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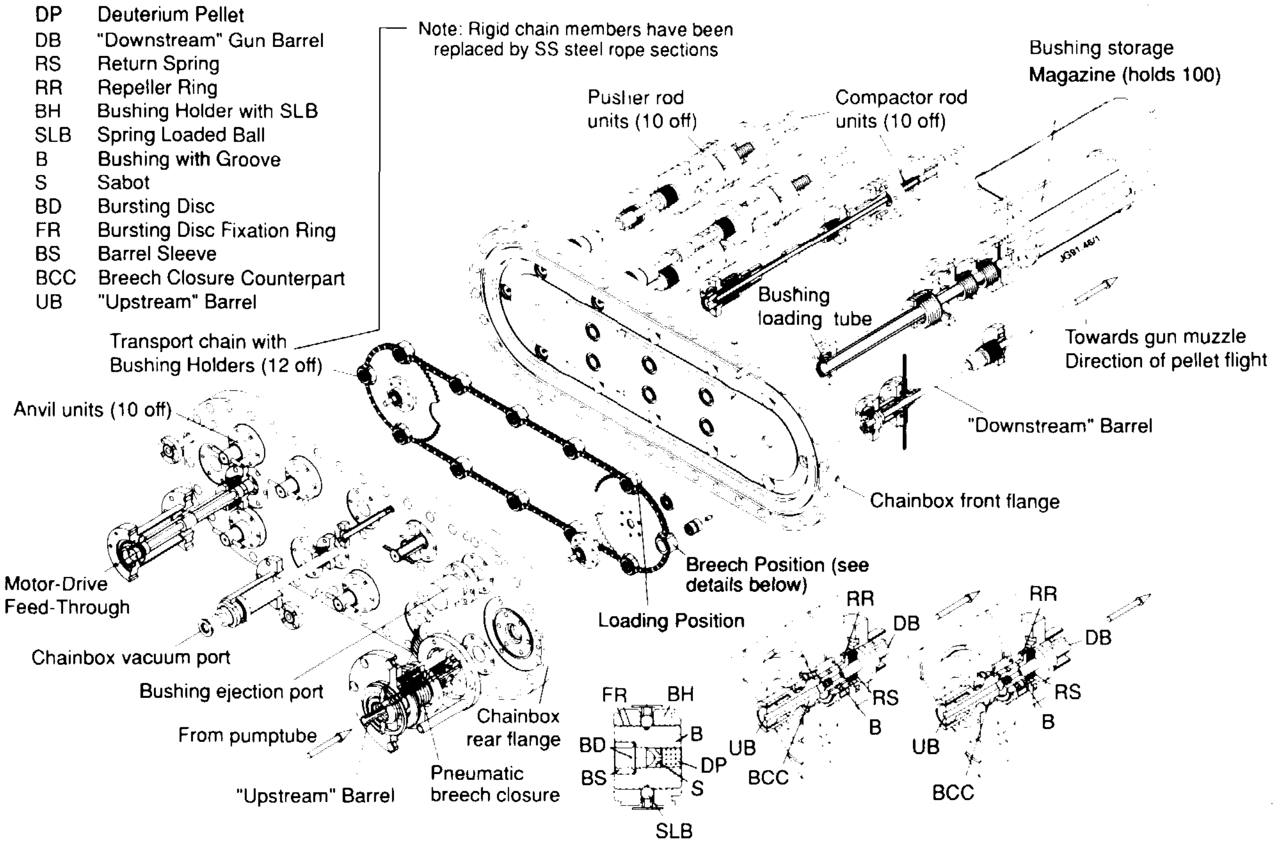

a) Bushing in Holder b) Breech Open c) Breech Closed

Exploded View of the Cryostat Cold Box of the JET High-Speed Pellet Launcher

FIGURE 2

the pusher rods against the anvils that forms the coldest part of the system (6-9 K), bushings can be cooled to such temperatures that deuterium gas being introduced through the hollow pusher rod shafts will condense in the free space in the bushing in front of the sabot. This procedure requires the cold box to go through a temperature cycle and therefore an entire batch of bushings (up to 10) needs to be filled simultaneously - sufficient in number to last an experimental session. Compactor rods concentric to the pusher rods permit the mechanical compacting of the ice should that be necessary. After formation of the pellet one bushing can be moved into the insufficiently cooled (around 80 K) breech (ca 8 s transient time) from which the pellet after pneumatic closure of the breech ca .1 s before firing can be shot. This procedure is a race against time since pellets cannot long withstand this thermally hostile environment. During the shot the breech is kept close by metal seal/gap action (ca 10^4 N force added by a similar contribution from the two-stage gun action on the upstream barrel end that is freely inserted into the compression head of the gun. The leak tightness requirements of the breech under the 2000 bar surge and the subsequent two-stage gun pump-down in order to warrant the required storage vacuum and temperature for the remaining pellets (near 10^{-6} mbar and not greater than 6 K) with only limited pumping access (around 1 l/s) are very demanding. In addition, the closure of the breech requires to provide the perfect (within .02 mm) alignment of the downstream barrel and the bushing in the (quite brutal) clamping action in order not to jeopardise the integrity of pellet and sabot during the acceleration. This was achieved by conical self-alignment of bushing and barrel but can only be guaranteed if the initial positioning of the bushing by the "chain" is within about .05 mm. Part of last year's work was concerned with this problem: the initial transport chain with rigid members was not sufficiently accurate to warrant this second condition and the hunting of tolerances moreover lead finally to even a deterioration of the initially achieved positioning performance. A complete redesign of positioning (chain) wheels, the fixing of the breech near wheel in indexed position by a ratchet and the replacement of the rigid chain members by pieces of elastic steel rope have finally ensured the desired precision.

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PELLET INJECTOR TECHNOLOGY AT JET

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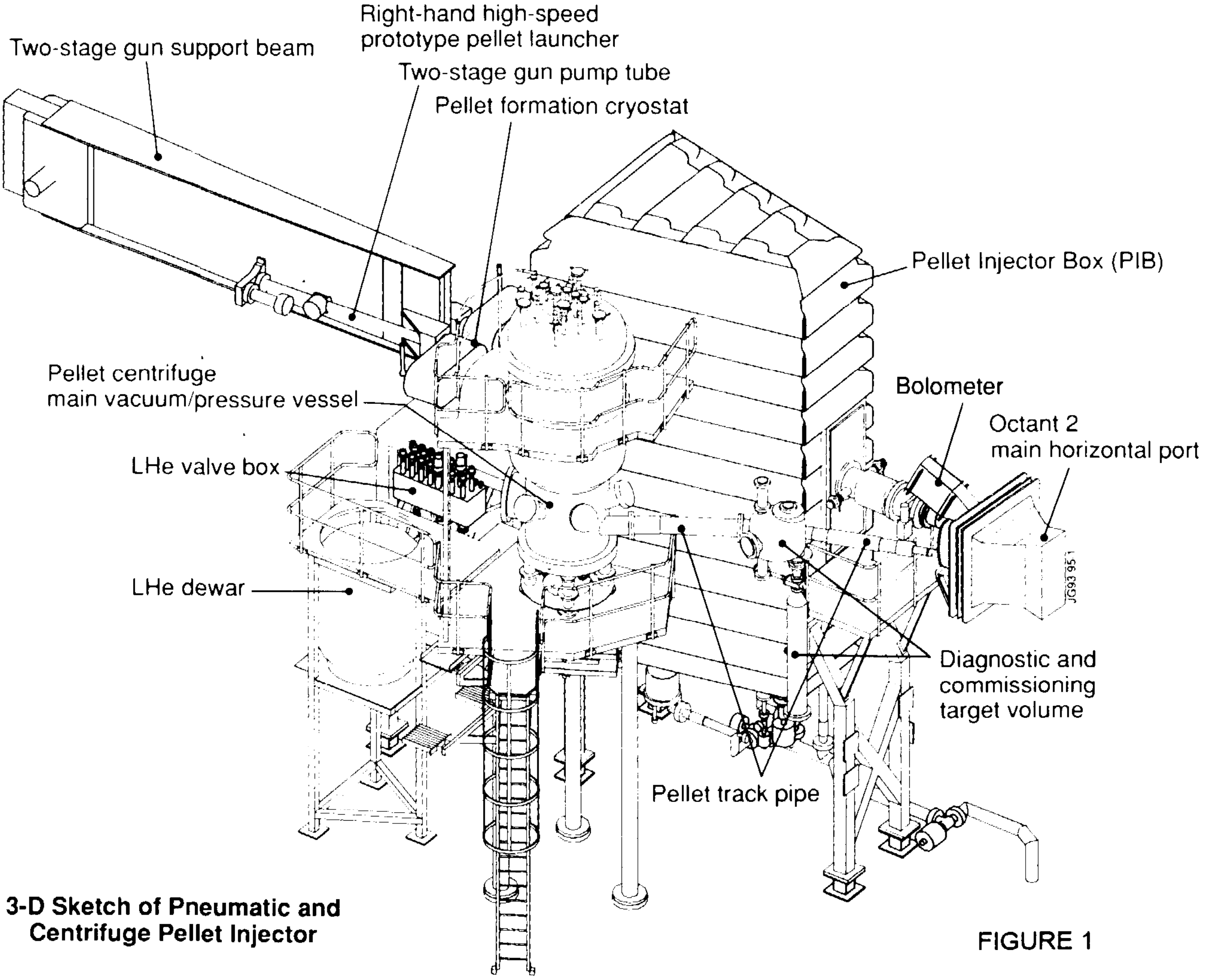
1. INTRODUCTION

The pneumatic repetitive ORNL (Oak Ridge National Laboratory) pellet launcher, which combined with the JET torus vacuum interface using the PIB (pellet injector box) formed the JET pellet injector since 1987, has been returned to the US in the first half of 1992. The majority of pellet experiments at JET so far have been carried out with this combination and a brief description and additional references can be found in [1]. Since 1985 JET has driven the development of high-speed launchers for preferentially deep deposition of fuel and has attempted to employ on the JET machine a practical trial single-pellet launcher (dubbed the PROTOTYPE and described in the following), simultaneously advancing a repetitive universal high-speed launcher (dubbed the Advanced Pellet Launcher or APL) for use up to and inclusive of the Active Phase of JET. This latter device has been cancelled in early stage of its detailed design because of a combination of budgetary problems and vanishing interest in the deep fuelling issue; more information on its design can be found in [4]. Despite of stringent economy measures JET still plans to install for the next operational campaign in 1994 the pneumatic high-speed pellet launcher (now with reduced options) as well as high flow rate pellet centrifuge, an addition to complement the divertor pump now being installed at JET. For both of these pellet launchers of JET design the paper will give a short account of their features and status of preparation. The torus hall scenario of the two pellet injectors on the JET machine can be seen in the schematic of fig.1 below.



3-D Sketch of Pneumatic and Centrifuge Pellet Injector

FIGURE 1

2. THE HIGH-SPEED SINGLE-PELLET LAUNCHER

2.1 Introduction

The pneumatic high-speed launcher PROTOTYPE is a 6 mm deuterium single-pellet device - 1 shot per tokamak pulse, 10 prepared shots per experimental session, 100 shots without manual attendance for typically a week of operation - which is to accelerate pellets to about 4 km/s; preparation are also undertaken to convert the pellet size to 5 mm if the programme would make this desirable. The launcher, of which 2 independent units have been built, uses a two-stage gun with a 3 m long, 60 mm ID pump tube and ca 0.9 kg titanium piston and propels the deuterium pellets which are produced outside the breech in a pellet formation and storage cryostat by means of a 6 mm plastic sabot, a piston that is protecting the pellet from the hot driver gas. This sabot is composed from two halves which separate in flight from the pellet trajectory by aerodynamic means, this permits the two halves to be eliminated by a shear cone. The removal of sabot as well as the considerable amount of driver gas (ca 10 barl / shot) from the pellet trajectory to the torus is managed by the PIB of 50 m^3 volume with its 8.10^6 l/s LHe cryo-condensation pump. The launcher, a testbed version of which had proven the used principles some years ago [e.g. 2], was to have operated on JET in the previous operational periods but due to design and development difficulties with the cryostat, which is the most delicate part of the launcher, the completion of commissioning was delayed. Its objectives are:

1. Deep or central injection of clean fuel, for the investigation of particle and energy transport issues, and for the extension of the performance of the PEP mode.
2. The scaling of penetration depth with speed to permit predictions for hotter plasmas and ITER.

2.2 Main Design Features

The high-speed pneumatic launcher consists of a two-stage light gas gun for the generation of the hot driver gas pulse and a pellet formation and storage cryostat covering the entire breech region of the barrel some 300 mm downstream from the exit nozzle of the two-stage gun pump tube. The pump tube is about 3 m long and 60 mm ID, from high-strength martensitic steel and works with a 0.9 kg titanium piston. On release of high-pressure gas (up to 200 bar) from a 3.5 l reservoir to the back of the piston, the latter compresses during the run towards the nozzle of the pump tube the foreland gas, which is being injected in front of it (ca 10 l of hydrogen at about 1 bar), to a level of 2000 bar in the nozzle and barrel breech region for times in the order of 2 milliseconds. The pressure builds up at the breech is controlled by a bursting disc in the breech (here about 300 bar bursting pressure) in the back of the deuterium pellet and the pellet starts with the bursting of this disc. Second-stage driver gas not being able to escape through the barrel in the shortness of time acts as cushion to the piston and leads to a dampened oscillation for the piston permitting its further use.

The heart of the cryostat is a cold box, operating at near LHe temperature, which embraces the breech region of the barrel; it is in turn surrounded by a guard vacuum vessel providing the thermal isolation vacuum. No LN_2 supplementary cooling is used in the design. The interior of the cold box is presented in an explosion view in fig. 2. The basic principle consists of a transport and storage system in cold environment in the form of a kind of chain with 12 equally distanced positions along its length in which bushings can be inserted in holders. Bushings are in essence short ca 22 mm long barrel sections, made from CuCr as a compromise with regard to thermal conductance and mechanical strength, which are preloaded with a bursting disc and a sabot. A sabot is a short plastic piston found to be necessary to shield the deuterium pellet during acceleration from the deteriorating influence of the hot driver gas for pellet velocities exceeding considerably about 3 km/s as was shown in the early pellet launcher experiments at the Ernst-Mach-Institut EMI, one of the early supporters of the JET development. Bursting discs are made from fully annealed stainless steel foil (ca 0.15 mm thick), cut into shape and being engraved by a central 8-beamed star for pre-determined rupture pattern by photo-etching. Sabots, composed from two interlinking (to take up shear forces during acceleration) halves of equal mass, are made by low cost precision-extruding of high-pressure poly-ethylene and -propylene (the better performance still to be evaluated) instead of by very expensively machining vespel (poly-imide) as was the case in the early testbed trials. A partial cavity in the back of the sabot provides the transverse gas dynamic forces which are to split the sabot when leaving the barrel and deflects the flight path of its halves sufficiently from the pellet trajectory to permit removal by shear cone techniques.

Ten bushings can be sequentially loaded in one batch into the transport chain in either warm or cold conditions from the magazine by indexing the chain. By pressing the bushings in their correct positions with

2.3 Accompanying Measures in Torus Hall and Commissioning Status

The adaptation of the launcher-torus interface, usually referred to as PIB services, for the acceptance of the launcher had been completed for previous campaigns but with the centre of the divertor plasma high against the mid plane of the torus by around 300 mm the fast pellet trajectory needed to be raised by a corresponding amount to permit central deposition. Therefore, PIB and two-stage gun support steelwork were raised accordingly and the octant 2 main horizontal port flange cover had to be modified.

The two-stage guns of the two launchers are commissioned and working so far to their specifications on the testbed: apart from the piston start position indication, that is currently being improved, there is no known weakness to be eliminated; single pistons have been used for more than 300 shots and usually are lost by accident in the shooting sequence, not by wear and tear.

The difficulties, which have been encountered in the lengthy commissioning, have indeed been almost all with the cryostat in which the inherent incompatibility of a high pressure, high energy content, high mechanical strength two-stage gun and barrel system (1-2000 bar, 300-3000 K) are to be matched with the cold box storage vacuum requirements (10^{-6} mbar, < 20 K) and basic thin-wall filigree cryogenic design. The first cryostat is in integral commissioning, i.e. all its subsystems are complying with their requirements; breech tightness has been demonstrated. At the time of writing this report, all measures to improve the precision of accurately aligning bushings with the upstream and downstream barrel ends and to ensure the further self-alignment during breech closure have been carried out and are proven to work so far in warm shooting. Cold (i.e. under LHe cooling) firing is being currently carried out with sabots only, to be closely followed by firing of cryo-condensed deuterium pellets. Formerly, successful attempts had been made to condense the correct amount of deuterium expected from the voids of the bushings to be filled with no noticeable condensed deuterium anywhere else (uninhibited mobility of movable mechanical parts).

The nature of the very complex formation and shooting procedure has it that success is only documented if and when finally in-flight photographs of good quality pellets are taken together with the (destructive) foot prints of pellets and sabot halves on the target. Although the manufacture of the two prototype cryostats is completed the assembly status of the second one lags behind the first one by a couple of weeks because modifications enforced by the commissioning work on the first one have to be carried over to the second one. Measures to provide the exchange parts (barrels, bushings and sabots) for the change from 6 mm to 5 mm pellets to be decided in time before the experimental campaign have been prepared.

3. THE PELLET CENTRIFUGE

3.1 Introduction

The pellet centrifuge, which is an expanded version of a similar device built at IPP Garching for ASDEX Upgrade, is to provide in its final version a quasi-continuous flow of 2 and 3 mm deuterium ice cube pellets at up to 40 s^{-1} (flow rates approaching 1000 mbar.l/s) for long pulses approaching 60 s at pellet speeds of 50 up to 600 m/s, with the capability of density feed-back operation. The range of pellet sizes and possible speeds covers a penetration depth variation by roughly a factor of 3.5 under the assumption of the NGS (Neutral Gas Shielding) model. In addition to the Garching design with its basic centrifuge rotor arm on top of a turbomolecular pump the JET centrifuge features a large ($>10^5$ l/s) cryopump in a volume enhanced vacuum tank (5 m^3) to cope with the higher pumping requirements of the larger gas loads at long pulses and an upgraded extruder design for the production of the much larger numbers of pellets. The experimental objective for the centrifuge are:

1. Fuelling the plasma with a source of deuterium particles at various depths beyond recycling layer and separatrix, thereby performing experiments with minimum recycling and combined gas puffing flows into the divertor.
2. Investigate the plasma boundary created by pellet injection and/or gas puffing for comparing the corresponding impurity influx and impurity removal effects in conjunction with divertor parameters.
3. Providing an appropriate fuelling source for long pulses towards steady state conditions.

The above flow rate parameters, particularly integrated over long pulses, are needed for continuous fuelling at high efficiency for a divertor with high pumping capability. It is felt that initially more modest parameters will be sufficient to match the experimental scenarios for the next divertor and that this will permit to reduce the requirement for the first stage of extruder design and therefore the corresponding developmental risk. So, initially the string of pellets per tokamak pulse may be limited to about 40 and 60 pellets of 3 and 2 mm, respectively.

The centrifuge unit has to be compatible with the requirements for the Active Phase of JET, i.e. radiation, remote handling and tritium compatible; the latter requirements come from the notion that the deuterium, that will have to be provided by the JET tritium plant, will be contaminated by a non-removable fraction of tritium. Therefore, the centrifuge needs to be tritium compatible to the extent that tritium operation can be thought of if tritium extrusion is physically possible and once certain peripheral measures will have been implemented.

3.2 Main Design Features

A schematic of the centrifuge main unit is shown in fig. 3. Mounted into the vacuum vessel bottom flange is the mechanical pellet accelerator, a titanium rotor arm with stresses always lower as those of the corresponding Garching arm, mounted on top of a near standard turbomolecular pump rotor (Pfeiffer TPH 5000). Accelerated pellets will leave the rotor to the left of the figure, guided by an about 4 m long track (not shown here) to the torus. The pellets will be produced by extrusion from an extruder unit of which 4 can in principle be made to comply with the acceptance angle of the so called stop cylinder; the latter one is also a feature taken over from the Garching design ensuring that the starting position of the pellet chopped from the extruded ice is self-regulated by a rotor connected blade in the stationary stop cylinder in order to force the accelerated pellet onto the correct outlet trajectory towards the rotor arm grove.

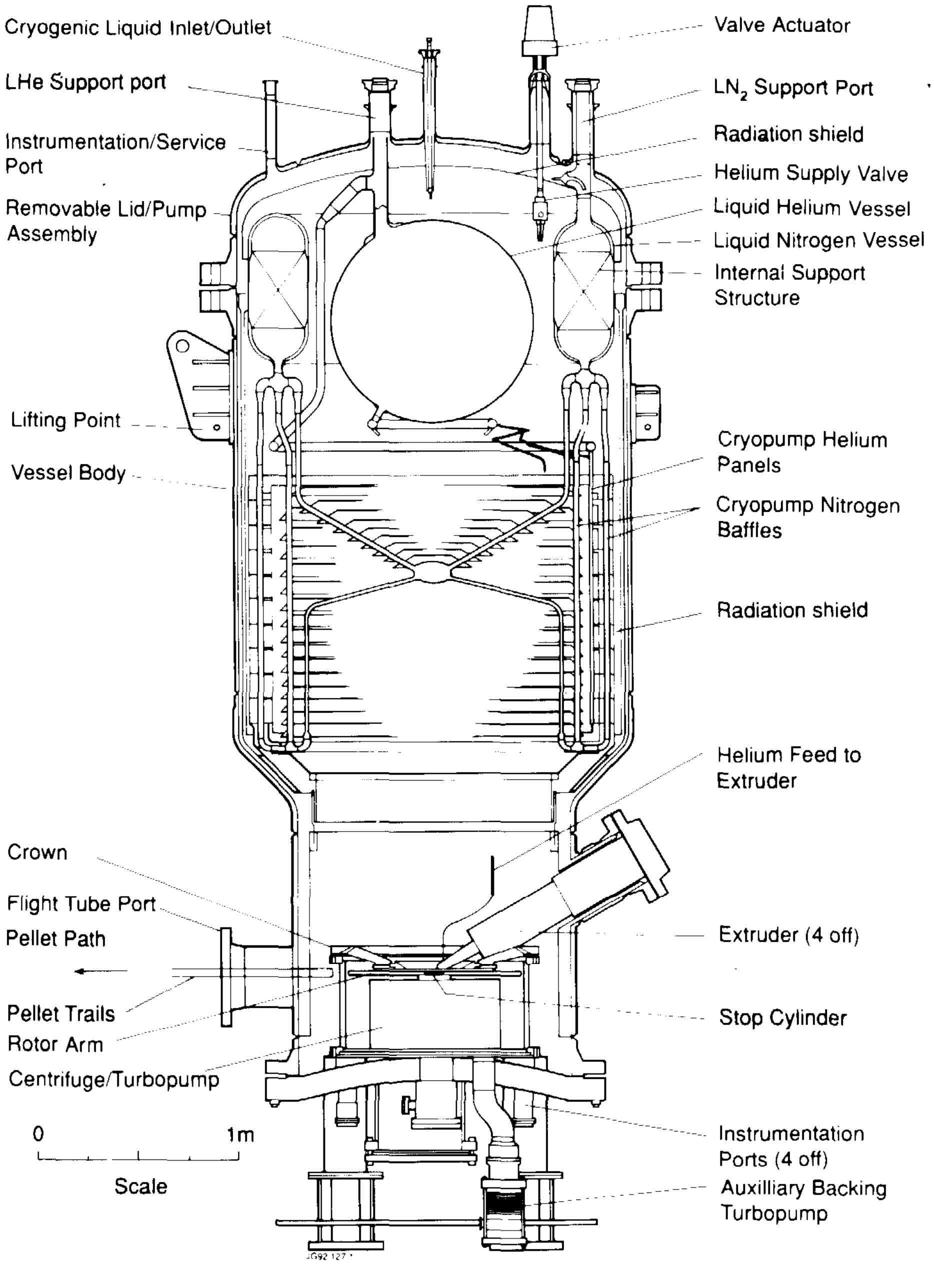


FIGURE 3

A large LHe cryo-condensation pump with LN_2 baffles provides adequate vacuum of lower than some 10^{-3} mbar needed for the operation of the TPH 5000 rotor and for the guard vacuum requirements for both pellets and extruders even at the highest of the expected loss flows from the pellet acceleration. The cryopump has been conceived in such a way that the centrifuge acceleration gas losses (due to pellet friction) are pumped upwards, the respective deuterium being condensed mainly on the inner cylinder formed by the LHe panels; the outer cylindrical side pumps the track losses via a ring gap in the baffle arrangement and keeps the vacuum there sufficiently low to avoid gas puffing into the torus and gas dynamic losses to the pellets. The local spherical LHe and toroidal LN_2 reservoirs provide coolants, that should last for at least one operational session and so permit to decouple the centrifuge unit sufficiently from coolant supply fluctuations generated by other systems.

The accumulated deuterium in the cryopump at the highest flow rates and pellet string lengths will be approaching the cryopump capacity (ca 2500 barl) for deuterium ice in a period of tokamak operation of roughly two days (possibly necessary centrifuge pellet conditioning not considered). According to JET hydrogen safety principles applied elsewhere, the 2500 barl in about 5 m^3 require the vacuum vessel to be a pressure vessel with a rating of 22 bar gauge to safely contain the worst accidental hydrogen/air mixture deflagration pressure in the event of an undetected air leak without the possibility of a (later) tritium escape. The design for vessel as well as the other components forming boundaries with the outside world has taken care of these requirements.

The extruder unit, of which fig. 4 shows a schematic, generates pellets by means of a piston that is being driven by a bellow-sealed hydraulic actuator and that extrudes deuterium ice at about 14 K, at which the ice solid state properties are favourable for extrusion, from a reservoir into a nozzle with a pellet typical cross section. At the end of the ca 180 mm long nozzle pellets will be chopped off the extruded ice rod with required rate by an electromagnetically driven chopper stud which forms a pellet that is then without further guidance dropped into the stop cylinder. According to the Garching experience the ice properties for cutting and acceleration are best at 7 K; the design therefore foresees a dynamic cooling of the deuterium ice during extrusion (at speeds of up to 160 mm/s) from 14 K at the nozzle entrance to 7 K at the exit; this is an area of operation outside known experience. Although extrapolations show that this is likely to succeed, a safe fall-back solution is the filling of the entire nozzle with extrudate and its static cool-down to 7 K: the number of pellets available then is limited by the available column length to be ca 40 to 60 pellets of 3 and 2 mm nominal dimension, respectively. This mode, which will require modest hardware changes against the final solution, will be used for the initial phase of operation; the full-blown commissioning can be subsequently attempted with mainly upgrading operational procedures.

Diagnostics for the monitoring of pellet parameters and their quality comprise microwave cavities for the mass measurement, light interrupters for speed measurement, stroboscopic camera monitoring the extrudate chopping process and in-flight flash photography of the accelerated pellets and an upgrade for the D_α light diagnostic, shared by the pneumatic launcher and giving an indication of the reception of the pellet by the plasma (e.g. penetration depth).

3.5 Status of Assembly

The centrifuge launcher is in an advanced state of procurement: delivery of major items of the core unit, i.e. the centrifuge rotor, the vacuum/pressure vessel and the components of the cryopump will all have been delivered in the coming months, somewhat late against their original contractual delivery date, so that their assembly on site can proceed towards a now projected completion in summer 93. Electrical and control installations for the torus hall have already been brought to near completion. The extruders, containing a higher degree of developmental features are being procured issuing many small high-tec manufacturing and treatment contracts; their design is complete. As was stated before, the upgrading of the performance from the initial limitation in total pellet numbers per tokamak pulse is largely a matter of adjustment of operational procedures. Some peripheral units, like the pellet track and the He return gas and deuterium pumping facilities, are trailing but they are not required at the start of commissioning and are therefore not expected to infringe with the goal of installing the centrifuge for operation in the torus hall for use in the experimental programme by the first half of 1994.

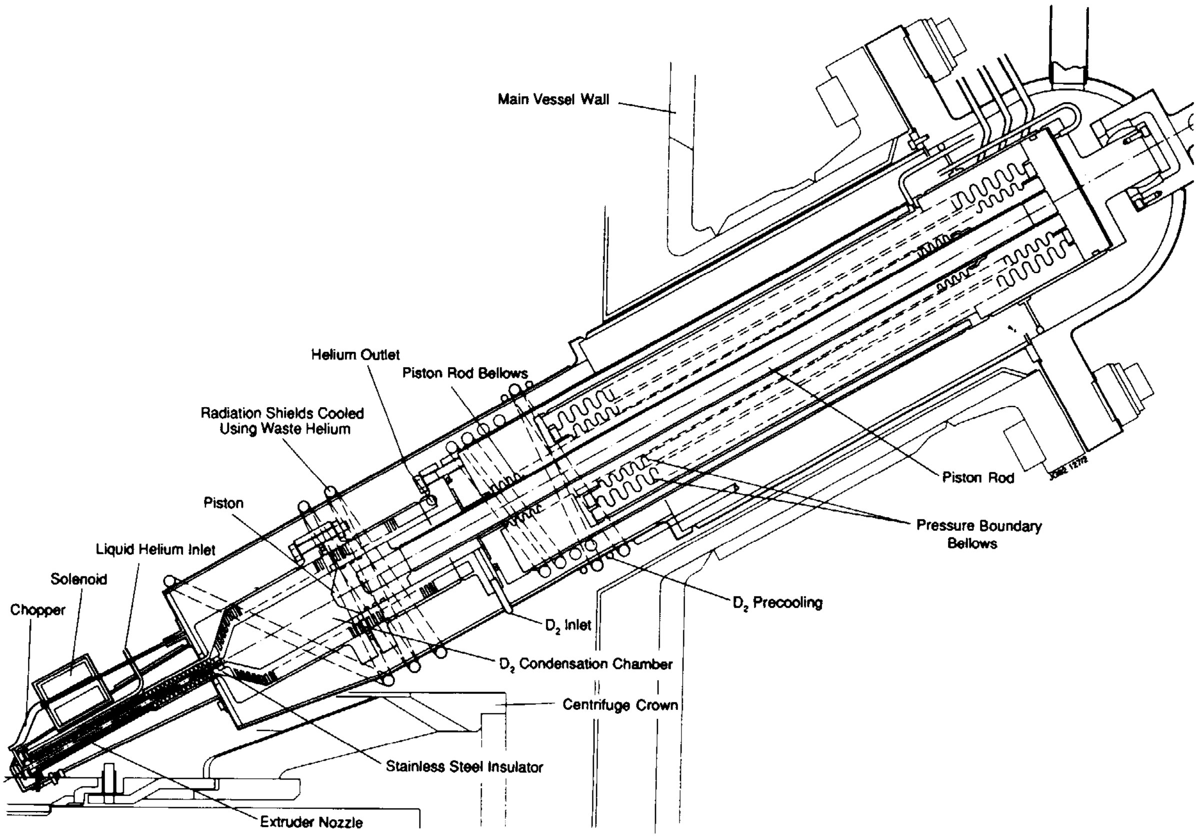
4. REFERENCES

[1] P.H. Kupschus et al., "The JET Multi-Pellet Injector and its Future Upgrades", Pellet Injection and Toroidal confinement, Proceedings of IAEA Technical Committee Meeting, Gut Ising, 24-26.10.1988, IAEA-TECDOC-534, 1989

[2] P.H. Kupschus et al., "Upgrading of the JET Pellet Injector by Employing a Two-Stage Light Gas Gun Prototype and Future Planning", Proc. 13th IEEE Sym[posium on Fusion Engineering, Knoxville, USA (1989), IEEE Cat No 89CH2820-9, Vol 2, pp 1293

[3] P.H. Kupschus et al., "The JET High-Speed Pellet Launcher Prototype - Development, Implementation and Operational Experience", Proc.16th Symposium on Fusion Technology (SOFT - 16), London, UK, (1990), Fusion Technology, North Holland, 1991, Vol 1, pp 268

[4] JET Annual Report 1991, Development & Future Plans, Pellet Injection, pp 167



JET High Through-put Deuterium Pellet Extruder

FIGURE 4