MODIFICATION OF THE CENTRAL REGION IN THE RIKEN AVF CYCLOTRON FOR ACCELERATION AT THE H=1 RF HARMONIC

S.B. Vorozhtsov#, V.L. Smirnov, JINR, Dubna, Russia
Akira Goto, RIKEN, Wako, Japan

Abstract

A highly advanced upgrade plan of the RIKEN AVF cyclotron is under way. The study is focused on the formulation of the new acceleration regimes in the AVF cyclotron by detailed orbit simulations. The extension of the acceleration energy region of light ions towards higher energies in the existing RF harmonic equal to 2 and the modification of the central geometry for the RF harmonic equal to 1 to allow an acceleration of protons at several tens of MeV are considered. The substantial redesign of the central electrode structure is needed to accelerate protons with reasonable values of the dee voltage. The new inflector geometry and the optimized central electrode structure have been formulated for the upgrade.

INTRODUCTION

A highly advanced upgrade plan of the RIKEN AVF cyclotron is under way [1]. The computer model of the AVF 3D electromagnetic field was prepared and successfully checked against the measurements [2].

The present study is focused on the formulation of the new acceleration regimes in the AVF cyclotron by detailed orbit simulations. Some experiments already conducted with the beams confirmed the selection of the machine parameters based on the beam dynamics simulations.

The new acceleration regimes include the extension of the acceleration energy region of light ions towards higher energies in the existing RF harmonic equal to 2 (H=2), and the modification of the central geometry for the RF harmonic equal to 1 (H=1) to make it possible an acceleration of protons at several tens of MeV. Clearly, with the realistic dee voltage of about 50 kV many particles would be lost in the channel of the Dee, since the existing structure of the central region (CR) was designed for the 2nd harmonic, not for the 1st one. Thus, the substantial redesign of the central electrode structure is needed to accelerate protons with reasonable values of the dee voltage.

The new inflector geometry and the optimized central electrode structure have been formulated for the upgrade.

PROTONS OF 20 MEV

In the H=2 regime the maximal experimentally available proton energy is 14 MeV for the existing electrode structure. It was found in simulations that under the restricted dee voltage of 50 kV acceleration of protons to the energy 23 MeV is also feasible there. Eventually, the energy of 20 MeV was selected for the detailed study, assuming application of the Flat Top (FT) system to suppress the energy spread in the extracted beam. Parameters of the regime are given in Table 1.

#vorozhtsov@jinr.ru

Table 1: Proton H=1 regime parameters. Structure S0 means the existing central geometry and S6 is the newly proposed geometry, which is shown in Fig. 5.

Structure	Final energy MeV	Frf MHz	Winj keV	Uinf, kV	Udee1 kV	Udee2 kV
S0	20	13.60	11.19	3.52	50	50
	23	14.54	11.41	3.71	50	50
S6	30	16.52	16.87	5.26	50	50

The main criteria for selecting the operational parameters of the regime were passing of the reference track as close as possible to the central line of the channel in the 1st Dee and clearance of the central electrodes to ensure maximal transmission of the ion bunch, and good centring of the particle trajectory in the following turns. Also, the RF phase excursion should provide the maximal possible energy gain per turn. For the 84º Dees and H=1 regime the RF phase should be as close as possible to 48ºRF. To ensure the conditions formulated above the Dee voltages and the RF particle phase in initial 4 acceleration gaps were varied.

The estimation of the bunch transmission started from preparing the initial particle distribution in the 6D phase space upstream of the inflector. In Fig. 1 the positions of the bunch at successive turns are given, black points being the lost particle locations. The main channel of the losses is the axial one. At the final radius, just at the entrance of the deflector, the projections of the particle 6D distribution are calculated. Rather large energy spread (~ 0.5 MeV) in the bunch can be explained below with the proposal of how to suppress it substantially.

SHARP TOP SYSTEM

The optimal particle RF phase at the entrance and exit of the Dee is shown schematically in Fig. 2 with the corresponding positions of the bunch (black ellipses) and the Dee voltage performance (red line).

Since the bunch does not sit at the top of the RF wave, the energy gain obtained by particles in the head and tail of the bunch substantially differs at the entrance of the Dee. But at the exit of the Dee the energy spread obtained at the entrance of the Dee gets compensated for to the same reason. The remnant energy spread in the bunch can be explained by the nonlinear dependence of the Dee voltage on time.

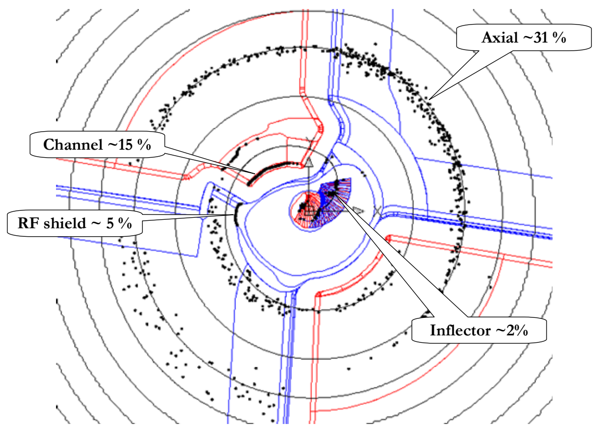

Figure 1: Total losses ~ 53% (Axial ~ 31 %)

The linearization of the Dee voltage performance with time could be reached by sharpening the red curve in Fig. 2 at the top by the FT system, which could be called now a Sharp Top (ST) system. The resulting Dee voltage performance is shown in Fig. 2 by a blue-dash curve. The optimal amplitude of the ST system is close to the FT regime but with the opposite sign wrt the main wave. The resulting energy spread at the final radius could be reduced by a factor of ~50. But considering small RF phase excursion during acceleration and also induced energy spread by some RF phase perturbation due to the radial betatron oscillation of the particles, the effect is just an order of magnitude. Some increase of the particle losses and the number of turns to reach the final radius accompany the effect. The resulting beam emittance at the final radius is shown in Fig. 3. There is striking reduction of the correlated radial emittance as compared to the main-wave-only regime.

INFLECTOR REDESIGN

The main limitation for increasing the proton energy in the existing central structure is the available maximal Dee voltage of 50kV. With this voltage, the particle with the energy higher than 23 MeV is not able to clear the central electrode structure at the 1st turn.

The size of the central structure is mainly determined by the existing inflector dimensions, and there is a substantial reserve in the RIKEN AVF cyclotron for miniaturization of the central electrode structure. Even some moderate minimization of the structure with the RF shield will permit an increase of the proton energy up to 30 MeV. But it would require some modification of the infrastructure around the inflector.

OPERATION DIAGRAM

The RIKEN AVF cyclotron operation diagram (Fig. 4) shows 3 regions, reflecting an advance in the energy for various accelerated ions: the yellow region presents the initial design stage of the cyclotron; the blue region is related to the recently proposed by the simulations and experimentally tested regimes, and finally, the green area reflects the energy advance in the present study, limited by the available maximal Dee voltage of 50 kV.

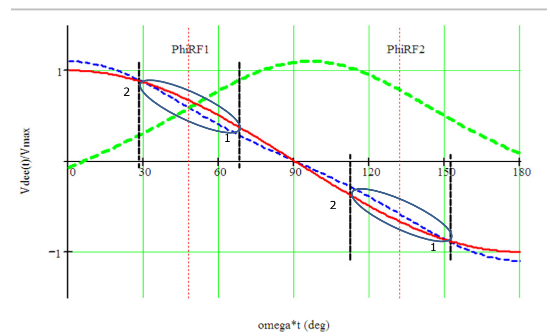

Figure 2: RF wave with the bunch positions at the entrance and exit of the dee. The principle of the energy compensation, PhRF1=48º.

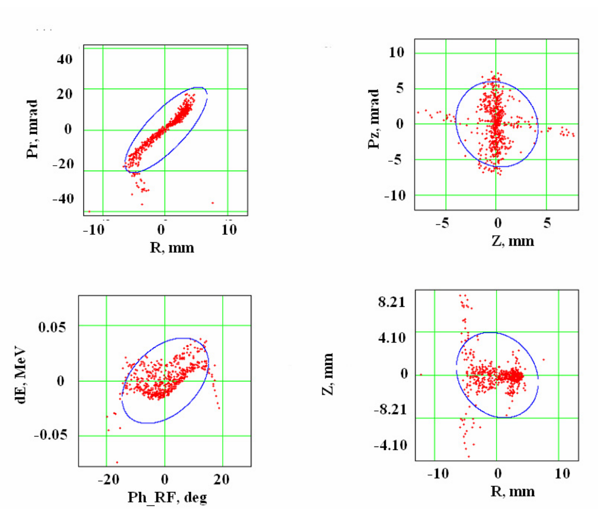

Figure 3: Beam emittance at the final radius, upstream of the deflector.

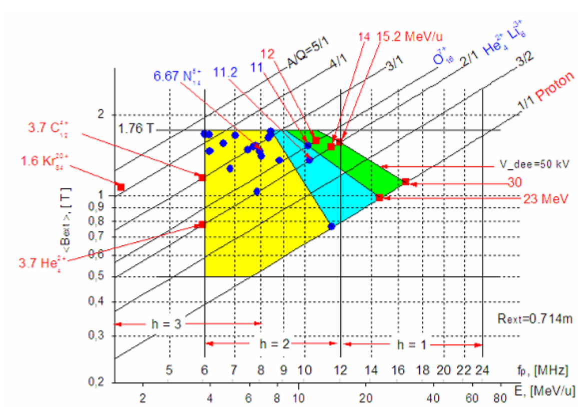

Figure 4: Acceleration performance of the RIKEN AVF cyclotron.

PROTONS OF 30 MEV

A set of the central configurations (S0 is the existing structure) were tried in an attempt to obtain good centering and transmission for as high proton energy as possible, simultaneously retaining the possibility to accelerate ions at the H=2 RF harmonic. As a result, we arrived at the compromised configuration S6 (see Fig. 5), which was investigated in detail below.

In acceleration of protons of 30 MeV, similar to the previous regime for protons of 20 MeV, the major channel of the particle losses is axial ion motion.

^{6}LI^{3+} OF 12.6 MEV/U

To check the viability of the eventually obtained S6 structure an acceleration of 6Li3+ with the maximal feasible energy was simulated. The lithium energy indicated in the operation diagram suggests the maximal Dee voltage 50 kV. But in reality there is some reduction of the Dee voltage dependent on the RF frequency of the regime. Experimentally available data on the issue show that in our case the maximal lithium energy at the acceleration at the H=2 RF harmonic is 12.6 MeV/u, and not 14 MeV/u, as was considered before. So, all subsequent studies for lithium are performed for this realistic energy. Presently, the experimentally tested regime corresponds to the lithium energy 11.2 MeV for the H=2 RF harmonic.

EMITTANCE PERTURBATION BY INFLECTOR

In the previous sections it was shown that the main channel of the particle losses in the central region is axial motion of ions. In reference [3] there is an attractive proposal as to how to mitigate the situation by modification of the inflector electrode surface in the manner presented in Fig. 6 (“bended” electrodes). This permits increasing the axial focusing in the inflector at the expense of some worsening of the radial focusing. The surface of the electrodes is not smooth as in the classical spiral inflector but folded at some optimal angle with the “valley” along the central line of the electrode surface. There is a compromised solution with the resulting reduction of the total losses [3].

The proposal was tested by simulations for the AVF Cyclotron, investigating an acceleration of 6Li3+ of 12.6 MeV/u. The “bended” inflector substantially reduces axial beam emittance at the exit of the inflector with some increase of the radial emittance.

An analysis of the overall losses during acceleration up to the final radius shows that there is simply redistribution of losses with the total losses staying at about the same level. Further optimization of the inflector electrodes and the regime parameters is needed to fully exploit the proposed modification of the inflector plates.

Figure 5: Comparison of the S6 structure with S0 (white lines).

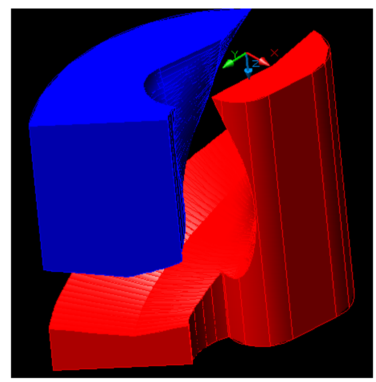

Figure 6: Inflector with the “bended” electrodes.

CONCLUSIONS

The final structure of the selected central region electrode for beam tests is presented in Fig. 5. The program of the forthcoming experiments with a beam is essentially based on these calculations.

ACKNOWLEDGMENTS

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REFERENCES

[1] S. Vorozhtsov et al. The Particle Accelerator Society of Japan (PASJ), Annual meeting, Aug. 5-7, 2009, Tokai, Japan.

[2] S.B. Vorozhtsov et al. CNS-REP-82, CNS Report. RIKEN-NC-AC-2. RIKEN, June 2009.

[3] B.N.Gikal et al. Proc. RuPAC 2008, Zvenigorod, Russia, p.127.