BEAM PHASE MEASUREMENT IN A 200 MEV CYCLOTRON

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Abstract

New beam phase measuring equipment is planned for the K 200 variable frequency separated-sector cyclotron at iThemba LABS. The first of fifteen new phase probes has been installed, near the extraction radius. The probe has been used to investigate the possibility of using a commercial lock-in amplifier with amplitude and phase measuring capabilities, and cancellation of the pick-up signal, without beam, with a harmonic generated from the dee voltage, before vectorial subtraction of the resulting signal from the beam signal. The results are discussed and a method to compensate for the instability of the pick-up signal is proposed.

INTRODUCTION

The separated-sector cyclotron and its two K 8 solid-pole injector cyclotrons at iThemba LABS [1], accelerate beams of light and heavy ions as well as polarized protons, and operate in the frequency range 8.6 to 26 MHz. Beams that vary in intensity from about 10 nA to 150 µA are used for neutron therapy, proton therapy, radioisotope production and nuclear physics research according to a fixed schedule involving several energy changes per week. This necessitates regular field isochronization using beam phase measurements that have up to now been done by displaying the amplified beam signal from a phase probe on one of the two multi-head probes on a Tektronix TDS 5052 Digital Phosphor Oscilloscope [2], triggered by a signal derived from the dee voltage, and noting the time while the probe is driven from the injection to the extraction radius. New trim coil settings are calculated from these measurements. A phase accuracy of about 2° is attained for beam currents as low as 50 nA by analog cancellation and digital subtraction of the harmonics, of which the first is by far the strongest, coupled from the dees to the phase probe. Analog cancellation is achieved by splitting the signal from the phase probe and selecting the first two harmonics from one of these signals by filtering and adding it to the remaining signal after amplification and passing it through manually adjustable phase shifters and attenuators for each of the two harmonics. Filtering has not been considered since that would change the beam pulse shape from which information about the beam is derived. Although the accuracy of the method is sufficient it is time consuming and the probe support also intercepts beam, which means that the beam phase in the cyclotron is not known during operation. New, non-interceptive phase probes with greater sensitivity are therefore planned. To avoid time-consuming development work the possibility of measuring the beam phase with a commercial RF lock-in amplifier model SR844 from Stanford Research Systems [3] was investigated. The signal processing in the amplifier is similar to those of phase measuring equipment that has been developed at cyclotron laboratories [4,5] for this purpose.

PHASE PROBES AND SIGNALS

The signal levels for different harmonics, with and without beam, have been measured on a multi-head probe (MHP) and a non-interceptive fixed phase probe that has been installed near the extraction radius on the side of a valley vacuum chamber to cover the last few orbits in the cyclotron. Since only the phase change with radius has to be determined and the beam phase cannot change quickly with radius in the cyclotron it is not imperative to use the first or second harmonic to ensure unique phase values. Other harmonics have therefore also been considered. The MHP electrodes, with a gap of 18 mm between them, have radial and azimuthal dimensions of 50 mm and cover at any position near injection, where the orbit separation is often 100 mm, one orbit at most. At extraction the orbit separation is 21 mm and at most two beam packets, that typically have a length of 300 mm, can be between the two plates. The fixed probe, with a gap size of 40 mm, has radial and azimuthal dimensions of 220 mm and 130 mm, respectively. Table 1 lists the combined signals from the top and bottom plates.

Table 1: Beam and pick-up signal levels on the fixed phase probe and a multi-head probe at radii of 1000 mm and 3600 mm for a dee voltage of 220 kV

Probe and radius	Harmonic Number	Signal levels (dBm)	
		93 µA beam	**no beam**
Fixed phase probe at extraction	1	-28.9	-48.8
	2	-25.6	-128.4
	3	-24.0	-133.0
	4	-22.1	-128.1
	5	-21.4	-130.1
		10 µA beam	**no beam**
MHP at 1000 mm	1	-43.0	-42.7
	2	-63.7	-110.3
	3	-60.2	-124.1
	4	-64.0	-113.1
	5	-59.9	-106.4
MHP at 3600 mm	1	-67.5	-63.3
	2	-62.0	-112.7
	3	-65.8	-122.9
	4	-60.8	-124.7
	5	-58.2	-126.7

The measurements were made using a network analyzer and a bandwidth of 30 Hz, for a main RF frequency of 16.37 MHz, which is about midway in the cyclotron frequency range, and the frequency that was most often available for measurements. Although the fixed probe is much closer to one of the dees than the MHP, and also much larger, the signal levels without beam are comparable to those of the MHP at a radius of 3600 mm. The pick-up levels may be very different at other radii and frequencies because of resonances in the 3.7 m long dees that form part of the vertical half-wave resonators. Adjustment of the top and bottom short-circuit plates of each of the two resonators to minimize the pick-up signal has been considered, but rejected because that would complicate the energy changes for which little time is available in the 24 hours per day seven days per week beam delivery schedule. Furthermore radially dependant deviations of the dees from symmetry with respect to the median plane, due to manufacturing errors, cannot be removed by short-circuit plate adjustments.

SETUP FOR PHASE MEASUREMENT

From the signal levels in Table 1 it is clear that unless some characteristic of the beam is modulated [6,7] with a frequency different from the harmonics of the main RF frequency, the signal without beam has to be subtracted vectorially from the signal with beam for phase measurements. Beam intensity modulation is not considered at present since the beam power is often in the order of 10 kW and may in future increase to 20 kW. Vectorial subtraction of the pick-up signal is based on amplitude and absolute phase measurement of signal with and without beam. At low beam currents the beam signal on its own could be of the same order as the pick-up signal or even much lower. In such cases the accuracy of amplitude and phase measurement required for vectorial subtraction cannot be achieved. If the pick-up signal, without beam, could be reduced to a level below that of the beam signal by addition of a signal with sufficient phase and amplitude stability, derived from the dee voltage, the required phase and amplitude measurement accuracy for vectorial subtraction is drastically reduced, and subtraction may, depending on the beam current, even be unnecessary. For instance, to measure the phase of a beam signal superimposed on a five times larger pick-up signal by vectorial subtraction to an accuracy of 3 degrees would require accuracies of 1% and 0.6 degrees for amplitude and phase measurement, respectively, depending on the phase difference between the beam and pick-up signals. If the pick-up signal could be reduced to a level equal to that of the beam signal, the required amplitude and phase measurement accuracies for the pick-up signal would be reduced to 5.6% and 1.8 degrees, respectively, again depending on the phase difference between the signals. For a pick-up level 20 times smaller than the beam signal, subtraction, based on phase and amplitude measurements, would not be necessary to obtain a phase measurement accuracy of 3 degrees.

In the layout of the test setup for phase measurements, shown in Fig. 1, the combined signals from the top and bottom plates of a phase probe are amplified and filtered before subtraction of the corresponding harmonic of the dee voltage generated by an Analog Devices [8] direct digital synthesizer chip AD9952. Two signals with independent phase and amplitude adjustment by computer control are available. One signal is used as a reference for the lock-in amplifier, and the other for cancellation of the pick-up signal, by adjustment of the amplitude and phase of the signal from the synthesizer, to minimize the voltage displayed on the lock-in amplifier, without beam. Accurate phase and amplitude measurements are therefore not required for cancellation of the pick-up signal, except that such measurements are useful to calculate the approximate phase and amplitude settings of the AD9952 synthesizer before final adjustment, in order to speed up the process. The harmonic of the dee voltage can also be selected by computer control, which means that in principle any of the harmonics in Table 1 can be used for phase measurement, provided a suitable filter is inserted to select the desired harmonic and reject the other harmonics and especially the main RF frequency to prevent overloading of the RF section of the lock-in amplifier.

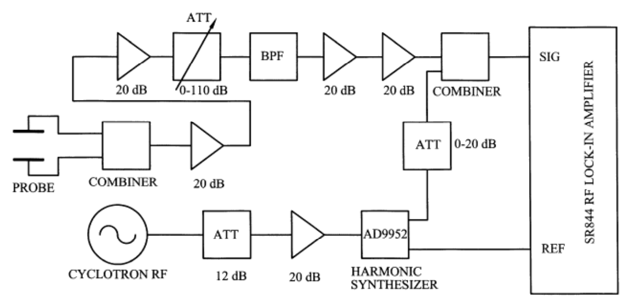

Figure 1: Layout of the test setup for beam phase measurement.

Four low-noise broadband amplifiers, model 0515A from Kuhne electronic GmbH [9], each with a gain of 20 dB, have been used to amplify the phase probe signals. With a total gain of 80 dB and a low but sufficient reference signal level, internal coupling between the reference and signal inputs of the SR844 becomes insignificant. Internal coupling can also be compensated for by adjustment of the amplitude and phase of the harmonic.

Measurements have shown that the amplitude and phase stability of the AD9952 synthesizer, with its 14 bit resolution for both amplitude and phase, over a period of days is sufficient for the present application and much better than that of the pick-up signal.

BEAM PHASE MEASUREMENTS

The beam phase measurements described below were made by cancellation of the pickup signal only and without subtraction of the pick-up signal from the signal with beam. The phase values were obtained with a one second time constant for a 24 dB/octave filter setting on the lock-in amplifier and are given in second harmonic degrees. Similar results were obtained with measurements at the fifth harmonic.

The results of measurements with the MHP near injection are shown in Table 2. At a radius of 950 mm, where the probe is less than a meter away from the nearest dee with a voltage of 220 kV, the pick-up signal of 31.9 mV was reduced to 100 μV by adjusting the phase and amplitude of the second harmonic generated by the AD9952 synthesizer. The initial phase and amplitude settings for the AD9952 were calculated from measurements of the phase and amplitude of the pick-up signal with the lock-in amplifier. Typically, the amplitude and phase values obtained in this way were within 5% and 2 degrees, respectively, of the final values after the signal without beam was minimized. The instability in the phase and amplitude of the pick-up signal limits the current at which the phase can be measured accurately at this position to about 50 nA. A longer phase probe with better shielding is required to measure the phase of beams with lower intensities.

Table 2: Beam phase measured at the second harmonic with the multi-head probe at a radius of 950 mm

Beam current (nA)	**Voltage (mV)**	**Phase (degrees)**
1000	51.0	0.0
505	26.4	-0.1
205	11.1	-0.2
100	5.26	-0.1
50	2.72	2.1

Table 3 shows the beam phase for different beam currents with the MHP at a radius of 3500 mm. The pick-up signal of 2.55 mV is about twelve times lower than at injection and was reduced to 10 μV. An accuracy of 3 degrees could be obtained for a beam current of 20 nA.

Table 3: Beam phase measured at the second harmonic with the multi-head probe at a radius of 3500 mm

Beam current (nA)	**Voltage (mV)**	**Phase (degrees)**
1000	31.4	0.0
500	14.5	0.0
200	5.90	0.0
100	3.03	0.0
52	1.57	0.4
20	0.57	1.7
10.5	0.30	3.5

The results of beam phase measurements with the fixed phase probe at extraction are shown in Table 4. The pick-up signal of 2.1 mV was reduced to 2 μV by adjusting the phase and amplitude of the second harmonic generated by the AD9952 harmonic synthesizer. The instability in the phase and amplitude of the pick-up signal limits the current at which a phase accuracy of 3 degrees can be obtained over a period of 10 minutes to 5 nA with this probe.

Table 4: Beam phase measured at the second harmonic with the non-interceptive probe at extraction

Beam current (nA)	**Voltage (mV)**	**Phase (degrees)**
1000	160	0.0
130	19.6	-2.4
10	1.48	-2.4
2.5	0.38	-1.9
1.2	.037	-0.5

CONCLUSIONS

The phase of beams with intensities in the nA range was measured with a commercially available lock-in amplifier, using a multi-head probe and the first non-interceptive phase probe that has been installed in the separated-sector cyclotron, by partly cancelling the pick-up signal with a harmonic derived from the dee voltage. The lowest current at which the beam phase could be measured was limited by the variation in the phase and amplitude of the pick-up signal during measurements. The measurement accuracy for low beam intensities can be improved further by using vectorial subtraction or by using a probe to measure changes in the phase and amplitude of the pick-up signal only to update the settings of the AD9952 synthesizer during measurements.

The dimensions of the multi-head probe electrodes are too small to measure beam phase at currents of a few nA, especially near injection where the orbits are far apart. The next phase probe, with improved shielding, will be installed near injection where pickup is most severe and the beam signals the smallest because of the large orbit separation. With final results for the most severe conditions known, the design of the final signal processing electronics can be done.

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