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PERFORMANCE & PROSPECTS OF THE RECONSTRUCTED CERN 600 MeV SYNCHRO-CYCLOTRON

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The CERN 600 MeV synchro-cyclotron was reconstructed during 1973/74 by introducing a hooded arc ion-source, a rotary condenser designed to raise the Dee-voltage and pulse repetition rate and an extraction channel using a current-bearing septum. The rebuilt accelerator has been in operation since January 1975. Beam characteristics and recent performance data are presented and results of the acceleration of $^3He^{++}$ are briefly described.

Introduction

The reconstruction of the CERN 600 MeV synchrocyclotron, undertaken during 1973/74, was designed to raise the 1 μA internal beam and the 7% extraction efficiency of the former accelerator (SC1) each by an order of magnitude.

Details of the project[1,2] and first results on the performance of SC2 have been published.[3-7] This report updates this information to March 1977.

Present Performance

SC2 has been in scheduled operation since January 1975, totalling 2757 hours for physics in 1975 and 4141 in 1976. Reliability was initially poor but improved gradually, averaging 95% between October 1976 and February 1977.

A summary of recent performance data is given in Table I where SC1 is compared to the SC2 design and values achieved. The column "Optimum" refers to performance under specific test-conditions and the data do not form a consistent set. E.g. the highest extracted beam of 1.5 μA was produced with a 2 μA internal beam, while the best internal beam of 4.3 μA was not extracted.

The success of the reconstruction is illustrated by the extraction-efficiency of more than 70%, unprecedented for a synchro-cyclotron, by the number of protons per pulse, which has exceeded the design value and by the high duty cycle in long-burst operation. The average internal beam, however, is low since SC2 still operates at one out of N possible FM Cycles. At present a usual value is N = 4 chosen to limit the power dissipation in the rotary condenser, but modifications made to the spare condenser in 1976 are intended to permit operation at N = 2.

Secondary particle fluxes from internal and external targets are listed in Table II. They are normalised to 1 μC of protons incident on the target and agree satisfactorily with earlier estimates given in Ref. 2 except for the LEPC π^- beam.

Recent Progress

With the aid of diagnostic targets which permit measurements of the internal beam characteristics at various radii the intensity of the accelerated beam was measured as function of $\dot{f}_0$, the initial rate of frequency modulation. The results, shown in Fig. 1, disagree with an earlier calculation which suggested a strong dependence of the beam current on $\dot{f}_0$ below - 10 MHz/ms (see e.g. Fig. 8 of Ref. 7). The discrepancy was found to be due to a misinterpretation of the computed results, and

Table I

CERN SC Performance Data 1976/77

		SC1	SC2		
			Design	Optimum	Average 1976
Proton kinetic energy	(MeV)	598	600	604	604
Internal beam	(μA)	1	10	4.3	1.5
Betatron amplitudes					
radial	(mm)	80	10		~10
axial	(mm)	20	10		12
Extracted proton beam	(μA)	0.07	7	1.5	1
Extraction efficiency	(%)				
short burst		7	70	75	70
long burst		5	70	69	50
Extracted beam emittance					
horizontal	(mm.mr)	5π			5π
vertical	(mm.mr)	18π			6π
Radio-frequency					
maximum	(MHz)	30.6	30.4		
minimum	(MHz)	16.6	16.7		
df/dt max.	(MHz/ms)	0.5	11		5
Pulse frequency	(Hz)	54.1	466	120	85
Oscillator power	(kW)	20	200	30	22
Energy gain per turn	(keV)	2.7	30	24	20
Protons per pulse		1.2×10^{11}	1.3×10^{11}	2.2×10^{11}	1.1×10^{11}
Long burst, duty cycle	(%)				
internal targets		25	30		30
external targets		10	60	82	50

Table II

Observations of Secondary Particle Fluxes at SC2

Channel	Sign & SC Field	p (MeV/c)	$\frac{\Delta p}{p}$ (% FWHM)	Flux (μC^{-1})	Beam Spot (cm^2)	Beam Composition (%) π	μ	e	n	Prediction (μC^{-1})
LEPC	+↓	156	8	2.5×10^5	100	40	30	30		10^5 π^+
LEPC	−↑	156	8	2.1×10^5	100	44	30	26		5×10^5 π^-*)
125	−↓	300	6	5.5×10^5	27					3×10^5 π^-
μ	−↓	127	14	5×10^4	50	1	90	9		5×10^4 μ^-
B	0↓	~1200		2.1×10^6	30				100	1.5×10^6 n
B	0↓	≥ 200		2.6×10^8	380				100	
C	+↓	250		6.6×10^6	100	30	30	40		
C	−↓	300	5	1.2×10^6	5	~75	~5	20		1.3×10^6 π^-

*) at 180 MeV/c

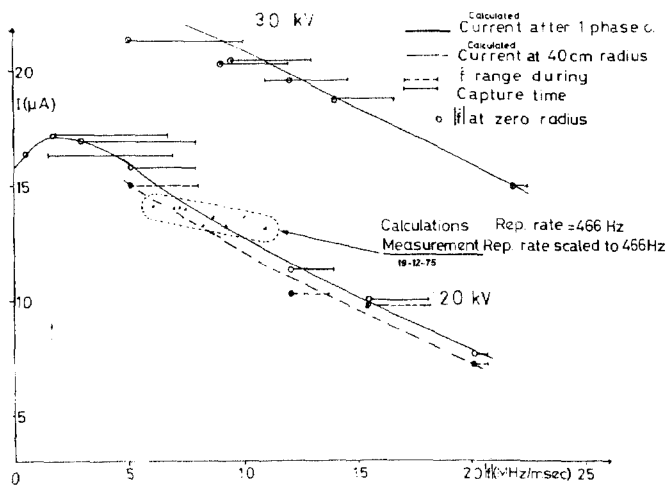

Fig. 1 - Internal proton beam as function of initial rate of frequency-modulation

there is now a satisfactory agreement between measurement and theory. Similarly the $V^{5/2}$ dependence of beam current on the Dee voltage V_D shown in Fig. 6 of Ref. 3 is seen in Fig. 4 to hold good only over a limited range, while for $V_D \geq 12$ kV the dependence is linear in accordance with theoretical predictions.[8]

A study of the beam-characteristics close to extraction has revealed a resonance between a beam stored at an orbital frequency of 16.9 MHz and an RF of 17.45 MHz appearing on the Dee. The nature of this phenomenon is not understood, but it was shown to be influenced by the radial position of the beam regenerator.

The time-distribution of the long-burst proton beam produced by the pulsed-field coils (PFC) (see Fig. 4 of Ref. 6) has been improved by using the Cee beam-stretching system instead of the Dee for the final stage of acceleration prior to ejection by the coils. Under present conditions of Dee operation at N = 4 this method also leads to a significant gain in duty-cycle. With both long-burst systems working in cascade at a repetition frequency of 360 Hz and the Dee system pulsed at 90 Hz an overall duty-cycle of 45% was observed, compared with 15% when using the PFC alone.[9]

The duty-cycle of this mode of operation has been further improved by the use of a transistorized current supply[10] instead of the thyristor supply described in Ref. 2. By suitably modulating the current the overall duty-cycle of the extracted beam was raised to 82%, the beam intensity being about 60% of that obtained in short burst.

Problems

In spite of three years' development work the rotary condenser has continued to be the principal cause of breakdowns. While RF, drive and control problems no longer affect operation at the present level of RF - power vacuum and mechanical troubles have limited the performance of the system during the past year and caused two prolonged suspensions of operation.

Intermittent leaks and a progressive misalignment of the rotor of condenser No. 1 necessitated a reduction of the Dee-voltage during several months of 1976 but these defects were remedied during the past year by minor modifications. Condenser No. 2, on the other hand, required a major intervention when, after eighteen months of successful operation and a subsequent overhaul, there was a sudden increase in the vibration-level of the rotor.

This defect was traced to a cracked insulating bushing protecting the ball-bearings. A dimensional check during dismantling showed various manufacturing faults and the 300 mm diameter bushing had to be replaced. To avoid a recurrence of the defect and to achieve greater reliability the alumina rings constituting the bushing were replaced by an assembly of 20 mm diameter rods shrunk between two steel rings. The new design is shown in section in Fig. 2. Its construction involved the remachining of the 340 mm diameter bore holding the assembly to a tolerance of 15 μm and a subsequent rebalancing of the rotor. This work has now been completed and the rotor has performed satisfactorily on test.

The 220 mm diameter rotary face seal, which separates the ball-bearing space from the high vacuum region of the condenser, is another weak element, many seals having shown excessive oil leakage without an identifiable reason. It is likely that the condensers still contain other hidden defects, whose identification will require much time and effort.

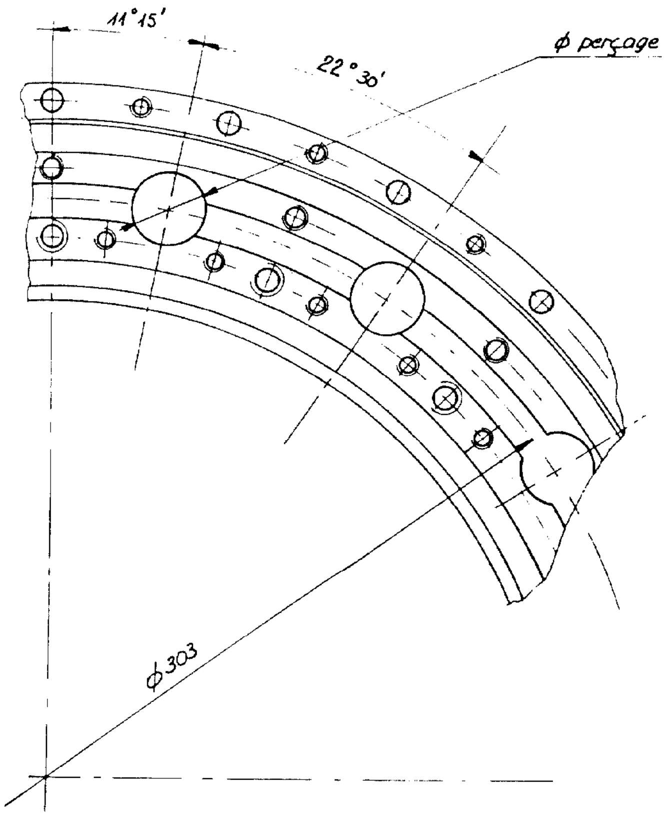

Fig. 2 - Rotor bushing with insulating rods

Prospects

There is nevertheless good reason to believe that the limitation of the beam current to 2 μA will gradually be lifted with the improving performance of the condensers. A current of about 4 μA, achieved under test with N = 3, should be available for operation in 1977 unless new defects come to light. The achievement of the full design current will still require much work, but meanwhile SC2 is able to supply protons for challenging physics programme ranging from particle-physics via the study of unstable nuclei to solid-state and biophysics.

To facilitate beam changes around the external pion production target and to reduce doses to personnel a new beam-layout has been designed. This will permit directing the extracted proton beam either onto the external pion target or into the underground experimental area without moving any beam elements or vacuum connections and will result in a gain of physics time.

The prospects for research are further enhanced by a modification designed to adapt SC2 to the acceleration of $^3He^{++}$ ions. The elements required for tuning the RF system to a frequency-range of 20-14 MHz have been designed and are being manufactured.[11,12] An attempt to test the production of $^3He^{++}$ ions in the present proton-source and their acceleration to 400 MeV was made in November 1976. It showed that it was possible to produce $^3He^{++}$ in adequate quantity and to accelerate them by using the low-frequency end of the proton cycle between 20.2 and 16.7 MHz.[13]

By raising the arc-current of the source from 1 A used for protons to 20 A, a 2 μA beam of $^3He^{++}$ was obtained at 58 cm orbit radius. With 17 kV Dee voltage 50 to 80% of this beam reached 400 MeV. The beam intensity as function of arc-current is shown in Fig. 3 and as function of Dee voltage in Fig. 4. The irradiation of a carbon target at 1.4 m radius showed a beam height of about 2 mm. The captured charge per pulse agrees with a theoretical prediction.[14] One may therefore assume that the modification of the radio-frequency resonator will suffice to produce a $^3He^{++}$ current of at least 1 μA at 914 MeV.

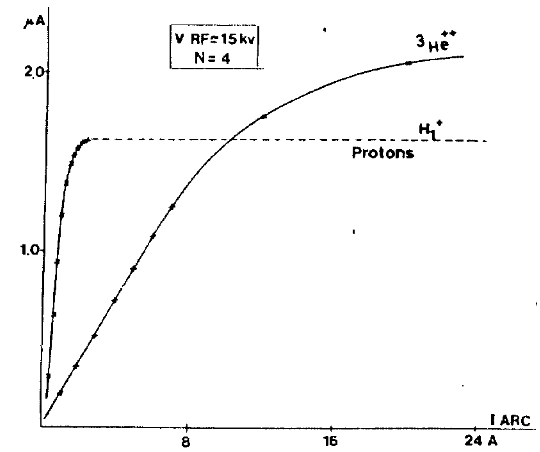

Fig. 3 - $^3He^{++}$ current as function of ion-source arc current

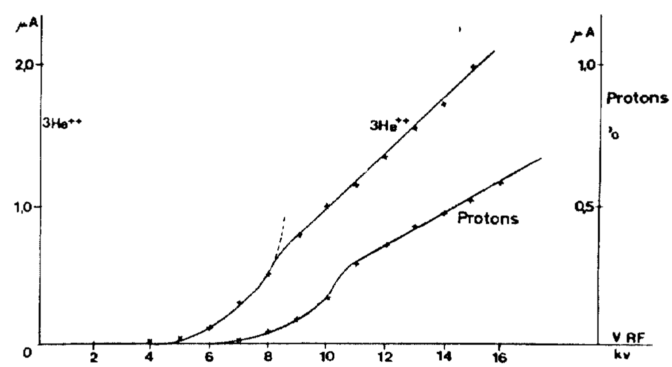

Fig. 4 - Proton & $^3He^{++}$ currents as function of Dee voltage

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