AN INJECTOR CYCLOTRON FOR ACCELERATION OF POLARISED AND HEAVY IONS AT THE NAC

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Summary. An injector cyclotron for acceleration of polarised and heavy ions is being constructed at the National Accelerator Centre. It is a four-sector, k=11 MeV solid-pole cyclotron with two ninety-degree dees. Beams from a polarised ion source and an ECR-source, presently under construction, will be injected axially into the injector. The characteristics of the k=11 injector and especially the arguments which led to its choice and configuration, in preference to a k=40 injector cyclotron, a PIG-source and stripping between the injector and the SSC, are discussed. The influence of the rather low k-value of the SSC at injection on the choice of a suitable injector cyclotron is pointed out.

Introduction

During the initial planning of the NAC facility provision was made for two injectors, i.e. a k=8 light ion injector cyclotron with an internal ion source, and a k=40 heavy ion cyclotron utilising a PIG-source and stripping in the transfer beamline between this machine and the k=200 separated sector cyclotron, the matching being dictated by the k-value of the main accelerator at injection. As new sources were developed and improved, it became imperative to review the proposal for the second injector (SPC2). Since ECR-sources can now deliver ions with charge states even higher than can be reached by stripping after acceleration by a k=40 cyclotron, stripping is no longer needed and the heavy ion injector need only have the same k-value at extraction as the open sector cyclotron at injection. Thus the second injector may be similar to the light ion injector in most respects. This option has many obvious advantages as far as ease and speed of design, construction and maintenance are concerned. Since polarised ions are to be accelerated as well by the second injector, and the ECR-source also being in any case an external source, axial injection will have to be used. The first injector is not suited to these applications.

The choice made between the two possible injector systems is discussed, and the design parameters and characteristics of the chosen k=11 cyclotron will be outlined.

Energy limitations on heavy ion acceleration imposed by the SSC

For mass numbers larger than four, the SSC k-values at injection and extraction are 11 and 220 respectively. The k-value at extraction limits the maximum energy which can be obtained for a given charge state, while the k-value at injection limits the highest average charge state that may be realised by stripping after pre-acceleration. The procedure for determining the average charge state that can be obtained by stripping is illustrated in Fig. 1. The average charge state obtained, after stripping by a carbon stripper foil, as a function of ion energy per nucleon is calculated from the empirical expression given by Sayer.[1]

$$\frac{Q}{Z} = 1 - 1.03\ \exp\left[\frac{-47.3\ \beta^{0.86}}{Z^{0.38}}\right]$$

The charge state of an ion as a function of its energy per nucleon at injection into the SSC is given by

$$\frac{Q}{A} = \sqrt{\frac{1}{k}\left(\frac{T}{A}\right)}$$

The two expressions for the charge state as functions of the energy per nucleon are presented in Fig. 1. The charge obtainable by stripping is then read off at the intersection of the two curves for a particular Z and A.

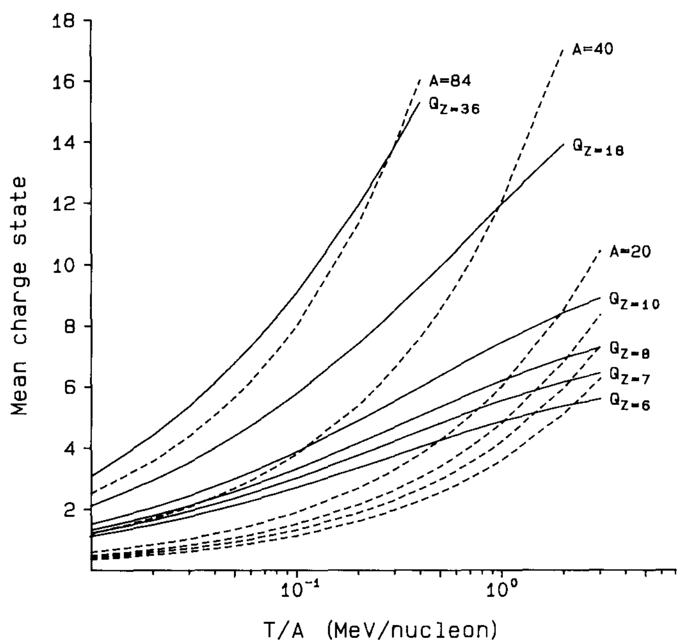

Fig. 1 Q/A Limitation by SSC injection k-value. The broken lines indicate the k=11 limit imposed by the SSC at injection for A = 12, 14, 16, 20, 40, and 84. The solid lines indicate the mean charge state after stripping for the Z-values indicated as a function of energy per nucleon. The operating point for a specific Z, A is then read off at the intersection of the two curves.

Comparison of stripping method and ECR source

In Table 1 the charge states, for a selected number of ions, that can be obtained by stripping before injection into the SSC are compared with those obainable from an ECR source for beam currents in excess of 40 particle nA at the source. The charge states from the ECR source are seen to be at least as high as those obtained by the stripping method. Also shown in this table are the k-values required for an injector cyclotron in order to deliver beams of sufficient energy for stripping to the necessary charge states. The maximum k-value needed, is seen to be 44, while a k-value of 11, i.e. the value at injection of the SSC, is required if an ECR source is used.

	Charge state			Injector k-value	
Ion	PIG	Stripped	ECR	Stripping	ECR
^{12}C	4	6	6	25	11
^{14}N	3	6	7	44	11
^{16}O	5	7	8	22	11
^{20}Ne	5	9	9	36	11
^{40}Ar	6	12	12	44	11
^{84}Kr	6	12	16	44	11
^{131}Xe	7	13	22	38	11

Table 1. Comparison of charge states that can be attained by stripping after pre-acceleration to those obtainable from an ECR source. Also given are the k-values required for the injector cyclotron in order to reach the given states.

Matching SPC2 to SSC

From Table 1 it is evident that the k-value of an injector to be used in conjunction with a PIG-source and stripping, would have to be at least 44 if the SSC is to be fully utilised. From the matching conditions, i.e. the energy at which the beam is extracted from SPC2 is also the energy at which it will be injected into the SSC, and that for consistent operation the RF frequencies of the two cyclotrons should be an integral multiple one of the other, one may derive the following matching equations

$$\frac{\rho_{1e}}{\rho_{2i}} = \frac{Q_2}{Q_1} \times \frac{B_2}{B_1} = \frac{nh_1}{h_2} \times \frac{\theta_2}{\theta_1}$$

where the subscript 1 refers to the injector, 2 to the SSC, i to injection and e to extraction: ρ is the orbit radius of curvature, Q the charge state, B the average magnetic flux density, h the harmonic number, θ is the ratio of the total length of an equilibrium orbit to the radius of curvature, and n is an integer or the inverse of an integer giving the ratio of the two RF frequencies. For the SSC the parameters are fixed at ρ_{2i} = 0.3898 m, θ_2 = 15.39 and B_2 = 1.23 T. For a k = 44 injector with $\theta_1 = 2\pi$, B_1 limited by saturation, and with n = 1, one then finds that B_1 = 1.339 T, ρ_{1e} = 0.716 m, and h_1/h_2 = 0.75 = 3/4 = 9/12. For a k = 11 injector on the other hand one finds B_1 = 1.004 T, ρ_{1e} = 0.477 m, and h_1/h_2 = 0.5 = 2/4 = 6/12. Thus in order to utilise stripping, the injector should be larger and have a higher magnetic flux. The flux needed is however still relatively low, and since this injector will also be used to accelerate protons and deuterons, it implies that in these cases the flux will be significantly below the maximum value possible. The same situation will arise when one decides to start using an ECR source with SPC2. Since the higher flux will be required only in exeptional cases for the highest energies and beam intensities, such an injector will not be an economical proposition. Since the harmonic numbers required are relatively high, one needs to be carefull not to choose a dee-angle which could lead to beam instabilities. This choice may also have the result that the maximum RF frequency attainable becomes less than 26 Mhz (e.g. for a single 180° dee, the large pole radius will prevent the short-circuiting plate to be moved in close enough to the centre), and thus that SPC2 will have to be operated at a lower frequency than the main cyclotron. In view of these considerations, it was decided to proceed with the k = 11 cyclotron as a second injector.

Magnet design

From field measurements on SPC1 it was clear that the average magnetic field in the pole gap falls more steeply than is required for SPC2. There are a number of ways in which this situation may be remedied, but in most cases it would entail a major departure from the design of SPC1. However, changing the magnetic sectors would not involve any structural changes to the SPC1 design, thus effecting great saving. We therefore decided to investigate the possibility of modifying the field by bevelling the sector edges.

Field calculations were carried out using the relaxation programs POFEL for three dimensional geometries, and VEPO2 for two dimensional geometries. The dimensions of SPC1 were used, but the sector edges were given various bevels. A cut of 4 x 4 mm proved to be the most successful means of obtaining the desired field shape. The relative reduction in the amount of material near the centre of the cyclotron is greater than at extraction radii, thus resulting in a decrease in the central average field relative to that at extraction radius. At high excitation the sharp corners of the sectors in SPC1 saturated in any case, so that this effect will be reduced in these instances.

Keeping their cross sectional area constant, the yoke pillars will be given a slightly different taper in order to facilitate the installation and removal of the trimmer and coupling capacitor assemblies. The outer trim-coil will be given a smaller radius and a sixth coil will be added at a radius value of 400 mm. The maximum current limit of all trim-coil power supplies will be increased to 200 A.

The steel components and coils for the main magnet of SPC2 have been ordered, and should be ready for magnetic field measurements during the first semester of 1987.

The RF-system

It was found that harmonic number h=2 in SPC1, and h=4 in the SSC gave no particular problems, but with harmonic numbers of 6 and 12 respectively, it proved much more difficult to tune the two cyclotrons. Running the system on the lower harmonic numbers only would limit the energy range for heavy ions considerably, e.g. 23 down to about 17 MeV for Ar. Alternatively, the present frequency range of SPC1 (8.6 to 26 MHz) would imply that accelerating these ions will necessitate operation at the higher harmonic numbers for most of the energy range. It would thus be advantageous to reduce the minimum RF frequency for acceleration of heavy ions at lower energies. The limiting factor is the lowest frequency at which the resonators of the SSC can be tuned, i.e. 6 MHz. To reduce the lowest frequency of the SPC1 resonators to 6 MHz would require the resonators to be lengthened to the extent that installing SPC2 would need major structural changes to the existing building. Increasing the dee capacitance by 455 pF would also have the desired effect on the lower frequency limit. Changing the dee height or liner gap would necessitate major departures from the design for SPC1. Tests on SPC1, made at low power levels, proved that an open concentric stub line, connected to the dee stem through an existing vacuum flange and an existing inlet through the outer conductor of the resonator, would enable the tuning of the resonator down to 6 MHz. The position of the stub line and its construction is shown in Fig. 2 below. Increasing the dee capacity implies increasing the required input power. However, this is offset by the fact that the acceleration of heavy ions to low energies would also require low dee voltages, thus reducing the required drive power. In order to prevent resonance effects on the open-ended stub line, the length should be less than a quarter wavelength at the highest frequency. The length required for a specific capacitance may be calculated from

$$\ell = \frac{1}{\beta}\,\mathrm{atan}\,\frac{1}{\omega C Z_0}$$

where $\beta = 2\pi/\lambda$. The impedance of the stub line is given by

$$Z = -\frac{j}{\omega C} = -jZ_0\cot\beta\ell$$

The stub line will be connected only for frequencies below 8.6 MHz: for all other frequencies the operating conditions will be as for SPC1.

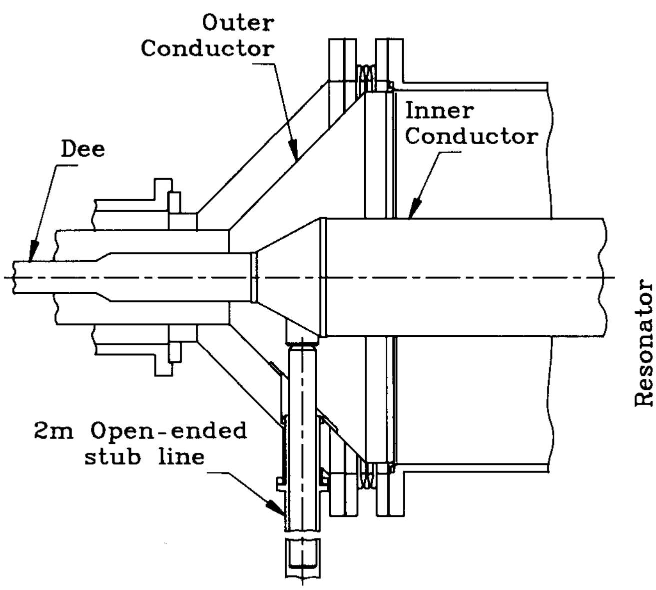

Fig. 2 Cross sectional view of the joint between the resonator and the vacuum chamber showing the location and construction of the proposed open ended tuning stub to enable operation of SPC2 at frequencies between 6 and 8.6 MHz.

The vacuum system

Favourable transmission of heavy-ion beams in SPC2 is strongly dependent on good vacuum. A transmission of 80% of the lowest energy (0.05 MeV/nucleon) of a ^{129}Xe beam will be possible with a vacuum of 2×10^{-5} Pa. With a vacuum of 1×10^{-4} Pa the transmission will be reduced to 35%.

The gas load of SPC2 is estimated to be 1.6×10^{-3} Pa.m^3.s^{-1}. Using metal seals wherever possible, the gas load may be reduced to 1×10^{-3} Pa.m^3.s^{-1}. To reach a pressure of 2×10^{-5} Pa a total pumping speed of 50 m^3.s^{-1} is needed. A more detailed calculation shows that a pressure of 4×10^{-5} Pa inside the vacuum chamber may be reached using the pumping system depicted in Fig. 3. On each of the two resonators a cryopump, with a pumping capacity of 3.6 m^3.s^{-1} for air, will be mounted. A turbo-molecular pump, 2.2 m^3.s^{-1}, as well as a cryopump, 5 m^3.s^{-1}, will be mounted directly on to the main vacuum chamber. The forepumps for the turbo-molecular pump will consist of a 350 m^3.s^{-1} Rootes pump and a 60 m^3.s^{-1} rotary vane pump. It will be possible to pump the system down to 1×10^{-4} Pa in 2.5 hours. Provision is also made for regeneration of the cryopumps and to procure a guard vacuum for the seals of the feedthroughs of the two radial probes.

External ion sources for SPC2

An ECR source is at present under construction and should be ready at the beginning of 1988. The source will be capable of delivering highly ionised heavy ions from gaseous as well as non-volatile elements. The specified emittance is 200π mm.mrad for 80% of the current at an extraction voltage of 12 kV.

A source for polarised protons and deuterons is also under construction and should be ready for delivery early in 1988. The guarranteed proton or deuteron current will be 90 μA for an emittance of 135π mm.mrad at 20 keV. The polarisation for a proton beam is better than 0.75. For deuterons the vector polarisation will be the same, and the tensor polarisation $p_{zz} \approx 0.75$, $p_{zz} \approx -1.5$.

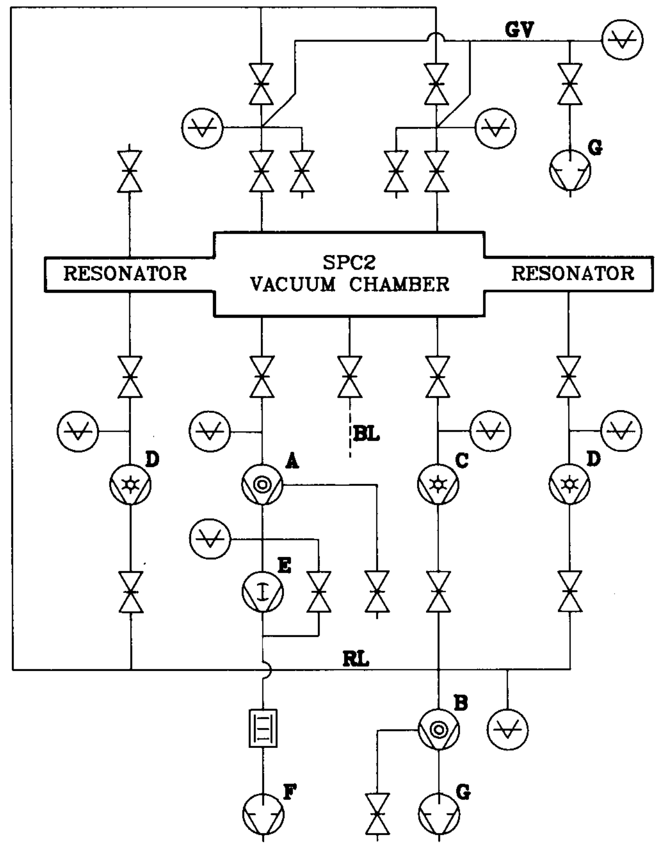

Fig. 3 Schematic diagram of the proposed vacuum system for the second injector cyclotron. In the figure A, C, D and F indicates pumps of capacities 2.2, 5, 3.6 and 60 m^3.s^{-1}, B 50 l.s^{-1}, and lastly E and G indicates pumps having capacities of 350 and 20 m^3.h^{-1} respectively. RL indicates the regeneration line, GV the guard vacuum line, and BL the external beam line.

Axial injection

The two external ion sources will be situated in the basement (Fig. 4). The polarised ion source will be on the most direct beam line to the injector. This beam line will utilise electrostatic bending and focusing elements exclusively in order to preserve polarisation. The ECR source will be on a side line, and the ions from this source will be injected into the direct line by a dipole magnet. The external beams will be injected axially into SPC2. After a study of the options for the axial injection/inflector combinations, it was decided to use on-axis injection through the lower yoke and pole in order to avoid the problems associated with first-harmonic magnetic field components introduced by off-axis channels. The inflectors will be of the spiral type, and use will be made of three constant geometry orbits (CGO) to cover most of the basic energy range of SPC2. A study of the light-ion orbits showed that, for the 34 and 17 turn CGO's, spiral inflecors may be designed with horizontal cross-section electrodes, thus eliminating the need for complex machining procedures in the manufacture of the inflectors. For the heavy ions on the 8 turn CGO however, it was found that the required electrical radius of the inflector becomes so large that it can not be accommodated in the pole gap of SPC2. In these cases resort must therefore be taken to the more complicated spiral inflector with tilted electrodes. Preliminary calculations showed that reasonable electrical radii are possible using such a design.

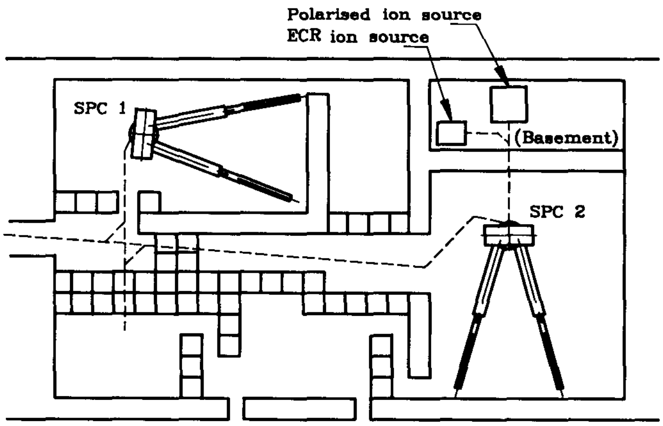

Fig. 4 Layout of the injector vaults in the existing building, showing the placement of the second injector cyclotron and the proposed beamlines to link up to the line from SPC1 to the SSC vault on the left. The two injectors will be on the same level, but the two ion sources will be on the basement level. The beamline from the polarised ion source will use electrostatic focusing and bending elements exclusively.

SPC2 design parameters

SPC2 will have two 90° Dees and four accelerating gaps. The RF system will be similar to that of SPC1. The magnet poles will also have four sectors like SPC1, but the edges of the sectors will be bevelled to modify the field in the central region to have a slightly smaller cone shape. Table 2 summarises the main characteristics for this injector. The energy ranges for a number of ions in selected charge states are shown in Fig. 5. Also shown are the energy ranges for the same ions after post-acceleration by the separated-sector cyclotron.

Extraction radius R_e	0.476 m
Average magnetic field at R_e	0.3 to 1.0 T
RF Frequency range	6 to 26 MHz
Harmonic numbers	2 and 6
Maximum peak Dee voltage (above 8.6 MHz)	60 kV
Maximum peak Dee voltage (below 8.6 MHz)	25 kV
Minimum peak Dee voltage	12 kV
Constant geometry orbit turn numbers	34, 17, and 8

Table 2. Summary of the characteristics of the second injector cyclotron.

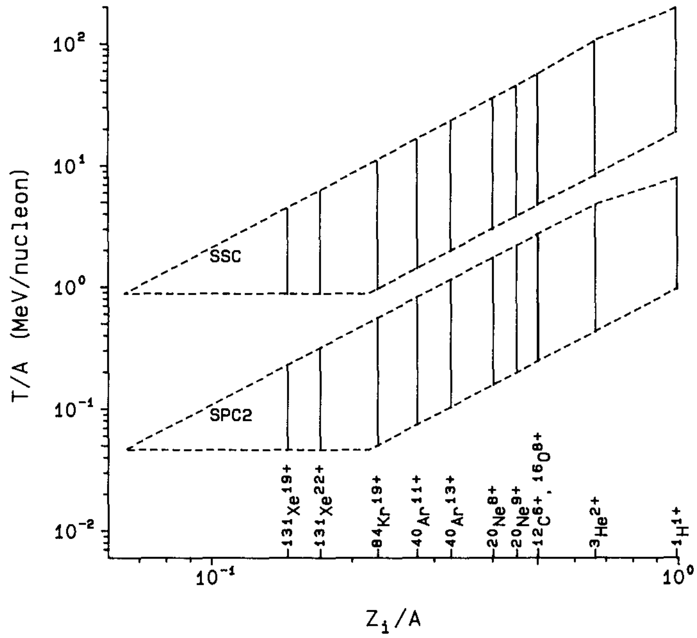

Fig. 5 Operating Conditions for SPC2 and SSC. The limitations imposed by the RF frequency range, Dee voltage range, and magnetic field magnitude and extent is taken into account in both cases.

References

1. R O Sayer, 2nd Conference on Electrostatic Accelerators, Strassburg, May 1977.

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