STORAGE OF HIGH-INTENSITY PROTON BUNCHES IN MOSCOW MESON FACILITY ISOCHRONOUS MAGNETIC RING

V.P.Belov, A.A.Kapustin, M.G.Nagajenko, Yu.P.Severgin, I.A.Shukeilo

D.V.Efremov Research Institute of Electrophysical Apparatus, 188631, Leningrad, USSR

Summary

Some details of particle storage in an isochronous magnetic ring with the goal of linac pulse compression are outlined. Bunched beam structure is maintained without RF bunching system. The distortions of isochronous circulation are studied. The numerical calculations refer to the Moscow meson facility storage ring.

Introduction

The general functions and principal parameters of the Moscow meson facility storage ring have been discussed elsewhere /1/, /2/. Time structure of the initial beam (100 μs macropulse duration, 100 Hz repetition rate) will be transformed. The most essential operating modes are as follows:

a) conversion of every linac macropulse into a single narrow bunch of 50-350 ns duration;

b) each linac macropulse stretching up to 10 ms, providing an almost continuous beam.

This paper deals with several features of pulse compression procedure.

The design parameters of the linac and storage ring, essential for our aim in view are listed below.

a) linac:	
H^- ion kinetic energy.	600 MeV
Macropulse duration.	100 μs
Peak beam current.	50 mA
Macropulse repetition rate . .	100 Hz
Micropulse repetition rate . .	200 MHz
Micropulse duration at injection azimuth	1,2 ns
Beam emittance	0,3 cm.mrad
Relative momentum spread . . .	$\pm 2\cdot 10^{-3}$
b) storage ring:	
Orbit circumference.	104,6 m
Circulation period	440 ns
Stored turns	226
Max. particle linear density .	$3\cdot 10^{11}$ m^{-1}
Stored bunch length.	10-80 m
Stored beam emittance.	3 cm.mrad

Isochronous storage

Time compression of the linac macropulse is achieved by multi-turn charge-changing injection and single-turn ejection as soon as filling process is terminated. One has to provide an azimuthal void to exclude beam loss during the rise time of kicker magnet field. Beam structure needed will be carved by the chopper, installed in an initial part of the linac.

It is reasonable to use an isochronous magnetic ring. We intend to tune it so that transition energy of the ring will be equal to linac output energy Circulation time does not depend on particle momenta. The storage ring lattice with the required circumference may be of isochronous design at rather low price, and short storage time (100 μs) tolerates small deviations from the exact isochronism without considerable bunch lengthening during storage. RF bunching system is absent in an isochronous storage ring. The ring of this type (IKOR) was studied by K.H.Reich /3/, and at the CERN PS experiments on long-term bunch confinement near the transition point were carried out /4/. They confirmed the possibility of isochronous ring realization. In a linear approximation the revolution period depends on the particle momentum as

$$\Delta T/T_0 = \eta(\Delta P/P_0) \quad , \quad \eta = \alpha - \gamma_0^{-2} \quad , \qquad (1)$$

where γ_0 is the relative energy, α is the momentum compaction factor.

Thus, the isochronous storage is possible in the ring with

$$\alpha = \gamma_0^{-2} \qquad (2)$$

The proton storage ring lattice of Moscow meson facility consisting of two achromatic periods has a variable momentum compaction factor of $0,32 < \alpha < 0,42$; $\alpha = 0,372$ corresponding to Eq.(2).

A plan view of the storage ring lattice is given in Fig.1, and Fig.2 shows dynamical functions on half of its circumference. More detailed view of the lattice, the description of its components operation and the arrangement of the rest of the equipment may be found elsewhere /1,2/. Quadrupoles K_3 (Fig.1) regulate the value of the dispersion function ψ and the factor α.

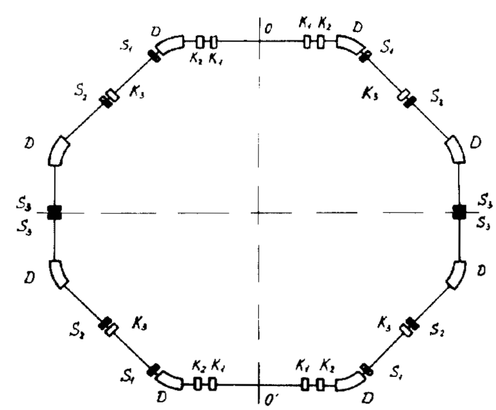

Fig.1. Plan view of proton storage ring at Moscow meson facility: D - dipoles; K_1,K_2,K_3 - quadrupoles; S_1,S_2,S_3 - sextupoles

CH2387-9/87/0000-0873 $1.00 © IEEE

PAC 1987

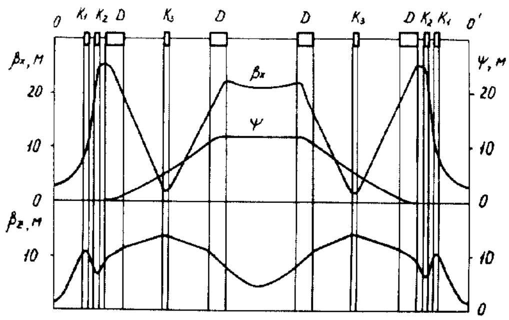

Fig.2. Dynamic functions for a lattice cell

Deviations from isochronism

There is a number of effects disturbing the isochronous circulation. Several nonlinear longitudinal effects resulting in systematic bunch lengthening (proportional to the circulation time) do not depend directly on intensity. Bunch lengthening averaged for a circulation period $\Delta\sigma$ is

$$\Delta\sigma = \frac{\partial\Delta\sigma}{\partial\varepsilon_x}\varepsilon_x + \frac{\partial\Delta\sigma}{\partial\varepsilon_z}\varepsilon_z + \frac{1}{2}\frac{\partial^2\Delta\sigma}{\partial\delta^2}\delta^2 + \dots \quad (3)$$

where ε_x, ε_z are Courant-Snyder invariants of radial and axial betatron oscillations, and $\delta = \Delta p/p_0$.

Expansion coefficients (3) corresponding to our lattice properties are related to transverse motion characteristics as follows:

$$\frac{\partial\Delta\sigma}{\partial\varepsilon_x} = \pi\frac{\partial\nu_x}{\partial\delta}, \quad \frac{\partial\Delta\sigma}{\partial\varepsilon_z} = \pi\frac{\partial\nu_z}{\partial\delta}, \quad (4)$$

where ν_x, ν_z are the betatron numbers, ψ is the dispersion function.
Hence, the compensation of the natural chromaticity eliminates emittance dependence of bunch lengthening. δ^2 - dependence of bunch lengthening can be eliminated by sextupole correction as well.

In the proton storage ring of Moscow meson facility ($\varepsilon_x = \varepsilon_z = 3$ cm.mrad, $|\delta|_{max} = 2\cdot10^{-3}$) with the natural chromaticity the total bunch lengthening amounts to $\Delta\sigma = 6{,}7\cdot10^{-4}$m per turn. If ejection is performed immediately after terminating the storage process, $\ell = \Delta\sigma\cdot K = 0{,}15$ m, which may be neglected. But correction is necessary, when the ejection is performed later or considerable sextupole nonlinearity in the lattice components takes place. That is why a set of sextupoles S_1-S_3 is provided (Fig.1).

Incoherent Coulomb shift of betatron oscillation frequencies limits the azimuthal proton density. At $(\Delta\nu_{x,z})_{max} = -0{,}10$ and transverse emittances $\varepsilon_{x,y} = 3$ cm.mrad the linear density should not exceed $dN/dS = 3\cdot10^{11}$ proton/m. Besides that the incoherent shift will be shown to result indirectly in deviations from isochronism.

It is necessary to point out, that in our case the incoherent Coulomb shift is rather important in spite of the storage is accompanied by 10-fold emittance growth. A flexible injection system /5/ facilitates nearly uniform filling of the beam cross-section during the storage. The azimuthal charge density should be also approximately uniform and the initial RF microstructure of an injected beam should be eliminated during the storage. To do it the orbit circumference is chosen so that it should not be divided exactly on the distance between the centres of adjacent microbunches.

Transverse electromagnetic forces inside the bunch modify external magnetic forces of the ring. It may be interpreted as the increase of the momentum compaction factor by $\Delta\alpha$, depending on the azimuthal charge density. So different particles have their own $\Delta\alpha$, if the azimuthal charge density is not uniform within the bunch. In particular, $\Delta\alpha = 0$ in bunch edges.

The equation for the dispersion function ψ is written as follows

$$\psi'' + g(\theta)\frac{R_0^2}{R^2}\psi = \frac{R_0^2}{R} - \frac{R_0^2}{R^2}\Delta g(\theta)\psi, \quad (5)$$

where

$$\Delta g(\theta) = -\frac{2Nr_p R_0\Gamma}{\pi\Lambda\, a(a+b)\beta^2\gamma^3}$$

takes into account space charge forces in the bunch. N is the number of protons in the bunch; $r_p = e^2/(m_p c^2)$; Λ is the bunch-factor; a, b are half-dimensions of the beam cross-section; Γ is the coefficient taking into account the effect of beam surroundings).

The solution of Eq.(6) is represented as follows

$$\psi = \psi_0 + \Delta\psi, \quad (6)$$

where ψ_0 is the dispersion function at low intensity and $\Delta\psi$ ($\Delta\psi/\psi_0 \ll 1$) is expressed by the relation

$$\Delta\psi(\theta) = \frac{R_0}{2\sin\nu_x\theta_0/2}\int_{\theta}^{\theta+\theta_0}\beta^{1/2}(\theta')\beta^{1/2}(\theta)\frac{\Delta g(\theta')}{R^2(\theta')}\psi_0(\theta')\times$$

$$\times\cos\left[\nu_x(\theta-\theta_0)+\chi(\theta)-\chi(\theta')+\nu_x\frac{\theta_0}{2}\right]d\theta', \quad (7)$$

θ_0 is the azimuthal length of the lattice cell.
A correction to the momentum compaction factor $\Delta\alpha$ is

$$\Delta\alpha = \frac{1}{\theta_0}\int_0^{\theta_0}\frac{\Delta\psi(\theta)}{R(\theta)}d\theta \quad (8)$$

Calculations referring to the Moscow meson facility storage ring result in $\Delta\alpha = 1{,}8\cdot10^{-2}$ at $dN/ds = 3\cdot10^{11}$ proton/m and uniform charge filling of the beam cross-section.

Azimuthal particle shift for K revolutions will reach the value

$$\Delta\ell = L\,\Delta\alpha\,|\Delta p/p|_{max}\cdot K, \quad (9)$$

resulting in $\Delta \ell$ = 0,84 m at the final moment of the storage.

It is worth noting, that inside the bunch tails the charge density is practically less than near its centre, thus, the azimuthal shift (9) is not in general bunch lengthening. The latter is less because of $\Delta\alpha \to 0$ in the bunch tails. The most significant azimuthal particle shifts occur in the middle part of the bunch.

Longitudinal particle repulsing

In a bunch with uniform azimuthal charge density the longitudinal Coulomb forces occur only on its edges. At nonuniform density they act along the whole bunch length, resulting in proton energy change. In the isochronous circulation mode the bunch length remains the same, but the bunch is radially deformed. With a bell-shaped distribution of charge density a head part of the bunch is accelerated and a tail one is decelerated.

Let's estimate energy change during the circulation. Assume, that the linear charge density decreases from the centre up to its edges according to the parabolic law. In this case, the longitudinal electric field increases linearly with a distance from the bunch centre

$$E_S(s) = \frac{3}{2}\,\frac{\varkappa N e}{\gamma^2 S_{max}^3}\,S\,, \qquad (10)$$

where N - is the number of particles;
S_{max} - is the bunch half-length;
S - is the distance from the bunch centre;
$\varkappa$ - is the factor in the specific case of the circular beam cross-section with a radius propagating along the axis of the circular transport channel with radius b, equal to $1+2\ln(b/a)$.

Assuming S=10 m, $S=S_{max}$, $N=3\cdot10^{12}$ and $\varkappa/\gamma^2$ = 1, one can find E_{Sm} = 0,65 V/cm. At the beginning of the storage E_{Sm} = 0, so with the linear intensity growth it is necessary to consider, that $\bar{E}_{Sm} = E_{Sm}/2$ on the average. During the storage the energy of boundary particles in the bunch changes by 0,78 MeV corresponding to relative momentum spread $(\Delta P/P_0)_{E_s} = \pm0{,}8\cdot10^{-3}$, this being comparable to momentum spread of the linac beam and this is to be taken into consideration in some cases.

As follows from Eq.(10), at the fixed linear charge density in the middle of the bunch the field strength on its edge depends on the length as $E_{Sm} \sim S_m^{-1}$, so the most sufficient disturbances of energy distribution occur in short bunches.

Longitudinal RF-instability

The longitudinal beam instability may result from bunch interaction with vacuum chamber walls and equipment, surrounding the beam, giving rise to momentum spread increase and azimuthal charge density modulation. Density fluctuations, whose wave length is comparable to or exceeds the beam cross-section, will result in betatron oscillation frequency modulation, which is unfavourable in our storage ring.

The instability threshold is rather low due to neighbourhood to the transition point. According to Keil-Schnell criterion /6/ the local current I_0 in the bunch should not exceed the value

$$I_0 \le F\,\frac{m_0c^2\beta^2\gamma|\eta|}{e\,|Z_L/n|}\left(\frac{\Delta P}{P_0}\right)^2, \qquad (11)$$

where Z_L/n is the longitudinal impedance divided by a number of the excited instability mode; $F\approx1$ is the factor depending on particle momentum distribution.

From Eq.(12) one derives for this case the impedance limitation at maximum stored current

$$|Z_L/n| \le 0.35\cdot10^3|\eta|\ \Omega \qquad (12)$$

At $|\eta| \simeq 10^{-2}$ it may be unreal to maintain impedance providing stability. But rise time for instability turns out to be comparable to or exceeding the storage time and it is the longer, the less $|\eta|$ is.

Conclusion

The investigation carried out shows, that the linac pulse may be compressed hundredfold using an isochronous storage ring without a R.F. bunching system. There is no need to maintain strictly isochronism conditions. For example at $|\eta| \le 0{,}02$ the bunch lengthening during the storage period of 100 μs will not exceed 2,5 m, that seems quite tolerable, unless the goal is to obtain short bunches of several meters long.

References

1. M.I.Grachev, V.M.Lobashev et al., Proc. 9th All-Union Conf. on Charged Particle Accelerators, Dubna, 1985, Vol.1 (1985), 343.
2. Yu.P.Severgin, I.A.Shukeilo, IEEE Trans. on Nucl.Sci., Vol.NS-32, 5(1985), 2709.
3. K.H.Reich, Proc. of the Workshop on High Intensity Accelerators and Compressor Rings. Karlsruhe, 1981, p.33.
4. R.Cappi, J.P.Delahaye, K.H.Reich, CERN/PS/OP/BR 81-9 (1981).
5. Yu.P.Severgin, G.P.Yushko, Proc.9th All-Union Conf. on Charged Particle Accelerators, Dubna, 1985, Vol.1 (1985), 356.
6. E.Keil, W.Schnell, CERN-ISR-TN-RF/69-48 (1969).