Recent developments at the Gustaf Werner Cyclotron and CELSIUS

D. Reistad
The Svedberg Laboratory
Box 533, S-751 21 UPPSALA, Sweden

Abstract

The Gustaf Werner cyclotron, which usually operates in isochronous mode, is used as a synchrocyclotron for high energy protons. In addition to its internal PIG ion source, it has been equipped with two external ion sources, an ECR source for heavy ions and a source for polarized protons and deuterons. The CELSIUS ring is used for intermediate-energy physics with thin internal targets. A major concern is to keep the experimental background small. The electron cooling system is helping this task, but is not yet very useful at the injection energy. The reasons behind this are becoming clear. A long shutdown in the fall of 1993 will bring further enhancements to both accelerators.

I. INTRODUCTION

The The (=Theodor) Svedberg Laboratory (TSL) in Uppsala, Sweden, is a Swedish national accelerator centre. It operates an EN tandem accelerator with maximum terminal potential of 6 MV, and the Gustaf Werner cyclotron with the CELSIUS cooler ring.

TSL "shall promote research by making available facilities for accelerator-based investigations, and by carrying out such research with its own resources." (Quotation from the laboratory statutes).

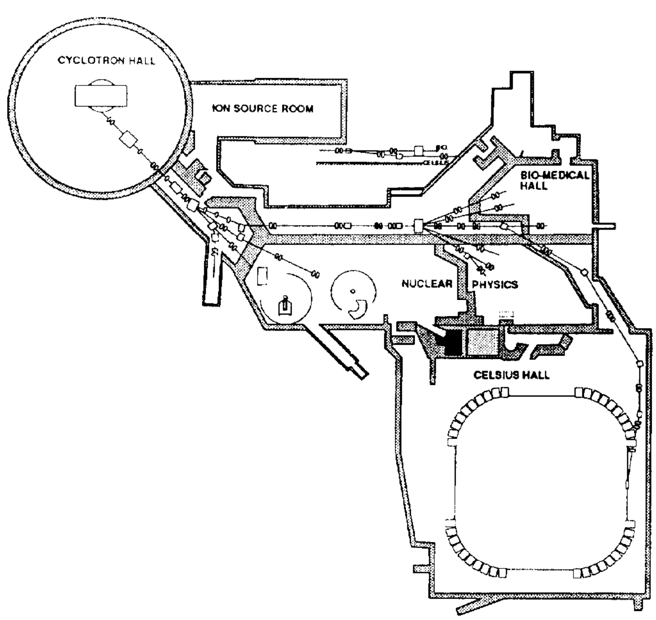

Fig. 1. The Gustaf Werner cyclotron complex. The CELSIUS ring has a circumference of 82 m.

The Gustaf Werner cyclotron complex is shown in fig. 1. The cyclotron [1,2], which has several different modes of operation, delivers beams of light and heavy ions for fixed target nuclear physics experiments, radionuclide production for hospital and scientific use, proton therapy, and acts as injector to the CELSIUS ring.

The CELSIUS ring [3] is used for physics experiments using stored ion beams interacting with very thin internal targets [4]. An electron cooling system is used to reduce the experimental background by increasing the stored beam lifetime.

II. THE GUSTAF WERNER CYCLOTRON

The Gustaf Werner cyclotron, initially built in the forties and early fifties as a (fixed-energy) 185 MeV proton synchrocyclotron with cylinder-symmetrical poles, converted during the eighties to a variable-energy multi-purpose sector-focused cyclotron, is now in use for a wide range of applications. It operates both as an isochronous cyclotron ("CW mode") and as a synchrocyclotron ("FM mode"). Its k-value 192, so it accelerates non-relativistic ions to an energy of $192\times Q^2/A$ MeV. The maximum energy for protons is 180 MeV, limited by saturation in the cyclotron magnet, power limitation in the extraction septum, and band-width and power limitations in the high-frequency system.

The three-sector geometry of the magnetic field provides sufficient vertical focusing during isochronous operation (when the magnetic field must satisfy $\langle B(r)\rangle \propto \gamma(r)$), except for protons above 105 MeV and for the highest energies of ^{3}He, when frequency modulation is necessary.

The cyclotron is now used during 15 eight-hour shifts per week. The ion species and the energy are changed frequently in order to satisfy the various needs of the users.

The cyclotron has been in operation in CW mode with an internal PIG ion source for light ions since 1987. In this mode the accelerating frequency is tunable between 12.25 and 24.5 MHz. Acceleration has been done using the harmonic numbers one and two. The maximum dee voltage is 50 kV.

In this mode the cyclotron accelerates the molecular ions H_2^+ and D_2^+ in order to inject protons and deuterons with stripping injection in CELSIUS, as well as He^+ in order to store alpha particles with the same method. Then the ion source is pulsed, with pulse length 8 ms. The peak accelerated beam current is up to 100 μA with H_2^+ and up to 30 μA with D_2^+ and He^+.

Radionuclide production is performed with 60-100 MeV protons with beam currents up to 10 μA.

The PIG ion source used in CW operation has a double-arc anode. This permits operation both with harmonic number one and two without changing the position of the source. The gas supplies to the two arcs are connected with each other. Especially during acceleration of the molecular ions used for stripping injection in CELSIUS, which are susceptible to break-up by collisions with the rest gas, it is necessary to avoid gas load from the arc that is not in use. Therefore, a dummy is mounted instead of the slit at that side. This is done by pulling out the source through an air lock. Since such changes have turned out to occur quite frequently a new design is underway, in which the two gas volumes are separated. This will significantly reduce the number of times that the internal source has to be pulled out, in order to change the slits.

Synchrocyclotron operation with an internal PIG source has been operational since 1991. Beam stretching is often used to provide a beam (macroscopic) duty factor of about 50 %. This is achieved by reducing the df/dt and the accelerating voltage during extraction. The pulse repetition frequency is presently up to 300 Hz. The accelerated beam current is about 2 nA/Hz at energies below 160 MeV and 1 nA/Hz at 180 MeV.

Synchrocyclotron acceleration is performed with harmonic number one and the frequency in the range between 17 and 24.5 MHz. The power tubes are operated as "broadband" amplifiers with bandwidth up to 2.2 MHz and dee voltages up to about 16 kV.

The PIG ion source used during operation in the FM mode is more compact than the one used in CW mode. This is necessary, due to the smaller dee voltage.

III. THE EXTERNAL ION SOURCES

Two external ion sources, an ECR source for heavy ions and an atomic-beam source for polarized protons and deuterons, have been installed at the cyclotron. The sources are placed outside the cyclotron hall next to an area for atomic-physics experiments, where heavy ion beams directly from the ECR source are used.

A. The ECR ion source

The ECR ion source [5], which was built in collaboration with the University of Jyväskylä, Finland, is based on the design of the room-temperature ECR source at NSCL, MSU, East Lansing, Michigan [6]. The source is vertically mounted and has a plasma chamber of 14 cm diameter and total length of 82 cm, surrounded by a sextupole of NdFeB permanent magnets, giving 0.27 T on the edge of the plasma chamber. An axial field of up to 0.52 T on the axis of the plasma chamber is obtained by 9 circular coils excited by four power supplies. To make the operation of the source more stable and reproducible [7], the original two-stage source has been rebuilt to a one-stage version with axial injection of the gas and of the 6.4 GHz microwave power. The gas supply to the ion source is provided through a line connected to the main gas and mixing gas bottles and regulated by two stepping-motor driven needle valves. The gases are chosen from a manifold of small bottles placed close to the source.

The ion source itself has been run with the noble gases up to xenon and with hydrogen, nitrogen, and oxygen. Hydrogen, helium, oxygen, nitrogen and krypton ions have also been accelerated through the cyclotron.

Heavy-ion beams have been brought directly from the ECR source to atomic physics experiments, and through the cyclotron for nuclear physics experiments, both with fixed targets and in the CELSIUS ring.

B. The Ion Source for Polarized Protons and Deuterons

The ion source for polarized protons and deuterons was built by Balzers/Pfeiffer at Asslar, Germany, with installation in Uppsala and beam tests during the first half of 1992. The source is based on the atomic-beam method, with state selection accomplished by multipole magnets and radiofrequency transitions. The dissociation of the molecules is obtained by a 27 MHz rf. discharge in a water-cooled Pyrex tube. The atoms then pass a nozzle, cooled to 30 K by a two-stage closed-cycle cryogenerator, to form an atomic beam. The geometry of the focusing sextupole and quadrupole magnets is optimized to give a high transmission to the center of the ionizer region. Radio-frequency transitions between different hyperfine-structure magnetic substates provide the required polarization of the beams. The rf. loops are located both between and after the focusing magnets. The differentially pumped beam source and the atomic-beam unit are built into one housing including an integrated turbomolecular pump system. This configuration ensures a high pumping speed close to the beam region.

The ion source is equipped with an ECR ionizer in which the plasma is confined axially and radially by a pair of solenoid magnets and a permanent sextupole magnet, end excited by microwave power at 2.45 GHz.

In April 1993 the first polarized protons were accelerated in the cyclotron. The degrees of positive and negative polarization of the extracted 100 MeV proton beam were measured to be 0.55 and -0.45 by a polarimeter based on *pd* scattering.

C. The beam transport system and injection

The ion beams from the two external ion sources are brought to a common horizontal beam line, which takes them to the top of the cyclotron, where they are bent down axially through a hole, drilled through the upper yoke and pole of the cyclotron magnet. Einzel lenses and magnetic quadrupoles are used as focusing elements in the beam transport system. Magnetic dipoles are used for bending the beam. In the vertical part within the upper cyclotron magnet, solenoids are used as focusing elements.

A spiral inflector bends the ion beam into the median plane of the cyclotron.

A buncher is installed to improve the transmission through the cyclotron, which has been as high as 10 % for protons. When the buncher was turned off, the proton transmission went down to 2 %.

IV. CELSIUS

Protons, deuterons, alpha particles and oxygen ions have been stored, accelerated, and exposed to internal targets in CELSIUS. The highest stored beam intensities are 4×10^{11}, 4×10^{10}, 1×10^{10}, and 3×10^{8} of protons, deuterons, alpha particles and oxygen ions respectively. Transmission from the injected intensity (with static magnets and without rf.) to accelerated (up to 2.1 GeV/*c* per charge) beam intensity is typically 25 – 50 %, due to the difference between the phase space area of the maximum rf. bucket which fits inside the CELSIUS momentum acceptance and the total longitudinal emittance of the injected beam from the cyclotron, and to losses during acceleration.

Since the dipole magnets of CELSIUS are not laminated [8], acceleration is performed slowly. This is acceptable for the use of the ring for physics experiments with very thin internal targets due to the long life-time of the stored beams. The machine cycle, which is used during physics runs, is typically five minutes long, with four minutes flat top, and a total of one minute spent for decrease and increase of the magnetic field and for injection.

Many experiments to be carried out at CELSIUS are devoted to studies of reactions with small cross sections. Such measurements require a very low background. A system of 11 pairs of plastic scintillator detectors, which is placed around the ring, has proven very useful to guide the operator while tuning the ring [3]. In addition, one pair of detectors is placed on the straight line going through the axis of the electron cooler, in order to measure the rate of atomic hydrogen, which is produced while cooling protons. This is used as an aid while tuning the electron cooling system. Two detectors, placed at each side of the cluster-jet target, have also been added to the system. These detect protons, which are elastically scattered in the target, and are used as a luminosity monitor.

At low energies (around 300 MeV) the background has been improved by trimming the beam with mechanical scrapers. The mechanical scrapers have not been useful at high energies.

The electron cooling system is used to improve the lifetime of accelerated beams. This is especially important to reduce the experimental background. A recent example (May 1993) is that the lifetime of 280 MeV alpha particles interacting with a neon target of 1.6×10^{13} cm^{-2} was increased from 40 s to 600 s by electron cooling.

A problem, which has made the electron cooling system less beneficial, particularly at the injection energy, where it should be possible to use electron cooling for accumulation, is that there is a rapid loss of stored beam intensity immediately during the first moment of exposure of the stored beam to the electron beam. We have called this effect "electron heating." Recent measurements indicate, that it is due to non-linear resonances, which are driven by the electrical field from the electrons. The diameter of the electron beam is smaller than the size of the stored beam before acceleration. These investigations continue.

V. NEAR FUTURE PLANS

There will be a long shutdown of the Gustaf Werner cyclotron and the CELSIUS ring during the period from August through October 1993. During this period, large cryo-panels will be installed inside the cyclotron, and cryogenic chevron baffles will be installed above the oil diffusion pumps of the cyclotron. This is intended to improve the vacuum in the cyclotron by one order of magnitude to become better than 10^{-5} Pascal (10^{-7} mbar) during operation with the external ion sources and a few times 10^{-5} Pascal during operation with the internal PIG source. This will improve the high-voltage characteristics of the cyclotron and the transmission of heavy ions. At the same time, a new control system will be implemented on the cyclotron [9]. This is the first step toward a unified control system for both CELSIUS and the cyclotron.

At CELSIUS, the shutdown will be used for measures to further reduce the experimental background. One of these will be to replace the vacuum chambers in the quadrupoles in order to increase the aperture near the internal target locations. The shutdown will also be used to mount a new collector on the electron cooling system. The collector is expected to have a collection efficiency which is exceeding that of the present collector, and is going to be built by the Budker Intitute of Nuclear Physics in Novosibirsk, Russia, according to principles developed there [10].

VI. REFERENCES

[1] S. Holm, Proc. 13th Int. Conf. on Cyclotrons and their Applications, Vancouver, Canada, July 6-10, 1992, p. 106.

[2] B. Lundström, B. Holmgren, ibid., p. 553.

[3] D. Reistad et al., ibid., p. 266.

[4] C. Ekström, Proc. 19th INS Symp. on Cooler Rings and their Applications, Tokyo, Japan, Nov. 5-8, 1990, p. 228.

[5] C. Ekström et al., Rev. Sci. Instr. 63 (1992) 2878.

[6] T.A. Antaya, Z.Q. Xie, Jül-Conf-57, 1986, p. 72.

[7] T.A. Antaya, J.Phys.Collo. C1 50 (1989) 707.

[8] G. Norman, D. Reistad, O. Johansson, Proc. 2nd European Particle Accelerator Conference, Nice, France, June 12-16, 1990, p. 881.

[9] K. Gajewski, L. Thuresson, O. Johansson, Proc. Int. Conf. on Accelerators and Large Experimental Physics Control Systems, Tsukuba, Japan, 11-15 November, 1991. p. 78.

[10] A.N. Sharapa, to be published.