THE BEAM PHASE MEASUREMENT SYSTEM FOR THE CYCLOTRONS AND BEAMLINES AT THE NAC

S. Schneider, P.G. Molteno
National Accelerator Centre, CSIR, P.O. Box 72, FAURE, 7131, REPUBLIC OF SOUTH AFRICA.

Summary

The beam phase measurement system of the NAC is based on numerous capacitive phase probes multiplexed to a double-heterodyne system, which makes use of the mixing technique across the 5 to 27 MHz frequency band and over a 100 dB dynamic range. The design requirements of the capacitive phase probes for the separated-sector cyclotron and for the low- and high-energy beamlines are discussed, as well as the layout and performance of the mixing system. Apart from monitoring the phase probes for the purpose of isochronous operation of the cyclotrons, the mixing system will facilitate phase synchronization of the cyclotrons and the buncher and will also be used for beam energy measurements.

1. Introduction

During the design of the beam phase measurement system, consisting of numerous distributed capacitive phase probes linked to a central signal processing system, we had to give special attention to the fact that the accelerator facility has to deliver various beams, from protons to heavy ions, with wide-ranging energies, beam pulse lengths and beam intensities. This imposes the following stringent requirements:

(i) a frequency range of more than 5:1;
(ii) a 100 dB dynamic range (for beam currents from 1 nA for some heavy ions to 100 μA protons; and
(iii) unwanted harmonics to be eliminated from the high harmonic content beam pulse signals.

The capacitive phase probes are designed for optimal signal pick-up taking into account the above requirements, space restrictions, and mechanical feasibility. The electronics is based on a double-heterodyne system making use of the mixing technique.[1] This system has been built and is suited to beam phase measurements over a very wide resonator frequency range, i.e. 5 to 27 MHz, as no critical timing adjustments have to be made with frequency changes.

2. Layout of the Beam Phase Measurement System

The beam phase measurement system for the accelerator facility is illustrated in figure 1. Provision has been made to later accommodate such measurement in the transfer beamline from a second injector cyclotron.

The first capacitive phase probe PT1 in the transfer beamline immediately after the k=8 solid-pole injector cyclotron (SPC1) is for monitoring the beam phase of the extracted beam with respect to the SPC1 RF system. The buncher phase can be optimised with PT2. The phase probes PT3 and PT4 together with PT1 are used for beam energy measurements with the time-of-flight method. PT5 is installed in the central region of the separated-sector cyclotron (SSC) and apart from monitoring the beam phase of the injected beam, it will also be used with PT2 and PT4 to monitor the bunch length and time structure[2] to ensure that the beam is injected with a longitudinal waist on the first valley centre-line of the SSC. Twenty capacitive phase probes are located along the valley centre-line of the SSC for monitoring isochronism, and the beam phase informa-

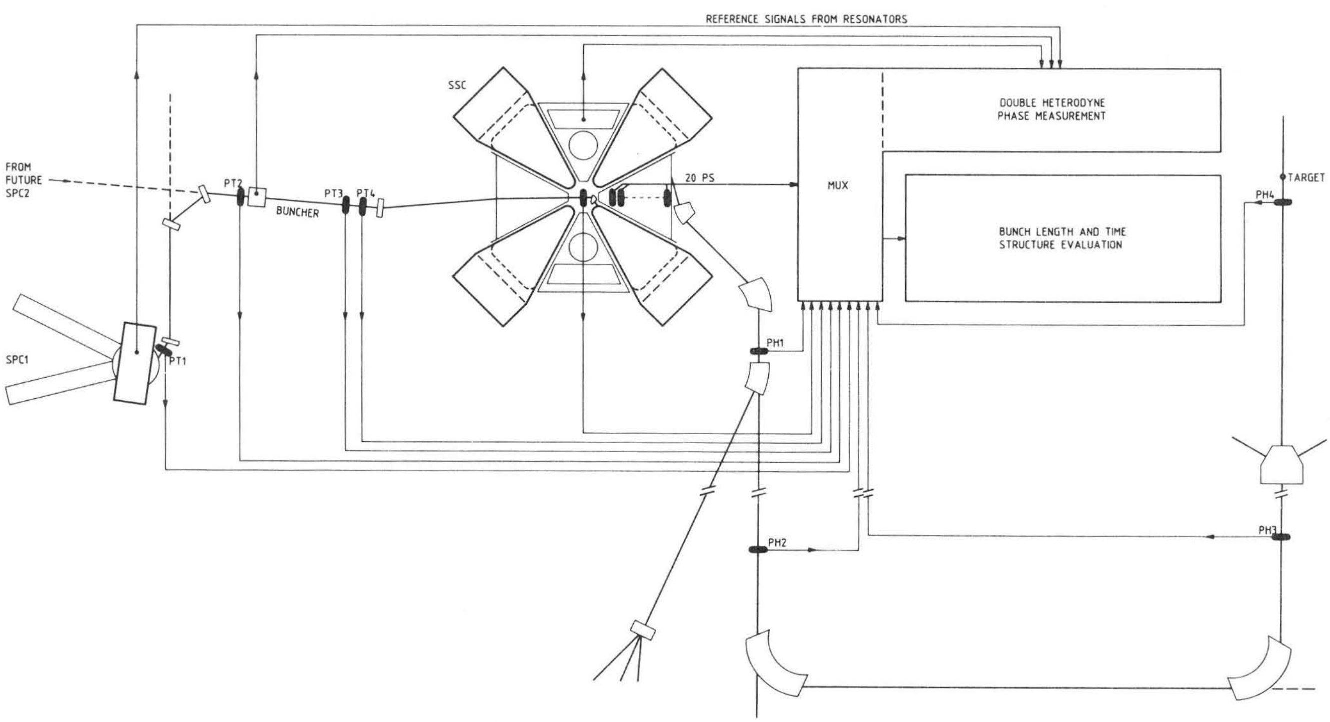

Fig. 1: The layout of the beam phase measurement system for the accelerator facility.

CH1996-3/84/0000-0411 $1.00 © 1984 IEEE

tion will be used for fine trim-coil current adjustments. The first two phase probes (PH1 and PH2) in the high-energy beamline will be used mainly for beam energy measurements. PH2, PH3 and PH4 will also monitor the bunch lengths to ensure longitudinal beam focussing on target in the experimental area.

All the above phase probes are to be linked to the multiplexer of the phase measurement electronics. Bunch length measurements and time-structure observation will not be carried out with this electronics. Three reference signals, one from an SPC1 resonator, one from an SSC resonator and one from the buncher, are also linked to the double-heterodyne phase measurement electronics. Only one reference signal is taken from each cyclotron since the maximum phase difference between the two resonators of each cyclotron is $\leq 0.1^{\circ}$.

3. Capacitive Phase Probes for Beamlines

The mechanical and electrical designs of the non-interceptive capacitive phase probes for the transfer beamline and the high-energy beamlines are in principle identical. However, various dimensions differ to optimize the design of each type of phase probe for its particular requirements, i.e. type of particle, beam size, energy, lower beam current limit and bunch length.

Each probe consists of an inner ring held by three adjustable ceramic studs with respect to an outer frame. For the phase probes of the transfer (high-energy) beamline the length of the inner ring is 30 mm (45 mm), and its aperture 60 mm (45 mm). Although a smaller probe radius yields a larger signal amplitude, the diameter of the phase probe in the transfer beamline is dictated by the large beam sizes expected. For further detail see reference 3.

Typical computed beam pulse signals are illustrated in figure 2 for the particular phase probe designs chosen for the low- and high-energy beamlines.

4. Capacitive Phase Probes for the SSC

Twenty capacitive phase probes are proposed for the SSC. These probes are presently in an advanced design stage and will be placed along a valley centre-line in the extraction valley vacuum chamber, as illustrated in figure 1. They are thus symmetrically spaced between the two resonators and at a maximum distance from the accelerating gaps. Their exact radial positions are defined by the trim-coil layout. Each probe consists of a pair of parallel plates supported above and below the median plane by two beams. Each plate is linked to the inner conductor of a coaxial cable whose outer insulation will be stripped for outgassing reasons. The solid copper screen will be insulated from the vacuum chamber and linked to the copper cover over the plates. Computations are currently being carried out to optimise the design of these probes for all beam requirements. For each probe pair the two signals are taken out of the vacuum chamber via N-type electrically insulated vacuum feedthroughs before they are summed to improve the signal-to-noise ratio. The smallest second-harmonic signal amplitude expected is about 100 μV/μA.[4]

5. The Double-heterodyne Beam Phase Measurement Electronics

The electronics for the beam phase measurement system is shown in figure 3 and a block diagram of the electronics is illustrated in figure 4. The beam phase information is obtained from a number of capacitive phase probes as described above. These signals are fed into the signal channel of the beam phase measurement electronics. The first item in this channel is a co-

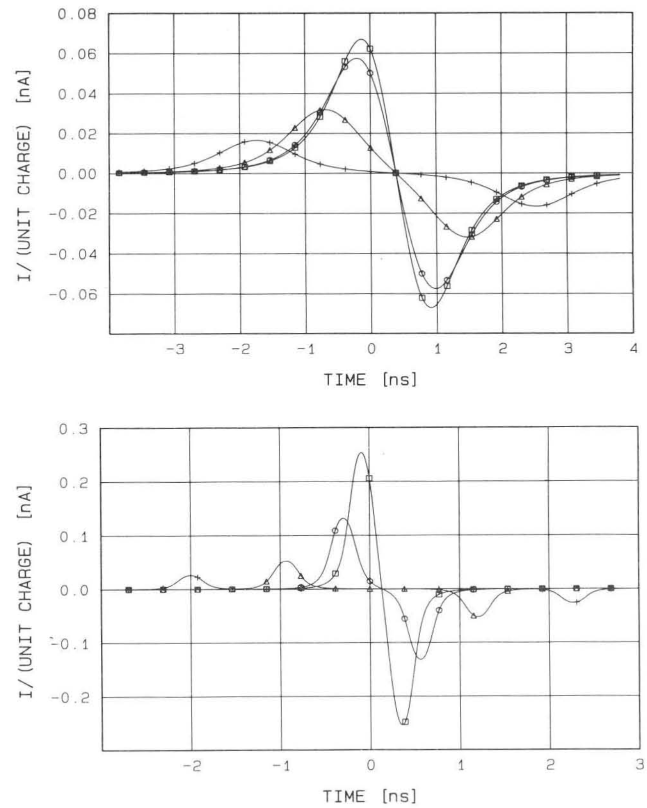

Fig. 2: Computed current signals from a capacitive phase probe in the low-energy beamline for 8 MeV protons (upper) and in the high-energy beamline for 200 MeV protons (lower). These signals have been computed for pulse widths of $4^{\circ}(\square)$, $8^{\circ}(o)$, $20^{\circ}(\Delta)$ amd $40^{\circ}(+)$. The pulse repetition frequency is 26 MHz.

axial relay multiplexer where provision has been made for 32 inputs. Relays were chosen to minimise phase error due to their low VSWR (1.01), low intermodulation performance, 80 dB isolation and repeatable electrical lengths. Their life time of 10^6 operations is acceptable when scan durations are kept short by automatic time-out. After the multiplexer the signal is amplified and with the aid of one of 5 bandpass filters (selected by reed relays) and a 54 MHz low-pass filter, all but the second harmonic of the beam pulse signal are eliminated. This filtering is essential to reduce the large contaminating fundamental RF signal at the front-end of the system, alleviating the requirements for wide dynamic range and high linearity expected of the amplifiers and mixers in the signal path. This filtering also removes unwanted intermodulation products at the second harmonic which cause phase contamination.

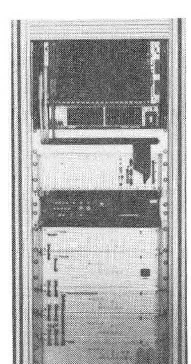

Fig. 3: The beam phase measurement electronics consisting of a CAMAC-crate (top), a microprocessor, a commercially available AF phasemeter and the double-heterodyne electronics in the lower 5 cardframes. The whole system is under direct control of a microprocessor interfaced to CAMAC.

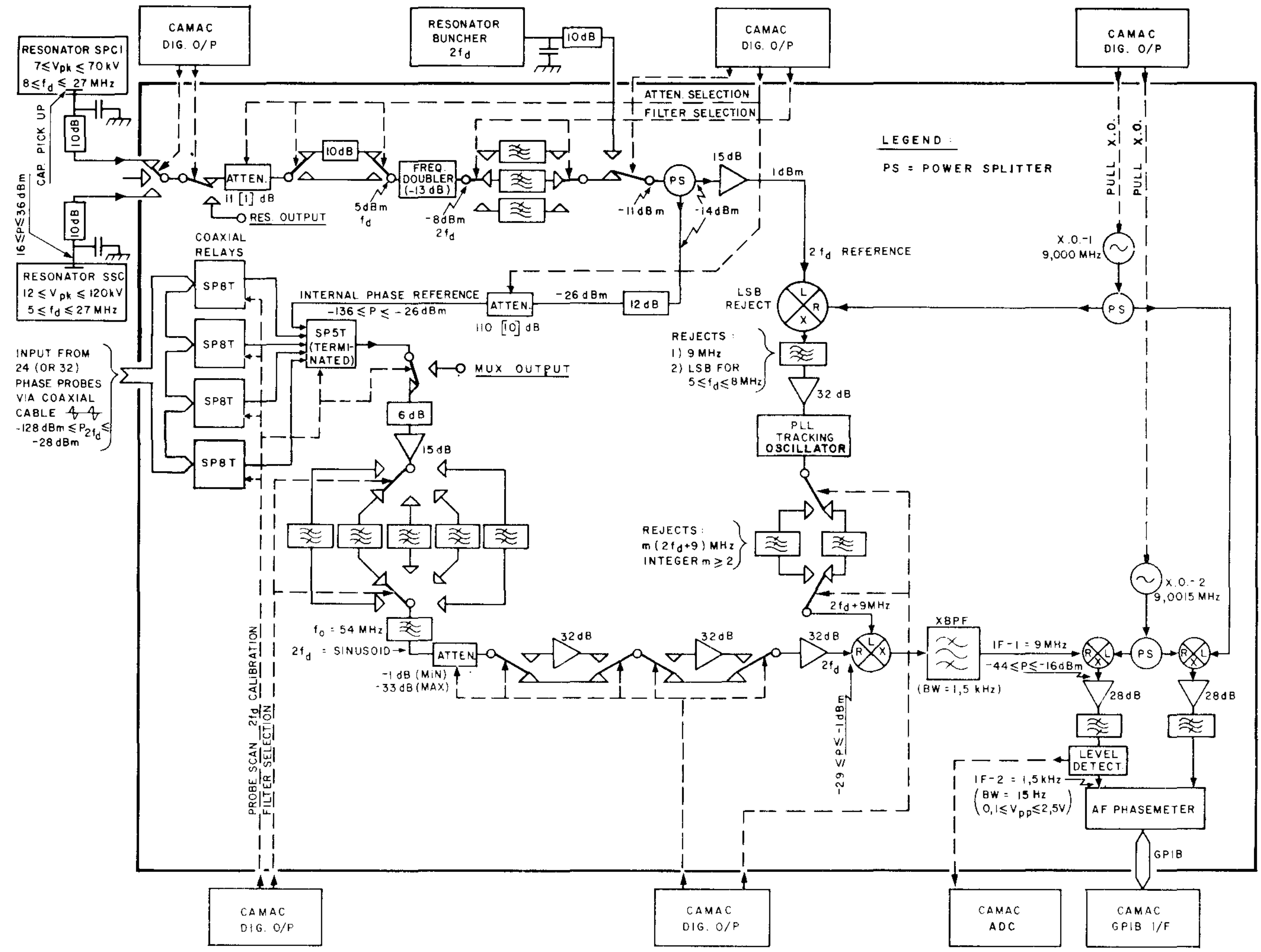

Fig. 4: Block diagram of the double-heterodyne beam phase measurement system.

The second harmonic $2f_d$ of the resonator frequency f_d is selected, because the RF contamination from the resonators is lower for the second harmonic than for the fundamental.[5,6] Various amplifiers and attenuators are inserted in the signal path to the main mixer to reduce dynamic range to comply with the restrictions of the AF phasemeter, and to maintain optimum signal levels at the RF ports of the mixers.

In the reference path the reference signal f_d is selected from RF probes at the cyclotron resonators. The second harmonic $2f_d$ of the resonator frequency is obtained with a frequency doubler followed by selectable low-pass filters. A special port is provided to insert a second harmonic reference signal directly, e.g., for the buncher operating at $2f_d$. Various amplifiers and attenuators again ensure the desired signal levels indicated in figure 4.

The reference signal, $\sin(2\omega_d t)$ where $\omega_d = 2\pi f_d$, is then mixed with a local oscillator signal, $\cos(\omega_x t)$ where $f_x = 9.000$ MHz, with lower sideband (i.e. 1 to 45 MHz) rejection, resulting in a signal $\sin(2\omega_d t+\omega_x t)$ with 19 MHz $\leq (2f_d+f_x) \leq 63$ MHz. The upper sideband was mainly selected to avoid mixing products with a frequency $(2f_d-f_x) = f_x$. However, since the single sideband (SSB) mixer allows sufficient breakthrough of the 9 MHz intermediate frequency (IF) signal and of unwanted mixing products to contaminate the true phase (measured to be as much as 6° phase error), a phase-locked loop tracking oscillator (PLL TO) was inserted. It locks over the full $(2f_d+f_x)$ frequency range with ≤ 2 dB amplitude variation. Insertion of a buffer amplifier and an 18 MHz high-pass filter between the SSB mixer output and the PLL TO input enabled lock to be maintained down to 19 MHz (i.e. $f_d = 5$ MHz) despite fall-off in rejection by the SSB mixer below 23 MHz, and also rejects f_x breakthrough. Two selectable low-pass filters in front of the main mixer ensure a clean $(2f_d+9)$ MHz signal, which is then mixed with a signal, $\sin(2\omega_d t+\phi_2+\phi_o)$, containing the beam phase information, where ϕ_2 is the phase of the second harmonic of the beam pulse signal with respect to the second harmonic of the RF and ϕ_o represents phase offset in the system.

With the aid of a 9 MHz crystal bandpass filter (BPF), with a 1.5 kHz bandwidth, an IF signal with a fixed crystal oscillator frequency of 9 MHz is obtained. This IF signal, $\cos(\omega_x t-\phi_2-\phi_o)$, is independent of the resonator frequency f_d, but contains the desired phase information ϕ_2. Most unwanted mixing products are thus eliminated.

This fixed frequency signal is then mixed with a second crystal oscillator frequency f_z=9.0015 MHz as shown in figure 4. After bandpass filtering this results in an AF signal $\sin(2\pi\times1.5\times10^3 t-\phi_2-\phi_o)$ still containing the beam phase information ϕ_2. Similarly the two crystal oscillator signals are mixed resulting also in an AF signal $\sin(2\pi\times1.5\times10^3 t)$. These 1.5 kHz bandpass filters have a narrow 15 Hz bandwidth. A commercially available AF zero-crossover detecting phasemeter with built-in IEEE-488 computer interface is then used to measure ϕ_2.

5.1 Unwanted Mixing Products and Filtering

Despite removal of many unwanted mixing products from the SSB mixer by the introduction of the PLL TO, some spurious 9 MHz products from the main mixer still result by the mechanisms $|nf_d - m(2f_d+9)| = 9$MHz and $|nf_d - m(2f_d+9) \pm 9| = 9$ MHz, for n, m integers. It was clear that harmonics of the $(2f_d+9)$ local oscillator (LO) signal should be filtered before injection into the mixer, hence the selectable 34.6 and 63.0 MHz LPF's after the PLL TO. Further, selectable BPF's were inserted early in the signal path to eliminate all but the wanted $2f_d$ component before significant amplification or injection into the main mixer. Five seventh-order elliptic BPF's are used, with each filter's band edge being the geometric mean of the band edges of its adjoining filters, giving band edges at 10.0, 14.0, 19.5, 27.5, 38.5 and 54.0 MHz. 15 dB of initial amplification is necessary to minimize noise figure, (preceded by 6 dB padding to minimize mis-matching phase error), but nonetheless intermodulation in the amplifier is minimized by the low signal levels involved and use of a highly linear, large-signal-handling amplifier.

A root problem lies in the choice of a low first IF of 9 MHz, whose harmonics lie in the LO and RF bands of the main mixer and which places the LO only 9 MHz away from the mixer RF. The choice arose from the ready availability of 9.000 and 9.0015 MHz crystal oscillators and filters, and the objective of finally measuring phase at AF where techniques for accuracy and digitisation are well established. A better choice might be to select the first IF above the $2f_d$ band, which would also shift the LO band well above the $2f_d$ band. A second heterodyne stage could still mix down to AF if the two crystal oscillators were phase locked together, thus retaining very narrow final bandwidth for low noise performance.

5.2 Calibration and Repeatability

The $2f_d$ RF reference signal is made available at the signal multiplexer as an internal reference for calibration. A constant phase step-attenuator in this path allows the reference level to match the incoming beam pulse signal level within 10 dB. Hereby, at any given frequency and signal level (gain setting), the imbalance of electrical length between the reference path (taken from the first power splitter) and the signal path (taken from the output of the multiplexer) may be measured and accounted for. Thus phase lags in either path, through amplifiers, switches, filters, mixers and the PLL TO, may alter with frequency, signal level and time drift, yet be subtracted from measured phase readings. All preceding circuitry in both paths is passive; the only component whose electrical length varies with amplitude is the frequency doubler (not strictly passive, since it is essentially a mixer incorporating diodes and transmission-line transformers), hence a constant phase attenuator precedes the doubler to maintain constant applied signal level. Phase stable semi-rigid coaxial cable is used to connect all probes to the inputs.

It is thus expected that phase readings at a given frequency will be long-term repeatable, independent of amplitude. Furthermore, accurate relative comparison of phases, independent of frequency, of the 20 SSC phase probes is expected owing to matching and physical symmetry of the probes and accurate balancing of the paths from the signal MUX back to the probes. The electrical length of the cable is non-dispersive.

Absolute determination of phase at any beam pulse phase probe with reference to resonator phase presents a problem. Firstly, each resonator RF probe consists of an RC voltage divider and toroidal transmission-line transformer divider whose phase response is dispersive. Secondly, determination of the electrical lengths of the reference path from each resonator RF probe up to the input of the internal reference to the signal MUX, and from each capacitive phase probe up to the corresponding port in the signal MUX, involves a number of absolute meaurements whose combined errors readily exceed 1° of phase. Thirdly, determination of the electrical length of the frequency doubler with its associated low-pass filter (LPF) has to be tabulated versus frequency and the measurements are very difficult owing to the problem of measuring absolute phase of a second harmonic with respect to its fundamental. Three selectable seventh-order elliptic LPF's eliminate the even harmonics $4f_d$ and higher by having break- and stop-frequencies respectively at 17.5 and 20.0 MHz, 30.8 and 35.0 MHz, and 54.0 and 61.6 MHz so that each filter has the same ratio of break- to stop-frequency.

5.3 Sensitivity

Mixing down to AF is attractive particularly because it enables a 20 Hz effective noise bandwidth to be achieved. Noise figure (NF) is limited by front-end padding for low VSWR and insertion loss of the front-end filters, giving a 12 dB NF. The expected minimum second harmonic signal amplitude of the phase probes of 100 μV/μA implies −130 dBm at 1 nA beam current and −110 dBm at 10 nA. A signal generator was used to simulate the $2f_d$ beam pulse component. With the integration constant of the AF phasemeter set at 0.03 s, the scatter of phase readings was $\pm 0.5^{\circ}$ at −110 dBm and $\pm 4^{\circ}$ at −130 dBm. Less scatter may be expected by selection of a longer integration constant and numerical averaging. Linearity was better than one degree for signals down to −110 dBm.

References

1. G.C.L. van Heusden et al., The HF-Phase Measuring Equipment of the Eindhoven AVF-Cyclotron, Proc. 7th Int. Conf. on Cycl. and their Applications, Aug. 1975, Zürich, p.353.

2. P. Strehl et al., Das Phasensondenmessystem am UNILAC. Sondendimensionierung und Signalauswertung, GSI 79-13, Dec. 1979, GSI Internal Report.

3. S. Schneider et al., The Beam Diagnostic System for the Transfer Beamline at the NAC. These proceedings.

4. G.C.L. van Heusden, W.M. Schulte, Signal Levels of Phase Probes, Technische Hogeschool Eindhoven, Internal Report NK233 (Oct. 1976).

5. W. Bräutigam et al., IEEE NS-26 (1979) 2375.

6. W.M. Schulte, The Theory of Accelerated Particles in AVF Cyclotrons, Thesis, (Eindhoven, 1978).

 CH1996-3/84/0000-0414 $1.00 © 1984 IEEE