OPERATIONAL EXPERIENCE OF THE RECONSTRUCTED UPPSALA SYNCHROCYCLOTRON

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Abstract. The reconstructed Gustaf Werner synchrocyclotron is now in operation as a variable energy, multi-particle, sectorfocussed cyclotron. The initial operation has been in a constant frequency, isochronous mode in which protons can be accelerated to a maximum of 110 MeV and heavy ions up to 200 Q^2/A MeV. The beam was first extracted at the end of May 1987 and the first nuclear physics experiments with protons and alpha-particles were made in November 1987. The obtained performance of the cyclotron facility is described and the future plans are discussed.

1. INTRODUCTION

The Gustaf Werner synchrocyclotron has been reconstructed from a classical synchrocyclotron with cylindrical poles to a sector focussed cyclotron which can be operated both in a constant frequency, isochronous mode and in a frequency modulated, synchrocyclotron mode[1),2)]. The cyclotron is one of three accelerators at the national accelerator centre in Uppsala, the The Svedberg Laboratory(TSL)[3)].

The synchrocyclotron was shut down in 1977 when funds were available to start the reconstruction programme for the cyclotron and to build the new experimental areas. The programme for the cyclotron comprised a complete rebuilding of all parts: the installation of a three sector pole geometry and trim coils, a new vacuum chamber, a new central region with a PIG ion source, an extraction system with electrostatic and magnetic channels and an rf-system capable of operating at fixed frequency with a high Q-value on the resonators and with modulated frequency with up to 10 % bandwidth.

The first internal beam in c.w mode was accelerated on November 6, 1986 and by completion of the extraction system the beam was extracted on May 29, 1987. About two months were used for optimizing the precessional 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 beam lines to the different experimental areas and to the CELSIUS ring were successively completed and by November 1987 the first nuclear physics experiment could start. Regular shift operation started in January 1988 with 5 shifts per week and this has successively increased to 15 per week. 80 % of the beam time is used for nuclear physics, 8% is used for solid state physics and isotope prodection. From March 1988 the beam has been delivered routinely about 12% of the time to the biological area for developement of equipment and procedures for treatment of malignant melanoma in the eye. Injection tests into the CELSIUS ring were started in May 1988.

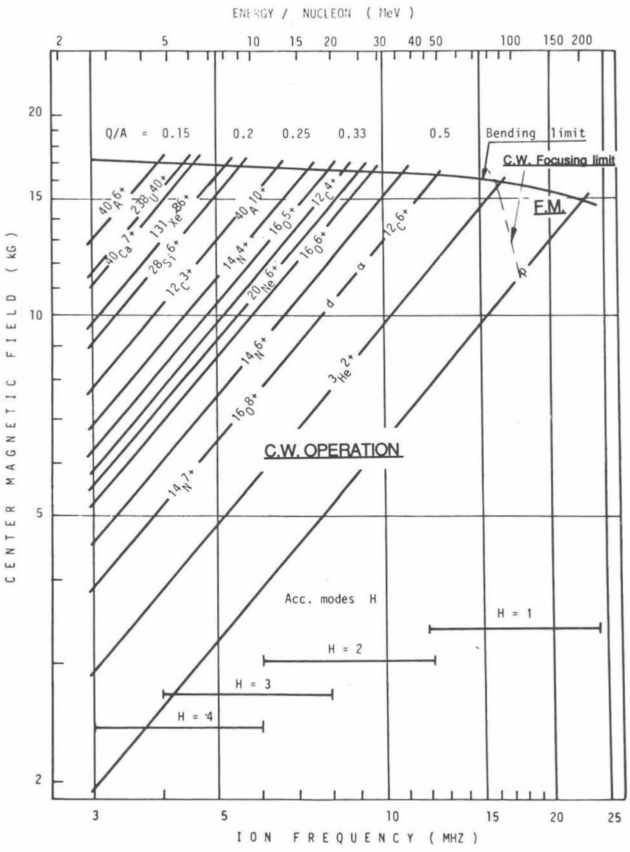

Fig. 1. Energy per nucleon, centre magnetic field and ion frequencies for some ions.

2. CYCLOTRON CHARACTERISTICS

Fig. 1 shows the basic characteristics of the beams for the rf frequency range 24-12 MHz, harmonics 1 to 4. The number of acceleration turns, required to reach the full energy is around 2400 when accelerating in c.w. mode on harmonic 1 and around 600 when accelerating on harmonic 2. Focussing limits in c.w.mode are for protons 110 MeV and for ^3He 250 MeV. Acceleration of protons to energies above 110 MeV requires frequency modulation with a bandwidth increasing to 10 % at 200 MeV.

Fig. 2 shows a median plane view of the cyclotron. A special feature of the cyclotron is that two different methods are available to extract the beam namely precessional and regenerative. For the latter method a "peeler" can be inserted behind the electrostatic deflector giving a field reduction with a gradient of 250 G/cm over an azimuth of 10 degrees and a "regenerator" behind the electromagnetic channel (EMC) giving an increase in the field by 300 G/cm over an azimuth of 12 degrees.

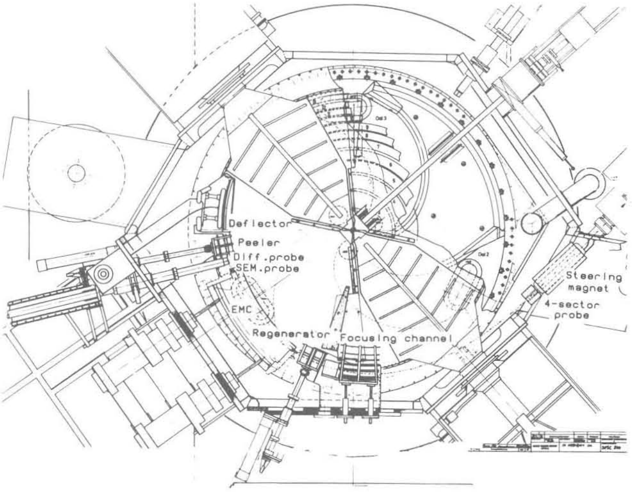

Fig. 2. Median plane wiev of the cyclotron

For measurements on the internal beam two differential probes are available. For alignment of the beam correctly two SEM-foils are mounted in front of the EMC and a 4-sector probe in front of the focussing channel and the steering magnet at the beam exit.

Fig. 3 shows the cyclotron as seen from the beam exit side with the horizontal beam line to the isotope production room and a 30 degree upward bend to the experimental areas for physics and biology and for injection into the CELSIUS ring. A Faraday Cup and a viewer at the cyclotron beam exit are followed by a quadrupole doublet, a fast closing valve, a graphite collimator system, a steering magnet and a slit system for emittance measurements.

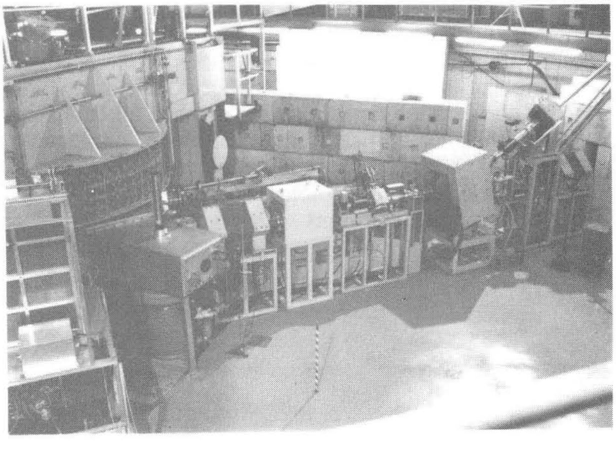

Fig. 3. Cyclotron seen from the beam exit side.

3. OPERATING RESULTS

After the first successful extraction, a test period of about two months was used to tune the beam and to optimize the extraction process. A $^{4}He^{2+}$ beam of 110 MeV accelerated on harmonic 2 and a proton beam of 72 MeV accelerated on harmonic 1 were used. The measured optimum transmission through the electrostatic channel was found to be over 80 % in both modes 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 close to 100% (No detectable beam losses measured with internal beam probes, remaining uncertainty due to secondary electrons) and the total extraction efficiency increased to over 80 %.

For tuning the cyclotron to a new particle energy, precalculated trimcoil settings are used. These are calculated using field data measured at five field levels. Linear interpolation between the fields is used. As a consequence very small trimming in the settings was required for field levels close to the measured ones, while somewhat more trimming was required for interpolated fields to get a proper phase behaviour. It is foreseen to use a higher order interpolation in the future to improve on this point.

The beam emittance has been measured at the exit of the cyclotron by means of a movable slit and a multiwire probe and found to be 9π mm-mrad full width in both planes on rf harmonic 1. The energy spread was measured on a 50 MeV proton beam by means of a solid state detector.With correct tuning of the cyclotron the measured Δ W/W is 2.10^{-3} FWHM. A slight mistuning of the cyclotron can cause an increase of this value, for example if parts of two precessional cycles are extracted simultaneously. The table 1 presents a list of all particles end energies tested so far and available on targets. To obtain new intermediate energies in general only a few hours are required for finding the correct setting of the rf-system and to optimize the extraction process.

Table 1

Ion	Harm	Energy(MeV)	Current (max. extr.)
p+	1	50, 60,72,90,100,105	10 µA
$^{4}He^{2+}$	2	50, 68,75,113, 120, 185	10 eµA
	1	200	
$^{12}C^{4+}$	2	155	200 enA
$^{16}O^{4+}$	3	120	100 enA
$^{16}O^{5+}$	2	320	100 enA

Internal $^{4}He^{2+}$ currents of 100 eµA have been accelerated, limitation in radius beeing the beam power on the measuring probes. With the ion source operating in a pulsed mode, peak currents of 700 µA have been measured close to the centre of the cyclotron. When such a beam is accelerated it represents a steadily increaseng load to the rf-system beeing 70 kW at 100 MeV. This causes the dee voltage to drop as the response time to rf-voltage regulation presently is not short enough. So far about 100 µA peak current have been extracted. Improvements on this point are of interest, especially for injection into the CELSIUS ring.

So far only precessional extraction has been tested, the reason beeing that the heavy experimental program has given very little time for development of the cyclotron. According to calculations regenerative beam extraction will give a smaller beam emittance but a larger energy spread. Presently all elements required for this type of extraction are installed and tests can hopefully be made in a near future.

The experimental programme comprises presently (spring 1989) six different projects in physics, one clinical project with narrow beam, namely treatment of malignant eye melanoma, two projects for production of isotopes in addition to the injection tests for the CELSIUS project. One important aspect in the operation of the cyclotron has therefore been to obtain high reproducibility. This is in particular important for the bio-medical project, as the beam has to be delivered to the treatment room exactly on time and with identical properties each time. A special safety system has been developed by means of which the dose given to the patient is controlled and which can shut off the beam when this dose is reached. Only a few nanoamps are required for the treatment which takes only about 25 seconds giving a local dose of 1500 rads. A maximum dose rate is set for the system and tests with a one thousend times increased intensity showed that beam was shut off before one permille of the maximum dose was given.

To obtain the required reproducibility the cyclotron magnet is always turned on in the same way, namely the current is increased to maximum and kept there for a given time and thereafter reduced to the required value. The beam transport magnets, quadrupoles as well as dipoles are also cycled up to maximum current in the same fashion.

4. EXPERIMENTAL FACILITIES

Fig. 4 shows a view of the entire experimental area to be used for cyclotron experiments. A specification of the beam lines connected to separate experimental halls is given in Table 2. Each beam line contains scanners and/or viewers to be used for beam diagnostics and Faraday cups which can be inserted at strategic positions along the beam lines to enable beam blocking and control of beam intensity.

Heavy radiation shielding between the halls permits access to halls adjacent to beam holding areas.

Table 2

Beam line	Area	Activity
A	Crypt	Irradiation Facilities
B	Marble Room	Neutron Production, Switchyard
C	Beam Corridor	Beam Transport to Bio-Medical Exp. Areas, Gamma Cave, CELSIUS
D	Blue Hall	Spectrometer Physics
E	Beam Dump	Irradiation Facility
F	Beam corridor	Injection line for CELSIUS
G,H	Bio-Medical Hall	Bio-Medical Experiments
I,K,L	Gamma Cave	Heavy-Ion Experiments

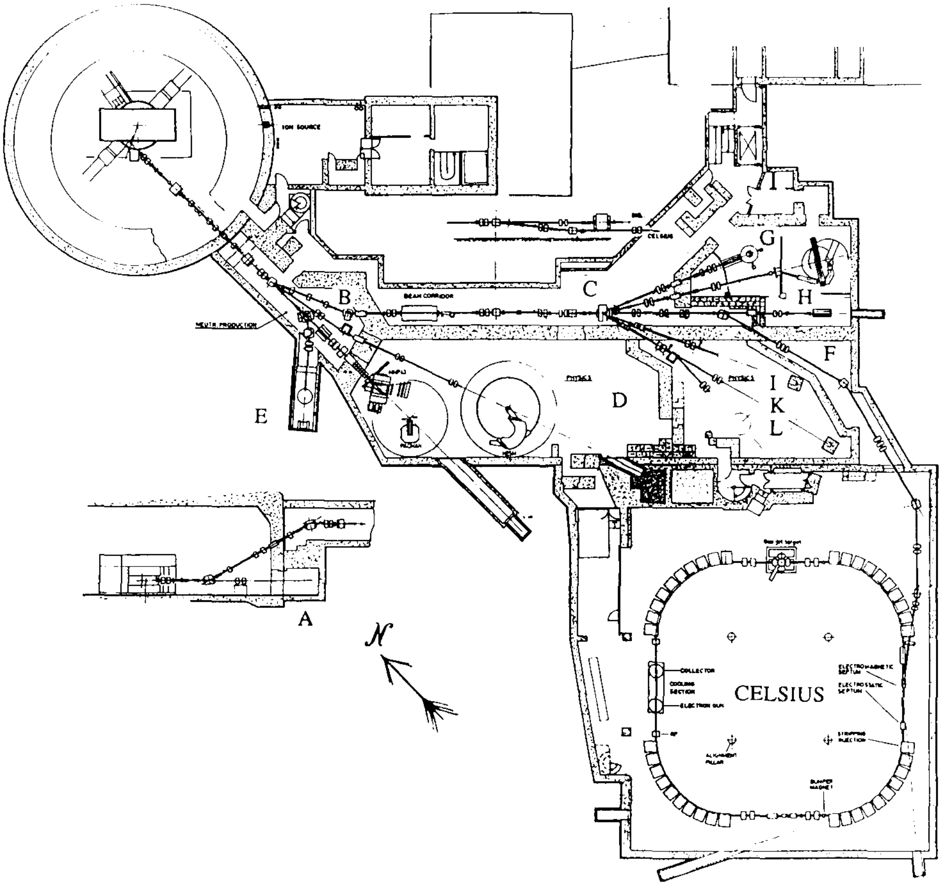

Fig. 4. Plan view of the facility with cyclotron hall, experimental areas and CELSIUS hall.

5. FUTURE PLANS

5.1 F.m.operation

The first tests with frequency modulation using a 4 kW broad band preamplifier with one dee system will be made during the time of this conference.A linear frequency sweep generator will be used for this test, the goal being to obtain a dee-voltage of 12 kV over a 1 MHz band, 20-19 MHz. The second test period will be after the summer shut-down when a programmable frequency generator, detectors and amplitude modulators will be tested. During the third test period both dee systems will be tested simultaneously, a special problem will be the functioning of phase-meters and phase-modulators with swept frequency. Hopefully acceleration can be tested in the fourth test period during the autumn.

5.2 External injection

An external heavy-ion source of ECR type is under construction for the cyclotron. The source is of similar construction as the room temperature ECR source at the superconducting cyclotron at NSCL, East Lansing, USA. In addition there is planned an external source for polarized protons and deuterons which is specified to deliver beams with up to 20 keV energy with intensities up to 50 µA within an emittance of 55 mm mrad$[\mathrm{MeV}]^{1/2}$ and with polarization higher than 75% of the theoretical values.

The polarized source will be placed in a room adjacent to the cyclotron vault and the ECR source in a separate building which has been buildt above the room for the polarized source. The ECR source will be used both for atomic phycics and for injection into the cyclotron. A beam transport system common for both sources will bring the beam to the vertical injection line to the center of the cyclotron. The construction of the ECR is carried out in Jyväskylä, Finland and the source will be delivered to Uppsala in May 1989. The polarized source is beeing purchased commercially and the delivery and installation are expected during 1990.

A preliminar lay out of the injection system is shown in fig. 5. A combination of quadrupoles, solenoides and einzel-lenses will be used as focussing elements. A pulsing system will be placed in the horizontal beam line and a buncher system in the vertical line in the cyclotron. The inflector will be of the spiral type to be used in harmonic 2,3 and possibly 4. A combined operation with an internal source will be required in the beginning for acceleration on harmonic 1.

References

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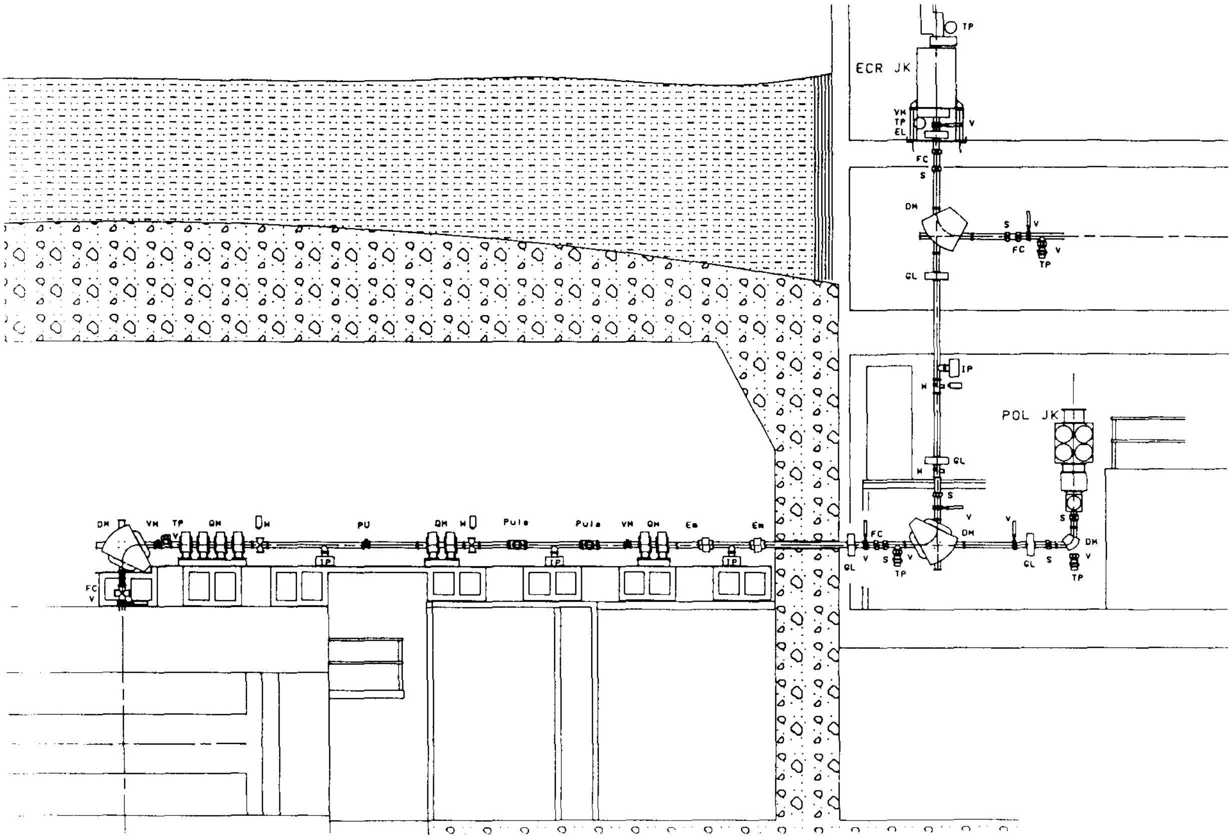

Fig. 5. Preliminar lay-out of the injection beam line