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A FEASIBILITY STUDY FOR THE CHARGE EXCHANGE INJECTION INTO THE KEK BOOSTER PROTON SYNCHROTRON

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Abstract

The space charge limit of the 500 MeV booster synchrotron (2.6×10^{12} ppp, 20 Hz) may be reached by 110 turn injection of 10 mA H^- beam from the linac. The charge exchange injection of H^- beam may give a higher phase space density in the synchrotron beam than the regular proton injection. The feasibility of constructing the injection system is shown for the H^- ion source (30 mA), the preaccelerator, the linac (10 mA), the injection optics and the charge exchange stripper.

I. Introduction

The charge exchange injection into proton synchrotrons (the injection of H^- and subsequent stripping to H^+) is becoming more promising and attractive[1] as the H^- output from direct extraction ion sources increases. The H^- yield from the hollow discharge duoplasmatron reaches 11 mA[2] (the normalized emittance $E_n \leq 0.1$ πcm·mrad) in the pure hydrogen mode, and 60 mA[2] ($E_n \sim 0.2$ πcm·mrad at 40 mA) in the hydrogen-cesium mode. The brightness figure of the H^- beam ($B = 2I^-/E_n^2 \sim 2 \times 10^9$ A/m^2/rad^2 at 40 mA) is not very far from that of the high current proton beam from the regular duoplasmatrons ($10^9 \sim 10^{11}$ A/m^2/rad^2). A Penning type source[3] at Novosibirsk delivers 150 mA of H^- beam from an emission slit of 0.5 mm × 10 mm. Higher intensities up to ~1A are obtainable from magnetron type sources.[4]

The charge exchange injection to the KEK 500 MeV booster synchrotron has many merits compared with the regular proton injection.

1) The space charge limit of the booster synchrotron (2.6×10^{12} ppp) may be more easily reached by the 110 turn injection of 10 mA, H^- beam from the linac (the charge exchange efficiency ~0.9 and the rf capture efficiency ~0.7). Taking a safety factor of two, let us assume the 200 turn injection.

2) A higher phase space density may be obtained in the synchrotron beam. The brightness figure of the coasting H^+ beam is higher than that of the injected H^- beam by a factor of M/G^2, M being the number of multiturn injection and G the emittance growth ($E_n \rightarrow GE_n$) due to the multiple scattering in the charge exchange stripper. The 200 turn injection with the emittance growth of twice ($M/G^2 = 50$) using an H^- ion source of 30 mA and $B \sim 2 \times 10^9$ A/m^2/rad^2 may be equivalent to the three turn injection using an H^+ ion source of 2A and $B \sim 10^{11}$ A/m^2/rad^2.

3) The injection becomes simpler; the closed orbit displacement may be smaller (~40 mm instead of ~60 mm) and no septum magnet is necessary.

4) The rf capture efficiency may be improved due to the smaller beam size (horizontally ~56 mm instead of ~100 mm).

5) The overall reliability of linac will increase for the operation at the low beam current.

The charge exchange injection has been studied in many laboratories as Novisibirsk, ANL, BNL and FNAL (Appendix I).

2. H^- Ion Source

Among the direct extraction sources, which are much simpler than the charge exchange type sources, the hollow discharge duoplasmatron (HDD) source has been well established and gives an axially symmetric beam (not in the Penning type or magnetron type sources). A reliable H^- ion source[2,5)] with the cesium vapour injection may be constructed with the following parameters:

H^- Current	30 mA
Extraction Voltage	40 KV (the gap ~10 mm)
Anode Aperture	2.5 mmϕ
Emittance (normalized)	≤ 0.2 πcm·mrad
Brightness	$\sim 2 \times 10^9$ A/m^2/rad^2
Arc Current	~150 A
Arc Voltage	~70 V
Pulse Width	0.5 ms
Repetition	20 pulses/s

Fig.1 shows a critical region around the anode, the intermediate electrode and the centre rod tip. The operational duoplasmatron at KEK may be easily modified to the HDD source by mounting an adjustable centre rod, and a cesium container. A compact pulsed gas valve will be mounted close to the HDD source in order to reduce the gas load which otherwise is bigger than for the regular duoplasmatron source because of the large anode aperture.

3. Preacceleration of H^- to 750 keV

Fig.2 shows a schematic configuration of the acceleration system. A small permanent dipole (~700 Gauss·cm) may be put behind the extractor in order to deflect away the intense electron output (1.5 A)[2] at the low energy stage. The collimators in the dipole are practically important to cut off the scattered electrons on the wall of the dipole. The deceleration following the extraction may help focus again the H^- beam whose size increases in the dipole.

4. Acceleration of H^- to 20 MeV

The H^- intensity of 10 mA within the normalized emittance of 0.5 πcm·mrad (the emittance = 2.5 πcm·mrad) may be easily obtained from the linac, because the reduction in the intensity by a factor of three and the emittance growth in the preaccelerator and linac by a factor of 2.5 are a conservative estimate even for an intense H^+ beam.[6]

The main modification required for the present linac is to lengthen the quadrupole flat top and rf pulse to 300 μs from 100 μs and 20 μs respectively.

5. Charge Exchange Injection into the 500 MeV Booster Synchrotron

There exist two possible schemes: the direct H^- injection into the target placed on the synchrotron orbit, and the H° injection[7] after stripping of H^- in an another target placed in the beam transfer line. Though the H° injection has also some merits (see Appendix II), the overall charge exchange efficiency from H^- to H^+ is low (50 ~ 55 %). It will be reasonable to adopt the direct H^- injection from the viewpoint of higher charge exchange efficiency (~90 %) and of simplicity (a single target).

Foil Thickness and Stripping Efficiency

Let us assume a carbon foil as a stripper, because other materials (for example, polyparaxylene as is successfully used in ANL) do not much change the discussion. The charge exchange efficiency of 90 % is obtainable for the foil thickness of 7.3×10^{17} atoms/cm^2 (~15 μg/cm^2) (see Fig.3). The multiple scattering angle (one-dimensional) is 2.06 mrad, if the effective number of multitraversal is taken as 100 because of the partial bypassing due to the betatron oscillation. The foil thickness may be increased up to ~100 μg/cm^2 depending on the easiness of handling (Appendix III).

H$^-$ Injection

The injection is made in the straight section S1 between two horizontally focusing sections (the lattice: FDFO). Fig.3 shows the geometrical relation among the injected H$^-$ beam, the coasing H$^+$ beam and the foil. The H$^-$ beam (10 mA) is injected during 200 turns on the closed orbit which is displaced by 40 mm during the injection by using bump magnets. The closed orbit is switched back quickly after the injection so that the coasting beam should not hit the stripper foil any more. The upper limit for the number of multiturn injection is 1100 (Appendix IV).

The matched injected beam has the horizontal size of $2A_h$ = 20 mm with the half-angle of 2.5 mrad ($\beta_h \sim 4$ m) and the vertical size of $2A_v$ = 16 mm with 3.2 mrad ($\beta_v \sim 2.5$ m). The charge exchange foil has a slightly larger width (22 mm) than the horizontal beam size.

Addition of the multiple scattering angle in the foil in quadruture gives horizontally the half-angle of 3.2 mrad with $2A_h$ = 22.8 mm ($E \sim 3.25$ πcm·mrad) and vertically 3.8 mrad with $2A_v$ = 17.2 mm ($E \sim 2.98$ πcm·mrad). The size of the coasting H$^+$ beam during and soon after the injection is big because of the closed orbit displacement due to random magnet errors and momentum spread. The horizontal half beam size at the foil position is 28 mm by summing up the beam size in the case of no random errors and no momentum spread (11.4 mm), the closed orbit displacement due to random errors (6.8 mm),$^{8)}$ and due to momentum spread (9.8 mm for $\Delta p/p = \pm 0.7$ %),$^{8)}$ while the vertical size is 17.8 mm by summing up the corresponding three contributions (8.6 mm, 9.2 mm$^{8)}$ and 0 mm$^{8)}$ respectively).

Foil Life

The life of polyparaxylene foils at 50 MeV is $10^{20} \sim 10^{21}$ protons/cm^2,$^{9)}$ while it scatters in a wide range (a few sec to weeks).$^{10)}$ The similar life may be obtained also at 20 MeV because the energy loss in the foil is roughly independent of the energy in this energy range. If we take the average foil life ~2×10^{20} protons/cm^2 and the effective foil area ~4 cm^2 the foil life (10 mA, 200 turn injection) is 28 hours. By using the foil exchanger$^{10)}$ as is successful at ANL, the foil system may not need a service for longer than a month.

6. Vacuum Requirements

As the stripping cross section $(H^- \to H^\circ)$ is one to three orders of magnitude larger than the recombination cross section $(H^+ \to H^\circ)$, the higher vacuum is required for H^- than for H^+. The vacuum requirement is most severe in the low energy beam transport as seen in Table I (the hydrogen gas pressure $\lesssim 8.5 \times 10^{-6}$ Torr for the H^- loss $\lesssim 1$ %).

Table I The gas pressure which causes 1% loss of H^- in each region.

	H_2	N_2	Note
750 keV Accelerating Column	Torr 2.7×10^{-5}	Torr 1.6×10^{-5}	Length ~30 cm $\sigma_{-10} \sim 3.5 \times 10^{-16}$ cm^2(H_2) at 40 keV $\sigma_{-10} \sim 6 \times 10^{-16}$ cm^2(N_2) at 40 keV
Low Energy Beam Transport	8.5×10^{-6}	1.9×10^{-6}	Length ~6 m $\sigma_{-10} \sim 5.5 \times 10^{-17}$ cm^2(H_2) $\sigma_{-10} \sim 2.5 \times 10^{-16}$ cm^2(N_2)
Linac	2.4×10^{-5}	5.4×10^{-6}	Length ~15.5 m $\sigma_{-10} \sim 4.5 \times 10^{-17}$ cm^2/E (in MeV) (H_2) $\sigma_{-10} \sim 2 \times 10^{-16}$ cm^2/E (in MeV) (N_2)

7. Conclusion

The charge exchange injection may relatively easily realize the space charge limit of the booster synchrotron, and thereby put a firm basis for the future plan such as 180 GeV - 180 GeV intersecting storage accelerator which is under discussion.

It is very desirable to start early to develope an H^- ion source, a pulsed gas valve[11] at 20 Hz and a thin foil system, while the developments in foreign laboratories show no extreme difficulty in any of these.

A gas jet (the length ~1 cm; the pressure ~20 Torr for CO_2) may be eventually a better stripper than the foil (see Appendix V).

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Appendix I Charge Exchange Injection in Other Laboratories

Table II shows the performances as well as the plans for the charge exchange injection in various laboratories.

ZGS

The H^- injection is envisaged for the 500 MeV Booster II synchrotron which is under construction. The 900 - 1200 turn injection (300 - 400 μs) of the 6 - 4.5 mA H^- beam (50 MeV) will give the coasting beam of 5×10^{12} protons (the stripping efficiency ~0.95, the matching efficiency ~0.90 and the capture efficiency ~0.70).[9] The improvement of the charge exchange ion source is directed both to increase the H^- output and to prevent the gridded anode-extractor system from the damage caused by the high repetition (30 Hz) operation. For this purpose, a sodium vapour jet is under construction to replace the hydrogen gas cell.[16]

AGS[14]

Since the proposal for the charge exchange injection (1972), the development of the direct extraction ion source of high H^- outputs has been successfully carried out, resulting in the H^- current of 60 mA[2] from the hollow discharge duoplasmatron source. The second preinjector is under construction to accelerate the H^- beam.

FNAL[15]

Due to a difficulty in the multiturn injection (3 - 4 turns) a new policy of one-to-two turn injection with as high as possible linac beam (H^+) has been adopted. The charge exchange injection is now under preparation as the future step by using a 100 mA H^- ion source of magnetron type developed at BNL. A study of the hollow discharge duoplasmatron source has also been made.

Table I Performances and plans (*) for the charge exchange injection

		Novosibirsk$^{7)}$	ZGS$^{12)}$ (Booster)	ZGS$^{13)}$	AGS$^{*14)}$	FNAL$^{*15)}$ (Booster)	KEK* (Booster)
Synchrotron Energy/GeV			0.2	12	33	8	0.5
Linac Energy/MeV		1 (V.G.)	50	50	200	200	20
H^- Ion Source	Type	Arc source	Duoplasmatron with charge exchange cell	Duoplasmatron with charge exchange cell	HDD†	HDD† or Magnetron type source	HDD†
	H^- Current/mA	1		3.5	20		30
	Normalized Emittance/cm·mrad				~0.3π		~0.2π
	Repetition		30		0.5 - 10	15	20
Injection	H^- Current/mA	~0.8	1 - 2	3			10
	Number of Multiturns	1500	300 - 600	~300	200	~100	200
	Duration/μs		200	540	~1000	~300	~130
	Stripper (the thickness in μg/cm^2)	H_2 gas tube ($H^- \to H^0$) H_2 gas jet ($H^0 \to H^+$)	Polyparaxylene foil (rotating) 30 - 70	Polyparaxylene foil ~ 60	Carbon-like foil ~240	Carbon-like foil	Carbon-like foil 15 - 30
	Charge Exchange Efficiency	~0.55 ($H^- \to H^0$) ~1 ($H^0 \to H^+$)	≥0.90	~1			>0.90
	Emittance Growth : G		2 ~ 3				1.2 ~ 1.5
	Maximum Coasting Protons	~10^{12}	8.5×10^{11}	2.9×10^{12}	6×10^{12}	~5×10^{12}	~2.6×10^{12}

†) Hollow Discharge Duoplasmatron.

Appendix II H° Injection

H^- is once converted to H° before the injection of H° to the synchrotron. The overall charge exchange efficiency ε_{-11} is given by the product of ε_{-10} (for $H^- \rightarrow H^\circ$) and ε_{01} ($H^\circ \rightarrow H^+$).

If we neglect σ_{-11} compared with σ_{-10} and σ_{01}, the optimum target thickness (in atoms/cm^2) for the neutralization process is given by

$$X_m = \ln(\sigma_{-10}/\sigma_{01})/(\sigma_{-10} - \sigma_{01}) \quad . \qquad \text{(A1)}$$

Taking $\sigma_{-10} \sim 1.1 \times 10^{-18}$ cm^2 and $\sigma_{01} \sim 3.6 \times 10^{-19}$ cm^2 for the H_2 gas target at 20 MeV, we find $X_m \sim 1.6 \times 10^{18}$ atoms/cm^2. The maximum neutralization efficiency ε_{-10} is given by

$$[\exp(-\sigma_{01}X_m) - \exp(-\sigma_{-10}X_m)]\,\sigma_{-10}/(\sigma_{-10} - \sigma_{01}) = 58\ \% . \qquad \text{(A2)}$$

The neutralization efficiency is rather small because a significant part of H° is further stripped to H^+ as the target thickness increases.

The neutralization target is more easily prepared than the target for $H^\circ \rightarrow H^+$, because of the small thermal load (no multitraversal) and of the easy handling (no high precision in the position, easy access, feasible differential pumping, etc.)

The distinct merit of the H° injection scheme lies in the charge neutrality, which allows the injection just on the closed orbit without an additional closed orbit distortion. This injection scheme requires the gas jet stripper (as in Novosibirsk$^{7)}$) or the quick removing of the stripper foil after the completion of the injection.

Appendix III Upper Limit for the Foil Thickness (L_t)

Too thin foils ($< 30\ \mu g/cm^2$ for polyparaxylene) are difficult to mount them on the foil holder[10]. Reasonably thick foils may be easier to handle.

An upper limit for the foil thickness comes from the multiple scattering in the foil. As the vertical aperture (6 cm) of the synchrotron is smaller than the horizontal aperture (10 cm), the beam loss appears first in the vertical betatron oscillation. The upper limit for the amplitude of betatron oscillation, 19.9 mm ($E \sim 5\ \pi$cm·mrad)[8], corresponds to the multiple scattering angle of 5.44 mrad:

$$\theta_{ms} = \frac{14}{40} \sqrt{0.5\ M\ L_t/L_R} \lesssim 5.44 \text{ mrad}, \tag{A3}$$

where L_R is the radiation length of the material. For carbon, $L_t \lesssim 108\ \mu g/cm^2$ ($M = 200$).

Another limit comes from the acceptable limit ($\Delta p/p < 0.7\ \%$)[8], of the energy loss in the foil and is written for carbon as

$$ML_t \lesssim 2.3 \times 10^4\ \mu g/cm^2 , \tag{A4}$$

which gives $L_t \lesssim 115\ \mu g/cm^2$.

From the above, the foil thickness may be safely increased a little more if the $15\ \mu g/cm^2$ foil is difficult to handle.

Appendix IV Upper Limit for Number of Multiturn Injection (M)

The limit comes from 1) the multiple scattering angle in the foil, 2) the energy loss in the foil and 3) the shrinkage of the closed orbit corresponding to the rising magnetic field.

The upper limit for the multiple scattering angle in the foil (Eq.A3) gives $M \lesssim 1450$ for $L_t = 15\ \mu g/cm^2$. The upper limit for the energy loss in the foil (Eq. A4) gives $M \lesssim 1500$. The upper limit of 10 mm for the shrinkage of the closed orbit gives $M = 1100$.

From the above, the number of multiturn injection should be smaller than 1100 (or 700) if the foil thickness is assumed to be $15\ \mu g/cm^2$ (or $30\ \mu g/cm^2$).

Appendix V Gas Jet Stripper

A sharply directed supersonic gas jet (typically, CO_2),[17] of a length of 1 cm and the pressure of 20 Torr (~7 × 10^{17} molecules/cm^2), will be another possibly better stripper than the foil. It has no short life as the foil has. No large displacement of the closed orbit is necessary for the purpose of clearing the coasting beam from the foil after the injection. Only much smaller displacement may be necessary in order to inject the H^- beam on the closed orbit. Most part of the gas is received in a receiver, and the rest of the gas which spreads into the vacuum tube of the synchrotron may be quickly pumped away both by ordinary vacuum pumps and by cold walls (-77°C) prepared around the gas jet. As the gas jet density is proportional to the injection energy, and the denser gas jet is more difficult to establish, the gas jet stripper is relatively more feasible at KEK than at ANL (50 MeV injection), FNAL (200 MeV) or BNL (200 MeV). The jet gas density of ~7 × 10^{17} molecules/cm^2 (CO_2), however, is much higher than in widely used gas jet ($\lesssim 10^{15} \sim 10^{17}$ molecules/cm^2) and may require some efforts to establish it. In Novosibirsk, the hydrogen gas jet (transverse dimension ~1 cm) of ~10^{17} atoms/cm^2 was successfully used.[7]

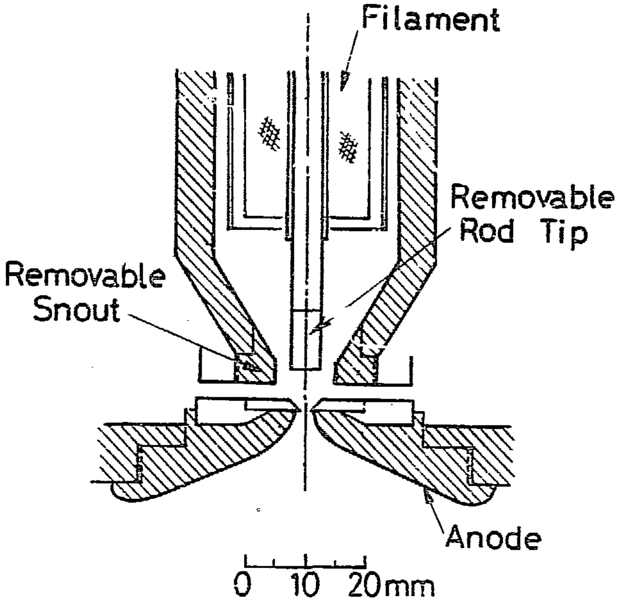

Fig.1 Configuration of the anode, intermediate electrode, rod tip and filament for the HDD source. The shaded parts are made of magnetic materials.

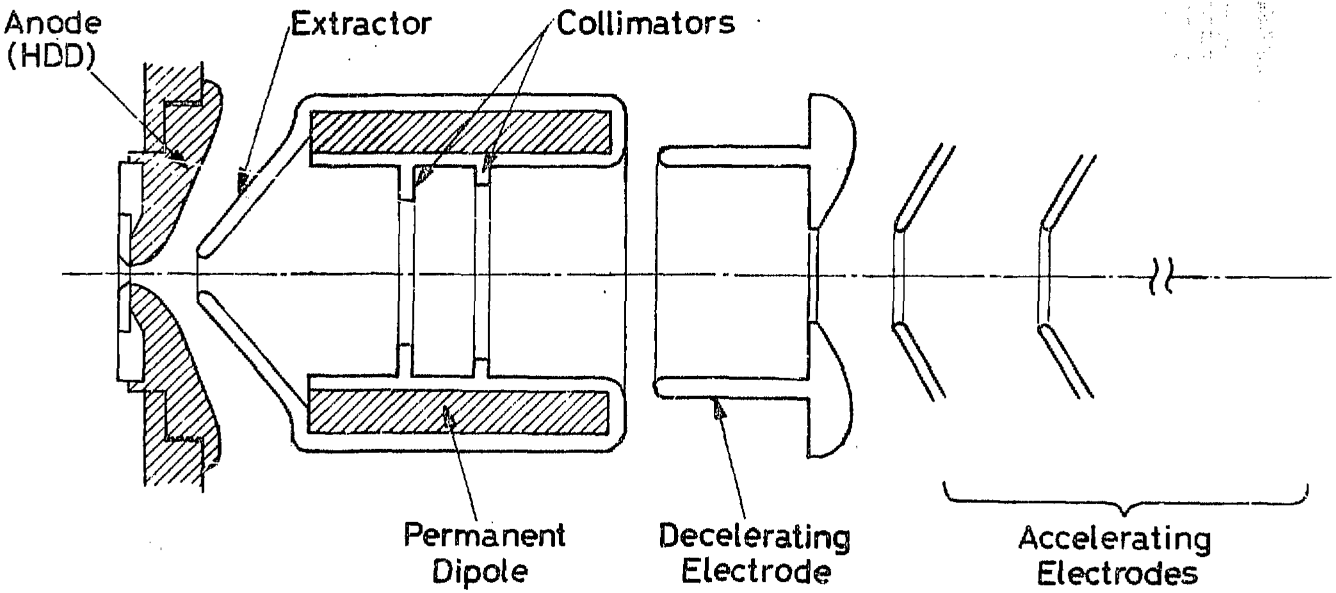

Fig.2 A schematic configuration of preacceleration

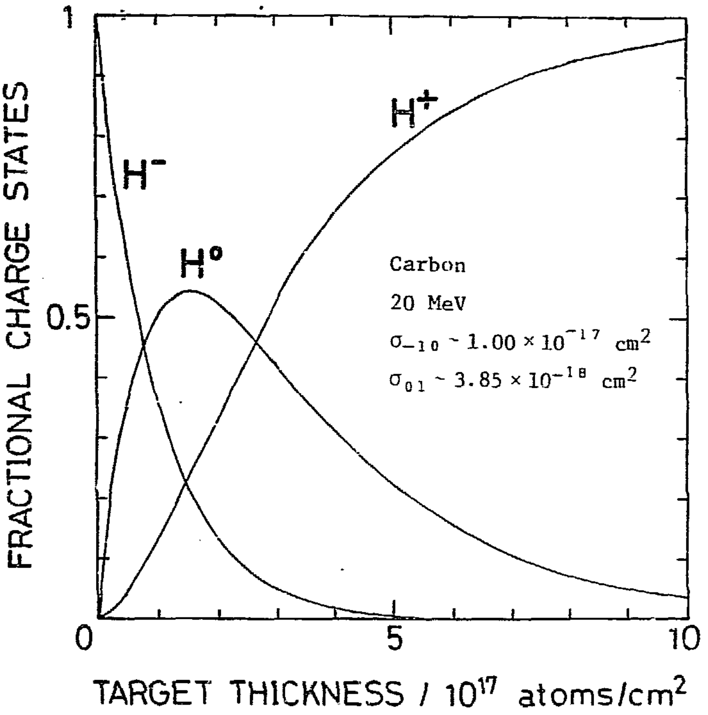

Fig.3 Components of different charge states obtained as the initially H^- beam passes through a carbon stripper.

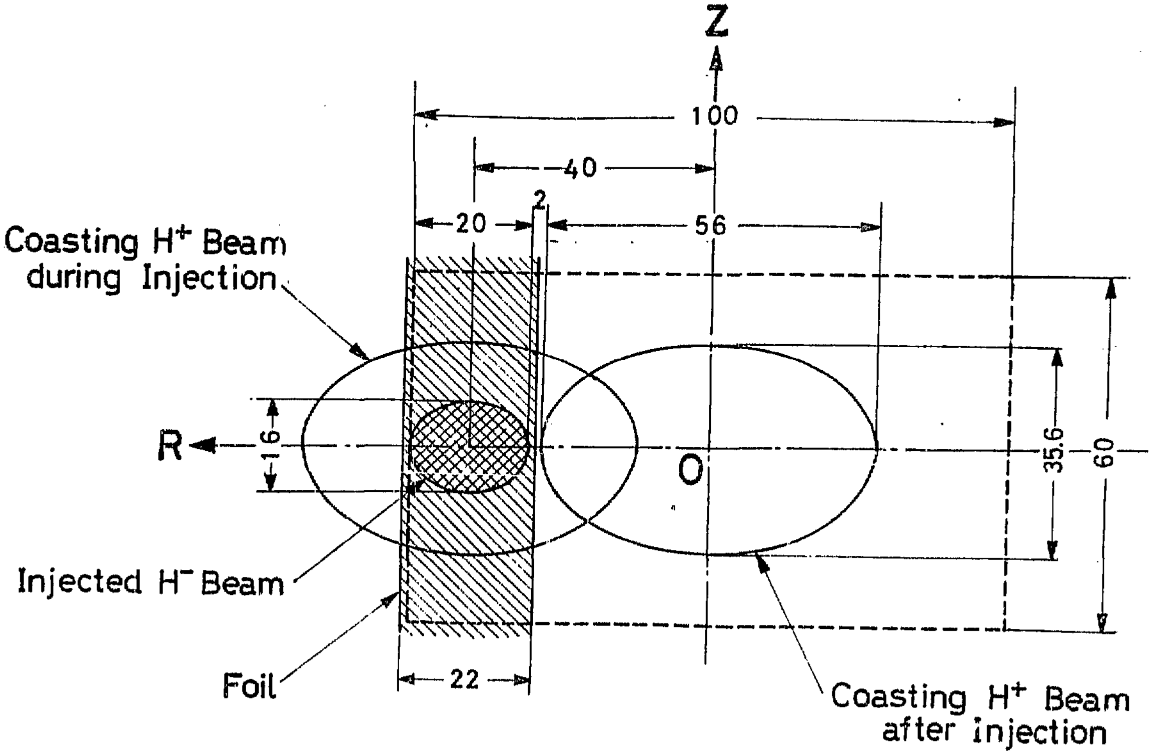

Fig.4 The relation between the foil and beam positions during and after the injection.