Transport of Helium Impurity in Alcator C-Mod*

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Summary

- Local density, temperature, and flow velocity measurements of helium in the Alcator C-Mod tokamak are provided by Charge Exchange Recombination Spectroscopy (CXRS).
- Measurements have been taken for L-, I-, and H-modes
- helium as an impurity and helium as the main ion
- $^3$He and $^4$He
- High time resolution puff experiment allows measurement of impurity transport parameters $v$ and $D$
- He impurity transport is strongly anomalous
- Steady state logarithmic density gradient provides ratio of transport parameters $v/D$
- The sensitivities of the logarithmic density gradient to several plasma parameters are given, and compared to predictions of neoclassical theory and analytical treatment of drift wave turbulence.
Introduction

- $^4$He is an unavoidable impurity in a thermonuclear reactor as a product of the D-T reaction (among others). Understanding the transport of helium is essential to avoiding excessive accumulation of the impurity which will increase radiative losses and dilute the fuel.

- Experiments on other tokamaks have shown that the transport coefficients depend heavily on the discharge regime and machine. Unfortunately, helium measurements in the literature ended some years ago, so data on some discharge regimes are unavailable.

- $^3$He is used for ICRF minority heating and mode conversion experiments. Local measurement improves determination of the deposition mode. Examination of profile effects is possible. These results may be compared with direct measurement of the mode with the phase contrast imaging (PCI) diagnostic.

- Gyrokinetic and gyrofluid simulations of turbulence identifies three pinch terms: curvature, thermodiffusion, parallel compression. For light impurities, all terms may be important. Only parallel compression is sensitive to $Z/A$ ($^4$He vs $^3$He).
Two Plasma Viewing Arrays

Poloidal array (20 channels)

Neutral Beam

Toroidal array (20 channels)

$^3$He ICRF resonance (50MHz 5.6T)

Poloidal coverage: 0.650m to 0.896m ($\rho \approx 0$ to 1)
Toroidal coverage: 0.720m to 0.839m ($\rho \approx 0.29$ to 0.79)
Physics of CXRS

- In core plasma, light impurities are fully ionized. Charge exchange with a neutral beam generates hydrogenic impurity ions which emit line spectra.

\[ e.g. \quad H^0_{beam} + He^{2+} \rightarrow H^+ + (He^{1+})^* \rightarrow H^+ + He^{1+} + \gamma \]

- From the spectrum,
  - impurity density via emissivity
  - velocity via Doppler shift
  - temperature via Doppler broadening

- At C-Mod, a 50keV diagnostic neutral beam operating in hydrogen is used as source of active charge exchange.

- The He^{1+} [n=4\rightarrow 3] 4686Å transition is used

- The beam is modulated to allow time-slice subtraction of the background.
Emission

For a general (non-Gaussian) impurity distribution, the emissivity is:

$$\varepsilon(\lambda)dVd\Omega = \frac{1}{4\pi} \sum_m n_{b,m} \int f(v) \sigma \left( \frac{1}{2} m |v - v_m|^2 \right) \sum_k a_k \delta \left[ \lambda - \lambda_k \left( 1 + \frac{v \cos \alpha}{c} \right) \right] d^3v$$

When the distribution is approximately Gaussian, the expression simplifies:

$$\varepsilon(\lambda)dVd\Omega = \frac{1}{4\pi} \sum_m n_{b,m} n_{He} q_{eff} \sum_k a_k \exp \left( - \frac{\left( \lambda - \lambda_k \left( 1 + \langle v \rangle \cos \alpha / c \right) \right)^2 m_{He} c^2}{2T \lambda_k^2} \right)$$

The effective rate coefficient, $q_{eff}$, combines the cross section for charge exchange into various initial energy states with a collisional-radiative model to compute the amount of photon emission. $q_{eff}$ depends on electron density, temperature, magnetic field, and effective $Z$. 

![Rate coefficient for production of photons](image)
He II 4686Å Spectrum

- Beam enhanced signal is obtained by subtracting background signal with beam off which is edge emission from cold ions and passive CXRS.
- Subtraction is imperfect because the background emission is evolving. This is a major source for noise introduced by analysis.

Spectral region near He II 4686Å line

Area of He II 4686Å line over time

Beam enhanced signal is obtained by subtracting background signal with beam off which is edge emission from cold ions and passive CXRS.
Subtraction is imperfect because the background emission is evolving. This is a major source for noise introduced by analysis.
Helium Line Fitting

4686A He\(^{1+}\) line is split by Zeeman effect
146 transition lines for He (n:4\(\rightarrow\)3)

Zeeman pattern is blended by instrument function and Doppler broadening, but is needed for proper width fitting. Pattern is polarized and depends on viewing angle.

Fit spectral data with model function

\[ y = a_0 \sum_{i=1}^{146} \exp\left(-\frac{x - \lambda_i (1 + a_1 / c)}{a_2}\right) + a_3 \]

use Levenberg-Marquadt solver “mpfit”

\( n_{He}(\rho_k) = a_0 \sqrt{\pi a_2} / H_k / \int n_b ds \)

\( v_{He}(\rho_k) \cdot s_k = a_1 - Y_k \)

\( T(\rho_k) = (a_2 - \Delta\lambda_{inst}) \frac{m_{3He}c^2}{\lambda_0^2} \)

\( H_k \) was obtained in multiple ways:
• bremsstrahlung – calculate throughput using measured continuum level and expected bremsstrahlung
• beam into gas – calculate from emission from beam fired into vessel filled with neutral helium gas
• radiometric – backlight with integrating sphere
• quasineutrality – scale to Thompson Scattering measurement of electron density for helium plasma
Density Profiles

- Density profiles tend to be hollow to flat
- Strong inward pinch at edge
- Core density is slightly increased with ICRF
- I-mode is an improved confinement regime that exhibits a temperature pedestal but no density pedestal; H-mode-like energy confinement but L-mode-like particle confinement
Plasma current scan
LH power 700kW.
For $I_p \sim 0.43\,\text{MA}$, plasma is fully non-inductive.
Higher plasma current generates a stronger inward pinch, increasing $^4\text{He}$ density and pushing peak inward.

Electron density scan with other parameters fixed, ohmic plasma
Not much effect on $^4\text{He}$ density
4He Lower Hybrid Insensitivity

LH power scan experiment
No clear sensitivity to LH power

LH phasing scan experiment
No visible sensitivity to LH phase

Background data taken during LH experiment shows little effect of LH on 4He density profile.
$^3$He Density vs Puff, Heating Regime Change

ICRF: 1.5MW@50MHz, 2MW@80MHz nl04 0.7-0.8, $B_T$ 5.5T

$^3$He concentration was scanned to change primary deposition mode from mode conversion to minority heating of $^3$He. For 75ms and 100ms puff ($n_{He}$ 4.5-5.5% $n_e$), we have strong minority heating, with substantial increase in stored energy.

Wave heating both modifies the profile shape via changes in temperature and fast ion distribution and is modified by the minority profile through local wave-particle interactions.
$^3$He $I_p$ Scan and $B_T$ scan

ICRF: 1.5MW@50MHz, 1.5MW@80MHz
nl04 0.8, $B_T$ 5.5T

Increasing current causes an increase in the $^3$He density due to increased inward pinch. Increasing current also shifts peak density radius inward.

ICRF: 1.5MW@50MHz, 2.5MW@80MHz
nl04 0.8, $I_p=1$MA

Increasing $^3$He puff duration increases the $^3$He density, but not linearly. For 75ms and 100ms puff, we have strong minority heating of $^3$He.
Edge Emission He$^{1+}$

- Without neutral beam, entire He$^{1+}$ emission comes from edge, where an equilibrium population of He$^{1+}$ exists in a balance of recombination, passive charge exchange, ionization.
- Use collisional radiative model (ADAS 205*) to estimate He$^{1+}$ population from edge radiances
  - CR model balances recombination, ionization, charge exchange, excitation, de-excitation, and emission using best known atomic cross sections.
- Helium remains in plasma long after many helium confinement times due to wall recycling. Edge emission gives a measurement of wall recycling needed for core transport simulation.

He\textsuperscript{1+} Confinement Mode Effects

- Sudden drop in edge emission in L-H transition by 50% and recovery in H-L transition
- L-I transition is gradual and not demarcated, but I-L transition is abrupt, with sudden rise in edge emission

Edge radiances plotted for multiple channels
Helium Transport

- Transport in a tokamaks is described in terms of neoclassical and anomalous contributions. The anomalous transport is taken to be due to turbulence. A complete understanding of turbulent transport is one of the forefront challenges facing the fusion community.

- Turbulent transport is the dominant impurity transport mechanism in Alcator C-mod, except within an internal transport barrier in some shots.

- C-mod operates in the banana collisional regime, where bounce frequency exceeds effective collision rate.

- In drift wave turbulence, correlations between electric potential oscillations and pressure oscillations generate finite gyro-averaged E x B drifts, leading to radial flux \( \Gamma_s = \langle \tilde{n}_s \tilde{v}_{Er} \rangle \)

- Density and temperature gradients and magnetic curvature act as sources of free energy for growth of turbulent oscillations.

- In toroidal geometry, ion temperature gradient (ITG), electron temperature gradient (ETG), and trapped electron modes (TEM) are important contributions to turbulent transport.

- In \(^3\)He mode conversion experiments, helium concentrations are too high to be treated as tracer particles \( (n_{He}/n_e \sim 0.05-0.30) \) so helium plays an active role in the drift wave analysis.
Transport Parameterization

- A standard empirical parameterization is to split the radial transport into a pinch (convection) term and a diffusion term

\[
\Gamma_s = -D_s \frac{dn_s}{dr} + v_s n_s
\]

- This parameterization works well for models with linear dependence on density such as neoclassical transport, and allows for direct comparison to experiment. For nonlinear models, an approximate \( v \) and \( D \) can be found.

- For a steady state plasma, \( \Gamma_s = 0 \). Under this condition, the ratio \( v/D \) is equal to the logarithmic density gradient which can be measured.

\[
\frac{v_s}{D_s} = \frac{1}{n_s} \frac{dn_s}{dr} \equiv -L_{n_s}^{-1}
\]

\[
R \frac{v_s}{D_s} = R \frac{1}{n_s} \frac{dn_s}{dr} \equiv -RL_{n_s}^{-1}
\]

- For puffing experiments, the impurity density is not in steady state. However, it is determined that shortly after puffing, the relationship is still approximately valid. This is because the edge recycling time constant \( >> \) particle confinement time
Helium Impurity Transport Experiment

Puff $^4$He ($\sim$3% $n_e$) into steady state discharges (Ohmic L-mode, ICRF I-mode)

To get v and D independently, require high time resolution profiles

- Camera frame time: 10ms
- Beam modulation duty cycle: 60ms on, 20ms off

Overcome the slower beam response by taking consecutive identical shots with displaced beam start times to fill out time points

Edge recycling is measured using He$^{1+}$ spectroscopy
Fitting Density Time Dependence

Puff response – combination of 3 shots

beam on (asterisk)

beam off (diamond)

shot 1120822...

020

023

024

Fit data with carefully chosen model function (2 shown)

Beam off fit: Obtain edge He\(^{1+}\) population via collisional-radiative model needed to model recycling

Beam on fit: Obtain core He\(^{2+}\) population

Use STRAHL to adjust v and D to match experiment

STRAHL* is a 1D transport code for evolving impurity populations with given transport coefficients

*R. Dux, STRAHL User Manual, Max-Planck-Institut für Plasmaphysik, IPP 10/30, 2006
Choose $^4$He input flux so that time dependent He$^{1+}$ population at edge matches measurement.

Then, adjust $v$ and $D$ until predicted He$^{2+}$ population matches CXRS measurement across all radii.

Due to noise in the measurement, a reduced parameter time-independent model was used for $v$ and $D$.

Measured transport ($v_0 = -3.2\text{m/s}, D = 0.8\text{m}^2/\text{s}$) is greater than neoclassical (NCLASS) prediction.

He Transport Comparison

- Measured He transport is strongly anomalous
- Although the values of $v$ and $D$ greatly exceed neoclassical, the ratio $v/D$ is quite similar to neoclassical
- Helium transport parameters as measured on different machines and discharges are listed

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$C_v$ is defined by: $v n_e = C_v D \frac{dn_e}{dr}$

Table refs.

a. The pinch velocity is 20-30m/s near the plasma edge
Parametric sensitivities

- Experimental parametric sensitivities may guide theoretical work and show the dominant contributions.

  - neoclassical:
    \[ \Gamma_z \propto -\nu_z \left\{ \frac{c_1}{Z_i n_i} \frac{\partial n_i}{\partial r} - \frac{c_2}{Z_e n_e} \frac{\partial n_e}{\partial r} + \frac{c_3}{T_e} \frac{\partial T_e}{\partial r} \right\} \]

  - TEM:
    - Growth rate decreasing with \( \nu_{*e} \)
    - inward thermodiffusion term, outward parallel compression term

  - ITG:
    - destabilized by
      \[ \eta_s = \frac{d \ln T_s}{d \ln n_s} = \frac{1/L_{T_s}}{1/L_{n_s}} > \frac{2}{3} \]
    - outward thermodiffusion term, inward parallel compression term

- See also, Rowan “Transport of light, trace impurities in Alcator C-Mod” Poster JP8
Experimental values from 123 shots are plotted, several time points per shot.

Diverse discharge conditions.

Electron density and temperature from Thomson scattering diagnostic.

Dotted line is a neoclassical scaling, neglecting thermodiffusion terms.

Neoclassical scaling is not adequate.

Hollow profiles with \( R/L_{nHe} < 0 \) in core are common.
\[ \frac{R}{L_{nHe}} \text{ vs } \frac{R}{L_{Te}} \]

- \( ^4\text{He} \) density from He CXRS poloidal view
- Electron temperature from Thompson scattering diagnostic
- An ion temperature gradient (ITG) instability exists when ratio of ion temperature gradient to ion density gradient exceeds a critical value

\[
\eta_i = \frac{\text{d} \ln T_{He}}{\text{d} \ln n_{He}} = \frac{R / L_{THe}}{R / L_{nHe}} > \frac{2}{3}
\]

- Below dotted line is ITG unstable region if \( T_e \) used as a proxy for \( T_{He} \)
- Lots of scatter, but correlation of density peaking with temperature peaking is suggestive of ITG
\[ \nu_{\text{eff}} = 0.1 \frac{Z_{\text{eff}} \langle n_e \rangle R}{\langle T_e \rangle^2} \sim \frac{\nu_{ei}}{\omega_{De}} \]

Expresses strength of collisional processes to characteristic turbulent processes.

123 \(^4\)He shots, data range: \(0.5 < \nu_{\text{eff}} < 4.2\)
Lowest effective collisionalities are seen in I-mode
Possible positive correlation at rho=0.6?
Expresses ratio of collision frequency to bounce time

\[ \nu_{*e} = \sqrt{2} \left( \frac{\nu_e q R}{\epsilon^{3/2} \nu_e} \right) \]

\( \nu_{*e} < \sim 1 \) indicates banana regime and destabilization of trapped electron modes

We see lower density peaking at lower \( \nu_{*e} \) which suggests that TEM is providing an outward pinch, consistent with parallel compression. At higher \( \nu_{*e} \), the slope flattens out, as TEM is not expected to play a role.
“poloidal” velocity is measured approximately vertically with 10 degree tilt into toroidal direction
“toroidal” velocity is measured at an approximately 40 degree angle from horizontal due to vessel space constraints
ICRF $^3$He resonance

Ion temperature is increased by ICRF heating
Temperature measurement somewhat inaccurate in core where beam penetration is low
3$^\text{He}$ Puff Heating Regime

Stored energy from EFIT calculation
Increase in stored energy during ICRF
Larger increase for 100ms puff.