A SURVEY OF SYNCHROCYCLOTRON PROJECTS

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ABSTRACT

The designsof five synchrocyclotron conversion projects are discussed and compared. The operational status of these machines is presented, along with a summary of plans for their future development.

I. Introduction

This paper is a survey and comparison of five synchrocyclotron (S.C.) projects. These machines are all based on conversion of an older S.C. and are in various stages of completion, from planning through operation. With modern technology, no one is building new S.C.'s from scratch, since the price of an isochronous cyclotron with more precise and intense beams is similar to the price of a new S.C. However, at laboratories which already have an old S.C., a considerable improvement can be achieved by replacing the ion source and rf system (including dee) with new designs, while also constructing a new extraction system. With no magnet modification, the beam energy is not changed, but intensity, duty factor, and extraction efficiency can be substantially improved. In other S.C. projects, the magnet pole tips are replaced and sector focusing may be added in order to achieve a rising average magnetic field to increase the beam energy. At this level of complexity, one might ask why not convert to an isochronous cyclotron. In most cases it was felt too difficult to achieve a focusing isochronous field without lowering the maximum beam energy substantially. There has been some debate on this matter.[1]

For a 500 to 600 MeV proton accelerator, beam intensities have resulted which yield very useful secondary meson beams. Although the proton beam intensities are 1 to 5% of the LAMPF, TRIUMF or SIN intensities, the price of the S.C. conversion is substantially lower than the cost of constructing a large meson factory accelerator. In addition, some of the S.C. conversions now have a variety of ion beams. This option is not available at those meson factories.

The lower energy S.C. conversions might be compared with the Indiana cyclotron complex. These machines are designed for operation with a number of different ions. Although the beam quality is not as good as that of the IUCF, the operation is much simpler, and again, the conversions are based on an existing facility, so are relatively inexpensive.

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II. Design Features

The five S.C. projects that will be discussed are at CERN,[2,3] Nevis,[4] Orsay,[5,6,7] Uppsala,[8,9] and the JINR at Dubna.[10,11,12] The basic features of the S.C. conversions are presented in Table I. The S.C.'s at CERN and Nevis have been running for some time, although the Nevis machine was shut down at the end of July; the CERN S.C. is running strong. The Orsay machine has recently been started up, and the Uppsala conversion is in the construction stage. The Dubna machine has been planned for some time, but the Dubna S.C. has not yet been shut down for the conversion work. Layouts of the S.C.'s are presented in Figs. 1-5.

A. Magnetic Field Configurations

The only one of the five conversion projects in which the magnetic field was not substantially altered is the CERN project. At Nevis and at Uppsala three sectors were used while in the Dubna design, four are planned. At Orsay, the pole tip diameter has been increased by 14%, in order to increase the proton energy from 157 to 200 MeV. The gap is unchanged, and azimuthal symmetry is retained. At Nevis, in order to have vertical focusing for the initial orbits, the sector tips were started at 6 mm radius, with a central vertical gap of only 19 mm. The other machines have more conventional central magnetic fields, without such strong vertical focusing on early orbits, but the weaker focusing is compensated to some extent by the larger vertical gap. The major fundamental beam intensity limitation in an S.C. (which must accelerate instantaneous beams about 100 times the average beam) is vertical space charge blowup during the first few turns.[13]

The Uppsala machine will have a magnetic field which requires a frequency sweep of only 10% for 185 MeV protons, and which can be made isochronous for other ions and for protons at energies below 110 MeV. Details are presented in these proceedings.[9]

The Orsay magnet presently has two operating points, and that group plans to implement continuous variation from E_{max} down to 0.85 E_{max} .

B. Ion Sources

All of the conversion projects have replaced the earlier "volcano" ion sources with "hooded arc" ion sources to supply good quality ion beams for injection. The "volcano" sources were located below the median plane and erupted ions into the central region. Consequently, the radial quality of the beam was very poor, because of the large apparent source. However, in those older machines the dee voltage was so low that ions from a chimney source would not clear the source on the first turn. With higher dee voltages now available, the chimney sources can be used to give a small apparent source with low emittance.

In most cases hot filament sources are used, although in the Nevis machine a cold cathode Penning source was used. This was switched to a source with a single hollow cathode last December. The arc is pulsed when the rf reaches the appropriate frequency. Thus the arc is only on about 1% of the time, and high arc currents and high extracted ion currents can be used. For example, at Nevis, currents of 50 to 75 mA are extracted from the source, which has arc currents of 10 to 15 amperes. The only peculiar ion source situation was at Nevis, where, because of the 6 mm radius beginning of the sector tips, the source is on the ground side of the dummy dee at about 16 mm radius. The entire source is pulsed to +35 kV to supply the extraction voltage. In the other machines the extraction voltage is supplied by the dee. The CERN ion source is unusual in its very small outside diameter of 6 mm.

C. RF Systems

All the machines but the Uppsala S.C. have a single dee-dummy rf system which is tuned by one or more rotating capacitors. In each case, higher dee voltage and higher repetition rate are depended upon to raise the average beam intensity. These parameters are summarized in Table II. Another advantage of modifying the magnet to a sector focused field with a radial increase is the resulting decrease in frequency sweep required of the rf system.

In the operating experience at both CERN and Nevis, mechanical problems appeared with the rotating capacitors. The problems were eventually solved. However, it is clear that the rotating capacitors are one of the limiting systems in achieving reliable operation at full repetition rate and at design rf voltage. They are large, with small tolerances, high speeds, high rf voltages, and must have a clean vacuum while being supported on lubricated bearings.

At the CERN S.C., the rotating capacitor blades were carefully designed to give an optimum $\omega(t)$ program, as well as rapid "flyback" in frequency. The frequency program was designed so that during acceleration with a constant dee voltage, no particles would be lost from the stable phase space for synchrotron oscillations.

The Nevis capacitors were designed to give a reasonable frequency program, and it was anticipated that optimum development of the synchronous phase angle would be obtained by controlling the dee voltage as a function of time during acceleration. This control was never achieved, however.

The Orsay group is presently using the old rotating capacitors and are constructing a new pair which will have a faster flyback and will permit acceleration at high dee voltage and, consequently, at high repetition rate.[6]

In the Nevis S.C., one of the magnet sectors is supported on insulators, inside the dee. This was done in order to get the sector tips near the center. The idea was viewed with alarm by the accelerator community, but in fact has worked well. The high purity Al_2O_3 or BeO insulator material is very strong in compression, and as long as it is adequately cooled, it maintains a low loss factor. It is important to make good rf joints between conducting mounts and insulator surfaces, to insure that loads are in compression (not shear) and to supply adequate cooling. The Nevis support insulators were cooled by flowing liquid or just by conduction to the magnet iron, depending on the losses expected.

To change the particles to be accelerated the CERN group adds a section of line between the rotating capacitor and dee line, while on the Orsay machine a sliding short is used to vary an inductor.

Because the Uppsala machine only requires a 10% frequency shift in its synchrocyclotron mode, its rf system is completely different from the rest. There are two dees which subtend 90° at small radius, and then at 42 cm the angle is reduced to reach 45° at full radius. A broadband system (with adjustable damping resistors) was chosen after tests indicated that a ferrite modulated system would have nearly as bad losses. Coarse tuning is accomplished by using sliding line terminating short circuits. This system is to be used for isochronous operation as well.

D. Extraction Systems

All five S.C. projects use or plan to use regenerative extraction with a slow mode. The regenerative extraction uses one or two iron components (regenerator or peeler and regenerator) to cause the tune to enter the $\nu_r = 1$ radial instability. An appropriate first harmonic causes exponentially increasing shifts of the orbit toward the septum. The components are adjusted so the ratio of beam entering the channel to that hitting the septum is optimized.

A potential problem with this method of extraction is vertical blowup resulting from entering the $\nu_r = 2\nu_z$ resonance. Since the regenerative system has $\nu_r \to 1$, this resonance is equivalent to $\nu_z = 1/2$. The beam moves a significant distance (a few cm) in a few turns before extraction, so it may be possible to postpone the resonance until the last turn. This is the situation with the Nevis S.C. Then the resonance does not have time to couple radial amplitudes into vertical ones. Rather the large ν_z simply causes over focusing and expands the vertical envelope by some factor. At Nevis the expansion is about 3-fold, and the resulting 2 cm high beam is all extracted.

The slow extraction can be accomplished either by stochastic acceleration with a Cee electrode or by slowly moving a "parked" beam into the extraction system with a ramped magnetic bump. This latter method has been used at CERN, Nevis and the present Dubna S.C.'s. The coils are a few turns about 1 m in the azimuthal direction by 0.3 m radially, and they are located at the full energy orbit radius. Currents which ramp over about 500 A generate a time varying first harmonic. The beam is accelerated to full energy, the rf turned off, and the harmonic is ramped to push the circulating beam slowly into the extraction system. At

CERN and Nevis, the current ramp is programmable to produce a nearly flat extracted beam pulse. Duty factors of up to 70% have been obtained with no rf microstructure.

The extraction systems all presently have magnetic channels with septa of 3 to 6 mm, and currents up to 12 kA (at CERN and Nevis). In addition, the Orsay group is planning an electrostatic deflector to precede the magnetic channel. The magnetic septum systems obtain extraction efficiencies of 60 to 70%. The Orsay group anticipates improvement of up to 95% with the electrostatic deflector.

The dramatic increase in efficiency (compared to preconversion extraction efficiencies around 5%) results from improved beam quality as well as from careful attention paid to controlling field shape both throughout the region of the regenerator (and peeler if present) and also near the small radius side of the magnetic channel. Over half the remaining losses are due to particles hitting the septum rather than due to vertical blowup. Since synchrotron oscillations spread the beam over an energy interval many times the single turn energy gain, even if there were no radial oscillations at all this problem would remain. An electrostatic deflector, in cases where there is sufficient room (as in the Orsay machine), will help. It may also simplify the $\nu_r = 2\nu_z$ problem, since the coherent radial amplitude that must be induced for extraction may be decreased.

III. Operating Experience

The CERN,[3] Nevis, and Orsay[6] machines have been operating, although the Nevis S.C. has been shut down recently. Both CERN and Nevis have run for some time for experimental physics, while the first tests of the Orsay machine took place last June. The two former machines are similar in their design goals. CERN has been running internal beams of 3.5 to 4 µA. Part of these beams is used with an internal target and the rest is extracted with about 70% efficiency. At CERN $^3He^{++}$ beams have also been run. The intensity is one-quarter that of proton beams. At the CERN S.C. the rf is run every other acceleration cycle. At Nevis every other cycle was also used, and typical beams on target were 1.5 to 2 µA, corresponding to about 3 µA internal beam.

Reliability at CERN[14] has been 95.9% of scheduled time in 1977. This gave 5779 hours to experimental physics. This figure represents a substantial improvement from 1976 when the rotating capacitor gave trouble. Since about December 1, the Nevis machine also ran well, running for experimental physics about 80% of the scheduled time. During the last month of operation, when 24 hr/day, 7 days/wk operation was scheduled entirely for experimental physics, the reliability dropped to 70%.

IV. Plans for the Near Future

The CERN S.C. is now capable of accelerating either protons or $^3He^{++}$ ions, which are mainly used by the ISOLDE (on-line isotope separator) in studies of nuclei far from stability. The development of a $^{12}C^{4+}$ beam is proceeding.[15] Estimates are for about 10^{11} ions/sec, and the energy would be 1.03 GeV or 86 MeV/nucleon. This project will involve building a modified resonator extension line, based on the existing one used for ^{3}He acceleration. Beams of $^{14}N^{5+}$, $^{16}O^{5+}$ and $^{19}F^{6+}$ (with lower intensity) may also be possible.

The Orsay S.C. has just "gotten on the air". Technical developments planned include the operation of the Cee electrode for slow extraction. Tests are planned for September 1978. The new rotating condenser will be completed and installed in place of the condenser from the old S.C. which is presently being used. The new condenser is designed to give a saw-tooth frequency program, with 70% of the time for acceleration. Furthermore, an improved vacuum system is hoped to permit operation at higher rf voltage. A number of other technical improvements[6] are foreseen at Orsay, involving a capability for continuously variable energy and the possibility of third-harmonic acceleration, as well as use of an electrostatic deflector to improve extraction efficiency.

The Uppsala machine was shut down for conversion in January 1977. Magnet measurements were scheduled for the second half of 1978 and a report on field trimming is being presented at this conference.[9]

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Table I

Basic Features of S.C. Conversions

S.C.	Particle	Energy MeV	Design Current (μA)	Typical Operating Current (μA)	Sectors	Extraction Efficiency
CERN	p	600	10	3.5(internal)	0	70%
	$^3He^{++}$	900		1 (internal)		
Nevis	p	560	10-20	1.7(on target)	3	65%
Orsay	p	200,170	4-10	-	0	65%
	^3He	283,238	4			
	^4He	217,182	4			
	d	108, 91	5			
Uppsala	p	185-200	1-10	-	3	
	p	120-185	10			
	p	40-120*	40			
	d	25-100*	40			
	$^3He^{++}$	250-280	2			
	$^3He^{++}$	75-250*	20			
	$^4He^{++}$	50-200*	20			
Dubna	p	700	25	-	4	50%

* Uppsala cyclotron running in isochronous mode.

Table II

RF Systems

S.C.	Particle	F Max (MHz)	F Min (MHz)	V_{dee} (kV Peak) (Max)	Repetition Rate (sec^{-1})	Rotating Capacitor Speed (r.p.m.)	Number of Rotating Capacitors	$V_{rot.cap.}$ (kV Peak) (Max)
CERN	p	30.4	16.7	20	360*	1350	1	30
	$^3He^{++}$	20	14		290*	1090		
Nevis	p	28.0	18.5	30	300*	1500	2	40
Orsay	p	-	-	(20)**	430 (700-1200)**	-	2	(35)**
Uppsala	p	24.09	21.80	16	1000	(broadband rf system)	0	-
Dubna	p	18.2	14.4	40-50	500-600	6000	2	40-50

* rf is turned on for every other acceleration cycle.

** values anticipated with new rotating capacitor.

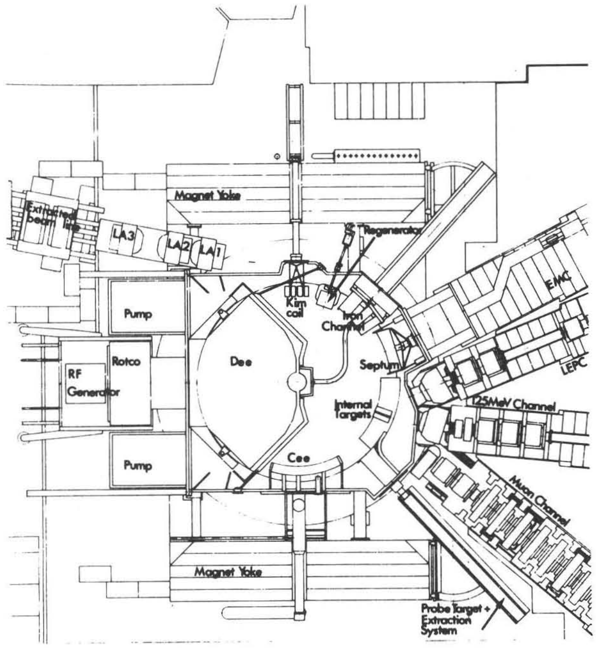

Fig. 1 Layout of the CERN SC showing the elements inside the vacuum tank, as well as locations of external equipment. The beam goes counter-clockwise.

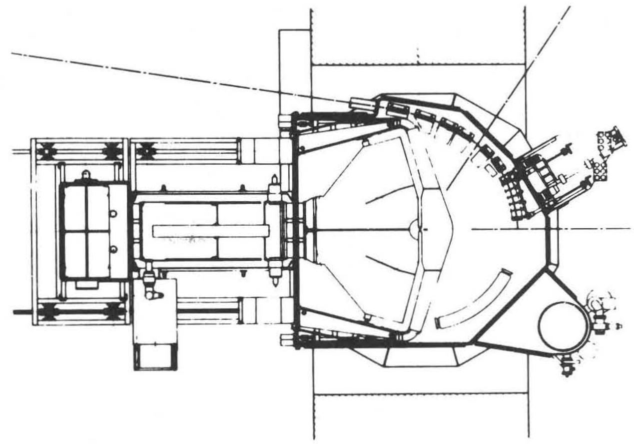

Fig. 3 Layout of the Orsay S.C., showing the resonator, Cee electrode (lower left) and extraction channel. The beam goes counter-clockwise.

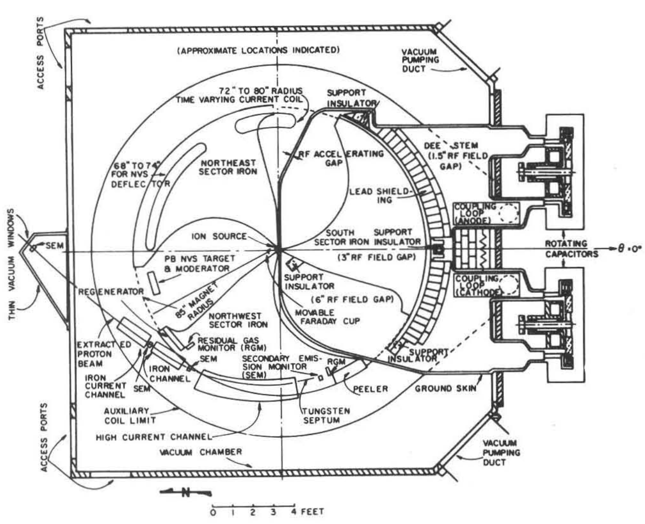

Fig. 2 Layout of the Nevis S.C. showing resonator, sectors, and extraction system. The south sector is supported on insulators. The beam goes clockwise.

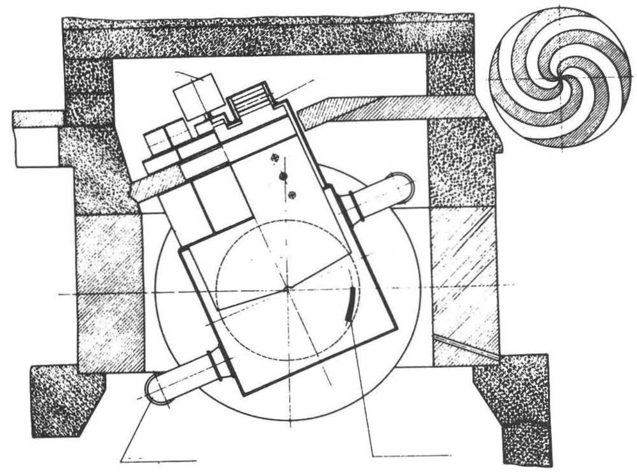

Fig. 4 Layout of the Dubna S.C. magnet and resonator. The insert in the upper right shows the four spiral sectors. The beam goes clockwise.

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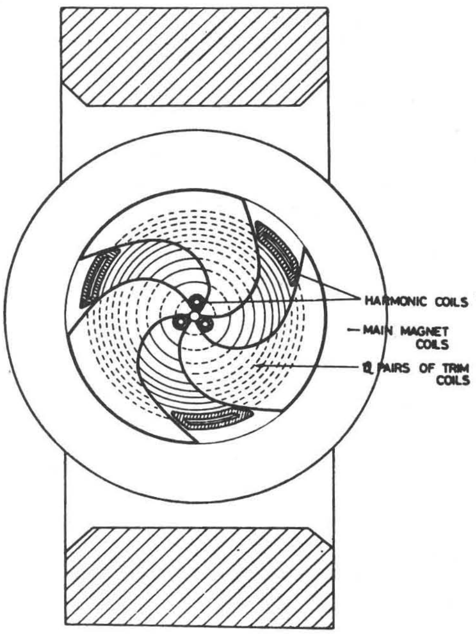

Fig. 5 Layout of Uppsala S.C. The two dees (not shown) subtend 90° until r = 42 cm, then the angle decreases to 45°.

** DISCUSSION **

D. CLARK: At Nevis, what did you find were the causes of the limitation of the internal beam current to 3.5 μA?

D. STORM: The ion source limited us to 80 nC/pulse (more typically 50) at small radius (after 1st phase oscillation). About half was lost later, during acceleration. Since we were running every other RF accelerating cycle (150/sec), the resulting full energy internal beam was typically 3.7 μA. The 80 nC captured from the source was consistent with the source current times the capture time, so we were not yet space charge limited in the central region.