RADIATION SHIELDING DESING FOR THE VISTA SPACECRAFT

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Abstract

An innovative concept for the direct utilisation of fusion energy with laser ignited (D,T) capsules for propulsion is presented with the so called VISTA (Vehicle for Interplanetary Space Transport Applications) concept. VISTA's overall geometry is that of a 50°-half-angle cone to avoid massive radioactive shielding. The 50°-half-angle maximizes the jet efficiency, and is determined by selecting the optimum pellet firing position along the axis of the cone with respect to the plane of the magnet coil. The pellet firing position is in the vacuum. By a total fusion power production of 17 500 MW with a repetition rate of 5 Hz and 3 500 MJ per shot, the propulsion power in form of charged particles has been calculated as ~ 7 000 MW, making ~ 40 % of the total fusion power. About 60 % of the fusion energy is carried by the leaking neutrons out of the pellet. Most of them (96 %) escape into vacuum without striking the space ship. Only 4 % enter the frozen hydrogen expellant in conical shape (about 50 gr.). Total peak nuclear heat generation in the coils is calculated as 4.7 mW/cm^3. The peak neutron heating is 1.9 mW/cm^3 and the peak γ-ray heating density is 2.8 mW/cm^3. However, volume averaged

nuclear heat generation in the coils is much lower. It is calculated as 0.18, 0.48 and 0.66 mW/cm^3 for neutron, γ-ray and total nuclear heating, respectively. Net shielding mass is found as 170 ton, making < 3 % of the vehicle mass.

I. Introduction

Fusion energy can make very high temperatures possible for the rocket propellant (> 10 000 °K) [1], reducing the propellant mass and minimizing the total mass of the space ship. In the past, various design concepts for fusion rocket propulsion in space were discussed [2-4].

The VISTA (Vehicle for Interplanetary Space Transport Applications) concept had been suggested by the scientists of the Lawrence Livermore National Laboratory, ETEC-Rocketdyne-Rockwell, Jet Propulsion Laboratory, and NASA, Johnson Space Center and has been described in refs. [1, 5-8], in detail.

The propulsion power limit in the VISTA concept will be set by the neutron and γ-ray heating of the super conducting coils in the magnets. The present work represents a further endeavor for the mass reduction of the radiation shielding of the VISTA spacecraft.

II. The Vista Space Craft

Fig. 1 shows the layout of the VISTA concept [5,6]. The primary spacecraft structure is a cone. Crew systems are located at the rim of the cone, buried inside the propellant tanks for added radiation-exposure protection. A 13-m-radius, 300-kA/cm^2 warm-super conducting magnet generates a magnetic field that has a peak strength of about 12 T and that defines the boundaries of a thrust chamber. Pellets are filled with liquid deuterium (D) and tritium (T) fuel. The fuel pellets and 50 gr. of solid hydrogen (H) expellant are accelerated, injected, and positioned in the thrust chamber at a repetition rate that is variable from zero up to about 30 Hz. Laser beams delivering about 5 MJ of 0.5 μm light with an efficiency of at least 6 % (at 1 000 K) are focused on the pellet to implode and release up to 3500 MJ in neutrons, X-rays, and plasma debris energy.

The fully ionized exhaust is guided with the help of a magnetic nozzle to propel the space ship. As charged particles will be affected in a magnetic field, both α-particles, as well as the unburned fraction of the fusion fuel debris will deliver the main propulsion power of the space ship. The hot propellant does not contact structural material. In this way, all material problems faced by the rocketry will be bypassed.

VISTA's overall geometry is that of a 50°-half-angle cone. This shape is required to avoid massive radioactive shielding over a solid space angle of 4π and to keep fusion neutrons (and X-rays) from striking and heating vehicle surfaces. Calculations have shown that the 50° half angle maximises jet efficiency, and it is determined in previous work, by selecting the optimum pellet firing position along the axis of the cone with respect to the plane of the magnet coil [5], in a manner similar to that done by Hyde [9].

The nuclear heat generation in magnet coils will be the major criterion for the size of the radiation shielding. For the superconducting magnet coils of terrestrial magnetic fusion reactors, Japanese scientists assume a design limit of 1 mW/cm^3 in ref. [10]. Russian scientists, working on ITER assume comparable design limits. For peak nuclear heating in super conducting magnet coils, they recommend 1 mW/cm^3 for "near term" magnet technology and 5 mW/cm^3 for more mature magnet technology in ref. [11]. One can expect that the design limit for warm superconductors will be even higher with the available technology beyond 2020.

III. Radiation Shield for Magnet Coils

Table 1 shows the main data of the radiation shielding. The composition of the winding matrix will depend on the state-of-the-art technology. It will be a warm superconductor, imbedded in a composite matrix. For neutronic calculations, an equivalent V_3Ga matrix has been assumed.

The magnet is shielded from the 14.1-MeV-(D,T) fusion neutrons, as shown in figure 2. The region in the shadow of the shielding where the circular coil is located is the rocket ship. This shape lets most of the neutrons escape into space. Due to the special geometry of the expellant and the spacecraft, only 3.9 % of the fusion neutrons can reach the hydrogen expellant.

Accordingly, the frozen hydrogen expellant is cast conically in a very thin polymer case, which will be fixed on a thin metallic bed, as shown in **Fig. 3.** Previous calculations have shown that this would allow one to obtain an important contribution to the radiation shielding of the super conducting magnets through a deflection of the neutrons into vacuum via intense neutron scattering reactions on hydrogen nuclei [7,8]. Of the neutrons entering the frozen hydrogen expellant, 8 % will continue on towards the shielding. The rest, again (92 %) will be deflected into vacuum. Thus, through the special conical geometry of the space craft and expellant, only a small fraction of the fusion neutrons (0.039x0.08 = 0.312 %) will reach the radiation shielding. This reduces, drastically, the radiation shielding mass for the super conducting magnets. The significant mass reduction of the radiation shielding warrants pursuing research and development work in aligning the axis of a conical frozen hydrogen expellant with the space craft structure through high precision target aiming techniques.

After compression, the (D,T) fuel shrinks from about 0.25 cm diameter to 0.006 cm internal radius and 0.011 cm external radius ($\Delta R = 0.005$ cm) with a mass density of $\rho = 600$ g/cm^3 and an areal density of $\rho.\Delta R = 3$ g/cm^2. The fusion neutron source becomes a tiny point at the apex of the target-expellant assembly in figures 1 and 3. All fusion neutrons that arrive at the spacecraft structure must first pass through the conical frozen hydrogen expellant.

IV. Neutronic Calculations

The calculated neutron energy deposition in the pellet is 3.7 MeV per fusion neutron. Together with the α's, the charged particles in the pellet debris carry already 7.2 MeV per fusion. By a repetition rate of 5 Hz and total fusion power of 5 (Hz) x 3 500 (MJ) = 17 500 MW, this would deliver a propulsion power of about 7 000 MW in form of charged particles which would constitute ~ 40 % of the total fusion power.

Penetration of the neutrons and γ-rays through the new radiation shielding structure is calculated with DORT [12] in (r-z) geometry with 5 neutron and 3 γ-ray macro groups in S_{16}-P_3 approximation with 160 directional space angles in order to suppress eventual ray effects in the course of S_N calculations through this high angular resolution.

IV.I. Nuclear Heat Release in the Magnet Coils

Figs. 4, 5 and 6 show, logarithmically, the neutron heating, γ-ray heating and total nuclear heat release, respectively, in μW/cm^3 in the magnet coils for a total fusion power of 17500 MW.

A peak in the total nuclear heat generation is observed at the lower left corner of the coils, corresponding to the weakest point of the shield where the coordinate system η-η' and ξ-ξ' is located (see figures 2 and 6) and is 4.7 mW/cm^3. The total nuclear heat production remains everywhere below the design limit in technology phase (5 mW/cm^3) recommended by ref. [11] and exceeds the design limit of 1 mW/cm^3 in ref. [10] in a very small coil region. By this shielding layout, the peak neutron heating for a fusion power of 17500 MW is 1.9 mW/cm^3 and the peak γ-ray heating density is 2.8 mW/cm^3. Volume averaged nuclear heating in the coils is much lower. It is 0.18, 0.48 and 0.66 mW/cm^3 for neutron, γ-ray and total nuclear heating, respectively.

The γ-ray heating in the magnet coils is higher than the neutron heating. In the early work with a very conservative design limit of 80 μW/cm^3 for the heat generation in superconducting coils for magnetic fusion, as it is recommended by ref. [13], net shielding mass was calculated as 595 ton [7]. In a recent work, with a 90 % enriched lithium, net shielding mass was calculated as 200 ton [8]. In the present work with natural lithium, net shielding mass is found to be 170 ton.

The integral thermal radiation from a totally polished and vacuum isolated aluminium (with ε = ~ 0.02-0.03) surface to magnet coils in figure 2 remains in the range of only a few Watts by cyrogenical helium temperatures. We assume that the nuclear heating in aluminium is removed separately. For the magnet coils, nuclear heating constitutes the main heat source.

V. Discussion

Radiation shielding requirement for a design concept with inertial fusion energy propulsion for manned or heavy cargo deep space missions beyond earth orbit has been investigated. Fusion power deposited in the inertial confined fuel pellet debris delivers the rocket propulsion with the help of a magnetic nozzle.

As a critical issue of this design, the nuclear heating of the super conducting magnet coils (126 ton) is considered. By a total vehicle mass of ~ 6000 ton, early work had found a shielding mass of 595 ton, making roughly 10 % of total mass, assuming a design limit of 80 $\mu W/cm^3$. The analysis has shown that higher design limit values (1 or 5 W/cm^3) of the super conducting coils help to reduce the mass requirements for the radiation shielding of the magnet coils of the VISTA space craft, considerably. Namely, shielding mass is reduced from 595 ton down to 170 ton, from ~ 10 % down to < 3 % of total mass. This important mass saving, over 400 ton would then allow the propellant mass, the mission range and the net cargo weight of the space craft to be increased.

Prospective developments in high temperature super conducting technology would increase design limits for nuclear heating, reduce both the radiation shielding mass as well as for waste heat radiator mass (due to higher waste heat temperature) of the vehicle.

ACKNOWLEDGMENT

This work is supported by the Research Fund of the Niðde University, Project #: FEB 99/01.

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Table 1 Composition of radiation shielding

Material		ρ (g/cm^3)	Thickness (cm)	Mass (tons)
Beryllium		1.84	4	9.3
1500K Liquid Lithium		0.41	~ 25	10
LiH		0.70	~ 80	115
Coil aluminium hoop		2.7	14	65
Coil Winding Matrix composition↓		4.3	60X60	126
Element	Weight fraction			
Vanadium	0.487			
Aluminum	0.315			
Carbon	0.103			
Gallium	0.079			
Hydrogen	0.016			
Total shielding mass without coil (tons)				200
Total shielding mass with coil (tons)				326

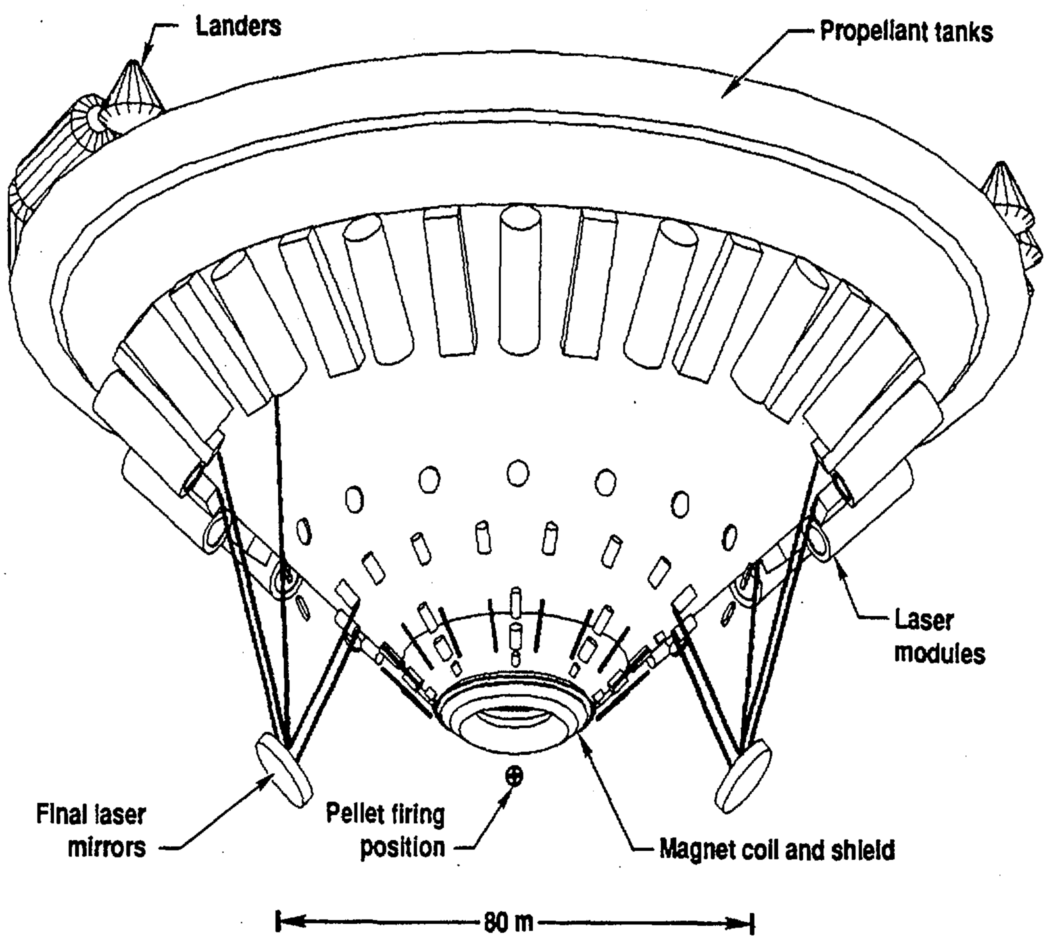

Figure 1: VISTA systems layout.

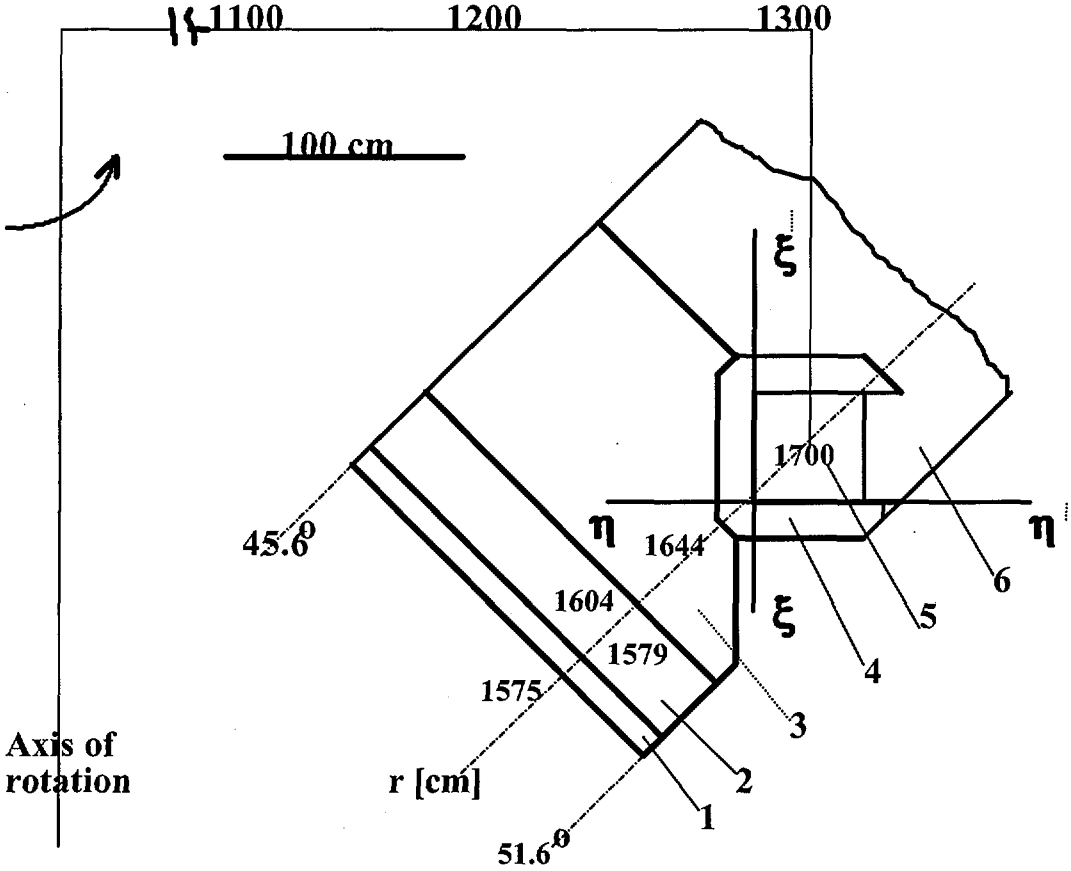

Figure 2: Geometrical model of the radiation shielding for magnet coils for neutronic calculations

Legend:
① **Beryllium**, 4 cm thick (X-ray shield); ② **Liquid lithium** (neutron shield); ③ **LiH** (neutron shield); ④ **Aluminium** (coil hoop); ⑤ **Magnet coils** (Weight fractions: 0.487 V, 0.315 Al, 0.103 C, 0.079 Ga, 0.016 H; cross section = 60X60 cm^2, rotation radius at the midpoint = 1300 cm); ⑥ **Spacecraft structure** (Aluminium; $\rho = 0.2$ gr/cm^3) of the space craft and expellant, only a small fraction of the fusion neutrons (0.039x0.08 = 0.312 %) will reach the radiation shielding. This reduces, drastically, the radiation shielding mass for the super conducting magnets. The significant mass reduction of the radiation shielding warrants

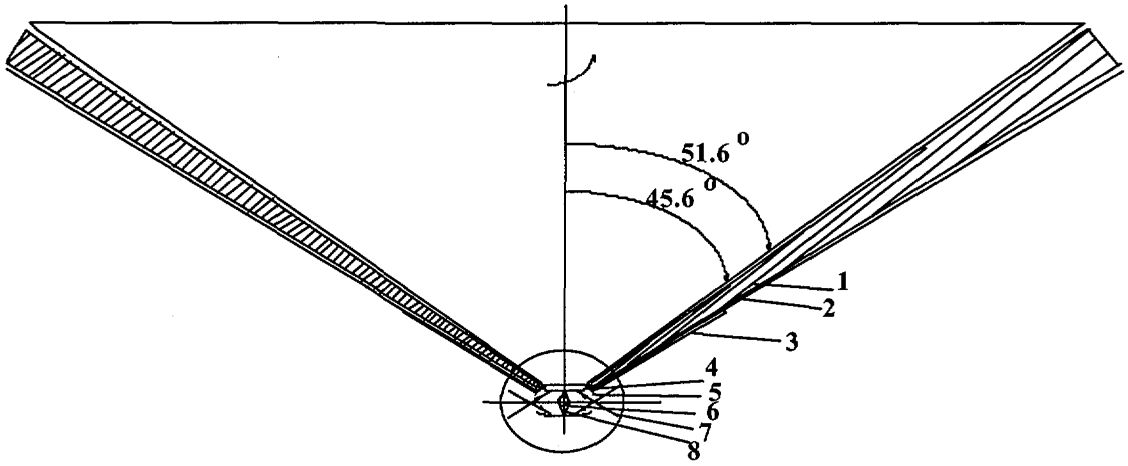

Figure 3: Rigid attachment of the fuel capsule and expellant

Legend

①Frozen hydrogen expellant; ②Plastic case; ③Metallic bed; ④Braze; ⑤Fuel capsule (High-z case); ⑥(D,T) fuel; ⑦Laser beams for indirect-drive target; ⑧Membrane (Myler)

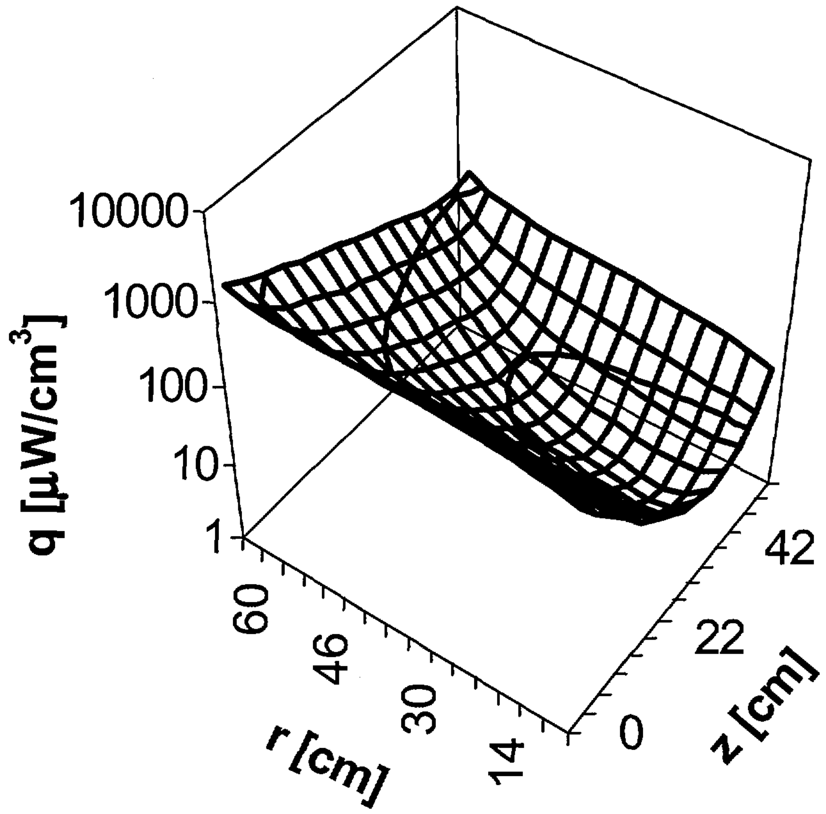

Figure 4: Neutron heating density in the magnet coils

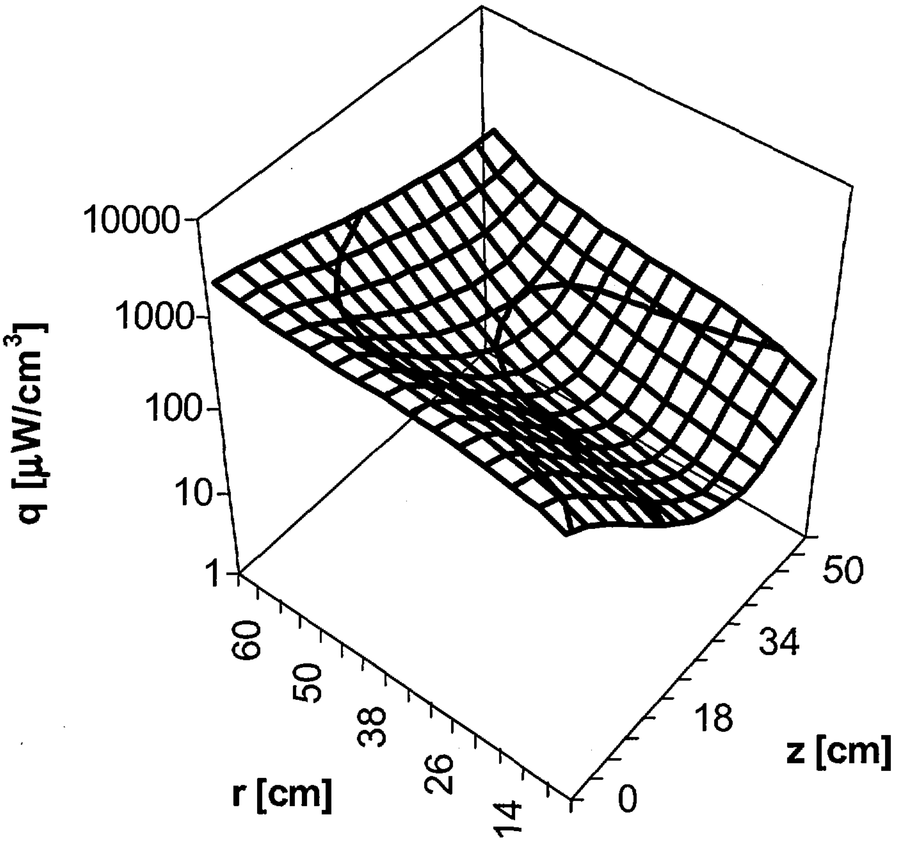

Figure 5: Gamma-ray heating density in the magnet coils

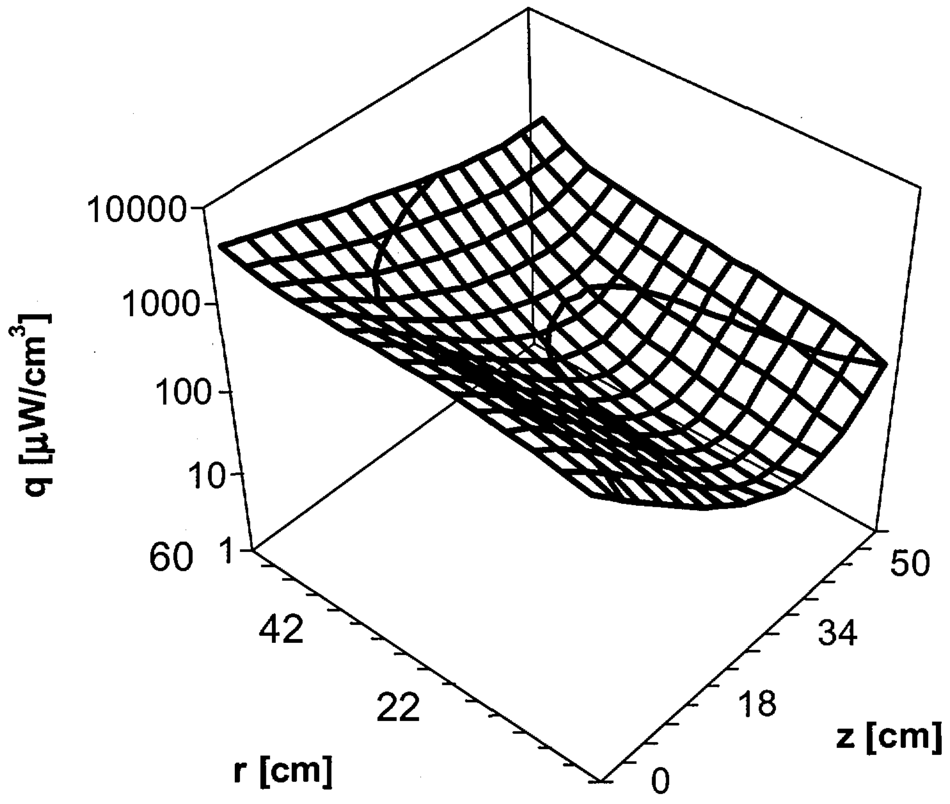

Figure 6: Total nuclear heating density in the magnet coils