# BEAM-PHASE MEASUREMENT IN THE AGOR-CYCLOTRON

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*Abstract*

The new beam-phase measurement system for the AGOR-cyclotron is described. Using intensity modulation of the injected beam the phase information is shifted to a frequency where no perturbation from the RF-resonators is present. Phase measurements with 1° accuracy can be performed for beam intensities down to 10 nA. The system also provides information from which the number of turns and the acceleration voltage can be derived. From the spectral information the bunch-length and the phase-acceptance have been obtained.

## INTRODUCTION

In the diagnostics toolbox for the tuning of the AGOR-cyclotron, designed along with the cyclotron, a beam-phase measurement system to optimise the isochronism has been included [1]. This system consists of thirteen pairs of phase probes mounted along the symmetry axis of one of the hill sectors and electronics similar to previously built systems [2,3].

Large perturbations from the RF-resonators, both at the fundamental and the second harmonic, preclude reliable phase measurements at a harmonic of the RF-frequency, for the beam intensities generally used (10 - 50 nA), in particular at the high frequencies used for the acceleration of proton beams. It was concluded that reliable phase measurements over the full operating range of the cyclotron during normal operation are only possible using intensity modulation to transfer the phase information to a frequency where no interference from the RF-resonators is present [4].

Different modulation and phase detection techniques have been evaluated, where attention has been given in particular to the ease of use during routine operation. This has resulted in a system where the existing buncher is used to produce the intensity modulation and a vector network analyser is used for the phase measurement.

## INTENSITY MODULATION

With beam intensity modulation the Fourier spectrum of the beam signal contains not only harmonics of the RF-frequency but also frequencies $f = n\, f_{RF} \pm m\, f_{mod}$, where $f_{mod}$ is the modulation frequency. At these frequencies the signal-to-perturbation ratio will be much better than at the harmonics of the RF-frequency, because there is no contribution from the RF-resonators. Although in principle any frequency $f_{mod}$ can be used there are convenient choices as well as constraints, as will become clear from the analysis below.

The beam-phase is measured with respect to a reference signal derived from the modulation signal and the acceleration voltage at a frequency $f = n\, f_{RF} \pm m\, f_{mod}$. The phase measured at a given radius consists of two contributions, one related to the isochronism of the magnetic field and one caused by the propagation of the modulation through the cyclotron (modulation slip). With $f_{mod} = \alpha\, f_{RF}$ one finds

$$\varphi(n,\pm m) = \pm 2\pi k h m \alpha + \delta(n \pm m\alpha) \qquad (1),$$

where $k$ is the number of turns the particles need to reach the radius of measurement, $h$ the harmonic mode and $\delta$ is the phase slip due to the isochronism.

In the AGOR-cyclotron particles need, independent of the harmonic mode $h = 2; 3$ or $4$), around 1000 RF-periods to pass through the machine, so the term due to the propagation of the modulation amounts to some 30° at extraction for $m = 1$ and $\alpha \approx 10^{-4}$. The modulation slip is determined by measuring the phase at two values of either $m$ or $\alpha$. An alternative, less accurate technique is to calculate $k$ through iteration on the basis of the acceleration voltage and the measured phase. The effect of the modulation on the second term in equation (1) can safely be neglected.

An interesting special case occurs for $h\,\alpha = l$ ($l \neq j\, h$), where the propagation term becomes $2\pi klm$ and thus drops out. Thus only one measurement is needed. This case corresponds to injecting the beam at a multiple of the orbital frequency $f_{orb} = f_{RF}/h$. In this case the effect of the modulation in the second term can certainly not be neglected.

### *Operational constraints*

A good signal-to-perturbation ratio has been obtained over the full operating range of the cyclotron in measurements with modulation frequencies $f_{mod} \approx 10^{-4}\, f_{RF}$ and with injection at (a multiple of) the orbital frequency.

Low frequency modulation is easily achieved by either chopping the injected beam or operating the buncher at a frequency slightly differing from the RF-frequency: $f_{bun} = f_{RF} \pm f_{mod} = f_{RF}\,(1 \pm \alpha)$. To inject the beam at the orbital frequency the buncher has to be retuned to a completely different frequency, which is not convenient during routine operation. It was therefore decided to use low modulation frequencies.

Because of the small frequency range of the chopper system (<400 Hz) we have opted for the buncher as beam intensity modulator. The reference signal for the phase measurement can conveniently be obtained by mixing the signals from the buncher and the accelerating cavities. The phase measurement is then performed at $f = f_{RF} + f_{bun} = 2\, f_{RF} \pm f_{mod}$.

## SIGNAL PROCESSING

### *Signal amplitude*

The beam induced signal on the pick-ups at the frequency of the measurement varies between ~50 and ~100 nV/nA. It depends on several parameters, such as RF-frequency, location of the pick-up, beam-phase, acceleration voltage and bunch width. The values observed are in reasonable agreement with simple calculations.

The signal on the pick-ups originating from the RF-resonators is orders of magnitude larger, at the highest RF-frequency the amplitude of the first harmonic is nearly 0.4 V, while the second harmonic amounts to 0.4 mV. Direct measurements at the second harmonic are clearly excluded and the first harmonic will have to be reduced very significantly to prevent saturation in the measurement chain.

### *Filtering*

The phase pick-ups are connected to the electronics via two multiplexers. The signals from the corresponding pick-ups above and below the median plane are added with a power combiner. Since the perturbations from the RF-resonators on the two pick-ups have a 180° phase difference this results in a significant reduction of the perturbation: depending on frequency and probe the first harmonic component of the perturbation is reduced by 30 to 40 dB. The second harmonic component is reduced by 20 to 30 dB. These differences are mainly caused by slight differences in the effective cable lengths between the probes and the combiner.

Further suppression of the first harmonic component is necessary to maximise the signal-to-noise ratio of the whole measurement chain. This is achieved with a switched six-fold band pass filter, which has a attenuation of at least 50 dB at the first harmonic for an insertion loss of 1.5 dB at the second harmonic, where the phase measurement is performed. The phase-shift of the filter is not relevant because the beam-phase is measured relative to the first probe.

### *Amplification*

Without amplification of the beam signal the vector network analyser determines the signal-to-noise ratio of the measurement chain. Due to conversion losses in the mixers etc. the analyser has a noise figure of about 30 dB, the minimum detectable signal amplitude is around –110 dBm (~1 µV). The signal-to-noise ratio of the measurement is improved by amplifying the signal with a wide band, low noise amplifier. The choice of the amplifier is a compromise between the minimisation of the noise figure (gain) and the increase of the second harmonic component due to distortion (2nd order intercept). The amplifier selected has a gain of 30 dB, a noise figure of 2.2 dB and a second order intercept at the output of –2 dBm. This results in an overall noise figure of 4.2 dB and a second harmonic component due to distortion below –100 dBm, well below the second harmonic already present in the signal.

### *Phase measurement*

At a beam intensity of 10 nA the amplified signal has a signal-to-noise ratio of at least 35 dB at the frequency where the measurement is performed. This is largely sufficient for a reliable beam-phase measurement without subtraction of the perturbation. However, perturbations have sometimes been observed, resulting in a signal-to-perturbation ratio to 15 dB in the most unfavourable case. These perturbations stem from the RF-resonators, their basic cause is not understood. Under these circumstances subtraction is necessary.

The signal is fed into a vector network analyser (HP 4195A), which is configured for network measurements. The network analyser and the system generating the input signals for the buncher and the RF-resonators are locked to a common 10 MHz reference signal. The measurement is performed in zero span mode at a resolution bandwidth of 300 Hz.

A high-accuracy beam-phase measurement requires a total of four measurements per probe: with and without beam at two different modulation frequencies. In case the systematic errors related to the perturbations and the modulation are less important a single measurement may be sufficient. To improve the statistical accuracy up to 400 datapoints per probe may be collected for a single measurement. For a 1° statistical accuracy in the measured beam-phase typically 100 datapoints per measurement are needed. A complete scan of four measurements per probe over all thirteen probes then takes three minutes.

## RESULTS

The measurement system developed can not only be used to optimise the isochronism of the magnetic field, but also to determine the number of turns and the acceleration voltage. Additionally, the phase-acceptance and the bunch-length can be determined from the Fourier-spectrum of the beam. Some examples are described below.

### *Isochronism*

The correctness of the measured beam-phase has been verified by comparing the measured and calculated effect of a known change in the magnetic field. An example is displayed in fig. 1. The phase profile has been measured with a beam current of 30 nA for two settings of trim coil 12. The error bars are of statistical nature only. The curve represents the phase difference calculated with the orbit code using the actual magnet settings and acceleration voltage. The acceleration voltage has been calibrated using X-rays. From the good agreement between measurements and calculations it is concluded that the beam-phase can be measured with an accuracy of 1° for beam intensities down to 10 nA.

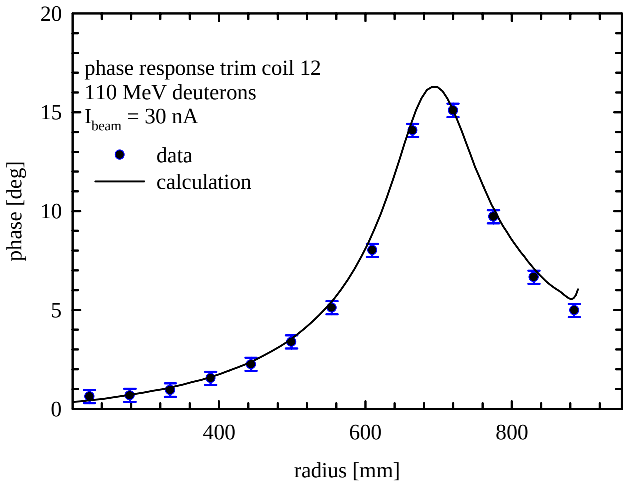


Figure 1: Measured and calculated phase change as a function of radius for $\Delta I = 30$ A in trim coil 12 for a 110 MeV deuteron beam.

### *Number of turns, acceleration voltage*

From the measurements at two frequencies not only the beam-phase but also the number of turns and the acceleration voltage can be extracted. Neglecting the small contribution $\delta m\alpha$ the difference of the two measurements is proportional to the number of turns. With $\alpha_1 = 10^{-3}$, $\alpha_2 = 10^{-4}$ and $m = 1$, typical values used for the measurements, the so-called modulation slip from injection to extraction is roughly 360° for all beams, independent of the harmonic mode $h = 2$, 3 or 4. The error in the phase measurement being about 1° this implies that the number of turns between any two probes can be measured with an accuracy of about one turn. Combined with the beam-phase this then allows the determination of the acceleration voltage per turn.

The validity of this approach has been verified for 110 MeV deuterons ($h = 2$) and $^{12}C^{2+}$ at 8 MeV per nucleon ($h = 4$). For the deuterons the number of turns was found to be 474, corresponding to a Dee-voltage of 46.5 kV; while the $^{12}C^{2+}$-ions need 216 turns, resulting in a Dee-voltage of 37 kV. These Dee-voltages are in agreement with the values derived from an X-ray calibration, thus showing the validity of the method.

### *Phase width and phase acceptance*

The amplitudes of the Fourier-components in the signal near harmonic $n$ of the RF-frequency are the product of amplitudes $A_i$ and $B_j$ of the decomposition of the phase acceptance A(t) and the bunch-shape B(t), respectively, where $|i \pm j| = n$. Complete reconstruction of A(t) and B(t) is in principle possible but has not yet been attempted. Assuming A(t) and B(t) to be square waves measured spectra have been fitted to determine the bunch-length and the phase acceptance. The Fourier-spectra of a 180 MeV deuteron beam around the second and tenth harmonic and a model-fit are displayed in fig. 2. Although the high order terms are not well reproduced the bunch-length and phase-acceptance could be determined to be $12 \pm 2°$ and $23 \pm 2°$, respectively. These values are consistent with the injection efficiencies observed for bunched and non-bunched beams.

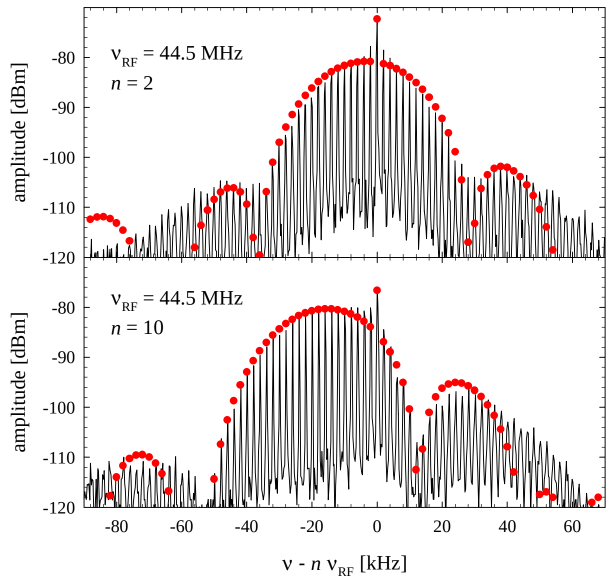


Figure 2: Fourier-spectra of 180 MeV deuteron around 2nd and 10th harmonic (full curve) and fit to the data (dots).

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