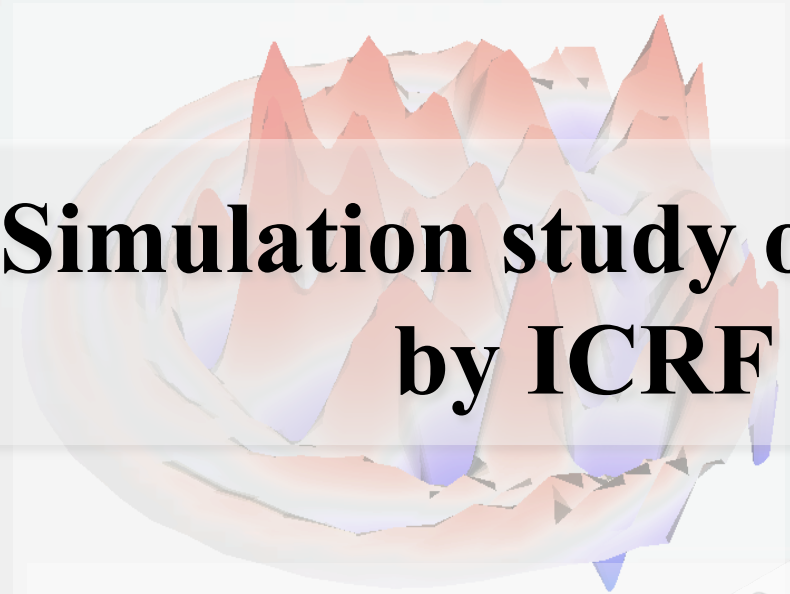

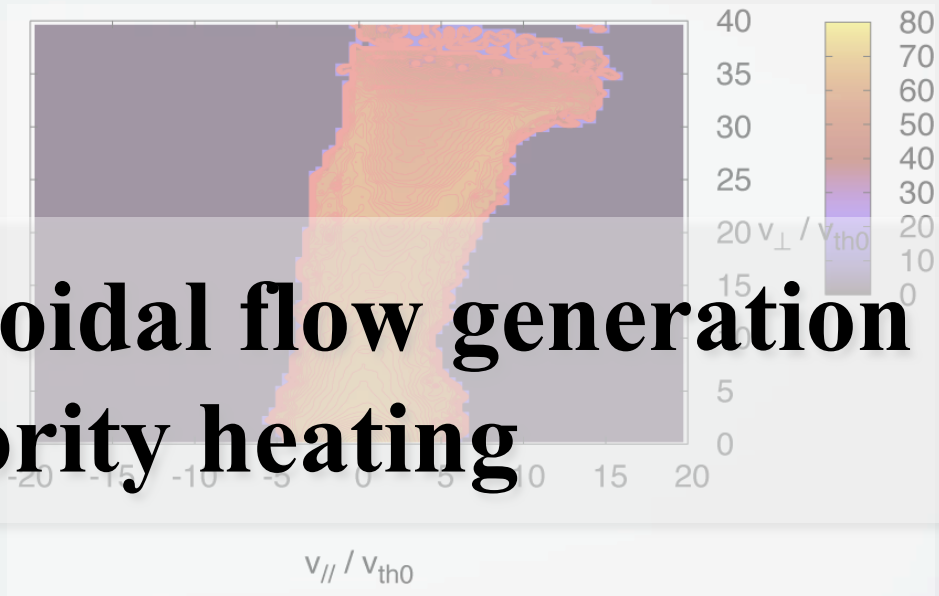

Simulation study of toroidal flow generation by ICRF minority heating

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*S. Murakami, IAEA-FEC2010, THW/P4-03

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Outline

- **Introduction**
  Toroidal flow by ICH
  Ohkawa model

- **Simulation Model**
  GNET: Drift kinetic equation solver in 5-D phase space.
  [Murakami, NF2000, NF2006]

- **Simulation Results**
  Two kinds of toroidal flows => $k_{//}$ dependency

- **Theoretical Analysis**
  Ohkawa model
  Toroidal drift model

- **Conclusions**

Introduction

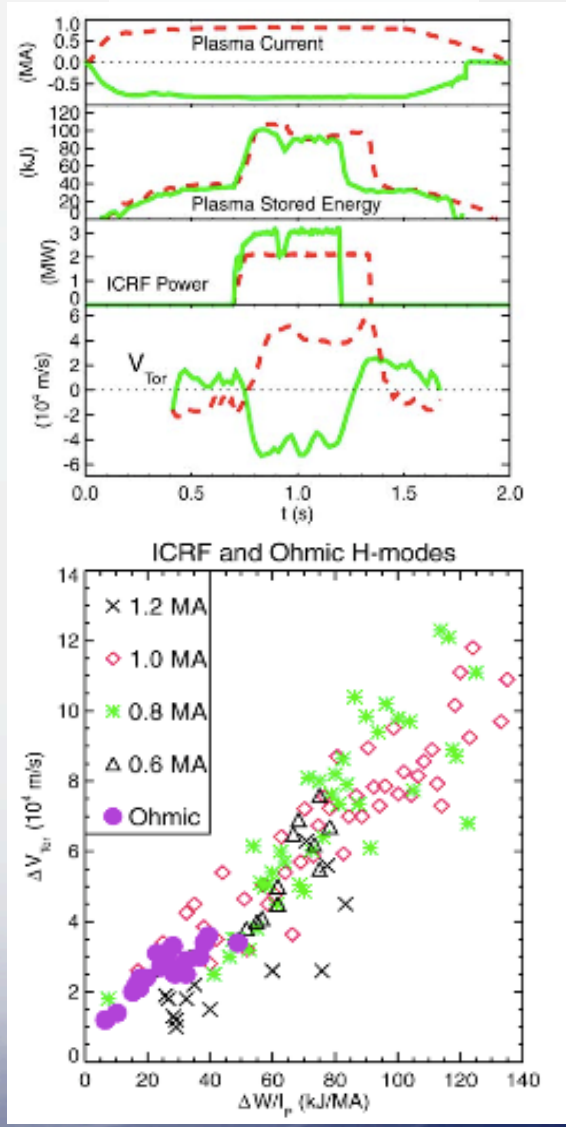
- **Important role of the plasma flow and its shear in the transport improvement is indicated by experimental observations.**
  => H-mode transition, ITB formation, RWM suppression

- **In future reactor rotation drive by NBIH would not be available. => Spontaneous rotation drive**

- **The spontaneous toroidal flow has been observed during ICRF heating with no direct momentum input in JET, Alcator C-Mod, Tore Supra and etc..**

- **Many theoretical studies have been done. However, further study is necessary to make clear the generating mechanism of spontaneous toroidal flow during ICRF heating.**

Alcator C-mod

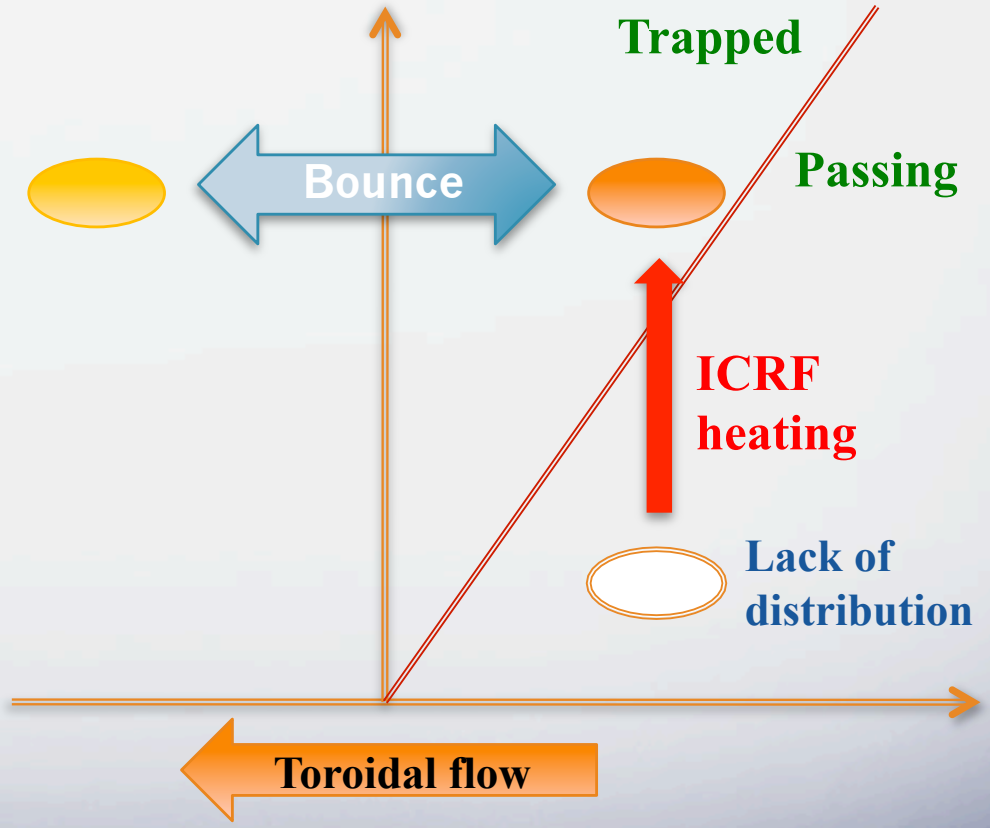


Rice J E et al. 2001 Nucl. Fusion 41 277

Toroidal sheared flow generation model [Ohkawa *et al.*]

- **Toroidal sheared flow generation model by a local ICRF heating**
  T. Ohkawa [Phys. Plasmas, 12 (2005) 094506]
  Assuming the ICRF waves with an asymmetric wave number, resonant ions lose their toroidal momentum due to the transition from the passing to the trapped particle and, then, the opposite direction toroidal flow would be generated.

- **Similar mechanism has been proposed in ECH and has been confirmed experimentally.**
  =>Differences from ECH mechanism
  Heating : multi interact. wt wave.
  Collision: small pitch ang. scatt.

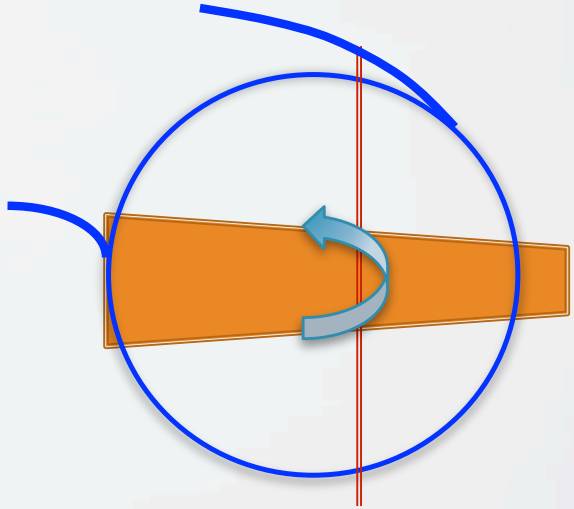


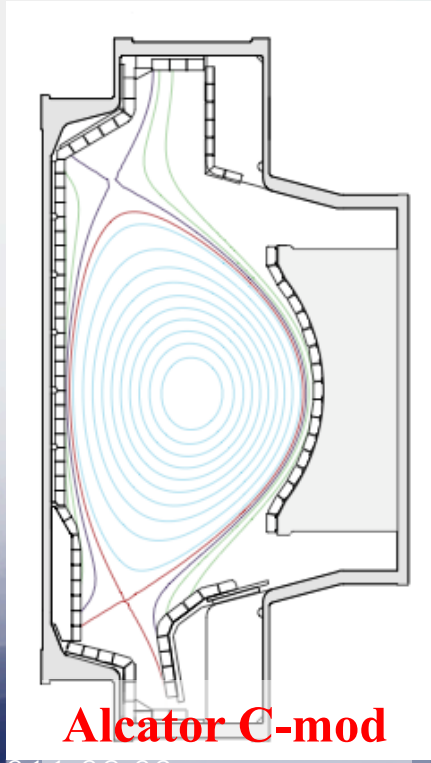
Introduction 2

- However, Ohkawa model is based on the simplified theory and the investigation of this model by the realistic simulation is required.
- We study the toroidal shear flow generation by a local ICRF heating using GNET code, in which the drift kinetic equation is solved in 5D phase-space.
  [Murakami, NF2000, NF2006]
- The Alcator C-Mod plasma is assumed as a first step.
  => R=0.67m, r~0.21m, Bt~5.5T
- A local ICRF wave field model is assumed;

$$E_{RF} = E_{RF0}\tanh\{0.3(1-\rho)\}\exp\{-(\sin\theta/0.3)^2\}$$

also a broader one is assumed.





ICH Simulation Model by GNET

- **GNET (Global NEoclassical Transport simulation code) [S. Murakami, NF2006, NF2000] solves the drift kinetic equation as a (time-dependent) initial value problem in 5D phase space based on the Monte Carlo technique.**

$$\frac{\partial f_{min}}{\partial t}+(\mathbf{v}_{//}+\mathbf{v}_D)\cdot\nabla f_{min}+\mathbf{a}\cdot\nabla_{\mathbf{v}} f_{min}-C(f_{min})-Q_{ICRF}(f_{min})-L_{particle}=S_{particle}$$

$C(f)$: linear Coulomb Collision Operator

Q_{ICRF} : ICRF heating term

wave-particle interaction model

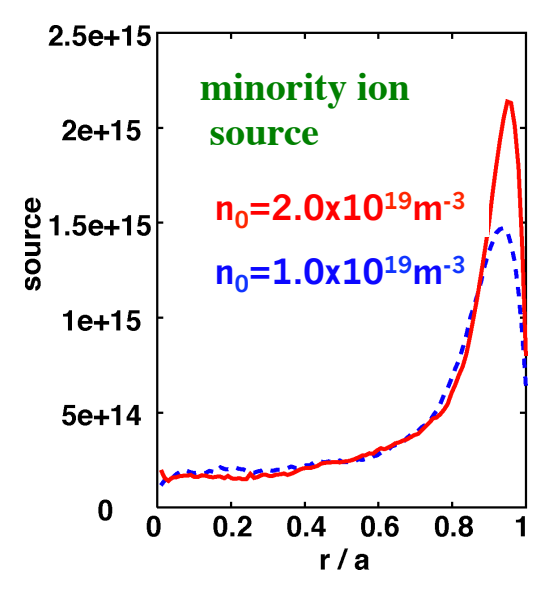
$S_{particle}$: particle source

=> by ionization of neutral particle (AURORA code)

$L_{particle}$: particle sink (loss)

=> Charge exchange loss

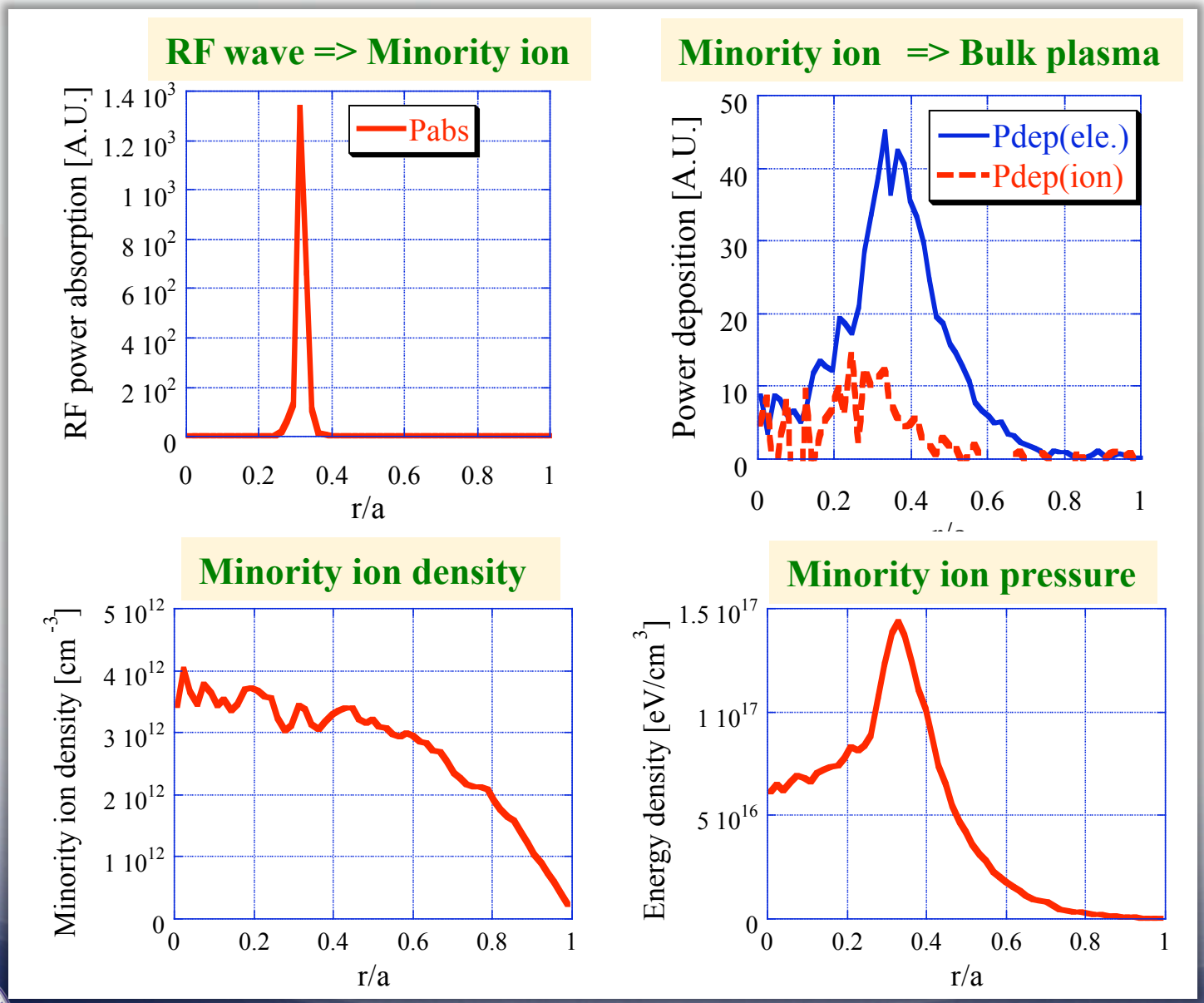
=> Orbit loss (outermost flux surface)



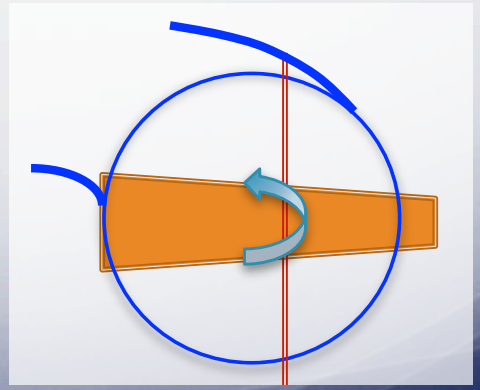
- **The minority ion distribution *f* is evaluated through a convolution of $S_{particle}$ with a characteristic time dependent Green function.**

Simulation Results

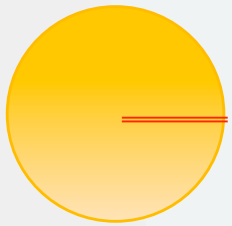
RF Wave Absorption and Heat Deposition

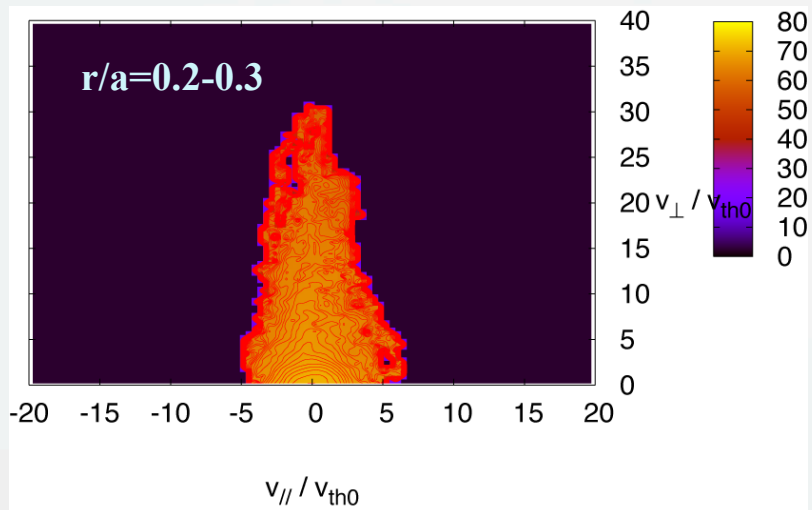


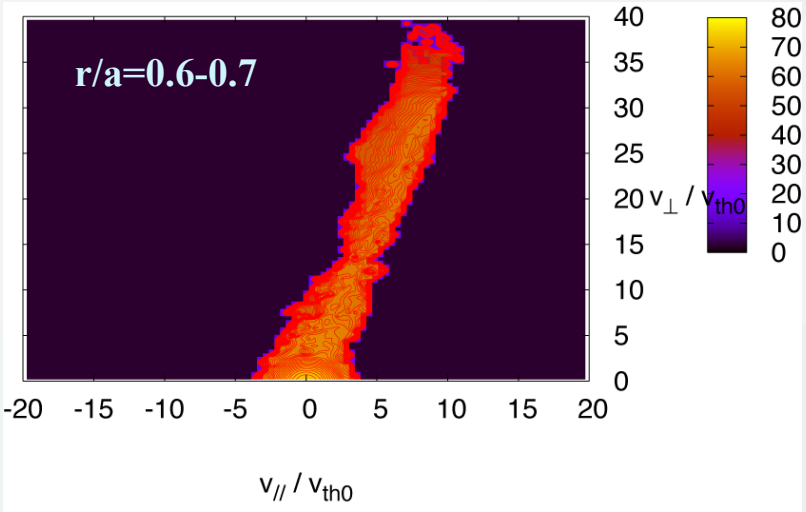
- E_{RF}=3kV/m (P_{abs}~0.4MW), $k_{//}$=5m^{-1}
- n_{e0}~8x10^{19}m^{-3} T_0~3.2keV
- B_0=5.4T, B_r=5.1T

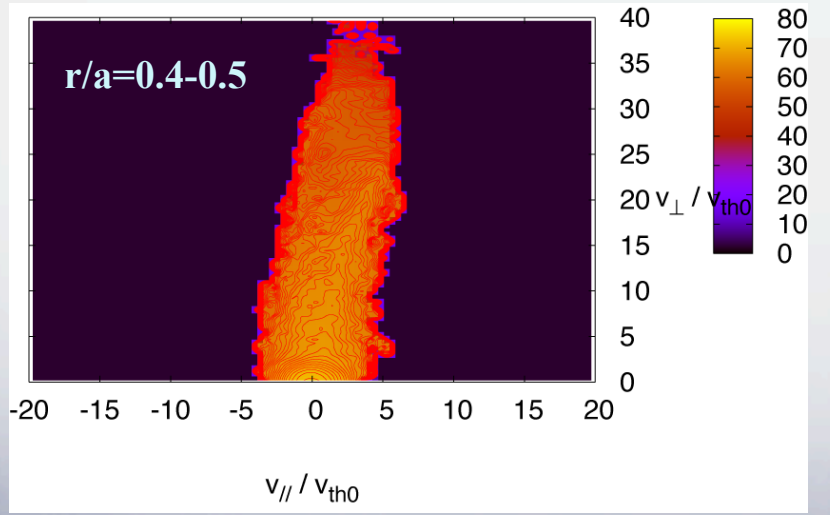


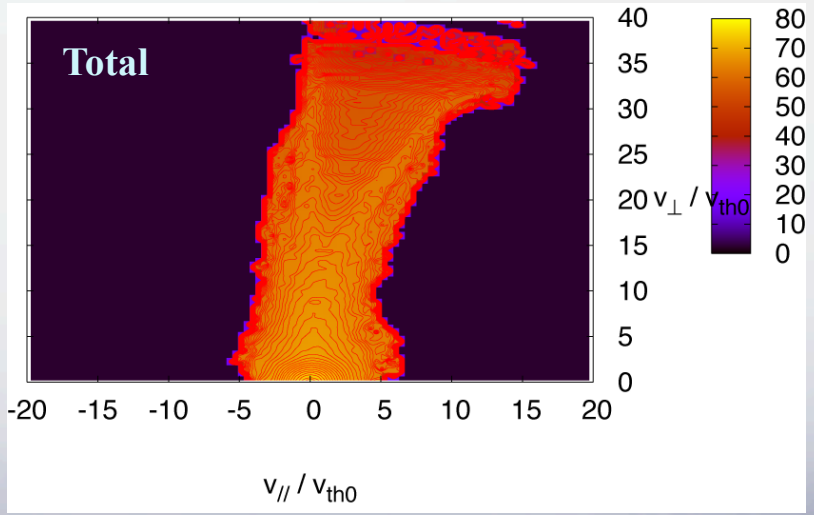
Minority Ion Distributions ($\theta_{poloidal}$=0)





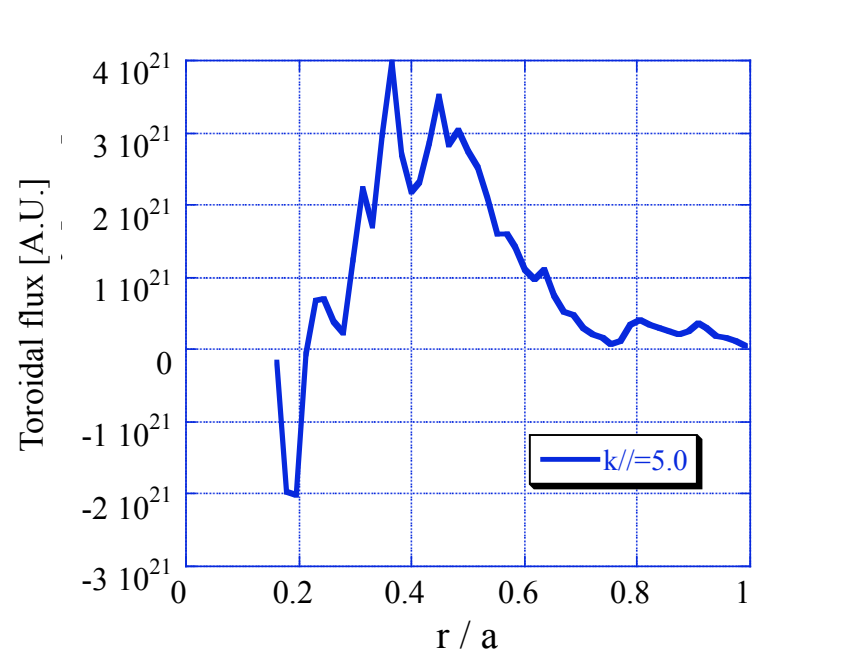


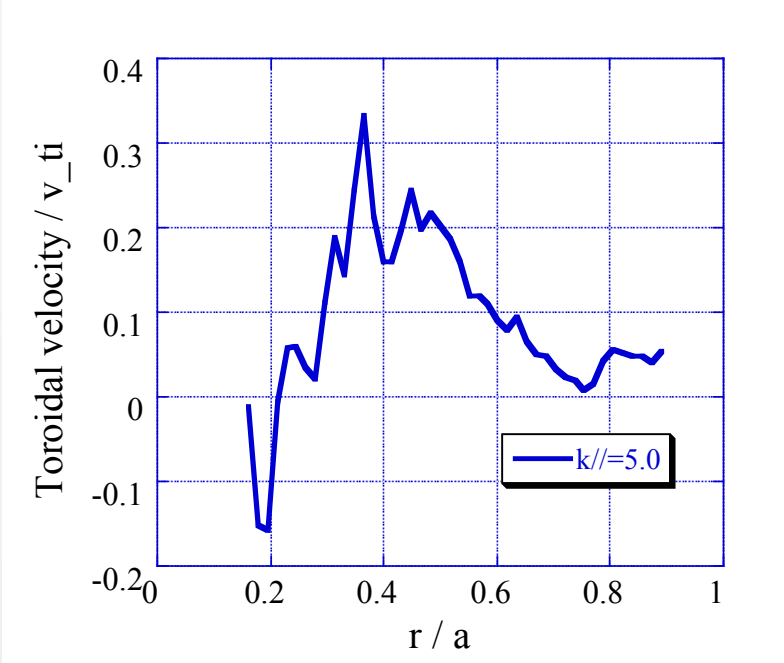




- **We can see strong asymmetry in the parallel velocity direction at the *r/a*=0.6~0.7 case.**

Toroidal Flux and averaged velocity





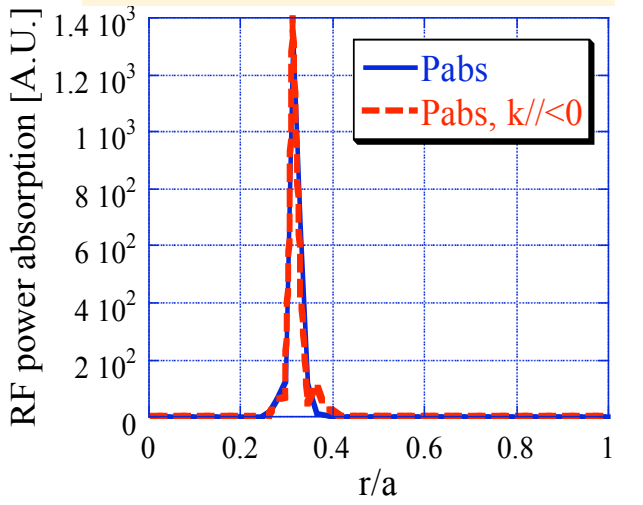
$$\langle nV_\phi \rangle = \frac{\iiint (v_{//\phi} + v_{d\phi}) f_{\min} dv d\phi d\vartheta}{\iiint d\phi d\vartheta}$$

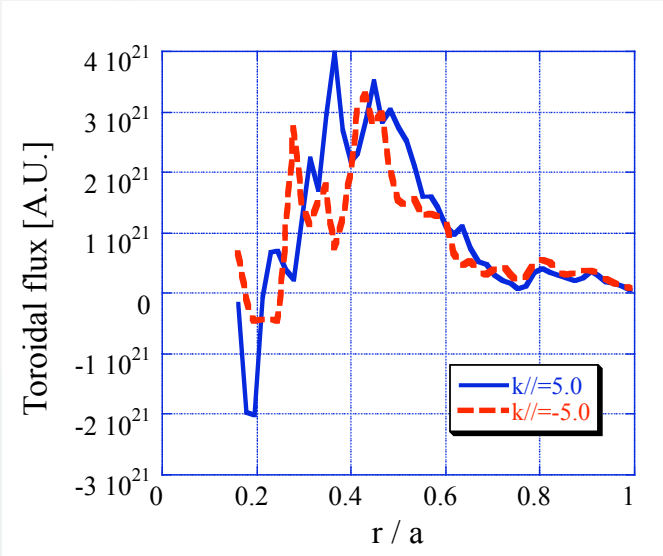
$$\langle V_\phi \rangle = \frac{\iiint (v_{//\phi} + v_{d\phi}) f_{\min} dv d\phi d\vartheta}{\iiint f_{\min} dv d\phi d\vartheta}$$

- **We can see a toroidal flow V/v_{thi}~0.3 which has a peak at r/a~0.4. (Background plasma is fixed; V=0.)**
- **Flow direction 'co' agrees with that of the exp. results in Alcator C-Mod. E_{RF}=3.0kV/m (P_{abs}~0.4MW), $k_{//}$=5m^{-1}, n_{e0}~8x10^{19}m^{-3}, T_0~3.2keV, B_0=5.4T, B_{res}=5.1T**

$k_{//}$ sign dependency (radial profile)

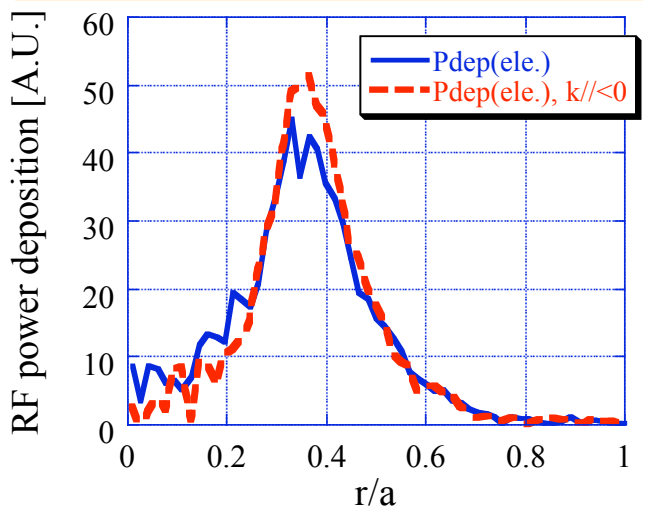
RF wave => Minority ion



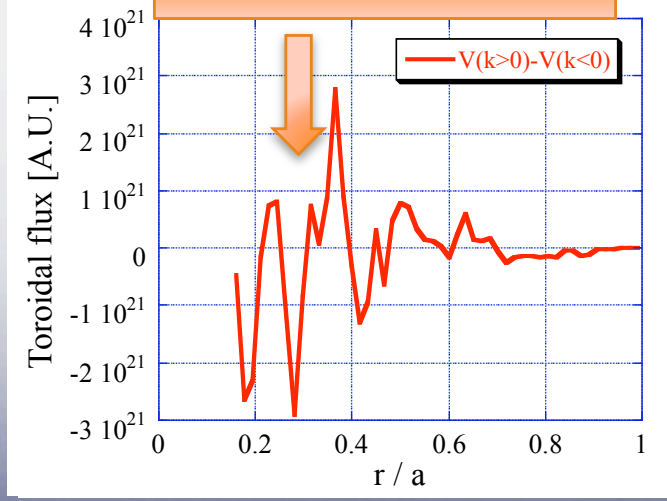


- We next study the $k_{//}$ sign dependency of the toroidal flow velocity.
- A difference r/a~0.3 (P_{abs} peak) is observed. but no clear difference can be seen in the P_{abs} and P_{dep}.

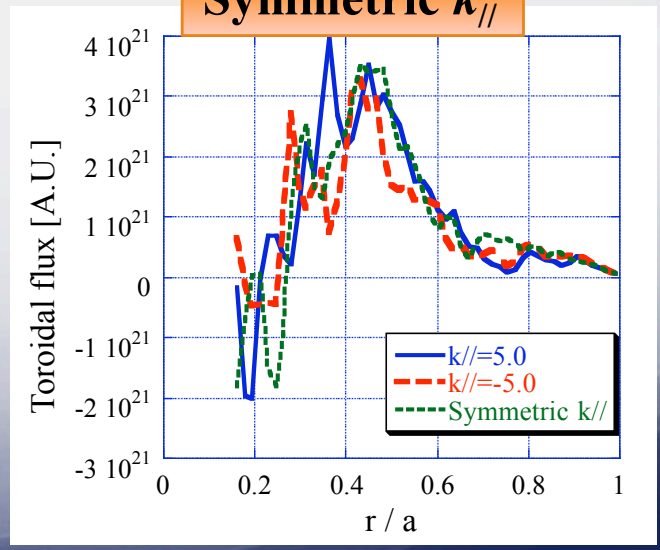
Minority ion => Bulk plasma



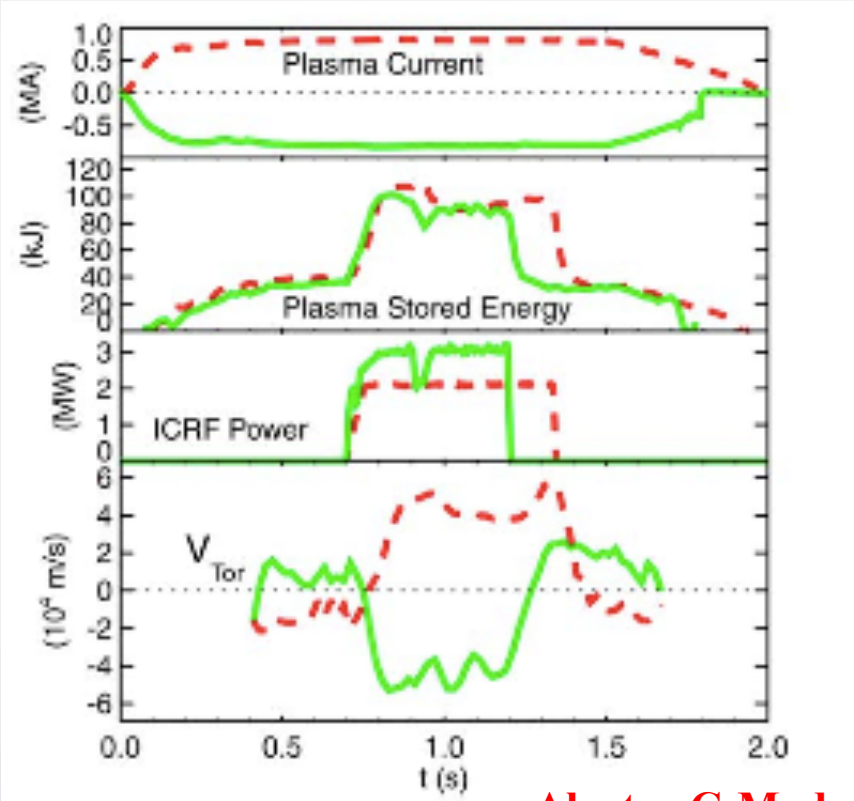
Difference of <*nV*>



Symmetric $k_{//}$

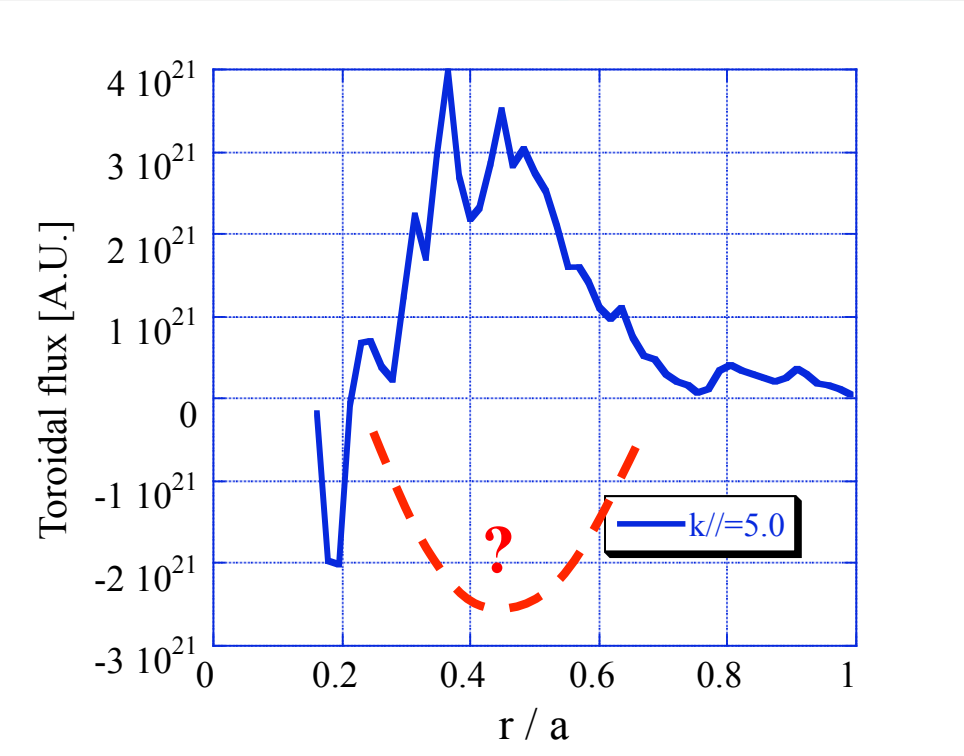


Change of Plasma Current Direction



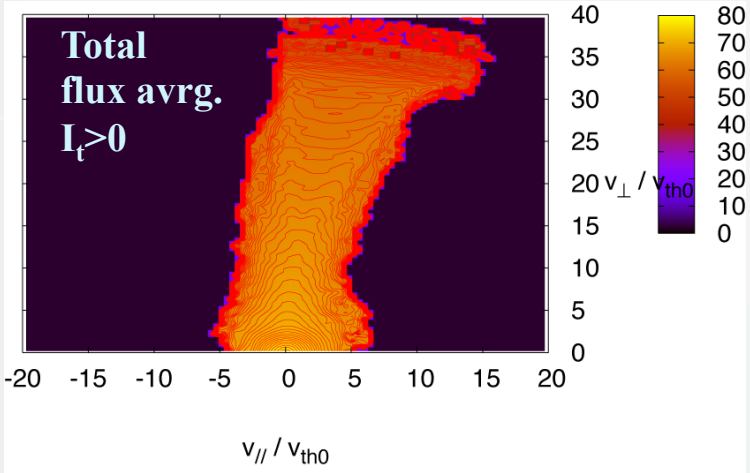
Alcator C-Mod

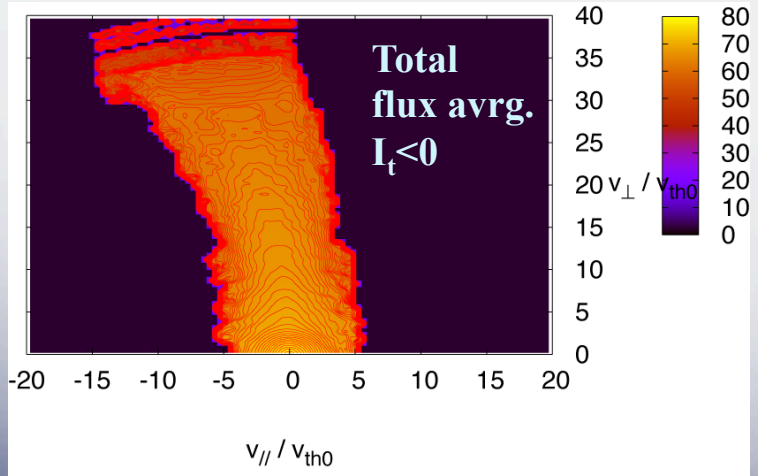
Rice J E et al. 2001 Nucl. Fusion 41 277

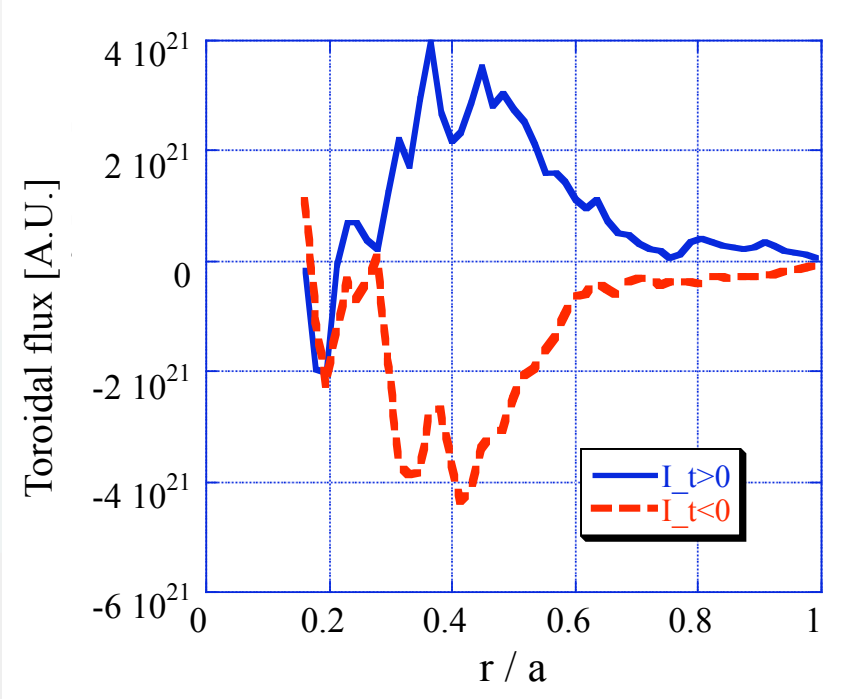


- We, next, investigate the direction change of the toridal flow **reversing the toroidal current.**
- The **toroidal flow reversal** has been observed in **Alcator C-Mod** when the toroidal plasma current changes the direction.

Change of Toroidal Current Direction (GNET)



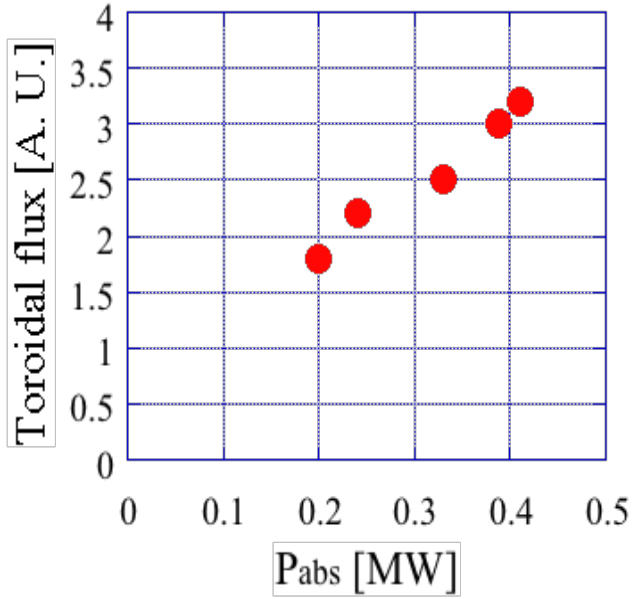




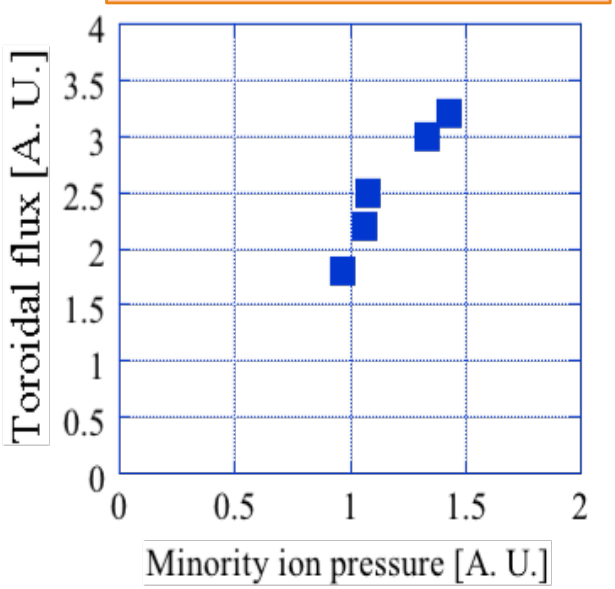
- The **flux avraged distributions function** shows an **opposite asymmetric distribution** from that of the previous case.
- The **toroidal flow reversal** has been also observed in the GNET results.
  => Consistent with the Alcator C-Mod.

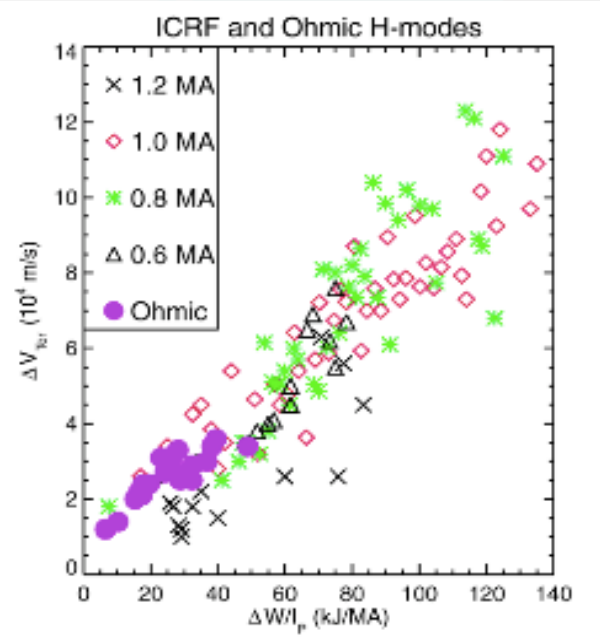
P_{abs} and p_{min} dependeces

RF Power dependency



Pressure dependency

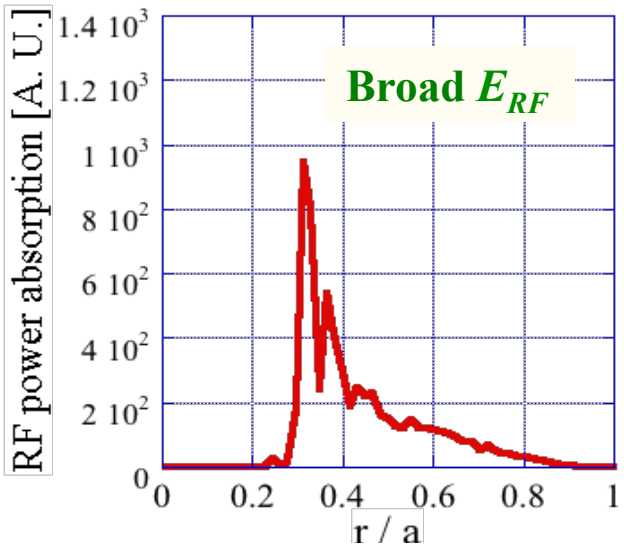




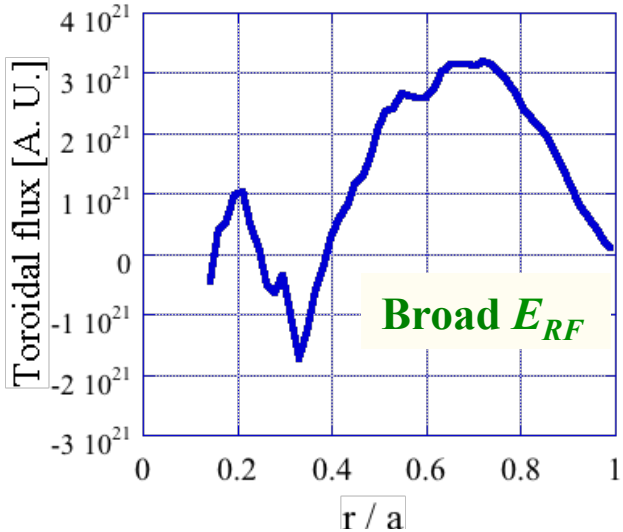
- **We next study the power and minority ion pressure dependency of nV_{tor}.**
- **ICRF heating:** $\Delta W_{ICRF} \simeq \eta(\tau_E + \tau_s/2)P_{abs}, \quad \eta = 1/(1+\tau_s/2\tau_{tail})$ **[Murakami, NF, 2000]**
- **Both cases show the linear dependencies and are consistent with the experimentally obtained scaling. [J.E. Rice et al. 2001 Nucl. Fusion 41 277]**

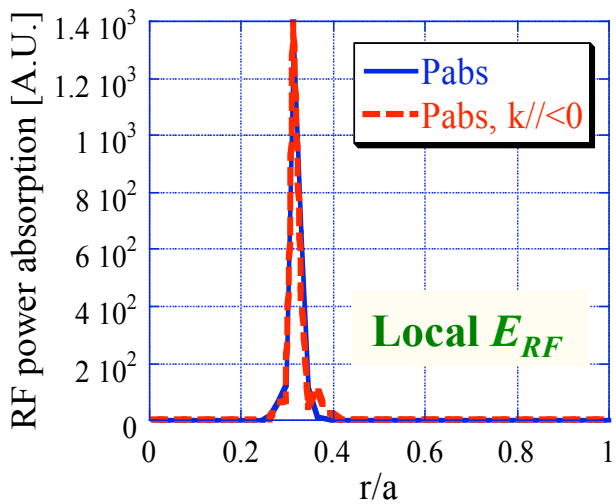
Effect of E_{RF} profile

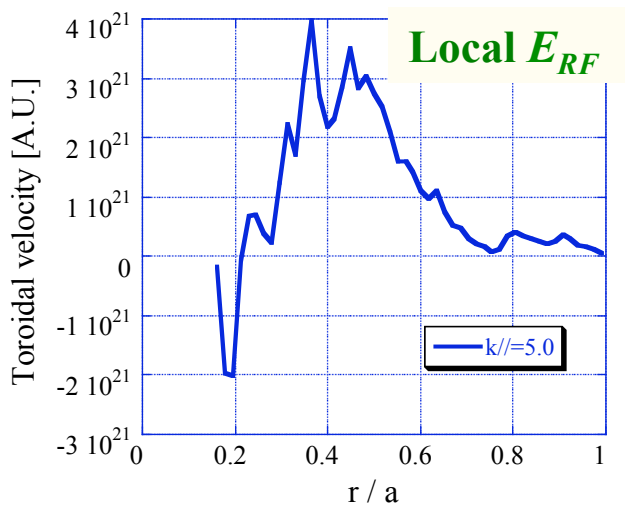
RF Power absorption



Toroidal flux







- **We study the Effect of E_{RF} profile on the V_{tor} assuming broader E_{RF} profile [Murakami, NF2006]**

$$E_{RF} = E_{RF0}\tanh\{(20(1-\rho)\} \times (1+\sqrt{\rho})\cos\theta$$

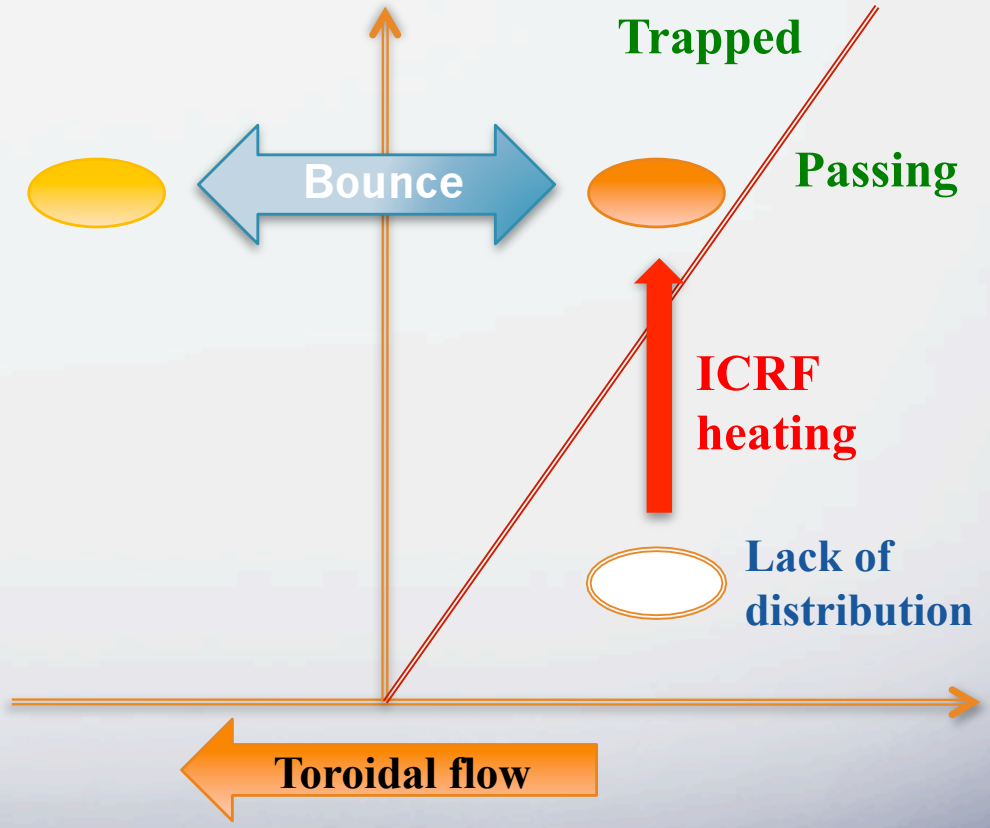
- **Broader Pabs is observed.**
- **Broader nV_{tor} profile is obserbed peaking at r/a~0.7.**
- **Similar amplitude of nV_{tor} is obtained with higher P_{abs}.**
  Broad: ~1.7MW
  Local:~0.4MW

Theoretical Analysis

Toroidal sheared flow generation model [Ohkawa *et al.*]

- **Toroidal sheared flow generation model by a local ICRF heating**
  T. Ohkawa [Phys. Plasmas, 12 (2005) 094506]
  Assuming the ICRF waves with an asymmetric wave number, resonant ions lose their toroidal momentum due to the transition from the passing to the trapped particle and, then, the opposite direction toroidal flow would be generated.

- **In this model obatined toroidal flow depends on the sign of k//.**
  => Origin of k// dependent flow?



Estimation of V_{tor} by Ohkawa model

- **We evaluate the toroidal shear flow using the Ohkawa model[PoP2005]. In this model the toroidal shear flow is predicted as**

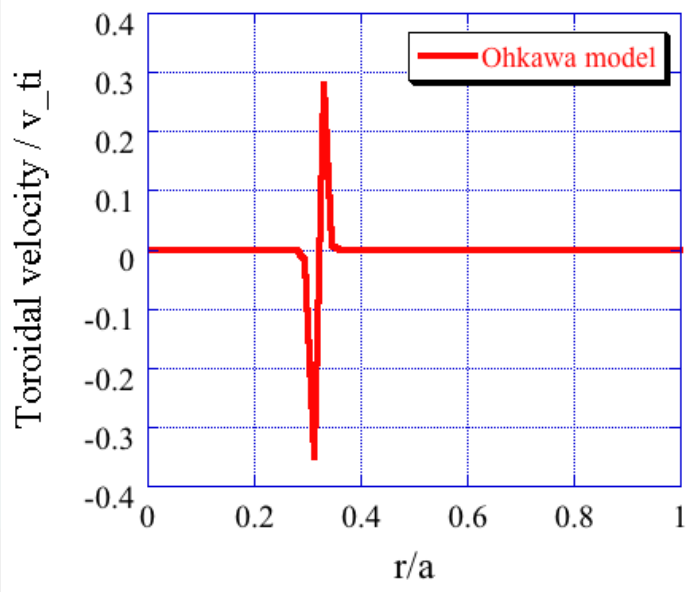
$$V_{tor} \simeq \frac{v_{thi}\Gamma\tau_{eff}}{n} = \frac{v_{thi}P_{abs}\tau_{eff}}{n_i T_i}\alpha\exp(-|\alpha|)$$

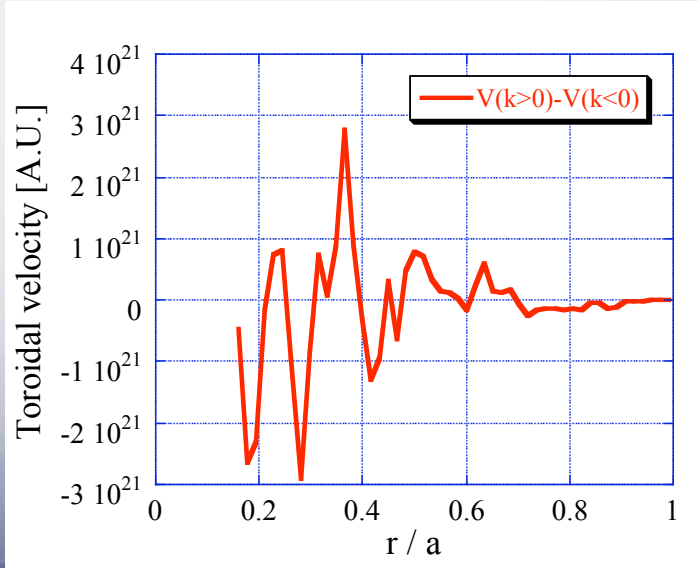
where

$$\alpha = (mu_{\|0}|u_{\|0}|/2T_i)\tan^2\theta_c, \quad u_{\|0} = (\omega - \Omega_c)/k_\|$$

and Γ and τ_{eff} are the ion trapping rate by the ICRF heating and the effective trapping time of the trapped ions. θ_c is the mirror pitch angle. τ_{eff} =1.0ms.

- **We obtained the similar toroidal shear flow. (Broaden by the finite banana width effect?) =>The toroidal flow near the power absorption region would be due to the mechanism proposed by the Ohkawa model.**





Averaged toroidal motion

- **The bounce averaged toroidal motion of energetic ion is**

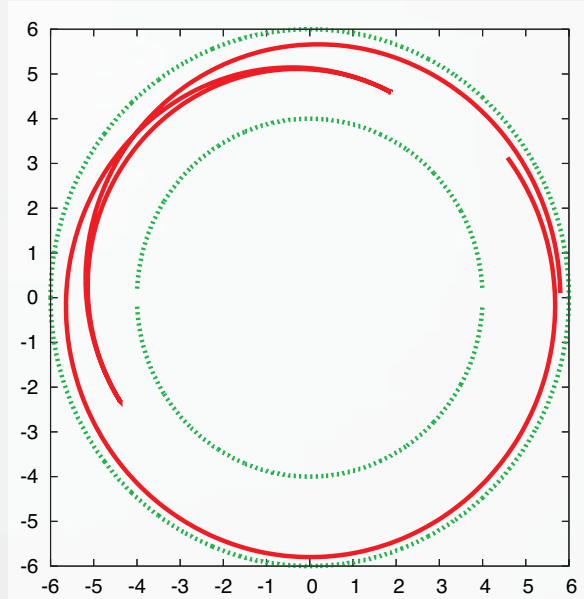
$$\bar{\dot{\zeta}} = \frac{1}{T}\oint dt\dot{\zeta} = \frac{1}{T}\oint d\theta\frac{\dot{\zeta}}{\dot{\theta}}.$$

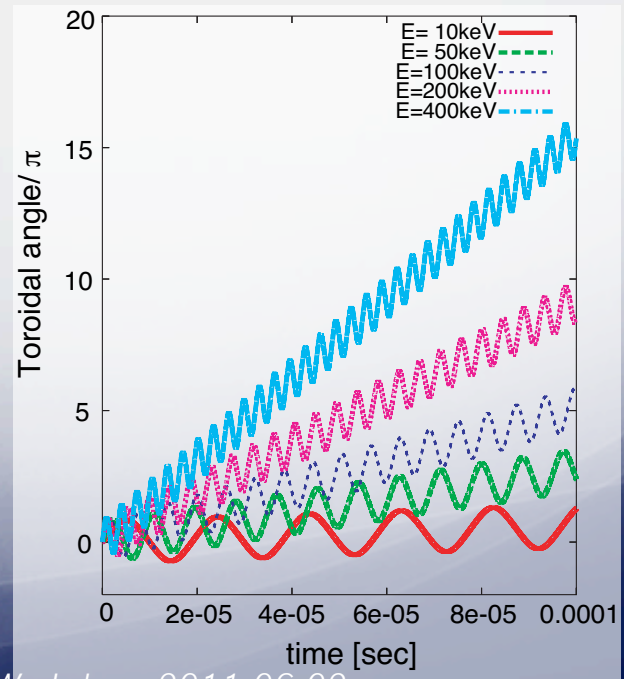
- **The equations for the poloidal and toroidal motions in the Boozer coordinates are**

$$\begin{aligned}\dot{\theta} &= \delta B'\frac{g}{\gamma} - \frac{e^2B^2\rho_c}{m}\frac{(\rho_c g' - 1/q)}{\gamma},\\ \dot{\zeta} &= \delta B'\frac{I}{\gamma} - \frac{e^2B^2\rho_c}{m}\frac{(\rho_c I' + 1)}{\gamma},\end{aligned}$$

where

$$\gamma = e[g(\rho_c I' + 1) - I(\rho_c g' - 1/q)],\ \delta = e^2\rho_c^2 B/m + \mu,$$
and $B' = dB/d\psi$.





Averaged toroidal motion of trapped ions

$$\bar{\dot{\zeta}} \simeq \frac{1}{T}\oint q d\theta - \frac{1}{T}\oint d\theta \Delta q(gq + I) + \frac{1}{T}\oint d\theta \rho_c q(g'q + I'),$$

where $\Delta = m\delta B'/e^2B^2\rho_c$

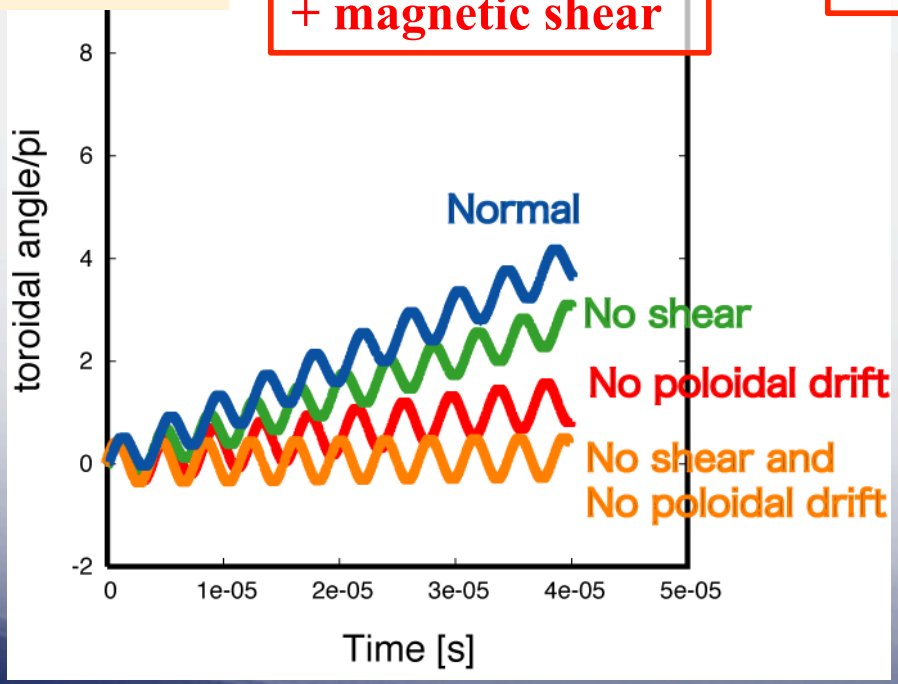
[R.B. White, "The Theory of Toroidally Confined Plasmas", 2001]

Poloidal drift

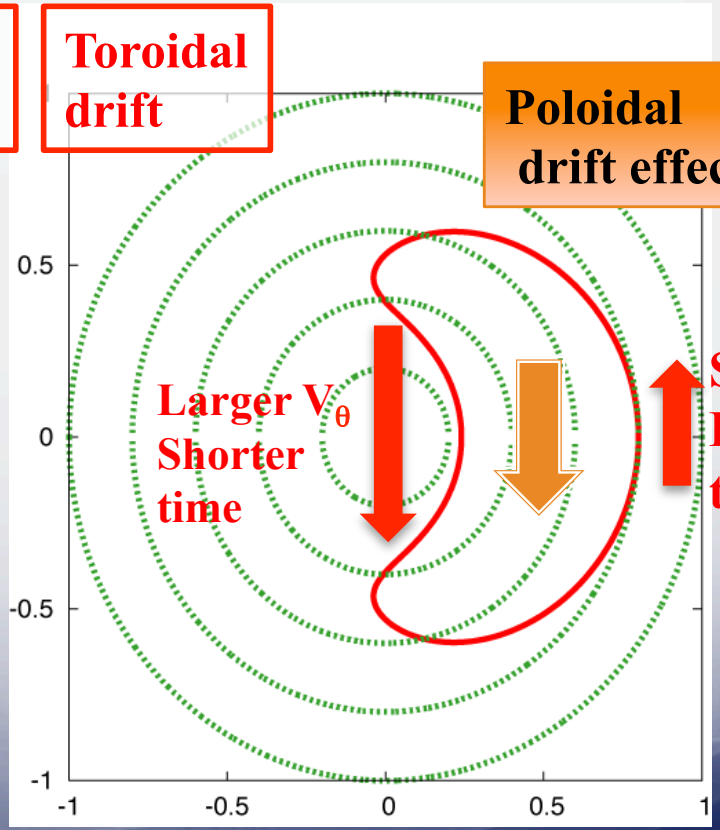
Toroidal drift

E=200keV
θ_p=75 degrees

Finite banana size + magnetic shear



Poloidal drift effect



Evaluation of Averaged Toroidal Flow

$$\bar{\dot{\zeta}} \simeq \frac{2gqq'\sqrt{2mW}}{eT}\int_{-\theta_b}^{\theta_b} d\theta \frac{\sqrt{1-B(\theta)/B(\theta_b)}}{B(\theta)}$$
$$- \frac{q(gq+I)\sqrt{2mW}}{eT}\int_{-\theta_b}^{\theta_b} d\theta \frac{2-B(\theta)/B(\theta_b)}{\sqrt{1-B(\theta)/B(\theta_b)}}\frac{1}{B^2}\frac{\partial B}{\partial \psi}.$$
$$\simeq \frac{4qsmv^2}{rReB_0}\frac{gq}{gq-I}\frac{E(\kappa)+(\kappa^2-1)K(\kappa)}{K(\kappa)}$$
$$+ \frac{qmv^2}{2rReB_0}\frac{gq+I}{gq-I}\frac{2E(\kappa)-K(\kappa)}{K(\kappa)}$$

Assume a simple tokamak

$$B(r,\theta) = B_0\{1-(r/R)\cos\theta\}$$

GNET dist.+Theory

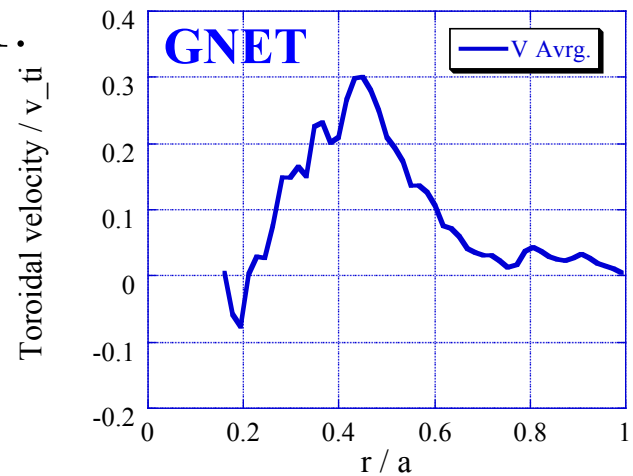
$$<\bar{\dot{\zeta}}> = \frac{\int \bar{\dot{\zeta}}(E) f_{\min}(E)dE}{\int f_{\min}(E)dE}$$

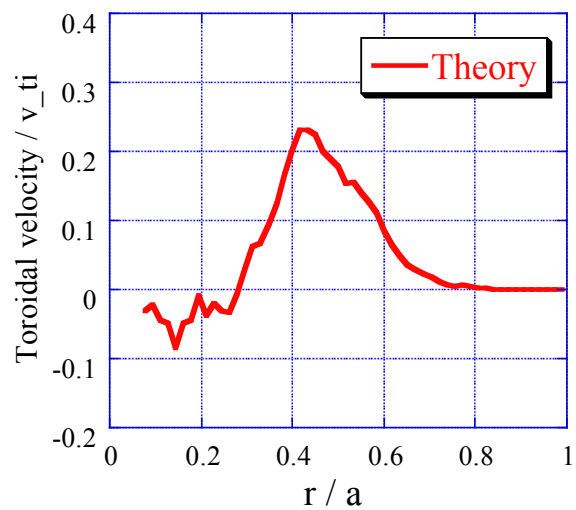
If we consider a limit $\kappa << 1$.

$$\bar{\dot{\zeta}} \simeq \frac{4qsE\kappa^2}{rReB_0} + \frac{qE(1-\kappa^2)}{rReB_0}$$

Finite banana size + magnetic shear

Poloidal drift





Conclusions

- We have studied the toroidal flow generation by the ICRF minority heating applying GNET code to the Alcator C-mod like tokamak plasma.
- We have found an asymmetry of velocity distribution function in the parallel direction and obtained two kinds of toroidal flows.
  - A sheared flow near P_{abs} peak (r/a~0.3) depending on $k_{//}$ sign.
    => the mechanism proposed by T. Ohkawa [PoP2005].
  - Larger toroidal flow independent of on $k_{//}$ sign.
    => the net toroidal motion of energetic tail ions.
- Future plan
  - Estimation of torque by energetic ion loss by ICH
    => Toroidal field ripple effect?
  - Comparisons with experimental results
  - Estimation of torque in ITER or reactor scale plasma
    => Necessary heating power?

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