A LAYOUT OF A 2.7 GeV AND 10 MW CYCLOTRON

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Considered in this paper are parameters of proton cyclotron complex for mean beam power of 10 MW resulting from the requirements of securing 100% beam extraction and reduction of used electric power costs. It leads to increase of injection energy, growth of proton final energy and proportional reduction of beam intensity as well as to application of resonance method for beam extraction with decreased energy gain per turn. Further decrease of consumed electric power is due to the employment of superconductive current coils, especially in the instance of high temperature superconductors.

Cyclotron Complex with Mean Beam Power of 10 MW

Mid-ninetieth have caused to feel a new interest in the development of high-current proton accelerators with mean beam power of 10 MW for applied purposes. In the capacity of such, «powerful» accelerators, may be used linear accelerators, cyclotrons and cyclotrons with separated orbits.

In 1995 C. Rubbia group (France) proposed to employ a cascade of three accelerators to achieve mean beam power of 10 MW. Ring cyclotrons are to be used for the last two steps of the cascade. Injection energy directed into last main ring was chosen equal to 100 MeV, final energy of 1 GeV $(Q_r = 2.15)$ at mean beam current of 10 mA[1]. Cyclotron complexes for analogical beam parameters are considered in PSI (Switzerland) and NSCL (USA). In all these projects energy gain per turn has been chosen at the level of 10 MeV with a view to reduce the effect of special charge and to secure 100% beam extraction by using the orbit separation in the process of acceleration. In is necessary to note here that at eV = 10 MeV/turn the number of revolutions in cyclotron will approach ~ 90, which in ideology corresponds to transferring to a cyclotron with separated orbits.

We assume that in practice the achievement of 10 mA beam intensity as well as indispensable orbit separation in the extraction zone will require the use of more that 10 MeV energy gain per turn, which would make the proposed way of obtaining the beam power economically inefficient. Thus, on PSI cyclotron (W_i = 72 MeV, eV = 3 MeV/turn) the intensity of the extraction beam was equal to 1.5 mA (beam power 0.9 MW).

Taking all this into consideration we disclose in this paper the possibility of achieving 10 MW beam power by using the increased proton final energy within the main cyclotron up to the value of 2.7 GeV and simultaneous decreasing beam intensity down to 3.7 mA and raising the injection energy to 200 MeV. (Table). Separation of orbits to ~ 1 cm on the injection radius is obtained at eV = 1 MeV/turn. Separation of orbits on the extraction radius at eV = 10 MeV/turn will be 2.3 mm which enables to achieve 100% extraction at the beam radius of 1 mm. In order to decrease the use of high-frequency power, which is due to high energy gain per turn on the zone of beam extraction its out put is considered on the basis of the integer resonance of free radial oscillations $Q_r = 4$ (final energy 2.7 GeV).

Table: Possible parameters of the «powerful» main cyclotron in usual and superconducting variants

Parameters	Value	
	Usual	Superconducting
Energy of injection, MeV	200	200
Final energy, GeV	2.7	2.7
Average current of the beam, mA	3.7	3.7
Power of the beam, MW	10	10
Magnetic field in the center, kG	2.5	5
Number of spirals	16	16
Parameters of Archimedes on r_f, cm	18.7	16.65
Spiral angle on r_f, degree	75	62
Variation of the field on the final radius, r_f,	1	2
Radius of the infinite energy, cm	1163.46	502.62
Initial radius of acceleration, cm	660	284
Final radius of acceleration, cm	1123.5	486.4
Average magnetic field on r_i, kG	3.12	5.93
Average magnetic field on r_f, kG	9.4	17.06
Frequency of axial oscillations	1.1	1.1
Frequency of radial oscillations	$1.22 \leq Q_r \leq 4$	$1.21 \leq Q_r \leq 4$
Frequency of rotation of particle, MHz	3.92	7.4
Working frequency, MHz	47.05	45.24
Multiplicity	12	6
Decrease energy gain per turn with radius, MeV	2 – 0.25	2 – 0.25
Number of cavities	4	4
2nd harmonic flat top cavity, MHz	94.1	90.48
Effectiveness of beam extraction on the basis of the integer resonance Q_r =4, %	100	100

Numeric values on integer resonance crossing and resonance method of beam extraction are connected with the use of the equation of radial oscillations with the account of energy gain per turn in explicit form [2]:

$$\rho'' + Q_r^2\rho + \frac{eV\gamma}{\overline{H}\sqrt{\gamma^2-1}}\rho' = \rho'' + Q_r^2\rho + \delta\rho' = -r\,\mathcal{E}_S \sin S\varphi\,,$$

where γ – is a relativistic factor, $\overline{H}$ and $\mathcal{E}_S = H_S/\overline{H}$ – mean magnetic field and a relative value of S-th harmonic of magnetic field vertical component on radius r, δ – coefficient of «electromagnetic» friction.

Dinamical crossing of integer resonance $Q_r = 2$ (W = 925 MeV, r = 1050 cm, $\overline{H}$ = 5000 G, δ = 0.46) and $Q_r = 3$ (W = 1840 MeV, r = 1094 cm, $\overline{H}$ = 7400 G, δ = 0.29) leads at eV = 2 MeV/turn and $H_2 = H_3 = 5$ G to maximum proton radial amplitudes of forced oscillations 1.1 cm and 0.9 cm correspondingly, which damping rapidly in postresonance zone. This is due to the fact that coefficient δ are much greater then 0.01.

Integer resonance affects trajectories of beam particles coherently. Therefore in the case of slow energy change normalized radial emmitance of monoenergy beam is preserved (the phenomenon of preservation space-time distribution of particles of beam) [2, 3]. Flat top of accelerating voltage produced by means of high frequency second harmonic reduces energy spread of beam particles.

Fig. show the behavior of amplitude for forced radial oscillations of proton ρ at dynamic passage of the integer resonance $S = Q_r = 4$ depending on eV, $H_4 = \overline{H}\mathcal{E}_4$ and δ.

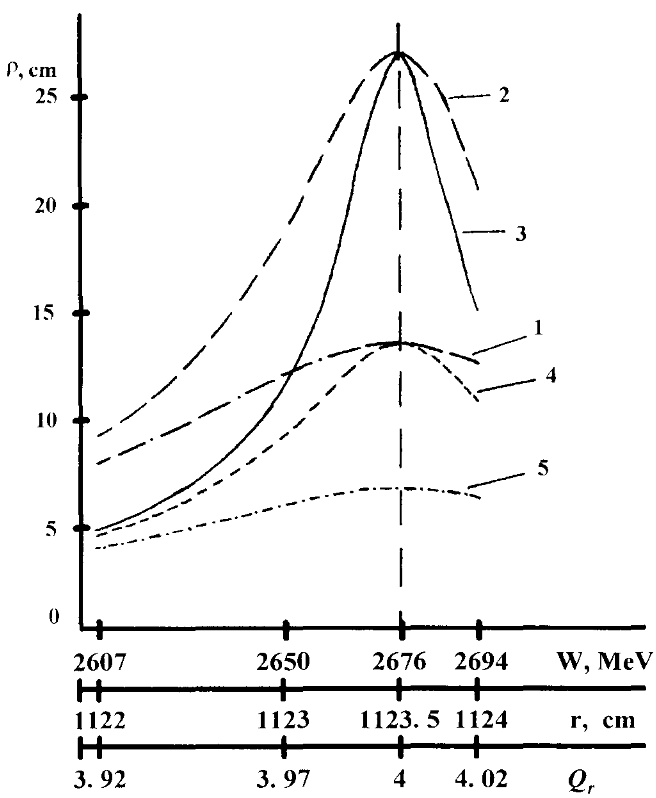

Fig: Amplitude of forced radial oscillations of proton ρ:

1. eV=1 MeV/turn, δ=0.11, H_4=50 G;
2. eV=0.5 MeV/turn, δ=0.055, H_4=50 G;
3. eV=0.25 MeV/turn, δ=0.022, H_4=25 G;
4. eV=0.5 MeV/turn, δ=0.055, H_4=25 G;
5. eV=1 MeV/turn, δ=0.11, H_4=25 G.

Orbits separation to 2.3 mm in case of resonance beam extraction lead to eV = 0.25 MeV/turn (δ = 0.022) at H_4=40 G $\left(\mathcal{E}_4 \approx 1\cdot 10^{-3}\right)$. With the increase of H_4 to 100 G $\left(\mathcal{E}_4 \approx 1\cdot 10^{-2}\right)$ the radial step of the orbit will be 5.6 mm. Thus, in case of resonance way of beam extraction energy gain per turn does not increase but decreases with the growth of radius in the process of acceleration from 2 to 0.25 MeV per turn in the extraction region beginning from 1122 cm, which leads to a substantial decrease of electric power used.

Transfer to superconductivity will make it possible to decrease almost twice the radial size of cyclotron and power used (Table). Magnetic field of superconducting ring cyclotron may be formed either with the help of coils alone [4, 5] or by coils together with saturated iron sectors [6]. Further perspective is connected with using of high temperature superconductors.

It is worth mentioning that developed in early eighties in Germany and Switzerland were the projects of cyclotron kaon factories for proton energies of several CeV and beam current more then 1mA [6,7].

In the first project known as KISS superconducting ring cyclotron raising the proton energy from 100 MeV to 2.5 GeV ($Q_r = 3.8$) with mean beam current 5 mA (beam power 12.5 MW). Magnetic field was formed with the help of iron sectors saturated by superconducting coils (NbTi). Energy gain per turn increased together with radius from 2 to 10 MeV. Orbit separation in the extraction zone will be 1.4 mm which will secure 100% beam extraction at its radial size 0.6 mm.

In the second project named ASTOR ring cyclotron was considered after cyclotron PSI which would raise the proton energy from 590 MeV to 2 GeV ($Q_r = 3.2$) at mean beam current 2 mA (beam power of 4 MW). Energy gain per turn changed with the increase of radius from 2.7 to 5 MeV/turn, which should secure 100% beam extraction.

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