PROTON WINDOW AND SUPERCONDUCTING CYCLOTRONS

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ABSTRACT:

Superconducting cyclotrons are particularly appropriate for acceleration of heavy ions. Strong magnetic field enables the achievement of high final energies at much smaller (2-3 times) radii than in the case of room temperature machines leading consequently to substantially lower construction and operational costs. Protons may be accelerated without experiencing potential blow up catastrophe, caused by the presence of the focusing limit and dangerous coupling resonance ($\nu_r+2\nu_z=3$) phenomena, only in the narow window of the operational region.

I. IRON CORED SUPERCONDUCTING CYCLOTRONS

In the case of an ordinary AVF cyclotron the concerned feromagnetic structure has a dominant role in production of average magnetic field and field modulation for the purpose of axial focusing. The operating limit of an ordinary AVF cyclotron at a smaller pole radii is determined by the magnet bending power. When conventional coil is replaced by a superconducting one, the bending limit becomes considerably higher than the focusing limit, the latter then becoming an operating limit for energy-per-nucleon achievements in the region of light nuclei. The most important types of the operating limits in the case of the iron cored superconducting cyclotrons are:

$T/A=K_f\ (Z/A)$ focusing limit

where $K_f \tilde{}(s)^{1/2}W_o/6.22\ Br$

and $s=1/2\ N^2/(N^2-1)\ (1+2\ tg^2\alpha)$ $W_o=931.5$ MeV

$\nu_r=N/2$ and $\nu_z=N/2$ stopband limit

$\nu_r+2\nu_z=3$ coupling resonance limit

$\nu_r=1$ and $\nu_z=1$ resonances

The resonance strength is determined by resonance I/J ratio where I=field periodicity and J=order of the perturbation force. Essential resonances I=N,2N cannot be avoided, while imperfection resonances $I \neq N., 2N,...$ are present only when imperfections are present in the cyclotron magnetic field. The most dangereous are the resonances characterized by the lowest J value ie. J=1. The most important is the $\nu_r=1/1$ (k=r/B dB/dr=0) resonance which appears at field minimum and maximum (at the center and extraction regions of the machine). The high energy machines operating in the high ν_r, ν_z domains are additionally characterized by the presence of the stop band and coupling resonances.

The stopband resonance limit and focusing limit are of a fundamental character. The coupling resonance limit can be crossed if the beam is perfectly centered and/or has the possibility to jump over the resonance. Less severe but still important are: saturation limit at $B_{av} < 2.35$ T and orbit separation limit.

II. PROTON WINDOW

In the early phase of design of MSU K500 superconducting cyclotron it was recognised that the problems of proton acceleration cannot be efficiently resolved in the type of machine which in the same time has to be used as a powerful heavy ion accelerator requiring to be designed with a sufficiently large radius in order to produce a sufficiently high bending constant K_b and large focusing constant to bending constant (K_f/K_b) ratio. Analytical considerations confirmed in the numerical analyses indicate that protons may be accelerated without experiencing potential blow up catastrophe, caused by the presence of the focusing limit and dangerous coupling resonance ($\nu_r+2\nu_z=3$) phenomena, only in the narow window of the operational region determined approximately by relation:

$$F-(3-\gamma)^{2/4} < \gamma^2-1 < F$$

where F=field flutter, and γ is the relativistic factor.

The results of numerical examination of these problems, using K500 and K800 magnetic field data confirme these predictions based on "smooth approximation" and "zero flutter" formulae |1| (see fig 1.).

The results of numerical examination of these problems, using K500 magnetic field data are given in figure 1. confirming the predictions based on "smooth approximation" and "zero flutter" formulae. If as an acceptable set of values of the extraction radii are accepted only the values in the close vicinity of the value R=26.5 ", it appears that:

1. The window for acceleration of protons, free of problems with $\nu_r+2\nu_z=3$ resonance and the lack of focusing power can be found in the region of proton energies between 125 and 155 MeV.

2. At the energy of 60 MeV the limit of fundamental character was found due to the appearence of $\nu_z=1.5$ stop band.

III. AIR CORE SUPERCONDUCTIONG CYCLOTRONS |1|

The prominent features of an air core design are:

- the mutually independent current settings in the superconducting main coil and flutter configuration
- the mutual independence of the symmetry numbers for accelerating system and flutter field configuration
- a considerable degree of freedom in accelerating system design
- considerable cost savings.

The limiting phenomena are under full control (see fig. 2). The maximum achievable proton energy per nucleon for air core superconducting cyclotrons is a function of the field-symmetry number

T/A=931.5 |(N-1.5)1/2-1| MeV/n.

The analyses of the fissibility of the air core cyclotron design satisfying the technical requirements at present status of the art has been performed up to the energies of 1 GeV/nucleon.|1|

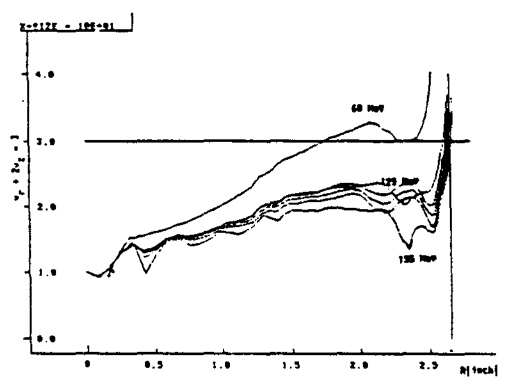


Fig. 1. Resonance $\nu_r+2\nu_z=3$ as a function of radius for protons in K500 magnetic field.

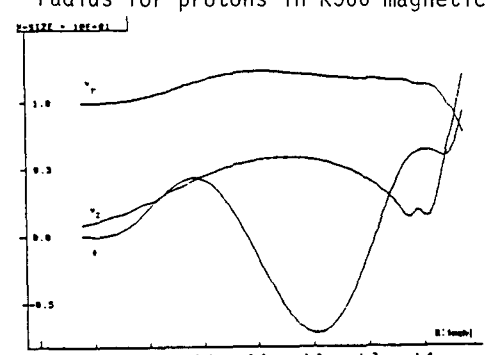


Fig.2. $\nu_r(1)$, $\nu_z(2)$ and phase slip (3) for air-core cyclotron magnetic field at proton energy of 115 MeV.

IV. HOW TO INCRESE THE OPENING OF THE PROTON WINDOW

The dangereous influences of the critical resonances caused by the proton window effects may be avioded or reduceded in several ways:

- MOVING OUT the critical resonance from the operational region changing field parameters or decreasing machine radius.

The Taylor expansion of the actual magnetic field gives an approximate expression for the "zero flutter" isochronous field:

$$Bisoc=3.11\ b/R\ (1+1/2\ b^2\ (r/R)^2\ (1-1/2\ (r/R)^2))$$

where $b=(v/c)max$.

It is relevant to note that an increament of the magnet pole radius R (what is the basic requirement for the achievement of sufficiently high values of K_f and K_b at b=const (constant proton maximum energy) implies the decreasing of the local values of isochronous magnetic field. This feature combined with the fact that iron cored superconducting cyclotrons are characterized by constant value of the modulation field amplitude, gives rise to the overdosing of focusing power at respective value of proton energy. The intervention in the opposite direction obviously improves a situation.

- JUMPING OVER THE RESONANCE. This approach requires the powerful and/or sophisticated acceleration system, being especially sutable for employment in case of air core cyclotrons

- CREATING FAST PASSAGE THROUGH THE CRITICAL REGION. This can be made by appropriate tayloring of the magnetic field at the cyclotron magnet edge.

- REDUCING FIELD FLUTTER IN EXTRACTION REGION, employing the radial cuts of the sectors in the extraction region. It may be possible in this way to reduce the flutter and obtain lower coupling resonance values in the critical region.

-INCREASING THE FIELD SYMMETRY NUMBER OR INCREASING THE PRESENCE OF THE HIGHER HARMONICS NUMBERS IN THE COMPOSITION OF THE MAGNETIC FIELD. This approach rises the value of stop band limit but in same time reduces the value of the focusing limit. The advantages of this approach will be fully examined during the development of AGOR cyclotron project exploring the various aspects of 200 MeV proton acceleration in K600 machine.

Once when hardware design is chosen but the lower boundary of the proton window is not removed the situation can be improved employing the orbit centering procedures to MINIMIZE the orbit off-centering, minimizing in the same time the possible resonance excitations, since centered orbits have the zero energy content in the oscillatory mode.

The sources of orbit off-centerings are:

- FIELD IMPERFECTIONS, which are quantitatively given by the values of field harmonics. The apparent errors in the zeroth and second harmonics of applied magnetic field change the value of ν_r, while the first harmonic shift the center of equilibrium orbit. The change of the value of the radial frequency is equivalent to the introduction of the non-linearities in radial phase space, while the presence of first harmonic introduce the shift of the orbit center which is equivalent to the generation of the oscillatory particle mode.

-ERRONEOUS ENTRY POINT at injection which is responsible for the eventual shift of the orbit center ie. generation of the particle oscillatory mode.

- ACCELERATION PROCESS which inherently induces the respective shift of the orbit center and related consequences in the particle motion.

In order to controll the phenomena produced by orbit off-centering the following questions have to be answered:
- what are the signatures of the centered orbits
- how to determine the accelerated orbit centers
- how to center the beam when arror is made

The various aspects of the determination of the AEO centers and signatures of the centered orbits together with the employment of the beam centering techniques using the first harmonic component of magnetic field and assymetric distribution of dee voltage in compensating the shift of the orbit centers are examined in references |2,3| The relevants features of this examinations are shown in self explanatory way in figs. 4,5,6,

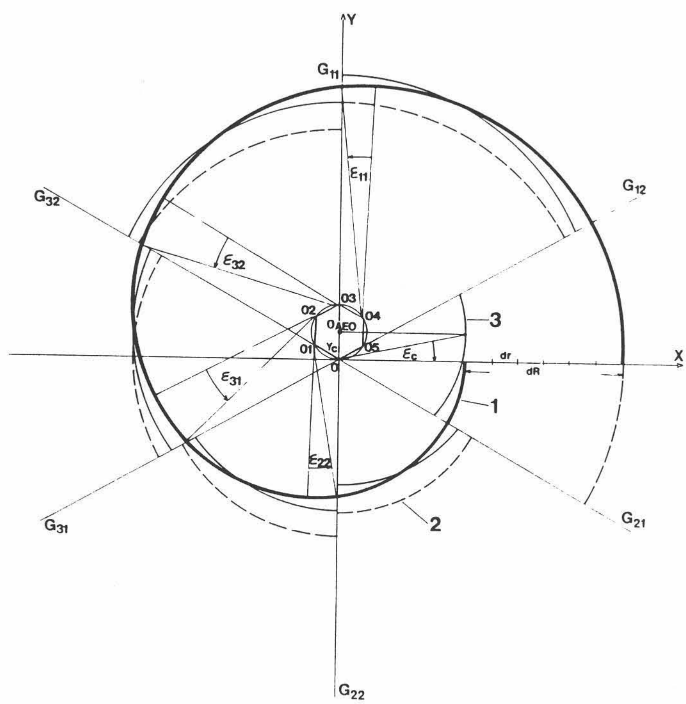


Fig.3. The relevant features of the particle trajectory in a homogenous magnetic field for N=3 dees. The particle is assumed to begin its motion from the SEO position at the midline between the two gaps. The particle trajectory remains the continous curve while the orbit center moves in discrete jumps describing an N-polygonial reqular geometrical form.

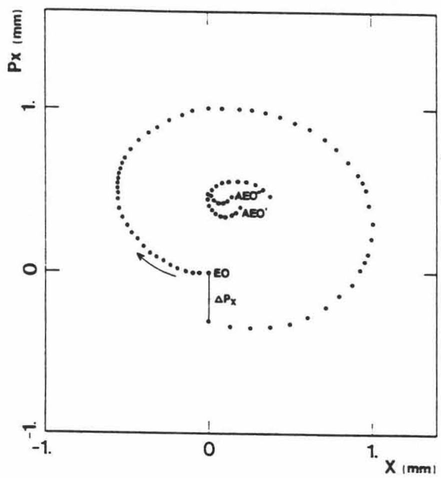


Fig.4. Change of the positions of the coordinate pairs x,p with energy. The AEO coordinates are determined iteratively as the average values of x and px of the precession cycle.

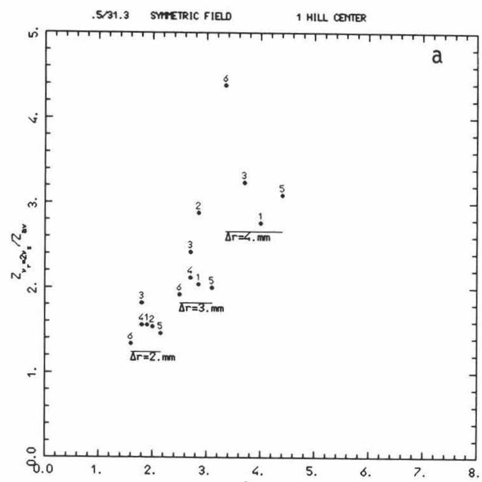
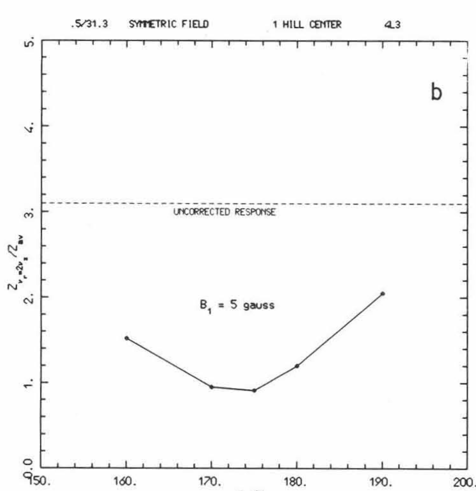


Fig.5. a.) The response in axial space defined as a maximum normalized axial displacement per turn at the Walkinshaw resonance, as a function of the orbit off-centeredness.



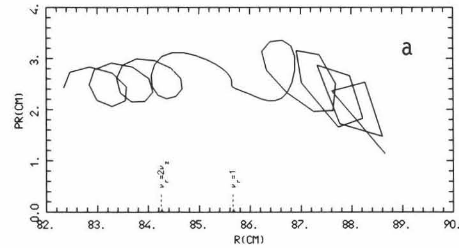
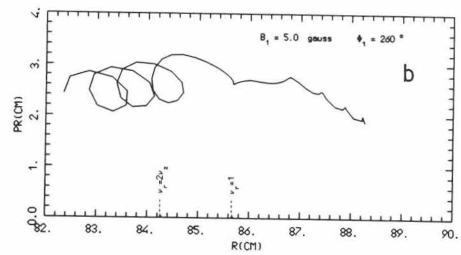
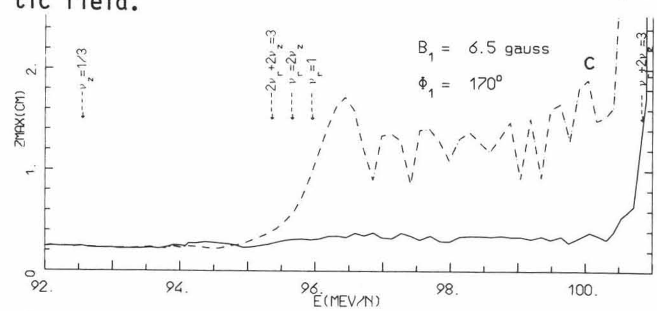


Fig.6. a) The radial phase space of mm off centered and



b) centered beam employing first harmonic of magnetic field.



c) Axial envelope of the off-centered (dashed line) and centered beam (solid line) empoloying first harmonic of magnetic field.

Fig.5.b) The change of the normalized axial response with the variation of the first harmonic phase (solid line) and uncorrected response (dashed line)

References:

1.K.M.Subotic, Europian Particle Accelerator Conference, Rome 1988, World Scientific 1989

2. Lj.S.Milinkovic, K.M.Subotic and E.Fabrici, Nuclear Instruments and Methods A 273 (1988) 87-96

3. Lj. Milinkovic, E.Fabrici and K.M.Subotic, Nucleare Instruments and Methods A 276 (1989)418-426