THE CERN SC AS A HEAVY ION ACCELERATOR

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ABSTRACT

Although it had been designed as a 600 MeV proton accelerator, the CERN synchrocyclotron was modified at the end of the 1970's to be able to accelerate ions up to mass 20. A programme of physics at ~100 MeV/N developed rapidly, at a time when most of today's custom-built heavy ion accelerators for more than 20 MeV/N were under construction or still on the drawing board. The intention was to enable physicists to perform some immediate experiments and then later to phase out this mode of operation as other machines came on-line. Thus the SC's ion programme was brought to a close at the beginning of 1986.

1. INTRODUCTION

The CERN 600 MeV synchrocyclotron gave its first beam as long ago as 1957. In 1974/75 the improvement programme[1] upgraded the machine to produce higher internal intensity (up to 8μA instead of the previous 1μA) and higher extraction efficiency (between 50% and 75% instead of the previous 5%). Users of the extracted beam were thus able to benefit from an increase of more than a factor 40 in intensity immediately, with a further factor of 2 available in principle, depending on optimisation of the performance of the rotating condenser. It was only possible, however, to accelerate protons.

First ideas on the acceleration of other particles were discussed in the mid-1970's, the emphasis being on d, α and ^3He initially[2]. At this time it was realised that with the advent of the new rf modulating element, the rotating condenser or rotco, it would be possible to shift the operating frequencies to the lower values needed for the acceleration of ions of lower charge/mass ratio, leaving the magnetic field as for proton acceleration. For protons, the frequency range is 30.2 to 16.8 MHz, whereas for $^3He^{2+}$ ions it is 20.3 to 13.9 MHz. Calculations showed that the insertion of a 1.2m section to transmission line between the dee and the rotco would allow the rf system to resonate at the required frequencies and so a project to construct such a line was quickly worked out, the intention being to make the minimum of changes both to the rf system and to other parts of the SC. Emphasis was put on $^3He^{2+}$ ions because of the high final energy of 303 MeV/N, and interest in d and α waned. First beam was accelerated in 1978.

During the preparation of the $^3He^{2+}$ project, calculations of voltage distributions inside the rotco, and new ideas on the shape of the inner conductor of the 1.2m section of transmission line showed that even lower frequencies were possible[3]. Thus ions of charge/mass ratio down to 0.33 and even to 0.25 could be envisaged, although changes inside the rotco and a new ion source and central geometry were also required if such ions were to be accelerated. It quickly became clear that there was a wide physics interest in beams of $^{12}C^{4+}$ of 86 MeV/N and $^{20}Ne^{5+}$ of 49 MeV/N, these beams being practically unavailable elsewhere in the world. It was decided to make the necessary modifications to the SC to produce these ion beams for a limited time until other machines such a GANIL, MSU, etc. came on line. Thus the SC accelerated $^{12}C^{4+}$ and other light ions from 1979 until the last run in April 1986.

2. $^3He^{2+}$ ACCELERATION

In order to lower the resonant frequency of the rf system, the simplest solution was to insert a 1.2m section of co-axial transmission line between the dee and the rotco. Figure 1 shows a photograph of the rotco and the transmission line as they are being connected to the three dee feedthroughs. The introduction of a 1.2m long transmission line meant that the vacuum system of the rotco had to be modified and enlarged, but the only changes made to the rotco itself, or to the rf generator, were the addition of filters for the unwanted higher frequencies. Detailed calculations were made to check that sensitive components in the rotco would not be subject to excessive voltages in the new frequency range.

Elsewhere at the SC no major changes were made. The PIG ion source which worked well for protons was expected to produce good intensities of $^3He^{2+}$ ions, although more power had to be fed to the filaments. Furthermore, the radiation-cooled chimney in which the plasma column is formed was not expected to be a limitation. Since the source consumes only around 0.5cc/min of gas, it was decided that it was not worth the cost of installing a ^3He recuperation system for the number of running hours which were expected for ^3He acceleration. With the pressure in the SC vacuum tank at the level of about 3.10^{-7} torr, beam losses during acceleration were not expected to be significant, especially for the fully-stripped $^3He^{2+}$ ions, so no improvements were necessary there.

Results were very encouraging in the first run in 1978. The rotco performed reasonably well, with the full 20 kV rf programme, but there were numerous rf discharges as the repetition rate was increased. Finally, acceptable running conditions were obtained by limiting the power by pulsing on one out of every three possible rf cycles. Prudence dictated that this duty cycle be accepted, but even so, the beam intensity produced was $\sim 3.10^{12}$ ions/sec. It was found that the frequency range available was somewhat larger than necessary and its optimisation, by modifying the dimensions of the inner conductor of the transmission line, became the object of a longer-term improvement project.

The users of the ^3He beam were enthusiastic, especially Isolde, the on-line isotope separator facility, where the use of ^3He ions of 303 MeV/N compared to 600 MeV protons offered some considerable advantages. Figure 2 shows the ratio of yields of Tl isotopes produced by bombarding a U target[4]. Protons and ^3He ions are compared. At the peak of the yield, the results are similar, but far from stability, especially on the neutron deficient side, there are factors from a few up to 10^2 to be gained by using ^3He ions. It should be

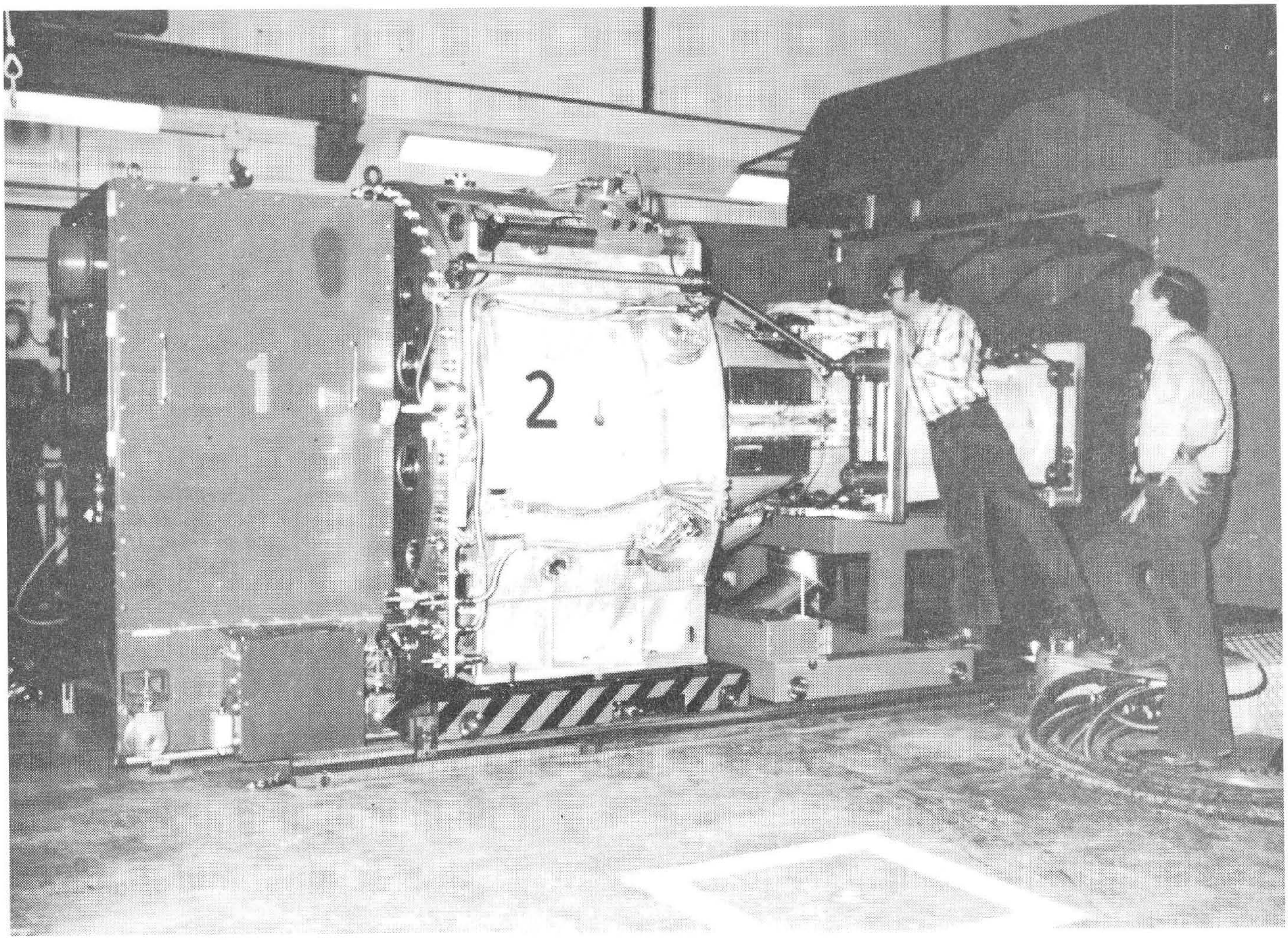

Figure 1 : Photograph of generator No. 1, rotco No. 2 and the 1.2m transmission line just before they are pushed along the rails to connect to the dee feedthroughs.

noted, however, that the intensity of ^3He ions has been normalised to that of the protons in Fig.2. In practice it was found that the ^3He intensity was too low by a factor of 3 or so to be generally useful.

It was decided to improve the $^3He^{2+}$ intensity in several ways. Clearly a factor 3 was potentially available by pulsing the rf on every possible cycle, but this required some improvements in the rotco (better filtering, elimination of sensitive elements, etc.). The rf programme could also be optimised by reconstructing the inner conductor of the transmission line. Finally, improvements could be made at the ion source, by feeding in more power. Work started on these improvements but because of limited personnel and the pressure from the development of other ion beams, the priority given to the project was very low.

3. CARBON AND OTHER IONS

During the $^3He^{2+}$ project in 1977/78 a great deal of work was done on ways of accelerating heavier ions in the SC with the minimum of expense. Efforts were concentrated on $^{12}C^{4+}$ initially, since this ion seemed likely to be within the capabilities of the ion source, and, at an energy of 86 MeV/N, would be in a new energy region for the users. Calculations showed that a new inner conductor consisting of parallel tubes could be constructed to fit in the already existing 1.2m transmission line, this would give the required resonant frequency range of 10.1 to 8.5 MHz. It was also demonstrated that the voltage distribution inside the rotco was acceptable at these low frequencies. While the new inner conductor was under construction, further calculations and model measurements showed that even lower frequencies were obtainable[5], down to the range 7.6 to 6.6 MHz (for particles of charge/mass ratio 1/4), if a small diameter tube was used as the inner conductor. Thus was born the idea of a switchable inner conductor in which tubes of appropriate diameters would be mechanically switched into position, thereby changing the impedance of the inner conductor and hence the resonant frequency range. It was this multi-frequency transmission line which was finally used to give $^{20}Ne^{5+}$ ions. The advantage of the multi-frequency line was that the resonant frequencies could be changed without the need for opening the vacuum system and making a change of tube diameter, implying a stop of several days.

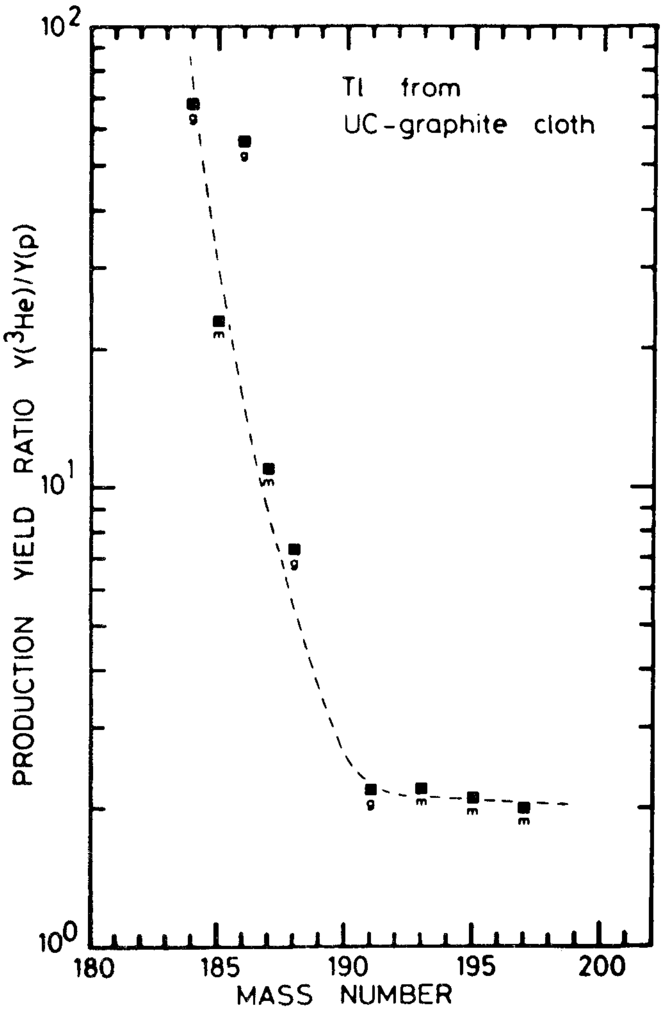

Figure 2 : The ratio of yields of isotopes of Tl produced by ^{3}He and protons, as a function of mass number.

Other changes necessary in the rf system were the construction of a new rf generator for the frequency range below 10 MHz, the installation of new, higher-inductance compensating coils inside the rotco, the replacement of certain filters and better shielding of the "end cap" of the rotco. These were important modifications and took some time to carry out : as time and further tests progressed, a number of smaller modifications were made inside the rotco so that one rotco in particular became the "ion" rotco and the other remained in "proton" mode.

A constant worry throughout the ion acceleration period was the performance of the rotco obtainable for a given frequency range and a given rf voltage level. Often a compromise had to be made between the desired voltage level (necessary for a high beam intensity) and the high discharge rate (several hundred discharges per hour). Thus sometimes a lower voltage had to be used so that there were not too many discharges, and this resulted in lower intensity beams for the users : it was found that for ion beams the rf voltage at the start of acceleration was much more critical than in the proton mode. These rf difficulties were worse with the lower frequencies of $^{20}Ne^{5+}$ acceleration, and on several occasions severe damage was caused to surfaces in the rotco, especially in the so-called "disc capacitor gap", resulting in the necessity to re-machine the surfaces.

For the ion source, $^{12}C^{4+}$ represented a challenge, because considerably more power would be required to ionize the atoms, and the SC's source has rather small dimensions, since it and the central geometry are inserted axially from below through a 20 cm diameter hole in the pole of the SC magnet. Measurements were made on the SC central region model magnet and high intensities of $^{12}C^{4+}$ were obtained. Carbon monoxide was chosen as the best source gas . A new power supply was designed to feed the extra power to the filaments, and a water-cooled chimney was constructed instead of the radiation-cooled proton version. This water-cooled version had a bigger diameter than its proton cousin, because the radius of the first orbit for an ion is inversely proportional to the square root of its charge/mass ratio : thus 1.73 in the case of $^{12}C^{4+}$, which gives more space at the centre. The larger source implied, clearly, a new central geometry as well.

Initially the filaments had a rather short lifetime, but gradually improvements were made to the thickness of the Ta wafer welded to the W base, and a lifetime of roughly 24 hours was obtained for $^{12}C^{4+}$ beams. Figure 3 shows a filament which has broken after 15 hours of operation with a $^{12}C^{4+}$ beam, together with its anticathode. Above is shown a new filament. Some data on filament lifetimes is given in Table 1, where the source gases are also shown for the different ions. It was found desirable in some cases to prepare mixtures of the source gas with small quantities (few %) of Kr to stabilise the plasma . Much more stable and reproducible conditions were obtained when Kr was used.

The range of ions produced at various times and with various versions of the rf system from 1979 to 1980 is shown in Table 2. $^{18}O^{6+}$ came to be the most popular ion since it looks less like a collection of α's than $^{12}C^{4+}$. The intensities given were measured with a Faraday cup at the exit of the cyclotron. Only rather imprecise measurements of the transmission from source to extraction are available, which indicate a loss of a factor of more than 3, mainly from the change of charge state of the accelerating ion in the poor vacuum of the SC tank. However, the extracted intensities were sufficiently large that the users, mostly involved in counter experiments, rarely needed the full intensity : this was convenient since it meant that collimators could be used to give good beam spots in the two heavily shielded zones where the experiments were situated.

One feature of the SC's beam which was much appreciated by the users was its time structure. The SC has a pulsed field or Kim coil which can be used to spread out the beam in time, giving a duty cycle of more than 50%. This mode of operation was in constant demand, but required somewhat delicate adjustment by the operators, much more so than in proton operation.

4. CONCLUSION

The SC ran in the ion mode for up to one third of its operating time from 1979 to 1980, and more than 50 physicists were involved in experiments. The ion programme at the SC has now been phased out as there exist several other machines in the world in the energy range up to 100 MeV/N. The intention is to run the SC primarily for Isolde (see Ref. 6) for 4000 hours per year in the future. Protons will be the main beam, but it is still our intention to optimise the $^3He^{2+}$ acceleration which had previously to be given very low priority : one distinct advantage of such a beam is that it leaves behind much less induced radioactivity than the 600 MeV proton beam.

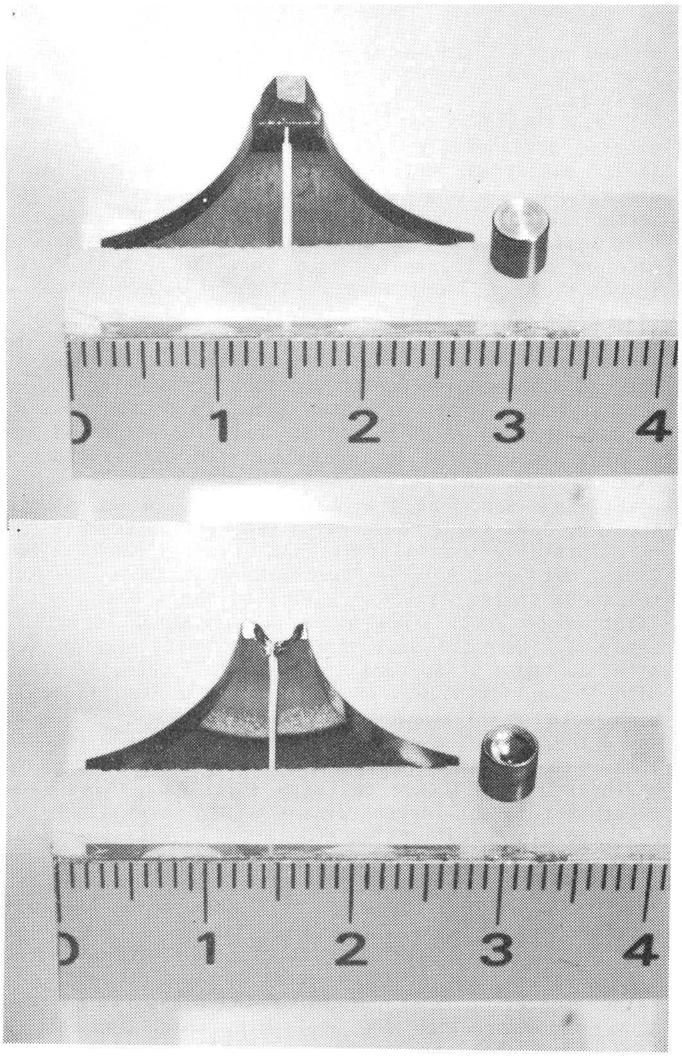

Figure 3 : Photograph showing a new filament and its anticathode, together with one which worked for 15 hours for a $^{12}C^{4+}$ beam. The Ta wafer can be seen on the W body.

Table 1 : Data on the ion source

Pulsed on for 60-70 µsec each cycle
Gas consumption ~0.3 cm^3/min
Plasma column 2mm diameter
Filaments W, or W with Ta tip
Filament exchange time ~1 to 1/2 hours
Arc currents from 2 to 8A

Particle	Filament lifetime	Source gas
Protons	> 150 hours	H_2
$^3He^{2+}$	49 hours (1980)	He
	85 hours (1982)	
$^{12}C^{4+}$	20 hours (1980)	CO
	50 hours (1985)	
$^{18}O^{6+}$	6 hours (1982)	$^{18}O_2$
	13 hours *)	
$^{20}Ne^{5+}$	10 hours (1985)	Ne
	22 hours *)	
$^{12}C^{3+}$	18 hours	$C^{18}O$ **)

*) with addition of a few % Kr gas to stabilise the plasma.
**) to avoid contamination with $^{16}O^{4+}$ ions

Table 2 : Ion beams at the SC

Particle	Energy (MeV/N)	Extracted intensity (part./sec)	Frequency range (MHz)
$^3He^{++}$	303	$>3x10^{12}$	20.3→13.9
$^3He^{+}$	85	$> 10^{13}$	10.1→ 8.5
$^{12}C^{4+}$	85	$> 10^{12}$	10.1→ 8.5
$^{15}N^{5+}$	85	$> 10^{11}$	10.1→ 8.5
$^{18}O^{6+}$	85	$\sim 3x10^{11}$	10.1→ 8.5
$^{16}O^{6+}$	107	$5x10^9$	11.6→ 9.4
$^{14}N^{5+}$	97	$\sim 10^9$	10.8→ 9.0
$^{20}Ne^{7+}$	94	$\sim 5x10^9$	10.6→ 8.9
$^{20}Ne^{6+}$	70	$\sim 3x10^{10}$	9.1→ 7.7
$^{20}Ne^{5+}$	49	$\sim 3x10^{11}$	7.6→ 6.6
$^{12}C^{3+}$	49	$> 10^{12}$	7.6→ 6.6

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