Particle Accelerators, 1994, Vol. 47, pp. 237–239
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CYCLOTRON OPTIONS FOR AN ISL POST-ACCELERATOR

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(Received 29 October 1993)

A brief review is made of some options for the use of cyclotrons as post-accelerators for an ISL project. Some comparisons with the linac option are made.

KEY WORDS: ISL, Cyclotrons, post-accelerators, LINAC

1 REQUIREMENTS

It is assumed that the post-accelerator is required to accelerate all mass values from A = 1 to 240, from energies of the 100 kV source platform to 25 MeV/u. This can be done by using various combinations of accelerators. This workshop concentrated on the use of linacs for this purpose, particularly at the difficult low energy region. However it is also interesting to see what is possible using cyclotrons.

2 OPTIONS

The options can be classified according to how many stages are used, what starting charge states are used and whether we use only cyclotrons or a combination of cyclotrons and linacs. We will design for the most difficult case, $A = 240$ at full energy of 25 MeV/u. Lower energies can be produced with lower cyclotron magnetic fields, and lower masses have higher Q/A values, giving the same energy with lower magnetic fields or fewer stages. Some options are listed as follows:

1. Use all cyclotrons

   A. Starting charge state Q = 1.

   B. Starting charge state is high.

2. RFQ first stage, Q = 1. Cyclotrons for later stages.

2.1 *Option 1A*

Option 1A uses all cyclotrons. The first question is: how many cyclotrons do we need? To determine this we use the equation for energy of a cyclotron: $E/A = K(Q/A)^2$, where K is the non-relativistic energy constant for the magnet, generally in MeV. This equation tells us, for example, that if we were to try to use only one stage, the K value would be over 10^6 MeV. This would be a Tevatron, entirely too large for a cyclotron. So we need to use the largest practical cyclotron and several stages. A good example is the successful NSCL K1200 at Michigan State University. The energies and charge states at each stage are as follows:

Stage	Q Accel.	Final E/A
1	1	.021
2	6	.75
3	35	25

The first stage would be injected axially by the 100 kV source beam. The second stage would be injected radially, with stripping by a carbon foil located near the cyclotron center so that the beam is centered after stripping. The third stage would be injected radially in a similar way. The injection stripping losses would be up to a factor of 6 in stripping in stages 2 and 3, or a factor of 36 total, for the case of 25 MeV/u, $A = 240$ shown. For lower energies and masses only 1 or 2 stages may be needed.

There are many questions to be studied in this system, including the problems with carbon foil stripping at only .021 MeV/u, and the various harmonics, rf frequencies and magnetic field levels for variable particle and energy operation.

2.2 *Option 1B*

If an ECR source is used, high charge states can be produced and the energy of one cyclotron is greatly increased. For example, to get 25 MeV/u, $A = 240$ beams, one K1200 cyclotron would need $Q = 35$. This is close to the peak of the charge state distribution of present advanced ECR sources. The great advantage of this system is the elimination of stripping foils and the resulting gain in transmission. The beam is stripped in the source. There are questions to answer about the efficiency of the source for converting atoms into high charge state ions, for gases and solids, and about reducing the gas flow from the target to the low value required by the ECR. The GANIL group is planning a system like this. If this idea works the linac post-accelerator would also become much simpler.

2.3 *Option 2*

In looking at Option 1A we see that the large K1200 Stage 1 cyclotron can reach only .021 MeV/u or 5.0 MeV. Using 3 dees, 6 gaps, at 100 kV each, it has about 500 keV/turn giving only 10 turns total. This doesn't make good use of the magnet. The reference design RFQ1 reaches .01 MeV/u and a slightly larger RFQ could probably reach .02 MeV/u. The RFQ is a much simpler and cheaper device than a K1200 cyclotron. So we could think of a first stage RFQ replacing the Stage 1 cyclotron of Option 1A. Its beam could be allowed to debunch and then a buncher would rebunch it to match the variable cyclotron frequency. Replacing Stage 2 of Option 1A with a linac would not have such an obvious advantage. One could also look at using cyclotrons after RFQ2 in the reference design.

3 CYCLOTRONS VS. LINACS

Cyclotron transmision is lower than that of linacs. For axial injection, the efficiency from source to extracted beam can be 20–25%. Part of this is the extraction efficiency, the ratio of external to internal beam, which can be 70%. The stripper foil losses are similar for both systems. The above Options 1A or 2 have 2 strippers, while the linac option has 3 strippers, with a the option of a stripper loop to replace some strippers. A stripper loop is not an option for the cyclotron since the stripping is necessary for injection into stages 2 and 3 of options 1A or 2.

Beam quality, transverse and longitudinal, can be excellent for a modern linac. It is worse for many cyclotrons because of multi-turn extraction, in which several turns are extracted at once, adding to both the transverse and longitudinal emittance. However some cyclotrons have developed single-turn extraction, giving excellent emittance, at the expense of intensity. Transmission is dependent on good bunching and careful beam control during the injection process. If good beam quality is produced in the first cyclotron, the transmission is high through the later stages. This area needs further study.

One component of the post-accelerator system is the high resolution separator, which is needed to separate the closely spaced isobars. The cyclotron separates closely spaced Q/A values by its basic resonant operation. The resolution is proportional to the number of turns and the harmonic number of the rf. Typical resolution available is $10^3 - 10^4$. The resolution can be varied by changing the dee voltage, which changes the number of turns. So the first cyclotron in the system could be used as a mass separator.