# STATUS OF THE CELSIUS PROJECT

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Abstract: CELSIUS is a storage-cooling-acceleration ring for protons and other ions from the Gustaf Werner Cyclotron in Uppsala, Sweden. The ring, which has a maximum rigidity of 7 Tm, is intended for intermediate-energy physics, elementary-particle physics, and heavy-ion physics with internal targets. The first injection into the completed ring with 70 MeV protons, using multiturn injection, took place in October 1988. About $10^8$ protons were stored with this method. More than two orders of magnitude higher stored proton beam intensities have subsequently been achieved, using stripping injection with $H_2^+$, using long (8 ms) pulse trains from the cyclotron and slowly moving the closed orbit away from the stripper foil with the bumper magnets. The proton beams have been accelerated, and exposed to thin internal targets. Electron cooling in a 10-300 keV, 0-3 A electron cooler has been demonstrated.

## General

CELSIUS [1,2] is a cooler storage ring for ions from the Gustaf Werner Cyclotron [3]. It is intended for high resolution nuclear and particle physics with stored and cooled beams interacting with very thin internal targets [4].

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 during the autumn of 1990, the particles will soon range from protons up to ions with $A \approx 100$, and will include polarized protons and deuterons.

The maximum magnetic rigidity 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. The next straight section is filled with diagnostics equipment, but may in the future also contain a secondary experimental station. The third straight section contains the electron cooler with its magnetic guiding system, a spin compensation solenoid, and the accelerating rf cavity. The fourth straight section is the main experimental straight section holding the internal targets.

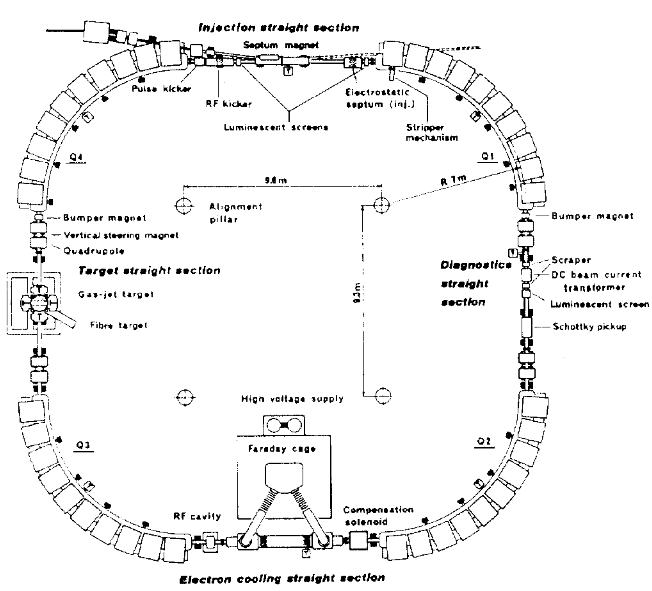


Fig. 1. Layout of the CELSIUS ring

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). Quadrupole doublets produce narrow waists (small $\beta$) at the centers of the target and diagnostics straight sections in order to optimize the lifetime of beams in the presence of internal targets, and to obtain good vertex definition in the experiments.

Fig. 2 shows the calculated horizontal and vertical $\beta$-values and horizontal dispersion in one quarter of the ring, together with the results of measurements of these quantities, obtained by doing small changes of the gradients in quadrupole magnets and dipole magnets with pole-face windings, and by varying the rf. frequency.

The working point which has been used recently is $Q_x$=1.59, $Q_y$=1.90. Transition would occur at 2.45 GeV/$c$, so the ring is presently always working below transition.

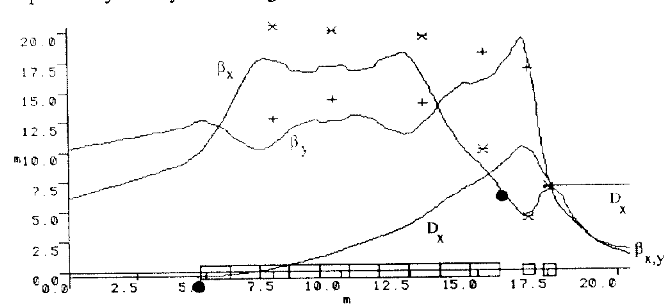


Fig. 2. Calculated horizontal and vertical $\beta$-values and horizontal dispersion in one quarter of the ring together with measurements of these quantities.

## Dipole magnets

The dipole magnets in CELSIUS were previously used in the ICE ring at CERN [5]. They are solid-core combined function magnets, with quadrupole strength of ±0.13 $m^{-2}$.

Another contribution to these proceedings deals with the problems of ramping the magnetic fields in these solid-core magnets [6].

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 magnetic field distributions have been computed for higher field levels. It turns out that saturation effects would influence the field distribution significantly at field levels above 1.2 T, which would correspond to a maximum momentum of 2.52 GeV/$c$, or a maximum kinetic energy for protons of 1.75 GeV. Such an upgrade of CELSIUS has been proposed.

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.

### Injection

Two different injection methods have been employed: "multi-turn injection" and "stripping injection". In both cases the position of the closed orbit on the injection straight section is displaced radially with two bumper magnets before the injection begins, and the injection is made during the time when the closed orbit is allowed to return to its normal position. Fig. 3 shows oscilloscope traces of the signal from a pickup electrode and the current in the bumper magnets, illustrating how the intensity builds up while the current in the bumper magnets returns quasi-exponentially to zero. Thereby the transverse phase space gets well filled.

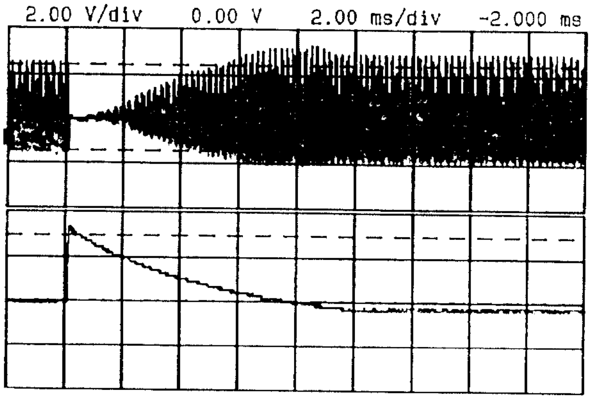


Fig. 3. Oscilloscope traces of the signal from a pickup electrode (upper) and the current in the bumper magnets (lower).

Multi-turn injection was the injection method which was tried first, and in October 1988 about $10^8$ protons of 70 MeV were stored for the first time in CELSIUS, using cyclotron beam pulse trains with a duration of about 30 μs (the shortest pulse trains the PIG ion source could produce), and a bumper time constant of 4 μs. The final deflection of the incoming beam before the injection is made with an electrostatic septum. In the electrostatic septum the field-free volume (where the stored beam is circulating) is separated from the volume where the incoming beam is deflected by an electrical field by a 0.1 mm thick molybdenum foil. The movement of the closed orbit must be fast enough that the ions do not come back to the septum at any subsequent turn at the wrong side (the outside) of that foil.

More than two orders of magnitude higher intensity of a circulating beam of protons has subsequently been achieved with stripping injection, converting 96 MeV ions of $H_2^+$ into pairs of 48 MeV protons in a 20 μg/cm$^2$ foil of carbon, which covers a part of the aperture, in the first ring dipole magnet. Thus the charge-to-mass ratio and therefore the radius of curvature in the magnetic field of the ions changes in the foil, in this case by a factor of 2. The circulating ions can return at the wrong side of the foil edge many times. Therefore the bumper time constant can be made much longer with stripping injection than with multiturn injection, and the injection can go on during a longer time. In the case of stripping injection of protons using 96 MeV $H_2^+$ ions the cyclotron pulse trains have been 8 ms long, and a bumper time constant of 4 ms has been used. The $H_2^+$ current was about 8 μA and $4\times10^{10}$ protons or 5% of the number of protons in the injected beam were stored.

Stripping injection will therefore be used whenever possible, even though the momentum of the injected particles is considerably less than the maximum momentum that the cyclotron can produce.

It has also been observed that protons can get injected with stripping injection into stable orbit in the ring even if the bumper magnets are not fired. An injection efficiency of about $2\times10^{-4}$ was observed for this case. The mechanism is thought to be due to scattering of a fraction the protons into the aperture by intrabeam scattering.

### Time cycles

CELSIUS has so far been operated in cycles with duration 75-120 s, with 60 s time lost in each cycle for ramping the magnets up and down, and for the flat bottom, and up to 60 s used as the data-taking part of the cycle during the flat top.

### Diagnostics and rf.

The beam diagnostics and the rf. system in CELSIUS are described in other contributions to these proceedings [7,8].

### Targets

The internal targets to be used in storage rings have to be very thin, in order not to create too short beam lifetime. Optimum target thicknesses range between $10^{14}$ and $10^{16}$ nuclei per cm$^2$. At CELSIUS, most of the work has been with a cluster-jet target [9]. This is similar to the cluster-jet target on the SPS at CERN, and has been producing target thicknesses of $3\times10^{14}$, $5\times10^{13}$, and $2.4\times10^{13}$ atoms per cm$^2$ of hydrogen, nitrogen, and argon, respectively. Targets of 7 μm carbon fibres have also been tested, but are generally too thick and produce beam lifetimes of less than a second for most beams in CELSIUS. The use of thinner fibres [10] will be attempted in the fall of 1990.

A "pellet" target, in which the stored beam will be exposed to a beam of frozen hydrogen spheres of 20 μm diameter is being developed for fundamental particle investigations in CELSIUS. This development is described in another contribution to these proceedings [11].

### Electron cooler

The electron cooler has been built by Sedláček of the Royal Institute of Technology (KTH) in Stockholm. A cross section of the electron cooler is shown in fig. 4. The electron gun launches a 20 mm diameter electron beam from a dispenser cathode. The cathode and the whole beam path is fully immersed in a homogeneous longitudinal magnetic field 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 is deflected in and out of the circulating beam by a superimposed dipole field.

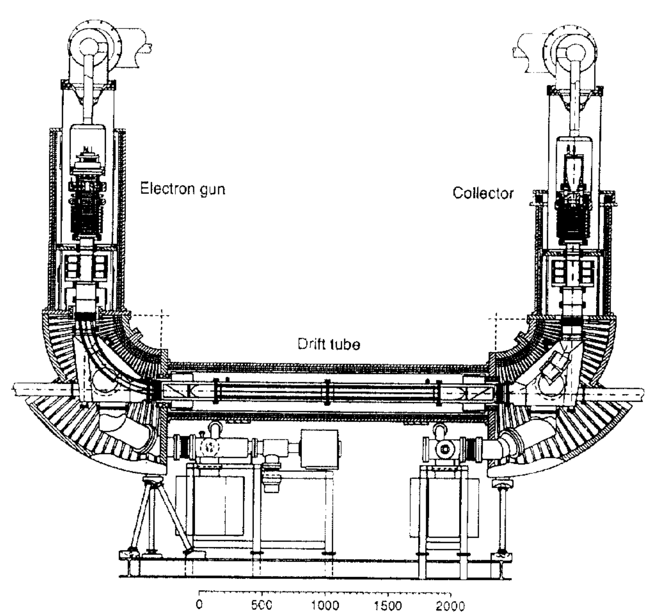


Fig. 4. Cross section of CELSIUS electron cooler.

The electrons are accelerated in a combination of NEC (National Electrostatics Corporation) accelerating columns to a maximum energy of 300 keV. For voltages above 70 kV the beam current is up to 3 A. At the collector side the electron beam is retarded in another accelerating column. After passing through the hole in the collector anode, which is at a potential of 1 kV above the cathode potential, the beam is again accelerated, and reaches the collector with a kinetic energy of a few keV.

Electron cooling has been tested at the proton injection energy (using stripping injection) of 48 MeV. The first observation was that of a severe reduction in proton beam lifetime as soon as the proton and electron beams were put together, see fig. 5.

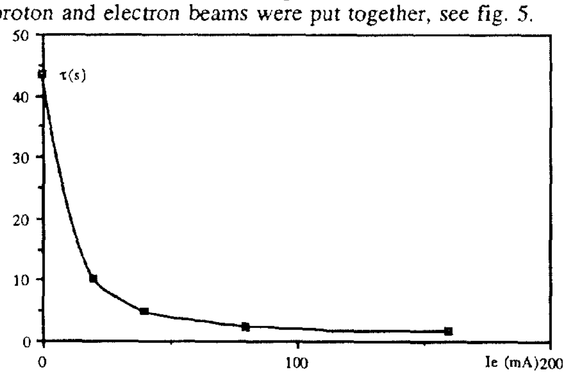


Fig. 5. Initial measurement of proton beam lifetime against electron beam current.

After tuning of the ring to a slightly different working point, and modifying the sextupole contribution to the magnetic fields in some of the dipole magnets, it was possible to restore the lifetime of the proton beam in the presence of an electron beam of 150 mA to about 3.3 s (still more than 10 times worse than what is routinely achieved without electrons), not seeing any cooling. After then tuning the electron beam voltage precisely so that the velocity of the electron beam matches that of the protons, and doing various fine adjustments of the electron and proton beam conditions, cooling was achieved, and the proton beam lifetime became more than 100 s. The momentum width in a bunched beam was measured to be less than $2\times10^{-4}$.

Accumulation with cooling was tested briefly, see fig. 6, which shows accumulation of $10^{10}$ protons with cooling, and the subsequent lifetime of about 120 s. The electron beam current was 150 mA. Fig. 7 shows a longitudinal Schottky spectrum of this beam, which shows clear evidence of splitting of the Schottky peaks, as has previously been observed at other electron coolers [12,13]

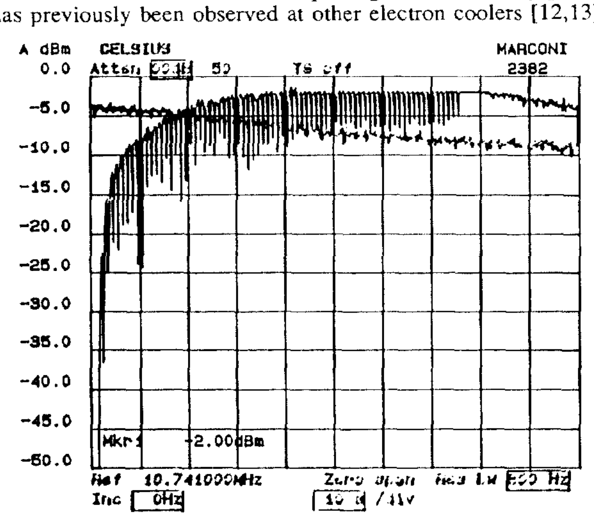


Fig. 6. Accumulation of $10^{10}$ protons with cooling. Beam was injected once every second. The electron beam current was 150 mA. Equilibrium was reached after about 30 seconds. Then the injections were stopped, and the subsequent decay of the beam intensity was observed. The beam lifetime was about 120 seconds.

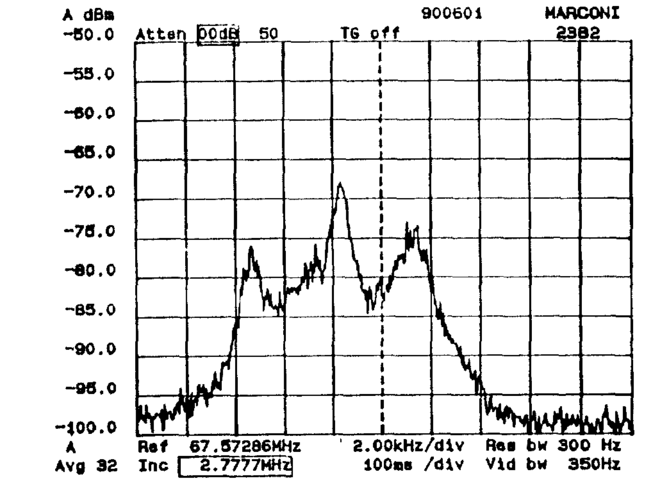


Fig. 7. Longitudinal Schottky spectrum of intense cooled beam, taken after doing accumulation with cooling. Splitting of the Schottky signal is observed, as well as a central peak, which is believed to be due to coherence in the beam due to self-bunching. Unstable bunching of the beam due to its own electromagnetic fields could also be observed on an oscilloscope.

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