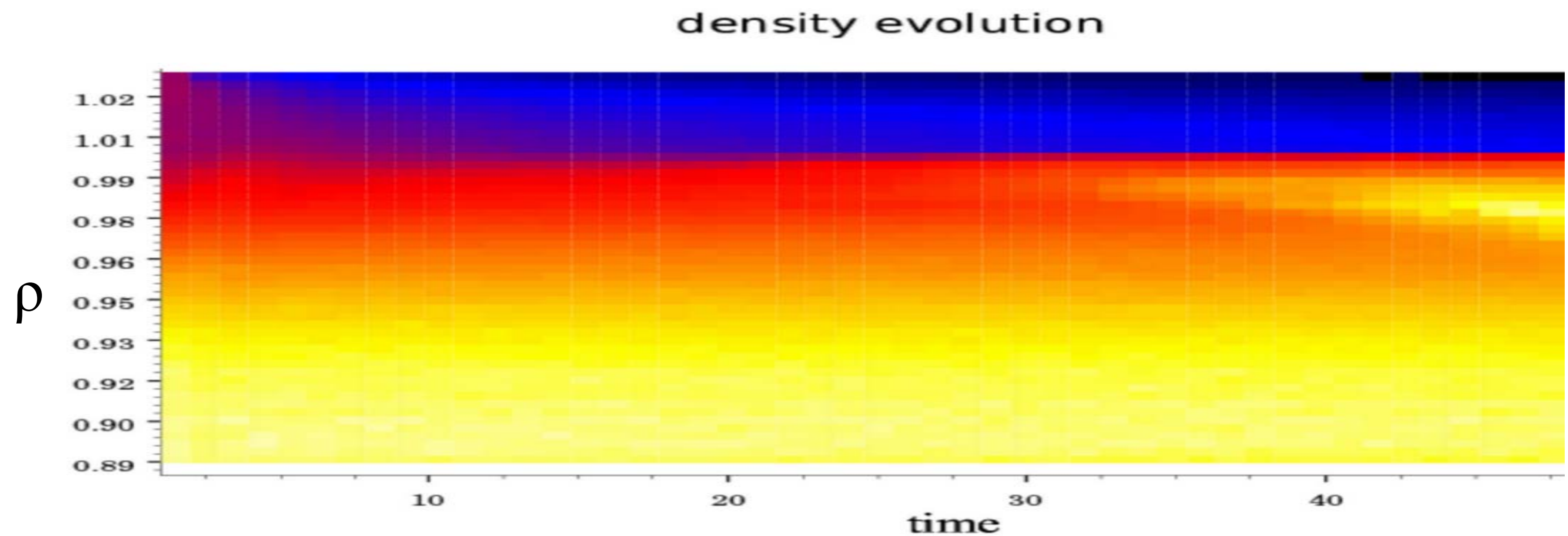
XGC Simulation Results

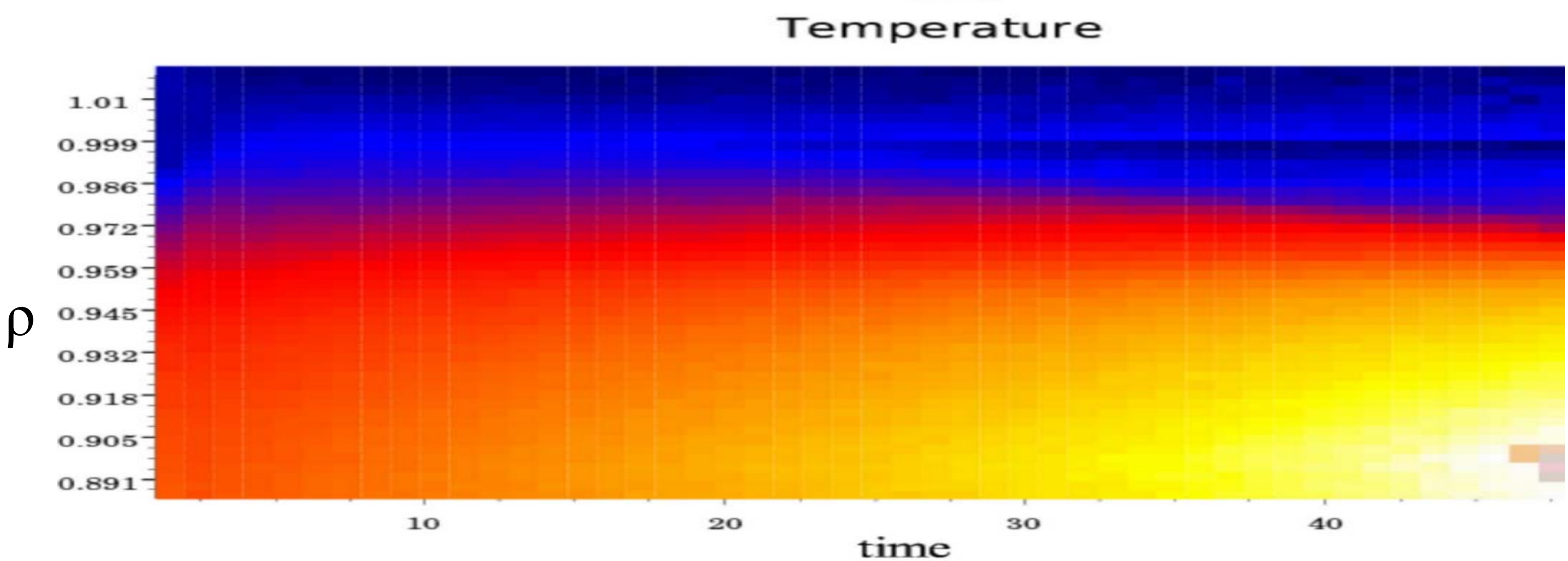
- Pedestal development for the original experimental equilibrium (DIII-D 113317)
  - Strong negative radial electric field near the separatrix region
  - Stronger gradients of plasma temperature and density
  - Narrowing of the pedestal width





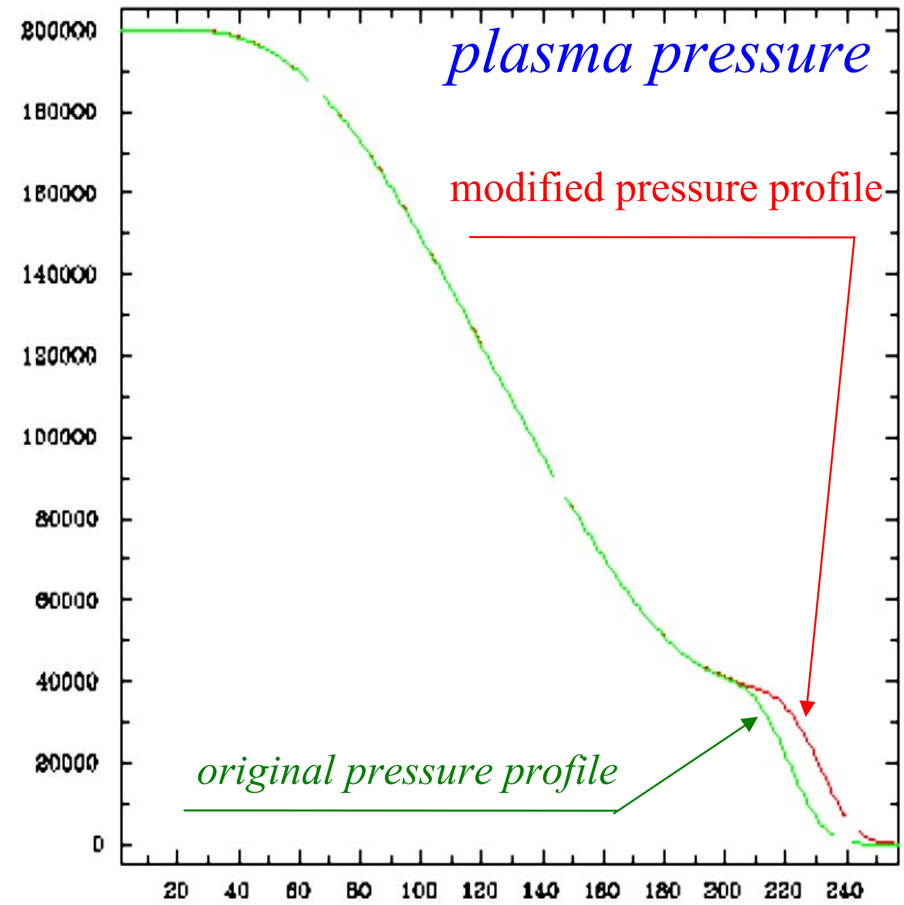
XGC Simulation Results





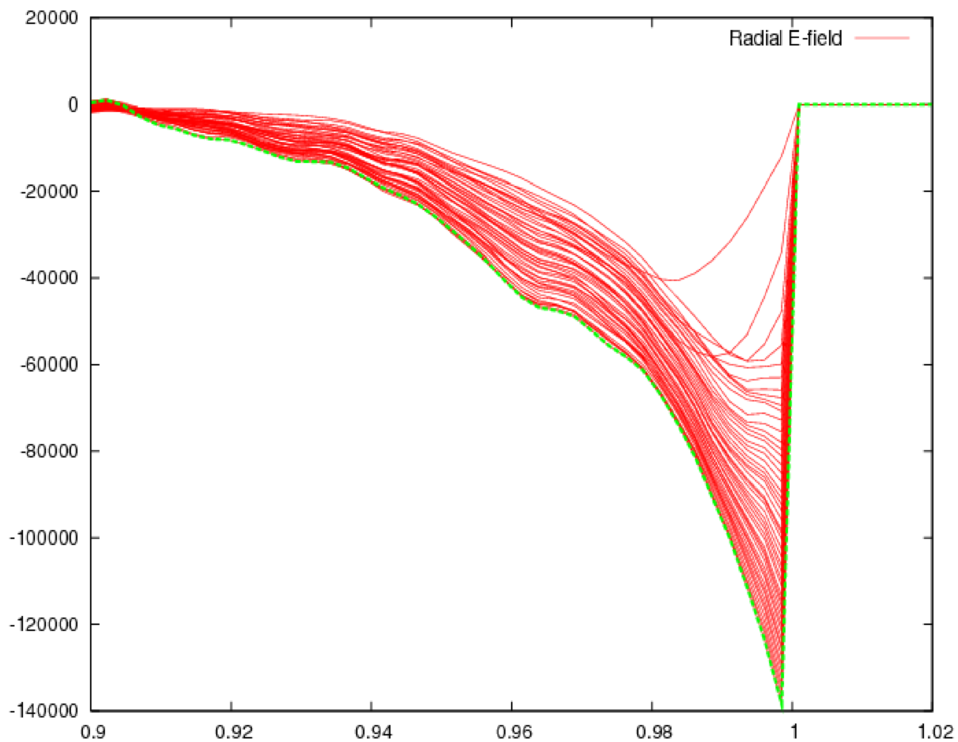
XGC Simulation Results

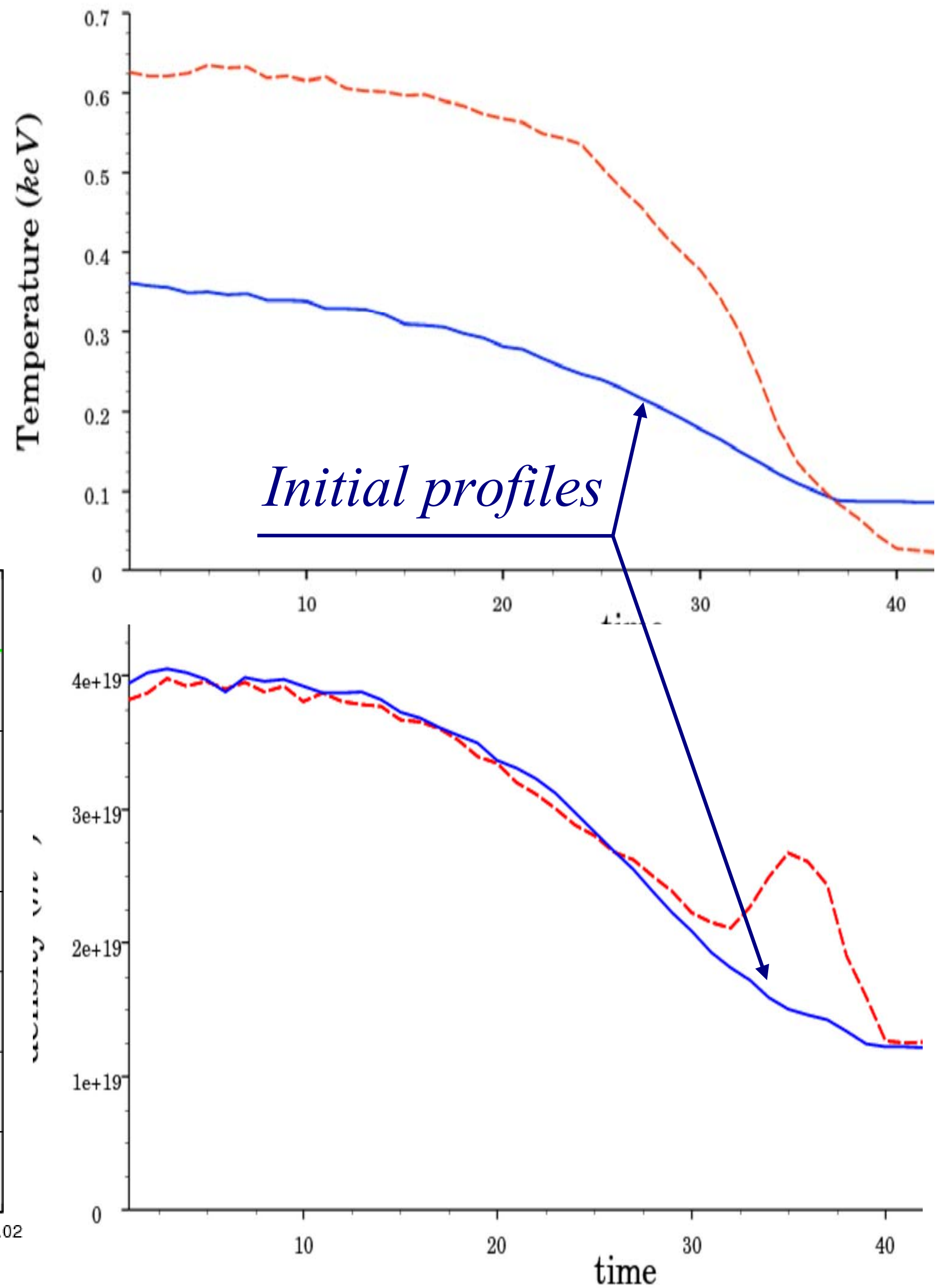
- In order to verify the importance of dynamic equilibrium solver in the XGC simulation, the original experimental equilibrium has been modified by reducing the pedestal width
- The resulting pedestal width is selected to be close to the final pedestal width computed in the XGC code in the previous simulation



XGC Simulation Results

- Pedestal development for the modified equilibrium with the pedestal width that is closer to the final XGC state
  - Radial electric field and temperature profiles are similar
  - The gradients for the density profile are much smaller





Conclusions

- New equilibrium solver that is based on Green's function solution is implemented and tested in the XGC edge gyrokinetic code
  - Due to feedback control of coil currents, the location of the separatrix can be fixed in the free boundary equilibrium solution
  - Dynamic evolution of equilibrium leads to minor changes in the resulting plasma profiles. In particular, it is shown that
    - The bootstrap current is lower in SOL region
    - The pedestal width is wider
- Dynamic evolution of equilibrium is demonstrated with the TEQ equilibrium code
  - Use of TEQ equilibrium with profiles that are close to the final XGC simulation state leads to different value of the normalized pressure gradient in the pedestal region, which might affect the MHD stability properties of the profiles
  - The TEQ equilibrium code is included in the XGC code to be used for dynamic evolution of equilibrium
  - The verification of the XGC-TEQ coupling is underway