STRIPPING INJECTION INTO THE NEW BOOSTER RING AT IUCF

K. Hedblom, Department of Radiation Sciences, Uppsala University, Box 535 S-75121 Uppsala
D.L. Friesel, IUCF, 2401 Milo B. Sampson Lane, Bloomington, IN 47808

Abstract

To increase the polarized proton beam intensity in the IUCF Cooler ring, this ring will be equipped with a new injector consisting of a 7 MeV linear accelerator and an 80 MeV Cooler Injection Synchrotron (CIS). The linear accelerator will accelerate negative hydrogen ions which will be strip-injected into CIS. Tracking calculations have been made to estimate the beam intensity that can be achieved within a specified emittance.

I. STRIPPING INJECTION OF H^- INTO CIS

The choice of injection mode in CIS is dictated by the still modest intensity available from present polarized ion sources. While the pulsed beam intensity capabilities of modern polarized H^+ and D^+ sources is impressive (> 200 μA) and growing, it is still about a factor of 20 smaller than required for single turn kick injection to provide the $2.5 \cdot 10^{10}$ particles desired for Cooler injection. This goal can only be achieved via stripping injection of polarized H^- and D^- ions.

Negative polarized hydrogen ions will be strip-injected into CIS to produce protons (deuterons) that will be accelerated to 80 MeV (65 MeV) [1]. With the high intensity polarized ion source (HIPIOS) [2] it is possible to produce a 20 μA polarized H^- beam. This beam will be accelerated by a radio frequency quadrupole (RFQ) to 3 MeV, and by a drift tube linac (DTL), to 7 MeV.

The injection elements in CIS are a 4 μg/cm^2 carbon stripper foil located at the center of the injection straight section, and two bumper magnets which are 180 ° apart in phase advance and centered about the stripper foil. The bumper magnets are used to displace the circulating beam during the injection so that incoming ions are injected close to the circulating orbit in order to keep the emittance small. The foil strips electrons from the injected hydrogen ions but it also scatters circulating particles during injection. Therefore the beam will be heated in both longitudinal and transverse phase spaces.

Stripping injection is usually accomplished by moving the circulating beam close to the foil edge so that circulating particles pass through the foil as few times as possible. For CIS however, the emittance of the injected beam is comparable with the maximum beam emittance that can be accepted and therefore it is necessary to bump the closed orbit onto the foil so that the injected and the circulating beams overlap. To prevent particles from passing through the foil on each turn, a stripper foil is used which has two unsupported edges. The foil strip width is the size of the injected beam. For a 7 MeV proton beam with 1.5π μm normalized emittance, the width of the strip would be 7.4 mm if the injected beam is matched with the β-function at the foil.

There might be a possibility to gain more intensity by focussing the injected beam on a narrower foil. The usable emittance must however be larger than the emittance of the injected beam.

It is more important to make the foil thin. A carbon foil as thin as 4 μg/cm^2 is available at IUCF now, but it might be worth while trying to make even thinner foils. Fig. 1 shows a 4.5 μg/cm^2 thin carbon foil with two unsupported edges.

II. THE EMITTANCE GROWTH AT THE STRIPPER FOIL

Each time a particle passes through the foil it loses energy and is scattered through a small angle. The energy loss causes a displacement of the closed orbit with resulting emittance growth. Since the energy loss is random it also heats the longitudinal motion. However, it is the multiple scattering and the closed orbit displacement which dominate the emittance growth. For protos and deuteros at the relevant energies, the emittance growth can be estimated roughly as

$$\Delta\epsilon = 2\beta^*\theta_{rms}^2 + 2Dx_\beta\Delta\delta/\beta^* \tag{1}$$

with

$$\theta_{rms} = \frac{6.8\,\mathrm{MeV}}{T}\sqrt{\frac{d}{47.2\,\mathrm{g/cm^2}}} \tag{2}$$

as the rms multiple scattering angle and

$$\Delta\delta = 0.077\,\mathrm{MeVg^{-1}cm^2}\,\frac{\ln(1.3\cdot 10^4\beta^2)}{\beta^2}\frac{d}{T} \tag{3}$$

as the average relative momentum loss. $\beta^* = 1.1$ m is the horizontal β-function at the foil, d is the foil thickness, $D = 1.7$ is the dispersion at the foil, x_β is the betatron oscillation displacement (≈ 3 mm) and βc is the velocity of the ion. The maximum number of foil passages a single proton (deuteron) can make before the emittance becomes too large is given by $\epsilon/\Delta\epsilon$. For a 7 MeV proton passing through a 4 μg/cm^2 carbon foil and with 10π μm as the maximum emittance at 80 MeV, the number of foil traversals is 100.

III. A COMPARISON BETWEEN THE BEAM AT INJECTION AND AT EXTRACTION

The normalized beam emittance from the ion source is 1.5π μm which is equivalent to a 3.6π μm un-normalized emittance at the extraction energy 80 MeV in CIS. On the other hand, the acceptance of the injection system in the Cooler ring is 2π μm. Therefore, even before considering the beam energy spread or the emittance growth at the stripper foil, only a fraction of the available beam can be injected into the Cooler. In addition, the Cooler has a longitudinal acceptance of $\Delta T/T = \pm 5\cdot 10^{-3}$ while the beam from the RFQ has an energy distribution with spread $\Delta T/T_{RFQ} = \pm 10\cdot 10^{-3}$. Therefore, more

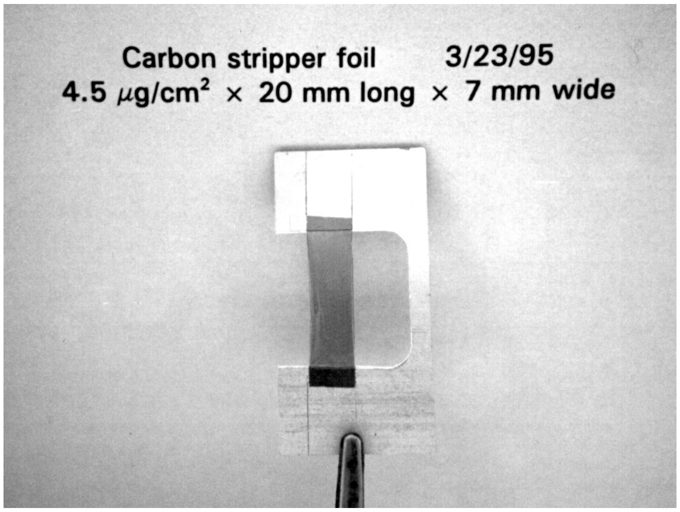

Figure 1. The 4.5 μg/cm^2 carbon stripper foil with two unsupported edges. The width of the foil is 7 mm.

than 70% of the particles from CIS will be outside the acceptance of the Cooler.

The usable fraction of the beam injected into CIS can be greatly improved by opening up the acceptance of the Cooler injection channel to 10π μm and by installing a de-buncher between the RFQ and CIS to reduce the beam energy spread by a factor of about five [3].

IV. CALCULATIONS ON STRIPPING INJECTION

To take into account the longitudinal and transverse phase space of the injected beam, tracking calculations for coasting beams in CIS were made. Since the aperture limits in the horizontal plane are more important than in the transverse plane, only the motion in the horizontal and in the momentum phase space were considered. 1000 test particles are injected at the stripper foil with a uniform transverse phase space distribution and a Gaussian momentum distribution. The intensity gain is obtained as an integral over the phase space and over the number of turns they can make within the usable emittance. Similar calculations have been made for CELSIUS in Uppsala [4], [5] and here the same atomic model of the stripper foil has been used.

Whenever a particle hits the stripper foil, its direction and its momentum is changed randomly to simulate the multiple scattering and the energy loss. The particle tracking is done twice in order to first obtain the average relative momentum loss $-\bar{\delta}$. On the second tracking pass the longitudinal and the transverse acceptance are taken into account. A particle is removed if its three-dimensional emittance

$$\epsilon = \frac{(x - D\delta)^2 + (\alpha(x - D\delta) + \beta^* x')^2}{\beta^*} + \frac{\epsilon_{max}(\delta - \bar{\delta})^2}{\hat{\delta}^2}$$

is larger than the usable emittance which corresponds to the aperture limit at the extraction energy. $\hat{\delta} = \pm 2.5 \cdot 10^{-3}$ is the longitudinal Cooler acceptance. Fig. 2 shows the projection of the usable emittance on the x, x'-plane.

In Table I results from the tracking calculations for 3 MeV and 7 MeV protons for a 4 μg/cm^2 carbon foil are tabulated. The intensity multiplication factor for 7 MeV protons with a 10π μm Cooler acceptance and without de-buncher is 190.

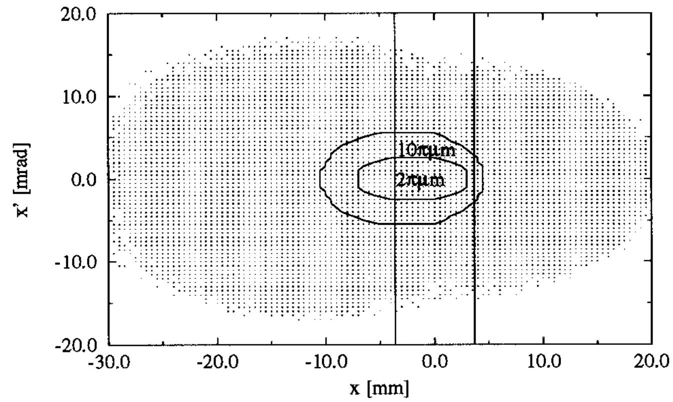

Figure 2. The usable emittance at the injection energy (7 MeV) for the 2π μm and 10π μm cooler acceptance. The emittances appear larger than they are because individual particles have different closed orbits. The vertical lines indicates the location of the stripper foil and the shaded area the CIS acceptance.

Increasing the injection energy from 3 MeV to 7 MeV improves the intensity by a factor of four as a result of smaller emittance growth at the foil. The average number of foil passages $\bar{h}$ that protons make during the injection is approximately four times larger for 7 MeV than for 3 MeV and is consistent with estimated values (eq.(1)).

Opening up the acceptance of the Cooler injection channel from 2π μm to 10π μm also results in a factor of four increase in intensity, mainly because the injected beam fits within the usable emittance. It is also because particles are forced to pass through the foil less frequently in order to stay inside the usable emittance. The larger emittance growth allowed improves the result by a factor less than 1.5 to be compared by a factor of five from eq. (1).

The de-buncher improves the results by 30%, mainly because the energy spread of the injected beam after the de-buncher is smaller than the longitudinal acceptance of the Cooler. The energy loss straggling, which heats the beam in the longitudinal phase space, is unimportant.

The intensity gain is shown versus time on the foil in Fig. 3. A factor of two in foil thickness reduction produces roughly a factor of two in intensity increase, which is expected since both $\theta_{rms}{}^2$ and $\Delta\delta$ are proportional to the foil thickness (eqs. (2) and (3)). However, since the lifetime is longer it would be necessary to inject longer for very thin foils. The maximum pulse lenght from the RFQ is 360 μs and therefore it is unsertain if foils thinner than 1 or 2 μg/cm^2 will improve the intensity further.

A mis-match of the injected beam with the β-function at the foil can improve the intesity up to 10% for the 10π μm aperture. The best result was obtained for a 0.5 m β-function of the injected beam and a corresponding stripper foil width of 5 mm.

V. CONCLUSIONS

Based on these calculations, it was desided to: 1) rise the injection energy from the original 3 MeV to 7 MeV to reduce the emittance growth at the stripper foil. This will be accompliced

Table I
Results from Tracking Calculations on Stripping Injection

Ion	T [MeV]	ϵ [$\pi\mu$m]	$\Delta T/T$	$\bar{h}$	τ [μs]	I/I_0
p	3	2	0.005	25	14	14
p	3	2	0.010	31	26	12
p	3	10	0.005	38	33	62
p	3	10	0.010	40	34	56
p	7	2	0.005	99	49	59
p	7	2	0.010	120	80	46
p	7	10	0.005	130	100	250
p	7	10	0.010	130	120	190
d	5	2	0.005	48	19	15
d	5	2	0.010	43	33	10
d	5	10	0.005	49	39	88
d	5	10	0.010	54	41	61

T is the injection energy, ϵ the Cooler acceptance, $\pm\Delta T/T$ the beam energy spread (90%), $\bar{h}$ the average number of foil passages, τ the $1/e$-lifetime and I/I_0 is the intensity gain.

by an additional linear accelerator (DTL) between the RFQ and CIS. 2) open up the Cooler injection channel as much as possible. 3) Install a debuncher in the CIS injection beam line to reduce the longitudinal energy spread from the two linear accelerators. With this modifications it is possible to gain a factor of 250 in intensity for protons. Assuming 50% transmission through the new injector this would produce $7.5 \cdot 10^9$ particles per pulse to be injected into the Cooler. To reach CIS perfomance goal which is $2.5 \cdot 10^{10}$ particles per pulse, the ion source intensity has to exceed 65 μA and the normalized beam emittance has to be smaller than 1.5π μm. I.e, to reach the CIS performance goal a three times brighter ion source than HIPIOS is needed.

VI. AKNOWLEDGEMENT

We wish to thank Bill Lowzowski for his work on manufacturing the stripper foils.

References

[1] D.L. Friesel, S.Y. Lee, *CIS, a Low Energy Injector for the IUCF Electron Cooled Storage Ring*, in these proceedings.

[2] M. Wedekind et. al., *The IUCF High Intensity Polarized Ion Source Project*, IEEE 93CH3279-7, 3184 (1993)

[3] A. Pei et al., *The Indiana University Cooler Injector Synchrotron RF System*, in these proceedings.

[4] K. Hedblom, A.Johansson, D. Reistad and A. Barany, *Calculations on Multiturn and Stripping Injection in CELSIUS.* in Proc. 3rd European Particle Accelerator Conference, Berlin, Germany, 24-28 March, 1992, ed. H. Henke, H. Homeyer, Ch. Petit-Jean-Genaz, 462

[5] K. Hedblom, *Calculations on Multiturn and Stripping Injection at CELSIUS.* TSL-Note 93-02 January 1993

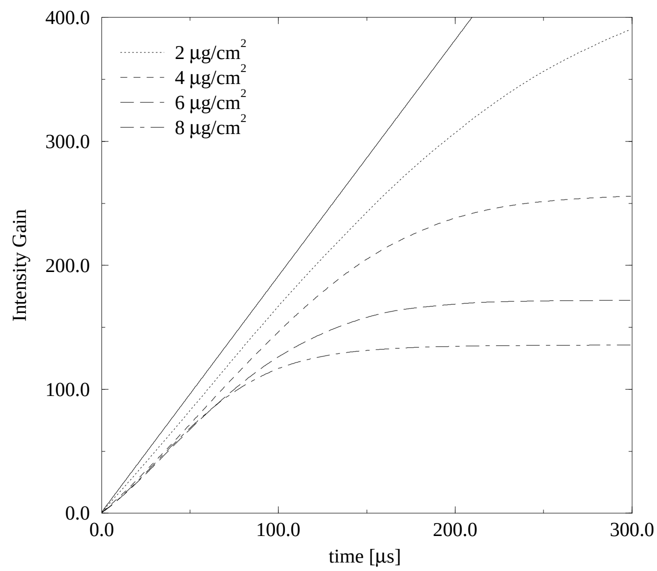

Figure 3. The intensity gain of 7 MeV protons plotted vs. the pulse lenght from the RFQ and for different foil thicknesses. The acceptance of the Cooler injetion channel was 10π μm. The solid line shows the gain calculated without energy loss or scattering at the foil.