Design of a Neutral Beam Injection System for STOR-U

Presented by
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On June 7, 2009
At the CAP Congress in Moncton
Division of Plasma Physics

Project supported by NSERC and completed partially in fulfillment of the requirements of the Engineering Physics Undergraduate Program at Queen’s University
Tokamak

- Confines plasma using magnetic fields
- Induce plasma current for heating until resistance becomes very low
- Injected energetic neutral fuel particles heat by collisions, ionize, then join plasma
- STOR-U, University of Saskatchewan
Neutral Beam Injector Subsystems

- Ion source: high current, hydrogen ions
- Accelerator: beam energy, focusing
- Neutralizer: charge exchange
- Residual ion dump, then drift to plasma
NBI Port Size

- Determined max port dimension
- Assumed maximum toroidal field coil size
- Tangential injection

16 cm MAX
Beam Power

• $P = I^2R$, compare $P_{\text{NBI}}$ to $I^2$ of previous tokamaks
• For STOR-U, $I = 0.4 \text{ kA} \rightarrow \sim 2 \text{ MW NBI}$

Data from [2].
Beam Energy

- Beam must penetrate plasma, but not pass through.
- For STOR-U, $T_i = 3.5$ keV $\rightarrow \sim 20$-100 keV NBI.
Calculating Neutral Fraction

\begin{align*}
\sigma_{10}: & \quad H^- + H_2 \rightarrow H^0 + e + H_2 \\
\sigma_{11}: & \quad H^- + H_2 \rightarrow H^+ + 2e + H_2 \\
\sigma_{01}: & \quad H^0 + H_2 \rightarrow H^+ + e + H_2 \\
\sigma_{0\bar{1}}: & \quad H^0 + H_2 \rightarrow H^0 + H_2^+ \\
\sigma_{10}: & \quad H^+ + H_2 \rightarrow H^0 + H_2^+ \\
\sigma_{1\bar{1}}: & \quad H^+ + H_2 \rightarrow H^- + 2H^+ \\
\end{align*}

\[
\frac{dn^-}{dz} = N(z)[n^0 \sigma_{0\bar{1}} + n^+ \sigma_{1\bar{1}} - n^- (\sigma_{10} + \sigma_{11})]
\]
\[
\frac{dn^0}{dz} = N(z)[n^- \sigma_{10} + n^+ \sigma_{10} - n^0 (\sigma_{0\bar{1}} + \sigma_{01})]
\]
\[
\frac{dn^+}{dz} = N(z)[n^- \sigma_{1\bar{1}} + n^0 \sigma_{01} - n^+ (\sigma_{1\bar{1}} + \sigma_{10})]
\]

- Cross sections tabulated by ORNL [21]
- N neutral gas density
- Initial N estimate from tokamak pressure [22]
- $z$ distance
- $n^0(0) = n^-(0) = 0$
- $n^+(0)$ arbitrary
\[
\sigma_{-10}^{}: \quad \overline{H}^- + H_2 \rightarrow \overline{H}^0 + e + H_2 \\
\sigma_{-11}^{}: \quad \overline{H}^- + H_2 \rightarrow \overline{H}^+ + 2e + H_2 \\
\sigma_{01}^{}: \quad \overline{H}^0 + H_2 \rightarrow \overline{H}^+ + e + H_2 \\
\sigma_{0\overline{1}}^{}: \quad \overline{H}^0 + H_2 \rightarrow \overline{H}^0 + H_2^+ \\
\sigma_{10}^{}: \quad H^+ + H_2 \rightarrow \overline{H}^0 + H_2^+ \\
\sigma_{1\overline{1}}^{}: \quad H^+ + H_2 \rightarrow \overline{H}^- + 2H^+
\]

<table>
<thead>
<tr>
<th>(\text{(cm}^2\text{)})</th>
<th>(20 \text{ keV})</th>
<th>(40 \text{ keV})</th>
<th>(70 \text{ keV})</th>
<th>(100 \text{ keV})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_{-10})</td>
<td>(8.36 \times 10^{-16})</td>
<td>(6.33 \times 10^{-16})</td>
<td>(4.82 \times 10^{-16})</td>
<td>(3.95 \times 10^{-16})</td>
</tr>
<tr>
<td>(\sigma_{-11})</td>
<td>(4.11 \times 10^{-17})</td>
<td>(3.97 \times 10^{-17})</td>
<td>(3.36 \times 10^{-17})</td>
<td>(2.84 \times 10^{-17})</td>
</tr>
<tr>
<td>(\sigma_{01})</td>
<td>(1.36 \times 10^{-16})</td>
<td>(1.54 \times 10^{-16})</td>
<td>(1.36 \times 10^{-16})</td>
<td>(1.10 \times 10^{-16})</td>
</tr>
<tr>
<td>(\sigma_{0\overline{1}})</td>
<td>(1.91 \times 10^{-18})</td>
<td>(9.93 \times 10^{-18})</td>
<td>(4.07 \times 10^{-18})</td>
<td>(1.68 \times 10^{-18})</td>
</tr>
<tr>
<td>(\sigma_{10})</td>
<td>(5.79 \times 10^{-16})</td>
<td>(2.50 \times 10^{-16})</td>
<td>(7.78 \times 10^{-17})</td>
<td>(2.91 \times 10^{-17})</td>
</tr>
<tr>
<td>(\sigma_{1\overline{1}})</td>
<td>(8.89 \times 10^{-18})</td>
<td>(2.21 \times 10^{-18})</td>
<td>(2.24 \times 10^{-19})</td>
<td>(3.15 \times 10^{-20})</td>
</tr>
</tbody>
</table>
Equilibrium properties:

- neutral fraction $\downarrow$ with $E \uparrow$
- $n^{-}$ small
- Not reached for long distance
Effect of Increasing Pressure

- Distance to achieve equilibrium proportional to $N$
- i.e. decrease neutralizer length by increasing pressure
- If pressure too high, “stripping” occurs
- Restricts pressure below $4 \times 10^{-3}$ torr [23]

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Distance for 90% of steady state value (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.3</td>
</tr>
<tr>
<td>40</td>
<td>0.5</td>
</tr>
<tr>
<td>70</td>
<td>0.9</td>
</tr>
<tr>
<td>100</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Effect of Increasing Energy

- Equilibrium fraction of neutrals decreases
- Must dump these residual ions after neutralizer $\rightarrow$ possible high power flux
- Required source current for 2 MW beam power dependent on energy

Steady State Percent

RID Power and Required Source Current
Ion Source Choice

- Comparison included consideration of
- Uniformity: optics optimized for specific current density
- Monatomic fraction: may lead to ions with $E_{\text{beam}}/2$, $E_{\text{beam}}/3$
- Noise: fluctuations in current

Image modified from [25]
Magnetic Multipole Source

- Filaments or RF used to generate plasma
- Quiescent, uniform plasma with high monatomic fraction

Image modified from [23]
Modified DuoPIGatron

- Uses magnetic cusps, but different method of plasma generation
- Performance not as good as multipole under aforementioned criteria, but satisfactory for STOR-U
- Formerly widely popular, so may be possible to obtain disused source

Image modified from [26]
Accelerator

• 3-grid design chosen with beamlets
• Grids will be curved to provide focusing
• Comparison done to previous comparable NBI accelerators to estimate divergence
• Maximum transmission distance calculated

<table>
<thead>
<tr>
<th>Source and aperture type</th>
<th>Tokamaks applied to</th>
<th>Max. design current (A)</th>
<th>Accel dimensions (cm)</th>
<th>Size of holes/slots</th>
<th>Number of holes/slots</th>
<th>Beam divergence (degrees)</th>
<th>Maximum Transmission Distance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multipole with holes</td>
<td>JET, MAST</td>
<td>60</td>
<td>16x45 → 30 diam</td>
<td>1.2-cm diam</td>
<td>262</td>
<td>0.7</td>
<td>6.1 m</td>
</tr>
<tr>
<td>DuoPiGatron with holes</td>
<td>ISX-B, PLT</td>
<td>60</td>
<td>22 diam</td>
<td>0.38 cm diam</td>
<td>1799</td>
<td>1.5</td>
<td>3.0 m</td>
</tr>
<tr>
<td>Multipole with slots</td>
<td>DIII-D, TFTR</td>
<td>83</td>
<td>12x48</td>
<td>0.6x12 cm</td>
<td>55</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>DuoPiGatron with slots</td>
<td>TFTR, DIII-D</td>
<td>60</td>
<td>13x43</td>
<td>0.6x12 cm</td>
<td>55</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>
STOR-U Team Parameters

- Parameters selected compared to those chosen by STOR-U team
- 3 MW close to 2 MW estimate
- 40 keV energy within 20-100 keV range
- Larger source required than predicted
Rejected Solutions

- Deuterium produces radioactive tritium
- Negative ion sources are very complicated and produce low current densities
Summary

- NBI to inject 2 MW H\(^+\) at 20-100 keV
- Require source that generates \(\sim 60\) A
- Lower current keeps beam dump load low
- Magnetic multipole has best performance
- Should seek disused modified DuoPIGatron sources
- Acceleration provided by 3 curved grids
- Estimates within an order of magnitude of STOR-U team’s of 3 MW and 40 keV
References I


References II


[22] Personal communication with Professor Jordan Morelli, Queens University.


Effect of Increasing Energy

- This assumes a 20% power loss along beamline (other than residual ion dump)
- Estimate based on beamline losses in previous comparable NBIs
- Example from PDX shown
Check to ensure neutralization can occur without excessive stripping.
\[ \sigma_{10} : \ H^+ + H_2 \rightarrow H^0 + H_2^+ \]
\[ \sigma_{01} : \ H^0 + H_2 \rightarrow H^+ + e + H_2 \]