REPORT ON THE CERN SC IMPROVEMENT PROGRAMME

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Abstract

The essential features of the reconstructed CERN 600 MeV Synchro-Cyclotron are a hooded-arc mid-plane ion source, a radio-frequency system modulated between 30.4 and 16.7 MHz at about 450 cycles per second, and an electro-magnetic extraction channel designed to extract over 70% of a 10 µA internal proton beam. Preparation of the material required for the reconstruction was started in 1967. The transformation of the synchro-cyclotron and of its associated equipment was carried out between June 1973 and September 1974. The principal phases of the reconstruction and recommissioning are described, and performance data of CERN SC2 are presented.

1. Introduction

The project for the modification of the CERN 600 MeV Synchro-Cyclotron has been described in many documents[1]-[4]. Papers submitted to earlier cyclotron conferences include a general description of the project[3], accounts of preliminary studies [5][6][7] and a status report of the work[4], giving details of the principal elements then under construction.

The principle of the modification, which consists in the replacement of the open ion-source conventionally used in synchro-cyclotrons by a mid-plane source, was suggested by one of the authors in 1963[8]. McKenzie's analysis of the factors limiting the beam intensity and extraction rate of synchro-cyclotrons[9][10], the development of efficient small-diameter hooded-arc ion sources[11] and the successful use of such a source in the Orsay 157 MeV Synchro-Cyclotron[12] demonstrated the feasibility and usefulness of such a modification. A number of projects for synchro-cyclotron (SC) improvement were based essentially on this concept. Of these the modification of the Harwell 110-inch SC[13] was carried out during 1968 and work is in progress at Nevis[14][15][16], JINR Dubna[17] and Orsay[18].

Dubna and Nevis based their design on an azimuthally varying field, the "sector focused synchro-cyclotron" first proposed by the Uppsala Group[19], while the CERN design, in common with those of Harwell and Orsay, is based on the axially symmetrical, weak focusing field of the conventional SC. The arguments relevant to this choice have been summarized by McKenzie[20]. Experience at Harwell, Nevis and CERN shows that both kinds of concept can be made to work. Aware that the choice of a weak focusing field would render the RF design more difficult CERN chose this solution in the hope that it would simplify the mechanical structure of the magnet and shorten the shutdown required for a conversion.

2. Technical Features

The technical features of the CERN modification are summarized in the following paragraphs. Details are given in the references quoted.

- A hooded arc source of 6 mm external diameter is mounted between two conical electrodes attached to the dee and dummy dee respectively. The assembly of ion source and "central geometry" is designed for optimal focusing and phase acceptance. It is introduced into the accelerator via an axial support and positioned by a system of eccentric gears. Refs: [4][6][21][22].

- An accelerating potential of 30 kV peak, frequency - modulated between 30.4 and 16.7 MHz at a repetition-rate of up to about 450 Hz, is provided by a self-excited, mechanically-tuned resonator. The mechanical tuning element is a rotary capacitor (rotco) formed by three rows of sixteen rotor teeth and four rows of stator blades shaped so as to obtain an optimized frequency programme throughout the cycle and a minimum flyback time. A spare system consisting of oscillator, rotco and electronics is held in readiness on a dummy load. By suitable adjustments, the RF system allows adiabatic beam-stacking prior to long-burst operation. Refs: [4][23][24][37].

- Regenerative beam extraction is effected via a magnetic channel whose first element is a current-bearing septum of 3 mm thickness and whose stray field is compensated by a number of auxiliary conductors. Refs: [4][5][25].

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- Radiation-cooled internal targets capable of independent movements in three dimensions are designed for use with an internal beam current of up to 20 μA. Refs: [4] [26].

- Secondary acceleration of stacked beams by a peripheral cee electrode produces long bursts on internal targets at an overall duty cycle of 10-20%. Long-burst operation of the extracted beam is possible with high energy resolution at an overall duty cycle of 8-15% via the cee and with a duty cycle of 70% (but with an increased energy spread) via a pulsed field coil. Ejection of the stored beam in about 1 μs can be produced by mounting a "fast kicker coil". Refs: [25] [27] [28] [29].

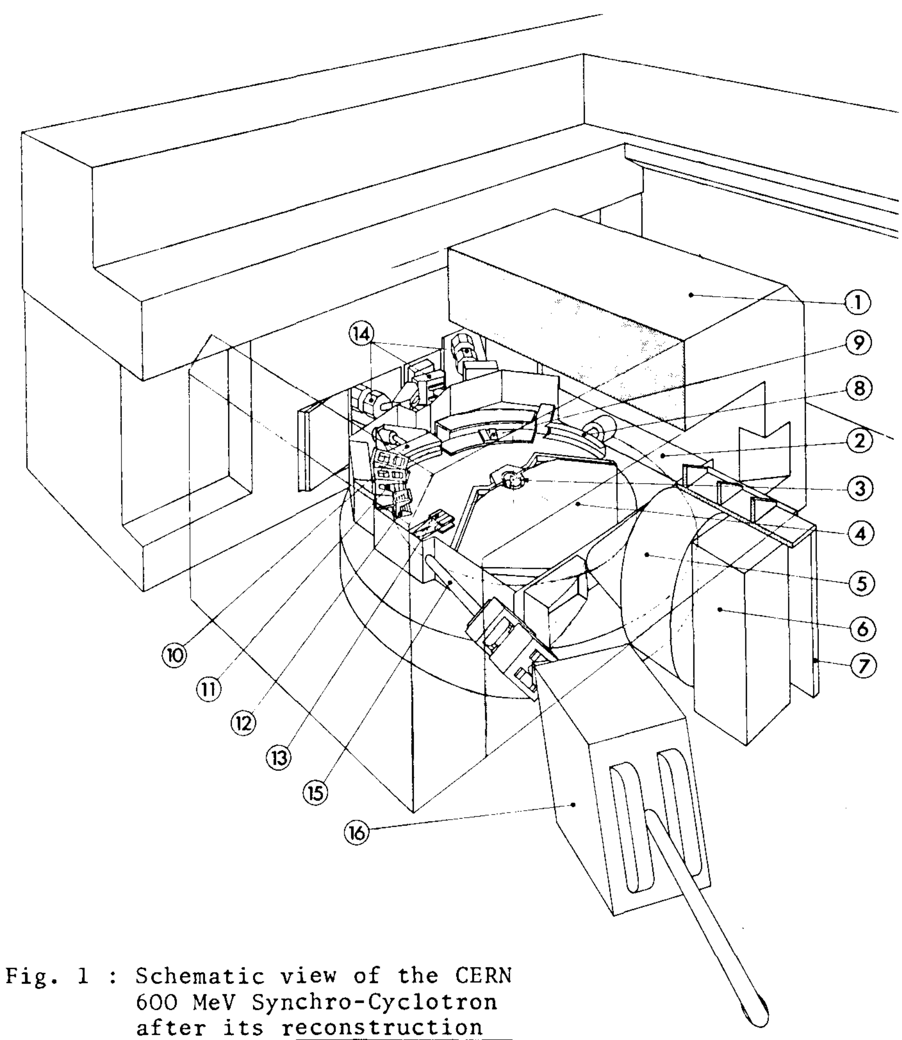
- All vulnerable elements lodged inside the vacuum tank, e.g. ion source, dee, targets, extraction channel and cee are removable from outside the tank to permit servicing despite the high activation produced during operation. Beam elements in the immediate vicinity of the machine are mounted on rails and can be withdrawn from the SC Hall for servicing. Ref: [4].

Fig. 1 gives a schematic view of the various elements installed at the SC.

3. The Reconstruction of the SC

3.1 Preparations

As finally constituted the project for the reconstruction of the SC involved not only the design, manufacture and installation of the elements listed in the preceding section but also the construction of three new buildings, the design and manufacture of a new vacuum-chamber, of new main field coils and pole-face shims and of the equipment necessary to drill a 22 cm diameter axial hole through the poles and the yoke.



(1) Yoke
(2) Vacuum Tank
(3) Ion Source
(4) Dee
(5) Rotary Capacitor
(6) RF Generator
(7) Magnetic Shielding
(8) Peripheral Cee
(9) Internal Targets
(10) Electro-Magnetic Extraction Channel
(11) Passive Magnetic Channel
(12) Regenerator
(13) Pulsed Field Coil
(14) Secondary Beams from Internal Targets
(15) Extracted Proton-Beam
(16) Vertical Bending Magnet

Fig. 1 : Schematic view of the CERN 600 MeV Synchro-Cyclotron after its reconstruction

Although the magnetic field configuration remained basically unchanged there was a need for an extensive programme of field measurements in order to establish and, if necessary, to correct the modifications of the field caused by the axial hole, the extraction channel and the magnetic shielding required for the rotary condenser. Since the time needed for these measurements enters directly into the length of the shutdown, care was taken to minimize it by preparing elaborate equipment for data taking and handling. Details are given in Ref. [30]).

The project further necessitated a complete reconstruction of the cable network, involving the removal and testing of all existing power and control-cables, the mounting of new cable trays and the installation of 235 km of cable using, wherever possible, recuperated material. Similarly the cooling network had to be modified and extended by the addition of new circuits. The shielding walls had to be strengthened and the system of secondary beams was entirely remade with a view to reducing personnel exposure to radiation during beam changes; where possible the opportunity was used to improve the yield and quality of secondary beams.

With the exception of the RF system all design work was performed at CERN, manufacture being mostly entrusted to industry. The radio-frequency system was designed and manufactured by industry on the basis of a CERN study. Difficulties encountered by the contractor delayed the project and the final testing and commissioning of the system was performed under CERN's responsibility with contractor's help[24]). The delay was used to complete and test many other elements and to prepare a detailed planning schedule for the transformation.

As far as possible all equipment required for installation during the shutdown was prepared and tested in advance. Network and critical-path planning techniques were applied in several cases so as to gain the experience necessary for the planning of the conversion, for which the work was first planned on a weekly and ultimately on a daily basis, using a CERN PERT computer programme. This programme was updated weekly; the output was distributed in the form of bar-charts and job lists. Particular care was taken in planning work in congested zones e.g. the SC bunker or the service areas. For these the engineer in charge of the work on the critical path was appointed to act as "site captain" and was empowered to make minor adjustments to the planning on the spot.

3.2 The Shutdown

The old SC was shut down on June 7th, 1973. It thereby escaped the ignominy of being put out of action by a flood which occurred a few days later. The magnet was ready for tests in November, having been dismantled, drilled, reassembled and fitted with the new coils and vacuum chamber. First vacuum tests revealed a major leak in a support ring carrying a flexible membrane between vacuum tank and magnet poles (see Fig. 2.3.1 in Ref. [4])). After repair it was decided to install a second membrane and to provide inter-joint pumping for added safety.

The required magnetic field at the centre was reached in two measuring and shimming-cycles, but it proved more difficult to reach the prescribed field configuration in the extraction region on account of many perturbing elements. Magnet measurements alternating with shimming and vacuum tests therefore occupied the first half of 1974. At the same time the ion-source and its support underwent final tests prior to installation and work on the RF system advanced sufficiently to permit a measurement of the frequency modulation programme under operating conditions of the rotco. The results showed that, with the nominal magnetic field, the capture and accelerating conditions were such that the design current could be exceeded and that there was no immediate need for the remachining of the rotco stator blades foreseen in the programme.

Vacuum tests of the dee revealed corrosion leaks of the copper-clad roll-bond aluminium plates used in the construction. After a temporary repair the installation of the RF System at the SC was completed in September and the first protons were accelerated on September 30th, 1974; they reached the design energy as the probe target used for beam monitoring was moved to full radius.

The beam extraction equipment was then installed and, after measurements of the spectrum of radial amplitudes, beam extraction was attempted and immediately achieved on November 21st, 1974.

The first protons were supplied to physics on December 17th; since then the machine, now called SC2, has been giving an increasing proportion of its time to physics experiments except for a two months' shutdown required to remove and replace the leaking dee panels. At present the machine operates on a weekly schedule of 21 eight-hour shifts, of which fourteen are used for physics, four for machine development and three for maintenance and cooling. About a third of the time has been lost through breakdowns.

4. Performance and Characteristics of SC2

4.1 Modes of Operation

While the RF System of SC2 is laid out for a peak dee voltage V_D of 30 kV, it has mostly operated at about V_D = 20 kV, which is sufficient to accelerate the design current. Operation was started with central electrodes optimized for V_D = 25 kV; these were later replaced by a central geometry designed for V_D = 15 kV.

The rotco was run at a pulse repetition rate f_R between 350 and 466 Hz, but the system was energized at one pulse in N, making the rate of output pulses f_R/N. For tests N = 16 is often used; present physics operation usually employs N = 5 but N = 2 has been used on occasion.

4.2 Basic Parameters

Fig. 2 shows the proton resonant frequency F corresponding to the magnetic field B(R) of Fig. 3.

$\dot{F}$ of Fig. 2 is the measured rate of frequency modulation under certain conditions of adjustment and at f_R = 350 Hz.

The value of the bucket parameter $\cos\phi_s$ for f_R = 350 Hz and V_D = 20 kV is indicated in Fig. 3. Fig. 4 shows the stable area in synchrotron phase space or "bucket area" for various values of f_R and for V_D = 20 kV; it suggests the possibility of a particle loss during acceleration between R = 1.0 and 1.8 m, whose occurrence was confirmed experimentally.

4.3 Internal Beam

The accelerated beam is measured with a charge-probe at R ≤ 60 cm, where the response is independent of radius. Fig. 5 shows the results of internal beam measurements as function of various parameters. The beam is seen to vary linearly with the RF duty cycle 1/N and the graph suggests that a beam of 7.5 μA would be accelerated at the full pulse rate (N = 1) and under the conditions indicated.

Similarly I_{int} varies linearly with the ion-source arc current over the range shown; extrapolating to N = 1 one obtains I_{int} = 7.6 μA for I_{arc} = 1.2 A.

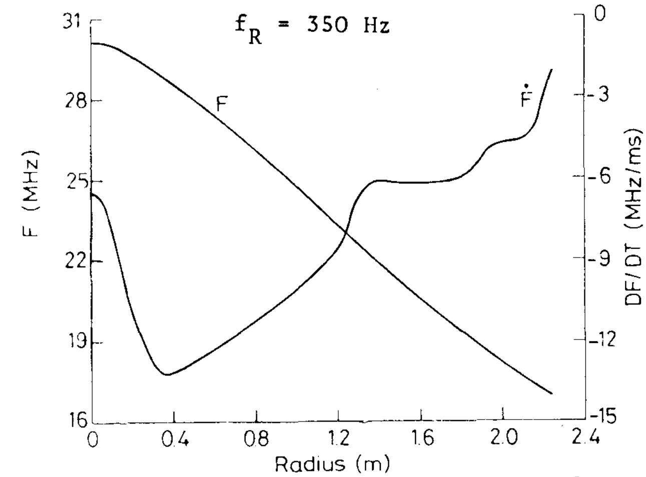


Fig. 2 : Resonant frequency and rate of frequency modulation at f_R = 350 Hz as function of radius

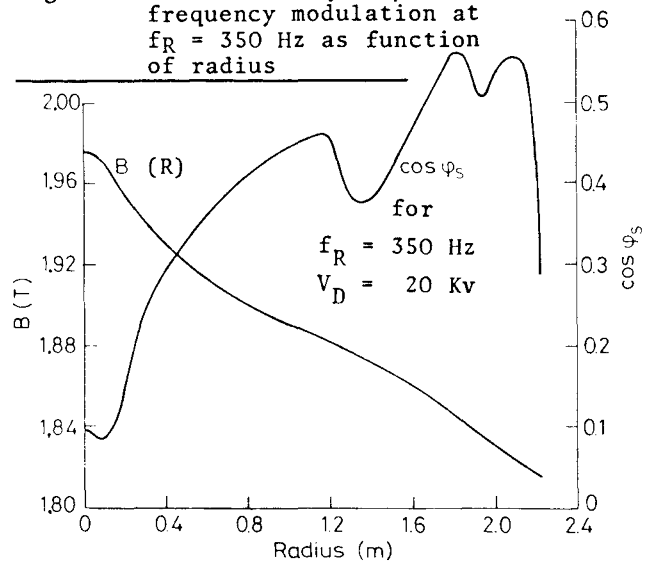


Fig. 3 : Magnetic field of SC2 and the cosine of the synchronous phase angle for f_R = 350 Hz and V_D = 20 kV as function of radius

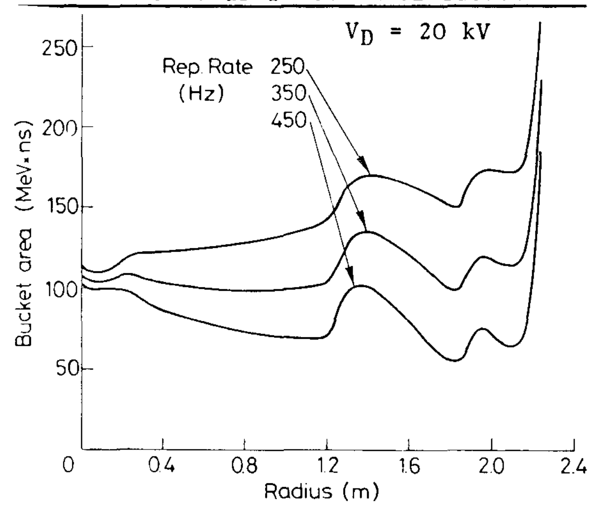


Fig. 4 : Bucket area as function of radius for V_D = 20 kV and different pulse repetition rates

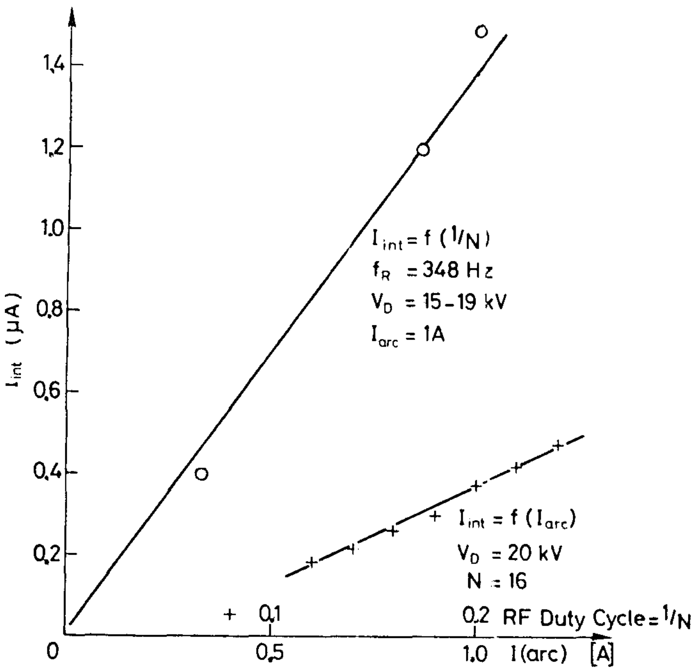


Fig. 5 : Internal beam as function of RF duty cycle and ion-source arc current

These figures suggest that the design intensity of 10 μA internal beam is well within reach and can be exceeded by raising V_D above its present value of 20 kV.

In Fig. 6 the internal beam current is plotted against V_D and is shown to be proportional to $V_D{}^{5/2}$.

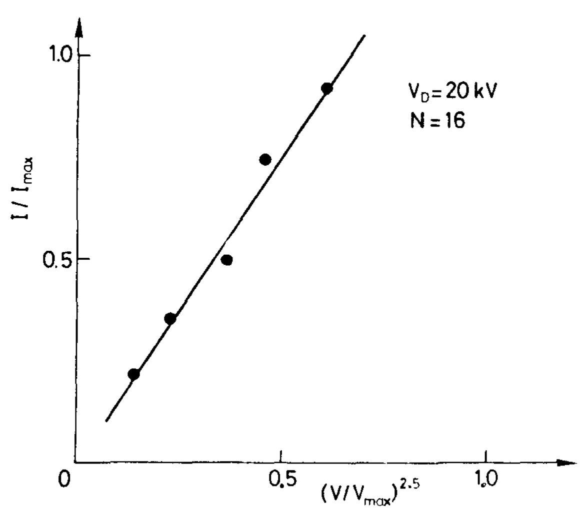


Fig. 6 : Internal beam as function of dee voltage

The geometrical properties of the internal beam were measured by the shadow probe method of Garren et al [31]) and by examining the time structure of secondaries from an internal target. The results, reported in Ref. [32]), show that both radial and axial amplitudes are below 1 cm.

4.4 Extracted Proton Beam

The extraction efficiency η of the system described in Ref. [25]) was estimated to be 73% on the basis of measured values of the magnetic field in the regenerator and channel regions and on the assumption that radial betatron amplitudes did not exceed 10 mm. Initial results based on a comparison between an internal beam measurement at R = 0.4 m and an intensity measurement of the extracted proton beam yielded η = 0.5 - an excellent result for a synchrocyclotron, but disappointingly low compared with the theoretical estimate.

Allardyce et al [33]) showed that the apparent inefficiency of the extraction system was due to a beam loss during acceleration and that the theoretical value of η could be reached by either raising V_D or reducing the rate of frequency modulation, as is suggested by Fig. 4. The data shown in Fig. 7 indicate that the derivatives

$$\frac{V_D}{\eta}\frac{\partial\eta}{\partial V_D} \quad \text{and} \quad \frac{\dot{\omega}}{\eta}\frac{\partial\eta}{\partial\dot{\omega}}$$

were equal and opposite as would be expected for a beam loss determined by $\cos\phi_s$.

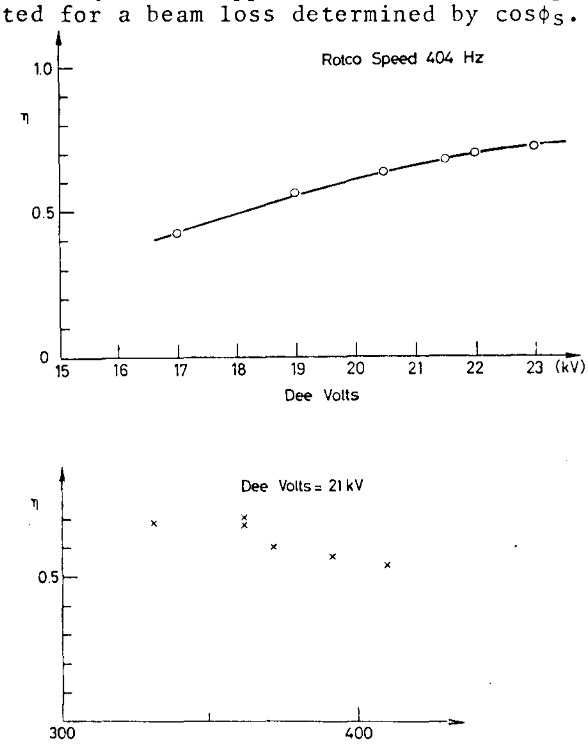


Fig. 7 : Extraction efficiency as function of dee-voltage and pulse repetition rate

The hypothesis of a beam loss at intermediate radii was further confirmed by activation measurements performed during the deerepanelling. They shows a strong maximum of activation between R = 1.20 and 1.70 m[38])

Beam emittance measurements are reported in Ref. [25]). The authors measured $E_H \cong E_V \cong 20\ \pi$ mm mrad, attributed mainly to scattering in two stainless steel windows. Corrections for this effect yield

$E_H = 4.7\ \pi$ mm mrad $\qquad E_V = 1.3\ \pi$ mm mrad

Field measurements suggest that the energy of the beam is between 602 and 604 MeV, depending on the position of the extraction system. The momentum spread has not yet been measured, but the transmission efficiency of 88 ± 2% measured between the SC and the Isolde target at the end of a 60 m beam line shows that the momentum spread lies well within the $\Delta p/p = 3 \times 10^{-2}$ transmitted by the channel.

Fig. 8 is the output of a wire chamber operating in vacuum and it shows the extracted beam profile at a waist formed by three quadrupoles in the SC Hall.

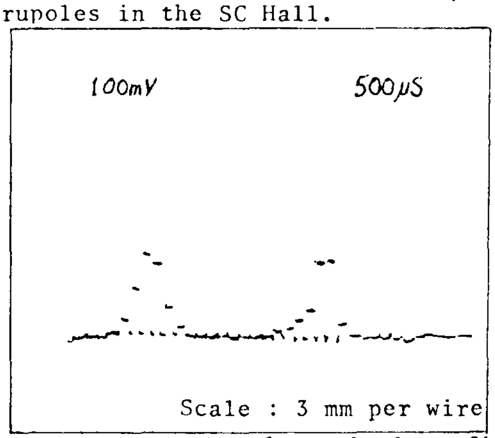


Fig. 8 : Horizontal and vertical profiles of the extracted proton beam, measured with a vacuum wire chamber

The most intense external proton beam reported so far has been 1.3 μA on the Isolde target when the transmission was about 70% and the RF system was operating at N = 2. The extracted beam was therefore close to 2 μA and was not limited by the machine. In fact, it overheated the Isolde target.

4.5 Long Burst Operation

Both long-burst systems referred to in sec. 2 have been operated successfully, but it has not yet been possible to operate adiabatic stacking at $\dot{F} = 0$ due to variations in the final frequency. These extend over 50 kHz and cause a 1.5 cm displacement of the stacked beam, which affects the time distribution of the output. V_D has therefore to be cut while $\dot{F} \neq 0$, and the energy spread of the stacked beam varies slightly from pulse to pulse.

The 1.2 ms flat output pulse produced by the pulsed field coil (PFC) gives a beam of duty cycle

$$D = 1.2 \times 10^{-3}\ f_R/N$$

which approaches 60% when f = 466 Hz and N = 1, but when f_R is reduced and N is increased by pulsing the RF system intermittently this mode of operation becomes less attractive. At present the SC frequently operates with N = 5 and the cee[29]), primarily intended for internal target operation, gives a somewhat better duty cycle than the pulsed-field coil even in the external p-beam and despite the RF microstructure of the output.

The extraction efficiency with the PFC is 0.92η where η is the value measured with dee acceleration to extraction radius; for the cee used at 10 kV peak without frequency or phase lock the corresponding value is 0.7η.

4.6 Secondary Beams

Since the repanelling of the dee in April/May 1975 both internal and external targets have been used for secondary production. Meson yields from internal targets and neutron yields from a liquid D_2 target appear to agree with the predictions of Refs. [34]) and [35]) when scaled for proton beam current. For example Zavattini [39]) has reported a stop-rate of 120 MeV/c muons of about 100/gm.μA internal beam. Against this, pion production from external targets, although offering greater gains, has not been studied thoroughly and no credible data are yet available.

Beam sharing between internal and external targets is possible but less rewarding than in SC1, where 95% of the internal beam was unextractable and could be used on an internal target without loss to the external beam. An axially moving fast internal target ("jumping" target) of new design has been tested.

5. Outlook

The present experience with SC2 gives every reason to believe that the design-performance as regards internal current will be reached. Extraction efficiency and long-burst operation are already close to their specified performance and may be further improved when the machine characteristics are better understood.

There is at present no great urge to raise the internal beam to its possible limits, but even at present beam levels the internal targets cause serious problems due to their high induced activity. Surface doses as high as 1000 rad/hr have been recorded on internal targets after prolonged use and long-lived isotopes are steadily building up in the target support. The vulnerability of the internal targets is a further argument which points to their suppression in the long run.

The space at the periphery of the pole-face now occupied for internal targets could possibly be used to lodge another element capable of improving the extraction efficiency. The prospect of accelerating $^{3}He^{++}$ and alphas[24][36] would further encourage this notion. However, the abolition of internal targets would necessitate the construction of a new underground experimental area for which no funds are available at present.

Acknowledgements

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DISCUSSION

H.G. BLOSSER: Why haven't you run particles on every pulse? When do you plan to try this?

E.G. MICHAELIS: Mainly for reasons of RF power, that is, we were trying to prevent voltage breakdown in the condenser which depends on the power dissipation while the electrodes are outgassing. For the moment we have been running on one condenser, the other one being under modification, so we did not want to take risks and therefore kept the power down as far as we could. There is also a difficulty with some cooling circuits. I think that we should be able to go towards a full repetition rate within the next few months. So far we have had no great incentive to do this because the only time we really tried to maximize our beam on an ISOLDE run we found that the experimentalists' target got too hot.

J.S.C. MCKEE: What was the total cost of the SC Improvement Programme and what proportion of that cost was devoted to remote-handling equipment?

E.G. MICHAELIS: I think our estimate on the cost of the Improvement Programme is something between 28-30 million Swiss francs. Now, what you call remote-handling really amounts to moving things by hand, but from the outside of the machine. I think it might have cost 2 or 3 million; but I have not got a figure.

F.G. TINTA: What kind of modifications are you contemplating for accelerating ^3He or ^4He, are they mainly RF? Which applications will the acceleration of He have?

E.G. MICHAELIS: I think Mr. Beger will be talking about this scheme which is under his particular care. The idea is, first of all, to extend the resonator which is the only means we have since we cannot vary impedance. The physics pressure comes mostly from the chemists and from ISOLDE who are looking for heavy particles in order to get yet more extravagant and exotic isotopes.