Parametric analysis of GDT- and GDMT-based neutron sources

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Outline

• Introduction
• Models and algorithms
• Numerical experiment setup
• Results and Discussion
• Summary
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High-power neutron sources (NSs)

**NS's types:**
- ADSs – accelerator-driven systems
- FNSs – fusion neutron sources

**Possible applications:**
- Material science
- Neutron scattering science
- Using within subcritical hybrids
Hybrid with a mirror-based NS

- Neutron shielding
- Li-blanket
- Plasma
- Heating beam injector
- Superconducting magnetic coils
- Subcritical fuel core
- Reflector
- Beam dump
The goal of the study

...is estimating capabilities of GDT- and GDMT-based fusion neutron sources as applied to using in hybrids

Searching for NS configurations with $Q_{eng} \approx 0.1 - 0.2$

Actually, $Q_{eng}$ as low as $5 \cdot 10^{-2}$ is acceptable
GDT and GDMT concepts

- **GDT:**
gas-dynamic trap, experimental facility at BINP

- **GDMT:**
gas-dynamic multiple-mirror trap, a kind of “concatenation” of mirror facilities operated at BINP
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DOL: the model for simulation of plasma in an axisymmetric mirror

Considered in the model are:

- Bounce-averaged kinetic equation for sloshing ions
- Particle and energy balance in background plasma
- Kinetic equation for plasma interactions with injected fast atoms
- Calculation of fusion reaction rates (with the finiteness of Larmor radii taken into account)
DOL: background plasma confinement regimes

- 4 main confinement regimes for background ions:
  - Collisional confinement by magnetic mirrors
  - Adiabatic confinement by mirrors
  - Collisional confinement by electrostatic potential
  - Adiabatic confinement by electrostatic potential

- Transient regimes are described by simple sum of confinement times

\[
\tau_{gd} \gg \tau_{kin} \iff L \gg \lambda \frac{\ln R}{R} \left( 1 - \frac{e_i \Delta \varphi_{mir}}{T_e} \right), \Delta \varphi_{mir} \leq 0
\]
Differential evolution

\[ f : \mathbb{R}^N \rightarrow \mathbb{R} \quad \text{Optimized function} \]

\[ x : \{ x_1, x_2, \ldots, x_N \} \in \mathbb{R}^N \quad \text{Parameter vector} \]

\[ X : \{ x_1, x_2, \ldots, x_k \} \quad \text{Set of parameter vectors} \]

1. Randomly get three different parameter vectors

\[ \{ a, b, c \} \subset X : \{ a, b, c \} \cap \{ x_i \} = \emptyset \]

2. Construct trial parameter vector

\[ x_i' = a + F (b - c) \]

3. Assign new value if the result is better than previous

\[ f (x_i') > f (x_i) : x_i = x_i' \]

4. Go to the step 1.

Direct search

\[ f : \mathbb{R}^N \rightarrow \mathbb{R} \quad \text{Optimized function} \]

\[ x : \{x_1, x_2, \ldots, x_N\} \in \mathbb{R}^N \quad \text{Parameter vector} \]

1. Construct \(2N\) of trial parameter vectors

\[ x_i : \{x_1, x_2, \ldots, x_i' = x_i + \Delta_i, \ldots, x_N\} \]

\[ x_{i+1} : \{x_1, x_2, \ldots, x_i' = x_i - \Delta_i, \ldots, x_N\} \]

2. Choose the best option from the constructed set

\[ x_{\text{best}} : f(x_{\text{best}}) = \max\left[ f(x_1), f(x_2), \ldots, f(x_{2N}) \right] \]

3. Replace parameter vector or reduce the scope

\[ f(x_{\text{best}}) > f(x) \quad ? \quad x = x_{\text{best}} : \Delta = \Delta / 2 \]

4. Go to the step 1.
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• Right-angle injection at mirror ratio $R_{\text{inj}} > 1$
• Fixed magnetic field in mirrors $B_{\text{max}} = 15$ T
Optimization layout

Optimization goal: $max(Q_{pl})$, $Q_{pl} = P_{fus}/P_{in}$

Varied parameters:
- $R_{\text{max}}$ – max. mirror ratio
- $R_{\text{inj}}$ – mirror ratio at the injector position
- $E_{\text{inj}}$ – energy of injected fast particles
- $J_{g}$ – gas feed to maintain background plasma density
- $r_{pl}$ – the radius of plasma column

Constraints:
- Transverse relative pressure $\beta_{\perp} \leq 0.5$
- Fraction of captured beam power $P_{\text{cap}}/P_{\text{in}} \leq 0.9$
- Nearly gas-dynamic regime of background ions confinement
Series of Calculations

**GDT**
\[ \tau_{\text{kin}} = k \times \tau_{\text{gd}} \]
\[ k = 1, 2, 5, \infty \]

**GDHT**
\[ \tau_{\text{kin}} = \tau_{\text{gd}} \]
\[ R_{\text{eff}} = N \times R_{\max} \]
\[ N = 5, 10, 20 \]

**NS-L**
\[ \tau_{\text{kin}} = \tau_{\text{gd}} \]
\[ L \in [10, 100] \text{ m} \]
\[ P_{\text{in}} = P_{\text{in},0} \sqrt{L/L_0} \]
\[ N = 1, 10 \]

**NS-P**
\[ \tau_{\text{kin}} = \tau_{\text{gd}} \]
\[ P_{\text{in}} \in [20, 140] \text{ MW} \]
\[ N = 1, 10 \]

\[ P_{\text{in},0} = 100 \text{ MW} \]
\[ L_0 = 20 \text{ m} \]

\[ Q_{\text{pl}} = Q_0 P^X L^Y \]
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### GDT Series

<table>
<thead>
<tr>
<th>Parameter</th>
<th>k = 1</th>
<th>k = 2</th>
<th>k = 5</th>
<th>k = ∞</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{inj}}$, keV</td>
<td>122</td>
<td>123</td>
<td>120</td>
<td>230</td>
</tr>
<tr>
<td>$J_g$, eq. kA</td>
<td>9.0</td>
<td>8.4</td>
<td>6.6</td>
<td>0</td>
</tr>
<tr>
<td>$T_e$, keV</td>
<td>1.0</td>
<td>1.1</td>
<td>1.3</td>
<td>21.2</td>
</tr>
<tr>
<td>$\tau_{gd}/\tau_{\text{kin}}$</td>
<td>1</td>
<td>0.5</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>$\beta_\perp$</td>
<td></td>
<td></td>
<td>$\approx 0.5$</td>
<td></td>
</tr>
<tr>
<td>$P_{\text{cap}}/P_{\text{in}}$</td>
<td>0.70</td>
<td>0.74</td>
<td>0.80</td>
<td>0.90</td>
</tr>
<tr>
<td>$10^2 Q_{\text{pl}}$</td>
<td>4.0</td>
<td>5.2</td>
<td>7.7</td>
<td>135.3</td>
</tr>
</tbody>
</table>

Fusion gain factors of GDT-based sources proved to be quite limited. The results leave a room for using GDT-based NSs in proof-of-principal facilities or testing stands.
Example of redundancy: magnetic field influence on fusion gain factors

- $R_{\text{inj}}$ and $R_{\text{max}}$ variables taken separately do not strongly affect achieved fusion gains

- However, smaller $R_{\text{inj}}$ and $R_{\text{max}}$ values are more favorable for using NS in a hybrid system
## GDMT Series

<table>
<thead>
<tr>
<th>Parameter</th>
<th>N = 5</th>
<th>N = 10</th>
<th>N = 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{inj}}$, keV</td>
<td>135</td>
<td>129</td>
<td>144</td>
</tr>
<tr>
<td>$J_g$, eq. kA</td>
<td>4.8</td>
<td>3.8</td>
<td>3.1</td>
</tr>
<tr>
<td>$T_e$, keV</td>
<td>1.7</td>
<td>2.1</td>
<td>2.5</td>
</tr>
<tr>
<td>$\tau_{gd}/\tau_{\text{kin}}$</td>
<td>$\approx 1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_\perp$</td>
<td>$\approx 0.5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{\text{cap}}/P_{\text{in}}$</td>
<td>0.78</td>
<td>0.86</td>
<td>0.87</td>
</tr>
<tr>
<td>$10^2 Q_{\text{pl}}$</td>
<td>10.4</td>
<td>16.3</td>
<td>22.7</td>
</tr>
</tbody>
</table>

Neutron generation efficiency comparable to that of ADSs can be reached for GDMT-based source at mirror-to-mirror distance $L_0 = 20 \text{ m}$ and heating power $P_{\text{in,0}} = 100 \text{ MW}$.
Fusion gain as a function of NS length and heating power

\[ Q_{pl} = Q_0 L^X P^Y, [L] = m, [P_{in}] = \text{MW} \]

\[ Q_0 = 1.4 \cdot 10^{-3} \pm 2 \cdot 10^{-4} \]
\[ X = -1.8 \cdot 10^{-1} \pm 2 \cdot 10^{-2} \]
\[ Y = 8.4 \cdot 10^{-1} \pm 3 \cdot 10^{-2} \]

\[ Q_0 = 1.1 \cdot 10^{-2} \pm 1 \cdot 10^{-3} \]
\[ X = -1.6 \cdot 10^{-2} \pm 1.8 \cdot 10^{-2} \]
\[ Y = 5.8 \cdot 10^{-1} \pm 3 \cdot 10^{-2} \]
Summary

• Performance of several NSs based on GDT and GDMT concepts has been considered.

• Each considered configuration has been optimized in order to determine the maximum achievable fusion gain.

• The results listed further are valid for trap configurations with mirror-to-mirror distances $L \in [10, 100]$ m, heating powers $P_{in} \in [20, 200]$ MW and magnetic field in the mirrors $B_{max} = 15$ T.

• Provided background plasma is kept in nearly gas-dynamic regime of confinement, one can expect achieving $Q_{pl} \approx 5\cdot10^{-2}$ in GDT-based NS and $Q_{pl} \approx 1.5\cdot10^{-1}$ in GDMT-based NS.

• Power-law relation between fusion gain, heating power and mirror-to-mirror distance has been obtained. It can be used further for fast upper-bound estimates of fusion gain factors achievable in mirror-based NSs similar to those considered in this study.
References


Thank you for your attention!
Differential evolution and Direct search algorithms: difference in the results

\[ Q_{pl} = q L^\alpha, \quad [L] = m \]

- Approximately the same power factors (\(\alpha\)) in the scalings
- In the case of GDMT-based NS the difference between fusion gain factors at equal lengths and heating powers is below 5 %