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INHOUD **SOMMAIRE**

Annales de l'Association Belge de Radioprotection, vol. 12, n° 4 (1987)

PROVISIONS FOR THE RADIOACTIVE OPERATION OF THE JET EXPERIMENT*

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SUMMARY.

The JET experiment has been designed to permit the investigation of plasmas with conditions such that the central region is dominated by fusion heating. There are major physics uncertainties concerning the behaviour of impurities and instabilities which will govern whether or not it is in fact possible to reach these conditions and it is the main aim of the planned experimental programme to resolve these uncertainties. The design of the apparatus, its diagnostic equipment, its buildings and the provision for remote handling, however, are all such that extensive experiments on a fully self sustaining D-T plasma can be safely undertaken if the necessary plasma conditions can be attained.

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* This paper was presented to the ANS Meeting held in Washington DC, November 1982.

Nuclear Fusion Research aims to make available a new energy resource for mankind. This energy is released when isotopes of hydrogen fuse to form helium. The process occurs naturally in the centre of the sun and similar very high temperature conditions are necessary to release fusion energy on earth. The most accessible reaction and the one which will be employed in the first fusion experiments is

$$ {}^{2}_{1}D + {}^{3}_{1}T \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n $$

$$ (3.52\ \text{MeV}) + (14.06\ \text{MeV}) \qquad (1) $$

The production of power by this reaction is thus inevitably associated with the production of a large number of neutrons, furthermore the hot reacting material (a tenuous fully ionized gas known as a plasma) necessarily emits a large flux of soft X rays and non-thermal behaviour in the plasma often gives rise to intense hard X ray production.

The JET Experiment

JET is a major European nuclear fusion experiment now in an advanced stage of construction on a site near the Culham Laboratory in England. The project is a joint venture of 11 European nations and the European Atomic Energy Community (EURATOM). The primary objective of JET is to bridge the gap between present experiments and a fusion reactor by obtaining and studying a plasma in conditions and with dimensions approaching those needed in a reactor. JET is a large tokamak device, the apparatus is illustrated in Fig. 1. It consists essentially of a vacuum vessel, a toroidal field magnet, a transformer and its primary coils. The conducting plasma which forms a toroid within a toroidal vacuum vessel acts as the secondary of the transformer. The field created by the plasma and the transformer coils is the poloidal field. The poloidal field system both drives the plasma current and provides its equilibrium. The D shaped plasma toroid has minor radii of -

1.25m x 2.1m and a major radius of 2.96. The iron transformer yoke is 12m high by 15m diameter, it weighs 2500 tonnes. The toroidal coils are supported against mechanical forces by a double walled toroidal shell outside the vacuum vessel. This shell is filled with borated concrete to provide an inner neutron shield.

The toroidal and poloidal field power supplies are a combined static and flywheel system. The two flywheel generators can supply 400MW and 2.6 GJ each while the static system supplied from the UK 400kV super grid has a capability of 600MW for 30s. The other major subsystems are the Neutral Beam and Radio-frequency (RF) Systems for plasma heating. These systems involve major construction programmes in themselves, requiring power handling systems with an input capacity of about 170 MW. The plasma systems are capable of driving a plasma current of up to 5MA for about 10s and the heating systems can provide similar pulse durations.

Programme and Radiation Levels

The project development plan foresees four phases in the operation of JET and these are summarised, with the purpose of each phase and the foreseen radiation levels, in Table 1. Planned dates and installed heating power are also indicated. It will be seen that initially there will be operation in hydrogen to establish the plasma conditions which can be obtained. and to assess various methods of heating the plasma. Next there will be a period of operation in deuterium while heating methods appropriate to that gas are explored and while neutron measurement techniques aimed at measuring the properties of a reacting plasma are developed. Finally if sufficiently promising results are obtained JET will be operated in deuterium-tritium mixtures to demonstrate reactor like conditions, if these conditions are obtained as many as 10^{24}, 14 MeV neutrons may be generated in a total of 10,000 discharges over a 2 year period. One advantage of this phased operation is that it enables the various radiation protection procedures to be established and validated at low radiation levels before proceeding to the ultimate high levels.

Design Provisions for Radioactive Operation

The JET assembly and buildings have been designed to permit the apparatus to operate safely at the highest radiation levels envisaged. Thus the apparatus has been designed to permit routine maintenance and repair by remote handling procedures and it stands within a biological shield designed to limit the exposure of JET staff to less than 100mRem/year and to reduce the level of radiation due to JET at the site boundary to less than the normal fluctuation in natural background levels. A difficulty in designing such a shield for a toroidal apparatus such as JET is that all the services and experimental measuring systems must have radial access to the load assembly. This problem is overcome in JET by providing a service basement and peripheral trench so that the main access routes are down the trench and across the basement and do not breach the shielding. This approach has proved so successful that there will be only about 6 penetrations (each < 0.2m diameter) of the radial and roof shield in JET, these penetrations will be provided with passive secondary shields.

The JET building configuration is designed to provide full protection against the following types of hazard at radiation levels corresponding to the maximum expected neutron production in D-T operation.

(i) Direct irradiation of people outside the torus hall by X-rays and neutrons generated during the discharge.

(ii) Activation of the air in the torus hall by neutrons produced during the discharge and the subsequent release of the active air.

(iii) Activation of ground water in the earth around and beneath the JET buildings.

(iv) Activation of the JET apparatus itself with the consequent release of γ-rays even when the discharge is not operating.

In order to contain these hazards and eliminate any effect on the general public, while reducing any risk to JET staff to levels similar to those encountered in normal safe occupations, the JET apparatus is built within a hall which is 35m x 35m x 25m high and has the following features.

(a) The walls are 2.8m thick concrete of which the inner 0.3m is borated concrete (0.7%B) up to 17 high and 2.5m (boron lined) above that height.

(b) The roof is 2.25m thick concrete with a 4cm thick borated lining (1.3%B).

(c) The main foundation floor is protected by a sub-floor above it. This sub-floor is 1m thick concrete with the top 0.24m borated (0.8%).

(d) The wall between the torus hall and the adjacent assembly hall is in fact divided into two walls, forming between them a radiation shielded test cell. The two walls together provide at least the total thickness given in (a).

(e) The Torus Hall is sealed and provided with air locks so that it can be held at a slight under pressure and so that the ventilation rate to the atmosphere can be held down to 2 air changes/day or less.

The effect of (a) and (b) is to ensure that direct radiation levels through the walls and by scattering in the air above the building (sky shine) are reduced to acceptably low values (22mRem/year at the radial wall and 62mRem/year average over the roof, 470mRem/year peak, both in the absence of penetrations).

The effect of (c) is to ensure that the irradiation of any ground water, which may have defeated the waterproof design of the foundation slab and so be seeping through it, is kept so low that no significant activation is carried by ground water; (in making this statement account is taken of the various holes that are necessary in the sub-floor).

The effect of (d) is to permit an air and radiation lock to be maintained when the crane is used to transfer material between Assembly Hall and Torus Hall. To this end the two separating walls have massive sliding doors to permit the crane to pass through each wall in turn. Crane access is permitted only when JET is not operating. Once a significant number of neutrons have been produced (say $> 10^{21}$) so that parts of the apparatus are activated, the doors in the two walls must not be opened simultaneously. Similarly when JET is operated, the two sets of doors must be closed, otherwise there would be a significant danger to any JET staff near the doors, and some small risk to any member of the public present at the site boundary in line with the doors. Conventional interlock schemes and operating procedures are reliable enough to ensure that JET is not operated with both doors open, so that this risk is eliminated.

The effect of (e) together with borated layers on the interior surfaces is to ensure that the activation level in the air ventilated from the Torus Hall is acceptably low (1200Ci/year N^{13} and 88Ci/year of Ar^{41}).

Two further hazards are to be guarded against. The first is that a CO_2 gas circulation system is provided in the double wall structure of the torus vacuum vessel for vacuum baking and cooling purposes. The circulator for this system is outside the shield wall. The 14 MeV neutron production will generate N^{16} by the 0^{16} (n,p)N^{16} reaction which with uninterrupted operation would give an unacceptable radiation level near the plant (1.5R/discharge). Consequently provision is made to reduce the CO_2 flow rate to a low value during and after the pulse so that advantage can be taken of the short half life of N^{16} (7.4s), this reduces the level near the plant to 32mR/year.

The remaining hazards are those associated with storage and handling of tritium which will be required on the JET site for Phase IV operation. The JET tritium system is being designed to contain these hazards to an acceptable level but is not yet finalised. The system is expected to comprise: a store for tritium gas, probably in 10λ bottles; a feed line to the gas injection system; pumps to exhaust used tritium from the vacuum vessel and a gas chromatograph isotope enrichment plant to permit recycling of used tritium. All parts of the system will either consist of all welded pipe work or be provided with secondary containment.

Extensive calculations have been made to assess the radiation and activation levels to be expected in the various parts of the JET complex, and results will be summarised in the oral presentation. In broad terms no access to the Torus Hall or Torus Basement will be possible during a discharge. Progressively as JET operates, activation will build up until restrictions on access to the Torus Hall are necessary even when JET is disabled. In D-T operation access to the basement will also be restricted and some restriction of access to the roof laboratory may be necessary to ensure that the dose to an individual does not exceed 100mRem/year in the presence of the planned penetrations and secondary shields. In all other areas the calculated dose is below 30mRem/year in full D-T operation, for instance in the control room it is only 10mRem/year or 2µRem/discharge.

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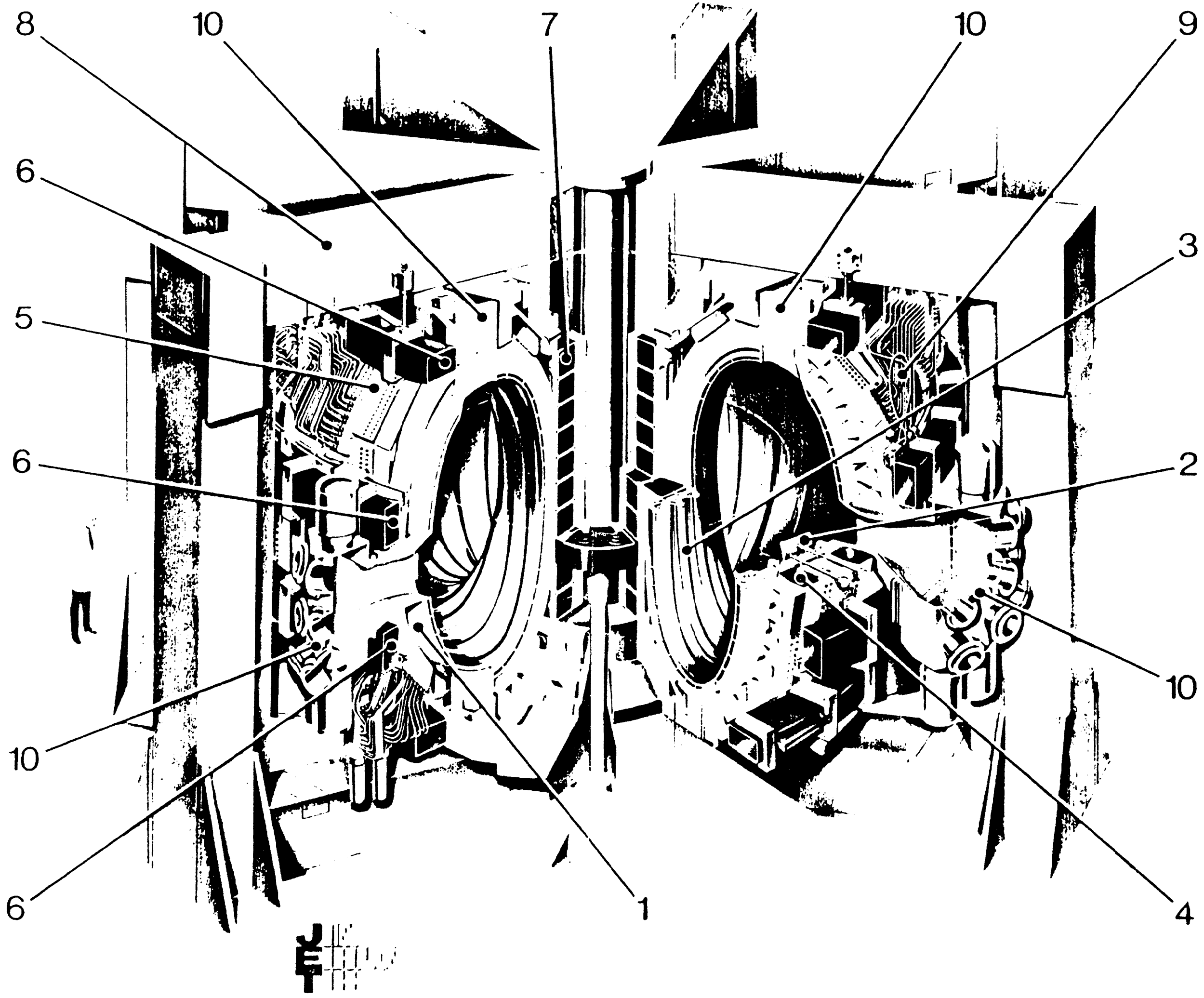

Fig. 1.

The JET apparatus

1. Vacuum vessel (double walled)
2. Material limiter defining the outer plasma edge
3. Poloidal protective shields to prevent the plasma touching the vessel
4. Toroidal field magnet of 32 D-shaped coils
5. Mechanical structure
6. Outer poloidal field coils
7. Inner poloidal field coils (primary or magnetising windings)
8. Iron magnetic circuit (core and eight return sections
9. Water and electrical connections for the toroidal field coils
10. Vertical and radial ports in the vacuum vessel.

Phases in the operation of JET

Phase	*Date*	*Heating Power (above ohmic)*	*Description*	*Objective*
I	mid 83	0	Commissioning initial operation ohmic only	Establish target plasma for heating
IIA	early 85 end 85	3MW 5MW	3MW ICRH 5MW 80keV (H) N.B.I. heating (~ 7MW total)	• Confinement Properties • Impurity control • n limits • compare with theory
IIB	1987	16MW	Progressively increase to 10MW 80keV (H) + 6MW ICRH (→12MW)	
IIIA	1988	19MW	Increase heating to full level including 10MW N.B.I. (14MW total) 160keV D for D—T plasma	• Establish limits to performance • Compare with theory • Decide if D—T is justified • Commission D—T systems
IIIB	1989	25MW	+ 15MW ICRH (30MW total)	
IV	1990's	25MW† + α-heating	D—T operation with α-heating dominant at least near axis.	• study approach to ignition • study plasmas with profile set by α-heating • find β limit in this system

† Total to plasma →> 35MW.

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Anticipated Radiation Level

The credible level is 5 x 10^{16} photoneutrons/year plus 500R/year of x-rays at a typical point in t torus hall. Levels up to 20 times this could occur in certain undesirable operating conditions.

10^{20} neutrons/year, may be produce in 1988, from 3,000 discharges. Later as operating experience improves the same number of neutr may be produced by as few as 200 discharges; if this is so, conditions will be right to procee to deuterium-tritium operation.

The minimum level for this type of operation to be worthwhile is ~5 x 10^{21} neutrons/year. The maximum credible level which will not be exceeded without formal discussion is 10^{24} neutrons in 2 years.

Table I.

RESUME.

L'expérience JET a été projetée en vue de permettre l'examen de plasmas comportant une région centrale à fusion thermique.
Il existe encore des incertitudes importantes concernant le comportement d'impuretés et d'instabilités qui ont un effet déterminant sur l'obtention de ce résultat et le but du programme de recherches est précisément de résoudre ces incertitudes.
La conception de l'instrument, son équipement diagnostique, son enceinte et ses possibilités de commande à distance sont tels que des expériences sur un plasma D-T auto-entretenu peuvent être entreprises en toute sécurité quand les caractéristiques nécessaires de plasma sont atteintes.

SAMENVATTING.

Het JET experiment werd opgesteld om plasmas, met thermische fusie in de centrale kern, te onderzoeken.
Er zijn nog belangrijke onzekerheden omtrent de gedraging van onzuiverheden en onstabiliteiten die bepalend zijn in het bereiken van het resultaat en het is dan ook het doel van ons onderzoeksprogramma deze onzekerheden op te heffen.
De opvatting van het toestel, de diagnostische uitrusting, de omheining in de voorziene afstandsbediening moeten uitgebreide experimenten op een zelf onderhoudend D-T plasma veilig toelaten zodra de nodige plasmavoorwaarden bereikt worden.

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Radiation Protection at the Neutrontherapy Facility at Louvain-la-Neuve

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6 nov. 1986

Abstract

The radiation hazards to the neutron therapy staff at Louvain-la-Neuve have been evaluated.

Dose equivalent levels were recorded in the treatment room during patient irradiation, for the p(65)+Be neutrons. Assuming a $Q = 10$, these levels amount up to 0.5 Sv.h^{-1} near to the patient, these are to be compared with absorbed dose levels equal to 15 Gy.h^{-1} at the peak depth in the patient. At the treatment room entrance they are reduced below 2-3 µSv.h^{-1} by means of a long maze. Q-values were determined at different locations of the facility with the use of a microdosimetry proportional counter.

Levels of induced radioactivity in the therapy room are reported and problems of radioactive contamination discussed. The whole-body dose equivalents to the neutron therapy staff are presented: although they are higher than for conventional radiotherapy, they remain far below the recommended dose limits.

Introduction

Associated with any fast neutron therapy facility are radiation hazards common with conventional radiotherapy and those which are specific to the use of neutrons. In particular, due to the high neutron energy, neutron induced radioactivity can be a matter of concern as an external and internal source of radiation to the personnel.

The hazards encountered by the staff will vary with their function. In general, medical staff (nurses and radiotherapists) will be exposed to external radiation due to the activation of the therapy equipment whilst the engineering and physics staff can be subject to both : external and internal radiation; the last one due to ingestion of radioactive material during maintenances.

Radiation protection data has been published at the neutron therapy facility at Hammersmith (Jones et al, 1971), at TAMVEC (Smathers et al, 1978) and at Edinburgh (Bonnet, 1983).

The neutron therapy facility at Louvain-la-Neuve

The cyclotron "CYCLONE" of the Catholic University of Louvain at Louvain-la-Neuve, was initially designed for physics experiments. In 1973 a neutron therapy program was decided and pretherapeutic irradiations were initiated. At present time the cyclotron runs 24 hours a day, 7 days a week and 10.4 % (rapport d'activité cyclone, 1984) of the machine time is dedicated for the neutron therapy program. This time is nearly equaly shared by radiation therapy and experimental work (dosimetry, microdosimetry, radiobiology,...).

Routine applications of neutron therapy started in 1978, 650 patients were treated at the end of 1985 (rapport d'activité cyclone, 1985).

A ground plan of the irradiation facilities, including both treatment rooms available is shown in figure 1. The first room, equiped with a vertical beam has been operational since 1978. In order to reduce dose equivalent levels at the control room a long entrance maze leads to the treatment room. A ground plan of this maze is shown in figure 2. Only data recorded in the first room will be presented. The second room, with a horizontal beam is constructed and is expected to be operational end 1987. A variable multi-leaf collimator is foreseen for the vertical beam.

Patient treatment was performed up to the end of 1981 with neutrons produced by bombarding a 10 mm thick Beryllium target with 50 MeV deuterons (d(50)+Be).

Since 1982 neutron beams for therapy are produced by bombarding a 17 mm thick Beryllium target with 65 MeV protons (p(65)+Be). In order to harden the neutron energy spectrum a 8.5 mm thick Carbon backstopper is used in combination with a 2 cm thick Polyethylene filter (Vynckier et al., 1983).

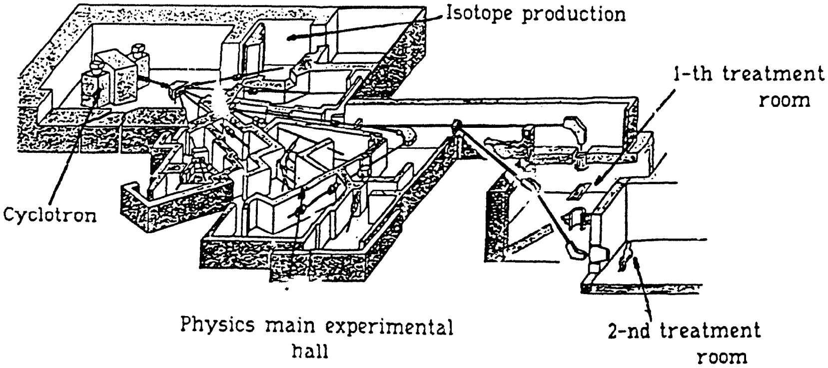

Figure 1: Ground-plan of the irradiation facilities at Louvain-la-Neuve.

Patient treatments are routinely performed with a proton beam current of 15 µA corresponding to a total dose rate of 25 cGy.min^{-1} at the peak depth in a phantom.

Collimation system consists of a fixed shield and a series of inserts (figure 3). For radiation protection purposes the Beryllium target, installed in a remotely handled brass support, is automatically removed out of the beam line after irradiation. This system allows at the same time the installation of two different targets (the former 10 mm thick Beryllium for 50 MeV deuterons and the 17 mm thick target for 65 MeV protons (Vynckier et al. ; 1983).

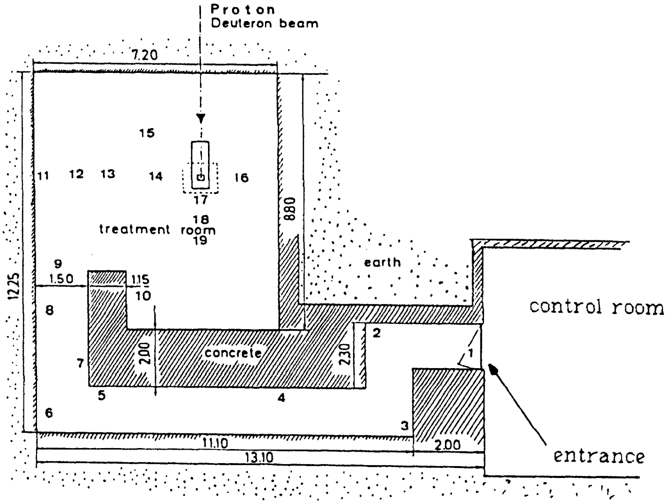

Figure 2 : Ground plan of the treatment room and entrance. The numbers correspond to the positions where the dose equivalent levels were recorded.

Induced radioactivity at the collimator after irradiation

It is obvious that at the end of the irradiations the main sources of induced activity will be located near the neutron production source, namely the target, the fixed part of the collimator and the inserts. For the evaluation of the build-up of the induced activity, therapy sessions were simulated. They consisted of repeated irradiations, separated by 10 minutes each, of 1Gy at a TSD of

162.5 cm and a depth of 10 cm in the phantom. The 10 minutes were chosen as a minimum time between two sessions. As a matter of fact, normal time between two sessions is longer and depends on the presence of the patients at the time of irradiation. The data presented here then correspond to a pessimistic view of the situation.

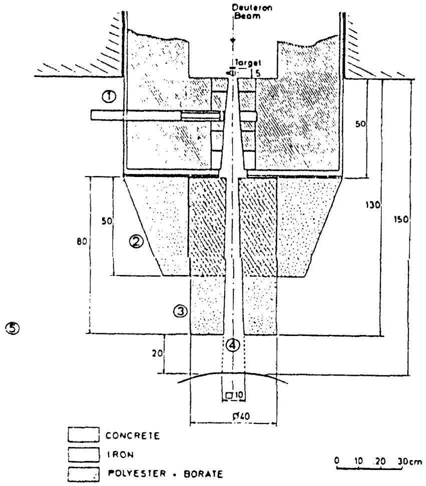

Figure 3. Schematic view of the vertical section of the collimator, including the position numbers where the absorbed dose due to the build-up of activation were recorded.

Dose rates were then recorded about 30 seconds (time necessary to enter) after each irradiation with a conventional 1 liter β-γ dose-rate meter at the points shown in figure 3.

The rapid build-up of dose rate due to activation is shown in Figure 4. Moreover, the advantage of withdrawing the target out of the beam axis, directly after irradiation, is clearly demonstrated. Indeed, after some irradiations, unacceptable dose rates up to about 7 mGy.h^{-1} are observed in the beam axis, with the irradiated target in position (point 4'). These dose rates are reduced by a factor of more than 10 with the target out of position (point 4). Futhermore, relative high dose rates are observed near the ceiling of the room (point 1), however these are reduced to an acceptable level (less than 200 µGy.h^{-1}) at a normal person height (point 2, 3 and 5).

Additional information was obtained by gamma spectrometry (using a 10 cm x 10 cm NaI crystal) of iron components of the collimator. The principal reactions dealing with short-live activation are believed to be $Fe^{54}(n,2n)Fe^{53}$ for Fe^{53} with$T_{1/2}$ = 8.5 min; $Fe^{56}(n,p)Mn^{56}$ and

$Mn^{55}(n,\gamma)Mn^{56}$ for Mn^{56} with $T_{1/2}$ = 155 min and $Mn^{55}(n,p)V^{52}$ and $Cr^{52}(n,p)V^{52}$ for V^{52} with $T_{1/2}$ = 3.8 min. As far as the long-live radionuclides are concerned, the $Fe^{54}(n,p)Mn^{54}$ reaction is dominating; $T_{1/2}$ for Mn^{54} is equal to 313 days. Studies are now undertaken, for the construction of the multi-leaf collimator, to minimize the influence of these elements by chosing the most appropriated iron composition.

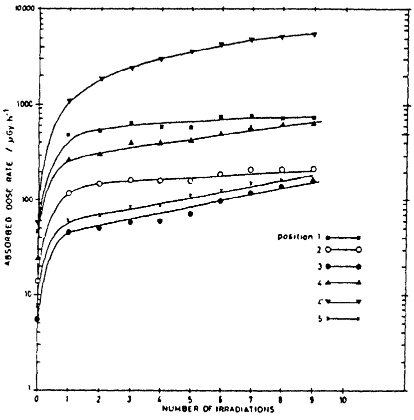

Figure 4 : build-up of absorbed dose rate due to build-up of induced activity near to the collimator. The numbers correspond to the positions in figure 3; 4' corresponds to the irradiated target in position and 4 corresponds to the target out of position (normal situation when staff is entering).

Dose equivalent levels in the treatment room during irradiation.

In order to check the efficiency in dose reduction of the entrance maze, dose equivalent rates were measured at several positions (see figure 2) in this maze and in the treatment room for the p(65)+Be neutrons. As neutron detectors three different types of proportional counters were used :

- a BF3 counter, type NM1, from Nuclear Interprice, UK;
- a Cramal 21 (He-3 filling) from Nardeux, France;
- a Dineutron counter (He-3 filling) from Nardeux, France;

- in addition, following the recommendations of the ICRU report n°40 (ICRU, 1986) dose equivalent rates, including the quality factor Q, were determined by means of a tissue-equivalent proportional counter. The microdosimetric spectra were measured at three positions with a LET proportional counter (Far West Technology (FWT) LET-1/2; 2.5mm build-up cap in A-150).

Tissue-equivalent proportional counters are used in radiation protection to determine dose equivalent rates in an environment where unknown photon and neutron components are present. Being filled at low TE-gas pressure, they offer the advantage to measure, on one hand the total absorbed dose in TE material, and on the other hand the lineal energy distribution. This distribution allows the evaluation of the mean quality factor (Q) using the quality factor relation Q(y).

Microdosimetry spectra are shown in figure 5 for 3 typical positions. They present the dose probability density d(y) as a function of the lineal energy y. The different peaks as a function of increasing lineal energy y correspond to the contribution to the total absorbed dose of the electrons from the gamma component (small y-values); the recoil protons (medium y-values); the alpha's and the heavy ions (high y-values) respectively . The variation when going from the beam axis (position 4) to the corridor (position 6) of each of the former contributions clearly illustrates the variation of the beam quality.

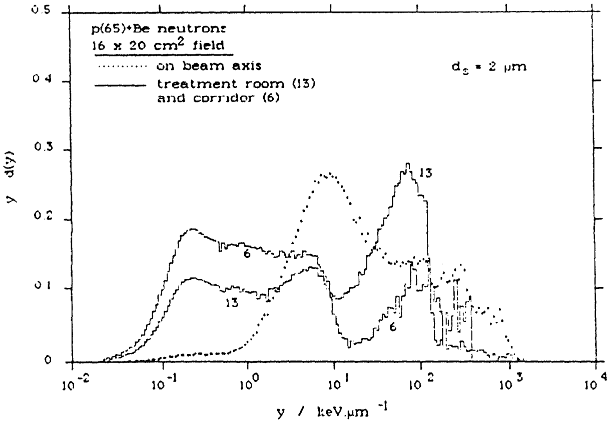

Figure 5 : Microdosimetry distributions for p(65)+Be neutrons as used at Louvain-la-Neuve for therapeutic applications. These spectra are measured at three different positions of the treatment room.

The calculated dose equivalent rates (H3) and Q-values are compared with the measured dose equivalent rates (H1 and H2) and Q-values in table 1.

position	H1 (Q1 = 10) mSv.h^{-1}	H2 mSv.h^{-1}	Q2	H3 mSv.h^{-1}	Q3
1	0.0020	0.0095	4.4	-	-
2	0.0043	0.026	4.6	-	-
3	0.037	0.162	4.3	-	-
4	0.18	0.713	4.2	-	-
5	1.68	4.58	4.2	-	-
6	7.32	9.91	4.7	8.54	4.1
7	20.4	18.6	4.8	-	-
8	48.0	29.0	5.0	-	-
9	312.	116.	5.1	-	-
10	468.	134.	5.2	-	-
11	408.	125.	5.2	-	-
12	432.	128.	5.2	-	-
13	480.	133.	5.2	322.	5.7
14	492.	133.	5.2	-	-
15	444.	136.	5.2	-	-
16	504.	138.	5.2	-	-
17	445.	136.	5.2	-	-
18	456.	142.	5.2	-	-
19	440.	136.	5.2	-	-

Table 1 : Dose equivalent rates and Q-values as measured at te positions shown in figure 2 by the three different proportional counters : BF3 H1 ; Dineutron H2; FWT TE LET-counter H3.

They were measured under normal treatment conditions e.a. p(65)+Be neutrons with a beam current on target of 15 µA. This results in a total absorbed dose rate at the peak depth in phantom of 25 cGy.min^{-1}.

The first column of table 1 (H1) shows the dose equivalent rates measured by means of the BF3 proportional counter taking into account a Q-value equal to 10. The results of the Cramal proportional counter are not shown. Indeed, after a correction for the energy dependence the results of both counters did agree closely for the positions 5 to 19 where a measurement with the Cramal counter was possible . With a Q = 10 a dose equivalent rate of about 0.5 Sv.h^{-1} is found in the treatment room. This is close to the rate found for the d(50)+Be neutrons (Meulders et al, 1979), used previously with a beam current of 5µA and leading to an absorbed dose rate at the peak depth in phantom of about 50 cGy.min^{-1}. Due to the long entrance maze this dose rate is reduced to about 2-3 µSv.h^{-1} at the control room.

The second column shows the results of the Dineutron proportional counter (H2) who allows, in addition to the dose equivalent rate, the determination of the Q-value. A Q-value of about 5 is found in the treatment room reduced to about 4 at the entrance. However, these data are difficult to compare to the microdosimetry data (sensitive to both : the neutron- and the gamma component) since this counter is only sensitive to neutrons. Differences are observed between the results of the different counters. These differences are to be attributed to the differences in response as a function of energy for the conventional remcounters.

Dose equivalent to the personnel

Figure 6 shows the whole-body dose equivalents received by the staff, over the period, neutron therapy has been performed, in addition, with the number of patients treated each year. As can be seen from this figure there is a wide variation with the function. For the medical staff, these doses are entirely due to activation of collimator and environment; they can be correlated to the number of patients treated. In the first period (1978-1981), when d(50)+Be neutrons were used, this corresponds in the worst case (nurses) to a dose received of about 0.07 mSv per patient treated, whilst for the second period (p(65)+Be) this number is increased to 0.15 mSv per patient treated.

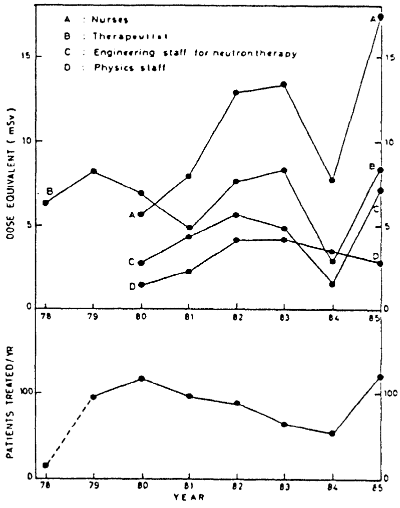

Figure 6: Dose equivalents received by the neutron staff per year and patients treated per

year over the period neutron therapy has been performed in Louvain-la-Neuve

The low scoring in 1984 is due to the stop of the treatments for 6 months in order to allow the construction of the second treatment room. As far as engineering and physics staff is concerned doses remain mostly below 5 mSv a year.

For the staff involved in the neutron therapy programme at TAMVEC (Smathers et al, 1978), dose equivalents were reported of 5.1 mSv per year for the physics staff and of 3.8 mSv per year for the nurses. At Edinburgh (Bonnet, 1983) 4.4 mSv was reported for the physics staff and 1.2 mSv for the radiographers (nurses). Altough the doses received for nurses at Louvain-la-Neuve are higher than the former ones, it must be remembered that, firsth, the energy in our centre is higher, leading to higher activation levels and secondly only one nurse is involved in the programme. Futhermore the doses received, depend also on the numbers of fields treated per day, the patient dose per field, the complexity of the field set-up and also to the working habits of the individuals. As far as the physics group is concerned, there is an agreement in doses received.

Conclusions

The dose equivalent levels in the treatment room were about 0.5 $mSv.h^{-1}$ and were efficiently reduced by a long entrance maze. In the treatment room, the quality factor Q of the neutron beam was equal to 4 and increased to about 6 towards the entrance (microdosimetry data).

Seven years of radiation monitoring in Louvain-la-Neuve have shown that doses received by the staff are higher than those received in conventional radiotherapy; however, in all cases they remain well below the recommended dose limits and are comparable with those received in other neutron therapy centres. Irradiation of the medical staff can be correlated with the number of patients treated. A reduction can be reached by chosing the appropriated iron composition for collimator (a multi-leaf collimator is under construction) in order to minimize activation and secondly by optimizing the time needed for patient positioning. In adition to the previous risk of external irradiation, the engineering and physics staff is exposed to the risk of ingestion of radioactive materials. This could be minimized by careful cleaning and monitoring procedures of the environment, together with wearing protective clothing and if necessary, dust masks during maintenances.

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RESUME

Nous avons évalué le risque d'irradiation du personnel du Centre de Neutronthérapie de Louvain-la-Neuve.

Les niveaux de doses équivalentes dans la salle de traitement pendant une irradiation thérapeutique par neutrons p(65)+Be ont été enregistrés. Pour Q=10, ces niveaux atteignent 0.5 Sv.h^{-1} à proximité directe du patient, valeur qui toutefois doit être comparée au débit de dose absorbée de 15 Gy.h^{-1} obtenue dans le patient, à la profondeur de la dose maximum. Le niveau de dose à l'entrée de la salle de traitement est réduit au dessous de 2-3 µSv.h^{-1} grâce à une chicane. Les valeurs de Q ont été déterminées à différents endroits à l'aide d'un compteur proportionnel microdosimétrique.

Les niveaux de radioactivité induits dans la salle de traitement sont présentés et les problèmes de contamination radioactive sont discutés. La dose totale équivalente au personnel est également présentée et, bien que plus élévée que pour la radiothérapie conventionnelle, celle-ci demeure largement en dessous des limites de dose recommandées.

SAMENVATTING

Problemen in de bestralingsbescherming van het neutronentherapie personneel te Louvain-la-Neuve werden onderzocht.

In de behandelingszaal werden tijdens de bestralingen de ekwivalente dosis debieten geregistreerd voor de p(65)+Be neutronen bundel. Indien men aanneemt dat de Q-waarde gelijk is aan 10, dan werden er debieten tot 0.5 Sv.h^{-1} geregistreerd nabij de patient wat vergeleken moet worden met geabsorbeerde dosis debieten van 15 Gy.h^{-1} op de piek diepte in de patient. Door toedoen van een lang labyrint werd aan de ingang een debiet opgemeten dat niet hoger is dan 2-3 µSv.h^{-1}. Q-waarden werden ook bepaald op verschillende localisaties in de bestralingszaal bij middel van een microdosimetrie teller.

Waarden van geïnduceerde radioäktiviteit in de behandelingskamer worden vermeld en de problemen van radioaktieve besmetting worden besproken. De totale ekwivalente lichaamsdosissen van het neutronentherapie personneel worden eveneens vermeld. Deze dosissen zijn hoger dan de dosissen ontvangen door het personneel bij gewone radiotherapie uitrustingen, maar blijven niettegenstaande veel lager dan de geldende limieten.

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CARACTERISTIQUES DU MINI-CYCLOTRON

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Résumé

Un demi siècle environ après son invention par et pour des physiciens nucléaires, à Berkeley, le cyclotron voit son champ d'application s'élargir : la médecine et l'industrie y ont recours chaque jour davantage.

Des exigences techniques et économiques nouvelles ont conduit une équipe de chercheurs de l'Université Catholique de Louvain, à développer de nouveaux concepts, puis à construire un prototype de cyclotron destiné à un marché en pleine expansion. Les principaux attraits pour l'utilisateur sont une consommation d'énergie très réduite, une grande robustesse et simplicité d'exploitation, et, enfin, une très haute intensité de faisceau extrait.

1. Introduction

La recherche dans le domaine des cyclotrons est une tradition à l'U.C.L. Dès 1947, les physiciens nucléaires installés dans le parc d'Arenberg, à Heverlee, entreprenaient la construction du premier cyclotron de Belgique, un des premiers d'Europe. En 1970, à l'occasion du transfert à Louvain-la-Neuve, l'U.C.L. se dotait d'un nouveau cyclotron qui allait devenir un des plus puissants d'Europe : Cyclone.

Aujourd'hui, le cyclotron se libère du seul rôle d'outil de laboratoire pour entrer dans les domaines de la médecine et des industries de pointe.

L'éventail de ses applications s'élargit de jour en jour : la demande croissante d'isotopes radioactifs pour la médecine nucléaire et l'utilisation de neutrons ou de faisceaux de protons dans la thérapie du cancer en sont deux exemples représentatifs.

Ces applications nouvelles demanderont, dans le futur, des machines plus performantes que ne le sont les cyclotrons actuels.

Les cyclotrons de demain, pour l'hôpital ou l'industrie, devront produire des faisceaux de haute intensité, être entièrement automatisés, ne requérir qu'un minimum de personnel pour leur maintenance et enfin consommer peu d'énergie.

2. Genese d'un cyclotron industriel.

C'est en travaillant sur ce problème, durant un stage à Berkeley, que j'étudie et publie le dessin conceptuel d'un cyclotron industriel de 40 MeV, pouvant accélérer 5 mA de faisceau, soit environ 100 fois plus que les cyclotrons actuels.

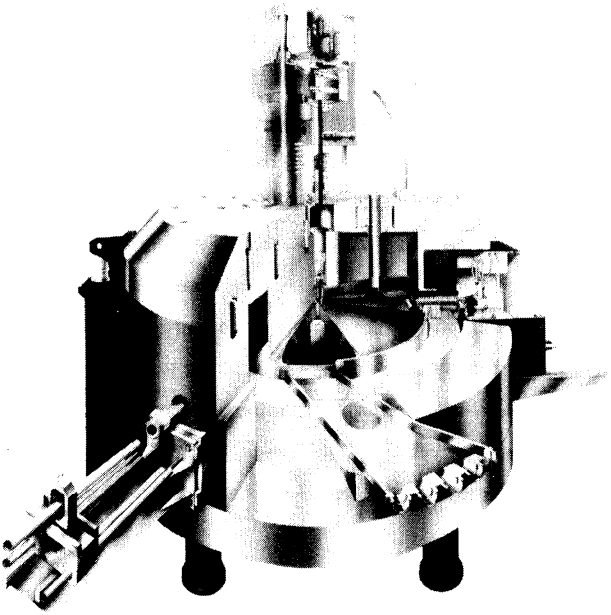
A mon retour en Belgique, fin 1984, sous l'impulsion du Professeur P. Macq, l'équipe prend une décision importante : essayer d'appliquer ce concept nouveau en matière de cyclotrons dans le dessin d'une machine qui pourrait être fabriquée par l'industrie belge à l'exportation.

Une étude de marché permet d'estimer la demande mondiale pour une machine de 30 MeV, à 3 ou 4 machines par an.

Les calculs et les modélisations sur ordinateur montrent que le cyclotron 30 MeV dessiné selon le nouveau concept pourrait avoir une consommation en énergie inférieure à 100 kW (soit 3 à 5 fois moins que les cyclotrons concurrents) et pourrait produire un faisceau extrait de 500 μA (soit 2 à 5 fois plus que les cyclotrons concurrents).

La société Ion Beam Applications (I.B.A.) est alors fondée en mars 1986 par l'U.C.L., l'I.R.E. et Transec pour assurer l'industrialisation et la commercialisation du nouveau cyclotron.

La construction du prototype, pour lequel la Région Wallonne accorde un prêt sans intérêt pour 75 % des coûts de développement, débute en octobre 1985 et c'est en décembre 1986, avec plus d'un an d'avance sur le planning initial que Cyclone 30 accélère son premier faisceau jusqu'à l'énergie maximum de 31,5 MeV.



Vue éclatée de Cyclone 30.

3. La technologie de Cyclone 30

Le dessin du nouveau cyclotron devait relever deux défis : une consommation d'énergie cinq fois plus faible que l'état actuel de la technique, et une intensité de courant extrait deux fois plus élevée.

Pour relever le premier défi, on a imaginé une structure tout à fait nouvelle pour l'aimant du cyclotron, en combinant les avantages des deux structures classiques (les cyclotrons compacts et les cyclotrons à secteurs séparés) et en évitant leurs inconvénients principaux. Les électrodes accélératrices du cyclotron compact (généralement retenu pour la production de radioisotopes), se placent entre les pôles de l'électro-aimant, imposant un entrefer assez large. Ceci a pour effet d'accroître la puissance électrique nécessaire pour produire le champ magnétique. De plus, à cause de leur emplacement, leur capacité par rapport à la masse est élevée, ce qui augmente la puissance de radiofréquence requise pour obtenir une tension accélératrice suffisante.

Dans le cyclotron à secteur séparés (conçu pour les hautes énergies et utilisé principalement dans la recherche), puisque les électrodes se trouvent entre les secteurs magnétiques, l'entrefer ainsi que la capacité des électrodes sont très fortement réduits, ce qui diminue la consommation électrique. Cependant, chaque secteur doit être doté de sa bobine d'excitation et le manque de place pour ces bobines implique une dissipation relativement importante. De plus, les cyclotrons à secteurs séparés demandent boîte à vide extrêmement complexe, un alignement délicat à réaliser et une énergie d'injection élevée, vu l'absence de champ magnétique au centre.

Dans le nouveau cyclotron, le champ magnétique est concentré dans quatre secteurs droits de 54 degrés où l'entrefer est très faible (3 cm).

Les bobines d'excitation, situées autour des secteurs magnétiques, étant de grande section et l'entrefer étant fortement réduit, la puissance électrique requise pour établir le champ magnétique n'est que de 7 kW au champ nominal, contre 300 kW pour le cyclotron comme Cyclone ou le cyclotron de l'I.R.E.

Ces secteurs sont séparés par des vallées où l'entrefer est d'un mètre environ. C'est à cet endroit que sont installées les cavités accélératrices.

Deux électrodes accélératrices (les "dees") de 30 degrés sont portées à un potentiel alternatif de 50 kV, avec une féquence de 66 MHz.

La faible capacité des "dees" et la géométrie particulière des résonnateurs permet d'obtenir cette tension de 50 kV en ne dissipant que 5 kW par cavité (contre 70 kW pour Cyclone à sa fréquence maximum).

Pour relever le second défi, la haute intensité, le nouveau cyclotron accélère non pas des protons, mais des ions négatifs H^-.

L'ion H^- est formé d'un proton, auquel sont accrochés deux électrons. Un tel ion négatif est assez instable et si l'on fait traverser à un ion H^- une mince couche de matière, il perd ses deux électrons et sort comme proton, c'est-à-dire en ayant changé le signe de sa charge électrique.

Cette particularité est mise à profit pour extraire un faisceau accéléré d'H^- d'un cyclotron avec un rendement de 100 %.

Les ions négatifs du nouveau cyclotron sont produits par une source externe et injectés axialement dans la machine.

En utilisant des ions négatifs, il est possible de réaliser un cyclotron à champ et fréquence fixes, donc très simple, et néanmoins d'obtenir une énergie variable du faisceau extrait en faisant varier le rayon auquel les H^-

sont épluchés en protons.

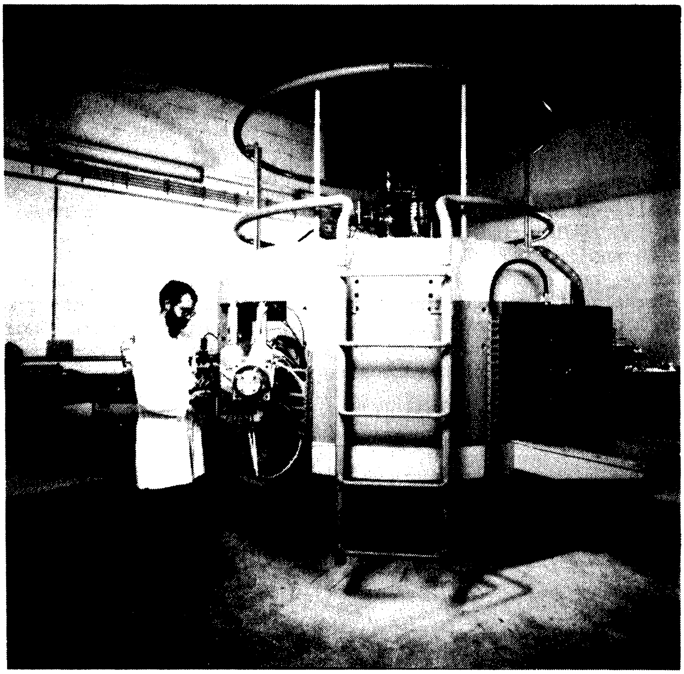
De plus, par l'utilisation d'éplucheurs partiels, il est possible d'extraire simultanément du cyclotron deux faisceaux d'énergie et d'intensité différentes.

Un dernier aspect de Cyclone 30, qui, rappelons-le, est destiné à une utilisation industrielle et médicale, réside dans le soin particulier apporté à son système de pilotage, de manière à rendre son fonctionnement entièrement automatique. Le démarrage, d'une série de faisceaux présélectionnés s'obtiendront sur simple pression d'une touche, sans pour autant supprimer l'option d'opération manuelle. Les contrôles et les sécurités sont traités par un contrôleur programmable industriel par l'intermédiaire d'un moniteur couleur de haute résolution, d'un clavier alphanumérique et de deux boutons virtuels. La grande souplesse du système simplifiera la tâche de l'opérateur. Le logiciel, présentera les fonctions usuelles de contrôle sous forme de "menus" et comprendra en outre une aide au dépistage de pannes.

4. Conclusion

Durant ces quarantes dernières années, la Belgique est restée à l'avant-garde de la communauté scientifique mondiale pour ses développements dans le domaine des cyclotrons.

Aujourd'hui, ce nouveau cyclotron est prêt à être exporté sur le marché mondial où les projets ne manquent pas et où l'acceuil réservé à cette machine s'est révelé plus qu'enthousiaste.



Le prototype Cyclone 30.

SAMENVATTING.

Ongeveer een halve eeuw na de uitvinding door en voor kernfysici van het cyclotron te Berkeley breiden haar toepassingen in geneeskunde en nijverheid zich elke dag meer en meer uit.

Nieuwe technische en economische eisen hebben een ploeg onderzoekers van de Katholieke Universiteit Louvain er toe geleid nieuwe opvattingen te ontwikkelen en een prototype cyclotron te bouwen dat bestemd is voor een markt in volle expansie. Meest aantrekkelijke voordelen voor de gebruiker zijn een laag energieverbruik, een grote stevigheid en eenvoud van gebruik en tenslotte een hoge intensiteit van de uitgestraalde bundel.

ABSTRACT.

About a half century after his invention by and for nuclear physicists in Berkeley, the cyclotron still extends his application field day after day in medicine and industry.

New technical and economical requirements brought a group of researcher of the Catholic University of Louvain to develop new concepts and to construct a cyclotron prototype for a fast expanding market. Main advant ges for the user are a low energy consumption, a great robustness and eas of operation and a very high intensity of the extracted beam.