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INJECTION, COOLING AND ACCUMULATION OF IONS FROM THE GUSTAF WERNER CYCLOTRON INTO THE CELSIUS COOLER-STORAGE RING

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Ions ranging from protons to neon have been injected into the CELSIUS cooler-storage ring from the Gustaf Werner cyclotron. Stripping injection is the most effective injection method, and is used whenever possible, but multiturn injection (without stripping) has to be used for polarized protons and deuterons. Multiturn injection will also be used when cyclotron beams of protons must be shared between CELSIUS and another user. With stripping injection, the useful cyclotron pulse train is up to 8 ms, whereas with multiturn injection, the useful pulse train is only about 10 µs. With stripping injection, good beam intensities ($10^{10}-10^{11}$ stored particles) of protons, deuterons, and alpha particles are reached with a single pulse train from the cyclotron. The intensity of beams of heavier ions and of beams which have been injected with multiturn injection is built up by accumulation with electron cooling. Thus, the intensity of $^{14}N^{7+}$, $^{16}O^{8+}$ and $^{20}Ne^{10+}$ was brought from 3×10^8, 9×10^7 and 4×10^7 which was achieved with a single injected pulse train, to 8×10^9, 5×10^9 and 2×10^9 during 30 s of accumulation, accepting four 8 ms pulse trains per s from the cyclotron.

1 Introduction

To inject a cyclotron beam into a storage ring is a different matter than to inject from another ring or other pulsed injector. The cyclotron beam has a modest intensity, but is available during an arbitrary period of time. Thus, in order to reach a high intensity of the circulating beam, injection has to take place during the time corresponding to many revolutions in the ring. High efficiency in the injection procedure is not necessarily the most important concern. To reach a high intensity by injecting over a long period of time, even with a modest efficiency, can be a practical alternative for a slow-cycling ring such as CELSIUS [1–3], which is injected from the Gustaf Werner cyclotron [3, 4].

Present and planned use of the CELSIUS ring is for nuclear and particle physics research with beams of unpolarized protons [5] and of other ions up to argon, and with beams of polarized protons and deuterons.

Unpolarized protons and deuterons, and alpha particles come from an internal PIG ion source in the cyclotron. All other ions come from one of two external ion sources; an ECR source for heavy ions and an atomic-beam source for polarized protons and deuterons [6].

When the cyclotron is used as injector for CELSIUS, it usually accelerates the ions to their maximum energy, determined by the bending limit, $192\times Q^2/A$.

CELSIUS has been built both for stripping injection and for multiturn injection (without stripping) [7]. For light ions the by far most effective injection method has turned out to be stripping injection. Therefore, this method is used for all unpolarized light ions (up to neon).

Multiturn injection has, at least for the present, to be used for polarized protons and deuterons. Multiturn injection will also be used for heavy ions (from argon and up).

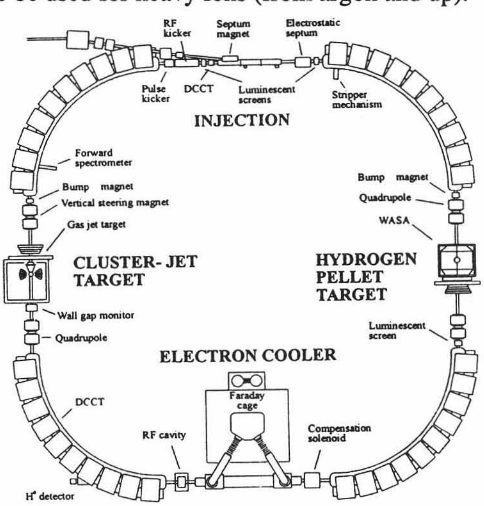

Figure 1: Layout of CELSIUS.

2 Injection hardware

Injection into the CELSIUS ring is in the horizontal plane and from the outside. The injection elements are a septum magnet, an electrostatic septum, and a mechanism, mounted in the first bending magnet of the ring, which holds two thin stripper foils of carbon. During stripping injection, one of the two foils is put in the way of the incoming beam. The foils have one open edge. The reason for having two foils is to make it possible to compare the performance of foils of different thicknesses.

Two bump magnets are used to displace the closed orbit during injection towards the outside, i.e. towards the electrostatic septum foil and the stripper foil. Both during multiturn injection and during stripping injection the injection

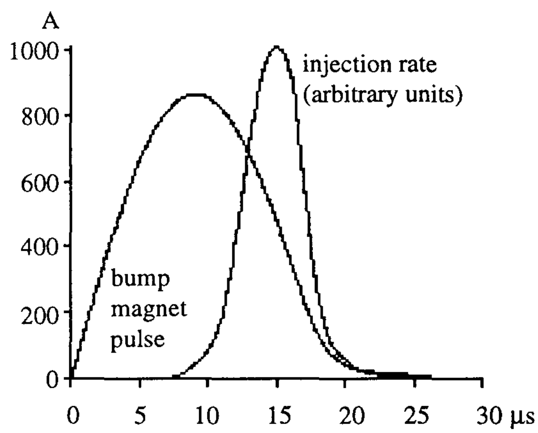

Figure 2: Typical bump magnet pulse used for multiturn injection of 180 MeV protons. 400 A corresponds to a bump magnet deflection angle of 1.4 mrad, giving a closed orbit bump of 17 mm at the electrostatic septum, which is positioned 36 mm from the closed orbit. The calculated rate of injection of protons, which will end up inside the acceptance, is also shown.

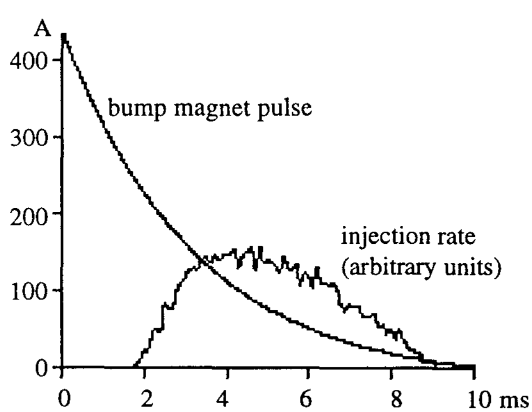

Figure 3: Typical bump magnet pulse used for stripping injection of 48 MeV protons. 100 A corresponds to 0.7 mradians bump magnet deflection angle which gives a closed orbit bump of 9 mm at the location of the stripper foil. The foil edge is at 20 mm from the closed orbit. The calculated rate of injection of protons, which will end up inside the acceptance is also shown.

process takes place during the time when the magnetic field in the bump magnets decreases with time.

During multiturn injection, the electrostatic septum is used to separate the paths of the injected beam and the circulating beam. The rate of displacement of the closed orbit due to the decay of the magnetic field in the bump magnets has to be rapid enough that (a sufficient fraction of) the circulating beam never appears on the wrong side of the elecrostatic septum foil during subsequent turns.

During stripping injection, the separation of paths of the incoming beam and the circulating beam is done by changing the charge state of the incoming beam in the stripper foil. The particles in the circulating beam can go through the stripper foil a number of times (determined by energy loss, multiple scattering, and electron capture in the foil) without being lost. Therefore, the bump magnets can change their magnetic field much more slowly during stripping injection than during multiturn injection, and the injected beam can be accepted during a longer period of time. This is why stripping injection gives much higher intensity than multiturn injection for light ions, which can go through the foil many times. Figures 2 and 3 show typical shapes of the bump magnet pulses used in practice at CELSIUS.

3 Stripping injection

CELSIUS is filled with 48 MeV unpolarized protons and 24 MeV unpolarized deuterons by stripping injection of H_2^+ and D_2^+ (molecular) beams from the cyclotron. 48 MeV alpha particles are injected by stripping injection of a $^4He^+$ beam from the cyclotron. Typical cyclotron beam currents of these ions, when pulsing the internal PIG ion source with pulse lengths of 8 ms, are between 50 and 100 particle µA, and typical stored beam intensities are 25-50 mA of protons, 5-10 mA of deuterons, and 2-5 mA of alpha particles

In order to do stripping injection of nitrogen, oxygen, and neon ions, beams of $^{14}N^{5+}$, $^{16}O^{5+}$, and $^{20}Ne^{6+}$ are created in the ECR source, and accelerated to 24.5, 18.7, and 17.3 MeV/u respectively in the cyclotron.

The advantage of stripping injection over multiturn injection gets lost for heavy ions ($Z \geq 18$). The energy loss in the foil becomes too big. Multiturn injection of argon ions (after stripping in a stripper foil in the beam line between cyclotron and CELSIUS) will be developed in the beginning of next year (1996).

4 Multiturn injection

Multiturn injection is done with polarized protons and deuterons. These can at present only be created as naked ions in our laboratory.

Another use of multiturn injection will be to make use of the 180 MeV proton beam, which is available while the cyclotron is idle between proton therapy treatments of patients (this will be tried out later this fall

1995), and as already mentioned, multiturn injection is the preferred method for heavy ions.

5 Tracking computations

We have done tracking computations in order to find the intensities to be expected with stripping injection and multiturn injection [7].

In the past, we calculated the stripping efficiency by using a simple cross section formula. Now, however, we have improved our model by calculating the stripping efficiency with the ETACHA code [9, 10].

A plot of the stripping efficiency against foil thickness shows an S-shaped curve, see fig. 4. The efficiency of the injection is proportional to the stripping efficiency and approximately proportional to the number of traversals through the foil that an ion can do without being lost, which is inversely proportional to the foil thickness. Therefore, the broad optimum for the stripper foil thickness (when optimizing for intensity and not for efficiency) is the thickness which corresponds to the highest ratio between stripping efficiency and foil thickness. For the energies in question here, these thicknesses are about 10 $\mu g/cm^2$ for protons, deuterons, and alpha particles, and about 50 $\mu g/cm^2$ for nitrogen, oxygen, and neon ions.

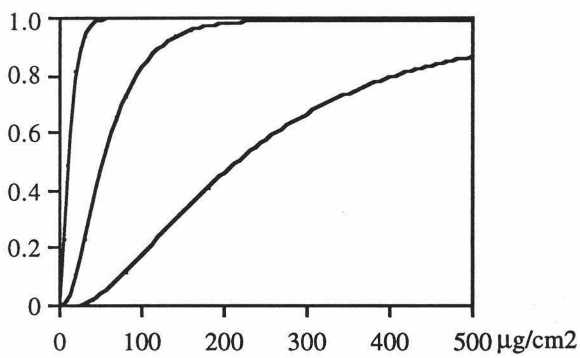

Figure 4: Stripping efficiency of 48 MeV H^-, 17.3 MeV/*u* Ne^{6+} and 17.3 MeV/*u* Ar^{12+} as a function of carbon foil thickness.

6 Electron cooling

The CELSIUS ring is equipped with an electron cooling system [11]. This is used for accumulation of weak beams, and often also to improve the quality of accelerated beams.

A magnesium-jet beam-profile monitor [12] has been built for CELSIUS by the Budker Institute of Nuclear Physics, Novosibirsk, Russia. A jet of magnesium vapour can be made to scan across the stored beam in the ring. To measure the horizontal beam profile, electrons are collected and detected while the jet is moved across the stored beam. Typical horizontal cooled beam emittances (1σ) are between 0.1π and 0.2π µm. As an example the profile of a cooled oxygen beam (470 MeV/*u*) is shown in fig. 5.

The magnesium-jet beam-profile monitor has also been used to measure transverse cooling times. To do this, the magnesium jet was put stationary on top of the maximum of the horizontal beam profile. The measurement was made by kicking the stored beam with a pulse kicker, which is normally used for ping-tune measurements, and observing the time required for the magnesium ion count rate to return to its original value.

The kicker is mounted at 45°, so that it excites the beam in both transverse planes at the same time. Figure 6 shows how the measured cooling time for 24.5 MeV/*u* $^{14}N^{7+}$ varies with kicker strength, expressed as $(\beta_x + \beta_y)\theta^2/2$. The measurement was made with an electron beam current of 112 mA. In the figure, we compare the measured cooling time with that calculated with a standard formula (valid for electron cooling with electrons that have a "flattened" velocity distribution) [13]. Cooling of betatron oscillations of small amplitude is "superfast," as has been observed elsewhere before [13, 14].

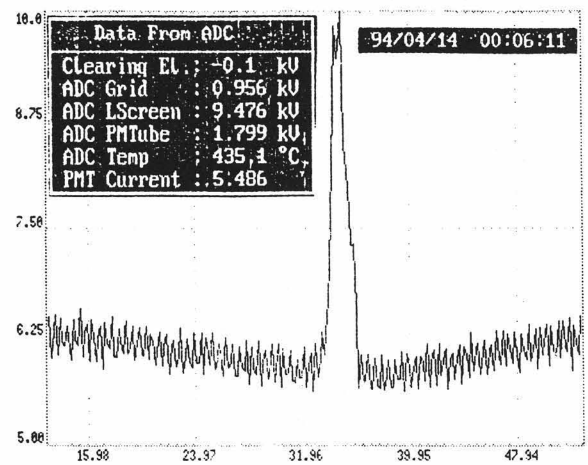

Figure 5: Horizontal profile of cooled beam of 470 MeV/*u* O^{8+}. The horizontal scale is in mm. The FWHM beam size is 1.5 mm, which with β = 2.8 m gives a 1 σ emittance of 0.15 µm.

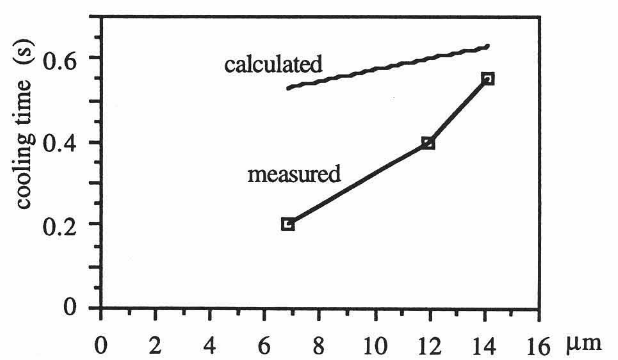

Figure 6: Measured and calculated cooling times for 24.5 MeV/*u* N^{7+}.

7. Accumulation with electron cooling

Accumulation with electron cooling in CELSIUS is done in the horizontal phase plane. The injected beam is cooled so that it only occupies a fraction of the acceptance, and a new injection is made, which injects particles that get larger betatron amplitude than the already stored and cooled beam particles have. This process is repeated for a pre-determined period in each machine cycle. This has usually been chosen as a compromise between duty factor to the experiment and requirement for intensity to 30 or 60 s.

Experience has shown, that accumulation with electron cooling works much better when the beam is unbunched than when it is bunched, and is therefore made without rf. We believe that when rf. is on the accumulation is disturbed by synchrobetatron resonances, driven by the non-linear electric field, which is present outside of the electron beam [15].

When accumulating with electron cooling, the bump amplitude must be chosen small enough that the particles which are already injected do not again hit the stripper foil. Figure 7 shows how the calculated multiplication factor during stripping injection of O^{8+} from O^{5+}, defined as the ratio between stored beam intensity and incoming beam intensity, varies with bump amplitude.

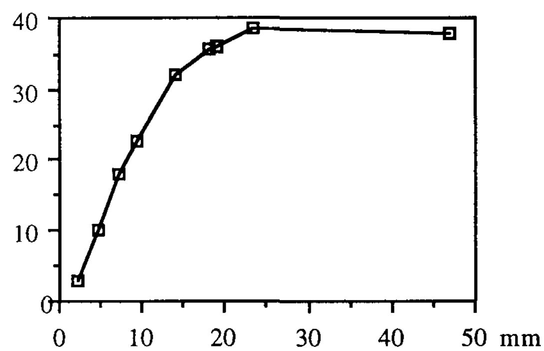

Figure 7: Calculated accumulation factor during stripping injection of oxygen plotted against bump amplitude, measured at the stripper foil, which is 20 mm from the undisturbed closed orbit.

It can be seen that the injected intensity ΔI is quite linear with the bump amplitude, $\Delta I = kA_{\text{bumper}}$ until the bump becomes as large as the separation between the undisturbed closed orbit and the edge of the stripper foil.

Following the injection the beam can be assumed to have a horizontal half-width of $x_{\text{foil}} e^{-\frac{t}{\tau}}$, where x_{foil} is the distance between the undisturbed closed orbit and the foil edge, and τ is the cooling time. Thus, the allowed bump amplitude, if the interval between injections is Δt, is $A_{\text{bumper}} = x_{\text{foil}} \left(1 - e^{-\frac{\Delta t}{\tau}} \right)$, and the rate of increase of the intensity per unit of time is $\Delta I / \Delta t = k x_{\text{foil}} \left(1 - e^{-\frac{\Delta t}{\tau}} \right) \Big/ \Delta t$. Thus, it pays (if again high intensity and not high efficiency is the issue), to choose $\Delta t \le \tau/2$ to reach about 80 % of the highest possible injection rate. So far, we have been limited by our bump magnet power supply to $\Delta t = 0.25$ s.

The intensity of $^{14}N^{7+}$, $^{16}O^{8+}$, and $^{20}Ne^{10+}$ was brought from 3×10^8, 9×10^7, and 4×10^7, which was achieved with a single injected pulse train, to 8×10^9, 5×10^9, and 2×10^9 during 30 s of accumulation, accepting four 8 ms pulse trains per second from the cyclotron.

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