THE S.I.N. INJECTOR CYCLOTRON

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A 250 cm pole diameter isochronous cyclotron is under construction for the Swiss Institute for Nuclear Research (S.I.N.) The design goal is described followed by a brief discussion of the machine.

Introduction

The 250 cm pole diameter isochronous cyclotron is designed for operation in two modes :

1. the acceleration of a high intensity proton beam ($\geq$100 μA) to 72 MeV at a fixed frequency of 50.7 MHz (3rd harmonic) for synchronised injection in the 590 MeV S.I.N. ring cyclotron ("injector mode").
2. the acceleration of beams of light and medium-heavy ions to a wide range of energies for nuclear physics use. The maximum energy for the various particles is $134(Z/A)^2$ MeV/nucleon, corresponding to a rigidity of 16.6 kGm. The maximum proton energy will be 75 MeV corresponding to 17.1 MHz, the minimum energy is 5 MeV/nucleon in first harmonic mode and 0.6 MeV/nucleon in third harmonic mode ("variable energy mode").
   A survey of the parameters for the various beams is given in Table I and in the operating diagram (fig. 1).

Table I

p	72 MeV	$\geq$100 μA	50.7 MHz (3rd harm.)
p	10- 75 MeV	25 μA	4.7-17.1 MHz (1st harm)
d	10- 65 MeV	25 μA	
$^4He^{2+}$	20-130 MeV	15 μA	
$^3He^{2+}$	15-150 MeV	15 μA	

A beam quality of 30 mm mrad, normalised at 50 MeV, 80% of the beam, is expected both in the horizontal and in the vertical phase plane. Energy resolution will be better than 0,3 % (FWHM). About 2 μA of medium-heavy ions, like $^{12}C^{4+}$, $^{14}N^{4+}$, $^{16}O^{4+}$ will be available. The main parts of the cyclotron are shown in figs 2 and 3. The magnet has a fourfold symmetry, the hill gap is 22 cm, the valley gap is 45 cm and the maximum spiral angle 55°. Twelve pairs of concentric correction coils and four pairs of harmonic coils are installed. The particles are accelerated in a one dee, dummy-dee geometry. Two separate RF-systems are provided to excite this dee: a driven 50 MHz-system (injector mode) and a 4.7-17.1 MHz self-oscillating system (variable energy mode). The vacuum system consists of a stainless steel vacuum chamber pumped by two oil diffusion pumps providing an effective pumping speed of 15,000 l/s. Additionally, a cryopump operating at a 20 K level is installed. The correction coils are located in a separate vacuum chamber at an intermediate pressure. Particles are produced either by a radially inserted hooded-arc ion source or by an axial injection system. They are extracted by an electrostatic deflector, a deflection coil and focussed in a magnetic channel (iron).

Magnetic fields

In the injector mode the magnetic field has to be isochronous at the frequency of 50.67 MHz and simultaneously the fringing field has to be suitable for precessional extraction at the required energy of 72 MeV. Once the magnet gap has been chosen, these requirements lead to an extraction radius of 1.054 m. Just before extraction radius an iron ridge is mounted on the hills to obtain a rapid decrease of ν_R with radius. The measured field shows a maximum phase excursion of 35° at a dee-voltage of 70 kV. Extraction takes place at ν_R = 0.92 (fig. 4). The variable energy mode is designed on the base of a constant orbit pattern (500 revolutions). This requires a maximum dee-voltage of 80 kV. A representative series of magnetic fields has been measured. They allow the acceleration and extraction of the various beams mentioned in Table I.

RF-systems

The 180 degree dee is in both operating modes part of a quarter-wavelength resonator (fig.2). The variable energy RF-system includes feed-through insulators and two parallel coaxial lines in air with movable shorting plates[2]. This self-oscillating system has two power oscillators with a maximum output of 120 kW each which are capacitively coupled to the resonator. The coupling is in air, close to the feed-through insulators. The oscillators are of the grounded grid type with ceramic triodes and variable capacitive feedback. A DC-bias is applied to the dee in order to prevent multipactoring. The dee-voltage is stabilised to better than 10^{-3}, the frequency to better than 10^{-5}. The latter stabilisation is achieved by regulating the position of the shorting plates and two trimming capacitors. A driven multi-stage amplifier is used for the injector mode since its phase must be locked to the RF-system of the ring cyclotron. The power is transmitted from the final 250 kW amplifier stage (AEG-Telefunken) by means of a 50 Ω rigid coaxial line, a 50 Ω vacuum feed-through and is capacitively coupled to the dee. In this mode the quarter-wavelength system is defined by a shorting bar inside the vacuum chamber, capable of carrying a shorting current of 15,000 A (peak) at a current density of 50 A/cm. The dee-voltage is stabilised to 10^{-3}. Phase differences with respect to a master oscillator are limited to less than 1 degree. The impedance of the amplifier load is kept at 50 Ω with a VSWR better than 1.4. The RF-systems and the vacuum chamber were built and assembled at our factory (fig. 5). A vacuum of 10^{-6} Torr was reached during the experiments. In the variable energy mode the complete frequency range was tested, the system operated as expected. In the experiments with the 50 MHz system no DC-bias on the dee was used which is possible in a driven RF-system. In the steady state multipactoring is avoided by reducing the relevant RF-gaps sufficiently. Starting is accomplished by applying a 20 kW power step with a 2 μs rise time. During the built-up of the dee-voltage (20 μs) the region in which multipactoring might occur will then travel along the dee so fast that a discharge cannot develop. The Q-value of the system turned out to be 5400, requiring 75 kW for 70 kV dee-voltage, without beam load.

Ion sources and axial injection

A hooded-arc ion source can be brought in radially. At arc power levels of 1 kW this source is operated with one "cold" cathode and a heated filament. The light ions are produced in this way. The filament can be replaced easily by a second cathode. The source will then be operated at a 5 kW level for the production of the medium-heavy ions. The features of a biased ion source in the cyclotron centre to be used to produce a high-intensity,

well-centred proton beam with good beam quality and large duty cycle as well as the construction of such a source are under study.
The axial injection system may be used in different ways, in particular: injecting a high-current, good-quality beam from a duoplasmatron, or a low-current moderate-quality beam from a polarised ion source, in first as well as in third harmonic mode. A system has been designed that is sufficiently flexible to allow the various operational modes. It consists of the following main parts :

1. Underneath the cyclotron two external ion sources are located : a polarised ion source will be installed by the University of Basle; a duoplasmatron (ORTEC) with associated beam line is used to produce the high-intensity proton and deuteron beams. A switch magnet allows the alternate use of these sources.
2. A beam guiding system is placed inside a 30 cm diameter axial hole in the lower part of the cyclotron magnet yoke. It consists of two triplets of magnetic quadrupole lenses of large aperture (90 mm), two sets of movable x- and y-slits, two Faraday cups and a buncher.
3. The beam is inflected by a plane electrostatic mirror, housed in a cylinder that is electrically connected to the dummy dee. Electrodes are attached to this cylinder defining the accelerating electric field in the first gap.

Several theoretical and experimental investigations have been carried out. We mention here a study of the properties of the inflector optics [3], central region studies and measurements of the residual magnetic fields at high magnet excitations [4]. This last work led to the construction of an iron shielding cage underneath the cyclotron (fig. 3) and to the application of a solenoid inside the axial hole with the purpose of compensating for the stray fields.

Central region

An extensive study of the particle orbits in the central region has been carried out, using the magnetic analogue method [5,6]. An automatic magnetic field measuring machine was built to facilitate the investigation of different central region geometries [7]. With the electric field data obtained from these analogue measurements we are able to calculate the particle motion in the horizontal and vertical phase plane. Special attention is paid to the design of this central region since, due to the two-fold purpose of the cyclotron, both first and third harmonic mode accelaration must be possible. Besides, the cyclotron must operate with a normal internal ion source and with an axial injection system. These different situations give rise, for instance, to different energy gains in the first gap crossing and, consequently, different orbit centre positions and vertical focussing. Optimisation of the central region includes : maximum horizontal and vertical phase plane acceptance, maximum time phase acceptance, minimum spread of orbit centres for different starting phases (mixing of longitudinal and transverse oscillations) and minimum displacement of the orbit centre from the cyclotron centre. By shaping the accelerating gap and the dee-aperture as a function of radius and carefully selecting the puller angle (especially sensitive in third harmonic operation) and its position we have been able to find a central region configuration which accepts about 300-400 mm mrad horizontally and 1,000 mm mrad vertically (normalised to 10 keV) and more than 10 % of the total RF-period in the different modes. Fig. 6 shows a lay-out of the central region with two examples of orbits for different modes of operation. The orbit centre spread due to the different starting phases results in a distribution of the particles over an area of about 2 mm^2. In all modes of operation the beam is centred within 2 mm.

Extraction

The particles are extracted by a 40° electrostatic deflector, followed by a deflection coil and a focussing magnetic channel. An orbit separation before deflection is to be generated by a first harmonic magnetic field component causing a precessional motion of the orbit centre beyond the radius where $\nu_R = 1$ [8, 9]. Calculations show that, for instance, the proton beam in the injector mode can obtain a total orbit separation of 5 mm with a first harmonic of 1.4 G. Extraction takes place at $\nu_R = 0.92$. Fig. 7 shows a stroboscopic picture of the motion of an area of 25 mm mrad in the horizontal phase plane during the last revolutions. The phase plane acceptance of the total extraction system is also shown. The extraction efficiency calculated is more than 80 % in this case; about 10 % is lost on the front part of the septum.
The electrostatic deflector consists of a copper septum and an aluminium electrode. The gap is 5 mm and the maximum voltage will be 70 kV. The deflection coil has been measured to give a maximum field drop of 2,000 G together with a positive gradient of 300 G/cm. Separate windings secure the compensation of disturbing fields outside the coil. The magnetic channel, consisting of three iron bars, gives a maximum gradient of 1,000 G/cm, which can be adjusted during operation by changing the relative position of the bars. This extraction system has a calculated acceptance of 30 mm mrad in the horizontal phase plane and 50 mm mrad in the vertical one. Special attention has been paid to the focussing and dispersive properties of this system in order to minimize the effective enlargement of the horizontal phase space area by the dispersion in the external beam.

Status

The cyclotron is being assembled at S.I.N.
The magnetic fields were measured in 1972, and the RF-systems were tested in 1972 in our factory in Eindhoven. The first internal beam experiments are scheduled for August 1973.

References

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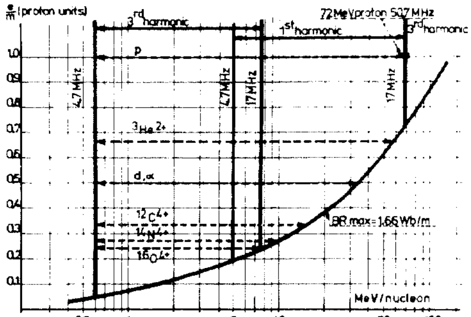

Fig. 1.
The energy range for several particles.

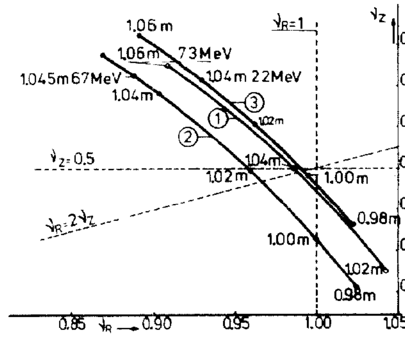

Fig. 4.
Diagram of ν_R - ν_Z, Curve 1 : 72 MeV p, 2 : 67 MeV d, 3 : 22 MeV d.

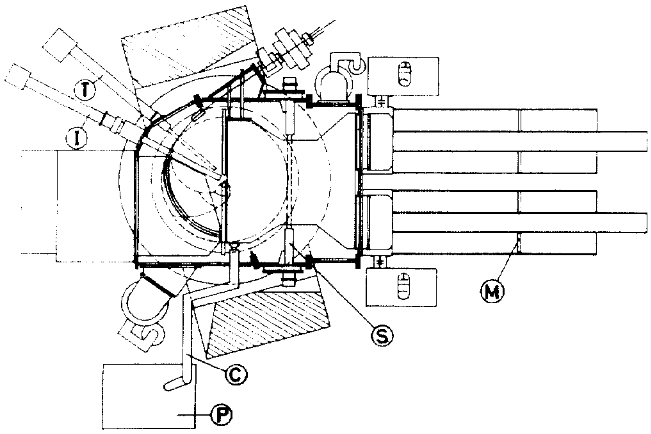

Fig. 2.
Horizontal cross-section of the cyclotron.
I : ion source, T : target, P : 48 - 52 MHz power amplifier, C : 50 Ω coaxial line, S : shorting bar for 50.7 MHz operation, M : movable shorting plate for variable energy mode.

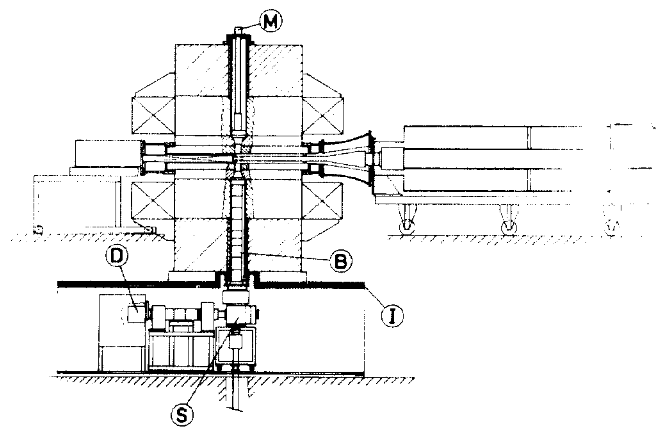

Fig. 3.
Vertical cross-section of the cyclotron.
D : duoplasmatron ion source, S : switch magnet, I : iron shielding, B : axial injection beam guiding system, M : electrostatic mirror holder.

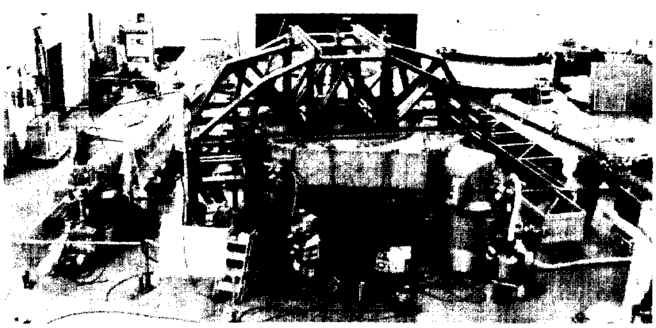

Fig. 5.
View of vacuum chamber and RF-system during test at the Eindhoven factory.

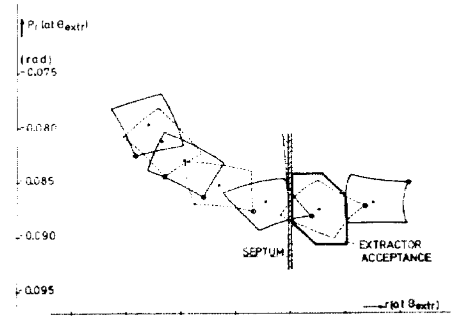

Fig. 7.
Stroboscopic view of 25 mm mrad phase plane areas in the extraction region.

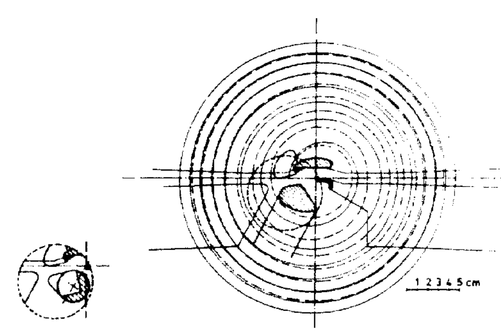

Fig. 6.
Central region geometry with internal source.
Drawn : "Constant orbit" particle trajectory for first-harmonic mode; dashed : particle starting with same initial conditions in third-harmonic mode (70 kV dee-voltage and 50 MHz). Insert shows the geometry for axial injection.