Evaluation of Anomalous Fast-Ion Losses in Alcator C-Mod

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Abstract

In recent Alcator C-Mod campaigns, the efficiency of H-minority RF heating has dropped to ~50%. To determine whether the poor heating efficiency is caused by anomalous losses of the energetic hydrogen tail, we compare the measured d-d beam-target neutron emission during injection of a perpendicular, 50-keV deuterium diagnostic beam against classical predictions by the TRANSP code.

We compare the beam-target emission to classical slowing down calculations in both normal and locked-mode discharges in a variety of plasma conditions (nebar = 0.7 - 2.7 $10^{20}$ m$^{-3}$, $I_p$ = 0.25 - 1.0 MA, $P_{\text{RF}}$ = 0 – 2 MW, $B_\phi$ = 4.1-5.4 Tesla) in the Ohmic and H-mode regimes both with and without locked modes.

No difference in neutron emission is observed between plasmas with and without locked modes, suggesting that locked modes do not cause additional fast-ion losses in these plasmas.
Motivation: is RF Heating Compromised by Fast Ion losses in C-MOD?

Trends:
- Density dependence
- Lower performance in plasmas with locked modes.
- $dW/dt$ at RF turn-on is less than $P_{RF}$. 

Graph shows data points for different plasma conditions with 0.8 MA and 1.0 MA, indicating possible locked modes.
There is also a Weak, Long-Term Trend Toward Decreased Performance
**Technique:** compare beam-target dd neutron emission during D-DNB injection to classical calculations.

**C-Mod Diagnostic Beam**
- 50 keV, \(\sim 4\) amps
- Injected radially on midplane
- Diameter \(\sim 8\) cm
- Classical fast-ion confinement is excellent.

Collisionless orbits of 50 keV deuterons injected at 90°, \(Z = 4\) cm, \(R=75, 83\) cm.
Deuterium DNB experiments
<table>
<thead>
<tr>
<th>SHOT</th>
<th>Plasma Regime</th>
<th>Locked Mode?</th>
<th>( I_p )</th>
<th>( B_t )</th>
<th>( P_{RF} )</th>
<th>( N_e(0) )</th>
<th>( T_e(0) )</th>
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**Plasma Conditions**

- **MA**: megaamperes
- **Tesla**: teslas
- **MW**: megawatts
- **10^20**: 10^20
- **keV**: kiloelectronvolts
- **KeV**: electronvolts
## Transp Beam and Neutron Calculations

<table>
<thead>
<tr>
<th>SHOT</th>
<th>Plasma Regime</th>
<th>Locked Mode?</th>
<th>DNB Power (kW)</th>
<th>Neutrons ($10^{12}$/sec)</th>
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<td></td>
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<td>Transp Pinj, Shine, Orbit, CX</td>
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</table>
First approach: global calculation of Expected neutron rate

- Comparison of measured and calculated neutron rates may give information on prompt losses of fast beam deuterons (and presumably on RF-heated H-minority tail)

- We will use TRANSP for the full-blown calculation, but here we present results of simplified calculations:
  - single $\tau_s$ for all fast DNB deuterons; ignore half- and third-energy components (<10% effect)
  - use $T_e(0)$
  - use $<n_e>$, $Z_{eff}$, and assume $Z_{imp} = 9$ to get $n_D$
Convolution integral

\[
R_{DD} \propto n_D n_{\text{fast}} \sigma_{DD}(E) v
\]

\[
R_{DD}(t) \propto n_D \int_0^\infty I_{\text{beam}}(t - \tau) \sigma_{DD}(E(\tau)) v(\tau) \, d\tau
\]

where \( v(t) = v_0 e^{-t/\tau_S} \)

\[
E(t) = \frac{1}{2} M_D v^2(t)
\]

and \( \sigma_{DD}(E) = \text{Duane formula in NRL formulary} \)

- Fit the convolution integral (using IDL curvefit) to neutron signal to determine \( \tau_S \) and normalization for each shot
Convolution CURVEFIT examples

- Fit to rise, fall, and ‘flattop’
Determining deuteron slowing down time from neutron rate

Deuteron slowing down time vs density

Run = 1030715
Ohmic L-mode

\[ \tau_s \text{ (ms)} \]

\[ \langle n_e \rangle \left(10^{20} \text{ m}^{-3}\right) \]
Locked modes do not affect slowing down time
Theoretical estimate of $\tau_s$ (classical)

$v_{\text{beam}} \gg v_D : \quad \tau^{ii}_s(s) \simeq 0.044/n_D(10^{20} \text{ m}^{-3})$

$v_{\text{beam}} \ll v_e : \quad \tau^{ie}_s(s) \simeq 0.020 T_e(\text{keV})^{3/2}/n_e(10^{20} \text{ m}^{-3})$

(I have used $\ln \Lambda = 20$ in the preceding expressions.)

Note that $\tau^{ii}_s \sim \tau^{ie}_s$

$$\tau_s = \frac{1}{\tau^{ii}_s + \tau^{ie}_s}$$
Calculated neutron rates from Global Model

![Graph showing measured/calculated \( R_n \) vs. \( \langle n_e \rangle \) for Run 1030715 in Ohmic L-mode. The graph includes data points for Green: not locked and Red: locked. The note indicates that \( Z_{\text{imp}} = 9 \) is assumed.](image)
Differences from Global Model:

- Models relevant beam physics: deposition, shine-thru, orbit losses, charge-exchange losses.
- Uses full profiles of electron temperature, density, etc.
A Wide Range of Plasma Densities Were Studied
Beam Deposition Profiles Range from Centrally-peaked to Edge-peaked
Temperature Profiles

- Ion temperature profile is calculated from $\chi_i = n \chi_{i,\text{neo}}$ with scale factor $n$ adjusted to match neutron emission during the Ohmic phase of the plasma.

- Calculated neutron emission varies ~ linearly with $T_e$ and is insensitive to $T_i$. 

![Graphs showing electron and ion temperature profiles](image)
Beam Shine-Thru is Small Except at the Lowest Density

Beam Shine-Through Power

\[ P_{DNB} \sim 135 \text{ kW} \]
Classical Beam Orbit Losses are Less Than 15% Except at Highest Densities

Power loss (kw)

\[ P_{\text{DNB}} \sim 135 \text{ kW} \]
Transp Neutron Simulations
(ordered by density)

- Shot 25
  - L-Mode locked
  - Neo 0.5
  - Ip 0.98

- Shot 23
  - L-Mode locked
  - Neo 1.0
  - Ip 0.97

- Shot 18
  - L-Mode locked
  - Neo 1.0
  - Ip 0.97

- Shot 24
  - L-Mode locked
  - Neo 1.3
  - Ip 0.97
Transp Neutron Simulations
(ordered by density)
Transp Neutron Simulations
(ordered by density)
Measured Beam-Target D-D Neutron Emission is a Factor ~2 less than Classical TRANSP Predictions for $N_{eo} > 1.6 \times 10^{20}$ m$^{-3}$
TRANSP Error Analysis in Medium-Density, Locked L-Mode

Nominal Analysis (black)

Error Analysis
- $Te$ +/- 10%
- $Ne$ +/- 10%
- $Z_{eff}$ +/- 15%
- $\langle Z \rangle$ = 6, 20

edge attenuation

- Attenuation of beam by edge neutral gas might explain the low neutron emission.
Measured neutron rate is just within measurement uncertainty. Dominant uncertainty is composition of impurity mix.

Possible beam attenuation at plasma edge would more than reconcile measured neutron rate with classical predictions.
TRANSP Error Analysis at Low Density

- Dominant uncertainty is composition of impurity mixture ... Zeff is high, so dilution is significant.
- Measured neutron emission is less than predicted by TRANSP, but within diagnostic uncertainty.
- Attenuation of beam by edge gas pressure is a negligible effect.
The customary diagnostic uncertainties do not reconcile the measured neutron rate with TRANSP.

Edge neutral pressure is low, so attenuation of beam by edge gas pressure is a negligible effect.
• Shot 32

Nominal Analysis (black)

Error Analysis

Te  +/- 10%
Ne  +/- 10%
Zeff +/- 15%

<Z> = 6, 20
edge attenuation

Excited-State Depo

• Measured neutron rate is anomalously low, outside of measurement uncertainties considered.
High Edge Neutral Pressure May Reduce Expected Neutron Emission by 20-40% in Some Plasmas

• Edge Pressures and expected attenuation are small at low- to moderate density
High Edge Neutral Pressure is Observed in Some High Density Plasmas
Estimated Beam Attenuation through Plasma Edge

![Graph showing Estimated Beam Attenuation through Plasma Edge](image)
Conclusions

• Both a simplified global analysis and standard TRANSP analysis show that the measured d-d beam-target neutron emission is a factor ~2 less than expected from classical fast ion confinement and thermalization.

• In some -- but not all – plasmas, the discrepancy is within diagnostic uncertainty. Error analysis is ongoing.

• These results disagree with long-standing observations of classical fast ion confinement and thermalization reported on a number of tokamaks and thus would appear to suggest a machine-specific anomaly, e.g. ripple due to coil misalignment.

• These experiments do not distinguish between anomalous loss of the beam ions versus anomalous slowing down. Anomalous losses of energetic ions might explain the RF heating results, but anomalous slowing down would not.