ORBIT PROGRAMMING AND ITS EXCELLENT RESULTS DURING THE COMMISSIONING OF THE INR CYCLOTRON

Mao-bai Chen, Zong-jao Yao, Sen-lin Xu, Wen-bin Sen
Institute of Nuclear Research, Shanghai, China

Introduction

The remodelling of the INR cyclotron has reached the point where both the internal and external beams of several energies have been successfully obtained without adjusting any parameters pre-set according to the orbit programming. The results of the beam measurement were in good agreement with the ones of our orbit programming. In this paper, the special consideration, principle ideas and some feature of the orbit programmed will be described. The results of the beam measurement will be discussed and compared with the ones of the orbit programming.

Orbit programming

The orbit programming described here is to program a central particle orbit from ion source to the entrance of the deflector, based on the measured magnetic field and calculated electric field with the beam quality and the convenience of operation considered. Prior to the orbit programming, three aspects of preparation works were carried out:
(1) The three dimensional electric field of the central region was calculated by using relaxation method, in which we modified the coefficients of the boundary smoothing correction[1] and made it possible for the small computer PDP-11 to be applied to calculate the complicated three dimensional electric field (Fig.1).[2] (2) A series of versatile codes suitable to small computer PDP-11 have been developed for the study of the particle dynamics in an isochronous cyclotron.[3] (3) An effective method and a systematic procedure for orbit programming have been explored.[4]

The orbit programming was set out from the fact that the ion source in our case can only be moved along one dimension, therefore, we have to mainly rely on the inner valley coils instead of adjusting the position of the ion source to center beam.[5]

To make the calculated magnitude and argument of both inner and outer valley coils as precisely as possible for beam centering and precessional extraction respectively, all first harmonics actually existing in the cyclotron including both static ones and acceleration ones are incorporated into the main magnetic field, of which the static harmonics are caused by magnet, sectors, coils and magnetic extraction devices and the acceleration ones are produced by the electric gap crossing resonance and the asymmetric dee voltage during successive gap crossings. In view of the same difficulty in adjusting the ion source, the option of a constant orbit geometry is preferred. Since the similarity theorems[6] are just appropriate to the uniform magnetic field, therefore, a code called DEEVP was written to make such theory suitable to the isochronous field to get excellent similarities among constant orbits.[7]

The principle ideas of the orbit programming are: (a) centering the beam at large radii from where the extraction calculation starts mainly by tuning the inner valley coils; (b) making particles have positive average phase at the first gap crossings to provide electric focusing and approach to 0° phase as entering into the isochronous region to get maximum energy gain by choosing a favourable initial phase and selecting the bump field; (c) achieving the energy focusing[8] of the beam and minimizing the energy spread by precisely optimizing the r.f frequency and locating phase selecting slits;[9] (d) accomplishing the precessional extraction by tuning the outer valley coils; (e) obtaining similar constant orbits by accurately calculating the dee voltage and carefully adjusting the r.f frequency.

The peculiar orbit feature programmed has been discussed in detail in paper.[5,7] The fixed figuration of the central region is schematically shown in Fig.2. Fig.3 is an acceleration phase plot for a typical centered constant orbit with 242 turns. It shows that beam is well centered within 1mm at the specific large radius and within linear region of phase space for the most of the acceleration. The parabolic shape of the energy E vs To curve for the last turn prior to extraction in Fig.4 shows that the central ray is correctly located at the top of the parabola and indicates that the r.f frequency optimization has been chosen for the "energy focusing".[10] The excellent similarities among the constant orbits with dee voltage ranging from 18kV to 62kV have been obtained, among other things, the identical fixed source-puller and first slit position and the difference in extraction radius and in incident angle to the deflector less than 1mm and 0.5° respectively make it possible for particles of variable energy to have fixed central and extraction system.

Beam measurement [11]

There are three differential probes located inside the cyclotron as shown in Fig.5 for the measurement of both beam space and time quality. Probe 1 can alternatively be a 5 finger probe to measure the axial distribution of the beam. However, differential plots were failed due to the poor dee voltage regulator and only one slit available. The "tip" and "body" of the probes were thus connected together in the measurement. With usual shadow measurement procedure, the beam width at three probe azimuths can be measured. The 50% measurement is used to determine the orbit pattern at same azimuths, from which the center error and coherent amplitude of the beam can be deduced. During the measurement, there is no need to have both "scallope" or "energy gain" correction, because

CH1996-3/84/0000-0347 $1.00 © 1984 IEEE

the particle trajectory being measured was calculated and printed in advance for comparison. The accuracy of such measurement with poor dee voltage regulator was confirmed by the reproducibility of the measured results and the fact that the various orbit patterns were first measured with deliberately changing some parameters and then calculated with same changed parameters, both values were in good agreement with each other. The measured beam width (Fig. 6) with periodicity of approximate $1/(Q_r-1)$ also ascertained the reliability of such measurement.

The probe 1 made of copper is also used as a stopping target in gamma ray time of flight measurement to measure the beam phase width and phase shift with the multichannel analyzer calibrated in degrees per channel; and to determine the particle phase and its phase history with the channel corresponding to zero degree r.f phase calibrated by using a modified Garren-Smith method. The gamma ray time of flight could be used as a beam tuning monitor. This technique was also applied to measure beam energy and energy shift. It seems to be that this method can judge the beam energy spread and multi-turn extraction.

The particles of various energies have been successfully accelerated to the radius prior to the extraction with no need for adjusting any parameters pre-set based on the orbit programming, except the main magnetic field due to the hysteresis. Under such circumstances, the difference between the programmed and measured values in the best case was generally 1-2mm in particle trajectory (Fig.7), and 2-3° in particle phase (Fig.8). The nice history of particle phase (Fig.9) shows not only the good isochronous of the static magnetic field also the accuracy of the main magnetic field tuned and r.f frequency pre-set as well as the well centering of the beam. The measured energy was in good agreement with the calculated one as following (MeV):

	calculated	gamma flight	nuclear reaction
P	29.99	29.94	
	20.08	20.07	
	14.98	14.79	14.82
	11.81	11.78	11.87
	8.78	8.67	8.8
D	15.79	15.54	
α	31.75	31.5	

All the above excellent results imply that particles were accelerated basically in the manner as we had programmed. Thus the beam loss with the radius must be small as shown in Fig.10, in which the more rapid decrease of the curve around R=350 mm was attributed to H_3 ions out of phase and the fluctuation of the curve was due to the poor dee voltage regulator. The fact that 8.78 MeV proton with 18.4 kV dee voltage has same beam intensity as 30 MeV proton with 62kV dee voltage ascertains that one constant orbit geometry with the fixed central region configuration (Fig.2) will cover all desired energy range. Since the programmed constant orbits have almost identical extraction radius and incident angle to the deflector, there is no need for adjusting the entrance of the deflector for particles of variable energy, but with different extraction efficiency ranging from 50-80% under unadjusted pre-set parameters. Just for not changing the deflector, which was designed for 30 MeV proton, to facilitate operation, it would be better to slightly adjust outer valley coils to increase the extraction efficiency better than 70%. As a result, the beam energy spread was a little deteriorated (Fig.11). The high extraction efficiency manifested the enough turn separation as programmed, even though the turn separation measurement by differential probe was failed. The various beams have been transported to three pipe lines with transport efficiency better than 90%. The maximum external beam intensity of 20 MeV proton was 30μa with 300c, 1ms pulse modulation and 1.5X5 mm exit slit of the ion source. The whole beam tuning work lasted for about two months.

References

1. Mao-bai Chen and Lind.D IEEE Trans NS-28 2636 (1981).
2. Mao-bai Chen and Wen-bin Sen Computing in Accelerator Design and Operation Europhysics Conference (1983.9).
3. Sen-Lin Xu and Mao-bai Chen INR internal Report (1983.4).
4. Mao-bai Chen, Sen-lin Xu and Wen-bin Sen Computing in Accelerator Design and Operation Europhysics Conference (1983.9).
5. Mao-bai Chen and Sen-lin Xu INR Internal Report (1983.10).
6. Reiser. M Second Int. Cyclotron Conf. 370 (1962).
7. Mao-bai Chen and Sen-lin Xu Second China-Japan Symposium on Accelerator and their Application (1983.10).
8. Gordon. M. M. N.I.M. 169, 332 (1980).
9. Blosser. H Fifth Int. Cyclotron Conf. 257 (1969).
10. Gordon. M. M. IEEE Trans NS-13 48 (1966).
11. Mao-bai Chen, Zong-jao Yao etc. INR Internal Report (1984.3).

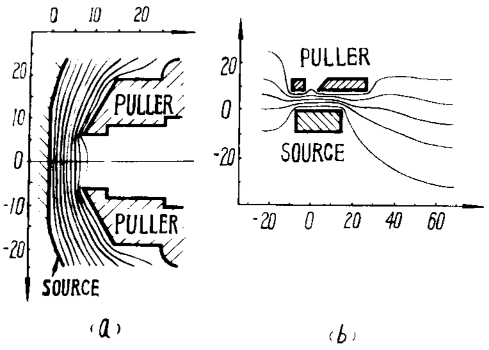

Fig.1 Calculated equipotentials of the central region. (a) vertical plane; (b) median plane.

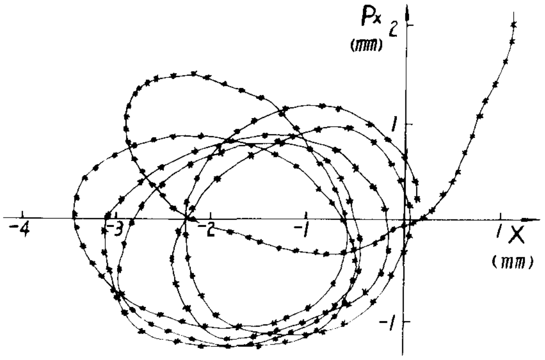

Fig.3 Acceleration phase plot for a centered proton orbit with E=29.23 Mev.

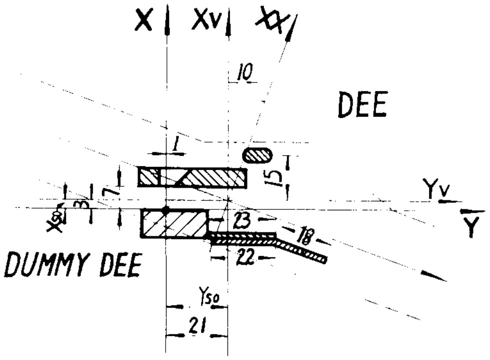

Fig.2 The scheme of the central region configuration for the constant orbit programmed.

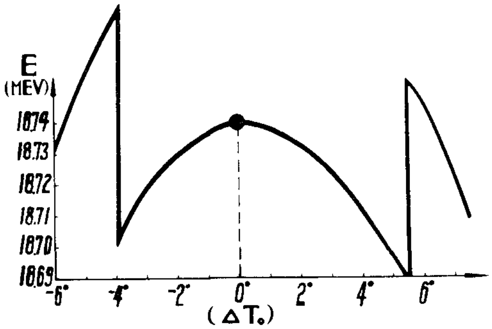

Fig.4 Final energy E prior to extraction vs initial phase difference ΔTo relative to the central orbit.

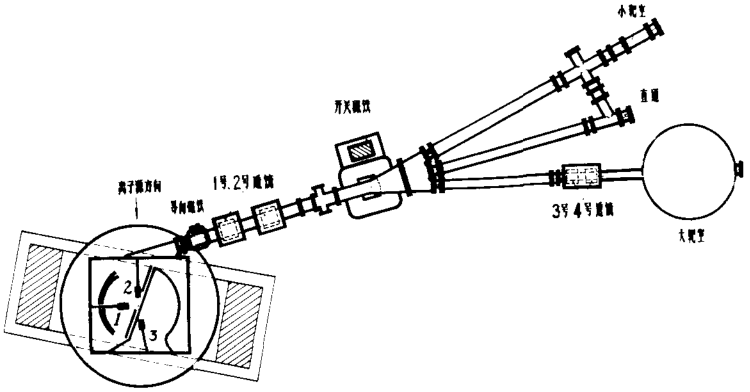

Fig.5 The scheme of the three internal probes and beam lines.

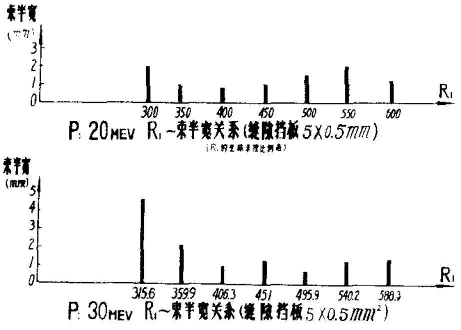

Fig.6 Beam half width vs radius.

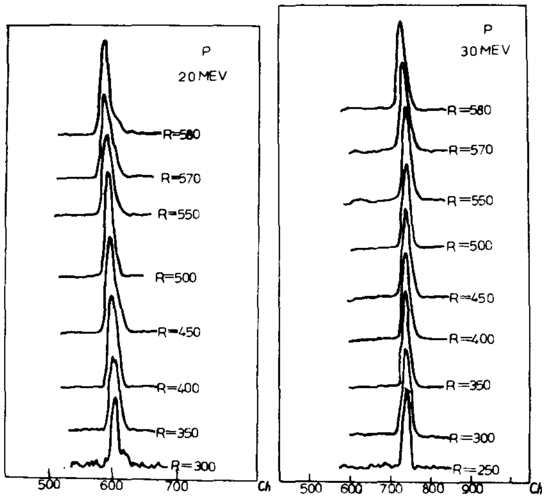

Fig.9 The nice particle phase history.

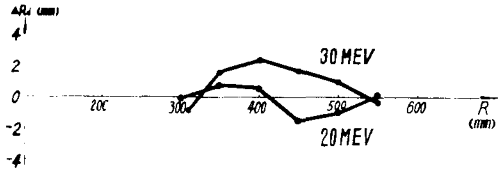

Fig.7 The difference in particle trajectory between measurement and calculation.

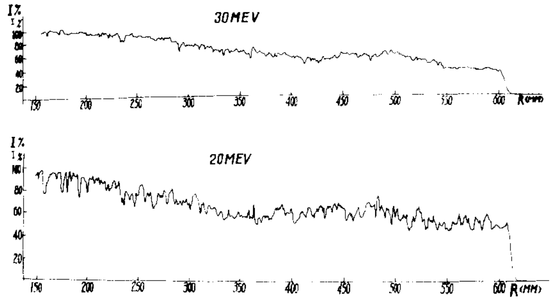

Fig.10 The beam intensity vs radius.

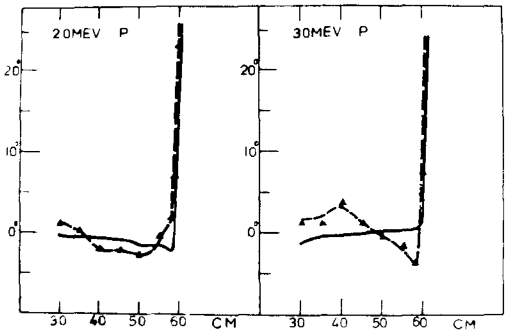

Fig.8 The difference in particle phase between measurement and calculation.

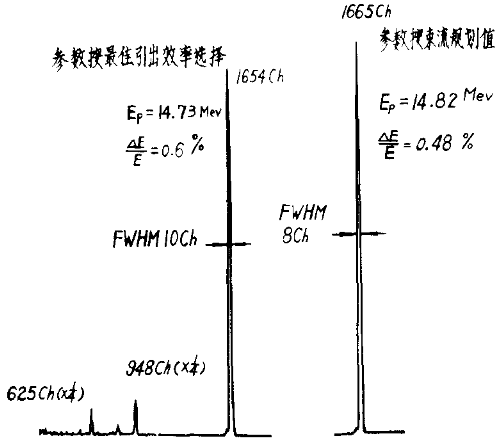

Fig.11 Beam energy resolution with parameters set according to orbit programming (right) and optimum extraction (left).