Experimental Tests Of Paleoclassical Transport

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Introduction. A new model for an irreducible minimum level of radial electron heat transport, the
paleoclassical model, was introduced at the 2004 IAEA meeting [1a]; its basic features [1b] and details [1c]
are now published. The key hypothesis of the paleoclassical model is that in resistive, current-carrying
toroidal plasmas the electron guiding centers diffuse with small bundles of poloidal magnetic flux on the
magnetic (“skin”) diffusion time scale. While this key hypothesis has yet to be proven from first principles,
it has been motivated phenomenologically [1c]. This paper carries the initial encouraging comparisons
with experimental data [1a] to the next higher level via a number of more detailed comparisons (about
half of the tests proposed in [1a]) of paleoclassical electron heat transport with experimental data from a
variety of toroidal plasma experiments. It also seeks to determine situations (mainly ohmic-level plasmas
and in the cooler plasma edge) where paleoclassical radial electron heat transport can be dominant.

Paleoclassical Model. The paleoclassical radial electron heat transport contribution to be added
to the right side of an electron energy balance equation is [1a,1c]

$$- (\nabla \cdot Q^{pc}) = \frac{M + 1}{V'} \frac{\partial^2}{\partial \rho^2} \left( V' \frac{\eta^{pc}}{\mu_0 a^2} \frac{3}{2 n_e T_e} \right) \approx \frac{1}{V'} \frac{\partial}{\partial \rho} \left[ V' n_e \frac{\chi^{pc}}{a^2} \left( \frac{\partial T_e}{\partial \rho} + \frac{\bar{a} T_e}{L_{Te}} \right) \right], \quad (1)$$

in which the paleoclassical electron heat transport contribution $\chi^{pc}$ and critical $T_e$ length scale $L_{Te}$ are [1a,1c]

$$\chi^{pc} = \frac{3}{2} (M + 1) D_\eta, \quad M = \min\{\ell_{max}, \lambda_e, \ell_{pc}\}, \quad D_\eta = \frac{\eta^{pc}}{\mu_0}, \quad \frac{1}{L_{Te}} \sim \frac{\partial}{\partial r} \ln (V'n_e D_\eta/\bar{a}^2). \quad (2)$$

Since $\chi^{pc}$ scales with magnetic field diffusivity $D_\eta$ and hence resistivity $\eta^{pc}$, it scales as $a^{1/2}T_e^{-3/2}$ at high $T_e$; it exceeds gyro-Bohm-scale transport $\chi^{gb} \sim f_B^2 T_e^{3/2}/aB^2$ for [1a,1c] $T_e \lesssim B(T)^2/a(m)^{1/2} f_B^{-1/3}$ keV.

Magnitude, Radial Profile. Comparisons of paleoclassical predictions with $\chi^{gb}$ experimental
“power balance” data are appropriate in the confinement region of tokamak plasmas, i.e., 0.4 $\lesssim$ $\rho$ $\lesssim$ 0.9 —
because sawteeth often occur for $\rho \lesssim 0.4$ and transport data usually have large uncertainties for $\rho \gtrsim 0.9$.
In the confinement region, tokamak plasmas are usually in the “collisionless” paleoclassical regime [1]
where $\ell_{max} \equiv \pi Rq n_{max}$ dominates and $M = n_{max} \equiv (\pi \delta |q'|)^{-1/2} \sim 10$. Comparisons [2] of $\chi^{pc}$
with experimental $\chi^{gb}$ data from 6 of the base ohmic-level $(T_e \lesssim 1$ keV) discharges in DIII-D beta [3a]
and collisionality [3b] scans show reasonable agreement — similar profiles and within about a factor of 2 in
magnitude, except near the edge. A “typical best case” comparison is shown in Fig. 1a. Here, $\chi^{pc}$
decreases as one approaches the edge $(\rho \gtrsim 0.8$ in Fig. 1a) because the collision length $\lambda_e$ becomes less than
$\ell_{max}$ and one transitions to the “collisional” (Alcator scaling) paleoclassical regime where $M = \lambda_e/\pi Rq$.
The fact that $\chi^{gb}$ increases with $\rho$ in this region could be caused by anomalous plasma transport induced
by resistive ballooning modes (RBMs) [4] in this $T_e \lesssim 400$ eV region of these ohmic L-mode type plasmas.

Additional Tests. In higher B field (5.3 T) Alcator C-Mod plasmas [5], the $\chi^{pc}$ is within a factor
of about 2 of the $\chi^{gb}$ in an L-mode shot and in an H-mode shot, but has a somewhat different radial profile
and the transition from collisionless to collisional paleoclassical transport occurs at $\rho \sim 0.5$. In DIII-D
plasmas which are quiescent between sawtooth crashes (due to a “bean-shaped” cross-section) [6], the $\chi^{pc}$
is found to be about a factor of 1.5 larger than and have the same radial profile as $\chi^{gb}$. Comparisons with
DIII-D “hybrid” discharges where $T_e \sim 2.5$ keV at $\rho \sim 0.5$ show [2] that $\chi^{pc}$ is a factor of 5–7 too small
to explain the $\chi^{gb}$ for these discharges, which have significant micro-turbulence fluctuations (presumably
due to ITG modes) and 3/2 NTMs in them. Finally, dynamic modeling using only the paleoclassical
transport model usually finds a $T_e$ “thermal run away” in the central region $\rho \lesssim 0.3$ since $\chi^{pc}$ decreases
with increasing $T_e$; this effect is exacerbated by the heat pinch (or minimum $L_{Te}$) effect embodied in (1).
Electron Internal Transport Barriers. Near a low order rational surface (e.g., \( q^o \equiv m^o/n^o = 3/2 \)), \( \ell_{\eta_e} \equiv \pi R q^o n^o \) dominates and \( M \simeq n^o \), which yields [1a,1c] electron “internal transport barriers” where \( \chi_e^{pc} \) is smaller by \((n^o+1)/n_{max} \approx 0.2\) over widths determined by magnetic shear [1]. These features produce transport barriers like those inferred [7] from the RTP “stair-step” experiments in which the central \( T_e \) decreased abruptly as radially highly localized ECH was moved radially outward past low order rational surfaces. Modeling of such RTP discharges with the paleoclassical model in (1) using \( 2\chi_e^{pc} \) is shown in Fig. 1b. As indicated, the paleoclassical model results approximate the “stair step” details of the \( T_e \) profile; but, like the DIII-D dynamic tests, “thermal runaway” occurs for \( \rho \lesssim 0.2 \) — unless a sawtooth \( T_e \) relaxation model is used in this region. TRANSP modeling using the paleoclassical model of the JT-60U plasmas [8a] that exhibit large \(|\nabla T_e|\) near \( q_{min} = 4 \) surfaces [8b] is currently underway.

Minimum Temperature Gradient Length? Ohmic and L-mode type plasmas have long been known to exhibit a heat pinch or minimum temperature gradient form of electron heat transport. The specific paleoclassical prediction for \( L_{T_e} \) at the end of (2) is currently being compared with C-Mod data.

Edge Plasmas Near Separatrix. As shown in Fig. 1a, as \( \rho \) increases toward the separatrix, \( \chi_e^{pc} \) is first in the collisional regime where \( \chi_e^{pc} \simeq (3/2)D_{\eta}(\lambda_e/\pi R q) \) decreases with \( \lambda_e \). It reaches a minimum where \( \lambda_e \sim \pi R q \); thereafter, \( M < 1 \) and \( \chi_e^{pc} \simeq (3/2)D_{\eta} \simeq \eta_{eff}[100/T_e(\text{eV})]^{3/2} \text{ m}^2/\text{s} \) [1a,1c]. Moving inward from the separatrix, \( T_e \) profile paleoclassical model predictions are: first an increasing \( T_e \) gradient with \( \eta_e \equiv \eta_{ped}/\eta_0 \), a maximum \( |\nabla T_e| \) where \( q \sim 5-10 \), then a decreasing \( T_e \) gradient, and finally a pedestal \( T_e \) determined by balancing paleoclassical transport against gyro-Bohm-scaled anomalous electron heat transport, \( \beta_{ped} \equiv \eta_{ped} T_{ped}^2/(2\mu_0) \propto (\eta_0^{3/2}/\eta_0 \mu_0/\eta_0 \alpha/\eta_0 q_0 f_\theta) \). These predictions agree qualitatively with DIII-D H-mode edge pedestal data between ELMs; detailed quantitative comparisons are being explored. Also, the paleoclassical model is being used in ASTRA for edge pedestal modeling.

Non-tokamak Experiments. The paleoclassical model [1a,1c] applies to axisymmetric toroidal current-carrying plasmas of all types — spherical tokamaks (STs), reversed field pinches (RFPs), and spheromaks — in regions where \( B_p^2/B_t^2 \ll 1 \). In NSTX L-mode plasmas the approximate magnitude of \( \chi_e^{pb} \) and its decrease with increasing \(|q'| \) in the reversed shear core region are captured by the paleoclassical model. For quiescent RFP plasmas such as those in MST PPCD discharges, \( \chi_e^{pc} \) for \( \rho \leq 0.5 \) apparently provides a lower bound on \( \chi_e^{pc} \). Finally, in the SSPX spheromak, \( n = 1 \) magnetic fluctuations are reduced in \( T_e > 100 \text{ eV} \) plasmas and \( \chi_e^{pc} \) may provide a lower bound on \( \chi_e^{pb} \) in the hot core when \( T_e \gtrsim 300 \text{ eV} \).

Conclusions About Paleoclassical Transport. From these various comparisons, we conclude that the paleoclassical model apparently sets the lower limit (factor \( \sim 2 \)) on radial electron heat transport in resistive, current-carrying toroidal plasmas — when it is not exceeded by fluctuation-induced transport due to RBMs for \( T_e \lesssim 400 \text{ eV} \) in L-mode plasmas, drift-wave-type micro-turbulence (ITGs, TEMs, ETGs) for \( T_e \gtrsim B^{2/3}a^{1/2}\text{keV} \) or magnetic fluctuations (Rechester-Rosenbluth effect), or core sawtooth effects.