SOME MODIFICATIONS OF VARIABLE-PHASE ASYNCHRONOUS CYCLOTRON

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ABSTRACT

Comparative performances for two modifications of 6-cavity wide-aperture Variable-Phase Asynchronous Cyclotrons to accelerate the protons and ions are given. All devices for the first approach are of conventional type while the second one has superconducting cavities. In such cyclotrons it is possible to reach the limits of continuous currents of a beam in hundreds mA and up to energy in several hundreds MeV.

1 INTRODUCTION

Variable-Phase Asynchronous Cyclotron (VPAC) in brief can be described as a large-radius and wide-aperture Separated Orbit Cyclotron (SOC) in which the opportunities of individual adjustment of an equilibrium phase of acceleration and integer value of inter-cavity harmonic number q are provided. Therefore, the time of a bunch motion in sectors is different and so, the isochronism of a motion of particles is broken and so-called mode of operation of asynchronous cyclotron occurs. Thus, there is a possibility of longitudinal bunch compression and corresponding increasing of acceleration efficiency.

An example of 4-cavity case of the VPAC for proton energy of 25.6 MeV, in which the value q changes from 9 to 7, is described in [1].

2 VPAC-1 AND VPAC-2

Calculations of the key parameters values of VPAC are based on relation

$$\frac{R_e}{R_i} = \frac{q_e \beta_e}{q_i \beta_i} = k \frac{q_e}{q_i}$$

where $k = \beta_e / \beta_i$, $(R_e - R_i) = L_w$ is radial length of working area of acceleration in the cavity. The indexes i and e corresponds to injection and extraction respectively. Then we obtain

$$R_i = \frac{L_w q_i}{k q_e - q_i}, \; R_e = \frac{k L_w q_e}{k q_e - q_i}.$$

Number of turns of the beam n and the average step of orbit-to-orbit separation ΔR are determined by expressions

$$n = \frac{E_e - E_i}{\Delta E_{turn}}, \qquad \Delta R = \frac{R_e - R_i}{n},$$

where the average value of energy gain per turn $\Delta E_{turn} = N_{cav} \Delta E_{gap}$, N_{cav} is number of cavities, ΔE_{gap} is average value of energy gain per gap. The approximate value of the maximum achievable extraction energy for the given type of the VPAC can be derived from the expression

$$\beta_e = \frac{R_i + L_w}{R_i q_e} q_i \beta_i .$$

From the last expression one can see that the increase of extraction energy can be achieved at constant value of L_w and n, either by change of q, or by reduction of R_i.

In the present work the results of development for two modifications of 6-cavity VPAC with conventional magnetic system are presented. In the first of them (VPAC-1), in order to increase the realizability of the model, the calculations are performed using the parameters of cavities, for which the high quality and reliability at operation were proved [2]. The second one (VPAC-2) has conventional magnetic system and superconducting (SC) cavities which are in principle similar to those described in [3].

All the cavities considered in this work have 10 beam channels with a gap increasing linearly with the radius of the machine and with constant value of transit-time factor T=0.95. In general, an increasing of cavity number leads to the decreasing of bending angle of the sector-magnets that leads to decrease of beam dispersion and to decrease of the field in magnets, providing their compactness.

The cavities of the VPAC-1 have usual cooling and the parameters similar to the PSI's cavities [2], in which the electric field E=3.3 MV/m, the working length is 4.2 m and the full length is about 6 m. Numerical calculations for the VPAC-1 and the VPAC-2 are carried out mainly with the use of Trace 3D beam-dynamics code [5]. The layout of sector elements, emittances and beam envelopes for the 1-st and the 10-th turns are shown in the Fig. 1 and the Fig. 2 respectively. The corresponding figures for the VPAC-2 case are similar. Comparison of the energy and phase spread values of the beam at the end of the 1-st turn

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with corresponding values at the end of the 10-th turn indicates the presence of bunch compression in the accelerator. The VPAC-2 has 6 SC cavities with electric field 6 MV/m. The main results of calculations are given in the Table 1.

Table 1. Key parameters of calculations of the VPAC-1 and the VPAC-2

Modification	VPAC-1	VPAC-2
Cavity type	Cu	SC
RF frequency (MHz)	50	50
Cavity field (MV/m)	3.3	6
Current (mA)	100	100
Vacuum chamber aperture (mm)	70	70
Aperture-to-beam-size ratio	10	10
Number of cavities	6	6
Number of sectors	12	12
Num. of bending magnets per sector	1	1
Bending angle (deg)	30	30
Field in bending magnets (T/m)	0.66-0.76	0.82-0.97
Quadrupole effective length (mm)	150/200	150/200
Quadrupole gradient (T/m)	4-23	6-23
Injection radius (m)	2.43	2
Injection energy (MeV)	3.4	3.5
Extraction radius (m)	6.525	6.184
Extraction energy (MeV)	29.235	40.45
Orbit-to-orbit separation (cm)	40-45	36-52
Initial rms emittance		
Transverse (x, y) (π mm-mrad)	2	2
Longitudinal (z) (π deg-keV)	140	140
Final rms emittance		
Transverse (x/y) (π mm-mrad)	1.05/0.68	0.79/0.59
Longitudinal (z) (π deg-keV)	55.97	43.8
Initial phase spread (deg)	23.67	23.67
Initial energy spread (keV)	24.4	24.4
Final phase spread (deg)	10.10	8.39
Final energy spread (keV)	8.46	5.4

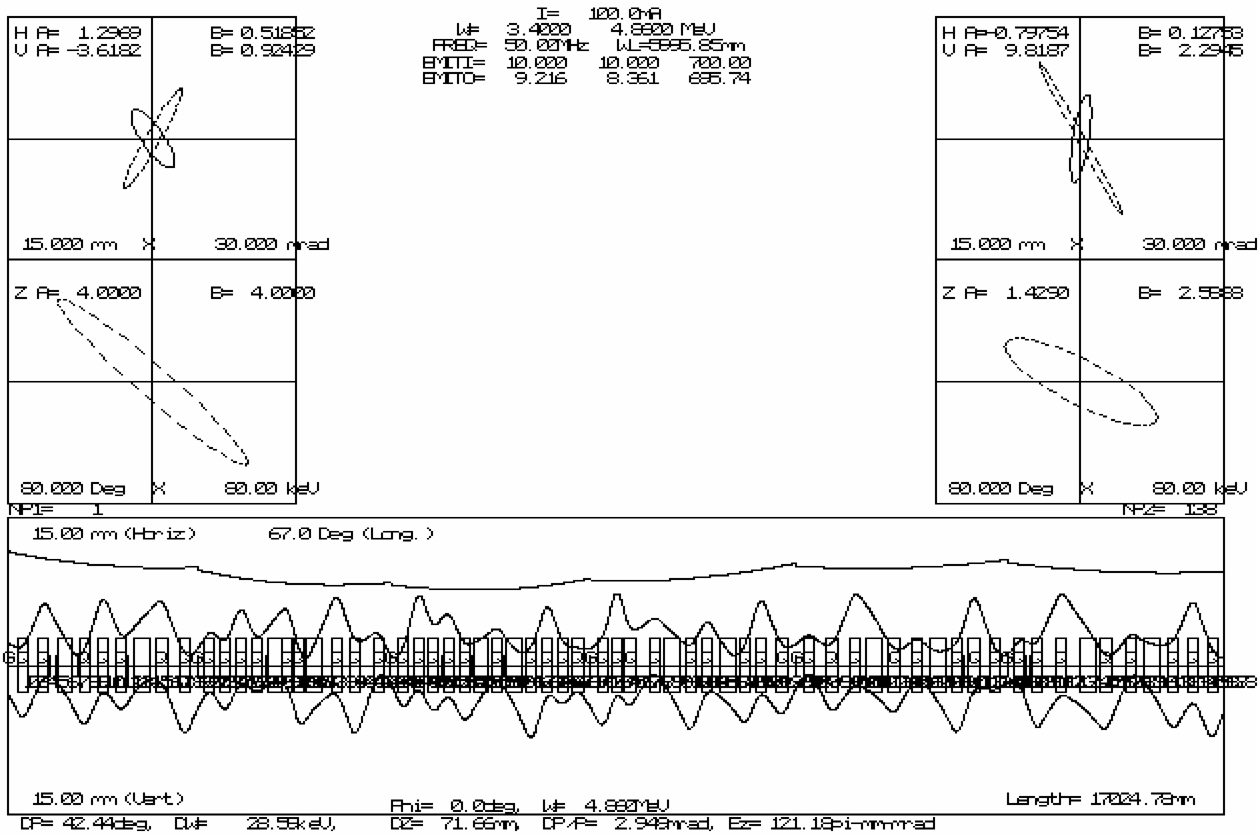

Fig. 1 Trace 3D output of beam dynamics of the 1-st turn of the VPAC-1

3 COMPARISON OF THE VPAC-1 AND THE VPAC-2

The estimations, which have been carried out by the method used in [3] show that wall losses in SC cavities of the VPAC-2 are less than several tens of Watts, i.e. from energetic point of view we have obvious advantage in the case of the VPAC-2, since rf-to-beam conversion efficiency for SC cavities (99 %) is considerably larger in comparison with the efficiency of VPAC-1 (55 %). Furthermore, using SC cavities gives us an opportunity to reduce injection radius and to increase extraction energy and also to improve the bunch compression conditions that allows to get small longitudinal bunch sizes and to

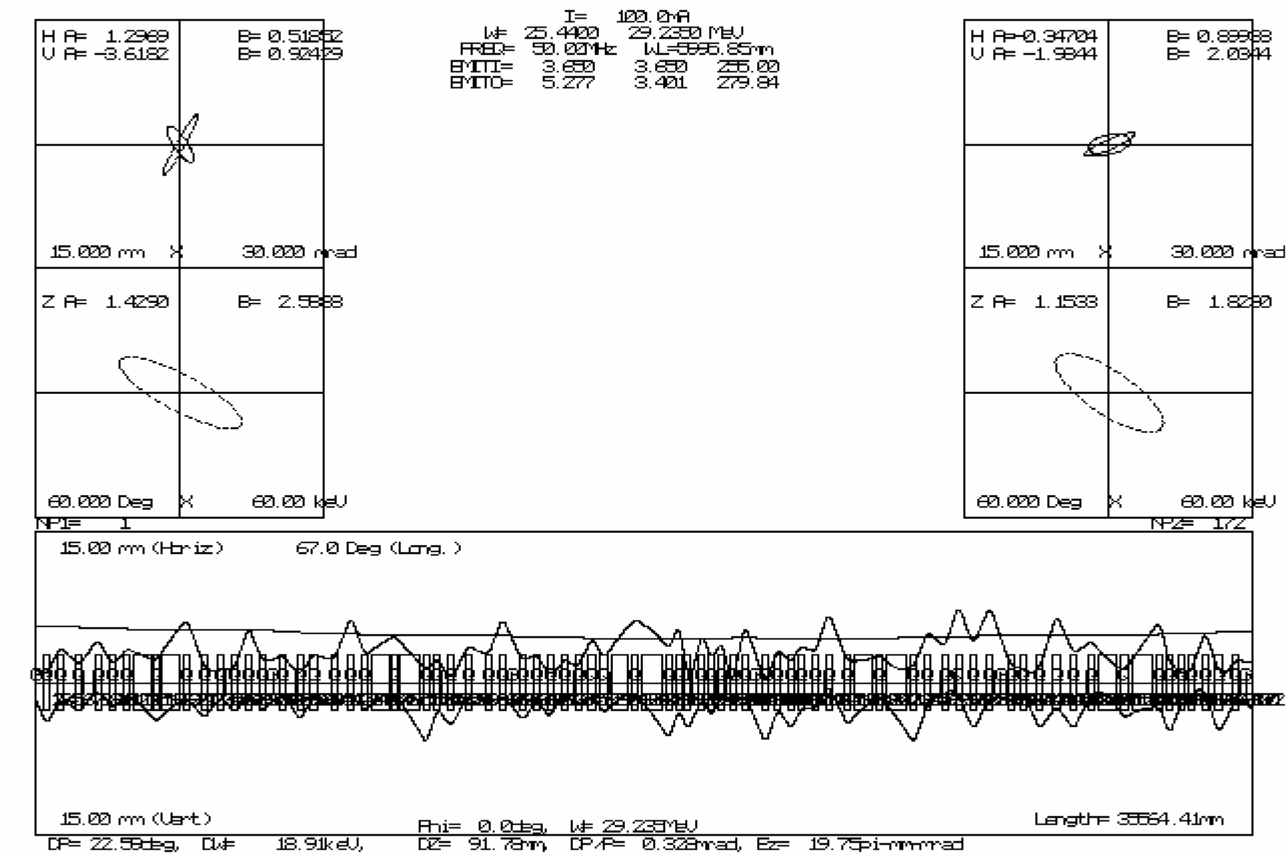

Fig. 2. Trace 3D output of beam dynamics of the 10-th turn of the VPAC-2

increase acceleration efficiency.

As an drawback of the VPAC-2 one can note the complexity of adjustment and operation. Furthermore, acceleration of high currents in completely SC cyclotrons is practically very problematic. That is due to the necessity to select a small value of the radius of injection and consequently the ratio of beam power to a unit area of accelerating rings becomes threateningly enormous. So, for example, for parameters of the TRITRON [3], the ratio of beam power to the area of accelerating rings at 100 mA current will be 1.07 MW/m^2 and for the parameters given in the work [4] it will be 0.96 MW/m^2. Such concentration of energy on the small area is explosive enough, while the same values for all three types of the VPAC are approximately 30-50 times less comparing to the values mentioned above, that is quite safe density of energy in unit volume of space. Therefore, at megawatts of beam power with energies up to several hundreds MeV the use of accelerators such as VPAC is attractive enough. The final choice for designing between the VPAC-1 and the VPAC-2 depends on opportunities and taste of designers.

4 CONCLUSION

In the given work only the principal possibilities of constructing of cyclotrons of new type are shown. The detailed consideration and optimization (choice of the type and number of cavities, construction of magnetic system, etc.) seems to be expedient to carry out for particularly chosen parameters of accelerating beam.

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