6-7 Gev PROTON SYNCHROTRON - INJECTOR FOR THE 1000 Gev CYBERNETIC ACCELERATOR

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The injector for the cybernetic accelerator in the form of a proton synchrotron with 50 duty cycles per second is shown to be feasible in this paper. The basic parameters of such a cyclic injector with the maximum energy of 6-7 Gev are listed.

The three-cascade method of acceleration involving a starting linear accelerator, a cyclic pre-accelerator ("booster") and a final cyclic accelerator was chosen while working out the general principles of the cybernetic accelerator / 1 /. But during further elaboration the field of possible injection methods was expanded. In particular the possibility to inject particles directly from a linear accelerator, with its energy reduced down to 100 Mev, appeared on the basis of the proposal to impose superfocussing during the starting period, made by A.A. Vasilyev / 2 /.

A cyclic-type injector is considered in this paper. According to the estimations, carried out by Sands / 3 /, a 300 Gev accelerator booster should have the energy of ~10 Gev The design study made by the Blewett's group / 4 /, indicates a 300 - 1000 Gev accelerator booster energy equal to 6 Gev. In designs of a 500 Gev accelerator by V.V.Vladimirsky et al. / 5 / the chosen booster energy is equal to 15 Gev.

a 1,5 Gev, 3 Gev and 6 Gev proton synchrotrons are proposed by C.Bronca / 6,7 / for injection into 60 Gev, 150 Gev and 300 Gev accelerators respectively.

So the chosen injection energies bear no regular dependence on the final energy. This results from the fact that the dependence of the booster and final accelerators total cost on the injection energy has a flat minimum / 8 /.

To certain extent this gives one a free hand in taking into account some other arguments, for instance, reasonable choice of accelerating stations power which can be estimated from the following retations (when $E_m \gg E_o$; the revolution frequency deviation and the total length of straight sections are small):

$$p \sim \frac{8\pi^2 E_m^4}{(300\alpha C T H_m)^2} \frac{1}{N Z_{res}} \approx \frac{8\pi^2 E_m^2 \rho^2}{(\alpha C T)^2 N Z_{res}} = \frac{32\pi^2 E_m^2 \rho_{II}^2}{(\alpha C T_{II})^2 N Z_{res}}$$

Where p - power (wt); E_m - final particle energy in the booster; α - factor, owing to the relation between the maximum and average particle revolution frequency; C - light velocity (cm/sec); T - acceleration time in booster; H_m - maximum magnetic flux intensity at the orbit; N - accelerating cavities number; Z_{res} - cavity impedance; ρ and ρ_{II} - booster and final accelerator electromagnets curvature radii; T_{II} - time duration of injection into the final ring ($T_{II} \approx 2\frac{\rho_{II}}{\rho_I} T$), the booster H time-dependence being sinusoidal.

The dependence of the required acceteration stations power P upon the ratio $\frac{Em^4}{T^2}$ leads to the increase of P by a factor of 40 if the chosen maximum energy Em is 15 Gev instead of Em = 6 Gev, and by a factor of 10^4 if the chosen acceleration time is T = 10 msec (50 duty cycles per second) instead of T = 1 sec. The operating conditions of the cybernetic accelerator make impossible the choice of large T since, otherwise, "the first revolution" operation would be too long. At the same time the relation $T = 0,5\ T_{II} \frac{R_1}{R_{II}}$, which follows from the requirement to have the final ring filled up uniformly with proton bunches over its circumference brings the necessity of choosing very small values of T. When $R_{II} = 5$ km, $R_I = 50$m and $T_{II} = 1$ sec we get T = 5msec, i.e. the repetition rate should be $\sim 100 \frac{1}{sec}$. Therefore the booster electromagnet should contain longer straight sections to avoid extreme power increase. These preliminary remarks taken into consideration, the chosen parameters are: Em = = 6 Gev, T = 10 msec (50 c/s) and $R_I = 60$ m. While fixing R_I the radius R_{II} was assumed to be 3300 m / 1 /. A linac, or ring phasotron, or isochronous cyclotron, or proton synchotron can be used to inject particles into the booster. At the present phase of the design study of a cybernetic accelerator booster a 100 Mev linac was chosen as a pre-booster. A synchorphasotron alternative for the prebooster is assumed to be investigated in future.

Magnetic System

At the kinetic energy of 6 Gev and reasonably chosen $H_m = 10^4_{oe}$ the booster radius of curvature will be 23m, which is close to the radius of curvature of the Erevan electron synchrotron electromagnet (ρ = 25.25 m) / 9 /. This electromagnet, which is designed for 50 cps resonant power supply, displayed good operating charachteristics and its manufacturing technology is mastered by the industry.

Its focussing properties are shown by preliminary calculations to meet the claims laid to the booster electromagnet. Therefore down in the paper we shall refer to the charachteristics of the Erevan electron synchrotron electromagnet (table I) though bearing in mind the fact, that it is not reasonable to predetermine the choise of this magnet for booster design at the present phase of the design study, when any design bears only illustrative character.

Aperture distribution

The maximum semiaperture of the vacuum chamber is 46 mm radially and 25 mm vertically. The aperture requirements at injection are determined mainly by the beam radius, amplitude of the radial synchrotron oscillations and the closed orbit shift. If the 100 Mev linac has emittance of $2,4 \cdot 10^{-3}$ sm.rad (the calculated value of the 70 Gev proton synchrotron linac injector) the beam radius in booster would be 7 mm. The energy spread in the injected beam of $\frac{\Delta E}{E} = +3 \cdot 10^{-3}$

(which is derived from the CERN and Brookhaven linear accelerators) will cause the amplitude of radial synchrotron oscillations of 4 mm. The equilibrium orbit displacement due to mis-alignment error δ will be ~ 20 times as mush as δ ($\frac{\pi}{\sqrt{2}Q\sin\pi Q}\frac{R}{\rho}\frac{n}{M^{1/2}} = 18$). Assuming δ = 0,25 mm, one gets Δ = 5 mm.

In fact, according to the CERN experience / 10 /, the real displacement owing mainly to the magnetic field distortion, is 4 times as much as the calculated value. Therefore, the displacement of up to 20 mm should be taken into consideration.

Thus, the vertical semiaperture is proved to be up and careful field correction will be necessary to get certain aperture reserve, as it takes place with the radial dimention of the chamber.

The emittance component of the booster output beam, corresponding to the input beam emittance of 2,4 · 10^{-3} sm.rad (with the increase of the magnetic flux intencity by the factor of 15) will be about 1.6 · 10^{-4} sm.rad., which is few times as little as the prescribed value of 1.8 · 10^{-4} cm. rad (the final ring admittance).

Accelerating field parameters (table II)

With the chosen parameters ρ = 25,25 m and R = 60 m we get

$$f_\infty = \frac{C}{2\pi R} = 795{,}63 \text{ kc/sec and } H_1 = \frac{E_0}{300\rho} = 1238{,}4 \text{ oe}.$$

The relatious $f_{rev} = f_\infty \frac{H}{\sqrt{H^2 + H_1^2}}$ and $\Delta E = \frac{E_0}{H_1} \cdot \frac{\dot{H}}{f_\infty}$ help to derive the values of the revolution frequencies at the beginning and at the end of acceleration, which are 341,5 kc/sec and 788,2 kc/sec respectively (the frequency overlap equals 2.6), and the maximum energy gain per revolution of 1,33 Mev. Therefore, the maximum amplitude of the accelerating voltage must be 2,67 Mv.

The synchrotron oscillation frequency (when q = 128) is equal to ~ 165 kc/s at the beginning and reduces to 3,75 kc/s by the end of the acceleration cycle. The tolerance of 10^{-3} for the adiabatic frequency deviation at injection correspondes to the orbit shift of ~ 0,7 mm (assuming, that the value of Q increases up to 9,25 due to the presence of long straight sections). While the revolution frequency increases, the tolerance for $\frac{\Delta f}{f}$ diminishes down to $\sim 5 \cdot 10^{-6}$ by the end of the acceleration cycle (in the case of program frequency control).

H.F. Acceleration System

To match the final repetition rate of accelerated particle bunches and the cybernetic accelerator accelerating field frequency one should accept the harmonic order q equal 128. The initial frequency of the accelerating voltage in this case equals 43.71 Mc/s and the final one equals 100.9 Mc/s. It is necessary to use a large number of accelerating devices in order to ensure 2.67 Mv amplitude of the accelerating field at reasonable power values. If mechanically tuned cavities are used for the purpose, one gets the cavity impedance ~6 kohm and it is necessary to use more than 100 cavities to reduce the power down to ~2Mvt. The reliability of such a system with so great number of mechanically tuned frequency controllers would be poor. Besides, a cavity with an impedance of 6 kohm at a frequency of 100mc/s and with the maximum cavity capacity of ~ 100 picofarad would have Q equal to ~400. It means that at the beginning of the acceleration cycle the half-width of the cavity pass=band would be several times as little as the synchrotron oscillation frequency. It would need a strong negative feedback in output h.f. cascades to fascilitate the realization of the beam lock system, for which complications in h.f. amplifying chanels would be necessary. Besides, the variation laws of the condensors capacitance have to be matched with the accuracy much better than 1% if the tuning is so sharp.

Ferrite loaded cavities would have the impedance of ~1 kohm. This diminishes the dificulties of realization of beam lock system and the accuracy of matching cavity tuning laws approaches ~ 5%. Further increase of the cavity number would prevent the required power from increasing. The required length of straight sections would be less than in the case of airfilled cavities which are longer than ferrite filled cavities.

In our case when R = 60m; and ρ = 25,25 m the total length of field free sections equals 215 m. 150 m of it can be occupied by cavities. Due to preliminary investigations, a cavity with the frequency band of 40-100 mc/s and a length of 20 cm (the outer diameter being also ~ 20 cm) can be made on the basis of nickel-zink ferrite with $\mu_0 \approx 40$. Consequently, about 750 such cavities can be taken (we chose the number equal to 720). Ferrite rings should be distributed over cavities following the same way as it is generally done with iron sheets while assembling electromagnets. In this case cavities tuning laws can be matched better than 1%, which permits tuning the cavities by the common exciting current controlled by one-cavity phase lock system. The rate of excitation has to be matched with the pass-band of ~ 1Mc/s, which is considerably more than the maximum synchrotron oscillation frequency. That is why excitation should be accomplished by the current flawing through the walls of a cavity. Power mains in conjuction with a quick-acting driven source can be used for the current supply.

It is reasonable to feed cavities from the common oscillator placed in the centre of the accelerator ring. The oscillator should be carried out as a block system where each block feeds a certain group of cavities to ensure reliability. If the chosen number of blocks is equal to 12, failure of even two of them will not interfere with the accelerator operation, for ~ 15% reduction in accelerating field amplitude doesn't influence the beam intencity. The blocks may be placed by the ring near the cavities too, but their central position is more convenient while voltage losses due to ~ 60 m feeders would not exceed 15 %. High frequency peak voltage of 3,7kv would be applied to each cavity if their total number equals

720. Therefore the peak power dissipated by a cavity with Z_{res} = 1 kohm equals 7 kwt and the peak required power approaches 5 Mwt. It determines the rated power of oscillator tubes. The average power dissipated by the cavities, equals $0,5\ (\frac{2}{\pi})^2 P_M = 0,2\ P_M$, i.e. 1 Mwt (when the time-dependence of H which determines Δ E and Δ U is sinusoidal). It is of the same order as the magnet power supply, the result which is the most desirable for high intencity accelerators. A HF system with 50% efficiency and 6 : 1 duty would consume ~300 kwt from the mains. Great efforts would be necessary in producing new kinds of ferrites in order to realize a system of ferrite loaded cavities. The samples available give Z res > 1 kohm within the frequency band of 40 - 100 Mc/s at small peak induction and at low cavity tuning frequency variation rate. If the rate of variation is increased up to $2,5 \cdot 10^{10}$ cps/sec Z res. decreases by several times (at a frequency of 40 Mc/s it drops from 7 kohm down to 1,5 - 2 kohm, and at a frequency of 100 Mc/s it becomes independent on the rate and equals 1 kohm).

Beam extraction

It will be necessary to elaborate a beam extractor to transport the beam from the booster into the cybernetic accelerator. The general solution of the question is known. Two stage deflecton of a beam from the orbit is used for the purpose. At the first stage a pulsed magnet whose field rise time is a small fraction of the final revolution period, has to cause betatron oscillations with amplitude equal to the semiaperture of the chamber ($\sim$ 5 cm). At a distance of 1/4 of betatron wavelength the particles enter the region with the stronger field excited by the second pulsed electromagnet (which has greater rise time but which is switched on somewhat earlier than the first one), and are deflected to the field free trajectory [illegible] Tentative calculations show that such an extraction system is feasible. The angle of deflection of particles by the first electromagnet equals the ratio of the excited oscillation amplitude (5 cm) to one forth of their wavelength (10 m) and equals 5 mrad. The production of magnetic field intencity H' of this electromagnet and its length l equals $1{,}2 \cdot 10^5$ oe cm (when Em = 7 Gev).

Therefore H equals 500 oe when l = 2 m. A system of two 2m long double-wire shorted lines would produce average field of 125 oe per 1000 a in each line if the lines are removed from the equilibrium orbit by $\pm$ 2,5 cm vertically (by the semiaperture of the chamber) and by + 2,5 cm radially (outside the orbit) and conductors are remoted from each other at a distance of 5 cm. Consequently the total current in each line has to equal 4 ka and the required voltage equals 15 kv if the inductance of the line is $\sim 2 \mu H$ and rise time is $0{,}1 \mu sec$. The second electromagnet has to excite field intencity greater than 10 koe, but since it is placed beyond the chamber region and can be excited slowly (at the end of acceleration cycle) the question of its designing is not a complicated one.

S U M M A R Y

The following conclusions can be summarized from the preliminary study of the question of injection particles from a proton synchrotron into the cybernatic accelerator:

Firstly, the proton synchrotron has to be of high repetition rate to meet "the first revolution" operation requirements. In this case, to avoid excessive rise of accelerating system HF power it is practicable to limit the total energy of particles to ~ 7 Gev, choose the injection energy higher than 100 Mev and extend the length of free sections for locating a larger number of accelerating devices, and in order to shorten the time of injection into the cybernetic accelerator to ~ 1 sec it is practicable to choose the repetition rate of bunches equalling to 50 c/s.

Secondly, at present the problem of designing the booster electromagnet with mains supply of the electromagnet has been solved. Requrements to the beam focussing are met, when the sizes of the chamber are ~ (10 x 5) cm. This results in completely realizable values of reactive energy in the electromagnet and in capacitance accumulator, and the power of losses is ~ 1 Mwt. The requirements laid to the booster electromagnet are fully met by electromagnets of high-energy synchrotrons. In particular, the Erevan synchrotron electromagnet can be used for the cybernetic accelerator injector.

2 Thirdly, the main problem of the booster is a system of accelerating field generation. Under the conditions stipulated in item I even with the employment of several hundreds of accelerating cavities the HF supply rated power reaches 5 Mwt, and the average one reaches 1 Mwt. Application of mechanical tuning can reduce the power by a factor of ~ 5. However this sharply diminishes reliability of the system functioning and complicates the beam feedback system. Therefore it seems practicable to accomplish the accelerating system on the basis of ferrite filled cavities, with their number increased to 720. In this case, preliminary measurements must be made of characteristics of ferrite rings with the aim of their uniform distribution among the cavities of rings with similar characteristics in the same way as it is done during distribution of iron sheets among the electromagnet packets. Using this method the spread of characteristics of cavities can be reduced to the value of $\sim 1\%$, which will permit realization of their tuning by a single source (or small number of sources) and will appreciably raise the reliability of accelerator operation.

To effect the HF supply of the cavities it is practicable to use a group of transmitters (12 for example) operating in the mode of amplifying the oscillations of the common exciter which is a component of the phase automatic tuning system.

Forthly, the beam can be extracted with the help of two fixed pulse electromagnets. For extraction of 90%

particles, an electromagnet with the magnetic field intensity of ~ 500 oe and the setting time of < 0.1 sec is necessary. The current supply of the electromagnet should be ~ 8 Ka at ~ 15 Kv voltage. The second electromagnet must have $>$ 10 Koe magnetic field intencity, but due to the low rate of the field rise its realization is not a complicated problem.

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Table I

The Erevan electron synchrotron electromagnet parameters

1.	Orbit curviature radius	ρ	25.248 m
2.	Average orbit radius	R	34.498 m
3.	Orbit magnetic field maximum intensity corresponding to 6-9 Gev energy	Hm	9074.6 oe
4.	Magnetic fueld intensity at injection	Hj	586.8 oe
5.	Number of magnetic units	N	48
6.	Length of a magnetic unit (iron part)	l	322.5 cm
7.	Focusing system structure		FOFDOD
8.	Field index	n	115
9.	Number of betatron oscillations per revolution	Q	5.375
10.	Useful width of the electromagnet gap	2 φ	96
11.	Useful height of the electromagnet gap	2 b	50 mm
12.	Distance between units along iron	l	1290 mm
13.	Number of focussing lenses pairs		12
14.	Distance from the asymptote to zero pole		222 m
15.	Thickness of steel sheets (Э-42)		0.5 mm
16.	Unit total weight		15.2 ton
17.	Energy stored in electromagnet	W_{em}	880 kj

18. Energy of capacitor batteries	W cap	350 kj
19. Capacitor batteries peak power		140 Mva
20. Deviding reactor inductance	L p	50 MH
21. A.C. total power	$P_{\sim}$	1 Mwt
22. D.c. power	P =	0.5 Mwt

Table II

Accelerating field characteristics

t μsec	H Oe	f kc/s	q frev Mc/s	$\dot{H}$ KOe/sec	ΔE Kev	ΔU kv	$q\,\dot{f}/f_{rev}$ Mc/s/sec	Fs Kc/s	$q^{1/2}F_s$ Kc/S	$(\frac{\Delta f}{f})_{ad}\cdot 10^3$	$(\frac{\Delta f}{f})_{F_s}\cdot 10^6$	$(\frac{\Delta U}{U})_{F_s}\cdot 10^5$
0-I	586.8	341.5	43.71	710	676	1352	25720	14.63	165.50	1.000	4.7	4.7
1.5	1000	500.0	64.0	710	676	1352	23025	9.651	109.20	0.737	7.2	7.1
2.1	1600	613.8	78.57	900	857	1714	19103	7.239	81.87	0.487	7.4	7.3
2.6	2000	676.2	86.55	1070	1019	2038	12848	5.620	63.56	0.328	7.2	7.2
3.1	2500	712.9	91.2	1200	1142	2284	8654	4.453	50.36	0.232	7.2	7.1
3.5	3000	735.6	94.16	1300	1238	2476	5930	3.599	40.70	0.163	7.2	7.1
4.2	4000	760.0	97.28	1400	1333	2666	2980	2.438	27.57	0.091	7.6	7.5
5.0	5000	772.1	98.82	1400	1333	2666	1597	1.703	19.26	0.054	8.5	8.4
5.7	6000	779.0	99.71	1400	1333	2666	949	1.237	13.99	0.033	9.6	9.5
6.1	6500	781.2	99.99	1350	1285	2570	728	1.047	11.84	0.026	10.6	10.5
6.5	7000	783.6	100.3	1250	1190	2380	544	0.860	9.828	0.019	12.3	12.2
6.9	7500	784.7	100.4	1150	1095	2190	405	0.720	8.143	0.016	14.4	14.3
7.3	8000	785.9	100.6	1050	999.6	1999.2	308	0.591	6.684	0.012	17.4	17.2
7.8	8500	787.0	100.7	900	857	1714	221	0.472	5.338	0.008	22.3	22.0
8.6	9074.6	788.2	100.9	650	618.1	1236.2	132	0.332	3.750	0.005	35.4	35.1