THE RF SYSTEM OF THE GUSTAF WERNER CYCLOTRON/SYNCHROCYCLOTRON

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ABSTRACT

The RF system of the reconstructed cyclotron has two modes of operation, CW mode (isochronous cyclotron) and FM mode (synchrocyclotron). In CW mode the two dee resonators work on f_{rf}/f_{ion}=1, 2 or 3. The RF frequency is variable in the range 12.25-24.5 MHz and the maxiaml dee voltages are 50 kV. In FM mode, which must be used for protons above 105 MeV, the same two dee resonators are used on fundamental frequency in the range 17-24.5 MHz as "broadband" systems without synchronously tuned cavities with FM bandwidths up to 2.2 MHz and dee voltages up to approx. 15 kV. The dee electrodes are phase locked during the FM sweep and are also used to stretch the beam macro pulse, a duty cycle of 50 % has so far been achieved for 180 MeV protons. Power consumption per system is 50 kW in CW mode and 140 kW in FM mode. The system has been in use in CW mode since 1987 and in FM mode since 1991.

1. GENERAL CHARACTERISTICS

The old Gustaf Werner Synchrocyclotron (operating from 1949 to 1977) was a conventional synchrocyclotron with a single dee tuned by a rotating capacitor from 33 MHz at start of acceleration to 26 MHz at extraction. The repetition rate was limited by the capacitor to 250 Hz, and could accelerate protons only to a fixed energy of 185 MeV. The improved accelerator should be able to accelerate a variety of ions to variable energies, and the solution found was a combination of isochronous cyclotron and sector focussed synchrocyclotron. For the RF system it was chosen to use two dee electrodes each covering an electrode angle from 72 degreees at centre to 45 degrees at full radius (Figure 1).[1) This permits operation on fundamental frequency as well as on harmonic numbers 2,3 and possibly 4 with a reasonable energy gain per turn (Fig. 2).

The introduction of sector focussing and cylindrical trimcoils makes isochronous acceleration possible for all particles except protons above 105 MeV and $^3He^{2+}$ above 260 MeV where frequency modulation still is required, but with a much smaller bandwidth. For 180 MeV protons the rel. bandwidth reduced from 24 % to 9 %[2)]. This makes it possible to avoid synchronously tuned dee cavities and instead use the power tubes as a broadband amplifiers.

All equipment inside the cyclotron vault is the same in both modes of operation with exception for the dee tips, which together with the other parts of the central region can be exchanged using an air lock and a remote handling mechanism. The RF synthesizer, detectors, modulators and preamplifiers are at present completely exchanged between FM and CW operation (the RF coaxial cables to and from the cyclotron vault are simply reconnected from one system to the other). The block diagram is esentially the same for the two modes of operation (Fig. 3).

2. THE DEE RESONATOR

The shape of the dee electrode was determined after full scale model tests. The dee is supported from the vacuum feedthrough and consists of a stainless steel structure clad by copper. The dee has an equivalent capacitance of approx. 300 pF and is tuned to $\lambda/4$ resonance by a shorted coaxial line outside the vacuum feedthrough with a movable short circuit plate (inner conductor 220 mm diameter, outer a rectangular box 1100x700 mm resulting in a characterisitc impedance of 120 Ω). The tuning range is 12.25 -24.5 MHz, and the Q value is at 24 MHz approx. 1600. Highest required dee voltage is 50 kV peak, corresponding to a short circuit current of 2500 A peak and a power loss of 30 kW. The short circuit plate (movable only with RF off) has beryllium copper spring contacts to the outer conductor and a pneumatic system to the inner conductor, where the linear current density is 36 A/cm. The vacuum feedthrough is equipped with a system to "swing" the dee with beam on to optimize the position of the dee with respect to the central region. A damping system dissipating up to 40 kW used in FM operation is located close to the inner end of the tuning box, and a fine tuning system (a plunger from the short circuit plate) is used in CW mode (Figs. 4 and 5).

3. THE FINAL AMPLIFIER

The final amplifier uses the tetrode Eimac 4CW100,000E in grounded cathode configuration. The filament has DC heating (3-phase full wave rectifier) and is RF grounded by kapton disc capacitors. The control grid is tuned to resonance by a variable stub and is terminated to 50 Ω, which gives a bandwidth sufficient for the FM operation. The anode is tuned by a variable vacuum capacitor and is coupled to the dee resonator through a tapered air coaxial line ending in a variable stub inside the dee resonator, serving as an inductance mutual to both cavities. The final amplifier moves together with the tuning plate of the dee resonator. The power supplies for the control grid bias (200-500 V, 100 mA), screen grid (1500 V, 1.2 A) and anode (4-12 kV, 15A) are all located more than 50 m from the cyclotron. The DC cables for anode and control grid enter their cavities from the low voltage end and require no RF chokes, only DC blocking capacitors (a cylindrical 5000 pF kapton capacitor built on coppered soft iron couples the anode to the resonator line, and also serves as a magnetic shield for the tube, which has to operate in a position where the stray field exceeds 200 gauss). A problem in the final amplifier was a self oscillation at 1.1 GHz, which was solved by filling the volume between control and screen grid connecting rings of the tube with ferrite.

4. THE RF SYSTEM IN ISOCHRONOUS MODE

The CW system is a conventional master oscillator-power amplifier system. The two coupled tuned circuits (anode and dee) produce an anode impedance curve vs. frequency with two peaks, and in CW mode operation is normally on a peak close to the dee resonator frequency, whereas the anode is detuned a few MHz to give the desired voltage transformation between anode and dee electrode. The RF amplitude and phase control is "standard" with voltage pickups (both inductive and capacitive) on the dee resonators used for control loops for amplitude and dee-dee phase together with other pickups (anode, control grid etc.). Fine tuning during operation is achieved by a servo system using the anode-to-grid phase signal as input. The fine tuning range is small, it corresponds to a movement of 1 mm on the main shorting plate at all frequencies, and the reponse time is of the order of a few seconds, which is enough to cover for the temperature drift but not for mechanical vibrations. The voltage stability is of the order 1/10000 and the dee voltage control loop has a bandwidth exceeding 10 kHz. The CW system has been in operation since 1987.

5. THE RF SYSTEM IN SYNCHROCYCLOTRON MODE

The FM system is more unique. There are no variable tuning elements used during the FM sweep, the frequency modulation is performed electronically. This has been performed previously in a smaller scale at CERN in the Micro-SC with a single dee electrode. The frequency source in the FM mode is a numerically controlled oscillator (NCO, Stanford Telecommunications STEL-2172) operated with a 2^{28} Hz (268.435456 MHz) clock oscillator (Fig. 6). The NCO is programmed during the frequency sweep by a computer memory 32 bits wide (of which 28 bits used for frequency program and the rest for triggers) and 32k long clocked at 1/40 of the master clock, giving a time resolution of 150 ns for the frequency program and a max. sweep time of 5 ms. Additional memories (clocked at 1/8 of the frequency program clock, time resolution 1.2 µs) are used to load six 12-bit DACs to give the analog waveforms required for dee voltage reference programs etc. The memories are loaded from an IBM compatible PC. The RF signal is amplified in broadband transistor preamplifiers with a peak output power of 4 kW.

In FM mode the dee resonators and the anodes are tuned to the centre frequency of the FM band, giving an anode impedance with two peaks, one close to the initial frequency and one close to the final frequency. Approx. 40 kW can be added to the dee resonator losses at 15 kV dee voltage by damping systems consisting of a pickup loop, a varaiable series capacitor and a water cooled 50 Ω resistor. This reduces the Q value from 1600 to 160 and gives a smoother shape on the phase transitions from input RF signal to dee voltage which occur when a peak is passed during the FM sweep (Fig. 7). Since the two dees have to be phase locked during FM acceleration the differences between the two systems must be minimized to allow the dee-dee phase control loop to be able to handle the phase transitions.

Broadband systems are very power consuming, the power is proportional to the equivalent electrode capacitance and the FM bandwidth[3]. The dee capacitance (approx. 300 pF, reduced as much as possible by cut-back of electrode angle, reduced aperture where possible and by mounting supporting structure and cooling pipes on the outside of the dee). Using fixed anode voltage supplies (so far the two anode supplies have been used in series operation in FM mode to provide a DC voltage of more than 20 kV) a max. dee voltage of 16 kV peak over a band 24.2 to 22 MHz would require more than 250 kW per system. Since the anode can tolerate only 100 kW and the dee resonator 40 kW some means to reduce power is necessary. The simplest solution is to reduce the time of operation at full dee voltage. Since most physics experiments require a beam macro duty factor better than that normally achieved in a synchrocyclotron beam stretching is necessary. To achieve this the FM frequency source is programmed to reduce df/dt during extraction and simultaneously the accelerating voltage is reduced to approx. 5 kV, keeping the phase stable "bucket area" constant. RF power is thus reduced to negligible levels during this time, which is an order of magnitude longer than the acceleration time, and hence the necessary reduction in duty cycle of the RF system is achieved (Fig. 8). A future solution for experiments requiring higher beam currents and higher repetition rates will be the use of amplitude modulation on the anode supply voltage using a pulse width modulation system similar to that of modern high power AM transmitters.

During 1991 first beams to experiments where delivered using the FM system. Typical extracted beam currents so far have been 1nA/Hz, and repetition rates up to 300 Hz have been used for short beam pulses and 170 Hz with macro duty cycle exceeding 50 % (Fig. 9).

6. REFERENCES

1) S. Dahlgren et al., "Conversion studies for the Uppsala Synchrocyclotron" in Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975) p.127-131

2) S.Holm, P-U Renberg, Magnetic field design for a combined fixed frequency and frequency modulated cyclotron, GWI-PH 8/78,1978

3) R. Giannini, A. Susini: Optimisation des paramètres des systèmes accélérateurs HF à large bande, CERN 68-18, 1968

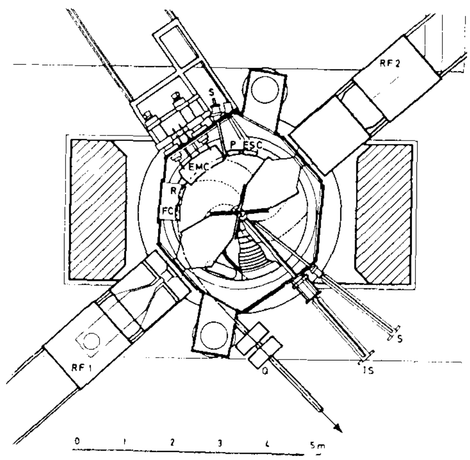

Figure 1. General layout of the cyclotron and the dee electrodes

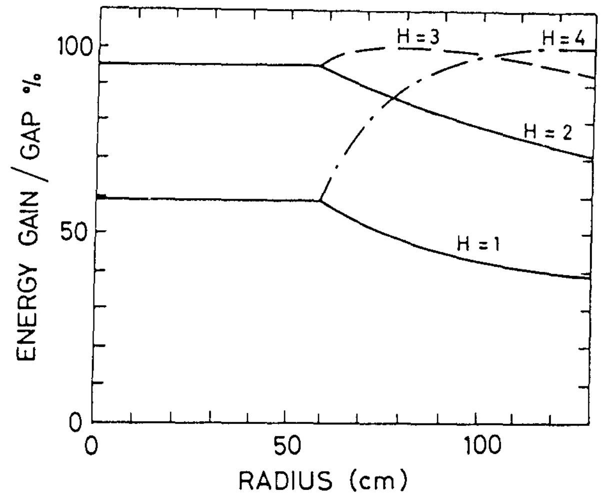

Figure 2. Energy gain per turn vs. radius for different values of H = f_{rf}/f_{ion}

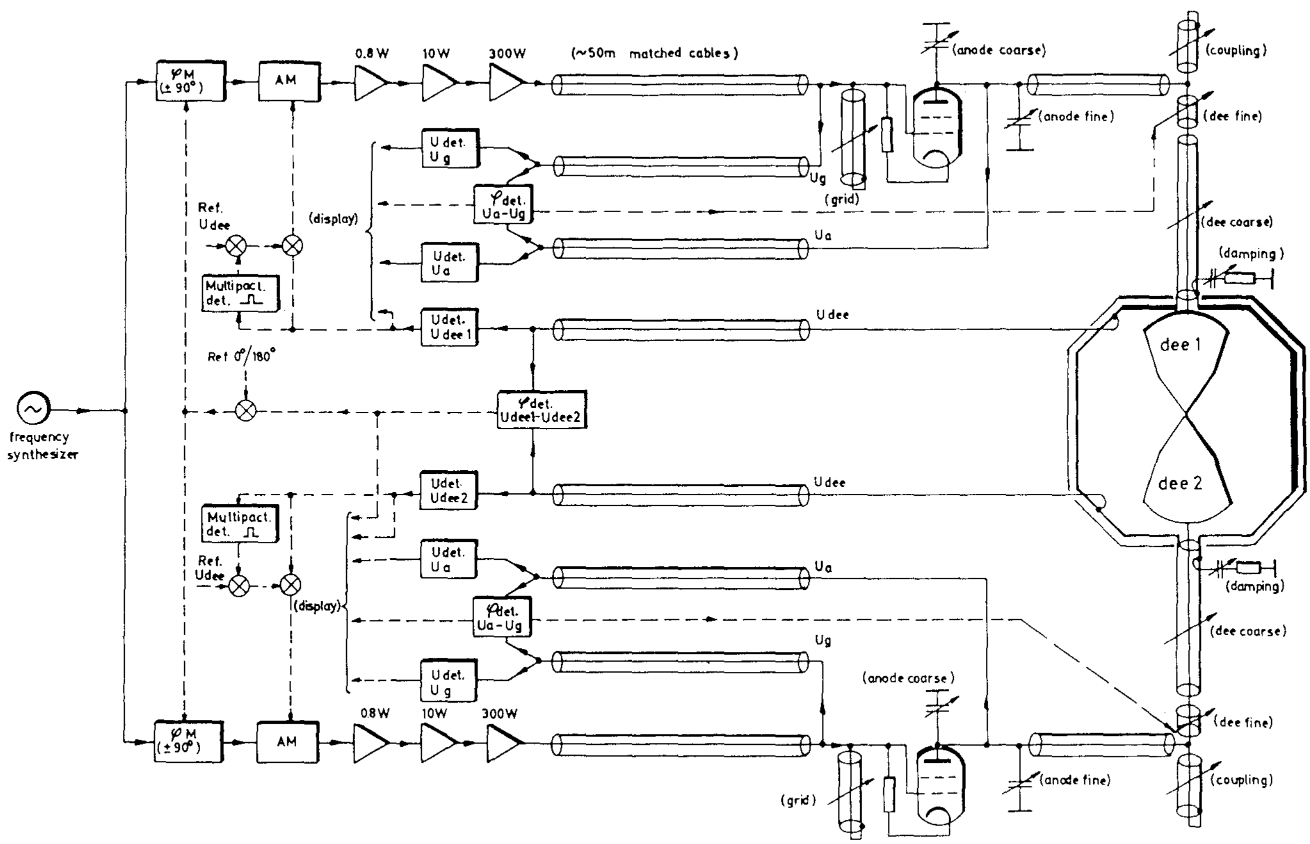

Figure 3. Block diagram of the RF system (CW mode)

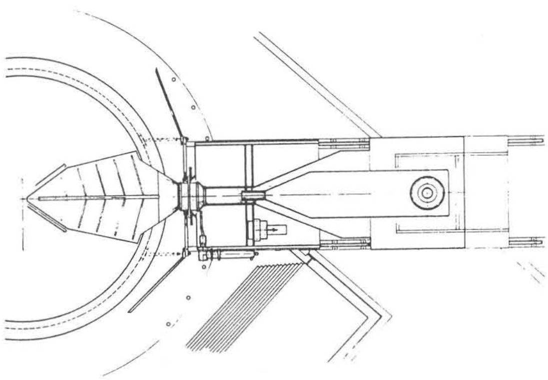

Figure 4. Top view of one RF system.

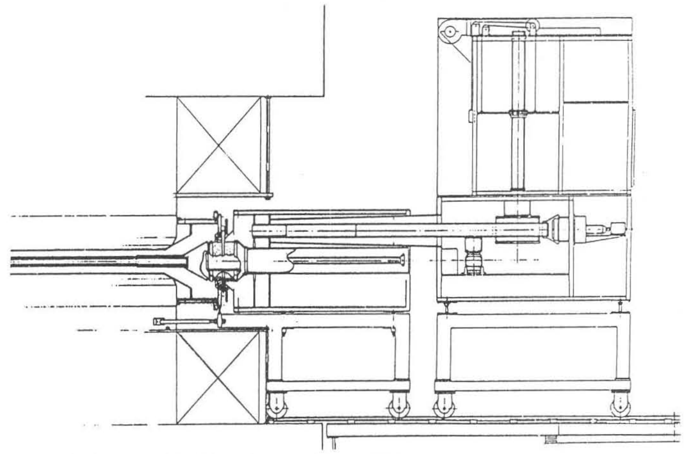

Figure 5. Side view of one RF system.

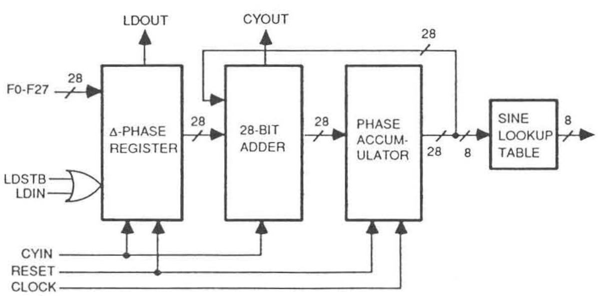

Figure 6. Numerically controlled oscillator (FM source).

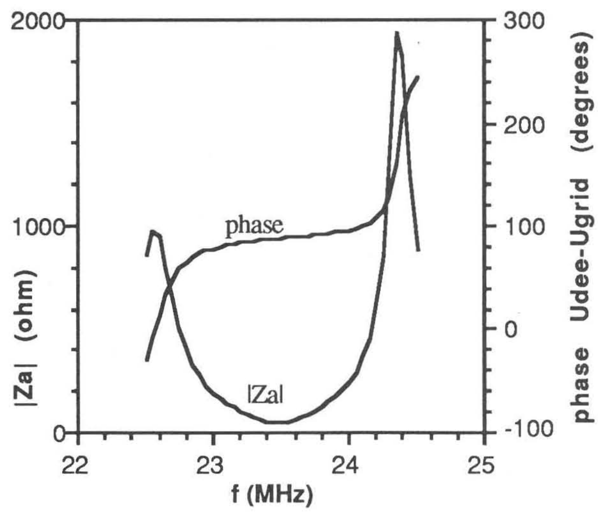

Figure 7. Anode impedance and phase between dee voltage and control grid.

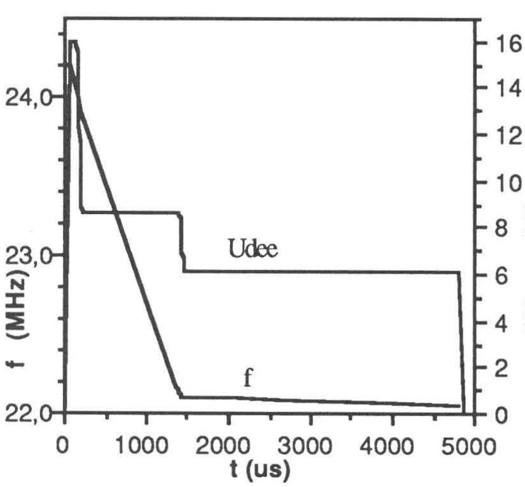

Figure 8. Programs for f(t) and $U_{dee}(t)$ used for 180 MeV protons with macro duty cycle of 50 %.

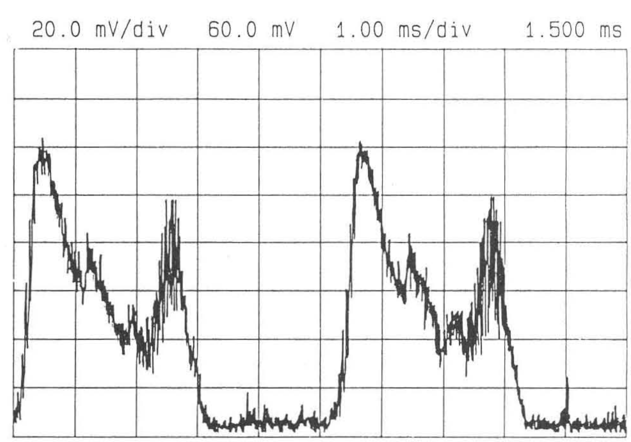

Fig. 9. Faraday cup measurement of a stretched 180 MeV proton beam with approx. 50 % duty cycle.