FSP Center for Plasma Edge Simulation

CPES
Center for Plasma Edge Simulation

C.S. Chang[a)]

on behaf of the CPES team

[a)] *Courant Institute of Mathematical Sciences, NYU*

CMCL

SciDAC
TCAP

Participants (Physicists, Math, Computer Science)

NYU (Lead Institution)	Chang[E], Strauss[E], Ku, Park, Weitzner, Greengard[E], Zorin, Zaslavski (consultant)
PPPL	Stotler[E], Lee[E], Hahm, Wang, Ethier, Samtaney, Feibush,
MIT	Sugiyama
Caltech	Cummings
Columbia U.	Keyes[E], Mark Adams
U. Colorado	Parker[E], Chen
UC Irvine	Lin, Nishimura
Lehigh U.	Kritz[E], Bateman, Pankin
Rutgers U.	Parashar
U. Tennessee at Knoxville	Beck
U. Utah	Parker
Hinton Associates	Hinton
ORNL	Schultz, Klasky[E], Worley, D'Azevedo
LBNL	Shoshani[E] and the SDM center

There are other active collaborators (Kevrekidis/Princeton U, etc)

Domestic Experimental Partners

M. Greenwald (MIT), R. Maingi (ORNL), S. Zweben (PPPL), etc

International Experimental Partners

Kamada (JT60-U), L. Horton (ASDEX-U), KSTAR, etc

Center for Plasma Edge Simulation

Aim: To understand and predict the L-H transition, pedestal buildup, ELM crash, pedestal scaling, scrape-off layer physics and wall load, *etc.*

Tools: Develop a new predictive integrated (first-principles) edge simulation framework by

1. Establishing a 5d edge **kinetic PIC** code **XGC** for **integrated** **N**eoclassical+**T**urbulence+**N**eutral simulation (Neoclassical in Phase 1, Electrostatic in Phase 2, Electromagnetic in Phase 3)
2. Developing an integrated simulation framework between **XGC** and an **MHD/2-Fluid ELM** code for **pedestal-ELM cycle.**

PIC edge kinetic code XGC

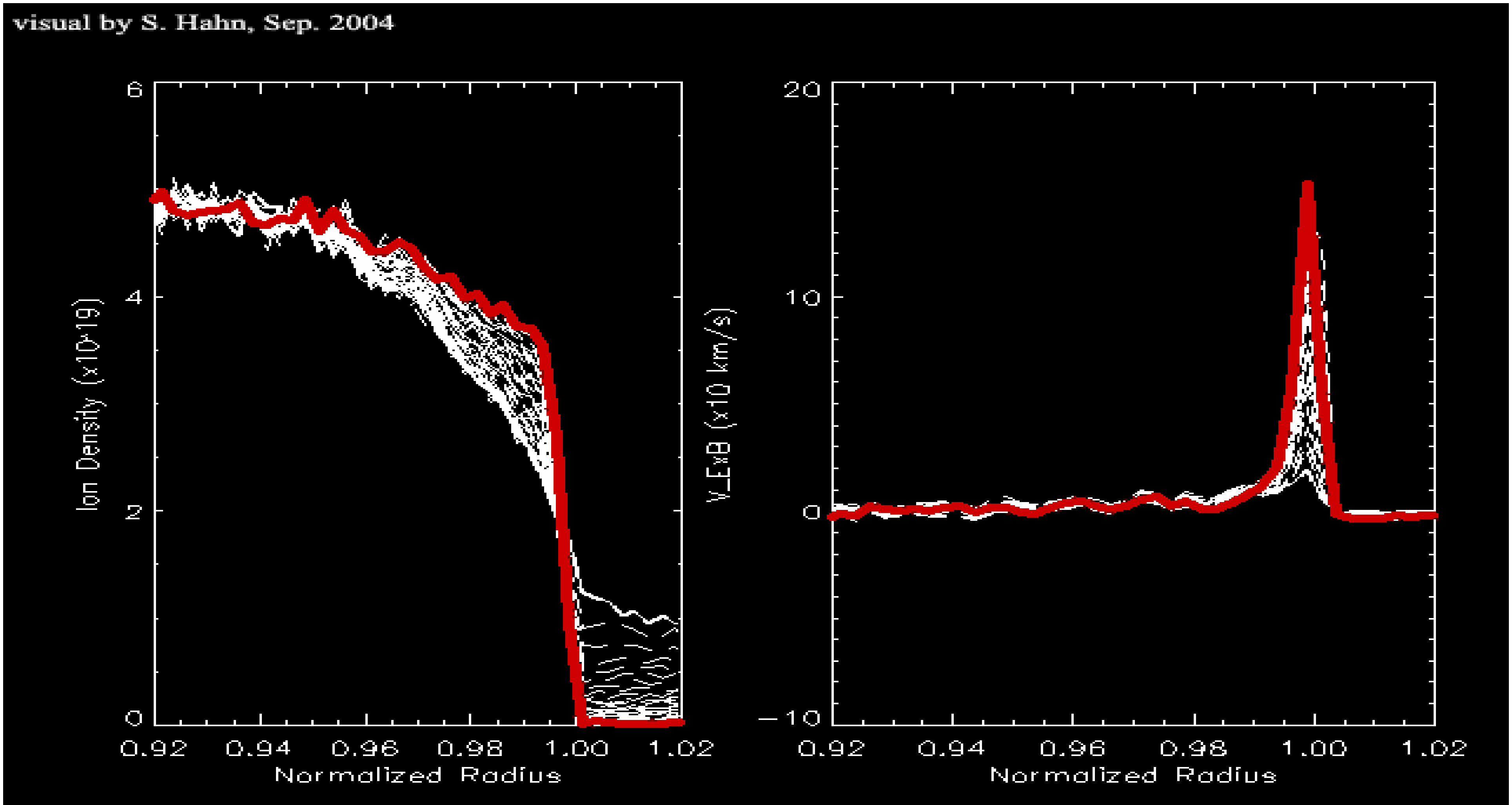
- XGC is a full-f code with time-constant particle weights.
- XGC self-consistently includes the 5D ion and electron kinetics, realistic magnetic and wall geometry, Monte Carlo neutral particle transport with wall recycling, conserving collisions, **bootstrap current evolution, neutral beam source, magnetic ripple**, etc.
- XGC-0 was a 5D ion neoclassical full-f code with E_r solver. It established the self-consistent ion neoclassical pedestal physics with neutral dynamics (2004 IAEA, 2005 Spring TTF and ITPA).
- **XGC-1 is a 5D ES turbulence+neoclassical code which includes the electron dynamics.**
- Flux bd: Plasma fluxes from core, neutral flux from wall

Nonlinearly saturated pedestal buildup by neutral ionization (B_0= 2.1T, T_i=500 eV)

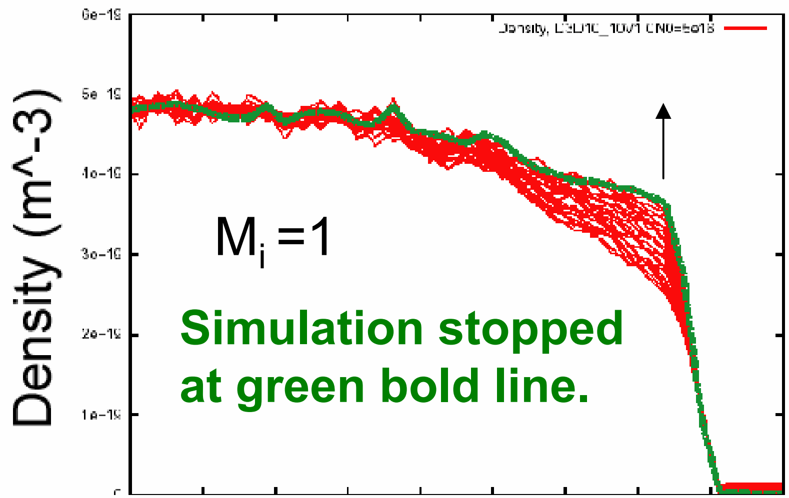
[164K particles on 1024 processors]

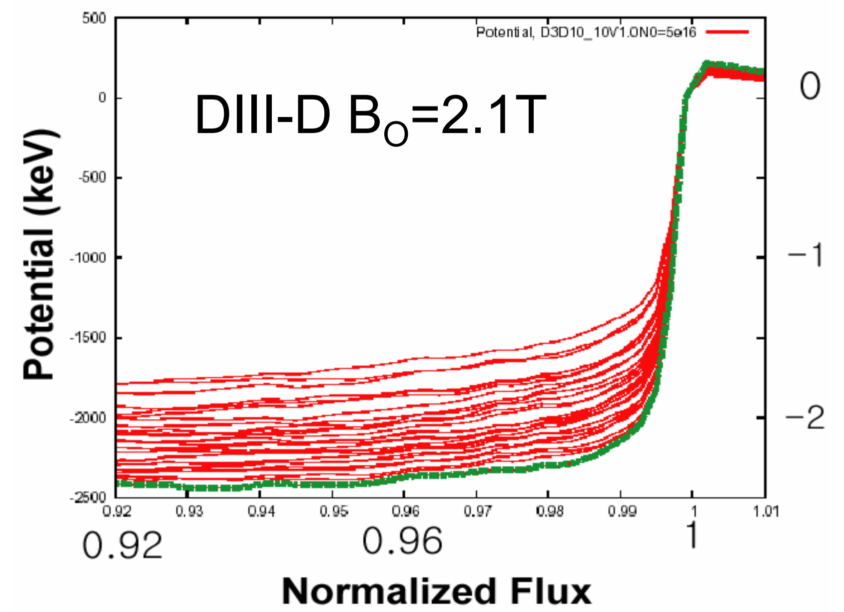
Plasma density

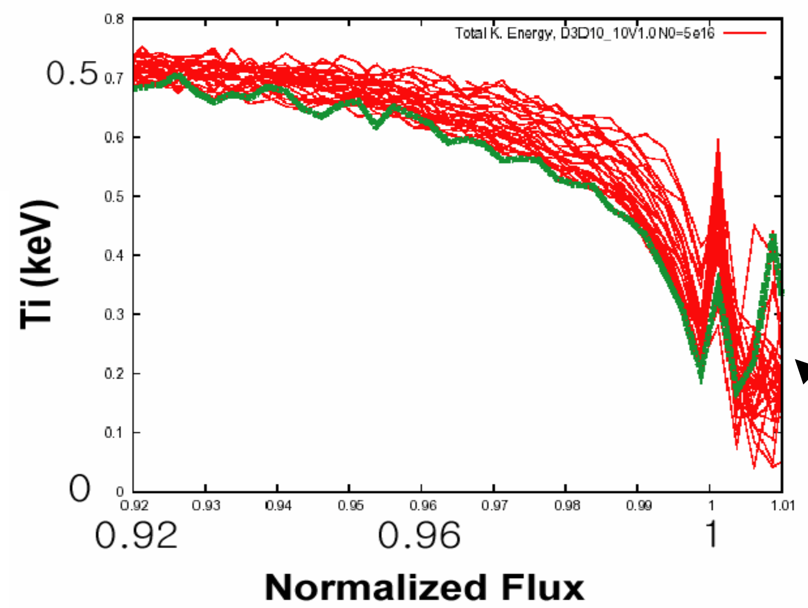
V_{ExB}



Nonlinearly saturated neoclassical Pedestal buildup by neutral ionization



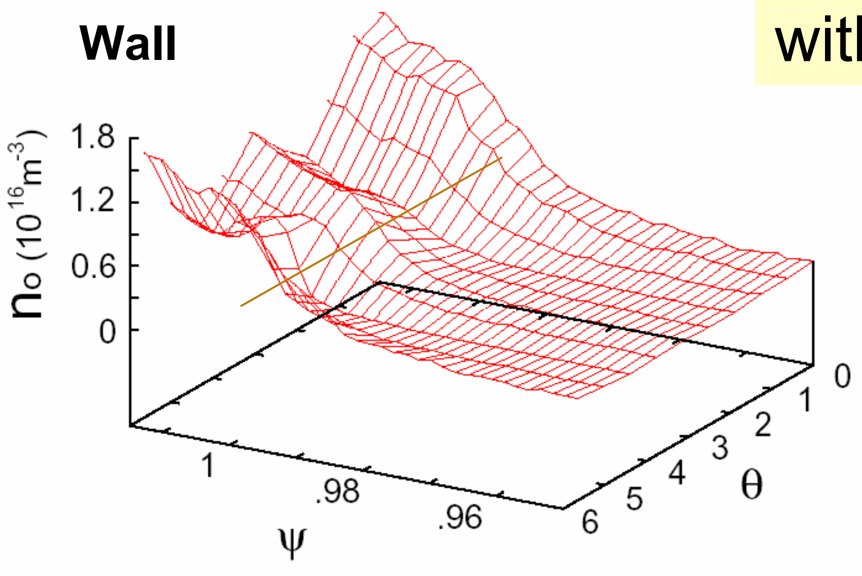


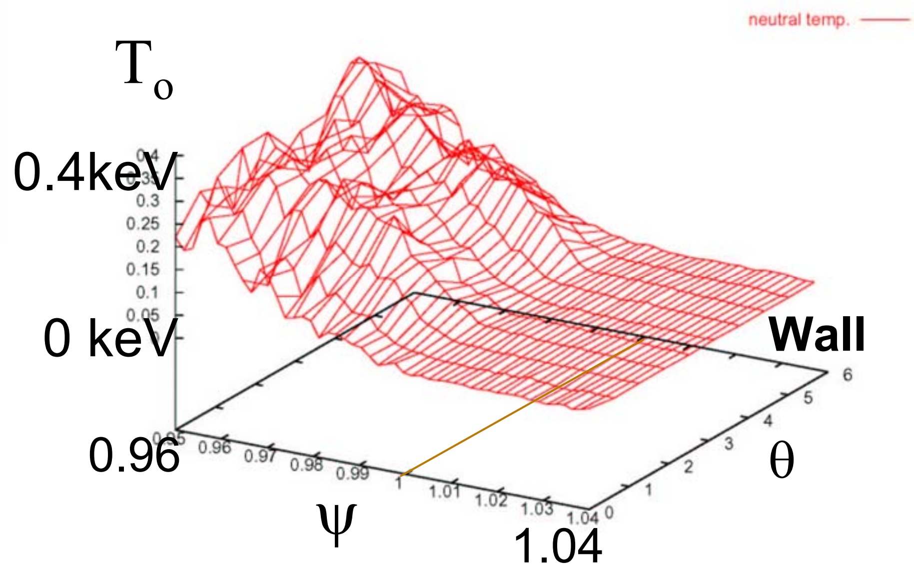


Broader T_i pedestal and tail ions in scrape-off

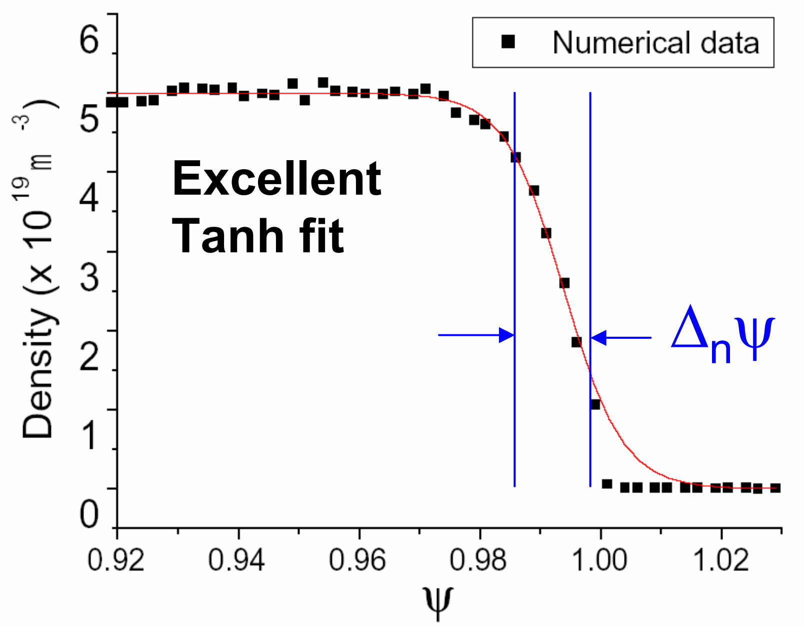
XGC Monte Carlo neutral particle PIC simulation (DIII-D)

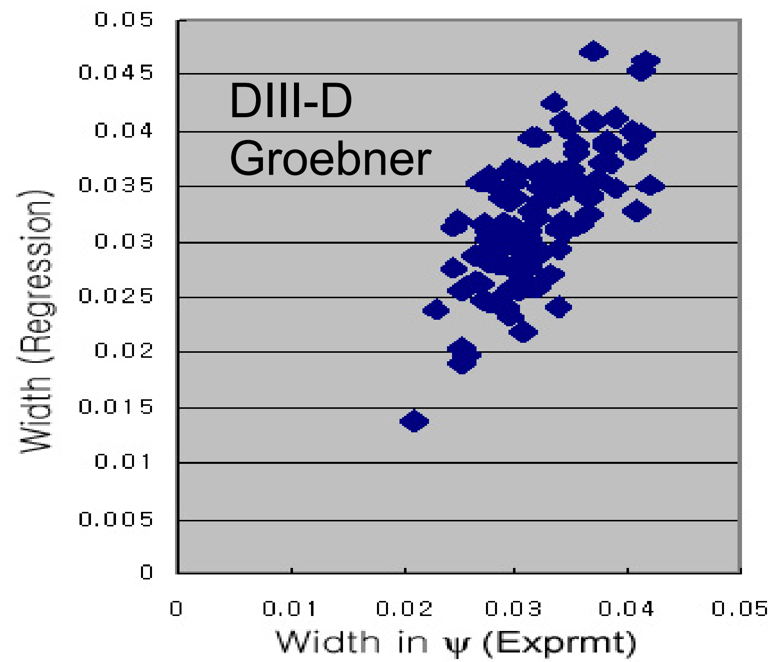
Difficult first-principles modeling with fluid neutrals when mfp ~ L_{Ped}





Pedestal Scaling law from XGC-0





XGC finds neoclassical density pedestal width scaling

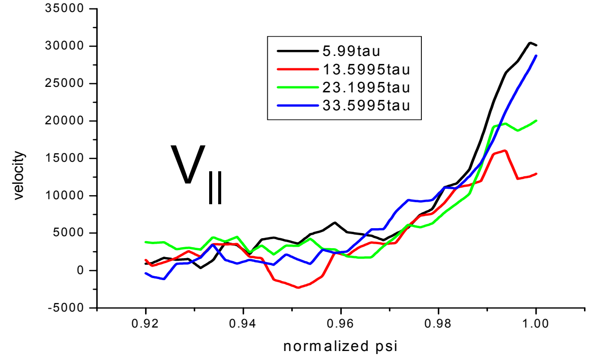
$$\Delta_n\psi(\text{neo}) \propto M_i^{1/2}\,(T_i^{0.5}-0.23)\,/B_T$$

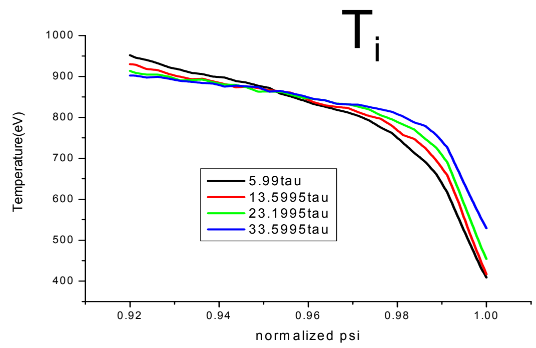
DIII-D data show (Chang-Groebner)

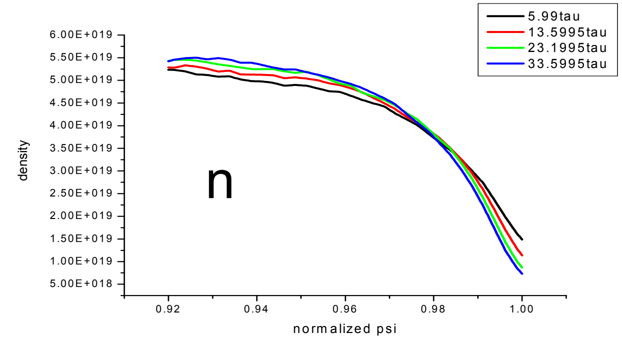
$$\Delta_n\psi(\text{exp}) = 0.075\,(T_i^{0.5}-0.22)/B_T + 0.0092\ n/q$$

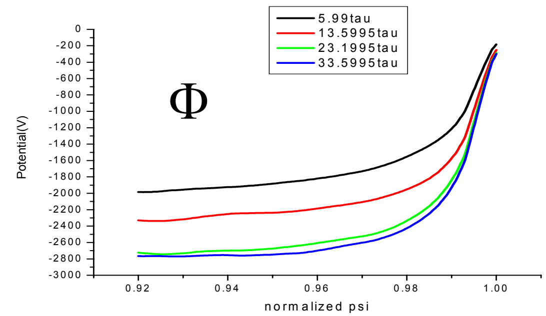
Scaling with the local variables

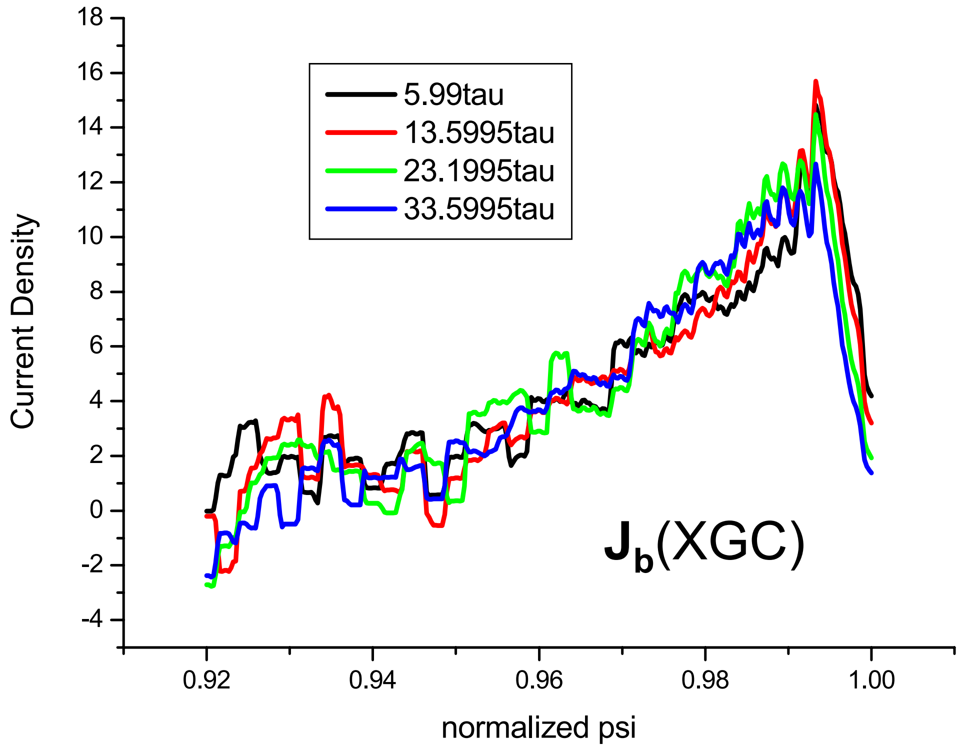
Steep-gradient bootstrap current in the edge pedestal

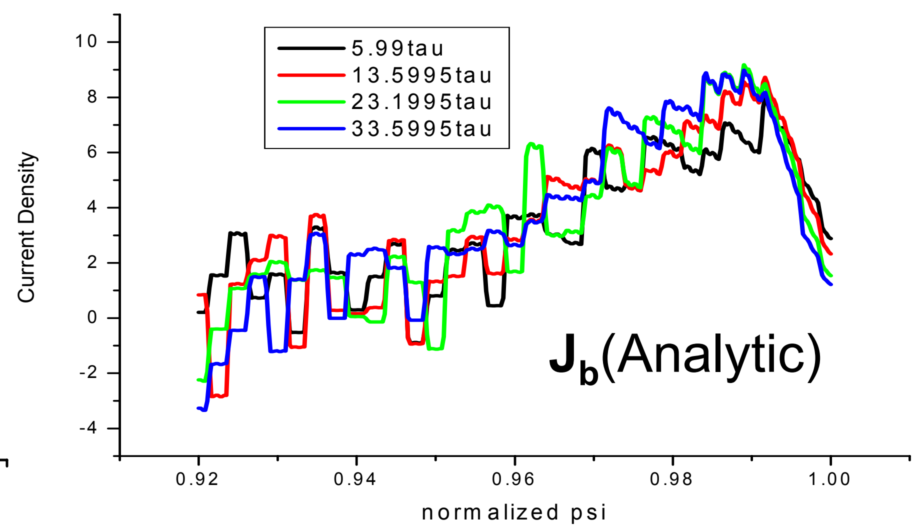




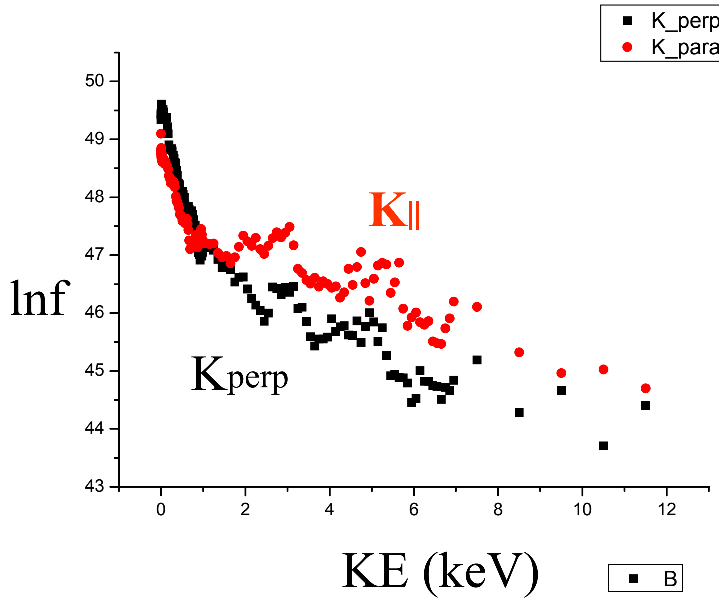


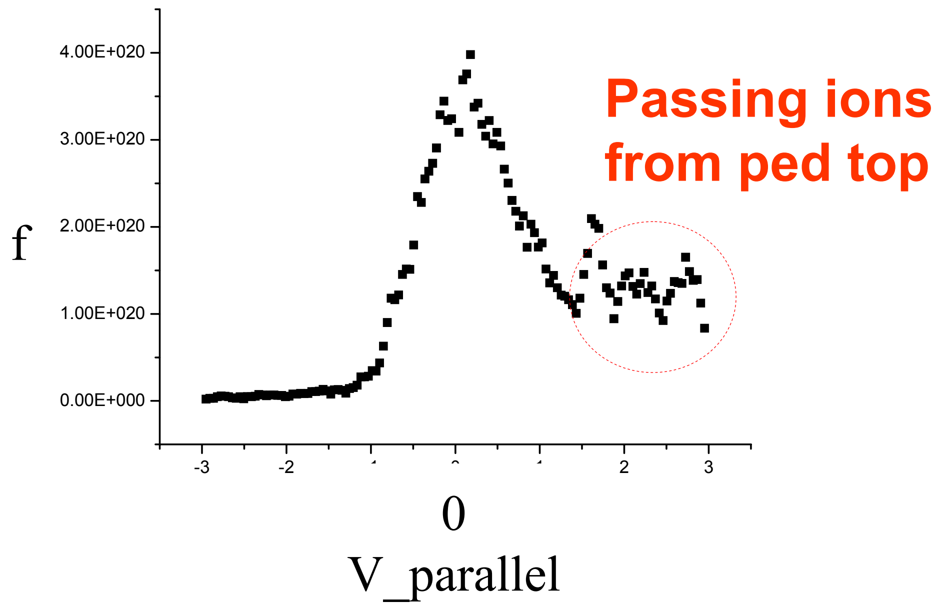


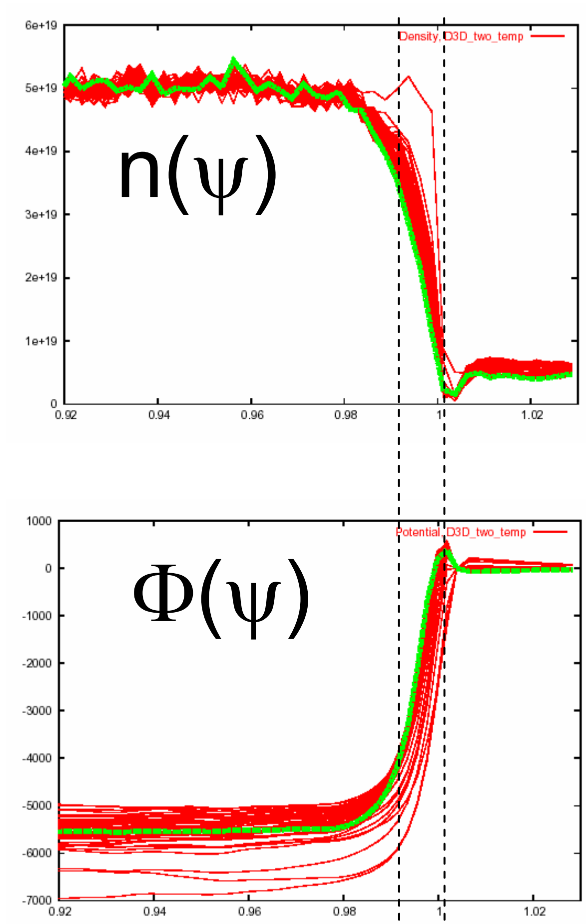




f_{i0} is non-Maxwellian in the pedestal and scrape-off







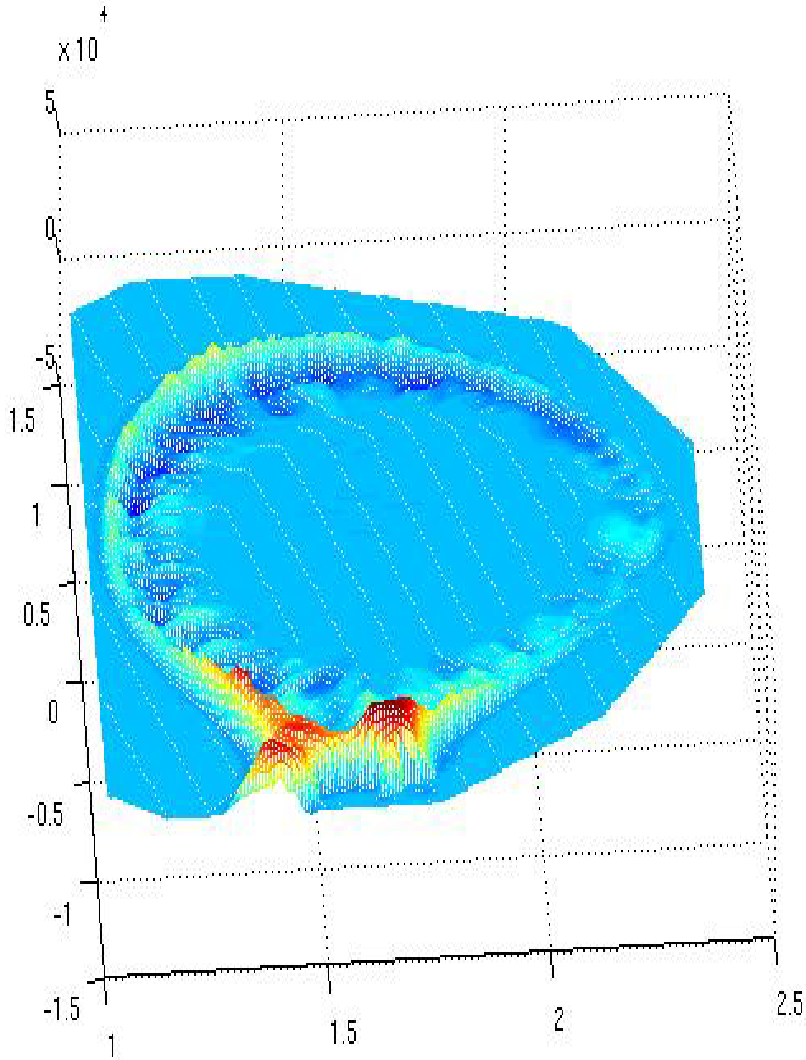
Normalized psi~[0.99,1.00]

Initial Accomplishment

- XGC-1 has been developed which uses a new mixed-f technique for integrated simulation of neoclassical and turbulence physics:

  Full-f ions/electrons for the fluctuation-averaged neoclassical, and adiabatic ($\rightarrow$ split-weight) electrons for electrostatic turbulence $n_e \propto n_0(\Phi_0) \exp[e\Phi_1/T_e]$.
- A new **QSC (Quiet Spline Collision)** technique is under development: fully nonlinear collisions with noise reduction which also allows faster particle push.
- We are trying to improve solvers before going into the longer time simulation of neoclassical and turbulence physics.
- **Neoclassical physics is being studied in the pedestal/scrape-off region [2d- Φ, V, n, T, J_b, etc].**

Early time solutions with the real electron mass

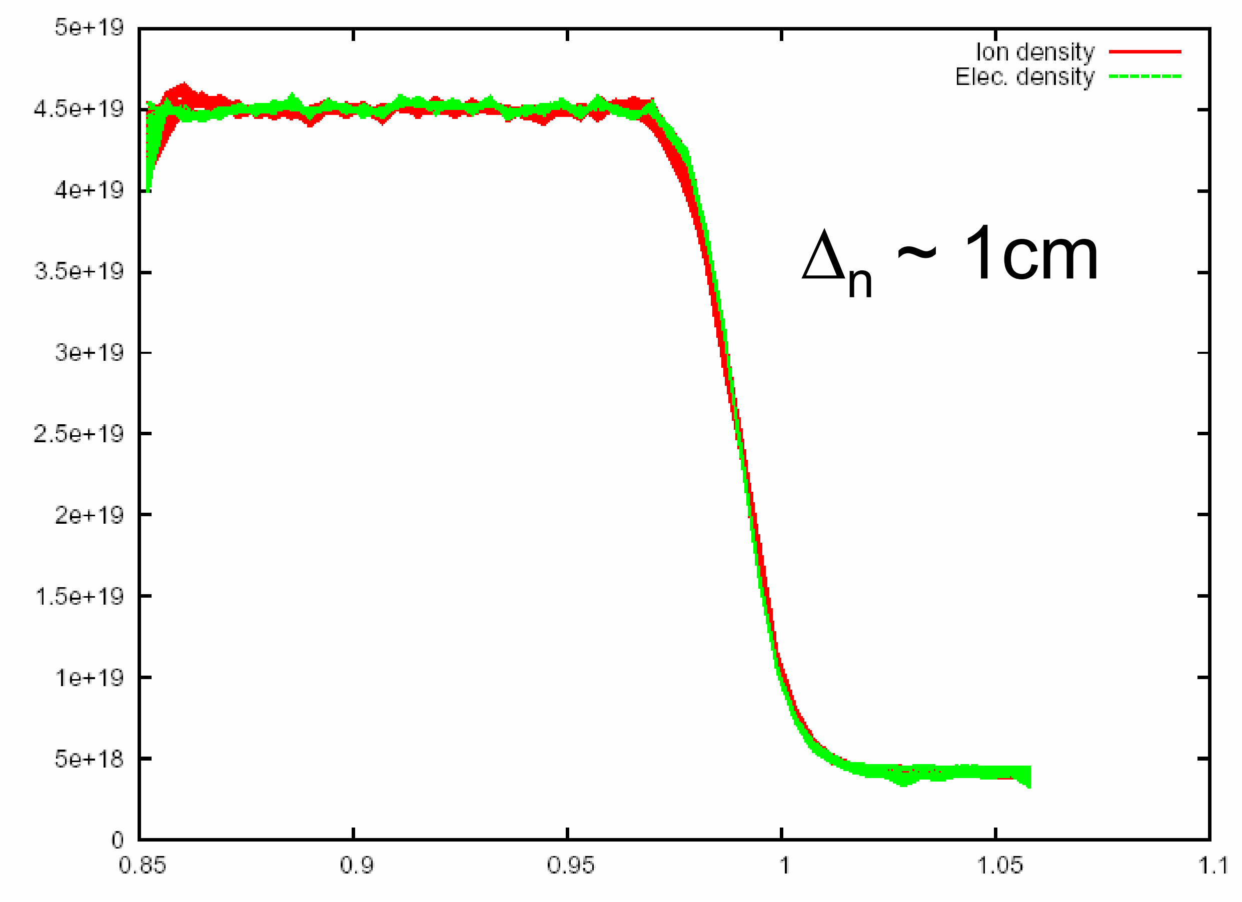


- Φ is higher at high-B side
  $\Rightarrow$ Transient neoclassical behavior
- Formation of a negative potential layer just inside the separatrix $\Rightarrow$H-mode layer
- Positive potential around the X-point (B_P ~0)
  $\Rightarrow$ Transient accumulation of positive charge

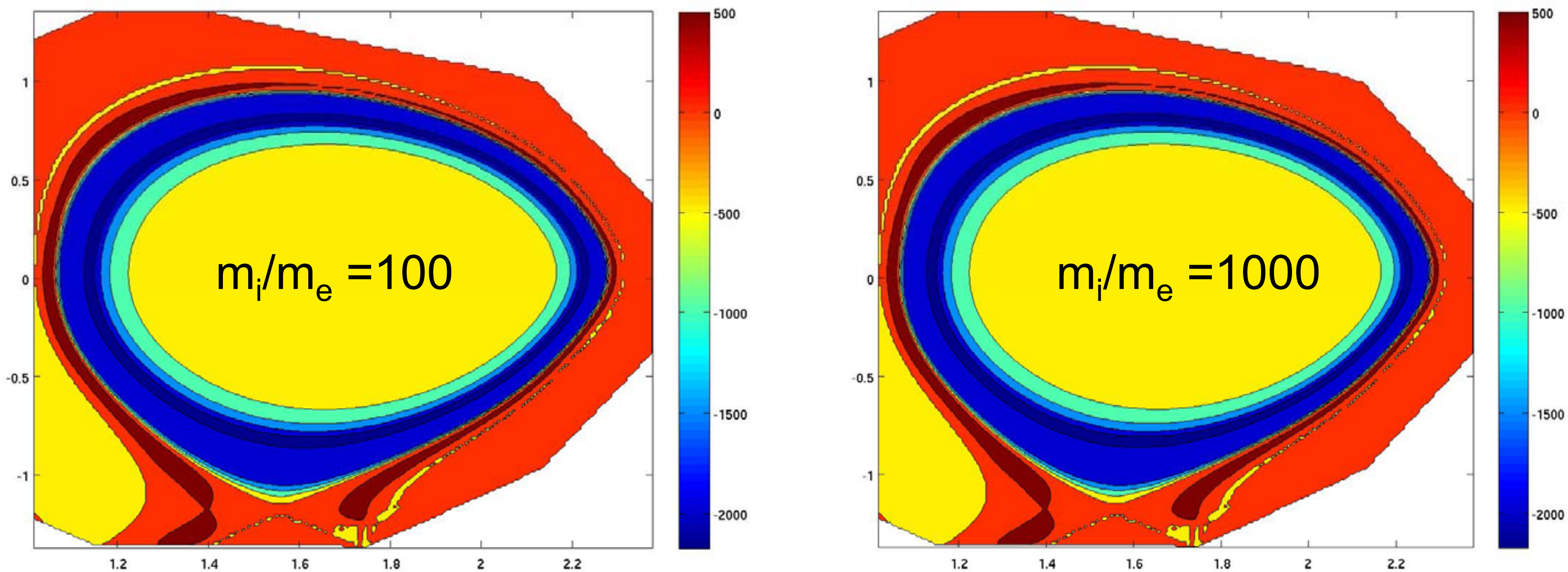
Neoclassical edge solutions from XGC

- The first self-consistent kinetic solution of edge flow structure
- We average the fluctuating Φ over a poloidal extent to obtain Φ_o. (1/2 flux-surface in closed and ~10 cm in the open field)
- Results shown are from $1\tau_{ib} = 2\pi R/v_i$ to 30 τ_{ib}.
- Code has been verified against the Hinton-Hazeltine parallel flow on the closed surfaces.

Density profile



Comparison of Φ_o between m_i/m_e = 100 and 1000 at $t=1\tau_{Ib}$ $\Rightarrow$100 is reasonable (10 was no good)

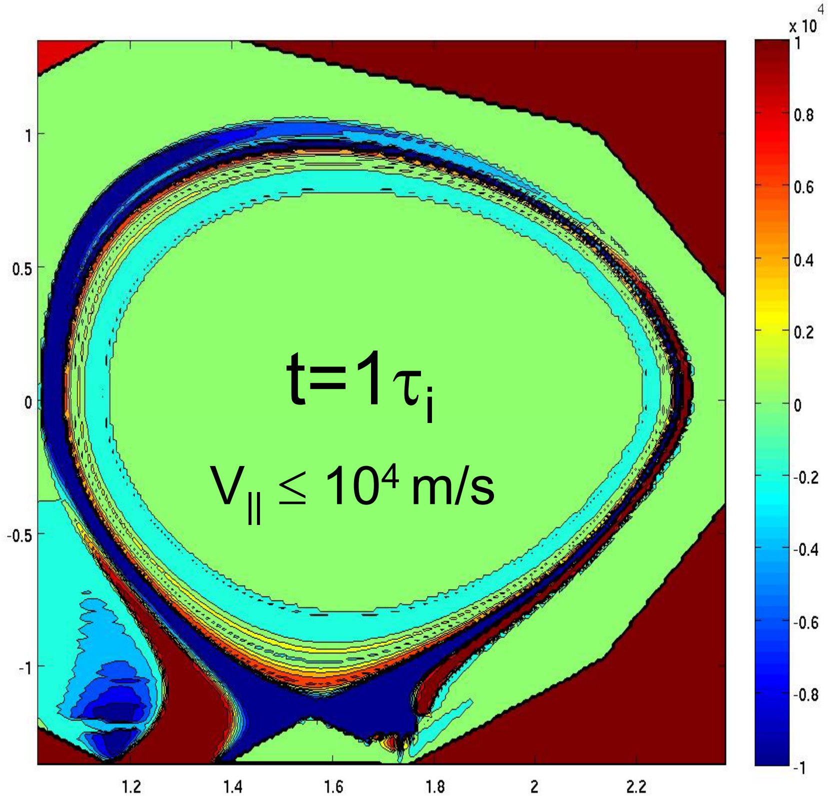


Similar

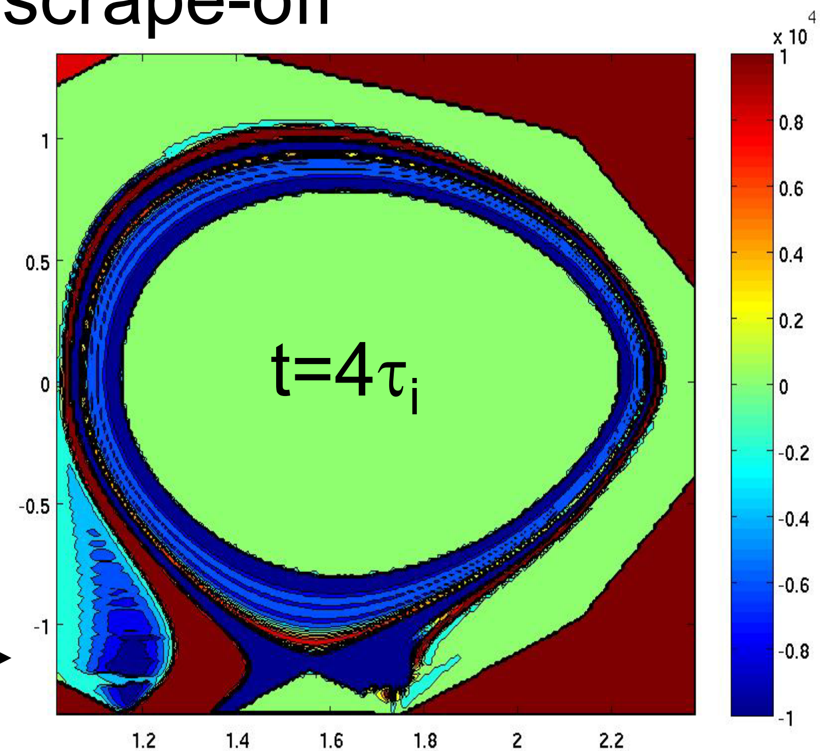
$\Phi<0$ in pedestal and >0 in scrape-off

Parallel plasma flow at t=1 and $4\tau_i$

(m_i/m_e = 100, shaved off at $\pm 1\times10^4$ m/s)

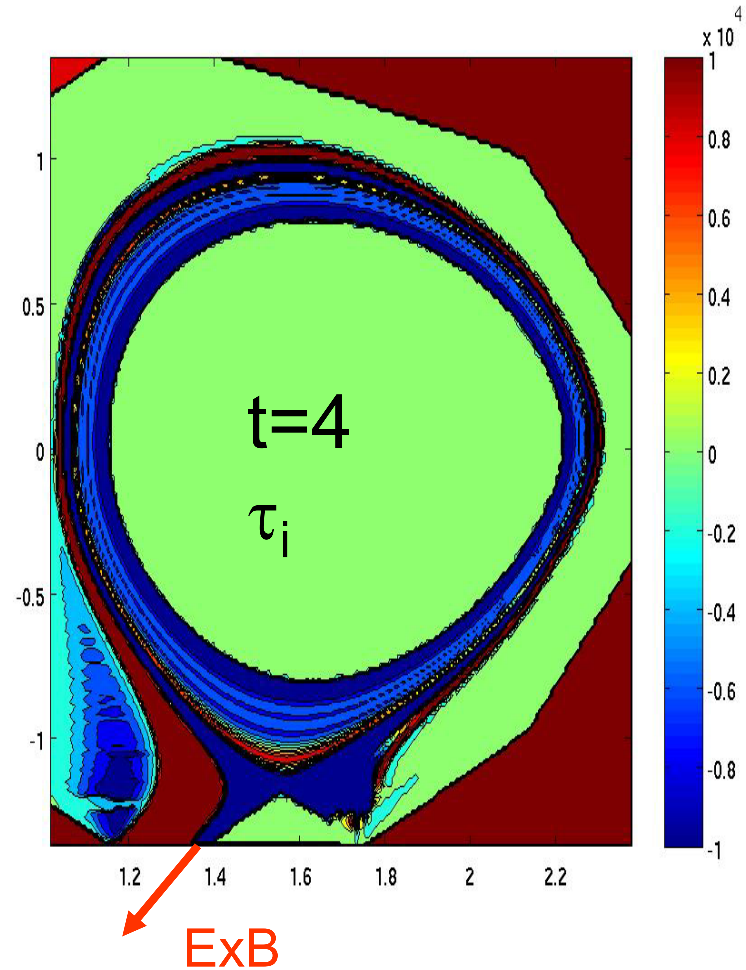


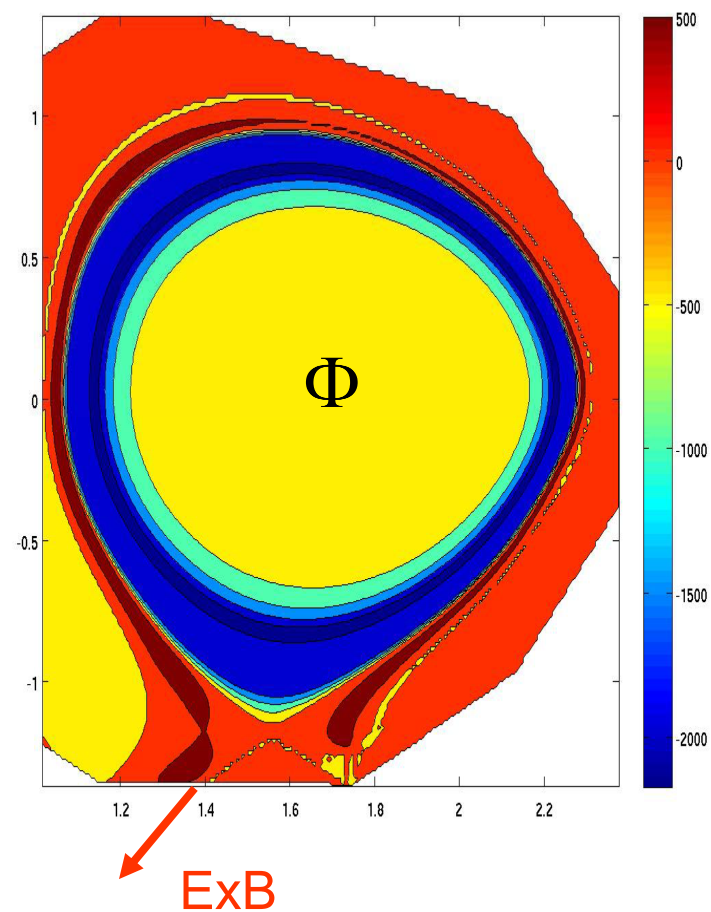
- counter-current flow near separatrix
- co-current flow in scrape-off



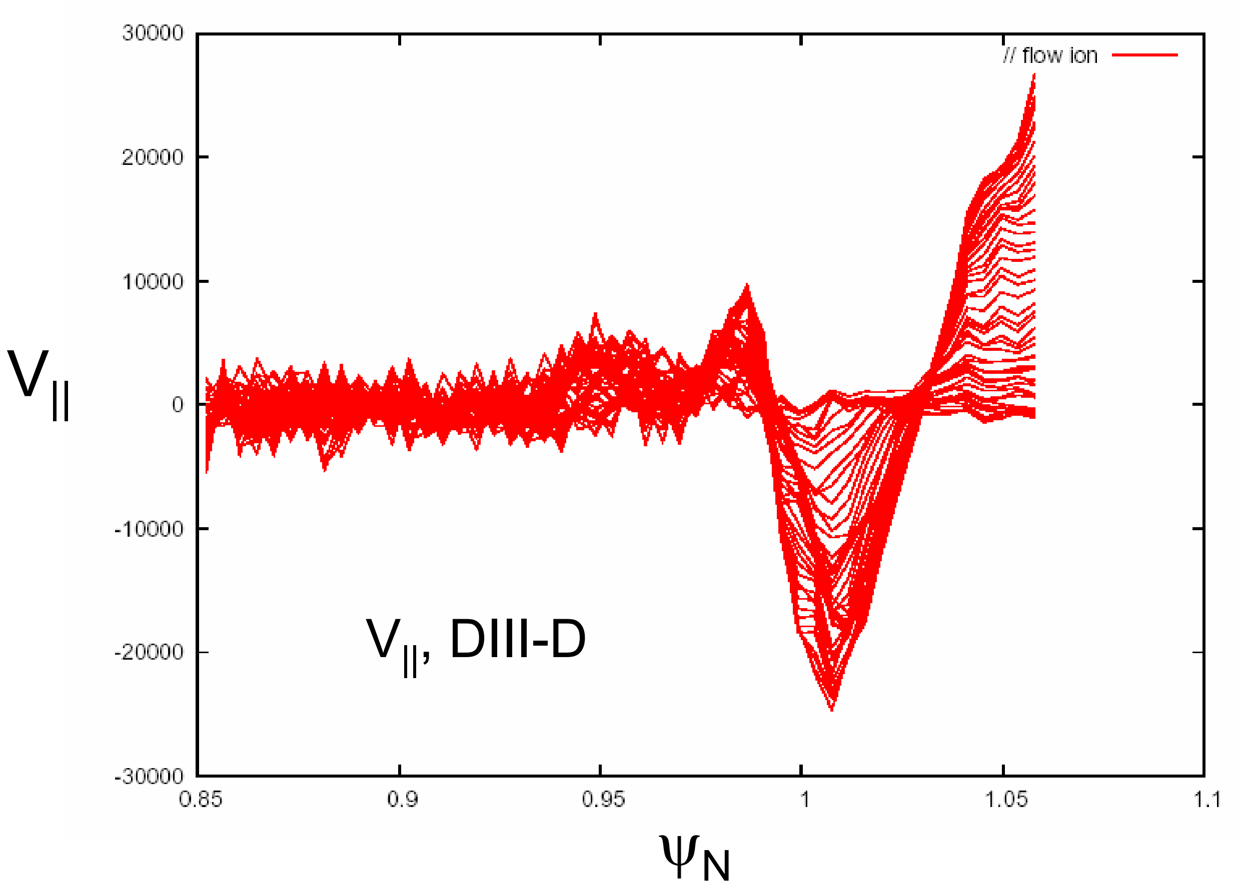
Sheared parallel flow in the inner divertor →

$V_{||} < 0$ in front of the inner divertor does not mean a plasma flow out of the material wall because of the ExB flow to the pump.

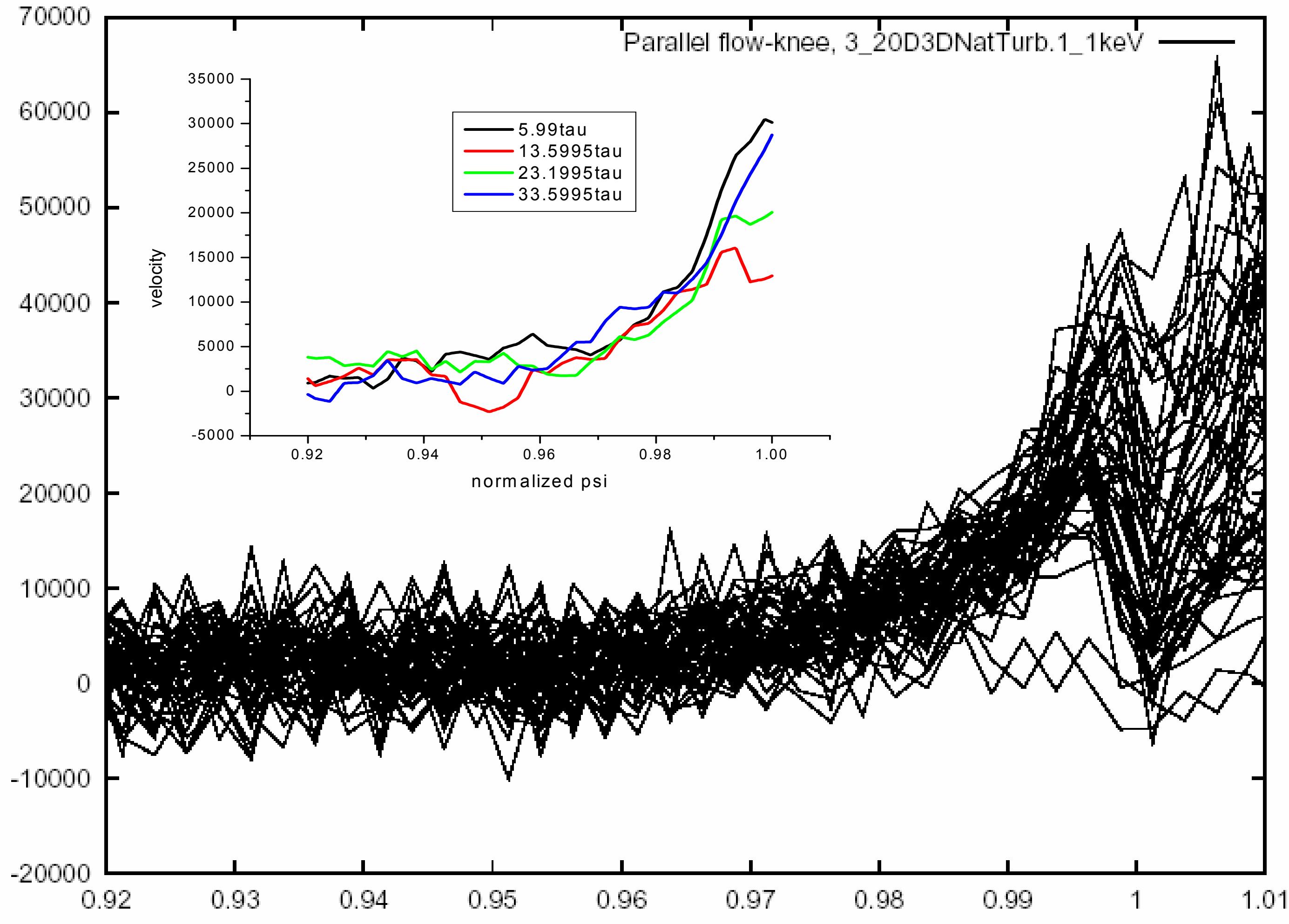




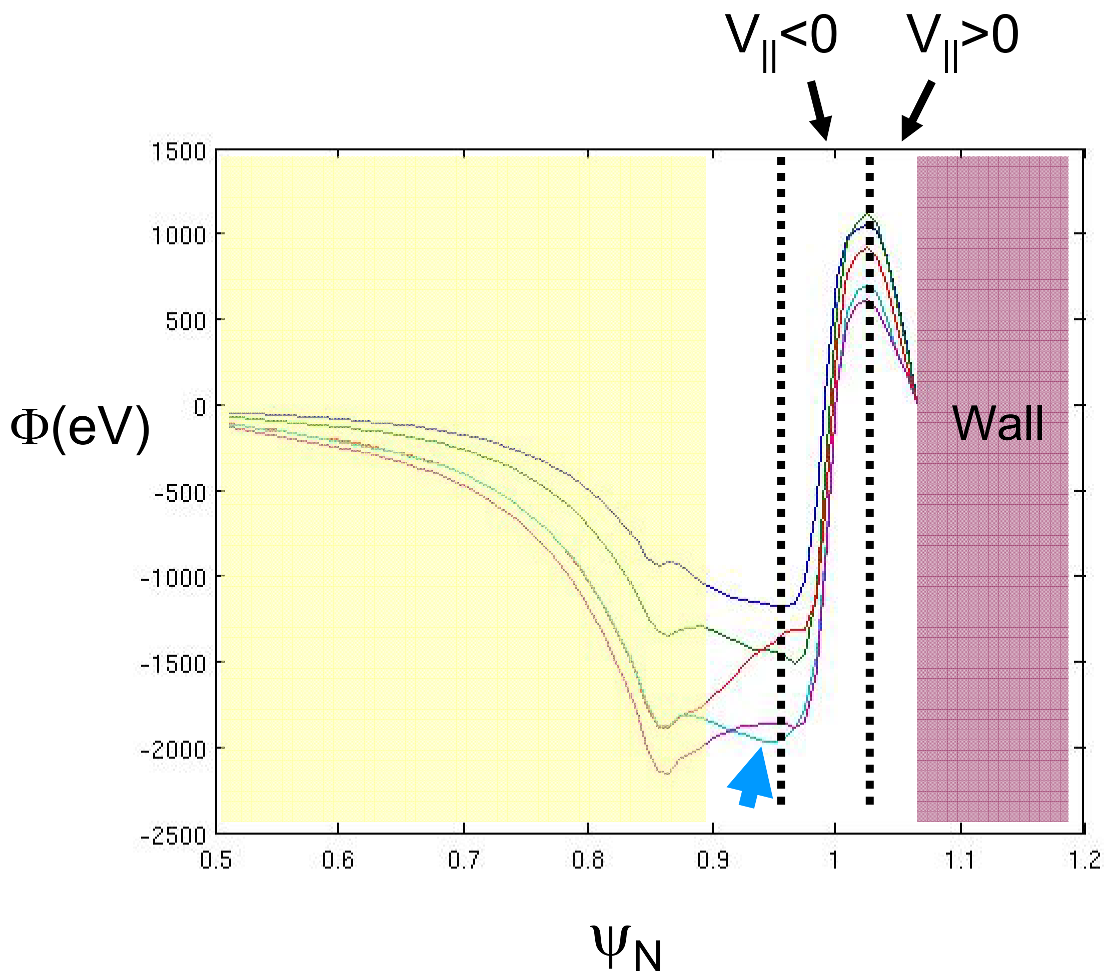
Neoclassical: $V_{||}$ <0 around separatrix with weak neutral effect (strongly sheared $V_{||}$), but >0 in the (far) scrape-off.



$V_{||}$ shows modified behavior with strong neutral collisions: $V_{||}>0$ throughout the whole edge (less shear)



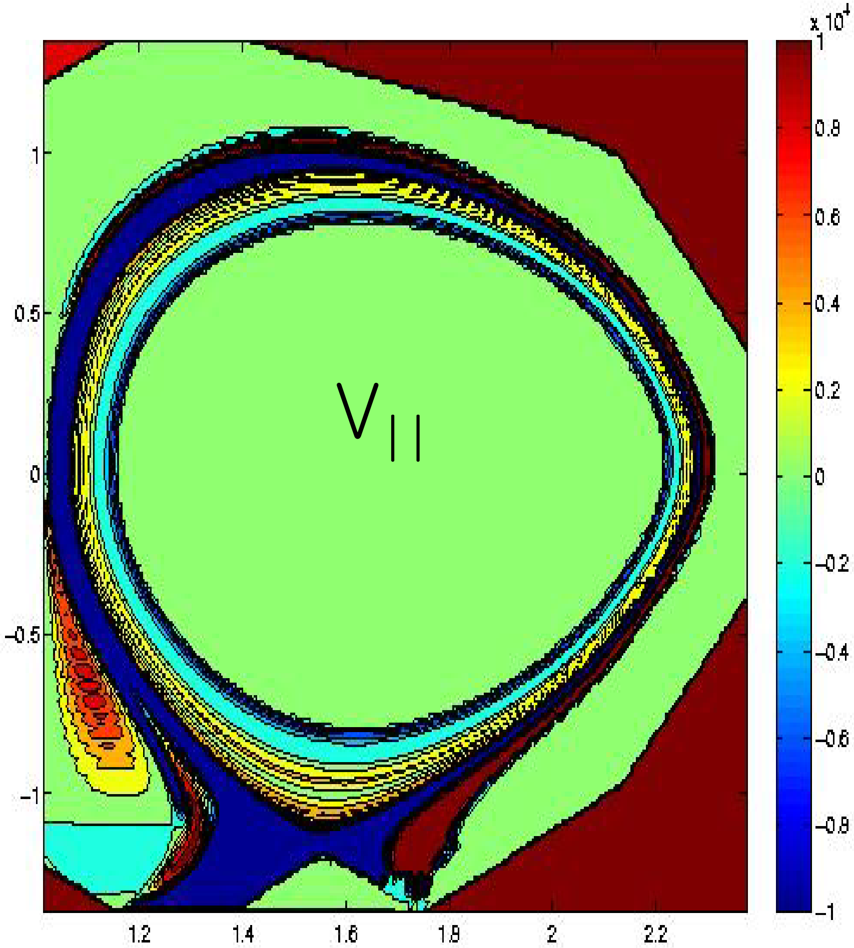
Potential profile roughly agrees with the flow direction in the edge

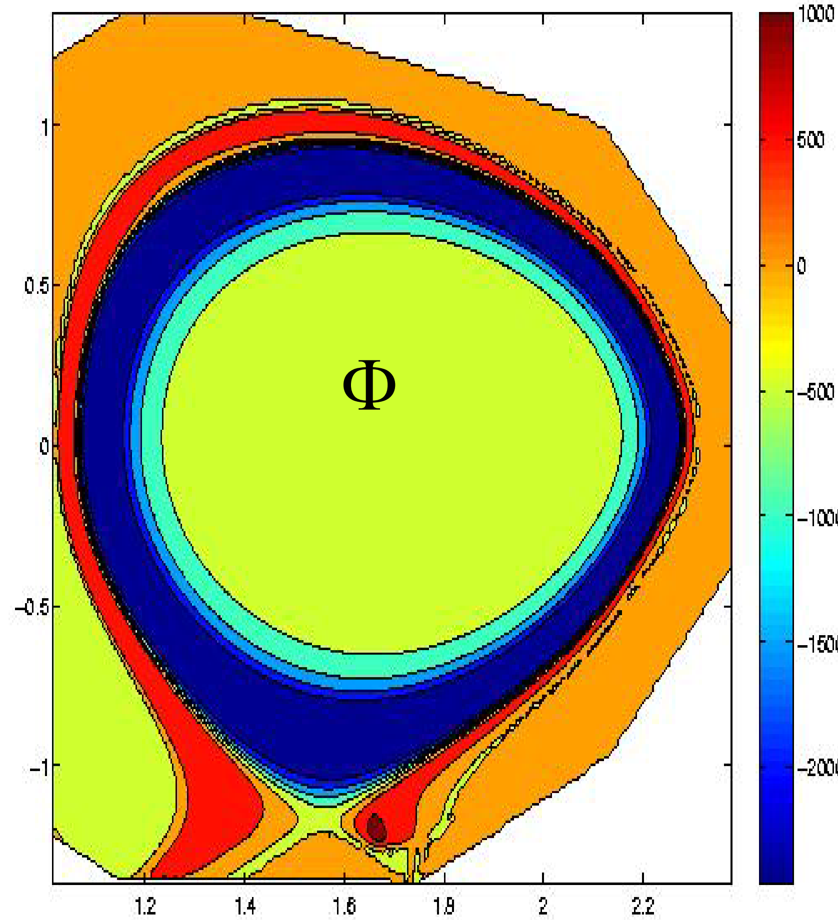


Reversed B_T and I_P

$V_{||}$ near separatrix (blue) is toward the inner divertor, but ExB?

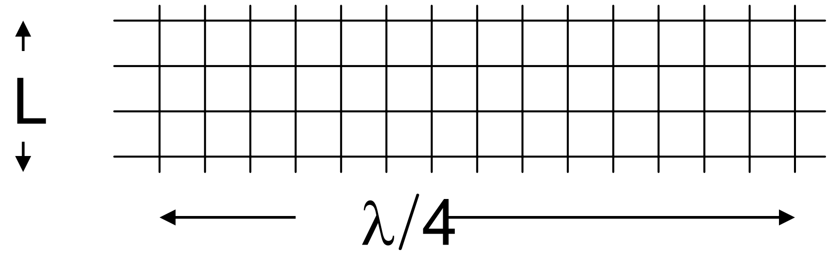
V_{ExB} near sepatrix is toward outer divertor, connecting to the away V_{ExB} flow in the scrape-off.





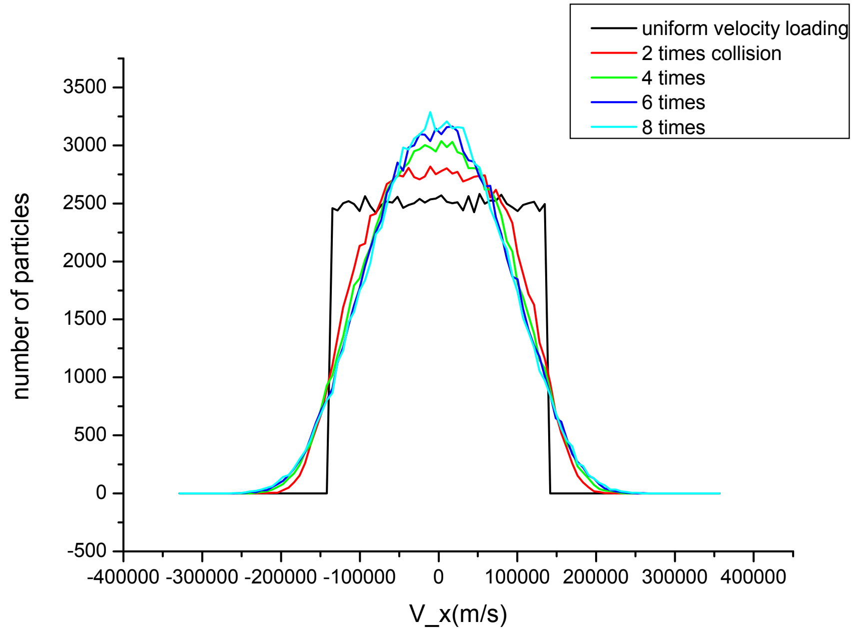
A new Quiet Spline Collision operation

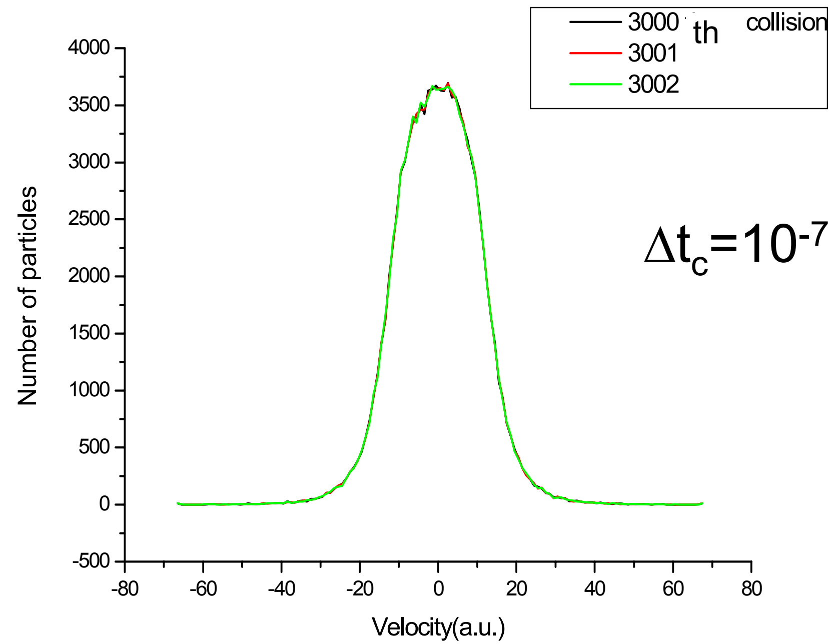
- PIC method has an excellent v-space resolution of neoclassical collisional physics
  $\Rightarrow$ Many published papers reproducing neoclassical phys.
- There is room for improvement.
- PIC Monte Carlo (MC) collisions $\Rightarrow$ MC noise.
- In order to reduce the collisional MC noise at low energy, XGC uses very frequent collision operations over extended cells ($\Delta t_c \leq 10^{-3}\, \tau_b$).
  $\Rightarrow$Cannot use cheap particle pushing techniques



- New methods are under development to reduce the MC noise, hence to speed up the simulation by increasing Δt_c
  - Gridless Quiet Spline Collisions (E. Yoon-CS Chang),
  - On Grid (F. Hinton, Lattice-Boltzman), (S. parker, 89) (Albreight, et al, 03),

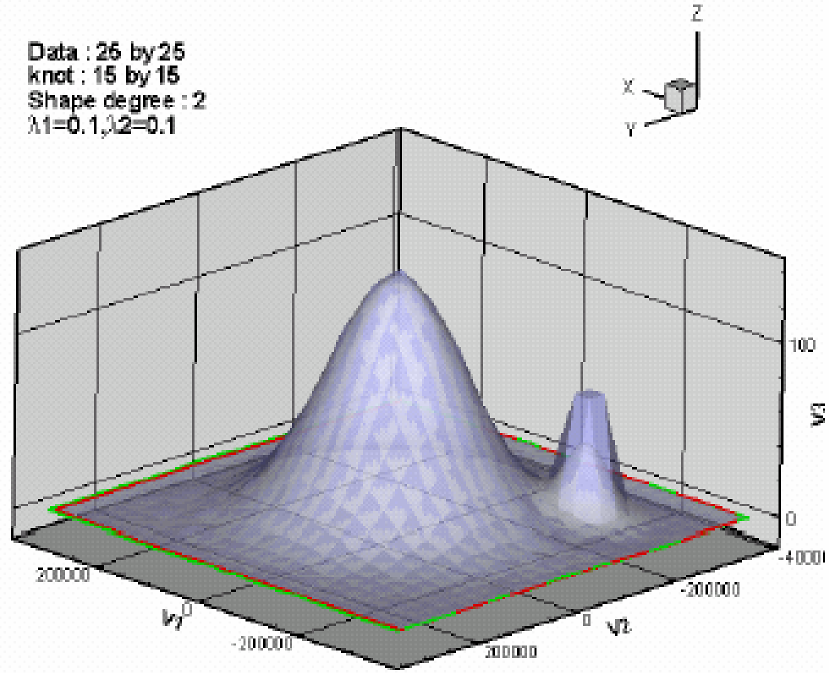
Monte Carlo Collisions is excellent at small Δt_c, but slows down the simulation





$\Delta t_c = 10^{-7}$ s

This level of MC noise reproduces the neoclassical physics well in XGC.



P-spline property : Conserve moments(means, variance)
Blue : Original, White : smoothing results

Noise reducing nonlinear FP collision scheme (QSC)

- 2D spline fit $f(v_1,v_2)$ from particles (noise smoothing)
- Use RMJ form to find $C(v_\perp v_\parallel)$
- Adjust weights according to the new $f(v_\perp v_\parallel)$

$$\gamma_{ss'} \equiv \frac{4\pi e_s^2 e_{s'}^2}{m_s} \ln \Lambda$$

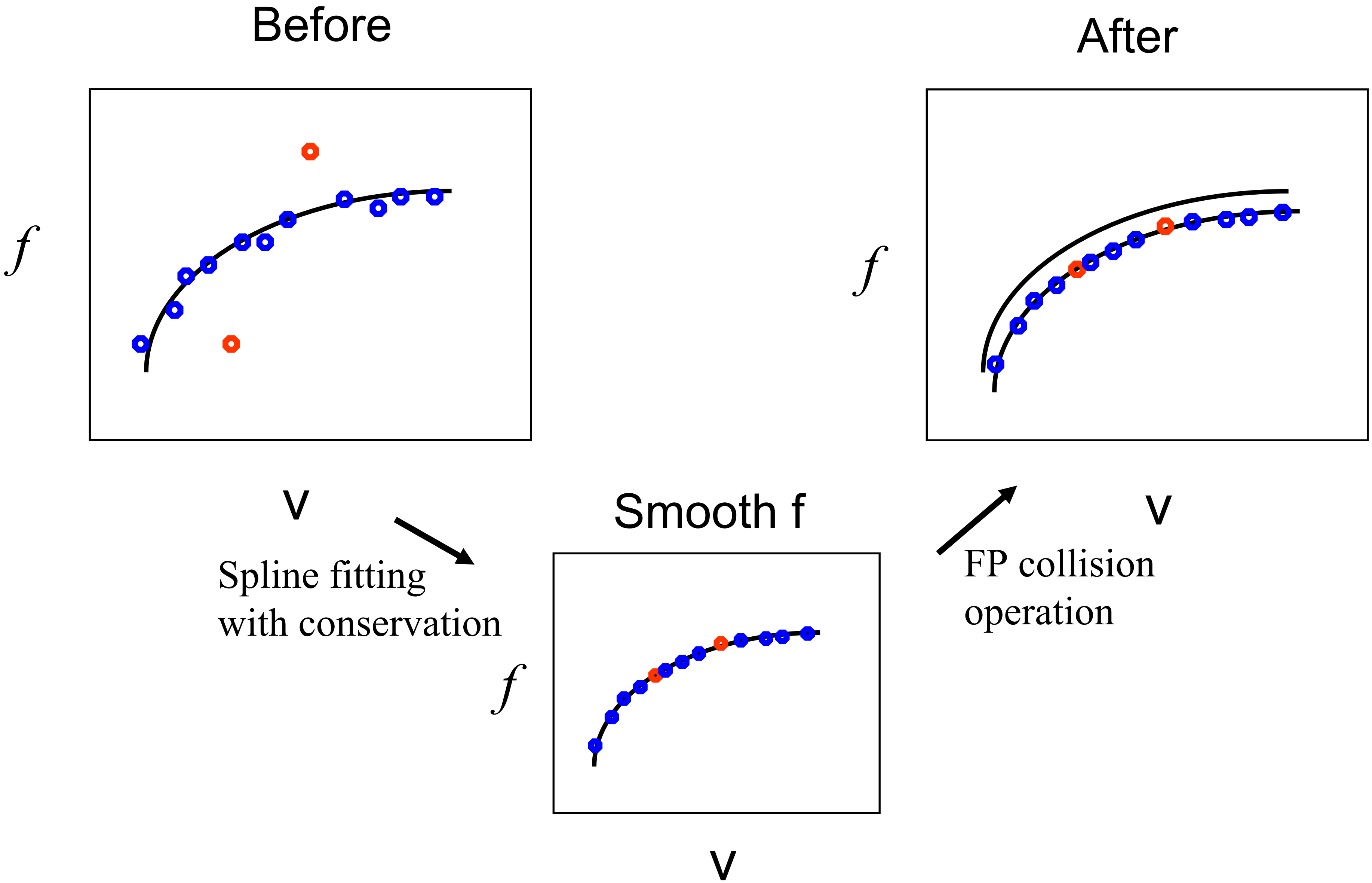
RMJ Form

$$C_{ss'} = \frac{\gamma_{ss'}}{2}\left\{ \frac{1}{m_s}\frac{\partial^2}{\partial v_\alpha \partial v_\beta}\left(f_s \frac{\partial^2 G_{s'}}{\partial v_\alpha \partial v_\beta}\right) - 2\left(\frac{1}{m_s}+\frac{1}{m_{s'}}\right)\frac{\partial}{\partial v_\alpha}\left(f_s \frac{\partial H_{s'}}{\partial v_\alpha}\right)\right\}$$

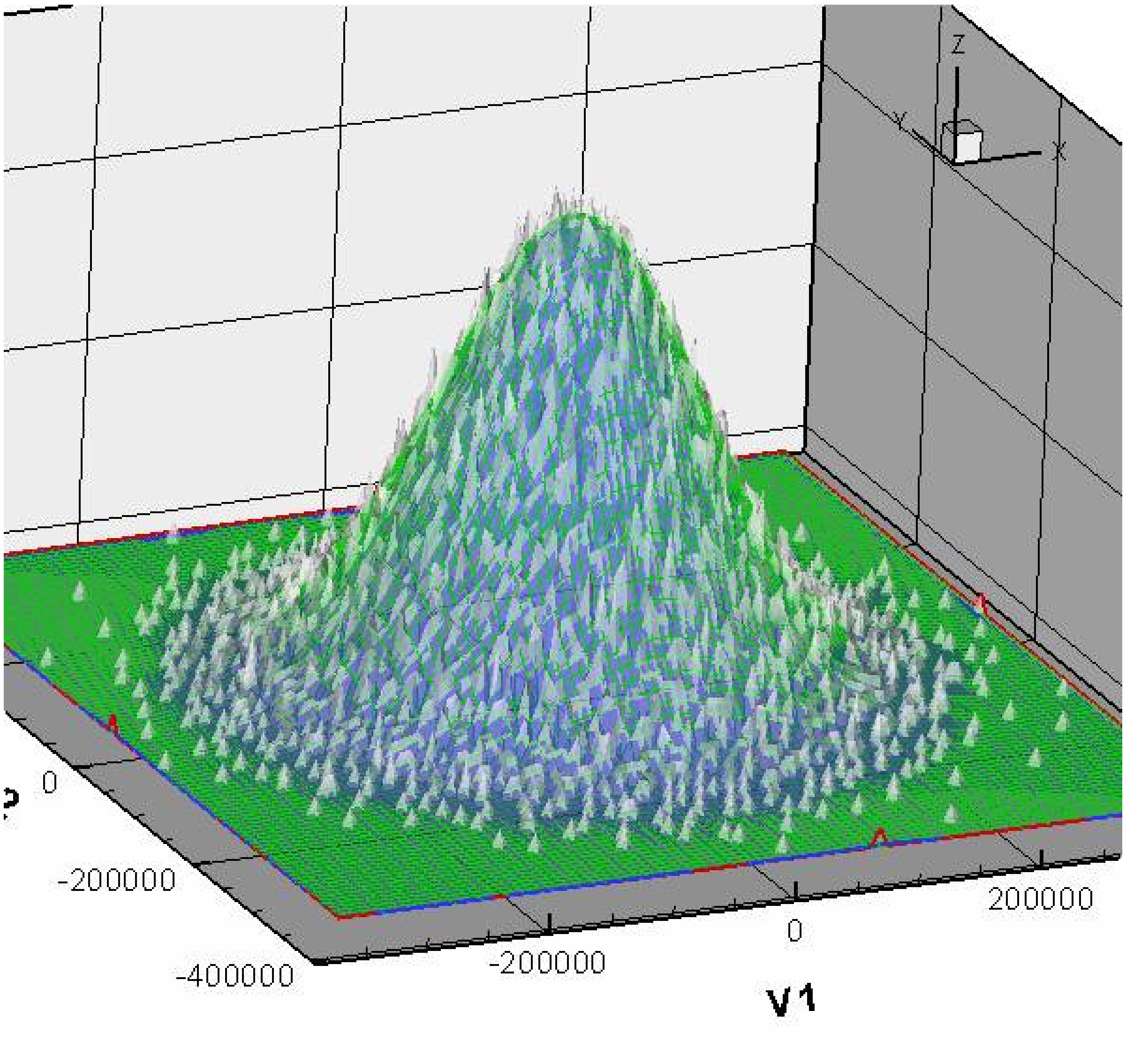
$$\nabla_v^2 G_s = 2H_s \ , \ \nabla_v^2 H_s = -4\pi f$$

$$G_s(\mathbf{v}) = \int d^3v' f_s u \ , \ H_s(\mathbf{v}) = \int d^3v' f_{s'} \frac{1}{u}$$

Particle noise can be removed to a desired degree during FP collision operatoin



3^{rd} order spline fit over 10,000 Random Maxwellian Particles (momentum and energy conserved)



Entropy production rate by the smoothing operation may not cause much inaccuracy to the coulomb collisions

$dS_C/dt = -\int d^3v \ln[f_o + f_1]\, C[f_1]$

$dS_N/dt = -\int d^3v \ln[\langle f \rangle + f_\delta]\, N[f_\delta]$

Thus, the noise smoothing operation may add inaccuracy to the collisions (but, conserving).

Smoothing Collision

$f_\delta N[f_\delta] \sim f_\delta^2/dt \propto \delta^2/dt \quad : \quad f_1 C[f_1] \sim \nu_{eff} f_1^2 \propto \nu_{eff} (\Delta_b/L)^2$

$\Rightarrow$ *The noise δ should not grow up to*

$(\nu_{eff} dt)^{1/2}\, (\Delta_b/L)$ *during each collision time interval*

~0.5 *~1*

CGL *pedestal*

Evidence has been seen from the XGC-RF code (a few hundred milliseconds delta-f runs with smoothing, J. Kwon).

Computing time comparison between two nonlinear PIC collision schemes

		100,000 particles	10,000 particles
Binary Monte Carlo Collisions (vector)			
	real	74m11.531s	0m 33.788s
	user	74m11.490s	0m 33.766s
	sys	0m 0.020s	0m 0.008s
Fokker-Planck Weight Collisions			
	real	0m 2.728s	0m 2.609s
	user	0m 2.276s	0m 2.180s
	sys	0m 0.152s	0m 0.144s

Future PLANS (Pre APS/IAEA 2006)

XGC edge kinetic code

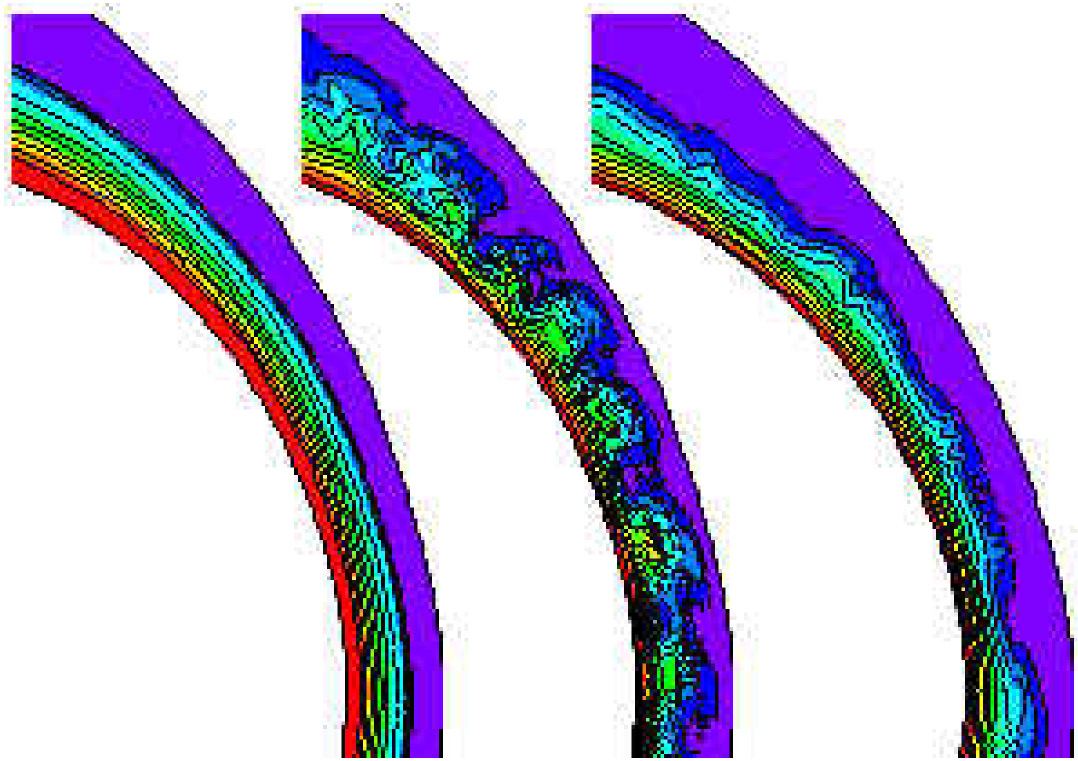
- Improve XGC-1 in the neoclassical environment
  - Improve the fluctuation average technique
  - Optimize solvers to the grid requirement
  (General/Direct → FEM/Direct-AMG → General/AMG)
- Implement the Quiet Spline Collision scheme
- V&V of neoclassical dynamics in pedestal/scrape-off
- Study the electrostatic turbulence with adiabatic electrons from the integrated edge simulation of **neoclassical+ES turbulence+neutral physics**

Integrated simulation of Kinetic and MHD/ELM

- Complete the first-phase integration framework between XGC and MHD/2fluid (no kinetic feedback from XGC during ELM/MHD crash)
- Particle monitoring and visualization

Initial XGC Coupling with an MHD/2fluid code has started (density, temperature, E_r, flow and bootstrap current profiles)

M3D



Pressure at t = 0, 67, and 106 Alfven times

Future plans (Post APS/IAEA 2006, and 2007)

XGC edge kinetic code

- Adiabatic electrons $\rightarrow$ split-weight electrons
- Study the non-adiabatic electron effect on electrostatic turbulence
- Begin implementing the E&M turbulence into XGC (2007-2008)

Integrated simulation of kinetic and MHD/ELM

- Implement the second-phase integration framework between XGC and MHD/2fluid (kinetic feedback during MHD/ELM crash)

A big question: Should we take advantage of the leadership class computing and push the limit to the complete full-f simulation of edge plasma? (up to ~ 20 τ_{ib} , extending time to experimental scale using multi-time simulation)