THE UPPSALA SYNCHROCYCLOTRON AND STORAGE RING PROJECT

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Summary

The Gustaf Werner cyclotron will after reconstruction operate both as a synchrocyclotron and as an isochronous cyclotron with K=200. A ring CELSIUS for storing, cooling and accelerating ions from the cyclotron is being built. The ring is mainly intended for experiments with thin internal targets. The status of both projects will be reviewed.

Introduction

A Swedish national accelerator center is being established in Uppsala, based on three different accelerators: the existing tandem van de Graaff, the synchrocyclotron under reconstruction and the CELSIUS ring for storing and cooling ions injected from the cyclotron.

The improvement program for the 185 MeV Gustaf Werner synchrocyclotron started in 1977 and aimed at the construction of a three-sector, variable-energy cyclotron. The necessary new buildings were approved and funded by the government in May 1981. Early in 1983 the power supply and control rooms were finished, and in May 1984 a 650 square meter area for physics and biomedical research will be completed. The present time plan predicts external ion beams from the cyclotron in the summer 1985.

CELSIUS, a storage ring with cooling capability will be connected to the cyclotron. The 1000 square meter hall, constructed to house this ring, is expected to be completed in February 1985. Injection of cyclotron beams into CELSIUS may start as early as in 1986.

Layout

The floor plan of cyclotron, cooling ring and experimental areas is shown in Figure 1. Note that all dedetails are not reproduced. For instance, the beam lines are not fully dressed, the injection into CELSIUS only indicated and the CELSIUS spectrometer much simplified.

Most of the buildings shown are below ground and closely surrounded by a number of other university buildings. The proximity to other houses has in fact been a major difficulty and explains much of the special features of the general layout.

Beam transport

Figure 1 shows the various beam lines planned. An isotope production area is located on the same level as the cyclotron. All other experimental positions will be about 5 meters above the cyclotron floor and the

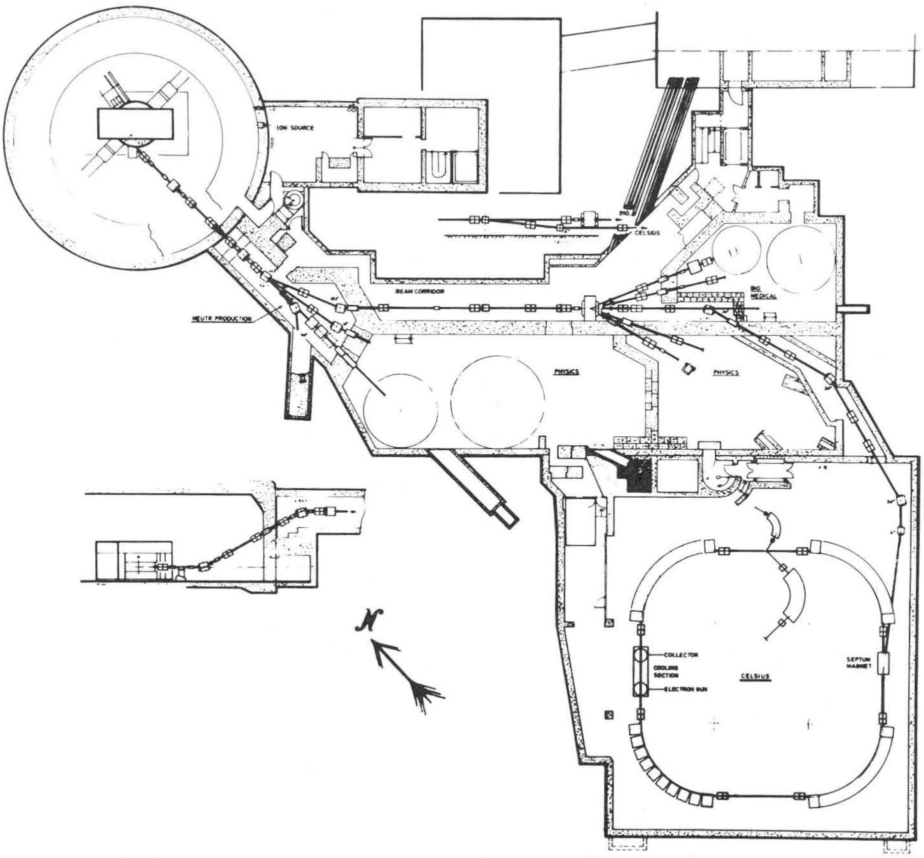

Figure 1 Floor plan of the cyclotron, the CELSIUS ring and the experimental areas.

beam will be brought to this level by two 30 degree magnets. The first target room will be used for neutron production. After this comes the physics area, which is divided into one room with two spectrometers, one 135 degree ion spectrometer and one pair spectrometer and finally a room for low-background gamma measurements. The biomedical research will be supplied with four different beam lines: broad and narrow beams as well as a micro-beam.

The beam transport line from the cyclotron to CELSIUS is over 100 meters long and made nearly achromatic, not to increase the good beam emittance from the cyclotron. Two switching magnets will allow short injection intervals into CELSIUS to minimize interference with other beam users, independent of what target position they may use.

The cyclotron

The reconstructed cyclotron will be able to operate either with frequency modulation or at fixed frequency. The FM mode must be used for protons in the energy range of 110 to 200 MeV, while protons of lower energy and heavier particles can be accelerated in CW mode. Figure 2 shows the energies obtainable for various particles.

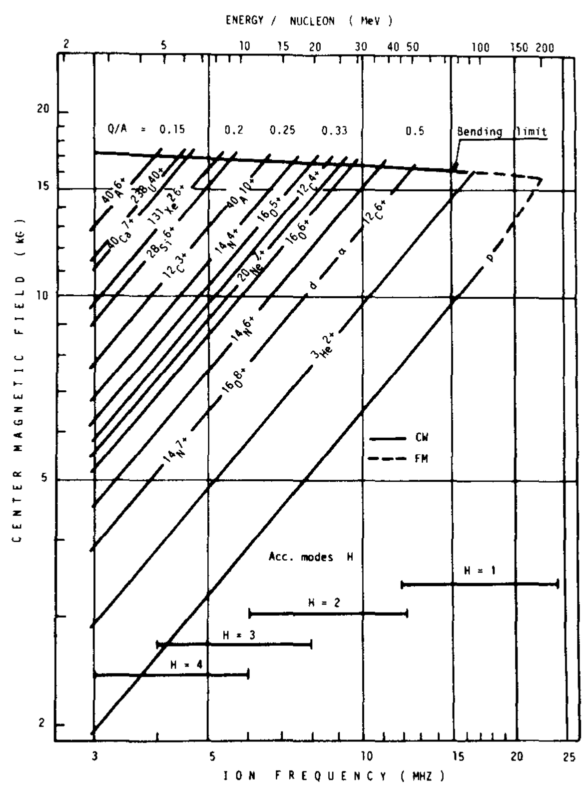

Figure 2 Final ion energies vs ion frequencies and harmonic number. Bending limit is shown.

The K value of the cyclotron has increased from 185 MeV to 200 MeV by the modified pole geometry. Protons in the very highest energy range (i e above 185 MeV) will be reached only at reduced modulation frequency due to the increased bandwidth requirements.

A plan of the cyclotron is shown in Figure 3.

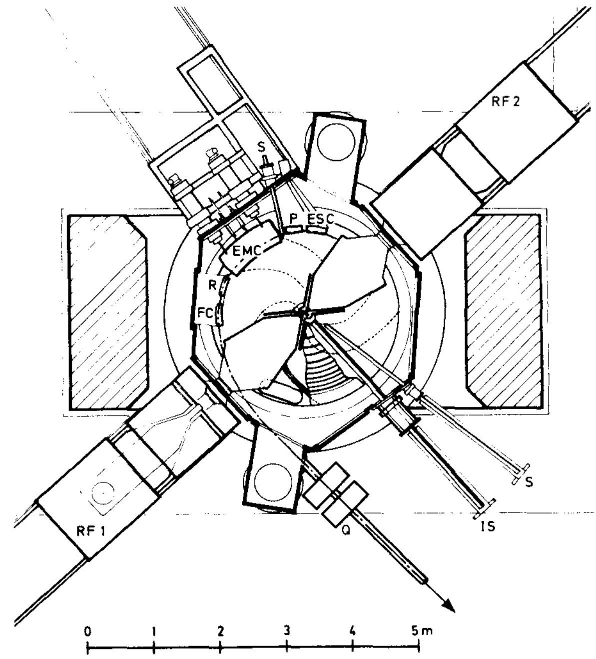

Figure 3 Cyclotron median plan with main components.

In addition to the installation of the new polegap geometry several modifications of the magnet were made:

- The main coils were reconditioned by resoldering all joints, about 1100, and by moulding the coil pancakes in epoxy.
- The thickness of the vertical yokes were increased by adding 5 cm of iron to the inner sides.
- A hydraulic lifting system was installed, which can lift the upper yoke and pole. This facilitates the installation of the vacuum chamber and other components in the pole gap.
- The central hole through the upper magnet yoke was enlarged and suitable vacuum seals installed in order to facilitate the installation of a vertical injection line.

A three-sector polegap geometry which is now installed was studied in an extensive set of field measurements and orbit calculations on a 1:4 model. The design philosophy for the field was given in ref [1].

The field of the full scale magnet has been mapped over the useful range of the cyclotron, from 2.5 to 17.3 kGauss. Some additional shimming was necessary in the central region to get the proper ν_z behaviour. In the extraction region detatchable parts of the hill sectors have been used for fine trimming of the field fall-off. Careful alignment of the pole plates and the hill sectors has resulted in a first harmonic field content of less than 5 Gauss. A microprocessor controlled system with 67 Hall plates is used for field mapping. The system permits a complete field map of 24000 points to be measured in one hour with an overall accuracy of one Gauss. Field measurements remain to be made of the trim coils, which so far only have been studied in model scale, and the extraction elements.

The acceleration will be performed by two identical RF system of the "master oscillator+power amplifier" type in both CW and FM modes (Fig 4).

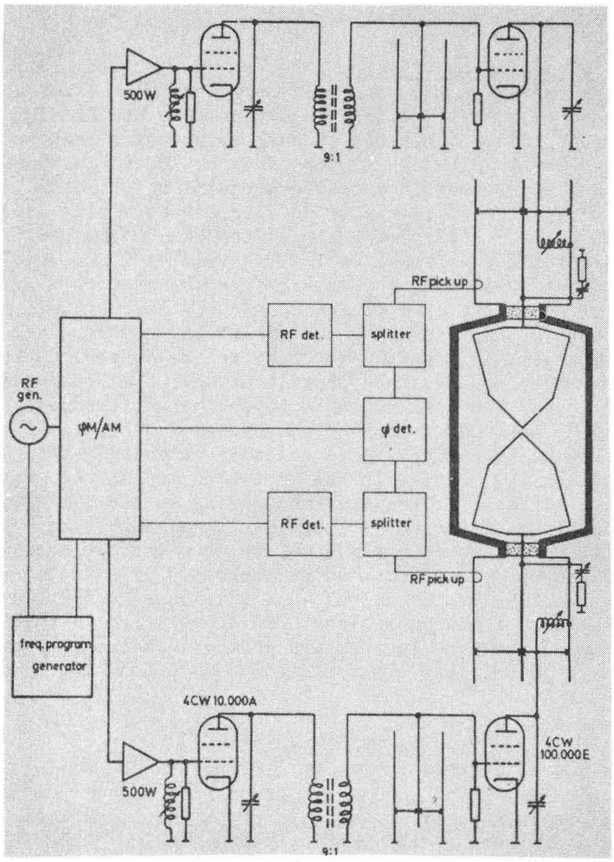

Figure 4 Block diagram of the RF system.

The amplifier chain of each system consists of a 1 kW, a 10 kW and a 100 kW stage. The systems are tunable from 12 to 24 MHz for operation on the harmonics number 1, 2, 3, and 4. The dee electrodes have an azimuthal width of 72 degrees at the center and 42 degrees at extraction. Built around a strong but light, supporting structure of stainless steel and clad by sheet copper (Fig 5), they are cantilevered from the vacuum feed-through and tuned by moving shorts in air. The equiva-

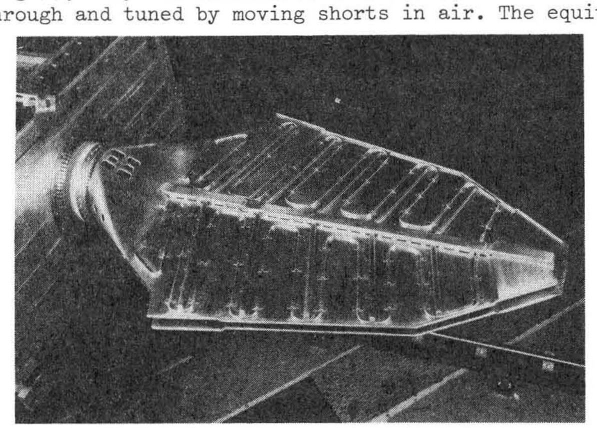

Figure 5 The dee electrode.

lent dee capacity is about 315 pF at 24 MHz. The natural quality factor is reduced in FM mode from about 2000 to 100 by connecting a 40 kW resistor in parallel to the dee stem. The maximum dee voltage is approximately 50 kV in CW mode and 12 kV in FM mode. The final amplifiers (capable to withstand an anode dissipation of 100 kW in the FM mode) are inductively coupled to the dee resonators and move together with the dee tuning shorts on a rail (Fig 6).

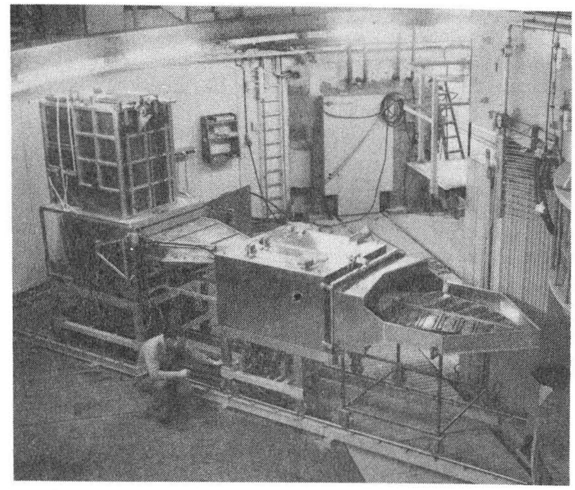

Figure 6 RF system: from left to right amplifier dee cavity tuning section and dee electrode in test chamber.

In the FM mode an anode modulator will have to be used to avoid excessive power loss in the final RF stage. A solution to this problem is to series connect the two 180 kW anode power supplies which have been constructed at GWI, and add an electronic modulator.

The cyclotron will initially be equipped with an internal PIG ion source with a double arc chimney for operation in both first and second harmonic with the same geometry. Due to the difference in dee voltage between FM and CW operation, different sized geometries have to be used. There are also plans for external injection. A special ion source room has been built for this purpose outside the cyclotron hall.

Beams will be extracted from the cyclotron with either regenerative or precessional techniques. A layout of the regenerative extraction system was proposed in an early study [2]. The two main deflecting elements are an electrostatic deflector (ESC) and an electromagnetic channel (EMC) (Fig 3). A passive focussing channel (FC) will be placed in the fringe field about 20 degrees downstream from the exit of the EMC. The ESC will operate with a maximum field of 125 kV/cm over 5 mm. The EMC, which is placed 20 degrees downstream from the ESC, will give a field reduction 2500 Gauss over an aperture of 20 mm. The 5 mm thick septum, which has an upper and a lower half, carries a current of 5 kA.

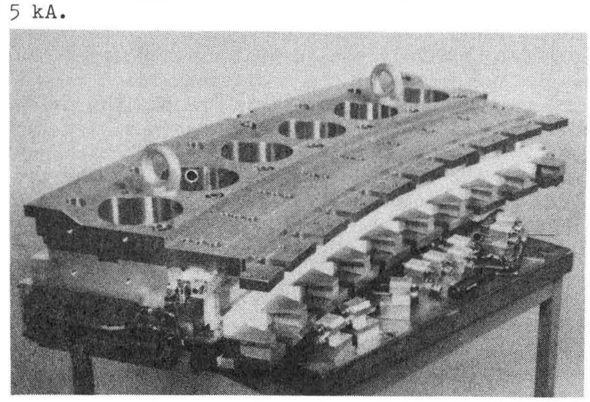

Figure 7 The electromagnetic channel (EMC).

Regenerative extraction will be used when operating in FM mode and in some cases of first harmonic CW operation when the energy gain per turn is low. A peeler (P) and a regenerator (R) will then be inserted before and after the EMC, respectively.

The vaccum chamber is designed with a prevacuum part housing the epoxy moulded trim coils. The construction material in the chamber is an aluminum alloy. In the high vacuum region most of the seals consist of soft aluminum wire. Conventional pumping by diffusion pumps backed by roots pumps is foreseen for the initial operation. The calculated ultimate vacuum lies in the 10^{-7} Torr range.

The cyclotron will be computer controlled with distributed microprocessors, organized at three levels. At the lowest level the processors (TMS 9995) will be integrated in the equipment serving both local control and communication with the higher level. The processors in the middle level will take care of the different systems such as magnet, RF and so on. The main computer (TMS 990-12) is connected to the control console and helps the operators to set and read the data bases in the lower systems.

Expected cyclotron performance

In Table 1 the expected performance of the reconstructed cyclotron is summarized, assuming an internal ion source. Estimated current for heavy ions are based on results from other cyclotrons.

Table 1

Ion	Energy (MeV)	Acc mode	Extr meth	Energy res %	Hor emitt mm-mrad	Estim intens (eμA)
P	110-200	1-FM	Reg	0.22	6-8	10-1
P	45-110	1-CW	Reg	0.5	4-5	40
P	45-110	1-CW	Prec	0.17	20	40
$^{3}He^{2+}$	250-267	1-FM	Reg	0.22	6-8	2
$^{3}He^{2+}$	137-250	1-CW	Reg	0.5	4-5	20
$^{3}He^{2+}$	35-137	2-CW	Prec	0.17	20	20
D	25-100	2-CW	Prec	0.17	20	40
$^{12}C^{4+}$	133-267	2-CW	Prec	0.17	20	5
$^{16}O^{5+}$	167-312	2-CW	Prec	0.17	20	10
$^{20}Ne^{7+}$	223-490	2-CW	Prec	0.17	20	0.1

When operating with frequency modulation the phenomenon most likely to limit the current will be space charge close to the centre of the cyclotron. Based on a simplified calculation of that limit the maximum external proton current in the high energy range will be around 10 μA. For CW acceleration of P and D beams, assuming conservatively 80 percent extraction efficiency, a maximum septum power of 1 kW will permit a 40 μA external beam. For heavier ions the ion source will be the limiting factor.

The ΔE values given for the FM case have been calculated assuming radial amplitudes less than 4 mm and a dee voltage for 185 MeV protons of 12 kV. Both the radial amplitudes and the accelerating voltage influence the energy spread of the external beam in the regenerative case. The smallest ΔE value possible for a given radial amplitude will be reached for the lowest accelerating voltage. The influence of the accelerating voltage is seen in Table 1 when comparing regenerative extraction in CW and FM modes; the latter uses a lower dee voltage. Comparing the radial emittance values of the extracted beam one finds that the regenerative method gives smaller values.

The cyclotron as injector

In FM operation the beam will be pulsed with a maximum frequency of 1000 Hz. For injection into the CELSIUS ring it may be desirable to have short pulse lengths in order to minimize the number of injection turns. The number of protons in a beam pulse will be at most $6 \cdot 10^{10}$, which is likely to suffice for most ring uses. With normal setting of the cyclotron in "short burst operation", the bucket half width will be 25 μs, the shortest pulse length possible from the cyclotron with a filled bucket. Due to the conditions for particle capture at the center of the cyclotron, however, the bucket will in practice be empty in the center. Cyclotron orbit studies have shown that the unfilled bucket will cause the beam pulse to be shortened, typically from 25 to 8 μs. A further reduction of the pulse length is possible by adiabatically increasing the accelerating voltage in the cyclotron and at the same time the rate of frequency change. As an example with a doubling of the dee voltage during a short time prior to extraction, which may be done without excessive power loss, df/dt can be increased by a factor 2.9 without loss of particles. This will cause a further reduction of the pulse length to about 3 μs. In this example, the time for capture at the cyclotron center was 12-17 μs. Thus the cyclotron caused bunching by a factor 5.

The CELSIUS Ring

The use of intense co-moving electrons for improving the properties of ion beams, first proposed by Budker in 1966[3], has become a topic of great interest and importance. The usefulness of the cooling technique in medium-energy physics was clearly demonstrated by the Indiana University Cyclotron Laboratory in their 1980 proposal for a Cooler described by Pollock[4]. After completion of the ICE (=Initial Cooling Experiment) project at CERN, the opportunity arose late in 1982 to acquire the magnets for use as part of a cooling and storage ring in Uppsala. An agreement was signed between CERN and Uppsala University, initiating the CELSIUS (=Cooling with ELectrons and Storing of Ions from the Uppsala Synchrocyclotron) project. Funds have been available for the project since 1983.

Building of the hall for the CELSIUS ring was recently begun and is expected to be completed in February 1985. The ring magnets and vacuum chambers have been transported from CERN and are now stored in Uppsala. All other components of the ring will be constructed in Uppsala and elsewhere. The design is not yet completed in all details, so that the numbers given in the following should be treated with some caution. The aim is to be able to inject the first ions into the ring in 1986. It is foreseen that a relatively long time will be needed to learn how to operate the machine. Early discussions on the research program indicate a need to use the ring to cool and accelerate light particles, such as protons or deuterons, but also to attempt cooling and acceleration of moderately heavy ions, perhaps up to mass numbers around 40.

Lattice

The ring will consist of four quadrants, the 90 degree bends being performed by ten closely spaced bending magnets with radially focussing (F) or defocussing (D) gradients. Two 9.3 m straight sections will be available for experiments and the remaining two 9.6 m straight sections will be used for injection and electron cooling. The present lattice calculations have assumed reflection symmetry about both experimental target positions and a supersymmetry of two. It may turn out that one would like to run under other conditions, e g it might be desirable to have only one

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straight section with especially small beta function, i e with a supersymmetry of one.

The bending magnets will be arranged in a pattern somewhat different from that used in ICE, namely DFDFDDFDFD (instead of DDFFDDFFDD). One quadrupole singlet will be added in the high-beta (injection and cooling) straight section and two quadrupole singlets in the low-beta section. This will give three adjustable parameters and all lattice calculations made so far have been limited to such cases. However, it is expected to be advantageous to have at least three additional adjustable parameters if requirements from the experiments are to be met. In ICE all D magnets were supplied with pole face windings, mainly for gradient adjustments. For CELSIUS a similar solution is being studied.

The CELSIUS straight sections are 2.0 (1.7) m longer than those in ICE but in spite of this it is clearly necessary to economize hard with straight section space. The necessary addition of sextupoles and higher multipoleswill thus largely have to be made in the combined function manner, e g quadrupoles and poleface windings may be designed to contain large sextupole field components.

CELSIUS will probably be run in a number of different tunes in order to match various experimental requirements. Calculations have indicated this to be feasible. In the following only one "reference" case will be mentioned, which was constructed to have large beta values at the injection and cooling sections and small beta values at the experimental targets. Also the dispersion was made close to zero in the cooling region. Only values from this reference case will be quoted in this paper (Table 2). The lattice functions for this case are shown in Figure 8 and the beam size for a typical injected beam before cooling in Figure 9. The horizontal acceptance is limited by the extent of the good-field region and the vertical acceptance by the height of the vacuum chamber.

Table 2 Some CELSIUS Parameters

Magnet ring	
Circumference	81.76 m
Maximum rigidity (at 2500 A)	6.25 T·m
Maximum power	815 kW
Bending radius	7.0 m
Working point for reference case	
Q_H	1.376
Q_V	2.824
γ_{tr}	1.914
In center of high-beta section	
β_H	10.43 m
β_V	8.85 m
D	0.39 m
In center of low-beta section	
β_H	0.326 m
β_V	0.333 m
D	6.502 m
Acceptance	
horizontal	40π mm·mrad
vertical	140π mm·mrad
Radiofrequence system	
Length .5 m	
Frequency range .7 to 5.0 MHz	
Voltage 2 kV	
Number of ferrites 8	
Electron cooling system	
Electron energy nominal	101 keV
Electron energy maximum	300 keV
Electron energy minimum	20 keV
Electron intensity	1.3 A
Electron temperature about	.1 eV rms
Electron beam diameter	0.02 m
Cooling straight section	2.5 m
Confining field	0.1 T

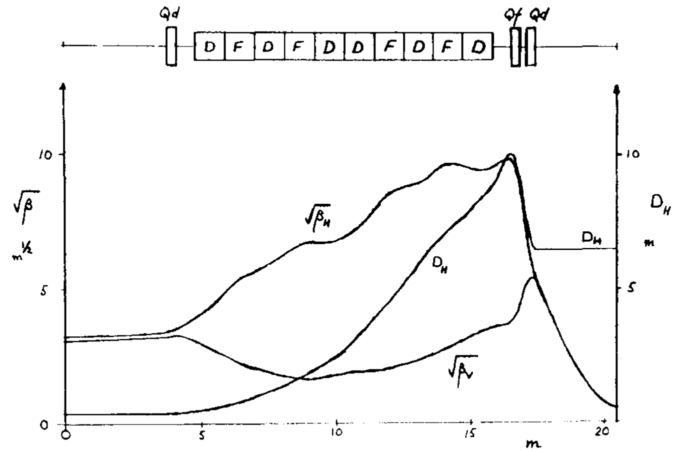

Figure 8 Beta functions and dispersion in one quadrant.

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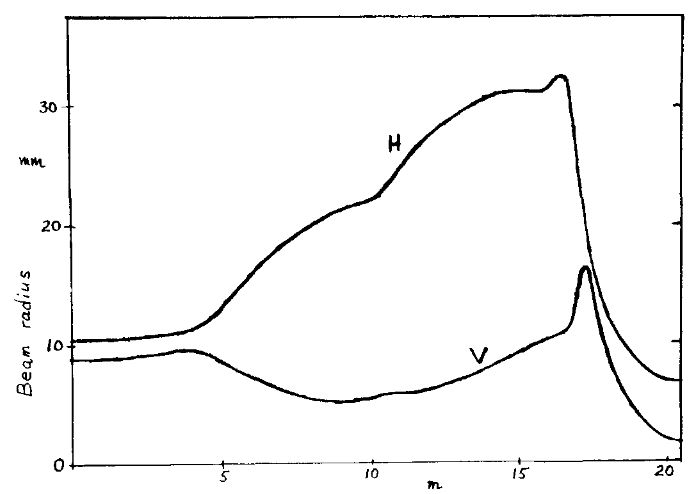

Figure 9 Half axes of uncooled beam with emittance and momentum spread typical for injection.

<u>Non-linear dynamics</u>
The studies of non-linear phenomena have only just begun but it is clear that strong sextupole fields must be added to correct for the chromaticity. Calculation of chromaticity (with the programme MAD) with no addition of correcting sextupoles but taking into account the effects of the sextupole components in the bending magnets, in the magnet gaps and in the fringe field regions at the ends of the 90 degree bends has yielded

$$Q'_H = -28.6$$

$$Q'_V = -3.3$$

The injected momentum spread is expected to be small (about .1 %) but even so the chromaticity should be reduced significantly by introducing corrections in the form of suitable sextupole fields.

Injection

The Gustaf Werner cyclotron has both advantages and limitations as an injector of ions (protons, deuterons, helium ions and other moderately heavy ions) into CELSIUS. The magnetic rigidity is limited to about 2.06 T·m, and, before better ion sources are installed, only low charge-states will be available for the heavier ions. Partially stripped ions accelerated in the cyclotron can be completely ionized by foil stripping before injection into CELSIUS. The low energy per nucleon of the heavier ions, i e low velocity, will require that the ring be operated at low magnetic fields, and also, if electron cooling is required before acceleration, that the electron cooling system can be operated at low voltages. The RF system must be able to handle the low frequencies associated with these heavier ions.

A significant advantage of using the cyclotron in FM mode for injection appears to be that high instantaneous beam intensities will be reached and thus complicated beam stacking in the ring may be avoided. By pulsing the ion source, similar results will be reached in the isochronous mode.

The technical details of the injection into CELSIUS have not been settled. Multiturn injection with the use of a number of bumper magnets will be attempted, requiring electromagnetic as well as electrostatic septa.

Electron cooling

The electron cooling system will be similar to the system studied at Fermilab [5]. The electron gun and collector will be bent 90 degrees by magnetic fields to coincide with the ion beam. The system will be optimized for 101 keV electrons, i e the energy corresponding to directly injected protons at 185 MeV.

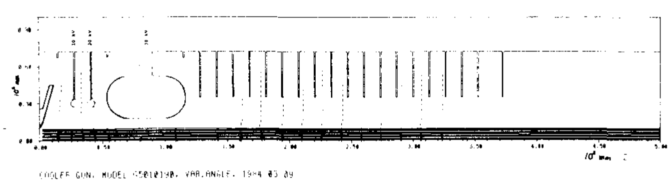

Figure 10

The design of the electron gun is almost completed (Fig 10). The anode to cathode voltage will be kept constant at 30 kV and variable energies reached through the use of an accelerating (decelerating) tube. Computer studies indicate that for the model gun transverse temperatures less than .1 eV rms can be achieved at 100 keV, and that the performance is only slightly worse at 300 or at 20 keV. The addition of an adjustable lens at the end of the acceleration tube is expected to improve the situation mainly away from 101 keV. It may be remarked that some numerical difficulties with existing computer programs of relevance for situations with well defined strong space charges have been remedied.

The maximum electron energy of 300 keV limits the energy of cooled protons to 551 MeV and ^{3}He to 550 MeV per nucleon. The energies for all other ions are magnetic field limited under the present circumstances. At a later stage an electron system suitable for cooling 1.2 GeV protons will be attempted.

RF system

The requirements on the RF system are relatively modest. The voltage needed for acceleration is indeed very small due to the slow acceleration process. A reasonable adiabatic capture efficiency is desirable and this means at least 2 kV. The choice for the frequency band was made so that all ions under present consideration can be accelerated either on the first or the second harmonic.

Vacuum

In order to achieve a favourable ratio of target interactions to collisions on residual gas atoms, very good vacuum will be required (10^{-11} to 10^{-12} Torr). A combination of sputter ion and sublimation pumps will be used.

Control system

The control system will be based on CAMAC units and an LSI 11/73 computer. The software and most hardware will have great similarities with existing systems at CERN (Linac and LEAR).

Acceleration

The acceleration process must be kept slow because of the non-laminated nature of the main bending magnets. Eddy currents must not be allowed to alter the field shape more that what can be tolerated in order not to lose the beam. Estimates based on measurements with compensated coils, and also calculations (6), indicate that a field increase by a factor of two should be possible in 10 seconds with so small changes in quadrupole and sextupole field components that the beam should stay stored. It is obvious, however, that much time and effort will have to be devoted to learning how to run the CELSIUS ring in cycles including acceleration.

The maximum field will be limited by the magnet current power supply to 0.89 T corresponding to a proton energy of 1158 MeV or a deuteron energy of 388 MeV per nucleon.

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