Proposed Michigan State University trans-uranic accelerator facility

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Presented by H. Blosser

ABSTRACT

This paper briefly describes the design of a versatile facility for accelerating ions of every element to energies sufficient to produce nuclear reactions on any target. The design utilises a large six-sector ring cyclotron with ~40 kG m average bending capability for the main acceleration. The present MSU cyclotron would be the light ion (p, d, ^{3}He, ^{4}He) injector. A number of possible heavy ion injectors are discussed, the field trimming problem is reviewed and initial studies of resonance transitions are described.

1. INTRODUCTION

The possible existence of 'islands' of nuclear stability well beyond the region of presently known nuclei is a topic of great current interest to physicists and chemists.[1] The most likely production processes for such super-heavy nuclei appear to be transfer reactions between a massive projectile and a massive target, such as ^{238}U(^{238}U, ^{178}Yb)^{298}114, etc. Due to the large coulomb repulsion, such a reaction will only take place at bombarding energies in the range of 6–9 MeV/nucleon which is well beyond the capability of present accelerators (assuming realistic values for the ion charge state). A number of groups are hence currently planning accelerators to produce the desired energetic ions—several of these are described in other papers at this session.

The major difference between the proposed MSU facility and those envisaged by other cyclotron groups is the much larger final stage cyclotron (40·7 kGm vs 29·4, 27·0, 26·5, etc.). This large final stage cyclotron can produce the required energy using ions in a much lower charge state (for Uranium 24+ is adequate vs 33, 36, 45, etc.). The costly heavy ion injector can therefore be smaller leading to a system which we believe to be less expensive in total and with a very elegant light ion capability as an important bonus (protons up to 600 MeV, deuterons to 360 MeV, etc.). The MSU plans also to give very serious consideration to use of a third cyclotron as the heavy ion injector whereas other U.S. groups plan to employ a large Van de Graaff for this purpose.

A brief paper such as this cannot give a complete description of the facility—for this, interested readers are referred to the MSU proposal document.[2] In this paper we briefly discuss several of the crucial problems of the design, namely: (a) the compatibility constraints of such a multi-accelerator system, (b) the field trimming requirements and limitations and (c) the tolerances associated with resonance transitions.

2. SYSTEM CONSTRAINTS

If all cyclotrons in a multi-cyclotron system are operated at the same rf frequency, numerous advantages accrue, namely: (a) phasing problems are minimised, (b) all buckets are filled, (c) space charge effects are minimised, (d) harmonic jumps occur at the same point in all the accelerators, (e) orbit scaling is maximised, etc. Given the single rf frequency, the rotation frequency of the particles in any of the cyclotrons must be an integral submultiple of the rf and one can proceed to draw the very useful dimensionless diagram given in Fig. 1 in which possible isochronous magnetic fields are plotted vs radius. The various harmonics give the curves labelled $n = 1, 2, 3, 6, 8, \ldots$, etc. Any cyclotron in

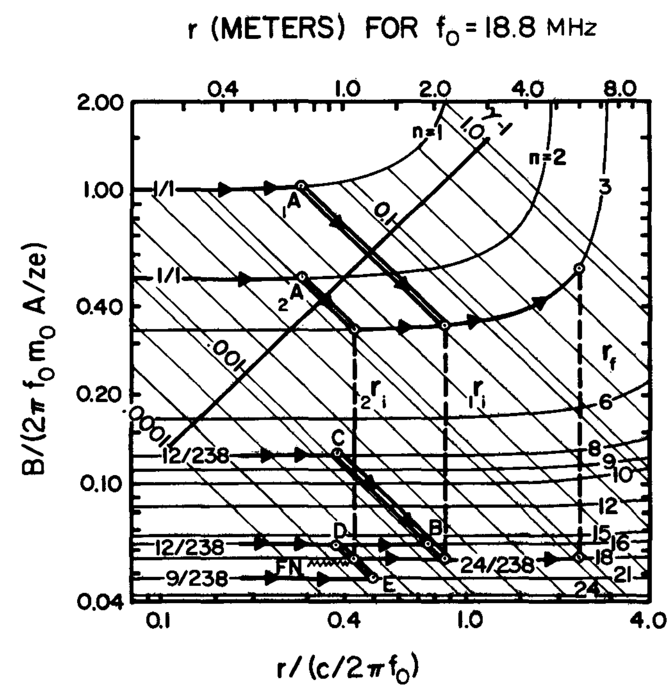

Fig. 1. Generalised logarithmic graph of isochronous magnetic fields vs radius for various harmonics n *= 1, 2, 3 . . ., etc.,* m_0c^2 *= 931 MeV,* f_0 *= rf accelerating frequency, and* Z *and* A *are charge and mass numbers for the accelerated ions. Fractional labels 1/1, 12/238 on some curves give design* Z/A *values for the proposed MSU facility. Straight lines slanted to the top left connect points of equal energy on the various field curves, the energy scale being as indicated on the* $\gamma - 1$ *axis (*m_0c^2 *units)*

the system must operate on one or the other of these isochronous field curves—at any transition point from one cyclotron to the next the harmonic number can change if desired as can the charge state of the ion. Such a transition does not however, involve an energy or velocity change and if the field and radius are plotted on log scales as in Fig. 1, then lines of constant energy are straight and slant upward to the left. The energy scale for these curves is given in $m_o c^2$ units by the heavy straight line slanting up to the right in the figure. Any transition from one cyclotron to the next must go along one of the constant energy lines and the ratio of radii in the two cyclotrons is hence completely determined by the selection of the harmonic number and is independent of field or charge state. Given a particular harmonic curve the magnetic field required to accelerate some selected ion in a specified charge state is obtained by reading the dimensionless field value from the graph and then converting to real units by inserting the A and Z of the ion into the expression for the field unit. The rf frequency appears in both field and radius units and a higher frequency is seen to linearly increase required fields and reciprocally decrease radii. The scale at the top of the graph gives radius in real units (metres) for a frequency of 18·8 MHz which is the maximum energy frequency for the proposed MSU facility.

Using the diagram, possible injection and radius options for the MSU proposal can be readily understood. We first somewhat arbitrarily select a trial Z/A of 0·1 for uranium and making allowance for flutter adequate for any ion we select harmonic 18 near the bottom of the diagram for acceleration of these ions. On this harmonic we reach the desired energy of 8·5 MeV/nucleon at a radius of 2·3 cyclotron units (or 6·0 m for f = 18·8 MHz with a required field of ~7 kG average or 17 kG peak). Fixing the maximum radius for the final cyclotron at this point and moving up the right hand vertical dashed line, r_f, we see that $n = 3$ is the highest usable harmonic and for $Z/A = 1$ the required magnetic field at 18·8 MHz is nearly the same as for 24/238 on $n = 18$. (The protons and uranium ions hence both require about the same magnet power supply capacity.) We wish to use the present cyclotron with r_{max} = 70 cm as the proton injector and we can accelerate protons on either first or second harmonic in this cyclotron out to point ${}_1A$ or ${}_2A$. In either case the transfer to the ring must go along the diagonal constant energy direction as indicated by the heavy double lines. Proton injection radii for the ring of 2·2 m or 1·1 m then result for the two cases and are indicated by the two heavy dashed lines ${}_1r_i$ and ${}_2r_i$ in the figure. These two radius lines intersect the $n = 18$ field line at energies of 1·0 and 0·3 MeV/nucleon which (not accidentally) are good energies for producing the 24+ charge state in a gas or foil respectively.

The 1·0 MeV/nucleon option of course requires a larger injector—two of the most interesting possibilities are indicated by the points B and C which are respectively a converted synchrocyclotron (point B almost exactly matches the parameters of the Carnegie Institute of Technology synchrocyclotron[3] for example) or a 1 m radius 30 kG superconducting or cryogenic cyclotron. This last option appears clearly feasible with present magnet technology[4] and is particularly valuable and appropriate for a heavy ion cyclotron where the extreme rigidity and low rotation frequency of the ions are always severe problems. (A previous MSU study has determined coil configurations appropriate for producing the necessary field flutter.[5])

The 0·3 MeV/nucleon needed for injection radius option ${}_2r_i$ is much easier to obtain—possible cyclotron options are indicated by points D and E and the zigzag line indicates an FN tandem. Note also that with option E the conservative choice of a 9+ charge state is compatible with existing field technology whereas the 12+ charge state presumed for the other cyclotron options represents a modest extrapolation beyond presently proved source technology. (For any of the heavy ion cyclotron injector options we assume a positive ion source located in the terminal of a Cockcroft-Walton and injecting into the cyclotron via a Saclay type system[6]–the initial radius is thus large enough to avoid gap factor problems even on the high harmonics contemplated–also the complete source and Cockcroft-Walton assembly could be readily set up in duplicate to allow for concurrent maintenance and operation.)

Finally, it should be noted that in the discussion herein we have effectively imposed one unnecessary constraint, namely that the rf frequency for the protons is taken to be the same as for the heavy ions. For our proposal this is natural since the required maximum magnetic field comes out to be nearly the same for both protons and heavy ions even with the constraint imposed. If this were not so one would certainly be strongly inclined to lift the constraint and assume different maximum energy frequencies for the light ions and the heavy ions. Two versions of Fig. 1 would then be necessary and also harmonic relationships might have to change in order to vary the final energy over a wide range.

3. FIELD TRIMMING REQUIREMENTS

Two key questions must be answered to establish the feasibility of trimming a field for both 600 MeV protons and heavy ions, namely: (a) can the trimming be accomplished with sufficient accuracy and (b) can the trim coil power be

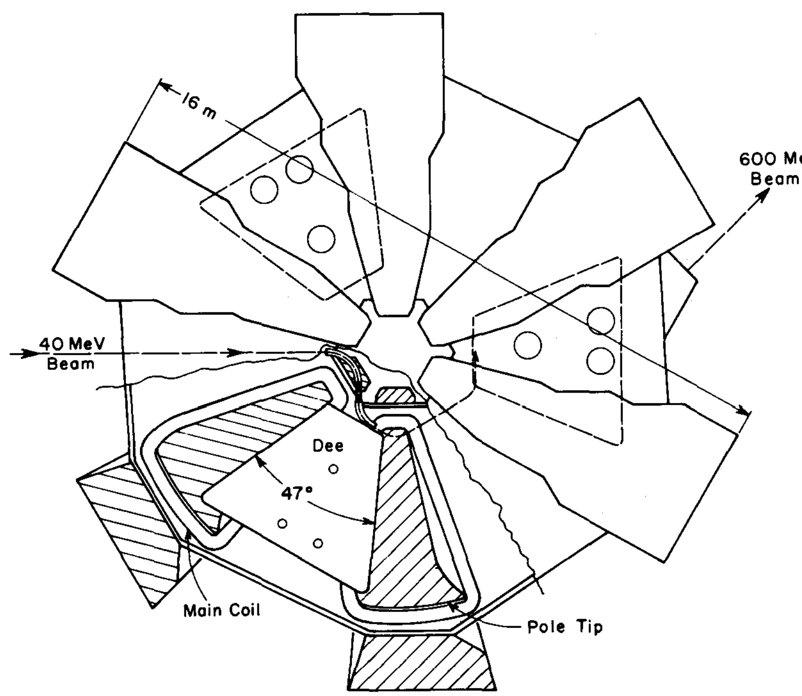

Fig. 2. Plan view of proposed ring cyclotron with central region option 1r

held to a reasonable level. Model magnet studies of coil effectiveness are of course necessary to establish a firm answer to these questions—until such studies are accomplished, which is a long term process, a reasonably accurate guess as to the severity of the trimming problem can be obtained from air core coil calculations.

To perform such calculations we have constructed an assumed 'iron' field, using the magnet shape shown in Fig. 2 which is a plan view of the large cyclotron, and using fringe field data from our small cyclotron which has the same minimum gap. We then introduce an array of air core coils and perform a least squares fit to trim the assumed iron field for proton and heavy ion operation. In these calculations the number of trimming coils is a parameter of crucial importance. If too many coils are employed, adjacent coils will frequently work against each other to achieve a minor improvement in the fit at enormous cost in kilowatts. If too few coils are used, the residual coil spacing ripple which is always left in the field becomes too large and produces excessive phase and focusing frequency excursions. After some searching a network of 44 coils spaced roughly according to turn density was selected as the best initial design configuration. This set of coils produced a fitted field for protons with closed orbit properties as shown in Fig. 3, and indicated a power requirement of about 1 mW for the complete coil network. Results for heavy ions are similar and are not shown.

A crucial feature of the Fig. 3 results are the oscillations in Q_r, Q_z, and $F(E)$* due to the coil structure. The focusing frequency oscillations which are typically

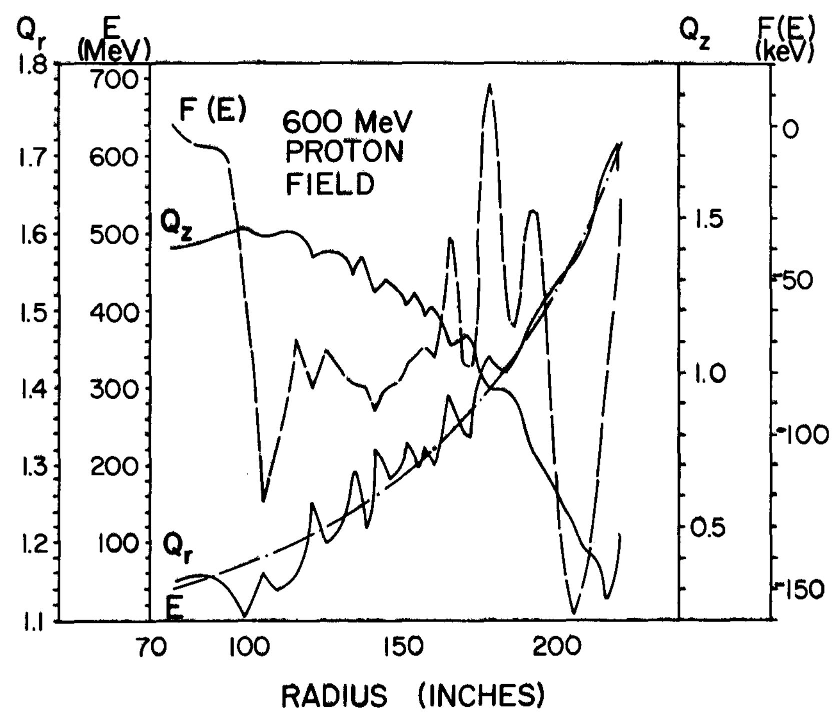

Fig. 3. Graph of energy, radial and axial focusing frequencies and phase slip integral vs radius in the trimmed magnetic field with trim coil currents set for proton operation. With an energy of 600 keV per turn the F(E) *curve gives a phase excursion of* $\pm 22°$

*The function $F(E)$ is defined such that $\sin \phi(E) - \sin \phi_0 = F(E)/V$ where V is the energy gain per turn.

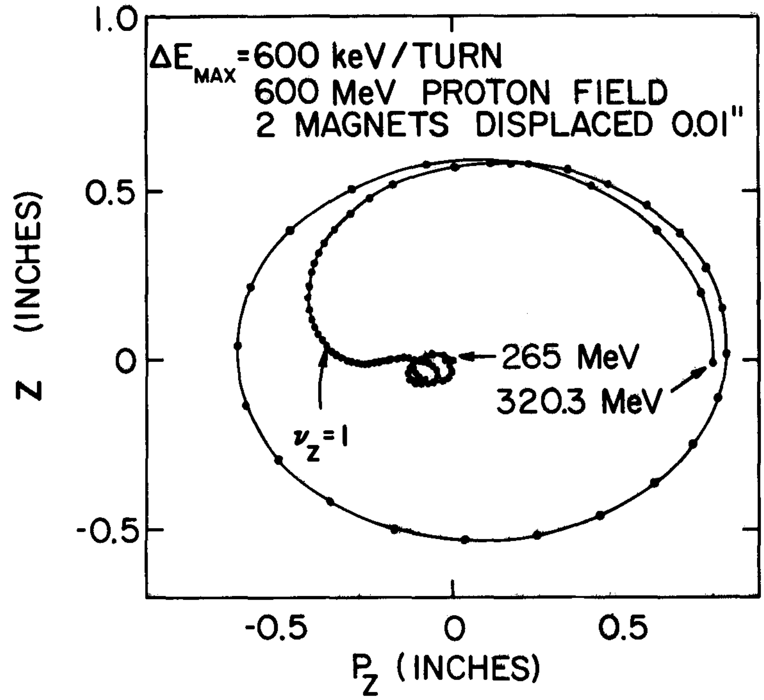

Fig. 4. Plot of Z vs P_Z on successive revolutions for an orbit accelerated through the $Q_Z = 1$ resonance. Two magnets 180° apart are displaced up and down by 0·01 in respectively

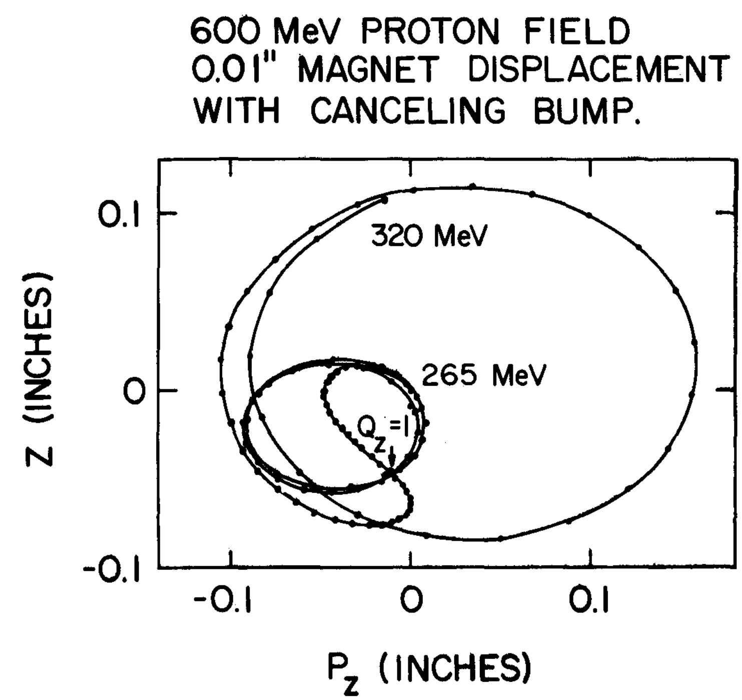

Fig. 5. Repeat of the acceleration run of Fig. 4 but with the median plane correcting coil turned on and roughly optimised. (Note the change in scale relative to Fig. 4)

±0·04 mean that 'smooth' field operating points which pass close to a resonance may in fact for a real field result in large numbers of turns just on the resonance and may well therefore require a much higher degree of magnet and orbit perfection than passing briskly through the resonance.

The *F(E)* oscillations imply a phase excursion of ±22° for the design energy gain per turn. This is quite acceptable for normal sinusoidal acceleration since, as is well known,[7] the linearity of the derivative of a sine wave over such an interval allows the effect of sliding off on one side of the wave to be compensated by a corresponding slide to the other side and, if an appropriate frequency adjustment is made, the beam energy spread is essentially identical to that in a perfectly isochronous field. In contrast if the rf were 'flat-topped' by addition of a second or third harmonic such a phase excursion would be catastrophic as regards the energy homogeneity since the strong nonlinearity of the derivative of a flat-topped wave means that the beam must remain continuously on the flat top or the energy smoothing benefit of the flat top is lost. To accomplish this with a reasonable phase interval for the beam would require a ten-fold reduction in the *F(E)* oscillations. In the absence of any realistic proposal for accomplishing such a reduction, we have omitted rf flat topping from the design.

4. RESONANCES

The relatively simple magnet shape envisaged in the proposed design leads to a high flutter which for heavy ions or low energy protons produces a $Q_z > 1$. On the other hand for high energy protons Q_z drops rapidly with energy due to the rapidly increasing radial gradient of the isochronous field and as seen in Fig. 3, the integral resonance $Q_z = 1$ must be passed at intermediate energy.

Guided by our experience in the existing cyclotron which passes the integral resonance $Q_r = 1$ at two locations without detectable beam disturbance, we propose to establish appropriate tolerances on magnet construction to eliminate beam disturbance at the $Q_z = 1$ resonance. At the same time, as a backup, we have established the existence of a simple two parameter correction for possible residual effects of the resonance.

Results of initial studies of this type on $Q_z = 1$ are shown in Figs 4 and 5 which are results of tracking of accelerated orbits in the same magnetic field as in Fig. 3. For Fig. 4, two opposite magnets have been displaced up and down by ±0·25 mm. The induced Z amplitude at the resonance implies that magnet mounts should be designed to hold this error to ±0·03 mm which is quite practical with modern techniques. Fig. 5 shows that even with ±0·25 mm magnet displacements the effect of the resonance can be largely eliminated by a simple two parameter trim coil compensation thus establishing the existence of the backup correction procedure. On the basis of these results we believe that $Q_z = 1$ can be passed with no great difficulty and with beam disturbances just as small as for the now customary $Q_r = 1$ transitions in smaller cyclotrons.

As expected, comparable computer studies for the $Q_r + Q_z = 2$ and $Q_r = Q_z$ coupling resonances indicate these to be much less severe than $Q_z = 1$ and detailed results are therefore omitted.

DISCUSSION

Speaker addressed: H. G. Blosser (MSU)

Question by R. S. Livingston (ORNL): How is economics introduced into the rather interesting chart on system constraints?
Answer: There is no easy way that we know of. The chart shows compatible combinations of cyclotrons–any such combination which looks attractive is then carried on to a detailed design and this design is used to prepare a cost estimate.

Question by J. A. Martin (ORNL): We all know that the energy gain and the harmonic number are important in determining the phase slip. Could you tell us the number of turns and the harmonic number for proton acceleration?
Answer: The proposed cyclotron would accelerate protons on third harmonic and would require about 1000 turns.

Question by E. G. Auld (UBC): What is the tolerance on the first harmonic of the magnetic field for heavy ion cyclotrons?
Answer: This tolerance is of course always proportional to $|1 - Q_r|$. Since $1 - Q_r$ is usually large for these machines, due to flutter effects, the tolerance is not severe.

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