RECENT COMMISSIONING RESULTS AT CELSIUS

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ABSTRACT

The CELSIUS storage ring, which is fed from the Gustaf Werner Cyclotron in Uppsala, has been brought into operation for physics. Protons, deuterons, α-particles, and oxygen ions have been stored, accelerated, and exposed to internal targets. These are a cluster-jet target with hydrogen, deuterium, argon, or nitrogen, and a carbon fibre target. The carbon fibre has been used to estimate beam profiles. The electron cooling system, which is on the ring, still gives an unexplained effect, sometimes heating rather than cooling the stored ion beam. A system of radiation detectors has been mounted around the ring to help to adjust the machine parameters for minimum background. A transverse feed-back system has been tested.

Some parameters of the CELSIUS ring	
Circumference	82 m
Max. magnetic field	1.0 T (1.2 T planned)
Max. momentum	2.1×Z GeV/c (at present)
Max. energy ($Z/A = 1/2$)	470×A MeV (at present)
Q_x, Q_y	1.63, 1.83
β_x, β_y at internal targets	1.4 m, 1.5 m
Electron beam voltage	5-300 kV
Electron beam current	0-3 A
Electron beam diameter	2 cm
Achieved intensities	
Proton intensity	2×10^{11}
Deuteron intensity	4×10^{10}
α-particle intensity	1×10^{10}
^{16}O intensity	3×10^{8}
Internal targets	
Cluster jet target	hydrogen 3×10^{14} atoms/cm^2
	nitrogen 4×10^{13} atoms/cm^2
	argon 2×10^{13} atoms/cm^2
Fibre target	7 µm carbon filaments
Pellet target[1]	20 µm hydrogen pellets

[1]Under development

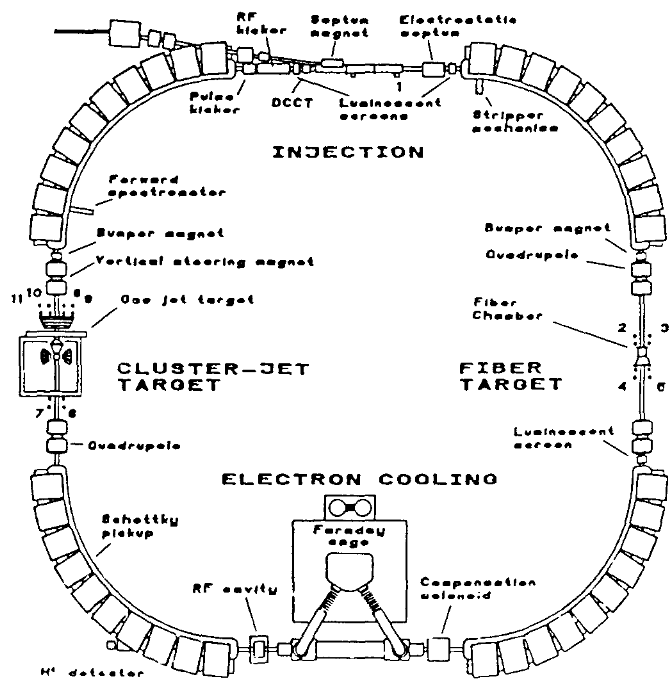

Fig. 1. Present layout of CELSIUS. The numbered dots represent radiation detector pairs, which are discussed in section 6 below.

1. INTRODUCTION

The CELSIUS ring has been described at the previous Cyclotron Conference [1], and other conferences [2-3]. A more complete description is available in the recent Progress Report from The Svedberg Laboratory [4]. The ring consists of four 90° arcs and four straight sections, see fig. 1, which shows the present layout.

One straight section is used for injection [5].

The hydrogen pellet target [6] and the WASA detector [7] are planned to be installed on the second straight section. They will then replace the fibre target scattering chamber, which is presently mounted there.

The third straight section holds the electron cooler [8] and a radio frequency cavity [9].

The fourth straight section holds the cluster-jet target [10], which is being used in the present physics experiments.

2. INJECTION

The ions that are injected into CELSIUS come from the Gustaf Werner Cyclotron [11-12], in which they usually have been brought to the maximum energy, $192 \times Q^2/A$ MeV.

The injection system of the ring must be versatile enough to cope with a variety of conditions. Therefore, both "multiturn injection" (without charge exchange) and "stripping injection" schemes are implemented [5].

The injection elements of the CELSIUS ring consist of electromagnetic and electrostatic septa, and a thin stripper foil, mounted on a mechanism in the first bending magnet of the ring. The present foil is of carbon with thickness 30 μg/cm^2.

Two bumper magnets displace the closed orbit during injection towards the septum foil and stripper foil, i.e., towards the outside of the ring. Both during "multiturn injection" and "stripping injection" the injection process takes place during an exponential decrease of the magnetic field in the bumper magnets.

During "multiturn injection," the electrostatic septum is used to separate the paths of the injected beam and the circulating beam. It was the first injection method to be tried in CELSIUS, in 1988. The cyclotron beam current was 30 μA. About 2×10^8 protons were stored. This is almost one order of magnitude less than what ought to be possible according to calculations [5]. The reason for the discrepancy could be inadequate matching between the transverse phase space occupied by the incoming beam and the transverse acceptance of the ring.

Stripping injection allows by far the best ratio between the stored beam current and the incoming beam current for light and moderately heavy ions, and is the preferred method to inject protons (using 96 MeV H_2^+ ions), deuterons (using 48 MeV D_2^+ ions), α-particles (using 48 MeV He^+ ions), and other ions up to Ar. This is even though the energy of the injected protons, deuterons, and α-particles is only 1/4 of the energy that could be available from the cyclotron, if the ions were accelerated in their naked states, and the energies of heavier ions is also always lower than for naked ions.

Achieved intensities are, for 48 MeV protons, 2×10^{11}, for 24 MeV deuterons, 4×10^{10}, and for 48 MeV α-particles, 1×10^{10}.

Electron cooling can be used in order to build up the intensity in cases when what is achieved with a single ordinary injection is much less than what corresponds to the stability limit of the ring [13-15]. Both multiturn injection and stripping injection can be combined with such accumulation with electron cooling. Once the cooling has shrunk the transverse beam dimensions, the bumper magnets can be activated again in order to displace the closed orbit, and another pulse train from the cyclotron can be injected, without that the stored beam is lost, provided that the stored beam is not displaced into the septum foil or stripper foil. Using this method in combination with stripping injection we have stored 2×10^7 of O^{8+}, starting with a cyclotron current of 6×10^{10} s^{-1}. The ion source in the cyclotron was pulsed with 1 ms pulse length and repetition rate of 4 Hz.

Another way to do stripping injection has been found. This is without using any time-varying elements in the ring at all, but by making use of the electron cooling system. A small fraction of the beam is hitting the stripper foil at a position in transverse phase space, which is so close to the acceptance, that the electron cooling system brings the ions into the acceptance fast enough that they never cross the foil again. Thus, this is an injection method with a very low efficiency, but with which large stored beam currents can be achieved by injecting for long enough. 3×10^8 oxygen ions were injected with this method by injecting 6×10^{10} s^{-1} during 20 s.

3. MODES OF OPERATION

CELSIUS can be operated in static mode or in cycles. In the static mode the machine parameters have constant values, and the energy of the stored beam remains at the value at injection. The static mode of operation is used only for machine development or accelerator physics purposes. During operation in the cyclic mode, the beam is accelerated to the energy, which is required for the experiment. Usually, the beam is brought into collision with the target only after that it has reached its final energy, but sometimes the physicists have found it useful to make use of the acceleration part of the cycle, to calibrate their detectors.

3.1. Acceleration

The variation of the magnetic field during a typical cycle is illustrated in fig. 2.

Since the dipole magnets of CELSIUS are not laminated [16], the acceleration is performed slowly; the standard period used for acceleration is 22 s so far. This is consistent with the use of the ring for experiments with ultra-thin internal targets; even though the overhead time per machine cycle typically totals 60 s the duty factor is acceptable, 50 % in two-minute cycles and 80 % in five-minute cycles.

So far cycles have been developed for acceleration of protons to several final energies between 200 MeV and 1300 MeV, and for experimental situations where a slow ramping of the proton energy is performed during the "flat" top. Examples of such slow ramps are from 270 to 310 MeV (π^0 threshold in p+p reactions) and from 1230 to 1300 MeV (η threshold in p+p reactions). The maximum intensity after acceleration obtained so far is 5×10^{10} protons at 1150 MeV and 1×10^{10} protons at 1300 MeV. α-particles have been accelerated to 600 MeV, and deuterons to several final energies up to 783 MeV where they (1×10^{10}) have also been cooled (measured $\Delta p/p = 3\times10^{-5}$). Oxygen ions, which were injected without using the bumper magnets as described above, have been accelerated to 1600 MeV.

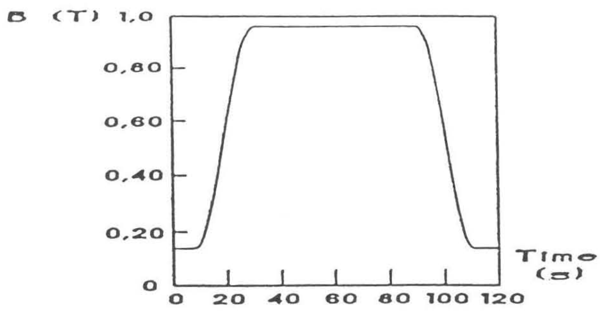

Fig. 2. Variation of the main magnetic field in CELSIUS during a cycle with acceleration of protons to 1.3 GeV.

Recent software developments allow us to prolong a cycle, which has been developed, by extending the flat top. We can also stop the function generators at any time in the cycle. This has been used to create machine cycles which are as long as 10 minutes.

3.2 Other manipulations

Several groups are going to make use of a part or all of the magnets in the quadrant of the ring which follows the target as a magnetic spectrometer [17].

Moving detectors, placed either inside of the quadrant as shown in fig. 3 or on the injection straight section, will detect reaction products. In order to protect the detectors from un-necessary irradiation, they are moved away from the beam during injection and acceleration, and moved into position at the beginning of the flat top.

One example of an experiment that makes use of the quadrant of the ring which follows the target is the study of giant resonances in heavy nuclei through inelastic scattering of heavy ions at several hundred MeV/nucleon. In this case the whole quadrant is required to distinguish the inelastically scattered heavy ions from the elastically scattered ones and from the beam. For this experiment a system of moveable detectors will be mounted on the injection straight section.

Then it is optimal to have 180° betatron phase shift between the target and the detectors, preferably in both planes. With the position of the detectors which was chosen, this implies the working point $Q_x = 1.80$, $Q_y = 1.85$. We have found that it is quite inefficient to inject with this working point. On the other hand, we have found that it is possible to let the working point jump after acceleration from the usual to this point with beam losses that do not exceed 20-30 %.

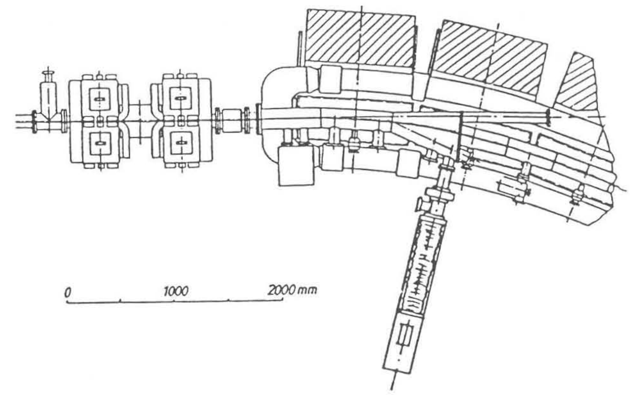

Fig. 3. Moveable detector arrangement to make use of the first magnets in quadrant 4 of CELSIUS as a spectrometer.

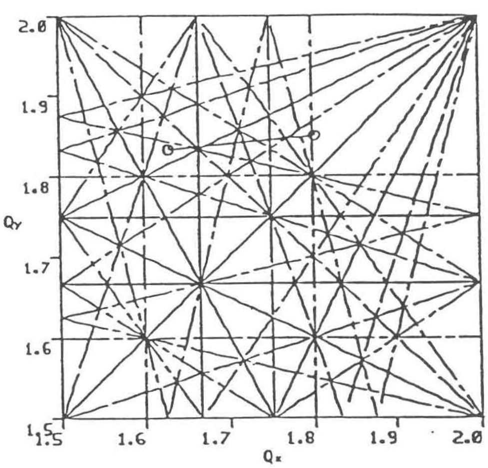

Fig. 4. Jump of working point to obtain required focusing for experiment, which uses quadrant 4 as a spectrometer.

4. Electron Cooling

Fig. 5 shows a cross section of the electron cooling system. The electron gun launches a 20 mm diameter electron beam from a dispenser cathode. The cathode and the whole beam path are fully immersed in a homogeneous longitudinal magnetic field of 0.1 - 0.15 T.

The electrons are accelerated in an electrostatic column to a maximum energy of 300 keV. For energies above 70 keV the beam current can amount to 3 A. At the collector side the electron beam is decelerated in another electrostatic column. After passing through a hole in the collector anode, which is at a potential of 0.1 - 0.4 kV above the cathode potential, the beam is again accelerated, and reaches the collector with a kinetic energy of 5 keV.

Electron cooling has been studied at the injection energies (using stripping injection) of protons (48 MeV), deuterons (24 MeV), oxygen ions (292 MeV), as well as after acceleration with 275 MeV protons and with 390 MeV, 600 MeV, and 783 MeV deuterons.

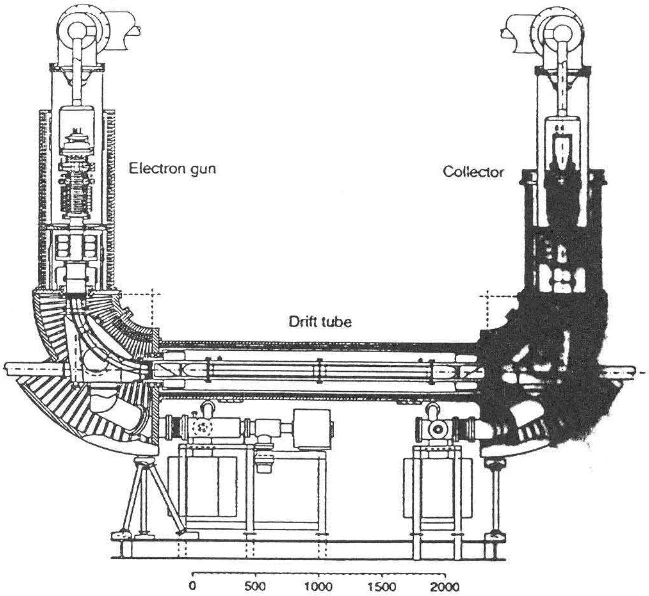

Fig. 5. Cross section of CELSIUS electron cooler.

Measurements of the longitudinal cooling time have been performed with bunched beams, where the momentum spread is proportional to the time spread in the bunch (unless space charge effects are important). The result of one such measurement is illustrated in fig. 6

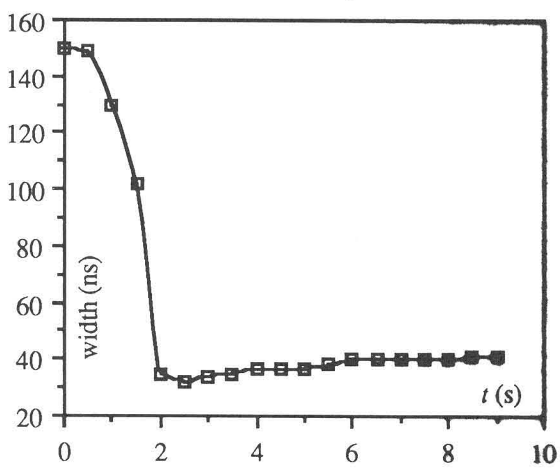

Fig. 6. Measured FWHM time spread of a bunch of 275 MeV protons during cooling with 410 mA of electrons.

The longitudinal drag rate has been measured with coasting beams of protons, deuterons, and oxygen ions with several energies. The measurement technique has been to step the output voltage from the electron cooler high voltage power supply, and to measure how the revolution frequency of the ions changes as a function of time after the step. Fig. 7 shows several measured scaled drag rates for 783 MeV deuterons and a single measured point for 296 MeV oxygen ions together with measured scaled drag rates from several other laboratories [15,18].

The drag rates measured at CELSIUS do not yet seem to be quite competitive with the best drag rates measured elsewhere. This may have to do with a disturbing phenomenon, which is not yet understood. There is an apparent "heating" of the stored ion beam by the electron beam as soon as the electron beam is put together with the ion beam. This heating causes a dramatic drop in lifetime of the stored ion beam, particularly when the ion beam has a low energy.

With no electrons present, the 48 MeV (injection energy) proton beam lifetime is typically 50 s.

An example of a measurement of the lifetime of a 48 MeV proton beam as a function of the electron current is shown in fig. 8.

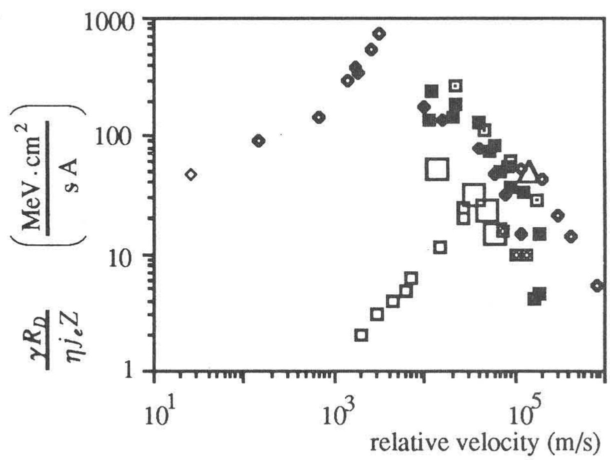

Fig. 7. Comparison between measured drag rates at NAP-M (65 MEV p)●, ICE (47 MeV p) ◻, FNAL (203 MEV p) ◼, LEAR (49 MeV p)◻, IUCF (45 MeV p)◆, INS (20 MeV p) ■, and CELSIUS with 783 MeV deuterons ◻, and 296 MeV oxygen ions △.

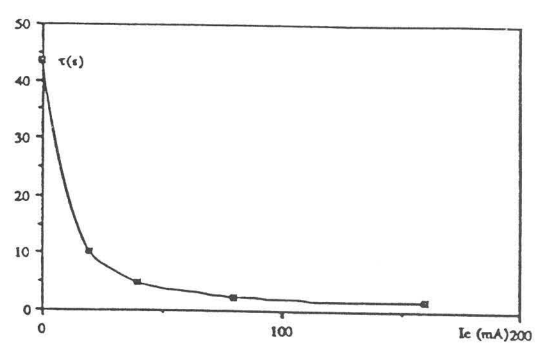

Fig. 8. Measurement of lifetime of a 48 MeV proton beam as a function of electron current.

As seen in fig. 8, the proton beam lifetime is approximately inversely proportional to the electron intensity. On the other hand, the proton beam lifetime does not depend on the proton intensity.

Similar effects were observed already with the electron cooler at the NAP-M ring at Novosibirsk, Russia [19]. There, the effect was attributed to slow electrons, which accumulated inside the electron beam. Neutrals were created in integrated sputter-ion pumps, which were operating in the longitudinal magnetic field of the electron cooler. These neutrals were ionized in the electron beam. The ions left the beam, but the slow electrons were left behind, trapped by the longitudinal magnetic field and the decelerating electric fields of the gun and the collector. In their paper [19] the Russians conclude, that a transverse electric field may be formed. The field is determined by the equilibrium between ionization and electrons leaving across the field lines or by recombination with ions. This field can be of the order of $W_i/e\rho_0$, where W_i is the ion energy (given by the sputter-ion pump voltage) and ρ_0 is the electron beam radius.

We have however measured the tune shifts, which are induced on the ion beam by the electron beam, and found that they are rather close to the predicted values, see fig. 9. We can therefore conclude that no large un-expected and un-compensated charge is stored inside the electron beam.

Similar effects have also been observed at the TARN II ring in Tokyo, Japan [15], and (to a less disturbing degree) at the Indiana Cooler in Bloomington, Indiana [20]. In Tokyo, a drastic change of the working point improved the stored beam lifetime. On the other hand, such effects have not been observed at the LEAR ring at CERN [21], nor at the TSR ring at Heidelberg [22], the ESR ring at Darmstadt [22], or the CRYRING in Stockholm [23].

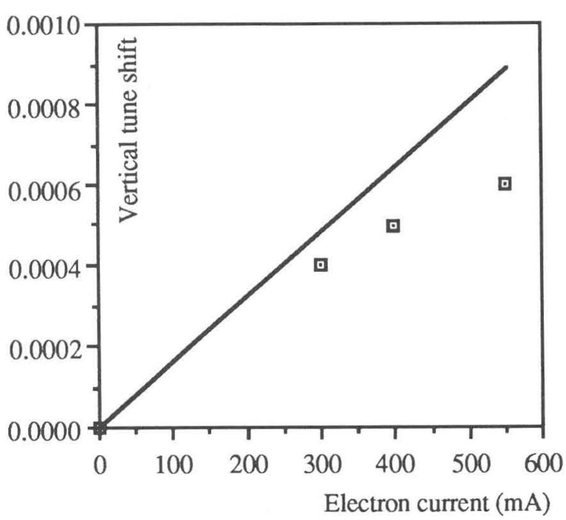

Fig. 9. Measured tune shift as a function of electron current. The measurement was done with 275 MeV protons. The calculated slope of the tune shift is also shown as a straight line.

It seems to be the electron coolers that have the best degree of vacuum, which are spared the effects of "electron heating."

The "heating" is present also when the beams have large relative velocity. From this we conclude that the problem is not simply due to drag force; i.e. that the electron beam is forcing the momentum of the stored ion beam outside the acceptance.

This "electron heating" effect is quite disturbing, because it makes it more complicated to operate the electron cooling system. When we want to cool the beam before and after acceleration, for example, then we have turn the electron current to zero during the acceleration in order not to get beam loss due to the electron heating effect.

Even more important, although the "electron heating" is compensated by the electron cooling when the electron and ion velocities are well enough matched, it seems that the heating is disturbing the electron cooling, so that the results obtained are not as good as they should be.

We have observed rf. signals at the Δ-outputs from the horizontal and vertical beam position monitors in the electron cooler. A typical spectrum as measured by a spectrum analyzer is shown in fig. 10.

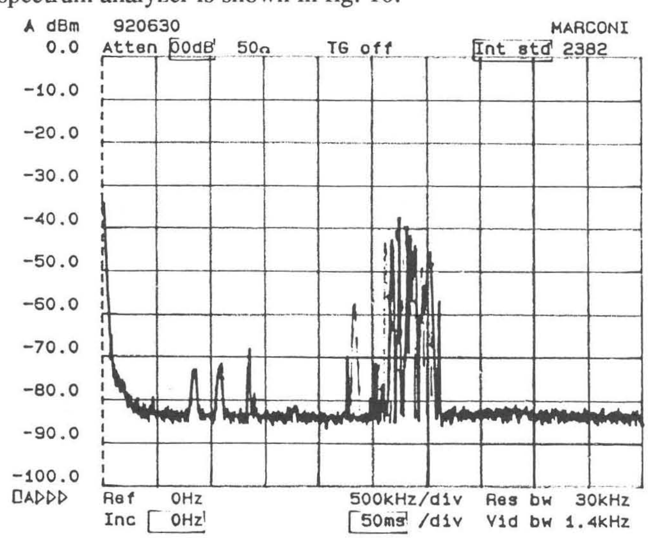

Fig. 10. Spectrum analyzer measurement of signal at Δ output from beam position monitor in electron cooler. The signals are essentially the same in both the horizontal and vertical planes, and the same at the monitor which is near the gun as at the one which is near the collector. The electron current was 300 mA and the voltage was 26 kV. The magnetic field was 0.1 T and the pressure in the cooler was 6×10^{-8} Pa.

There are no signals at the same frequency at the corresponding Σ-output from the beam position monitors.

These signals indicate the presence of transverse motions of the electron beam, of about the same amplitude in both transverse planes.

For a longitudinal magnetic field of 1.0 T the central frequency is about 2.5 MHz. It varies as $1/B$ and has a very small positive derivative with respect to electron beam voltage, and small positive derivatives with respect to electron beam current and rest gas pressure.

If these signals indicate the presence of coherent transverse motions of the electron beam, then the amplitude of these motions varies randomly between about 3 and 15 µm.

The frequency band observed includes the eigenfrequencies $4-Q_y \approx 2.4$ MHz and $4-Q_x \approx 2.7$ MHz.

It is therefore our present hypothesis, that the electron beam for some reason is oscillating in both transverse planes, and that the resulting electrical field is exciting the stored beam at one or several of its betatron eigenfrequencies (rf. knockout).

5. The cluster-jet target system.

The cluster-jet target system [10] has been in operation for experiments since 1989 using target beams of hydrogen, deuterium, nitrogen, and argon. The target thicknesses are 3×10^{14} atoms/cm^2 for hydrogen and deuterium, 4×10^{13} atoms/cm^2 for nitrogen, and 2×10^{13} atoms/cm^2 for argon. When the system is running with these target thicknesses the pressure in the scattering chamber becomes 2×10^{-5} Pa.

In order to increase the solid angle that is available for the nuclear reaction products, a new central scattering chamber for the cluster-jet target has been constructed [10]. A schematic view of the new scattering chamber is shown in fig. 11.

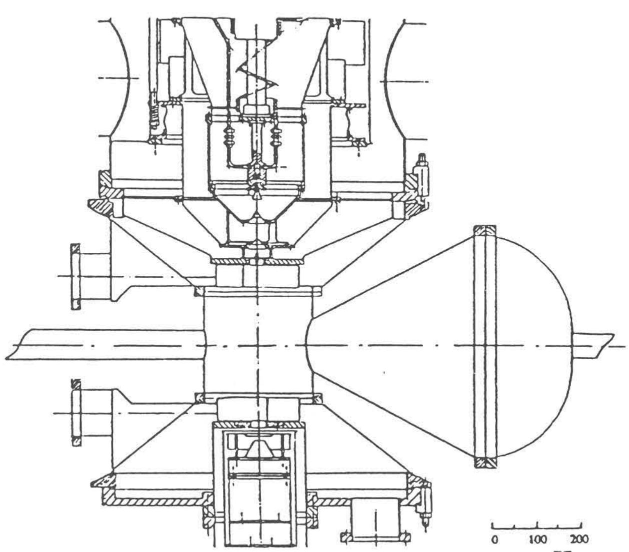

Fig. 11. Schematic view of the new scattering chamber connected to the cluster-jet target.

The new chamber consists of three parts, two permanent chambers including the valves towards the target beam source and the beam dump, and an exchangeable central chamber.

The new central chamber allows a large fraction of the horizontal plane and ±35° vertically to be covered by external detectors outside the thin-walled central cylinder, and between 3° and 25° for external forward detection by using a thin-walled forward window [24].

6. Stray radiation detectors

Many experiments to be carried out at the CELSIUS ring are devoted to studies of reactions with small cross sections. Such measurements require careful tuning of the accelerator in order to minimize the background count rate (as the background we consider particles emerging from interactions between the beam particles and the vacuum chamber and all other objects in the ring except the target).

In order to guide the operator while tuning the ring, we have built a system to monitor the beam losses. This consists of 11 pairs of plastic scintillator counters placed around the ring. The detectors are rectangular with dimensions $5\times50\times40$ mm^3. The detectors pairs are put in the median plane of the ring, at distances ranging between 60 mm and 250 mm from the beam. The positions of the detector pairs are indicated with dots in fig. 1. The numbering of the detectors is also shown in fig. 1.

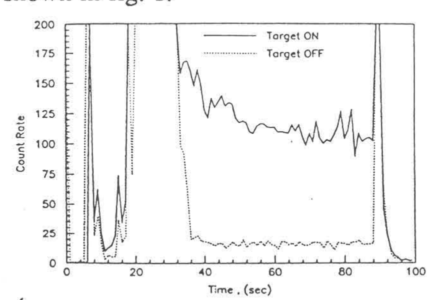

Fig. 11'. Count rates, measured with detector pair #9, in cycle with acceleration of protons to 1150 MeV, with and without hydrogen target.

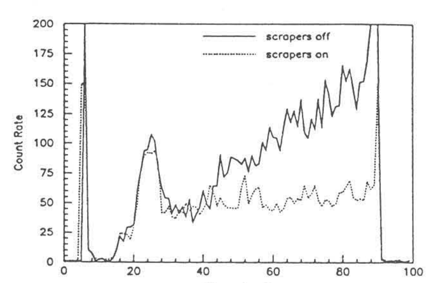

Fig. 12. Count rates, measured with detector pair #8, in cycle with acceleration of protons to 500 MeV, with and without using the scrapers.

As examples of measurements made with this system, we show in fig. 11 measured count rates during a cycle with acceleration to 1150 MeV at detector pair #9 with and without the hydrogen target, and in fig. 12 measured count rates during a cycle with acceleration to 500 MeV with and without using the horizontal scrapers, which are located on the second straight section. We see that the background is high during the acceleration, which is finished at $t = 30$ s. Then the synchronism between magnetic field and rf. frequency is less good than during the flat top, which lasts from 30 s to 90 s. At 90 s the beam is dumped, resulting in a peak in the background.

We observe that the background gets reduced when using the scrapers. On the other hand we have not yet observed any general decrease in background when using the electron cooling system. This may have to do with the unexplained effects of "electron heating" discussed in section 4 above.

7. Beam profile measurements

The radiation monitor pair #4 has also been used to estimate the horizontal beam profile. The 7 μm carbon fibre was moved through the beam with a velocity of 50 mm/s. It moved twice through the beam, in opposite directions, at cycle times $t \approx 40$ s and $t \approx 70$ s. In fig. 13 is shown how the count rate at the detector pair #4 varied as a function of time when the fibre moved through the beam. The beam size appears much larger when the detector is moved "inwards," than when it is moved "outwards". During this measurement the rf. system of the ring was turned off. The protons are decelerated during the traversal through the fibre. Since the dispersion at the target is positive, the fibre will repeatedly "see" protons which it has previously decelerated when it moves inwards. On the other hand, when it moves outwards, it will only see each proton once, and a true beam profile measurement is obtained.

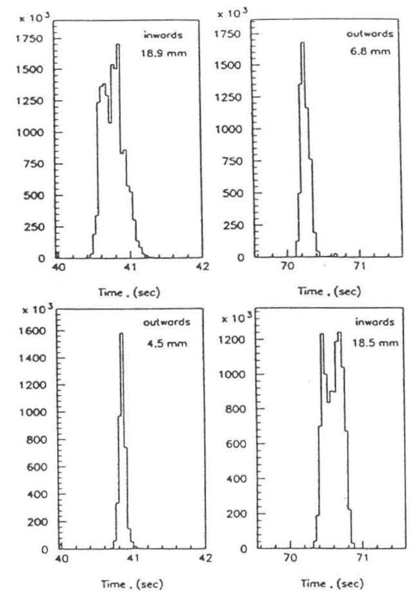

Fig. 13. Measurement of beam profile of 500 MeV proton beam with carbon fibre.

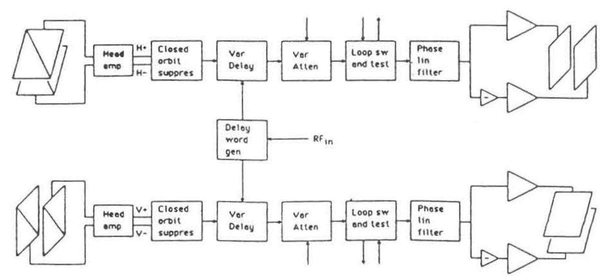

Fig. 14. The Transverse Feed-back System.

8. Transverse feed-back system

The phase space density limit that is first met in small cooler rings is that of transverse instabilities. Therefore, feed-back systems to damp transverse instabilities have been developed at several laboratories [25-28].

Such a system has also been constructed for CELSIUS. It is essentially a copy of the feed-back system built for LEAR, and uses circuit boards built for CELSIUS by members of the PS Division at CERN. It is now being tested on the CELSIUS ring. A block diagram of the feed-back system is shown in fig. 14.

Transverse oscillations of the beam are measured with a beam position monitor, and corrected by a kicker located at a position that is approximately an odd number of quarter wavelengths of betatron oscillations away from the monitor.

The "Closed Orbit Suppressor" shown in the block diagram in fig. 14 suppresses the signal from the closed orbit position error at the beam position monitor by a technique that virtually moves the centre of the monitor towards the closed orbit position. Thus only the deviations due to instabilities are measured. This is done electronically by giving the two pick-up electrodes of the beam position monitor a different weight, calculated from the closed orbit position measurement. The closed orbit component of the signal is normally, by far, the largest one. The "Closed Orbit Suppressor" therefore makes it possible to increase the loop gain without increasing the power of the amplifier. A good degree of suppression is hence important. A variable delay is achieved by switching in or out different delay cables, with propagation times in binary progression. The delay is controlled from the revolution frequency, by a "Delay Word

Generator." This makes it possible to use the feed-back system during acceleration. At the "Loop Switch and Test Unit" test signals can be added and the response checked with the loop open as well as closed.

The "Phase Linear Filter" keeps the phase linear up to a frequency where the gain has dropped by 40 dB. This is important, since otherwise high frequency oscillations could be amplified rather than damped.

Tests of the transverse feed-back system have been performed since November 1991. These tests have shown that the system can eliminate particle losses, that otherwise take place during electron cooling, and that it also can eliminate losses that may take place during acceleration if the working point is not controlled carefully enough.

9. CONCLUSIONS

The CELSIUS ring has been brought into operation for nuclear and particle physics with internal targets. High intensities of protons, deuterons and α-particles have been stored by stripping injection and accelerated to various energies (up to 1300 MeV for protons).

The intensities achieved with "multi-turn" injection (without charge exchange) are lower than expected.

An unexplained effect, causing "electron heating" makes the operation of the electron cooler difficult, and less beneficial. This effect is under investigation.

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