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Abstract

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The work on pellet injection within the framework of the HIBALL reactor study for inertial confinement fusion is summarized. The results on the physical feasibility of a pneumatic and a magnetic pellet acceleration and proposals for adequate pellet carriers are given, reference parameter values are presented. Both investigated methods are compared and evaluated with respect to the technical status of the components of a pellet injection system to give a concluding recommendation.

Zusammenfassung

Vergleich von pneumatischer und elektromagnetischer Pelletinjektion für Trägheitsfusions-Reaktorkammern

Es werden die Arbeiten zur Pelletinjektion im Rahmen der HIBALL-Reaktorstudie zusammengefaßt. Die Ergebnisse zur physikalischen Machbarkeit einer pneumatischen und einer elektromagnetischen Pelletbeschleunigung sowie Vorschläge für entsprechende Pelletträger werden angegeben, Referenzparameterwerte werden präsentiert. Beide untersuchten Methoden werden verglichen und bezüglich des technischen Standes der Komponenten eines Pellet-Injektionssystems bewertet, um eine abschließende Empfehlung zu geben.

Table of Contents | Page

I.	Introduction	1
II.	Pneumatic Pellet Injection System	2
II.1	General	2
II.2	Gas Gun Technology	3
II.3	Sabot	5
II.3.1	Reference Design for HIBALL	6
II.3.2	Concepts for Sabot Detachment and Recovery	9
II.4	Coupling of Gas Gun and Reactor Cavity	14
II.5	Summary	15
III.	Electromagnetic Pellet Injection System	18
III.1	General	18
III.2	Magnetic Linear Accelerator	20
III.3	Sabot, Reference Design for HIBALL	22
III.4	Injection System	27
III.5	Summary	27
IV.	Comparative Evaluation and Concluding Remarks	30
IV.1	Accelerator	30
IV.2	Sabot	31
IV.3	Other System Components	32
IV.4	Conclusion	33

I. Introduction

In order to generate energy from nuclear fusion by means of inertial confinement, targets (pellets) filled with fusion fuel must be accurately injected into a reactor cavity at a frequency of some hertz. In the cavity the pellets will be exposed to highly intensive, concentrated laser or corpuscular beams. When using cryogenic pellets their suitable velocity and injection frequency depends particularly on the thermal influences in the reactor cavity prior to the microexplosion; one has to reckon with pellet velocities ranging from 100 to 1000 m/s.

The HIBALL study concerning an inertial confinement fusion reactor with heavy ion beams as driver for the energy generation from the pellet / 1 / gave rise for the paper in hand. For the first draft the pneumatic method has been chosen for the pellet injection and data for the design of an injection system with gas gun have been calculated.

Within the framework of further studies on HIBALL the possibility of electromagnetic pellet injection has been dealt with as an alternative to the pneumatic method. In this connection the physical feasibility of pellet acceleration by means of a magnetic linear accelerator as well as a railgun has been investigated. In / 2 / sets of reference parameter values for the pellet reference velocity of 200 m/s have been indicated for both methods.

The main intension of this study is to give a first technological evaluation of the various components of a pellet injection system with regard to a comparison of pneumatic and electromagnetic pellet injection.

For this purpose the results obtained up to now for each of the two methods are summarized and supplemented in some points in connection with an assessment of the system-related feasibility.

Chapter II as well as chapter III deal with the accelerator, the sabot and the other system components. Finally, the pros and cons of the two pellet injection systems are compared and evaluated.

II. Pneumatic Pellet Injection System

II.1 General

In spite of partially different requirements, the experimental experience with light gas guns for the refuelling of magnetic confinement installations can be utilized for the injection of targets (pellets) for inertial confinement fusion. In particular, the problem of coupling a high pressure driven gas gun with an evacuated reactor chamber ($\sim 10^{-4}$ Torr for HIBALL and $\sim 10^{-9}$ Torr for present tokamaks) is common to both the pellet injection for heavy ion inertial confinement and the injection of pellets (cylinders of solid deuterium) into vacuum chambers of magnetic confinement installations. Cryogenic projectiles ($\sim$ 4 K) are provided for both applications and an injection frequency of 5 Hz and of the order of 10 Hz, respectively, should be achieved. The requirements on pellet intactness during acceleration are, however, different. Pneumatic pellet injection for inertial confinement requires a protecting capsule for the pellet during the acceleration. Such a capsule is called sabot in the following. This necessitates a concept for the detachment of the sabot from the pellet following the acceleration process. Furthermore the requirements imposed on the reproducibility of the pellet velocity and on the aiming accuracy are different and, in particular, higher for inertial confinement (see / 1 /).

II.2 Gas Gun Technology

To date, pellet velocities of nearly 1000 m/s have been obtained for solid deuterium cylinders ("pellets") of about 1 mg with a propellant gas pressure of up to 40 bar with pellet injectors on tokamaks at Oak Ridge and IPP/Garching / 3 - 5 /, see Table 1. Hydrogen or helium at room temperature is used as propellant gas. For the ISX-B pellet injector, for example, the acceleration length is 17 cm and the amount of propellant gas released per shot is about 10 Torr l of helium.

The reference data of a HIBALL pneumatic pellet injector are based on a pellet velocity of 200 m/s and were calculated for a projectile mass (pellet + pellet carrier) of 2 g / 1 /. Assuming an overall gas gun efficiency of 0.5, a necessary propellant gas pressure of 5 bar in the reservoir was calculated for an acceleration length of 2 m and a barrel diameter of 1 cm resulting in a propellant gas quantity of 608 Torr l of deuterium per shot.

In contrast to the application for refuelling magnetic confinement installations, a pellet injector for an inertial confinement fusion reactor need not be designed to create the projectile, which in the case of present injectors for magnetic confinement fusion is effected before each single shot. As regards inertial confinement it can be stated that the pellets are produced outside the injector and are stock-piled. With reference to the load mechanism, gas guns for inertial confinement fusion are technically less complicated than those for magnetic confinement.

Constructor MCF Installation	Pellet Size/Mass	Pellet Velocity [m/s]	Propellant Gas Pressure/Type [bar]		Barrel Length [mm]	Angle Spread
ORNL						
ISX-B	3.7×10^{19} H/ 6×10^{-5} g	300		He	3.2	
	l = Ø = 1 mm	1000	28		17	± 0.6°
IPP/Garching						
W VII A	3.4×10^{19} D/ $\sim 10^{-4}$ g	350 - 550	6 - 18	H_2		± 1.3°
	l = Ø = 0.9 mm					
ASDEX	3×10^{20} D/ $\sim 10^{-3}$ g	900	40	H_2		± 0.3°
	l = 1.5 mm					
	Ø = 3 mm					
Risø						
Dante	5×10^{17} D_2/ 3×10^{-6} g	100 - 200		H_2		± 0.5°
	l = Ø = 0.4 mm					
TFR	8×10^{18} D_2/ 5×10^{-5} g	640 ± 60	18	H_2	11.5	± 1°
	l = 2.3 mm					
	Ø = 0.6 mm					

Table 1: Data for pellet injection on magnetic confinement fusion installations / 3 - 5 /

The requirements on the trigger accuracy and rise time of the fast electromagnetically controlled gas valves are, however, higher for inertial confinement pellet injectors. Thus, for example, a reproducibility of the pellet velocity of less than 6 % is required for the HIBALL scenario in order to guarantee a coarse synchronization with the ion pulse motion according to the synchronization scheme described in / 1 /.

The gas valves of pneumatic pellet injectors have to be designed for opening frequencies of some Hz for both magnetic confinement and for inertial confinement. Their reliability for continuous operation in commercial fusion reactors still has to be verified.

II.3 Sabot

The necessity of embedding the pellet into a protecting capsule (sabot) for pneumatic injection into inertial confinement fusion reactors results from the cryogenity of the pellets containing solid DT on the one hand, and from the requirement that the pellet should neither be completely damaged nor injured on its surface on the other hand. In detail, the sabot should protect the pellet from the propellant gas and the residual gas within the gun barrel; moreover, it should insulate the pellet from frictional heating and provide straight guidance of the pellet during acceleration. The latter guarantees a small angle scattering of the projectile on leaving the muzzle of the gun. Consequently a suitable concept for the detachment of the sabot from the pellet and for the recovery of the sabot parts must be developed.

II.3.1 Reference Design for HIBALL

The insulation of the pellet from frictional heating and stable pellet storage during acceleration must be guaranteed by suitable material selection and fashioning of the sabot. Furthermore, the division of the sabot must be chosen to correspond to the type of sabot detachment after the acceleration period.

The sabot design presented in Fig. 1 is proposed as a reference design for HIBALL. It provides an area a_1 of some mm^2 in contact with the pellet in order to compensate the inertia force of the pellet mass during the acceleration (rate of acceleration : 10^4 m/s^2). Moreover, the pellet is stabilized by two additional annular bearings (a_2 and a_3) which only allow a relatively small heat transfer.

The frictional heat is produced at the annular contact areas A_1 and A_2. The main contribution to possible pellet heating occurs via path $\overline{P_1 P_2}$. Assuming only a one-dimensional heat transfer between P_1, P_2 and P_3, the temperature curve was calculated using a heat transfer code from the University of Wisconsin for a frictional heating power q_f of 50 W/cm^2 at P_1 and an acceleration time of 20 ms. q_f was calculated from the values given in Table 2. Teflon was chosen as the sabot material because of its relatively low thermal diffusivity and its small friction coefficient on steel (gun barrel material). A value of 1 bar was chosen for the contact pressure, which corresponds to the order of the propellant gas pressure. Even for the frictional heating power of 50 W/cm^2 resulting from this contact pressure and assuming a one-dimensional heat transport, it is not possible to confirm any temperature increase within the pellet for this sabot design / 6 /, see Fig. 2.

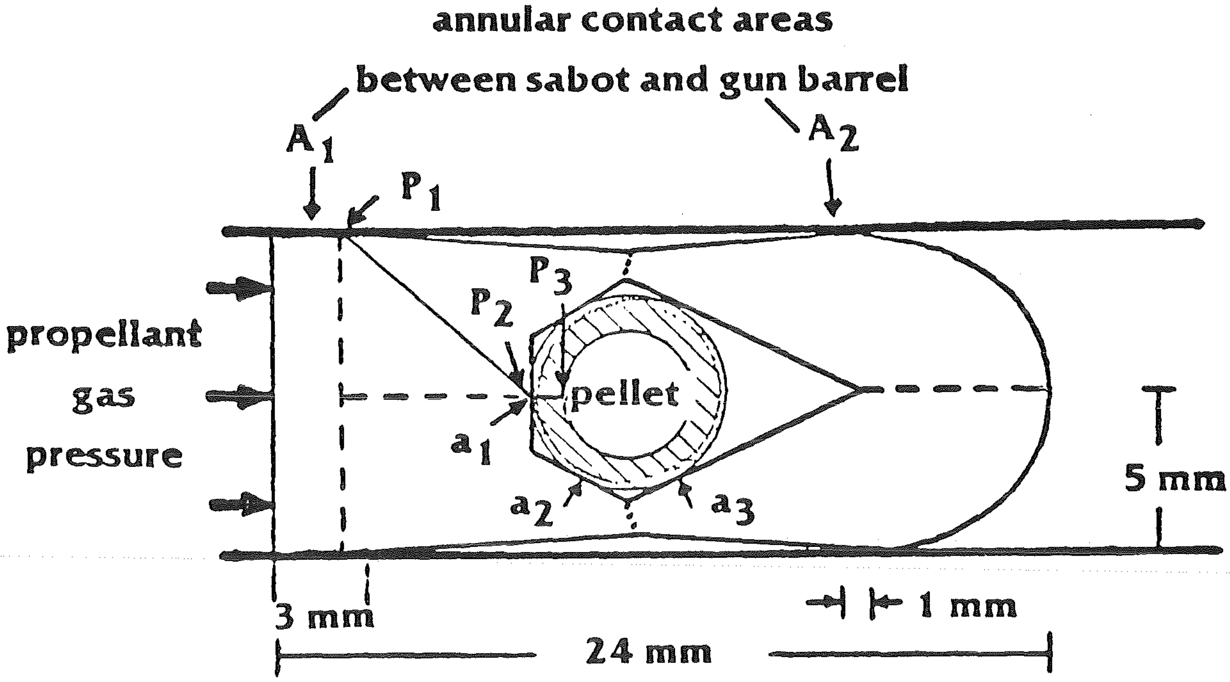


Fig. 1: Reference design of the sabot for a pneumatic pellet injection system for HIBALL; ... and ---: alternative possibilities of sabot division.

Friction coefficient (Teflon on steel)	f	0.05
Contact pressure	p_f	10^5 N/m²
Projectile velocity (mean value)	v_f	100 m/s

Table 2: Data for the calculation of the frictional heating power, $q_f = f \cdot p_f \cdot v_f$

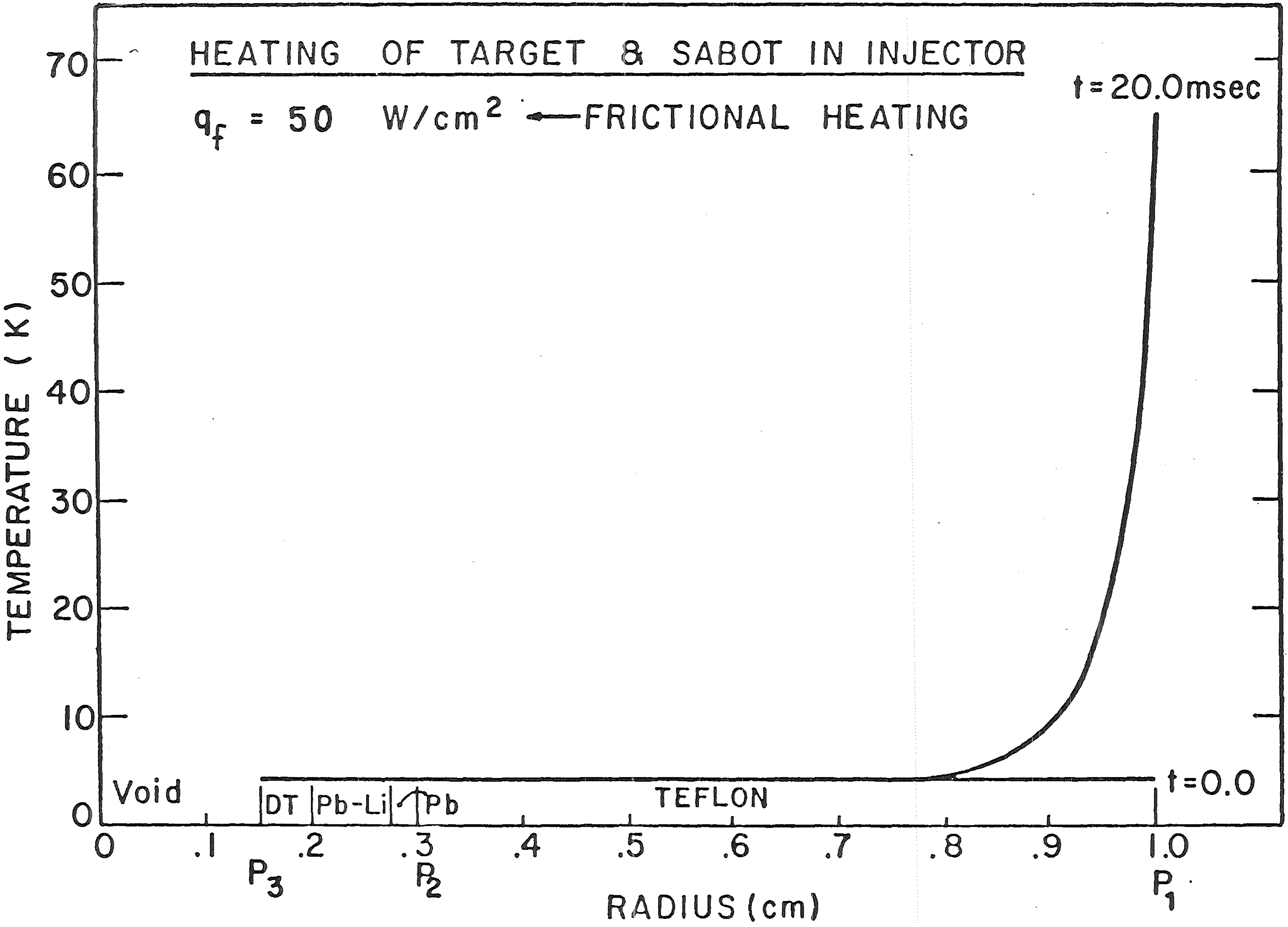


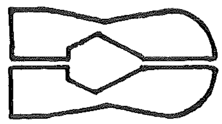
Fig. 2: Temperature distribution for pellet and sabot along $\overline{P_1 P_2 P_3}$ (see Fig. 1) from frictional heating during acceleration / 6 /.

From this result it is obvious that different organic materials with an even larger friction coefficient than Teflon can be considered, but, in contrast, have lower specific material costs and do not contain fluorine (possibility of formation of hydrofluoric acid in contact with the propellant gas deuterium).

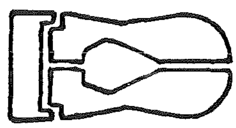
II.3.2 Concepts for Sabot Detachment and Recovery

Three possible ways of dividing the sabot are discussed in the following each resulting in a different detachment mechanism.

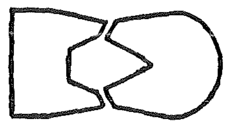
① Longitudinal divison



② Divison such as ① with an additional transversal disk



③ Division perpendicular to the acceleration axis



Using concept ① the detachment of the sabot from the pellet can be effected by centrifugal forces / 7 /. This requires the rotation of the projectile during acceleration, for example, by adjusting it into a rifled barrel. It could be disadvantageous that an asymmetric detachment of the sabot parts, possibly caused by aerodynamic effects, could result in a non-sero lateral force of reaction on the pellet. This could necessitate a corresponding correction of the pellet path in order to achieve the required aiming accuracy. Futhermore the influx of propellant gas between the sabot parts can hardly be excluded. This could be prevented by an additional transversal disk on the propellant gas side, see concept ②. For this concept, however, an additional mechanism must be provided to push the disk away from the injection axis. Even if such a mechanism is available it would be more suitable to divide the sabot perpendicular to the axis of acceleration according to concept (3).

This concept is advantageous because the detachment of the sabot parts from the pellet can be performed parallel to the axis of motion, so that on principle no lateral forces act on the pellet. It is suitable to effect the separation of the sabot parts at the final section of the gun barrel using electromagnetic forces. Conducting metallic rings, e. g. of copper, can be attached to both sabot parts perpendicular to the axis of motion, see Fig. 3. Two magnetic coils with a distance which is somewhat shorter than the distance of the two metallic rings are placed around the final section of the gun barrel. When the sabot has reached the position as shown in Fig. 3 after the acceleration process, both coils are fed with currents triggered by means of a light barrier which is intersected by the front part of the sabot. Consequently currents are induced into the metallic rings producing magnetic fields which are opposite to the field of the corresponding magnetic coil. Thus the backward part of the sabot is decelerated and the front part is accelerated, so that both sabot parts are detached from the pellet. Both magnetic coils should be fed with opposite currents in order to obtain a minimum magnetic field on the pellet.

To obtain a separation distance of 10 mm, i.e. the order of diameter of the HIBALL pellet, over a traveling distance of the sabot of 0.2 m the velocity of the front part of the sabot must be increased from 200 to 205 m/s and the backward part must be decelerated to

195 m/s. The time of action of the magnetic field on the metallic rings corresponds to the travelling time over a distance of the coil radius, roughly. Assuming a reference value of 1 cm and a sabot velocity of 200 m/s, the time of action, i.e. the acceleration or deceleration time, respectively, amounts to 50 µs. A change of absolutely 5 m/s during 50 µs corresponds to a mean rate of acceleration of 10^5 m/s^2. Assuming a radius of the metallic rings of 5 mm and a mass of 1 g to be accelerated, the magnetic induction generated by the current of the field coils must be about 2 T.

Instead of metallic rings, permanent magnets could also be used on the sabot.

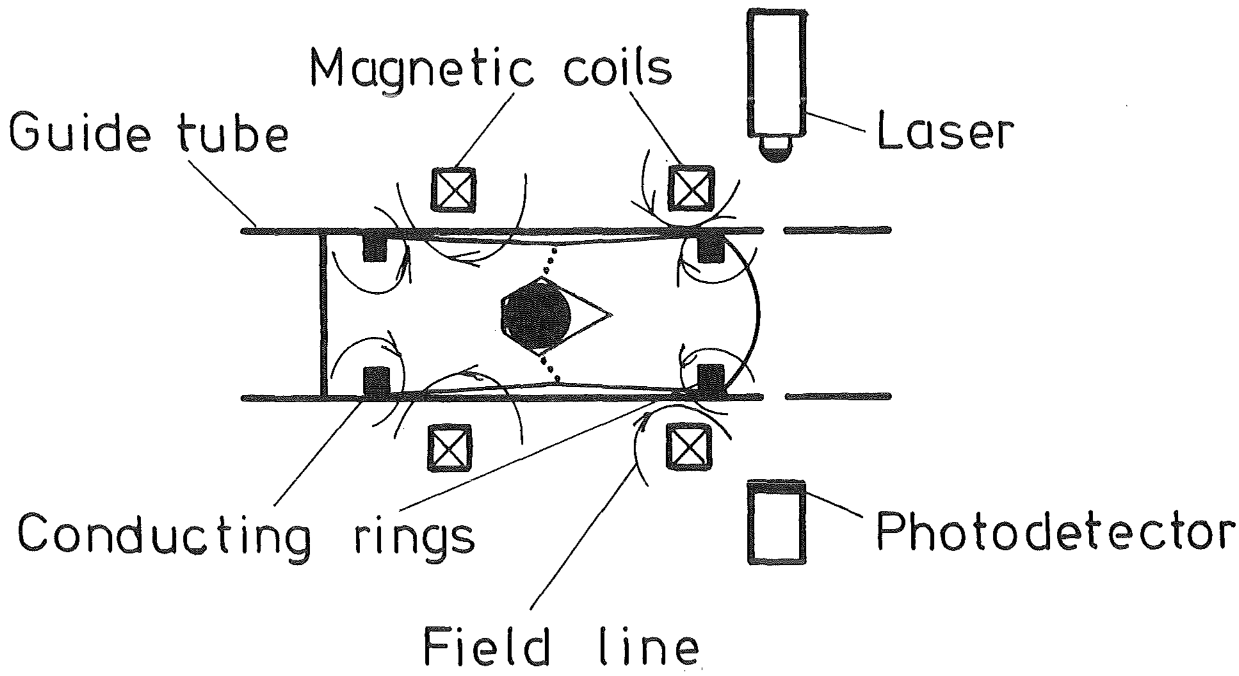


Fig. 3: Concept of detachment of the sabot from the pellet for a transversal division of the sabot; ... boundary of the sabot parts.

The deflection of each of the sabot parts from the injection axis can be effected by another magnetic coil behind the muzzle of the gun barrel; the axis of this coil must be inclined relative to the injection axis. This coil is also triggered by a light barrier, see Fig. 4a.

Alternatively to the electromagnetical deflection, the mechanical method can also be taken into account using a piston or a rotating cam disk, see Fig. 4b.

In general it may be suitable to use a low-temperature liquid as a decelerating medium for the sabot parts after their deflection. In the case of a cryogenic sabot which ought to be re-used, it must additionally be guaranteed that no destruction of the sabot parts occurs due to a temperature shock.

Last but not least, a concept as sketched in Fig. 4c should be taken into account. After having separated the sabot parts from the pellet according to concept ③, both sabot parts are guided by a curved tube in which an opening is provided for the escape of the pellet. Thus the sabot parts can be directly collected and, moreover, can be stopped over a relatively short distance. This can be attained, for example, by designing the guiding tube with a small but increasing curvature, which coasts into a suitable, low-temperature liquid, as early as possible (flooded tube with a perforated wall), see Fig. 4c (not to scale).

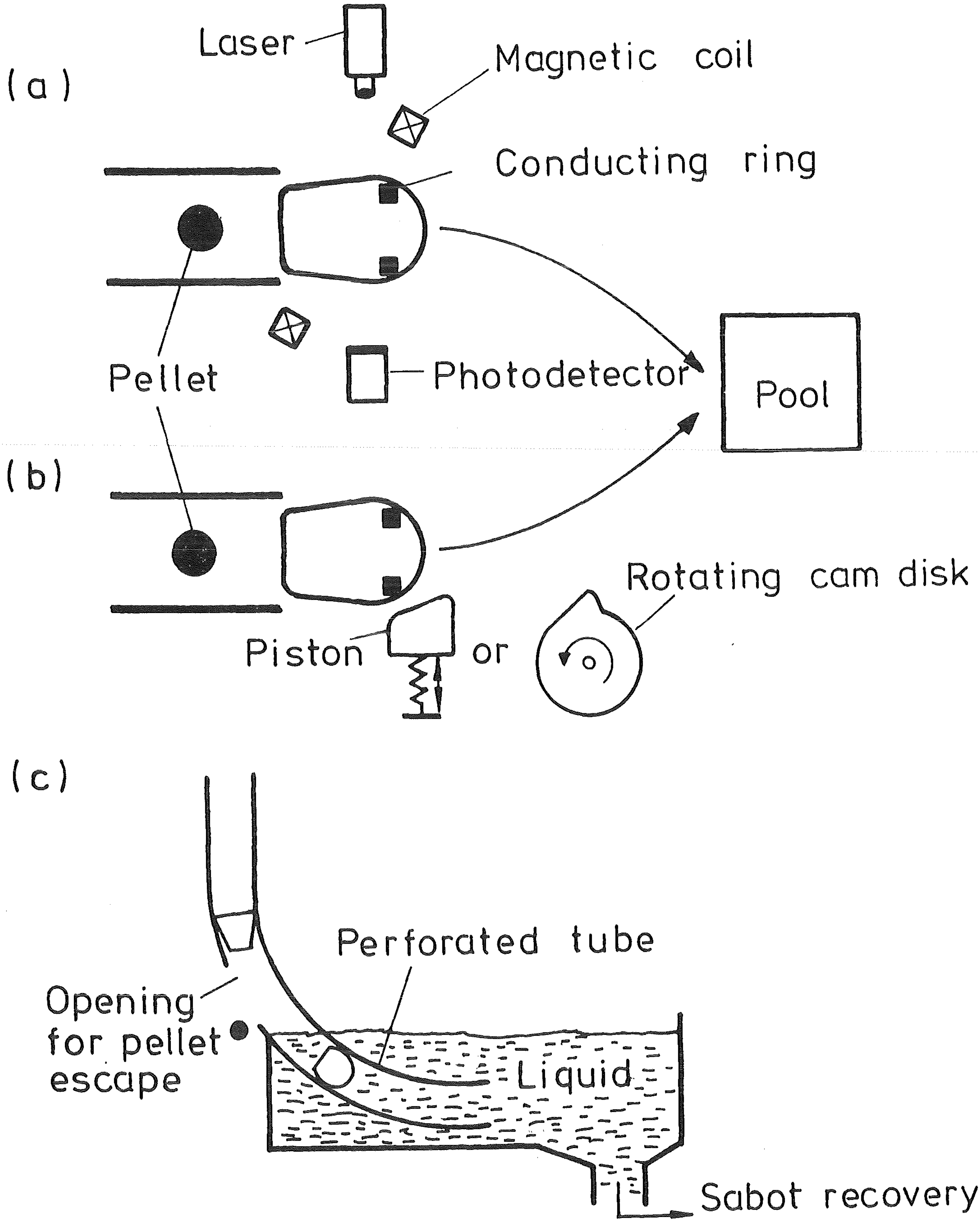


Fig. 4: Concepts for the deflection and the recovery of the sabot (not to scale), (a) Electromagnetically, (b, c) Mechanically

II.4 Coupling of Gas Gun and Reactor Cavity

Taking an overall gas gun efficiency of 0.5 into consideration, a propellant gas quantity of 608 Torr l (i.e. 141 mg) Deuterium per shot was calculated for the acceleration of a 2 g projectile to a velocity of 200 m/s over a distance of 2 m / 1 /. On the basis of an initial pressure of 1 Torr and a maximum final pressure of only 2 Torr in the buffer cavity between the gas gun and the injection channel of the top reactor shield, a buffer volume of 877 l is needed assuming an adiabatic expansion of the propellant gas and a pumping time of 0.2 s.

Based on a mean pressure of 1.5 Torr in the buffer cavity and an injection channel diameter of 1 cm, it was calculated that a maximum Deuterium quantity of 1.6 mg streams into the reactor cavity per shot. This results in a Deuterium partial pressure of less than 10^{-5} Torr in the HIBALL reactor cavity which is one order of magnitude below the reactor cavity pressure required just before the microexplosion.

Questions related to the aerodynamics at the gas gun muzzle, in particular, the interaction of the outstreaming propellant gas with the bare pellet must be investigated in more detail by means of experimental tests where it has to be optimized for the specific sabot concept.

II.5 Summary

A scheme relating the basic requirements and the technical tasks of each of the system components of a pneumatic pellet injection system within the framework of the HIBALL study / 1 / is given in Fig. 5. The essential results, the future tasks for the development and open questions for each of the system components are listed in Table 3.

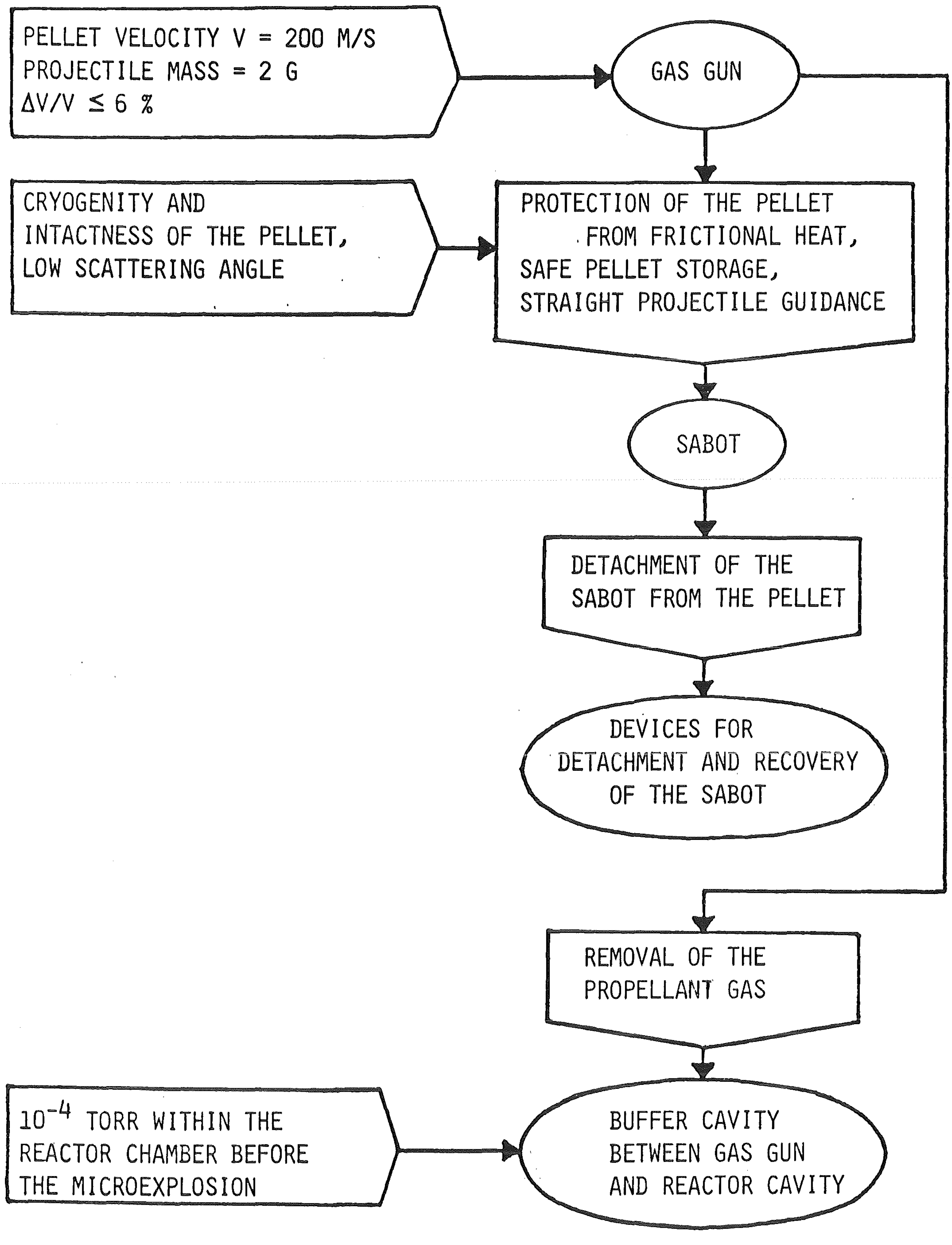


Fig. 5: Basic Requirements, System Components and Technical Tasks for a pneumatic pellet injection system for HIBALL / 1 /.

System Component of a Pneumatic Pellet Injection System	Results and Design Proposals for HIBALL	Future Tasks, More Detailed Investigations
Gas gun	reference data for pellet acceleration: $l_a = 2$ m, $t_a = 20$ ms $p_r = 5$ bar, $(pV)_o = 608$ Torr l $\eta_g = 0.5$ fast electromagnetic gas valves available	identification of an optimum gas pressure regime in accordance with the requirements on and the capabilities of fast gas valves gas gun efficiency, reproducibility of the pellet velocity . trigger accuracy of the gas valve and rise time of gas pressure, stability of the accelerating pressure . high frequency ($\sim$10 Hz) continuous operation of gas valves, muzzle design
Sabot	reference design (Teflon, axi-symmetric pellet storage) . frictional heat transfer to the pellet negligible . 3 concepts for division	abrasion, wear, re-utilization (survivability), material costs
Devices for detachment and recovery of the sabot	some conceptual proposals based on electromagnetic or mechanical principles	experimental tests for identification of the most suitable concept
Buffer cavity	reference proposal: p_b: 1 to 2 Torr, $V_b = 877$ l 1.6 mg deuterium per shot into reactor cavity	experimental verification, buffer cavity design under consideration of the concept for the detachment and the recovery of the sabot

Table 3: Results and design proposals for a pneumatic pellet injection system for HIBALL and general tasks for future investigations (meaning of the parameters see text)

III Electromagnetic Pellet Injection System

III.1 General

On the basis of the fundamental requirement for the pellet injection of HIBALL, i.e. of a cryogenic pellet, which is neither to be heated up nor damaged by the acceleration, a sabot, which, moreover, ensures straight guidance of the pellet and prevents the propelling force from directly acting on the pellet, is planned for the electromagnetic acceleration.

The physical feasibility of pellet acceleration by means of a magnetic linear accelerator, was investigated in / 2 / using a sabot with different types of driving bodies: non-ferromagnetic cylinder, ferromagnetic cylinder, superconducting ring. Acceleration according to the railgun principle was also examined. It was shown that these methods permit acceleration of projectiles with a mass of the order of 1 g to 200 m/s (pellet reference velocity for HIBALL) over a distance of 1 m, corresponding to an acceleration time of 10 ms. This is suitable for the spatial and temporal pellet injection scenario outlined for HIBALL in / 1 /.

In contrast to pneumatic pellet injection, pellet acceleration with a magnetic linear accelerator does not require a buffer cavity for the propellant gas between accelerator and reactor cavity. Contrary to this, however, if the railgun method is applied, residual gas must be present between the rails for the generation of the plasma arc, e.g. in the order of 0.1 Torr according to / 8 /. This is some orders of magnitude above the desired residual gas pressure of at least 10^{-4} Torr in a HIBALL reactor cavity prior to the microexplosion. Furthermore, the interaction of the plasma arc with the rail surfaces and the surface of the sabot on the plasma arc side seems to be basically disadvantageous. It is very questionable whether the permanent erosion of these surfaces permits the desired continuous operation. In any case, the erosion products would always have to be effectively removed and the rails would have to be replaced from time to time depending on the intensity of the erosion, as the close fit of the sabot deteriorats. Moreover, the surface quality of the rails influences the properties of the plasma arc, a fact which can finally lead to inadequate reproducibility of the projectile acceleration (pellet velocity) and to insufficient trigger accuracy of the acceleration process.

All in all, pellet acceleration using a railgun seems to be less advantageous than the application of a magnetic linear accelerator, and it is therefore not recommended as reference method for an electromagnetic pellet acceleration for HIBALL.

The results from / 2 / for the pellet acceleration using a magnetic linear accelerator are summarized in the following.

III.2 Magnetic Linear Accelerator

In principle, a magnetic linear accelerator consists of a set of magnetic coils connected in series, see Fig. 6. A magnetic coil spacing equal to the size of the coil radius was assumed for the calculation of the acceleration length of a pellet injector in / 2 /. This was established as being 1 cm because of the given pellet radius of 3 mm / 1 /. In order to fulfil the requirements for pellet injection, namely 200 m/s for the pellet velocity and an acceleration distance of the order of 1 m, magnetic inductions of some teslas are necessary on the axis of the accelerator coils in the case of the driving body designs given in / 2 /. This is feasible with present-day magnetic coil technology.

The most suitable mode of operation for a magnetic linear accelerator for pellet injection, however, still has to be identified. At present the principle of the travelling magnetic wave accelerator is under considerable discussion with reference to the acceleration of projectiles for impact fusion / 9, 10 /; this application even aims at projectile velocities of up to 100 km/s.

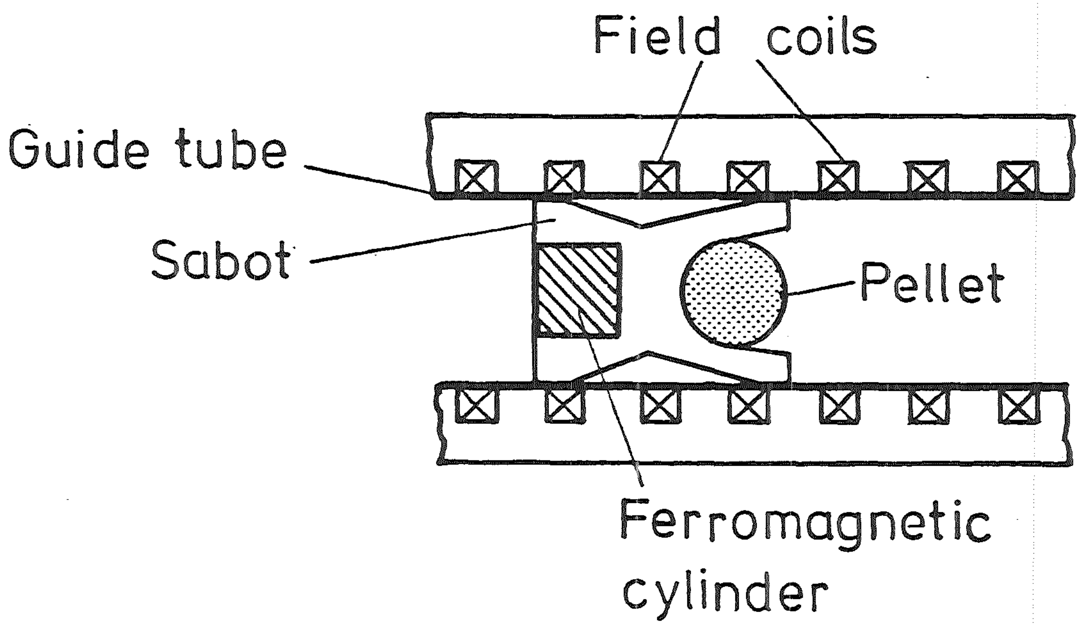


Fig. 6: Scheme of a magnetic linear accelerator for pellet injection into inertial confinement fusion reactor chambers.

III.3 Sabot, Reference Design for HIBALL

Various possible driving bodies of the sabot for magnetic linear acceleration were examined in / 2 /:

- Non-ferromagnetic cylinder (copper)
- Ferromagnetic cylinder
- Superconducting ring

The magnetic moment of a non-ferromagnetic, conducting cylinder is generated by current induction, that of the ferromagnetic cylinder by magnetization and that of the superconducting ring by flux entrapment (cooling to less than the critical temperature of the superconductor in a magnetic field).

All in all, a ferromagnetic driving body is most suitable, as its application requires the lowest technical expenditure. The magnetization of the ferromagnetic cylinder is continuously in saturation during acceleration as a magnetic induction of some teslas is necessary for the accelerating magnetic field for the current purpose of pellet acceleration to 200 m/s over a distance of the order of 1 m. Disadvantageous for the application of a superconducting ring is the fact that the maximum possible magnetic moment, i.e. the maximum superconducting current generating this moment, decreases with increasing temperature and increasing intensity of the outer magnetic field (the critical temperature of the superconductor is fundamentally the upper limit). Thus, e.g. inductive heating of the normal-conductive component of the superconductor would cause a corresponding reduction of the maximum magnetic moment of the ring and hence of the acceleration strength of the sabot, which can only be compensated by an intensification of the accelerating magnetic field up to a certain limit / 2 /.

The concept with a ferromagnetic driving body (cylinder) as sketched in Fig. 7a is proposed as a reference design of a sabot for magnetic pellet acceleration for HIBALL. The total mass M of the projectile amounts to approximately 4.5 g for the dimensions, indicated in Fig. 7a, if a plastic material is used for the sabot. This is advantageous because of the low density ($\sim$ 1 g/cm³) - in connection with a sufficient tensile strength. The mass M_c of the driving body amounts to 2.25 g, resulting in a mass ratio M/M_c of 2; the acceleration distance is generally proportional to M/M_c / 2 /. The distance between the driving body and the pellet was selected to be approximately the same as the coil diameter, in order to considerably reduce an interaction of the magnetic field of that coil which is currently active for the acceleration of the driving body on the pellet. Such an interaction can be excluded by appropriate lengthening of the sabot. Shielding of the pellet by a metal funnel is also possible.

The firm seat of the pellet during acceleration is effected by the pressing into the funnel-shaped holder due to the inertia force exercised on the pellet. During the transport to the loading device of the accelerator the sabot can be closed with a lid.

Fig. 7b presents the acceleration distance resulting for such a sabot with $M/M_c = 2$ for a projectile velocity of 200 m/s in dependence on the mean effective gradient $\delta_x B$ of the coils for a magnetic linear accelerator, whereby the coils have a distance (= radius r_f) of 1 cm. The curves are valid for ferromagnetic driving body material with ρ_f/B_c equal to 3400 and 7300 kg/T m³ resp., whereby ρ_f is the density and B_c the saturation magnetization of the driving body. The value 3400 kg/T m^3 is characteristic for high-permeability materials e.g. Permendur with a saturation magnetization of 2.5 T. A gradient of 85 T/m is therefore necessary for an acceleration distance of 2 m. If permanent magnets are used - characteristic value ρ_f/B_c = 7300 kg/Tm³ - $\delta_x B$ must be approximately twice as high, see Fig. 7b.

Table 4 presents a list of the reference values for the sabot and the accelerator. They are valid for the HIBALL pellet velocity of 200 m/s. As in the case of the pneumatic pellet injection system according to / 1 /, an acceleration distance of 2 m was selected; the same schedule therefore results for the pellet injection.

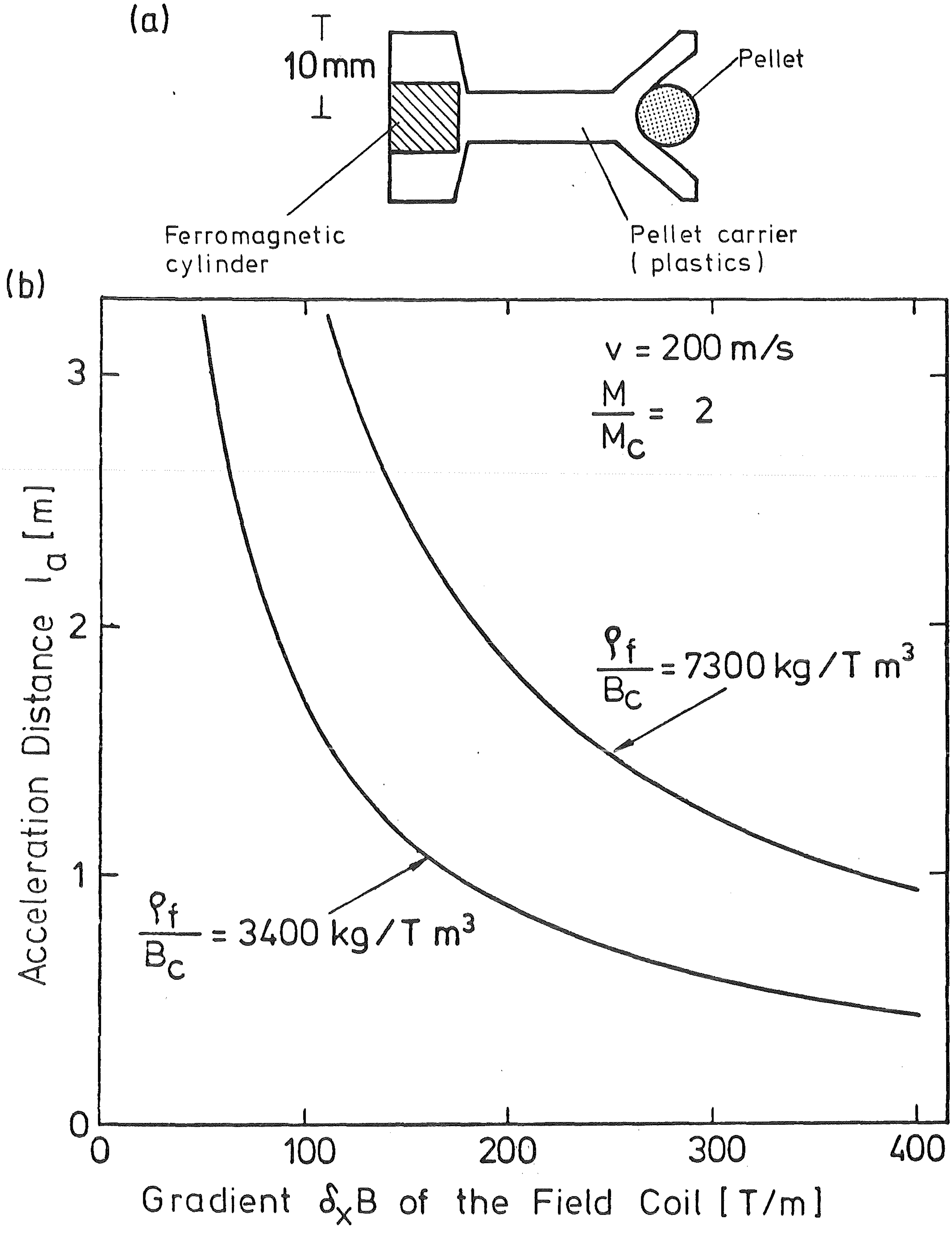


Fig. 7: Pellet acceleration by a magnetic linear accelerator:
(a) Sabot with a ferromagnetic driving body;
(b) Acceleration length in dependence on the mean effective gradient of the field coils.

Pellet velocity	v	200 m/s
Driving body:		
material		Permendur
density	ρ_f	8.3 g/cm³
saturation value of magnetic induction	B_c	2.45 T
cylinder radius	r_c	3.5 mm
cylinder length	l_c	7 mm
mass	M_c	2.25 g
Pellet carrier mass (material: plastic)	M_T	1.9 g
pellet mass	M_p	0.35 g
projectile mass	M	4.5 g
Ratio of projectile mass to driving body mass	M/M_c	2
Field coils:		
effective gradient of magnetic induction	$\delta_x B$	85 T/m
radius	r_f	1 cm
current intensity (to generate B_o)	I_f	19 kA
magnetic induction in the center of the coil	B_o	1.2 T
coil spacing		1 cm
number of coils		100
Acceleration distance	l_a	2 m
Time of acceleration	t_a	20 ms

<u>Table 4:</u> Reference parameter values for a projectile acceleration to 200 m/s by means of a cylindrical driving body made from Permendur

III.4 Injection System

One important advantage of a magnetic pellet injection system over a pneumatic system is the simple separation of sabot and pellet by means of magnetic deceleration of the sabot. This, moreover, implies an easy recovery scheme. The pellet continues to move uninfluenced and, at the end of the deceleration section, the sabot enters one cylindrical compartment of a sabot catcher which subsequently rotates, clearing the field for the next pellet, see Fig. 8.

The empty sabot is transported to a station in which its specifications are checked. Sabots with too high abrasion or other defects are sorted out; reusable sabots, on the other hand, are subjected to renewed cooling, are subsequently loaded with a pellet and are transported to the loading device of the magnetic accelerator.

The pellet passes through one channel of the neutron shield, which subsequently rotates in order to shield the pellet accelerator with its solid part.

III.5 Summary

The essential results, future tasks and open questions for the pellet acceleration by a magnetic linear accelerator using a sabot with ferromagnetic driving body are summarized in Table 5.

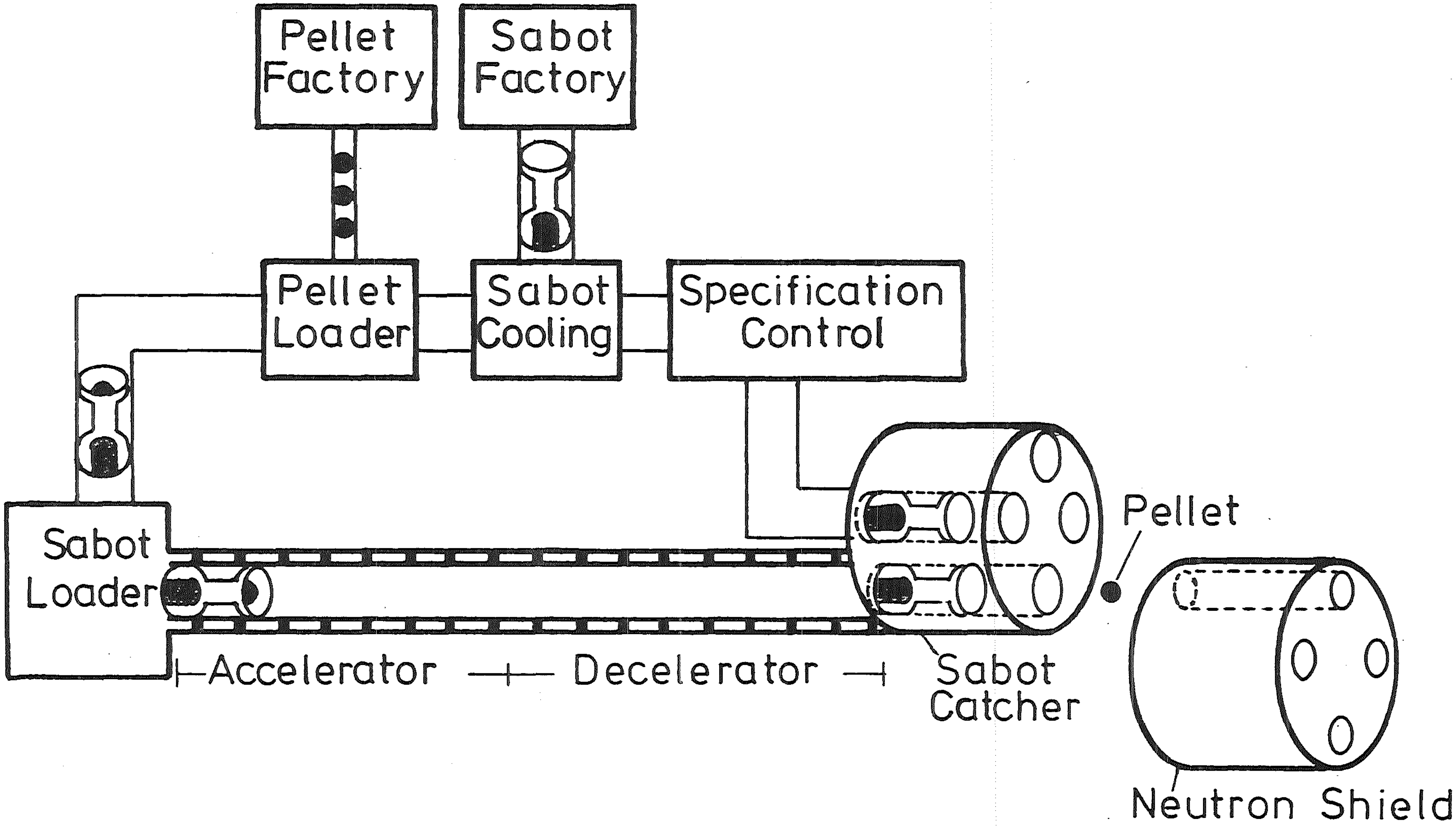


Fig. 8: Scheme of an electromagnetic pellet injection system

System Component of a Electromagnetic Pellet Injection System	Results and Design Proposals for HIBALL	Future Tasks, More Detailed Investigations
Magnetic linear accelerator	reference design for pellet acceleration: $l_a = 2$ m, $t_a = 20$ ms, field coils: radius and spacing = 1 cm $B_o = 1.2$ T, $\delta_x B = 85$ T/m	identification of the most suitable operation mode of the magnetic linac (travelling magnetic wave accelerator?)
Sabot	ferromagnetic cylinder as a driving body is most suitable because of the lowest technical expenditure, reference design: $M_c = 2.25$ g, $M = 4.5$ g, $B_c = 2.5$ T	more detailed sabot design: . material of pellet carrier and guide tube . shielding of the pellet from the magnetic field . re-utilization of the sabot

Table 5: Results and design proposals for an electromagnetic pellet injection system with a magnetic linear accelerator for HIBALL and general tasks for future investigations (meaning of the parameters see Table 4)

IV. Comparative Evaluation and Concluding Remarks

IV.1 Accelerator

The acceleration of a projectile with a mass of the order of 1 g to a velocity of 200 m/s (reference velocity of a HIBALL pellet) over a distance of 1 m is technically feasible for both the pneumatic and the magnetic acceleration / 1,2 /. Concerning the technical complexity a pneumatic accelerator needs less expenditure than a magnetic linear accelerator, whereas the latter is advantageous because of the well proved electromotor technology. Furthermore, a reliable continuous operation with about 10 hertz still has to be proved for the key component of a pneumatic accelerator namely the electromagnetically controlled gas valve. On the other hand, the most suitable operation mode still has to be identified for a magnetic linear accelerator.

For both accelerator types their capability of reproducing the pellet velocity and the trigger accuracy for starting the accelerator has to be investigated and tested. A high reproducibility of the pellet velocity, e.g. a relative accuracy of the order of 1 %, seems harder to be fulfilled by a pneumatic accelerator, first of all depending on the capabilities of the gas valves. On one hand the constraints from this requirement are tightly linked to the basic question of providing for a pellet flight correction behind the muzzle and, on the other hand, to the specific requirements on the schedule for the synchronization of the pellet with the ion pulse motion, which depends on the specific driver scenario; an example is given in / 1 /.

The guide tube must be held at a sufficiently low temperature if a cryogenic pellet and sabot is used. Effective cooling to dissipate frictional heat must be provided. Concerning the pneumatic acceleration the pressure within the guide tube must be reduced to a sufficiently low level after each shot in contrast to the magnetic case where the pressure of the accelerator tube has only to be held at a constant level.

IV.2 Sabot

Although there are, for both methods, first proposals for a sabot which realize their main tasks, namely the straight guidance of the pellet and its protection from mechanical destruction and from frictional heat during the acceleration period, further detailed design work in combination with acceleration tests of sabot prototypes should be done.

To safe material a high re-utilization rate must be aimed which requires suitable material selection and design of the bearings of the sabot for its guiding (low abrasion rate). The sabot should effectively be protected from direct neutron irradiation, in order to guarantee a low activation rate per shot, because the total number of sabot re-utilizations is also limited by the total activation level of the sabot material.

A general problem is the effect of the sabot detachment (recoil forces) on the pellet motion. The angular spread of the bare pellet behind the accelerator muzzle is the decisive criterium for the necessity or renunciation of an active pellet guidance (pellet flight correction). Generally, the detachment and the recovery of the sabot is more complex for the pneumatic pellet injection, see Section II.3.2. Here we have a clear advantage for the magnetic method with its open sabot because of no disadvantageous interaction with a guide tube gas. A magnetic decelerator can be used for the stopping of the sabot resulting in a single recovery mechanism for the sabot, see Section III.4.

IV.3 Other System Components

Concerning the application for a fusion reactor with a heavy ion driver a principal but not disqualifying disadvantage of the pneumatic pellet injection compared to the magnetic one is the necessity of coupling a high pressure system, the gas gun, with an evacuated reactor cavity. But a buffer cavity between both systems can be provided and designed in such a way that the influx of an untolerable quantity of propellant gas into the reactor cavity is avoided, see Section II.4 and / 1 /.

Independently of the method of pellet acceleration the injection system must guarantee an effective neutron shielding, e. g. by a rotating neutron shield as sketched in Fig. 8.

If a sabot re-utilization is intended an installation must be provided where the specifications of the sabots are controlled. In the case of an injection system using cryogenic pellets an additional installation for the cooling of the sabot is necessary before being loaded with pellets. Last but not least suitable devices for the loading of the accelerator with a sabot must be designed for the specific accelerator types.

IV.4 Conclusion

It is confirmed that no fatal physical or technical disadvantage excludes one of the two investigated pellet acceleration methods. Both can be recommended for the application of pellet injection into inertial confinement fusion reactor chambers but none of them is clearly superior to the other. There are several technical problems still to be solved, in particular, with respect to a reliable continuous operation of the pellet accelerator and the sabot design which have finally to be investigated by an experimental program.

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