NEW METHODS FOR STABILIZING DEE VOLTAGE AND BEAM R.F. PHASE

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Abstract

A short term peak to peak Dee voltage stability of 10^{-4} is obtained by introducing a "ripple memory" in the voltage regulation system. The ripple memory consists of a shift register storing the drive signal needed to cancel the ripple. The stored signal is continuously updated. It is shown that the memory can be added to existing systems, reducing ripple by up to two orders of magnitude.

A beam phase detection system which can be used at nanoampère beam currents is described. The beam bursts are detected by high input impedance pick-up probes. Synchronous detection of a low frequency beam intensity modulation is used to eliminate any Dee voltage interference. Theoretical and experimental values of the output noise level are given.

Introduction

An upgrading program has been started at the K.V.I. with the aim of improving the particle transmission efficiency from the cyclotron to the experimentalists target. The cyclotron, which is currently operating in multiturn extraction mode, will be upgraded so that single turn or near single turn extraction will also be available.

The most critical cyclotron parameters for single turn extraction are the stability of the Dee voltage and beam rf phase, the phase width of the beam and the beam phase as a function of radius in the cyclotron. The beam phase versus radius should be chosen in such a way that the energy stability and energy focussing conditions[1] are satisfied.

Furthermore the transmission through the energy analyzing system can probably be increased and stabilized by a method similar to the one used at the Bonn Isochronous Cyclotron. There the beam current difference on the slits of the energy analyzing system has succesfully been used as input to the Dee voltage regulation system[2].

Conditions for single turn extraction

Since the K.V.I. cyclotron is operated in constant orbit mode with a large number of turns (N=500), the requirements for single turn operation are rather severe. Preliminary calculations[3] showed that a beam burst phase width of 4^{o}, a stability of magnetic field and rf frequency of $\pm 1.10^{-5}$ and a Dee voltage stability of $\pm 2.5.10^{-4}$ are needed for single turn extraction.

Although single turn extraction has not yet been achieved, encouraging results have been obtained with respect to these requirements.

Experiments confirmed that a phase width of 4^{o} can be obtained by means of vertical slits located at the first and fifth turn.

The long term frequency stability is at present $\pm 1.10^{-6}$. The short term stability is $\pm 1.10^{-5}$; it will be improved by replacing the slow motor drive of the trimming capacitor by a fast pneumatic system.

The necessary magnetic field stability can be obtained with modern regulation techniques, but instead of wholly relying on the long term stability of the power supplies of the cyclotron magnet and the trimcoils, one can also directly stabilize the beam phase by establishing a feedback from a number of beam phase detectors to judiciously chosen power supplies.[4]. Beam phase detectors will also be very helpful in trimming the magnetic field in order to obtain the optimum beam phase versus radius.

Although the Dee voltage stability needed for single turn extraction amounts to 5.10^{-4}, a stability of $\pm 1.10^{-4}$ will be required for obtaining maximum transmission efficiency through the energy analyzing magnet, which has a resolution of 2.10^{-4}.

Since the realization of the required Dee voltage stability and the design of a phase detector capable of monitoring beams from 10nA to 100μA seemed to be the most difficult elements in the project it was decided to start with these problems.

Dee voltage stabilization using a ripple memory

Regarding Dee voltage stability it is important to distinguish between long term and short term stability. The determining factor where long term drift is considered, is the temperature coefficient of the capacitive Dee voltage divider. This problem can be solved by addition of a fine regulation with a feedback signal proportional to the beam energy. This signal can be derived from the beam energy analyzing system[2].

The short term stability is essentially determined by ripple and noise, the level of which is inversely proportional to the gain of the closed loop stabilizing system. The main pole in the transfer function of this system is due to the Q-factor of the resonator, which changes with the resonator frequency. Adequate compensation of the main pole is therefore not possible, which limits the gain-bandwidth product of the control system. At the K.V.I. cyclotron the maximum closed loop gain extends over approximately 10^{3}Hz.

Measurements showed that ripple is the main contributor to short term instability, even after careful elimination of sources of ripple in the control electronics and the main power-supply. Since the ripple is periodic and its waveshape changes only slowly in time, a periodic compensation signal can be added to the output signal of the conventional controller. The period of the compensation signal should be equal to the longest period in the ripple, which generally is the period of the mains. In a practical system the compensation signal should automatically be synthesized from the error signal in the control loop. It should be updated as fast as is necessary to track changes in the ripple waveshape.

A control system which satisfies these requirements has been built and is currently used in the Dee voltage stabilizer for the K.V.I. cyclotron. A simplified diagram of the system is shown in fig. 1.

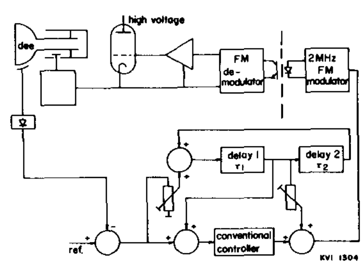

Fig. 1. Simplified diagram of the Dee voltage control system with ripple memory.

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The required periodic compensation signal is stored in a lossless analog delay line, the output of which is connected to its input. In this way the analog delay line constitutes a "ripple memory". The ripple memory consists of two parts, with delays τ_1 and τ_2 respectively while $\tau_1 >> \tau_2$. Such an analog delay line can be built using bucket brigade delay lines. The sum of the two delays is adjusted to be equal to the mains period. The Dee voltage error signal is added to the ripple waveshape circulating in the memory; it is also conventionally connected to the input of a P-I controller. The output of the first part of the delay is used as the output of the ripple memory and is connected, together with the output of the P-I controller, to the input of the controlled system.

As can be intuitively expected, stable operation is achieved if τ_2 approximately equals the transient response time t_p of the controlled system.

Experience with the Dee voltage stabilizer indicates that stable operation is achieved for

$$0.5\ t_p < \tau_2 < 2\ t_p$$

Typical results obtained with this stabilizer are shown in the oscilloscope traces of fig. 2. The upper trace in fig. 2a shows the Dee voltage error signal in the situation that only the conventional controller is used. The peak to peak relative error in this case is approximately 3.10^{-3}.

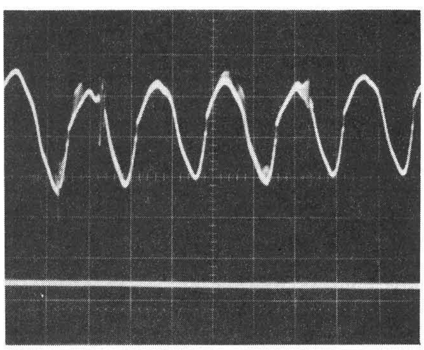

Fig. 2a. The Dee voltage error signal when only the conventional controller is used.
hor. sensitivity: 10msec/div
vert. sensitivity: 1.10^{-3} relative error/div

The upper trace in fig. 2b shows the error signal when the ripple memory is switched on. The vertical amplification of the oscilloscope has been increased by a factor 4 with respect to fig. 2a.

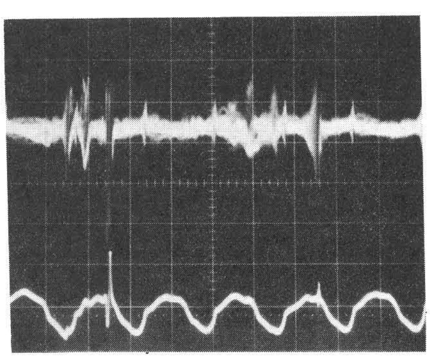

Fig. 2b. Upper trace: the Dee voltage error signal when the ripple memory is switched on.
hor. sensitivity: 10msec/div
vert. sensitivity: $2.5.10^{-4}$ relative error/div
Lower trace: the signal circulating in the ripple memory

The exposure time of the photographs was 2 seconds: several non-periodic transients show up in the error signal of fig. 2b. However, the relative error is smaller than 2.10^{-4} peak to peak for more than 90% of the time. The lower trace of fig. 2a shows the signal circulating in the ripple memory. In the present system the characteristic time for updating this signal is approximately 1 second.

The line width of the upper trace in fig. 2b represents the noise level on the Dee voltage. The noise, which for a large part can be traced to the ion source, has occasionally been observed to be $\pm\ 3.10^{-4}$. It is not yet clear whether these high noise levels can be reduced by choosing other ion source settings.

Beam phase detection

The detection systems which will be discussed here use one or more charge sensitive probes located inside the cyclotron to obtain a beam signal which is further processed in a phase detector. Their performance is generally limited by rf interference of the Dee voltage on the pick-up probe signal, and to lesser extent by statistical noise.

a) Pick-up probes

At the K.V.I. good results have been obtained with high input impedance pick-up probes[5].

The high input impedance is obtained by connecting a broad band MOS FET input amplifier directly to the pick-up plate. The amplifier is thus situated inside the cyclotron vacuum chamber. Such an active pick-up probe yields a signal which is proportional to the charge above the pick-up plate. A typical output signal is shown in fig. 3.

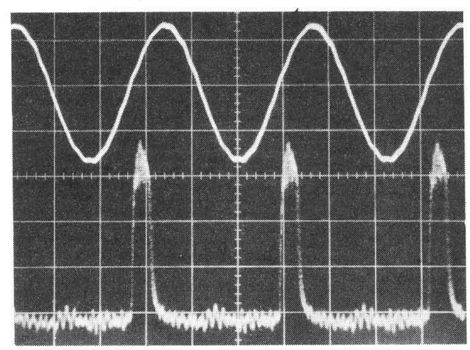

Fig. 3. Typical output signal of an active pick-up probe. Beam current: 1μA
hor. sensitivity: 50ns/div

A much simpler probe consists of an electrostatic pick-up electrode directly connected to 50Ω cable. Such low impedance passive probes have been described by e.g. F. Schutte et al.[6]. Fourier analysis of the passive probe signal shows that the amplitude of the first few harmonics is approximatively given by:

$$p_n = 2M\Delta\phi ZnI \qquad (1)$$

with M: number of turns above the pick-up plate
$\Delta\phi$: azimuthal length of the probe
Z: input impedance
n: harmonic number
I: beam current

with Z = 50Ω equation (1) yields

$$\frac{p_n}{I} = 0.1M\Delta\phi n\ \mathrm{mV/\mu A} \qquad (2)$$

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In the case of an active probe the amplitude of the first few harmonics of the signal on the pick-up plates is given by:

$$a = \frac{M\Delta\phi I}{\pi C f_d} \qquad (3)$$

with C: probe input capacity
f_d: rf frequency

With C ≈ 5 pF equation (3) gives

$$a = 6.4 M\Delta\phi \text{ mV}/\mu\text{A} \qquad (4)$$

b) Phase detection systems

At the Cyclotron Laboratory of the Eindhoven Technical University and the Julich Isochronous Cyclotron a "single harmonic phase detector" has been developed[7]. In this detector the phase of only one harmonic of the pick-up signal is measured. As the even harmonic amplitude of the rf interference is generally small, the 2nd harmonic is often used. The method is accurate even for low beam currents.

The sensitivity is ultimately limited by statistical noise. The standard deviation of the measured beam phase is given by[8]

$$\sigma = \frac{\sqrt{2 f_B P_n(2f)}}{2A_2} \qquad (5)$$

where f_B is the noise equivalent bandwidth of the lowpass filter at the output of the second harmonic detection system, $P_n(2f)$ the noise spectral density of the pick-up probe signal and A_2 the amplitude of the 2nd harmonic of the detected beam signal.

In the case of a passive probe the pick-up signal is generally amplified by a 50Ω amplifier. At rf frequencies the noise figure of such an amplifier can be as low as 1dB, yielding a noise spectral density of

$$P_n \simeq 4kTR = 0.83 \text{ nV}^2/\text{Hz}$$

The MOS FET generates more noise than a bipolar transistor, resulting in a noise spectral density of about 1.6 nV^2/Hz for the active probe.

With (2), (4) and (5) numerical values for σ can be obtained. In the case of 2nd harmonic detection one obtains for the passive probe

$$\sigma_p = \frac{5.3}{M\Delta\phi I\sqrt{\tau}} \text{ rd} \qquad (6)$$

and for the active probe

$$\sigma_a = \frac{0.23}{M\Delta\phi I\sqrt{\tau}} \text{ rd} \qquad (7)$$

where it was assumed that the lowpass filter at the detection system output is a simple RC filter with $RC = I = \frac{1}{4} f_B$.

With M=5 turns, $\Delta\phi = 5^0$, I=1nA and τ=1s, the result is

$$\sigma_p = 0.2^0 \quad \text{and} \quad \sigma_a = 0.01^\circ$$

which demonstrates the superior noise performance of the active probes. Nevertheless in practice errors due to picked up rf are in both cases likely to exceed these statistical noise levels.

At the K.V.I. a somewhat different phase detector has been built, which has a comparable noise performance but which uses synchronous detection for suppressing Dee voltage interference. A block diagram of this system is shown in fig. 4.

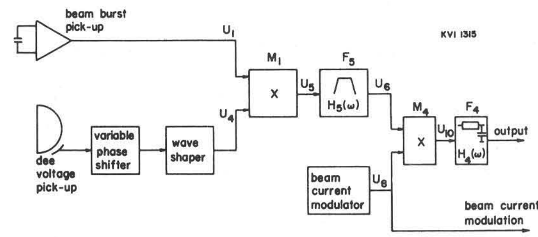

Fig. 4. Block diagram of the synchronous beam phase detector.

In the mixer M1 the pick-up probe signal U1 is multiplied with a monitor wave U4 derived from the Dee voltage. The beam current is modulated with a low frequency signal U8. The output of mixer M1 is then also modulated with the same frequency. This modulation is superimposed upon possible rf interference signals which are not modulated. The modulated signal is retrieved from the interference with the synchronous detector M4. The bandpass filter F5 limits the non modulated signal amplitude at the input of M4.

Experiments were performed with two different monitor wave shapes U4. The two monitor waves are shown on the oscilloscope display of fig. 5. The important feature of the short bipolar pulse shown in fig. 5 is a reduction of the statistical noise because the noisy signal U1 will be stopped by the mixer M1 when U4 is zero.

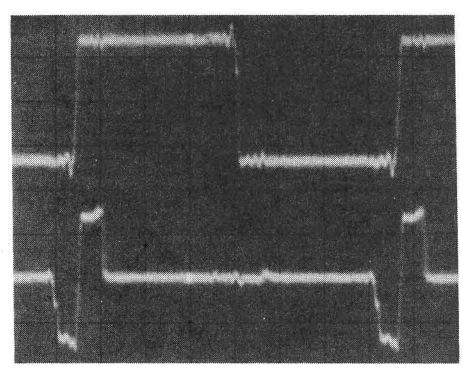

Fig. 5. Showing two possible monitor waves U4.

The detector has been used on the K.V.I. cyclotron with beam currents as low as 2nA, but as an independent beam phase measurement, using γ-timing for example, has not been performed yet, quantitative results about the accuracy are not available.

The RMS output error due to statistical noise in the pick-up signal U1 can be calculated[8]. If an active pick-up probe is used, the RMS error is given by

$$\sigma = \sqrt{2 f_B P_n} \cdot \frac{\sqrt{\beta}}{\sqrt{\rho}} \cdot \frac{\Phi f_D C \pi}{M\Delta\phi I\sqrt{\tau}} \qquad (8)$$

where on-off beam modulation has been assumed, with an off/on ratio ρ<<1 and where Φ represents the FWHM phase width of the pick-up signal and β the duty cycle of the monitor wave (β=1 for the square wave of fig. 5 and β∿o.15 for the bipolar pulse of fig. 5).

With M=5 turns, $\Delta\phi = 5^o$, I=1nA, τ=1s, $P_n = 3.2 \text{ nV}^2/\text{Hz}$,

$\Phi=20^{o}$, $f_D=10MHz$, $\beta=1$ and $\rho=0.01$ equation 8 yields

$$\sigma = 0.03^{o}$$

In offline experiments, using a noise source and a pick-up pulse generated by a pulse generator, the measured noise levels exceeded the theoretical values by about 50%.

The noise performance is comparable to the results obtained for the 2nd harmonic detector. The very low beam currents at which the synchronous detector can be used indicate however that this system is practically insensitive to rf interference; statistical noise will then indeed be the only sensitivity limiting factor.

References

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