The AEG compact cyclotron

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ABSTRACT

A recently developed 43 in cyclotron—maximum energy 22 MeV protons—for application in physics, medicine, and (with some modifications) technology will be described.

1. INTRODUCTION

The AEG-Compact Cyclotron has been designed for a wide range of applications. Besides the well-known requirements of a cyclotron, the design of this machine had to include some new features for use in the medical and technical field.

The design and specification of a compact cyclotron has to take into consideration physical as well as commercial aspects. The design should include the requirements for the production of isotopes, the production of neutrons, activation-analysis, and other tasks (not yet defined) in nuclear research. This means that the cyclotron should be available for several applications without changing the basic design. This all-round application should not lead to a very expensive design, which would defeat its original purpose—on the contrary, it should be relatively inexpensive.

There are several ways of obtaining an optimal solution to achieve this. Besides the already mentioned conditions we took into account the experience gained by the earlier design of compact cyclotrons outside our company.

We arrived at the conclusion that the compact cyclotrons of the first generation have been obsolete in many aspects and do not meet today's requirements. The general tendency is towards:

higher maximum energy (>20 MeV)
higher beam quality (<20 mm mrad)
large range of energy variation (i.e. 1-20 MeV)
small energy spread (<0·5%)
large beam intensities
internal (>500 μA protons)
external (e.g. 100 μA)
beam pulsing

reliability in machine operation (e.g. 10 μA ^{3}He for a period of 8 h without interruptions during routine operation. Supervision of the generated dose and automatic shut down of the machine if a preset value is exceeded)

easy operation of the machine by an extremely small number of buttons (it should be sufficient to have the machine operated by, for example, a medical assistant)

easy maintenance

small space requirements, no basement

low investment costs, low operating expenses

After taking all these requirements into account, which naturally are not completely to be realised, it seemed important to us to design a machine with built-in reserves. If necessary the machine should be developed further without changing the major components. This is of great importance because the complete scope of requirements, especially in the medical field, is not known yet.

The design of the AEG-Compact Cyclotron should include most of the above-mentioned points. In the following the cyclotron will be described.

2. SPECIFICATIONS

Table 1 gives the beam specifications of the AEG-Compact Cyclotron. The cyclotron can be built in fixed energy or in variable energy versions, though the variable energy machine was not tested until recently.

Table 1. AEG-COMPACT CYCLOTRON

	Fixed energy cyclotron			
	Internal beam		*Extracted beam*	
Particles	*Energy* (MeV)	*Intensity* (μA)	*Energy* (MeV)	*Intensity* (μA)
Protons	1–22	1000	22	100
Deuterons	0·5–11	1000	11	100
^{4}He	1–22	50	22	25
^{3}He	3–29	50	29	25

	Variable energy cyclotron			
	Internal beam		*Extracted beam*	
Particles	*Energy* (MeV)	*Intensity* (μA)	*Energy* (MeV)	*Intensity* (μA)
Protons	1–18	1000	4·5–18	100
Deuterons	0·5–9	1000	2·5–9	100
^{4}He	1–18	50	4·5–18	25
^{3}He	3–23	50	8–23	25

Beam extraction rate: >70%
Beam energy resolution: <0·5%
Beam quality (protons): <π × 15 mm mrad (radial and axial)

Table 2. AEG-COMPACT CYCLOTRON

Magnet	Pole diam.	1·09	m (43 in)
	Air gap (hill)	5·4	cm (2·1 in)
	Air gap (valley)	17·5	cm (6·9 in)
	Number of sectors	4	
	Average magnetic field (max)	14	kG
	Hill field (max)	19	kG
	Valley field (max)	.8	kG
	Magnet current stability	$\pm 1 \times 10^{-4}$	
Rf system	Number of accelerating gaps	4	
	Accelerating voltage	45	kV
	Frequency stability	$\pm 2 \times 10^{-4}$	
	Fixed energy cyclotron		
	Accelerating frequency		
	p, d, ^{4}He	43	MHz
	^{3}He	28·6	MHz
	Frequency range	±0·5	%
	Variable energy cyclotron		
	Frequency range	18–38	MHz
Ion source	Filament current (max)	330	A
	Filament voltage	2·5	V
	Arc current (max)	5	A
	Arc voltage (max)	400	V
Vacuum system	Vacuum pressure	10^{-5}	torr
	2 oil diffusion pumps, each	1000	l/s
	1 two-stage mechanical pump	30	m^3/h
Overall dimensions	Length	2·30	m (7·5 ft)
	Width	2·70	m (8·9 ft)
	Height	2·15	m (7·0 ft)
	Total weight, ca.	30	metric tons
	Connected power, ca.	150	kVA

Table 2 gives the overall specifications of the machine. The pole plates are designed in a four-sector geometry. The cyclotron accelerates deuterons, $^3He^{2+}$ and $^4He^{2+}$ ions in the 4 ω-mode, and protons in the 2 ω-mode. The rf accelerating system consists of two dees assembled in two opposite valleys. The fixed energy machine works at two frequencies. 43 MHz for p, d, ^{4}He and 28·6 MHz for ^{3}He ions. In order to obtain very good beam quality, the maximum energy is reduced by about 20% in comparison with the fixed energy version, due to the fringing field.

Fig. 1 shows the magnetic field vs machine radius for the fixed energy machine. Fig. 2 gives the flutter factor.

A cone of 1·5% is superimposed on the magnetic field in the centre. It reaches zero at a radius of about 150 mm.

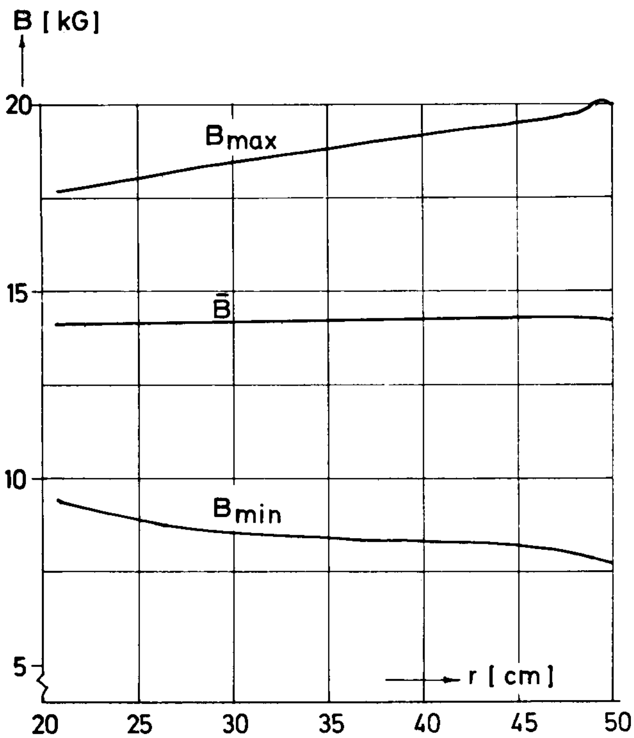

Fig. 1. Magnetic field vs radius

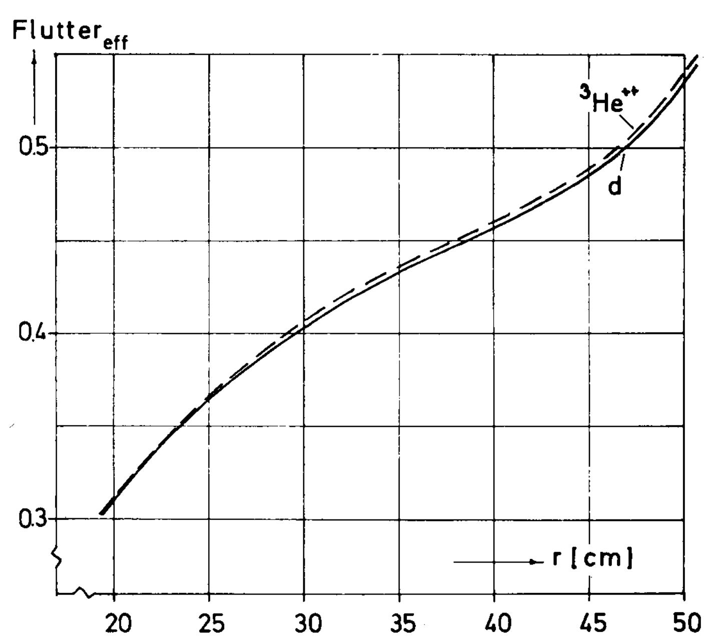

Fig. 2. Flutter factor vs radius

3. SYSTEM DESCRIPTION

3.1. *Magnet and rf*

The magnet is of a closed type with a four-fold cross-section. The four return paths of the magnet are realised by the four corners of the square (Fig. 3).

Access to the internal portion of the machine is therefore available on four sides, by openings of approximately 20 X 60 cm (8 X 24 in) each. This gives a free path to the valleys of the pole plates, which are arranged opposite the windows. The centre region of the poles forms a plateau which is demountable. A target is located in one of the valley-sectors for measurements and experiments with the internal beam. The adjustable elements for beam extraction are located in the opposite valley.

The rf resonance circuit consists of two dees, which are constructed as $\lambda/4$ lines and are connected at the centre. They are located in two opposite valleys of the pole plates. The outer and inner conductors are water cooled. The line length is adjusted at the lower end by a movable shorting bar in the external resonator tank. A ceramic isolator seals the resonator against the vacuum of the machine. The resonator itself continues at an angle of 90° to the dee-system.

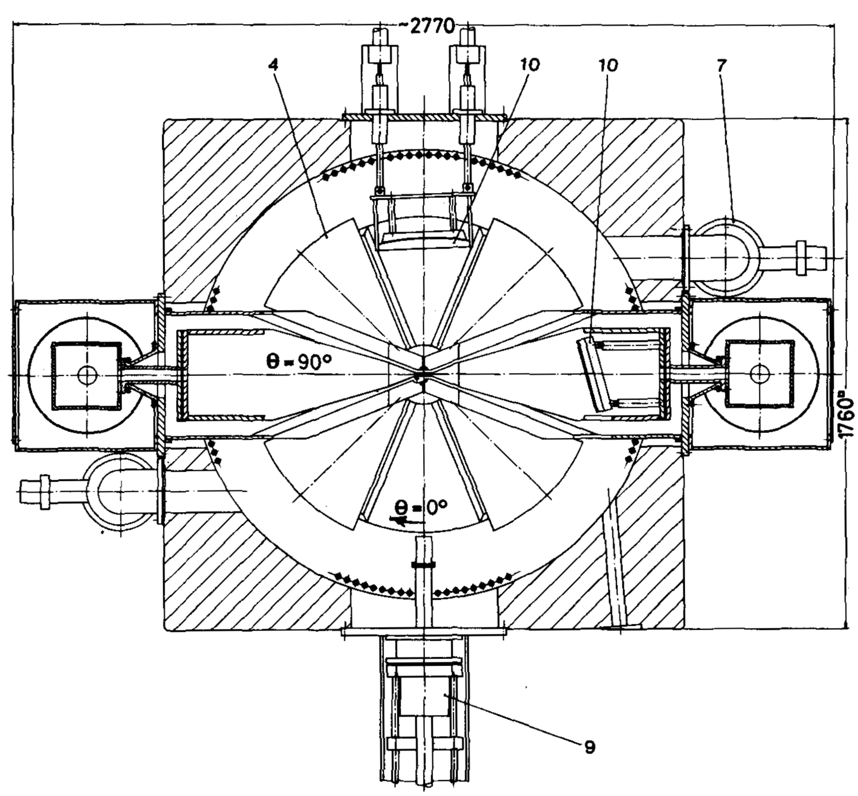

Fig. 3. Horizontal cross-section; 4. Correction coils; 7. Diffusion pump; 9. Internal target; 10. Extraction system

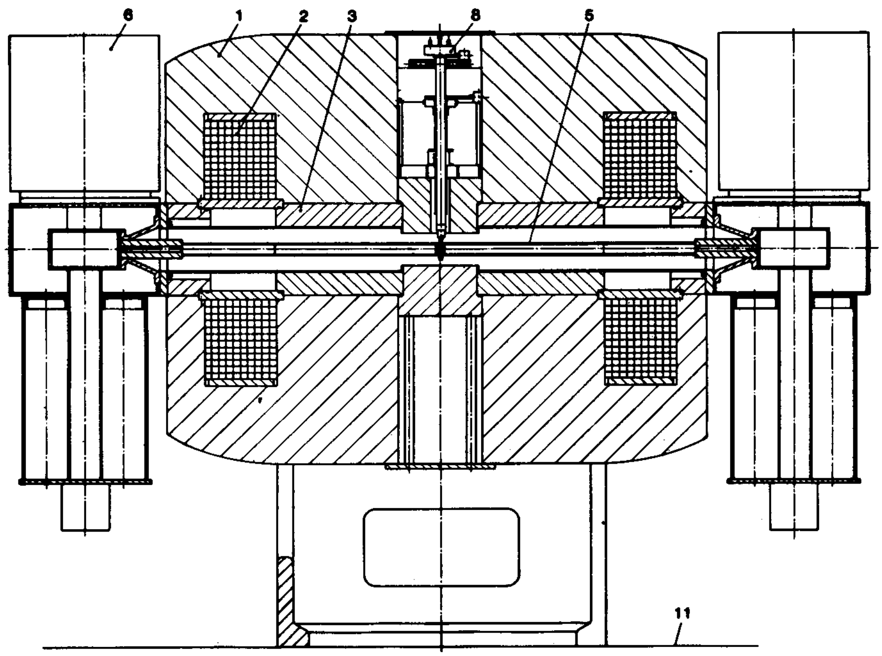

Fig. 4. Vertical cross-section; 1. Magnet yoke; 2. Main coils; 3. Pole plate; 5. rf system; 6. rf generator; 8. Ion source; 11. Floor

The rf generator is located above the resonator. The rf skin losses of the accelerating system are approximately 20 kW. The maximum accelerating voltage in the central region of the machine is 45 kV.

The rf generator is of a self-excited single-stage type. The generator tube is a water-cooled power triode and operates as a Huth-Kuehn oscillator in a grounded cathode circuit. The output power of the rf generator is 60 kW at a dee voltage of 50 kV peak. It is capacitance coupled to the accelerating system. The radio frequency is regulated to better than $\pm 2 \times 10^{-4}$.

3.2. *Vacuum*

The design of the magnet, consisting of upper, middle, and lower yokes, made it possible to build a tight evacuable box without any separate vacuum chamber.

The pumping equipment used to evacuate the accelerating area between the pole plates and the ring channel, concentric to the pole axis, consists of two oil diffusion pumps with a capacity of 1000 l/s each, backed by a two-stage mechanical pump with a capacity of 30 m^3/h. Two water-cooled baffles located on the top of each oil diffusion pump, are used to prevent backstreaming of the oil vapour. A fast acting, electro-pneumatically operated valve is mounted between each pump and the vacuum chamber.

During pump-down to 1×10^{-2} torr (in approximately 10 min), the mechanical pump is connected directly to the chamber via a by-pass. During this operation, the hot diffusion pumps are connected to a forevacuum reservoir. This vacuum system concept also allows the evacuation of a target-changing lock during normal machine operation. The vacuum system includes complete instrumentation and all control devices required for pressure controlled automatic operation.

3.3. *Coils*

The main magnet coils, each located within a cavity in the upper and lower yokes, are isolated from the vacuum chamber by two rings which provide a vacuum closure. The square copper conductors have a cross-section of 12 × 12 mm (0·47 in × 0·47 in) and a square internal opening of 6 × 6 mm (0·23 in × 0·23 in) for water cooling. The power dissipated in the coils is about 40 kW.

The magnet current is regulated to within 1×10^{-4}, using transistor regulation. A precision shunt is used to provide a voltage for comparison with a highly stable Zener reference voltage. The difference between these two voltages is the error signal which drives an operational amplifier, which in turn activates transistors.

The trim coils permit the adjustment of the field shape as required for each different particle. The system consists of eight individual sector-shaped trays, mounted on the hill sectors. They contain four individual coils each. Upper and lower coils on each sector are connected in series, and the four trim coil pairs in each sector are arranged so that they help one another in adding to the magnetic field toward the outer radii. The power required by the trim coil system is less than 800 W.

The power supply permits continuous adjustment of the trim coil current for each coil pair by Helipot from −100 to +100%. Current stability is better than 1×10^{-3} at maximum current.

3.4. *Ion source*

An internal ion source is provided in the standard version of the compact cyclotron. The source is fed vertically through the upper yoke into the centre of the machine. A motor-driven adjusting device enables the ion source to be put into the most suitable position for any kind of particle.

The ion source is of the Livingston type and represents a proven design used in all cyclotrons built by AEG. The chimney is made of graphite. The source is equipped with a tantalum-reflector, supported in boron nitride.

For $^{3}He^{2+}$ and $^{4}He^{2+}$ production the same geometry is used, but the chimney is made from molybdenum and tantalum. The upper part of the chimney with the extraction slot is made of tantalum. The extraction slot is somewhat larger than for protons and deuterons and the reflector is of a modified size. This type has been well proved for He-acceleration in the Jülich Cyclotron, with a high life expectancy.

The ions are extracted by the 45 kV accelerating voltage. Besides the puller, there is no other defining slit in the injection area of the accelerating system.

For injection of ions from an external ion source, the internal ion source, being fed vertically through the upper yoke, may be replaced by a beam guiding system. For inflection the hyperboloid-inflector described by R. W. Müller[1] will be used.

For a quick change from internal to external ions the beam guiding system may be mounted in the existing vertical hole in the lower yoke (Fig. 2). In this case the central part of the lower pole plate may be replaced by a similar one with the necessary hole.

3.5. *Extraction*

The extraction system consists of an electrostatic deflector and a magnetic channel. The position of the extraction elements is given in Fig. 1. The electrostatic deflector mounted in a valley sector, has a length of 35°, its entrance is positioned at θ = 160°. The following valley houses a magnetic channel working as an ion optics system. The field imperfections caused by this channel have been compensated by iron shims.

The questions of beam extraction in the compact cyclotron are discussed in a separate paper by H. Liesem.[5]

3.6. *General design*

Fig. 5 gives a view of the machine outlines. As can be seen in the horizontal view the support of the machine has a very small area. All leads are fed centrally

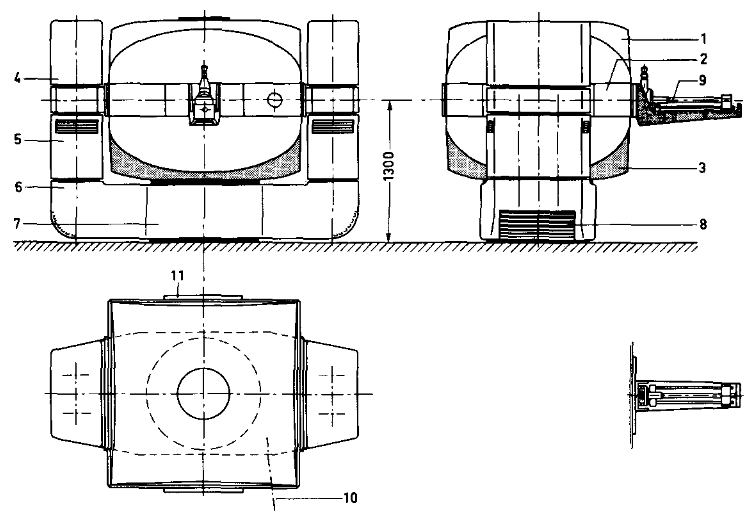

Fig. 5. Views of the cyclotron. 1. Upper yoke; 2. Centre yoke and vacuum chamber; 3. Lower yoke; 4. rf generator; 5. Diffusion pump; 6. Mechanical pump; 7. Auxiliary equipment; 8. Ventilation; 9. Target lock and insertion equipment; 10. Beam transport piping; 11. Window

through the support. This enables the cyclotron to be turned around its own vertical centre axis.

Another turning device allows the compact cyclotron to be turned around a vertical axis, about 7 m outside the cyclotron. Such an arrangement may be useful for scattering experiments combined with time of flight measurements.

The machine is operated from a control desk about 9 ft long, on which all control switches, potentiometers, and indicating instruments are located. The machine is protected by an interlock system against dangerous operating conditions.

Four electrical power supply cabinets are furnished with the standard machine—without external beam guiding system. The dimensions of each of these cabinets are 1·65 m × 0·7 m × 2 m (5·4 ft × 2·3 ft × 6·5 ft). All electrical power supplies are remotely controlled and need no local control during machine operation.

DISCUSSION

Speaker addressed: H. Liesem (AEG)

Question by J. L. Need (New England Nuclear Corporation): On the slides you show 1 mA internal and 100 μA external beam current. What currents have you actually obtained?
Answer: These are design currents. The machine is not yet built.

Comment by G. Schatz (Karlsruhe): At the Karlsruhe isochronous cyclotron, also built by AEG, we have run basically the same ion-source at 1·0 to 1·2 mA for more than 80 h for our time-of-flight experiments so I think this current can easily be achieved.

Comment by G. O. Hendry (Cyclotron Corporation): I would like to comment that extracting 100 μA of 20 MeV protons is rather difficult because of troubles with the septum.

Question by J. L. Need (NENC): You have a large magnet gap. What do you expect the vertical amplitude of the beam to be?
Answer: 4 mm.

Question by A. A. van Kranenburg (Philips): Did I understand that you use your internal ion source for fourth harmonic acceleration of deuterium and ^{4}He?
Answer: Yes.

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