FFAG Synchrocyclotron as a Booster for Linac

V.P. Dmitrievsky, A.A. Glazov, L.M. Onischenko, S.B. Vorozhtsov, N.L. Zaplatin
Laboratory of Nuclear Problems
Joint Institute for Nuclear Research
Dubna
Russia

1 INTRODUCTION

At present time in Europe there arises an interest in constructing a pulsed neutron source driven by a proton accelerator with energy $1.6 \div 3.2$ GeV and average beam power about 5 MWt. Beam pulse duration has to be less than 0.3 μs at the repetition rate $50 \div 100$ Hz [1–4]. Such an accelerator complex would produce the average neutron flux $> 10^{15}$ n/cm^{2}s at the proton beam pulse intensity of order 10^{14} p/pulse.

2 REASONS FOR CHOOSING PARAMETERS

Two possible schemes of the complex are considered: 1) linac + storage ring and 2) injector linac + FFAG phasotron. In this paper some features of the second scheme are discussed.

Two different modes, $Q_r > \gamma$ and $Q_r < \gamma$, can be realized for the FFAG accelerator since the transition through the critical energy ($1 - \alpha\gamma^2 = 1 - \gamma^2/Q_r^2 = 0$, $Q_r^2 \cong 1 + k$) in the phasotron energy range should be excluded. Here Q_r is the free radial oscillations frequency, $\gamma = E/E_0$, $\alpha \cong 1/Q_r^2$ is the closed orbit compaction factor, k is the magnetic field index $[B = B_0(\frac{r}{r_0})^k]$, E is the full energy.

The main problem to be solved when designing this accelerator arises from a very large number of protons ($2 \cdot 10^{14}$) in the separatrix (or in the group of them in one cycle when the RF frequency is harmonic of the orbit one). Since the momentum is $P = eB \cdot r$, then in the FFAG energy range $P_1/P_0 = (r_1/r_0)^{k+1}$ and the beam phase-radial size Δr_n at the radius r will be $\frac{\Delta r_n}{r} = \frac{1}{(k+1)\beta^2}\frac{\Delta E}{E}$, where ΔE is the maximum energy spread of the particles inside the separatrix, which is equal to $\frac{\Delta E}{E_s} = \frac{2\dot\varphi_{max}}{\omega K}$, $K = \frac{k}{1+k}\frac{1}{\beta^2} - 1$; ω_s and E_s are the equilibrium values of the particle angular frequency and of the total energy, $\beta^2 = 1 - 1/\gamma^2$, $\dot\varphi_{max} = \omega_s\sqrt{\frac{KeV}{\pi E_s}} \cdot \sqrt{C + \sin\varphi_s - \varphi_s\cos\varphi_s}$. Here eV$\cos\varphi_s$ is the synchronous energy gain per turn, C is a parameter, related to the beam phase space, $\dot\varphi = \omega - \omega_s$. In these terms

$$\frac{\Delta r_n}{r} = \frac{2\dot\varphi_{max}}{Q_r^2\beta^2\omega_s K}. \qquad (1)$$

From (1) it follows that with $k > 10$ the beam phase-radial size does not exceed 2 cm. Indeed, for the FFAG accelerator parameters from [1] $k = 13.4$; $eV = 200$ keV, $< r_1 >= 2800$ cm, $E = 2438$ MeV and $\cos\varphi_s = 0.5$ – $\Delta r_n \cong 1.9$ cm. This beam size is unacceptable because of the high charge density $> 10^{10}$ p/cm^3, which increases (as follows from the computation in [1]) the vertical beam emittance to $650 \cdot 10^{-6}$ π·mrad and the horizontal one to $500 \cdot 10^{-6}$ π·mrad, the transverse beam dimensions being 13.0×13.2 cm^2.

With these dimensions, unusual for modern accelerators, the charge density problems could be solved, but arises a problem of the magnet aperture inside which the theory linearity should be ensured for the whole beam cross-section.

The radial structure of the FFAG suggested in [1] simplifies the solution of the problem a little.

The spiral structure has some advantages for $Q_r < \gamma_i$, where γ_i is related to the injection energy. For this structure the maximum accelerator radius is decreased (B is increased), the radial-phase size of the beam is increased ($k < 1$), at the same time the limitation on the phase stability due to space charge is decreased.

The latter advantage depends on the sign of $d\omega/dE$; if it is negative, the frequency of the phase oscillations is increased under influence of the space charge. Thus, the phase stability does not break down even for the space charge density $10^9 \div 10^{10}$ p/cm^3. This phase stability limitation arises at $d\omega/dE > 0$ because of the longitudinal electric field produced by the space charge:

$$\mathcal{E}_x = -\frac{d\Phi}{dx} \text{ in beam-bunch system;}$$
$$\mathcal{E}_{x\,l} = -\frac{1}{\gamma^2}\frac{d\Phi}{dx} \text{ in lab.system,} \qquad (2)$$

where

$$\Phi = \int_{U'} \frac{\rho(x', y', z')}{\sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2}},$$

U' is the beam charge volume, $\rho(x'\,y'\,z')$ is the beam charge density distribution in the volume U'.

The phase stability is violated for the structure with $\frac{d\omega}{dE} > 0$ when

$$\left[\frac{d\mathcal{E}_x}{dx}\right]_{x=0} \geq \frac{\gamma^2 V \sin\varphi_s}{2\pi r^2}. \qquad (3)$$

where eV is the maximum energy gain per turn; when the beam moves along the x axis, parameter $x' = 0$ corresponds to the centre of the beam with the symmetric distribution of the space charge $[\rho(x') = \rho(-x')]$.

As to the space charge density limitation for $\frac{d\omega}{dE} < 0$ because of the negative mass effect, it has to be specially analyzed by computation.

Table 1 lists the FFAG accelerator parameters for the radial and spiral structures of the magnetic field.

Table 1:

Parameter	Radial structure[1]	Spiral structure
Injection energy, MeV	430	430
Extraction energy, MeV	1600	1600
Maximum radius, m	26.5	4.5
Radial width, m	1.8	2.0
Magnetic field index k	11.8	0.44
Number of sectors	16	6
Maximum B_+ field, T	4.0	4.4
Maximum B_- field, T	-2.0	0
Spiral angle, degree	0	45
Radial free oscillation frequency, Q_r	4.26	1.2
Axial free oscillation frequency, Q_z	3.26	1.8
RF frequency range, MHz	1.45÷1.72	13.92÷9.70
Orbit frequency sweep, %	+19	-30
Resonator RF voltage, kV	20	100
Number of resonators	10	3
Repetition rate, Hz	100/50	100/50

It is planned to make a more detailed design of the FFAG accelerator if the interest in the spallation neutron source is kept.

3 CONCLUSION

It is possible in principle to use an FFAG phasotron as a booster after the linac injector to accelerate protons up to 1.6 GeV with the intensity $\sim 2 \cdot 10^{14}$ p/pulse and repetition rate in the range $50 \div 100$ Hz. Yet it still has to be done the detailed consideration is necessary, and he cost of this complex must be compared with the one of the linear accelerator, producing the full energy beam.

As to the magnet structure with $d\omega/dE < 0$ (in comparison with $d\omega/dE > 0$) for the FFAG accelerator, it seems to be more promising.

4 ADDITIONAL INFORMATION

The work was done in accordance with agreement between New accelerator division JINR, Dubna and group ESS (S. Martin,K. Ziegler).

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