Center for Plasma Edge Simulation

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Understanding plasma transport in RMP using XGC0 particle code

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In collaboration with
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Acknowledgement to DIII-D RMP team

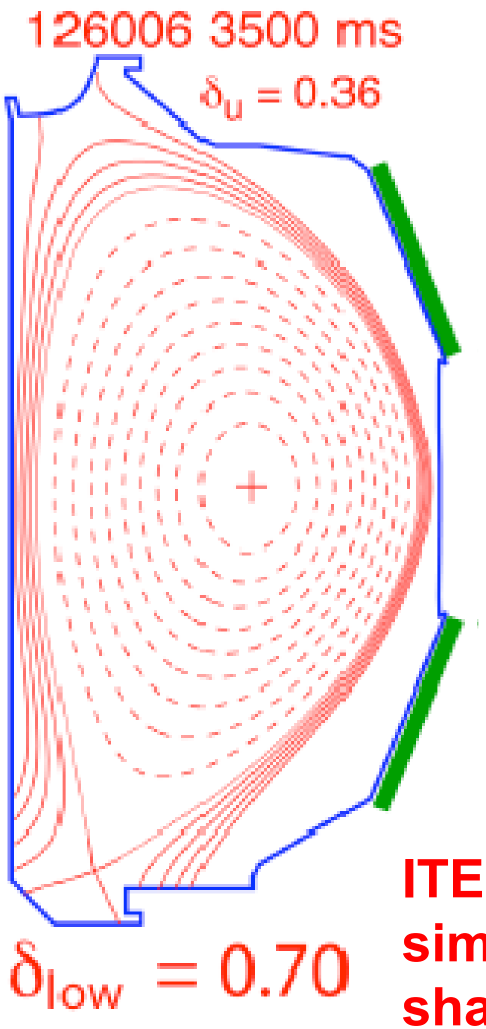
SciDAC FSP Prototype Center for Plasma Edge Simulation

Observed phenomena on DIII-D

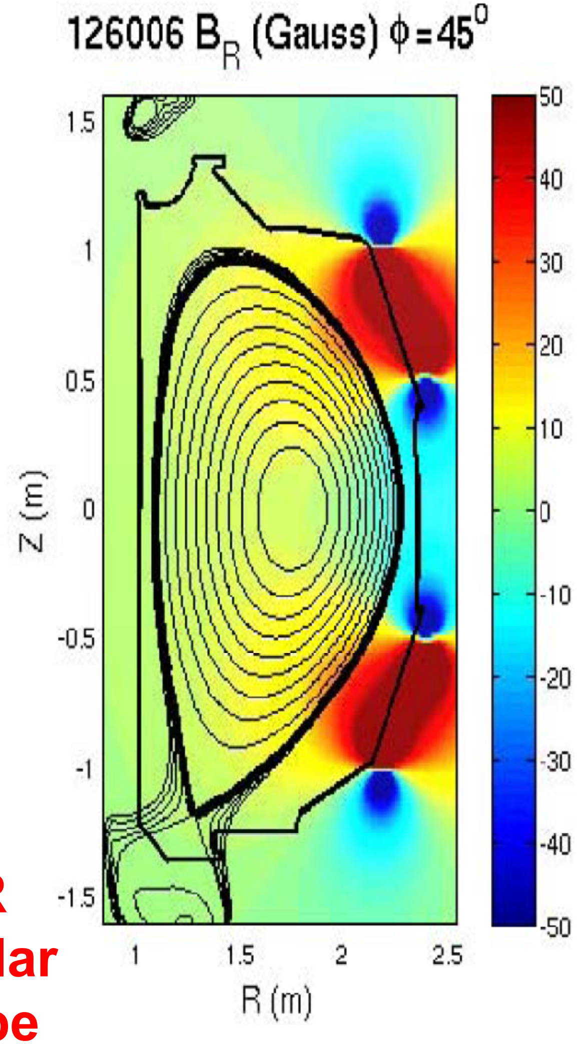
- **Burrell, et al, PPCF 47, B37(05); Evans, et al, Nature Physics 2, 419 (06)**
- q=m/n=11/3,12/3,13/3 within pedestal region and $\delta B/B \sim 3\times10^{-4}$
- ITER relevant collisionality: electron collisionality ~ 0.1

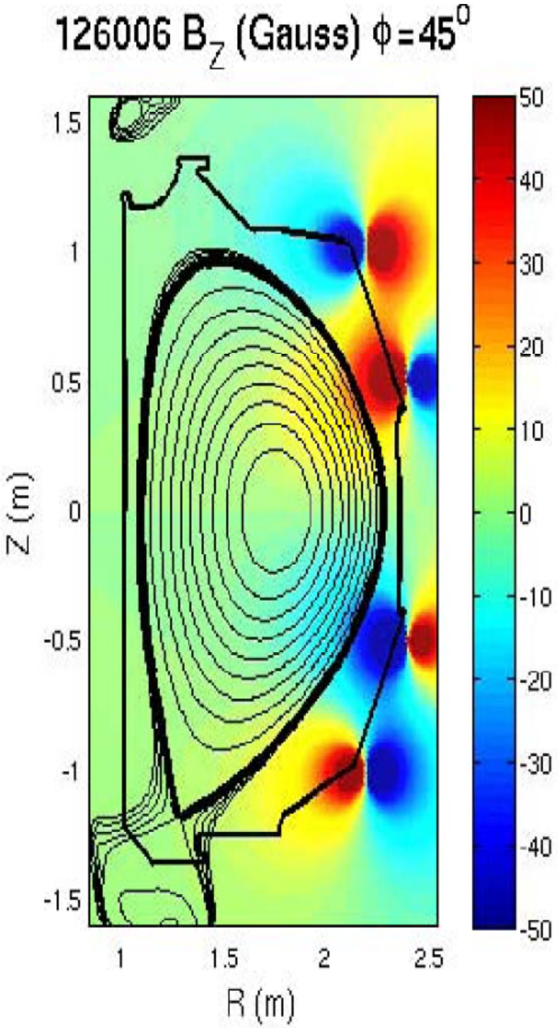
- Density collapses (below 2×10^{19} m^{-3}), but not the temperatures
- Toroidal rotation increases promptly by RMP
- T_i increases significantly, T_e steepens just inside the separatrix with little change of ∇P there.
- E_r well persists at narrow radial width just inside the separatrix

B-quilibrium (126006) and vacuum RMP profiles (from I. Joseph)


126006 3500 ms

ITER similar shape


126006 B_R (Gauss) $\phi = 45^0$


126006 B_Z (Gauss) $\phi = 45^0$

Simulation condition

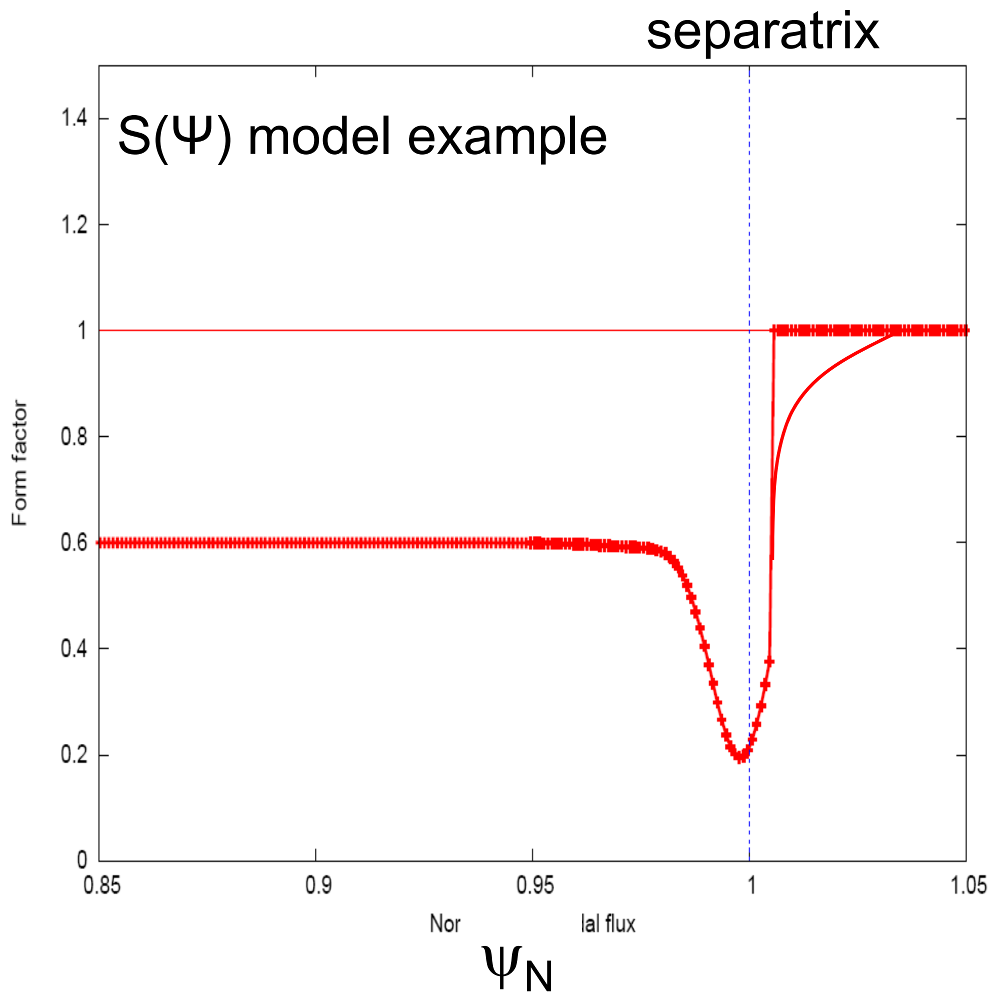
- Use reduced m_i / m_e (=1000) for time saving (~5% error)
- We use both vacuum RMP and a screened RMP model
- RMP is turned on after a neoclassical quasi-steady equilibrium is established (~10 ion toroidal transit time).
- Total simulation time ~60 ion toroidal transits (~5 ms in physical time)
- The goal is to compare the plasma before and after the RMP and to understand the underlying transport physics
- Neutral recycling rate = 0.9 (active pumping)
- Heat flux from core: 3.5 MW to ions and 3.5 MW to electrons
- A random walk anomalous radial diffusion of $D=0.1 m^2/sec$ is superimposed on the Lagrangian particle guiding center motion. Later on, we found $D= 0.25\ m^2/s$ is more appropriate (from experimental comparison).

Plasma shielding effect can be examined by multiplying a model screening form factor S(Ψ)

$$\delta\mathbf{B} = \nabla\times(S(\psi)\ \delta\mathbf{A}_{vac})$$

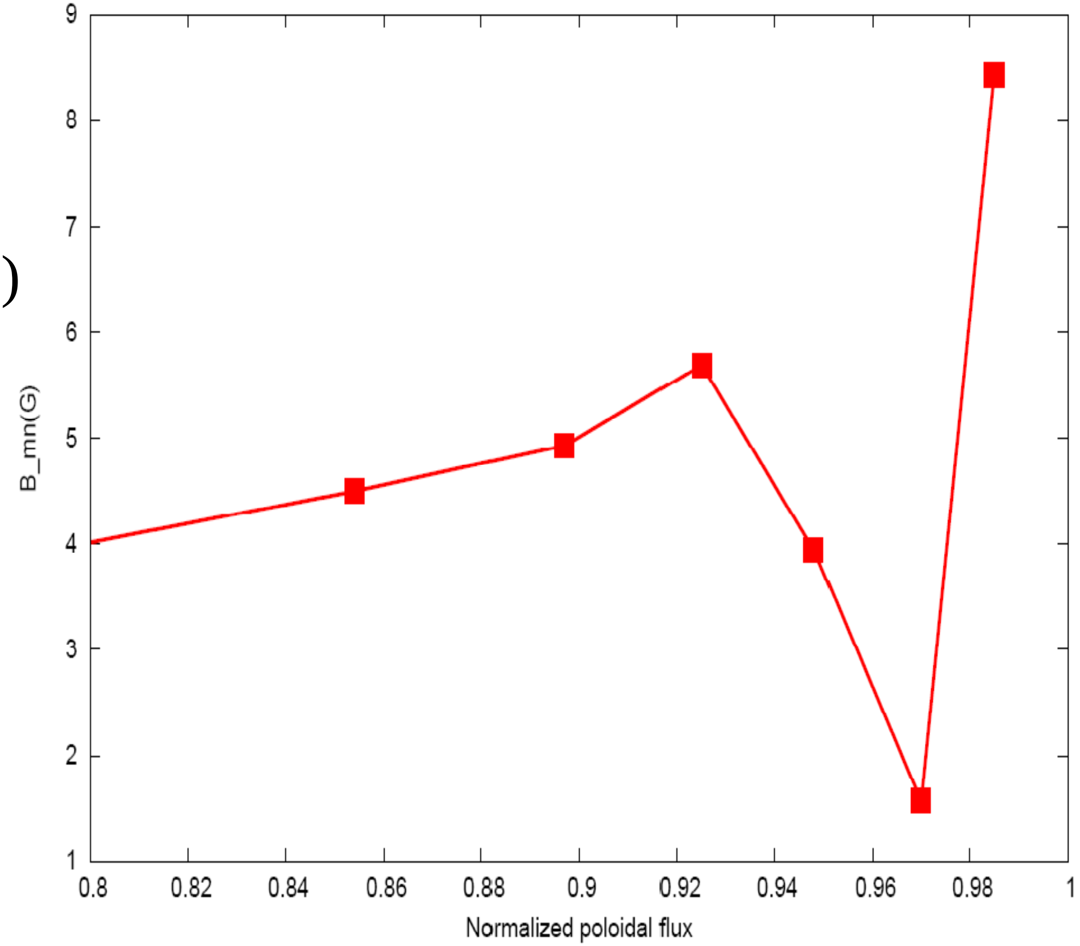
[Fitzpatrick (98), J. Park, et al., and Strauss, et al, IAEA2008]

- Strong plasma rotation can screen RMP penetration
- Plasma can also amplify RMP by resonant interaction



Example: IPEC ideal MHD simulation shows RMP screening with a local minimum inside separatrix

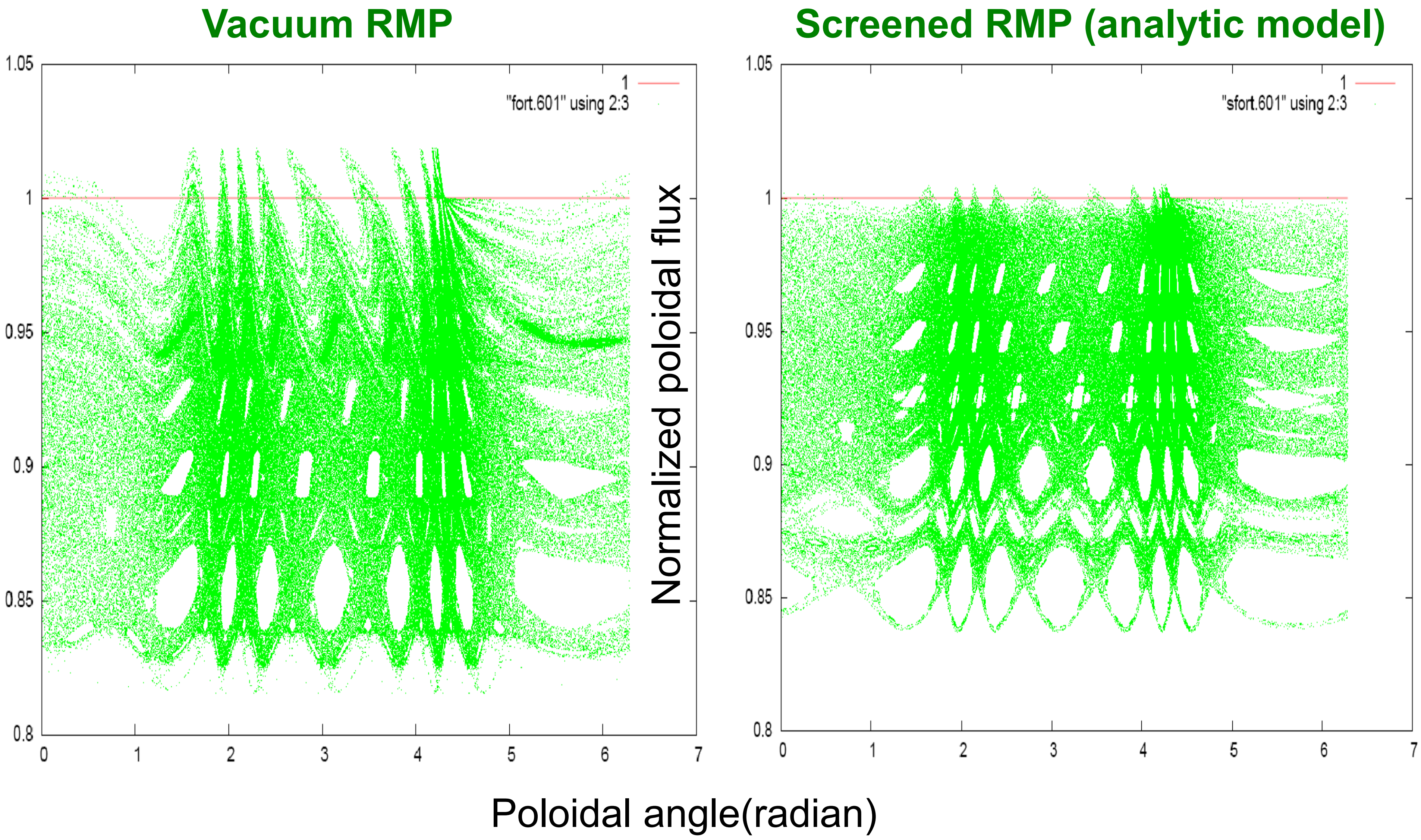
IPEC: ideally perturbed equilibrium code, **J.K.Park, PoP 14, 052110 (2007)**



IPEC results for 126006 provided by J.K.Park

Radial magnetic field components here is in Hamada coordinates

Poincare plots for vacuum and screened RMP fields



Theoretical quasilinear electron heat flux in a collisionless limit

Rechester-Rosenbluth PRL (1978)

- Heat transport along the stochastic magnetic field assuming maxwellian distribution function for electron ensemble

$$\Gamma_r = -\frac{1}{\sqrt{\pi}} D_m V_{the} \left(\frac{1}{n}\frac{\partial n}{\partial r} + \frac{1}{2T_e}\frac{\partial T_e}{\partial r} + \frac{eE_r}{T_e} \right) n,$$

$$Q_r = -\frac{2}{\sqrt{\pi}} D_m V_{the} \left(\frac{1}{n}\frac{\partial n}{\partial r} + \frac{3}{2T_e}\frac{\partial T_e}{\partial r} + \frac{eE_r}{T_e} \right) nT_e,$$

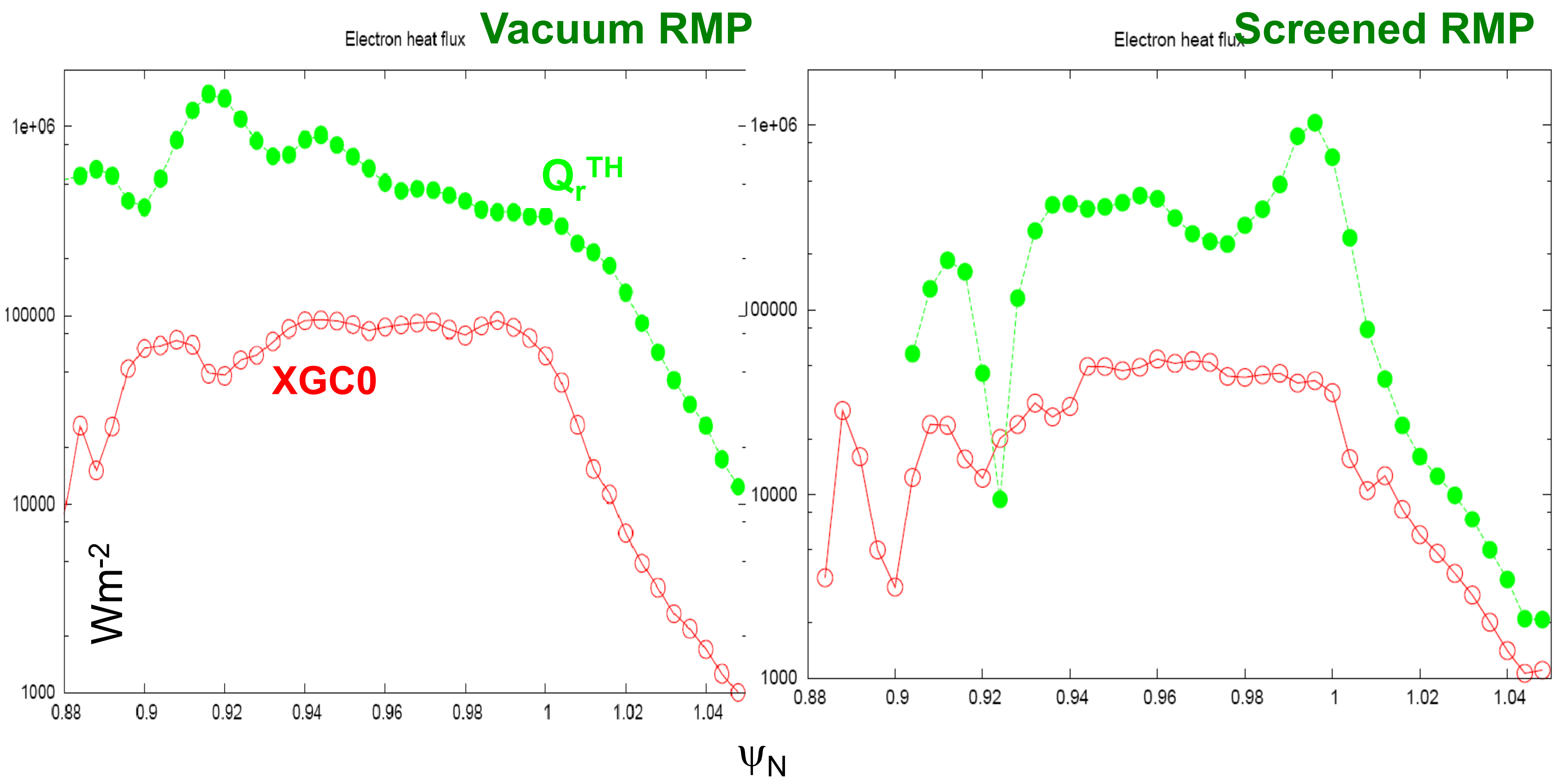
where quasilinear expression for field line diffusion coefficient D_m is given by $D_m = \pi q R_0 |\delta B / B|^2$ which is evaluated at each resonance surface.

- Setting Γ_r to zero gives theoretical ambipolar radial electric field and the corresponding heat flux expression

$$E_r^{TH} = -\frac{T_e}{e}\left[\frac{1}{n}\frac{\partial n}{\partial r} + \frac{1}{2T}\frac{\partial T}{\partial r} \right],$$

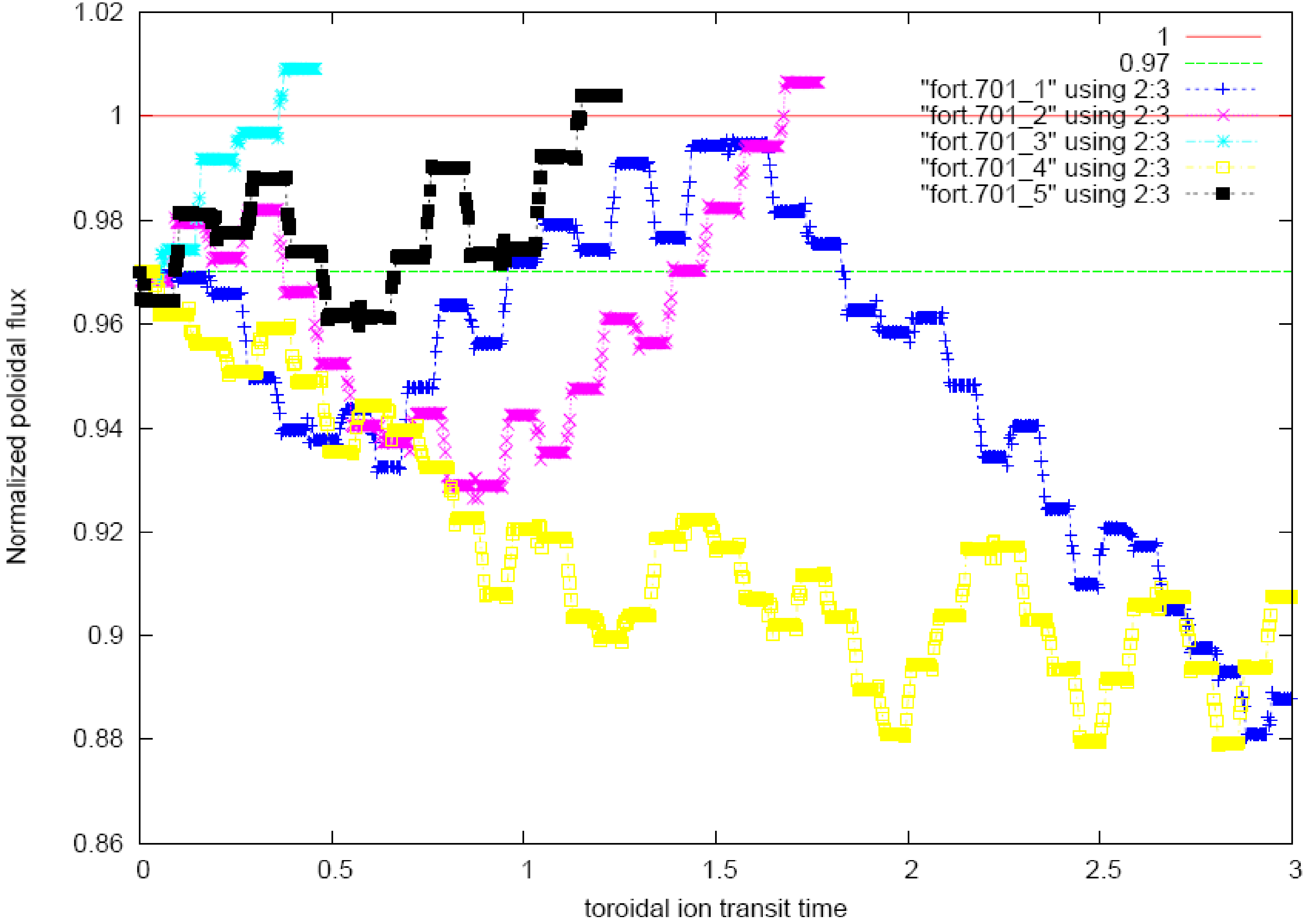
$$Q_r^{TH} = -\frac{2}{\sqrt{\pi}} D_m V_{the}\, n \frac{\partial T}{\partial r}$$

XGC0 electron heat flux is much smaller than Collisionless Rechester-Rosenbluth



Actual heat flux is much different from Rechester-Rosenbluth formula due to several nonideal effects such as incomplete chaos, Er, mirror trapping, etc.

Single electron motions in Vacuum RMP: Far from Rechester-Rosenbluth type

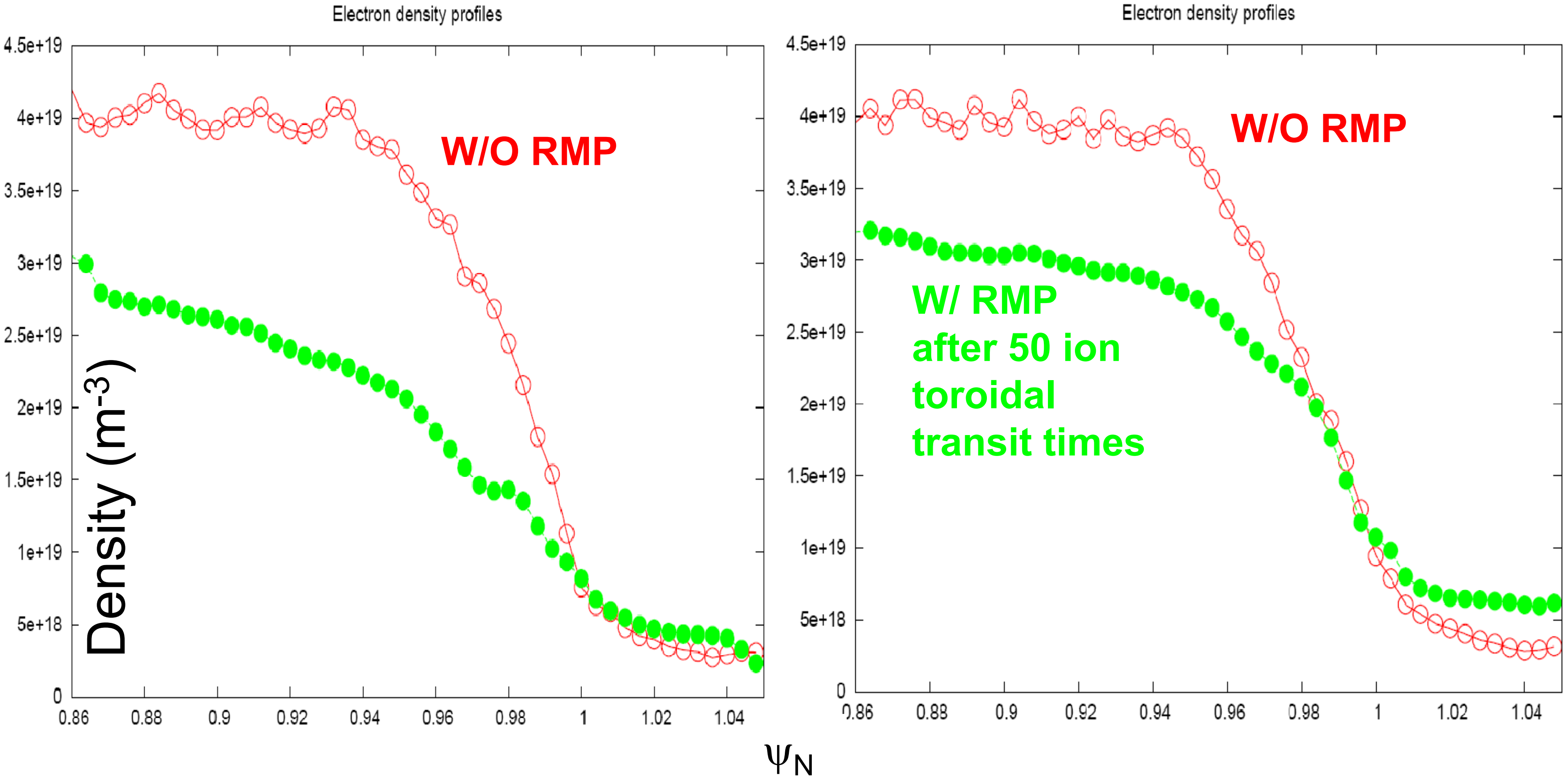


Density is reduced by RMPs

Recycling coefficient=0.9

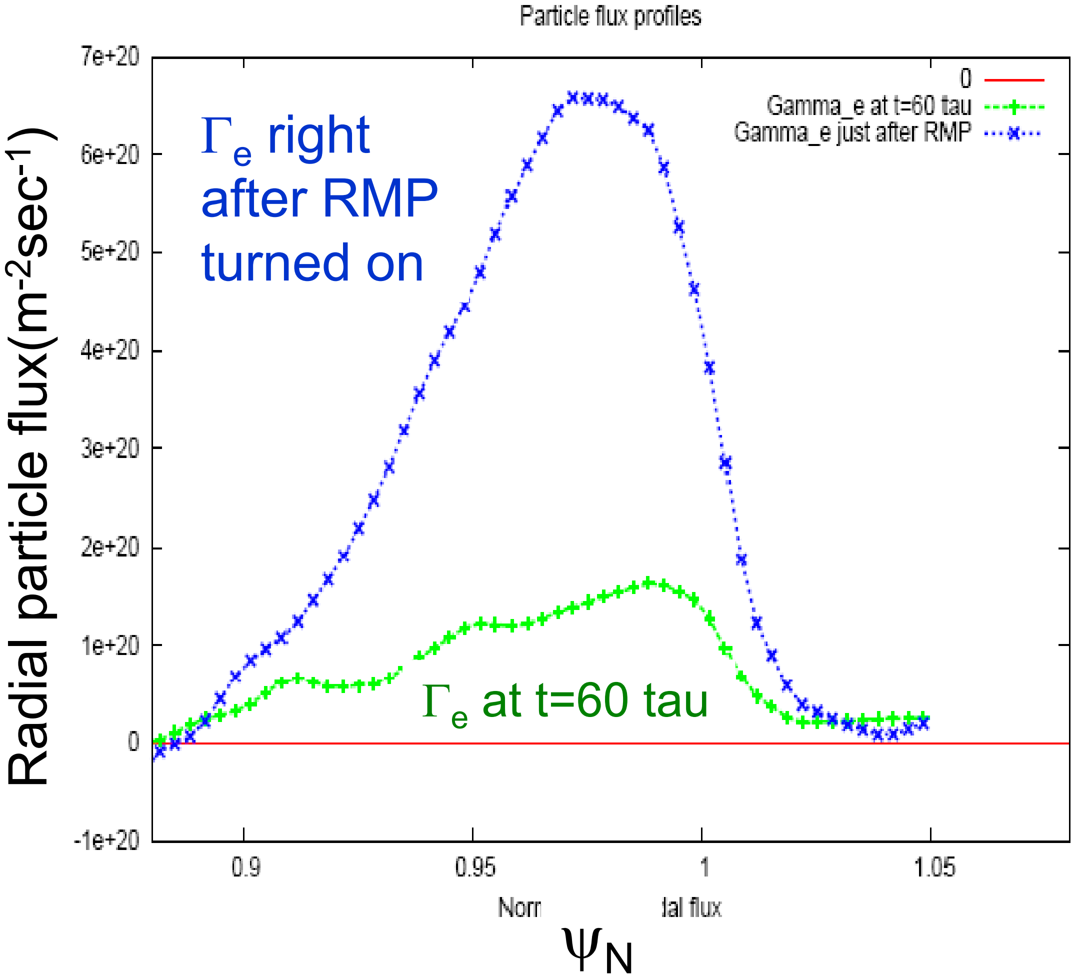
Vacuum RMP

Screened RMP



- As soon as RMP is turned on, density drops promptly

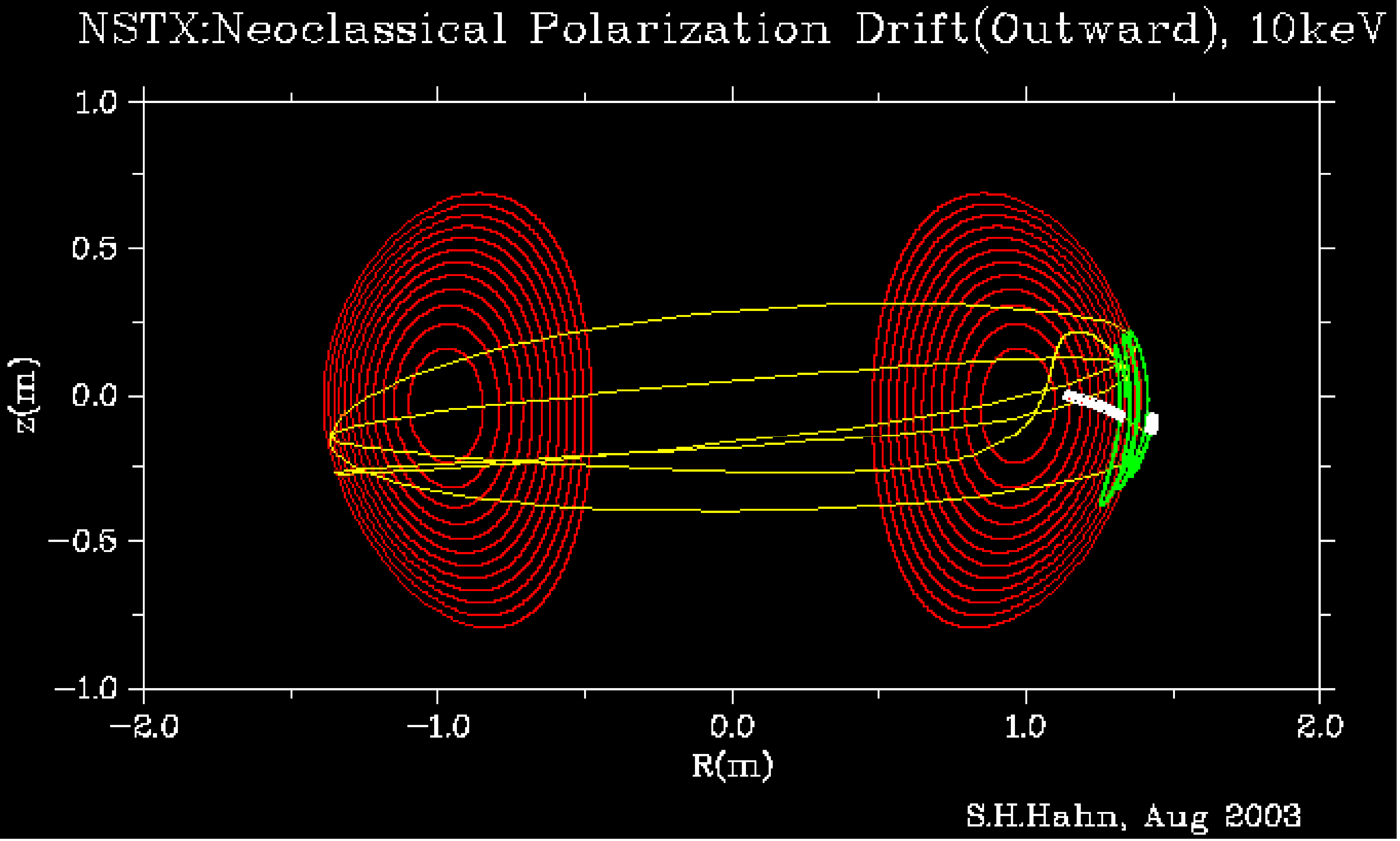
Radial particle flux after RMP



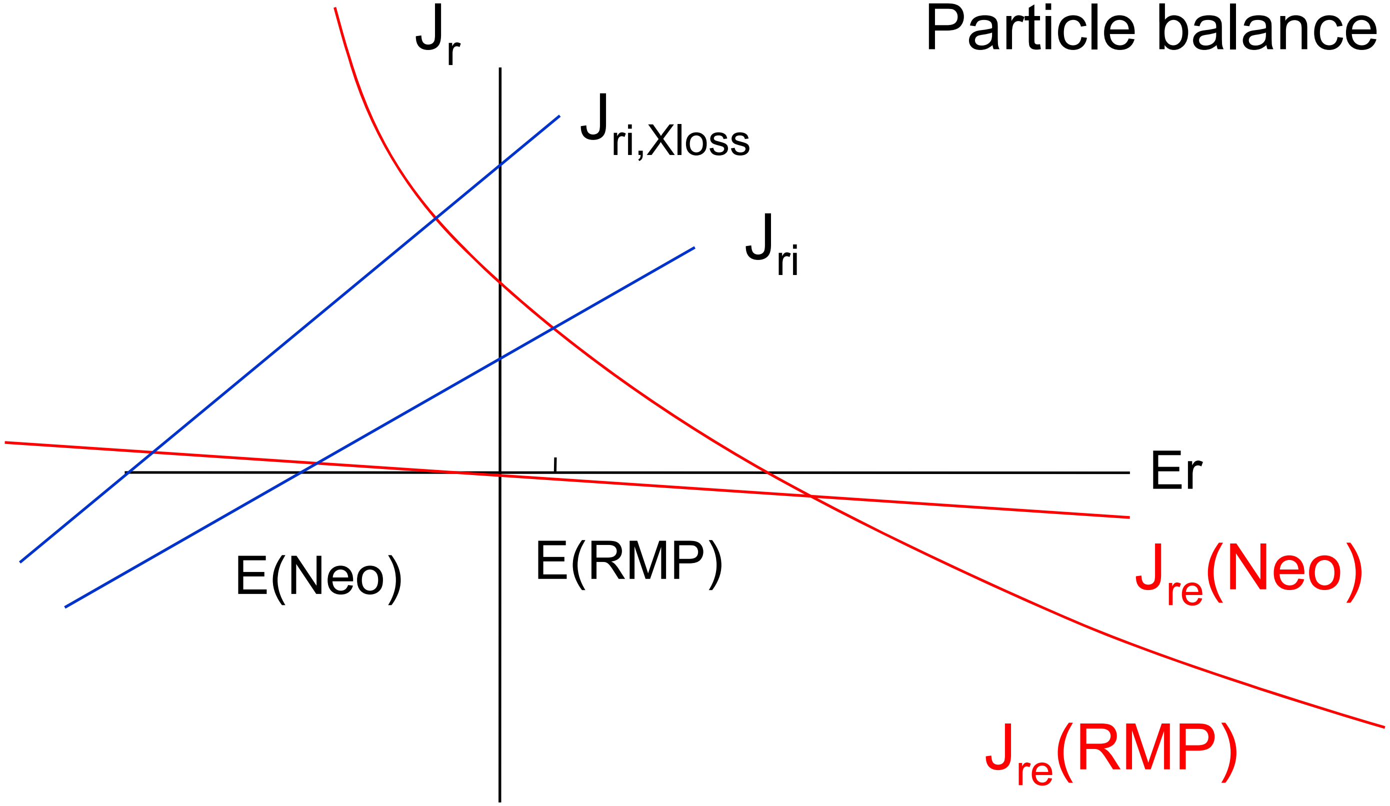
Radial particle flux is maximal right after RMP application, and then decays to quasi-steady state. E_r adjusts itself to achieve $\Gamma_i(E_{RMP}) = \Gamma_e(E_{RMP})$ for $E_{RMP} \neq E_{neo}$

Initial ion flux is from strong polarization drift

[Baek, Ku, Chang, PoP, 13, 012503 (2006)]



Particle balance

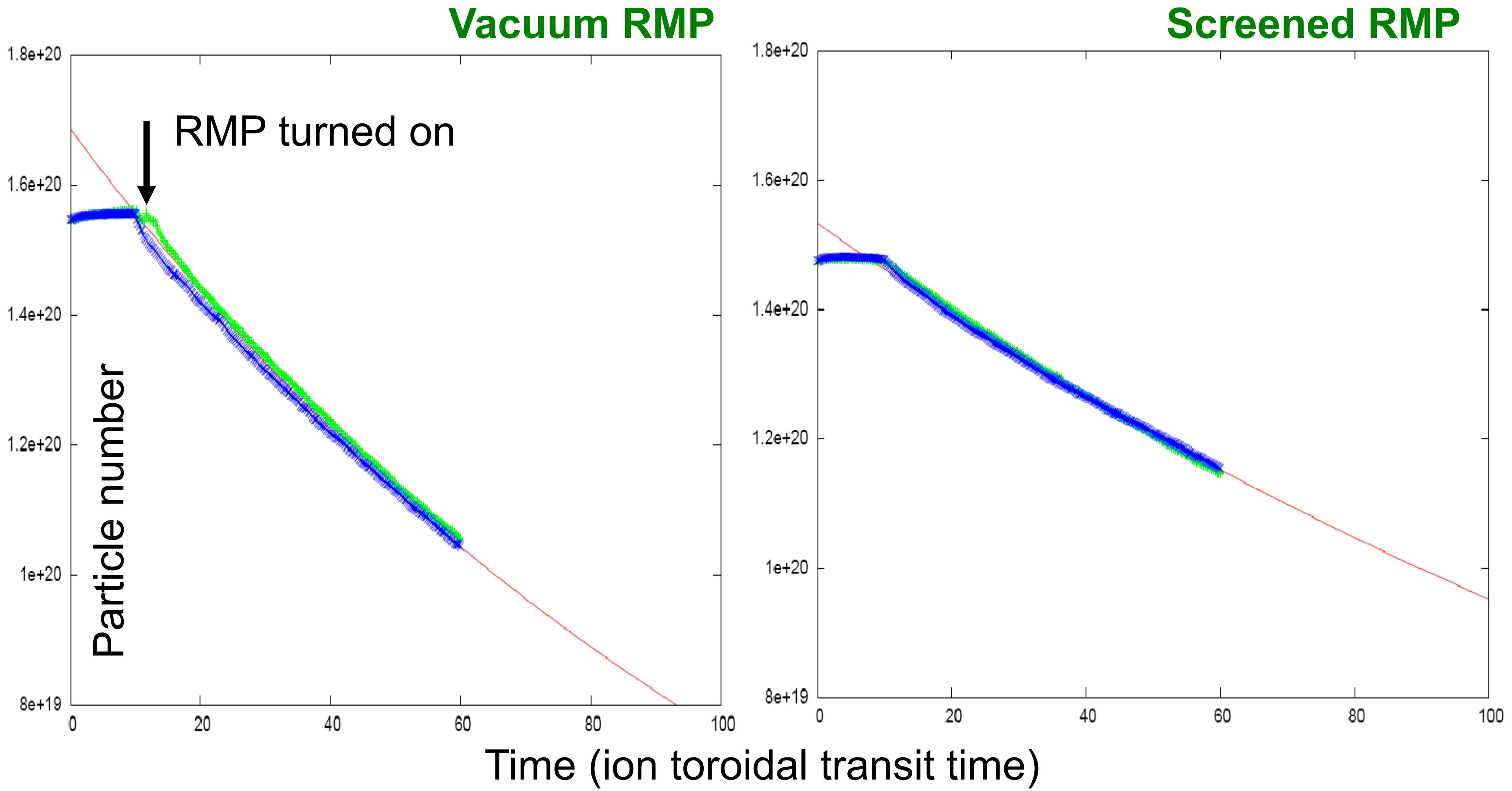


Neoclassical transport is automatically ambipolar only in neoclassical equilibrium ⇒ strong radial conductivity.

E(Neo)

$$\mathbf{u_{i\,\parallel} = (cT_i/eB_p)[k\,d\mathit{log}T_i/dr - d\mathit{log}\;p_i/dr - (e/T_i)d\phi/dr]}$$

Temporal changes of particle content inside the separatrix gives density e-folding time



Vacuum RMP

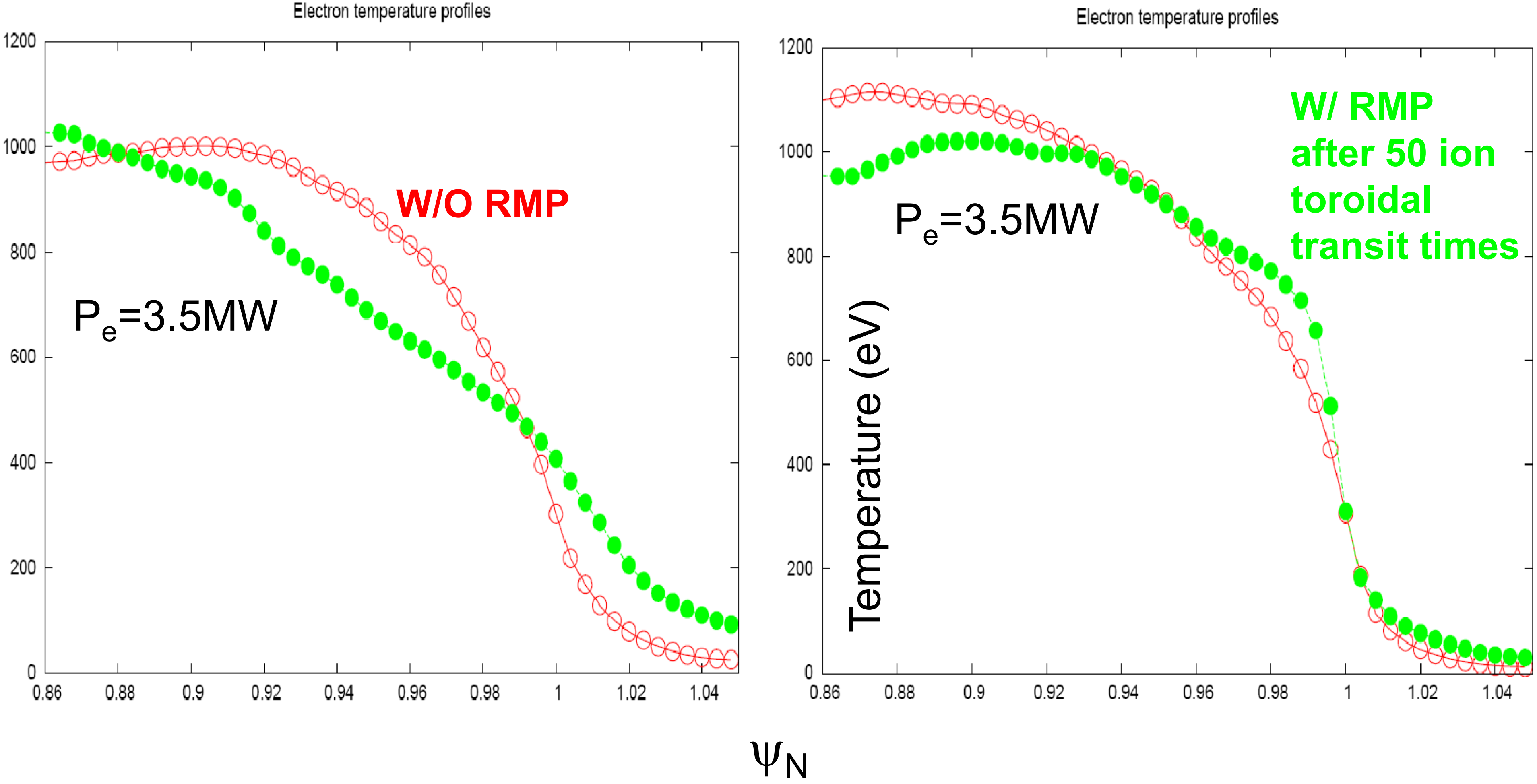
Screened RMP

RMP turned on

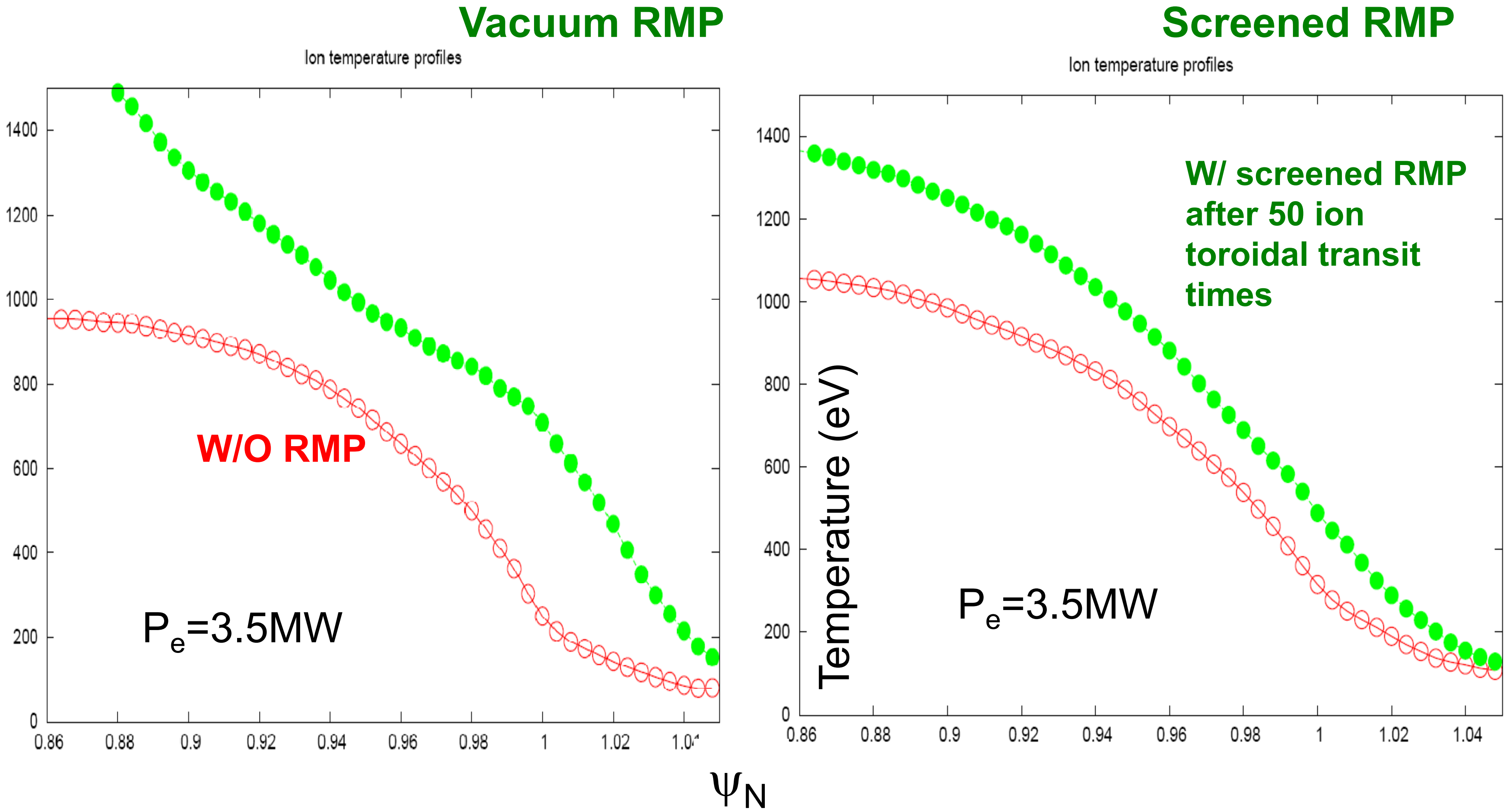
- Density e-folding time is about 10 ms for vacuum RMP and 20 ms for screened RMP.

Electron temperature profile steepens near the separatrix under screened RMP

Vacuum RMP **Screened RMP**

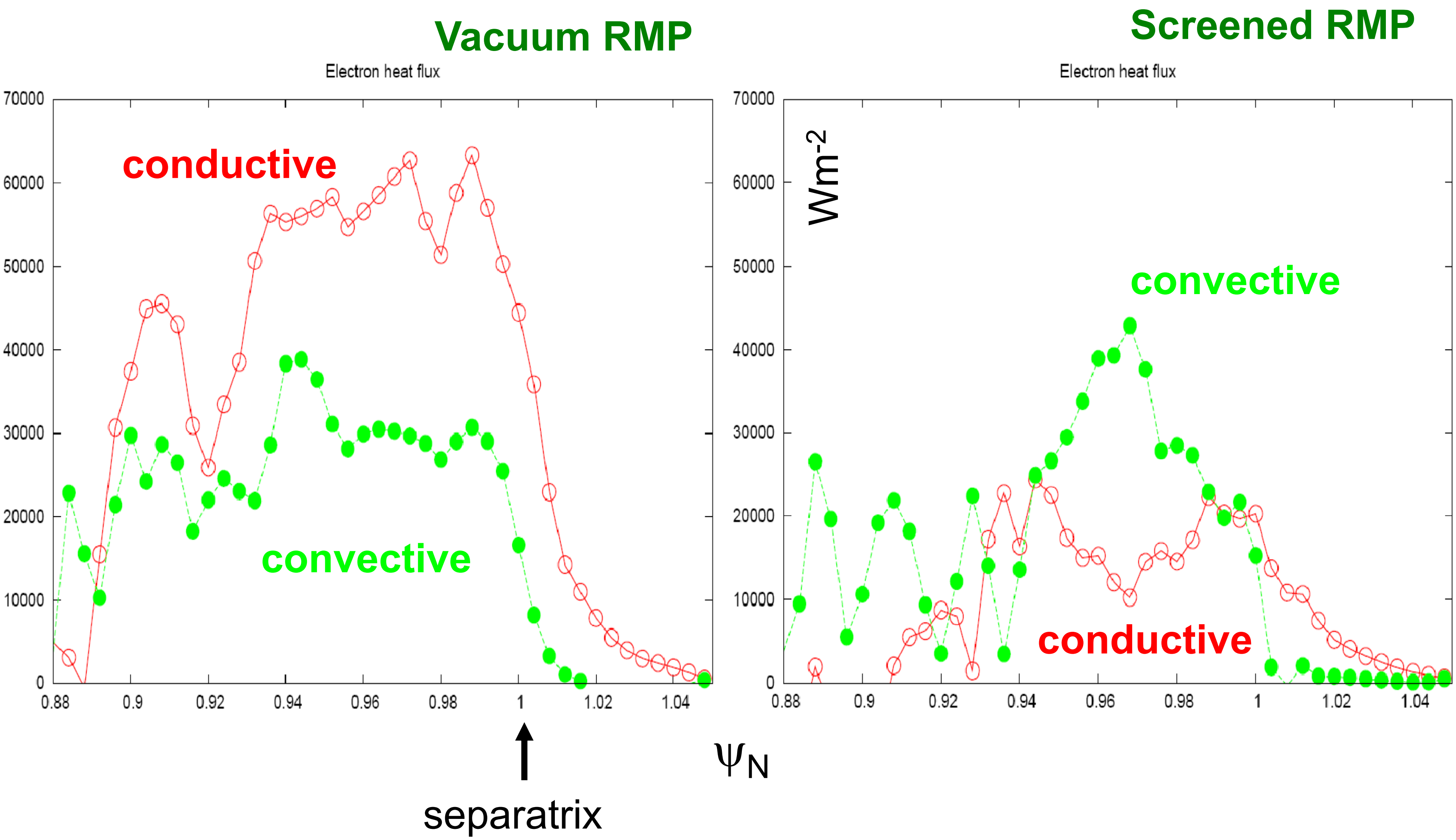


Ion temperature continues to rise, fueled by strong heat flow from core (ion thermal transport is still low under RMP, and the density is lower)

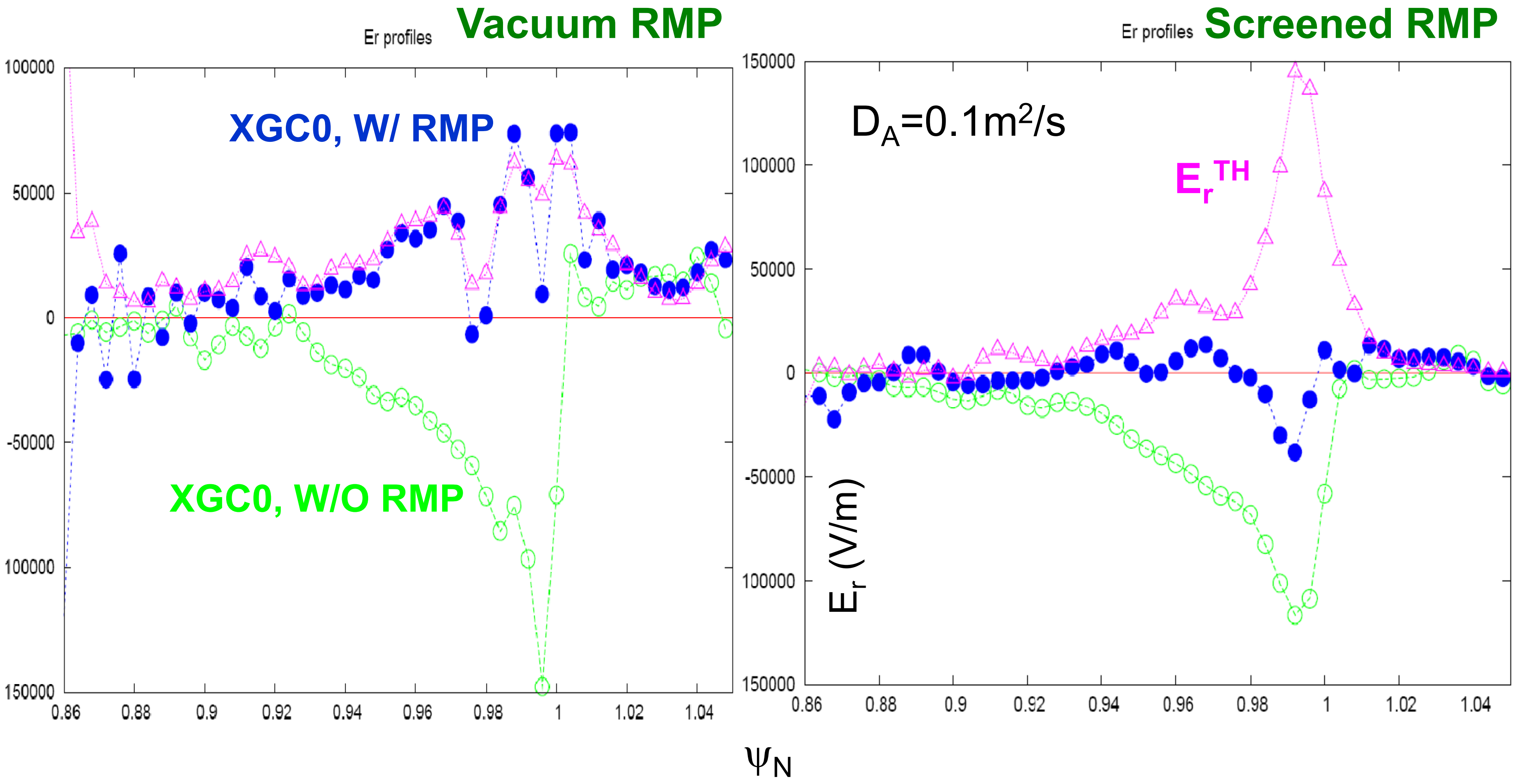


- T_e does not rise as much due to RMP enhanced heat transport.

Conductive radial electron heat loss ~ convective, inside the separatrix

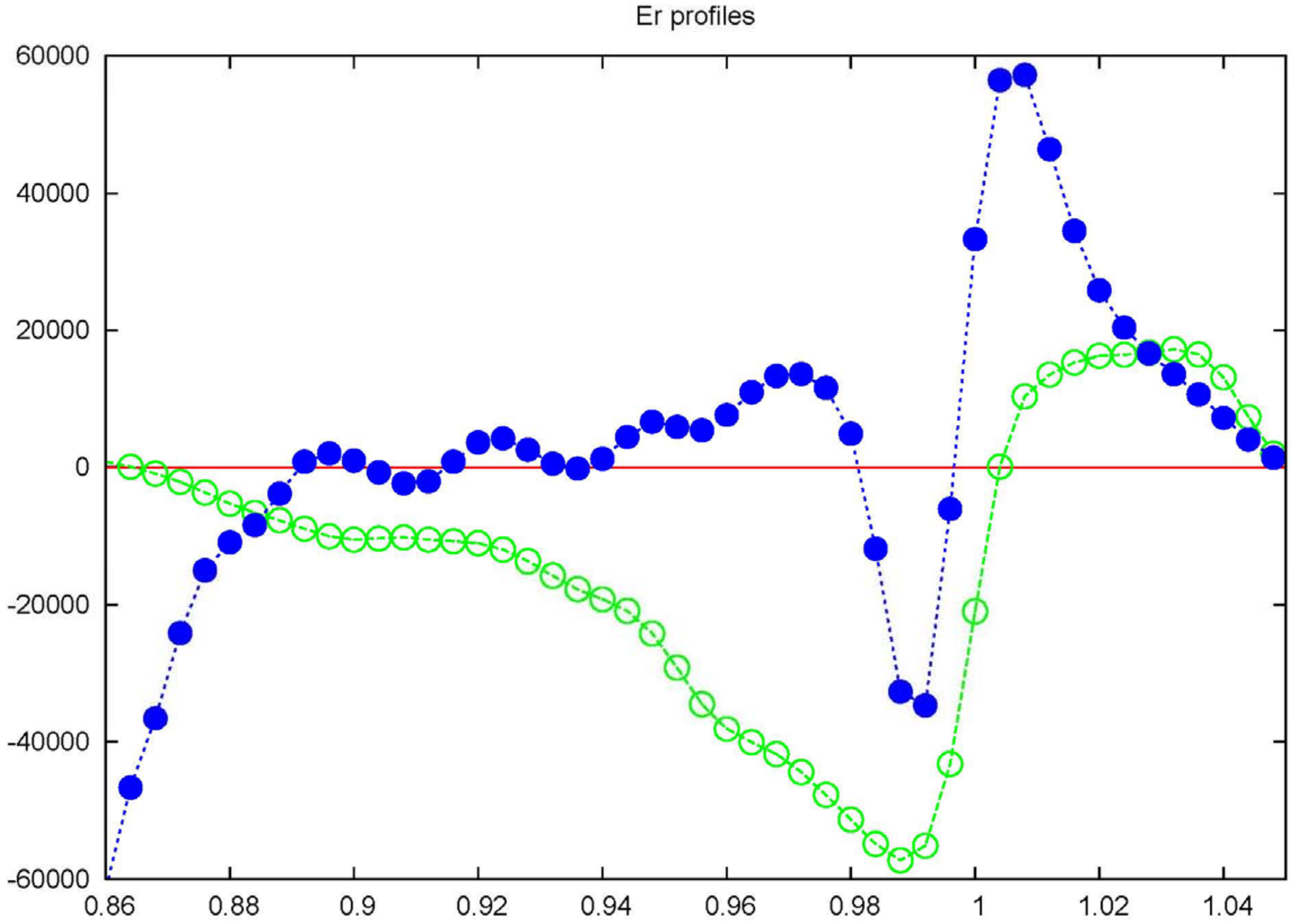


Narrow radial electric field well (from ion X-loss) can persist under screened RMPs



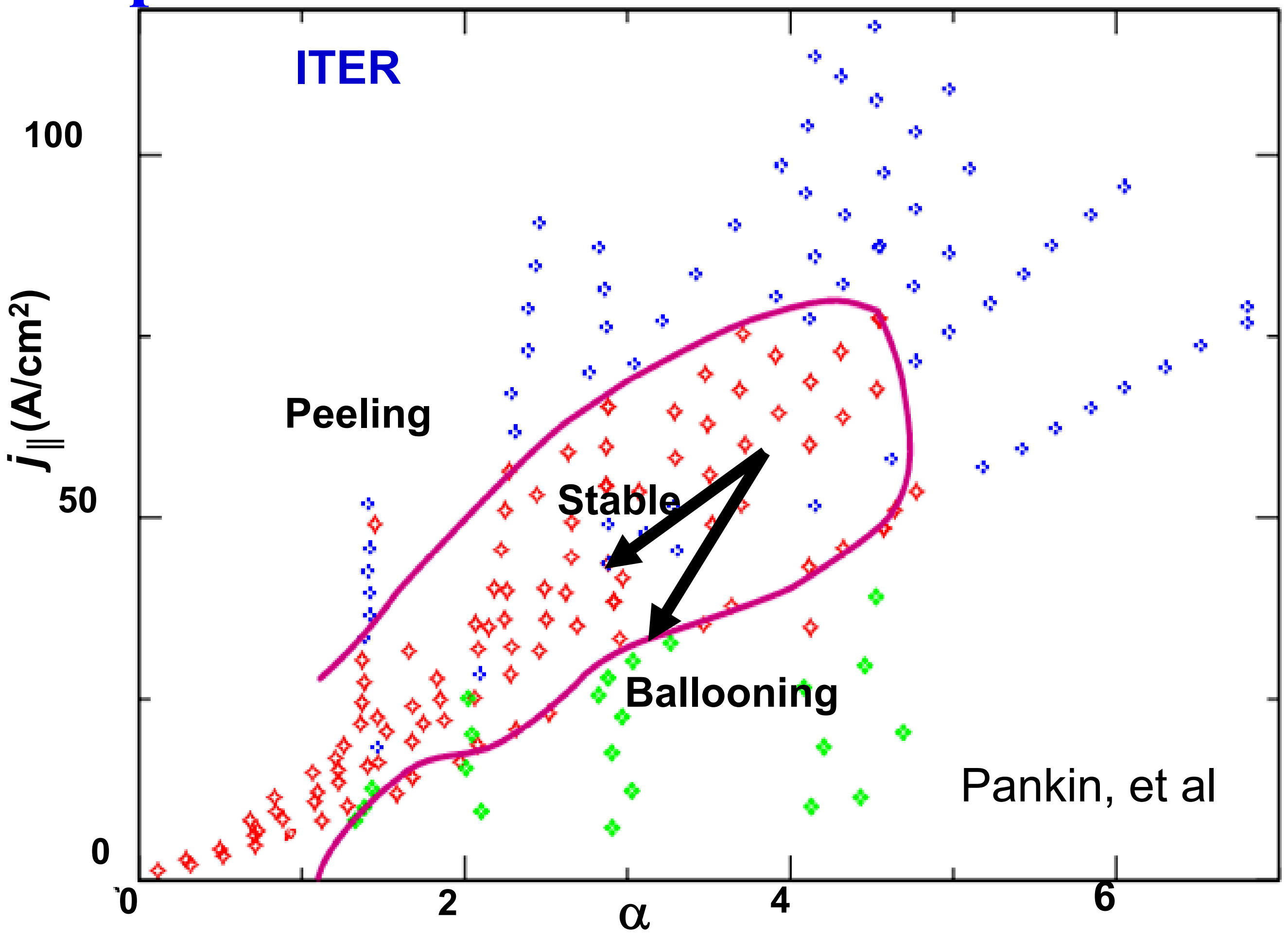
- Electron confining E_r from Einstein mobility relation is similar to XGC0 Er in vacuum RMP but much different in screened RMP

When we increase D_A to $0.25 m^2/s$, we get a much better agreement with experiment → another prediction for D_A

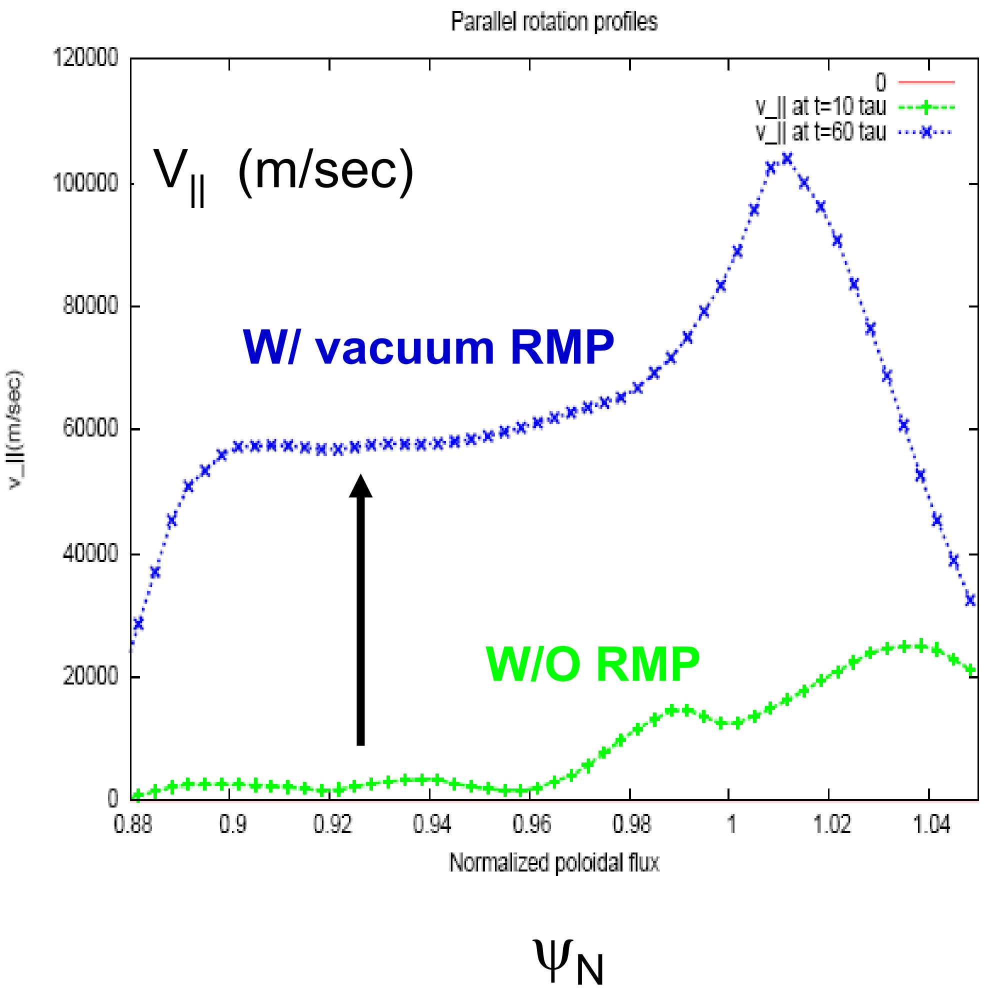


Different RMP effect on NSTX from DIII-D?

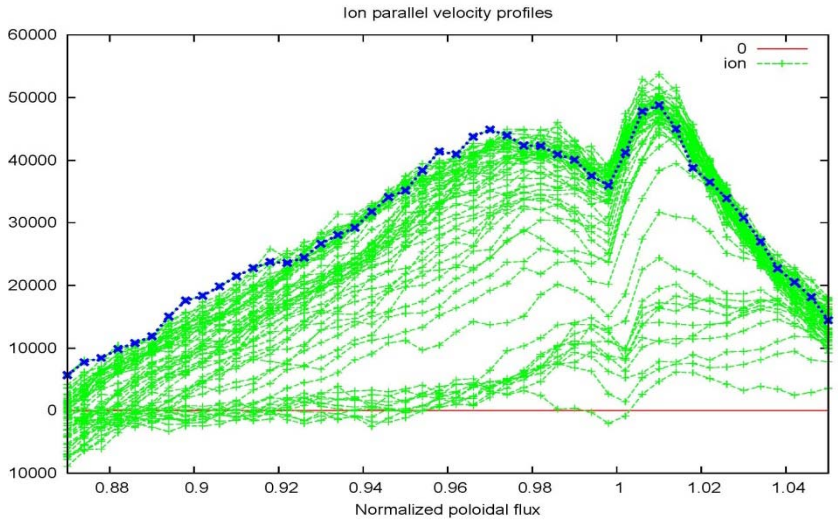
Self-consistent boostrap current is needed for a better prediction of the RMP effect on ELM



Parallel rotation increases significantly by RMPs



W/ screened RMP



The observed phenomena on DIII-D have been reproduced.

Black part is from the vacuum RMP, predicted from XGC0 before experimental collaboration

- Density collapses (below 2×10^{19} m^{-3}), but not the temperatures
- T_i increases significantly, Te does not collapse.
- Toroidal rotation increases promptly by RMP

Red part is from screened RMP model, after experimental collaboration

- T_e steepens just inside the separatrix (screened RMP), with little change of ∇P there
- E_r well persists at narrow radial width just inside the separatrix (screened RMP): ion X-loss effect surfaces up at lower RMP

We think we have the basic understanding of the RMP transport.

We will improve the plasma screening effect from the XGC-M3D framework (NIMROD?).

At the same time, we can study the RMP concept improvement using the XGC-Elite framework.