Measurement, modeling, and analysis of the neutral density profile in MST

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Neutral density profiles necessary for plasma analysis

• Neutral particles interact with the plasma in two important ways:
  • Through ionization, serve as the plasma’s fuel
  • Through charge exchange, can act as a loss mechanism for charged particles

• Neutral density profile $n_0(R,Z)$ is important for analysis of:
  • Electron source term
    $$ S = n_0 n_e \langle \sigma v \rangle_{ionization} $$
  • Particle confinement time
    $$ \tau_p = \frac{\int n_e \, dV}{\int \left( S - \frac{\partial n_e}{\partial t} \right) \, dV} $$
  • Energetic ion charge-exchange rates
  • CHERS data (fractional abundances of impurity charge states)
  • NPA data (signal is a result of charge-exchange processes)
Outline

• Measurements
  • $D_\alpha$ emission detector array

• Modeling
  • NENE Monte Carlo neutral transport modeling
  • Fitting to data
  • Neutral sourcing choices

• Analysis
  • Consistency with CHERS predictions
  • Fast ion charge exchange losses
  • NPA data analysis
Neutral density derived from $D_\alpha$ line emission measurements

- 656.1 nm line emission generated from neutral/electron collisions

$$\gamma_{D_\alpha} = n_0 n_e \langle \sigma v \rangle_{\text{excitation}}$$

- Calibrated filtered photodiode array provides 16 line-integrated measurements
NENE models neutral transport through MST plasma

- NENE is a Monte Carlo code that simulates neutral particle transport through a plasma
  - Sources a neutral at plasma edge
  - Identifies mean free path and probability of ionization based on input plasma conditions
  - Tracks particle until it scatters (CX), ionizes, or hits a wall

- Written by F. Auriemma and R. Lorenzini for RFX and adapted for MST

NENE

Wall materials

Measured $n_e$, $T_e$, $T_i$

Neutral source

Monte-Carlo particle tracking
Atomic Physics
TRIM wall interactions

$\rightarrow n_0(R,Z)$
NENE used with $D_\alpha$ emission to generate $n_0$ profile

Wall materials → Monte-Carlo particle tracking
Measured $n_e, T_e, T_i$ → Atomic Physics
Neutral source → TRIM wall interactions

→ $n_0(R,Z)$

Create 3 profiles with different neutral sources

Map to flux coordinates

Analysis routine

Mix profiles with varying coefficients

Calculate $D_\alpha$ emission

Minimize $\chi^2$ against $D_\alpha$ detector data

Minimum found

Generate solution $n_0(R,Z)$

Calculate source term, $\tau_p$, etc.

\[ n_0(R, Z) = \sum_{i=1}^{3} a_i \ n_{0,i}(R, Z) \]
Multiple NENE models used as basis functions

- We use 3 NENE models with different neutral source options as basis functions to fit our observed $D_\alpha$ emission

$$n_0(R, Z) = \sum_{i=1}^{3} a_i \, n_{0,i}(R, Z)$$

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**Proton/wall collisions**

- No profile
- $D_\alpha$ profile
- Line-integrated $D_\alpha$ emission

**Limiter emission**

- No profile
- $D_\alpha$ profile
- Line-integrated $D_\alpha$ emission

**50ev monoenergetic**

- No profile
- $D_\alpha$ profile
- Line-integrated $D_\alpha$ emission

**Solution**

- No profile
- $D_\alpha$ profile
- Line-integrated $D_\alpha$ emission
Core $n_0 \sim 10^9$ cm$^{-3}$ in typical MST discharges

<table>
<thead>
<tr>
<th>Plasma</th>
<th># shots</th>
<th>Core $n_0$ (cm$^{-3}$)</th>
<th>Edge $n_0$ (cm$^{-3}$)</th>
<th>$\tau_p$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard F=0</td>
<td>116</td>
<td>$2.3 \times 10^9$</td>
<td>$5.6 \times 10^{11}$</td>
<td>1.9</td>
</tr>
<tr>
<td>Standard F= -0.2</td>
<td>95</td>
<td>$2.2 \times 10^9$</td>
<td>$6.2 \times 10^{11}$</td>
<td>1.6</td>
</tr>
<tr>
<td>PPCD</td>
<td>63</td>
<td>$6.5 \times 10^8$</td>
<td>$1.3 \times 10^{11}$</td>
<td>17.3</td>
</tr>
</tbody>
</table>

F=0

Z=0 neutral density

$10^{12}$

$10^{11}$

$10^{10}$

$10^{9}$

$10^{8}$

$r_{\text{minor}}$ (m)

F=-0.2

Z=0 neutral density

PPCD

Z=0 neutral density
Neutral energy choice affects core density

- As you increase source neutral energy, models better match data, but core \( n_0 \) rises and results become unrealistic.
- Best profile may differ based on expected results.
- 50 ev used as default.
Time evolution illustrates neutral sourcing during sawteeth

- NENE models equilibrium at a single time point
- Series of equilibria with $\Delta t = 0.25$ ms used to study time behavior
- $n_0$ increases at sawteeth due to plasma/wall interaction
- $n_0$ increases during gas puffing and current ramp-down
Profile time evolution – away from sawtooth

Plasma current

Gas Puffing

Core $D_\alpha$

Core $n_0 \left(10^{10} \text{ cm}^{-3}\right)$

$D_\alpha$ emission

$n_0$ profile
Profile time evolution – at sawtooth

Plasma current

Gas Puffing

Core $D_\alpha$

Core $n_0 \left(10^{10} \text{ cm}^{-3}\right)$

$D_\alpha$ emission

$n_0$ profile
Profile time evolution – end of shot

Plasma current

Gas Puffing

Core $D_\alpha$

Core $n_0$ ($10^{10} \text{ cm}^{-3}$)

$D_\alpha$ emission

$n_0$ profile
Neutral density critical to CHERS analysis

- $n_0$ is important for determining fractional abundances of impurity ions
- $n_0$ can be predicted based on CHERS measurements of multiple impurity charge states

$r/a$ vs. $N_{\text{index}} / N_{\text{total}}$

- Core $n_0 = 10^9$ cm$^{-3}$
- Core $n_0 = 10^{10}$ cm$^{-3}$
Results consistent with CHERS $n_0$ predictions

- CHERS predicts $n_0$ at several radial locations.

- To match predictions, a 250 ev neutral energy profile was necessary to increase core $n_0$.
  - Plasma above is 520 kA PPCD, so some increase in neutral energy might be expected.
Neutral charge exchange plays a role in NBI ion confinement

- Fast ions can be injected with the 25keV NBI
- Fast ion loss rates can be inferred from neutron signal decay rate and knowledge of slowing-down processes

\[ \Gamma_n \propto \int_V n_f i n_i \langle \sigma_d d(E_f)\rangle v_{fi} dV \]

\[ \frac{1}{\tau_n} \approx \frac{1}{\tau_{fi}} + \frac{1}{\tau_{cl}} \]

- One loss mechanism for fast ions is charge exchange with neutrals

\[ - \frac{dn_{fi}}{dt} = n_f i n_0 \langle \sigma v \rangle_{cx} \quad \Rightarrow \quad \tau_{cx} = \frac{1}{n_0 \langle \sigma v \rangle_{cx}} \]
Neutral charge exchange plays a role in NBI ion confinement

- TRANSP models predict charge exchange is the primary loss mechanism for NBI ions in MST

- In extreme case, $\tau_{fi}$ becomes a lower bound on $\tau_{cx}$

$$\tau_{cx} = \frac{1}{n_0 \langle \sigma v \rangle_{cx}} \quad \frac{1}{\tau_{fi}} \simeq \frac{1}{\tau_{cx}} + \frac{1}{\tau_{other}} \quad \therefore \quad \tau_{fi} \leq \tau_{cx}$$

- Large error bars (not shown), but order of magnitude agreement with TRANSP prediction
ANPA measures fast ion energy spectrum

- NPAs measure energy spectrum of fast neutrals (fast ions that have charge-exchanged)
- MST’s ANPA measures 0.5-30 keV ions with H/D mass separation

\[ \text{Signal strength } \propto n_0 n_{fi} \langle \sigma v \rangle_{cx} \]
ANPA signal analysis dependent on $n_0$

Signal strength $\propto n_0 n_{fi} \langle \sigma v \rangle_{cx}$

- NPA signal level is dependent on $n_0$ at the location of the collision

- Magnetic events increase both $n_{fi}$ and $n_0$; must decouple
  - Must know ion profile as well neutral profile
  - Can also use neutron signal, which has much weaker $n_0$ dependence

![Graph showing ANPA signal and Core $D_\alpha$ over time](image)
Summary

• Background neutral density is an important parameter for analysis of plasmas, particularly NPA signal analysis

• Neutral density is calculated in MST by comparing NENE models with measured $D_\alpha$ light emission

• Neutral density estimates show rough agreement with CHERS data and fast ion confinement times
Summary

• Background neutral density is an important parameter for analysis of plasmas, particularly upcoming NPA signal analysis.

• Neutral density is calculated in MST by comparing NENE models with measured $D_\alpha$ light emission.

• Neutral density estimates show rough agreement with CHERS data and fast ion confinement times.

Questions?