Length and Power Scalings of GDT– and GDMT–based Neutron Sources

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Abstract. The paper is dedicated to the analysis of fusion neutron sources (NSs) based on gas–dynamic trap and the concept of gas–dynamic multiple–mirror trap. The configurations considered are predominantly designed for the use within subcritical hybrids. The main focus of the study has been on what fusion gain can be achieved by the NSs depending on their mirror–to–mirror distance and the output power of heating systems. The analysis comprised optimizing parameters of each NS of given length and power so as to maximize its fusion gain. To provide physical credibility of the results, the searched–for NS configurations were to comply with a number of constraints on plasma characteristics. Particularly, background (maxwellized) ions had to be confined in nearly gas–dynamic regime, while transverse relative plasma pressure was limited by 0.5 from above. Lengths and heating powers of considered NSs ranged from 10 to 100 m and from 20 to 200 MW respectively. On the basis of obtained data the coefficients of a power–law relation between fusion gain factors, lengths and heating powers have been estimated.

INTRODUCTION

Fission–fusion hybrids represent a type of facilities which can be employed in the framework of modern nuclear power technology for incinerating long–lived transuranic isotopes of spent nuclear fuel or for breeding fissile isotopes. Providing a number of benefits in comparison with accelerator–driven systems (ADSs) or tokamaks, mirror traps have been considered since the beginning of 1970s as a possible basis for neutron sources (NSs) of fission–fusion hybrids (see Fig. 1 for schematic layout of a hybrid with a mirror–based NS). Mirror traps feature employment of expanders instead of divertors and do not require plasma currents for achieving plasma stability, which alleviates the material sustainability challenges as compared to the tokamak case. On the other hand, fusion NSs (and mirror–based ones in particular) provide neutron generation rate per electricity grid power unit (P_{grid}) comparable to that of ADSs at relatively modest engineering fusion gain $Q_{eng} = P_{fus}/P_{grid} \approx 0.1 - 0.2$ (here P_{fus} is the total fusion power) [1].

The goal of the presented work has been assessing the characteristics of neutron sources based on gas–dynamic trap (GDT) [2, 3] and gas–dynamic multiple–mirror trap (GDMT) [4] concepts. In mathematical terms the task of the study has been formulated as maximizing plasma fusion gain ($Q_{pl} = P_{fus}/P_{in}$, P_{in} being the output power of heating systems) by the optimization of main trap parameters (the energy of injected fast neutrals, gas feed to the facility, plasma column radius, etc.). Regarding methodology, numerical models used and the setup of numerical experiment, this work is similar to the study discussed in [5], and should be considered as its continuation. This time however we are interested in what fusion gain can be achieved by “optimal” neutron sources depending on the mirror–to–mirror distance L and the power of heating beams P_{in}, while the previous study was mainly focused on Q_{pl} dependence on the regime of confinement of background plasma at fixed facility length $L_0 = 20$ m and heating power $P_{in,0} = 100$ MW.

NUMERICAL EXPERIMENT SETUP

This section is primarily dedicated to the differences of simulation setup used in current study from the one described in [5]. One should address the mentioned paper for a more detailed description of applied simulation techniques and

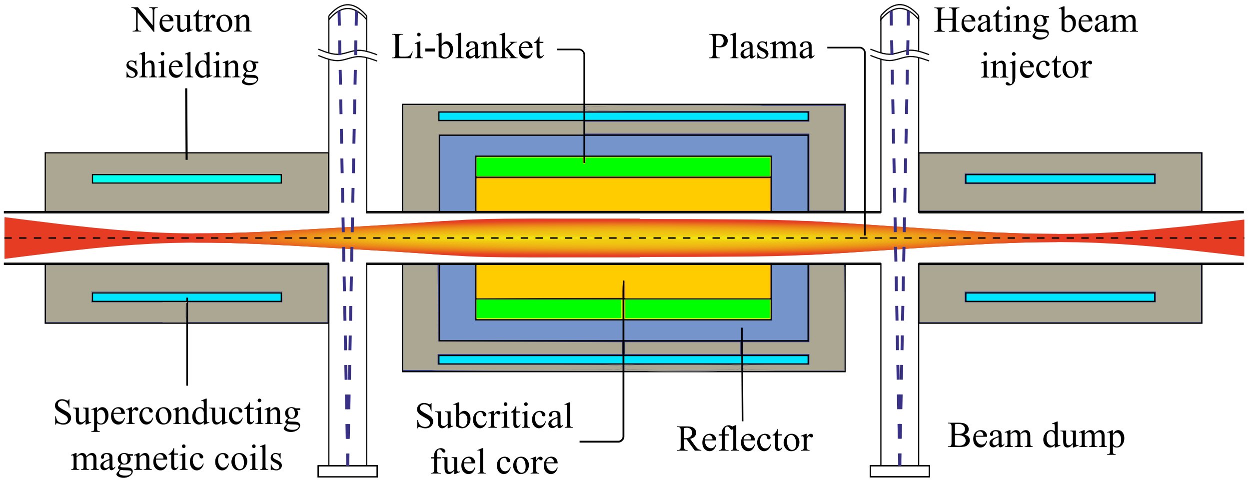

FIGURE 1. Layout of a subcritical fission–fusion system with a neutron source based on a mirror trap [5].

assumptions. The simulation of plasma processes in mirror–based NS was carried out by means of 1D numerical model DOL [6], while the differential evolution (DE) [7] was applied as the main algorithm to perform the search of optimal trap configuration. As opposed to the work [5], simple direct search algorithm (further referred to just as "direct search" or DS) was also used during the study. The algorithm can be described as separately varying each of optimized NS parameters and gradually reducing the variation step until the fusion gain maximum is determined with a given accuracy. Using an algorithm of such kind certainly does not provide reliable calculation of global Q_{pl} maximum, although it requires very modest computational resources as compared to the differential evolution. On the other hand, if some set of parameters not too different from the optimal one is chosen as a starting point of the DS algorithm and Q_{pl} function dependence on its arguments is smooth enough, one can expect acquiring sound results with direct search. For the reasons described in the preceding two sentences DS–related calculations were backed by the results obtained with differential evolution method. As it will be seen from the next section, the results provided by the two algorithms are indeed found in good agreement under this condition.

General NS layout used in calculations coincided with the one presented in Fig. 1. Neutral beam injection was considered as the only plasma heating method. As previously in [5], the magnetic field strength in the mirror regions was kept equal to 15 T in all NS configurations. Effective mirror ratio $R_{eff} = 10 \cdot R_{max}$ (here R_{max} is the maximum mirror ratio) was used to take into account axial losses suppression in GDMT–based NSs. Values of the following variables were optimized during the search of Q_{pl} maximum: the energy of injected neutrals, plasma radius, maximum mirror ratio and gas feed to the facility. The searched–for NS configurations were to comply with a set of constraints on plasma characteristics. Firstly, transverse relative plasma pressure was not to exceed 0.5, i.e. its value had to be under the limit reached in GDT experiments [8]. Beam capture by plasma was constrained by 90 %. Finally, background ions were required to be confined in nearly gas–dynamic regime to provide suppression of MHD– and micro–instabilities. Formally the last condition is expressed as $\tau_{gd} \geq \tau_{kin}$, where τ_{gd} and τ_{kin} are, respectively, the times of gas–dynamic and adiabatic confinement.

Carried out calculations were divided into two series. The series further referred to as "NS–L" have been focused on estimating the dependence of NS fusion gain on L under the assumption of P_{in} growing as square root of the device length, $P_{in} = P_{in,0} \cdot \sqrt{L/L_0}$. $P_{in,0}$ and L_0 correspond to the basic NS configuration previously considered in [5] (see Table 1 for parameters of the basic NSs). Fusion gain dependence on heating power at the device length $L = L_0$ has been considered in another series, "NS–P". Together these two series enable us to construct a scaling of the form

$$Q_{pl} = Q_0 L^X P_{in}^Y, \ [L] = \mathrm{m}, \ [P_{in}] = \mathrm{MW}, \tag{1}$$

which determines the upper bound of fusion gain achievable by GDT– and GDMT–based neutron sources of given length and heating power under the conditions specified in the previous paragraph. To verify the obtained scaling two additional "out–of–series" optimizations have been performed (one for each of the NS types) with heating power and NS length equaling 200 MW and 40 m respectively.

TABLE 1. Main characteristics of GDT– and GDMT–based NS configurations considered in [5]. All fast–particle energy losses are given in megawatts.

Parameter	GDT	GDMT	Parameter	GDT	GDMT
		Optimized parameters			
Energy of injected neutrals, keV	122	129	Plasma radius, cm	35	23
Maximum mirror ratio	35	11	Mirror ratio at inj. position	2.6	1.0
		Plasma data			
Beam capture, %	64	81	Transverse relative pressure	0.5	0.5
Electron temperature, keV	1.0	2.1	Ion temperature, keV	0.8	3.3
Fast ions density, 10^{13} cm^{-3}	2.1	7.6	Background ions density, 10^{13} cm^{-3}	3.9	7.0
Gas–dynamic conf. time, ms	1.8	4.5	Adiabatic conf. time, ms	1.8	4.5
		Power balance			
Electron–induced energy loss	47.7	52.9	Charge–exchange loss	7.2	8.8
Ion–induced energy loss	8.0	17.4	Axial losses	1.3	2.2
Fusion gain factor, %	4	16			

RESULTS AND DISCUSSION

The results of performed calculations are shown in Fig. 2 and 3. Figure 3 also includes the values of Q_0, X and Y coefficients from the Equation 1 fitted to the numerical data. The results obtained can be qualitatively explained in the following way. Elongation of the neutron source leads to increase in plasma volume and corresponding decrease in the density of fast ions, given constant power of plasma heating ($P_{in} = const$). This inevitably reduces the fusion gain as far as fusion reactions are mainly provided by the interactions involving fast ions. The decrease in fusion gain is mitigated to a large extent by lower densities of background ions and higher electron temperatures achievable in longer traps due to the growth of gas–dynamic confinement time with L. As a result, X coefficient in Equation 1 proves to be negative and small in value for both NS types. Concerning fusion gain dependence on heating power, it proved to be below the expectations grounded on simple analytical estimates ($Q_{pl} \propto P_{in}^{3/2}$). This is explained by shifting the allowed parameter domain determined by the condition $\tau_{gd} \geq \tau_{kin}$ to the area of lower confinement times at the heating power rising. In other words, background plasma tends to be denser in high–power NS configurations while the electron temperature remains relatively low, which results in increased rate of electron–induced energy losses from fast ion component.

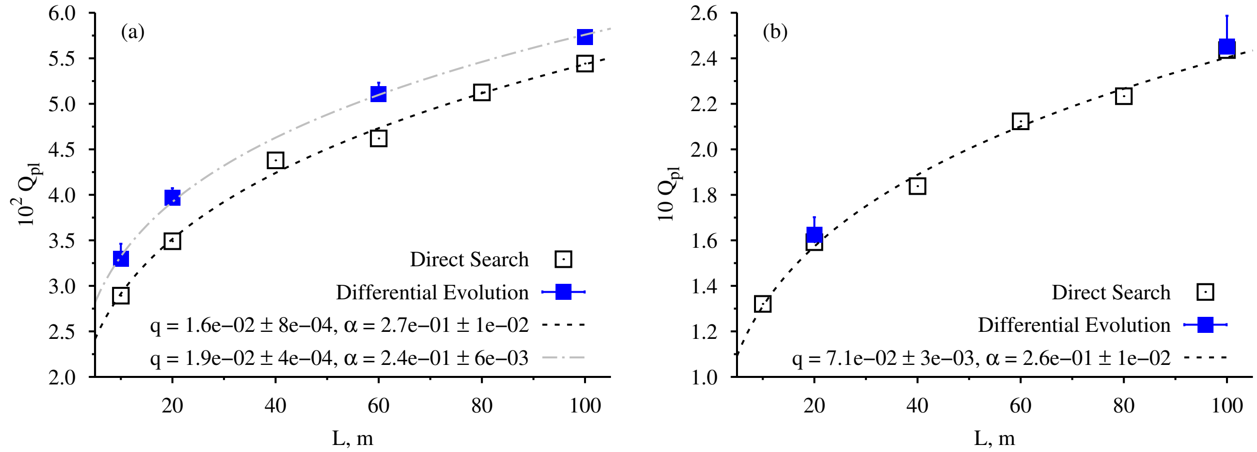

FIGURE 2. Fusion gain factor dependence on mirror–to–mirror distance obtained in NS–L series for (a) GDT– and (b) GDMT–based NSs. Markers denote the results of optimization. Dashed curves correspond to a power–law scaling $Q_{pl} = q \cdot L^{\alpha}$ with its coefficients fitted to the numerical data.

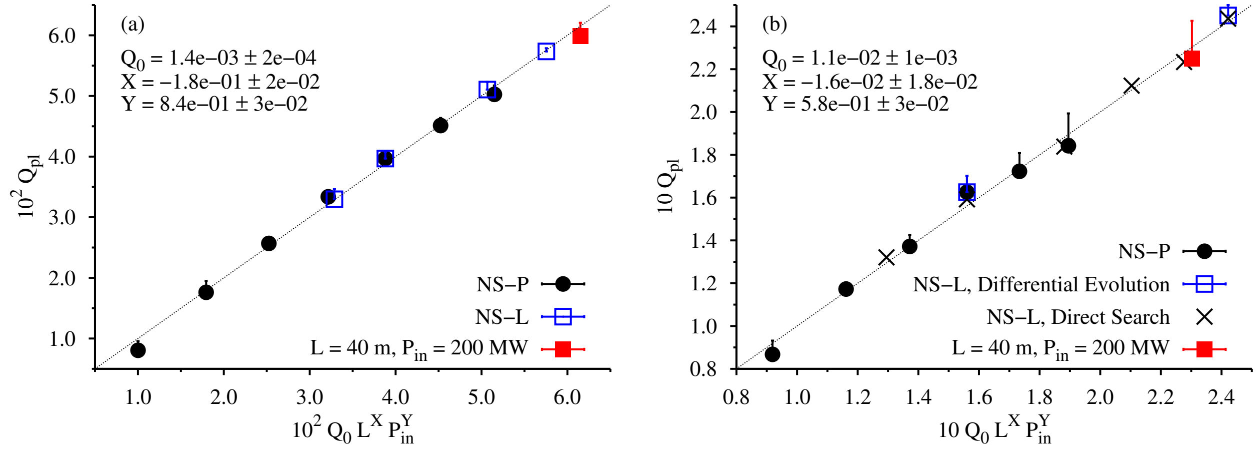

FIGURE 3. Matching of the results of NS–L and NS–P series with power–law scaling from Equation 1 for (a) GDT– and (b) GDMT–based NSs. Represented Q_0, X and Y quantities correspond to the Equation 1 coefficients fitted to the numerical data. Unless otherwise stated, DE–related results are shown. Red markers denote the results of additional calculations for scaling verification.

CONCLUSIONS

Neutron sources based on two mirror concepts (GDT and GDMT) were considered in this study. The main goal was to determine the fusion gains achievable in neutron sources of different lengths ($L \in [10; 100]$ m) and heating powers ($P_{in} \in [20; 200]$ MW). The analysis comprised optimizing parameters of each NS of given length and power so as to maximize its fusion gain. The optimized NS configurations were to comply with a number of constraints on plasma characteristics so as to provide physical credibility of the results. The data obtained were fitted by power law of the form $Q_{pl} = Q_0 L^X P_{in}^Y$, which can be used further for fast upper–bound estimates of fusion gain factors in neutron sources close to ones considered in current study.

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