Status Report on the CERN Synchrocyclotron Improvement Programme

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ABSTRACT

In order to increase the internal beam current of the CERN SC from its present value of $\sim 1\ \mu A$ to $\sim 10\ \mu A$ and to improve its radial quality, the pulse repetition rate will be raised from 54 Hz to ~ 500 Hz and the dee voltage increased to 30 kV and the present open Penning source will be replaced by a hooded arc source. The principal features and the expected performance of the design are outlined and the modification of extraction and pulse stretching are indicated.

1. INTRODUCTION

In common with other projects raising the beam intensity of synchrocyclotrons the CERN SC improvement programme relies on the use of a hooded arc source, a narrow-gap geometry and an increased accelerating voltage. These were first proposed by McKenzie[1,2] as means of overcoming the space charge limitations of the conventional open ion source. Practical experience with accelerators[3,4] and central region studies[5,6,7] have shown the effectiveness of such an arrangement. Its adoption still leaves several possibilities for further acceleration, i.e.

(1) retention of weak focusing and full range frequency modulation,
(2) partial isochronism with limited sector focusing,
(3) full isochronism, i.e. conversion to a relativistic cyclotron.

The merits of the different solutions have recently been compared by Blosser.[8] He showed that conversion to isochronism need not lead to a drastic loss of maximum energy and that its difficulties are not necessarily greater than those of options (1) and (2).

CERN has adopted the first possibility. The reasons for this choice and the basic concepts of the project have been outlined in a number of documents.[9,10] These show that the principal motives for CERN were the wish to limit the length of the shutdown needed for a modification, the decision to retain internal targets and the present beam layout, and the conviction that the existing installation would make it difficult to use the higher beam currents potentially furnished by a partially or fully isochronous machine.

The continued use of internal targets appears justified in view of recent measurements[11,12] showing that their efficiencies are considerably higher than previously assumed,[13] while the efficiencies of external targets must be limited to a few per cent if good secondary optics and resolution are required.

2. BASIC CONCEPTS FOR THE IMPROVEMENT OF THE CERN SC

2.1. *Aims*

The aims of the CERN design is a machine

(1) capable of accelerating about 10 times the present number of protons to the present energy of ~600 MeV,
(2) fitted for operation with internal targets and an extracted proton beam,
(3) possessing an extraction efficiency large compared with the present 5-7%,
(4) providing beams of large and possibly also of very small duty cycle,
(5) capable of being used and serviced for a period of five to ten years.

2.2. *General features*

The principal characteristics and the main numerical parameters of the project are listed in Table 1. Some details on the design and performance of individual elements are given in the following sections.

3. PRESENT STATUS

3.1. *Ion source*

Galiana[14] has obtained instantaneous proton currents of the order 100 mA from hot cathode sources of the dimensions given in Table 1. Limitations arising from filament lifetime have been overcome by new types of composite and coaxial filaments, the latter avoiding electrical torques during pulsing.

The improved machine will have the source mechanically integrated into a rigid source assembly comprising the source itself, the puller electrode or electrodes, and the conical accelerating electrodes out to a radius of ~6 cm where electrical contacts are made with the dee and dummy dee (see Fig. 3, reference 14). This source assembly is positioned by and supplied through a vertical support of eccentric cylinders introduced through an axial hole in the lower pole face.

Various source assemblies have been tested in the CERN SC Central Region Model using rf extraction. This places the source off-centre and requires different assemblies for field-up and field-down operation.

A d.c.-biased source capable of operating with the magnetic field in either direction[15] is under study.[14]

Table 1. CHARACTERISTICS AND BASIC PARAMETERS FOR THE IMPROVED CERN SC

Maximum proton energy:	600 MeV		
Average internal current:	10 μA		
Magnetic field (reversible):			
At centre	19·7 kG	At extraction radius	18·1 kG
Extraction radius	2·25 m	K value for $r < 0{\cdot}2$ m	2
Ion source:			
Hot cathode hooded arc, rf extraction, axial support, and positioning.			
Outer diam.	6 mm	Chimney slit	1 × 10 mm^2
Inner diam.	4 mm	Arc current	2 to 5 A
Plasma column diam.	2 mm	Pulse length	~35 μs
Rf system:			
Modulation range	30·0–16·77 MHz	Peak accelerating voltage	30 kV
Acceleration time	1383 μs	$(df/dt)_{min}$	−15·65 MHz/ms
Repetition rate	466 Hz		
Adiabatic beam stacking between 16·87 and 17·30 MHz.			
Resonator:			
$\lambda/2$ capacity loaded, modulated by rotary capacitor, electrical length ≈5 m.			
Characteristic impedance: maximum 25 Ω, minimum 2 Ω.			
Rotary capacitor (3 rows of 16 teeth):			
Outer diam.	1·5 m	Voltage at minimum gap	15 kV
Rotor speed	1747 rpm	Electrical gap	1 to 4 mm
Maximum voltage	35 kV	Capacitance	0·5 to ~7 nF
Coupling capacitor to stub:			
Constant capacitance	20 nF	Electrical gap	0·3 mm
Oscillator (self-excited tetrode, amplitude modulated):			
Variable coupling capacitor to oscillator:	max. ≈700 pF, min. ≈100 pF		
Constant voltage at oscillator:	10 kV		
Maximum oscillator power:	150 kW		
Main dee:			
180° to r = 0·6 m.			
Cut back by 15° at 0·6, 0·95, and 1·3 m from vertical symmetry plane.			
Aperture: 60 mm for $r < 1{\cdot}89$ m, 120 mm in target region.			
Maximum radius	2·35 m	d.c. bias	~2 kV
Central dummy dee:			
Radius	0·40 m	d.c. bias	as main dee
Internal targets:			
Universal target ranges: radial 2·0–2·3 m, azimuthal 42°.			
Extraction system:			
Non-linear regenerative, first channel section electromagnetic, others iron. Regenerator 56° behind channel entrance, computed efficiency $\lesssim$85%.			
Electromagnetic section:			
Septum thickness	2·5 mm	Field reduction	2 kG
Current	12 kA	Power consumption	~86 kW

Table 1. CHARACTERISTICS AND BASIC PARAMETERS FOR THE IMPROVED CERN SC *(continued)*

	Peripheral cee:		
Single sweep operation (provisional design).			
Dimensions: angular	45°	Modulation range	~160 kHz
radial	200 mm	Tuning range	16·87–17·30 MHz
Axial aperture	120 mm	Power consumption	~50 kW
Stacking radii	2·15–2·25 m	Installed power	~100 kW
Peak voltage	~18 kV		
	Extraction coil (provisional design):		
Angular extension	18°	Peak current	~3·2 kA
Axial aperture	120 mm	Peak magnetic field	200 G
Slow operation:		*Fast operation* (1 μs):	
Peak voltage	30 V	Peak voltage	16 kV
Power consumption	5 kW	Power consumption	40 kW
	Expected proton beam properties:		
Long burst extracted proton beam:			
By cee:		*By coil:*	
Energy spread	0·5 MeV	Energy spread	$\lesssim$3 MeV
Micro duty cycle	10–20%	Micro duty cycle	100%
Macro duty cycle	80%	Macro duty cycle	85%
Emittances: radial <15 mm mrad, vertical <25 mm mrad.			
Short burst extracted proton beam by coil:			
Pulse length	1 μs	Energy spread	$\lesssim$3 MeV
Duty cycle	0·05%		
Long burst on internal targets by cee:			
Duty cycle	10–20%		

3.2. *Central region studies*

The behaviour of the beam in the central region has been subject to extensive theoretical studies[16–20] and various geometries have been designed with the aim of optimising the range of rf phases available for capture. Several assemblies have been tested experimentally in the Central Region Model,[7] where beam intensities somewhat in excess of the calculated values have been observed. Recent measurements have given equivalent currents of ~20 μA for the improved SC.

Shadow measurements of radial betatron amplitudes at 22 cm radius confirm the existence of an amplitude build-up introduced by a movement of the orbit centre at small radii and large phase angles.[7] This effect may be weakened at the expense of internal beam current and technical difficulties in the rf system by operating with initial equilibrium phases φ_S at values of cos φ_S larger than 0·1 at which the beam current is optimised.[7,17]

3.3. *Rf system*

The new main rf system has to furnish 30 kV on the dee gap over a frequency range from 30·0 to 16·7 MHz with a repetition rate of ~500 Hz. To comply

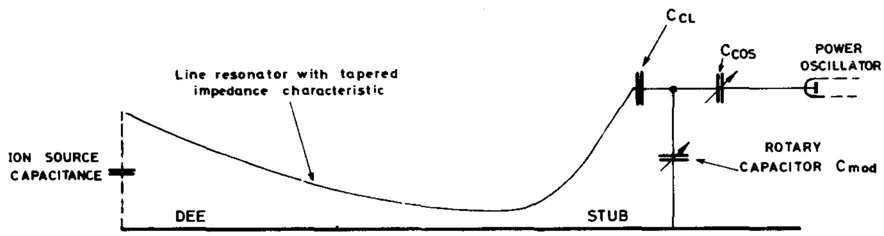

Fig. 1. Principal equivalent circuit for the new rf system

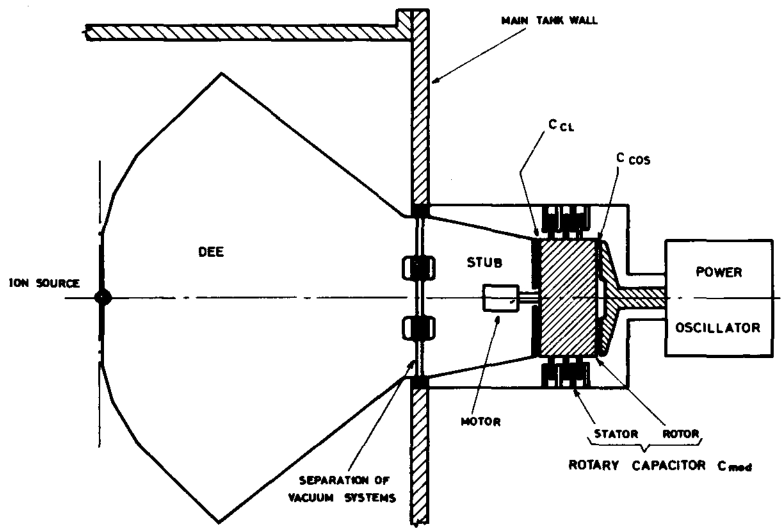

Fig. 2. Principal mechanical arrangement for the new rf system

with these requirements a system based on a rotary capacitor of a rather sophisticated design has been proposed.[21-24]

To minimise the dee capacity the cut-back form indicated in Table 1 was adopted. Computer studies have shown that the proposed form does not give a significant contribution to the radial betatron amplitude such as has been predicted and observed at the Harwell Synchrocyclotron.[25]

Fig. 1 shows the equivalent circuit of the rf system. In it the dee and dee stem are represented by a transmission line with a carefully designed tapered impedance distribution, into which the rf power is fed through a system consisting of the rotary modulation capacitor C_{mod} and the rotary coupling capacitor C_{cos} synchronised on the same shaft, and the fixed coupling capacitor C_{CL}. The role of C_{cos} is to provide a constant load to the oscillator over the whole frequency range. A schematic view of the layout is shown in Fig. 2.

The designer's problem is to find an impedance distribution in the line section which achieves the required variation of the resonant frequency (see Table 1) for practicable values of C_{mod} while keeping the potentials across the capacitors within tolerable limits. Numerical studies of the problem have provided a range of acceptable solutions, of which some have been tested on a one-fifth scale model of the entire system. A separate study of breakdown phenomena in rf fields has shown that the calculated potentials across the small capacitor gaps can be maintained if suitable precautions are taken with regard to the surface treatment of the electrodes and by avoiding traces of hydrocarbon vapours in the vacuum. The latter necessitates a separate turbomolecular pump system for the rotary capacitor.

The shapes of the stator and rotor blades have been chosen to provide a frequency vs time function (Fig. 3) which fulfils the following three requirements[26] (Fig. 4):

(1) cos φ_s should start close to its theoretical optimum, 0·1.

(2) In order to be sure to retain all captured particles, even in the presence of unforeseeable errors, the canonical bucket area A should be given a 5% increase during the first 100 μs and a further 5% increase during the rest of the modulation cycle.

(3) The flyback time should be as short as technically feasible.

Provisions will be made to deposit the beam adiabatically at a radius chosen within certain limits for further acceleration or displacement by one of the proposed beam stretching devices.

A study of the beam loading problem is envisaged. As a preliminary a theoretical model capable of describing the various cross modes in the cut-back dee has been worked out.[27] A study to define the local impedances of the dee is in progress.

The observation of parasitic resonances in the one-fifth scale model[28] necessitated the redesign of the rotary capacitor, which is now cantilevered and fed coaxially. Its design also attempts to minimise the rf currents flowing through the ball bearings by letting these be parts of bridge circuits.

The manufacture of the entire accelerating system, consisting of oscillator, modulator, rotary capacitor, and resonator, including the dee, is being undertaken by a contractor. Delivery is scheduled for August 1971 and will determine the date of the shutdown.

3.4. *Beam extraction*

Beam extraction by a non-linear regenerative system in weak focusing

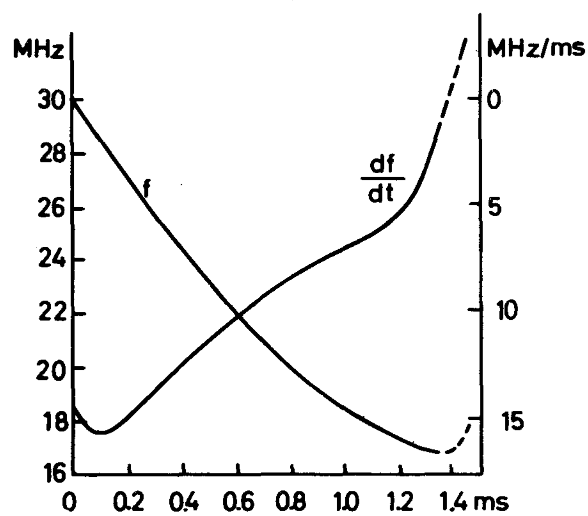

Fig. 3. Frequency vs time function for the improved CERN SC. It is chosen to minimise the acceleration time (1·383 ms)

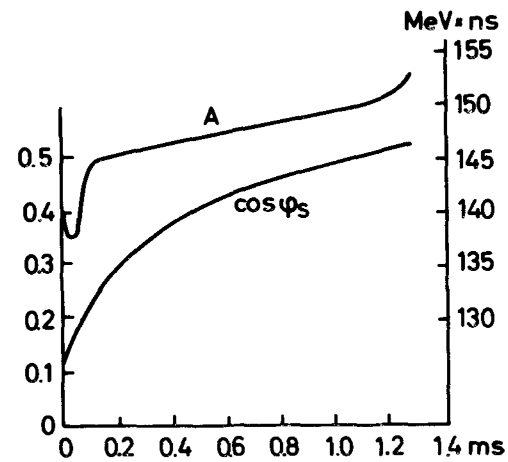

Fig. 4. Bucket parameters for the improved CERN SC. The bucket area A *(right scale) is chosen to increase by 10% over the acceleration period. The resulting cos φ_s (left scale) rises from 0·13 to 0·52. The small minimum in the* A *curve stems from the desire to have a smooth* f(t) *curve (Fig. 3)*

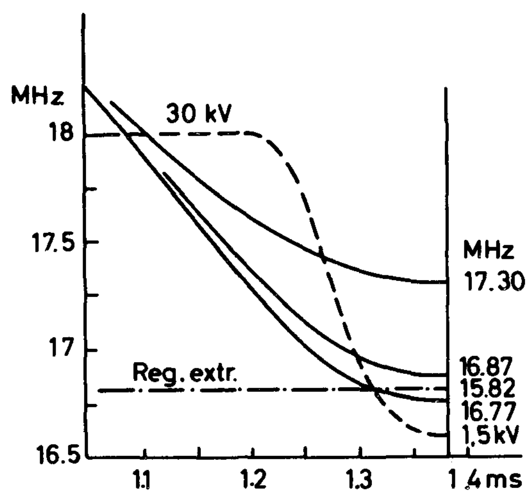

Fig. 5. Details at end of acceleration period showing the nominal rf vs time (lower full curve) as well as frequency (upper full curves) and voltage (dashed curve) functions for adiabatic stacking. The regenerative extraction occurs at 15·82 MHz

synchrocyclotron fields has been subject to orbit studies by Paul[29] and by Lindbäck,[30] who have shown the deleterious effect of pre-existing betatron amplitudes and of field distortions in the vicinity of the magnetic channel.

The present betatron amplitudes $A_r \sim 10$ cm and $A_z \sim 1{\cdot}5$ cm observed in the CERN SC should both be reduced to less than 1 cm with the introduction of the calutron source. According to Lindbäck this alone would at least double the extraction efficiency and improve the energy resolution of the extracted beam considerably.

A further gain can be expected if the strong disturbance of the field near the channel can be avoided, since it leads to a rapid growth of the vertical amplitude in the last turn before extraction. To minimise the effect of the stray field we therefore plan to use an electrical channel of coaxial type similar to that proposed by Morpurgo[31] in the first section of the extraction channel.

A tentative design of a curved concrete insulated channel has been made by Susini and Giannini.[32] Copper conductors are arranged to produce a field distribution similar to that of a coaxial cable; a 2·5 mm septum and an anti-septum produce stray field cancellation. A similar channel has been proposed by Cohen *et al*[33] for the Columbia SC.

Blosser[8] has recently suggested preceding the magnetic channel by an electrostatic deflector and has predicted extraction efficiencies of up to 80% for such a system. Unfortunately the presence of internal targets and the associated beam transport makes the adoption of this idea difficult at CERN.

3.5. *Long and short burst*

Long burst operation is at present provided by a peripheral cee operating on the beam deposited at storage radius by the main rf. Duty cycles exceeding 30% are obtained with internal targets; for the extracted beam 10% is a normal value. The capture efficiency of the cee is about 50–60%. A pulsed magnetic field perturbation, such as the system developed by Danilov *et al*[34] at Dubna is considerably more efficient and produces an output free from rf structure.

However, it is difficult at the CERN SC to find a coil position which will give a long burst operation for internal targets as well as for the extracted proton beam. Our coil will be positioned for proton extraction opposite the regenerator.

Lindbäck[35] has shown that the capture efficiency of a cee system can be large (90–100%) if the beam storage is performed by reducing both the rf voltage and frequency slope adiabatically to zero (Fig. 5). Provided that the radial amplitudes in the stored beam are <1 cm the cee will be capable of giving an extracted beam of greatly reduced energy spread ($\approx 0{\cdot}5$ MeV).

In an attempt to combine the advantages of a cee system and a pulsed coil Susini[36,37] has recently proposed to place a pulsed coil inside a cee. Operated with a suitable power supply such a coil would also permit a very fast beam ejection in ~ 20 turns ($\sim 1\ \mu s$). This possibility is of interest for very low count-rate experiments in which the background is not due to the machine.

3.6. *External beams*

The external beam system of the CERN SC is highly developed and we do not envisage any fundamental change. However, most beam lines will have to be re-designed; to permit servicing of the beam transport elements we plan to place them on rails and to withdraw them through the shielding wall. We shall use this opportunity to add an inflector magnet to the present low-energy pion beam from internal targets, thereby increasing its versatility. We are also studying the possibility of very low energy pions from an external target. Pion beams of good quality of 50 MeV or less would have considerable research potential. Present beam intensities, which are of order 10^5 particles/s for pion beams and 5×10^{11} for the extracted proton beam should increase by an order of magnitude. We hope for larger gains in the extracted proton beam and secondary beams derived from it.

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