Self-consistent Modeling of the Pedestal in Tokamak Plasmas

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Outline

- **Edge Physics in Tokamak**
- **CPES Framework**
  - ☐ **Guiding center XGC0 code code**
  - ☐ **Gyrokinetic XGC1 code**
  - ☐ **Kepler Workflow for Code Coupling**
- **Code Coupling Efforts**
  - ☐ **TEQ Equilibrium Code**
  - ☐ **ELITE ideal MHD stability code**
  - ☐ **M3D and NIMROD extended MHD codes**
- **Simulation of ELM cycle with the XGC code**
- **Effects of anomalous transport**

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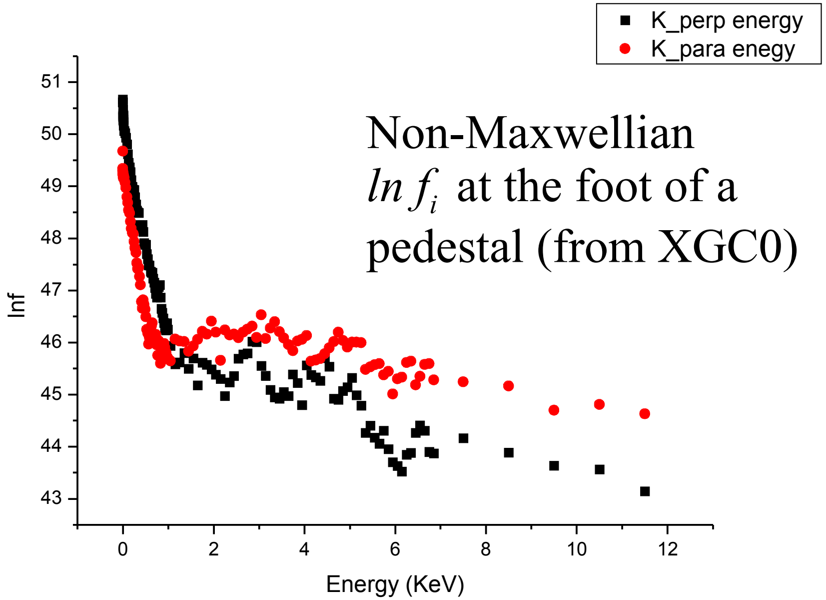
Edge Physics in Tokamaks

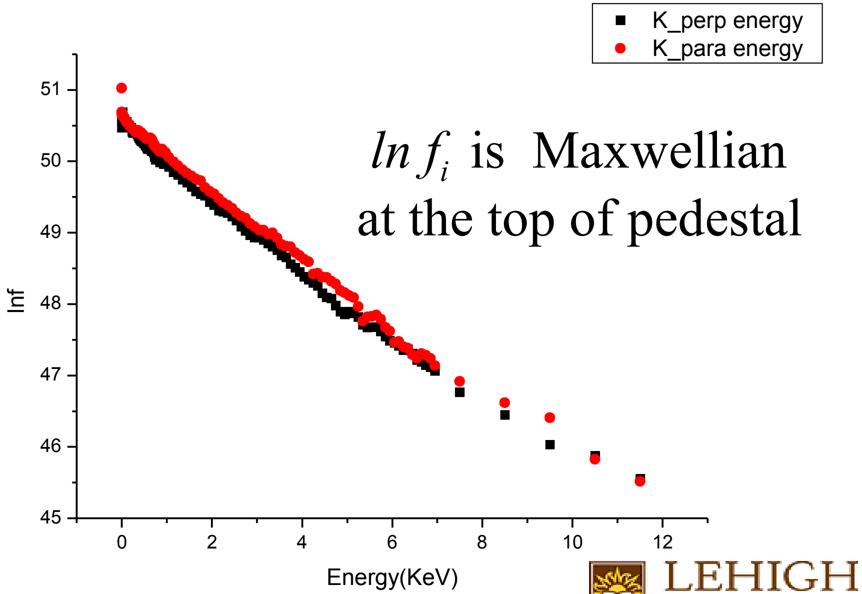
- **The problem requires time dependent, integrated understanding of**
  - ☐ Edge kinetic neoclassical physics
    - Edge ions have steep gradients and non-Maxwellian
  - ☐ Edge kinetic turbulence physics
  - ☐ Core turbulence and MHD physics
  - ☐ Large scale edge localized modes (ELMs)
  - ☐ Neutral, impurity and atomic physics
  - ☐ Scrape-off-layer physics
  - ☐ Wall load, neutral recycling, and sputtering
  - ☐ Energetic particle influx from core
  - ☐ RF interaction of edge plasma
  - ☐ 3D magnetic field effects

Kinetic Plasma in the Edge

- **Orbit losses (X-loss)**
- **Non-Maxwellian ions in pedestal and near scrape-off due to steep gradient**
- **Non-Maxwellian ions and electrons due to open field lines**
- **Not a conventional neoclassical plasma**

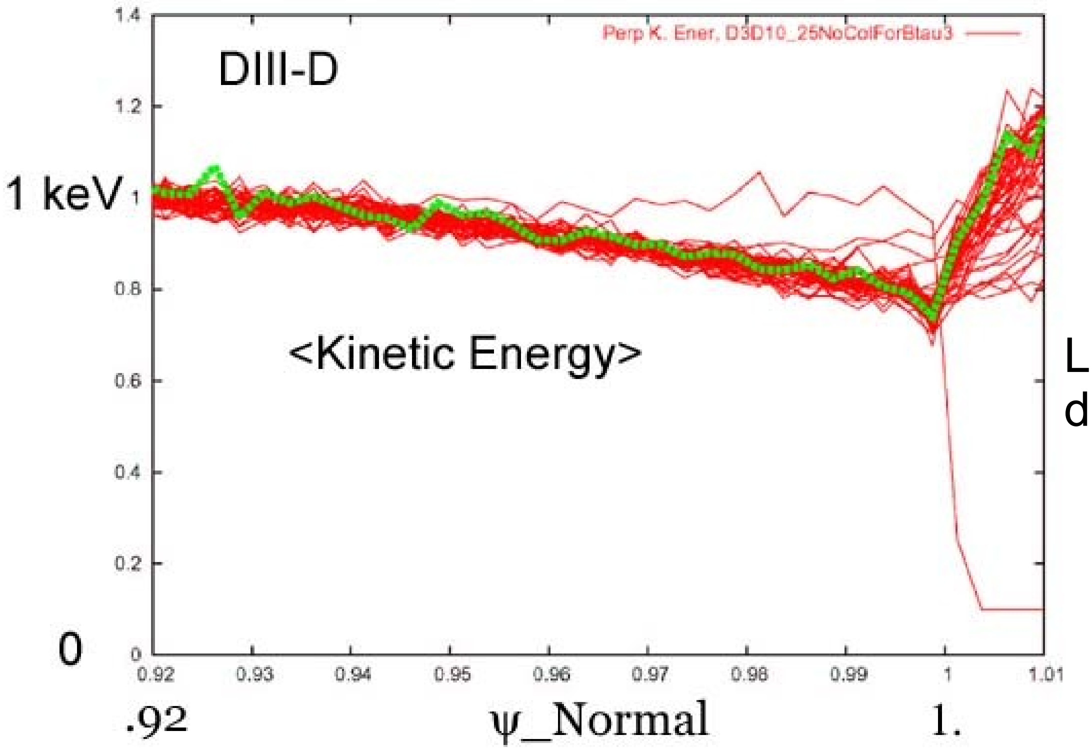


Non-Maxwellian
$ln\ f_i$ at the foot of a
pedestal (from XGC0)



$ln\ f_i$ is Maxwellian
at the top of pedestal

Edge ions are Non-Maxwellian



Low pedestal density

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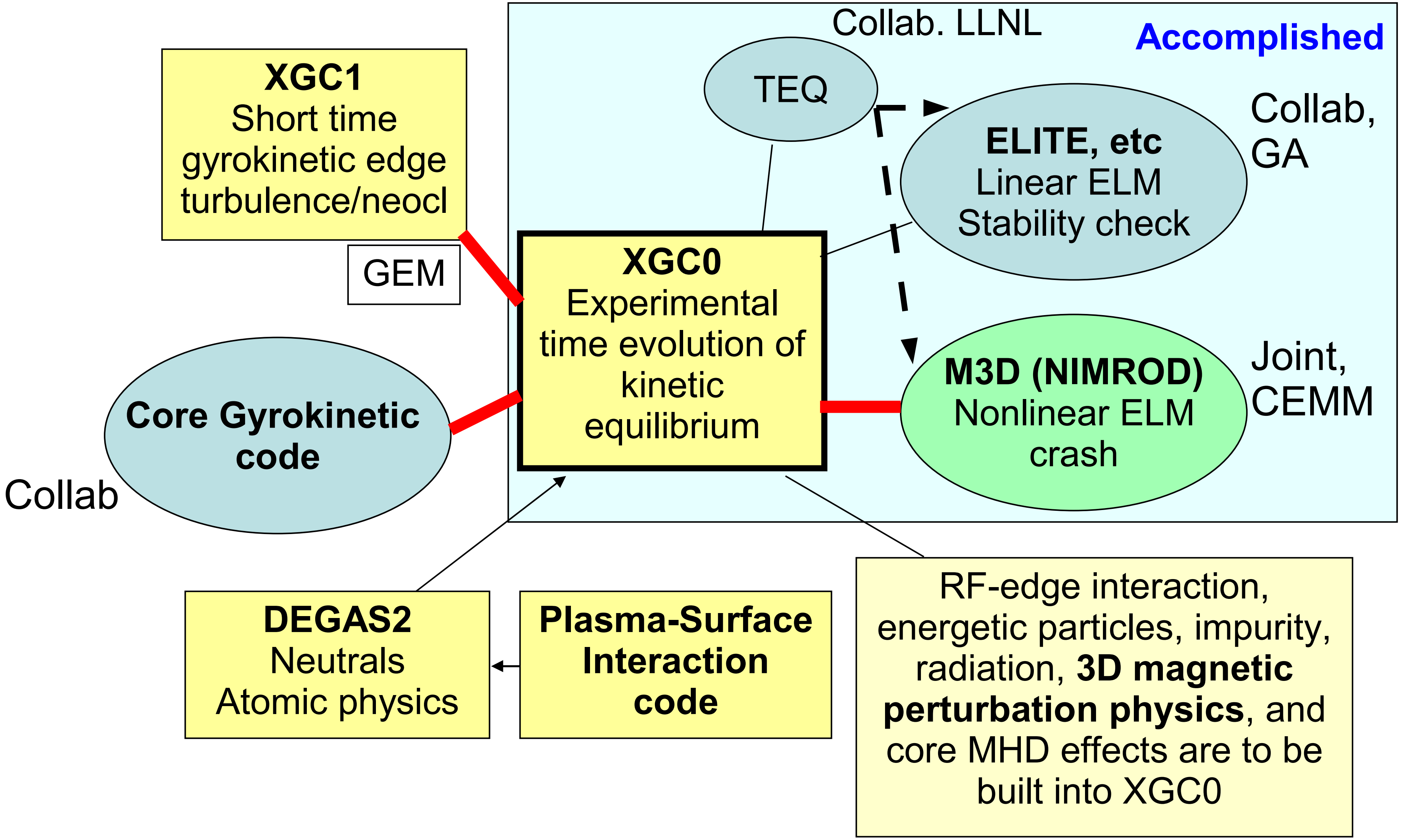
Kinetic code for tokamak edge simulation

- **Challenges for Edge Kinetic Modeling**
  - ☐ **Special treatment for open field lines and divertor geometry is required**
  - ☐ **Steep gradient and X-transport generate strong neoclassical E-field and highly non-maxwellian distribution functions**
  - ☐ **Neutral collision and ionization plays an important role in the H-mode pedestal build up**
- **XGC : X-point included Gyrokinetic Code**
  - ☐ **Full-f particle code for ions and electrons including neutral collisions**
  - ☐ **XGC0 : Guiding Center code. Average-out turbulent E-field**
  - ☐ **XGC1 : Electro-static gyrokinetic code**

CPES Framework of Multiscale Code Integration



Accomplished

Collab. LLNL

TEQ

ELITE, etc
Linear ELM
Stability check

Collab,
GA

XGC1
Short time
gyrokinetic edge
turbulence/neocl

GEM

XGC0
Experimental
time evolution of
kinetic
equilibrium

M3D (NIMROD)
Nonlinear ELM
crash

Joint,
CEMM

Core Gyrokinetic code

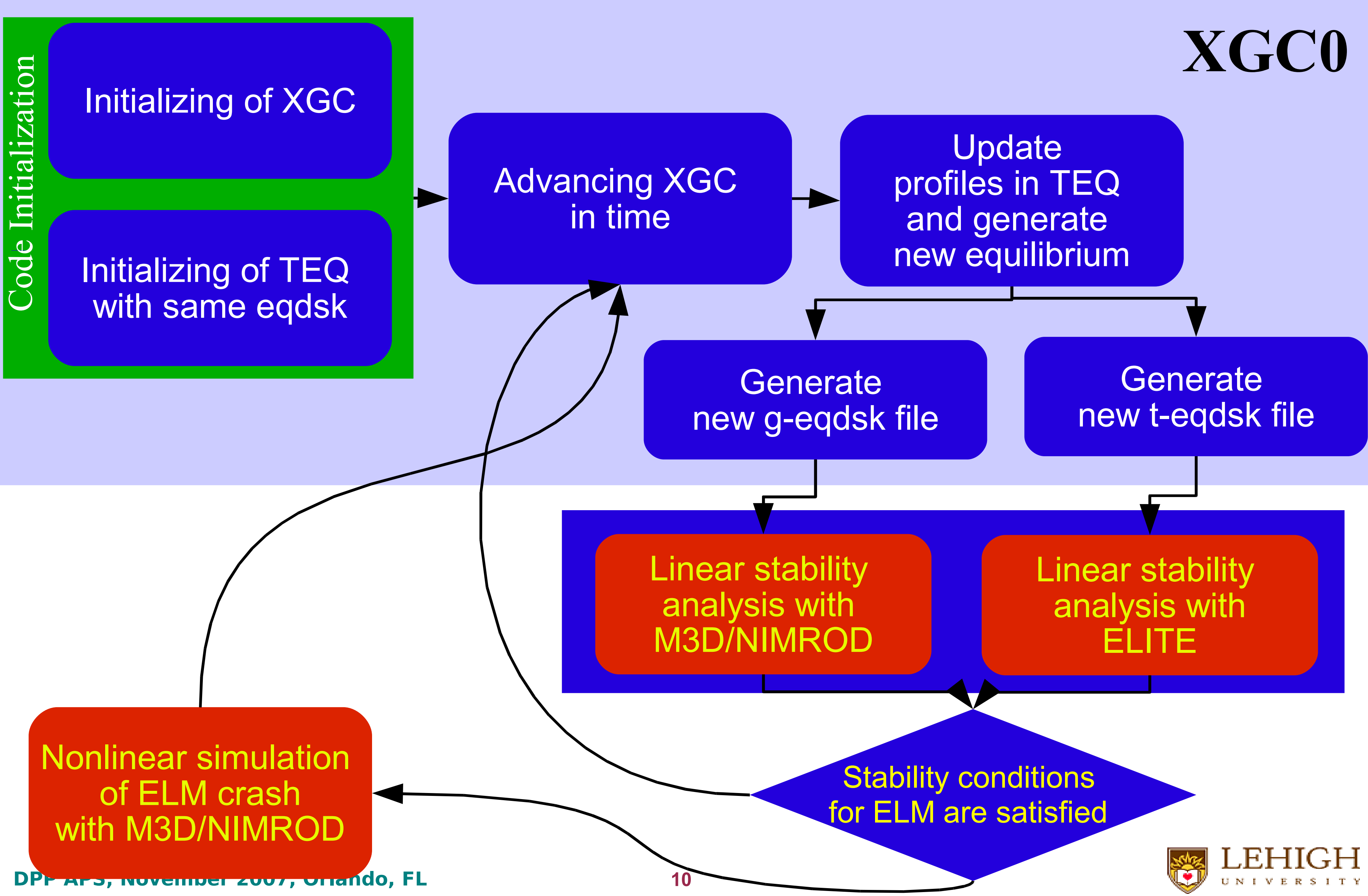
Collab

DEGAS2
Neutrals
Atomic physics

Plasma-Surface Interaction code

RF-edge interaction, energetic particles, impurity, radiation, **3D magnetic perturbation physics**, and core MHD effects are to be built into XGC0

XGC-M3D/NIMROD coupling



XGC0 Edge Kinetic Code

- **Long time simulation of kinetic equilibrium and transport**
- **5D guiding center dynamics**
- **1D solution for electric field: axisymmetric component of E_r**
- **Ion/electron/neutral, full-f**
- **Z_{eff} in the current version**
- **Conserving collisions**
- **$\Phi(\psi)$ electric potential solver**
- **XGC0 will integrate in all the other physics components**
- **XGC0 evaluates kinetic bootstrap current, and the corresponding Grad-Shafranov equilibrium B evolution**
- **Kepler integration framework for automatic coupling of XGC0-Elite-M3D is established for pedestal-ELM cycle**
- **Integration of DEGAS2 into XGC0 is to produce the first fully kinetic, edge plasma-neutral transport code**

XGC1 Edge Gyrokinetic Code

- Particle-in-cell 5D gyrokinetic code in f90
- 3D solution for electric field
- Integrated neoclassical and turbulence
- Unstructured mesh
- Realistic numerical g_eqdsk geometry with X-point
- Conserving collisions
- Full-f ions and electrons (neutrals with recycling)
- Can run in a mixed-f mode
- (Noise dissipation by physical collisions)
- Heat (particle) flux from core
- Particle source from neutral ionization
- (Heat/particle sink through transport, atomic physics and wall interaction)
- Solver: $E_r \neq 0$ at inside and $\Phi=0$ at wall

Collisions in XGC

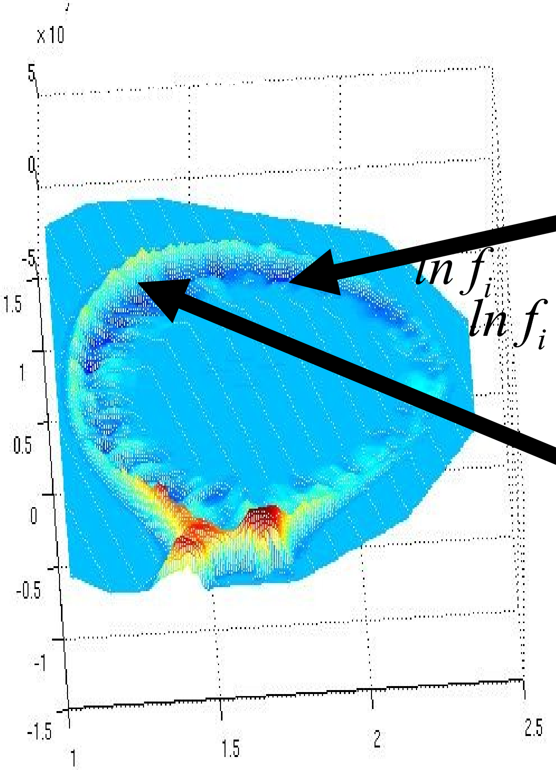
- **Conserving MC Ion-Plasma Coulomb Collision**
  - **Monte-Carlo collision with time evolving Maxwellian background**
  - **Conserving Collision algorithm : Conserving Energy and Momentum**

    Z.Lin, W.M. Tang, W.W. Lee, Phys. Plasmas, (1995)
    W.X. Wang, et. al. Plasma Phys. Contr. Fusion, (1999)
- **Ion-Neutral Collision**
  - **Monte Carlo 2D neutral transport**
  - **Elastic collision : velocity randomize**

  - **Charge exchange : velocity exchange**

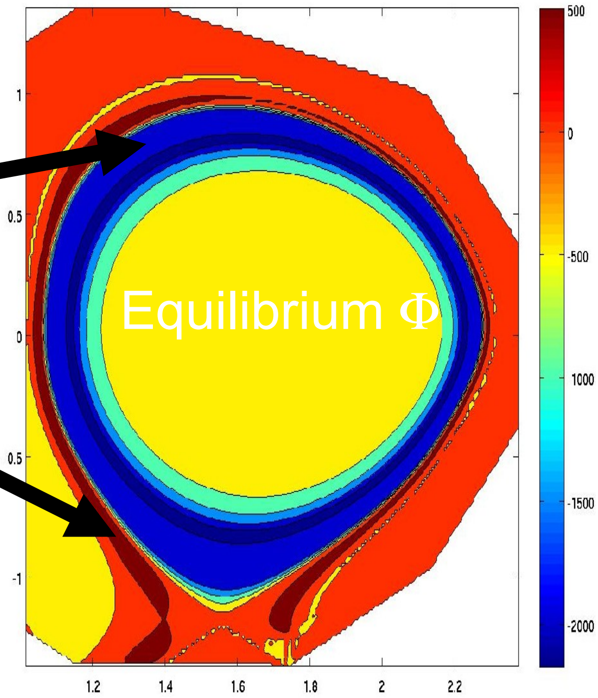
  - **Ionization : ion birth and neutral elimination**

XGC1 will Provide Turbulence Flux to XGC0



Negative potential well in H-layer (dark blue)

Positive potential hill in scrape-off (yellow-brown)



First 3D electrostatic solution across separatrix has been obtained from XGC1

2D neoclassical potential distribution has been extracted from 3D by toroidal averaging and poloidal-time smoothing

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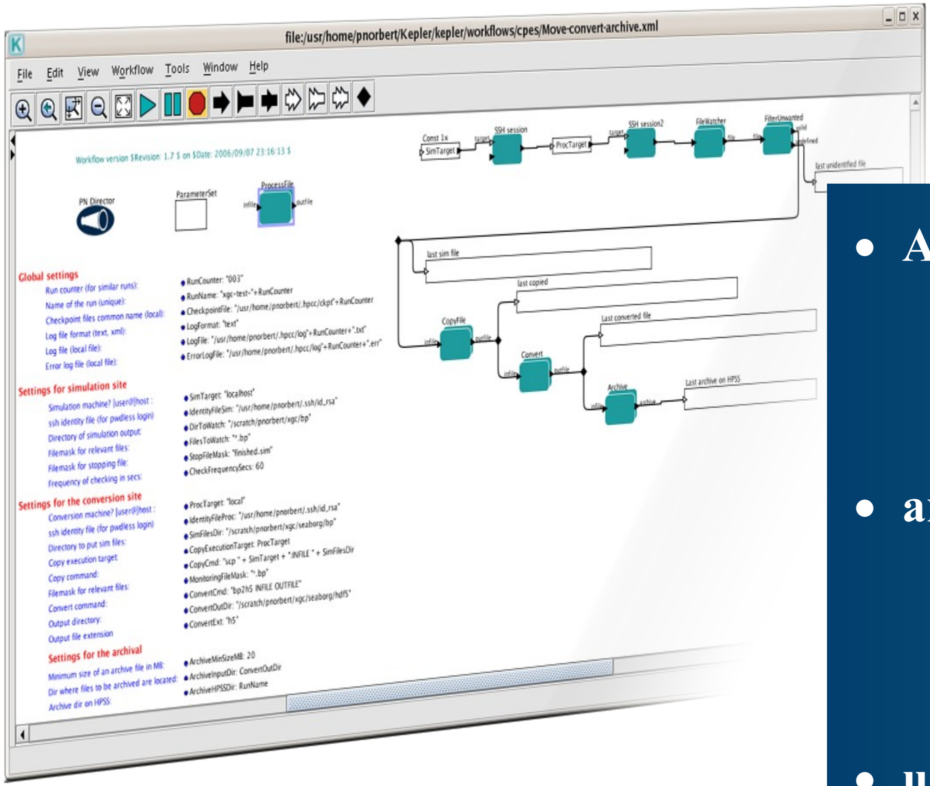
Workflow automation



Workflow version $Revision: 1.7 $ on $Date: 2006/09/07 23:16:13 $

Global settings

Run counter (for similar runs):	RunCounter: "003"
Name of the run (unique):	RunName: "xgc-test-"+RunCounter
Checkpoint files common name (local):	CheckpointFile: "/usr/home/pnorbert/.hpcc/ckpt"+RunCounter
Log file format (text, xml):	LogFormat: "text"
Log file (local file):	LogFile: "/usr/home/pnorbert/.hpcc/log"+RunCounter+".txt"
Error log file (local file):	ErrorLogFile: "/usr/home/pnorbert/.hpcc/log"+RunCounter+".err"

Settings for simulation site

Simulation machine? [user@]host :	SimTarget: "localhost"
ssh identity file (for pwdless login)	IdentityFileSim: "/usr/home/pnorbert/.ssh/id_rsa"
Directory of simulation output	DirToWatch: "/scratch/pnorbert/xgc/bp"
Filemask for relevant files:	FilesToWatch: "*.bp"
Filemask for stopping file:	StopFileMask: "finished.sim"
Frequency of checking in secs:	CheckFrequencySecs: 60

Settings for the conversion site

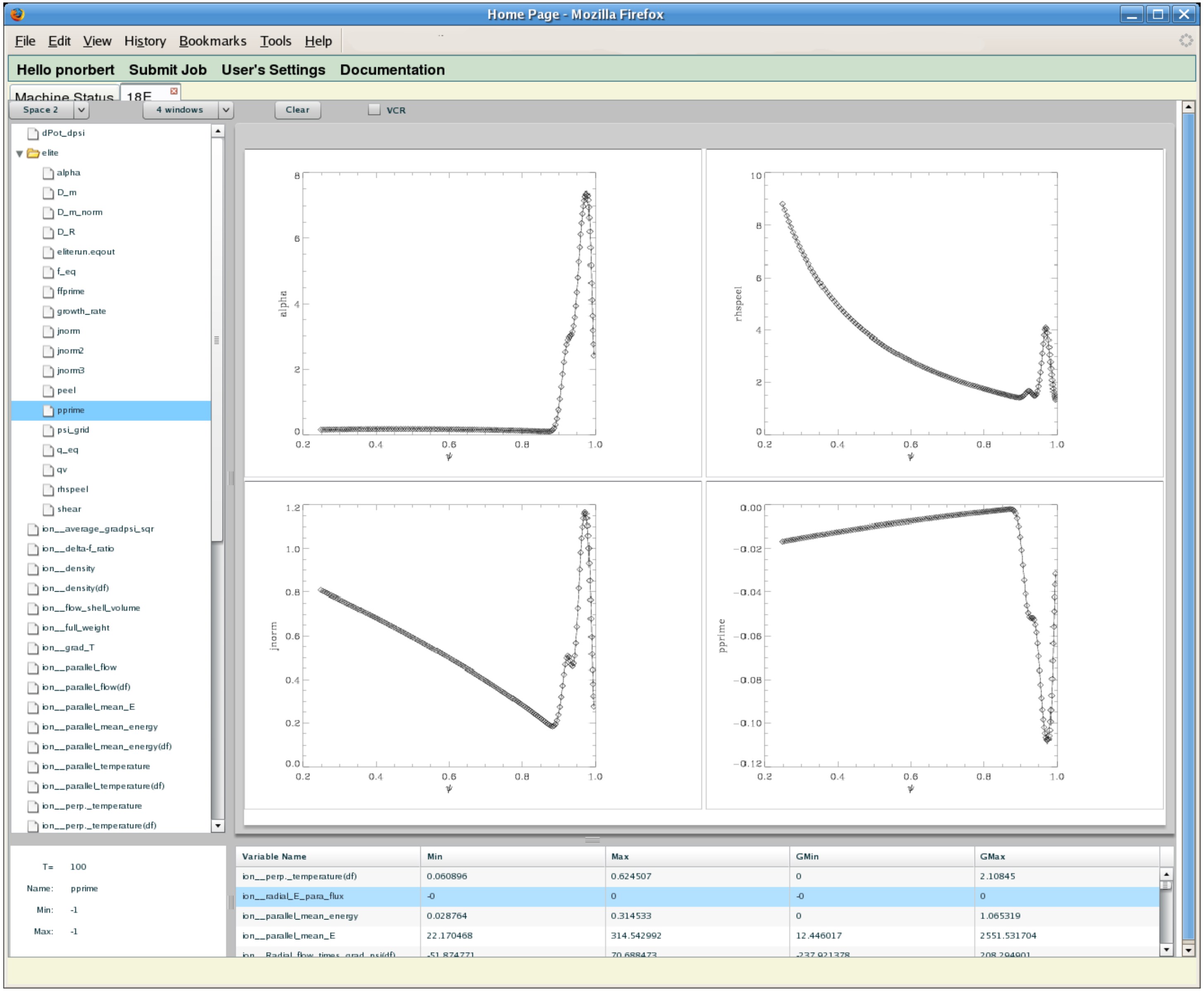
Conversion machine? [user@]host :	ProcTarget: "local"
ssh identity file (for pwdless login)	IdentityFileProc: "/usr/home/pnorbert/.ssh/id_rsa"
Directory to put sim files:	SimFilesDir: "/scratch/pnorbert/xgc/seaborg/bp"
Copy execution target	CopyExecutionTarget: ProcTarget
Copy command:	CopyCmd: "scp " + SimTarget + ":INFILE " + SimFilesDir
Filemask for relevant files:	MonitoringFileMask: "*.bp"
Convert command:	ConvertCmd: "bp2h5 INFILE OUTFILE"
Output directory:	ConvertOutDir: "/scratch/pnorbert/xgc/seaborg/hdf5"
Output file extension	ConvertExt: "h5"

Settings for the archival

Minimum size of an archive file in MB:	ArchiveMinSizeMB: 20
Dir where files to be archived are located:	ArchiveInputDir: ConvertOutDir
Archive dir on HPSS:	ArchiveHPSSDir: RunName

- Automate the **data processing** pipeline
  - transfer of simulation output to the e2e system, execution of conversion routines, image creation, archival
- and the **code coupling** pipeline
  - check linear stability and compute new equilibrium on the e2e system
  - run crash simulation if needed
- using the **Kepler** workflow system.
- Requirements for Petascale computing
  - Easy to use
  - Dashboard front-end
  - Autonomic
  - Parallel processing
  - Robustness
  - Configurability

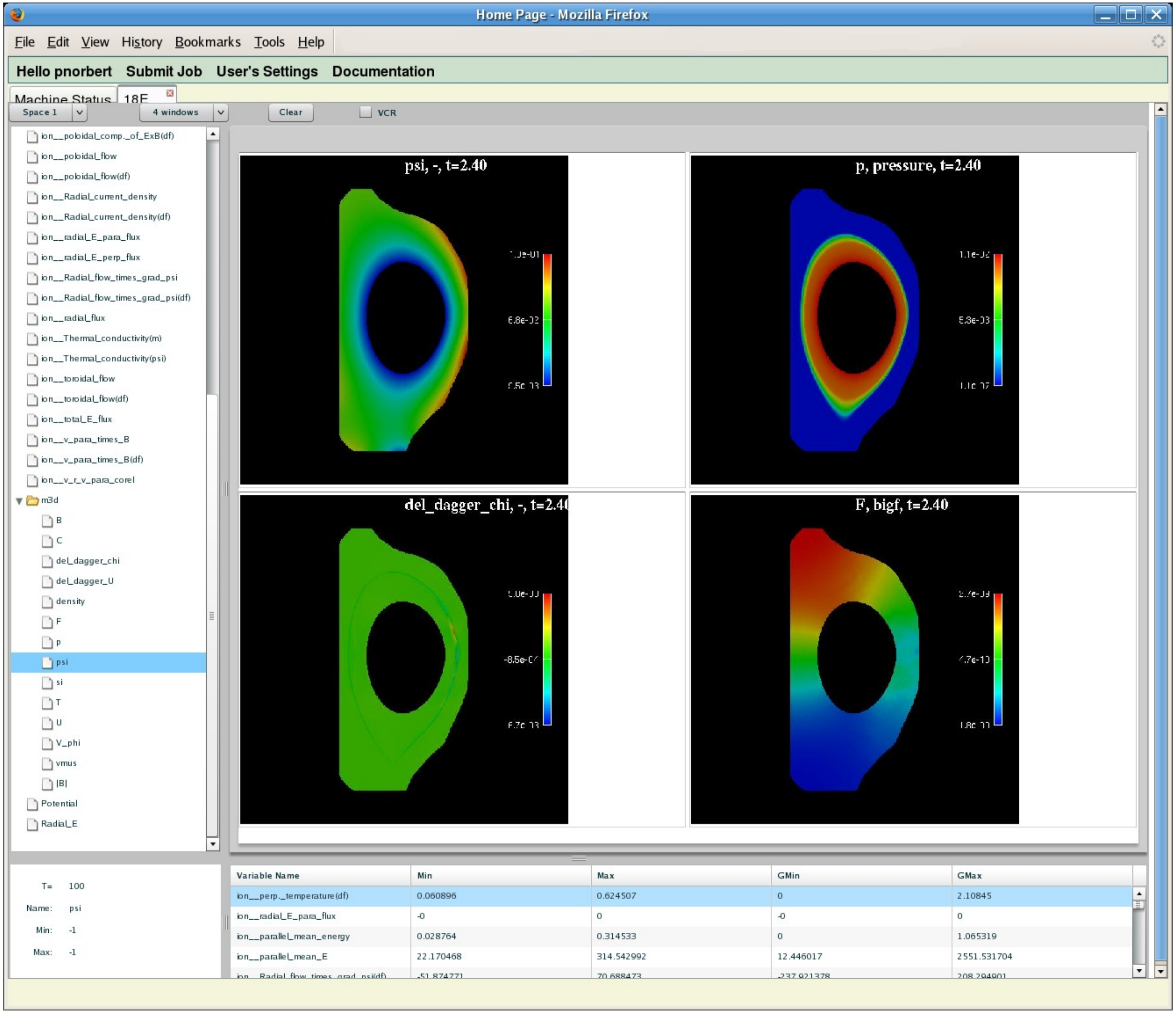
Monitoring ELITE output on dashboard



T= 100
Name: pprime
Min: -1
Max: -1

Variable Name	Min	Max	GMin	GMax
ion__perp._temperature(df)	0.060896	0.624507	0	2.10845
ion__radial_E_para_flux	-0	0	-0	0
ion__parallel_mean_energy	0.028764	0.314533	0	1.065319
ion__parallel_mean_E	22.170468	314.542992	12.446017	2551.531704
ion__Radial_flow_times_grad_psi(df)	-51.874771	70.688473	-237.921378	208.294901

Monitoring M3D output on dashboard



T= 100

Name: psi

Min: -1

Max: -1

Variable Name	Min	Max	GMin	GMax
ion__perp._temperature(df)	0.060896	0.624507	0	2.10845
ion__radial_E_para_flux	-0	0	-0	0
ion__parallel_mean_energy	0.028764	0.314533	0	1.065319
ion__parallel_mean_E	22.170468	314.542992	12.446017	2551.531704
ion__Radial_flow_times_grad_psi(df)	-51.874771	70.688473	-237.921378	208.294901

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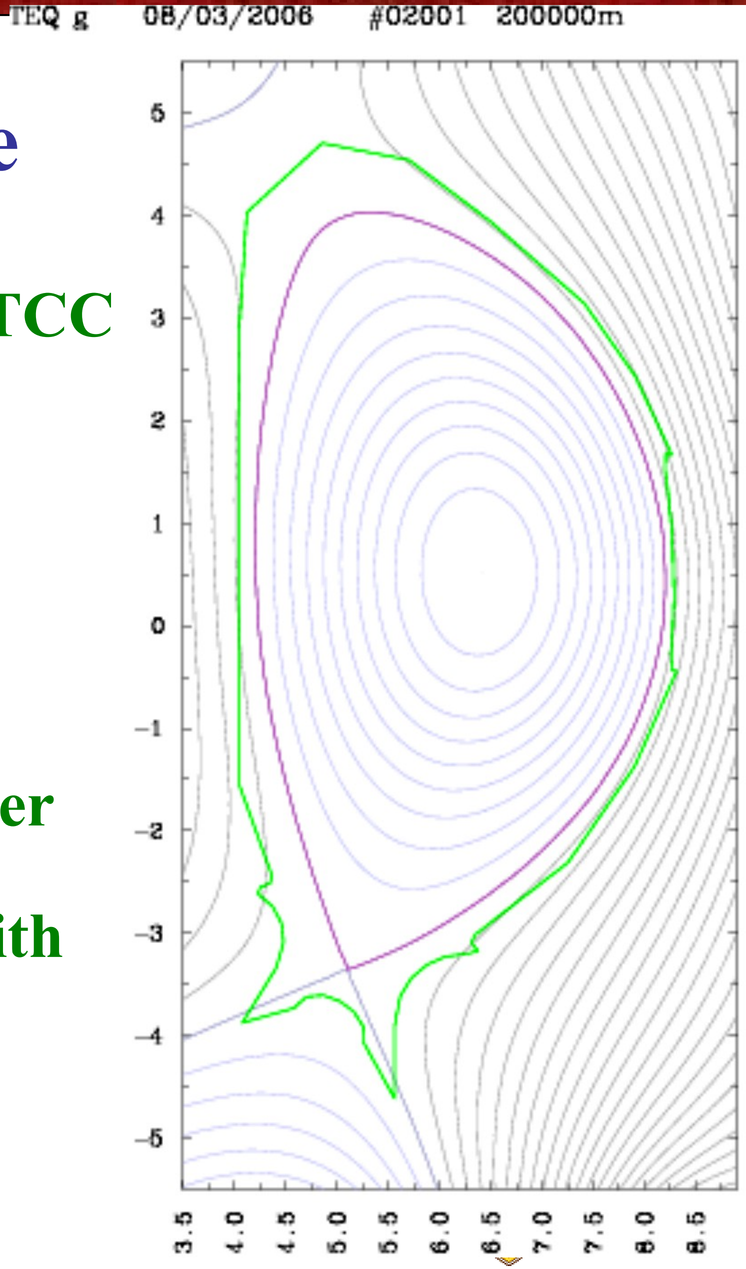
Generating Equilibrium for MHD Studies

- TEQ code — direct & inverse equilibrium solver
  - –Extracted from CORSICA code as NTCC module
  - –Can be used both for prescribed boundary and
    free boundary equilibria
  - –Parameterized pressure and current density profiles
  - –Free-boundary TEQ equilibrium solver applied to generate new equilibria, including scrape-off region, for use with non-ideal MHD NIMROD code



TEQ equilibrium solver in XGC

- **Advantages relevant to coupling with other MHD codes**
  - **TEQ module reads eqdsk files that can be easily converted from g-eqdsk files that are recognized by XGC code**
  - **TEQ module can generate g- and t-eqdsk files during dynamic updates of equilibrium in XGC code**
    - g-files are recognized by NIMROD code
    - t-files are recognized by ELITE code
- **Dynamic gyro-kinetic modeling with XGC code**
  - **Advanced 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 codes such as M3D and NIMROD**

Equilibria available in TEQ module

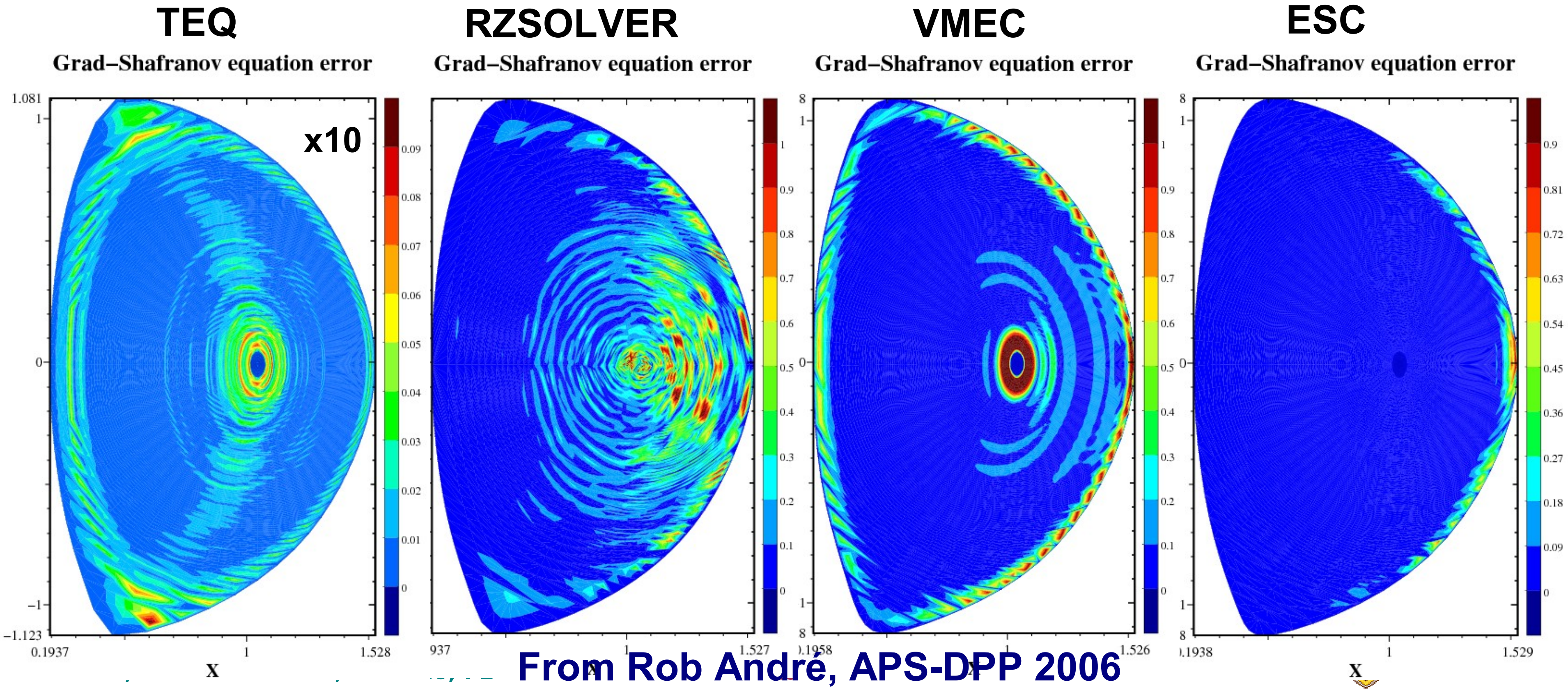
- **Initial equilibrium profiles that comes with the TEQ module are included in the XGC code**

  - **D3D**
  - **NSTX**
  - **CMOD**
  - **MAST**
  - **MAST-SN**
  - **MAST-DN**
  - **ITER**
  - **ITER_FDR**
  - **FIRE**
  - **IGNITOR_SOF**
  - **JET**
  - **SSPX_BCS**
  - **SSPX_BCM**
  - **KSTAR**
  - **MST**
  - **PEGASUS**
  - **PEGASUS_SNL**
  - **EAST_SNL**
  - **TFTR**

- **Caltrans code can be used to convert existing g-eqdsk files to TEQ ini files**
- **“DEADSTART” procedure is design to build new design initial configurations within**

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

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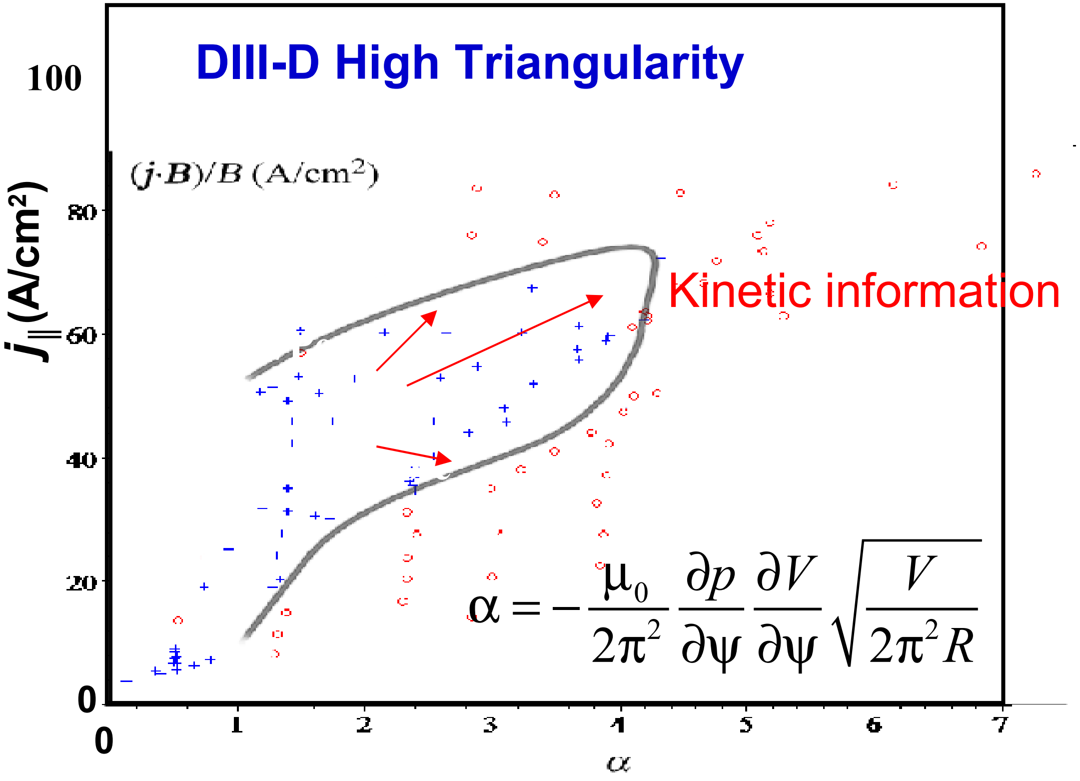
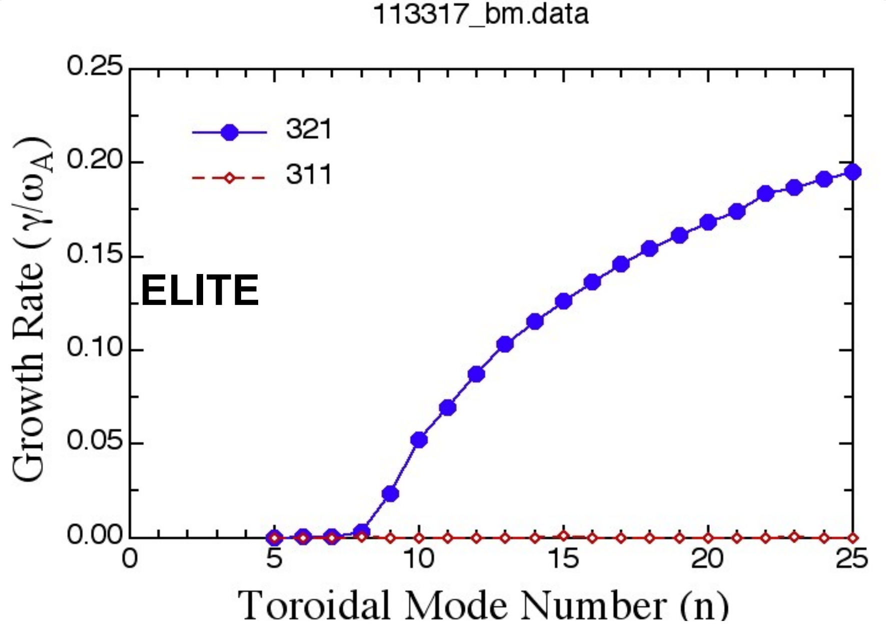
Coupling with the ELITE linear stability code

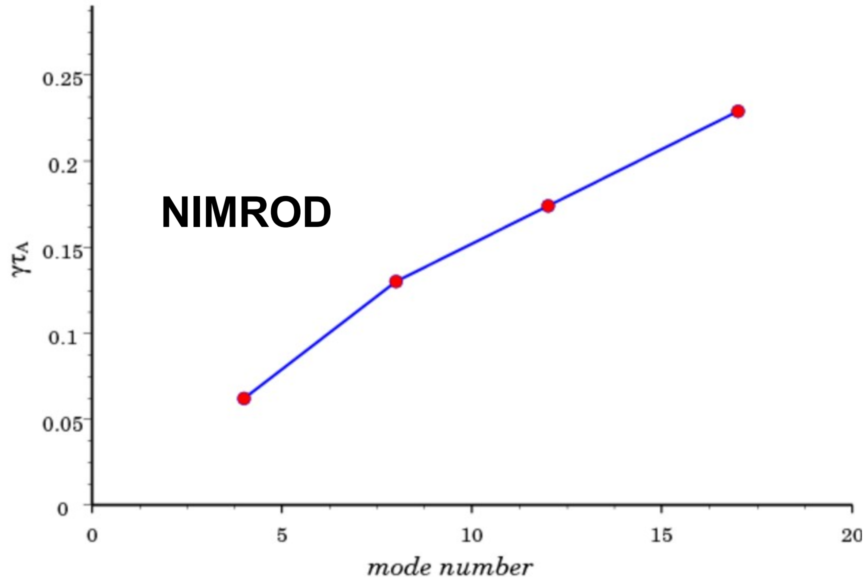
- ELITE code is provided by P. Snyder and H. Wilson
- Intermediate to high n (> 5) ideal MHD instabilities
- Extension of the ballooning formalism through two orders in 1/n
- Peeling-ballooning stability bounds



$$\alpha = -\frac{\mu_0}{2\pi^2}\frac{\partial p}{\partial \psi}\frac{\partial V}{\partial \psi}\sqrt{\frac{V}{2\pi^2 R}}$$

ELITE/NIMROD Benchmarking





- TEQ code was used to alter experimentally based equilibrium computed with EFIT code for the DIII-D discharge 113317 with well resolved pedestal area
- The growth rates computed in ELITE and NIMROD codes agree reasonably well for large toroidal mode numbers
- The ELITE code yields complete stabilization of modes with n<8, while the NIMROD code yields nonzero growth rate for these modes
- Except of this difference, the growth rates agree remarkably well in this case

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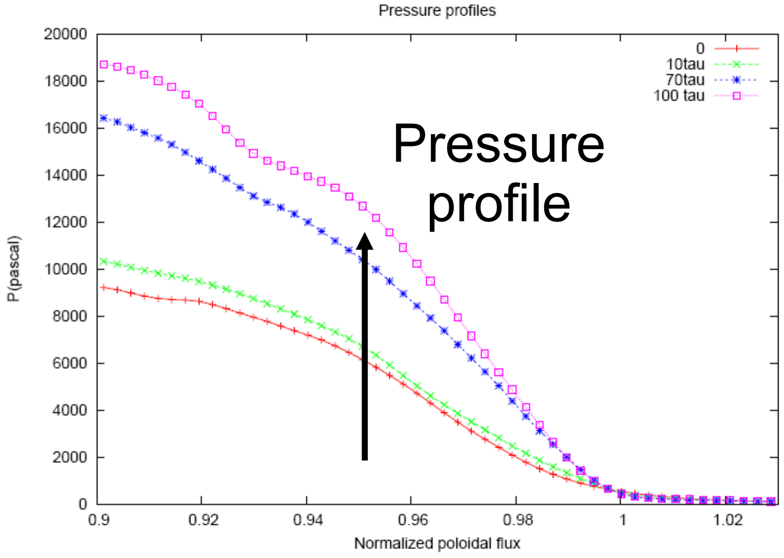
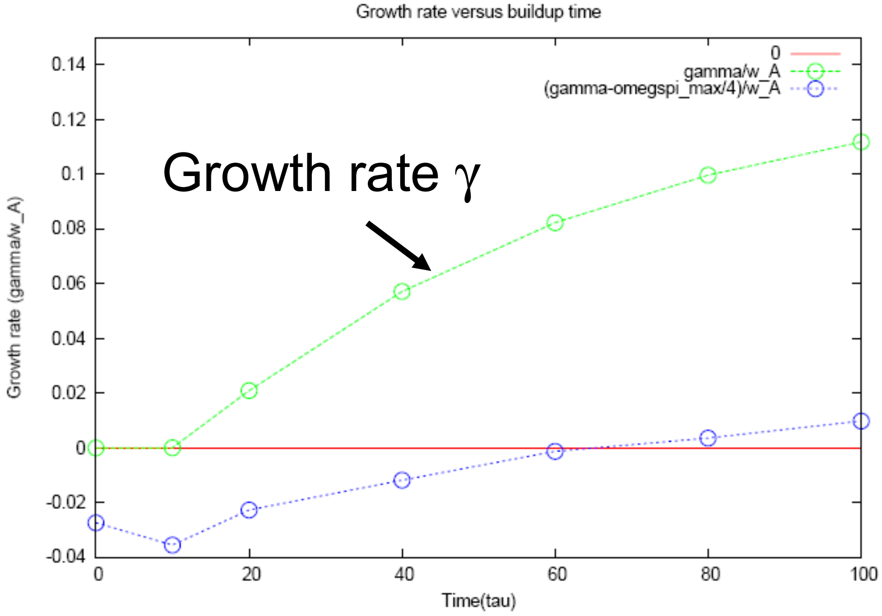
ELITE Code Monitors Peeling-Ballooning Stability Conditions

Pedestal buildup by XGC0



Pressure profile

ψ_N



Growth rate γ

Neoclassical dominant pedestal growth (D_{Anom}= 0.05m²/s, ballooning)

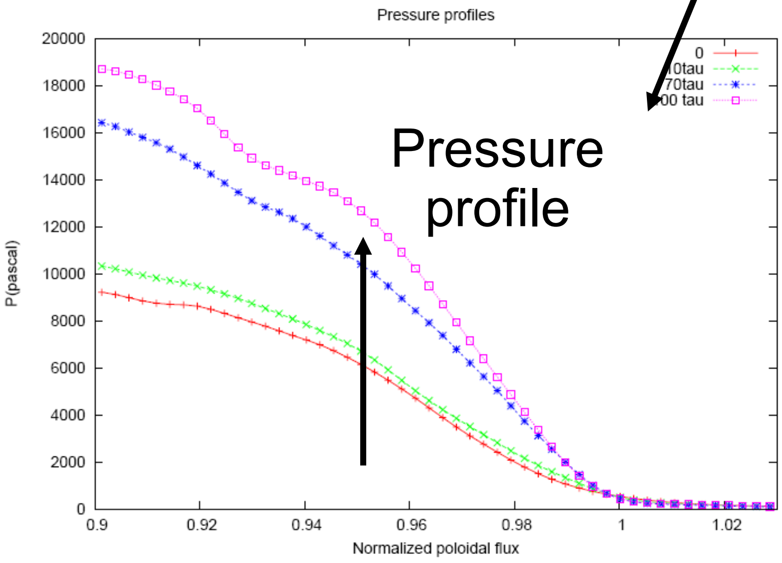
Type-I ELM unstable around 70τ

Coupled XGC0-MHD simulation of ELM cycle

Linear stability check (Elite)

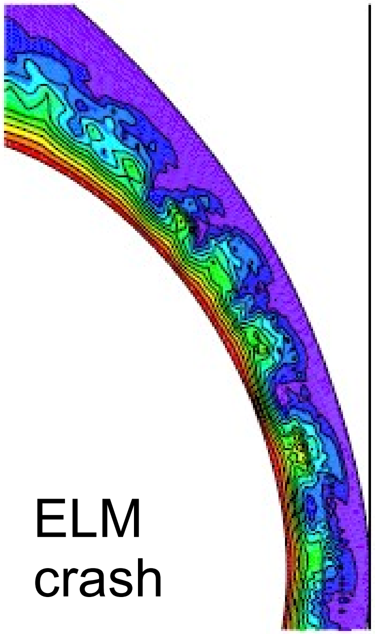
Pedestal buildup by XGC0

ELM crash by M3D

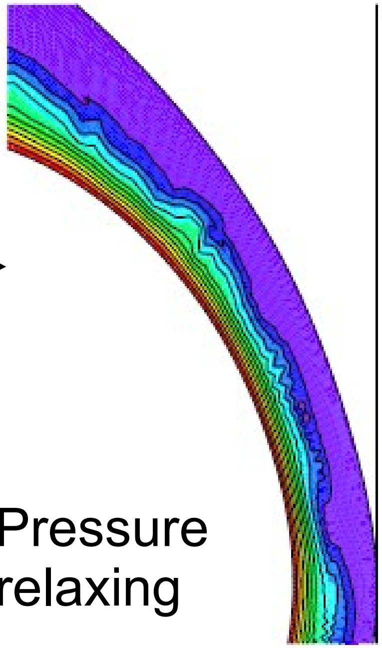


Pressure profile

ψ_N



ELM crash



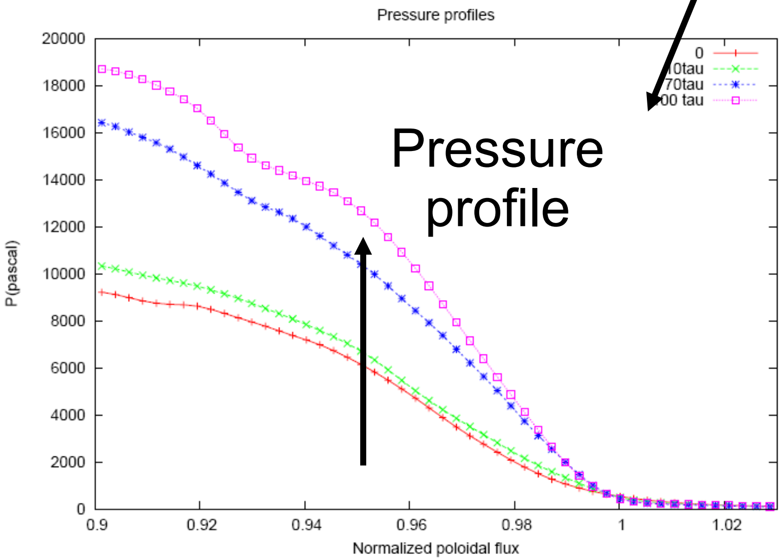
Pressure relaxing

Coupled XGC0-MHD simulation of ELM cycle

Linear stability check (Elite)

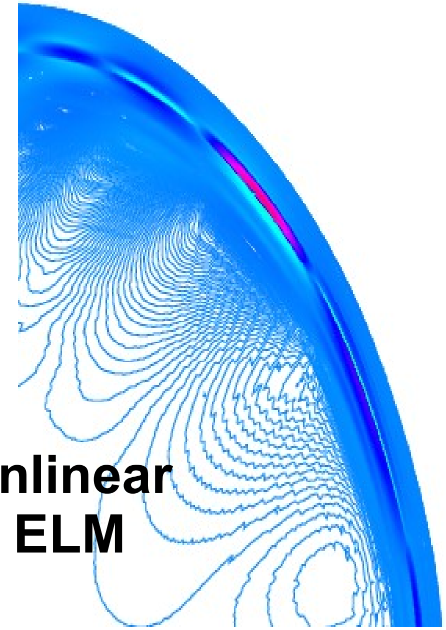
Pedestal buildup by XGC0

ELM crash by NIMROD



Pressure profile

ψ_N



early nonlinear stage of ELM crash

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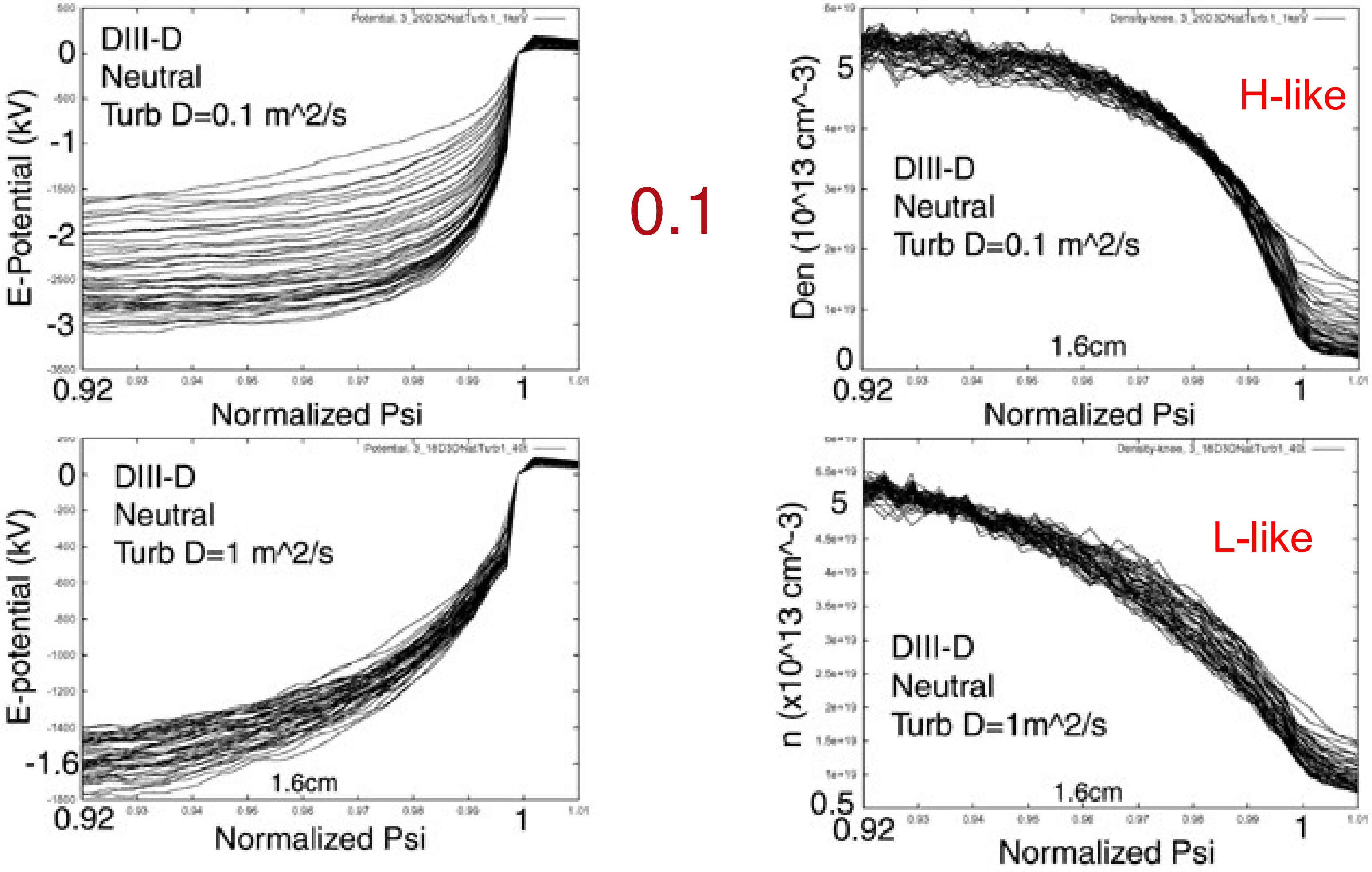
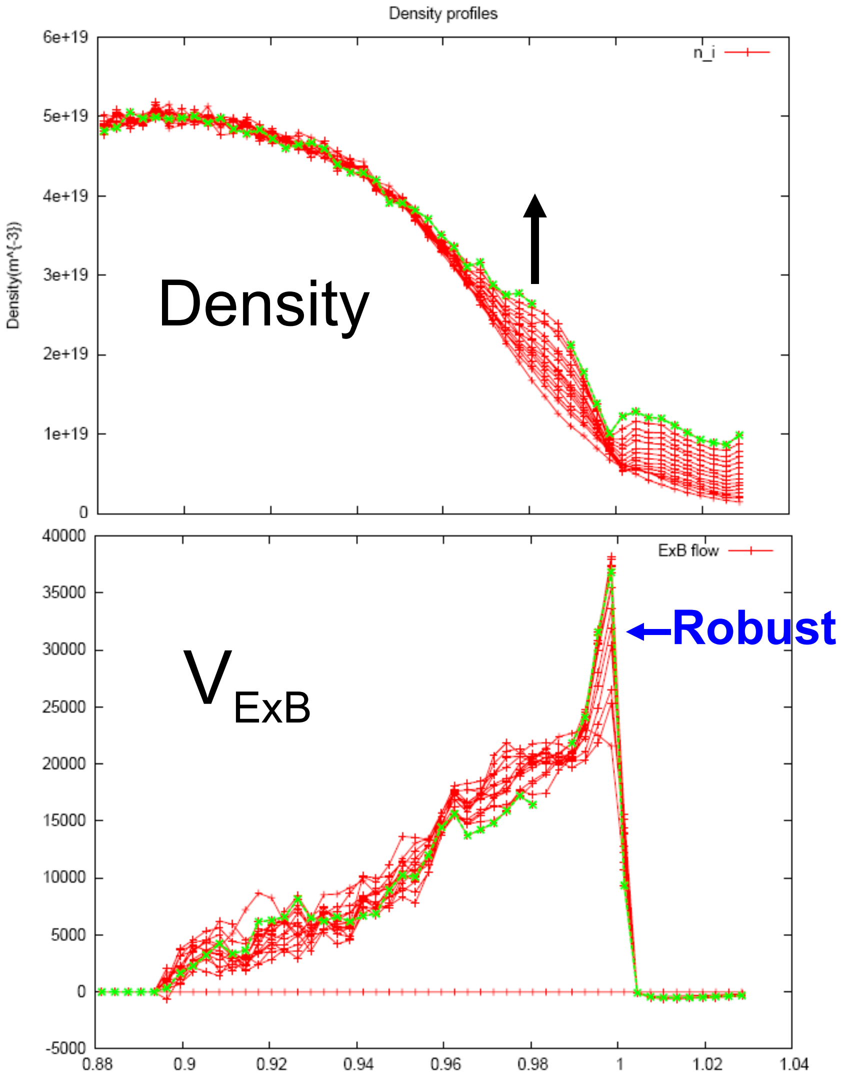
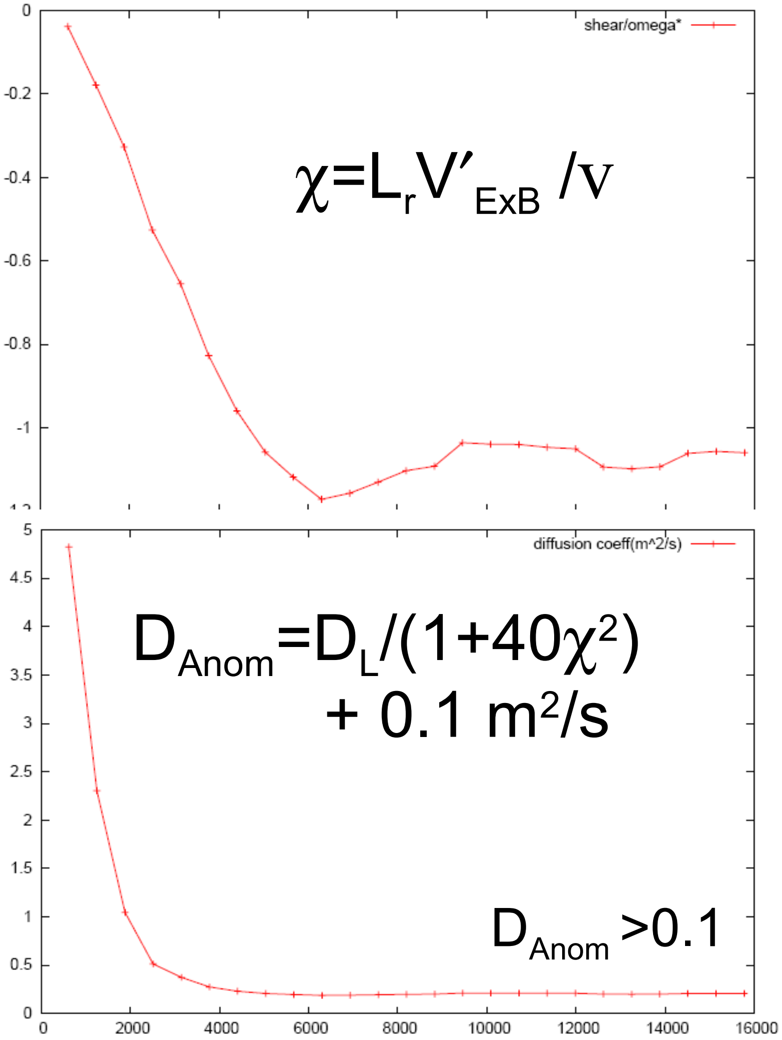
Effect of Anomalous Transport



Model for Anomalous Diffusion XGC0





$\chi = L_r V'_{ExB} / \nu$

$D_{Anom} = D_L / (1 + 40\chi^2)$
$+ 0.1\ m^2/s$

$D_{Anom} > 0.1$

Summary

- Recent advance in the CPES project are presented
- XGC framework for code couping
  - ☐ Guiding center XGC0 code is used as a kernel for plasma edge simulations
  - ☐ Direct equilibrium solver TEQ generate new equilibrium solution as plasma profiles evolve in XGC0
  - ☐ Ideal MHD linear stability code ELITE is used to verify peeling-ballooning stability properties of the plasma profiles computed with XGC0
  - ☐ M3D and NIMROD code used for modeling of evolution of ELM crashes
  - ☐ Gyro-kinetic XGC1 code will provide information on anomalous fluxes to XGC0
- All codes are coupled through the Kepler workflow
- Effects of anomalous transport are studied with XGC0
  - ☐ Formation of flow shear profiles at the plasma edge is associated with the formation of edge transport barrier

Last Slide