BEAM PHASE MEASUREMENT IN THE AGOR CYCLOTRON

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Abstract

Beam phase measurement to optimize the isochronism is an essential part of the diagnostics in multi-particle, variable energy cyclotrons. In the AGOR cyclotron an array of 13 non-intercepting beam phase pick-ups is installed. To reduce the large disturbances from the RF system the measurements are traditionally performed at the 2nd harmonic of the RF frequency. To further improve the sensitivity intensity modulation of the beam has been introduced. Measurements with the different methods are presented, demonstrating that the intensity modulation strongly improves the sensitivity of the measurement. Useful beam phase measurements can now be made for beam intensities down to 10 nA.

The AGOR facility

The AGOR cyclotron has been designed to accelerate all elements, explicitly including protons. The maximum energy per nucleon for ions is $600(Q/A)^2$ MeV, while protons can be accelerated to a maximum energy of 200 MeV. The magnetic field is produced by two sets of superconducting coils and can vary from 1.7 to 4 T. Fifteen sets of correction windings are mounted on the

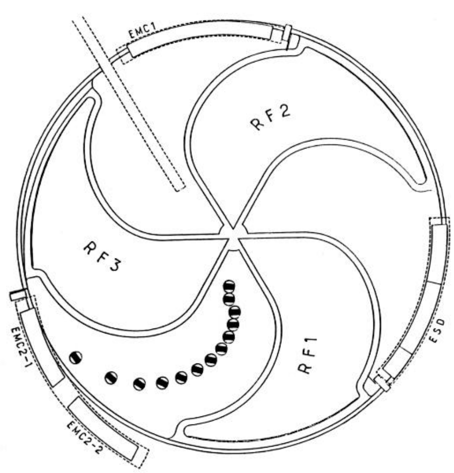

Figure 1. Cross-section through the median plane

three-fold symmetric iron hill sectors, which are located between the three RF cavities as shown in figure 1. These cavities provide the accelerating voltage for the beam and operate in the frequency range of 24 to 64 MHz, at harmonic mode 2, 3 or 4.

Extraction of the beam from the cyclotron is accomplished by successively an electrostatic channel, a room temperature electromagnetic channel, a super-conducting electromagnetic channel and finally a superconducting quadrupole doublet.

Motivation for beam phase measurements

Cyclotrons operate without longitudinal phase stability, and therefore there is no automatic feedback from the RF system on the beam, like in synchrotrons. The magnetic field and thus the beam phase is affected by different mechanisms:

- Accuracy of calculated setttings for different beams. For most beams the magnetic field values have to be obtained from interpolation in field maps. These are available at 20 points in the operating diagram for the main coils. This leads to inaccuracies of the reference for the magnetic field of 3-5 10^{-4}.
- There are tight tolerances on the isochronism of the magnetic field. For protons (h = 2) a maximum field error of $\Delta B/B \sim 1.5\ 10^{-4}$ results in a phase slip of 90^o , when acceleration stops.
- The reproducibility of the magnetic field is adversely affected by long term variations of the temperature of the magnet iron, causing changes of the saturation magnetization of 0.2 mT/K [1].
- Accumulation of phase slip can also increase vertical beam blow-up in regions with weak vertical focusing because of the increased time spent in the region.
- The precessional extraction process is very sensitive for amplitude and phase of field perturbations. This sensitivity is strongly enhanced by large phase errors. As in the non-isochronous fringe field the phase slip rapidly builds up even with optimal tuning, reproducibility of the extraction strongly depends on control of the isochronism.

Inaccuracies in the magnetic field thus directly influence the acceleration and extraction process. Therefore precise and reproducible tuning of the magnetic field is essential. Measurement of the beam phase is the tool to achieve this. The ultimate goal for such a phase measurement system is a push-button operation with only minor impact on routine operation.

Experimental hardware

In the AGOR cyclotron an array of 13 non-destructive beam phase pick-ups has been installed, see figure 1 for their location. Each probe consists of two electrodes placed symmetrically with respect to the median plane. The probes are connected to multiplexers mounted on the top and bottom of the cyclotron yoke as close as possible to the probes, while maintaining serviceability. The outputs of the multiplexers are connected to the input of the phase measurement system, outside the cyclotron vault, by means of double-shielded coaxial cables. These cables are carefully matched in length to keep phase errors to a minimum. See figure 2 for a schematic of the system. Besides beam induced signal there is also signal induced by the RF cavities. Due to the coupling of the magnetic and electric fields the signals from the RF system on the two electrodes of a probe are 180 degrees out of phase, while the beam signals of both electrodes are in phase. For this reason one of the first components in the phase measurement system is a power combiner, which reduces the RF components and its harmonics, while the beam induced signals are added. An attenuation of at least 20 dB on the fundamental RF frequency is obtained in this way. A further reduction of the first harmonic perturbation is still necessary in order to avoid saturation in the next components. Additional attenuation of about 30 dB is obtained with coaxial stub filters. The final stage is a wideband amplifier to better match the signal to the dynamic range of the network analyzer.

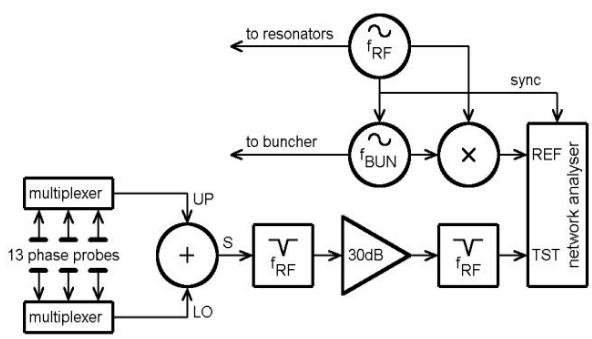

Figure 2. Schematic of phase measurement system

Signal processing and experimental results

In this section the different methods, which have been used to measure the beam phase, are described. In all cases the resolution bandwidth of the network analyzer is set to 300 Hz and the maximum acquisition memory (400 measurements) of the instrument is used to improve the signal-to-noise ratio further. Under these conditions a measurement takes about 15 seconds per probe, which is considered acceptable for the planned routine measurements.

Second harmonic measurement

Traditionally phase measurements are performed on the second harmonic of the RF frequency [2,3,4]. This is because the ratio of beam induced over RF induced voltages is more favourable. Because at the second harmonic still unambiguous phase can be obtained [2], measurements at even higher harmonics have not been attempted. The measurements show that in the absence of beam, there still exists a second harmonic component on the signals of the probes. This signal grows strongly with increasing frequency and limits the operational frequency range of this method[4]. The nature of this growth is not understood. Because of this perturbing signal the measurements, if at all possible, have to be done with and without beam and the beam phase is extracted by vectorial subtraction. Figure 3 shows the result of such a measurement. The reference signal for the network analyzer is obtained from a frequency doubler. The data are corrected for the different azimuthal positions of the inner two probes. The cyclotron was tuned for an 8 MeV/A C^{2+} ion beam and there was significant intensity loss during the acceleration cycle because of charge exchange between the beam and the residual gas. Nevertheless, at the low RF frequency used for this beam, clean results are obtained even at outer radii where the intensity was approximately 10 nA.

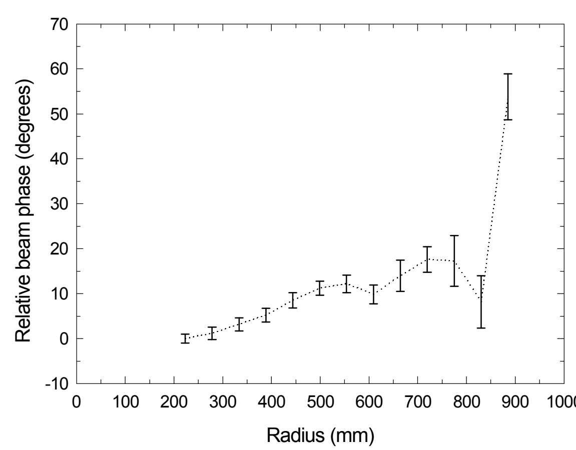

Figure 3. Phase measurement at the second harmonic of the RF frequency

Intensity modulation of the beam

By modulating the beam with a frequency slightly different from the RF frequency, beam phase information will appear in the Fourier spectra at multiples of that modulation frequency. Figure 4 shows frequency spectra obtained this way. The figure shows very strong beam induced spectral lines at multiples of the modulation frequency.

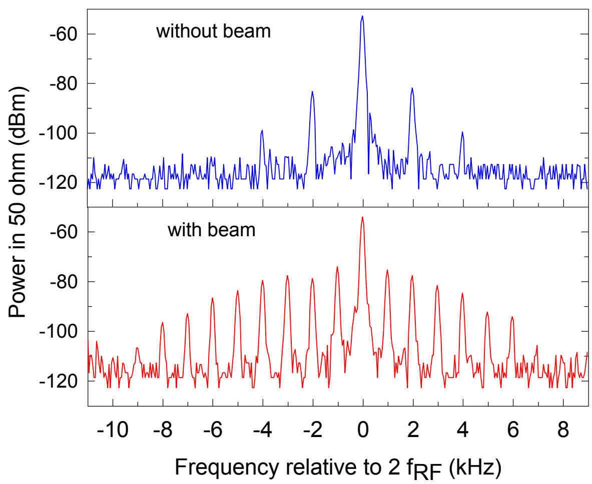

Figure 4. Probe signals with and without beam

Figure 5 shows results of measurements for two different modulation frequencies. The measured phase profiles show an additional phase slip proportional to the modulation frequency. The actual phase profile can be calculated from a set of measurements at two modulation frequencies. This result is also shown in figure 5. It shows that at the modulation frequency of 1 kHz the differences between measured and calculated profiles are rather small. The figure suggests to use even lower modulation frequencies. The resolution bandwidth of the network analyser and the measurement time limit the minimum value for the modulation frequency to about 1 kHz. By modulating the intensity with the buncher at the orbital frequency, the phase slip of the modulation changes in multiples of 2π. In this way direct phase measurements are possible. This method requires exact phase locking of the signal generators for the RF and the buncher. The frequency range of the buncher limits the applicability of this method.

Discussion

We have demonstrated that with low frequency modulation of the beam and the appropriate signal processing phase measurements over the whole frequency range of the RF system can be obtained. The method is also sensitive enough that it can be used for beam intensities down to 10 nA. The use of a network analyzer as central part of the signal processing electronics has proven to be very advantageous for the low intensity beams.

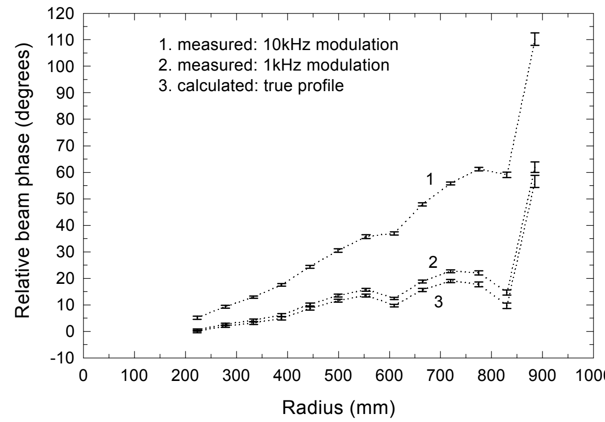

Figure 5. Phase measurements by low-frequency modulation

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The status of the beam phase measurement system is that we have to implement automatic and remote control of the different components. Further we have to feedback the results of phase measurements for calculating optimal correction coil settings.

Acknowledgements

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