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BEAM EXTRACTION STUDIES FOR THE PROPOSED SUPERCONDUCTING CYCLOTRON AT THE UNIVERSITY OF MILAN.

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Introduction

Studies for the beam extraction from the proposed K=540 superconducting cyclotron have been so far concentrated on an extraction scheme which makes use only of electrostatic deflectors and conventional passive or active magnetic channels. Use of supertubes seems not to be strictly necessary. Besides, operational experience with these devices is still limited so that we prefer not to include them, at this stage, in the design.

Calculations reported here use magnetic field maps obtained as described elsewhere(1). Since beam extraction is, at least for some light ions, the ultimate limit in the machine maximum energy, it was checked that variations in the maps, compatible with uncertainties in the calculations or the geometry, would not drastically alter the present results.

Main machine characteristics are given in detail elsewhere(2,3). For the purpose of this paper we recall that pole radius is 90 cm, operating average magnetic fields are between 41 Kgauss and 22 Kgauss, for heavy and light ions respectively. Maximum energy is between ~ 14 and ~ 55 MeV/nucleon, again for heavy and light ions, while for each ion an energy variation down to one fourth of the maximum is envisaged.

Outline of the Extraction Scheme.

The fringing field behaviour is a key aspect for the design of any extraction scheme. At present it is also the least precisely known of magnetic field properties, pending model measurements(3), and on whether an open or closed yoke structure shall be ultimately adopted. Superposition of the iron generated field and a large field from the coils produces the kind of fringing field shown in fig. 1, for an average level of 31.8 Kgauss, at different azimuths. The insert in the figure defines the azimuths with respect to the sector configuration. Regions around the beginning or the end of a hill are characterized by steep, non constant, gradients. Beam getting out at these azimuths between radii of 90 cm (pole edge) and 100 cm tend to be severely affected in their phase space behaviour, showing large distortions. Beams getting out of the pole around the middle of a valley seem instead to be much easier to keep reasonably focused.

Extraction should also be as fast as possible. Two deflectors are a sort of minimum requirement for our field, given the maximum electric fields which can be reasonably achieved, ($\sim$140 kV/cm), and the azimuthal length, about 40°, which can fit either in a hill or in a valley. Design considerations, like easier access etc., favour deflectors in the hills. Possibility of a third deflector, which would then forcedly be inside a dee, i.e. in a valley, is left open, either for increasing the upper energy limits of the machine, or easing electric field requirements. Calculations on this possibility are in progress.

As for the magnetic channel, preliminary studies have shown that screening effects which can reasonably be achieved, i.e. up to few Kgauss at most, do not significantly improve extraction. Radially focusing gradients are instead necessary. As a consequence, use of only focusing channels, with no screening effects, is envisaged. Their action is therefore only apparent on the phase space of extracted beams, and not on the behaviour of reference rays.

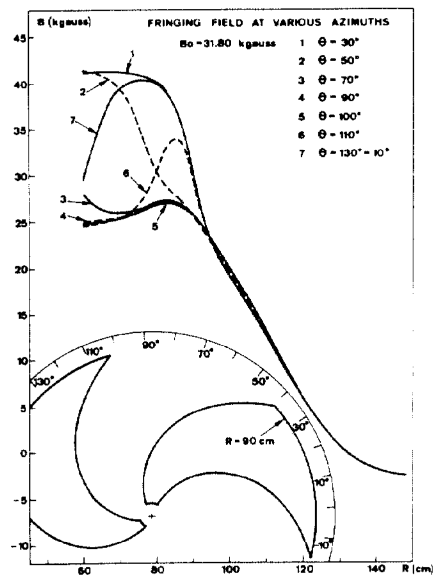

Fig. 1. Radial behaviour of the fringing field, at different azimuths, at a level of 31.8 Kgauss.

With the choices outlined above, the reference extraction path is shown in fig. 2 for a Cu^{21+} ion, with an energy of 37.8 MeV/nucleon. This, together with light ions, is among the particles more difficult to extract, i.e. requiring the highest electric field in the deflector. Details are given in the figure in a self-explanatory way. The particle radius at the entrance of the first deflector is 82.7 cm, and it is taken from accelerated orbit code runs, where the particle was started 20 turns before the onset of the $\nu_r = 1$ resonance. At the extraction radius $\nu_r = 0.8$, and a first harmonic amplitude of 5 gauss has been used to excite the $\nu_r = 1$ resonance. Moreover, acceleration at the gap crossings occuring between the deflectors is also taken into account. While the trajectory shown here is obtained for a 130 kV/cm electric field on both deflectors, calculations show that a reasonable latitude in these electric fields is possible. Practically the same extraction path can be obtained if the field on the first deflector is raised to 140 kV/cm, and the second one lowered to 90 kV/cm. This finding can be of considerable importance, if a gap widening of the second deflector is needed in order to accomodate the beam, which becomes radially defocused, as will be seen later. This in turn makes more difficult to reach electric fields as high as in the first deflector, where the gap can be smaller.

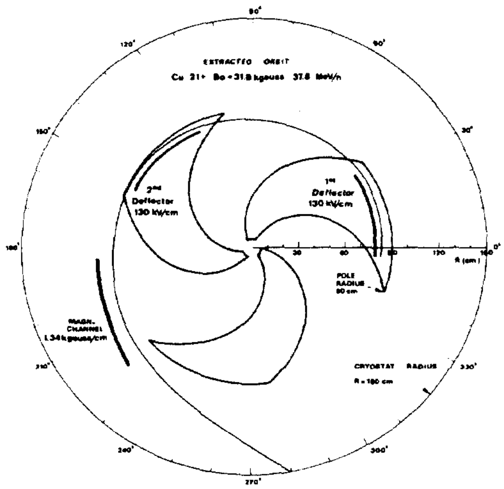

Fig.2. Extraction path for a Cu21+ ion, at 37.8 MeV/ nucl., both for 130 kV/cm on the two deflectors and 140 kV/cm on the first and 90 kV/cm on the second one.

Similar trajectories could be obtained for a complete set of representative ions, involving, in some cases, lower electric fields, down for example to 110 kV/cm for U^{38+} ions at 14 MeV/nucleon. Taking into account the injection scheme(4), which supposes particles to be injected along the valley between the two deflectors, the present extraction scheme looks very favourable, with extracted beams running nearly parallel to the injected ones.

Phase Space Behaviour

Starting conditions for a representative phase space at the entrance of the first deflector are obtained via accelerated orbit code runs. An example for Cu^{21+} ions, at 37.8 MeV/nucleon and for the radial phase space, is given in fig. 3, for an emittance of 4 mm

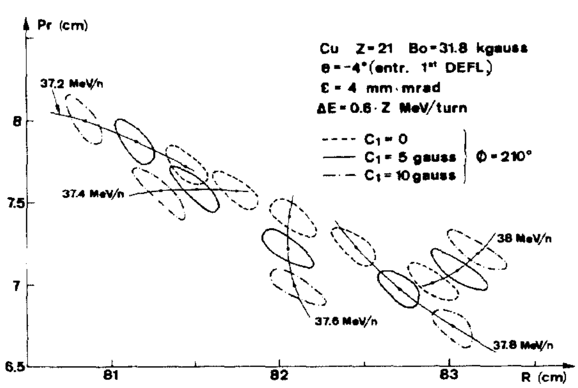

Fig. 3. Radial phase plots of an accelerated beam, without 1st harmonic, and with 5 and 10 Gauss 1st harmonic amplitude.

mrad. Other details are listed in the figure. Phase space tracking in the extraction system has quickly shown the paramount importance of additional radial focusing via a magnetic channel. An example of how critical the gradient of the latter can be is shown in fig. 4, for

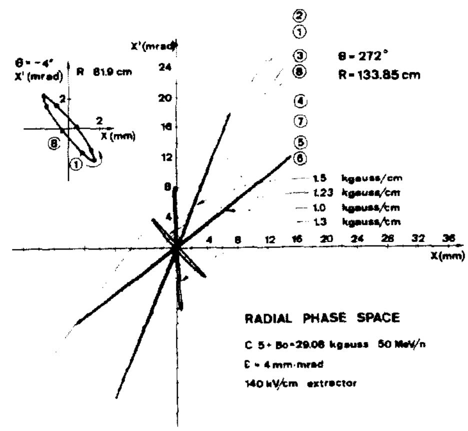

Fig. 4. Effect of different gradients of the magnetic channel on the radial phase space of the extracted beam as observed near the exit from the cryostat.

the radial phase space at a radius of 1.35 m, i.e. near the cryostat outer radius. Sharp differences are observed, for gradients variations of 10%-20%, meaning that gradient optimization may be required for the various extracted beams.

Systematic studies over a large set of representative ions have shown that a convenient magnetic channel could start at a radius of 91 cm, i.e. immediately outside the pole, and be about 40° long, as indicated also in fig. 2. Optimum gradients vary then between $\sim$ 1.1 and $\sim$ 1.7 Kgauss/cm. Since at this stage, with two deflectors, trajectories vary slightly at the pole border, while having a constant position and angle of exit from the cryostat, the channel should be movable over an azimuthal range of about 20°. It is not ruled out, however, that further development of the extraction scheme can bring about an essentially fixed position for the channel.

A picture of the phase space behaviour of the extracted beam is shown, for both radial and axial phase spaces, in fig. 5, at some key points along the extraction path. While the example is referred to Cu^{21+} ions at 37.8 MeV/nucleon, essentially identical results are obtained for any other ion. It is seen that indeed some radial widening of the beam takes place, but it looks tolerable, being confined to approximately 7-8 mm. Gap in the first deflector can be restricted to 5 mm, while in the second one up to 7-8 mm may be necessary. The beam reaches a maximum width of about 1.8 cm in the magnetic channel, and emerges well focused from the cryostat, at R=150 cm, thus not presenting problems for the successive handling by quadrupole lenses.

Hardware.

Electrostatic deflector - Holding high electric fields, with the limited axial gap of 70 mm available in the hills, may pose problems. We have therefore built a deflector which has been tested in the magnetic field, up to 22 Kgauss, of the Milan AVF cyclotron. The deflector is 30 cm long, with gap variable between 5 and 10 mm, height of the high voltage electrode of 20 mm, and axial clearance towards the grounded molybdenum sparking anodes of 20 and 25 mm. The latter value corresponds to a total axial gap of 70 mm. Voltage holding capability seems so far essentially limited by the axial gap along the magnetic field. In the case of 60 mm total height

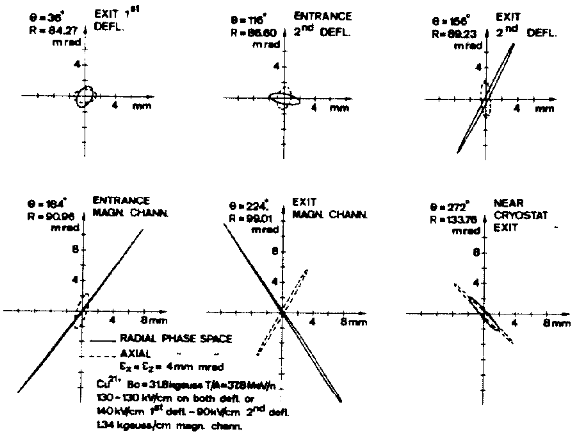

Fig. 5 . Radial (continuous line) and axial (dotted) phase space behaviour for a Cu 21+ beam of 37.8 MeV/nucl., at the various points indicated , along the trajectory of fig. 2.

(20 mm axial gap) a maximum voltage of 85 kV could be held for long periods for a 5 mm transverse gap, thus yielding an extractor field of 170 kV/cm. In the case of 7.5 and 10 mm gaps, the voltage was at most 90 kV, therefore corresponding to extractor fields of 120 and 90 kV cm respectively. Measurements for a 70 mm axial gap are in progress.

While these results are still preliminary, they show however that no impassable difficulties should arise in obtaining the performances required by the extraction scheme described here. In particular, they point out that lowering the field in the second deflector, having a larger (7-8 mm) gap, may indeed be necesary, while safe margins exist for the first , 5 mm gap, deflector. It is therefore reassuring that this possibility, as mentioned in the preceding paragraph, has been explored and found to work.

Magnetic channel. At present both passive and active channels are being considered. The former, made up by slabs of saturated iron, are easier to build and calculations show that the necessary gradients could be obtained. Control of the focusing gradient, however, can only be obtained by varying the relative positions of the slabs. Besides, the perturbation induced at the radii of the last accelerated orbits is of the order of several tens of gauss and requires therefore a large correction by harmonic coils.

An active, superconducting,channel has also been studied, which consists schematically of two pairs of neighbouring coils above and below the median place, excited in opposite directions. With 1 to 2 x 10^4 A turns in each coil, gradients of the order of 1-1.5 Kgauss/cm can be produced and varied by varying the coil excitation. Gradients seem to be fairly constant across the 1.8 cm radial width required by the beam, and the field perturbation in the extraction region is reduced down to a few gauss.

Summary.

The preliminary extraction scheme described here does not seem, in principle, to offer any major obstacles.

Further development should go towards:
i) minimizing the problem of adapting the contour of deflectors to the trajectories of different ions, given the rather different orbits scalloping at high and low magnetic fields. ii) minimize the range of movements required for the extraction elements. iii) verify the possibility of insertion of a third deflector, iiii) verify the possibility of an essentially constant,fixed, gradient for the magnetic channel, in which case a passive channel could be adopted.

Work on these issues is in progress, and will be completed as soon as magnetic field data from the 1:6 scale model are available.

References.

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