EXTERNAL INJECTION INTO PHASOTRON

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Abstract

The opportunity of the external injection into the JINR Phasotron [1] by the scheme [2] shown in Fig.1 is discussed. H^- ions are converted to neutral H^0 atoms by the gas stripper or by the laser photon beam. The neutral beam is injected in the Phasotron median plane. It is converted to H^+ by the stripping foil on the 40 cm radius and is captured to the separatrix.

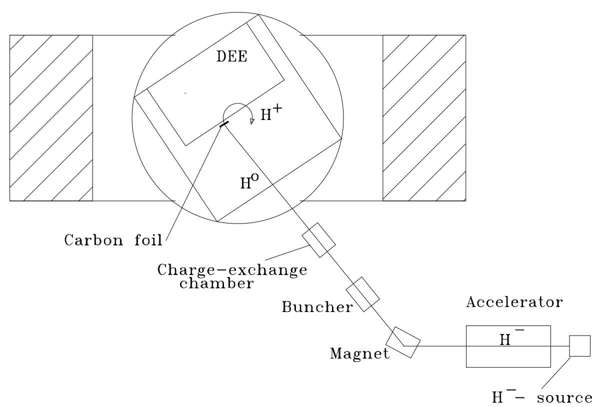

Figure 1: Scheme of the beam external injection into Phasotron.

1 INTRODUCTION

Now the proton beam current in the Phasotron is equal to 5 μA. With the frequency modulation rate of 250 Hz and the capturing time of 20 μs the duty cycle is 0.005. Hence the pulse current is 1 mA or 1.25×10^{11} particles per pulse. If we want to increase the beam intensity 10 times it should be 1.25×10^{12} particles per pulse. The capturing process needs the computer simulation. Now we discuss some preliminary considerations.

Under the capturing of the particles from the machine center (from the internal ion source) the main factor limiting the beam intensity is the weakness of the vertical focusing. For the 1 MeV beam energy this limitation is eliminated since the vertical oscillation frequency is $Q_z \approx 0.1$ on the radius 17 cm.

For the same reason (weakness of the vertical focusing) and due to the fact that only the particles near the maximum energy gain (i.e. near zero of the r.f. phase) are able to leave aside the ion source, the phase range of the particles involved in acceleration is limited by less then 30°. The capturing of particles with nonzero initial energy allows, as we suppose, acceleration of all the particles lying in the phase stability region. With $\cos\varphi_s = 0.2$, this region ranges from -75° to 150°.

Thus, we suppose that external injection allows us to accelerate the whole injected beam. The intensity of this beam has to be more than 10 mA in the pulse with a time duration of 20÷25 μs and a modulation rate of 250 Hz.

Let us examine the requirements to each element of the scheme under consideration.

2 CHARGE-EXCHANGE FOIL

2.1 Foil thickness

The cross-section for detachment of one electron is approximately $\sigma_{01} = 1.54\times10^{-16}$ cm^2 for the 10 MeV hydrogen atom [3]. To decrease the atomic beam intensity by “e” times (i.e. to convert atoms to protons because of electron detachment), the foil thickness must be $\delta_1 = 1/\sigma_{01}$ atoms/cm^2. For the 99% ionization efficiency the foil thickness δ has to be increased by a factor of 4.6 . Table 1 shows for two different beam energies the carbon foil thickness and the average energy loss δE of the particles passing through this foil.

Table 1: Parameters of the carbon foil

Particle energy, (MeV)	δ (atoms/cm^2)	δ (μg/cm^2)	δE (keV)
1.0	3.0×10^{16}	0.6	0.138
10.0	2.3×10^{17}	4.6	0.220

As follows from the tables it is necessary to use very thin foils. At present the foil as thin as 5 μg/cm^2 can be made [4], but they are rather works of art. Really available are foils of 20 μg/cm^2 or 10^{18}atoms/cm^2 [5]. The 1 MeV proton, once passing through a such foil, will lose δE = 4.6 keV; the 10 MeV (≈ 0.88 keV).

2.2 Multiplicity of passing through the foil

During the capture process the protons will pass through the foil many times. Exact multiplicity could be found by the computer simulation of the capture process. However, some estimation can be done assuming that the proton leaves the foil region after the first phase oscillation. In this case it will pass through the foil not more than 3 times.

The radial gain ΔR depends on the energy gain ΔE as

$$\frac{\Delta E}{E} = \beta^2\gamma\ (1+n)\frac{\Delta R}{R}$$

Supposing that ΔE is equal to the energy gain of the synchronous particle, which is 22 keV, one will find ΔR and the corresponding maximum number Nmax of the proton passes through the foil of 1 cm in radial size.

Table 2: Multiplicity of passing through the foil

E (MeV)	R (cm)	ΔR (cm)	N	Nmax = 3N
1	17	0.187	5.3	16
10	40	0.044	22.7	68
40	75	0.022	45.4	136

2.3 Transversal emittance growth

The multiple Coulomb scattering due to the foil passing results in the growth the transversal emittance. One can express the resulting emittance as [6]

$$\varepsilon = \bar{\varepsilon} + \tfrac{N}{2}\tfrac{R}{Q}\delta\sigma_c\bar{\chi}^2$$

where $\bar{\varepsilon}$ - is the initial emittance, N - is the number of passes through the foil, R - is the foil radius, Q - is the betatron frequency for this radius, δ - is the foil thickness, σ_c - is the Coulomb scattering cross-section, $\bar{\chi}^2$ - is the mean-square scattering angle.

It is well know [7] that

$$\sigma\bar{\chi}^2 = \frac{4\pi z^2 r_p^2 \lg\left(183z^{-1/3}\right)}{\gamma^2\beta^4}$$

where Z - is the atomic number of the scattering nucleus, $r_p = 1.53\times10^{-16}$ cm - is the classical proton radius, γ and β - are the proton relative energy and velocity.

For the 20 $\mu g/cm^2$ carbon foil the vertical oscillation emittance growth is defined by the figures from Table 3.

Table 3: Growth of the vertical emittance

R (cm)	E (MeV)	Q_z	Nmax	$\Delta\varepsilon_z$, norm. (mm×mrad)
17	1	0.1	16	0.92 π
40	10	0.15	68	0.2 π
75	40	0.2	136	0.07 π

2.4 Power dissipated in the foil

As was mentioned above, the 10 MeV proton (or H^0 atom) loses about δE = 0.88 keV for one pass through 20 $\mu g/cm^2$ carbon foil. With the pulse current 10 mA, the dissipated pulse power is 8.8 W for one pass and 600 W for the maximum number of passes. Then the average power (duty cycle 0.005) is 3 W.

The foil life time depends on the dissipated power. As follows from the experience [5] the dissipated power does not limit the foil life time if the power density is less than 1 W/cm^2. From this point of view it is desirable to decrease the power dissipation in the foil by a factor of 2÷4 by decreasing the foil thickness to 10÷5 $\mu g/cm^2$ For the 1 MeV injection energy, such foil thickness reduction is also useful for limiting the emittance growth.

3 H^- BEAM NEUTRALIZATION - H^0 BEAM GENERATION

3.1 Stripping foil

The foil thickness needed for the 99% charge-exchange efficiency are given in Table 4. As follows from these data, the available foils (5÷20 $\mu g/cm^2$) can be used to convert H^- to H^0 only for the energy of 40 MeV or more.

Table 4: Thickness of the stripping foil

Energy (MeV)	δ_{-10} ($\mu g/cm^2$)	δ_{-11} ($\mu g/cm^2$)
1	6.6×10^{-2}	4.2×10^{-1}
10	3.8×10^{-1}	7.5
40	5	~20

3.2 Laser beam

Let us consider the one electron photodetachment with a laser beam. The cross-section of the photodetachment depends on the photon energy. The maximum cross-section for detachment one electron from H^- is equal to 4×10^{-17} cm^2 for the photon energy 1.4 eV (wave length ≈10^4 Å) [8]. The maximum two-electron detachment cross-sections about 10^{-19} cm^2 for the photon energy 10 eV. What a photon beam does one need?

The laser beam of N photons with uniform intensity over an area S makes up one-interaction-long target for H^- ions if $N/S=1/\sigma = 2.5\times10^{16}$ photons/cm^2. The photon beam energy density will ≈ 5.6 mJ/cm^2. Then the full energy of the photon pulse beam to convert an beam of area S_B with the 99% probability (4.6 interaction lengths) will be

$$E_{\gamma t} = 4.6 S_B \tfrac{E_\gamma N}{S} \approx (25\ mJ/cm^2)\times S_B$$

For the photon pulse duration t=20 μs the pulse power will be $P = E_{\gamma t}/t = 1.25\times10^3\times S_B$ W. The average power for S_B=1 cm^2 and the pulse rate 250 Hz is equal 6.25 W. A CO_2-laser with such parameter available from industry.

3.3 Electric dissociation by the magnetic field

This way is used for example in LANL [9] for injection into proton storage ring. The coupling energy of a second electron is only 0.755 eV. The electric field E, which results from the motion of the H^- ion in the magnetic field B in the H^- ion rest frame, is given by

$$E = \beta\gamma cB$$

The lifetime τ of the H^- ions in the magnetic field was calculated and measured by many authors [10]. The results can be described by a functional dependence $\tau(E)$ of the form

$$\tau(E) = \left(A_1/E\right)\exp\left(A_2/E\right)$$

where $A_1 = 1.05\times10^{-14}$ s×MV/cm, $A_2 = 49.25$ MV/cm.. The electric dissociation by the magnetic field can be used only for H^- ions with energy more than 100 MeV.

3.5 Gas stripper

In some cases a gas stripper is used [11]. The gas target is surrounded by a drift chamber evacuated by a diffusion pump with a rate of 1500 l/s. The gas target volume is coupled with the drift chamber by tubes 6 mm in diameter and 5 cm long. The pressure in the drift chamber was 5×10^{-6} Torr while in the target volume the pressure could be increased up to 5×10^{-2} Torr, allowing regulation of the gas target density in the range $(0.5\div30)\times10^{15}$ atoms/cm^2 for Ar or N_2 and $(2\div200)\times10^{15}$ atoms/cm^2 for H or He. As is shown in Table 4, a target like this could be used to convert H^- ions into neutral hydrogen atoms [12].

4 H^- ION SOURCES

As was mentioned above, the ion source intensity has to be 10÷50 mA in the 20÷25 μs pulse with the pulse rate 250 Hz and with the normalized emittances (0.5÷1.0) π mm×mrad.

At present the volume continuous-wave H^- sources provide the intensity 10 mA with the normalized emittance $\varepsilon_n = 0.44\ \pi$ mm×mrad [13]. The latter is used for injection in the cyclotron TR30 as well as in the 900 kV tandem accelerator to provide the 1.8 MeV protons with intensity 10 mA. The discharge power of this H^- source is of the order of 5 kW.

4 ACCELERATOR

The choice of the accelerator type strictly depends on the final accelerator energy. For the 1 MeV energy, the direct accelerator is more suitable. For the energy range 3÷7 MeV, the RFQ-type accelerator- can be used.

5 CONCLUSION

The above consideration proves the possibility of realizing the external injection into the Phasotron. The computer simulation of the capture process will allow the optimal injection energy and hence the accelerator type to be chosen.

The authors wish to thank G.G. Gulbekyan and B.N. Gikal for helpful information about the charge-exchange foils.

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