BEAM PHASE MEASUREMENT IN THE AGOR-CYCLOTRON

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The AGOR cyclotron is equipped with thirteen phase probes for optimization of the isochronism. The beam phase is measured at the 2nd harmonic of the RF frequency, in order to be able to suppress the large RF interference from the nearby resonators. At low RF frequencies a phase accuracy of 1 deg. is obtained for a 30 nA beam; at high RF frequencies interference at the 2nd harmonic causes a strong degradation of the accuracy. Since good optimization of the isochronism is a critical factor in producing beams of these relativistic ions, alternative schemes for phase measurement are being investigated based on chopping the beam and on injecting at a sub-harmonic of the RF frequency.

1 Introduction

The AGOR-cyclotron is equipped with thirteen phase probes, which are mounted along the axis of one of the hill sectors, thus allowing a direct and non-destructive measurement of the phase history of the beam [1]. The radial range covered by the probes is 234 mm to 885 mm, so that the isochronism can be optimized all the way to extraction. This is particularly important for high energy protons and ^{3}He ions, which make a relatively large number of turns at large radius, where detailed control of the field shape is difficult. The probes consist of a pair of 50 Ω stripline pick-ups of 20 mm wide and 50 mm long, mounted on opposite sides of the median plane.

2 Electronics and data-processing

The signals of the top and bottom probes are connected to the read-out electronics through two 14-channel multiplexers, mounted on the magnet yoke. The doubly shielded 50 Ω coaxial cables between the probes and the multiplexer have been phase matched to about 1°. In the design of the multiplexer care has been taken to minimize reflections and cross-talk by maintaining 50Ω characteristic impedance throughout and by terminating all inputs to the coaxial relays not used for connection to a given probe as well as all non-used probes in 50 Ω. Furthermore, the signal of each probe passes through the same number of relays and the electrical pathlength through the multiplexer is the same for all probes within 1°. The 14th channel of the multiplexer is terminated in 50 Ω; it is used to verify the pick-up of RF perturbations in the cabling and electronics (with the exception of the cabling between the multiplier and the probes).
From the multiplexer the signals from the top and bottom probes are transported to the measurement electronics above the cyclotron vault through doubly shielded coaxial cables that run along the same trajectory ,as far as feasible, to avoid phase shifts due to temperature differences between the two cables. The cables have been phase matched with a variable delay line to better than 1° after installation.
The signals from the top and bottom probes are first added in a passive combiner. As has been observed previously [2] the signals induced on the two probes by the RF resonators (fundamental frequency as well as possible harmonics) have 180° phase difference, while the signals induced by the beam are in phase. Consequently the signal from the RF resonators is to a large extent cancelled by adding the signal from the two probes. The combined signal is then fed through a tuned delayline filter. In the filter the signal is split in two branches; by adjusting the delay in one branch and the attenuation in the other branch the component at the RF frequency is suppressed by 100 dB (fig. 1).

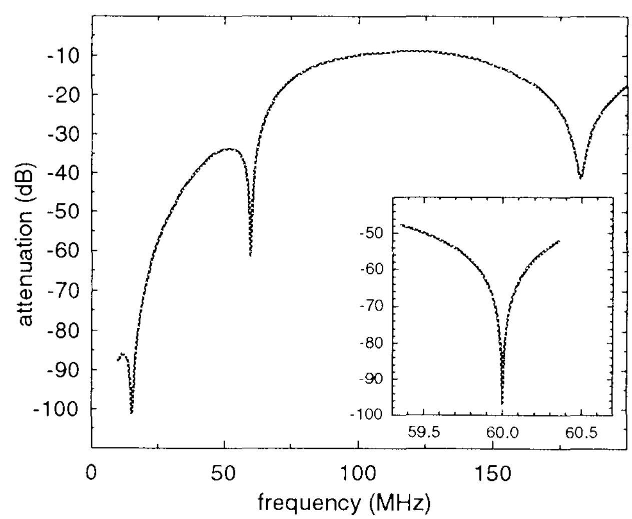

fig. 1 Attenuation of delayline filter as a function of frequency for an RF frequency of 60 MHz

The output signal of the filter is amplified by about 20 dB with a low noise, wide band amplifier and then fed into the 50 Ω input of an HP8508A vector voltmeter. The reference signal for the phase measurement is provided by the reference generator of the RF system. After frequency doubling it is passed through an adjustable low-pass filter. The vector voltmeter measures both the relative phase and amplitude of the signal from the phase probe with respect to the reference signal. It thus provides information not only on the phase of the beam but also on its intensity at the position of the probe.

The measurements show that also in absence of beam a 2nd harmonic component exists in the signal of the probes, despite the absence of a resonance in the resonator at this frequency. The amplitude of this component is of the same order of magnitude as that induced by the beam and it strongly grows with frequency (fig. 2). It has been observed that this signal has a phase with respect to the reference signal which varies only slightly with time. It is thus possible to extract the information on the 2nd harmonic component induced by the beam by vectorial subtraction of measurements with and without beam. The accuracy obtained in this way is about 1° for a 10 nA beam of 200 MeV α-particles, which is accelerated at an RF frequency of 34.1 MHz. At higher RF frequencies the accuracy decreases and around 60 MHz, the RF frequency for the acceleration of 190 MeV protons, it has become too low to use the phase measurements for optimization of the isochronism. This problem has prompted the search for alternate phase measurement schemes, as efforts to reduce the perturbation of the signal by the RF resonators have not yet been successful.

3 Optimization of isochronism

For the calculation of the corrections to the currents in the main and trim coils two methods have been used so far.

In the first method the thirteen phase measurements are converted into a phase profile at 100 radii by interpolation. With the equilibrium orbit code the differences in the currents in two main and fifteen trim coils between the theoretical setting yielding a flat phase profile and the setting giving the "measured" phase profile are calculated. These are then used as corrections on the actual current settings. Since the calculation requires the construction of a fieldmap by interpolation in the grid of measured fieldmaps it is rather time consuming.

For the second method the derivatives $\dfrac{d\,\sin(\varphi)_i}{d\,I_j}$ of the phase at probe i (i = 1..13) with respect to the current in coil j (j = 1..17) are used. These are a by-product of the calculation of the theoretical settings with the equilibrium orbit program for a given beam. The corrections to the coil currents are then found by fitting to the measured phases. As only thirteen phase measurements are available the user has to decide which coils are used in the fitting.

4 Alternative schemes

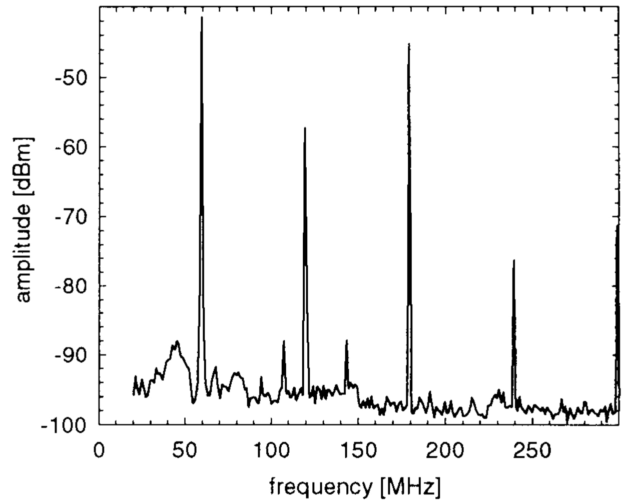

fig. 3 Spectrum on a phase probe without beam after delay line filter

As mentioned in the above the need for phase measurements is strongest for the most relativistic beams, while, the accuracy of the phase measurements is low because of strong 2nd harmonic interference from the RF system. In fact interference from the RF system is seen at all harmonics of the RF frequency (fig. 3). This observation was the trigger to investigate the possibilities to perform phase measurements at a frequency which is not an harmonic of the RF frequency. Two possibilities are being considered:

- The orbital frequency of the ions in combination with injection at a sub-harmonic of the RF frequency.
- A fixed low frequency together with chopping of the beam.

4.1 Orbital frequency with sub-harmonic injection

In general beam is injected into the cyclotron at the RF frequency. When operating a cyclotron in the Nth harmonic mode this implies that the particles at a given radius are localized at N azimuths. A stroboscopic view shows N "spokes" of beam, which rotate at the orbital frequency of the ions. By changing the injection frequency to the oribital frequency or some other specific fraction of the RF frequency one can arrange that only one "spoke" remains or at least that in one "spoke" the intensity is considerably higher than in the others. As a result the signal induced by the beam on the phase probes will contain a component at the orbital frequency and its harmonics. The signal-to-noise ratio for this component is expected to be very large, because the interference from the RF system does not contain this component. The scheme for a phase measurement at the orbital frequency is the same as that for the measurement at the 2nd harmonic.

4.2 Low frequency with chopping

By chopping the injected beam at a low frequency (225 Hz in our case) sidebands are created around each harmonic of the RF frequency in the Fourier spectrum of the signal induced by the beam. These sidebands do not suffer from interference from the RF system and consequently have a very large signal-to-noise ratio (fig. 4), thus allowing a precise measurement of the beam phase at this frequency. The spectra show that even at this relatively low RF frequency the interference from the RF system has the same amplitude as the signal from the beam for a beam intensity of 30 nA.

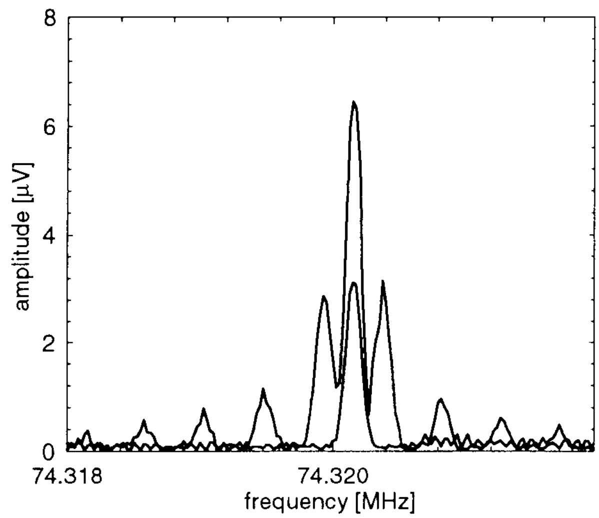

fig. 4 Spectrum on a phase probe around the 2nd harmonic with and without beam; the beam is chopped at 225 Hz

In fig. 5 the scheme of the measurement setup behind the delay line filter is shown. By mixing the amplified output signal of the filter with two signals at the 2nd harmonic of the RF frequency, which are shifted in phase by 90°, two low frequency signals are produced, which are proportional to sin(φ) and cos(φ), where φ is the phase of the 2nd harmonic in the signal from the beam with respect to the reference signal. These signals are detected with lock-in amplifiers synchronized with the chopper signal.

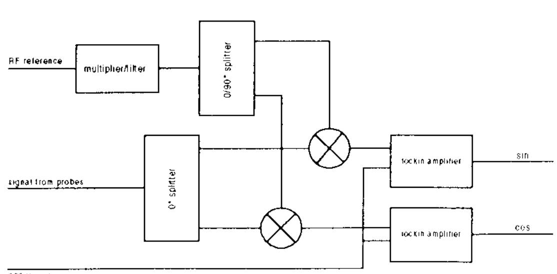

fig. 5 Setup for phase measurement at 225 Hz

Measurements with this method, using signals from a synthesizer set at the same amplitude as those from the beam, are shown in fig. 6. The ordinate in the figure represents the phase shift applied to the reference signal while keeping the "beam signal" constant. The curves represent a fit with sine and cosine with a common amplitude and offset.

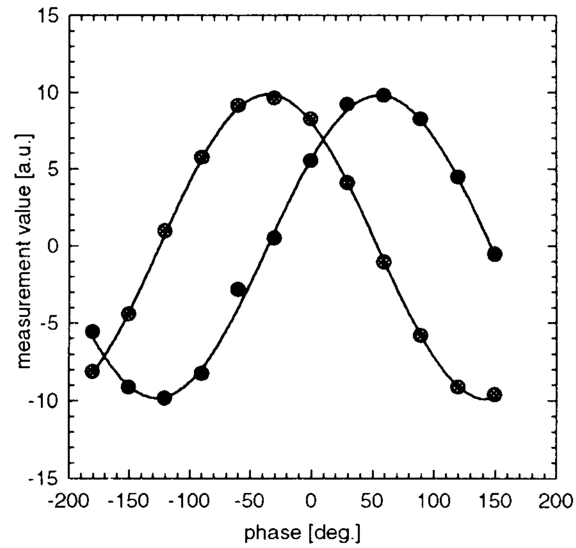

fig. 6 Measurement of sin(φ) and cos(φ) with the setup of fig. 5 with a common fit to both measurements

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References

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