Theory and Simulation Research for KSTAR at NFRI

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KSTAR

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Contents

Introduction

➢ Two projects for theory and simulation research at NFRI

- Internal theory & simulation project

  - One of KSTAR research projects
  - covering Pedestal, MHD stability, Operation scenario, Divertor/SOL areas
  - now, about 8 regular members & 6 graduate students from SNU, KAIST etc.

- WCI (world-class-institute) project

  - A government-support project for 5 years (2009.12 – 2014. 11)
  - mostly focusing on Turbulent transport, including transport barrier, area
  - now, about 11 regular members (Korean: 7, Foreigner : 4)

Pedestal and ELM control

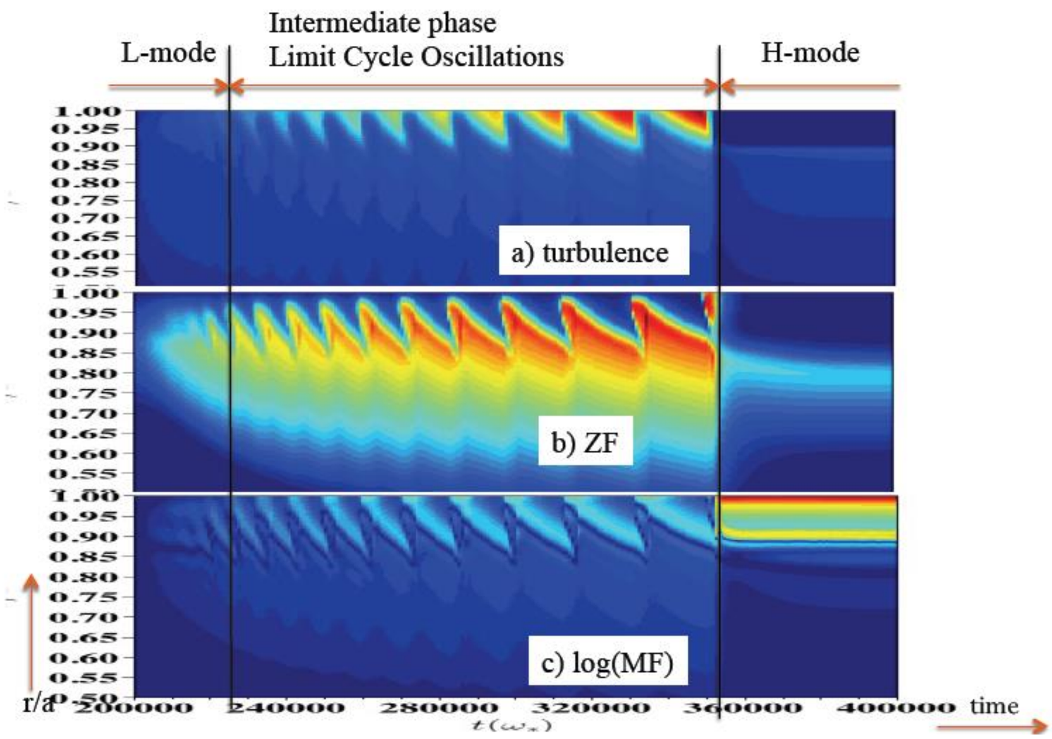
- Strong emphases in relation to the H-mode and ELM control experiments in KSTAR, and also as ITER urgent issues

- trying to cover most sub-areas with a more self-consistent, integrated modeling

  * L-H transition trigger & power threshold
  * Pedestal build-up process
  * Pedestal stability and structure
  * Nonlinear ELM behavior
  * ELM control by RMP, pellet etc.

L-H transition and power threshold

- One of the main research topics of the WCI group
- Focusing on the 1.5D predator-pray model, involving turbulent intensity, ZF, MF



- Reproduce some features of L-I-H transition
- **I-phase** identified as a multi-predator-prey oscillations of ZF, mean flow and intensity
- Oscillating **ZF as a trigger** to L-H transition

- trying to do a more self-consistent simulation with the study of power threshold scaling
- A more accurate calculation of neoclassical Er (by grad-Pi or ion orbit loss) also underway

Pedestal build-up

- Recent experiments show pedestal structure change during build-up phase, such as
  - inward penetration of width with the early saturation of gradient
  - different pedestal width evolution of n, T, V_t etc.

- A simple 1.5D transport code under development to model the build-up process
  - in the consideration of ExB shear stabilization & KBM-like mode excitation

$$\frac{\partial}{\partial t} n + \frac{1}{r}\frac{\partial}{\partial r}\left(r D_n \frac{\partial n}{\partial r} \right) = S_n \qquad (n_e = n_i)$$

$$\frac{\partial}{\partial t} T + \frac{1}{r}\frac{\partial}{\partial r}\left(r \chi_i \frac{\partial T}{\partial r} \right) = Q_T \qquad (T_e = T_i)$$

$$\frac{\partial}{\partial t} V_t + \frac{1}{r}\frac{\partial}{\partial r}\left(r \chi_\phi \frac{\partial V_T}{\partial r} \right) = P_V$$

where

$$D_n = D_{neo} + \frac{C_n \gamma_{lin}^{max}}{1 + C_E |\hat{\gamma}_{ExB}|^2}$$

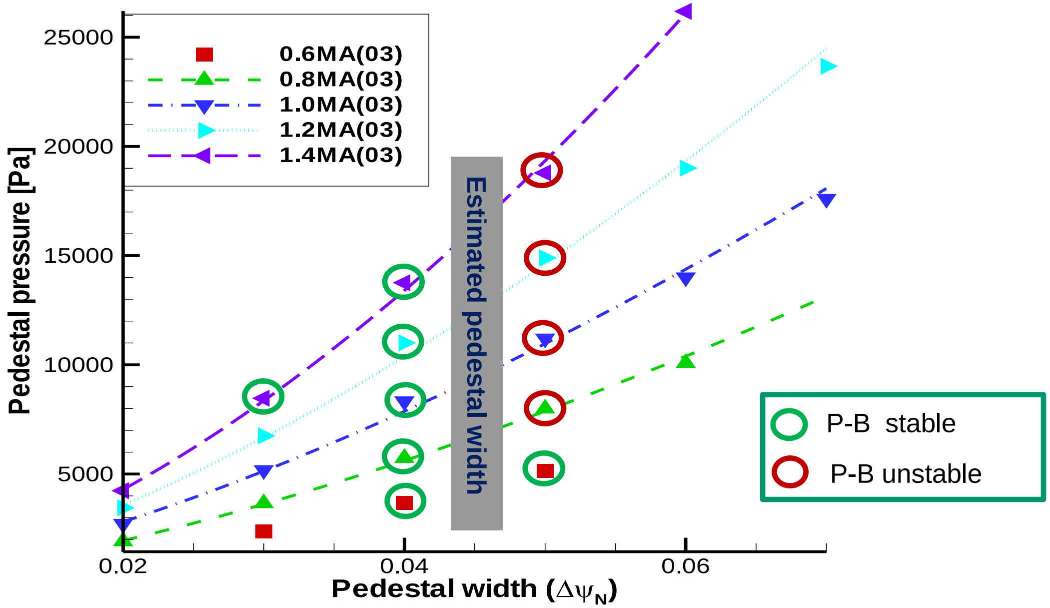
with γ_{lin}^{max} the maximum linear growth rate, and $\hat{\gamma}_{ExB}$ the ExB shearing rate

- Also, a flux-driven simulation using the global BOUT++ code underway for a more self-consistent calculation of the pedestal build-up process including turbulence dynamics

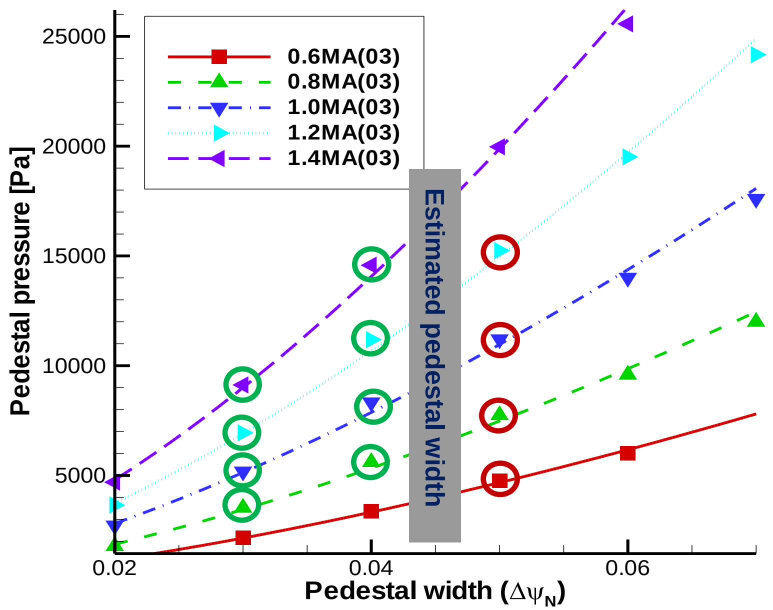
Pedestal stability and structure

- Particularly important from its close relevance to the global performance
- A more theory-based model, EPED one, proposed recently for the pedestal structure
- A predictive calculation of KSTAR pedestal structure done using the EPED model with a more detailed study on various parameter dependence (I_p, B, n, ν*, shape etc.)

(a) I_P dependence at a fixed B_T = 2T



(b) I_P dependence at a fixed q_{95} = 3.5

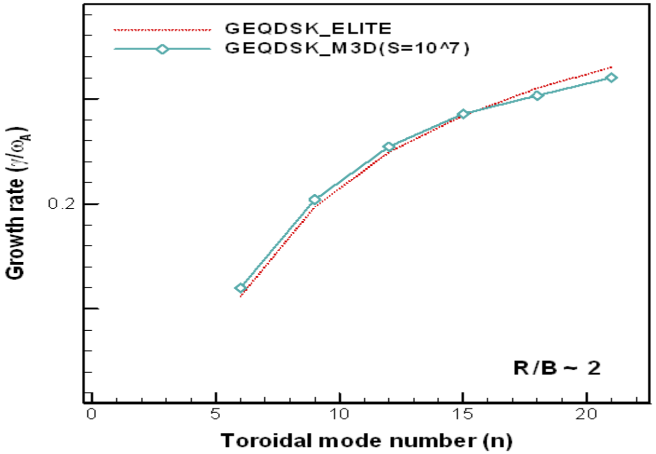


- Pedestal height rapidly increases with I_P ($\propto I_P^{1.5}$) => an important role to $\tau_{E,H} \propto I_P^{0.97}$
- Pedestal width almost independent of I_P => no relevance to poloidal ion Lamar radius

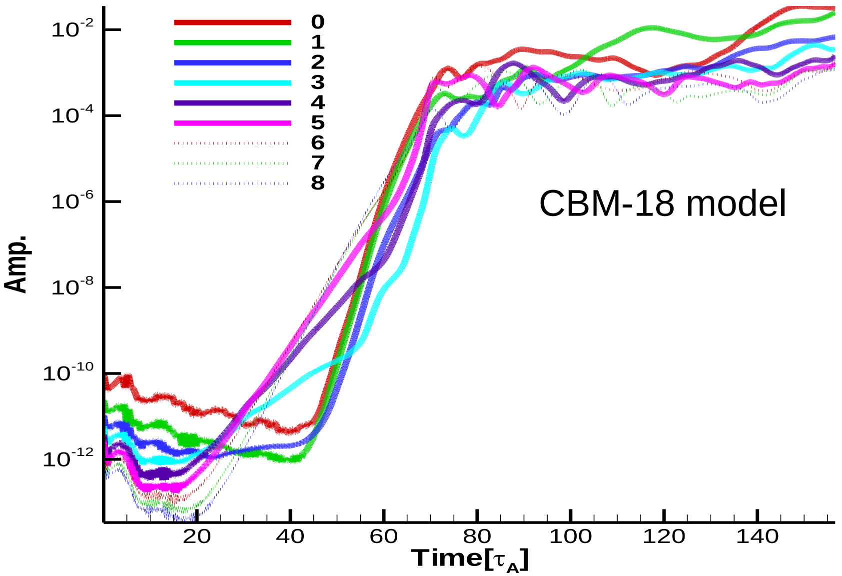
Nonlinear ELM behavior

- ELM is believed to be due to the destabilization of the P-B mode, but still not clear
  - how the nonlinear destabilization occurs
  - what is the origin of different ELM types (type-I, II, III, small ELMs etc.)
  - how ELM behavior change occurs with various ELM control tools

- Nonlinear simulation started using M3D & BOUT++ (in collaboration with PPPL/LLNL)
  - linear benchmark done first between M3D-ELITE for the CBM18 circular plasma
  - nonlinear simulation being performed for the CBM18 & D-shape KSTAR plasmas



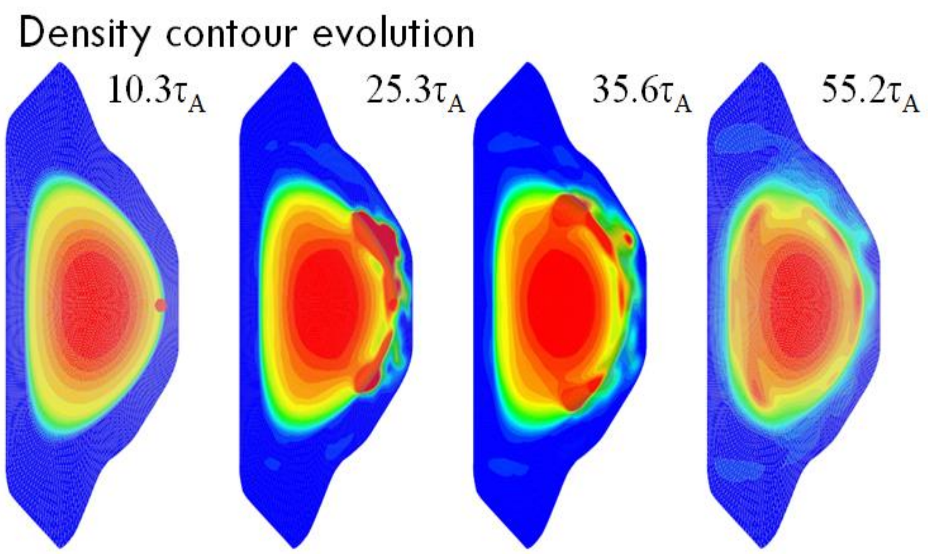
Relatively good agreement between M3D and ELITE codes



Dominant mode changes from medium-n to low-n during the nonlinear evolution

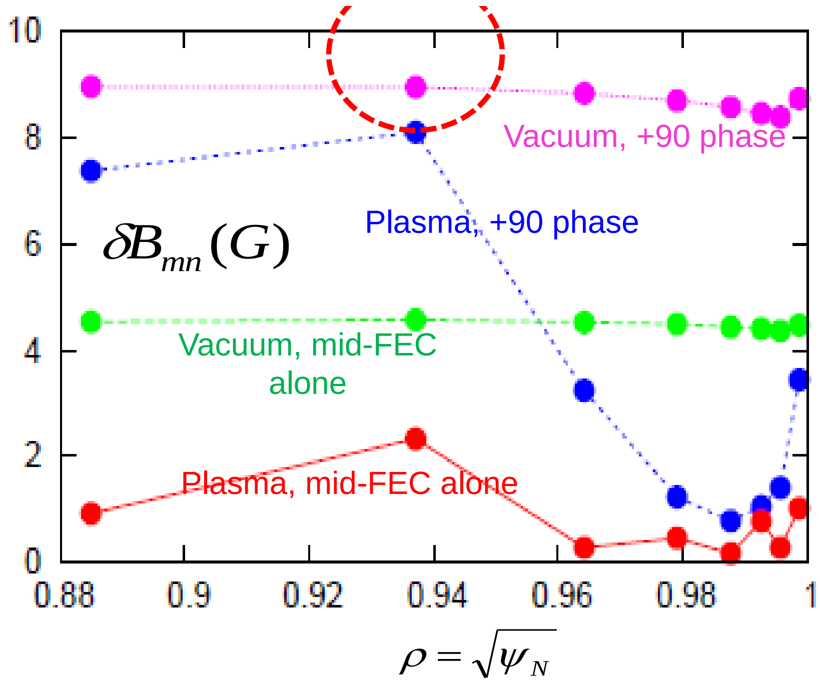
ELM control (Pellet, RMP etc.)

- Pellet pace-making : a preliminary simulation done for the KSTAR plasma model using M3D



- ELM generation observed with pellet injection

- RMP control : RMP field penetration calculated for KSTAR plasma using XGC0 + M3D codes



- Strong shielding occurs, except near pedestal top in the +90 phase

$\Rightarrow$ may explain why RMP suppression observed only in +90 phase?

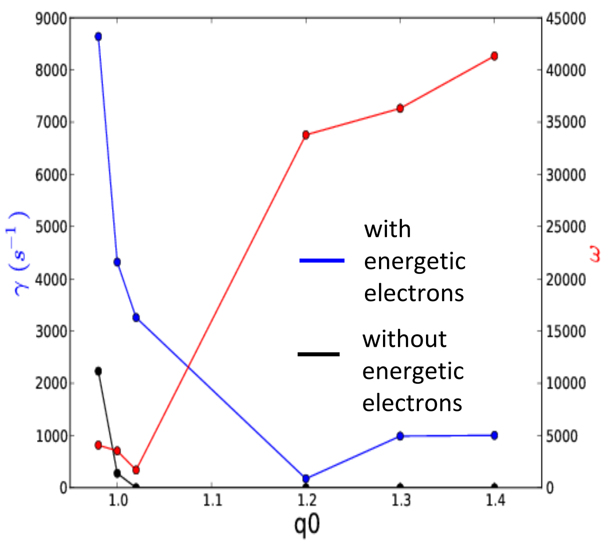
MHD Stability and Energetic Particles

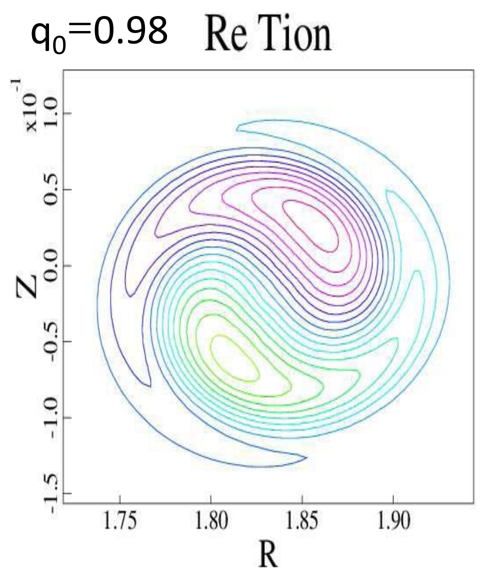
- Now, focusing on the subjects related to the KSTAR initial experiments, with relatively small manpower

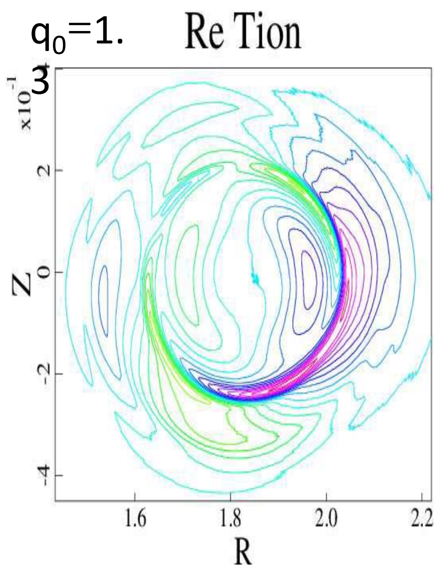
  * Sawtooth and internal MHD modes with ECH/ECCD effect
  * Disruption load and characteristics in KSTAR model
  * Fast ions loss with 3D perturbed field

Sawtooth & Internal MHD modes with ECH/ECCD effect

- Several interesting behaviors observed with ECH/ECCD in KSTAR
  - Dual flux tubes in the core of sawtoothing plasma [G.S. Yun et al, PRL(2012)]
  - Excitation of internal MHD modes, as a possible source of rotation damping [J. Seol et al, PRL(2012)]
  - Destabilization of 2/1 tearing mode during ramp-up (H.H. Lee et al., recently accepted in PRL)
- These believed due to energetic electron itself or change of q-profile
- A simulation study started using NIMROD code to see the energetic electron effect
  - similar method with the energetic ion case, but with the change of mass and charge
- Up to the artificial M_e>0.01M_i, no big difference between energetic ions and electrons, and some destabilization of internal MHD mode observed near q_0 ~1

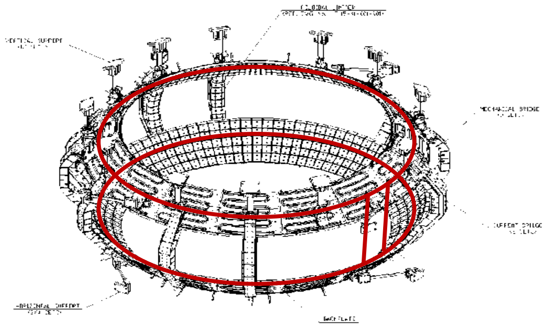




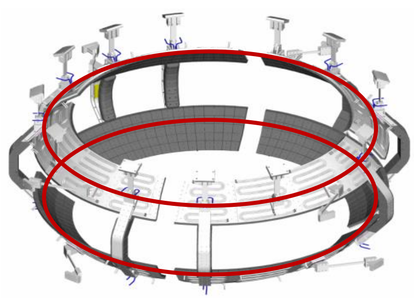


Disruption load and characteristics in KSTAR

- KSTAR passive stabilizer modified to no saddle structure during the final fabrication phase
- Disruption simulation done using TSC to estimate the load for the new structure
  - about one order increase in growth rate, while about 6 times decrease in vertical force

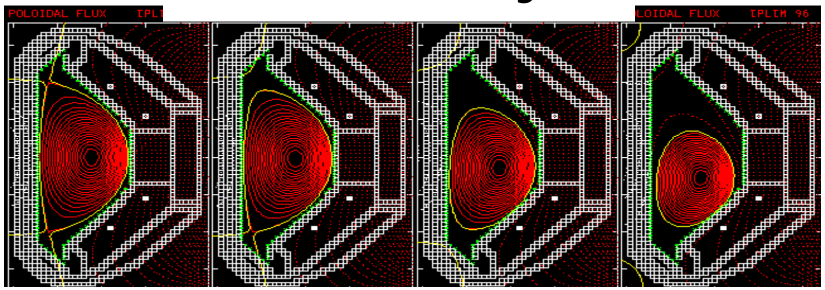


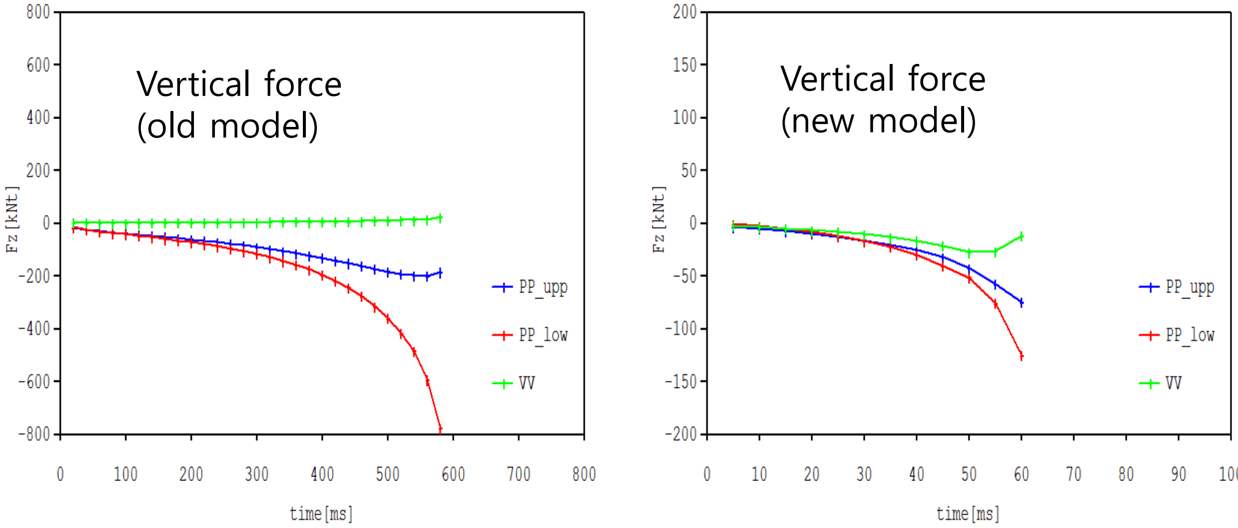
Saddle loop with current bridge



No saddle

VDE simulation using TSC





- A more detailed 3D simulation using M3D code to be performed (in collaboration with PPPL)

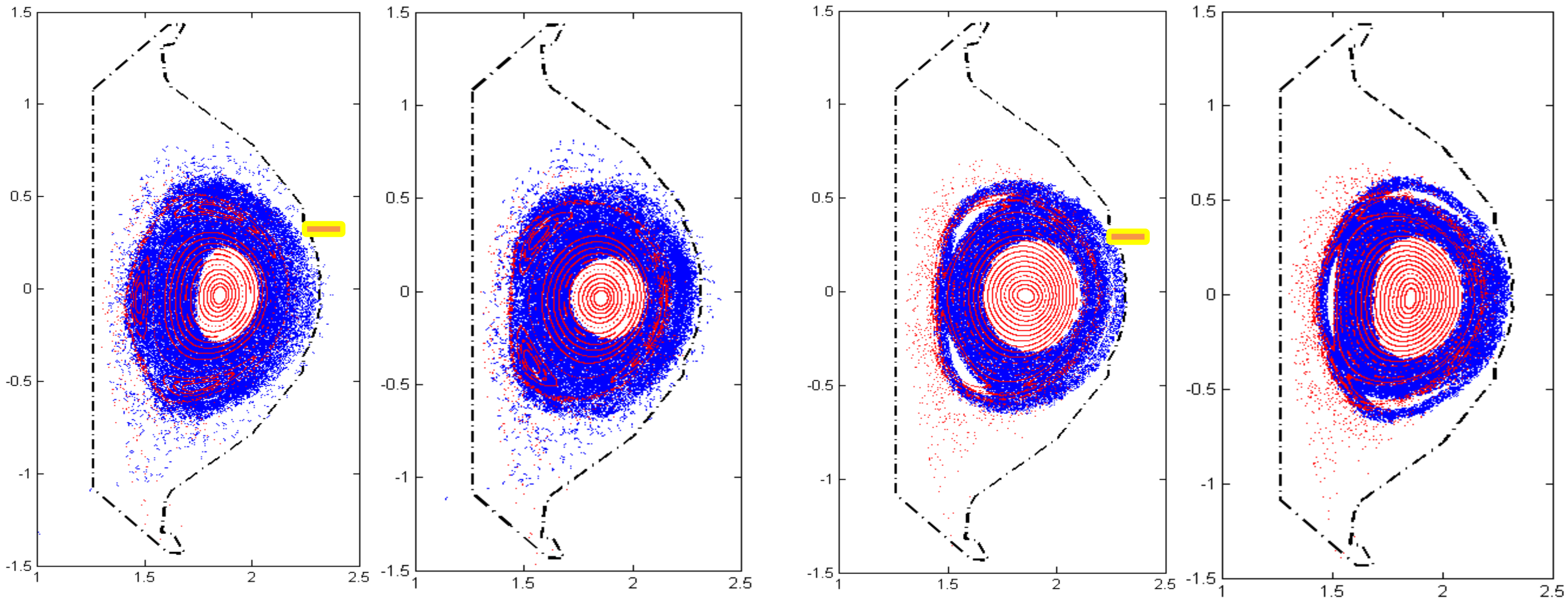
Fast ions loss with 3D perturbed field

- Experimental study being performed in KSTAR for the fast ions loss due to the external applied edge magnetic field in relation to ELM control by RMP

  - fast ions orbit being calculated using the Lorentz-orbit code, to analyze the data

Shot# 9056, near t=5.0sec

Shot# 9092, near t=6.0sec



C-port (FILD position)

K-port (opposite position)

C-port (FILD position)

K-port (opposite position)

- Various energetic particles driven modes being also observed in KSTAR
  - Linear stability analysis and nonlinear simulation study to be performed soon

Operation Scenario and Divertor/SOL

- Now, focusing on the near-term KSTAR operation scenarios, in relation to the upgrade of KSTAR heating/CD & divertor/fueling systems

  * Hybrid scenario and heating/CD optimization for the 2nd phase
  * Detached divertor operation

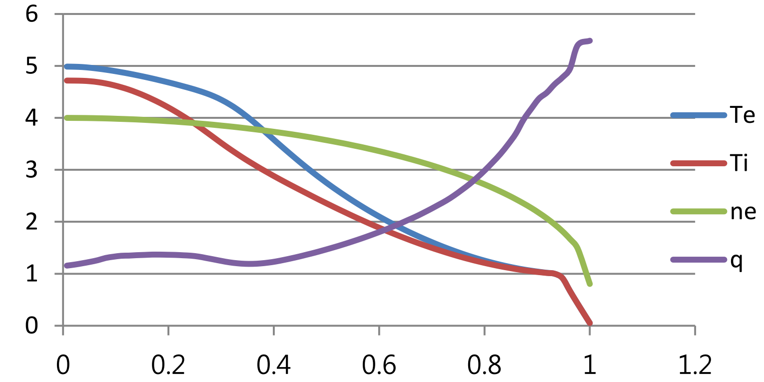
- Relatively small manpower, particularly in divertor/SOL area

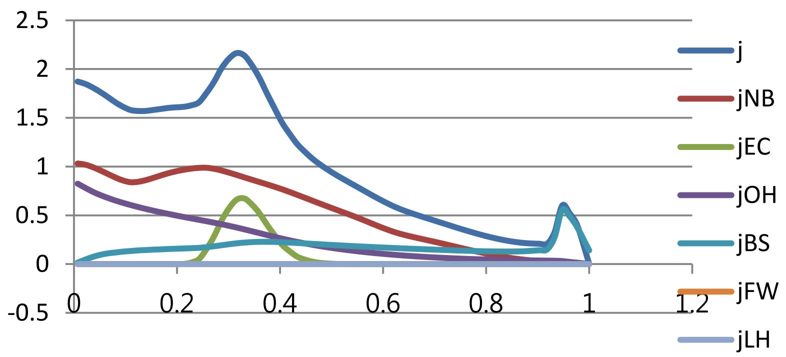
Hybrid scenario & Heating/CD system optimization

- Some design issues in relation to the upgrade of KSTAR heating/CD systems
  - NBI2 : on-axis or off-axis, co or counter
  - LHCD : optimum $n_{||}$ value for the CD efficiency maximization

Hybrid scenario modeling by using CRONOS

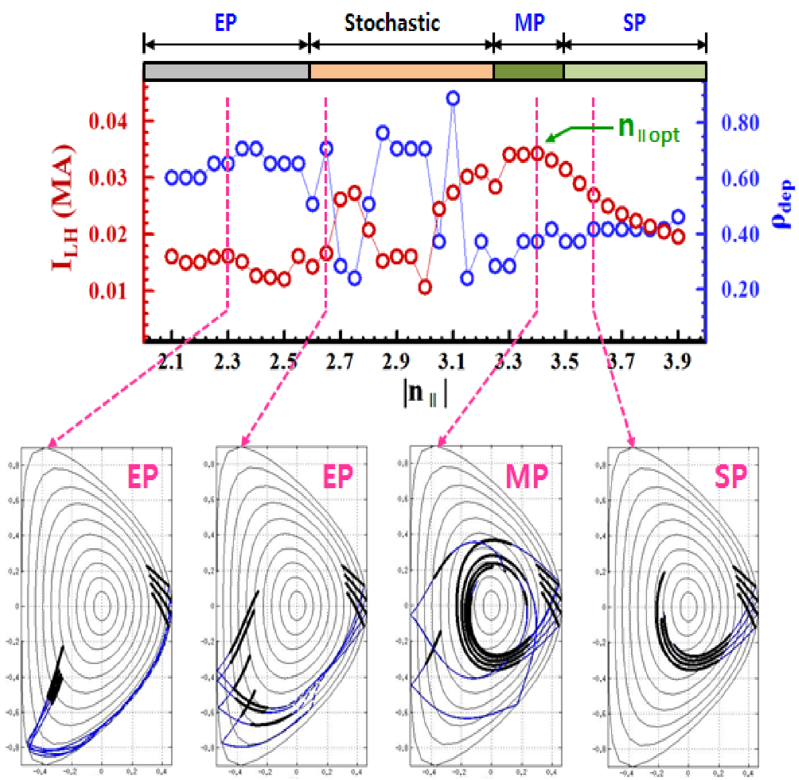
(for P_{NBI} = 4MW(co, on)+2MW(co, off-axis), P_{ECH} = 2MW)



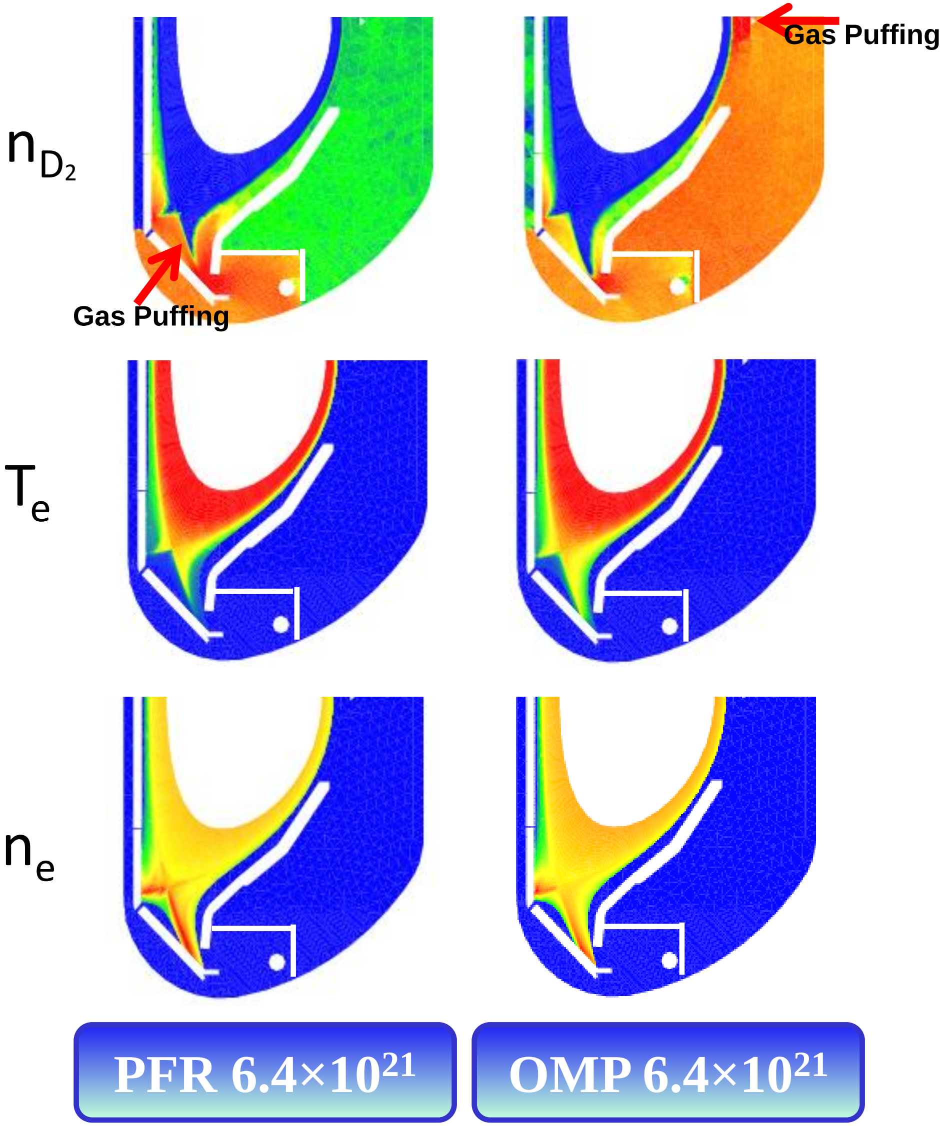


KSTAR LHCD calculation by using C3PO/LUKE

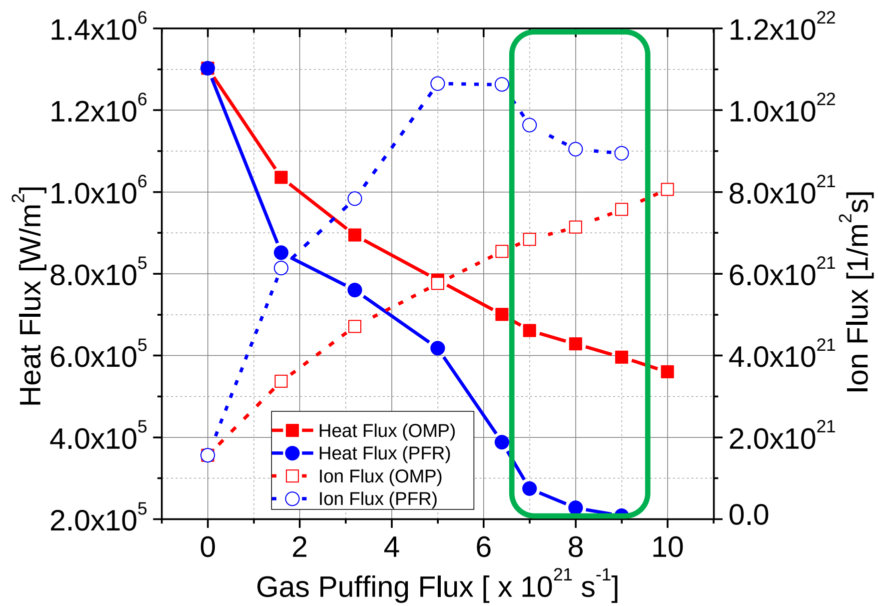
(target KSTAR plasma: n_e=5.0, I_P=1.0, B_T=2.0, P_{NBI}=3.5, P_{EC}=1.0, and P_{LH}=0.5)



Detached divertor operation & Gas-puffing system optimization



Average Flux on the Outer Divertors



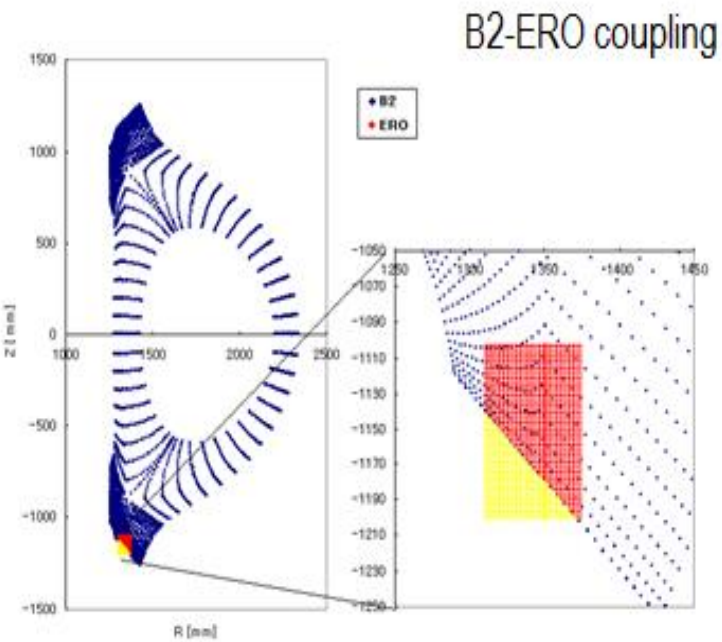
- Gas puffing on the PFR region is attractive to control neutral particles outside passive plates.
- When gas puffed on the PFR region, Heat flux decreased more effectively compared with OMP gas puffing cases.
- Gas puffing on the PFR region makes detachment when gas puffed more than $7\times10^{21} D_2/s$.

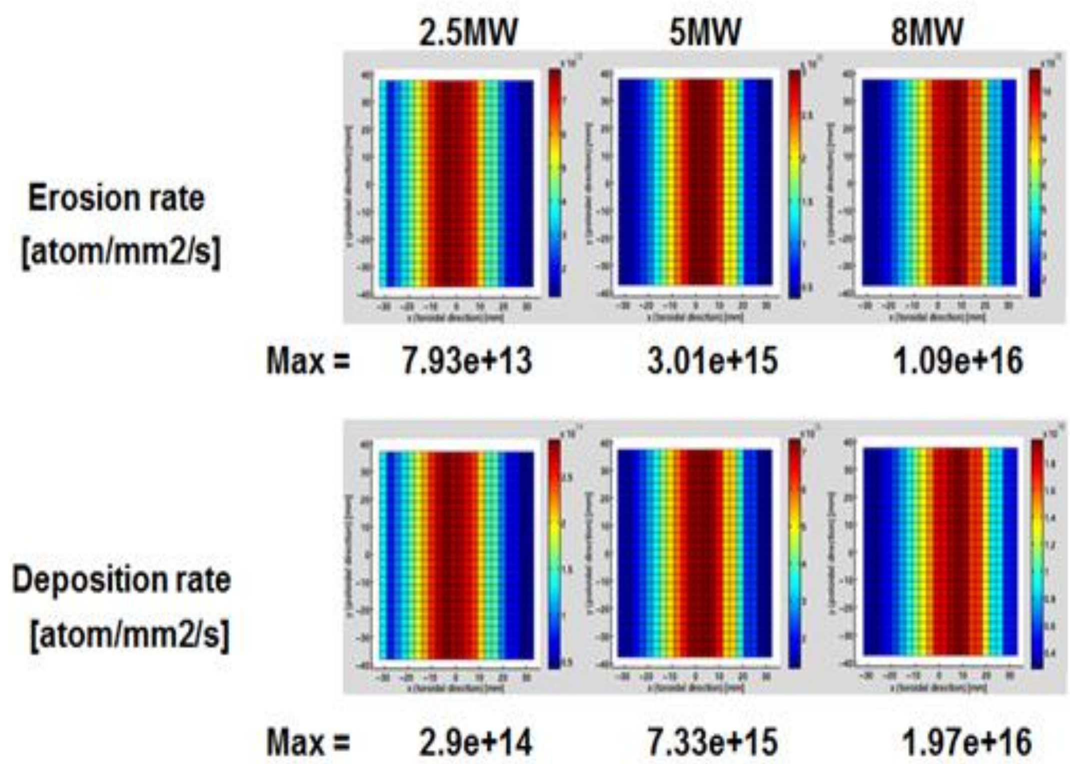
KSTAR

Plasma-wall Interaction

- A preliminary simulation study of erosion, deposition rates of C in KSTAR divertor plate being performed through the coupling of B2 and ERO codes

  - Initial results show how erosion & deposition rates increase with heating power in the relatively low divertor-region plasma temperature case (Te ~Ti ~ 1-10eV)





Turbulence and Transport

- Extensive studies being performed for various subjects, such as

  * intrinsic rotation
  * ITB formation
  * ETB formation
  * non-local transport etc.

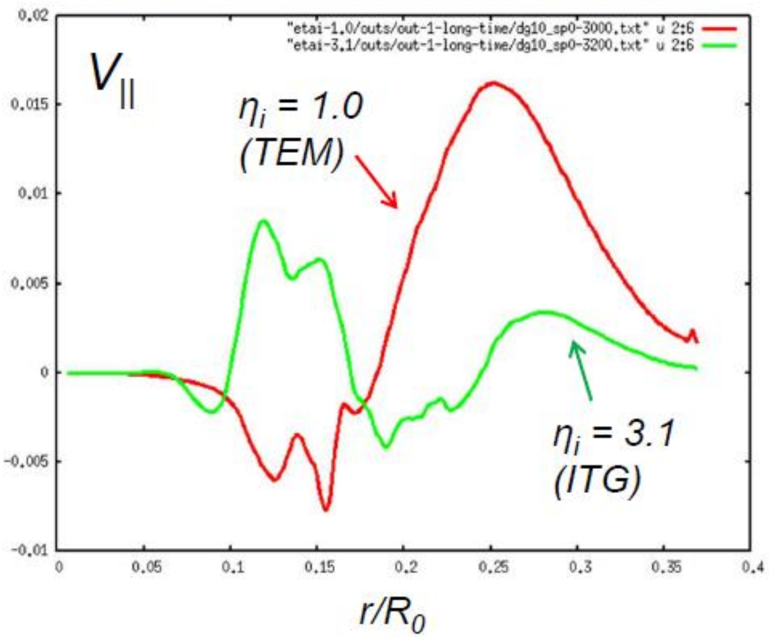
- Also, a substantial effort being made for the development of the global (or full-f) codes, based on the gyrofuild, gyrokinetic, and hybrid schemes

  * global electromagnetic gyrofluid code based on BOUT++
  * full-f electrostatic gyrokinetic code using semi-Lagragian method
  * full-f electromagnetic hybrid code by combining ion-gyrokinetic & electon-fluid

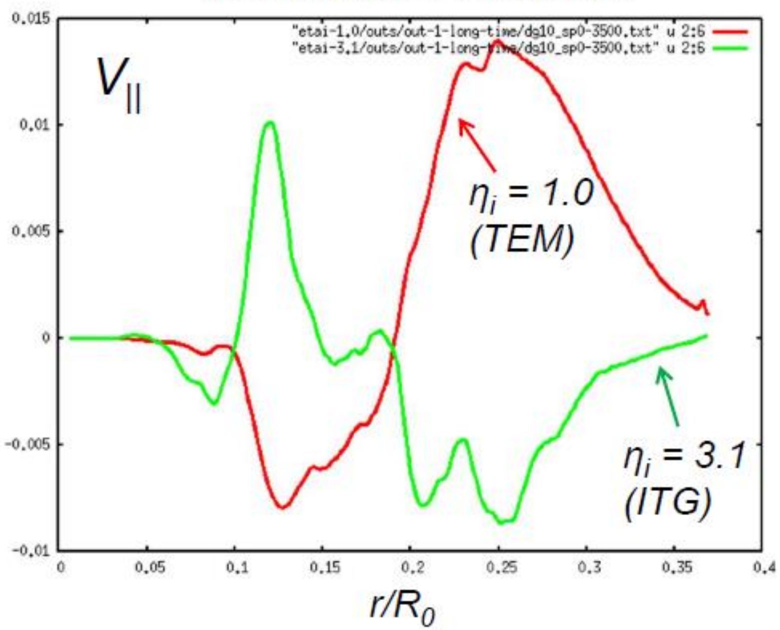
Gyrokinetic simulation study of intrinsic rotation generation

- Sign flip in intrinsic torque observed with the dominant turbulence transition between TEM ↔ ITG from the simulation using gKPSP code (δf PIC gyrokinetic code)
- Dipolar pattern of intrinsic flow profile → boundary condition decide net sign of rotation in plasma

Immediate after nonlinear saturation



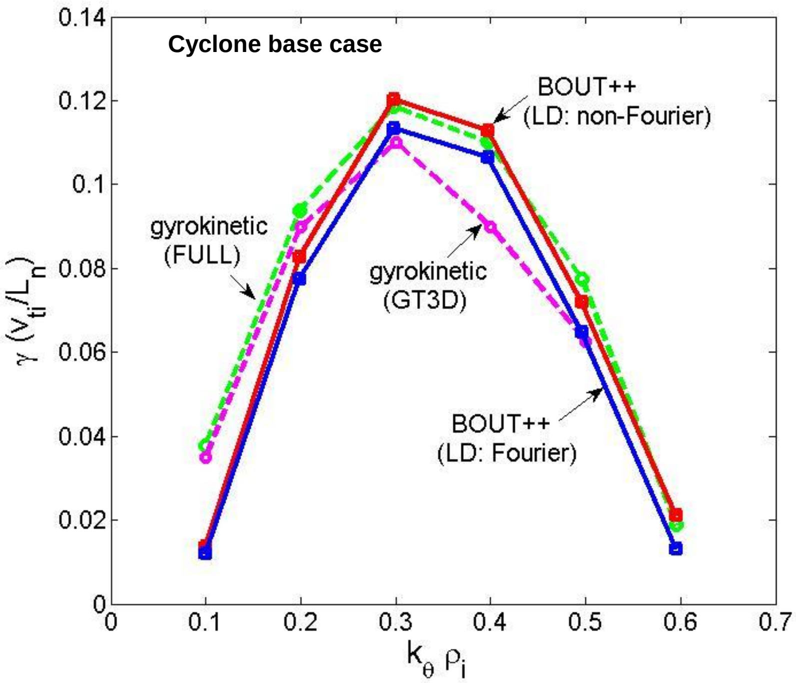
After nonlinear saturation

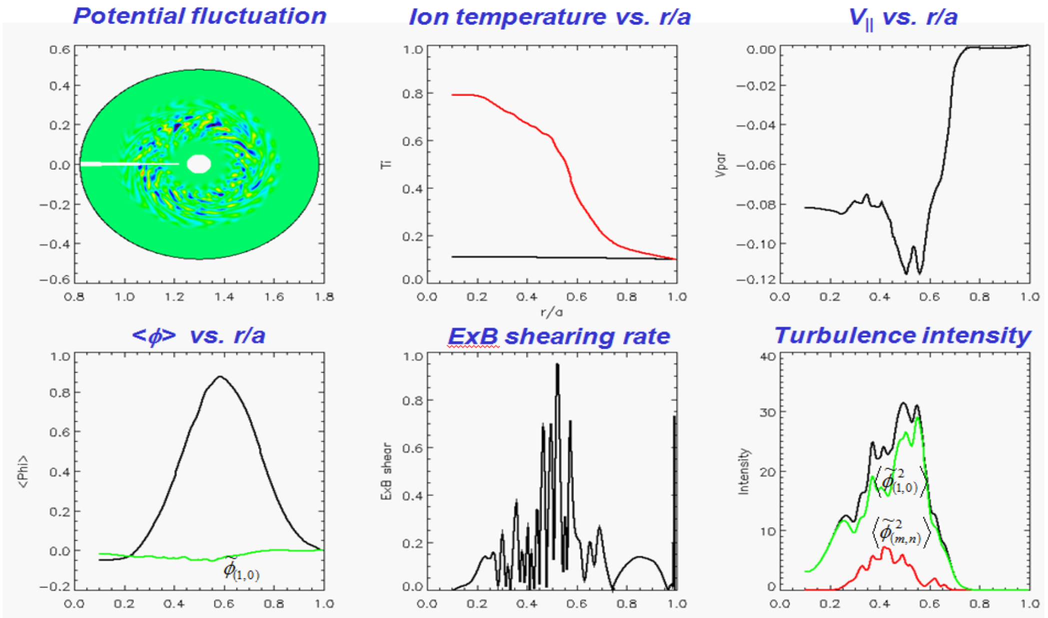


- Rotation damping observed in ECH plasma may due to ITG → TEM transition & resulting torque reversal (experimental data analysis underway)

Development of global EM gyro-fluid code

- A global core gyrofluid code developed using **BOUT++** framework ***(LLNL collaboration)***
- Linear calculations for ITG show excellent agreements with gyro-kinetic results
- Initially, nonlinear simulation underway for the flux-driven ITB formation (with non-resonant modes), as well as ETB formation

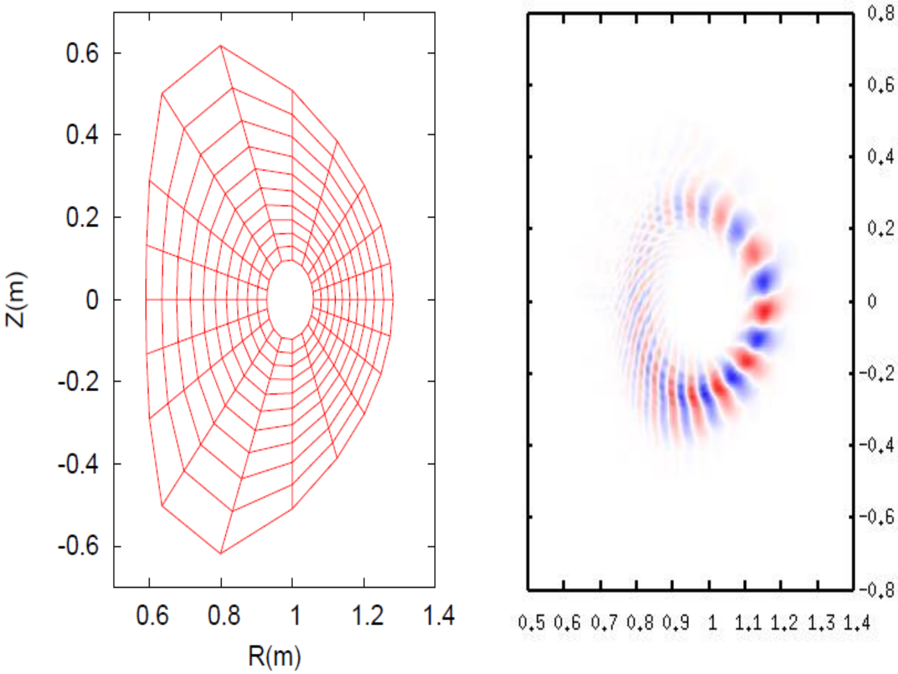




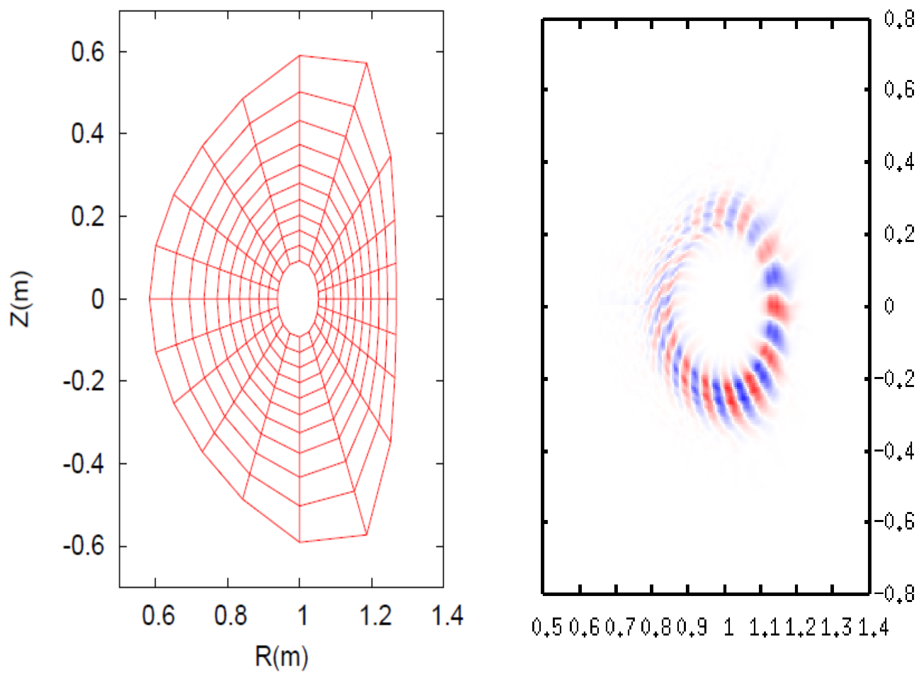
Development of full-f ES gyro-kinetic code

- using Semi-Lagrangian scheme to combine the advantages of both PIC and continuum codes
- Coulomb collision operator included for full neoclassical physics simulation
- General geometry i.e. shaped equilibrium configuration

D-shape



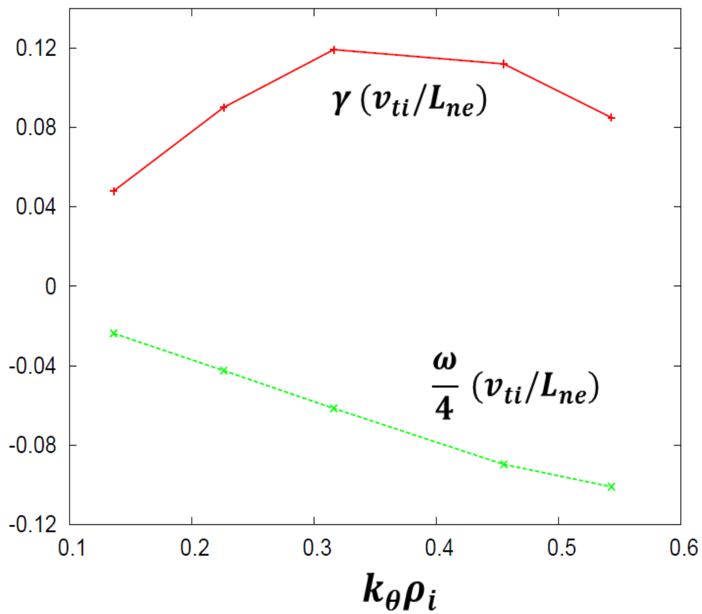
Inverted D-shape



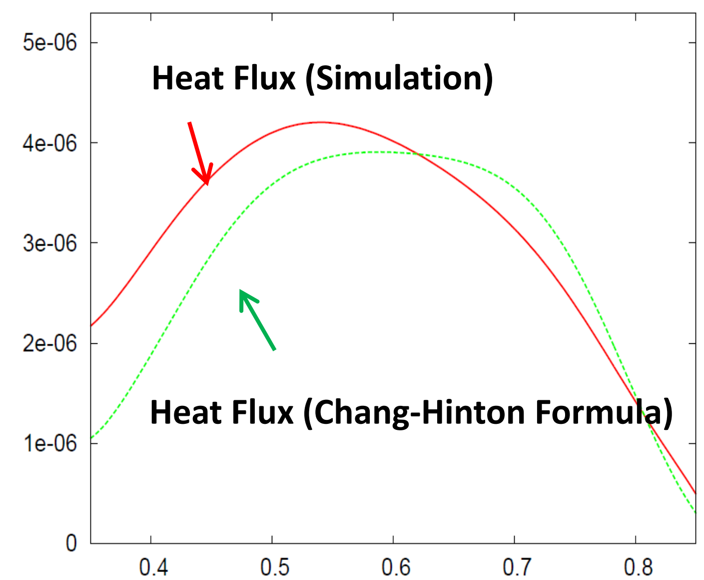
Development of full-F ES gyro-kinetic code

- Almost finished in the electrostatic limit
- Benchmark test results are in good agreement with theory and previous works.

Linear ITG simulation with cyclone parameters



Neoclassical benchmark test



- Nonlinear benchmark simulation to be performed soon
- The code will be also extended to the EM code by using hybrid scheme

Summary

- Theory and simulation research for KSTAR at NFRI now being performed over most areas through the two projects (WCI & internal)

- Relatively, strong emphases being put on the Pedestal and ELM control area in relation to H-mode experiments in KSTAR

- A substantial effort also being made for the Turbulence and Transport area, with the development of global (or full-f) integrated simulation codes, based on the gyrofluid, gyrokinetic, and hybrid schemes

- Research activities in other areas, such as MHD stability, energetic particles, operation scenario, divertor/SOL are still relatively weak

- So, particularly hoping to increase more collaborations on these areas

Future Collaboration Opportunities (PPPL)

- Energetic particles

  - Linear stability analysis and nonlinear simulation of TAE, BAE, EPM etc.
  - Transport effect by energetic particle driven modes etc.

- MHD stability & disruption

  - 3D physics, Linear MHD stability analysis of LM, NTM, RWM etc.
  - Nonlinear simulation of resistive MHD modes
  - 3D disruption simulation with 2D or 3D structure model etc.

- Operation scenario and Divertor/SOL

  - Advanced operation scenario modeling for KSTAR
  - Plasma-wall interaction modeling etc.

- Transport and Pedestal

  - Global integrated simulation over whole region using full-f gyrokinetic or hybrid code etc.