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ACCELERATOR FOR THE PRODUCTION OF VERY HIGH NEUTRON YIELDS OF 14 MeV*

J. B. HOURST**, M. ROCHE**, Is-sur-Tille

This paper describes an electrostatic, low-energy, high-current accelerator for the production of intense neutron flux (14 MeV). The accelerating voltage lies between 160 and 200 kV, and the total current is 200 mA. The DT reaction gives yields of 6×10^{11} ns^{-1} cm^{-2} for a neutron emission of 8×10^{12} ns^{-1} in the 4π. In order to obtain the dissipation of the power carried by the deuteron beam, with a density which may exceed 10 kW cm^{-2}, a 500 cm^2 tritiated titanium ring is deposited on the rotating target holder so that the diameter of the neutron source is smaller than 50 mm. In addition to giving the possibility of reducing to 1 mm the distance between the sample and the active surface, it thus makes it possible to obtain very intense yields. The device has been designed for an intensive operation, a special attention being given to the problem of breakdowns. Moreover, the rail-guided carriage mechanism allows the automatic changing of target holders.

УСКОРИТЕЛЬ ДЛЯ БОЛЬШОГО ВЫХОДА НЕЙТРОНОВ С ЭНЕРГИЕЙ 14 МэВ

В работе описан электростатический низкоэнергетический и высокочастотный ускоритель для получения интенсивного потока нейтронов (14 Мэв). Ускоряющее напряжение находится в пределах 160–200 кВ и полный ток равен 200 мА. Для $T(d, n)He^4$ *реакции имеется выход* 6.10^{12} $n.c^{-1}.cм^{-2}$ *при испускании нейтронов* 8.10^{12} $n.c^{-1}$ *в пространственном углу* 4π. Для рассеяния энергии дейтериевого пучка, плотность которой может превышать 10 кВт.см$^{-2}$, насыщенное тритием титановое кольцо площадью 500 см^2 напылено на вращающуюся мишень таким образом, что диаметр источника нейтронов меньше, чем 50 мм. Имеющаяся возможность довести расстояние между образцом и активной поверхностью до 1 мм позволяет получать выходы нейтронов большой интенсивности. Устройство сконструировано для эксплуатации в интенсивном режиме работы, специальное внимание уделено проблеме его выхода из строя. Кроме того, специальный управляемый механизм в виде каретки позволяет осуществлять автоматическую замену мишеней.

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** Commissariat a l'Energies Atomique, Centre d'Etudes de Valduc, B. P. 14, F-21120 IS-SUR--TILLE.

I. INTRODUCTION

For a number of years, there has been a need for very high 14 MeV neutron source in various uses such as neutron-therapy or studies of materials for the construction of future fusion reactors. After improving the technique of electrostatic accelerators as much as possible, we felt that we would not be able to overcome certain limits without dealing with a basic new conception of this kind of accelerators. In that sense the accelerating voltage of the deuteron flux was defined to be comprised between 160 and 200 kV, these values giving the best compromise between the problem of target cooling and the neutron emission: this means that, between those limits, we can obtain the greatest number of neutrons per kW dissipated in the target. The acceleration is achieved within a single, very short "gap", using an ultra-vacuum technique to treat both the electrodes and the chamber; this procedure has been used in order to limit the break-down rate as much as possible in the same way as this is required in case of intensive use.

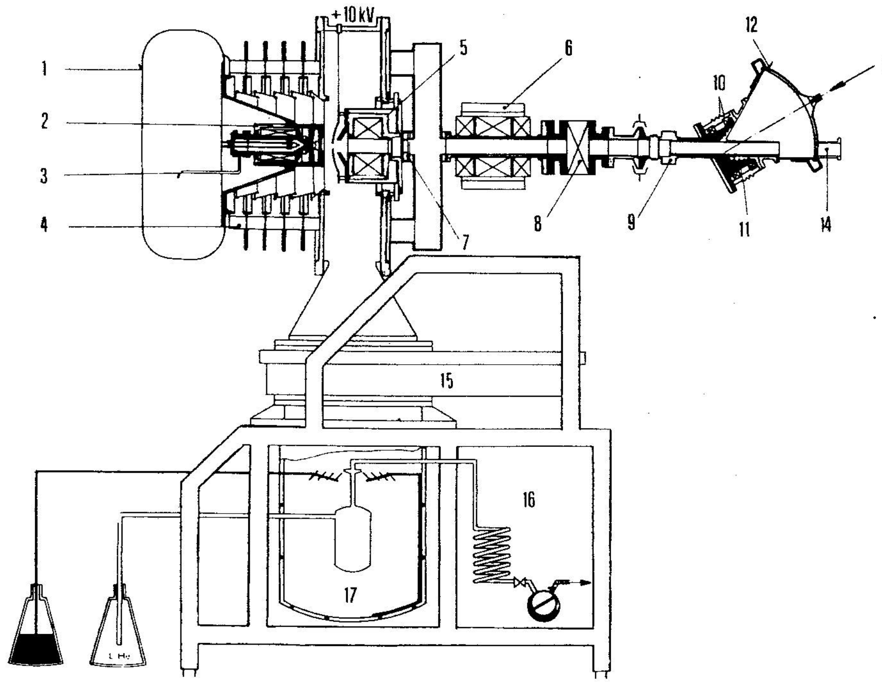

Fig. 1. Scheme of the accelerator LANCELOT. 1) Anticorona dome, 2) ion source, 3) deuterium inlet, 4) insulating column, 5) magnetic lens, 6) quadrupole triplet, 7) diaphragm, 8) valve, 9) cooled tube, 10) cooled rotating seals, 11) primary vacuum, 12) rotating target, 13) cooling target, 14) sample chamber, 15) valve, 16) helium cooled pumping circuit, 17) cryogene pump.

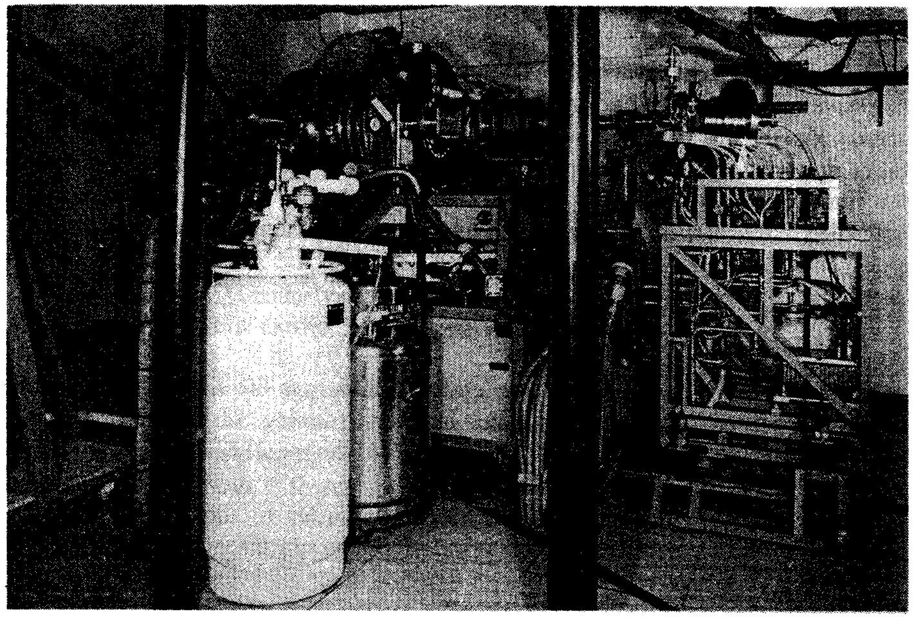

Fig. 2. General view of the accelerator LANCELOT.

Duoplasmatron was selected as ion source due to the necessity of obtaining routine ion currents over 200 mA with a very high proportion of monoatomic ions. Finally, the target configuration was selected as a function of the final aim, namely to obtain very high fluxes: this, firstly, presupposes that very high yields are achieved and, secondly, requires a favorable sample-target configuration (Fig. 1). To meet these requirements, a rotating target was selected. [1], [2], [3].

A very low breakdown rate, even at the maximum accelerating voltage (200 kV) made it possible to have this accelerator in routine operation for several years. Yields of 8×10^{12} ns^{-1} and fluxes of 6×10^{11} n $cm^{-2}s^{-1}$ are thus obtained on the target with an average life-time of 7 hours.

II. GENERAL CONFIGURATION

II.1. Cell

The LANCELOT accelerator is mounted in a 10 m × 7 m cell (Fig. 2). Next to it, another 3 m × 7 m room is used for changing tritiated targets. The thickness of the concrete walls and ceilings has been designed to ensure biological protection: the walls and the armoured door are 1.40 m thick, and the roof 50 cm plus 2 m of earth on it.

II.2. Ventilation

The relatively high quantity of tritium used (1000 curies per target) required intensive ventilation and personnel protection facilities. Both the accelerator rooms are equipped with a ventilation system capable of completely renewing the air five times per hour under normal conditions, with a possibility to do it contamination ten times per hour in case of contaminaion.

Furthermore, a special, compressed-air network is connected to air-masks for emergencies in case of light contamination.

II.3. Target carriers (Fig. 3)

In the present operation of the accelerator, the average life-time of the tritiated target is 7 hours. After the accelerator has been running for over 7 hours, the activation level of the target and the components of the target carrier are very high: about 20 Rems at 5 cm from the impact of the beam. It is therefore necessary to wait a few days before changing the target. In order to increase the rate of operation of the accelerator, a system was designed to run three consecutive or not consecutive 7 hours irradiations with no personal intervention close to the accelerator. This system is made of 3 similar carriages on which the target holders are mounted and all the equipment necessary for their operation. The carriages can

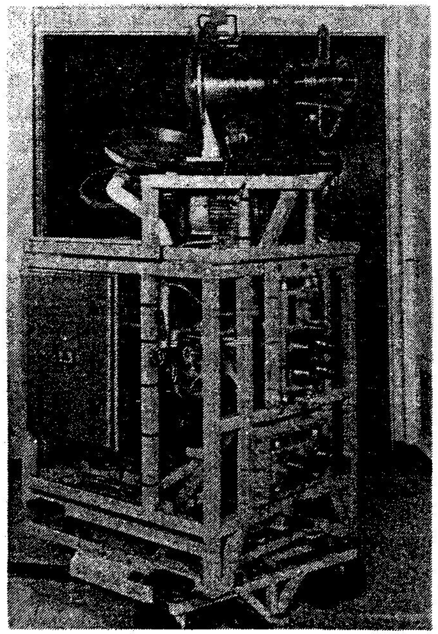

Fig. 3. Target carrier.

be moved inside the cell; they are guided on a rail on the ground and controlled from the control room.

Moreover, their front side is equipped with connected seals (vacuum flange, fluids connectors) for an automatic conection with the accelerator.

II.4. Experimental facilities

II.4.1. Under test system carriage

Acarriage, moving similarly as the target holder, is used to bring the system to be irradiated closer to or farther from the target.

II.4.2. Pneumatic transport

A pneumatic transport system is used to carry a sample forward and withdraw it very quickly (in about 3 seconds after the end of the irradiation.

III. ACCELERATOR DESIGN

III.1. General principle

The deuterons are extracted from the plasma in the expansion cup of a duoplasmatron source. The plasma is therefore in direct contact with the accelerating field, this field is axially distributed according to the potential obtained with Pierce electrodes geometry. Assuming a non saturated emission:

$$V = \frac{3^{4/3} \times 2^{-1/3}}{4} \left(\frac{4\pi J}{\varepsilon_0}\right)^{2/3} \left(\frac{e}{m}\right)^{-1/3} x^{4/3}$$

J being the current density.

The electrode shape was designed [4] by numerical computation, in order to reach a parallel and large diameter beam at the outlet of the accelerating field so as to minimize the problems of beam transport. Moreover, it presupposes that the surface of the plasma bubble remains perfectly plane; However, this is certainly not the case here since a display of the beam in the accelerator gap (visualisation of the recombinations) shows a rather obvious convergence at low currents. This can only be eliminated, with an increased current, for accelerating voltages below 80 kV. It appears that, the lower the convergence, the better the transport output. The convergence could be reduced increasing the 135° angle of the electrode-anode.

It should be noted, however, that this effect minimizes the „sprikling" of the electrode-cathode hole, which makes it possible to avoid breakdowns and compensates for the lens-hole effect resulting from the impossibility of suddenly connecting the $X^{4/3}$ potential of the accelerating area with the constant potential in the slide tube.

The current densities J for a deuteron beam, assuming a plane plasma bubble, are given by the following formulas:

$$J = \frac{3.82 \times 10^{-8} V^{3/2}}{d^2}$$

or

$$J = 2.39 \times 10^{-8} \frac{E^2_{max}}{V_0}$$

expressed in MKSA units, d being the distance between the electrodes as measured from their axes.

With $d = 3$ cm, and $V = 150$ kV, we have $J = 0.247$ Acm^{-2}.

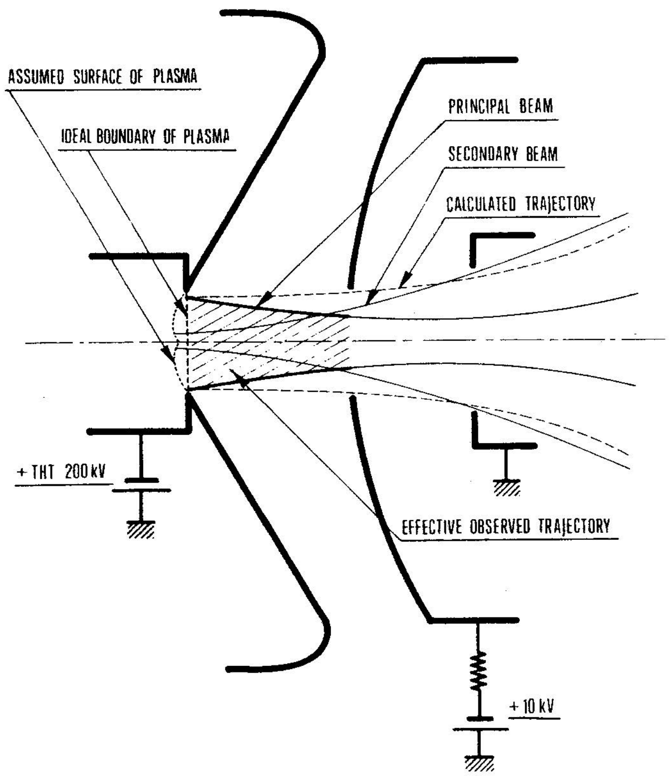

Fig. 4. Beam trajectories.

The presence of a residual magnetic field in the expansion cup causes the plasma to be confined on the axis, thus creating a prominence of the plasma bubble on the axis [6]: this creates a highly divergent secondary beam affecting the transport output. (Fig. 4).

A crucial problem is the trapping of secondary electrons going upwards in the accelerating gap due to the potential well resulting from the space charge of the beam. Solving this problem is essential since it affects the electrode-anode behaviour and, moreover, it has a significant effect on the conditions of beam focalization. Indeed, it appears these conditions are optimal when the trapping potential is maintained at a limit level under which the electrons will reach the accelerating gap. This can be explained by the space charge in the "cross-over" section which is located immediately behind the extraction electrode (cathode) and can be depleted as a function of the voltage applied to it. Obviously, in the case of a low voltage, the electrons penetrate the "cross-over" section in depth, which decreases the beam divergence. Fig. 5 shows various configurations of lines of field [6] for an accelerated current of 100 mA at 150 keV. Fig. (a) shows the trap open, due to insufficient polarization. In Fig. (b), the polarization is 1 800 V and reaches nearly the closing limit. In Fig. (c), the trap is completely closed to electrons with an energy below 100 eV. It is difficult to assess the temperature of the electrons with an energy below the potential well are to be found in the beam, which may be 480 V, for example, for a 50 mm Ø, 100 mA beam of 150 keV deuterons. A 2 280 V trap voltage is therefore necessary to prevent all electrons from passing through, but in that case the low-energy electron cloud is too far remote from the "cross-over" to achieve a satisfactory neutralization of the cross-over section. A compromise must thus be found. Experimental results confirm the computed

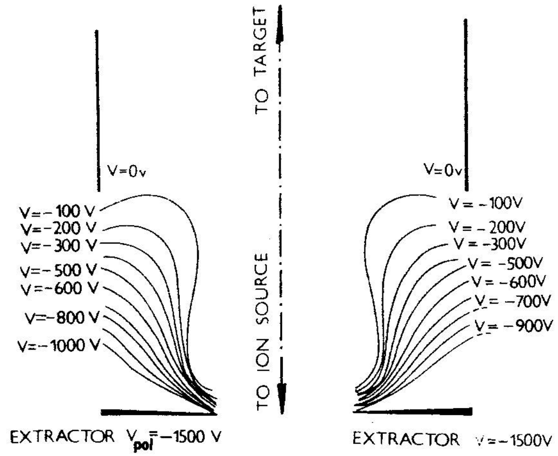

Fig. 5. Various configurations of lines of field.

trap values. The trap supply problem should also be stressed since a constant voltage has to be maintained on the electrode most of the time; it must still allow rapid potential changes to disconnect the avalanche mechanisms, which are a possible source of breakdowns. In the latter case, it should be able to withstand the discharge of the high voltage power supply capacity.

Selecting a very short "gap" has a favourable effect on the acceleration of high intensity currents since very high fields are opposed to the transversal and longitudinal effects of the space charge. This, however, raises the technological problem of maintaining fields up to 70—100 kV cm^{-1}. It was therefore necessary to select [5] very carefully polished and cleaned titanium electrodes and a vacuum chamber of an ultrahigh vacuum type.

III.2. Ion source

It is a "duoplasmatron" type source (Fig. 6). This type of source was improved to routinely maintain continuous 25 A arc current. During the trial period, the source was proved to withstand 60 A continuous. This was achieved, on the one hand, through the development of a new cathode type, a so-called "oven-cathode" in which the emission results from indirectly heated oxides and, on the other hand, by

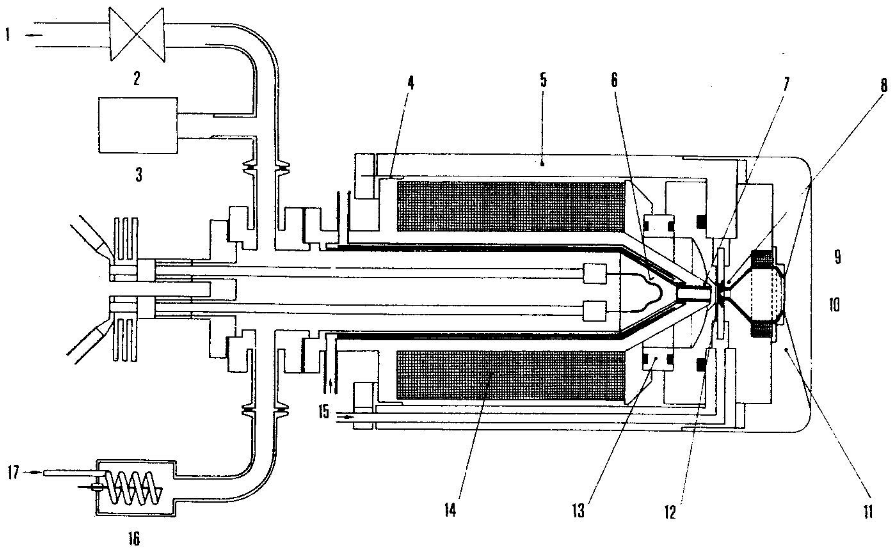

Fig. 6. Duoplasmatron scheme. 1) vacuum, 2) valve, 3) vacuum gauge, 4) gap, 5) magnetic circuit, 6) cathode, 7) intermediate electrode, 8) external pole, 9) expansion cup coil, 10) expansion cup, 11) accelerating electrode, 12) anode gap, 13) alumina insulator, 14) main magnet coil, 15) water, 16) pressure control, 17) deuterium.

the strong cooling of parts heated by the arc (anode hole, intermediate electrode hole, ...). High arc currents were aimed at, in order to achieve not only high currents but very high rates of atomic ions as well, which is a favourable condition for the beam transport with magnetic focalization and for the life-time of the targets. The plasma coming out of the anode expands in a cup, the walls of which are covered with aluminum to prevent any recombination [7]. The optical qualities

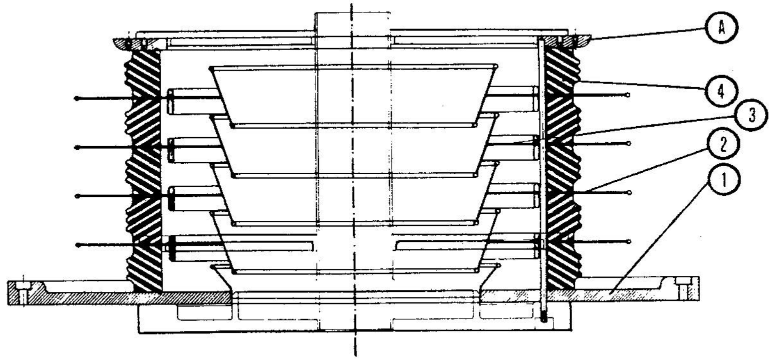

Fig. 7. Accelerating tube scheme.

of the beam are thus improved. Experiments with a longitudinal magnetic field in this cup have shown a substantially increased current to the detriment of the optical qualities of the beam, with a decrease in its transmission output. This solution has therefore been abandoned.

The 25 A continuous operating cathodes [8] have an approximate lifetime of 300 hours. On the test-bench, this source yielded 600 mA with a 50 A arc current over long periods. It is routinely used with a 200 mA yield of deuterons.

III.3. Accelerating tube

Fig. 7 shows the design of the accelerating tube. It is composed of a base plate fitted on the main body of the accelerator, with five HV porcelain rings, of a 500 mm inside diameter. Between the rings are inserted stainless steel plates; finally, a plate is included, holding the ion source. The whole system is glued with araldite. An indium seal is fitted between the araldite layer and the inner part of the tube to prevent any araldite outgassing. (Fig. 8).

Several, 120 MΩ resistors are installed between each plate in order to scatter the potential along the whole tube.

An outer plastic envelope covers the tube, with a slight freon overpressure, to prevent discharges.

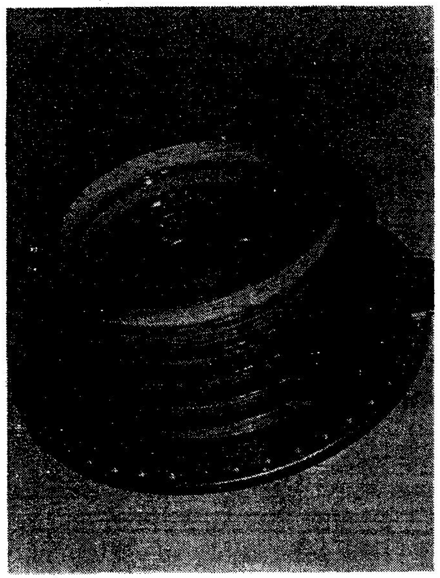

Fig. 8. Accelerating tube.

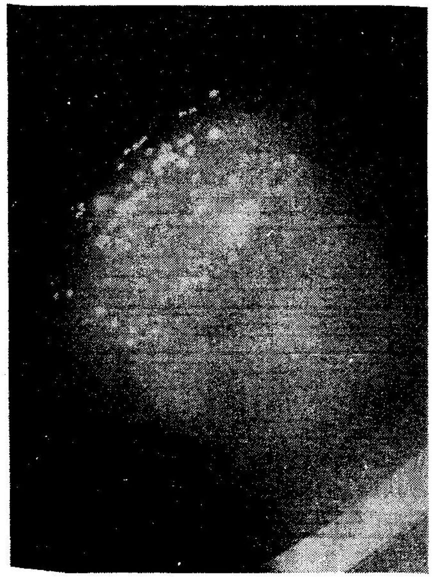

Fig. 9. Beam impact on a neutral target.

III.4. Beam focalization

Various conditions require a 2 m transport of the beam before reaching the target on which it should be focused on a 5 cm Ø spot. A focusing system should therefore compensate for the natural divergence of the beam. Assuming that the space charge is not neutralized, a series of calculations shows that it is nearly impossible to solve the problem. Fortunately, the interaction of the beam with the residual gas in the tube is an electron source which, when added to the electron source produced by the secondary electrons from the target, is sufficient to fill with „cold electrons" the potential well created by the beam and therefore to greatly reduce it. Thus the focusing can be first insured with a 77 000 AT lens with a 40 mm Ø central hole, fitted immediately behind the extraction electrode. This gives a 1 tesla axial field on a 20 cm length. The focal distance for the atomic deuterons is given by the following formula:

$$\frac{d}{f}=\frac{1}{1.78\times 10^{8}}\frac{(NI)^{2}}{V} \quad \text{in MKSA}$$

with V being the acceleration voltage and d the lens diameter.

The beam then passes through a quadrupole triplet with magnetic focusing.

The advantage of the magnetic focusing is that there is no breakdown problem in contrast to the electrostatic focusing.

Another advantage is that it makes a mass selection of the beam ions: this is advantageous at low energies, when molecular deuterons yield few neutrons while uselessly heating the targets, thus decreasing their lifetime, This, however, may be a drawback when an operation with a mixed $D+T$ beam is desired.

Fig. 9 shows a photograph of the beam impact on a dead copper target. The figure shows bright, very heated spots and so the nonhomogeneous repartition of the beam; this is probably due to an unstable plasma beam leading to a filament-type structure. This remains when the beam is swept in the shape of sinewave by magnetic deflection. This would tend to prove that the phenomenon is connected with the local characteristics of the target dealing with the secondary emisssion of electrons. The emission level is higher on the hot spots and this causes the beam to be locally neutralized; it locally increases its density which, in turn, increases the spot temperature. It was noted that the bright spots had very high stability and that the only way of changing their location was to momentarily switch the beam off.

It may be assumed that the phenomenon no longer exists with a rotating target; however, no observation could be made in that case.

III.5. Rotating target

Two principal reasons have lead to choose a rotating target: (i) the smallest source (here 50 mm in diameter), (ii) a temperature of the tritiated slice as low as possible to avoid outgassing of the contained tritium.

Still with the aim of maximalizing the fluence densities, the target was designed in such a way that the sample could be located as close as possible to the active surface. This distance could be reduced down to 1 mm.

The major problem concerns the rotating seal, which has to meet the following requirements: to allow a higher rotation speed, to offer room enough for the beam to pass it through (80 mm Ø for example), to insure sufficient tightness so that the pressure in the tube remains below 10^{-4} torr without polluting the chamber with hydrocarbon emission and, finally, to be strongly cooled.

The target (Fig. 10) is composed of a 1 mm thick, coldbeaten Cu baseplate in the shape of a portion of a sphere 1, the rotation of which is driven by a conical frustroom 2 within which the beam is propagated. The ring-shaped (R_{int} = 295 mm, R_{ext} = 345 mm), tritiated titanium deposit is 400 μg cm^{-2} thick and contains 1000 curies of tritium. Two high-precision rollerbearings 3 allow a vibration free, 1500 rpm rotation. The tightness is ensured through two plane seals 4 the fixed part of which is pushed by a jack 5 using the pressure of the seal cooling water. The cavity 6 between the seal is kept under primary vacuum thanks to a differential pumping, so that the leakage into the secondary chamber is negligible.

A cooled, electrically insulated tube 7 makes it possible to avoid any heating of the lateral walls of the cone 2 and provides for beam losses measurement.

The cooling water comes through pipes 9 and is centrifugated between 2 and 8. The cooling thus obtained is very efficient due to the high circulation speed of the water on the target.

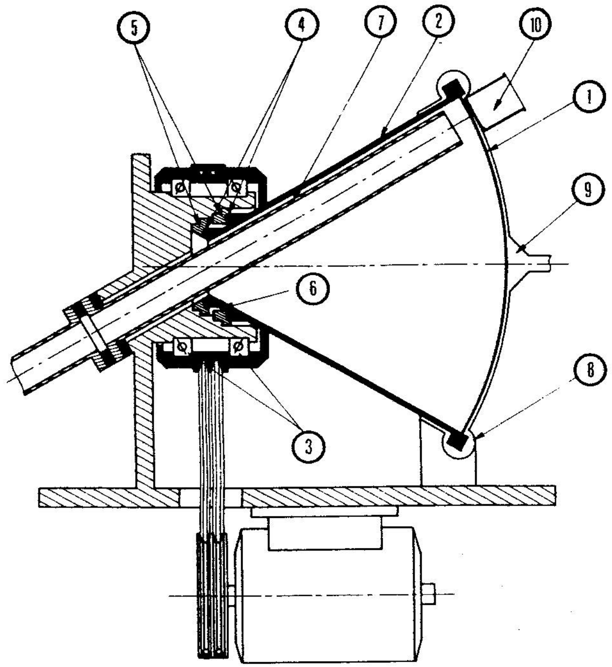

Fig. 10. Target carried scheme.

III.6. Pumping

The necessity of obtaining and maintaining a very clean (that is, hydrocarbon free) vacuum while taking into account the significant hydrogen leakage from the duoplasmtron (about 100 cm^3h^{-1} NTP) led to selecting the following system:

(i) primary pumping, either with a liquid nitrogen cooled, zeolith trap in the general case or with a dry pumping device allowing the recuperation of gases in the secondary pump.

(ii) secondary pumping: with an Air Liquide CM 500 cryogenic pump with

Table 1

Material used, according to the desired total integrated dose

Material	Fluence n cm^{-2}	Reaction
Al	$10^{13} < \Phi < 10^{14}$	$^{27}Al(n, \alpha)\,^{24}Na$
Ni	$10^{14} < \Phi < 10^{15}$	$^{58}Ni(n, p)\,^{58}Co$
Fe	$10^{15} < \Phi < 10^{16}$	$^{54}Fe(n, p)\,^{54}Mn$
Cu	$\Phi > 10^{16}$	$^{63}Cu(n, \alpha)\,^{60}Co$

a 10.000 ls^{-1} hydrogen output. The cryogenic pump is automatically supplied with liquid nitrogen from a 1200 liter tank and with helium from a 50 liter tank.

The liquid helium consuption is about 50 liter per week taking into account evaporation losses in the tanker, filling losses and considering the fact that the liquid to be pumped is hydrogen.

III.7. H V supply

The characteristics of this supply (HAEFFELY — 200 kV — 300 mA) are obtained through double wave rectifying after increasing the voltage through the transformer. The assembling of the rectifying device domposed of Si diodes was designed in such a way as to allow an easy removal an substitution. So that the HV supply, which is located in the accelerator cell, may degenerate in time and there must exist the possibility of changing the diodes rapidly.

The high voltage has a residual ondulation of about 12 %, which creates no difficulty with the beam acceleration and transport.

III.8. H V head

The various power supplies required by the ion source operation are relocated in a secondary HV head fitter on top of an insulation transformer (250 kV insulated, 6 kVA power). Tubes are used for all the electronics, this being required by the neutron environment. The power supply of the duoplasmatron arc is current regulated.

All necessary information related to source driving are transmitted to the mass potential through optical fibers. The power supplies are pneumatically controlled.

Special consideration was granted to protection against flash effects: ferrite rings are fitted on the supply cables to the source, which has greatly improved the reliability of the whole system.

IV. MONITORING

Two fission chambers (U 238 and Np), located at different distances, give monitoring indications when the irradiated samples are sufficiently far from the target to get an homogenous flux. If the sample under test is placed close to the target, activation detectors are fixed on the sample. Table 1 gives the material used, according to the desired total integrated dose.

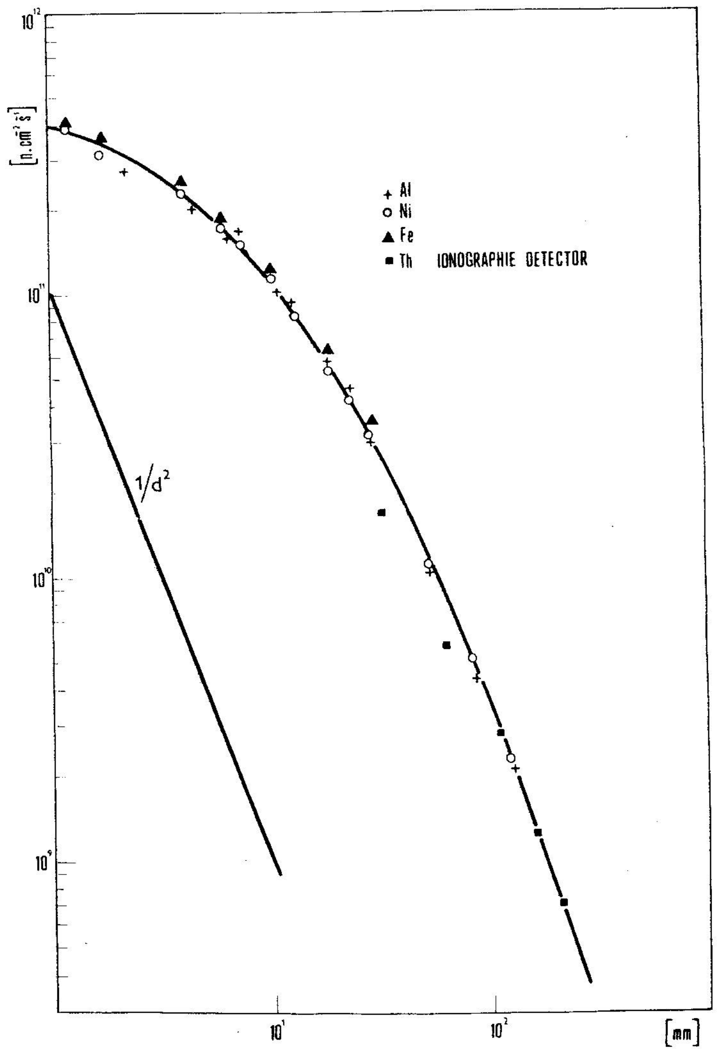

Fig. 11. Yield decreasing as a function of the distance.

V. RESULTS AND PERFORMANCE

V.1. Electrical operation

A routine operation of the accelerator over a period of more than a year has give the following performances: Accelerating voltage 160 kV; accelerated current 160 mA; target current 110 mA; extraction electrode current 1 mA; arc current 25 A; gas pressure 133 Pa; breakdown rate 0 to 0.3 shot per hour.

Experiment have been made to increase the present performance and the following results have been obtained over short durations: Maximum voltage 200 kV; maximum current 180 mA; breakdown rate ~2 shot per hour.

V.2. Neutron perfomances

Neutron emission: 8×10^{12} ns^{-1} at the target beginning, 1 to 1.5×10^{12} ns^{-1} at the target end. Half life-time: 3 hours.

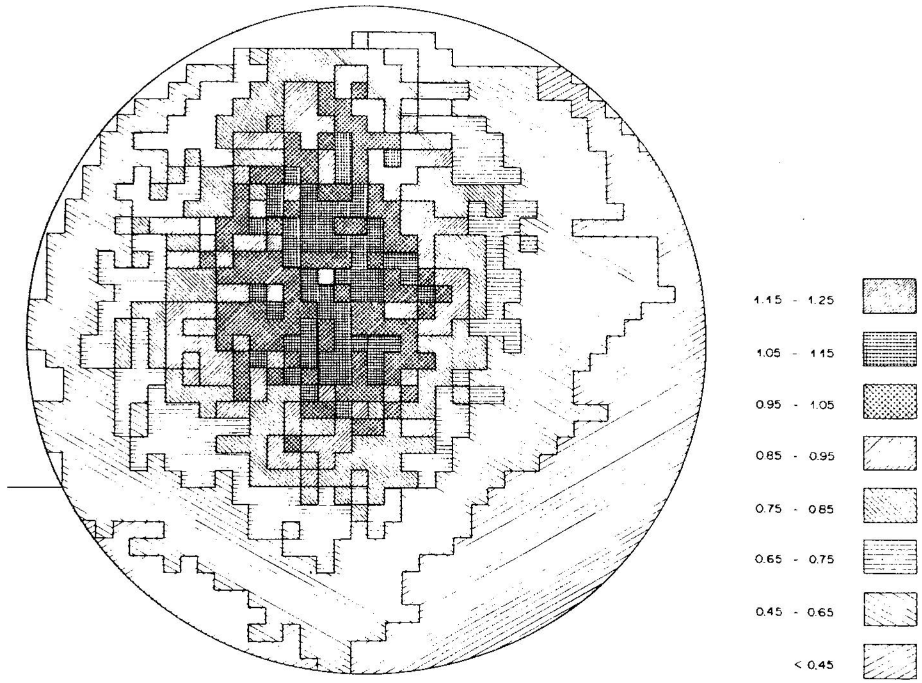

Fig. 12. Isoflux map at a distance from the target $d = 1$ mm. Track detectors with Th^{232} of the diameter 50 mm have been used for this map.

V.3. Dosimetric results: [9]

The dosimetric results concern: (i) the dose rate versus the axial distance from the target (Fig. 11), (ii) the iradiation homogenity near the target (Fig. 12) and far from it.

The different methods used are: (i) the activation method: in the present work. Al has been used, with a 0.118 barn cross-section for the $^{27}Al(n, \alpha)\,^{24}Na$ reaction. (ii) the fission chamber method: two kinds of fission chambers have been used: U^{238} and Np^{237}. These chambers are mounted on a remote controlled device, allowing the distance to vary with a good precision. (iii) track detectors: in order to measure the flux homogeneity in the test volume, we use Th track detectors. Since the example given in Fig. 12 the homogeneity has been improved, thanks to a magnet sweeping the beam on the target.

VI. CONCLUSION

With the present performances, the LANCELOT accelerator allows many irradiation experiments.

Nevertheless, we think it is possible to improve perceptibly these reuslts. Efforts are to be spent principally on the targets to enhance their life-time: this can be obtained by increasing the titanium layer from 400 $\mu g\ cm^{-2}$ to 10 $mg\ cm^{-2}$.

On the other hand, it was proved that the accelerator could work with a D, T beam. Recent experiments have been made in this respect. So, with a 160 mA accelerated beam, we have obtained 80 mA on the target. The neutron emission has been $3 \times 10^{12}\ ns^{-1}$ for several hours. But there are many additional problems caused by the manipulation of tritium: extraction from the pump, cleaning and re-injection into the ion source.

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