# STATUS REPORT ON THE UPPSALA SYNCHROCYCLOTRON AND CELSIUS COOLER RING PROJECT

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## Summary

The design features and the current status of the two accelerators are described. The reconstructed Gustaf Werner cyclotron has a K-value of 200 and will operate as a synchrocyclotron for protons above 110 MeV and as an isochronous cyclotron for lower energy protons and for heavier ions. The beams from the cyclotron will be used both for experiments and for injections into the CELSIUS ring. In this ring the particles will be stored, accelerated, cooled with electrons and used for high resolution physics with internal targets. The maximum proton energy is 1160 MeV and the corresponding K-value for heavy ions is 1870.

## Introduction

The Svedberg Laboratory, newly established as a national accelerator laboratory in Uppsala, comprises three accelerators, the tandem van de Graff accelerator, the modified Gustaf Werner cyclotron and the cooler-storage ring CELSIUS. Together these accelerators will offer the research community a versatile facility with a wide range of ions and energies. For instance, protons will be available from about 1 MeV to 1160 MeV, argon ions up to 325 MeV per nucleon, and other ions up to mass number 100 will be available with energies up to the corresponding rigidity. The facility will be used for diversified research in natural science and medicine.[1] The present paper gives the status of the two accelerators under construction, the Gustaf Werner synchrocyclotron and the cooler-storage ring, CELSIUS. An overview of the facility is shown in Fig. 1. The cyclotron will deliver beams both to the CELSIUS ring and to experimental areas for isotope and neutron production, intermediate energy light-ion nuclear physics, low background heavy-ion experiments, and to areas for biology and medicine.

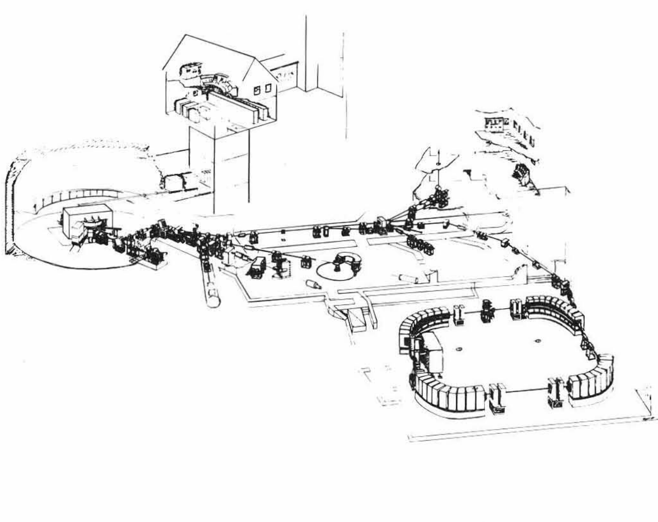

Fig. 1. Artists view of the laboratory showing the cyclotron, the experimental areas, the CELSIUS ring and the control rooms.

## The cyclotron

A proposal to rebuild the Gustaf Werner synchrocyclotron using a combination of sector focussing and frequency modulation was made in 1965 after two years of theoretical studies and model measurements.[2] In 1974 money were granted to start more detailed magnet studies by means of a 1:4 scale model of the synchrocyclotron magnet. In 1977 funds were available and the cyclotron was shut down for the present reconstruction. The initial plans[3] were to operate only with frequency modulation (f.m.) for all ions and not to use trim coils. The model measurements showed, however, that frequency modulation can be restricted to protons and helium-3 ions of the highest energies if trim coils are used, and that all other ions can be accelerated with constant frequency.

A description of the reconstruction programme was given in the tenth international cyclotron conference.[4] This programme comprises a complete reconstruction of all parts of the cyclotron including a conversion from the original weak focussing to sector focussing and a construction of an rf-system capable of operating both at a constant frequency and with frequency modulation.

### Cyclotron magnet

The extensive magnetic field shimming and measuring programme was finished in the spring of 1985 when the final field maps were made. These comprise two types of fields:

a. basic fields at five magnet excitations in the range 0.5 to 1.74 T and the corresponding
b. correction fields from 13 pairs of circular gradient coils and two sets of harmonic trim coils as well as field contributions from the extraction elements: peeler, regenerator, focussing and electromagnetic channels.

All intermediate field settings are obtained by interpolation in the tables of basic and correction fields. With the sector shape chosen sufficient vertical focussing is maintained for radial gradients below 20 G/cm close to the maximum radius. This limits the c.w. acceleration of protons to energies below 110 MeV and also implies a bandwidth of almost 10 per cent for protons which are to be accelerated to the maximum energy of 200 MeV.

### Radio frequency system

The acceleration is performed by means of two dees, each driven by a power amplifier chain and a common rf generator. Each amplifier chain consists of a 2 kW broad-band amplifier and a 100 kW tuned stage. The systems are tunable from 12 to 24 MHz. The final amplifiers are inductively coupled to the dee-resonating cavity and move together with a coarse-tuning short circuit on a rail when the resonant frequency of the cavity is changed. The dees have an azimuthal width of 72 degrees up to a radius of 58 cm, where a cut back of the dee angle is made in order to reduce the dee capacity. The tips of the dees at the central region are exchangeable in order to permit an optimum solution concerning dee angles and geometries for harmonic operation up to fourth harmonic.

The problem of operation in both c.w. and f.m. modes is solved by artificially broadening the resonance of the system in the f.m. mode by introducing a resistor, which absorbs 40 kW of the rf power, in parallel to the dee stem. The resonance of the power tube is tuned to a slightly different frequency than that of the cavity which gives a passband with two peaks.

Power test with the first rf system started in June 1984 with the dee in an airfilled test chamber simulating the vacuum chamber of the cyclotron. Dee voltages of 30 kV were attained at 24 MHz. A problem at this stage was a self oscillation of the 100 kW tube at 1.1 GHz. After many attempts a successful solution to this problem was found. Ferrite rods were inserted in a small volume inside the tube socket, and the amplifier has since been stable.

In January 1986 the first rf system was installed in the vacuum chamber in the cyclotron magnet and power tests with vacuum started. The dee voltage in c.w. mode was increased to 50 kV, the maximum value to be used at 24 MHz. At this voltage a current of approx. 2500 A flows in the dee resonator and the skin losses are about 30 kW. In some places a temperature rise higher than expected was found and additional cooling was therefore installed close to the rf flange on the vacuum chamber and on the vacuum feedthrough.

Operation of the 100 kW power tube in the stray field from the magnet (approx. 100 G) has so far not presented any difficulties, but as a precaution anode blocking capacitors with soft iron shielding have been manufactured.

## Vacuum

The installation of the new aluminum vacuum chamber started in July 1985. The chamber consists of an upper and a lower part with an intermediate seal of soft aluminium wire. The upper part, which is in form of a lid, is attached to the upper yoke which can be lifted by a hydraulic jack system in order to permit easy access to the interior of the cyclotron.

The final installation of the chamber and the r.f. liners was made during the autumn 1985. After connection of vacuum pumps and pump control system, high vacuum tests started in December, 1985. Two conventional oil diffusion pumps, each with a baffled capacity of 9000 l/sec are used for high vacuum pumping. Backing pumps are a 1000 m3/h Roots pump and two 170 m3/h rotary vane pumps, each provided with a zeolith trap. The prevacuum pumps are also backing a 700 l/sec oil diffusion pump which is used for evacuating the intermediate vacuum region, in which the trim coils are located. The vacuum control processor is an industrial programmable controller. Different operational modes such as high vacuum pumping, bypass pumping, pump stand by etc. can be chosen either locally via a control panel or from the control room via the control computer.

To be able to accelerate heavy ions with high transmission through the cyclotron, the design pressure is 2.10-7 Pa. So far 8.10-7 Pa has been obtained with the intermediate vacuum region connected to the high vacuum region without separate pumping.

## Ion source and central region

The cyclotron is initially equipped with an internal cold cathode ion source of the penning ionization type. Sources and central geometries of different size must be used in f.m. and c.w. modes because of the difference in accelerating voltage. In the c.w. mode, due to the high dee voltage available, the source has a double arc anode, which permits operation both in the first and the second harmonic without change of the position of the source. The cathode material, consisting of small discs of e.g. lanthanum hexaboride (LaB6) or hafnium carbide (HfC) is mounted in tantalum holders. These are screwed on water cooled supports which are common for both arc chimneys.

The ion source is inserted into the cyclotron through a vacuum lock at the side of the vacuum chamber and guided on rails to the centre, Fig. 2. Exchange of the cathodes can be made through a second vacuum lock. A special tool is foreseen with which it will be possible to exchange the complete central geometry without breaking the vacuum.

Funding has recently been granted for an Electron Cyclotron Resonance (ECR) source which will be built in collaboration with the Department of Physics of the University of Jyväskylä in Finland. The ECR ion source will be placed in a room adjacent to the cyclotron. A source for polarized light ions has also recently been funded.

In order to permit the installation of the external injection system, the hole through the upper yoke of the magnet has been enlarged to give space for a beam guiding system from the top of the magnet to the median plane. The detailed design of the whole injection system will start shortly.

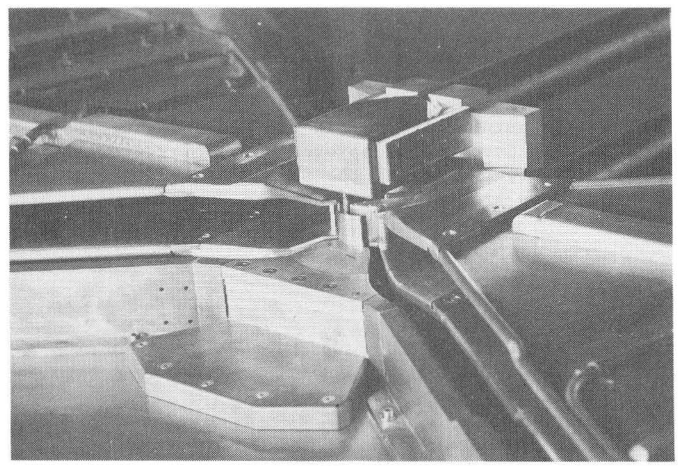

Fig. 2. Photo showing the central region of the cyclotron with the double arc ion source.

## Extraction

Two different extraction methods will be used: Precessional and regenerative. Precessional extraction can be used only when one operates in a c.w. mode with relatively few number of turns in the cyclotron due to phase shift effects in the magnetic fringe field.

The extraction using the regenerative method, on the other hand, takes place before any appreciable phase shift effects due to the fringe field have occurred and therefore this method is suitable in the f.m. mode where the energy gain per turn approaches zero for some particles. Also in the c.w. mode when accelerating on first harmonic, the energy gain per turn is rather low and therefore it might be necessary to use this extraction method.

The properties of the extracted beam will differ for the two extraction methods, both concerning energy spread and emittance. In the precessional mode the whole radial phase space of each beam phase will normally be extracted in two turns with the corresponding energy spread and about 20 mm-mrad emittance. In the regenerative case the particles have to pass an unstable fixpoint in the radial phase plane before the turn separation starts to grow. This point is first reached by those particles of the same energy having the largest betatron amplitudes, and they are first extracted. The different betatron amplitudes are thus transforming into different energies of the extracted beam. In a typical case of protons around 180 MeV, amplitudes up to 4 mm will be extracted in 23 turns corresponding to 460 keV energy spread. The extracted emittance, on the other hand, will in this case be smaller, about 5 mm-mrad.

### Status

All essential parts of the cyclotron required for tests with internal beam are now in operation. Initial runs with α-particles will be made in the near future.

## Cooler-storage ring "CELSIUS"

"CELSIUS" is the name of the cooler-storage ring for intermediate energy ion physics under construction in Uppsala. The ring will store ion beams from the synchrocyclotron and will be provided with an rf. cavity for acceleration up to a rigidity of 6.25 Tm (corresponding to an energy of 1.16 GeV for protons or 388 MeV for ions with charge to mass ration 1/2). It will be used mainly for physics with internal targets, and be equipped with an electron cooling device.

The CELSIUS project was initiated in the summer of 1982. At that time the ICE ring at CERN, which had been used to test methods of phase-space cooling of antiprotons, was to be dismantled. The possibility of using these magnets in a cooler-storage ring for intermediate energy ion physics was investigated in Uppsala during the autumn of 1982. In the beginning of 1983 the Swedish Government approved the cooler-storage ring project, and during the summer of 1983 the magnets were brought from Geneva to Uppsala.

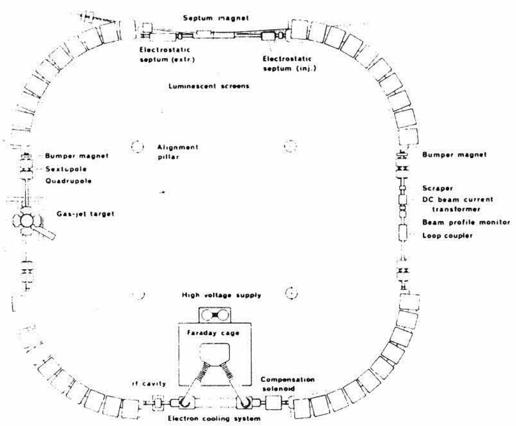


Fig. 3.

### Layout

The adopted layout of the CELSIUS ring is shown in fig. 3. Like the ICE ring, CELSIUS consists of four $90^{o}$ -arcs and four straight sections. 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 in the present layout practically filled up with diagnostics equipment. 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. In fig. 3 a gas-jet target is indicated. Also other targets, like the hydrogen or deuterium pellet target and the fibre target which are developed for CELSIUS by the Studsvik Science Research Laboratory may be used in this position.

### Magnets

The magnets are combined function magnets, i.e. they have built-in gradients in their magnetic fields. They are basi :ally of two types, D (radially defocussing) and F ( radially focussing). Their bending radius is 7 m. The magnets are made of solid non-laminated steel. The eddy current effects in the magnets will be compensated by active pole-face and back-leg windings.

### Quadrupoles

The design of the eight quadrupoles in CELSIUS is essentially copied from that of the quadrupoles of the LEAR machine at CERN (28). Thus the CELSIUS quadrupoles have exactly the same cross section as the LEAR quadrupoles, but a 0,1 m shorter effective length (0,4 m instead of 0.5m).

### Injection

Two different injection techniques will be used - "normal multiturn" injection and "charge-exchange" ("stripping") injection.

Both during normal multiturn injection and during charge-exchange injection, two bumper magnets will be used to move the closed orbit laterally on the injection straight section.

The bumper magnets will be at their maximum excitation just before the injection starts, so that the closed orbit is displaced to a position near the electrostatic septum, and their magnetic field will decrease quasi-exponentially during the injection process, so that the closed orbit returns to the centre or the vacuum chamber.

With the expected horizontal emittance of the cyclotron beam (of 4 π mm·mr) and the expected acceptance of CELSIUS (of 80·π-100·π mm·mr) ions can be stored during about 10 revolutions. For 200 MeV protons this corresponds to an injection time of 5 μs or corresponding to the beam pulse length from the synchrocyclotron. About $10^{11}$ proton can be injected in this way.

Normal multiturn injection will only be used for such ions that are already fully stripped in the cyclotron (i.e. only the very lightest ions), since the charge-exchange injection technique will offer the possibility of a higher stored beam current.

Also during the charge-exchange injection process, the closed orbit will initially be moved towards the side of the available aperture. The external beam transport system will be adjusted so that the partially stripped or molecular ions hit the stripping foil (see below) in the proper position. It is necessary that the foil is thick enough so that complete stripping occurs with high propability. The stored ions can then pass through the foil many times without being lost. The bumper magnet field can thus be reduced to zero much more slowly than during normal multiturn injection and many more revolutions can be made useful in the stacking process.

### Electron cooler

The electron cooler for CELSIUS is being designed, built and tested at the Royal Institute of Technology in Stockholm. Its basic design is similar to that of the Fermilab electron cooler, which is placed in the first bending magnets in CELSIUS.

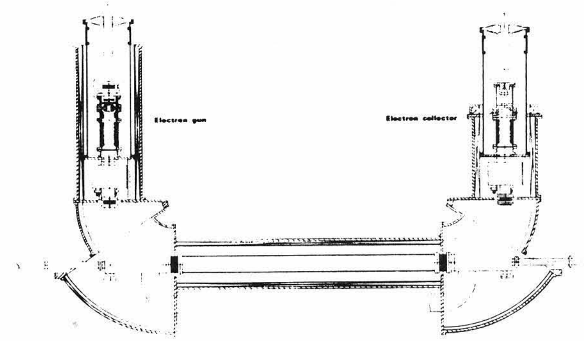


Fig. 4

A cross section view of the electron cooler is shown in Fig. 4. The electron beam will be completely immersed in a longitudinal magnetic field of about 0.15 T. This is created by three straight solenoids and two toroids. Each toroid is divided in a large 55° toroid and a smaller 35° toroid in order to provide entrance and exit apertures for the circulating beam.

The 20 mm wide electron beam is emitted from a dispenser cathode, accelerated up to a maximum of 40 keV by the potential of the anode, and further accelerated up to a maximum of 300 keV by the action of an accelerating column. The maximum beam current will be 3 A above 40 kV and limited by constant perveance below that. The design of the electron gun has been determined through extensive computer modeling.

The collector will be similar to that of Fermilab. The electron beam will be decelerated in another accelerating column, then go through the collector anode, which will be at a potential of about 1 kV above the cathode potential. After leaving the anode the beam will again be accelerated and will impinge on the collector with a kinetic energy of 3 - 4 keV.

In accordance with the experience at Fermilab it is expected that an ion cloud will be formed in the region of the potential minimum near the collector anode . Inside the cloud the ions will compensate the space charge of the electrons, and create an almost constant potential. This reduces the requirement for electron energy gain between this potential minimum and the collector (to supress backward acceleration of electrons, without the ion cloud there is a significant space sharge depression in the electron beam). The ion cloud must be stable for reliable capture of the beam in the collector. It was observed at Fermilab that the formation of the ion cloud had a time constant of about 1 s. They had a vacuum of $2 \cdot 10^{-7}$ Pa whereas the vacuum in CELSIUS is going to be $10^{-9}$ Pa. The time constant for the formation of the ion cloud in the CELSIUS collector could become prohibitively long. Therefore a controlled hydrogen leak is foreseen by small holes in the collector anode, connected to a hydrogen reservoir through a valve.

## Radiofrequency system

CELSIUS will be equipped with a ferrite loaded TEM mode rf cavity for acceleration and deceleration of the beam. It operates in the frequency range from 0.4 MHz to 5 MHz and has an rf voltage capability of 2 kV.

## Vacuum

Since CELSIUS must be capable of handling low-energy heavy-ions a very good vacuum is required. The design pressure is $10^{-9}$ Pa. Therefore all materials that are exposed to the vacuum are metallic, ceramic or glass. Most parts of the vacuum chamber are made of stainless steel grade AISI 316LN which retains its hardness even after the heat treatment at 950°C for 2 hours in vacuum which is made to reduce the outgassing rate to $10^{-9}$ Pa·m/s. This steel is very austenitic and therefore nonmagnetic. All parts that will be in contact with the ultra-high vacuum will be cleaned thoroughly, including treatment in ultrasonic bath and perclorethylene vapour. Each time the system has been exposed to air, it will be baked at about 200°C.

There will be turbomolecular pumps for pre-pumping to $10^{-4}$ Pa. Continuous pumping is performed by ion pumps and from $10^{-6}$ Pa also by titanium sublimation pumps.

## Status

The present activities are centered arount magnetic field measurements in the main magnets, and around the acquisition of various other pieces of equipment.

The magnetic field measurements are made both in a static mode and while ramping the magnetic fields in the magnets in order to obtain exact knowledge on the magnitude of the eddy current effects.

All hardware except the electron cooler will be installed by the summer of 1987. At that time it is hoped to attempt injection for the first time. The electron cooler will be installed during 1988 which is also when serious utilization for physics will begin.

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