STATUS REPORT ON THE GUSTAF WERNER CYCLOTRON IN UPPSALA

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ABSTRACT

The reconstructed Gustaf Werner synchrocyclotron has now been in operation with external beam since May 29, 1987. Until May 1991 it was operating only in the isochronous mode accelerating protons to about 100 MeV and heavier ions to energies corresponding to 200 q^2/A. The main use of the cyclotron has been for physics experiments, proton therapy of malignant melanoma in the eye and arterio-venous malformations (AVM) in the brain, production of isotopes and injection into the CELSIUS ring. In May 31, 1991 a proton beam of 180 MeV was extracted for the first time using frequency modulation but no beam stretching was used. In the beginning of October 1991 work was done to stretch the beam and the results showed that a duty cycle of more than 50 % can be obtained with full repetition rate. The performance of the cyclotron and the obtained results will be described.

1. GENERAL CHARACTERISTICS

The synchrocyclotron was shut down in 1977 for the present reconstruction from cylindrical poles to 3-fold sector geometry. The original ideas were to operate only with frequency modulation using broad band amplifiers. Model measurements, which were started in 1974, showed however that frequency modulation could be restricted to protons above 100 MeV and Helium-3 above 240 MeV. All other ions could be accelerated with fixed frequency. With the sector shape chosen the band-width is about 10 % for the highest energy protons, about 190 MeV.

After installation of the new pole-gap geometry in 1979 the field measurements were started in 1980. The fields were mapped over the useful range, 0.25 to 1.73 T. Vertical focussing is maintained with fields having gradients smaller than 0.2 T/m. The high effect tests of the highfrequency system were started in June 1984 and the field measuring programme finished in June 1985. In December 1985 high vacuum pumping started and in January 1986 high frequency tests of the rf system began. On November 6, 1986 the first internal beam of $^4He^{2+}$ was accelerated and on May 29, 1987 the $^4He^{2+}$ beam was extracted for the first time. About two months were used to optimize the extraction process using a $^4He^{2+}$ beam of 110 MeV accelerated on harmonic 2 and a proton beam of 72 MeV accelerated on harmonic 1. The measured optimum transmission through the electrostatic channel was found to be over 80 % in both modes of acceleration and the total extraction efficiency about 65 %.

After installation of a pair of slits on the first and second turn on the harmonic 1 orbit at the centre of the cyclotron the transmission through the electrostatic deflector increased to nearly 100 % and the total extraction efficiency to over 80 %.

On November 6, 1987 nuclear physics experiments were started and the first eye melanoma treatments were made on April 11, 1989 and presently 20 patients have been treated for eye melanoma and 7 patients for AVM in the brain.

For acceleration of heavy ions an internal ion source was used from the beginning. After installation of the ECR-source, the first alpha beam from the ECR-source was accelerated to the experimental hall on November 20, 1990 and later on the same week a beam of $^{16}O^{5+}$ was accelerated to the same experimental hall for testing of a detector system.

The first extracted beam in the synchrocyclotron mode using regenerative extraction was obtained on May 31,1991, when a beam of 70 nA was extracted using a repetition rate of 70 Hz. The beam was extracted during 7 µsec, which gives a peak current of 140 µA. A special frequency program is used to stretch the beam to prolonge the extracted beam pulse. Calculations have shown that a duty cycle of 40 % can be obtained if the time derivative of the accelerating frequency is changed from 1.6 to 0.03 MHz/msec just before extraction. The beam is then spilled out during 1.3 msec out of a total accelerating time of 3.2 msec. It is also foreseen to increase the repetition rate to 300 Hz which will give an extracted beam of about 0.3 µA.

The first test with slow extraction started the second week of October 1991. The length of the stretched beam was successively increased by lowering the sweep rate at extraction from 0.03 to 0.012 MHz/msec. With a sweep length of 4.2 msec this corresponds to a duty cycle of 52 %.

A problem which has appeared when using high rf-voltage is a vacuum leak to the intermediate vacuum system caused by expansion of the vacuum chamber. To prevent this leak to appear, conical pressure plates have been mounted during August 1991, in order to keep the oring seals under pressure even if the vacuum chamber expands. Tests made at the end of October 1991 with a dee-voltage of 50 kV and a frequency of 24 MHz showed that the leak no longer appears. The RF system is described in a separate paper.

2. ION SOURCES AND BEAM INJECTION

The cyclotron has initially been been equipped with an internal ion source of the cold cathode type. In the c.w. mode, due to the high voltage available, up to 50 kV, the source has a double-arc anode, which permits operation in both first and second harmonic mode without changing the the position of the source. Fig.1 shows the initial medianplane orbits in this case.

In the FM case the highest voltage is 16 kV, which gives sufficient turn separation to clear a closed internal source. A separate geometry is used in this case. By using a special jigg it is possible to change the geometries without breaking the vacuum.Table 1 presents a summary of particles and energies tested so far and available on target.

The external ion source of the ECR-type was buildt in collaboration with the Department of Physics of the University of Jyväskylä in Finland and it is of the same type as the room temparature ECR source at NSCL, East Lancing, USA. The source is vertically mounted and has a plasma chamber of 14 cm diameter and a total length of 82 cm, surrounded by a sextupole of NdFeB permanent magnets giving 0.27 T at the edge of the plasma chamber. An axial field of maximum 0.52 T on the axis of the plasma chamber is obtained by 9 circular coils excited by four 250 A, 60 V and 80 V magnet power supplies. To increase the flexibility in magnetic field variations, additional power supplies will be added to the coils. The original two-stage source has been rebuildt to a one-stage version with an axial injection of the 6.4 GHz micro-wave power. The gas supply to the ion source is provided through a line connected to the main gas bottles and regulated by two stepmotor-driven needle valves. The gases are chosen from a manifold of small gas bottles placed close to the source. The ion source has been tested with the noble gases helium, neon, argon and xenon and with nitrogen and oxygen. An example of charge state distribution of argon

TABLE 1

Ion	Harm	Energy(MeV)	Current (max. extr)
p^+	1	50,55,60,72, 87,94,99,103	10 μA
	2	41, 45	10 μA
H^{2+}	1	100	50 μA pulse
d^+	2	40	1 μA
$^4He^{2+}$	2	50,68,75,113, 120,185	10 eμA
	1	200	1 "
$^{12}C^{4+}$	2	155, 260	200 enA
$^{12}C^{5+}$	2	380	100 enA
$^{14}N^{5+}$	2	340	100 enA
$^{14}N^{6+}$	2	480	60 enA
$^{16}O^{4+}$	3	120	400 enA
$^{16}O^{5+}$	2	300	100 enA
$^{16}O^{6+}$	2	355	60 enA
p^+	1	180, FM 70 Hz	70 nA

ions, analyzed in a 90^0 magnet, is shown in fig. 2. The mixing gas was in this case nitrogen. The data were obtained with a slit opening of 15 mm after the bending magnet. In the case of xenon and a slit opening of 3 mm, the resolution is very much improved with a clear isotope separation within the different charge states.

The ECR source is located in a separate house close to the cyclotron hall and connected to the cyclotron through a 25 m long beam line. A photo of the ECR source is shown at the end of this report. Fig.4 shows the lay-out of the injection beam line. The vertical part of the beam line contains solenoids and steering magnets and a 90^0 bending magnet. In the horizontal part of the beam line quadrupoles and electrostatic lenses are used for focussing and also special iron shieldings to minimize the steering effect of the stray field from the cyclotron magnet. The ion beam is deflected 90^0 down axially through the upper yoke of the cyclotron and finally focussed on a spiral inflector in the median plane using a combination of the field from Glaser lenses and the field in the vertical hole in the magnet yoke.

The spiral inflector is constructed with a ratio of 2.6 between the electric radius, which is the same as the height of the spiral, and the magnetic radius. The highest injection voltage is 20 kV for protons in the CW mode harmonic 1 accerated to 100 Mev, and 12.5 kV for heavy ions accelerated to 50 MeV/nucleon. The central geometry for harmonic 2 and 3 is shown in Fig. 3. When changing from harmonic 2 and 3 to harmonic 1 the spiral inflector is turned 55^0 and a prolonged tip of the dee is installed. In FM mode the highest injection voltage is 6.6 kV and a spiral inflector and a central region of smaller dimensions are used. To increase the intensity accepted by the cyclotron a special bunching system has been buildt. Recent tests have shown that the intensity can be increased by a factor of nearly 5 by using this system. The control of the ECR source and the beam transport system to the cyclotron is made either locally or remotely from the cyclotron control room using a programmable logic controler and a PC system.

A commercially manufactured source for polarized protons and deuterons is installed as shown in Fig. 4. It is specified to deliver beams with up to 20 keV energy with an emittance of 55 mm-mrad[MeV]$^{1/2}$ and a figure of merit $p^2I >$ 41 μA for protons and $p^2I >$ 18 μA for deuterons, where p is the polarization and I the intensity.

3. BEAM EXTRACTION

For extracting the beam two different methods are used:

- In CW mode, when the accelerating voltage is sufficiently high, precessional extraction is used.
- In FM mode regenerative extraction is used.

The main deflecting elements are an electrostatic deflector (ESC) and an electromagnetic channel (EMC). The beam enters first the deflector which has a carbon septum with a thickness of 0.5 mm. Here the beam gets a radial deflection by the electric field between the septum and the high voltage electrode, which causes it to jump the 5 mm thick current septum of the EMC, which is placed 20 degrees from the exit of the ESC. In the EMC the field is reduced by up to 0.25 T. The increased orbit curvature inside the channel directs the beam through the fringe field of the magnet. Before leaving the magnet, the beam passes a radially focussing, passive channel and a radial steering magnet, which is used to align the beam along the axis of the beam transport system.

When precessional extraction is used, a small first harmonic component of the field is used to displace the orbit centre of the beam as it passes the radial resonance $Q_r = 1$ close to extraction. As Q_r decreases when the beam is accelerated into the fringe field, the beam starts to process, which creates a turn separation of the orbits, propotional to the displacement of the orbit centre and the precession frequency. Due to the fall-off of the magnetic field, the whole procedure is accompanied by a slip of phase, which sets a lower limit to the dee voltage which can be used for this mode of extraction. Another important factor is the presence of the Walkinshaw resonance ($Q_r = 2Q_z$), a coupling resonance between the radial and the vertical motion, which can cause a vertical blow-up of the beam if it is too much off centre. Special harmonic coils are used to eliminate the unwanted first harmonic component in the field and to add the wanted one.

When regenerative extraction is used the extraction point lies at a smaller radius where the phase shifts are unimportant. Therefore this method is suitable in the FM mode where the energy gain approaches zero for some particles. Two more magnetic elements have then to be inserted before and after the EMC: a "peeler" (P) and a "regenerator" (R). The peeler gives a negative gradient of max 250 G/cm and the regenerator a positive gradient of max 300 G/cm. If certain conditions are fulfilled concerning the azimuthal width and the strength of the peeler and the regenerator gradients, the radial oscillation frequency, Q_r , is locked to 1 when the beam is accelerated into these field gradients. As the energy increases, the beam approaches an unstable fixpoint in the radial phase plane, becomes radially unstable and the turn separation starts to grow approximately exponentially, while the vertical motion is kept stable. The calculation shows that this type of extraction gives a smaller emittance but a somewhat increased energy spread.

4. VACUUM SYSTEM

The pumping system for high vacuum consists of two baffled diffusion pumps each giving with the baffles 9000 l/s and for the intermediate vacuum, where the trimcoils are located, a diffusion pump of 700 l/s. They are backed by a Roots-pump of 1000 m^3/h. The pumping is fully automized by means of an industrial programmable controller of type Modicon 484.

5. DIAGNOSTIC SYSTEM

The diagnostic system consists of two radially moving probes, placed at opposite sides of the cyclotron and are used to measure the beam intensity at different radii. One of them is located after the electrostatic deflector to allow measurements of the extraction efficiency and to control the transmission of the beam through the electromagnetic channel and the focussing channel to the external beam. Before and after the electromagnetic channel secondary emission foils are placed for alignment purposes. Four-sector probes are placed on the entrance to the focussing channel and at the beam exit. They are normally not hit by the beam, but used in the procedure of optimizing the setting of the deflecting elements.

6. CONTROL SYSTEM

The control system is based on the use of distributed microprocessors arranged at three levels, the lowest being integrated in the equipment and the middle taking care of whole subsystems such as magnets, rf-system, diagnostics etc. The main computer is connected to the control console and takes care of setting and reading parameters via a database. The safety system is based on industrial programmable controllers. Via a special bus system the computer can read on-off status and registers in the controllers and also set special status bits. A separate computer system is used for the radiation protection and the interlock system.

7. EXPERIMENTAL FACILITIES

Fig. 5 shows a view of the entire experimental area which is used for experiments with the beam from the cyclotron. A specification of the beam lines to different experimental halls is given in table 2. Each beam line contains scanners or viewers to be used for beam diagnostics and Faraday cups which can be inserted at strategic positions for measuring the beam intensity. Heavy radiation shielding between the halls permits access to halls adjecent to beam holding areas.

Beam line A

The irradiation facilities in the Crypt consist of a system containing a viewer plate, which is moved into the position where the target will be placed and used for controlling and trimming the beam position and size. When this in done the target is moved into place for irradiation. A rabbit system is connected to the target mechanism, by means of which the irradiated target can be transported to a nearby placed hot cell. Special water tanks are placed on both sides of the target to moderate the neutron flux from the target.

Beam line B

Beam line B brings the beam by a 30 degree bend up to the level of the experimental halls: Blue Hall, Bio-Medical Hall and the Gamma Hall. The Marble Room is used as a switch-yard for the beam to different experiments such as (n,p) to study isovector multipole resonances with the spectrometer LISA. The pair spectrometer PACMAN, in which intermediate energy photons are produced in the target by the reaction ^{11}B(p, gamma)^{12}C, features large solid angle, wide momentum bite, excellent energy and angular resolution and efficient background rejection to enable measurements of cross sections of a few nb/sr.

TABLE 2

Beam line	Area	Activity
A	Crypt	Irradiation facilities
B	Marble Room	Neutron production Switchyard
	Blue Hall	PACMAN, LISA spectrometers
C	Beam corridor:	Beam transport to: Bio-medical experimental areas, Gamma hall, CELSIUS
D	Blue Hall	Spectrometer physics
E	Beam Dump	Irradiation Facility
F	Beam corridor	Injection line for CELSIUS
G,H	Bio-Medical	Bio-Medical Experiments Hall
I,K,L	Gamma Hall	Heavy Ion Experiments
Y	C-hall, Ion-source room	Injection of heavy ions and polarized particles

Beam line C

Beam line C is used for transporting the beam to the Bio-Medical areas, to the Gamma Hall and to the injection line for CELSIUS.

Beam line D

The beam line D is used for spectrometer physics with the renovated High Energy Spectrometer Magnet(HESM)

Beam line E

The beam line E takes care of remaining charged particles after the beam has passed through the neutron target. In addition to the beam dump, a facility for irradiation of materials
is planned.

Beam line F

The beam line F starts in the beam corridor by a downward bend to a 0.74 m lower level. It is bent 90 degrees by means of three 30 degree magnets to enter the CELSIUS hall, leaving space for experimental equipment in the gamma hall.

Beam lines G, H and I, K, L

A switching magnet in the beam corridor is used to direct the beam to the beam lines G and H, which are used for radiotherapy with narrow and broad beams and to the beam lines I, K and L which are used for experiments with heavy ions.

Beam line Y

The beam line Y is from the external sources. Special iron hubs are used to screen off the stray magnetic field from the cyclotron magnet.

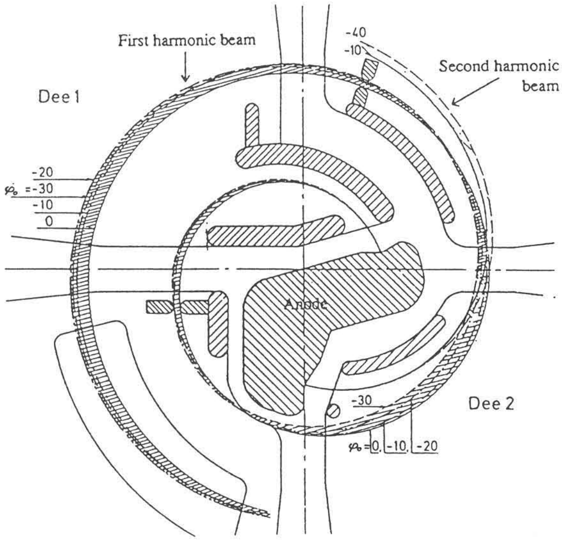

Fig. 1. Central region in the CW case with internal ion source. Double arc anode permits operation both with first and second harmonic.

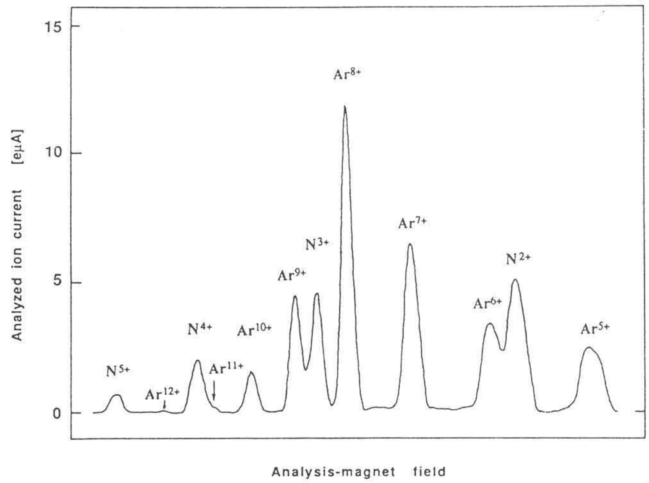

Fig. 2. Charge state distribution of argon ions analyzed with a 90-degree magnet.

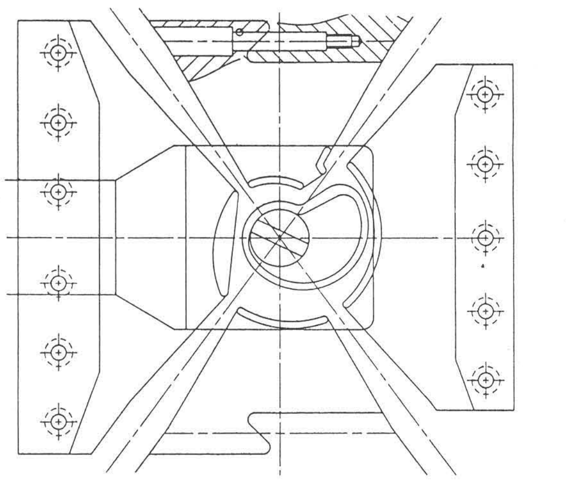

Fig. 3. Central region for harmonic 2 and 3 with external injection.

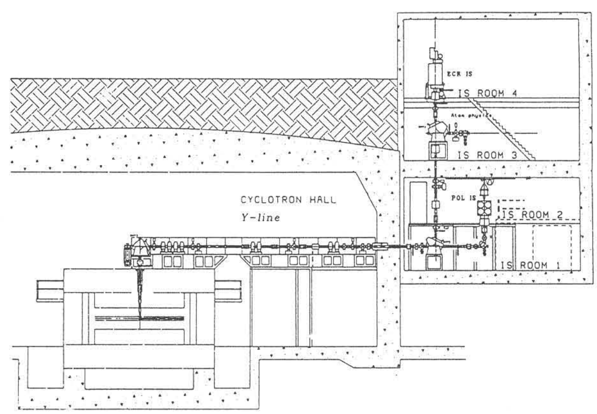

Fig. 4. Lay-out of the external beam line

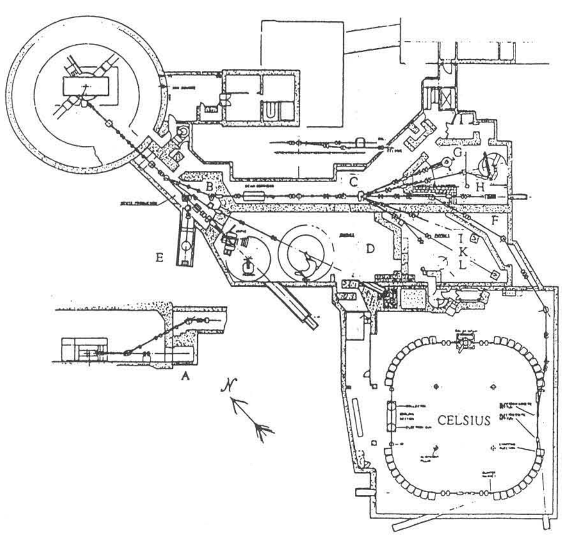

Fig. 5. View of the accelerators and the experimental areas as described in table 2.

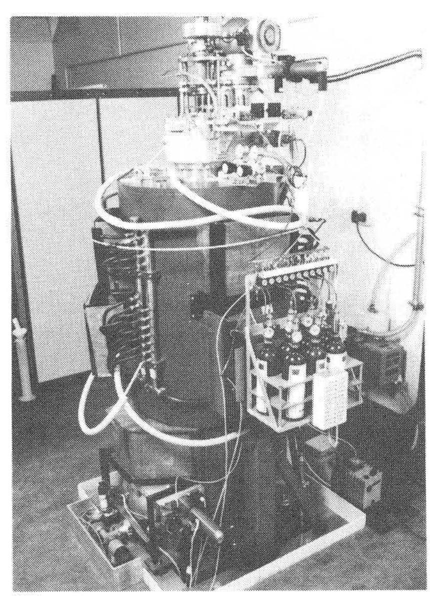

Fig. 6. Photo of the ECR source