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Observation of non diffusive term of toroidal momentum transport in the JFT-2M tokamak

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Toroidal rotation velocity profiles are measured with multi-chord charge-exchange spectroscopy for the discharge that the neutral beams are interchanged from parallel (co) to anti-parallel (counter) to the direction of the plasma current. Transport analysis of toroidal momentum in the transient phase suggests the existence of non-diffusive term in the toroidal momentum transport. This non-diffusive term appears as spontaneous source of the toroidal momentum in the direction of anti-parallel to the plasma current.

Keywords: Toroidal rotation, Neutral beam injection, Momentum transport, Non-diffusive transport

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One of the important issue of transport is to evaluate the transport coefficient particle, momentum, and heat flux. Theoretically, transport matrix has nine coefficients for particle, momentum, and energy flux. The diagonal elements are diffusive terms D, χ_i (χ_e), μ_ϕ and off diagonal terms are considered to be non-diffusive terms. In the particle flux, the significant particle pinch (inward convective velocity) was found to be necessary to explain the peaked electron density profile in ohmic tokamak plasma, since the particle source is localized near the plasma edge. However in the heat and momentum transport, only diffusive terms of heat or momentum flux were discussed in the most transport analysis[1-4]. This is because the heat or momentum deposition are more less localized near the plasma center in most discharge and even diffusive model can explain the measured temperature or rotation velocity profile in the steady state. Recently the inward heat flux was found in the off-axis ECH heating experiment in DIII-D[5]. The peaked electron temperature profile can not be explained by diffusive model, because the deposition profile of ECH is well localized at half of plasma minor radius. This experiment suggests a non-diffusive term of electron heat flux. However, no report on non-diffusive term of momentum transport has been published. In this paper, we present time evolution of toroidal rotation velocity profiles measured with multi-point charge-exchange spectroscopy. Transport analysis of toroidal momentum is done for the transient phase, in which the toroidal rotation velocity changes its sign because of the interchange of the injected neutral beam direction.

JFT-2M is a tokamak with major radius R = 1.3 m and minor radius a = 0.35 m. It has two tangential neutral beams, one is in parallel (co-injection) and the other is anti-parallel (counter-injection) to the plasma current. We interchange the neutral beams from co-injection to counter-injection to study the response of toroidal rotation velocity, keeping the absorbed power constant. These series of experiments were done under the conditions of a toroidal field B_t of 1.3 T, a plasma current Ip of 240 kA, with deuterium working gas, limiter configuration, an elongation κ of 1.2, and NBI power of 0.5-0.6 MW at an injection energy of 32 keV. The profiles of the toroidal rotation velocity, v_ϕ, and ion temperature Ti, profiles are measured with multi-channel charge exchange spectroscopy (CXS) every 16.6 ms using CVI (Δn=8-7) charge-exchange line emission.[6] The time evolution of electron temperature at the center $T_e(0)$ is measured with soft X-ray PHA with 50 ms integration. Profiles of electron temperature and density n_e are obtained with a 13-channel Thomson scattering (TS) system. The line-averaged density e is given by a 3-channel FIR laser interferometer, and the total stored energy Wp is estimated from diamagnetic loops.

Figure 1 shows the profile of toroidal momentum ($m_i n_i v_\phi$) for the discharges that the direction of injected neutral beam is interchanged from co- to counte- and from counter- to co- to the plasma current. The absorbed power of co-NBI is 0.49 MW, and that of counter-NBI is 0.56 MW. Here m_i is ion mass (deutron). Since the toroidal rotation velocity of bulk plasma is not able to be measured with CXS, the toroidal rotation velocity of fully stripped carbon is used as plasma rotation velocity v_ϕ. here we assume $n_i = n_e$. As long as impurities are fully stripped and rotate as fast as bulk ions (deutron), the total momentum of bulk and impurities, $n_i m_i v_\phi + \Sigma n_I m_I v_\phi \sim n_e m_i v_\phi$, because of the neutrality of plasma $n_i Z_i + \Sigma n_I Z_I = n_e$. The density profiles are measured with Thomson scattering in the steady state phase of toroidal rotation (not in the steady of electron density) in co-injection and counter-injection phase (t = 690 ms and t=890 ms) and these measured profiles are well fitted by a parabolic-shaped profile raised to some power as $n_e(r)=n_e(0)(1-r^2)^{\alpha}$ [$\alpha = 1 \sim 2$]. Then $n_e(0)$ and α are given by two line-averaged densities measured at $\rho = 0.24$ and $\rho = 0.6$ in the transient phase. The data at t = 742 ms shows the profile of toroidal momentum in the steady state until the neutral beams are interchanged at t= 750 ms. These profiles are considered to be the initial profiles of the transient phase. The toroidal rotation reaches almost steady state values at t = 825ms (75ms after the interchange of neutral beams). The electron density increases gradually after the neutral beams are interchanged from co-injection to counter-injection, while it decreases after the neutral beams are interchanged from counter-injection to co-injection. However the change of electron density within the time resolution of CXS measurements (16.6ms) is 5% and it gives only small contribution to the change of toroidal momentum in the transient phase from t = 750 ms to t = 825 ms. The toroidal momentum in the steady state of counter-injection phase are two to three times larger than that in co-injection phase, although the injected neutral beam power is comparable between co-injection and counter-injection. This is due to the reduction of the momentum diffusivity or/and the existence of other source of the momentum which is not driven by neutral beam. In this article we call the latter as the spontaneous source of the momentum. The transport analysis in the transient phase gives the momentum diffusivity and spontaneous source of the toroidal momentum, although the steady state analysis can give only the momentum diffusivity.

Radial flux of toroidal momentum is estimated from the time derivative of toroidal momentum and the toroidal force driven by injected neutral beam as

$$\Gamma_M(r) = \frac{1}{r}\int_0^r \left(\frac{\partial(m_i n_i(r)\, v_\phi(r))}{\partial t} - f_{NBI}(r) \right) r dr \tag{1}$$

Where $f_{NBI}(r)$ is a toroidal force calculated with beam deposition code and positive values is defined as the force in the direction of co-injection. When the momentum flux $\Gamma_M(r)$ is proportional to the gradient of toroidal momentum $(m_i n_i v_\phi)$, the momentum transport is considered to be pure diffusive. By subtracting and averaging values measured at two time slices, the momentum flux and toroidal momentum gradient are evaluated at t = 767, 783, 800, 817, 833, and 850 ms. Figure 2 shows the momentum flux as a function of toroidal momentum gradient for the discharges that the neutral beams are interchanged from co-injection to counter-injection and from co-injection to counter-injection. These figures clearly show the finite offset momentum flux at zero gradient of toroidal momentum for $\rho < 0.6$, although this spontaneous momentum flux near the plasma edge at $\rho = 0.8$ has large uncertainty due to the fact that the gradient of toroidal momentum is too small. This spontaneous momentum flux is found always negative (counter direction) both for co-injection [Fig2(b)] and counter-injection [Fig2(a)]. The toroidal momentum flux contributed by neutral beam driven force f_{NBI} is -0.016 $N.m^{-2}$ for counter-injection and 0.017 $N.m^{-2}$ for co-injection at ρ = 0.6. The spontaneous momentum flux observed is 1/5 - 1/2 of beam driven momentum flux in the core region. The toroidal rotation velocity in ohmic phase can be evaluated, if the measurements are done after the neutral beam is injected within short time (8 ms) compared to the toroidal momentum confinement time (>30ms). The toroidal rotation measured with short neutral beam injection (co-injection and counter-injection) is always in the counter direction . This results are consistent with the toroidal rotation in the counter direction for ohmic plasma (see for instance the results of PDX[7]) and the toroidal rotation in counter direction with perpendicular neutral beam injection on JIPP T-IIU tokamak[8]. The spontaneous toroidal rotation in ohmic phase is consistent with the spontaneous source of the momentum in counter direction discussed above. One of the candidate of the spontaneous source of the momentum is jxB force due to the fast ion orbit loss current. In these discharges, the ion orbit loss calculated is negligible (1%) for co-injection, while it has significant fraction (11%) for counter-injection. However the spontaneous source of the momentum in co-injection observed are even higher than that in counter-injection. If the ion orbit loss causes the spontaneous momentum flux, it should increase towards plasma edge, but the measured spontaneous momentum flux does not show such trend. Therefore we can conclude that the ion orbit loss is not the main cause of this spontaneous momentum flux. This flux suggests the existence of off-diagonal term of transport. The data is not precise enough to study the parameter dependence of the spontaneous momentum flux.

Theory for the spontaneous source of the momentum has been developed (see eg [9].) In order to present an order-of-estimate examination for the present theory, the observed spontaneous term is related to the temperature gradient. Here we simply assume that it is driven by the gradient of ion temperature and try to derive the coefficient of off-diagonal term;

$$\Gamma_M = \mu_\phi \frac{\partial(m_i n_i v_\phi)}{\partial r} + \mu_{\phi/\Delta T} \frac{v_{th}}{T_i} \frac{\partial(m_i n_i T_i)}{\partial r} \quad (2)$$

Here v_{th} is a thermal velocity and μ_ϕ, $\mu_{\phi/\Delta T}$ are diagonal and off-diagonal coefficients for the momentum transport. Figure 3 and Figure 4 show the radial profiles of ion temperature and these coefficients for the discharges that the neutral beams are interchanged from co-injection to counter-injection and counter-injection to co-injection. The ion energy confinement is higher in counter-injection phase than in the co-injection phase[10], however the ion temperature in counter-injection phase shown in Fig3(a) is lower than that in co-injection phase. This is because the ion temperature does not reach its steady state value at t = 783 ms (33ms after the neutral beams are exchanged). These ion temperature profiles are more less similar to that before the neutral beams are exchanged. The momentum diffusivity μ_ϕ is derived from the slope of the two time sliced data measured at 767 and 800ms. The data indicated "co to counter" stands for the momentum diffusivity in counter-injection phase 16 - 50 ms after the neutral beams are interchanged. The magnitude of momentum diffusivity μ_ϕ in counter-injection phase is very similar to that in the co-injection phase, while the toroidal rotation velocity and toroidal momentum in counter-injection are two to three times larger than that in co-injection. We note here the steady state analysis with the assumption of no spontaneous source of the momentum gives the momentum diffusivity μ_ϕ of 0.35 m^2/s for co-injection and 0.14 m^2/s for counter-injection at $\rho = 0.5$. The energy confinement is 18 ms (t=690ms) for co-injection phase and 24 ms (t=890ms) for counter-injection. The improvement of momentum confinement is expected well after the neutral beams are interchanged from co-injection to counter-injection due to the peaking of electron density. However the density peaking is slow (100 to 150 ms) compared with the change of toroidal rotation velocity[10]. Therefore the momentum diffusivity estimated in the transient phase (< 50ms) does not show any reduction in counterinejction. The off-diagonal coefficient are estimated from the offset of momentum flux and ion temperature gradient measured. The off-diagonal coefficients are of the order 10^{-3} m^2/s for these discharges. In order to confirm that this non-diffusive terms are driven by the ion temperature gradient, we need more measurements of spontaneous source of the momentum with wide range of various ion temperature gradient.

In the analysis described here, we assume the bulk toroidal rotation velocity is identical to that of carbon, which is measured with CXS. If the bulk toroidal rotation is different from carbon rotation, toroidal momentum of the bulk plasma should be treated separately from that of carbon. However no bulk toroidal rotation has been measured in JFT-2M. Here we estimated how much velocity difference between carbon and bulk ion is required, if there is no net spontaneous momentum flux in the plasma. The carbon density in this experiment is about 5 %, which is estimated from CXS emission. For example, the carbon offset momentum flux at r = 0.61 for the discharge counter to co is 0.003 Nm^{-2}, which is 20% of beam driven momentum. If there is no net spontaneous momentum source, the bulk ions has same offset momentum source in the direction of co-injection and the absolute values of bulk rotation velocity in co-injection should be 1.5 times larger than that in counter-injection. However the absolute value of carbon rotation in co-injection is 50km/s and it is much smaller than that in counter-injection (100km/s). The velocity difference between bulk ion and carbon impurity should be quite large (40km/s) if there is no net spontaneous momentum. To confirm the spontaneous momentum sourcre measured in JFT-2M, more measurements on other impurities and bulk plasma if possible is needed. However the transient behavior of carbon toroidal rotation at the interchange of neutral beams observed in JFT-2M can not explain by pure diffusive transport model and it suggests the possibility of off-diagonal, at least non-diffusive, terms of momentum transport. The correlation of the spontaneous term with the temperature gradient is presented for an example. This would provide an order-of-magnitude estimate for the off-diagonal term to examine theoretical studies. The experimental discrimination of the influences from the gradients of the density and temperature requires future research.

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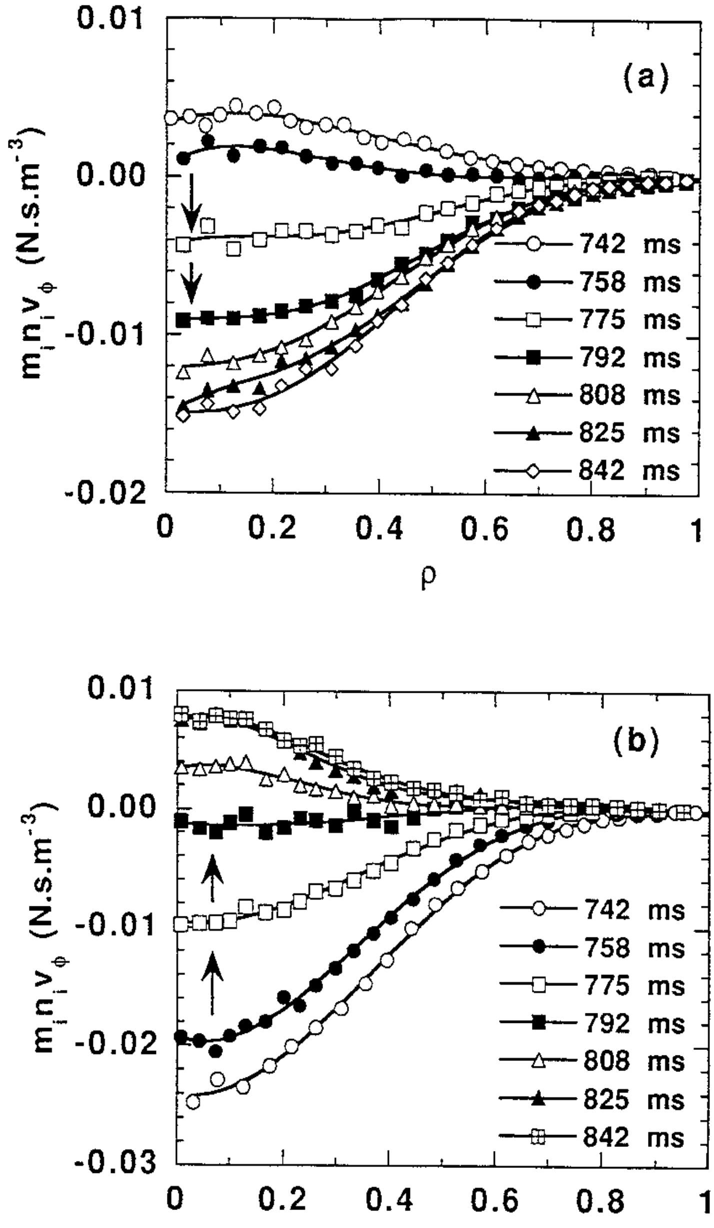
Figure Caption

Fig.1 Radial profile of toroidal momentum in the transient phase of the discharges that the direction of NBI is reversed. (a) The co-injection is activated from 550 ms to 750 ms and the counter-injection is on from 750 ms to 950 ms. (b) The ctr-NBI is activated from 550 ms to 750 ms and the co-NBI is on from 750 ms to 950 ms.

Fig.2 Radial flux of toroidal momentum as a function of the gradient of toroidal momentum for the discharges that the direction of NBI is reversed (a) from co to counter and (b) from counter to co for various averaged minor radius. The six points for each radius stand for the measured values at 767, 783, 800, 817, 833, 850 ms.

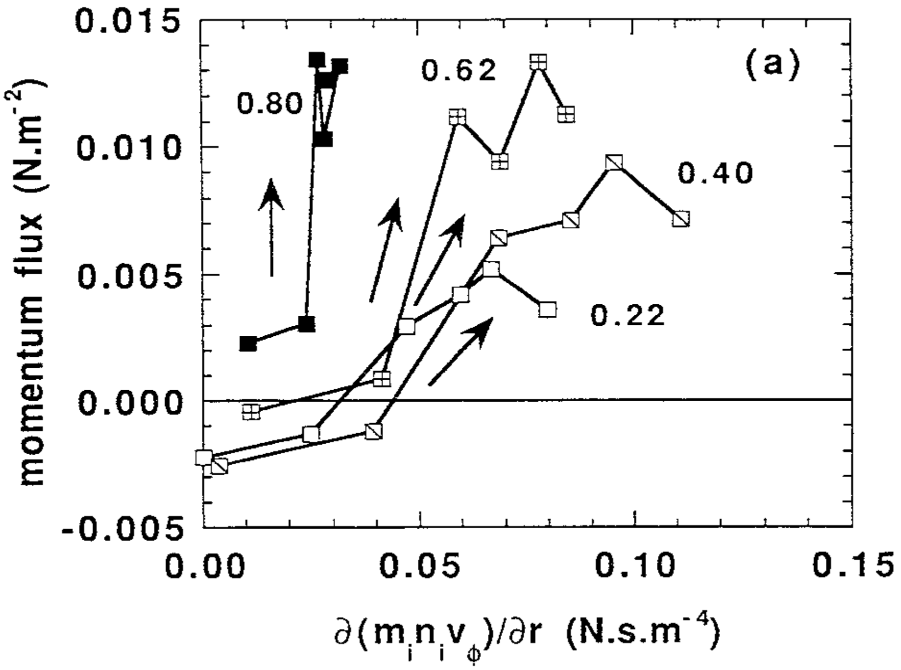
Fig. 3 Radial profiles of ion temperature at t = 783 ms for the discharges of (a) co to counter and (b) counter to co neutral beam injection.

Fig. 4 Radial profiles of (a) momentum diffusivity and (b) off-diagonal coefficient derived from two values of momentum flux and momentum gradient measured at 767 and 800 ms.

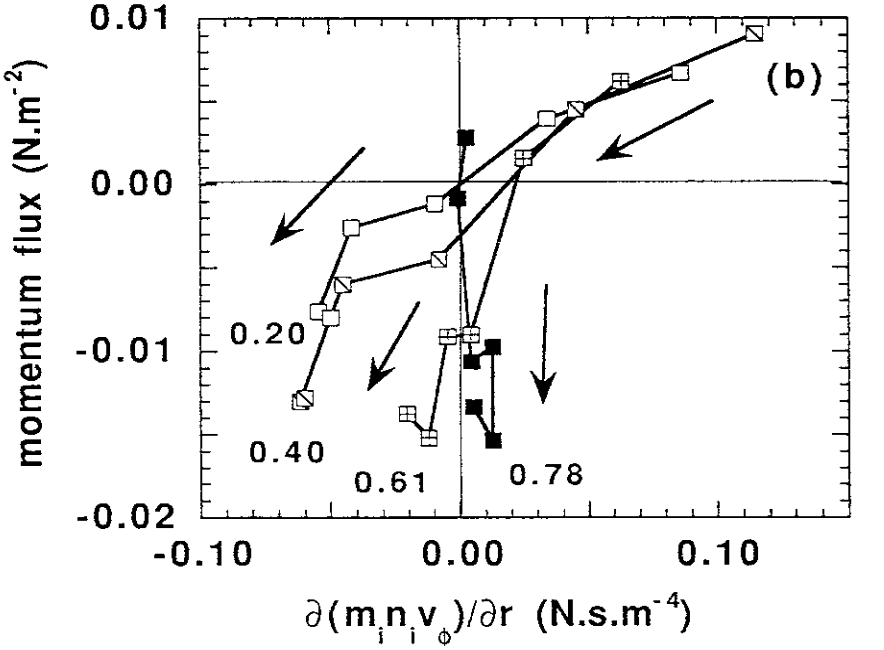


(a)
0.01
0.00
-0.01
-0.02
0
0.2
0.4
0.6
0.8
1
ρ
742 ms
758 ms
775 ms
792 ms
808 ms
825 ms
842 ms
(b)
0.01
0.00
-0.01
-0.02
-0.03
ρ

Figure 1



(a)
0.80
0.62
0.40
0.22
momentum flux (N.m^{-2})
$\partial(m_i n_i v_\phi)/\partial r$ (N.s.m^{-4})



(b)
0.20
0.40
0.61
0.78
momentum flux (N.m^{-2})
$\partial(m_i n_i v_\phi)/\partial r$ (N.s.m^{-4})

Figure 2

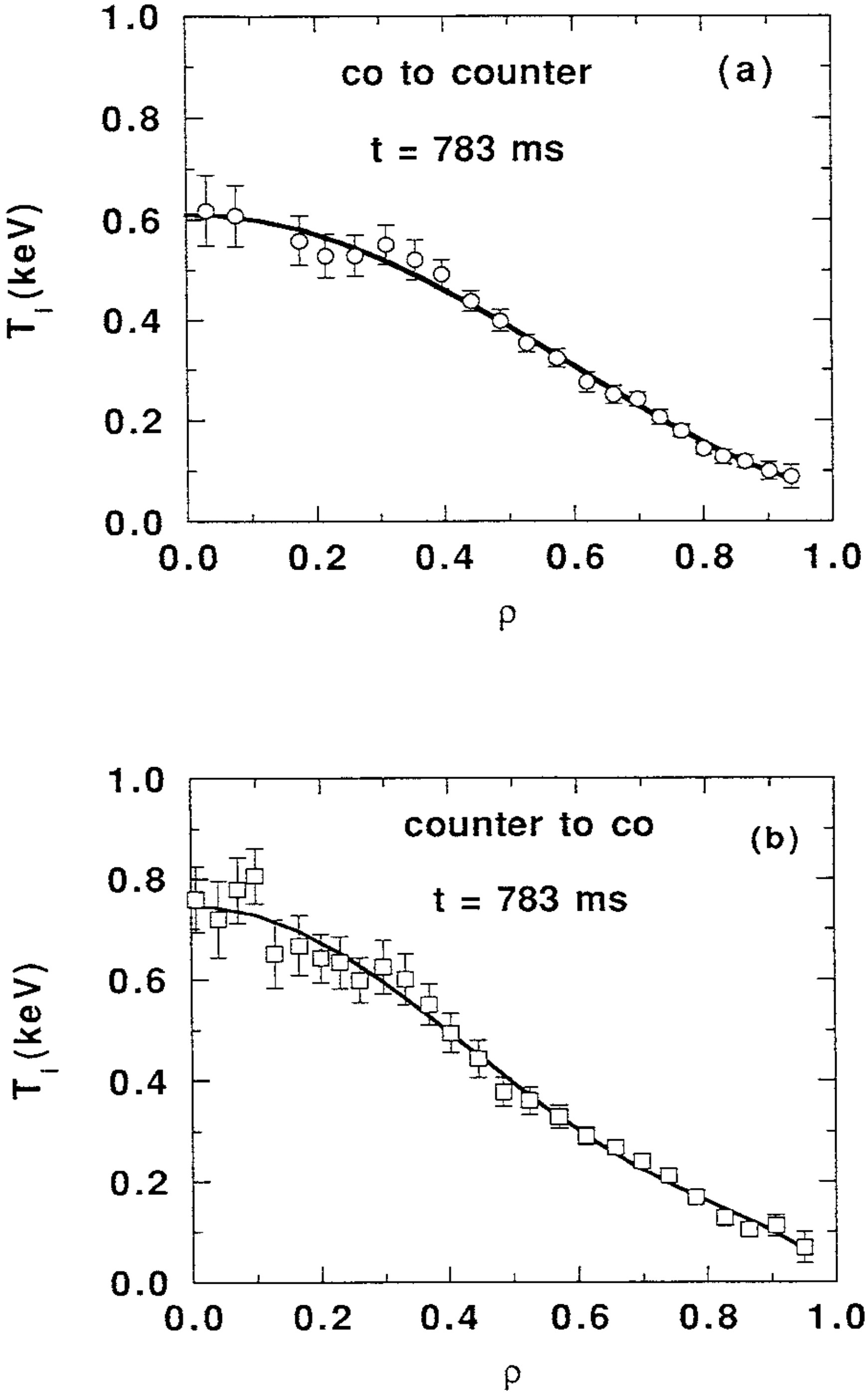


Figure 3

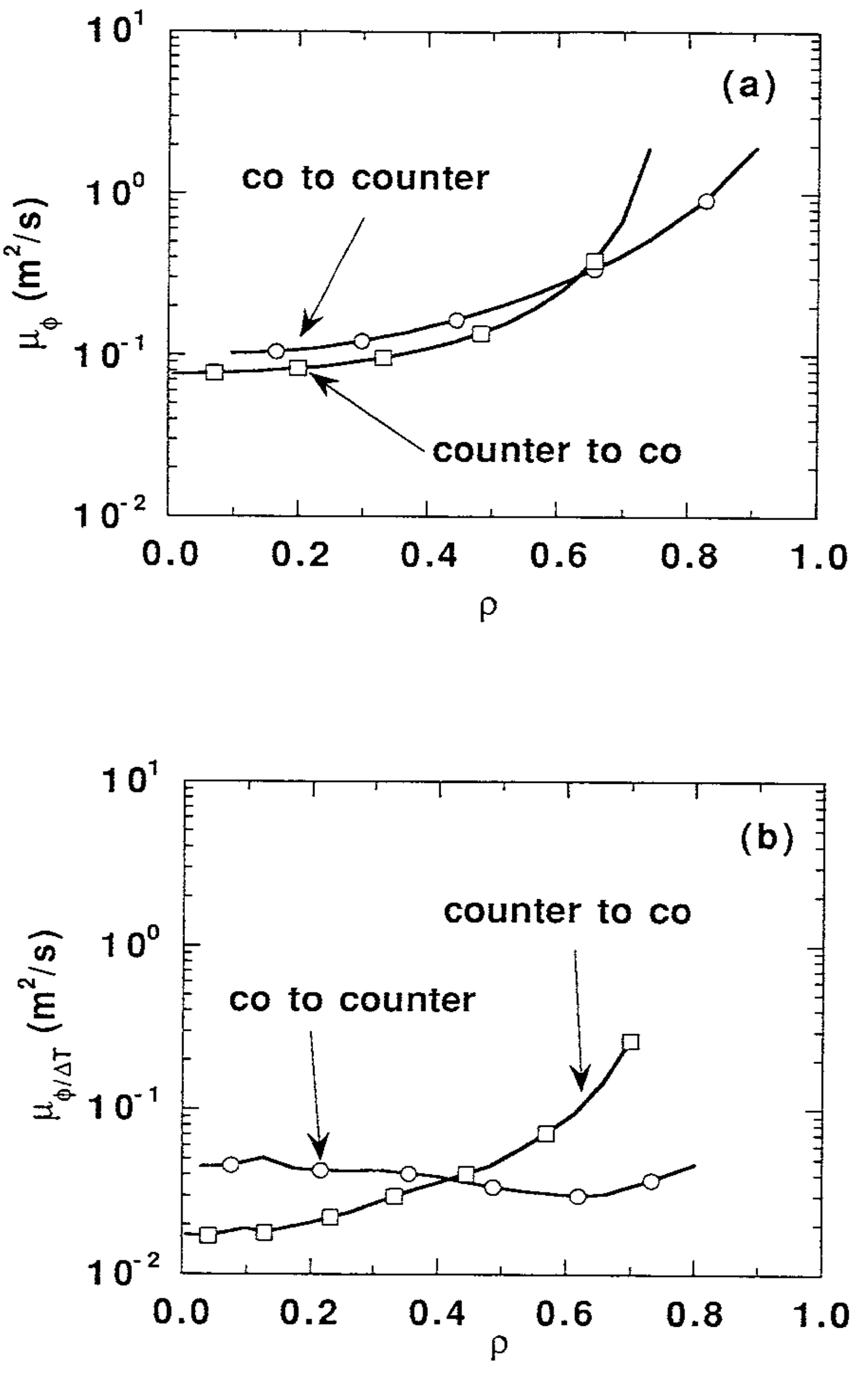

(a)
co to counter
counter to co
μ_ϕ (m^2/s)
10^1
10^0
10^{-1}
10^{-2}
0.0
0.2
0.4
0.6
0.8
1.0
ρ
(b)
counter to co
co to counter
$\mu_{\phi/\Delta T}$ (m^2/s)
10^1
10^0
10^{-1}
10^{-2}
0.0
0.2
0.4
0.6
0.8
1.0
ρ

Figure 4

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