IONSCAN
A Program for Optimizing Charge-State Combinations and Calculating Operating Parameters for the Chalk River Superconducting Cyclotron

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Abstract

A program has been developed, IONSCAN, which analyzes all possible charge-state combinations within the design limits of the Tandem Accelerator Superconducting Cyclotron (TASCC) facility at Chalk River. The selection of the optimum charge-states is essential for the successful operation of the two accelerators. IONSCAN also calculates other machine parameters, for selected charge-state combinations, and pinpoints possible difficulties. The structure of the program is described, the calculated parameters are discussed and an example is given.

I. INTRODUCTION

The superconducting cyclotron [1] is an energy booster for the 15 MV Tandem. Negative heavy ions are produced and pre-accelerated in the injector. During acceleration the ion beam is stripped twice, first in the Tandem and again at the inner equilibrium orbit near the center of the cyclotron. Figure 1 shows the midplane section of the cyclotron. An isochronous magnetic field is achieved by optimization of the inner and outer coil currents of the magnet as well as thirteen sets of eight trim rods each. Acceleration over 100-250 turns is provided by four dees. Single-turn, resonant ($\nu_r = 1$) extraction is initiated by introduction of a first harmonic with the outermost trim rods. The beam is then deflected by an electrostatic deflector into the superconducting extraction channel. The channel has three independent sets of steering coils as well as a gradient winding [2]. Note that none of the extraction elements is movable.

II. IONSCAN

IONSCAN is an interactive program, the only input parameters being ion type, extraction energy and cut-off parameters for cases where the stripping efficiencies are unacceptably low. The program calculates system parameters with analytical formulas and parameterizations of precalculated values obtained from the beam-dynamics code SUPERGOBLIN [3]. Some of the parameters have been modified as a result of operating experience with about 40 different beams.

There are a number of operating limits to be considered when the charge-state combination is optimized. These limits and calculated operating parameters shown in the flow-chart in Figure 2 are discussed in the following:

Magnetic field. The main magnetic field has to be between 2.4 T and 5.1 T. More precisely, the inner and outer coil currents of the magnet, which produce a roughly isochronous field, must be within certain allowed ranges and preferably lie within the previously mapped ranges.

Injection radius and energy. To match the injected beam to an accelerated equilibrium orbit after stripping in the cyclotron only one combination of stripping radius, injection energy and rf-phase for each dee-voltage is the optimum. The stripping foil can be radially moved between 145 mm and 265 mm to achieve this combination. IONSCAN calculates the injection radius to an accuracy of ± 2 mm and the injection energy to ± 2%. Both values serve as starting values for SUPERGOBLIN, which then finds the final injection parameters.

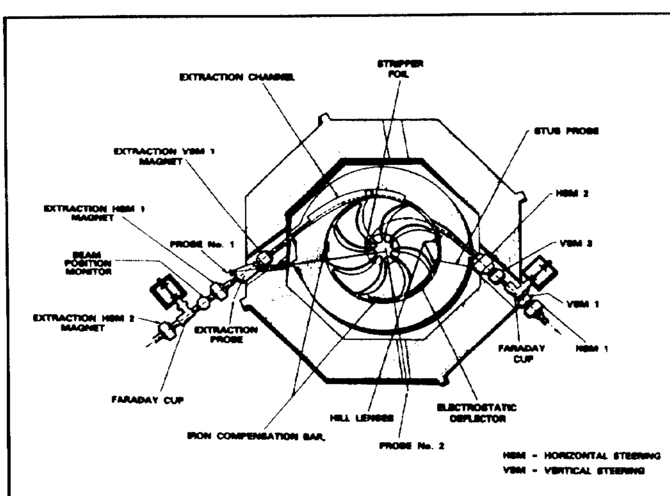

Figure 1. Midplane section of the Chalk River superconducting cyclotron.

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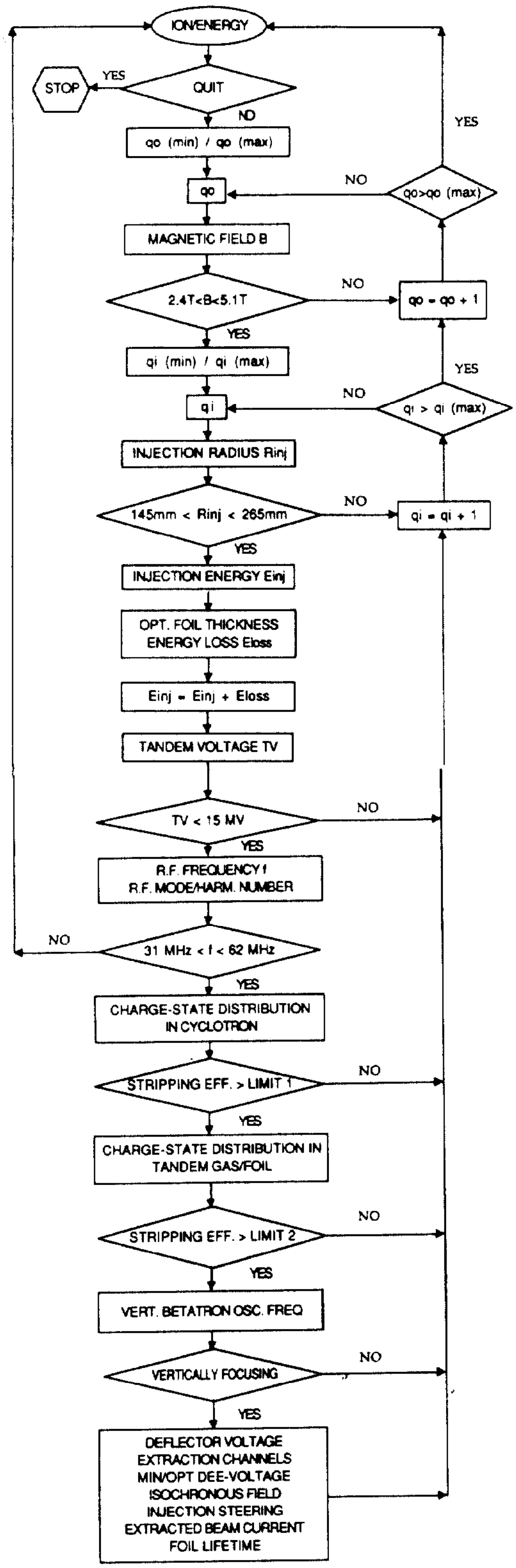

Figure 2. Flow-chart of IONSCAN. q_i is the injected charge-state and q_o is the stripped charge-state in the cyclotron. Boxes represent calculations.

Foil thickness and energy-loss in the cyclotron. IONSCAN calculates the optimum foil thickness [4, 5] and the energy-loss in the foil. Most often a 20 $\mu g/cm^2$ carbon foil is used.

Tandem voltage. After an upgrade in 1988 the maximum voltage of the Tandem is 15 MV. The required voltage for a particular beam is calculated from the cyclotron injection energy, so the accuracy is again $\pm$ 2%. The Tandem voltage limit can easily be changed to explore the benefits of future upgrades.

Rf frequency, harmonic number and mode. The rf cavity is tunable from 31 MHz to 62 MHz. For energies between 3 MeV/u and 50 MeV/u it operates in 0-mode (dees in phase) at harmonic number 4, or in pi-mode (dees 180 degrees out of phase) at harmonic numbers 2 or 6.

Charge-state distributions. The charge-state distributions for stripping in the Tandem (gas and foil) and in the cyclotron are calculated with a modified formula by H. D. Betz [5]. For more accurate information, which in many cases is essential, measured data [6, 7, 8] have to be consulted. If the stripping efficiencies are considered to be too low to be useful at this point in the program the next charge-state combination is analyzed.

Vertical focusing. For light, high-energy ions the vertical focusing limit in the cyclotron maybe reached. Good estimates of the vertical betatron frequency are calculated by analytical formulas [9, 10]. However, "unpredictable" minima in the vertical betatron frequency may appear at outer radii. Consequently, additional beam-dynamics calculations must be done for beams close to the focusing limit.

Deflector voltage. The deflector voltage is not treated by the program as a firm limit as it is constantly improving [11]. IONSCAN calculations of the required voltage are based on precalculated SUPERGOBLIN data and operating experience. The value calculated by IONSCAN serves as a starting value to SUPERGOBLIN, which finds the final extraction parameters.

Extraction-channel currents. The current limits of the superconducting extraction channel are not treated as firm limits either. In practice, 90% of the critical currents are considered to be the upper limits. However, if one or two channel currents are required by IONSCAN to be run beyond their limits, beam extraction may still be possible if one or several of the remaining extraction elements are used for compensation. In this way we have been able to extract beams at a main magnetic field as low as 2.5 T. IONSCAN calculations of the required extraction-channel currents are based on precalculated SUPERGOBLIN data and operating experience. The IONSCAN values serve again as starting values for SUPERGOBLIN, which finds the final extraction parameters. In addition, IONSCAN calculates the critical currents for each section of the channel.

Dee-voltage. IONSCAN calculates the minimum dee-voltage necessary for the beam to clear the foil frame on completing the first turn. It also calculates the dee-voltage required to accelerate the beam to extraction radius in 120 turns or as close to 120 as possible.

Isochronous magnetic field. An approximate isochronous field is calculated for subsequent optimization of the inner and outer coil currents. Fine adjustment of the field is achieved with the trim rods. An additional beam-dynamics code is utilized for this.

In addition to the parameters discussed above, the program calculates the approximate cyclotron foil lifetime [4], the approximate extracted-beam intensity and the injection-steerer current.

III. EXAMPLE

During 1986 and 1987 several attempts to extract ^{79}Br at 20 MeV/u were made but without success. The reason was insufficient deflector voltage. At that time the maximum Tandem voltage was 13 MV and only one charge-state combination ($q_i/q_o=6/20$) gave a reasonable stripping efficiency in the cyclotron. After the Tandem upgrade more charge-state combinations became feasible. For a conservative Tandem limit of 14 MV, Figure 3 shows that there are now four possible combinations if we consider only a discrepancy from the optimum of less than half a charge-state. The additional possibilities are $q_i/q_o=7/21$, 8/23 and 9/24. If a limitation of 50 kV is placed on the deflector voltage (which, at the time, was the highest for a 7 mm gap) only the last two combinations remain. The $q_i/q_o=8/24$ combination requires the lowest deflector voltage and has the best stripping efficiency in the cyclotron, but the stripping efficiency in the Tandem is only half of that of the $q_i/q_o=8/23$ case and the Tandem voltage turns out to be at the 14 MV limit. We chose the $q_i/q_o=8/23$ combination, with which a beam was successfully extracted.

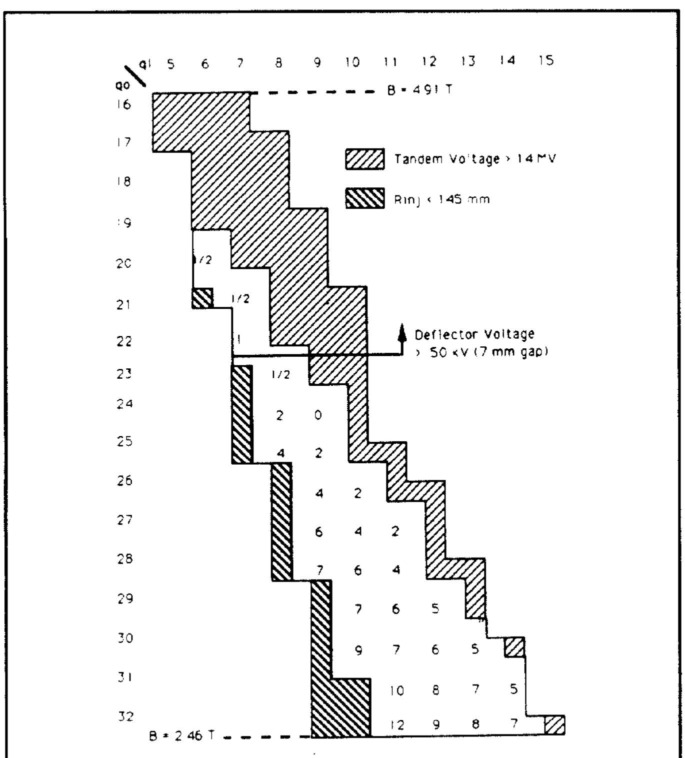

Figure 3. Selected properties of each analyzed charge-state combination for ^{79}Br at 20 Mev/u. The numbers represent the deviation from the optimum charge-state in units of charge-states.

IV. SUMMARY

The program IONSCAN is extremely helpful for efficient evaluation and subsequent selection of the optimum charge-state combination at TASCC. It also calculates many important operating parameters for both accelerators and pinpoints possible difficulties. Future plans for development include incorporation of measured stripping data and refinement of the calculations of injection and extraction parameters to minimize additional beam-dynamics calculations.

V. REFERENCES

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