OPERATIONAL EXPERIENCE WITH THE 500 μA H^- ISOTOPE PRODUCTION CYCLOTRON CYCLONE 30

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Introduction

The 30 MeV H^- prototype cyclotron CYCLONE 30[1],[2] (CYClotron of LOuvain-la-NEuve) operates since July 1987 for the production of a large variety of radioisotopes used in medicine and industry and for preliminary experiments related to the radioactive ion beam facility[3] under construction at the Catholic University of Louvain. CYCLONE 30 is a fixed-field, fixed-frequency cyclotron accelerating H^- ions up to a maximum energy of 31.5 MeV with a total design intensity of 500 μA. The magnet has an unusual structure : four separate sectors, surrounded by a single water-cooled copper coil produce a strongly focusing field using as little as 7.2 kW of power. With two low loss RF-cavities, entirely located in opposite valleys, 50 kV is obtained on two 30° Dees. This cyclotron is equipped with an external H^- MULTICUSP ion source. A set of two remotely positioned carbon stripping foils allow the simultaneous extraction of two variable energy proton beams. The overall design, aiming at a versatible and yet simple, variable energy, high productivity, isotope production cyclotron resulted a.o. in an extremely high energy conversion efficiency : the whole system requires less than 90 kW of electrical power for the production of 15 kW of beam power on external targets. Controlled by a high level industrial controller, its operation is fully automatic. The prototype is shown on figures 1 and 2. Table 1 lists the main characteristics of CYCLONE 30.

Magnet structure

The magnet consists of four straight sectors, 40 cm high, mounted on a single iron disk and surrounded by a single water-cooled copper coil. This unusual structure, specially designed to reduce considerably the electrical power required to generate the magnetic field, combines the advantages of both separated sector and compact cyclotrons while eliminating their respective drawbacks.

Advantages due to the separated sector-like design are :

- a small hill gap (3 cm), leading to a low number of ampere turns ;
- plenty of space in between sectors allowing for vertical resonators entirely located in the valleys and low capacitiy Dees ;
- a magnetic guiding field having perfect four-fold symmetry and strong axial focusing.

Advantages related to the compact cyclotron like aspects are :

- simply circular, large cross section, low current density main coil ;
- simple cylindrical vacuum chamber ;
- perfect mechanical positioning of the sectors with respect to each other ;
- magnetic field extending to the centre allowing for an internal ion source or axial injection at low energy.

Fig. 1 : General view of CYCLONE 30.

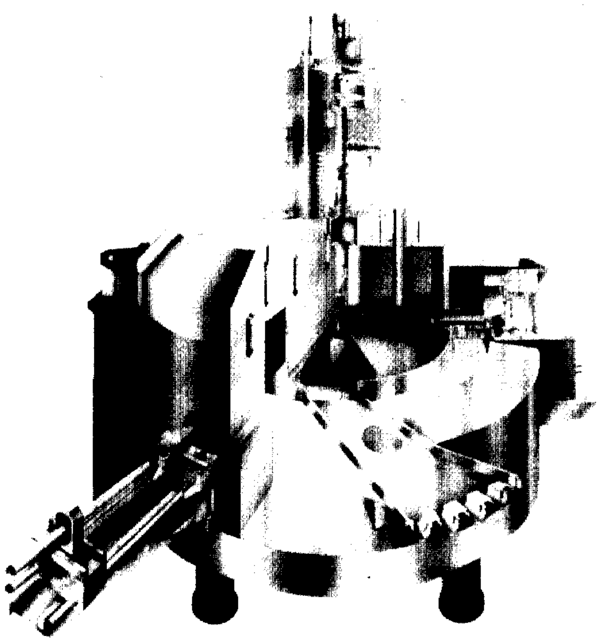

Fig. 2 : Schematic view of CYCLONE 30.

Since CYCLONE 30 has a fixed field (the energy of the extracted beams is varied by changing the radius of the extraction strippers), isochronism is achieved by appropriate pole shaping ; no trim coils are needed. For simplicity, the gap is held constant but the sector angle is adjusted radially to obtain the required average field at each radius. To allow for straightforward shimming of the sector angle, the sectors have been provided with removable side faces. The isochronous field is then obtained using an iterative procedure requiring three classical operations per step : field mapping, computing of the deviation from isochronism at a large number of radii and correction of the thickness of the removable side plates, subsequent remachining of the pole face side plates. The process is repeated until the computed RF-phase shift of the beam is below ± 10° up to an energy of 31 MeV for protons.

The result is an economical magnet with only 7.2 kW required to produce the nominal field. Beam tests have shown that the phase history is uniform and flat as computed. Interesting in this design is also that the field is relatively insensitive to current variations in the main coil : the tuning peak has a relative F.W.H.M. of 2×10^{-3} at maximum beam energy.

The RF system

The beam is accelerated by two 30° Dees at 65.5 MHz, corresponding to the 4th harmonic of the orbital frequency. The low loss RF-cavities are entirely located in opposite valleys. They contain the Dees which are supported on vertical lines resonating in a half-wavelength mode. Each cavity requires about 5 kW of RF power to obtain 50 kV on the Dee. The Dees are connected together in the centre below the median plane to allow space for the injection inflector. RF-power is fed to the system by a single 25 kW amplifier (10 kW for losses plus 15 kW for beam acceleration) installed near the median plane and directly coupled capacitively to one of the cavities.

Symmetrically, on the other cavity, the fine tuning capacitor is installed. The final 25 kW amplifier and the 2 kW driver amplifier use zero-bias grounded grid triodes. This design gives the system unconditional stability and high efficiency. Grid and screen-grid power supplies are eliminated.

Injection

H^- acceleration was choosen because of the obvious advantages related to the extraction by stripping of very high beam intensities and energy variability. However, internal negative PIG sources require high gas flow for the production of intense beams. At the same time a good vacuum is indispensable in the acceleration region to assure low loss transmission. To overcome these two conflicting requirements the H^- ions are produced in an external, differentially pumped, MULTICUSP[4] source and injected along the axis of the cyclotron. The source is biased at 28 kV, delivering 2 mA of H^- beam with 5 kW of arc power. Optical elements between the source and the median plane consist of a set of two 15° permanent magnet deflection magnets to separate neutral and H^- beams, an Einzel lens, a combined beam stop/profile measuring electrode, a two gap gridded buncher, a solenoid lens inside the cyclotron yoke to focus the beam at the inflector entrance and a pseudo-cylindrical (Pabot-Belmont) inflector.

The low injection energy combined with the relatively high acceleration mode (4th) and the high acceptance requirement led to an optimized design of the central region as shown on figure 3. All the gaps on the first turn are precisely confined by posts tó decrease transit time effects and to allow the particles to gain enough energy to get around the centre. The grounded part of the central region geometry is machined out of one single piece assuring mechanical stability and accuracy.

Using the RF-buncher, an injection efficiency of 35 % has been reached at an injected current level of 100 μA ; at 1 mA, 25 % efficiency has been reached with an injection voltage of 29 kV and a Dee voltage of 53 kV.

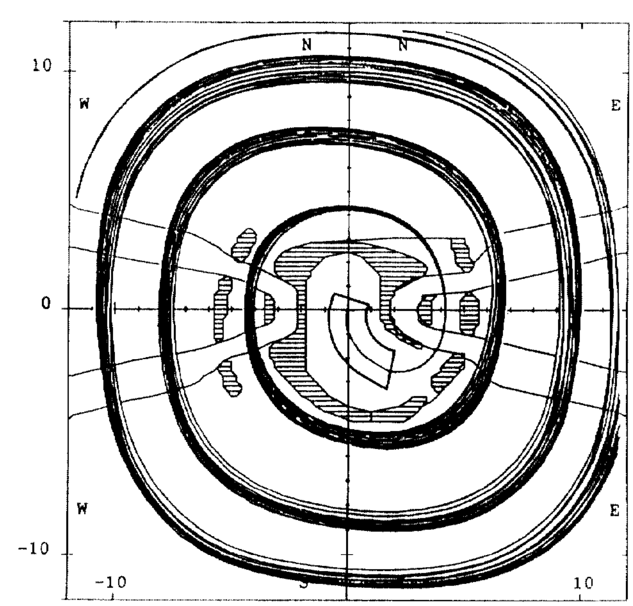

Fig. 3 : Central region layout.

Extraction

The extraction of the beam is based on H^- ions stripping, occurring when the H^- ions cross a thin carbon foil. The H^- ions are transformed into protons and bent out of the cyclotron by the magnetic field with essentially 100 % efficiency.

The stripping foils are mounted on two stripping probes, located on opposite sectors. Each probe is radially and azimutally adjustable, so that extracted beams at various energies are always directed towards the centre of the port selection magnets.

The strippers are made of carbon foils 40 $\mu g/cm^2$ thick or of carbon fibres to allow partial interception of the beam and extraction of two beams at different energy levels or different currents at the same time.

Each probe carries only one stripping foil, but is used with an air-lock and an automatic foil-changing mechanism, located outside the cyclotron yoke. The cyclotron does not have to be opened to change the foils and one set of foils allows 2000 hours of uninterrupted operation.

The extraction geometry and the relative positioning of the strippers on the sectors allow the beams to cross the sector edge at an angle closer to 90°, minimizing defocusing and higher order distortion associated with small angle crossings.

The path length in the magnetic field and the angle at which the sector edge is crossed vary as a function of extraction energy. It follows that the position of the virtual objects vary both in the horinzontal and the vertical plane. Table 2 shows measured values at different energies.

In any case, the beam characteristics are such that for production targets located near the cyclotron, no additional focusing is required.

E (MeV)	Plane	L_o* (cm)
30	HOR	83
	VERT	10
20	HOR	96
	VERT	31
15	HOR	133
	VERT	62

*L_o = distance between virtual object and centre of port selection magnet (upstream)

Table 2.

Control

The cyclotron is entirely controlled by a high level multi-processor- multilanguage industrial controller (SIMATIC[1]). The operator station includes a coulour graphic display, an industrial grade keyboard, two "virtual" knobs which are assigned by software to various cyclotron parameters, and a printer.

Normal cyclotron operation is fully automatic, and is based on a set of preset beams.

Operational experience has proven that this control system is extremely reliable, flexible and user-friendly.

[1] trade mark of SIEMENS A.G.

Beam			
type of ions :	- extracted	H^+	
	- accelerated	H^-	
energy (variable)		15-30	MeV
maximum intensity	- guaranteed	350	μA
	- expected	500	μA
number of exit ports : up to		10	
number of simultaneous extr. beams		2	
normalized emittance of the			
extracted beam	- horizontally	≤ 10	π.mm.mrad
	- vertically	≤ 5	π.mm.mrad
Power consumption			
at low beam power		≤ 60	kW
at full beam power		≤ 90	kW
Magnetic structure			
number of sectors		4	
sector angle (radially varying)		54-58	degrees
hill field		1.7	Tesla
valley field		0.12	Tesla
D.C. power in the coils		7.2	kW
iron weight		45	tons
copper weight		4	tons
R.F. system			
nber of dees (conn. at the centre)		2	
dee angle (effective)		30	degrees
harmonic mode		4	
frequency (fixed)		65.5	MHz
dee voltage (nominal)		50.0	kV
dissipated R.F. power	- per dee	5.5	kW
	- beam accel.	15.0	kW
Injection			
type of source (external)			"MULTICUSP"
filament power		0.5	kW
filament lifetime		≥ 200	hours
arc power		5	kW
H_2 flow		10...20	st.cc/min
source bias		28	kV
injected H^- current		2	mA

Table 1 : CYCLONE 30 parameters

Conclusion

Over the whole energy range (15-31 MeV), 350 μA stable have been extracted on target. The operation with two simultaneous beams both at equal and different energies, and at various current levels on each target has been tested successfully. Further development work mainly on the source and the injection system is going on to demonstrate the 500 μA goal.

References

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