APPLICATIONS OF THE COMPACT CYCLOTRON OF THE GERMAN CANCER RESEARCH CENTER IN NUCLEAR MEDICINE, NEUTRON THERAPY AND RADIATION BIOPHYSICS.+)

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Abstract

The present facilities of the medical cyclotron in the German Cancer Research Center are outlined.

This summary includes methods and thick target yields for radionuclide production and their applications in nuclear medical diagnosis and dosimetry in preparation of radiotherapy with fast neutrons.

1. General Concept

The construction of the compact cyclotron as a fixed energy 4-sector isochronos cyclotron[1] is based on the requirements of medical and biological applications[2] such as high beam currents at moderate energies, the ability to accelerate p,d,^{3}He and α-particles, internal target facility, good focusing and extraction efficiency, easy handling, compact structure, and relatively low cost.

With an initial two years of development, a further two years of construction and testing by AEG-Telefunken, and two more years of operation at the German Cancer Research Center the cyclotron has proved to meet most of the user requirements. A summary of the essential construction and output data is given in table 1.

Table 1: Essential design parameters[1] and output data of the Heidelberg compact cyclotron. Data in parenthesis are short time peak values.

Design parameters:

Number of sectors	4
Pole diameter	109 cm
Hill sector gap min.	5.4cm
Valley sector gap	17.5cm
Average magnetic field max.	14 kG
Hill sector field max.	19 kG
Valley sector field	8 kG
Number of acceleration gaps	4
Accelerating voltage	45 kV
Accelerating frequency:	
p,d,α	41.6-42.6MHz
^{3}He^{++}	28.6MHz
Total dissipation power	150 kW
Weight	30 t

Continuation Tab.1 see next page

Measured output data:

particle	max.energy (MeV)	beam currents int. (µA)	ext. (µA)	extraction eff. (%)
p	21.5	500(1250)	54(88)	56(60)
d	10.7	500(1250)	50(105)	60(80)
^{3}He^{++}	28.0	50(60)	16(25)	54(57)
α	21.4	50(53)	17(27)	56(62)

The ion beam is extracted by precessional extraction using one electrostatic deflector and an inactive magnetic channel[3].

2. Beam Transport System

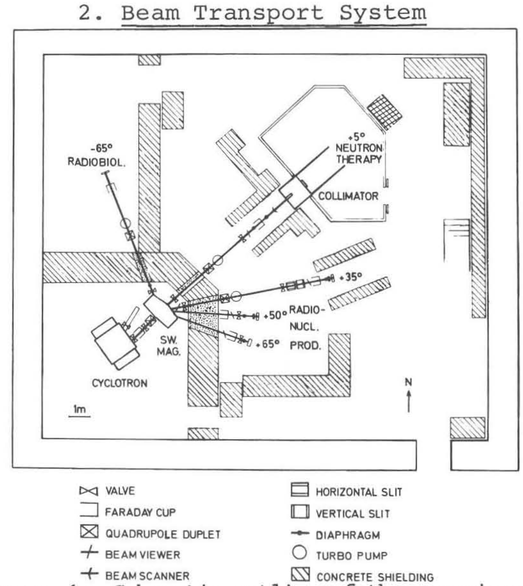

Figure 1: Schematic outline of the experimental area, and beam transport system

The beam transport system consists of one switching magnet for deflections from +65° to -65° with 7 beam pipe connections, 5 of which are at present in operation (Fig.1). The magnetic quadrupole lenses have an aperture of 100mm and a maximum field gradient of 0,7 kG/cm. The vacuum pipes are made from aluminum for reasons of contamination and have an inner diameter of 94mm. They are evacuated by turbo molecular pumps to avoid target reactions with carbohydrate crack products. The acceptance of the beam guiding system is sufficient to achieve a transparency of 85-90% with an

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emittance of the cyclotron of about π x20mm mrad in the horizontal direction and beam cross-sections of less than 15x15mm^2 at the target. For irradiation of small targets (enriched or expensive material) the beam spot diameter can be lowered to about 10x10 mm^2 for not too high beam currents. For most applications, however, cross-sections of about 20mm diameter are sufficient.

3. Applications

In 1974 the cyclotron was in operation for 1821 hrs with one shift per day. From this, 587 hrs, i.e. 32% could be used for experiments including optimization of beam extraction and matching.

We are presently overhauling the machine and beam guiding system and installing accessories to increase reliability and reproducibility and to decrease the time for the starting phase and trouble shooting which previously took about 60% of the time.

From the experimental time for biomedical applications, 70% was taken by radionuclide production, 22% by neutron spectrometry and by mixed neutron and gamma dosimetry in preparation of fast neutron therapy, 6% by radiobiological work and 1,5% by other radiochemical activities. Moreover, microdosimetric measurements for the determination of the physical neutron beam quality and additional radiobiological experiments to estimate the RBE of the neutron beam at different doses, both in connection with neutron therapy, started in early 1975.

3.1 Radionuclide production

Methods of nuclide production and radiopharmacological preparations are developed including determination of thick target yields (table 2) for various reactions, optimization with respect to output, concurring reactions, preparation and control methods, and the construction of special targets (Fig.2). The importance of the special nuclides for certain nuclearmedical diagnostic procedures is described elsewhere[4].

Table 2: Measured thick target yields of the most abundant nuclear reactions which can be initiated with the ion beams of the compact cyclotron.

radionuclide half-life	reaction	yield[a] µCi/µAh	max.beam[b] current (µA)	practical yield[a] mCi/hr
^{18}F 110 min	$^{20}Ne(d,\alpha)$	17000	20	300
^{13}N 10 min	$^{16}O(p,\alpha)$	116000	5	200[d]
^{61}Cu 3.4 hrs	Ni(d,xn)	635	20	12,7[e]
^{67}Ga 78 hrs	Zn(d,xn)	120	20	2,4
	Zn(p,xn)	330	5	1,65

Table 2 (continued):

^{99}Mo 66 hrs	$^{100}Mo(p,pn)$[c]	1100	10	11,0
^{111}In 2.8d	$^{112}Cd(p,2n)$	400	10	4,0
^{123}I 13 hrs	$^{124}Te(p,2n)$[c]	1260	5	6,3
^{197m}Hg 24 hrs	$^{197}Au(d,2n)$	25	20	0,5
^{197}Hg 64 hrs	$^{197}Au(d,2n)$	44	20	0,88
^{203}Pb 52 hrs	$^{203}Tl(d,2n)$	250	10	2,5

a) at the end of irradiation, b) dependent on cyclotron and target capacity, c) enriched target, d) mCi/20 min, e) chemical yield not calculated

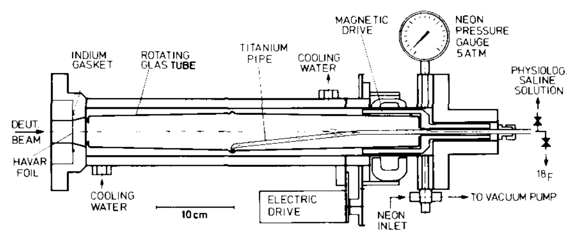

Figure 2: Target for the production of ^{18}F from which 3260 mCi were delivered in 1974

For details refer to F.Helus[5]

3.2 Neutron therapy

A deuterium gas target was constructed to produce neutrons of maximum mean energy and dose rate[6] by the reactions $D(d,n)^3He$ and D(d,np)D. The mean energy of the neutrons is 8.5 MeV at a maximum deuteron energy of 10.6 MeV and a deuterium gas pressure of 11 atm in the target. The dose rate in air in a distance of 1 m from the target entrance foil is 51.2 rads/min x 100 µA. The dose rate and neutron spectra were determined for beam currents up to 70 µA and gas pressures between 5 and 13 atm[7]. The gamma dose in air is less than 1% of the neutron dose. Beam profiles and neutron to gamma ratios were measured varying the field size (Fig.3).

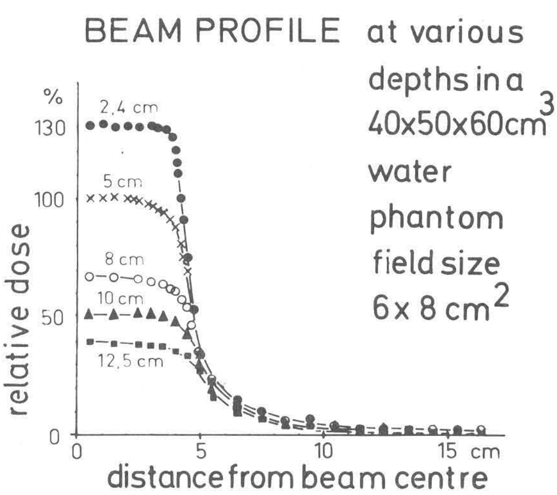

Figure 3: Profile of the collimated neutron beam measured in a water phantom with a 1 cm diameter TE ionization chamber

The neutron therapy program is processed in cooperation with the Universitäts-Strahlenklinik/Heidelberg and sponsored by the Federal Government.

3.3 Radiobiology

Studies on recovery and repair effects after irradiation with densely ionizing particles are performed once to twice a week by a guest group of the Gesellschaft für Strahlenforschung/Frankfurt. The beam is passed into free air by a thin foil to penetrate two ionization chambers with the cell samples in between. The energy of the external beam is varied by absorption layers. For particulars refer to H.Liesem et al.[8].

Experiments have been started to determine the dependence of RBE on neutron dose down to low dose ranges. In connection with microdosimetric studies (see 3.4) an attempt is made to explain this dependence by the model of "dual radiation action theory" proposed by Rossi and Kellerer[9]. As a test system HeLa S3 cancer cells are used. The method consists in counting the different distributions of single cell proliferation after irradiation with fast neutrons and gamma rays[10].

3.4 Microdosimetry

Physical aspects of the radiation quality[11] of the neutron beam are examined in context with the fast neutron therapy program. The dependence of radiation quality on the energy spectrum in free air and tissue is determined with a Rossi-counter of variable gas pressure[10]. The work is performed by a guest group from the Universität des Saarlandes in Homburg/Saar.

To a small extent experimental time was available for other radiochemical activities such as ^{18}F exchange labelling and reactions between atoms in excited states.

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