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THE CERN SYNCHROCYCLOTRON TODAY

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Abstract.- The CERN synchrocyclotron (K = 800) is currently enjoying a phase of intense exploitation following the rather slow build-up after the reconstruction programme of 1974-1975. After a great deal of rebuilding and improvements the rotating condensers are both now able to operate at full repetition rate with a dee voltage of 20 kV, producing an internal beam of more than 7 μA of 600 MeV protons, of which up to ∿ 5 μA has been extracted. Recently, an interest in particles other than protons has developed, and it was found that certain ions could be accelerated by making relatively minor modifications to the machine. $^{3}He^{2+}$ ions of 303 MeV/N have been used since 1978 and there have been several runs with $^{3}He^{+}$, $^{12}C^{4+}$ and $^{15}N^{5+}$ ions since then. These ions have an energy of 86 MeV/N and are produced at very high intensities. Construction work is under way on a modification to the RF system to enable the acceleration of other ions, for examble $^{20}Ne^{6+}$ and $^{20}Ne^{5+}$, for which ion source tests have already given encouraging results.

1. Introduction.- The SC has operated for about 6000h per year for the last four years, with a breakdown rate of less than 5% for three of those years, which increased to 20% in 1980 due to problems with the rotating condensers. For the first 8 months of this year, however, the fault rate has fallen again. The machine supports the Isolde programme and about 13 other experiments, involving a total of between 200 and 250 physicists, most of whom commute to CERN from their home laboratories.

The reliability and the performance of the rotating condensers (rotcos) has improved dramatically since the early days after the SC improvement programme (SCIP[1]) of 1974-1975, although they still remain the main source of problems. Progress was reported at the 1978 Conference [2] and has since been consolidated in two areas. Firstly, both rotcos have now been upgraded so that they can operate with a dee voltage of 20 kV at the full repetition rate, i.e. they can be pulsed on every possible RF cycle rather than only once every N cycles. Secondly, the SC has been modified to allow the acceleration of various ions other than protons. This facility has proved very popular and was scheduled for about 1/3 of the total physics time in 1980. These advances will be discussed below, and a summary of the present performance of the machine is also given.

The layout of the SC at the start of 1981 when it was accelerating carbon ions is shown in Fig. 1.

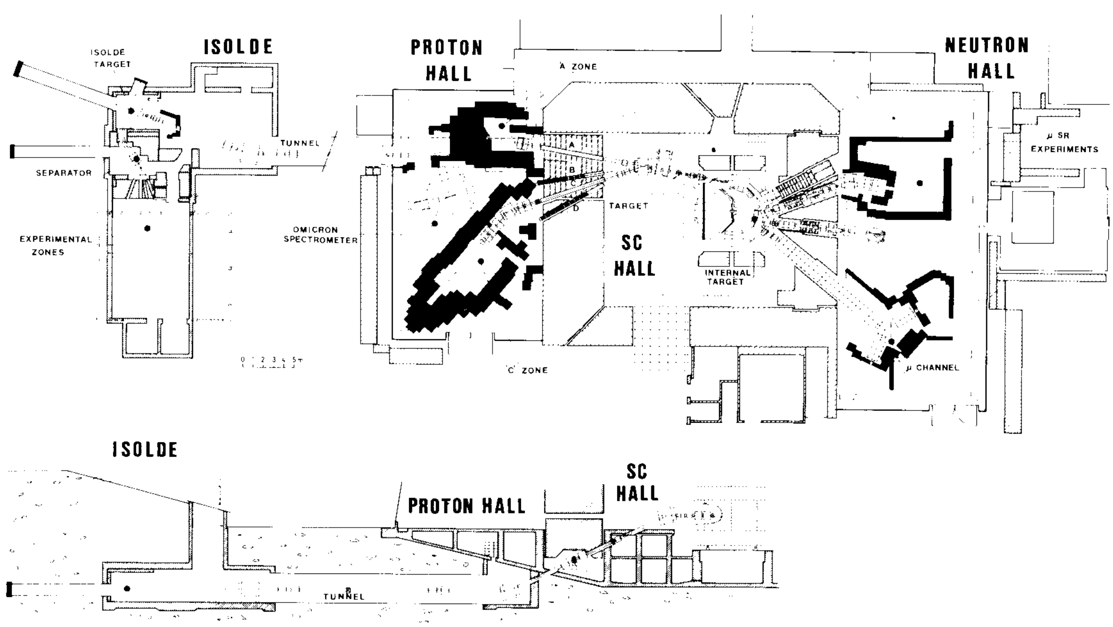

Fig. 1: The layout of the CERN SC in early 1981. The heavily shielded zones in the Proton Hall receive the intense heavy ion beams.

2. Full power operation.- From 1975 till 1978 the rotating condensers (rotcos) underwent pratically continuous modification and improvement as construction faults were eliminated and weak elements were replaced. Power dissipation inside the rotcos limited their pulsing rate to 1 in every N possible RF cycles, but by the last International Cyclotron Conference in 1978 [2)] one rotco could reach 20 kV and the other 18 kV, in both cases at a duty cycle of 1 in 2. This allowed an internal beam current of ∿ 4 μA in routine operation, which was the redefined SCIP goal. However, for operational reasons the upgrading work on the two rotcos had not progressed equally, and it was not until 1980 that they attained the same degree of improvement, with cooled blocking capacitors and cooled vacuum capacitors installed. In fact, the work was slowed down by the decision to accelerate carbon ions, requiring replacement of the compensating coils (see below).

At this level of improvement a rotco could in principle work at 20 kV with N = 1 (i.e. pulsing on every possible RF cycle), but such a high power run was not attempted because the situation had never been reached that one rotco worked at the machine, while the other stood by as a spare, already tested and waiting to run. However, in August 1980 this happy state of affairs prevailed and for the first time rotco 2 ran on the SC at 20 kV, 1 in 1, producing an internal beam intensity of 7 - 8 μA and an extracted beam of 5 μA, which was immediately used by two groups. The usual problem of induced radioactivity around the cyclotron was of course amplified by this intensity and so in order to reduce the radiation doses to personnel, as well as to hope for improved reliability with rotcos running at less than their maximum rated performance, it was decided to regard 4 μA as the normal maximum internal beam current (i.e. 1 in 2 operation) but to offer full power operation if a group justified their need for the highest intensity at the weekly schedule meeting and if, in addition, a working spare rotco were available.

The first high intensity run ended abruptly when a ceramic section of the motor drive shaft broke, causing the motor to be flooded with cooling water; such a breakdown had occured once before, but was not due to the fact that the rotco was running at full power at the time. After the repair, however, there were problems linked to power dissipation in the rotco when the glass insulator in a pumping duct melted. The fault was caused by RF losses in a poor batch of pyrex tube in both rotcos and was cured by changing to a good quality ceramic tube.

During the last year rotco 2 has been modified to allow carbon acceleration (for which originally only rotco 1 had been modified in 1979, see section 3) and this work plus a series of relatively minor faults has resulted in rotco 1 being used on the accelerator for pratically the whole of a 12-month period, the first time that a rotco has worked for so long. The problems concerned mainly the blocking capacitors between the motor and the inner conductor which have disintegrated on several occasions. Water cooling has now been installed, together with an improved mounting arrangement, but it is not yet clear whether the problem is finally resolved. This year has also seen a near catastrophe when a turbopump seized and pieces of the turbine blades were sucked into the rotating rotco. Surprisingly no damage resulted and the rotco was back in operation after a few days' cleaning. Finally, in July 1981 a second full power run was made, this time with rotco 1.

3. The SC as a heavy ion accelerator.-

3.1 $^3He^{2+}$.- Interest in the acceleration of particles other than protons began some years ago, and the initial success of the $^3He^{2+}$ programme was noted at the last conference in 1978 [2)]. The proton frequency modulation range of 30.1 MHz to 16.8 MHz must be reduced considerably for the acceleration of other ions.

$^3He^{2+}$ acceleration is achieved by inserting a 1.2 m long transmission line between the dee and the rotco, with all the modifications to the magnetic shielding and to the pumping system that this entails. The ion source does not change, there being simply an exchange of the source gas bottle and the installation of a new, more powerful generator to increase the power supplied to the arc. This results in a $^3He^{2+}$ intensity delivered to Isolde of 0.5pμA in fast burst mode, with the rotco working at 20 kV, 1 in 3. The Isolde group have made extensive tests of production target yields to compare the efficiency of $^3He^{2+}$ ions at 303 MeV/N with protons at 600 MeV. The conclusion [3)] was that for the production of many isotopes, especially those far from stability, $^3He^{2+}$ could be 2 orders of magnitude more effective than protons. A typical yield curve is shown in fig. 2 for the production of Tl isotopes from a ThC_2 target. However, it must be noted that the yields are normalized to the same number of incident particles and that the $^3He^{2+}$ intensity in practice is less than that of protons by a factor of up to 5. Thus, to benefit fully from the high yields in the case of $^3He^{2+}$ bombardment it is necessary to increase the $^3He^{2+}$ intensity by a factor of this order, which will be attempted during the coming year.

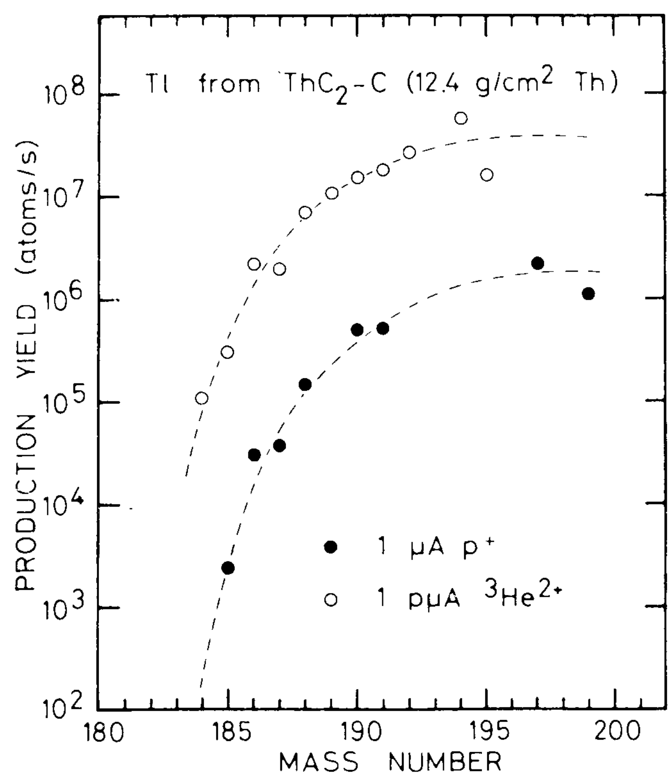

Fig. 2: Production yields of Tl isotopes from 600 MeV proton-induced and 910 MeV $^3He^{2+}$-induced reactions in a ThC_2-graphite target heated to 2000°.

3.2 $^{12}C^{4+}$ and other ions with charge/mass ratio of 1/3.- The SC requires rather more modification to accelerate ions with a charge/mass ratio of 1/3. It was found by measurements on the 1/5 scale model that the radiofrequency system could be made to resonate in the required frequency range by reconstructing the 1.2 m extension line used for $^{3}He^{2+}$ acceleration; the line becomes particularly simple in this case, the inner conductor consisting simply of 2 parallel tubes. In this way the necessity to accelerate on a harmonic was avoided and the pumping line installed for the $^{3}He^{2+}$ case could be retained. However, it was necessary to increase the inductance of the compensating coils inside the rotco from the "proton" value of 100 µH to 400 µH. The new coils (8 of them) were installed first on rotco 1 in 1979, the design incorporating removable shorting bars to return the inductance to 100 µH whenever proton acceleration is required. Rotco 2 was modified in the same way early in 1981.

Fine tuning of the frequency range to that required for the acceleration of particles of charge/mass ratio 1/3 is obtained by the motorized vacuum capacitors. These were found to be essential for the optimization of the time structure of the beam during "carbon" operation, i.e. to tailor the programme such that $\dot{f} = 0$ at the required frequency. Both rotcos are now able to work in the "carbon" range and the conversion takes a few hours, followed by pumping and RF conditioning. The beam energy is 86 MeV/N and it should be noted that even though partially stripped ions are accelerated, the pressure of $< 3\ 10^{-7}$ torr in the SC's vacuum tank causes very little loss by charge exchange on the residual gas molecules.

Another modification to the machine to allow carbon acceleration concerns the ion source. More power has to be supplied to the arc in order to produce the higher charge states, and consequently the source chimney must be water-cooled; this requires a larger diameter than the "proton" chimney but because the radius of the first orbit is greater for $^{12}C^{4+}$ than for protons, there is enough room at the centre. Consequently, a new source and central geometry were constructed which are inserted via the axial hole in the yoke whenever carbon operation is scheduled; this requires about 1 shift. In addition, a new source power supply was constructed to give higher voltage and current to the arc. During routine operation on $^{12}C^{4+}$ ions, filament lifetimes of ∿ 22 hours are obtained, which is very convenient from an operational standpoint.

Finally, in order to exploit the carbon ions, modifications have to be made to the experimental zones. These were designed to receive 10^{10} to 10^{11} ions/s and thus had to be well shielded, which is the situation shown in fig. 1. The $^{12}C^{4+}$ ions are stripped to $^{12}C^{6+}$ at the exit from the accelerator before being sent into the Proton Hall; they may also be degraded in energy by means of a graphite block, and good quality beams down to 30 MeV/N have been obtained in this way, with a reduction in intensity of about a factor 20. Very high intensity ion beams have been extracted from the SC (see summary) and it has therefore been relatively easy to collimate to produce the desired beam properties in the Proton Hall. Several other ions, for example $^{3}He^{+}$, $^{15}N^{5+}$ with charge/mass ratio of 1/3 have also been used as have $^{16}O^{6+}$ and $^{14}N^{5+}$ whose ratio is slightly different from 1/3. These latter ions could only be produced in fast burst and were not very intense (∿ 10^{9}/sec) because the RF could not be properly optimized for them.

4. Slow burst operation.- The Isolde group is interested in producing secondary beams of radioactive isotopes from a production target and so is not concerned by the time structure of the primary beam. Consequently, they use the SC in "fast burst" mode in which beam bursts of ∿ 40 µs length occur once every RF modulation cylce (up to 400 Hz, depending on the rotco duty cycle). Practically every other user, however, requires beam to be spread out in time as uniformly as possible, otherwise there are count rate problems in detectors. The production of a suitably stretched beam can be achieved with an accelerating cee electrode [4] or with a pulsed field coil (the so-called Kim Coil) [5]. This latter mode of operation produces a beam with no RF microstructure because it is stored prior to extraction and makes many turns in the accelerator, thereby losing all RF phase information. Results reported by users give total duty cycles of over 50%, both during proton operation and with heavy ions, and this has become one of the most attractive features of the accelerator. The photograph in fig. 3 shows the time structure of a beam. The vertical axis is proportional to intensity and a residual very small "spike" is all that remains of the fast burst, the intensity being spread out over most of the ∿ 5 msec until the next cycle.

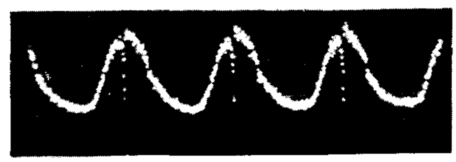

Fig. 3: Time structure of the extracted beam using the Kim Coil.

Such has been the success of the Kim Coil that it has been decided to use it exclusively whenever slow burst operation is requested. The cee electrode has thus been rendered obsolete and has been removed from the vacuum tank. The Kim Coil is easy to replace in the event of a breakdown, and two spare assemblies are available; the principal fault which has occured twice has been the fracture of a cooling pipe due to metal fatigue under the continual vibrations, but the clamping arrangement has now been redesigned, so that this problem should not recur.

5. The acceleration of very low intensities.- Several users have recently requested irradiations of various detectors by both protons and ions of very low intensity, in the range of 10^{2} to 10^{6}/s. Since the SC's usual intensities are many order of magnitude higher than this it was interesting to try to find ways of reducing the intensity in a controllable and reproducible way. Tests showed that the beam intensity could be reduced in several ways. The ion source arc current could be reduced and would run in a stable way at 10^{-3} of the normal beam intensity: the beam limiter (a vertical plate at the centre of the machine which may be raised to reduce the vertical height of the beam) gave a reduction of a factor 10; finally the ion source could be pulsed much too early or too late for acceptance by the accelerating bucket, which gave a factor of ∿ 10^{-5}. The source timing proved to be the essential element in producing the desired low intensities.

6. Summary of the SC's performance.- The table shows the intensities of particles which have been extracted from the SC in slow burst mode using the Kim Coil: their energies and the frequency range required for acceleration are also shown. Other ions have been used on several occasions, such as $^{16}O^{6+}$ at 107 MeV/N and $^{14}N^{5+}$ at 97 MeV/N, but at lower intensities because the radiofrequency system could not be properly optimized for them. These are shown in the second part of the

table. The last three ions in the table are expected in 1982 when the new line is ready (see section 7).

Particle	Energy	Extracted intensity (ions/s)	Frequency range (MHz)
Protons	602 MeV	> 3 10^{12}	30.1 → 16.9
$^3He^{2+}$	303 MeV/N	3 10^{12}	20.3 → 13.9
$^3He^{+}$	86 MeV/N	> 10^{13}	10.1 → 8.5
$^{12}C^{4+}$	86 MeV/N	> 10^{12}	10.1 → 8.5
$^{15}N^{5+}$	86 MeV/N	> 10^{11}	10.1 → 8.5
$^{16}O^{6+}$	107 MeV/N	∿ 10^{9}	11.4 → 9.4
$^{14}N^{5+}$	97 MeV/N	∿ 10^{9}	10.8 → 9.0
$^{20}Ne^{6+}$	70 MeV/N		9.1 → 7.7
$^{20}Ne^{5+}$	49 MeV/N		7.6 → 6.6
$^{12}C^{3+}$	49 MeV/N		7.6 → 6.6

These high intensities are produced by a PIG ion source of the hooded arc type which has a chimney inner diameter of only 4 mm in the case of proton acceleration. The source is pulsed on for 50 µs at the start of every RF cycle. Filament lifetimes for the routine acceleration of protons, $^3He^{2+}$ ions and $^{12}C^{4+}$ ions are ∿ 150 hours, ∿ 50 hours and ∿ 22 hours respectively.

7. Future developments.-

7.1 ^{20}Ne ions.- Following the success of the "carbon" programme, requests were made by the users for heavier ions of an energy above 50 MeV/N. Furthermore, it became clear that a fairly rapid change-over from one ion to another would be an extremely desirable feature. A study was undertaken which resulted in the design of a remotely switchable "universal" transmission line between dee and rotco: this line uses the same 1.2 m long vacuum vessel as is used for $^3He^{2+}$ and $^{12}C^{4+}$ acceleration, but is made so that the inner conductor is formed by a combination of one or more of five parallel tubes of different diameters which may be switched in or out remotely. The different combinations of tubes produce resonant frequencies which cover the range required for the acceleration of particles with charge/mass ratio from $\gtrsim$ 1/3 to $\lesssim$ 1/4.

The intention is to accelerate $^{20}Ne^{6+}$ ions to 70 MeV/N and $^{20}Ne^{5+}$ ions to 49 MeV/N, as well as to continue to offer $^{12}C^{4+}$ ions of 86 MeV/N. Clearly, $^{12}C^{3+}$ ions of 49 MeV/N will be accelerated in the same way as $^{20}Ne^{5+}$ and it is hoped that $^{16}O^{6+}$ ions of 107 MeV/N will also be achieved. The frequency ranges are given in section 6 above. The enormous advantage of a remotely switchable line is that the frequency range can be altered without having to break the vacuum, which means that pumpdown and RF conditioning, often amounting to a loss of several days' physics time, can be avoided. Construction work is under way on the new transmission line, but high power tests and the fine tuning of the various frequency ranges have still to be programmed. However, a first run using the new system is envisaged for early 1982.

Another feature of the switchable line described above is that the frequency range may be altered to accelerate the same ion in a different charge state, e.g. $^{20}Ne^{6+}$ and $^{20}Ne^{5+}$ or $^{12}C^{4+}$ and $^{12}C^{3+}$. This results in a different energy and will probably be a better way to alter the bombarding energy in a particular experiment than the present technique, which consists of installing a graphite degrader of the appropriate thickness. Clearly, with the new method the beam optics will be the same in the two cases, and there should be a gain for the ion source since, for example $^{12}C^{3+}$ ions are produced more abundantly than $^{12}C^{4+}$ ions, which will in practice means that, other things being equal, the filament lifetime should increase during the acceleration of the lower charge state ions.

During the last carbon period in early 1981 tests were carried out with the ion source to establish what conditions of arc current and gas supply were required for the production of $^{20}Ne^{6+}$ ions. The "carbon" RF system does not allow the acceleration of these ions to extraction radius, but they could be accelerated and detected at 50 cm inside the SC vacuum tank. The impressive result of these tests was that more than 1.5 10^{12} ions/s were produced for roughly the same input power to the source as for $^{12}C^{4+}$ ions. Thus, quite high intensities of 70 MeV/N ^{20}Ne ions should be available once the new "universal" line is ready.

Finally, it should be noted that the acceleration of the ions $^{40}Ar^{9+}$ and $^{40}Ar^{10+}$ should become possible with the new line. Whether or not the ion source is capable of producing any or enough ions in these high charge states is of course an open question, but as there is considerable interest from the users, an attempt will be made.

7.2 $^3He^{2+}$ intensity.- It was mentioned in section 3.1 that the Isolde group have found that the use of $^3He^{2+}$ ions at 303 MeV/N gives advantages over 600 MeV protons for the production of isotopes far from stability, but that the intensity delivered by the SC was too small by a factor of about 5. This factor can in principle be found by making a series of small improvements in various areas: the ion source arc current can be increased further before saturation is reached: the rotco should be able now to withstand 1 in 1 or at least 1 in 2 operation (for $^3He^{2+}$ it has so far only been used at maximum 1 in 3): finally losses in acceleration can be reduced by a proper tailoring of the RF programme. This latter improvement is not trivial but represents a modification to the universal line to make it work at the higher frequencies of $^3He^{2+}$ acceleration. Unfortunately, no way has been found to extend the range of the switchable line so that it covers both the carbon/neon region discussed above and the higher frequencies required for $^3He^{2+}$ acceleration. A modification to the line is essential, consisting of the replacement of the inner conductor by two large diameter tubes, which takes several days to install. The effect on the physics programme can, however, be minimized by careful scheduling.

Acknowledgements
This summary of the present status of the SC was prepared after numerous discussions with G. Le Dallic, J.H.B. Madsen, F. Nitsch, P.H. Standley and S. Talas.

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