STATUS OF THE CELSIUS COOLER-STORAGE RING PROJECT

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ABSTRACT

The CELSIUS ring at The Svedberg Laboratory in Uppsala, Sweden is presently being commissioned, and has stored and accelerated its first beams of protons. The stored beams have been scattered against a thin fibre of carbon, which was mounted vertically and displaced horizontally through the beam. It was found that the lifetime of the stored beam depends strongly on the transverse position of the fibre; the lifetime having a maximum when the fibre is placed in the center of the beam.

The ring will soon store and accelerate, and also cool with electron cooling other beams (from protons to ions with $A \approx 100$, including polarized protons and deuterons) from the Gustaf Werner Cyclotron, and will be used for nuclear and particle physics with high resolution using thin internal targets.

A general purpose experimental station with a cluster gas-jet target and a fibre target has been installed in the ring. The target has been tested with hydrogen, nitrogen, and argon, showing well-bounded intensity profiles.

Fibres of carbon and refractory metals show promising properties as internal targets for high-luminosity experiments. A "pellet" target (to be developed) will produce solid hydrogen pellets with a diameter of about 20 μm.

DESCRIPTION OF THE PROJECT

General

CELSIUS[1] is a cooler storage ring for particles, which have been accelerated in the Gustaf Werner Cyclotron.[2]

This ring is intended for high resolution nuclear and particle physics with stored and cooled beams interacting with thin internal targets.

Since the cyclotron's internal PIG ion source will be supplemented both with an external ECR ion source and with an external polarized ion source, the particles will range from protons up to ions with $A \approx 100$, and will include polarized protons and deuterons.

The maximum magnetic rigidity of the ring is at present 7.0 Tm (1 T · 7 m) corresponding to a momentum per charge of 2.1 GeV/c or a kinetic energy of 1360 MeV for protons and 470 MeV per nucleon for particles with charge to mass ratio 1/2.

The layout of the CELSIUS ring is shown in fig. 1. The ring consists of four 90° bends and four straight sections. The circumference is 82 m. Each bend consists of 10 bending magnets which share a common coil. One straight section contains the injection elements, and has space reserved for a possible future addition of an extraction system. The next straight section is practically filled with diagnostics equipment, but may in the future also contain a second experimental station. The third straight section contains the electron cooler with its magnetic guiding system, a compensation solenoid, and the accelerating rf. cavity. The fourth straight section is the main experimental straight section which will hold one out of several internal targets, see below. A few theoretical lattice parameters are given below:

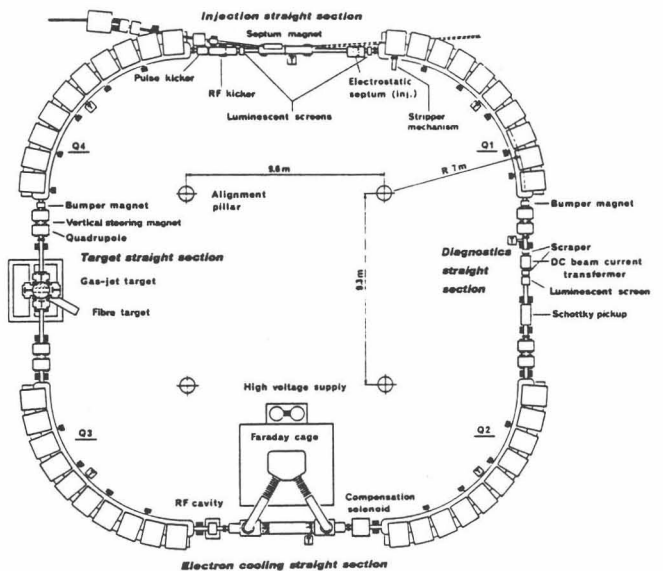|	
Q_x, Q_y	1.68, 1.90
Q_x', Q_y'	$-5.07, -2.18$
γ_{tr}	2.67
β_x, β_y, D_x (diagn., target s.s.)	1.13, 1.29, 6.61 m
β_x, β_y, D_x (inj., cooling s.s.)	8.06, 5.84, -1.58 m
β_x, β_y, D_x (max)	25.18, 17.98, 9.84 m

Fig. 1. Layout of the CELSIUS ring.

The magnet system in CELSIUS is reflection symmetric about centers of opposing straight sections. Thus there are four quadrants with identical lattice functions (disregarding the influence of the electron cooler and its magnetic guiding system).

The beam has narrow waists (small β) at the centers of the target and diagnostics straight sections, and is relatively parallel (large β) on the injection and cooling straight sections.

There are quadrupole doublets at the beginning and end of the target and the diagnostics straight sections.

Vertical closed orbit control is assured by vertical steering magnets, which are placed in the center of each quadrupole doublet.

Time Cycles

CELSIUS is normally operated in cycles with duration 1-100 s. Fig. 2 shows the variation of the magnetic field during a cycle which includes acceleration from 70 MeV to 600 MeV, and which recently has been successfully tried. There is a time window for injection, during which a beam pulse is to be received from the cyclotron. The acceleration typically takes 10 - 20 s. At the experimental field level the beam is normally to be exposed to the internal target, and cooled (except for protons with energy above 550 MeV, which travel faster than electrons of the maximum energy of 300 keV, and will only be cooled at the injection energy). After a certain period of time, determined by the beam life-time and the required preparation time of the beam, the magnetic fields return to the values for injection, and a new beam is injected from the cyclotron. In the tested 600 MeV cycle (fig. 2) the time taken to return the magnetic field to the value for injection, and the time spent at that value, are quite long, in order to get a well-known field distribution at the injection moment. More efficient cycles will be developed in the future.
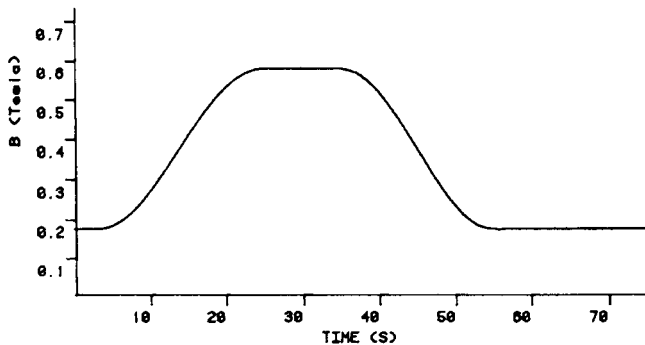

Fig. 2. Variation of the magnetic field during a tested cycle which includes acceleration from 70 MeV to 600 MeV.

Dipole Magnets

The dipole magnets in CELSIUS were previously used in the ICE ring at CERN[3]. They are solid-core combined function magnets, with quadrupole strength of ± 0.13 m^{-2}.

The maximum field is presently 1.0 T, limited by the power supply, Magnetic field measurements have been performed up to this field level.

The bending radius is 7.0 m. There are pole-face windings in four D-magnets per sector. These are used to adjust the sextupole- as well as the quadrupole-field in these magnets. There are also back-leg windings in three magnets in each sector for horizontal closed orbit control.

During the acceleration the field in the magnets rises. Eddy

currents are induced in the solid-core steel of the magnets.[4] These eddy currents tend to delay the change of the magnetic field, and to influence the magnetic field distribution in the magnets, and therefore must be compensated. A set of pick-up coils is permanently installed in one of the quadrants of CELSIUS, and is used to measure the magnetic field once every 500 milliseconds during the whole cycle at three different radial positions in each magnet. The information obtained by integrating the output voltage from these pick-up coils is used to find correct function-generator tables for the main magnet power supply, the pole-face windings power supplies, and the back-leg windings power supplies. This is done by successive iterations.[5] They are also used to program the quadrupole magnet power supplies in order that the currents in the quadrupole magnets become proportional to the average field strength in the dipole magnets. Each time the experimental conditions are to be changed a few new iterations have to be performed (unless appropriate tables are known from previous experience). This system has been tested and successful accelerations have been performed, see below.

Injection

Two different injection methods will be employed: "Normal multi-turn injection" and "stripping (charge-exchange) injection." "Normal multi-turn injection" is the method that has been tested so far. The closed orbit is first displaced with two bumper magnets on the injection straight section to a position close to the "septum", which separates the injection path from the circulating beam.[6] The injection takes place during the time when the closed orbit is allowed to return quasi-exponentially to its normal position.

Also during "stripping injection" the closed orbit will be displaced with the bumper magnets to one side of the vacuum chamber at the beginning, and it will be gradually moved back to the center of the vacuum chamber during the injection process. In this case the particles will hit a stripper foil, typically $20 - 100$ µg/cm^2 of carbon placed in the first CELSIUS bending magnet that is passed by the injected particles. There they will loose the last one or few electrons and become fully stripped. This injection method will be used for such particles which are not fully stripped during acceleration in the cyclotron, and can be stripped of one or several electrons when they are injected into CELSIUS, and is expected to become the most effective method of injecting ions into CELSIUS.

Diagnostics

There are 8 combined horizontal and vertical electrostatic pick-ups to measure the position of the beam at the beginning and end of each bending section. They are used both to measure the position and intensity of the ions that make the the first turn in the ring, to measure the position of the closed orbit when the beam has become stored, and to measure the intensity of the stored beam. One of them is also used in a servo loop in order to control the phase of the accelerating radio-frequency system.

Four luminescent screens in the ring are very useful in order to get the beam to circulate the first turn

A Schottky pickup will be used together with a spectrum analyzer for measurements of the momentum spread, the horizontal and vertical tunes and chromaticities, and the transverse rms. beam size.

Electron cooler

The electron cooler has been built by Sedlaček of the Royal Institute of Technology (KTH) in Stockholm.[7] The electron beam will be completely immersed in a homogeneous longitudinal magnetic field of up to 0.18 T produced by straight solenoids on the 2.5 m long interaction region and on the gun and collector parts, and by magnetic toroids in which the electron beam will be deflected in and out of the circulating beam, see fig. 3.

The electron beam voltage will be up to 300 kV. For voltages above 70 kV the beam current will be up to 2.8 A. The electron beam diameter will be 20 mm.

Extensive computer modeling studies of the electron gun and the electron collector have been made.

The longitudinal component of the magnetic field has been measured with a Hall plate, which was pulled along the path of the electron beam on a rail. Correction solenoids placed near the transitions between the straight solenoids and the toroids reduce variations of the longitudinal magnetic field component from about 0.05 T to 0.001 T

A pencil electron beam (about 0.1 mm diameter, 4 kV, 20 μA) has been used to determine the shape of the magnetic field lines in the electron cooler, and a system of correction windings are now (May 1989) being made in order to compensate for the measured transverse field components.

Experimental stations and targets

A general-purpose experimental station, including a cluster gas-jet target, a fibre target, and a common scattering chamber, has been installed on the target straight section.[8]

The cluster gas-jet target consists of a differentially pumped beam source where the cluster beam is formed by pushing a gas through a cooled nozzle. After passing a skimmer and a set of collimators the beam enters the scattering chamber. It is finally collected in a cryogenic beam dump. The cross section of the target beam at the intersection with the circulating CELSIUS beam, 250 mm from the nozzle, is oval-shaped, defined by the oval skimmer, with a length of 8 mm along the circulating beam and 5 mm across. The target beam profiles are shown to be very well bounded. Target thicknesses of $3 \cdot 10^{14}$, $5 \cdot 10^{13}$ and $2.4 \cdot 10^{13}$ atoms/cm^2 have been obtained for hydrogen, nitrogen and argon, respectively. The gas pressure in the scattering chamber with the target beam running is 10^{-7} mbar .

Tests have been made already with carbon fibre targets, which are mounted vertically in a holder, see below. Fibres of the refractory elements carbon, molybdenum and tungsten, and of carbide compounds, with diameters of about 5 μm show promising properties for use as internal targets in high luminosity experiments.

This is true also for a proposed "pellet" target, in which the stored beam will be exposed to a beam of frozen hydrogen spheres of 20 μm diameter).

Ultra-High Vacuum

CELSIUS is designed for a degree of vacuum of 10^{-11} mbar.[9] This degree of vacuum is required for operation with heavy ions, in particular when they are not fully stripped. Therefore all materials that are exposed to the vacuum are metallic, ceramic, or glass, and most parts of the vacuum chambers are made from stainless steel grade AISI 316 LN, which retains both its hardness (particularly necessary in the Con-Flat knife-edges) and its non-magnetic properties even after the so-called vacuum firing (heat treatment at 950°C for 2 hours in vacuum of 10^{-5} mbar or better), which is necessary in order to reduce the content of hydrogen in the stainless steel.

The entire vacuum system will be baked to 300°C except for a few components, which are limited to 200°C.
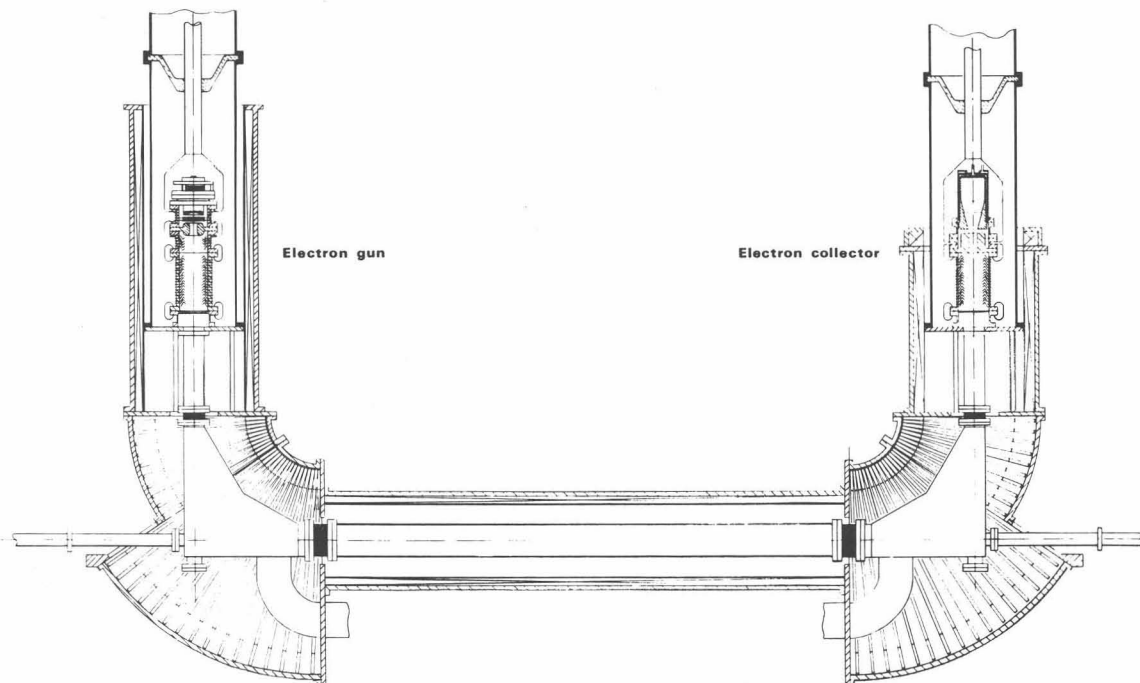

Fig. 3. Cross section view of the electron cooler.

COMMISSIONING AND TESTING STATUS

Tests of the CELSIUS ring have so far made use of 70 MeV protons from the cyclotron, this being an ion which is used by other users and quite often tuned up at the cyclotron. The injection method used so far (May 1989) has been "normal multi-turn injection." The cyclotron has been run at the first harmonic at 14 MHz, producing pulse trains of about 20 μs duration (determined by the duration of the pulsing of the cyclotron ion source). Each cyclotron bucket contains some 1.5×10^7 protons. The number of stored protons achieved so far is not more than 1.2×10^8, which is less than expected by one order of magnitude. The reasons for the low injection efficiency are not yet understood.

The stored beam of 70 MeV protons has been scattered on a vertically mounted and horizontally moveable 7 μm thick carbon fibre. The beam life-time was studied as a function of the fibre position, see fig. 4. It was found that there is a maximum in the life-time, in this case about 20 ms, when the fibre is placed at the center of the beam. This observation agrees with predictions.[6] The explanation has to do with that there is horizontal dispersion at the target. If the fibre is placed at the side of the beam where the ions have a somewhat increased probability to appear when they have a high momentum, then these ions have a higher than average probability to hit the fibre. This will (for a very short while) produce some momentum cooling, but the position of the closed orbit, which belongs to these ions, will jump away from the actual positions of the ions when they hit the fibre. Thus transverse heating will be produced. If on the other hand the fibre is placed at the other side of the beam, where the ions tend to have a lower momentum than average, then the fibre will (for a very short while) produce transverse cooling but longitudinal heating. If the fibre is not placed exactly at the center of the beam, then the effects will be cumulative, since the ions have an increased probability to hit the fibre at a particular phase of the synchrotron oscillations.
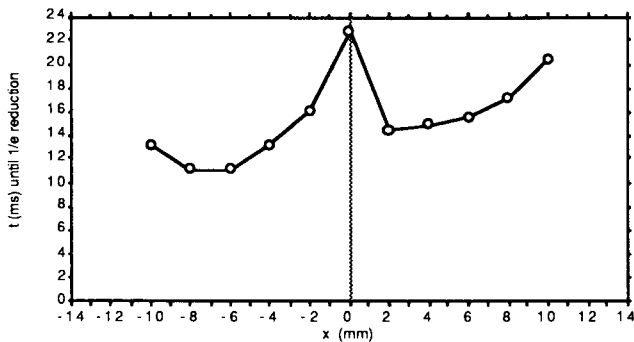

Fig. 4. Life-time of stored beam of 70 MeV protons interacting with a vertical 7μm carbon fibre, plotted as a function of horizontal fibre position.

Scattered protons were observed in a detector telescope in 12° forward direction. This measurement was used to confirm the measurement of the number of stored protons, which was made with the pickup electrodes in the ring, and also to measure the horizontal profile of the beam at the target location, see fig. 5, which shows such a measurement with the rf. system on and off. It is evident from the measurement that the number of stored protons is higher when the rf. is off. This matter requires further study. The horizontal shift of the beam between the two cases is due to the the effect of the energy loss in the fibre and the dispersion at the target location.

The stored beam has been accelerated to 600 MeV. The horizontal and vertical tunes are not yet perfectly constant during the acceleration, see fig. 6.
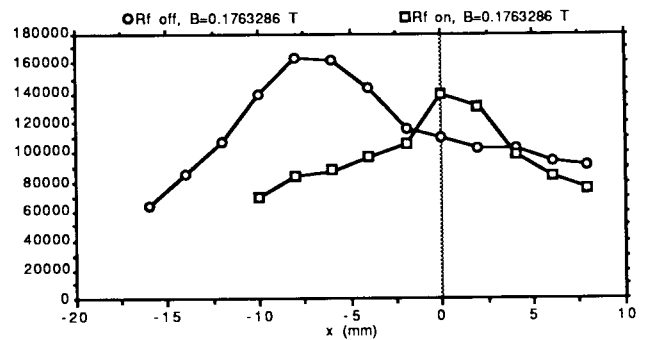

Fig. 5. Horizontal beam profiles at target location measured with fibre and detector telescope.
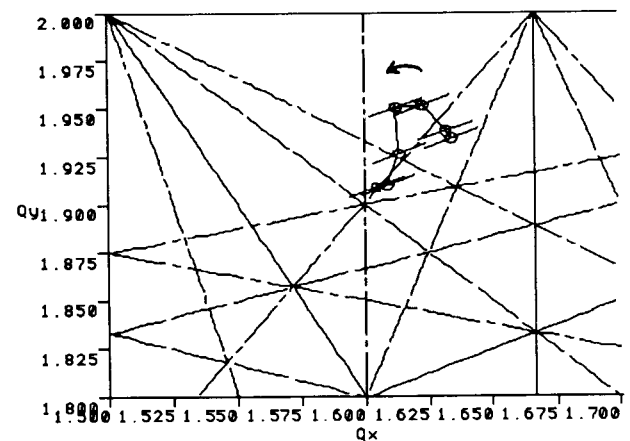

Fig. 6. Variation of horizontal and vertical tunes during acceleration to 600 MeV. The short slanted lines represent the tune spread due to the chromaticities and the measured cyclotron momentum spread

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