The GDT-based fusion neutron source as driver of a minor actinides burner

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Abstract

At present, accelerator driven systems seem to have a good chance to play an important role in a long-term sustainable utilization of fission reactor technology. In particular, they offer several advantages compared to reactors regarding the incineration of minor actinides. However, such systems demand strong neutron sources. The spallation neutron source is favored for this purpose thanks to the high neutron emission intensity achievable. The Budker Institute of Nuclear Physics Novosibirsk develops an intense 14 MeV fusion neutron source on the base of the gas dynamic trap (GDT), which is primarily destined for an irradiation facility for fusion material research. The potential of this neutron source as driver of a minor actinides burner was studied by means of neutron transport calculations and compared with a spallation source. A simple model of the burner had been derived from a numerical benchmark that was conducted by the OECD NEA. The paper presents and discusses the main results of the study and finally draws the conclusion that both the source strength and the efficiency of the GDT-based neutron source must be substantially increased. Moreover, advices are derived, which show that stretching the neutron production volume and raising the electron temperature of the GDT plasma could accomplish the desired improvements.

Keywords: Accelerator driven systems, Minor actinides burner, Spallation neutron source, Fusion neutron source, Gas dynamic trap device

1. Introduction

To become a long-term sustainable option for the world´s energy supply fission reactor technology must minimize its high-level waste, which finally has to be disposed. To solve the problem, worldwide great R&D effort is made to develop new closed fuel cycle options. Long-lived fission products and, in particular, minor actinides (MA) are the components of the spent nuclear fuel which cause the most concern. Regarding the incineration of minor actinides, systems producing and confining the high-energetic (fast) neutrons have the highest efficiency. These systems can be built as fast reactors and as sub-critical nuclear fuel systems, the so-called driven systems, which are fed with neutrons from an external neutron source. At present, the spallation neutron source is favored for this purpose thanks to the high neutron emission intensity achievable. Compared to fast reactors the combined accelerator driven system (ADS) has several advantages. The most important are the higher possible burning efficiency and the enhanced inherent safety characteristics [1], [2], [3]. Therefore this development line is intensively pursued by several research projects, e.g. by the project EUROTRANS of the European Union [4].

The Budker Institute of Nuclear Physics Novosibirsk made the proposal for a continuous 14 MeV neutron source based on the gas dynamic trap plasma device [5], [6]. This neutron source is primarily destined for an irradiation test facility of materials that must be developed for the fusion DEMO reactor. A research project of the Budker Institute aims at completing the database of the GDT in the range of high plasma parameters, which are relevant for the neutron source, and at demonstrating its feasibility and suitability by a hydrogen-prototype [7].

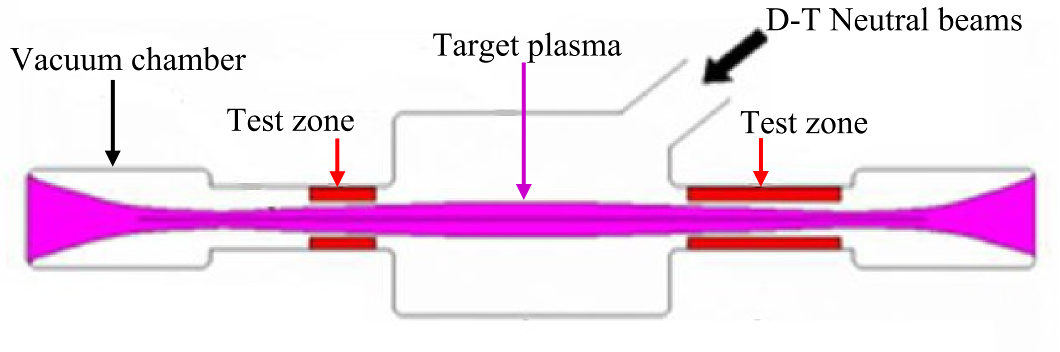

Fig. 1. Schematic exposition of the GDT-based neutron source.

Figure 1 shows a schematic exposition of the GDT-based neutron source proposed as irradiation facility for fusion material research. A system of magnetic coils generates an axially symmetric magnetic well along the axis of the vacuum chamber. In the central chamber the magnetic field confines the so-called target plasma in a gas dynamic regime, which is characterized by collisional particle losses into the end chambers of the device. An inclined injection of a mixture of high-energetic deuterium/tritium atoms produces deuterons and tritons oscillating back and forth between the hills of the magnetic field. The ion density peaks near their turning points yield the volumes of intense fusion neutron production [5], [6].

The situation outlined before raises the questions whether the GDT-based neutron source could also be a candidate for driving a sub-critical system dedicated to nuclear waste transmutation and how this option does compare with the spallation based ADS? The technical idea would be to put up the GDT vertically and to surround both neutron production zones by a sub-critical system. The answers on these questions are the objective of the present paper. By means of the Monte Carlo code MCNP-4C2 [8] and the nuclear data library JENDL-3.3 [9] neutron transport calculations were carried out for a minor actinides burner the scheme of which originally has been defined as a numerical benchmark exercise for spallation based ADS by the Nuclear Science Committee of the OECD NEA [10] and afterwards was slightly modified in Ref. [11]. Basic neutron characteristics of the system were calculated for the cases when operated with both the spallation source and the GDT neutron source. The analysis of the results makes clear what are the differences between both cases regarding the neutronics and what they have in common. The results also show that both the emission intensity of the GDT-based neutron source and, especially, its energetic efficiency must be considerably increased. For that purpose, primarily two possibilities can be used: The increase of the electron temperature of the GDT plasma and stretching the neutron production volume. First calculation results of such an elongated MA-burner are presented. They indicate that both measures could accomplish the desired improvements.

2. Characteristics of spallation and fusion neutron sources as drivers of a sub-critical MA-burner

2.1. Calculation models

The cylindrical system shown in Fig. 2 served as basis for the calculation models, which were used for studying the neutron physical differences between the spallation and fusion driven burners. The core is loaded with uranium-free fuel composed of plutonium and minor actinides in a mass ratio of about 32:68 wt%. Lead-bismuth eutectic is the material of the spallation target, of the buffer and of the coolant. The proton beam is injected from above centrally onto the target. The geometric data and nuclear densities were taken from Ref. [11].

The spallation source was modeled as described in Ref. [10]: Ten homogeneous cylindrical discs of radius r=10 cm and height h=10 cm. The neutron energy spectrum is given in a 122-group structure with a lethargy width of 0.1 between 100 eV and 20 MeV. The DT fusion source was modeled as homogeneous distribution in a voided cylinder with radius r=10 cm, height h=50 cm and positioned in the center of the system. The energy spectrum was the fusion peak with the mean energy of 14.1 MeV. In addition, an artificial source version was modeled to especially point out the influence of the different energy spectra. For that, the fusion source was simulated, but with the spallation energy spectrum. In Table 1 this source option is denoted as “mixed” source.

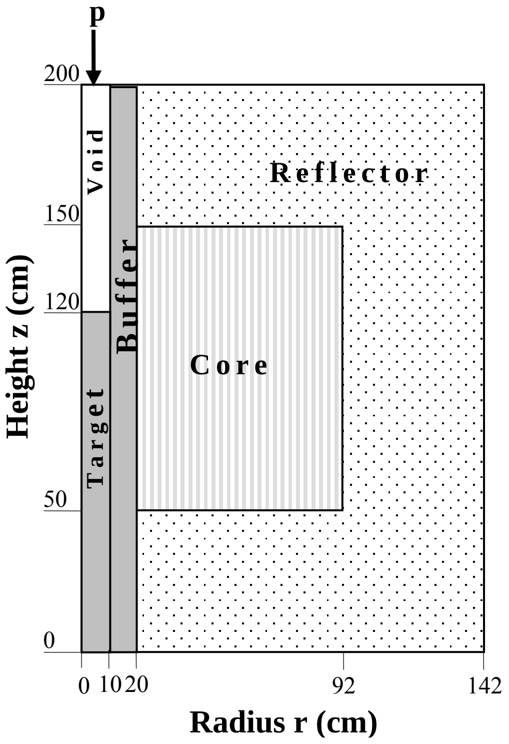

Fig. 2. (r,z) geometry model of the MA-burner with spallation target, from Ref. [11].

Neutron transport calculations were done for three geometry configurations:

- System A: The configuration as shown in Fig. 2.
- System B: The configuration of Fig. 2, but without target and buffer.
- System C: The configuration of Fig. 2, but without the target.

System A is for the spallation driven system, and, B and C for the fusion driven system. For each of them two types of transport calculations were performed – with a given external source and a reactor criticality calculation. They were done with the MCNP-4C2 code using the point-wise cross-sections from the Japanese Evaluated Nuclear Data Library JENDL-3.3.

2.2. Calculation results and discussion

2.2.1. Integral parameters

The MCNP code calculates a lot of integral parameters and offers the user to extract information on the distribution of the neutron flux or of certain flux integrals in space and energy. Integral parameters are mean values of specific quantities that are related to one neutron history. The most important parameter is the effective multiplication factor k_{eff}, which is determined by a criticality calculation [12]. Other important parameters of a sub-critical reactor are:

M_{eff} – Mean number of neutrons emitted from fission reactions in a fission chain that was initiated by one fission neutron of the sub-critical reactor. This quantity is designated as multiplicity of a fission neutron and is related to k_{eff} by

$$M_{eff} = k_{eff} / (1 - k_{eff}) . \tag{1}$$

$\bar{\nu}$ – Mean number of neutrons emitted per fission.

M_S – Mean number of neutrons emitted from fissions per source neutron. This quantity is called the multiplicity of a source neutron.

k_S – "Subcriticality" of the system [13], which is related to M_S by

$$M_S = k_S / (1 - k_S) . \tag{2}$$

φ^* – Relation of the multiplicity of a source neutron of the driven system to the multiplicity of a fission source neutron

$$\varphi^{*} = M_{S} \big/ M_{eff} \ . \tag{3}$$

h_{fis} – Mean energy released by fissions per source particle in MeV (“fission heating”). With this quantity the fission power P_{fis} released in the core, can be calculated for a given source intensity S

$$P_{fis} = S \cdot h_{fis} \, . \tag{4}$$

$r_{n,2n}$ – Mean number of neutrons emitted from n,2n reactions per source particle.

Table 1 gives the calculation results. The accuracy of the results was sufficiently high. For instance, the statistical errors of the k_{eff} values are not greater than $2\text{x}10^{-4}$, or, those of the fission heating values about $1\text{x}10^{-2}$ MeV only. The results of the reactor calculations show that buffer and target are helpful for better closing the system at its inside what results in a higher multiplicity M_{eff} of the fission neutrons.

Table 1.

Calculated integral parameters

Calculation option	**Parameter**	**Geometry system**		
		A	**B**	**C**
Reactor calculation	k_{eff}	0.95856	0.95008	0.95817
	M_{eff}	23.1	19.0	22.9
	$\bar{\nu}$	3.090	3.092	3.090
Calculation with source				
Spallation	M_S	21.49		
	k_S	0.95554		
	h_{fis}	1316		
	φ^*	0.929		
	$r_{n,2n}$	0.088		
DT fusion	M_S		34.75	44.38
	k_S		0.97203	0.97796
	h_{fis}		2119	2710
	φ^*		1.826	1.937
	$r_{n,2n}$		1.20	1.73
Mixed	M_S		17.49	
	k_S		0.94526	
	h_{fis}		1070	
	φ^*		0.907	
	$r_{n,2n}$		0.065	

The results of the calculations with the external sources reveal a striking advantage of the fusion neutron source compared with the spallation source. This fact arises in the considerable higher multiplicities M_S of the fusion neutrons up to more than a factor two, and, consequently, in a higher fission heating per source particle. This advantage is also expressed by the correspondingly higher parameter φ^*. The results of the two calculations for system B point out that the effect is caused by the difference of the source energy spectra. The reason of this phenomenon becomes clear by comparing the n,2n reaction rates of the various systems: The primary 14 MeV fusion neutrons initiate much more n,2n reactions than the spallation neutrons in both the core medium and in the target/buffer zone. Inspecting the cross sections reveals that the Pb and Bi nuclei of the coolant bring this effect about.

2.2.2. Distributions of neutron flux and flux integrals

The radial and energy dependencies of the neutron flux were calculated for four systems: ADS – geometry system A with the spallation source, GDT-DS (GDT driven system) – geometry system B with the fusion source, GDT-DS+B – geometry system C with the fusion source, ´Reactor´ – stands for the static reactor eigenfunction of the geometry system A. The fluxes were estimated as mean values over the volumes of rings with a wall thickness of 2 cm and a height of 50 cm around the mid-plane of the core. Figure 3 shows the energy-integrated fluxes per source intensity of 1 n/s. The flux values are marked at the radial mid-point of an estimation ring zone. In case of ´Reactor´ the calculated values per fission neutron have been multiplied by the multiplicity M_{eff}. The figure illustrates two facts: Firstly, that the curves for both fusion driven systems lie considerably above that for the ADS, the fact, which results from the n,2n reactions discussed in sub-section 2.2.1 and, secondly, the noticeably steeper slopes of the neutron flux in outward direction compared to the flux profile in the corresponding critical system.

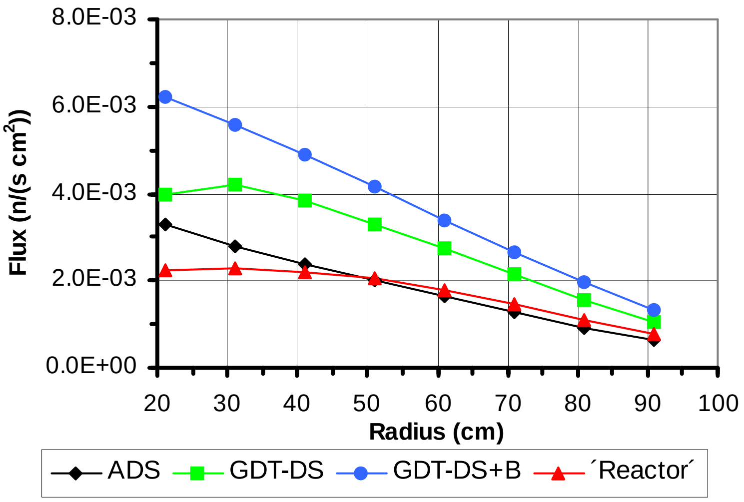

Fig. 3. Radial dependencies of energy integrated neutron fluxes.

The burn-up of actinides not only depends on the magnitude of the neutron flux, but also on its energy spectrum. Therefore, the differences of the flux spectra within the cores of the various systems and their variations along the radius are of interest. However, remarkable differences can be observed quite near to the inside of the core only. Figure 4 shows the normalized spectra of energy group-wise integrated fluxes in the innermost estimation ring of the core. The upper boundaries of the broad energy groups are: 0.01, 0.1, 1, 2, 5, 10 and 20 MeV. The hardest neutron spectrum has the GDT-DS system where a low peak at 14 MeV appears and the spectrum part down to 1 MeV is slightly raised up by moderated fusion neutrons. The ´Reactor´ shows the softest flux spectrum. The spectra of ADS and GDT-DS+B are very similar and lie between the limiting cases. Already at the radius of 31 cm the spectra differ within 5 per cent only and adjust completely further outward. Because of the marginal differences between the neutron spectra in the cores of the spallation and fusion neutron driven burners one must expect that the burning rates of minor actinides will scale with the induced fission power in both cases.

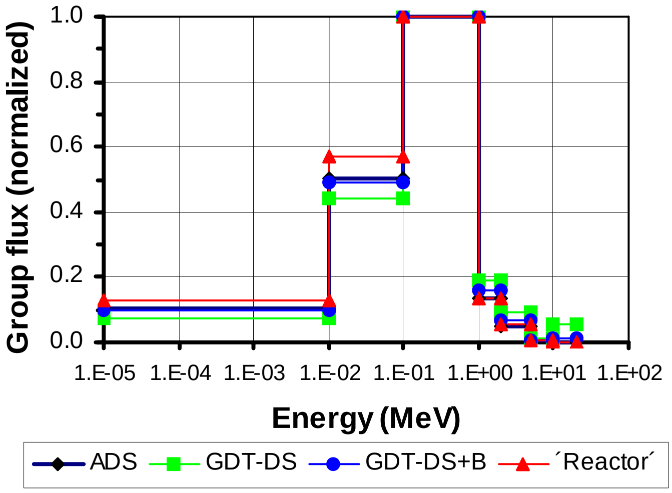

Fig. 4. Normalized spectra of group fluxes at the radius of 21 cm.

The height dependencies of neutron flux, fission power and DPA rate (DPA – displacements per atom for iron) were calculated near to the inner core surface where their maximum values appear (see Fig. 3). These quantities were estimated as mean values averaged on the volumes of an estimation ring of 1 cm thickness around the inner core surface that was divided in 10 cm high sub-zones. As example, Fig. 5 shows the height distributions of the power peak factor, which is defined as quotient of the local power density and the mean power density averaged over the whole core. Figures 3 and 5 illustrate a basic disadvantage of a driven system: The power distribution is considerably stronger peaked than that of the corresponding reactor.

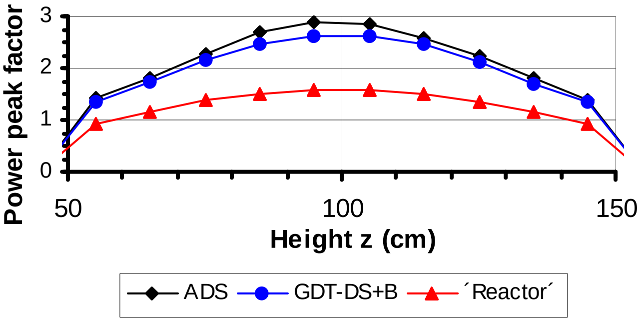

Fig. 5. Height distributions of power peak factors.

3. GDT-driven MA-burners

3.1. Use of the GDT "basic version"

For the GDT neutron source several proposals exist. They all were developed as 14 MeV neutron source for fusion material research. At first, we consider the so-called "basic version", which is described in Ref. [6]. Special features of this version are that the mirror coils generating a magnetic field strength on axis of 13 Tesla are to be superconducting and a deuterium-tritium mixture is injected as neutral beams with the energy of 65 keV only. The project assumes to supply a total neutron power of 1.25 MW of what about 0.44 MW can be localized in volumes of high source intensity with a length of 0.5 meters each on both sides of the device (see Fig. 1). So, one gets the corresponding total source intensity: S_{GDT}=1.95x10^{17} n/s. In reality the effective source strength would be somewhat greater because of the contribution by the neutron production outside of the 0.5 m peaks. To produce this intensity an electric power input into the neutral beam injection system of 60 MW is necessary. Considering various possibilities of power recovery at the GDT device a reduction of the net electric power input down to 50 MW seems to be realistic. With these data one gets the energetic price for the emission intensity of 1 neutron per second: p_{GDT}=2.56x10^{-10} W/(n/s). Assuming for the spallation neutron source the parameters: proton energy – 1 GeV, neutron yield at Pb/Bi eutectic target – 20 n/p [14] and an accelerator efficiency of 50 %, then one gets the energetic price p_{ADS}=1.60x10^{-11} W/(n/s), which is more than one order of magnitude less than that of the GDT neutron source.

To maximally use the neutron production of the GDT one has to operate two MA-burners, one on each side of the device supplied with an intensity of about $S_{GDT/2}$=0.98x10^{17} n/s. This value is substantially smaller than that, which is aimed for a commercial use of minor acitinides burners. For such a facility the driver should deliver more than 10^{18} neutrons per second. From the source intensity $S_{GDT/2}$ and the calculated parameter h_{fis} given in Table 1 it follows in accordance with Eq. (4) that the sub-critical system GDT-DS+B considered in chapter 2 would produce the fission power P_{fis}=42 MW only. Assuming an efficiency of 40 % for the thermal to electrical power conversion the Q-factor of the facility would be even less than one: Q=0.67. Here, it must be pointed out that the Q-factor is not only the efficiency parameter for the power balance of the system, but, represents also the efficiency parameter of the destruction of trans-uranium isotopes by the burner. In case of the spallation source and assuming the same parameters as given above one can derive that an accelerator delivering the proton current I_p=1.6 mA would generate the same fission power in the system ADS. But, in this case the Q-factor amounts to Q=5.25. The source intensity would be S_{ADS}=2x10^{17} n/s. Since the additional multiplication of the fusion neutrons by n,2n reactions as pointed out in sub-section 2.2.1 the spallation source must deliver a two times higher intensity.

The facts discussed before make clear that the "basic version" of the GDT neutron source does not supply the neutron source strength that would be necessary for serving as driver of a sub-critical MA-burner of commercial scale. In addition, the efficiency of its neutron production is about one order of magnitude below that of a comparable ADS. Therefore, one has to search for potentialities of improvements. One option, which would not have any consequences for the driven sub-critical system is the increase of the electron temperature T_e of the GDT-plasma. This measure would reduce the energy loss rate of the high-energetic deuterons and tritons and, thereby, increase the fusion reaction rate considerably. Figure 7 illustrates the special situation with this plasma parameter for the case of the "basic version". The diagram shows the Q-factor of the MA-burner in dependence on the electron temperature of the GDT-plasma. The self-consistent simulation model of the GDT device with the input parameters given at the beginning of this section yields the electron temperature of about 3.5 keV, represented as the marked (**x**) end point of the curve. For the "basic version" a special cooling of the electrons down to T_e=0.75 keV has been introduced. The corresponding point of the curve is marked by the dot. This measure was undertaken to exclude the area of higher temperatures where the stability of mirror confined plasmas is not yet experimentally proven. The value T_e=0.75 keV was recently achieved in the experiment GAMMA-10 [15]. The diagram points out that the source strength of the "basic version" and accordingly the Q-factor of the driven MA-burner could be increased by more than a factor 3 up to $Q \approx 2.2$ provided that the condition on the electron temperature could be withdrawn. Future investigations within the GDT neutron source project should aim at this problem.

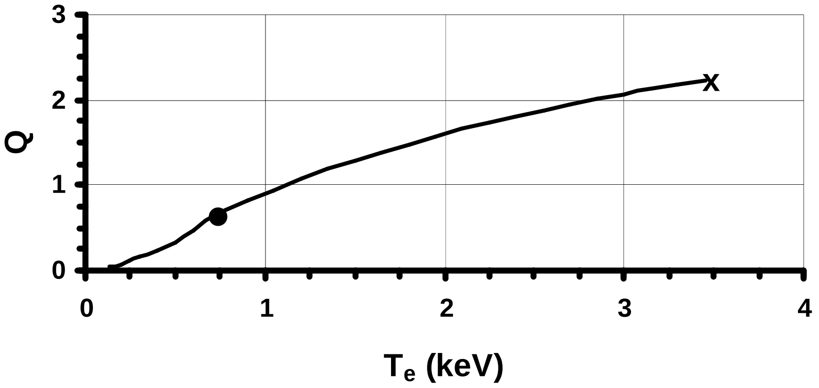

Fig. 7. The Q-factor of the MA-burner driven by the „basic version" of the GDT neutron source in dependence on the electron temperature.

3.2. Use of a GDT "stretched version"

In addition to the increase of the electron temperature discussed in the preceding section the GDT offers another possibility for the improvement of its neutron source parameters. By modifying the external magnetic field the ratio of the emission intensities of both neutron production volumes can be varied. Moreover, these zones can be longitudinally extended, and, even certain axial profiles of the neutron intensity could be adjusted.

The "basic version" of the neutron source was optimized so as to minimize the power consumption down to 60 MW and supplying a power current density of fusion neutrons through the inside of a test zone of 2 MW/m^2. In this case, the axial extension of the regions with high neutron emission intensity is relatively small compared to the length of the central part of the device. The proposal to stretch the volumes of intense neutron production aims at delivering a greater fraction of all neutrons totally produced by the whole GDT plasma for the dedicated use and at the same time keeping the plasma just in the state of the "basic version". Estimates show that by this measure the energy loss rate of the high-energetic deuterons/tritons will not considerably increase and can be compensated by increasing the neutral beam injection power only moderately.

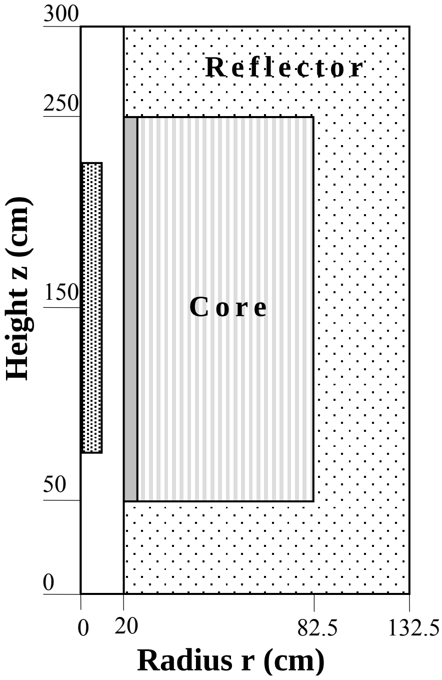

Fig. 6. Elongated MA-burner with a stretched GDT neutron source.

The stretching of the source volume demands a corresponding elongation of the burner. As first step, the system shown in Fig. 6 was considered. Compared to system C the main changes are:

- The core height is 2 meters.
- The radius of the inner hole was extended up to 20 cm because of technical reasons.
- The buffer extends over the core height and its thickness was chosen 7.5 cm.

- The outer radius of the core was determined so that $k_{eff}\approx0.97$.

The fusion source was simulated in the same way as described in section 2.1 but now with a source cylinder of length 1.5 m. The material compositions were kept unchanged. Though this is not correct, we used this approximate approach for the first study to get a rough insight in the physical changes.

For the "stretched version" of the GDT neutron source the following parameters were assumed:

– Net electric power input	- 83 MW
– Total neutron emission intensity, S_{GDT}	- $6.86\text{x}10^{17}$ n/s
– Electron temperature, T_e	- 0.75 keV

Compared to the "basic version", the source strength is more than three times higher and the energetic price of the neutron intensity p_{GDT}=$1.2\text{x}10^{-10}$ W/(n/s) is more than two times lower. The MCNP calculation for the extended burner with the "stretched" source version gave the fission heating per source particle h_{fis}=3358 MeV. Thus, one extended burner generates 185 MW fission power, instead of 42 MW in case of the "basic version" with the original burner, and, its Q-factor amounts to Q=1.78. Compared to the driven system GDT-DS+B, the main part of the improvement comes from the stronger neutron source, but, a certain portion also results from the higher self-multiplication M_{eff} of the burner by its greater criticality k_{eff}=0.9701 (see Table 2). On the other hand, one has also to note that the parameter φ^* slightly decreased: φ^*=1.69, mainly because of the enlarged radius of the inner hole. Furthermore, it is noteworthy that in spite of the greater core volume, which increased from 2.53 m^3 to 3.80 m^3, the mean fission power density increased by almost the factor 3. So, the calculation results for the extended driven MA-burner are encouraging. Considering additionally the possibility of increasing the electron temperature discussed in section 3.1 then a Q-factor of $Q \approx 5$ could be possible.

From the development of liquid metal cooled fast reactors it is known that their positive coolant void effect is of highest safety relevance. This circumstance led to core designs with diameter-to-height ratios greater than one. Therefore, criticality calculations were carried out for several void cases of the longitudinally extended burner where the coolant was removed from core, reflector and buffer. Table 2 gives the calculated effective multiplication factors. The statistical errors were less than 2×10^{-4}.

Table 2.

Effective multiplication factors calculated for several voided states of the elongated MA-burner

		System voided from top down to			
	No void	**upper core edge**	**mid-plane of core**	**lower core edge**	**entire system**
k_{eff}	0.9701	0.9676	0.9810	0.9964	0.9925

The void effect is known to be the result of two components: the negative contribution of loosing reflector and the positive contribution of neutron spectrum hardening. As expected, the results show that the maximum net void effect appears if the system is voided down to the lower core edge. However, it turns out that even in this case the system is still sub-critical. Obviously, the negative contribution from reducing the reflector is enforced by opening the inner hole when the system is voided. This result strengthens the motivation for further investigations in the direction of “stretched” GDT-driven transmutation systems.

4. Conclusions

The results that hitherto could be derived from studying the potential of the GDT-based 14 MeV neutron source as driver of a MA-burner give rise to the following main conclusions:

- Comparing the fission neutron generations that are initiated in average by one spallation or by one 14 MeV neutron reveals that a factor of about two only can be gained by the fusion neutron, though it has about ten times more energy. This gain results from the higher n,2n reaction rate that mainly occurs in collisions with the nuclei of the Pb/Bi eutectic coolant.
- A 14 MeV neutron has a substantially higher fission probability in collisions with nuclei of the fuel than a mean spallation neutron. However, since the number of primary fusion neutrons is very small compared to all other neutrons even in the region near to the source they do not remarkably modify the spectrum of the neutron flux. Thus, the total destruction rate of trans-uranium nuclei per unit of neutron flux will be practically the same as in the case of the spallation source.
- The project of the “basic version” of the GDT-based neutron source that has been proposed as irradiation facility for fusion material research turns out to deliver one order of magnitude less neutrons than would be necessary for a MA-burner of commercial scale.
- The Q-factor, which is a quantity characterizing both the power balance of the MA-burner and the efficiency of the destruction of trans-uranium isotopes by fissions, results clearly less than one Q=0.67, whereas, in case of the spallation source it amounts to Q=5.25.

- An increase of the electron temperature of the GDT-plasma up to the self-consistent value would result in an increase of the Q-factor by a factor of about three. The realization of this possibility demands further research of the GDT plasma stability.
- The GDT neutron source offers the possibility for longitudinally stretching the neutron production volume. Thereby, the total strength and the energetic efficiency of the source can be substantially increased. Encouraging results were obtained from the first study of a longitudinally extended burner. Together with the possibility of increasing the electron temperature of the GDT plasma such a system would generate about thirteen times more fission power and achieve a Q-factor greater than five.

The latest findings encourage further optimization of the GDT-based neutron source as driver of a sub-critical MA-burner.

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